Grant Agreement No: 731086

AMICI

Accelerator and Magnet Infrastructure for Cooperation and Innovation

Horizon 2020 / Coordination and Support Action (CSA)

DELIVERABLE REPORT

REPORT ON KEY TECHNOLOGICAL AREAS SURVEY AND PROSPECTIVE OUTLOOK

REPORT ON THE TECHNOLOGICAL ROADMAPS FOR THE DIFFERENT KTA

DELIVERABLES: D2.1 AND D2.2

Document identifier:	AMICI-D2.1-D2.2
Due date of deliverable:	31/03/2019
Report release date:	27/10/2019
Work package:	WP2 Strategy
Lead beneficiaries:	IN2P3-CEA
Document status:	Final

Delivery Slip

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1. INTRODUCTION

The report aims to provide a strategic view on the science and technology roadmaps for the future accelerator and SC magnet based Research Infrastructures (RIs) in Europe and worldwide. For this purpose, we collected the scientific agendas and timelines of the upcoming projects and categorized by their application fields. Thereafter, we analysed the future machine targeted performances and expressed in term of technical requirements. Knowing the current technical development effort made by accelerator and SC magnet communities, we identified a set of Key Technological Areas (KTAs) in which critical performance progresses, allowing meeting the future projects challenging needs, are anticipated or expected. We provide short descriptions of the different KTAs selected and their main promising development axes in the following, with more detailed descriptions provided in the report annex. The Annex also includes a short strategy note about the enabling laser technology.

Within the AMICI Technological Facility partners, we identified the Technological Infrastructures (TIs) where cutting-edge technical developments are/could be pursued, aiming at performance breakthrough, cost saving or reliability improvement on a given KTA. This allows defining the technological roadmap for the different KTAs, showing thereby the opportunities and needs that could orient and sustain the activity of the TI, in some case with a small upgrade investment.

2. GLOBAL LANDSCAPE OF FUTURE ACCELERATOR AND HIGH FIELD MAGNET PROJECTS

Research Infrastructures based on Accelerators and large Superconducting Magnets are enabling scientific instruments to advance and push the limits of pure human knowledge and of societal welfare. Motivated by the successful operation of the existing Research Infrastructures and building on engineering progress, more powerful facilities are currently under study.

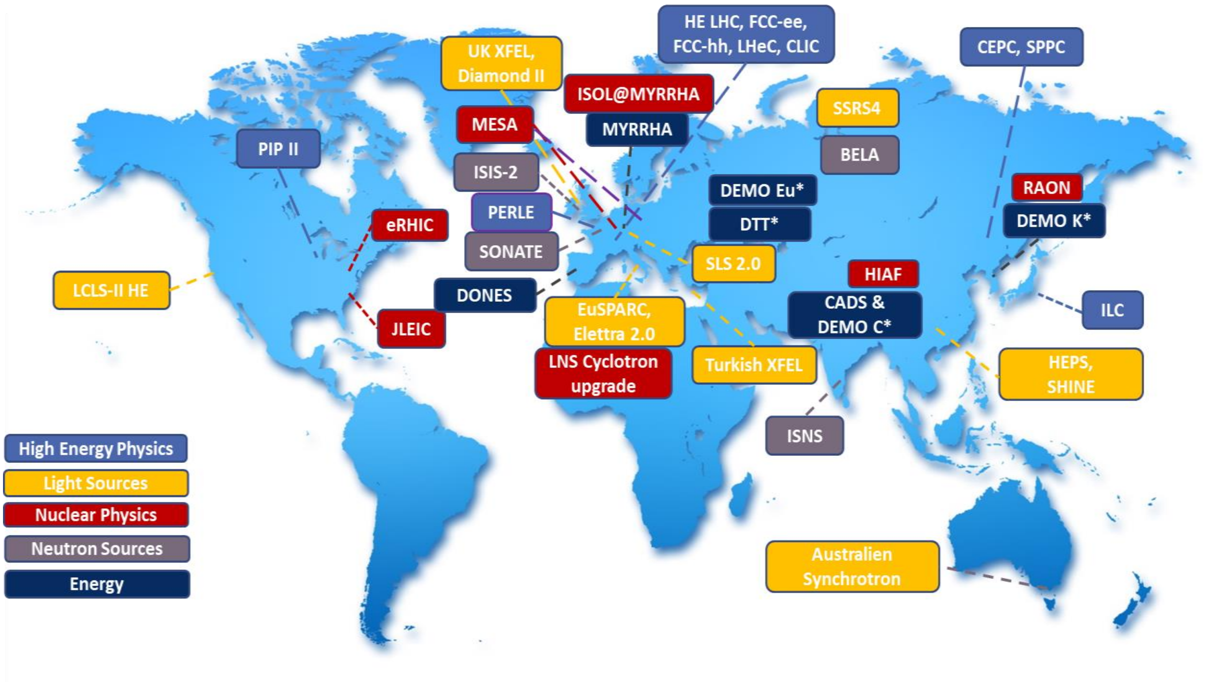

Figure 1: Global landscape of future accelerator projects

The map, shown in Fig.1, illustrates the rich Global Landscape of the proposed future Research Infrastructures worldwide serving a wide range of applications from science to technology, spanning fundamental, applied and technological research.

Among the application fields presented in the global landscape above, high-energy physics and nuclear physics are usually the main driving trends of accelerator research and developments. For most of the related machines, the main pursued objectives are:

- Energy increase,
- Intensity and/or luminosity increase
- Higher efficiency
- Higher reliability
- All of these previous objectives coupled with cost reduction (either capital or operation cost).

Thus, all the challenges in accelerator science and technology derive from all these objectives and usually, upstream R&D has to be conducted between 10-30 years before machine construction. These preparation phases are important ones in the project timelines: they are crucial to meet the requirements of novel accelerators or to develop new materials/processes to accelerate particles.

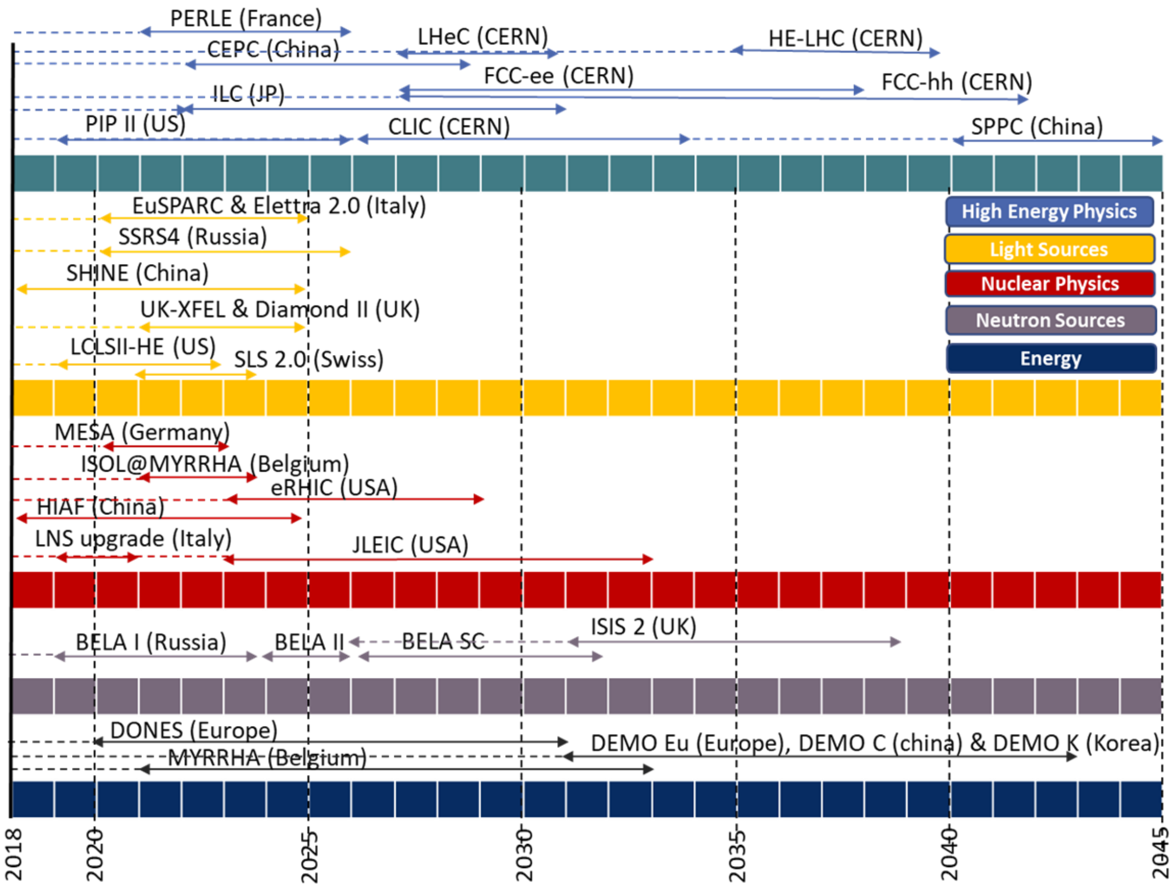

Figure 2: Future accelerators project timelines

The timelines, shown in Fig.2, of the proposed future Research Infrastructures highlights the planning strategy distinction between:

a) multi-billion Euro international projects like the large high-energy colliders and the nuclear fusion demonstrators: at such high costs, these projects are planned over several decades by collaborations representing one science community, and must undergo a down-selection until at most one facility is built to serve a common research goal.

b) Billion-range regional projects like the synchrotron or FEL light sources, generally planned by one country over a decade: these projects serve several science-user communities organized in small collaborations running experiments in parallel and during a limited time. Competition between the facilities built at several places worldwide leads to innovation and improved modes of operation, and thus to increasing steadily the scientific reach of these facilities.

Radio-medecine uses particles like photons (X-rays and gamma-rays), electrons, protons, neutrons, various atomic nuclei to penetrate living tissue, for non-invasive imaging of internal organs, or at higher energies selectively destroy malignant tissue.

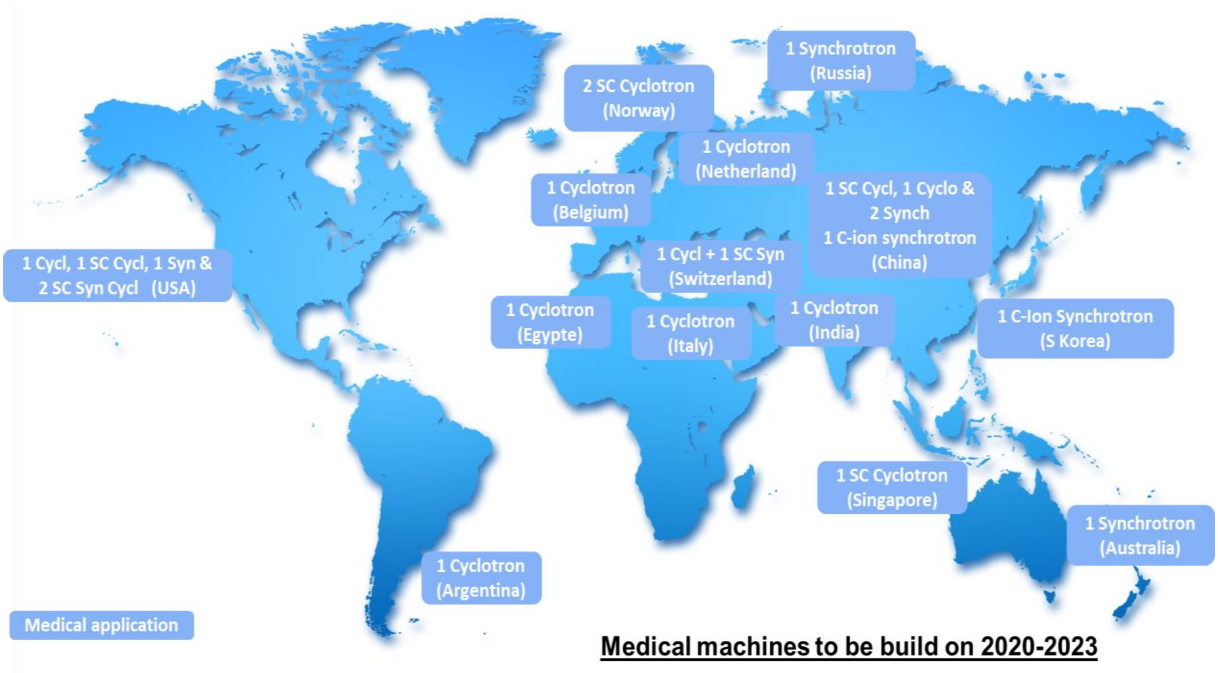

Figure 3: Global landscape of proposed future medical accelerators for proton therapy

This map illustrates the worldwide landscape of proton-therapy medical accelerators, based on state-of-the-art cyclotrons or synchrotrons whose construction is scheduled in 2020-2023, mostly at oncology centres.

Besides radio-medicine, health applications of superconducting magnets encompass mainly the magnetic resonance imaging (MRI) scanners when coupled to radio-frequency antennas, and compact gantry systems around hadron-therapy facilities. Health application of accelerators encompasses also the production of radio-nuclides used for disease diagnostics and treatment.

3. THE SELECTION OF KEY TECHNOLOGICAL AREAS (KTA)

By scrutinizing the landscape of the future accelerator projects presented in Figure 1 of the previous section, one can classify the machines according to the following criteria:

- Accelerated particles: leptons vs. hadrons accelerators
- Operation mode : pulsed vs. Continuous Wave (CW)
- Accelerating section: normal conducting vs. superconducting technology
- Accelerator geometry: linear vs. circular
- Size: small vs. large machine
- The wide range of beam parameters: current, luminosity, power…

Obviously, each criteria or combination of criteria within the classification above appeal specific technology areas. Depending on the performances targeted by the future Research Infrastructures, real technological breakthroughs might be needed to push the limits of the state of the art and meet the challenging requirements. Technological development in some areas could also be carried out to enhance reliability of the future machines, or to increase their energetic efficiency, lowering the machine costs for construction and operation.

We define as Key Technological Area (KTA), the one responding to one or several criteria from the following:

- Cutting-edge technology of high interest for accelerator or SC magnet communities.
- Being widely needed for the future projects
- Presenting a high technical development potential to meet the future machine requirements
- Presenting a high technical development potential to reduce construction and operation costs
- Being critically dependent on single/very few vendor(s)

According to these choice criteria, eight KTAs were identified and their required development fields determined and summarised in the following table.

Table 1: identified Key technological Areas and needed developments for future projects

	Key Technology Areas	Needed Developments
1	Particle sources	High intensity heavy ions, positron sources, polarized beams
2	Magnets and vacuum systems	Permanent magnets, Small chambers evacuation
3	High field SC magnets	High-Tc conductors, Cost reduction
4	Normal Conducting RF structures	High precision fabrication and tuning, RF breakdown
5	Superconducting RF cavities	Surface treatments, Robotics, Cost reduction
6	Radio Frequency power sources	CW sources, Solid State Amplifiers, High efficiency
7	Cryogenics	High efficiency, Cryo-coolers, Cryo-safety
8	Beam instrumentation	Optical and RF diagnostics, Fast electronics and feedback

Table 2 shows the need on KTAs further development for the major Research Infrastructures of the global landscape, taking into account the KTA choice criteria:

Tableau 2: Key technological Area (KTA) being developed for future major Research Infrastructures

	Particle sources	Magnet and Vacuum systems	High Field SC magnets	Normal Conducting RF structures	Superconducting RF cavities	RF power sources	Cryogenics	Instrumentation
ILC	•				•	•	•	•
FCC	•	•	•		•		•	•
PIP-II, MYRRHA					•	•	•	•
JLEIC	•		•	•		•		•
eRHIC, LHeC					•		•	•
DIAMOND2, SLS2		•				•		•
LCLS2-HE, SHINE		•			•		•	•
DONES	•	•		•	•	•	•	•
DEMOs	•		•			•	•	
PERLE					•	•		•
BELA, compact neutron sources	•			•				•

4. KTA SHORT DESCRIPTIONS

4.1. PARTICLE SOURCES

4.1.1. Description

Ion sources determine the research potential of the accelerator or post-accelerator facilities. The essential parameters are the ion species and the ion current intensity. Proton accelerators (e.g. LHC, SNS, ESS, etc…) are using high intensity H+ or H- ion sources, while nuclear physics is based on the widest range of stable ions from Helium to heavy stable ions (e.g. Lead or Uranium). Radioactive ions beams are using secondary sources including a target. Fusion reactor are using MeV-energy intense ions sources (e.g. D-) for neutral injection in the plasma as a heating mechanism. For spatial (e.g. ion thruster) and industry (e.g. ion beam lithography) application, compactness and reliability are crucial properties of the ion sources. There is also a strong interest in material science for ion traps producing highly charge ions at rest.

Pushing the intensity of positrons sources is mandatory for linear colliders, together with polarization, and for very low energy positron beams used in anti-matter research and material science.

4.1.2. Advances: High intensity heavy ions, positron sources, polarized beams

- Electron Cyclotron Resonance (ECR) ion source breakthroughs in intensity can be expected by increasing the microwave RF frequency (up to 45 GHz) and using superconducting coils (up to 11 T with Nb3Sn or HTSC) to match the resonance condition. On the other hand, the standard ECR sources (0.8 T, 2.45 GHz) can increase their power efficiency, ease of operation and compactness by using permanent magnets for spatial and industry applications.
- Electron Beam ion sources (EBIS) are more efficient for highly charge heavy ion sources. A large range of studies is in progress to improve their reliability and ease of operation.

- The creation of electron-positron pairs in matter is the basic mechanism for the positron sources; hence, thermal effects on the solid target limit the beam intensity. New schemes are proposed using intense photon radiation from laser collision or undulators, preferably superconducting, or atomic crystals, followed by photon conversion on thin targets. Some schemes are amenable to producing polarized positron beams, others to producing muon pairs.

4.2. MAGNETS AND VACUUM SYSTEMS

4.2.1. Description

Warm magnet technology is indeed basic for guiding particle beams along accelerators, with a widespread group of laboratories and industries capable of producing and testing conventional magnets in large series. However, new promising beam transport techniques have recently been discovered or implemented successfully (e.g. ultimate-brilliance synchrotron-radiation storage rings (DLSR), fixed-field alternating gradient accelerators (FFAG), beam channels for plasma acceleration) that extend the design and manufacturability needs for warm magnets, be they resistive magnets or permanent magnets, beyond their current state of the art. In many cases, small gap vacuum chambers with high pumping speed and low desorption are required to implement these techniques.

4.2.2. Advances: Special Function Magnets, Permanent Magnets, Small Vacuum Chambers

- Manufacturing of combined function magnets with complex magnetic polar pieces
- Permanent magnets introducing high permeability material like Neodymium or Praseodymium
- Coating of small aperture vacuum chambers using the Non-Evaporable-Getter (NEG) technology
- Surface treatment of vacuum chamber to reduce secondary electron emission yield.

4.3. HIGH FIELD SUPERCONDUCTING MAGNETS

4.3.1. Description

Large and powerful high-field superconducting magnets are used routinely in science, research and technological development (RTD) and in medical diagnostics, using Magnetic Resonance Imaging (MRI), and the latter representing the biggest current market for superconductivity. In addition, superconductors bring potentially large energy savings in electric power applications, with demonstrations of power cables, transformers, motors or current limiters already have been made.

There is a strong drive on new superconductor developments to increase the power of hadron colliders and MRI for scientific research, and for tokamaks for the next demonstrators by raising the magnetic field strength in large volumes using new innovative superconducting materials, such as Nb3Sn or High Temperature Superconductors (HTS), and developing cable and coil innovative cooling technologies.

4.3.2. Advances: Nb3Sn and High-Tc conductors, Cryo-cooling, Cost reduction

- Development and use of ultimate performance Nb3Sn conductors, the most mature option so far, to overcome cost and coil fabrication issues.
- Development and use of HTS conductors still needing R&D on material science to electromechanical engineering.
- Innovative conductor and cold mass cooling methods to increase the operating temperature margin.
- Reinforcement of the conductor mechanical strength to take on much higher internal magnetic forces.

4.4. NORMAL CONDUCTING RF STRUCTURES

4.4.1. Description

Radio Frequency acceleration technology (normal conducting) was introduced 90 years ago (e.g. drift tube linacs) and is still the standard reference for acceleration, used in the majority of particle accelerators worldwide. There are irreplaceable in the front-end injection systems of proton and ion linear accelerators (e.g, Radio-Frequency-Quadrupole). Normal-conducting RF cavities are characterised by a large variety of designs (single cell, multi-cell, TE-mode, TM-mode, RFQ, etc.), operating frequencies (from the kHz to the multi-GHz range), operating modes (CW or pulsed, tunable or fixed frequency, coupled or stand-alone, etc.), and of construction technologies (Cu-plated or full copper, bolted, welded or brazed). The availability of simple designs using conventional fabrication techniques makes normal-conducting RF accessible to small universities and laboratories without the need for specialised infrastructure. Conversely, sophisticated designs reaching challenging parameters and/or large-scale productions require specific technological infrastructure for the manufacturing and for the processing of the cavities.

4.4.2. Advances: High precision fabrication and tuning, RF breakdown

- The main ongoing developments for accelerating RF cavities are related to increasing the accelerating gradient to reduce the length the accelerator, and to increasing the power efficiency. This latter challenge leads to increasing the operating frequency reducing at the same time the cavity dimensions, thus imposing additional challenges on the manufacturing in terms of precision machining and surface quality.
- Given the pressing need of proton or ion high intensity injectors, the fabrication of RFQs in industry requires sophisticated machining, thermal treatment and firing of ultra-pure copper, with commonalities with the fabrication of high power RF input couplers and CW RF guns. Consolidating these techniques over time and regions would benefit to the lead time and cost of their fabrication

4.5. SUPERCONDUCTING RF CAVITIES AND CRYOMODULES

4.5.1. Description

The past two decades have seen the advent of superconducting RF cavities in most of the accelerators recently built or under construction, resulting from the dramatic breakthroughs in the accelerating field (from 5 MV/m to 30 MV/m) and cryogenic consumption at roughly constant fabrication cost and unsurpassed operation efficiency. After LEP200 operational success, the usage of niobium based SRF technology became widespread and almost unavoidable for circular and linear accelerator projects using electron, proton and heavy ion beams in pulsed or CW mode or operation. It also opened up new operation modes included beam recirculation and beam energy recovery, and new applications like SRF electron guns and transverse deflection. Furthermore, some advances are still the result of recent R&D demonstrating that higher performances are to be expected in the medium term future.

4.5.2. Advances: Surface treatments, New Materials, Particle-free Assembly and Robotics, Cost reduction

- High Q_0 / high gradient SRF structures, requesting special furnaces, and other demanding infrastructure
- Surface preparation of SRF cavities requesting innovative sophisticated surface modification methods like electro-polishing, nitrogen doping or infusion
- New fabrication techniques using large grain bulk niobium or coated cavities with higher Tc material
- SRF electron sources of high demand for future high repetition rate FEL operation
- Optimized cryostat design for particle-free assembly and robotics, and cost reduction.

4.6. RADIO-FREQUENCY POWER SOURCES

4.6.1. Description

The electrical power consumption of future accelerators will be driven to a large part by their RF systems. A significant part of the initial investment and running cost of the large scale machines will be determined by the purchasing cost and the efficiency of their RF sources. Increasing the efficiency of existing RF systems to higher levels means several millions euros saved per year on the electricity bill. The upcoming large scale accelerators are expected to require RF power in the range of 10 to 100 MW (for comparison, the Large Hadron Collider (LHC) has a total RF drive of 5 MW). This is particularly true for electrons colliders, circular (e.g. FCC-ee or CEPC) or linear (e.g. ILC or CLIC), High power hadron Linacs (e.g. PIP2) and Accelerator Driven Systems (e.g. MYRRHA).

4.6.2. Advances: High Efficiency for Klystrons and Modulators, Solid State Amplifiers

- Modulators**:** today's modulator are already operating with very high efficiency (85-92%) almost independent of their output power (kW-MW), Voltage (1-100kV), and pulse length. For short pulses (<500 μs), the modulator rise time becomes an important factor in the system efficiency and this is where further developments, such as the Stacked Multi-Level (SML) design, are expected to make a significant difference.
- Klystrons: Current State of the art Klystrons can deliver a maximum efficiency of approximatively 65%. The limiting factor is the electron bunch profile as it approaches the output cavity of klystrons, as well as the velocity of the lowest electron leaving the output gap. With the advance of modern beam dynamics tools, number of novel electron bunching mechanisms such as the Core Oscillation Method (COM), the Bunching, Alignment and Collecting (BAC) method and the Core Stabilisation Method (CSM), have shown an improve on the efficiency through numerical investigations.
- Solid State Amplifiers (SSA): SSAs promise cost efficient RF power generation and the advantages of modular systems. This imply an effective combination of the single units (of 1 kW) to reach high power values (> 100 kW). A promising solution is to use combiner cavities that combine all the output of single units in one stage. The difficulty still to match hundreds of input antennas and minimise the reflected power due to manufacturing tolerances of the electronics or to failed units.

4.7. CRYOGENICS

4.7.1. Description

Cryogenics is a base technology for the numerous worldwide research facilities that utilize large superconducting (SC) magnets or SC particle accelerators, be it with superconductive radio-frequency cavities or high-field magnets. The rarity and potential shortage of helium gas, as the most used cooling liquid for the large facilities, call for critical advances in reducing the overall helium and raising efficiency, as well as alternative cryo-cooling technologies.

Industry, especially European firms, and research laboratories are leading these developments. European PED certification is not fully adapted to the peculiar risk and technical solutions of the Helium cryostats used in accelerators.

4.7.2. Advances: High efficiency, Cryo-coolers, Cryo-safety

- Higher efficiency cryo-plants through improved performance sub-system components such as heat exchangers, turbines, instrumentation and process control optimisation,
- Cryo-coolers adopting development technologies employed from space industry applications and possibly new cryogenic fluid mixtures,

- Safety specifically for accelerator equipment, by developing dynamic models for improving mitigation of cryogenic incidents and new European standards to certify cryostat design and fabrication.

4.8. BEAM INSTRUMENTATION

4.8.1. Introduction

Beam instrumentation is the accelerator artificial intelligence: it keeps particle beams running under control and brings it to its required performance level. As an analogy, beams stored during one day on powerful circular accelerators travel the same distance as the orbit of Pluto (about 30 billion kilometers), while keeping their sub-millimeter orbit and size characteristics. Beam instrumentation includes:

- beam diagnostics, i.e. instruments that sense the electro/optical signals of charged particles and monitor their evolution;
- front-end systems, i.e. ultra-fast electronics systems that process these signals and dynamically generate corrective actions;
- control systems, i.e. specialized software suites that command and regulate the operation of the many technical individual constituents and systems cooperating collectively to stabilize the accelerator operation, from the beam source to beam delivery.

4.8.2. Advances: Optical and RF diagnostics, Digital and Fast electronics, Feedback Algorithms

- Non-invasive diagnostics based on RF or optical signals, particularly for high intensity beams.
- Longitudinal diagnostics for ultra-short bunches based in RF structures, electro-optics or Terahertz detectors.
- Digital conversion of electric or light signals with high resolution and large bandwidth.
- Ultra-fast electronics based on parallel developments in computer industry and high-speed communications
- Innovative feedback algorithms in control systems, e.g. software development to handle normal operation and fault detection, hardware for personnel and machine protection, machine learning methods capable of detecting patterns in data and using them to achieve desired automation tasks.

5. TECHNOLOGICAL ROADMAPS FOR THE DIFFERENT KTA

5.1. ROLE OF AMICI TECHNOLOGICAL FACILITIES IN KTAS DEVELOPMENT

Once the KTAs defined and their promising technological development axis briefly described, we summarise in Table 3 the matching of KTAs development effort with the Technological Facilities (TFs) that constitute the current AMICI Technology Infrastructure. For the checked entries, scientists at TFs recognize pursuing cutting-edge technical developments aimed at breakthroughs in performance, cost or reliability of the given KTA.

Table 3: The Role of AMICI Technological Facilities for the Development of Key Technology Areas

	Particle sources	Magnet and Vacuum systems	High Field SC magnets	Normal Conducting RF structures	Superconducting RF cavities	RF power sources	Cryogenics	Instrumentation
CEA	•		•	•	•		•	
CERN		•	•	•	•		•	•
DESY		•		•	•	•	•	•
INFN	•		•	•	•			
IFJ-PAN		•	•				•	•
CNRS	•	•		•	•			•
STFC		•		•	•		•	•
UU				•		•		
PSI	•	•	•	•		•		•
KIT		•	•			•	•	•

The table shows that KTAs development is well balanced between AMICI TIs. This is a good indicator of possible synergies between AMICI TFs in order to share experiences and knowledge. It is also the opportunity to perform complementary tests improving thus the development efficiency.

A refined analysis at the level of the individual technical platforms, taking into account the development axis pursued for each KTA, would help to judge if there is redundancy between TIs, or in the contrary, define new needs on TI to cover a KTA development axe sub-explored.

5.2. EXAMPLES OF UPGRADE NEEDS FOR AMICI TECHNOLOGICAL INFRASTRUCTURES

KTA - Cryogenics:

- CEA wishes to upgrade the existing cryoplants to higher capacity (250 l/h cold box with a 35 K helium distribution) to ease parallel operation on SC cavities for different projects and to adapt to mass production, and to simultaneously to continue SC magnet test program (e.g. FCC) with much higher electrical efficiency.

KTA - Superconducting RF cavities:

- STFC wishes to upgrade the SRF equipment by a horizontal cryostat allowing integrated cavity, coupler and tuner tests of production cavities. Such an upgrade would significantly enhance SRF testing validation capability prior to cryomodule integration.
- INFN wishes to upgrade of the SC cavities test facility at LNL, especially He and N distribution system, before operating them reliably with laboratories or industries.

KTA - Normal Conducting RF structures:

INFN wished to create or promote new copper coating facilities for large RF structures because of the very small number of facilities in Europe with the appropriate skills and equipment.

KTA- Magnets and vacuum systems:

STFC wishes to upgrade of the material deposition facilities:

- to allow long structures treatment (NEG deposition) to enhance pumping capability in long insertion devices with ultra-narrow apertures.
- to be able to treat large and complex SRF cavity geometries with high Tc and/or multi-layer thin films, in order to demonstrate high performance capability, following smaller scale validation

KTA- Radio Frequency power sources:

- FREIA wishes to develop a new solid-state power station (400 kW peak power at 352 MHz) in order to maximise the efficiency while delivering variable power levels to the superconductive cavities.

6. CONCLUSIONS

The evolution of Global Landscape needs continuous effort from the AMICI project.

The current descriptions of KTAs and their needed/promising advances are provided in 1-2 page per KTA (*Cf.* ANNEX). This also requires continuous revision to follow the main achievements and determine the new development needs.

The AMICI Technology Infrastructure is, to first order, well equipped and staffed to host the KTAs further developments. Nevertheless, some upgrades are still needed for some TIs to:

- Increase the testing capacity to adapt to mass production during RIs construction.
- To enhance the reliability of the TIs before addressing new projects with mass production or open the access to external users (academics or industries).
- To adapt to the need of future projects (higher testing power, higher cooling needs, bigger structures, different frequencies…)
- To acquire/develop a technology critically mastered by very few companies in order to prepare the knowledge transfer to industries when needed (future RIs construction).

The analysis of the AMICI TI role in KTAs development should be refined at the level of the individual technical platforms, taking into account the development axis pursued for each KTA, to judge the complementarity or redundancy between AMICI Technological Facilities. This detailed analysis is also necessary to define new needs to cover new KTA development field. Platform availability and needed upgrades have also to be taken into account.

At a later stage, a dialog with our industrial partners should establish their need and prospects, on a case-by-case basis.

7. ANNEX: LASER TECHNOLOGY

Lasers are indeed an enabling technology for the future of accelerators, in particular in their application to electron photo-injectors, beam diagnostics (laser wire & interferometer, electro-optical sampling), compact light sources (via inverse Compton scattering) and, of course, laser-plasma acceleration to bring accelerating fields higher than 1 GV/m.

However, we did not retain Lasers as a Key Technology Area for several reasons, some revisable with time:

- for all applications other than laser-plasma acceleration, lasers are mostly developed in industry and purchased 'on the shelf'.
- laser-plasma acceleration is based on high power lasers with the outstanding challenge to reach high repetition rate and efficiency, similar to RF accelerators. With the strong Laser communities involved both in industry and academia, developments are very fast (e.g. fiber lasers, Tm:YLF lasers) resulting in a rapidly changing landscape.
- the global landscape of future accelerators does not yet include projects based on laser-plasma acceleration, the first criterion for KTA. In Europe the looming project is Eu-PRAXIA, with its Conceptual Design Report soon to be released. However, several proof-of-principle projects are under construction (e.g cSTART@KIT). Lasers are not the only drivers of plasma acceleration since beam-driven projects, like FACET or AWAKE, are based on short proton pulses, rather than high power lasers.
- in most national laboratories, the plasma and laser expertise are not held by the accelerator department but by matter or atomic physics departments. However some institutes (e.g. CERN, IN2P3 and STFC) are starting to hire plasma and laser experts for the development of plasma acceleration.
- none of AMICI technical platforms is based on, or supports laser development. One may argue that this is missing and that AMICI should recommend strengthening this technology.

The critical recommendation to allow Laser to become a Key Technology Area for future accelerator projects is that a strong alliance is needed to federate and coordinate the efforts.

8. ANNEX: KTA JUSTIFICATION AND ROADMAP

8.1. PARTICLE SOURCES

8.1.1. ECR ion sources

8.1.1.1. Introduction

Born in Europe (France, LPSC Grenoble) around 40 years ago, the new generation of ECR ion sources, with increasing microwave frequency and also SC coil versions, were wide-spread world-wide but with Europe remaining at the forefront level (INFN-LNS, JYFL-Jyvaskyla, LPSC-GANIL, MSU, LBNL, RIKEN et al.). Nowadays top-of-the-world performances are obtained at IMP-Lanzhou (China) and Riken (Japan), with impressive values of charge state and current with sources at 18, 24, 28 GHz. The next proposed version is a 45 GHz frequency ECRIS, with Nb3Sn coil solenoids at more than 11 T magnetic field. Moreover, ECR ion sources are extremely reliable so even their most updated versions could soon be strong working contenders for our present and future facilities in Europe too.

8.1.1.2. Applications

The range of applications is wide, and of sure and growing interest for public-private partnership.

- Synchrotron Radiation Treatment facilities, based on ECR ion sources for beam generation, were 5 in 2012, while in 2018 they are 10, and additional 8 are planned.

- PIMS (Positive Ion Mass Spectrometry), based on ECRIS's, is a future alternative to negative-beam Tandem based Accelerator Mass Spectrometry.
- Charge breeders for radioactive ion beams are in a fast expansion phase: at LPSC-Grenoble, INFN-Legnaro, GANIL-Caen, Texas A&M (USA), TRIUMF (Canada), etc.
- Intense and high power beams are increasingly required, for science and application purposes, and 2,45 GHz ECRIS's delivering from 10 mA of H+, He+, He2+ beams are requested (and being developed at IMP-Lanzhou), up to 125 mA proton and deuteron beams are also required for irradiation facility and neutron production
- All-permanent-magnet ECRIS's, which – when properly designed - are compact and easier to use, could have easier industrial applications in the future, compared to traditional RT or SC ones.

8.1.1.3. Technology areas involved.

To the development of ECRIS's a number of associated KTA are correlated: development of klystrons and gyrotrons, permanent magnets. Here are some technologies that would be necessary of the ion source development:

- RF klystron, gyrotron, traveling wave tube amplifiers (TWTA) and solid state amplifiers (SSA), leading to higher power and higher frequency;
- antennas and directive waveguide inside the source (Vlasov launcher), the coupling of the RF wave to the plasma being an active research field in ECR ion sources;
- Nb3Sn superconducting coils, for the solenoid or sextupole magnets, and High Temperature Superconducting Magnets (HTSM) with He-free cryocoolers to lower the price and reduce the size of the ECR ion sources while keeping a high level of performance;
- development of Gas Injection System (GIS) with very low mass flow below 1/10 sccm;
- development of inductive or resistive oven technology with capability of long term operation to produce metallic ion beams widely use in accelerators.

Therefore, not only companies specialized in ion sources, but also those assisting with these advanced technologies could be benefit from their developments.

8.1.1.4. AMICI KTA Criteria.

A. Being a cutting-edge technology of high interest in the accelerator or SC magnet communities
Present applications: in NP labs for stable and exotic beams, synchrotron-based cancer treatment facilities; high I facilities for science and applications; …
B. Being widely needed for the future projects: perspective applications in Accelerator Mass Spectrometry, high-P accelerators, as well as future facilities of the group described at the previous point.
C. Presenting a high development potential allowing to meet the needs of future challenging machines: higher and higher charge states and currents, through the application of gyrotron frequencies and the corresponding development of high-H magnets.
D. Presenting a high development potential allowing to reduce the construction and/or operation costs of future machines: increasing current and charge state, they will either increase the scope of future ion facilities or lessen their cost

E. Being critically dependent on single/very few vendor(s): yes, few vendors, ECRIS's are mostly developed in labs; if they were available on the market, they would likely be very much requested for several applications

8.1.2. Electron Beam Ion Sources.

8.1.2.1. Introduction

EBIS ion sources are in a good expansion phase too, with their extreme q values, although they may be more delicate to manipulate, to a certain extent. They were first developed in Russia in the 70's, being adopted by Orsay and Saclay (F) later on, and then spreading to LLNL and BNL in the USA and Freiburg and Dresden (D) later on. At BNL, a high current high charge state EBIS (e.g. Xe^{36+}) was developed. Potential drawbacks vs ECRIs's: they are pulsed; they are less easy to operate and maintain.

8.1.2.2. Applications

EBIS source are the easiest way to make heavy element ions, high charge ion beams. They are used for charge breeding in exotic beam facilities or for efficient ion traps for precision experiments. They could be interesting in the future also as injectors of linear accelerators. Small A/q values, even for the heaviest beams, could allow sparing significantly on the cost of the downstream accelerator (acceleration efficiency growing proportionally to q for linacs and to q^2 for cyclotrons). EBIS is proposed as a replacement of ECRIS for Synchrotron Radiation Treatment facilities, as a purer beam is achieved and the cost of the facility significantly reduced.

8.1.2.3. Technology areas involved.

Most EBIS/EBIT are based on superconducting magnets, with a nice cross-link to another KTA in AMICI as in the case of ECRIS's. Others are in NC (even permanent) magnets. Already one company in Germany delivers EBIS and EBIT commercially. They even offer a full irradiation facility based on and EBIS. The potential for an increasing market is there.

8.1.2.4. KTA Criteria.

A. Being a cutting-edge technology of high interest in the accelerator or SC magnet communities: it applies to both the accelerator community in general, since they allow very efficient accelerators, and to the SC magnets community, since most are based on SC solenoids.
B. Being widely needed for the future projects: once issues concerning their reliability will be solved, and when high charge state will be associated to high beam currents, they will be the natural choice for several ion accelerator injectors.
C. Presenting a high development potential allowing to meet the needs of future challenging machines: same comment as for the previous point
D. Presenting a high development potential allowing to reduce the construction and/or operation costs of future machines: their main advantage is that, when both high charge state and high average currents shall be achieved, together with improved reliability, they will allow substantial cost reduction for a large fraction of future ion accelerators
E. Being critically dependent on single/very few vendor(s): one (?) single vendor at present

8.1.3. Large beam size large current ion sources for Nuclear Fusion Reactors.

8.1.3.1. Introduction

Light beam(H, D) sources, with +1 or -1 charge states and current up to A range (e.g. arc discharge multicusp, or plasma based), with grid acceleration and with exceptionally wide beams (even 0,5 m size) are largely requested for Neutral Beam Injectors for nuclear fusion reactors. Ion source and beams have to satisfy ever-increasing challenges from fusion physics, in particular:

- Optimization of H- production
- Beam quality and HV holding time (with and without source cesiation in case of negatively charged ones)
- Control of high intensity beam space charge
- Control of beam induced voltage breakdown
- Control of secondary plasma/back-streaming ions

8.1.3.2. Applications.

These sources are needed in neutral beam injectors, allowing heating of plasmas, to start a sustained nuclear fusion reaction. Neutral high-energy particles transfers kinetic energy to the plasma, increasing its temperature.

8.1.3.3. Technology areas involved.

Mechanical design and realization of accelerating grids. Surface low SEY materials.

8.1.3.4. KTA Criteria.

F. Being a cutting-edge technology of high interest in the accelerator or SC magnet communities: multi-beamlets acceleration up to 1 A is a not yet achieved challenge, albeit essential for future nuclear fusion plants.
G. Being widely needed for the future projects: although the multi-beamlet application is specific of NF plants, optimization of the single beams is crucial for several H-, D- and H,D accelerators.
H. Presenting a high development potential allowing to meet the needs of future challenging machines: the breaking through validated solutions will be soon widely distributed to several machines
I. Presenting a high development potential allowing to reduce the construction and/or operation costs of future machines: it is widely acknowledged that, without neutral beam injectors, future nuclear fusion plants won’t work to specs (self-sustainability of the plasma discharge)
J. Being critically dependent on single/very few vendor(s): industry could help the labs on individual developments, keeping ready to provide the full product in some ten years from now or so.

8.2. MAGNETS AND VACUUM SYSTEMS

8.2.1. Permanent Magnets and Resistive Magnets.

8.2.1.1. Introduction

Warm magnet technology is indeed basic for guiding particle beams along accelerators, with a widespread group of laboratories and industries capable of producing and testing conventional magnets in large series. However, new promising beam transport techniques have recently been discovered or implemented successfully (e.g. ultimate-brilliance synchrotron-radiation storage rings, fixed-field alternating gradient accelerators, beam channel for plasma acceleration) that extent the design and manufacturability needs for warm magnets, be it resistive magnet or permanent magnets, beyond their current state of the art. In many cases, small aperture vacuum chambers with high pumping and low desorption are required to implement these techniques.

8.2.1.2. Applications

The development of small aperture vacuum chamber technology has opened the possibility to implement Multi Bend Achromat (MBA) lattices in existing Synchroton Radiation facilities to get Diffraction Limited Storage Rings (DLSR), and have triggered the design of new facilities. In addition, a new generation of energy recovery linacs (ERL) based on Fixed-Field Alternating Gradient (FFAG) single beam line requiring innovative magnets, are developed overseas for compact X-Rays sources, and potential application in proton therapy for cancer, and as proton sources for high intensity neutron production.

8.2.1.3. Technology areas involved

DLSR lattices require a high number of magnets, which can be made with permanent magnet (PM) technology as the vacuum chamber aperture is getting smaller. The main advantage of PM technology for this application is the possibility to reach high performance (strong focusing for example) with a limited size while requiring virtually no operation cost (green lattice). PM technology remains complex to assemble and PM magnets may require to be tuned on dedicated magnetic measurement apparatus. While many laboratories master these technologies across the world, very few magnet companies master them. Moreover, PM technology is sensitive to temperature and radiation, which could interfere with operation stability: efficient temperature stabilization and radiation protection schemes must be developed.

Conventional magnet technology can also be used for gradient magnets and strong focusing magnets (and any other type of magnets) by introducing high permeability material like vanadium permendur. This material is complex to machine and expensive. It is therefore necessary to optimize the existing designs so that this material is used only where it is needed while reducing their impact on the additional assembly costs. More generally, gradient and focusing magnet designs already exists but some R&D and engineering work is still needed to tailor the magnets the DLSR needs.

Finally, permanent magnet technology remains key for synchrotron light source insertion devices (undulator, wiggler). Among the different technologies that could be further developed are the cryogenic permanent magnet undulators or the delta undulator technology. With the development of DLSR, new (shorter period, high K, narrow gap) and more accurate devices (phase errors) will be needed to meet new needs. These high performance devices will have to be characterized and tuned through high performance magnetic measurement benches. These benches are widely developed in the Synchrotron light sources labs but few of them have the ability to measure and tune undulators with rather challenging narrow and closed aperture. Some effort will be needed to bring these new insertion devices and their associated measurement system to the mature technology level.

Small gap vacuum chambers represent a key technology in modern accelerator technology. It is an essential pre-requisite for using complex, longitudinal space consuming magnet lattices. Non-Evaporable getter coating is key as it reduces the outgassing and thus the number of lumped pumps can be reduced, resulting in an even more compact vacuum system. A good understanding of the coating technology is mandatory to build a modern cost-efficient vacuum system. The transfer of this technology from the laboratory chamber coating facilities to industry to support larger scale projects needs further maturation.

8.2.1.4. AMICI KTA Criteria.

F. Being a cutting-edge technology of high interest in the accelerator or SC magnet communities Present applications: for the newest (4th) generation of light source synchrotron aiming at highest brilliance with lattices approaching the diffraction-limited beam emittance. Also for energy recovery linacs (ERL) based on FFAG recirculation in a single beam chamber allowing the construction of compact and energy-friendly facilities.
G. Being widely needed for the future projects: several 3rd generation light source upgrades (e.g. ESRF, PETRA IV, SOLEIL) and new projects (HEPS-TF in Beijing, etc…), exploiting the breakthrough pioneered by MAX-IV in Sweden. Compact ERL like CBETA and PERLE will soon demonstrate the potentiality of this innovative accelerator concept.
H. Presenting a high development potential allowing meeting the needs of future challenging machines: small aperture undulators made with permanent or resistive magnets placed inside of the vacuum chambers. Combined function transport magnets for DLSR lattices and FFAG transport beam lines.
I. Presenting a high development potential allowing reducing the construction and/or operation costs of future machines: upgrades of existing synchrotron light sources to reach higher record brilliance in the same tunnel layout. Energy recovery linacs allowing compact accelerator with minimal RF power and beam disposal.
J. Being critically dependent on single/very few vendor(s): no.

8.2.1.5. Areas of expected technological advances:

- Manufacturing of combined function magnets with complex magnetic polar pieces.
- Permanent magnets introducing high permeability material like Neodymium or Praseodymium.
- Coating of small aperture vacuum chambers using the Non-Evaporable-Getter (NEG) technology or reducing the electron secondary-emission yield.

8.3. HIGH FIELD SUPERCONDUCTING MAGNETS

8.3.1. Introduction

Today large and powerful high field superconducting magnets are routinely used in science, research and technological development (RTD) and in medical diagnosis, using Magnetic Resonance Imaging (MRI), the latter representing the biggest current market for superconductivity. In addition, the superconductors may also result in potentially large energy savings in power applications, and demonstrations of power cables, transformers, motors or current limiters have already been made.

8.3.2. Applications

AMICI partners have a long history in design and manufacturing of superconducting magnets for high-energy and nuclear physics accelerators (HERA, LHC, FAIR, etc.) and for particle detectors (Aleph, ATLAS, CMS, R3B-Glad, etc.)

In parallel, the considerable expertise acquired on these large projects have enabled AMICI partners to move to other applications: health applications (MRI, gantries for proton therapy), thermonuclear fusion (Tore Supra, W7-X, JT-60SA, ITER), intense high magnetic fields (LNCMI, EMFL), energy production (superconducting generator for wind turbines), etc..

In all theses applications, AMICI partners are working on the next generation of magnets to increase the magnetic field strenght in large volumes, by using new innovative superconducting materials (Nb3Sn, HTS, ..) and by developing innovative technologies.

8.3.3. Technology areas involved

Challenges on key technological areas to build bigger and stronger magnets are the following:

- Development and use of ultimate performance Nb3Sn conductors:
  Nb3Sn is the most mature option for magnets on future accelerators and high field magnets. Research and development are currently developed on focusing magnets and high-field magnets for the luminosity and energy upgrade projects of the LHC, HL-LHC, HE-LHC and FCC. Recent advances on the Nb3Sn FRESCA2 (Facility for the REception of Superconducting CAbles) magnet with a record field of 14.6 T in a 100 mm aperture and the test of an HTS inserts generating an additional fields provide a glimpse of a possible horizon for the 20 T. These magnets are incorporated into the R&D programme for future circular colliders (FCC) including a 16 T short model dipole.

- Development and use of HTS conductors:
  HTS conductors still need high tech R&D (from material science to electromagnetic/electromechanical engineering) to be implemented in high field magnet at affordable costs. AMICI partners are working on the implementation of several materials and manufacturing technologies including the characterization of physical properties (critical current, mechanical and thermal properties, etc) and the manufacturing processes (winding, impregnation, assembly, etc.). AMICI partners are involved in high-field magnets projects (> 30 T) using both hybrid and fully superconducting magnets. For this, the use of Nb3Sn and HTS superconductors are

essential and the associated technologies must be developed in partnership with high-field user laboratories in Europe.

The first objective is the development of second-generation high temperature superconducting (HTS) magnets to be installed as inserts in high-field hybrid magnets at 40 T in 5 to 10 cm apertures to increase performance and reduce energy consumption. The second and ultimate goal is to manufacture a superconducting “user magnet” of more than 40 T integrating a low temperature superconducting (LTS) part and an HTS part allowing Europe to become the leader of the international community of high field magnets. This more particularly concerns the development of HTS inserts embedded in hybrid magnets to reach fields of more than 60 T. In parallel, HTS R&D is aiming to study the problems inherent in HTS conductors and magnets; examples of areas of research currently being studied are : NI (No Insulation), MI (Metal as Insulation) and PI (Partial Insulation) windings, screening currents and the mechanics of non-impregnated coils.

- Increase the operating temperature margin and simplify the cryogenics:

  In order to increase the operating margin, the internal cooling of superconducting magnet for accelerator needs experimental investigation of steady state and transient heat transfer within the superconducting coil for the optimization of the coil with respect to heat transfer . This subject deals with heat transfer in confined geometry (micro-channel and porous media) and serves to understand the thermodynamic of magnet quench. In parallel, numerical simulation is being developed for helium heat transfer in steady state and transient regimes including phase change from superfluid helium to vapour state.

  After the success of thermosiphon cooling loop for large superconducting magnets (ALEPH, CMS at CERN, R3B-GLAD at GSI), optimization is still required for cryogenic autonomous gravity assisted circulation loops used by device asking for remote cooling source, such as magnet in sensitive environment (high field or radiation) . Small loops have been studied and installed (WAVE at ORPHEE). Cryogenic gravity assisted circulation loops for large HTS cryomagnetic system are also concerned, essentially for two-phase flow nitrogen.

  In order to install a remote cooling source in any layout, development of thermal links is permanent. Autonomous non-gravity assisted thermal link for the cooling of cryogenic system has been initiated by using the so-called Pulsating Heat Pipes (PHP) which can work without gravity at different temperature (He, Ne, N2…). These are the perfect candidate for space application, rotating device and cryogen-free magnetic system, especially for new generation of HTS superconducting devices. Numerical modelling of PHP for the understanding of the thermodynamic of such thermal link and their design is underway. Additionally, involvement in medical applications, such as for superconducting RF antennas for Micro Magnetic Resonance Imaging analysis on small regions such as skins, articulations or small animals , requires constant development of cryogen free autonomous cooling system and associated high conductive and flexible thermal links.

- Reinforcement of the conductor mechanical strength and protection the coils against quenches:

  AMICI partners are involved in several upstream R&D programmes to develop new design tools, in particular numerical tools, which could be used for future projects in the field of superconducting magnets to understand and be able to accurately predict the mechanical and electrical quench behaviour of the conductors and the magnets. AMICI partners have begun a mechanical simulation programmes for the superconducting cable manufacturing and utilisation process,. The final aim of this research programme is to achieve a mechanical model integrating the various scales of the cable in operation. 3D mechanical models of the conductor will gradually be coupled with the higher scale (homogenised 3D models of complete magnets) and with the lower scale (2D models of composite strands showing superconductor filaments). This will help the development of mechanically

reinforced conductors together with new material development working at cryogenics temperature, necessary to withstand the increasing level of mechanical stresses and forces.
Research is also being carried out on the system approach, with the implementation of multiphysics platforms for developing and coupling software in different fields (mechanical, thermal, fluidic, magnetism, quench behaviour etc.).
AMICI partners have also an expertise in the field of safety system for detecting quench in superconducting magnets (Magnet Safety System MSS). The increasing complexity of the magnets requires the use of numerical techniques in order to process the more complex detection equations or a greater number of measurement channels, requiring a greater density of electronic equipment. Integration of FPGA (Field Programmable Gate Array) type component into a MSS requires specific developments for isolated measurements of the high voltage, the digitization of the data and the MSS software of the FPGA. It also includes R&D on the acquisition systems associated with the MSS, the function of which is to memorise the measurements when quench occurs.

8.3.4. AMICI KTA Criteria.

A. Being a cutting-edge technology of high interest in the accelerator or SC magnet communities
The development of new superconducting conductors and technologies are necessary for the next generation of large high field magnets. The current NbTi technology limit the field at 12 T and the use of Nb3Sn or HTS conductor will push this limit. In parallel, the management of the high level of mechanical stresses and stored energies requires new tools and materials to modelise the behaviour of the future magnets and reinforce their components.
B. Being widely needed for the future projects: Perspective applications in future projects of accelerators (FCC hh, HE-LHC, FAIR, etc) and high field magnets (EMFL, MRI, Demo fusion machine ,..) designed in Europe are very promising and could represent very important market share in the future.
C. Presenting a high development potential allowing to meet the needs of future challenging machines: Future Nb3Sn and HTS conductors and technologies will allow the generation of the higher magnetic fields required by the future challenging machines.
D. Presenting a high development potential allowing to reduce the construction and/or operation costs of future machines: Use of superconductivity in high field magnets allow a reduction of the electrical consumption and a reduction of the size and cost of the installations.
E. Being critically dependent on single/very few vendor(s): no

8.4. NORMAL CONDUCTING RF STRUCTURES

8.4.1. Introduction

Radio Frequency acceleration technology (normal conducting) was introduced 90 years ago and is still the standard reference for acceleration, used in the wide majority of particle accelerators worldwide. Only a tiny fraction of the more than 30'000 particle accelerators in operation worldwide make use of superconducting RF, while laser based acceleration is only at its infancy, not yet in use on operational machines. Normal-conducting RF cavities are characterised by a large variety of designs (single cell, multi-cell, TE-mode, TM-mode, etc.), operating frequencies (from the kHz to the multi-GHz range), operating modes (CW or pulsed, tunable or fixed frequency, coupled or stand-alone, etc.), and of construction technologies (Cu-plated or full copper, bolted welded or brazed). The availability of simple designs using conventional fabrication techniques makes normal-conducting RF accessible to small University and laboratories without the need for specialised infrastructure. Conversely, sophisticated designs reaching challenging parameters and/or large-scale productions requires specific technological infrastructure for the manufacturing and for the processing of the cavities. Although there is an increasing number of companies capable of providing normal-conducting RF cavities, with the exception of few large linac projects this market is characterised by small quantities based on unique designs that are often built "in-house".

The main ongoing developments in this field are related to increasing the accelerating gradient to reduce the dimensions of the accelerating system, and to increase the power efficiency. This latter challenge leads to increasing the operating frequency reducing at the same time the cavity dimensions, thus imposing additional challenges on the manufacturing.

8.4.2. Applications.

Originally used in synchrotrons, cyclotrons and linear accelerators for fundamental research, normal-conducting RF technology has expanded to accelerators for applied science, medicine and industry. The most widespread normal-conducting RF cavity system is the one used for radiotherapy medical linacs, with more than 10'000 units operating worldwide.

The application pushing the progress towards higher accelerating fields is the linear collider for particle physics, which needs to reach energies in the TeV range keeping an acceptable accelerator length. In particular, the CLIC team at CERN has made a substantial advance in the understanding of high-field breakdown phenomena and in the surface preparation and conditioning techniques required to achieve high fields, making stable operation at gradients of 100 MV/m conceivable for future projects.

In parallel with high gradients, construction of small-size complex RF modules is another challenge for linear colliders, shared with modern normal-conducting FEL and other projects.

For the acceleration of protons and ions, the main challenge is in the RF cavities for the linac injector, which are particularly complex because they need to adapt to the low and rapidly increasing particle velocity. An example is the Radio Frequency Quadrupole (RFQ), required in the initial stage of any hadron accelerator, which presents at the same time challenges in terms of metallurgy, precision machining, vacuum brazing, and RF tuning.

8.4.3. Technology areas involved.

- Precision machining of copper: machining accuracy of tens of microns are often required, difficult to achieve on copper because of its thermal behavior. Special machines and workshops are needed.
- Copper coatings on large complex surfaces: in alternative to bulk copper, a layer (usually few tens of micron) of copper galvanically deposited over another material (usually steel) can provide the required conductivity. In particular, when the parts to be plated are large and complex, only few specialized technological infrastructures are capable of producing the coating. The limited market for copper coatings makes that this technology infrastructure is usually built and maintained by the Technology Infrastructure.
- Precision brazing and welding: connecting parts with high precision can be done by welding or by brazing. In particular high-precision brazing of sophisticated designs like Radio Frequency Quadrupoles (RFQ's) is particularly challenging and requires large brazing facilities and special competences that are difficult to find in industry.
- Conditioning to high fields: after assembly, high-field cavities requires a high-power conditioning that can last days or weeks and is done in high-power test stands that are an essential part of the technological chain for the production of high-gradient RF cavities.

8.4.4. AMICI KTA Criteria.

A. Being a cutting-edge technology of high interest in the accelerator or SC magnet communities
High-gradient acceleration at high power efficiency is essential for normal-conducting linear collider designs like CLIC. RFQs are used at the front of any hadron accelerator and for challenging beam parameters their construction present many challenges not yet completely overcome. Wide-band accelerating cavities are being constantly improved for the needs of low-energy synchrotrons.
B. Being widely needed for the future projects: even if superconducting RF is progressing, proton and ion accelerators will always need a warm RFQ-based injector. Normal-conductivity remains economically favourable for high-energy linacs at low duty cycle and will be used by many future projects.
C. Presenting a high development potential allowing to meet the needs of future challenging machines: High-gradient high-frequency operation has the potential to reduce the footprint not only of colliders for physics, but also of FEL's (Compact Light study), of Compton-based photon sources (SMART light), and of medical accelerators for future FLASH therapy.
D. Presenting a high development potential allowing to reduce the construction and/or operation costs of future machines: see above, the size of the accelerator is one of the main components of its cost.
E. Being critically dependent on single/very few vendor(s): no.

8.5. SUPERCONDUCTING RF CAVITIES AND CRYOMODULES

8.5.1. Introduction

The past two decades have seen the advent of superconducting RF cavities in most of the accelerators recently build or under construction, resulting from the dramatic breakthroughs in the accelerating field (from 5 MV/m to 30 MV/m) and cryogenic consumption at roughly constant fabrication cost and insurpassed operation efficiency. After LEP200 operational success, the usage of Niobium based SRF technology became widespread and almost unavoidable for circular and linear accelerator projects using electron, proton and heavy ion beams in pulsed or CW mode or operation. It also opened up new operation modes included beam recirculation and beam energy recovery, and new applications like SRF electron guns. Furthermore, some advances are still the result of recent R&D demonstrating that higher performances are to be expected in the medium term future.

The specific categories encompassed within this Key Technology Area (KTA) include:

i. High Q_0 / high gradient SRF structures
ii. Surface preparation of SRF cavities
iii. New fabrication techniques
iv. SRF electron sources
v. Cryostats

8.5.2. Justification of the choice of the KTA according to the criteria set previously.

Matching these categories against the associated judgement criteria as defined for the AMICI KTA is shown in Table 1, with the KTA criteria of selection identified as:

A. Being a cutting-edge technology of high interest in the accelerator or SC magnet communities,
B. Being widely needed for the future projects,
C. Presenting a high development potential allowing to meet the needs of future challenging machines,
D. Presenting a high development potential allowing to reduce the construction and/or operation costs of future machines,
E. Being critically dependent on single/very few vendor(s).

Table 1: SRF Technology Categories and match against KTA criteria

	KTA Criteria					
	1	2	3	4	5	Acceptance Level
SRF Technology	Being a cutting edge technology of high interest in accelerator or SC magnet communities	Being widely needed for future projects	Presenting a high development potential allowing to meet the needs of future challenging machines	Presenting a high development potential allowing to reduce the construction and/or operation costs of future machines	Being critically dependent on single/very few vendor(s)	Match: 5 – excellent 4 – very good 3 – good 2 – marginal 1 – poor 0 – N/A
High Q0 / high gradient SRF structures	High Q0 SRF structures are demanded for all large scale superconducting accelerators since low cryogenic operation costs are of utmost importance. Continuous wave (CW) accelerators can only be built with highest Q0 structures since cryogenic plants would otherwise	With the success of the European XFEL almost all actually built and future large scale research facilities rely on SRF technology. Highest Q0 is required to limit the cryogenic power to a reasonable level, and high accelerating gradients allow for	The request for higher beam energies and CW operation is demanding. The SRF technology has still large potential, and development is ongoing worldwide. Europe plays and should continue to play a major role by sustainable research.	Recent research shows the path towards decreased operation costs: highest Q0 even for high accelerating gradients, close to the theoretical physics limit.	Worldwide, the production of high Q0 / high gradient accelerating structures is in the hands of basically two vendors. The unstable ordering situation – large and expensive research facilities are constructed only sporadically – is challenging. New vendors are only developed using	5

	become unrealistically large.	reasonably short machines.			political driven / strategic budgets.	
Surface preparation of SRF cavities	Surface preparation requires state-of-the-art clean room techniques, challenging etching procedures (electro-polishing and buffered chemical polishing, both using hydrofluoric acid), and sophisticated surface modification methods like Nitrogen doping or infusion. In some cases successfully applied techniques are actually not stable enough to finish R&D efforts. Surface preparation of SRF cavities is clearly cutting edge technology.	All present and future projects rely on respective infrastructure. Some few laboratories have larger scale facilities in operation which is clearly to the benefit of other projects. Recently started large scale projects use these existing platforms. Further R&D is widely needed for future projects. Collaboration exists and needs to be sustained.	Actually studied surface preparation techniques need to become more stable. There is still high development potential. In parallel knowledge transfer to industry is essential since large scale production of structures including surface preparation can only be done at vendors. Projects need structures delivered ready for cold RF testing.	Only a stable and successful surface preparation allows the construction and later operation of large facilities. Unstable surface preparation leads to a repetitive preparation and cold RF testing which then become a real cost driver.	The quality of SRF accelerating structures strongly depends on surface preparation. Due to often unstable recipes vendors usually do not accept the performance guarantee. The risk is too high. Stable surface preparation can support and even relax the customer / vendor relation.	4
New fabrication techniques	Different fabrication techniques are under development. Some use old ideas like Nb3Sn sputtering on copper, others follow completely new techniques using laser welding of precisely machined bulk Niobium subassemblies. Goal is the production of cheaper structures with state-of-the-art performance.	Future projects could strongly profit from the development of new fabrication techniques.	The development potential is high. Recent results with sputtered structures are promising.	Successfully applied new techniques would clearly reduce the construction costs of superconducting accelerators.	At present, sputtering is done in research laboratories. The mentioned laser welding of precisely machined subassemblies is under study at one single company contracted by one research laboratory within the international SRF community.	3
SRF electron sources	CW superconducting accelerators require CW operated injectors including the respective sources. The development of an SRF electron source (gun) is ongoing since decades. Its use is extremely promising but until today none of the built guns is sufficiently reliable to be used for large scale research facilities. The technology is demanding and absolutely cutting edge since cathodes need to be introduced in superconducting particle clean structures.	Almost all future projects aim for CW operation in which the particle beam time structure can perfectly match with the needs of scientific users.	Scientific users of e.g. Free Electron Lasers would love CW operated SRF sources. The produced time structure of the FEL photon pulses could be perfectly matched to the experiments needs. The time scale given by the physics of studied processes would define the electron bunch repetition rate inside a CW operated superconducting linac.	At present no reliable CW injector exists. Neither using SRF electron sources nor other normal conducting. There is highest development potential.	The production of SRF electron sources can only be done at the vendors of SRF structures.	4
Cryostats	Cryostats for SRF structures always adopt the structure geometry. Different and often challenging designs are used. Low cryogenic load is essential. The technical solution is usually sophisticated, with the consequence that extensive testing on test benches is a must. Even large scale projects test basically all accelerator modules. The tests always include cryogenic load measurements since assembly errors need to be excluded.	All SRF based accelerators need cryostats. At present most of the future projects are using SRF structures.	Since SRF structures are always adapted to the particle beam to be accelerated, the chosen design varies (e.g. low vs. high-ß structures). The cryostat design and technology follows the structure design.	The larger the project the more important is a cost optimized cryostat design. Production in series requires qualification of vendors which always goes together with construction cost reduction. Low cryogenic static load design is a must.	There are more cryostat vendors than SRF structure producers. Nevertheless, some dependency exists on known vendors. Qualification of vendors for the production of larger series usually takes into account experience and company history.	5

8.5.3. Description of the state of the art in each KTA

8.5.3.1. High Q0 / high gradient SRF structures

High Q0 SRF structures are demanded for all large scale superconducting accelerators since low cryogenic operation costs are of utmost importance. Continuous wave (CW) accelerators can only be built with highest Q0 structures since cryogenic plants would otherwise become unrealistically large.

With the success of the European XFEL almost all actually built and future large scale research facilities rely on SRF technology. Highest Q0 is required to limit the cryogenic power to a reasonable level, and high accelerating gradients allow for reasonably short machines.

The request for higher beam energies and CW operation is demanding. The SRF technology has still large potential, and development is ongoing worldwide. Europe plays and should continue to play a major role by sustainable research. Other key-players can be found in the U.S. as well as in Asia. Recent research shows the path towards decreased operation costs: highest Q0 even for high accelerating gradients, close to the theoretical physics limit. The preparation of the structures' surface requires special furnaces, and other demanding infrastructure (see 2.2). Within AMICI, several partners joined for collaborative work.

Worldwide, the production of high Q0 / high gradient accelerating structures is in the hands of a very small number of vendors. The unstable ordering situation – large and expensive research facilities are constructed only sporadically – is challenging. New vendors are only developed using political driven / strategic budgets.

8.5.4. Surface preparation of SRF cavities

Surface preparation requires state-of-the-art clean room techniques, challenging etching procedures (electro-polishing and buffered chemical polishing, both using hydrofluoric acid), and sophisticated surface modification methods like Nitrogen doping or infusion. In some cases, successfully applied techniques are actually not stable enough to finish R&D efforts. Surface preparation of SRF cavities is clearly cutting-edge technology. Within AMICI, several institutes operate technology platforms required for successful R&D.

All present and future projects rely on respective infrastructure. Some few laboratories have larger scale facilities in operation, which is clearly to the benefit of other projects. Recently started large-scale projects use these existing platforms. Further R&D is widely needed for future projects. Collaboration exists and needs to be sustained.

Actually studied surface preparation techniques need to become more stable. There is still high development potential. In parallel, knowledge transfer to industry is essential since large-scale production of structures including surface preparation can only be done at vendors. Projects need structures delivered ready for cold RF testing.

Only a stable and successful surface preparation allows the construction and later operation of large facilities. Unstable surface preparation leads to a repetitive preparation and cold RF testing which then become a real cost driver.

8.5.5. New fabrication techniques

Different fabrication techniques are under development. Some use old ideas like Nb3Sn sputtering on copper, others follow completely new techniques using laser welding of precisely machined bulk Niobium subassemblies. Goal is the production of cheaper structures with state-of-the-art performance. Future projects could strongly profit from the development of new fabrication techniques. The development potential is high. Recent results with sputtered structures are promising. Successfully applied new techniques would clearly reduce the construction costs of superconducting accelerators.

At present, sputtering is done in research laboratories. The mentioned laser welding of precisely machined subassemblies is under study at one single company contracted by one research laboratory within the international SRF community.

8.5.6. SRF electron sources

CW superconducting accelerators require CW operated injectors including the respective sources. The development of an SRF electron source (gun) is ongoing since decades. Its use is extremely promising but until today none of the built guns is sufficiently reliable to be used for large scale research facilities. The technology is demanding and absolutely cutting edge since cathodes need to be introduced in superconducting particle clean structures.Almost all future projects aim for CW operation in which the particle beam time structure can perfectly match with the needs of scientific users. Scientific users of e.g. Free Electron Lasers would love CW operated SRF sources. The produced time structure of the FEL photon pulses could be perfectly matched to the experiments needs. The time scale given by the physics of studied processes would define the bunch repetition rate inside a CW operated superconducting linac. At present, no reliable CW injector exists. Neither using SRF electron sources nor other normal conducting solutions.

8.5.7. Cryostats

All SRF based accelerators need cryostats which always adopt the structure geometry. Different and often challenging designs are used. Low cryogenic load is essential. The technical solution is usually sophisticated, with the consequence that extensive testing on test benches is a must. Even large scale projects test basically all accelerator modules. The tests always include cryogenic load measurements since assembly errors need to be excluded. Since SRF structures are always adapted to the particle beam to be accelerated, the chosen design varies (e.g. low vs. high-ß structures). The cryostat design and technology follows the structure design.

The larger the project the more important is a cost optimized cryostat design. Production in series requires qualification of vendors, which always goes together with construction cost reduction. Low cryogenic static load design is a must. There are more cryostat vendors than SRF structure producers. Nevertheless, some dependency exists on known vendors. Qualification of vendors for the production of larger series usually takes into account experience and company history.

8.5.8. New explored R&D paths to improve the performances and meet future project needs: Future development roadmap.

8.5.8.1. High Q0 / high gradient SRF structures

The optimum surface treatment for SRF structures is unknown. The R&D path tries hard to understand the physics behind injecting e.g. Nitrogen into the RF relevant surface layer. Modification of the mean free path length, reduction and/or manipulation of vacancies supporting or changing the creation of e.g. nano-hydrides of different size are the goal.

8.5.8.2. Surface preparation of SRF cavities

Infrastructure exists and in principal supports the application of surface treatment recipes. The path towards reliably applying such techniques is a long rocky road.

8.5.8.3. New fabrication techniques

Superconducting layers on copper were tried out long time ago. Until today bulk Niobium cavities are performing better. Studies should be continued. Other ideas like sandwiches of isolators and superconductors, are also of interest.

8.5.8.4. SRF electron sources

Reliable CW electron sources are urgently needed with in next decade. Further R&D is strongly required. This includes the successful production of the source itself but also the integration in a test injector allowing detailed studies of beam properties, and long time performance.

8.5.8.5. Cryostats

Cryostats will always be adapted to the needs. Insufficient experience exists with the shipping of assembled accelerator modules. Detailed studies can improve the design ideas.

8.5.9. If applicable, where these R&D is (or could be) made in the AMICI Technology Infrastructures (TI)

From the registered AMICI Technological Infrastructures as available on the H2020 AMICI website (http://eu-amici.eu/technology_infrastructure) the following are expected to provide platform opportunities to develop the R&D identified for the SRF Technology KTA as discussed:

- CEA Saclay
- CERN
- CNRS / IN2P3
- DESY
- FREIA / UU
- INFN LASA
- STFC

The AMICI core member IFJ-PAN does not operate platforms but contributes with an SRF expert team available to support activities at other partners.

8.6. RADIO-FREQUENCY POWER SOURCES

8.6.1. Introduction:

The electrical power consumption of future accelerators will be driven to a large part by their RF systems. The upcoming large scale accelerators are expected to require RF power in the range of 10 to 100 MW. This is particularly true for electrons colliders, circular (FCC-ee or CEPC) or linear (ILC or CLIC), and to a minor level high power hadron linacs (PIP2) or Accelerator Driven System (MYRRHA). For comparison, the currently operational Large Hadron Collider (LHC) has a total RF drive of 5 MW as its electrical consumption is mostly dominated by magnet systems.

Therefore, an efficient energy conversion of electrical gird power into radio frequency power is becoming a determining factor in the approval process for the future large machines, as a significant part of the initial investment and running costs will be determined by the cost and efficiency of their RF systems.

8.6.2. RF power sources: Today's technologies and future development:

8.6.2.1. Modulators:

For most high-power RF sources operation, we need to transform the electrical gird voltage to a High-Voltage (HV: case of Continuous Wave (CW) operation mode) and to generate a pulsed pattern (case of pulsed operation mode). These functions are filled by modulators.

For CW operation, the modulator is basically a HV power supply feeding gridded tubes (IOTs or tetrodes), whereas for HV pulsed mode, the modulator form itself the pulsed pattern using various developed topologies according to the pulse lengths and the voltages needed, then supply the non-gridded tubes (Klystrons).

Today's modulator are already operating with very high efficiency (85-92%) almost independent of their output power (kW-MW), Voltage (1-100kV), and pulse length. For short pulses (<500 µs), the modulator rise time becomes an important factor in the system efficiency and this is where further developments, such as the Stacked Multi-Level (SML) design, are expected to make a significant difference.

8.6.2.2. Klystrons

Klystrons are attractive RF sources, owing to their stability, the wide operating frequency range (0.3 to 15 GHz), their large gain, offering a high output power in the MW range and a long lifetime reaching up to 40kh. However, they need a HV input higher than 100 kV which mean expensive modulators. Moreover, their gain curve saturates at full output power meaning that klystrons are operated below full output power and thus, below maximum efficiency. Current State of the art Klystrons can deliver a maximum efficiency of approximatively 65%. A significant amount of energy is effectively wasted as heat. The limiting factor is the electron bunch profile as it approaches the output cavity of klystrons, as well as the velocity of the lowest electron leaving the output gap. With the progress of beam dynamics tools, number of novel electron bunching mechanisms such as the Core Oscillation Method (COM), the Bunching, Alignment and Collecting (BAC) method and the Core Stabilisation Method (CSM), have shown an improve on the efficiency through numerical investigations by about ten of percent, which means several millions of Euros saved per year on electricity consumption.

8.6.2.3. Solid State Amplifiers (SSAs)

SSAs promise cost efficient RF power generation and the advantages of modular systems. This imply an effective combination of the single units of 1 kW (as there is no significant commercial market for higher power transistors, it is unlikely that this value will be increased significantly in the near future) to reach high power values (up to 100 kW), allowing hot-swapping of faulty units during operation. Most of today's systems operate at frequencies below 1.3 GHz with DC to RF efficiency below 55%. In most accelerator scenarios, the RF amplifiers have to withstand significant amounts of reflected power and if the amplifier itself cannot withstand these reflections, circulators are used to deviate power into water-cooled loads. For SSAs, the addition of circulators for all single units and/or for the combined output often makes the whole system too expensive. A promising solution to reach power values larger than 100 kW, is to use combiner cavities that combine all the output of single units in one stage. The difficulty still to match hundreds of input antennas and minimise the reflected power due to manufacturing tolerances of the electronics or to failed units.

8.6.2.4. Inductive Output Tubes (IOTs)

IOTs have less gain than klystrons, which puts their input power needs within reach of commercially available solid state amplifiers. As they don't need a long drift space like klystrons, IOTs are quite compact and therefore cost efficient. IOTs and all gridded tubes (tetrodes and diacrodes®) are limited in their frequency reach by the distance of the control grid from the cathode. The RF period has to be smaller than the time of flight from cathode to the grid. Therefore, the frequency of IOTs is limited to around 1.3 GHz. The maximum power of single beam IOTs is limited to around 100kW. In order to benefit of the advantages of IOTs for MW-class RF amplifiers, prototypes of multi-beam IOT's with input power > 1MW were developed by industrial.

8.6.3. Conclusions:

In the range between tens of kw to 100kW, SSAs have to compete with tetrodes in the low frequency range and with IOTs in the higher frequency range. In both cases, the efficiency of the SSAs is lower than the competition. However, in some cases, the modularity of solid state systems may outweigh this disadvantage and there the combining cavities are most likely the way towards higher power units. The development of multi-beam IOTs, which may rival klystron-based systems is encouraging but it may still take some engineering effort to make beam as reliable and cost-efficient as their counterparts. Higher frequency (>1.3 GHz) and high power ranges (MW) are only covered by klystrons. The development of high efficiency klystrons and klystron linearisation algorithms is highly promising and will make klystrons not only more efficient, but smaller with increased average output power, and it will lower the HV needs, reducing thereby the needs for HV protection and making the modulators cheaper.

8.6.4. AMICI KTA Criteria.

A. Being a cutting-edge technology of high interest in the accelerator or SC magnet communities: The electrical power consumption of future accelerators will be driven to a large part by their RF systems. A significant part of the initial investment and running cost of the large-scale machines will be determined by the purchasing cost and the efficiency of their RF sources. Increasing the efficiency of existing RF systems to higher levels means several millions euros saved per year on the electricity bill.

B. Being widely needed for the future projects: The upcoming large-scale accelerators are expected to require RF power in the range of 10 to 100 MW (for comparison, the Large Hadron Collider (LHC) has a total RF drive of 5 MW). This is particularly true for electrons colliders, circular (e.g. FCC-ee or CEPC) or linear (e.g. ILC or CLIC), High power hadron Linacs (e.g. PIP2) and Accelerator Driven Systems (e.g. MYRRHA).

C. Presenting a high development potential allowing to meet the needs of future challenging machines:
   - Modulators: today's modulator are already operating with very high efficiency (85-92%) almost independent of their output power (kW-MW), Voltage (1-100kV), and pulse length. For short pulses (<500 μs), the modulator rise time becomes an important factor in the system efficiency and this is where further developments, such as the Stacked Multi-Level (SML) design, are expected to make a significant difference.
   - Inductive Output Tubes (IOTs): In order to benefit of the advantages of IOTs for MW-class RF amplifiers, prototypes of multi-beam IOT's with input power > 1MW were developed by industry.

D. Presenting a high development potential allowing to reduce the construction and/or operation costs of future machines:
   - Klystrons: Current State of the art Klystrons can deliver a maximum efficiency of approximatively 65%. The limiting factor is the electron bunch profile as it approaches the output cavity of klystrons, as well as the velocity of the lowest electron leaving the output gap. With the advance of modern beam dynamics tools, number of novel electron bunching mechanisms such as the Core Oscillation Method (COM), the Bunching, Alignment and Collecting (BAC) method and the Core Stabilisation Method (CSM), have shown an improve on the efficiency through numerical investigations.

- Solid State Amplifiers (SSA): SSAs promise cost efficient RF power generation and the advantages of modular systems. This imply an effective combination of the single units (of 1 kW) to reach high power values (> 100kW). A promising solution is to use combiner cavities that combine all the output of single units in one stage. The difficulty still to match hundreds of input antennas and minimise the reflected power due to manufacturing tolerances of the electronics or to failed units.

E. Being critically dependent on single/very few vendor(s): The overall market for tetrodes is relatively small, that's why many tubes references are no longer produced. In addition, very few companies are capable and willing to build tetrode-based RF amplifiers. However, for IOTs that are another king of gridded tubes, as they are used for broadcasting digital signals, there is a commercially viable market, which mean that long-term availability seems relatively secure.

8.7. CRYOGENICS

8.7.1. Introduction

Cryogenics is a base technology for the numerous worldwide research facilities that utilize large superconducting (SC) magnets or SC particle accelerators, be it with superconductive radio-frequency cavities or high-field magnets. The rarity and potential shortage of Helium gas, as the most used cooling liquid for the large facilities, call for critical advances in reducing the overall Helium and energy consumption, as well as alternative cryo-cooling technologies. Industry, especially European firms, and research laboratories are leading these developments.

The specific categories encompassed within this Key Technology Area (KTA) include:

vi. High efficiency cryo-plants,
vii. Cryogenic distribution,
viii. Cryostat insulation,
ix. Cryo-coolers,
x. Cryogenic safety.

8.7.2. Justification of the choice of the KTA according to the criteria (one or many) set previously (criteria are remind below).

Matching these categories against the associated judgement criteria as defined for the AMICI KTA is shown in Table 1, with the KTA criteria of selection identified as:

A. Being a cutting-edge technology of high interest in the accelerator or SC magnet communities,
B. Being widely needed for the future projects,
C. Presenting a high development potential allowing to meet the needs of future challenging machines,
D. Presenting a high development potential allowing to reduce the construction and/or operation costs of future machines,
E. Being critically dependent on single/very few vendor(s).

Table 2: Cryogenics categories and match against KTA criteria

	KTA Criteria					
	1	2	3	4	5	
Cryogenics KTA	**Being a cutting edge technology of high interest in accelerator or SC magnet communities**	**Being widely needed for future projects**	**Presenting a high development potential allowing to meet the needs of future challenging machines**	**Presenting a high development potential allowing to reduce the construction and/or operation costs of future machines**	**Being critically dependent on single/very few vendor(s)**	**Acceptance Level (Match: 5 - excellent, 4 - Very Good, 3 - Good, 2 - Marginal and 1 - Poor, 0 - N/A)**
High Efficiency Cryoplants	Of particular demand for high capacity, CW machines which have a fundamental equipment to increase the plant Coefficient of Performance (CoP) for both accelerator and SC magnet systems	High efficiencies are demanded for all plant implementations, however the costs benefits are expected to be more expansive for large capacity systems	Operation reliability and availability becomes a primary driver in terms of development opportunities, which focus primarily on sub-system components, such as heat exchangers, turbines and distribution systems. System instrumentation and diagnostics are areas which can have significant operational benefits in terms of early fault failure diagnosis, process control and system optimisation	Improved operational efficiency directly provides operational cost benefit, the focus therefore being to reduce thermal leaks in all stages of the cryogenic distribution. Improving the analysis capability through improved instrumentation. Looking at ways in which sub-system standardisation can be achieved, thereby reducing both capital and ongoing maintenance costs of critical components and also reducing long lead times for specialist and more expensive components	For integrated system configurations, the community has critical dependence on only 2 globally recognised vendors for turn-key solutions. For distributed systems, the number of vendors increase, however this field is still only likely to be limited to 5-10 recognised companies.	4
Cryogenic distribution (including Cryogenic processes)	Is the main limiting factor for large scale , high-efficiency cryoplants. Optimising Cryogenic process is the key requirement in operating accelerators reliably (Controller cool down and warm up, achieving high pressure and temperature stability in the presence of variable dynamic loads) for both accelerator and SC magnet systems	Optimised systems required to minimise heat loads, helium leakages, maximising efficiency, reliability, helium recovery and improved safety performance. Design optimisation required to ensure intermediate temperature transitions including two phase flows are managed effectively with minimal loss introduction	High potential for improvements - configuration, sub-system technologies, state of the art instrumentation (e.g. fibre Bragg gratings to measure distributed temperatures and stresses) Location of 2K heat exchanger and optimum assessment of intermediate temperature losses are key drivers.	Standardisation of sub-system components can be primary mechanism for capital cost reduction and optimised sub-system design and/or configuration to reduce heat losses are the primary operational cost drivers.	Significant vendor opportunities exist for cyogenic distribution systems with a healthy global competition	5
Cryostat insulation	Minimal opportunities exist specifically for cryostat insulation as standardised existing approaches undertaken are deemed sufficient. Impact directly influences the static cryostat loads experienced	Fundamentally required for all SC accelerator and magnet system integration	Lots of scope for improvements relating to sub-system component designs (specific for application) and materials utilised 1. carbon-fibre opportunities - strength, insulation and cost 2. Use of Helium Sorption pumps to manage small helium leaks dynamically with high reliability	Increased insulation performance, reduces the cryogenic load and consequently its operating cost. Alternative materials may reduce capital costs of sub-system components and standardisation approaches may also provide some cost reductions	Very few vendors who can provide complete cryostat insulation systems, typically then performed by laboratory who procure sub-system components - shields, supports, transfer lines etc., who then integrate complete cryostat system. Many vendors available to provide sub-system components	3
Cryo-coolers	Certainly high interest in magnet field, not used very much in SRF systems primarily due to high capacity and low temperatures, thereby limiting Cryocooler applicability	Extensively utilised for SC magnets (mainly utilising helium re-condensing techniques using Cryocoolers), requiring modest cooling requirements. Offer high reliability,	Ineffecincies is biggest weakness and opportunities exist to develop improved designs, utilising innovative techniques and lower loss materials	Reduced distribution losses directly reduce the system capital costs, as minimal distribution systems are required. For large scale plants, improved cryocooler efficiencies could offer a significant capital cost benefit.	Very large commenrcial market, lots of vendors and growing rapidly	4
Cryogenic safety	Certainly of high interests in all large and small scale systems.	Current approach to safety design is mostly based on extreme conditions only. Extensive studies and development are needed to adress safety issues under dynamic opertaing conditions.	in following areas - (1) developing processes (including simulations) for indetifying dynamic failuer modes and schemes for generating early warning signs (2) develping and qualifying new materials and devices (3) establishment of harmonised safety standards and compliance to regulations	in following areas: (1) developing harmanised safety standrads at global level (2) develping and qualifying new engineering materials and devices for improving safety (3) minimising MTBF	Very large range of vendors from process industries sector (with high have capability to fullfill most of the safey needs in Cryogenics. But opportunities still exist for developing safety processes, devices and accessories operating in the temperature range below ~ 80K.	5

8.7.3. Description of the state of the art in each KTA

8.7.3.1. Cryogenics: High Efficiency Cryoplants

High efficiency cryoplants are striving to maximise the Carnot efficiency achievable for practical cryogenic liquefier and refrigeration systems. State-of-the-Art performance is most notably achieved for large-scale plant installations (i.e. >1 kW @ 1.8/2K), such as at CERN, Jlab and DESY. Equivalent efficiency levels are not typically achieved for smaller scale cryoplant systems. The ‘turn-down’ capacity becomes a critically limiting factor for large CW SRF cryoplants, whereby effective management of large dynamic loads becomes the dominant factor, compared to the static load. Currently the 4.5 kW @ 2K cryoplant supports the CEBAF 12 GeV polarised electron source and provides the highest 2K capacity, operating efficiency and dynamic range of any cryogenic system currently in operation.

8.7.3.2. Cryogenic Distribution

State-of-the-Art cryogenic distribution systems will typically employ a modular and flexible configuration for its delivery approach, ensuring it has ability to adapt to varying capacity demands. Such systems invariably employ innovative control processes, utilising advanced instrumentation, with inherently optimised safety management systems. In large accelerator installations, cryogenic distribution losses become significant in terms of the overall cooling demand. This may be solved by decentralised and highly efficient local mid-size cryoplants, which are not offered on the market today.

8.7.3.3. Cryostat Insulation

Innovative materials selection will typically dictate highest performance capability, through optimised conduction control within the cryostat insulation environments. The focus predominantly is for high performance materials which provide support for the internal cryostat components in terms of outgassing, heat leak control and robustness.

8.7.3.4. Cryo-coolers

The State-of-the-Art performance capability for cryo-coolers is fundamentally dictated by their adaptiveness to a wide variety of application sectors in industry and science. Cryocoolers cover the small-scale power range and are limited in efficiency due to their working principle. Striving to achieve higher efficiencies and capacities at lower temperatures, in order to make such technologies more attractive to SRF applications is a key driving motivation. Their advantage is a relatively small technical effort for local cooling.

8.7.3.5. Cryogenic Safety

While State-of-the-Art protection concepts rely on worst-case considerations with static loads, dynamic simulation of risk scenarios is needed in order to exploit small design/safety margins for cutting-edge performance of accelerator equipment. Cryogenic safety is a crucial aspect of helium cryostat design and a new European Standard for "Helium cryostats – protection against excessive pressure" is being developed with support from AMICI WP5.3 in order to harmonise the understanding of risk and technical solutions.

8.7.4. Future development roadmap

8.7.4.1. Cryogenics: High Efficiency Cryoplant

Improved performance sub-system components such as: heat exchangers, turbines, instrumentation and process control optimisation.

8.7.4.2. Cryogenic Distribution

Improved performance for process control would be a primary development requirement, along with system configuration optimisation and improved performance in terms of cold-valve technologies and safety management of the integrated system.

8.7.4.3. Cryostat Insulation

Material selection for insulation environments and innovative pumping technologies i.e. sorption pumps could provide a path to higher performance capability.

8.7.4.4. Cryo-coolers

Innovative materials and adopting development technologies employed from space industry applications, would provide high heat capacity and improved insulation performance. A two orders of magnitude cooling power gap currently exists between cryo-coolers and cryoplants. New cryogenic fluid mixtures offer the opportunity for efficient and cost-effective cryogenic cooling in the mid-scale power range for decentralised local cooling of accelerator equipment. Larger numbers of smaller cryo-cooler units also offers a better market for cryogenic industry.

8.7.4.5. Cryogenic Safety

First models that describe the process dynamics in cryogenic incidents must be developed further and validated experimentally. The future goal is to develop dynamic models for cryogenic incidents, which are harmonised and generally accepted for the dimensioning of pressure relief devices.

8.7.5. If applicable, where these R&D is (or could be) made in the AMICI Technology Infrastructures (TI) or European companies.

From the registered AMICI Technological Infrastructures as available on the H2020 AMICI website (http://eu-amici.eu/technology_infrastructure), the following are expected to provide platform opportunities to develop the R&D identified for the Cryogenics KTA as discussed:

CEA Saclay:

Test stations for SC magnets and large cryogenic components

High efficiency cryo-plants,
cryogenic distribution,
cryostat insulation,
cryo-coolers.

Characterization stations at cryogenic temperature

cryogenic distribution,
cryostat insulation,
cryo-coolers.

CERN:

Cryogenic Laboratory and Tensile Facility

cryogenic distribution,
cryostat insulation,
cryo-coolers.

CNRS:

Cryogenic Test Facilities and Test Stands

cryogenic distribution,
cryostat insulation,

Uppsala University:

The FREIA Research Infrastructure

cryogenic distribution,
cryostat insulation,

INFN:

Test station for Accelerator Magnets

cryogenic distribution,
cryostat insulation,
cryo-coolers.

STFC:

Cryogenic Test Laboratory

cryogenic distribution,
cryostat insulation,
cryo-coolers.

Cryogenics Companies

Krio System (Poland)
CryoDiffusion (France)
DeMaco (Netherlands)
Air Liquide (France)
Linde (Switzerland)
Criotec (Italy)