THE GLOBAL LANDSCAPE AND THE KEY TECHNOLOGY AREAS

THE FUTURE ACCELERATOR AND MAGNET BASED RESEARCH INFRASTRUCTURES AND THE KEY TECHNOLOGY AREAS SUSTAINING THEM

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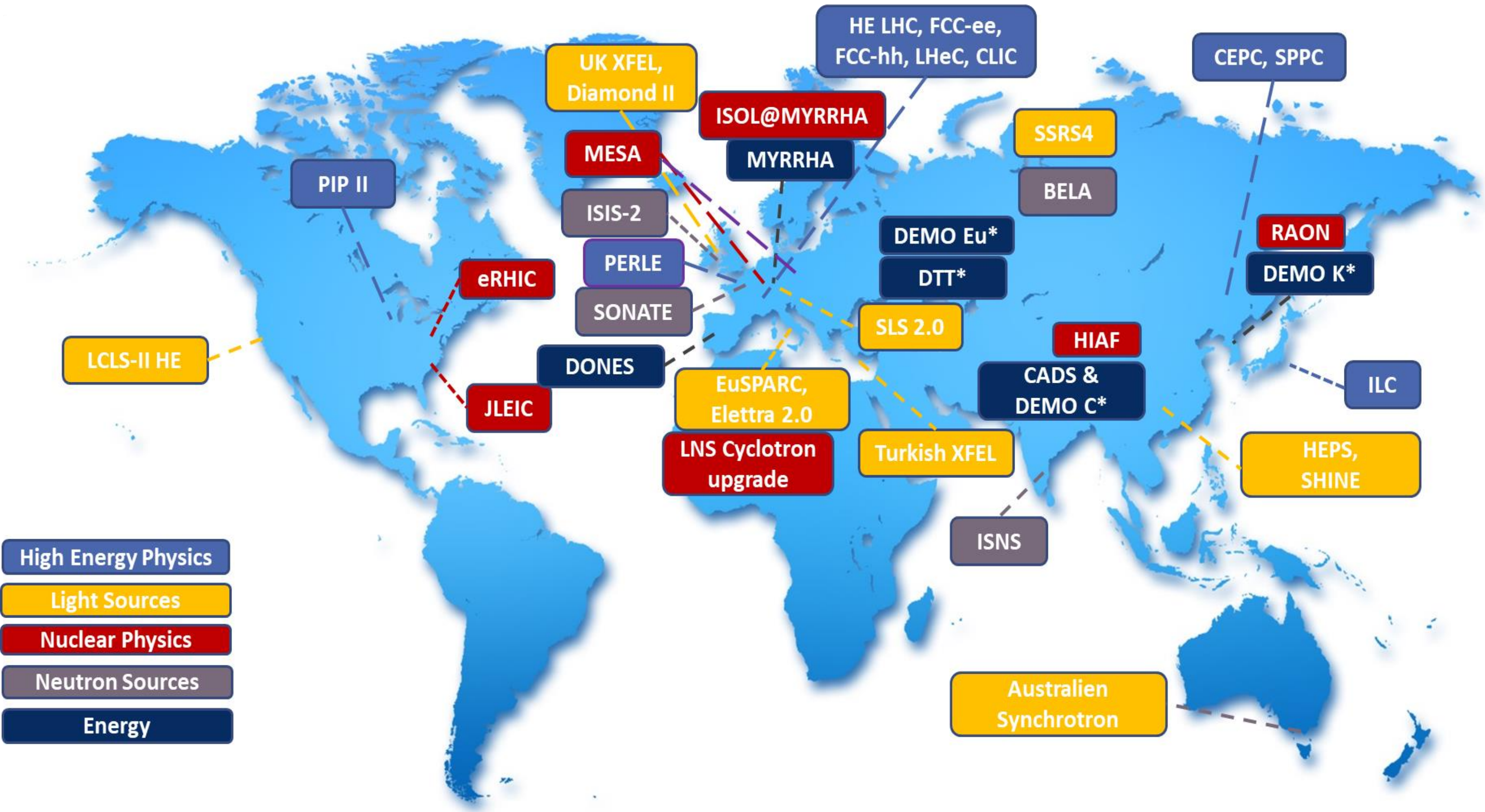
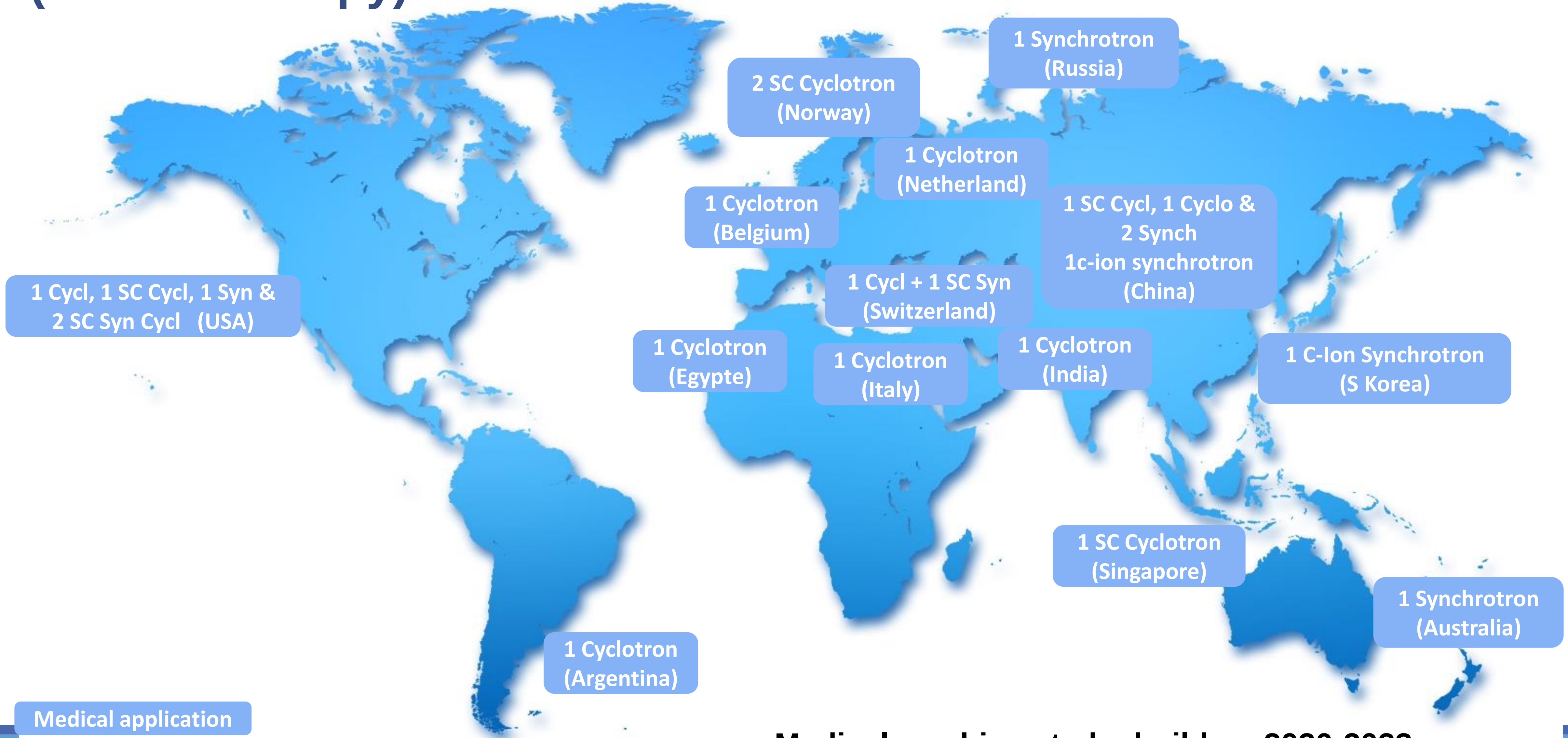
The Global landscape of Accelerator and SC Magnets Future Projects (non medical)



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 under study. The map 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.

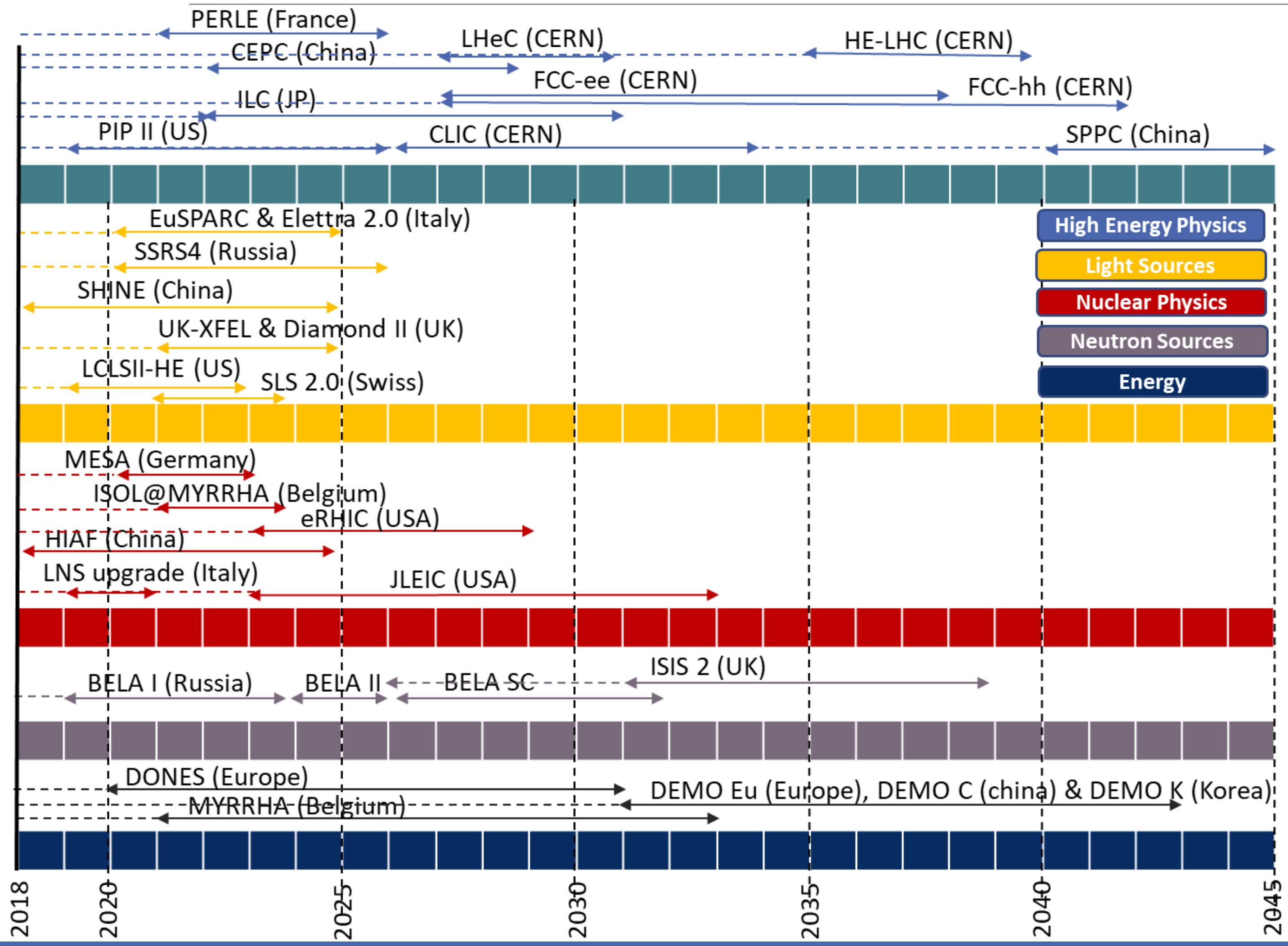
Global Landscape of Proposed Future Medical Accelerators (Proton-therapy):



Medical application

Medical machines to be build on 2020-2023

The Global landscape: Furture Projects Timeline



This timeline 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.

Key Technological Areas (KTA) being developed for future major projects

	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	•			•				•

This table shows which KTAs are being further developed for the major Research Infrastructures of the global landscape, based on the following criteria:

1. being widely needed for the future projects
2. presenting a high development potential allowing to meet the needs of future challenging machines
3. presenting a high development potential allowing to reduce the construction and/or operation costs of future machines

Developments needed in Key Technological Areas

	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

0 - Lasers

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, Lasers have not been retained as a Key Technology Area for several reasons, not all very solid:

- 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. **A strong alliance is needed, not to duplicate efforts**.

1 - Particle sources

Ion sources determine the research potential of the accelerator or post-accelerator facilities. The essential parameters are the ion species, the ion current intensity and the polarization. Proton accelerators (e.g. LHC, SNS, ESS, etc…) are using high intensity H+ or H- ion sources, while heavy ions accelerator are 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 reactors are using MeV-energy intense ion sources (e.g. D-) for neutral injection as a plasma 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 charged ions at rest.

For electron sources, the new generation of CW FELs calls for high current high repetition rate (10 kHz-1 MHz) RF photo-injectors, a possible new application of superconducting RF cavities. Pushing the intensity of positron sources is mandatory for colliders, together with polarization, and for very low energy positron beams used in anti-matter research and material science. Creating low-emittance energetic muon beams would open the way for a new generation of lepton colliders.

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 are 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 are considered to produce muon pairs.

2 - Magnets and vacuum systems

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.

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.

3 - High Field Superconducting Magnets

Large and powerful high-field superconducting magnets are routinely used in science, research and technological development (RTD) and in medical diagnostics, using Magnetic Resonance Imaging (MRI), the latter representing the biggest current market for superconductivity. In addition, superconductors bring potentially large energy savings in 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 Nb_3Sn or High Temperature Superconductors (HTS), and developing cable and coil innovative cooling technologies.

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 - Normal Conducting RF Stuctures

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.

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 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 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 some 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

5 - Superconducting RF cavities

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.

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 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 CW FEL operation
- Optimized cryostat design for particle-free assembly and robotics, and cost reduction.

6 - Radio-Frequency Power Sources

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).

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 (> 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.

7 - Cryogenics

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.

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.

8 - Beam Instrumentation

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.

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.

The Role of AMICI Technological Facilities for the Development 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		•	•			•	•	•

This table shows the **matching** of KTAs with the Technological Facilities 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.

Conclusions

- The evolution of Global Landscape needs continuous effort from the AMICI project.
- The **descriptions of Key Technology Areas** and their needed/promising advances are developed in 1-2 page per KTA, in a document which, together with the description of the Global Landscape, is to be delivered to the EC in a couple of weeks.
- All AMICI deliverable reports are public and will be available in October 2019 on the AMICI web page.

  http://eu-amici.eu/about/documents

- **The AMICI Technology Infrastructure is, to first order, well equipped and staffed to host the KTAs further developments**.
- This overall statement shoud be refined at the level of the individual technical platforms, taking into account platform availability and needed upgrades.
- We are ready to dialog with our industrial partners to see how we can bring them in the picture, on a case-by-case basis.