CHALLENGES OF THE HIGH CURRENT PROTOTYPE ACCELERATOR OF IFMIF/EVEDA

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Abstract

LIPAc, under installation in Rokkasho aims to produce a 125 mA CW deuteron beam accelerated from 100 keV up to 5 MeV through the world longest RFQ and up to 9 MeV after a SRF Linac housing eight 175 MHz HWR superconducting cavities. It will become the validating prototype of IFMIF's accelerators. The objective of IFMIF is to generate a neutron flux of 10^{18} $m^{-2}s^{-1}$ at 14 MeV for fusion materials testing, by using 2 x 125 mA CW 40 MeV D^+ beams impacting on a 25 mm thick liquid lithium jet flowing at 15 m/s. The first attempt to validate the high current accelerator required for fusion materials testing was in the US in the early 80s under FMIT project with a H_2^+ 100 mA CW 2 MeV linac. The accelerator know-how has matured since the times of FMIT conception in the 70s. Today, operating the required accelerator seems feasible thanks to the understanding of the beam halo physics and the three main technological breakthroughs in accelerator technology: a) the ECR ion source for light ions developed at Chalk River Laboratories in the early 1990s, b) the RFQ operation of protons in CW with 100 mA demonstrated by LEDA in Los Alamos in the late 1990s, and c) the growing maturity of superconducting resonators for light hadrons and low-β beams achieved in recent years.

WHY ACCELERATORS IN CW MODE FOR FUSION MATERIALS RESEARCH?

Intensive efforts have been in place last two decades towards continuously higher average beam power linacs driven by their large variety of applications, namely, condensed matter physics, hybrid subcritical reactors for nuclear waste transmutation, rare isotope nuclear physics, neutrino factories and fusion materials research [1,2]. In particular, the latter has been fueling high current accelerators technology through last 40 years [3]; fusion materials research started in the early 1970s following the observation of the degradation of irradiated materials used in the first commercial fission reactors and has continued sustainedly since [4]. The development of CW accelerator was intimately linked with this need since that time as we will see next. Future fusion power plants will be based on the $^2H + {}^3H \rightarrow {}^3He\ (3.5MeV) + n\ (14.1MeV)$ reactions. The α-particle will be mainly absorbed in the plasma, in turn the 14.1 MeV neutron generated will be absorbed in the blanket of the fusion reactor. The technological challenges of fusion energy are intimately linked with the availability of suitable materials capable of reliably withstanding the severe operational conditions of fusion reactors [4]. The hard mono-energetic spectrum associated with the deuterium–tritium fusion neutrons (14.1MeV compared to < 2 MeV on average for fission neutrons) releases significant amounts of hydrogen and helium as transmutation products that will lead to a (at present undetermined) degradation of structural materials after a few years of operation of a fusion power plant. The accumulation of gas in the materials microstructure is intimately related with the colliding neutron energy, for steels e. g. through $^{54}Fe(n,\alpha)^{51}Cr$ and $^{54}Fe(n,p)^{54}Mn$ reactions, which are responsible for most of the He^{2+} and H^+ produced with an incident neutron energy threshold at 2.9 MeV and 0.9 MeV respectively. Therefore fission neutron sources, cannot fit the testing requirements for fusion materials since the transmuted He production rates are far from fusion reactor (actually around 0.3 appm He/dpa). In turn, spallation sources generate light ions that induce measurable changes of material properties above 10 dpa and about one order of magnitude higher appm He/dpa than fusion neutrons [5]. Neutrons of 14 MeV can be obtained through Li(d,xn) stripping reactions, explained theoretically by Serber in 1947 [6], that presents a broad peak typically at $0.4E_{deuteron}$, and a spectrum with a sharp maximum energy a few MeV above the incident deuteron energy. A 3 GW fusion reactor will exhibit neutron fluxes around 10^{18} $m^{-2}s^{-1}$ with dpa_{NRT} [7] rates above 15 dpa_{NRT}/year of operation [8]. The maximization of the flux of neutrons to reach timely dpa_{NRT} values comparable to those in a fusion reactor demands beam average currents in the order of 10^2 mA to reach the needed flux, in 100% duty cycle, i.e. CW mode, and high facility availabilities. The needed Li(d,xn) facility therefore shall exhibit 1) in the order of MW deuteron beam average powers and 2) liquid lithium targets with a suitable 2.1) thickness to fully absorb the deuterons and maximize the available neutron flux and 2.2) flow to efficiently absorb the beam power and evacuate the heat deposited [9].

IFMIF/EVEDA SUCCESS FOR A TIMELY FUSION RELEVANT NEUTRON SOURCE

Neutrons with suitable fluxes and spectra for fusion materials testing, generated via Li(d,xn) nuclear reactions, are expected to be available by the middle of the next decade [10]. The International Fusion Materials Irradiation Facility (IFMIF) project is successfully developing its Engineering Validation and Engineering Design Activities (EVEDA) phase under the Broader Approach Agreement between Japan and Europe in the field of fusion energy research. EVEDA is the combination of the Engineering Design Activities (EDA) and the Engineering Validation Activities (EVA) phase. The EDA phase was accomplished in 2013 on schedule with the delivery of the design of the facility [9], backed by the experience gained in former phases and projects (FMIT, the Fusion Materials Irradiation Test facility in the US in the early 80s, and ESNIT, the Energy Selective Neutron Irradiation Test Facility in Japan in the early 90s). In turn, the EVA phase has succeeded in its broad mandate, only missing the Accelerator Facility validation [11].

IFMIF consists of two 125 mA 40 MeV deuteron linear accelerators operating in CW mode, each with a 200 mm x 50 mm beam cross section, impacting concurrently on a 25 +/-1 mm thick lithium jet flowing at 15 m/s at 250 °C capable of providing above 20 dpa_{NRT} per year under 14 MeV neutrons in a volume of 500 cm^3. This volume will house around 1000 testing specimens in 12 capsules independently cooled with He gas at selected target irradiation temperatures (with two sets of specimens fitted in each capsule). The EVA phase focused on the Accelerator, the Target and the Test facility. In this EVEDA phase, it has been demonstrated the stable long-term flow of the lithium screen within specified conditions in the EVEDA Lithium Test Loop (ELTL) in Oarai, Japan, thanks to stable operation of the 15 m/s lithium flow at 250 °C during 25 consecutive days with surface-wave amplitudes in the 25 mm thick jet within the specified +/-1 mm range [12]. In turn, the concept of the High-Flux Test Module has been validated in Karlsruhe (Germany) with the construction and successful testing of a full scale prototype [13]. The validation activities under EVA phase have been far more extensive, an overview has been recently published [11].

IFMIF's accelerators are being validated with the Linear IFMIF Prototype Accelerator (LIPAc) under installation and commissioning in Rokkasho, Japan [14]. The LIPAc aims to run 125 mA CW mode beam of deuterons at 9 MeV output energy of a SRF linac (the 40 MeV output energy of IFMIF's accelerators will be obtained with three additional superconducting cryomodules [9]). Collective phenomena driven by space charge forces become the main limitation on achieving high intensity beams. In low-β regions, the beam outward radial Coulomb forces prevail over the inward radial Ampere ones, and they mutually cancel in the relativistic domain. Thus, space charge repulsive forces are stronger the lower the beam energy is. Just as LEDA, the Low Energy Demonstration Accelerator [15] was the validating prototype of Acceleration Production of Tritium project [16], the successful operation of LIPAc at 9 MeV in CW downstream of the first cryomodule will validate IFMIF's accelerators. It is worth recalling that upon APT cancellation, LEDA was proposed to the fusion materials community [17] to bridge with IFMIF. The LIPAc components have been designed and manufactured mainly by the European institutes and it is currently installed and commissioned in the Rokkasho Fusion Institute (see Fig. 1).

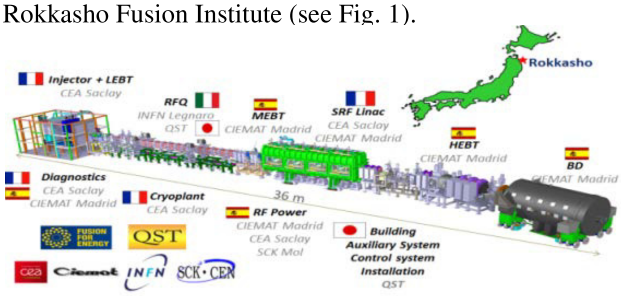

Figure 1: Breakdown of the contribution for LIPAc.

CW HYDROGEN LINACS, 30 YEARS OF ENDEAVOURS

FMIT project, in the US in the early 80s, is the start of modern acceleration driven systems [18]. These could not be conceived technically without the invention of the Radio Frequency Quadrupole (RFQ) in 1969 by Teplyakov and Kapchinsky [19], which efficiently bridged the keV energy beam ranges from the ion source to few-MeV energy. The 70-year-old Alvarez type Drift Tube Linac (DTL) approach demands cavities with increasing lengths proportional to β. Furthermore, the focusing strength of magnetic fields is driven by Lorentz forces. Thus for low-β beams quadrupole focusing in DTLs is not efficient and integration of equipment cumbersome. In turn, at energies >100MeV, the effective shunt impedance starts to decrease, becoming less effective than other accelerating structures. Thus, DTLs are suitable for a narrow beam energy window ($0.05<\beta<0.4$). The electrical focusing, independent of the particle speed, and pre-bunching capability of the accelerating RFQ structures allowed a major step in hadron accelerator capabilities. Fortunately, the accelerator know-how has matured in all possible aspects since the times of FMIT conception in the 1970s; today, operating 125 mA deuteron beam at 40 MeV in CW with high availabilities, though challenging, seems feasible thanks to the understanding of the beam halo physics [20] and three main technological breakthroughs in accelerator technology: a) the ECR ion source for light ions developed at Chalk River Laboratories in the early 1990s [21], b) the RFQ operation of H^+ in CW with 100 mA demonstrated by LEDA in Los Alamos in the late 1990s [22], and c) the growing maturity of superconducting resonators for light hadrons and low-β beams (typically $0.03 < \beta < 0.2$ [23]) achieved in recent years [24].

The first attempt for a CW low-β high current hydrogen accelerator in FMIT taught us the challenge [25]; our technology was not ready. The operation was strongly affected by the cathode based poorly performing ion sources with two crucial shortcomings: a) the availability of the cathode and b) the quality of the beam from its source. The cathode of an ion source is constantly bombarded by ions, which erodes the cathode material, impacting its shape, composition, and microstructure, and rapidly degrading its design performance; this effect is obviously enhanced with high currents and duty cycles. In FMIT, 130 mA of H_2^+ in CW at 75 keV was targeted as beam input for its RFQ; a poor efficiency in the gas fraction demanded currents above 200 mA through the LEBT, this fact degraded the vacuum and the beam quality. The FMIT RFQ succeeded in operating to the design CW field (vane-tip fields of 1.68 Kilpatrick) and accelerated more than 50 mA of H_2^+ to full energy (2 MeV) in CW. However, thermal expansion decreased the operating frequency by 170 kHz from start up to full-power operation. Thermal stresses were directly responsible for most of the problems encountered when duty cycles were increased, which were mostly solved by attaching additional cooling lines and by accommodating thermal expansion RF shielded joints wherever possible. Excessive gas loads leading to pressures of 10^{-5} mbar caused swiftly thermal runaway of ion pumps. Multipacting was also observed with dark areas in various parts of the 4 m-long RFQ; which were successfully overcome with TiN coating). Deuteron beam was not used to avoid activation problems under the wrong assumption that H_2^+ would behave similarly, however stripping and dissociation of H_2^+ led to large neutral and H^+ beam halos which damaged output beamline components. In 1984, the project was cancelled due to escalating costs [26], driven by the impossibility to reach the target of 100 mA CW H_2^+ at 2 MeV [25].

In 1991, a technological breakthrough took place with the successful development of Electron-Cyclotron Resonance (ECR) principle for hydrogen ion sources, widely used since early 80s with heavy ions as injector for cyclotrons. This concept is based on the excitation of a cold plasma by the resonant absorption of microwaves by electrons orbiting in a suitable magnetic field for the production of a high quality ion beam. T. Taylor successfully developed such an approach for H^+ beam at Chalk River Laboratories [21], and it has been widely used since early 90s. The operation of a high current proton beam in CW through an RFQ was eventually achieved in 1999 with LEDA [22]. The RFQ of LEDA accepted a 75 keV, 110 mA DC proton beam from the ERC injector with ~94% transmission. It succeeded to operate in CW for >110 h. No bending magnet for ion fraction separation was present in the LEBT, counting with two solenoids and steerers. A beam matching improvement was achieved by reducing the distance from the second solenoid to the RFQ and the installation of an electron trap at the entrance of the RFQ to prevent electrons from flowing forward, and contributing to the space charge compensation of the beam. The success of LEDA would have not been possible without the lessons learnt with FMIT endeavours, the rough way, almost 20 years before. In addition to the thermal stresses and hot spots faced in FMIT; thermal expansion induces a complex impact on resonant frequencies given the combination of capacitive and inductive effects and enhancement of losses if not adequately tuned during operation. LEDA's RFQ consisted of an 8-m-long resonant cavity at 350 MHz taking protons to 6.7 MeV, with four vanes providing a significantly larger aperture and gap voltage in the accelerating section than all preceding RFQs. The tuning during operation was achieved with two independent cooling circuits for the capacitive and inductive parts of electrodes. To reduce the beam loss and optimize the needed RFQ length, a large aperture was maintained together with an increase in the vane voltage to counter the decrease in the transverse focusing strength as the vane modulation increased. Insufficient transmission and misleading measurements of current (input current surprisingly less than output current 8m downstream) were overcome with the addition of an electron trap in the LEBT right before the RFQ entrance and a reduction in the distance from the second solenoid from 30 cm to 15 cm which allowed adequate beam matching and transmission reliably >90%. Unexpectedly high activation values were measured at the high energy end of the RFQ; this gave signs of high beam losses at that location; by operating the RFQ with fields about 10% above the design value, the magnitude of the beam loss was reduced.

The interest in using superconducting structures is usually driven by space optimizations and operational costs, thanks to a dramatic reduction of power consumption, even considering the needed cryogenic power and cost of helium. Superconducting cavities present surface resistance scaling with ω^2, so RF power losses are non-negligible; however, these are several orders of magnitude lower than normal conducting ones. Their theoretical and practical development last 20 years, allows today's consideration of reaching the desired 40 MeV deuteron energies without an Alvarez-type Drift Tube Linac (DTL), which would operate in LIPAc possibly under impossible conditions. The use of superconducting cavities would allow an increase of the beam aperture, with beneficial impact on beam losses and equipment activation. The demonstration of the feasibility for $0.2<\beta<0.6$ proton beams [23] paved the way for a new operational window at even lower β, in a more reliable manner than Alvarez-type-based linacs for high currents. In the existing machines, the most used resonator type is the Quarter-Wave Resonator (QWR), preferred for its relatively low cost, easy mechanical assembly, and high performance at low-β [24]; however, the electric and magnetic dipole field components induced by the asymmetry of its shape, might cause beam undesired vertical steering. The Half-Wave Resonator (HWR) approach is similar to the QWR one, but their intrinsic symmetry cancels the QWR steering effect. This makes the HWR suitable for high current applications with low-β beams, keeping most of the QWR virtues without the main drawback. HWR also show improved mechanical vibration properties over QWRs [27]. Today, our technology is ready for the challenge, the recent successful operation of protons in CW mode through 176 MHz HWR superconducting cavities up to 4 MeV in SARAF [28] shows the way forward, however only 1 mA was reliably achieved. The conversion into beam thermal energy of free mismatch energy is the cause of the beam halo growth. In FMIT times, the best possible alignment of the equipment handled uncertainties of 100 µm, today alignment with those precisions is feasible, which presents an strong impact on beam halo growth mitigation.

CHALLENGES OF LIPAC

LIPAc will become the first of a kind in many technical aspects. It will be the first high power CW linac [2]. The technical design incorporates the best possible technology and available world accelerators knowhow. We aim at operating in CW 125 mA deuteron beam at 9 MeV, which means a huge step from what has been achieved to date. The implementation of lessons learnt from previous experiences in our design allows to facing the challenge with optimism.

The injector, developed by CEA Saclay, implements the ECR concept of Chalk River laboratories [21] (and successfully operated in SILHI since 1996 [29]) at 140 mA and 100 kV with a five-electrode beam extraction system. This performance settles the operational point slightly beyond present achievements. Two boron nitride disks protect the entrance of the waveguide and the plasma electrode from ion bombardment, and help to mitigate space charge phenomena. The extracted beam is matched to the RFQ entrance thanks to a dual solenoid focusing scheme; in turn, the transverse emittance values at the output of the LEBT <0.3π mm·mrad and 95% D+ fraction anticipates a transmission >90% at the 5 MeV output of the RFQ as per simulations [30,31]. The compressed 2.05 m long LEBT of LIPAc counts with two solenoids and H/V steerers, presenting a sector valve between them to minimize the distance of the 2nd solenoid to the entrance of the RFQ, where an electron repeller is located. In addition, an 8º cone is placed at the entrance of the RFQ to trap the metastable species that will minimize further beam losses in the RFQ.

The RFQ is a four vane structure resonating at 175 MHz with variable average aperture profile and ramped voltage [27]. It has been designed and constructed in Legnaro National Laboratories of INFN; with its 9.7 m long will become the longest, but its target 625 kW beam average power will remain slightly lower than LEDA's. The RFQ is subdivided in three super-modules with the cooling system adapted to this architecture, with two cooling circuits acting separately in the inductive and capacitive part for each of them, following the tuning approach successfully validated in LEDA for the first time [28]. The resonant frequency is controlled acting on the difference between vane and tank temperature. The shortcomings at low energies due to space charge effects led to choosing the high input energy of 100 keV with the aforementioned challenging emittance values, which will keep losses below 10% until the end of the "gentle buncher" and below 10^{-6} in the high energy part [32]. The validation of the tuning and stabilization procedures was established following low power tests on an aluminium real scale RFQ, which determined the mode spectra and the electric field distribution with the bead-pulling technique. The vacuum performance under operation is achieved with cryopumps, with their high pumping capacity for hydrogen.

SC technology can be efficiently used in pulsed proton high-power linacs as demonstrated at SNS; it can also be used in CW mode with low-β protons [28]. The baseline configuration defined in historical concepts of IFMIF for the deuteron beam acceleration from 5 to 40 MeV relied on a DTL. The technical feasibility of currents in the order of 100 mA in CW through Alvarez type structures exhibited possibly unsurmountable challenges [2]. The superconducting solution for the accelerator portion of IFMIF offered two main advantages compared with the more conventional DTL: a) linac length reduction (~10 m) and b) electrical power saving (~6 MW) with a positive impact on operational costs [33]. HWRs at 175 Hz and 4.5MV/m was the choice. The resonant frequency of the cavities will be mechanically tuned (range +30 kHz, resolution 200Hz). The RF couplers provide 200 kW maximum in TW mode to the HWR. The beam focusing and drive is performed by sets of superconducting solenoids/steerers and cryogenic beam position monitors interleaved with the HWR cavities.

Risks linked to uncontrolled beam halo when operating in the 100 mA region were already faced dramatically in FMIT, but experiments with LEDA in 2001 unravelled its origin [20]. Careful alignment of interfacing equipment and a dual beam core-halo matching approach developed under the EVEDA phase [34] will be implemented. To determine the beam halo along the SRF linac, cryogenic CVD μ-loss monitors have been conceived and their feasibility demonstrated by CEA Saclay. We intend to install three azimuthally on each of the eight solenoids interleaved the SC cavities. In addition, two scrapers with four movable jaws, also interleaved between the first three magnets of the MEBT [35], will stop the beam halo and potential out-of-energy particles coming from the RFQ. Each jaw is capable of withstanding a beam power of up to 500 W (2 kW per scraper). High current and low beam energy has demanded intense non-interceptive diagnostic development [36].

Optimal amplitude and phase stability of the beam is essential for an efficient beam transfer and minimization of beam losses. Microphonics, the changes in cavity frequency caused by coupling to vibration sources from the external world, might be encountered, typically they are enhanced at low frequencies in CW mode [22,26], but solutions could be implemented upon the identification of the source. The non-relativistic nature of low-β proton beam leads to a higher influence of the cavity field fluctuations driven by phase slippage as the beam traverses the consecutive cavities. The operation in pulsed mode during the commissioning phases and the tuning of the SRF Linac will likely become more difficult than CW mode operation due to the transients at the beginning of each beam pulse. Ponderomotive instabilities induced by Lorentz forces on the limited stiffness thin-walled cavities might be encountered, possibly however a careful design of the RF feedback and the LLRF should eliminate potential problems, even for the pulsed mode operation [37].

PROJECT ORGANIZATION

More and more, large scientific projects are of international nature through 'in-kind' contribution from various countries involved. Basically, all large accelerator and fusion projects nowadays under construction are of this nature, also future ones will. The coordination of these projects, generally framed by the settling of a new organization, presents inherent common difficulties. Remarkably, the Broader Approach is distinguished by the success on its three on-going 'in-kind' type projects (together with IFMIF/EVEDA, the superconducting tokamak JT-60SA under construction in Naka, and IFERC that, among other sub-projects, counts with the supercomputer HELIOS under operation in Rokkasho). The contributions are coordinated by the Implementing Agencies (QST and F4E), and defined by Procurement Arrangements and Secondment Arrangements (in Europe mainly backed by voluntary contributions from National Governments and defined by Agreement of Collaborations between National Institutions and F4E). In LIPAc, a reduced Project Team (PT) based in Rokkasho Fusion Center, together with both F4E and QST, form an Integrated Project Team (IPT). The reduced number of stake-holders in the project management, and the trustful and collaborative atmosphere we have developed, allows the IPT the efficient coordination of the project and continuous implementation of best possible efforts to enhance team spirit. In turn, an Integrated LIPAc Installation and Commissioning (ILIC) Unit, managed by a Japanese member of the Project Team to enhance communication, is full responsible of the activities related with our accelerator construction in Rokkasho. This team is formed not only by the PT members and Japanese Home Team members permanently on-site, but also by the members of the European Home Teams from the involved labs that are continuously visiting Rokkasho. Our successful experience shows that an efficient management of an ‘in-kind’ project demands trustful working dynamic and fluent communication channels among all parties. In addition, the project management shall manage to also build a trustful relation with its Governing Boards. Team spirit by the acknowledgment of all stake-holders of the sharing of the same goals is essential to reach, but this grows with project maturity. The team coordinating the project shall be generous in their effort, empathical with those who are designing and constructing the equipments and collaborative in all possible aspects with the involved National Institutes. The technical challenges ahead are enormous, but in IFMIF/EVEDA we are succeeding with all our mandate, that in the other validating activities, was also breaking through present technological borders. The efficient working dynamic we have managed to develop allows us to trust on also meeting our mandate for LIPAc within schedule and assigned budget.

CONCLUSION

The IFMIF/EVEDA project is a challenging endeavour, but we are succeeding in our difficult mandate, that goes beyond accelerator technologies. In what concerns these last, LIPAc, with 125 mA CW at 9 MeV will become 1st high power proton/deuteron linac. Best possible available technologies are implemented in the design. The high currents handled make beam halo issues become a concern, a beam core-halo matching approach has been developed [34]. The commissioning phases will be carried out with protons at half current and half energy than nominal operation with deuterons (same perveance), allowing hands-on maintenance. Amplitude and phase stability in the SRF Linac will be challenging, likely heavier in pulse mode during first stages of commissioning phases. A clever design of the LLRF is being implemented [37]. The injector developed by CEA is being successfully commissioned in Rokkasho during 2015 [38] and will continue through 2016. An operational point for protons in pulsed mode has been identified and matched with simulations [39]. The 9.7 m long RFQ developed by Legnaro National Laboratories of INFN is installed in Rokkasho, together with the MEBT developed by CIEMAT and the D-Plate jointly developed by CEA and CIEMAT. Beam commissioning at 5 MeV will start after its tuning and conditioning; the time required is difficult to anticipate, but it is expected to have both accomplished during 2016. The 1.6 MW RF power provided by its 8 RF power chains developed by CIEMAT, will be commissioned during 2016. The MEBT and D-Plate are already under commissioning in Rokkasho (see Fig. 2). The assembly of the SRF linac will start the during 2017 in a Clean Room ISO 5 in Rokkasho under the coordination of F4E. With the superconducting cavities already stamped by KHK, the challenge of accelerating the beam at 9 MeV, initially at 0.1% duty cycle, is expected to start by the end of 2017 for the full accomplishment within the project allocated time until December 2019. An extensive fiducialization of the LIPAc accelerator hall (> 120 fiducials and a survey pillar) allows us to reliably meet the alignment precisions within +/-100 µm [40] defined from beam simulations to keep beam losses within hands-on maintenance requirements [41]. We expect the approval for the construction of a Li(d,xn) fusion relevant neutron source to take place this decade to count with fusion relevant neutrons for materials characterization the second half of next decade, compliant with world fusion energy roadmaps.

Figure 2: View of LIPAc in Rokkasho with its D-plate, MEBT, the 9.7 m long RFQ and Ion source + LEBT.

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