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LIPAc, THE 125mA / 9MeV / CW DEUTERON IFMIF'S PROTOTYPE ACCELERATOR: WHAT LESSONS HAVE WE LEARNT FROM LEDA?

F. Scantamburlo, J. Knaster, Y. Okumura, IFMIF/EVEDA Project Team, Rokkasho, Japan
A. Kasugai, H. Shidara, JAEA, Rokkasho, Japan
N. Chauvin, R. Gobin, P.A.P. Nghiem, CEA Saclay, France

Abstract

The Engineering Validation and Engineering Design Activities (EVEDA) phase of IFMIF aims at running a 9 MeV / 125 mA / CW deuteron accelerator to demonstrate the feasibility of IFMIF's 40 MeV / 125 mA / CW accelerator with components mainly designed and constructed in European labs. LEDA was operated successfully in 1999-2001 as a 6.7 MeV / 100 mA / CW proton accelerator with high availability. The present paper assesses the experience gained in LEDA and explains how LIPAc, the IFMIF prototype accelerator, is inheriting its role of breaking through technological boundaries.

IFMIF

A fusion relevant neutron source is almost four decades long pending step for the successful development of fusion energy. In commercial fusion reactors, neutrons fluxes in the order of 10^{18} $m^{-2}s^{-1}$ with an energy of 14.1 MeV will occur, which will be absorbed in its first wall, a complex combination of layers of different materials that aims to maximizing the conversion of neutrons into thermal energy and breeding tritium, undergoing potentially >15 dpa_{NRT} per year of operation [1, 2]. This irradiation will degrade structural materials in a presently unknown manner. IFMIF, the International Fusion Materials Irradiation Facility, will generate a neutron flux with a broad peak at 14 MeV by Li(d,xn) reactions thanks to two parallel deuteron accelerators colliding in a liquid Li screen. The energy of the beam (40 MeV) and the current of the parallel accelerators (2 x 125 mA) have been tuned to maximize the neutrons flux and reach irradiation conditions comparable to those in the first wall of a fusion reactor and will allow qualification and characterization of suitable materials [3].

LIPAc & LEDA COMMONALITIES

IFMIF, presently in its engineering validation and engineering design activities (EVEDA) phase framed by the Broader Approach Agreement between Japan and Europe, will demonstrate the feasibility of its two 5 MW deuteron accelerators thanks to LIPAc, the Linear IFMIF Prototype Accelerator, that will accelerate a beam of deuterons at 125 mA current in CW with only the first superconducting accelerating stage up to 9 MeV, cloning IFMIF accelerators layout until that energy. The characteristics of LIPAc have been defined elsewhere [4]; in turn, the status of the other validation activities addressing the Target Facility and Test Facility have been recently described [5].

Whereas IFMIF target deuteron energy is 40 MeV, in the 90s of last century, APT, the Accelerator Production of Tritium project in the US aimed to accelerate in CW a beam of protons above 1 GeV up to a beam average power of 100 MW. Conceived for military applications, APT aimed at producing the needed tritium to efficiently maintain the nuclear defence capability, potentially degraded by the 5.5% annual decay to ^{3}He. However, being a back-up route of tritium production through commercial light water fission reactors, a decision to prioritize this last was taken on December 1998 [6]. APT accelerator was designed for minimum possible beam loss aiming hands-on maintenance supported on three aspects: 1) the 800-MeV LANSCE proton linac at Los Alamos, 2) a theoretical understanding of the dominant halo-forming mechanism, and 3) a conservative design maximizing beam quality at low energies and providing large apertures at high energies [7]. The strategy to minimize beam loss in APT was to produce a strongly focused matched high-quality beam in the low-energy normal-conducting linac, including an RFQ, as input beam at few MeV energy into large-aperture superconducting cryomodules; this established a new technology base for high-current CW proton linacs. To validate this aforementioned strategy, LEDA, the Low Energy Demonstration Accelerator, was designed, constructed and successfully commissioned reaching the target beam performance at low-β with 100 mA in CW at 6.7 MeV at the exit of an 8 m long RFQ. More than 110 h cumulative time at >90 mA in CW was achieved [8]. The successful demonstration early this century of the superconducting half-wave spoke resonators, originally conceived for heavy ions [9], for low-β proton beams [10] paved the way to our LIPAc concept to validate IFMIF's.

SPACE-CHARGE AND BEAM HALO

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. The motion of the particles in the beam depends both on external fields and on the particles self-fields. Interaction between intra-beam particles can be twofold: 1. driven by a smooth electric field from the combined effect of particles, the 'space-charge force', and 2. driven by binary collisions between close particles encounters. As early as 1991, it was already suggested that the most important potential cause of beam loss in the planned high-current linacs would be space-charge-induced growth emittance

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and beam mismatches halo enhancement [11]. In fact, in linacs, differently than in synchrotrons and storage rings, the beam spends a short time transiting, thus intra-beam scattering driven by individual collisions have typically insufficient time to develop; conversely, collective phenomena driven by space-charge forces become the main limitation to achieve high intensity beams. In low β-regions, the beam radial outward Gauss forces prevail over the inward radial Ampere ones through

$$F_r = e(E_r - \beta c B_\theta) = \frac{eE_r}{\gamma^2} \quad (1)$$

with E_r being linear with r for a cylindrical uniform charge density, but mutually cancelling in relativistic domain. By Liouville's theorem, the density in phase space of non-interacting particles in a conservative dynamical system along the trajectory of a particle is invariant [12], what leads to the conservation of the beam emittance, however the presence of non-linear space charge forces in non-relativistic beams can distort phase space contours and cause emittance growth leading to the formation of a low density beam halo surrounding the core of the beam. Beam halo plays a key role in high-current accelerators becoming the main driver for beam losses, which are to be minimized to remain below the convention for hands-on maintenance of 1 mSv/h at 30 cm distance of the equipment [13]. In general, one refers to the tails outside the beam core as beam halo; a consensus on its definition is not yet achieved though. Years of controversy on the underpinning physics were overcome thanks to the installation in LEDA, after the success of its initial APT's concept validation scope, of 52-quadrupole periodic-focusing beam-transport channel at the 6.7 MeV output energy of the RFQ that allowed 10 mismatch oscillations aiming at understanding the beam-halo formation. The experimental results support both models of free mismatch energy conversion into beam thermal energy, predicting a maximum emittance growth and of particle-core nonlinear parametric resonance, leading to maximum halo amplitude [14]. The beam core/halo different dynamics have recently led to a novel beam matching method [15]. Furthermore, a precise determination of their boundaries has been proposed, allowing the characterisation of the halo and the core independently [16].

Developing the intra-beam transverse equation of motion of an individual particle with (1), one can easily extract the dimensionless generalized perveance [17], K, as the figure of merit of the impact of space charge in the beam

$$K = \frac{eI}{2\pi\varepsilon_0 m_0 v^3 \gamma^3} \quad (2)$$

independent of the beam geometry and allowing a direct comparison of the relevance of space charge in different accelerators. Due to their very high beam intensity, LIPAc as well as IFMIF, followed by LEDA, will have by far the highest beam power at a given energy, and for a given beam power, its K is higher by at least two orders of magnitude compared to the most powerful linacs [15]. The high beam average power at low energies of LEDA and LIPAc is apparent in the next figure.

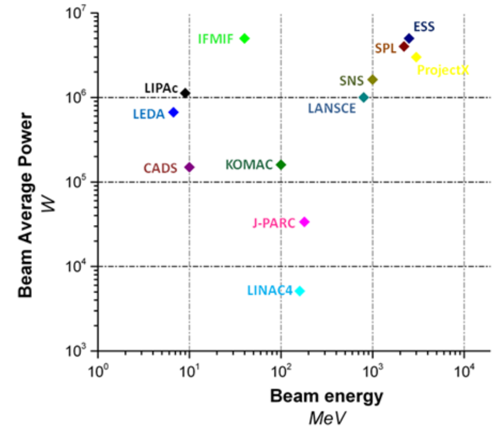

Figure 1: Beam average power of past, present (target performance) and planned linacs.

LESSONS FROM LEDA

LEDA's injector took advantage of the breakthrough of beam extraction performance on proton sources achieved by Chalk River team in 1991 [18] through Electron-Cyclotron Resonance (ECR) at 2.45 GHz, that doubling the proton fraction capabilities allowed proton currents above 100 mA with low emittance and enhancement of availability, potentially serving as direct input beam for the RFQ. LEDA injected a beam in the RFQ with >130 mA current at 75 keV with emittance values <0.20π mm·mrad and proton fractions >90%. No bending magnet to separate H_2^+ and H_3^+ from protons was present in the LEBT, which in turn, counted with two solenoids and steerers. A beam matching improvement was achieved by reducing the distance from the 2nd solenoid to the RFQ and the installation of an electron trap in the entrance of the RFQ to prevent electrons from flowing forward, and contributing to the space-charge compensation of the beam [19]. IFMIF's injector is mainly based on the experience gained by SILHI, the 2.45 GHz ECR ion source future injector of IPHI, under operation in Saclay since 1996 demonstrating availabilities above 99% [20]. Space-charge compensation was achieved by heavy ion injection [21]. In turn, the 2.05 m long LEBT of IFMIF counts with 2 solenoids and H/V steerers, presenting a sector valve between them to minimize the distance of the 2nd 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 D_2^+ and the metastable D_3^+ species that will minimize further beam losses in the RFQ. A beam performance within targeted specifications of 100 keV with currents >140 mA and emittance values <0.3π mm·mrad has been achieved during the acceptance tests in Saclay [22].

The first RFQ operated in CW was developed in the early 80s for FMIT (Fusion Materials Irradiation Test Facility), the main ancestor of IFMIF, which accelerated up to 2 MeV a H_2^+ beam [23]. The experience gained with CW high power beams from RFQs has been unfortunately very limited since [24]. LEDA's RFQ holds still today the

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record on beam average power with 670 kW, and will remain so long. LEDA's RFQ consisted of 8 m long resonant cavity excited in the TE21 mode at 350 MHz, with four vanes presenting significantly larger aperture and gap voltage in the accelerating section than all precedent RFQs. With constant focusing strength and constant gap voltage, as vane modulation increases adapted to the growing beam energy, the aperture must shrink and losses tend to increase; in addition, with the growing energy, the cell length increases, and for a given modulation, the accelerating gradient decreases. To reduce beam loss and optimize the RFQ needed length, a large aperture was maintained together with an increase of the vane voltage to counter effect the decrease in transverse focusing strength as the vane modulation increases. However, simulations indicated that small perturbations would distort the field distribution, thus, four 2-m-long RFQs were resonantly coupled to form the 8-m-long LEDA RFQ [25]. In turn, the resonator of IFMIF RFQ is a four vane structure resonating at 175 MHz with variable average aperture profile and ramped voltage [26]. With its 9.6 m long will become the longest, but with 625 kW beam average power, 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 [27]. The resonant frequency is controlled acting on the difference between vane and tank temperature. Given the similarities between LEDA and LIPAc's RFQ, the RF conditioning scheduled on 2015 should require similar timing; LEDA succeeded within 4 months [28]. Furthermore, better vacuum performance under operation is expected thanks to the cryopumps present in LIPAc.

CONCLUSIONS

The developments towards the realization of the 100 mA in CW and 1 GeV beam energy linac related with APT in the 90s were not fruitless despite its cancellation. The success of LEDA, its validation accelerator prototype [8] and the ensuing validation of superconducting half-wave spoke resonators for low-β proton beams [10], both in Los Alamos, paved the way to LIPAc's concept, which inherits from LEDA the role of breaking through present linac technological borders. The interest in the community of the technological successes of LEDA led to a vast quantity of thorough publications that allow us to anticipate possible scenarios during the soon arriving LIPAc commissioning and operation phases giving us confidence in the success of our efforts towards the validation of the concept of IFMIF's accelerator. LEDA aimed at its end, unsuccessfully, to be upgraded and serve as deuteron accelerator for an early neutron source to fill the gap until IFMIF was constructed [29]. It was not possible, but we are indebted for their efforts.

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