ESS-Bilbao light-ion linear accelerator and neutron source: design and applications

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ESS-Bilbao light-ion linear accelerator and neutron source: design and applications

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Abstract. The baseline design for the ESS-Bilbao light-ion linear accelerator and neutron source has been completed and the normal conducting section of the linac is at present under construction. The machine has been designed to be compliant with ESS specifications following the international guidelines of such project as described in Ref. [1]. The new accelerator facility in Bilbao will serve as a base for support of activities on accelerator physics carried out in Spain and southern Europe in the frame of different ongoing international collaborations. Also, a number of applications have been envisaged in the new Bilbao facility for the outgoing light ion beams as well as from fast neutrons produced by low-energy neutron-capture targets, which are briefly described.

1. Introduction

The ESS-Bilbao (ESSB) light ion linear accelerator has been conceived as a multi-purpose machine, useful as the core of a new standalone accelerator facility in southern Europe giving support to local beam users and accelerator physicists, as well as fulfilling specifications so as to serve as a driving injector for the European Spallation Source (ESS) once this latter project gets off the ground.

The ESSB project aims to develop significant in-house capabilities needed to support the country participation in a good number of accelerator projects worldwide (IFMIF/EVEDA, LINAC4/SPL, FAIR, XFEL, ESRF upgrades, ISIS-FETS etc.). In this context, the designed modular, multipurpose accelerator should serve as a benchmark for components and subsystems relevant for the ESS project as well as to provide the Spanish science and technology network with hands-on experience on power accelerators science and technology, a task long overdue. Likewise, local specialised industry who has identified a number of opportunities within this niche of activity, should also largely benefit from the new facility.

This document reports on the current status of the ongoing projects aimed at building the first, normal conducting section of the accelerator as well as a test cryomodule comprising two superconducting spoke resonators which would demonstrate the feasibility of this technology under beam in the second section of the linac. Also, some foreseen applications of the generated light ion and neutron beams are summarised. The current concept entirely deals with a proton/H^- accelerator facility, being the possibility of using a common injector both for protons and low-energy deuteron beams under study.

2. Proton/light ion linac design

The basic parameters of the Bilbao accelerator are shown in Table 1. All the accelerator structures either planned or under development at present are meant to satisfy the stringent ESS demands [1], so that the developed technology could be eventually used in the lower energy part of ESS linac. The only pending decision on the normal conducting components of the machine refers to the possibility of including a second line for accelerating deuterons to low energies, in addition to the ordinary proton acceleration line. The advantage of deuterons with respect to protons is the high neutron yield when impinging on targets with moderate energies and the remarkable angular dependence of the fast neutron spectrum, which can be very useful in many contexts, as is the case for instance of Nuclear Physics applications. The current status of the linac components is described in the following.

Table 1. ESS Bilbao proton accelerator main parameters.

Max. proton current	90 mA
Max. final energy	300 MeV
Max. beam power	75 kW
Max. repetition rate	50 Hz
Pulse length	1.5 ms
Bunch frequency	352.2 MHz
Max. cavity gradient	9 MV/m

2.1. Ion sources

The first Bilbao ion source is now close to completion and to start commissioning. It comprises an H^- Penning-trap source based upon the ISIS-FETS design [2] able to deliver a 70 mA ion beam in pulses of up to 1.5 ms duration and typical repetition rates of 50 Hz. A comprehensive set of diagnostics which includes current measuring devices such as AD and DC current transformers and a Faraday cup, a retarding potential analyzer for determination of particle energy, a beam emittance monitor of pepperpot type and a CCD camera have already been installed within a diagnostics vessel. Stable proton production started in early spring 2010. Figs. 1 and 2 display the hydrogen plasma pulses framed by the oscilloscope and the characteristic hydrogen plasma luminescence.

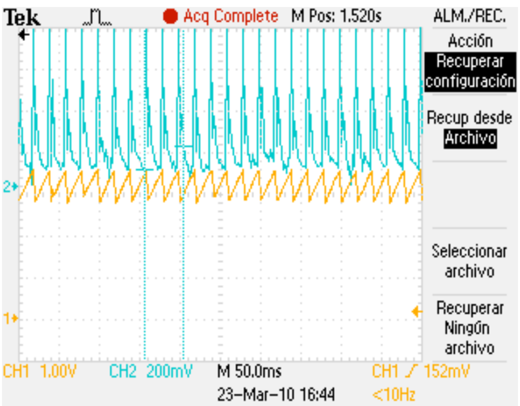

Figure 1. Plasma pulses in the H^- ion source.

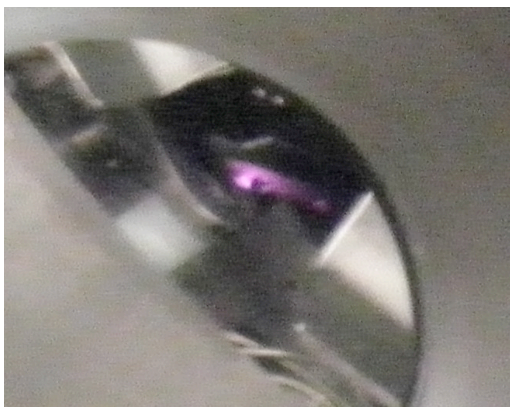

Figure 2. Hydrogen plasma luminescence in the H^- ion source.

In parallel with the development of the H^- source, the construction of a new pulsed, proton/deuteron ECR source is underway following a design as sketched in Fig. 3. Here, plasma formation proceeds via sequential electron impact ionization. Plasmas are confined for times of the order of 10 ms under an applied field the magnitude of which is roughly given in tesla units by B= f / 28, where f stands for the RF frequency. Here we have chosen to operate in fully pulsed operation using and S-band klystron with f = 2.7 GHz and able to deliver up to 1.2 kW of RF power. The rationale of using a klystron rather than a conventional magnetron as other sources do is to get better adapted to the pulsed regime as well as to increase the useful critical plasma density, which depends on the RF frequency as f^2.

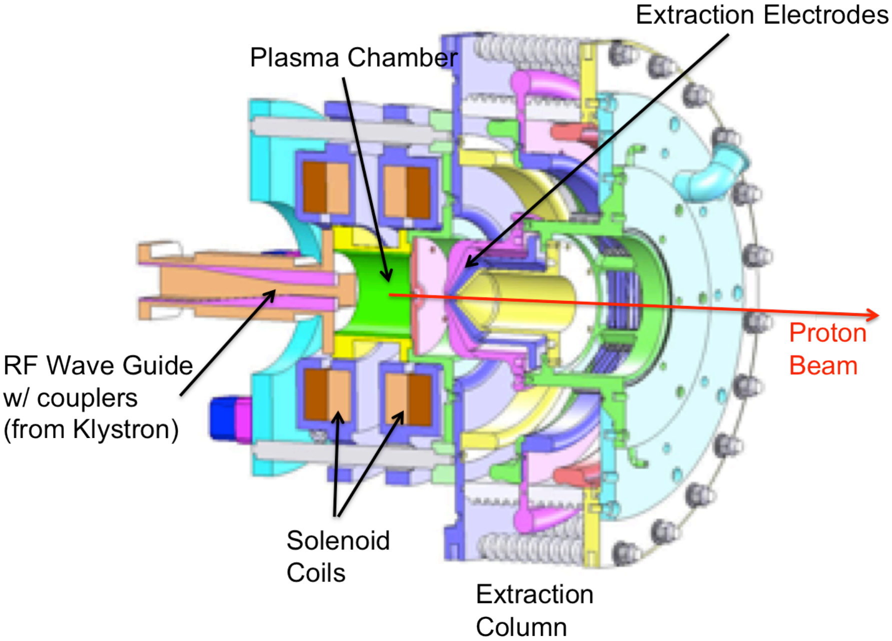

Figure 3. Design of the H^+ microwave-driven ion source.

2.2. Low energy beam transport (LEBT)
The goal of the LEBT is to transport the beam from the ion source and to fit it into the acceptance of Radio Frequency Quadrupole (RFQ). Beam dynamics simulations on beam transport through this structure can be carried out using a linearised version of the Kapchinskij-Vladimirskij equation [3] or using general particle tracking codes. The Bilbao LEBT will be based on a four-solenoid design using for the purpose a set of magnets and corresponding PSUs, which are a slightly rescaled version of those previously built and operated at RAL as a part of the on-going Front End Test Stand collaboration [2]. This long design for the LEBT is needed to enhace its versatility so that it can successfully handle H^+, H^- and D^+ beams which requires to fully control the four degrees of freedom of beam transport. Also, both the beam generated in the microwave driven proton source and general non-axially symmetric beams such as that produced by the Penning source and other possible sources need to be focused by the LEBT. The structure is thus built using four magnets which incorporate built-in Lambertson dipoles for beam steering as well as the relevant diagnostics equipment as shown in Figure 4. The LEBT has been designed also to stand a good vacuum, which is essential to minimise stripping losses of the H^- beam and to tightly control charge compensation processes.

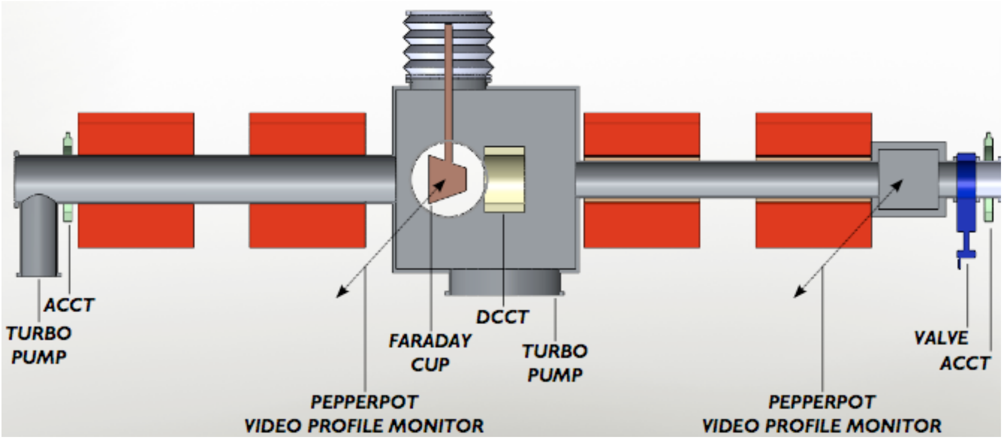

Figure 4. Four-solenoid LEBT and diagnostics.

2.3. Radio Frequency Quadrupole (RFQ)

To meet the challenging requirements of MW range spallation sources [1], the RFQ is a key element. Extensive numerical calculations involving particle dynamics within the RFQ, together with electromagnetic design and thermal and mechanical simulations of the resonant structure are currently being carried out in the frame of an international collaboration with RAL, Imperial College, ASTeC, Warwick University and University of the Basque Country (UPV/EHU). The Bilbao RFQ will thus be essentially a rescaled version up to 352.2 MHz of the one at present under development at ISIS/Imperial College (324 MHz). The design contains a minimum amount of brazing thus enabling proper maintenance and repairs, while simultaneously guarantees robust performance fulfilling specifications as to eventually serve as injector for the ESS.

The concept considers four 1m long resonantly-coupled sections of 4-vane structures (4m total length) coupled through two coupling cells delivering a beam of 3 MeV and a maximum current of 100 mA on output, having normalized output emittances not larger than 0.20 [π-mm-mrad] for both horizontal and vertical directions and a longitudinal emittance of 0.30 [π-mm-mrad]. The required RF power comes to be about 1 MW to be delivered by a single klystron, out of which some 380 kW go to the beam. The aperture radius which may take values between 3.8 mm and 4.3 mm and the vane voltages which are distributed from some 80 kV up to 130 kV provide the conditions for a transmission better than 95 %.

2.4. Drift Tube Linac (DTL)

The last normal conducting structure in the Bilbao linac to accelerate protons up to energies above 3 MeV is three-tank Alvarez-type DTL which should be able to raise the beam up to a final energy of 40 MeV. The design upon we rely on is an adaption of that developed for the Linac4 project which employs a FOFODODO lattice made upon permanent magnets of some 45 mm in length and able to provide a gradient of 55.5 T m^{-1}. The first tank with a length of 4.6 m and a bore radius of 10 mm provides a beam with a final energy of 13 MeV and second and third with lengths of 5.12 m and 4.87 m yield energies at their output of 27.3 MeV and 40.5 MeV respectively. The tanks comprise sets of drift tubes suspended from a girder by a single cylindrical structure in numbers of 45, 30 and 22 for the three three tanks respectively. A recent agreement with CERN to support the Linac4 project by participating in the construction of their machine will help us to adapt their design to our purposes. All the drift tubes and permanent magnet quadrupoles both for Linac4 and our own accelerator will thus be developed in the Bilbao area.

Every DTL tank is powered by a single klystron. Beam dynamics simulations with different beam currents and codes depict a well matched beam with emittances within specification even tough a chopper line right after the RFQ may be necesary to provide enough flexibility to match different currents into a DTL with fixed magnetic gradients. The main advantage of using permanent magnetic quadrupoles to provide the transverse focusing is that they reduce the cost of the focusing system, simplify the assembly of the drift tubes, and raise the shunt impedance by enabling smaller drift tube diameters. A relatively high accelerating gradient has been adopted in the DTL (3.3 MV/m the first tank and 3.5 MV/m in tanks 2 and 3) in order to reduce its length.

2.5. Superconducting section

The superconduting section of Bilbao linac will drive the protons from 40 MeV up to 300 MeV, and will be based on double and triple-spoke resonators which have been already designed [4]. A double-spoke cavity aluminium cold model of such design (shown in Figure 5) has been built and its accelerating fields and RF response have been measured and contrasted with the design codes prediction. Room temperature tests of tuners and couplers for these resonators are on the way. Also the aim for the coming period is to develop a trial cryomodule containing a basic acceleration cell comprising two niobium resonators and a superferric focusing element. An ongoing collaboration with ACS (France) has recently taken off the ground aiming to produce the first prototype of such cryomodule in the near future, which could allow us to test spoke cavities under beam for the first time.

Figure 5. Double-spoke resonator cold model.

3. Proton and neutron envisaged applications

Both proton and neutron beams are expected to be used by a local user community showing an ever increasing interest in using charged particle beams for several disparate branches of physical and biomedical sciences.

Foreseeable applications of proton beams, by the three beam ports at 3 MeV, 20 MeV and 40 MeV are geared towards applications within:

- Proton Beam Lithography
- Ion Beam Analysis (PIGE, ERDA, PIXE…)
- Ion Track Technology
- High-energy TOF-SIMS
- Experimental radiation therapy on living cells and tissues
- Radiation Biology, particularly within the field of radiation controlled mutagenesis.

Foreseeable applications of neutron beams are focused onto:

- Development of Reflector/Moderator engineering concepts,
- The use of thermal and cold neutron beamlines for,

- Development of neutron detectors suitable for spallation sources,
- An instrument training station,
- A beampost for developing neutron velocity selectors and other neutron optics equipment.
- Fast neutrons beam ports are also envisaged to develop applications,
- On fast-neutron Time-Of-Flight geared towards the measurement of cross sections of nuclei of interest within Nuclear Astrophysics and other areas of basic nuclear science,
- Devoted to metrological application to calibrate fast neutron detectors,
- Involving experiments on neutron propagation in inert media such as Pb, or graphite,
- To study the kinetics of subcritical systems.

From the list given above, let us emphasize that typical applications of proton beams will focus on their use for materials science purposes (lithography, micro-processing of ultrahard materials, irradiation treatments for semiconductors etc.) as well as for some selected applications within the biosciences). In turn, a low-energy (40 MeV) target for (p,n) reactions on light solid materials (^{9}Be, ^{7}Li) is at present under conceptual development. Such a target is able to provide significant neutron fluxes according to some preliminary calculations with results shown in Table 2. Rather than geared towards experiments on Condensed Matter Sciences its main applications are within the field of general neutron instrumentation. In addition, the development of such a target will also fill an increasing gap felt by the Nuclear Physics community dealing with a range of topics going from measurements of neutron cross-sections to applications in Astroparticle Physics [5].

Table 2. Neutron yield (n mA^{-1} sr^{-1}) at different angles for 40 MeV protons on a Be target.

Angle	0º	15º	40º
0 < E < 10 MeV	3.30 10^{13}	3.17 10^{13}	2.48 10^{13}
10 < E < 20 MeV	3.91 10^{12}	4.25 10^{12}	3.14 10^{12}
20 < E < 30 MeV	2.35 10^{12}	2.15 10^{12}	1.06 10^{12}
30 < E < 40 MeV	1.64 10^{12}	7.17 10^{11}	1.58 10^{11}
Total	4.08 10^{13}	3.87 10^{13}	2.90 10^{13}

As a general conclusion application-wise it is very remarkable the fact that just the normal conducting section of the accelerator, which is well in its way and is expected to be ready in a few years, should be enough to begin doing serious science in the new Bilbao facility and give service to a large number of users. As far as neutron production is concerned, the neutron yield figures displayed in Table 2 show that a great variety of applications supporting an ever growing user community can be envisaged.

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