A SUPERCONDUCTING PROTON LINAC FOR THE ESS-BILBAO ACCELERATOR*

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Abstract

A revised layout for the proton linear accelerator as proposed by the European Spallation Source-Bilbao (Spain) bid to host the installation is here described. The new machine concept aims to incorporate advances which have been registered within the field of high power accelerators during the last decade. Particularly relevant are the ongoing works within Magnetic Fusion activities (IFMIF/EVEDA), waste transmutation (EUROTRANS) or radioactive ion beam (EURISOL) and heavy-ion physics (FAIR, SPIRAL2) which have lead to significantly shorter accelerators incorporating state-of-the-art technology which mainly replaces decades-old copper (normal-conducting, NC) drift-tubes, coupled-cavity LINACs or some other accelerating structures employed for energies beyond $50\,MeV$ or so by superconducting cavities (SC) of a wholly new kind. In addition, the development of a brand new H^- injector for LHC known as LINAC4 offers the possibility of profiting from clear synergies between the two projects, particularly regarding front-end elements such as the radio-frequency quadrupole and low-energy drift-tube LINAC (DTL). The design of such a new accelerator layout will be critically dependent upon the development and/or adaptation of low β superconducting cavities already developed for some of the referred projects into those adequate for pulsed operation and high duty cycle.

THE ESS-BILBAO ACCELERATOR CONCEPT

The current ESS-Bilbao (ESS-B) proposal complies with the basic machine specifications contained in the ESFRIfiche published within the ESFRI 2006 Roadmap on Research Infrastructures [1]. This comprises a phased approach starting with the construction of a linear accelerator providing $2\,millisecond$ pulses of $1.334\,GeV$ protons which impinge on a liquid metal target with an average beam power of $5.1\,MW$, 16.67 times per second. A maximum of 20 instruments could possibly be accommodated all around the equatorial plane of this target station. The latter is by design optimized for the production of long-wavelength neutrons which will largely benefit studies on most areas of the Condensed Matter Sciences to address problems requiring low energy-transfers under relatively high signal/noise ratios. A second target station, able to feed some other 20 beam-lines will have to be built during a second construction phase. As initially planned it will consist on a liquid metal target fed by $2 \times 0.6\,microsecond$ pulses at a frequency of 50 times a second and similar beam energy and power.

The ESS *Reference Linac*

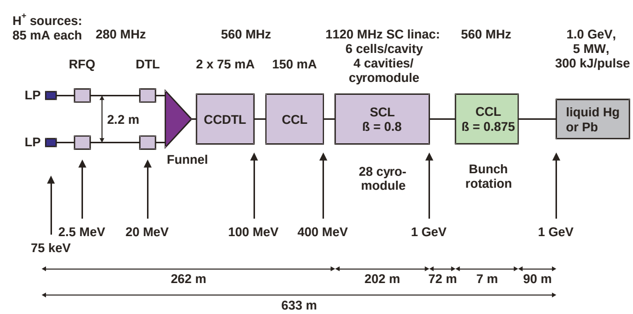

Figure 1: Schematic view of the ESS accelerator as proposed in Refs.[2] and [3].

Our present layout adheres to suggestions made by ESS-Initiative, and seeks to enter a full baseline design phase for a machine based upon a $150\,mA$ H^+ proton beam current. In the original documents, which are the 2003 Technical Report [2] as well as by recent update [3], such intensity is to be delivered by a tandem of two proton ion sources of some $85\,mA$ each funnelled after the two beams are accelerated up to about $20\,MeV$. As schematically shown in Fig.1, acceleration up to $100\,MeV$ is provided by a Coupled Cavity Drift Tube (CCDTL) followed by a Coupled Cavity Linac (CCL) which aims to provides acceleration up to $400\,MeV$.

Further acceleration up to $1\,GeV$ is provided by a SC section which comprises a set of 28 cryo-modules with $\beta = 0.8$ having four cavities per module and six cells per cavity. Modest gradient of some $10.2\,MV/m$ are projected for such a section. Finally, a coupled-cavity Linac for energy-ramping and/or bunch rotation with $\beta = 0.875$ is positioned $72\,m$ downstream of the LINAC end. Its main

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purposes are to reduce the energy spread to about $\pm 2\,MeV$ at the injection into the transport to target line, as well as to allow the installation of a dipole magnet somewhere within the $90\,m$ beam transport line in order to reduce the flux of back-streaming neutrons. Such cavity for bunch rotation (BR) is excited by a $20\,MV$ rotation voltage and $3.5\,MW$ peak RF power.

As far as the operation frequencies are concerned, the front-end, NC LINAC the SC LINAC abd the BR cavity, as sketched above have as working frequencies those already published [2]. These are $280\,MHz$ for the front-end, $560\,MHz$ for the NC LINAC and BR cavity and $1120\,MHz$ for the superconducting section, which makes some three frequency jumps.

The ESS-B *alternative design*

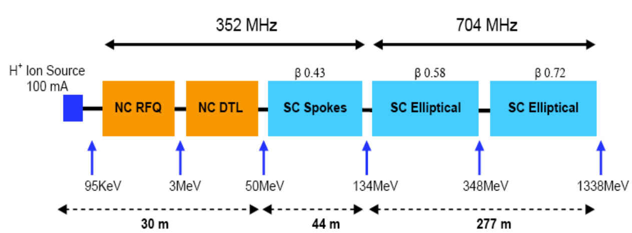

Figure 2: The proposed ESS-B superconducting proton accelerator.

The main thrust towards seeking alternative and an up to date design for the ESS-B accelerator is grounded upon two facts. First, successful operation of MW neutron sources such as the Spallation Neutron Source at ORNL has shown that SC technology is nowadays a proven thing for MW-range neutron sources and indeed, transition from warm to SC acceleration takes place at $186\,MeV$ and a set of 23 cryomodules yields a $1\,GeV$ beam [4]. Moreover, current activities developed during the last few years within several Europe-wide initiatives such as the CARE (Coordinated Accelerator Research in Europe) and EUROTRANS (TRANSmutation of High Level Nuclear Waste in an Accelerator Driven System) programmes which have resulted in very significant advances in both ion source and low-energy acceleration technologies which will surely have a relevant impact on the proposed accelerator design. Such advances which have taken place well after the ESS reference design was published have shown that:

- Low β, superconducting cavities came forward as an alternative to classic Alvarez-type DTL tubes [5], and in fact, these are considered nowadays to be the technology of choice for a wide range of accelerating energies, $0.1 < \beta < 0.6$.
- Superconducting TEM-class cavities have RF losses some 100 times less than conventional copper cavities and thus provide an economical and efficient use of RF power which is not offset by the expense incurred in cryogenic systems operation. In addition, if compared with NC LINACs, they provide a larger beam aperture, enhanced mechanical stability due to operation at cryogenic temperatures as well as negligible beam steering effects. Furthermore, by construction they are highly modular structures which can be controlled independently [8, 9, 10].
- Funnel structures such as that appearing in the figure above constitute one of the most complicated parts of the accelerator. In fact, although the principles of the proposed funnel scheme were advanced a long time ago, there is no similar piece of equipment operating in the world today. Its expected performance results from compensation of several effects (space-charge, beam rigidity, etc.) and therefore the development of such a funnel concept will involve a substantial R&D effort which could be avoided if a single proton source providing the whole current were available. Contrary to statements contained in Ref.[3], we do believe that there is nowadays a firm basis to develop an ECR proton source meeting the required specification.
- Recent estimations for construction and operational costs for the superconducting option for IFMIF [11], show that up to 20% of the accelerator capital costs could be reduced if low β cavities of spoke, half- or quarter-wave geometries are adopted instead of conventional normal conducting DTL tubes. In addition, a cost reduction of 9% has been estimated for the operational period. While such estimations should not be taken at their face value, because of a number of unstated uncertainties, they do conform with recent experience from SNS where it is found that the cost of the superconducting option was found to be comparable to that for the warm machine.

SOME PENDING R&D ISSUES

The arguments given above seem to us to be explicit enough so that a number or activities need to be started towards the exploration of a baseline design which incorporates up to date advances in superconducting technologies. In some more detail, our current tasks comprise the evaluation of,

I) The use of a single proton source capable to deliver proton currents of $150\,mA$ or above. Prototypes for such proton injector, delivering some $5000\,hours/year$ with low downtimes have been reported in the literature [6]. Proton sources such as SILHI at CEA have already produced currents of $130\,mA$ at low duty factors [7]. The rationale behind such an effort stems from the possibility of avoiding the use of the funnel section which still constitutes one of the main show-stoppers of the 2003 concept, and has not changed up to this very day.

II) The use of superconducting TEM-class cavities (half-wave, quarter-wave re-entrant, CH etc.) for medium energy ($20\,MeV$ $100\,MeV$) acceleration. The technology has already been developed, mostly geared towards applications within IFMIF and SPIRAL2 projects and could provide a cost effective substitute for the copper cavities both in terms of fabrication and operation, since as can be gauged by comparison of both schemes herein shown, the total length of the accelerator would be significantly reduced.

III) An additional issue concerns the possible synergies with ongoing accelerator projects such as LINAC4 [12]. Since we could easily adopt CERN frequencies of $352\,MHz$ and $704\,MHz$ and a sole frequency jump, we see no reason why ESS-B could not profit from well advanced equipment already under construction stages such are the RFQ and low-energy DTL.

The schematic view of the proposed ESS-B accelerator profits from ideas developed at CEA/SACLAY and is shown in Fig.2. Its main features if compared to the present ESS Reference design are:

• By choosing frequencies of $352\,MHz$ and $704\,MHz$, important synergies with LINAC4 are found. The design of both the new $3\,m$ RFQ and the 3-tanks DTL composed by 110 drift tubes with a total length of $18.7\,m$ can be readily incorporated into the ESS-B baseline.

• A transition into a SC section composed by low $\beta = 0.43$ cavities is set after reaching an acceleration within the normal conducting LINAC of $50\,MeV$. Such transition does not represent a serious challenge. In fact some current designs such as that for EURISOL contemplate a series of half-wave resonators with $\beta = 0.09$ and $\beta = 0.15$ right after the RFQ, followed by a set of 3 spoke cavities with $\beta = 0.3$ which have and incoming beam of $60\,MeV$.

• The total length of the LINAC is reduced to 351 down from the $633\,m$ of the reference specification.

• Accelerating gradients of $8\,MV/m$, $12\,MV/m$ and $16\,MV/m$ are required to drive the three SC sections of the accelerator. These are to be compared with the mark of $10.2\,MV/m$ set in the reference specification but should be considered as rather moderate if compared with the physical limit for bulk Nb $\approx .\,50\,MV/m$ or that of $30\,MV/m$ which is considered as safe as far as field emission.

• The requirements for power couplers comes to be of $1\,MW$ which is comparable to that quoted in the reference design [3]. Couplers have been tested up to $2\,MW$ at SNS and J-PARC and should not present insurmountable difficulties even if a power of $1.5\,MW$ is sought.

• The ESS-B concept involves only one frequency jump, contrary to the three required by the reference specification. While methods to handle such discontinuities have been devised [13], such abrupt transitions induce some unwanted effects which should be avoided as much as one can.

• Its built-in highly modular structure enables fast dynamic compensation of cavity failures, which allows those cavities adjacent to the failed unit to be retuned without having to stop the beam [14], which provides a firm ground for highly reliable operation of the LINAC.

There are a number of pending issues to which attention needs to be paid and which will require significant development and prototyping efforts. To start with, at the time of writing the maximum allowable proton current coming out of an ECR for production purposes is of the order of $100\,mA$. An increase up to $150\,mA$ will surely require a redesign of the SILHI source to cope with space charge effects.

The quest for competitive low β cavities hinges on state of the art technology dealing with the stringent requirements in the manufacture and post-processing of such devices. The issue of choosing the most suitable device is expected to be settled in the coming months. Also, halo or electron cloud growth [15] should be of concern due to the high currents involved. For such an avail, experience gained within the electron cloud experiments carried out for LHC will for sure be of much help. Finally, extensive multi particle beam dynamics calculations need to be carried out in order to investigate the role of coupled bunch instabilities which should be controlled using active feedback systems.

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