BASELINE DESIGN FOR THE ESS-BILBAO SUPERCONDUCTING PROTON ACCELERATOR*

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Abstract

A baseline design for the proton linear accelerator as proposed by the European Spallation Source-Bilbao bid (ESS-B) to host the installation is here described. The new machine concept profits from advances registered within the field of high power accelerators during the last decade. The design of such a new accelerator layout heavily relies upon low-medium beta superconducting spoke resonators which are already under development.

INTRODUCTION

The present paper addresses a revised layout for the proton linear accelerator proposed as a driver for the European Spallation Source (ESS). A recent workshop held at Bilbao (Spain) [1] has resulted in a thorough revision of the machine concept as described in the ESFRI fiche [2] and has arrived to an agreement concerning the general *linac* parameters which are summarized in Table 1. Compared to previous specifications $(5\ \mathrm{MW}, 1\ \mathrm{GeV}, 150\ \mathrm{mA}, 16.7\ \mathrm{Hz})$, the current parameter set proposes a stepwise increment of the proton current starting at $70\ \mathrm{mA}$ which has been decreased from the original proposal of $150\ \mathrm{mA}$ in order to simplify the *linac* design and to increase its reliability. Apart from that, the final energy has been increased, keeping the footprint of the accelerator the same by increasing the accelerating gradient. The pulse length has been decreased down to a maximum of $1.5\ \mathrm{ms}$ to ease the demands on beam physics as well as due to requirements from the neutron community, and the repetition rate has been increased to $20\ \mathrm{Hz}$. The later modification enables to keep the average pulse current low and also serves to avoid possible problems related to operation at $1/3$ of the grid power frequency. Finally, and for the users point of view, the pulse and repetition rate also suffice all their requirements.

The tentative *linac* parameters given above are consistent with SRF technology available today or that is expected to be in a 2 to 3 year period. No fundamental issue has been identified even if there is still a large amount of work that remains to be done toward the engineering of various components.

The design of such a new accelerator layout will be critically dependent upon the development and/or adaptation of low and medium β superconducting cavities already developed for some of the referred projects into those adequate for pulsed operation and high duty cycle. The current paper elaborates on concepts perviously discussed [3]. We here present the first steps towards the fulfillment of the recommended parameters during the recent workshop [1]. This new machine concept aims to incorporate advances which have been registered within the field of high power accelerators during the last decade, and particular synergies have become evident concerning efforts being carried out to provide a higher brightness injector for LHC at CERN within the Linac4/SPL project.

Table 1: General Linac Parameters

Parameter	Value
Ion Species	H^+
Beam Power	5 MW
Repetition Rate	20 Hz
Beam Pulse Length	1.5 ms
Beam Energy	2.2 GeV
RF Frequency(Front end /High energy)	352.2 MHz / 704.4 MHz
Maximum peak power per cavity	1.2 MW
Cavity Gradient(@β=1)	15 MV/m
Average pulse current	75 mA
Transition energy to SRF	40∼50 MeV

SPOKE CAVITY SECTION

There has been considerable progress in the development of superconducting cavities for both low-to-medium and high β regimes. Particularly important are developments concerning cavity technology for rather low $(\beta \leq 0.1)$ energies based upon spoke- half-wave-resonators or CH structures. The technology has already been developed, mostly geared towards applications within IFMIF, EURISOL, EUROTRANS and SPIRAL2 projects and could provide a cost effective substitute for the copper cavities both in terms of fabrication and operation, since the total length of the accelerator would be significantly reduced. Our current design considers a transition into a SC section composed by low $\beta = 0.35$ double-spoke cavities (DSR) after reaching an acceleration within the normal conducting *linac* of $50\ \mathrm{MeV}$, followed by a set of triple-spoke cavities (TSR) with $\beta = 0.59$ which have and incoming beam of $150\ \mathrm{MeV}$.

* Work supported by ESS-BILBAO
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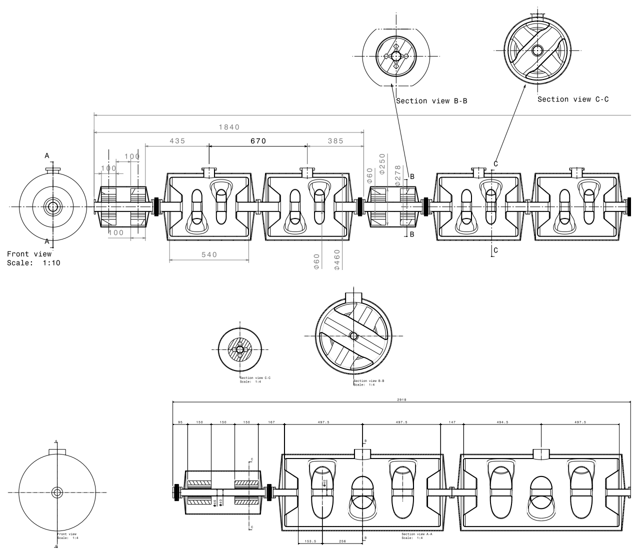

Figure 1: Upper frame: Super-ferric quad doublet and $\beta_g = 0.35$ DSR cavity layout. Bottom Frame: Super-ferric quad doublet and $\beta_g = 0.59$ TSR cavity layout.

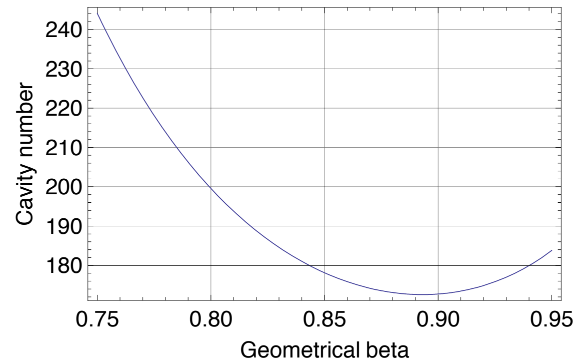

Figure 2: Number of 5 cell cavities required to accelerate the beam between 450 MeV and 2.2 GeV as a function of β_g. A value of E_o of 25 MV/m and a synchronous phase of -25^o have been assumed.

ACCELERATION BY A MULTICELL ELLIPTICAL CAVITY

Analytical Method

The modification in the initial (140 mA|1.4 GeV|2.0 ms|16.7 Hz) for a more reliable (75 mA|2.2 GeV|1.5 ms|20.0 Hz) configuration [1] motivated the authors to question, wether maintain or go for a different configuration in order to fulfill the new requirements. Based on this, we present a basic but powerful study to approach to the new elliptical cavity design requirements.

The on axis electric field of an N cells elliptical cavity of peak field E_o may be approximately represented, neglecting the beam pipes at the ends, by a sinusoidal of N half periods.

$$E_z(z) = E_o \sin\left(\frac{2\pi z}{\beta_g \lambda}\right) \tag{1}$$

Where we consider the origin at the beginning of the first cell. The maximum acceleration of a particle of speed β, may be integrated [4] analytically to obtain:

$$V(\beta) = \begin{cases} E_o \frac{\beta^2 \beta_g \lambda}{\pi\left(\beta^2 - \beta_g^2\right)} \cos \frac{N\pi\beta_g}{2\beta} & \text{if } N \text{ is odd,} \\ \\ E_o \frac{\beta^2 \beta_g \lambda}{\pi\left(\beta^2 - \beta_g^2\right)} \sin \frac{N\pi\beta_g}{2\beta} & \text{if } N \text{ is even.} \end{cases} \tag{2}$$

For a non-ultrarelativistic beam, the speed of the particles varies along the *linac*. Therefore, ideally, each multicell cavity would have a different β_g so as to operate near the optimum regime. However, this would require each cavity to be different (large number of different spares), entailing an increase in the capital cost of the *linac*. From the practical point of view, it is desirable to reduce the number of different cavities —actually, of different cryo-modules, so as to reduce capital costs and increase the repairability of the machine.

The energy gain per cavity can be expressed as $W_{n+1} - W_n = eV(\beta)$, where n is the cavity number. This equation may be approximated by a continuous differential equation where the number of cavities required to accelerate the beam between two given velocities can be calculated as follows:

$$n(\beta_g, \beta_1 \rightarrow \beta_2) = \int_{\beta_1}^{\beta_2} \frac{\cos\phi_s}{eV(\beta)} \frac{m_0 c^2 \beta}{\left(1-\beta^2\right)^{3/2}} \, d\beta \tag{3}$$

In order to continue, we need to fix the number of cells we are going to use, as always there is a compromise, the more we use the narrower our gain function will be, and therefore the less flexible it becomes. Furthermore, in order to avoid the monopole HOM within the pass band induced by even cell cavities. We believe $N = 5$ represents a good compromise; higher number of cells are more likely to have trapped modes, as well as the sensitivity of the beam to HOM-s also increases with the cell number [5].

We can now plot n vs. β_g, to obtain the optimum type of cavity in a certain energy regime. Fig. 2 shows that a minimum number of 173 5-cell cavities of β_g equal 0.893 will accelerate the beam between 450 MeV and 2.2 GeV. The exact number of cavities will depend on the available peak accelerating gradient and the chosen synchronous phase, but the optimal β_g remains the same.

As the energy of the particles moves from the optimal point for a certain family, the efficiency of the acceleration decreases. Therefore, it may be interesting to use several cavity families. In the two families case, the total number of cavities to accelerate the beam between β_1 and β_2 must be minimized. Fig. 3 shows that a total number of 165 cavities of β_g equal 0.82 and 0.94, with a transition β of

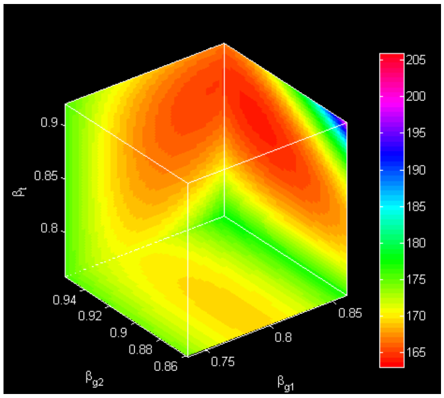

Figure 3: Total number of $\{\beta_{g1} + \beta_{g2}\}$ cavities required to accelerate the beam between 450 MeV and 2.2 GeV. A minimum of 165 is required for $\beta_{g1} = 0.82$, $\beta_{g2} = 0.94$, and transition $\beta = 0.86$.

0.86 are required, using the same conditions as above. It is interesting to observe, that the saving is only of 8 cavities when compared with the results of the previous section. This is due to the fact that starting point of 450 MeV is relatively high; and, in this region the velocity is changing quite slowly with energy.

Choice of the Optimal β_g by FEM *Simulations*

Compared to more realistic on-axis electric field calculated by means of ANSYS® program following the [11, 12] design guidelines, the main difference with the field postulated in Eq. 1 is the presence of an evanescent field in the beam pipes, which is specially remarkable on the right side, where the diameter has been enlarged to provide a stronger coupling with the power coupler. Such effect, displaces the optimum value for β_g towards lower values. Using the on-axis electric field of the cavities calculated using the Finite Element Method (FEM) to obtain the number of cavities required, it is possible to use Eq. 3 to calculate the maximum accelerating voltage for each energy of the entering ions. Fig. 4, represents voltage gain as a function of β, for a set of studied designs: $\beta_g = 0.84$, $\beta_g = 0.87$ (presented in Fig. 5) and $\beta_g = 0.90$.

After some simulations, we find the $\beta_g = 0.87$ cavity (equivalent to sinusoidal $\beta_g = 0.89$) is optimal or near optimal within the proposed range $[450 \text{ MeV} - 2.2 \text{ GeV}]$. It is interesting to note, that the sharp slope of the voltage vs. β curve at the low end of the energy range, makes safer to use a cavity with lower β_g, so that in case the previous section does not reach its full energy, the impact on the final energy is not so marked.

CONCLUSIONS & FUTURE WORK

Once the spoke cavities accelerate the beam up-to 450 MeV, it seems that the use of a single family of elliptical cavities is the most wise choice. After a set of minimum geometrical parameters is set up, it is time to move

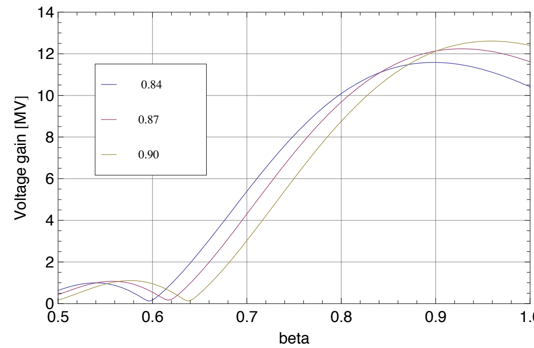

Figure 4: Voltage gain for the different β_g cavities, where $\phi_s = 0$.

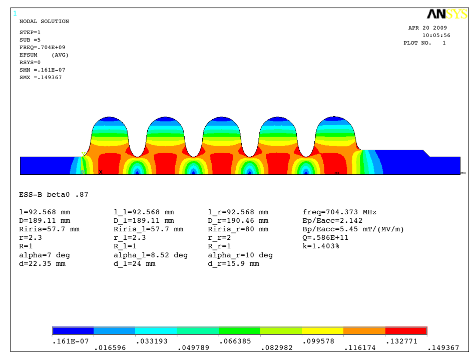

Figure 5: Relative electric field intensity of the designed $\beta_g = 0.87$ structure.

on and go for a more advance multi-particle simulations, which will help us understanding and refining instrument figures.

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