DESIGN OF A SUPERCONDUCTING 352MHZ FULLY JACKETED DOUBLE-SPOKE RESONATOR FOR THE ESS-BILBAO PROTON LINAC

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Abstract

The baseline design for the ESS-Bilbao light-ion linear accelerator and neutron source (a facility compliant with the ESS-AB requirements) has been completed and the normal conducting section of the linac (RFQ and DTL) is at present under detailed design and construction. Starting at 50 MeV, it is proposed to follow this section with a superconducting section composed of double and triple spoke cavities grouped in cryomodules respectively by 2 or 3 cavities reaching a maximum energy of 300 MeV. After an initial R&D program on spoke cavities with an aluminum model, detailed electromagnetic and mechanical studies of a beta 0.50, 352MHz, double spoke cavity were performed. The results of the calculations are presented in this paper. It is proposed to continue this development by the construction and test of bulk niobium cavities prototypes and the study of a cryomodule with two cavities that could be tested with beam at the ESS-Bilbao facility.

THE ESS-BILBAO LINAC PROJECT

The main accelerator components are summarized in the following table 1. It consists mainly of components which will operate at room temperature, followed by a test cryomodule housing two Double-Spoke superconducting Resonators (DSR) [1].

Table 1: ESS-Bilbao Linac Main Parameters

Beam intensity	75	[mA]
Beam structure	20-30 1.8	[Hz] [ms]
Linac components	Output energy [MeV]	Length [m]
RFQ, 352.2 MHz	3	4
DTL, 352.2 MHz	50	15
Double-Spoke Resonators, 352.2 MHz, beta 0.35	60	4

Two Ion Sources are presently developed: a Penning trap H- source based upon the ISIS-FETS design, and a new ECR H+ source. A copper 4 vanes RFQ has been completely designed and is ready for fabrication. Three Alvarez DTL tanks will raise the beam up to an energy of 50 MeV. The DTL design is an adaptation of what has been developed for the LINAC4 project at CERN, which employs a lattice made upon permanent magnets.

A preliminary sketch of the Spoke cryomodule's lattice is presented in Fig. 1. It includes two Double Spoke SC resonators and a super ferric quadrupole doublet focusing magnets. Details of beam dynamics calculations with this lattice have been presented in [2]. The RF design of the DSR cavities should be compatible with the ESS project requirements. As a first step, two activities were developed:

- A complete Electromagnetic and Mechanical design of a DSR cavity (βg = 0.50),
- The construction of a model of a DSR cavity (βg = 0.39) built in aluminum. This cavity model will be used for testing numerical tools, experimental RF measurements techniques, tuners and couplers studies [3].

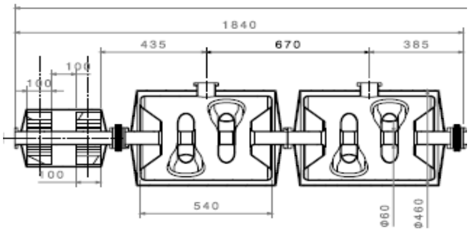

Figure 1: DSR Spoke cryomodule.

DOUBLE SPOKE RESONATOR DESIGN

Electromagnetic Optimization

Table 2: Initial Goals for DSR Design

Frequency	352.2	[MHz]
Optimal beta	0.50	
Accelerating gradient Eacc	8.5	[MV/m]
Qo (low field)	5.10^9	
Epk/Eacc	4.1	
Bpk/Eacc	9.0	[mT/(MV/m)]
Beam tube aperture	50	[mm]
Fundamental port coupler diameter (min)	56	[mm]
Beam tube diameter (min)	50	[mm]

The initial goals, presented in Table 2, for the DSR complete design were evaluated starting from recent studies [4] and vertical and horizontal test results of prototypes.

The cavity has been modeled directly by using 3D CAD tool of CST Studio Suite 2012 [5]. The first mode

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which is calculated for a Spoke cavity is the fundamental mode TM_{010} used for acceleration. A benchmark has been performed to determine the number of meshcells used with hexahedral mesh for the iterative calculations. We observed a convergence from approximately 100000 meshcells for both Epk/Eacc and Bpk/Eacc ratios and geometrical factor as well. The frequency has been adjusted, after a final run performed with 2 millions meshcells, by changing the cavity diameter.

The optimization process has been divided into three parts: 1/ Optimization of the geometry without any additional ports (i.e. fundamental RF coupler port or pick-up port and additional ports for cleaning). 2/ RF coupler integration on the cavity body and external Q factor calculation. 3/Final calculation with all ports:RF coupler, pick-up probe port and ports dedicated to the cavity preparation (BCP etching and high pressure rinsing).

The final geometry is a general compromise between several main considerations: minimizing Epk/Eacc and Bpk/Eacc ratios, while maximizing the value of the accelerating voltage (Vacc=Vo.T) for beta=0.50, and keeping the overall geometry compatible, as much as possible, with some “simple” fabrication technics. Several important geometrical parameters were optimized:

- The distance between the two spoke bars
- The spoke bar base radius and the cavity length
- The width of the spoke bar center
- The beam tube aperture

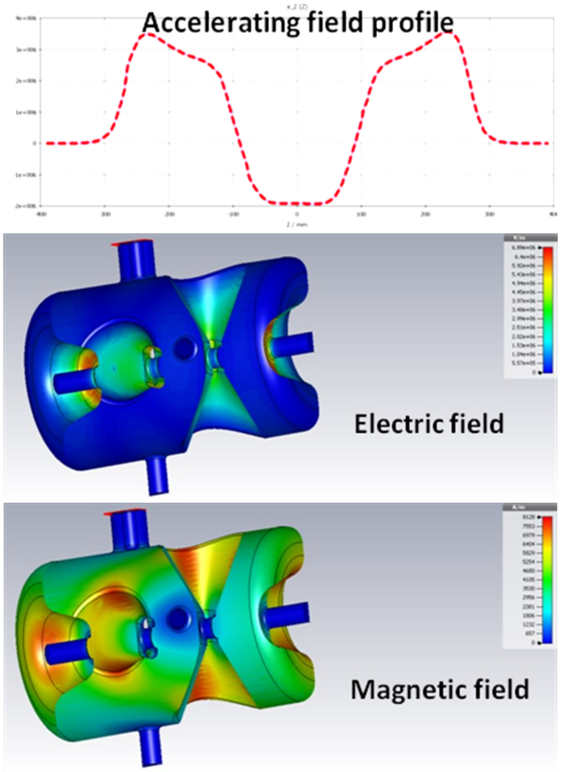

Figure 2: a) Axial Field Distribution, b) 3D Electric Field, c) 3D Magnetic Field.

The coupler port was finally positioned into a high electric field area in order to get the right Qext value ($\sim 2.4\ 10^5$) but, above all, into a low magnetic field area in order to avoid extra losses on the coupler port and antenna surfaces.

The final results obtained through this optimization procedure are presented in Table 3.

Table 3: Final DSR Optimized Parameters

Vacc (=Vo.T) @ beta 0.50	0.96	[MV/m]
Lacc (=3/2.beta.c/f)	0.639	[m]
Accelerating gradient Eacc	8.5	[MV/m]
G	132	[Ohm]
Epk/Eacc	4.56	
Bpk/Eacc	6.76	[mT/(MV/m)]
r/Q @ beta 0.50	418	[Ohm]

The accelerating field profile on the beam axis, as well as the electric and magnetic field 3D distributions are presented in Fig. 2

Mechanical Optimization

Starting with the optimized 3D cavity model by electro-magnetic analysis, as described before, a complete mechanical design of the cavity has been initiated. Three main aspects were investigated: the cavity sensitivity to Niobium wall thickness variations, the integration of a stainless steel Helium vessel and the stiffening of the cavity using additional parts.

All the cavity ports were positioned with their final dimensions:

- Beam tubes diameter was fixed to 56 mm (max. diameter compatible with the use of standard DN63CF flanges).
- Fundamental Coupler Port: diam. 100 mm
- 3 additional ports (for cleaning preparation and pick-up antenna): diam. 56 mm

The material of the helium vessel is stainless steel with a thickness of 3 mm. This choice has been made in order to make the fabrication easier. The drawback is that the helium vessel could not be used to stiffen the cavity as it is usually done with helium vessel made of Titanium. Thus, some specific ribs had to be added on each end-cup; “daisy” ribs and “donut” stiffener (=half-tube shape) for mainly pressure vacuum stability.

To perform the mechanical study of the cavity, the following methodology was adopted:

- **Mechanical analysis without stiffeners:** Localize the weakest areas of the cavity and find the minimum thickness to achieve the specifications.
- **Mechanical analysis with several types of stiffeners:** Optimize different types of ribs (shape, size, thickness)

By considering the mechanical loads and stresses with the cavity under vacuum and, taking into account some manufacturing considerations, the thickness of all walls of the cavity was investigated. Several stiffeners were added in order to get the cavity more rigid, with respect to the external pressure (Fig.3):

- Two “donut” stiffeners, welded on the flat area of the end-cups,
- Six ribs at the connection between the end-cups and the beam tubes.

In conclusion, a thickness of 4 mm was chosen for all Niobium components.

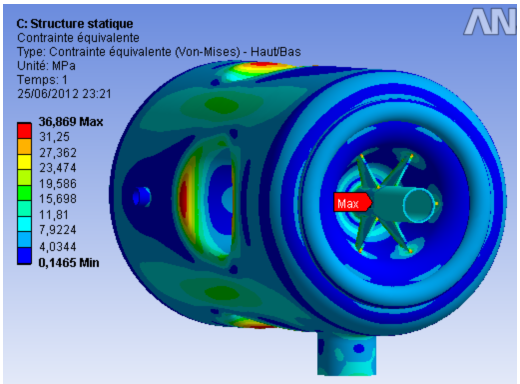

Figure 3: Von Misses stresses values for a static load of 1 bar.

The main dimensions of the DSR with its Helium vessel are presented in Fig. 4.

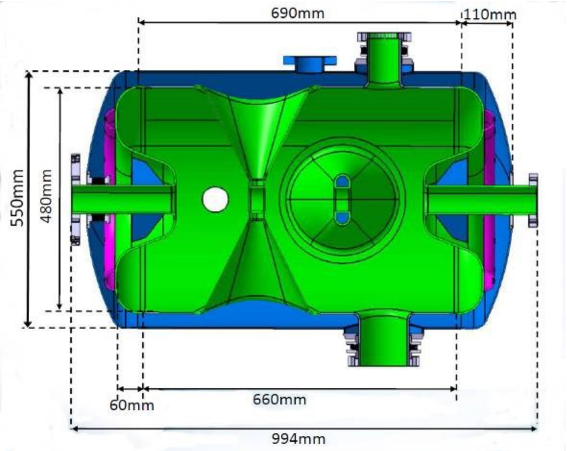

Figure 4: Main DSR dimensions.

Two important aspects of the cavity mechanical behavior were also analyzed:

- The tuning sensitivity by deformation along the longitudinal axis. This evaluation was performed by using a combined E.M. and Mechanical analysis (Table 4)

Table 4. DSR Mechanical Parameters

Cavity stiffness, Kc	14	[kN/mm]
Tuning sensitivity, Δf/Δx	236	[kHz/mm]

- The mechanical eigenmodes of the cavity (Table 5) which could be excited by external sources (so-called microphonics like pumping and cryogenic systems, leading to cavity walls deformations (Fig. 5) and frequency perturbations. The goal is to have a first eigenmode value far away from 50 Hz and compare the higher eigenmodes with the harmonic modes of the excitation sources (multiples of 50 Hz).

Table 5: Modal Analysis of the First Dangerous Modes

Mode number	Frequency [Hz]
1 & 2	275
3	336
4	380
5	409
6	417

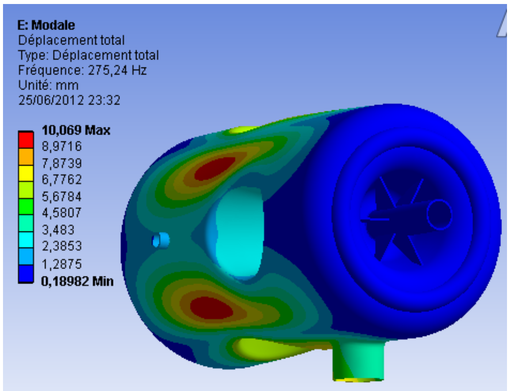

Figure 5: First mechanical mode @ 275 Hz.

DSR MODEL MEASUREMENTS

A model of a double spoke resonant cavity (operating frequency 352.2 MHz, βg=0.39) has been designed and fabricated in aluminum by the ESS-Bilbao laboratory [3]. The cavity and associated test bench is shown in Fig. 6. The RF measurements have involved the determination of the main cavity parameters, in particular the accelerating electric field profile along the cavity axis by means of a fully automated bead-pull method. Electromagnetic numerical simulations and RF measurements have been also performed to identify the most suitable position for the fundamental power coupler port.

A special and original development performed with this model is the study of a tuning system by using a superconducting plunger. This tuning method has been successfully designed and tested for the Spiral-2 QWR beta 0.12 cavities [6,7]. Electromagnetic and thermal simulations of this system have been performed. Plungers are simulated as cylindrical volumes subtracted from the internal cavity volume.

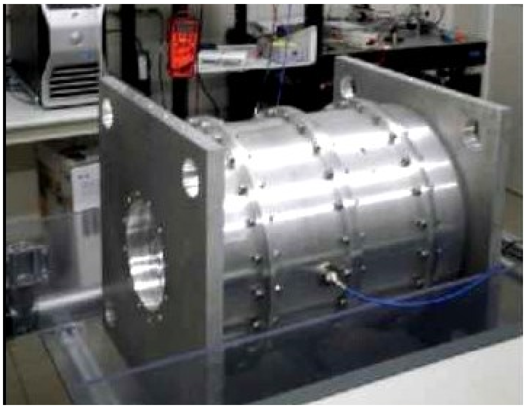

Figure 6: DSR aluminium model.

Different positions on the cavity walls and different plunger diameters have been calculated in order to reach a good compromise between the detuning and the extra losses.

A plunger with diameter of 40 mm was installed on the cavity wall (Fig. 7) and the results, comparing the RF measurements to the electromagnetic simulations, are presented in Fig. 8.

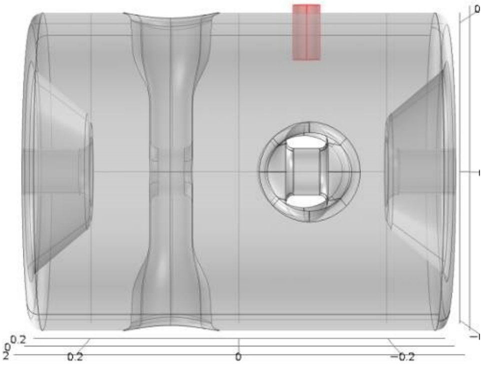

Figure 7: Drawing of the tuning plunger installed on the DSR cavity.

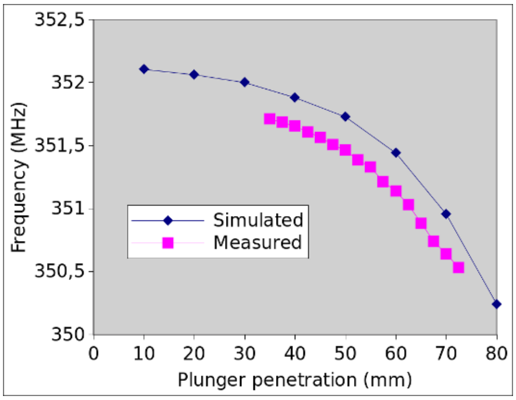

Figure 8: Simulated and measured values obtained with a 40 mm diameter tuning plunger.

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