STIFFENED MEDIUM BETA 704 MHZ ELLIPTICAL CAVITY FOR A PULSED PROTON LINAC

P. Bosland, S. Chel, G. Devanz, Y. Gasser, P. Hardy, J. Plouin, J.-P. Poupeau, D. Roudier, B. Visentin, CEA-Saclay F-91191 Gif-sur-Yvette, France

Abstract

Recent developments on high duty cycle high intensity proton linac have used, in the high energy part, the superconducting technology because it is considered to be advantageous in terms of power consumption, construction cost and beam loss. In the framework of the European CARE/HIPPI program, we investigate different options to use the same superconducting technology even in the low energy part of the linac (from 5 MeV to 200 MeV). Different kind of superconducting structures (CH structures, spoke or elliptical cavities) are necessary to cover this whole energy range. Since the higher energy part will be equipped with elliptical cavities, we propose a 704 MHz elliptical cavity which could be advantageously used in the range 80 MeV up to 200 MeV. An optimized design of this cavity for running in pulsed mode is presented. The sensitivity of the cavity to pulsed RF is investigated to assess the efficiency of the stiffening scheme.

INTRODUCTION

In the framework of the CARE-HIPPI program, several prototypes of low beta cavities are developed. An elliptical 704 MHz, 5-cells $\beta_g = 0.47$ cavity was designed to be operated at high gradients in pulsed mode. The high aspect ratio of the individual cells of this low beta cavities make them very sensitive to Lorentz force detuning. Previously developed cavities make use of stiffening rings in the irises region, which have proven to effectively reduce the static Lorentz coefficient $K_L = \Delta f/E_{acc}^2$. In continuous operation, this static detuning can easily be compensated using the cold tuning system. However, it is practically difficult to predict the mechanical boundary conditions of the cavity in a cryomodule, therefore K_L computations for both free and fixed ends are generally presented to assess the efficiency of a cavity stiffening scheme. In the case of medium beta elliptical cavities, these values are typically apart by a factor 15, which makes any prediction of the detuning problematic. Our approach is to use a more effective stiffening to reduce the spread in static K_L values and lower the dynamic Lorentz detuning. Too large a dynamic detuning would be too demanding for a fast piezo tuner, or require unacceptable RF power overhead.

CAVITY DESIGN

The design guidelines are the following: The high current operation requires a large beam aperture. Here the iris diameter is 80 mm. High beam intensity combined with high gradient operation means a large power has to be transferred to the beam. A high power coaxial fundamental power couplers (FPC) is developed in the CARE-HIPPI programme to fill the requirements not only of a high intensity injector, but also of the higher energy part of a superconducting proton driver, like SPL [1]. In the 650 MeV to 3.5 GeV section, the maximum peak power transferred by the FPCs is of the order of 1 MW, with a 5 % duty cycle. The coupler design is based on a 50 Ω coaxial line, 100 mm in diameter. The impact of such coupler characteristics combined with external Qs in the range 5. 10^5 to 10^6, is a large beam tube diameter, in our case 130 mm. The cavity is made symmetric, which reduces the number of half-cell shapes. This causes a 5 % reduction of the r/Q compared to an asymmetrical optimized for efficiency with a second beam tube 80 mm in diameter [2]. The RF parameters are summarized in table 1.

Table 1: Cavity RF parameters

	Design values
Frequency [MHz]	704.4
Epk/Eacc	3.36
Bpk/Eacc [mT/(MV/m)]	5.59
r/Q [Ω]	173
G [Ω]	161
Q_0 @ 2K Rs=8 nΩ	2 10^{10}
Optimal β	0.52
Geometrical β	0.47
Total length [mm]	832

In high RRR bulk niobium elliptical cavities, surface fields Epk=40 MV/m and Bpk=80mT can be obtained provided the preparation is conforming to the standard sequence of 120µm BCP, HPR and assembly in class 100 clean room. Within these limits, the present cavity would be limited first by Epk at Eacc=12 MV/m and would yield a voltage of 6 MV per resonator. The operating temperature is 1.8-2 K. The beam tube which supports the FPC is enclosed in the stainless steel helium vessel for two reasons: first, the coupler is very close to the iris of the adjacent cell, which has to be mechanically stiffened, the connection of the helium vessel to the beam tube would have required more space. Second, it is easier to stiffen the helium tank itself with four welded wings (Fig. 1). A benefit of the FPC base being cooled by helium is to get rid of the thermal instability which may occur in conduction cooled beam tubes supporting high power FPCs. The opposite beam tube is long enough to accommodate an optional HOM coupler, 40 mm in diameter, and a cold tuning system equipped with piezo actuators.

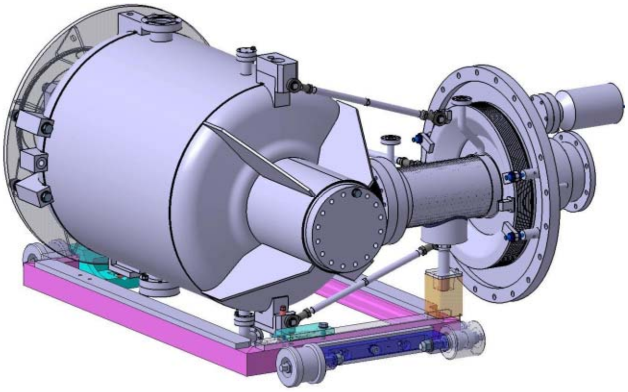

Figure 1: complete cavity equipped with the helium vessel and vacuum part of the FPC.

CAVITY STIFFENING

Several parameters affect the sensitivity to Lorentz detuning, wall thickness, position and number of stiffening rings, external stiffness k_{ext}. The later results from the combination of the tuner and helium vessel and generally explains the difference between computed fixed-ends K_Ls and actual measurement. The cavity wall thickness is fixed to 4 mm, and a reduction to 2 mm in the equator weld region was taken into account in all the calculations. A first optimisation of one set of rings gave an optimal position at R1 = 62 mm. The minimum K_L (fixed ends) is -3.4 Hz/(MV/m)² which is a tolerable value. But for realistic boundary conditions, this value cannot be reached. A second set of rings added at a greater radius R2 = 110 mm can help reducing the sensitivity of the static Lorentz coefficient to the cavity boundary conditions, as demonstrates figure 2, while keeping a sufficient tunability. Extra stiffeners are located around the end cells irises on the beam tube side. This is mandatory to get a balanced stiffness across all the cells. All the stiffeners have to be drilled to allow for helium flow.

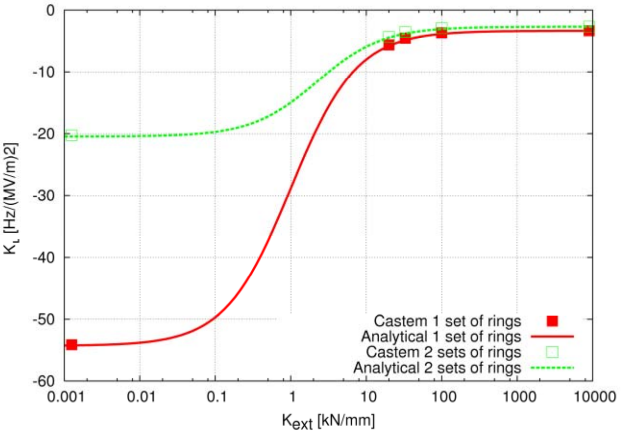

Figure 2: Static K_L sensitivity to boundary conditions

The numerical calculation of K_L is using the flexible structural FEM toolbox Castem for which a program has been written to implement the Slater perturbation method in 2D, using the EM field computed with Superfish. The solid lines in Fig. 2 correspond to the analytical approximation which simply takes into account the cavity shrinkage due to the radiation pressure [3]. The $\Delta f/\Delta l$ coefficient and cavity stiffness needed in this model are also computed using Castem. For realistic helium vessel and tuner parameters, the external stiffness should be in the range 5 to 30 kN/mm and the gain of using 2 rings instead of 1 is reflected by a reduction of K_L between 20 and 30 %. The other static parameters are summarized in table 2.

Table 2: Cavity RF/mechanical parameters

	1 ring	**2 rings**
Cavity stiffness [kN/mm]	1.0	2.25
Tuning sensitivity $\Delta f/\Delta l$ [kHz/mm]	330	295
K_L @ k_{ext} = 30 kN/mm [Hz/(MV/m)²]	-5	-3.9
Δf @ 12 MV/m, k_{ext} = 30kN/mm [Hz]	-720	-560
K_L with fixed ends	-3.4	-2.7
K_L with free ends	-54.2	-20.3

DYNAMIC BEHAVIOR

The impact of using 2 sets of rings has to be evaluated for dynamic detuning. The direct cavity environment has to be included in the simulations. The helium vessel and the tuner models do not need to be detailed but to ought to provide a correct mass and spring constant distributions. The cavity is supposed to have a cylindrical symmetry thus only 2D modeling is carried out. The first step is to compute the first N mechanical modes of the structure, which are defined by their modal displacements $\mathbf{X}_m$, frequency f_m and create a modal basis. The quality factor Q_m has to be introduced for each mode since the linear modeling does not provide any source of damping. The Lorentz force is projected on the modal basis, which makes the calculation of the response of the mechanical system to an arbitrary time domain modulation of the force very fast. The system characterization is best described by the Lorentz transfer function, which can be obtained by stepping the frequency of the sinusoidal modulation of the radiation pressure and evaluating the steady state amplitude of the resulting cavity detuning. First step is to compare the mode frequencies with one and two sets of rings. In the following example, the combination the tuner stiffness was assumed at a value of 50 kN/mm and the He vessel 100 kN/mm, the equivalent external stiffness is $k_{ex\ t}$= 33 kN/mm The tuner mass is estimated to 30 kg and the end flanges closing the cavity were included in the simulation. All the mechanical modes have been given a quality factor of 50. The truncation frequency is 5 kHz, the corresponding number of mechanical modes included in the simulation is 50. The amplitude of the Lorentz transfer function for 1 and 2 sets of rings in the lower frequency part of the spectrum is shown on figure 3.

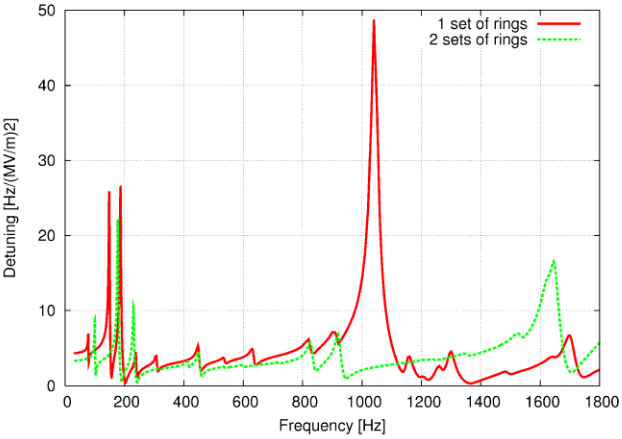

Figure 3: Simulated Lorentz detuning transfer functions

In the 2 rings case, most modes have a higher frequency and a lower coupling to the Lorentz detuning.

CAVITY MEASUREMENTS

The cavity has been built by Accel GmbH. Only a part of the helium vessel is assembled around the FPC port to allow field flatness adjustment, as shown on figure 4.

Figure 4: the HIPPI cavity as delivered

Upon delivery, the cavity wall thickness has been measured in the circular region extending from the equators to the outer rings. The actual thickness is between 3 and 3.8 mm. Only one half-cell is thinner, with a thickness going down to 2.8 mm. The tuning of individual cells is achieved by coupling heavy tuning plates to the outer stiffening rings using the 12 circular holes and $\phi = 10$ mm stainless steel needles. As received, the cavity frequency was 3.5 MHz below its correct value and the first bead-pull measurements indicated that the first cell close to the FPC port was the most detuned cell. The initial state was a pi mode frequency of 699.77 MHz with a field flatness of 30 %. The cavity was installed on the tuning bench for field flatness and frequency adjustment. Then a chemical polishing of 100 µm was carried out using a FNP-1.2 acid mixture using our vertical integrated BCP station (fig. 5).

Figure 5: the cavity on the automated BCP station

The cavity was shipped to CERN for a 650°C heat treatment. The field flatness and frequency had to be re-adjusted. The final pi mode frequency is 701.63 MHz and the field flatness is 91 %. The measured tuning coefficient $\Delta f/\Delta l$ is 290 kHz/mm, which is very close to the computed value of 295 kHz/mm. A 20 µm BPC was applied before ultra-pure water high pressure rinsing in the clean room. The final assembly was done in the class 100 area of clean room and the cavity is now ready for the first cryogenic test. Otherwise mentioned, all the cavity treatments have been carried out at Saclay.

AKNOWLEDGMENTS

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 “Structuring the European Research Area” programme (CARE, contract number RII3-CT-2003-506395). Work carried out using the SUPRATech GIS infrastructures with the financial support from Region d’Ile de France.

REFERENCES

[1] Conceptual Design of the SPL II, F. Gerick et al., CERN-2006-006.

[2] J.-L. Biarrotte et al., ”704 MHz superconducting cavities for a high intensity proton accelerator”, proc of 9th SRF workshop, 1999, Santa Fe, USA.

[2] G. Devanz et al., “Numerical simulation of dynamic Lorentz detuning of sc cavities”, proc. of EPAC02, Paris, France.