OPTIMIZED RF DESIGN OF 704 MHZ BETA=1 CAVITY FOR PULSED PROTON DRIVERS

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Abstract

The high energy part of the Superconducting Proton Linac at CERN (SPL) is composed of two families of elliptical 704 MHz cavities with respective beta's of 0.65 and 1.0. These cavities are aimed to work in pulsed mode (50Hz, duty cycle 5%), with a beam current of 40 mA and RF peak power up to 1 MW.

At CEA-Saclay, in the frame of the FP7/EUCARD program (European Coordination for Accelerator Research & Development), we designed the beta =1 cavity. Since this cavity should reach a challenging gradient of 25 MV/m in operation, the RF design has been carefully optimized. Precise location of high power coupler has been determined to achieve the optimal external coupling at full beam current, and monopole high order modes have been identified and characterized. In order to keep the extra power required to stabilize the accelerating field in operation, we studied the mechanical behaviour of the cavity and how it influences the RF characteristics.

RF OPTIMIZATION OF THE GEOMETRICAL PARAMETERS

The β=1 SPL cavity is aimed to work in the pulse mode, with the set of machine parameters resulting from the optimization of the SPL accelerator design [1] given in Table 1.

Table 1 : Design parameters for the β=1 part of the SPL accelerator

RF frequency	**704.4 MHz**
Cavity β	**1**
Number of cells	**5**
Accelerating gradient (Eacc)	**25 MV/m**
Average pulse current (Ibeam)	**40 mA**
Synchronous phase (φs)	**-15 °**
Peak RF power	**1 MW**
Repetition frequency	**50 Hz**
Duty cycle	**5%**
Operating Temperature	**2 K**

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As the design gradient of 704.4 MHz - β = 1 cavities is 6 % above the gradient specified for XFEL superconducting cavities (25 MV/m instead of 23.4 MV/m), we used the elliptical TTF cavity [2] as a starting design. Thus the geometry of inner cells is resulting from a scaling from 1300 MHz down to 704.4 MHz

The shape of each outer cell has been adjusted separately to optimize the RF parameters while fitting on beam tubes with different diameters. Though smaller diameters could help to increase the shunt impedance, a 140 mm diameter is fixed on one side due to fundamental power coupler (FPC) geometry and Qext specification. Since the new Saclay V frequency piezo-tuner has to fit the beam tube of opposite side, diameter is fixed to the maximum value (130 mm). Our reference cavity ends with 80 mm diameter flanges, which means tapered tubes at both side of the cavity. From flange to flange, the overall length of the cavity is 1393 mm.

The RF parameters associated with this geometry are summarized in Table 2.

Table 2: RF parameters of the β = 1 SPL cavity

Frequency [MHz]	**704.4**
Bpk/Eacc [mT/(MV/m)]	**4.20**
Epk/Eacc	**1.99**
G [Ohm]	**270**
Cell to cell coupling	**1.92 %**
r/Q [Ohms]	**566**
Lacc = Ngap.β.λ/2 [m]	**1.0647**
Maximum energy gain @ Bpk = 100 mT	**25 MeV**

The accelerating mode (π-mode) in the optimized SPL cavity is shown on Figure 1.

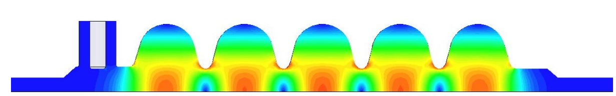

Figure 1: E field of the TM01 fundamental mode in the beta=1 704.4 MHz SPL cavity.

The BCS resistance has been calculated using the formula [3]:

$$R_{BCS} = 2.10^{-4}\frac{1}{T}\left(\frac{f}{1.5}\right)^{2}e^{-17.67/T}$$

(where f is the frequency in GHz and T the operating temperature in K), and is equal to $R_{BCS} = 3.2\ n\Omega$ at 2 K. The actual value for the surface resistance will be slightly increased by the residual resistance, depending on the material and on the magnetic field remaining during the cavity cool-down. Measurements on a 704 MHz cavity in a vertical cryostat have shown the possibility to get a residual resistance of 2.2 nΩ in very good conditions [4]. With such a value, we could expect a surface resistance Rs = 5.4 nΩ at 2 K, for low fields tests, associated to a quality factor $Q_0 = 5*10^{10}$.

FUNDAMENTAL POWER COUPLER

The optimal external quality factor of the fundamental power coupler (FPC) with the cavity is given by the formula:

$$Q_{ext} = \frac{E_{acc}.L_{acc}}{\frac{r}{Q}.I_{beam}.\cos(\varphi_s)}$$

With our set of cavity and beam parameters the optimal Q_{ext} is: $Q_{ext,opt} = 1.2*10^6$.

Considering the very good performances (up to 1.2 MW at 10% duty cycle) already obtained with the power couplers developed and tested in the frame of the CARE/HIPPI program [5,6], we used the same 50 Ohms - Ø 100 mm coaxial coupler for this cavity.

Both distances coupler-to-iris and antenna tip-to-cavity axis have been adjusted to match the optimal coupling value, as shown on Figure 3. The solution with 85 mm between the iris and the coupler axis has been chosen because it lowers the overall length of the cavity and the antenna penetration while leaving enough room between the iris and coupler for the helium tank (see Figure 2).

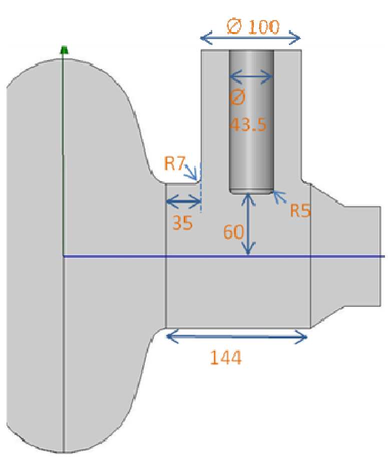

Figure 2: Dimensions of the coupler port (in mm).

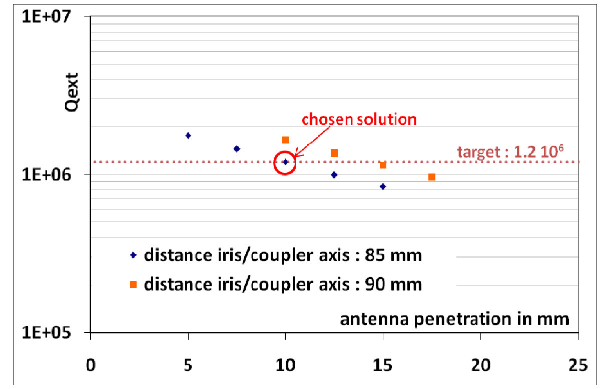

Figure 3: Optimization of the coupler position and the antenna penetration.

HIGH ORDER MODES

Monopole modes have been identified for frequencies lower than 2.865 GHz, which is the cut-off frequency of the TM01 in the Ø80 mm tube. For each of these modes, maximal r/Q is determined as the β=v/c of proton beams varies from 0.8 to 1. Values are plotted on the fig. 4 and β's of the most dangerous modes (r/Q > 10 Ω) are in red. The design and implementation of HOM dampers for this β=1 cavity is under study.

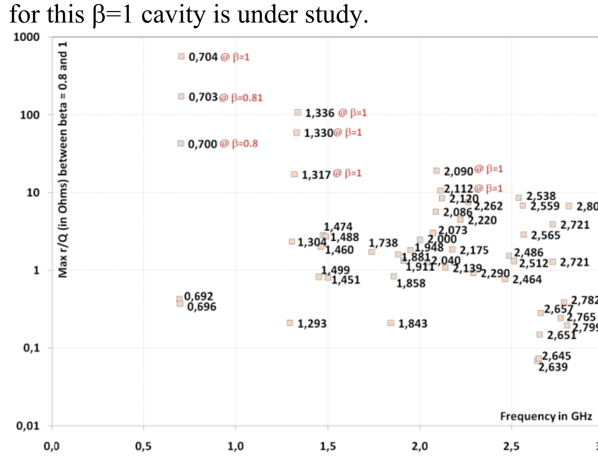

Figure 4: Monopole High Order Modes with frequency and maximal r/Q for particle beta's between 0.8 and 1.

FREQUENCY SENSITIVITY TO MECHANICAL DEFORMATIONS

The thickness of the cavity has been fixed to 3 mm which is a compromise between cavity stiffness, heat exchange and cavity weight. However, reduction of the thickness to 2 mm at each equator for EB welding has been taken into account.

For cavities operating at high gradient and in pulsed mode, sensitivity to the Lorenz force is especially critical. It is thus important to limit the effects of the Lorenz force detuning, characterized by the coefficient $K_L = \Delta f/E_{acc}^2$. Thanks to stiffening rings welded between adjacent cells, Lorentz detuning is kept at reasonable level. After calculations to minimize the value of $|K_L|$ for the cavity with fixed ends, 3 mm thickness rings located at 91 mm from the cavity axis are chosen.

Table 3 : Mechanical parameters of the β = 1 SPL cavity

Nominal wall thickness [mm]	3
Cavity stiffness Kcav [kN/mm]	3.84
Tuning sensitivity Δf/Δz [kHz/mm]	164
KL with fixed ends [Hz/(MV/m)²]	-0.55
KL with free ends [Hz/(MV/m)²]	-5
Pressure sensitivity KP [Hz/mbar] (fixed	1.2

The mechanical parameters of the cavity with the taper and with the stiffening rings (Rring = 91 mm) are given in Table 3.

K_P measures the resonance frequency shift induced by the differential pressure P between outside and inside of the cavity: $K_P = \Delta f/P$.

Figure 5 shows the variation of K_L with respect to the external stiffness experienced by the cavity, calculated by the analytic formula

$$K_L = K_{L\infty} + \frac{\Delta f}{\Delta z}\frac{\overrightarrow{F_\infty}.\overrightarrow{u_z}/{E_{acc}}^2}{K_{ext} + K_{cav}}$$

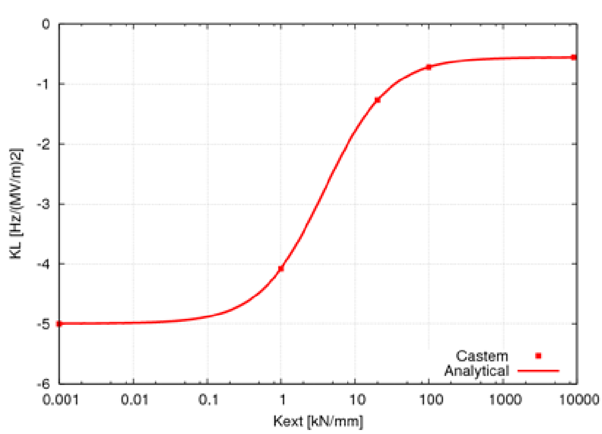

Figure 5: K_L vs external stiffness K_{ext}. Analytic curve and points calculated by CASTEM2000.

During operation, the load on the cavity is a combination of both helium tank and the tuning system stiffness. On a previous version of Saclay tuner, very similar to the tuner designed for the SPL cavity, the estimated stiffness at room temperature was 35 kN/mm. As stiffness of the optimized titanium helium tank of the SPL cavity is 65 kN/mm, the resulting external stiffness Kext is close to 23 kN/mm. For this value, we expect a detuning coefficient $|K_L| \approx 1.2$ Hz/(MV/m)² leading to a frequency shift in cw mode of 750 Hz at 25 MV/m.

Considering the relative values of cavity bandwidth and frequency detuning at operating gradient of both SPL and HIPPI [7] cavities, indicates that the phase variation of the SPL cavity in operation would be lower that the phase variation of the HIPPI cavity. As Lorentz detuning compensation has been demonstrated in pulsed mode for the HIPPI cavity [8,9], we expect that the detuning in pulsed mode should be manageable for the SPL cavities.

TUNERS

SPL cavities will be equipped with piezo tuners, able to operate both in slow and fast mode for respectively RF frequency tuning and Lorentz force compensation in pulsed mode. As already mentioned, these new lateral tuners (referenced as Saclay- V type) are based on the tuner developed for the 704 MHz beta=0.5 HIPPI cavity which we qualified at cold and under vacuum. Only some changes were necessary to make it fit the SPL cavity: use of Ti flange of the Helium tank to ease assembling on cavity strings (Fig. 6), resizing of some stainless steel pieces to make it compatible with 130 mm beam tube diameter, more room for HOM couplers and new piezo frame with optimized stiffness. Other characteristics are identical.

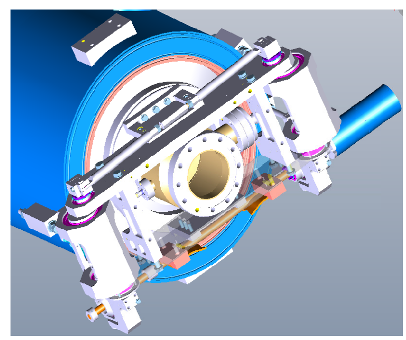

Figure 6: 3D drawing of the tuner on the SPL cavity.

Several such tuners have been fabricated (Fig. 7) in the frame of a CERN-CEA-CNRS contract called ‘Contribution Exceptionnelle de la France au CERN’. Some will be used for qualification tests foreseen the second half of current year, and others will equip the cavities of a short prototype cryomodule to be developed in the next years.

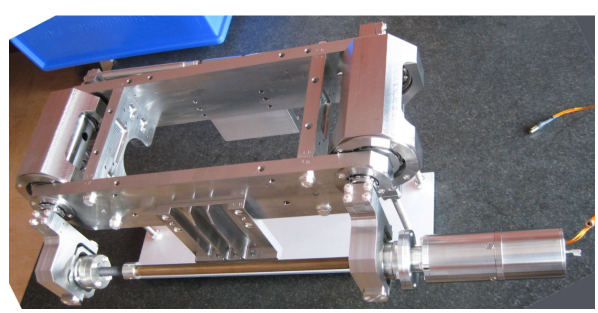

Figure 7: Part of a tuner in preparation of qualification test.

SACLAY PROTOTYPE

A prototype SPL β=1 cavity will be fabricated and tested by CEA-Saclay with its helium vessel made of Titanium. The mechanical design of this prototype allows its assembly with FPC and tuner, as well as its integration in horizontal cryostat for possible further tests.

Helium Vessel

The helium tank is made out of titanium to limit the differential shrinkage with niobium during the cooling down. All the flanges and pick-ups are made of Nb or Nb/Ti to be directly welded on the cavity. Only the FPC flange is in stainless steel with copper gasket to be compatible with the HIPPI coupler and for safety reasons; this flange is brazed on the cavity FPC port, while the tank is welded on this port by the intermediary of a Ti piece. Hydroformed Ti bellows are welded between cavity and tank on the tuner side. The prototype inserted in its helium vessel is shown in Figure 8.

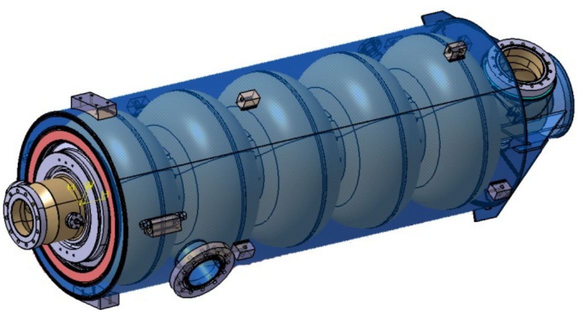

Figure 8: Saclay cavity prototype in its helium tank.

HOM Ports

The Saclay prototype will be fabricated before the completion of the HOM couplers. Nevertheless, the cavity is equipped with two HOM ports, allowing the possibility to make further tests with HOM couplers.

EQUIPMENT FOR CAVITY PREPARATION

Cavity Tuning Set-up

After delivery and before tests in vertical cryostat, the cavity will be tuned at room temperature to achieve the field flatness. A new tuning set-up will be installed to this intend at CEA-Saclay, and will allow a cell-by-cell tuning between plates (in yellow on the picture) fixed to the stiffening rings of the cavity (Figure 9).

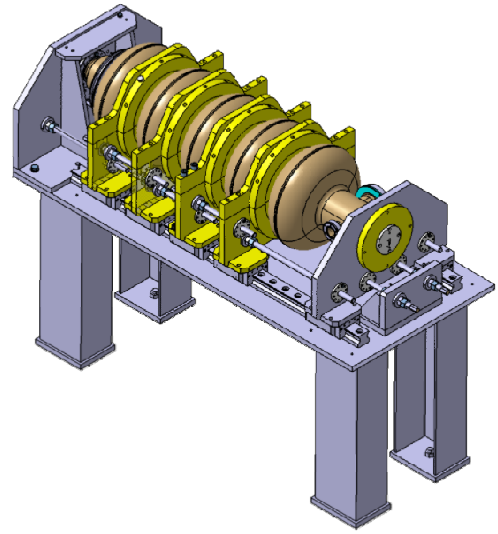

Figure 9: tuning set-up for field flatness achievement at room temperature.

Vertical Electro-polishing

A vertical electro-polishing set-up has been developed by CEA in the frame of EUCARD, and will be used for the treatment of SPL cavities. This set-up has been recently installed at Saclay [10] (Figure 10).

Figure 10: New vertical electro-polishing set-up.

ACKNOWLEDGEMENTS

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP7 programme (EuCARD, contract number 227579).

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