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INFN-LASA DESIGN AND PROTOTYPING ACTIVITY FOR PIP-II

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Abstract

The design of the PIP-II medium-β, 5-cell, 650 MHz SRF elliptical cavity and the first steps of its prototyping activity are here presented. A design based on a three dies fabrication model has been chosen and fully characterized in terms of electromagnetic and mechanical parameters. Goal of the optimization has been to realize a highly performant cavity for CW operation with reasonably good performances when pulsed. A prototyping phase started with the production of three single-cell cavities used to validate the LASA model and to develop an optimal recipe for RF surface treatment according to the state-of-the-art of the high-Q frontier.

INTRODUCTION

The Fermilab PIP-II Linac is designed to deliver an average proton beam current of 2 mA at an energy of 800 MeV, to be fully compatible with Continuous Wave (CW) operation [1]. One main section of the Linac is the 650 MHz superconducting part of β_G = 0.61 that contains 33 five-cell low beta cavities (LB650), accelerating proton beam from 185 MeV to 500 MeV.

INFN-LASA is going to join the international partnership to provide a novel design for the LB650 cavities, fully plug compatible with the Fermilab Cryomodule design, i.e. beam pipes, couplers, Helium tank, tuners and so on.

This paper describes the INFN-LASA design of LB650 cavity, including both ElectroMagnetic (EM) and mechanical designs with detailed reasons for the choice of geometric parameters. Based on these choices, three single-cell prototypes are being fabricated to validate the design, and to explore the road for the development of five-cell cavities in near future, being two complete cavities already planned.

CAVITY DESIGN

PIP-II cavities are required to be compatible with CW operation. Since in this CW operational mode the RF duty factor is not a knob for tuning the dynamic heat load, a high accelerating efficiency in terms of R/Q is instead necessary. A high R/Q principally requires small iris aperture and small wall-angle; this may lead to difficulties in Field Flatness tuning, cavity surface treatment and cleaning. In addition, the relatively small beam current of PIP-II results in high external Q (Q_{ex}) of the cavity that implies a narrow bandwidth of the accelerating mode. In order to have a stable beam acceleration, a strict control of the Lorentz Force Detuning and microphonic is required, not only with stiffening rings but also by a proper shape of the cells.

Rationales

The cavity parameter R/Q is mainly determined by aperture sizes. A smaller aperture is preferred for high R/Q, even if this choice decreases significantly the cell-to-cell coupling, k_{cc}. The k_{cc} obviously affects the sensitivity of the field profile of the π-mode to frequency error of individual cells. This field flatness sensitivity is measured by the ratio [2, 3] $N^2/(\beta k_{cc})$, where N is the number of cells, β is the relative velocity and k_{cc} is the cell-to-cell coupling.

It is favourable to keep this ratio low. A list of some successful cavities is used for comparison, as shown in Table 1. Taking TESLA ratio as reference, the PIP-II LB650 cavity shall have k_{cc}≥0.95%.

Table 1: Comparison of Cell-To-Cell Coupling

Cav	N	β	k_{cc} (%)	$N^2/(\beta k_{cc})$
TESLA	9	1	1.87	4331
SNS MB	6	0.61	1.52	3883
ESS MB	6	0.67	1.55	3467
PIP-II LB650	5	0.61	**0.95**	4331

The Buildcavity [4] and Superfish [5] codes are used for the cavity design. In Buildcavity, seven parameters are used to design a half-cell: R_{iris}, D, alpha, R, r, d and L, respectively iris radius, equator diameter, side wall angle, equator ellipse (B/A) and iris ellipse (b/a) ratio and length.

The half-cell shape is designed iteratively. Starting from an initial half-cell shape with R_{iris} =48.0 mm, D=196.0 mm, alpha= 2°, R=1, r=1.7, d= 14 mm and L =70.4 mm, we change only the iris radius to find the relationship between k_{cc} and R/Q. By studying both the k_{cc} and R/Q versus R_{iris}, it can be seen that the cell-to-cell coupling monotonically decreases with rising R/Q. Due to this reason, the k_{cc} = 0.95 % is chosen to obtain the maximum R/Q. Meanwhile, the iris diameter of 88 mm can be fixed.

Other parameters, such as L, r, R and d are optimized based on their own functions. L is constrained by the geometric beta, namely 0.61. Iris elliptical ratio is adjusted to have a minimum E_{peak}/E_{acc}. Equator elliptical ratio R is set to 1 to obtain a round shape, beneficial to geometric factor G and to mitigate Multipacting. While a small d is favored by k_{cc} it may lead to difficulties for fabrication of the iris region. Hence, d is chosen according to the minimum requirement of fabrication.

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EM CAVITY DESIGN

Based on the above consideration, the inner cell (IC) has been designed for LB650 cavity. Additional considerations are necessary in the design of the End Cell (EC). In fact, the EC contains the end tube for connecting the cavity into the string. The design of the EC must consider these contributions to guarantee a proper resonance frequency and hence the required field flatness. Moreover, beam pipe diameter is required to be larger than iris aperture of inner cells to allow damping of HOM. A usual way to tune the EC, compensating for the extra volume of the beam pipe tube, is to create an extra volume in magnetic region near equator by tuning R (=B/A) and wall angle, but this asymmetric cell section may become critical for surface treatment, cleaning as well as for HOM distribution.

In our design, we use another strategy to tune the end cell by increasing the equator diameter, particularly effective when the beam pipe size is clearly larger than inner aperture, such as in our case. This approach can bring two advantages: almost round equator region, and the nearly symmetric end cell. A shape comparison of inner cell and end cell shows good symmetry with respect to the cell centre. The equator radius of end cell indeed is 1.15 mm larger than the inner cell one and thus requires a third cell shape.

Table 2: RF Parameters of INFN-LASA Design

Parameters	INFN-design	FNAL_upd
β_{geo}	0.61	0.61
Frequency (MHz)	650	650
Number of cells	5	5
Iris diameter (mm)	88	83
Cell-to-cell coupling, k_{cc} (%)	0.95 (↗+23%)	0.75
Freq. sep. π-4π/5 (MHz)	0.57	
Eq. diameter – IC (mm)	389.8	389.9
Eq. diameter – EC (mm)	392.1 (+2.3)	
Wall angle – IC (°)	2	2
Wall angle - EC (°)	2	0.7
Effective length (10*L_{hc}, mm)	704	705
Optimum βopt	0.65	
Epeak/Eacc @βopt	2.40 (↗+3%)	2.33
Bpeak/Eacc (mT/(MV/m)) @βopt	4.48 (↗+2%)	4.41
R/Q (Ω) @βopt	340 (↘-4%)	356
G (Ω) @βopt	193	187

Considering the compatibility with the interfaces of the cryomodule designed by FNAL, including beam pipes, couplers, tuner and He tank, a design for PIP-II LB650 cavity is proposed by INFN-LASA, as shown in Table 2. Compared to FNAL design [6], we increased the cell-to-cell coupling with a slight sacrifice on R/Q and peak fields, but leading to a larger separation between π and 4/5π modes. Thanks to our special tuning procedure for end cells, we obtain a larger geometric factor G while keeping the sidewall angle always at 2°, avoiding potentially negative value during the cavity field flatness tuning stage.

High Order Mode Issue

We have assessed HOM risk in our cavity design, including cryogenic loss, longitudinal and transverse beam instabilities. Due to the relatively low beam current, we don't expect "Klystron-type" instability, and beam break up (BBU) instabilities induced by HOM [7, 8]. Concerning the cryogenic loss that is mainly induced by HOM monopoles, attention needs to be paid to modes close to machine lines (ML), i.e. harmonics to 162.5 MHz, due to the possible frequency shift caused by fabrication tolerance.

The power loss induced by an exactly resonant HOM can be estimated by the formula: $P_{loss} \approx U_{HOM}^2/[(R/Q)Q_0]$, where $U_{HOM} = \frac{1}{2}I(R/Q)Q_L$, namely $P_{loss} \propto (R/Q)Q_L^2$ [8]. Assuming maximum CW-operation current at $I = 5$ mA for PIP-II Linac, and $Q_0 = 10^{10}$ in the LB650 cavity, if we want P_{loss} much smaller than the sum of the static heat load and the cryogenic losses due to the accelerating mode, about 20 W per cavity [9], it requires the HOM: $(R/Q)Q_L^2 \ll 3 \times 10^{16}$.

In LASA-design LB650 cavity, the monopoles have been searched up to a band above cut-off frequency (f_{cut}) of beam pipe, at 1945 MHz. Among these, no trapped mode is found above f_{cut}, and below f_{cut}, there are only two passbands of HOM monopoles. In order to estimate the effect of these HOM if they are shifted on the ML, we simulate their max R/Q and their loaded Q with the antenna geometry provided by FNAL [6].

Fig. 1 shows all the $(R/Q)Q_L^2$ for the HOM monopoles under f_{cut}. As we can see, all of them are much smaller than 3×10^{16}, hence their HOM-induced power loss will be negligible. Among these modes, two of them are trapped-like, one at 1470.5 MHz and the other at 1618.5 MHz, being last mode in each passband, respectively, as shown in Fig. 1. The later one has the maximum potential power loss in these two passbands.

It is worth to mention that in the simulation, we used the default distance of antenna tip to axis at 54 mm, corresponding $Q_{ext} = 1.3 \times 10^7$ for the accelerating mode, 20% higher than the required value. It means that with the required Q_{ext} for π-mode, the loaded Q for HOM will be even lower. Besides, due to the R/Q dependence on beta, an average value will be less than the maximum R/Q used in the calculation. Both these two points will further decrease the HOM induced power loss.

Concerning the above preliminary study, we do not expect danger from HOM effect in our cavity. Nevertheless, studies on full HOM modes finding and the more detailed HOM frequency shift due to fabrication tolerance are undergoing.

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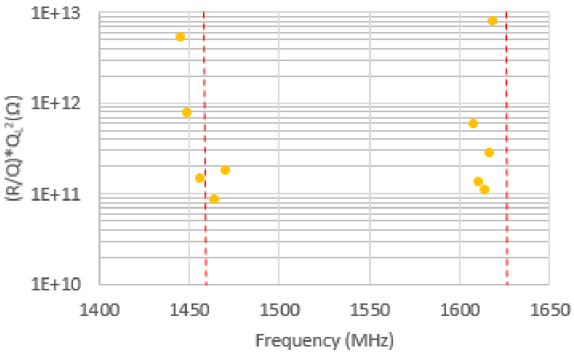

Figure 1: HOM monopoles under cut-off frequency in INFN-LASA LB650 cavity (red lines denote machine lines).

Considering standard Niobium mechanical parameters, a cavity thickness at 4.2 mm is chosen based on our study, balancing between the cavity stiffness and heat conducting. We apply stiffening rings both at end cell and at inner cells to provide enough suppression of detuning. Comparing to double stiffening rings between inner cells, one stiffening ring is preferred due to its sufficiency and simplicity. Fig. 2 is the 3D drawing of the cavity with the single stiffening rings.

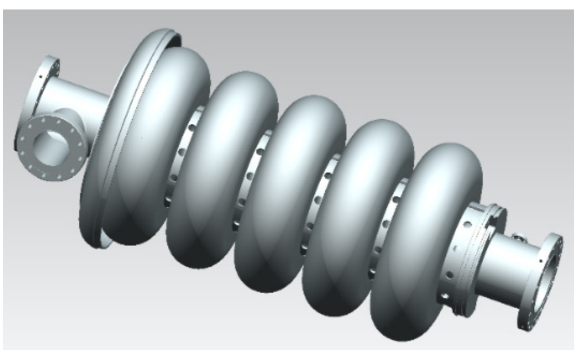

Figure 2: 3D rendering of the cavity with single stiffening ring on all irises.

Pressure sensitivity of this design is shown in Fig. 3. Lorentz Force Detuning (LFD) follows the same path. Our study shows a best LFD suppression with inner stiffening rings at about r = 70 mm, while microphonic suppression prefers larger radius.

The latter is even more important in CW operation; hence it is emphasized in our case. After balancing LFD and microphonics contributions, considering a 40 kN/mm external stiffness (tuner), a radius of 90 mm for both internal (between cells) and external stiffening rings is chosen.

The mechanical design parameters, based on the previous discussed considerations, are summarized in Table 3.

The search for the right compromise led us to a final solution that reduces the pressure sensitivity close to zero, only with a negligible loss on the LFD response, compared to the FNAL specs (-1.2 Hz/(MV)^2).

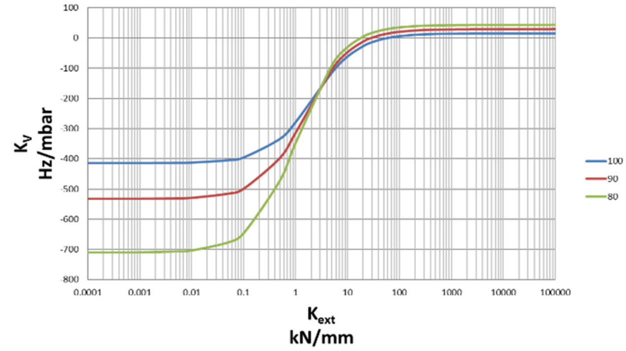

Figure 3: Pressure sensitivity vs External Stiffness.

Table 3: Mechanical Parameters of LB650 Cavity of INFN-LASA Design

Internal stiffening rings radius	90 mm
External stiffening rings radius	90 mm
Stiffness	1.57 kN/mm
Frequency sensitivity	223 kHz/mm
LFD @ 40 kN/mm	-1.43 Hz/(MV)^2
Pressure sensitivity @ 40 kN/mm	8.0 Hz/mbar
Max Pressure @ 50 MPa	2.9 bar
Max Displacement @ 50 MPa	2.1 mm

PRODUCTION

In order to validate our cavity design and the procedures of fabrication and surface treatments, we are producing 3 single-cell cavities, two in large grain Nb and the other in fine grain. The single cell cavities are planned to be fabricated in industry, EP surface treated, and finally vertical tested in INFN-LASA. Nevertheless, several upgrading of infrastructure has to be done, including supporting frame on insert.

The production of two multi-cell prototypes is also on the way.

CONCLUSION

INFN-LASA, an international partner to Fermilab PIP-II project, has proposed a new design of LB650 cavity. We have studied the criteria for cell-to-cell coupling, the effect of LFD and microphonic versus cavity geometric parameters. Based on the minimum acceptable cell-to-cell coupling, we have designed a cavity with highest accelerating efficiency, and with good suppressing of LFD and microphonic detuning by choosing the proper radius of single stiffening rings. In particular, the cavity is designed with slightly larger end cells to provide both good field flatness and quasi-symmetric geometry with almost round equator. Preliminary study on HOM shows no danger to both the beam stability and cryogenic loss. Three single-cell prototypes are going to be fabricated to verify the design and relative procedure and also two multi-cells prototypes are to be manufactured by the end of the year.

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