RF DESIGN OPTIMIZATION FOR NEW INJECTOR CRYOUNIT AT CEBAF*

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Abstract

A new injector superconducting RF (SRF) cryounit with one new 2-cell, β=0.6 cavity plus one refurbished 7-cell, β=0.97, C100 style cavity has been re-designed and optimized for the engineering compatibility of existing module for CEBAF operation. The optimization of 2-cell cavity shape for longitudinal beam dynamics of acceleration from 200 keV to 533 keV and the minimization of transverse kick due to the waveguide couplers to less than 1 mrad have been considered. Operating at 1497 MHz, two cavities have been designed into the same footprint of the CEBAF original quarter cryomodule to deliver an injection beam energy of 5 MeV with less than 0.27^{o} rms bunch length and a maximum energy spread of 5 keV.

SPECIFICATION AND LAYOUT

The new SRF booster section of the CEBFA injector after the bunching and capture sections has been designed and built recently until the cavity qualifications. This cryounit used to be two 5-cell cavities built within a quarter CEBAF cryomodule. In order to overcome the difficulties during the beam tuning up operation for the CEBAF injection particularly for the new 12 GeV machine, this new unit contains a low beta cavity which can handle the low energy electron beam (~200 keV) well both in bunching and acceleration processes without blowing emittance up. After electrons reaching nearly relativistic (β≈0.9), acceleration can be taken by new C100 style cavity in high gradient and later β=1 cryomodule. The beam dynamic analysis has been done by using the scheme of Figure 1, i.e. a 2-cell, low β cavity plus a 7-cell, β=0.97 cavity. The RF design including the fundamental power coupler (FPC), HOM damping and frequency tuning has been considered for the engineering compatibility of existing quarter cryomodule and also the beam dynamic requirement. Table 1 lists the design specification derived from the beam dynamic analysis and beam user requirement. The minimization of transverse RF kick induced by the FPCs without a skew quadruple effect (x-y coupling) on the beam trajectory is critical for the cavity design. The cavity electric field was specified in the peak value in the middle of cavity cell on beam axis. Conversion of these values into the cavity gradients E_{acc} including transit time factor (TTF) or beam voltages V_c can be seen in Table 1. The RF structure has been

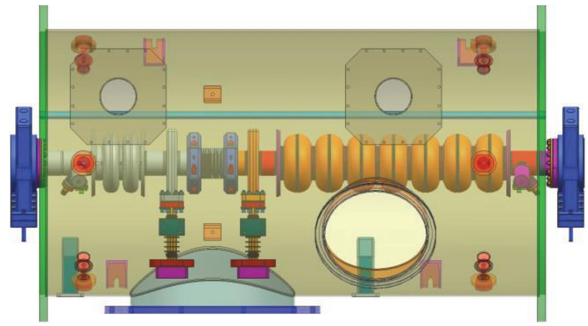

Figure 1: Top view of new injector cryounit, electrons beam runs from the left of 2-cell to the right of 7-cell.

Table 1: Injector Cryounit Design Specification

Cavity type	2-cell	7-cell
End beam energy (MeV)	0.533	5
Peak on axis E field (MV/m) nominal / (range)	4.6 (2-8)	13.2 (8-26)
E_{acc} including TTF (MV/m) nominal / (range)	2.5 (1.1-4.5)	7.0 (4.2-13.8)
Beam voltage V_c (MV) nominal / (range)	0.33 (0.13-0.54)	4.9 (3-10)
Beam current I (mA) nominal/max	0.38/1.0	
Geometry β_g	0.6	0.97
Q_0 at nominal gradient	>8.E9	>8.E9
Off-crest phase setup ϕ_b (deg)	-17	-15
FPC Q_{ext}	6E6	9E6
HOMs Q_{ext}	<1E8	<1E8
FPC RF kick dP_y/P_z (mrad)	<1	<2
Beam energy spread (keV)	-	<5
Beam bunch length (deg)	-	<0.27

designed like in the C100 style which keeps up-down symmetry of cavity-coupler geometry relative to beam axis. This symmetry is a key feature to eliminate skew quadruple effects [1].

2-CELL CAVITY SHAPE OPTIMIZATION

Several 2-cell cavity designs were considered. The final 2-cell cavity shape chosen to be β_g=0.6 (magenta 2D profile in Figure 2) was compromised due to a few factors:

1. Lower geometry beta cavity gives less R/Q change over large injection energy range.

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2. Beam pipe radius is consistent with the CEBAF cavity components.
3. Smaller iris radius than beam pipe's gives higher R/Q value.
4. Straight wall slope gives higher R/Q*G value, thus lower wall loss.
5. Thicker iris nose gives more room for easy access of stiffening ring welding.
6. The cavity is operated at low gradients, so the surface fields have less concern.
7. Uses the modified scissor-jack tuner developed for the APS crab cavity project.
8. All electric fields have almost the same slope when crossing zero (in Figure 4) which makes the beam bunching effect nearly the same.

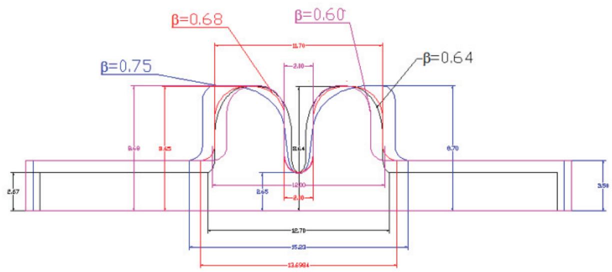

Figure 2: Different low−β, 2-cell cavity 2D geometry shapes, β=0.6 with beam pipe radius of 3.5cm was the final choice.

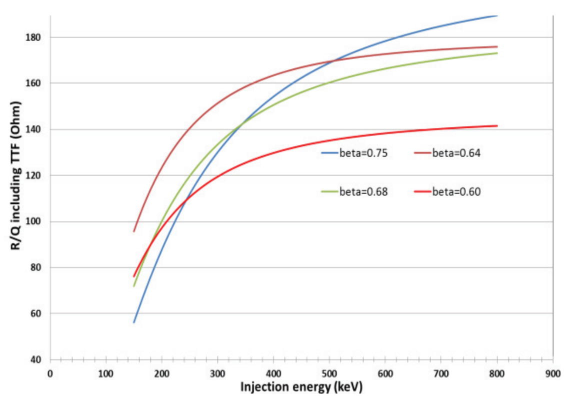

Figure 3: R/Q change as function of injection energy for different 2-cell cavity shapes calculated by SuperFish.

SuperFish calculated RF parameters for this 2-cell elliptical cavity are summarized in Table 2. The HOM and FPC couplers are all adapted from the C100 cavity design as shown in Figure 5, except the distance of FPC centreline to the end iris D, which determines the coupling Q_{ext}.

COUPLING Q CALCULATION

The optimum value of coupling Q_{ext} has been derived from reference [2] based on the normal operation parameters in Table 1, but let coupling to drive 1 mA maximum beam current for the future injector upgrade. In this case, microphonics are not a dominate load for RF power. So the optimum Qext would be 6×10^6 for the 2-cell cavity and 9×10^6 for the 7-cell cavity. Using a 3-stub tuner to increase Q_{ext} is a provision for the lower beam current operation.

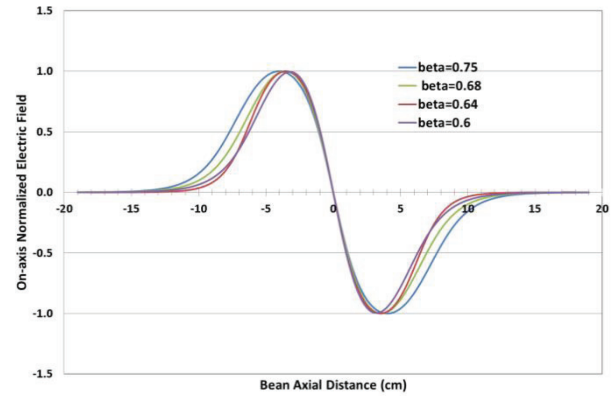

Figure 4: Normalized on-axis electric field from different 2-cell cavity shapes.

Table 2: RF design parameters of 2-cell cavity

Parameters	β_g=0.6, 2-cell cavity
Frequency, MHz	1494.297
R/Q including TTF, Ω for β_b=0.7, 200 keV	98.2 (98.8, MathCAD)
Transit Time Factor (TTF) for β_b=0.7, 200 keV	0.607 (0.609, MathCAD)
E_s/E_{acc}	1.638
B_s/E_{acc}, mT/(MV/m)	3.341
Geometry Factor, Ω	172.38
Active Acceleration Length, mm	12.000
Tuning Sensitivity (4 mm wall thick), MHz/mm	2.63 (ANSYS)
Equator Trim Coefficient, MHz/mm	7.15

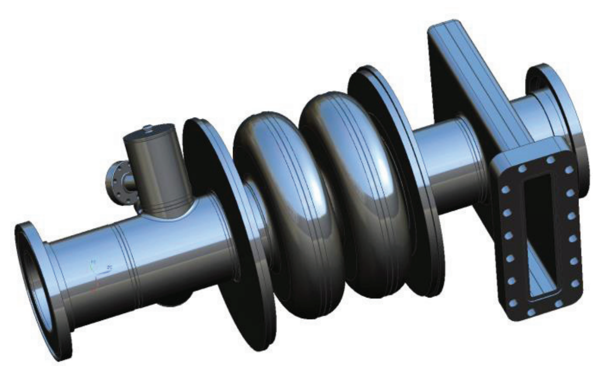

Figure 5: CAD picture of 2-cell cavity with C100 style waveguide coupler with beam entrance on left.

In the coupler design, both dimensions of D and the FPC stub length L from the beam axis to the stub end determine the coupling Q_{ext}. The length L is critical to the transverse kick to the beam bunches to be discussed in next section, so the D was varied after optimization of L in order to get designed Q_{ext}. The Q_{ext} calculation was done by the CST MWS. We have found following exponential expressions described the Q_{ext} for 2-cell and 7-cell cavities, where D is in mm, L=100mm:

$$Q_{ext,2cell} = 34.022544exp(0.122028D)$$
$$Q_{ext,7cell} = 173.9849exp(0.1259314D)$$

For the 2-cell, D=99 mm Q_{ext}=6.0×10^6, for the 7-cell D=86 mm, Q_{ext}=8.8×10^6. For 1 mA beam current operation, based on the helium pressure fluctuation induced frequency detuning [3] and off-crest angle setup values in Table 1, the calculated klystron power [2] is 1457 W for the E_{acc}=9 MV/m of 2-cell and 8160 W for the E_{acc}=10 MV/m of 7-cell respectively.

COUPLER KICK MINIMIZATION

Asymmetry of RF coupler relative to axial symmetric cavity would induce a transverse kick by the RF power feeding to the cavity, and minimization of this effect is particularly important for the low momentum beam bunches to preserve their emittances. The C100 style waveguide FPC has been modified with its stub length L in 1/4 of guided wavelength λ_g [4]. By this design principle, the vertical magnetic field at the waveguide location should be nearly zero to minimize the horizontal RF kick. This kick is also a function of cavity voltage V_c, beam current I, off-crest phase ϕ_b and up-stream/down-stream of the cavity relative to the beam. This length L had been designed in 100 mm by the simulation of HFSS with dummy antenna as the beam loading [5]. We have found recently that the mixed RF waveforms in the cavity-coupler transition field can be reconstructed by two highly accurate 3D eigen solutions:

$$\vec{E} = (E_H - jE_E)e^{j\omega t}$$
$$\vec{H} = (H_E + jH_H)e^{j\omega t}$$

Here (E_E, H_E) and (E_H, H_H) are the renormalized EM fields calculated with electric and magnetic boundaries at the FPC waveguide port respectively. The field renormalizations only depend on the parameters in the following tables. The detail of calculation method and the RF field combination technique in the CST MWS has been published in reference [6]. One set of recombined EM fields has been imported to the GPT tracking program to cross-check the kick angle calculation for the 2-cell cavity coupler. The result is consistent to this method. We just list the CST calculation results in following tables.

Table 3: Coupler kick calculation result for 2-cell cavity

D (mm)	L (mm)	Q_{ext}	I (mA)	Φ_b (deg)	V_c (MV)	dP_y/P_z (mrad)
99	**100**	6.0E6	1.0	-17	0.1-0.9	0.23-0.25
99	**100**	6.0E6	1.0	0	0.1-0.9	0.23-0.24
99	**100**	6.0E6	1.0	17	0.1-0.9	0.23-0.24
99	**100**	6.0E6	0.38	-17	0.1-0.9	0.17-0.22
99	**100**	6.0E6	0.38	17	0.1-0.9	0.16-0.19
100	120	8.6E6	1.0	-17	0.1-0.9	0.71-0.34
100	120	8.6E6	1.0	17	0.1-0.9	0.83-0.59
100	120	8.6E6	0.38	-17	0.1-0.9	0.38-0.31
100	120	8.6E6	0.38	17	0.1-0.9	0.49-0.40
93	80	5.8E6	1.0	-17	0.1-0.9	0.11-0.06
93	80	5.8E6	1.0	17	0.1-0.9	0.14-0.10
92	60	7.8e6	1.0	-17	0.1-0.9	0.22-1.31
92	60	7.8e6	1.0	17	0.1-0.9	0.16-1.23
92	60	7.8e6	0.38	-17	0.1-0.9	0.31-2.44
92	60	7.8e6	0.38	17	0.1-0.9	0.26-2.38

Table 4: Coupler kick calculation result for 7-cell cavity

D (mm)	L (mm)	Q_{ext}	I (mA)	Φ_b (deg)	V_c (MV)	dP_y/P_z (mrad)
86	**100**	8.8E6	1.0	-15	3-10	1.89-2.06
86	**100**	8.8E6	1.0	15	3-10	1.71-1.78
86	**100**	8.8E6	0.38	-15	3-10	0.76-1.04
86	**100**	8.8E6	0.38	15	3-10	0.65-0.77

It can be concluded from the kick angle calculation $\mathbf{dP_y/P_z}$ in Table 3, the changes of beam current I, voltage V_c and phase Φ_b have a relative weak effect on the kick angle when the stub length L is about 1/4 of λ_g, which is 75mm in this case. At other stub lengths far from 1/4 λ_g, the kick angle dependence of beam parameters becomes stronger. The current L=100 mm FPC design for both 2-cell and 7-cell cavities has satisfied design specification in Table 1, except when the 7-cell cavity runs at the highest voltage, the kick angle is marginally exceeding the 2.0 mrad.

ACKNOWLEDGEMENT

Authors would like to thank Frank Marhauser for his early design work on this subject and Feisi He for his CST macro programming for the RF kick calculation.

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ISBN 978-3-95450-122-9