DESIGN OF NORMAL CONDUCTING 325 MHZ CROSSBAR H-TYPE RESONATORS AT FERMILAB*

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Abstract

The warm section of the proposed High Intensity Neutrino Source at Fermilab is designed to accelerate H- ions and protons from 2.5 MeV to 10 MeV (β=0.0744 to β=0.1422). Originating from the ion source, the beam gets accelerated by a radio frequency quadrupole first, then by a medium energy beam transport (two buncher cavities and a chopper) and finally travels through 16 normal-conducting resonators, all separated by superconducting solenoids individually enclosed in cryostats. For the next stage of the Front End LINAC, beyond 10 MeV, the design uses superconducting spoke resonators that accelerates the beam until beta=0.61.

The electromagnetic design and optimization of all the 325 MHz room temperature crossbar H-type (RTCH) resonators is presented. In particular, a detailed description of the mechanical design, of its performance and the issues related to the fabrication of the first prototype (β=0.0744) are presented. The design of the prototype for the input coupler that will be used in the resonators is also included.

INTRODUCTION

The FNAL High Intensity Neutrino Source (HINS) is a 8 GeV superconducting H- LINAC with primary mission of enabling 2 MW beam power at 120 GeV for the Fermilab Main Injector neutrino program. Fermilab's approach in this development is to align this effort more closely with the laboratory's International Linear Collider (ILC) strategy.

Superconducting (SC) cavities operating at 1300 MHz and originally developed for the electron-positron linear collider can be directly applied for acceleration of $\tilde{H}$ or proton beams above 1.2 GeV. Squeezed ILC-style cavities designed for β_G=0.81 can be used in the energy range from ~400 MeV to 1.2 GeV. The Front End LINAC in the energy range from 10 MeV to 400 MeV is a section operating at the 4th sub-harmonic of the ILC frequency [1] and is based on SC spoke resonators running at 325 MHz.[2,3].

One of the new paradigms introduced into the front end design is the adoption as primary lattice focusing elements of short, high field superconducting solenoids, and a low energy transition at 10 MeV from room temperature to superconducting radio-frequency (RF) acceleration. To provide adiabatic variation of the wave numbers, the real-estate accelerating gradient has to change from ~0.75 MV/m – valid at the radio frequency quadrupole (RFQ) end – to ~2 MV/m – valid at the beginning of SC section. This can be achieved by using short RT accelerating cavities incorporated into solenoidal focusing lattice. The use of short normal conducting resonators up to ~10 MeV reduces the number of different types of SC cavities and provides adiabatic beam matching. By focusing the beam via SC solenoids we obtain a more compact lattice and a shorter focusing period [4].

Our studies show that the most appropriate RT accelerating structure in the energy range 2.5-15 MeV is a cross-bar H-type (CH) cavity [5] operating at 325 MHz.

ELECTROMAGNETIC DESIGN AND OPTIMIZATION OF THE RTCH RESONATORS

In general, H-mode cavities have no competitor in low energy range. However, the current HINS LINAC design is based on the scheme with RF power fan-out from one klystron to multiple cavities, which puts additional limitations on power consumption by RT and each other accelerating section. Besides that, the focusing lattice makes our CH cavities very short, comprising 4 and 5 accelerating gaps only, and for short H-mode cavities shunt impedance is reduced significantly. Therefore it was especially important for our room temperature CH cavities to maximize the shunt impedance.

The RT accelerating section between medium energy beam transport (MEBT) and the SC part of the accelerator comprises 16 cavities (four 4-gap cavities and twelve 5-gap ones). The beam energy from 2.5 MeV gets accelerated up to 10 MeV. Each cavity consists of 3-4 identical cells with geometrical beta corresponding to the relevant beam velocity at the cavity mid plane. Moreover, in order to simplify production, all cavities drift tubes are identical (except length) and cross-bars or spokes have the same basic shape. In order to accommodate the tight space requirements we refused end-cell volume tuning and adopted simple flat walls to close cavities. Given these assumptions, the following optimization strategy was applied:

1) For cavities no.1, 4, 5, 8, 11, 14 and 16 a single cell optimization (or in other words infinite structure optimization) with respect to shunt impedance was performed.
2) The results were compared with mechanical properties and manufacturability. If needed we repeated step 1).
3) Simulation of multi-cell cavities with required cell numbers was performed. If needed we repeated step 1)..

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4) Tolerances and influence of mechanical fixtures like tuners was determined.
5) Interpolation of dimensions and parameters for the cavities that were not simulated was performed as well.

The basic parameters of the CH cavities are summarized in Table 1. The shunt impedance is defined here as R_{sh} = V2/2P_{copper}. The total power consumption for the 16 resonators is 280 kW.

Table 1: Main Parameters of the RTCH Resonators

Cavity number	Beta of cavity	Rsh MΩ	Q	Voltage eff, MV
1	0.07437	5.196	9270	0.233107
2	0.077096	5.45	9662	0.305553
3	0.080441	5.65	10051	0.367743
4	0.084211	5.792	10461	0.425032
5	0.088233	8.617	10772	0.434359
6	0.09235	9.02	11078	0.46784
7	0.096797	9.41	11374	0.526789
8	0.101528	9.766	11680	0.570348
9	0.106271	10.12	11945	0.582932
10	0.111067	10.45	12220	0.609035
11	0.115949	10.737	12465	0.632117
12	0.120984	11.04	12750	0.685361
13	0.126222	11.31	13005	0.740279
14	0.131596	11.584	13271	0.787771
15	0.137085	11.79	13494	0.842331
16	0.142159	11.977	13723	0.818503

MECHANICAL DESIGN OF THE FIRST RTCH RESONATOR PROTOTYPE

The first resonator of the series, currently being fabricated for prototyping, is a triple-spoke structure with a period of 34.3mm and an overall flange to flange dimension of 236.9mm (Figure 1).

The main body is a 10 mm thick cylinder made of oxygen free electronic copper (Cu-OFE) with an internal diameter of 364 mm and a longitudinal dimension of 177.2 mm. The spokes are arranged at 45° angles to accommodate a vacuum port located at the bottom for easier mounting of the ion pump. Magnetic coupling is achieved through the copper port placed atop onto which a stainless steel transition ring is brazed to allow welding of the flange. Two plunger type tuners adjust the resonant frequency by ±0.7 MHz in a feedback loop system matching the phase of the input signal to the phase of the resonant signal inside the cavity. This latter signal is measured with a probe whose port carries a 1-1/3” conflat flange. The resonator is connected with the other components of the lattice using NW40 flanges fastened via hinged clamps.

Due to the internal vacuum, the mechanical structure of the RTCH resonator must withstand an inward differential pressure of 1 atm on all the outer surfaces.

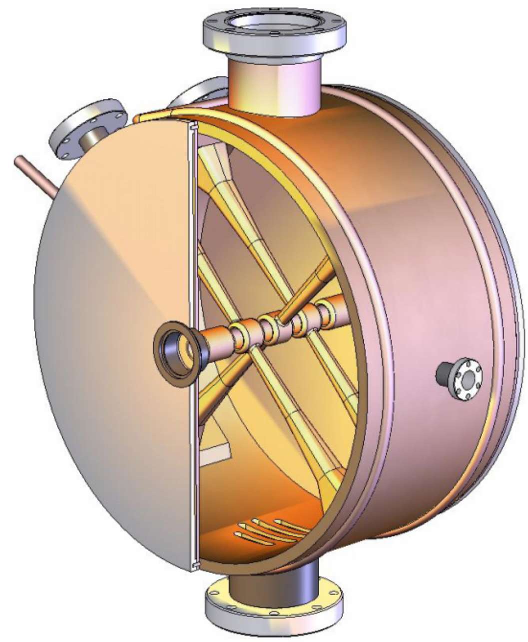


Figure 1: 3d view of the RTCH resonator prototype. The end wall is partially hidden to show the 45° crossed spokes.

To accommodate different requirements, i.e. RF performance while assuring structural integrity and limiting the overall longitudinal space, the end walls are designed using an outer 5 mm stainless steel plate and a 3 mm Cu-OFE plate. These plates are separated by a 2 mm air gap.

The predicted maximum von Mises stress for the outer stainless steel plate is 127 MPa and its maximum deformation 1.02 mm. The deformation of the inner copper plate is instead only 47 μm. See Figure 2.

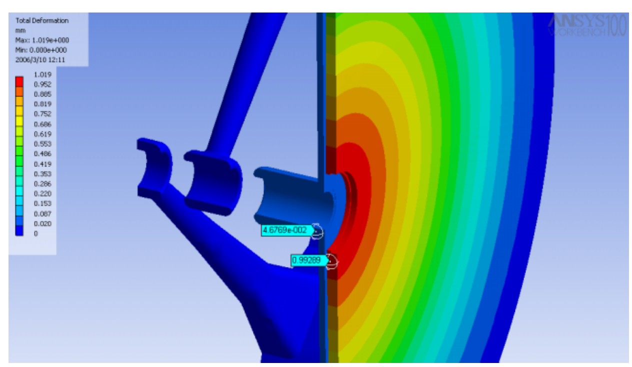


Figure 2: Total deformation in mm of the double-layer end wall under vacuum. Only ¼ of the cavity is shown for clarity. For FEA efficiency, the structure symmetry has been invoked and only 1/2 of the structure analyzed.

Since the surface currents induced in the resonator generate a 32W heat load per spoke, an appropriate cooling system has been designed and its performance simulated. An 8mm ID copper tube was brazed on the resonator outer surface inside grooves to improve the surface heat exchange with the tubing. The assumed water flow rate is 1 Gal/min. No cooling was adopted inside the spokes.

The stems thermal expansion, induced by the ~7.5°C temperature difference along the spokes, creates stress build up on the drift tubes. To mitigate this effect, 2mm fillets are present at the interface between the stems and the drift tubes. The resulting maximum von Mises stress in this region is below 48 MPa and the maximum total deformation is about 7 µm. Buckling analysis of the spokes was also performed; for the given temperature gradients, results showed safety factors of 40 and up, confirming the effectiveness of the adopted cooling system. Subsequent resonators will require suitable cooling systems as the heat loads for each type of resonator vary (for example resonator no.16 has heat loads about 4 times higher than resonator no.1) .

Fabrication

The prototype fabrication is in its final stages. The main body was originally forged from a Cu-OFE cylindrical blank and rough-machined. An annealing treatment was carried out before the final finishing. The spokes were machined following the same roughing-annealing-finishing cycle and later brazed in the main body using a special fixture. The drift tubes, stems and bases of the spokes were fabricated as a single part from a solid blank as to avoid complicated brazing cycles otherwise required.

Quality control was performed at Fermilab using coordinate measuring machines on aluminum samples of the spokes and later on copper parts prior to assembly.

INPUT COUPLER DESIGN

RF design of the main power coupler was done using Ansoft high frequency structure simulator software. Electric field in the equator surface of the cavity is very small (fig. 3) and the quality factor of the cavity is only $Q=5\cdot10^3\div10^4$. Due to its small coupling with the cavity an antenna-type coupler cannot be used.

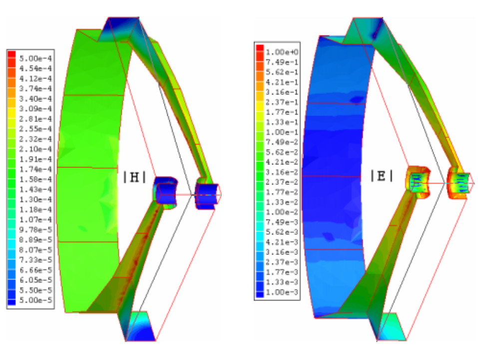
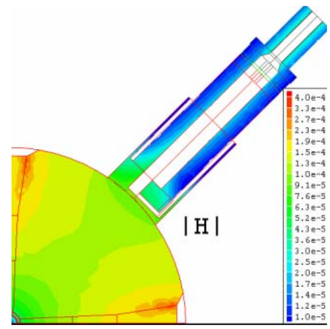


Figure 3: Magnetic and electric fields on cavity surface.

The optimum position for the magnetic coupler is at 45° with respect to the spoke planes, where the surface electric field is at its minimum and the magnetic field is suffienciently high. The 16 cavities consume a different amount of power starting at 10 kW for the first cavity up to 50 kW for the last one. Also, given the fact that the geometry of the cavities is different, each resonator has an individual loaded quality factor.

The power coupler must be able to supply a power of 75 kW. The average power loss on the coupler loop surface is minimized and does not exceed 1W of average power.



CH no.16 with coupler		
L, mm	F, MHz	Qext
180	325.048	2173
190	324.789	4400
200	324.647	10215
210	324.598	26398

Figure 4: Dependency of frequency (F) and external quality factor (Q_{ext}) from distance between cavity axis and coupler tip (L) for the 16th resonator.

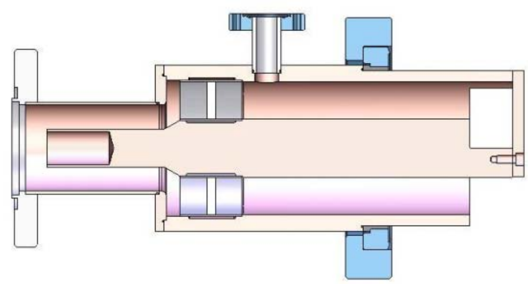


Figure 5: Sectioned view of the power coupler.

With the goal to use a standard coupler for all the cavities, it is necessary to adjust the initial coupling. This will be achieved choosing individual lengths for each coupler port. To compensate eventual manufacturing errors a rotatable flange welded to a stainless steel transition will allow independent adjustments of Q_{ext}. An alumina ceramic window is utilized to separate cavity vacuum from surrounding air.

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