HIGH GRADIENT SUPERCONDUCTING CAVITY DEVELOPMENT FOR FFAG*

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Abstract

Like the cyclotron, the Fixed Field Alternating Gradient accelerator (FFAG) is a compact accelerator with a variety of applications in industry and medicine. High intensity, fixed-field compact accelerators require enhanced orbit separation to minimize beam losses especially at extraction. A 900 MeV FFAG, which fits in a 2.4 m x 4.4 m space, requires a total continuous-wave voltage of ~20 MV per turn and the accelerator cavities must fit in two 2 m straight sections. This high voltage can be generated using 4 superconducting (SC) cavities operating at a harmonic of the beam revolution, 150 or 200 MHz in this case. However, as with cyclotrons, the FFAG requires a large horizontal acceptance presenting a challenging problem for SRF cavity design. In this work, we present a SC cavity design with a 50 cm x 1 cm beam aperture, including an electrodynamics optimization, multiphysics analysis and the initial plan for the high-power couplers. Each cavity will be powered by two 100 kW RF couplers to accelerate a 1 mA average beam current

CAVITY TYPE

Several cavity types were considered including a coaxial half-wave resonator (HWR), an H-resonator and a rectangular cavity. Each of these options has advantages and disadvantages. Simulations of the simple non-optimized cavities have been performed to quantify their performance and size. These results are used to determine which option to pursue in more detail for the accelerator design. A peak surface magnetic field of 160 mT was chosen as a design constraint for this analysis because this value is experimentally achievable [1].

The first cavity type considered is a simple HWR model, a section of coaxial line (Fig.1a). As the resonant frequency is determined by the cavity length and the diameter defines optimal beta for acceleration, HWR should be 1 m long and 40 cm in diameter. Table 1 summarizes the main parameters of this cavity. While evaluating the HWR it was noticed that the velocity acceptance of the resonator was not broad enough to provide uniform acceleration over the proton velocity range. This is not possible because the accelerating voltage is a maximum in the center of the cavity and falls off sinusoidally as the protons move to the ends of the HWR; this field non-uniformity gives a varying voltage gain for protons in orbits of varying energies where the voltage gain is low at injection and at extraction. A low voltage gain correlates with a smaller orbit separation and makes injection and extraction difficult. The cavities to be discussed next do not have this issue and therefore the HWR option was dropped.

* This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357 and ANL WFO No. 85F092

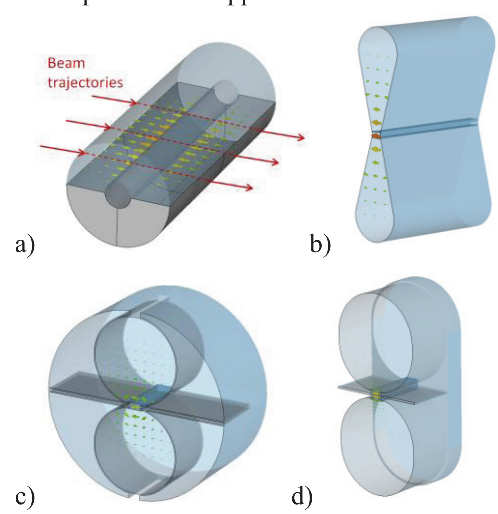


Figure 1: Considered cavity shapes: HWR (a), rectangular (b), H-resonator with (c) and without (d) a tank.

Table 1: RF Parameters of Different Cavity Types (V_{center}/V_{end} – voltage gains of a 200 / 900 MeV proton passing through the center / edge of the gap)

Parameter	HWR	H-resonator	Rectangular
Frequency, MHz		150	
B_{peak}, mT		160	
V_{center}, MV	4.65	2.73	4.11
V_{edge}, MV	1.82	2.51	3.56

To avoid the problem caused by the varying voltage gain in the HWR, it is advantageous to consider a single gap accelerating structure. One option is an H-resonator which performs well at low frequencies and low velocities [2]. Two types of H-cavities were considered: one with (Fig.1c) and one without (Fig.1d) a tank. The cavity with a tank has dimensions of 1m x 1m x 1m and 160 mT peak magnetic fields on the edges limit the voltage gain to a twice less the design value. Removing the tank decreases peak fields and thus increases the maximum achievable voltage. Though peak magnetic field drops under 160 mT, this structure has limits for

ISBN 978-3-95450-128-1

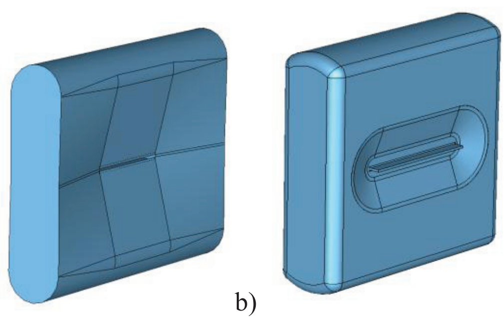
further optimization due to the sharp edges of the electrode's side end.

A cavity geometry that avoids the magnetic field maxima on the edges is a rectangular one (see Fig.1b). A rectangular cavity operating in the TM010 mode concentrates the electric field around the beam aperture and gives a voltage gain which meets our criteria, see Table 1. The dimensions of such cavity (1m x 1.5m x 0.35m) are smaller than those of the H-resonator with a tank but larger than the HWR dimensions. As the rectangular cavity is a reasonable compromise between the dimensions and cavity performance, it was chosen for further optimization.

CAVITY OPTIMIZATION

Shape Optimization

We investigated several ways to improve the performance of the rectangular cavity: shape optimization, accelerating gap width optimization and resonant frequency optimization.



a) b)

Figure 2: Rectangular cavity shapes before (a) and after (b) optimization.

To keep the electric field concentrated around the beam aperture while distributing the magnetic field over a larger volume, a taper which extends the cavity width was introduced, making the cavity reentrant (see Fig.2a). Here, the section in the center of the cavity remains the same while the sections at both ends of the cavity have race-track shapes and a larger area. Such a cavity design has smaller dimensions for the same volume.

The voltage gain of a proton with energy of 200 MeV passing through the center of the accelerating gap normalized to 160 mT peak magnetic field was calculated for different gap widths, frequencies and cavity transverse dimensions. The results shown in Fig.3 indicate that the 150 MHz structure has a potentially higher voltage or lower peak magnetic field at a fixed voltage, while the 200 MHz 1m structure is more compact.

Further optimization of the cavity shape, which includes the rounding of all edges and an improved reentrant nose shape (see Fig.2b), reduced the peak magnetic field by more than 15% and the transverse dimensions by more than 10cm.

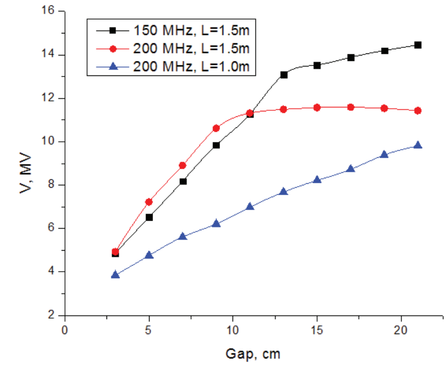


Figure 3: Maximum voltage gain as a function of gap width.

Multipacting Discharge

Although the RF parameters of the rectangular cavity seem to be very good, the parallel plates and rounded edges can lead to dangerous multipacting discharge. The estimations done with CST Particle Studio (PS) predict a slowly-developing multipacting discharge for all voltage levels above ~0.3 MV with maximum discharge growth at ~1.4 MV.

a) b)

Figure 4: Areas of secondary particles growth in rectangular (a) and elliptical (b) cavities.

It is known [3] that in the elliptical cell shape the magnetic field varies along the cavity wall such that there are no stable trajectories and electrons drift toward the equator in several RF cycles. At the equator the surface electric field vanishes, and the emitted electrons do not gain any energy and the discharge is stopped.

Two-point multipacting between opposite sides of the cavity is still possible but the energy gain at normal operating fields is high enough such that the SEY is < 1.

Figure 4b shows the shape of the elliptical-cell cavity as well as Particle Studio simulation results which still predict two-point multipacting about the equator. The RF parameters of this cavity are compared to those of the rectangular cavity in Table 2. All of the elliptical cavity parameters are worse except for the multipacting discharge.

Table 2: RF Parameters for Several Cavity Geometries Investigated Here

Parameter	Rectangular (Fig 1a)	Rectangular (Fig 1b)	Elliptical
Length, cm	100	100	120
Height, cm	104.5	92.9	142
$V_e(\beta=0.56)$,MV	4.67	4.66	4.68
$V_c(\beta=0.78)$,MV	6.72	6.71	6.89
$V_e(\beta=0.86)$,MV	5.00	5.00	5.00
R/Q, Ω	82.8	89.7	75.0
G, Ω	147.9	150.2	134.2
B_{peak}, mT	92.1	72.7	77.2
E_{peak}, MV/m	55.2	47.0	48.1

CAVITY DESIGN

The first issue in the mechanical design is the RF coupler. Analytical estimations show that the cavity should be overcoupled with an external Q-factor of ~ $1.9*10^6$. The most convenient place for the coupler port is at the cavity sides perpendicular to the beam pipe. In this area, the magnetic field is strong, so a magnetic coupling loop was considered as an option. The required coupling can be achieved with this coupler, although the RF losses caused by the magnetic field are extremely high and it is a major technological challenge to remove heat from the central conductor.

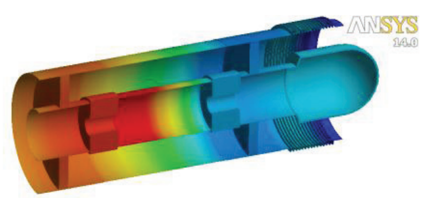


Figure 5: Temperature map of 100kW electric RF power coupler operating at cavity resonance (red 356K, blue 2K).

For an electric coupler, the inner conductor is not connected to the 2K zone and therefore is more convenient to cool down. A coupler placed at the cavity aperture or at the cavity side does not couple to the cavity and cannot be used. The only way to provide RF power to the cavity is to place the coupler in front or back of the cavity. Accelerating 1 mA beam from 200 MeV to 900 MeV with four 5MV-cavities requires 175 kW of RF power. It is more convenient to use two 100 kW couplers for the reasons of coupler dimensions and cost. Figure 5 shows the temperature map for such a coupler operating at 100 kW. The 6 1/8'' coupler consists of a warm window, a thermal transition, a cold window and bellows sections.

The complete mechanical design presented in Fig.6 includes: 1 - niobium shell, 2 – RF ports, 3 – extra ports for cleaning and polishing, 4 – double nose plates for frequency tuning, 5 – stainless steel helium jacket. The cavity is constrained by the rails (6) as shown in Fig.6. Preliminary structural simulation results predict deformations of ~1.1mm for the niobium shell and ~0.6mm for the stainless steel jacket in the magnetic field area due to the pressure difference from 0 to 1 atmosphere.

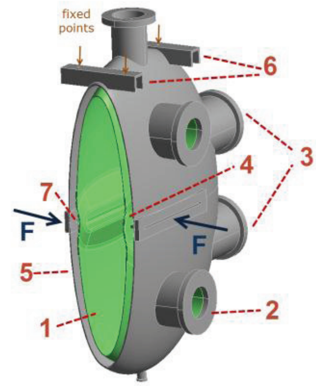


Figure 6: Mechanical design of elliptical cavity.

The frequency sensitivity to changes in the helium pressure can be reduced from +1.18 Hz/Pa to -0.58 Hz/Pa by adding bellows (7) in the beam area. Slow frequency tuning can be performed by pushing on the beam ports. Here, the slow tuning sensitivity will be equal to -7.7 kHz/kN.

SUMMARY

Different cavity shapes were studied and the optimum between performance and dimensions is achieved for a rectangular cavity in comparison to HWR and H-resonator. Two options of the 200 MHz cavity were studied: "rectangular" and "elliptical". Due to the multipacting discharge in rectangular cavity, the elliptical cavity may be a preferable option. The shape optimization of this cavity allowed achieving reasonable RF parameters and peak fields for the required 5MV. A 100 kW RF coupler has also been designed. An initial mechanical design was created and structural analysis has been performed. The cavity can be made structurally stable. Additional effort will be necessary to complete the multipacting study, optimization of the structural stability to reduce the fabrication cost, optimization of the RF coupler design.

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