High gradient Superconducting Cavity Development for FFAGs

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Cyclotrons'13

September 16, 2013

Vancouver, BC, Canada

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U.S. DEPARTMENT OF ENERGY

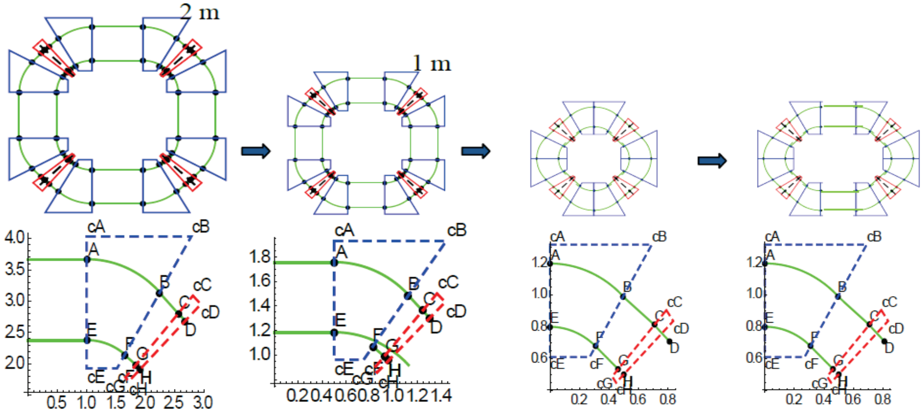
Outline

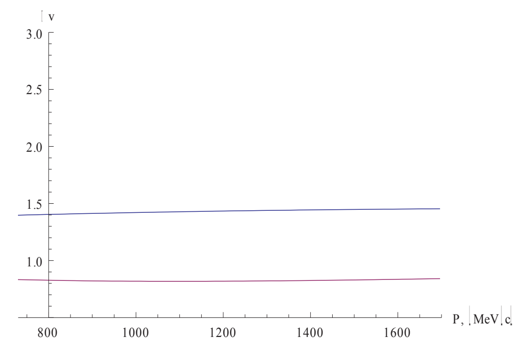
- **Motivation and Background**
  - Next generation ultra-compact, high-energy fixed field accelerators
  - Medical, security, energy applications
  - CW FFAGs ; i.e. strong-focusing cyclotrons
    - Relativistic energies: ~200 MeV – 1 GeV
    - Ultra-compact
    - Constant machine tunes (optimized gradients)
    - High mA currents (low losses)

- **These machines require high gradient acceleration; SCRF required for**
  - Compactness
  - Low extraction losses
  - Large horizontal aperture of the FFAG, like the cyclotron, is a challenging problem for SCRF design

NEXT-generation CW high-energy Fixed-field Compact Accelerators

- Reverse gradient required for vertical envelope
- Isochronous or CW (serpentine channel relaxes tolerances)
- Stable tune, large energy range
- The footprint of CW FFAG accelerators is decreasing rapidly





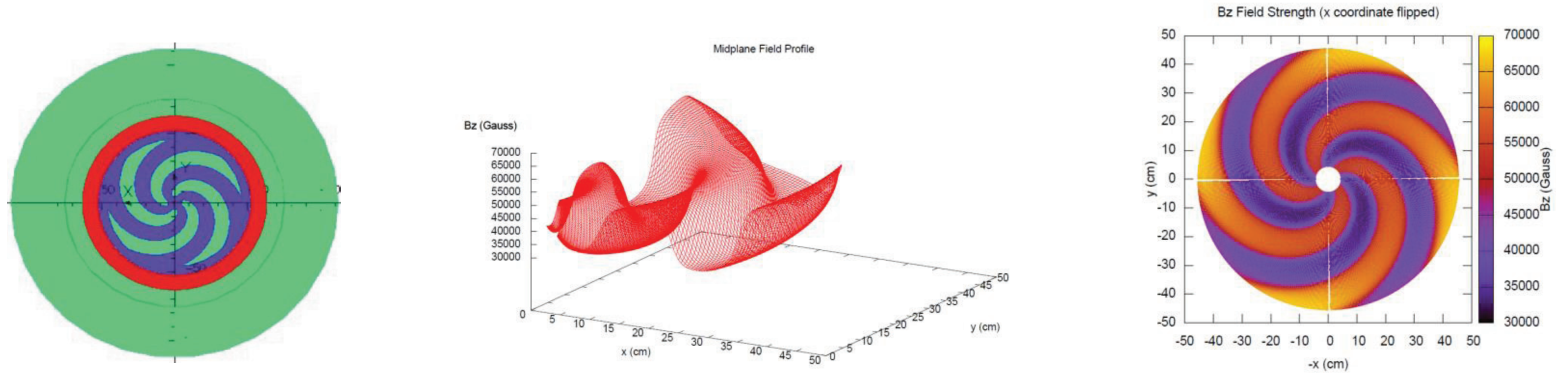
Machine tunes:

ν_r ~1.4

ν_z ~0.8 – factor of ~4 > than compact cyclotron

Modeling Cyclotrons

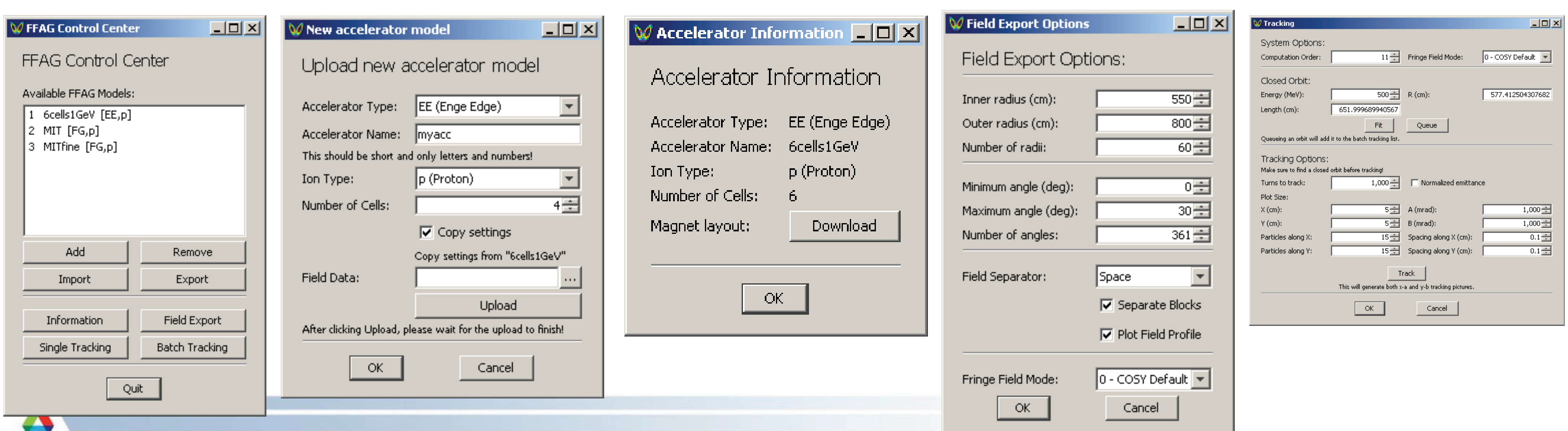
- Supplied OPERA field data
- Two approaches:
  - A highly accurate tracking through a high-order field map using FACT/COSY
    - Field maps are constructed by expressing the azimuthal fields in Fourier modes and the radial in Gaussians wavelets for accurate interpolation
  - Particle tracking in the code ZGOUBI using the OPERA data directly and linear interpolation



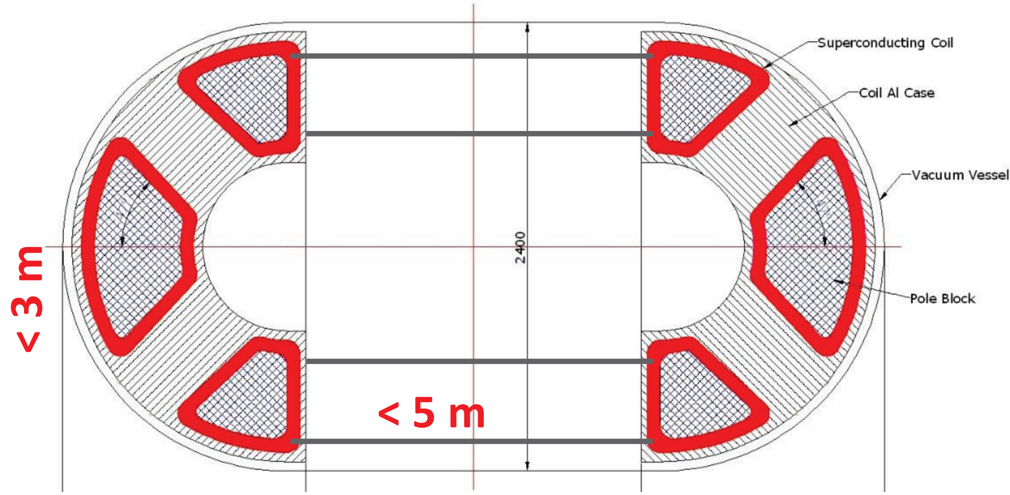
Opera field data plotted in the midplane for one quadrant and showing spiral sectors.

Modeling, Design and Optimizing

- Most advanced modeling, design, and optimization of fixed-field accelerators – both FFAGs and cyclotrons -
  - production runs
  - advanced optimization
    - The lowest order Fourier mode in the cyclotron, for example, can be re-fit to correct dynamics
- Simple user interface allows switching fixed-field modes and rapid computation
  - Performance can be optimized and iterated with magnet design



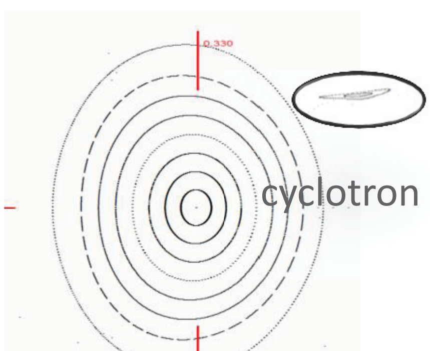
MAGNETS and modeling



Parameter	Units	Value
Number of magnets		6
Number of SC coils		12
Peak magnetic field on coils	T	7
Magnet Beam Pipe gap	mm	50
Superconductor type		NbTi
Operating Temperature	K	4.0
Superconducting cable		Rutherford
Coil ampere-turns	MA	3.0
Magnet system height	M	~1
Total Weight	tons	~10

One straight section occupied by RF cavities and injection/extraction in the other

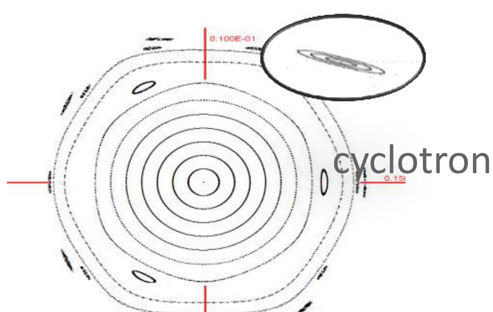
FFAG Horizontal / Vertical Stable beam area @200 MeV



80 mm x 293 mr

$\varepsilon_H = 23{,}440\pi$ *mm-mr*

ε_{norm} = ***16,059π mm-mr***

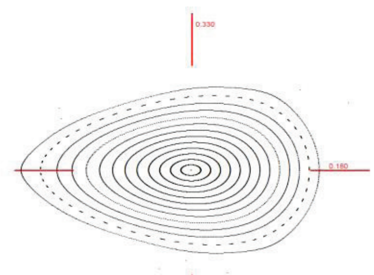


10 mm x 9 mr

$\varepsilon_V = 90\pi$ *mm-mr*

ε_{norm} = ***62π mm-mr***

FFAG Horizontal Stable beam area @1000 MeV vs. DA of 800 MeV Daeδalus cyclotron*



Tracked: 130 mm x 165 mr

$\varepsilon = 21450\pi$ *mm-mr*

ε_{norm} = ***38820π mm-mr***

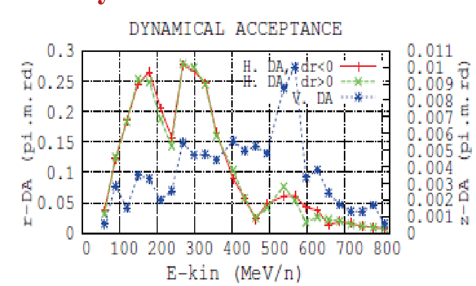


Figure 8: 500-turn DA (normalized) as a function of energy. Left axis : Horizontal DA, for either $dr < 0$, or $dr > 0$, wrt. closed orbit. Right axis : Vertical DA.

F. Meot, et. al., Proc. IPAC2012

Tracking: Horizontal – 1 cm steps, Vertical – 1 mm steps

*FFAG vert. stable area at aperture limits.

Acceleration Gradient required for low-loss extraction

Reference radius in center of straight for the energy orbits preceding extraction. For an accelerating gradient of ~20 MV/m orbits are sufficiently separated for a “clean” (beam size: 1.14 cm; ε=10π mm-mr normalized) or low-loss extraction through a septum magnet.

Kinetic Energy (MeV)	Acc Gradient per turn (MV)	R_S Radius @center of straight (m)	Δr (cm)
800		1.1955	
785	15	1.1879	0.76
775	25	1.1816	1.39
765	35	1.1751	2.04

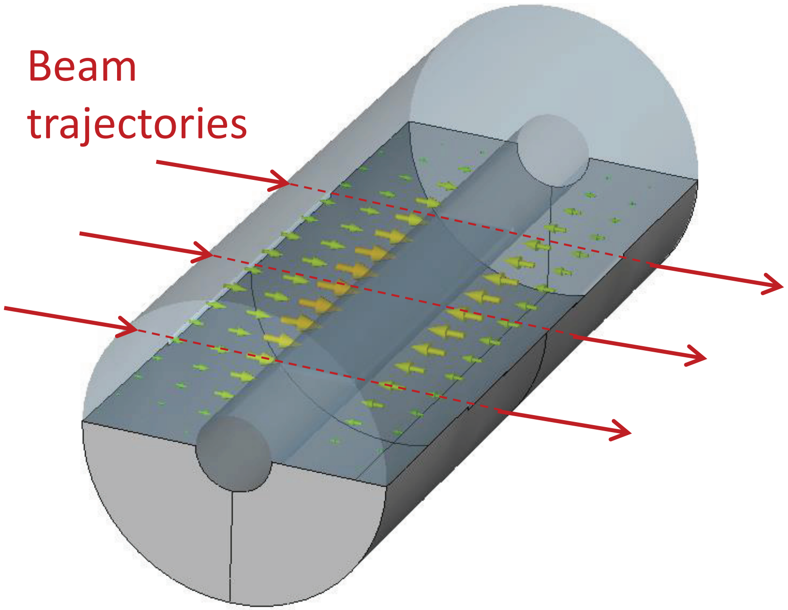
For 20 MV/turn, and a 2m straight section, we require 10 MV/m – implies a SCRF cryomodule – in order to achieve extraction with manageable shielding, radiation levels, and activation. This requirement drove the design of the high-energy stage.

Design specifications

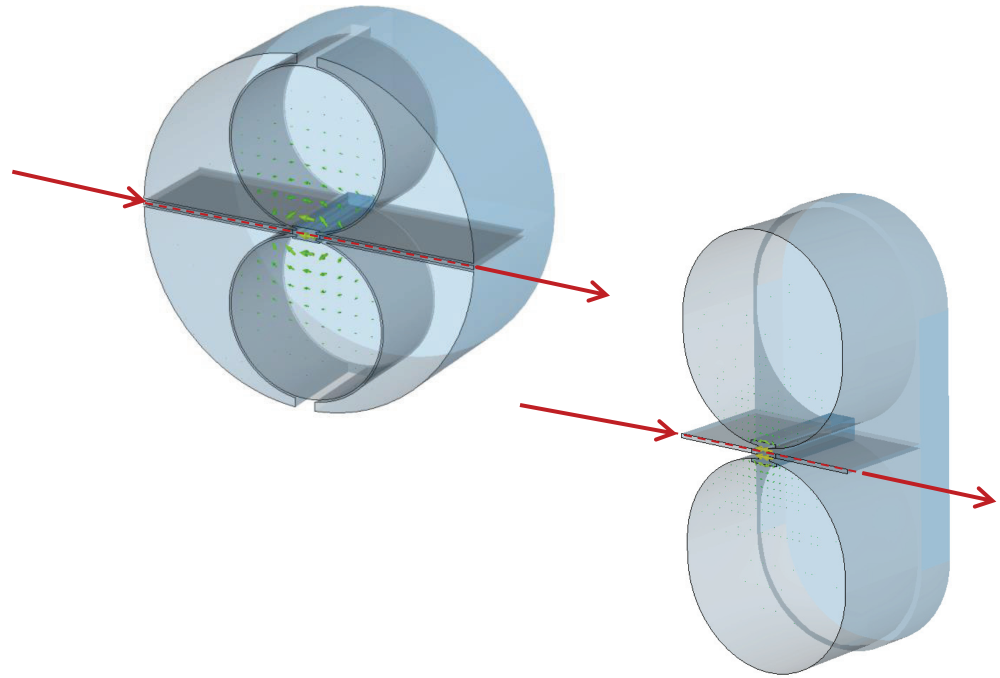
- Large horizontal beam aperture of 50 cm
- Cavity should operate at 150 or 200 MHz (harmonic of the revolution frequency)
- Should provide at least 5 MV for proton beam with energies 200 – 900 MeV
- Peak magnetic field should be no more than 160 mT (preferably, 120 mT or less)
- Peak electric field should be minimized
- Cavity dimensions should be minimized

Cavity options

- Half-wave resonator



H-Resonators

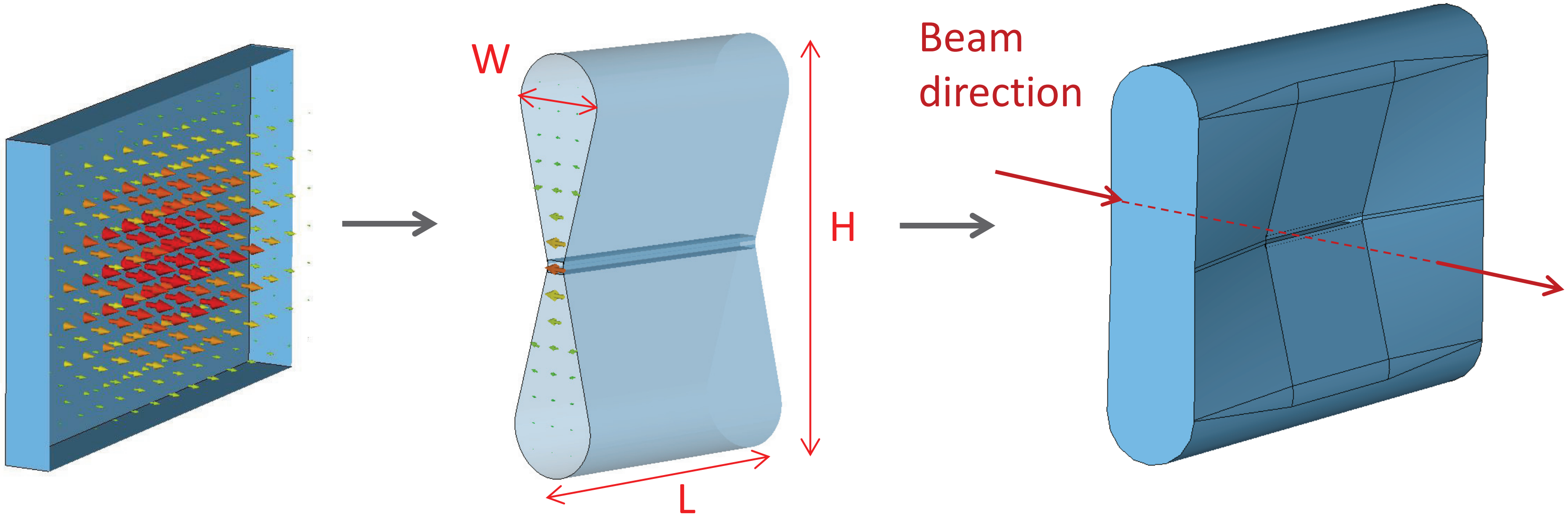


HWR is very dependent on particle velocity
Can't be used efficiently for such a wide range of particle energies

Dimensions are very large as is peak magnetic field on the electrode edge

Rectangular Cavity

- Rectangular cavity operating at H101 mode has electric field concentrated in the center of the wall
- To concentrate electric field at beam aperture, we introduced tapers
- To reduce peak magnetic field the blending was introduced



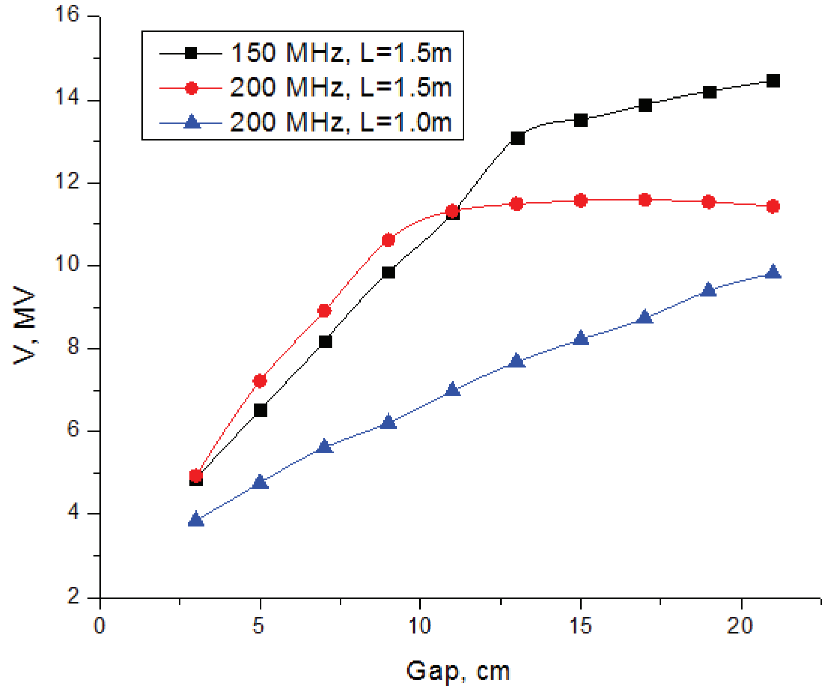
Gap and Frequency Optimization

- The voltage at 160 mT maximum field dependence on gap length was calculated for cavities with different frequencies and lengths

Beam Energy = 200 MeV

Voltage in the center of the aperture

Peak magnetic field = 160 mT

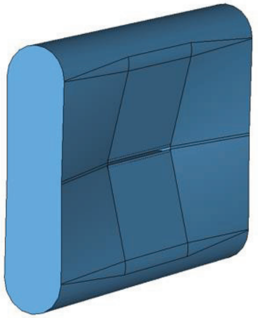


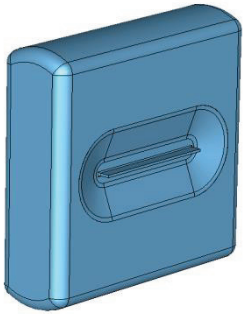
150 MHz 1.5 m structure has a potentially higher possible voltage or lower peak magnetic field at 5 MV

200 MHz structure is more compact

Cavity shape optimization

- A taper was introduced to distribute the magnetic field over a larger volume keeping the electric field concentrated around the beam aperture
- Such a cavity design has smaller dimensions for the same volume
- All edges were rounded and improved reentrant nose shape reduced the peak magnetic field by more than 15% and the transverse dimensions by more than 10 cm
- Final study was an elliptical cell shape where the magnetic field varies along the cavity wall such that there are no stable electron trajectories and multipacting is inhibited

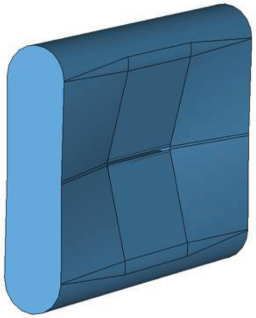


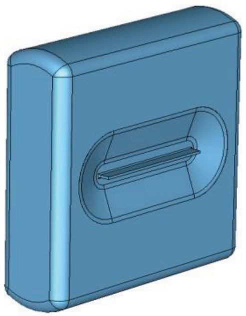


Comparison of different cavity geometries

Parameters of the different cavity designs.

Parameter	Rectangular top	Rectangular middle	Elliptical bottom
Frequency, MHz	200	200	200
Length, cm	100	100	120
Height, cm	104.5	92.9	142
Voltage (β=0.56, edge), MV	4.67	4.66	4.68
Voltage (β=0.78, center) , MV	6.72	6.71	6.89
Voltage (β=0.86, edge) , MV	5.00	5.00	5.00
R/Q (β=0.86, edge), Ohms	82.8	89.7	75.0
G, Ohms	147.9	150.2	134.2
Peak magnetic field, mT	92.1	72.7	77.2
Peak electric field, MV/m	55.2	47.0	48.1



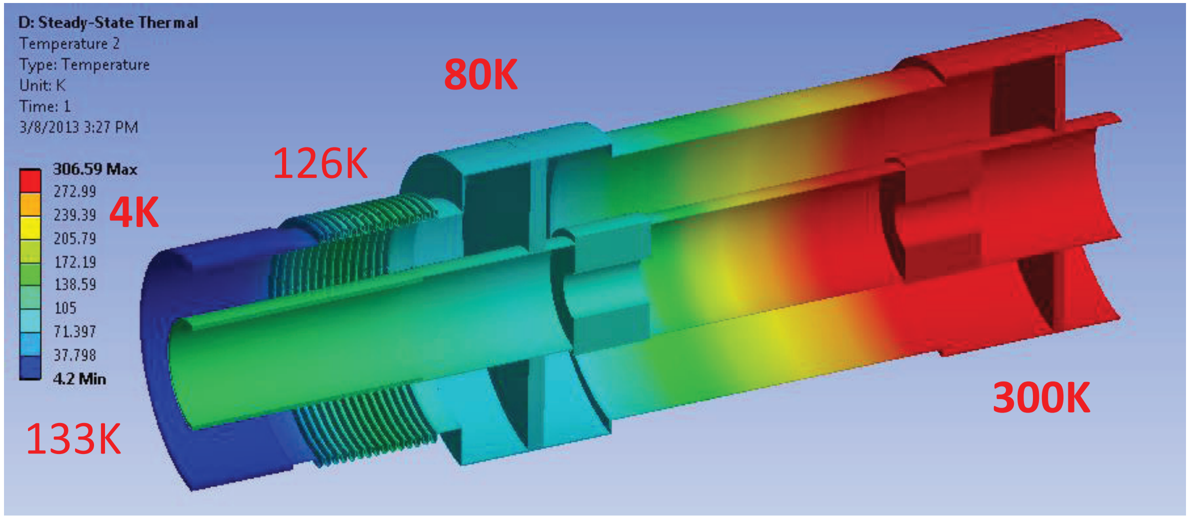


The RF performance degrades at higher frequencies.

- Rectangular cavity is better than elliptical by all parameters except multipactor resistivity

RF input coupler design

- As 1 mA beam is accelerated by 4 cavities from 200 to 900 MeV, each cavity requires about 175 kW of power
- One of the options is to attach 2 100kW couplers to the cavity

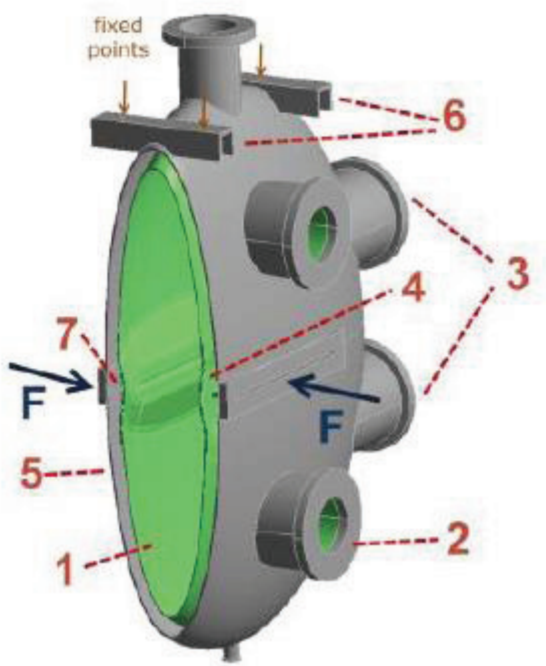


Heat Flows:
To 4K = 9.8W
To 60K = 92.0W
From 300K = 18.8W

ANSYS estimations show no significant overheating

Magnetic power coupling and mechanical design

- External Q-factor should be ~ $1.9*10^6$
- Preliminary results predict ~1.1mm Nb and ~0.6mm SS deformation at magnetic field area



The complete mechanical design:
1 – niobium shell, 2 – RF ports, 3- extra ports, 4 – frequency tuning, 5 – steel jacket, 6 – rails

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

- Two options of 200 MHz cavities were studied: "rectangular" and " elliptical". The "elliptical" option has been introduced to avoid multipacting (MP) problem. The latter can be problem for rectangular cavity
- However, the rectangular option provides better parameters (peak fields, dimensions etc)
- 100 kW RF coupler has been designed. More studies are needed to minimize cryogenic load.
- Initial mechanical design was created and structural analysis has been performed. Both cavities can be made structurally stable.