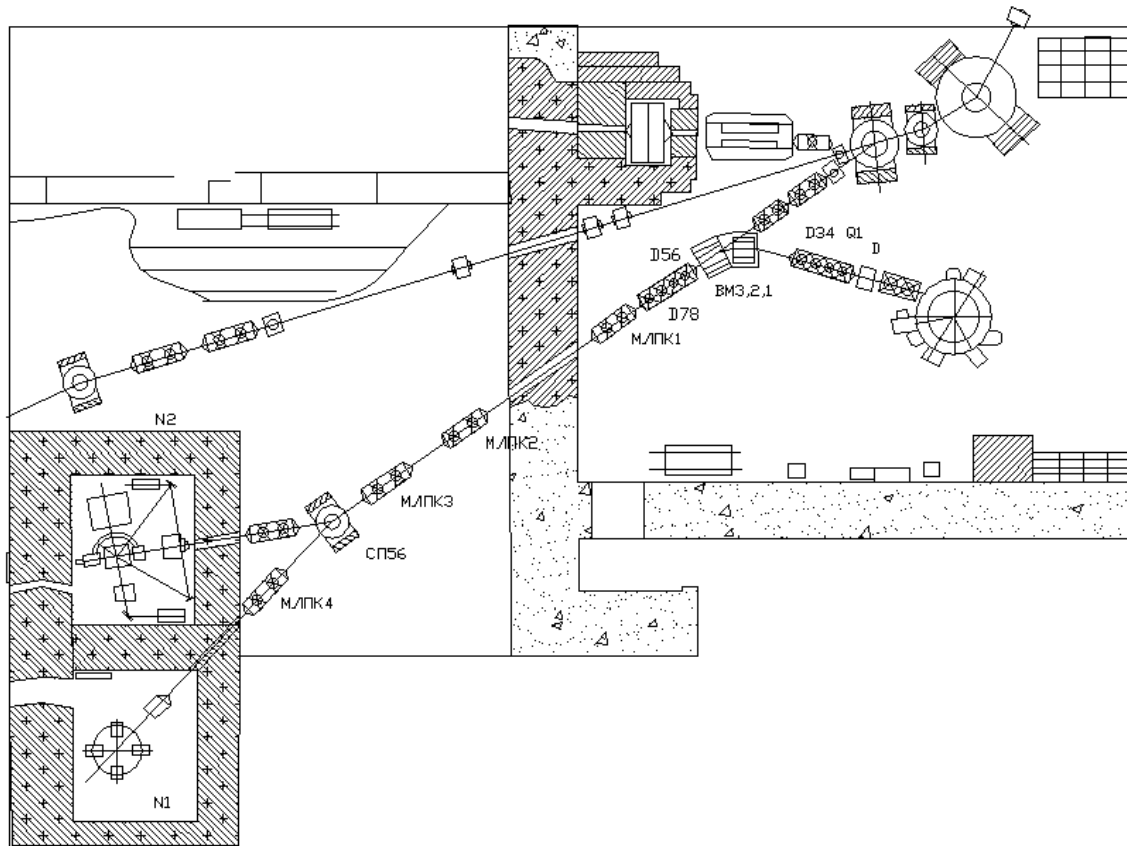


SC230 superconducting cyclotron

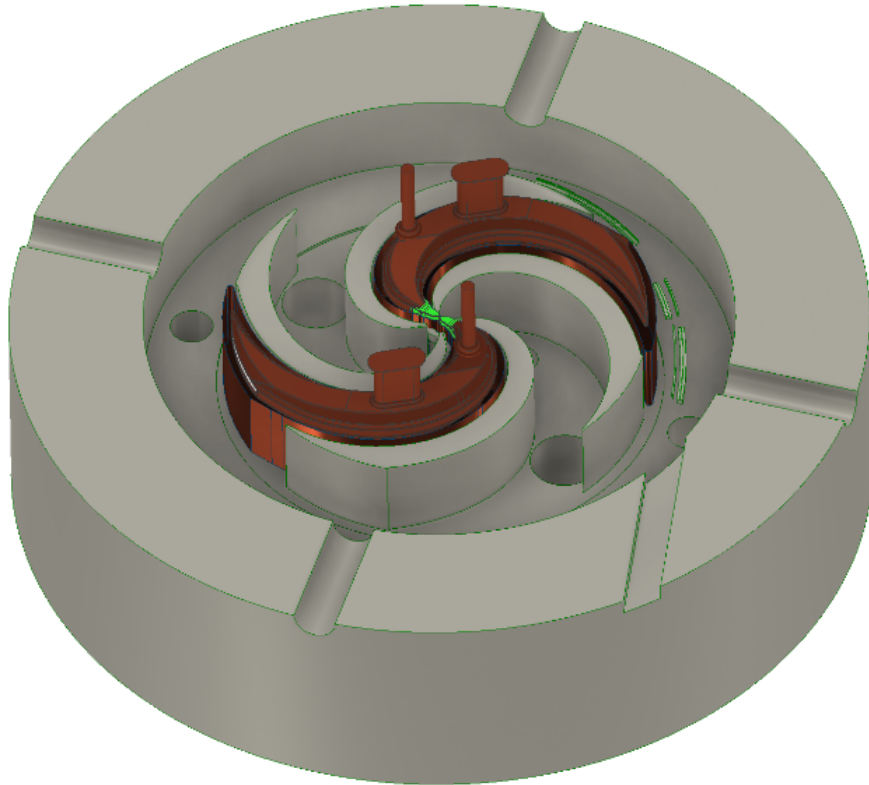
SC200 project



Dubna "Fazatron"
Originally build in 1949
Modernised in 1984

1mln \$ per year
3MW power

SC200 -> SC230



Mass	55 Tonn
RF Freq	91.4 MHz
Coil current	740 kA-t
Ion source	PIG
Sector azimuthal length	20-35 deg
Vertical gap between sectors	38->9 mm Decreasing to extraction. Not elliptical!
Valley depth	270mm



- What's next
- SC200/202 has faced many engineering problems.
- For JINR it is not necessary to build a competitive cyclotron for proton therapy. We have to replace the "Fazatron"
- Reliability is very important.
- Low power consumption is very welcome.
- Running costs should be low.
- Size does not matter, however it has to be reasonable.
- High quality of the beam should be the main feature.



MOTIVATION

- We need a cyclotron that delivers 200-230 MeV
- Why a cyclotron? Isochronous cyclotron is a reliable tool, usually cheap and convenient to operate
- Isochronous cyclotron must use proven and reliable solutions, engineering solutions dictate the solutions for beam dynamics, not the other way around

230 MeV proton for therapy

Synchrocyclotron	Cyclotron	Synchrotron
IBA S2C2, Mevion	IBA C235, Varian	Hitachi etc...
5T, 9T	1.5-3 T	-
Super-compact	Compact	Large
Constant Magnet field, Variable RF	Constant Magnet field, Constant RF	Variable..
Constant energy	Constant energy	Variable energy
Low current, less then 20 nA	High current upto 1 mA	Low current, high quality

Does size
matter?

The cyclotron can not win the weight
race!

SC200, Sumitomo, Pronova are all 3T
cyclotrons, and weigh above 50Tonn

IBA S2C2 SC and Mevion are lighter
and more compact.

New Synchrotrons project are very
compact.

Does size matter?

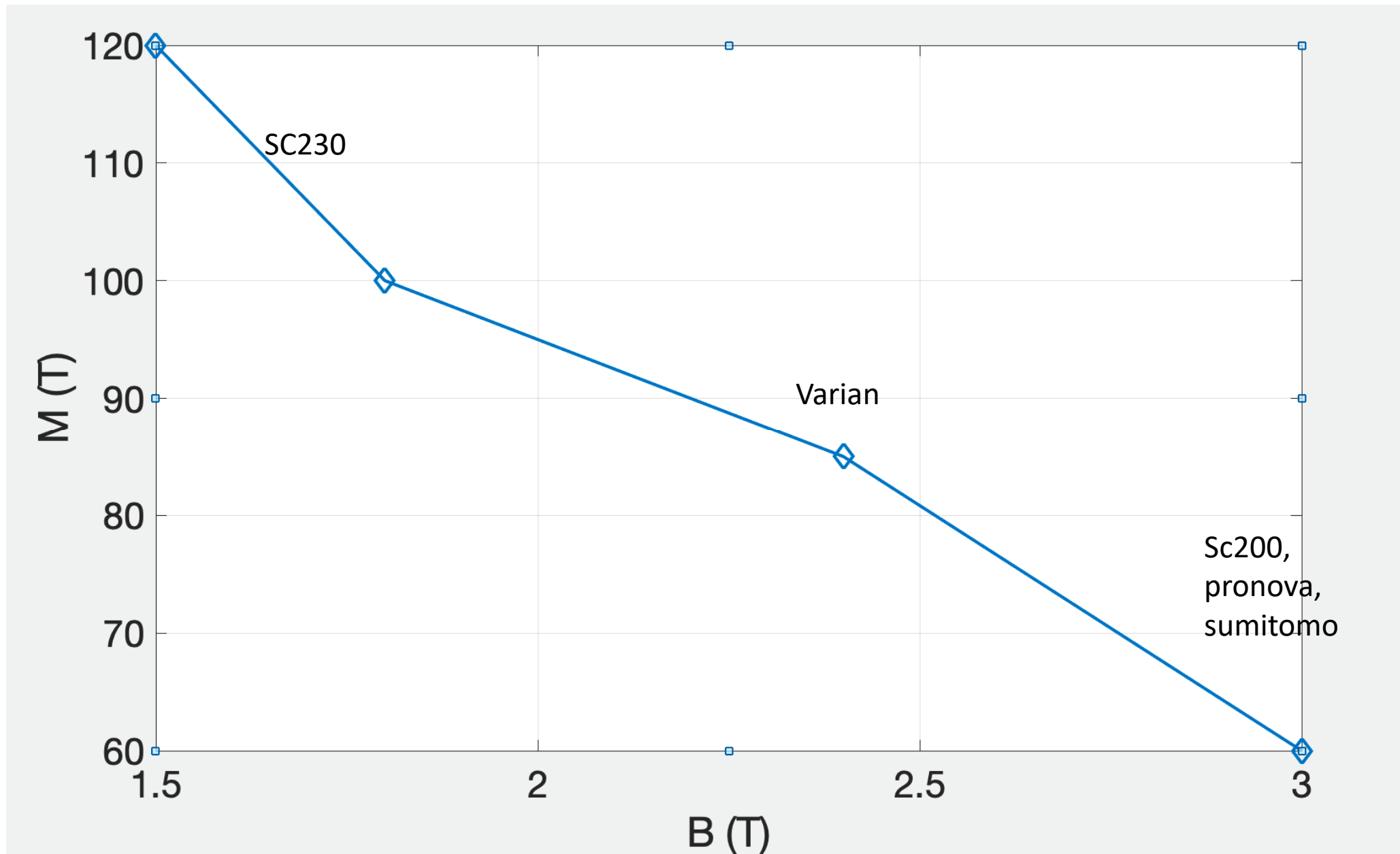
The cyclotron should focus on its PRO's and minimize the CONS, but without damaging the PRO side.

Flutter is the key parameter, high flutter means less spiral angle, means more efficient RF system and other advantages.

How to achieve high flutter? Deep valley, low sector gap (not extremely low), LOW FIELD

Why low field?

- Small A-turns number. Even for superconducting cyclotron there are many advantages in low A-turns. Superconducting wire is expensive, and reducing the A-turns leads to reducing the coil cross-section, low field means low stresses in coil, higher A/mm² can be achieved. Potential for FIRST HTS cyclotron.
- Possibility of using conventional resistive coil 😊 Easy to use, cheap, convenient operation



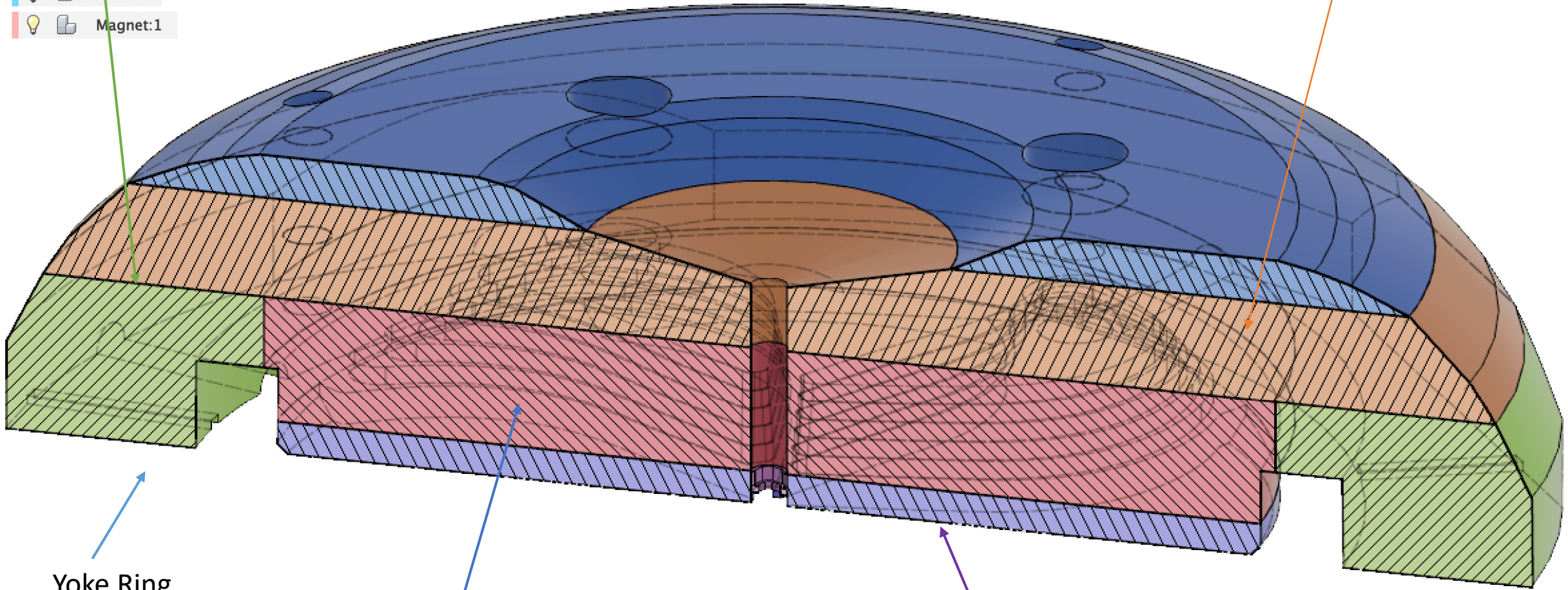
Yoke material	St.1010
Average magnetic field (R_o/R_{extr}), T	1.5/1.9
Extraction radius, m	1.27
Pole diameter, m	2.7
Magnet diameter, m	4
Magnet height, m	1.64
Hill gap, mm	50
Valley gap, max, m	0.7
A*turns, (1 coil)	185 000
Magnetic field in the coil, T (max.)	2.0
Cryostat and coils weight, tonne	5
Magnet weight, tonne	130
Coil dimensions, mm ²	55x35
Vertical gap between coils, mm	150

Yoke Disk 20 Tonn

Total weight 65 Tonn (half)

Shield 14Tonn

- Files:1
- Magnet:1



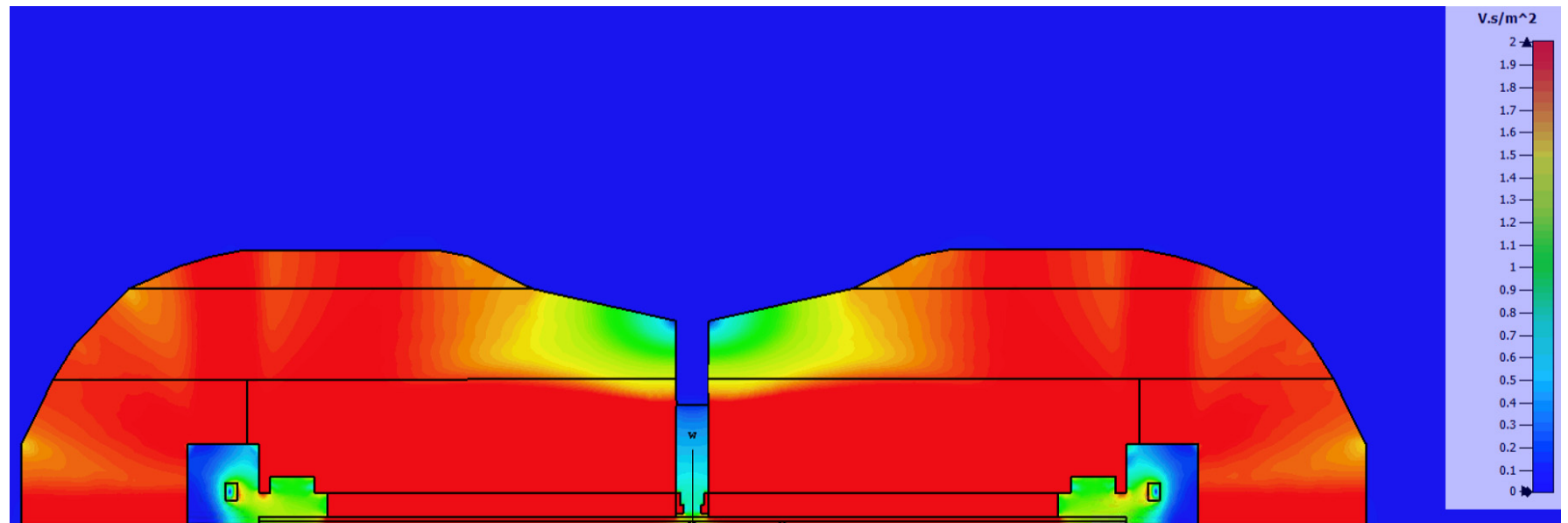
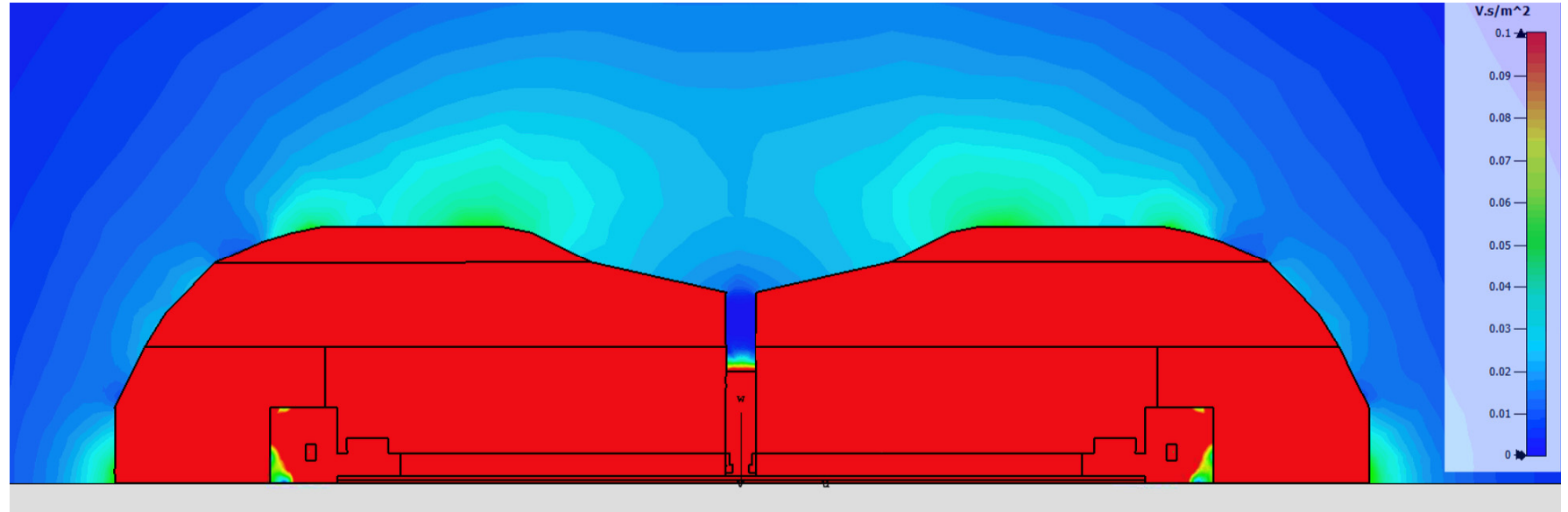
Yoke Ring
20 Tonn

Sector_Valley_Base
8.5 Tonn

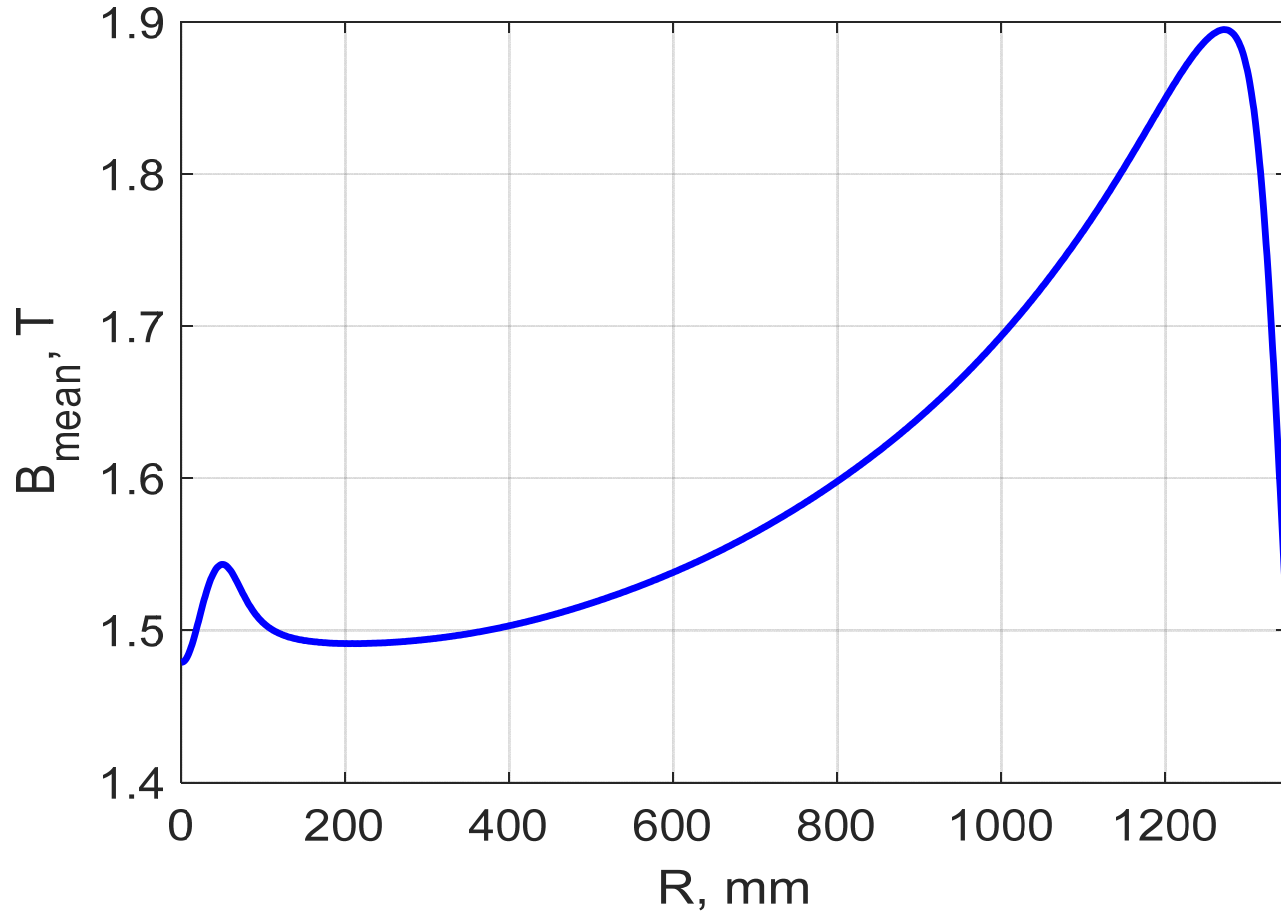
Sectors_M (median plane)
400 kg x 4

Goals:

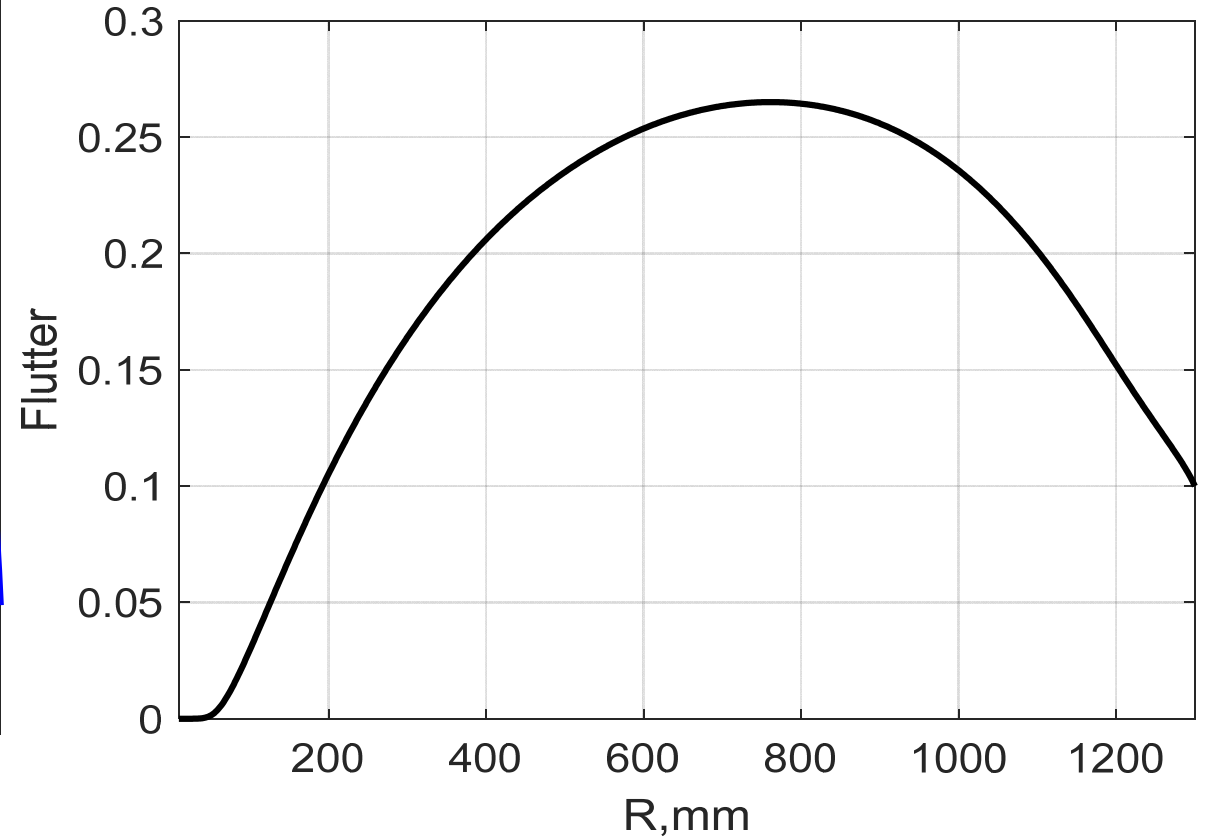
- 1) Keep the steel1010 in full saturation everywhere
- 2) Stray field limited to few hundreds Gauss outside



Magnet

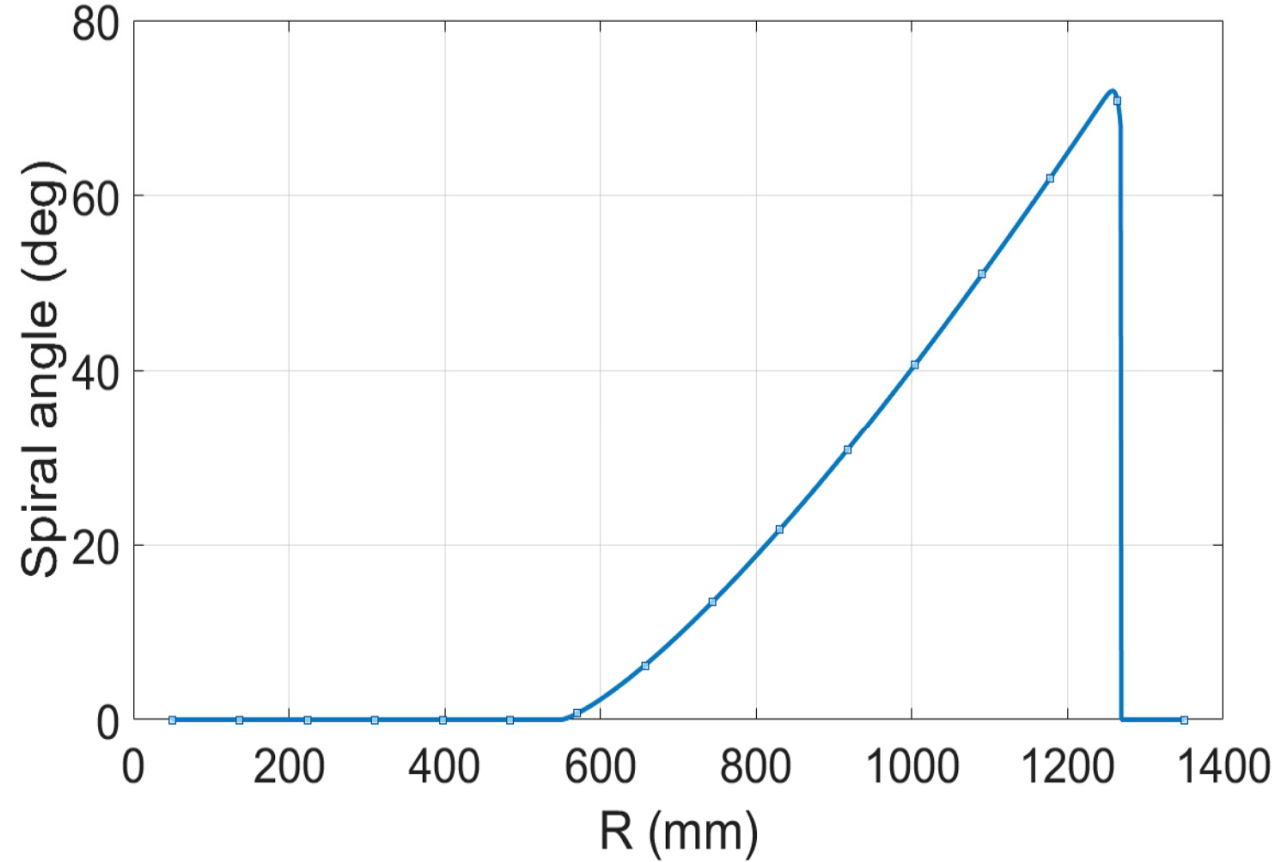
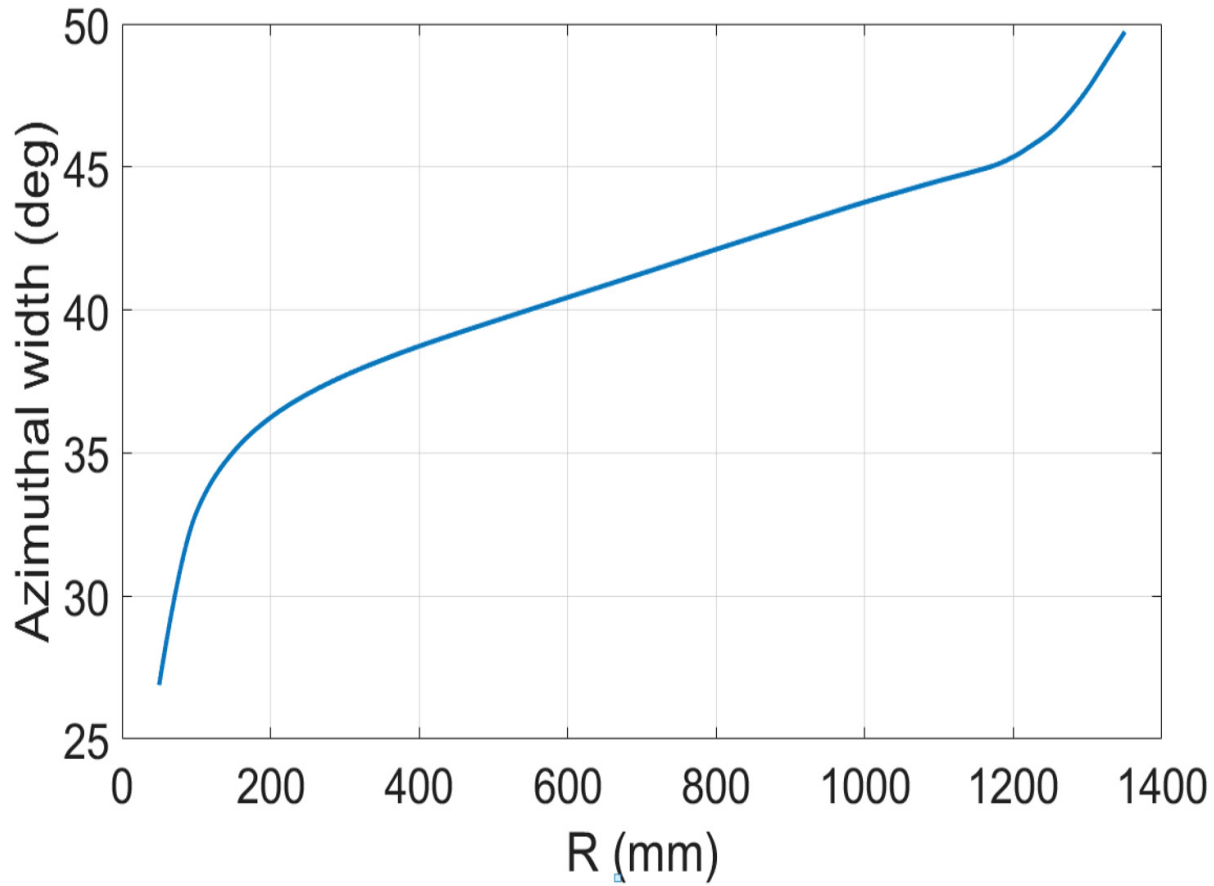


Average magnetic field along the radius.

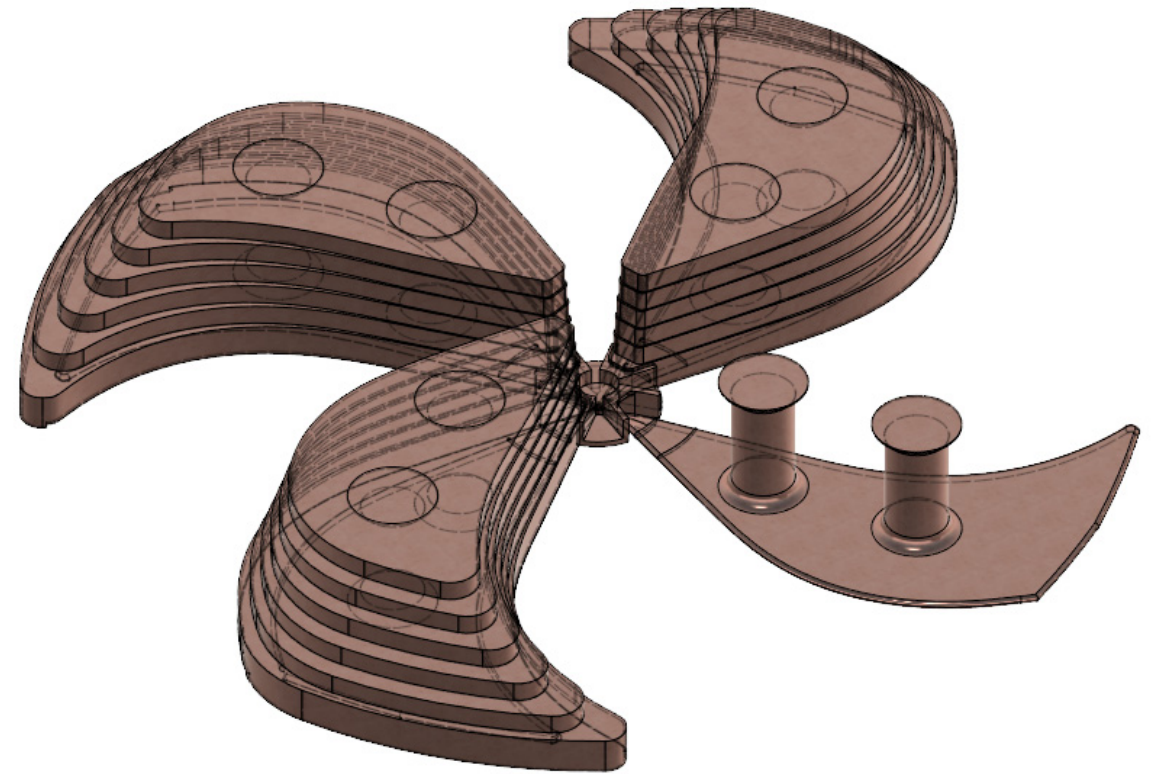
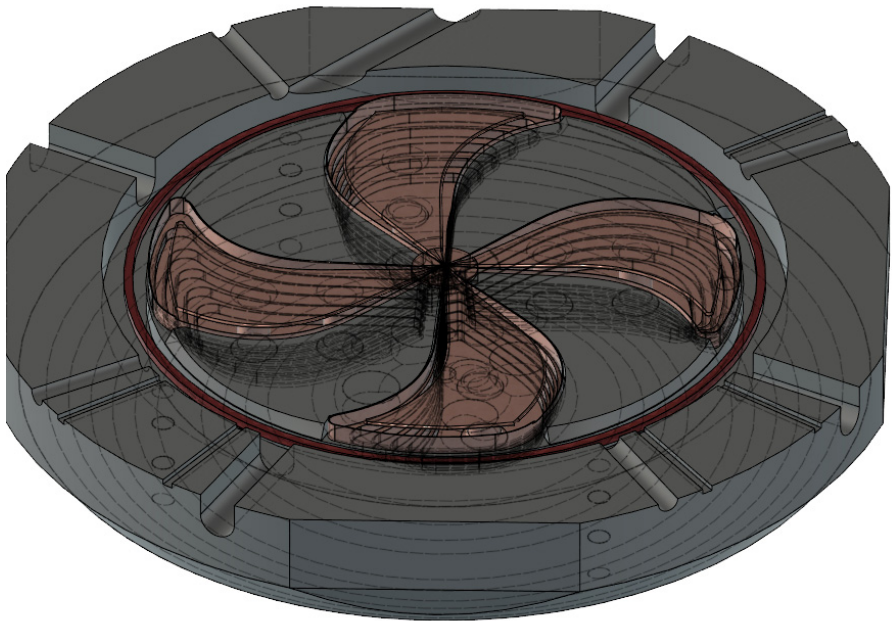


Flutter along the radius.

Ideal width of sectors: 45deg - 5deg - 20mm

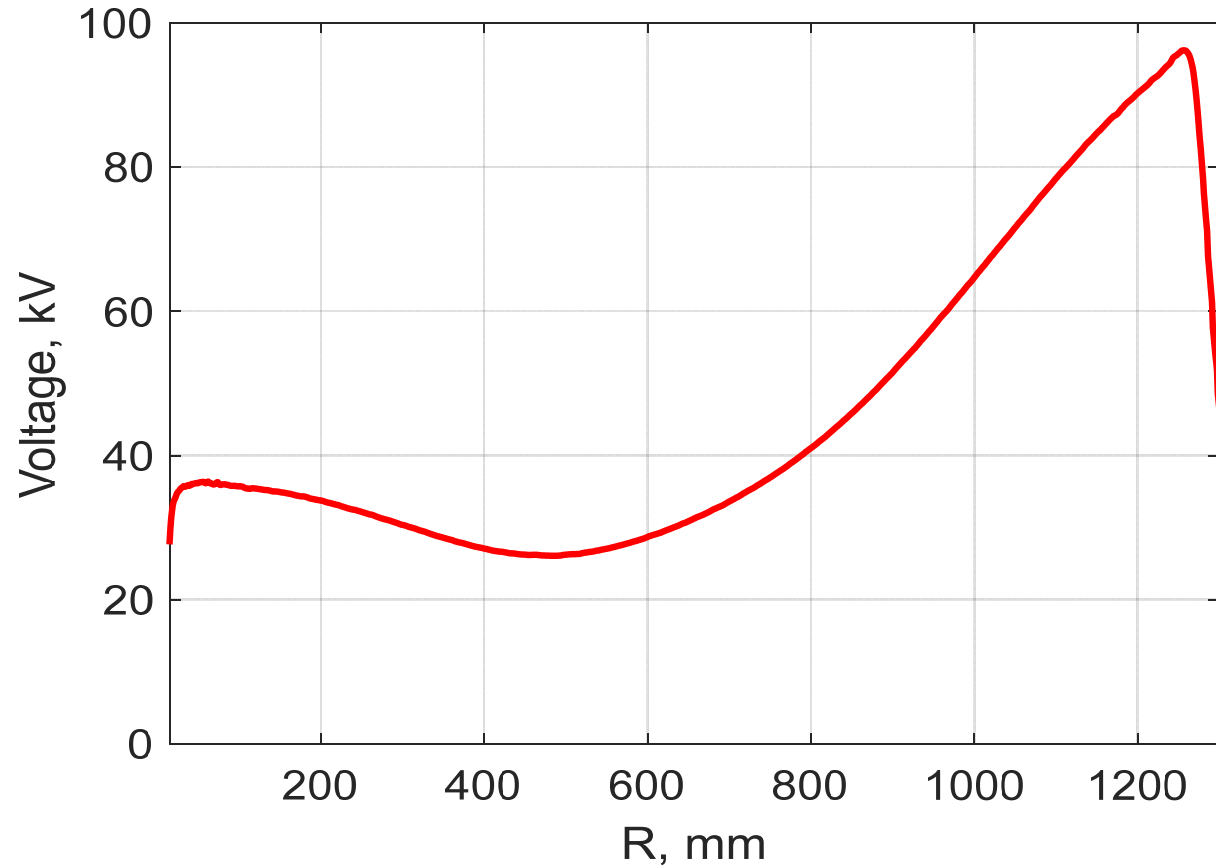


RF system
91.5 Mhz
4 cavities
4th harmonic mode
43 kW losses

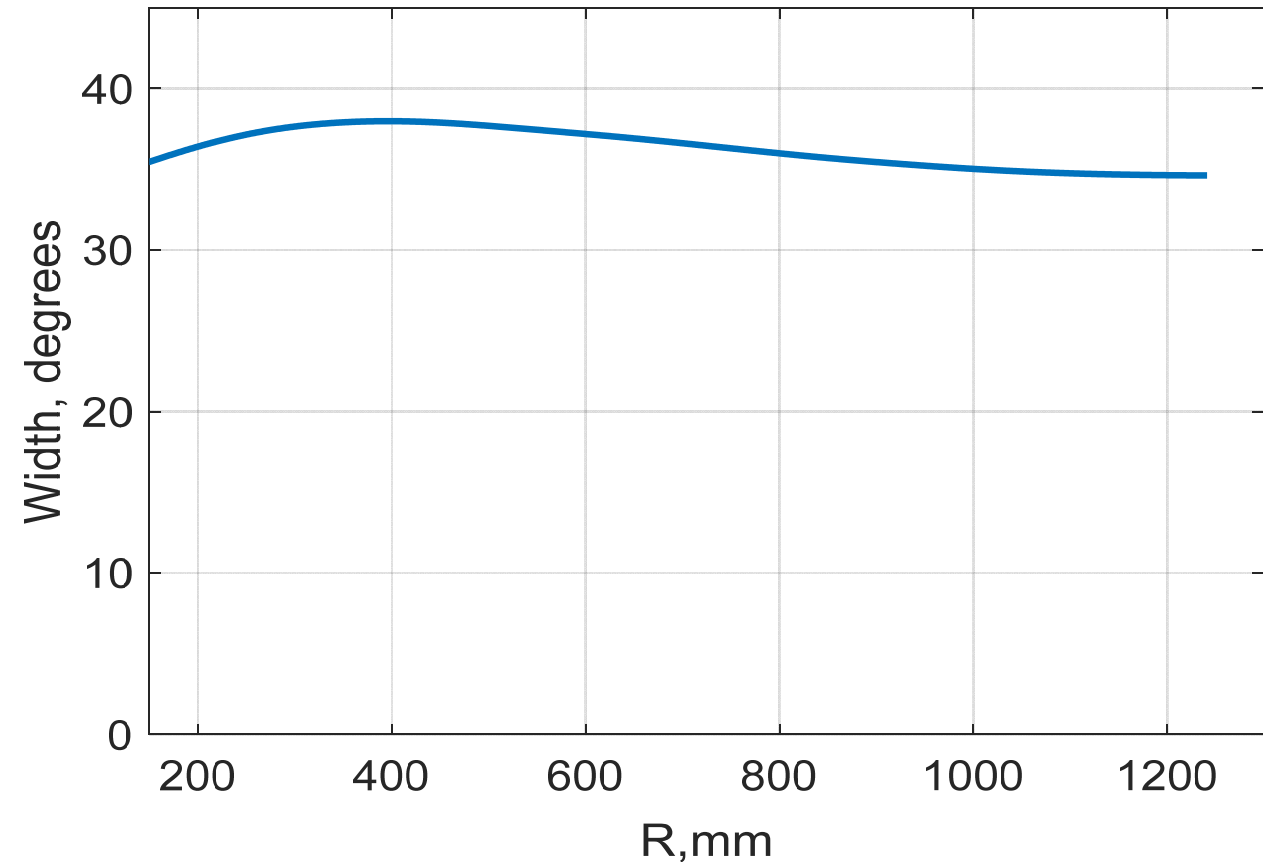


RF cavities simulation.

Power consumption 43 kW, $Q=13500$

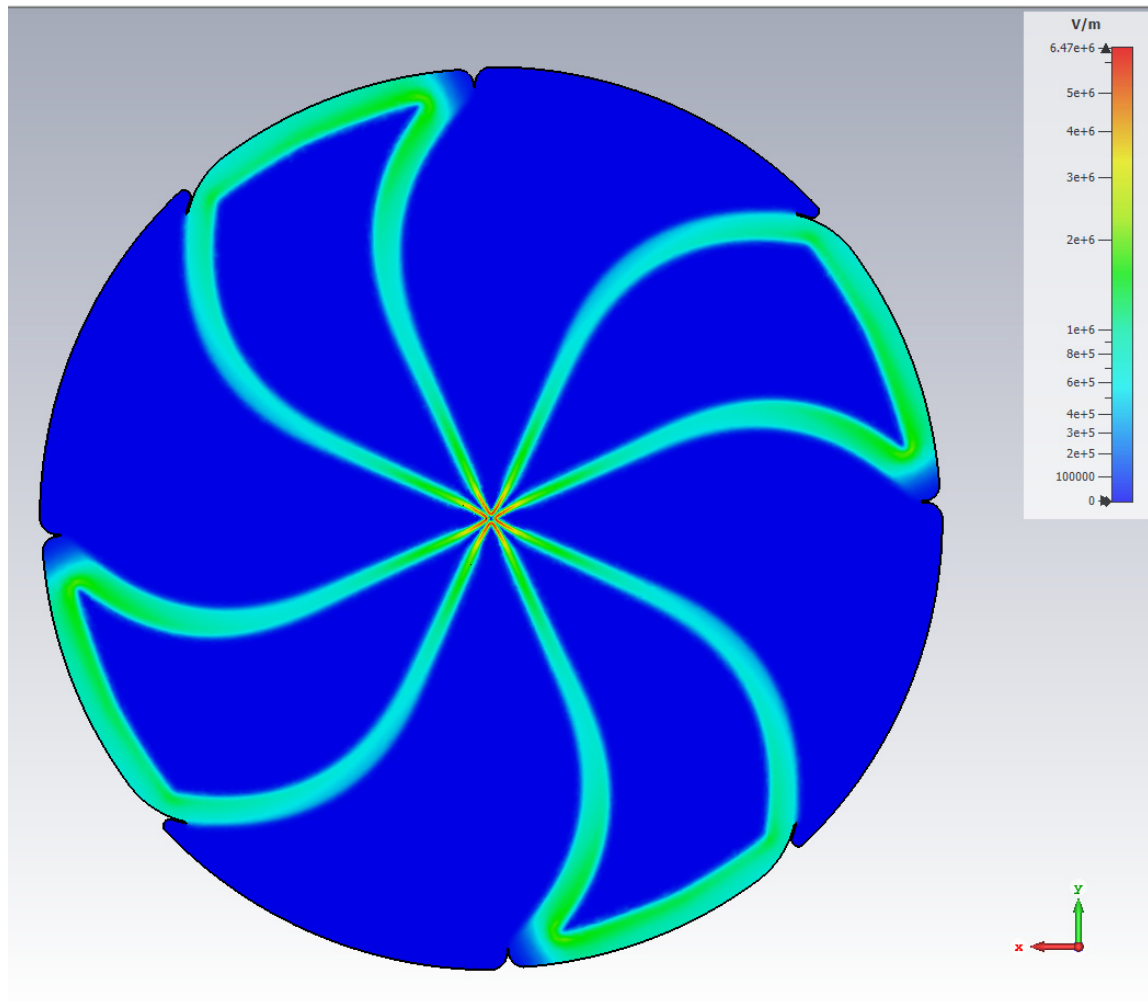


Accelerating voltage along radius

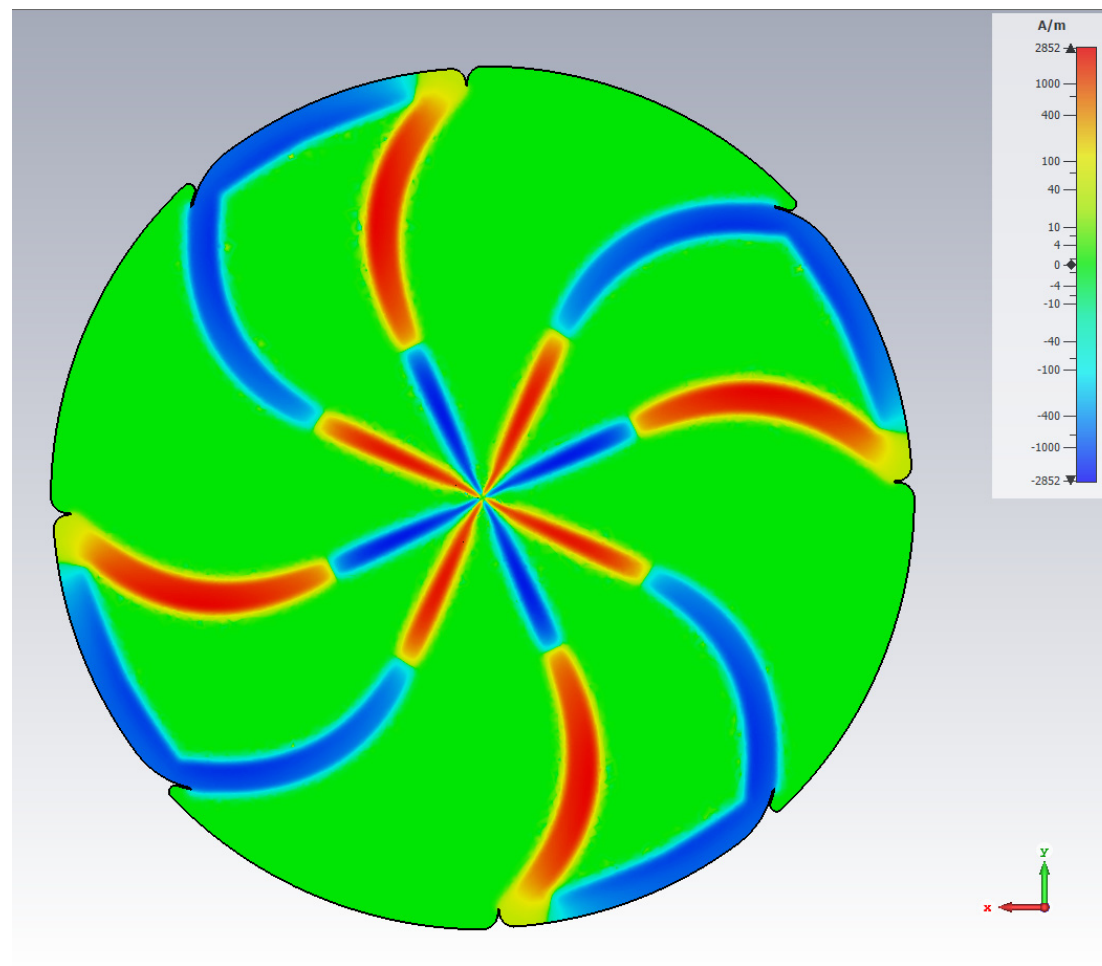


Azimuth extension between maximums of accelerating field

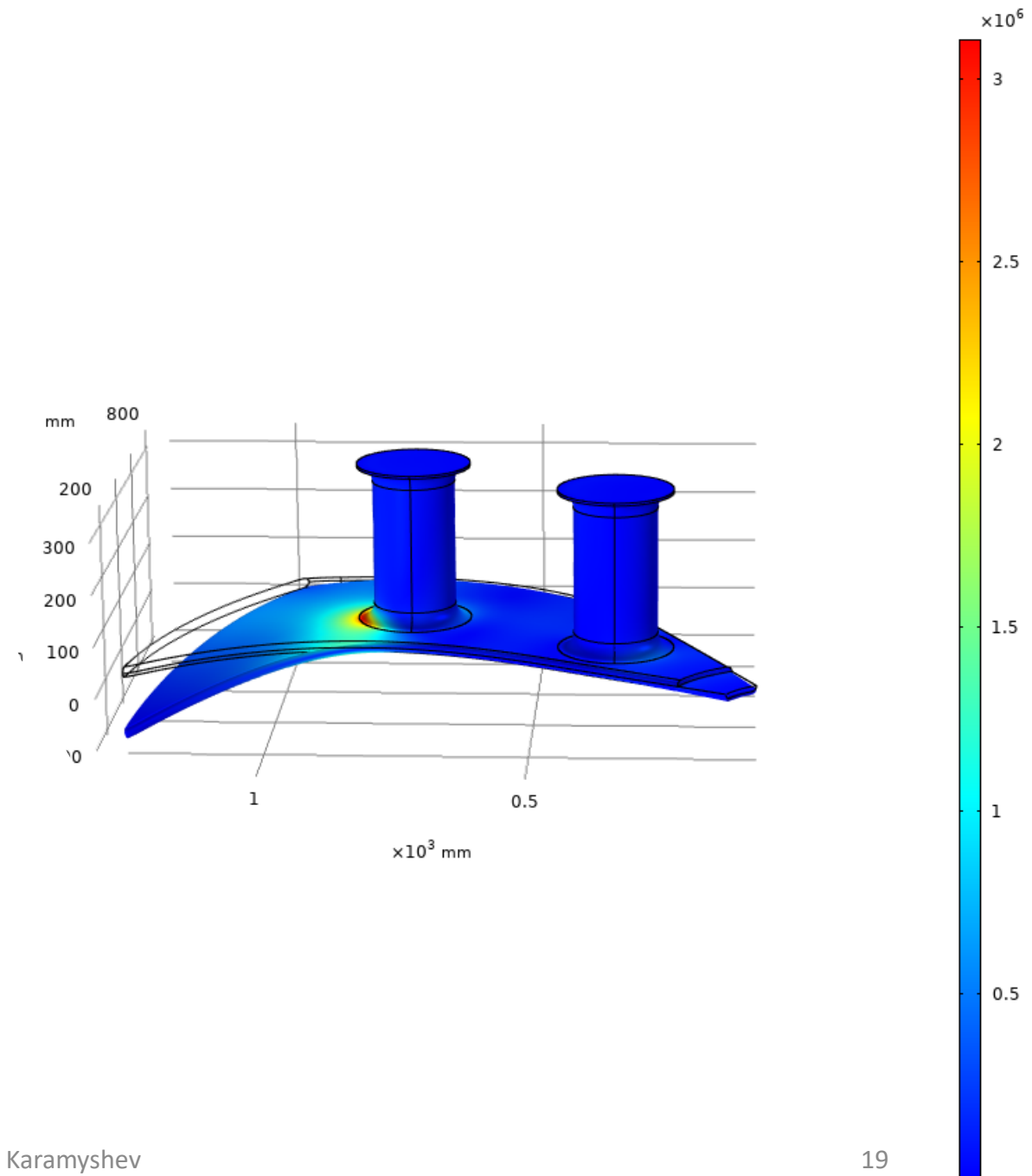
E field



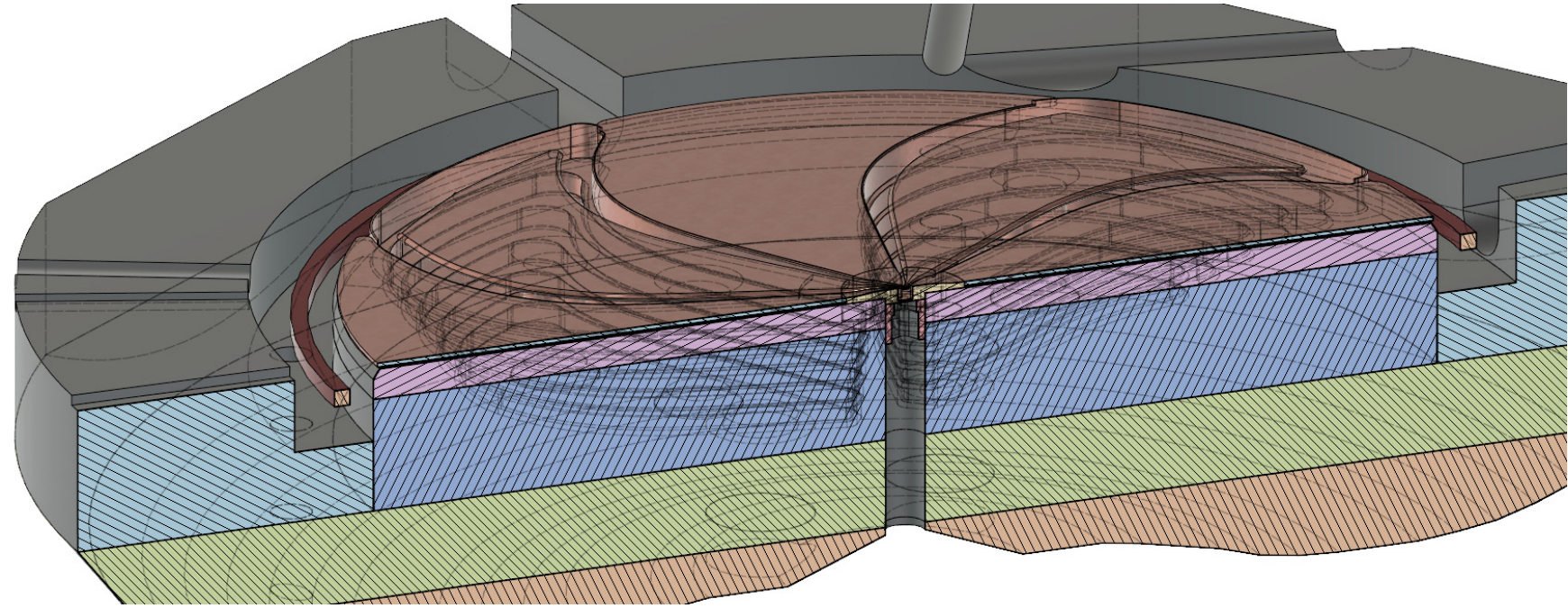
B field



-
- Stress analysis of the Dee
 - 2 stemm design is good for mechanical rigidity
 - No significant problems



- Coil dimensions: 55mm x 35mm
- Inner diameter: 1420mm
- Vertical gap: 150mm



Coil Max B = 2 Tesla

Vertical Force between coils is about 1 Tonn.
In S200 it is 100Tonn

Very low radial stress → "self-sustain coil"

I= 185 kA-turns

Current density = $185000/55/35=96 \text{ A/mm}^2$. (Too conservative, has to be at least 300A/mm^2)

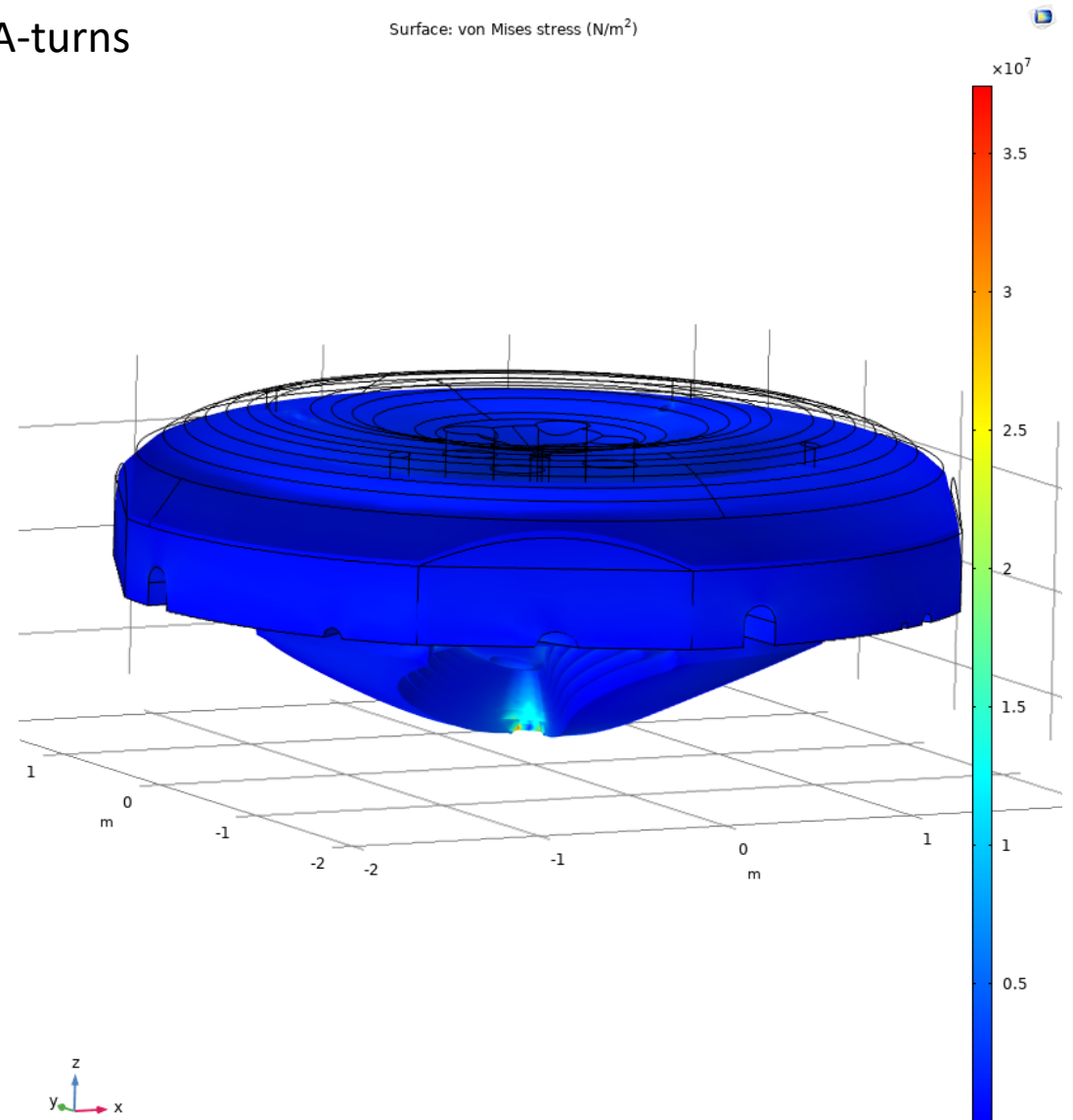
Update of the project with more optimal cryostat design is under development.
HTS option looks very tempting.

Weight can be reduced down to 110 Tonn.

Element	Force Z (Tonn)
Disk	-500
Ring	-350
Shield	-70
Base	-260
Sector_M	+136

Coil current = 180kA-turns

Surface: von Mises stress (N/m²)

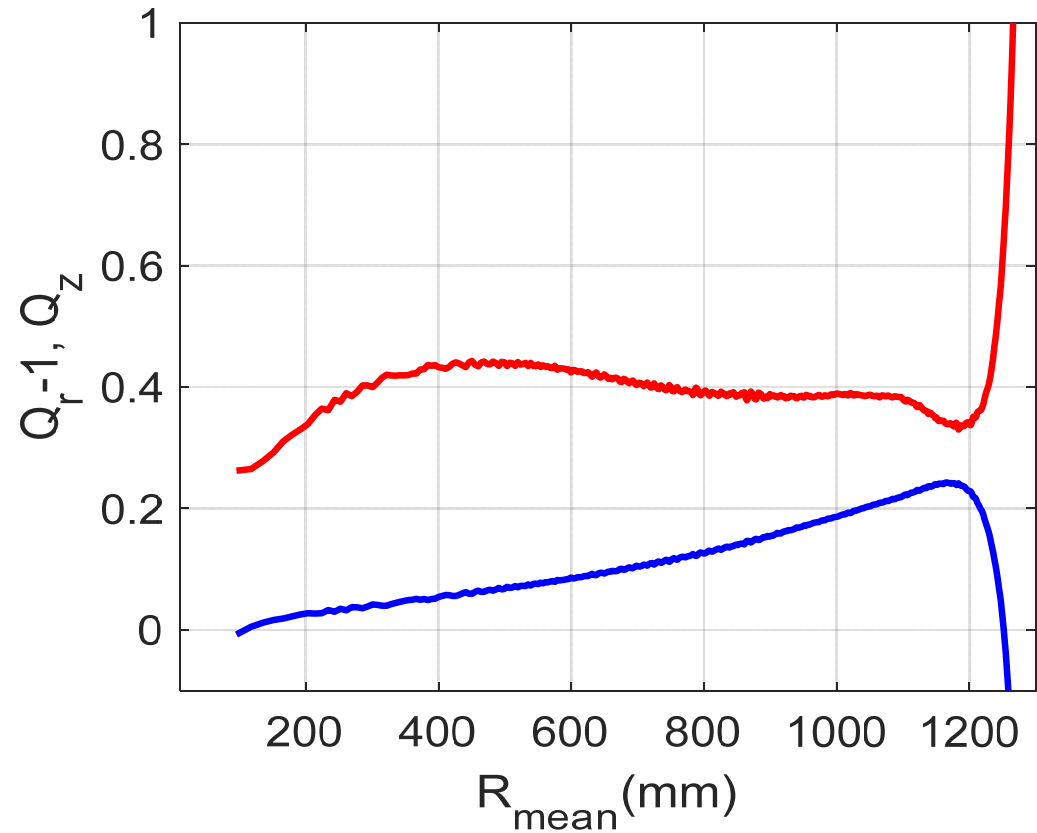


Deformation * 1e4

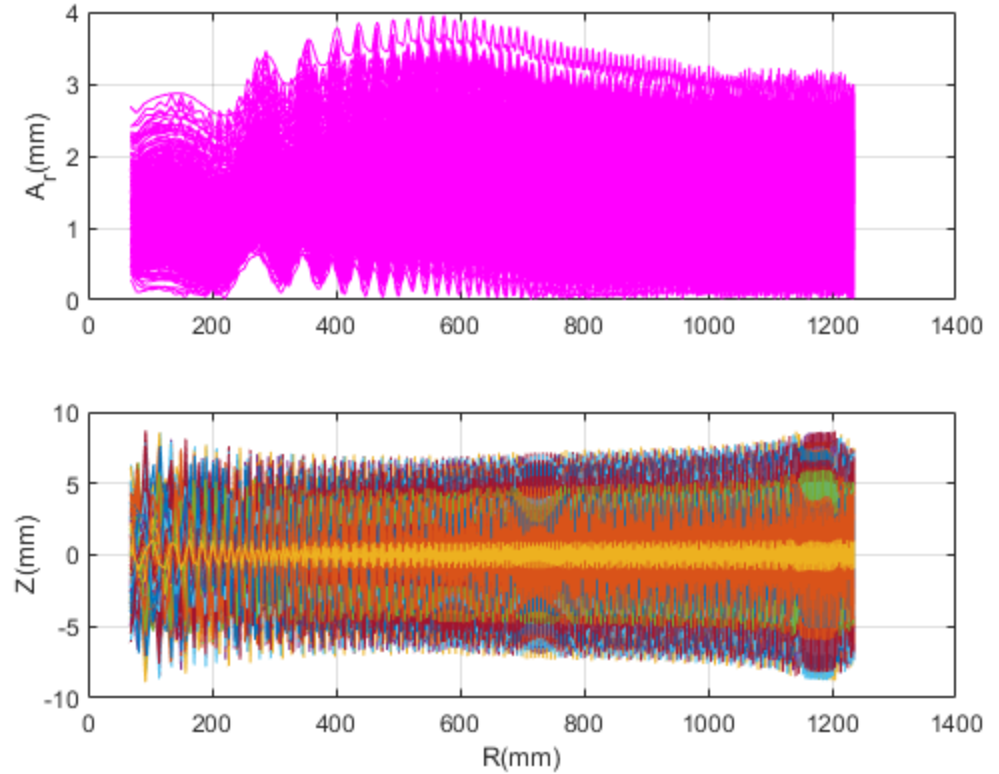
Max deformation less then 0.07 mm

Need more detailed study with exact screws locations and dimension => TBD during detailed engineering design

Beam dynamics

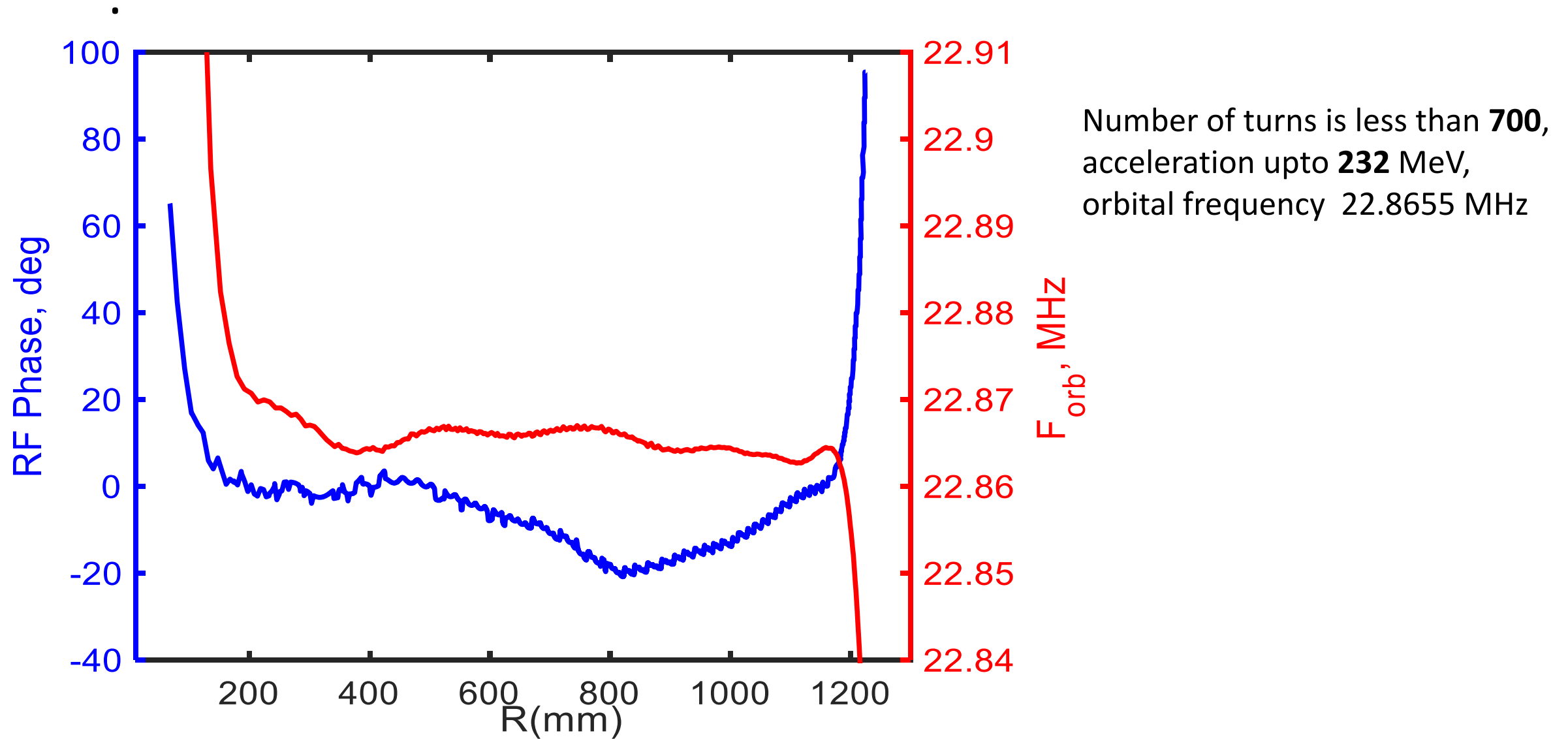


Vertical and radial betatrone tunes.

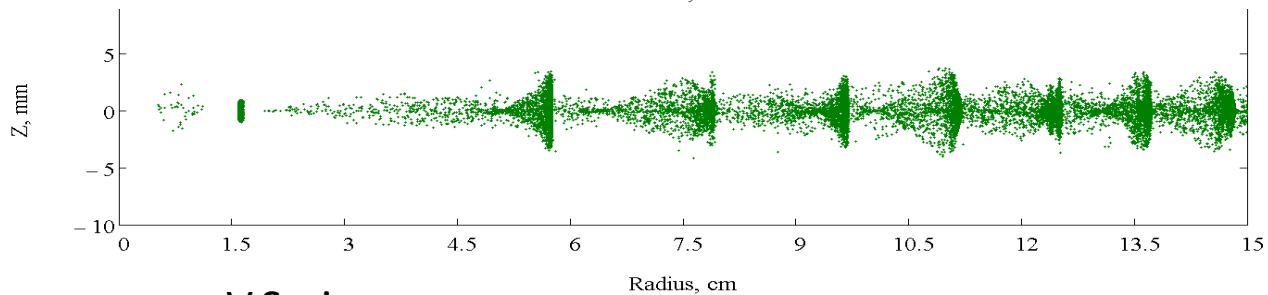
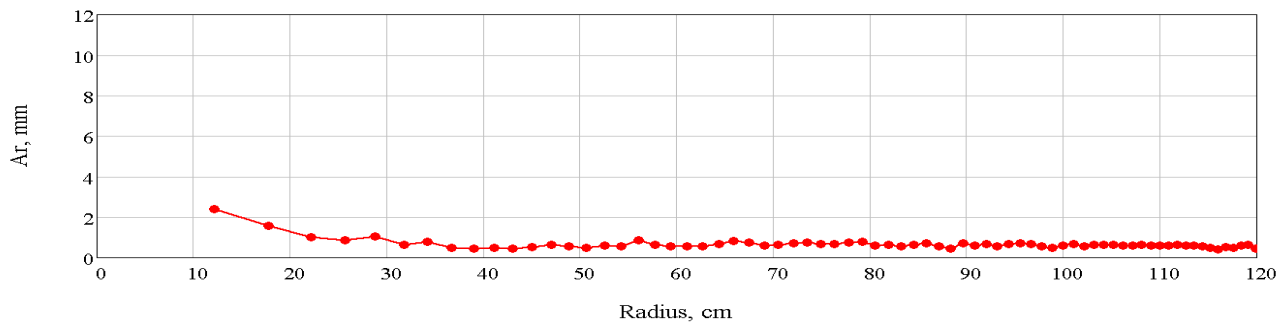
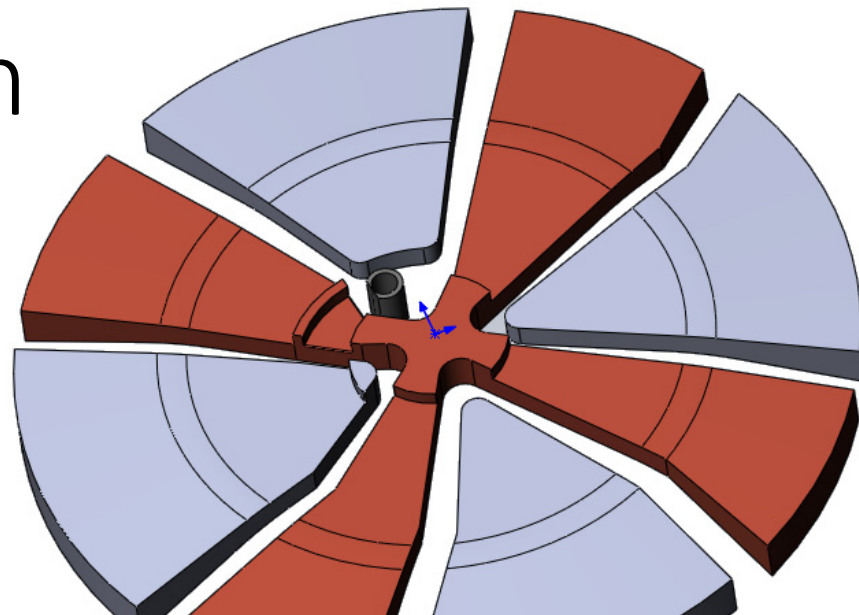
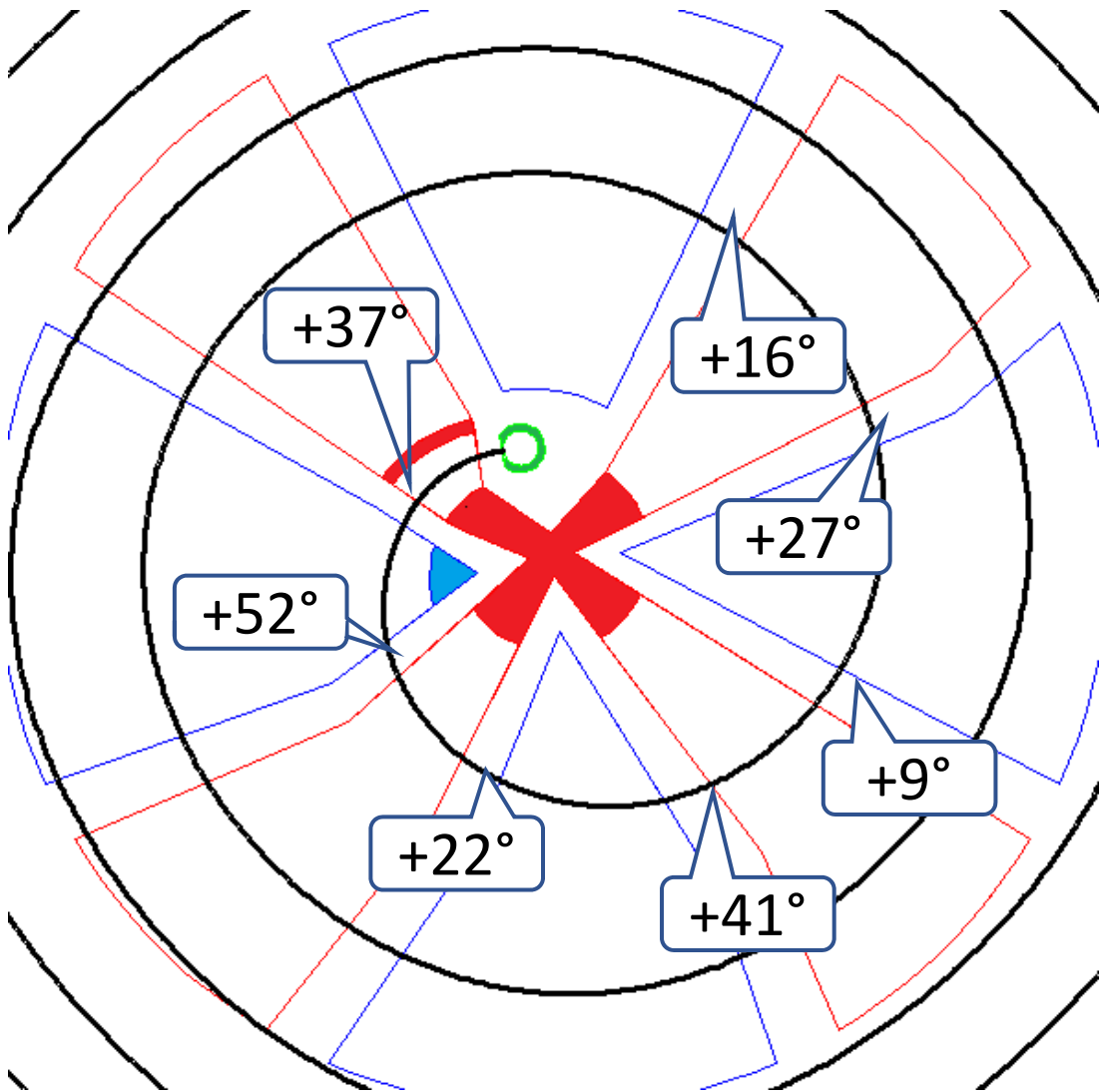


Amplitudes of radial oscillations and vertical motion of the beam.

Phase motion of the reference particle (blue line). Orbital frequency against mean radius (red line).



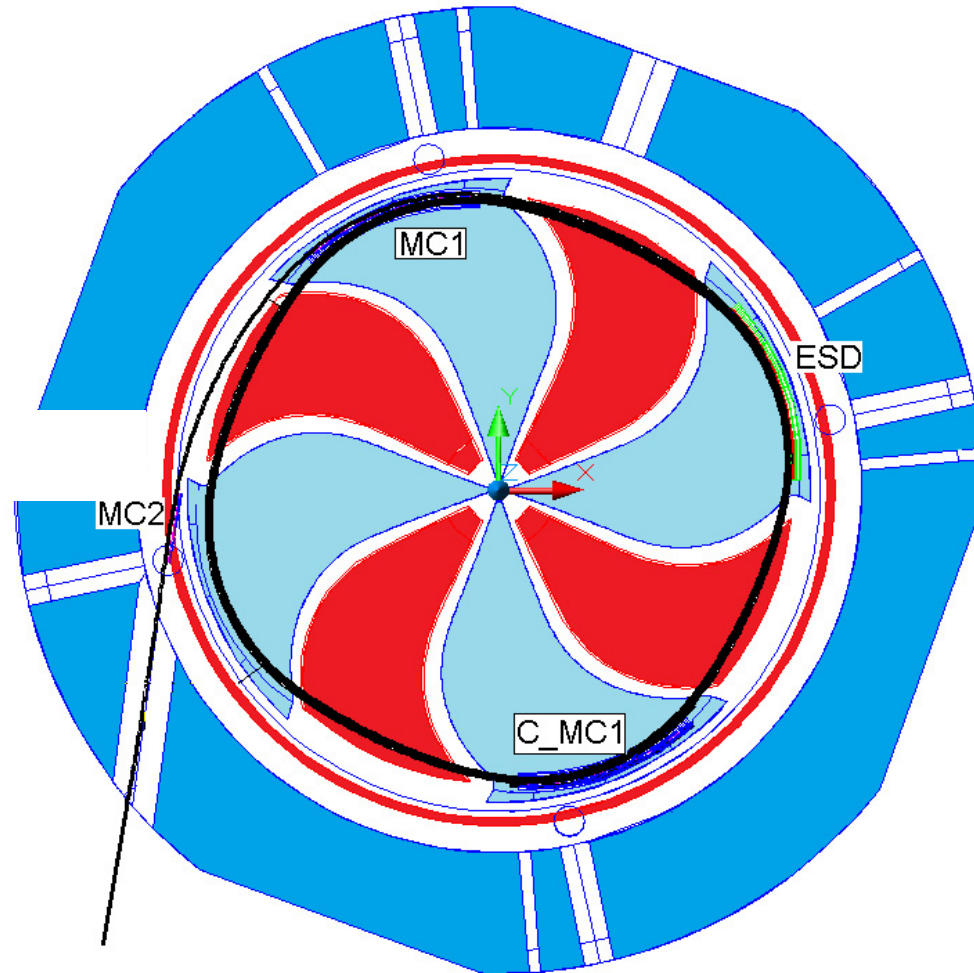
Central region



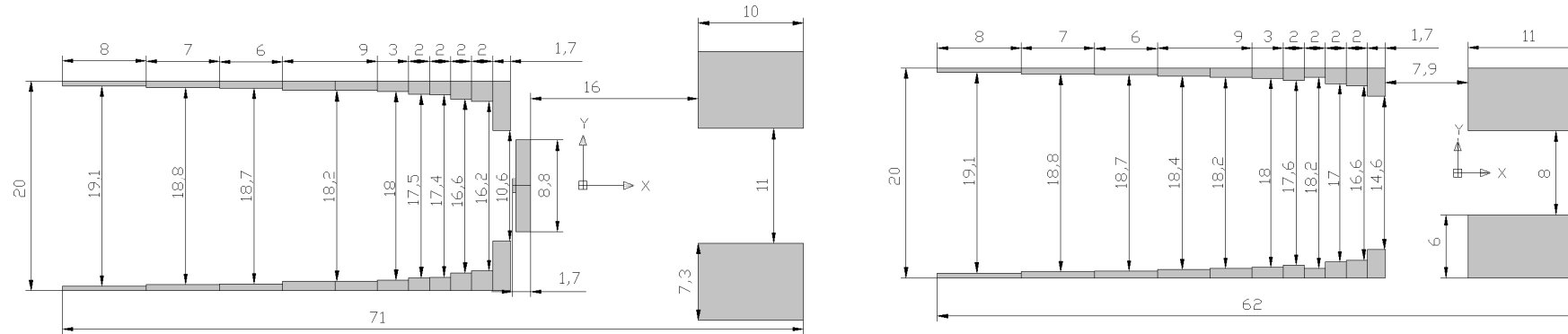
V.Smirnov

New extraction system consists of single ESD (100 kV/cm), two magnetic channels (-0.18 T, 13 T/m, -0.19 T, 25 T/m), and a single compensator of the first channel

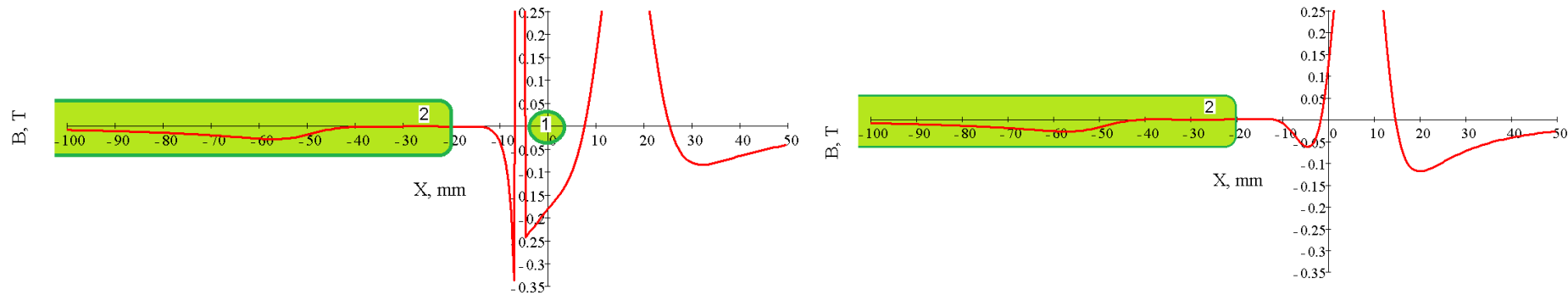
- V.L. Smirnov



Cross-section and field contribution of MC1 (left) and C_MC1 (right).
 The channel length is 820 mm. Central field -0.18 T, field gradient 0.13 T/m.
 Distance between deflected (1) and circulating (2) beam is ~20 mm.



- V.L. Smirnov

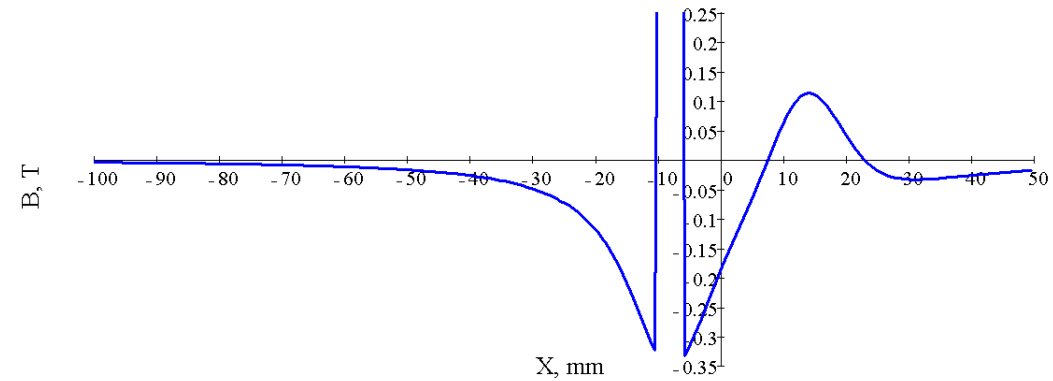
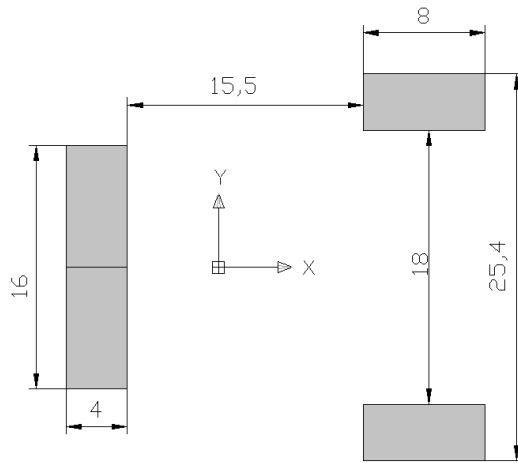


To cyclotron
 center

MC2 cross-section and field contribution.

The channel length is 300 mm. Central field -0.19 T, field gradient 0.25 T/m.

Distance between deflected and circulating beam is ~110 mm.



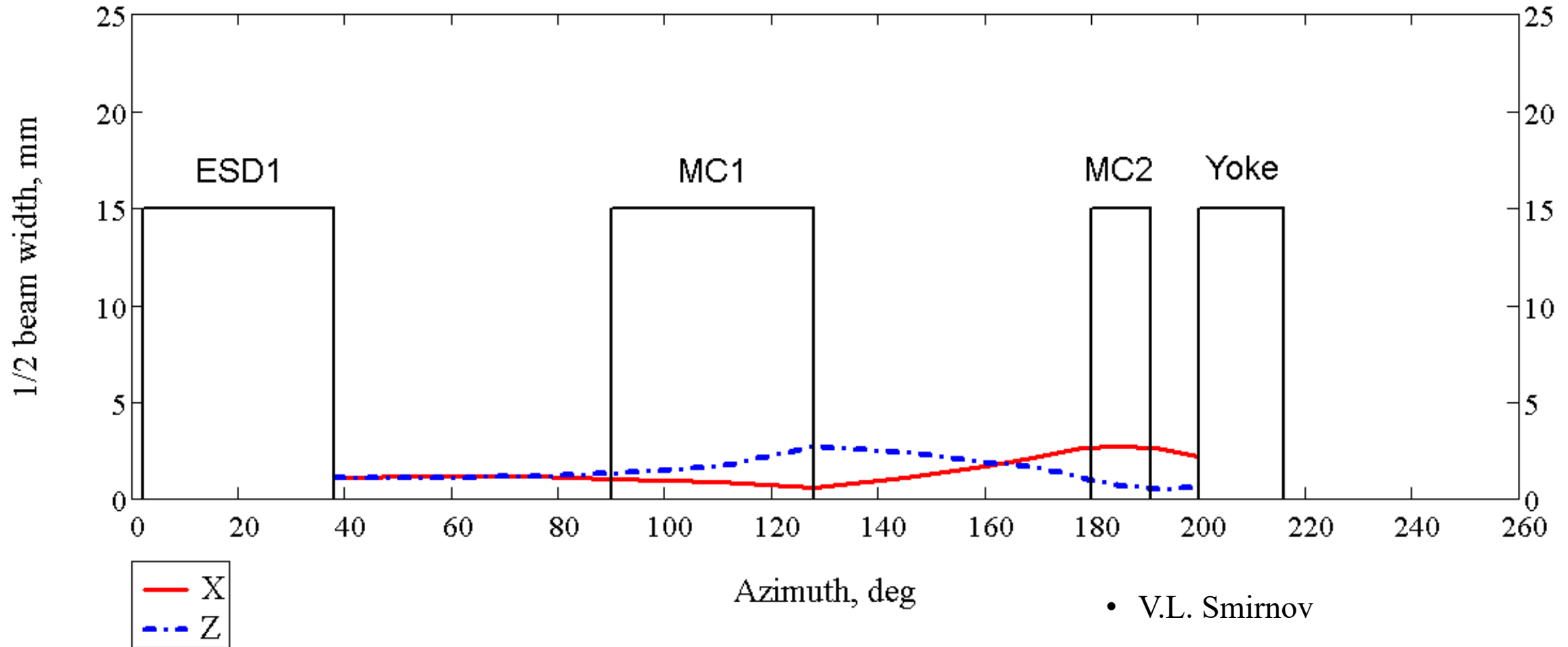
- V.L. Smirnov



To cyclotron

center

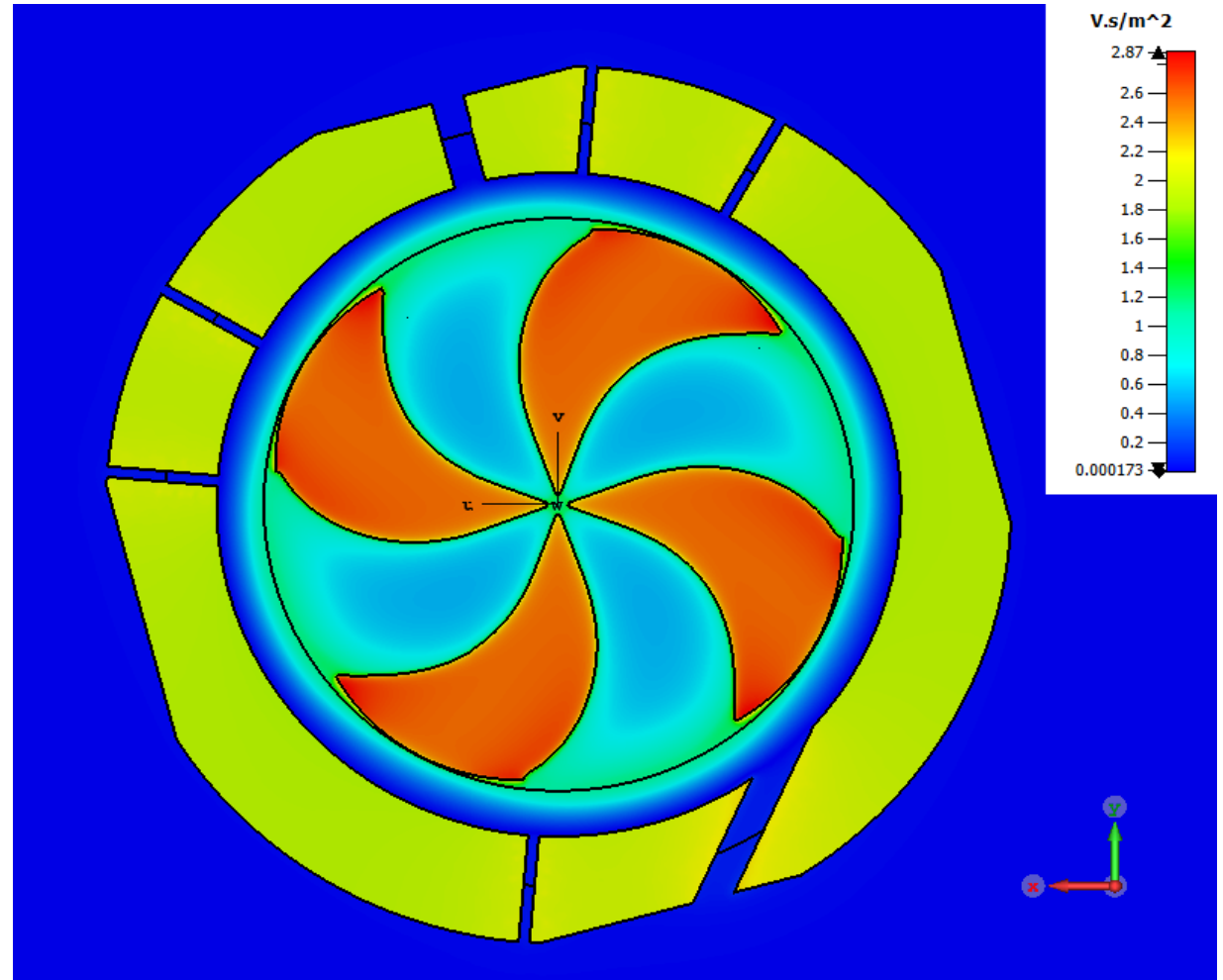
Beam envelopes during extraction (2σ).



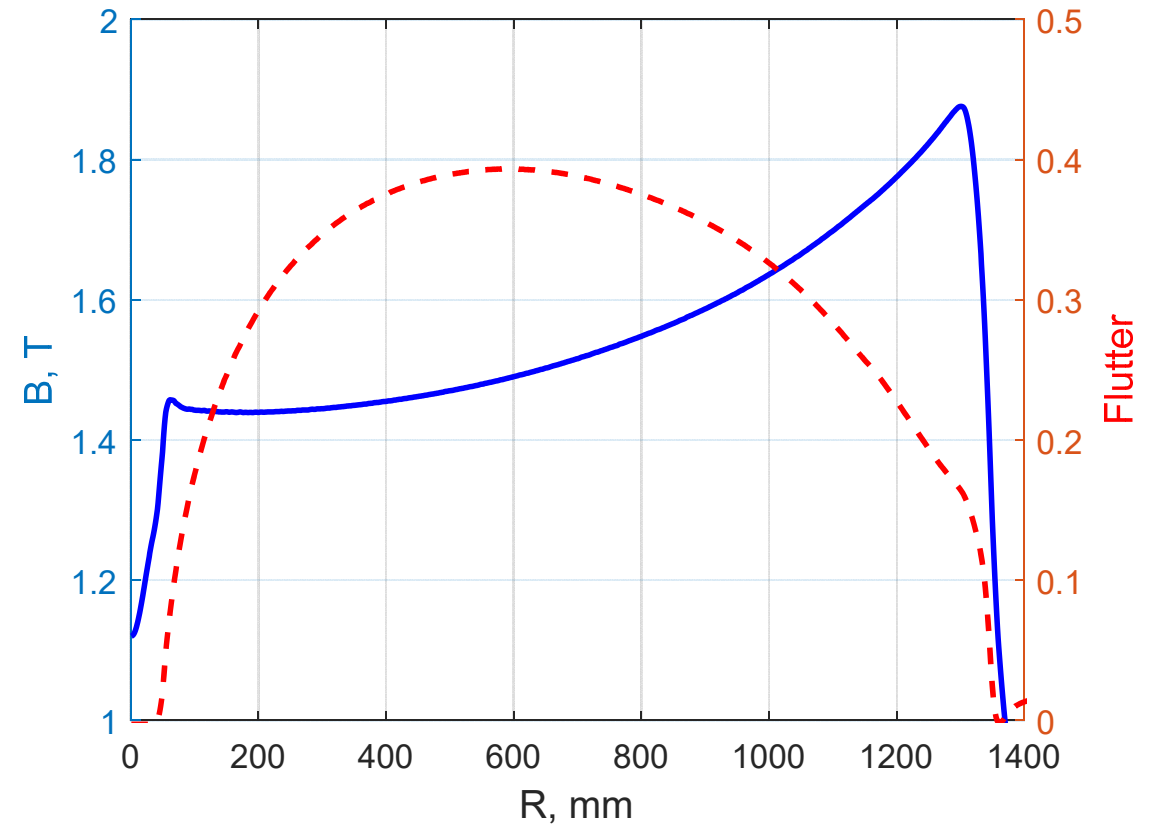
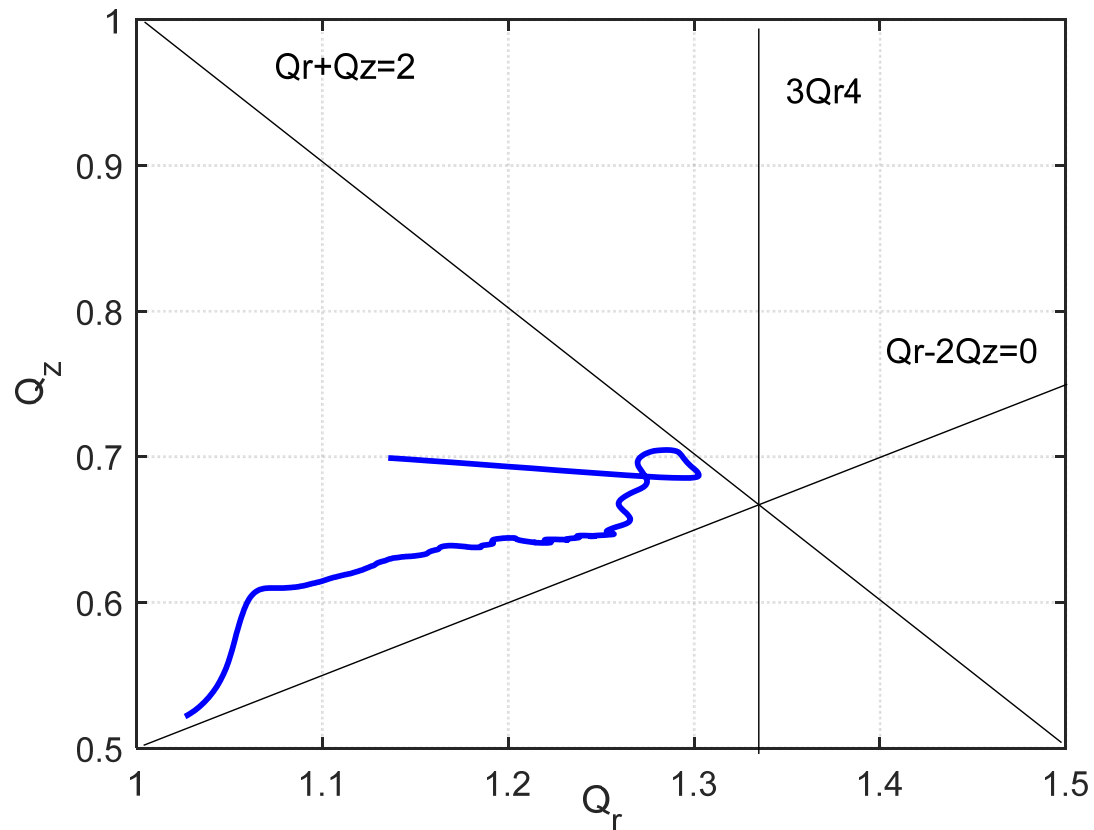
Do we need Super-Conductivity?

Let's try copper coil!

Parameter	
Magnet type	resistive
Ion source	PIG
Final energy, MeV	240
Pole radius, mm	1350
Mean magnetic field (center), T	1.45
Dimensions (height×diameter), m	1.62 × 3.95
Weight, tonnes	140
Hill/Valley field, T	1.8/0.4
Hill/Valley gap, mm	15/700
A*Turn number	120 000
Magnet power consumption, kW	140
RF frequency, MHz	89
Harmonic number	4
Voltage, kV	50-100
RF power, kW	50
Turn number	800
Beam intensity, μA	1.0
Extraction type	ESD



The "Warm" option. Gap between sectors is 15 mm



SC vs Copper

Copper is cheaper

SC is always on, easy to operate, faster to start the beam

SC is lighter

SC option has 50mm gap vs 15mm gap.

4 RF cavities vs 2 RF cavities

Must use HTS!

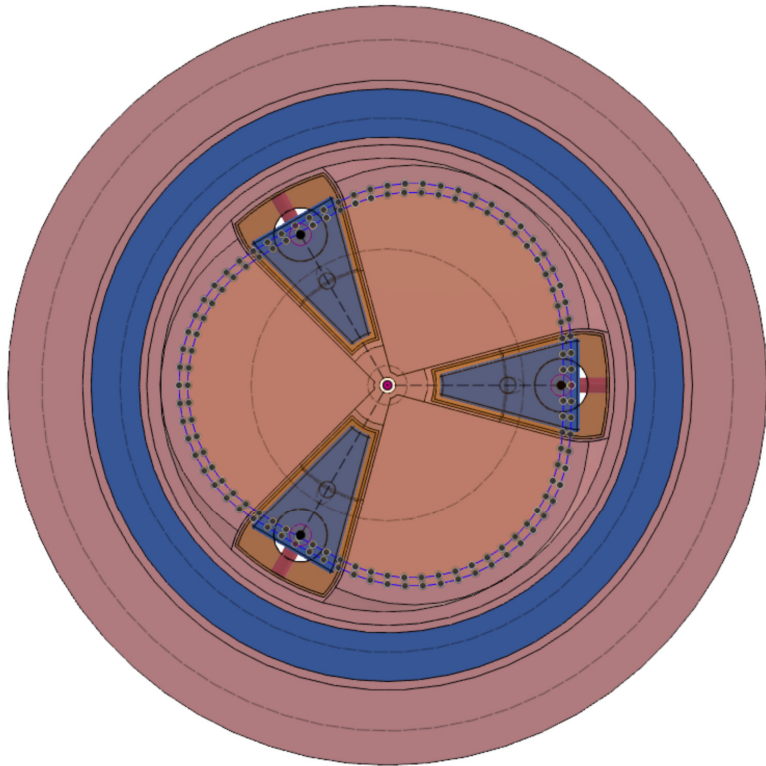
Conclusion

- SC230 is a fairly simple cyclotron
- Power efficient
- Cheap to build
- No engineering challenges

By sacrificing the weight we gain power efficiency and simplicity of low magnetic field.

Superconductivity is a good choice even for low field.

Thank you!



A concept of
15 MeV
cyclotron.
Poster
TUP033

3/6 Sector hybrid
6th harmonic acceleration

6.5 Tonn
5kW Total power