The design of the center region of MSC230 cyclotron

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08.12.022

Participants: Superconducting Cyclotron MSC230

Project participants:

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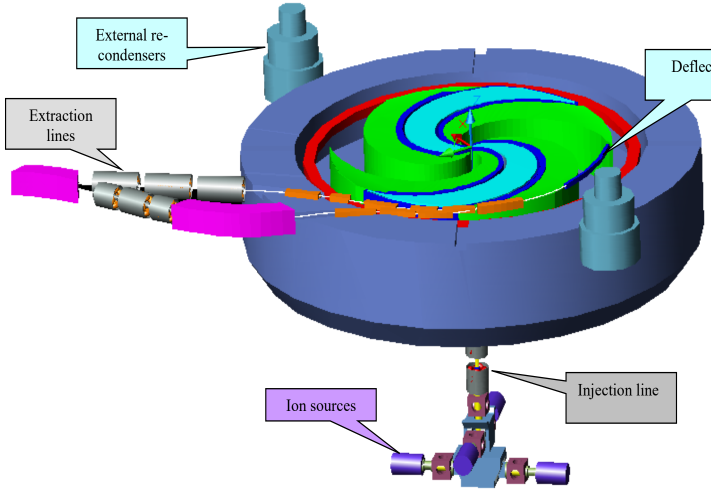
St. Petersburg, Efremov Institute of Electrophysical Apparatus (**NIIEFA**)

JINR's medical cyclotrons designs

Collaboration with IBA (Belgium).
Project of carbon superconducting cyclotron C400.
Proton cyclotron C235-V3 for Dimitrovgrad.

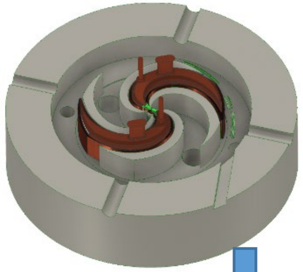


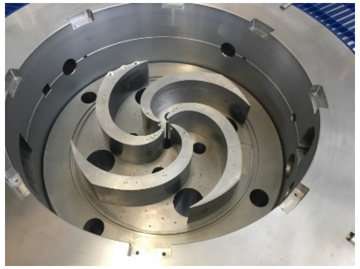
IBA-JINR collaboration designed the C400 superconducting cyclotron for carbon therapy.

C235 V3 cyclotron (IBA, Belgium) for the hospital center of radiation medicine in Dimitrovgrad was assembled in Dubna.

Collaboration with ASIPP (Hefei, China)
Superconducting proton cyclotron SC200

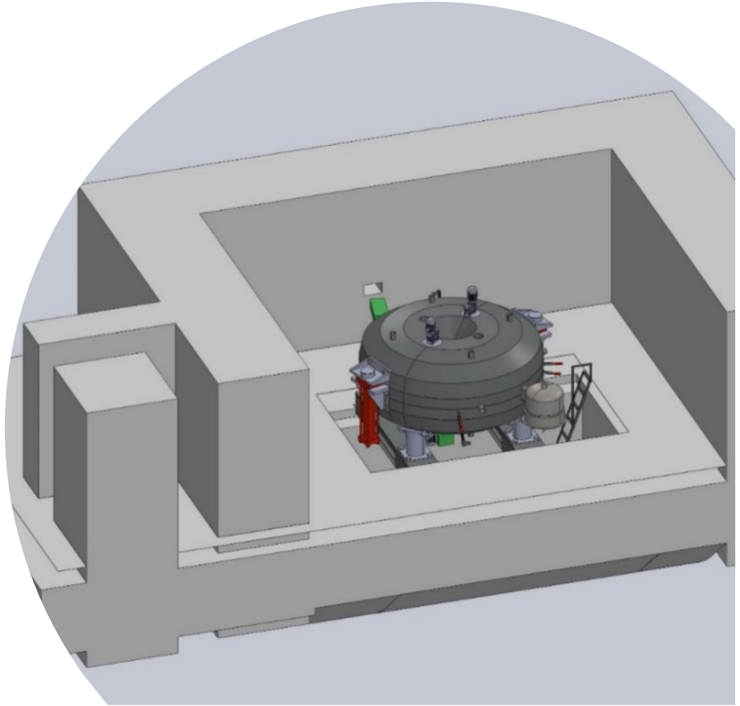
From JINR project to successful start-up in Hefei!



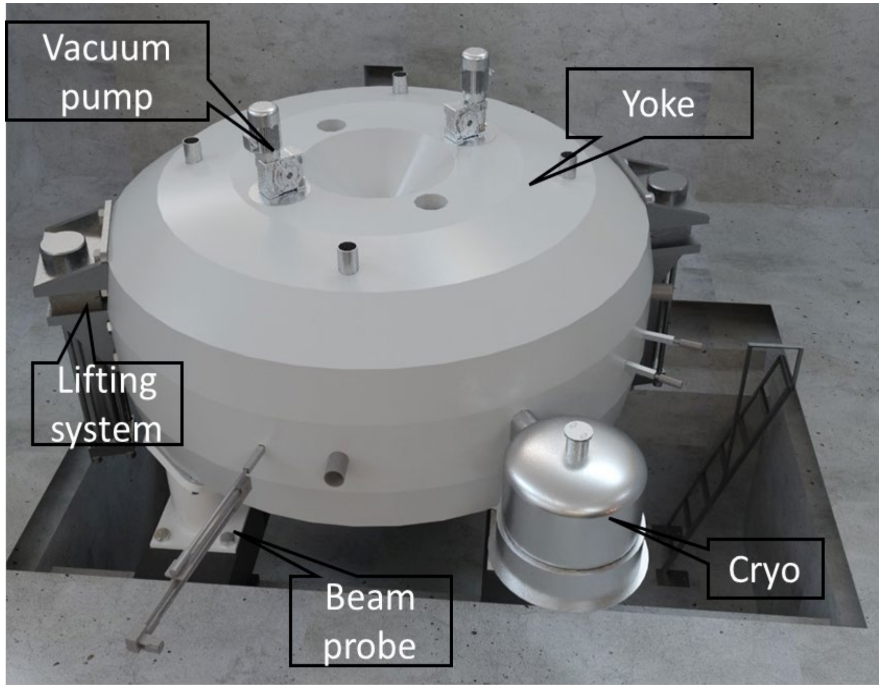


Superconducting Cyclotron MSC230 for the Medical Technical Complex in JINR

- MSC230 stands for Medical Super Conducting cyclotron of 230 MeV energy
- MSC230 is a source of a high-intensity proton beam.
- Possibilities for equipment modernization at the Medical Technical Complex of DLNP JINR
- Delivering high dose rate irradiation for FLASH therapy studies

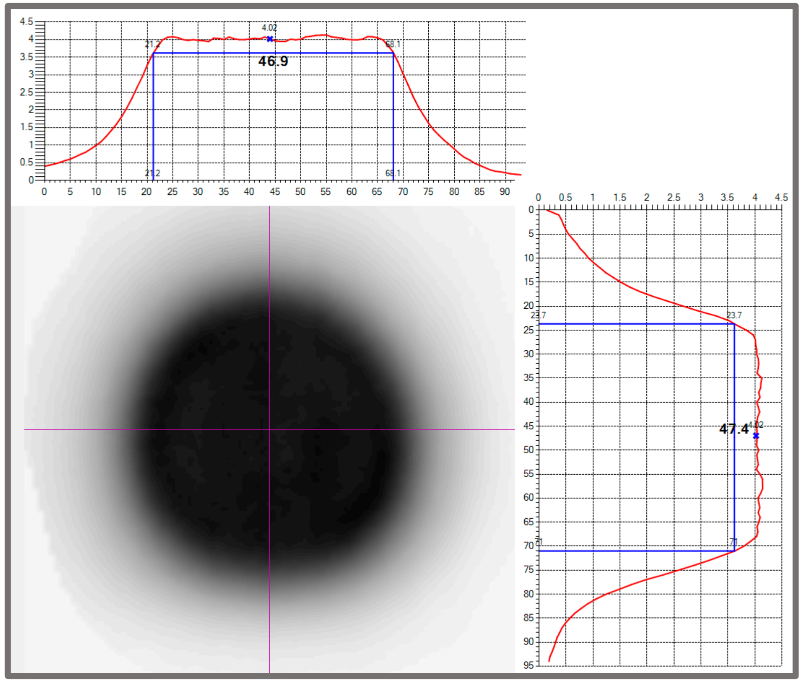


Model of MSC230 placed in the bunker



Computer model of MSC230

FLASH therapy studies



*Proton **beam profiles** for studying the effect of FLASH therapy on biological objects. (formed at the MTC, based on the **Phazotron** accelerator)*
Dose field width at 90% level is ~47 mm
Dose field uniformity is not worse than ±5%

FLASH – new method of proton therapy consisting in irradiation with ultrashort (less than 0.5 s) pulses.

Compared to radiation therapy at a conventional dose rate (**1–7 Gy/min**), FLASH irradiation is performed at a dose rate **~ 100 Gy/s** .
In order to deliver 100 Grey/second**, extracted beam current should be at least 10 μA**.

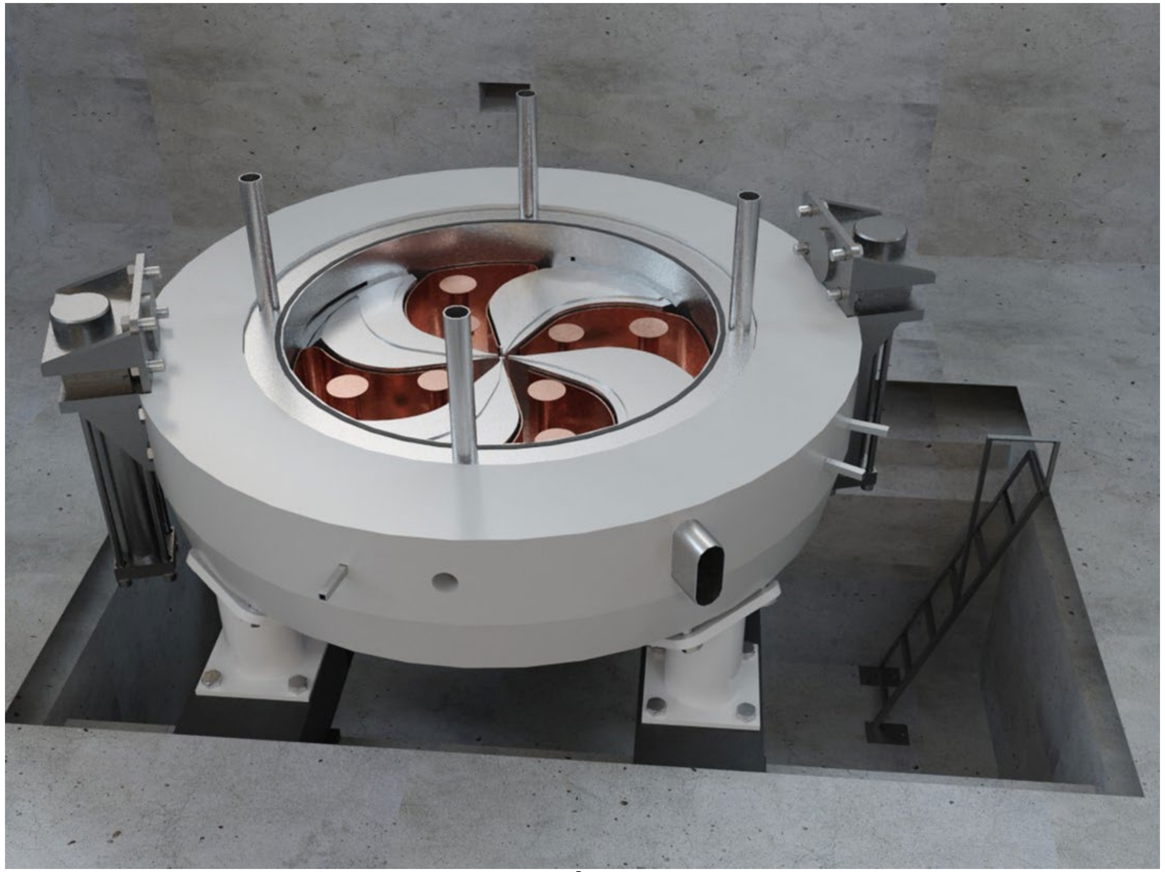
- Healthy tissue is better able to withstand FLASH radiation, while the level of damage to the tumor is the same as with conventional treatment.
- Allows for more effective treatment of radioresistant tumors, as well as recurrent diseases
- Reduces the number of treatments

Agapov A.V., Mitsyn G.V., Molokanov A.G., Shipulin K.N, Shvidky S.V.,

Comparison of parameters of cyclotrons for proton therapy

	IBA C235	Varian Proscan	MSC230
DYoke, m	4.34	3.2	3.7
Height, m	2.1	1.7	1.7
$B_{0,}$ T	1.7	2.4	1.7
Coil	Resistive	NbTi	NbTi or HTS
Weight, tonnes	210	90	100
Extraction energy, MeV	235	250	230
RF system	2 x 4th Harmonic 106.5 MHz	4x 2nd Harmonic 72 MHz	4x 4th Harmonic 106.5 MHz
RF Power	55 kW	120 kW	55 kW
Gap between poles	95/9 mm elliptic	50 mm	50 mm
ESD voltage	170-180 kV/cm	80-100 kV/cm	80-100 kV/cm

Main parameters of MSC 230



- Low power consumption.
- Reasonable size.
- Minimum engineering efforts and challenges.
- High quality of the beam.

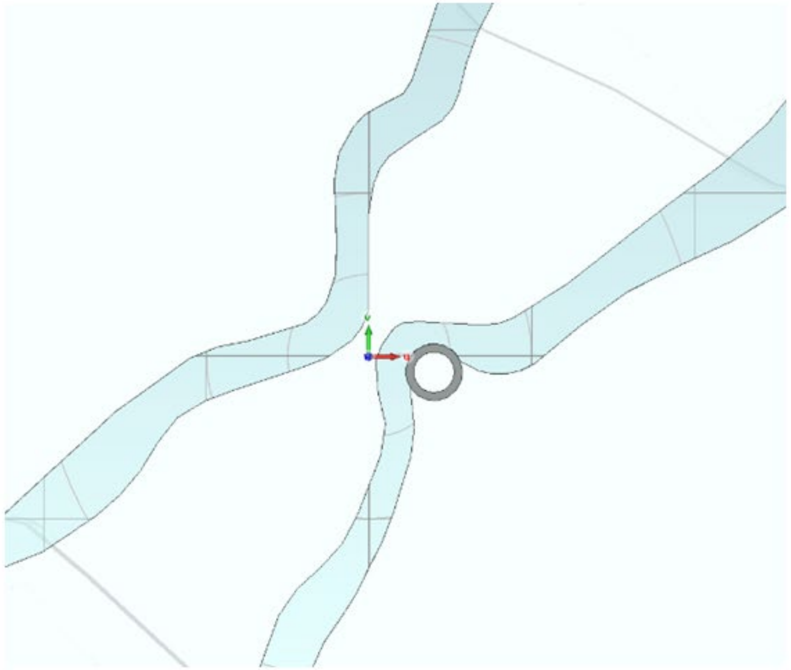
Magnet type	Compact, SC coil, warm yoke
Ion source	PIG
Final energy, MeV	230
Pole radius, mm	1070
Mean magn. field (center), T	1.7
Dimensions (height×width), m	1.7 × 3.7
Weight, tonnes	100
Hill/Valley gap, mm	50/700
A*Turn number	270 000
RF frequency, MHz	106.5
Harmonic number	4
Number of RF cavities	4
Voltage, center/extraction kV	40/110
RF power, kW	55
Number of turns	500
Beam intensity, μA	10
Extraction type	ESD

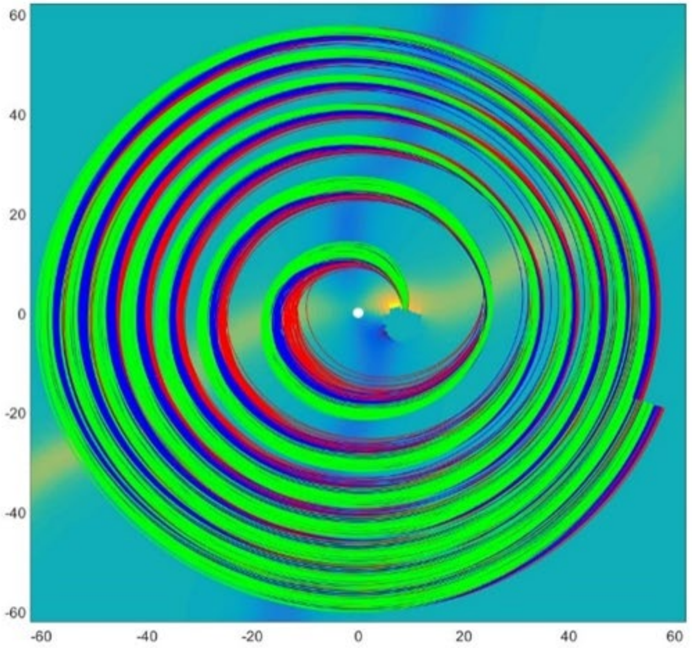
Current status

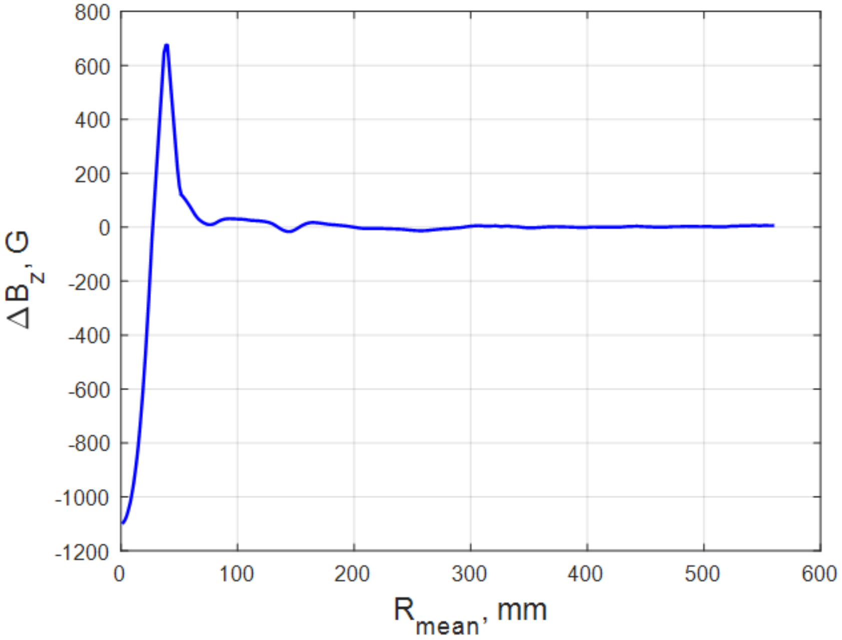
- The development, modeling and optimization of the components of the cyclotron has been carried out. (simulations of the beam dynamics, magnet, accelerating system, etc.)
- Terms of reference for the implementation of the project were formed
- Agreement with NIIEFA signed
- **Ongoing**: Coordination and preliminary design of the cryostat and the superconducting coils

Central region of **SC200**

View of the dee tips and ion source position.
First turns in the cyclotron (40 RF deg).







- JINR's design of the center: 350 nA internal beam achieved experimentally (400 predicted)
- Challenges caused by high central magnetic field (3 T): construction of the bump makes the field in the very center lower than isochronous -> lagging particles at the beginning start to lag even more (the phase reached 60 deg)
- Solved by varying the size of the gaps in the center to increase the efficiency of proton extraction from the source and at the same time avoid breakdowns

Central region of **MSC230:** tasks

- Provide the possibility of forming a **well-centered accelerated beam** (less than 1 mm at a radius of 100 mm), consistent with the acceptance of the accelerator. Phase acceptance ± 20° RF
- By selecting the position of the accelerating gaps, ensure sufficient **vertical focusing** by the electric field in the first and second turn
- Minimize the probability of break-downs

Reducing the probability of break-downs

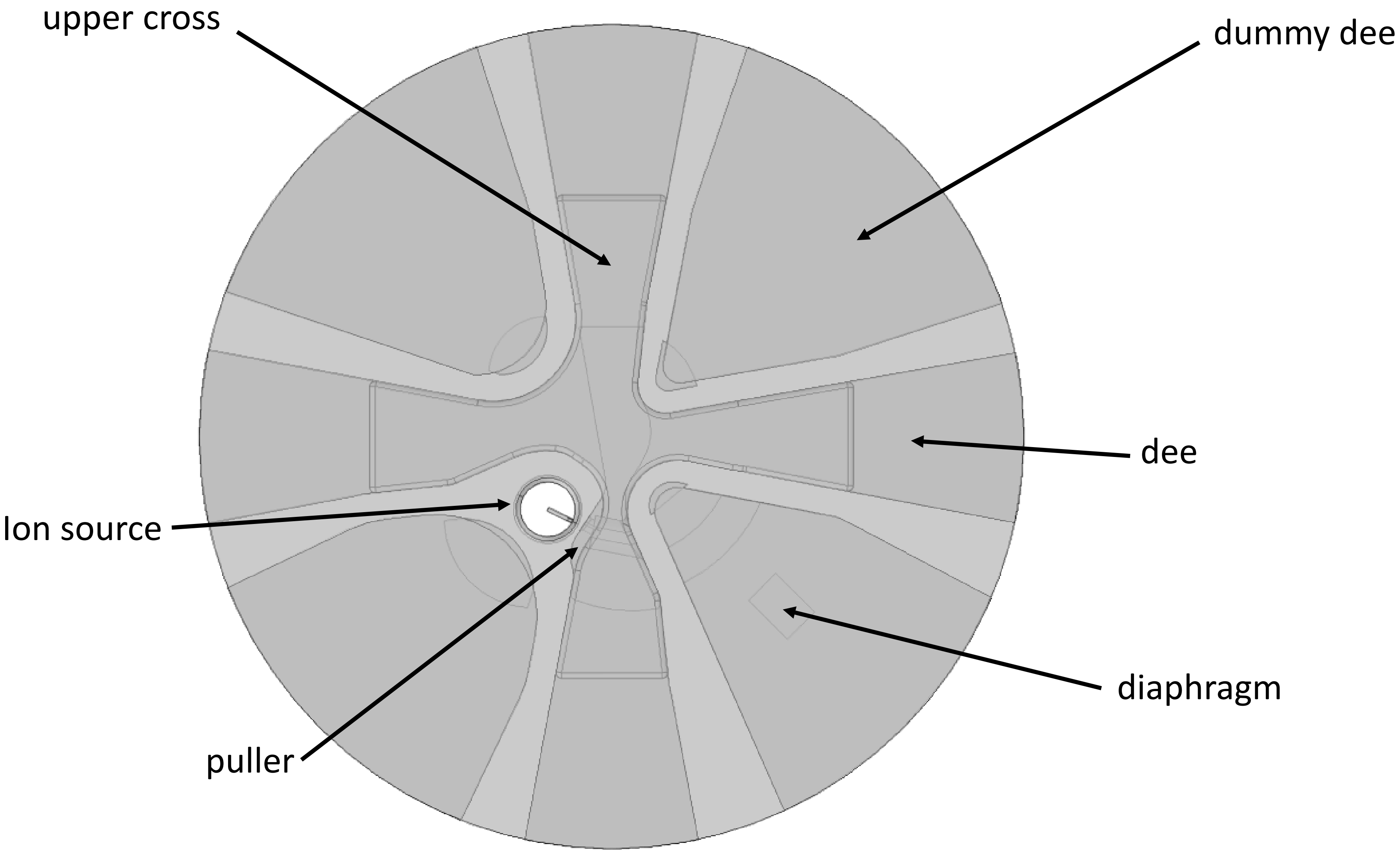
- Accelerating voltage is the central region – **30-40 kV**;
- RF system operates at **106.5 MHz**;
- Kilpatrick criterion: maximum value of the intensity **Es = 120 kV/cm**;
- In the direction, perpendicular to the magnetic field lines, the magnetic field prevents electrical break-down -> the electric field strength can be 1.5 higher than the Kilpatrick limit;
- Therefore, **gap width is 2 mm** (can be increased to 2.5 mm by moving the puller);
- Corner rounding is necessary to reduce the values of local electric fields.

Design of the structure of the central region

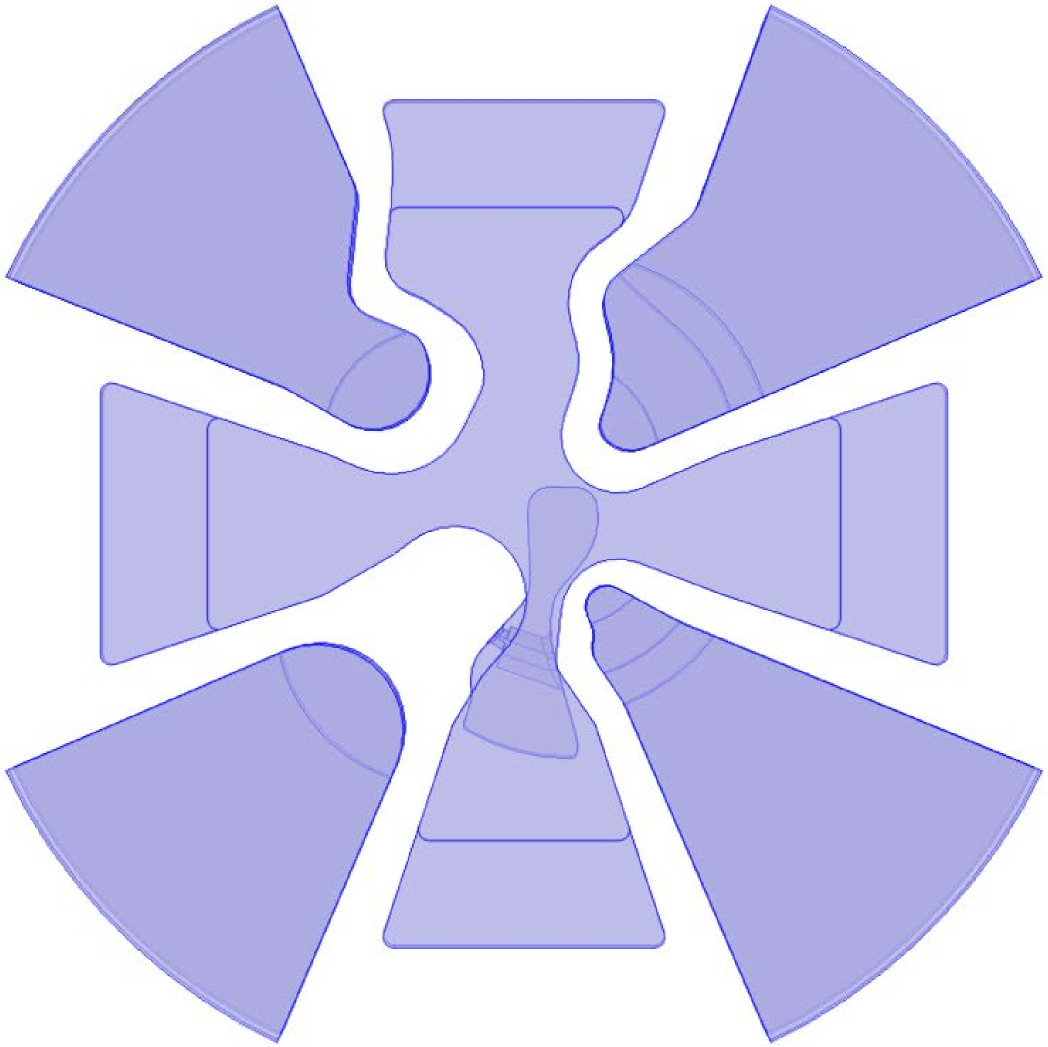
Two separate designs (working with the same RF system) to improve beam quality:

1. Axially-symmetric central region design
2. Optimized central region design

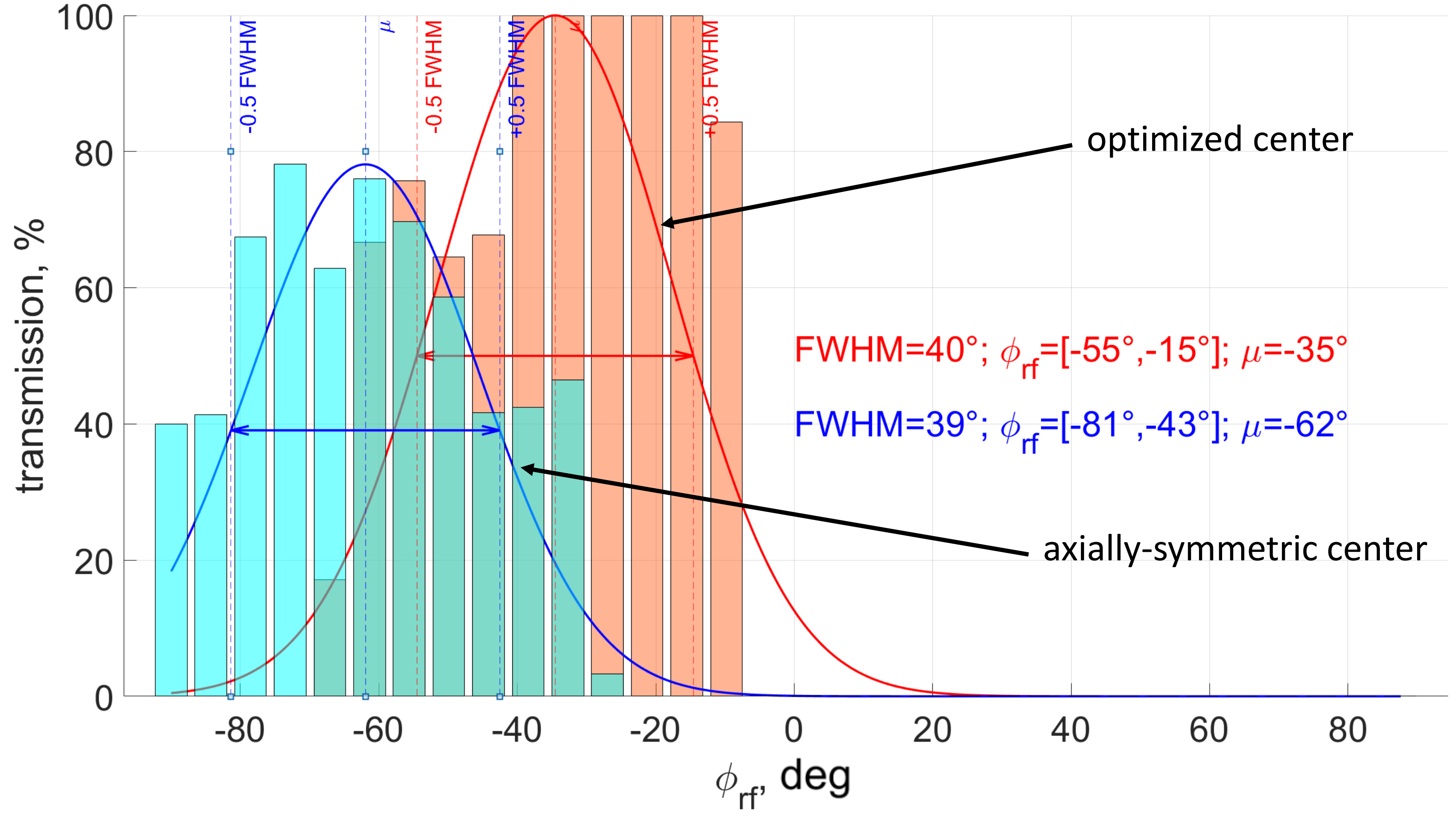
Structure of the central region: axially-symmetric



Structure of the central region: optimized

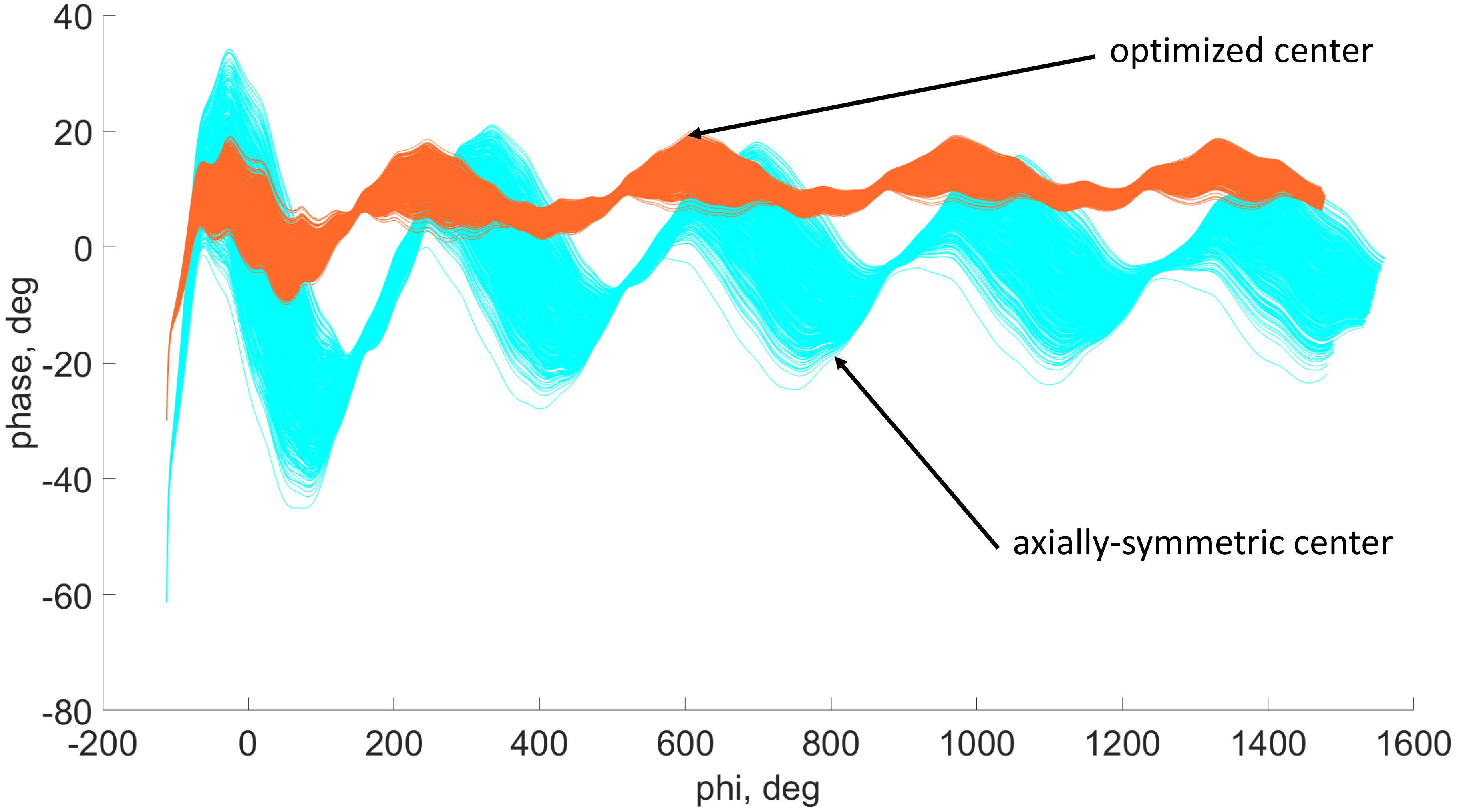


Phase acceptance – axially-symmetric/optimized center



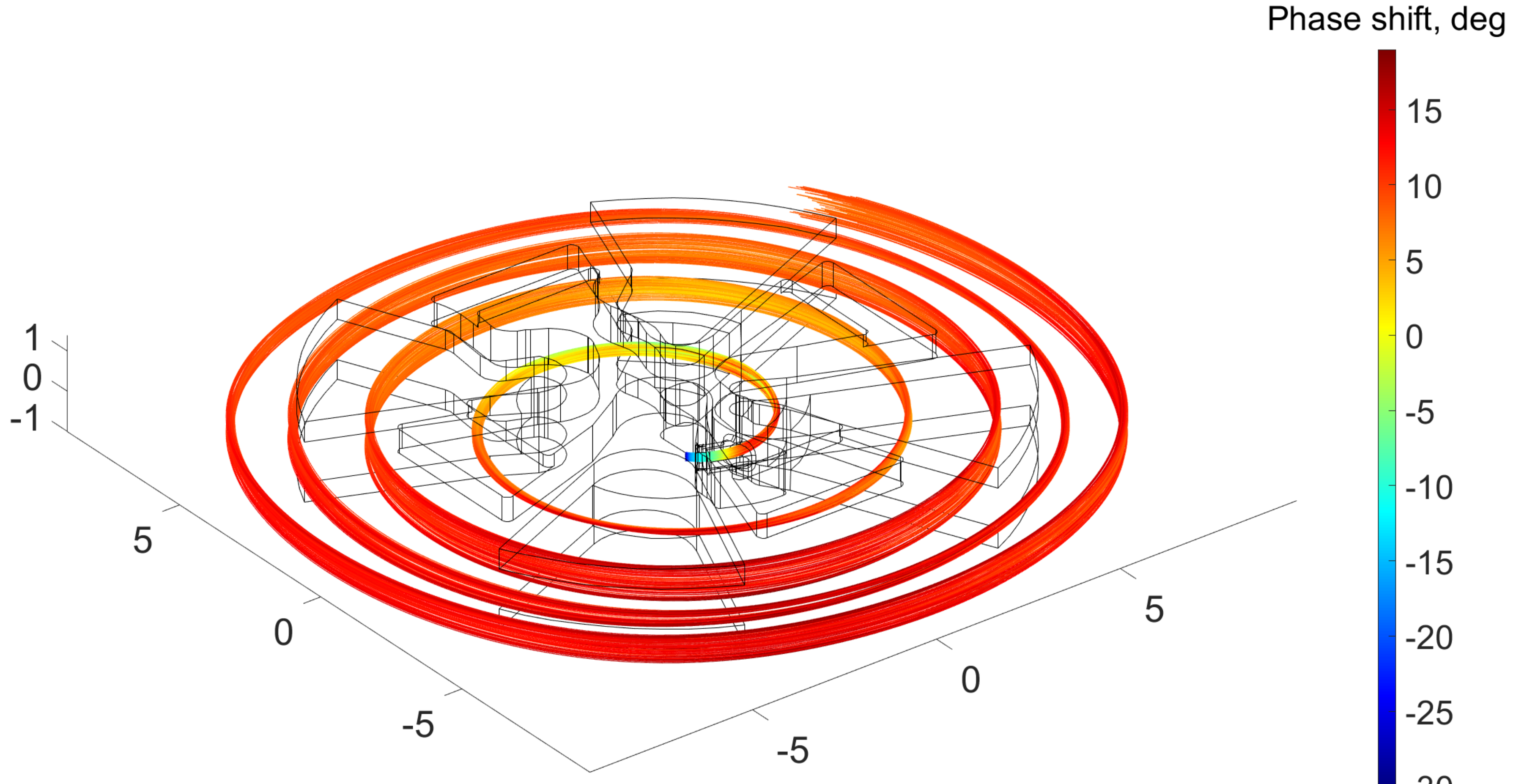
Integral transmission: axially-symmetric - **19.8%** /optimized - **27.7%**

Phase shift – axially-symmetric/optimized center

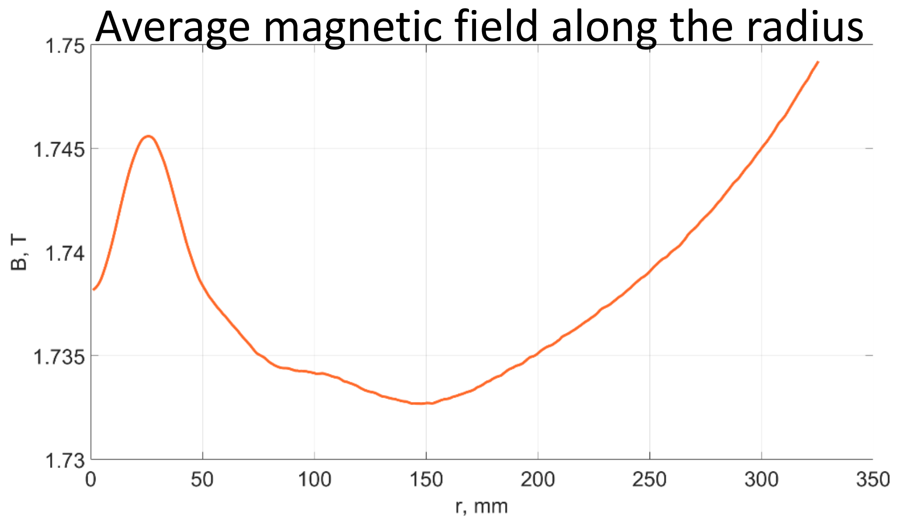


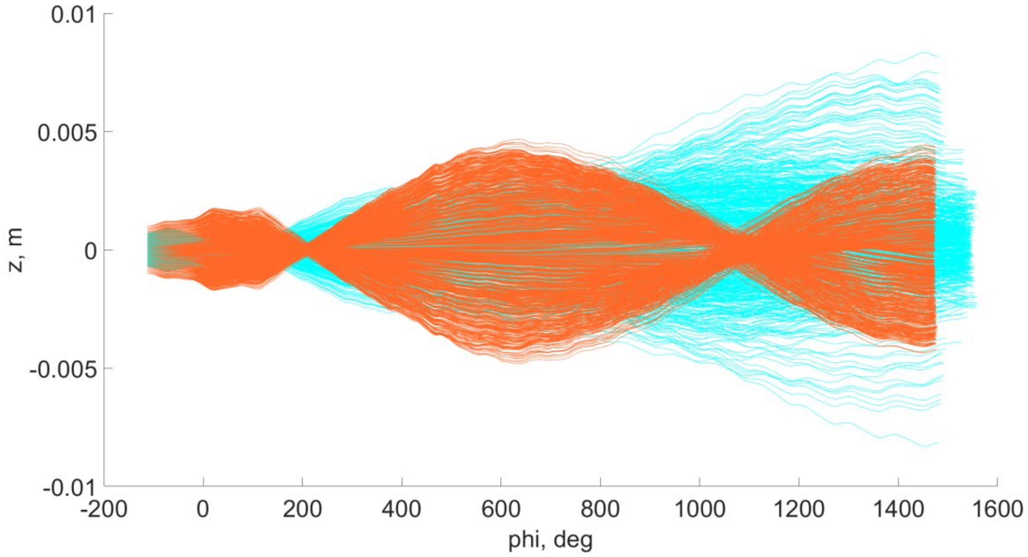
Phase shift vs. angle. Positive phase corresponds to the lagging particle.

Phase shift (axially-symmetric, initial RF phase = -30 deg)



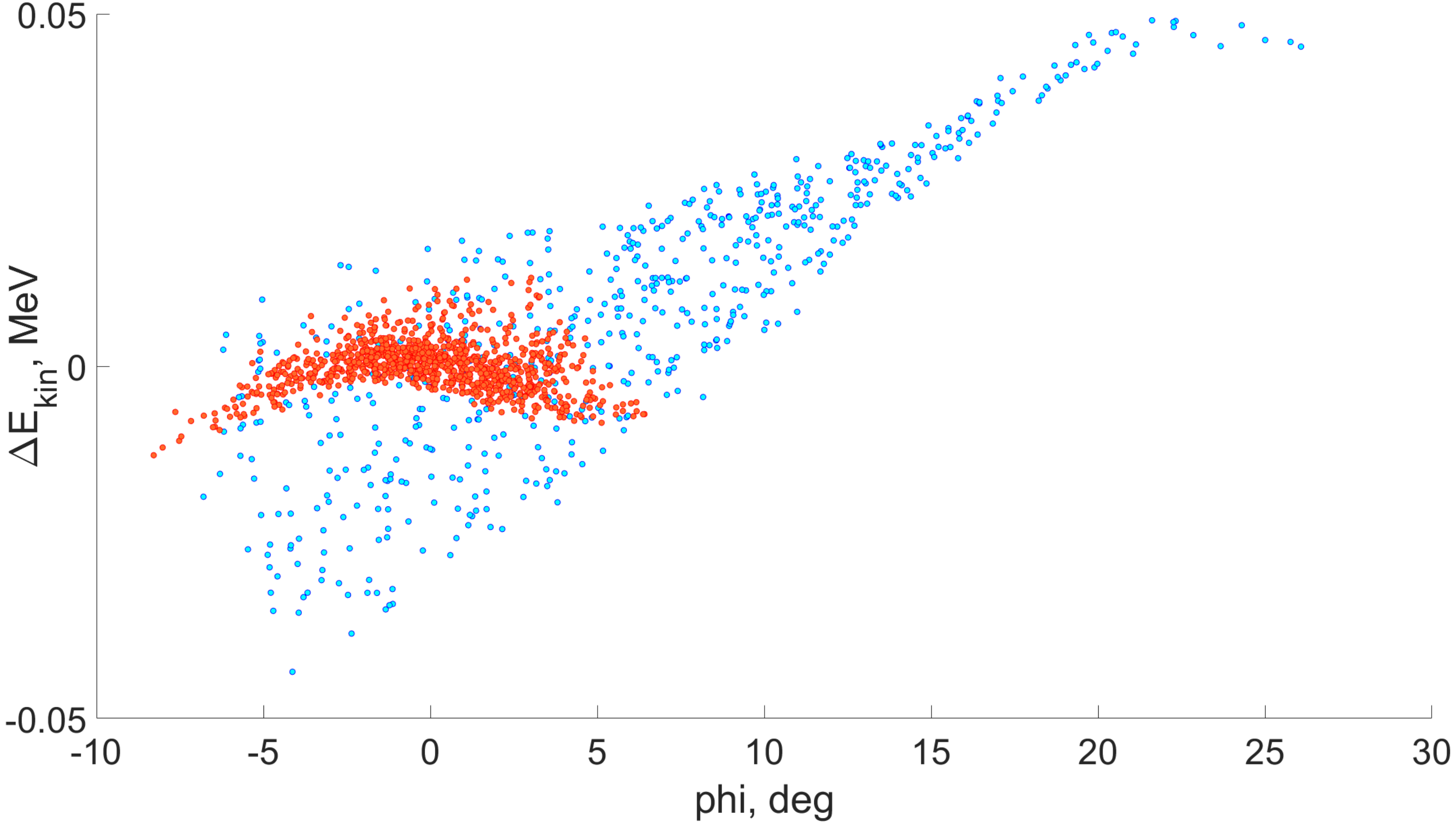
Vertical focusing





- To provide vertical focusing, we create a bump (radial gradient) of the magnetic field (80-100 Gauss)
- Magnetic focusing caused by the decreasing magnetic field begins after a radius R = 30 mm
- For R< 30 mm: accelerating electric field provides vertical focusing of lagging particles

Variation in energy gain – optimized/axially-symmetric center



Variation in the kinetic energies of the particles at R=10 cm.

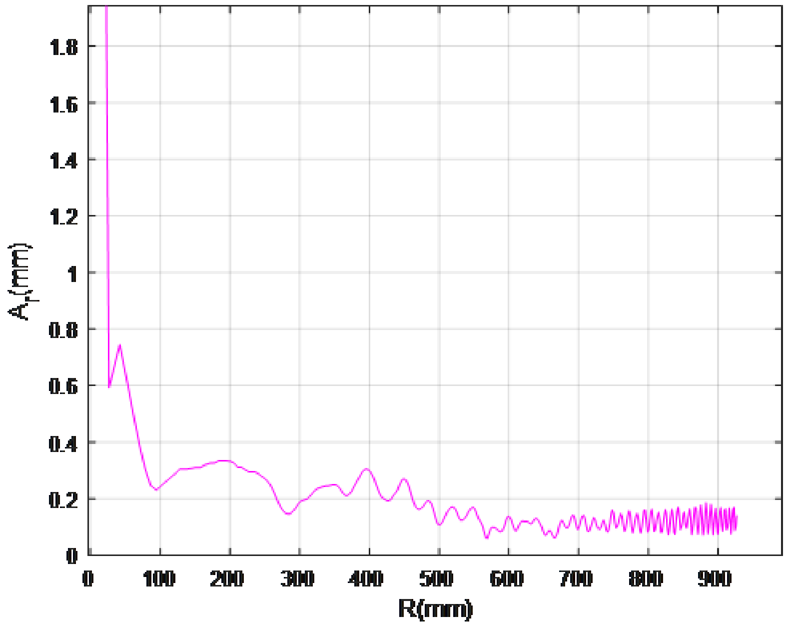
Conclusion

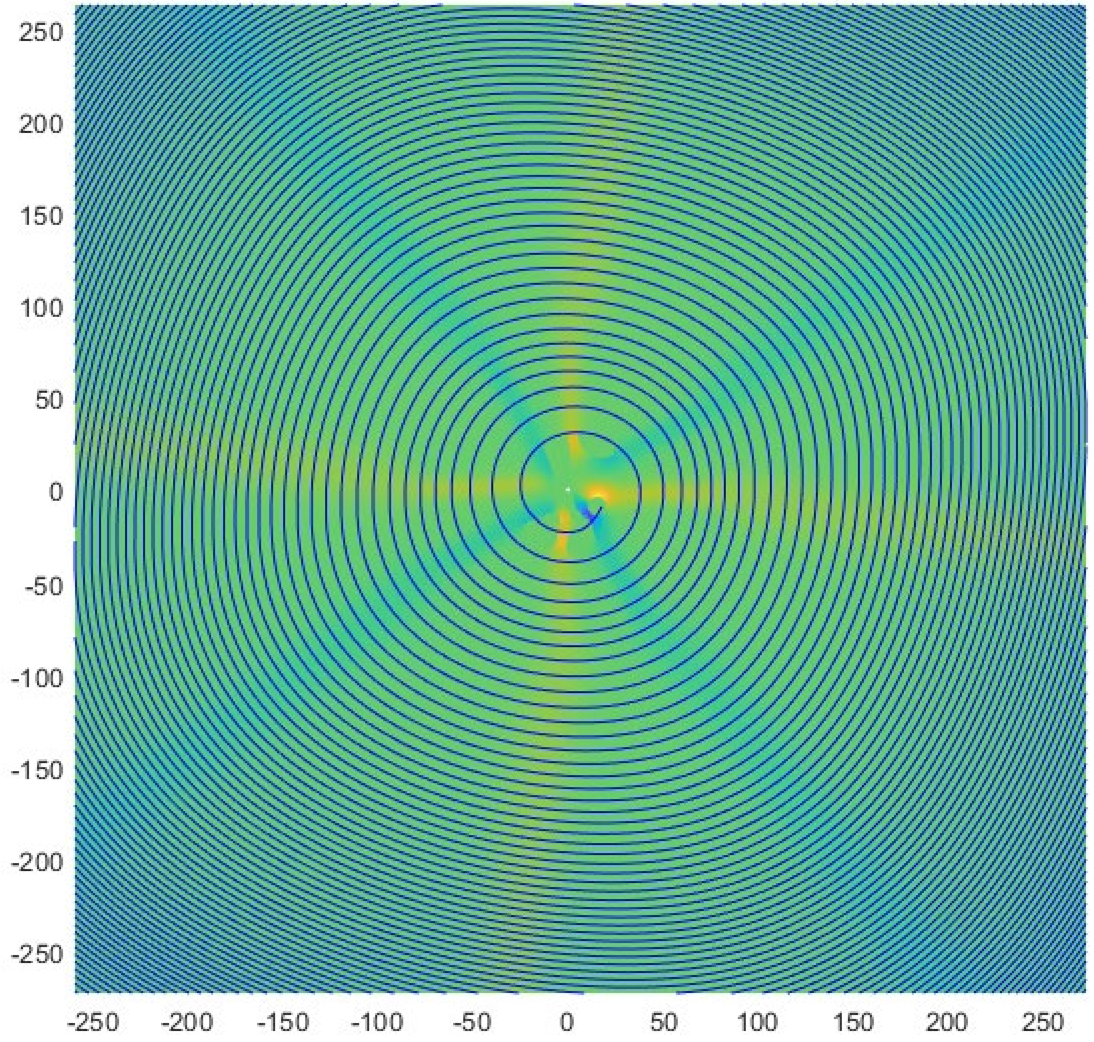
- Central region structure and overview was presented
- Axially-symmetric and optimized designs we compared: optimized design has better beam properties (lower phase shift variation, lower energy gain variation)
- Axially-symmetric central region design can be used for RF tuning, optimized version works with the same RF system and has better beam properties
- Simulation shows good phase acceptance, making it possible to reach beam intensity, required for FLASH therapy

Thank you for your attention

Extra slides

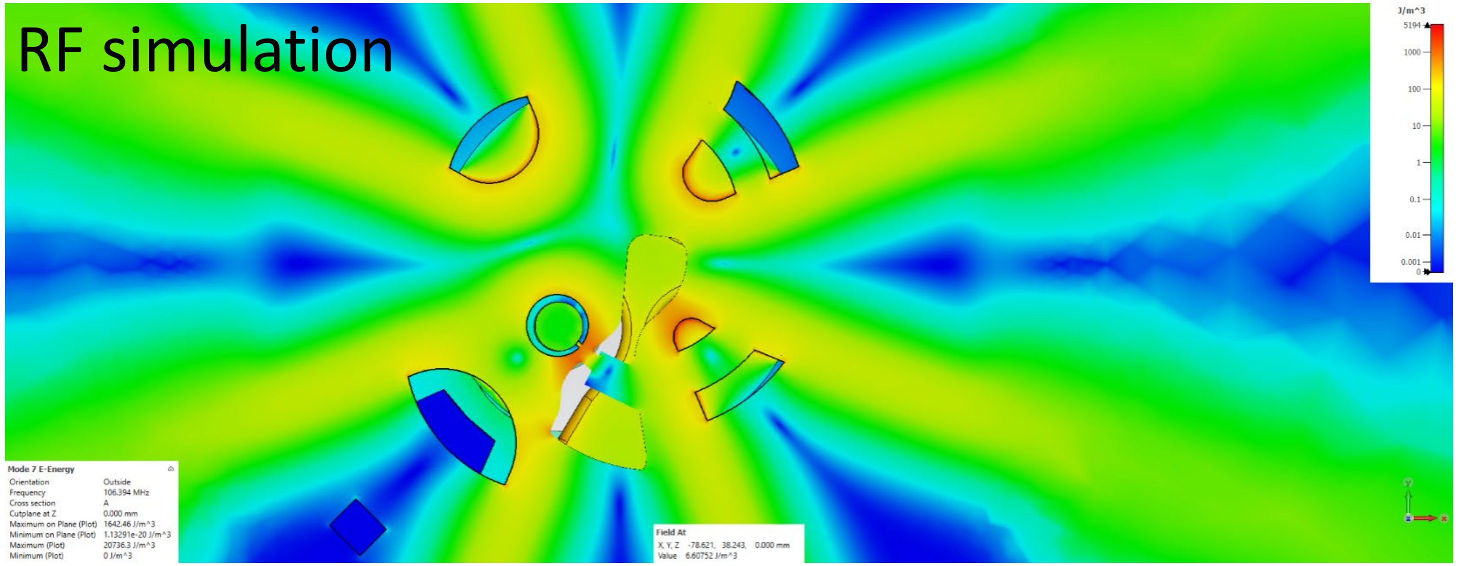
Centering

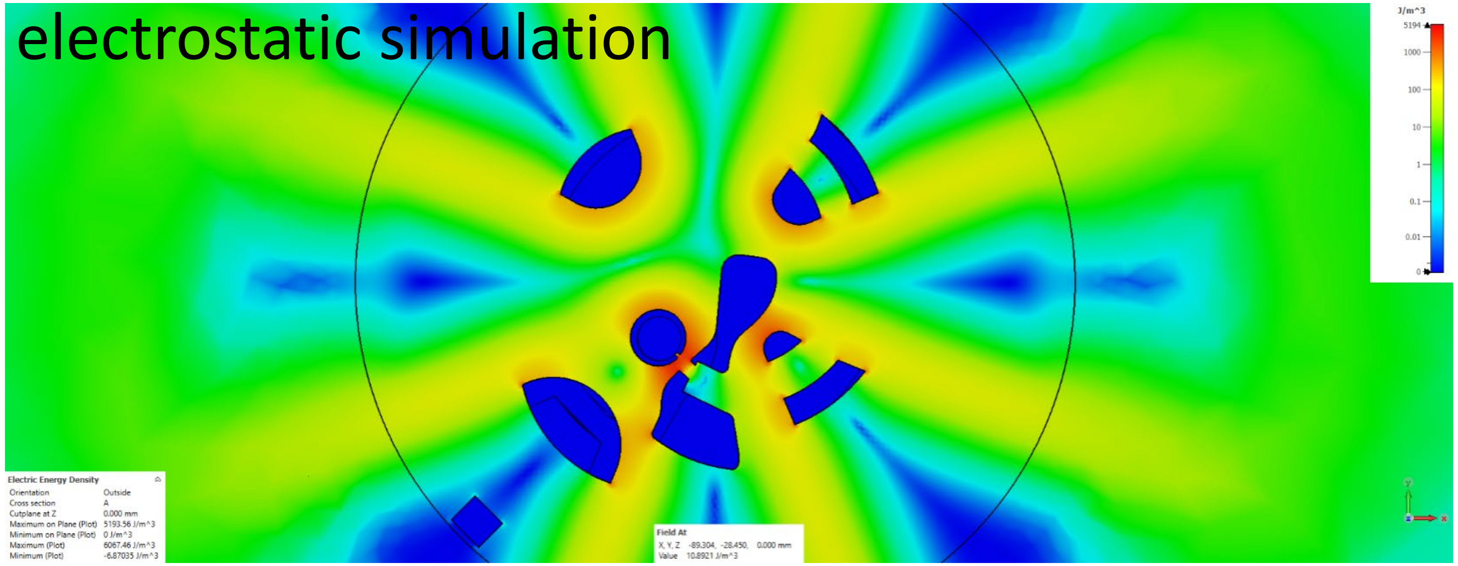




1. Backtracking (central particle) – optimization of the field map
2. Diaphragm is used to reduce the amplitude of radial radial oscillations of the beam of particles

Electrostatic/RF simulation





The accelerating voltage across the gap of the RF cavity, calculated by integration of electric field along the particle trajectory:

$$V = \int_{gap} E_s \cdot ds$$

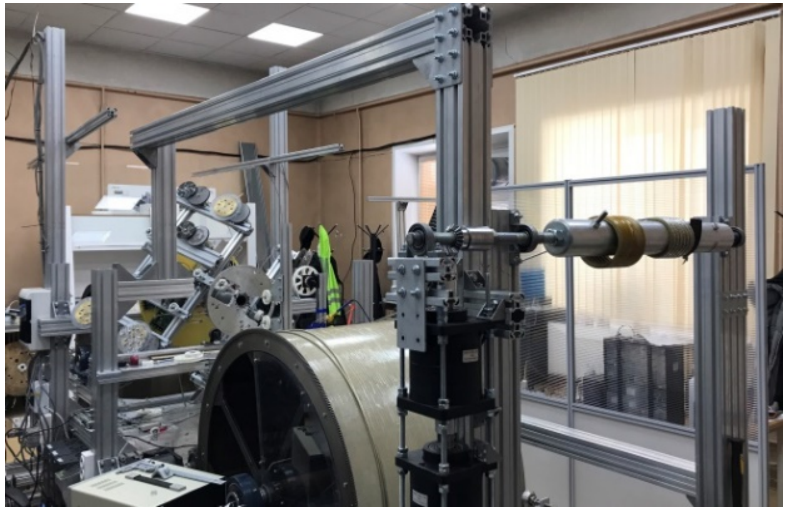
For the first gap:

$$\Delta V = V_{ES} - V_{RF} \approx 10kV$$

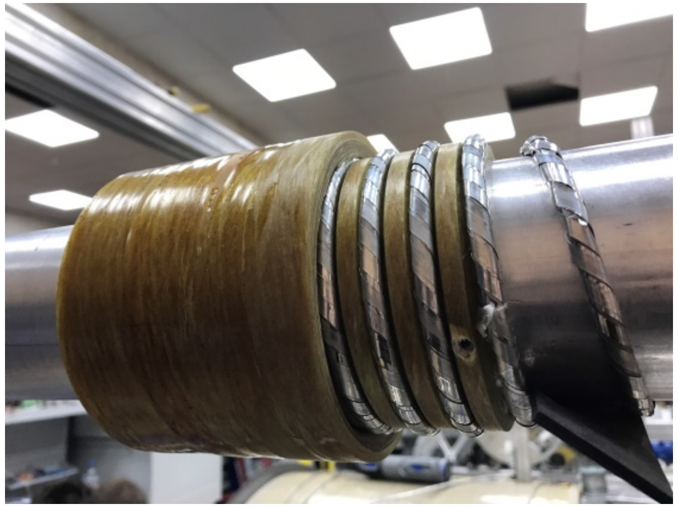
Superconducting coil for MSC230

Magnetic field in the center of the cyclotron is **1.7 T**. The low magnetic field is advantageous not only for beam extraction and shimming, but also for the **superconducting coil design**, since the critical current is highly dependent on the magnetic field in the coil.

In the MSC230 cyclotron, **NbTi** can be used to produce coils; however, the design of the cyclotron allows the use of high-temperature superconducting (**HTSC**) materials, that have great potential. **The technique developed for NICA at VBLHEP** can be applied to the manufacture of MSC230 windings.



Unit for winding solenoids



Six-turn sample

Photo: Hodzhibagiyan G.G, Nikiforov D.N., Novikov M.S.