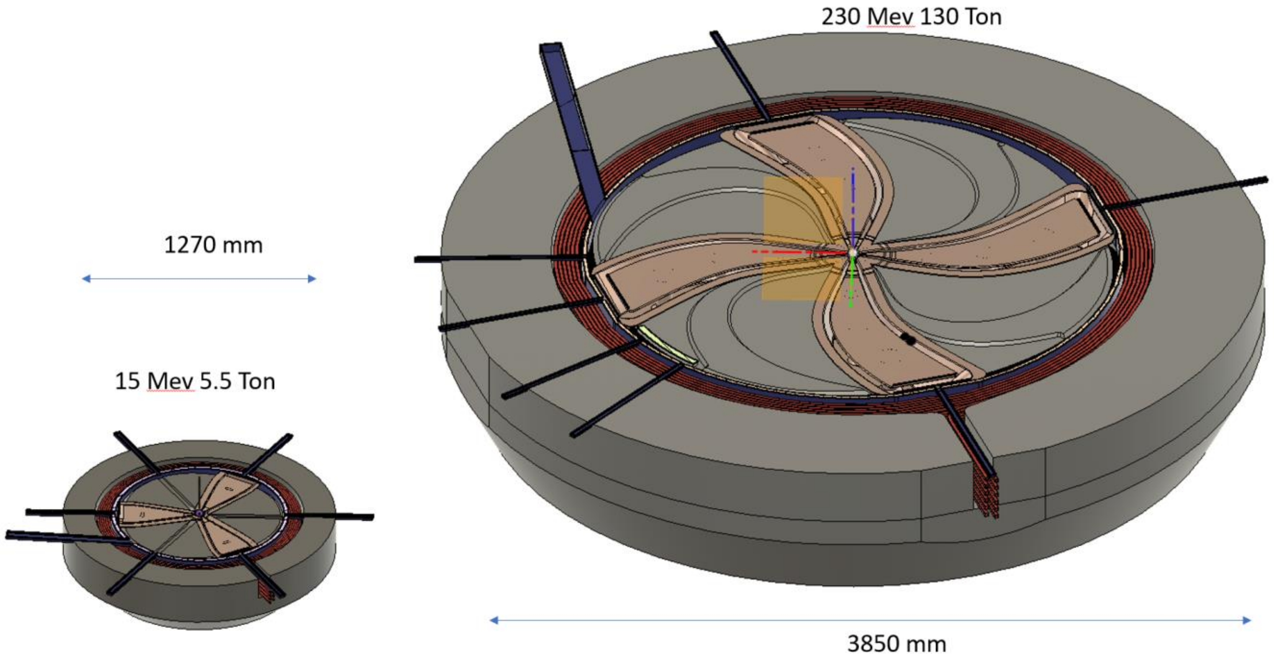
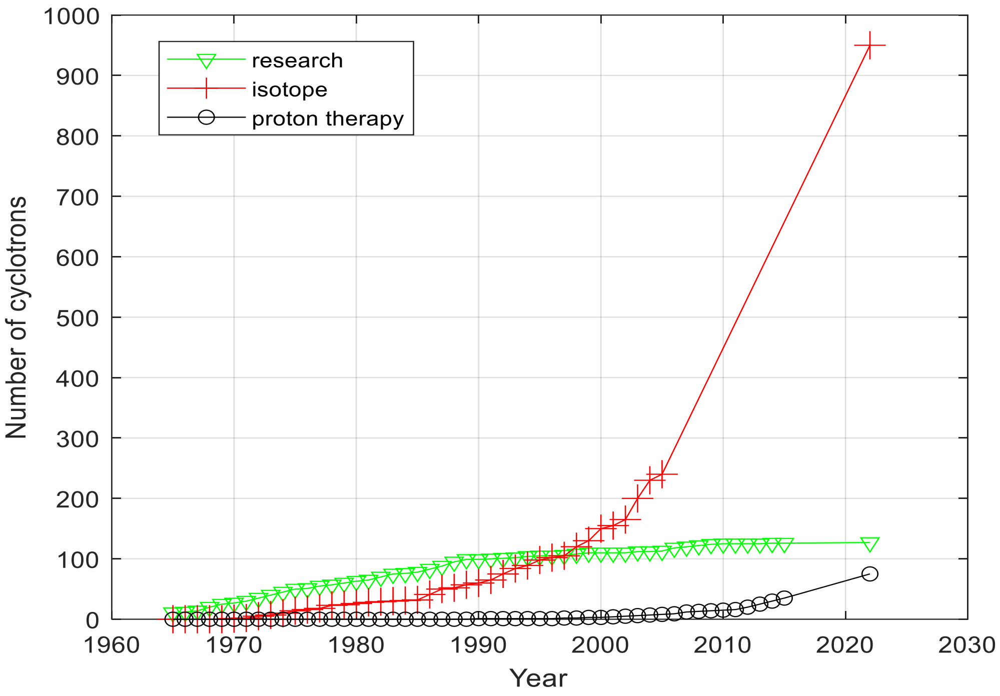
A new concept of cyclotrons for medical applications.
15 to 230 MeV

Oleg Karamyshev.



Motivation



Demand for cyclotrons for isotope production and proton therapy is growing.
Cyclotrons have limited lifetime due to irradiation etc., need to replace older cyclotrons with new ones.
Cyclotrons are becoming better: more compact, cheaper, more reliable, power efficient.

Number of cyclotrons. The green triangles are cyclotrons in operation at research centers, the red crosses the cyclotron for medical radioisotopes production, and the black circles cyclotron for proton therapy [1]. Graphs are updated for year 2020 by data from [2, 3].

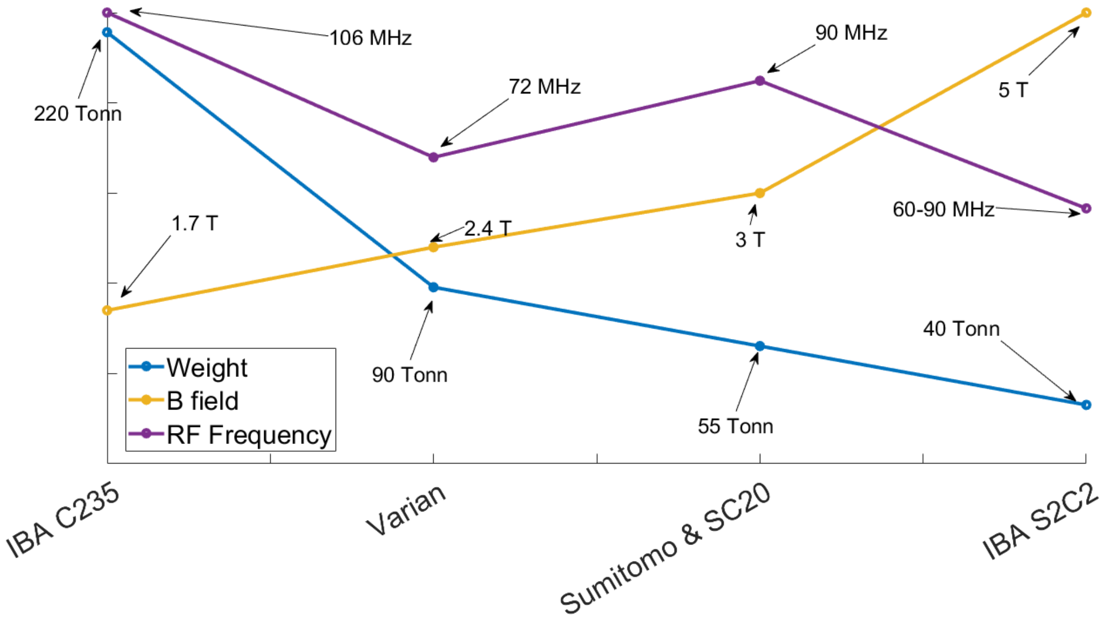
•[1]Calabretta L., Seidel M., 50 Years of Cyclotron Development, IEEE Trans.Nucl.Sci. 63 (2016) 2, 965-99, DOI: 10.1109/TNS.2015.2499238.
•[2]Schaffer P. et al. Direct Production Of 99mTc via 100Mo(p,2n) on Small Medical Cyclotrons // Physics Procedia 66 (2015) 383 – 395.
•[3]https://www.ptcog.ch/index.php/facilities-in-operation

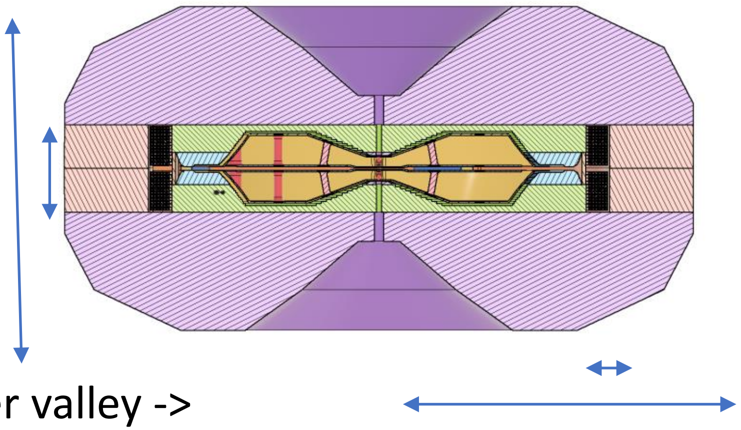
The new concept.

The main goal is to make a light and compact design.

In past years the trend was to increase B field, thus decrease pole radius.

I propose a different way, make RF and Coil more compact by increasing RF frequency, decreasing the dimensions of the valley, which leads to less A-turns in magnet, thus making the coil smaller, which will lead to smaller yoke.

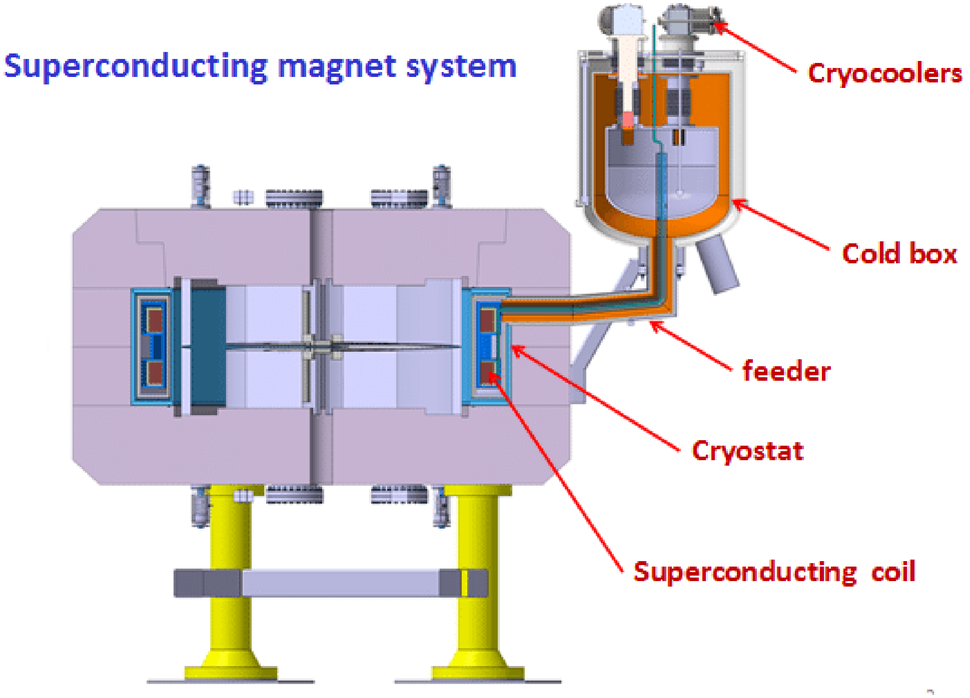




Smaller valley -> smaller height

Smaller coil -> smaller yoke radius

Superconductivity. The good the bad and the ugly.



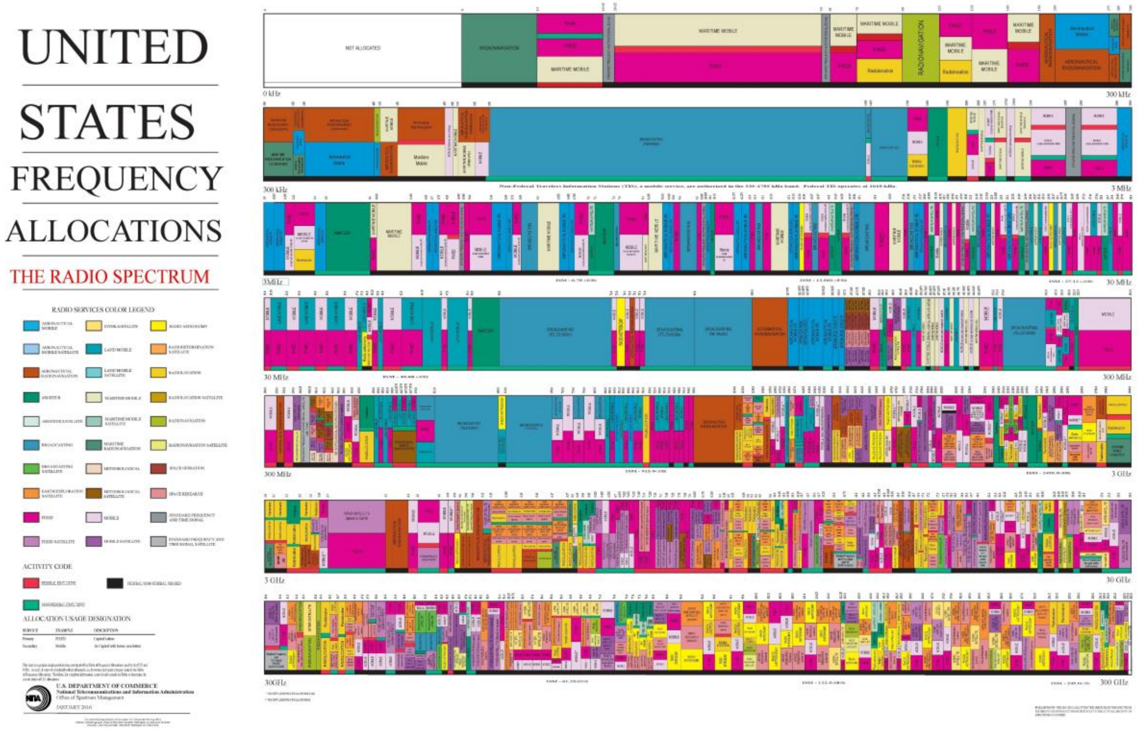
Early model of SC200 cyclotron

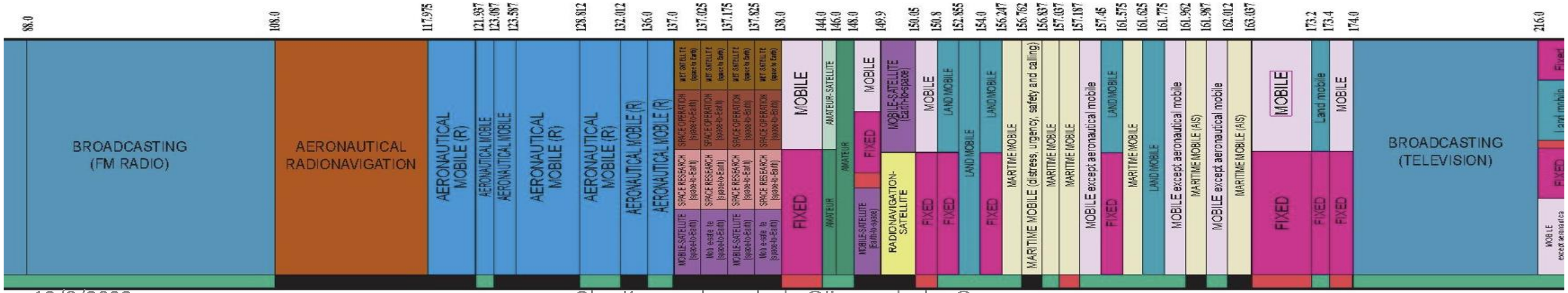
Compact? Yes, the pole is smaller, but cryogenics equipment around cyclotron is huge!
Dry magnets with cryocoolers are more compact, but
Power efficient? Cryocoolers consume power 24x7 during operation and more during cooling down.
Long time to turn on/off the magnet.
Long time to cool down.
Expensive.
Requires service.

Superconducting cyclotrons do not exist! We only have cyclotrons with superconducting coil.
Cyclotron is an accelerator, number one is accelerating system, magnet just keeps the beam focused and arrive in time! No superconducting RF yet works in cyclotrons.

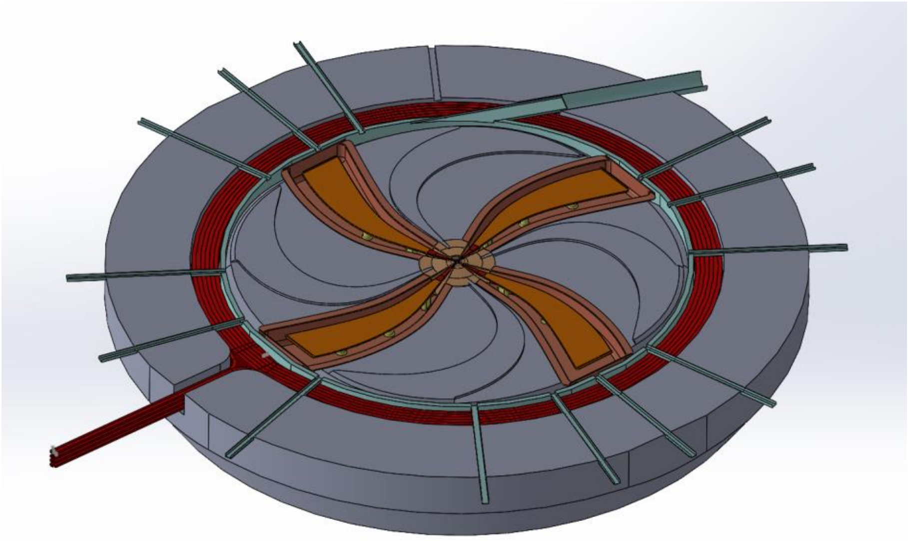
Increase RF frequency, but how much?

Below 108 MHz
145 MHz
between 174 and 216 MHz



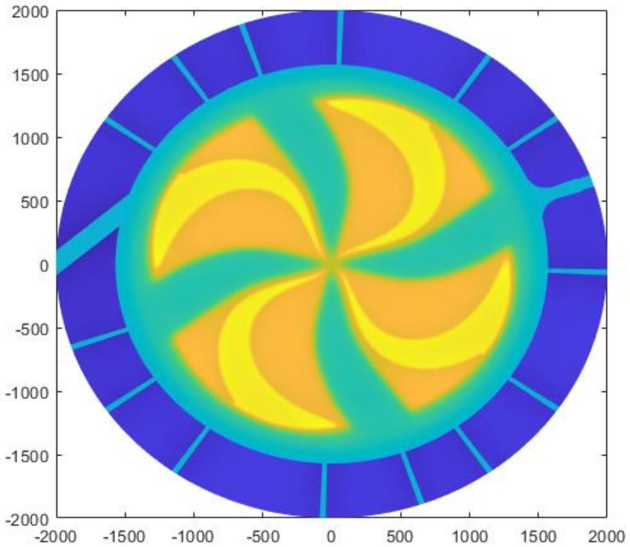


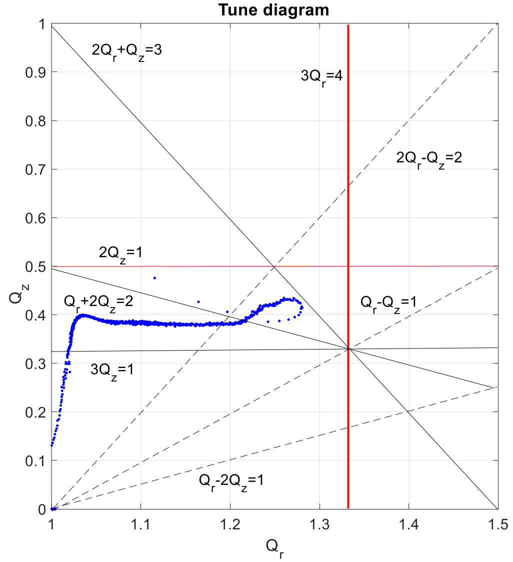
The “flagship” 230 MeV, 4 sectors, harmonic 8 180 MHz. Smaller energy models are going to be derived from the big cyclotron.

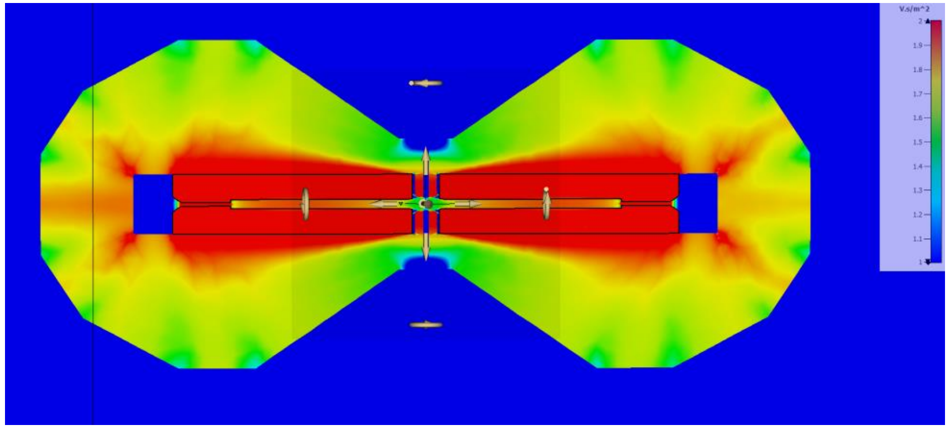


Virtual prototyping.
A single model, that integrates every major system of accelerator, if changes are applied to one of the system, other system automatically adjusted and re-simulated.

Magnet type	**Compact, copper coils**
Number of sectors	4
Material of magnet	Steel 1010
Sector and Valley gap	20/50 mm, 320 mm
Weight of magnet	130 Tonn
Coil type	2x4 double pancakes
Nominal current/total A-turn	1224A, 57kA-turns
Conductor type	$15x25mm^2$
Cooling pressure, water speed	4 bar, 1.95 m/s
Power consumption	80 kW
Water temperature rise	15 degrees

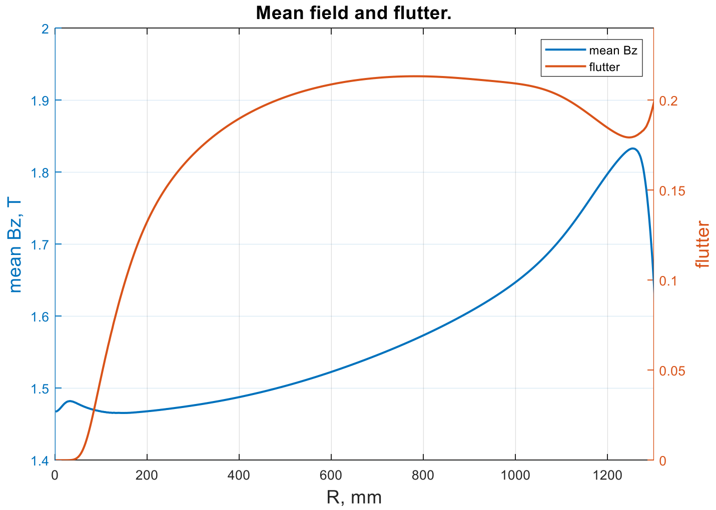


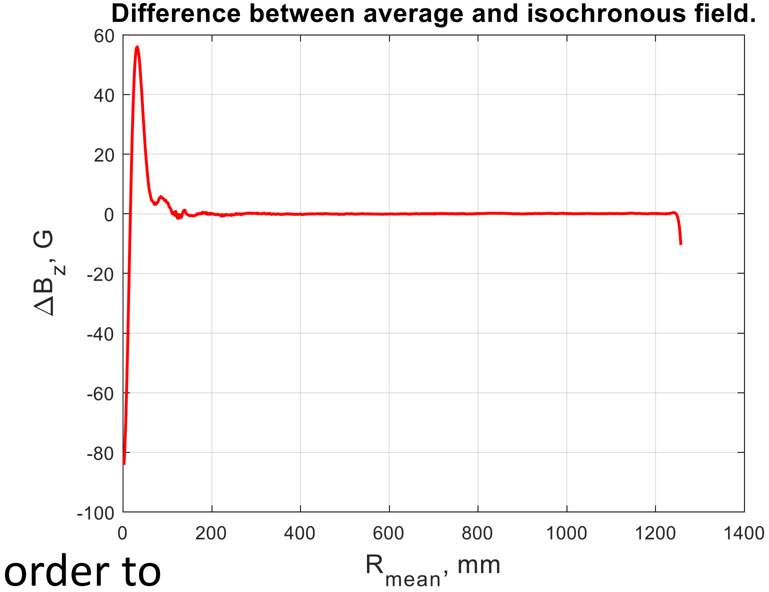




Magnetic field CST simulation

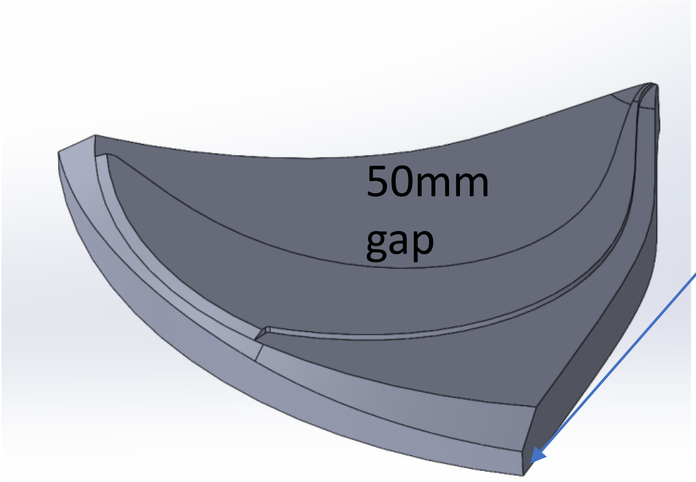
Field in sectors – just over 2.2 Tesla
Field in yoke 1.7-1.8T
Optimal for low A-turns, but not too big yoke

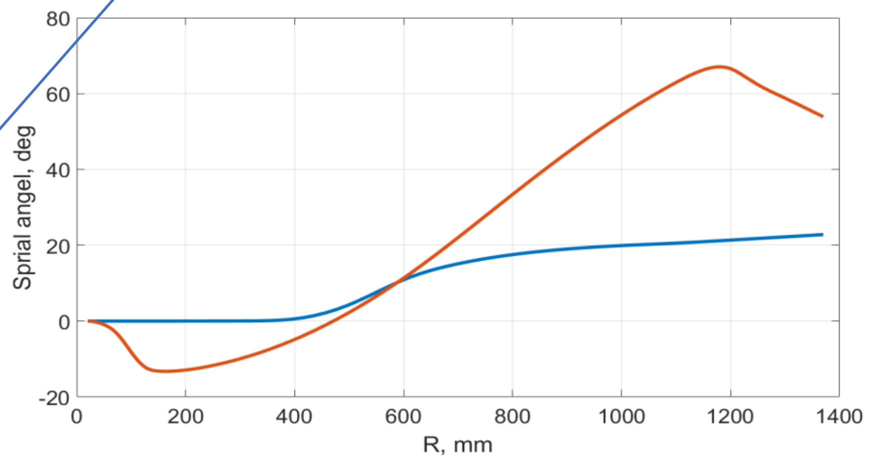




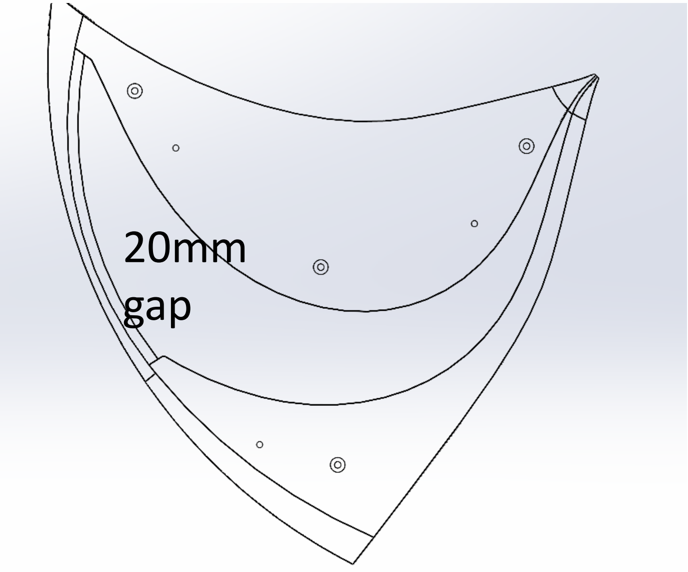
Field isochrononised to +- 0.2 Gauss in order to study small effects in beam dynamics such as phase compression effect

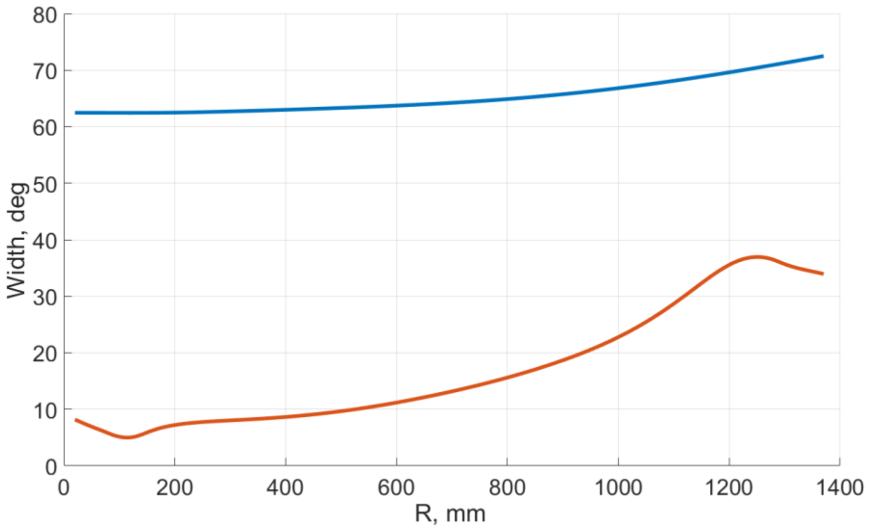
Double gap sector, double spiral, chamfered along beam trajectory





Spiral angle of the sector

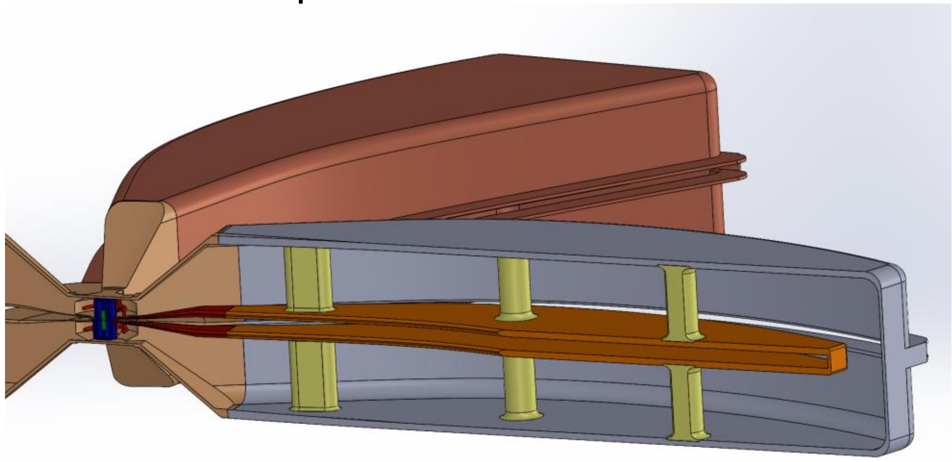


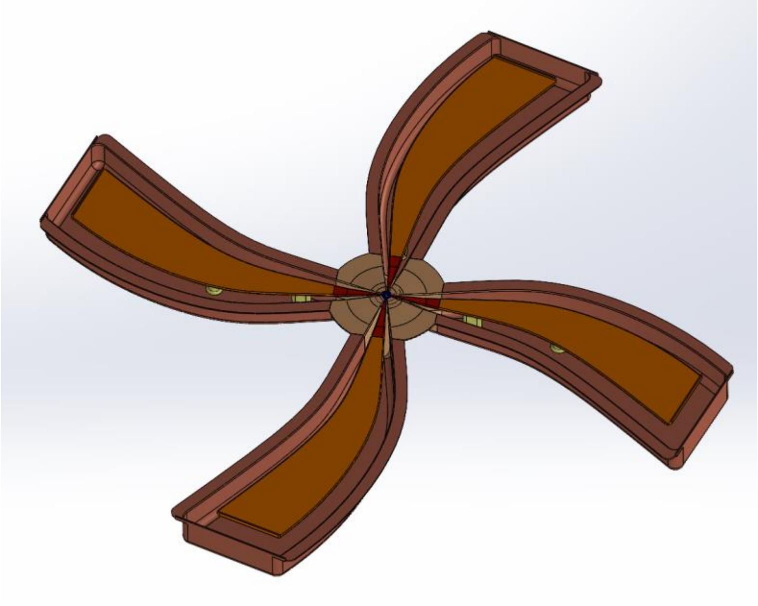


Azimuthal width sector

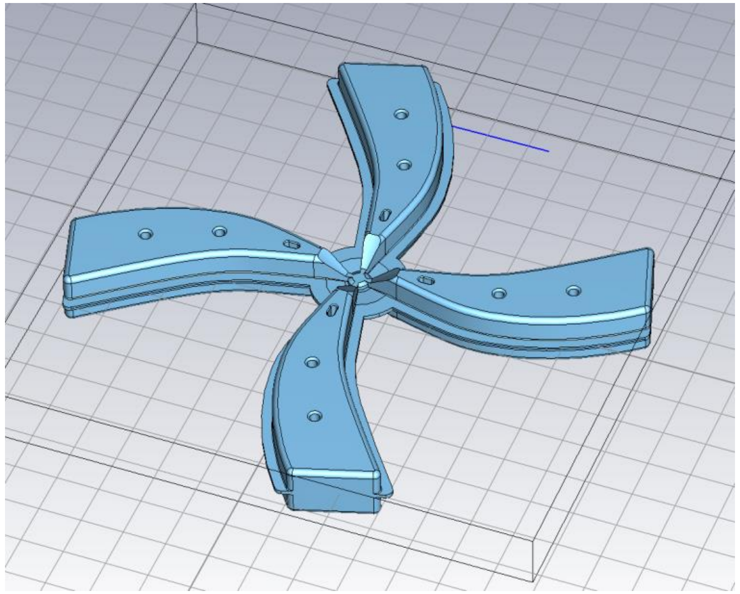
Frequency, MHz	180
Harmonic number	8
Q-factor	11000
Voltage center/extraction, kV	30/160
Power loss	30-50 kW total

vertical plane cross-section

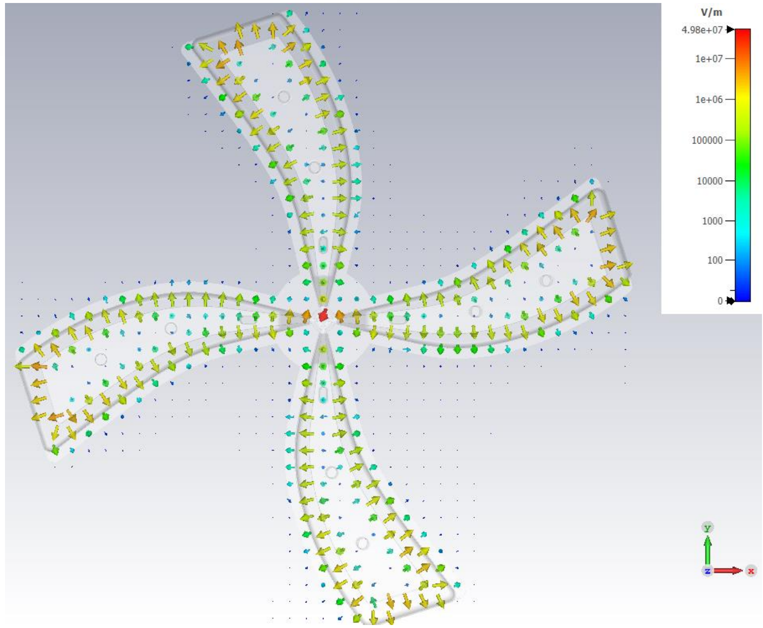




Median plane cross-section



Vacuum or “reversed” model to obtain field map



Solved model

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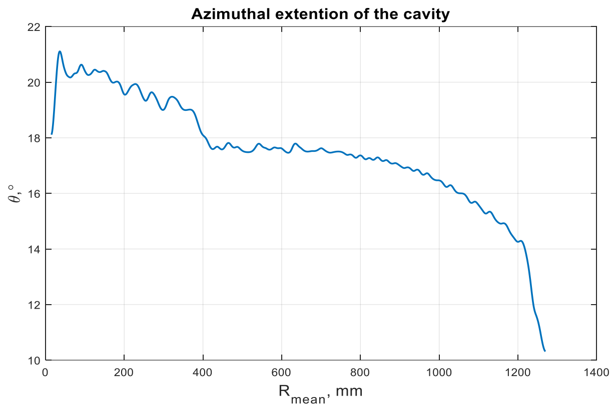
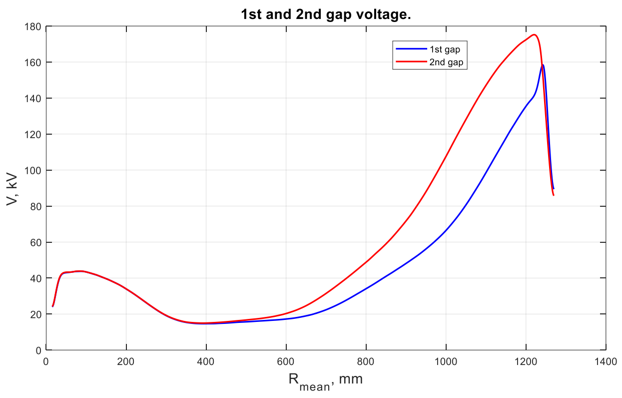
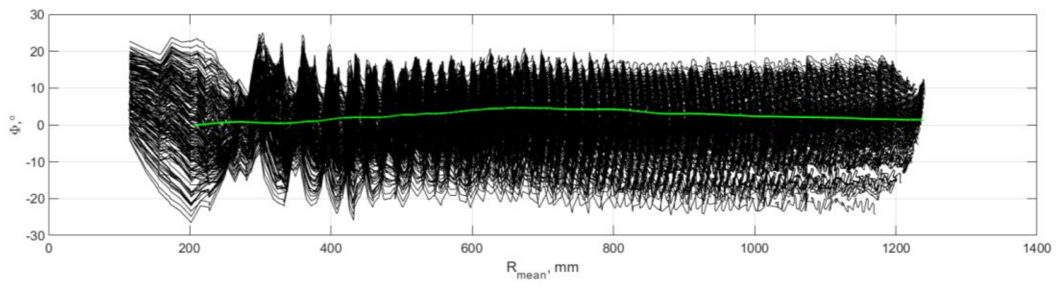


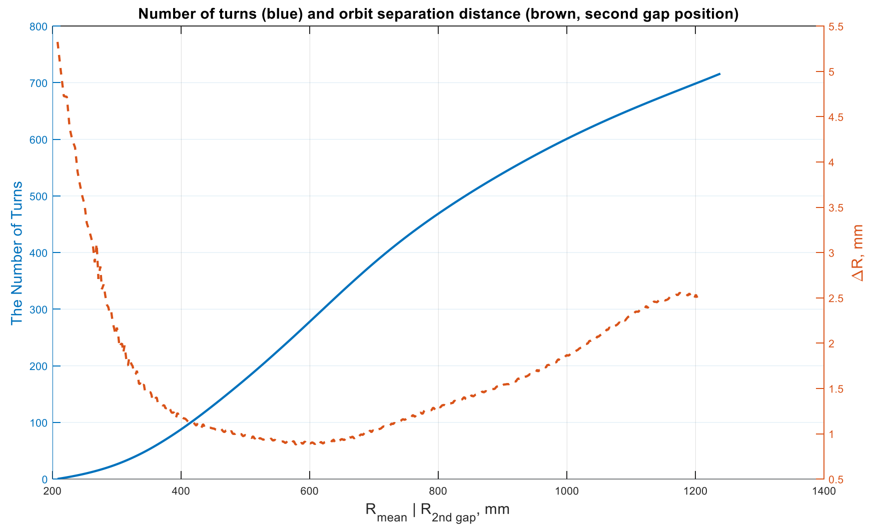


Voltage distribution along radius.

Cyclotron was simulated in CST studio and beam dynamics studies performed. CORD code was used for estimation of the field characteristics. CORD is providing particle dynamics analysis based on a combination of magnetic field map analysis with electric field map analysis.

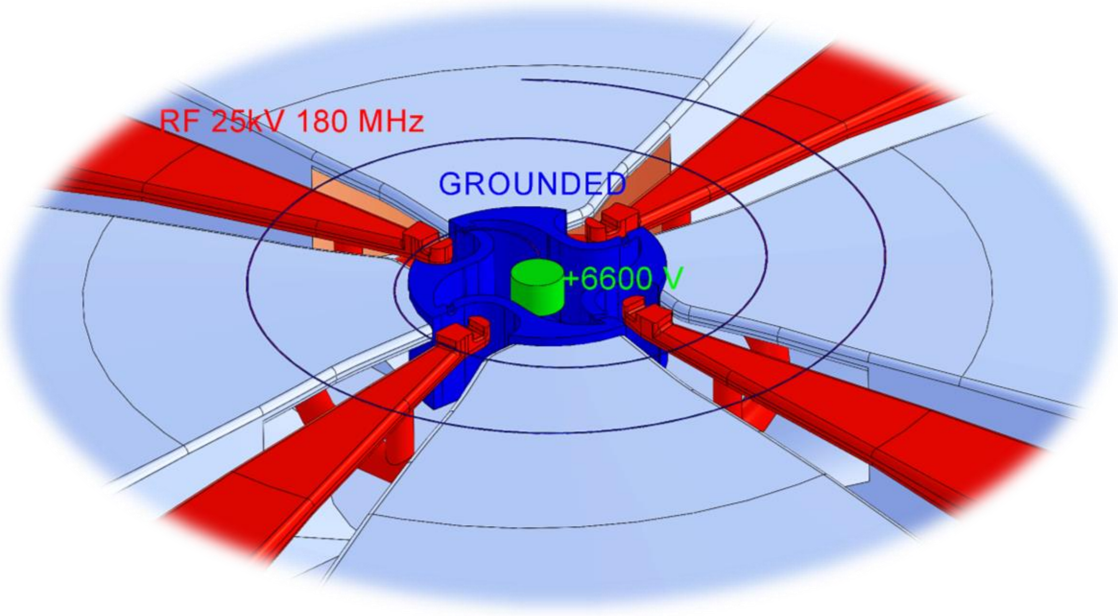


Integral phase slip along the radius. Positive phase corresponds to the lagging particle. Black lines – phase motion of the beam from particle tracking, green line - CORD

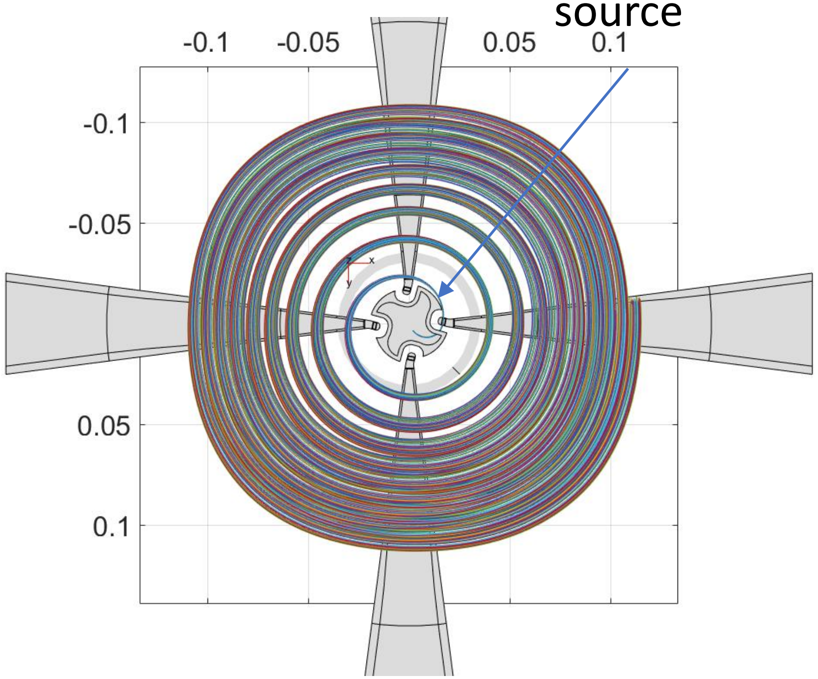


Number of turns (blue solid line) and orbit separation distance (red dash line) in the cyclotron along the radius.

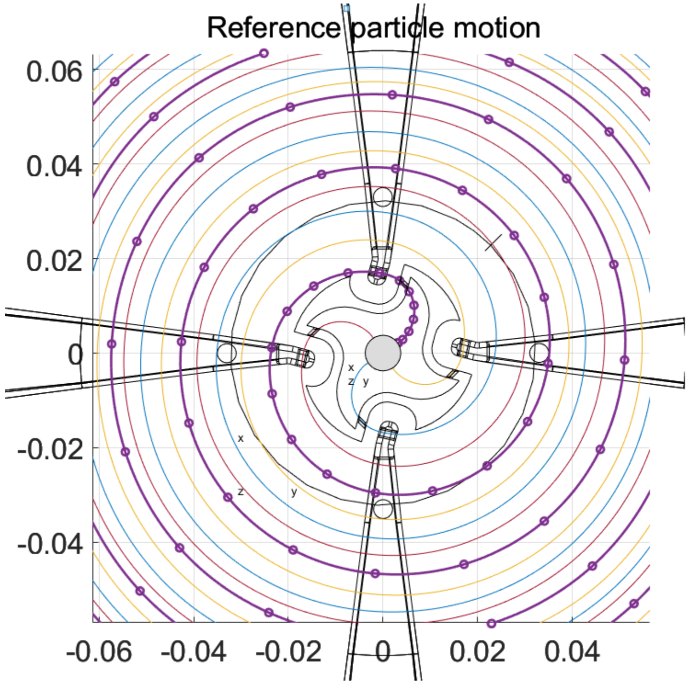
Central region. Is capture an issue for high frequency? – Yes, but there is a solution. If we start from 0 eV, there will be 0 particles captured at 180 MHz, however even small initial speed of 5 keV allows to capture up to 15 deg. External injection is of course an obvious solution but there is an alternative.

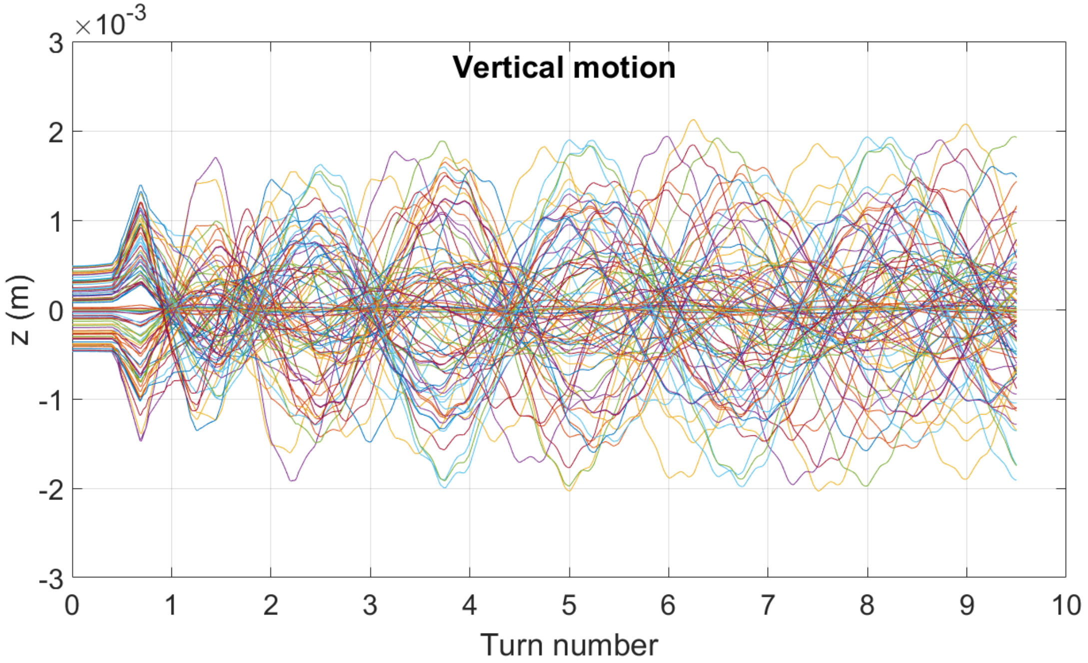


The “Ninja Star” housing of the ion source



4 bunches can be injected simultaneously, due to 4-fold symmetry



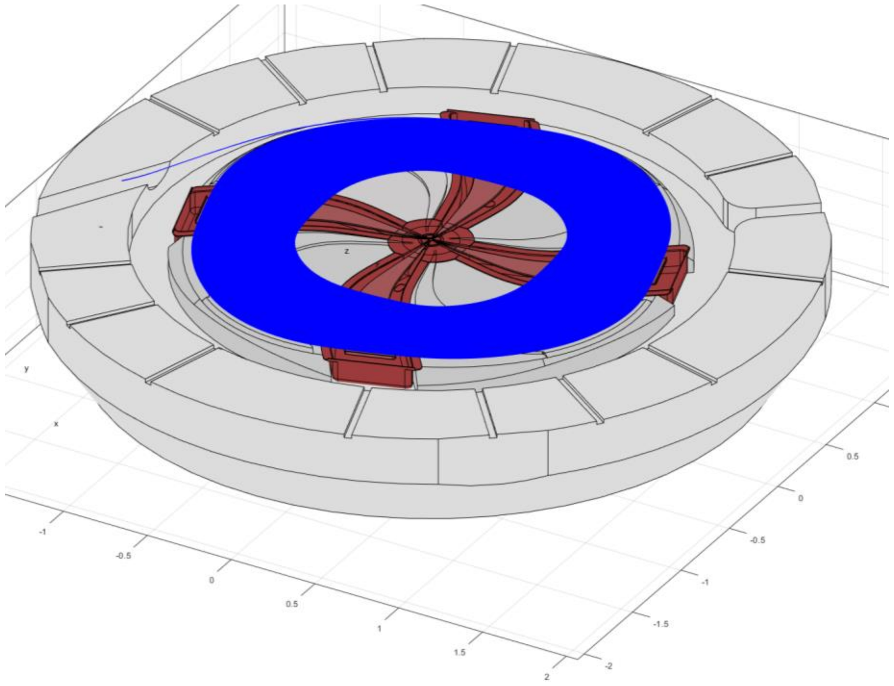


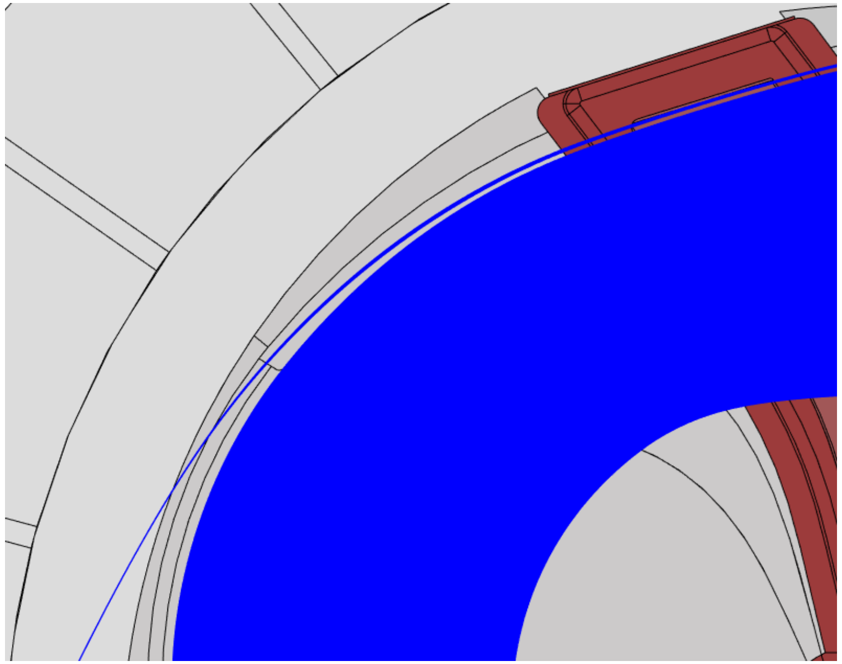
Four trajectories of reference particles are shown. Dots mark every 90 RF degrees

Advantages of the proposed scheme of central region:

- at least 4 times higher current, as 4 bunches captured at the same time
- Much higher capture in each 1st gap due to initial acceleration. In this case from 0 to 15 deg RF.
- Only protons arrive to the RF puller, less erosion of RF parts.
- Improved vacuum in the cyclotron, as ion source is separated from the rest of the chamber by "Ninja star" housing. Additional pump can be used to pump gas from ion source from the inside of the Ninja star.

Of course, 8 harmonic acceleration is not an ideal option for truly high power cyclotron, however such design if used with 4th harmonic acceleration, especially with even higher voltage on the source can lead to 10mA currents and higher.



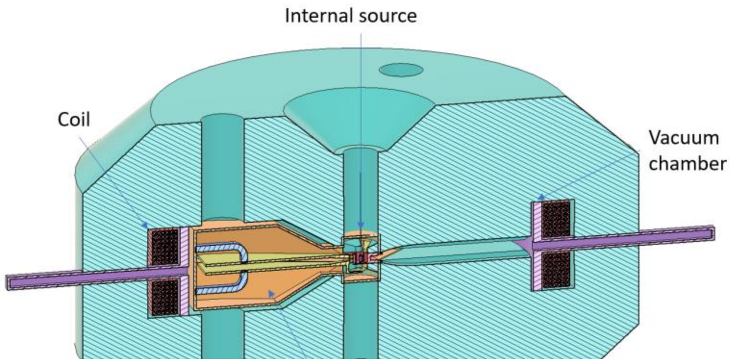


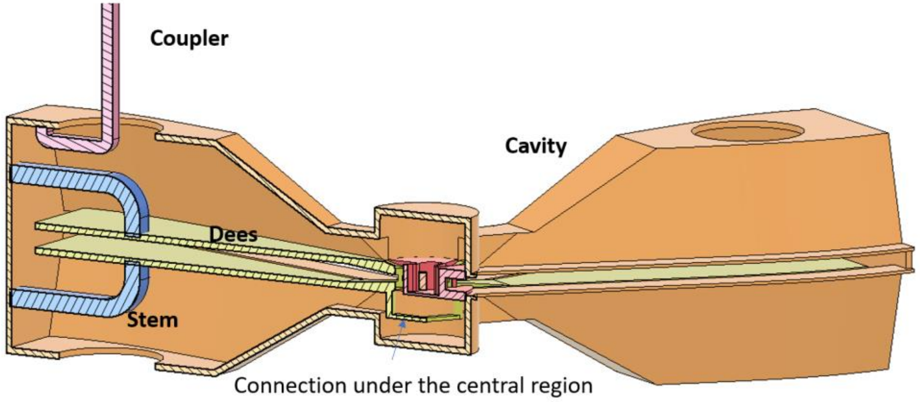
The beam extraction for this machine will be carried out by means of 1 electrostatic deflector (ESD), located between the sectors, and 2 passive focusing magnetic channels (MC1 and MC2). We restricted electric field in deflector by the value of 80 kV/cm.

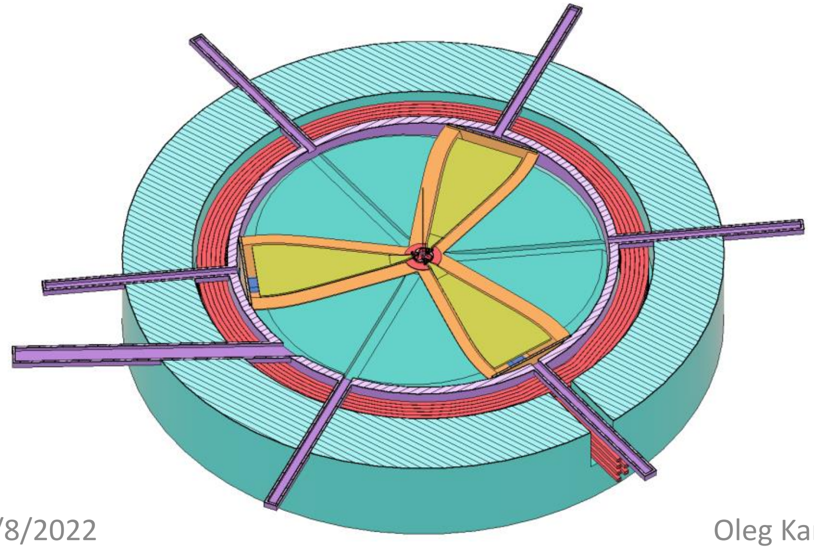
The beam, after being pulled with the deflector, passes through the accelerating RF-cavities and magnetic channels. Passive magnetic channels are located inside sector’s gap, the first one decreases the average magnetic field for 1500 Gs and provides gradient of 1000 Gs/cm, the second one only provides a gradient of 1000 Gs/cm.

This extraction scheme is presented as a proof-of-concept, author is currently analyzing alternative scheme.

First example: 15 MeV, 3 sectors, harmonic 6 145 MHz 4 sector design and harmonic 8 180 Mhz is under development







Magnet type	Electromagnet with resistive coil
Ion source	Internal/External
Final energy MeV	15
Final radius, mm	360
Mean magn. field, T	1.55
Dimentions (h×d), mm	750 × 1290
Weight, kg	5500
Hill/Valley field, T	2.2/0.4
Hill/Valley gap,mm	+- 25/210
A*Turn number	27 000
Magnet power consumption, kW	25
RF freq., MHz	145
Harmonic number	6
Voltage, kV	30-50
RF power, kW	8
Turn number	120
Beam intensity, µA	Up to 1000
Extraction type	stripping foil

Conclusion:

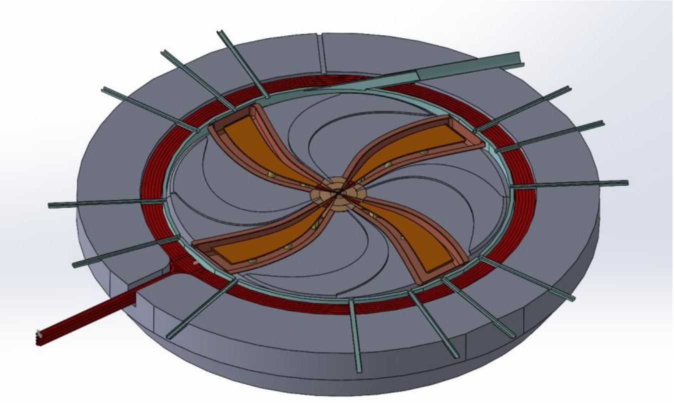
New concept of cyclotrons for medical application has been developed.

The advantages of the concept are:

- Compact but non-superconducting, thus cheaper.
- All cyclotrons in the line from 15 to 230 MeV will share same RF frequency, making many parts identical along the whole line
- The design is simple and robust, no extreme solutions, moderate currents, power, voltages on deflector etc.

Looking for partnership to advance from virtual

Prototyping to real prototypes!



One more thing.

You might have an impression that I don’t like superconductivity.

I just don’t like liquid helium temperatures.

The problem of HTS – can’t work at high temperatures

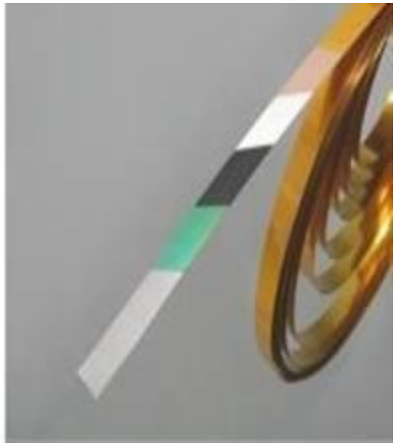
At magnetic field.

But! If magnetic field on the coil is low, then HIGH

Temperature superconductor can be used at >70K

Which would significantly reduce power

Consumption and cost of cryogenics.



YBCO HTS tape

Thank you for attention!

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