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A COUPLED CYCLOTRON SOLUTION FOR CARBON IONS ACCELERATION

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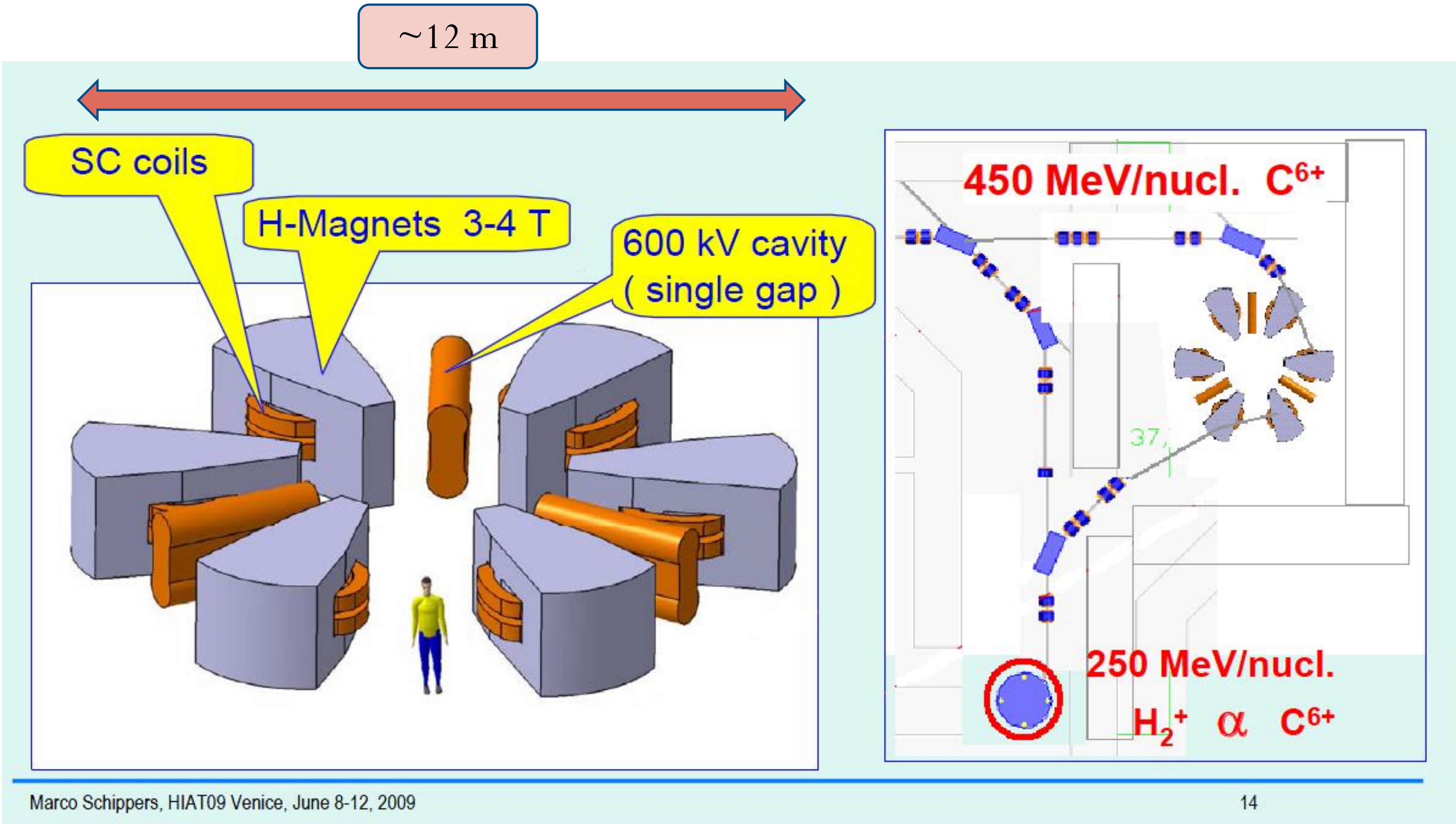
Background & Motivation

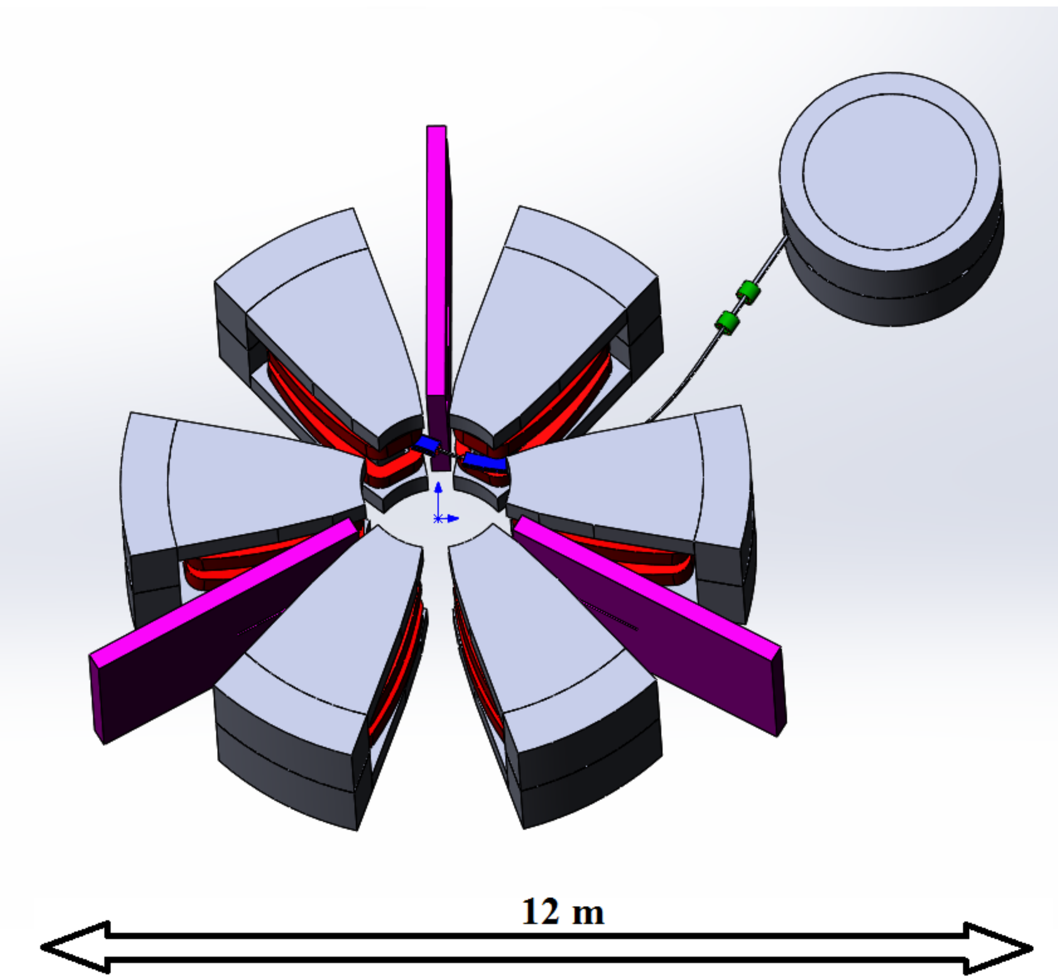
Carbon therapy facilities (Energy ~400 MeV/u)

- Synchrotrons:
  - HIT (Heidelberg, Germany), E_f=430 MeV/u, L_{max}(+injector)≈40m
  - CNAO (Pavia, Italy), E_f=400 MeV/u , L_{max} (+injector) ≈24m
  - HIMM (IMP, China), E_f=400 MeV/u , L_{max} (+injector) ≈27m
  - …
- Cyclotrons:
  - C400 (IBA-JINR), E_f=400 MeV/u, L_{max}≈7m
- FFAG:
  - Pamela (Oxford, UK), E_f=400 MeV/u, L_{max} (+injector) ≈25m
  - FFAG (NIRS, Japan), E_f=400 MeV/u , L_{max}≈23m

SSC (PSI, Switzerland), 450 MeV/u

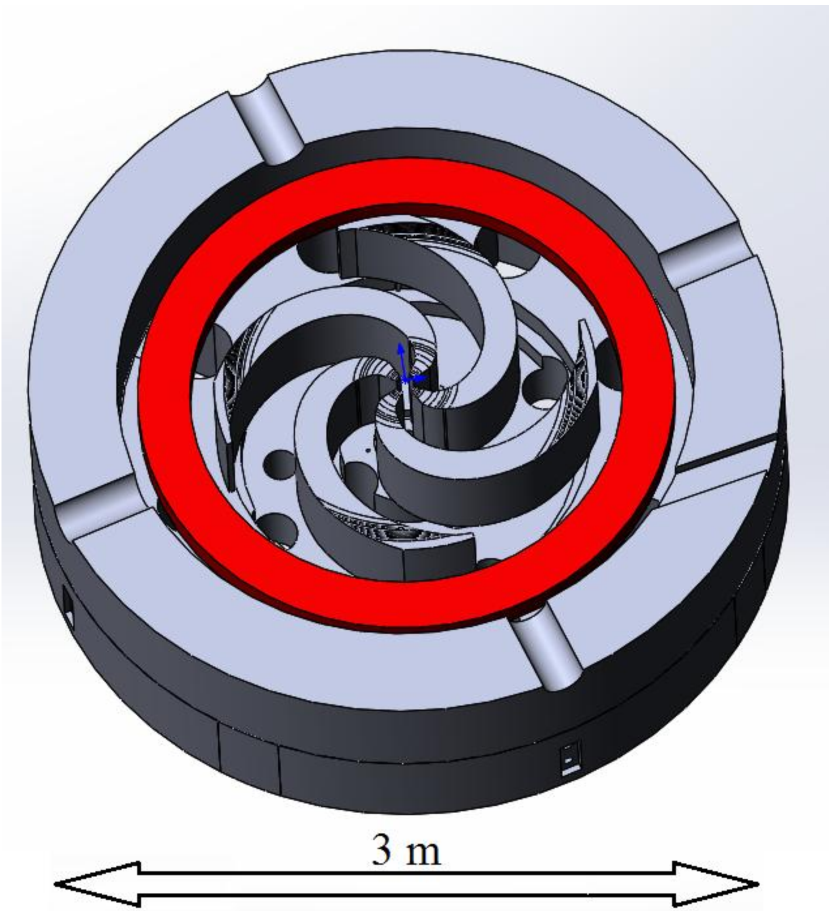


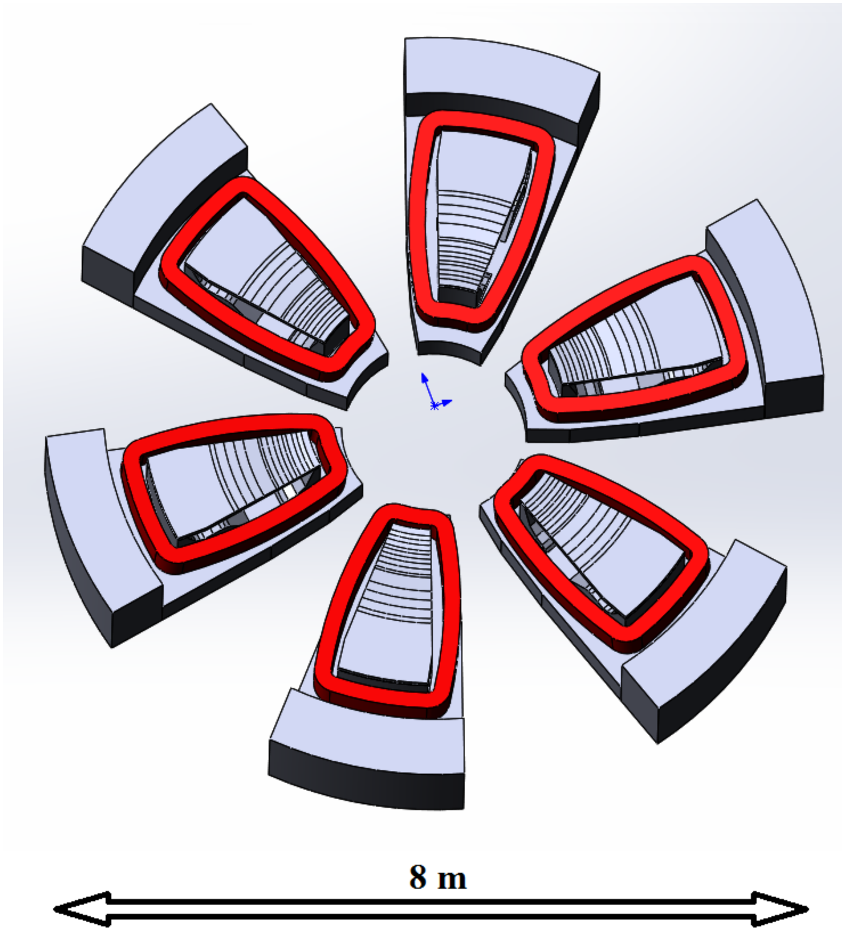
Acceleration complex ($^{12}C^{6+}$, 400 MeV/u.)



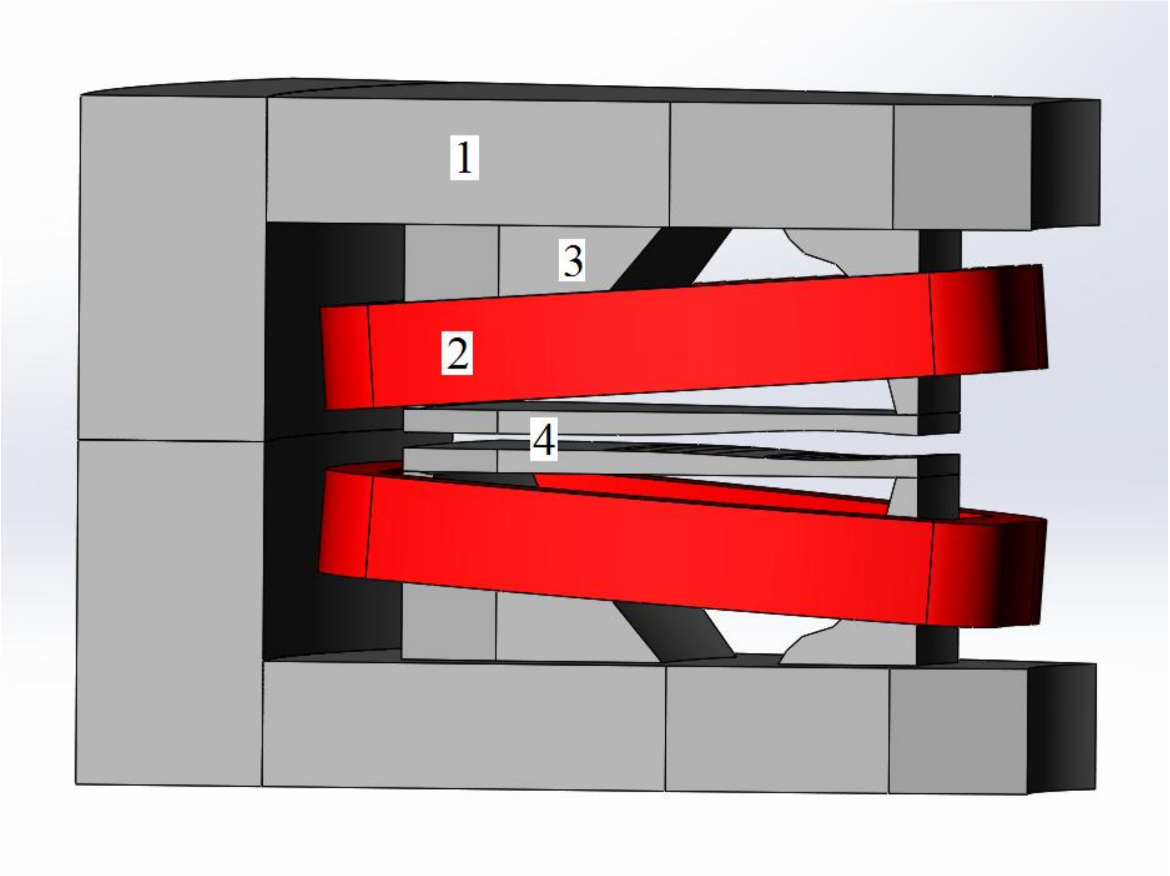
Parameter of the booster	Value
Ion type	$^{12}C^{6+}$
Number of sectors	6
RF frequency	73.56 MHz
RF mode	6
RF system	3×200 kV
Average magnetic field: injection/extraction	1.64 T/2.11 T
Maximal magnetic field: injection/extraction	4.22 T/6.40 T
Injection energy	70 MeV/u
Extraction energy	400 MeV/u
Injection radius	143 cm
Extraction radius	278 cm
Air gap between sectors	88-135 mm
Dimensions: diameter × height	8 m × 2.2 m
Total weight (sectors + coils)	310 t

Cyclotron-injector (B_0=2.4 T, Weight 90 t, E_f=70 MeV/u, Ions $^{12}C^{6+}$, H_2^+) & Booster





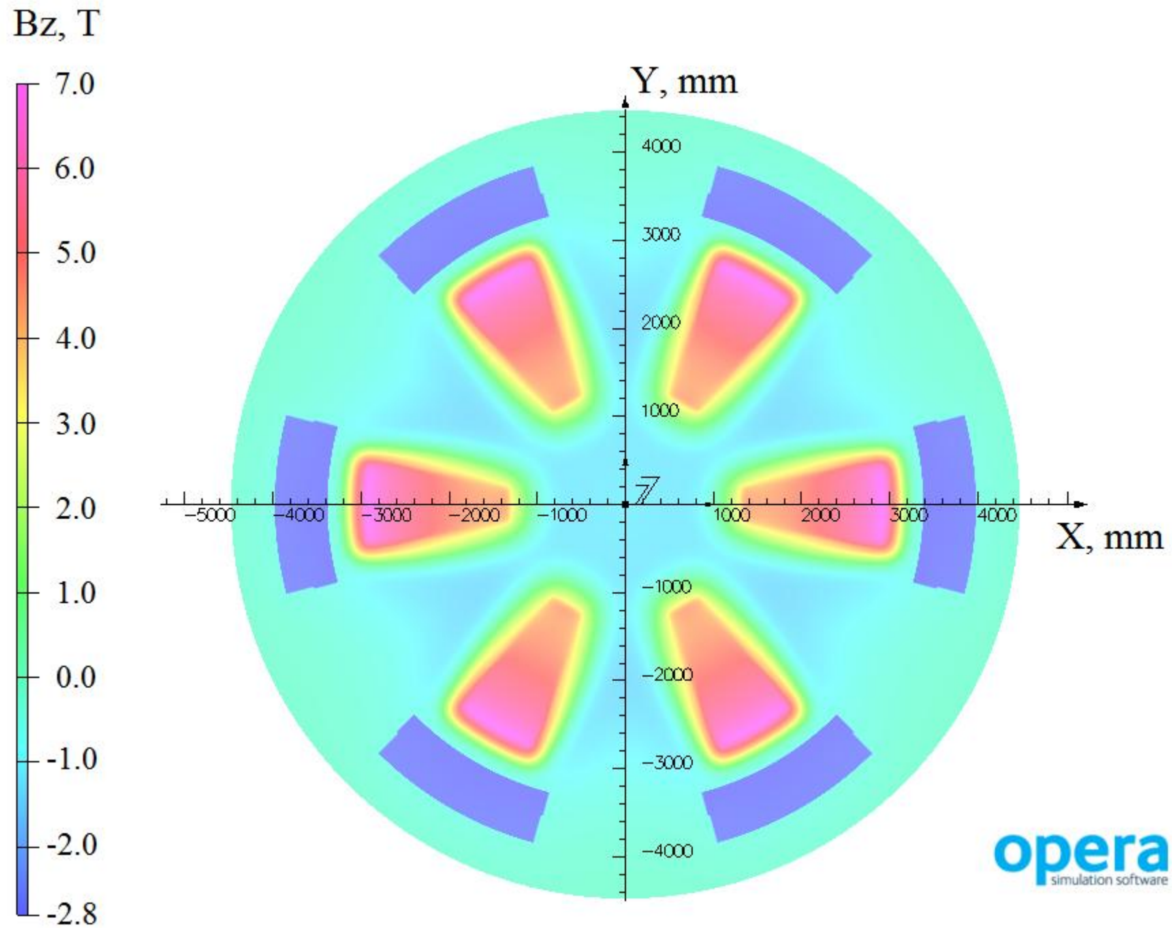
Sector magnet parameters:
yoke (1) length ×width×height: 3.1×2.0×2.2 m
weight 50 t, coil (2) engineering current density 62 A/mm^2, coil cross section 170×330 mm^2, axial angle between upper and lower coils 8 degrees. The pole (3) and pole tip (4) have axial profile.



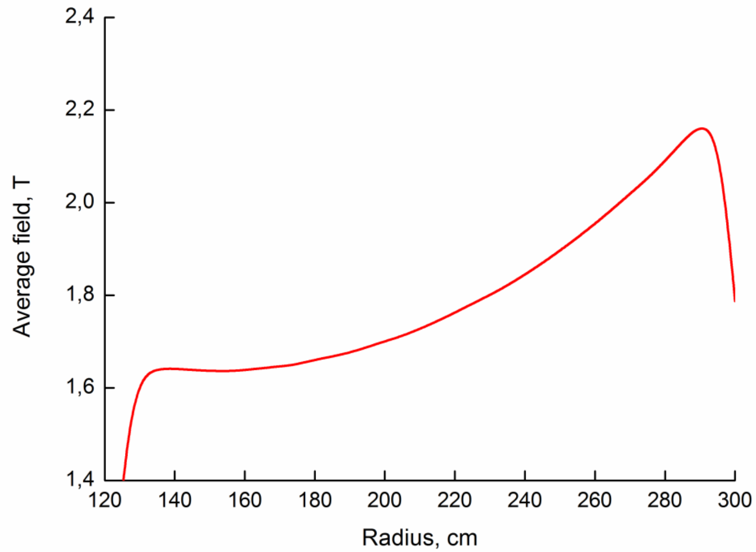
Magnetic field value:

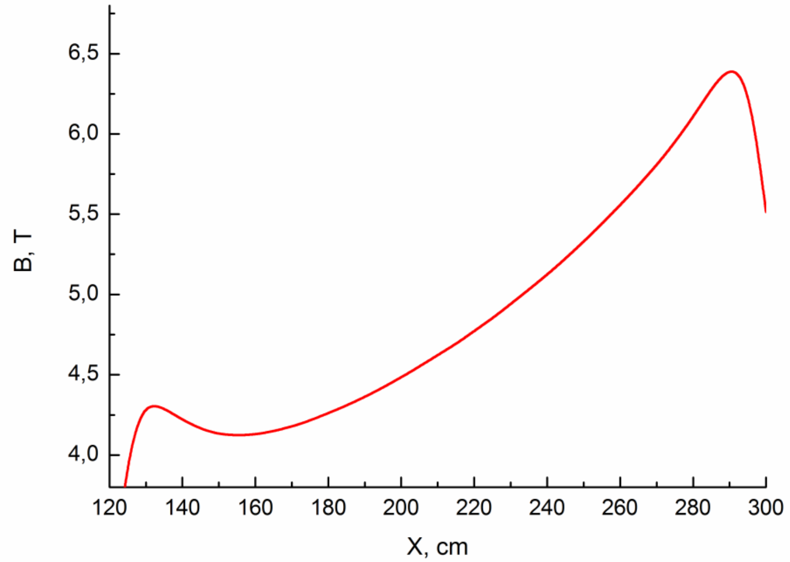
Center: -1.1 T; Hill: 7 T; Valley: -1.3 T;

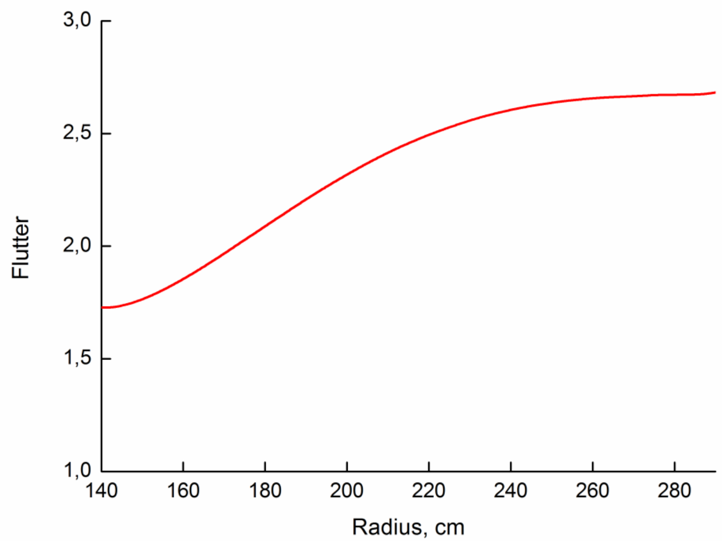
Yoke: -2.7 T; Coil: 7.2 T.



Average magnetic field, sector field and flutter

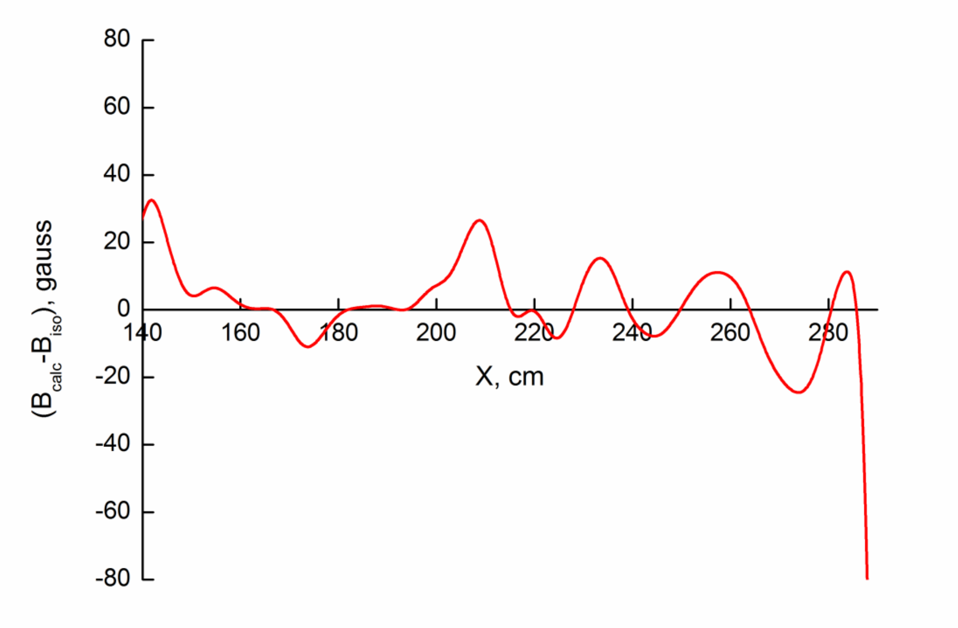


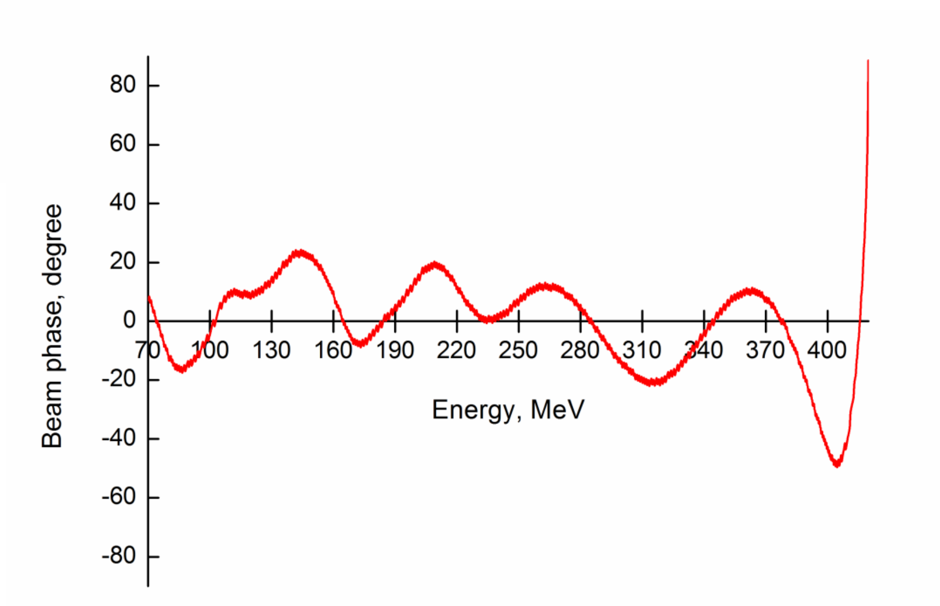




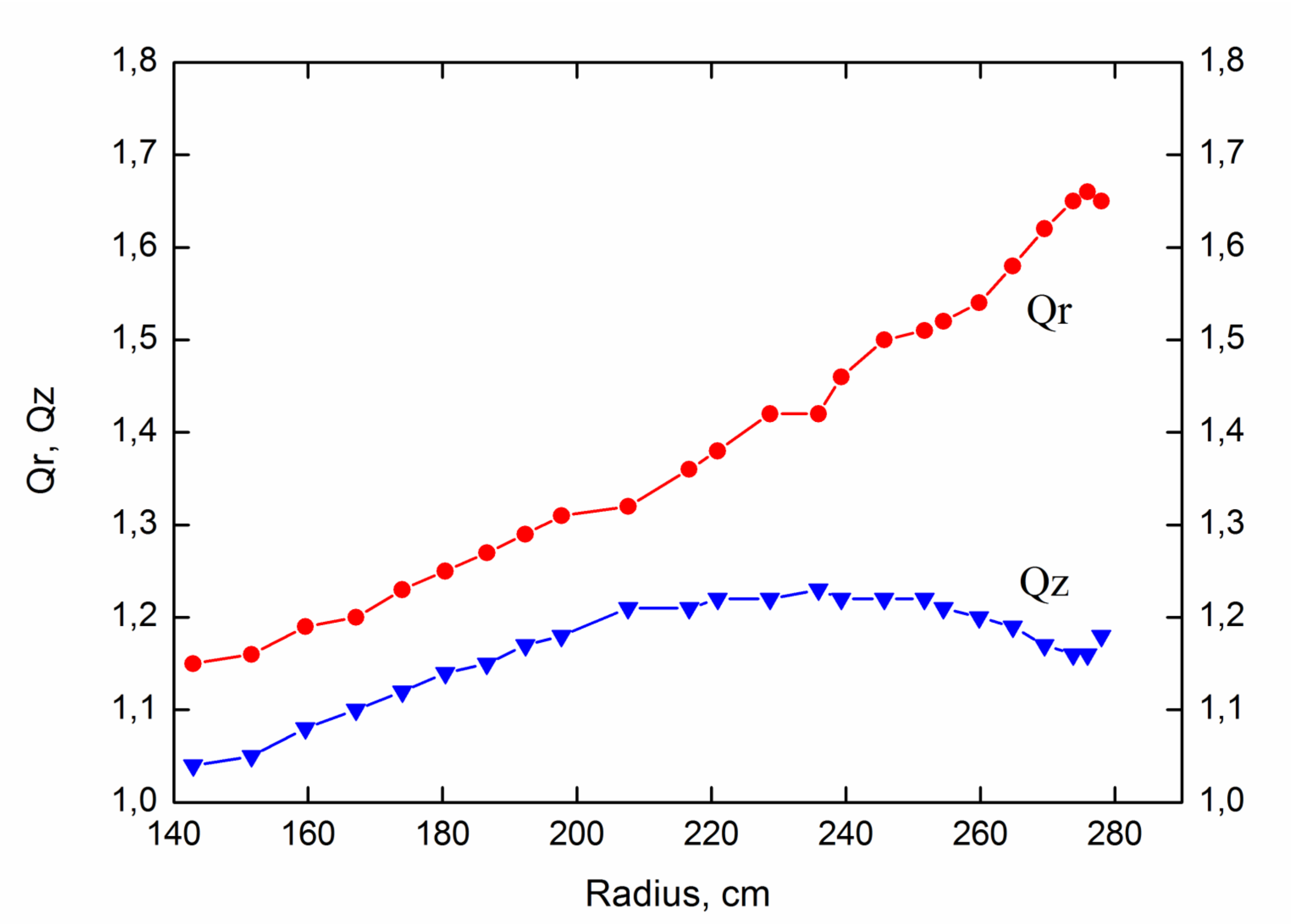
Deviation of the sector field from isochronous one (upper plot). Beam RF phase (lower)

$N_{turns} \approx 1200$ (3 gaps with 200 kV)

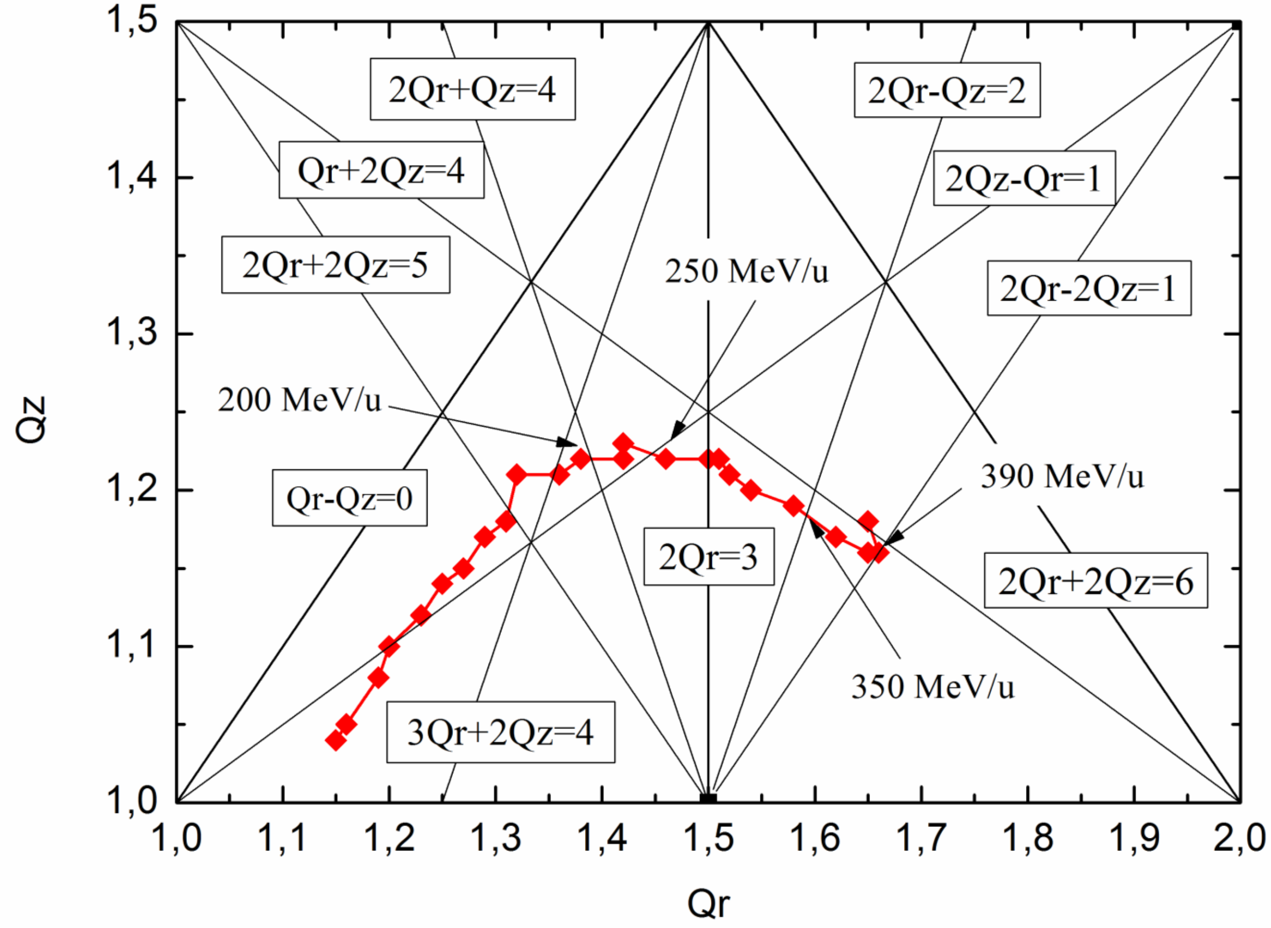




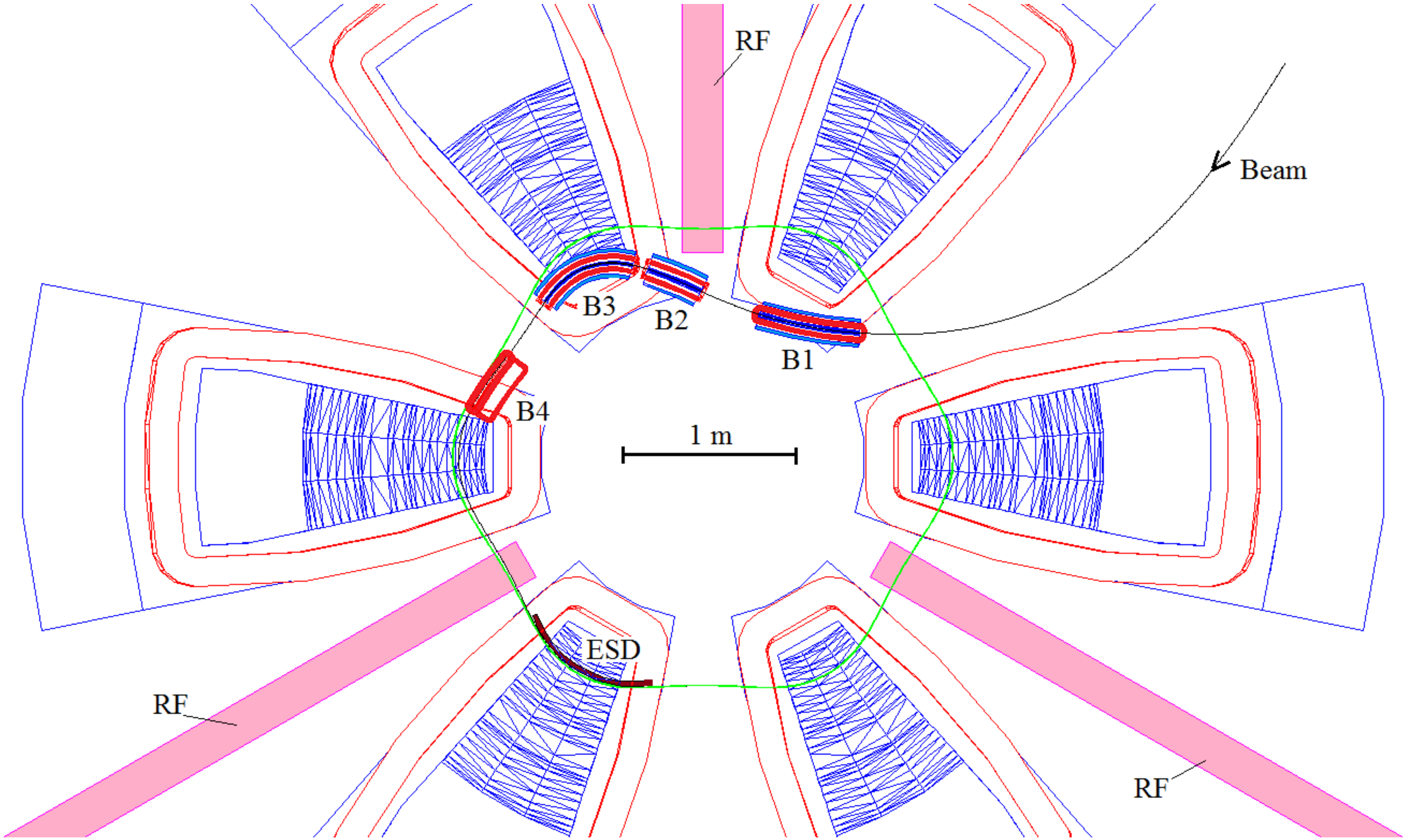
Betatron frequencies (by tracing)



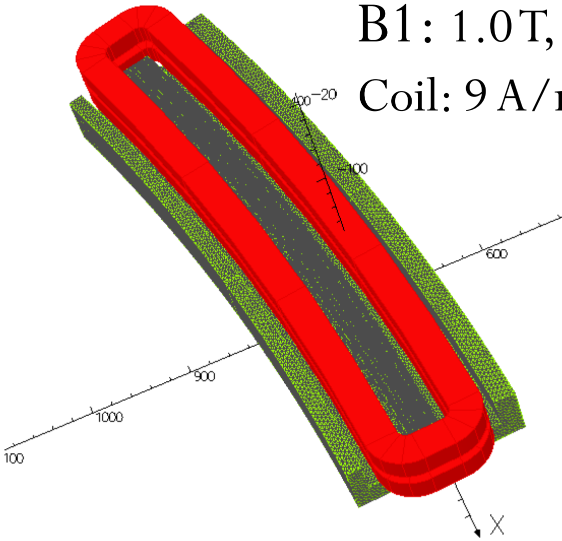
Tune diagram



Injection system:

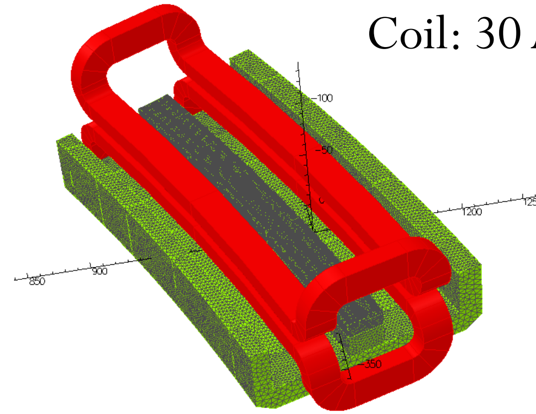


Magnetic dipoles of injection system



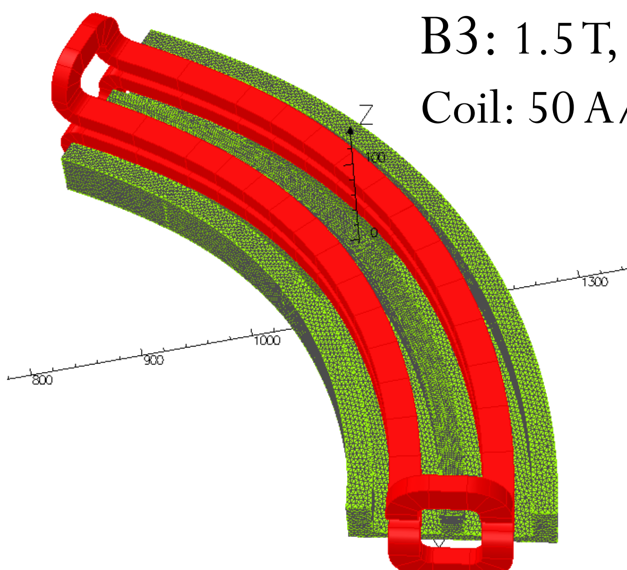
B1: 1.0 T, 5 T/m

Coil: 9 A/mm^2



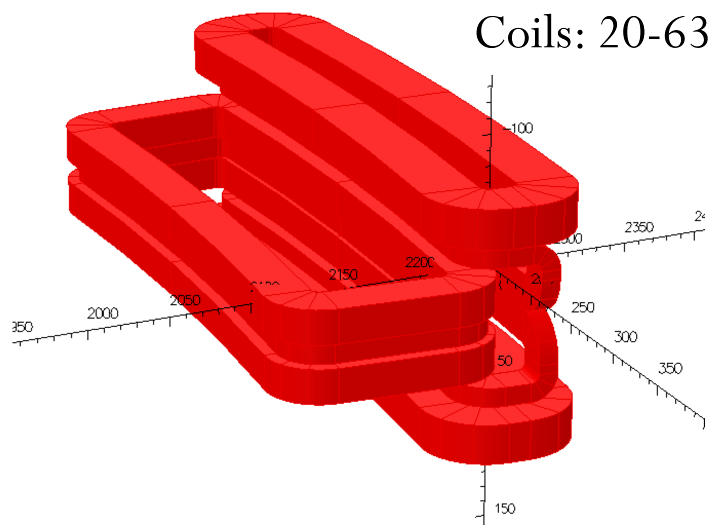
B2: 1.4 T, 4 T/m

Coil: 30 A/mm^2



B3: 1.5 T, 5 T/m

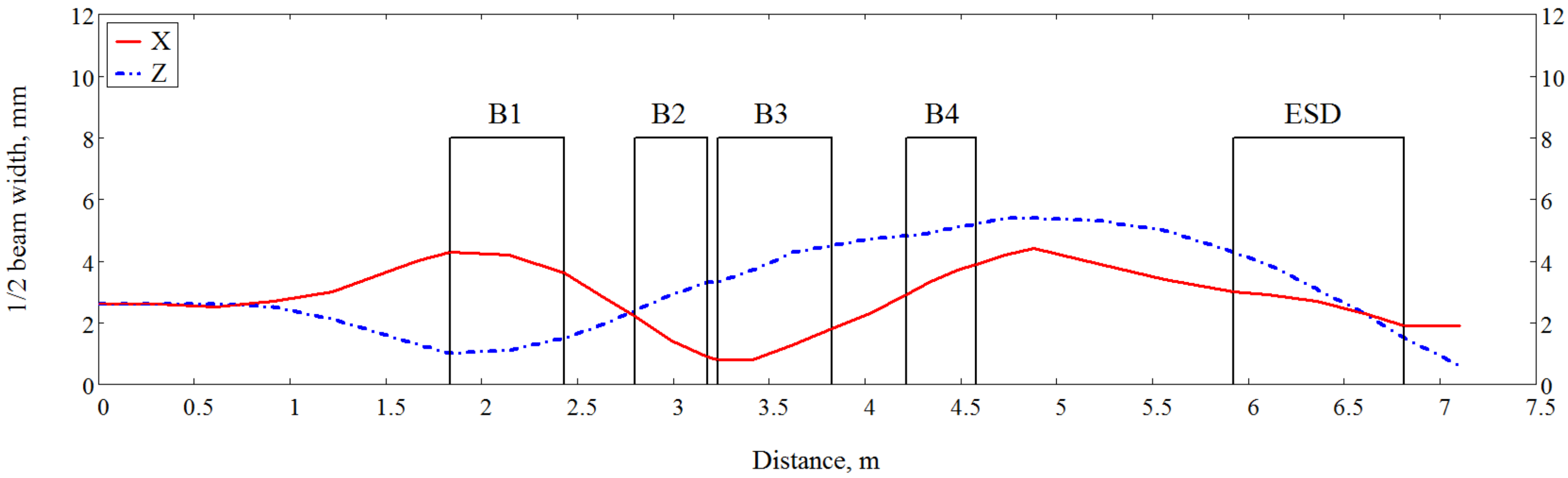
Coil: 50 A/mm^2



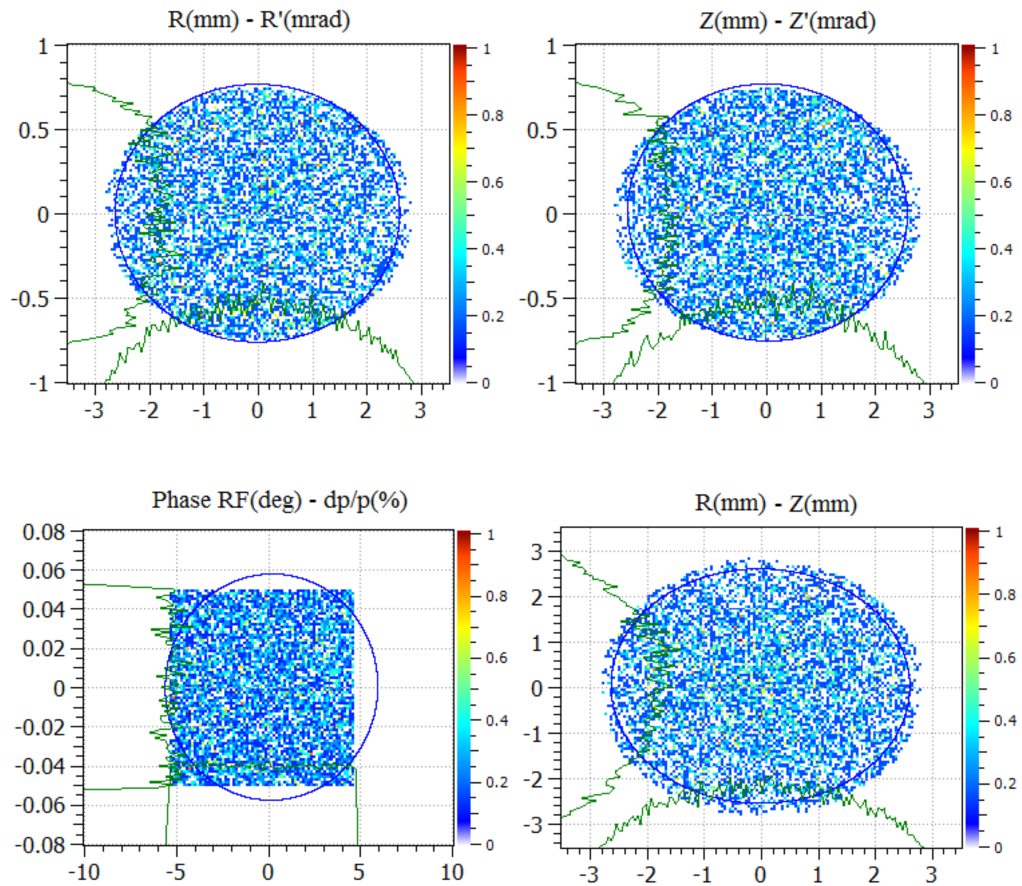
B4: 0.8 T, 3 T/m

Coils: 20-63 A/mm^2

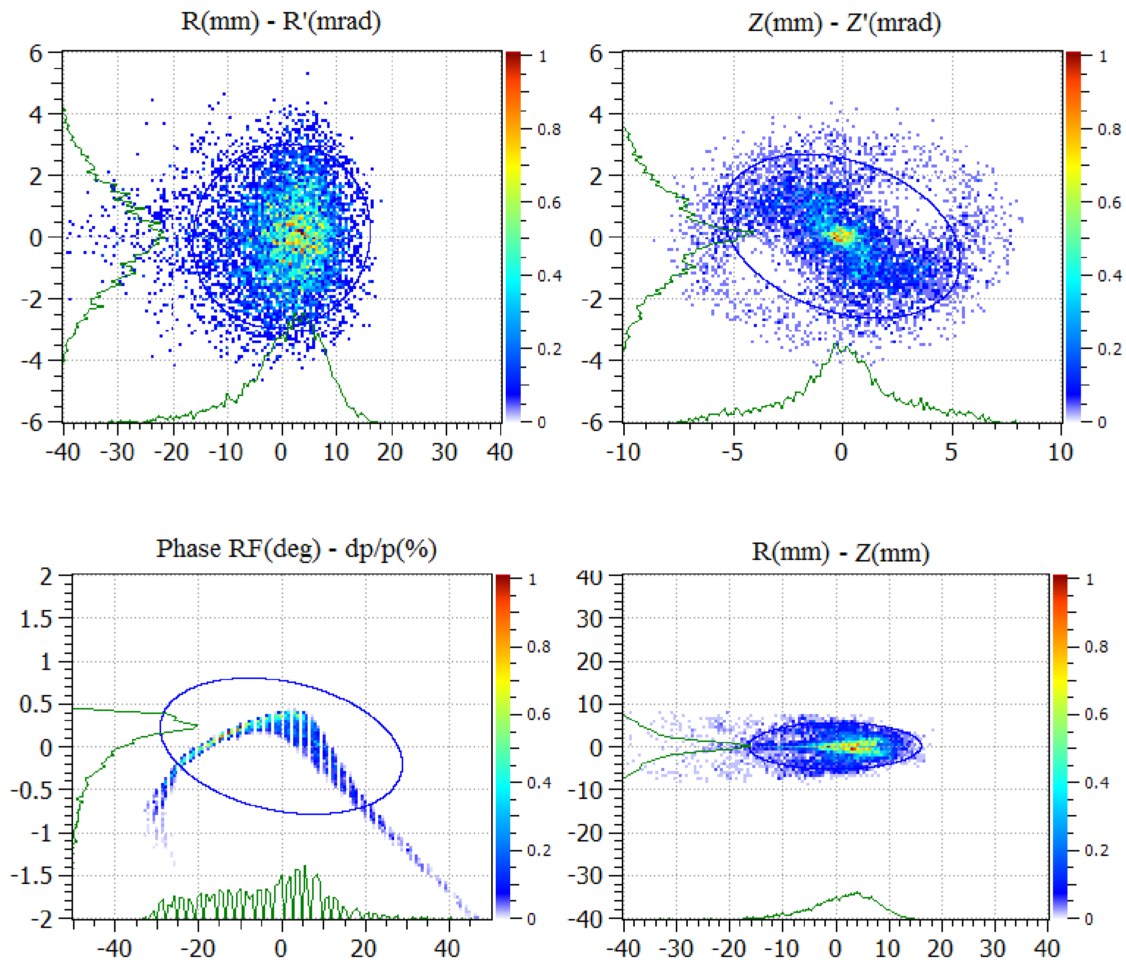
Beam envelopes during injection



It’s needed to have very good beam from injector (εx, $\varepsilon z \leq 2\ \pi \cdot$mm$\cdot$mrad, dE $\leq$0.1%)



Beam emittances at the final radius ($E_{average}$ = 405 MeV/u)



Summary

- Design of the main cyclotron magnet and its injection system was attempted
  - 3D programs for magnetic fields calculation and particle tracing were used
- As an injector, a SC compact cyclotron can be used
  - Such the machine is feasible, and there are examples of the operating cyclotrons (Varian 250 MeV, the same magnetic rigidity)
- Beam dynamics was studied
  - Beam transmission from injection entrance to the final radius was 85% (particles losses on the ESD septum)

Notes & Plans

- Some critical points of this project:
  - High coil current density of the main magnet (62 A/mm^2 with field value 7.2 T in the coil)
  - Difficult assembly of the magnetic dipoles of the injection system (high coil current density & few space for cryostat)
  - Strict requirements for the beam quality from injector (εx, $\varepsilon z \leq 2\ \pi \cdot$mm$\cdot$mrad, dE $\leq$0.2%)
- Next steps:
  - Accelerating system design
  - Extraction system development
  - Coil forces analysis
  - Cyclotron-injector design
  - Study of the resonances crossing
  - …

Thank you for your attention…