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Comparison of Superconducting 230 MeV/u Synchro- and Isochronous Cyclotron Designs for Therapy with Cyclinacs

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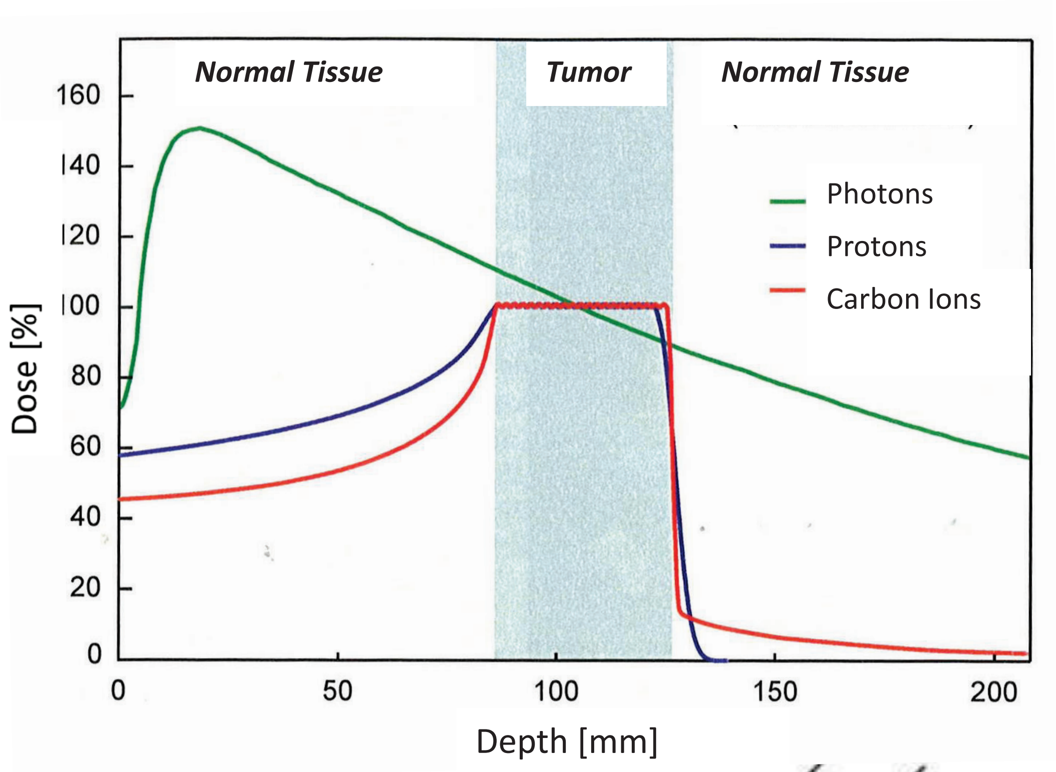
- Disclaimer: the precise references of all figures and tables presented are listed in EPFL PhD Thesis 5156 (2011).

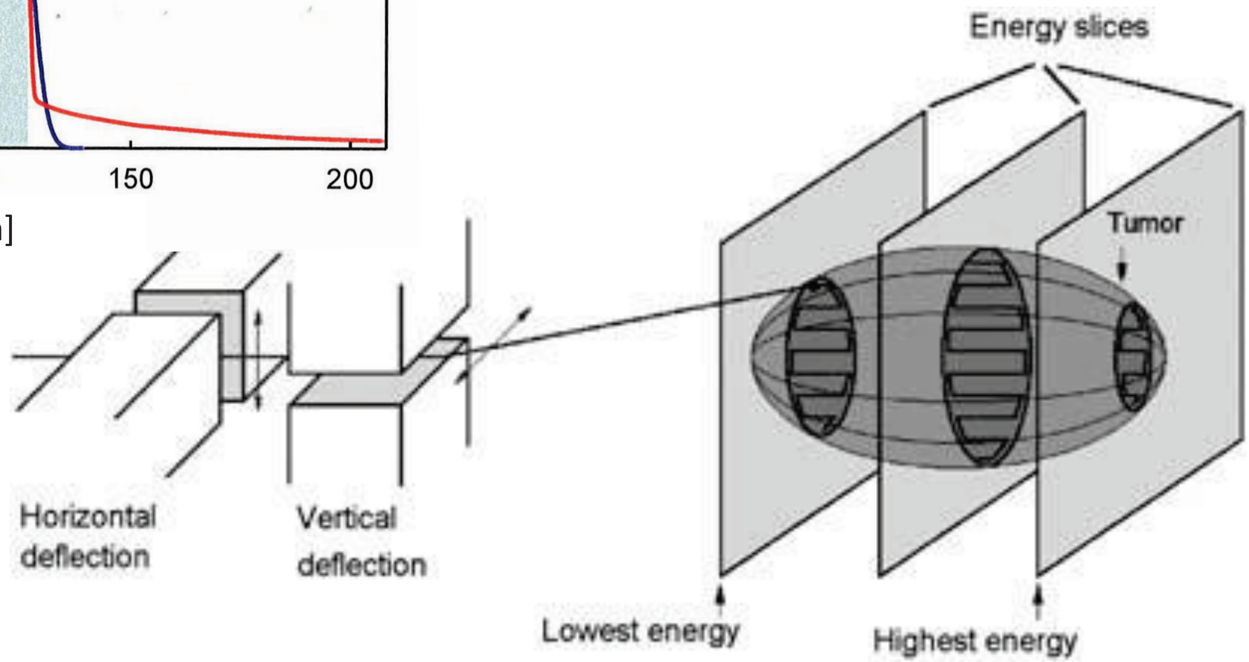
Ion beam therapy development is linked to accelerators



- Protons and Carbon ions are effective in treatment of **deep-seated tumors**

but

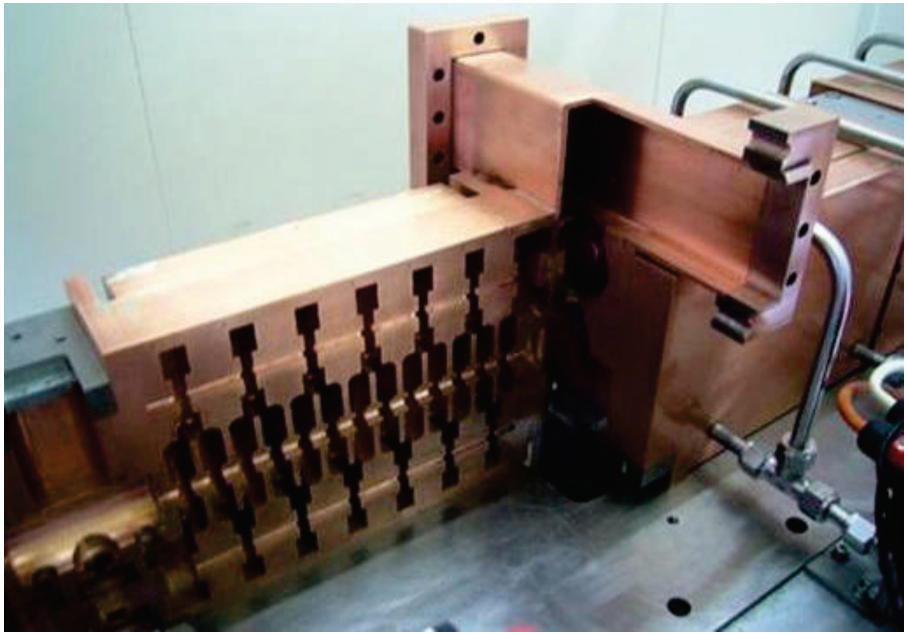
require **advanced accelerators** (230 MeV, 400 MeV/u for 27 cm in water)



- Modern challenge: treatment of **moving organs**

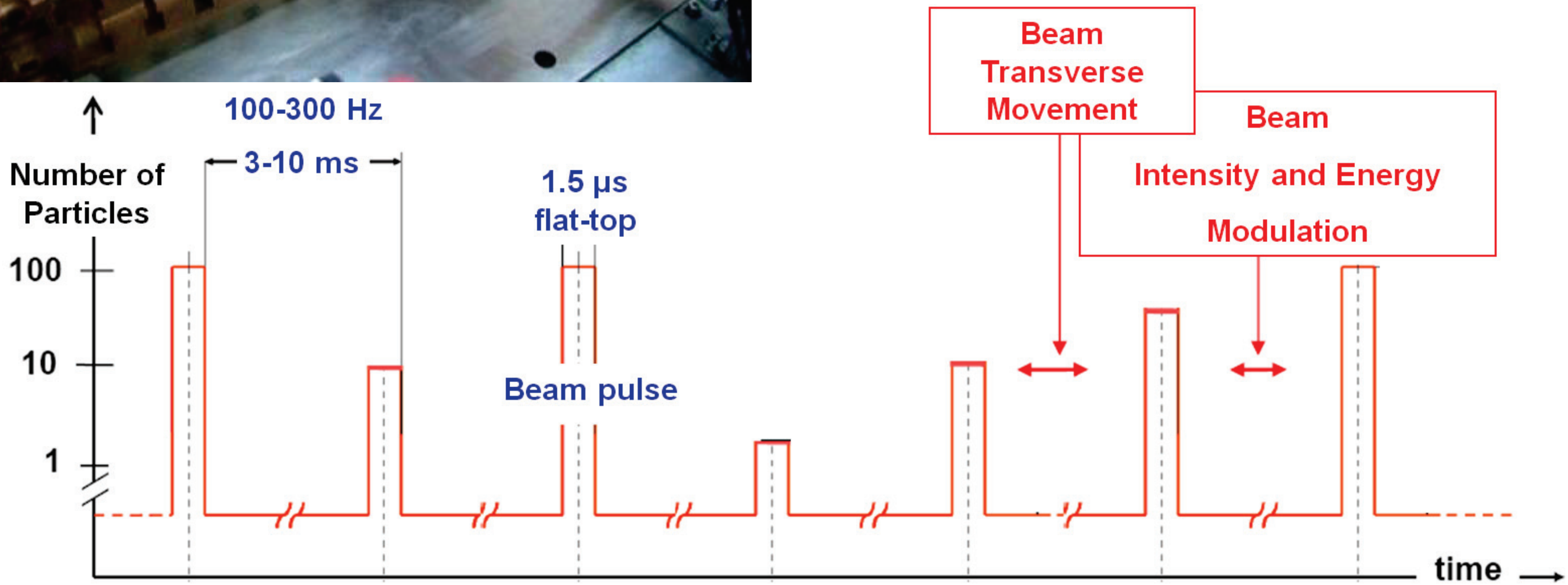
- **stable** beam currents and **fast scanning**

Linacs are interesting future candidates



Linac module prototype (TERA)

- high-frequency, high-gradient **Carbon Booster for Therapy in Oncology (CABOTO) :** C^{6+}/H_2^+ beams up to **400 MeV/u**



AIM OF STUDY

new superconducting compact (as opposed to separated-sector) **cyclotron designs**, delivering C^{6+}/H_2^+ beams for **injection in CABOTO**

comparative study of synchrocyclotron (SC) and isochronous cyclotron (IC) at **230 MeV/u**

2-phase center:

1) protontherapy of deep-seated tumors with cyclotron+degrader
2) carbon ion therapy of deep-seated tumors with cyclotron+linac

Same design methods and constraints for the 2 cyclotron designs

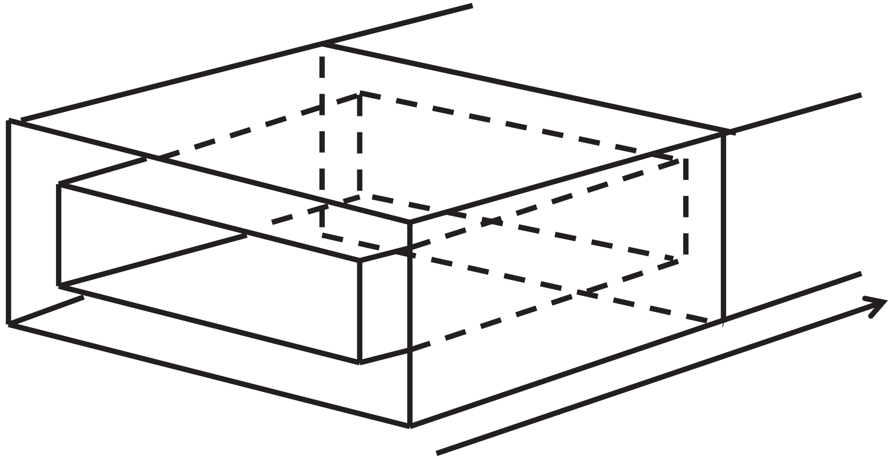
Magnet Design
(OPERA, ALANEW)

- **conservative superconducting coil** constraints (10 cm for cryostat, 40 A/mm^2, stress resistance)
- **stringent stray field** limit: 50 mT anywhere outside the cyclotron

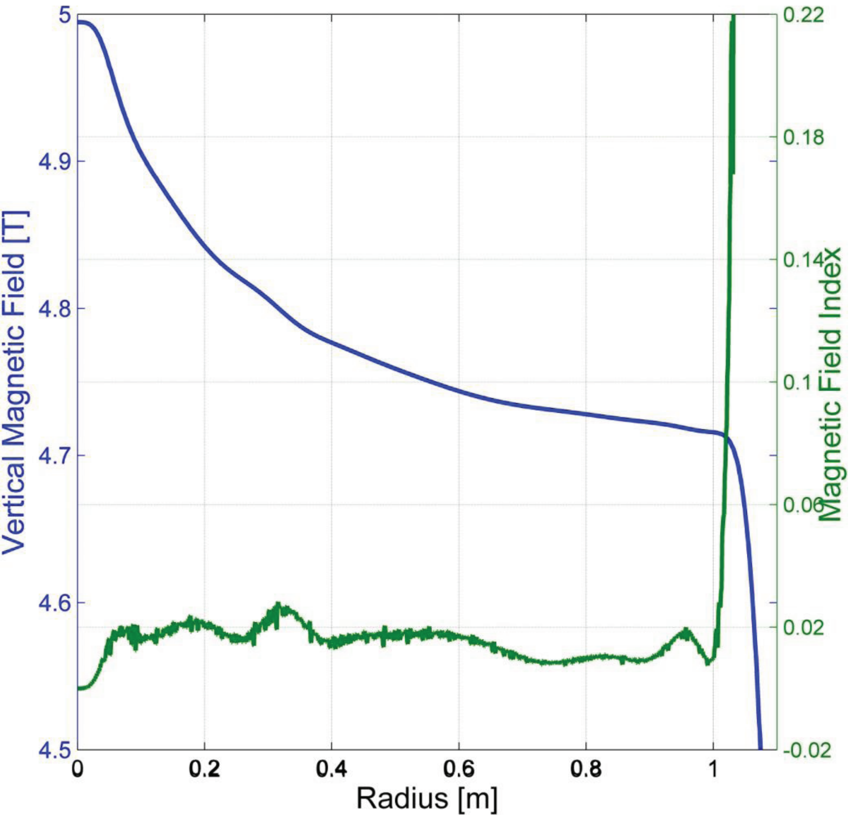
Beam Dynamics
(ORBLA, NAJO, OPERA3D)

RF Design
(Matlab, OPERA, HFSS)

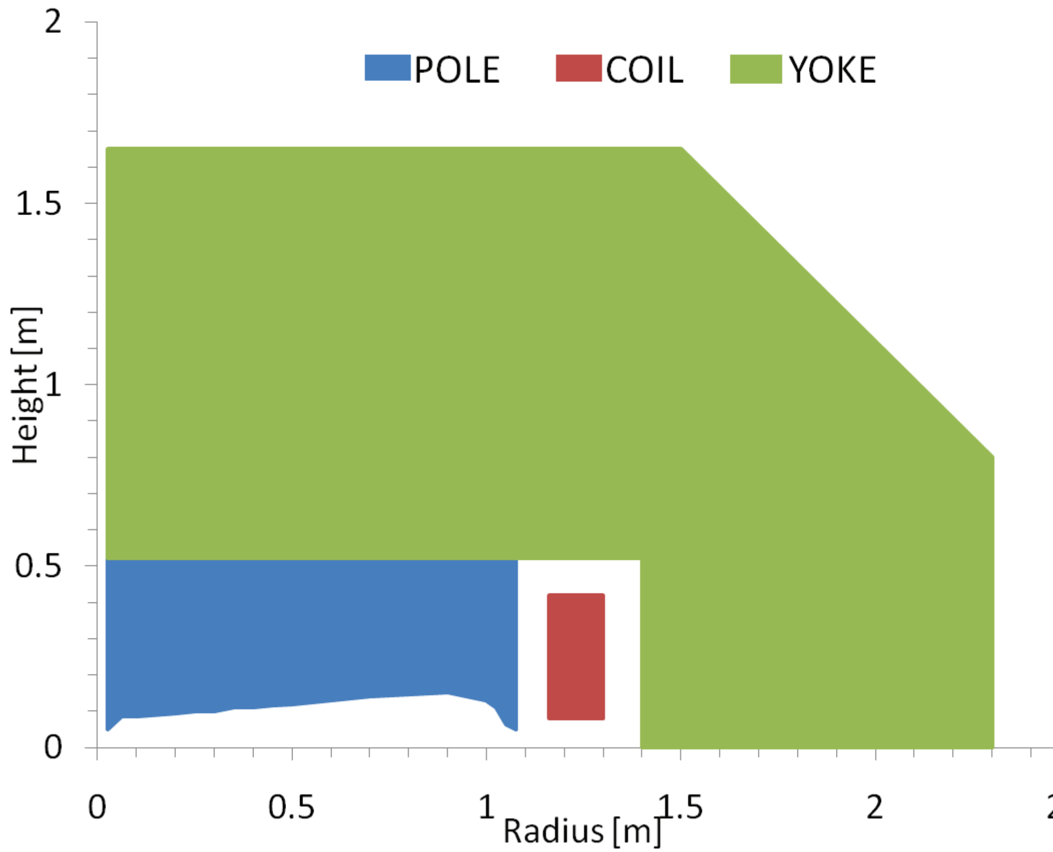
- sections of **coaxial transmission lines**
- characteristic impedances and local current densities estimated with **approximate formulas** and **validated by simulations** (10 % discrepancy)



Magnet characterized by 5 T central field and axisymmetric pole

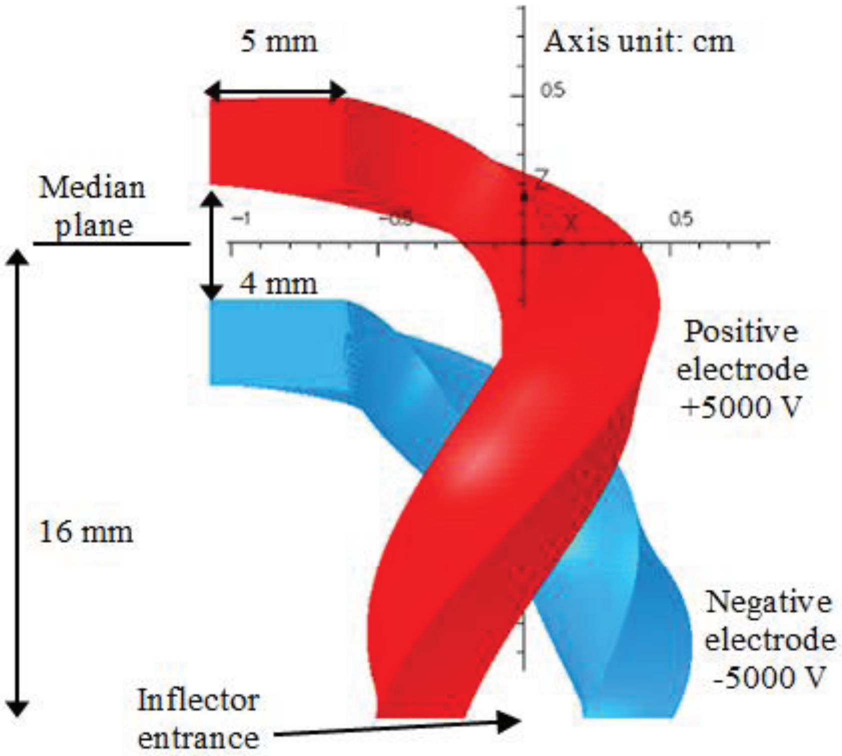


- Constant Betatron Tunes: 0.14 (vertical), 0.99 (radial)
- No resonance crossing during acceleration (Walkinshaw)



- 2D symmetry
- Pole aperture: ± 5 cm

Injection by spiral inflector requires special geometry



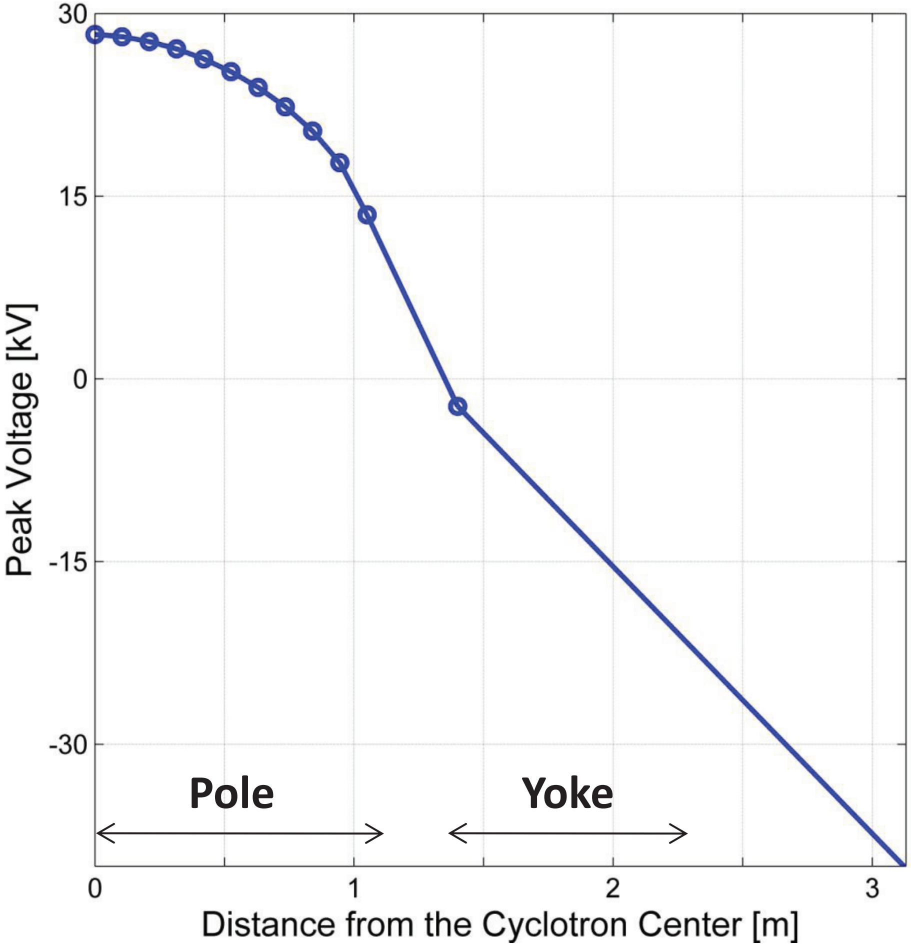
Injection Energy	10 keV/u
Magnetic Radius	5.75 mm
Electric Radius (Inflector Height)	16.0 mm
Tilt Angle	0.0°
Electrode Gap	4.0 mm
Electrode Width	5.0 mm
Applied Voltage	± 5000 V

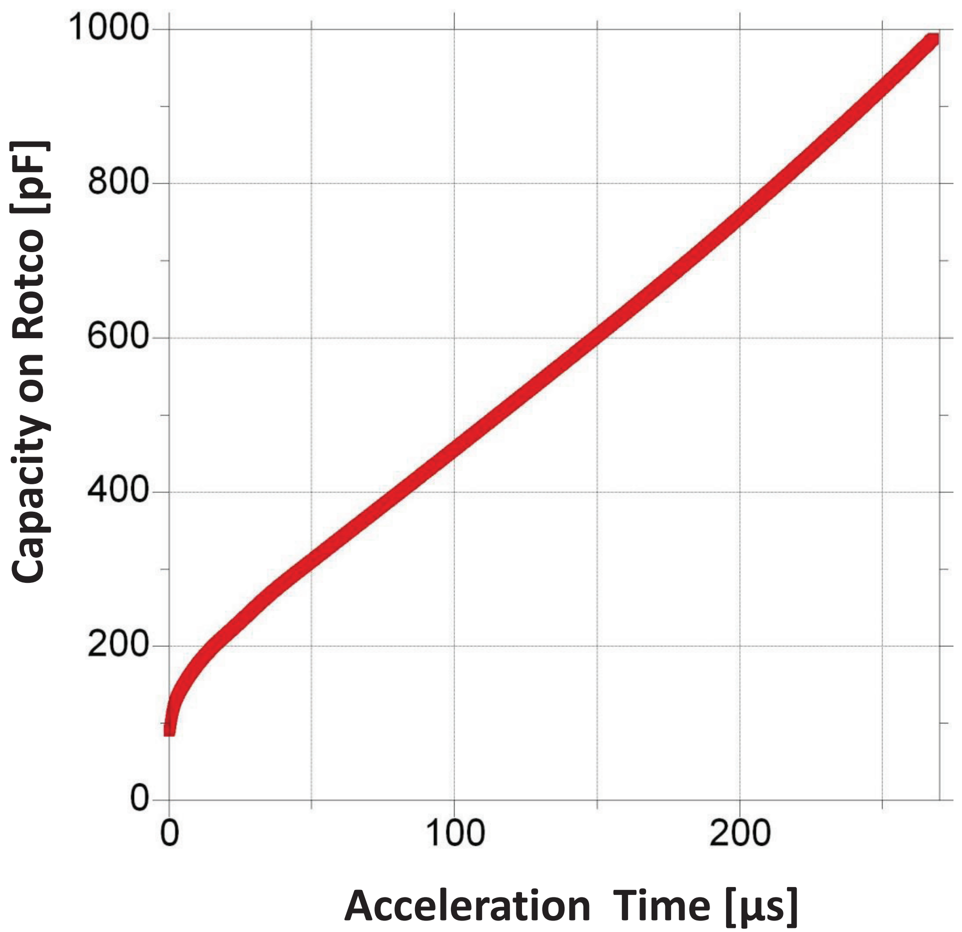
- **complex** mechanical structure:
  - strongly spiralled geometry
  - **correction wires** (2.5% field uniformity)
  - aperture hole in housing

- no beam losses through inflector and offcenter of 3 mm

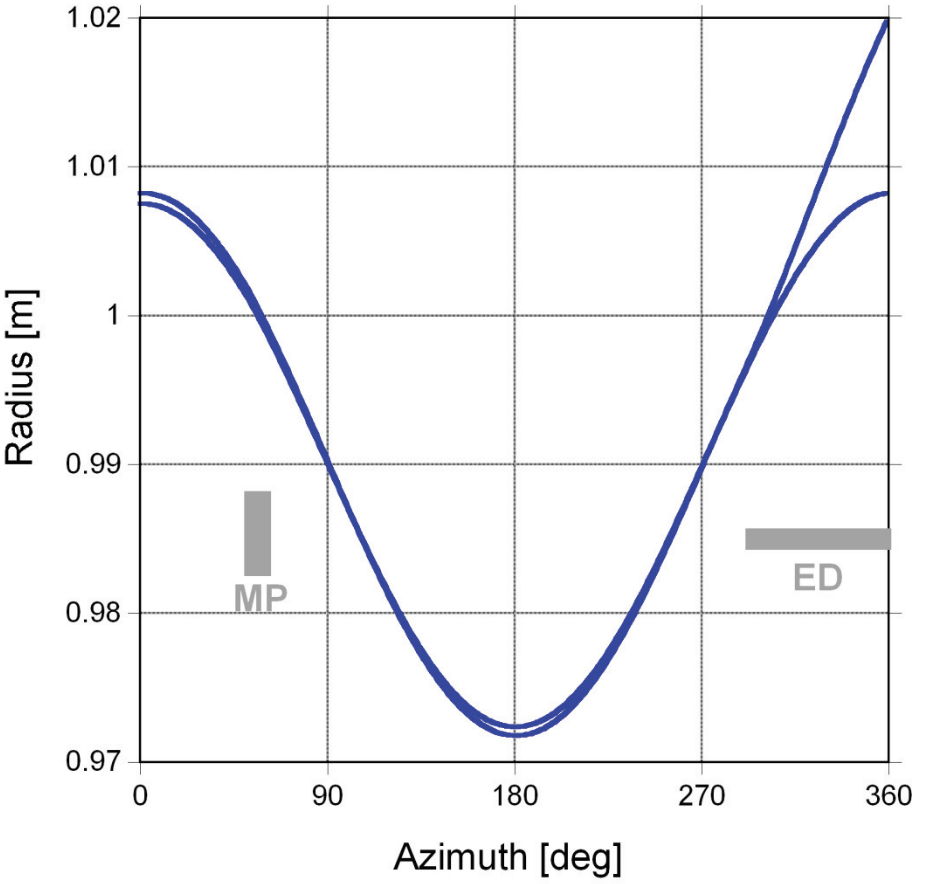
RF modulation requires large and delicate Rotco

- **λ/2 resonator : 180° Dee/ transmission line / Rotco**
- **30-38 Mhz** (Q-value: 2500, harmonic 1)
- **Capacity range technically feasible** (Orsay SC200)
- **RF power supply** of **30 kW**



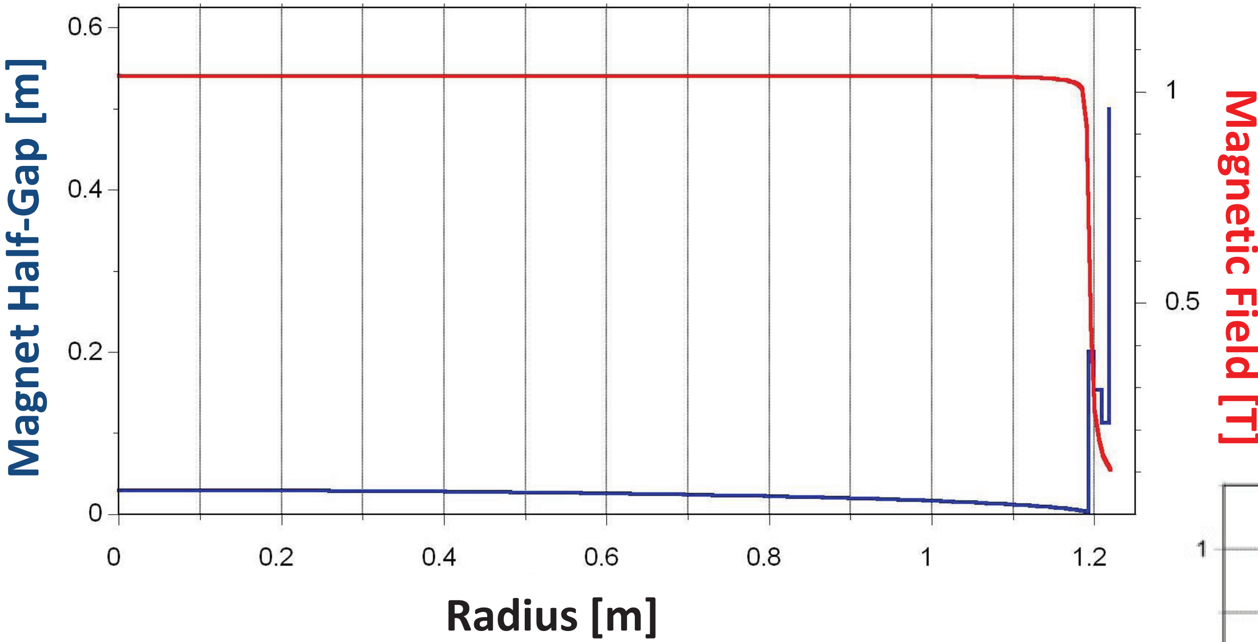


Resonant ejection requires special magnetostatic perturbation



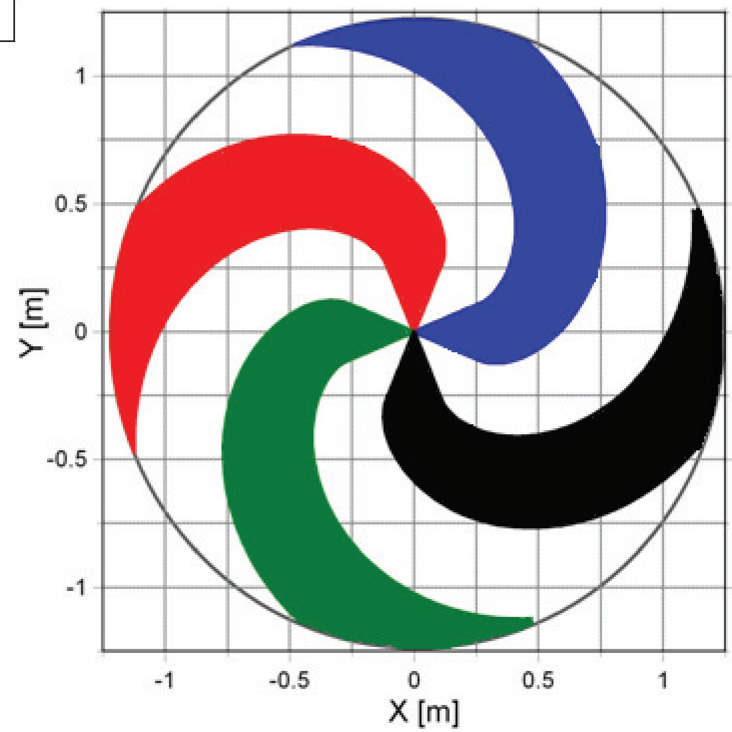
- **Magnetostatic perturbation** (MP) excites ν_r=1 and beam ejected with **electrostatic deflector** (ED)
- 0.1 T amplitude and 5° azimuthal width
- **no emittance growth**
- 140 turns
- 30 % beam losses

Magnet characterized by 3.2 T central field and elliptical pole gaps



- **highest field** for elliptical pole

- 4 sectors
- Hill gap: 3 cm to 3 mm
- Valley gap: 50 cm to 11 cm
- Hill azimuthal width: 45°



- **Limited spiraling** (from radius of 0.4 m): max 85° hill axis rotation (COMET)

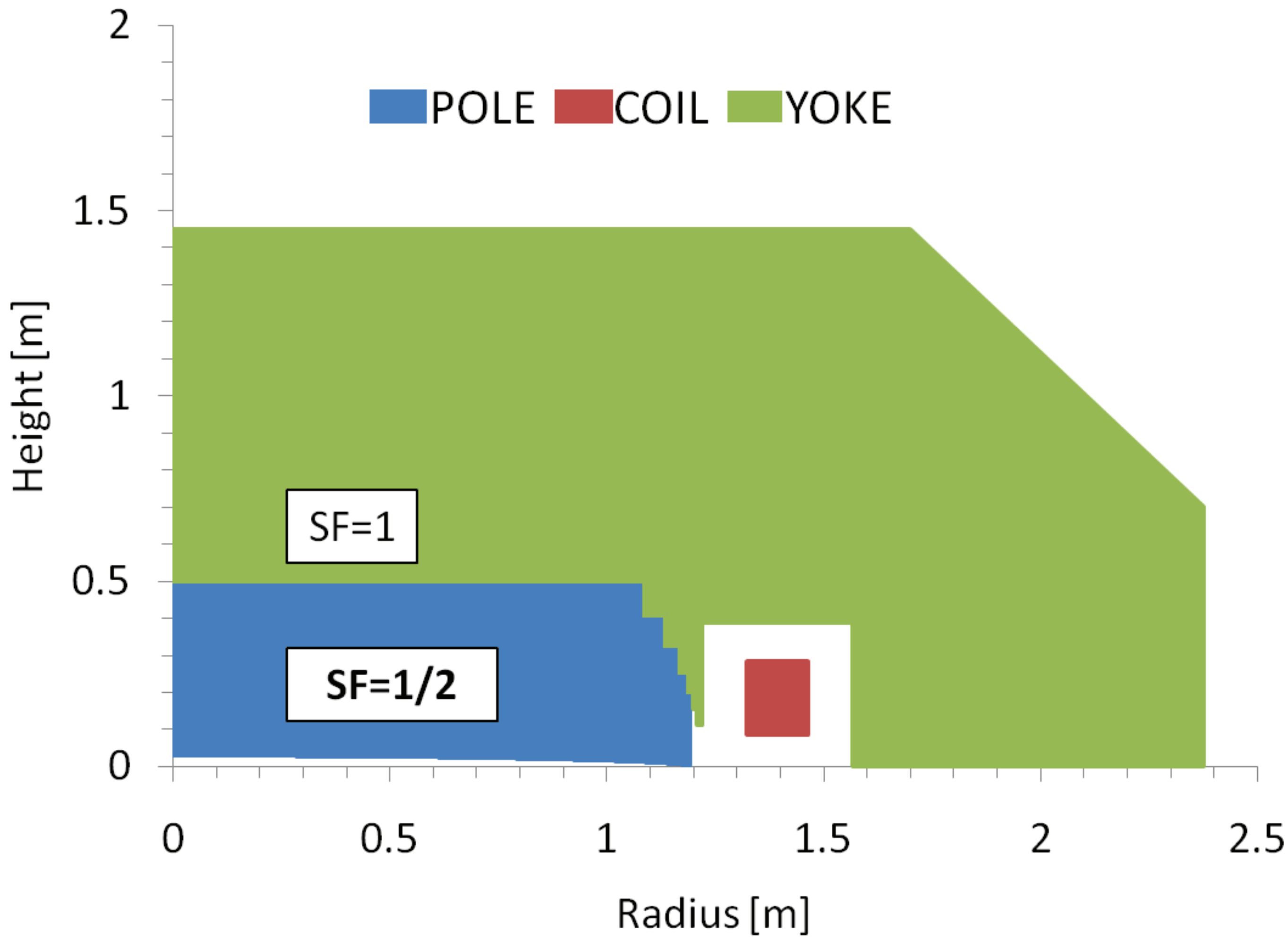
- Vertical Betatron Tunes between 0.2 and 0.5

2D model ensures field isochronism

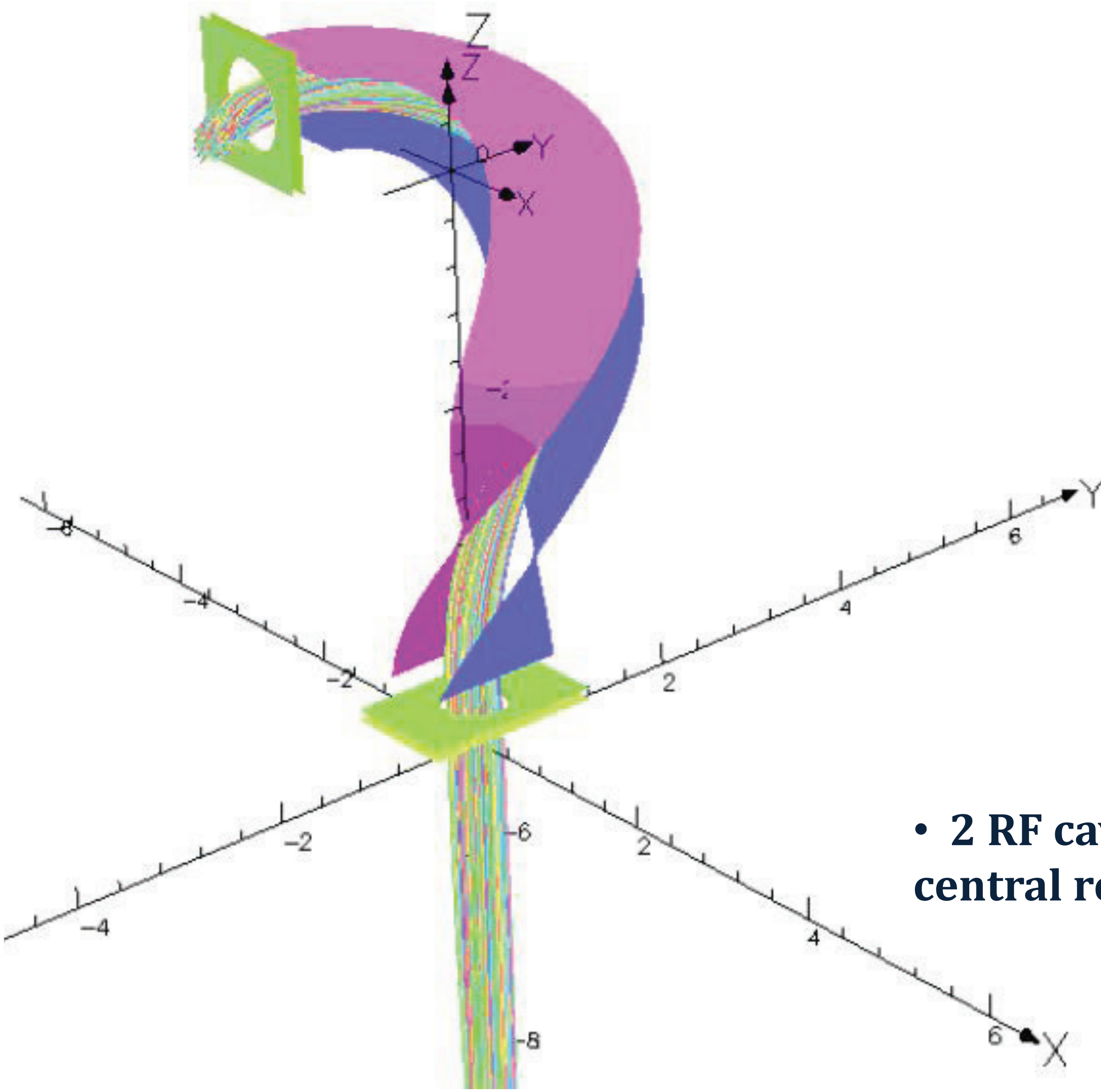
- 2D model with **stacking factors** (SF)

- field **isochronous within 1 %** (for q/A =1/2)

- over-estimation of iron weight



Injection with same spiral inflector as that of SCENT cyclotron



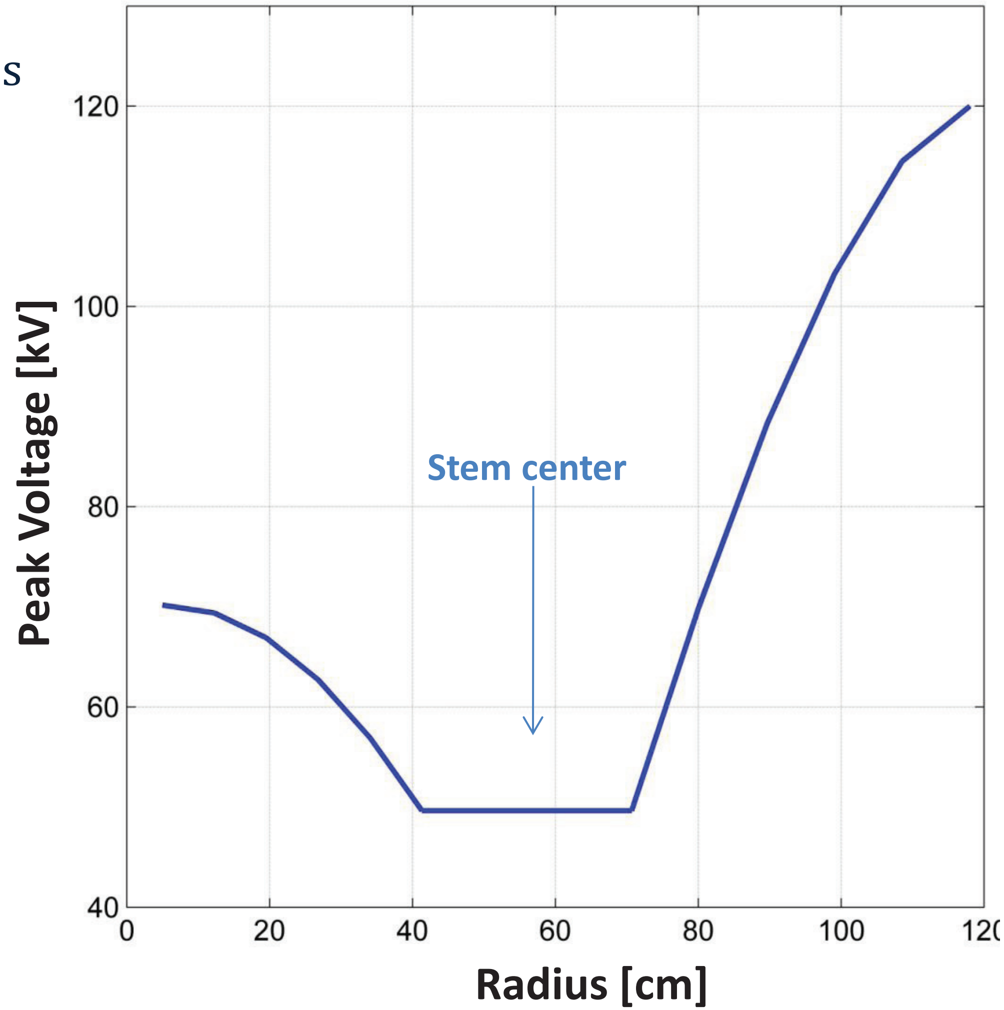
Injection Energy	25 keV/u
Magnetic Radius	14 mm
Electric Radius	43 mm
Tilt angle	0.0°
Electrode Gap	6 mm
Electrode Width	12 mm
Applied Voltage	± 6 kV

SCENT (INFN-LNS)

- **2 RF cavities** instead of 4 -> modification of **central region electrodes**

RF system with 2 cavities in valleys

- **λ\2 resonator** with 1 stem on both sides of the median plane
- 4^{th} harmonic: 98 MHz
- valley spiraling neglected
- **Q-value: 7100**
- **power supply : 100 kW**

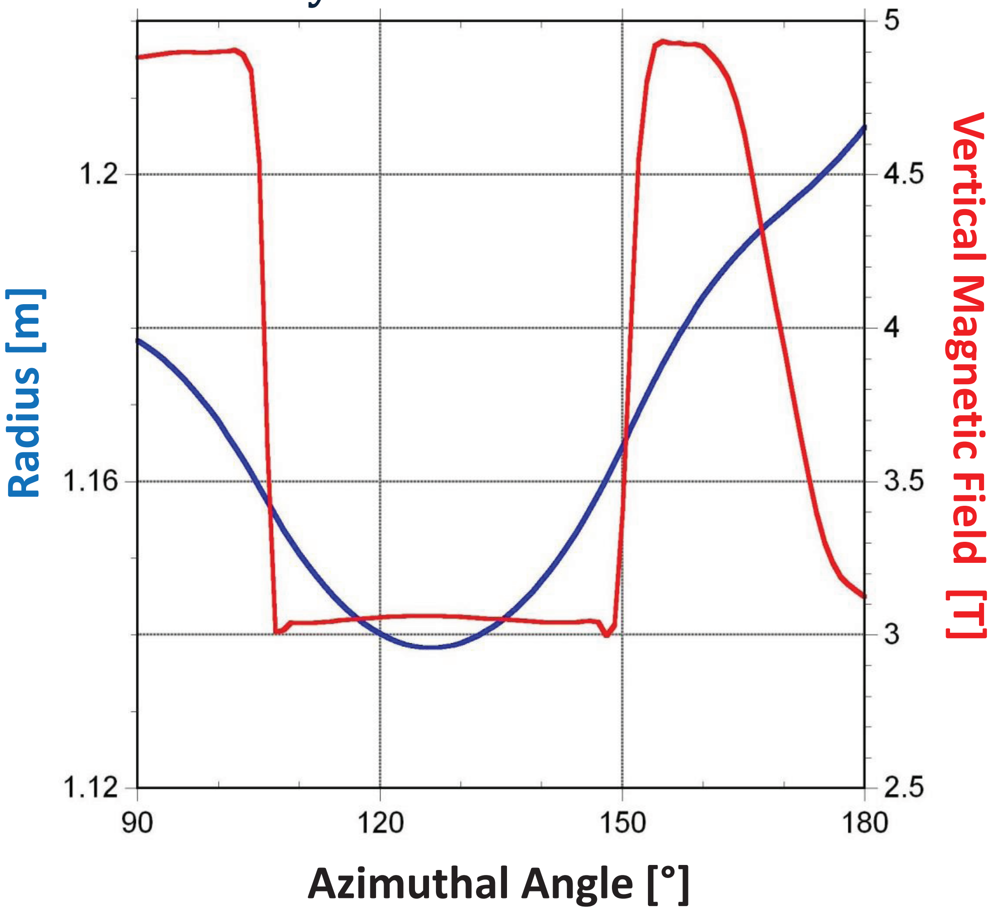


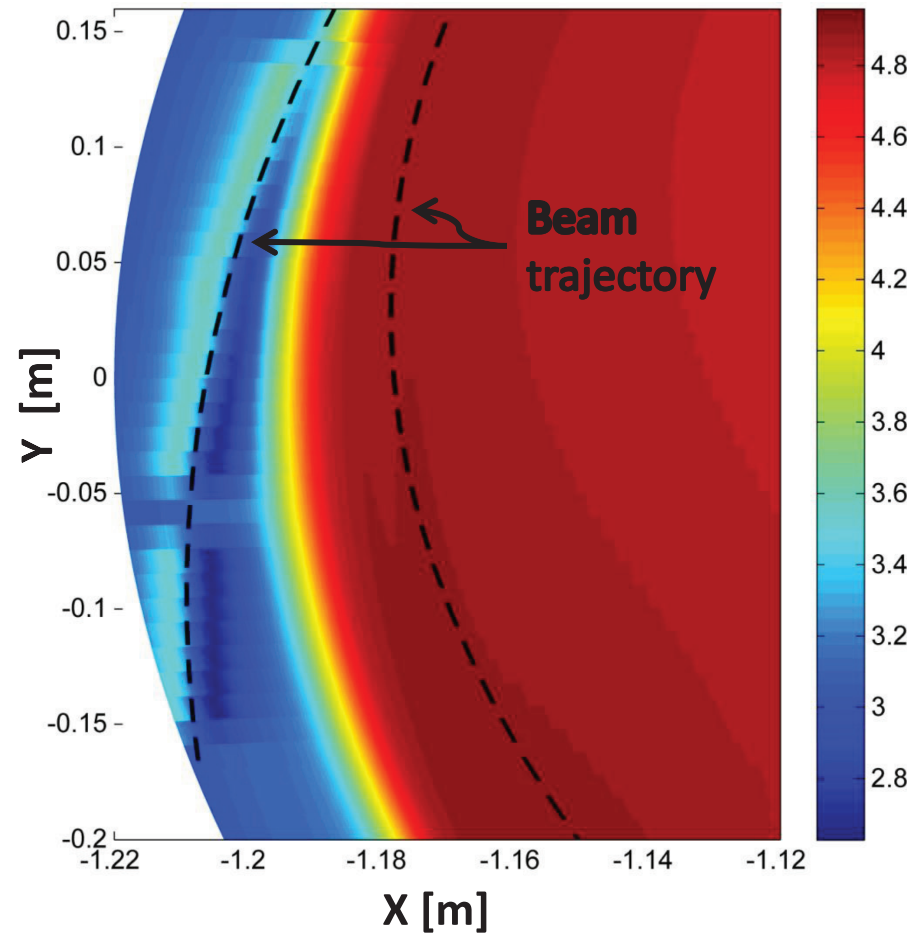
Ejection with only one ED in free valley

• natural mean radial **gain per turn 0.6 mm**

• only **one ED** (14 MV/m) in **valley with no RF cavity**

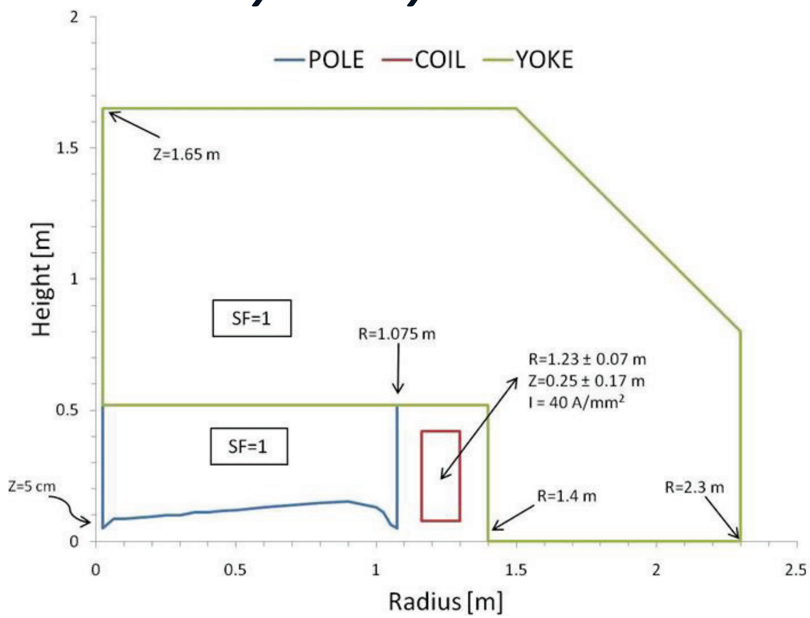
• **strong field drop** corrected with **a magnetic channel** (150 T/m)



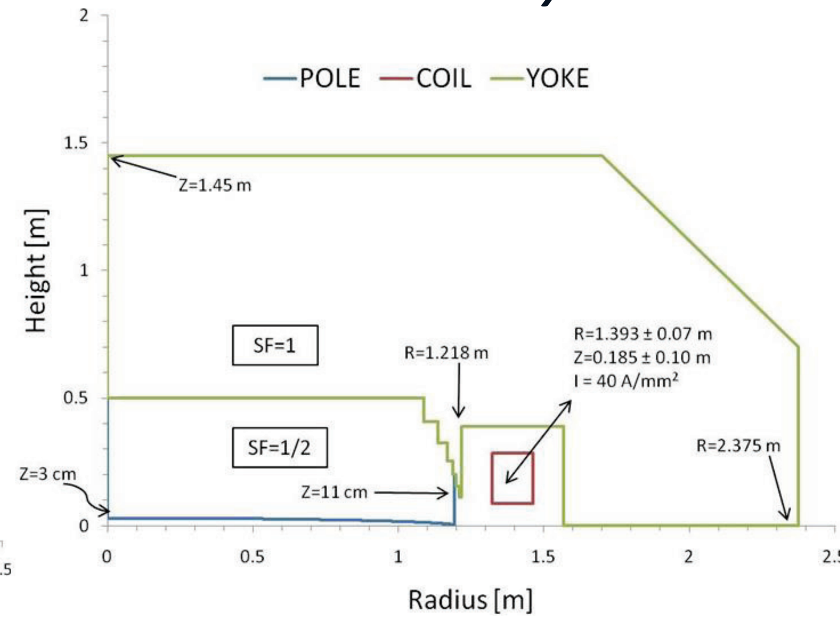


SUMMARY

Synchrocyclotron



Isochronous Cyclotron



Design Limits

- artificial magnetic perturbation
- 1st order Taylor expansion in Z of median plane magnetic field

- magnetic field corrections for H_2^+
- cavity geometry (stem)

Further Studies

- 3D model of magnet
- ejection beam tracking with more precise code

- 3D model of magnet
- 3D model of RF cavity

IC is most compatible cyclotron for injection in CABOTO

	IC	SC
q/A	1/2	
Output Energy	230 MeV/u (kinetic)	
Central Field	3.2 T	5.0 T
Pole Type	4 Sectors	Axi-symmetric
Pole Radius	1.2 m	1.1 m
Total Current/Coil	1,1 MA.turns	1.9 MA.turns
Ion Sources	At least 2 (external)	
RF cavities	2 (h=4)	1 (h=1)
RF	98 MHz	38-30 MHz
Voltage at Injection	70 kV peak	28 kV peak
Voltage at Ejection	120 kV peak	28 kV peak
RF Power Supply	100 kW	30 kW
Ejection Method	ED	Bump + ED
Yoke Diameter/Height	4.75 / 2.9 m	4.6 / 3.3 m
Iron Weight	310 tons	330 tons

⇨ **IC is as heavy as but more reliable than SC**

THANK YOU FOR YOUR ATTENTION