PAUL SCHERRER INSTITUT

A novel design of a **cyclotron based** accelerator system for multi-ion therapy

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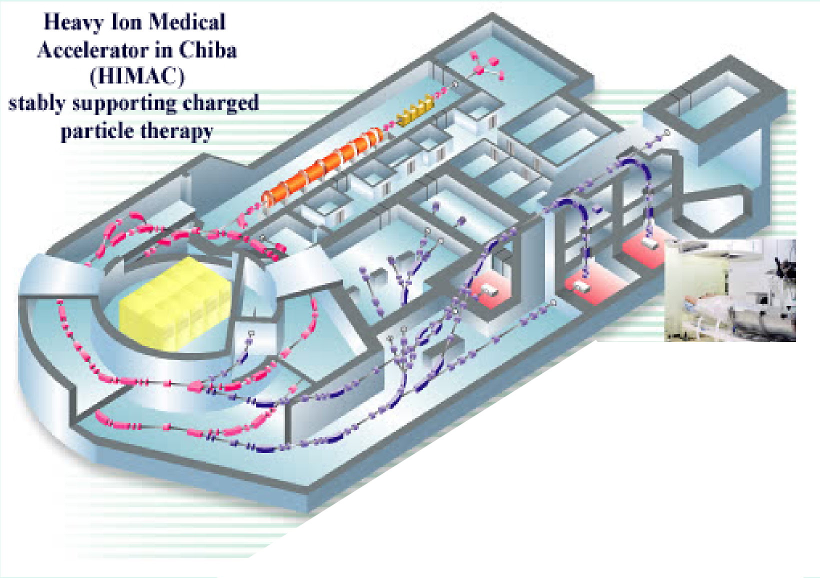
Demand for "heavy" ion therapy



<u>Present facilities:</u>

(Berkeley)

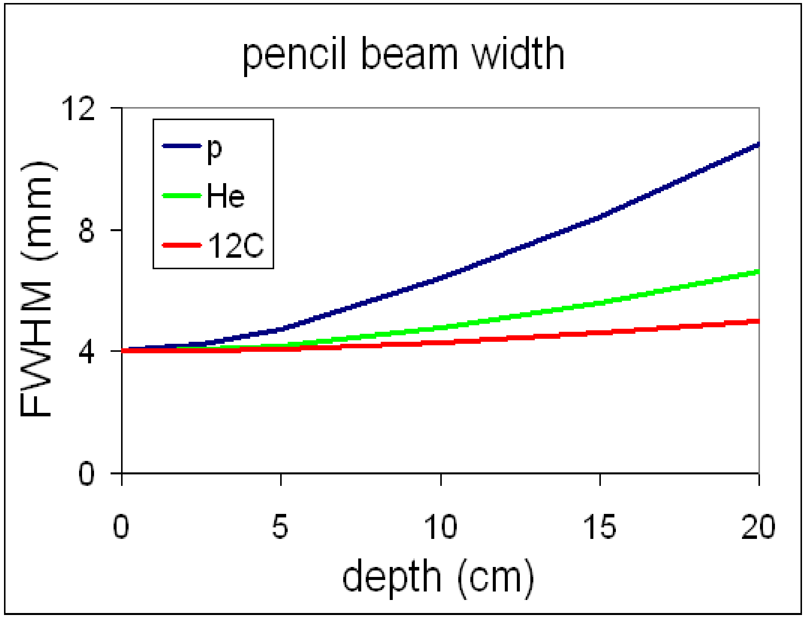
Himac, Chiba

HIBMC, Hyogo

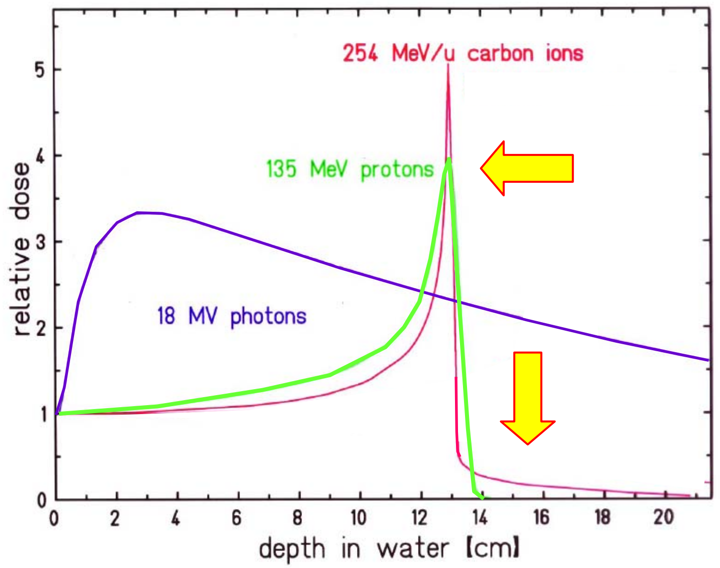
(GSI)

Difference 1 with protons: Dose distribution

transversal (scattering)



depth-dose distribution

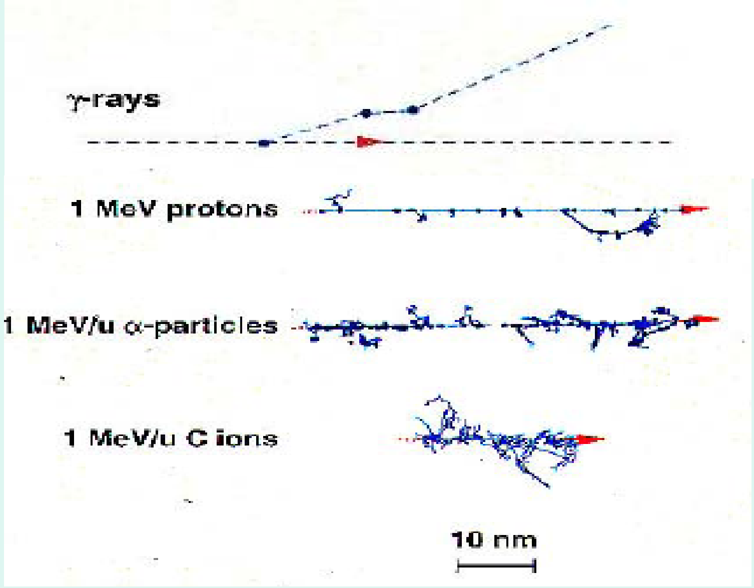


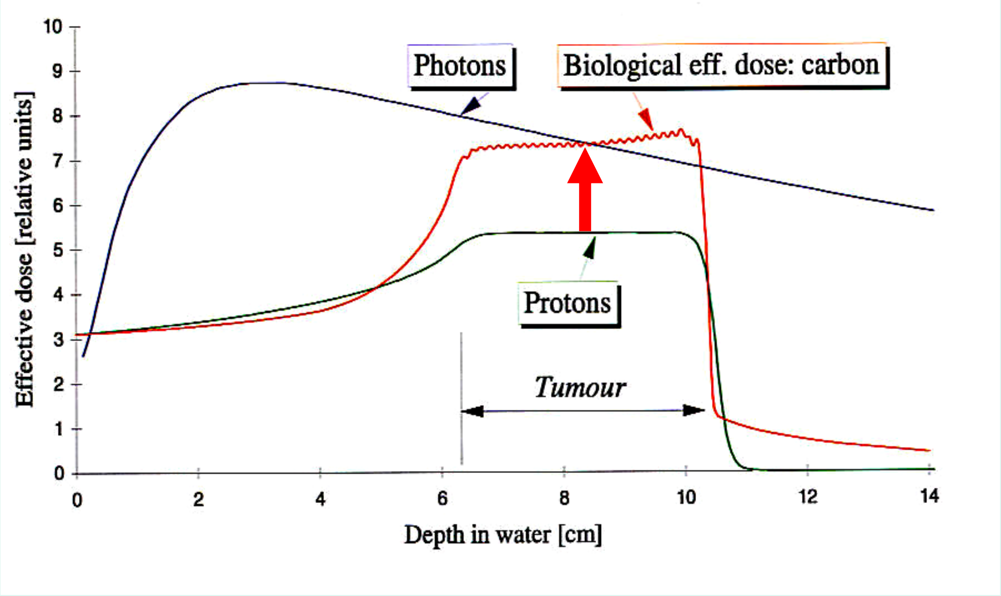
Difference 2: **R**adio **B**iological **E**ffect

for same biological result (e.g. cell killing):

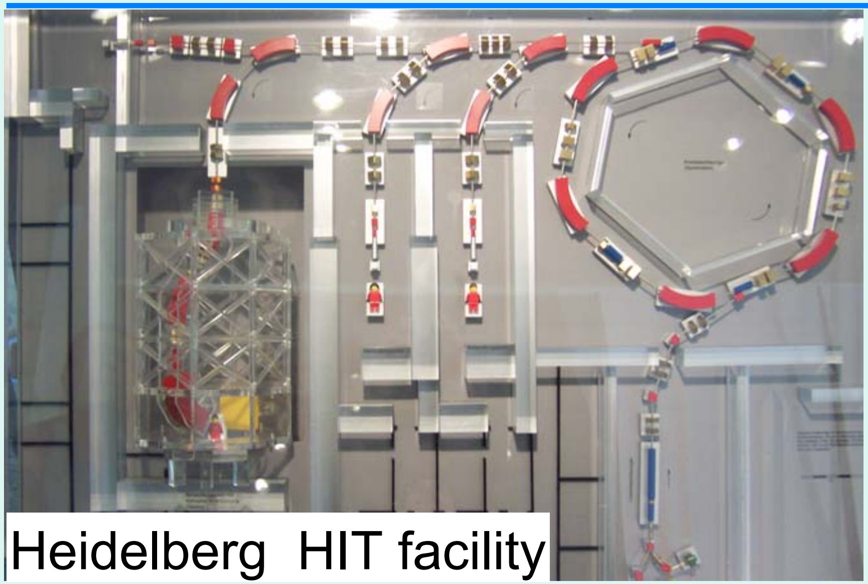
$$RBE = \frac{XrayDose}{CarbonDose}$$

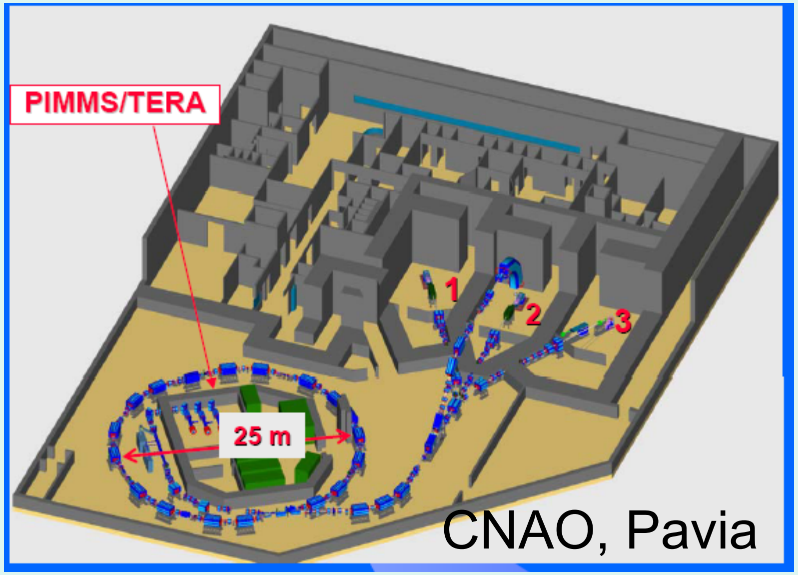
	Peak RBE	**Plateau** RBE
Proton	1.1	1.0
Helium	1.5	1.3
Carbon	3	2





Currently: synchrotron facilities





<u>Coming up:</u>

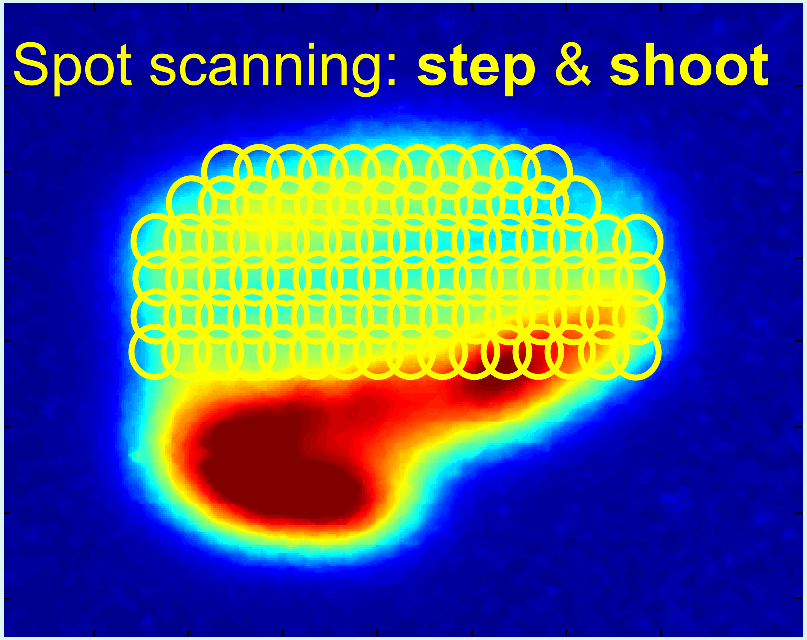
HIT, Japan, Pavia, Kiel, Marburg,….

<u>Vendors are offering </u>(often in collaboration with laboratories):

- synchrotron (Siemens, PIMS, NIRS)
- cyclotron 250, 300, 400 MeV/nucl (IBA, Catania, JINR)

Scanning → best dose distribution

Method currently used at PSI (p), GSI and Houston (p):
Spot scanning technique



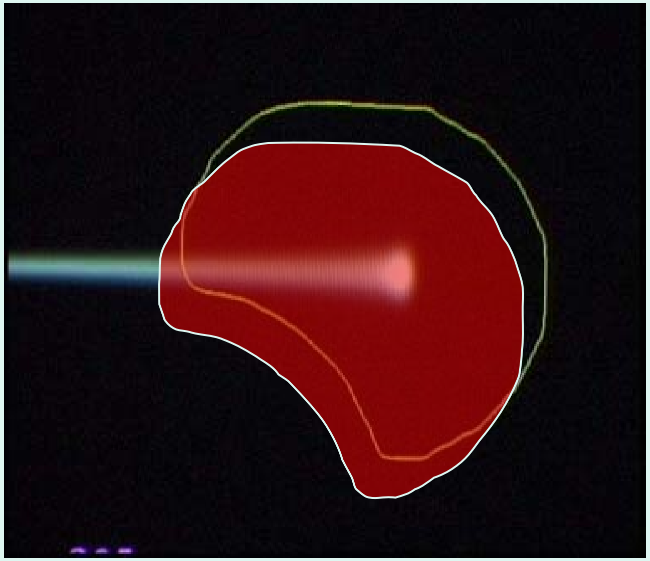
Beam size 7 mm FWHM
5 mm steps

10‘000 spots/liter (21 x 21 x 21)
Dose painted only once

~1 Gy / liter/minute

The problem in dynamical treatments:

Organ motion

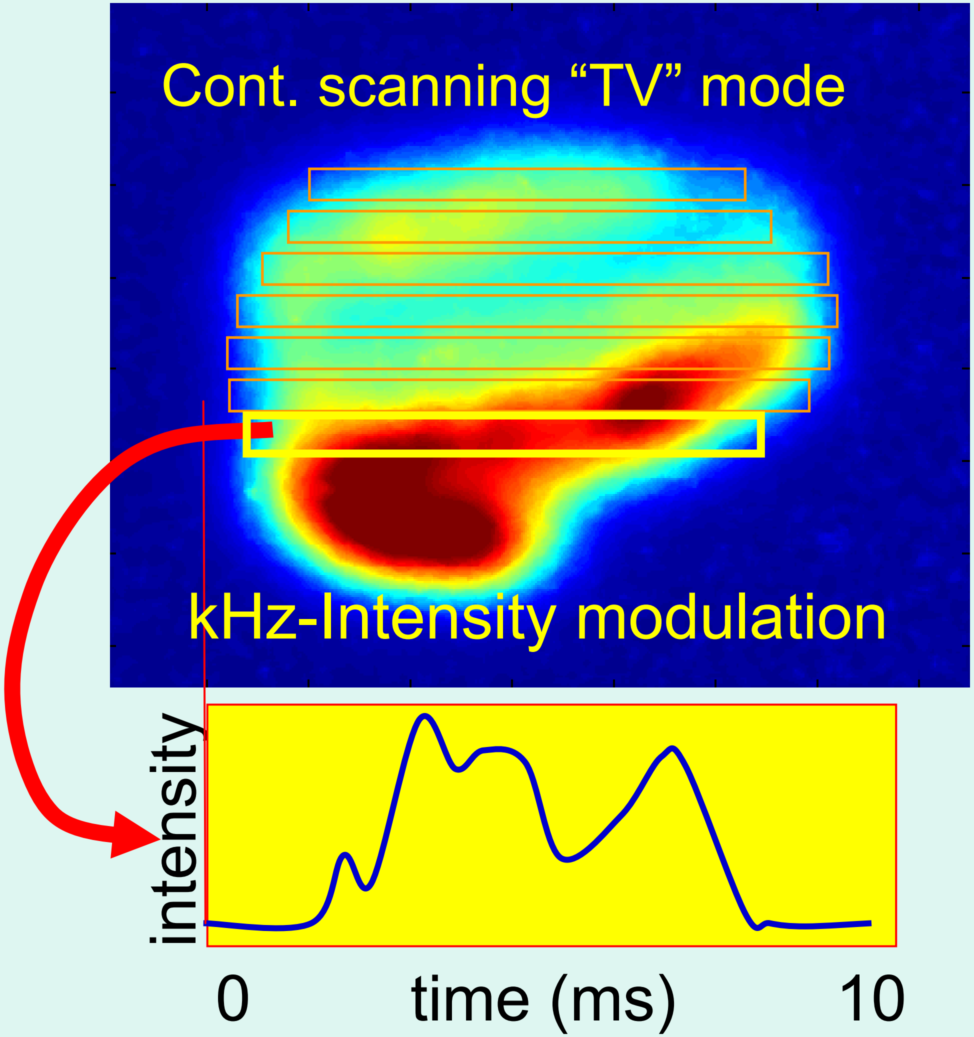


➔Danger to underdose and overdose

Limitation of spot scanning (step & shoot)
- **too slow** for moving targets

Solutions: fast scanning / gating / tracking

Fast scan mode: continuous



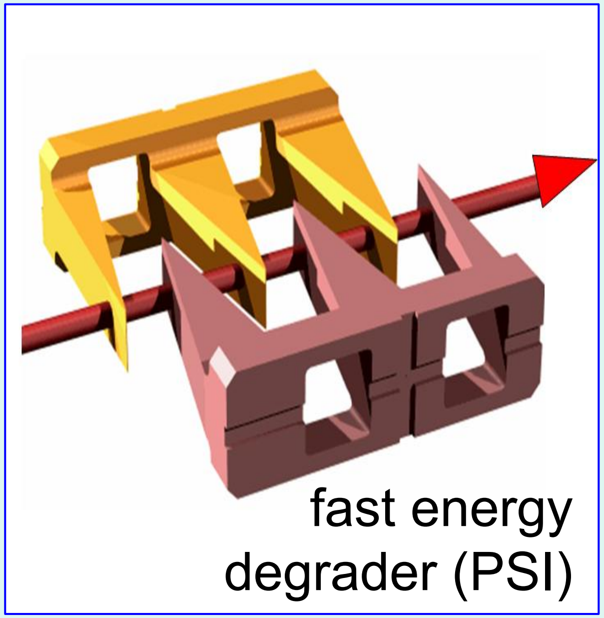
7 s for a 1 liter volume.
=> Target repainting possible:
17 scans / 2 min.

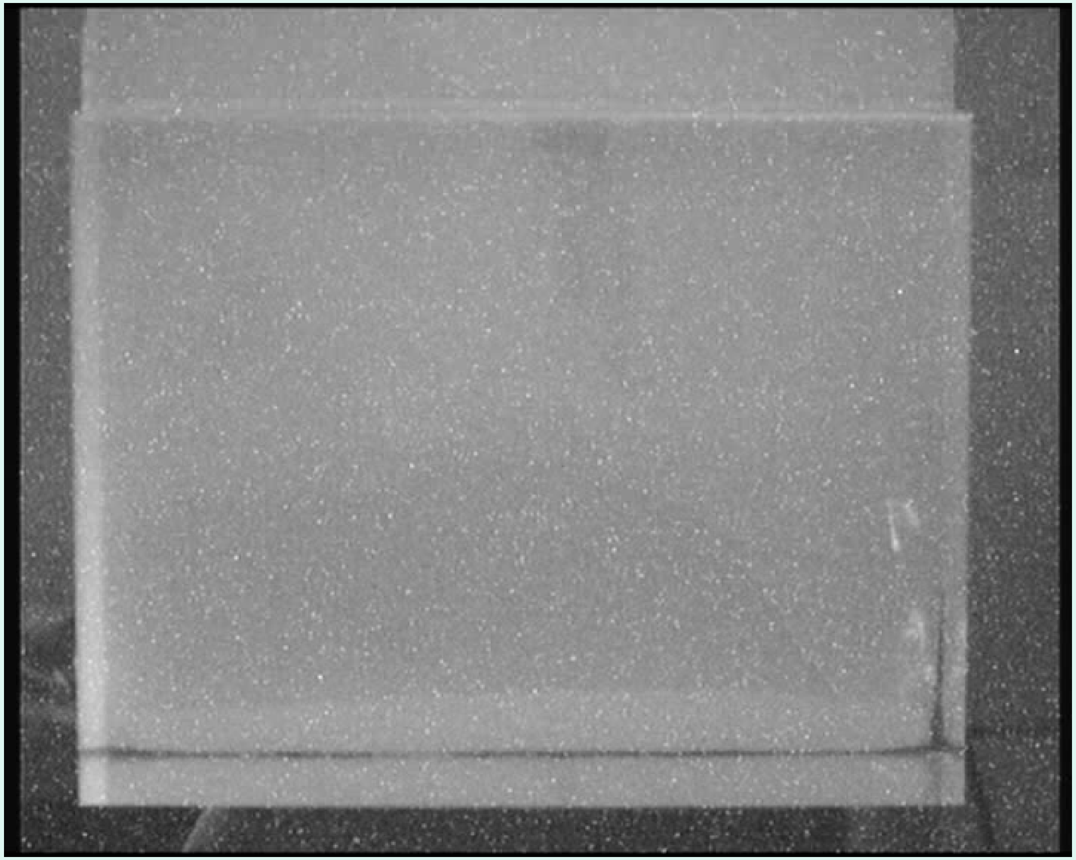
Possible strategies:
- Gating
- Fast repainting
- Tracking

Requirements for accelerator:
- enough intensity
- **continuous** and stable beam
- fast adjustable **intensity**
- fast adjustable **energy**

=> Cyclotron is optimal choice

Energy change: ΔR=5 mm in 80 ms

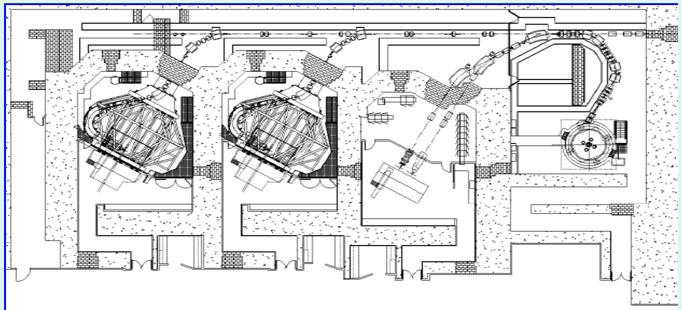




Video: David Meer, Eros Pedroni

ScanDemo_5.wmv

Typical cyclotron facility

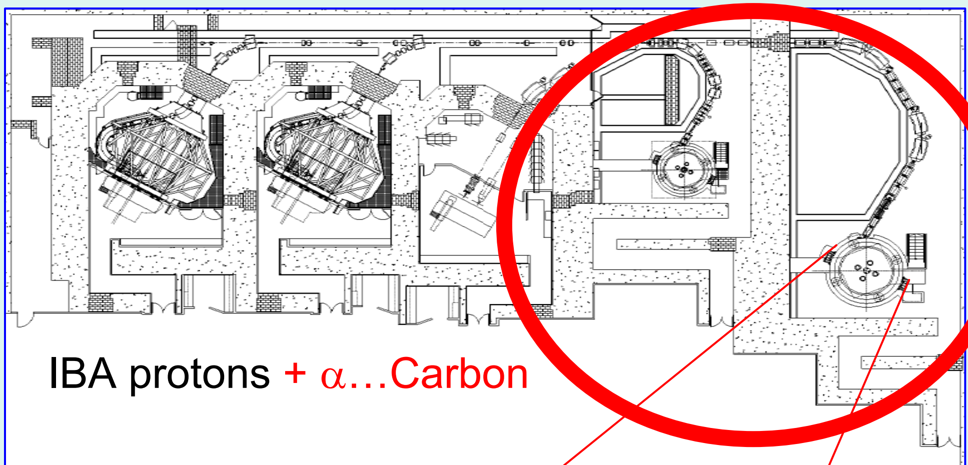


IBA protons

Observations:

- Protons are "proven work tools" (also covered by insurances)
- Carbon is interesting
- Carbon offers research possibilities
- One prefers to start with protons

Typical cyclotron facility

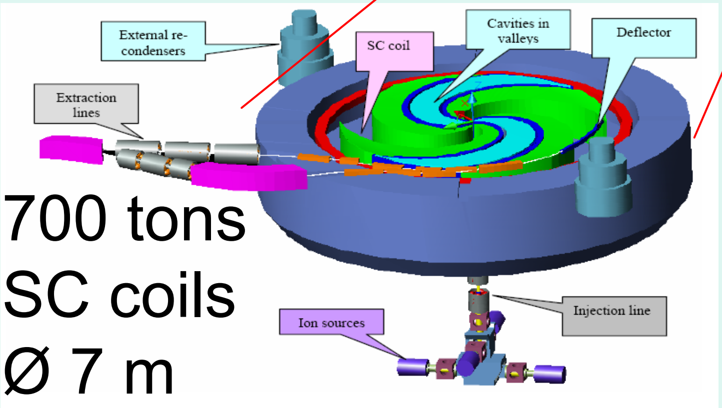


IBA protons + α…Carbon

Observations:

- Protons are “proven work tools” (also covered by insurances)
- Carbon is interesting
- Carbon offers research possibilities
- One prefers to start with protons

=> Often two-phases desired



700 tons
SC coils
Ø 7 m

Figure 1: Artist’s view of the median plane in the 400 MeV/amu Carbon/Proton superconducting cyclotron.

Int. Conf. Cyclotron and appl, Tokyo 2004

IBA C400 CYCLOTRON PROJECT FOR HADRON THERAPY

Y. Jongen, M. Abs, W. Beeckman, A. Blondin, W. Kleeven, D. Vandeplassche, S. Zaremba, IBA, Belgium
V. Aleksandrov, A. Glazov, S. Gurskiy, G. Karamysheva, N. Kazarinov, S. Kostromin, N. Morozov, E. Samsonov, V. Shevtsov, G. Shirkov, E. Syresin, A. Tuzikov, JINR, Russia.

A novel idea:

Two steps: injector and booster

AND:

injector also provides He and (limited) carbon beams

	Beams from injector cyclotron: 250 MeV/nucl. (4.86 Tm)			From Booster (6. 83 Tm)
	Proton (**H_2^+ ions**)	Helium 2+ (α)	Carbon 6+	Carbon 6+ 450 MeV/n
Range in water (cm)	38.3	38.3	12.7	33.3

A possible injection cyclotron:

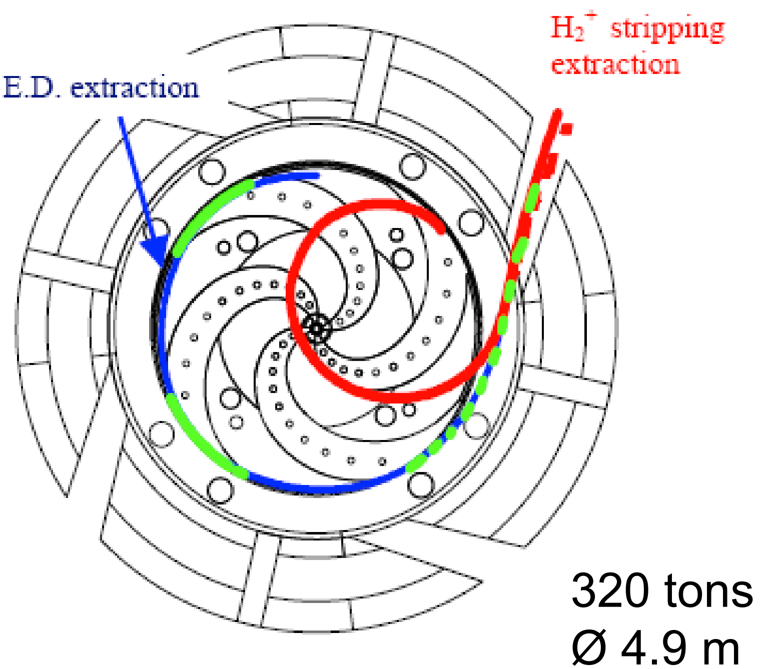


Figure 3: Layout of the cyclotron with overdrawn the extraction trajectories by E.D. and by stripper. The E.D. and the M.C. positions are also shown.

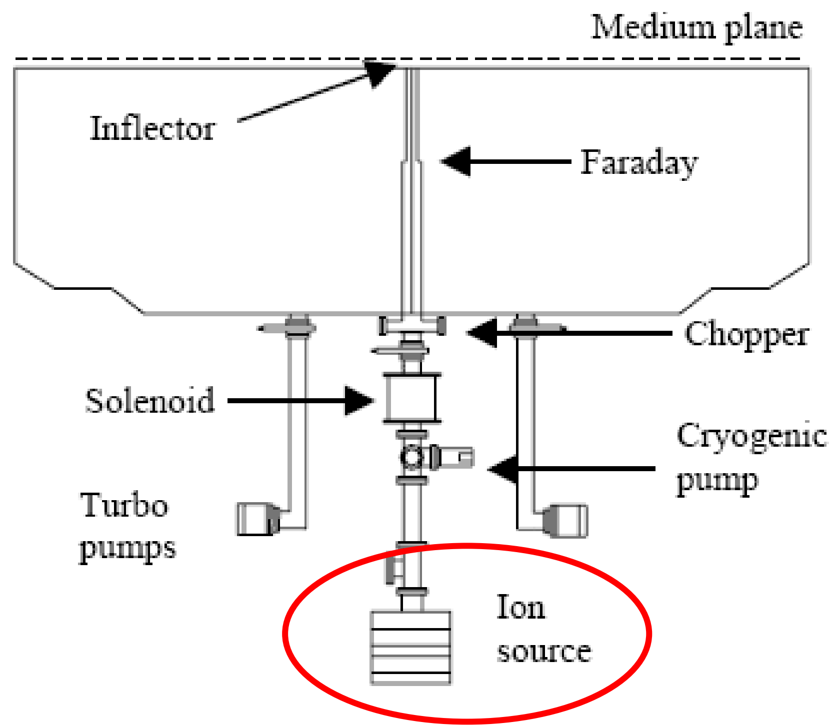


Figure 4: Layout of the axial injection line and part of vacuum plant

LNS CATANIA PROJECT FOR THERAPY AND RADIOISOTOPE PRODUCTION

L.Calabretta, G. Cuttone, M. Re, D. Rifuggiato, LNS-INFN, Catania, Italy
M.Maggiore, University of Catania, LNS-INFN, Italy

Cyclotron conference, Tokyo 2004

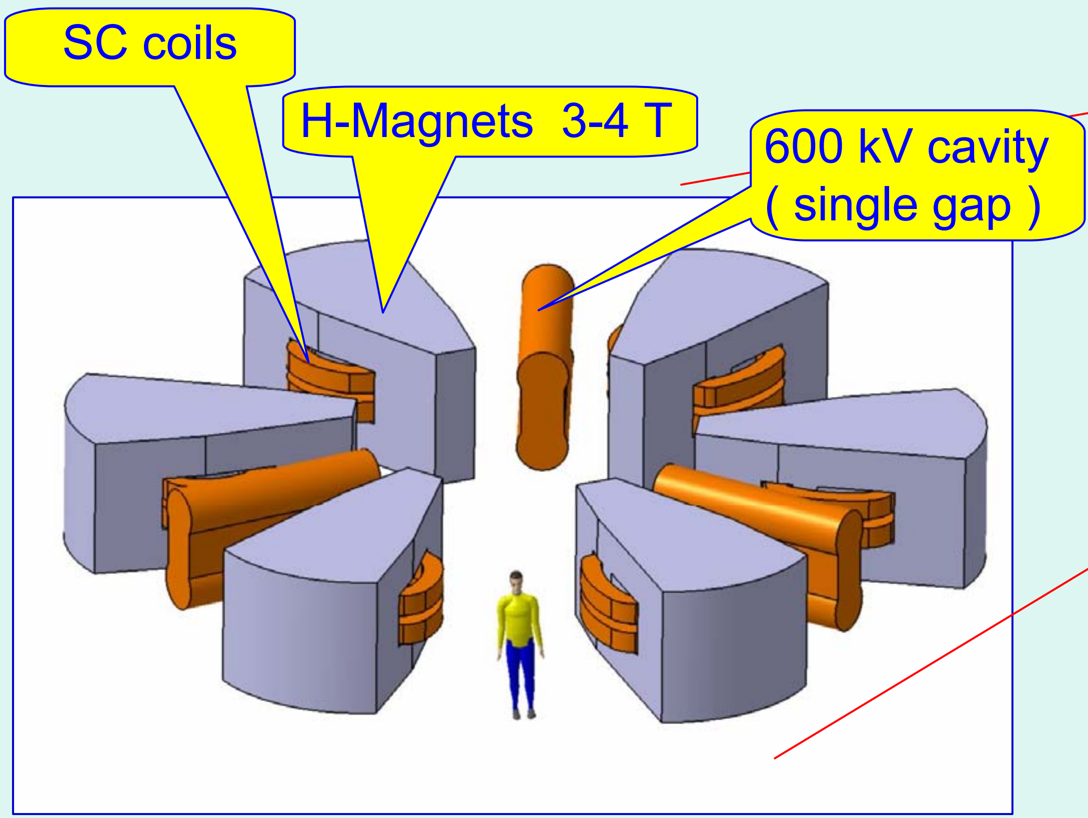
novel idea: sep. sector cyclotron as **booster**

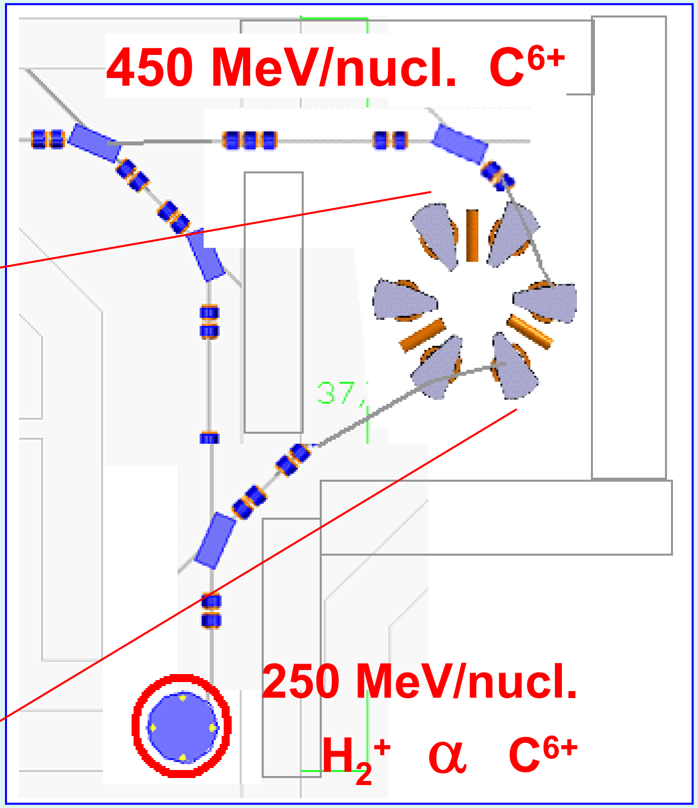
Separate locations of injector and booster !

Start with protons AND

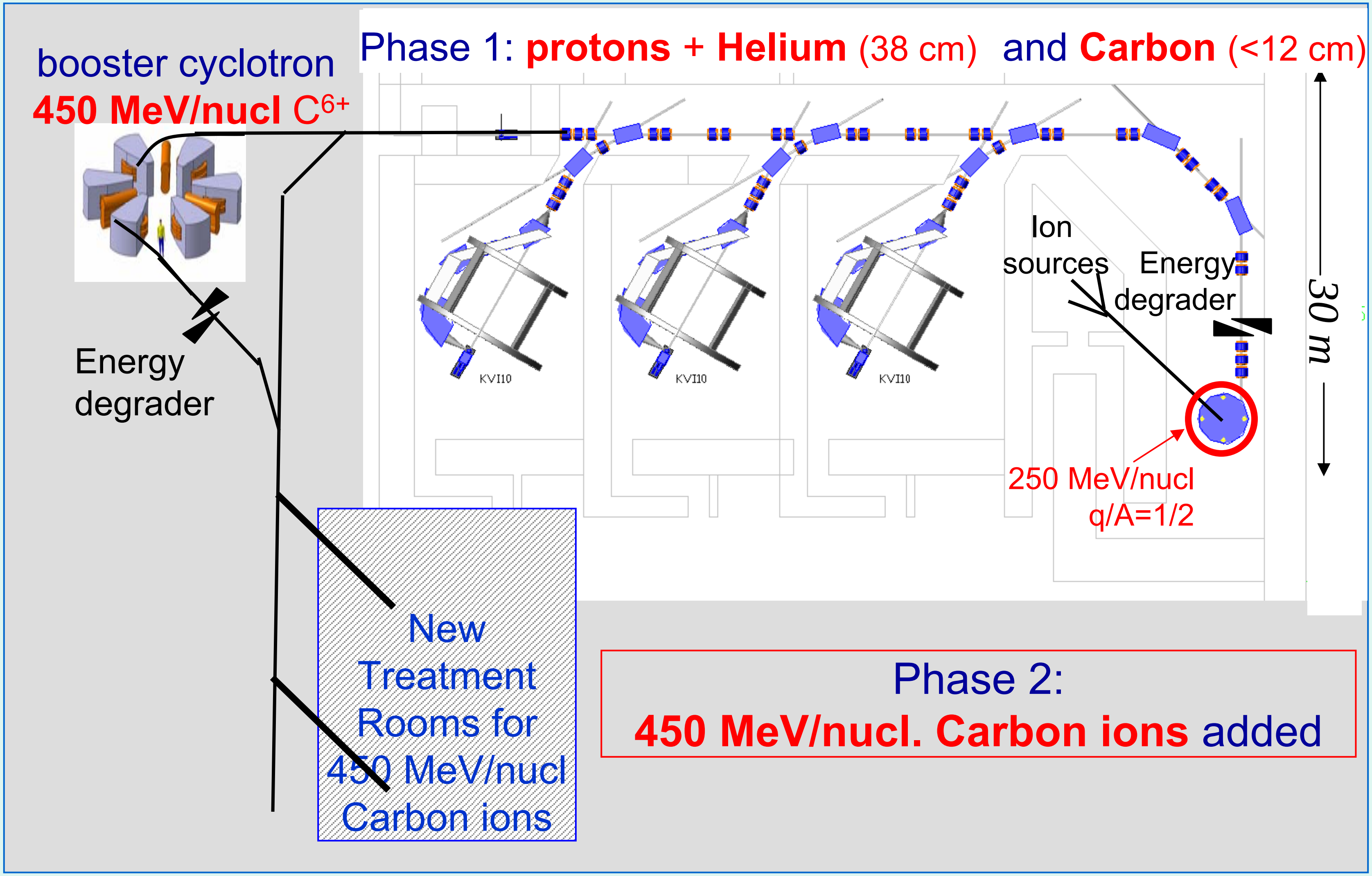
α + (up to 12.5 cm:) Carbon

Second step: also 450 MeV/nucl Carbon

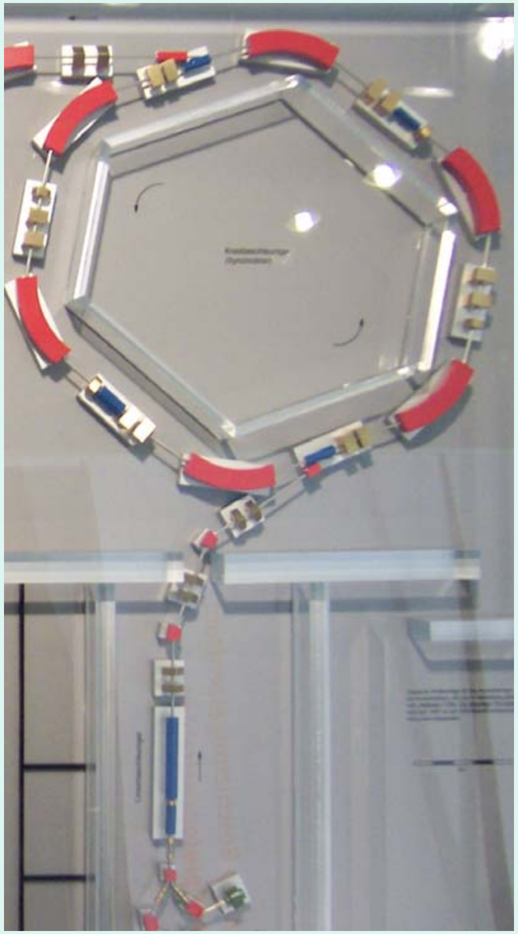


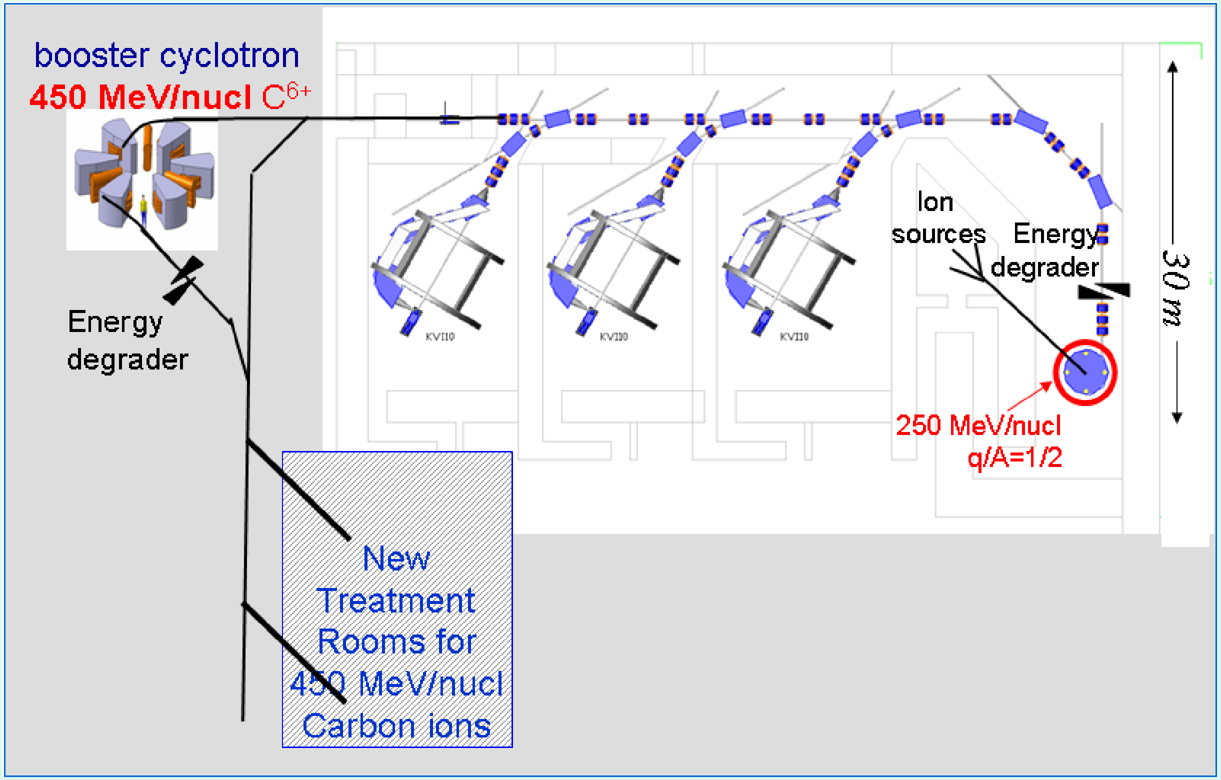


system layout



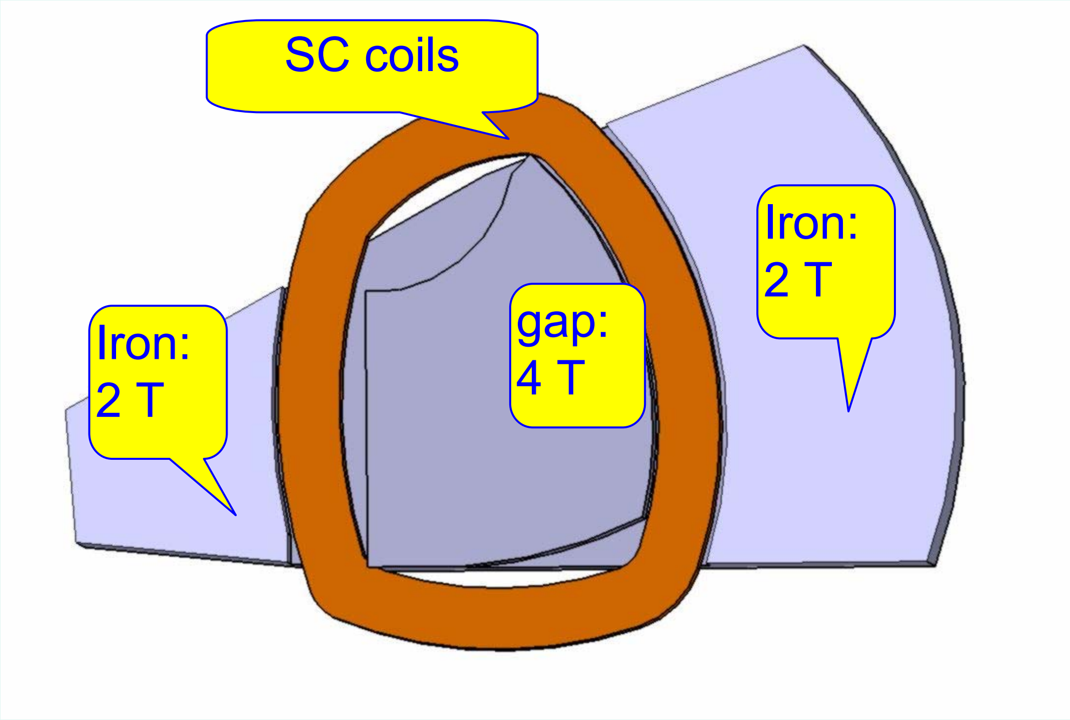
layout compared to a synchrotron





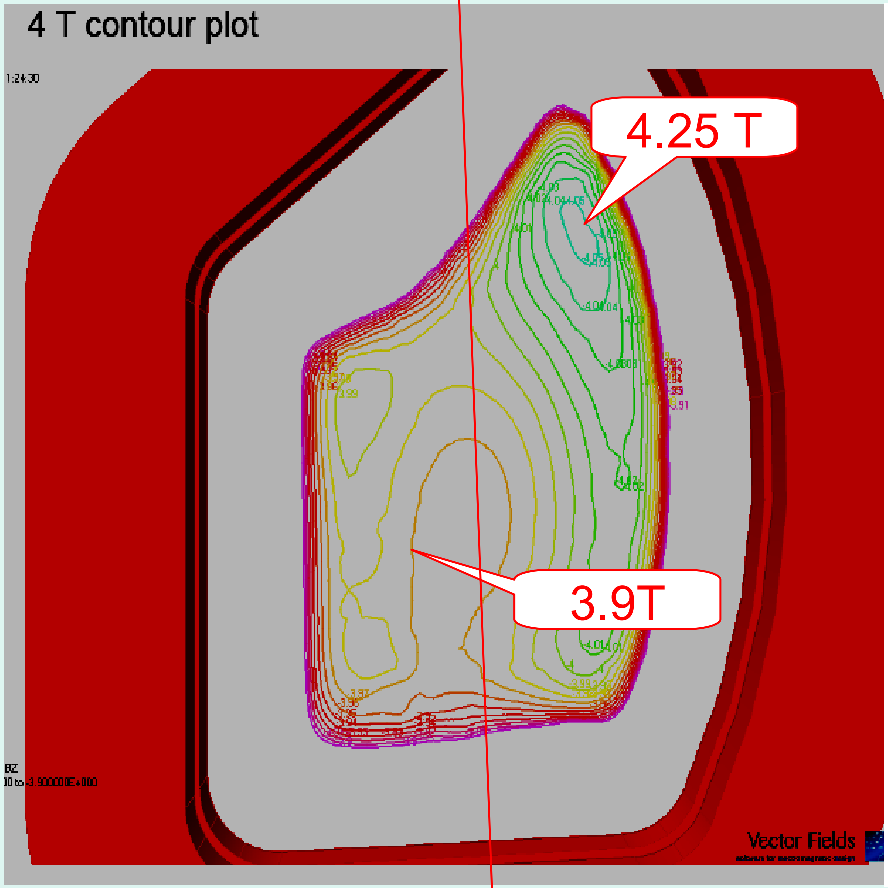
Design issues: sector magnet

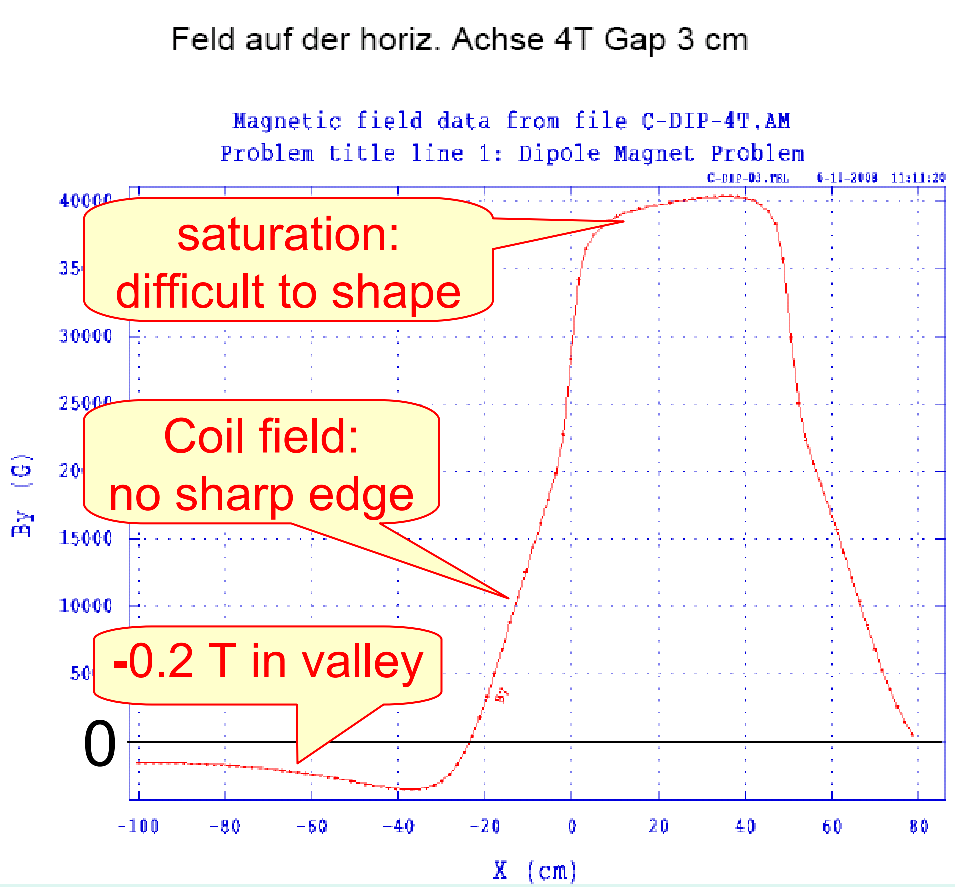
Magnet types	H-magnets , superconducting coils
Magnetic field	4 Tesla



Problems with 4 T design

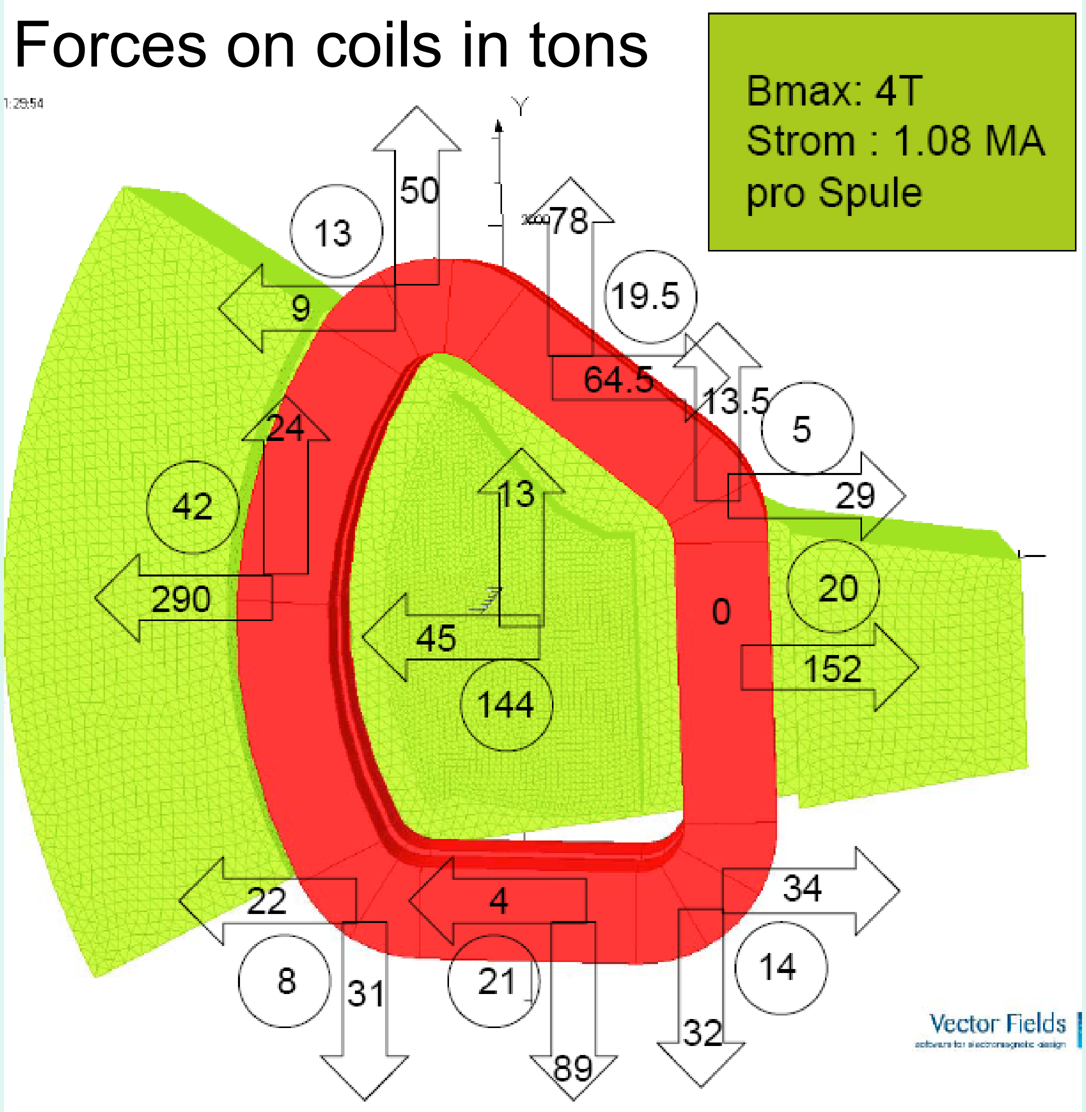
- Field energy 20-25 MJ → quench protection?
- Field shaping: iron and coil contributions





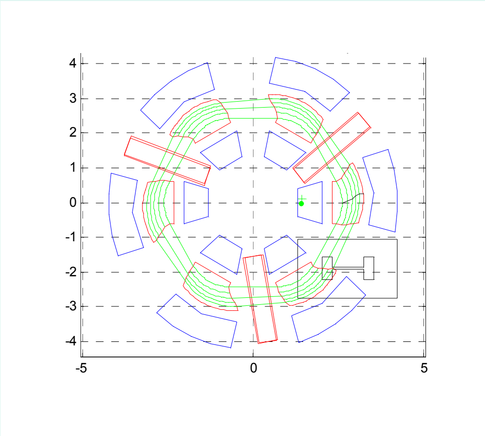
Other problems with 4 T design

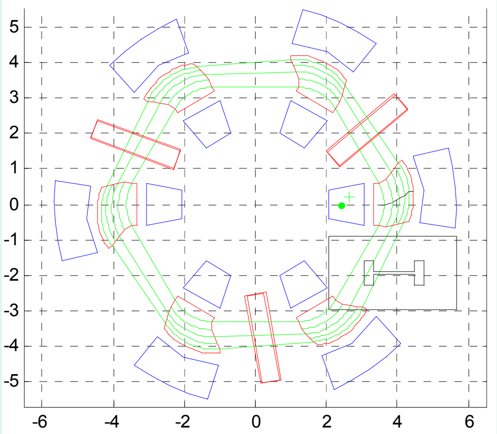
- Forces on coils

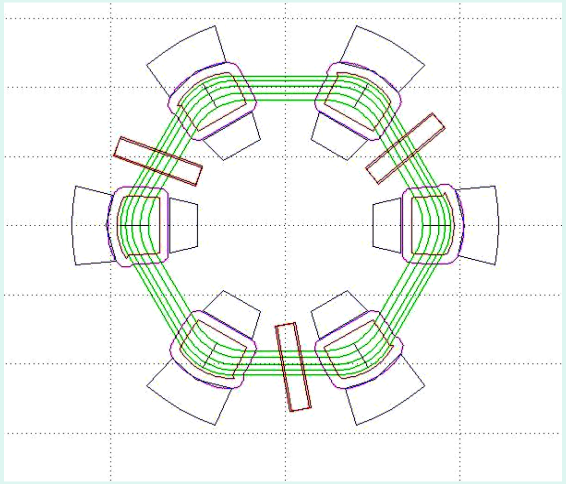


options

	3T	4T	3-4 T
Weight (tons)	400	500	550
Size ∅ (m)	8.5	12	12



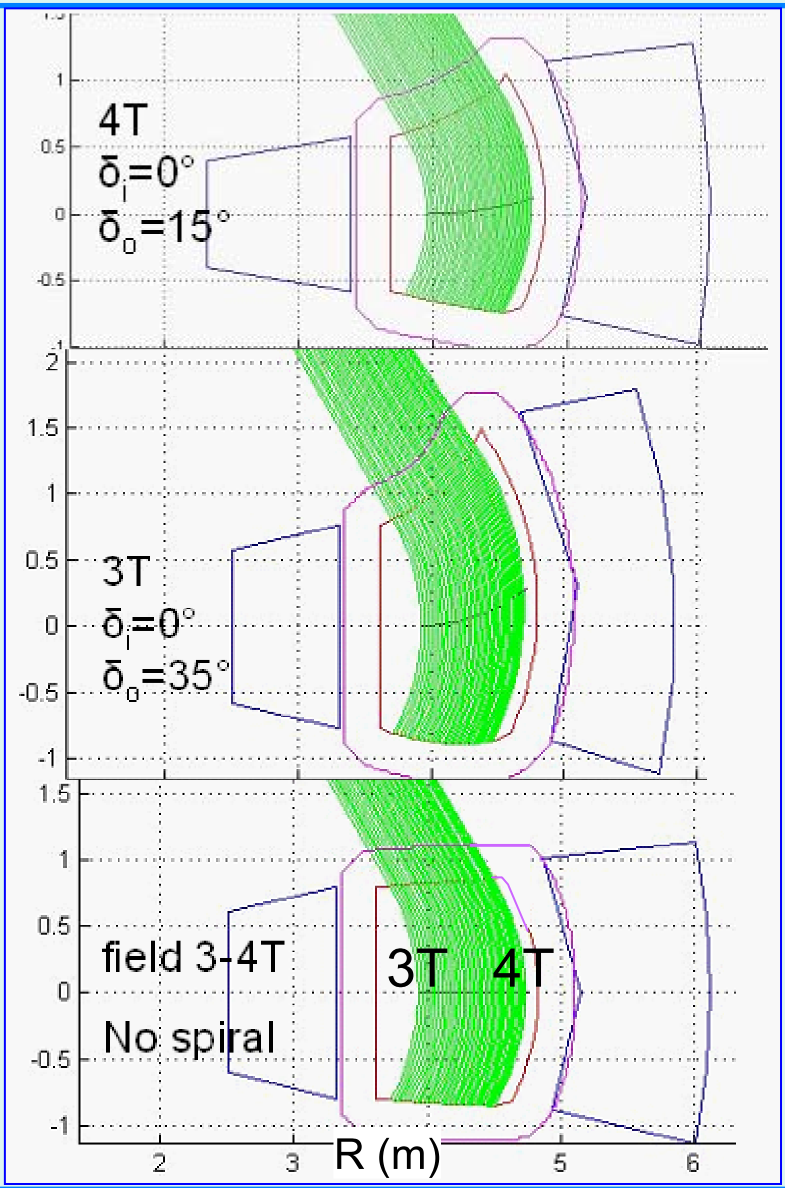




10 m

spreadsheet designs 92h8 92h10 92h12

magnet designs being studied



4 T design:

+ relatively short
● problems with strong field

3 T design:

+ magnet less problematic
● long → less space in valley
● edge at concave side too sharp

gradient 3→4 T design:

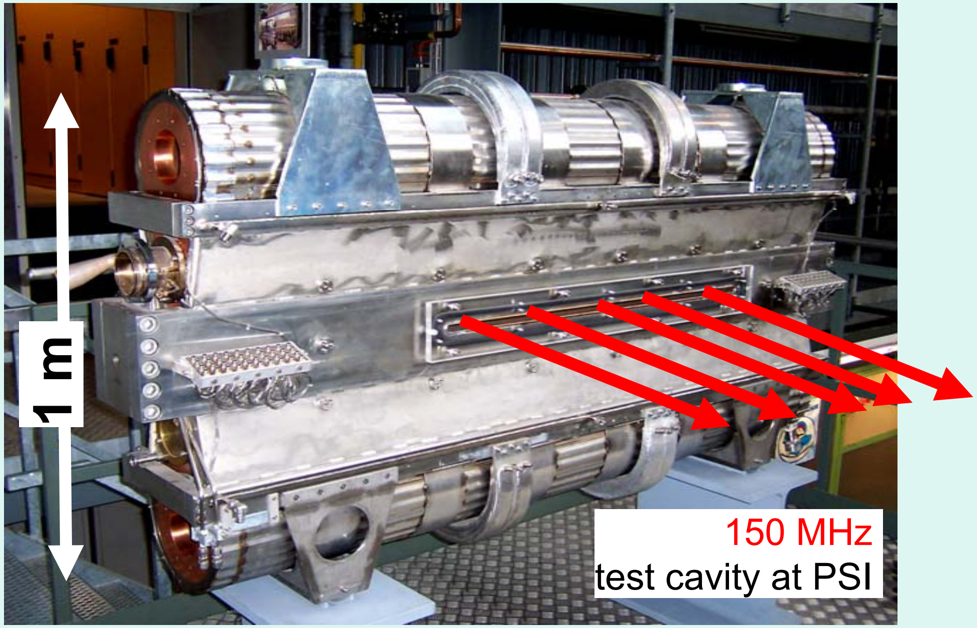
+ magnet less problematic
+ relatively short
+ coil can add to gradient
+ rotate magnet => incr. ν_z

an option: 2.5→3.2 T

Design issues: RF system

RF frequency	92 MHz; 3 single gap cavities, 600 kV
ΔE per turn	~ 0.9 MeV/nucl at extraction

"Scaled 150 MHz test cavity":
Height 1.0 m→1.5 m



<u>Advantages of single gap :</u>

- high ΔE per turn: 3x**600**x½ **keV**
- less space azimuthally
- smallest vacuum volume

=> high injection and extraction efficiencies are expected

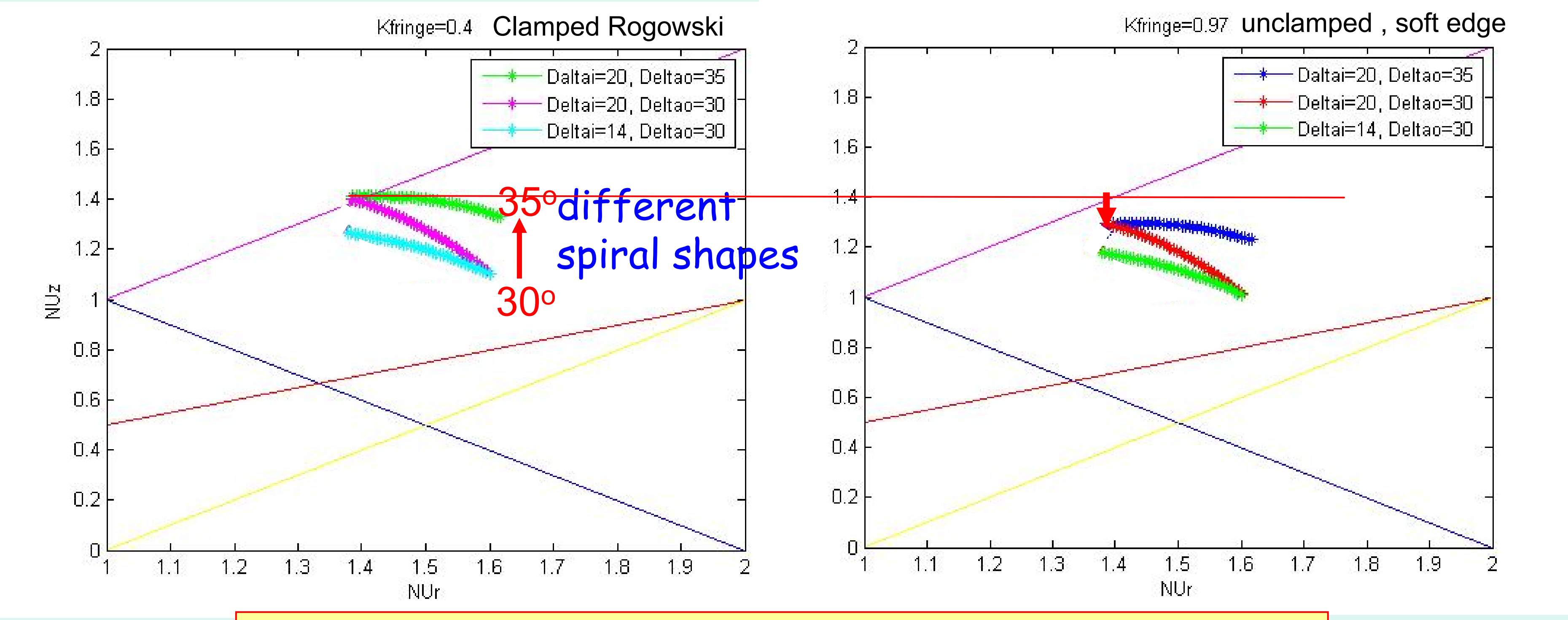
Tune sensitivity calculations

Betatron frequencies $\nu_{r,z}$

Calculated from Phase advance μ in 1 sector: $$\nu_{r,z} = \frac{n_{\sec} . \mu_{r,z}}{2\pi}$$

Sharp fringe field

Soft edge fringe field

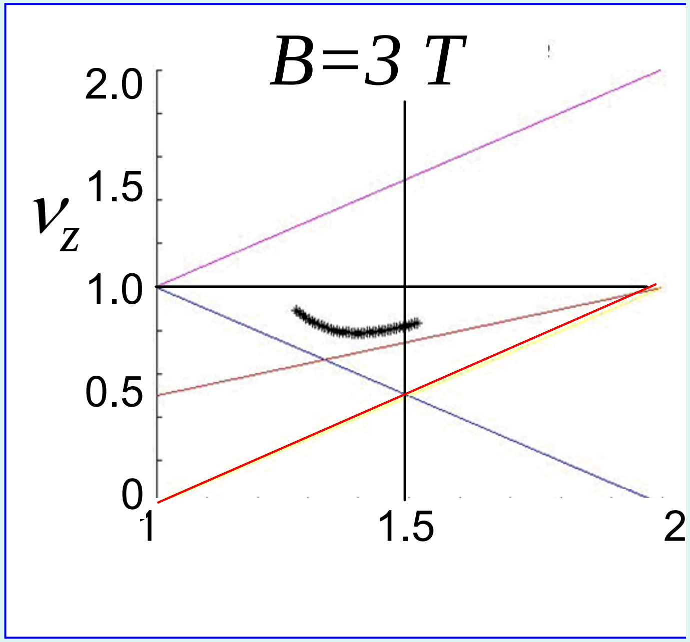


=> Ample possibilities for optimization !

Tune diagrams of booster options

3T homog. field, h=12

Spiral max= 35°



vr=vz
vr+vz=2
vr=2vz
vr-vz=1

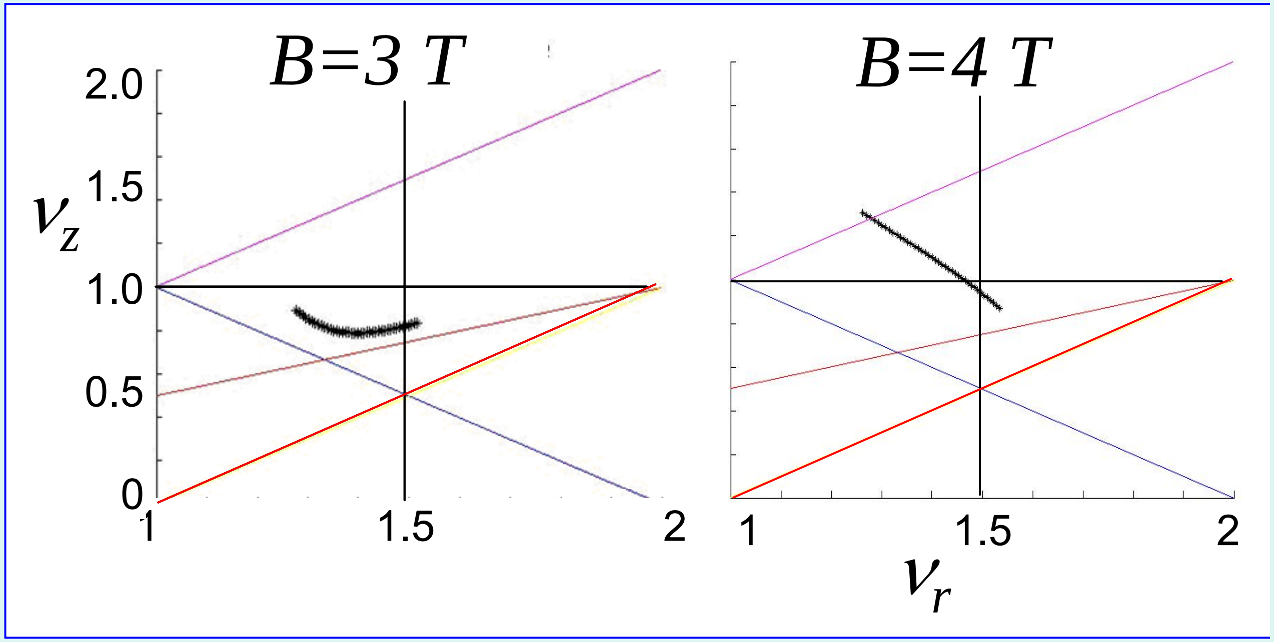
Tune diagrams of booster options

3T homog. field, h=12

Spiral max= 35°

4T homog. field, h=12

Spiral max= 15°



vr=vz
vr+vz=2
vr=2vz
vr-vz=1

Tune diagrams of booster options

3T homog. field, h=12

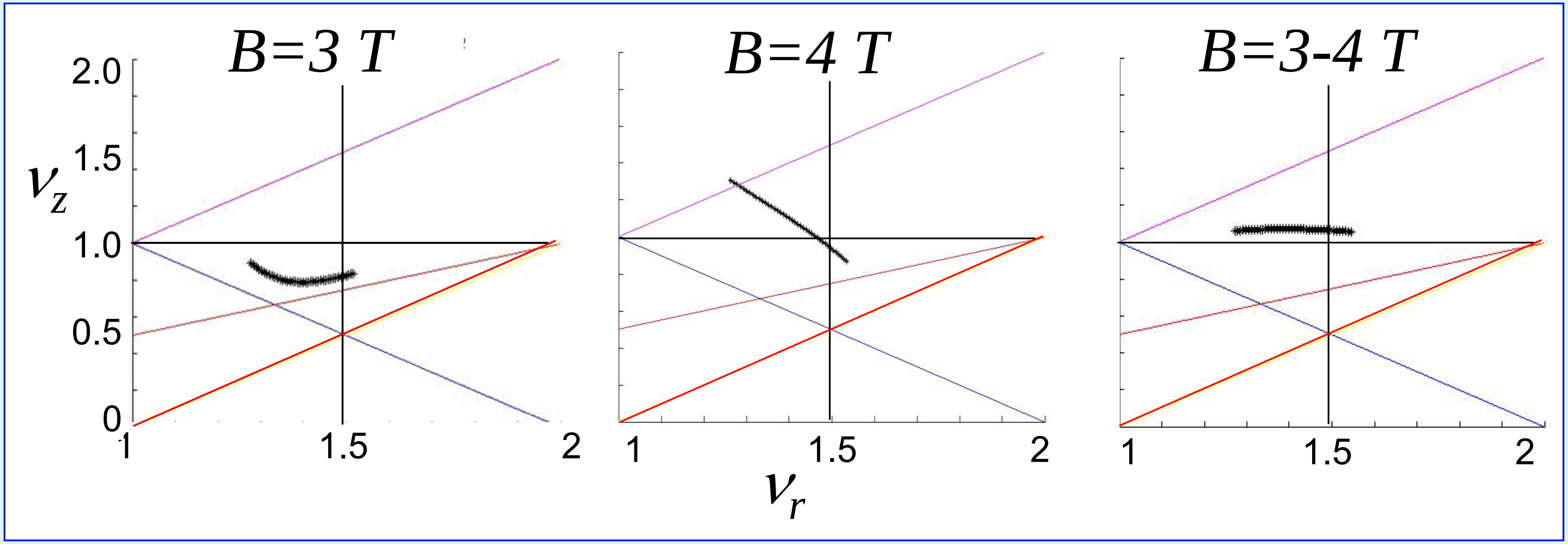
Spiral max= 35°

4T homog. field, h=12

Spiral max= 15°

3-4T linear field, h=12

No spiral



vr=vz
vr+vz=2
vr=2vz
vr-vz=1

⇒ far away from dangerous resonances

⇒ tune diagram easy to optimize

⇒ $\nu_r \approx 1.5$ for injection and extraction: 90° phase adv/sector

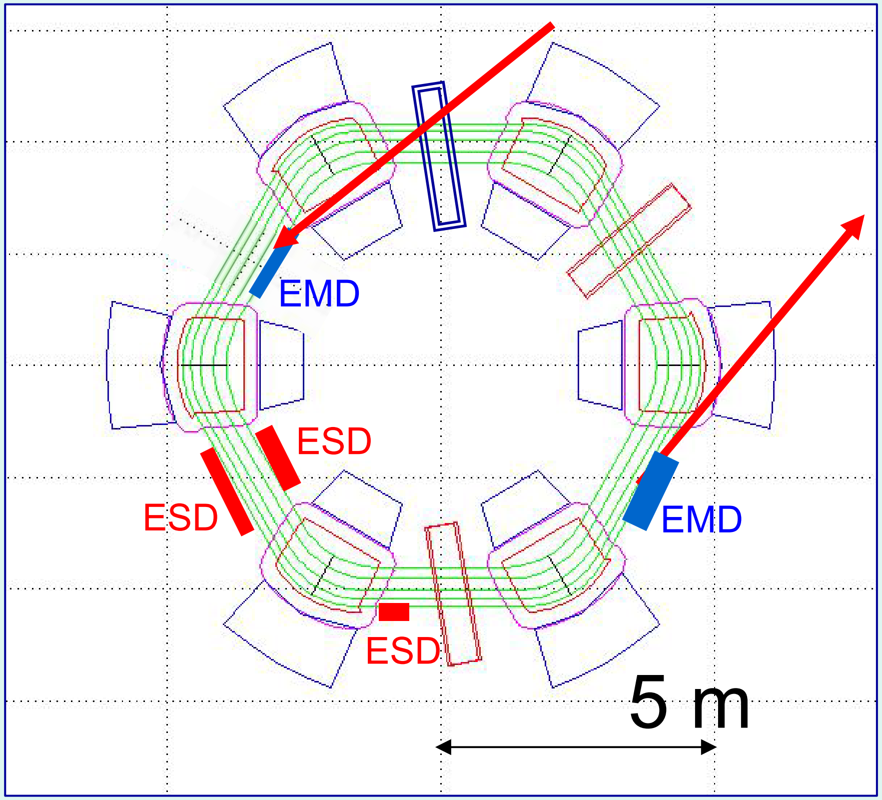
⇒ **robust design** of beam dynamics

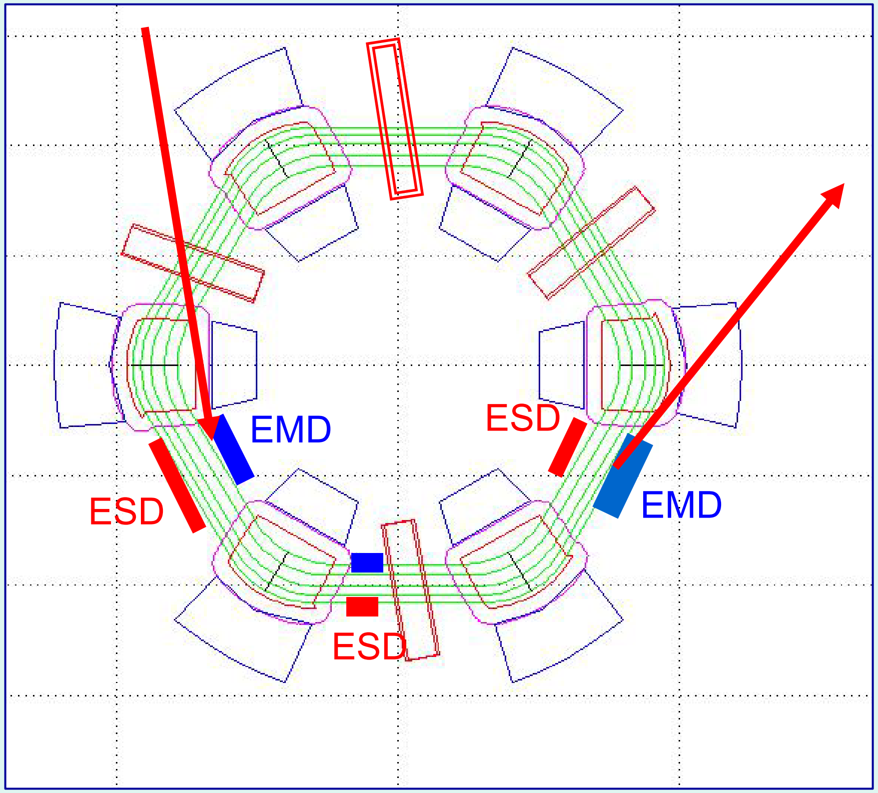
Injection/ Extraction scenarios: use ν_r=1.5

orbit separation at inj/extr :

2.4 / 2.5 mm   3.1 / 3.6 mm

3-4 T,   3 cavities (not sym.)   4 cavities



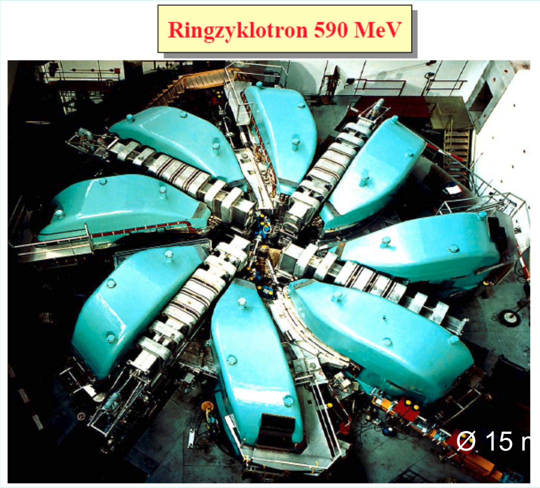


Advantages of proposed system

- 2 phase approach possible (first protons)
- in first phase already α and (up to 12.5 cm) Carbon
- Booster should be **simpler** than single cyclotron

> 95% availability

- Use of proven **well established techniques**:
  - Injector: **existing similar SC** cyclotrons (ACCEL/PSI, Groningen, Catania, East Lansing)
  - Booster: extremely **reliable ring** cyclotrons at PSI (injector 2 + ring cyclotron for neutron source)



- High fields in magnets: **stable and reproducible**
- **Low power** of SC magnets
- Beam dynamics in Booster **“relaxed” and robust:**
  - no problems with resonances
  - many degrees of freedom to design
  - ample vertical focusing
  - large orbit separation => high extraction efficiency

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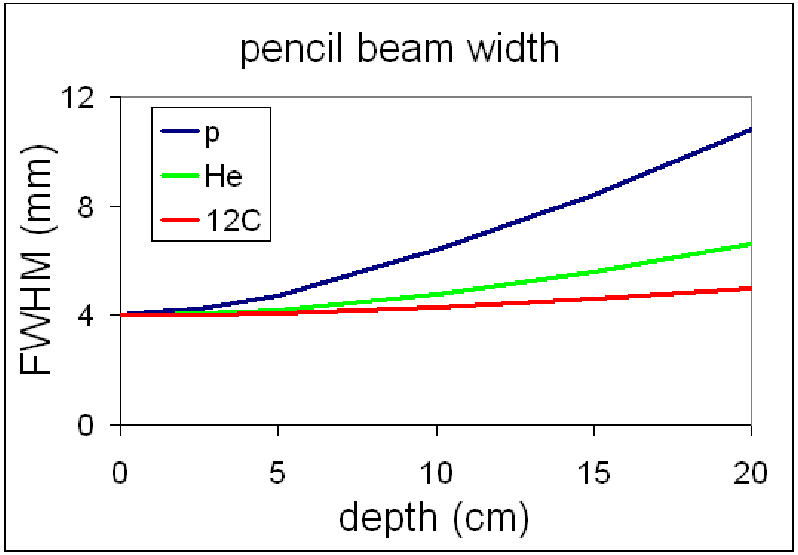
The long road still to go…..

- (parameters of) Injector Cyclotron
- optimize field and sector shape
- magnet design: - field with gradient
  - minimize iron
  - forces
- injection and extraction
- cost estimate
- partner (industry and/or lab)

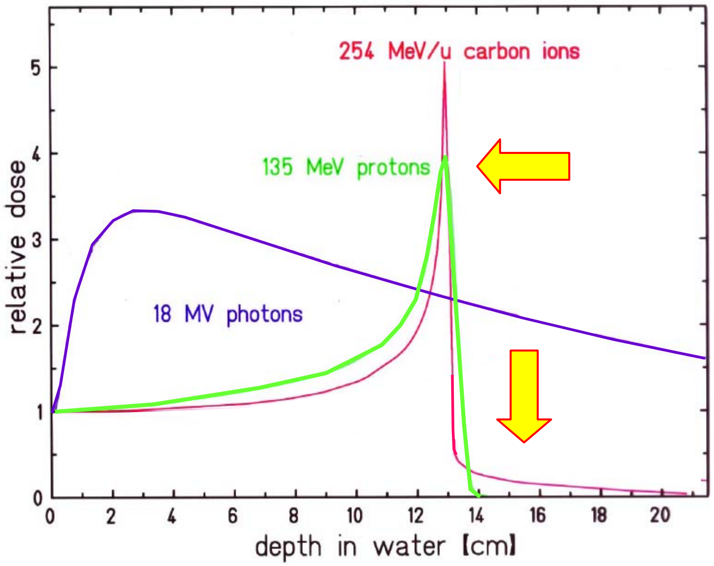
The long road still to go.....

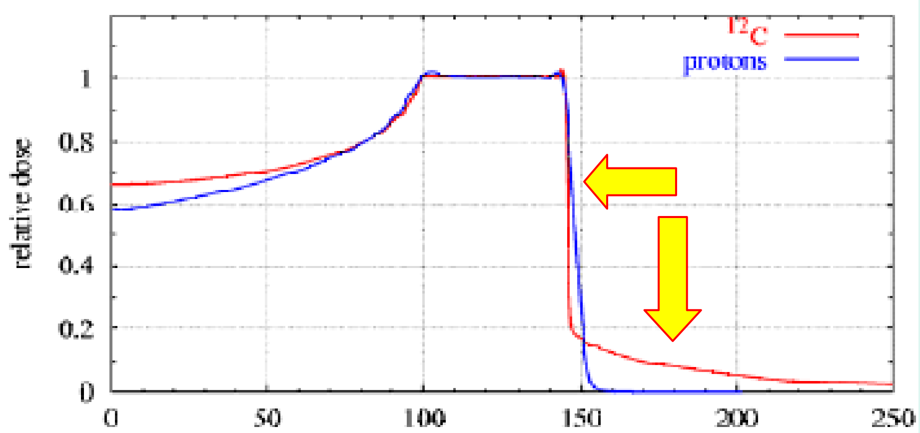
Difference 1 with protons: Dose distribution

transversal (scattering)



depth-dose distribution



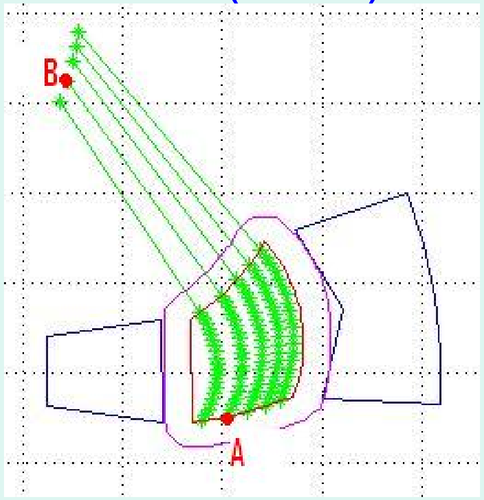


Quick design tool

Matlab program that calculates tunes from basic parameters

=> get a **quick impression** of the design and **sensitivities**

Tunes calculated from **transport matrix** M_{sec} of 1 sector (A→B):



$$M_{\sec} = M_{drift} * M_{exit} * M_{bend} * M_{entrance}$$

Phase advance μ in 1 sector:

$$\mu = \arccos(\frac{1}{2} trace(M_{\sec}))$$

$$\nu_{r,z} = \frac{n_{\sec} . \mu_{r,z}}{2\pi}$$