GaToroid

A Novel Concept for a Superconducting Compact and Lightweight Gantry for Hadron Therapy

Presented by L. Bottura

IOP - Workshop on Accelerator Technology for Particle Therapy
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The starting point

- Ion therapy gantries are **massive**, because of:
  - Required integral bending field and aperture, resulting in large (size and weight) magnets
  - Stability requirements during rotation, calling for a stiff and heavy structure
- Basic idea:
  - **Use superconductors** to increase the bending field in large bore magnets (increase acceptance)
    - More compact magnets, weight reduction, energy efficiency
  - Devise a **magnetic configuration which does not need to be rotated** to focus beams on the patient
    - Reduce the stability requirements on the gantry, hence mass and footprint

Outline

- The idea
- Development of the idea
  - Beams in a toroidal field
  - Toroidal magnet design
  - Vector magnet design
  - Beam tracking studies
- Features and futures
- Summary

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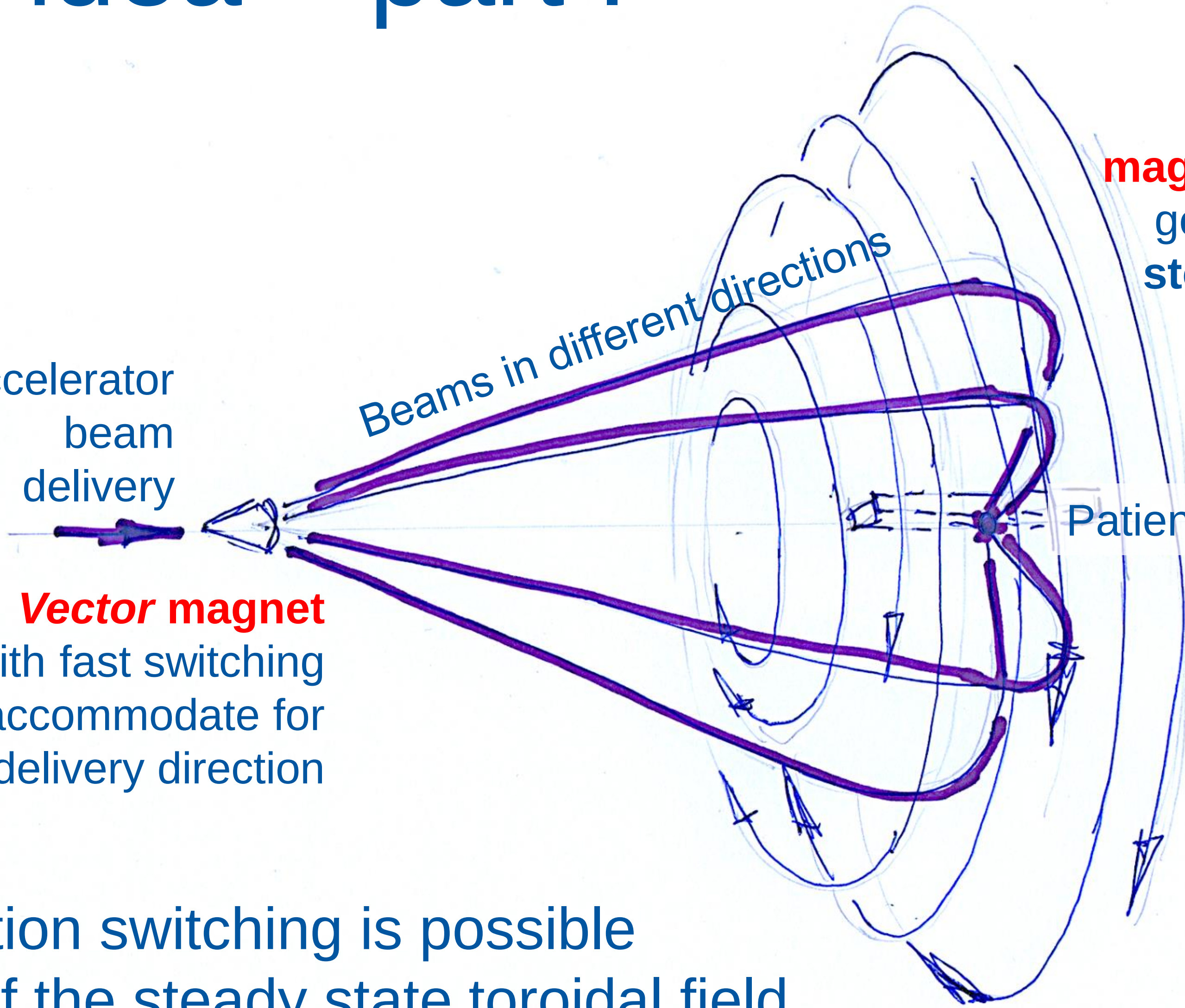
The idea – part I



Toroidal magnetic field generated in **steady-state**

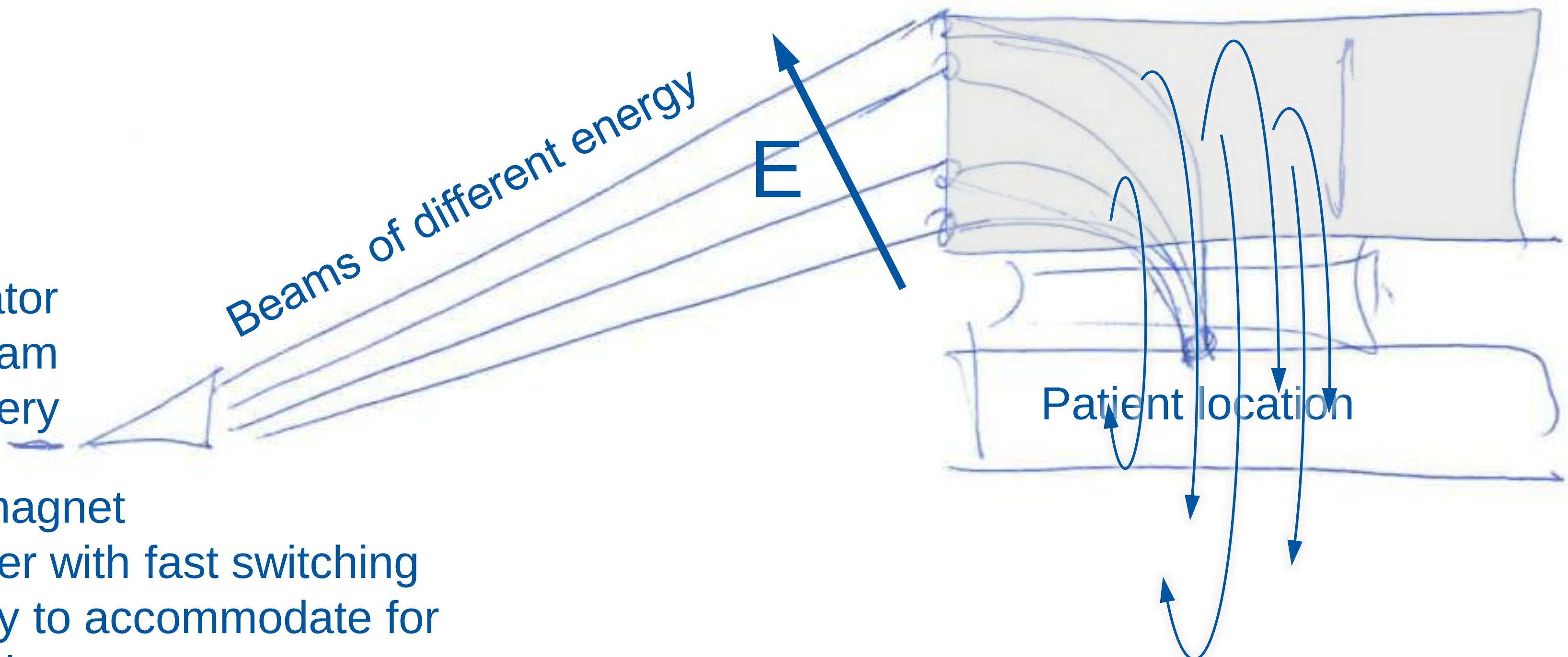
Accelerator beam delivery

***Vector* magnet**
X-Y kicker with fast switching capability to accommodate for change of delivery direction

Fast direction switching is possible because of the steady state toroidal field

The idea – part II

Large acceptance superconducting magnet with **toroidal periodicity** operated in **steady-state**



Accelerator beam delivery

Vector magnet
X-Y kicker with fast switching capability to accommodate for energy change

Fast energy switching possible because of steady state field and large acceptance

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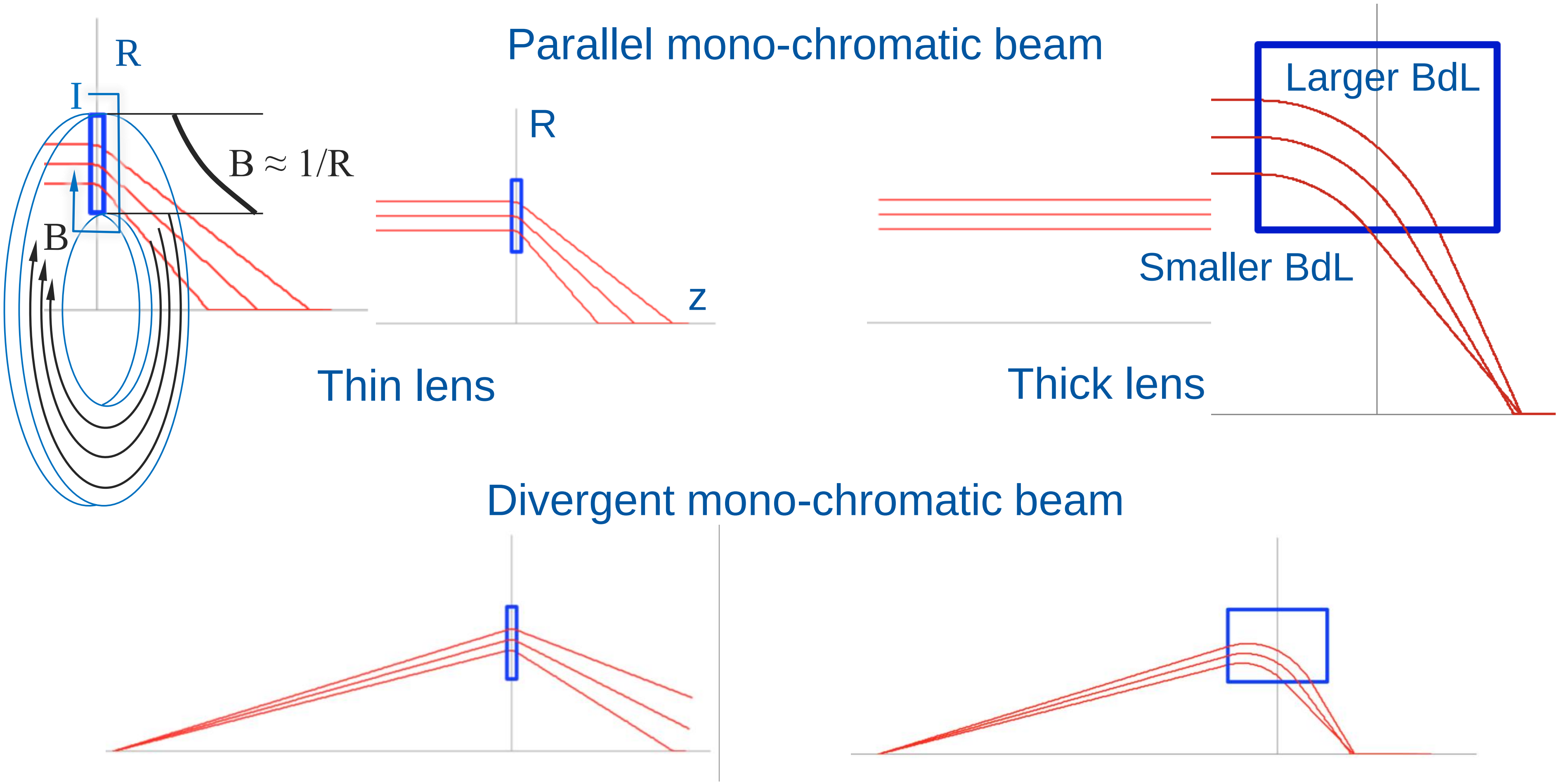
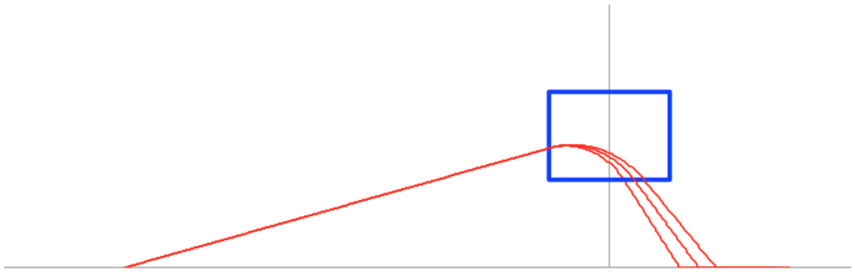
Focusing effect of a toroidal field

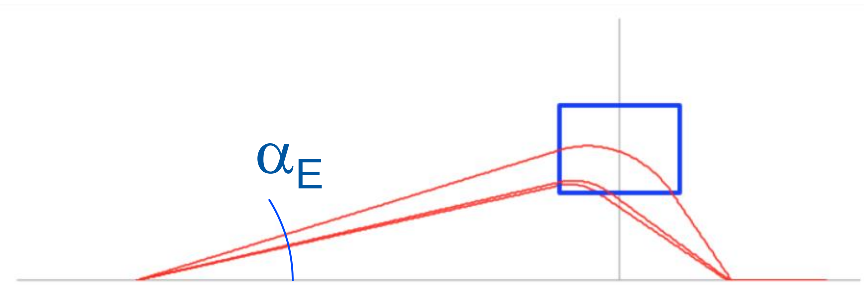


A toroidal field of finite length has a net in-plane focussing effect on a mono-chromatic beam (due to the BdL)

Focusing effect of a toroidal field

Parallel and divergent beams of different p/q





Beams of different p/q originating at the same vertex and with identical angle are focused on different spots

It is possible to focus the beams on one spot by choosing the initial angle of the beam profiting from the BdL effect

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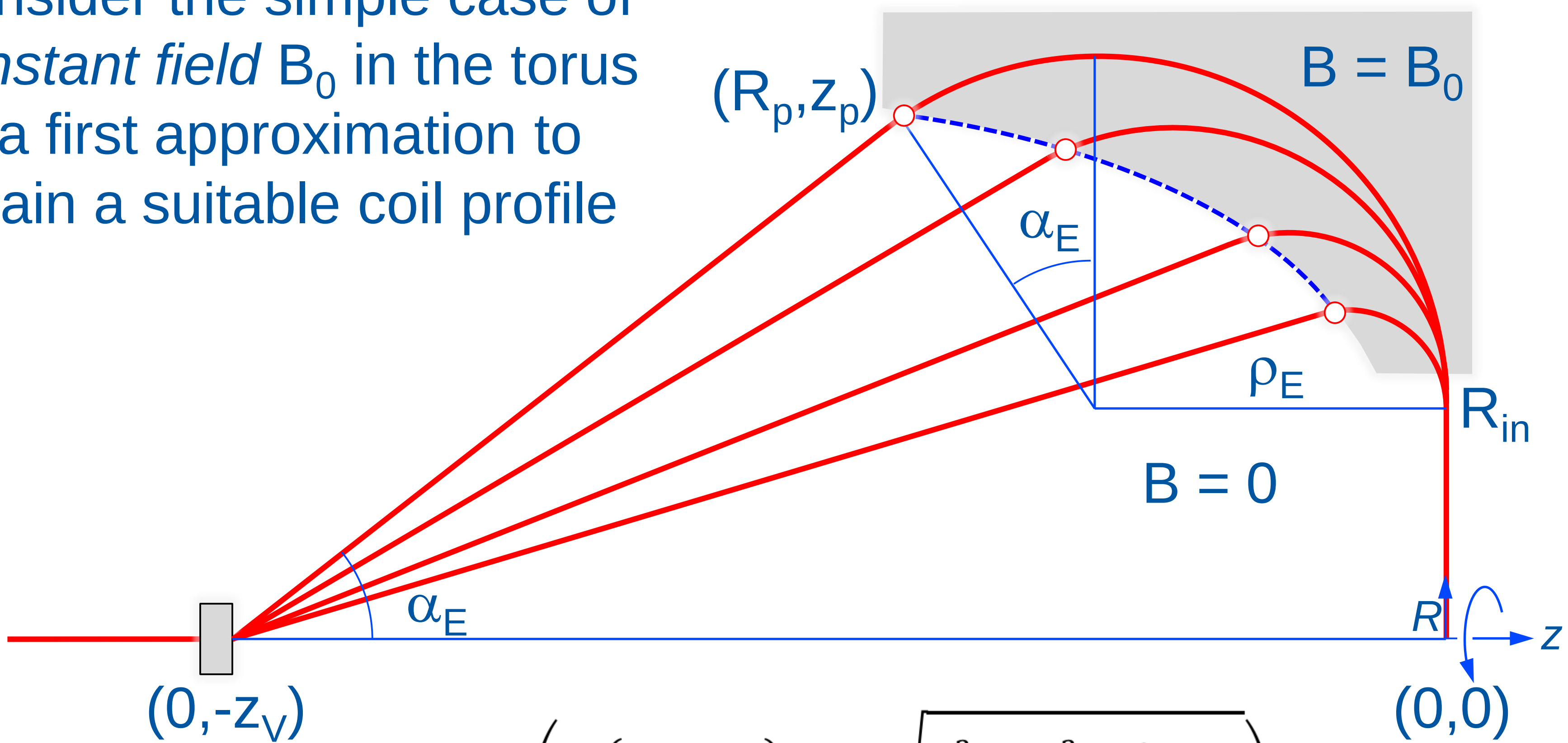
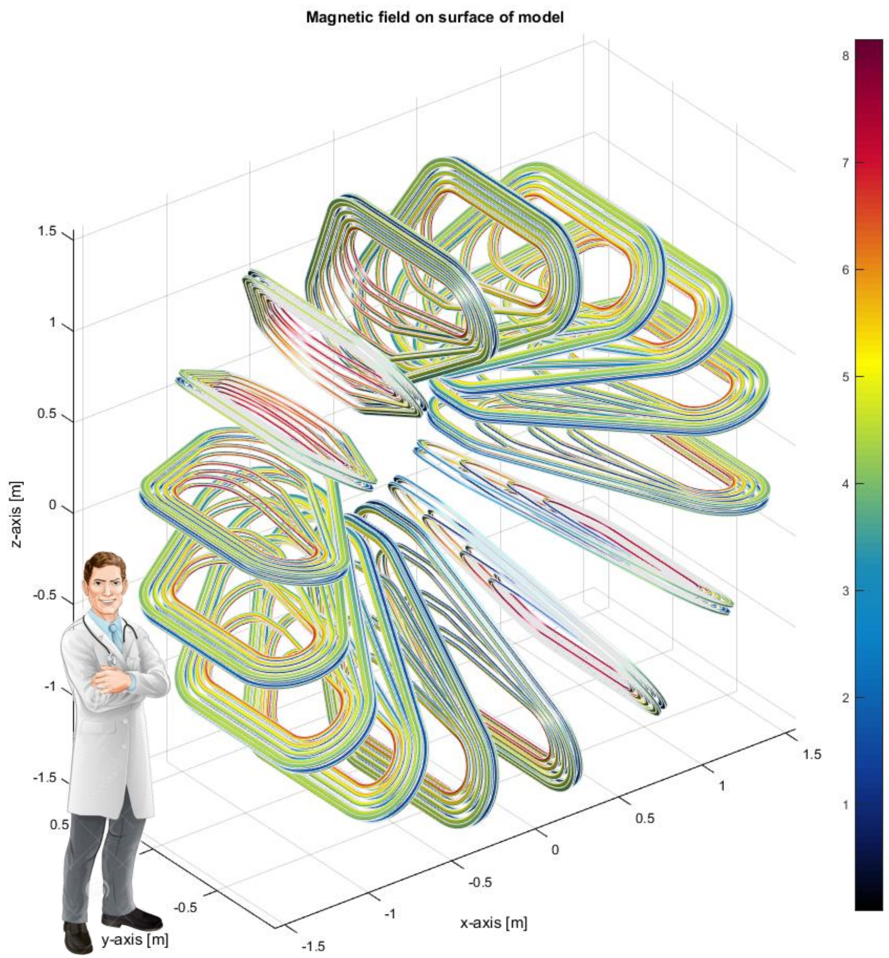
Ideal coil profile

Consider the simple case of *constant field* B_0 in the torus as a first approximation to obtain a suitable coil profile



$$\alpha_E = arcsin\left(\frac{\rho_E(z_V-\rho_E)+R_{in}\sqrt{R_{in}^2+z_V^2-2z_V\rho_E}}{(z_V-\rho_E)^2+R_{in}^2}\right)$$

A GaToroid for protons (the smallest possible size)



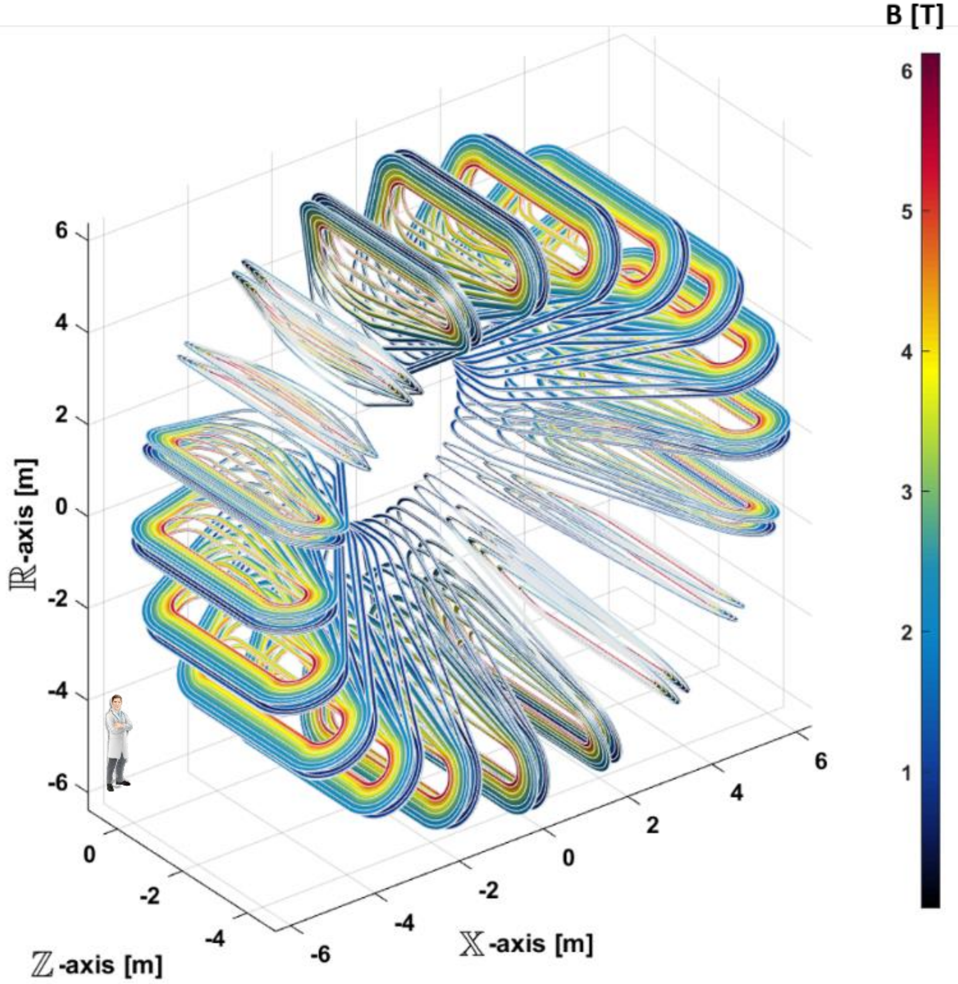
Number of angles	16
Peak magnetic field	8 T
Stored Energy	30 MJ

Coil dimension	1.5 m x 1 m
Torus dimension	1.5 m x 3 m
Bore size	0.8 m
Vector Magnet position	4.5 m

Operating temperature	4.2 K
Operating current	1.8 kA

Estimated total mass	25 tons

A GaToroid for ions (the largest possible size)



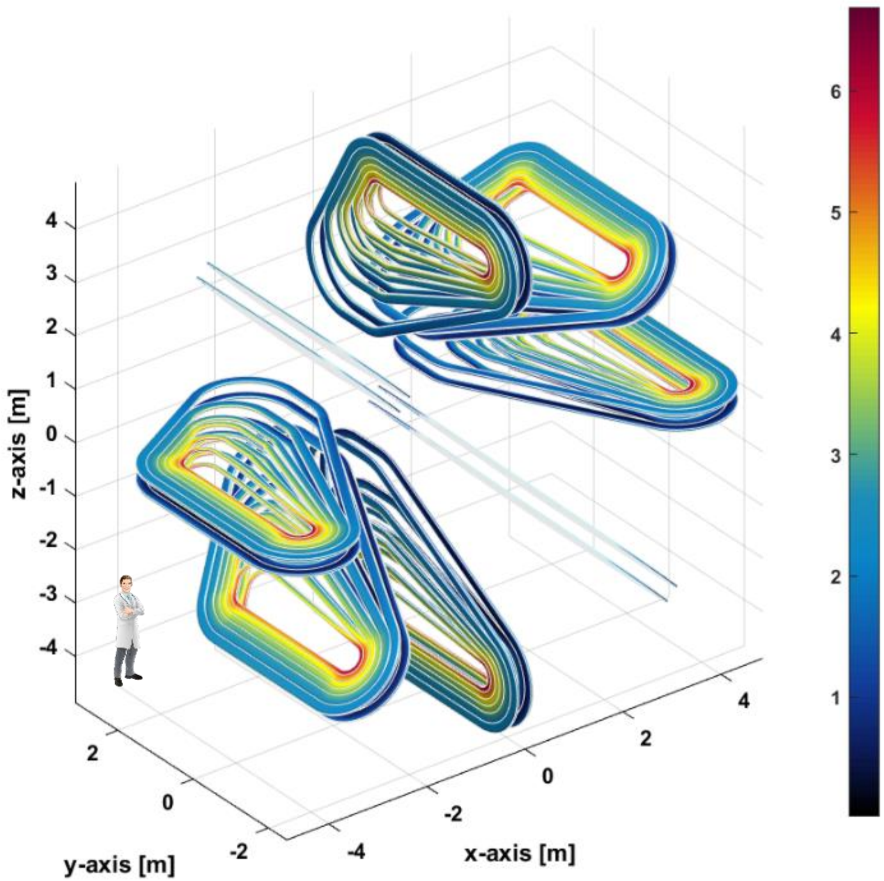
Number of angles	20
Peak magnetic field	6.1 T
Stored Energy	1300 MJ

Coil dimension	5.8 m x 4.5 m
Torus dimension	5.8 m x 12.8 m
Bore size	3.7 m
Vector Magnet position	9.2 m

Operating temperature	4.2 K
Operating current	10.8 kA

Estimated total mass	300 tons

A GaToroid for ions (medium size)



Number of angles	8
Peak magnetic field	6.7 T
Stored Energy	420 MJ

Coil dimension	5.6 m x 3.7 m
Torus dimension	5.6 m x 9.7 m
Bore size	2.25 m
Vector Magnet position	4.2 m

Operating temperature	4.2 K
Operating current	10.8 kA

Estimated total mass	130 tons

Single particle tracking

Excellent acceptance and iso-centric properties

A typical session

Courtesy of CERN media service

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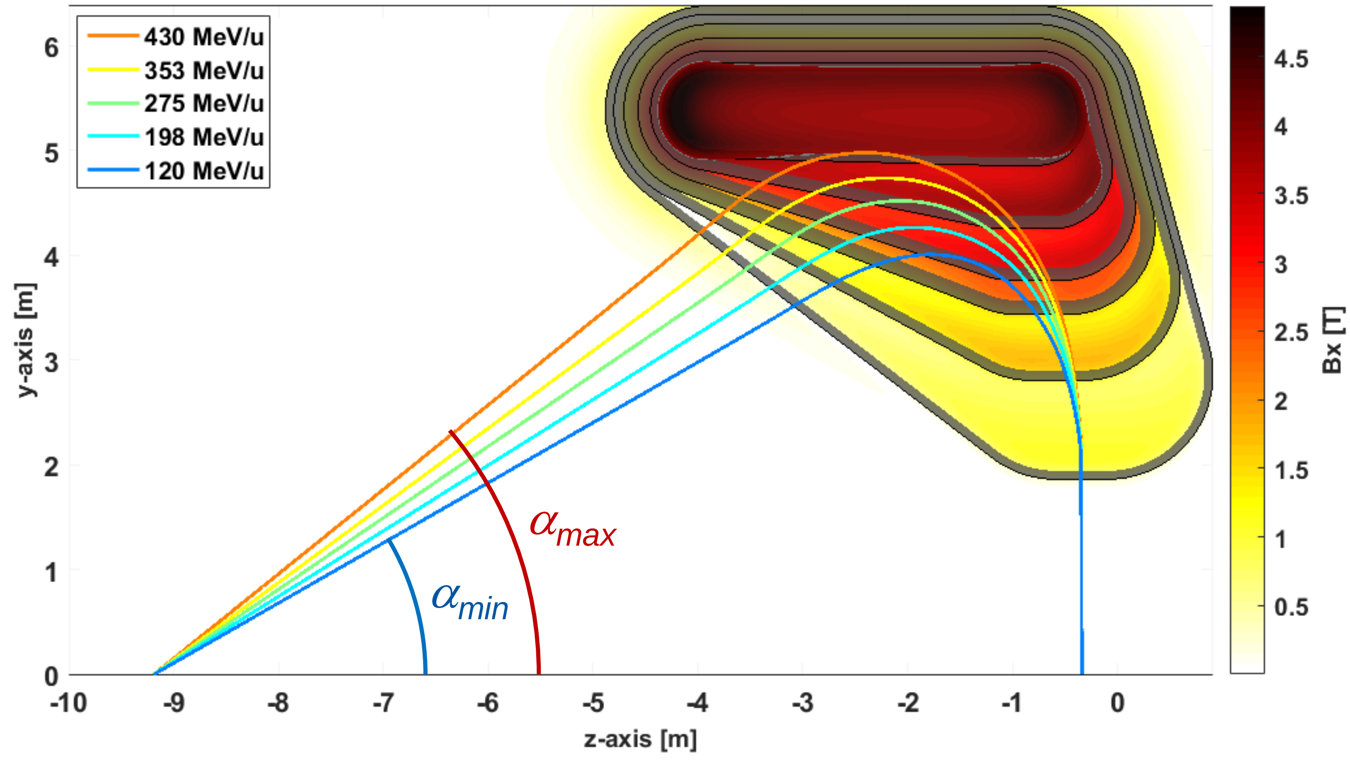
Vector magnet functional spec



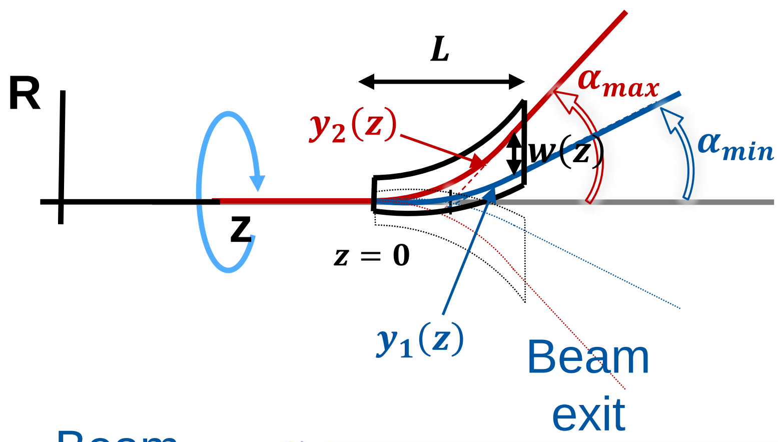
Proton: ° ($\pm 2°$ for scanning along z direction), beam rigidity $(B\rho)_{min} = 1.2\ T.m$

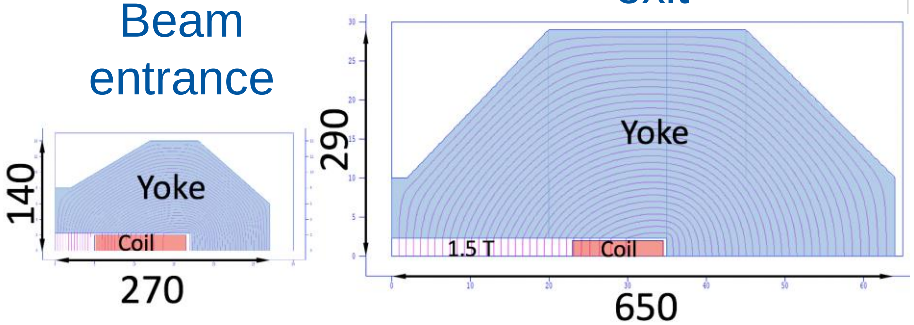
Carbon-ion : $\alpha_{max} = 33° + 2° \alpha_{min} = 17° - 2° = 15 = 35°$ ($\pm 2°$ for scanning along z direction), beam rigidity $(B\rho)_{max} = 6.6\ T.m$

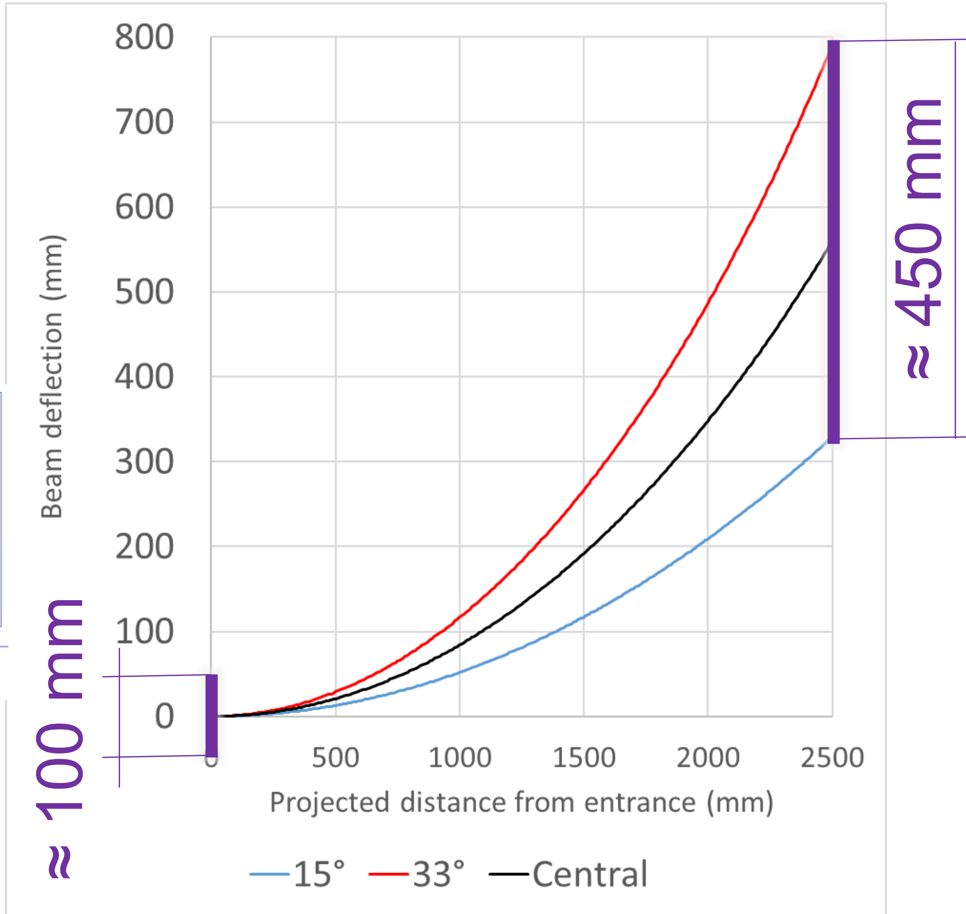
Scanning and accuracy

- Scanning 300 mm (sagittal) x 200 mm (transverse) requires kicks at the vector magnet of the order of ± 45mrad (polar) x ±15 mrad (azimuthal)
  - Main challenges are the width of the beam windows and the design of a downstream scanner magnet for the polar kick
- A 1 mm position accuracy requires a precision in the kick of the order of **0.2 mrad** in both planes
  - **Main challenge is the precision of the vector magnet (order of 2 units absolute)**

A rotating vector magnet







The mass of a tapered magnet is < 5 tons

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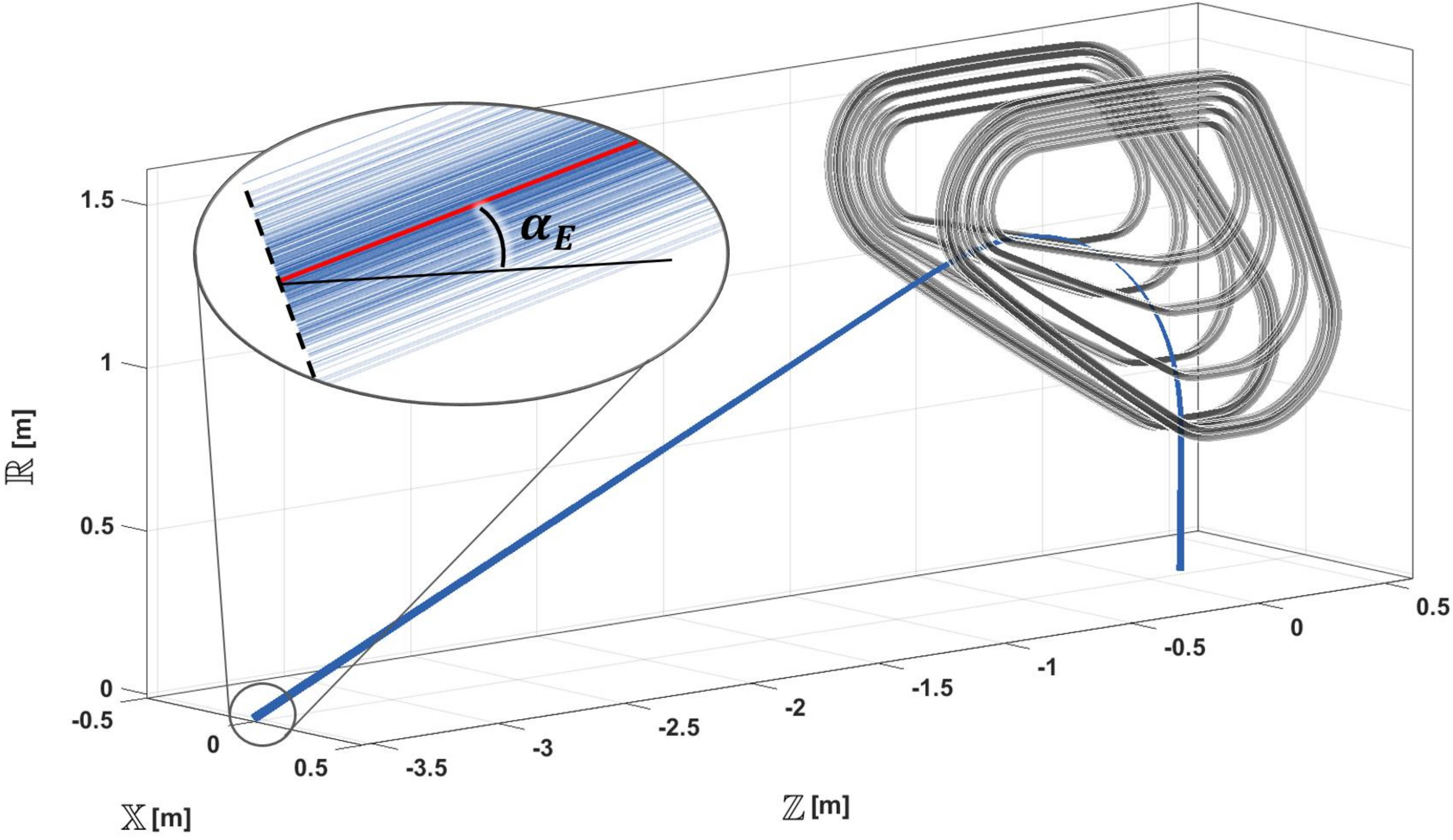
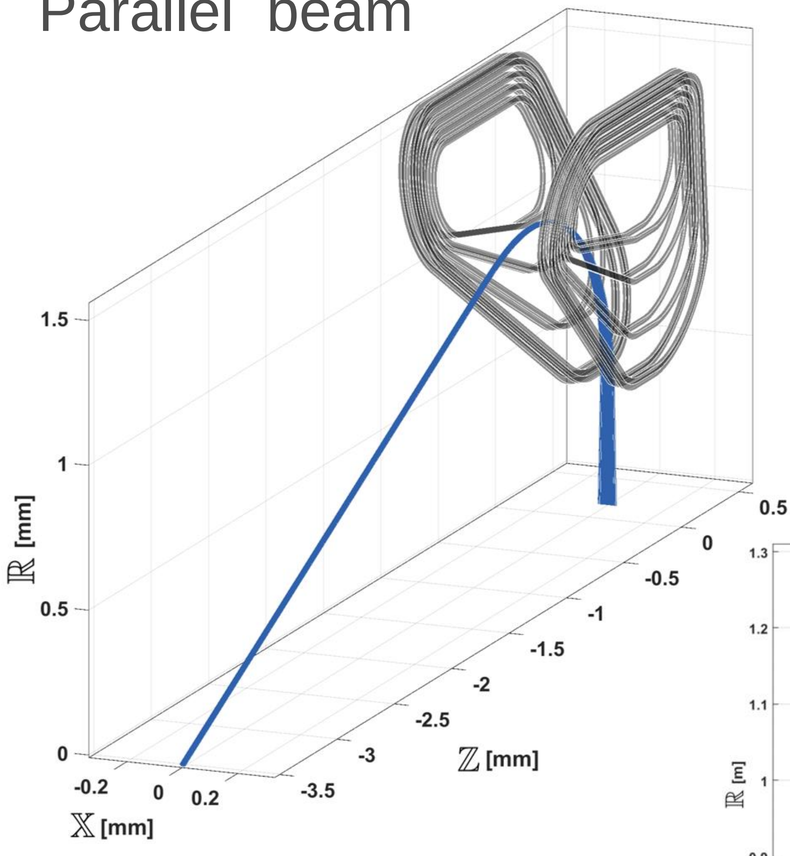
3-D Tracking

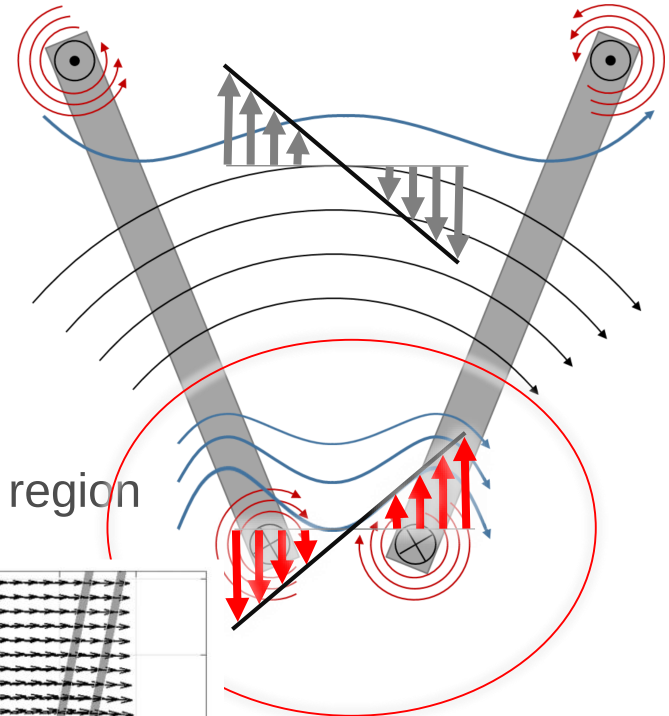


3-D Tracking

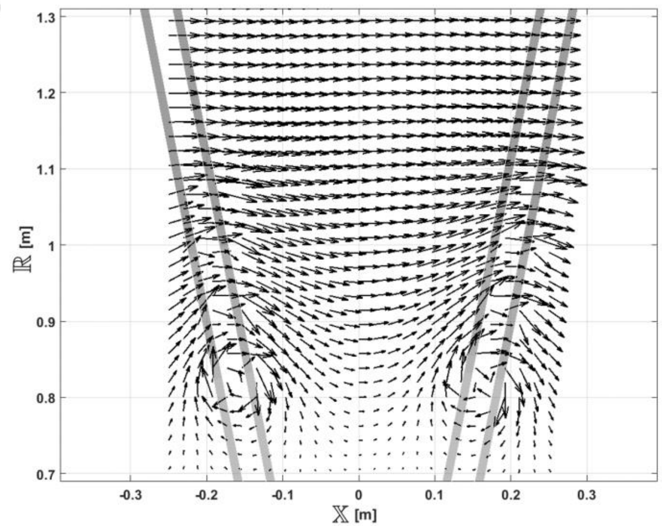
Parallel beam



Focusing region



Defocusing region



Defocusing effect of the particle beam

3-D Tracking

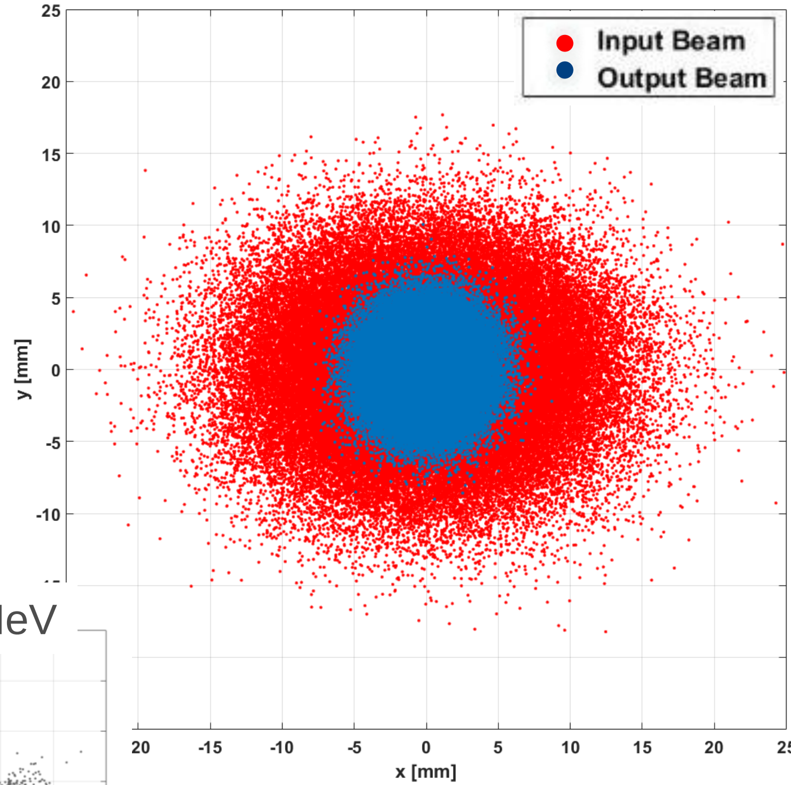
Convergent beam as input

$$\alpha_X = 9.5 \quad \beta_X = 35$$
$$\alpha_Y = 4.8 \quad \beta_Y = 20$$

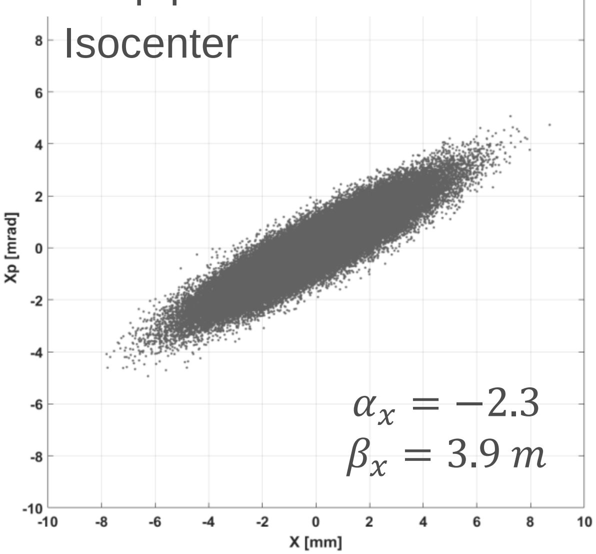
$\boldsymbol{\beta}$ → beam size

$\boldsymbol{\alpha}$ → beam divergence

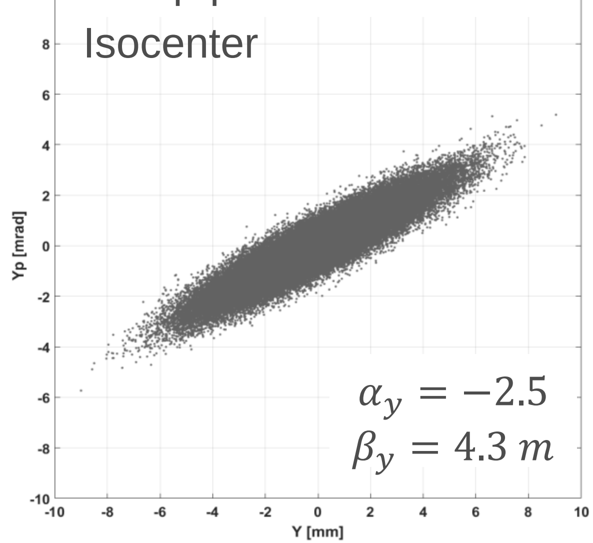
X-Y plane – 250 MeV



X-Xp plane – 250 MeV



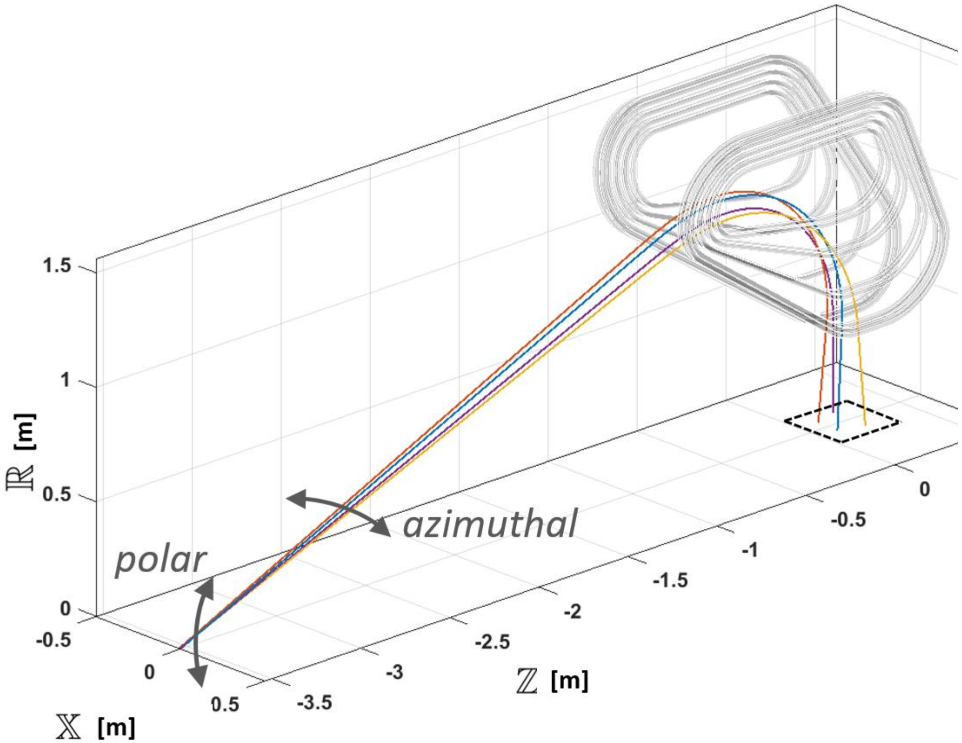
Y-Yp plane – 250 MeV



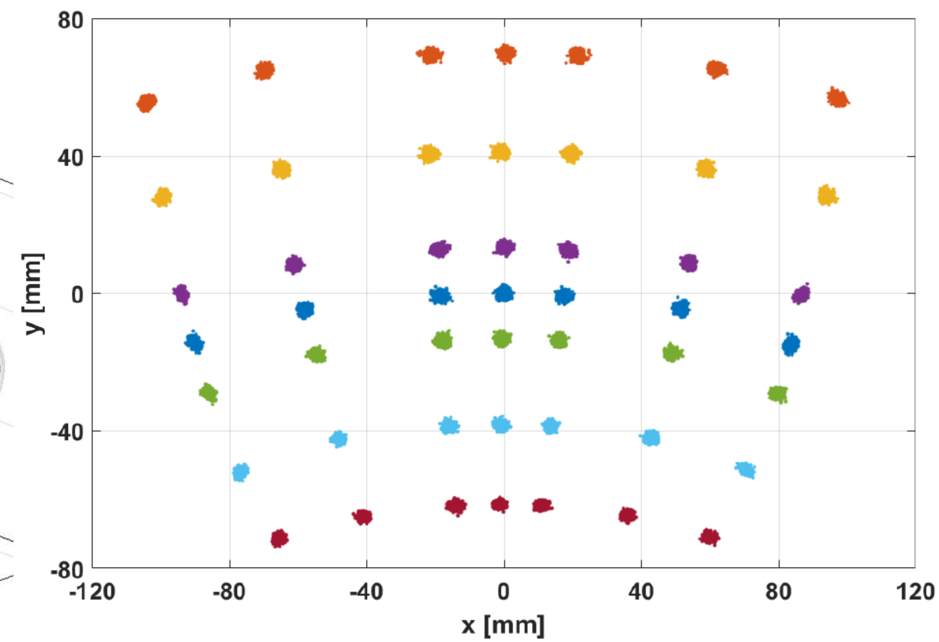
Painting (pencil scan)

Polar: ±45 mrad → ± 150 mm
Azimuthal: ±15 mrad → ± 100 mm

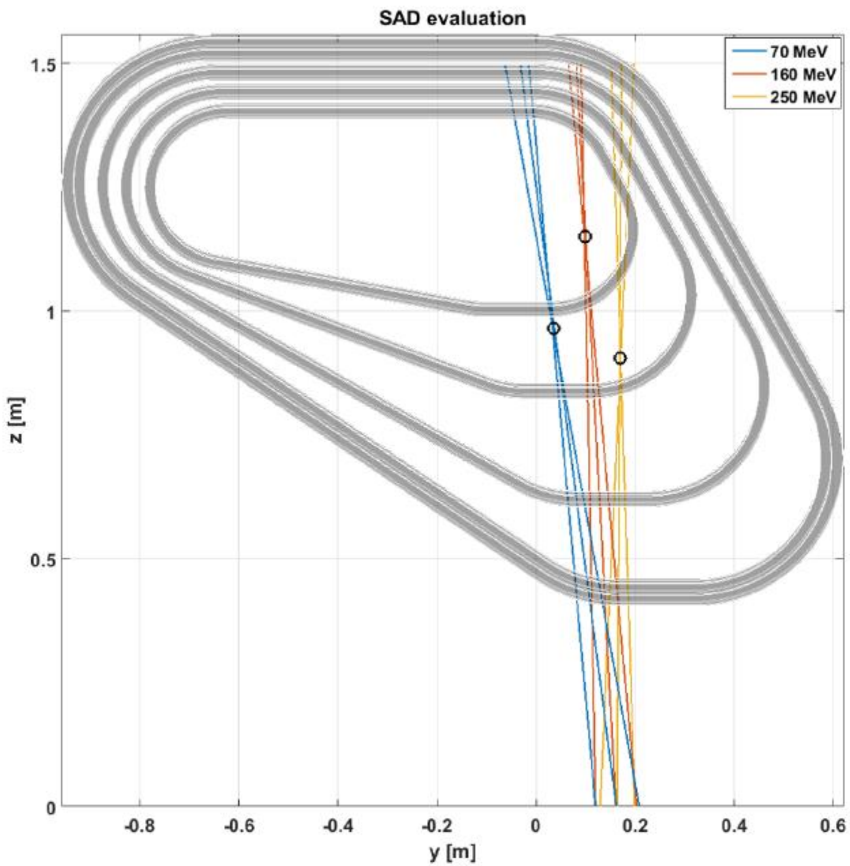
<u>Downside</u>:
The vector must be very accurate

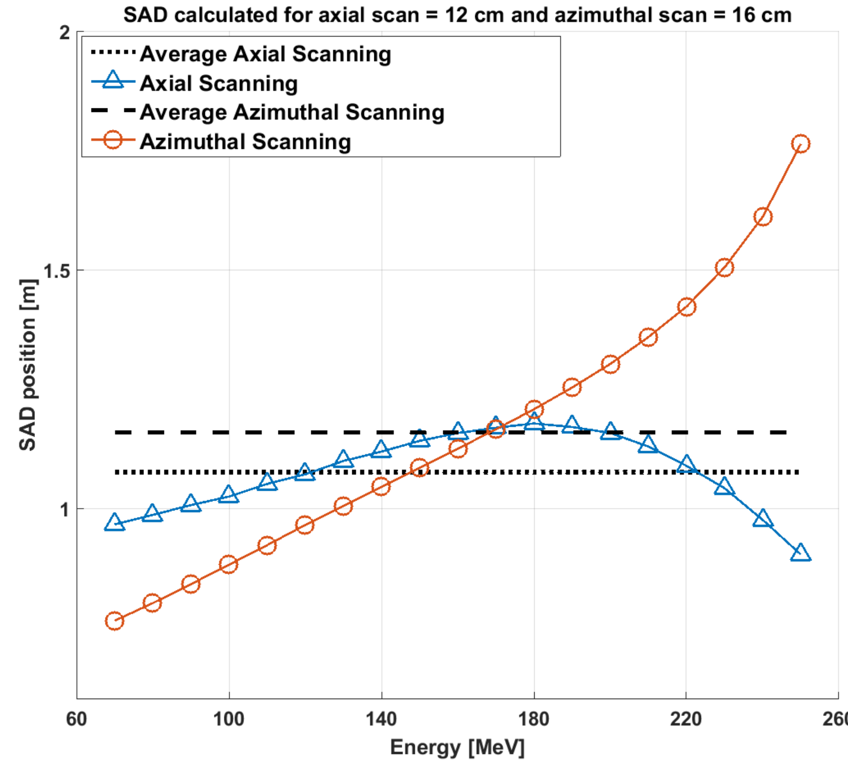


Natural response matrix at **isocenter**



Painting (SAD)





SAD is quite small (~ 1m)* and variable with energy

→ Further optimization required on the coil shape

The Source-to-Axis Distance (SAD): Virtual point source to the isocentre

*Similar to the SAD of gantries with downstream scanning system

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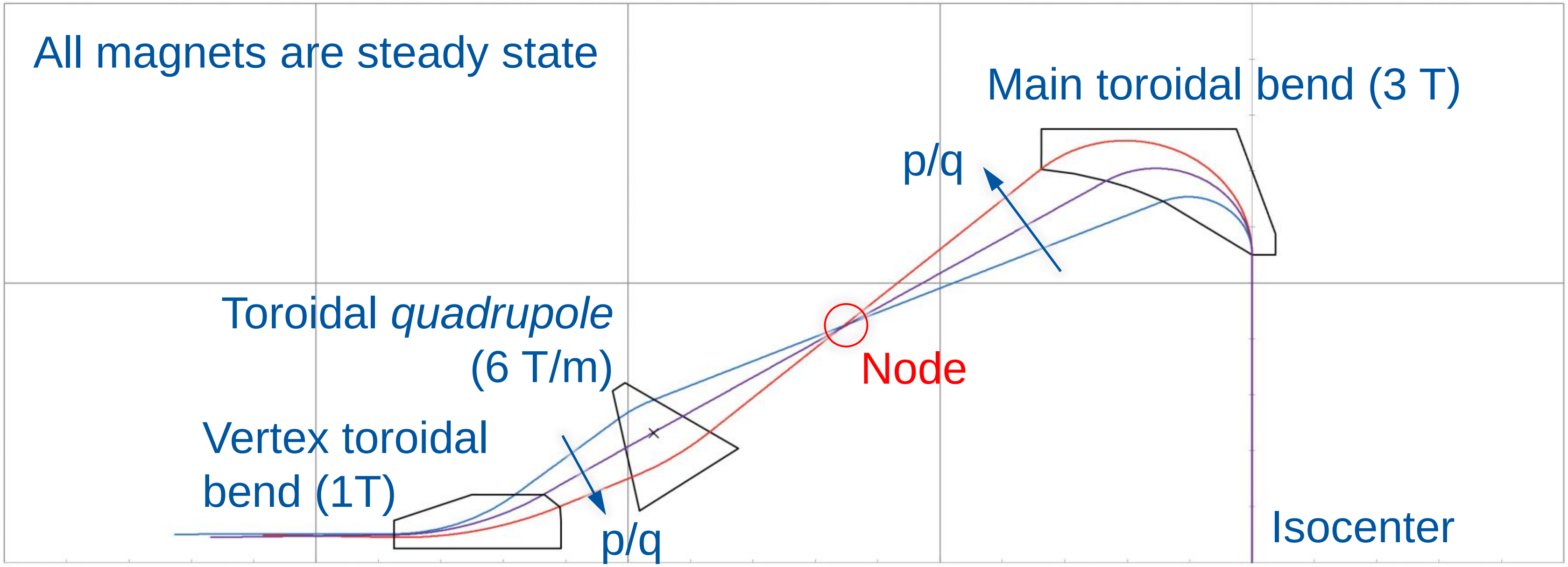
A toroidal transfer line

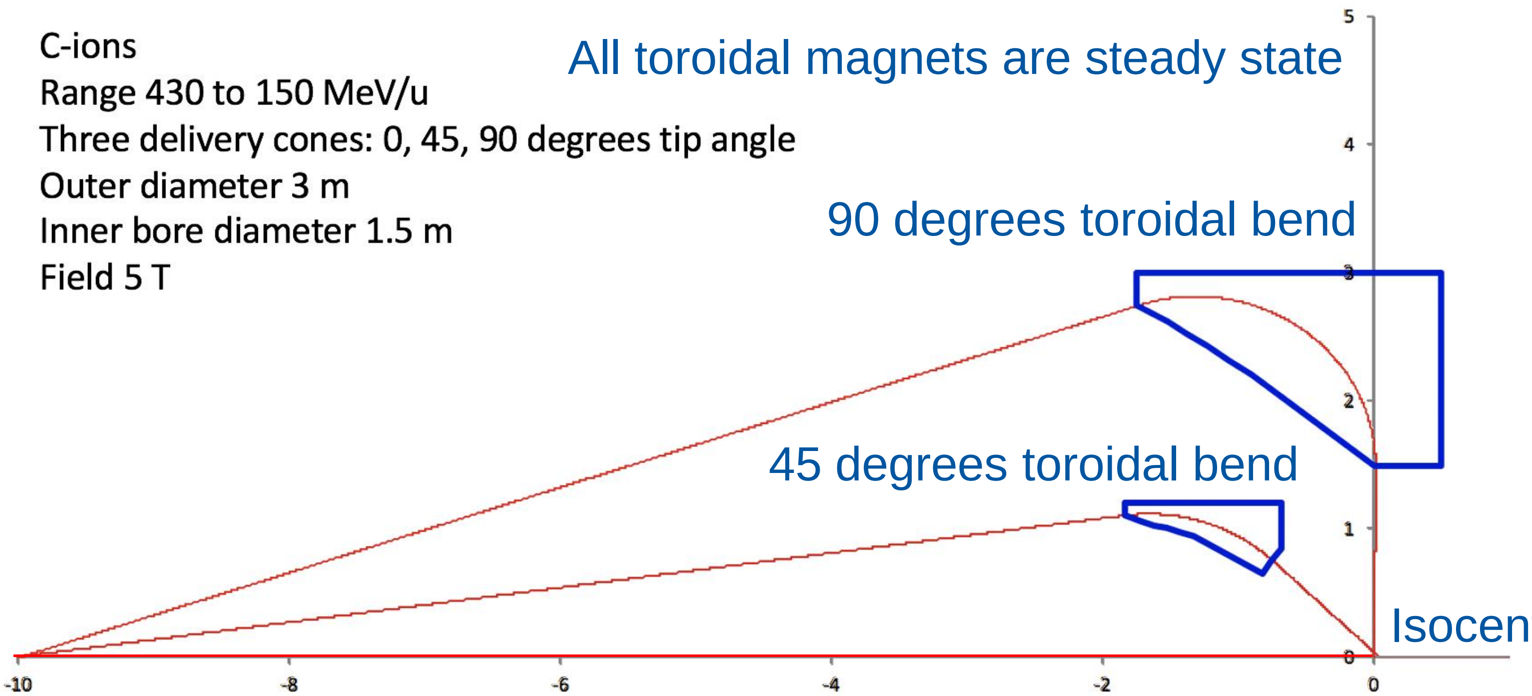


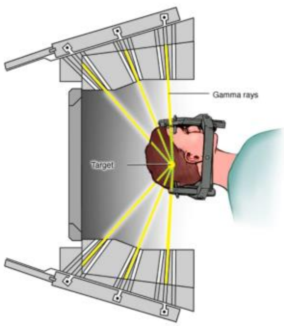
This is the equivalent of a **large acceptance transfer line** which could allow the introduction of scanners and collimators at the nodes and may yield more robust beam transmission properties, also recolving the accuracy issues at the single vector magnet

Additional equipment's (e.g. scanner magnets, collimators) are multiplied

Leksell "hadron knife"

C-ions
Range 430 to 150 MeV/u
Three delivery cones: 0, 45, 90 degrees tip angle
Outer diameter 3 m
Inner bore diameter 1.5 m
Field 5 T



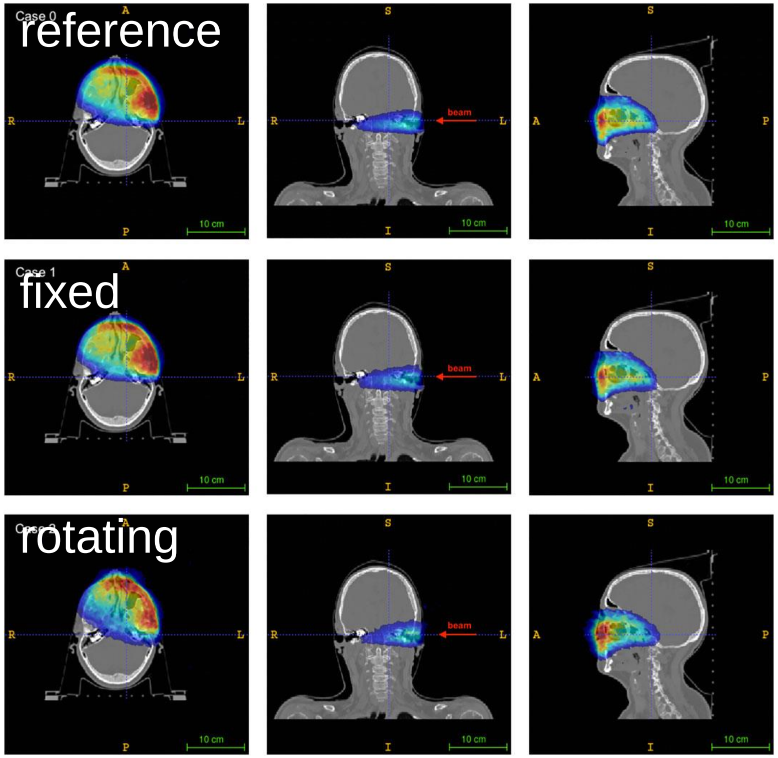


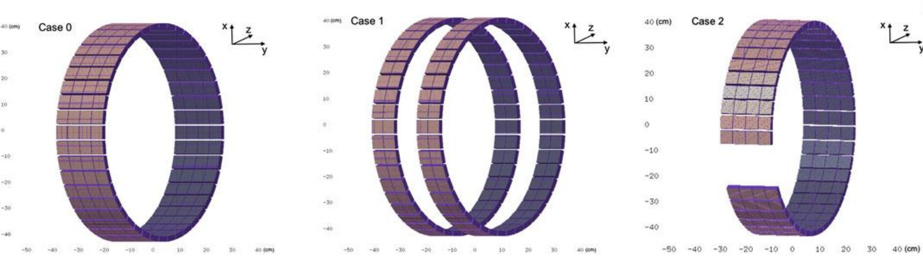
This could provide the possibility to irradiate an arbitrary location from a half-sphere **without moving the patient** inside the magnet

Diagnostics require true 3-D capabilities

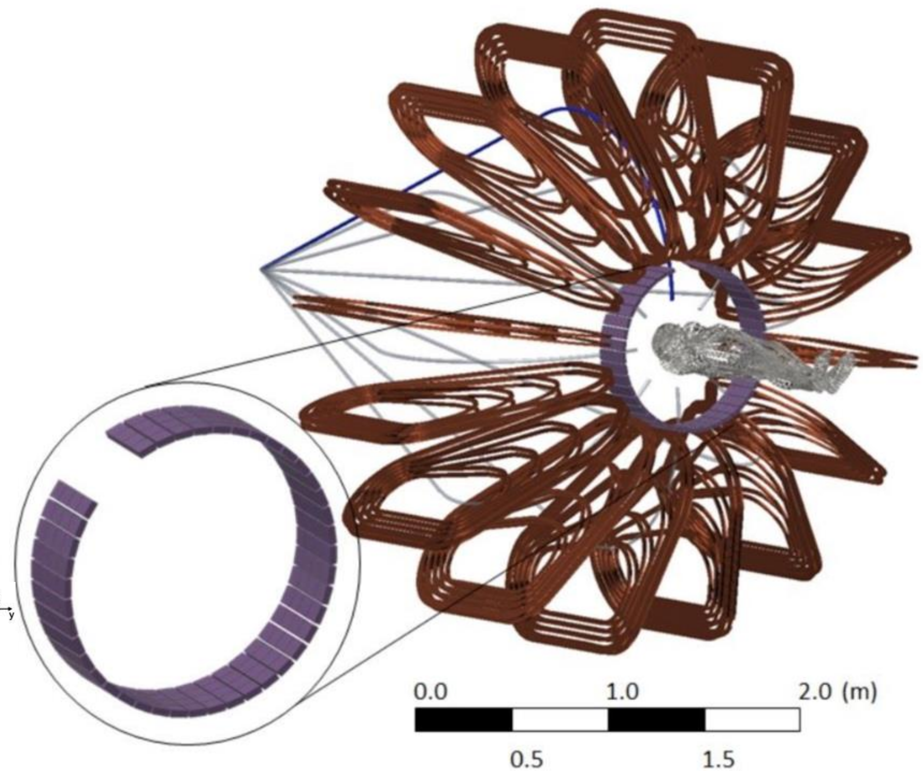
Integrated system

Small bore GaToroid with integrated beam monitoring (UFSD) and online range monitoring (PET)





reference fixed rotating



PET rings

Front. Phys., 30 November 2020, https://doi.org/10.3389/fphy.2020.566679

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Summary – the "+++"

- Static structure, does not require high rigidity and stability for rotation
- Steady state operation, no AC loss, optimal for the use of superconductor, comes with a reliability premium (see HEP detectors as a relevant example)
- High-field design has the potential for reduced foot-print and mass (and cost)

- *A fast dose delivery from multiple angles and energy is a new operating mode, and could be the basis for a major change of treatment planning*

Summary – the "---"

- Discrete delivery angles, limited to (at most) N_{coils} beam lines (typically a few to 20)
- Large stored energy and cold mass volume, slow operation (CD/WU, powering)
- Beam pipe (vacuum) has complex shape and large dimensions (could use cryogenic vacuum)
- All beam position control and accuracy issues in the baseline version are concentrated in the vector magnet unit (see alternative designs)

- *The formalism of beam transport in toroidal fields is not available*

A balance

- It is an intriguing idea
  - Innovative magnetic configuration and beam optics
  - Potential for a change in the operating mode and performance of hadron therapy facilities
- But there is still much work to do
  - Beam optics design (and validation)
  - Connection and matching to the accelerator through the “vector magnet unit” (may be an obsolete concept in the case of the toroidal transfer line)
  - **System integration with the medical environment**
  - And of course, some magnet engineering
- The next level, beyond the proof-of-principle (work on-going) would require focus on a specific and small gantry realization for demonstration purposes

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GaToroid

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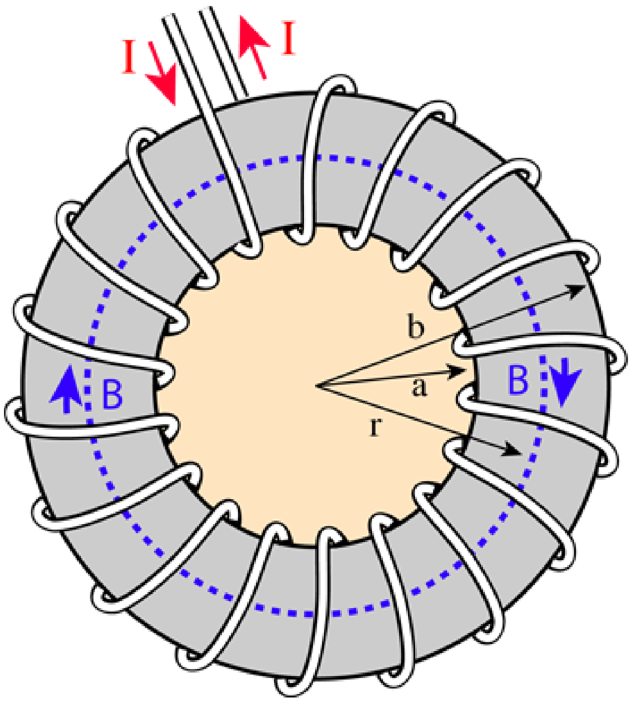
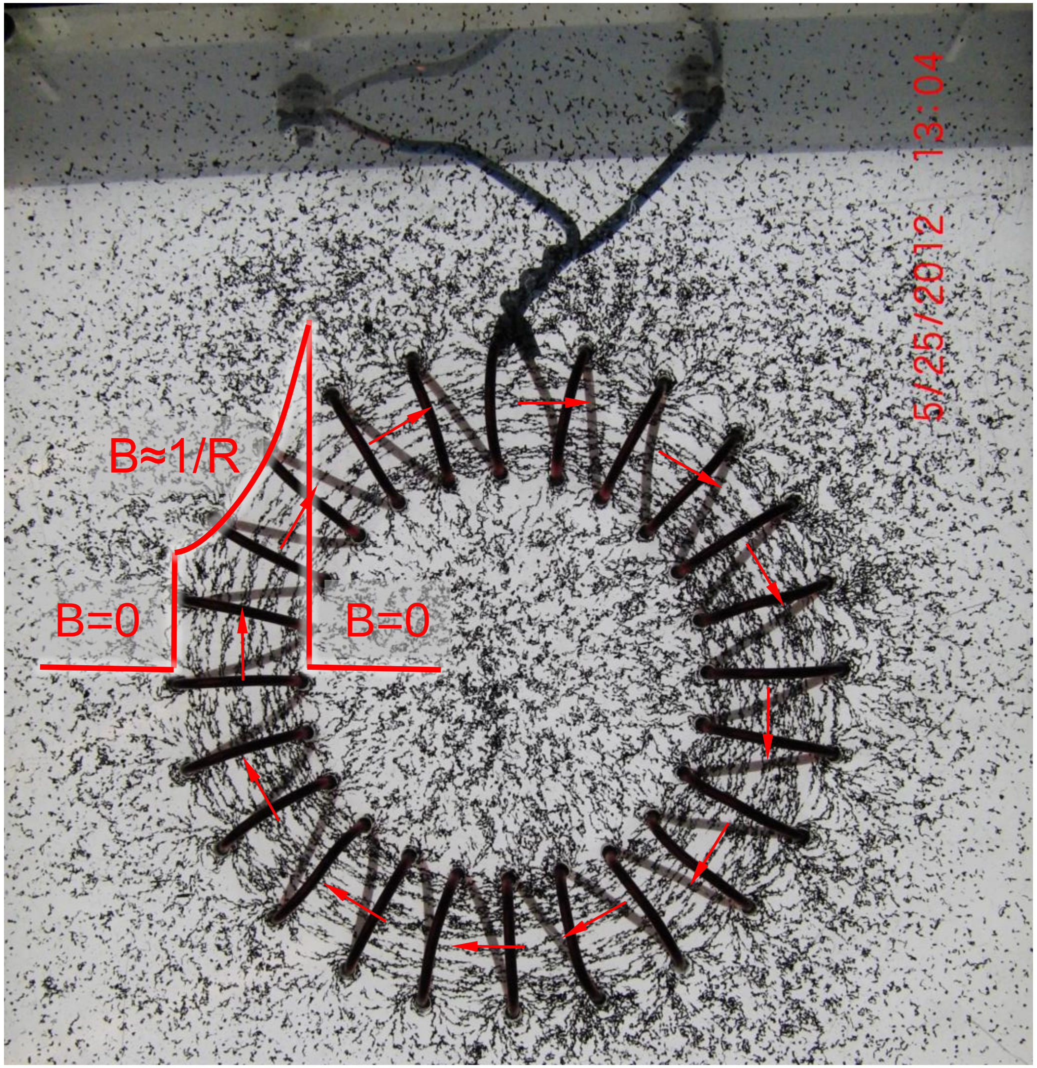
Ideal toroidal field

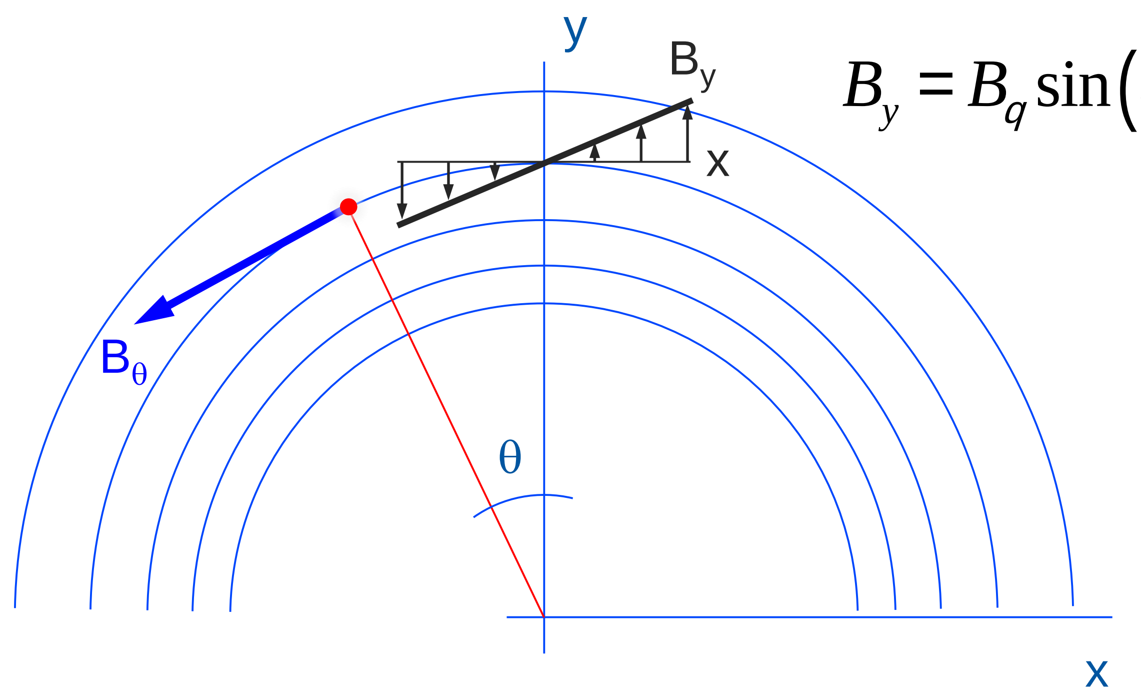
$$B_\theta = \frac{\mu_0 N I}{2\pi r}$$





Focusing effect of a toroidal field

Particles traveling out of the (R,z) plane



$$B_y = B_q \sin(q) \text{ » } B_q x$$

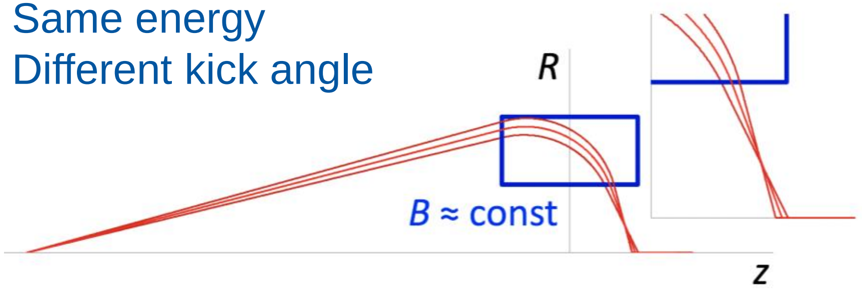
Out-of-planes beam originating at the vertex with an angle θ with respect to the (R,z) plane experience a focusing field (*simil-quadrupole*)

An ideal toroidal field can focus in two planes

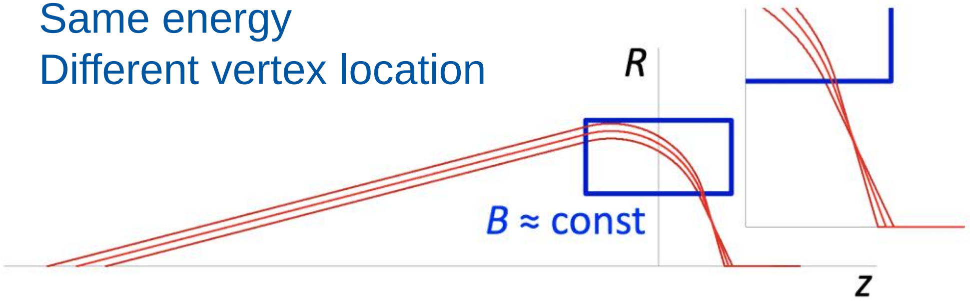
The principle of scanning

Effect of a (small) change of kick angle and vertex location

Same energy
Different kick angle



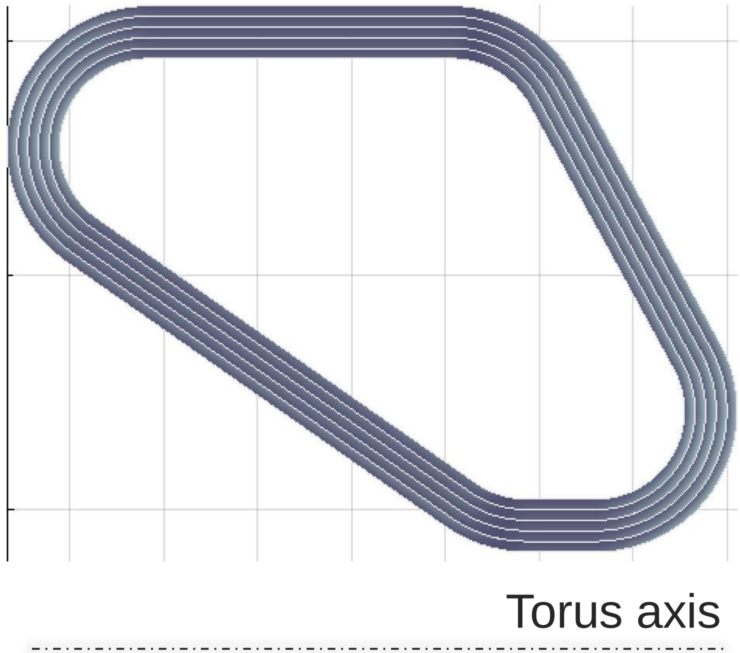
Same energy
Different vertex location

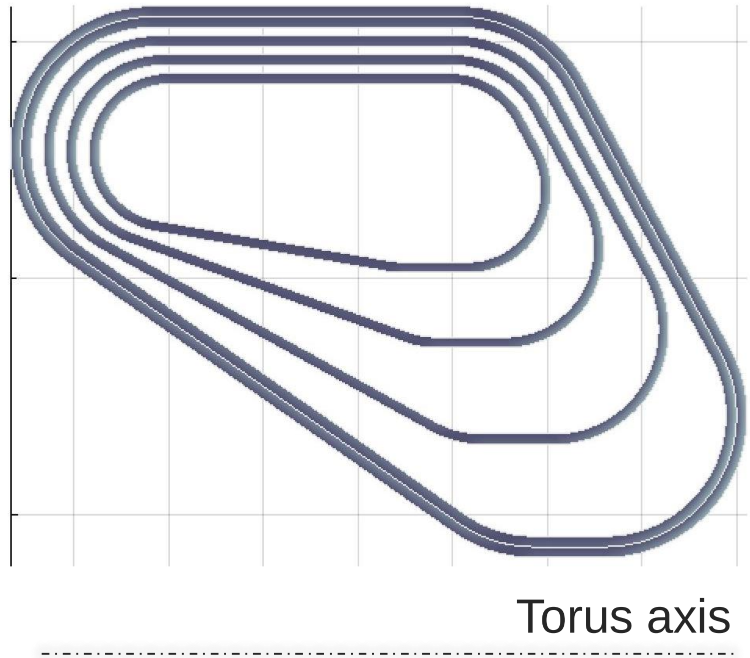


A small change in the kick angle at the vector magnet causes a motion of the point where the beam arrives on the axis

A similar effect is obtained by a motion of the location of the vertex of the vector magnet

Graded coil design



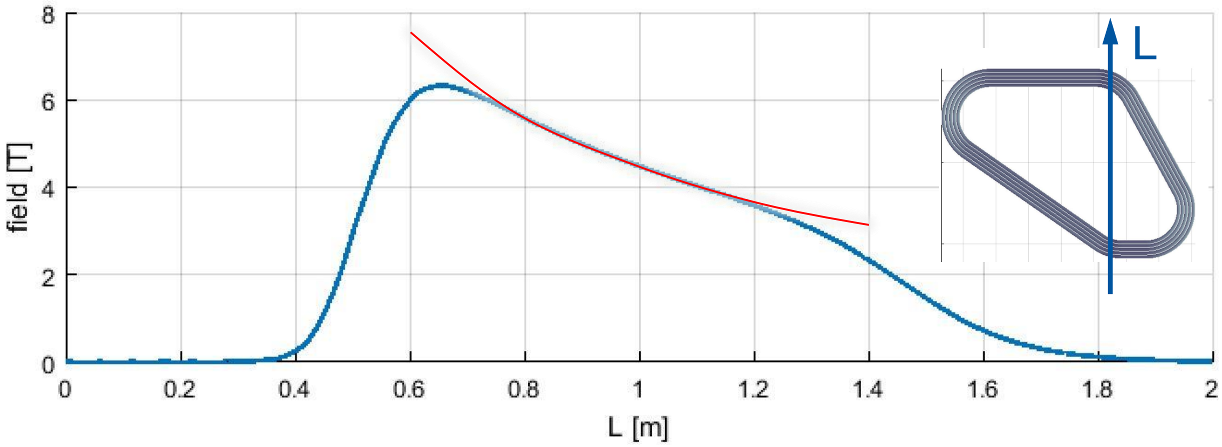


Simple coil winding (no grading)
The field profile has a $1/R$ dependence

Graded coil winding with spaced inboard leg
The field profile can be modified to a $1/R^n$ dependence where n is the field index

Effect of grading

Field profile on a line originating at the patient location and oriented radially outwards

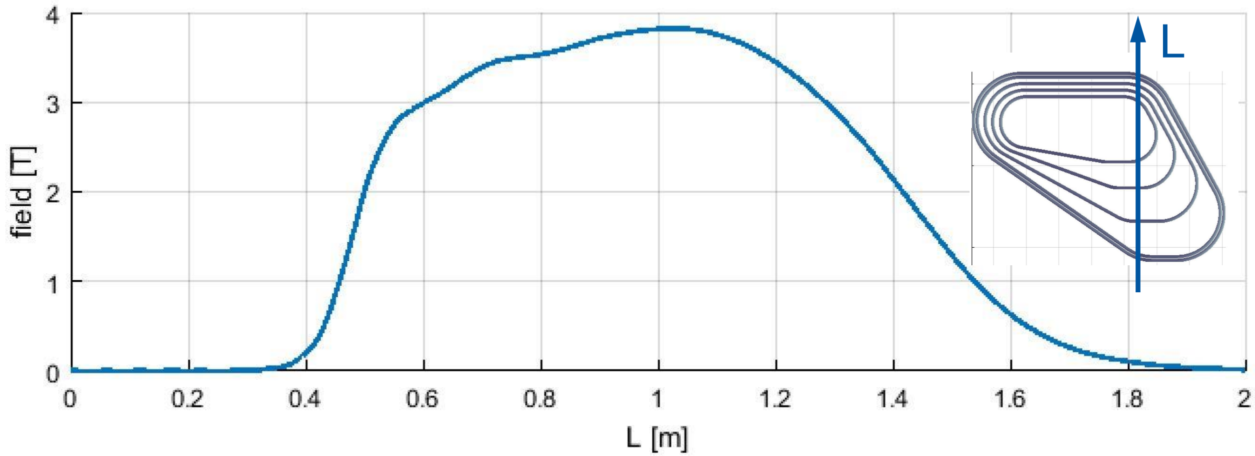


Non-graded coil winding

The field has the expected 1/*R* dependence in the coil bore

Graded coil winding

The 1/*R* dependence of the field is modified by the geometry of the winding (negative field index possible)



Number of coils

Bore diameter

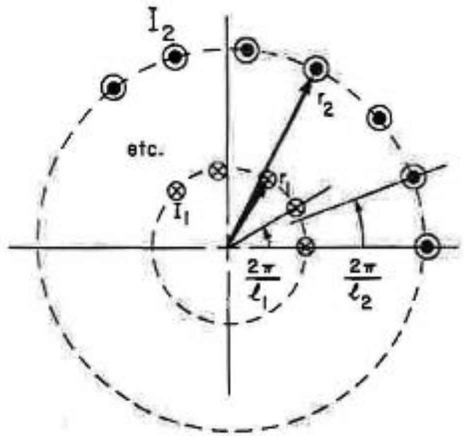
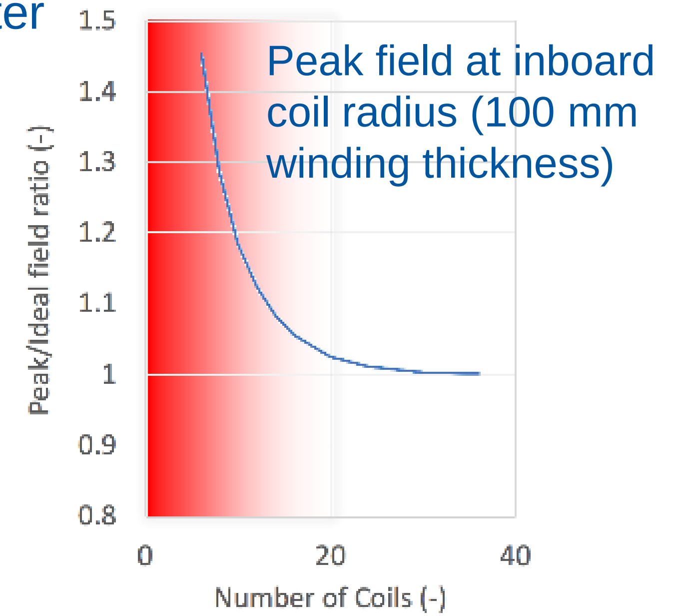
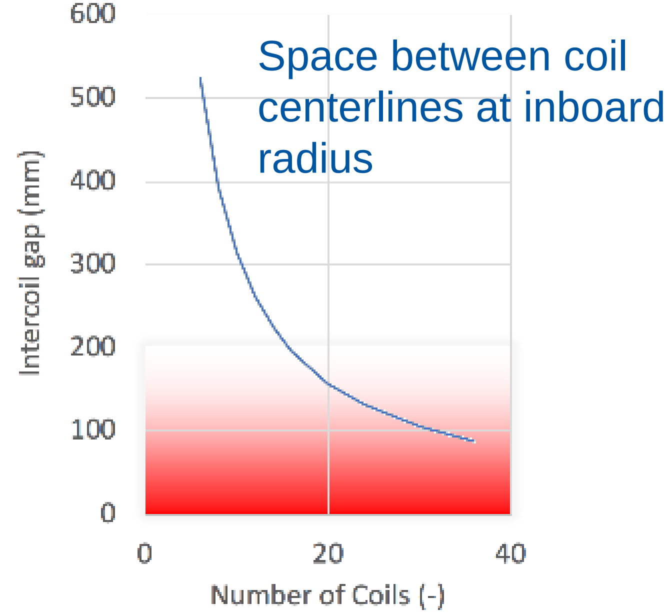


Figure 3.42 Model of toroidal field coils composed of l_1 filaments carrying current I_1 at a radius r_1, and l_2 filaments carrying current I_2 at a radius r_2 such that $I_1 l_1 = I_2 l_2 = Il$.

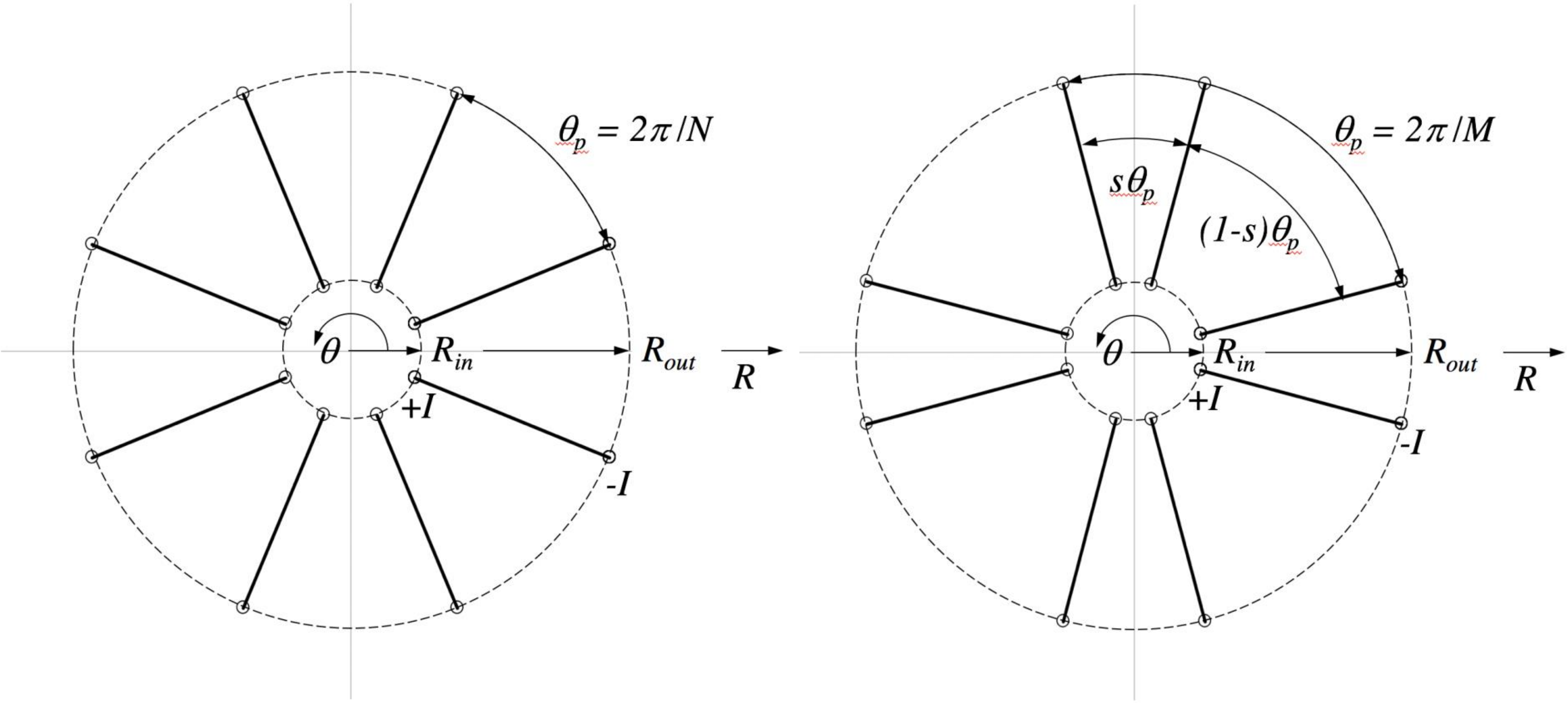
$$B_\phi = \frac{\mu_0 I l}{2\pi r}\left\{\frac{\rho_2^2 - \rho_2 cos(l_2\phi)}{1 - 2\rho_2 cos(l_2\phi) + \rho_2^2} - \frac{\rho_1^{-2} - \rho_1^{-1} cos(l_1\phi)}{1 - 2\rho_1^{-1} cos(l_1\phi) + \rho_1^{-2}} + 1\right\}$$

- A practical range of coils is 10 to 20
  - Less coils result in high peak field for the same bending strength (field leakage)
  - More coils leave too little space for the beam passage

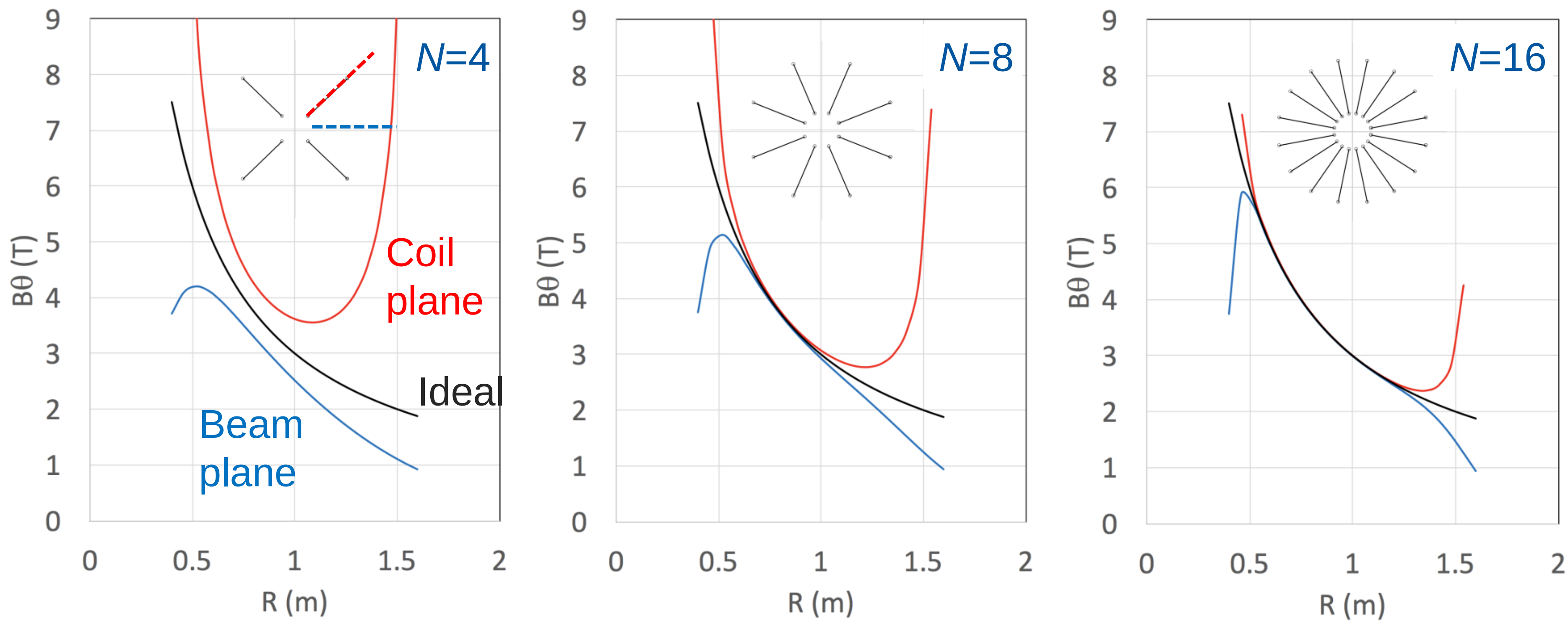




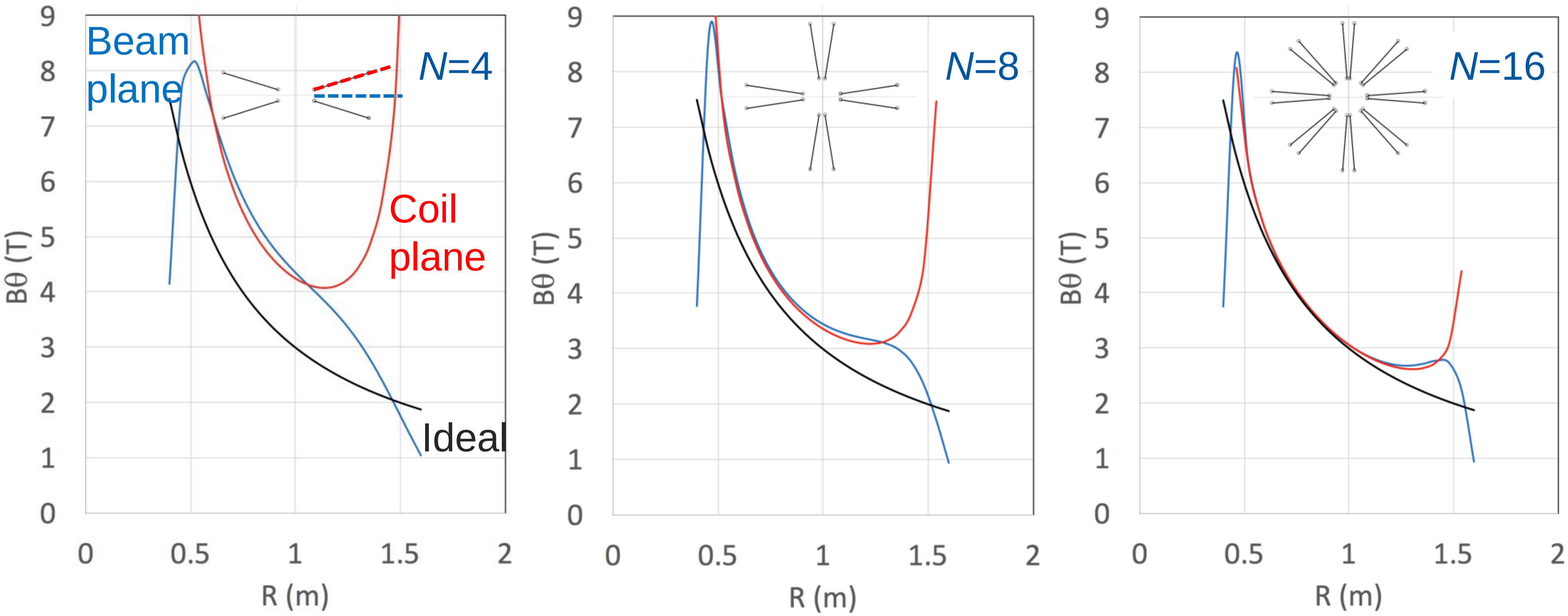
Regular/Non-regular spacing



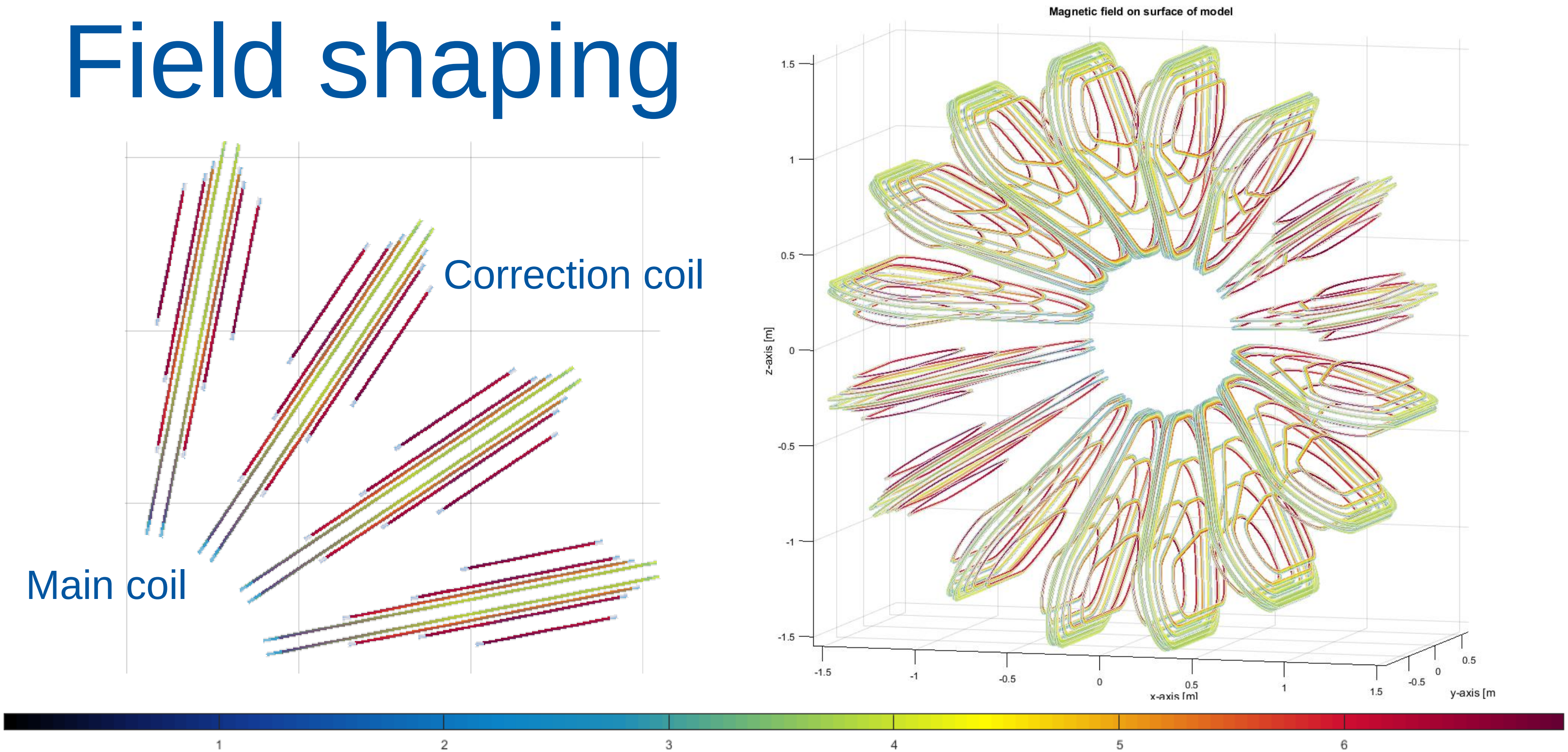
Field distribution – regular



Field distribution – non-regular



Field shaping



- The field can be shaped using inserts and correction coils, the peak field is reduced
- For the moment we limit ourselves to a **flat coil**

Toroidal multipoles

$$\psi(\xi,\eta,\phi) = M^{\phi}_{00}\phi + \sqrt{\cosh(\xi)-\cos(\eta)}\sum_{m=1}^{M}\sum_{n=0}^{N} Q^{n}_{m-\frac{1}{2}}(\cosh(\xi))$$

$$\Big[M^{cc}_{m,n}\cos(n\phi)\cos(m\eta) + M^{cs}_{m,n}\cos(n\phi)\sin(m\eta)$$

$$+ M^{s,c}_{mn}\sin(n\phi)\cos(m\eta) + M^{s,s}_{mn}\sin(n\phi)\sin(m\eta)\Big]$$

Multipole expansion of the magnetic scalar potential in toroidal coordinates

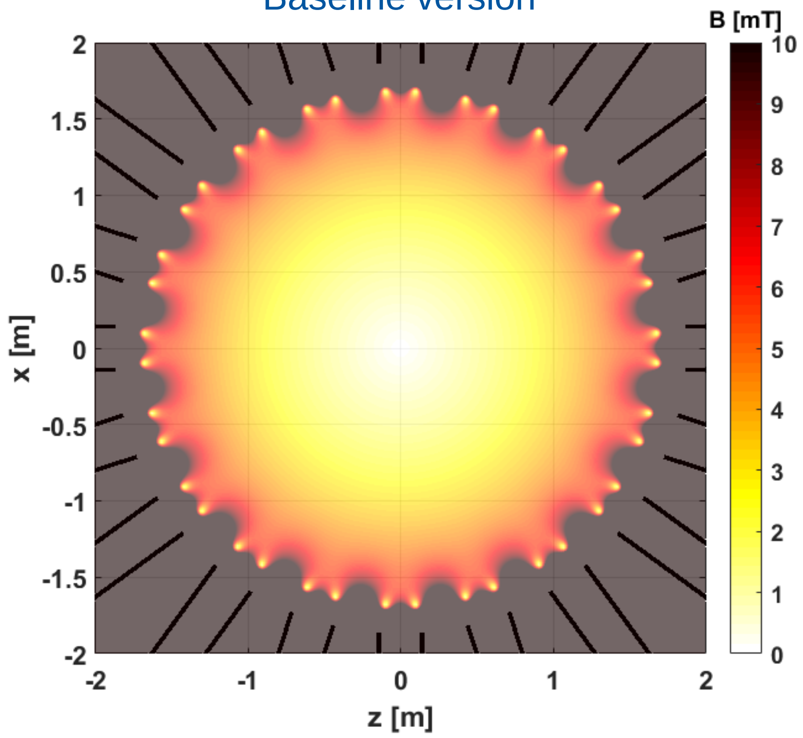
$$I = \frac{2\,\pi}{\mu_0} M^{\phi}_{00}$$

Ideal toroidal field contribution (1/R)

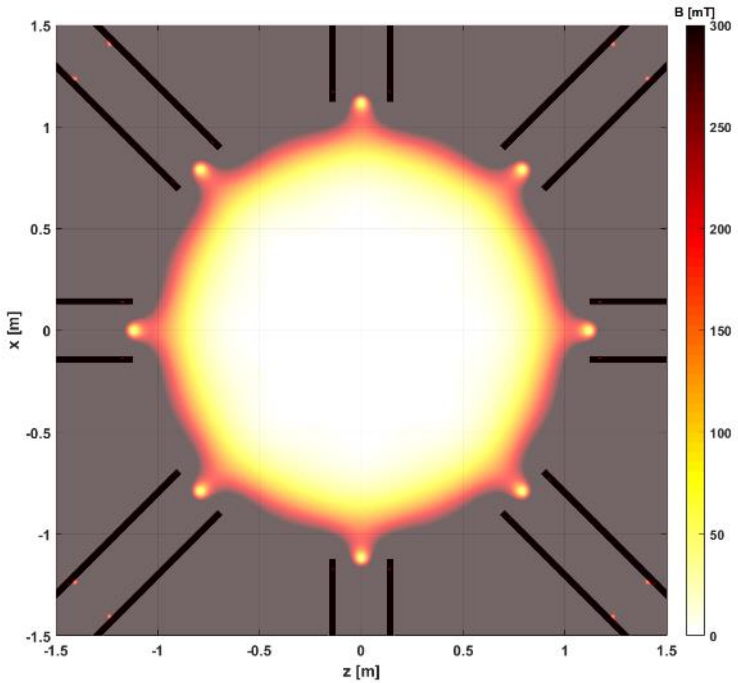
Geometry and design

Magnetic field in the bore

Baseline version



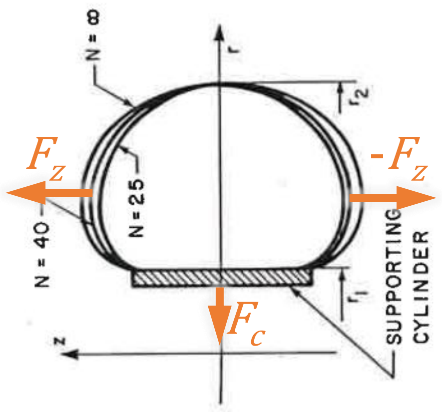
Reduced size version

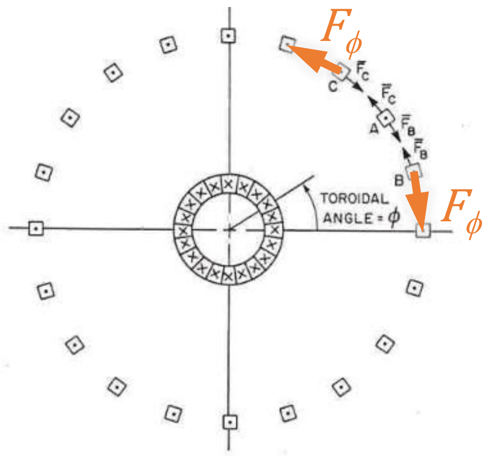


For both versions, we report that the magnetic field remain below 10 mT inside the bore, where the patient lays.

Mechanical analysis

Lorentz forces





$$\gamma = \frac{R_{minor}}{R_{major}}$$

$$F_z = \frac{\mu_0 N I^2}{4\pi} ln\left(\frac{1+\gamma}{1-\gamma}\right)$$

$$F_c = \frac{\mu_0 N I^2}{2}\left(1 - \frac{1}{\sqrt{1-\gamma^2}}\right)$$

The main forces acting on a toroidal magnet are

- An in-plane force F_z *pulling the coil apart* (zero resultant)
- An in-plane centering force F_c
- An out-of-plane force F_Φ in case of fault

Increasing the number of channels increases the forces, the mass and cost linearly.
Increasing the bore size has similar effects on mass on costs.

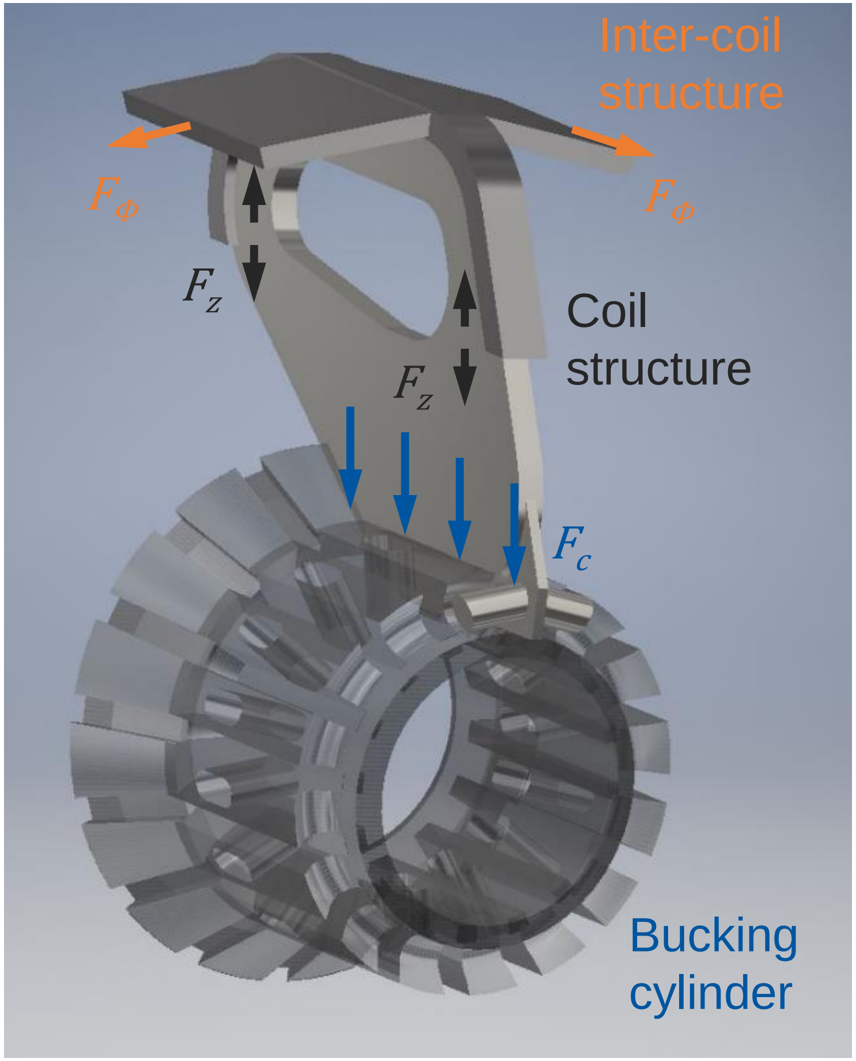
Mechanical analysis

Proton GaToroid

Winding force - F_z	2 MN/coil
w_{coil}	50 mm
t_{coil}	300 mm
σ_{coil}	150 Mpa

Centering force - F_c	1.34 MN/coil
$t_{cylinder}$	60 mm
$\sigma_{cylinder}$	120 Mpa

Fault force - F_Φ	1.77 MN/coil
$t_{intercoil}$	60 mm
$\sigma_{intercoil}$	50 Mpa



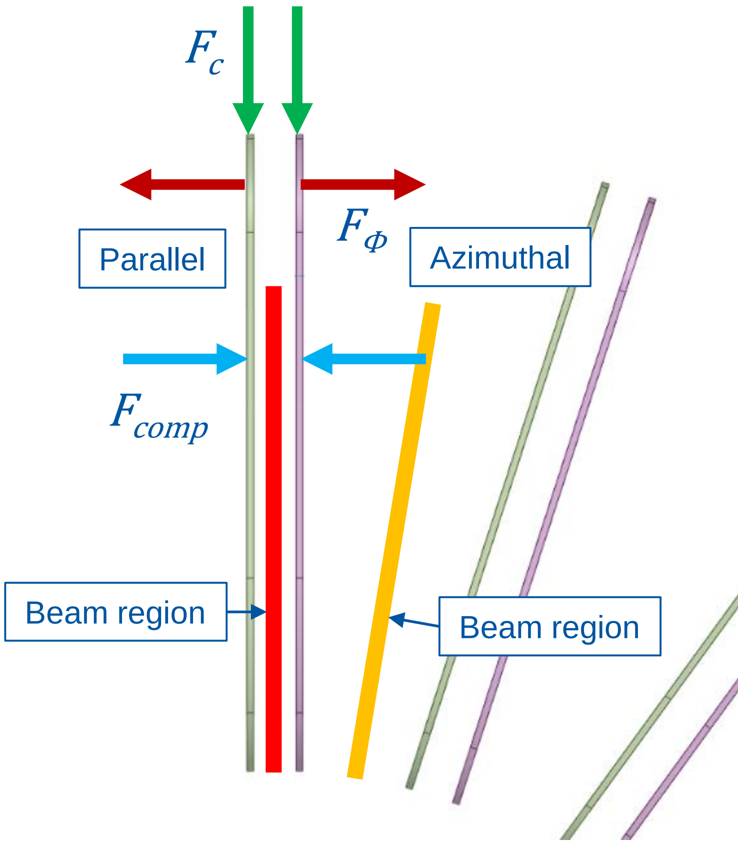
Mechanical analysis

Beam paths considerations

Centering force − F_c	6.3 MN/coil
Fault force − F_Φ	15 MN/coil
Winding force - F_z	10 MN/coil
Compressive force - F_{comp}	8.4 MN/coil

- **Parallel:** the beam passes in the channel between 2 parallel coils.
    - the beam can sweep most of the channel
    - the space in the channel cannot be filled as the beam passes through it.

- **Azimuthal:** the beam passes between 2 angled coils.
    - space between double pancake coils can be filled with material to carry compressive forces



→Solution (material, design) could be found for the **parallel** beam path but will lead to increase weight and large moments

→**Azimuthal** seems much more feasible mechanically speaking

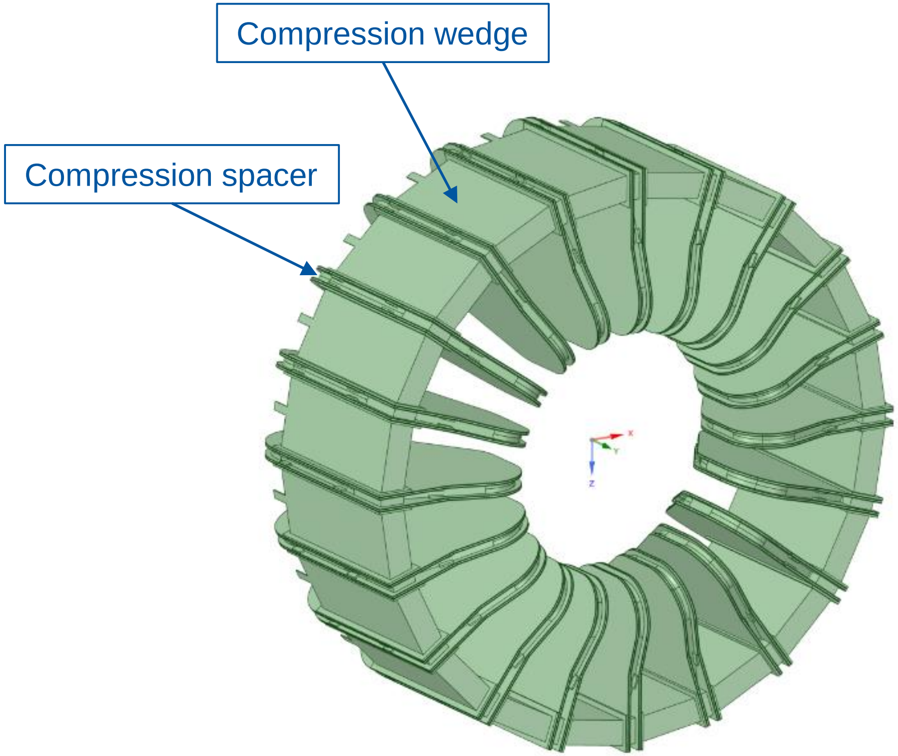
Mechanical analysis
Cold mass components

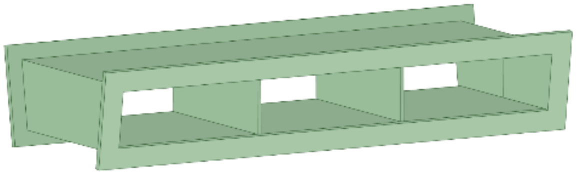
Still a highly simplified structure with two main structural components:
- Compression wedge
- Compression spacer
- Coil structure

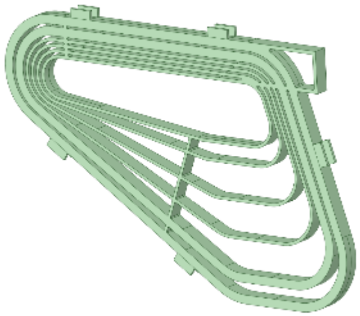
Missing large scale system components:
- Central cylinder forming the bore
- Thermal shield and cooling system

- Cold contraction not included in simulations
- Full system under gravity not studied

- Plausible but heavy (est. 270 tons cold mass)







Mechanical analysis

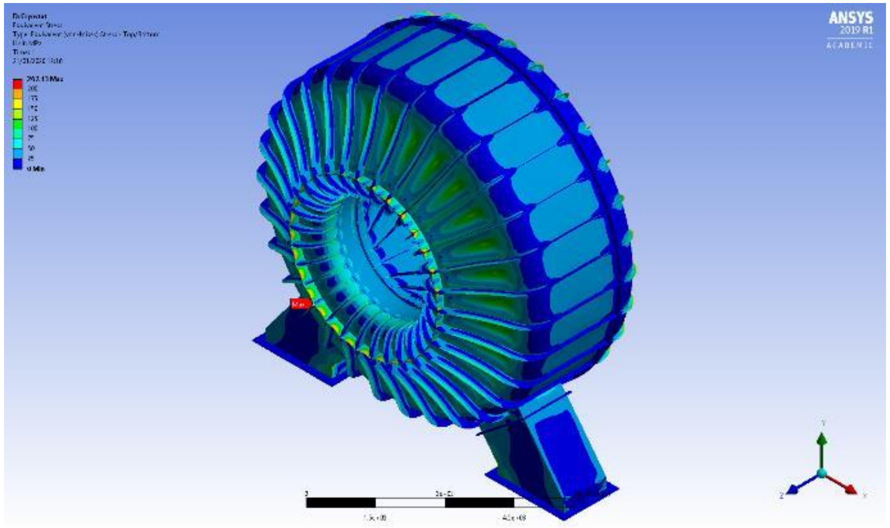
Cryostat

A simplified idea at this point with

- Aluminum thermal shield
- LHC type GFRE posts
- Stainless Steel structure

- Stress state acceptable

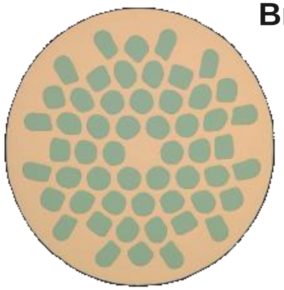
- Total estimated mass: 300 tons



Conductor

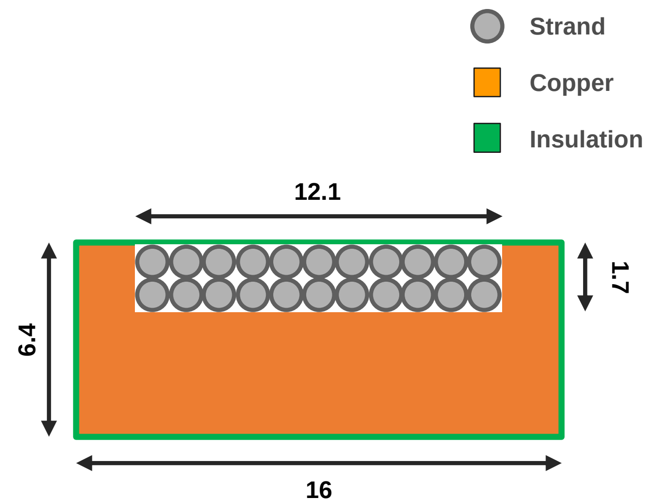
Cu-(NbTi) in Cu profile

Strand example:
Bruker F54-1.35



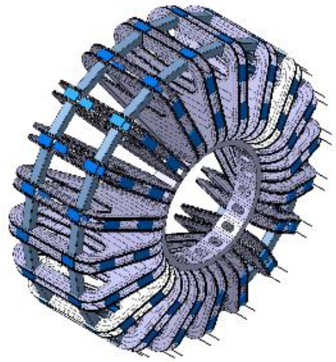
Reference conductor in case of quench protection with 20 external dump resistors.

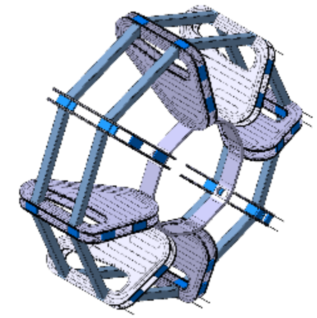
Type	Rutherford cable embedded in Copper profile
Number of strands	22
Strand diameter	1 mm
Cu:Sc (strand)	1.35
Cu:Sc (with profile)	12.5
Critical current	16 kA (4.2K, 6T)
Eng. Current density	68 A/mm2



Solution with Aluminum stabilizer instead of copper are worth considering and are being studied

Cryogenics
Heat loads





Heat loads [W]	Baseline version		Reduced size version	
	4.2 K	**50 K**	**4.2 K**	**50 K**
Post support	7	153	3	62
Current leads (QH / DR)				
• Self-cooled	24 / 496		24 / 212	
• HTS	2 / 50	118	2 / 22	50
Radiation	7	467	3	328
Total (QH / DR)	**38 / 64**	**620 / 738**	**30 / 28**	**390 / 440**

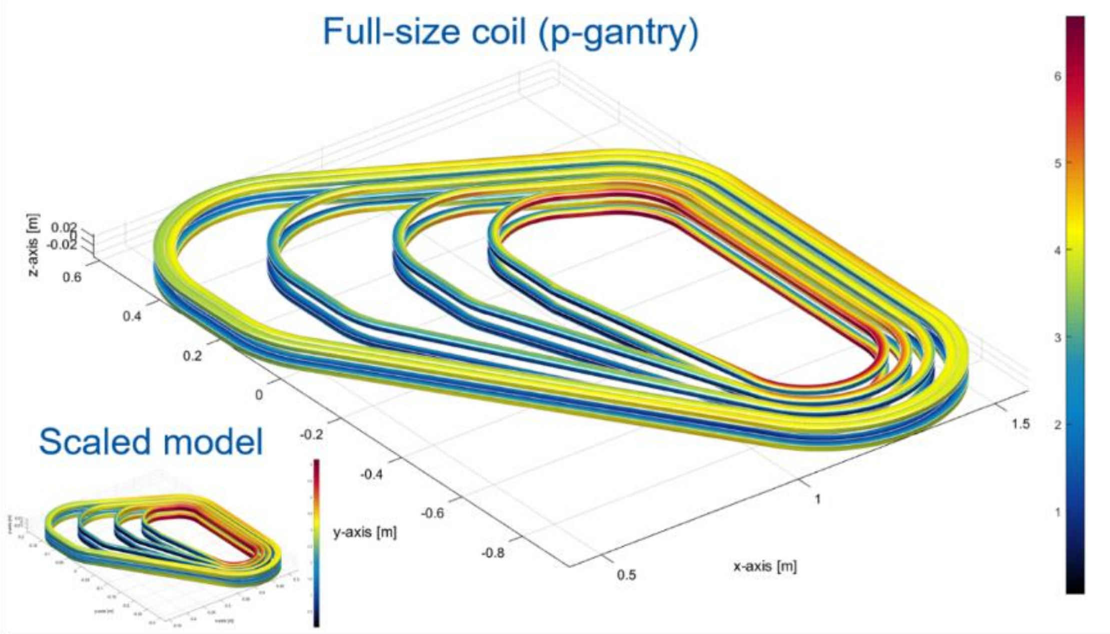
Broad estimated values are not out of order and the thermal loads on the Carbon ions GaToroid are very manageable.

Demonstrator

Build a Single coil scaled down from the proton design by factor 3 so we can test it at CERN:

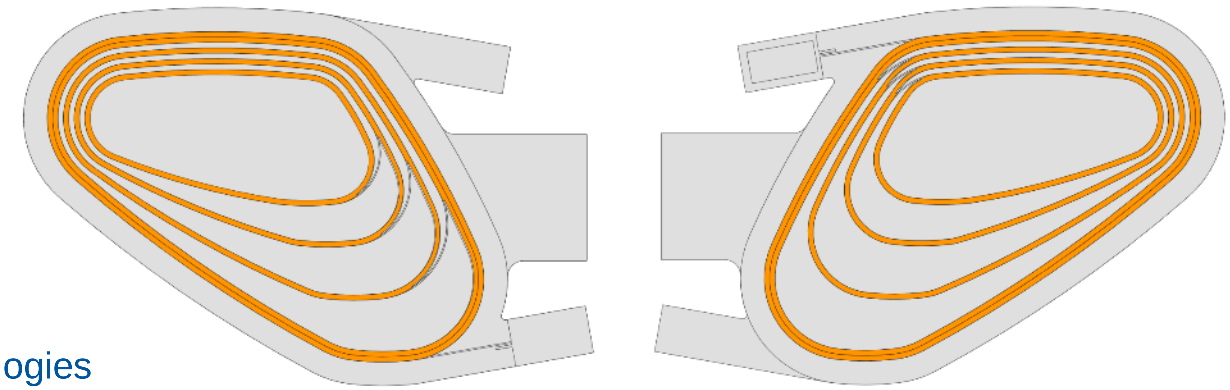
- Magnet performance
- Quench protection
- Field quality
- Coil manufacturing

Issues, faced and solved during the manufacturing of the coil are relevant to the Carbon GaToroid

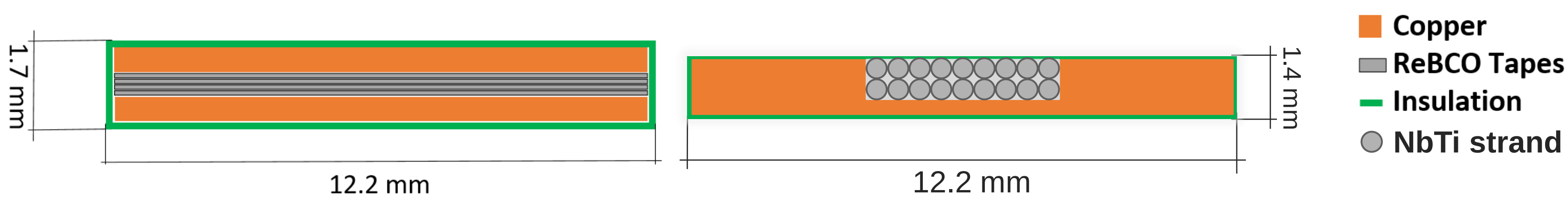


Demonstrator

Strategy



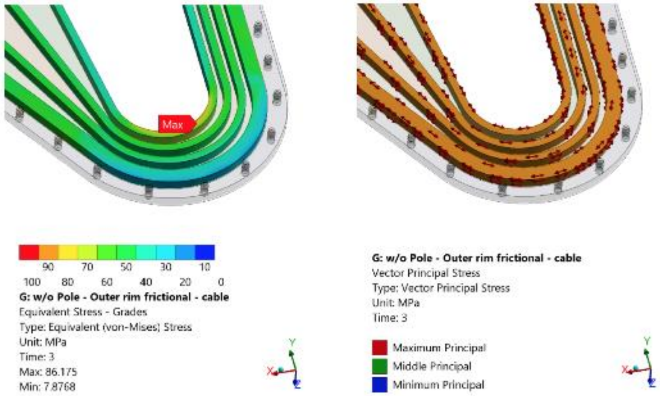
- Develop HTS related technologies
  - Winding machine
  - Impregnation study
  - Layer jump
  - Joints development
- Wind and test a demonstrator with HTS conductor (Phase 1)
- Wind and test a demonstrator with LS NbTi conductor (opening Phase 2)
  - Copper stabilizer for LTS cable



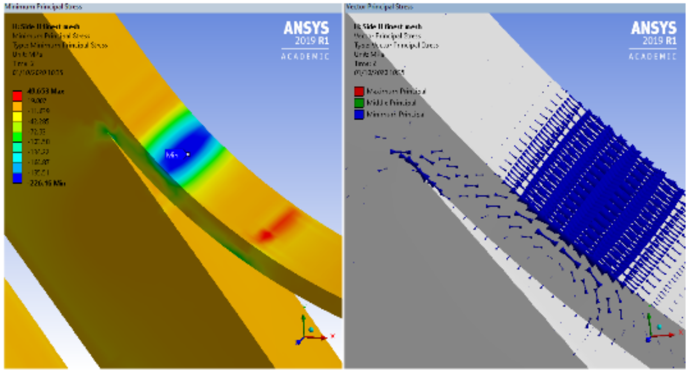
Demonstrator
Analysis

Mechanical analysis are using Lorentz forces from magnetic simulation and effect of temperature to help in determining several key concepts and in updating the design:

- Material: Stainless Steel (TCE & Stress)
- Selective impregnation is required

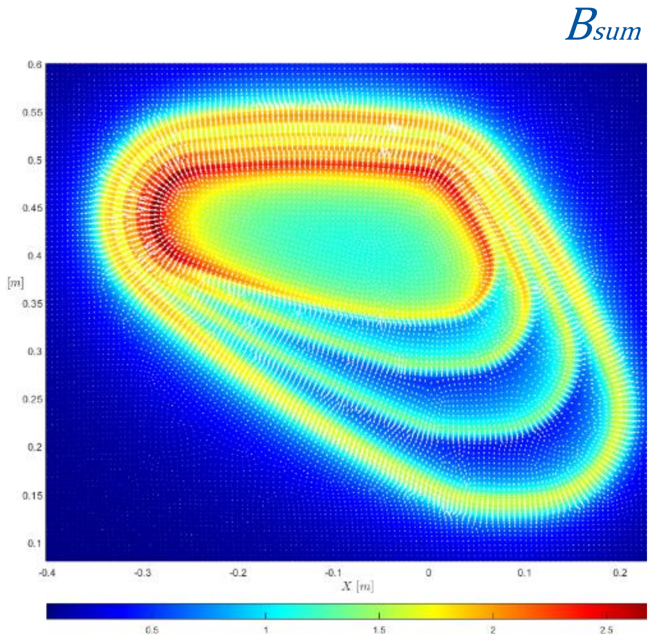


Grade jump detailed study is on-going to determine the behaviors of the HTS tape in these critical regions.



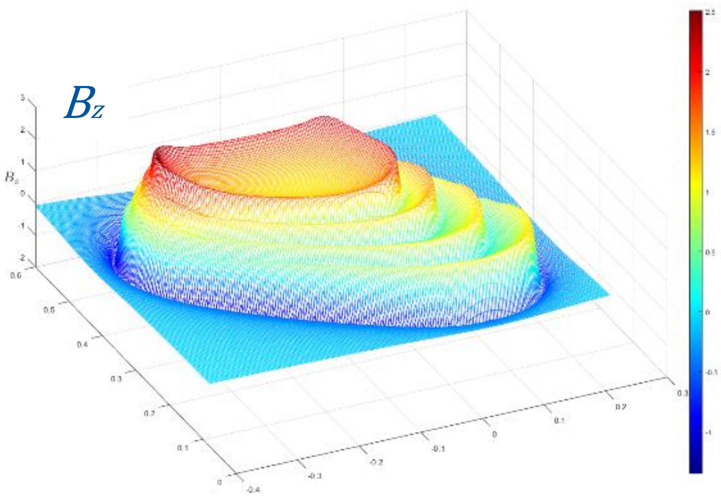
Demonstrator

Analysis



Magnetic simulations can now be performed rapidly and adapted to the latest design providing:

- Field map
- Lorentz forces



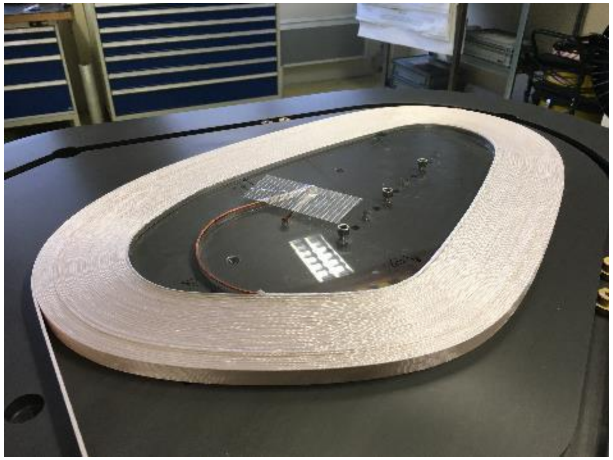
The field map will be a reference for the placement of the magnetic sensors used to confirm the simulation during the test

Sensors will measure Bz and should located where the gradient is the lowest to reduce positioning induced errors.

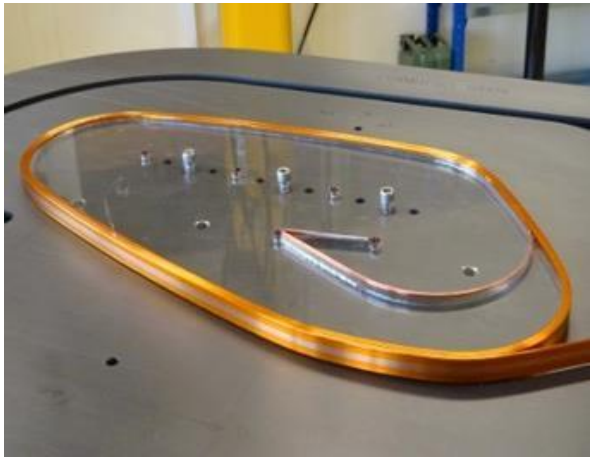
Demonstrator

Winding table

All 7 spools of the winding machine are operational and commissioned



Test with dummy tape and **fiberglass sleeve** conclusive

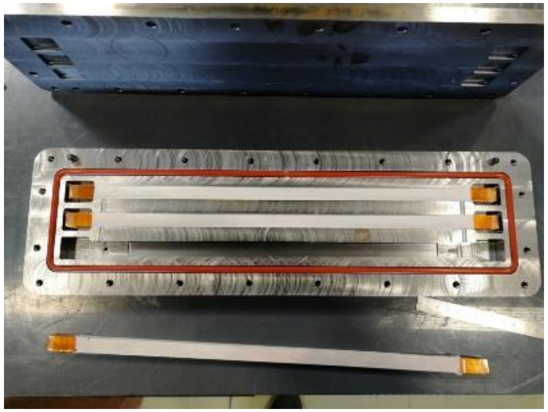


Test with dummy tape and **C-shape polyimide** conclusive

Thanks to J. Mazet, N. Bourcey, F.O. Pincot
L. Henschel, P.A. Contat, J.C. Perez *et al.* in 927

Demonstrator

Impregnation study



4 Dummy cable stacks

		STACK CONFIGURATION				PROCESS			
Sample Test #	Stack #	Insulation	Resin	Additive	Compression	Preparation	Impregnation	Electrical test	Cut and VI
1	1-3	Fiber glass	MY750	No	High	Done	Done	Done	Done
2	4-6	Fiber glass	CTD101K	No	High	Done	Done	Done	Done
3	7-9	Fiber glass	CTD101K	No	Low	Done	Done	Done	Done
4	10-12	Fiber glass	MY750	No	Low	Done	Done	Done	
5	13-15	C-Shape Polyimide	CTD101K	No	Low	Done	Done	NO TEST	
6	16-18	C-Shape Polyimide	MY750	No	Low	Done	Done	NO TEST ?	
5.2	19-21	C-Shape Polyimide	CTD101K	No	Low	Done	Done	Done	
7	22-24	C-Shape Polyimide	Mix61	No	Low	Done	On-going		
8	25-27	Fiber glass	Mix61	No	Low	On-going			

To check:

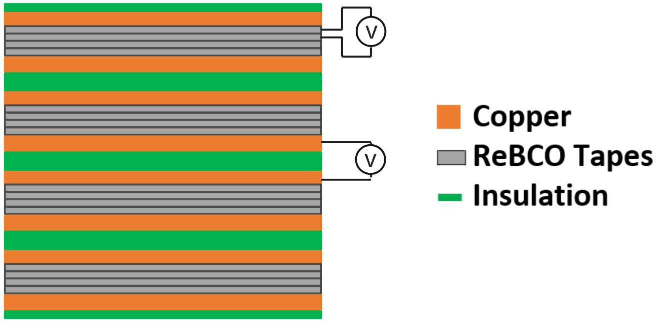
- Reproducibility
- Electrical insulation between cables
- Electrical contact between tapes
- Impregnation quality (voids, bubbles)
- Cracks
- Mechanical properties

To do:

- Electrical test at room Temp. and at 77K
- Electrical test after 10 low Temp. cycles

- Cut and visual inspection
- Delaminate and visual inspection

- Thermal contraction measurements
- Mechanical tests

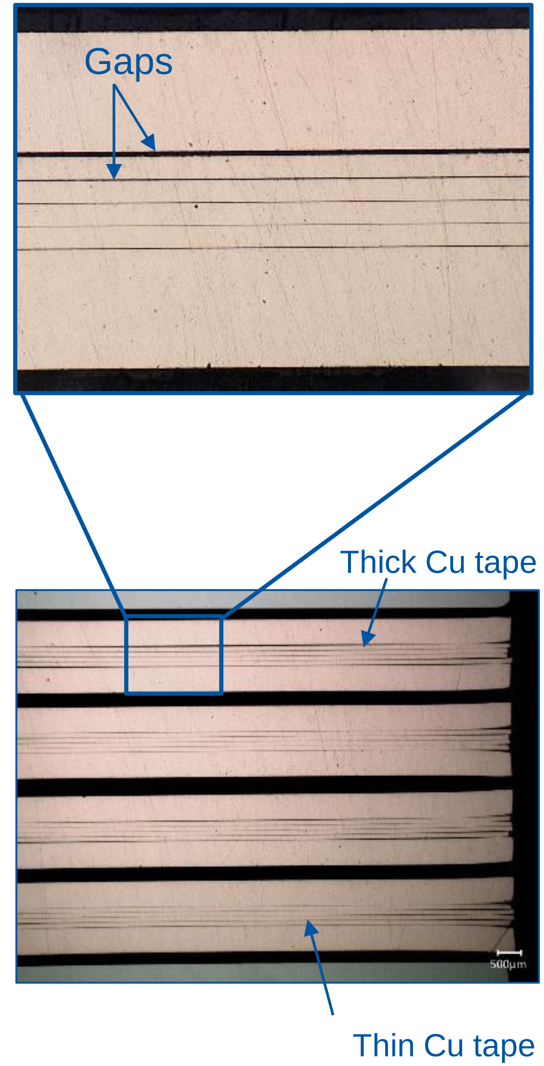


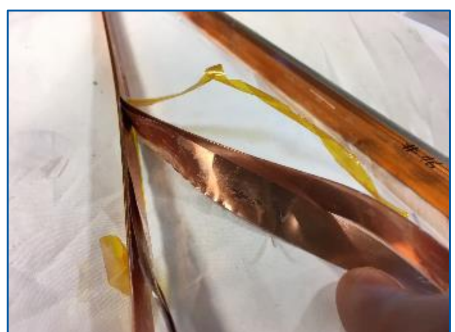
Thanks to J. Mazet, N. Bourcey, F.O. Pincot
L. Henschel, P.A. Contat, J.C. Perez *et al.* in 927

Demonstrator

Impregnation study

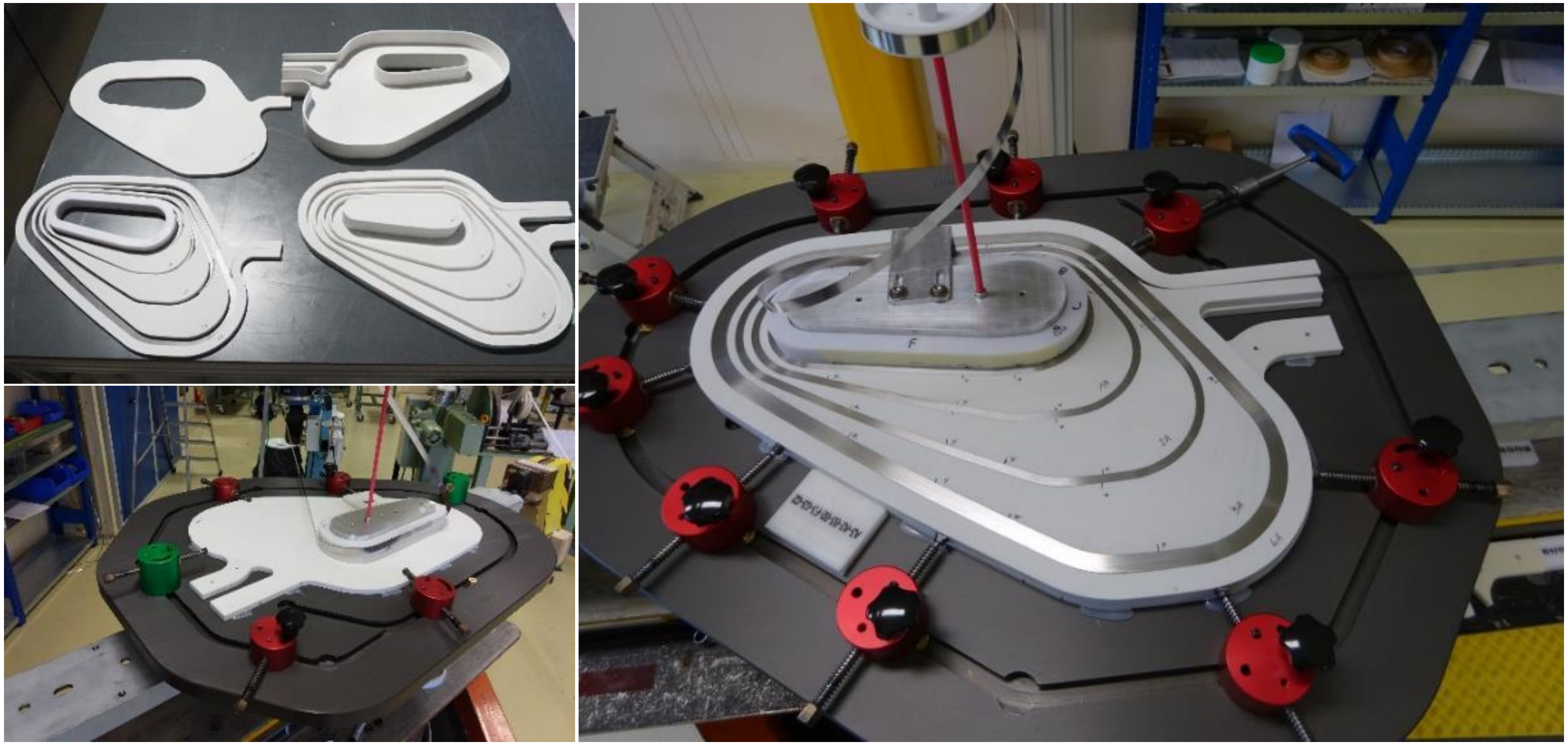
Stack samples			Fiberglass sleeve				Polymide C-shape	
			High compression		Low compression		Low compression	
			MY750	CTD101K	MY750	CTD101K	MY750	CTD101K
Peeling observations			A fair continuous pull is necessary	Very easy after a first crack			Very easy once the polyimide removed	
Visual observations	Impregnation between cables		FB is impregnated but it did not wet the cable	FB is impregnated and it partially wet the cable			The impregnation is good under the polymide on both side of the "C"	
	Resin between tapes		Several traces	Few traces			Few traces	
	Gap between cables		329 µm	334 µm		426 µm		
Electrical tests	Resistance between cables	Before thermal cycles	705 GΩ	1869 GΩ	2162 GΩ	2610 GΩ		3000 GΩ
		After thermal cycles	593 GΩ	1964 GΩ	882 GΩ	1269 GΩ		2913 GΩ
	Resistance between tapes	Before thermal cycles	3.01 mΩ	2.22 mΩ	2.32 mΩ	2.49 mΩ		1.94 mΩ
		After thermal cycles	3.21 mΩ	2.26 mΩ	2.20 mΩ	1.75 mΩ		1.68 mΩ
		At 77K	0.520 mΩ	0.362 mΩ	0.333 mΩ	0.349 mΩ		





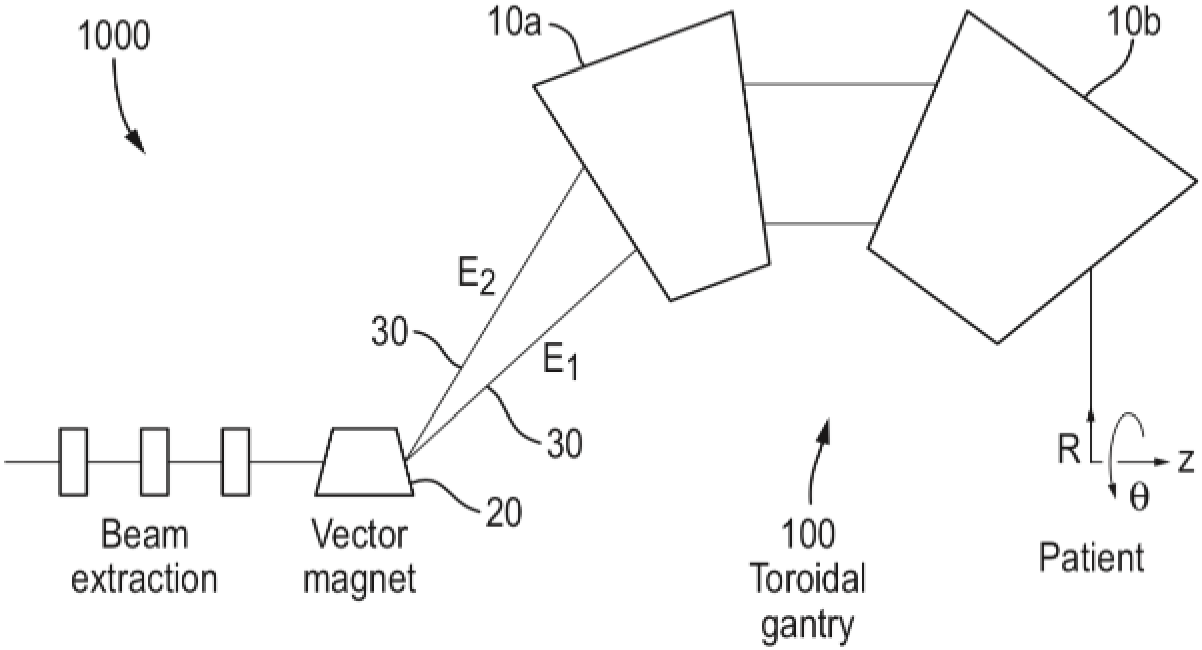
Demonstrator

Technology development



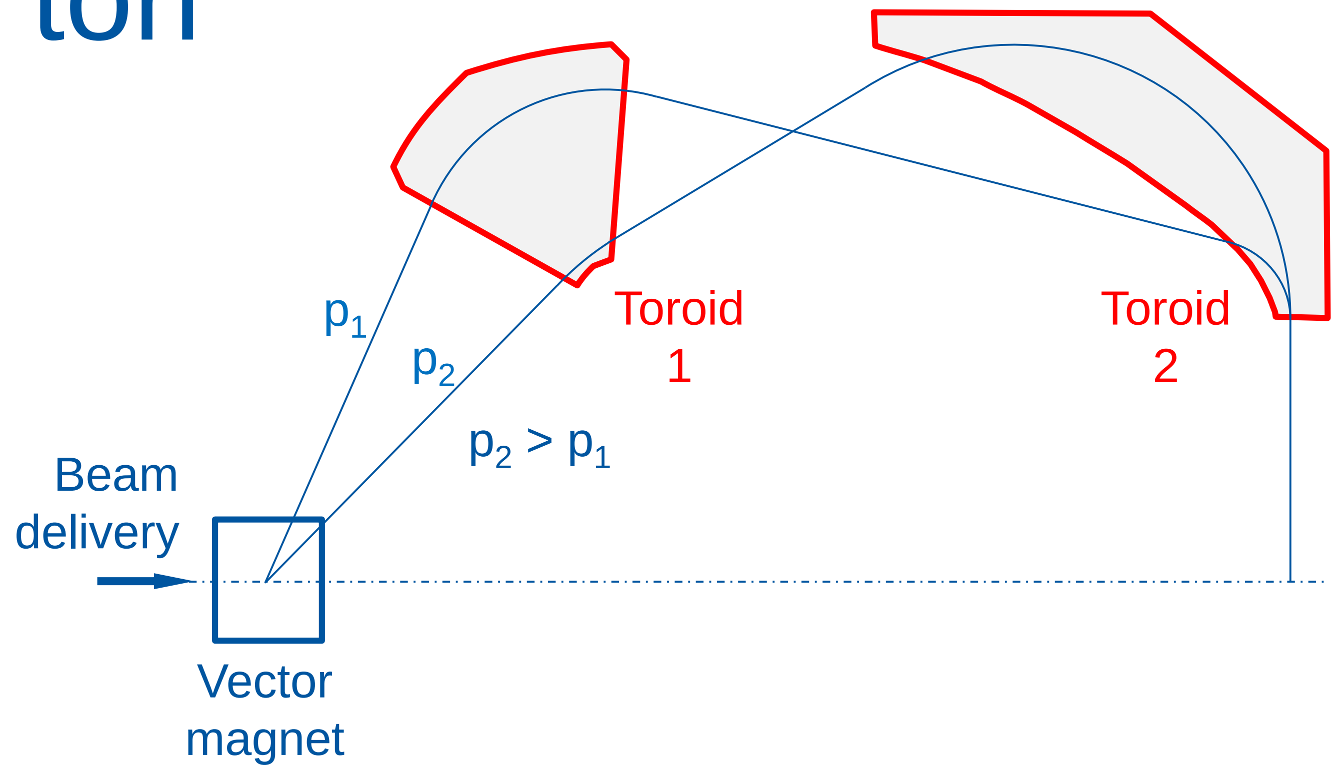
Stainless Steel dummy winding with 3D printed spacers

Beam transport



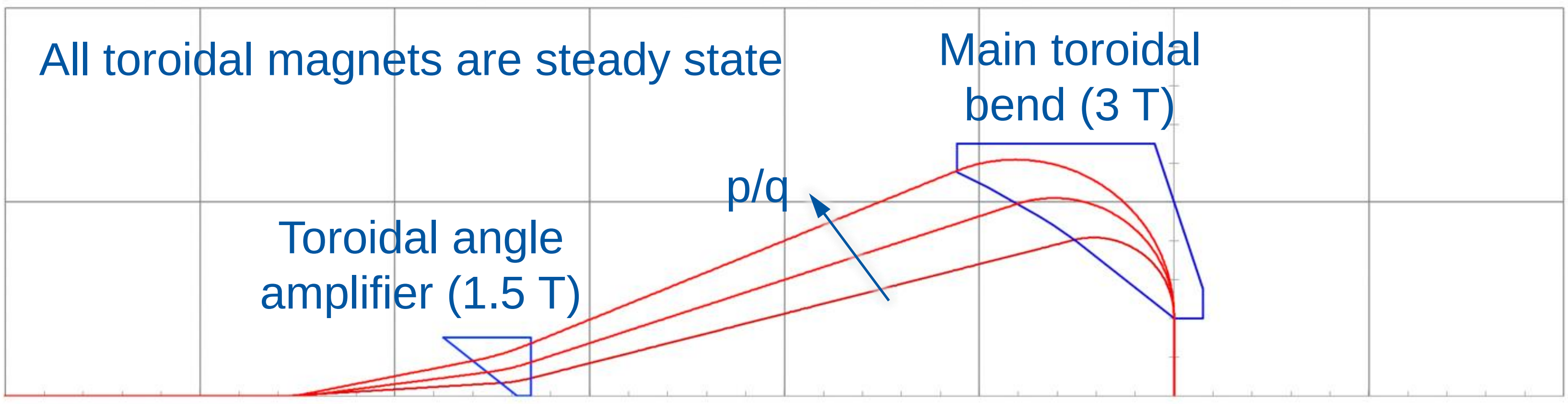
- A sequence of toroids could be devised to mock the properties of a beam transmission line
- We limit the present design and analysis to a **single torus**

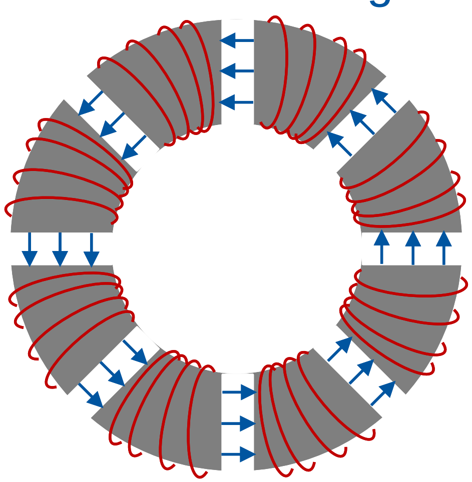
Multiple tori



- An interesting “incarnation”, but it makes the vector magnet even more demanding. See later for a better option
- We still limit the present design and analysis to a **single torus**

A toroidal angle amplifier





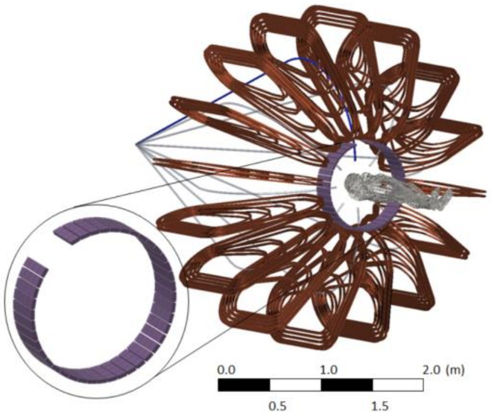
The requirements for the kick are reduced by a factor two in this realization

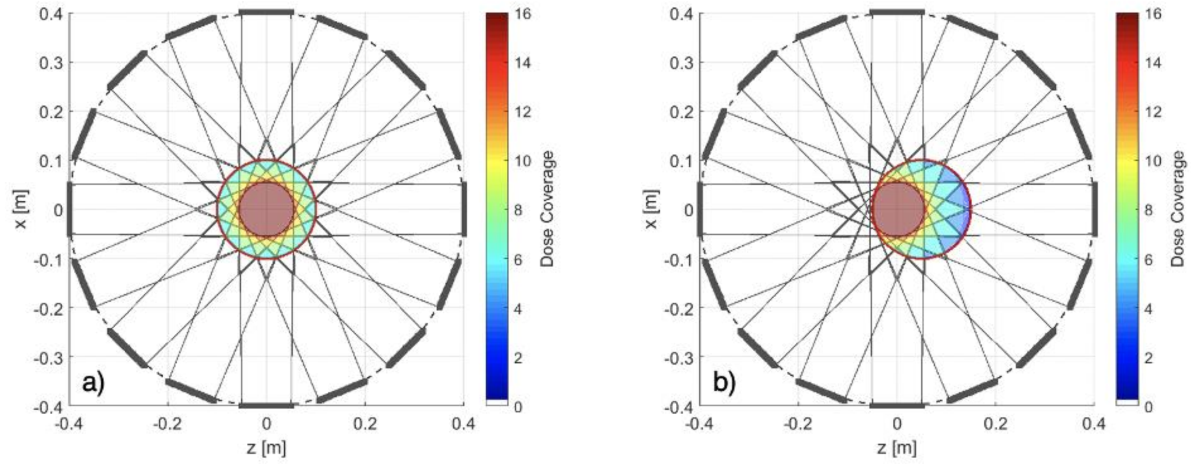
This could make a fast x-y kicker magnet feasible ?!?

Error tolerance is also reduced by factor two

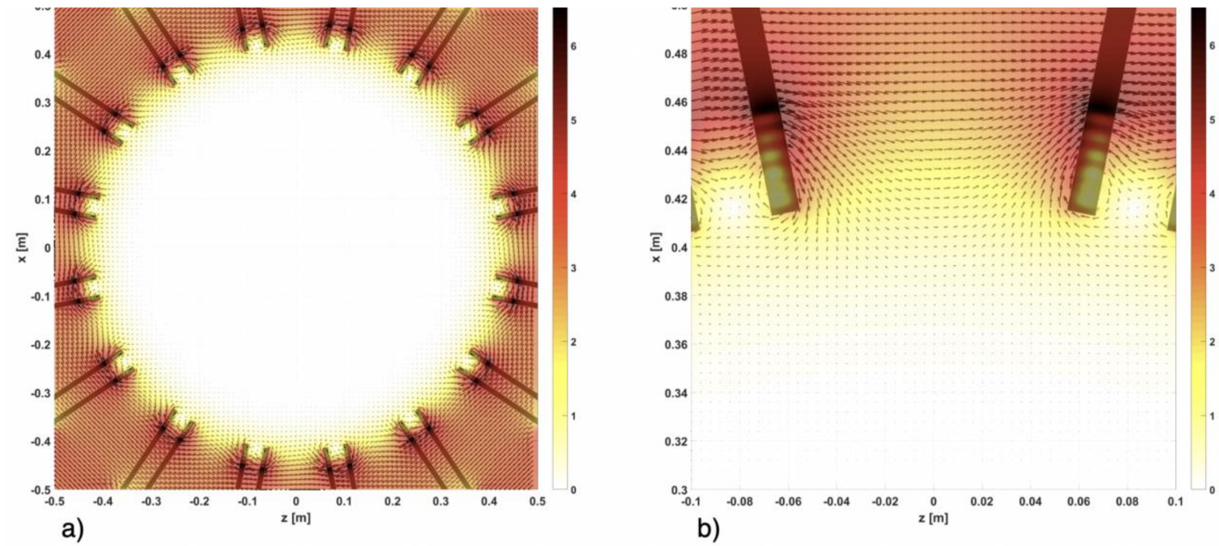
ATTRACT-H2I2 – Layout

Number of windows from which a volume is reachable



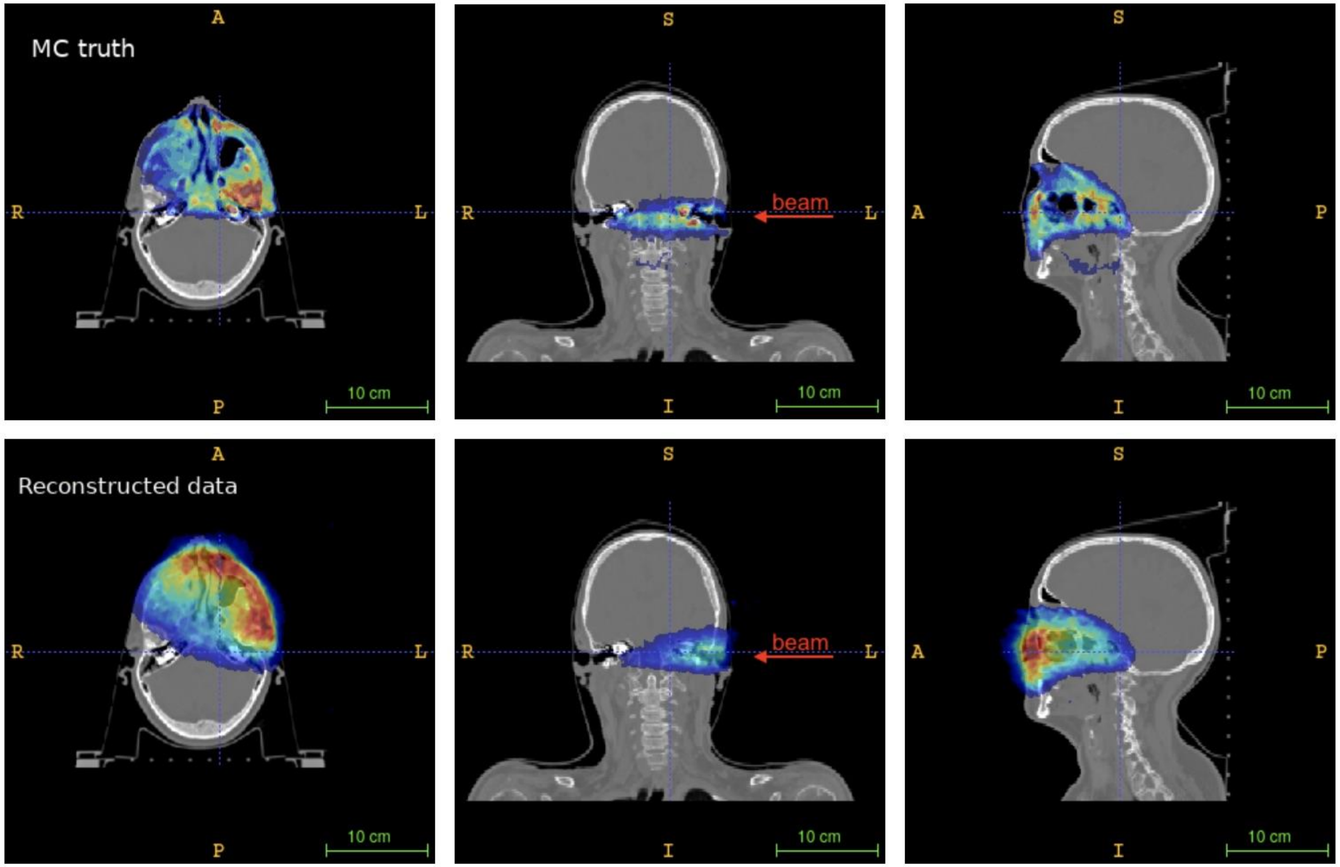


Residual magnetic field in the bore



Courtesy of P. Cerello

ATTRACT-H2I2 – PET



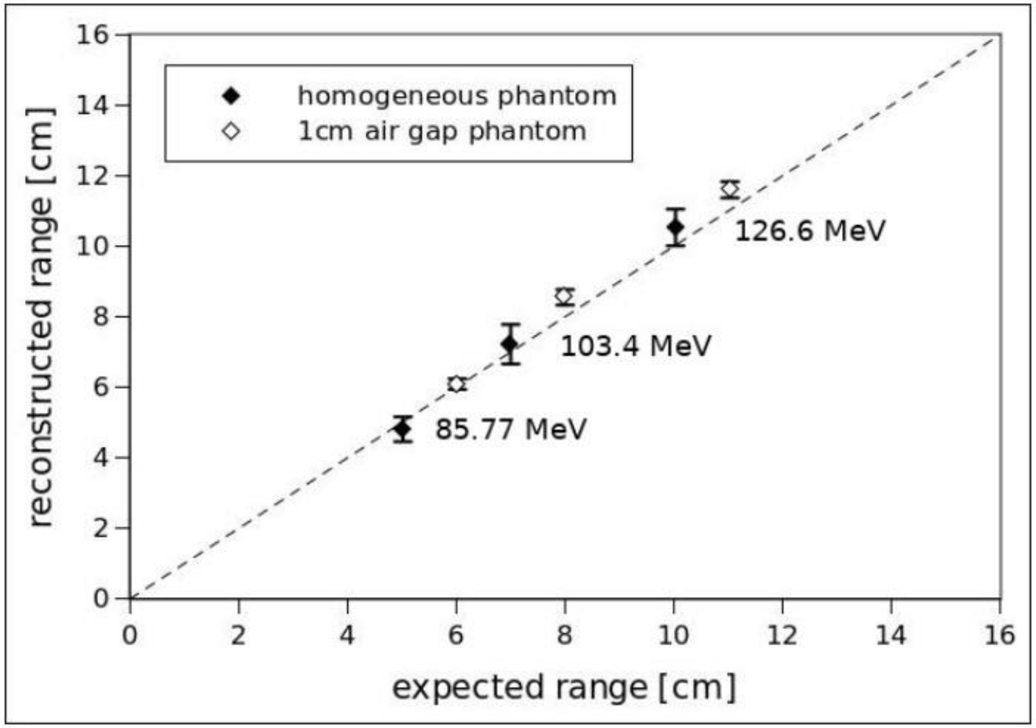
CNAO treatment plan

Adenoid Cystic Carcinoma (ACC)

1.8 x 10^9 protons in the [62, 141] MeV range

Range agreement within 1…2 mm

ATTRACT-H2I2 – Photons



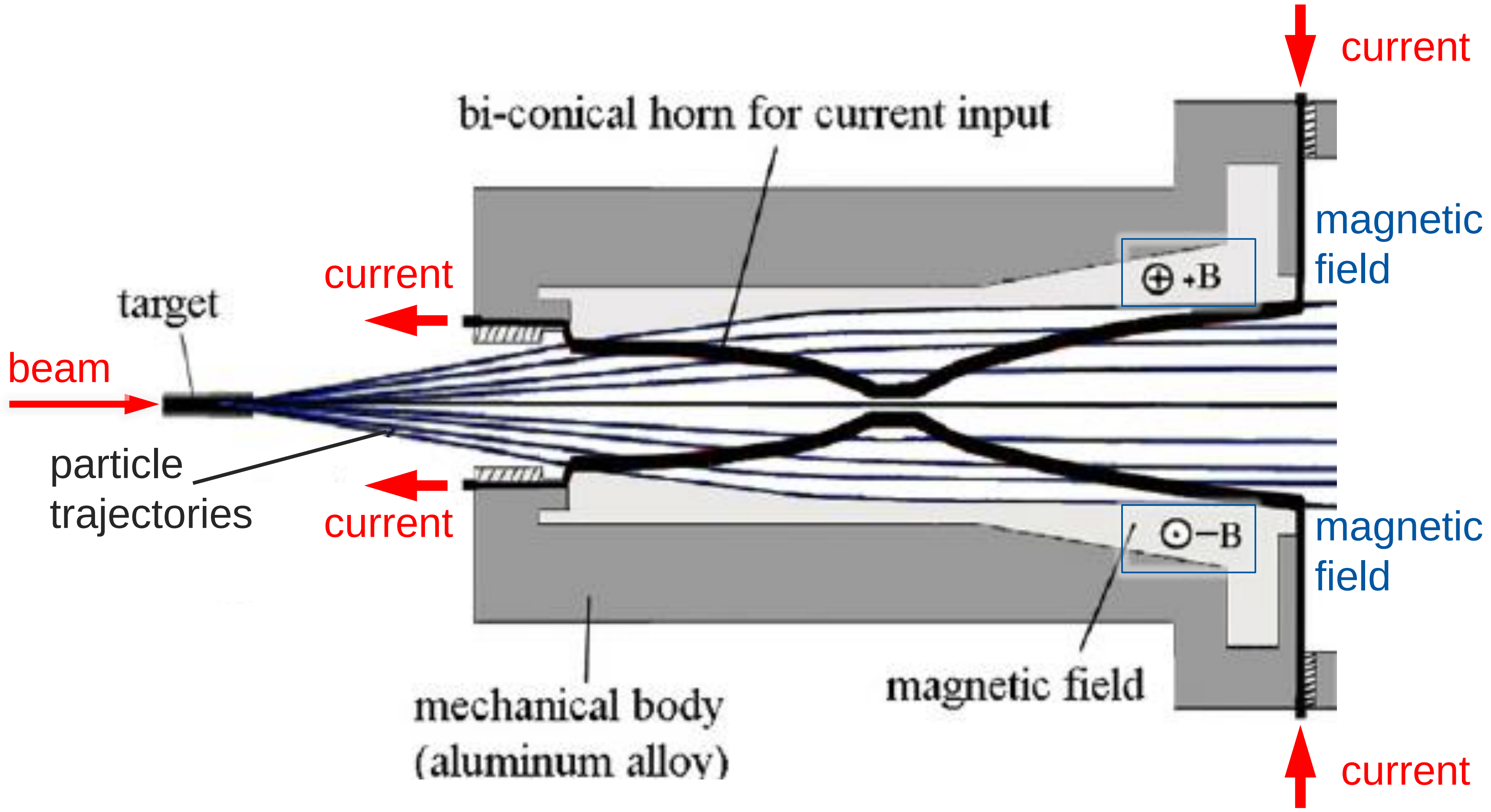
t_{start}: fast silicon beam monitor
t_{stop}: 'single' event on PET crystals
Emission point along the beam line

Single spot on a 10x10x20 cm^3 PMMA phantom

10^7 protons @ 85.8, 103.4, 126.6 MeV

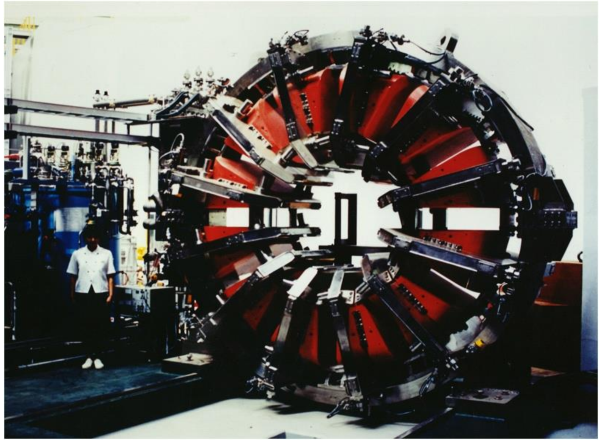
Range agreement within 4…6 mm

Previous art: the magnetic horn

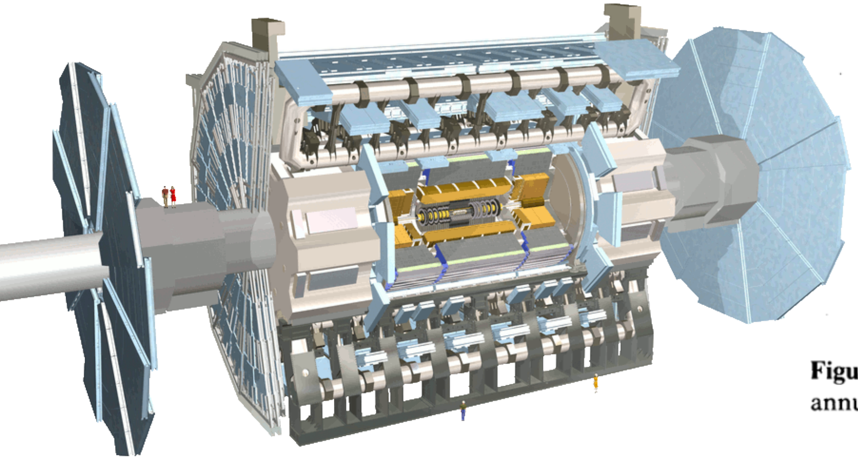


NIM-A 637:16-24 · February 2011

Previous art: spectrometers



TREK at KEK



ATLAS at CERN

"Orange" spectrometer

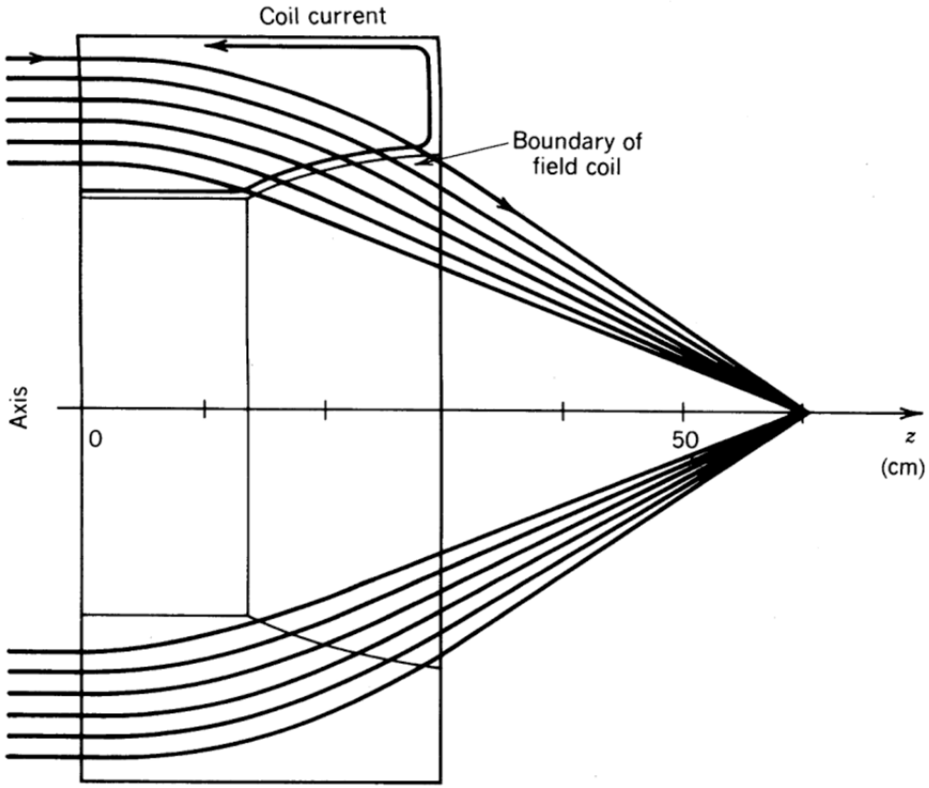
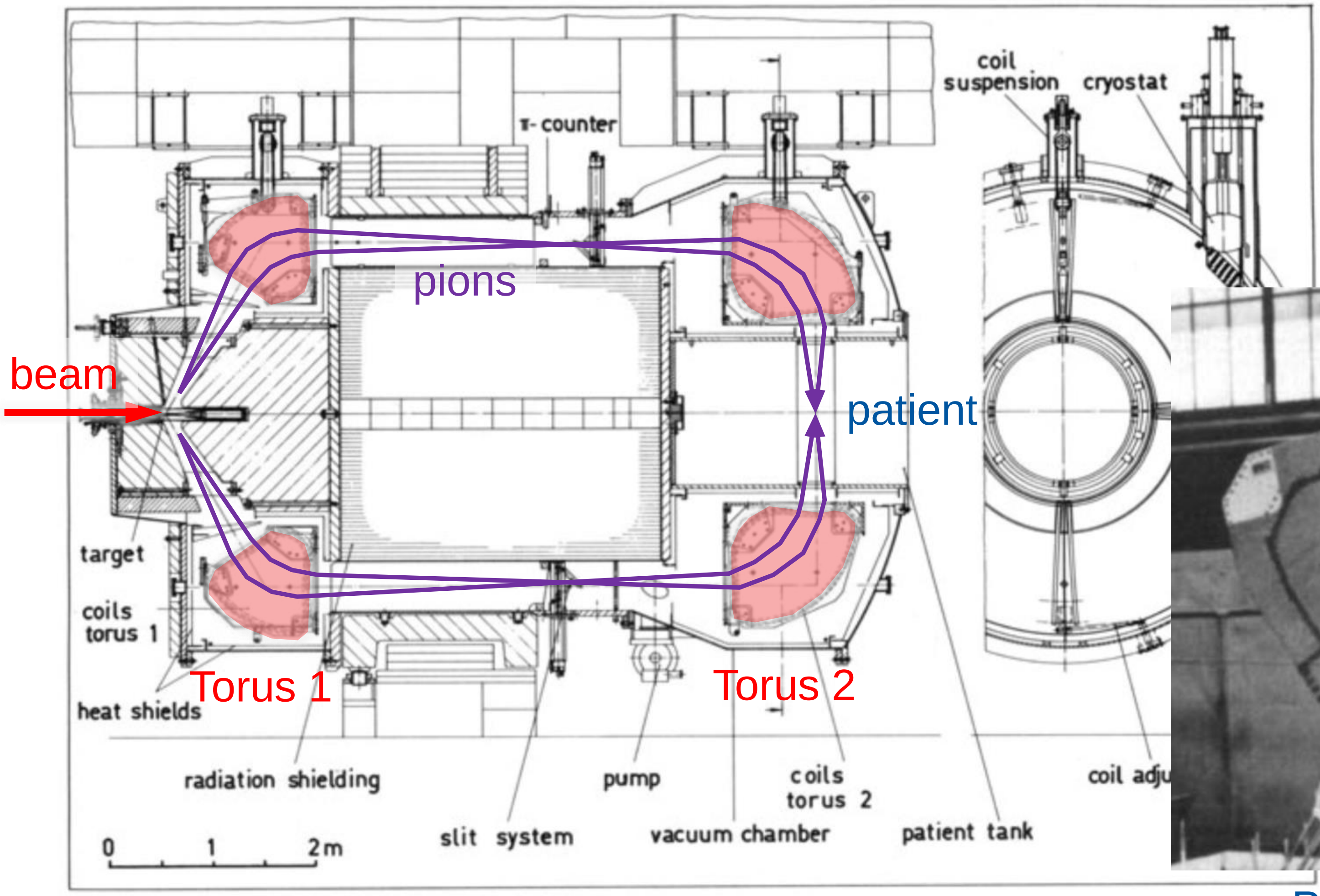


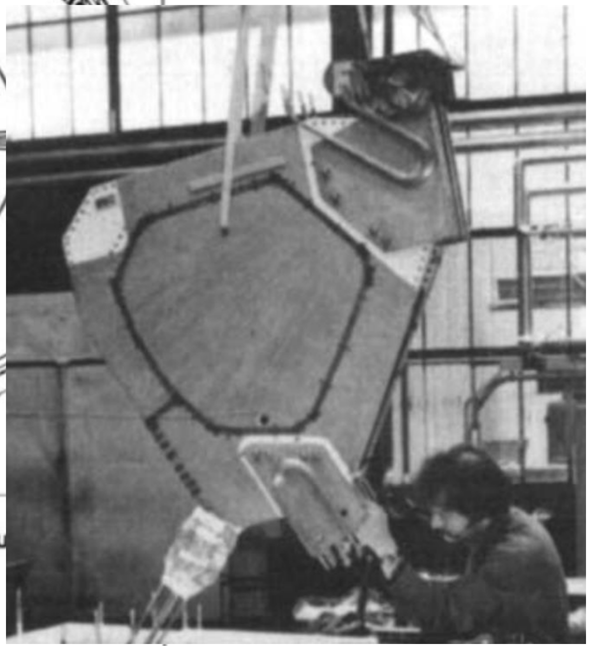
Figure 6.19 Particle orbits in a toroidal field lens with an exit boundary optimized for focusing an annular beam to a spot.

S. Humphries
Principles of Charged Particle Acceleration, April 1986

Previous art: the PIOTRON at PSI



J. Zellweger, Adv. Cryo. Eng.ng, 35A, 232-238, 1980



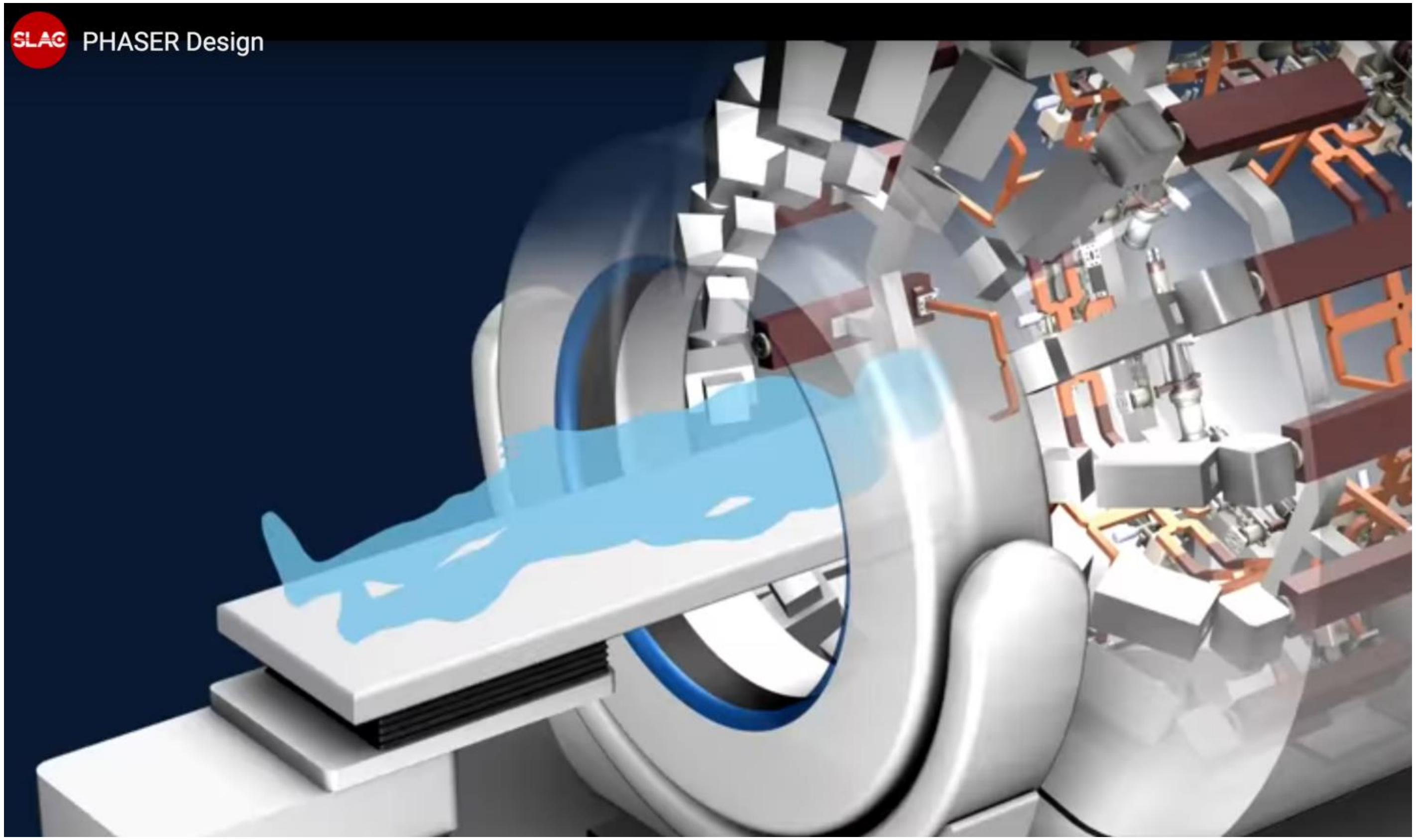
Prototype torus 1 coil

H. Benz, Cryogenics, 19, 435, 1979

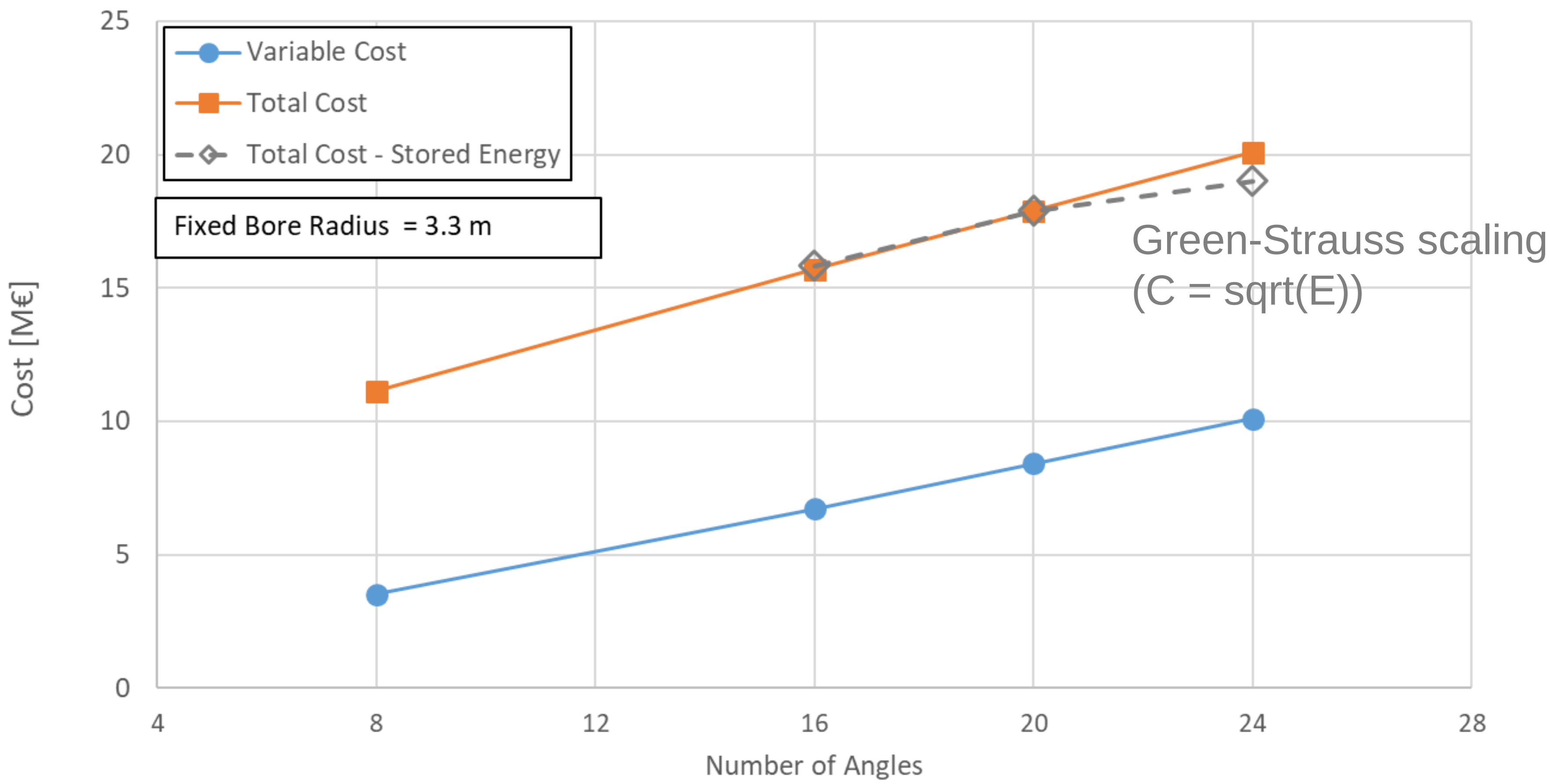
Other similar ideas

The future of fighting cancer: Zapping tumors in less than a second

November 28, 2018, SLAC National Accelerator Laboratory



Cost scaling (non binding)



Relatively large influence of the number of channels

Genesis of the idea

- A human mission to Mars means sending astronauts into interplanetary space for a minimum of a year, resulting in an integrated dose in the range of 1 Sv, mainly from Galactic Cosmic Rays (GCR)
- A *magnetic shielding* has been studied (NASA, ESA, SR2S) to deflect incoming particles and thus reduce exposure
- Hopefully the magnet polarity is right…
- Luckily, in the meantime NASA is developing Hydrogenated Boron Nitride Nanotubes, or H-BNNT’s, as lightweight radiation shield