GaToroid: A Novel Superconducting Compact and Lightweight Gantry for Hadron Therapy

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CERN KT Seminar, 22 November 2018

Project co-funded by the CERN Budget for Knowledge Transfer to Medical Applications

Outline

- Hadron therapy, why and how
- The need of a “gantry”
- The idea
- Development of the idea: a basic design
  - Magnetic design and magnet geometry
  - Beam optics, tracking, painting
  - Superconductor
  - Mechanics
  - Quench protection
- Some outstanding issues and a development plan
- Conclusions and perspective

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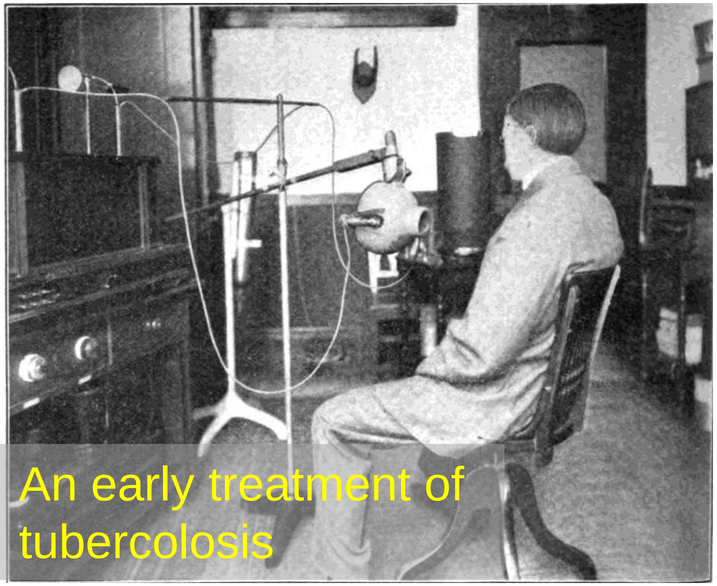
Radiation therapy

- *Radiotherapy* is a treatment that uses high doses of ionizing radiation to kill cancerous cells by damaging their DNA, and as a result shrink tumor volume
- First use of radiation to treat diseases can be traced to the late 1800's (possibly 1896, E. Grubbé at the Hahnemann Medical College of Chicago, a homeopathic clinic)

E. Grubbé (1875-1960)



An early treatment of tubercolosis

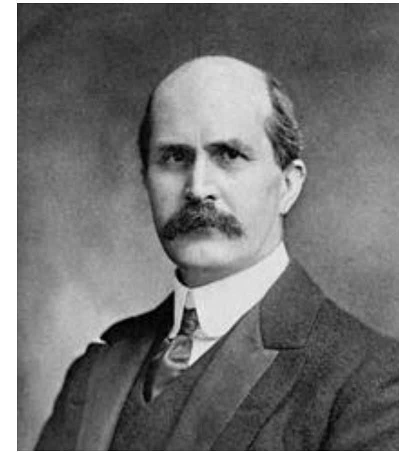
N.M. Eberhardt, Popular Electricity, 1910

A modern linear accelerator machine for photon therapy

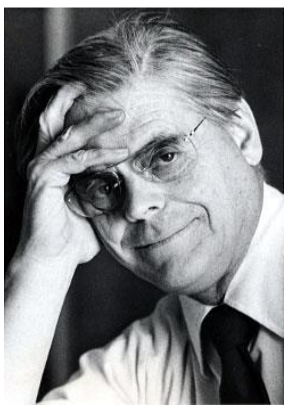
Clinac iX System, Varian, 2004

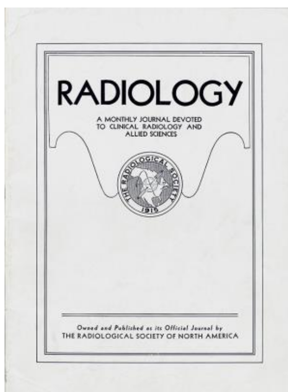
Hadron therapy

- Various types of ionizing radiation can be used for therapy:
  - Photons, Electrons, **Hadrons**
    - **Protons**
    - **Ions (He, C, Ne, …)**
    - Neutrons
    - Pions

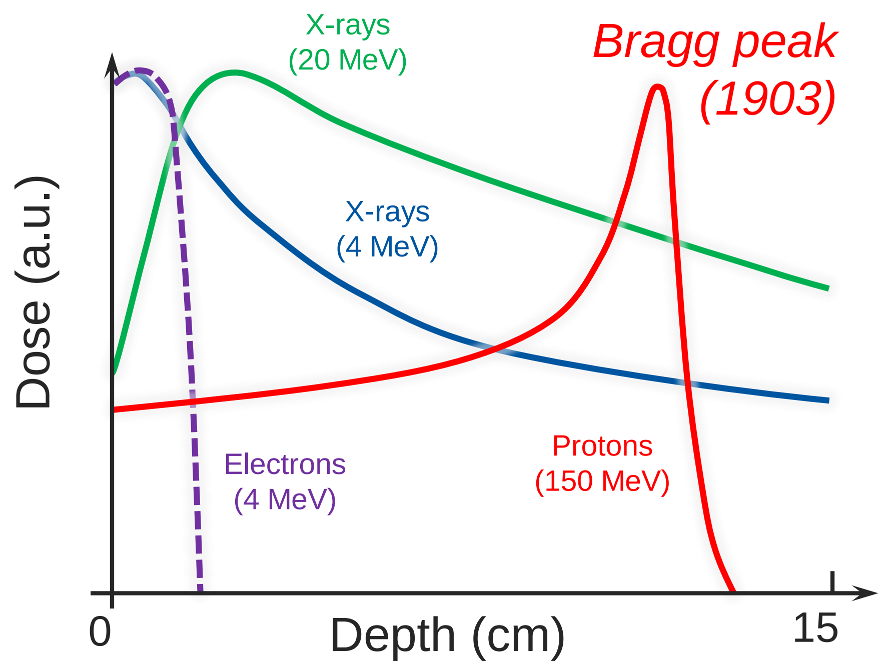


W.H. Bragg (1862-1942)
Nobel Prize in Physics 1915



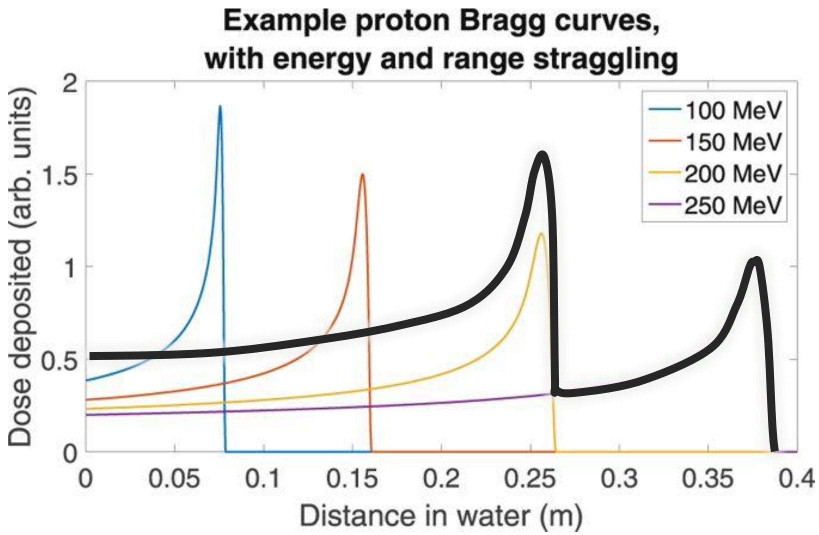


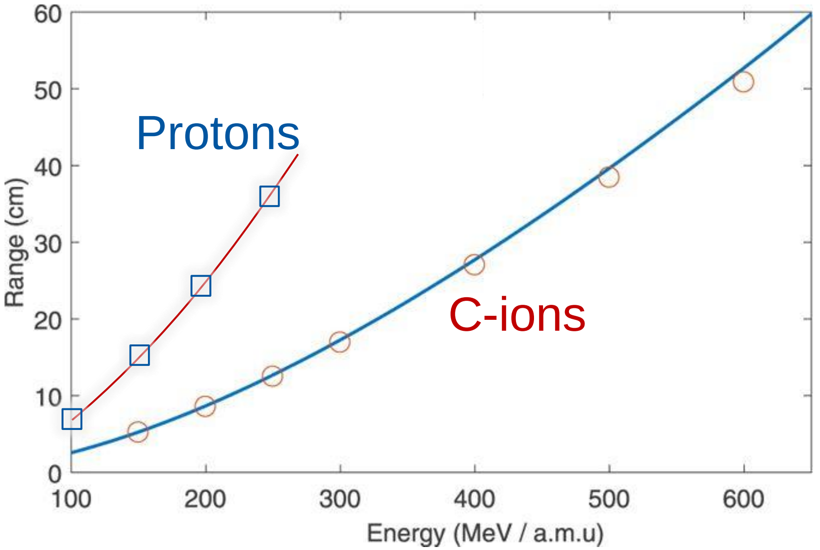
R.R. Wilson (1914-2000)
Radiological Use of Fast Protons
Radiology 1946;47:487-91.



Ranges of energy

- The depth of the Bragg peak depends on the particle type and its energy
- The typical energy range required to reach deep seated tumors is about 50…250 MeV for protons, and 100…500 MeV/u for carbon ions (to be compared to 2…20 MeV for photons)
- Note how the effect of beams of different energies can be super-imposed to deposit partial doses and treat tumors over a given depth





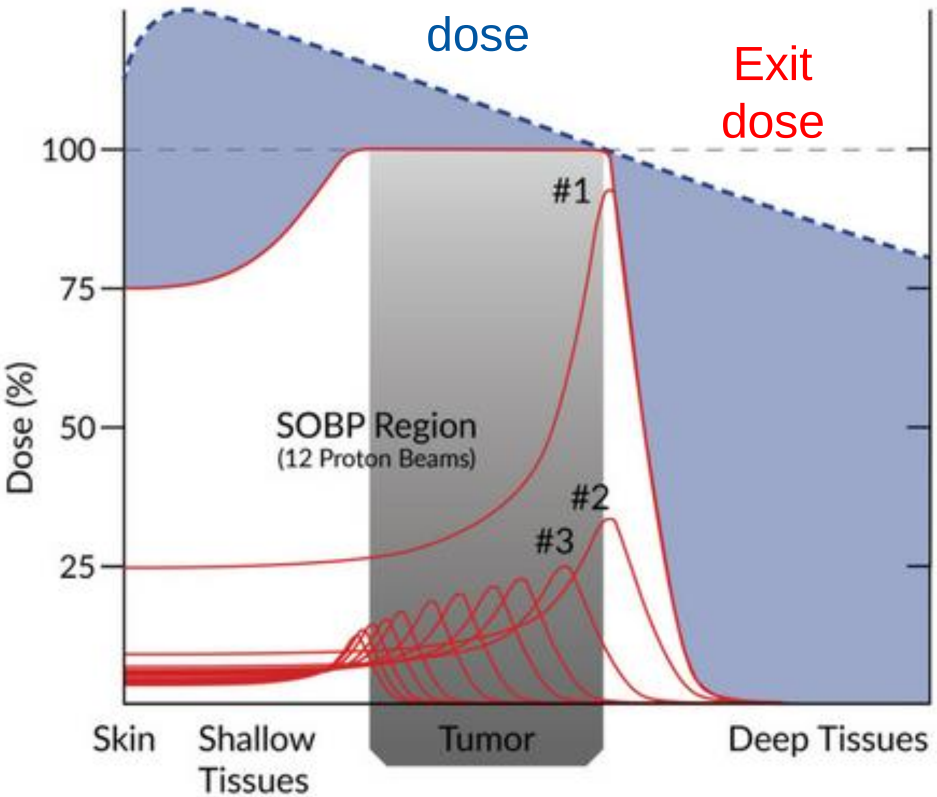
Scientific Reports, 7, 9781, 2017

Hadrons vs. photons

Entrance dose

Useful dose

Exit dose

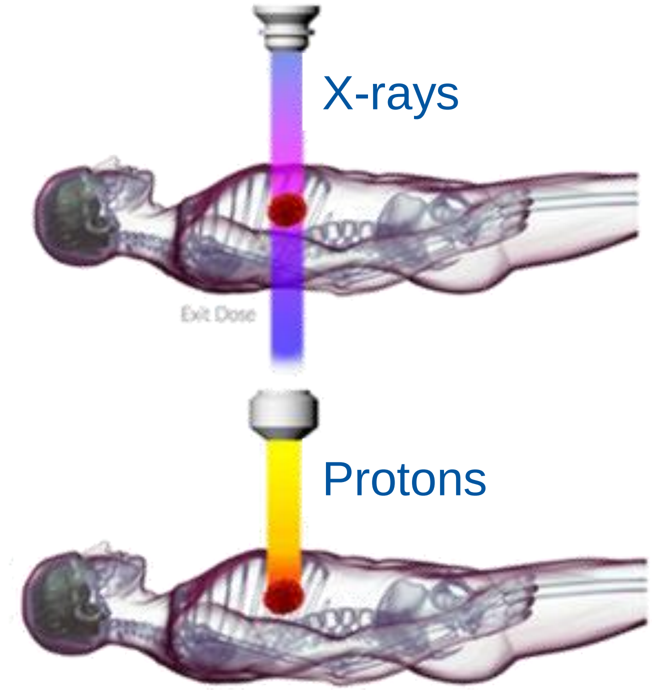


Beam

SOBP: Spread Out Bragg Peak

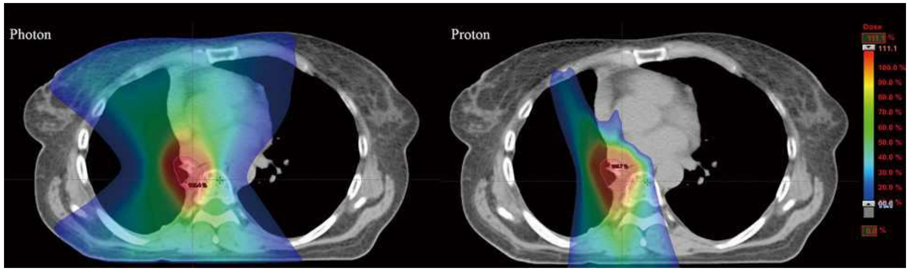
X-rays

Protons



X-rays

Protons

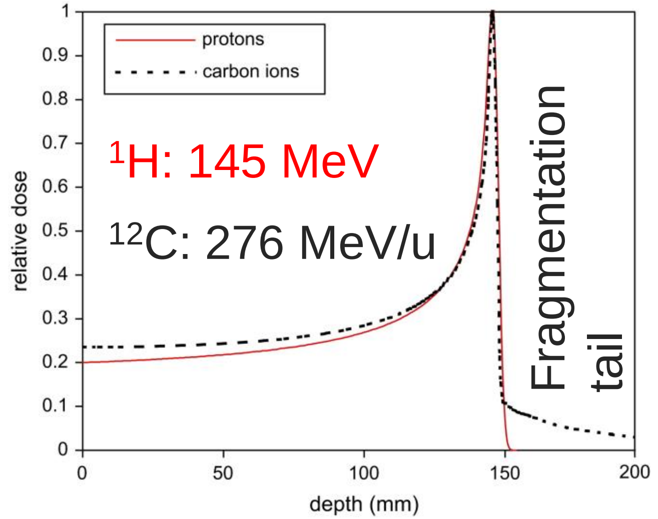


Translational Lung Cancer Research, 6(2), 2017

Protons vs. ions

- LET: Linear Energy Transfer
  - Linear energy density deposited by a ionizing radiation in the material
- RBE: Relative Biological Effectiveness
  - Ratio of biological effectiveness of ionizing radiation with respect to a reference one (X-rays) of identical deposited energy
- Penumbra
  - Width of the lateral band with a given dose range

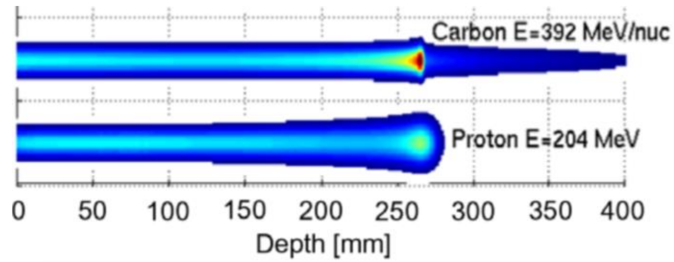
Ions may have an advantage !



Int. J. of Radiation Oncology Biology Physics, 70(1), 262-266, 2008

Typical values of RBE

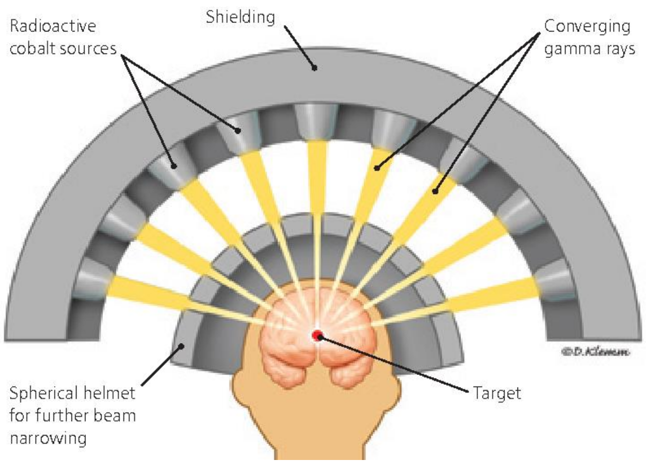
Particle	photon	neutron	proton pion	alpha heavy ion
RBE	1	2…20	2	20

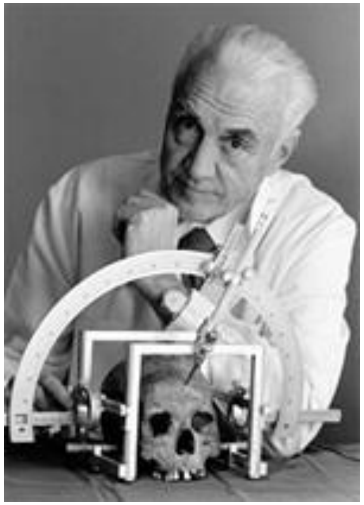


Radiotherapy and Oncology 95, 3–22, 2010

This is still an on-going and controversial debate

Stereotaxis





The “Gamma Knife” - Lars Leksell, 1968

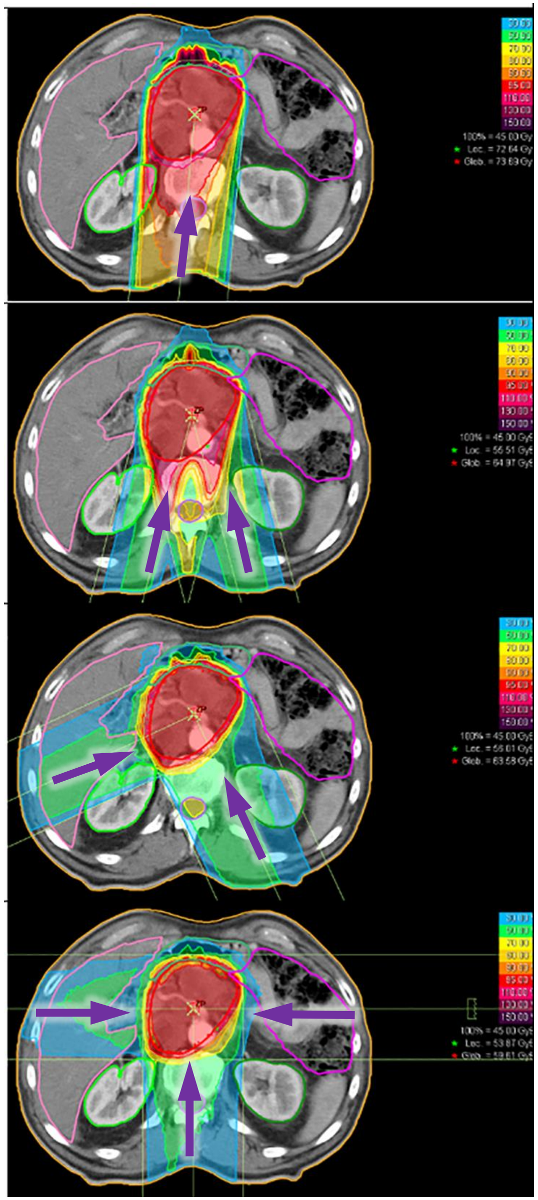
- Several precisely collimated beams can be super-imposed to obtain a good conformal mapping of the PTV (Planning Target Volume) derived from the GTV (Gross Tumor Volume) diagnosed with imaging techniques

1 C-ion beam

2 C-ion beams

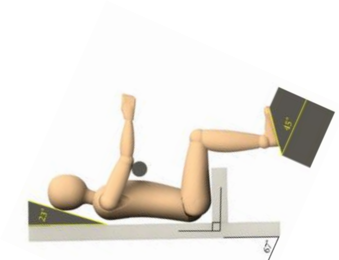
2 C-ion beams

3 C-ion beams

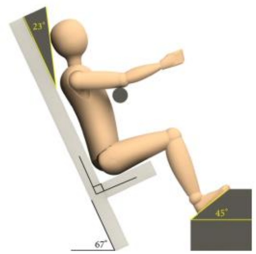


PLoS ONE 11(10): e0164473, 2016

Can we move the patient ?

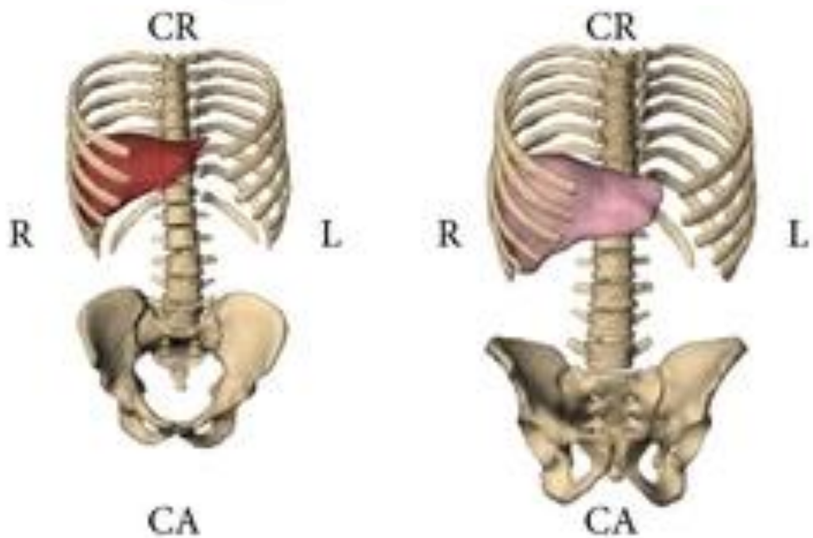


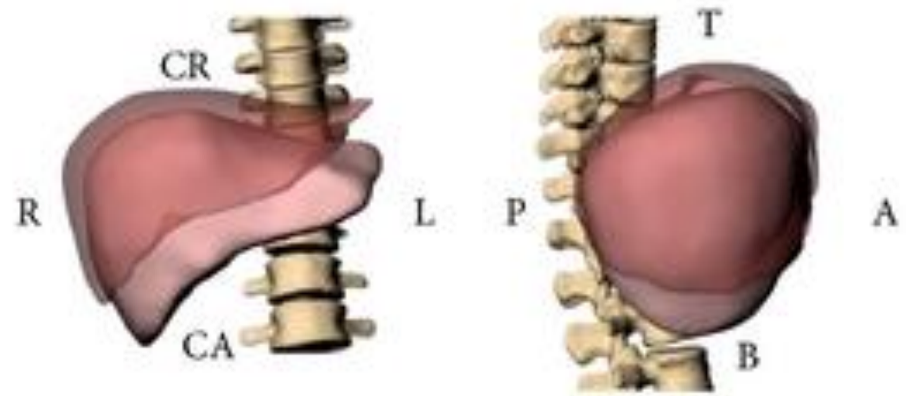
supine



seated

Motion of human liver due to change in body orientation. The typical order of magnitude of the change of organ position is 20 mm



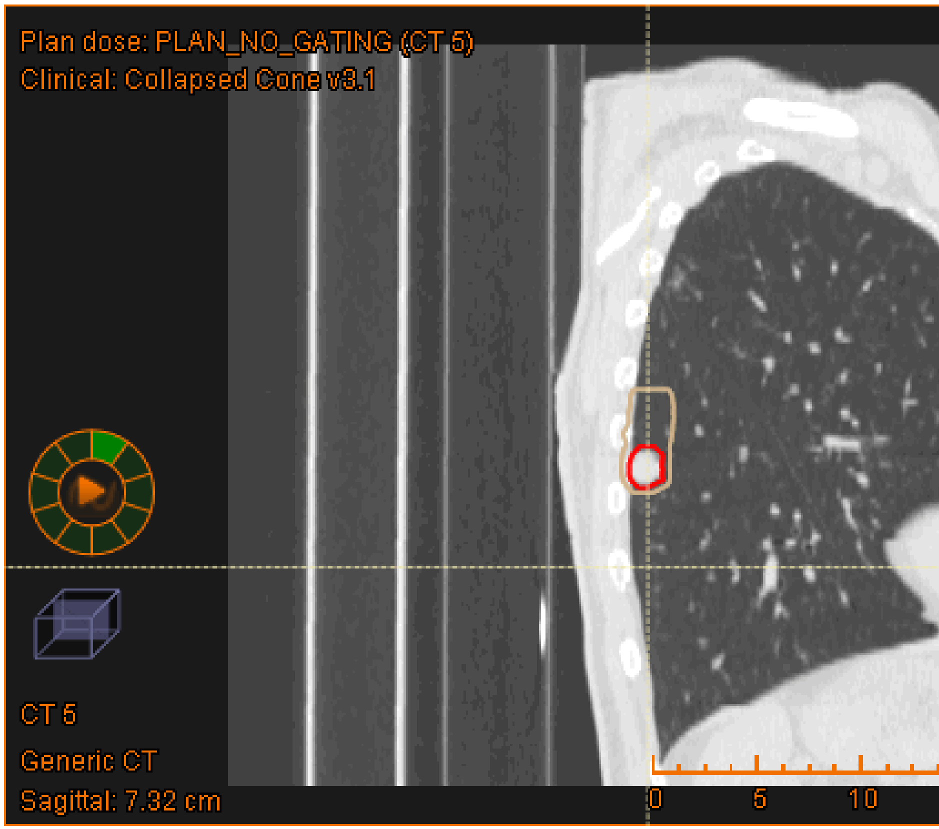


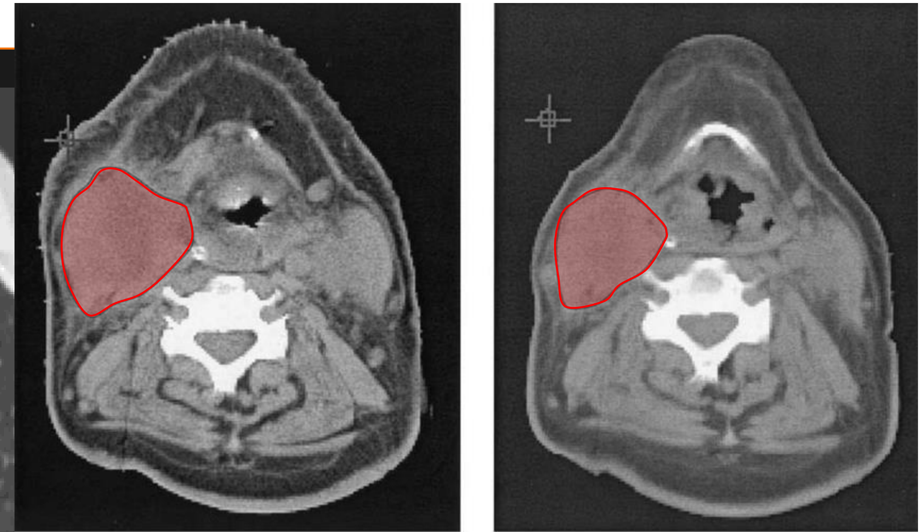
Computational and Mathematical Methods in Medicine
Volume 2013, Article ID 419821

Only small motions can be tolerated because of the accuracy requested by the organ positioning (besides other minor issues…)

(On other “movements”)

Initial CT 3 weeks into treatment





(a) (b)

Int. J. of Radiation Oncology Biology Physics 59(4), 960-970, 2004

The dose needs to be delivered precisely and rapidly

Moving organs and changes in morphology are a challenge

Engineers vs. Physicians

- *The ideal subject of radiotherapy for an engineer is a homogeneous, perfectly rigid and immobile patient*

- *Alas, this is not a very interesting subject for a practicing physician*

- Anatomy, motion and changes are major challenges for any radiotherapy. An **in-vivo** and **on-line** imaging and range measurement would be the **holy grail of radio-therapy** (this is not the topic of this talk, but may be related to it)

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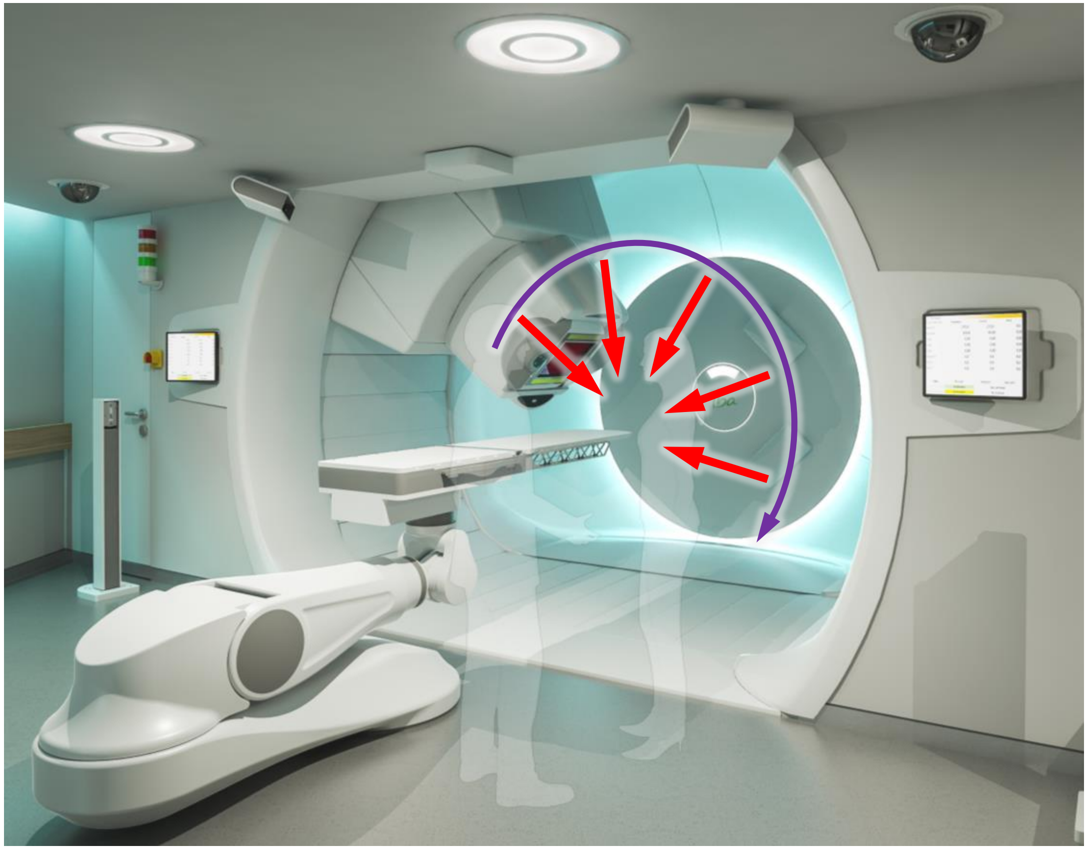
A better option – “move” the beam !

Multiple beam lines

Treatment room at CNAO Pavia (IT)

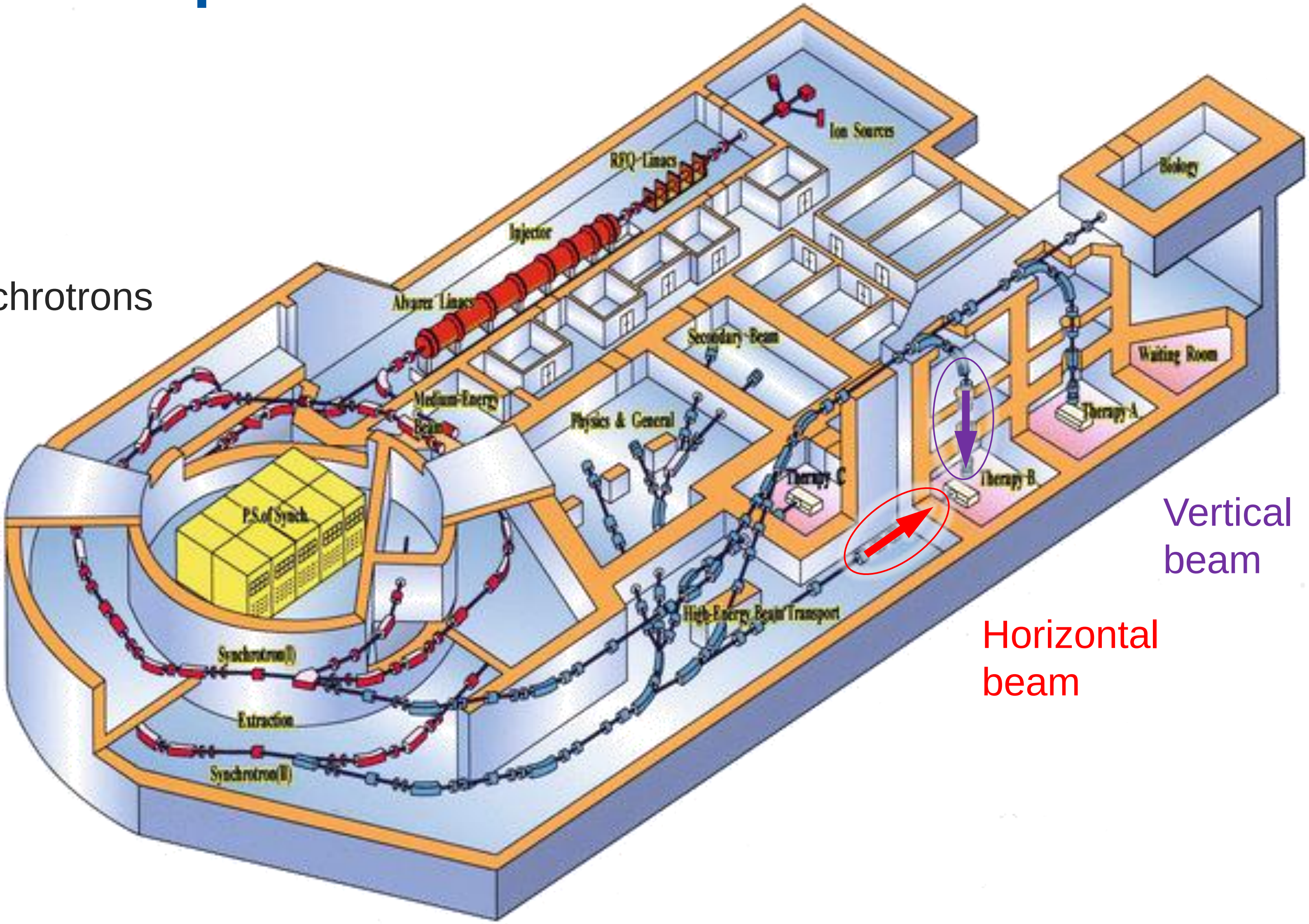
Moving beam line (**gantry**)



ProteusONE proton therapy machine, IBA

Multiple beam lines

Two synchrotrons

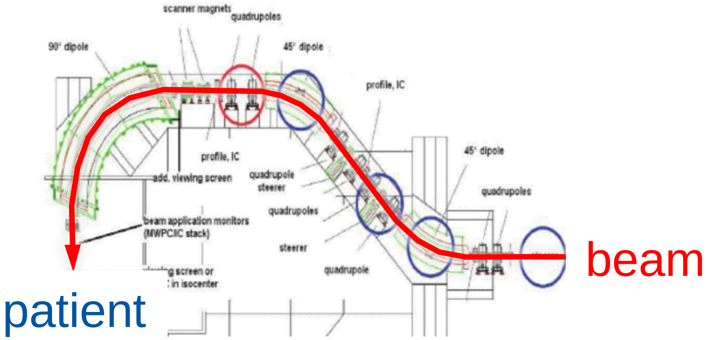


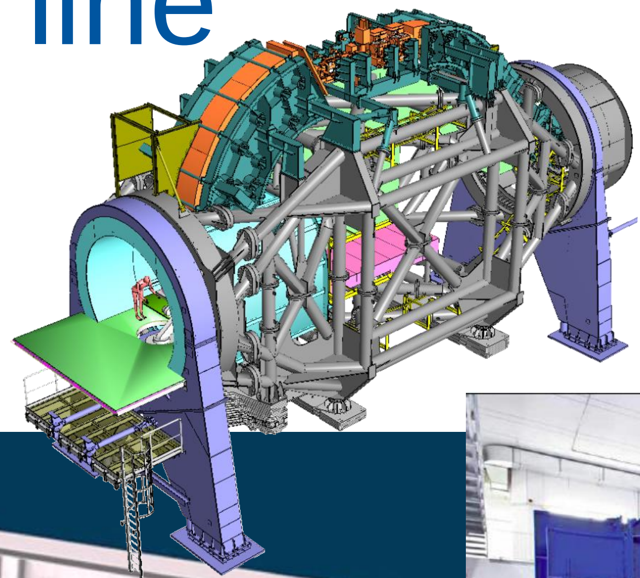
Vertical beam

Horizontal beam

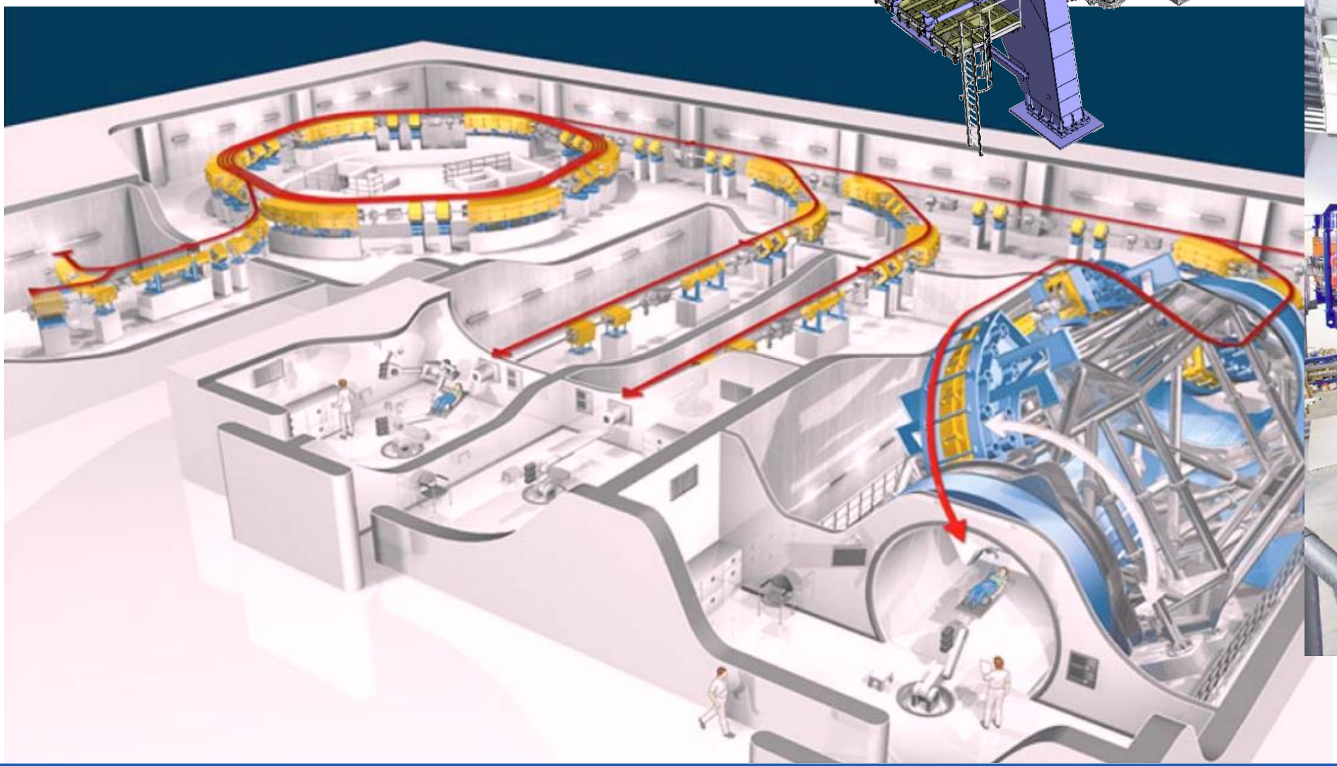
HIMAC: Heavy Ion Medical Accelerator in Chiba (Chiba, JA)

Moving beam line





Beam line embarked in a rigid and precise rotating structure

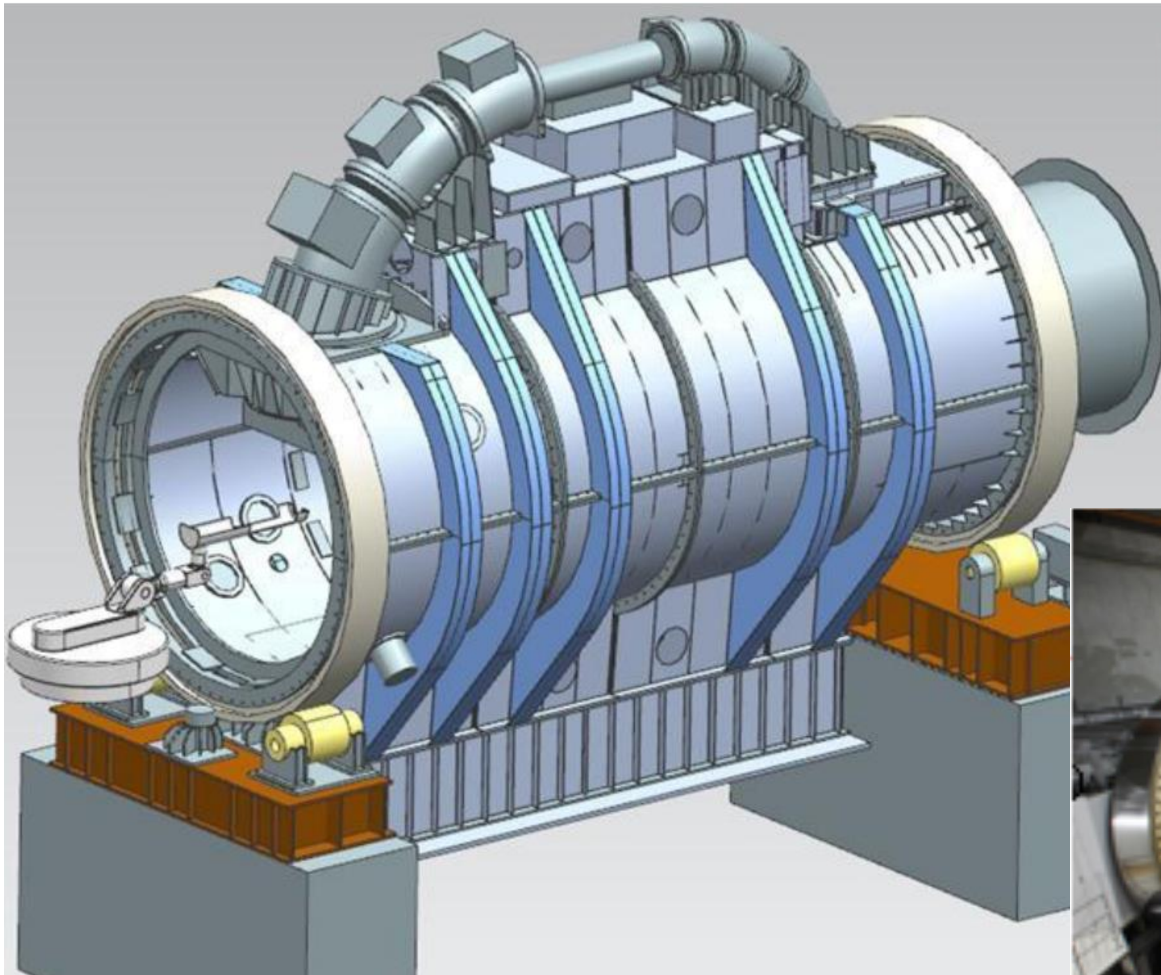


The “Heidelberg” Gantry

Heidelberg Ion-Beam Therapy (HIT)

Maximum field = 1.8 T
Length = 25 m
Diameter = 13 m
Weight = 670 tons

Heavy Ion Medical Accelerator in Chiba (HIMAC)



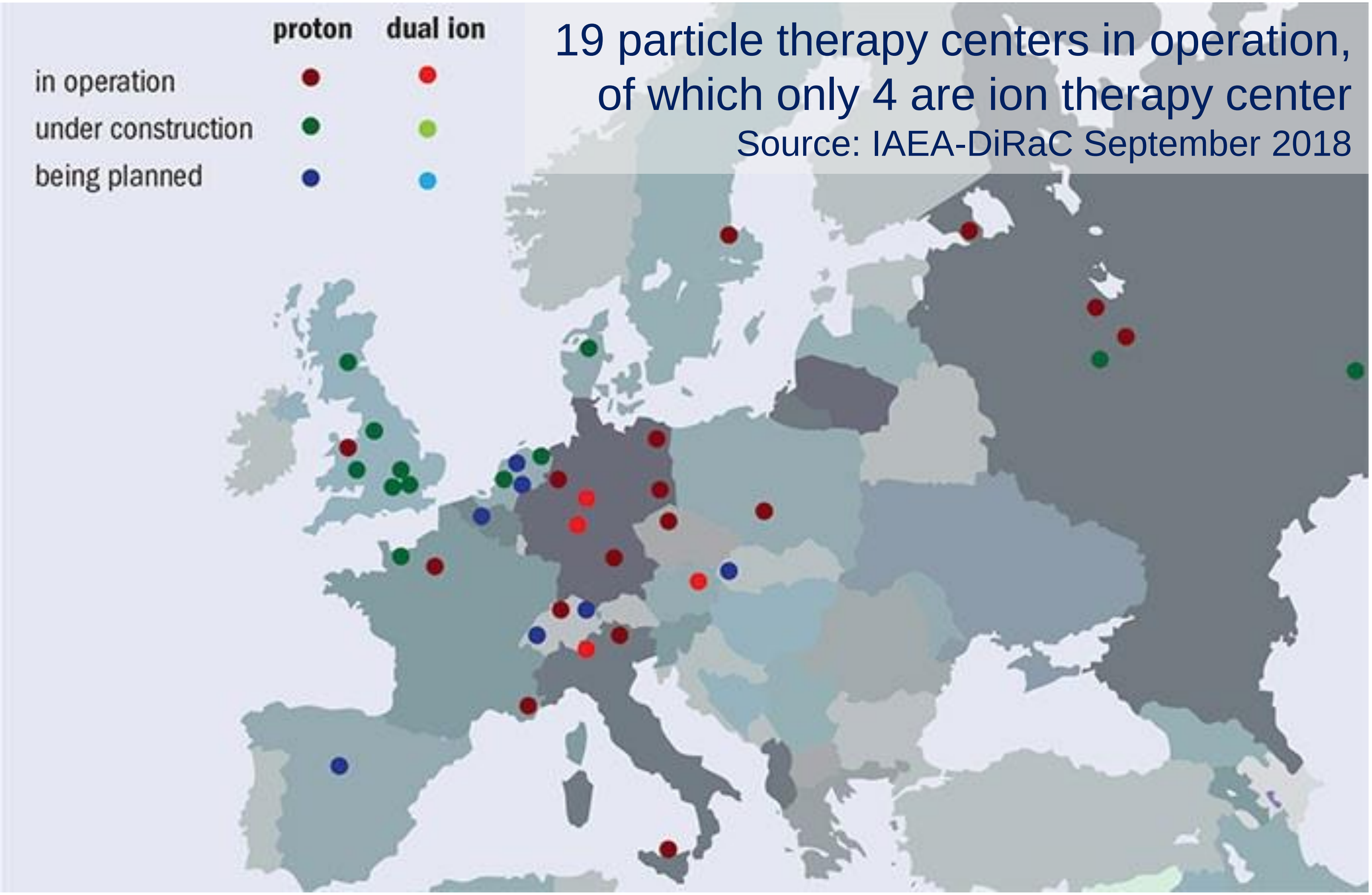
Maximum field = 2.88 T
Length = 13 m
Diameter = 10 m
Weight = 350 tons

Two fundamental questions before we continue

How many such installations are available or planned ?

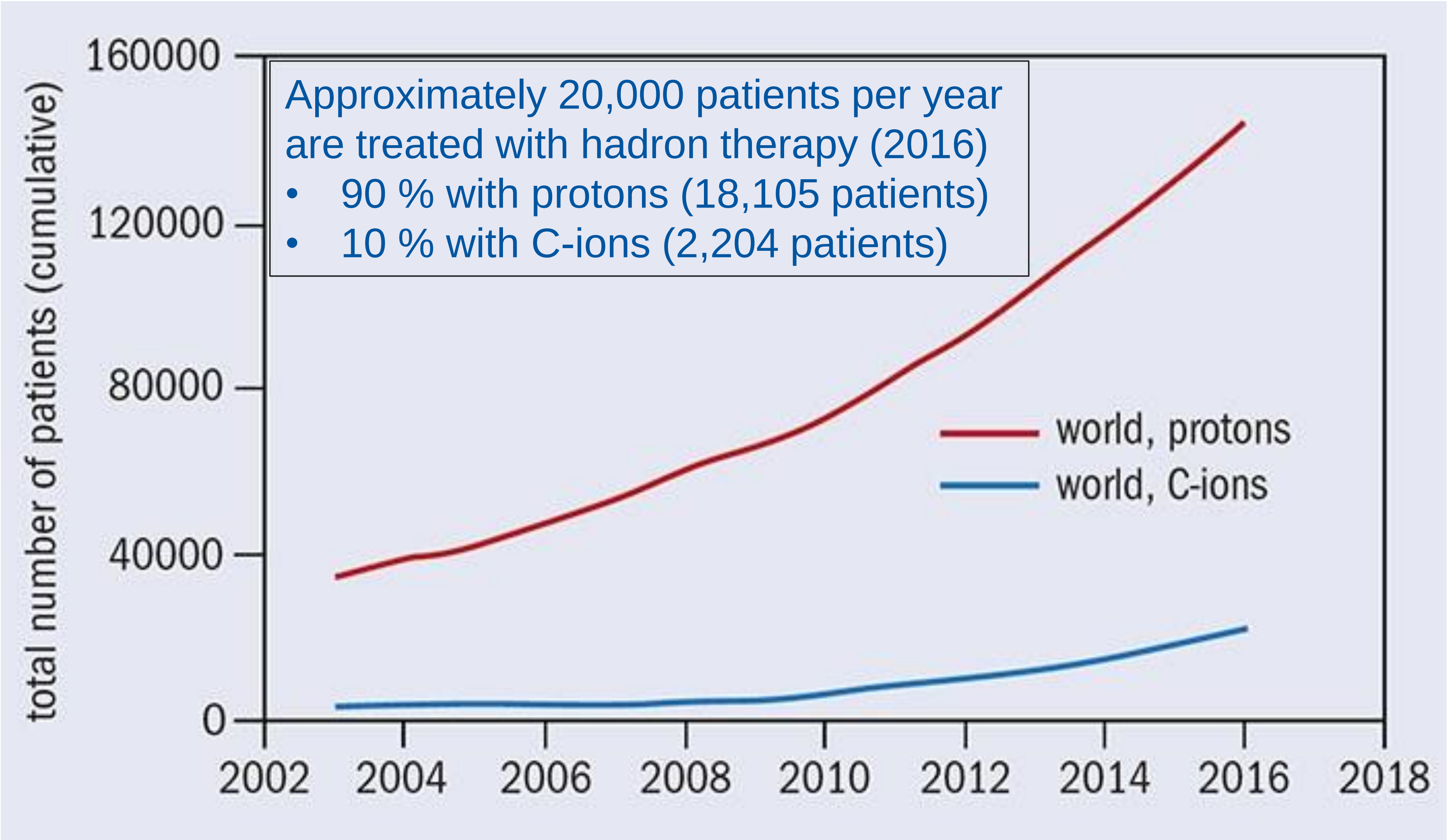
For how many patients, and who would benefit from them ?

EU landscape of hadron therapy



19 particle therapy centers in operation, of which only 4 are ion therapy center
Source: IAEA-DiRaC September 2018

Hadron therapy patients



A great potential !

- Radiation therapy can benefit approximately 50% (J. Borras, Radiotherapy and Oncology, 119, 2016) of newly diagnosed cancer cases:
  - 7 million patients of the 14 million diagnosed in 2014, and 10 million patients of the 20 million projected in 2030
- Hadron therapy has better therapeutical potential for 15% to 20% (B. Gimelius. Acta Oncologia, 44, 2005) of the above cases:
  - 1.5 million patients/year at present, and a projected 2 million patients/year in 2030 vs. the actual treatment capacity of 20,000 patients/year

Yes, but…

Putting profits before health: Siemens abandons cancer therapy

Is spending on proton beam therapy for cancer going too far, too fast?

Cost of particle therapy

How costly is particle therapy? Cost analysis of external beam radiotherapy with carbon-ions, protons and photons

Some people have recognised the rashness of the dash to introduce these machines, which have been described as the world's "most costly and complicated medical device"

Radiology > Therapeutic Radiology

Wise Buy? Proton Beam Therapy

— It helps only a few, and at a wildly extravagant cost

by Paul Raeburn, Contributing Writer, MedPage Today

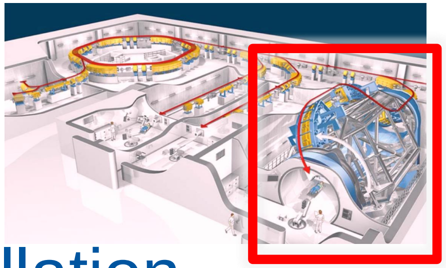
May 19, 2017

- **Hadron therapy is expensive**, with a price tag ranging from 20 to 200 MEUR, an order of magnitude more than a *state-of-the-art* radiotherapy facility
- **Hadron therapy is bulky**, requiring accelerator and beam delivery which do not fit a "single room"
- **Patient recruitment** to "feed" the facility is an inconvenient process both to patients and doctors

CERN

Can hadron therapy be **smaller, faster, cheaper** ?

Focus on the gantry



- Gantries are about half of the whole installation
- Hadron therapy gantries are massive, because of:
  - Required integral bending field, limited by the performance of resistive electromagnets (about 1 T)
  - Stability requirements during rotation (about 1 mm)
- Basic idea:
  - Use superconductors to increase the bending field in large bore magnets (acceptance)
    - More compact magnets, weight reduction, energy efficiency
  - Devise a magnetic configuration which does not need to be rotated nor ramped to focus the beam on the patient
    - Reduce the stability requirements on the gantry, hence mass and footprint

Many are working on this

Easier said than done…

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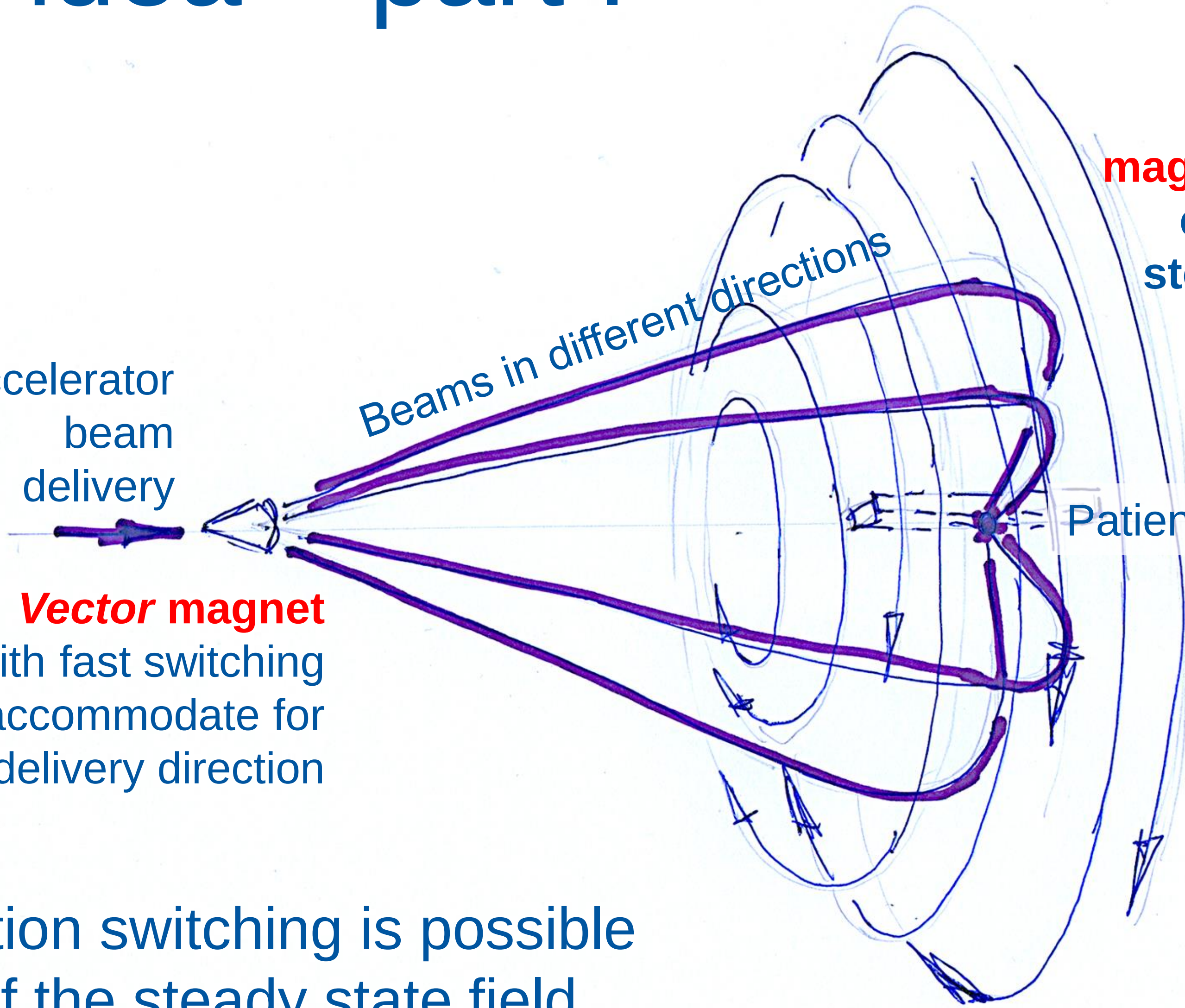
The idea – part I

Accelerator
beam
delivery



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

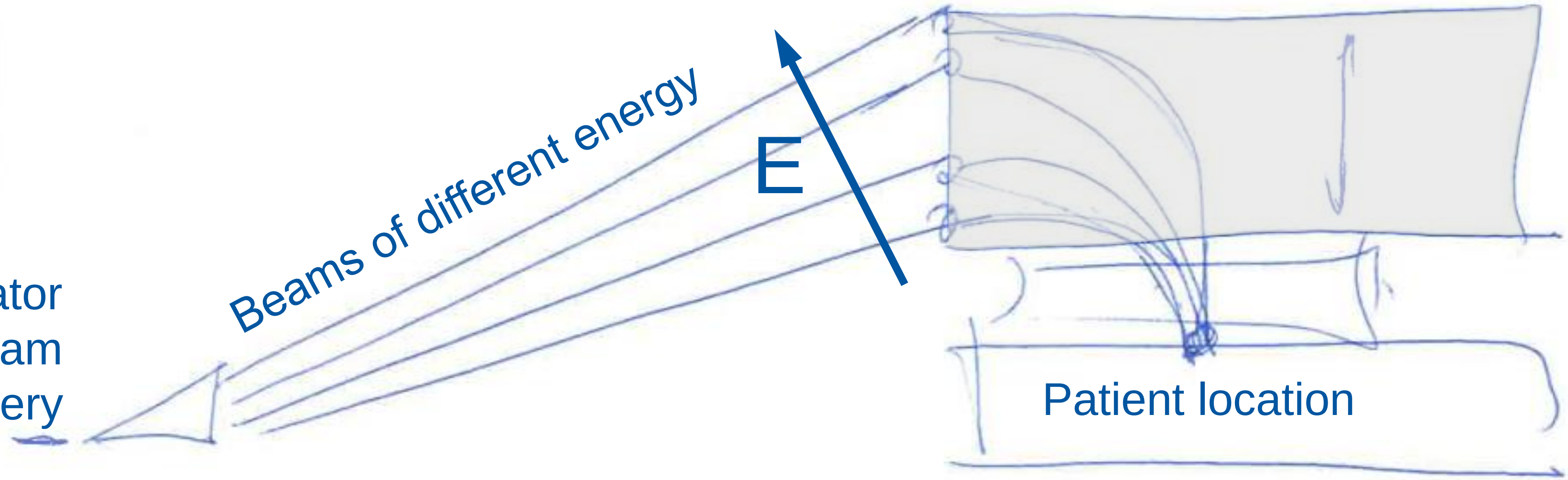
***Vector* magnet**
X-Y kicker with fast switching capability to accommodate for change of delivery direction

Fast direction switching is possible because of the steady state field

L. Bottura, A Gantry and Apparatus for Focusing Beams of Charged Particles, European Patent Application EP 18173426.0, May 2018

The idea – part II

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

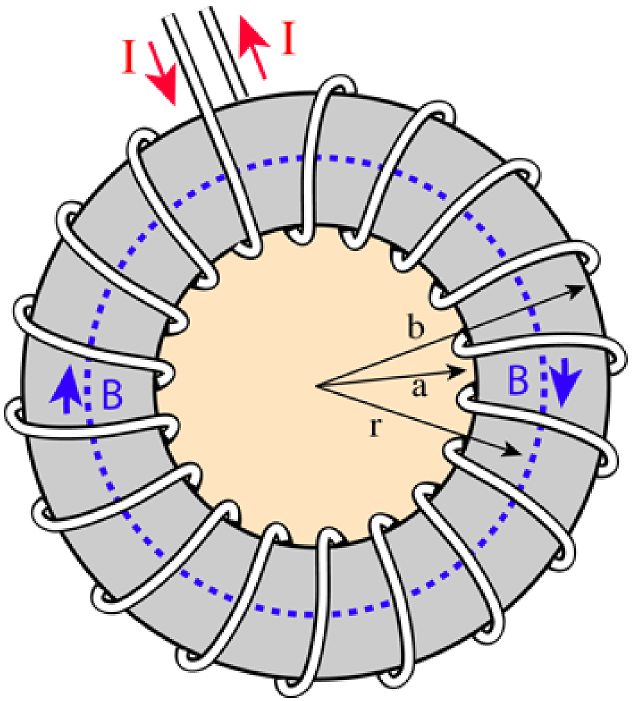


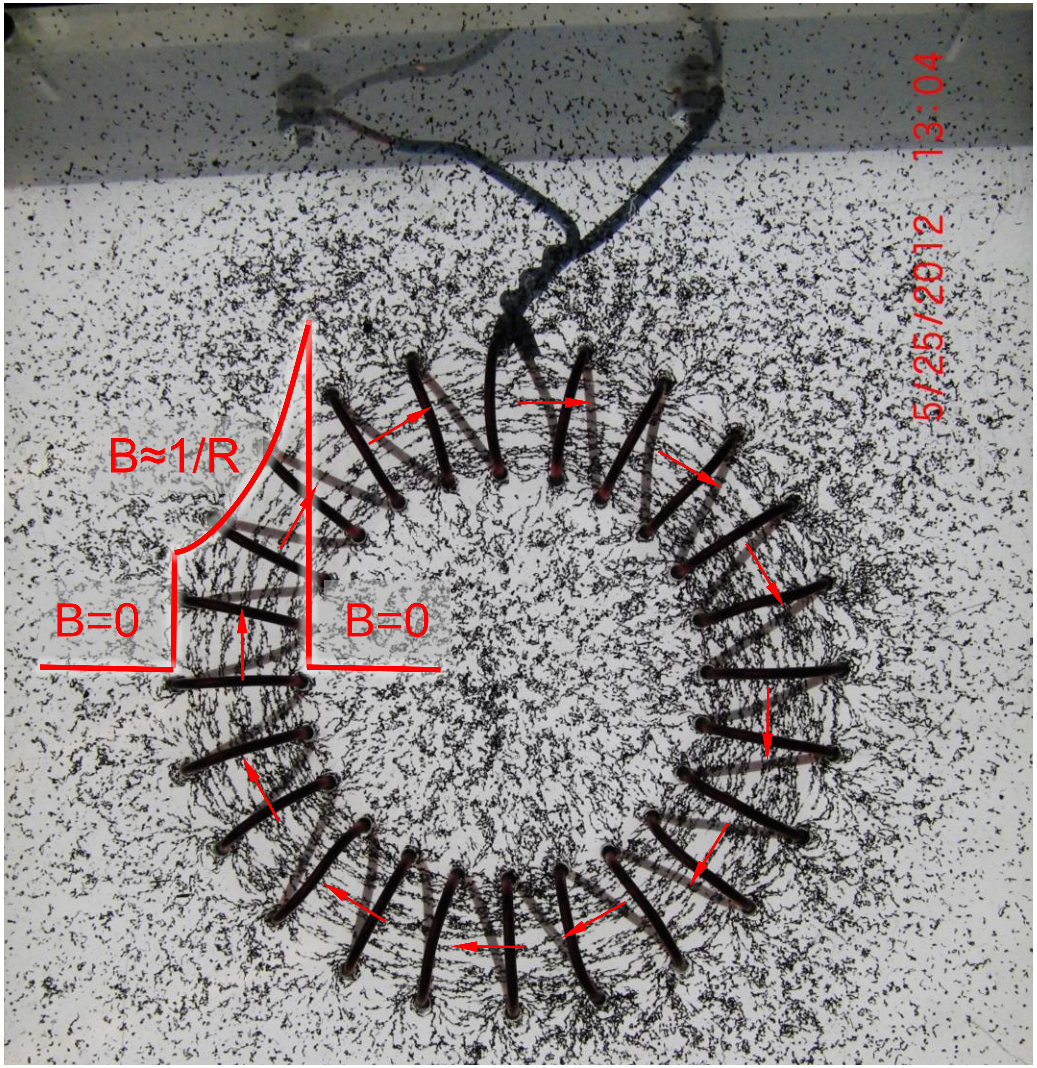
Vector magnet
X-Y kicker with fast switching capability to accommodate for energy change

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

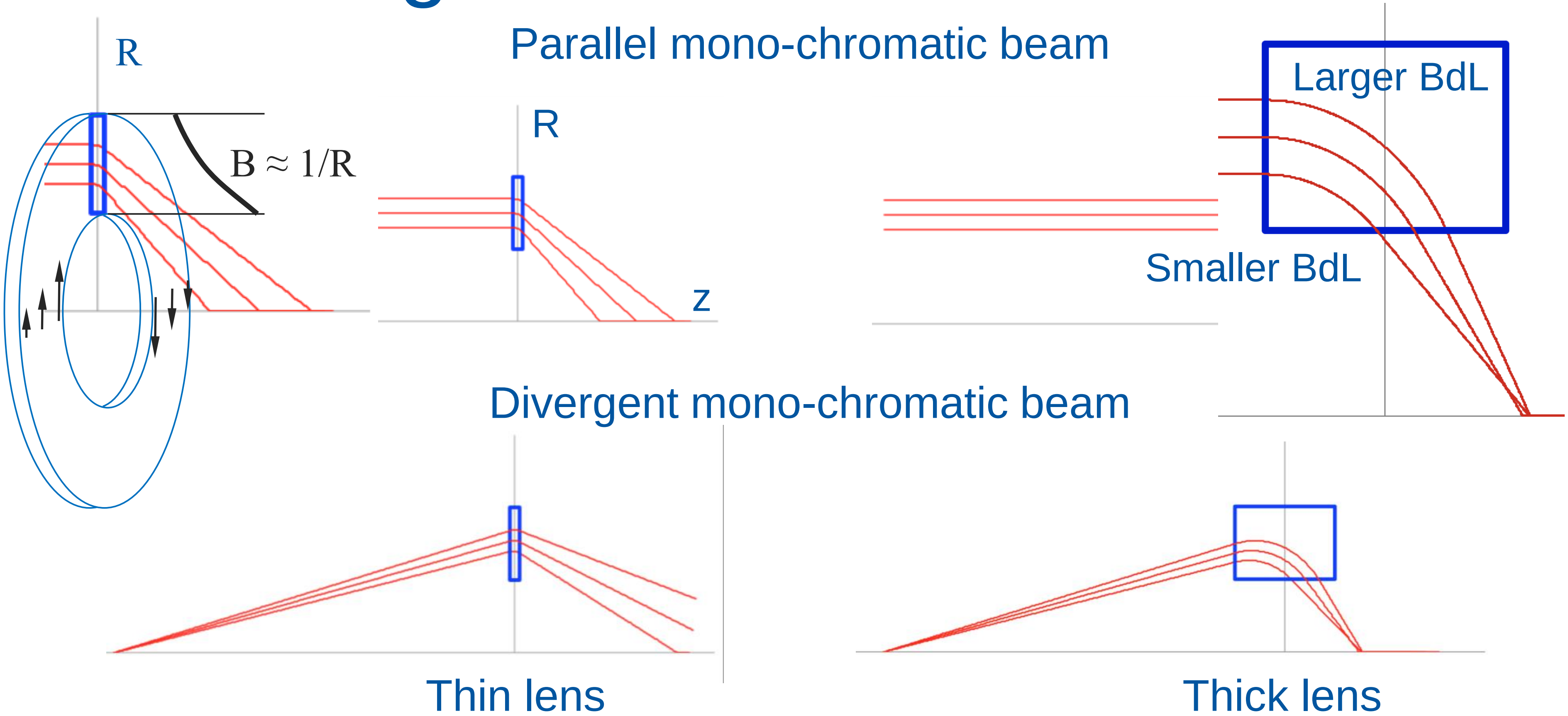
Ideal toroidal field

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





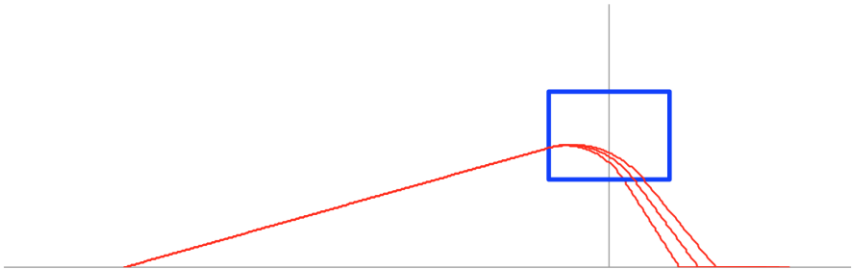
Focusing effect of a toroidal field

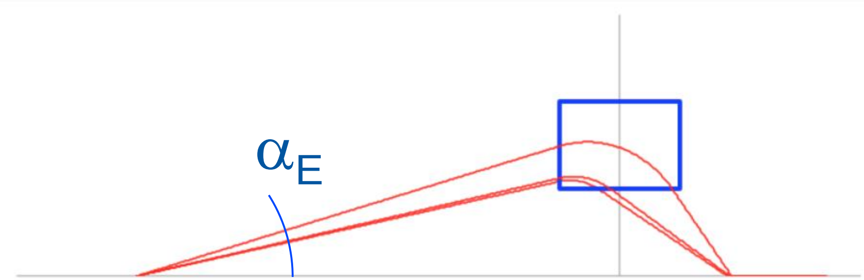


A toroidal field of finite length has a net in-plane focusing effect on a mono-chromatic beam (due to the BdL)

Focusing effect of a toroidal field

Parallel and divergent beams of different p/q



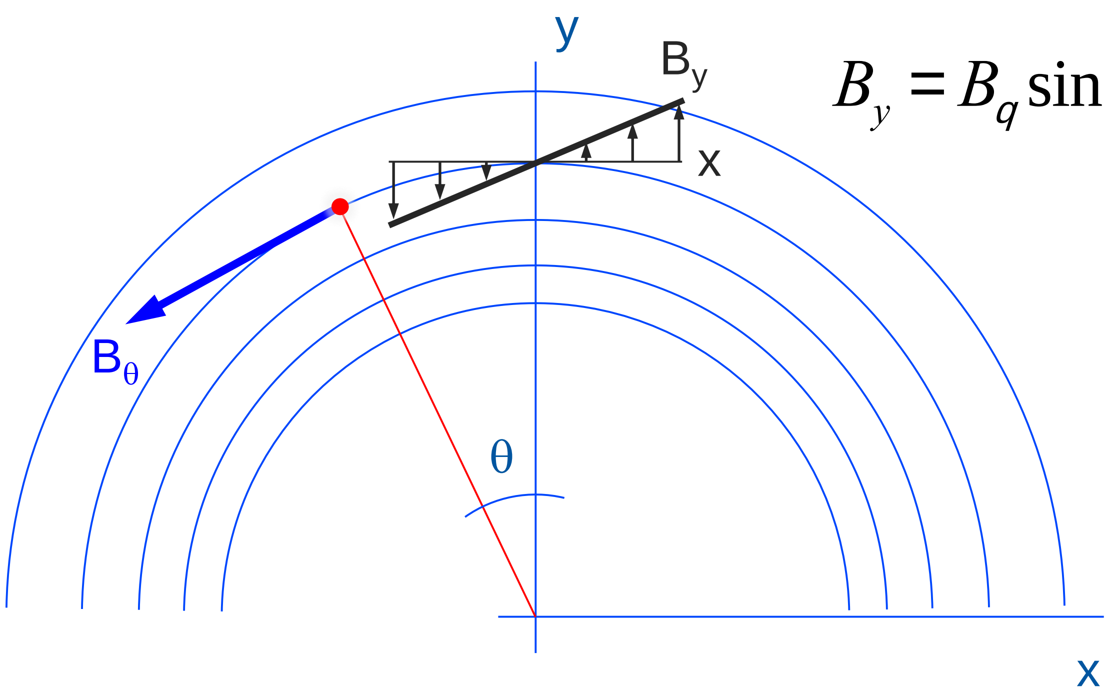


Beams of different p/q originating at the same vertex and with identical angle are focused on different spots

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

Focusing effect of a toroidal field

Particles traveling out of the (R,z) plane



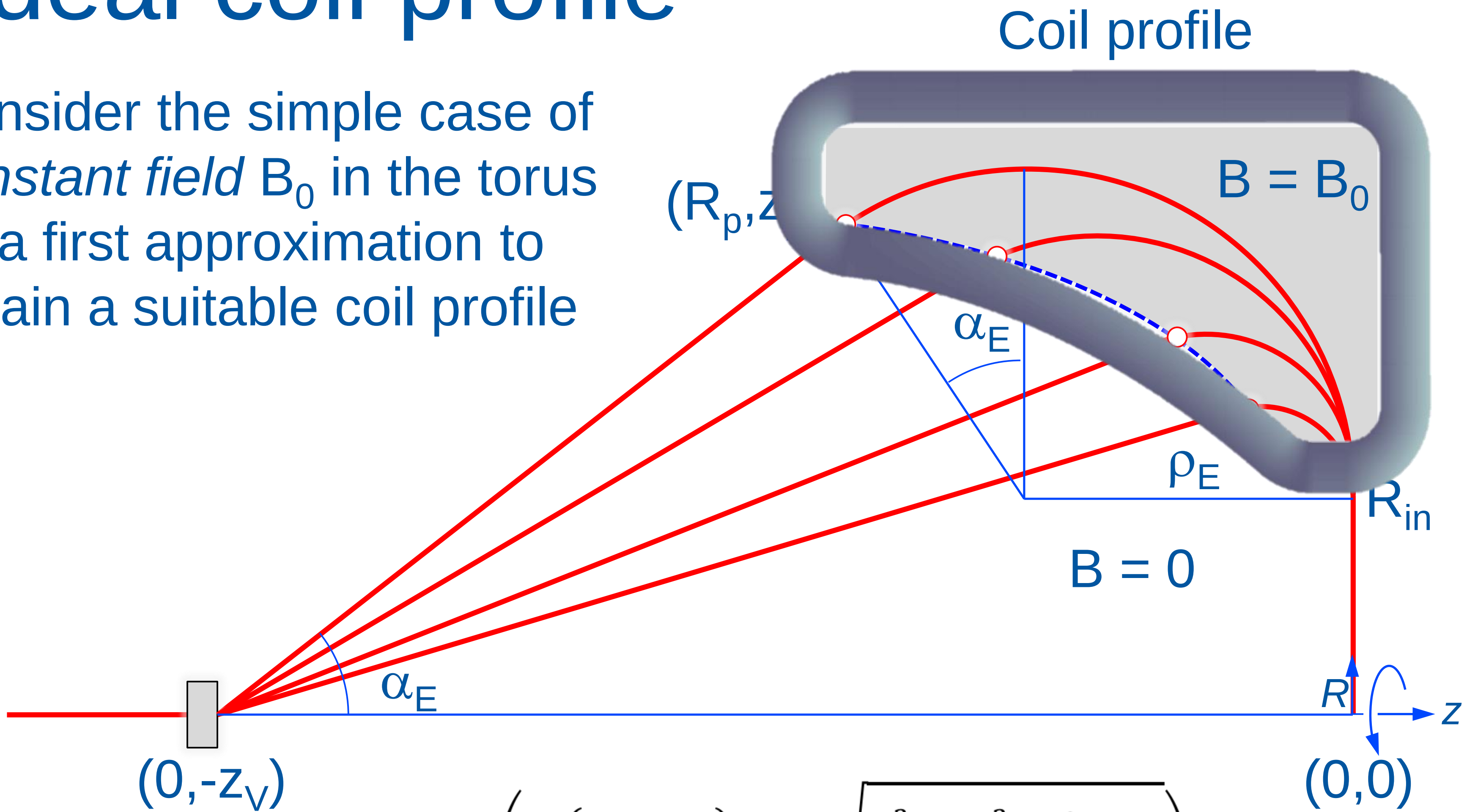
$$B_y = B_q \sin(q) » B_q x$$

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*)

A toroidal field focusses in two planes

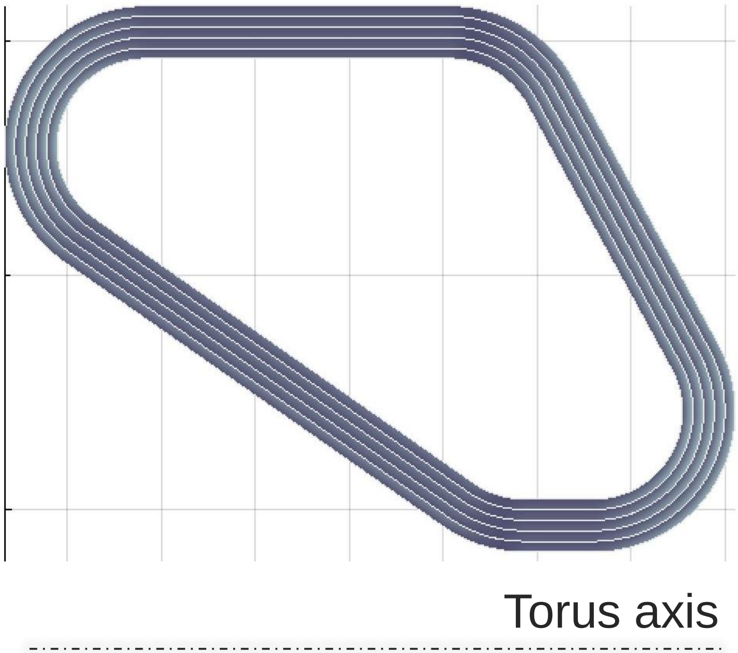
Ideal coil profile

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

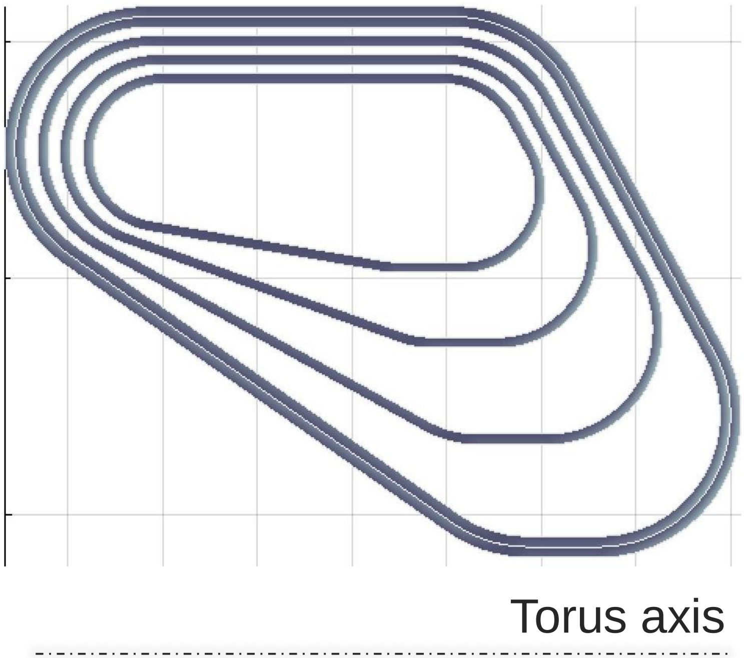


$$\alpha_E = arcsin\left(\frac{\rho_E(z_V - \rho_E) + R_{in}\sqrt{R_{in}^2 + z_V^2 - 2z_V\rho_E}}{(z_V - \rho_E)^2 + R_{in}^2}\right)$$

Graded coil design



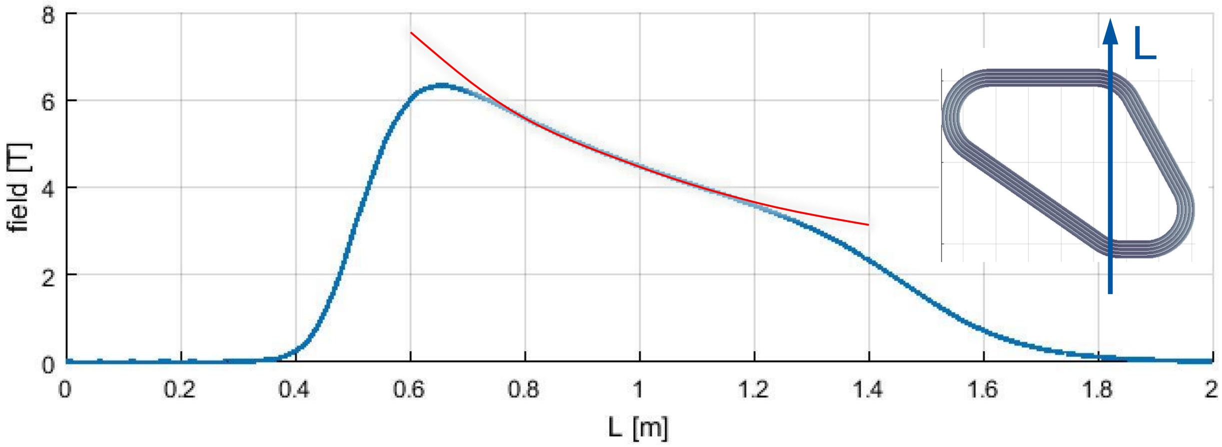
Simple coil winding (no grading)
The field profile has a $1/R$ dependence



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

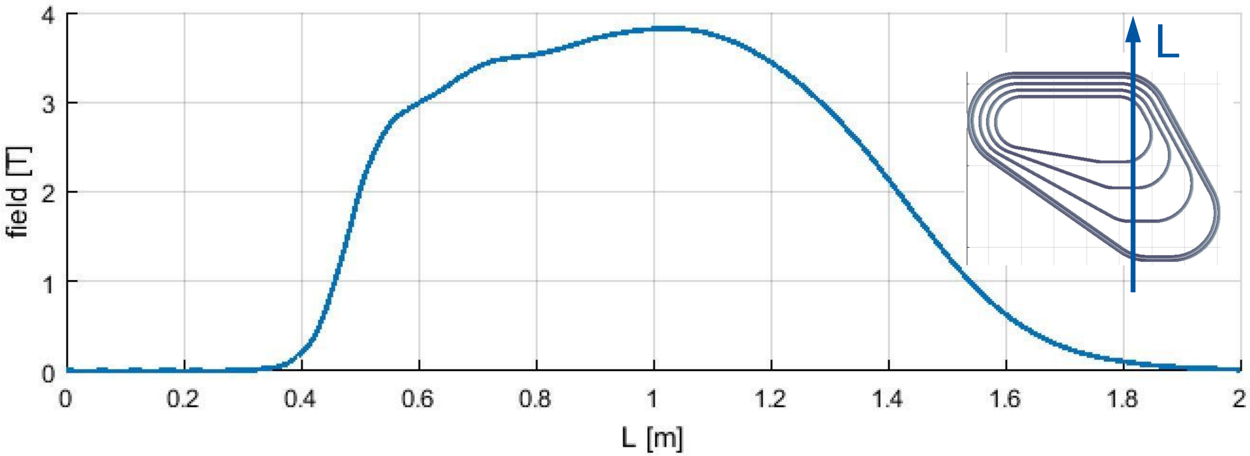


Non-graded coil winding

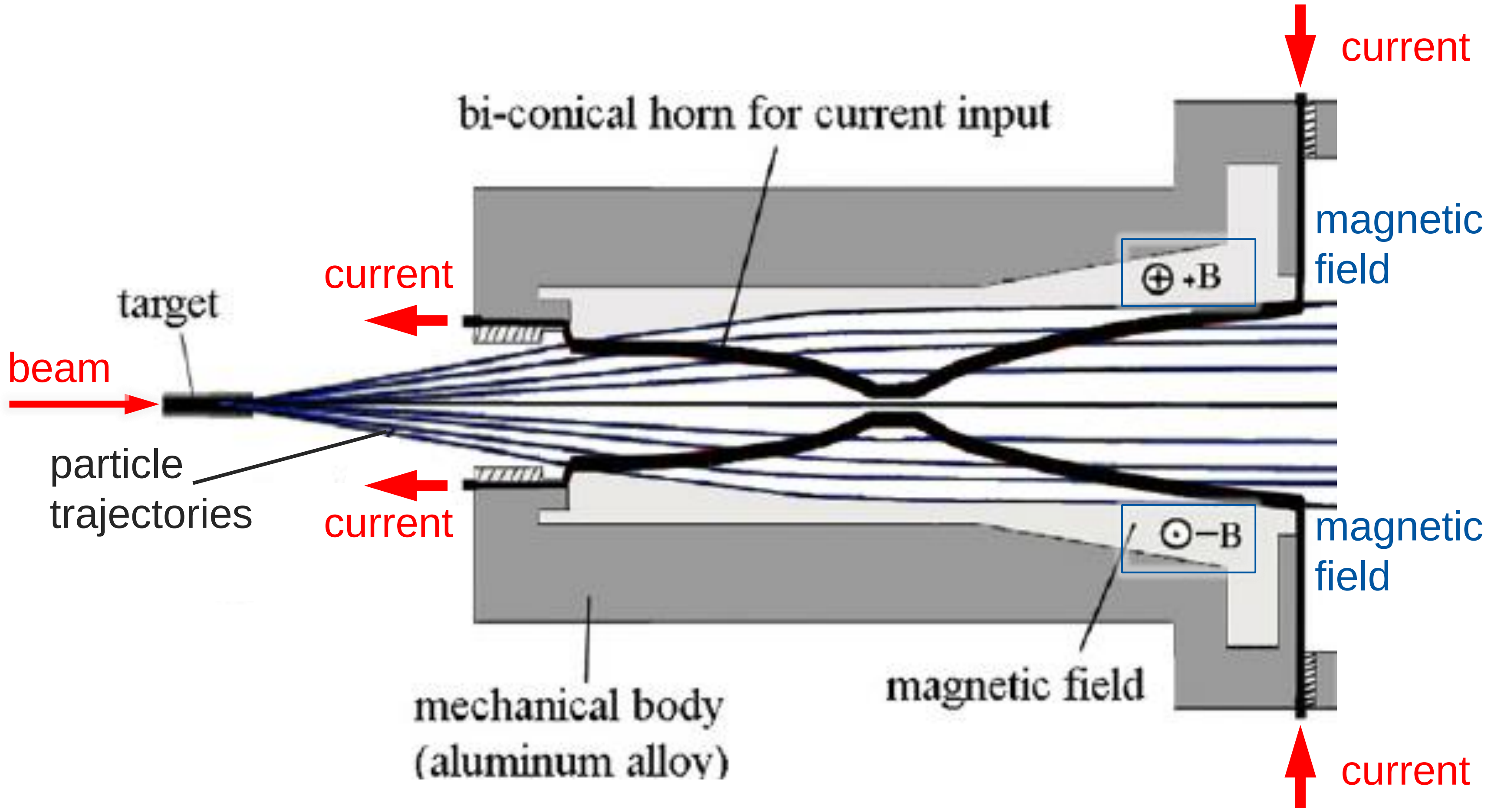
The field has the expected 1/*R* dependence in the coil bore

Graded coil winding

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

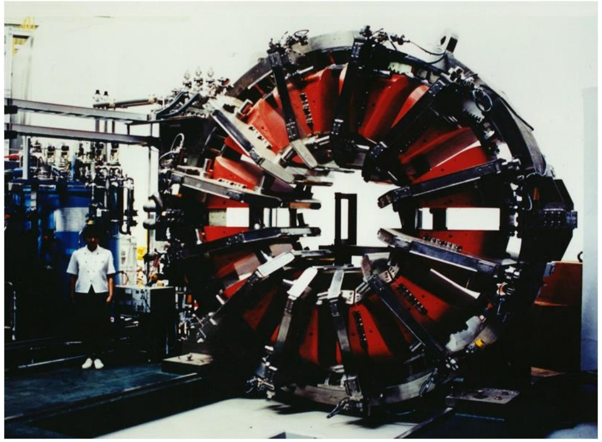


Previous art: the magnetic horn

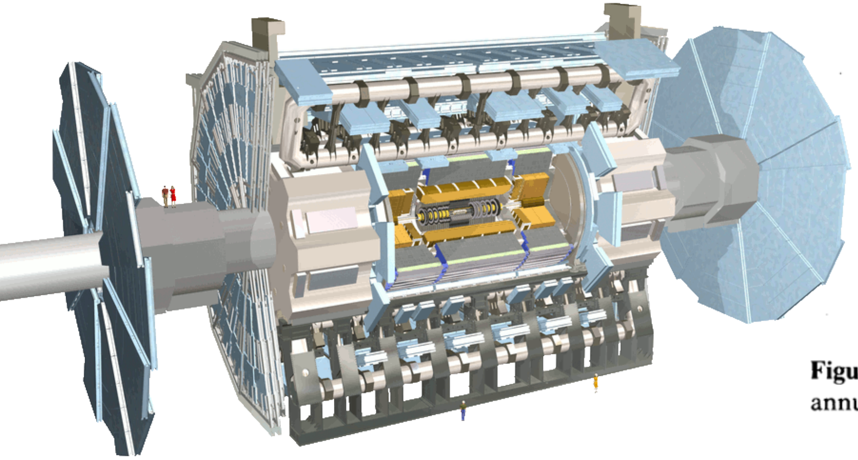


NIM-A 637:16-24 · February 2011

Previous art: spectrometers



TREK at KEK



ATLAS at CERN

"Orange" spectrometer

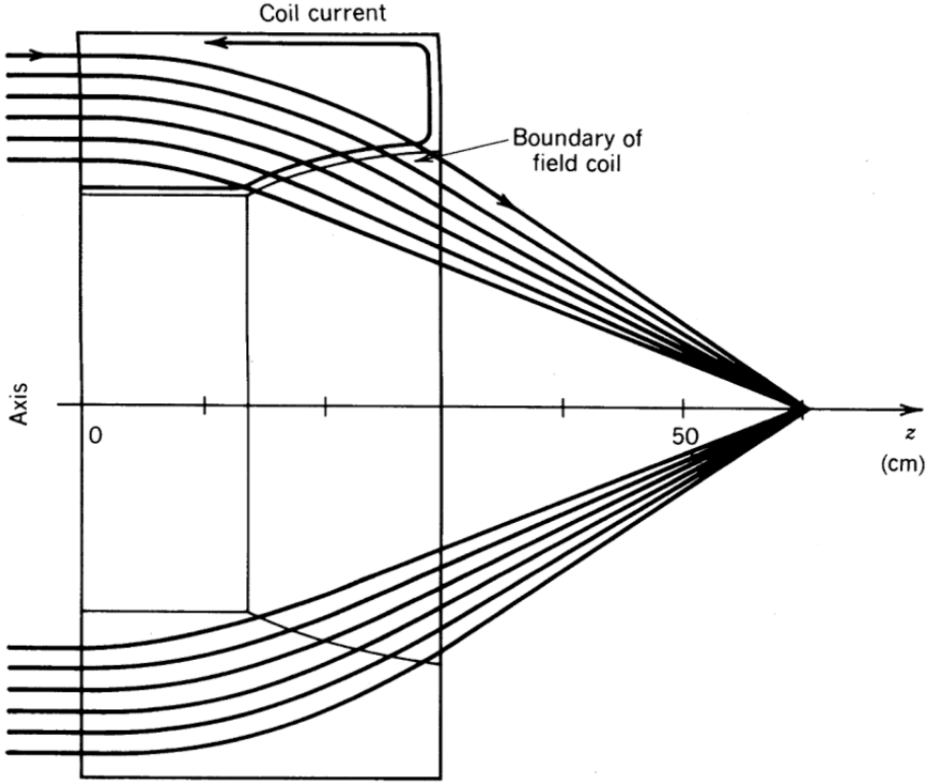
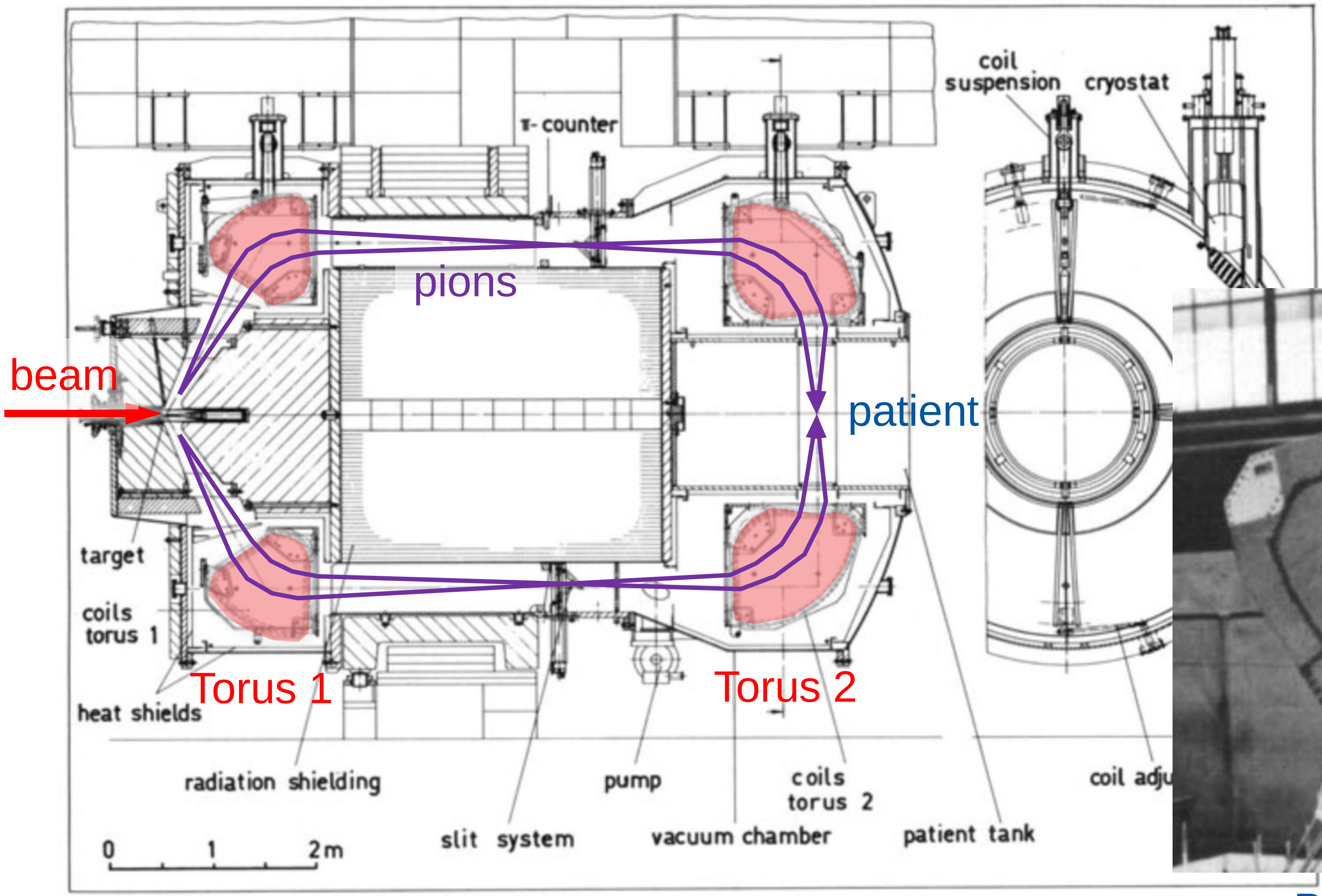
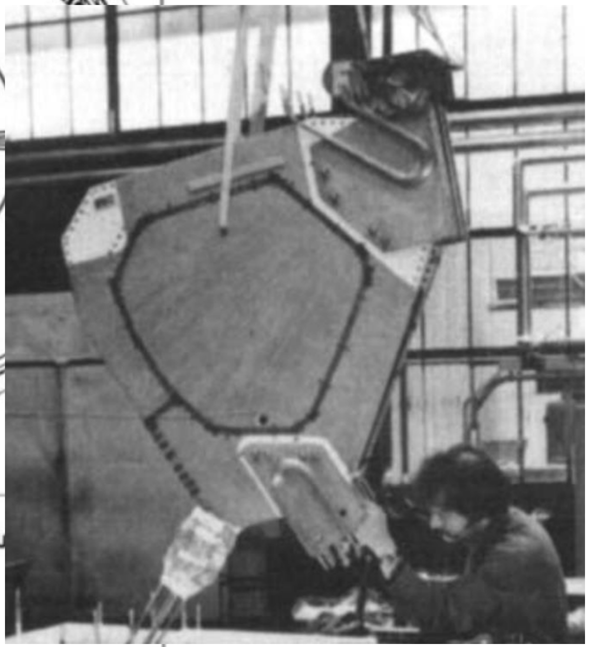


Figure 6.19 Particle orbits in a toroidal field lens with an exit boundary optimized for focusing an annular beam to a spot.

S. Humphries
Principles of Charged Particle Acceleration, April 1986

Previous art: the PIOTRON at PSI





Prototype torus 1 coil

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

H. Benz, Cryogenics, 19, 435, 1979

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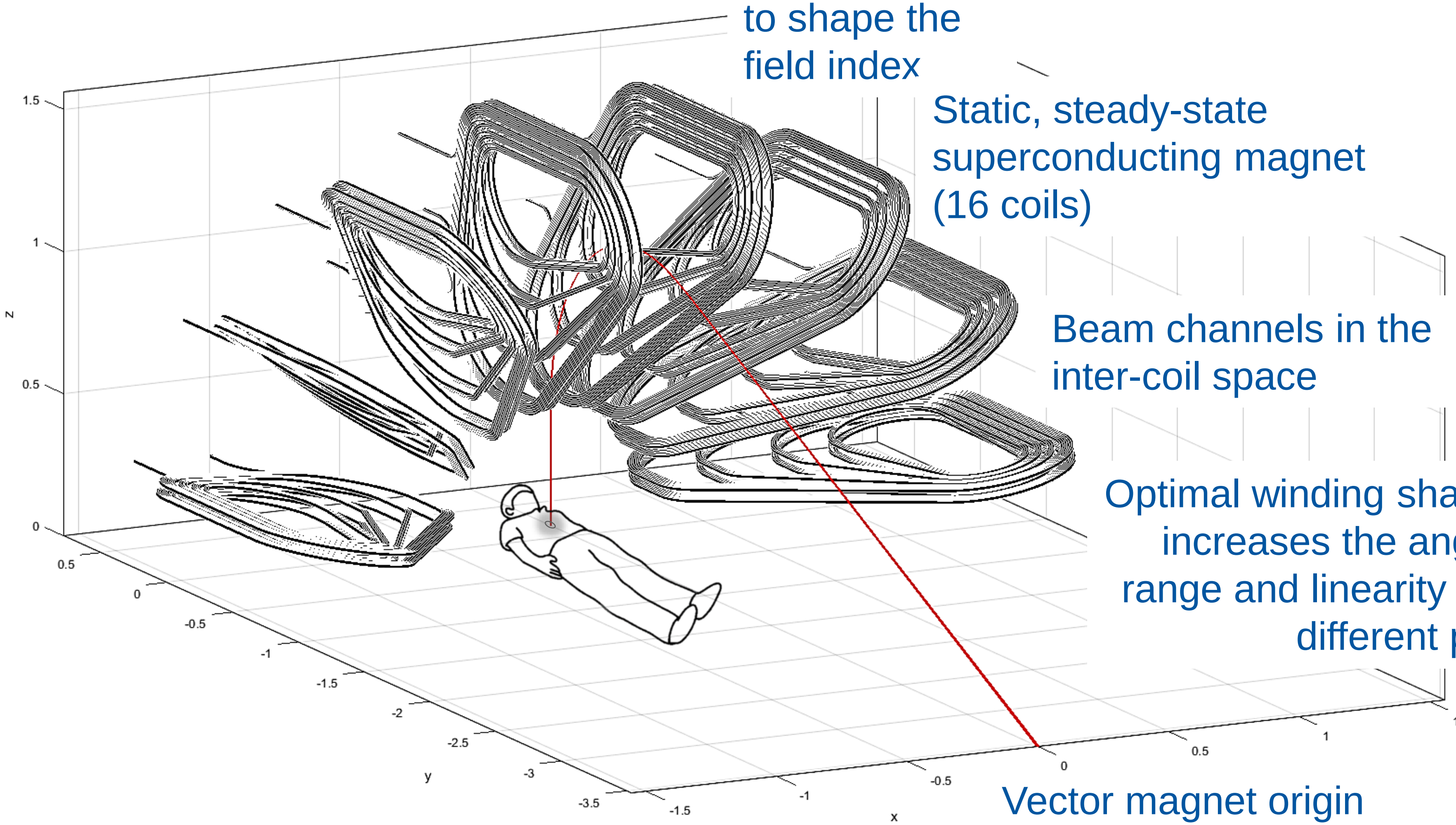
Putting it all together



Graded coils to shape the field index

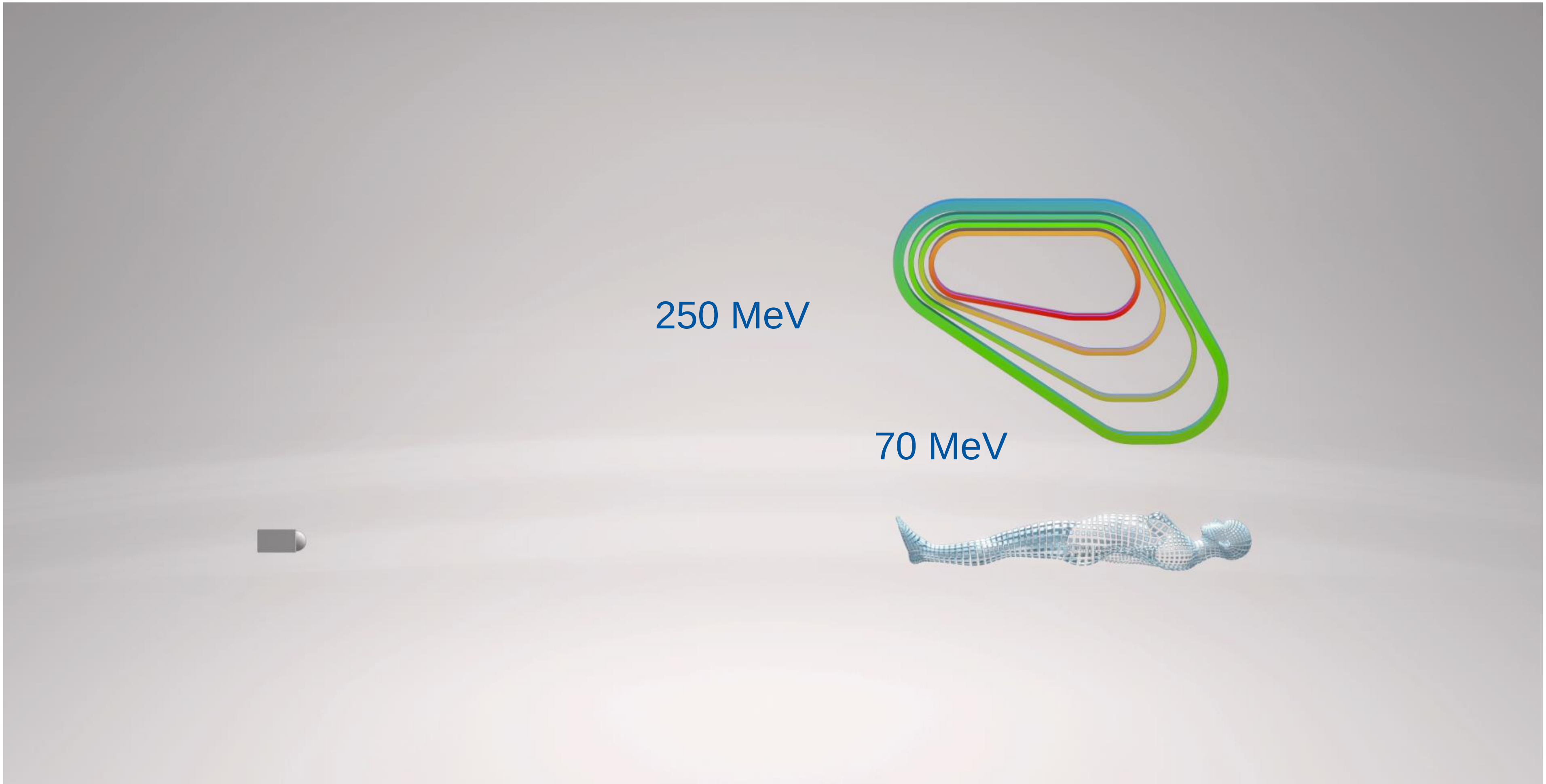
Static, steady-state superconducting magnet (16 coils)

Beam channels in the inter-coil space

Optimal winding shape increases the angle range and linearity for different p/q

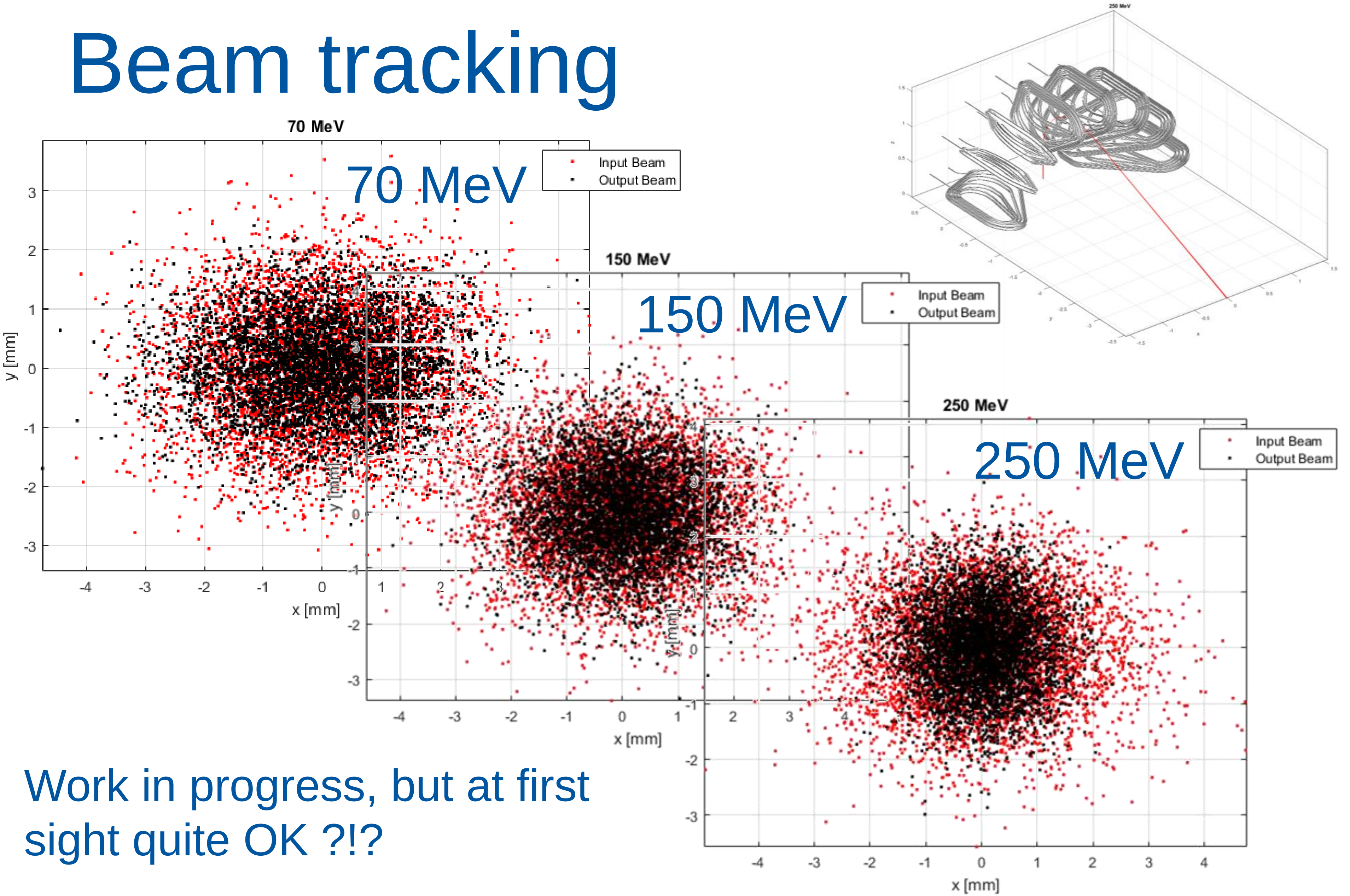
Vector magnet origin

Single particle tracking



Excellent acceptance and iso-centric properties

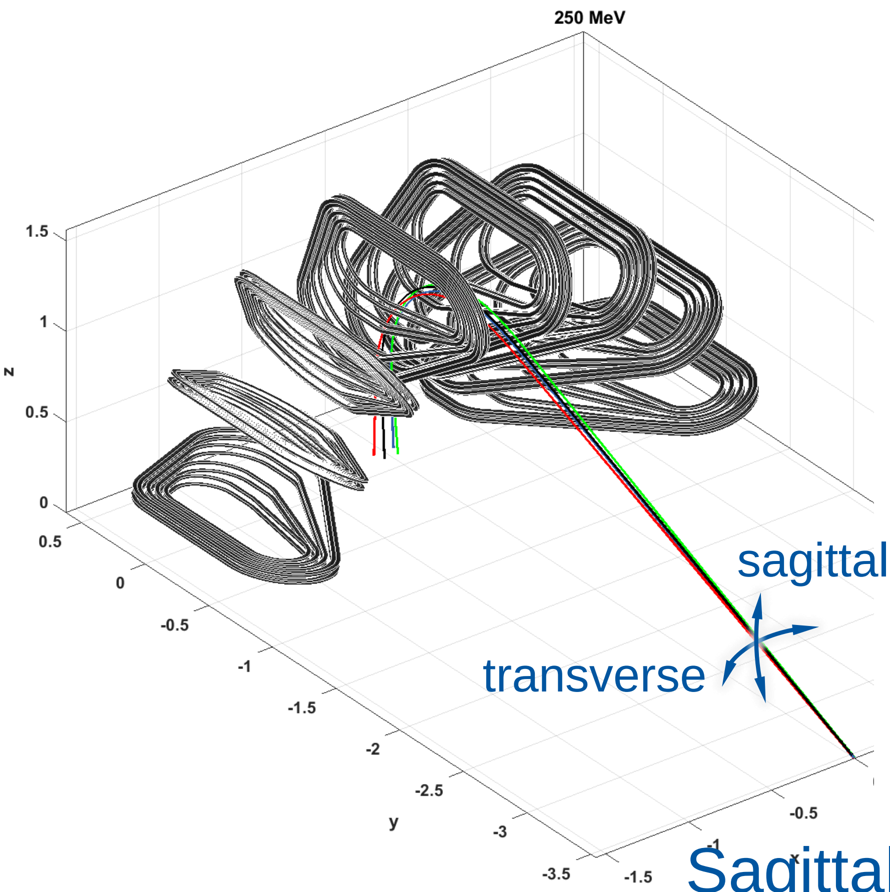
Beam tracking



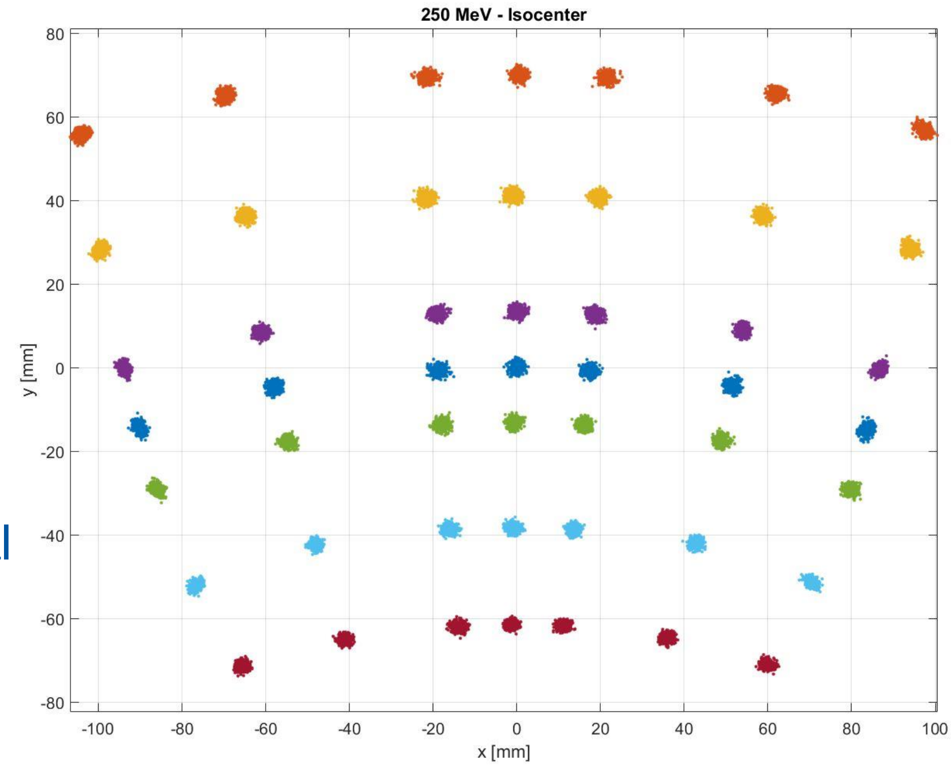
Work in progress, but at first sight quite OK ?!?

A typical session

Proof of principle of "painting"



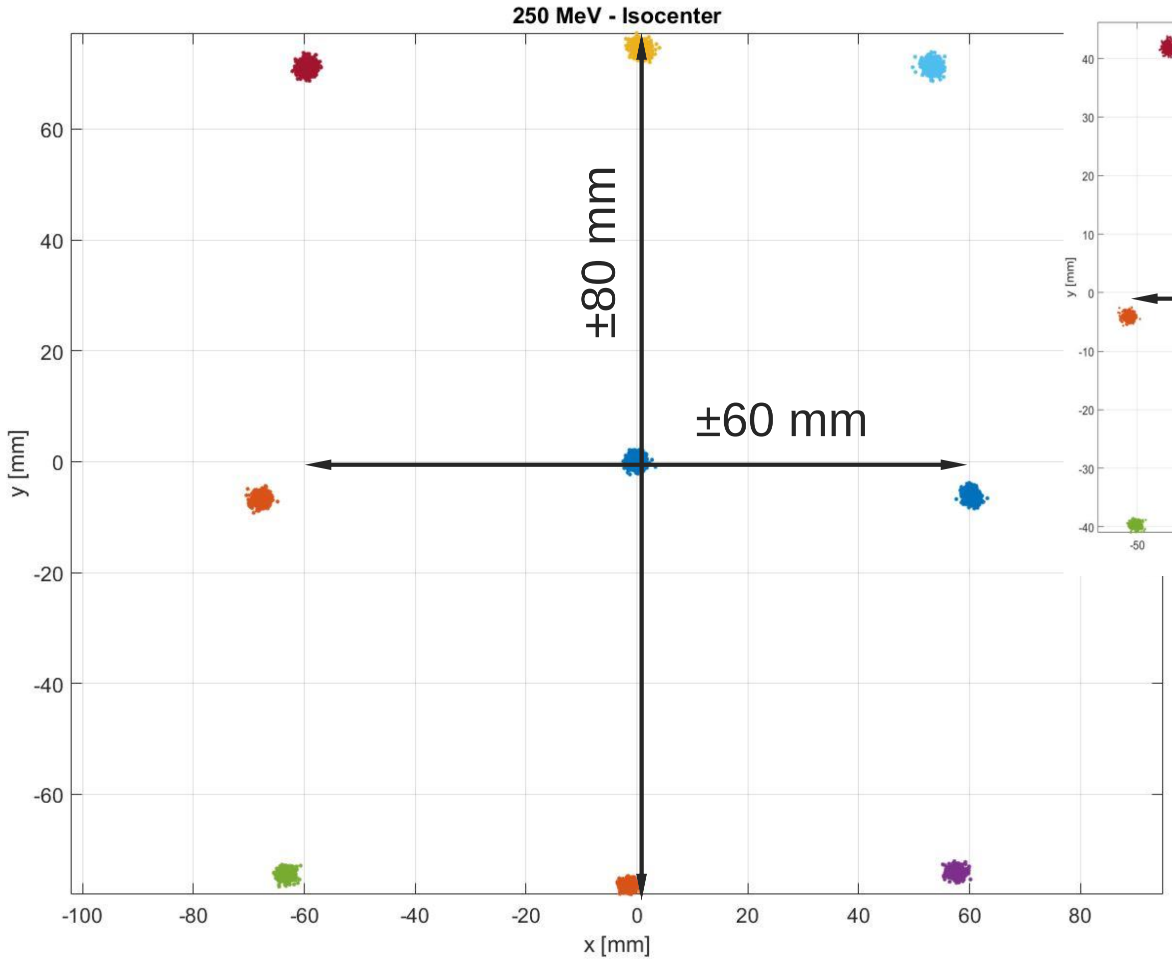
Natural response matrix

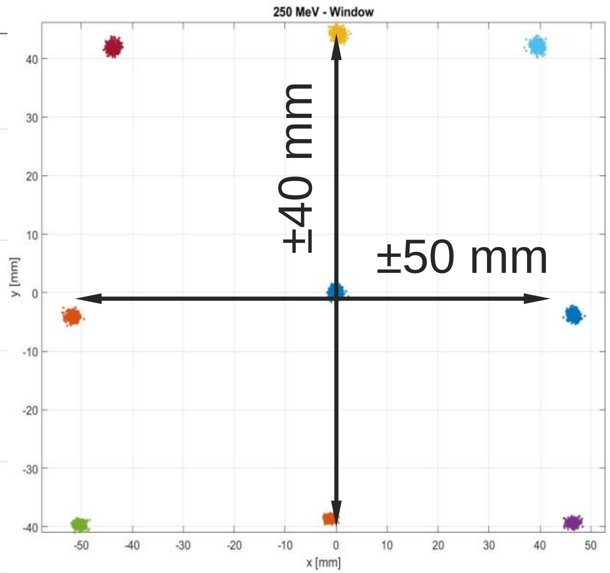


Sagittal: ±60 mm with ±1 deg kick

Transverse: ±50 mm with ±0.4 deg kick

Adjusted painting angles

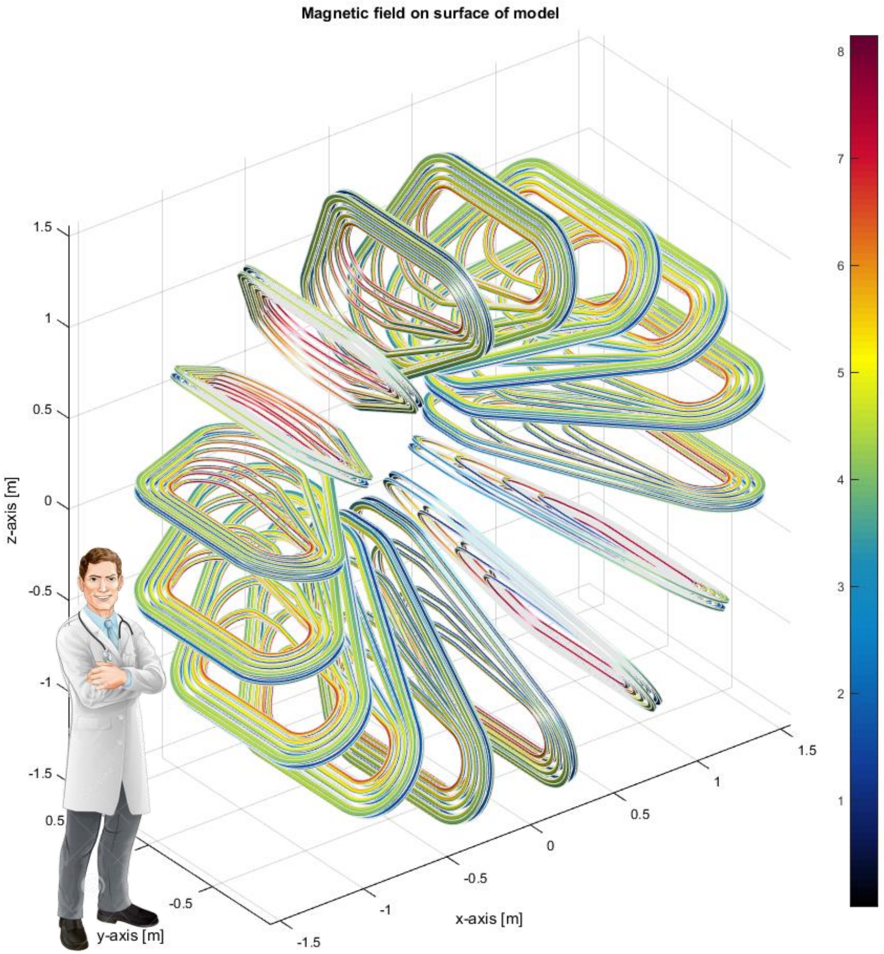




At the beam port the window is reduced to ±40 mm by ±50 mm

Adjusted kick angles to obtain square painting response

GaToroid for protons

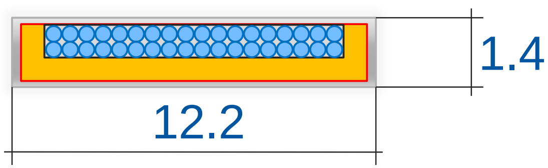


- Number of coils: 16 (-)
- Ampere-turns: 1.4 (MA-turn)
- Peak Field on coil: 8 (T)
- Coil dimension: ~1.5 x 1 (m x m)
- Torus dimensions: ~1.5 x 3 (m x m)
- **Estimated mass: 12 (tons)**
- Total Stored energy: 30 MJ
  (LHC dipole ~7 MJ)
- Operating current: 1800 A
- J_E = 100…140 A/mm^2
- Coil Inductance: 1.1 H

- Operating Temperature
  - 4.5 K (LTS)
  - 20 K (HTS)

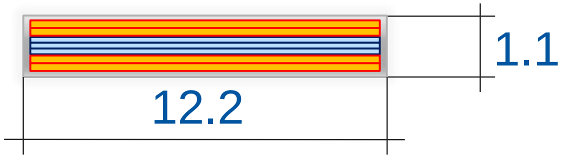
Superconductor

- LTS option (Nb-Ti)
  - 36 strands (0.5 mm) Rutherford
  - Soldered Cu-profile
  - Polyimide/glass insulation
  - Epoxy impregnated



- I_{op} = 1800 A
- T_{op} = 4.5 K
- J_E = 105 A/mm^2

- HTS option (REBCO)
  - 3 SC tapes (12x0.1 mm)
  - 4 Co-wound Cu tapes (12x0.125 mm)
  - Polyimide/glass insulation
  - Epoxy impregnated

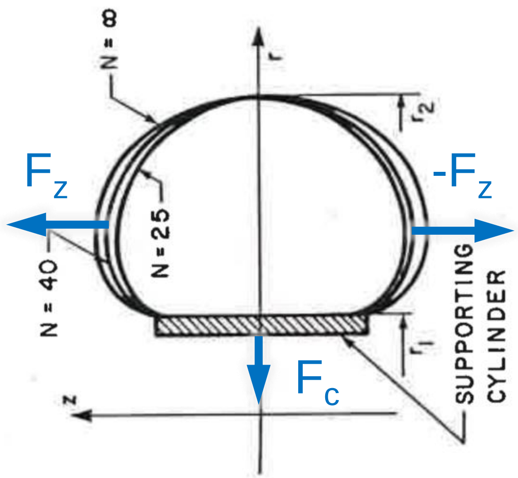


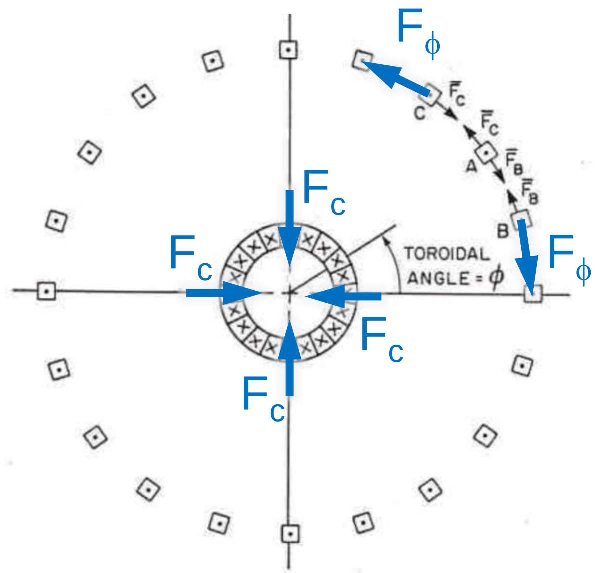
- I_{op} = 1800 A
- T_{op} = 20 K
- J_E = 135 A/mm^2

NOTE: more options considered: PI/NI HTS tapes

Modest operating current: persistent mode ?

Mechanical design





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

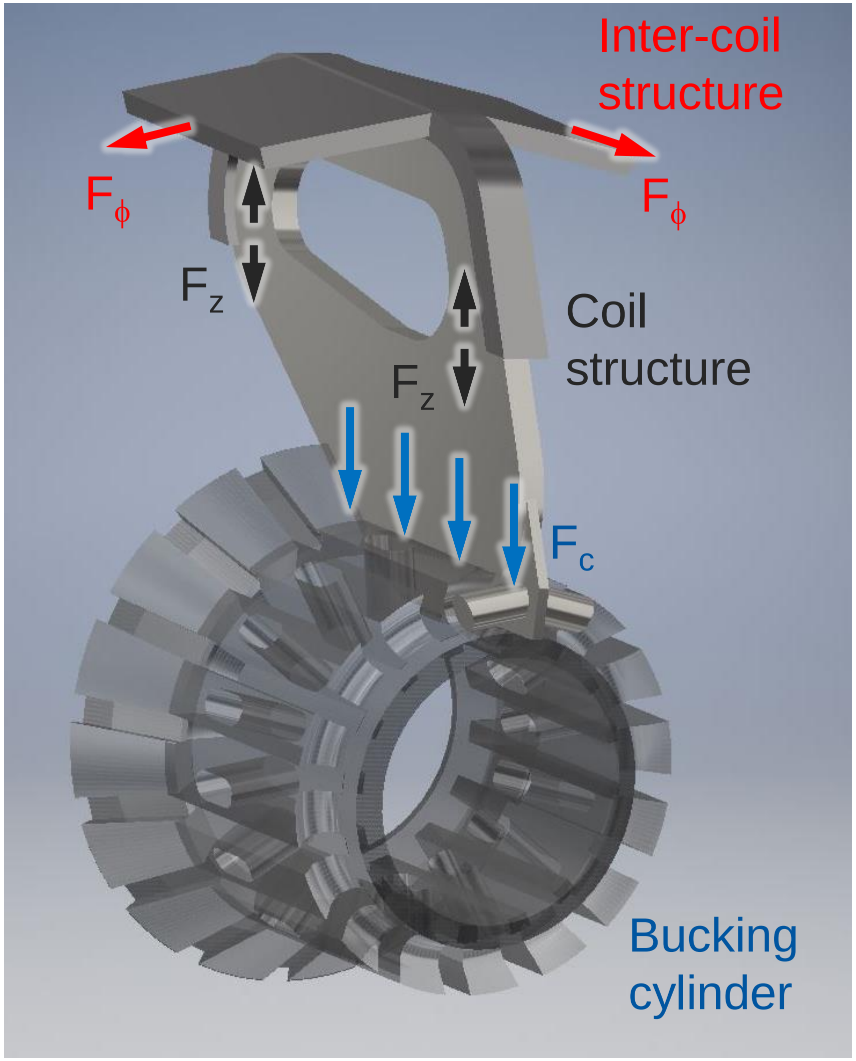
$$F_z = \frac{\mu_0 N I^2}{4\pi} ln\left(\frac{1+\gamma}{1-\gamma}\right)$$

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

R.J. Thome, J.M. Tarrh, MHD and Fusion Magnets, John Wiley & Sons Inc, 1982

- 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

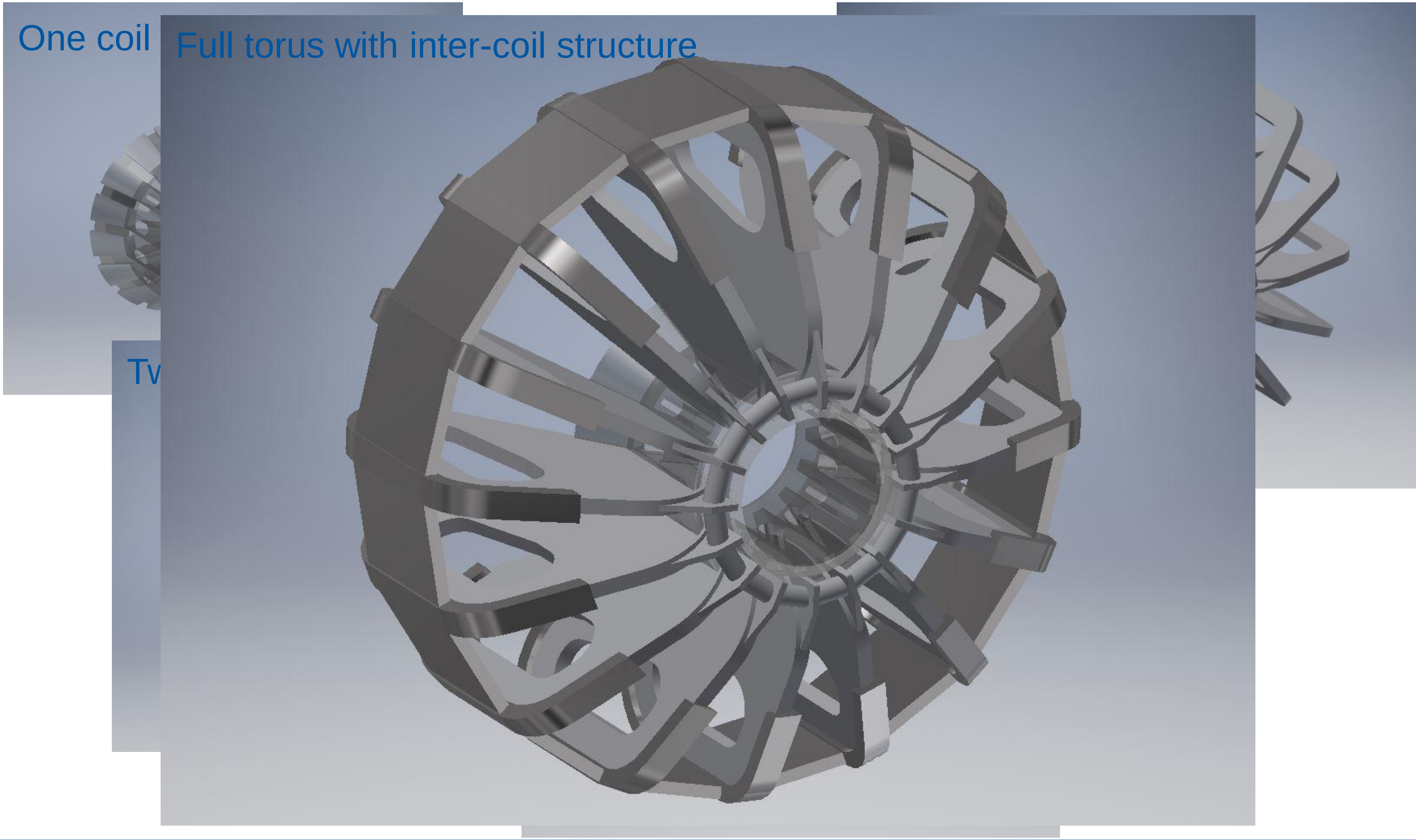
Mechanical design concept



- Winding force
  - $F_z = 2$ MN/coil
  - $w_{coil} = 50$ mm
  - $t_{coil} = 300$ mm
  - $\sigma_{coil} = 150$ MPa
- Centering force
  - $F_c = 1.43$ MN/coil
  - $t_{cylinder} = 60$ mm
  - $\sigma_{cylinder} = 120$ MPa
- Out-of-plane force
  - $F_\phi = 1.55$ MN/coil
  - $t_{intercoil} = 60$ mm
  - $\sigma_{inter\text{-}coil} = 50$ MPa

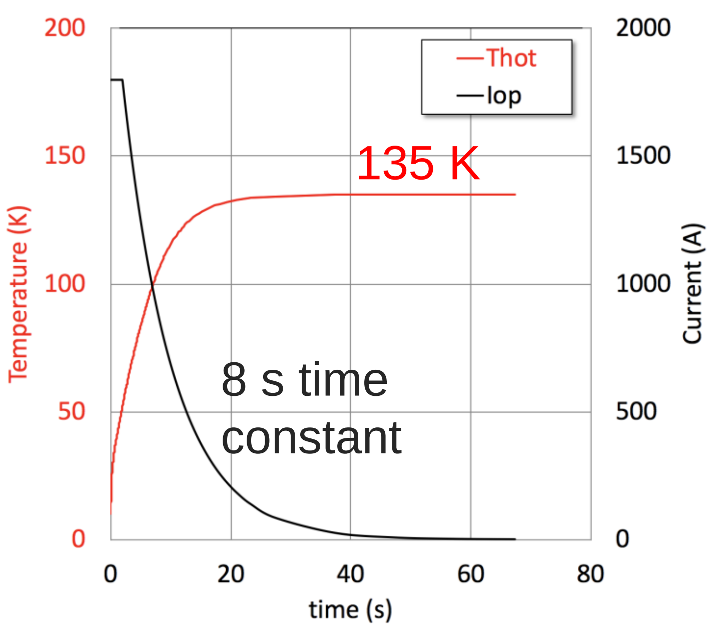
Can be conveniently built with lightweight Al alloys

Mechanical assembly

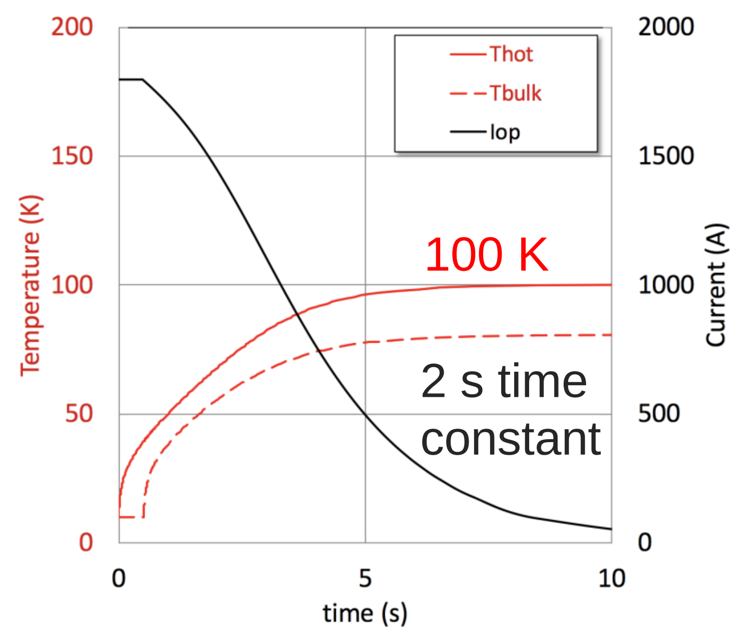


Powering and protection (LTS)

- External dump
  - Two powering circuits of eight coils in series
  - 2 s quench detection
  - ± 1 kV dump voltage

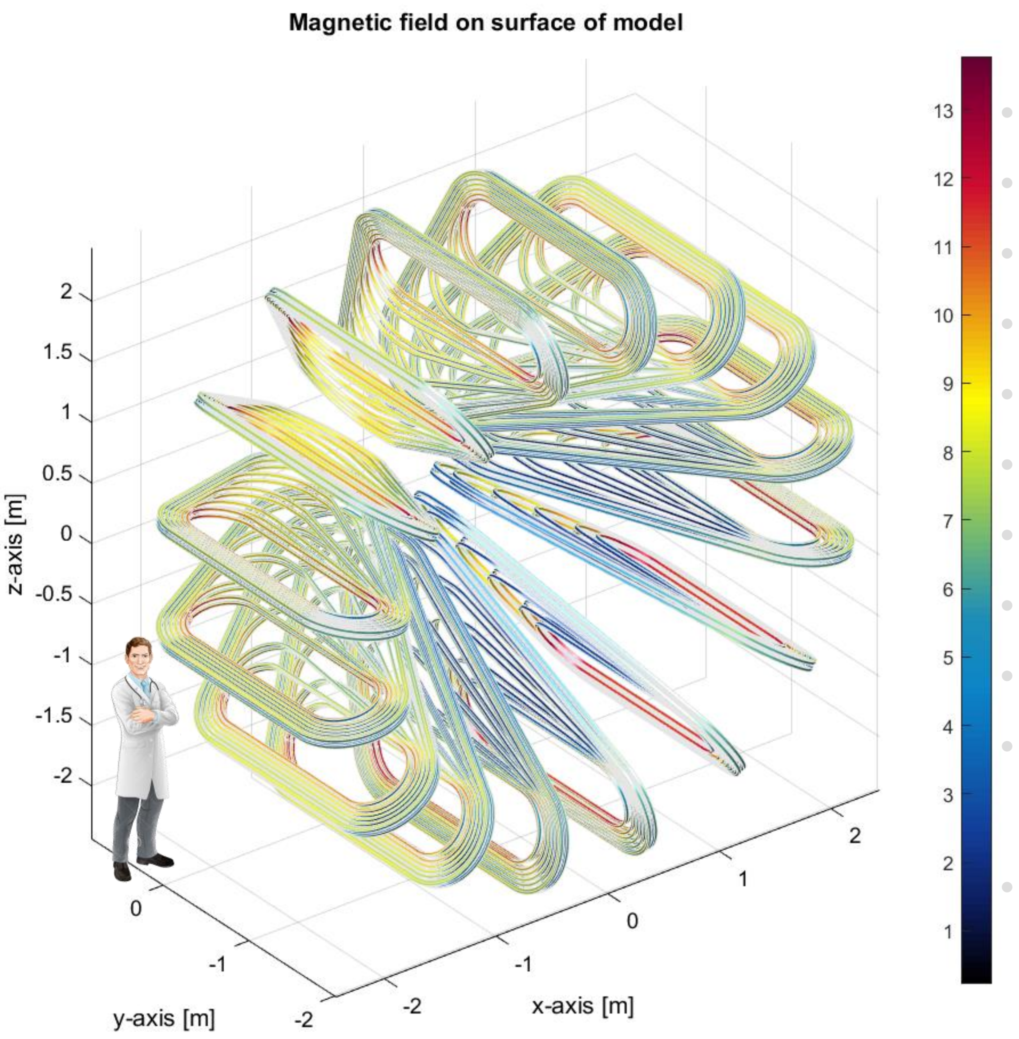


- Internal
  - Series powering with diodes (persistent ?)
  - 500 ms quench detection
  - Internal quench heaters



Feasible with classical techniques, but this is where NI/PI HTS tapes may help

GaToroid for C-ions



- Number of coils: 16 (-)
- Ampere-turns: 3 (MA-turns)
- Peak Field on coil: 13.8 (T)
- Coil dimension: ~3 x 2 (m x m)
- Torus dimensions: ~3 x 5 (m x m)
- **Estimated mass: ~50 (tons)**
- Total Stored energy: 370 (MJ)
- Operating current: 6 (kA)
- J_E = 200…300 (A/mm^2)
- Coil Inductance: 0.3 (H)

- Operating Temperature
  - 4.5 K (LTS)
  - 10 K (HTS)

There is quite some work to be done here…

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Some issues…

- Field multipoles (and dynamics, HTS ?!?), and its relation to beam physics
  - Beam transfer matrix and matching to accelerator
- Quench protection
  - Non-insulated or metal-insulated winding (HTS ?!?)
- Mechanics and fabrication
  - Coil structure, forces and stress
  - Winding technology, joints
- Beam vacuum
- Thermal engineering
  - Cooling technology, shields and cryostat, supports
- The C-ions gantry
- Material and system cost (HTS ?!?)
- Qualification for therapy
- …

Development plan

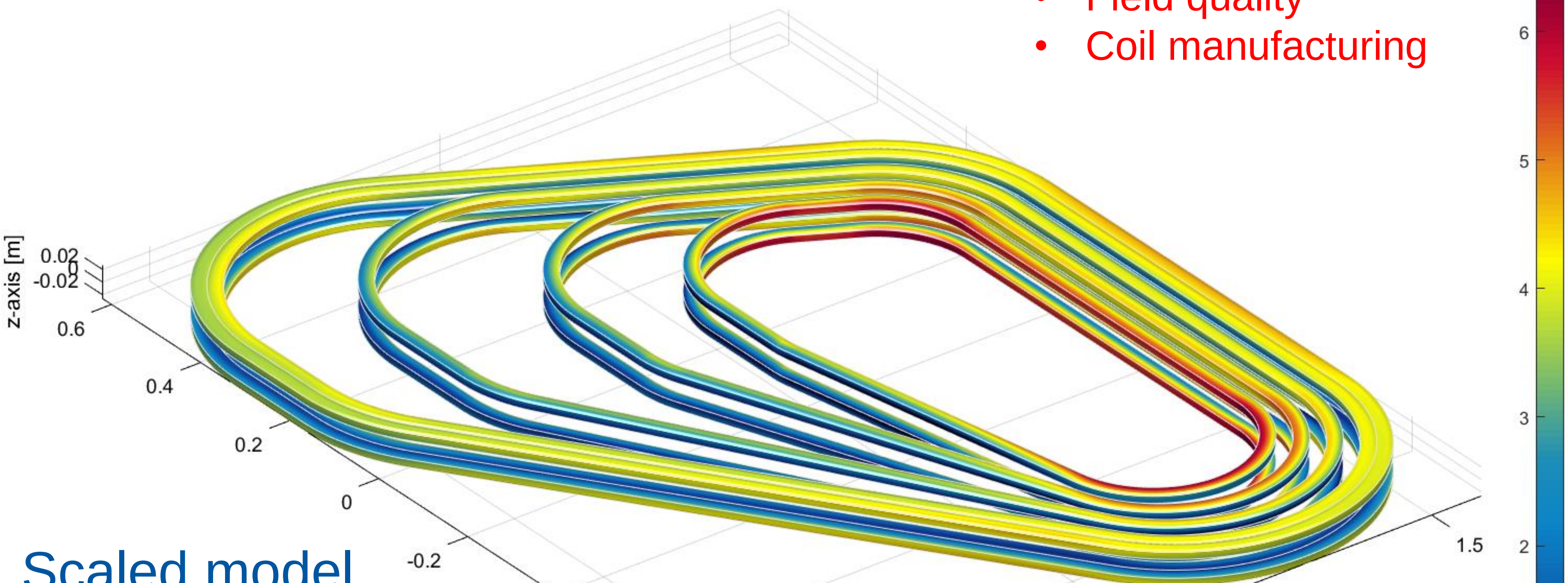
- Year 1
  - Gantry conceptual design
  - Beam transmission analysis
  - Mechanical studies and demonstrator design
- Year 2
  - Protection, powering, cooling design
  - Winding and assembly procedure, procurement of parts and tooling, tests
- Year 3:
  - Winding and test of HTS demonstrator
  - Final evaluation and preliminary design of gantry system

- CERN-KT supported effort taking place in TE department
- 1 fully financed PhD dedicated to this work (**three cheers for Enrico !!!**)

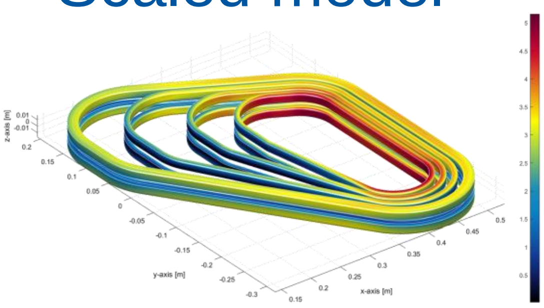
Demonstrator

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

Full-size coil (p-gantry)



Scaled model



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How competitive is GaToroid ?

Parameter		Pro Beam	Proteus One	R330	S250i	Hitachi	GaToroid protons
Radius	[m]	5.5	3.6	≈ 4	4.3	4	1.5
Length	[m]	≈ 9.5	9.5	≈ 10	4.3	≈ 8	≈ 6
Weight	[tons]	270	110		17	125	12
Rot. angle	[deg]	360	220	180	190	360	360/N

Parameter		HIT	HIMAC	FFAG	Riesen-rad	GaToroid C-ions
Radius	[m]	6.5	5.5	4.2	8.5	2.5
Length	[m]	25	13	8	16	≈ 10
Weight	[tons]	670	350		350	50
Rot. angle	[deg]	360	360	360	360	360/N

At least two times smaller, ten times lighter !

Conclusions

- This idea has a touch of insanity, but…
- … if it works it could result in a quantum step towards compact gantries and ease wide-spread application of hadron therapy:
  - **Single room facility** (as for an MRI magnet !)
  - Low consumption, steady operation, fast switching of energy and direction
  - **New treatment possibilities** and protocols
  - Integration of **new diagnostics and imaging devices**
- We are looking forward to feedback from the design and prototyping work, the next couple of years will tell !

Project co-funded by the CERN Budget for
Knowledge Transfer to Medical Applications

www.cern.ch

With our grateful thanks to:

Manuela Cirilli, Rita Ferreira, Giovanni Porcellana, Amy Bilton for the motivation, experience, opportunities and ideas that they steadily provide;

Linn Tvede (KT), Daniel Dominguez (IR) and the CERN Design and Visual Identity Service for some astounding graphics;

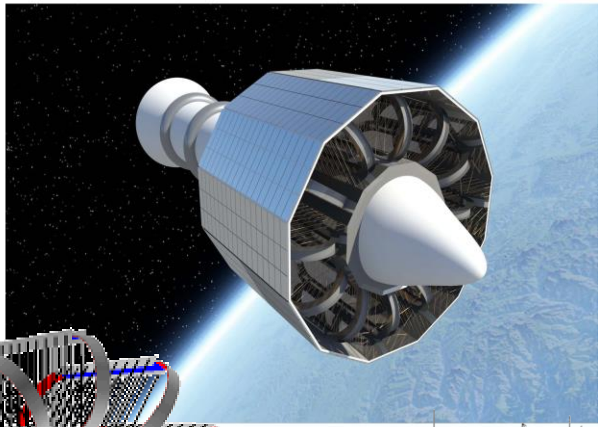
Mar Capeans and Miguel Jimenez (TE) for the appreciation and support of this crazy idea;

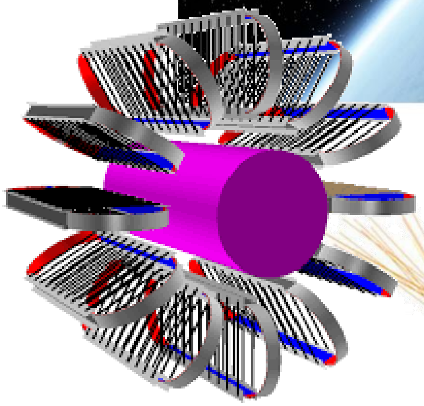
Jacky Mazet, Francois-Olivier Pincot, Juan Carlos Perez (TE) for actually doing the work.

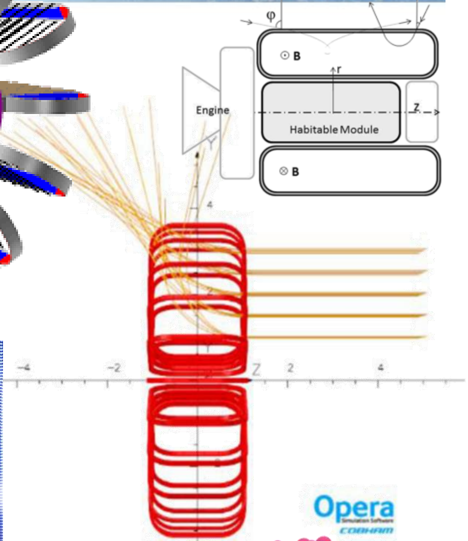
A mio padre, ne sarebbe stato contento

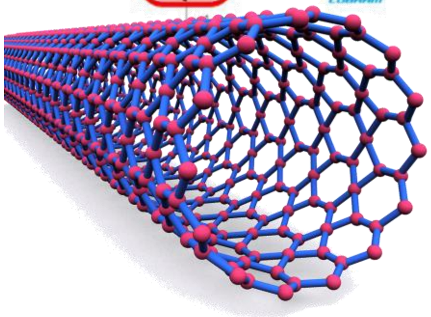
Genesis of the idea

- 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









Pro's and con's

Static structure, does not require high rigidity and stability vs. load changes

Discrete delivery angles, limited to (at most) N_{coils} beam lines

Steady state operation, no AC loss, optimal use of superconductor

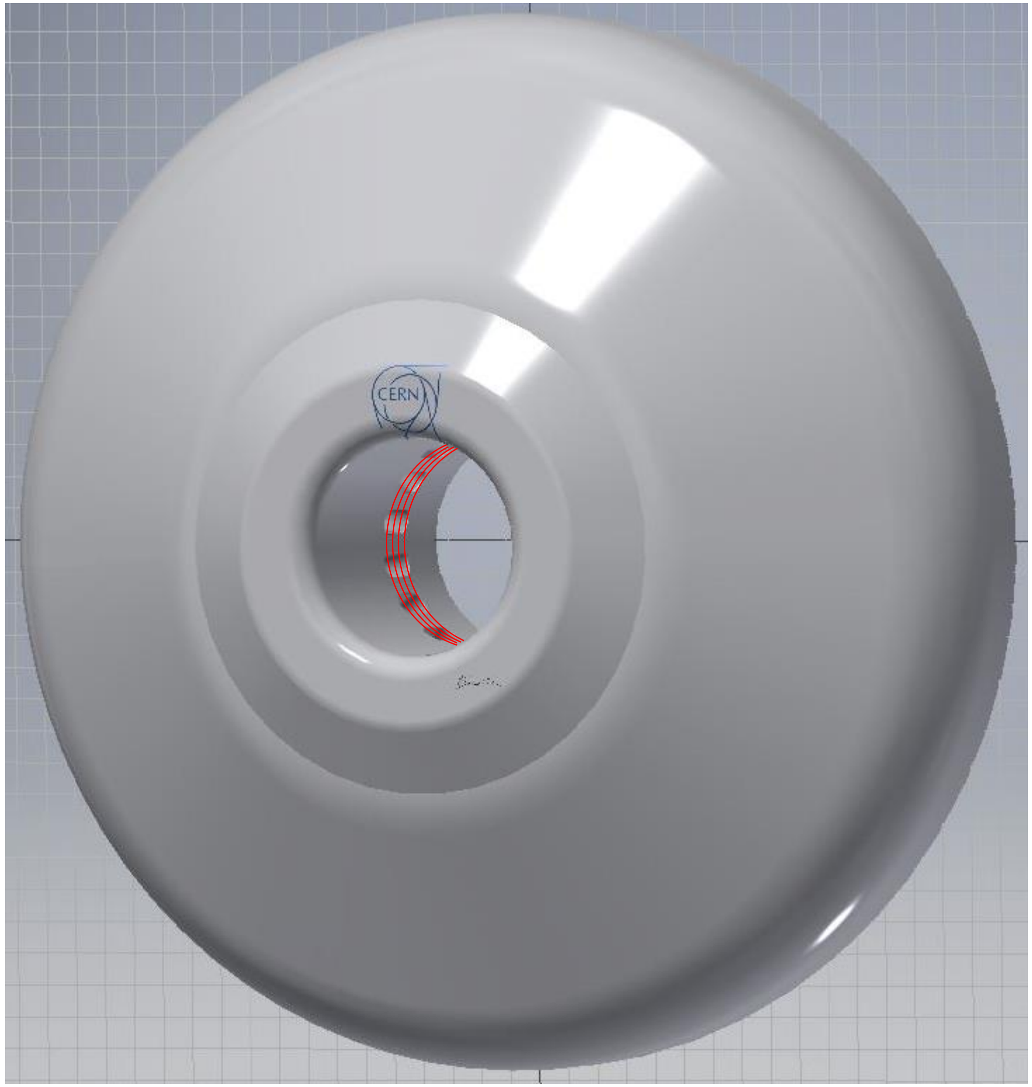
Large stored energy and cold mass volume

High-field design results in reduced foot-print and mass

Beam pipe has a complex shape and large dimensions

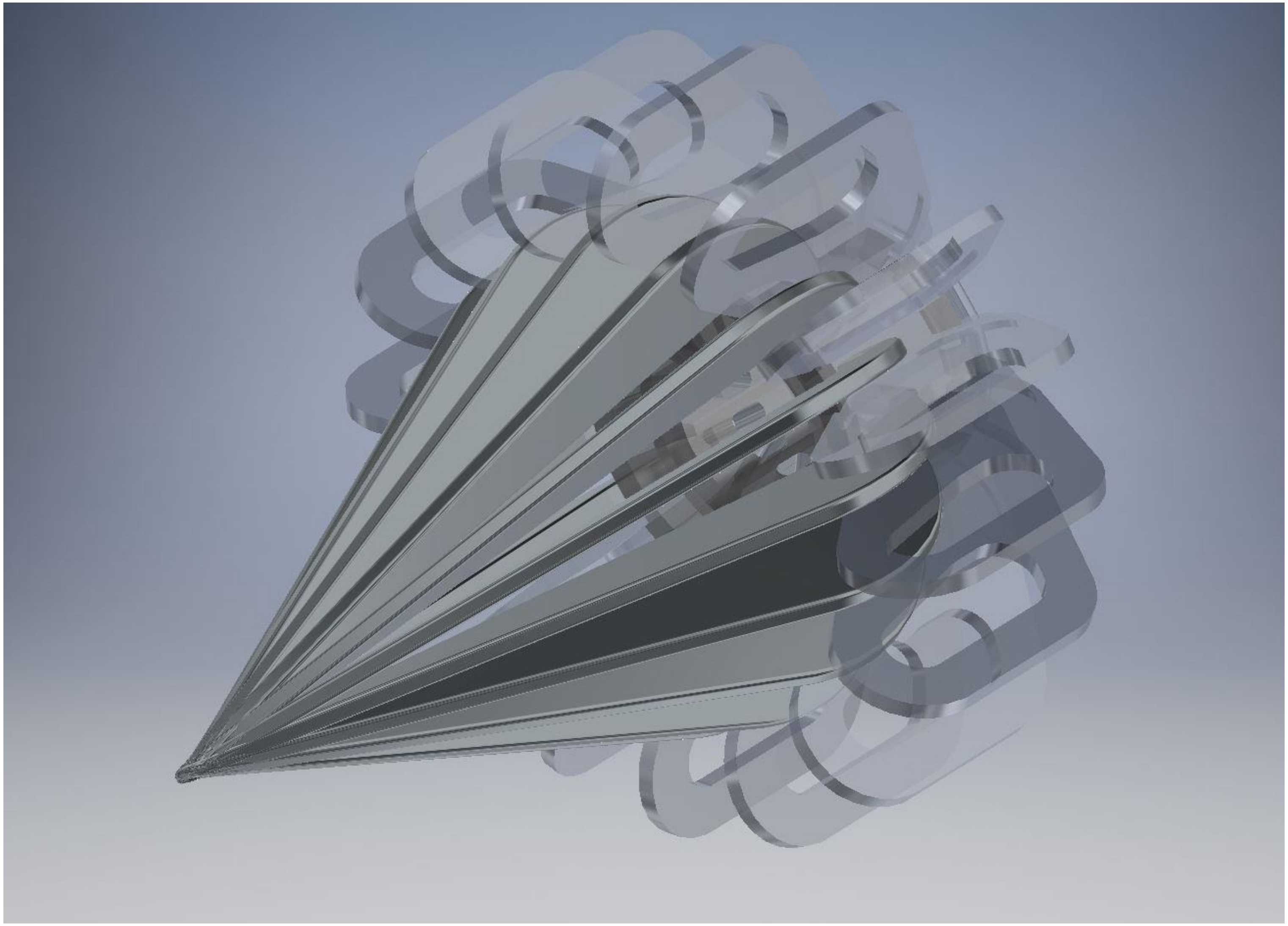
A fast dose delivery from multiple angles and energy is a new operating mode, and represents a major change of treatment planning dose delivery

On the matter of diagnostics



The inner space is field-free and can be enlarged to accommodate instruments (beam detectors, PET chambers, …) for *in-vivo* diagnostics

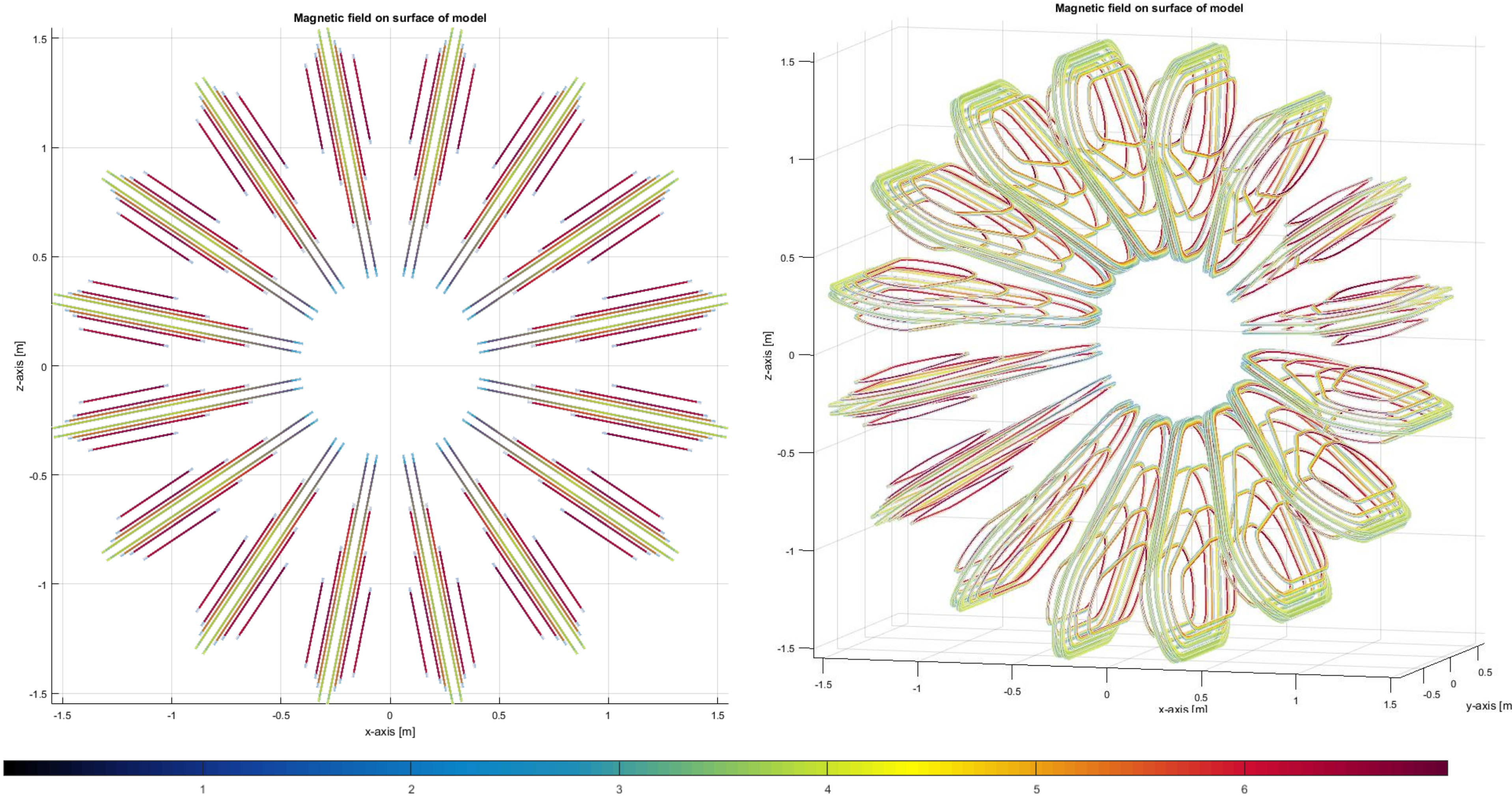
On the matter of beam pipe



The *beam pipe* has a rather complex configuration, a feasibility study is required to determine whether a common vacuum is preferred

On the matter of field shaping

$B_{peak} \approx 7T$ (was 8 T in the reference version)



Further coil geometry optimization in 3D is possible to reduce the peak field on the conductor and introduce corrections

On the matter of field and beams

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

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

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

Multipole expansion of the magnetic scalar potential in toroidal coordinates

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

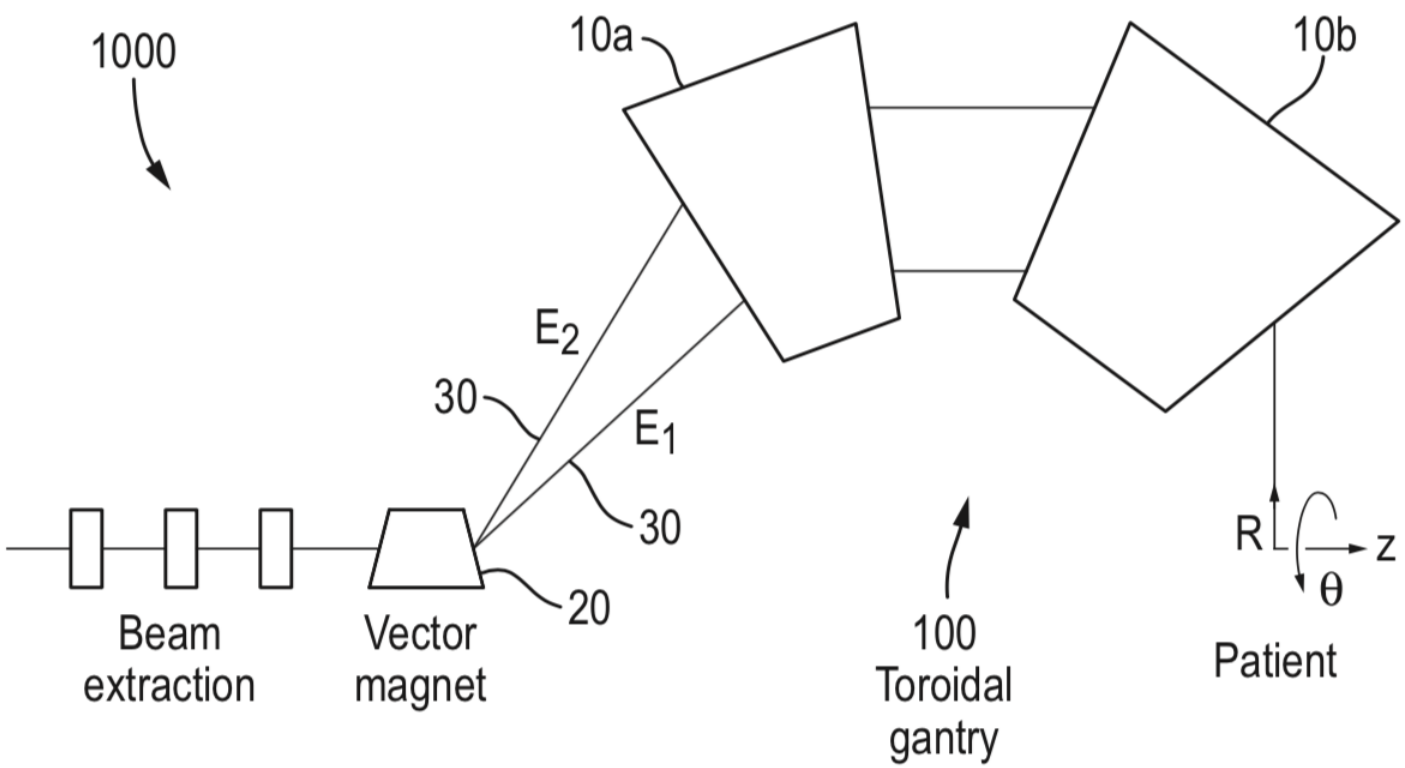
Ideal toroidal field contribution (1/R)

CERN

It would be highly desirable to link the field multipoles, generated by a given coil geometry, to the beam optics

On the matter of beam optics

Fig. 1



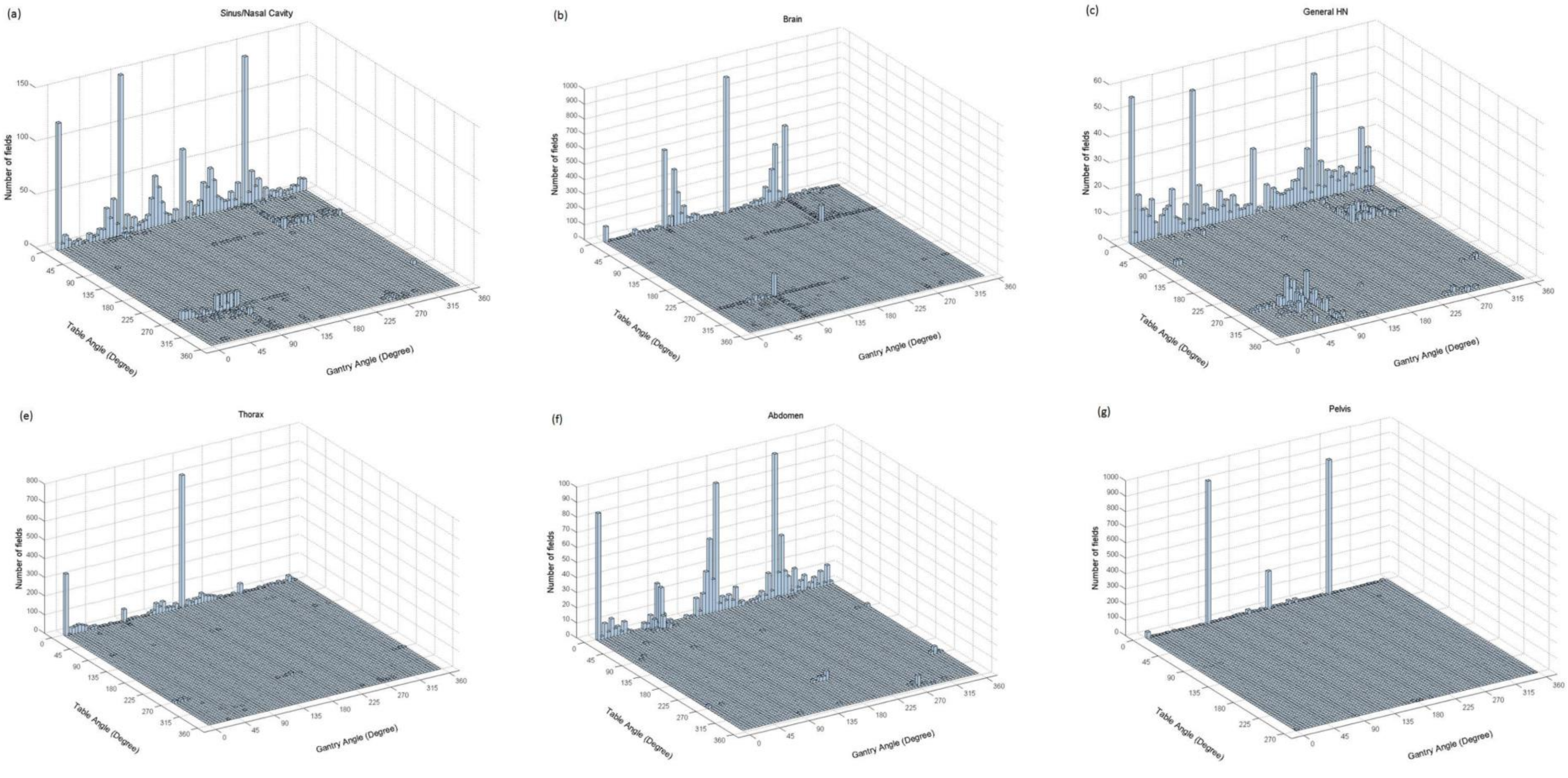
A sequence of toroids could be devised to mock the properties of a beam transmission line

On the matter of cost

	Conventional Radiotherapy	Proton Beam	Carbon Ion Beam
Accelerator	LINAC	Cyclotron or Synchrotron	Synchrotron
Typical beam energy range	4-25 MeV	60–250 MeV	120–430 MeV
Treatment rooms	One room per LINAC	Single to five rooms	Typically three treatment rooms and research room
Publicly reported costs (likely equipment only)	5 MUSD (per LINAC and gantry)	34-260 MUSD (single to multi-room facility)	180-290 MUSD (multi-room facility)
Operational costs (utilities, maintenance, cleaning, administration)	$4.51 million (2 room facility)	$8.8 million (3 room facility)	$17.9 million (3 room facility)
Staffing costs	$4.25 million (2 room facility)	$10.4 million (3 room facility)	$10.4 million (3 room facility)
Treatment Fraction Cost Ratio	1	3.2	4.8
Equipment lifespan	10 years	30 years or more	30 years or more

The *target window* for the gantry cost is 3 MUSD to 5 MUSD (protons) and 20 MUSD to 30 MUSD (C-ions)

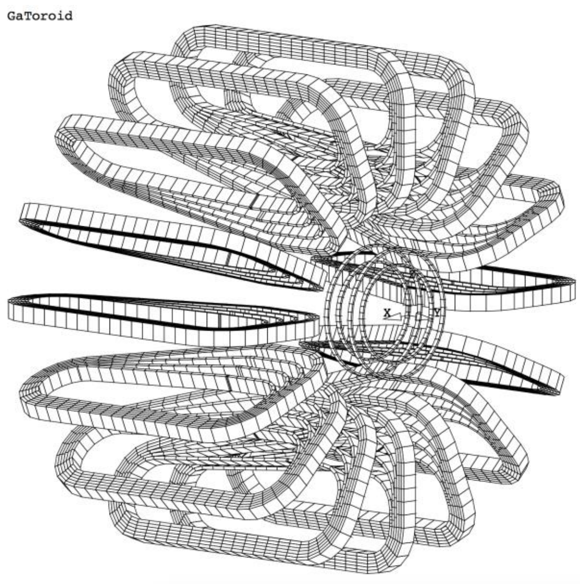
On the matter of angles

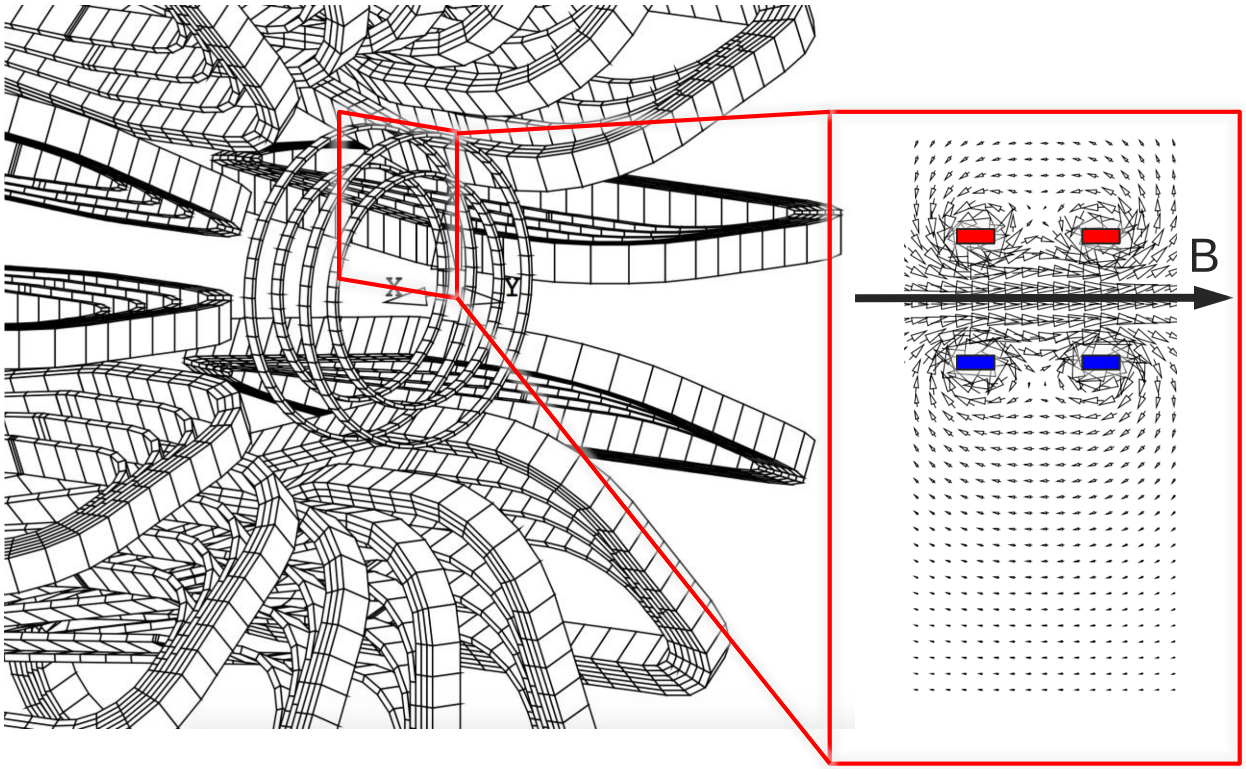


Susu Yan, *et al.* “Reassessment of the Necessity of the Proton Gantry: Analysis of Beam Orientations From 4332 Treatments at the Massachusetts General Hospital Proton Center Over the Past 10 Years”, Int J Radiation Onc Biol Phys, Vol. 95, No.1.

The distribution of delivery angles tends to be peaked around “cardinal” angles, and discrete delivery directions should not pose a limit

On the painting





Additional *steerer* “solenoid” in the free bore of the toroid

Transverse painting can be done using a solenoid corrector placed in the field-free the bore

Landscape of hadron therapy

Number of Radiotherapy Machines Per Million People