MAGNETS FOR MEDICAL APPLICATIONS

Part I: Overview of Medical Accelerators and Gantries

Mauro Pivi, MedAustron
01.12.2023

ACCELERATORS IN OPERATING FACILITIES

Cyclotrons and Synchrotrons

CLASSIC CYCLOTRONS

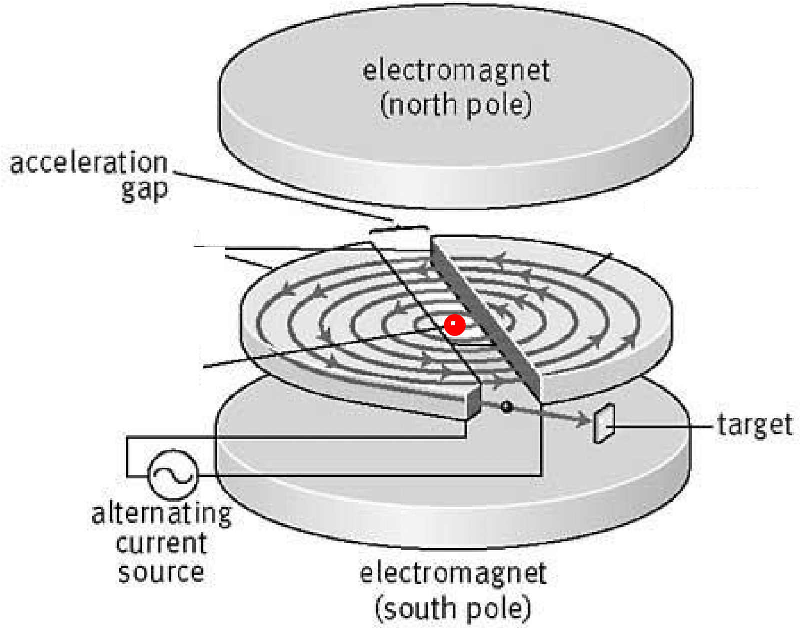
Invented by Ernest Lawrence in 1930

Working principle

- Beam injected in the center
- Accelerated by the electric field in the gap

$$\Delta E_{gap} = V_{Dee}$$

- Magnetic field causes beam to spiral till extraction



From Lorentz force:

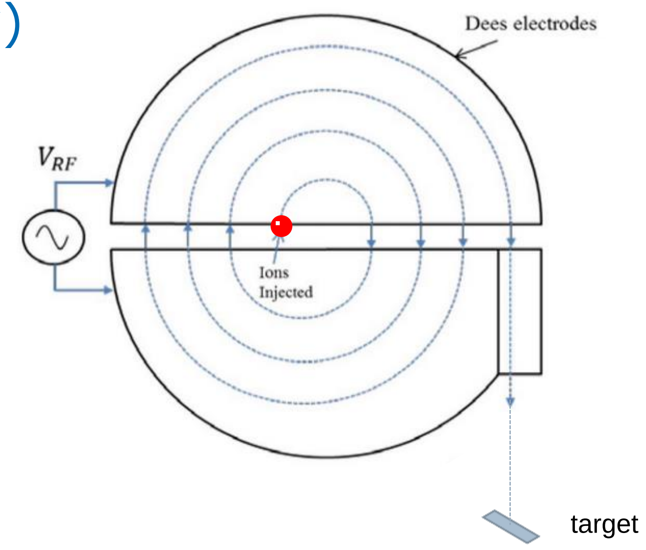
$$T_{turn} = \frac{2\pi\, m}{Bq}$$

independent on the particle radius, energy and time

- RF system constant frequency
- Particle mass increases due to relativity (v/c > 0.2) and particles go out of synch with RF.

by courtesy of Valeria Rizzoglio

MODERN CYCLOTRONS (cope with relativity)



SYNCHRO-CYCLOTRONS

- Magnetic field shaped as classical cyclotron
- RF frequency decreases with radius

$$\omega_{RF}(r) = \omega_o / \gamma(r)$$

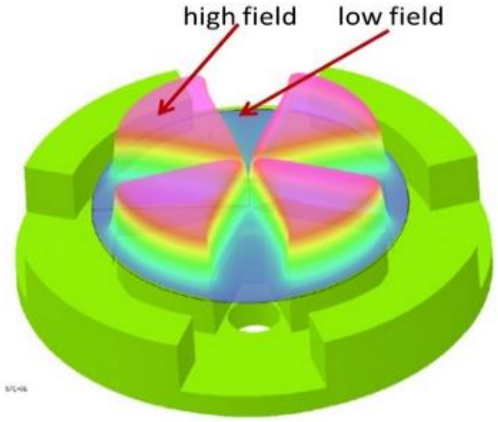
ISOCHRONOUS CYCLOTRONS

- RF frequency constant
- Magnetic field increases with radius

$$B_r = \gamma(r) \cdot B_o$$

Azimuthal field: focusing effect

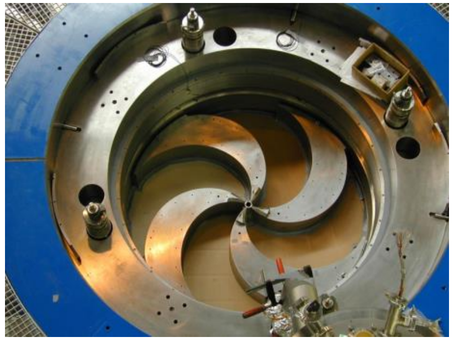
Alternate high- (hills) with low-field (valleys)



W. Kleeven, Cyclotrons: Magnetic Design and Beam Dynamics, CAS school 2015

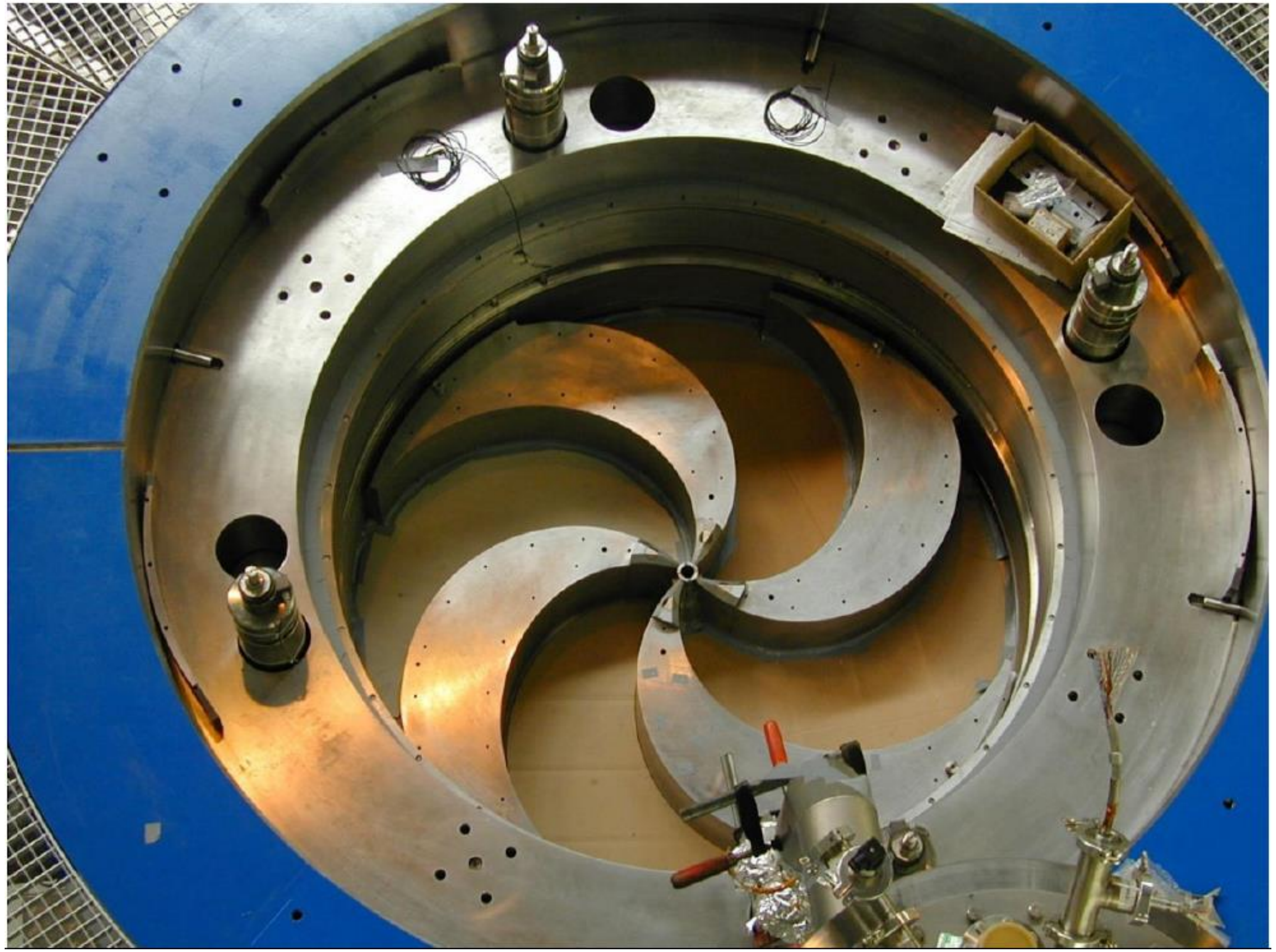
Spıral shaped hills

Maximized focusing



Varian/Accel – PSI Comet

MODERN CYCLOTRONS

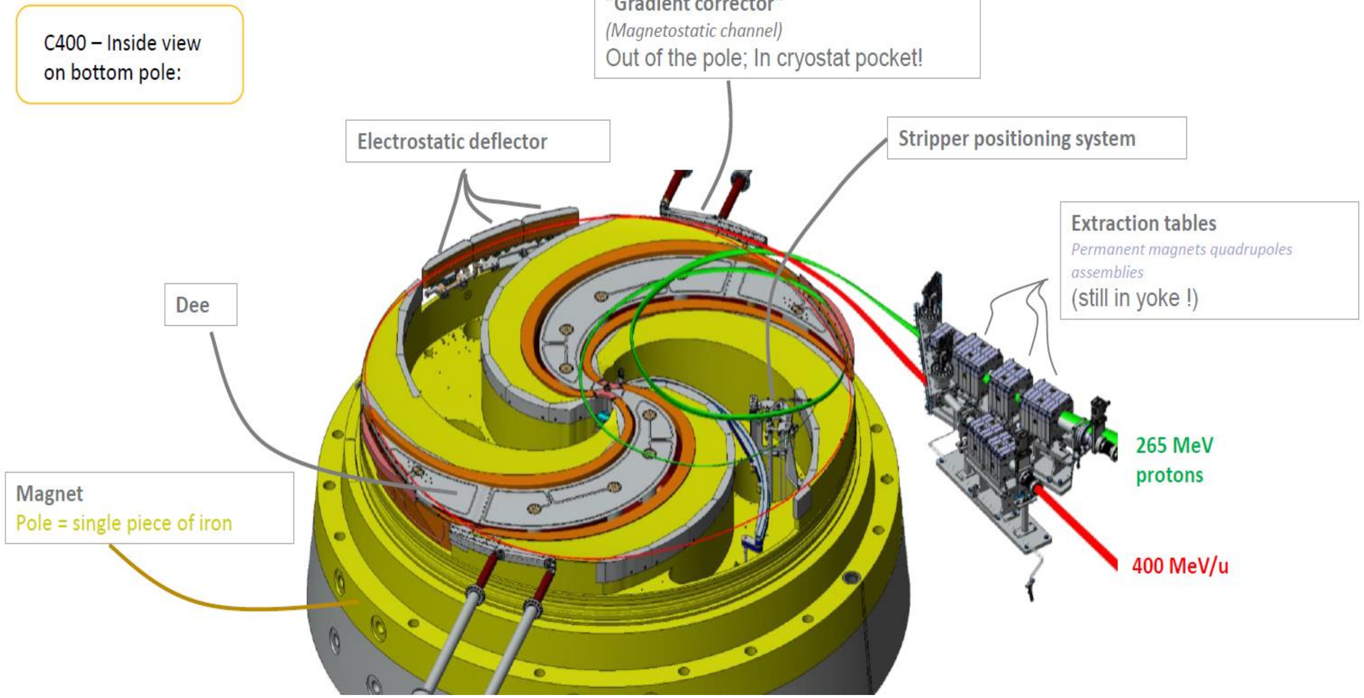


Spiral-sector magnets
for strong focusing

SUPERCONDUCTING CYCLOTRON

IBA & SAPHYN

Carbon 400MeV



- Large "compact" magnet
  - 740 Tons – 7m diameter yoke - pole radius 1.87m
  - **pole** is **4-fold symmetry / Elliptical gap / Spiralized poles**
- Cryogenic coils
  - max field 4.5T,
  - **2 sub-coils/coil** to adapt field to particle masses discrepancies.

By courtesy of Laurent Maunoury, Normandy Hadrontherapy

ADVANTAGES OF CYCLOTRONS

Simplicity & Reliability

Lowest Costs and Size

"On the shelf" solution

Intense Beams

Rapidly and accurately modulate the beam current

ACCELERATORS IN OPERATING FACILITIES

Cyclotrons and Synchrotrons

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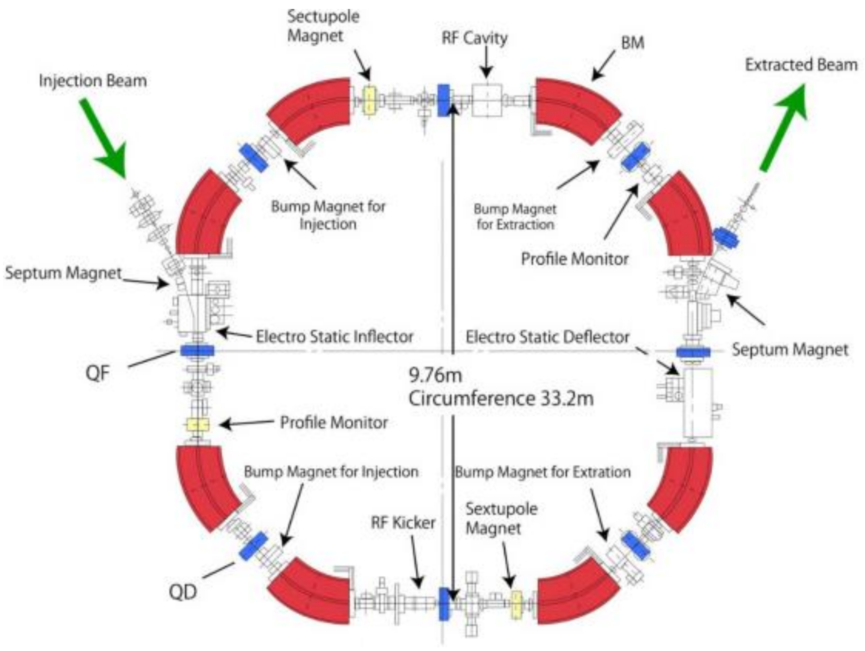
SYNCHROTRONS

Working principle

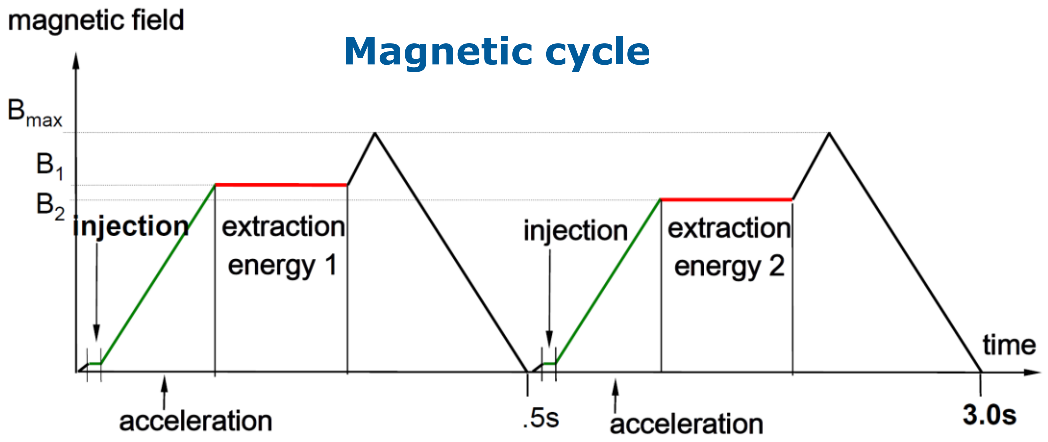
- Beam is injected in the ring from an injector beam line
- Accelerated by the RF cavity
- The magnetic fields are increased ‘synchronously’ to RF

$$\frac{p}{Bq} = r = const$$

- Strong focusing
- Beam extracted at the desired energy



Magnetic cycle



Timing events (MedAustron)

Injection + acceleration : < 1 s

Extraction : 0.1 – 10 s

SYNCHROTRON DESIGNS

Hitachi

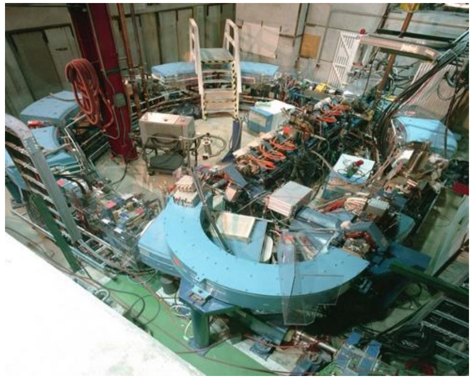
- Proton only
- 6 dipoles
- 7.8 m diameter

https://www.hitachi.com/businesses/healthcare/products-support/pbt/hybeat/index.html

ProTom

- Proton only
- 8 dipoles
- 4.9 m diameter

https://www.protominternational.com



Loma Linda

- Proton only
- 8 dipoles
- 6 m diameter

http://www.tassausa.org

CNAO, MedAustron, HIT, MIT, HIMAC Japan, Shanghai China

- Proton and Carbon ions
- 16 dipoles
- ~25 m diameter

ADVANTAGES OF SYNCHROTRONS

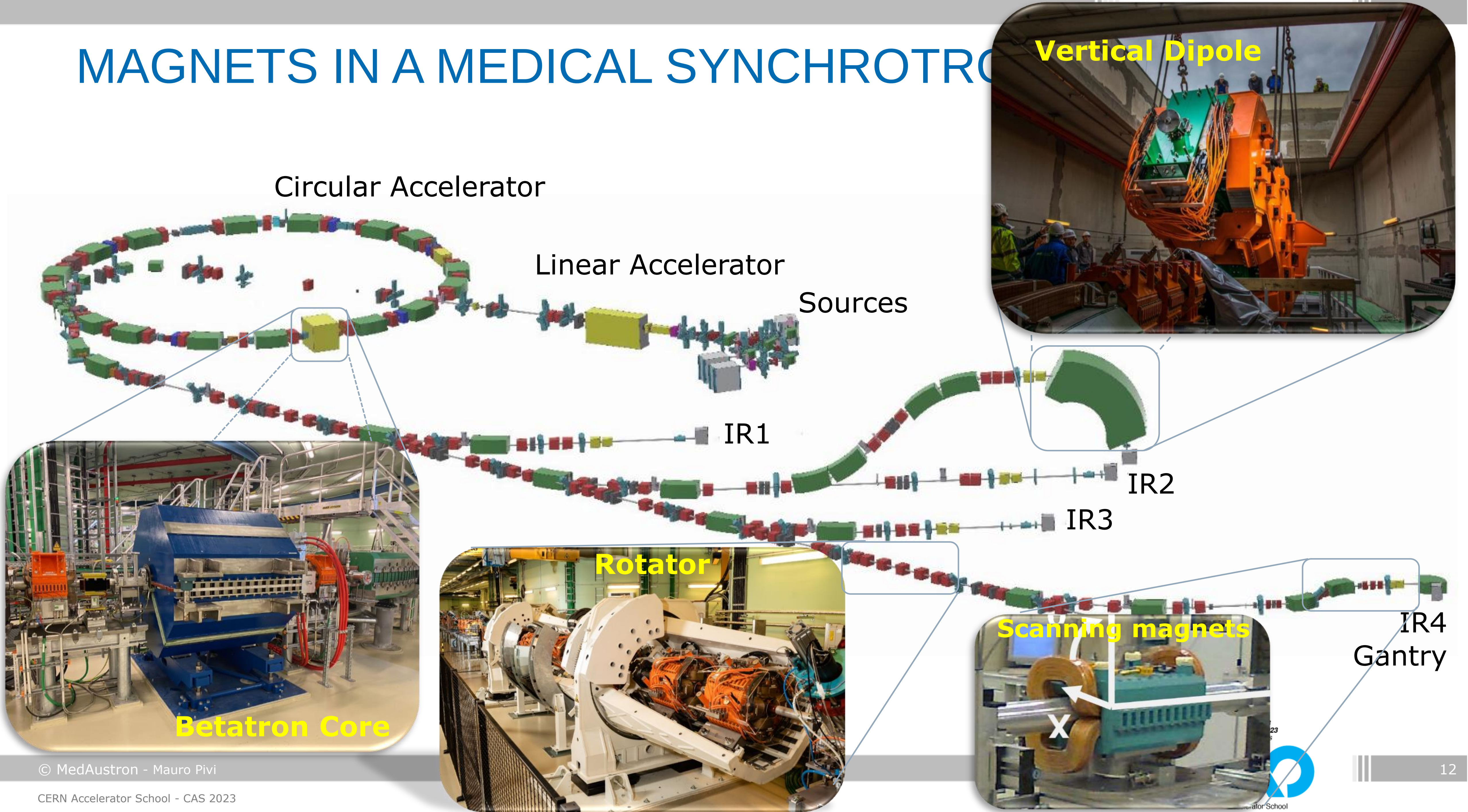
Variable Beam Energy

Reduced Beam Losses

Smaller Emittance/ Beam Sizes

Multi-ions

MAGNETS IN A MEDICAL SYNCHROTRO



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MAIN DIFFERENCES CYCLOTRON/SYNCHROTRON

Footprint of Accelerator	Degrader to set beam energy in Cyclotrons vs Variable energy in Synchrotrons (but slower)	Intensity affected by degrader vs Constant beam intensity

GANTRIES

A gantry is a structure that rigidly holds in place the guidance magnets, dipoles and quadrupoles, for ion beam therapy. The term “gantry” refers to the whole rotating mechanical structure and beam line.

The gantry rotates around the patient enabling the ion beam to enter the tumor in all directions. The rotation angle is typically either 180° or 360° depending on the design choice.

An accelerator is needed to provide the beam to the gantry.

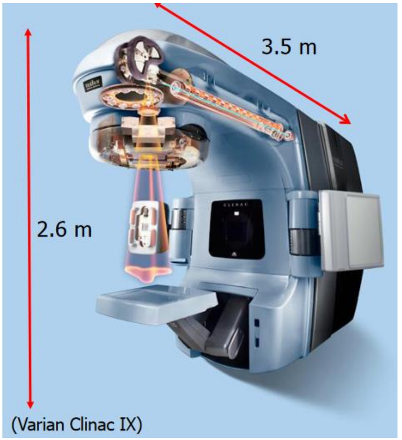
GANTRIES

Conventional radiotherapy

Swing diameter : 2.6 m

Length : 3.5 m

Weight : ~9 t



Proton therapy (PSI Gantry 2)

Swing diameter : 7.5 m / Length : 8.9 m

Weight : 200 t

First Carbon Gantry (HIT)

Swing diameter: 13m

Length: 21 m

Weight: 600 t

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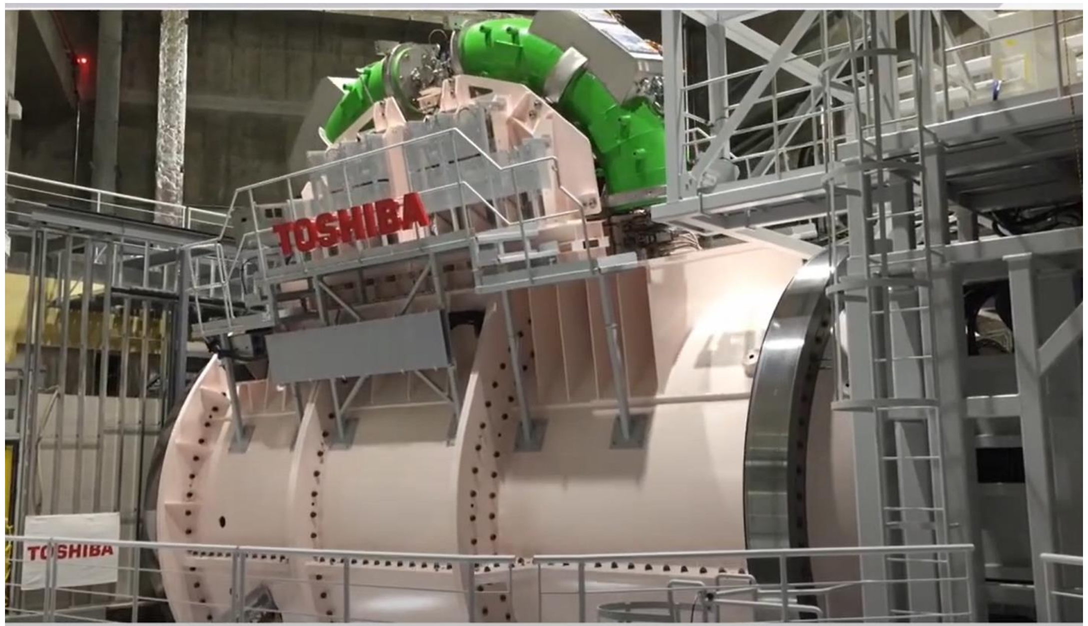
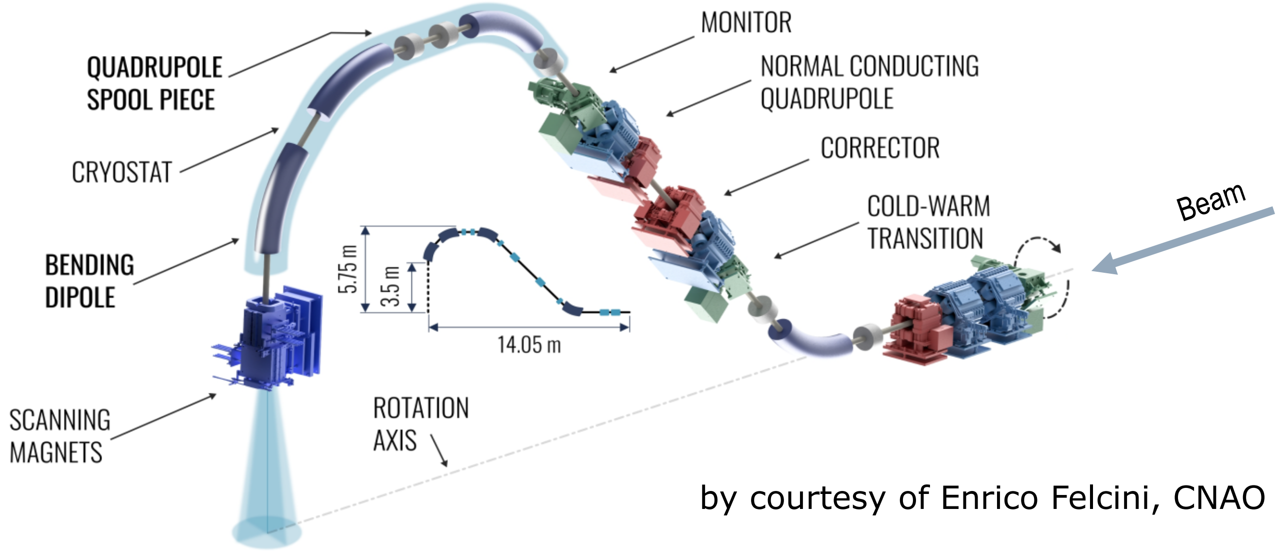
SUPERCONDUCTING GANTRIES

Carbon and heavy-ions gantries



Compact rotating gantry at Yamagata University

EuroSIG project: a novel superconducting ion gantry



by courtesy of Enrico Felcini, CNAO

MAGNETS FOR MEDICAL APPLICATIONS

Part II: The MedAustron experience

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Mauro Pivi, MedAustron

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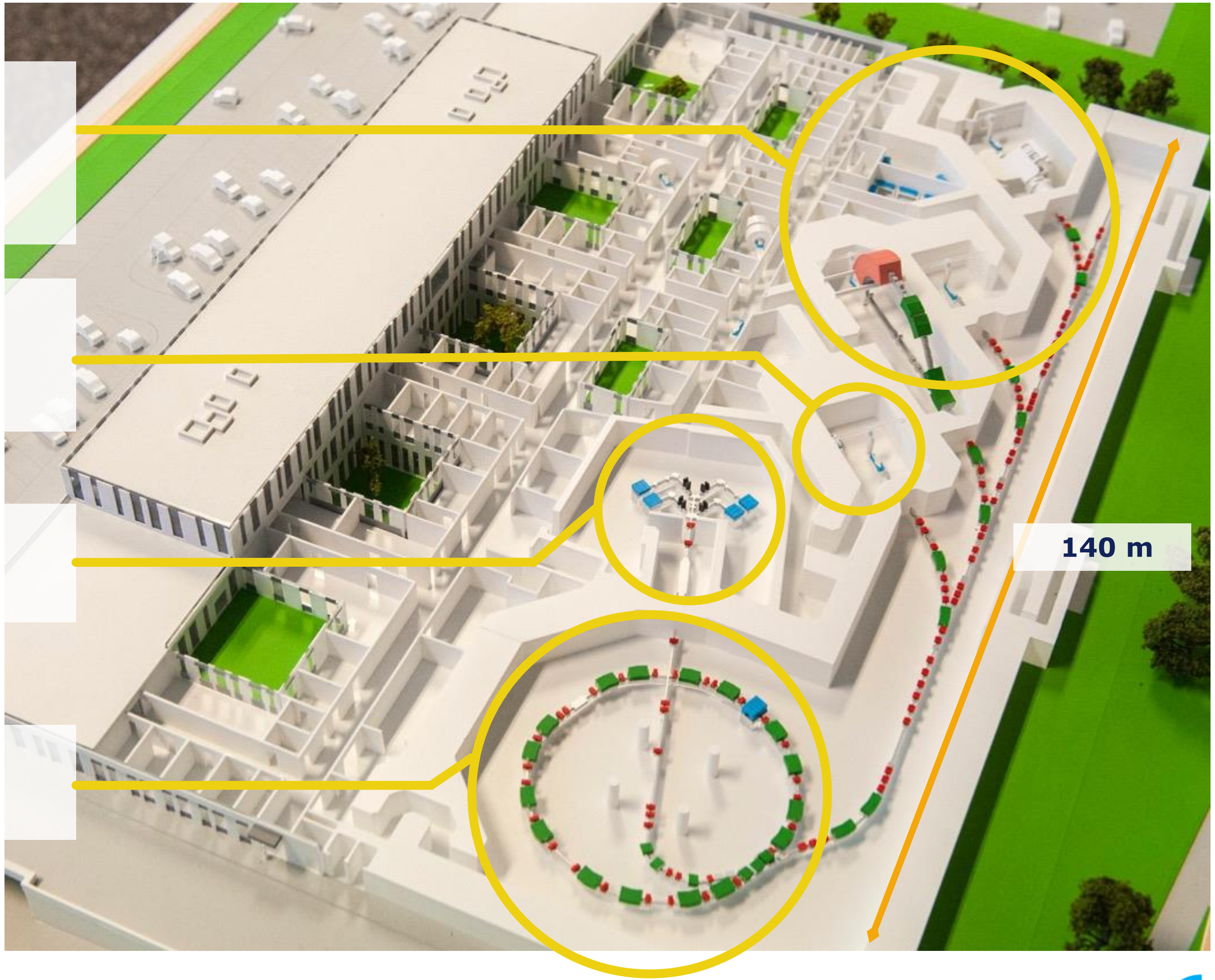
FACILITY OVERVIEW

Irradiation Rooms
Three rooms for patient treatments including a gantry room

Research
Irradiation room for non-clinical research

Ion Sources
and linear accelerator

Synchrotron
circular accelerator



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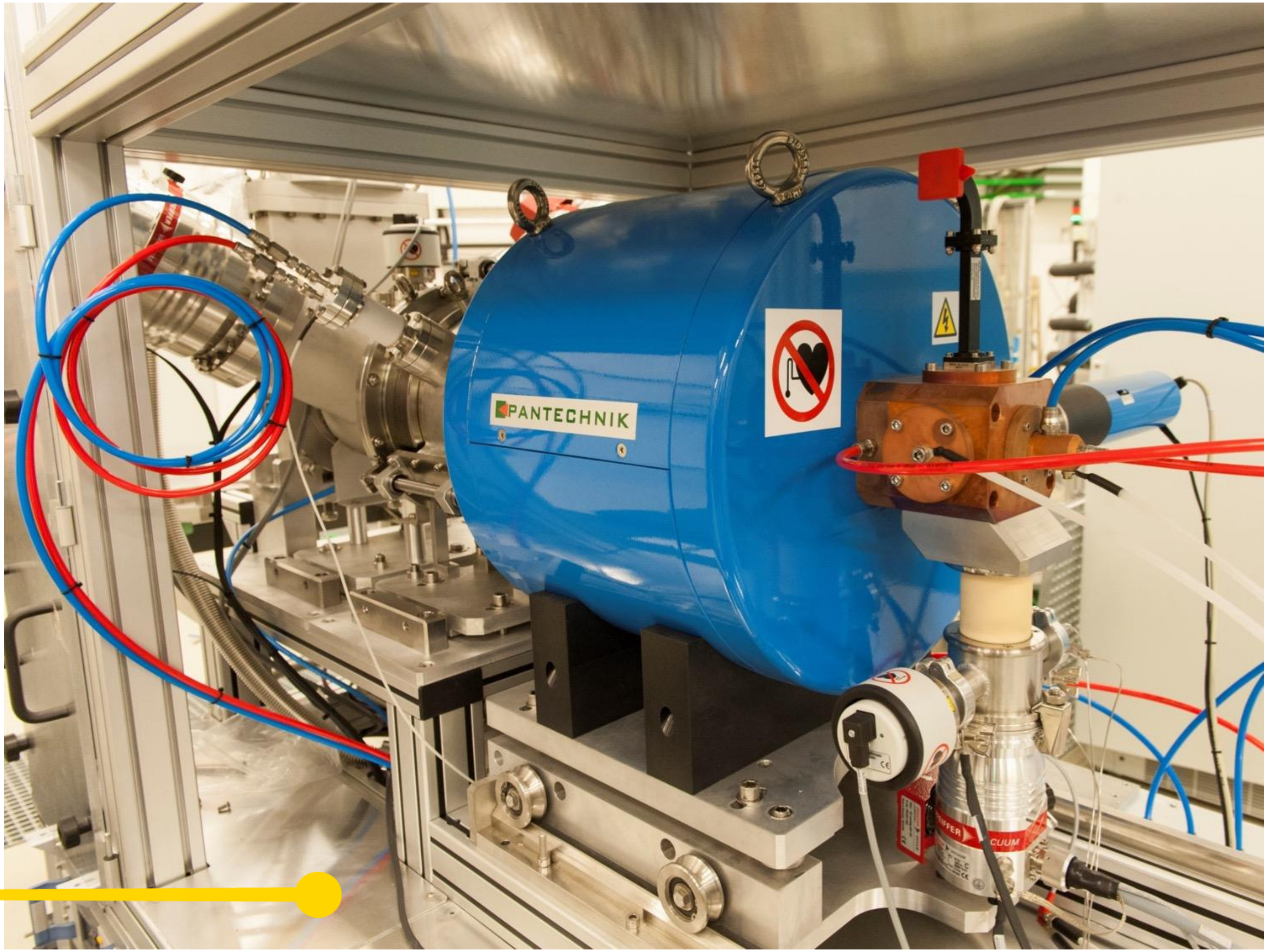
STARTING POINT OF THE BEAMS: ION SOURCES



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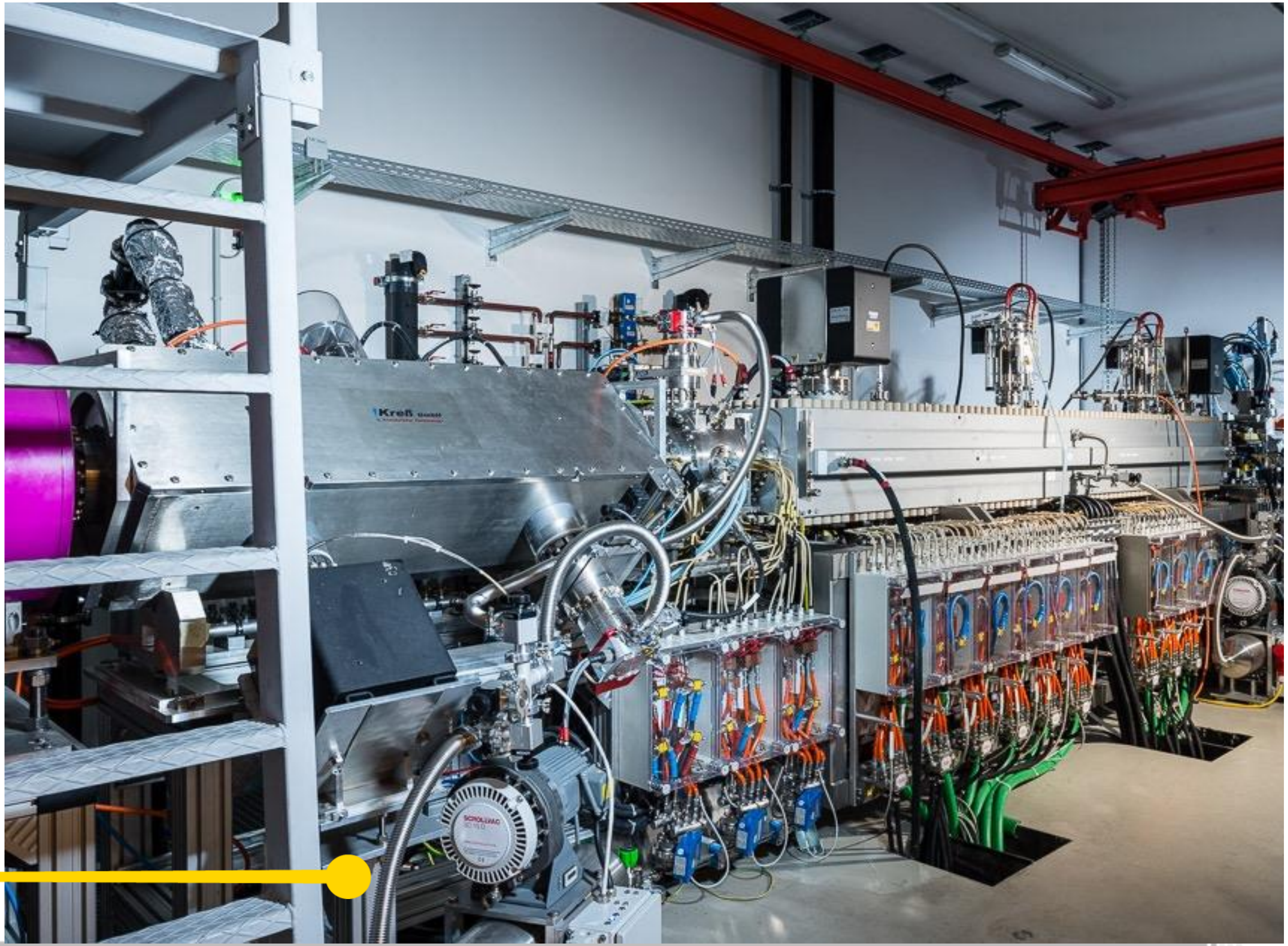
FIRST STAGE ACCELERATION: THE LINAC



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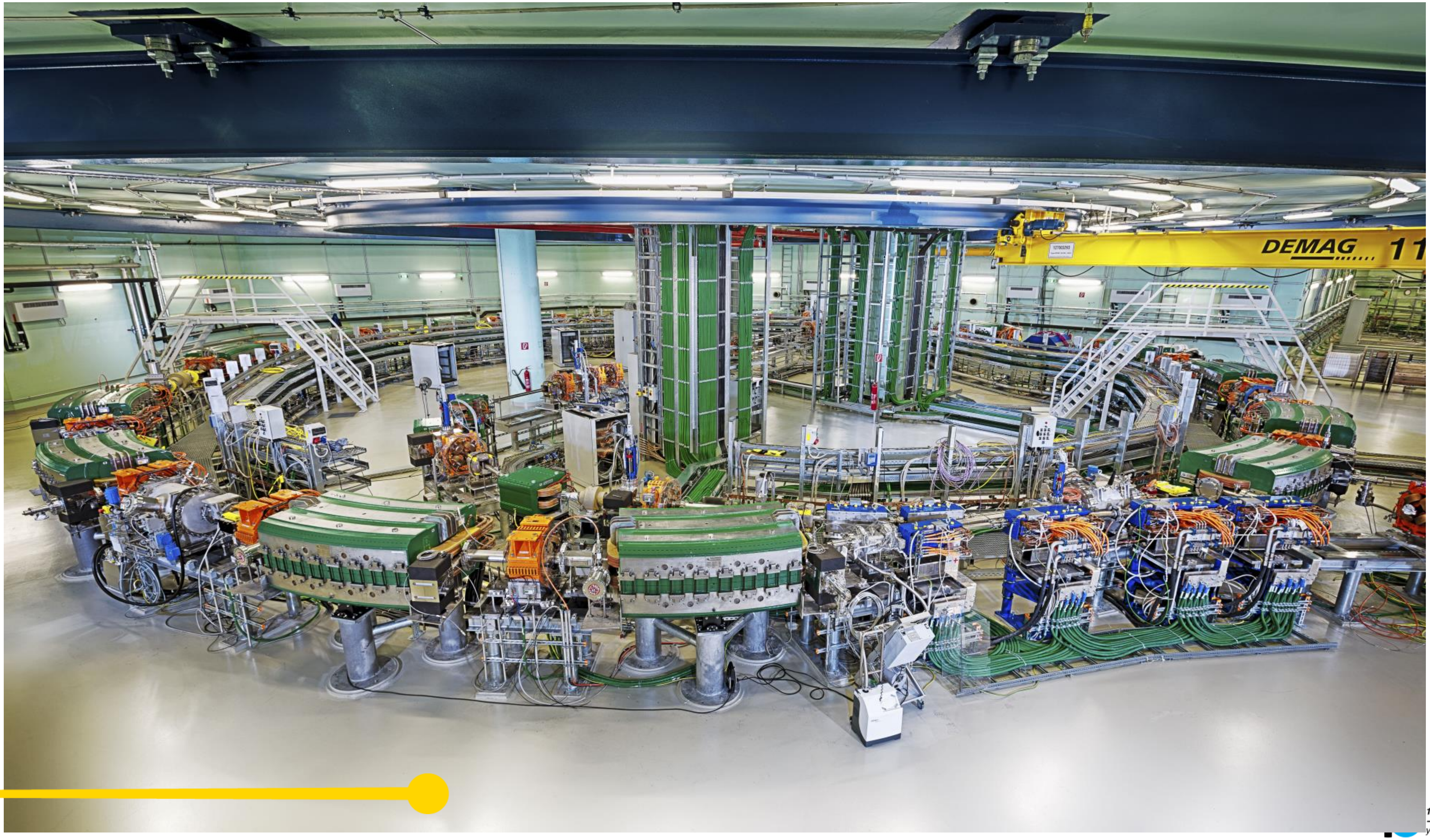
ACCELERATION TO HIGH ENERGY: SYNCHROTRON



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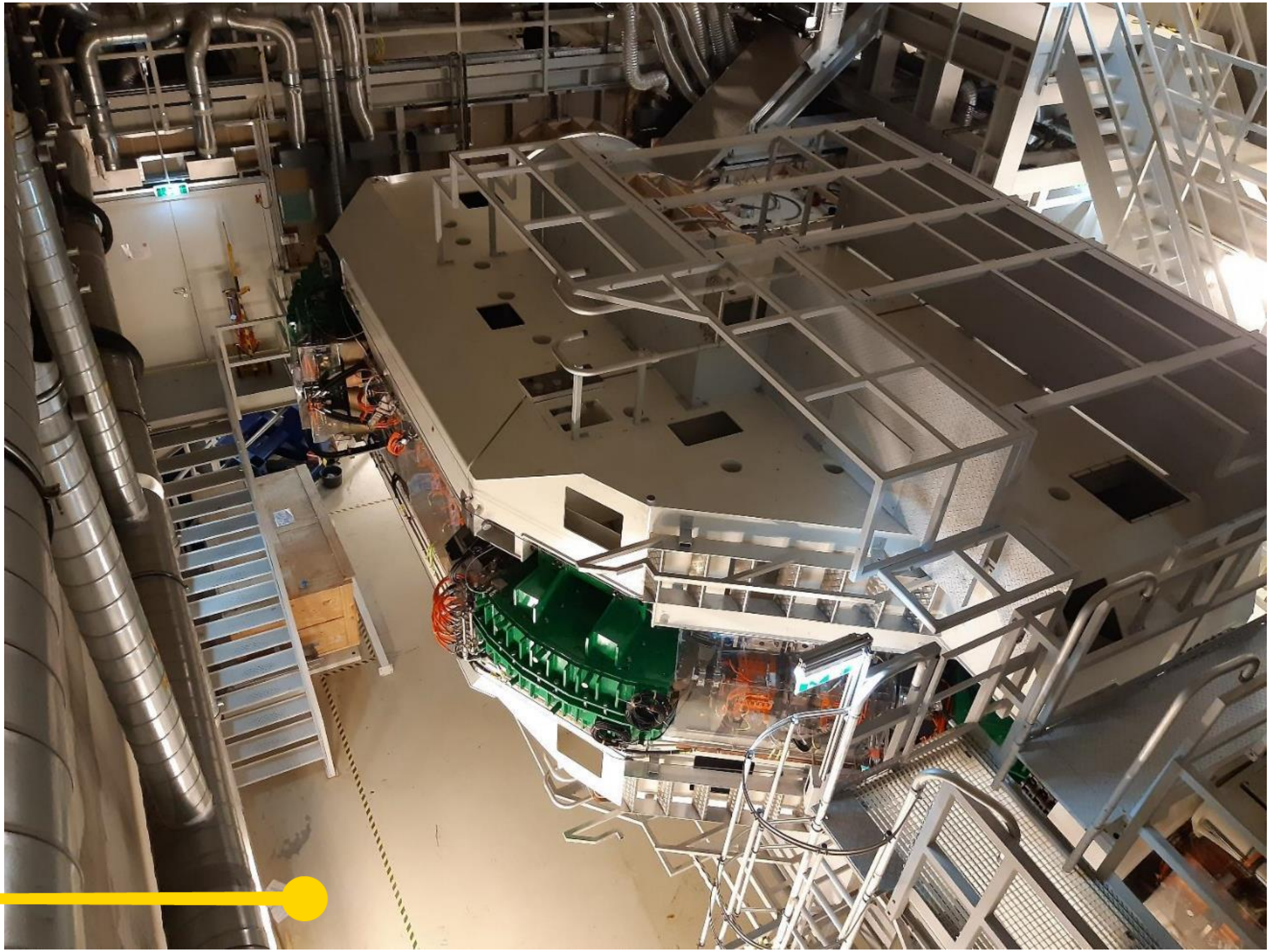
HIGH ENERGY TRANSFER LINE - HEBT

PROTON GANTRY



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IRRADIATION ROOM AND PATIENT POSITIONING

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MAGNETS: FROM SPECIFICATION TO OPERATION

To design a magnet for medical accelerators, several operational considerations need to be taken into account.

Factors that influence the choice of material, magnet size and the overall design include: maximum required magnetic field to bend proton and carbon maximum energy, magnet/ic length, dipole’s edge angles, magnet aperture, “good field” region, fringe fields and compensation, higher order multipole field components, powering magnets in series or parallel, current ramping speed/time, magnetic field stabilization, eddy currents, hysteresis and history effects, thermal effects.

Magnet requirements are specified by the beam optics designers, i.e. accelerator physicists and engineers.

MAGNETS: FROM SPECIFICATION TO OPERATION

Specifications by beam optics experts

- Principles of operation
- Requirements

Designer and Manufacturer

- Design
- Manufacturing & Magnetic Measurements → Acceptance

Back to the beam optics experts

- Installation
- Beam Commissioning & Measurements with beam

Operation

- Clinical Operation

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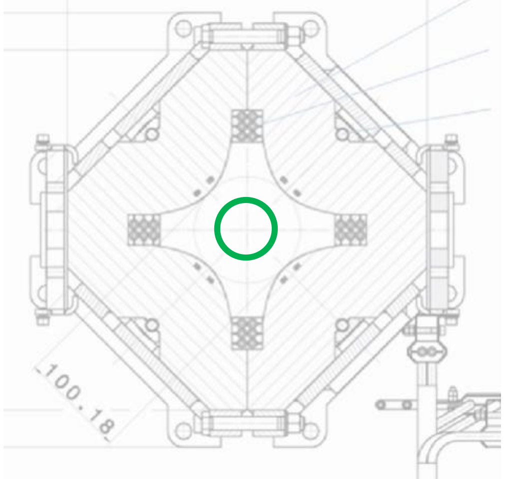
PRINCIPLES OF OPERATION

GOOD FIELD REGION

In the magnet design phase, an important specification is the ‘good field region’ within the magnet aperture. The good field region corresponds to the full extent of the beam in size and position within the magnet:

$$Aperture = \pm \left(\underbrace{n \cdot \sqrt{\underbrace{\beta\varepsilon}_{\text{betatron envelope}} + \underbrace{D^2 \left(\frac{\Delta p}{p_0}\right)^2_{spread}}_{\text{momentum envelope}}} + \text{Closed orbit}}_{\text{Good field region}} + \underbrace{\text{margins}}_{\text{poor field region}} \right)$$



The beam envelope and the beam closed-orbit determine the good-field region where the highest magnetic field quality is required.

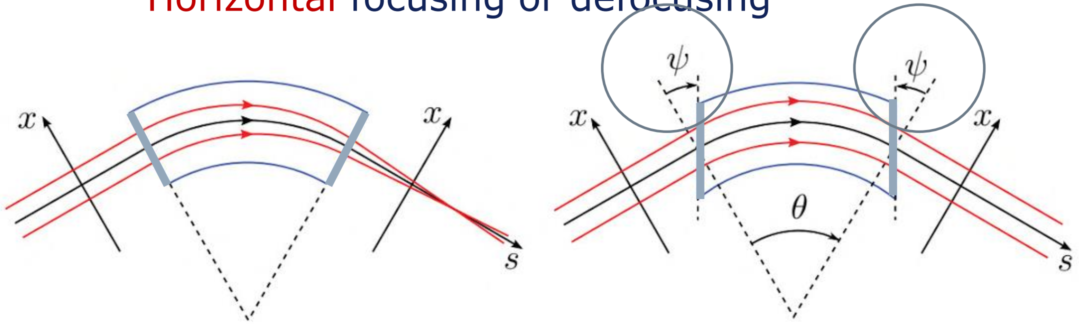
PRINCIPLES OF OPERATION

DIPOLE - EDGE ANGLES

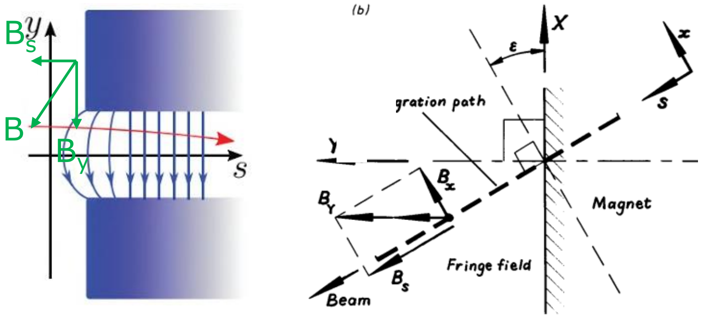
Horizontal focusing/defocusing of the dipole is a geometric effect. When the pole face is rotated with respect to the reference trajectory, a particle has to travel a longer or shorter distance. This effect is particularly important for (1) the synchrotron dipoles and for (2) large dipoles just upstream of the patient.

The origin of the vertical focusing or defocusing is the longitudinal component of the fringe field that increases with vertical displacement. The rotation of the pole faces leads to particles crossing the fringe fields at an angle and experiences a vertical deflection.

Horizontal focusing or defocusing



Vertical focusing or defocusing



courtesy of Ivan Strasik

[Ref] A. Wolski, Beam dynamics in high energy particle accelerators link
[Ref] P. Bryant, The principles of circular accelerators and storage rings

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PRINCIPLES OF OPERATION

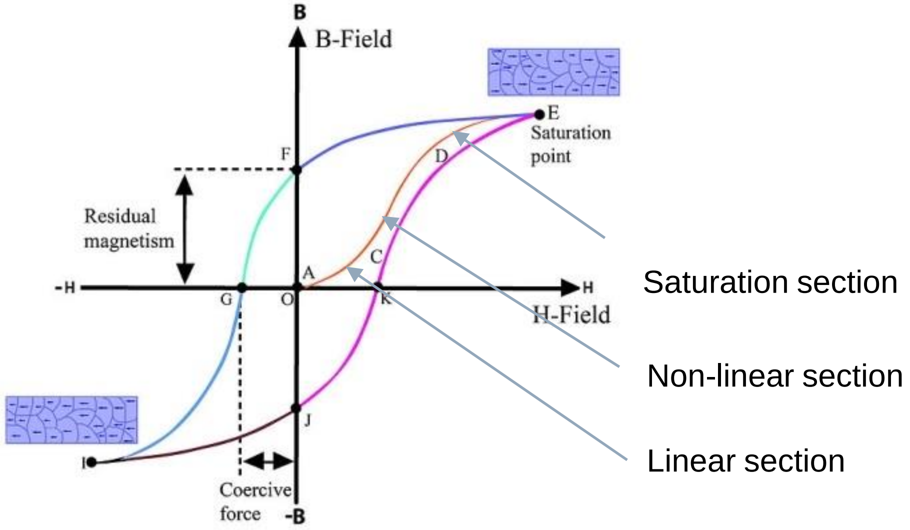
MAGNET CONDITIONING

Before operating the magnets, in order for the magnetic field to be reproducible from cycle to cycle, a magnet “conditioning” or “magnetization” procedure is performed. Named differently at facilities around the world: ‘cycling’, ‘washing’, ‘hysteresis loops’, magnets ‘training’, “initial magnetization” …

Magnet conditioning must be performed, with main goals:

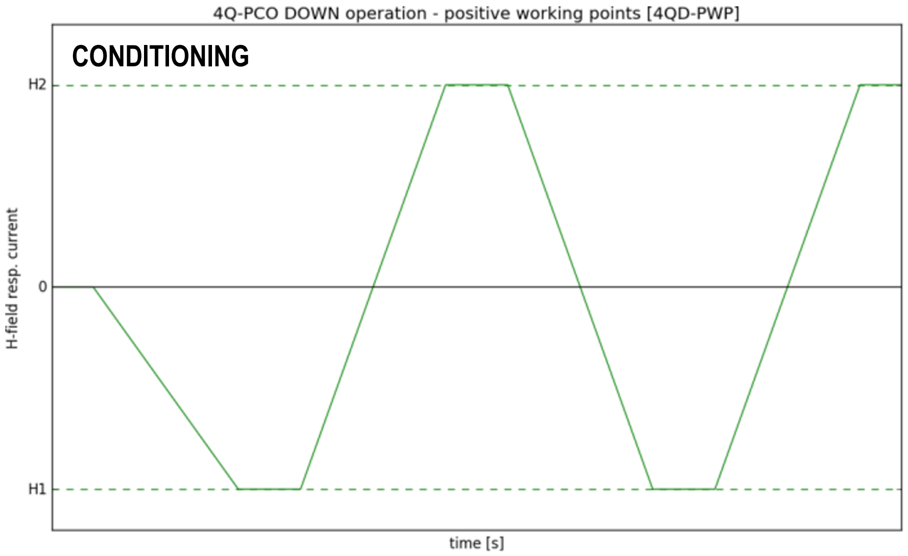
- Establish reproducible magnet conditions
- Re-establish the conditions used when measuring the magnets to match the *as-built* accelerator with simulations.

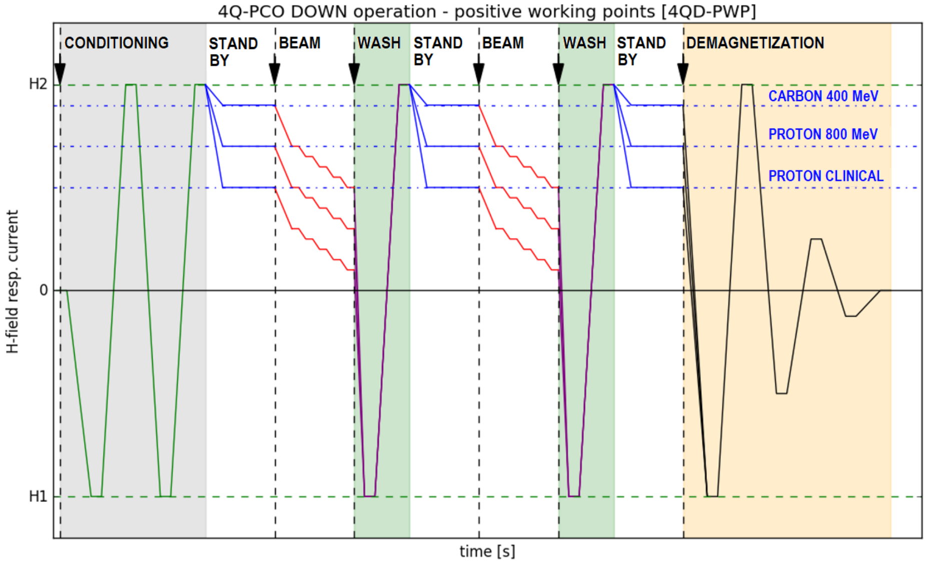
The result of the application of an external H-field, via current through coils in the magnet, is a B-field, with a pattern that can be split into three sections: (1) linear (2) non-linear (3) saturation.



The same H-field value or current results in different B-fields depending on the previous applied magnetic field (in the figure: points I to E curve or E to I curve) or 'history' of the magnet.

A reproducible setup independent of previously applied magnetic fields has to be generated by performing multiple <u>loops</u> in current/magnetic field.





drawing courtesy of Alex Wastl

With a sufficient number of loops (1, 2 or 3) the procedure establishes the ‘base magnetization’, to ensure the previous “history” is removed without dependence on the previously applied H-fields and the B-field is predictable and reproducible. A one loop “wash” procedure is also applied to reset the current maximum level.

PRINCIPLES OF OPERATION

DOWNWARD CURRENT OPERATION

In the extraction beam line, all the magnets move “downward” in absolute magnetic field or current steps, before the following beam injection occurs.

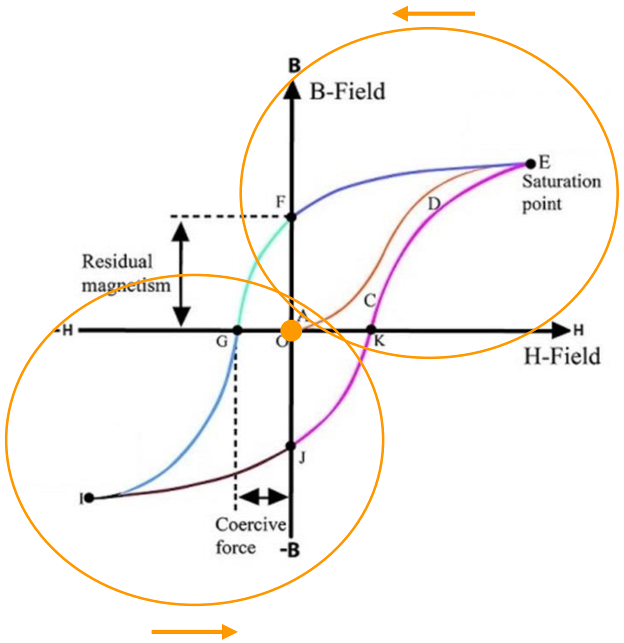
Thus, in a treatment plan, the tumor slices are irradiated in strict order of decreasing beam energy.

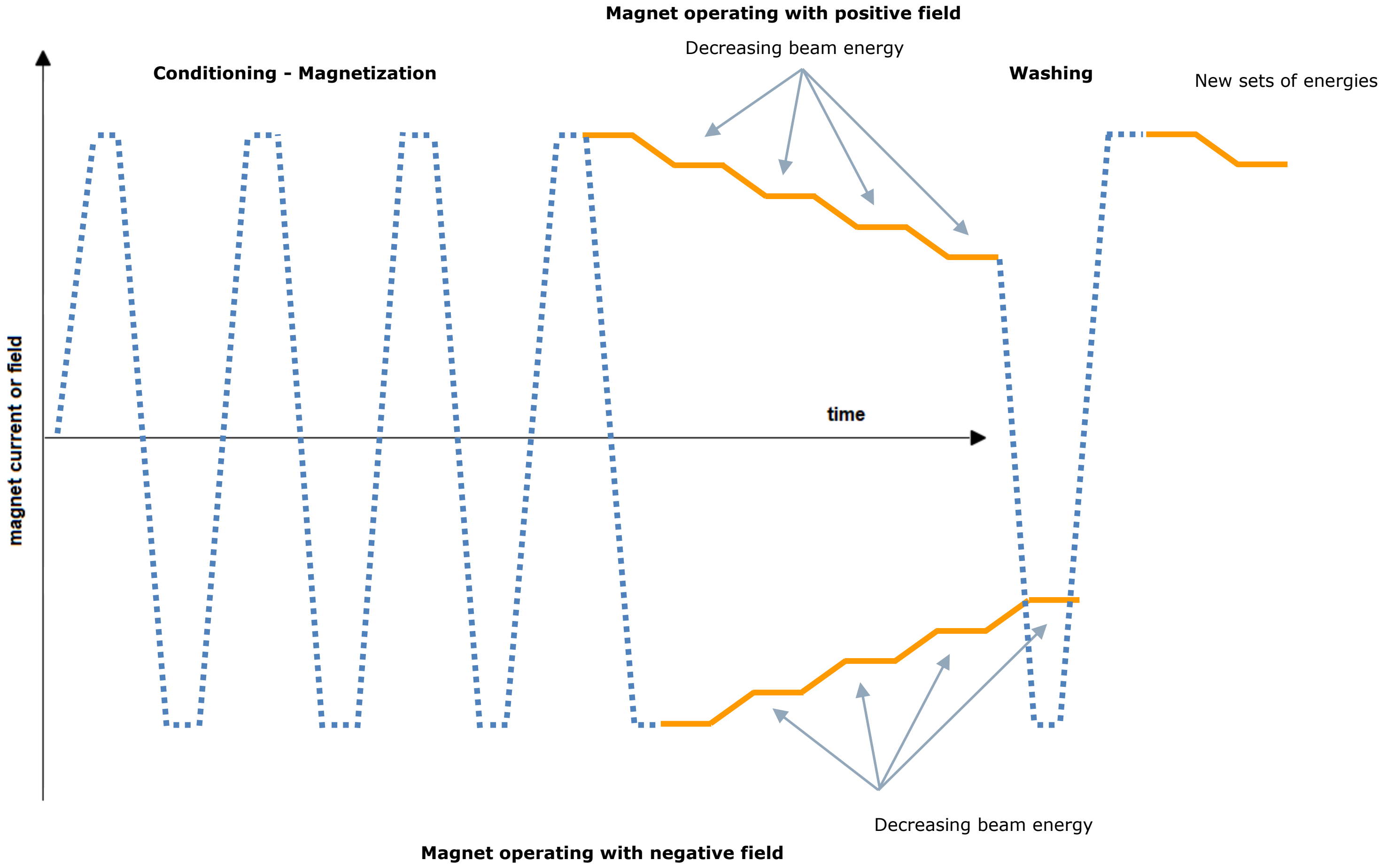
The magnets are following the “downward” curve of the hysteresis curve.

Actually a design choice: at MedAustron the operation is strictly downward. At CNAO, Pavia, Italy and other accelerators, the magnet operation is “upward”.

PRINCIPLES OF OPERATION

Downward operation in the extraction line: decreasing magnetic field in absolute terms





REQUIREMENTS

Requirements of most importance for medical applications are:

- Reproducibility of the magnetic field
- Magnetic field homogeneity (rather than highest magnetic fields)
- Beam repeatability: position, spot size at patient location

DESIGN AND MANUFACTURING

Once the requirements, specifications and tolerances have been defined and the magnet design is ready for construction, it is as well important to specify the procedure and the details of the test measurements following the manufacturing of the magnet.

MAGNETIC TEST MEASUREMENTS

Magnetic test measurements at *in-house* facility (if available!) or at manufacturer. It would be important to:

- use the same/similar power converter supply as in future accelerator operations.
- perform the initial magnet conditioning procedure as in future operations with 1, 2, 3, … *N* carefully chosen number of loops + demagnetization after measurements.
- measure with the same ramping speed/time that will be used in future operations. Additional measurements with different ramping speeds for future timing optimizations.
- measure the field in the same operation cycle: “downward” (or “upward”) current and in steps corresponding to the beam energy steps as in future operations.

MAGNETIC TEST MEASUREMENTS

1. Test that all specified requirements for the magnet are met:

   - Maximum magnetic field, magnetic length, dipole's edge angles, "good field" region, higher order magnetic field components, current ramping speed/time and related magnetic field stabilization time, eddy currents, edge fringe fields and iterative compensation.

2. Using the measurement procedure as in later operations: i.e. (1) conditioning (2) ramping speed (3) downward current, characterize:

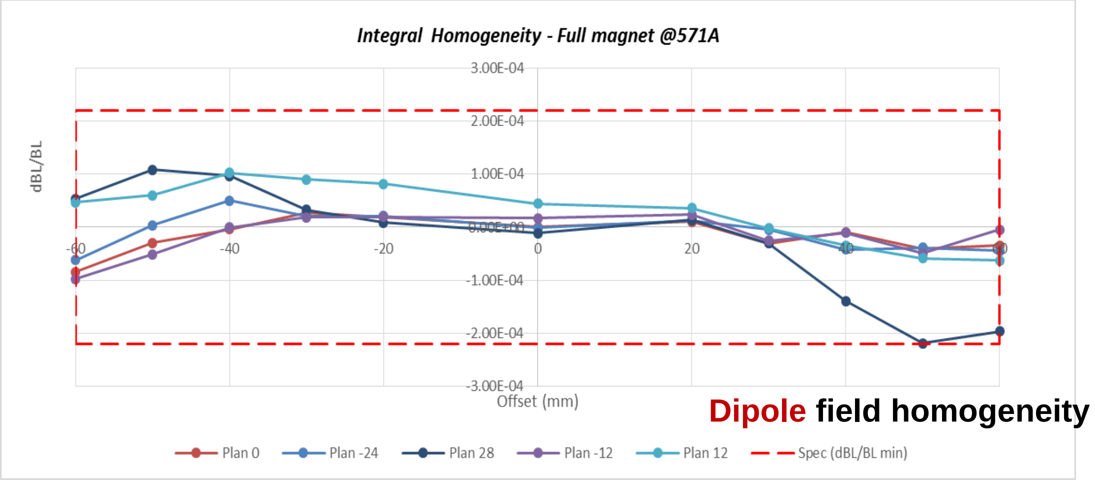
   - The "B-to-I" transfer function.
   - Hysteresis effects: characterize the field going against hysteresis. Particularly important for "scanning" magnets.
   - History effects: measure varying the number of steps to reach a current set point, see below.
   - Thermal effects: i.e. measure the magnetic field with "warm or cold" magnet.

Typical default measurements

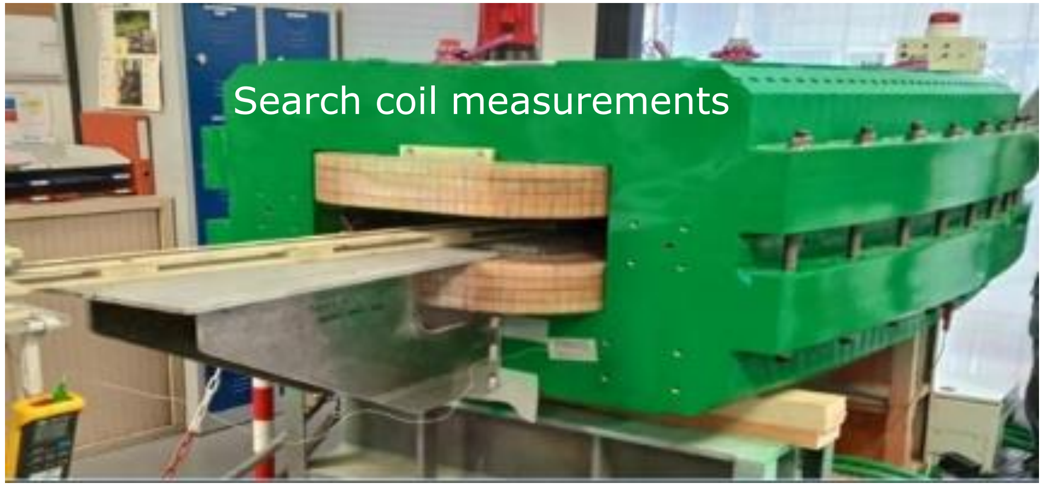
These tests might not be obvious

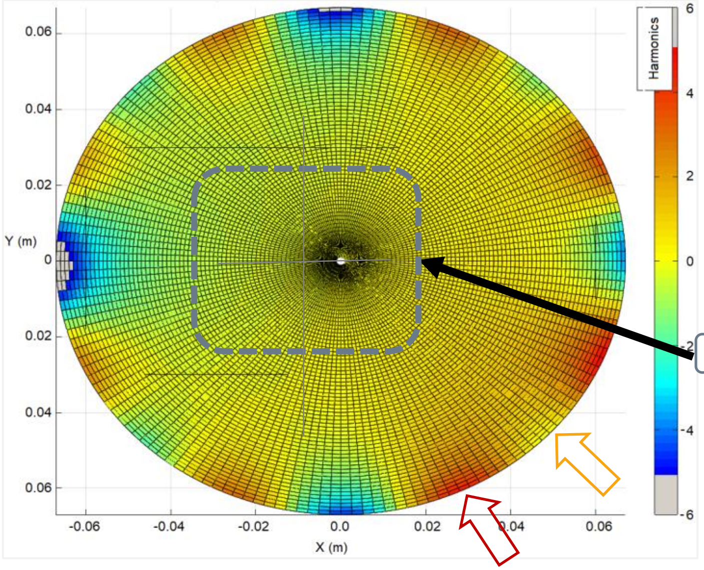
MAGNETIC TEST MEASUREMENTS

HOMOGENEITY, HIGHER ORDER MULTIPOLES, GOOD FIELD REGION



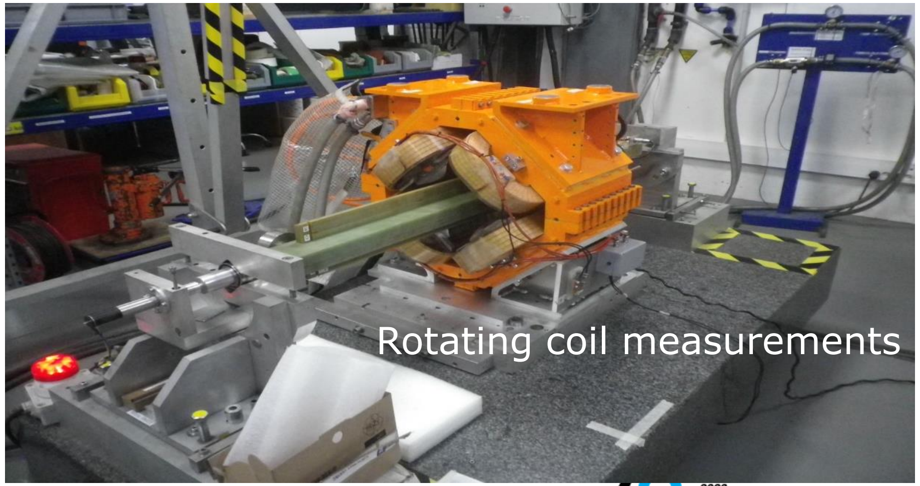
Dipole field homogeneity





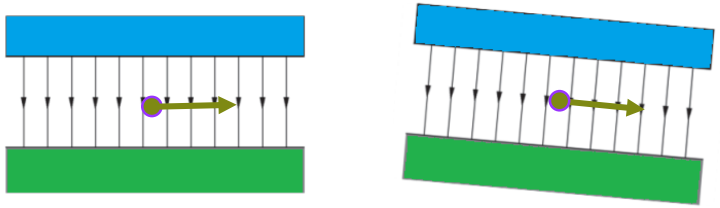
Quadrupole field reconstruction and higher order field components from measurements.

Verifying the **Good field region:**
The good field region is offset because the Quadrupole should be placed in a highly dispersive region of the beam line, where the beam is also offset horizontally.



INSTALLATION

TOLERANCES FOR MAGNETS MIS-ALIGNMENT



Example: a dipole rotation generates a vertical kick

Magnets mis-alignments generate:

- Distortion of the particle closed orbit
- Emittance increase: very important in low emittance rings
- Spread and shift in tunes and chromaticity
- Dispersion increase

Mis-alignment tolerances are specified for the magnetic center rather than the mechanical center.

Optics simulations are performed to define the acceptable level of magnets mis-alignment. Example: ± 0.1 mm for all positions x, y, s and ± 0.1 mrad for all rotation angles*.

*Values are indicative, since the effective tolerances are highly dependent on the beam optics.

INSTALLATION

THE MEDAUSTRON EXPERIENCE

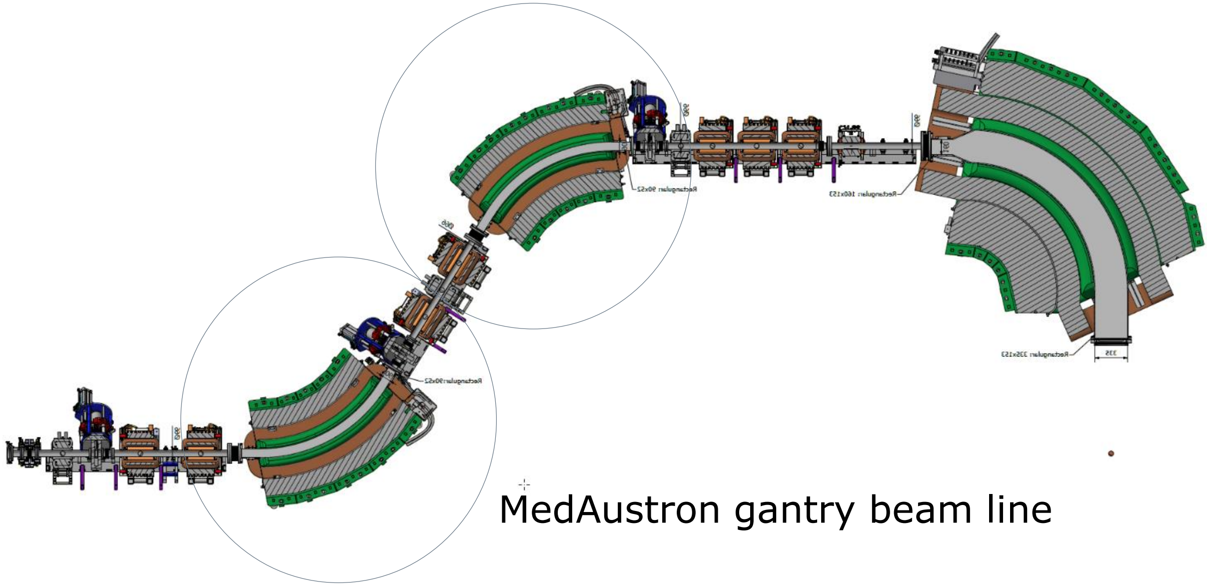
At MedAustron and at other institutes, magnets alignment is typically and on average within ± 0.1 mm r.m.s.

Though, installation issues are not rare ..

INSTALLATION

FROM THE MEDAUSTRON EXPERIENCE

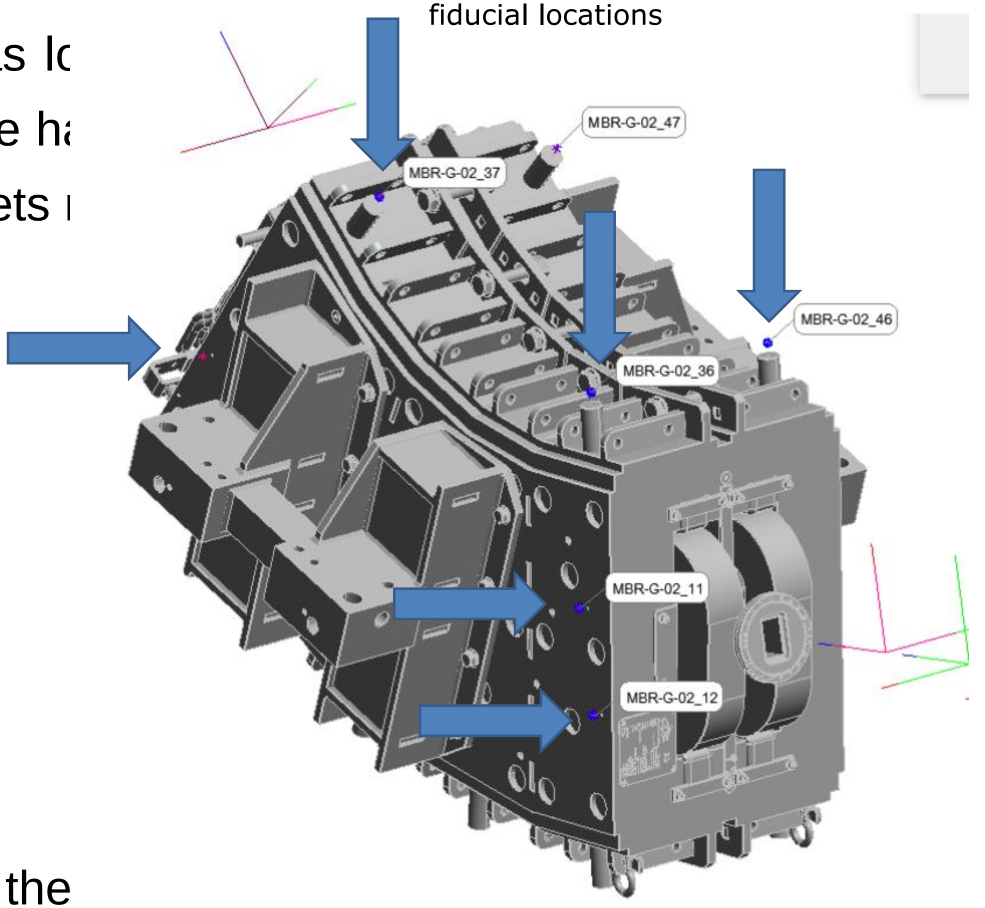
At the start of the gantry beam commissioning, the beam was lo irradiation room. To be able to send the beam to the room, we ha very high corrector strengths. This is an indication that magnets



MedAustron gantry beam line

Simulations pointed to two dipoles to be re-aligned. After the straightforwardly be sent to the room without correcting the orbit.

Gantry dipoles:
fiducial locations



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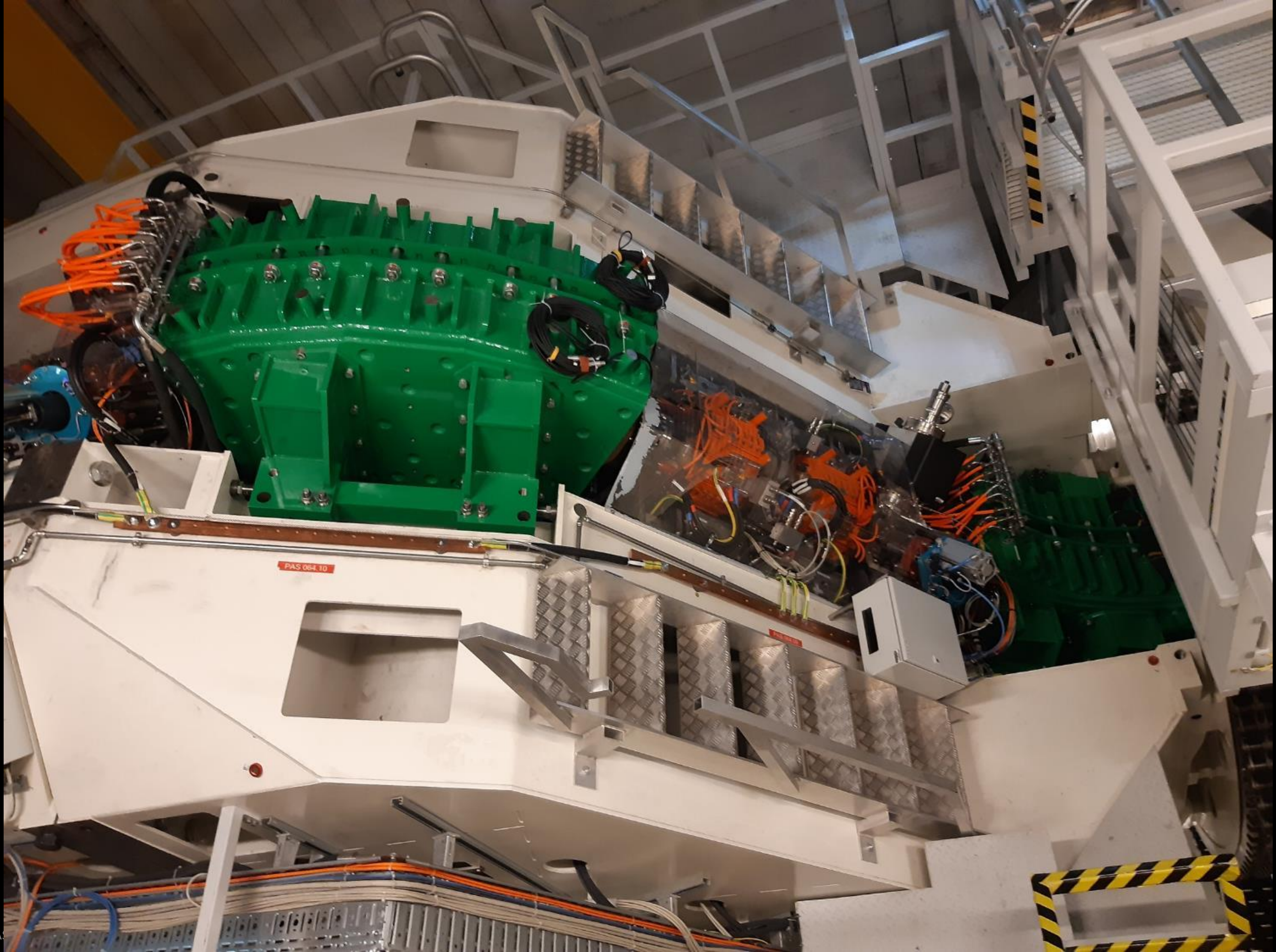
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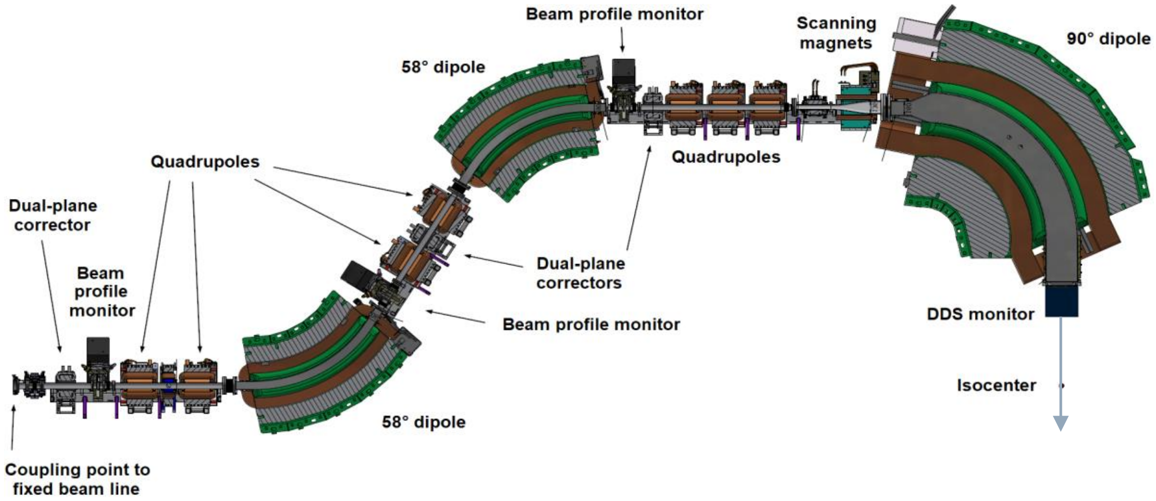
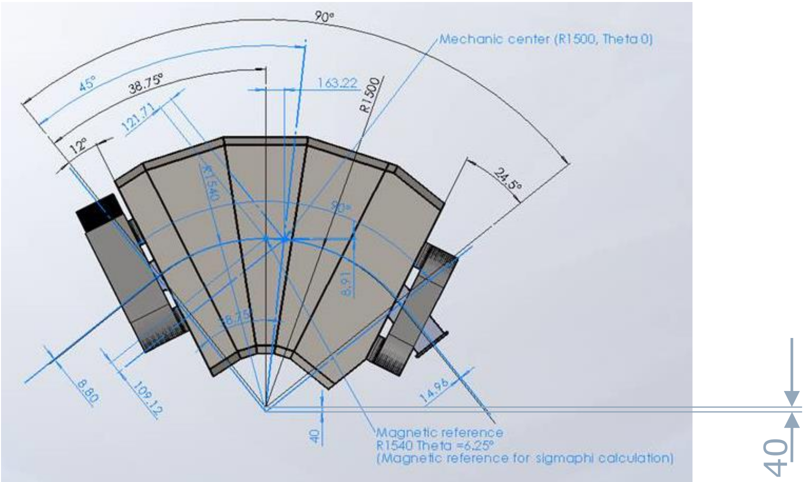
INSTALLATION

FROM THE MEDAUSTRON EXPERIENCE

The last 90° dipole of the gantry beam line was built with a difference between the magnetic radius and the mechanical radius of 40 mm. It was then installed with a ~6° rotation to take this difference into account. As a consequence,



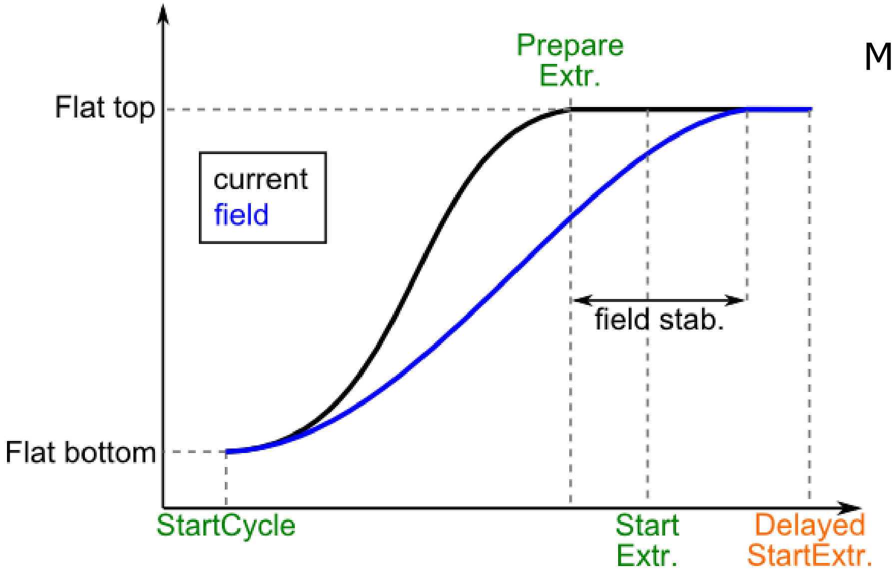


the beam would reach the isocenter with an angle of 4 mrad. To compensate for this beam angle, the upstream scanning magnets have been set with a corresponding counter-offset angular kick.

BEAM COMMISSIONING

FIELD STABILIZATION

The magnetic field follow the current with a delay that depends on several effects as eddy currents, yoke material, impedance.



Magnetic field of the synchrotron dipoles

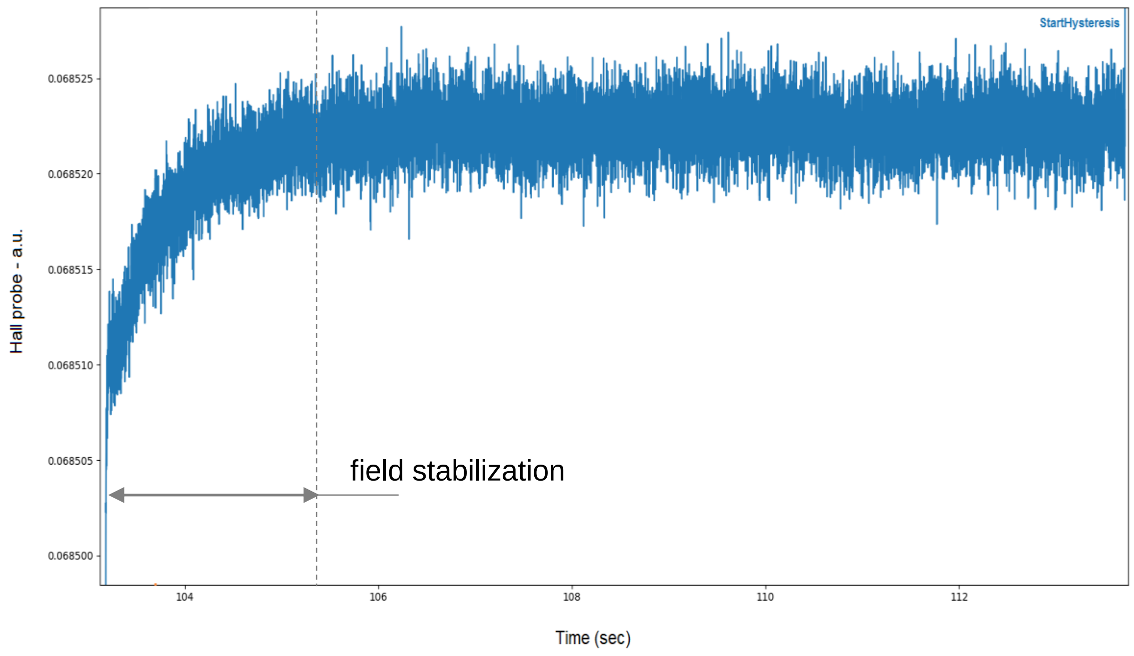
diagram courtesy of Alex Wastl

To allow for the field to stabilize, the beam extraction is delayed from the synchrotron.

Similarly, the stabilization time of the HEBT extraction magnets must be taken into account.

BEAM COMMISSIONING

FIELD STABILIZATION

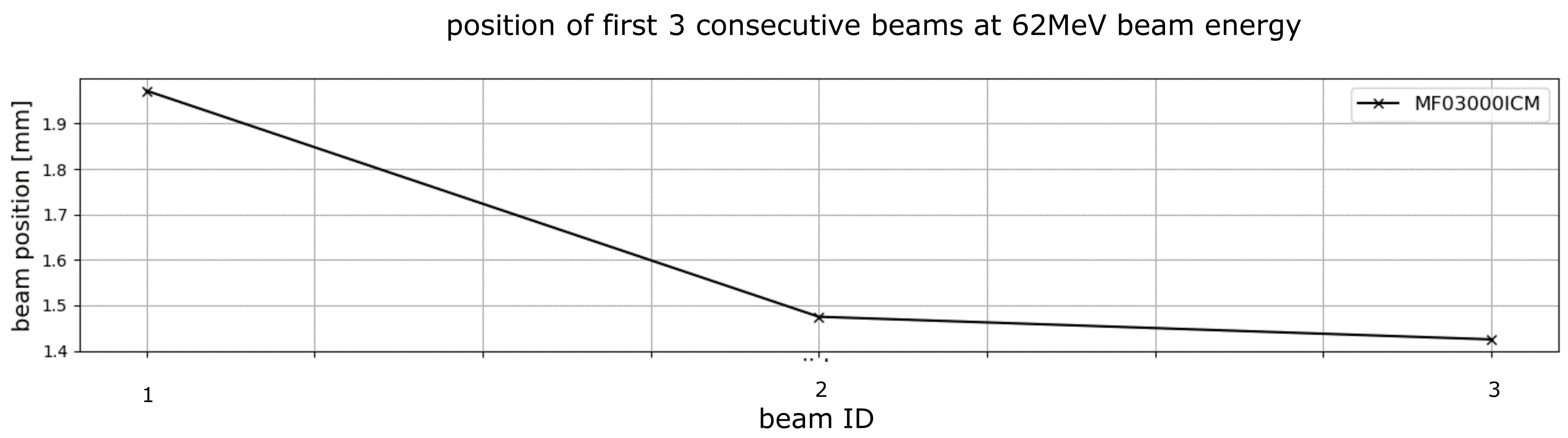


Direct measurement of the magnetic field of the synchrotron dipoles. After the current has reached the setpoint, the magnetic field needs ~2 seconds to stabilize at flat top.

BEAM COMMISSIONING

CROSS TALKING: SYNCHROTRON AND HEBT MAGNETS

“First beam” issue: after changing the beam energy, the 1st beam has a different position in the irradiation room with respect to the following beams 2nd, 3rd…



A (long) investigation, pointed out the cause of the issue being the interference between the magnetic fields of a synchrotron dipole and a magnetic septa dipole of the extraction line.

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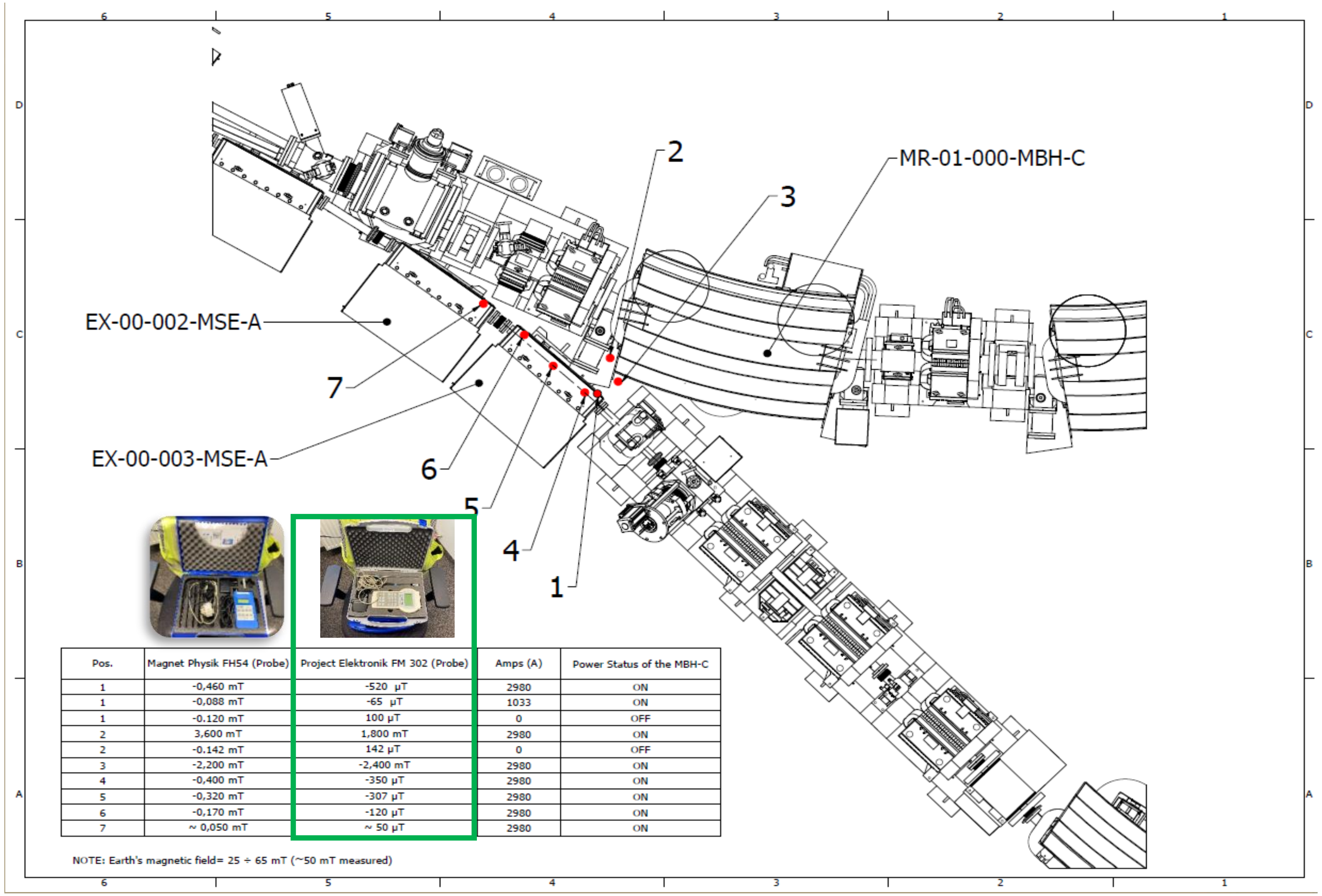
CROSS TALKING: SYNCHROTRON AND HEBT MAGNETS



Pos.	Magnet Physik FH54 (Probe)	Project Elektronik FM 302 (Probe)	Amps (A)	Power Status of the MBH-C
1	-0,460 mT	-520 µT	2980	ON
1	-0,088 mT	-65 µT	1033	ON
1	-0.120 mT	100 µT	0	OFF
2	3,600 mT	1,800 mT	2980	ON
2	-0.142 mT	142 µT	0	OFF
3	-2,200 mT	-2,400 mT	2980	ON
4	-0,400 mT	-350 µT	2980	ON
5	-0,320 mT	-307 µT	2980	ON
6	-0,170 mT	-120 µT	2980	ON
7	~ 0,050 mT	~ 50 µT	2980	ON

NOTE: Earth's magnetic field= 25 ÷ 65 mT (~50 mT measured)

One of the countermeasures tested: shielding the MSE dipole from the MBH dipole.

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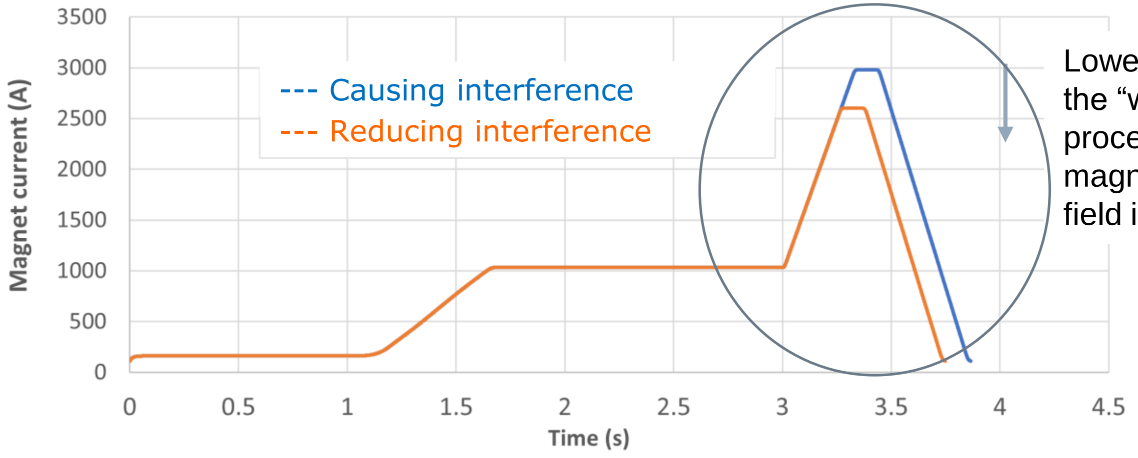
CROSS TALKING: SYNCHROTRON AND HEBT MAGNETS

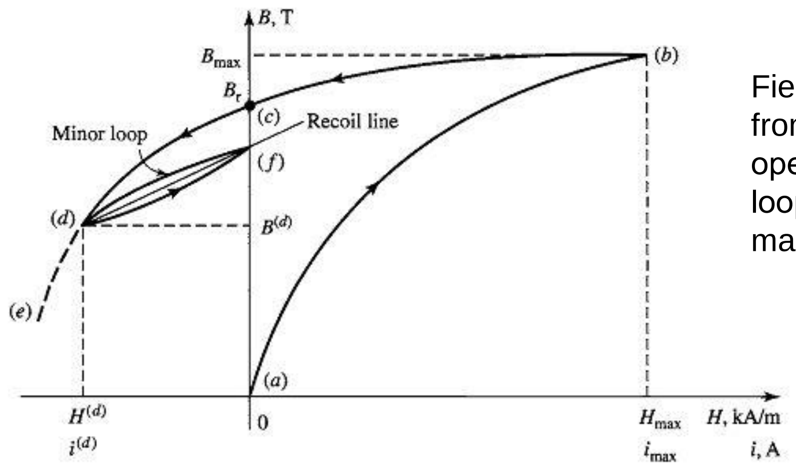
Conclusions: the ramping up “washing” procedure of the main ring dipoles interferes with the magnetization of the magnetic septa, opening a “minor loop” in its hysteresis curve and causing the first beam position to be different to the following beams.

Synchrotron dipole MBH 1



Lowered the peak of the “washing” procedure on first magnet to reduce field interference.

Magnetic septa MSE 2



Field interference from first magnet opens a “minor loop” on second magnet

The changes in magnetic septa MSE field are very small (up to 500 uT with a Δkick ~20 urad) but noticeable in the irradiation room. The solution was to reduce the current peak of the “washing” for the synchrotron dipoles MBH, that reduced the “first” beam issue to an acceptable level.

TACHG52099, #18919, #19696, #21003, #21179

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HISTORY EFFECTS

History effects occur when the magnetic field of a magnet varies depending on the immediately preceding “history” of the magnet current and how the current setpoint is approached.

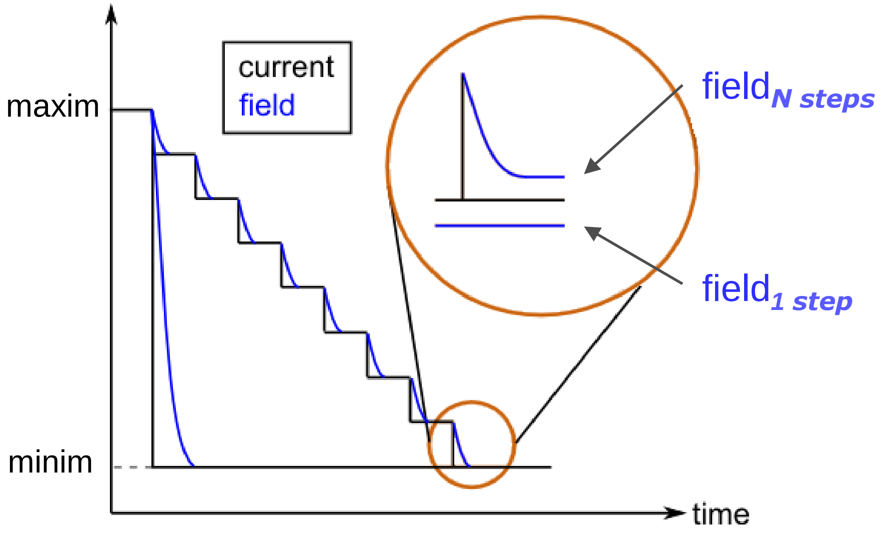

Figure. In both cases, the final set point is identical in current but the magnetic field is different between 1 step or N steps.

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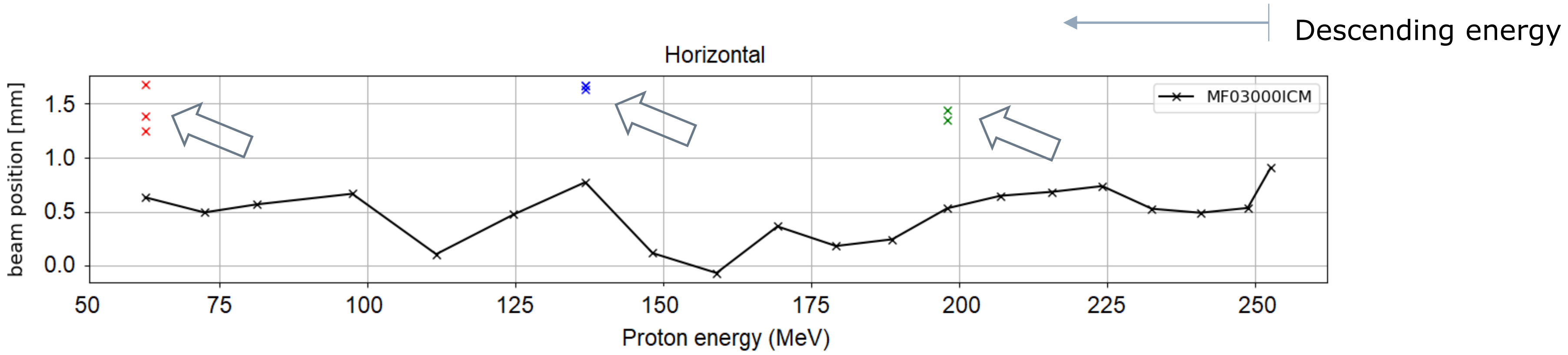
HISTORY EFFECTS

Example of history effects measured with beam: the beam position in the irradiation room while decreasing from maximum to minimum current in 20 steps or in 3 single steps.



History effects are most likely due to eddy currents that are developing differently in different ramping scenarios and influencing the path on the hysteresis curve.

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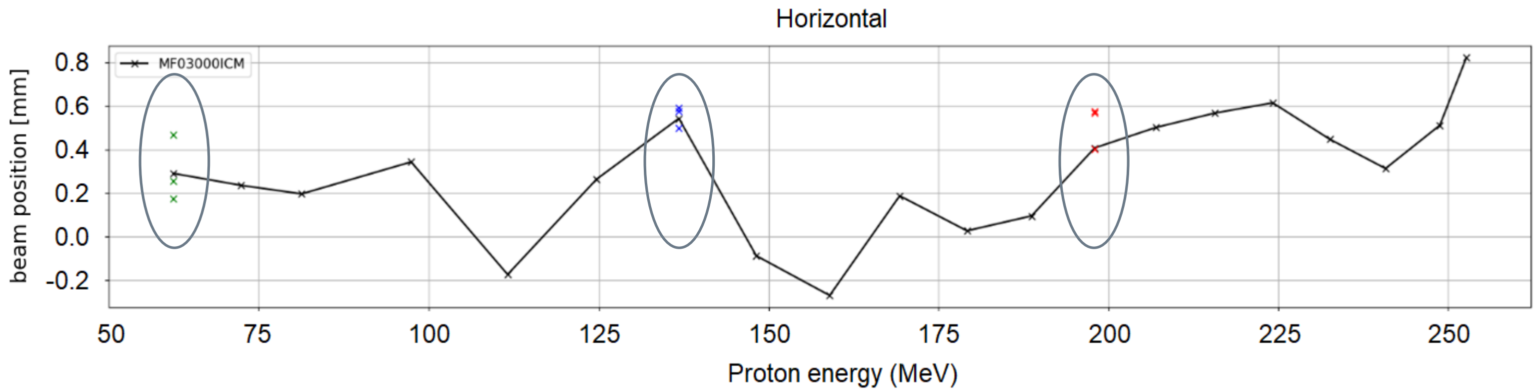
Thus, the most effective way to mitigate history effects is to reduce* the magnets current ramp rates.



History effects mitigated by varying the current ramp rates of dipoles.

History effects should be characterized, e.g. for large dipoles, by magnetic measurements before installing the magnet into the beam line.

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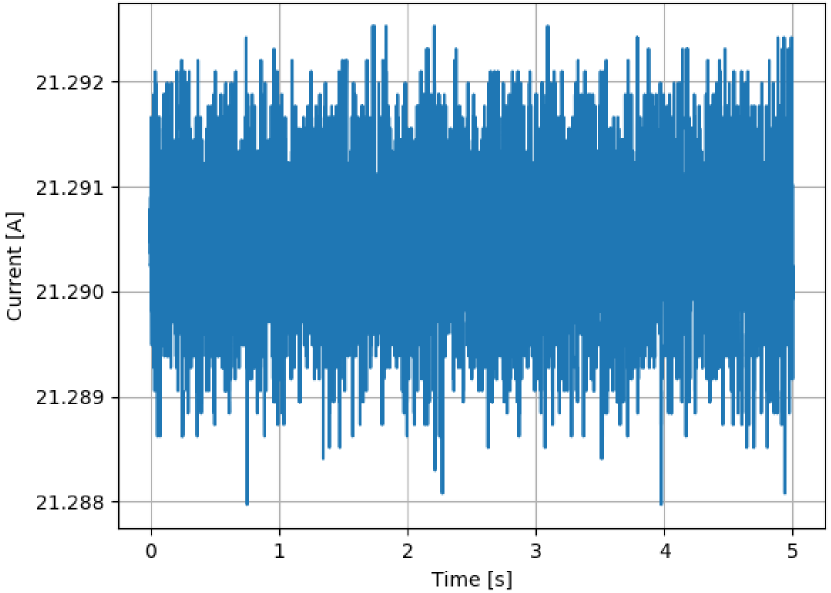
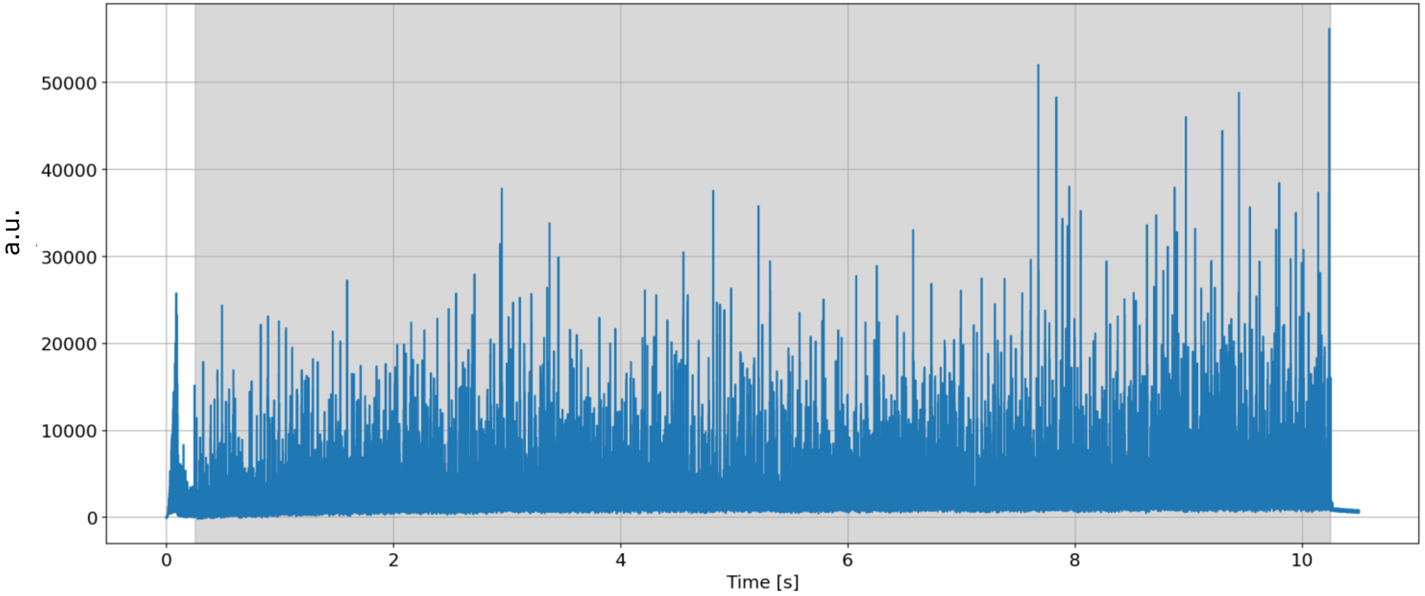
BEAM INTENSITY RIPPLES

Ripples in the power converters of the synchrotron magnets generate ripples in beam intensity through the extraction process, causing a relative motion in tune between the beam and the extraction resonance.

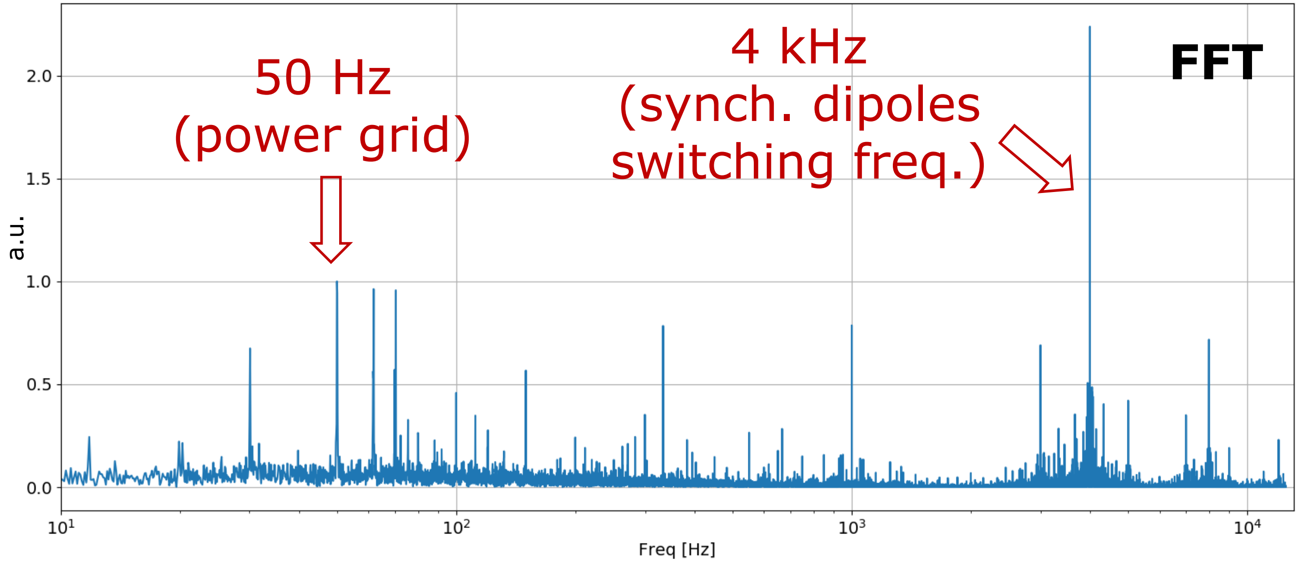
Magnets current ripples

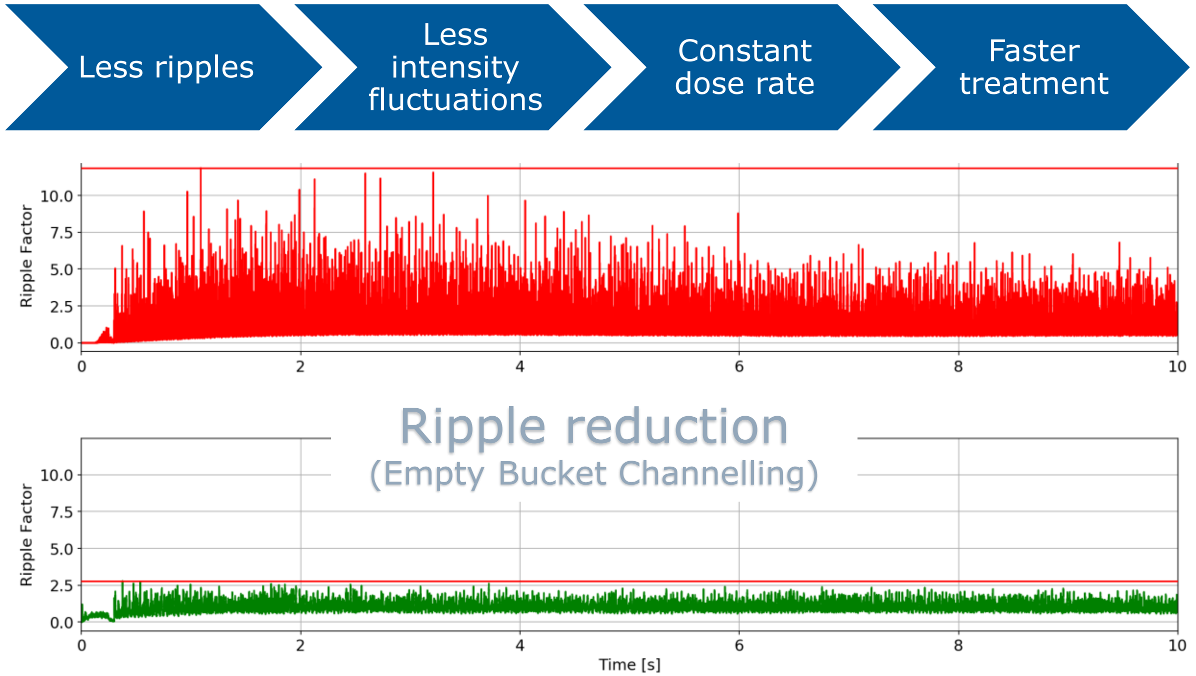


Intensity ripples of the extracted beam



The Fast Fourier Transform of the measured extracted beam intensity reveals the operating frequencies of the synchrotron magnets’ power converters.





Reducing the intensity ripples allows for faster treatment time.

courtesy of Florian Kühteubl, Fabien Plassard

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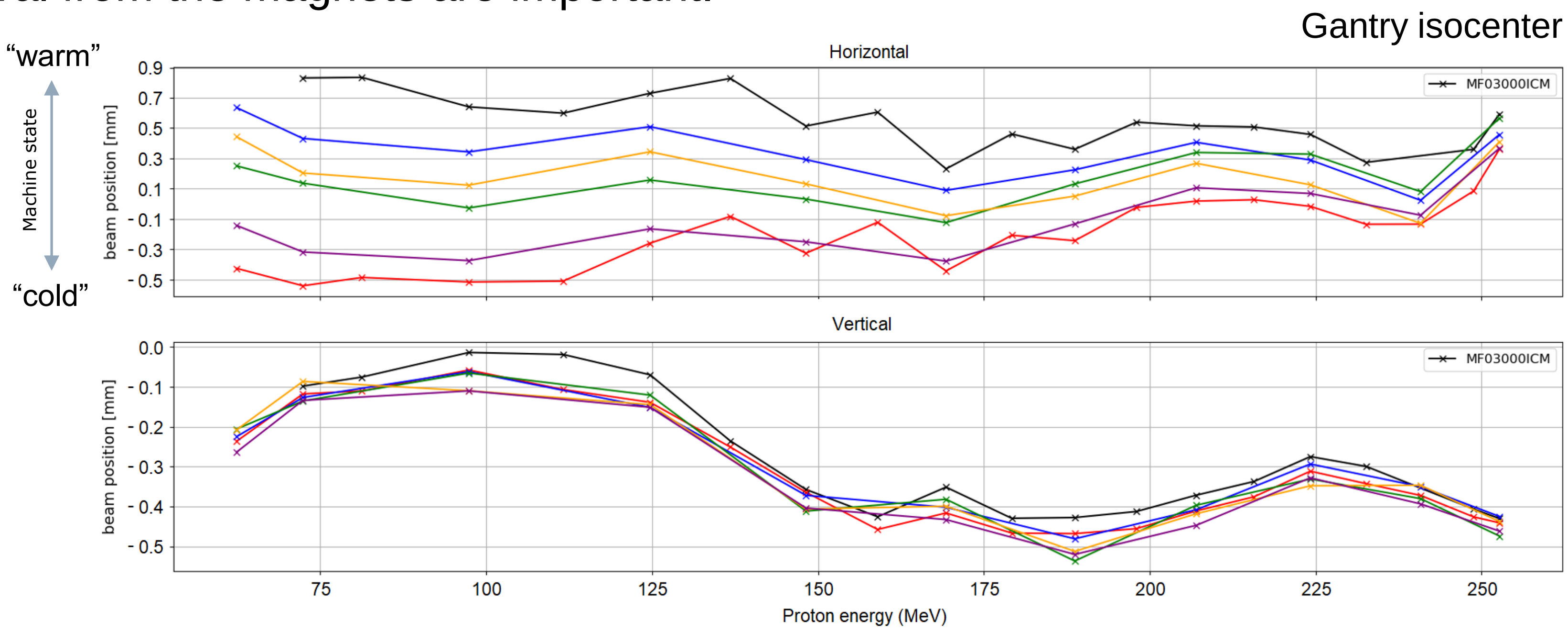
THERMAL EFFECTS

The magnetic field might be affected by the temperature of the magnet. Proper cooling and heat removal from the magnets are important.



We observed a significant beam position offset in the horizontal plane. The lower the beam energy the larger the offset.

1983 —2023 years
The CERN Accelerator School

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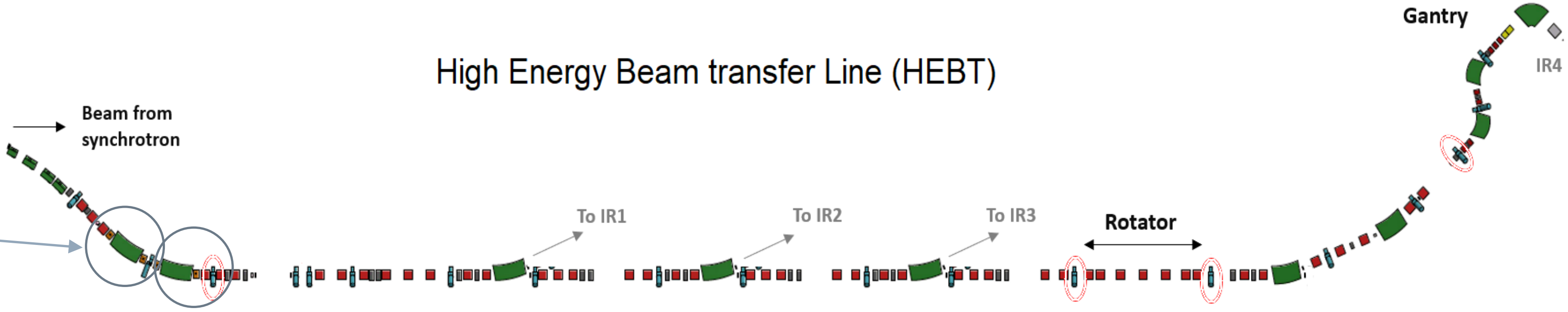
THERMAL EFFECTS

Following an investigation, our conclusion is that the beam position offset is linked to a heating up and inadequate cooling of some HEBT dipole magnets.



Optics simulations pin pointed to two dipoles. Then, applied changes to two suspected dipoles:

- The cooling water flow of two dipoles was unbalanced and it was readjusted.
- The colling water temperature was lowered by 1 degree to 17.8º.

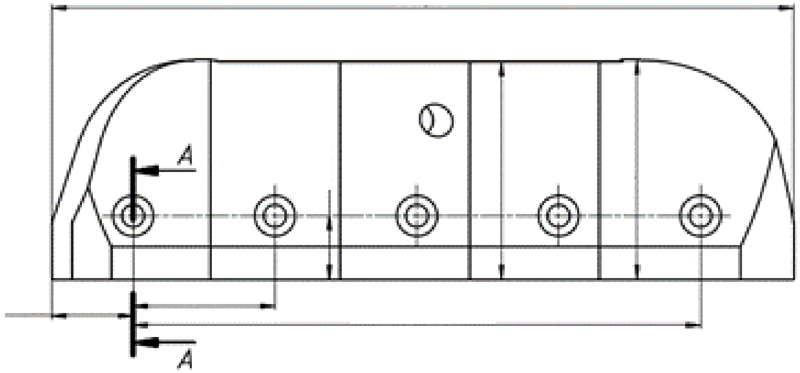
After these two changes, the beam offset was significantly reduced.

SYNCHROTRON SHIMS INCIDENT 2016

- Sept 2016:
  - **suddenly significant beam losses** in the main ring
  - root cause identification: shims detaching
- Oct 2016: preparation and planning for a solution
  - implementation
- Nov 2016:
  - implementation: opening up every of the 16 dipoles, removal and installation of coils, closing
  - Main Ring and HEBT beam re-commissioning
- Dec 2016: **first patient treatment**

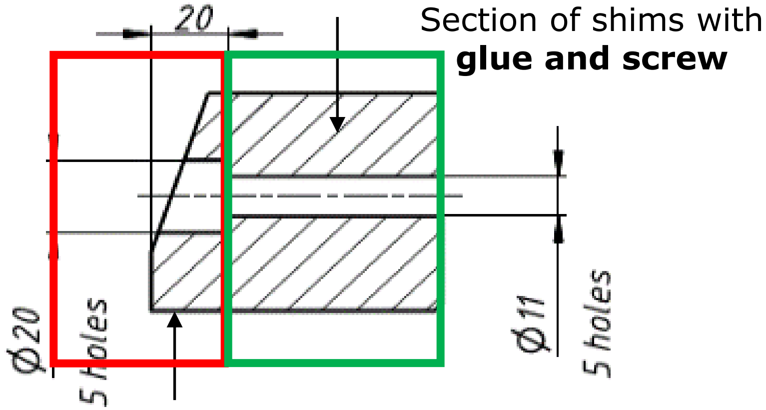
CERN played a key role in solving the issue

SYNCHROTRON SHIMS INCIDENT 2016



Every main ring dipole magnets have shims on both ends of both yokes

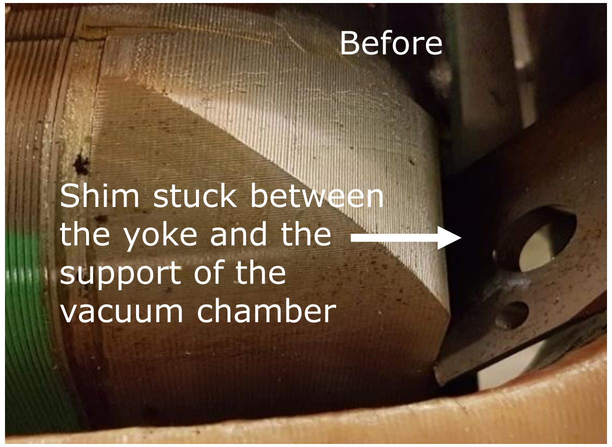
Each shim is divided into 5 blocks

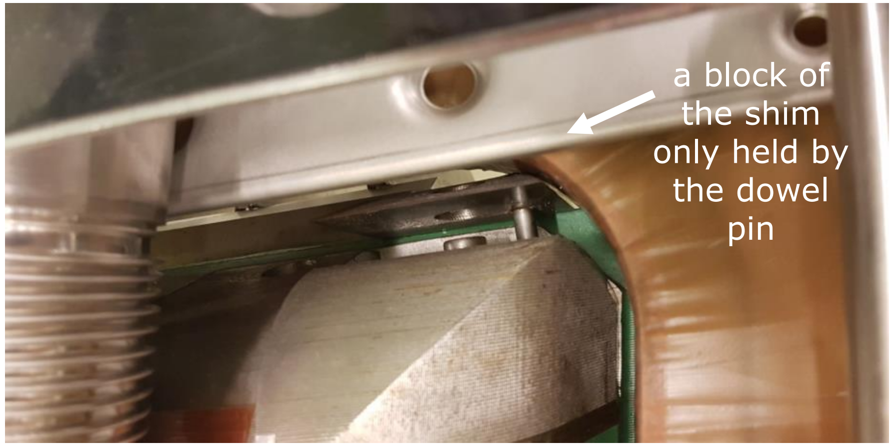


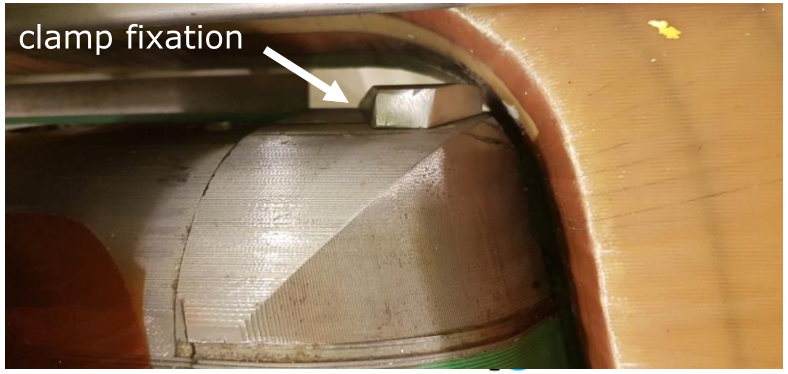
Section of shims **only glued** together

For all broken shims the same root cause:

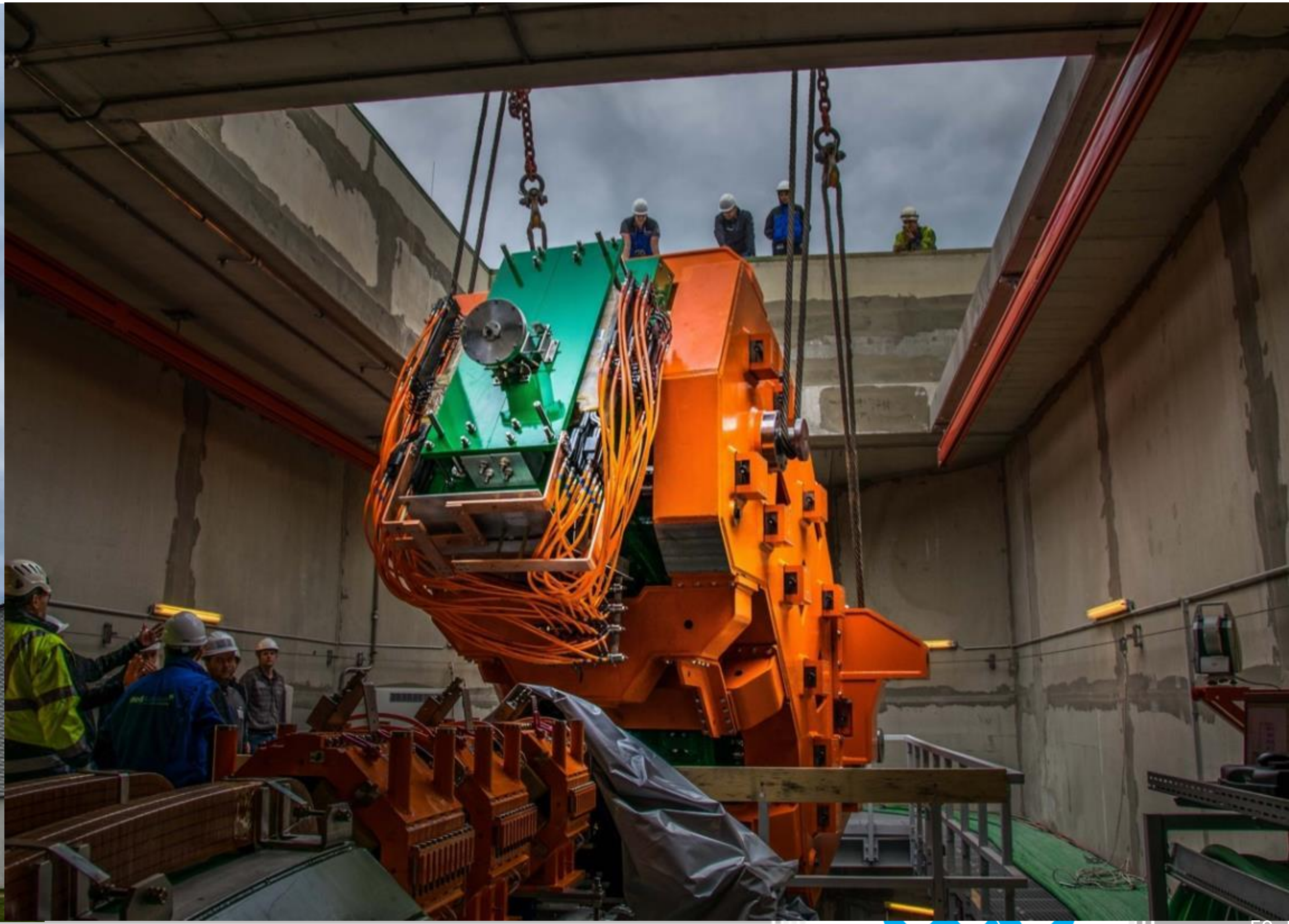
- The screw is only fixing the laminations with a hole of 11 mm.
- The laminations with the counterbore of 20 mm were only held by the epoxy glue.
- The 1.5 Tesla field caused a too high stress for the glued connection.







VERTICAL BEAM LINE – "THE DIPOLE"



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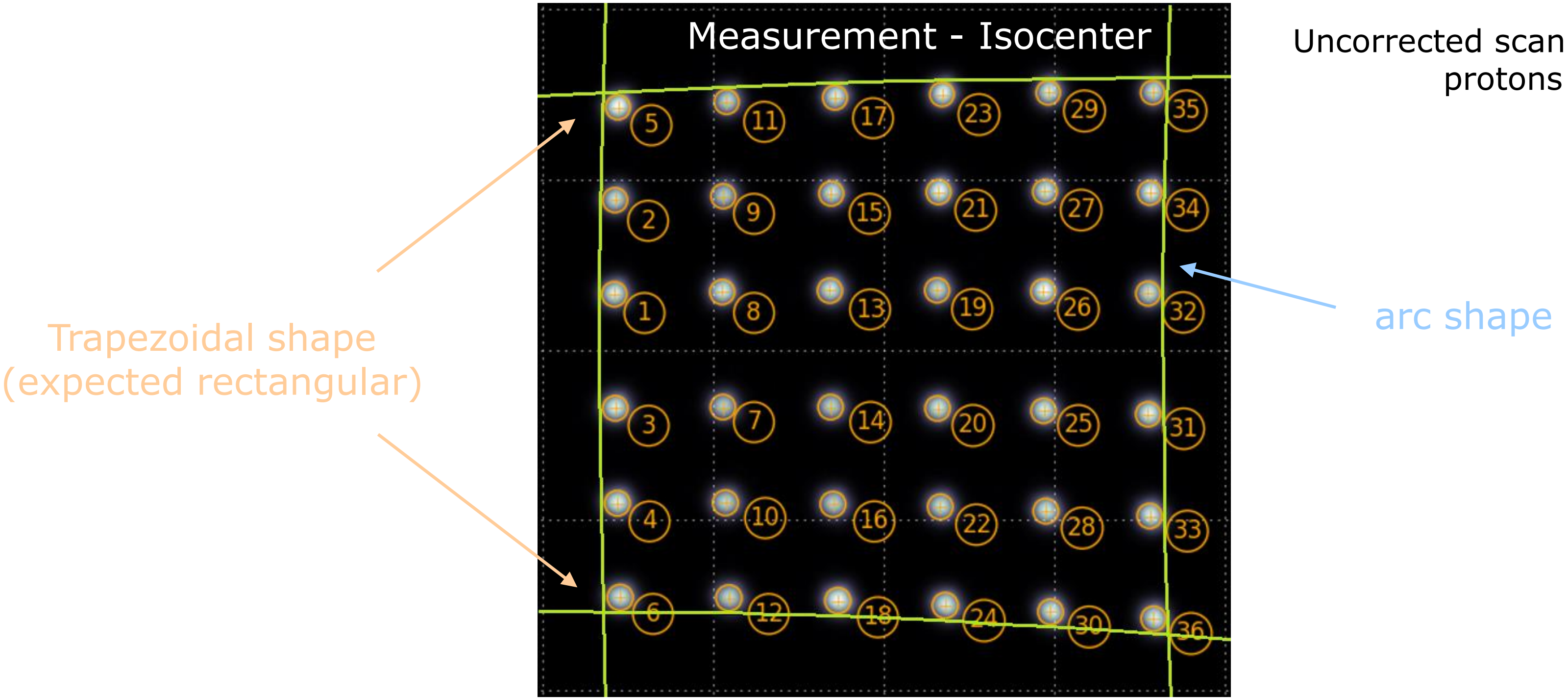
IRRADIATION FIELD DEFORMATION

- Upstream scanning magnets are turned ON: the beam as measured downstream of the Vertical beam line (large) 90º dipole at the room isocenter is deformed in a trapezoidal shape.



Uncorrected scanning irradiation field
protons 252.7MeV

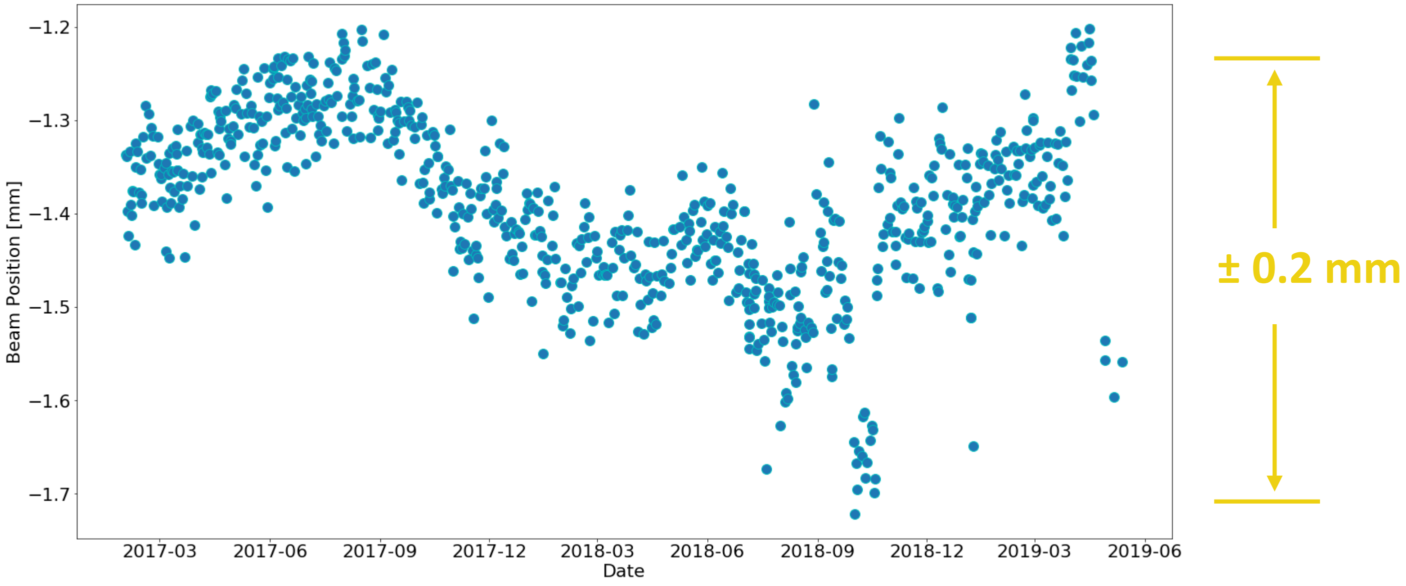
by courtesy of Ivan Strasik

Responsible of the field deformation are the sextupolar component and the fringe fields of the 90º dipole.

OPERATIONS: STABILITY AND REPRODUCIBILITY

High machine stability:

- Rigorous internal process for changes implementation
- Magnetization cycles & field stabilization under control
- 2 x Quality Assurance daily



Protons: beam position monitored > 2 years: ±0.2mm

© MedAustron - Mauro Pivi

SUMMARY & OUTLOOK

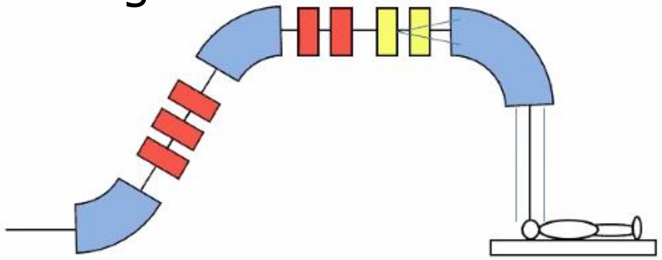
An overview of particle accelerators for medical applications and the MedAustron experience and lesson learned bringing magnets from concept to operation.

Outlook:

- B-field regulation in the synchrotron: increase field accuracy, reduce time for field stabilization and potentially reduce washing
- Multi-energy extraction: magnetic field control important
- Superconducting magnets accelerator/gantry to reduce the beam line footprint

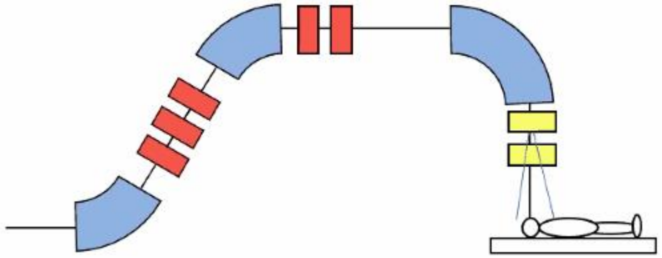
SCANNING MAGNETS LOCATION

Upstream scanning



- **Large aperture dipole: weight and power consumption**
- **Parallel scanning**
- **Reduced radius of gantry for same irradiation field**

Downstream scanning



- **Large gantry radius and large room size**
- **Small aperture dipole and vacuum chamber**

by courtesy of Marco Pullia, CNAO