Requirements on small machines

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thanks to EBG MedAustron colleagues and the CERN magnet/ BTS experts

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OUTLINE

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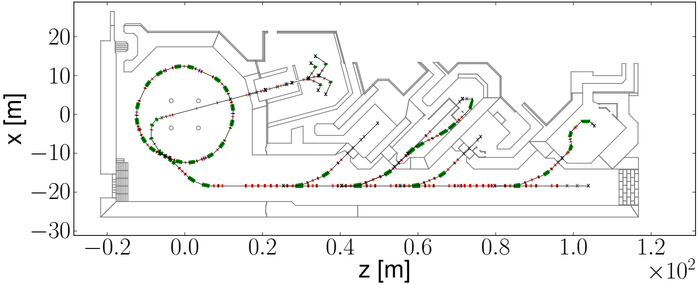
What is special about small machines?

Small but beautiful

EBG MedAustron



- Synchrotron based hadron therapy center
- Based on CERN-PIMMS & technical implementation by CNAO
- Accelerator developed under the guidance of / at CERN

  → incl. e.g. magnet design & magnetic measurements.
- Currently in the MEBT beam commissioning phase

Small machine specialties 1

- Often green-field facilities - little or no expertise
  - Staff learned previously on other types of machines

    $\rightarrow$ "wrong" specifications
  - Experts are only needed for some time and then move on
  - 24/7/365 operation with only rudimentary trained staff
- Very small optics team
  - No time for detailed studies
  - Once machine is set up, it must run maintenance free without experts
- Uptime requirements: $> 95\%$ @ 24/7/340

  e.g. uninterrupted patient treatment
- Even less money, time, non-accelerator environment, ...

Small machine specialties 2

- Machines very densely packed
  - MedAustron synchrotron: 111 elements in 80m circumference
  - Elements influence each other
- Design and construction phase often overlapping
  - Some magnet parameters must be frozen before they are designed
- Some machines do not "care" about some emittance growth
- Multi-turn injections with design-60%-loss
  - Communication to injector guys who talk about 98%emittance...
- Many different cycles $\rightarrow$ automated cycle building

Small machines specialties 3

- Low energy $\rightarrow$ Short magnets with large aperture
- Slow resonant extraction $\rightarrow$ large horizontal aperture
- Large bending angles with small radius e.g. 90°, r = 1.5m
- Large edge-angles e.g. 23°
- Special magnets like betatron core, rotating elements...
- Off-momentum operation $\rightarrow$ beam not centered in dispersive regions!

  MedAustron: $\frac{\Delta p}{p}|_{center} = 3.5 \cdot 10^{-3} \rightarrow \Delta x = 2.8cm$

Small machine specialties 4

- "Large" number of different magnets but in small quantities
  - No real "series production"
  - e.g. MedAustron: 400 magnets, 52 different magnet types!
  - $\rightarrow$ try to use same laminations for different types
- Outsourcing to industry (partially including magnetic field measurements)

Requirement finding

Actually, it's quite basic

Requirement finding

- Analytical considerations (e.g. orbit, tune shift)
- Particle tracking studies
- Find out what's possible and design the machine accordingly
- See what other comparable machines required

Dipoles 1

- Field uniformity between dipoles:
  - Tolerances are set to what is feasible and then correctors are added as required by simulated orbit excursions.
  - HIT powers each dipole individually
- Field uniformity within individual dipoles:
  - Given by the slow resonant extraction
  - Preservation of spiral step from electric to at magnetic extraction septum.
  - MedAustron: For $\Delta B/B = \pm 2 \cdot 10^{-4} \rightarrow$ the trajectory is shifted by 1 mm reducing the gap at the magnetic extraction septum

Dipoles 2 - Eddy currents

Case:

- Magnet laminations: 1.5 mm
- Vacuum chamber thickness: 0.3 mm
- $\dot{B}$: 3 T/s
- Field level: Injection: 7 MeV/u $=$ 0.18 T

Effect:

- Field delays $\tau = 95\mu$s $\rightarrow$ B-train (during the resonant extraction wanted!)
- Nonlinearities: $\Delta B/B = 1.8 \cdot 10^{-3}$

MedAustron:

- Laminations: 1mm; Vacuum chamber: 0.4mm corrugated Inconell
- Particle tracking studies showed no effects for much thicker chambers...

Gradient uniformity within individual quadrupoles

- Distortion of the working line in the tune diagram.
  - Requirement: $\Delta Q < \pm 0.00075$ in either plane. (together with other errors, $\Delta Q = \pm 0.001$)
  - $\rightarrow \Delta(GL)/(GL) = \pm 5 \cdot 10{-}4$
- Stability of the extraction separatrix
  - $\mu_{x,MXR \rightarrow ESE} \rightarrow \alpha_{beamatESE}$
  - Separatrix angle change of 0.1 mrad $\approx$ 1%beam loss on the septum wires.

$\rightarrow$ in practice: fine tune for optimal performance

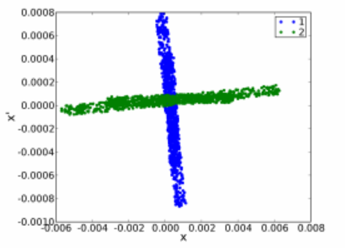
$\rightarrow$ on the other hand: at MedAustron, the lattice tune defines the extraction energy...

HEBT: “Bar of charge“ - error study

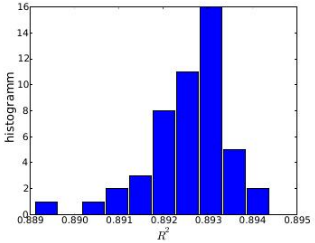
What is the figure of merit of the impact of field distortions on the horizontal phase-space of a slow resonantly extracted beam?

→ the R^2 of a line fit to it.

Bar of charge in H-phase space

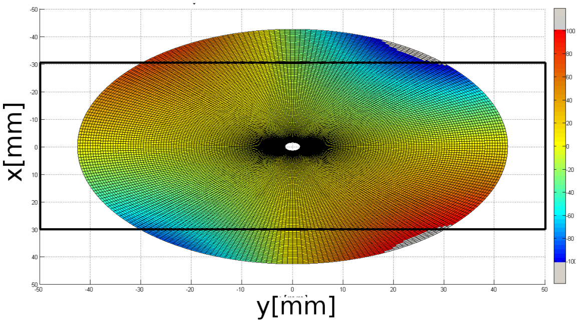


Simulation output: R^2 of line fit



Field quality measurement data representation

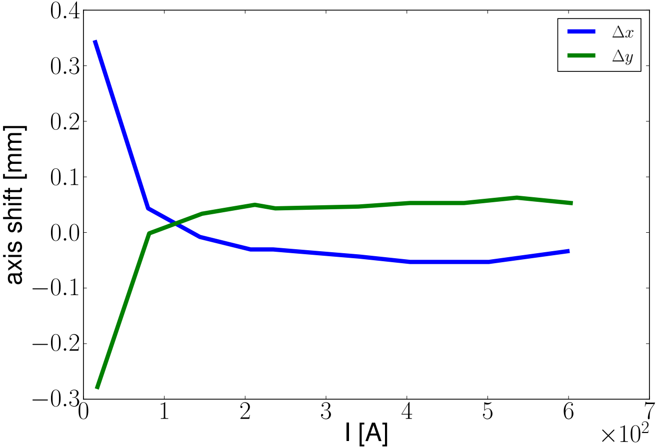
- Harmonic coefficients examples: see later
- 2D plot of $\Delta B/B$



Practical examples

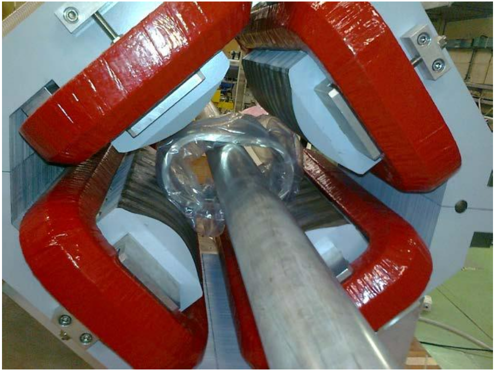
What we have encountered so far...

Quadrupoles: Systematic shift of the magnetic axis



Usually, simulations assume Gaussian distributed errors

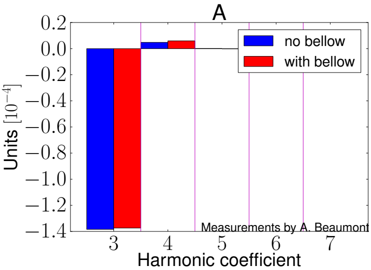
Space constraint: Bellows in Quadrupoles

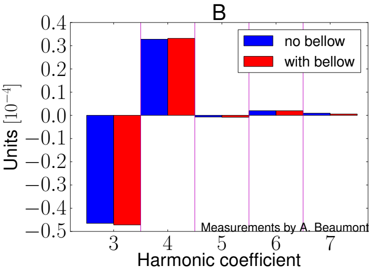


Also: BPM in resonant sextupole ("fast" ramping)

Space constraint: Bellows in Quadrupoles (measurements)

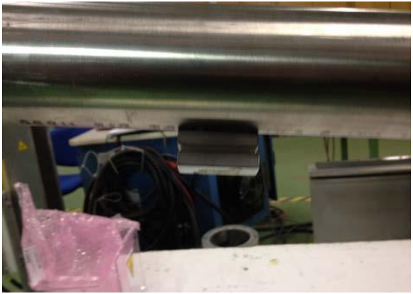
MedAustron performed field quality comparison studies for with/without bellow.





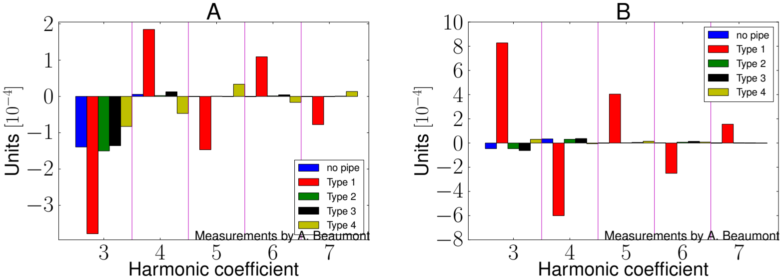
$\rightarrow$ luckily no effect (in DC..)

Vacuum pipe welding technology



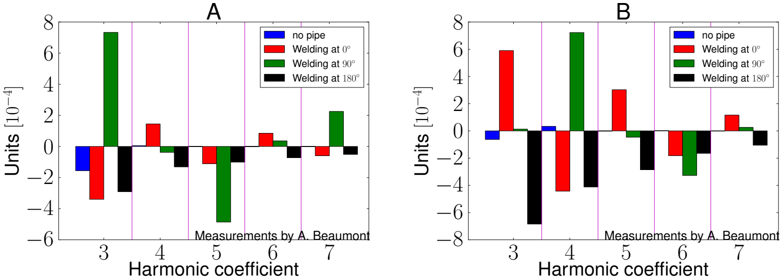
- Permanent magnet shows significantly magnetic properties at one position on the ring over it full length
- Location of the weld difficult to detect visually.

Choice of vacuum pipe welding technology



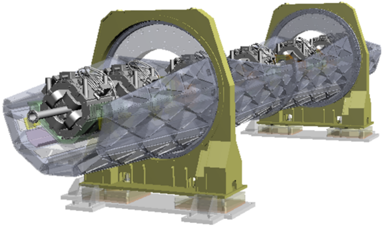
Field quality degraded by up to a factor 23!

Vacuum pipe welding: At which angle to put it?



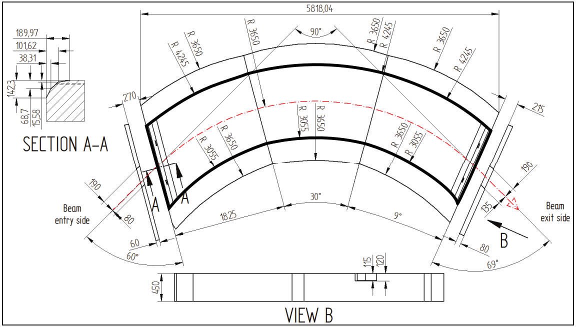
→ The angular location of the weld does have quite an impact...

Rotator



- Can the magnet be turned without loss of field quality, moving magnet axis center?
- Field measurements performed for the different angles

Large angle dipoles

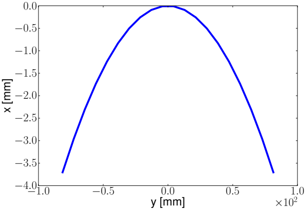


- $\alpha = 90°$
- $\rho = 3.65$ m
- e1 = 30°, e2 = 21°
- Aperture: 20 x 20 cm x cm
- B = 1.8 T

Large angle magnets continued

- Optics model: Quad - Dipole - Quad
- Inherent nonlinearities & coupling
  - Very large beam off-sets due to beam scanning
  - Quadrupole powered in series with scanning magnet (like PSI - gantry 2)
  - MAD-X 2nd order, other simulation programs completely fail...
- How to compare to magnet designer tracking?
- No dedicated vacuum chamber
- And then we drill a hole into the yoke....

(for X-ray "beam eye view", PSI - gantry 2)



Some more...

- Magnetic septa
  - Stray field measured where circulating one is
  - MedAustron: ramps while beam is already circulating in synchrotron...
- Coating of ceramic chambers in fast pulsed magnets magnets
  - Why in low intensity machines? (charging up). Coating specs?
  - Impact on rise time?
- Solenoid: (first iteration): only had two alignment target holders....
- Betatron core (Induction acceleration for driving the beam into the resonance)
  - Beam must not see any magnetic field
  - Power converter control loop on induced voltage of pick-up coil
- Insulate chambers on one side? Grounding of them?

Summary

- Do not under-estimate small machines
- Simulations always assume a sum of all effects! e.g. incl alignment, incl vacuum chambers...
- Extend to: "beam meets vacuum chamber meets magnets"...
- There must be a common understanding and very close communication!

Acknowledgements

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  - M. Benedikt
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