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Wir schaffen Wissen – heute für morgen

Consequences of fast beam scanning on gantry design

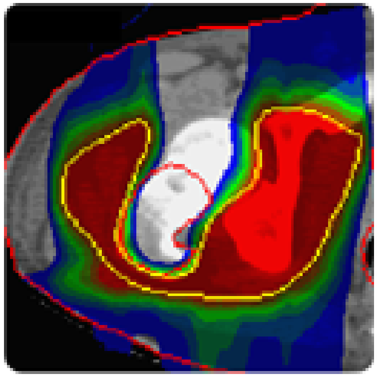
Dr. Serena Psoroulas
Center for Proton Therapy, Paul Scherrer Institut

EUCard-2 meeting: Super Conductivity and other new Developments in Gantry Design for Particle Therapy

Bad Zurzach, Switzerland, 17.09.2015

Convenience

Improved conformity (Intensity Modulated PT)



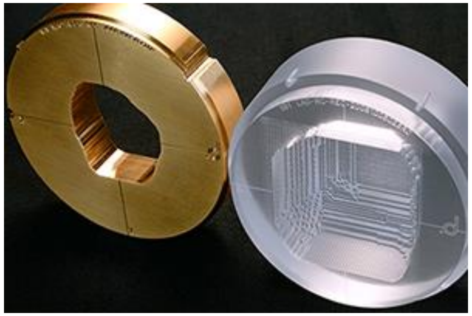
T. Lomax, PSI

Why fast beam scanning?

Safety wrt motion uncertainties

Lower skin dose to patient

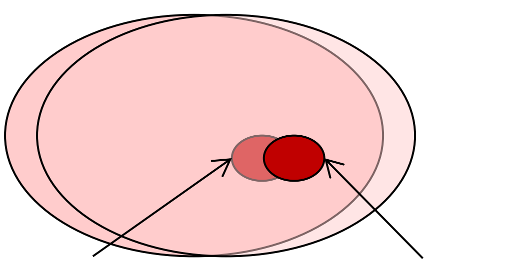
No patient-specific hardware

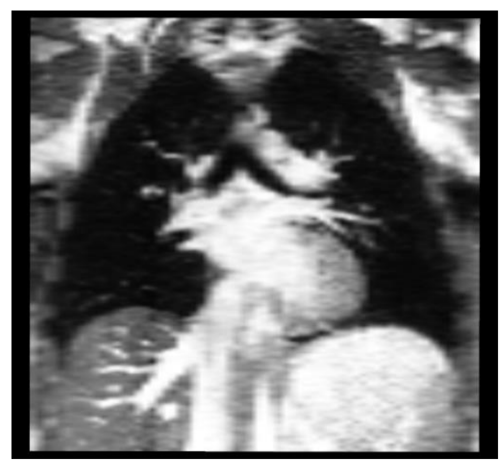


.decimal, Inc.

Why fast beam scanning?

Motion





D. Boye, PSI

Why fast beam scanning?

Convenience:

General reduction of treatment time

Gantry 1	170-45’000 spots/field	1-30 minutes/field
Gantry 2	700-8’000 spots/field	20 s – 1 minute/field

patients’ data

- G1: slow scanning in 1 lateral dimension (dispersive dim.)
- G2: fast scanning in 3-d
  - 11-40 energy layers
  - 100 ms energy-switching

Resilience to motion uncertainty:

Drifts: lower probability due to faster treatment

Periodic motion: flexibility to implement motion mitigation

- Breath-hold
- Rescanning
- Gating

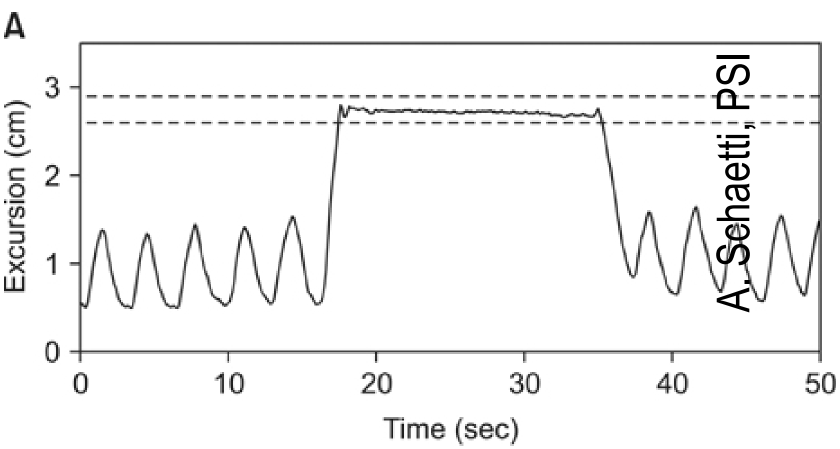
Without large increase in total treatment time

Potential for moving targets with fast scanning

Motion mitigation for periodic motion:

- **Rescanning**: scan target volume repeatedly to avoid interplay
- **Gating**: irradiate only during part of the breathing cycle
- **Breath hold**: irradiate only while the patient is holding his/her breath

In all cases, **time scale is < 20 s!**
Requires fast scanning in all three dimensions (as in G2)



Radiat Oncol J. 2014 Jun;32(2):84-94

Outline

1. **Scanning requirements**

2. **Impact on gantry design**

Magnets for fast scanning

Imaging for online monitoring

3. **Conclusions**

Scanning requirements

Scanning requirements

No single 'recipe'- but there are **general requirements to be fulfilled**

1. **Energy precision and accuracy: < 1%**
2. **Dose precision and accuracy: 2%**
3. **Beam lateral precision and accuracy: < 1 mm**
4. **«Reasonable» time for irradiation**
   - combination of dose rate, machine performance
   - depends also on what you want to treat

Strong correlation with gantry design

Lateral precision and time performance are not independent

- Power supply rise/settling time
- Transient magnetic field effects
- Hysteresis effects and magnet ramps/cycling

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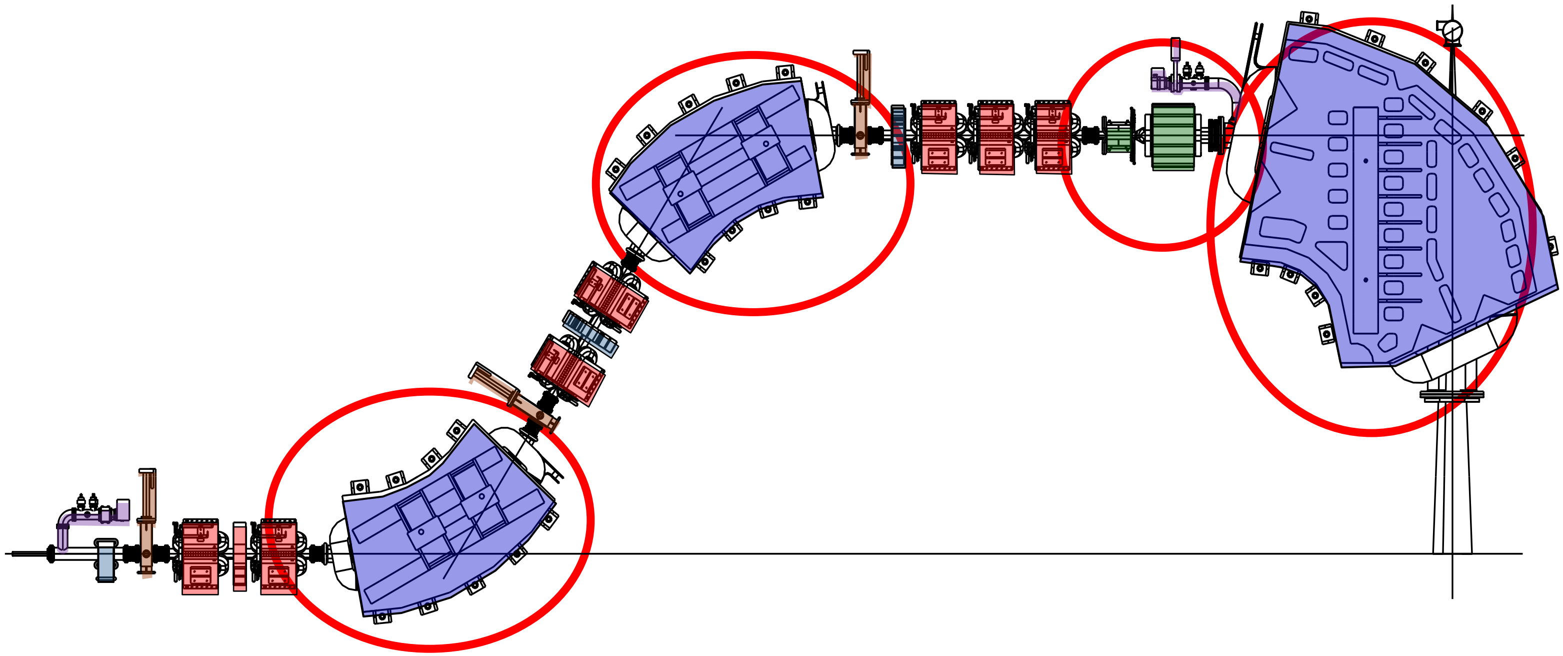
What is the impact on gantry magnets?

1. Scanner magnets
2. Bending magnets

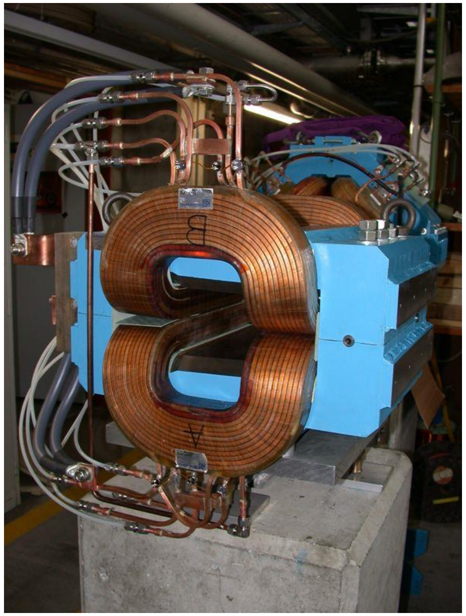


PAUL SCHERRER INSTITUT PSI

How to realize fast beam changes? – Scanner magnets

Fast scanner magnets and control **developed at PSI**

Pictures: PSI magnet section



Dispersive direction:
Max 0.4 T

Transverse direction
Max 0.2 T

Highly dynamic magnet power supply + controller

Künzi, R., & Jenni, F. (2006). Fast Magnet Power Supplies for Dynamic Proton Beam Control for Tumor Treatment

Scanner magnets
Faster scanning in transverse direction

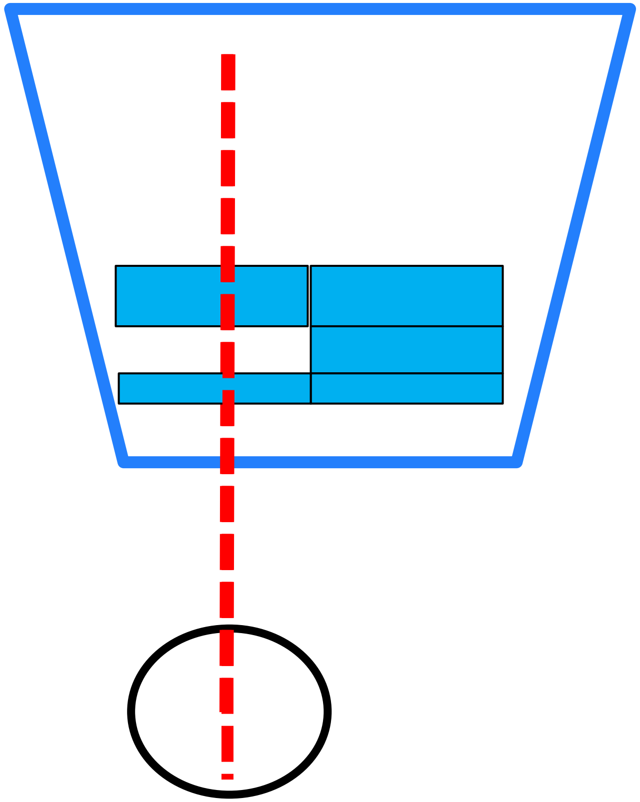
Ferrite core to avoid eddy currents

How to realize fast beam changes? - Energy changes

Energy switching strategy: either **upstream (at or shortly after accelerator) or downstream (gantry nozzle)**

Downstream: Range shifters

- ✚ Fastest energy change (no magnets change required)
- − Beam size and penumbra quickly degraded
- − Higher dose to patient



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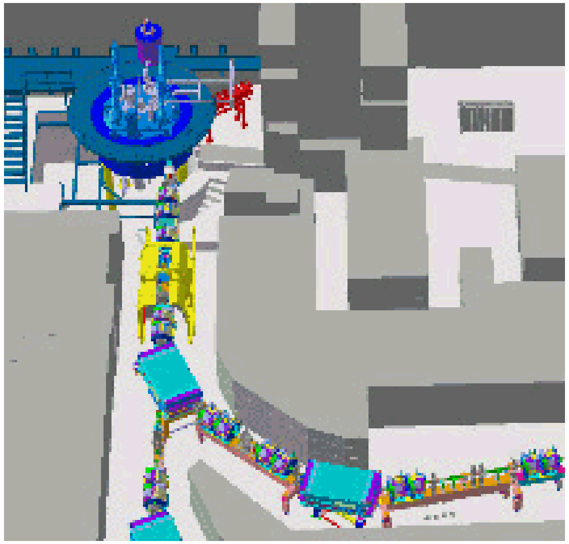

PSI COMET + beamline

Upstream: Cyclotron + ESS

- Degrader system
- − Magnets performance
  - ESS
  - Transport magnets
  - Gantry magnets
- + Beam at isocentre as selected at ESS

How to realize fast beam changes? - Energy changes

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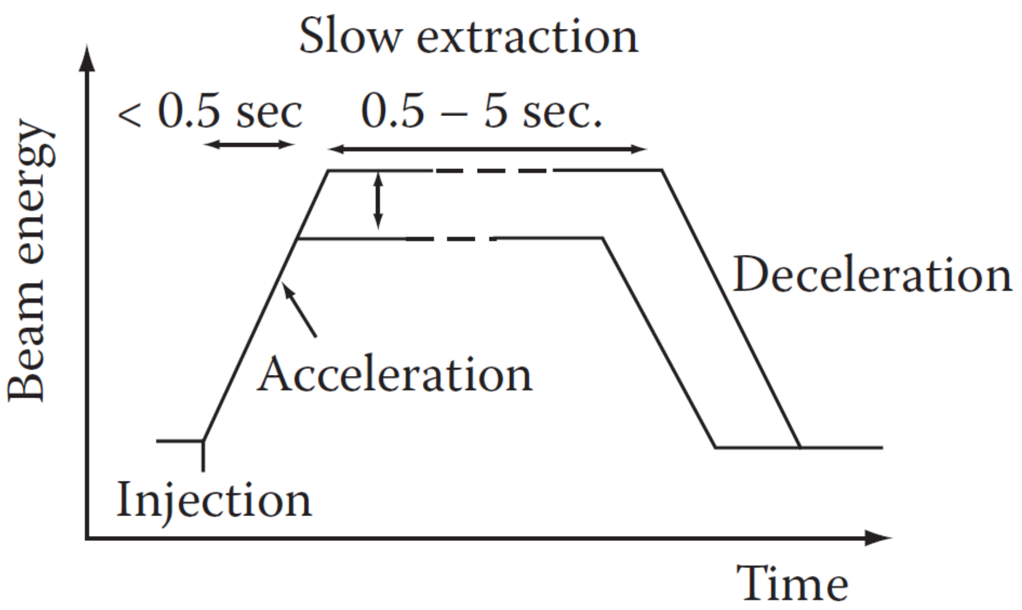

Upstream: Synchrotron

- Accelerator timing is the bottleneck
+ Low number of range shifters
- Limited number of particles/spill

Pictures from M. Schippers, from Paganetti, H. (Ed.). (2011), *Proton Therapy Physics* (eBook - PD). CRC press.

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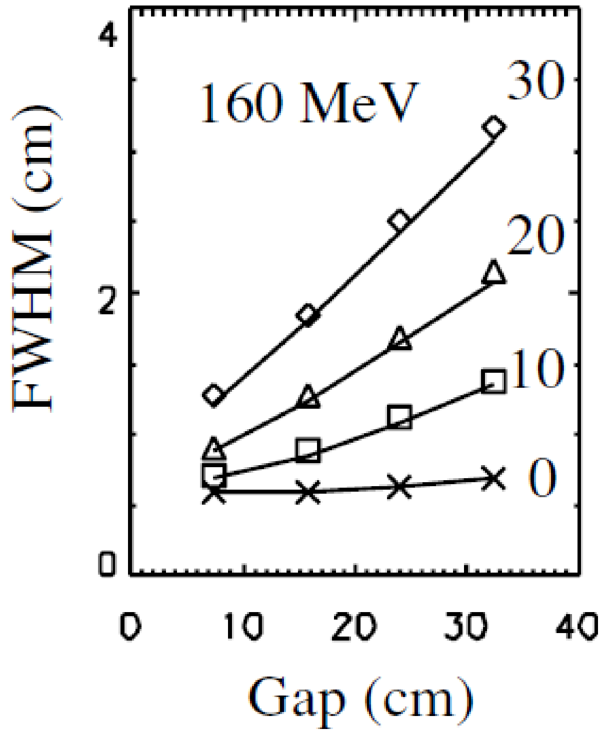
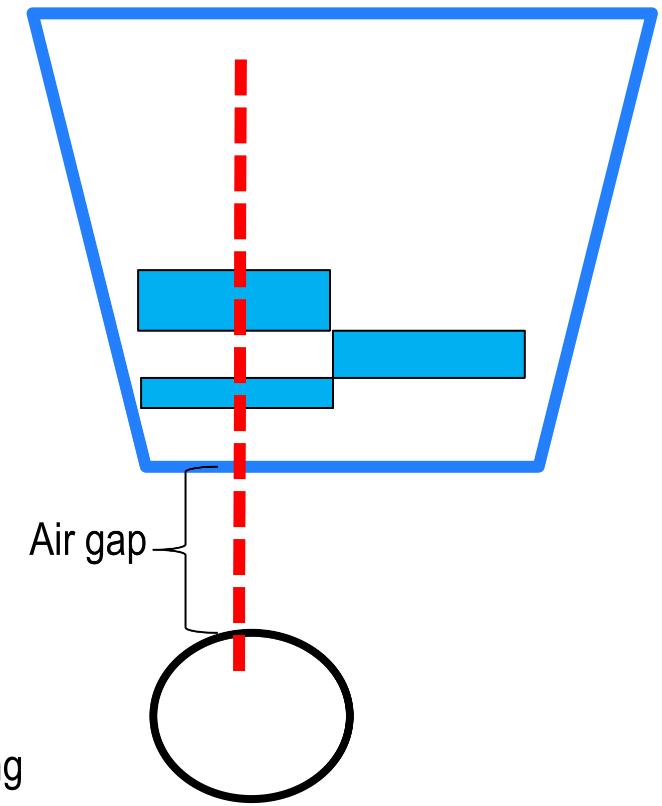
Impact of energy switching strategy at isocentre

Gantry 1



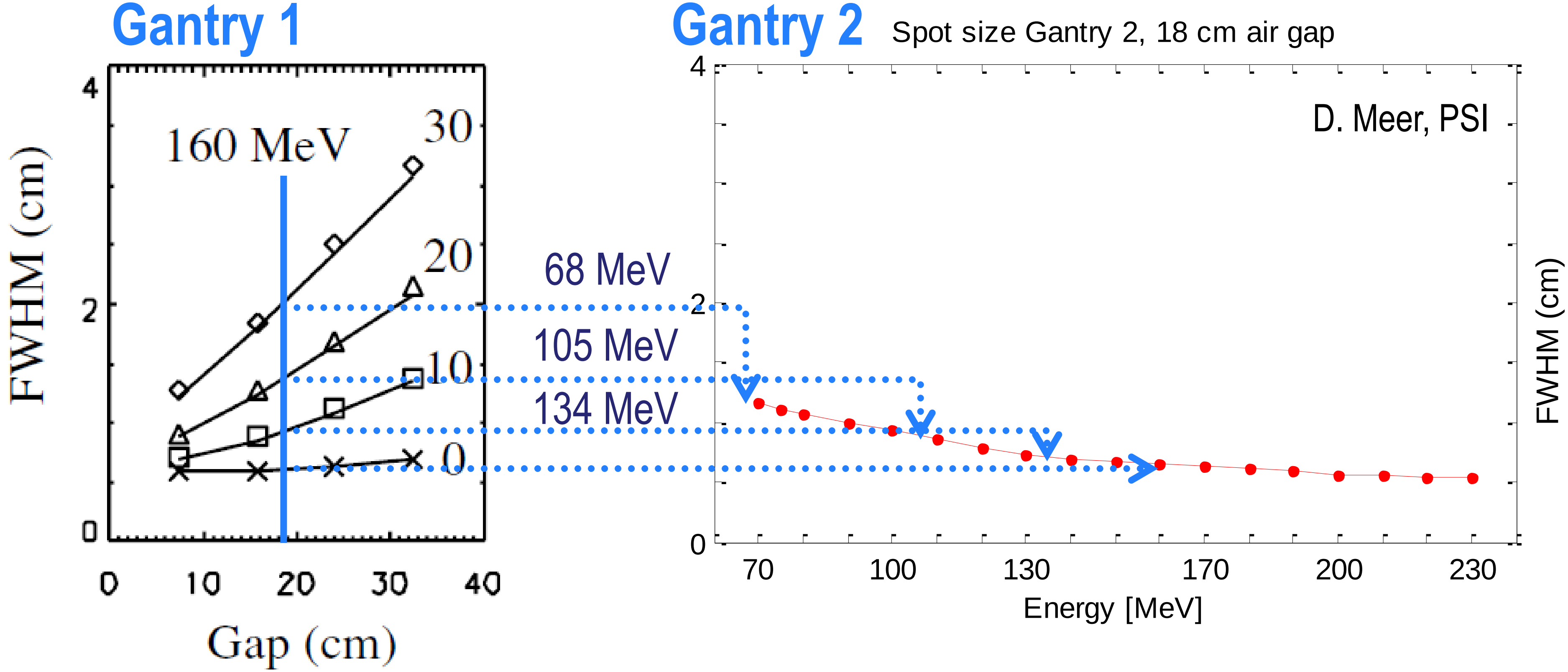
Broadening of the beam width in air due to scattering of the range shifter plates (0, 10, 20, 30: number of range shifter plates) as a function of air gap. From Pedroni et al., 2005



Impact of energy switching strategy at isocentre

Gantry 1

Gantry 2



Broadening of the beam width in air due to scattering of the range shifter plates (0, 10, 20, 30: number of range shifter plates) as a function of air gap. From Pedroni et al., 2005

Beam width in air at iso-center as a function of beam energy

Range shifter = compromise on beam size and penumbra

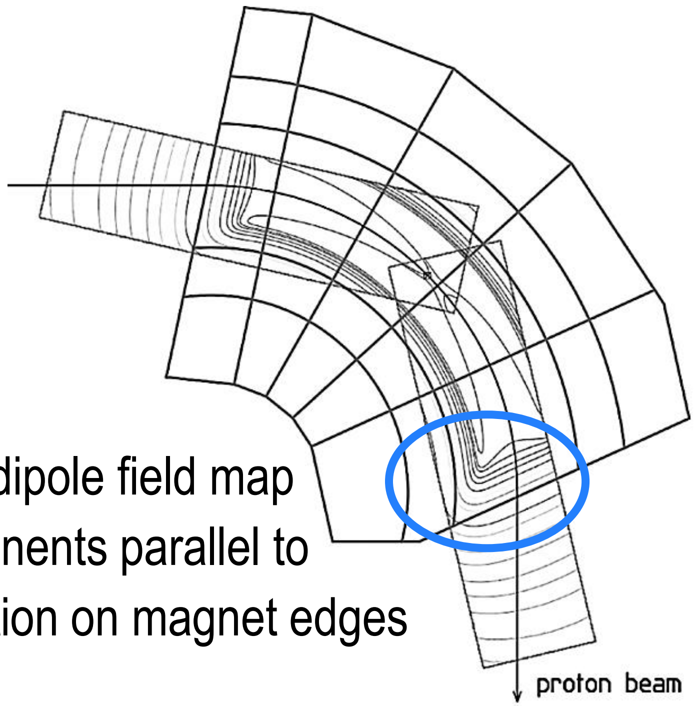
Scanning machines mostly rely on upstream beam changes

How to realize fast beam changes? - Bending magnets

Energy changes = changes in magnetic field = **Eddy currents**

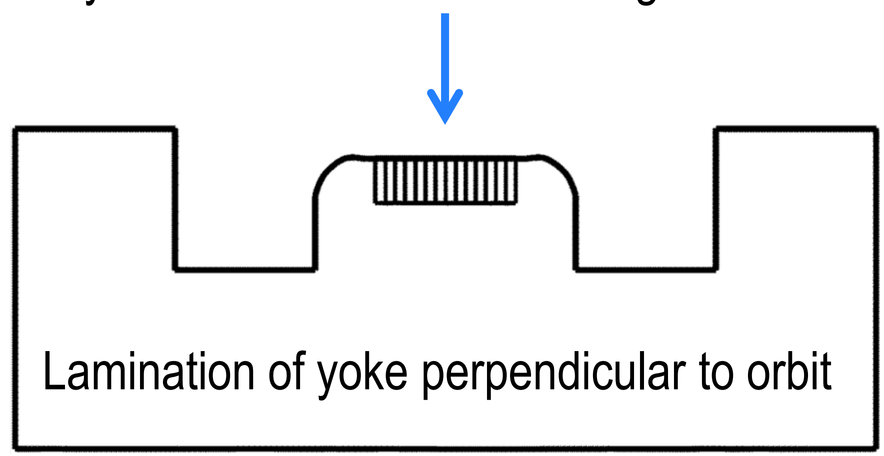
G2 bending magnets: 1.53 T – due to manufacturing constraints

Lamination helps suppressing the effect – up to a limited degree



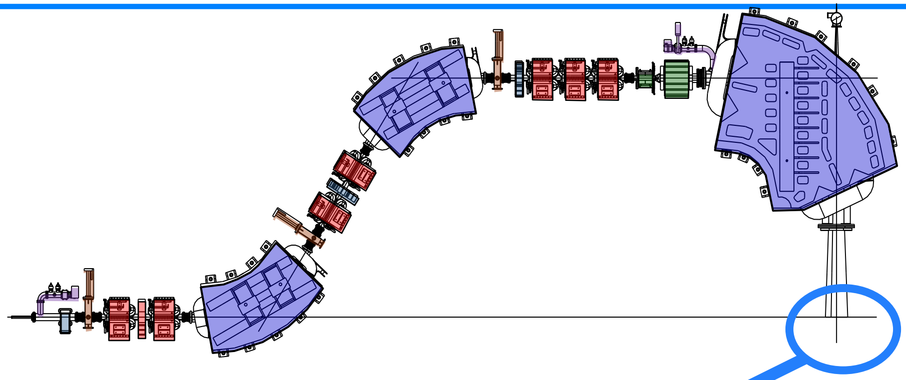
AMF3 dipole field map
Components parallel to lamination on magnet edges

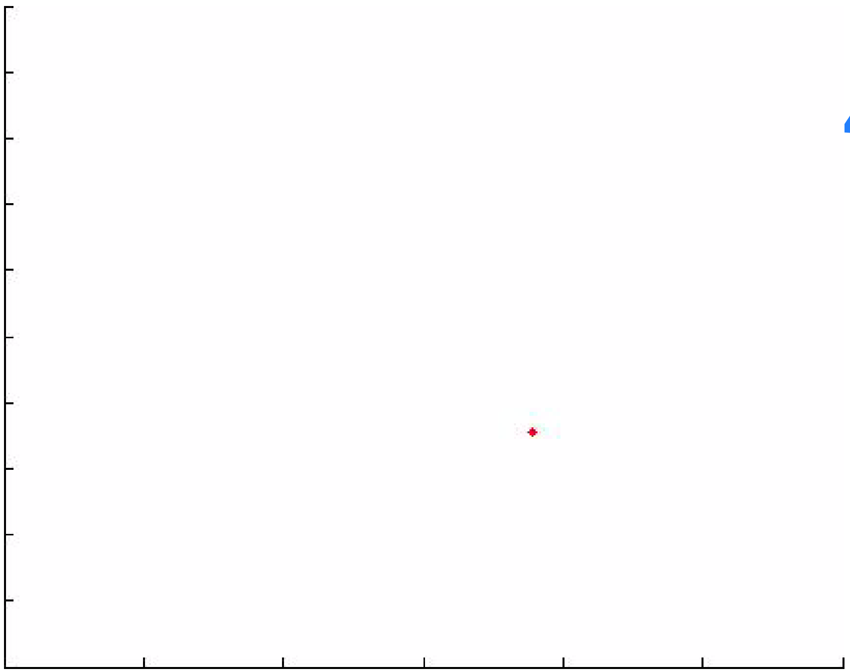
Lamination parallel to particle orbit reduces eddy currents in entrance/exit region



Gabard, A., et al. (2010). Magnetic Measurements and Commissioning of the Fast Ramped 90 deg. Bending Magnet in the PROSCAN Gantry 2 Project at PSI. *IEEE Transactions on Applied Superconductivity*, *20*.

Spot position drift at isocentre





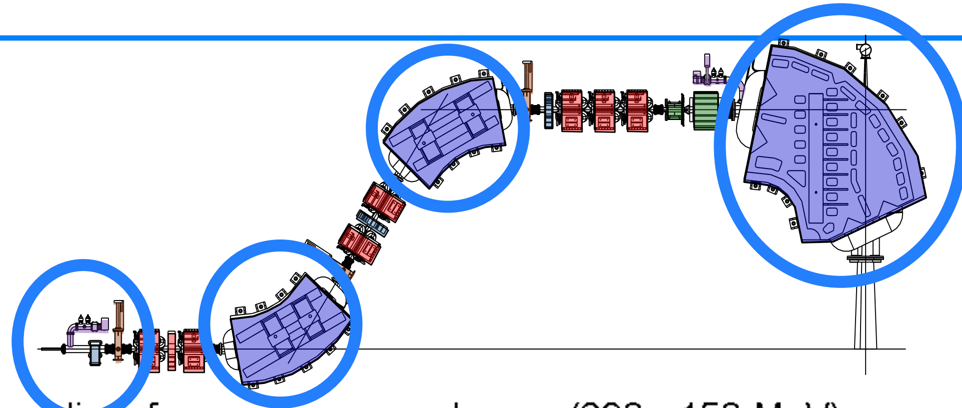
0.5 mm

Spot position at isocentre after three energy changes (increasing ΔE)

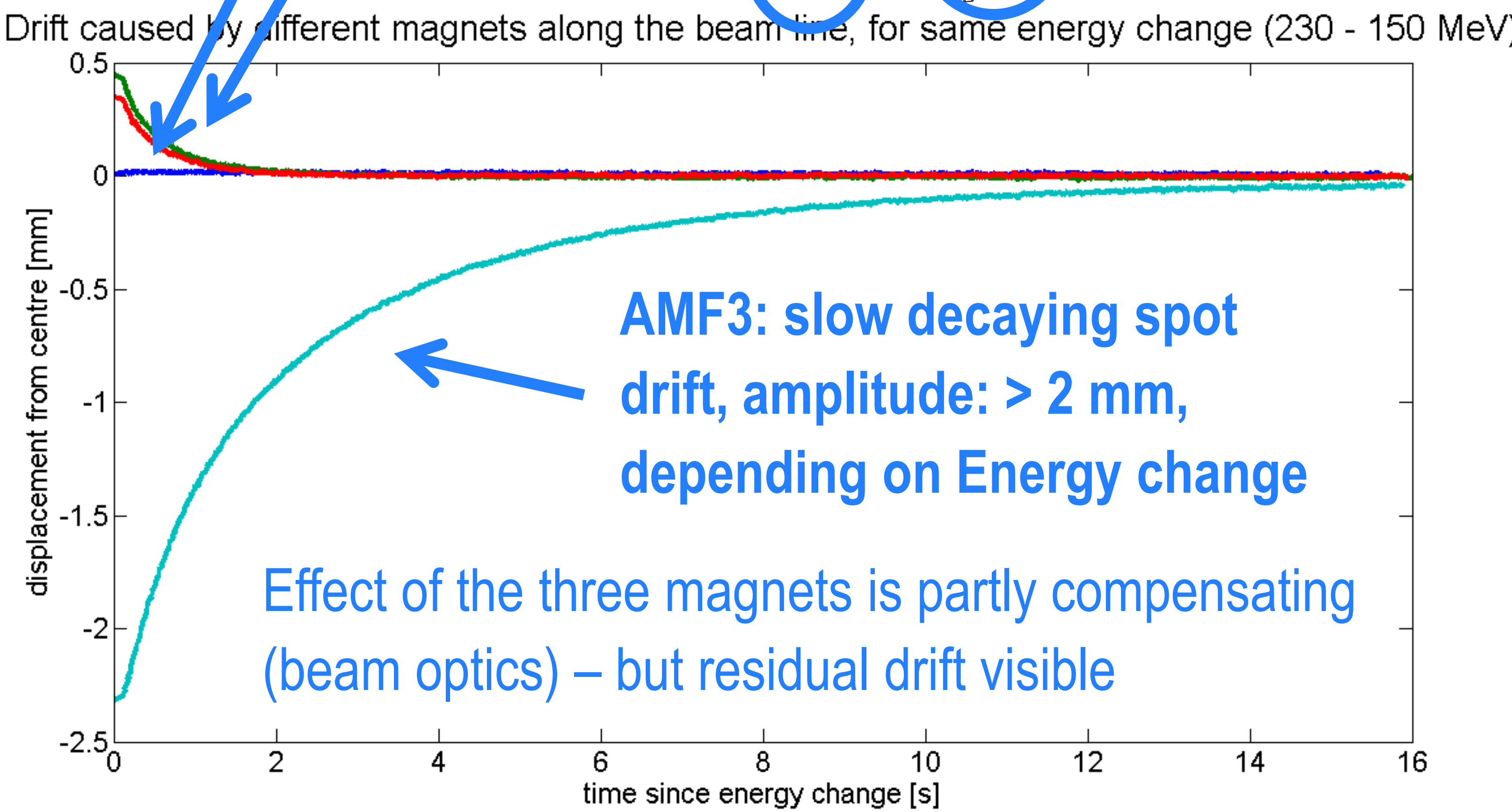
Spot position drift at isocentre

AMA1 and upstream magnets: no impact on spot position (thanks to **coupling point collimator**)

AMF1 – AMF2: exponential spot drift, decay within 1 s, effect < 0.5 mm



Dispersive direction ONLY!!



G2: Online correction of the spot drift

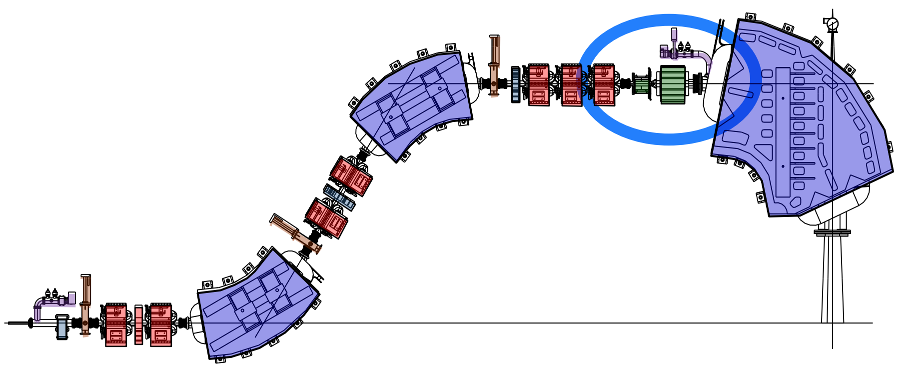
Upstream scanning: scanner magnets before last bending magnet

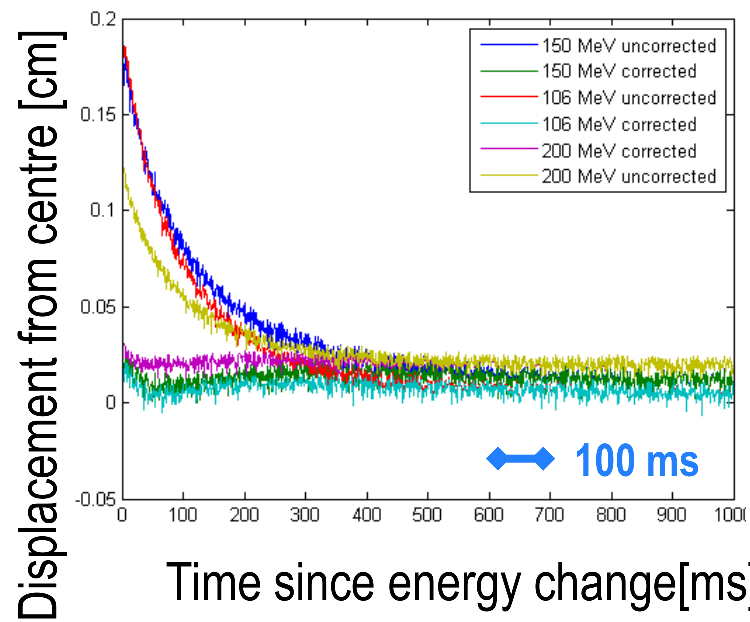
Advantages: parallel beam at isocentre

AMF3 dominates spot drift at isocentre

Use scanner magnets to correct spot drift online!

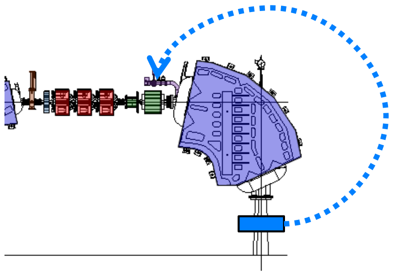
- Time-dependent correction to the scanner magnet current



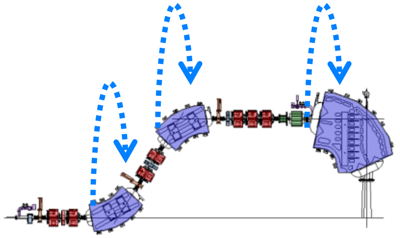


Other solutions to hysteresis and magnetisation effects

- **Feed-back from position monitor**
  - Position monitor is based on ionization chamber
    - Signal is delayed + limited resolution (depending on spot dose)
  - Correction after beam is applied; slow correction to avoid oscillations
  - A good solution for slow “drifts” (example: drifts in non-dispersive direction at PSI Gantry 1)



- **Magnet power supply regulates on (measured) magnetic field instead of current**
  - Needs high resolution measurement (better than 10^-4)!
  - Integration of signal is required; operates on second time scale
    - Will such a feed-back system also work on the 10 ms time scale?
  - Example: HIT (since 2012)



PhD thesis E. Feldmeier: Feldkorrekturregelung für dynamische Prozesse in normalleitenden Magneten

Future option: large momentum acceptance

Is it possible to avoid fast magnetic field changes?

Large momentum acceptance!

Common gantries: momentum acceptance < 0.5%

Limiting factor: dispersion function along the gantry

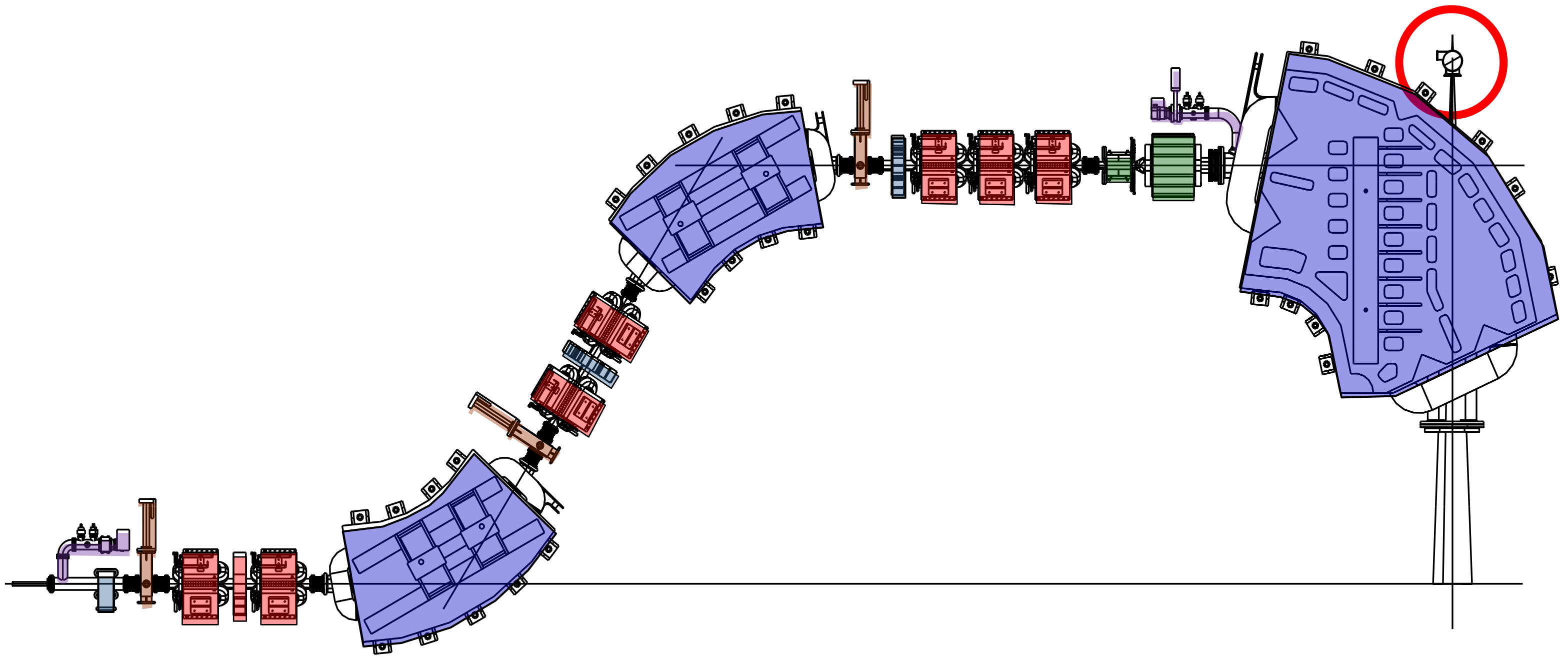
Large momentum acceptance – options for future (SC) gantries?

Challenges:

- More *complex optics*
- Careful *matching* from transport beam line to gantry
- *Energy-dependent spot position shifts* at isocentre (eg: NS-FFAG)
- *Prototype*?

Need more investigation!

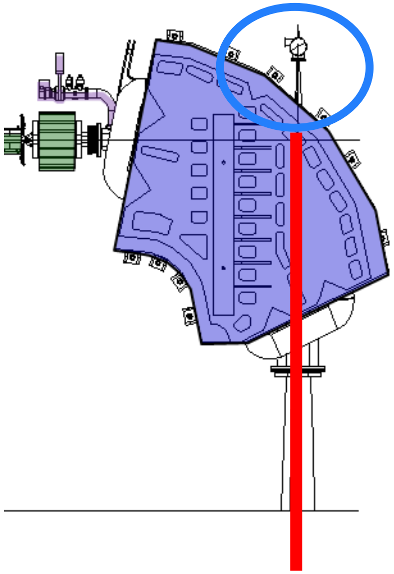
What is the impact of imaging on gantry design?



Imaging for advanced scanning

Inter- and intra-fraction motion:

Imaging the patient in the treatment position



Beam's-Eye-View: X-ray images/fluoroscopy along beam path

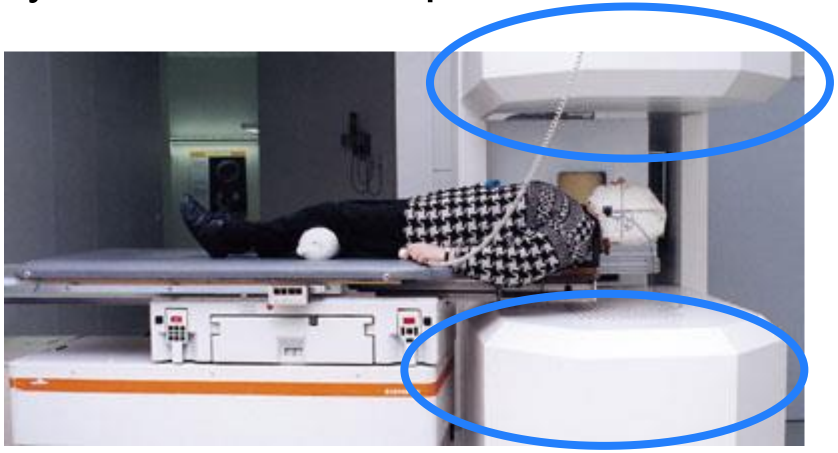
Requires hole in magnet yoke!

Cone Beam CT (Penn radiation Oncology and IBA) may have an impact on gantry layout

Online verification:

- PET
- Prompt gamma
- Proton tomography

High interest in the field – but not yet fully used in clinical practice



Picture of the GSI carbon-ion therapy facility's first patient (CERN Courier, Nov 27, 1998). PET cameras are positioned above and below the head and the beam enters through the window behind.

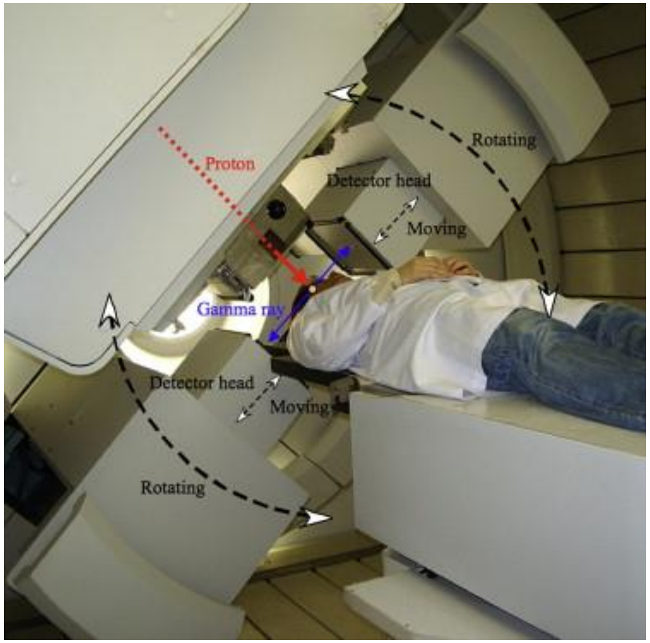
Impact of imaging on gantry design

Direct impact:

- BEV: needs *hole in magnet yoke* + panels
- Cone Beam: *panels etc, gantry rotation*
- *PET rings*?
- *Proton Tomography setup*?

360 deg. Gantries have advantages as structure can usually accommodate such devices – more challenging for a compact gantry

IBA



Nishio T, et al, Int J Radiat Oncol Biol Phys. 2010;76:277–286.

Conclusions

Strong motivation for fast beam scanning in proton therapy

- Convenience: higher throughput
- Future: moving targets indications

Technical challenges of fast scanning have a strong impact on gantry design:

- ***Magnet design and operation***
- ***Integrated imaging***

PT under pressure for cost/benefit ratio wrt conventional therapy

- **Future machines cannot afford making stronger compromises**

Thank you for your attention!