PAUL SCHERRER INSTITUT

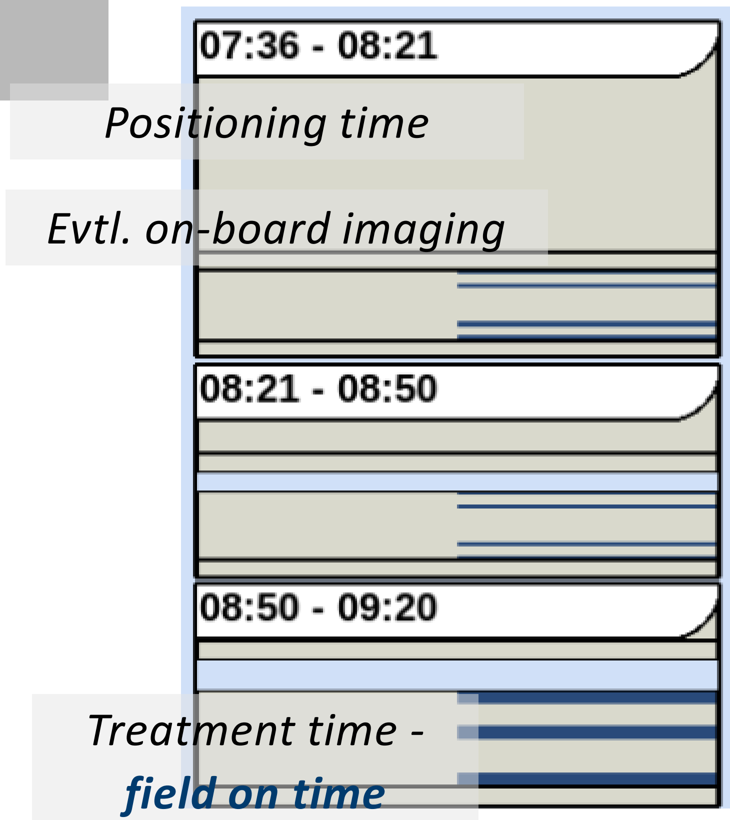
Dr. Serena Psoroulas :: Technology development :: Centre for Proton therapy

Motivation and challenges of fast dose delivery

EUCARD Workshop on Innovative Delivery Systems in Particle Therapy
Torino, 23.02.2017

Treatment times vs room occupancy times in the PSI Centre for Proton Therapy

Gantry 2



Actual patient times on 22.02.2017

Room occupancy affected by many factors

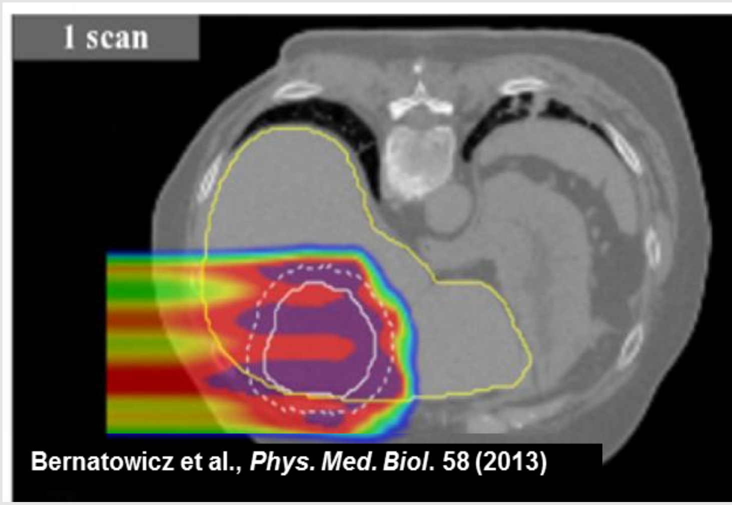
Treatment times of order of 1-2 Gy/L/min common in clinical facilities

Fast room switching advantageous for multi-room facilities

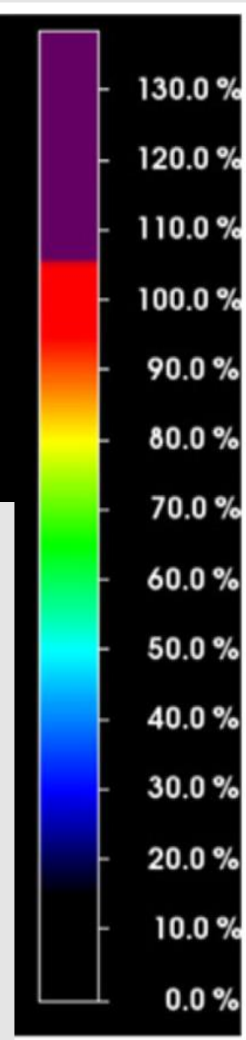
*Why **faster** scanning? Challenges?*

Motivation: moving tumours

Interplay effect with pencil beam scanning



Bernatowicz et al., *Phys. Med. Biol.* 58 (2013)



Overdosage (clinically not acceptable)

100 % = Target dose

Underdosage (clinically not acceptable)

Free breathing:

- Interference between motion of target and motion of beam across the different spots leads to hot/cold spots (interplay effect)
- Dose blurring at the edges

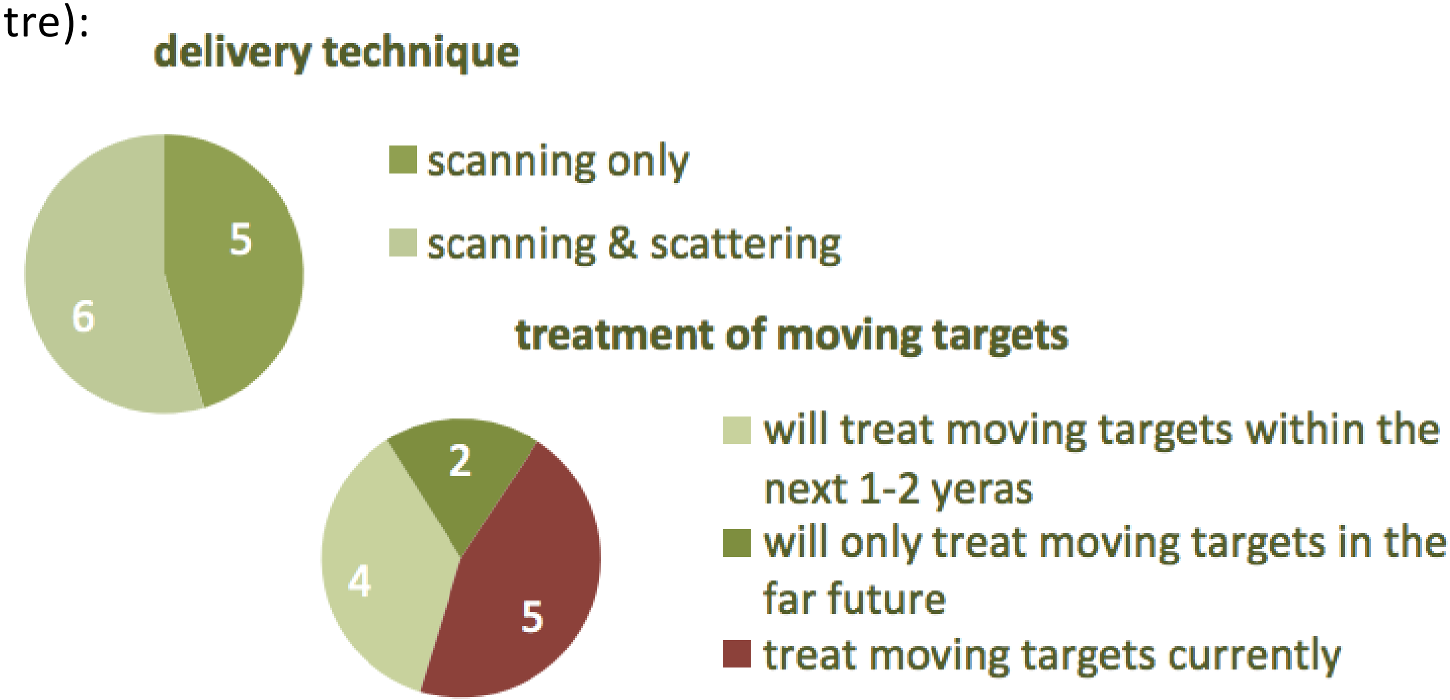
What technique to treat moving targets?

Results of informal survey from A. Knopf (UMCG):

Scanned beams preferred to scattering even for motion cases; but high need for

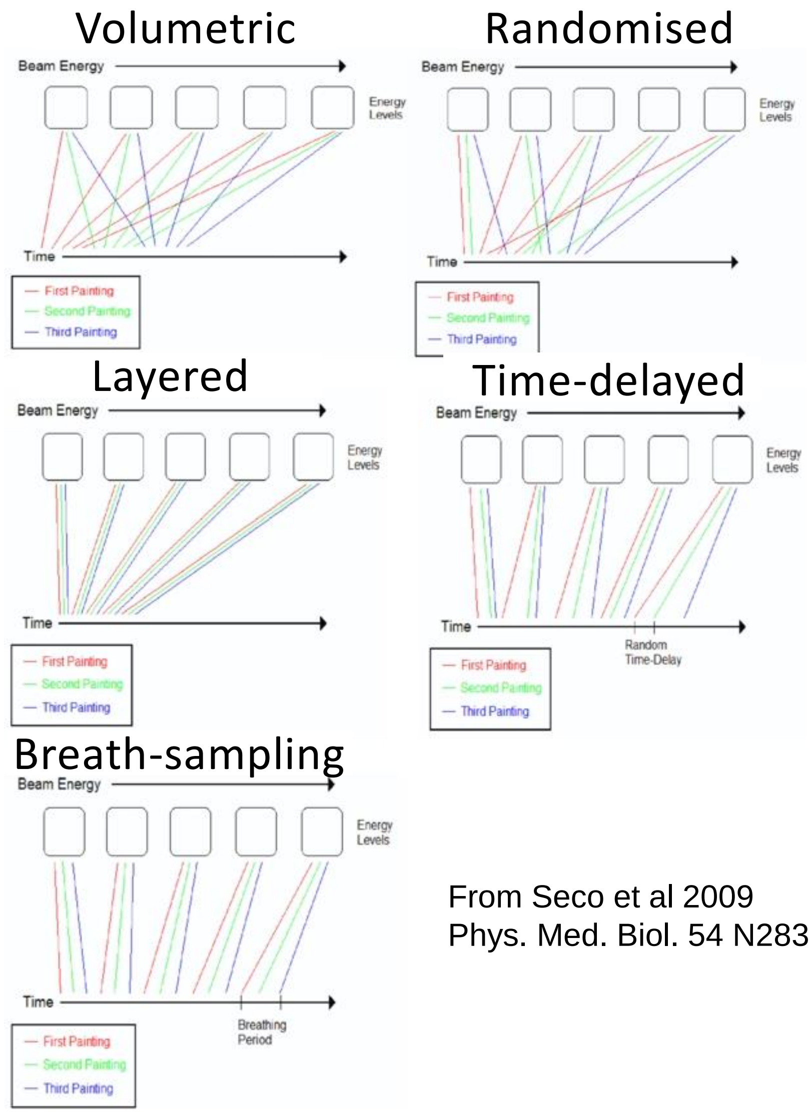
- *Fast scanning*
- *Appropriate motion mitigation technique*

Report on 11 centers (9 proton centres, 1 carbon centre, 1 proton + carbon centre):



A. Knopf, 4DTP workshop 2015

Rescanning and machine performance



From Seco et al 2009
Phys. Med. Biol. 54 N283

Goal: average hot-cold spots by re-applying the same field several times

Time 1 layer << breathing period

Affected by delivery performance as:
- **Energy switching time**
- **Beam stability after energy switching**

Results in increase of treatment time
Choice of rescanning strategy: likely machine-dependent!

Gating and machine performance

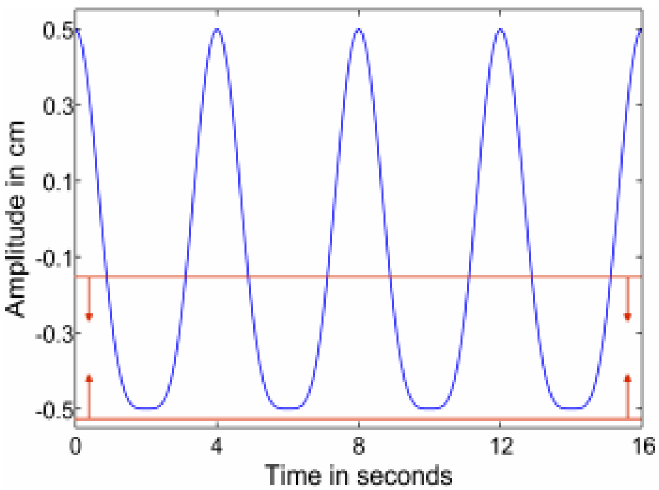
Goal: reduce amplitude of motion
Trigger delivery by monitoring in real time tumour motion (or its surrogate)

Residual motion interplay to be suppressed using additional mitigation (eg rescanning) or appropriate planning parameters

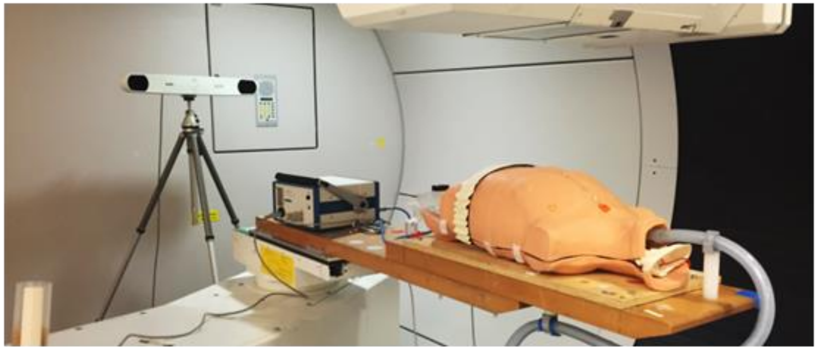
Affected by:

- **Low efficiency in beam application**, particularly for synchrotrons (unless special excitation cycles are used)

Results in increase of treatment time

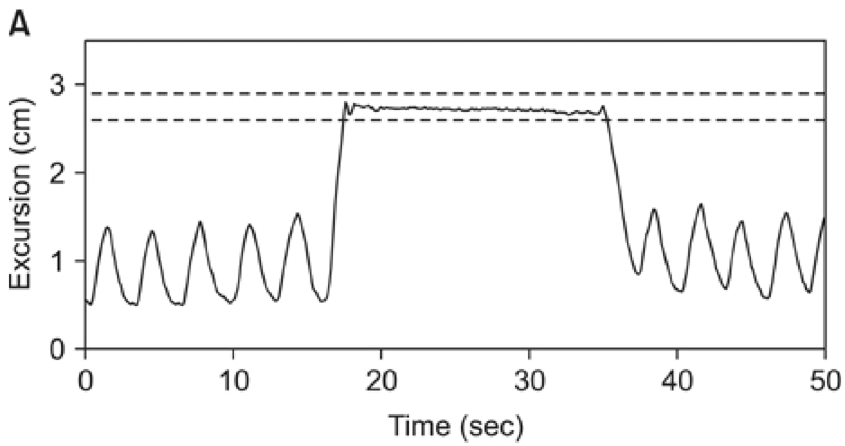


A. Schaetti, PSI



G. Fattori et al, Testing of optical tracking gating system at PSI Gantry 2 (in preparation)

Breath hold and machine performance



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

Goal: quasi-static irradiation of tumours in thorax/upper abdomen achieved with patient's cooperation

Affected by:

- **Total scanning time through volume**

As well as:

- Reproducibility between breath-holds
- Patient's breath-hold length (**Breath-hold windows ~20 s**)

Requires:

- Fast scanning in all three dimensions
- Precise patient monitoring

Techniques such as apnea might relax the timing requirements

Tracking and machine performance

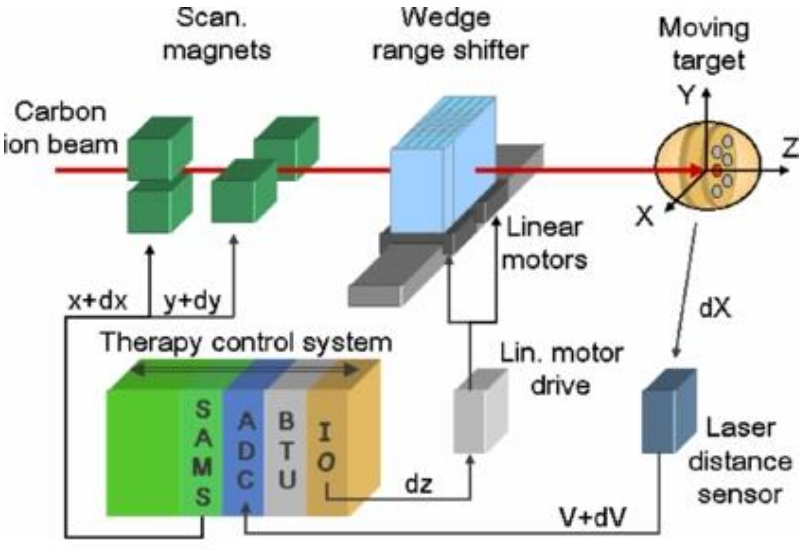
Goal: compensate for CTV motion

Affected by:

- **Changes of WEPL along beam axis**
- Target deformation
- **Reaction time of tracking (and adaptation) system**
- **Reproducibility of motion** (particularly in inhomogeneous tissues)

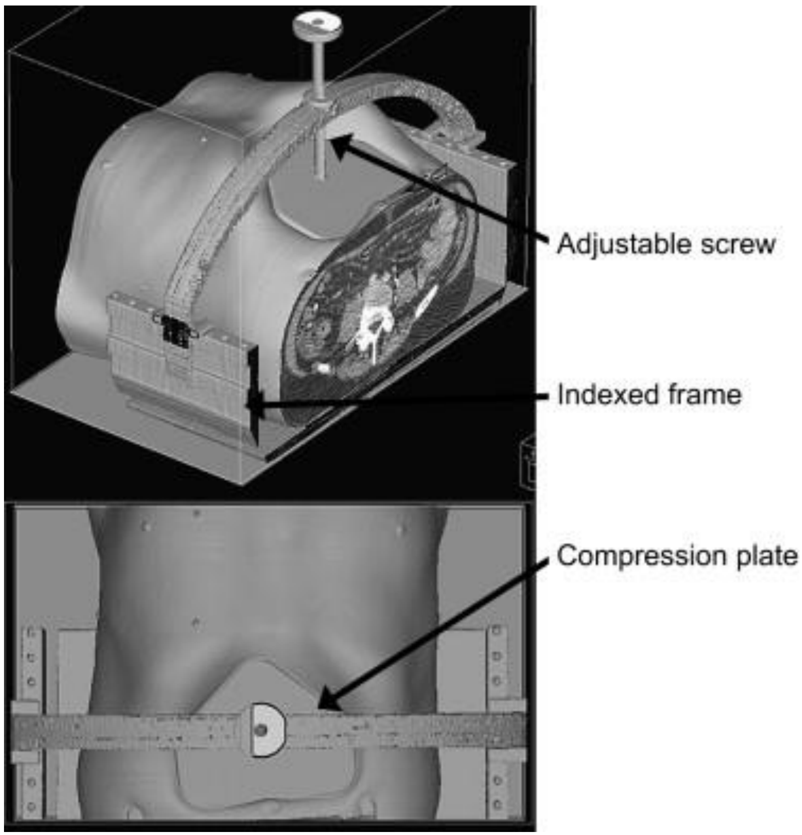
Requires:

- Real time monitoring of the internal anatomy
- Fast monitoring of changes in WEPL
- Fast adaptation of beam configuration (most challenging: range)
- Appropriate treatment planning parameters



From N. Saito et al 2009
Phys. Med. Biol. 54 4849

How about immobilisation?



Eccles, C. L., et al (2011), IJROB *79*(2), 602–608.

Immobilisation is a primary mean of motion/interplay mitigation:

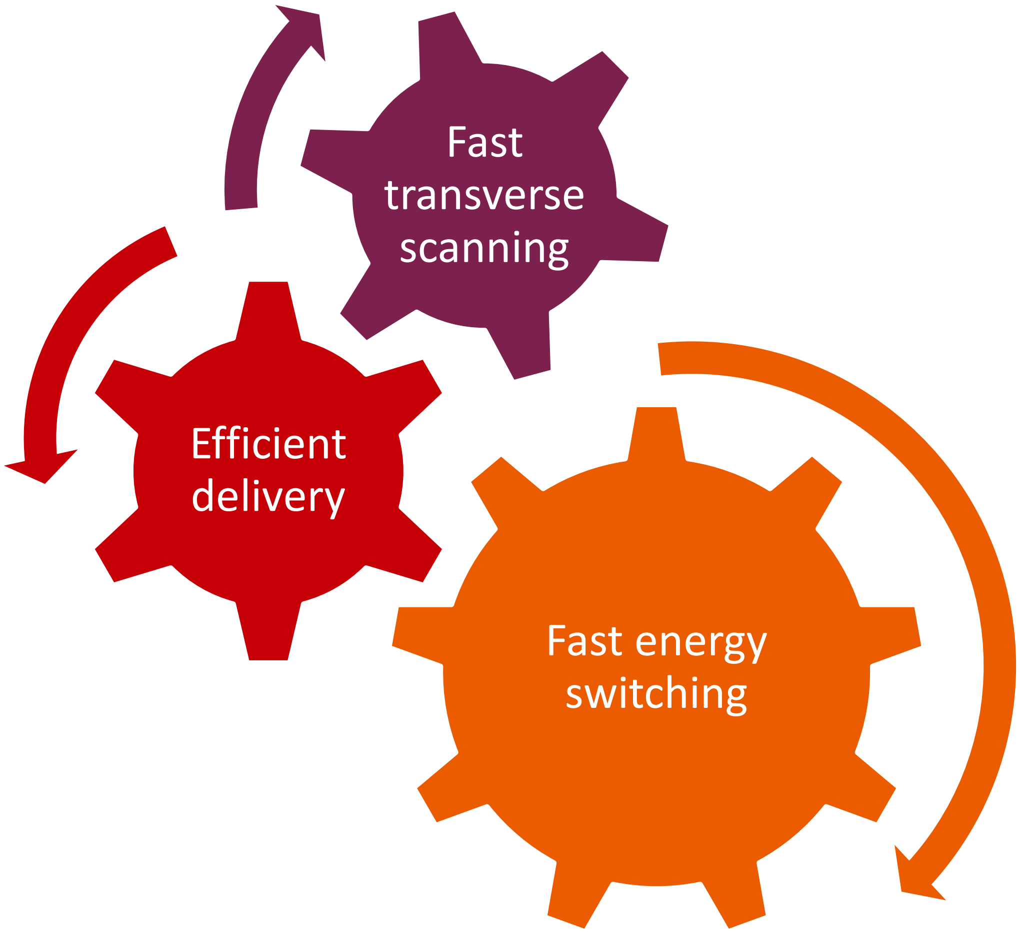
- Abdominal compression (liver cases)
- Rectal balloon (prostate cases)

BUT:

- Residual motion often not completely negligible (eg compression)
- Static configuration achieved for few minutes, then changes in the anatomy can occur (eg drifts)

Immobilisation will work best with fast scanning (and if needed, combined with motion mitigation)

Fast scanning
to make motion mitigation possible



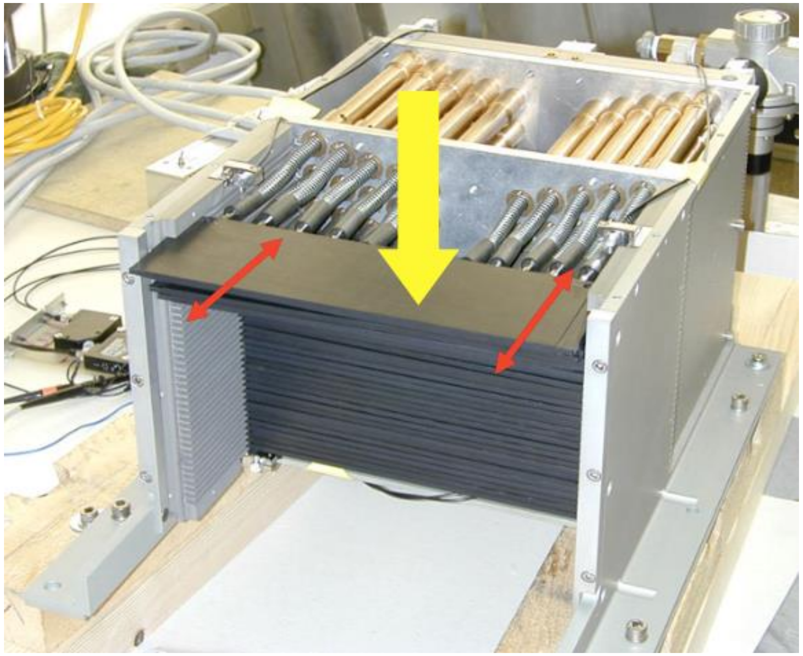
Fast scanning in depth: energy switching strategy and beam stability

Energy switching strategies for cyclotrons

Cyclotrons provide single energy: need for energy degradation

- **Upstream**: energy degradation after cyclotron
  Need to adapt all magnets in the beam line: settling time is the bottleneck!

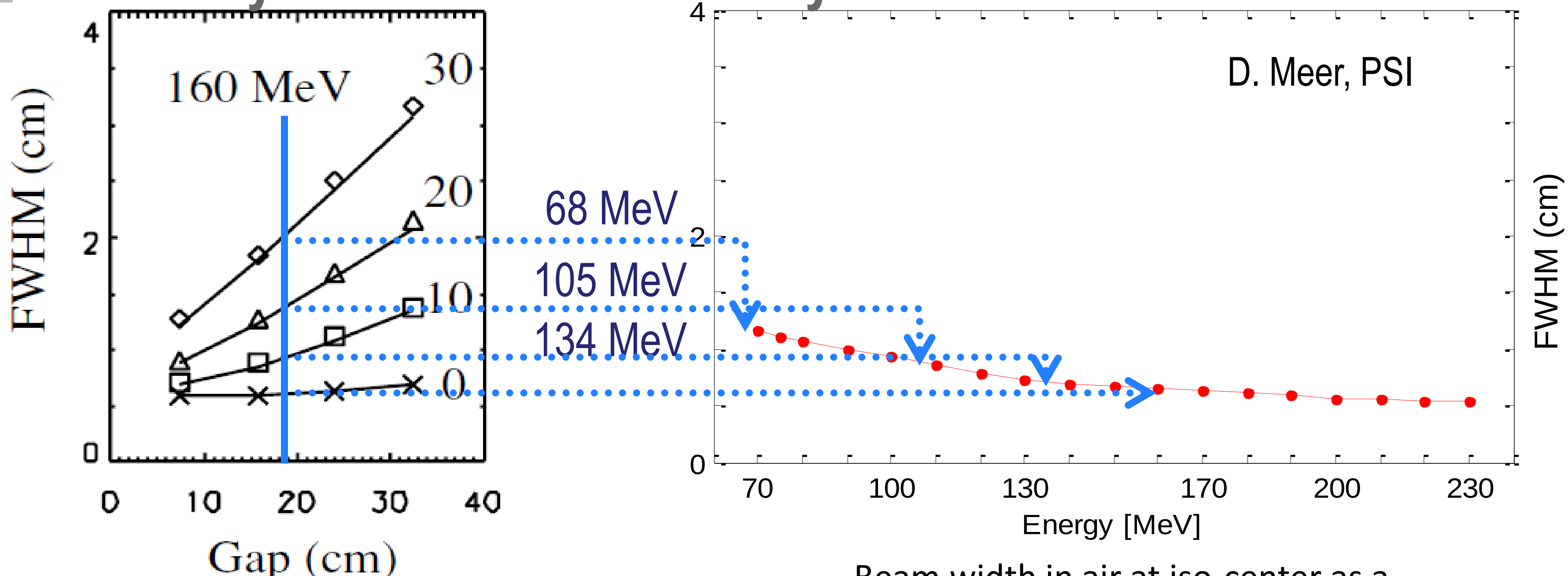
- **Downstream**: range shifter or ridge filter before patient
  Can reach fast switching (50 ms), but at the price of beam size



Impact of energy switching strategy on beam size (PSI gantries)

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

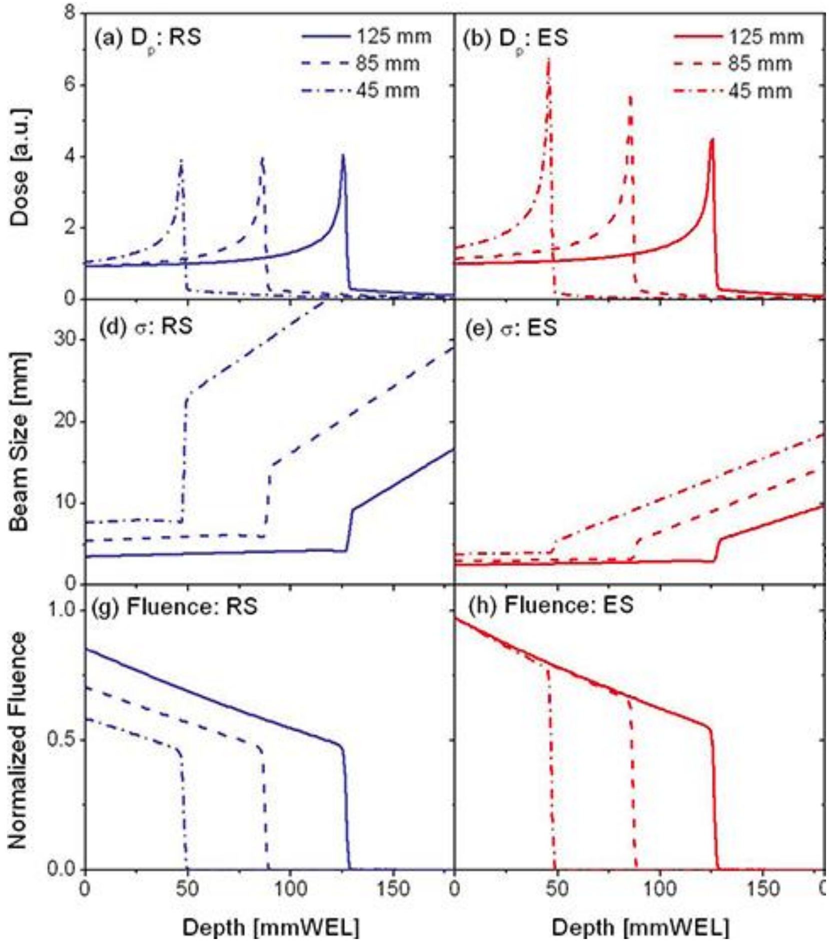
Cyclotron facilities nowadays mostly rely on upstream beam changes

Exception: Mevion

PAUL SCHERRER INSTITUT

Impact of energy switching strategy on beam size in synchrotrons (HIMAC simulation)

downstream upstream



Inaniwa, et al. 2012, Med. Phys., 39: 2820–2825.

Upstream changes benefit synchrotrons, but **from timing point of view a range shifter is still a strong advantage**

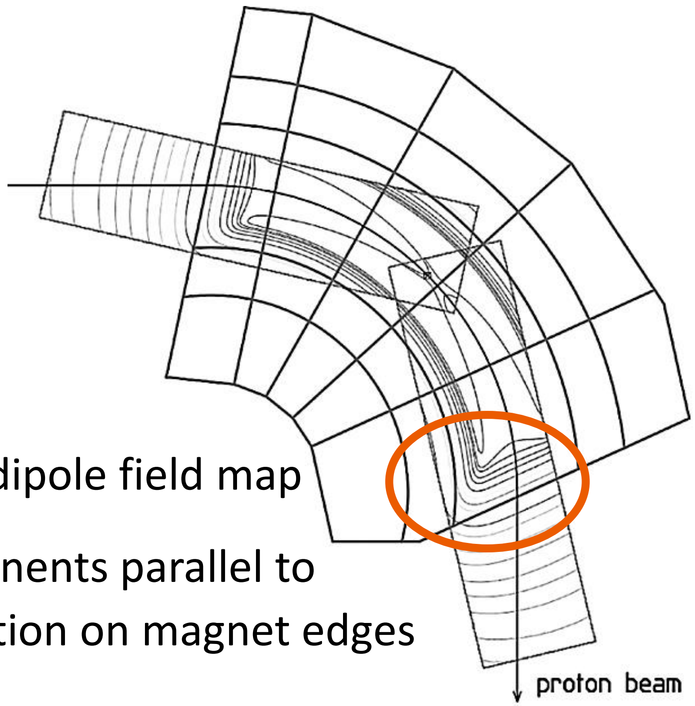
Under investigation: extended flattop with multiple energies

Impact of fast energy changes on bending magnets

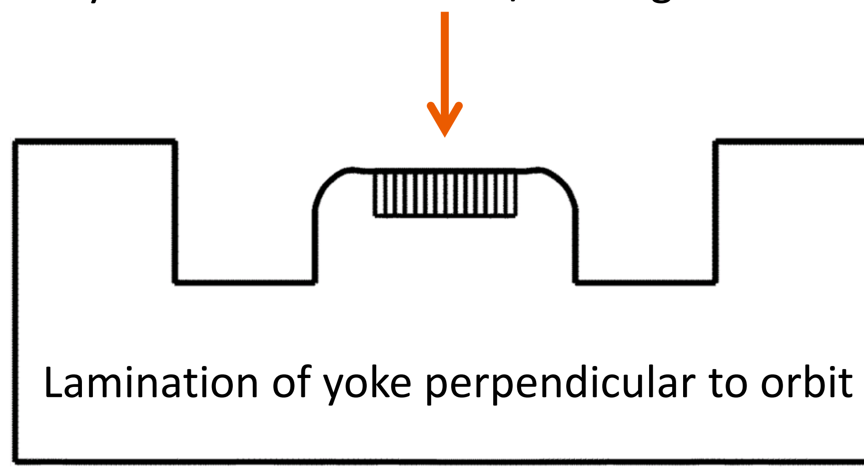
- Energy changes = changes in magnetic field = **Eddy currents**
- **Lamination helps suppressing the effect – up to a limited degree**

AMF3 dipole field map

Components parallel to lamination on magnet edges

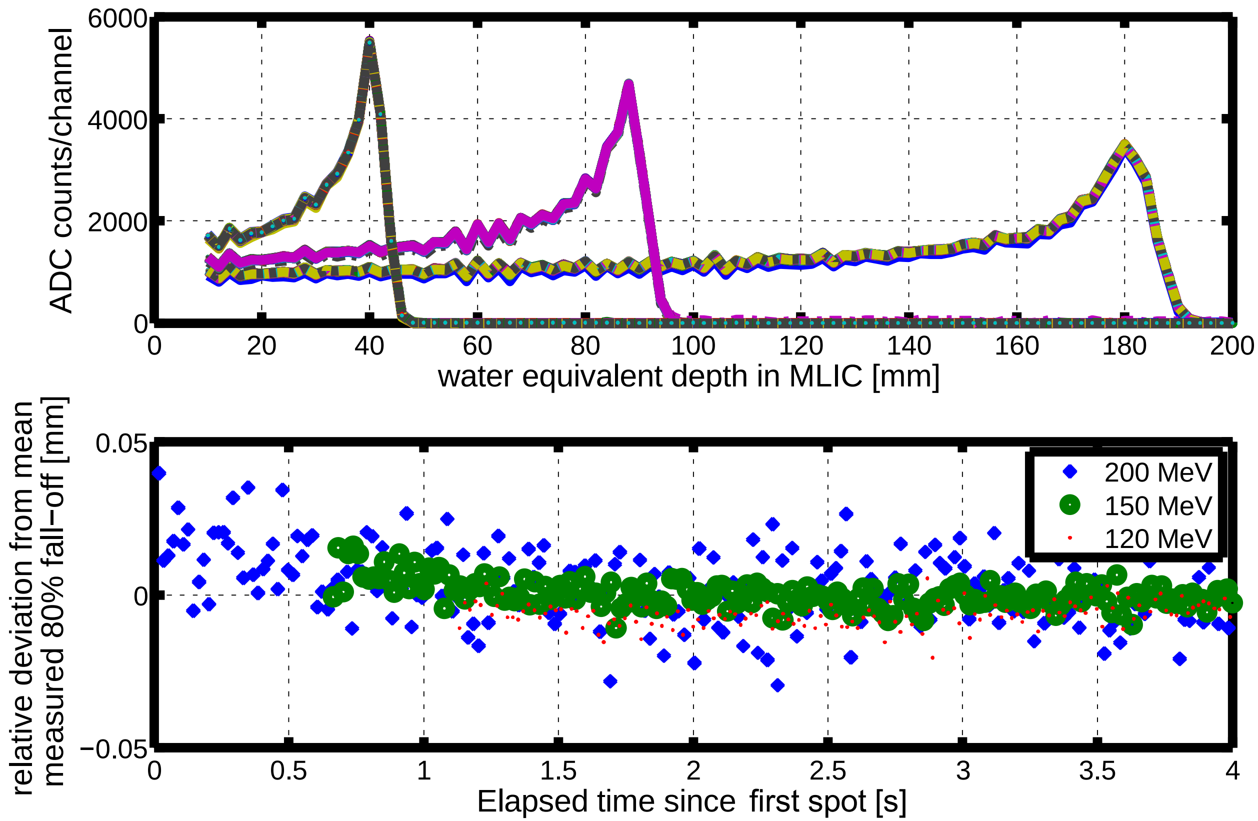


Lamination parallel to particle orbit reduces eddy currents in entrance/exit region



Gabard, A., et al. (2010), *IEEE Transactions on Applied Superconductivity*, *20*.

Experimental validation of constancy of range with fast energy changes



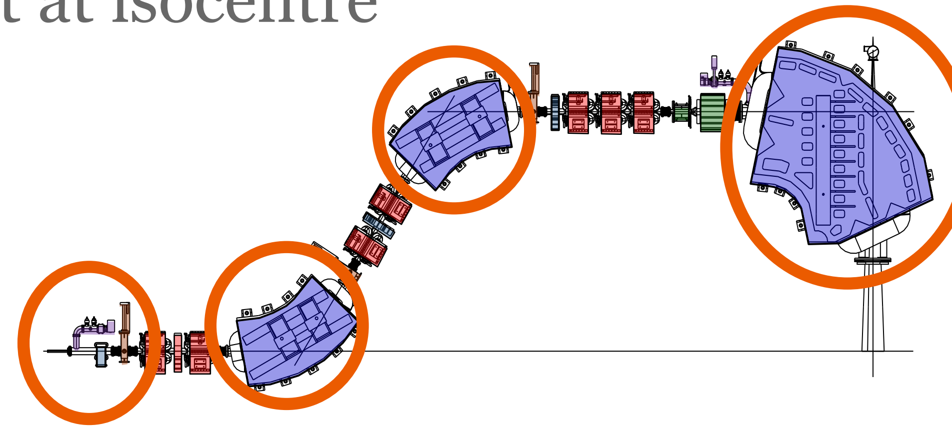
Measurements of range following a **100 ms energy change**

20 ms beam delivery/spot

Range constancy better than 0.05 mm

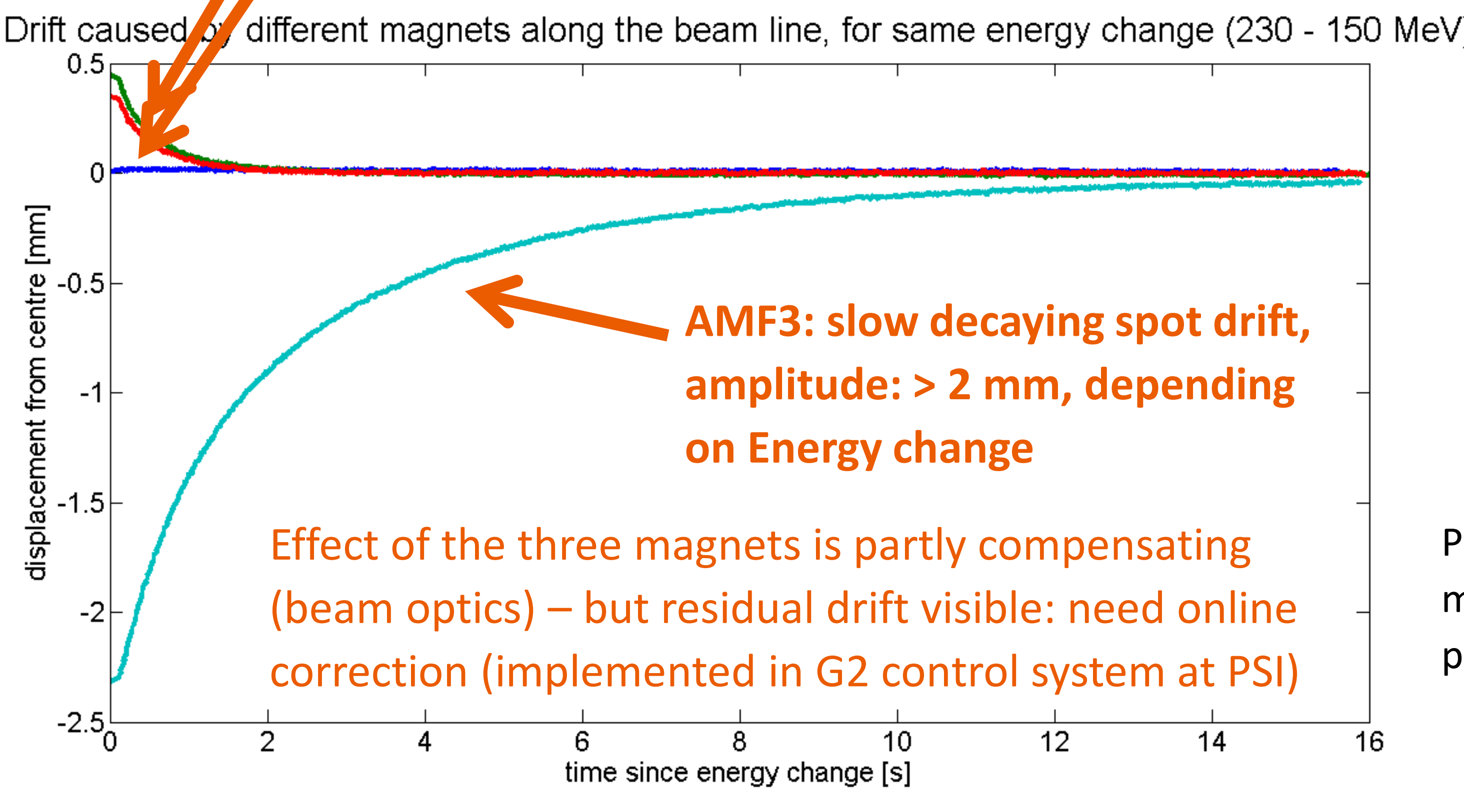
Psoroulas et al, manuscript in preparation

Spot position drift at isocentre



AMA1 and upstream magnets:
no impact on spot position

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



Dispersive direction ONLY!!

AMF3: slow decaying spot drift, amplitude: > 2 mm, depending on Energy change

Effect of the three magnets is partly compensating (beam optics) – but residual drift visible: need online correction (implemented in G2 control system at PSI)

Psoroulas et al, manuscript in preparation

PAUL SCHERRER INSTITUT PSI

Consequences for motion mitigation techniques

Rescanning

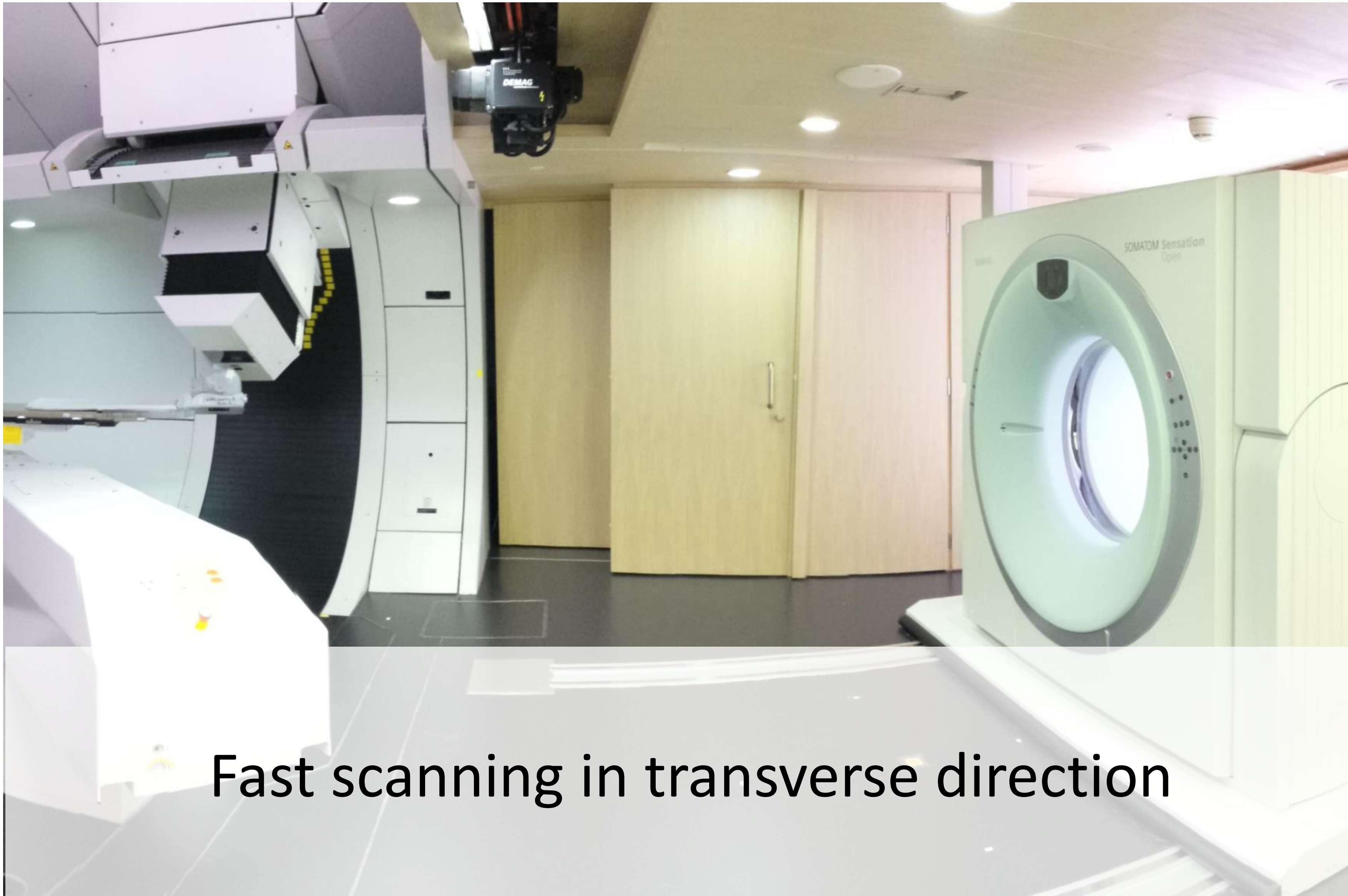
- ***Strong impact of energy switching time, affecting the preferred strategy*** (e.g. Bernatowicz et al, PMB 58(22), 2013)

Gating and breath hold

- For upstream energy switching systems: need ***low switching times***!
- For synchrotrons: need synchronisation with accelerator (see later)

Tracking

- Need: ***5 mm range compensation within 10 ms*** (Saito, et al., PMB 54(15), 2009)
  - Current systems cannot match such requirements

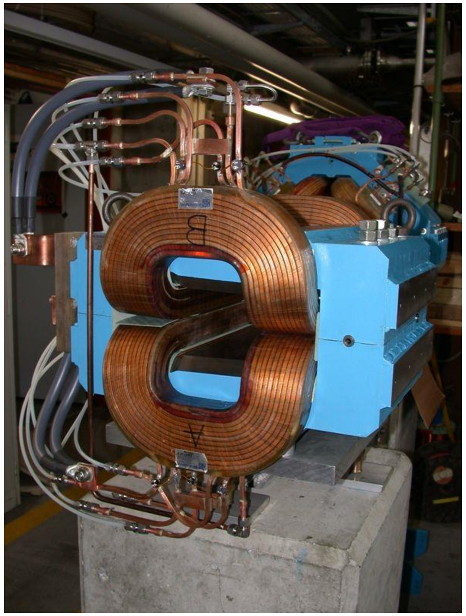


Fast scanning in transverse direction

Fast scanning: scanning magnets

Pictures: PSI magnet section

- **Scanning magnets capable of reaching up to 2 cm/ms**
- Ferrite core: no hysteresis/eddy currents effects at the expense of field size
- *Future: air-core magnets?* (in combination with laser-pulsed acceleration)



Dispersive direction:

Max 0.4 T

Transverse direction

Max 0.2 T

Ferrite core to avoid eddy currents

Current pencil beam scanning technique: dose-driven

Step-and-shoot approach pioneered at PSI and GSI and commonly used in all centres:

- Beam intensity constant (evtl. fixed by the smallest spot length)
- Position constant
- *Dose-driven: once all protons for one position have been delivered, move to the next*

Very robust technique, from a time when beam intensity was not very stable...

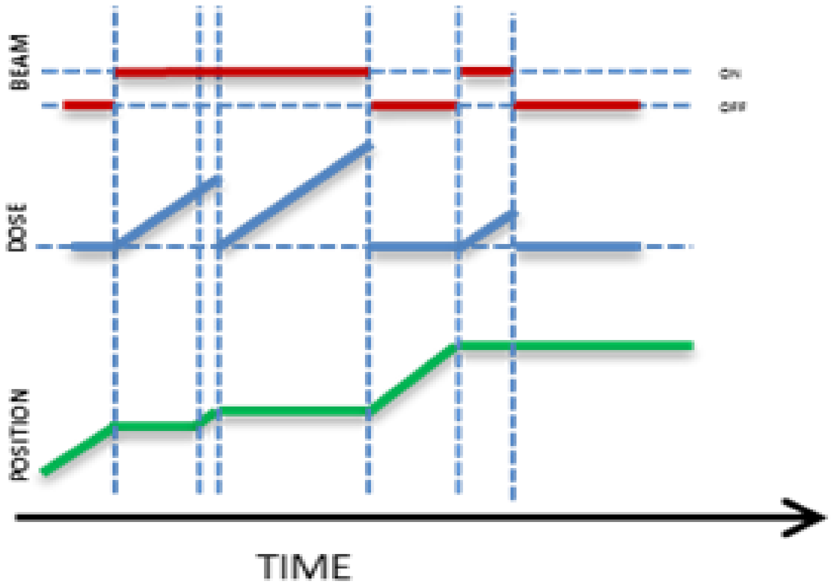
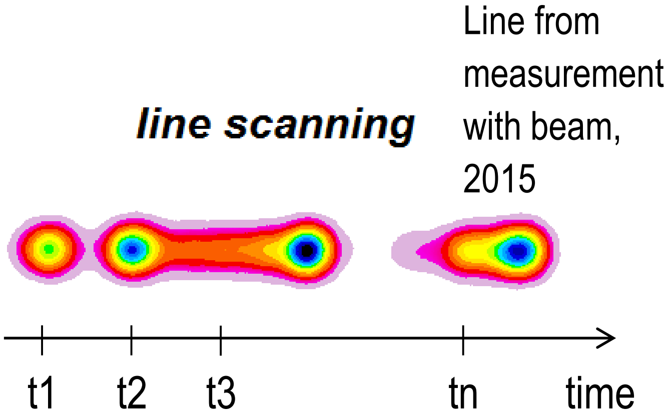
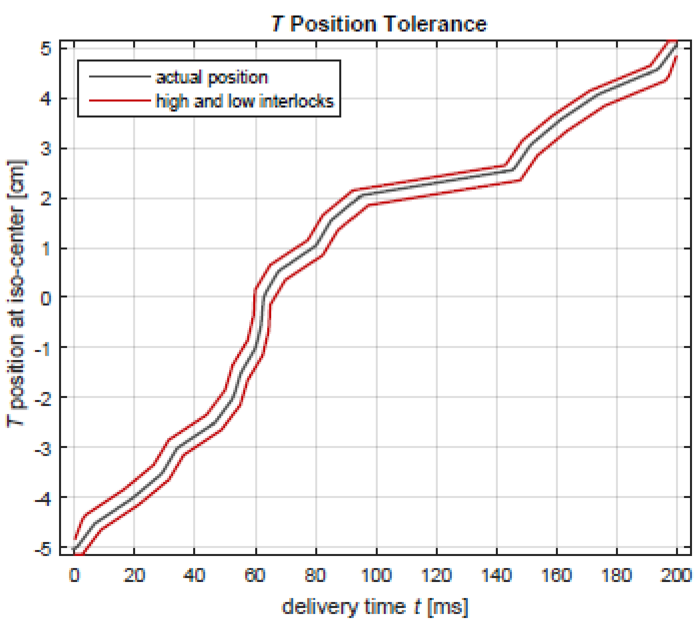


Image courtesy of Varian Medical Systems, Inc. All rights reserved.

Alternative: time driven





G. Klimpki et al., submitted; talk tomorrow

All delivery techniques can be implemented also in *time-driven* mode:
Dose at patients is defined as instantaneous beam current and scanning speed

Implemented by Sumitomo (independently also at PSI) to improve timing performance
- Continuous speed modulation
- Continuous beam delivery

Requires:
- **Stable beam currents**
- **Closed-loop control of quantities (to react to instabilities)**
- **High-rate monitoring signals (to eventually trigger interlocks)**

Consequences for motion mitigation techniques

Rescanning:

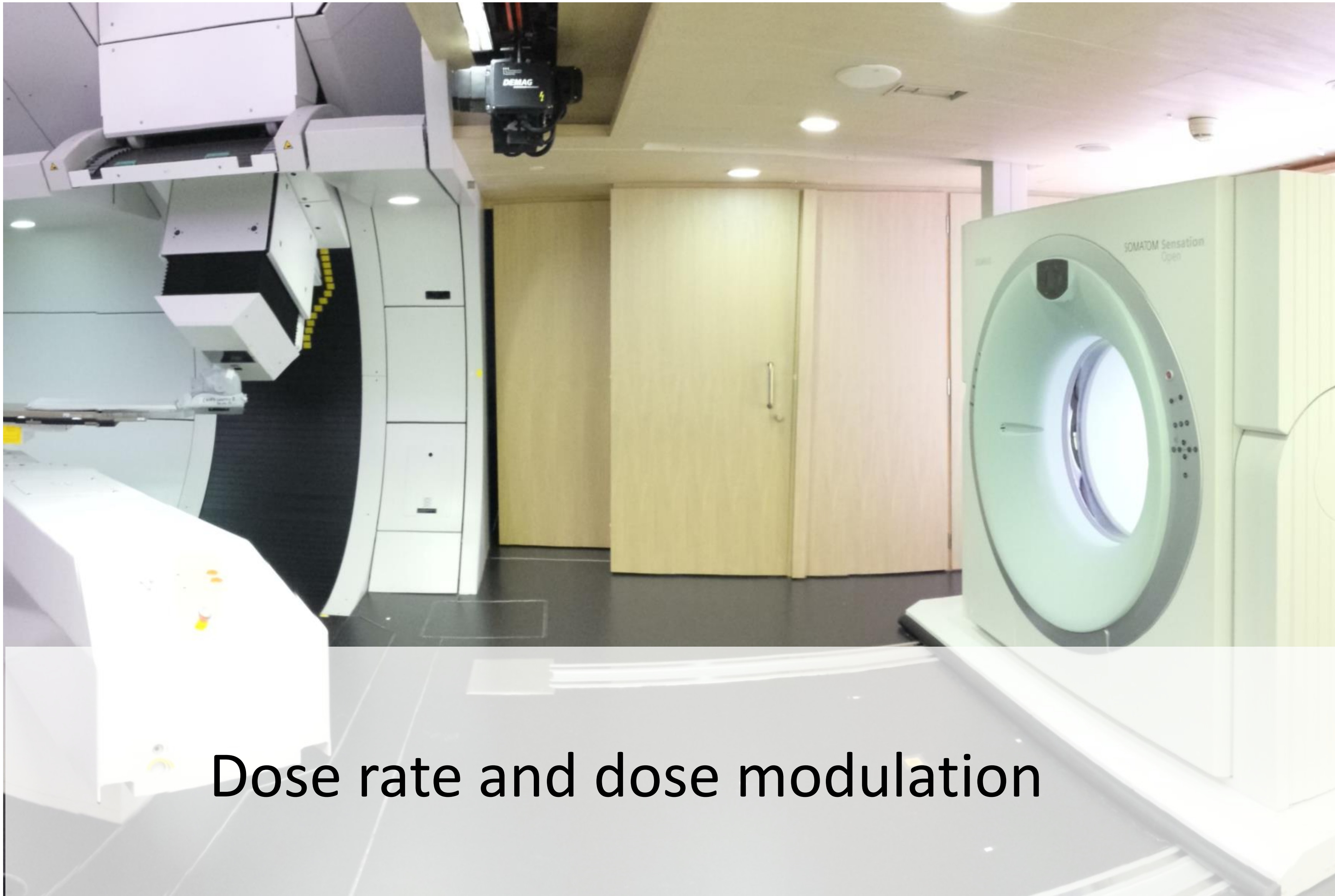
- ***Higher scanning speeds (for the same beam current) means more rescanning***
  - Possible issue: minimum number of monitor units

Gating/breath hold

- Higher scanning speeds ***without increase in beam current*** might not win enough time…

Tracking

- ***Speeds > 0.5 cm/ms are already enough for corrections*****!**



Dose rate and dose modulation

Maximum beam current and treatment time

Maximum beam current is the decisive factor for reducing treatment time

Affected by:

- **Shielding considerations**
  - Beam losses in accelerator, along the beam line etc
- **Patient safety system reaction time**
  - Dose delivered in case of an incident constrained by safety standards
- **Injection/extraction**
  - For synchrotrons external source: limitation in injector, space charge, ring emittance acceptance
  - For cyclotrons with internal source: source characteristics, speed of modulation, extraction efficiency
- **Beam losses/inefficiency after accelerator**

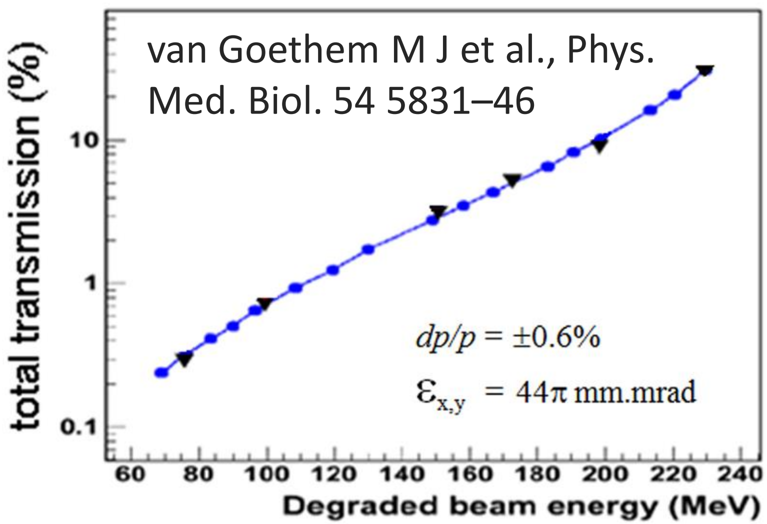
Beam losses in transport with upstream energy selection system

Degrader highly impacts beam divergence

Additional collimation to match following beam line causes large *energy dependent transmission losses*

At PSI: intensity compensation strategies to flatten the transmission curve

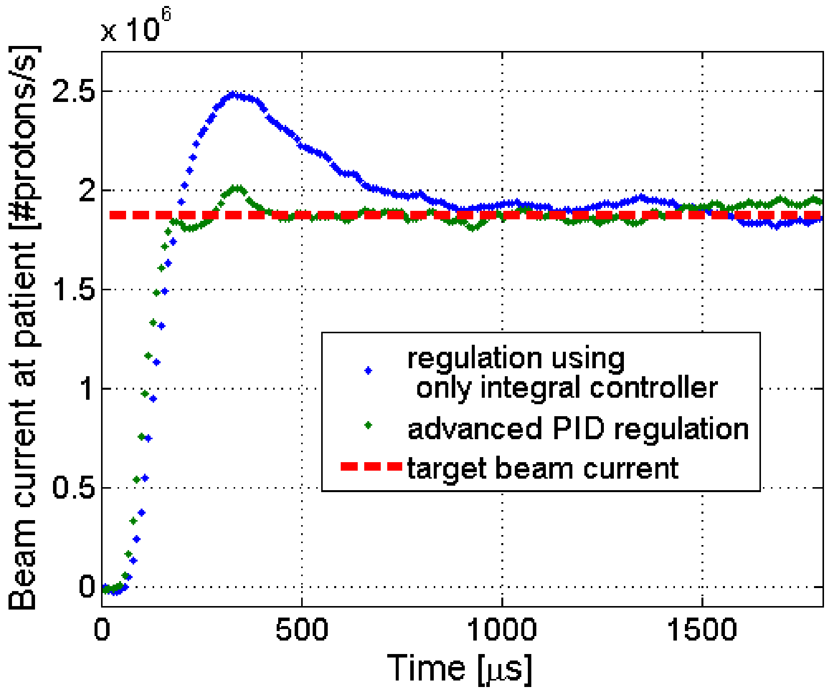
- Use current from the accelerator
- Use focussing/defocussing elements in the beam line
- Different degrader materials (under investigation...)



PAUL SCHERRER INSTITUT

Fast scanning: beam intensity modulation

- Dose-driven approaches: can rely on slow (~s) regulations loop
- Time-driven scanning approaches rely on stability of beam current
  - In G2 conditions, current should settle within ~150 µs
  - **Need closed-loop controller, fast detectors, and fast power supplies**

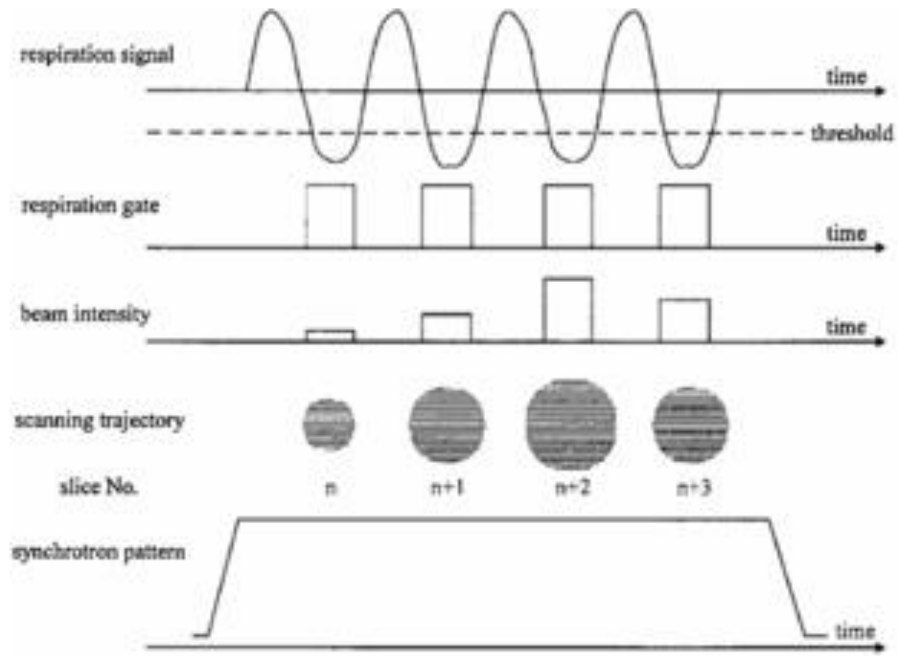


Psoroulas et al, CYC2016

Phase controlled rescanning and gating

Phase controlled rescanning: layered rescanning adapting beam current to deliver one layer in one gating window

- Requires *control of the beam intensity*
- *In combination with extended flat tops and range shifter* (to avoid dead times due to acceleration cycle)
- *Beam intensity primarily will depend on number of rescans* – and it might be too low to deliver…



Furukawa et al., 2007, Med. Phys., 34: 1085–1097

Rescanning and deliverable spots

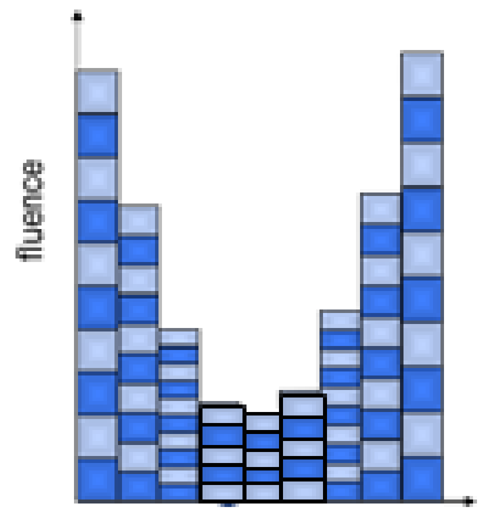
When rescanning low-weighted spots/layers, the minimum number of MU deliverable by the system can be easily reached – what to do?

a) *Skip those spots*
number of skipped spots will depend on the number of rescans

b) *Limit the maximum number of rescans*
the spots contributing less to the total dose decide the number of rescans

c) *Increase the minimum MU*
will depend on the number of rescans

d) *'Smart rescanning'*: apply a different number of rescans per each spot, compatible with MU constraint (implemented at PSI)



Actis et al, PTCOG 55

Consequences for motion mitigation techniques

Rescanning

- Higher flexibility in beam current might help – but not always…
- ***Minimum number of MU*** affects max number of rescans

Gating/Breath hold

- ***More affected by beam current limitations***
  - cyclotrons: extraction efficency, ESS losses
  - synchrotrons: extraction technique, number of particles in ring
  - Pulsed beams (synchrocyclotrons)?

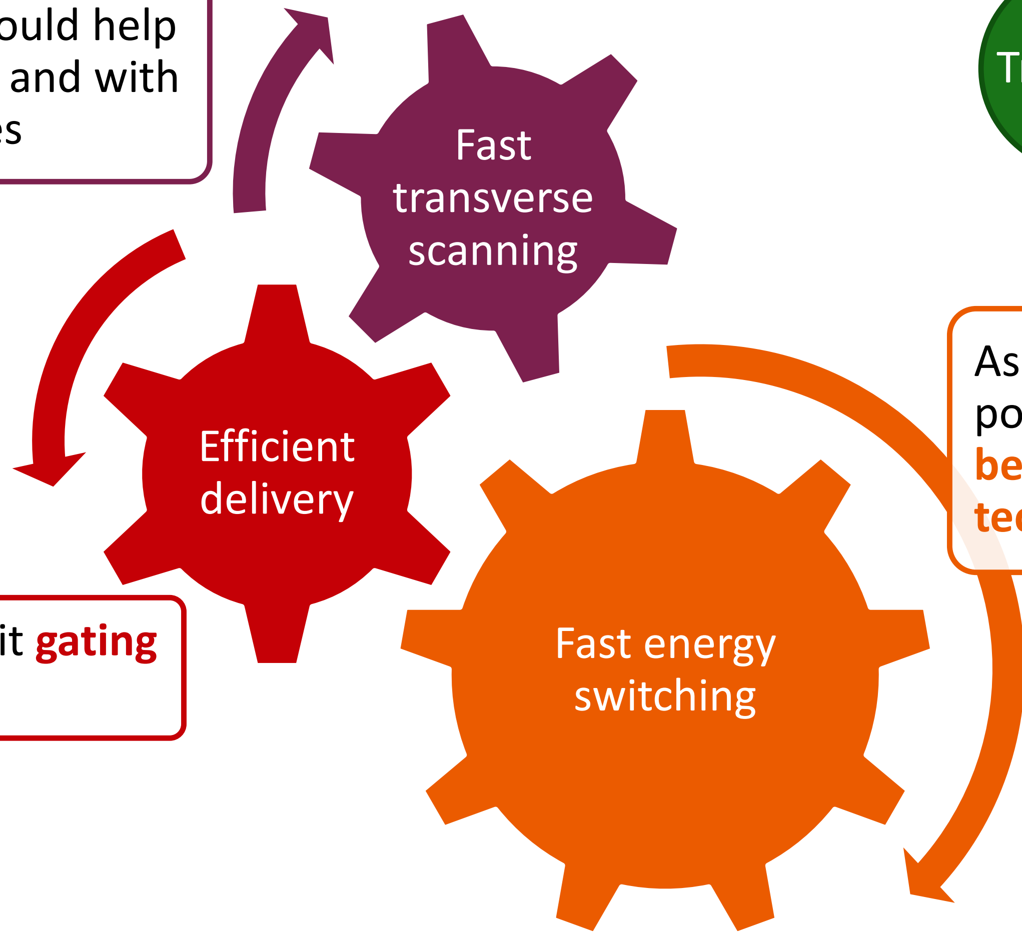
Tracking

- Beam modulation to correct for deformations/rotations of the target (Luechtenborg et al, IFMBE proc., 2009)
  - ***Complex predictive algorithm*** required to account for off-axis dose of other raster positions

Fast scanning to make motion mitigation possible

Higher speeds could help with **rescanning** and with higher dose rates

Tracking?



As low as possible! Will **benefit all techniques**

Will mainly benefit **gating and breath hold**

Improving scanning is still substantial work!

Thank you for your attention!