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Challenges in fast beam current control inside the cyclotron for fast beam delivery in proton therapy

21st International Conference on Cyclotrons and their Applications

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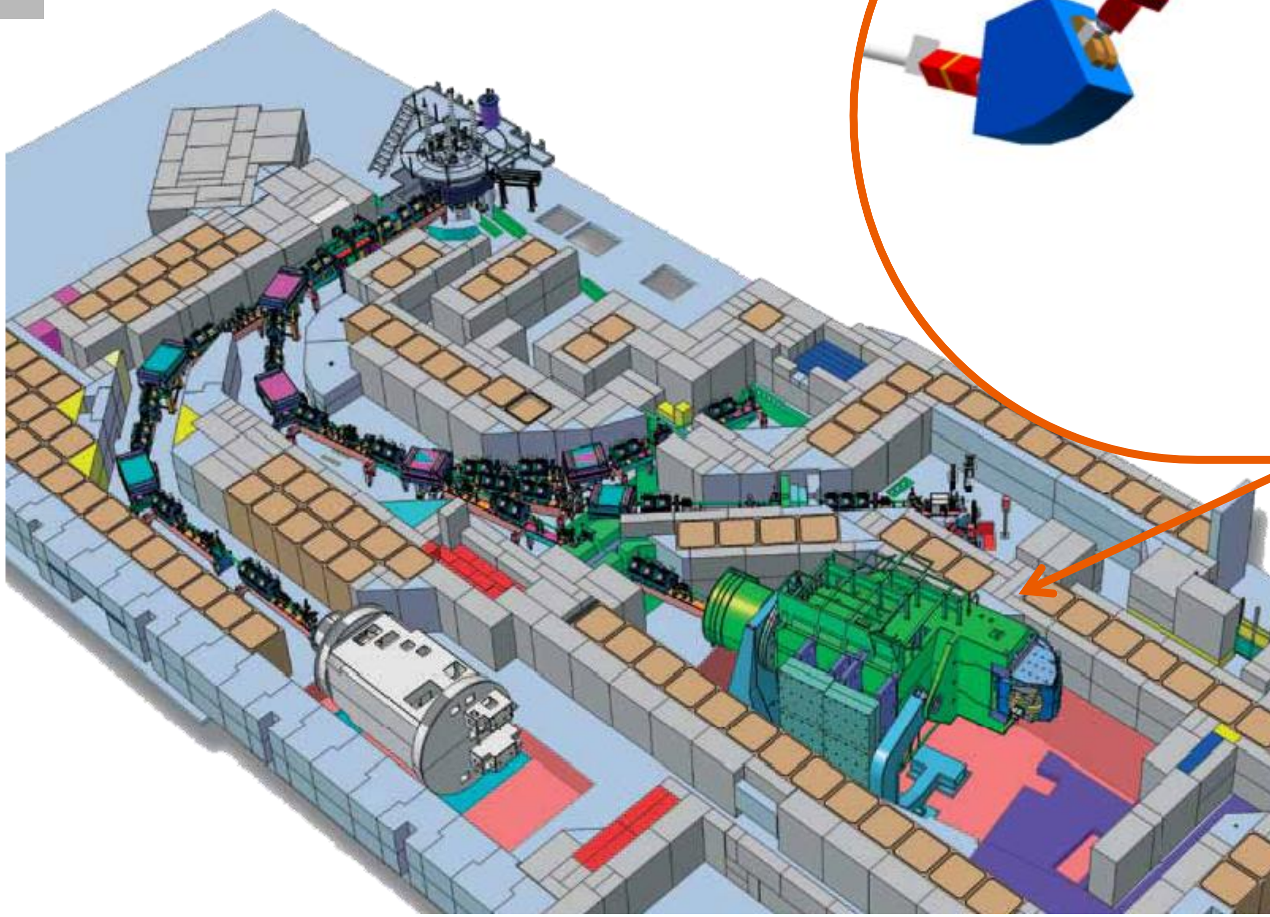
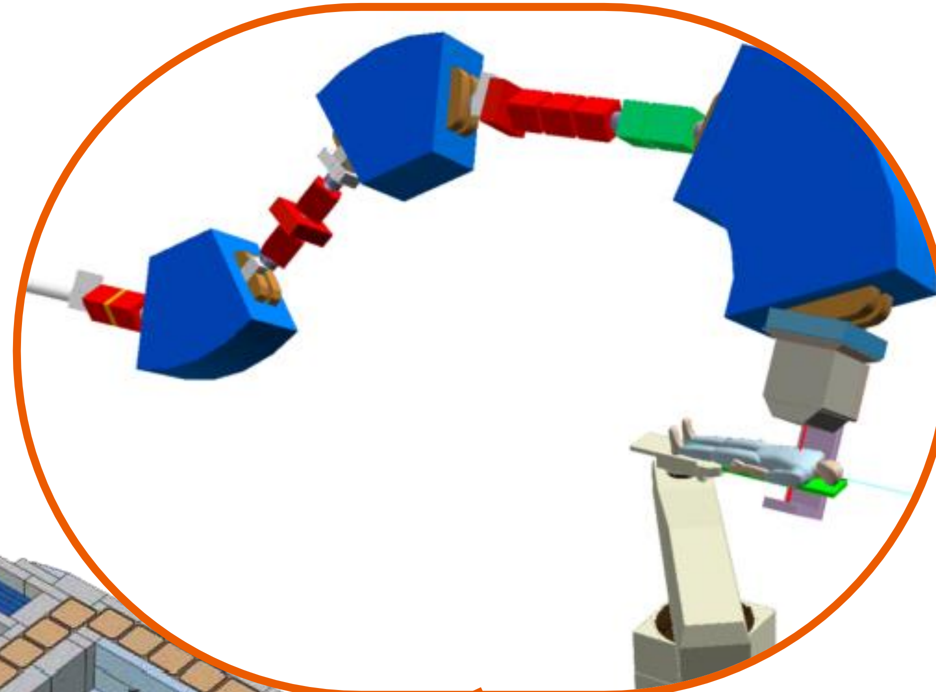
Background: proton therapy for (moving) tumours

The PROSCAN facility at PSI and Gantry 2

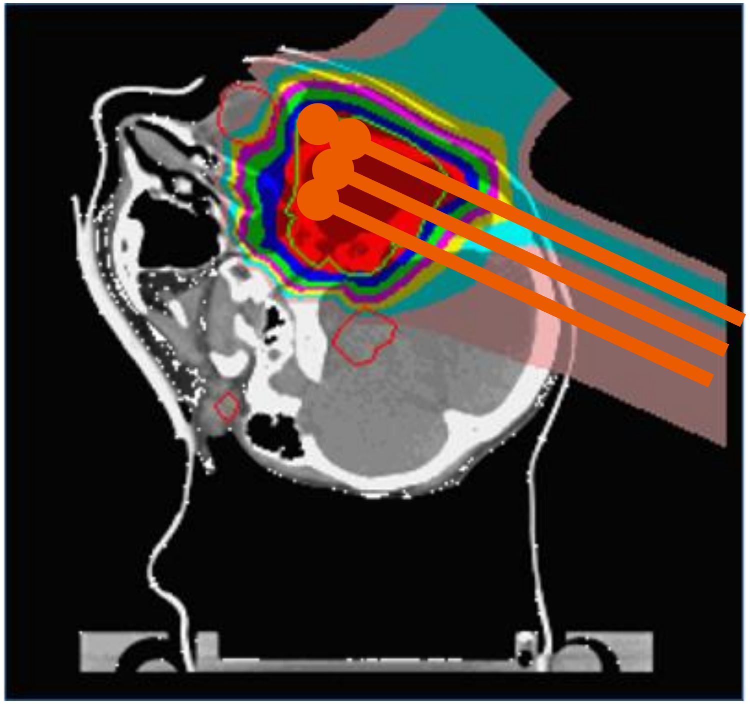




- 2 cm/ms max scan speed
- Max 1 nA beam current in treatment area (safety limit)

Proton therapy standard indications

- Proton therapy main indications: static tumours surrounded by sensitive organs (eg: brain tumours)
  - **Spot scanning** technique: beam is **moved sequentially through volume**, stopping in each position for the time needed to deliver the prescribed dose



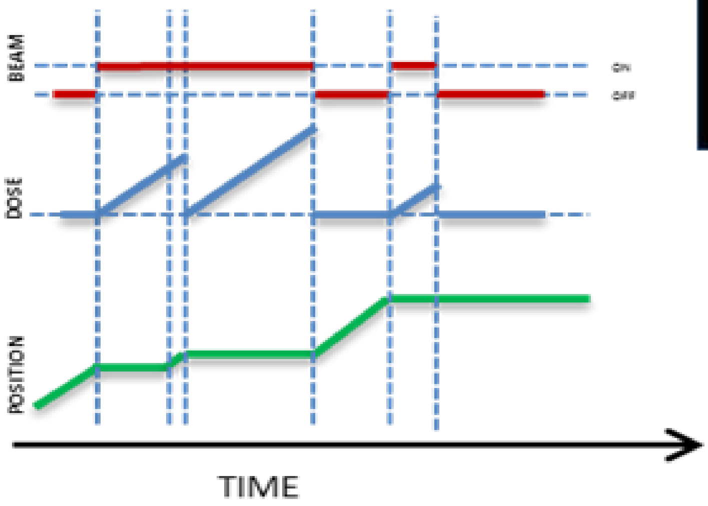
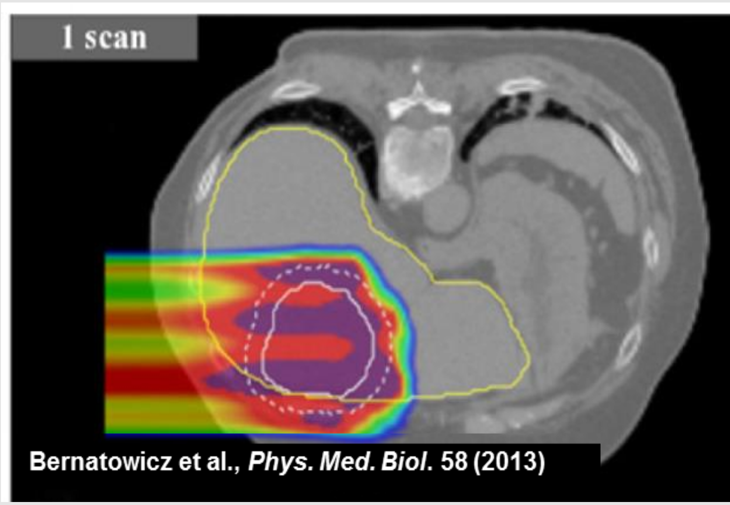
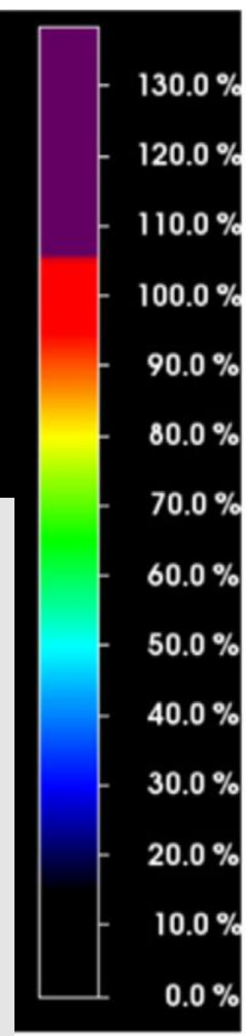


Image courtesy of Varian Medical Systems, Inc.

Moving tumours with proton therapy





Overdosage (clinically not acceptable)

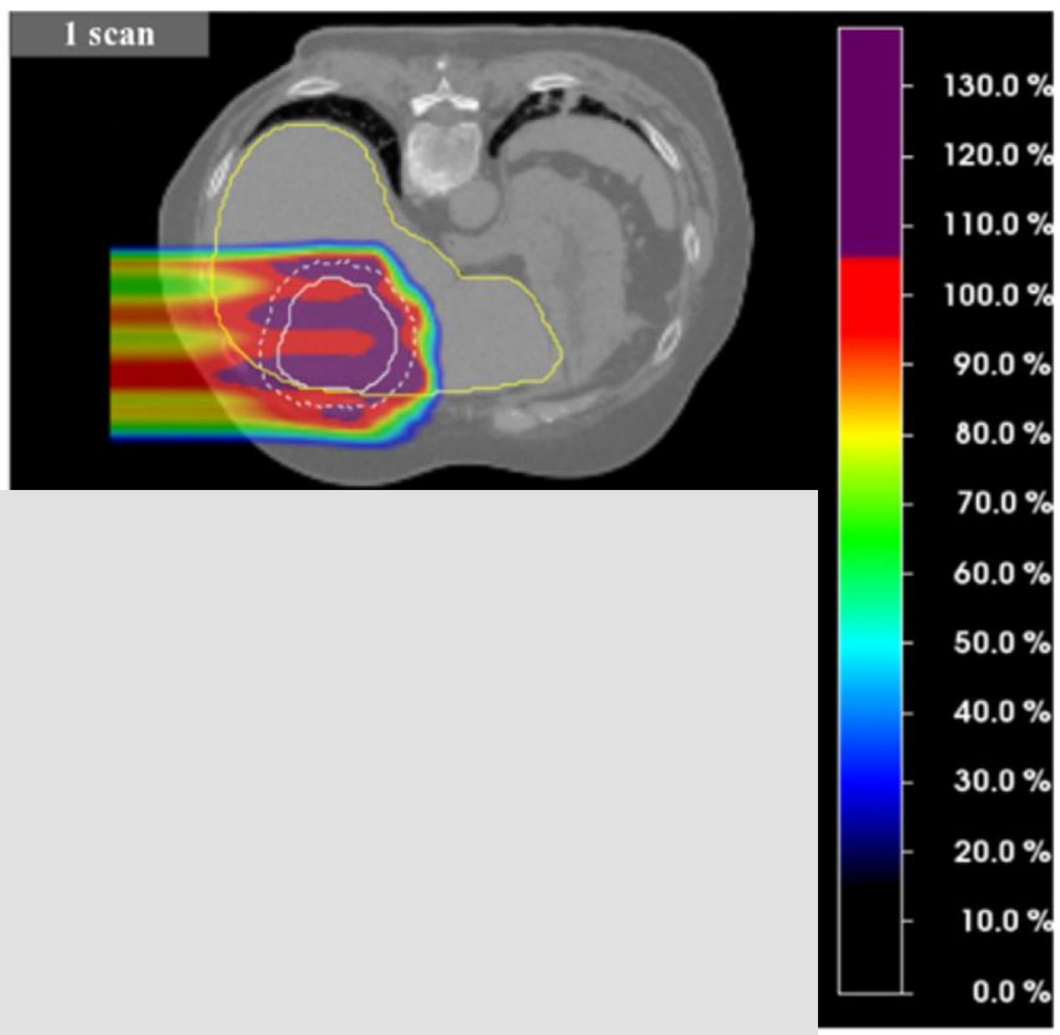
100 % = Target dose

Underdosage (clinically not acceptable)

Due to patient 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

Free breathing and rescanning



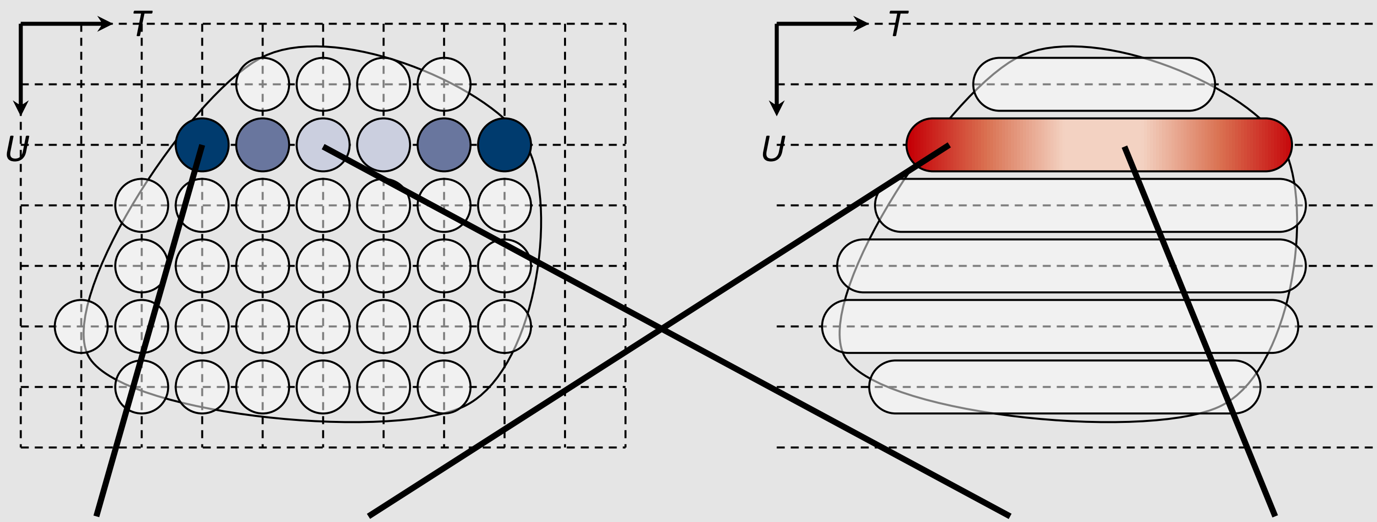
- Moving tumour require motion mitigation strategies
  – Eg: rescanning

- Price: longer treatment times!
- Goal: efficient beam

New technique for fast irradiation: continuous line scanning

Discrete spot scanning (SS):
Beam motion driven by integrated number of protons measured per spot

Continuous line scanning (CLS):
Full flexibility in speed and beam current modulation, known (monitored) at any time

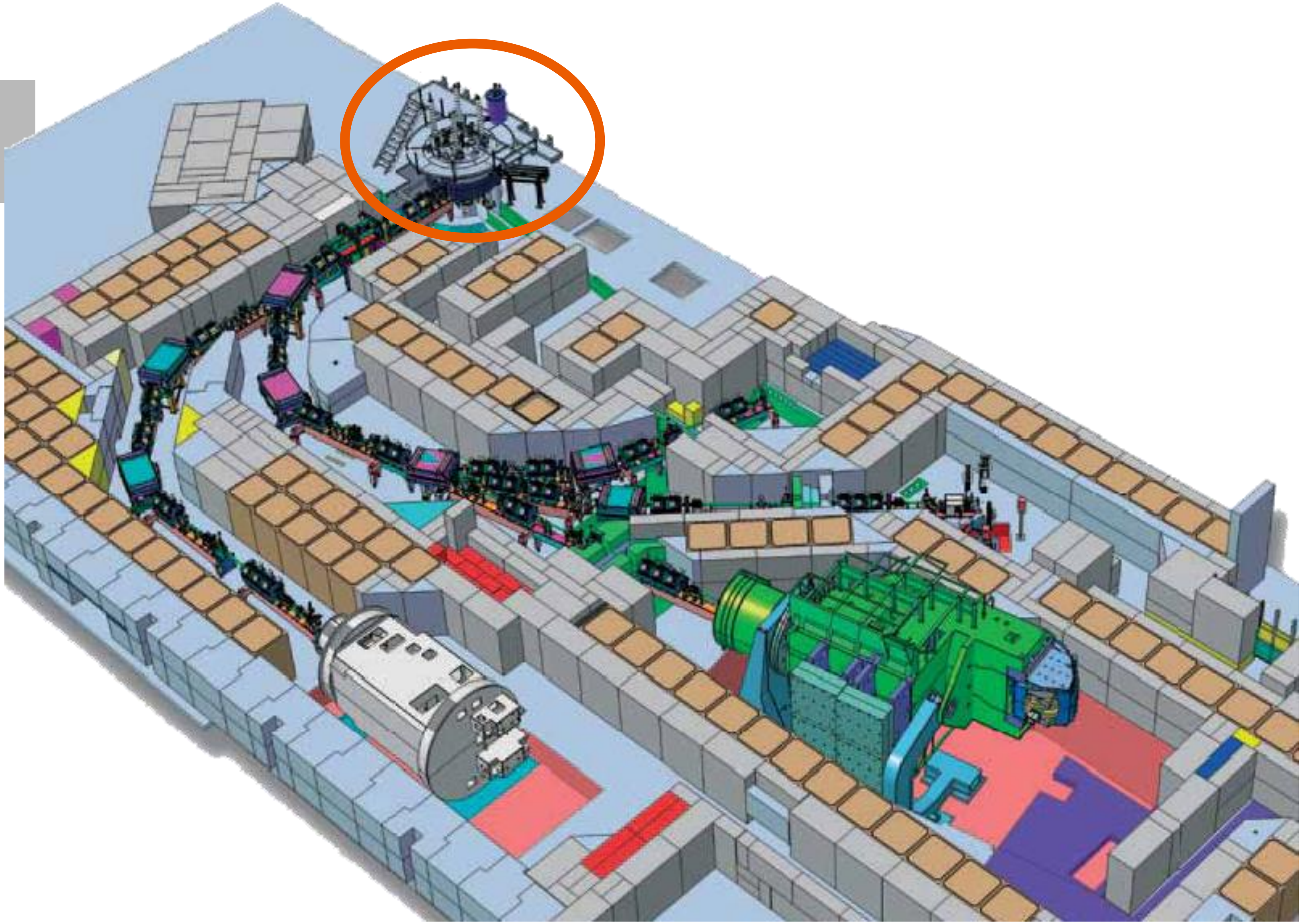


high dose ↔ low speed

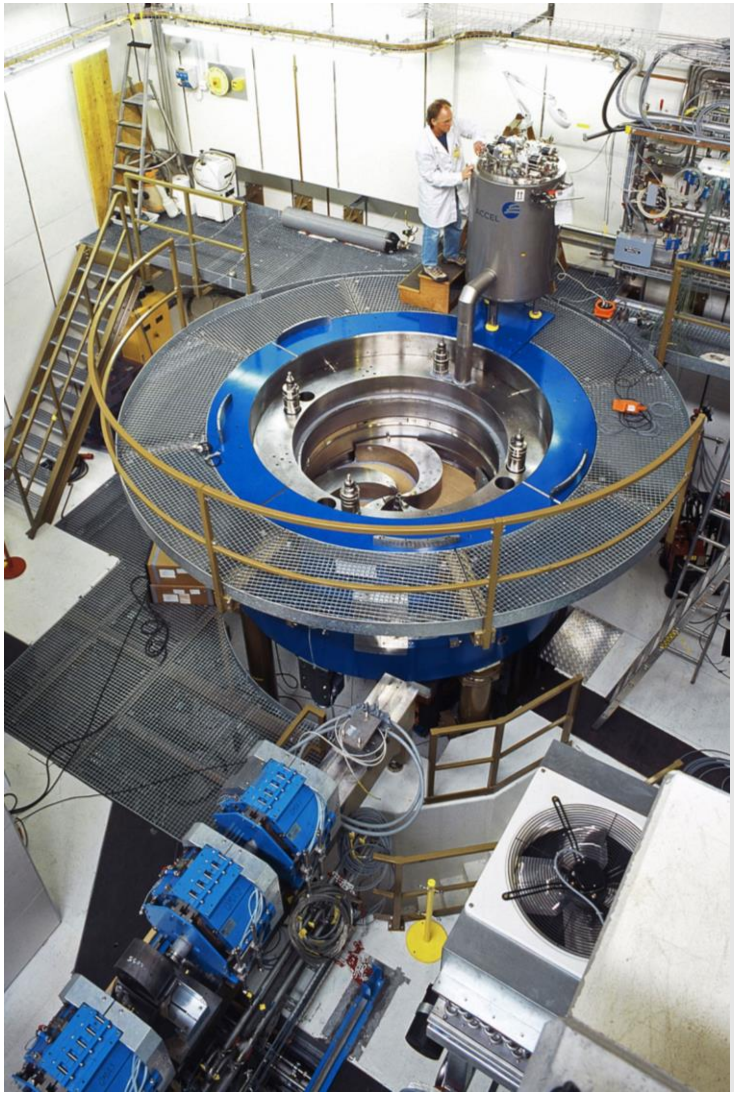
low dose ↔ high speed
+ additional current modulation directly from the accelerator

PSI design for CLS

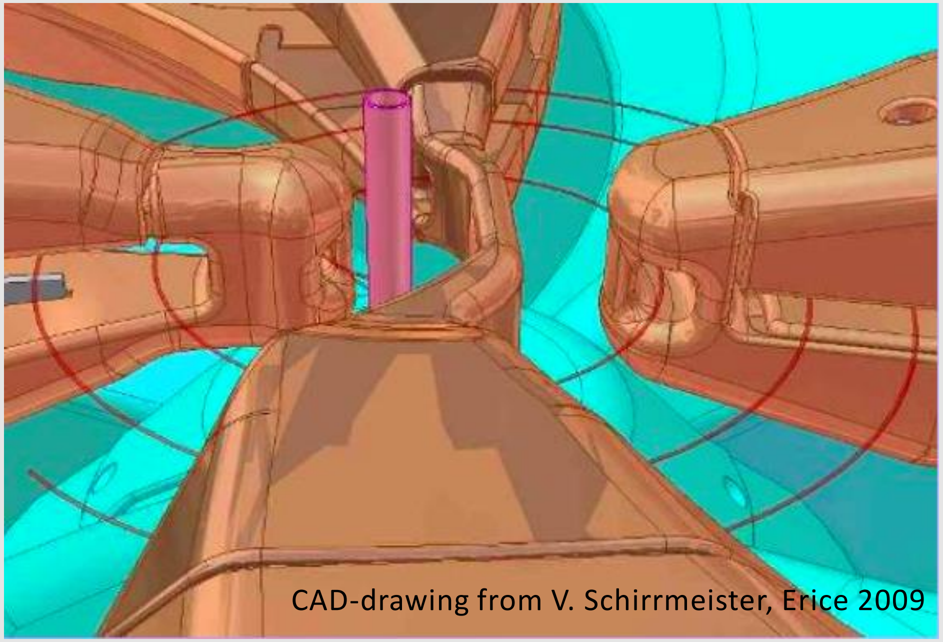
PROSCAN's cyclotron: COMET



COMET – COmpact Medical cycloTron

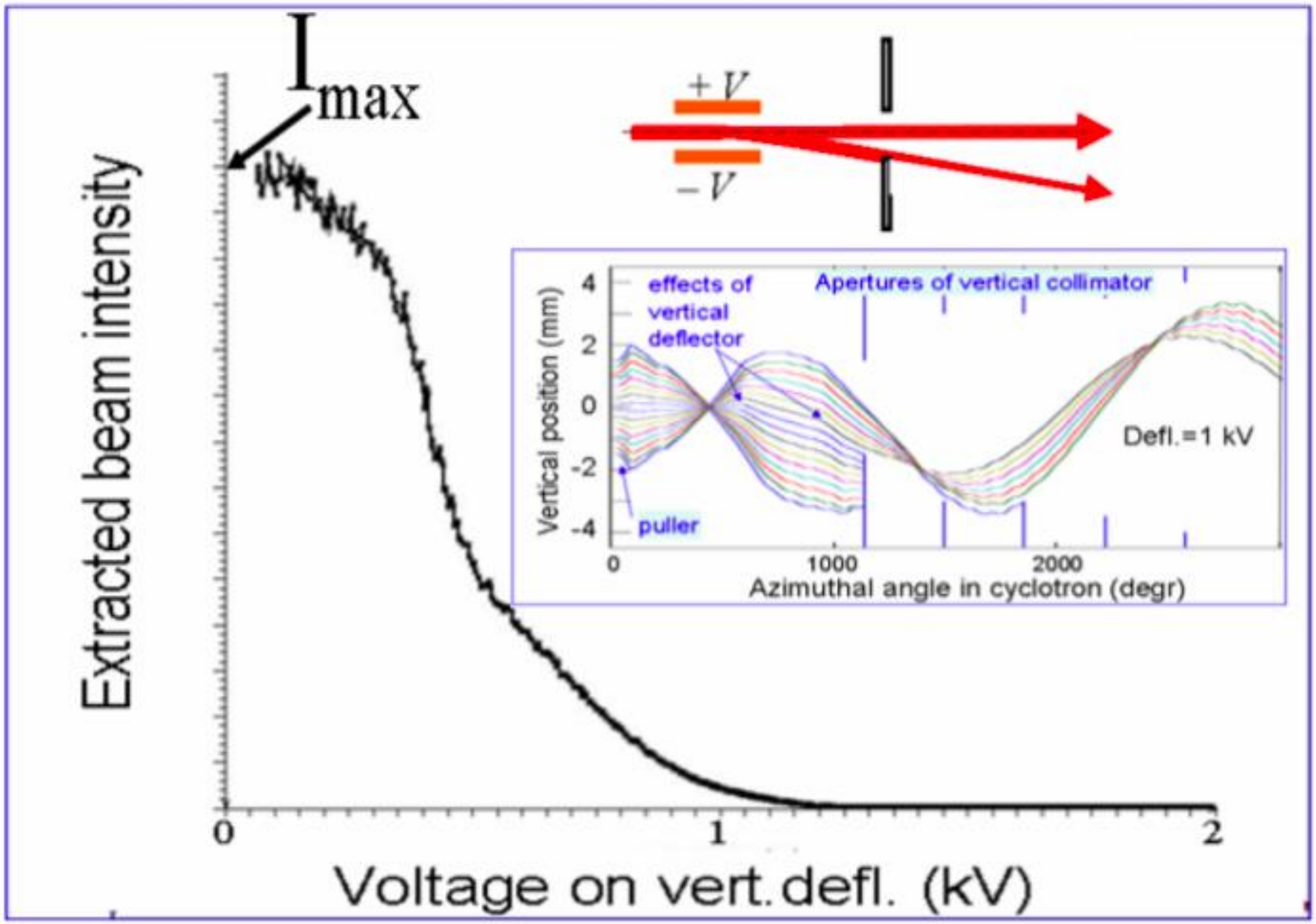


- Superconducting cyclotron (ACCEL/Varian)
- 250 MeV extracted beam, 24/7 operation
- Constant beam current extracted from ion source
- Beam intensity modulated with internal vertical electrostatic deflector



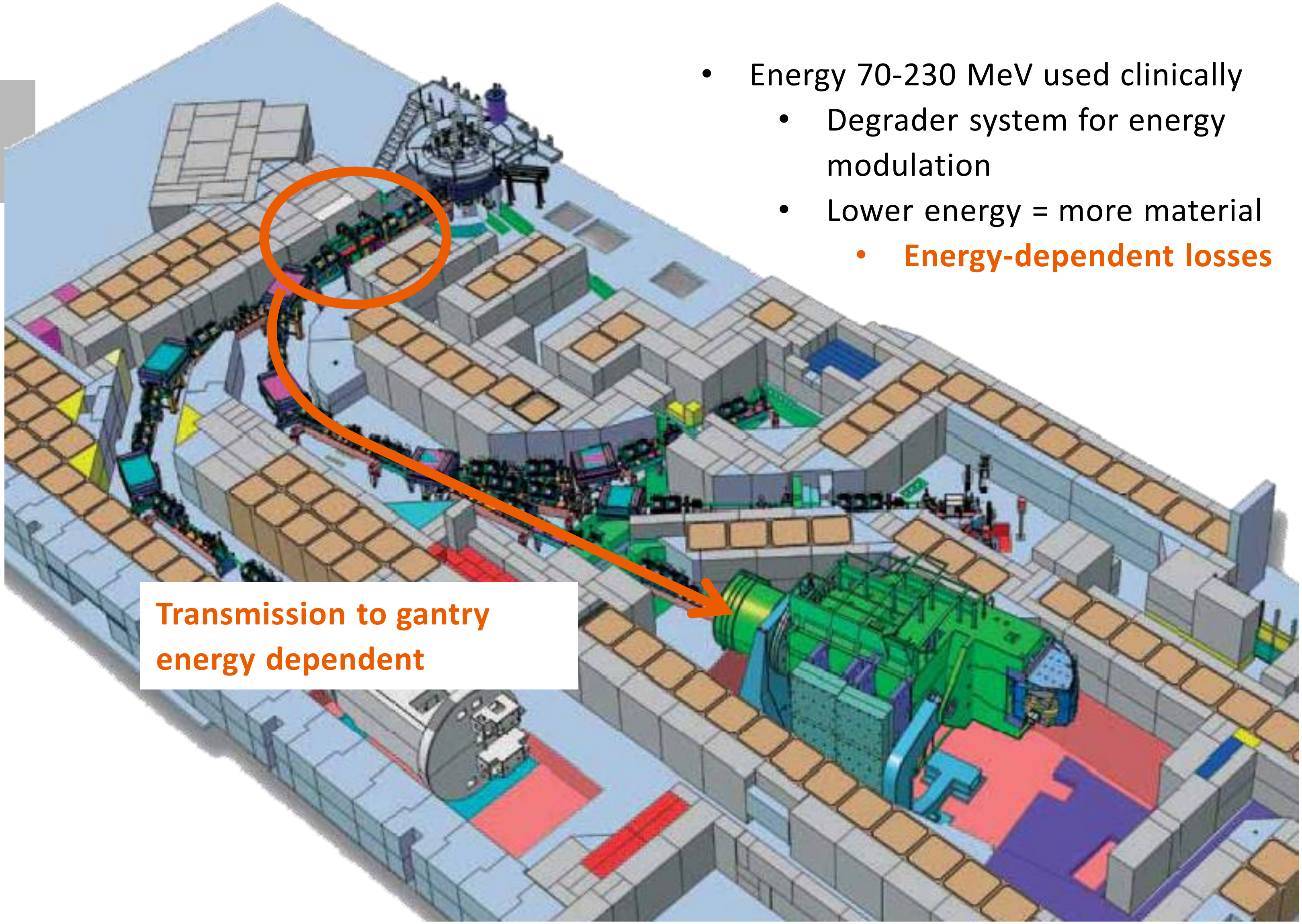
CAD-drawing from V. Schirrmeister, Erice 2009

Beam intensity modulation: vertical deflector + ‘chopper’



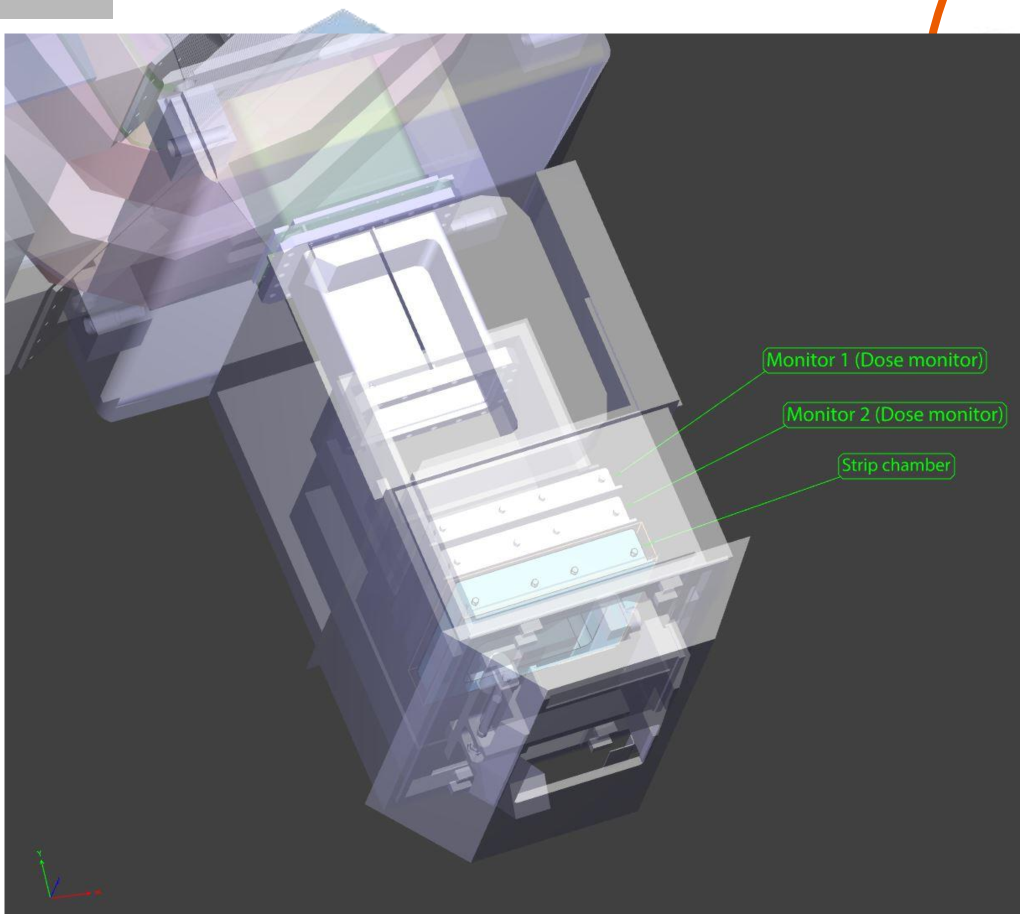
Schippers et al, FRM1CIO04 Proceedings of CYCLOTRONS 2010, Lanzhou, China

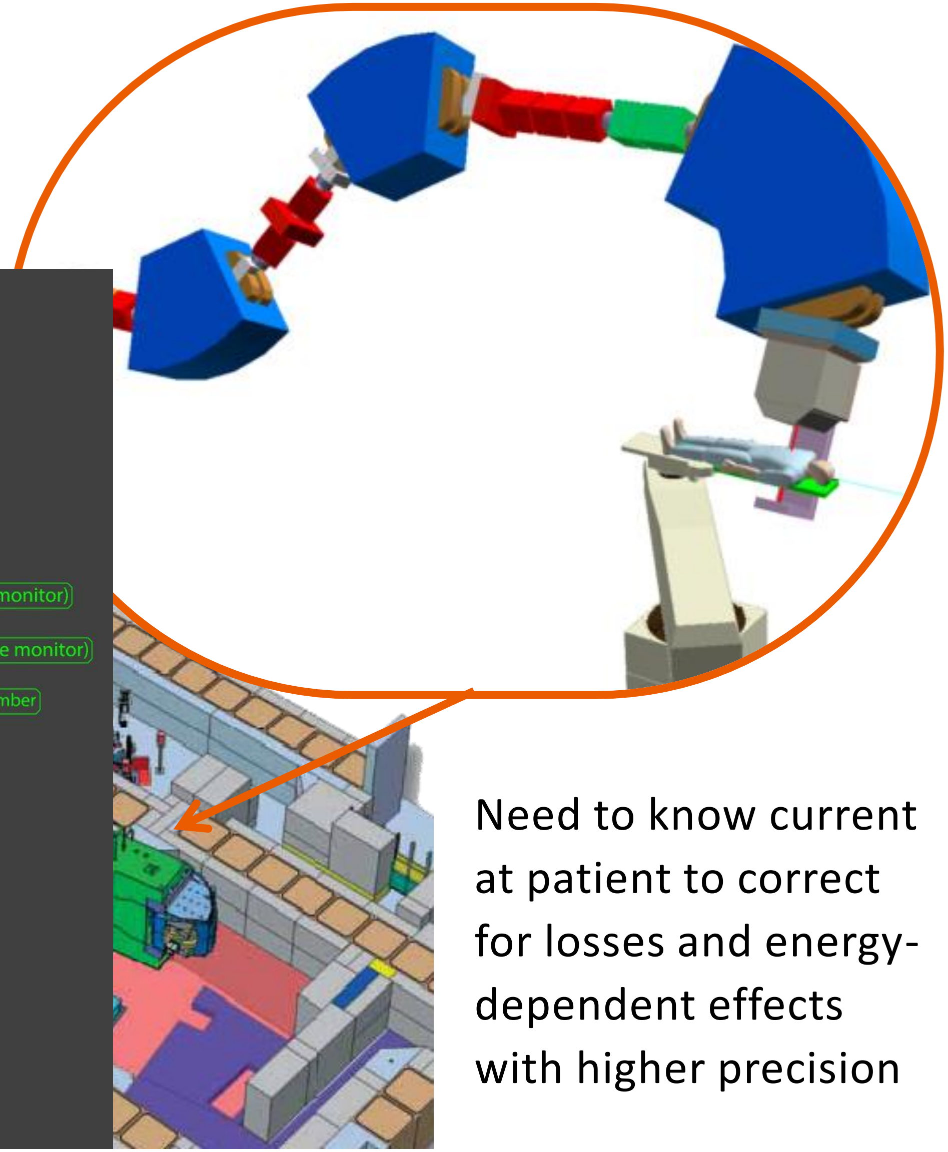
PROSCAN’s beam transport to Gantry 2



- Energy 70-230 MeV used clinically
  - Degrader system for energy modulation
  - Lower energy = more material
    - **Energy-dependent losses**

Beam current monitoring at Gantry 2

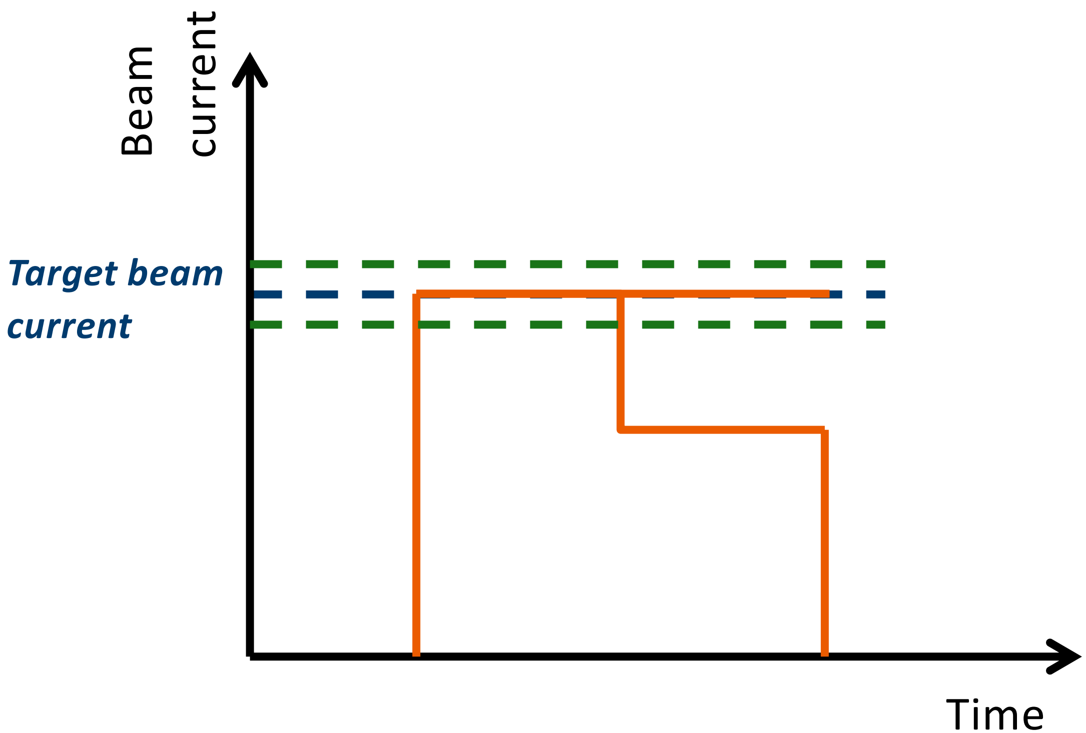




Need to know current at patient to correct for losses and energy-dependent effects with higher precision

Beam current control for CLS

What does CLS need in term of beam current control?



1. Turn on the beam, reach target beam current in minimum time (< 150 µs)
2. Keep current within tolerance, minimum deviation (few percent)
3. Realise fast, precise current modulation as required from treatment plan
4. Turn off the beam at end of field or in case of interlock as quickly as possible

To achieve maximum speed:
direct control of VD from control system

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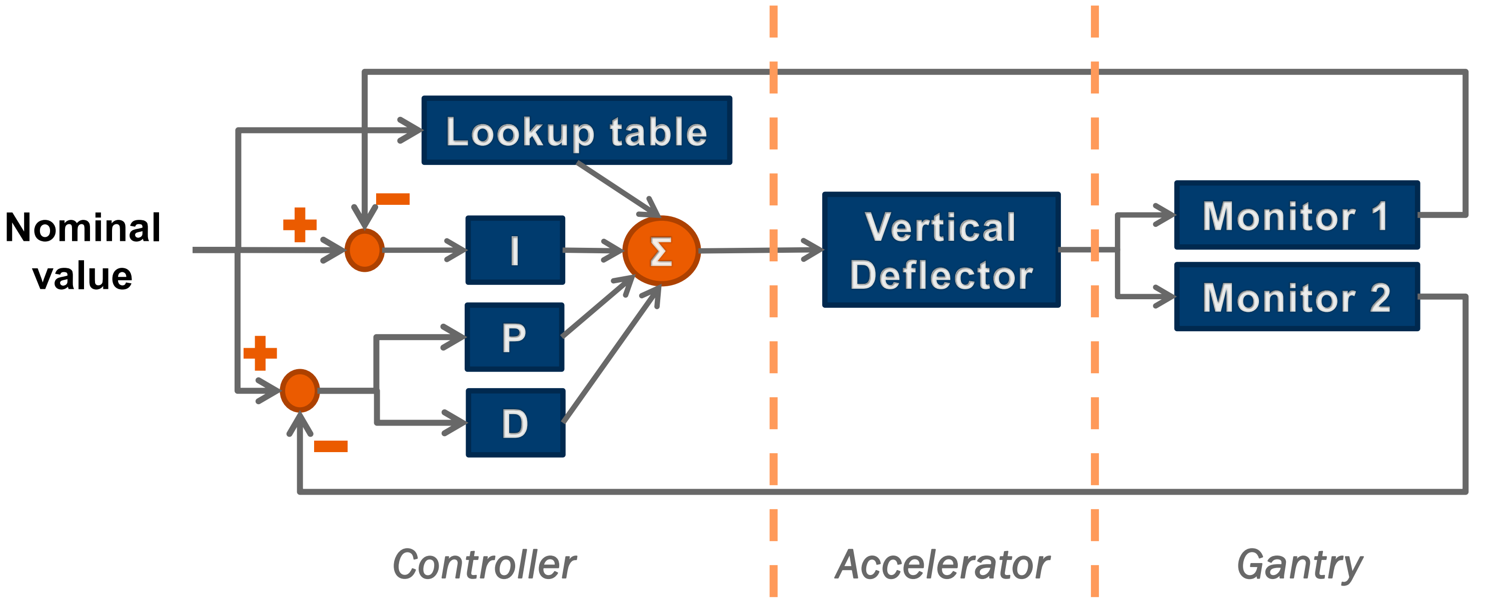
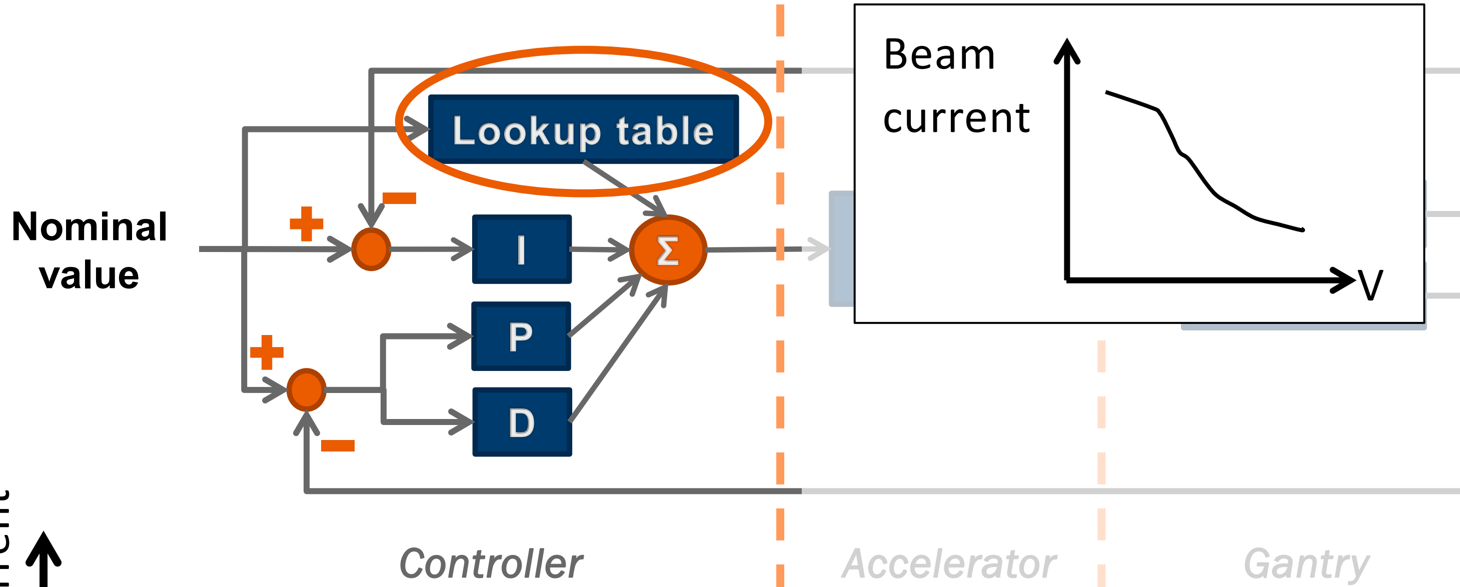
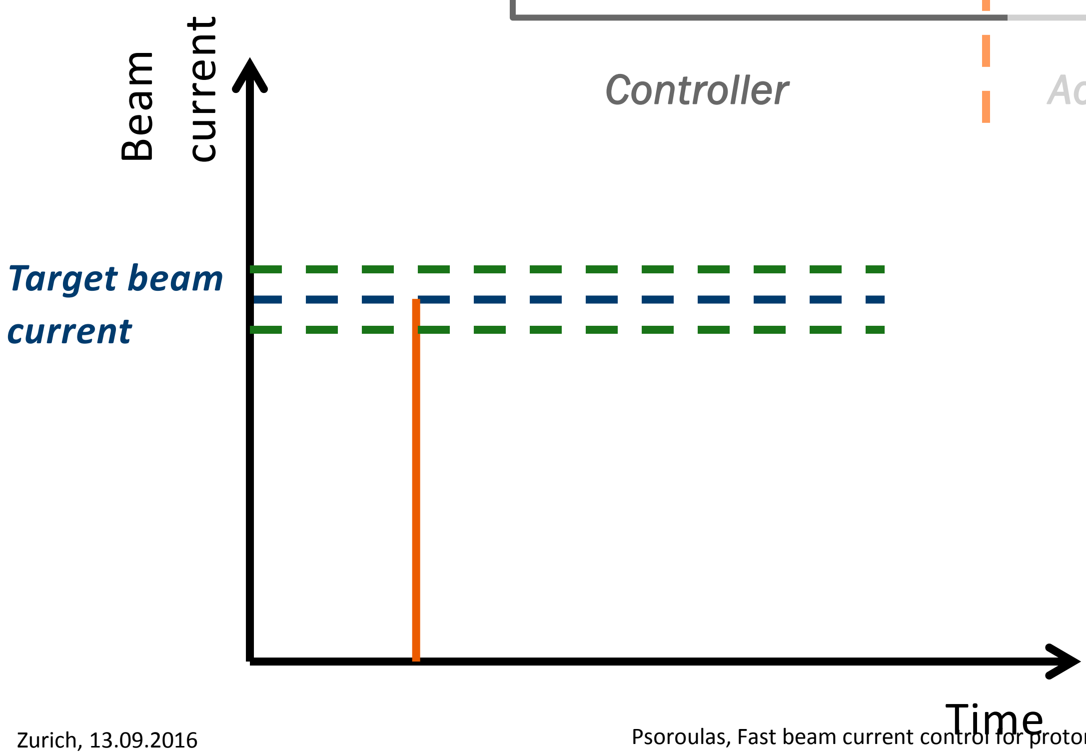
Intensity modulation control prototype



- Lookup table for feed forward, dual input for feedback
- Goal: beam current sets within monitor's charge collection time (<**150 µs**).
- Monitor sampling rate: 10 µs time resolution.

PID controller architecture: Feedforward

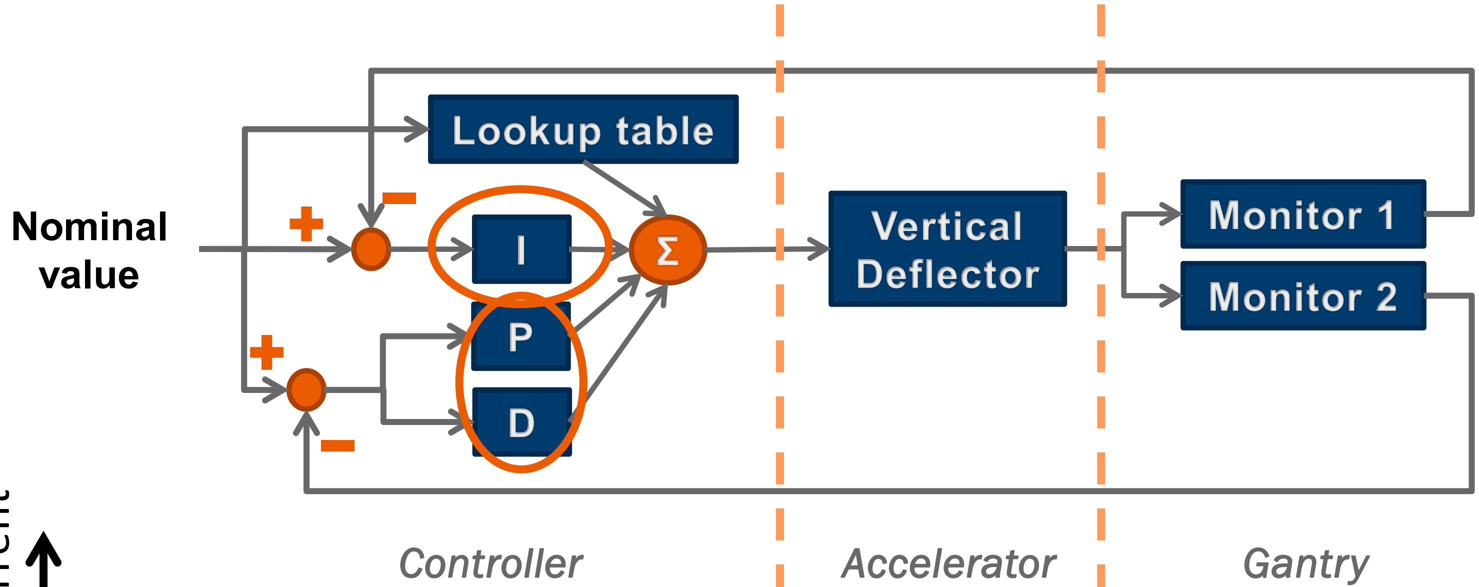


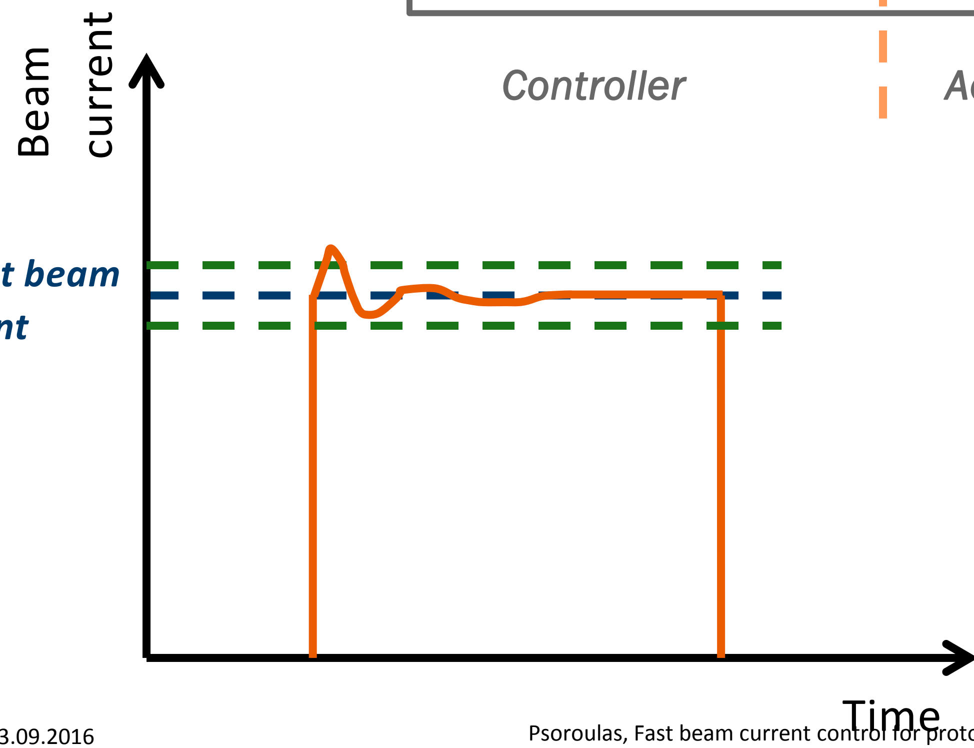


Feed Forward for faster settling time:

- lookup table vertical deflector voltage vs beam current at gantry
- built regularly (at least daily) to account for changes

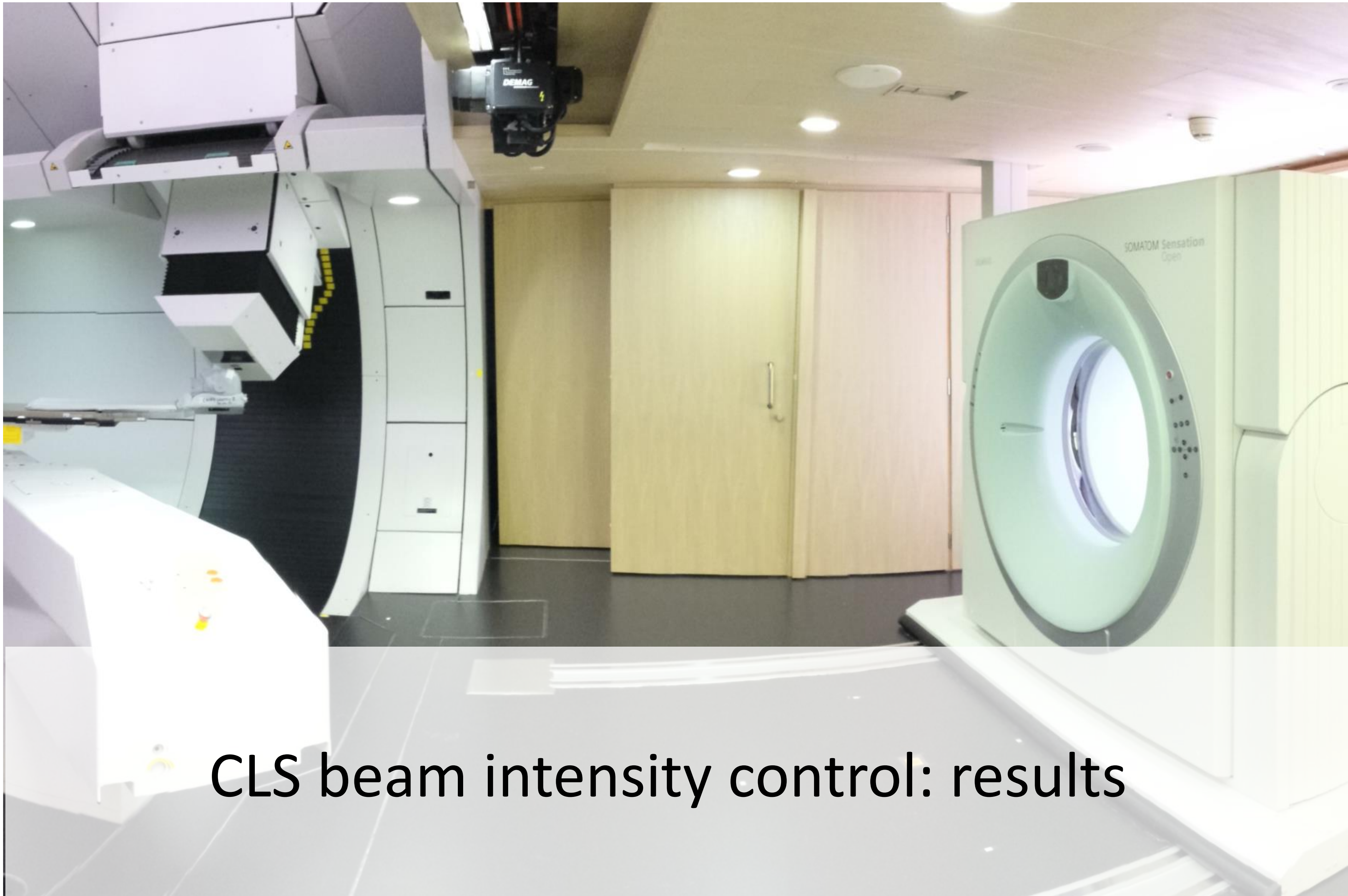
PID controller architecture: Feedback





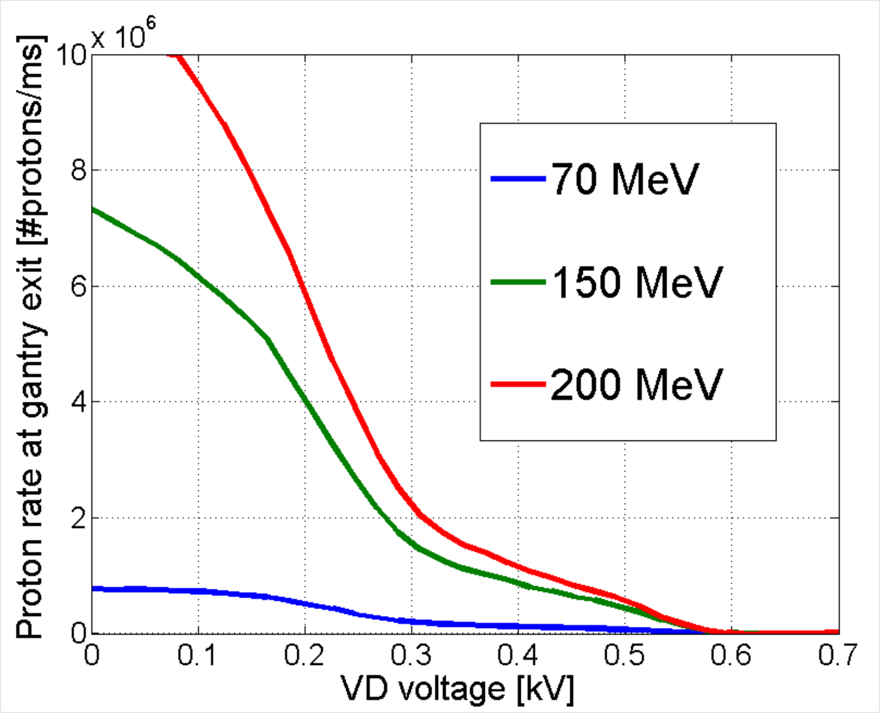
Feedback for beam current precision:

- Integral (*I*) controller fed by an accurate (but slow) beam current monitor
- a faster monitor feeds a proportional derivative (*P,D*) controller to reduce settling time after fast changes



CLS beam intensity control: results

VD lookup table characteristics

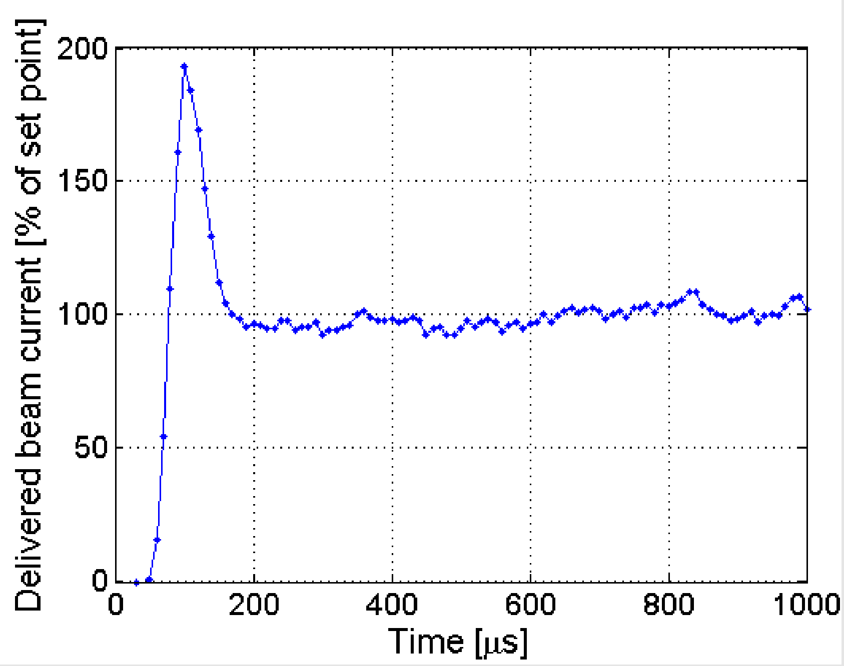


Beam current at patient strongly affected by energy

- Shape similar for all energies
- **Curves scale according to transmission**, easy to measure (e.g. during morning machine setup)

Low energies (**< 100 MeV**) suffer from low transmission: **improvements to optics/degrader material** under investigation, to improve transmission

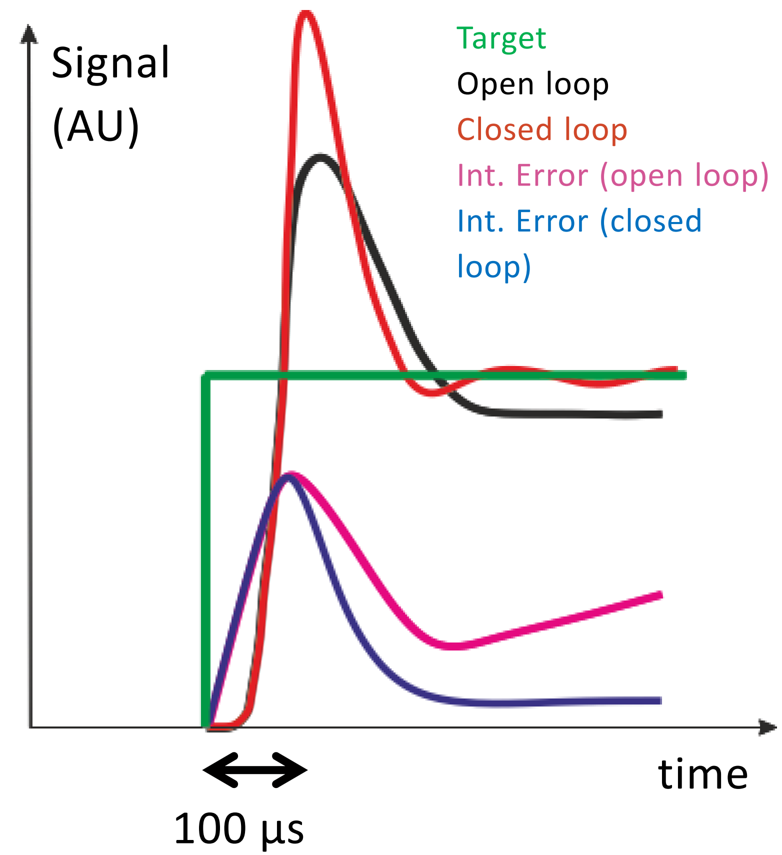
Open loop characteristics



- Observed **high beam current overshoots when setting the current in open loop** (only feedforward)
  - Reduce height: impedance match under investigation with PS supplier (SigmaPhi)
  - Limited room for reducing capacitance and improve timing (PS radiation damage)
- Improved feedforward: **LUT built using both overshoot and stable value from open loop measurements** (performed during machine setup)

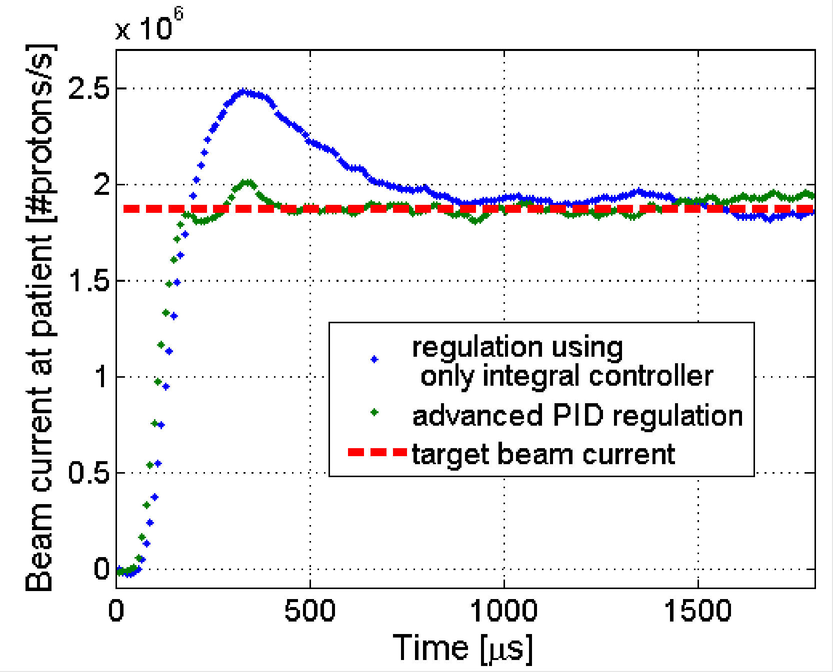
Regulation challenges in current design

- PS Overshoots must be corrected by the controller, but occur at the beginning of the line!
- **Regulation performance dominated by slowest dose monitor**:
  - Collection time, electronics rise time etc affect speed of correction
  - High integrator gain causes overcorrection and instabilities
- Both PS overshoot and monitor delay cause a **large error since the beginning of the line**
  - Faster monitor: reduce reaction time
  - LUT built from overshoot and average values: better first estimate

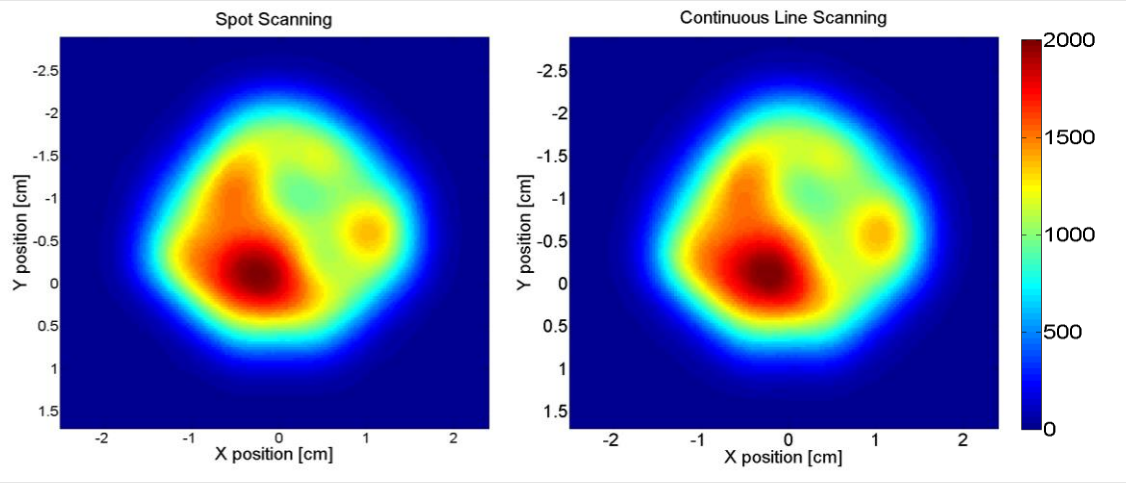


Performance of improved feedforward and dual input for feedback

- Improved regulation loop:
  - Less dependence on overshoot height: it is accounted for in the LUT
  - Faster rise time – faster reaction to changes
  - **Set current reached within 150 microseconds**



Comparison spot vs line scanning – delivery of global fields (study ongoing)



Dose transverse to the primary beam direction from the gantry is measured with a scintillating screen coupled to a CCD camera.

Further investigation towards clinical application:

- *Safety system* (monitoring, handling of interlocks)
- *Performance with motion mitigation techniques*
- *Treatment planning*

Psoroulas et al., PTCOG 2016; Klimpki et al., ICTR-PHE 2016; Fattori et al., AAPM 2016

Conclusions

- Continuous Line scanning is the ideal candidate for motion mitigated pencil beam scanning with protons
- ***High sensitivity to beam conditions: need good control of beam intensity***

- Beam intensity control at the COMET cyclotron and Gantry 2:
  - Vertical Deflector inside the cyclotron used for ***fast beam modulation***
  - Challenge of the setup: cope with PS overshoot and limited monitor reaction time with ***improved feedforward design and dual input for feedback***

- ***Future steps***:
  - Fine tune precision of the system to achieve best performance
  - ***Further development towards clinical application*** (monitoring, motion management etc)

Open to new indications – while keeping delivery efficiency