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Grischa Klimpki :: Center for Proton Therapy :: Paul Scherrer Institute

Verification of highly dynamic dose delivery

EuCARD² Workshop on Innovative Delivery Systems in Particle Therapy

Molecular Biotechnology Center, Torino, February 24, 2017

Why do we need a verification system?

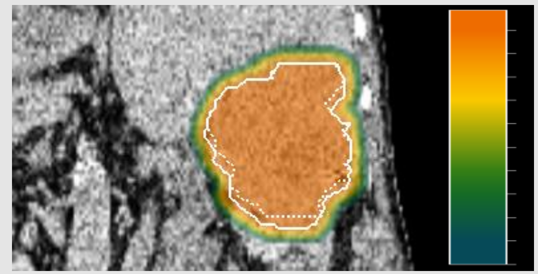
http://phandroid.s3.amazonaws.com/wp-content/uploads/2016/09/galaxy-note-7-2.jpg

intro

What is highly dynamic dose delivery?

Clinical example

- liver tumor (460 ccm)
- single field (0.6 Gy)



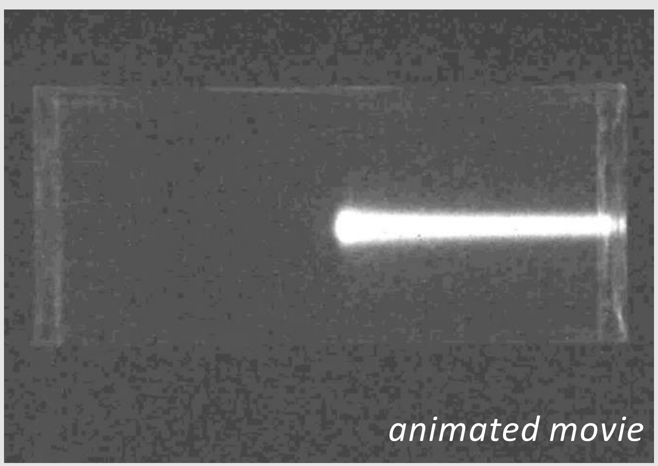
100%

50%

0%

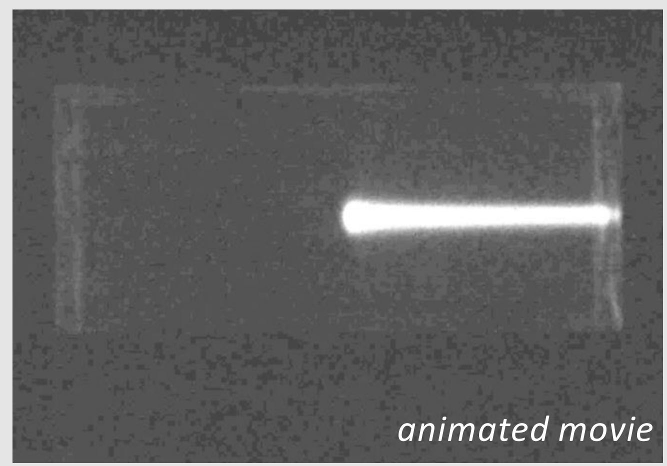
discrete scanning

52 sec.



continuous scanning

26 sec.



What is highly dynamic dose delivery?

Fast and flexible form of patient irradiation

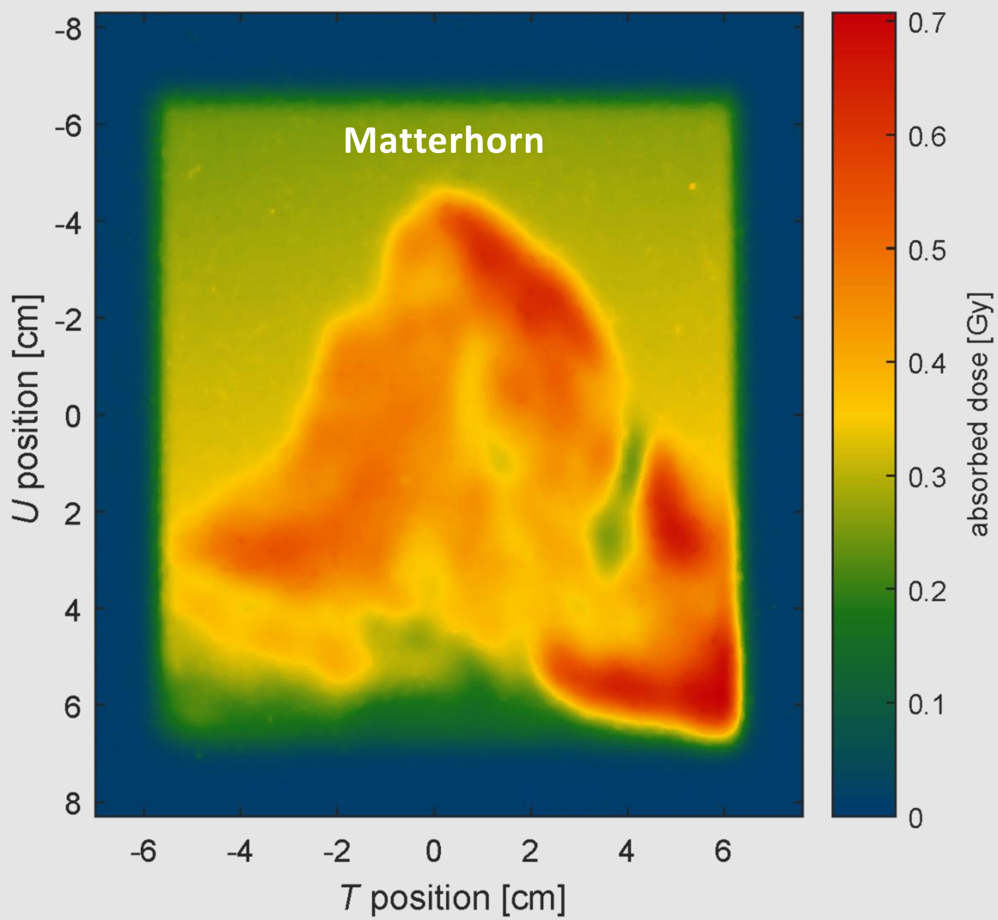
F A S T

- (quasi) continuous beam of high current (~ 5 nA)
- high duty cycle ($\Delta t_{beam}/\Delta t_{total}$ > 75%) due to:
  (a) minimized energy switching time (~ 100 ms)
  (b) continuous lateral scanning (speed ~ 2 cm/ms)

F L E X I B L E

- steer beam to any point in the lateral plane
- modulate lateral scan speed at any time
- modulate beam current at any time

What is highly dynamic dose delivery?



- delivery of arbitrary dose distributions
- high dose modulation
- fast, yet accurate irradiation
- regulation in real-time

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Which requirements arise?

S A F E T Y

- less beam-off intervals
  → non-destructive verification in real-time
- high modulation in beam current and scan speed
  → independent supervision of both quantities
- redundant checks whenever beam is off

H A R D W A R E

- frequent modulation of beam current
  → fast ionization chambers (ICs) (< 100 µs)
- scanning fast with reduced beam current
  → regions of very low dose
  → weak signal in position-sensitive ICs

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Which requirements arise?

present our implementation

for a *cyclotron-based* and

***time-driven* delivery system**

Gantry 2

PSI Gantry 2

PSI Gantry 2

- Patient treatments since November 2013 using **pencil beam scanning**

- Current mode operation: **discrete scanning**

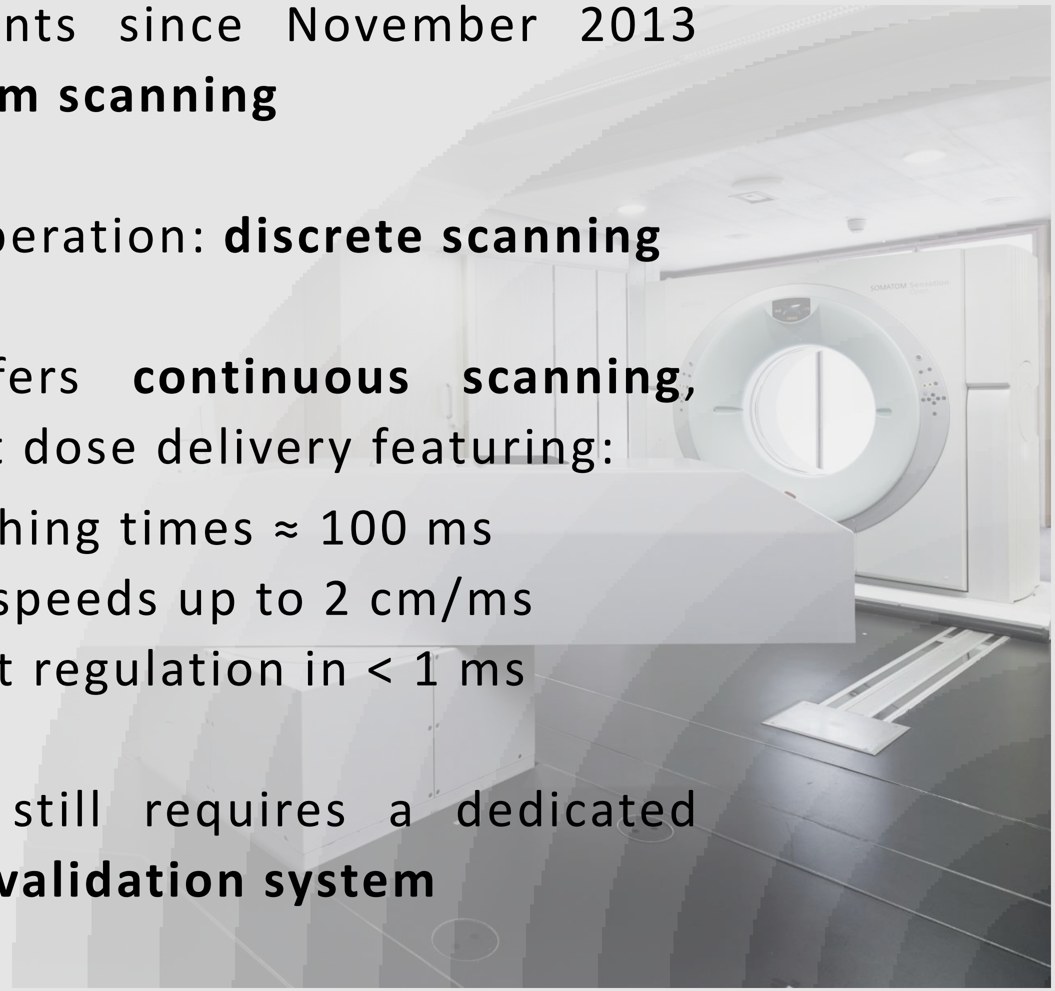
- Additionally offers **continuous scanning**, designed for fast dose delivery featuring:

  (a) energy switching times ≈ 100 ms

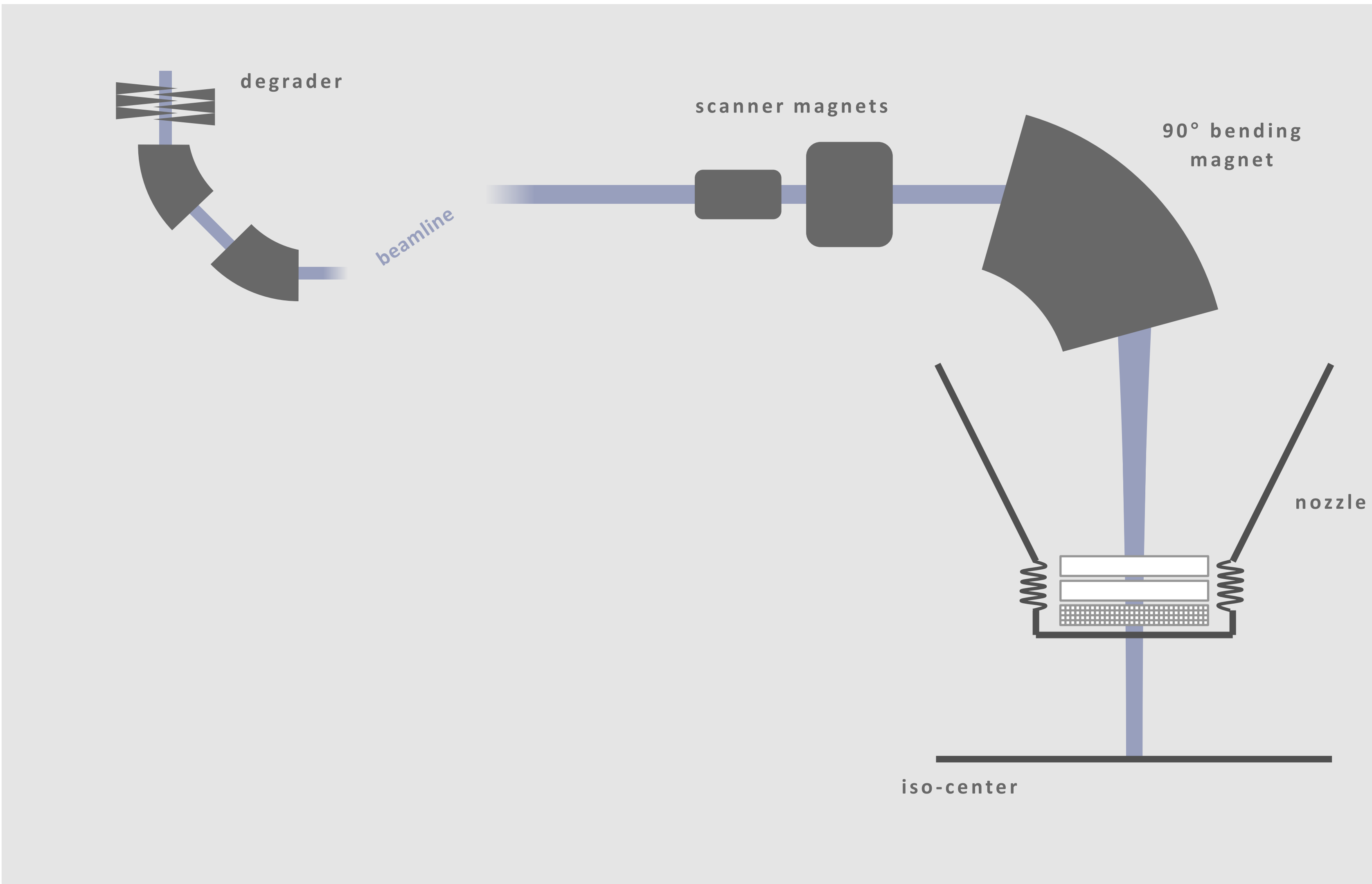
  (b) lateral scan speeds up to 2 cm/ms

  (c) beam current regulation in < 1 ms

- Clinical go-live still requires a dedicated **monitoring and validation system**



Beam monitors for continuous scanning



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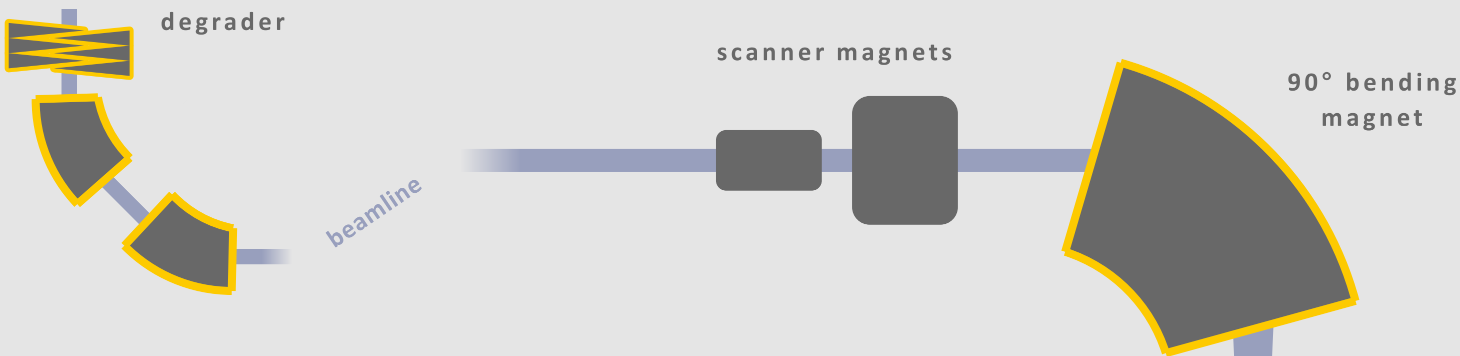
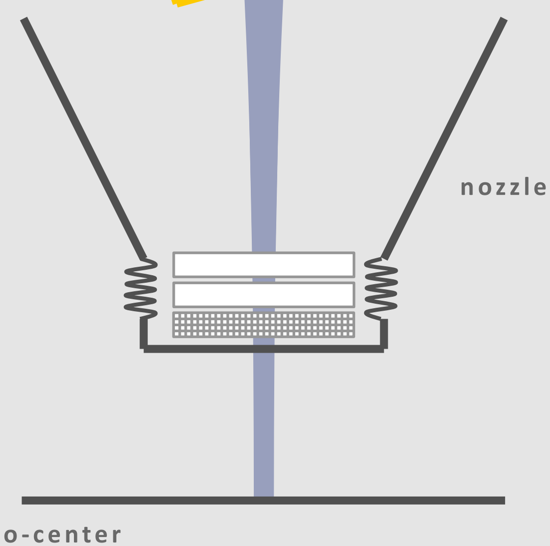


- **Energy:** selection & tuning

  (Hall probes, potentiometers)



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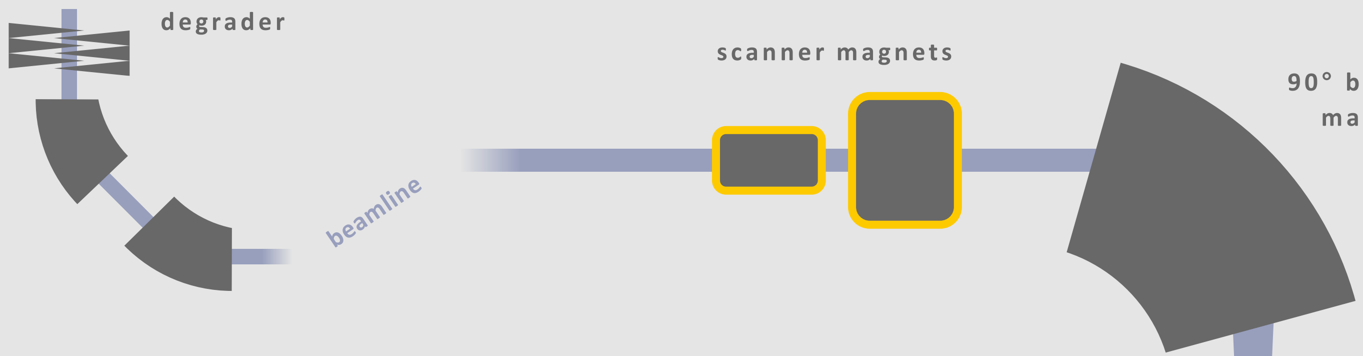

- **Energy:** selection & tuning

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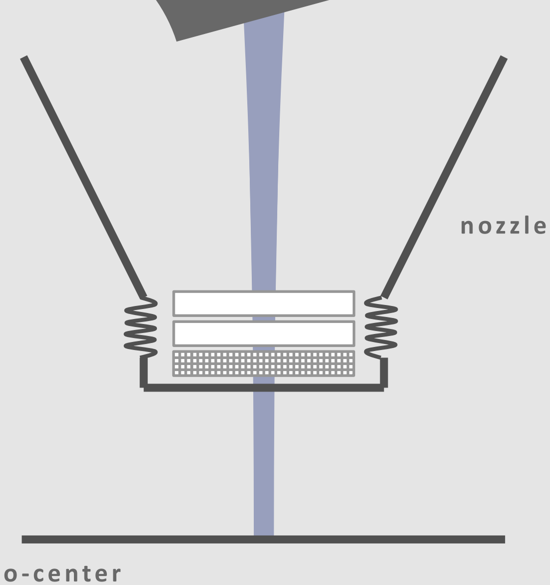
- **Position:** Hall probes

  (one-axis, SENIS)



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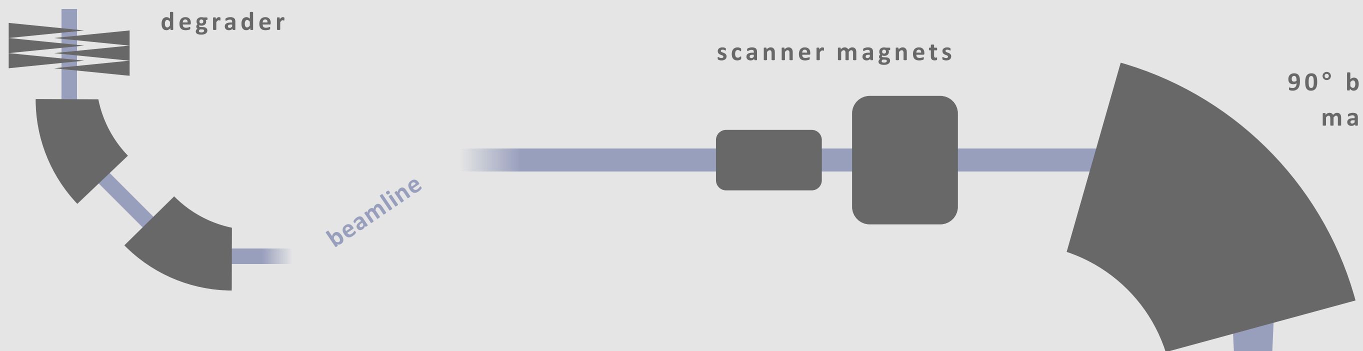

- **Energy:** selection & tuning

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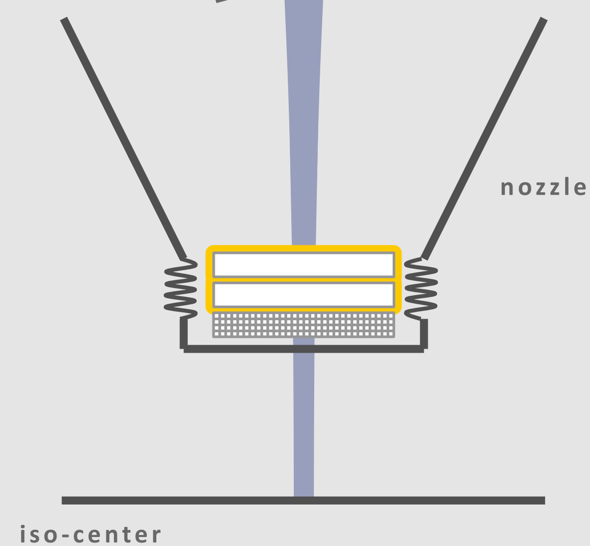
- **Position:** Hall probes

  (one-axis, SENIS)

- **Dose:** parallel-plate ICs

  (90/350 µs charge collection)



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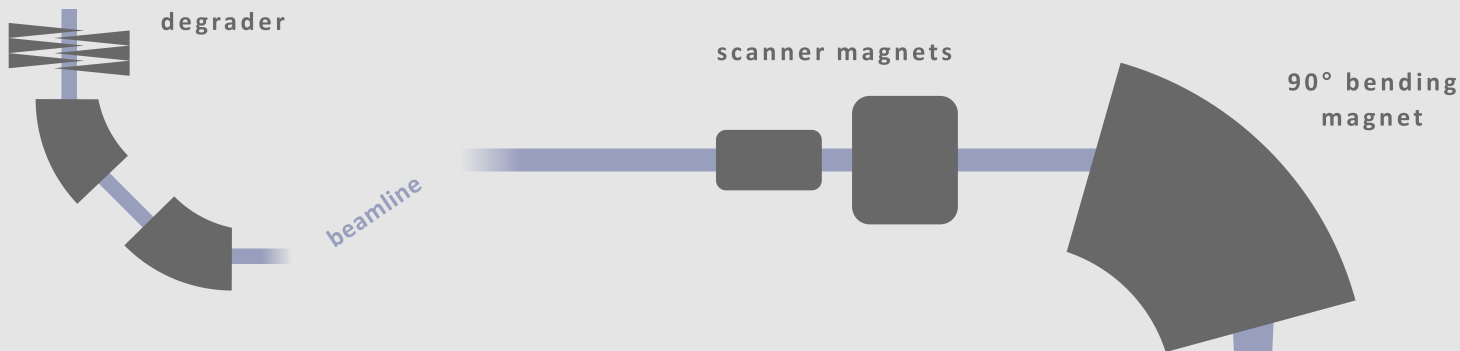

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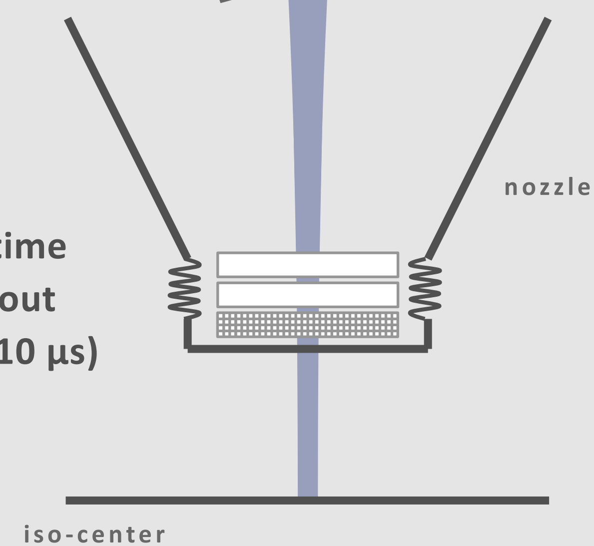
real-time readout (every 10 µs)



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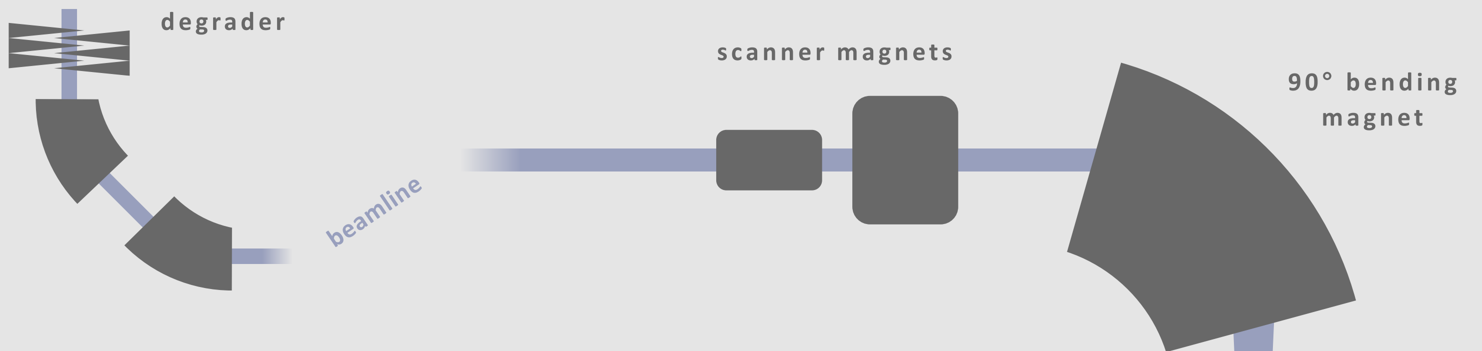

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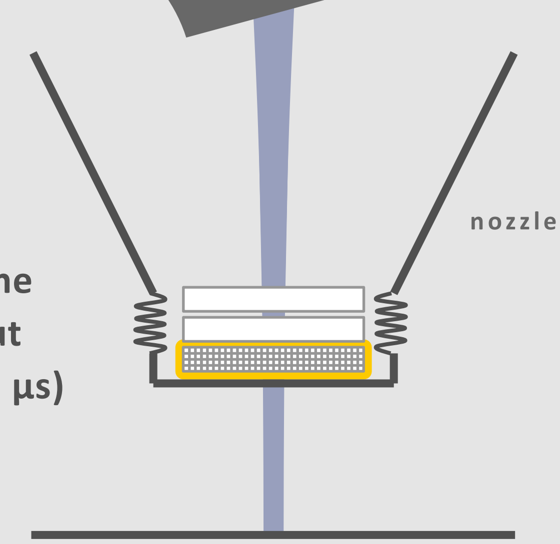
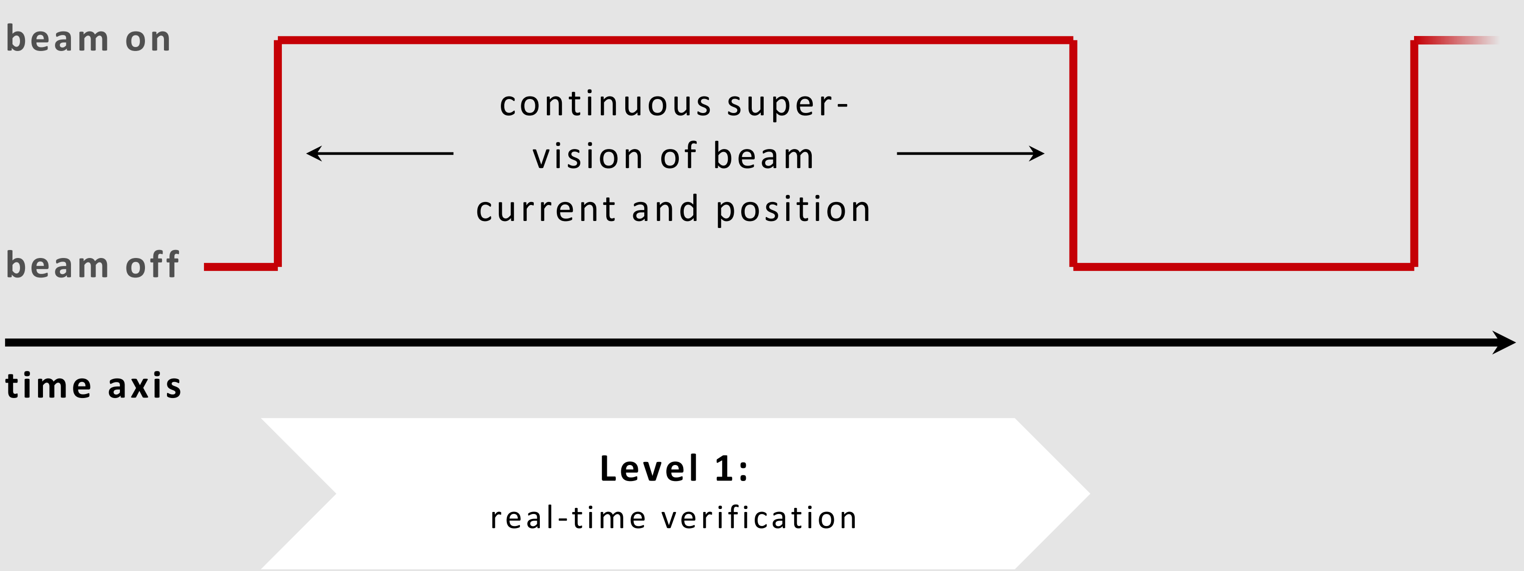
  (Hall probes, potentiometers)
- **Position:** Hall probes
  (one-axis, SENIS)
- **Dose:** parallel-plate ICs
  (90/350 µs charge collection)
- **Shape:** strip monitor
  (88 x 128, 2 mm strip width)

real-time readout (every 10 µs)



Verification concept

- **Level 1:** Real-time verification *during* the application of a line to prevent *radiation incidents*



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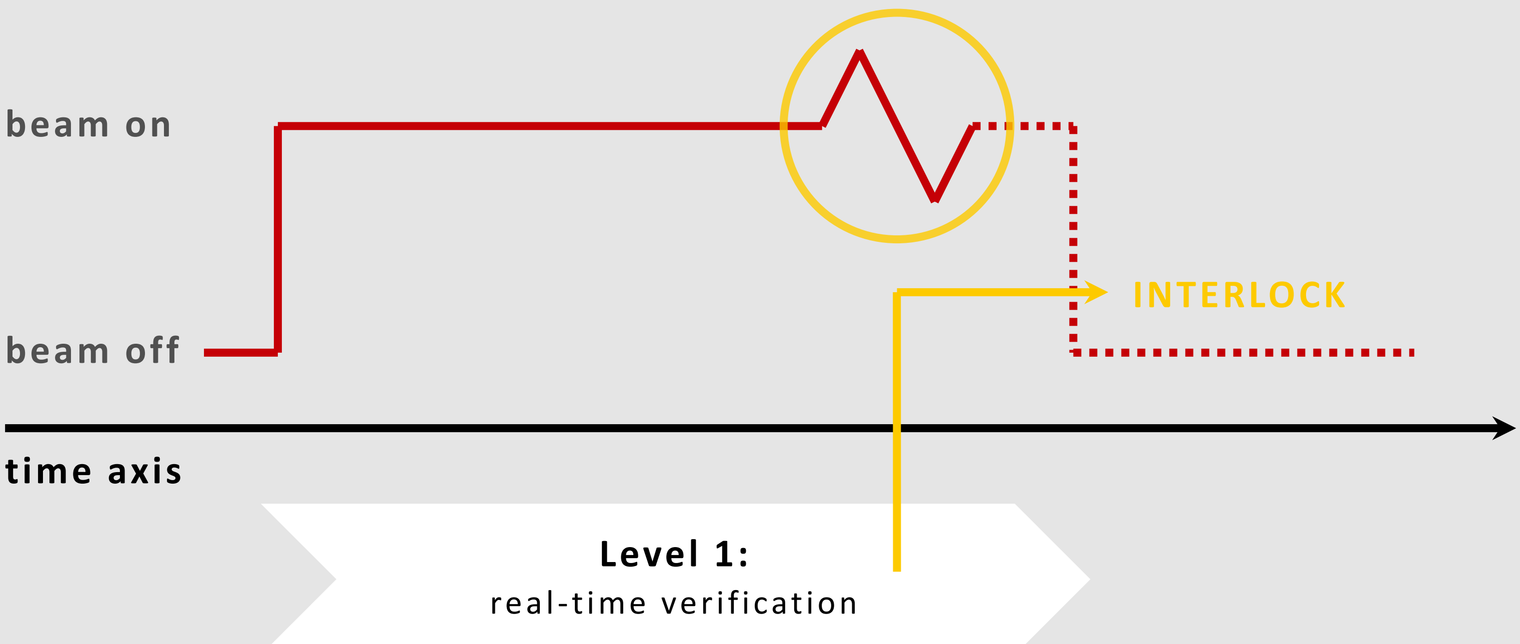
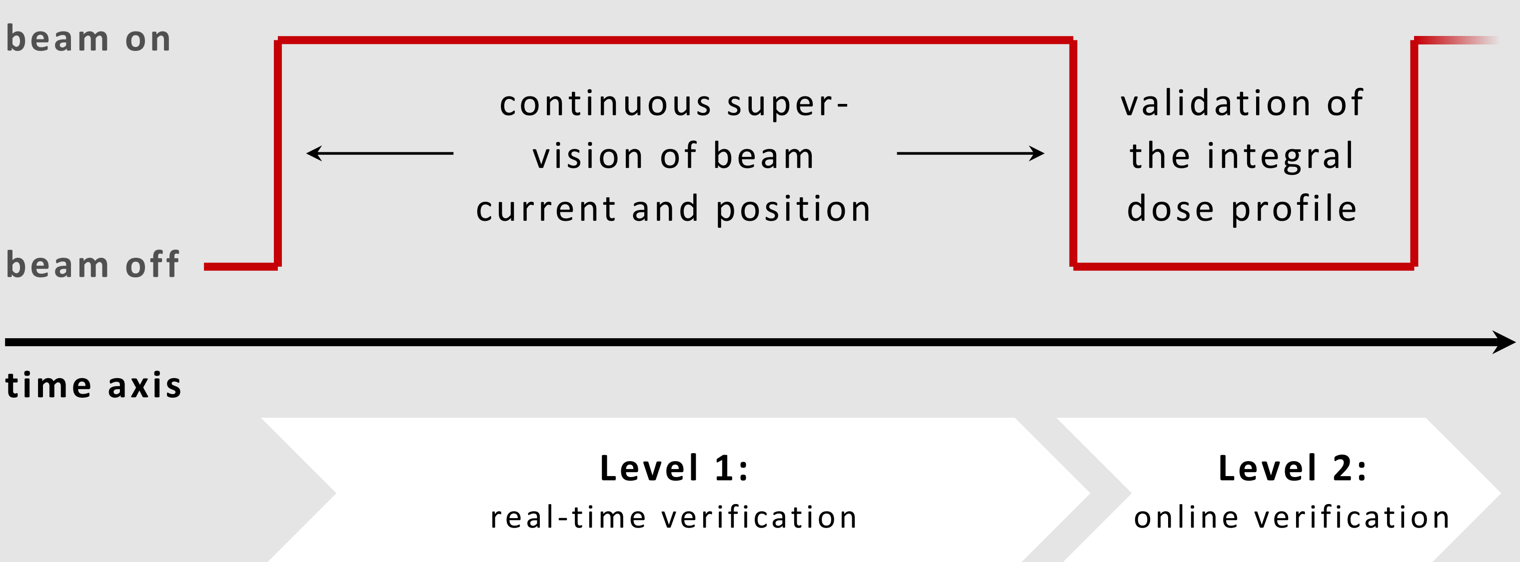


Verification concept

- **Level 1:** Real-time verification *during* the application of a line to prevent *radiation incidents*
- **Level 2:** Online verification *after* the application of a line to assess and validate *delivery accuracy*



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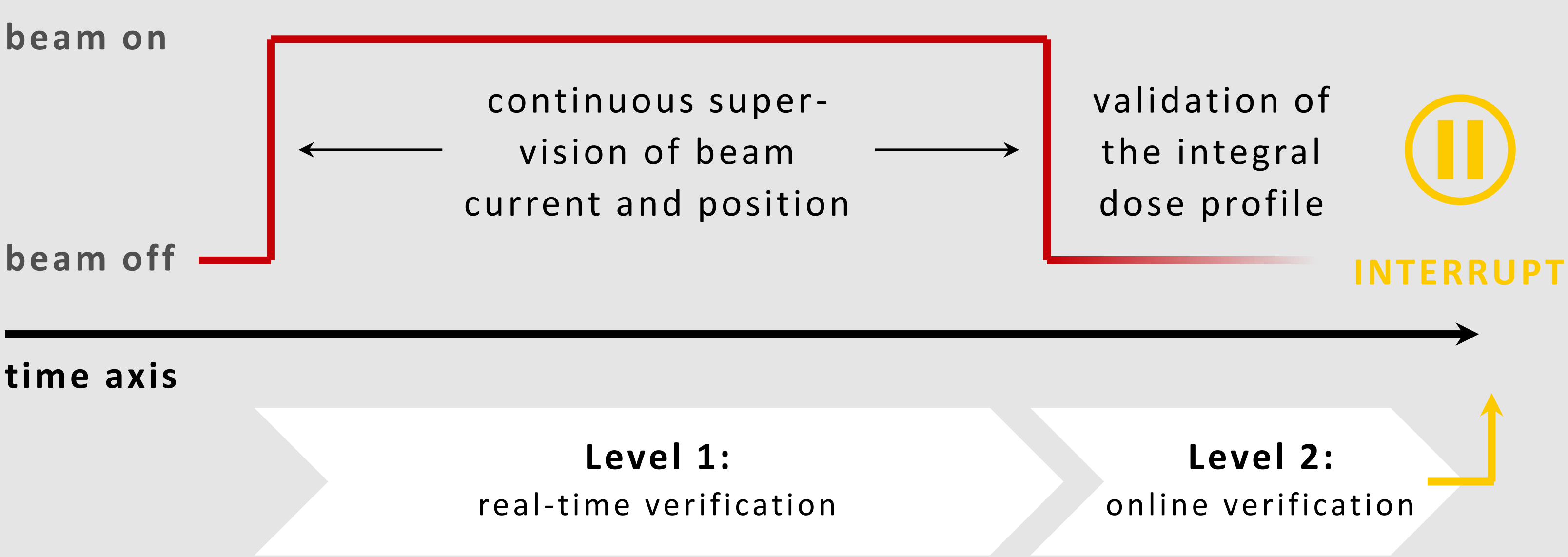


level 1

Definition of delivery error

- Errors occur rarely and randomly.
- Restrict magnitude of delivery errors to

  → hot/cold spots of ± 2% of fraction dose[1,2]

dose

± 36 mGy

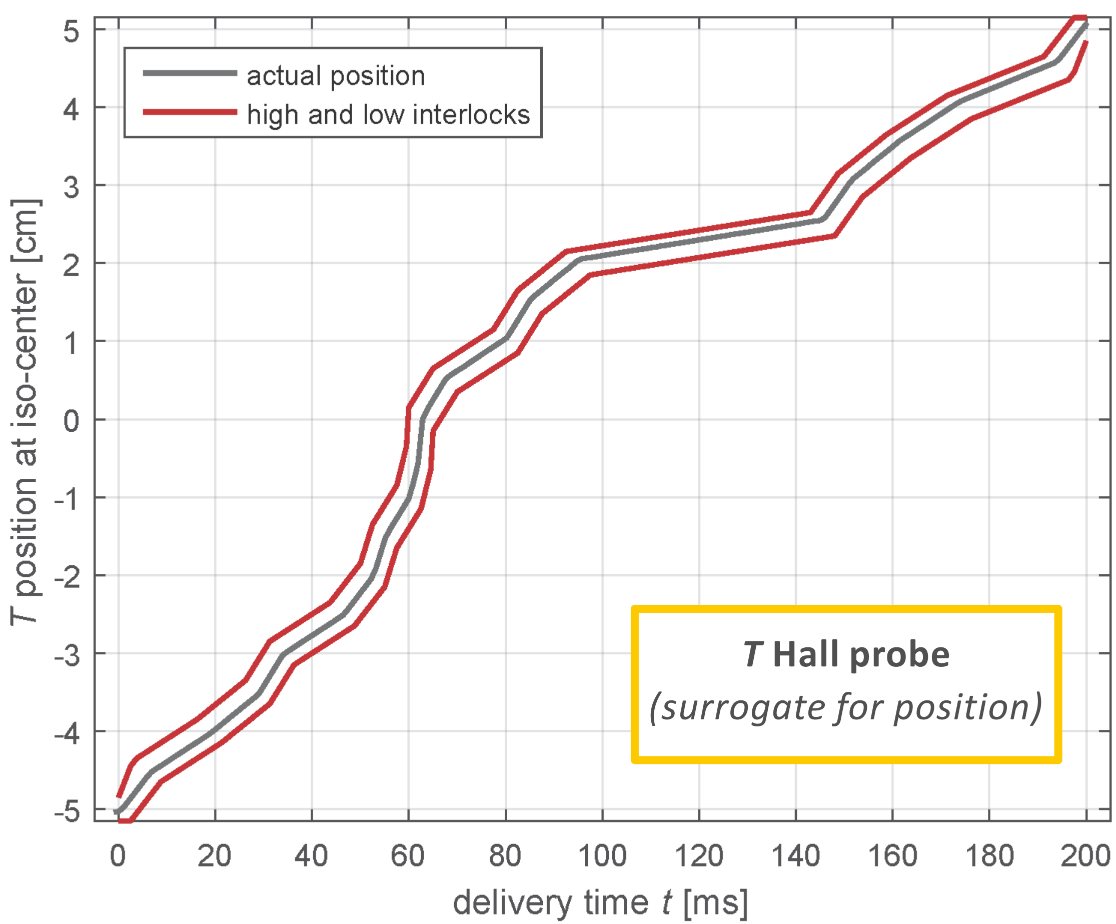
position

± 1.5 mm

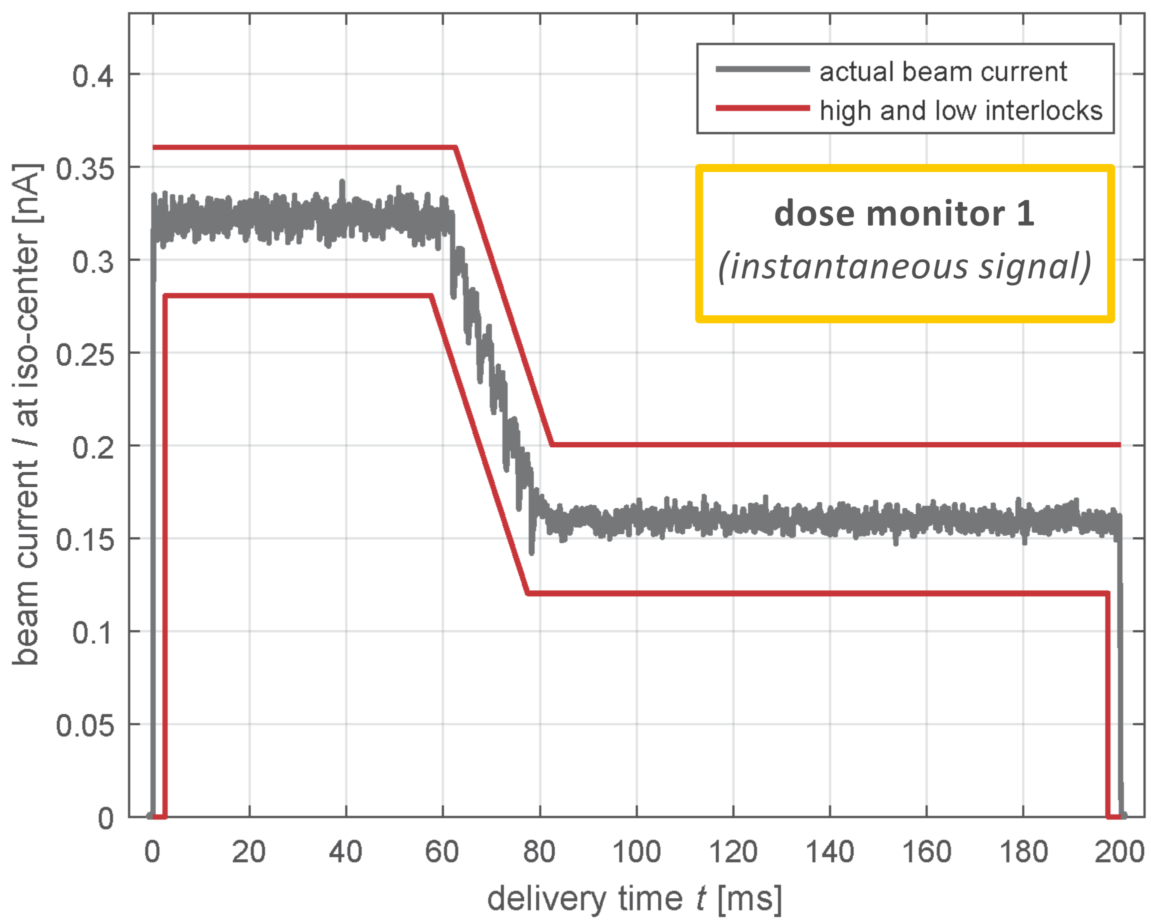
- Still no effect on clinical outcome

[1] ICRU. *Journal of the ICRU* **7**(2), 29-48 (2007).
[2] IEC. Medical electrical equipment. 60601-2-64 (2014).

Tolerance band for beam position



Tolerance band for beam current



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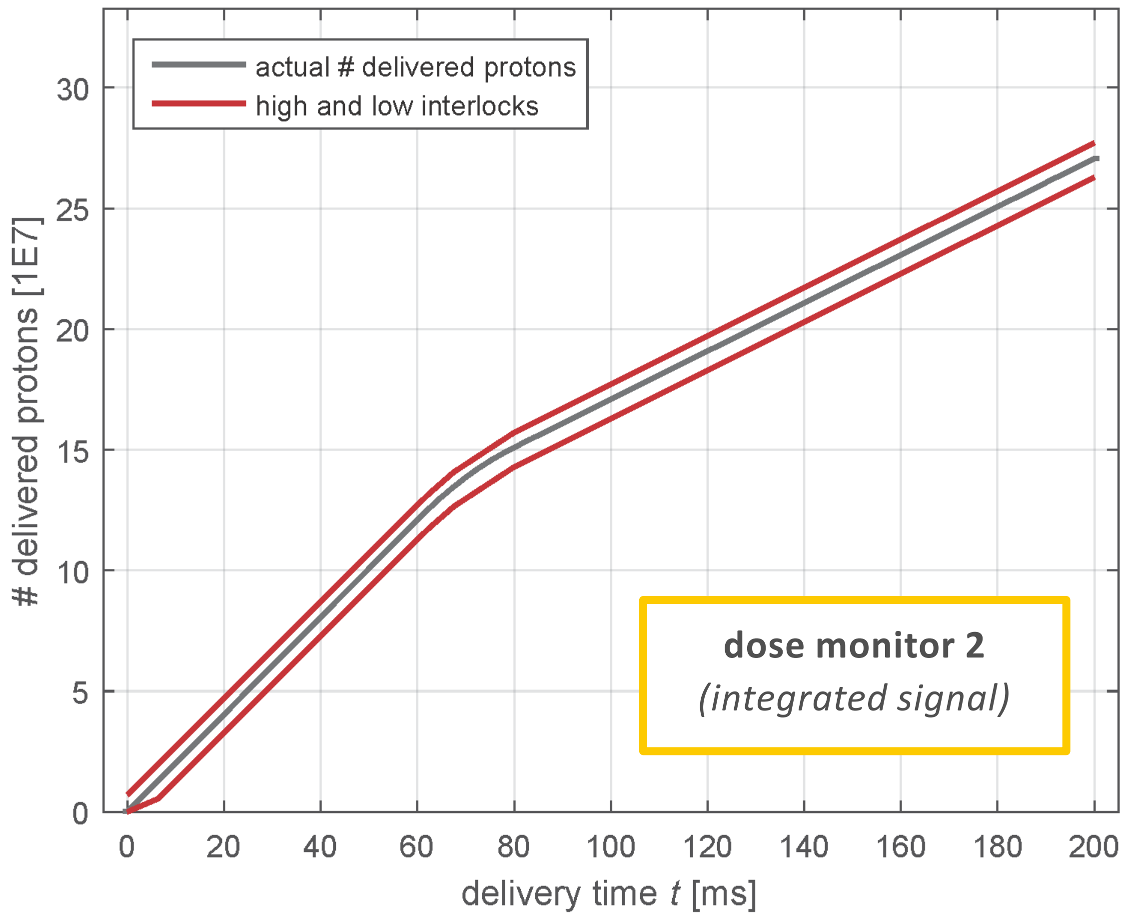
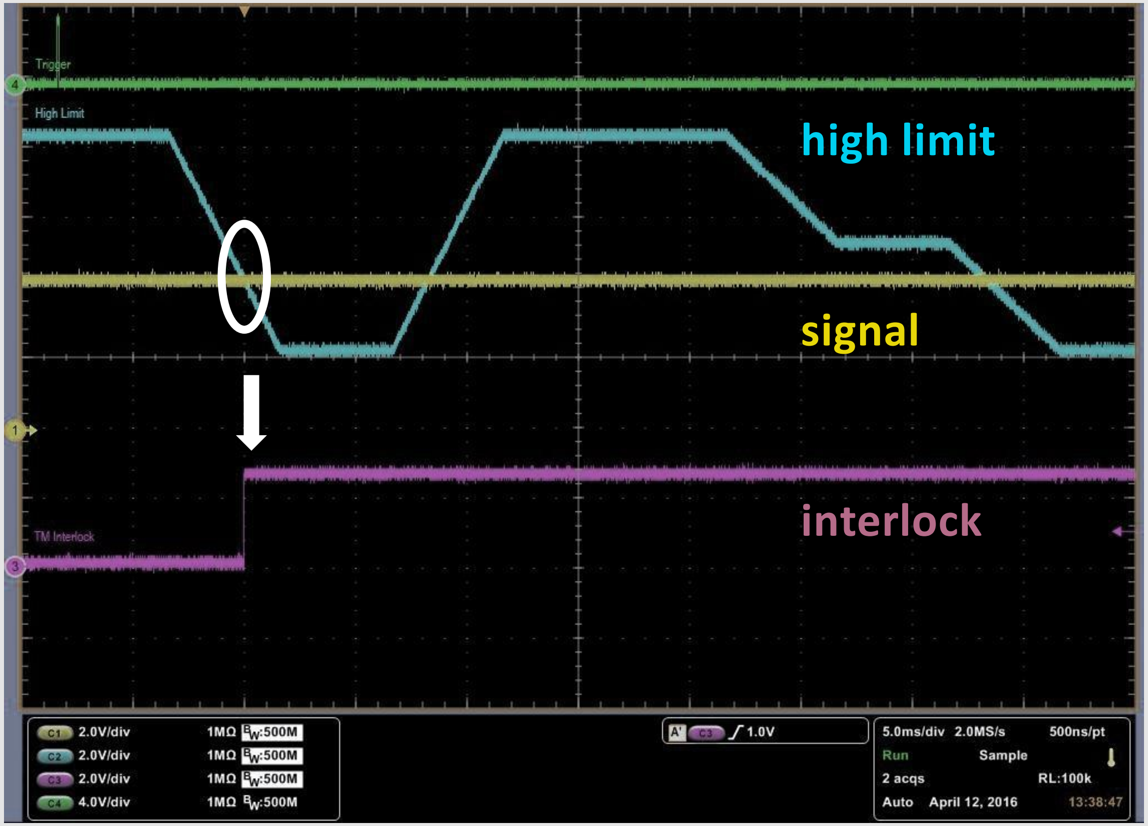
Tolerance band for deposited dose



Testing interlock functionality

Response of our test system to tolerance violations



level 2

What about smaller inaccuracies?

EXAMPLES

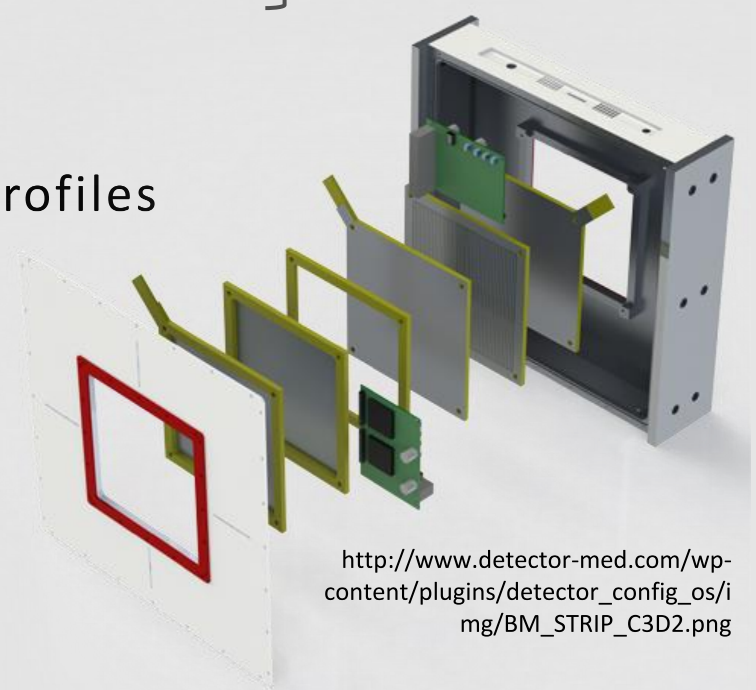
- rather noisy beam current
- slight offset in beam position
- unexpected instability in regulation

remain undetected by safety level 1

SOLUTION

- assessment of integrated profiles
  → absolute dose
  → direct position
- 88 x 128 strip monitor

  (DE.TEC.TOR, Torino)

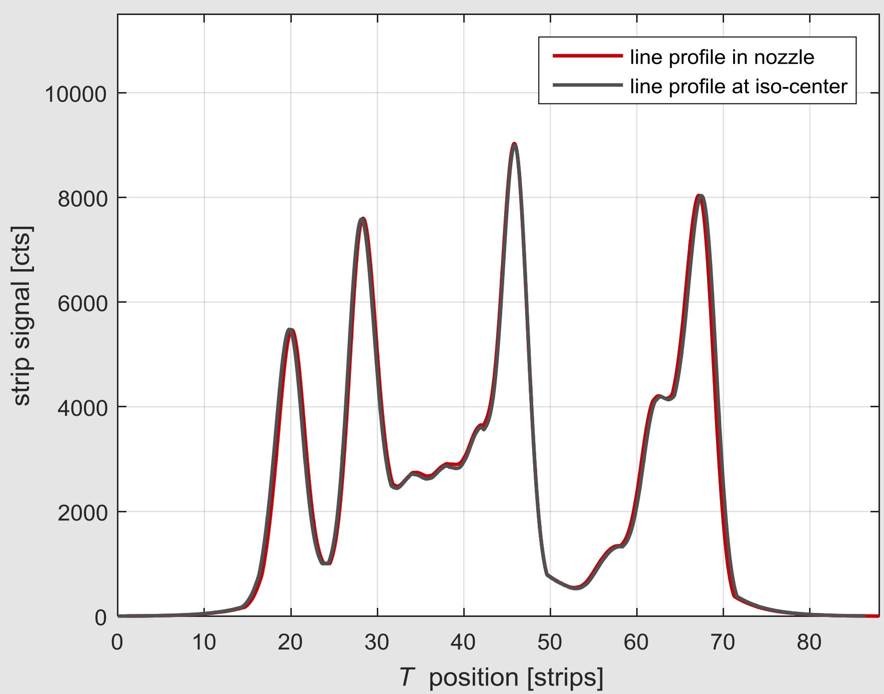


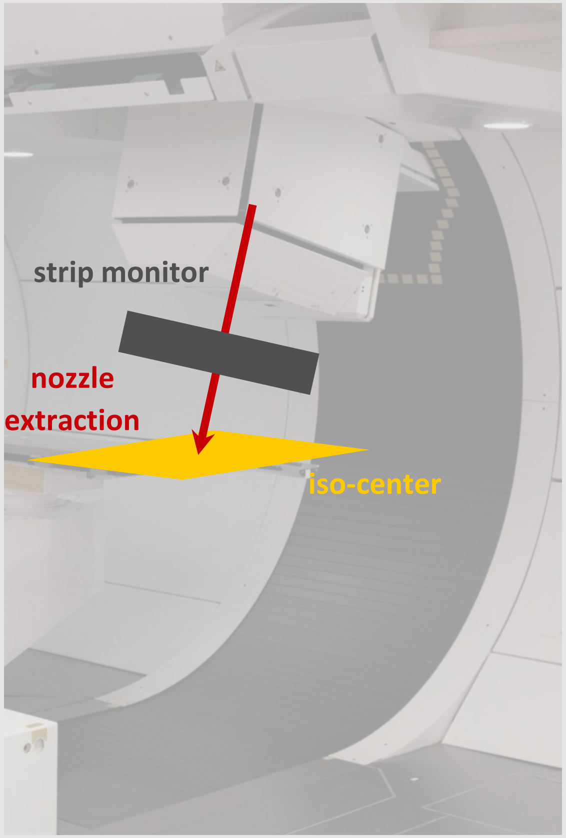
http://www.detector-med.com/wp-content/plugins/detector_config_os/img/BM_STRIP_C3D2.png

Profiles in the nozzle plane

Retracting nozzle and strip monitor

Δ*s* = 27 cm

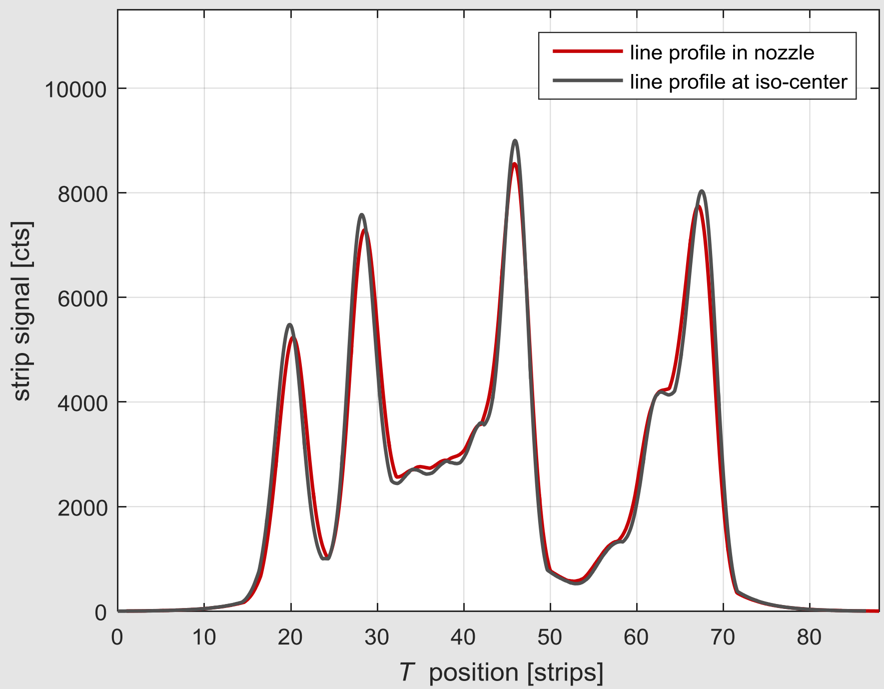


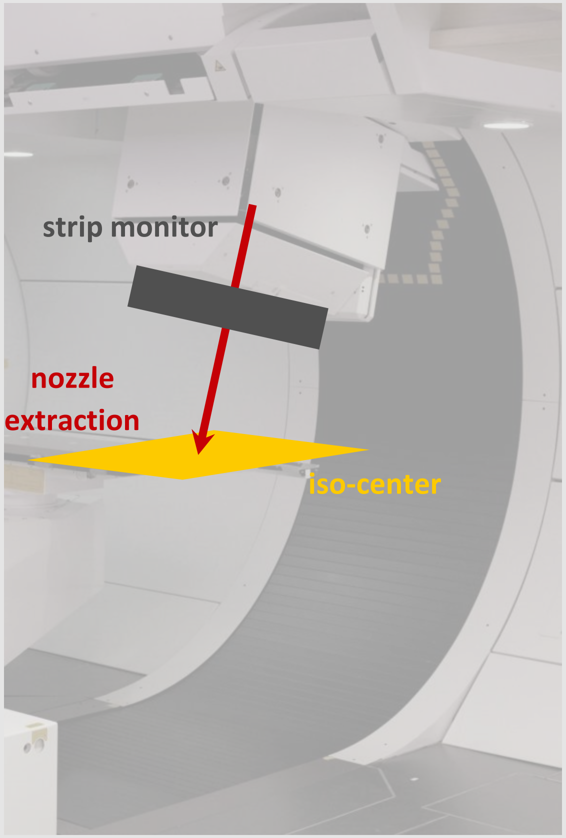


Profiles in the nozzle plane

Retracting nozzle and strip monitor

Δ*s* = 14 cm

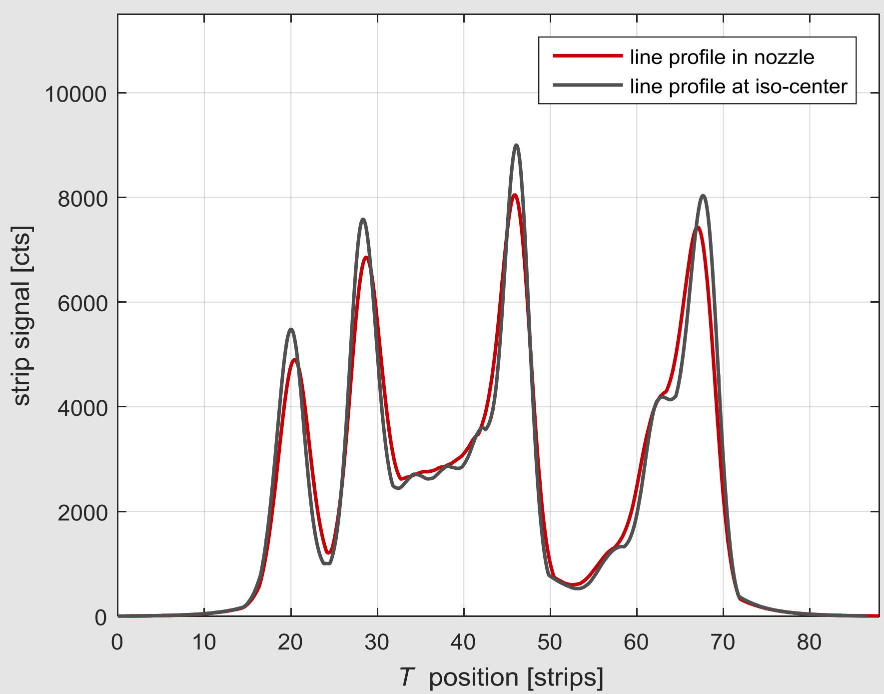


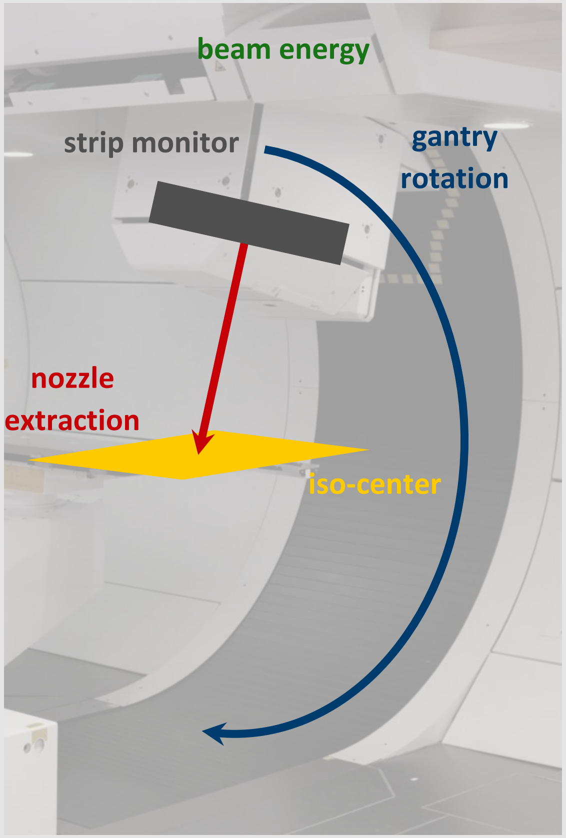


Profiles in the nozzle plane

Retracting nozzle and strip monitor

Δ*s* = 1 cm





Beam profile parameterization

The shape of the pencil beam in the nozzle plane depends on (at least) *five* parameters:

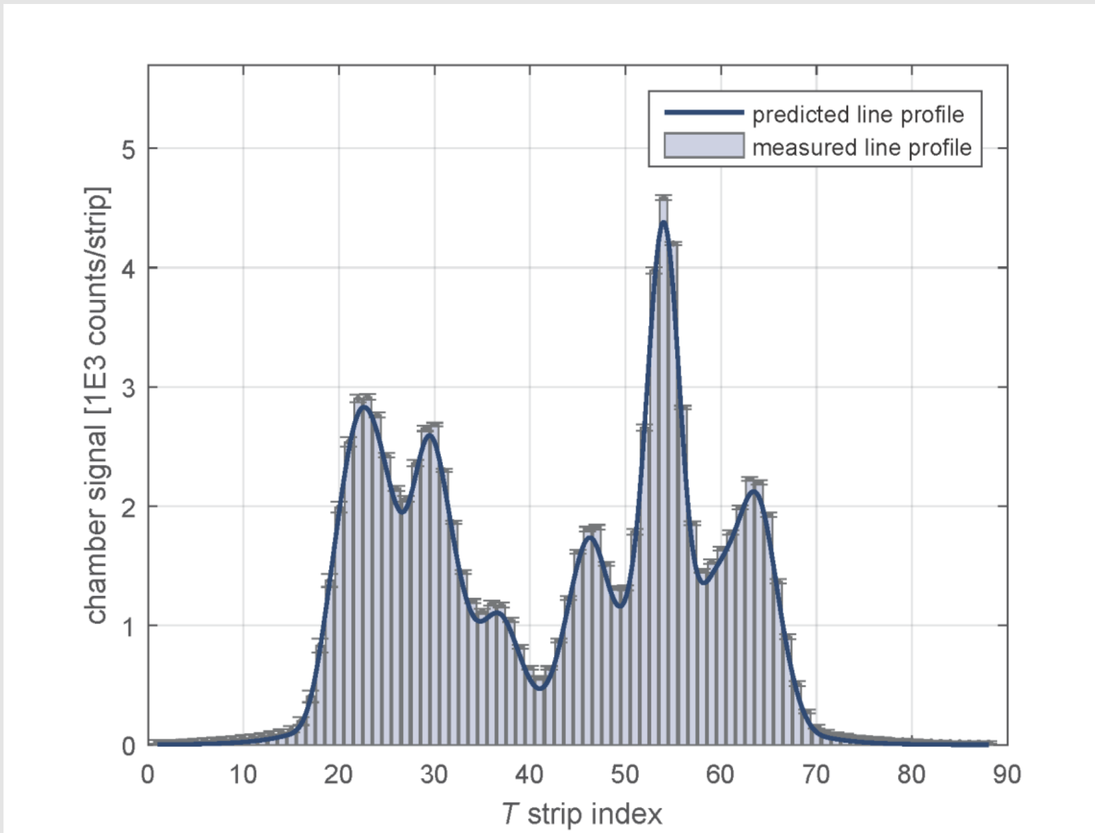
- beam energy E
- nozzle extraction Δs
- gantry angle α
- lateral T position
- lateral U position

The dependencies are *coupled* and, therefore, complicated to model accurately.

Our solution: Acquire a comprehensive beam shape look-up table (LUT) and interpolate it smoothly in all five dimensions

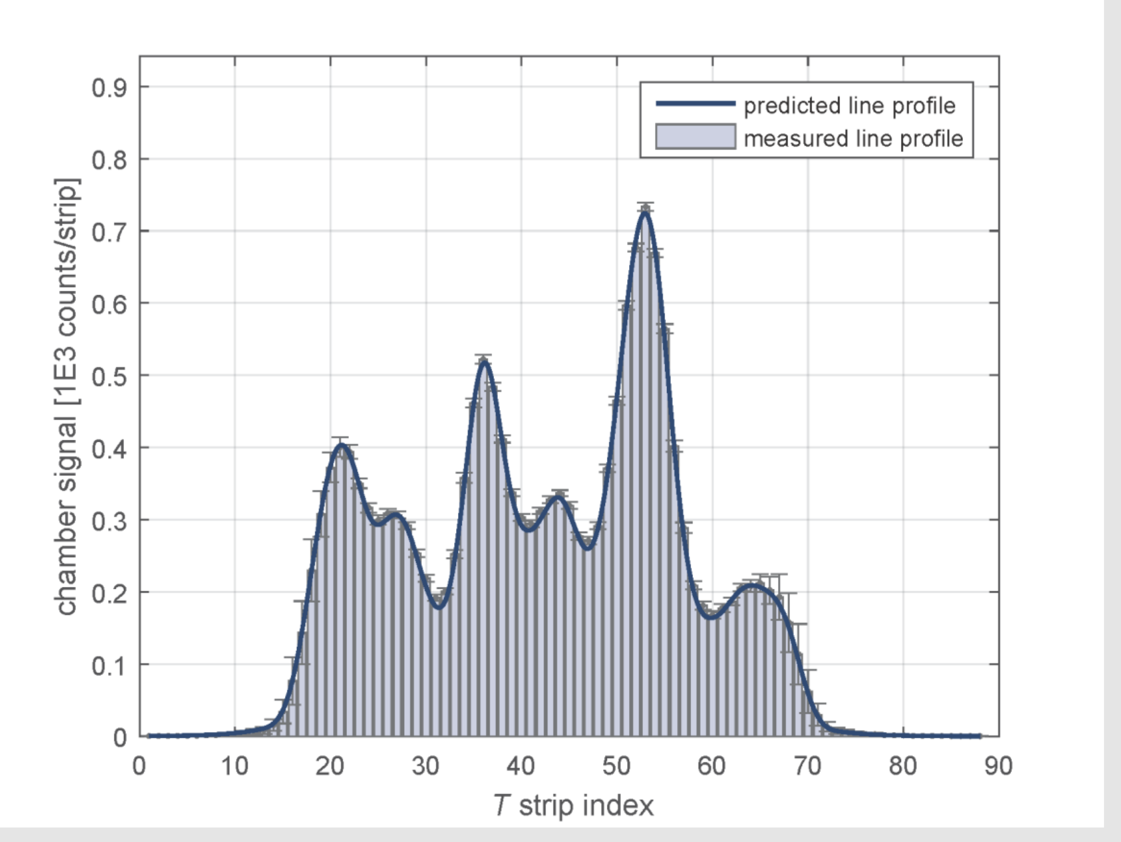
Predicted vs. measured dose profiles

Comparison for (α,E,Δs,U) = (0°, 150 MeV, 27 cm, 0 cm)



Predicted vs. measured dose profiles

Comparison for (α,E,Δs,U) = (15°, 115 MeV, 25 cm, 5 cm)



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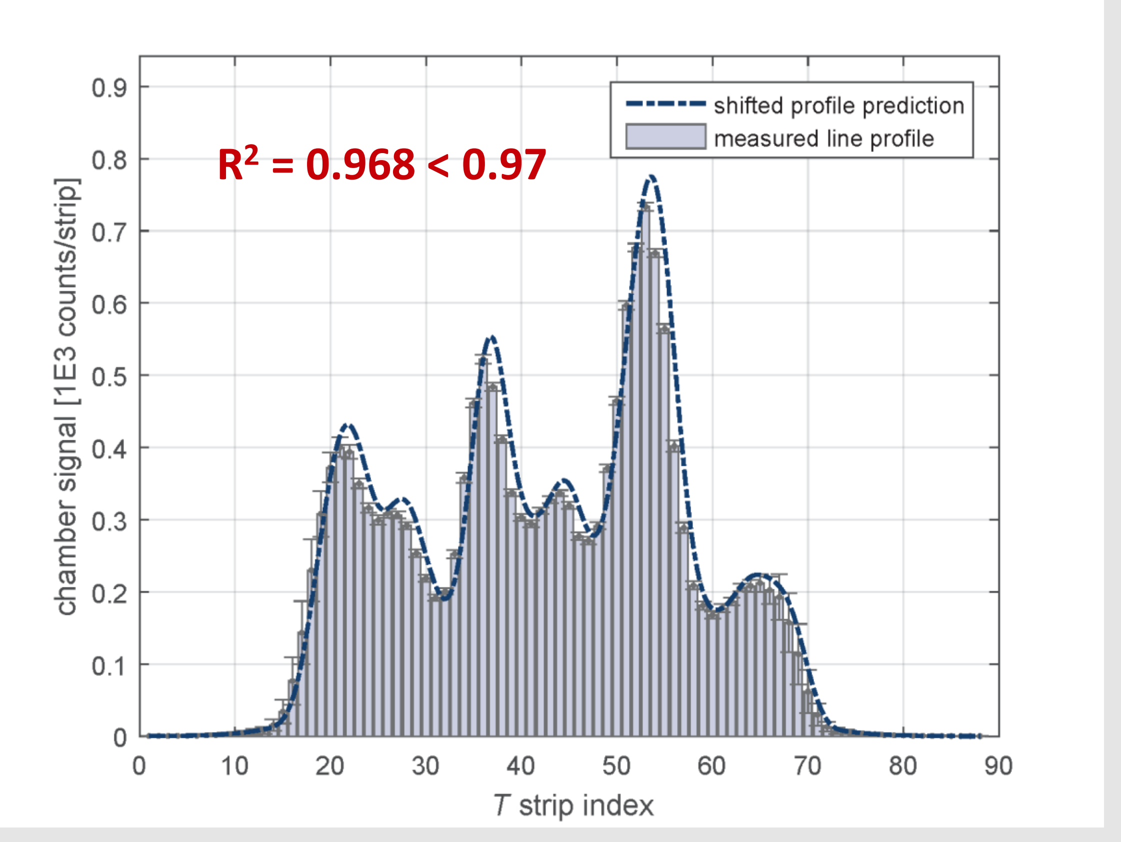
Metrics of comparison

Limits derived from successfully delivery patient plans:

- **Integrated strip signal**
  → maximum deviations: ± 10%
- **Profile center of gravity**
  → maximum differences: ± 1.5 mm
- **Profile symmetry**
  → maximum deviations: ± 10%
- **R^2 value**
  → minimum score: 0.97
- **Gamma pass rate at 2%, 2mm**
  → minimum score: 0.70

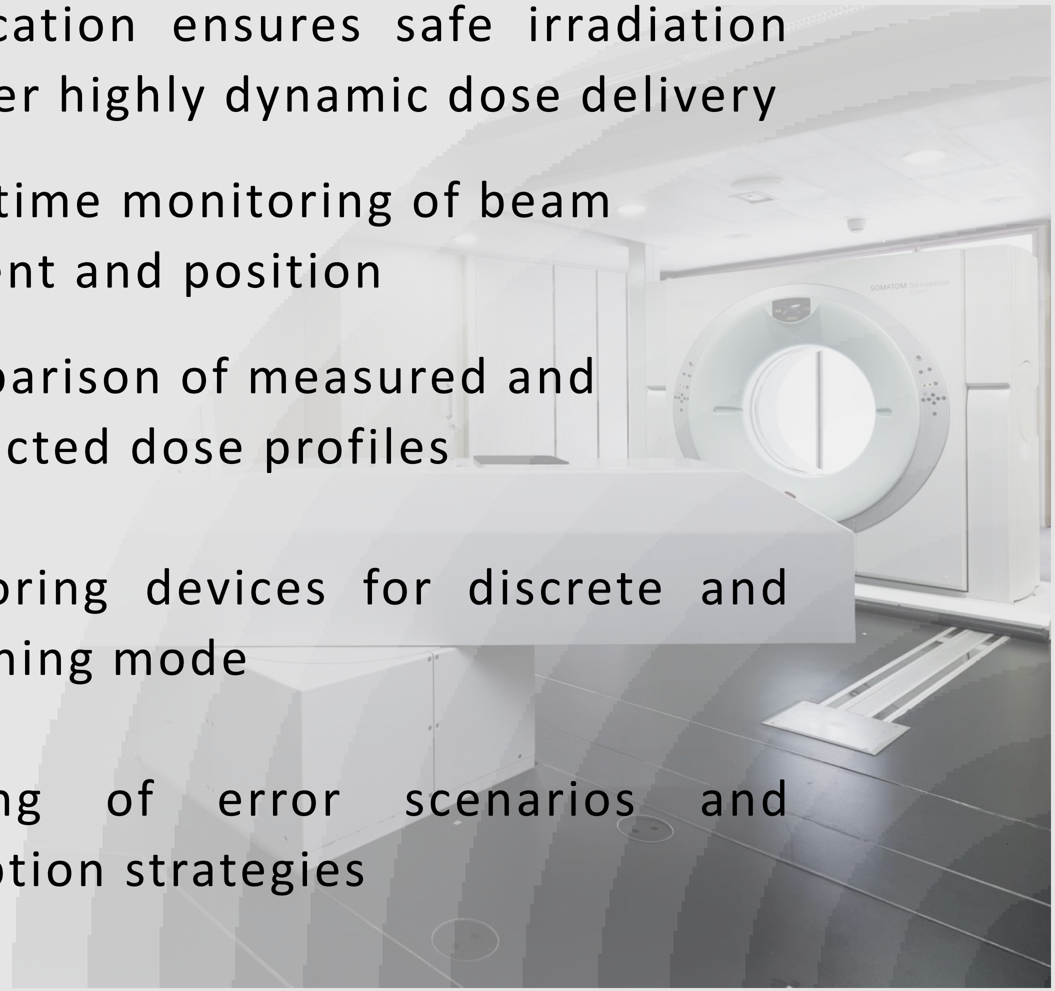
Example of violated comparison

Comparison for (α,E,Δs,U) = (15°, 115 MeV, 25 cm, 5 cm)



conclusion

Not a recipe for every system, but ...



- Two-level verification ensures safe irradiation on Gantry 2 under highly dynamic dose delivery

  level 1: real-time monitoring of beam current and position

  level 2: comparison of measured and predicted dose profiles

- Identical monitoring devices for discrete and continuous scanning mode

- *Ongoing*: testing of error scenarios and interlock resumption strategies

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Wir schaffen Wissen – heute für morgen

Thank you for your attention!

We acknowledge the support of our software and electronics engineers.

This work is partly funded by the Giuliana and Giorgio Stefanini Foundation.