

Verification of highly dynamic dose delivery

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Other Conference Item

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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>

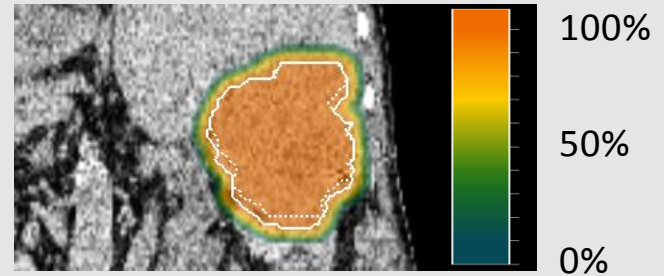


intro

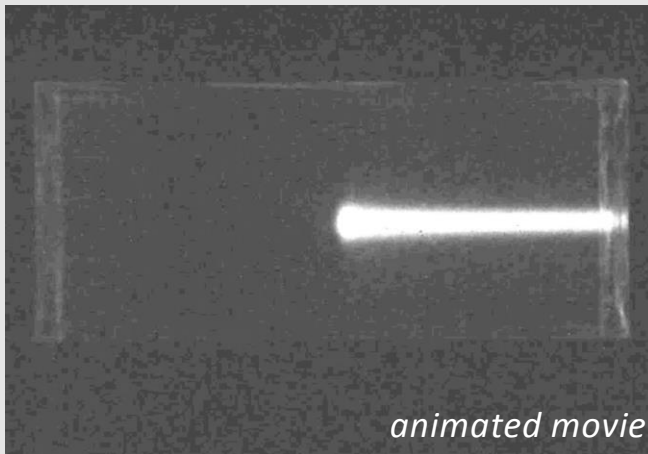
What is highly dynamic dose delivery?

Clinical example

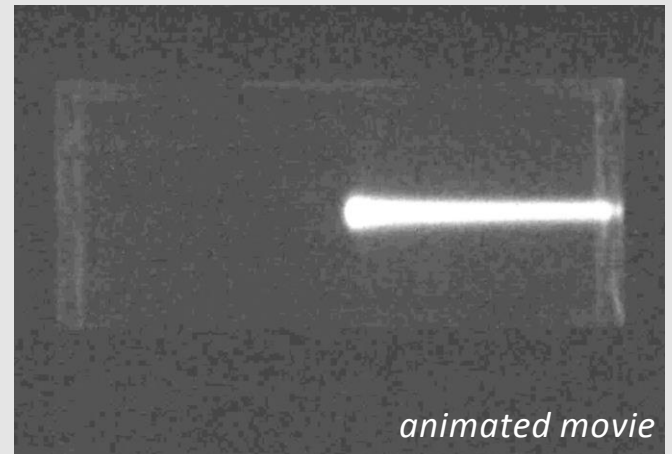
- liver tumor (460 ccm)
- single field (0.6 Gy)



discrete scanning
52 sec.



continuous scanning
26 sec.



Fast and flexible form of patient irradiation

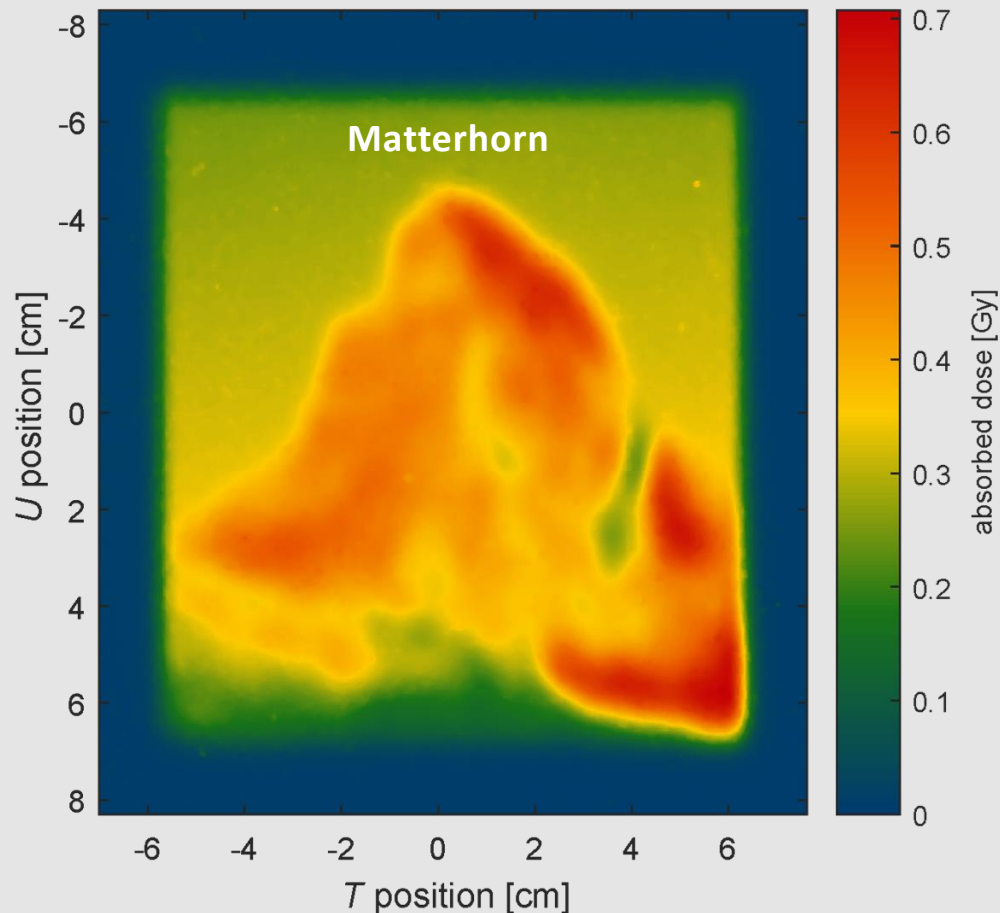
F A S T

- (quasi) continuous beam of high current (~ 5 nA)
- high duty cycle ($\Delta t_{\text{beam}}/\Delta t_{\text{total}} > 75\%$) 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

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) ($< 100 \mu\text{s}$)
- scanning fast with reduced beam current
→ regions of very low dose
→ weak signal in position-sensitive ICs

Which requirements arise?

**present our implementation
for a *cyclotron-based* and
time-driven delivery system**



Gantry 2

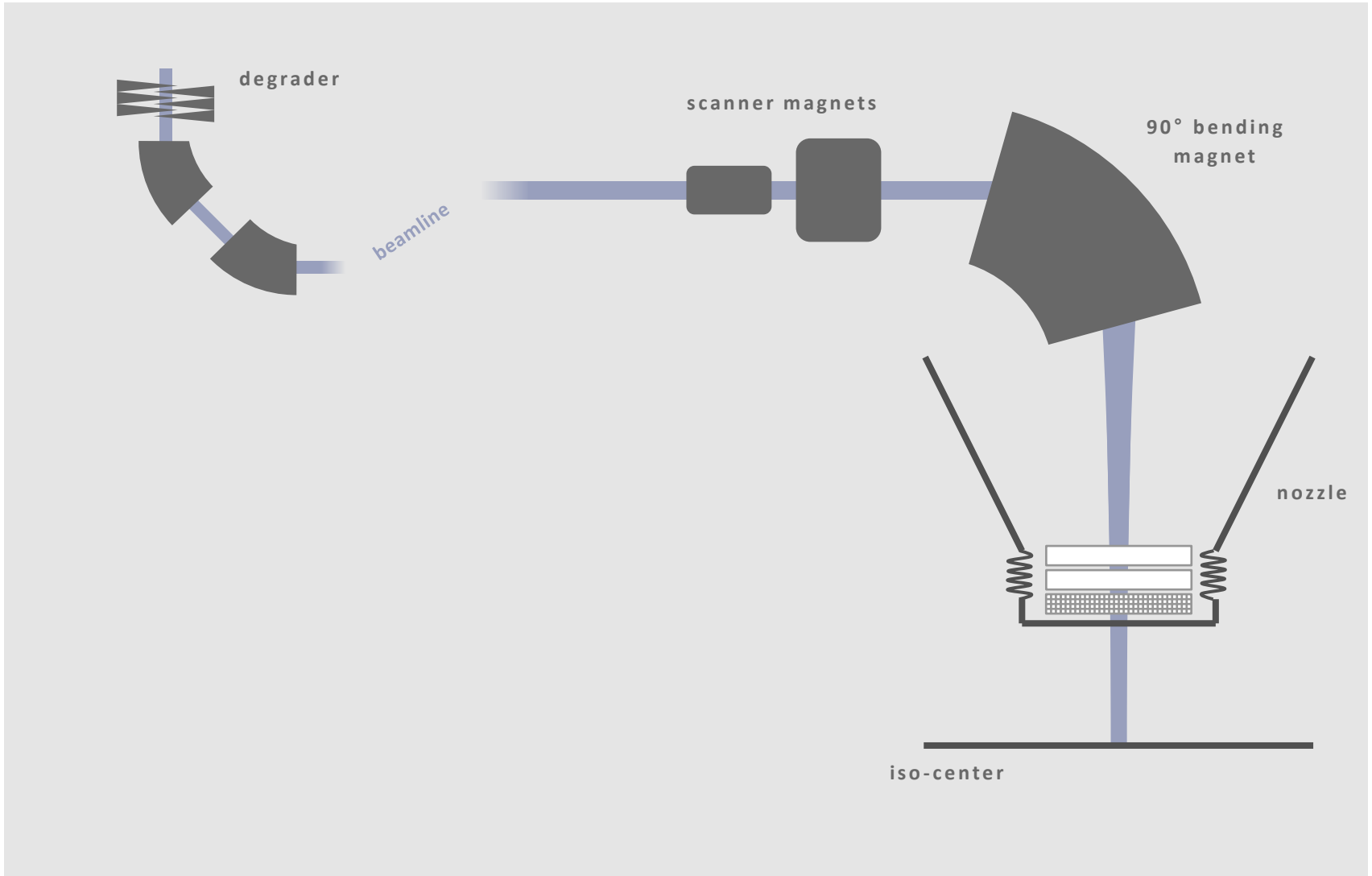
PSI Gantry 2



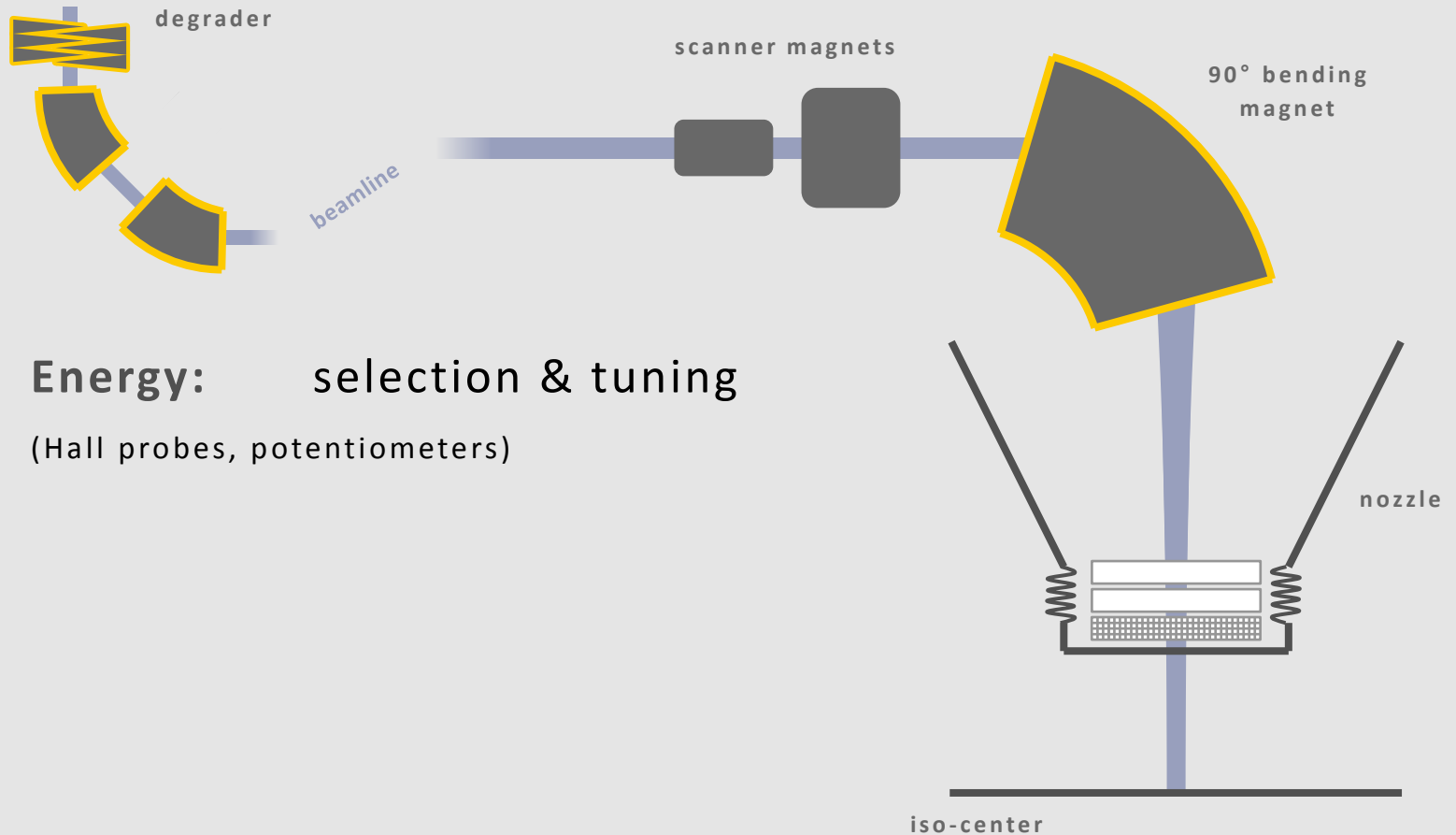
- Patient treatments since November 2013 using **pencil beam scanning**
- Current mode operation: **discrete scanning**
- Additionally offers **continuous scanning**, designed for fast dose delivery featuring:
 - (a) energy switching times ≈ 100 ms
 - (b) lateral scan speeds up to 2 cm/ms
 - (c) beam current regulation in < 1 ms
- Clinical go-live still requires a dedicated **monitoring and validation system**



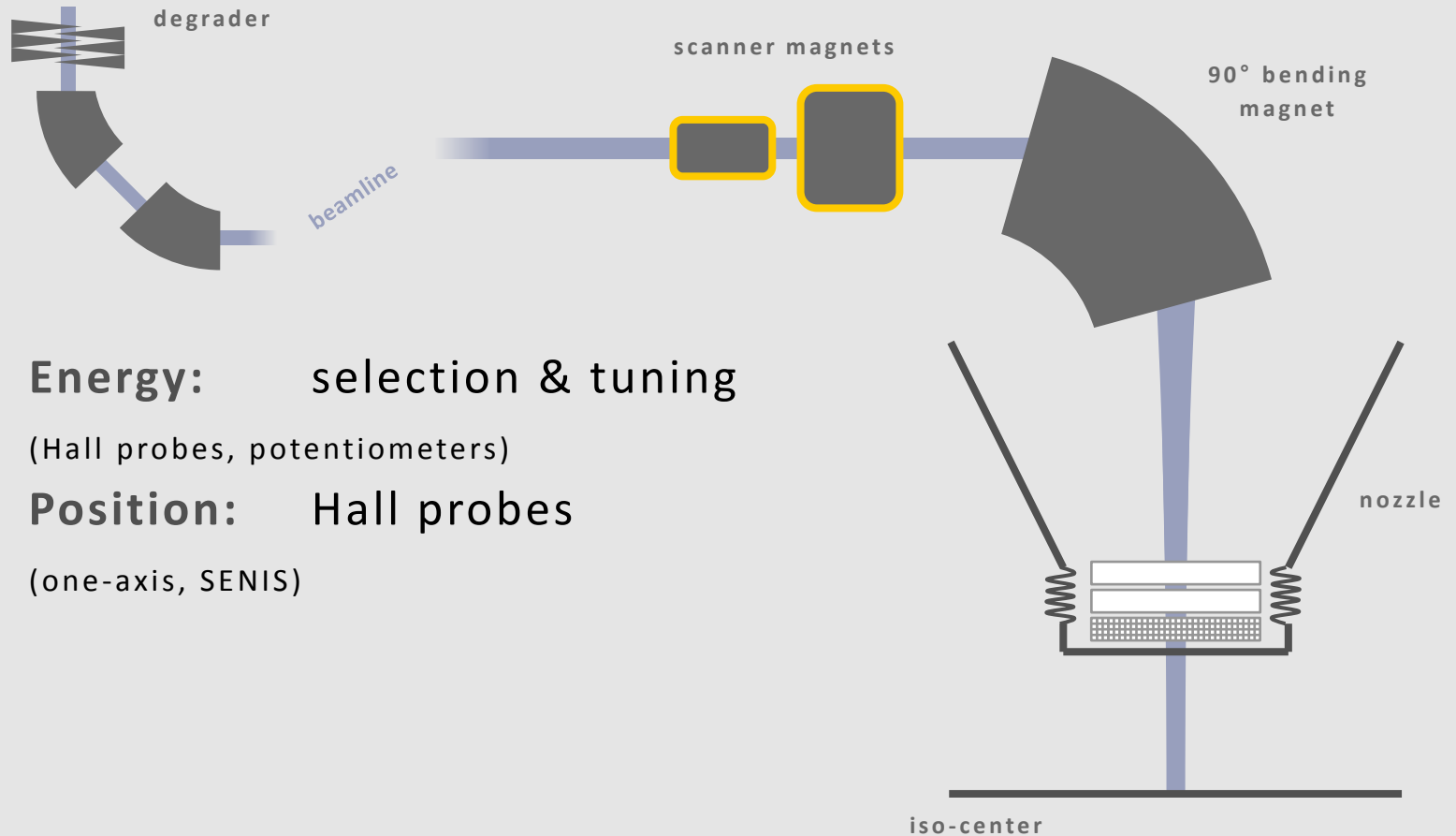
Beam monitors for continuous scanning



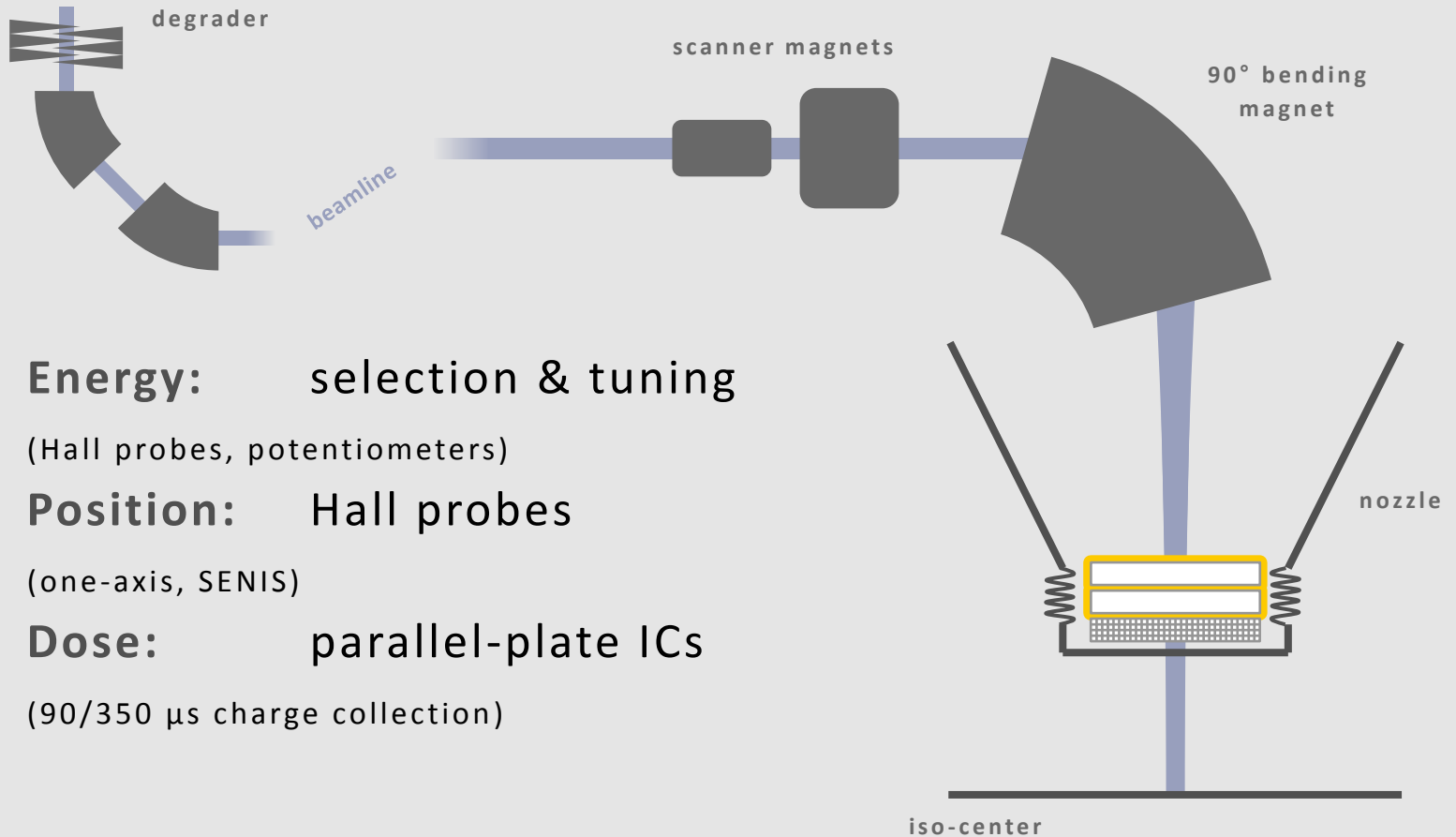
Beam monitors for continuous scanning



Beam monitors for continuous scanning

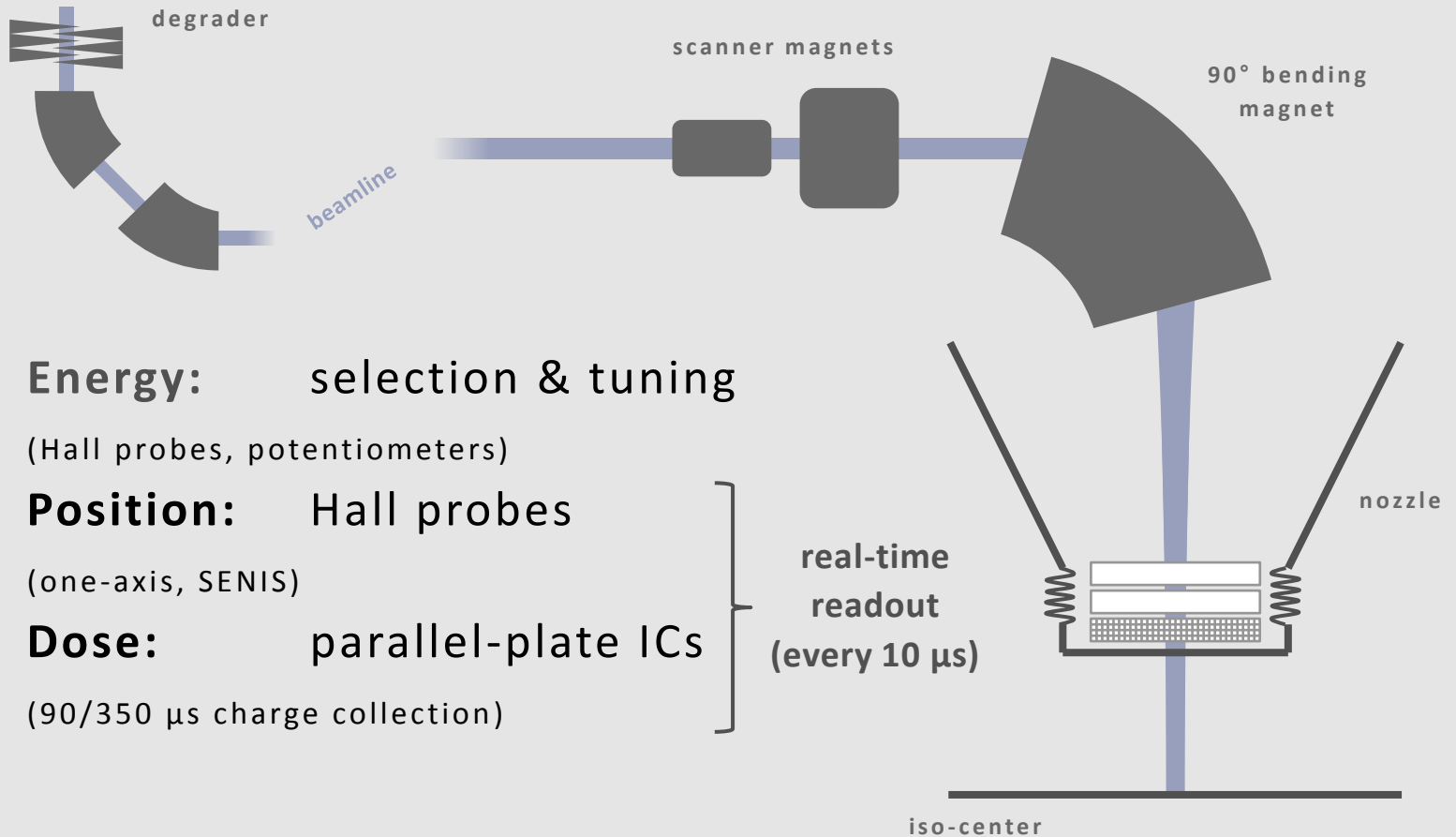


Beam monitors for continuous scanning

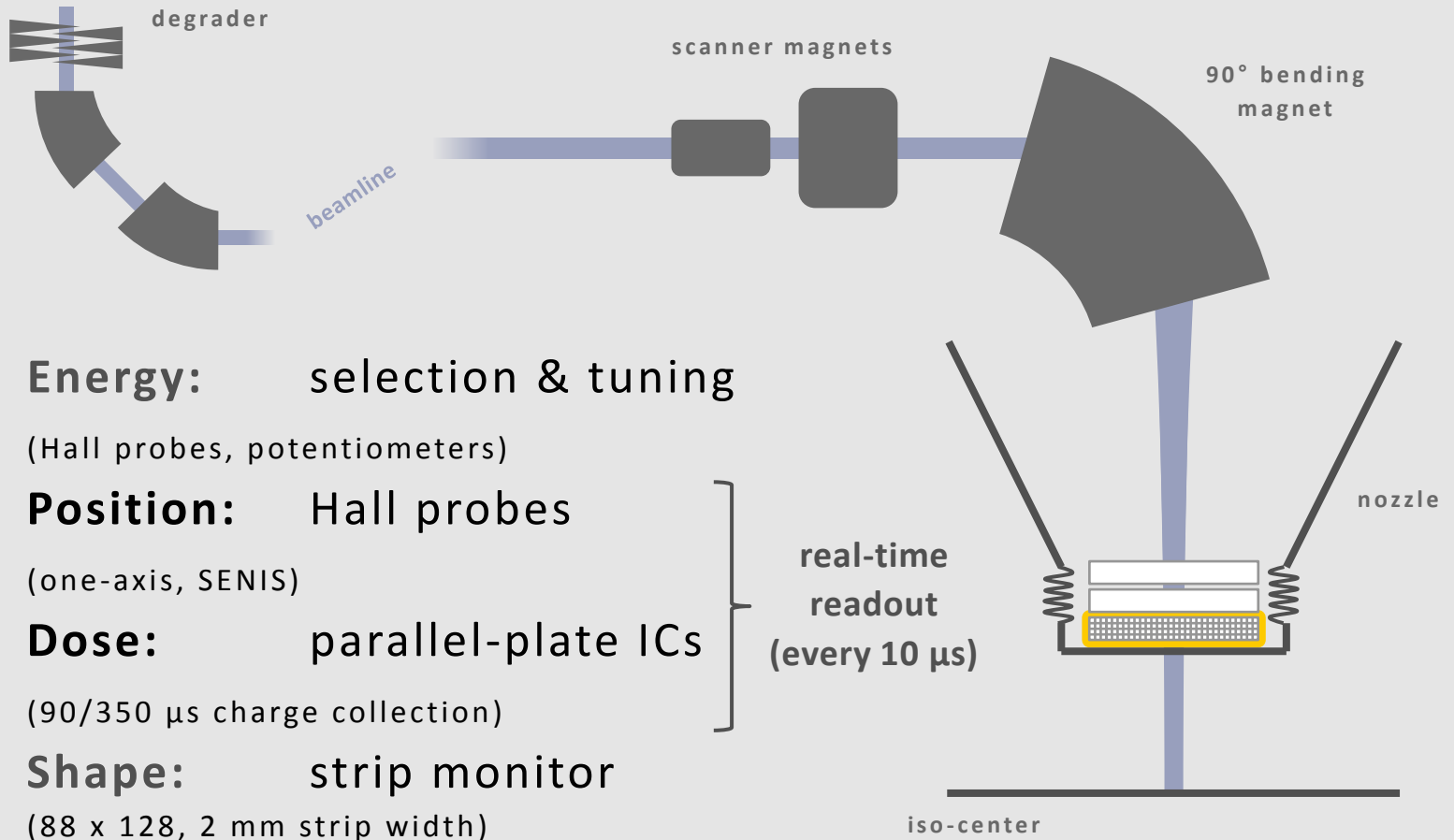


- **Energy:** selection & tuning
(Hall probes, potentiometers)
- **Position:** Hall probes
(one-axis, SENIS)
- **Dose:** parallel-plate ICs
(90/350 μs charge collection)

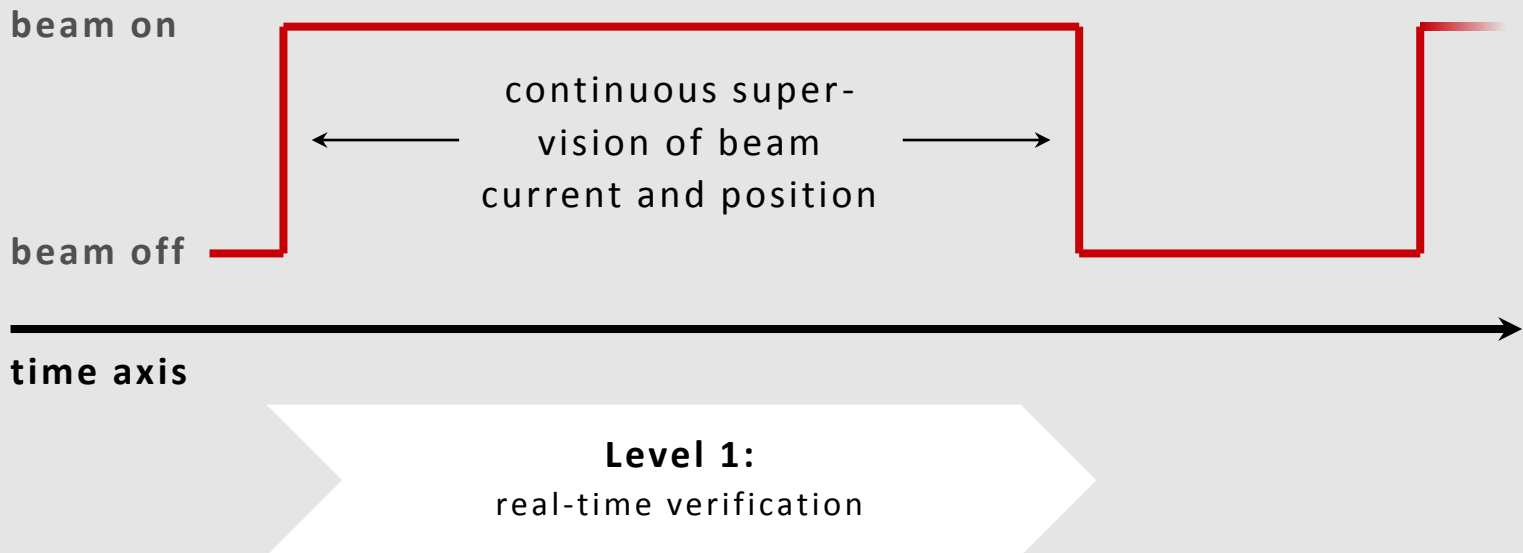
Beam monitors for continuous scanning



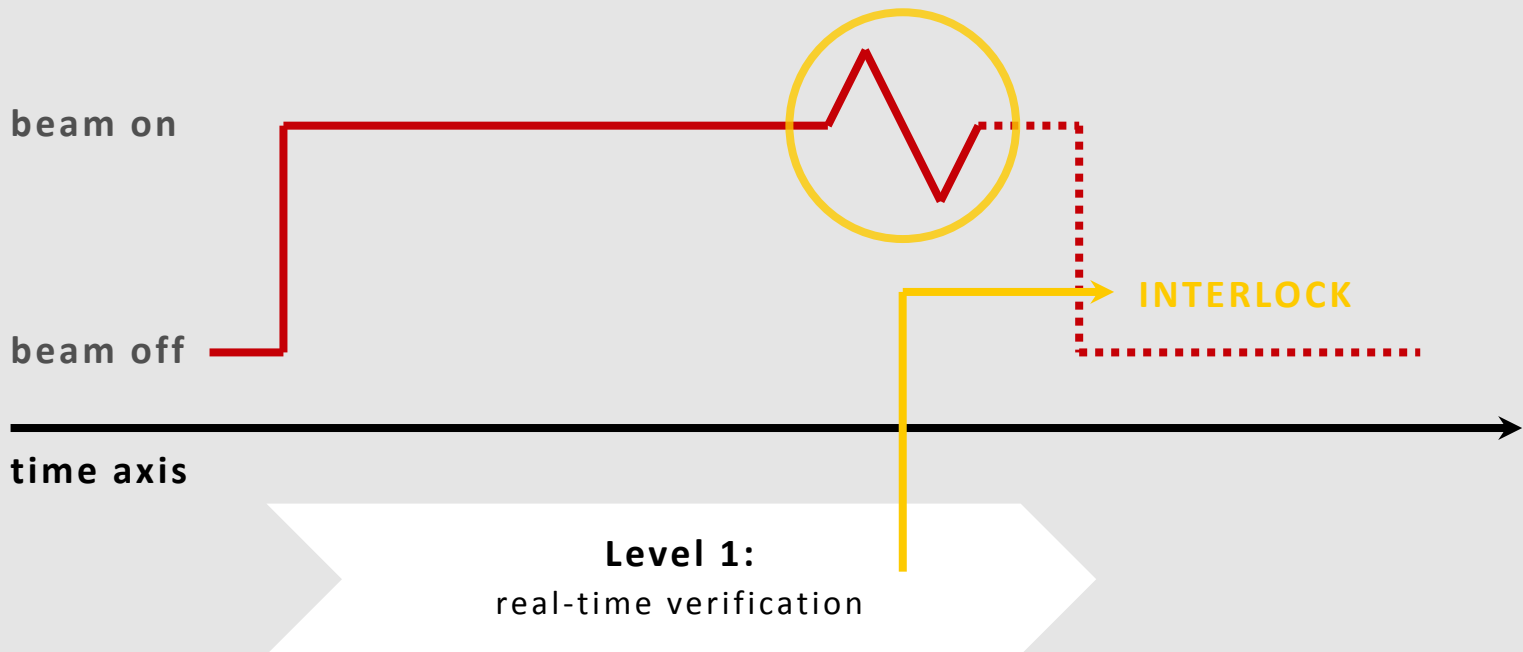
Beam monitors for continuous scanning



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

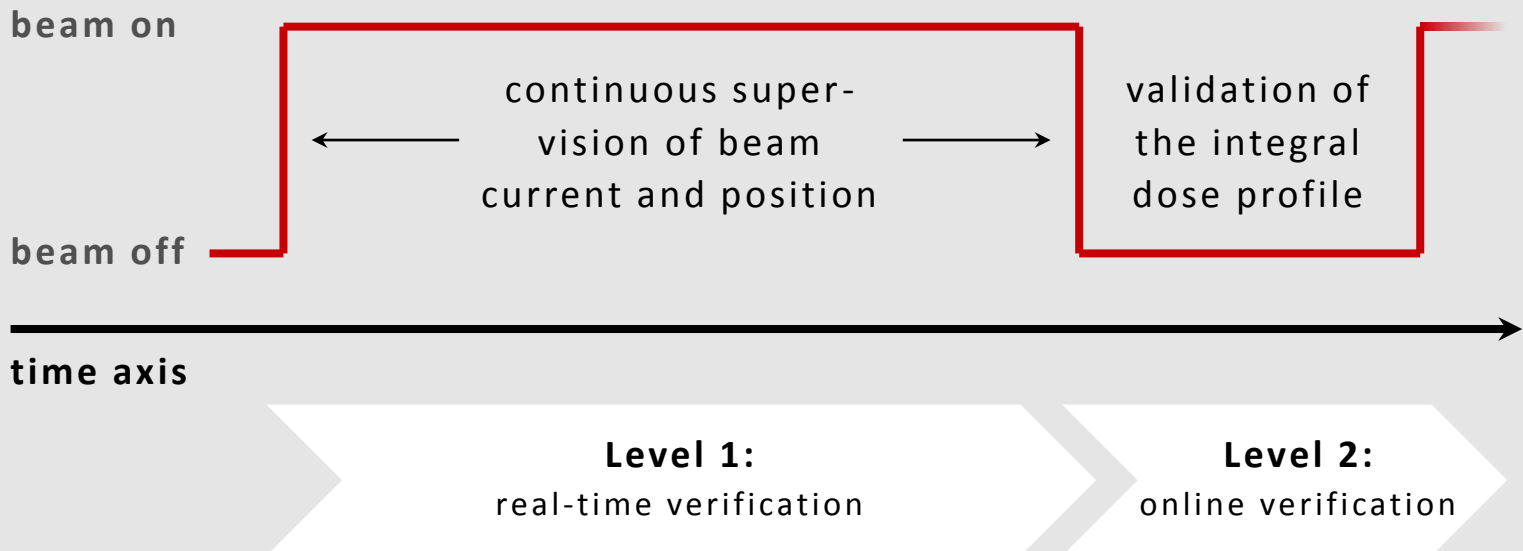


- **Level 1:** Real-time verification *during* the application of a line to prevent *radiation incidents*



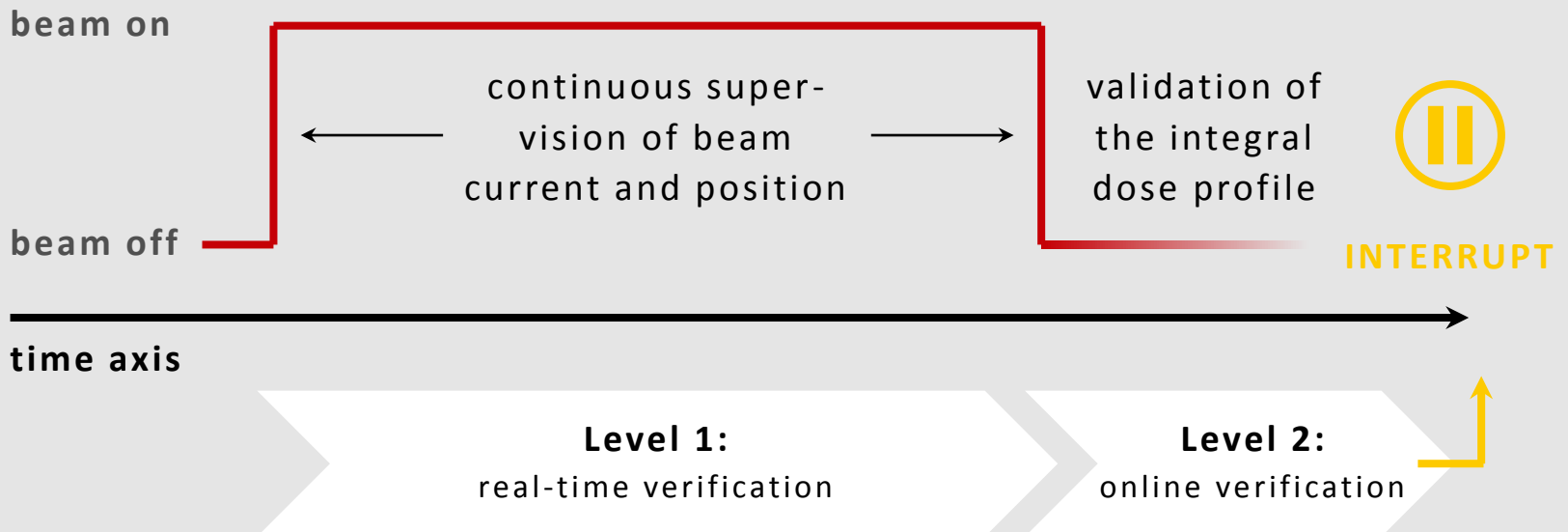
Verification concept

- **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*



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*

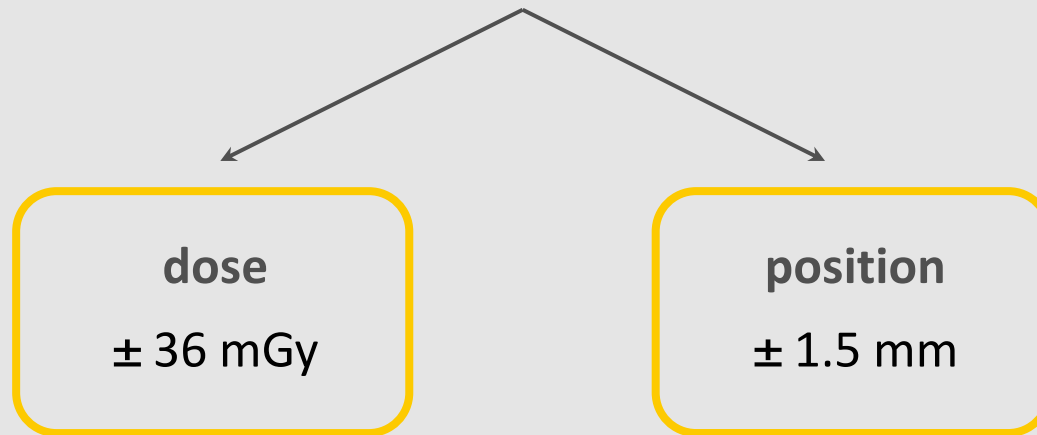




level 1

Definition of delivery error

- Errors occur rarely and randomly.
- Restrict magnitude of delivery errors to
→ hot/cold spots of $\pm 2\%$ of fraction dose^{1,2}

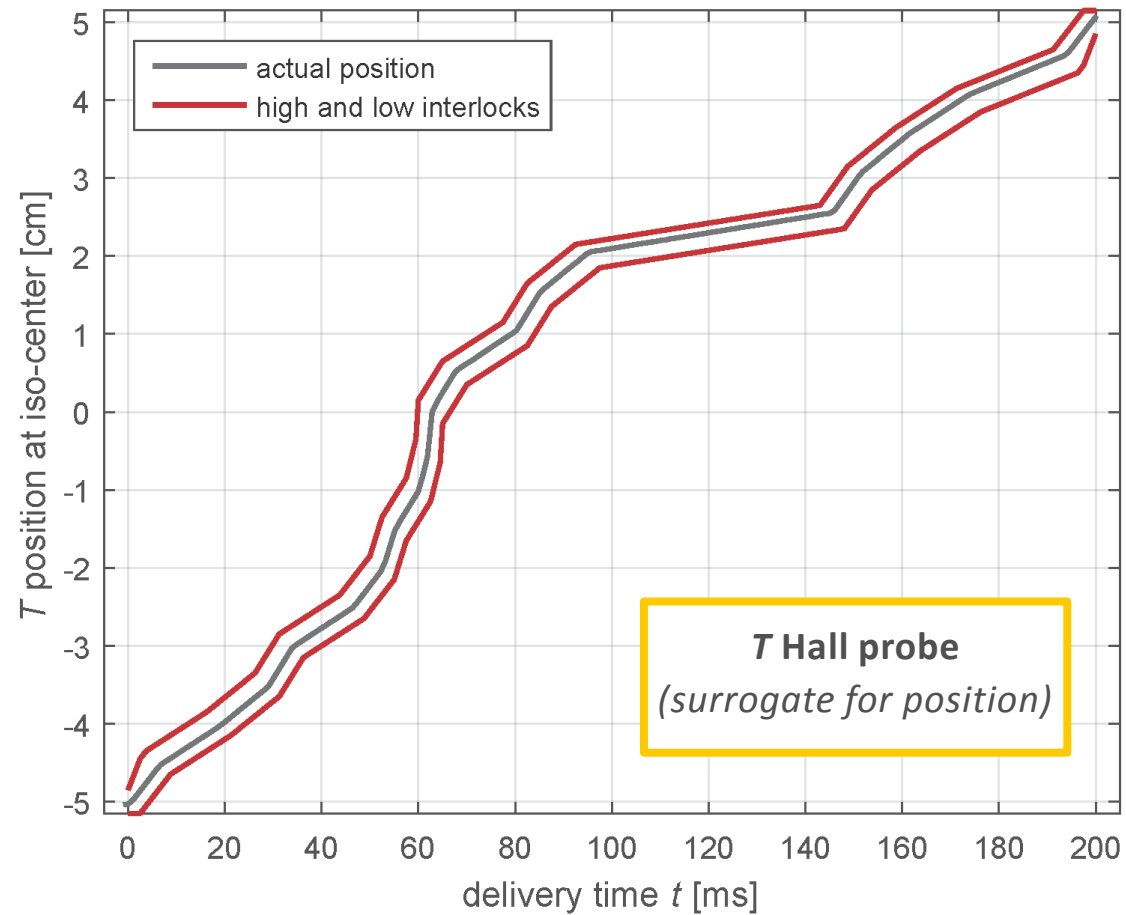


- Still no effect on clinical outcome

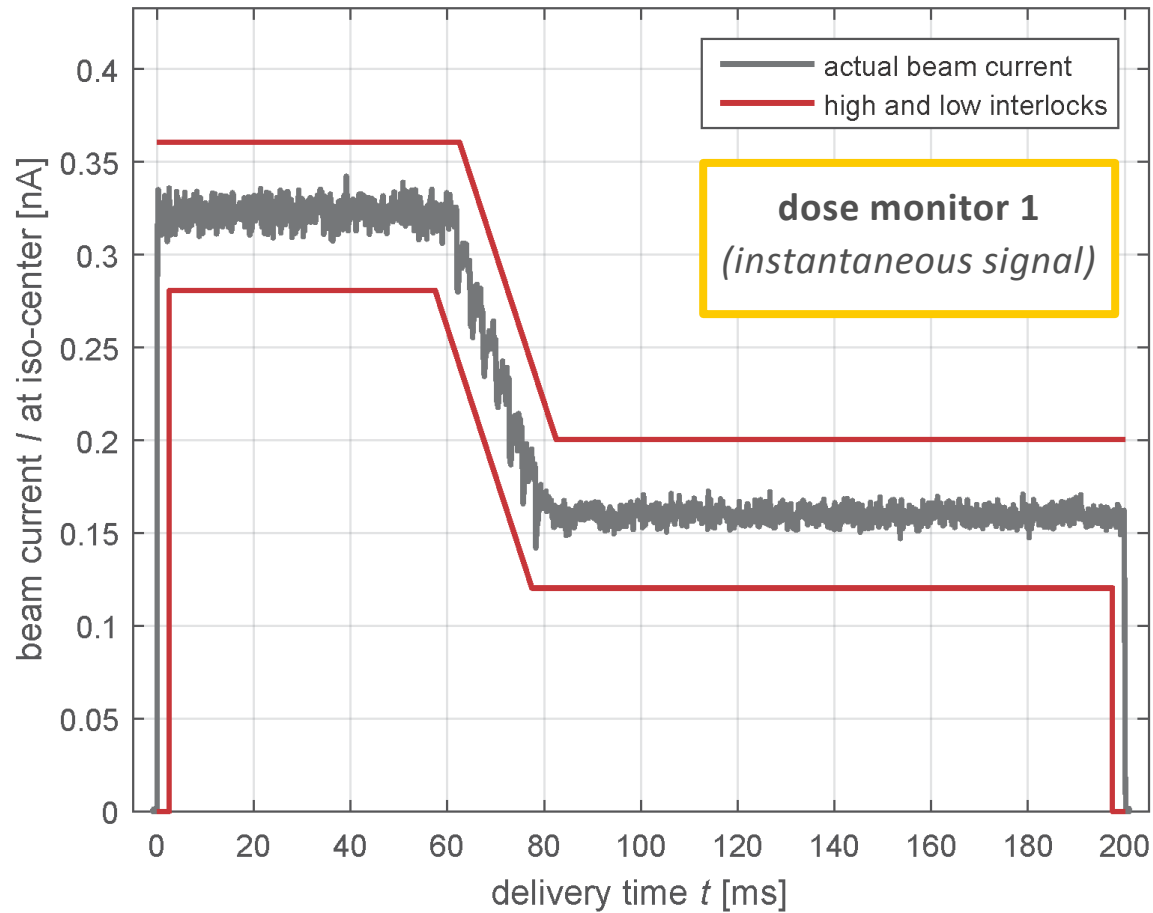
¹ ICRU. *Journal of the ICRU* 7(2), 29-48 (2007).

² IEC. Medical electrical equipment. 60601-2-64 (2014).

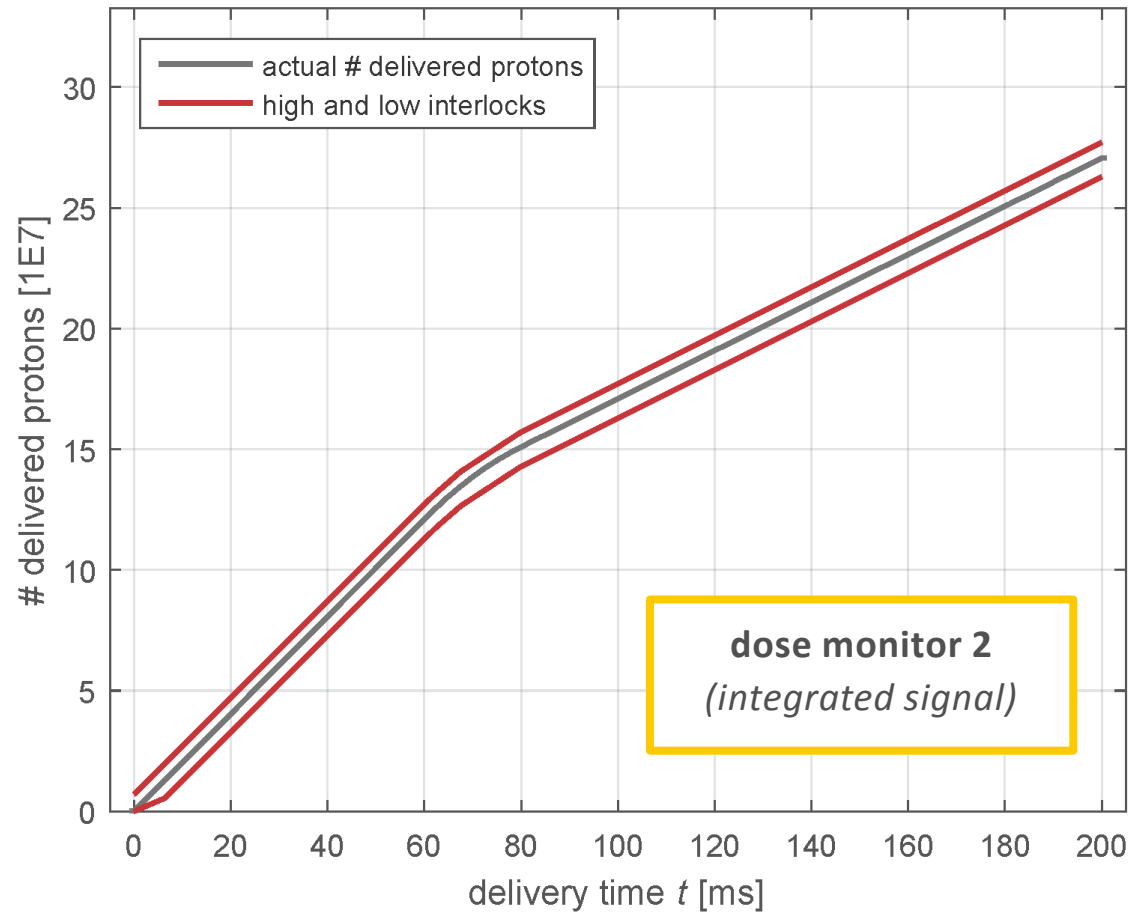
Tolerance band for beam position



Tolerance band for beam current

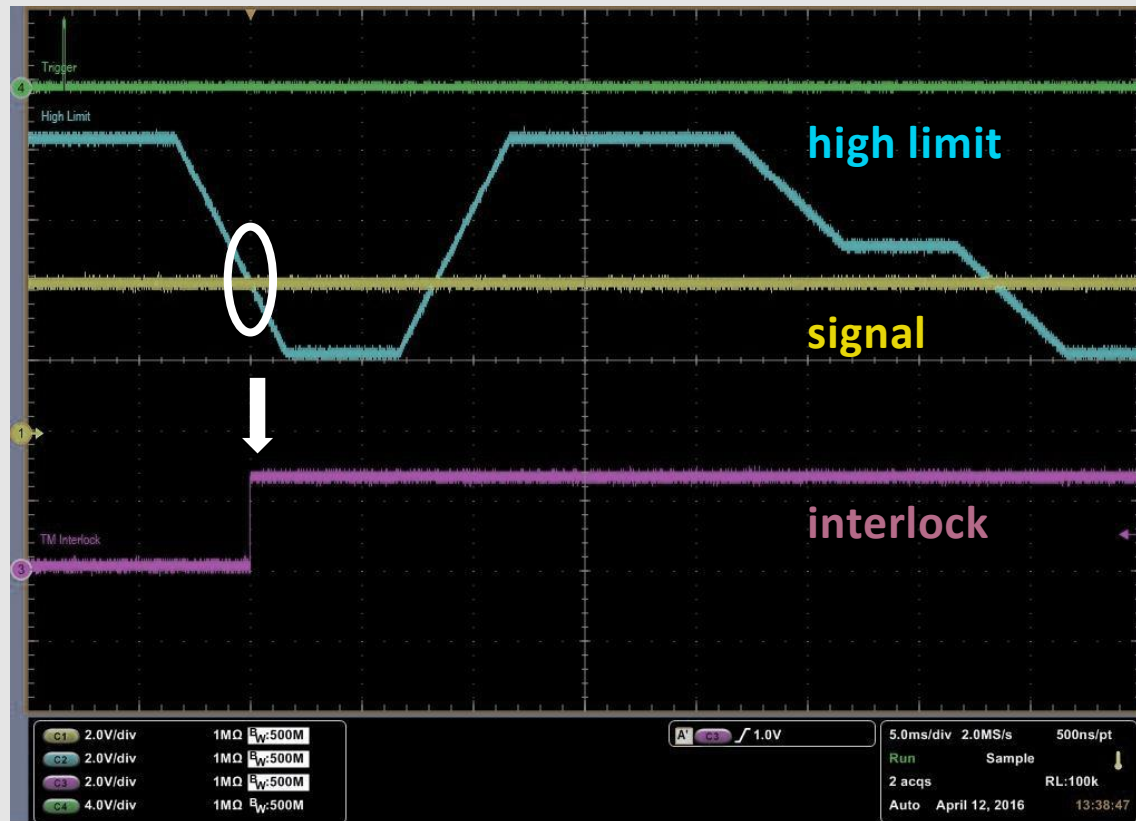


Tolerance band for deposited dose



Testing interlock functionality

Response of our test system to tolerance violations





level 2

What about smaller inaccuracies?

EXAMPLES

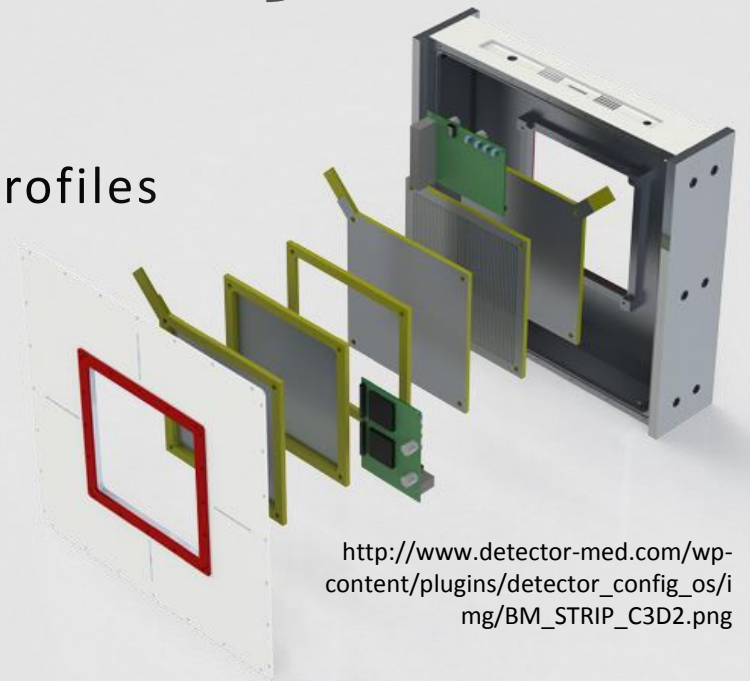
- rather noisy beam current
- slight offset in beam position
- unexpected instability in regulation

} remain undetected
by safety level 1

SOLUTION

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

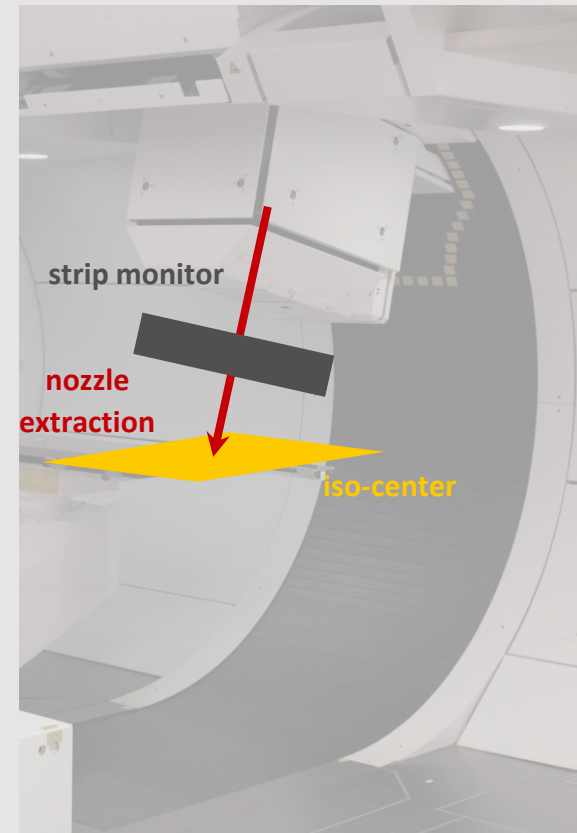
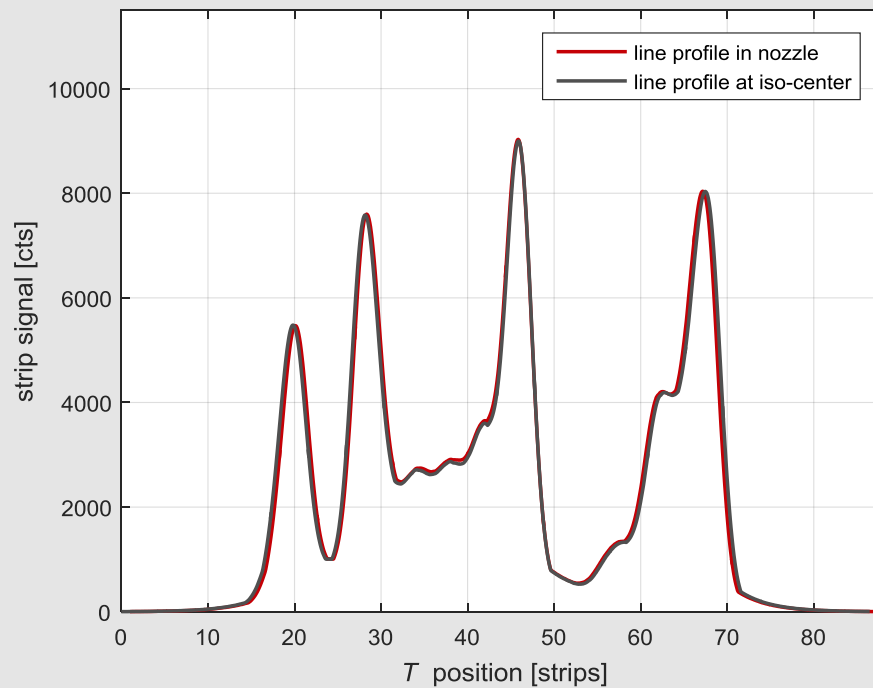
(DE.TEC.TOR, Torino)



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

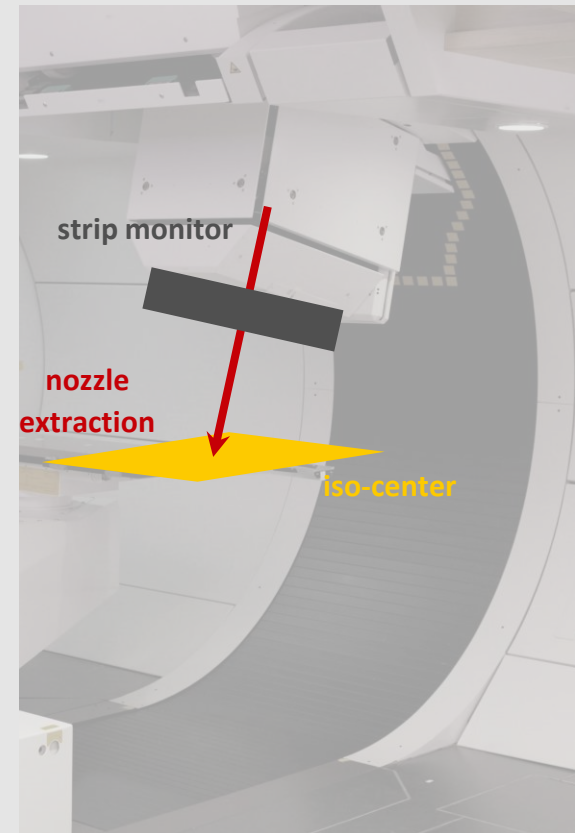
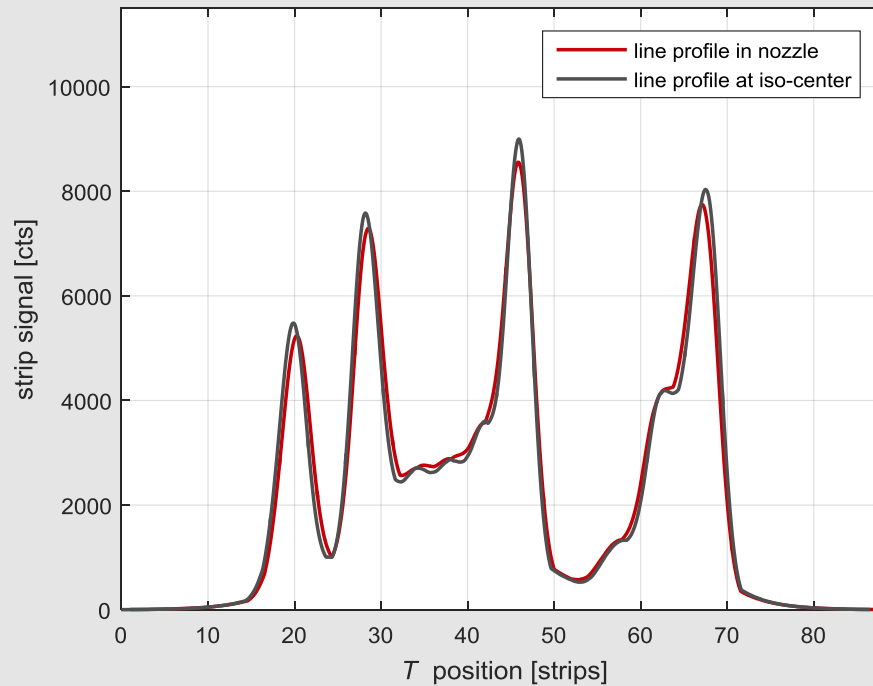
Retracting nozzle and strip monitor

$\Delta s = 27 \text{ cm}$



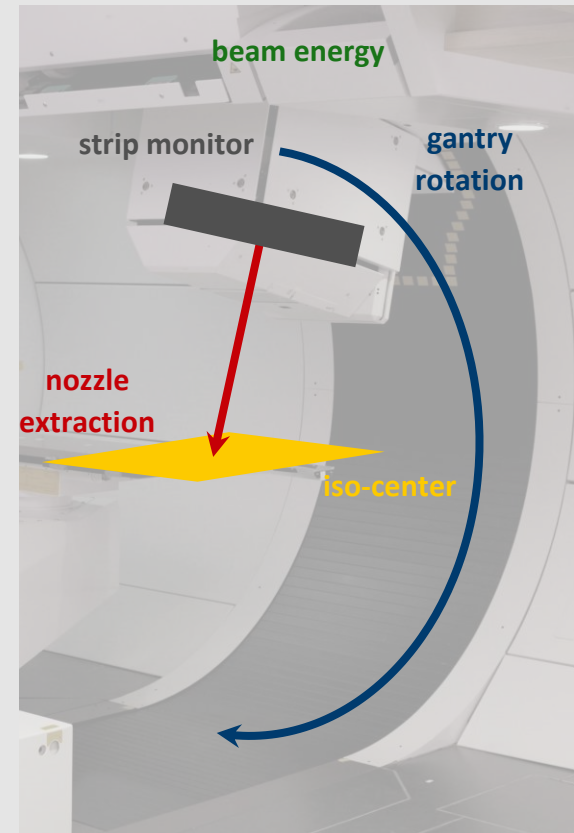
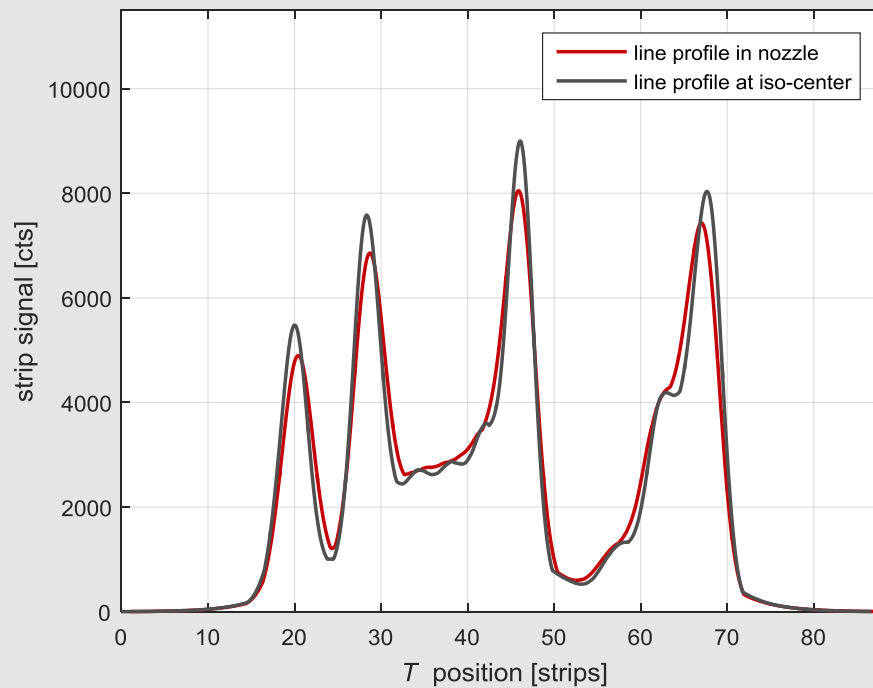
Retracting nozzle and strip monitor

$\Delta s = 14 \text{ cm}$



Retracting nozzle and strip monitor

$\Delta s = 1 \text{ cm}$



Beam profile parameterization

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

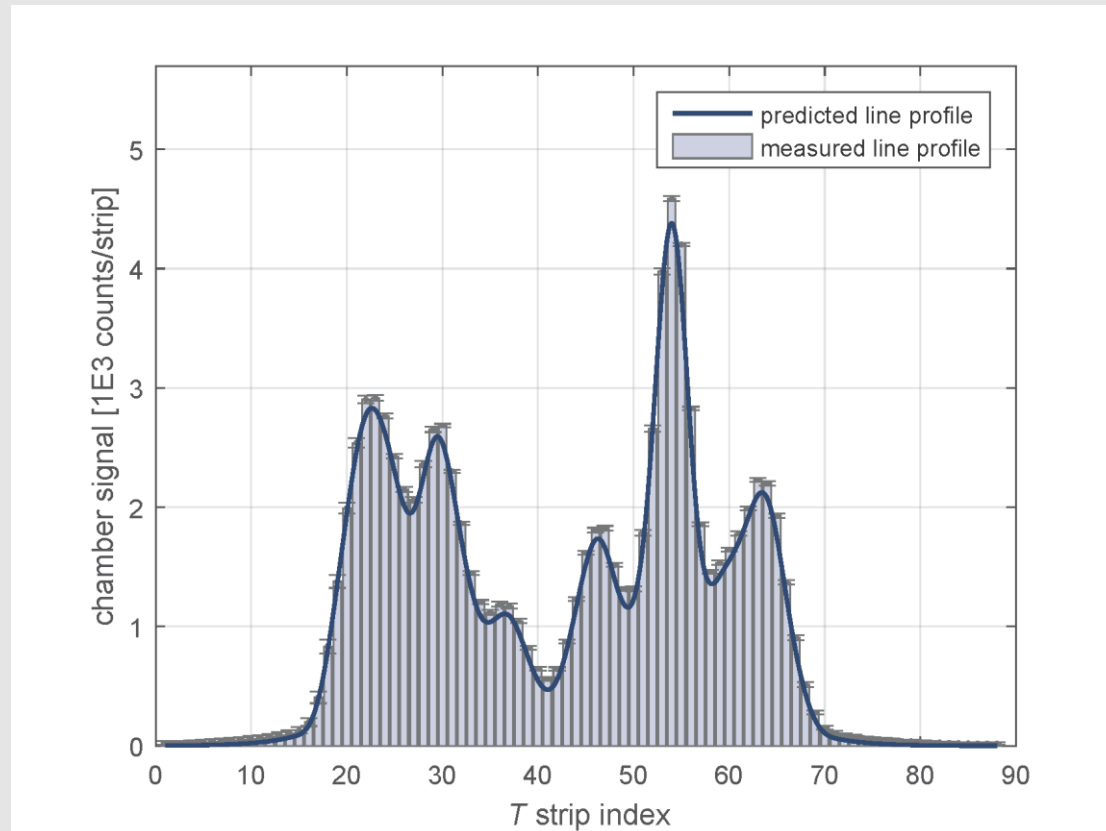
- beam energy E
- nozzle extraction Δs
- gantry angle α
- lateral T position
- lateral U position

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

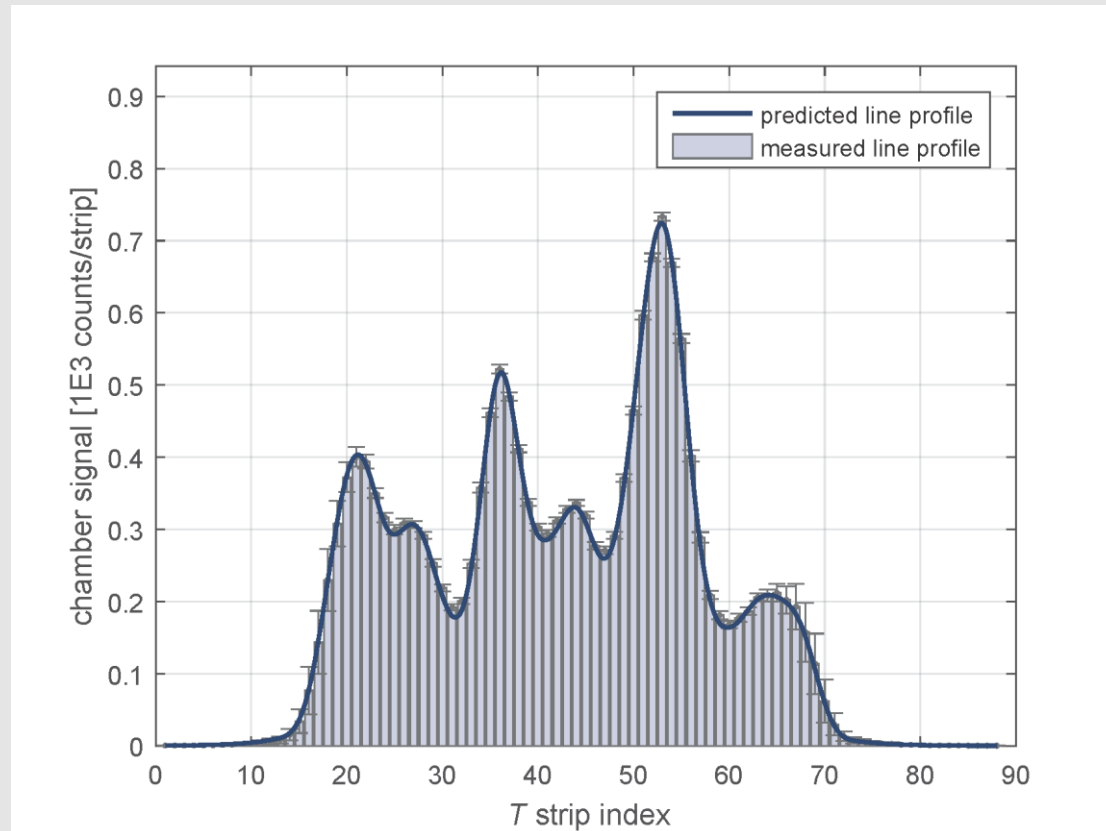
Predicted vs. measured dose profiles

Comparison for $(\alpha, E, \Delta s, U) = (0^\circ, 150 \text{ MeV}, 27 \text{ cm}, 0 \text{ cm})$



Predicted vs. measured dose profiles

Comparison for $(\alpha, E, \Delta s, U) = (15^\circ, 115 \text{ MeV}, 25 \text{ cm}, 5 \text{ cm})$

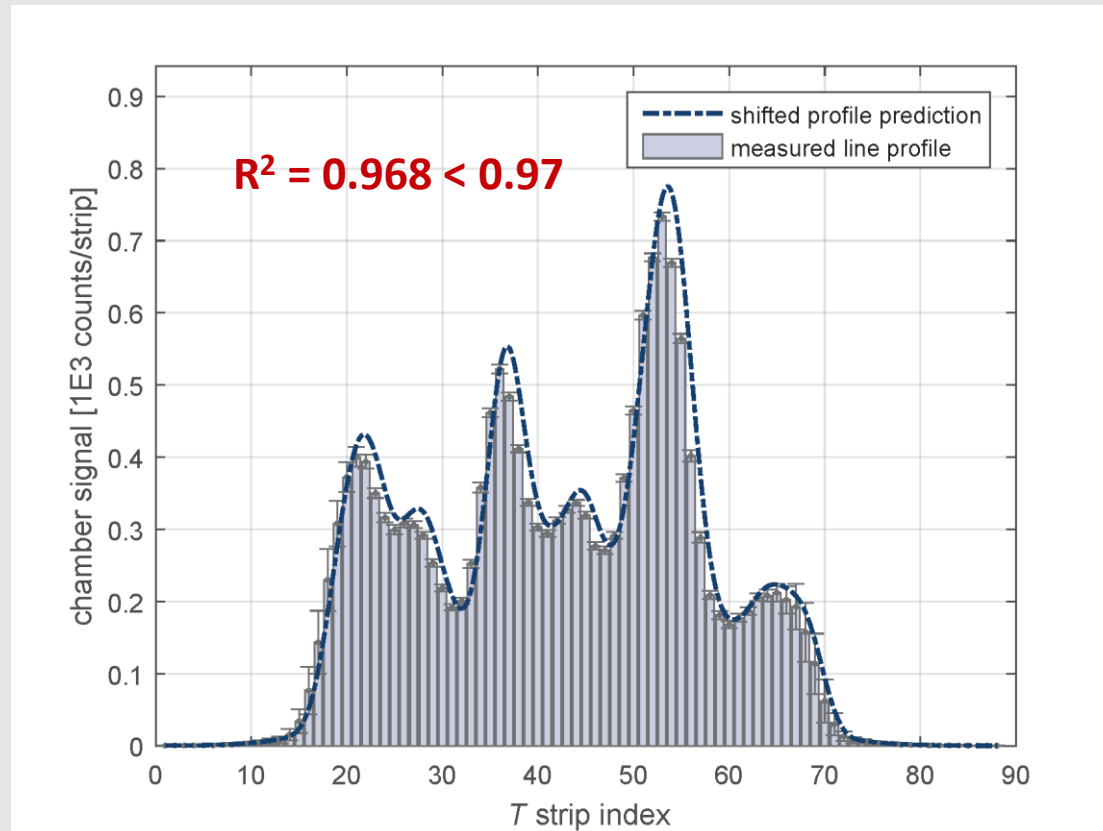


Limits derived from successfully delivery patient plans:

- **Integrated strip signal**
→ maximum deviations: $\pm 10\%$
- **Profile center of gravity**
→ maximum differences: $\pm 1.5 \text{ mm}$
- **Profile symmetry**
→ maximum deviations: $\pm 10\%$
- **R² value**
→ minimum score: 0.97
- **Gamma pass rate at 2%, 2mm**
→ minimum score: 0.70

Example of violated comparison

Comparison for $(\alpha, E, \Delta s, U) = (15^\circ, 115 \text{ MeV}, 25 \text{ cm}, 5 \text{ cm})$





conclusion

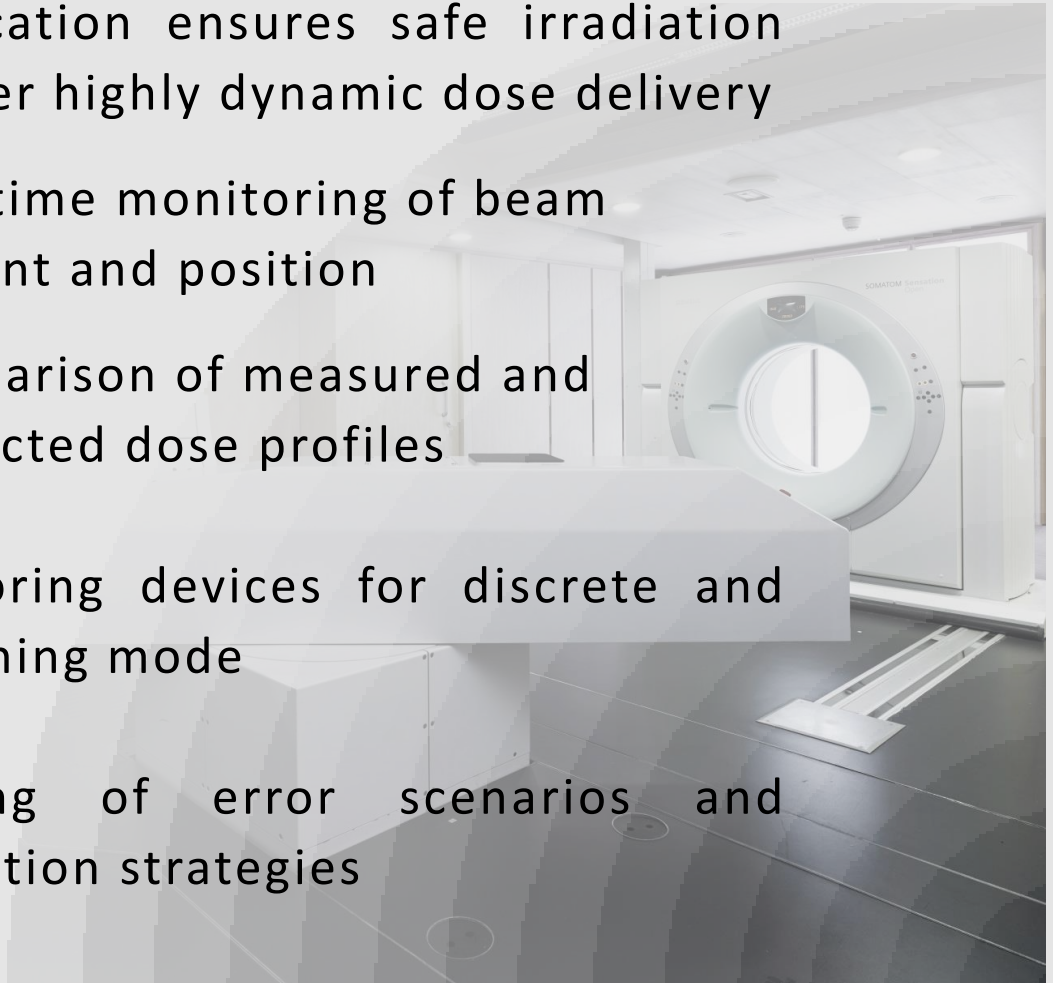
Not a recipe for every system, but ...

- 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



**Thank you for
your attention!**

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the support of
our software and
electronics engineers.*

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and Giorgio Stefanini
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