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Verification of highly dynamic dose delivery

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Why do we need a verification system?
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.
What is highly dynamic dose delivery?

Fast and flexible form of patient irradiation

**FAST**
- (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)

**FLEXIBLE**
- 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 µs)
- scanning fast with reduced beam current
  - regions of very low dose
  - weak signal in position-sensitive ICs
present our implementation for a \textit{cyclotron-based} and \textit{time-driven} delivery system
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 $\approx 100$ 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

degraded

beamline

scanner magnets

90° bending magnet

nozzle

iso-center
 Beam monitors for continuous scanning

- **Energy:** selection & tuning
  
  *(Hall probes, potentiometers)*
Beam monitors for continuous scanning

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

![Diagram of beam monitoring system](image)
• **Level 1:** Real-time verification *during* the application of a line to prevent *radiation incidents*
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Verification concept

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- **Level 2:** Online verification *after* the application of a line to assess and validate *delivery accuracy*
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Definition of delivery error

- Errors occur rarely and randomly.
- Restrict magnitude of delivery errors to
  - hot/cold spots of ± 2% of fraction dose\(^1,2\)

\[ \text{dose} \quad \pm 36 \text{ mGy} \]
\[ \text{position} \quad \pm 1.5 \text{ mm} \]

- 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

Graph showing the position at iso-center versus delivery time. The graph includes two lines:
- Black: actual position
- Red: high and low interlocks

Yellow box: "T Hall probe (surrogate for position)"
Tolerance band for beam current

**dose monitor 1**
*(instantaneous signal)*
Tolerance band for deposited dose

![Graph showing the relationship between delivery time and the number of delivered protons for dose monitor 2. The graph includes lines for actual delivered protons and high and low interlocks.]
Testing interlock functionality

Response of our test system to tolerance violations
What about smaller inaccuracies?

**Examples**

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

**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

remain undetected by safety level 1
Profiles in the nozzle plane

Retracting nozzle and strip monitor

$\Delta s = 27 \text{ cm}$
Profiles in the nozzle plane

Retracting nozzle and strip monitor

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

![Graph showing strip signal vs. position](image.png)
Profiles in the nozzle plane

Retracting nozzle and strip monitor

\[ \Delta s = 1 \text{ cm} \]

![Graph showing profiles in the nozzle plane with labels for various components such as beam energy, gantry rotation, strip monitor, and nozzle extraction.](image)
The shape of the pencil beam in the nozzle plane depends on (at least) five parameters:

- beam energy $E$
- nozzle extraction $\Delta s$
- gantry angle $\alpha$
- 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.
Comparison for $(\alpha, E, \Delta s, U) = (0^\circ, 150 \text{ MeV}, 27 \text{ cm}, 0 \text{ cm})$
Comparison for \((\alpha, E, \Delta s, U) = (15^\circ, 115 \text{ MeV}, 25 \text{ cm}, 5 \text{ cm})\)
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%

- **R² value**
  - minimum score: 0.97

- **Gamma pass rate at 2%, 2mm**
  - minimum score: 0.70
Example of violated comparison

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

\[ R^2 = 0.968 < 0.97 \]
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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