Conception of prompt-gamma detector for online ion therapy monitoring

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Prompt-Gamma (PG) ion therapy monitoring

Ion therapy:

- **High ballistic precision**
- **Uncertainties** on ion range estimation

Online ion therapy monitoring:

- Real time **Bragg Peak** location by detection of **secondary particles**: **Prompt Gamma**
- Improvement of treatment accuracy
Prompt-Gamma (PG) ion therapy monitoring

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PG features:

- $1 < E_{PG} < 10 \text{ MeV}$
- $0.01 \gamma.p^{-1}.cm^{-1}$
- PG spatial correlation
- $\langle T_{PG} \rangle < 1 \text{ ps} \Rightarrow \text{Time correlation}$

Graph showing deposition energy and PG vertex profile over depth.
Prompt-Gamma (PG) ion therapy monitoring

**Ion therapy:**

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- ✗ **Uncertainties** on ion range estimation

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  - **Prompt Gamma**

  ⇒ Improvement of treatment accuracy

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**PG features**

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- ✓ **PG spatial correlation**
- ✓ $\langle T_{PG} \rangle < 1$ ps ⇒ **Time correlation**

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**Time Of Flight (TOF) online monitoring**
PG Timing (PGT): concept

**Detection system**

**Proton Beam**

**Target**

\[ T_{\text{proton}} + T_{\text{PG}} \] distribution measurement

- Monitoring in real time
- High detection efficiency
- Neutron rejection by TOF
- TOF limited at the bunch width
- Time resolution \( \approx 1 \text{ ns rms} \)
**Introduction**

Prompt Gamma Time Imaging

Characterization of the detection pixel

Medycic experiments

**PG Timing (PGT): concept**

**Detection system**

Proton Beam

Transit time $T_{\text{proton}}$

Target

$T_{\text{proton}} + T_{\text{PG}}$ distribution measurement

- Monitoring in real time
- High detection efficiency
- Neutron rejection by TOF
- TOF limited at the bunch width

$\Rightarrow$ Time resolution $\approx 1 \text{ ns rms}$

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**Increase PGT sensitivity:**

- Single proton regime
- Diamond beam monitor

Time resolution: **101 ps rms**

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Goal: proton range estimation at the very beginning of the irradiation (10^7-10^8 protons) in single proton regime
Prompt Gamma Time Imaging

Goal: proton range estimation at the **very beginning of the irradiation** (10^7-10^8 protons) in single proton regime

**Diamond-based beam monitor**

**Time of flight Imaging ArRAy (TIARA):**
- ≈ 30 small-size Cerenkov radiators

**Vertex Reconstruction:**

\[ T_{\text{Start}} - T_{\text{Stop}} = T_{\text{proton}} + T_{\text{PG}} \]
Simulation: Detection of a proton range shift

Longitudinal shift sensitivity

![Diagram showing the detection of a proton range shift with a linear fit and 2σ and 1σ errors.](attachment:image.png)
Simulation: Detection of a proton range shift

Longitudinal shift sensitivity

Proton Beam

Air cavity

PG

Detection surface

Air cavity thickness [cm] 0.0 0.1 0.2 0.3 0.4 0.5

Measured shift [cm] 0.0 0.1 0.2 0.3 0.4

Linear fit

$2\sigma$ errors

$1\sigma$ errors

$10^8$ protons

Transverse shift sensitivity

Proton Beam

Air cavity

PG

Detection surface

Y-axis beam position [cm] 0.0 0.1 0.2 0.3 0.4 0.5

Measured shift [cm] -0.1 0.0 0.1 0.2 0.3 0.4

Linear fit

$2\sigma$ errors

$1\sigma$ errors

$10^8$ protons
### Simulation results

<table>
<thead>
<tr>
<th>Number of protons</th>
<th>Longitudinal shift</th>
<th>Transverse shift</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10^7$</td>
<td>$10^8$</td>
</tr>
<tr>
<td>Number of PG detected</td>
<td>$3 \times 10^3$</td>
<td>$3 \times 10^4$</td>
</tr>
<tr>
<td>Expected sensitivity at $1\sigma$ (mm)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Expected sensitivity at $2\sigma$ (mm)</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

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A time-of-flight-based reconstruction for real-time prompt-gamma imaging in proton therapy

[https://doi.org/10.1088/1361-6560/ac03ca](https://doi.org/10.1088/1361-6560/ac03ca)
Characterization of TIARA pixel detector
Characterization of TIARA pixel detector

SiPM photon counting mode

Counts

Amplitude [mV]
Characterization of TIARA pixel detector

Intrinsic SiPM time resolution

\[ \text{Rms time resolution [ps]} \approx \frac{1}{\sqrt{N_{\text{phot}}}} \]

- FBK 35
- FBK 40
- Hamamatsu 3050
- Hamamatsu 3075
Characterization of TIARA pixel detector

**Intrinsic SiPM time resolution**

\[
\text{Rms time resolution [ps]} \approx \frac{1}{\sqrt{N_{\text{phot}}}}
\]

**SiPM photon counting mode**

**Time resolution of Cerenkov + SiPM with $^{60}\text{Co}$**

\[
\sigma_t = 190(5.0)\text{ps rms}
\]
Experiments: performance of our detection system

**Experiment 1** of June 2021:
- 60 MeV proton beam irradiation
- 1 cm thick PMMA
Experiments: performance of our detection system

**Experiment 1 of June 2021:**
- 60 MeV proton beam irradiation
- 1 cm thick PMMA

**Number of detected optical photons**

![Graph showing charge spectrum](image_url)

- PMMA
- PG
- PbF$_2$ + SiPM
- Diamond
- 60 MeV Proton beam

**Normalized counts**

- $\times 10^{-2}$
- $\times 10^{3}$

**Pixel time resolution**

- $\sigma_t$ diamond-PG detector: 134.9(15.4) ps rms
Experiments: performance of our detection system

**Experiment 1 of June 2021:**
- 60 MeV proton beam irradiation
- 1 cm thick PMMA

Number of detected optical photons

Pixel time resolution

\[ \sigma_t \text{ diamond-PG detector: } 134.9(15.4) \text{ps rms} \]