ION BEAM MONITORING USING BRMESSTRAHLUNG X-RAYS

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WORLDWIDE CANCER STATISTICS

- 17 million of new cases of cancer worldwide in 2018
  - Lung (2.09 million cases), Breast (2.09 million cases), Colorectal (1.80 million cases), Prostate (1.28 million cases), Skin cancer (1.04 million cases), Stomach (1.03 million cases)
- 9.6 million deaths in 2018
- 27.5 million of new cases expected in 2040

CANCER TREATMENT

- Surgery: Ablation of the tumour
- Chemotherapy: Treatment using chemical drugs
- Radiotherapy: Treatment using ionizing radiations

Therapeutic approaches can also mix the different technics

Figure 1: Fraction of treatment cancer technics in France during 2016.
**RADIOThERAPY**

**External radiotherapy**
- Ionizing radiations from particle accelerator
  - Photon beam
  - Electron beam
  - Ion beam

**Brachytherapy**
- Radioactive source in contact with the tumor

**Internal Vectorized Radiotherapy**
- Radionuclide coupled with chemical vector

**Framework of our study**

**PROTON BEAM:**
- High and localised deposited dose
  (Bragg peak)

**PHOTON BEAM:**
- Exponential attenuation of the deposited dose in the medium
  (Reference beam in radiotherapy)

*Figure 2: Schematic view of the depth-dose profile for photon and proton beams.*
The Spread-out Bragg Peak is the weighted sum of different Bragg in order to conform the deposited dose to the tumor thickness.

Figure 3: Spread-out Bragg Peak from proton beam of 68MeV.
Figure 4: Comparison of the dose distribution obtained with proton beams (left) and photon beams (right) for the treatment of ocular cancer

- Proton beams decrease the deposited dose outside the tumor
- Mostly used for pediatric, brain and eye cancer.
**Interaction Proton/Matter:**

- X-ray production
  - Ionisation / Excitation
  - Bremsstrahlung
- γ photon production
  - Gamma prompt production from nuclear interaction
  - Annihilation of positron from β⁺ emitter created by the radiation
- Magnitude of cross sections for photon production
  - Gamma prompt: ~ 10 mbarn
  - RX bremsstrahlung: ~ $10^2$ mbarn


*Figure 5: Schematic view of particles emitted from the irradiated medium after interaction with a proton beam.*
NON-INVASIVE ONLINE BEAM MONITORING

**Different approaches:**
- Positron Emission Tomography
  - Online beam range verification
- Uncertainties on the beam range (several mm): delayed decay
  

- γ prompt measurement
  - Online beam range monitoring
  - Small delayed decay
  
  Testa, Rad. Env. Biophy., 2010

- X-ray bremsstrahlung
  - Beam imaging
  - Beam range monitoring
  

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**Figure 6:** Schematic view of the different online beam monitoring approach.
**Bremsstrahlung:**
- X-ray emissions from the deceleration of the charged particles in the medium
- X-ray energy is proportional to the energy loss of the charged particles
- Continuous component of the X-ray spectrum

**Composantes du Bremsstrahlung:**
- QFEB: Quasi-Free Electron Bremsstrahlung
- SEB: Secondary Electron Bremsstrahlung
- AB: Atomic Bremsstrahlung
- NB: Nuclear Bremsstrahlung
- Cross section:

\[
\frac{d^2\sigma^i}{d\Omega d\omega} = F_1^i(E_p, Z_p, Z_T, h\omega) \cdot F_2^i(\theta) \quad [1]
\]

Pasher, Phys. Rev., 1990

**Bremsstrahlung interest:**
- Directly link to the deposited dose
- Significant cross sections
- Sensitive to the medium attenuation
  - Low energy: elementary composition of the medium
  - High energy: density of the medium


**Figure 7:** Schematic view of the bremsstrahlung X-rays emitted from different processes.
Method developed for radiobiology:
- Demonstrated for alpha particles
- Valid for homogeneous medium with a thin thickness

\[ D [Gy] = \phi [cm^{-2}] \cdot LET \left[ \frac{MeV.cm^2}{g} \right] \cdot 1.6 \times 10^{-10} \] [2]

In this state, not applicable in clinic:
- Heterogeneous medium
  - Impossibility to get the fluence and LET
  - Medium attenuation

Aim of the study
- Proof of feasibility to monitor proton beam using bremsstrahlung X-rays
- Cross section measurement
- Fundamental study to model the bremsstrahlung spectrum
- Extend the method to clinical application

\[ N_X^{Br} = N_p \cdot \int_{E_p}^{E_p} \epsilon(hv) \cdot \frac{d\sigma^{Br}}{d\Omega dhv} (E_p, hv) \cdot A(hv) dhv dE_p \] [3]
**EXPERIMENTAL SET-UP**

**H+ Beam:**
- 17MeV/u
- 30MeV
- 40MeV
- 50MeV

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**Silicon detector:**
- Promotes the detection of low energy photons (between 1 and 30keV)
- Minimise the target-detector distance
- Crystal thickness: 450µm

**Carbon Target:**
- Cross section measurement
- Single-element target

**PMMA target:**
- $Z_{eff} = 6.47 \approx Z_{eau} = 7.42$
- Close to biological medium

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**Beam stop:**
- Measure of the beam fluence
- $N_p = \frac{Q}{Z_p \times e}$

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**Two acquisitions:**
- Background: Measure of the ambiant activation and fluence with the beam stop
- Measure of the bremsstrahlung X-rays emitted by the PMMA target

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Figure 8: Schematic view of the experimental set-up to measure bremsstrahlung spectra and cross sections

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CONTEXT – BEAM MONITORING METHOD – RESULTS – CONCLUSION

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EXPERIMENTAL SET-UP

**Figure 9**: Photography of the experimental set-up.

**Figure 10**: Photography of the beam line output with a silicon detector looking at the PMMA target.

**Figure 11**: Raw spectra of background and bremsstrahlung acquisitions.
Figure 12: Bremsstrahlung cross sections for a Carbon target bombarded with proton beams of 16.9MeV/u, 30.1MeV, 39.3MeV and 49.6MeV.

- **Significant agreement** between the experimental data and the model
- Cross section measured are closed to literature
  - Ishii: For proton beam of 20MeV at the photon energy of 7keV: **0.01 barn/keV.sr**
  - Measure: For proton beam of 16.9MeV at the photon energy of 7keV: **0.008 barn/keV.sr**
    

- The disagreement at high energy photon could be explained with the noise induced by the target

- Fundamental contributions of the spectrum
  - QFEB
  - SEB
**Figure 13**: Experimental (grey line) and simulated (black dashed line) bremsstrahlung spectra from the 1000µm PMMA thick target bombarded with proton beams of 16.9MeV/u, 30.1MeV, 39.3MeV and 49.6MeV.

- **PMMA target**: significant agreement between model and bremsstrahlung spectra
- **Signal measured** comes from bremsstrahlung
- **Shape of the spectra**:
  - Photon with an Energy > 15keV are attenuated because of the detector efficiency
  - Photon with an energy < 5keV are attenuated because of the air attenuation
Photon with an energy $< 5$keV are attenuated because of the target-detector distance and the detection efficiency.

Photon with an energy $> 15$keV are attenuated because of the detector efficiency.

**Figure 13: Experimental (grey line) and simulated (black dashed line) bremsstrahlung spectra from the 1000µm PMMA thick target bombarded with proton beams of 16.9MeV/u, 30.1MeV, 39.3MeV and 49.6MeV.**
**Beam Energy Monitoring**

- $E_{\text{mean}}$ increases with the beam energy.
- FWHM increases with the beam energy.
- Fraction of high energy photon (>15keV) increases.

### Table: Beam Energy vs. $E_{\text{mean}}$ and FWHM

<table>
<thead>
<tr>
<th>Beam Energy (MeV)</th>
<th>$E_{\text{mean}}$ (keV)</th>
<th>FWHM (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.9</td>
<td>6.167±0.200</td>
<td>4.160±0.200</td>
</tr>
<tr>
<td>30.1</td>
<td>6.676±0.200</td>
<td>7.667±0.200</td>
</tr>
<tr>
<td>39.3</td>
<td>7.154±0.200</td>
<td>8.238±0.200</td>
</tr>
<tr>
<td>49.6</td>
<td>8.023±0.200</td>
<td>8.745±0.200</td>
</tr>
</tbody>
</table>

- The bremsstrahlung spectrum hardening with the increase of the beam energy is explained with the bremsstrahlung cross sections variations.
- Proton beam energy can be monitored with the bremsstrahlung X-rays.
- Observation are only valid for this set-up because of the detector efficiency and medium attenuation.

Figure 14: Bremsstrahlung spectra from 1000µm PMMA thick target bombarded with 16.9MeV/U, 30.12MeV, 39.3MeV and 49.6MeV proton beams (energy at the target surface).
Bremsstrahlung yield grows with the proton beam energy.

Good agreement with the model.

Bremsstrahlung yield saturation.

Figure 15: Bremsstrahlung yield versus the PMMA thickness target bombarded with proton beam of 16.9MeV/U, 30.12MeV, 39.3MeV and 49.6MeV.

Target thickness can be monitored with the bremsstrahlung X-rays until the target thickness limit where the bremsstrahlung yield saturates.
Figure 15: Bremsstrahlung yield versus the PMMA thickness target bombarded with proton beam of 16.9MeV/U, 30.12MeV, 39.3MeV and 49.6MeV.

Target thickness can be monitored with the bremsstrahlung X-rays until the target thickness limit where the bremsstrahlung yield saturates.

Good agreement with the model
BEAM RANGE MONITORING WITH BREMSSTRAHLUNG X-RAYS
**BREMSSTRAHLUNG SCAN**

Figure 16: Experimental set-up of the bremsstrahlung scan for a water tank bombarded with proton beam of 68MeV.
BREMSSTRAHLUNG SCAN

Figure 17: Photographies of the experimental set-up of the bremsstrahlung scan for a water tank bombarded with proton beam of 68MeV.
Bremsstrahlung spectra evolve with the beam energy.

Link with the deposited dose should be investigated.

Figure 18: Depth-dose profile of the FLUKA simulation (Data were normalised). Bremstrahlung spectra at different depth are also presented.
CONCLUSION AND OUTSKIRTS

- **Ion beam monitoring using Bremsstrahlung X-rays**
  - Cross section measured on carbon target: proof of the **significant sensitivity** for the method
  - Bremsstrahlung **model validated** with the experimental data
  - **Beam energy can be monitored** with the bremsstrahlung for proton beams in the frame of radiobiology experiment
  - **Results are only valid for the set-up** used because of the detector efficiency and medium attenuation

- **Outskirts**
  - **Monte-Carlo simulations are required** to improve the set-up and to develop an X-ray camera
  - Link with the deposited dose should be investigate
• M. J. Berger et al, Stopping power and range tables for electrons, protons and helium ions, NIST standard reference database 124, (2017).