

HIGH ENERGY ION BEAM MONITORING: X-RAYS BREMSSTRAHLUNG PRODUCTION CROSS SECTION MEASUREMENTS FOR CARBON TARGET

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MEDICAL CONTEXT

WORLDWIDE CANCER STATISTICS

(World Health Organisation Report 2018)

- **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

DIFFERENT WAYS TO TREAT THE CANCER

Surgery : Ablation of the tumour

Chemotherapy : Treatment using chemical drugs

Radiotherapy : Treatment using ionizing radiations

Hadrontherapy when using external ion beams

SPREAD-OUT BRAGG PEAK (SOBP)

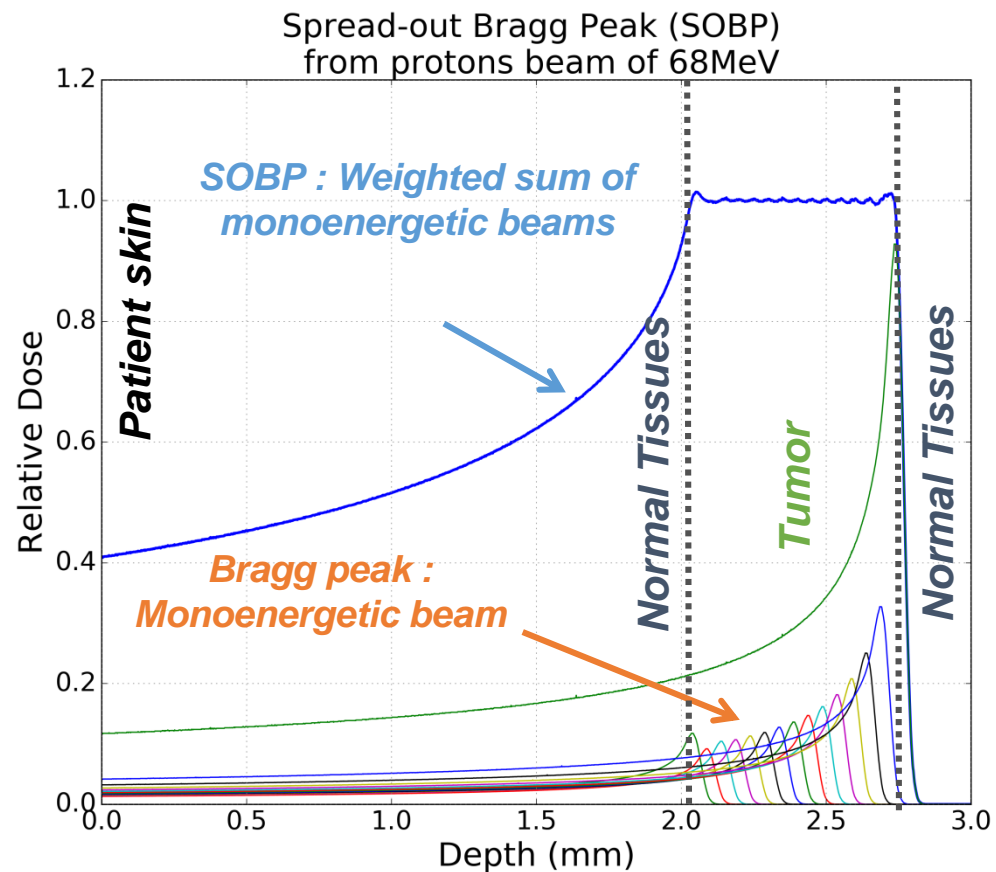
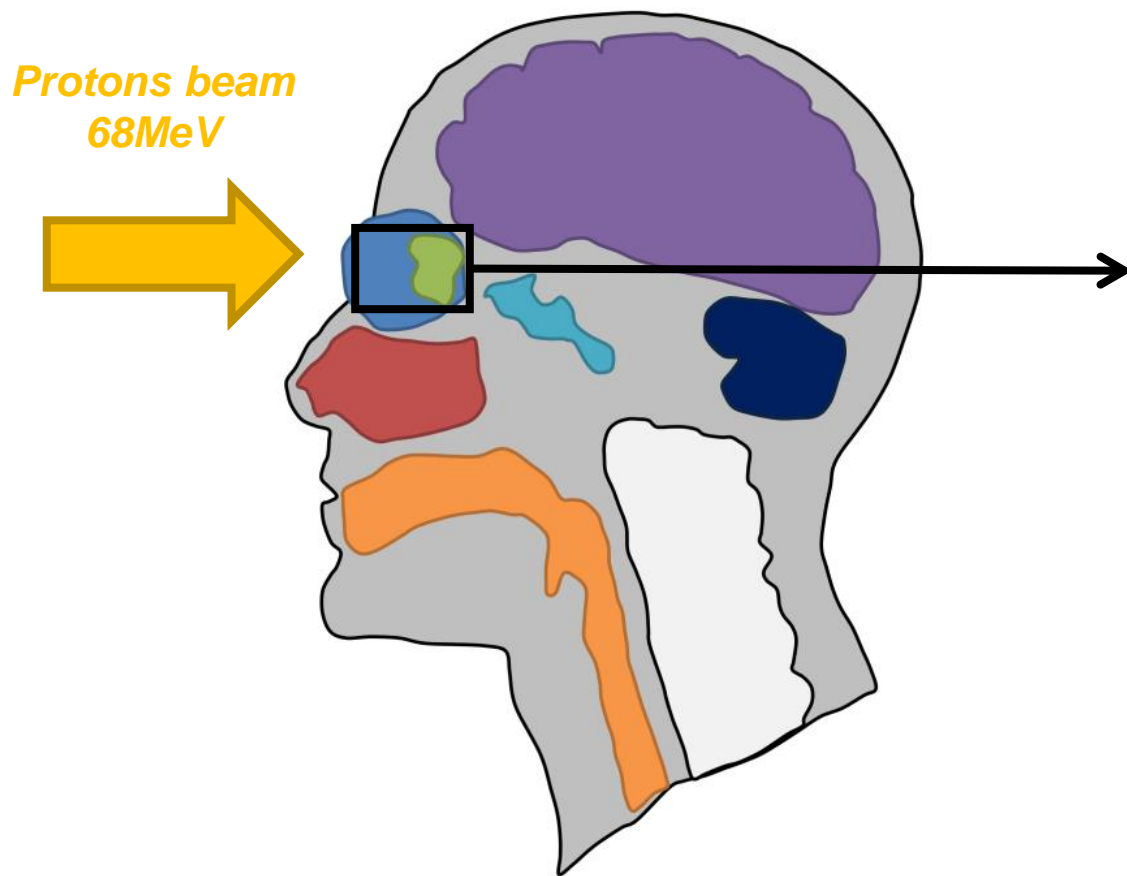


Figure 1 : Spread-Out Bragg Peak (SOBP) for protons of 68 MeV.



SOBP : High and localised deposited dose = **Beam monitoring required**

SECONDARY PARTICLES PRODUCTION

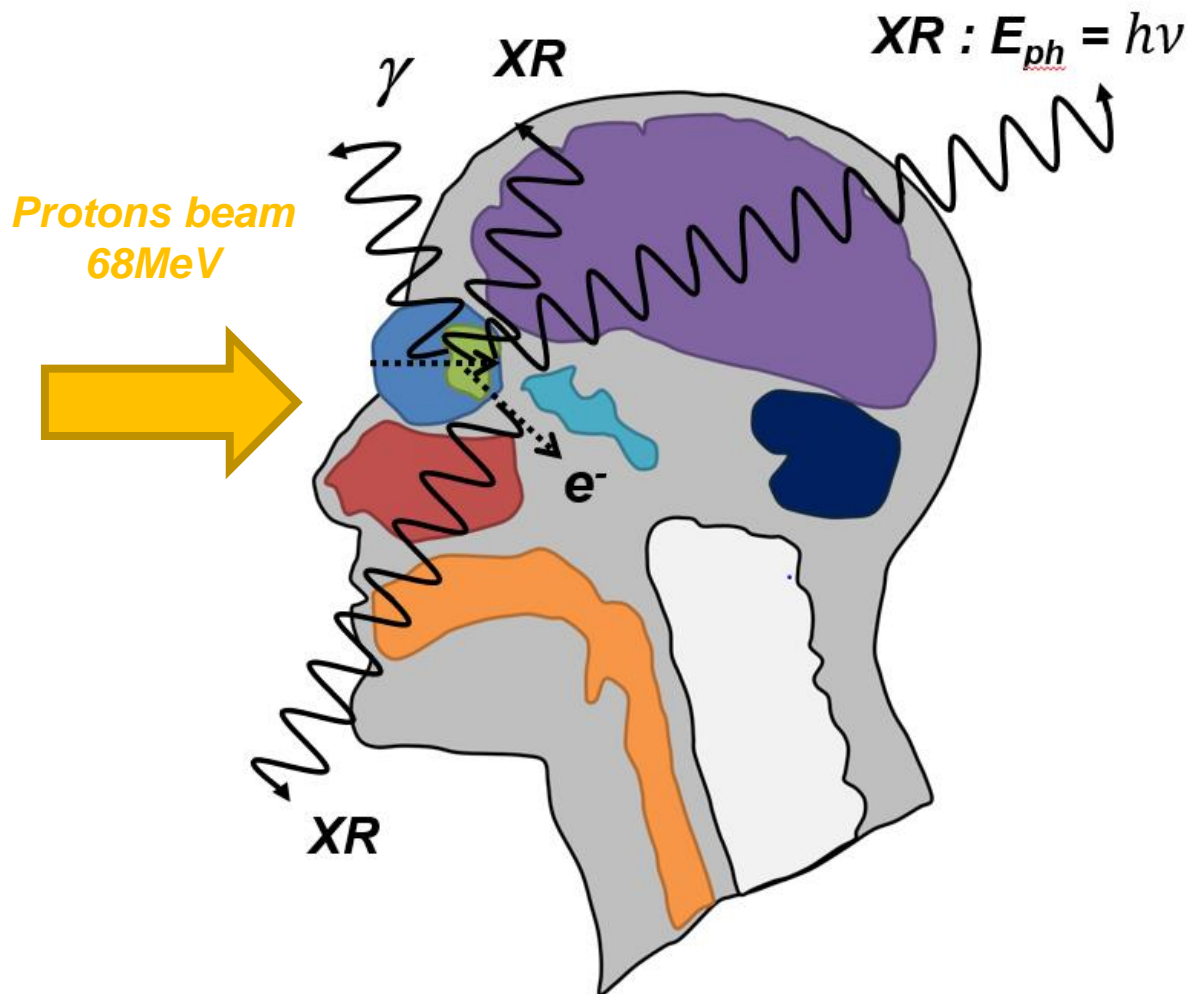


Figure 2 : Schematic view of particles emitted from the irradiated medium after interaction with a proton beam.

Non-invasive method to monitor ion beam are based on the detection of the secondary particles produced in the irradiated medium



Ion beam interaction with 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

NON-INVASIVE METHODS : DIFFERENT WAYS

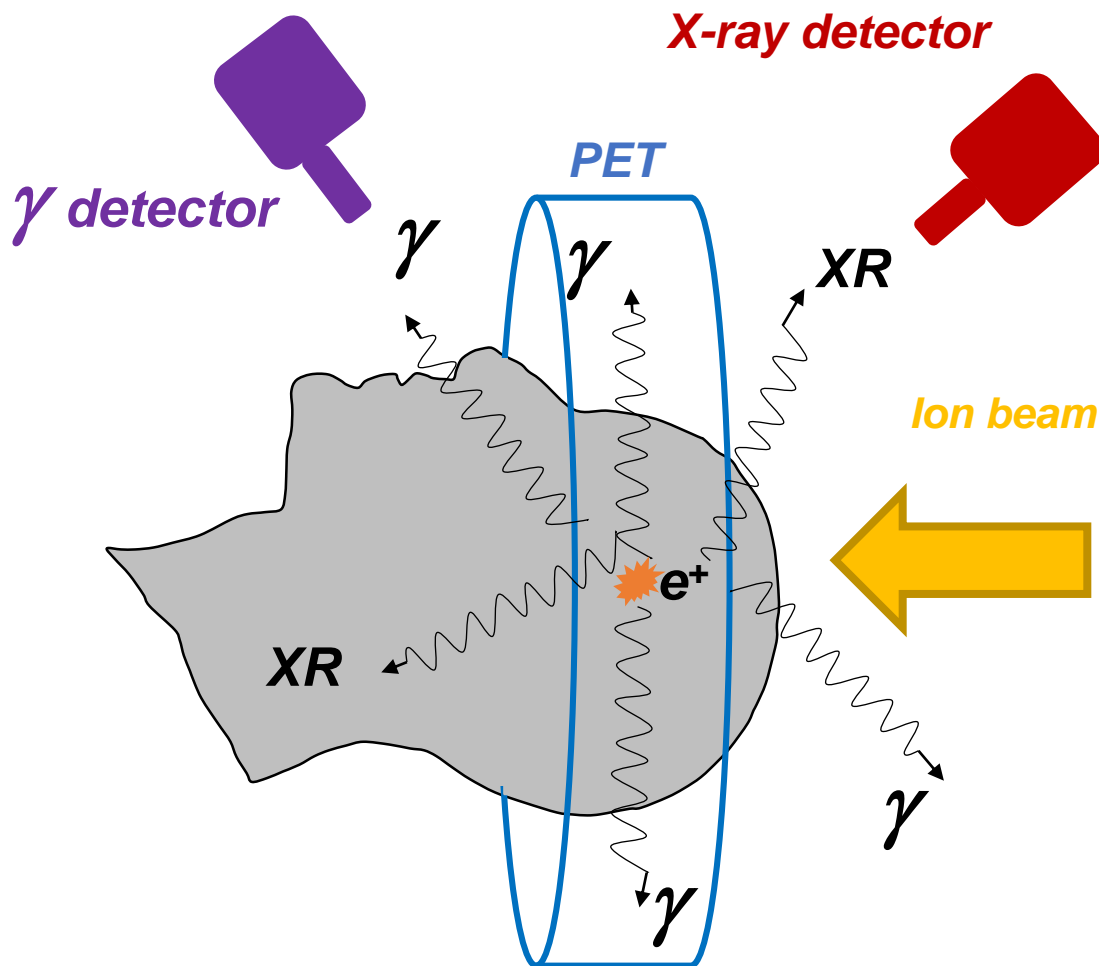


Figure 3 : Schematic view of the different online beam monitoring approach.

• Positron Emission Tomography (PET)

- Used in clinic applications
- Used for online beam range verification
- **Uncertainties on beam range measurement** (several mm)
 - β^+ emitter activity fall-out after irradiation
 - Uncertainties on PET/CT registration
 - Low statistics counts

Parodi, Med. Phys., 2018

• γ prompt detection

- Develop to avoid the β^+ activity fall-out
- **Higher cross-section** than the β^+ emitter production
- Used for online beam range verification
- Less sensitive to the attenuation (γ energy : MeV)
- **Uncertainties on beam range measurement** (several mm)
- **Detector development required** to maximize the detection of photons with MeV range energy

Verburg, Phys. Med. Biol., 2014

Krimmer, NIM A, 2018

• Bremsstrahlung

- Just several studies in the litterature
- Only studied to measure the beam range

Yamaguchi, Med. Phys, 2020

THE BREMSSTRAHLUNG X-RAYS

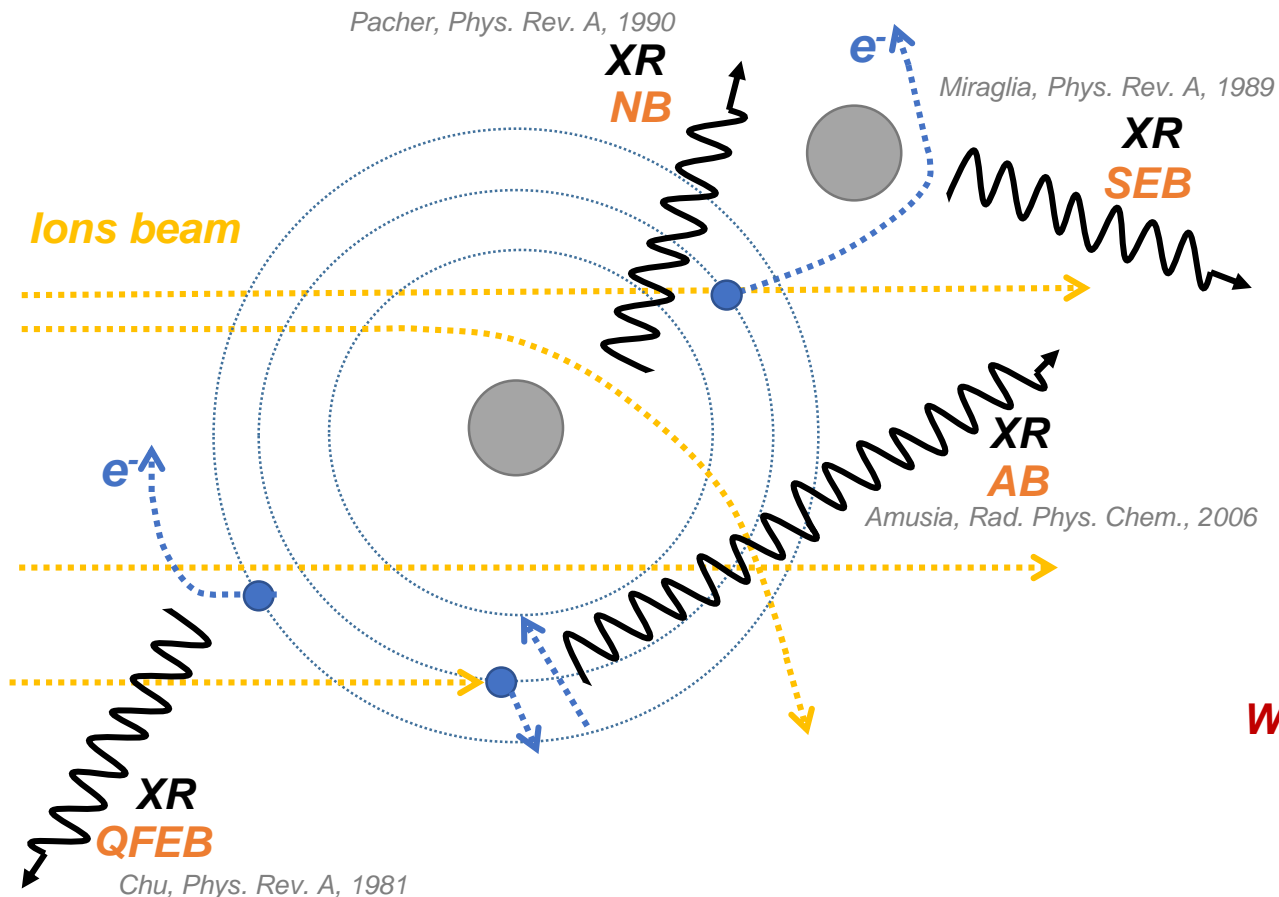


Figure 4 : Schematic view for the bremsstrahlung X-rays emitted from different processes.

• 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 part of the X-ray spectrum

• Bremsstrahlung processes

- QFEB : Quasi-Free Electron Bremsstrahlung
- SEB : Secondary Electron Bremsstrahlung
- AB : Atomic Bremsstrahlung
- NB : Nuclear Bremsstrahlung

Why should we study the Bremsstrahlung ?

- **Directly link to the deposited dose**
- **Sensitive to the medium attenuation**
 - Low energy X-rays : medium chemical composition
 - High energy X-rays : medium density

THE BREMSSTRAHLUNG CROSS-SECTION

- **Theoretical model of the bremsstrahlung cross-section was developed in context of PIXE (Particle Induced X-Ray Emission)**
- **Models only valid for ion beams with an energy lower to 20 MeV**

Chu, Phys. Rev. A, 1981 ; Miraglia, Phys. Rev. A, 1989 ; Pacher, Phys. Rev. A, 1990 ; Amusia, Rad. Phys. Chem., 2006 ; Ishii, Rad. Phys. Chem., 2006 ; Ishii, NIM B., 2018

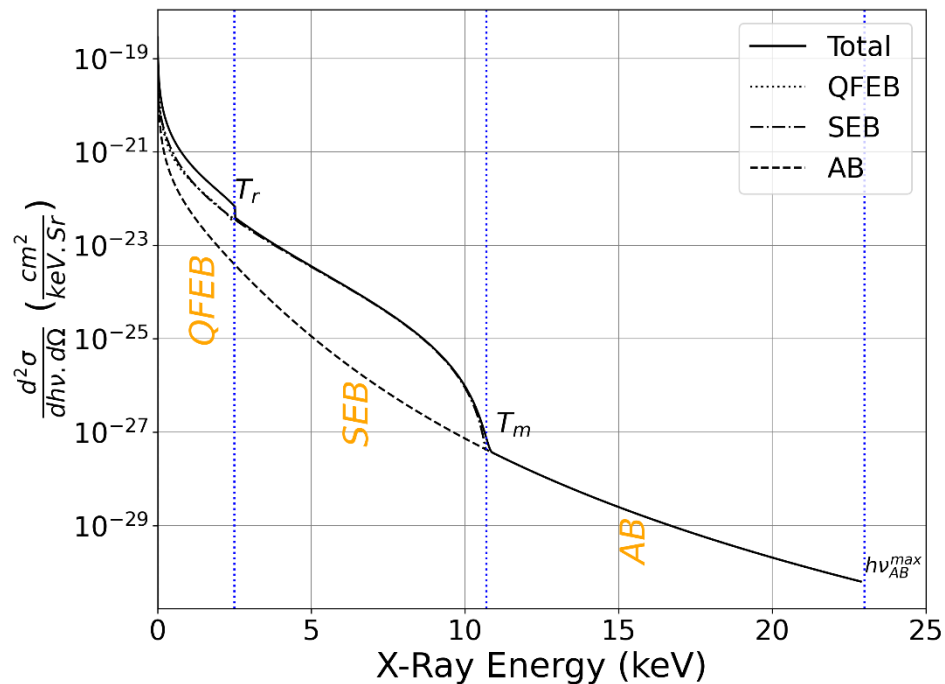


Figure 5 : Theoretical bremsstrahlung cross section from a carbon target irradiated with protons of 5 MeV.

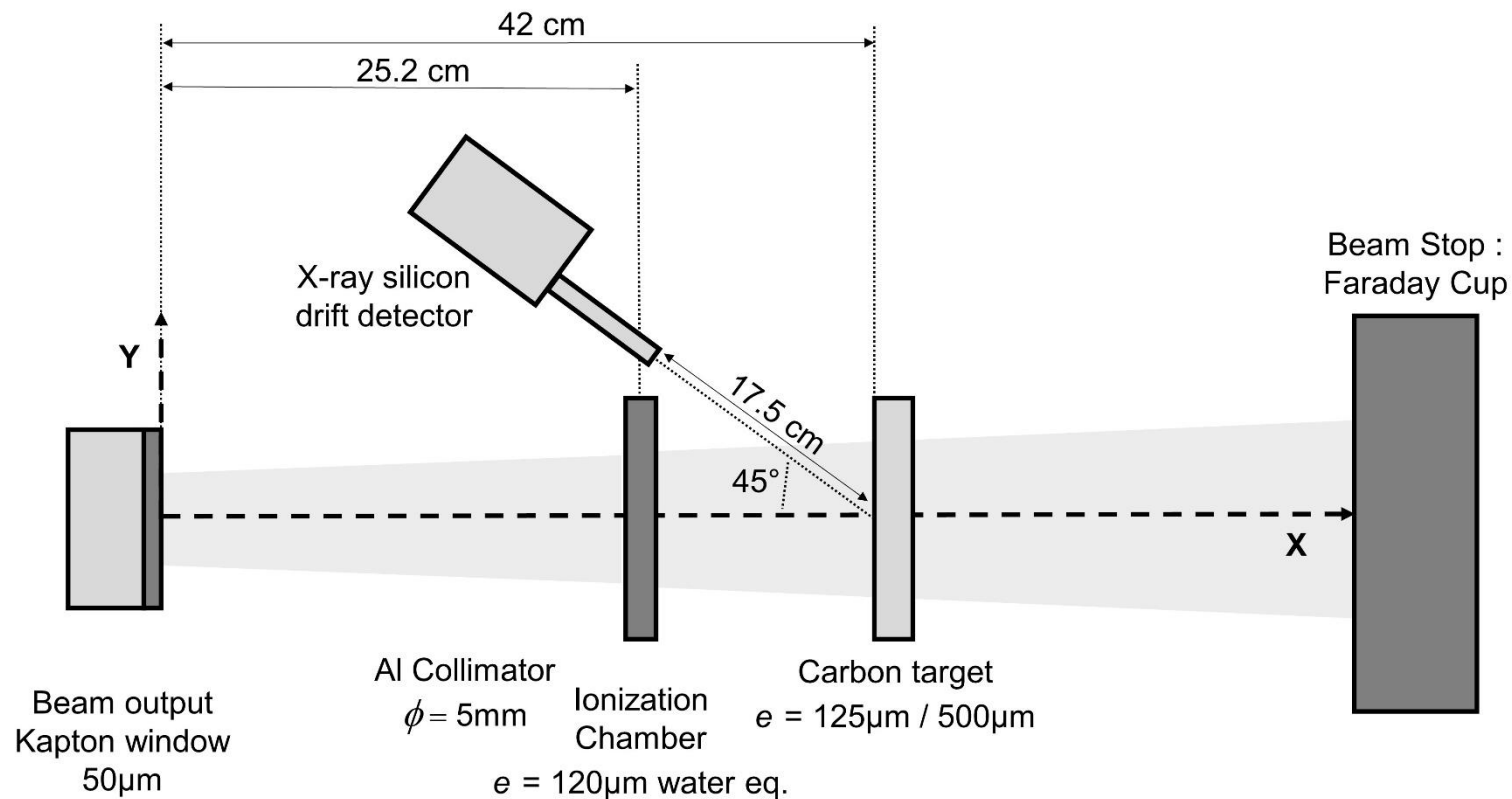
Theoretical cross section models

$$\frac{d^2 \sigma^{Tot}}{d\Omega dh\nu} = \sum_{i=1}^N \frac{d^2 \sigma^i}{d\Omega dh\nu} (E_p, Z_p, Z_T, h\nu, \theta) = \sum_{i=1}^N F_1^i(E_p, Z_p, Z_T, h\nu) \cdot F_2^i(\theta)$$

Maximum X-ray energy produced for each bremsstrahlung process

$$h\nu_{max}^{QFEB} = T_r < h\nu_{max}^{SEB} = T_m < h\nu_{max}^{AB} < h\nu_{max}^{NB} \propto E_p$$

EXPERIMENTAL SET-UP



Purpose:

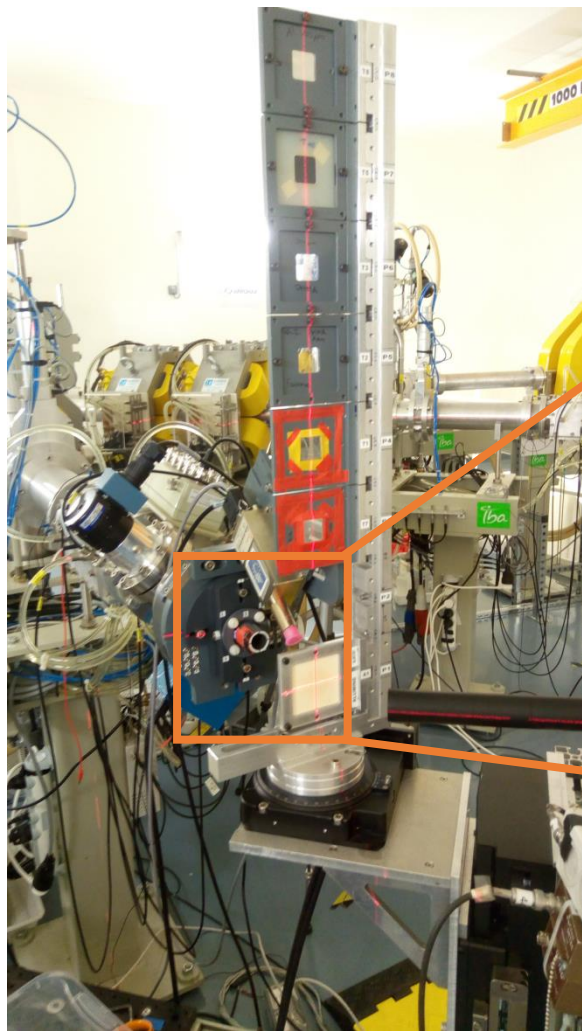
- To study the sensitivity of the method by measuring bremsstrahlung cross sections
- To study the theoretical bremsstrahlung cross section models in the ARRONAX beam energy range (17–70 MeV)

Experimental set-up:

- **Alpha** beam of 62 MeV
- **Protons** beams of 15, 29, 33, 39 and 49 MeV
- **Carbon** target:
 - Monoatomic target
 - Present in chemical composition of the biological samples

Figure 6 : Schematic view of the experimental set-up to measure bremsstrahlung spectra and cross section.

MEASUREMENT OF THE X-RAYS SPECTRA



Background (without target) and bremsstrahlung (with target) measurements

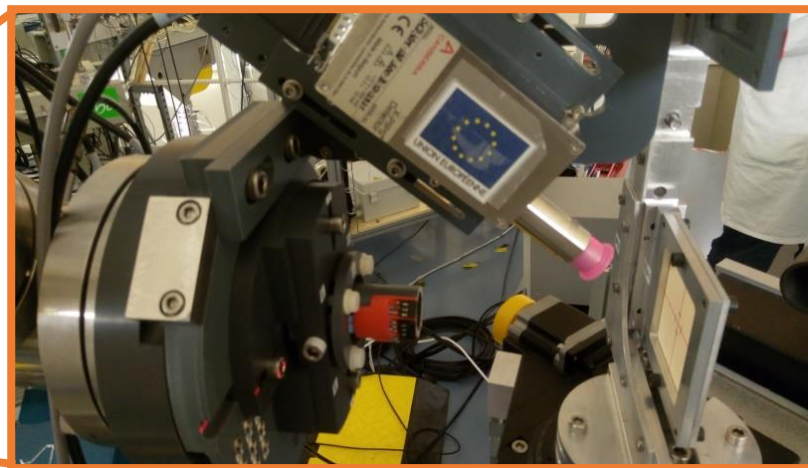
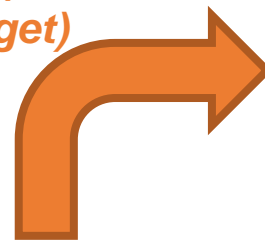


Figure 8 : Photography of the Silicon Drift Detector (SDD)

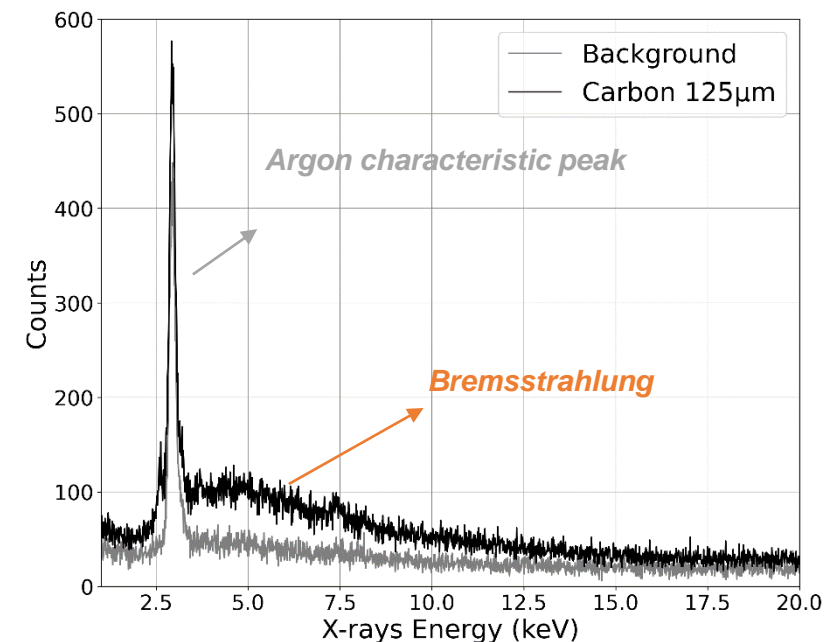


Figure 9 : X-rays raw spectra measured for protons of 40 MeV on a carbon target.



How retrieve the bremsstrahlung signal ?

- Normalisation of the X-rays spectra with the number of incident particles
- Removal of the background counts

Figure 7 : Photography of the experimental set-up.

SIMULATION OF THE BREMSSTRAHLUNG SPECTRA

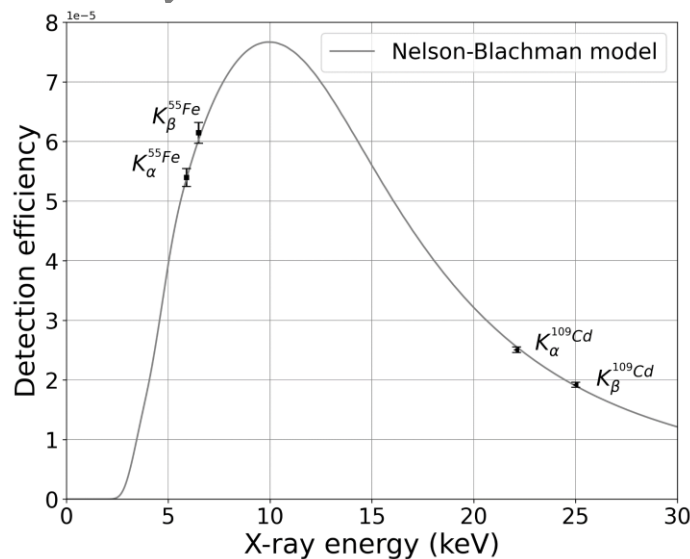
Number of the bremsstrahlung X-rays detected

$$N_X^{Br} = N_p \cdot \int_{E_p^i, hv}^{E_p^t} \varepsilon(hv) \cdot \frac{d\sigma^{Tot}}{d\Omega dhv}(E_p, hv) \cdot \mathcal{A}(hv) dhv dE_p$$

Number of incident particles

Total bremsstrahlung cross section

Medium attenuation



Mohanty, NIM A, 2008

Figure 10 : SDD efficiency simulated (line) and measured (dots).

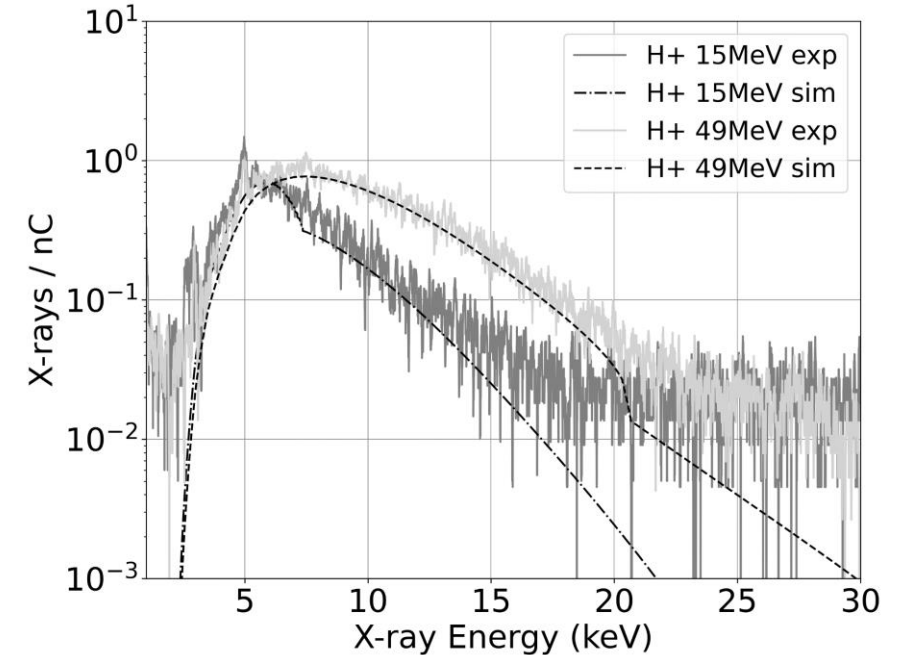


Figure 11 : Bremsstrahlung X-rays spectra simulated and measured for protons of 15 MeV and 49 MeV on a carbon target.



- Good agreement for low energy X-rays
- Underestimation of the model for high energy X-rays : Compton radiation are not taken into account
- QFEB/SEB transition : fall-off because the model does not take into account the electron target velocities

CROSS SECTION MEASUREMENT RESULTS

Calculation of cross-sections:

- For the k^{th} X-ray energy :

$$\frac{d\sigma}{dh\nu} = \frac{1}{dh\nu} \sum_{k=1}^N \frac{N_k^{XR} \cdot M_C}{N_p \cdot \varepsilon_k \cdot \mathcal{A}_k \cdot \mathcal{N}_a}$$

- M_C : Carbon's molar mass
- \mathcal{N}_a : Avogadro constant
- Energy detection window of 0.4 keV to satisfy a significant statistics (>1000 counts)
- \mathcal{A}_k : The medium attenuation is calculated with the NIST (XCOM) coefficient
- The real target thickness is calculated after mass measurements

$$e_{\text{carbon}} = \frac{m_{\text{carbon}}}{S_{\text{carbon}} \cdot \rho_{\text{carbon}}}$$



Comparison with literature data:

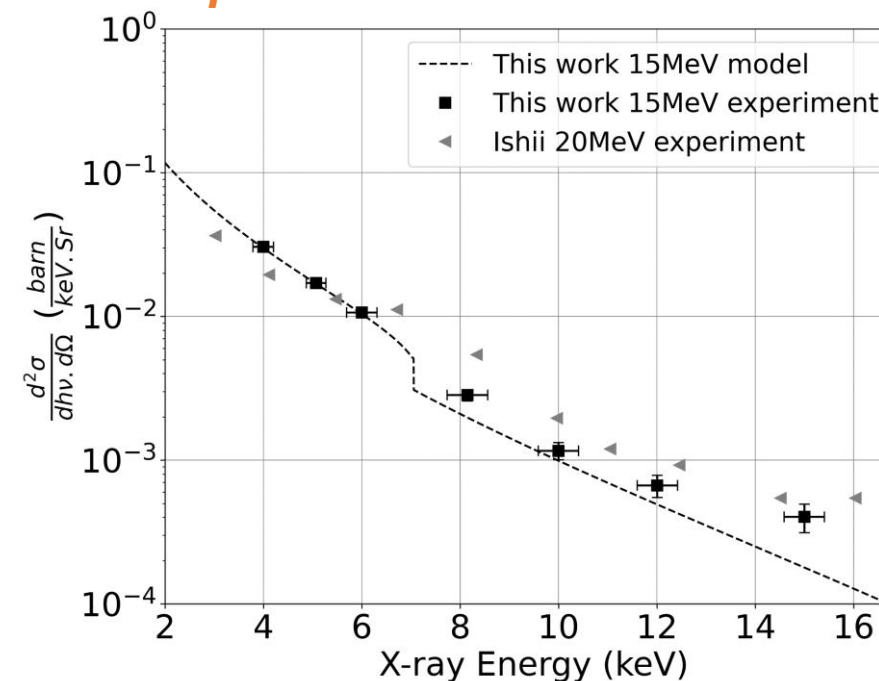


Figure 12 : Differential bremsstrahlung cross section for protons 15 MeV and 20 MeV (Ishii) on a carbon target.



- Significant agreement with the literature
- Discrepancies due to beam energy difference and the carbon thickness difference
- Compton scattering is not included in the model

CROSS SECTION MEASUREMENT RESULTS

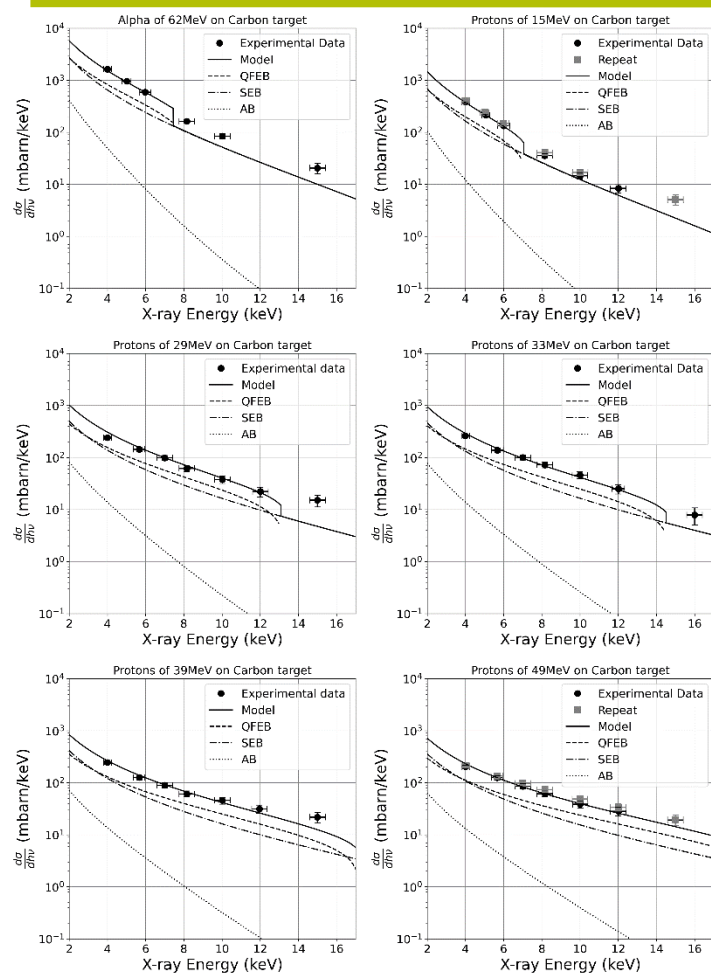


Figure 13 : Differential bremsstrahlung cross sections simulated (lines) and measured (dots) for alpha beam of 62 MeV and protons beams of 15 MeV, 29 MeV, 33 MeV and 49 MeV on a carbon target.

- Cross sections measured :
 - 10 mbarn.keV⁻¹ to 1 barn.keV⁻¹
 - **Significant signal for ion beam monitoring**
- **Some measurement were repeated :**
 - Protons of 15 MeV and 49 MeV
 - Deviations under 3%
- Theoretical bremsstrahlung cross section models :
 - Good agreement for low X-rays energies ($< h\nu_{max}^{QFEB}$)
 - Discrepancies for high energies : Compton scattering is not included in the model
 - **Validity of the models for the ARRONAX ion beam range (up to 50 MeV)**
 - Measurements required for clinical energy beams (> 100 MeV)

CONCLUSION AND OUTSKIRTS

- **Bremsstrahlung cross sections were measured**
 - Alpha beam of 62 MeV
 - Protons beams in the ARRONAX beam energy range (<50 MeV)
- **The magnitude of the bremsstrahlung cross sections measured indicates the significant sensitivity of the bremsstrahlung signal**
 - Possibility to use the bremsstrahlung signal for ion beam monitoring
- **Simulation of the bremsstrahlung cross sections**
 - Based on the theoretical works from PIXE
 - Comparison with measurements showing a significant agreement
 - QFEB and SEB are the main bremsstrahlung processes
 - Validity of the models for ion beams < 50 MeV
 - Simulation can be improved by taking into account the Compton scattering and the electrons target velocities to have better agreement with the measurements
- **The Bremsstrahlung radiations are a promising tool for hadrontherapy applications**
 - Cross sections measurements are required for clinical energy beam (> 100 MeV)
 - Link between the bremsstrahlung signal and the deposited dose should be investigated