Production yields of β^+ emitters for range verification in proton therapy

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Range verification in protontherapy

The treatment of tumors with protons allows delivering a high dose over the affected volume while strongly sparing the adjacent healthy tissues, but currently the technique is not fully exploited because of the safety margins applied to the treatment planning accounting for uncertainties in the range of the beam.

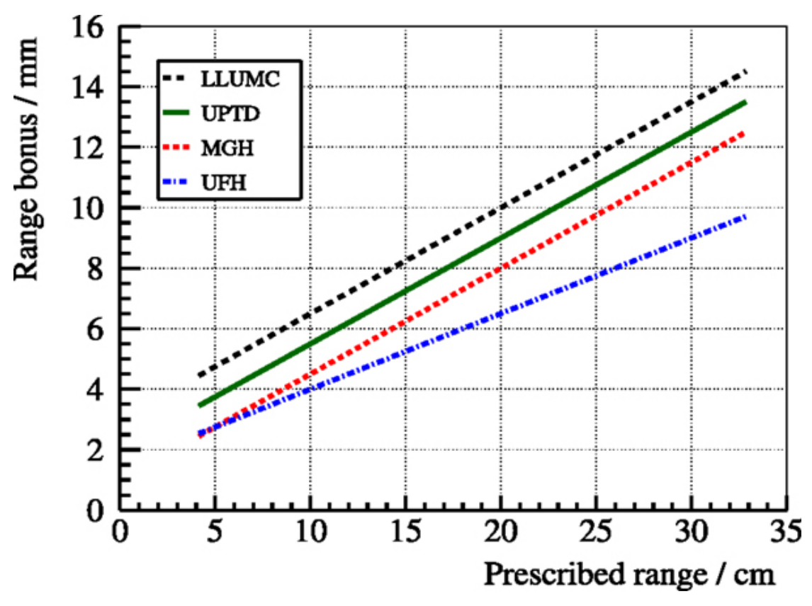


Fig. 1. Safety margins applied at different clinical proton therapy facilities.
[Paganetti, PMB 57 (2012)]

Solution: In-vivo range verification via the observation of the γ-ray emitted by the β^+ isotopes produced by the beam in the patient.

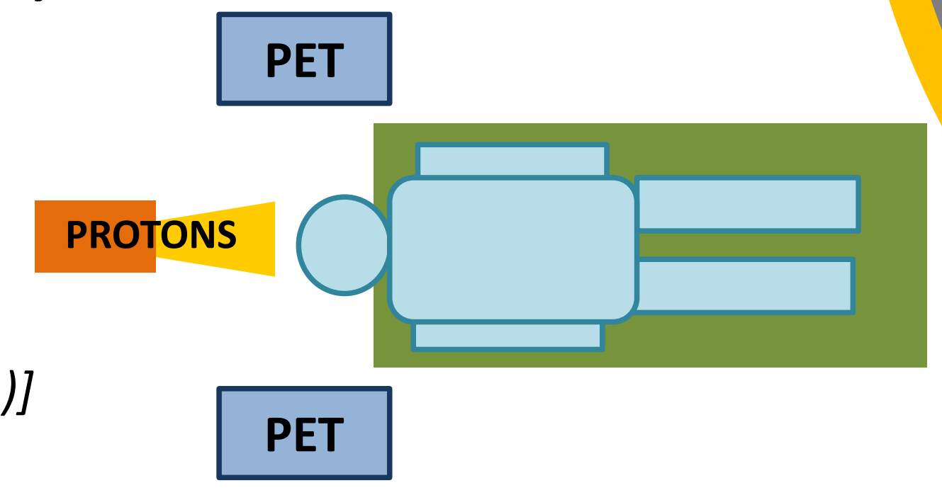
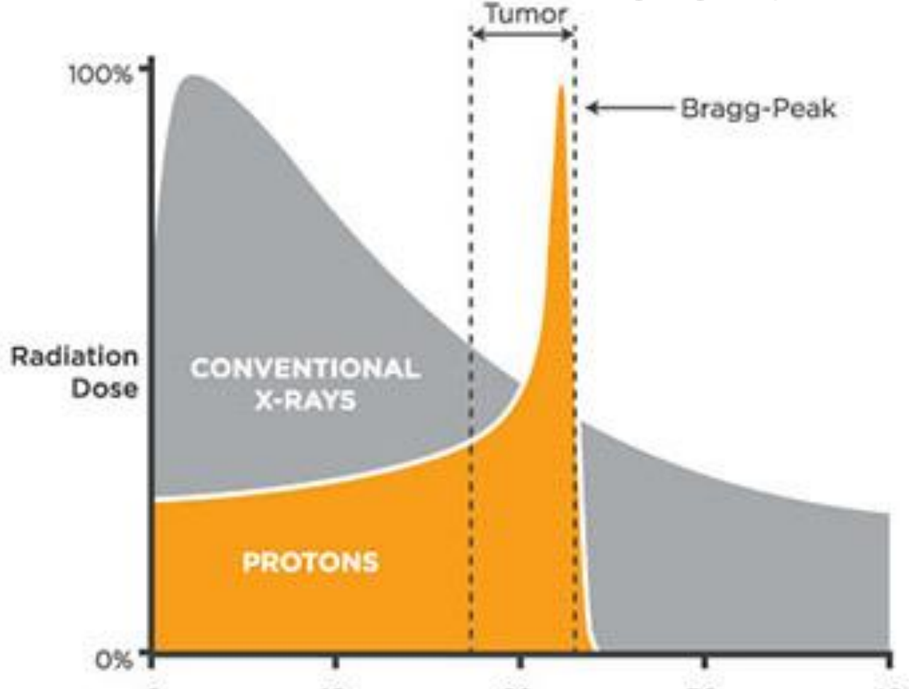


Fig. 2 Schematic use of in-vivo PET range verification.
[Zhu et al., Theranostics 3 (2013)]

Making the most out of the Bragg peak



Need of data for production yields

The basis of PET-based range verification is the comparison of the expected (according to the treatment planning) and observed measured with a PET) distributions of 511 keV γ-rays from the annihilation of β+ emitters such as: **^{11}C, ^{12,13}N, ^{15}O, ^{29}P or ^{38m}K.**

The expected distribution are calculated from the cross sections of the corresponding proton induced reactions, which are known quite poorly if one considers the energy up to 230 MeV.

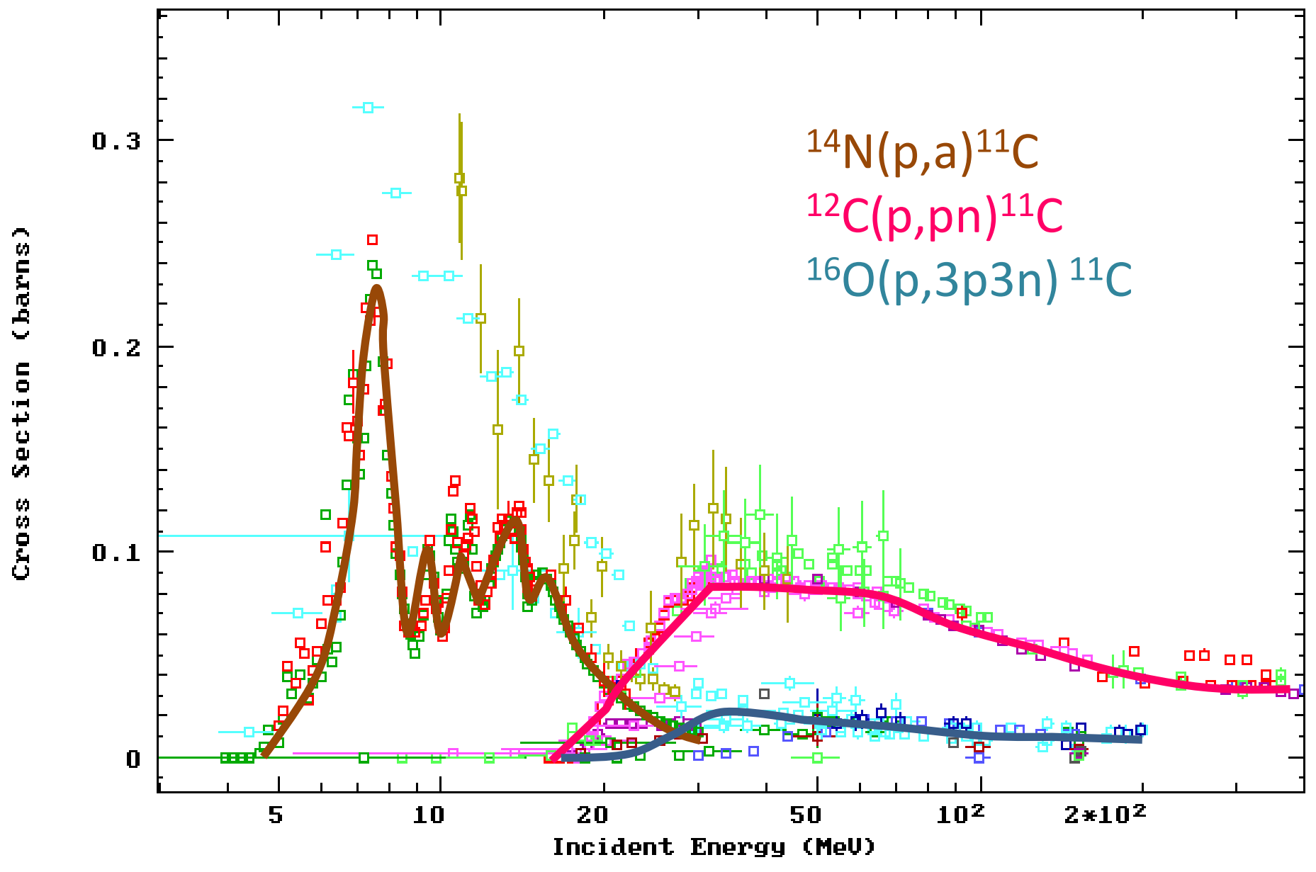


Fig. 3. Available data in EXFOR for the production cross sections of ^{11}C from carbon, oxygen and nitrogen. It is one of the best known reactions, but yet there are sizable discrepancies between different measurements.

Measurement of β^+ emitters production yields below 18 MeV at CNA

Step 1. Irradiation of multi-layer targets: the full range of interest in one shot

Fig. 4. Multi-layer targets made as a stack of thin (~200 μm) films of PE (C_2H_4), PMMA ($C_5O_2H_8$) and Nylon-6 ($C_6H_{11}NO$) are mounted on a moving target holder in order to perform consecutive irradiations without accessing the bunker.

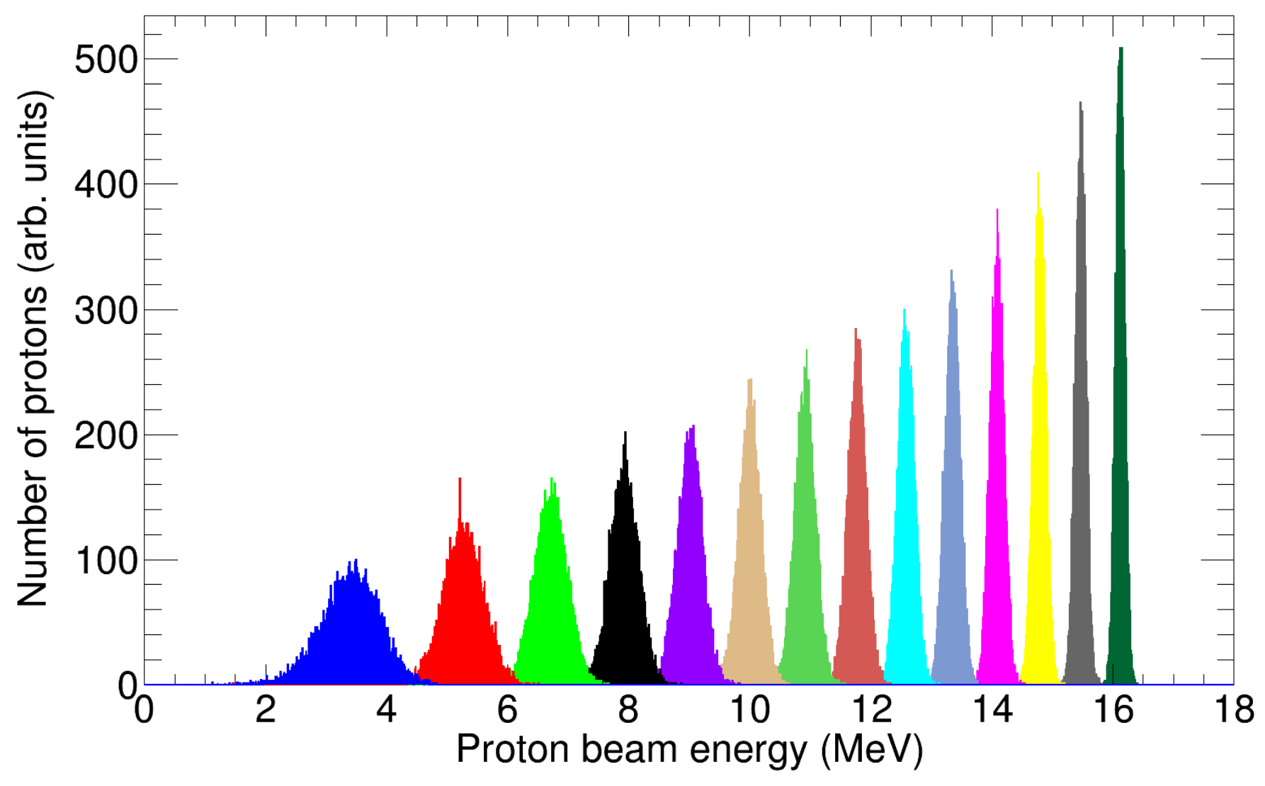


Fig. 5. The beam energy degrades when traversing the stack of targets, hence the energy of the protons incident in each film is well defined.

Step 2. Measure the activity of each film (46 in total) simultaneously in a PET scanner

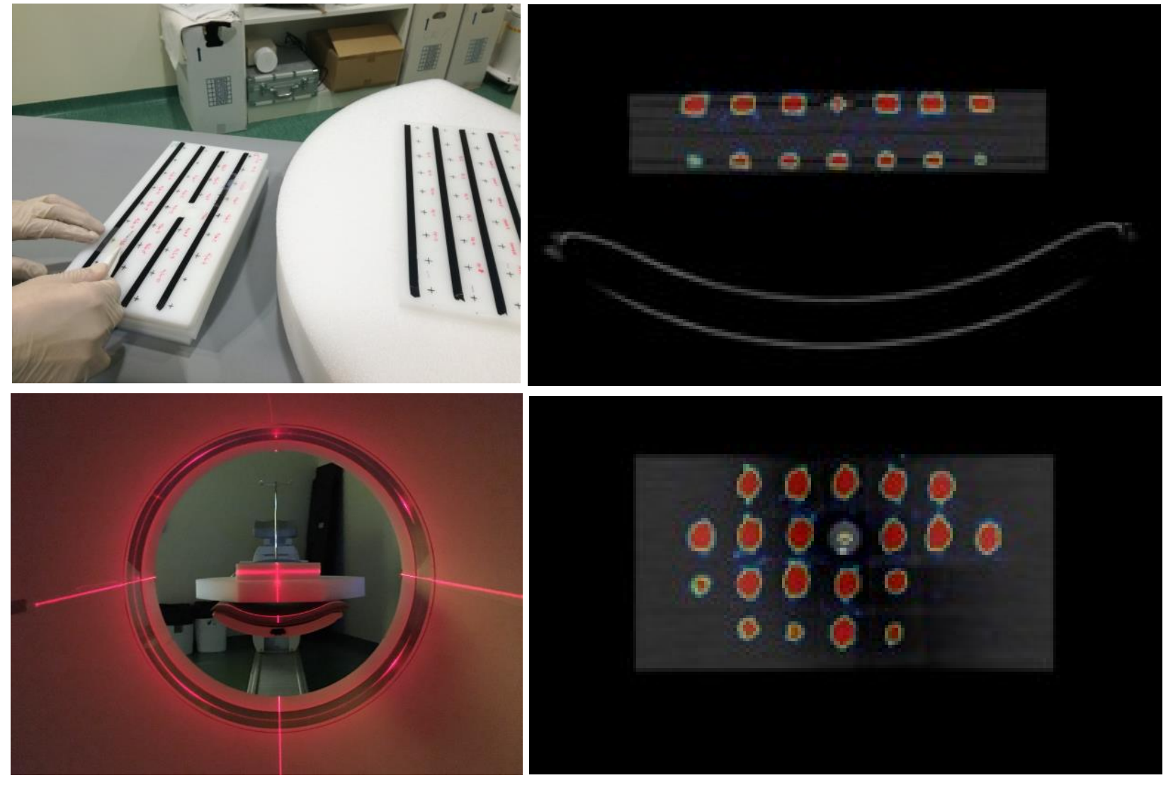


Fig. 6. The stacks are dismounted and each film is placed in a well defined position of a PE matrix that serves as convertor for the positrons into the corresponding pair of 511 keV γ-rays, which are then measured with a clinical PET scanner in a dynamic data acquisition (1 minute steps).

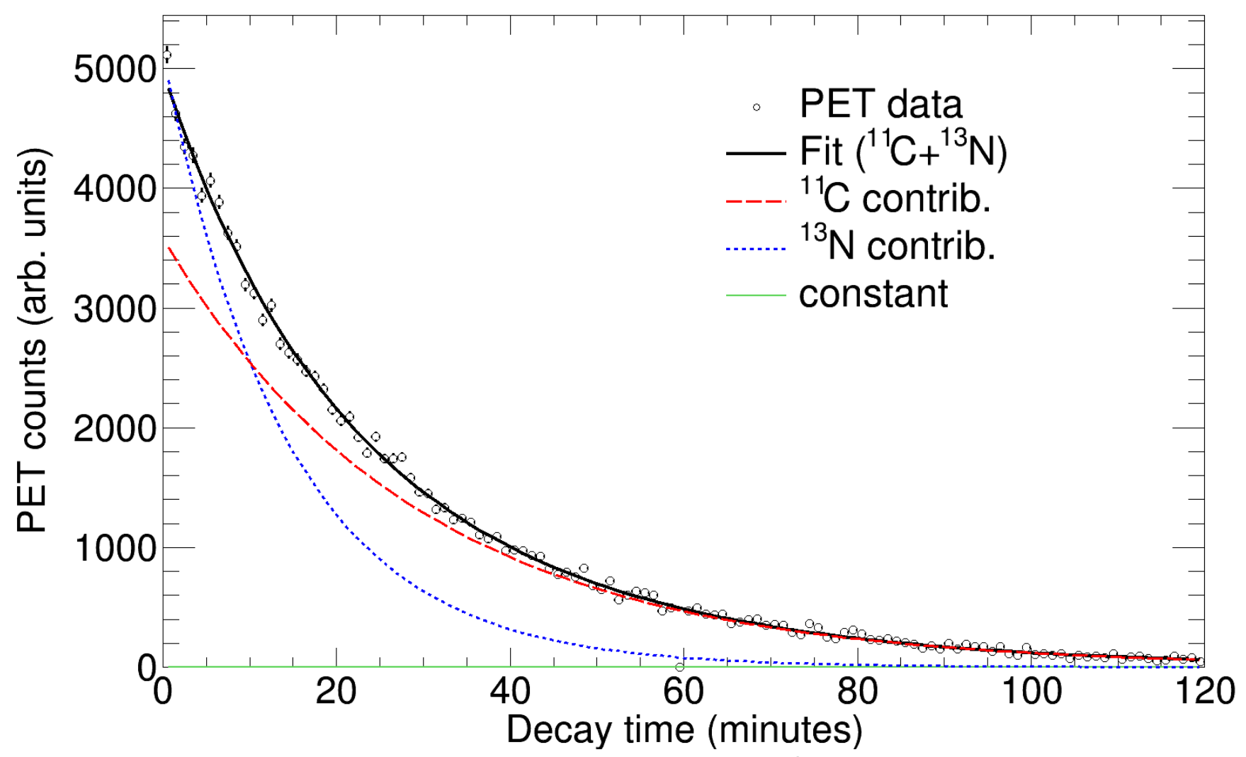


Fig. 7. The decay curves for each position (i.e. film of a given material which the beam has traversed with a given energy) are analyzed in terms of the sum of two exponential decays with the half-lives of ^{11}C ($t_{1/2}$=20,4 min) and ^{13}N ($t_{1/2}$=9,97 min). This corresponds to the second Nylon-6 layer (E_p=15,8(4) MeV).

Step 3. Extract the cross sections for the reactions on C, N & O producing β^+ emitters

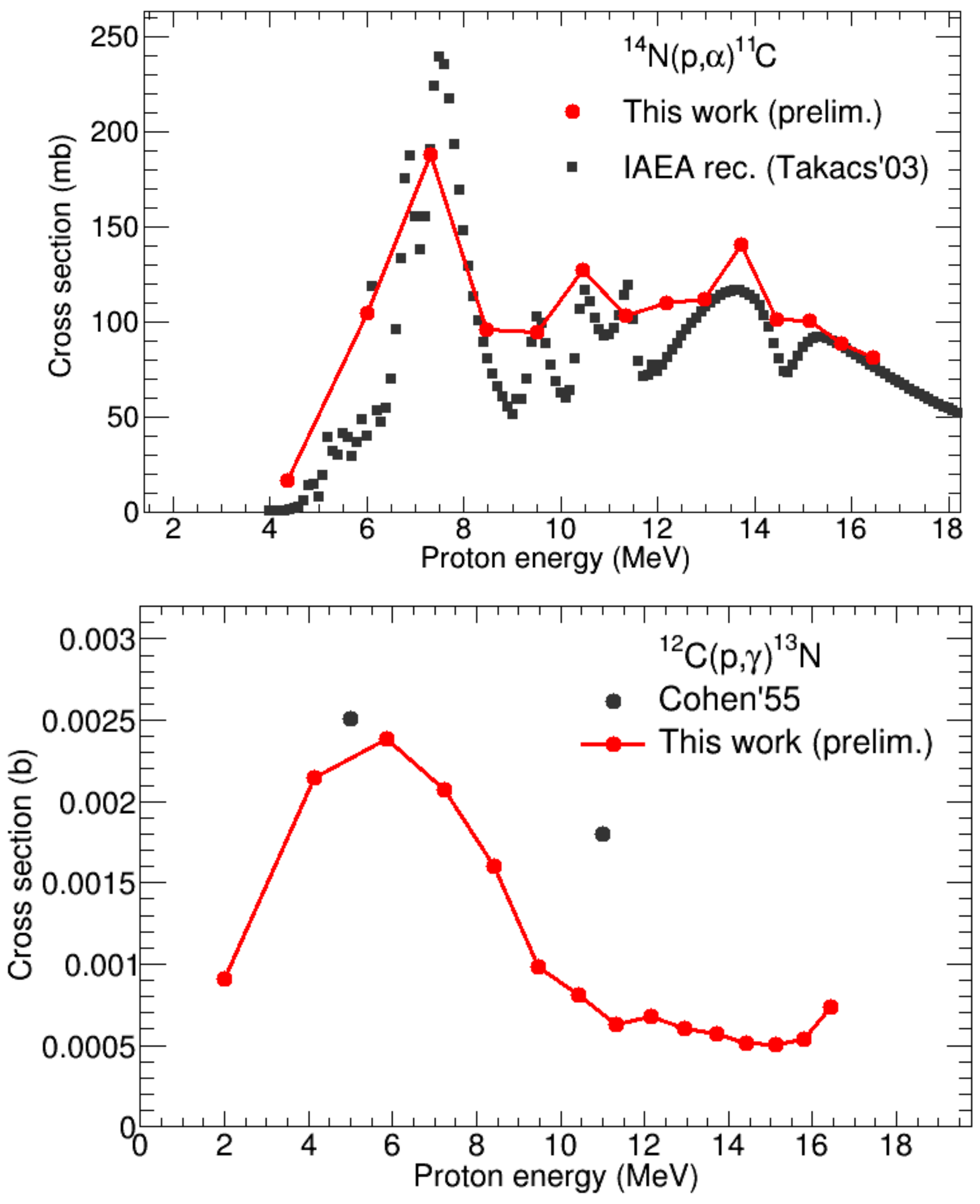


Fig. 8. The cross sections are calculated considering the fitting, the thickness and composition of each film, and the corresponding proton energy. The agreement is good with the IAEA evaluation of Takacs (2003) for the well known ^{14}N(p,α)^{11}C *and* ^{16}O(p,α)^{13}N reactions (top panel). In other cases this work shows sizable differences with the previous data, for instance for ^{12}C(p,pn)^{11}C (bottom panel).

Prospects for measurements up to 230 MeV

The technique of irradiating multi-layer targets can be used to study β^+ production reaction in the range of interest up to 230 MeV, this will be done at a clinical beam.

In the case of short-lived isotopes such as ^{29}P or ^{38m}K, a different set-up is needed because all the decay occurs within seconds after the irradiation.

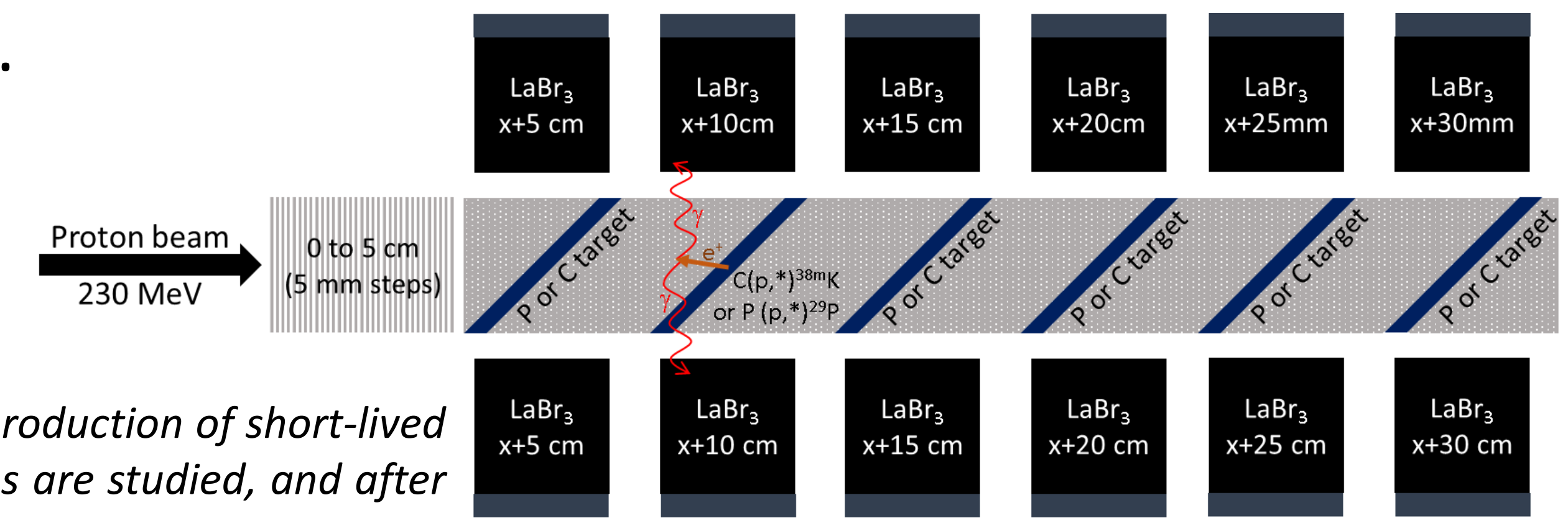


Fig. 9. Schematic view of the set-up being tested at CNA for measuring the cross section for production of short-lived isotopes between consecutive spills at a clinical proton beam. In each irradiation six energies are studied, and after each measurement a 5 mm PE layer is added in front of the phantom, thus shifting the energy in each target.

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