



Super-FRS EC meeting
December 2022



Status: G-PAC proposals S469

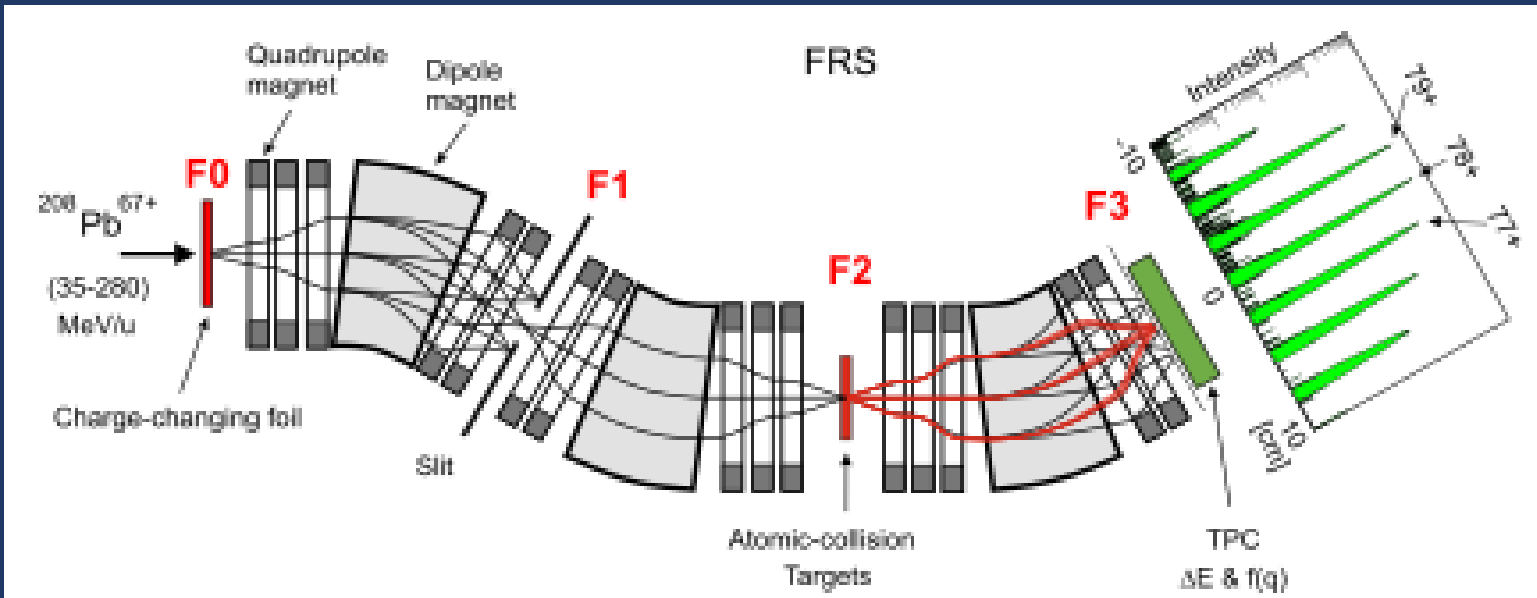
“Accurate slowing-down measurements of heavy ions (Xe, Pb, U) in gases and solids in the kinetic energy range of (30 to 300) MeV/u with the high-resolution magnetic spectrometer FRS”

S. Purushothaman (Spokesperson)¹, H. Geissel (Co-Spokesperson)^{1,2}, H. Weick (Co-Spokesperson)¹, S. Bagchi¹, T. Dickel², P. Egelhof¹, T. Grahn³, E. Haettner¹, A. Jokinen³, B. Kindler¹, G. Kraft¹, N. Kuzminchuk-Feuerstein¹, B. Lommel¹, C.C. Montanari⁴, Z. Patyk⁵, S. Pietri¹, Y. Pivovarov⁶, W.R. Plaß¹, A. Prochazka¹, C. Scheidenberger^{1,2}, V.P. Shevelko⁸, D. Severin¹, P. Sigmund⁷, A. Sørensen⁹, T. Stöhlker¹, Y. K. Tanaka¹, B. Voss¹, J.S. Winfield¹, M. Winkler¹

& Super-FRS experiment collaboration

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The experiment



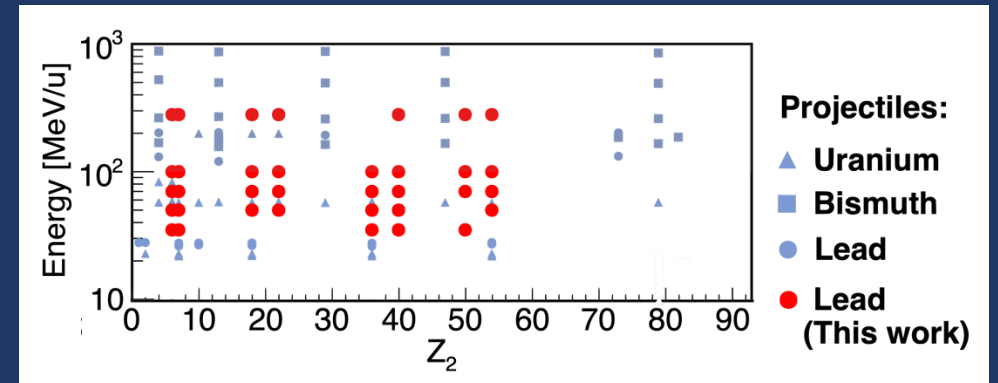
What are we interested in?

- Very heavy ions: ^{238}U , ^{209}Bi , ^{208}Pb
- Involvement of many charge states q , which complicates theoretical predictions.
- The experimental data are scarce.
- The gas-solid difference has been ignored in theory.

Projectile from SIS-18
^{208}Pb
35, 50, 70, 100, 280 MeV/u

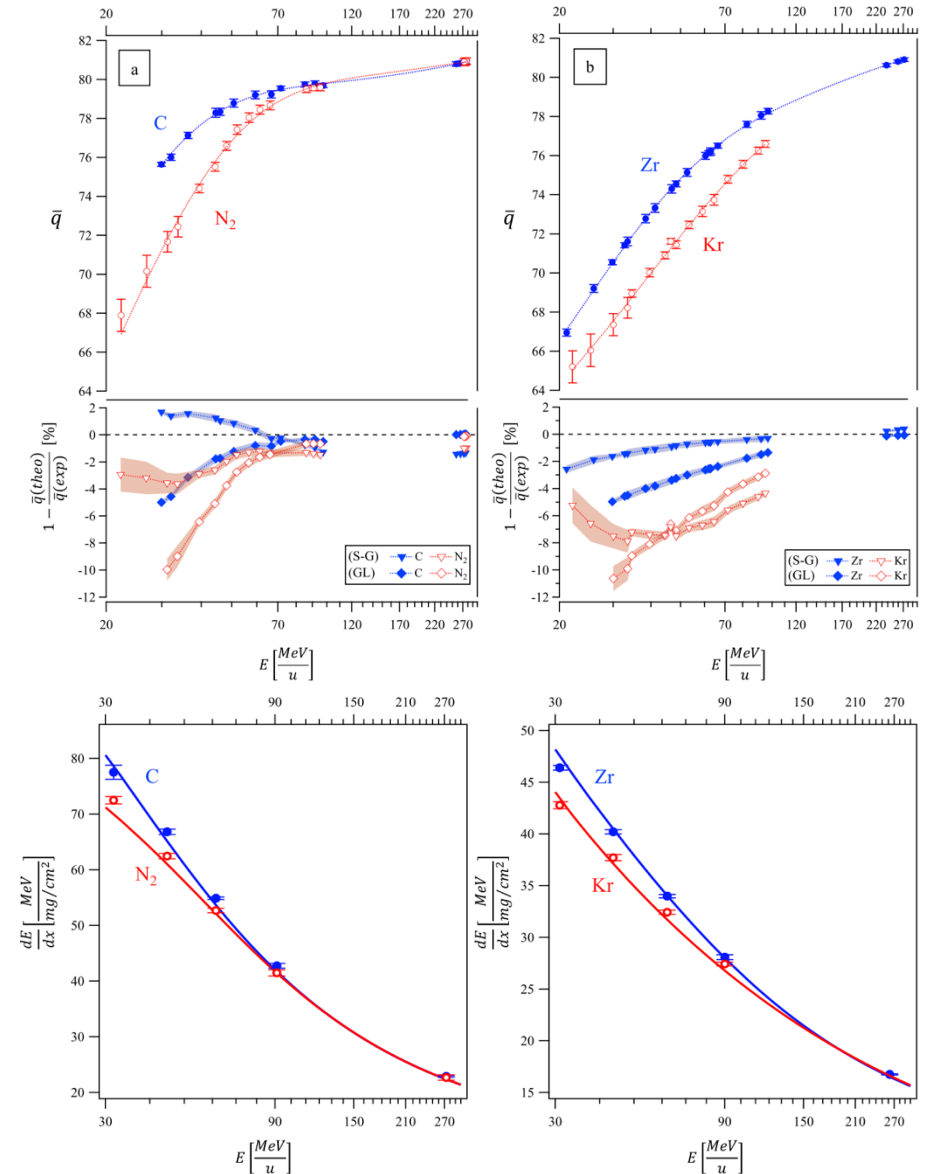
Targets	
2 - 327 mg/cm ²	2 - 524 mg/cm ²
Gases	Solids
$^{14}\text{N}_2$	^{12}C
^{40}Ar	^{48}Ti
^{84}Kr	^{90}Zr
^{136}Xe	^{150}Sn
C_3H_6	$(\text{C}_3\text{H}_6)_n$

~400 $B\rho$ settings for ~800 spectra!!



Main results

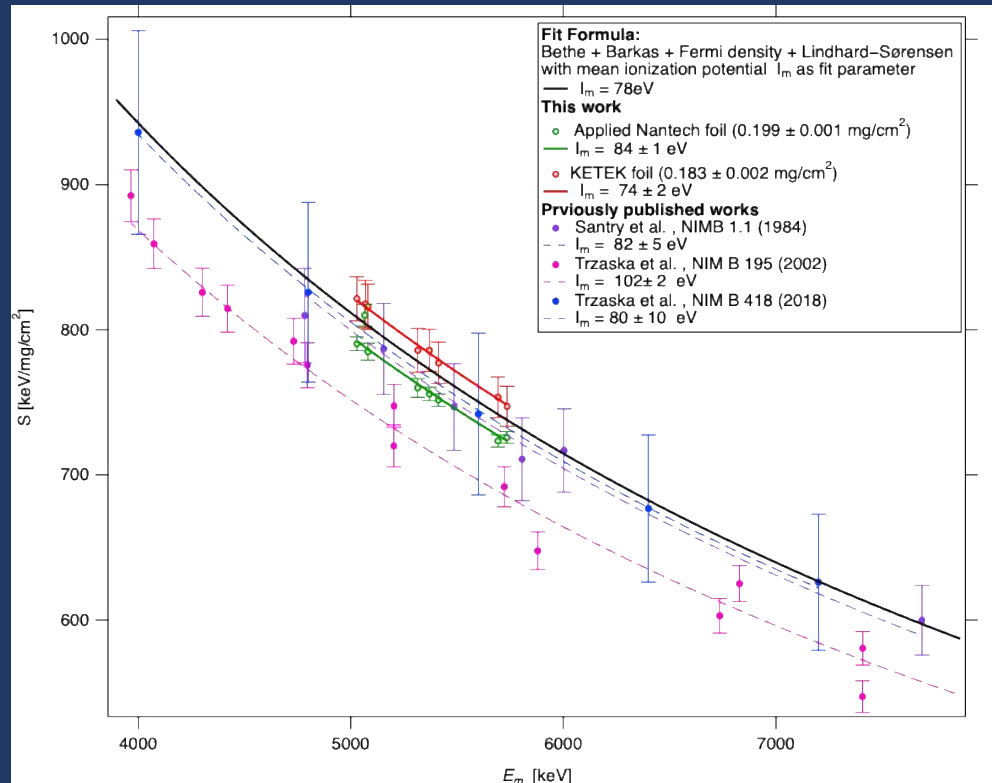
- For the first time, both the mean charge states and stopping powers of ^{208}Pb ions at 35-280 MeV/u in gases and solids have been measured simultaneously with an accuracy of 1%.
- The Bohr-Lindhard density effect for stopping powers is unambiguously verified in the energy range of the present experiment.
- When the projectiles are nearly fully ionized the gas-solid difference vanishes.
- An unprecedented accuracy of better than 3 % has been achieved when the measured mean charge-states are implemented in the Lindhard Sørensen theory.



Graphenic Carbon Vacuum Windows

Major achievement of S4609 proposal: Stopping Powers of Gases Measured with <1% Accuracy

Thickness < 1 μm and can handle a 1-bar differential pressure.



High accuracy measurement of graphenic carbon stopping power using alpha particle energy loss measurements

Konstantina Botsiou, Master Thesis, TU Darmstadt (2024)

Publication status

Physics Department Award, Tohoku University – Best Doctoral Thesis 2021

Accurate Measurements of the Gas-Solid Difference in Stopping-Powers and Charge-State Distributions of Lead Ions in the Energy Range of (30-300) MeV/u

(鉛イオンビームを用いた核子あたり30-300 MeV/u領域における阻止能と荷電状態分布に現れるGas-Solid Differenceの精密測定)

Doctoral Dissertation

by

Shunki ISHIKAWA

Department of Physics
Graduate School of Science
Tohoku University

2021



Accurate simultaneous lead stopping power and charge-state measurements in gases and solids: Benchmark data for basic atomic theory and nuclear applications

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ABSTRACT

We have measured for the first time simultaneously both the mean charge states and stopping powers of (25–280) MeV/u ²⁰⁸Pb ions in gases and solids with an accuracy of 1%. The existence at lower energies and disappearance at higher of density effects in the charge-state distribution and the corresponding stopping power are directly confirmed and comparisons with widely used theories and simulations for heavy ions demonstrate strong deviations of up to 27%. However, at unexpected precision power of better than 3% has been achieved for the energy loss when the measured mean charge states are implemented in the Lindhard-Sørensen theory. Our present benchmark data contribute to an improved understanding of the basic atomic collision processes and to numerous applications in nuclear physics. Extending the GANIL data [1] to higher accuracy and energies, we can now answer at which velocities the Bohr-Lindhard density effect in stopping will vanish.
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When fast ions penetrate through matter, they primarily lose their kinetic energy due to elastic and inelastic collisions with the atoms of the material traversed [2,3]. In addition, the ions change their direction and may even change the ionic charge states, depending on the velocity and element number. Charge-changing collisions and the resulting charge-state distribution are character-

What is still to be done

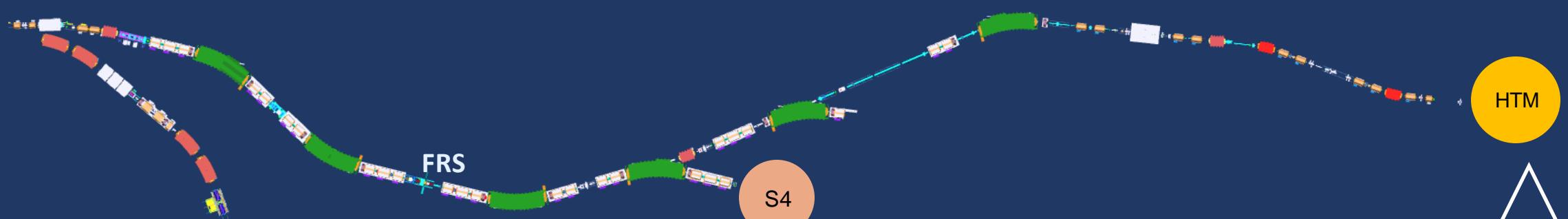
- Publish the extensive data on charge-state distribution and stopping power measured during this experiment (Ar - Ti, Xe - Sn, C3H6 - (C3H6)n).
 - This data is analysed as part of Shunki Ishikawa's doctoral thesis.
- Analyse and publish the straggling data.
- Use the charge-state measurements to extend and validate the computer code ETACHA.
 - ETACHA is the only charge-state simulation code that accounts for the temporary population of excited states during target passage.

Status: G-PAC proposals S533

“Measurements of nuclear and atomic interactions needed for ion-beam therapy with positron emitters of carbon and oxygen”

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SIS-18

Symmetric branch of FRS - S4

- Atomic and nuclear interactions
- In-beam PET imaging
- Depth dose measurements in water
- Total and charge-changing cross-section

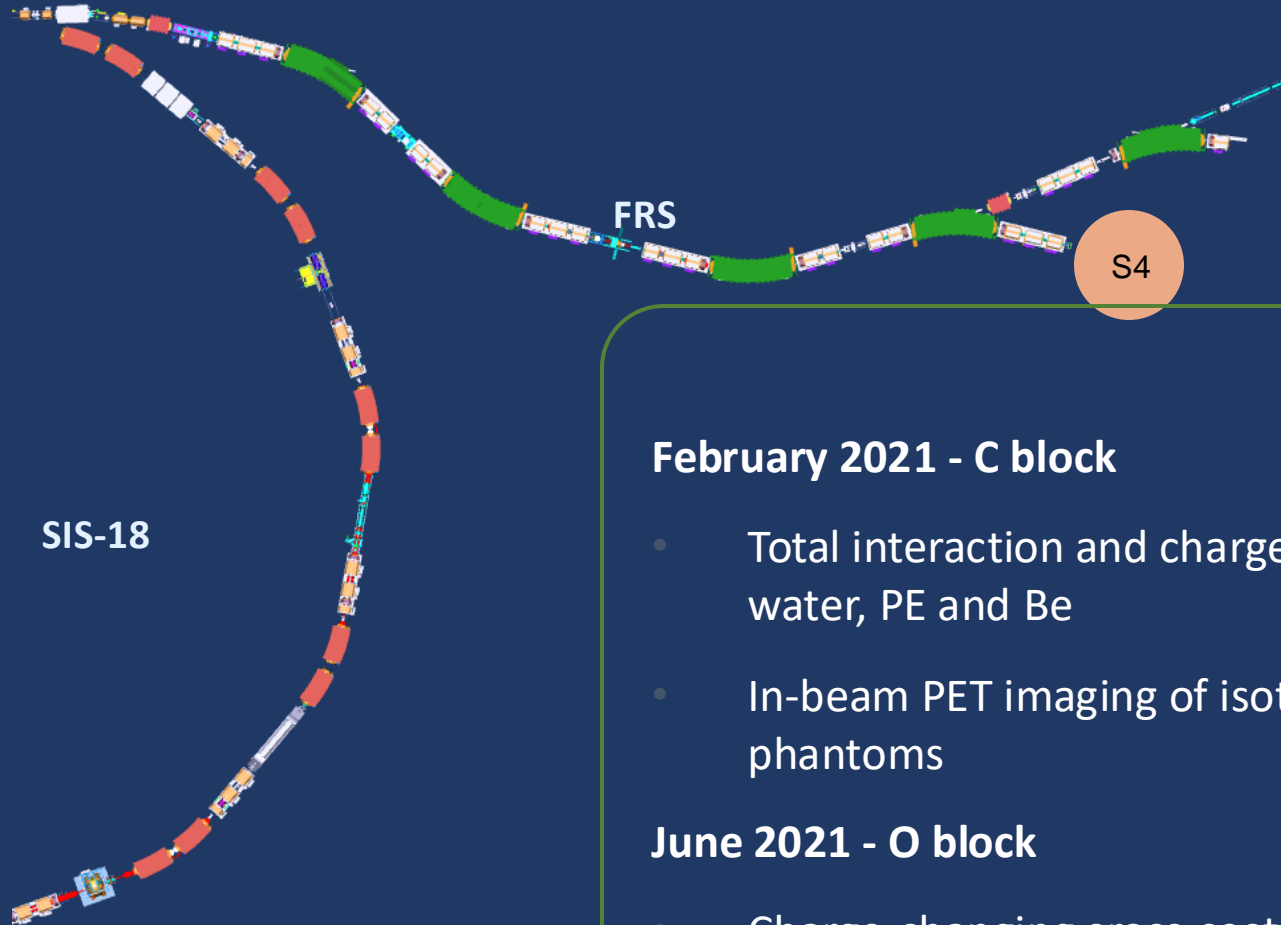


HTM

Medical cave – HTM

- Biomedical Application
- Transport RIB from FRS to HTM
- Visualise RIB using PET and hybrid γ -PET detector
- Validate therapeutic potential of RIB in animals





February 2021 - C block

- Total interaction and charge-changing cross-section of $^{10,11,12}\text{C}$ in carbon, water, PE and Be
- In-beam PET imaging of isotopically pure $^{10,11,12}\text{C}$ implanted in PMMA and PE phantoms

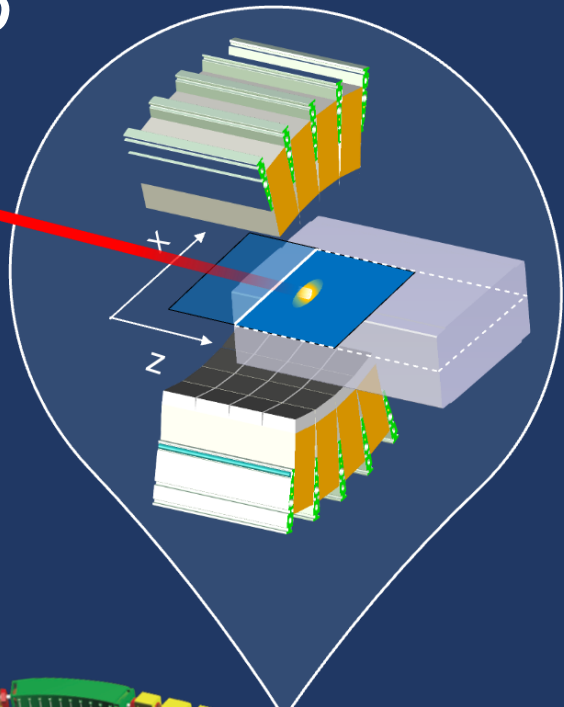
June 2021 - O block

- Charge-changing cross-section of $^{14,15,16}\text{O}$ in carbon, Water, PE
- In-beam PET imaging of isotopically pure $^{14,15,16}\text{O}$ implanted in PMMA and PE phantoms

PET imaging at FRS

Carbon \rightarrow ^{11}C & ^{10}C
Oxygen \rightarrow ^{15}O & ^{14}O

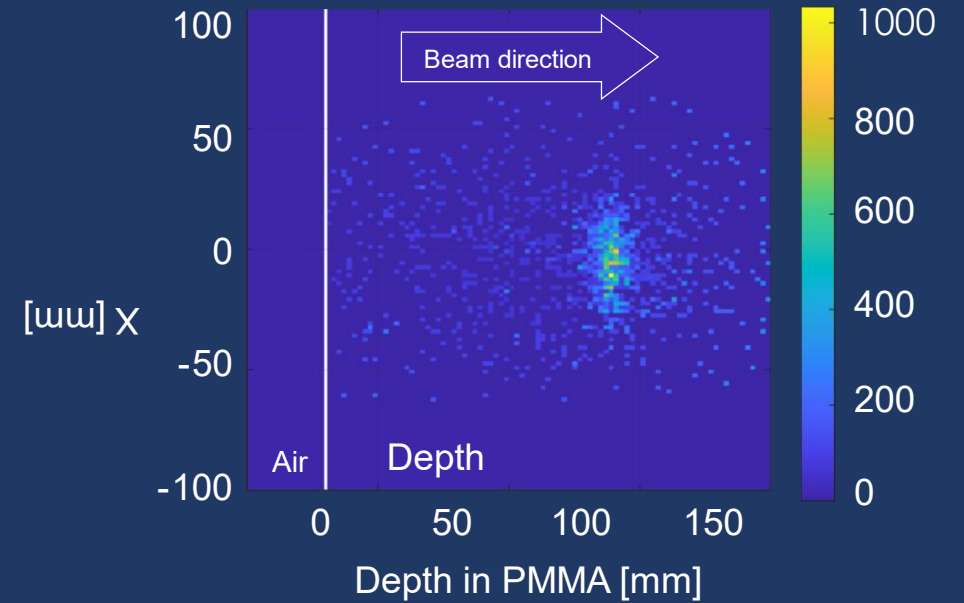
Positron emitting
beams from FRS



FRS

S4 - Symmetric branch of FRS
PET imaging setup

2D PET image of ^{14}O
After 4 implantation cycles



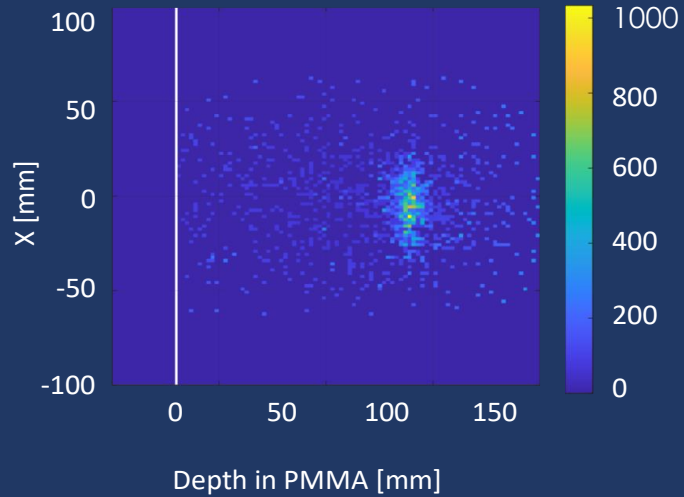
1/6th of a Siemens Biograph
mCT clinical scanner

Peter Dendooven

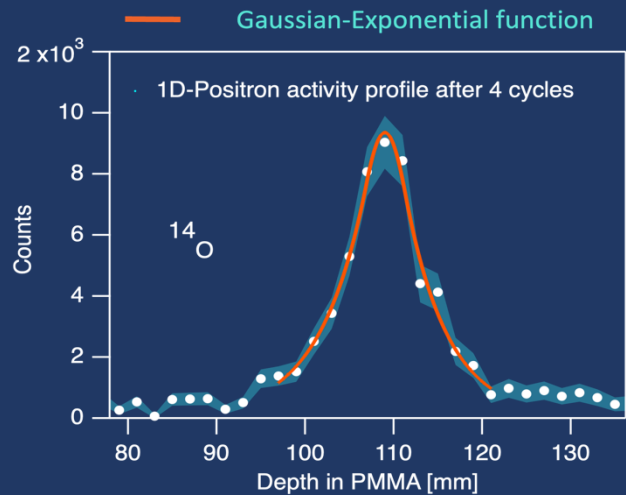


Evaluation of the positron activity: Peak position and its uncertainty

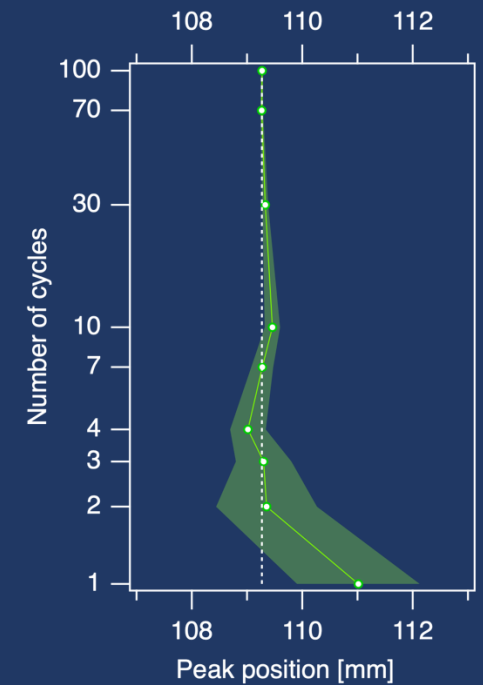
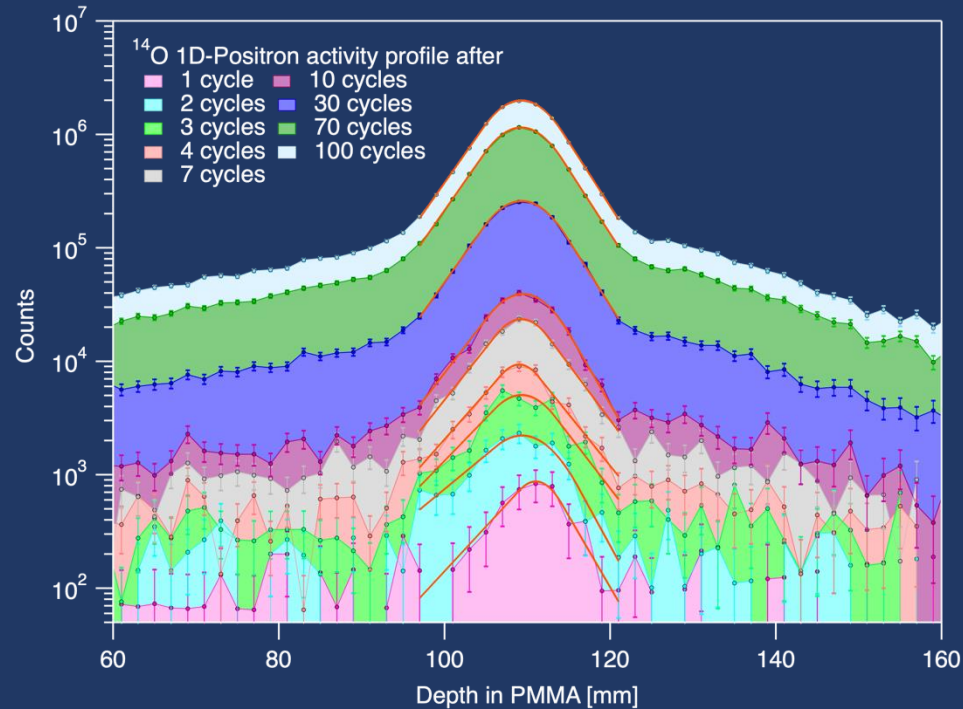
2D PET image of ^{14}O after 4 implantation cycles



Projection to the beam axis

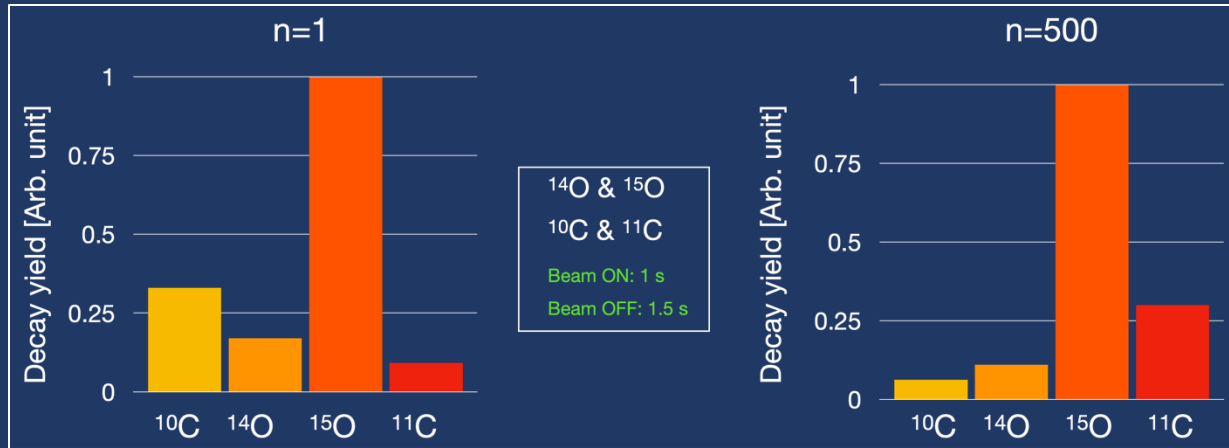
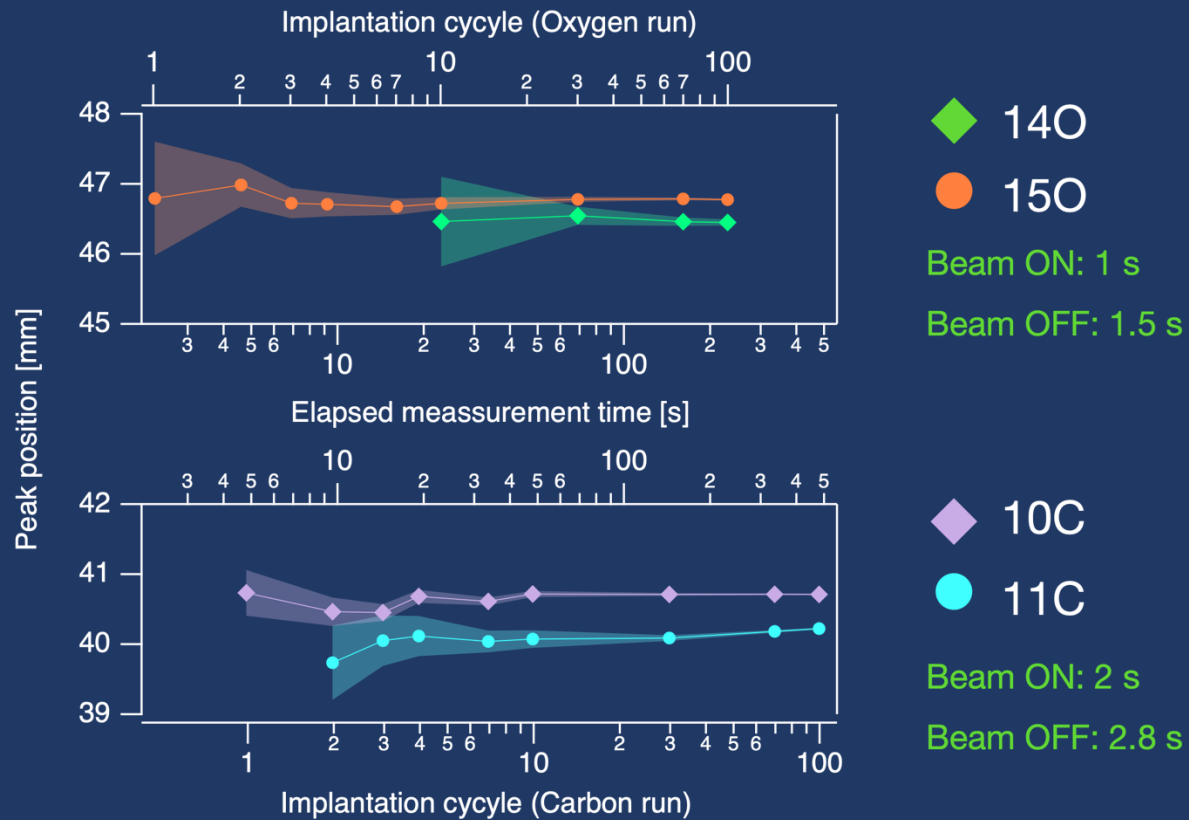


Cumulative positron activity profiles 1D activity profiles during irradiation



Quasi-real-time range monitoring

Which is the best positron emitting therapy beam



Publication status



www.nature.com/scientificreports

scientific reports

OPEN Quasi-real-time range monitoring by in-beam PET: a case for ^{15}O

S. Purushothaman^{1,2,3}, D. Kostyleva⁴, P. Dendooven⁵, E. Haettner⁶, H. Geissel^{1,2,3}, C. Schuy¹, U. Weber¹, D. Boscolo¹, T. Dickel^{1,2,3}, C. Graeff¹, C. Hornung⁷, E. Kazantseva⁸, N. Kuzminchuk^{9,10}, I. Mukha¹¹, S. Pietri¹², H. Roesch¹³, Y. K. Tanaka¹⁴, J. Zhao¹⁵, M. Durante^{16,17}, K. Parodi¹⁸ & C. Scheidenberger^{1,3,19}

A fast and reliable range monitoring method is required to take full advantage of the high linear energy transfer provided by heavy ions like carbon and oxygen while minimizing the damage to healthy tissue due to range uncertainties. Quasi-real-time range monitoring using in-beam positron emission tomography (PET) with therapeutic beams of positron-emitters of carbon and oxygen is a promising approach. The number of implanted ions and the time required for an unambiguous range verification are decisive factors for choosing a candidate isotope. An experimental study was performed at the FRS fragment-separator of GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany, to investigate the evolution of the positron annihilation activity profiles during the implantation of ^{10}O and ^{15}O ion beams in a PMMA phantom. The positron activity profile was imaged by a dual-panel version of a Siemens Biograph mCT PET scanner. Results from a similar experiment using ion beams of carbon positron-emitters ^{12}C and ^{13}C performed at the same experimental setup were used for comparison. Owing to their shorter half-lives, the number of implanted ions required for a precise positron annihilation activity peak determination is lower for ^{15}O compared to ^{12}C and likewise for ^{10}O compared to ^{13}C , but the lower production cross-sections make it difficult to produce them at therapeutically relevant intensities. With a similar production cross-section and a 10 times shorter half-life than ^{12}C , ^{15}O provides a faster conclusive positron annihilation activity peak position determination for a lower number of implanted ions compared to ^{12}C . A figure of merit formulation was developed for the quantitative comparison of therapy-relevant positron-emitting beams in the context of quasi-real-time beam monitoring. In conclusion, this study demonstrates that among the positron emitters of carbon and oxygen, ^{15}O is the most feasible candidate for quasi-real-time range monitoring by in-beam PET that can be produced at therapeutically relevant intensities. Additionally, this study demonstrated that the in-flight production and separation mode can produce beams of therapeutic quality, in terms of purity, energy, and energy spread.

Proton therapy is currently the most widespread type of ion beam therapy. The rationale behind using ions heavier than protons for radiation therapy is the reduced lateral scattering with increasing mass and the higher relative biological effectiveness (RBE) in the tumor region. The facility for ions heavier than protons has a downside characterized by higher investment costs, typically ranging from 2 to 4 times more expensive and the cost per treatment of carbon ions is about 3–4 times higher than that of conventional therapy with X-rays. Additionally, the heavy ions have the issue of unavoidable projectile fragmentation, which leads to an undesirable dose tail distal to the target. Carbon has been identified as an excellent compromise ion due to its favorable characteristics. It exhibits the best ratio of biologically effective dose in the tumor compared to the entrance channel for numerous indications. Consequently, carbon is presently the most widely utilized ion at all light ion

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Nuclear Inst. and Methods in Physics Research, A (2023) 16:464



Depth dose measurements in water for ^{11}C and ^{10}C beams with therapy relevant energies

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Ion optics

ABSTRACT

Owing to the favorable depth-dose distribution and the radiobiological properties of heavy ion radiation, ion beam therapy shows an improved success-toxicity ratio compared to conventional radiotherapy. The sharp dose gradients and very high doses in the Bragg peak region, which represent the target physical advantage of ion beam therapy, make it also extremely sensitive to range uncertainties. The use of ^{11}C and ^{10}C ion beams would be ideal for simultaneous treatment and accurate online range monitoring through PET imaging. Since all the underground primary ions are potentially contributing to the PET signal, these beams offer an improved image quality while preserving the physical and radiobiological advantages of the stable counterparts. The challenging production of radioactive ion beams and the difficulties in reaching high intensities, have discouraged their clinical application. In this context, the project Biomedical Applications of Radioactive Ion Beams (BARBI) started at GSI Helmholtzzentrum für Schwerionenforschung GmbH with the main goal to assess the technical feasibility and investigate possible advantages of radioactive ion beams on the pre-clinical level. During the first experimental campaign ^{11}C and ^{10}C beams were produced and isotopically separated with the Fragment Separator (FRS) at GSI. The β^+ -radioactive ion beams were produced with a beam purity of 99% for all the beams investigated (except one case where it was 98%) and intensities potentially sufficient to treat a small animal tumor within few minutes of irradiation time, $\sim 10^7$ particles per spill for the ^{11}C and $\sim 10^6$ particles per spill for the ^{10}C beam, respectively. The impact of different optical parameters on the depth dose distribution was studied with a precision water column system. In this work, the measured depth dose distributions are presented together with results from Monte Carlo simulations using the FLUKA software.

1. Introduction

The use of β^+ -radioactive ion beams (RIB) such as ^{11}C and ^{10}C for simultaneous range verification and treatment, could represent a major improvement for heavy ion therapy applications [1–3].

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Phys. Med. Biol. 68 (2023) 166103



Precision of the PET activity range during irradiation with ^{10}C , ^{11}C , and ^{12}C beams

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Radioactive ion beams,
Carbon ions,
PET, range verification

Abstract

Objective. Beams of stable ions have been a well-established tool for radiotherapy for many decades. In the case of ion beam therapy with stable ^{12}C ions, the positron emitters ^{10}C are produced via projectile and target fragmentation, and their decays enable visualization of the beam via positron emission tomography (PET). However, the PET activity peak matches the Bragg peak only roughly and PET counting statistics is low. These issues can be mitigated by using a short-lived positron emitter as a therapeutic beam. Approach. An experiment studying the precision of the measurement of ranges of positron-emitting carbon isotopes by means of PET has been performed at the FRS fragment-separator facility of GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany. The PET scanner used in the experiment is a dual-panel version of a Siemens Biograph mCT PET scanner. Main results. High-quality in-beam PET images and activity distributions have been measured from the in-flight produced positron emitting isotopes ^{11}C and ^{10}C implanted into homogeneous PMMA phantoms. Taking advantage of the high statistics obtained in this experiment, we investigated the time evolution of the uncertainty of the range determined by means of PET during the course of irradiation, and show that the uncertainty improves with the inverse square root of the number of PET counts. The uncertainty is thus fully determined by the PET counting statistics. During the delivery of 1.6×10^7 ions in 4 spills for a total duration of 19.2 s, the PET activity range uncertainty for ^{10}C , ^{11}C and ^{12}C is 0.04 mm, 0.7 mm and 1.3 mm, respectively. The gain in precision related to the PET counting statistics is thus much larger when going from ^{12}C to ^{10}C than when going from ^{12}C to ^{11}C . The much better precision for ^{10}C is due to its much shorter half-life, which, contrary to the case of ^{11}C , also enables to include the in-spill data in the image formation. Significance. Our results can be used to estimate the contribution from PET counting statistics to the precision of range determination in a particular carbon



Production and separation of positron emitters for hadron therapy at FRS-Cave M

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ABSTRACT

The Fragment Separator FRS at GSI is a versatile spectrometer and separator for experiments with relativistic in-flight separated short-lived exotic beams. One branch of the FRS is connected to the target hall where the bio-medical cave (Cave M) is located. Recently a joint activity between the experimental groups of the FRS and the Biophysics at the GSI and Department of Physics at LMU, was started to perform biomedical experiments relevant for hadron therapy with positron emitting carbon and oxygen beams. This paper presents the new ion-optical mode and commissioning results of the FRS-Cave M branch where positron emitting ^{10}C ions were produced for the medical cave for the first time. An overall conversion efficiency of 2.2×10^{-10} ^{10}C fragments per primary ^{12}C ion accelerated in the synchrotron SIS18 was reached.

1. Introduction

The European project on Biomedical Applications of Radioactive Beams, BARBI, was launched at GSI in 2021. It aims at pre-clinical validation of in-beam visualization and ion-beam therapy with positron-emitting isotopes of carbon and oxygen [1–3]. The fragment separator FRS [4] at GSI, a versatile separator and spectrometer, is ideal for the production and in-flight separation of positron emitters. Although both the FRS and the biomedical Cave M at GSI are long existing, the possibility of using fragment beams (starting from the production target at F0 up to the dipole magnet between F7 and F8) has never been explored before. The BARBI project triggered the development and first commissioning results are presented here.

2. New ion-optical mode from FRS target to Cave M

As part of the planned experiments with radioactive ion beams at Cave M, an ion-optical mode using the existing GSI beamlines as

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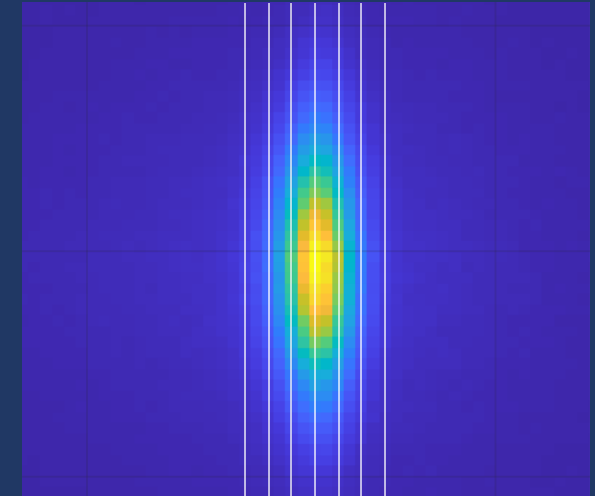
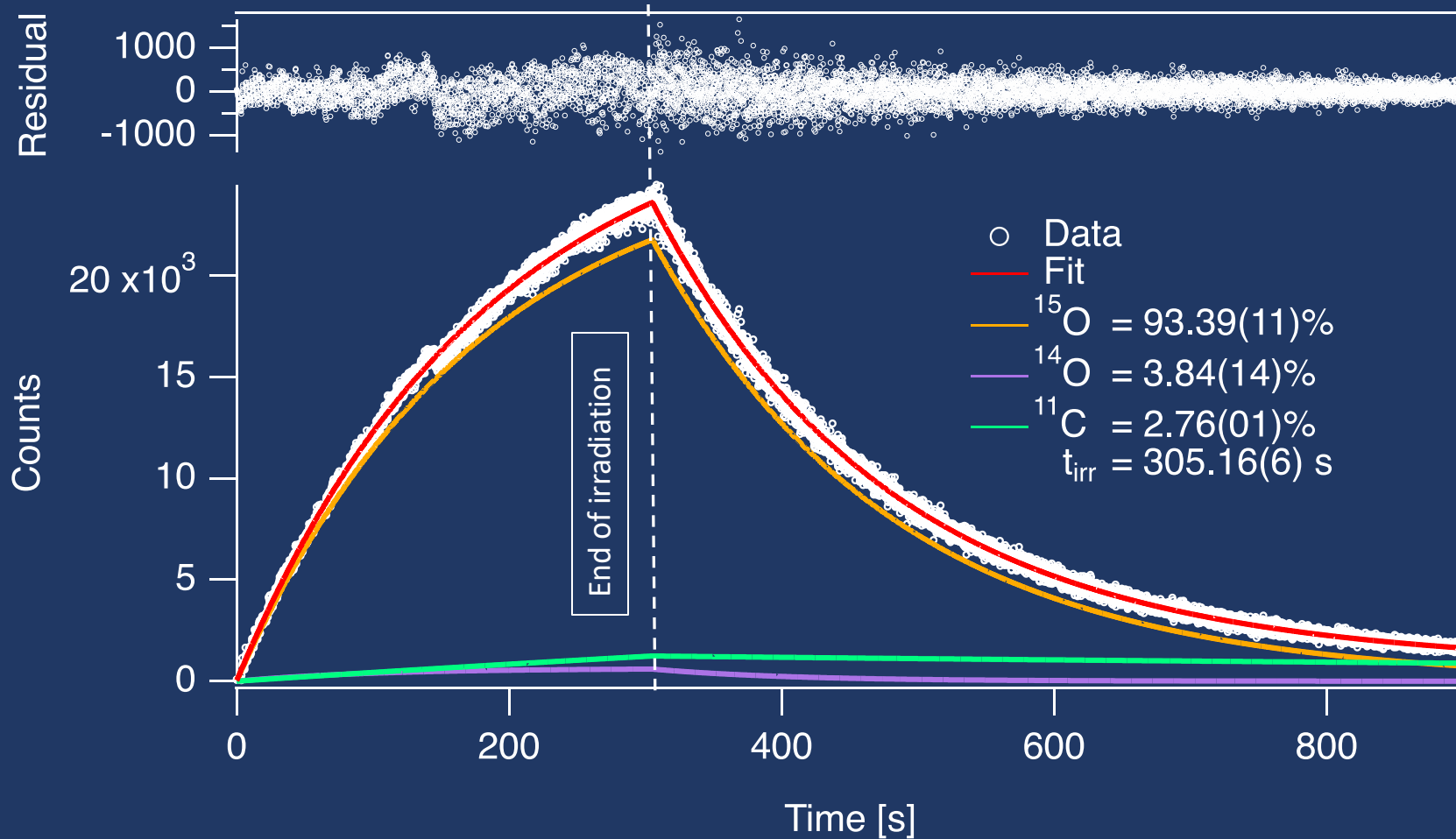
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Upcoming publications

Ongoing analysis:

- Total interaction and charge-changing cross-section of $^{10,11,12}\text{C}$ in carbon, water, PE and Be (Rinku Kumar Prajapat)
- Charge-changing cross-section of $^{14,15,16}\text{O}$ in carbon, Water, PE (Daria Kostyleva)

Next Steps and Opportunities



5-B-8 $J^{\pi} 2^+$ 770 (3) ms ec β^+ 100% $\beta^+ \alpha$	6-C-10 $J^{\pi} 0^+$ 19.290 (12) s ec β^+ 100%	6-C-11 $J^{\pi} 3/2^-$ 20.364 (14) min ec β^+ 100%	7-N-13 $J^{\pi} 1/2^-$ 9.965 (4) min ec β^+ 100%	8-O-14 $J^{\pi} 0^+$ 70.606 (18) s ec β^+ 100%	8-O-15 $J^{\pi} 1/2^-$ 122.24 (16) s ec β^+ 100%
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