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. Bagchi[1], T. Dickel[2], P. Egelhof[1], T. Grahn[3], E. Haettner[1], A. Jokinen[3], B. Kindler[1], G. Kraft[1],N. Kuzminchuk-Feuerstein[1], B. Lommel[1], C.C. Montanari[4], Z. Patyk[5], S. Pietri[1], Y. Pivovarov[6], W.R. Plaß[1], A. Prochazka[1], C. Scheidenberger[1,2], V.P. Shevelko[8], D. Severin[1], P. Sigmund[7], A. Sørensen[9], T. Stöhlker[1], Y. K. Tanaka[1], B. Voss[1], J.S. Winfield[1], M. Winkler[1]
& Super-FRS experiment collaboration

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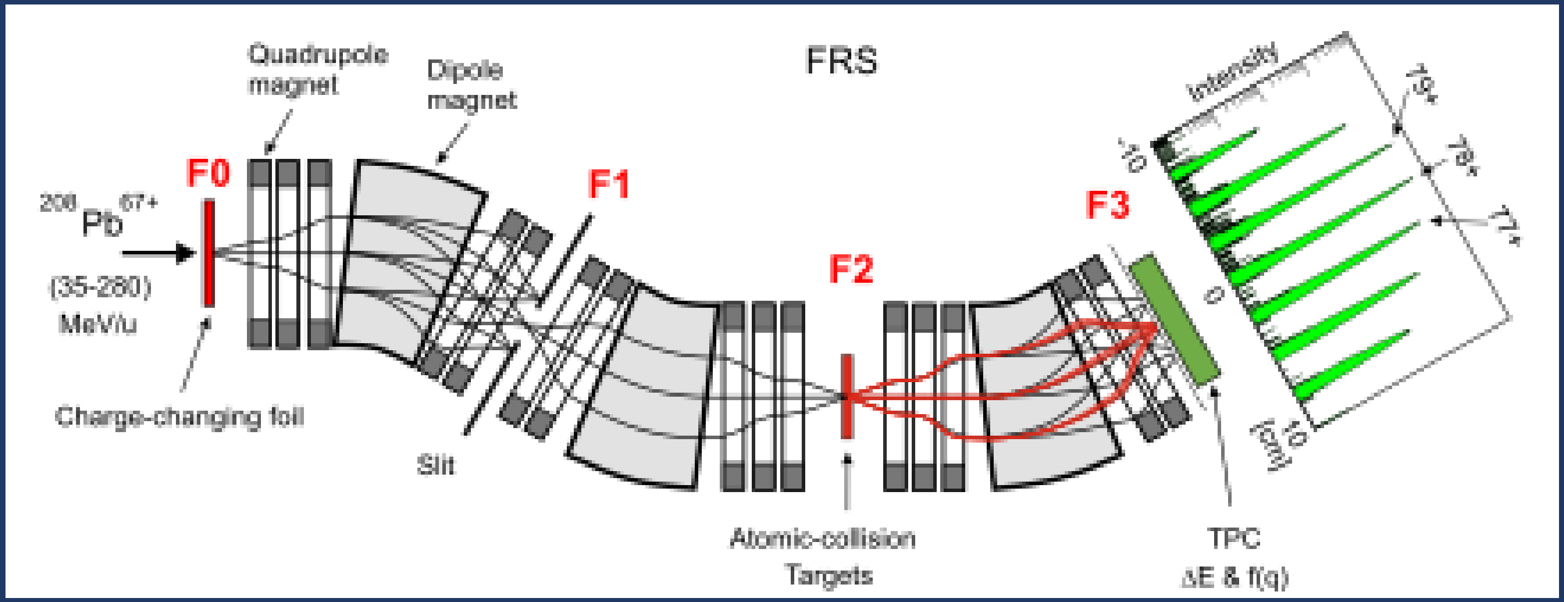
Sivaji Purushothaman for the Super-FRS EC

The experiment



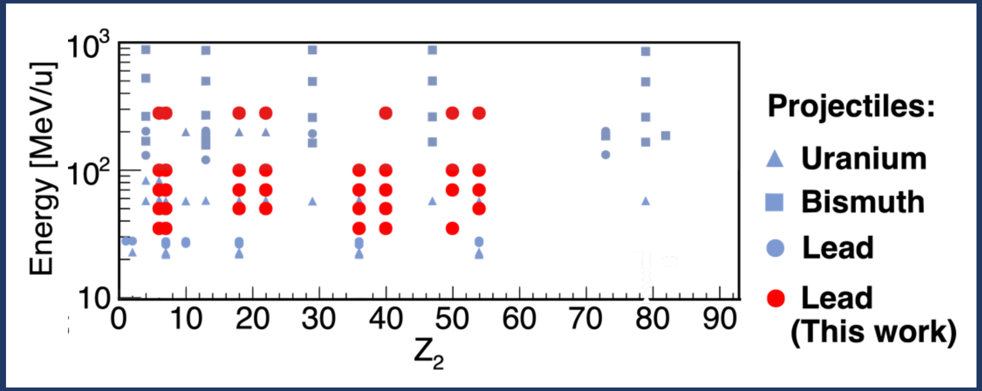
What are we interested in?

- 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

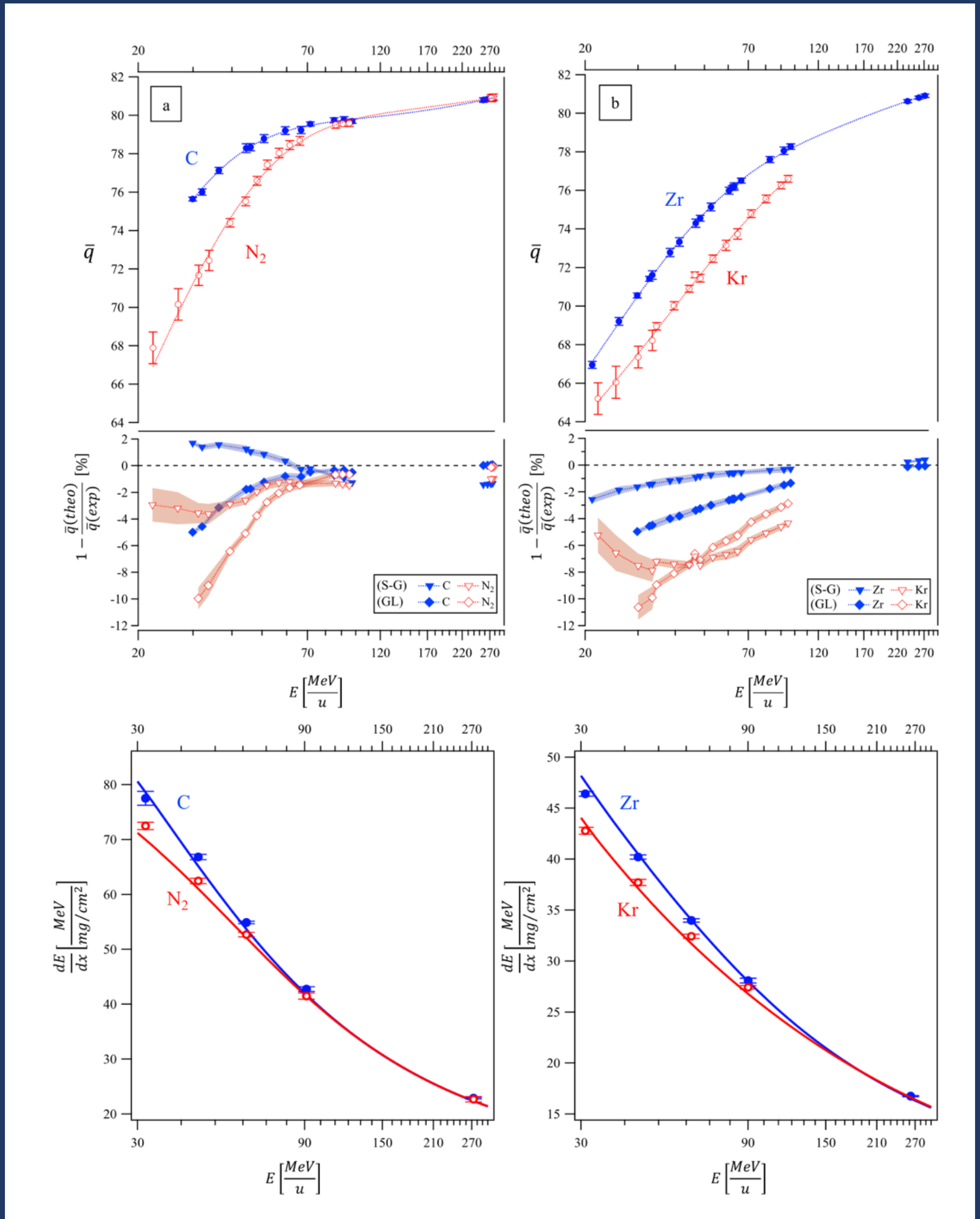
Targets	
2 - 327 mg/cm^2	2 - 524 mg/cm^2
Gases	Solids
$_7N_2$	$_6C$
$_{18}Ar$	$_{22}Ti$
$_{36}Kr$	$_{40}Zr$
$_{54}Xe$	$_{50}Sn$
C_3H_6	$(C_3H_6)_n$

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



Main results

- For the first time, both the mean charge states and stopping powers of 208Pb 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.

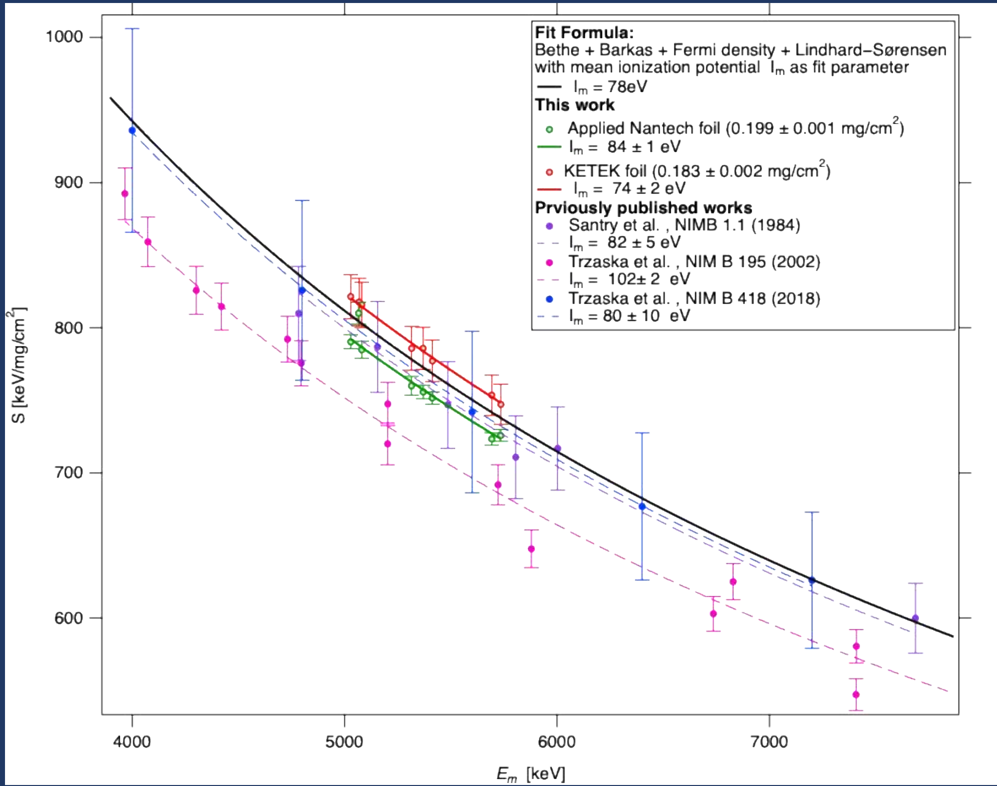


S. Ishikawa et al., Physics Letters B 846 (2023) 13

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)

Outlook

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

Physics Letters B 846 (2023) 138220

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

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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A R T I C L E   I N F O

Article history:
Received 9 June 2023
Received in revised form 6 September 2023
Accepted 27 September 2023
Available online 4 October 2023
Editor: D.F. Geesaman

Keywords:
Heavy ion
Stopping power
Mean charge state
Bohr-Lindhard density effect

A B S T R A C T

We have measured for the first time simultaneously both the mean charge states and stopping powers of (35–280) MeV/u ^{208}Pb 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, an unprecedented prediction 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.

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-

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[1] Part of doctoral thesis.

https://doi.org/10.1016/j.physletb.2023.138220

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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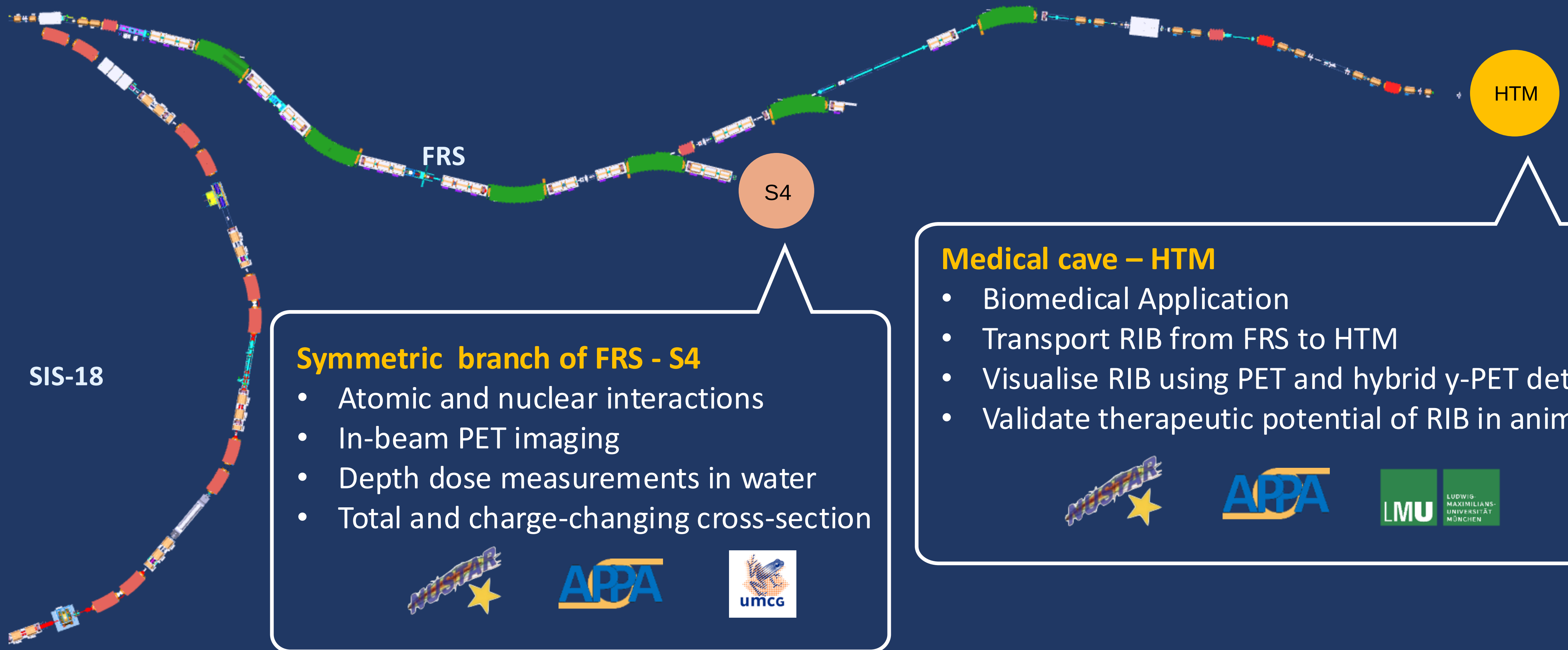
Sivaji Purushothaman for the Super-FRS EC

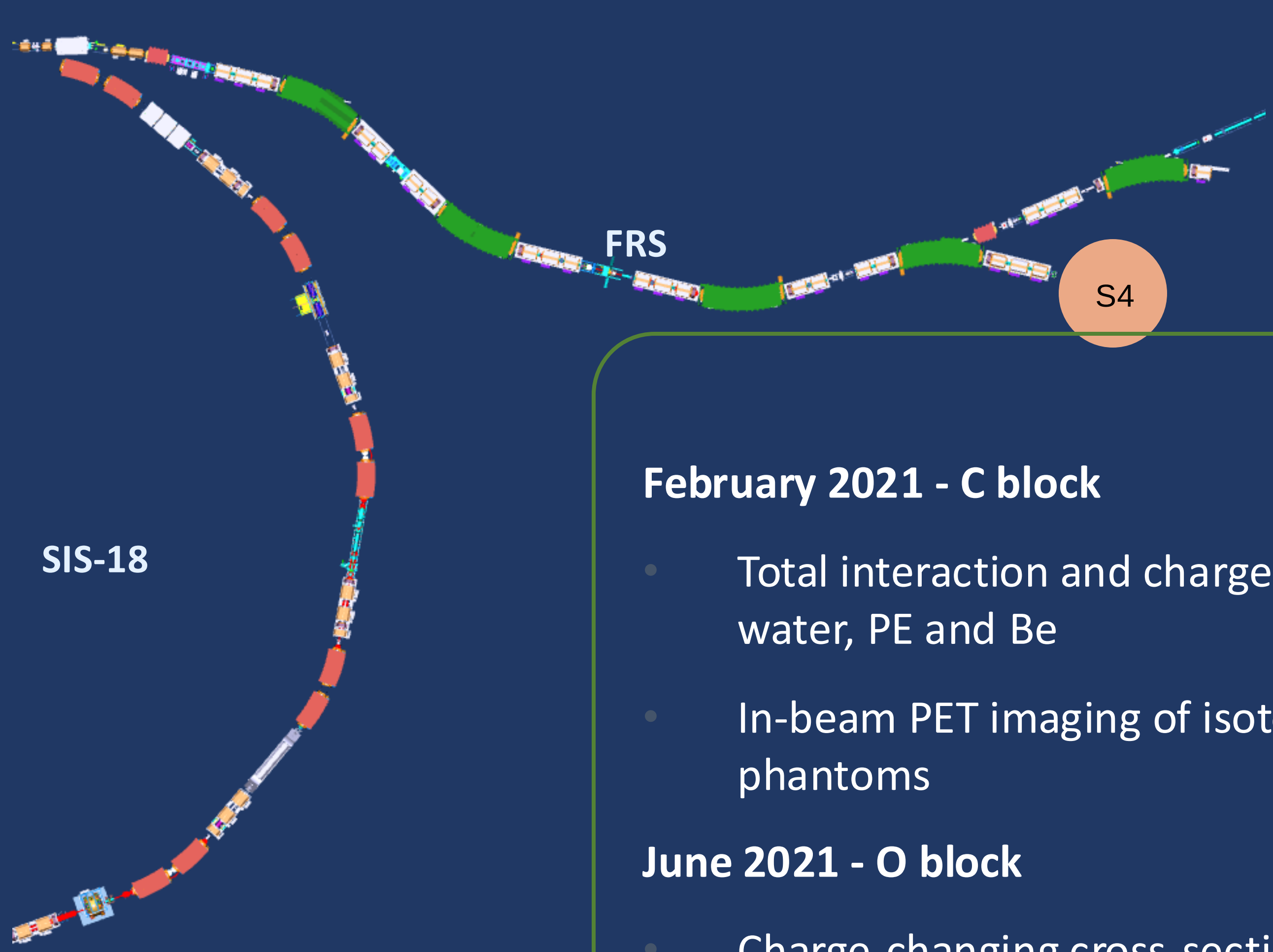


Symmetric branch of FRS - S4

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

Medical cave – HTM

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



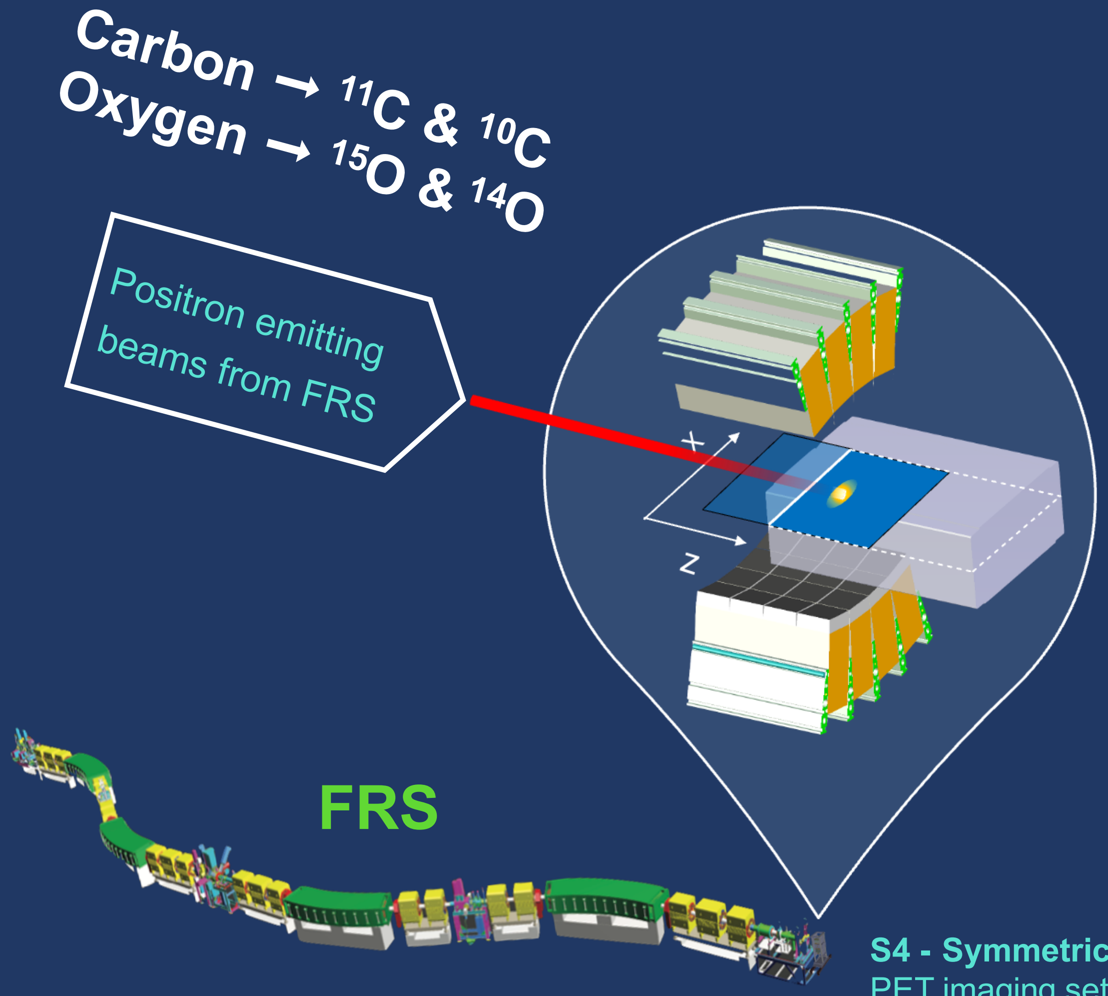
February 2021 - C block

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

June 2021 - O block

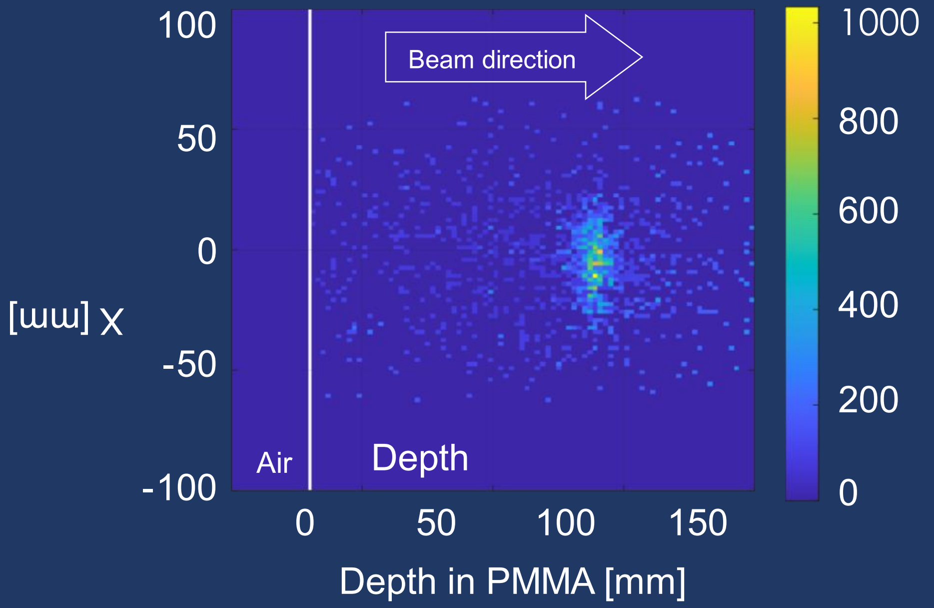
- Charge-changing cross-section of ^{14,15,16}O in carbon, Water, PE
- In-beam PET imaging of isotopically pure ^{14,15,16}O implanted in PMMA and PE phantoms

PET imaging at FRS



S4 - Symmetric branch of FRS
PET imaging setup

2D PET image of 14O
After 4 implantation cycles

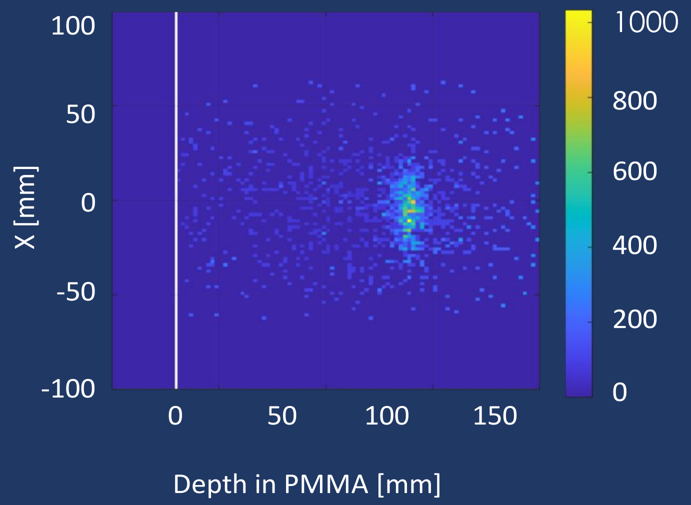


1/6th of a Siemens Biograph mCT clinical scanner
Peter Dendooven
umcg

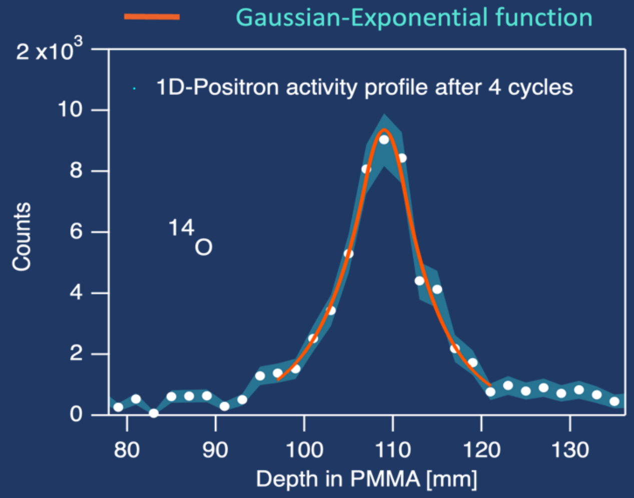
Purushothaman, Sivaji, et al., Sci Rep 13, 18788 (2023)
Kostyleva, Daria, et al. Phys. Med. Biol 1 (2023)

Evaluation of the positron activity: Peak position and its uncertainty

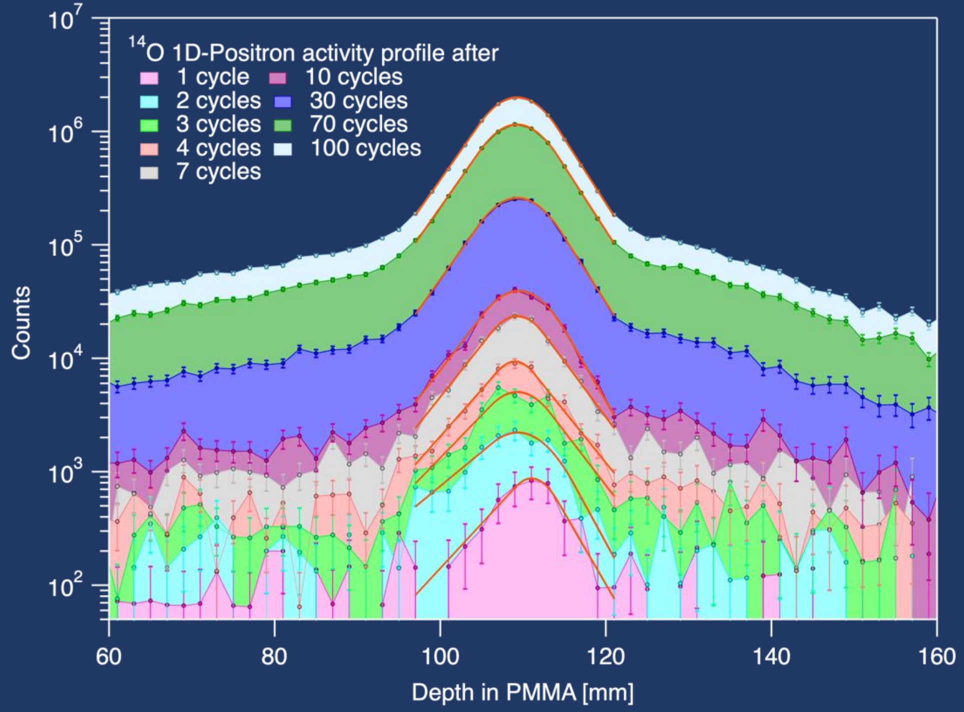
2D PET image of 14O after 4 implantation cycles

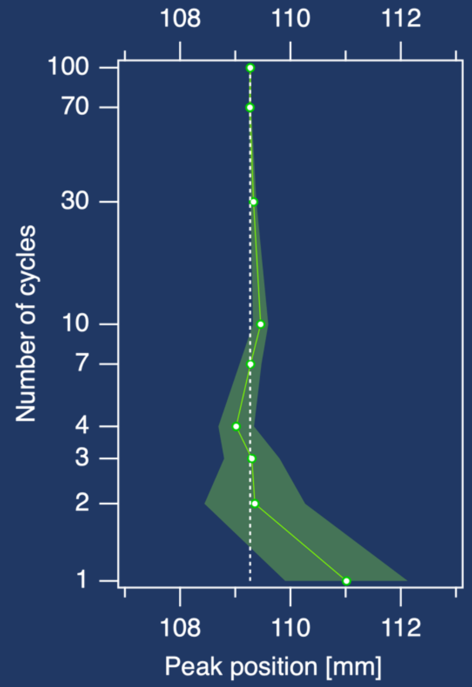


Projection to the beam axis



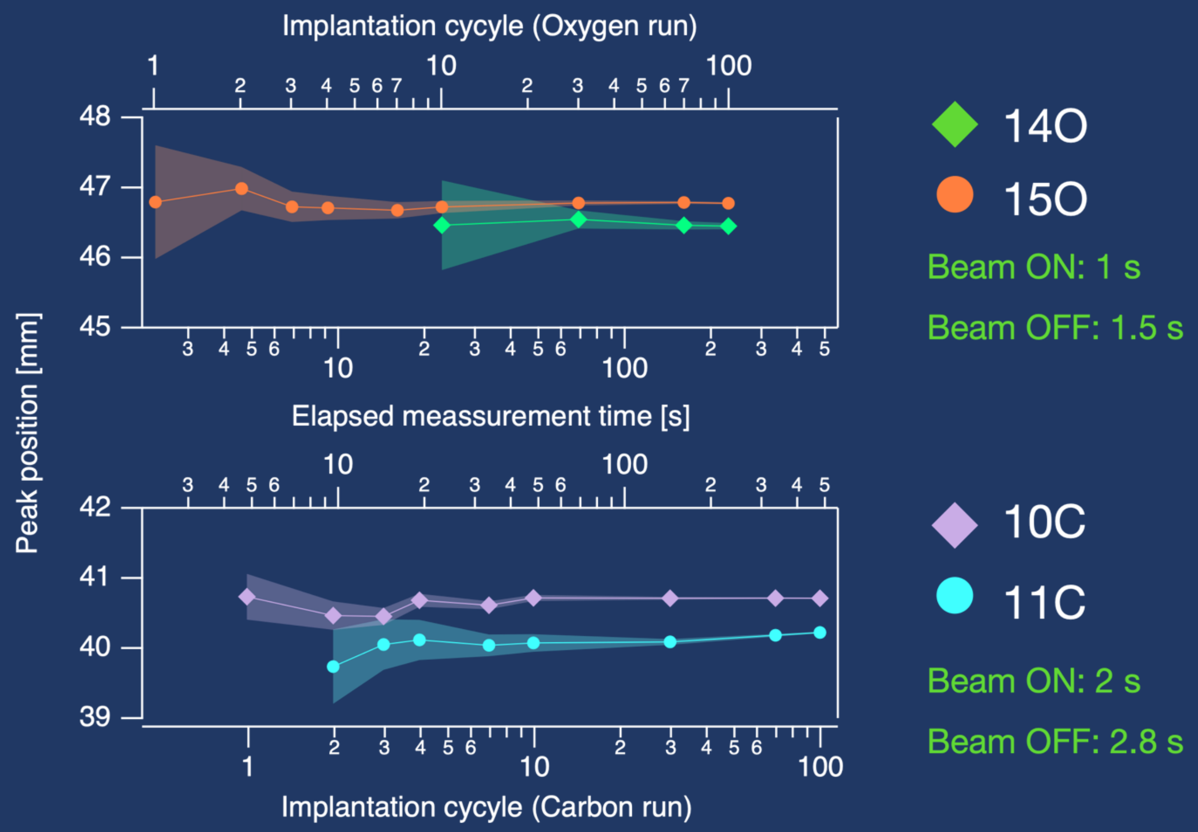
Cumulative positron activity profiles 1D activity profiles during irradiation

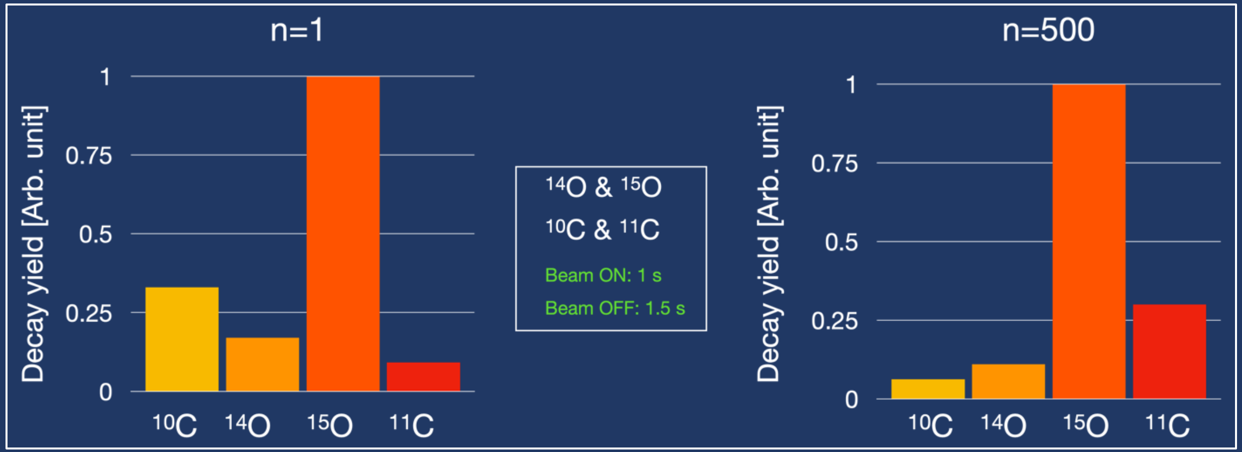




Quasi-real-time range monitoring

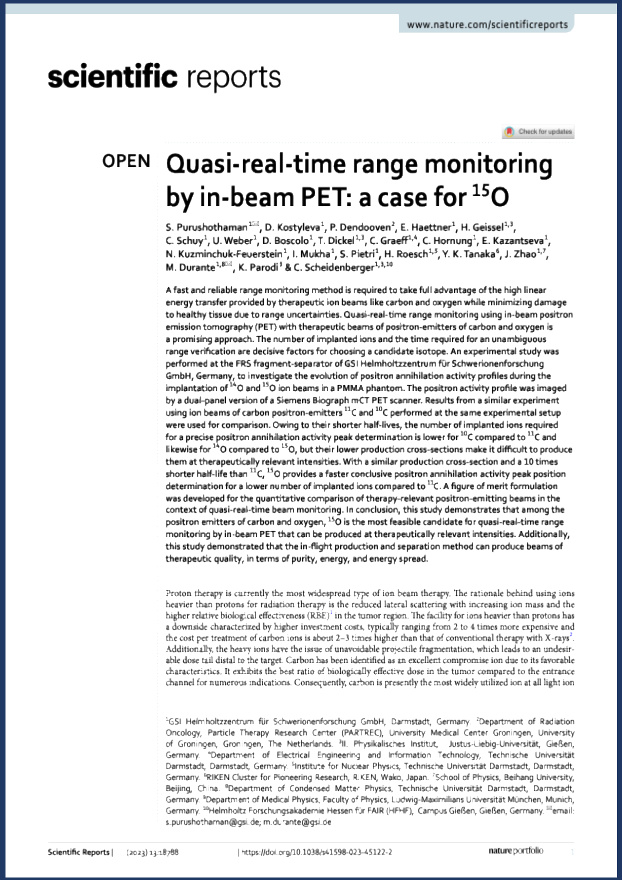
Which is the best positron emitting therapy beam





Purushothaman, Sivaji, et al., Sci Rep 13, 18788 (2023)
Kostyleva, Daria, et al. Phys. Med. Biol 1 (2023)

Publication status



Upcoming publications

Ongoing analysis:

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

Next Steps and Opportunities