

# Investigating single-particle states in $^{111}\text{Sn}$ through $d(^{110}\text{Sn}, p)$ with ISS

Joochun (Jason) Park

Focused workshop on rare isotope physics

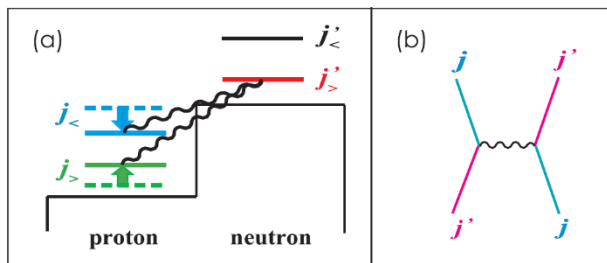
Nov. 26, 2022



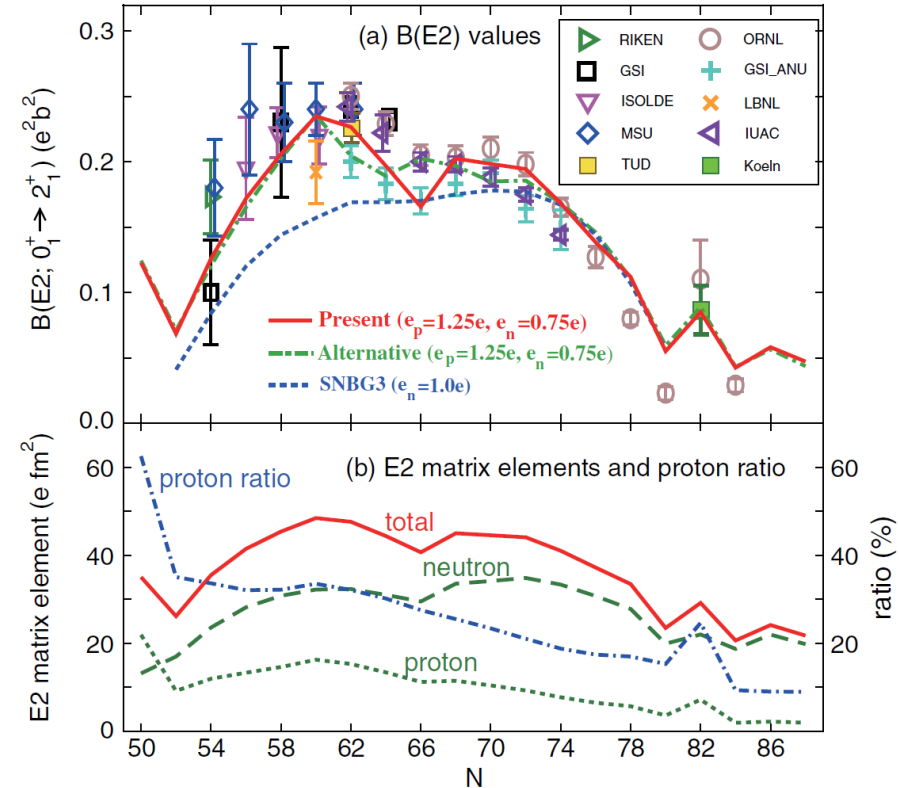
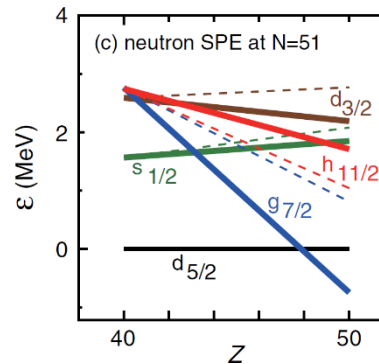
# Uncovering structural evolution towards $^{100}\text{Sn}$

One of few double shell closures without direct spectroscopy results yet, must characterize single-particle vs collective phenomena along the isotopic chain

Proton-neutron tensor monopole interaction as an explanation for decreasing  $E(5/2^+)-E(7/2^+)$  gap observed in  $N = 51$  isotones

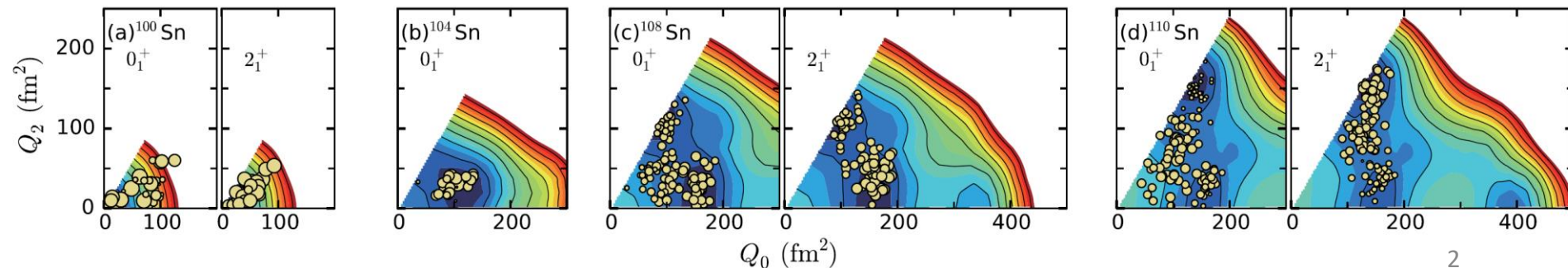


T. Otsuka et al., PRL 95, 232502 (2005)  
and PRL 104, 012501 (2010)

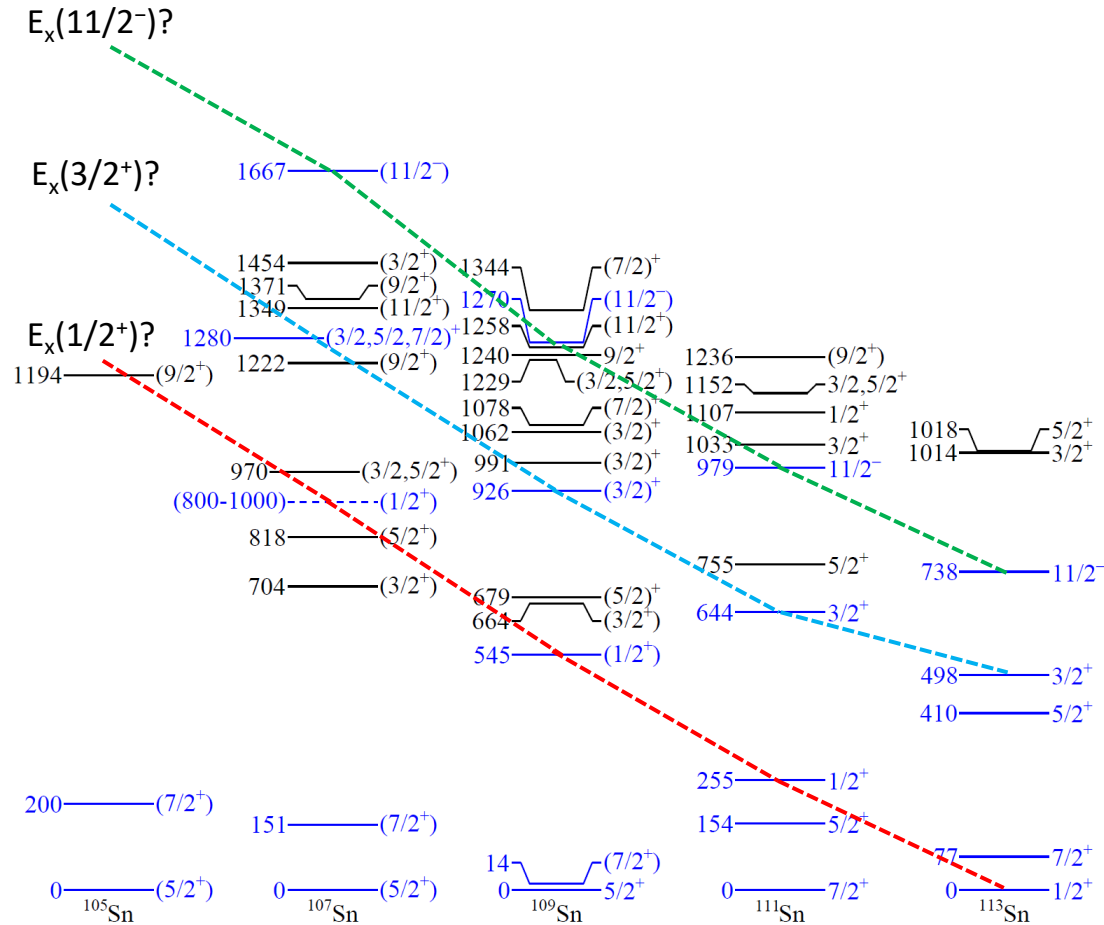


T. Togashi et al., PRL 121, 062501 (2018)

Deformation as a possible explanation for large  $B(E2)$  values in light Sn isotopes, reaching maximum at  $^{110}\text{Sn}$  ( $N = 60$ )



# Single-particle state candidates and energy trends in $^{105-113}\text{Sn}$



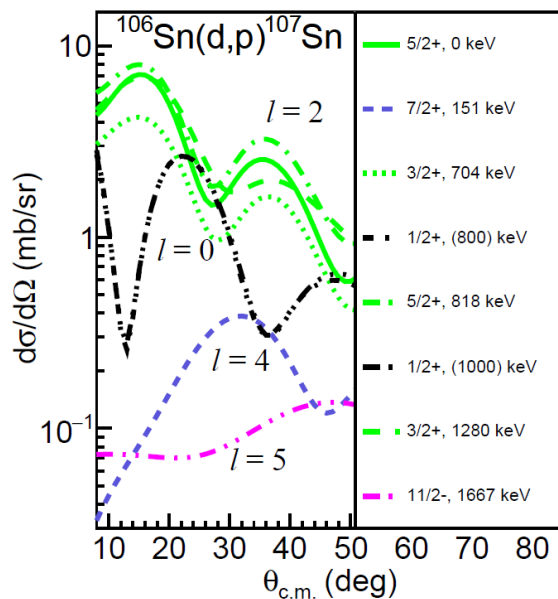
Tentative spin assignments based on beta-decay studies with  $\gamma\gamma$  coincidences

Previously suggested single-particle states in blue, to be clearly determined through (d,p)

Energy of the unknown  $1/2^+$  state in  $^{107}\text{Sn}$  and identification of  $11/2^-$  states (intruder orbit) particularly interesting, in addition to the S-factors

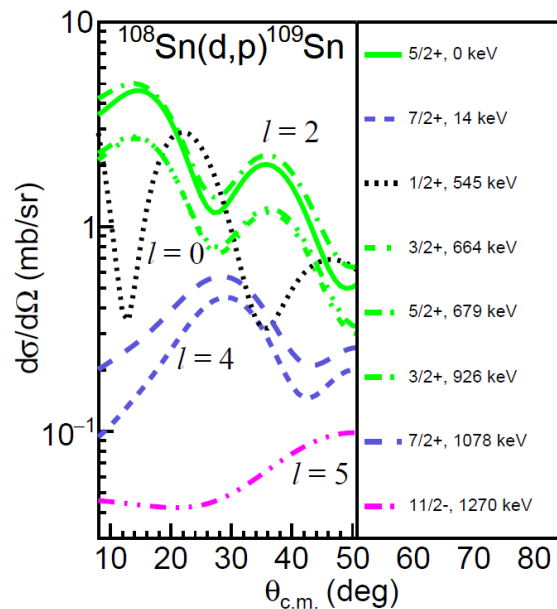
# (d,p) cross section calculations with DWBA

Relevant neutron orbitals above  $N = 50$ :  $1g_{7/2}$ ,  $2d_{5/2}$ ,  $2d_{3/2}$ ,  $3s_{1/2}$ ,  $1h_{11/2}$



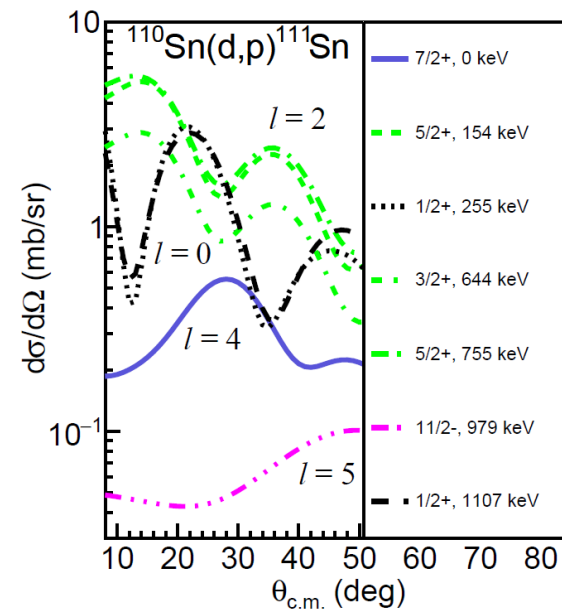
Entrance channel parameters:

H. An and C. Cai, PRC 73, 054605 (2006)



Exit channel parameters:

A.J. Koning and J.P. Delaroche, NPA 713, 231 (2003)



Automatic binding potential depth adjustment in FRESKO

I. Thompson, Compt. Phys. Rep. 7, 167 (1988)

Priority on measuring  $l = 5$  transfers to  $11/2^-$  states with sufficient statistics

Angular distribution trends well separated as a function of  $l$  for spin assignments

# Beam time requests and expected statistics/spectra

Reaction/ target	Intensity and beam time	$E_x$ (keV)	$J^\pi$	$\Delta L$	$\sigma$ (mb)	Proton counts
$^{106}\text{Sn}(d,p)^{107}\text{Sn}$ at 8 MeV/u on $165\text{-}\mu\text{g}/\text{cm}^2$ $\text{CD}_2$	$1 \times 10^5/\text{s}$ for 24 shifts	0	$5/2^+$	2	4.436	1378
		151	$(7/2^+)$	4	0.461	143
		704	$(3/2^+)$	2	3.444	1070
		818	$(5/2^+)$	2	6.576	2043
		(800-1000)	$(1/2^+)$	0	2.031-2.072	631-644
		1280	$(3/2^+)$	2	5.641	1753
$^{108}\text{Sn}(d,p)^{109}\text{Sn}$ at 8 MeV/u on $165\text{-}\mu\text{g}/\text{cm}^2$ $\text{CD}_2$	$5 \times 10^5/\text{s}$ for 12 shifts	1667	$(11/2^-)$	5	0.220	68
		0	$5/2^+$	2	3.893	3018
		14	$(7/2^+)$	4	0.547	424
		545	$(1/2^+)$	0	2.220	1722
		664	$(3/2^+)$	2	2.357	1828
		679	$(5/2^+)$	2	2.411	1869
$^{110}\text{Sn}(d,p)^{111}\text{Sn}$ at 8 MeV/u on $165\text{-}\mu\text{g}/\text{cm}^2$ $\text{CD}_2$	$5 \times 10^5/\text{s}$ for 12 shifts	926	$(3/2^+)$	2	2.463	1910
		1078	$(7/2^+)$	4	0.750	581
		1270	$(11/2^-)$	5	0.141	109
		0	$7/2^+$	4	0.685	532
		154	$5/2^+$	2	4.378	3401
		255	$1/2^+$	0	2.346	1822
$^{107}\text{Sn}$		644	$3/2^+$	2	2.553	1983
		755	$5/2^+$	2	4.813	3738
		979	$11/2^-$	5	0.147	114
		1107	$1/2^+$	0	2.458	1909

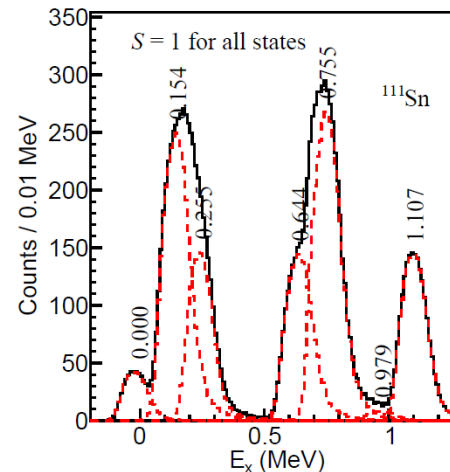
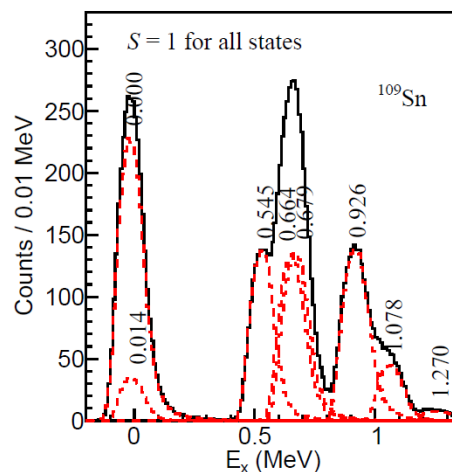
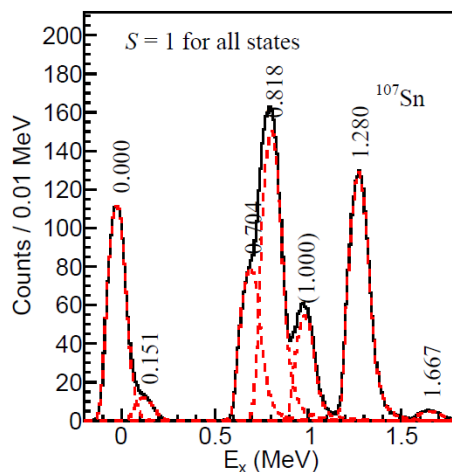
Transfer reaction quenching by 0.55 applied

[B. P. Kay, J. P. Shiffer, S. J. Freeman, PRL 111, 042502 (2013)]

Statistics comparable to  $d(^{206}\text{Hg},p)^{207}\text{Hg}$  results

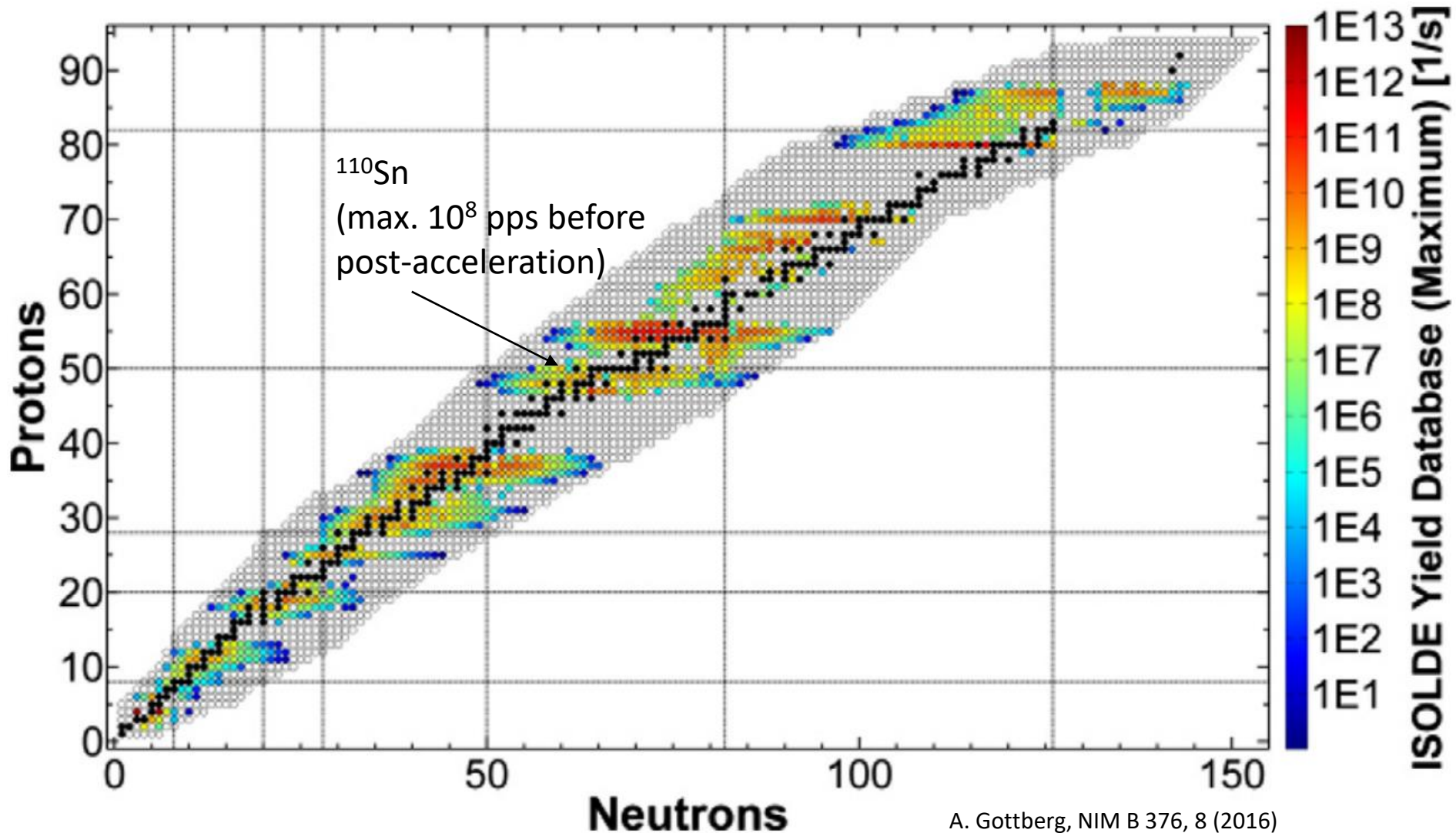
Beam time set to measure transfers to  $11/2^-$  states with  $\sim 10^2$  counts at nominal RIB intensities, updated cross sections and lower  $E_{\text{beam}}$  can improve these numbers by 70-100%

Search for  $1/2^+$  single-particle state in  $^{107}\text{Sn}$  in  $E_x$  range 800-1000 keV with little dependence on cross section





# CERN-ISOLDE yields

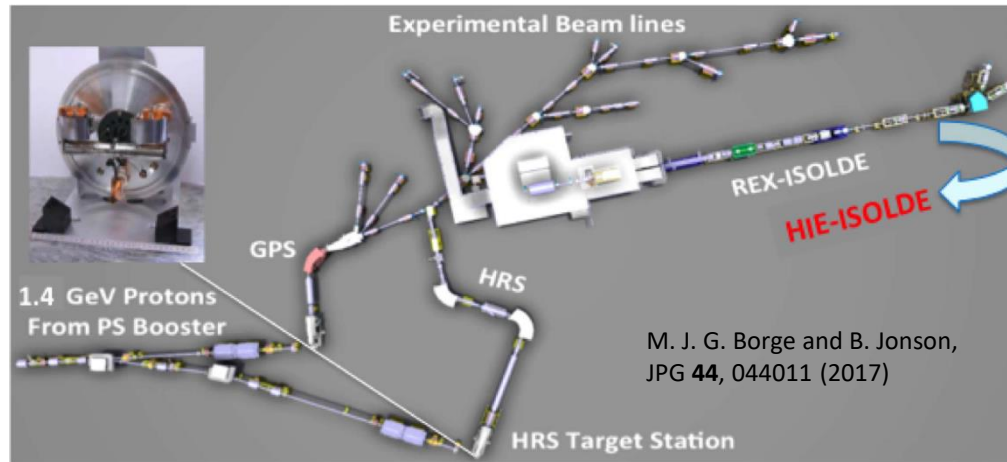


1.4-GeV proton synchrotron booster (PSB) for RIB production through spallation  
Various primary targets with elements' atomic number from 6 (C) to 92 (U)

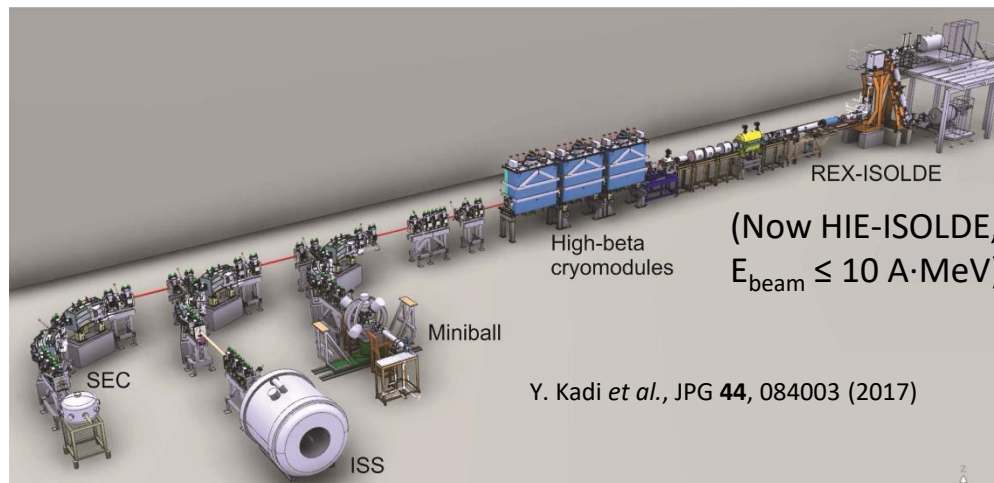
# Radioactive $^{110}\text{Sn}$ beam production at CERN HIE-ISOLDE

Proton from PS booster on  $\text{LaC}_x$  target

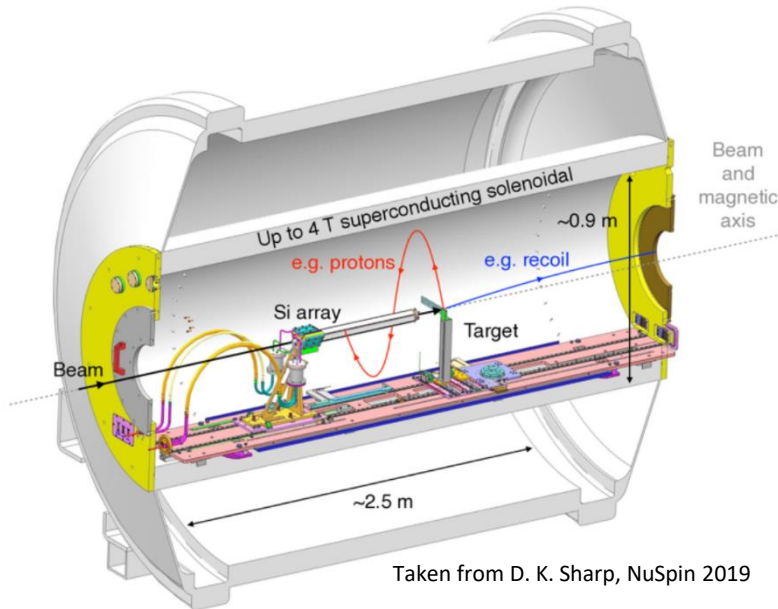
$^{110}\text{In}$  isobaric contamination suppressed with extraction scheme and Resonance Ionization Laser Ion Source (RILIS)



Post-accelerated beam through GPS to HIE-ISOLDE,  
towards ISS among multiple experiment stations

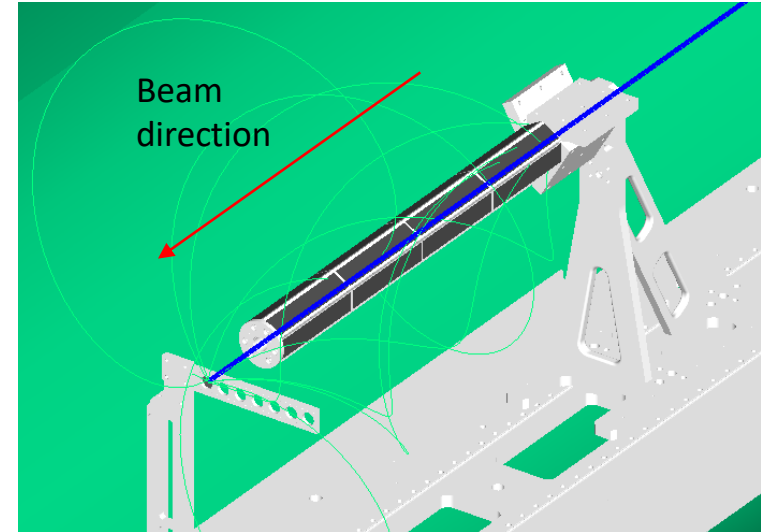


# ISS spectrometer for (d,p) in inverse kinematics



Taken from D. K. Sharp, NuSpin 2019

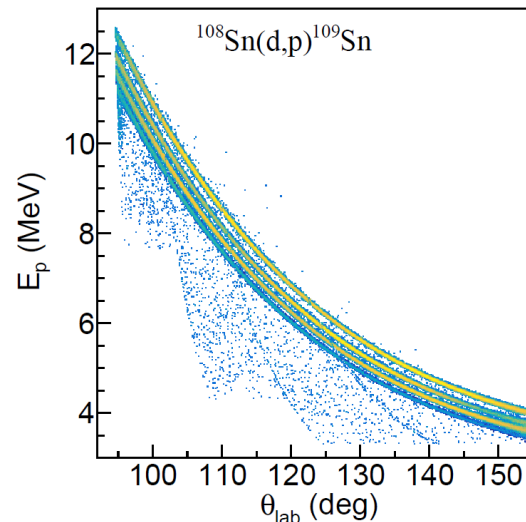
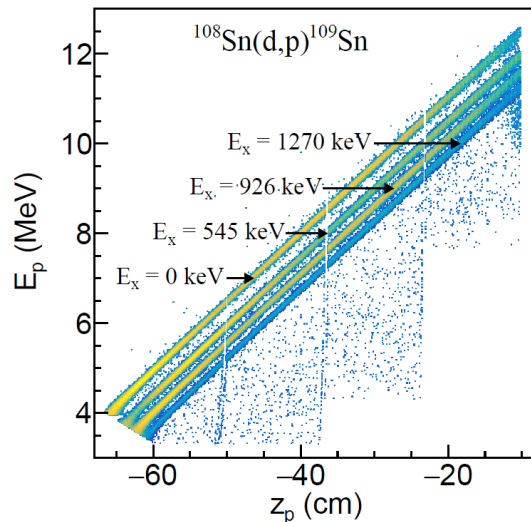
Proposed B-field strength: 2.5 T



1-mm thick DSSDs arranged in hexagonal tube  
94% Si strip/70%  $\phi$  coverage  
z-coverage: (-61 cm, -11 cm) from the target  
At  $E_{\text{beam}} = 8 \text{ A} \cdot \text{MeV}$ , ISS array covers  $10^\circ < \theta_{\text{c.m.}} < 45^\circ$

## NPTool simulation of ISS

A. Matta et al. J. Phys. G 43, 045113 (2016) and M. Labiche



Particle kinematics in  
solenoidal magnetic field

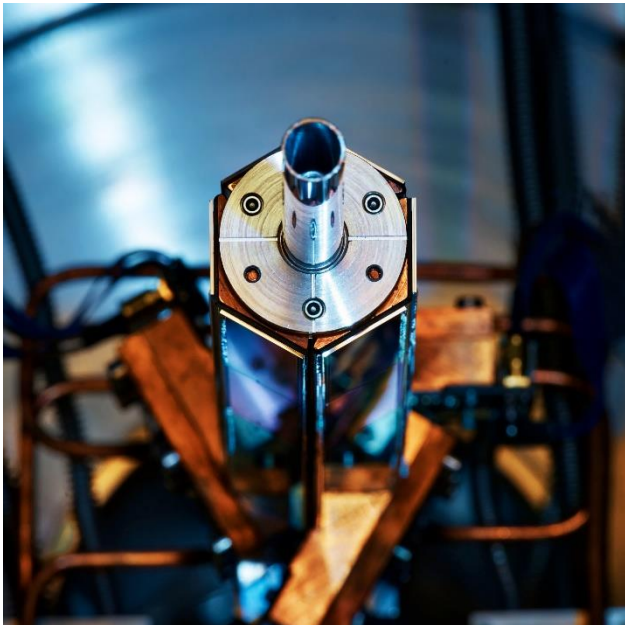
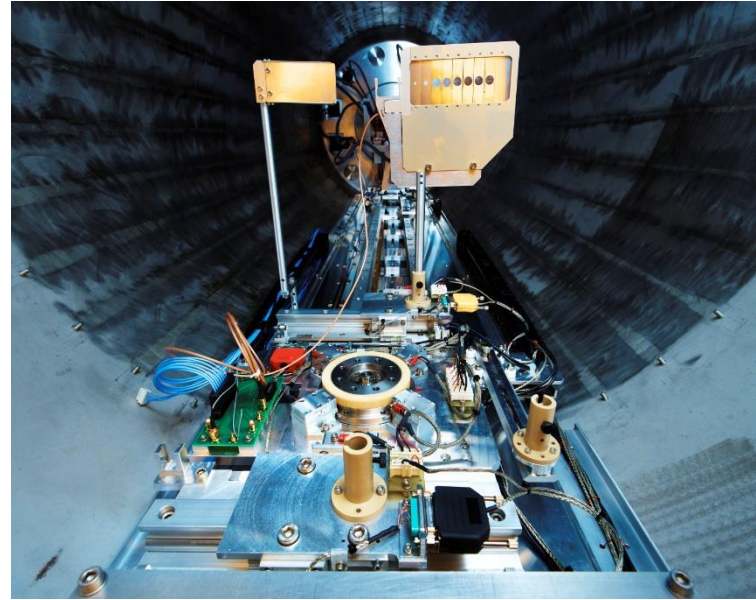
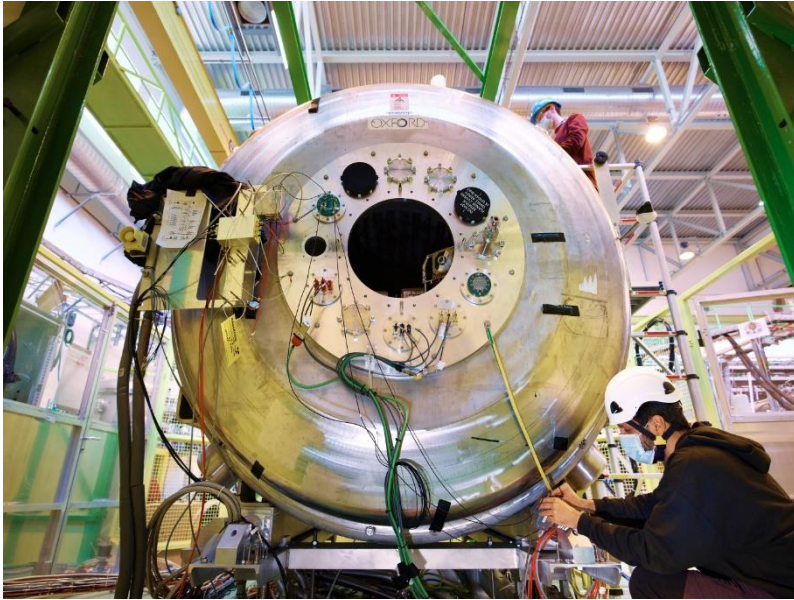
$$E_{\text{lab}} = E_{\text{cm}} - \frac{1}{2} m V_{\text{cm}}^2 + \left( \frac{m V_{\text{cm}}}{T_{\text{cyc}}} \right) z$$

$$T_{\text{cyc}} = (2\pi/B)(m/qe)$$

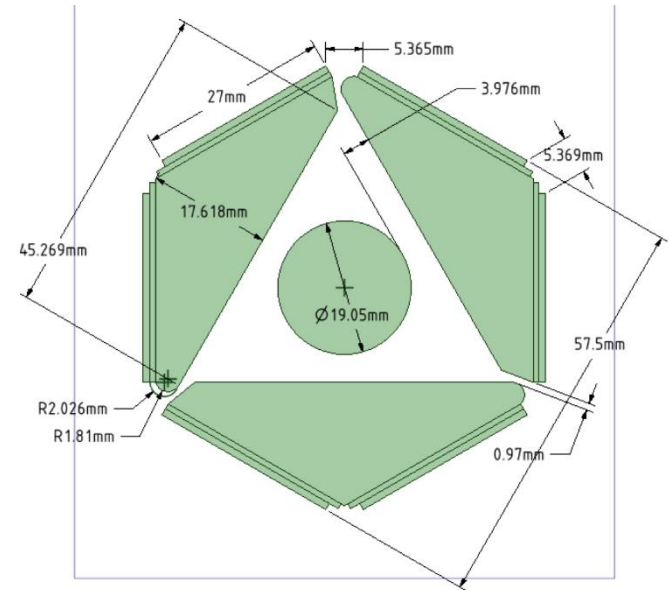
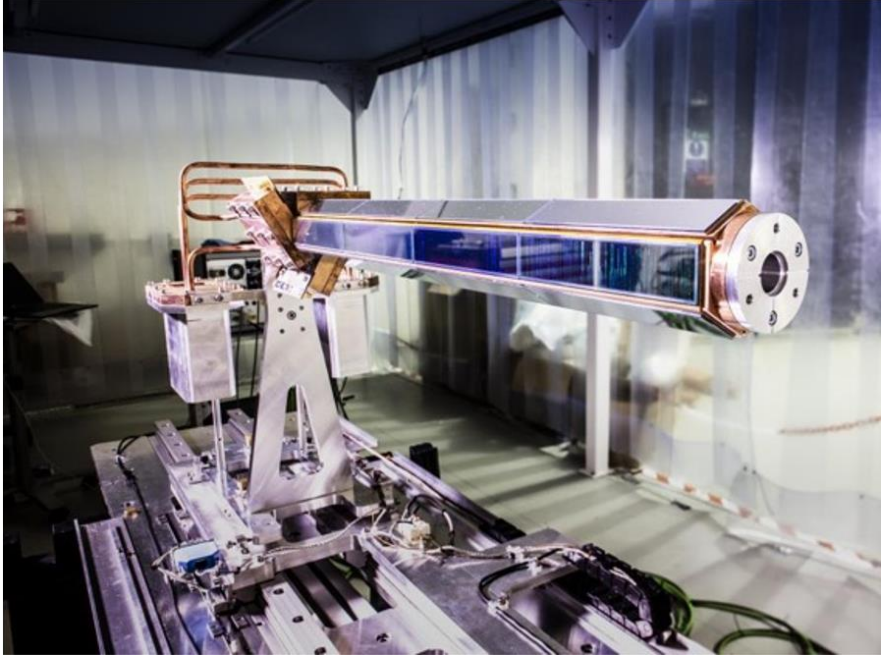
$$z = (v_0 \cos(\theta_{\text{cm}}) + V_{\text{cm}}) \frac{r \left[ 2\pi - 2 \arcsin \left( \frac{r_0}{2r} \right) \right]}{v_0 \sin(\theta_{\text{cm}})}$$



# ISS spectrometer photos



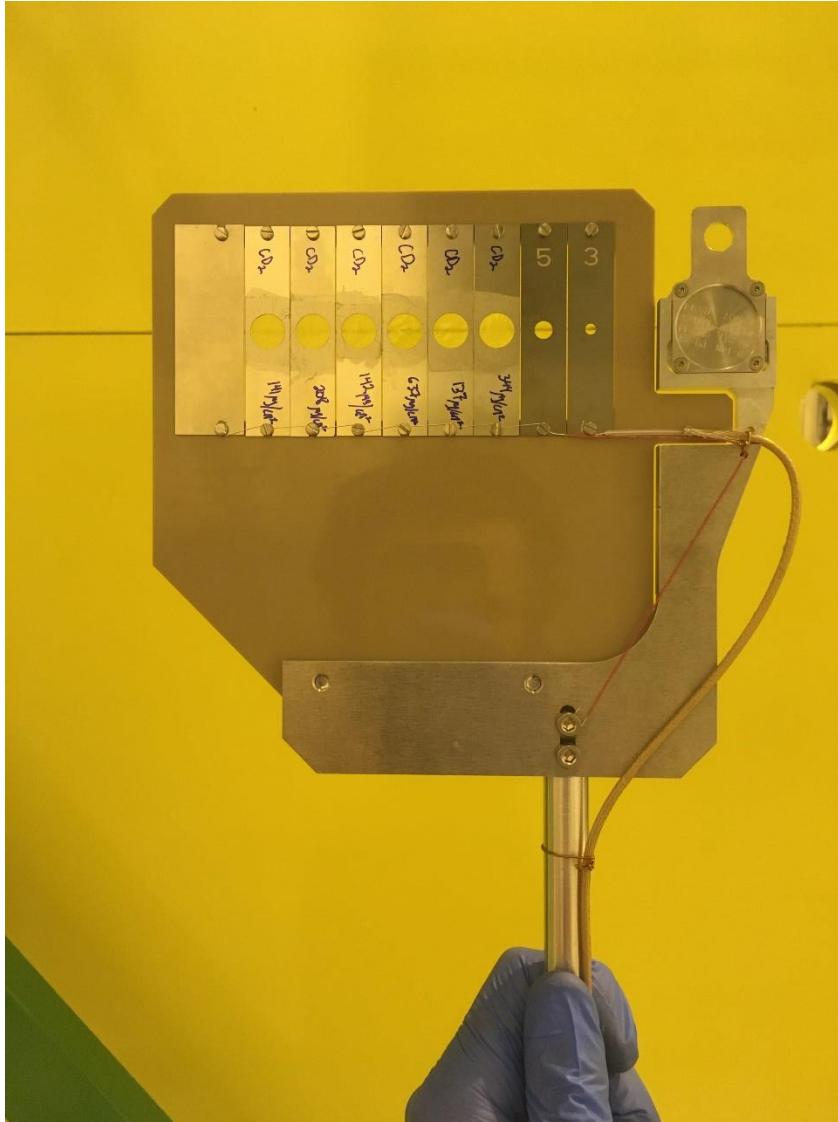
# Si barrel array for ISS



- Micron BB21: DSSSD of 128 p-side strips, 11 n-side strips
- DSSSD dimensions:  $125 \times 27 \times 1 \text{ mm}^2$
- 3 modules,  $\sim 70\%$  coverage in  $\phi$  accounting for gaps
- 4 sections (z coverage), 0.5-mm gaps in between for 94% coverage
- ASIC on-chip ADC serial readout (no PSA)
- Distance to target adjustable depending on kinematics



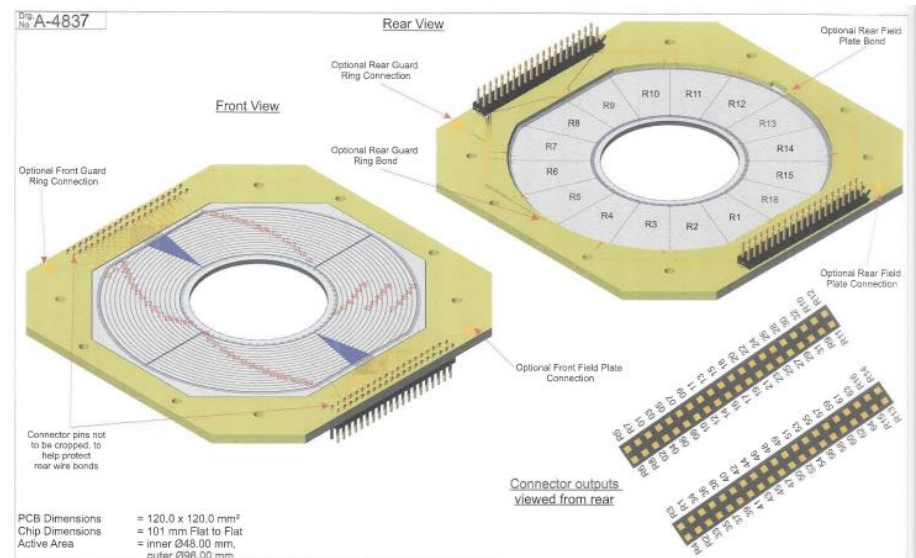
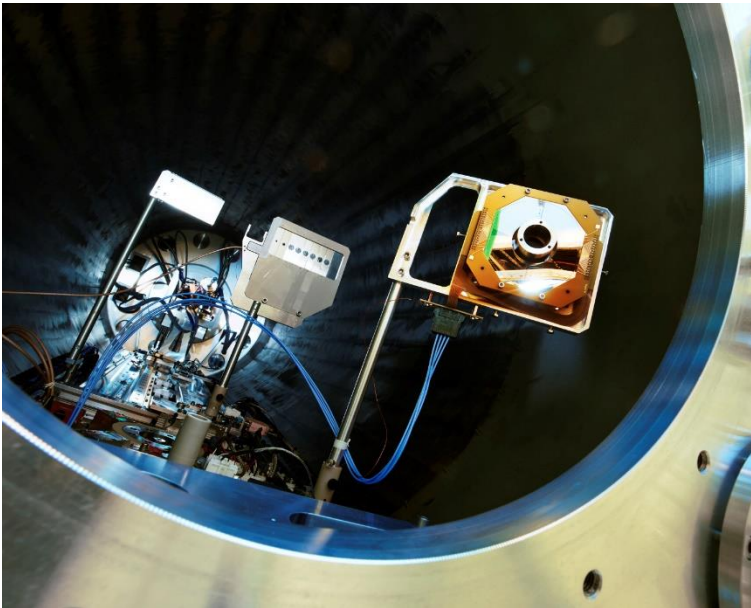
# Target ladder + alpha source holder



- 6 targets + 2 apertures for beam tuning
  - Reversible alpha source holder
  - Connected to drive motor that is turned on only when switching targets (eliminate noise)
- 
- $\text{CD}_2$  targets used (not same as photo):
    - $97 \mu\text{g}/\text{cm}^2$
    - $103 \mu\text{g}/\text{cm}^2$
    - $108 \mu\text{g}/\text{cm}^2$
    - $117 \mu\text{g}/\text{cm}^2$
    - $129 \mu\text{m}^2$
    - $209 \mu\text{g}/\text{cm}^2$

5/6 targets thinner than the proposed thickness of 165  $\mu\text{g}/\text{cm}^2$  for better  $\Delta E/E$

# Elastic Luminosity (ELUM) detector



- Detect elastically scattered particles for beam intensity normalization
- Micron S1 DSSSD
- Signals summed together for each quadrant, data from 4 quadrants
- Blocker to control event rate (only a fraction of  $\theta_{\text{lab}}$  accepted)

# Run summary

**IS686**  
**110 Sn**  
 isslocal@issdaqpc2  
 password: nuclear  
 iss I <3 (t,p) for Twiki

**TARGET-ARRAY DISTANCE: 110.000 mm**  
**TARGET: 3 209µg/cm² (elag:2318)**  
**BEAM ENERGY: 8.00 MeV/u**  
**PROTON CURRENT: 0.44 µA**

- CHECK DAQS ARE SYNCED REGULARLY  
 ↳ check in /TapeData/IS686/ events.root → timing folder  
 ↳ MAGIC SYNC BUTTON → issdaqpc2 MIDAS (white background)  
 • ISS Experiment Control  
 • Data Acquisition Run Control  
 • Drop down menu
- CHECK KILIS/GPS MONITOR IS UP TO DATE  
 ↳ if not, TURN OFF/ON
- CHECK NEIGHBOUR READ OUT IS ENABLED  
 ↳ issdaqpc2 MIDAS  
 • ISS Experiment control  
 • ISS Hardware control  
 • ASIC Setup (User)

**ALWAYS OFF: XLH1, XLH2, XLH3, XLH4**

**GOOD RUNS in isslocal@issdaqpc2/TapeData/IS686**

**NEW RUN EVERY 5 HRS**

**Pos 8, 97 µg/cm²**  
 R3\_0 → R3\_1  
 R4\_0 missing section on ASIC module 0  
 R5\_0  
 R6\_0  
 R7\_0  
 R8\_0  
 R9\_0  
 R10\_0  
 R11\_0  
 R12\_0  
 R13\_0  
 R14\_0  
 R15\_0  
 R16\_0  
 R17\_0  
 R18\_0  
 R19\_0  
 R20\_0  
 R21\_0  
 R22\_0  
 R23\_0  
 R24\_0  
 R25\_0  
 R26\_0  
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 R32\_0  
 R33\_0  
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 R92\_0  
 R93\_0  
 R94\_0  
 R95\_0  
 R96\_0  
 R97\_0  
 R98\_0  
 R99\_0  
 R100\_0

**Pos 6, 108 µg/cm²**  
 R25\_0 → R25\_1  
 R26\_0 → R26\_1  
 R27\_0 → R27\_1  
 R28\_0 → R28\_1  
 R29\_0 → R29\_1  
 R30\_0 → R30\_1  
 R31\_0 → R31\_1  
 R32\_0 → R32\_1  
 R33\_0 → R33\_1  
 R34\_0 → R34\_1  
 R35\_0 → R35\_1  
 R36\_0 → R36\_1  
 R37\_0 → R37\_1  
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 R39\_0 → R39\_1  
 R40\_0 → R40\_1  
 R41\_0 → R41\_1  
 R42\_0 → R42\_1  
 R43\_0 → R43\_1  
 R44\_0 → R44\_1  
 R45\_0 → R45\_1  
 R46\_0 → R46\_1  
 R47\_0 → R47\_1  
 R48\_0 → R48\_1  
 R49\_0 → R49\_1  
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 R91\_0 → R91\_1  
 R92\_0 → R92\_1  
 R93\_0 → R93\_1  
 R94\_0 → R94\_1  
 R95\_0 → R95\_1  
 R96\_0 → R96\_1  
 R97\_0 → R97\_1  
 R98\_0 → R98\_1  
 R99\_0 → R99\_1  
 R100\_0 → R100\_1

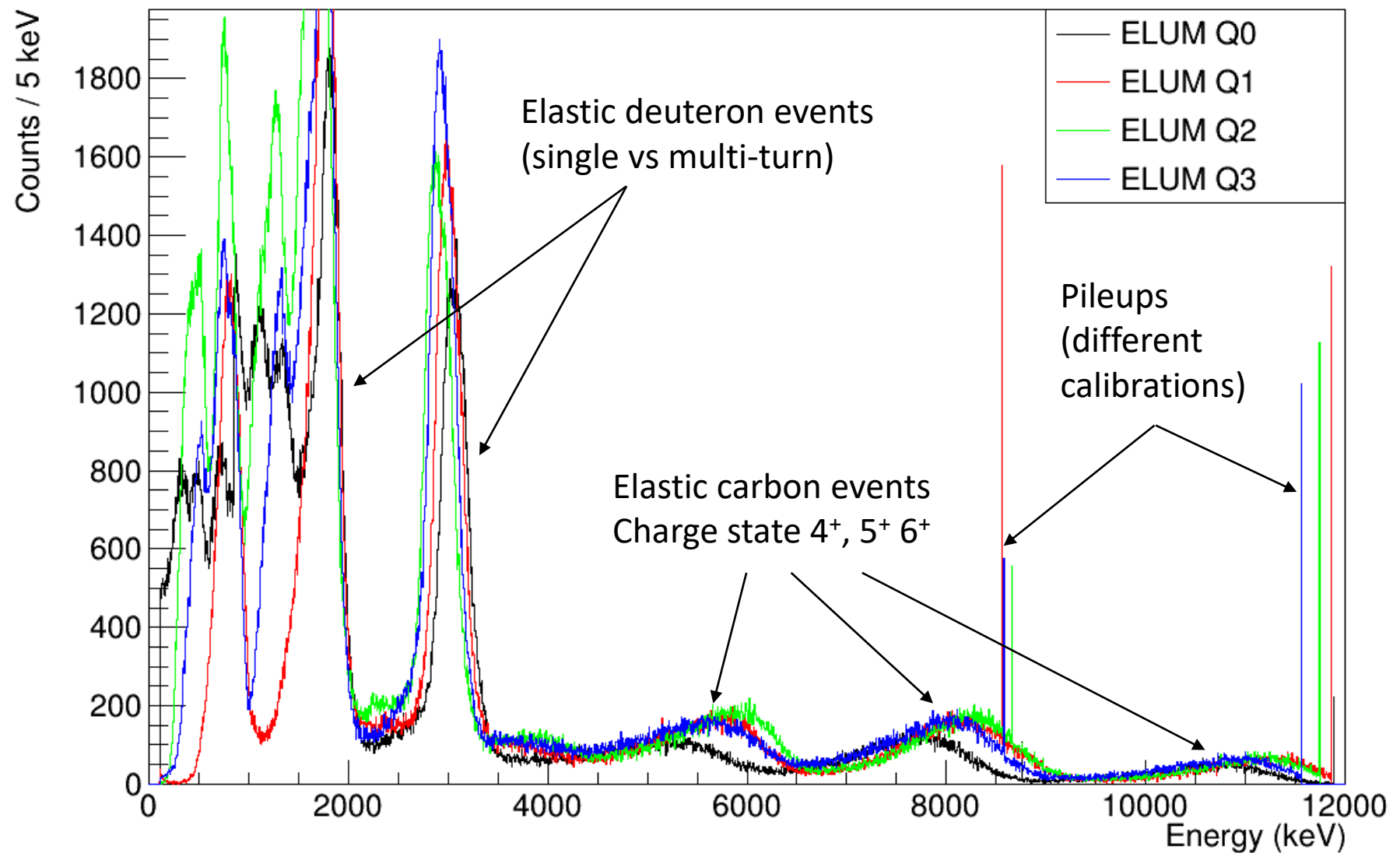
**Pos 7, 129 µg/cm²**  
 R79\_0 → R79\_1  
 R80\_0 → R80\_1  
 R81\_0 → R81\_1  
 R82\_0 → R82\_1  
 R83\_0 → R83\_1  
 R84\_0 → R84\_1  
 R85\_0 → R85\_1  
 R86\_0 → R86\_1  
 R87\_0 → R87\_1  
 R88\_0 → R88\_1  
 R89\_0 → R89\_1  
 R90\_0 → R90\_1  
 R91\_0 → R91\_1  
 R92\_0 → R92\_1  
 R93\_0 → R93\_1  
 R94\_0 → R94\_1  
 R95\_0 → R95\_1  
 R96\_0 → R96\_1  
 R97\_0 → R97\_1  
 R98\_0 → R98\_1  
 R99\_0 → R99\_1  
 R100\_0 → R100\_1

**Pos 3, 209 µg/cm²**  
 R92\_0 → R92\_1  
 R93\_0 → R93\_1  
 R94\_0 → R94\_1  
 R95\_0 → R95\_1  
 R96\_0 → R96\_1  
 R97\_0 → R97\_1  
 R98\_0 → R98\_1  
 R99\_0 → R99\_1  
 R100\_0 → R100\_1

- $E(^{110}\text{Sn}) = 8.00 \text{ A} \cdot \text{MeV} (\pm 0.3\%)$ , very pure –  $R(^{110}\text{In}/^{110}\text{Sn}) \sim 0.1\%$
- Beam start/end: Sep. 29, 13:00 – Oct. 5 07:30  
 ~6 days > 4 days assigned!
- Beam intensities: 0.30-0.5 µA protons,  $\sim 10^7$   $^{110}\text{Sn}$  pps  
 [0.03 µA protons during recoil detector test, down to  $\sim 5 \times 10^5$  pps]

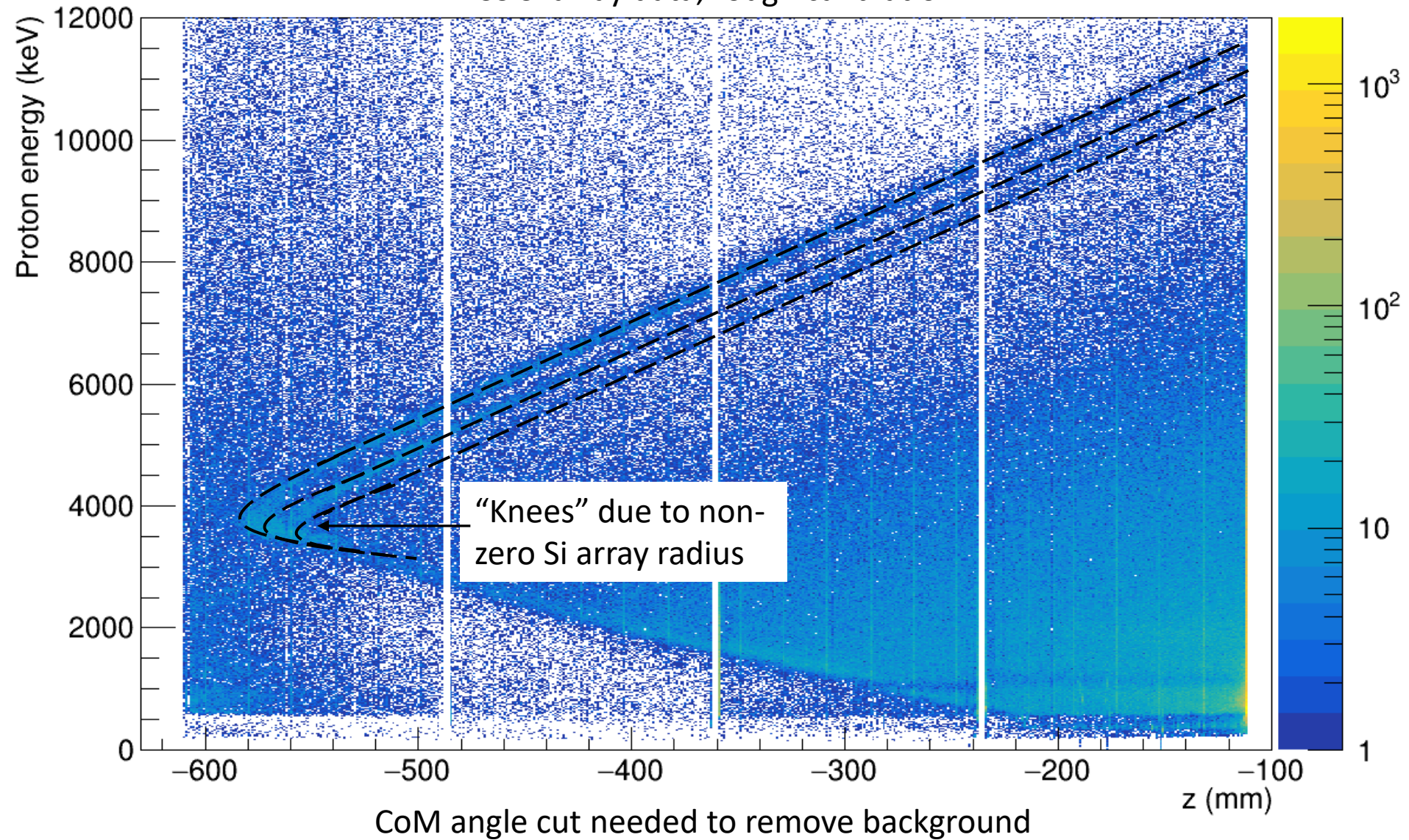


# Preliminary spectra



# Preliminary spectra

ISS Si array data, rough calibration

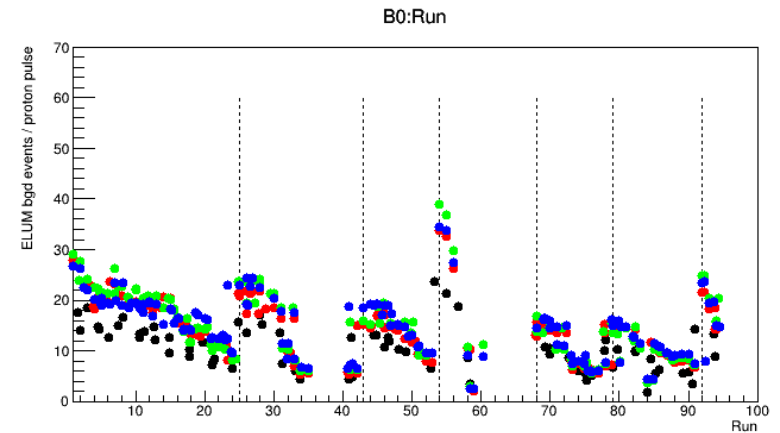
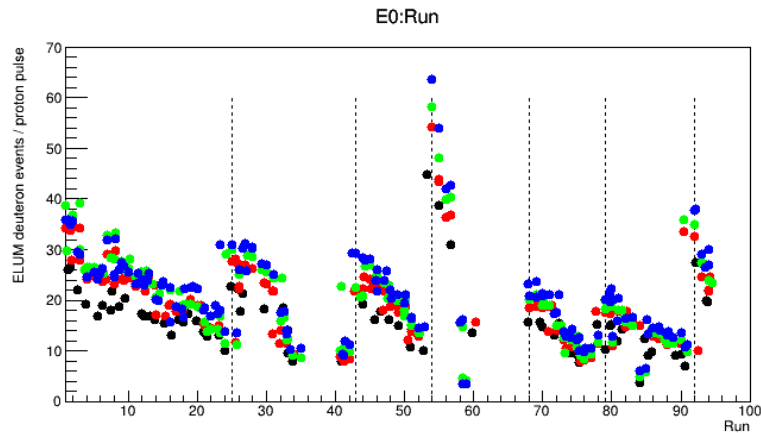
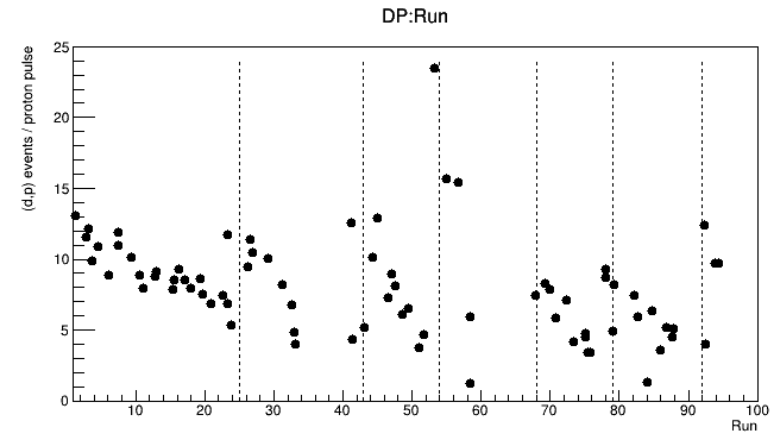
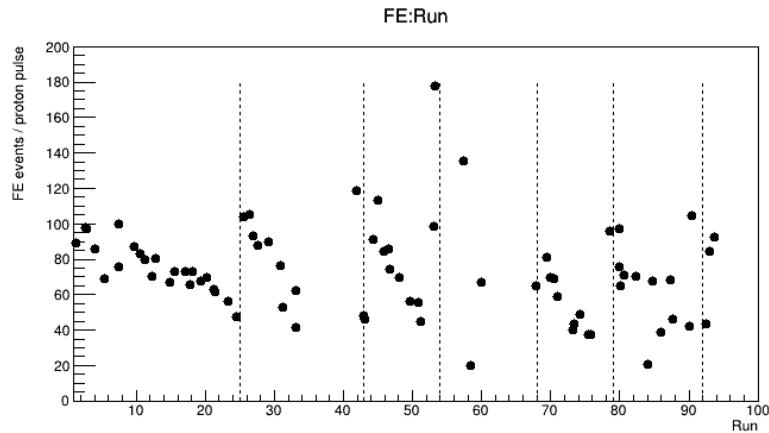


# Decreasing event rates

Counts divided by proton pulse  $\rightarrow$  normalized event rate (intensity not considered)

Gated on high-excitation energy bump

Counts under expected (d,p) peaks

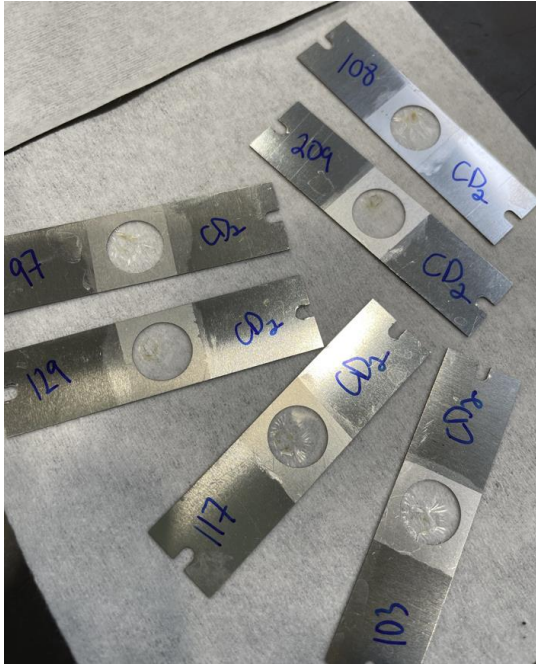


ELUM deuteron signal

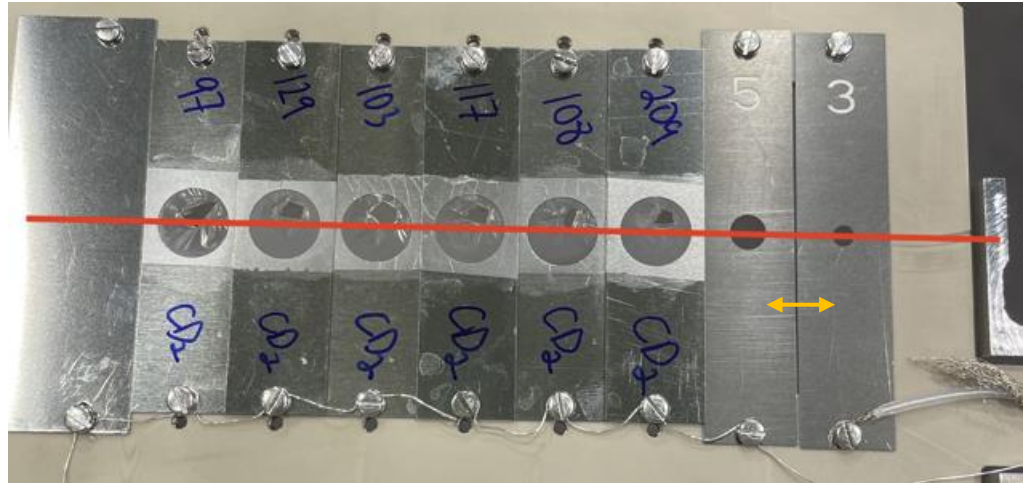
ELUM carbon signal



# Postmortem analysis



All 6 CD<sub>2</sub> targets with holes!



- Hole shapes are irregular
- Hole positions rather consistent; little beam drift
- Small gap between 3-mm/5-mm apertures  
→ To be considered in beam offset calculations
- Pure carbon target unavailable then

Cross section should be analyzed carefully with ELUM data

# Summary

- $d(^{110}\text{Sn}, p)^{111}\text{Sn}$  experiment with ISS successful, more beam time than asked
- Beam intensity too high for recoil detector and  $\text{CD}_2$  secondary target  
→ much more statistics, but dependence on reliable beam composition
- Refined calibrations, channel diagnostics to be carried out

<u>Name</u>	<u>Institution</u>
Sean Freeman	CERN
Daniel Clarke	University of Manchester
Sam Bennett	University of Manchester
Sam Reeve	University of Manchester
Joakim Cederkall	Lund university
Majid Chishti	Lund university
Claes Fahlander	Lund university
Jedrek Iwanicki	University of Warsaw
Chris Page	University of York
Maria Vittoria Managlia	Chalmers University of Technology
Anna Kawecka	Chalmers University of Technology
Ben Kim	Sungkyunkwan University
Andy Chae	Sungkyunkwan University
Minju Kim	Sungkyunkwan University
Suso Pereira Lopez	CENS, IBS
Sunji Kim	CENS, IBS
Jason Park	CENS, IBS
Ismael Martel	University of Huelva
Annie Dolan	University of Liverpool
Liam Gaffney	University of Liverpool
Joonas Ojala	University of Liverpool
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Experiment  
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Many thanks!