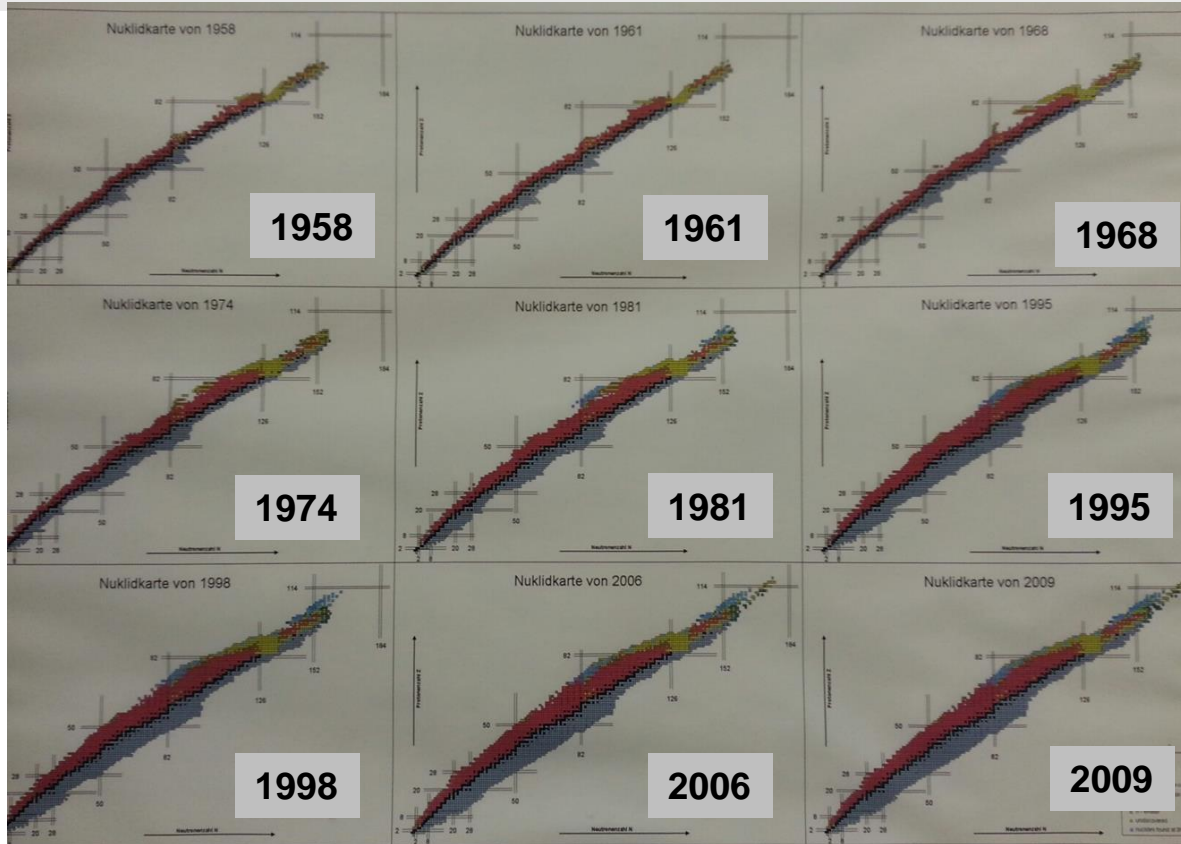


New isotopes search experiments at GSI and prospective for FAIR

Stephane Pietri, SFC

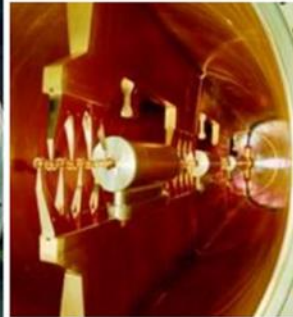
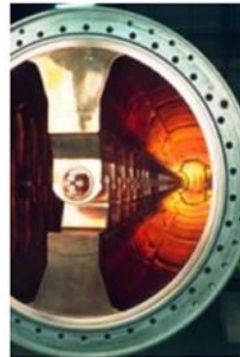
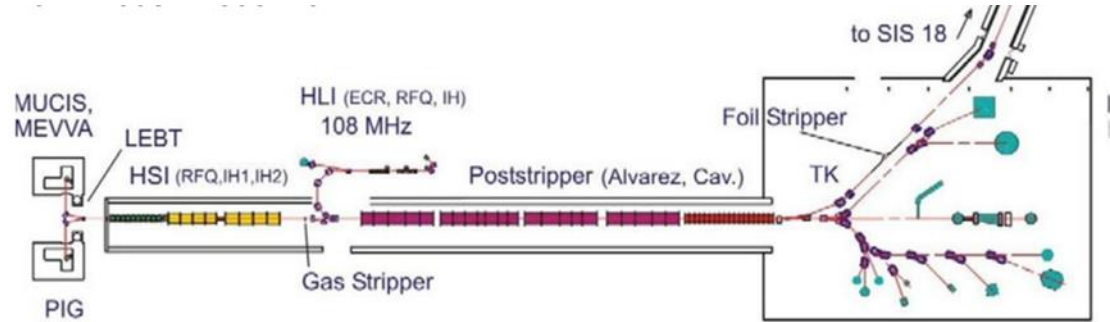
GSI Helmholtzzentrum für Schwerionenforschung

Nucleus production since the 50s

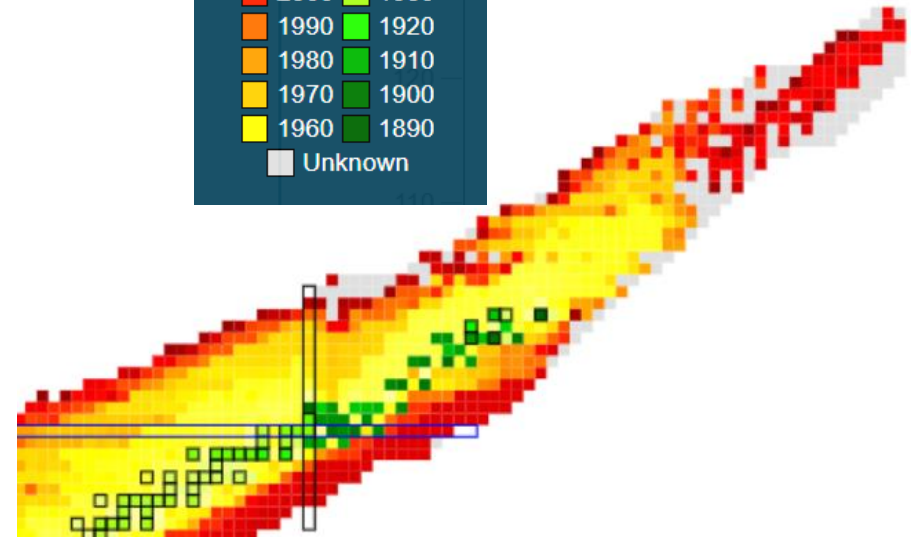
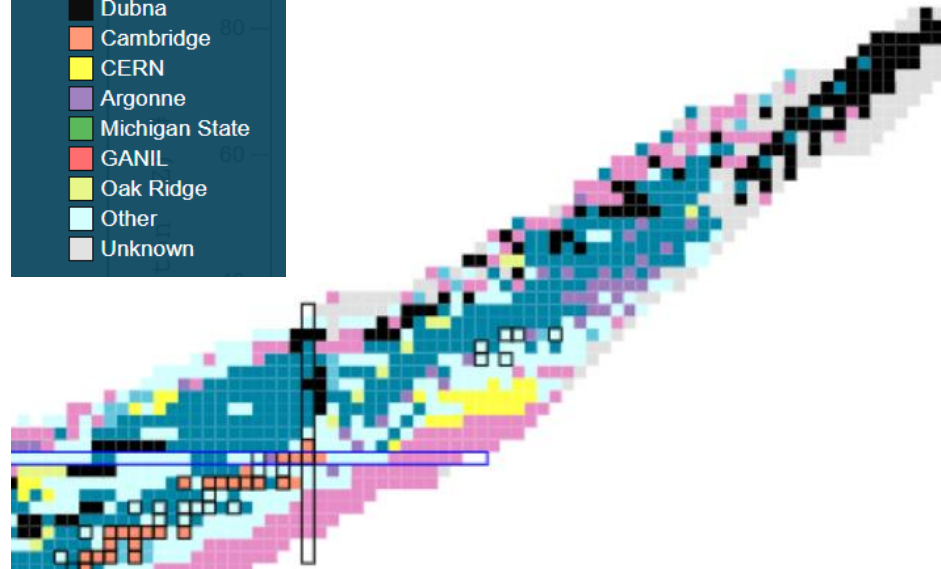
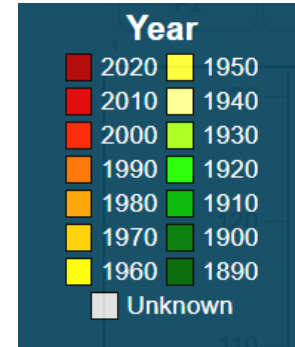
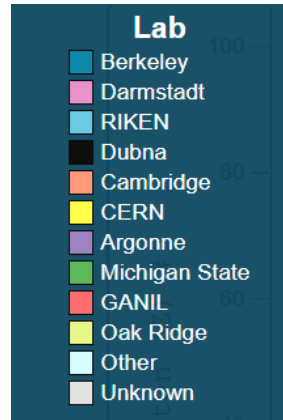


UNILAC – UNiversal Linear ACcelerator

- UNILAC, everything from p to U, up to coulomb barrier
- Equipment procured in from 1969, transformers in 1970
- First experiments 1975



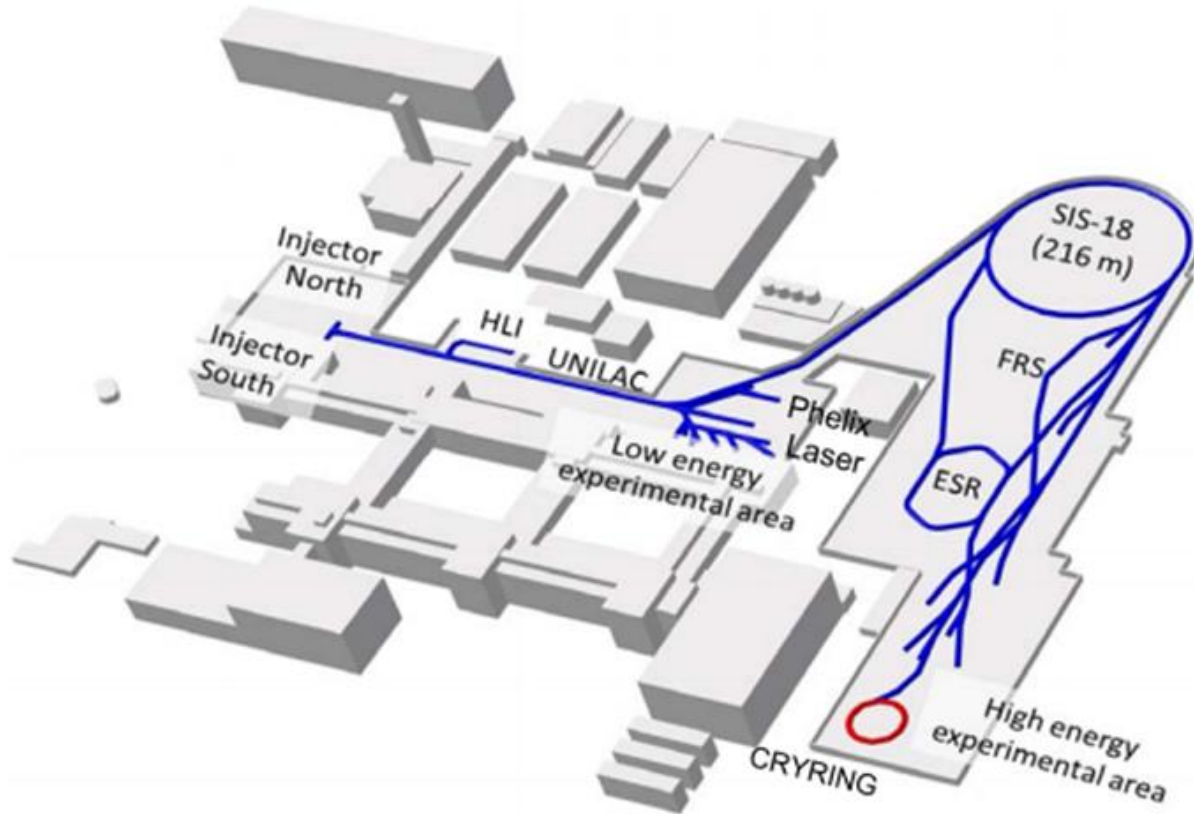
Ship + UNILAC – New elements and new isotopes



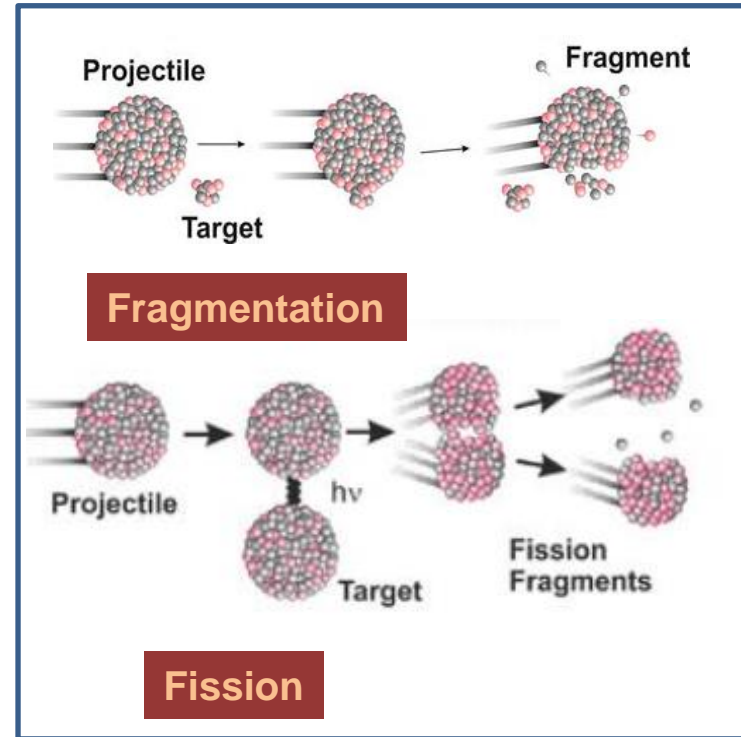
from <https://www.nndc.bnl.gov/nudat3/>

From 1990, new machine

- UNILAC as injector
- SIS18 → allows 18 Tm
- 18 Tm for ^{238}U
 - 200 MeV.U if U^{28+} good for intensity
 - 1000 MeV.U if U^{73+} higher energies

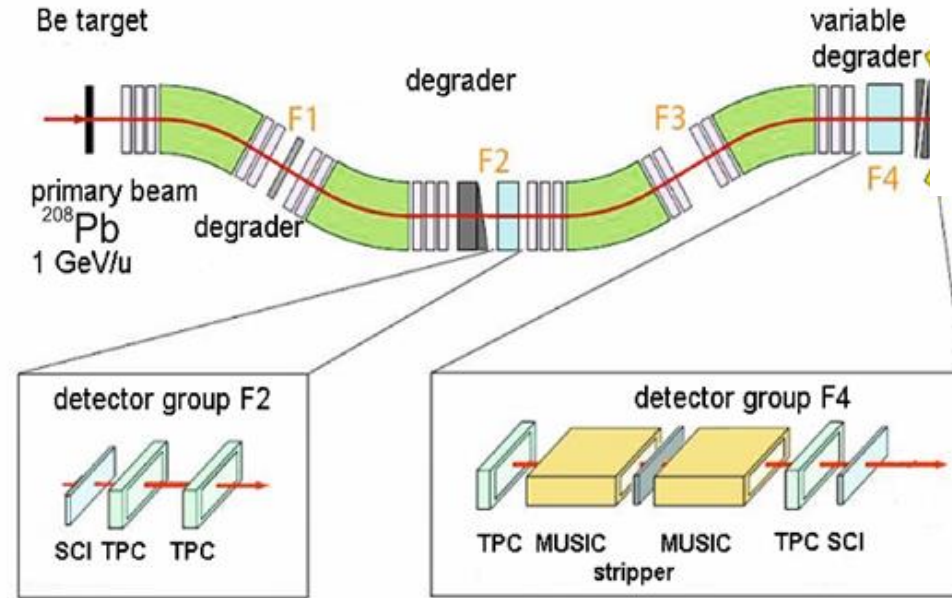


- Productions mechanisms used:
- Fragmentation
 - momentum spread of fragment increases with number of nucleus abraded
 - for production, target always Be (or C)
- Fission,
 - high angle and momentum due to repulsion. Effect notable at 1 GeV.U
 - Target either Pb for coulomb fission or Be for fragmentation fission
 - Mechanism always present, Pb fissions at high momentum



Separator : FRagment Separator (FRS)

- Separation: $B\rho$ - ΔE - $B\rho$
 - first selection : $B\rho \propto (A/Q) \cdot \beta\gamma$
 - degraders: $\Delta E : B\rho' = B\rho - f(Z^2)$.
 - second selection on $B\rho'$
- Identification: $B\rho$ - ΔE -TOF
 - $B\rho$ from magnet set rigidity, positions at focal planes and ion optic coefficients
 - $\beta\gamma$ from TOF
 - Q from ΔE in MUSIC (Ionisation chamber) with correction β





Nuclear Physics A

Volume 616, Issues 1–2, 14 April 1997, Pages 352–362



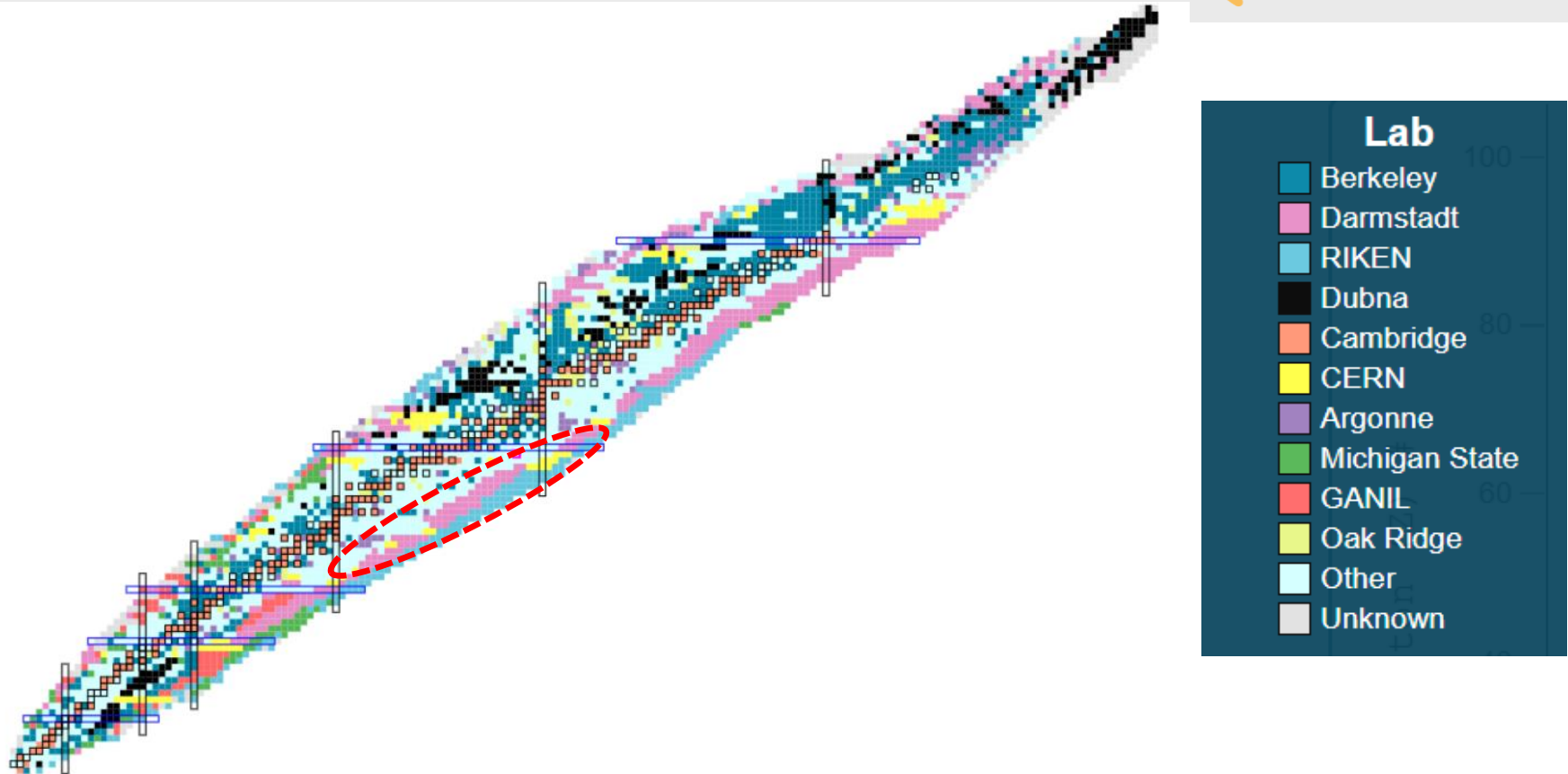
Identification of more than a 100 new isotopes from ^{238}U projectile fission and beams of neutron-rich nuclei at BRENDA

M. Bernas¹, P. Armbruster², S. Czajkowski², C. Donzaud¹, H. Geissel²,
F. Ameil², Ph. Dessagne³, C. Engelmann², A. Heinz⁵, Z. Janas⁴, C.
Kozuharov², Ch. Miede³, G. Münzenberg², M. Pfützner⁴,
C. Böcksteigel⁵, K.-H. Schmidt², W. Schwab², C. Stéphan¹, K.
Sümmerer², L. Tassan-Got¹...B. Voss⁵

Abstract

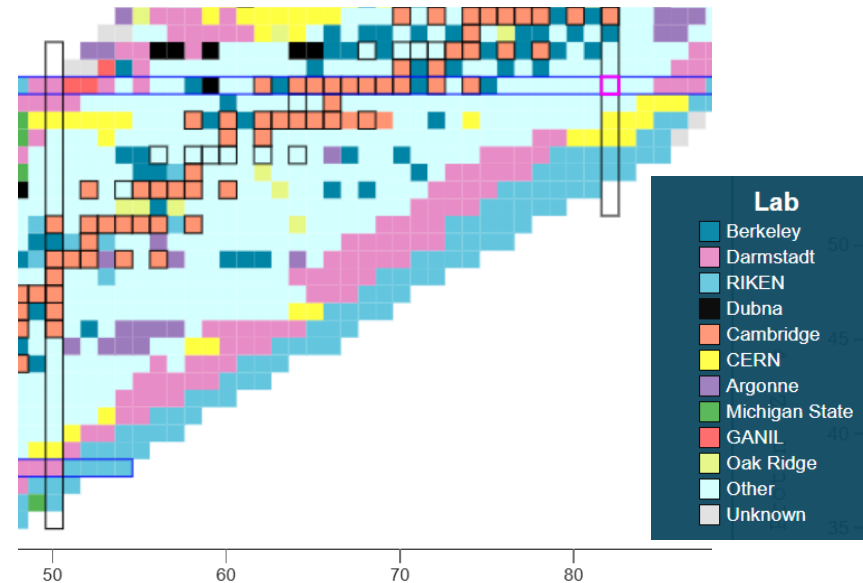
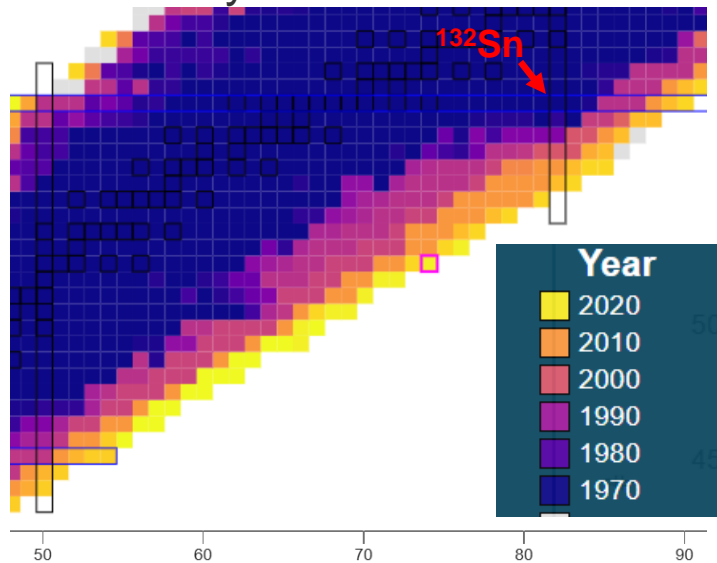
Projectile fission of ^{238}U was investigated at a bombarding energy of 750 A·MeV using Pb and Be targets. The fully stripped forward emitted fragments from Ti to Cs were analyzed with the Fragment Separator (FRS) and unambiguously identified by their energy-loss and time-of-flight. The magnetic selection of the largest momenta acted as a trigger of the low-energy fission component. More than a hundred new nuclear species were identified including the ^{78}Ni , for which a cross-section of 300 pb was measured.

Current isotope discoveries



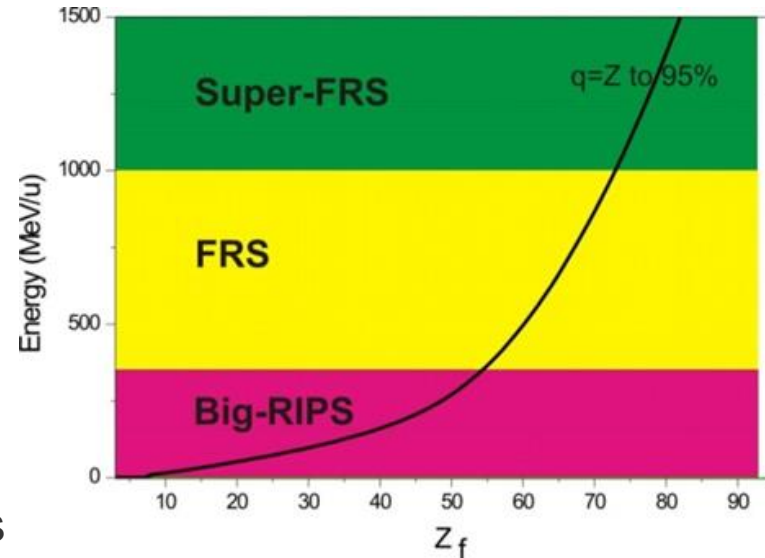
RIKEN Big-RIPS, very high intensities

- Big Rips is second generation in flight spectrometer, like Super-FRS, 2009
- Uses $B\rho - \Delta E - B\rho - \Delta E - B\rho$ method
- U intensity higher at Riken than GSI, hard to go much further with increase intensity



GSI uses higher energies

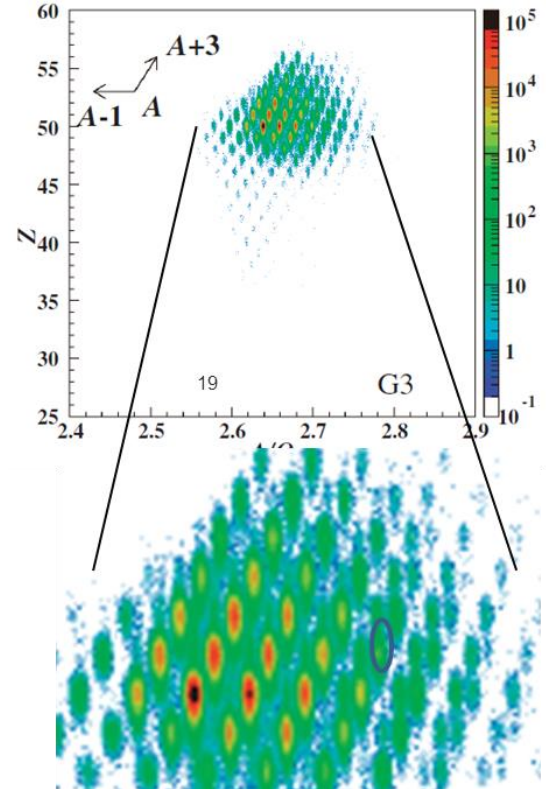
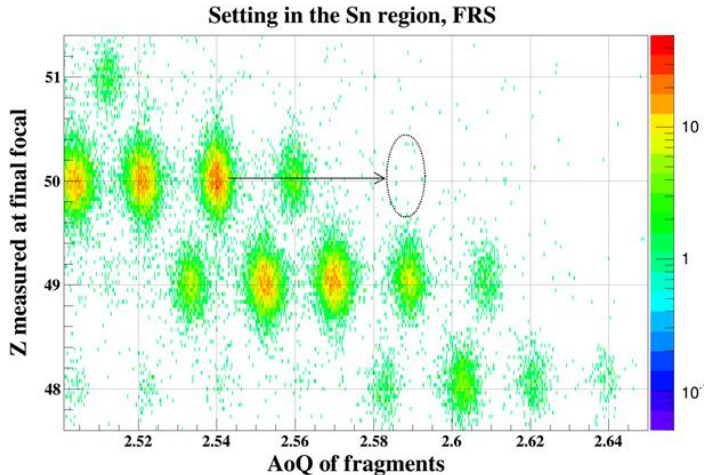
- Charge state issue for in flight fragmentation
- In flight fragmentation requires matter in spectrometer :
 - detectors for identification
 - degraders for separation
- Higher Z higher electron pick up
- Higher Z more energy loss
- Z identification, based on 2x Q measurements (10% charge state 1% miss identification)



- Nuclei in matter:
 - faster it goes more chance to loose electrons (>few 10 MeV.U)
 - more charged it is higher chance to capture electrons
- ➔ passing through matter creates an equilibrium of those two effects
 - @ 1500 MeV.U for Uranium in matter ➔ 73% $^{238}\text{U}^{92+}$, 25% $^{238}\text{U}^{91+}$, 2% $^{238}\text{U}^{90+}$... SIS100
 - @ 900 MeV.U, for Uranium in matter ➔ 46% $^{238}\text{U}^{92+}$, 43% $^{238}\text{U}^{91+}$, 9% $^{238}\text{U}^{90+}$...
 - @ 600 MeV.U, for Uranium in matter ➔ 21% $^{238}\text{U}^{92+}$, 49% $^{238}\text{U}^{91+}$, 28% $^{238}\text{U}^{90+}$...
 - @ 300 MeV.U, for Uranium in matter ➔ 10% $^{238}\text{U}^{92+}$, 17% $^{238}\text{U}^{91+}$, 70% $^{238}\text{U}^{90+}$...
 - @ 150 MeV.U, for Uranium in matter ➔ 0% $^{238}\text{U}^{92+}$, 10% $^{238}\text{U}^{91+}$, 73% $^{238}\text{U}^{90+}$...
- ➔ for ^{212}Pb after target
 - @ 900 MeV.U for Pb in matter ➔ 71% $^{212}\text{Pb}^{82+}$, 25% $^{212}\text{Pb}^{81+}$, 2% $^{212}\text{Pb}^{80+}$...
 - @ 600 MeV.U for Pb in matter ➔ 49% $^{212}\text{Pb}^{82+}$, 42% $^{212}\text{Pb}^{81+}$, 8% $^{212}\text{Pb}^{80+}$...

Example comparison 2014, U primary beam

- Charge state reach next focal plane with $A/Q = A/(Z-1)$
- Could strip again in the detectors
 - Big RIBS (345 MeV.U on Be setting Sn) J. Phys. Soc. Jpn., Vol. 79, No. 7 T. Ohnishi et al.
 - FRS (750 MeV.U on Be, Sn setting), S411 October 2014



2009 – same machine, but higher duty cycle

- In preparation of FAIR duty cycle of SIS18 increased by more than 1 order of magnitude (faster ramping magnets) → decide to do again U+Be experiment

Physics Letters B

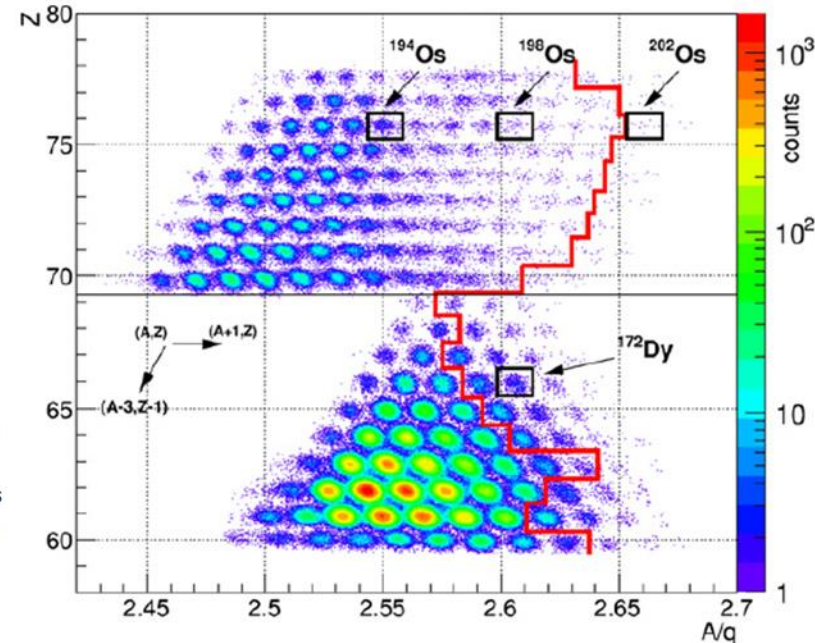
Volume 717, Issues 4–5, 31 October 2012, Pages 371-375

Discovery and cross-section measurement of neutron-rich isotopes in the element range from neodymium to platinum with the FRS

J. Kurcewicz^a, F. Farinon^{a,b,1}, H. Geissel^{a,b}, S. Pietri^a, C. Nociforo^a, A. Prochazka^{a,b}, H. Weick^a, J.S. Winfield^a, A. Estradé^{a,c}, P.R.P. Allegro^d, A. Bail^e, G. Bélier^e, J. Benlliure^f, G. Benzoni^g, M. Bunce^h, M. Bowry^h, R. Caballero-Folchⁱ, I. Dillmann^{a,b}, A. Evdokimov^{a,b}, J. Gerl^a, Ph. Woods^f

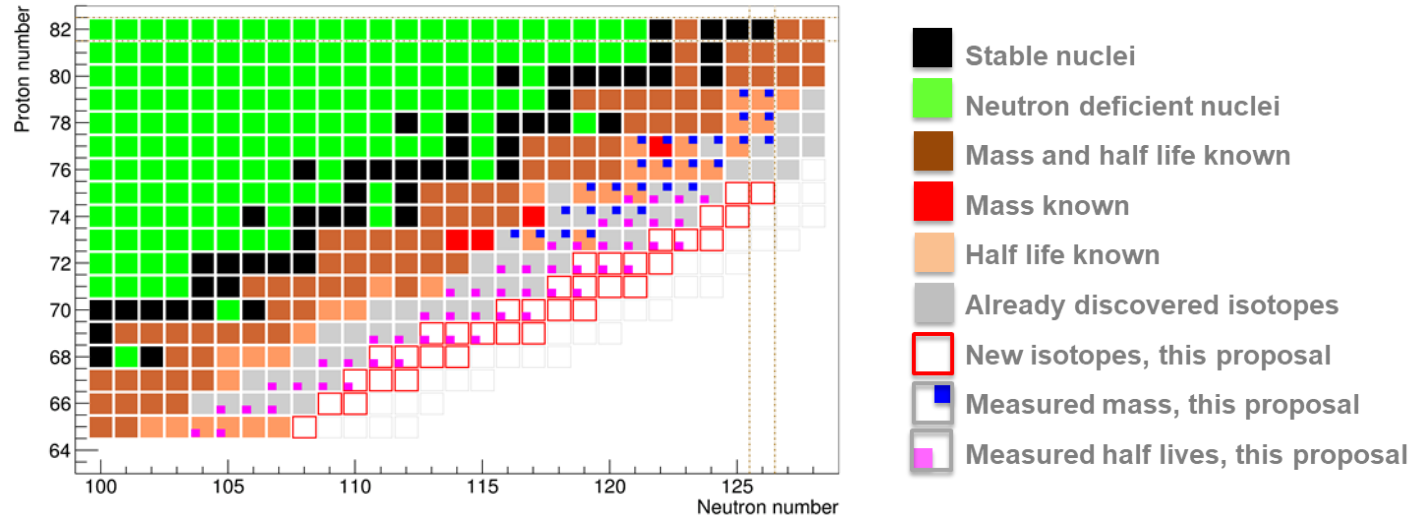
Abstract

Using the high-resolution performance of the fragment separator FRS at GSI we have discovered 60 new neutron-rich isotopes in the atomic number range of $60 \leq Z \leq 78$. The new isotopes were unambiguously identified in reactions with a ^{238}U beam impinging on a Be target at 1 GeV/nucleon. The production cross-section for the new isotopes have been measured down to the pico-barn level and compared with predictions of different model calculations. For elements above hafnium fragmentation is the dominant reaction mechanism which creates the new isotopes, whereas fission plays a dominant role for the production of the new isotopes up to thulium.



2017 – submit new proposal for news isotopes

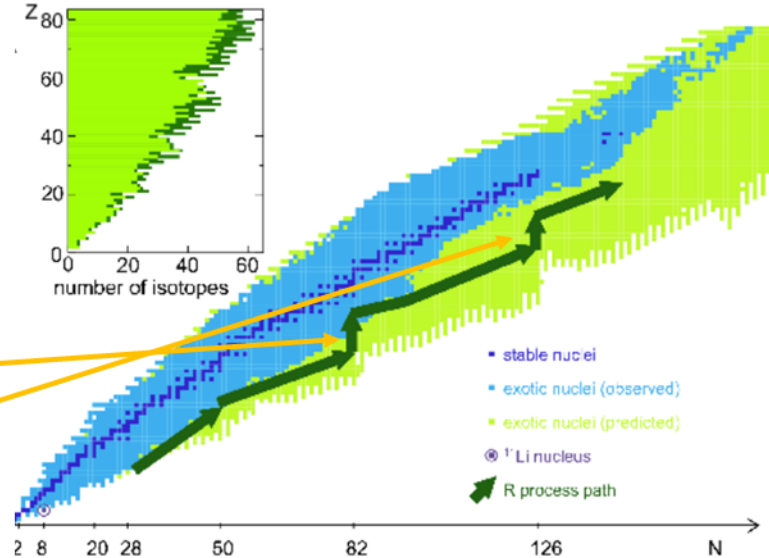
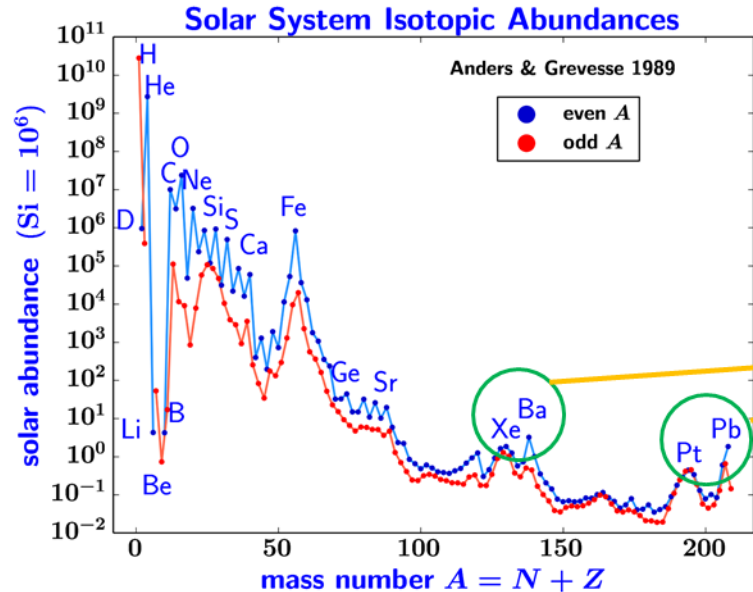
- Production around Os difficult with U, better with Pb
- Last experiment with upgraded SIS18 were decay experiments with long extraction (10 s)
- New isotope search, combined with masses and beta-life times



Interest in the region

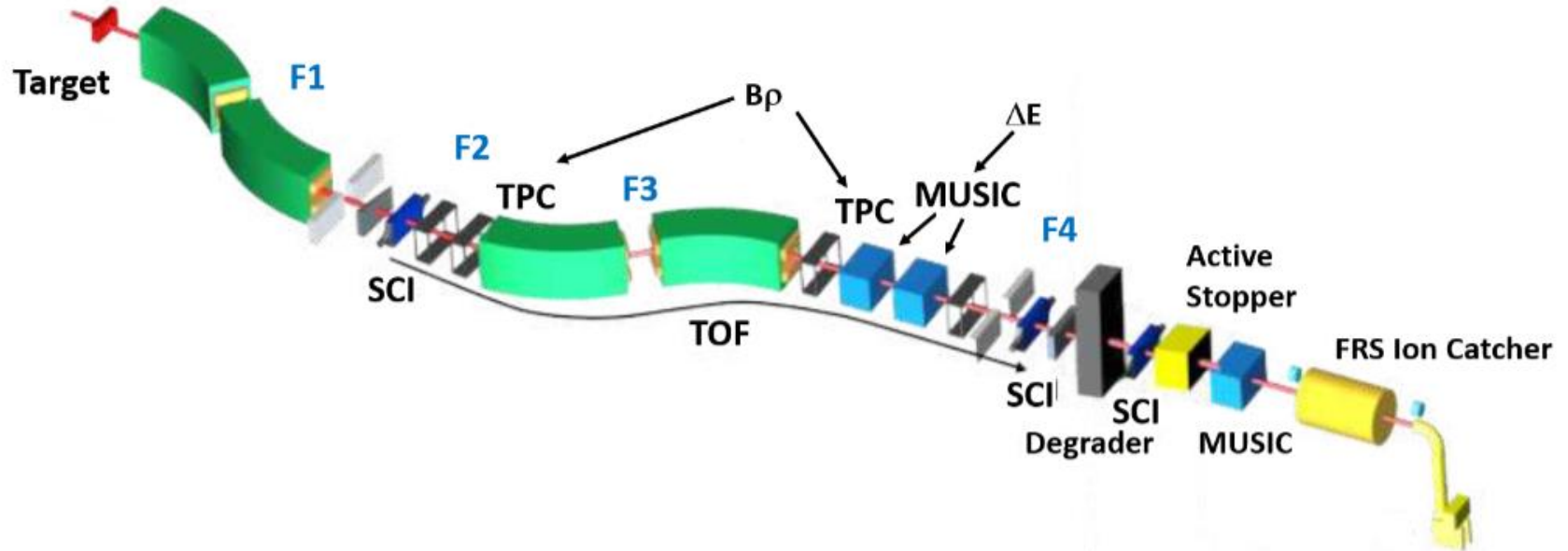
- β life times, masses and existence → linked to R process studies

Evolution of shell structure in exotic nuclei - Otsuka, Takaharu *et al.* Rev.Mod.Phys. 92 (2020) no.1, 015002 arXiv:1805.06501 [nucl-th]



The nuclear chart as a function of neutron number, N and Z . Each nucleus is specified by Z and N . Blue squares: Exotic nuclei experimentally observed. Light brown squares, v squares denote those predicted by ν [cite{koura2005}](#). The ^{11}Li nucleus is \odot . A possible path of the r process is indicated by the green arrows. Inset: Number of isotopes as a function of Z based on [cite{koura2005}](#). The light and dark green colors represent observed and predicted isotopes respectively. Adapted from [cite{otsuka_nobel,otsuka_nuprec}](#)

FRS in configuration for S468 experiment



First setting calibration

- ^{208}Pb , for detector calibration
- ^{205}Au , for mass measurement and mass tagging
- Ancillary: ion catcher



First setting calibration

- ^{208}Pb , for detector calibration
- ^{205}Au , for mass measurement and mass tagging
- Ancillary: ion catcher

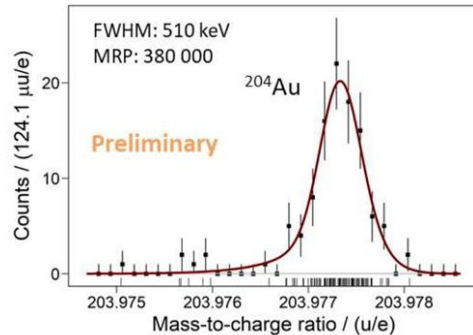
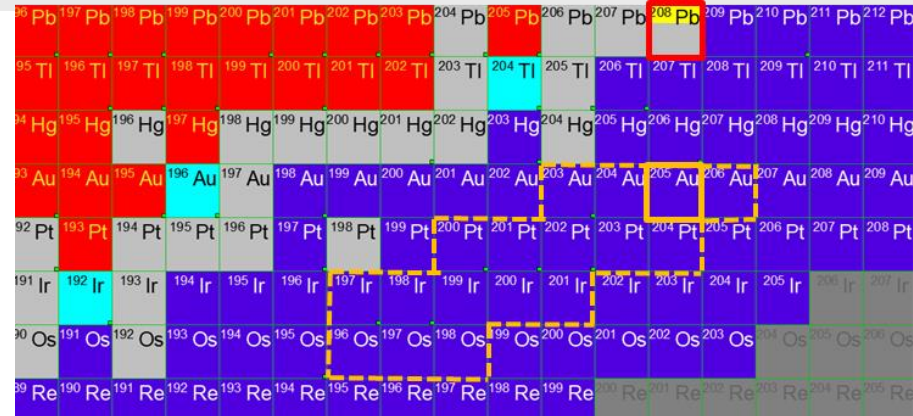
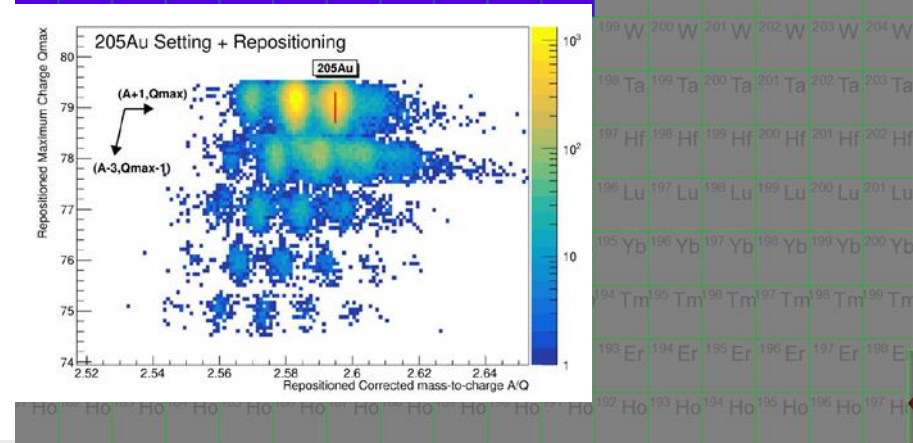
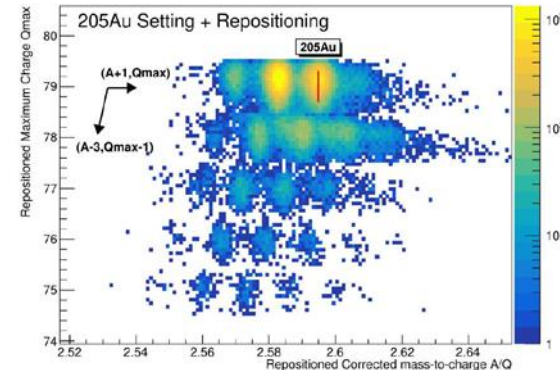


Abbildung 13.16.: Mass measurement inside the Ion Catcher's MR-TOF-MS, taken from [29, 112], which shows the mass-to-charge ratio on the x-axis and the counts on the y-axis. The ^{204}Au isotope could be clearly identified by closing the S4 slits to -8 mm and 12 mm.



First setting calibration

- ^{208}Pb , for detector calibration
- ^{205}Au , for mass measurement and mass tagging
- Ancillary: ion catcher
- **Problem unseen: when increasing intensity slits were not closed**

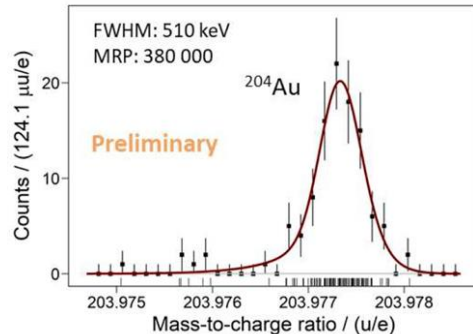
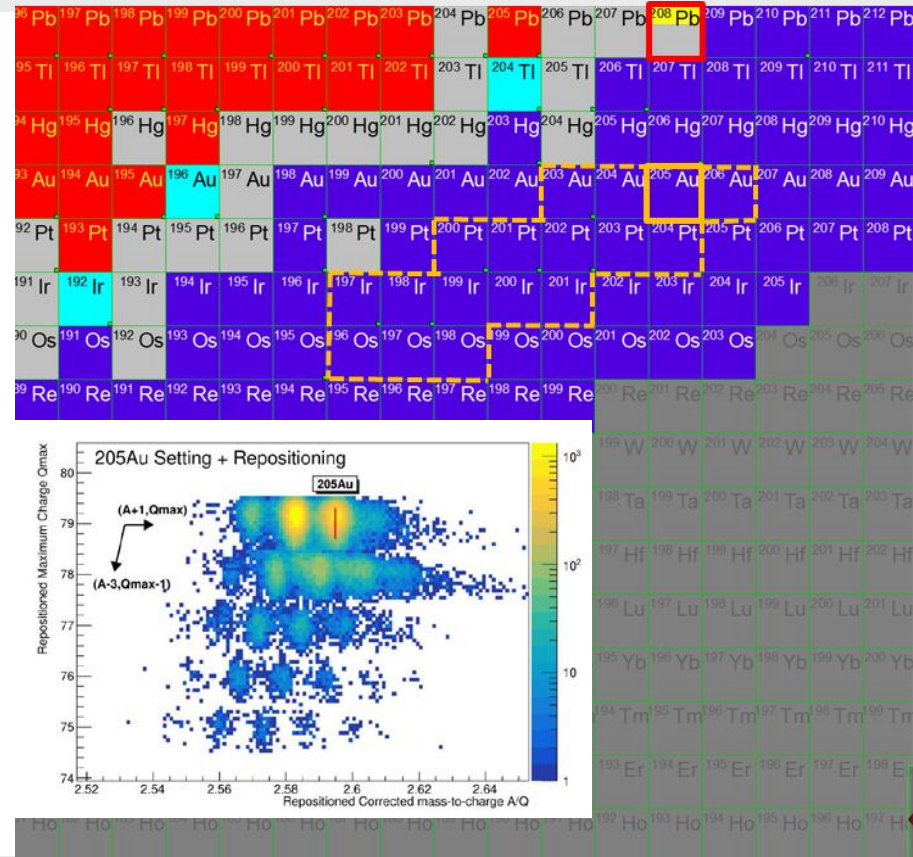
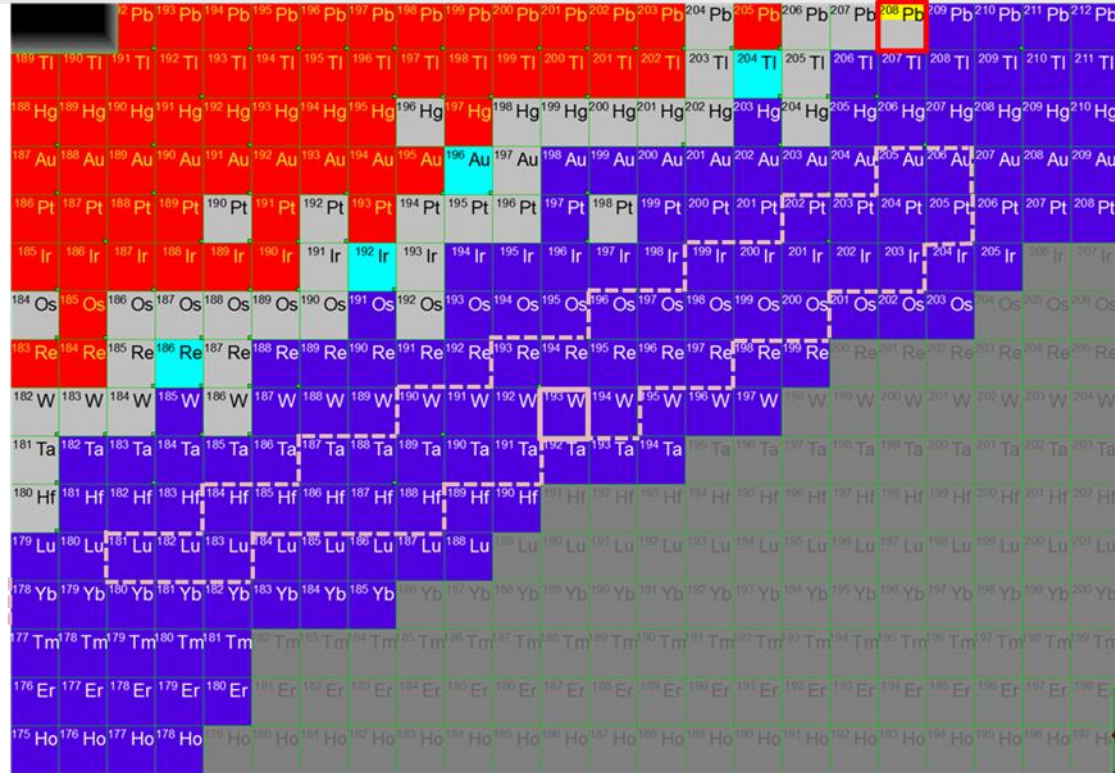
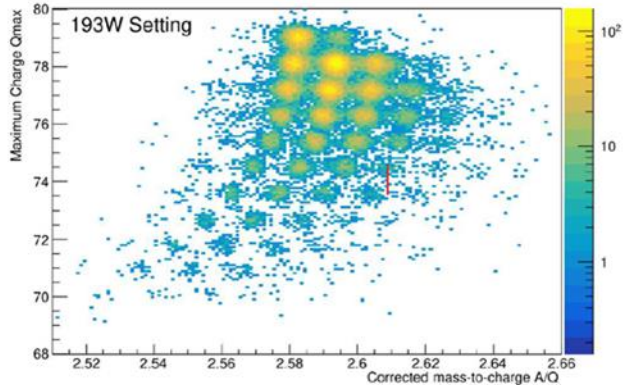


Abbildung 13.16.: Mass measurement inside the Ion Catcher's MR-TOF-MS, taken from [29, 112], which shows the mass-to-charge ratio on the x-axis and the counts on the y-axis. The ^{204}Au isotope could be clearly identified by closing the S4 slits to 8 mm and 12 mm.

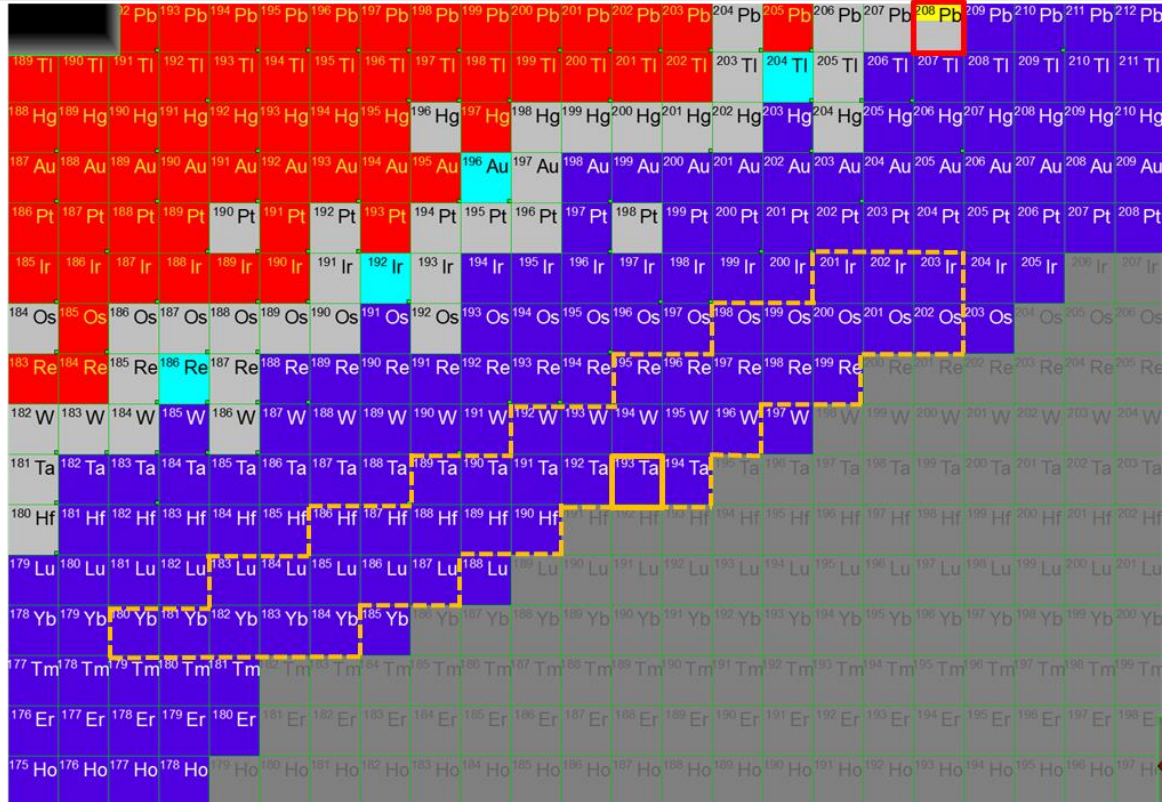
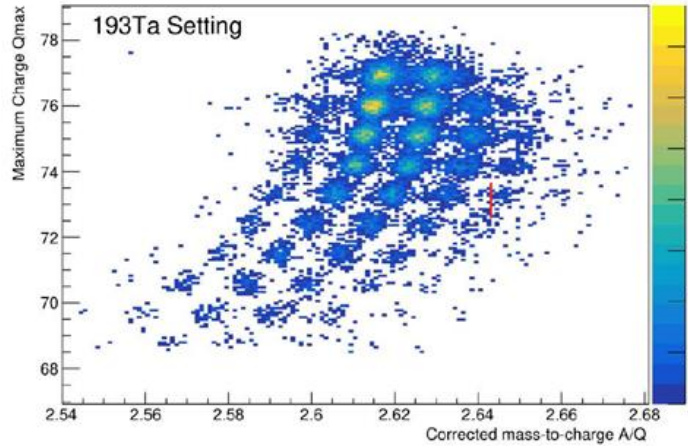


^{190}W setting

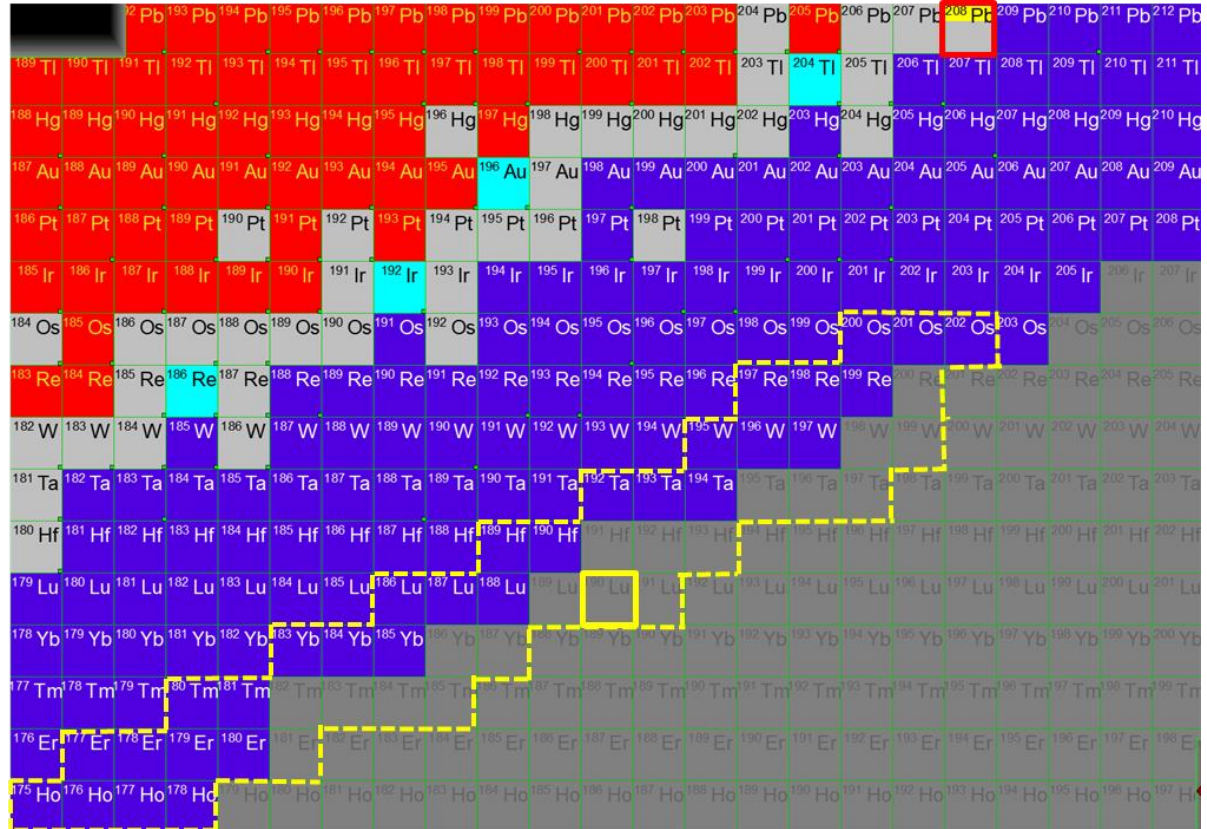
- First main fragment setting
- Goal mass measurement



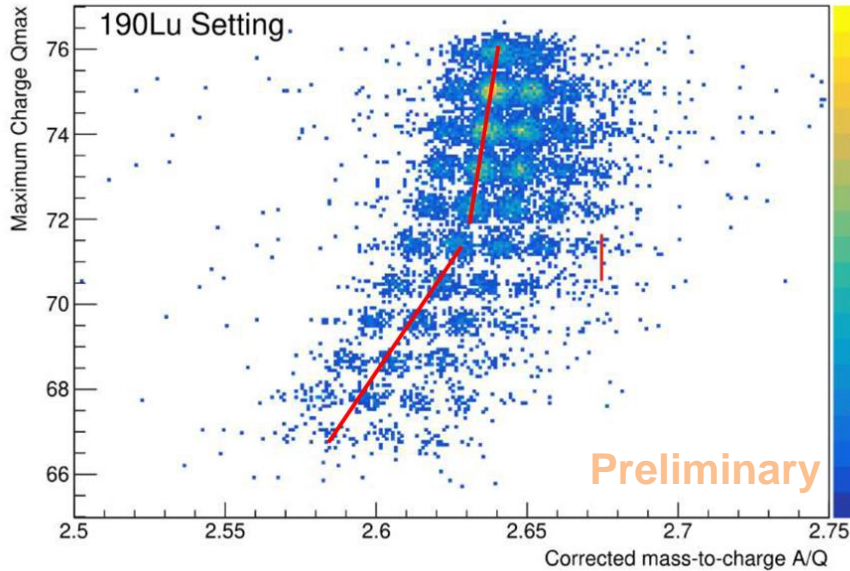
^{193}Ta , for beta lifetime



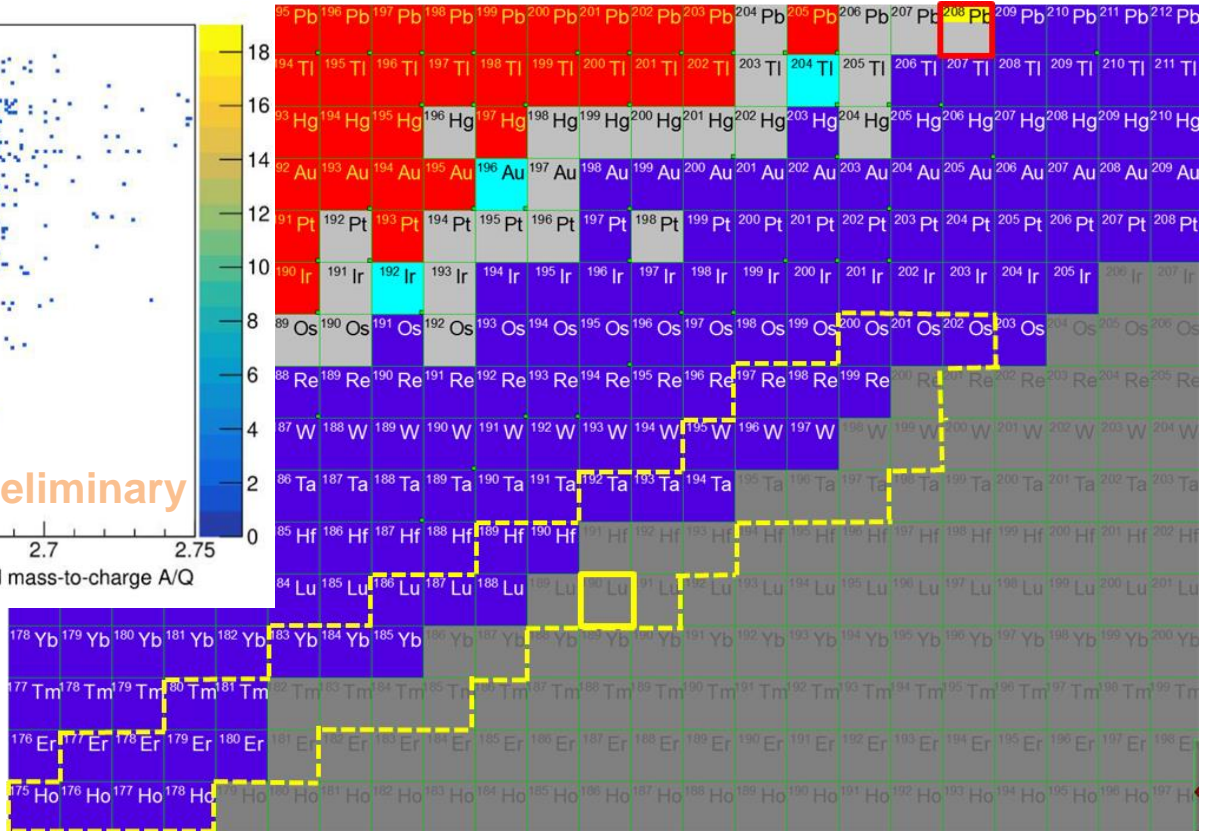
Main new isotope search setting: ^{190}Lu



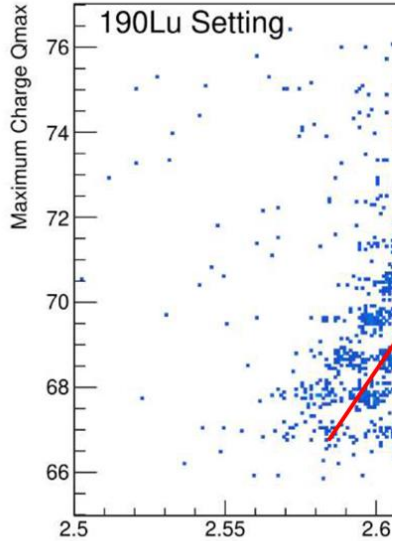
Main new isotope search setting: ^{190}Lu



slope change and counts drop after center

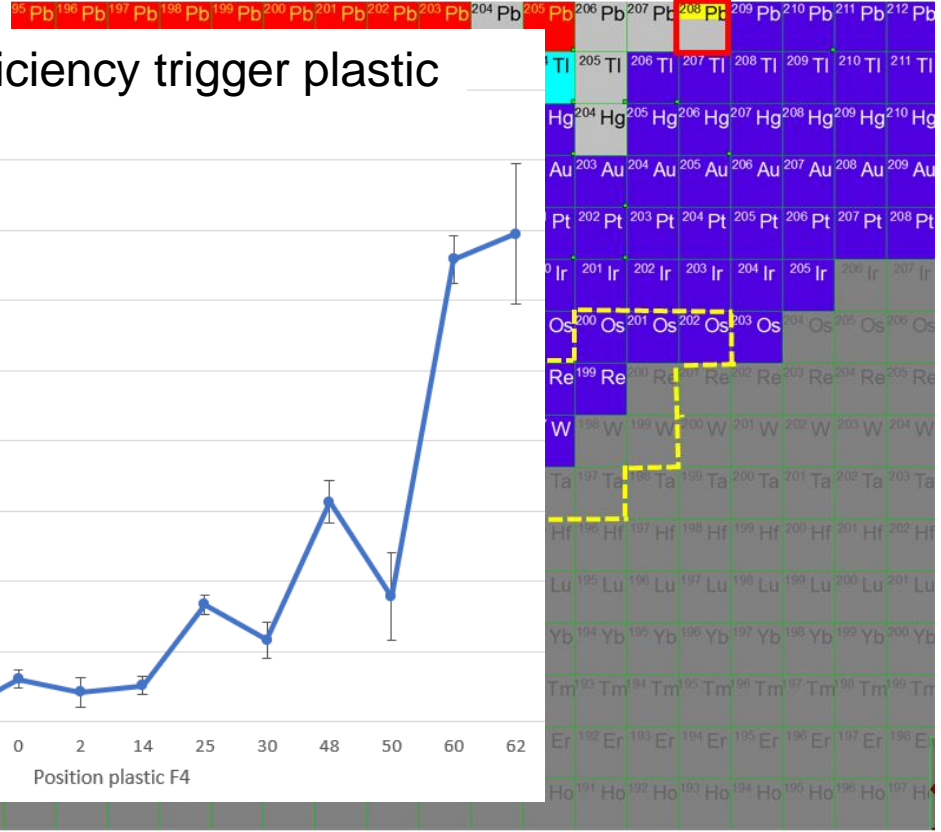
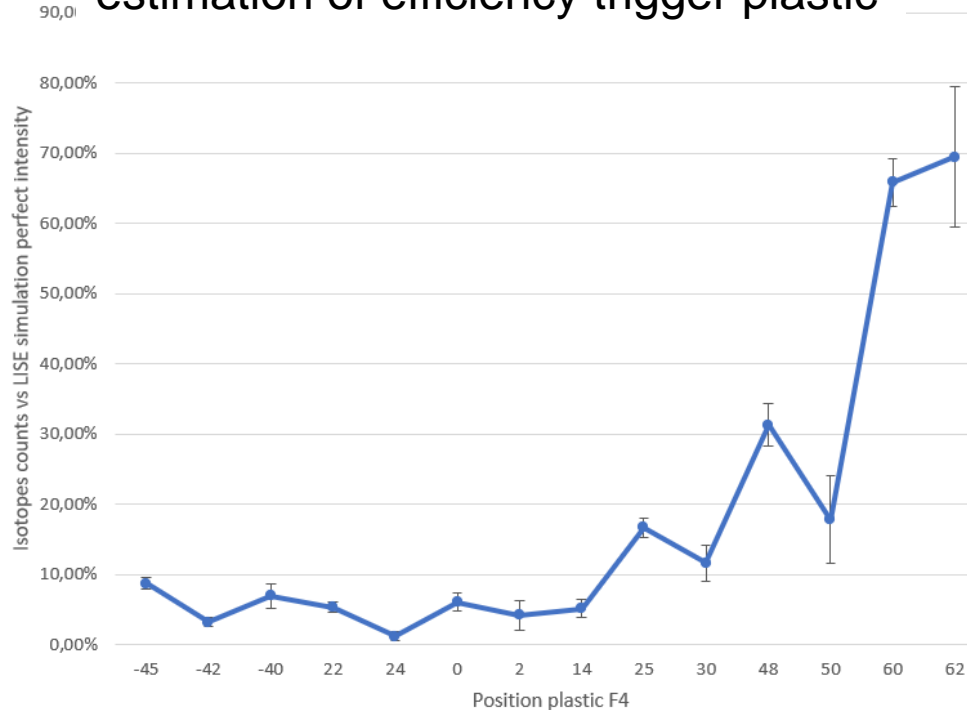


Main new isotope search setting: ^{190}Lu



slope change and drop after center

estimation of efficiency trigger plastic

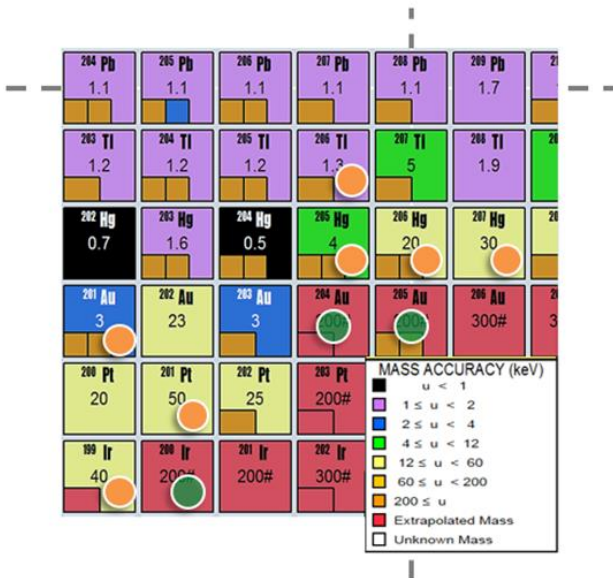
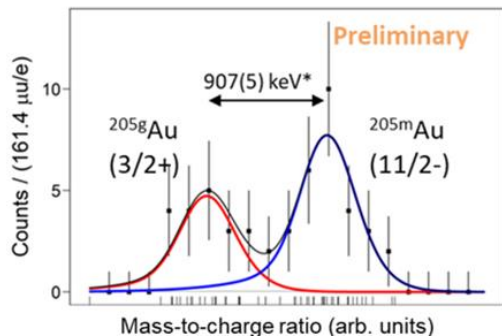
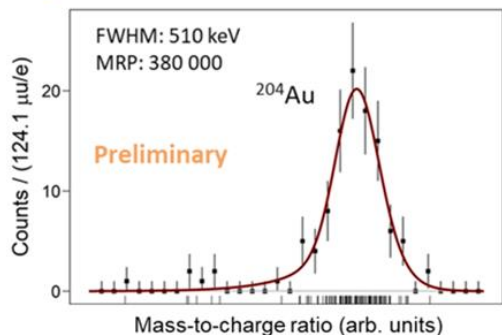


Mass measurement results

Preliminary results:

→ 11 direct mass measurements, including:

- 3 for the first time: ^{204}Au , ^{205}Au , ^{200}Ir
- 7 first direct mass measurements



Large-scale mapping of mass surface in the region is of high importance.

D Amanbayev, K. Mahajan, W. Plass, et al., in preparation

- Despite Covid and burnt plastic(s) we claim 5 new isotopes discovered (submitted to Phys. Lett. B) ^{184}Tm , ^{195}Ta , ^{198}W , ^{200}Re , and ^{201}Re
- Experiment April 2020, submission April 2026 (second analysis needed)

- Despite Covid and burnt plastic(s) we claim 5 new isotopes discovered (submitted to Phys. Lett. B) ^{184}Tm , ^{195}Ta , ^{198}W , ^{200}Re , and ^{201}Re
- Experiment April 2020, submission April 2026 (second analysis needed)
- in the mean time publication from FRIB

	^{182}Tm counts	^{183}Tm counts	^{186}Yb counts	^{187}Yb counts	^{190}Lu counts
2024 discovery	29	7	27	3	5
confirmed in S468	30	5	13	1	6

Table 6.1: Comparison of the counts of the isotopes during in the first discovery in 2024 [71] and the S468 experiment.

H. Roesch PhD

[71] O. B. Tarasov et al. “Observation of New Isotopes in the Fragmentation of ^{198}Pt at FRIB”. In: *Physical Review Letters* 132.7 (2024), p. 072501. DOI: 10.1103/PhysRevLett.132.072501.

- Despite Covid and burnt plastic(s) we claim 5 new isotopes discovered (submitted to Phys. Lett. B) ^{184}Tm , ^{195}Ta , ^{198}W , ^{200}Re , and ^{201}Re
- Experiment April 2020, submission April 2026 (second analysis needed)
- in the mean time publication from FRIB

	^{182}Tm counts	^{183}Tm counts	^{186}Yb counts	^{187}Yb counts	^{190}Lu counts
2024 discovery	29	7	27	3	5
confirmed in S468	30	5	13	1	6

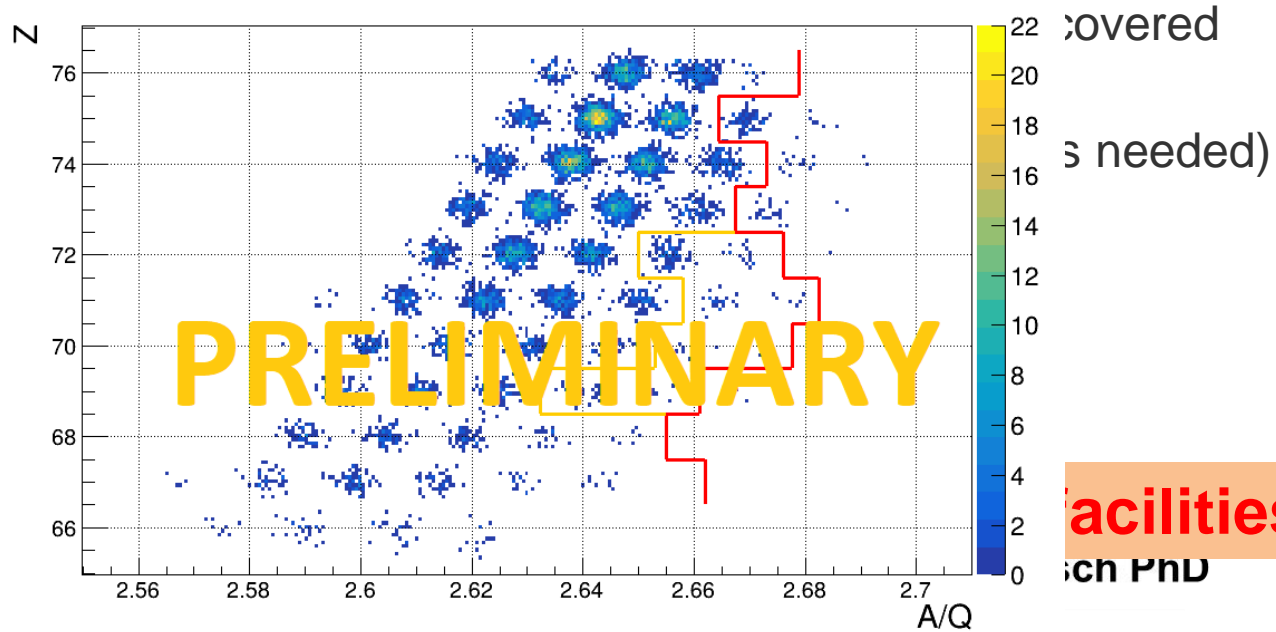
FRS still competing with last generation facilities!

H. Roesch PhD

[71] O. B. Tarasov et al. "Observation of New Isotopes in the Fragmentation of ^{198}Pt at FRIB". In: *Physical Review Letters* 132.7 (2024), p. 072501. DOI: 10.1103/PhysRevLett.132.072501.

Results S468 new isotopes

- Despite Coverage (submitted)
- Experiment
- in the near



FRS s

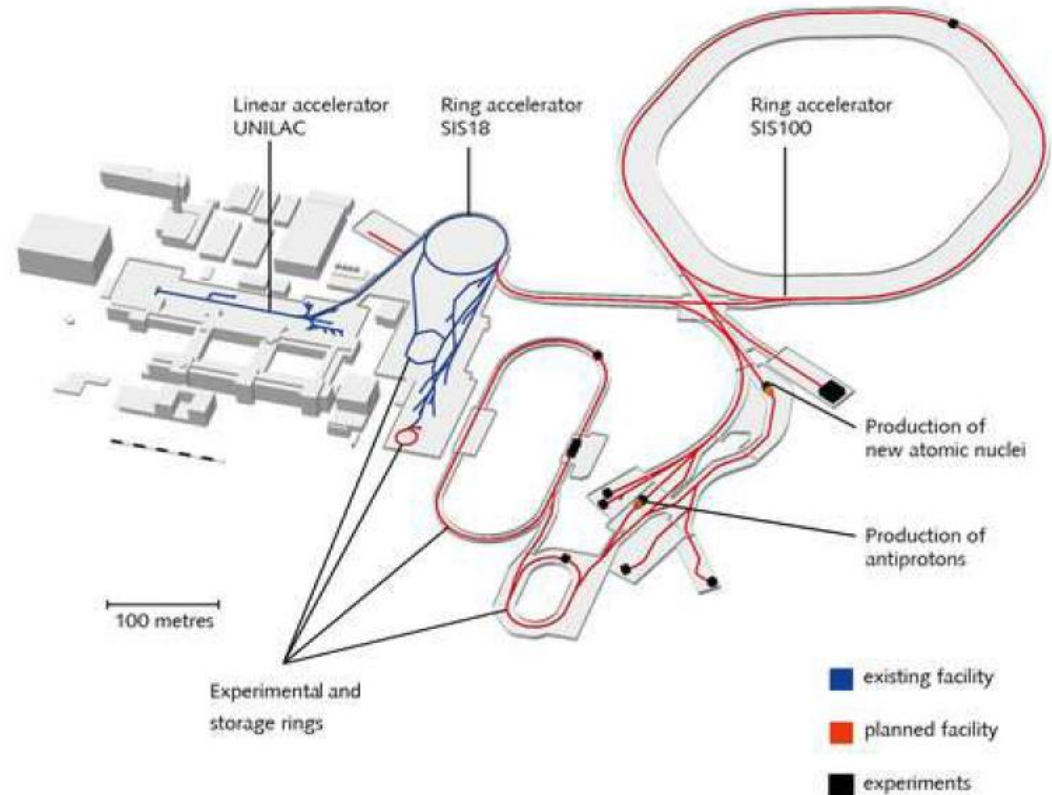
Facilities!
ich PhD

[71] O. B. Tarasov et al. “Observation of New Isotopes in the Fragmentation of 198Pt at FRIB”. In: *Physical Review Letters* 132.7 (2024), p. 072501. DOI: 10.1103/PhysRevLett.132.072501.

New facility being installed

- New ring : SIS100
 - 100 Tm, \rightarrow 2.5 GeV.U $^{238}\text{U}^{28+}$
 - $5 \cdot 10^{11}$ U per spill
- New separator

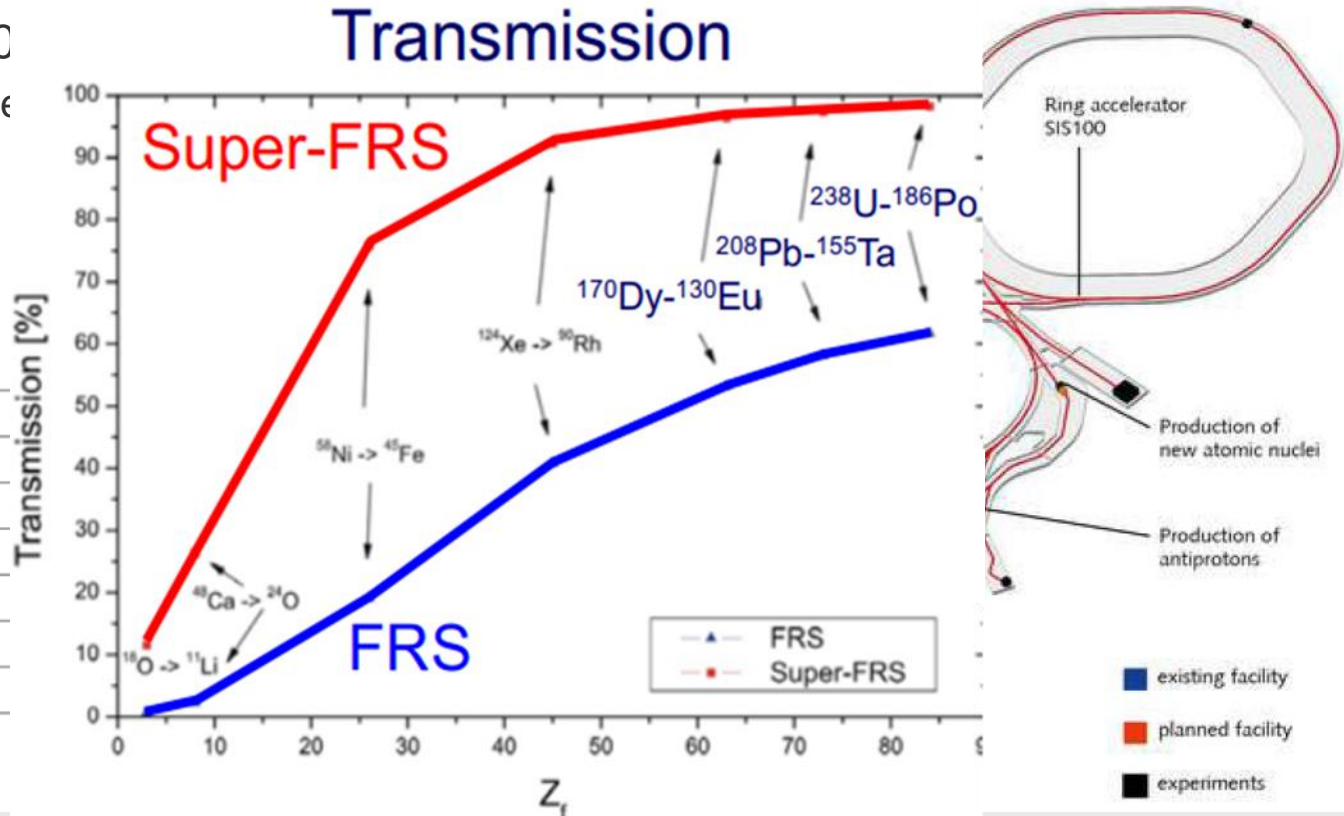
	FRS	SFRS
stage	2	3
Br Tm	18	20
dp/p	1%	2.5%
x ang mrad	7.5	40
y ang mrad	7.5	20
resolving P	1500	1500



New facility being installed

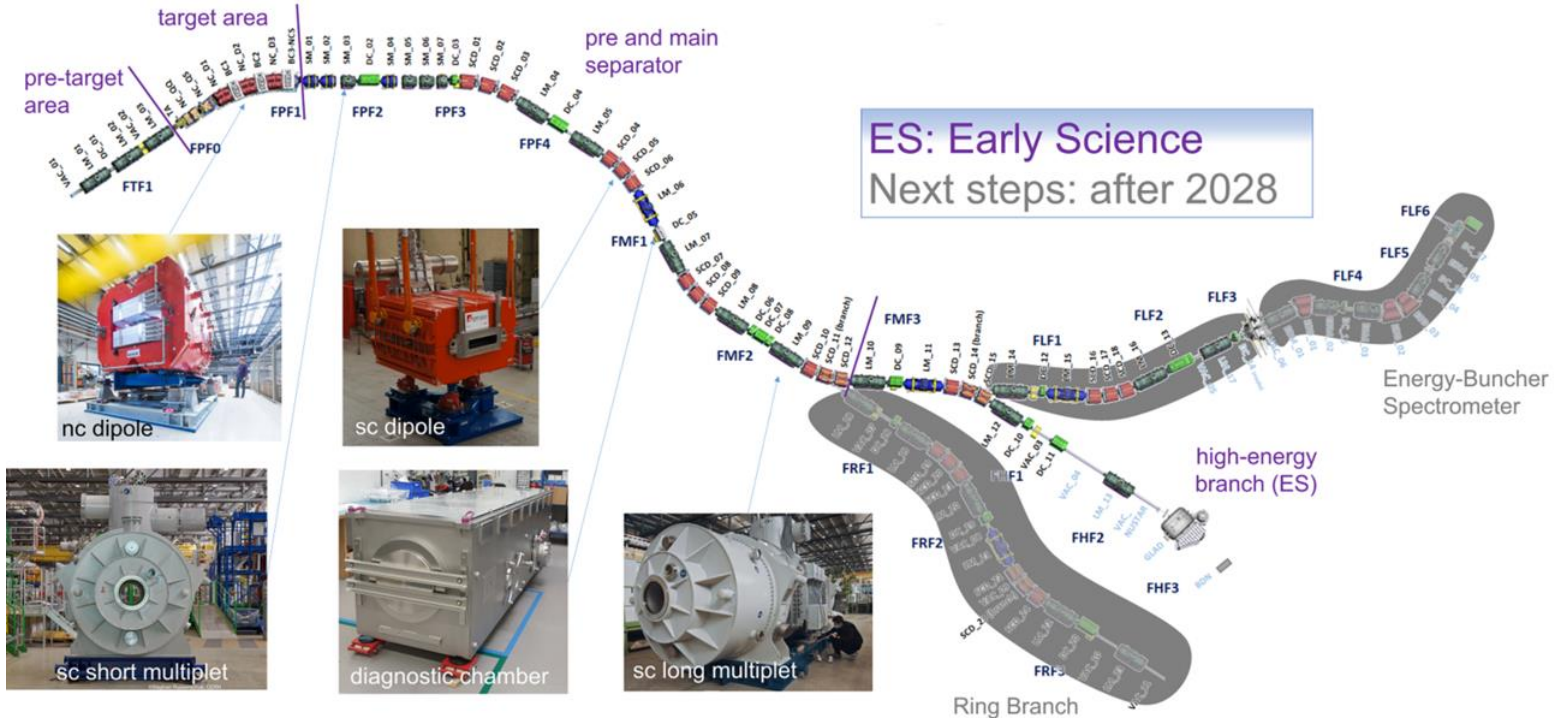
- New ring : SIS100
 - 100 Tm, → 2.5 GeV
 - $5 \cdot 10^{11}$ U per spill
- New separator

	FRS	SFRS
stage	2	3
Br Tm	18	20
dp/p	1%	2.5%
x ang mrad	7.5	40
y ang mrad	7.5	20
resolving P	1500	1500



Machine Super-FRS for ES and commissioning

- Super-FRS $B\rho - \Delta E - B\rho - \Delta E - B\rho$ spectrometer with higher acceptance



Super-FRS – general overview, changing ^{238}U to ^{212}Pb

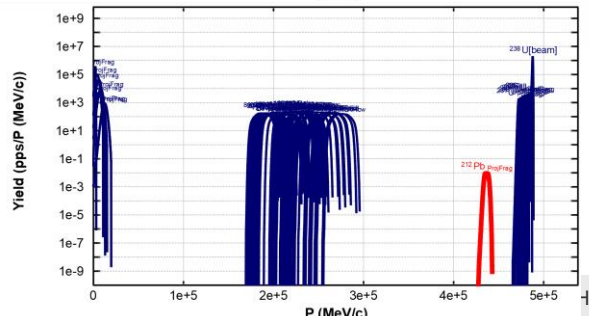
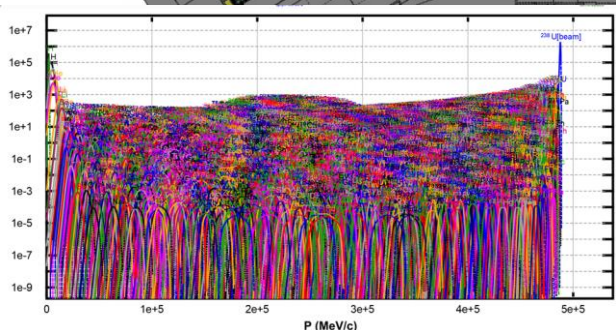
Pre-target
Focusing system

Pre-separator

Target area

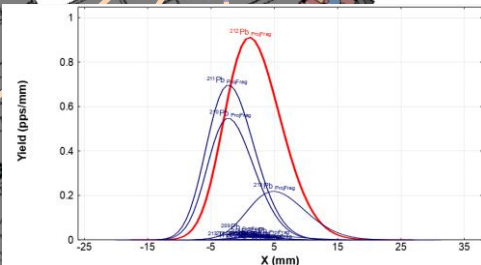
Supply building,
lab, control room

Low Energy Branch
not ES



Main separator

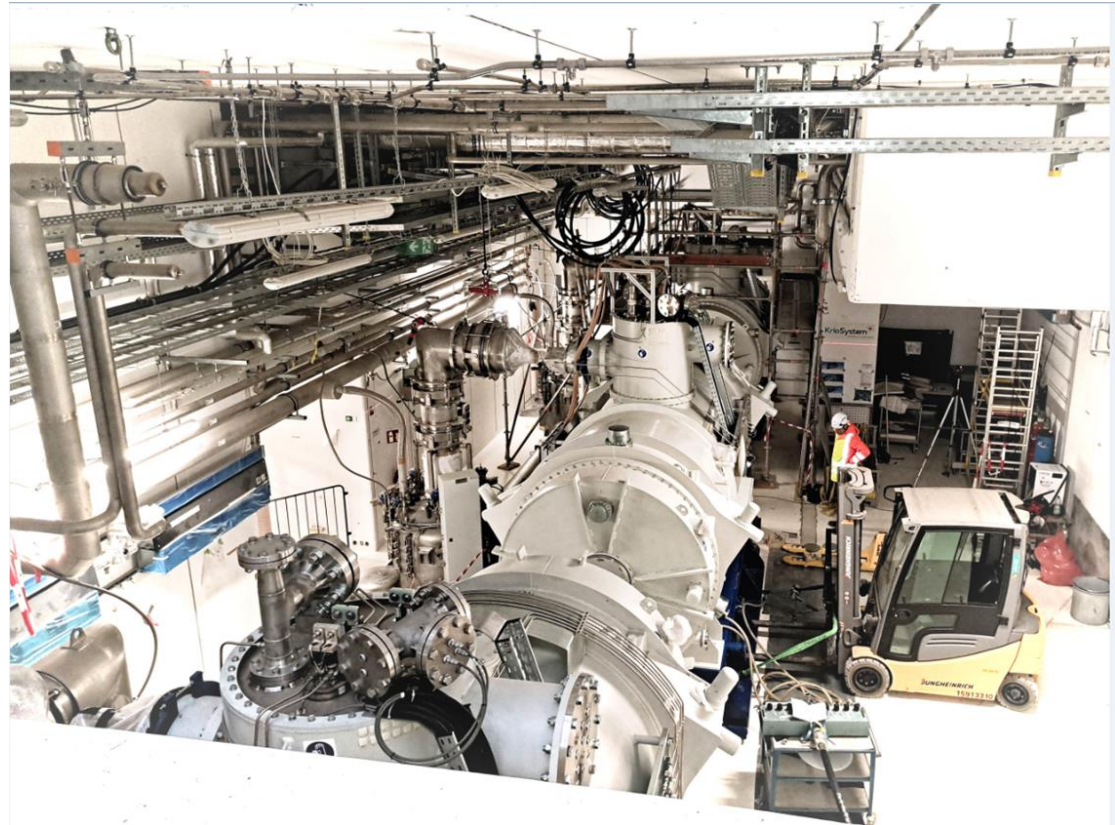
Ring branch,
not ES



FHF2, HEB cave,
R3B NUSTAR

Status Super-FRS

- Installation ongoing
- Aim beam commissioning end 2027
- First physics runs 2028



Latest development

- 5th February 2026, fire
- An old 1970 transformer burnt when switched on for pre-testing
- Fire on the supply gallery, accelerator intact
- Transformer was planned to be replaced in two years as judged being critical
- New instrumentation being developed
- Staged reparation/replacement is discussed with ministry, JSC, MAC and internal Task Force.
- Start FAIR beam commissioning in 2027, first physics runs 2028 with high intensity, high Z high intensity in the following year(s)



- Calculations from ideas of experiments

Transmission	^{191}Lu	^{192}Lu	^{193}Lu	^{194}Lu	^{195}Lu	^{196}Lu	^{197}Lu
FRS	17%	20%	18%	17%	13%	10%	5%
S-FRS	23%	35%	41%	41%	40%	30%	22%

Table 1: transmission along an isotopic chain, comparing FRS to Super-FRS with the same amount of matter present in degraders and standard FRS detector suit or Early Science detectors for Super-FRS.

- Objective: U fragmentation, higher Z (need the high energy of SIS100)
- Third objective: proton rich U fragments, use higher separation of Super-FRS

Production of New Isotopes Near the Heavy-element Nucleosynthesis Path

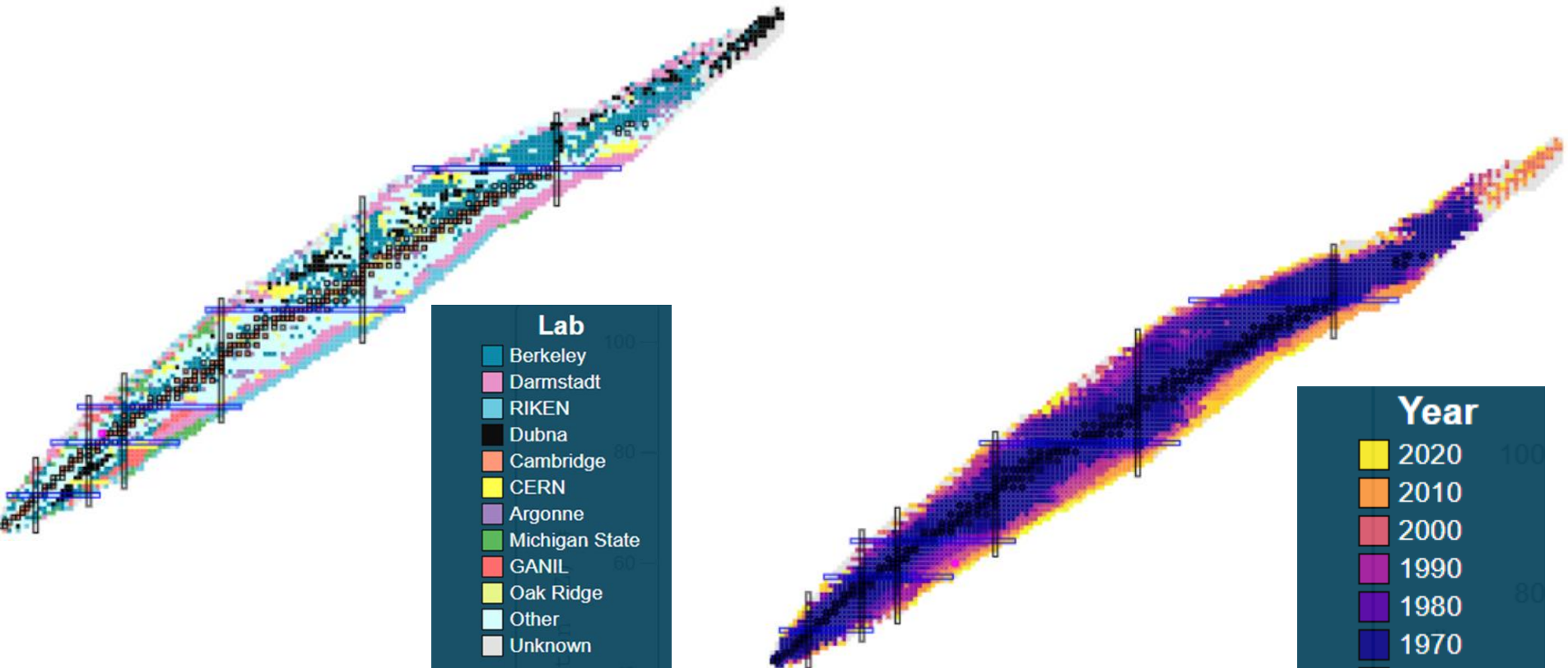
S. Pietri^{a,*}, H.A. Rösch-Kabadayi^{a,b,c}, J. Enders^{b,c}, T. Grahn^{d,e}, J.-P. Hucka^{b,c}, T. Kurtukian-Nieto^{f,g}, M. Luoma^{d,e}, A.M. Bruce^h, T. Dickel^{a,i}, E. Haettner^a, C. Hornung^a, D. Kostyleva^a, W.R. Plaß^{a,i}, H. Weick^a, J. Wirtz^{a,b}, J. Zhao^a, H.M. Albers^a, D. Amanbayev^{a,c,i}, S. Ayet San Andres^j, J. Äystö^{d,e}, S. Bagchi^{a,1}, S. Beck^{a,i}, J. Benlluire^k, J. Bergmannⁱ, Z. Brencic^{l,u}, H. Geissel^{a,2}, F. Greiner^a, L. Gröfⁱ, M.N. Harakeh^m, A. Heinzⁿ, C.E. Jones^{h,3}, N. Kalantar-Nayestanaki^m, A. Kankainen^{d,e}, A. Kelic-Heil^a, B. Kindler^a, G. Kripko-Koncz^{c,i,4}, N. Kuzuminchuk^a, B. Lommel^a, K. Mahajan^{c,i}, I. Miskunⁱ, A. Mistry^a, A. Mollaebrahimi^{a,i}, I. Mukha^a, G. Münzenberg^{a,2}, M. Pfützner^o, Zs. Podolyák^p, S. Purushotaman^a, C. Rappold^f, P.H. Regan^{p,q}, J.L. Rodríguez-Sánchez^{k,5}, C. Scheidenberger^{a,c,i}, H. Simon^a, J. Taieb^{r,s}, Y.K. Tanaka^{a,t}, H. Törnqvist^a, M. Vencelj^l, J. Vesic^l, J.S. Winfield^{a,2}, M. Winkler^a, for the Super-FRS Experiment Collaboration

Letter of Intent new Isotope Search at Super-FRS

S. Pietri¹, T. Grahn^{2,3}, J. Wirtz^{1,4}, A. Ali¹, A. Anders¹, J. Hetzel¹, V. Isensee^{1,4}, D. Kallendorf^{1,4}, E. Kazantseva¹, A. Bruce⁵, J. Enders⁴, T. Dickel¹, R. Gebel¹, T. Kurtukian⁶, H. Simon¹, D. Urner¹, H. Weick¹, M. Winkler¹...to be completed and the Super-FRS EC,

- Nuclei in matter:
 - faster it goes more chance to loose electrons (>few 10 MeV.U)
 - more charged it is higher chance to capture electrons
- ➔ passing through matter creates an equilibrium of those two effects
 - **@1500 MeV.U for Uranium in matter ➔ 73% $^{238}\text{U}^{92+}$, 25% $^{238}\text{U}^{91+}$, 2% $^{238}\text{U}^{90+}$... SIS100**
 - @ 900 MeV.U, for Uranium in matter ➔ 46% $^{238}\text{U}^{92+}$, 43% $^{238}\text{U}^{91+}$, 9% $^{238}\text{U}^{90+}$...
 - @ 600 MeV.U, for Uranium in matter ➔ 21% $^{238}\text{U}^{92+}$, 49% $^{238}\text{U}^{91+}$, 28% $^{238}\text{U}^{90+}$...
 - @ 300 MeV.U, for Uranium in matter ➔ 10% $^{238}\text{U}^{92+}$, 17% $^{238}\text{U}^{91+}$, 70% $^{238}\text{U}^{90+}$...
 - @ 150 MeV.U, for Uranium in matter ➔ 0% $^{238}\text{U}^{92+}$, 10% $^{238}\text{U}^{91+}$, 73% $^{238}\text{U}^{90+}$...
- ➔ for ^{212}Pb after target
 - @900 MeV.U for Pb in matter ➔ 71% $^{212}\text{Pb}^{82+}$, 25% $^{212}\text{Pb}^{81+}$, 2% $^{212}\text{Pb}^{80+}$...
 - @600 MeV.U for Pb in matter ➔ 49% $^{212}\text{Pb}^{82+}$, 42% $^{212}\text{Pb}^{81+}$, 8% $^{212}\text{Pb}^{80+}$...

New facilities broad new regions discovered



... to answer how

