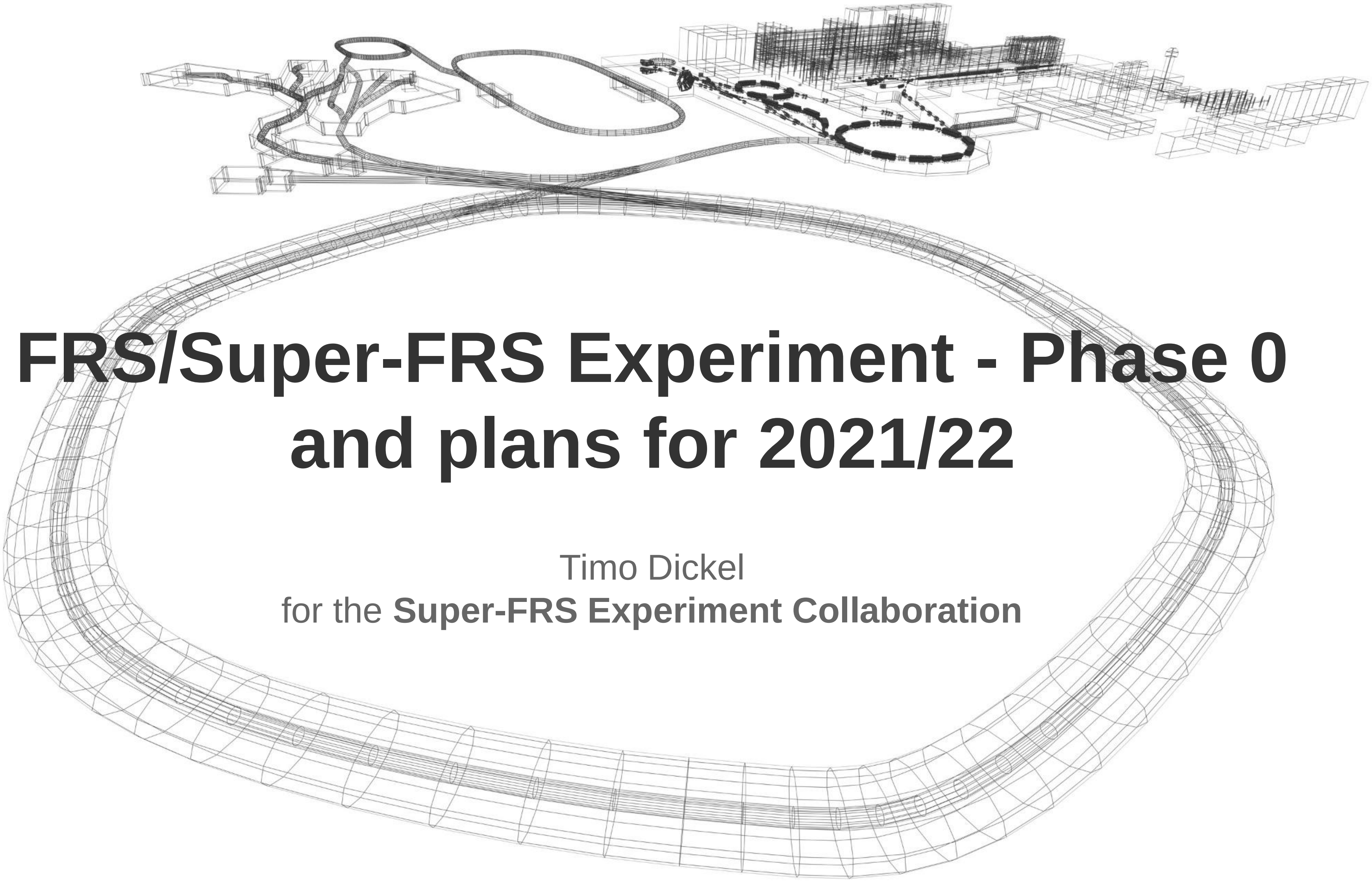


FRS/Super-FRS Experiment - Phase 0 and plans for 2021/22

Timo Dickel
for the **Super-FRS Experiment Collaboration**

Results from engineering run: Commissioning of the three branches

Technical/General achievements

- All standard detectors tested with beam:
  - Beam intensity monitors, current grids, MWPCs, TPCs, scintillators, in total approximately ~ 30 detectors
- Data acquisition
- Particle identification in-flight
- Training with the new control system
- Optics visualization and steering and modification with LSA-Mirko and gicosyback

Experiments at the three branches

- HFS
  - DESPEC
    - Ar beam and Ar fragments
    - U beam and U fragments
  - Ion Catcher
    - U beam and U fragments
  - Isotope search
    - Test of experiment-specific active stopper
  - Energy loss measurements
    - Proof of principle measurement
    - Measurement at low magnetic rigidity
- Cave C
  - R3B: Ar beam and Ar fragments
- ESR via FRS
  - U beam was injected and stored in the ESR

FRS: Status of experiments

Experiment ID	Spokesperson	Ranking [A/A-]	Shifts granted		Shifts carried out 2018+19		Shifts carried out 2020	
			main	parasitic	main	parasitic	main	parasitic
S457	Itahashi, Kenta	**A-**	**18**	**18**			6	
S474	Plass, Wolfgang	**A**	**21**	**-**			17	
S468	Pietri, Stephane	**A**	**14**	**8**			33	
S469	Purushothaman, Sivaji	**A**	**-**	**12**			11	
S459+ (S443, S459, S472)		**A**	**9**	**-**			7	
S482	Hornung, Christine	**A**	**9**	**-**			8	

Σ = 82 shifts

In addition, the collaboration contributed to the following experiments

S467 (Paschalis, Shell evolution along Z=20)	17 shifts
E121 (Litvinov, Bound-state beta decay of ^{205}Tl^{81+})	31 shifts
E127 (Reifarth, p-induced reaction rates on radioactive isotopes)	16 shifts
S480 (Regan, Seniority transitions and EM transition rates in ^{94}Pd)	17 shifts
S481 (Witt, Test of the fibre detector and AIDA active implanter)	6 shifts

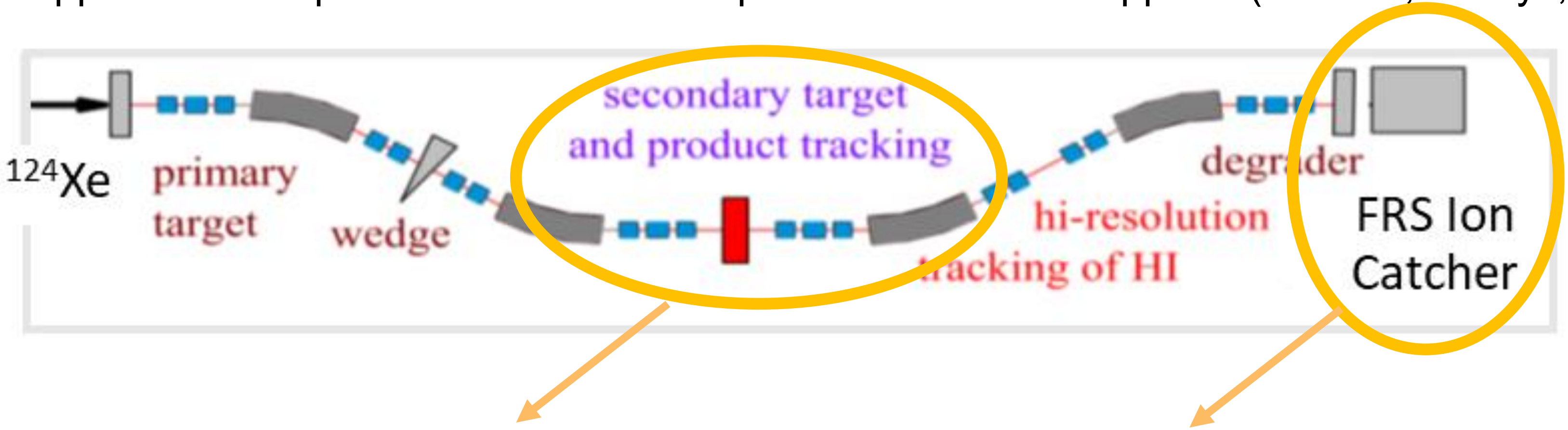
Σ = 87 shifts

169 shifts FRS in total

Highlights S459+:
EXPERT and FRS Ion Catcher

Multiple use of the secondary beams for increased physics output and efficiency:

- In-flight reaction studies at central focal plane (EXPERT)
- Stopped beam experiments at final focal plane with “active stoppers” (masses, decays, …)



EXPERT:

- ^{69}Br and ^{73}Rb produced in secondary reactions
- Life-times determined by tracking residual particles of in-flight-decays
- Properties of ^{69}Br,^{73}Rb are of interest for understanding the rp-process nucleo-synthesis
- ~10^6 ions of ^{70}Br and ^{74}Rb impinged on the secondary target → **~80 and ~40 events of 1*p*-decays registered in-flight of ^{69}Br and ^{73}Rb, respectively**

ION CATCHER:

- Ion Catcher is used as **active beam stopper**, ‘re-using’ part of the beam that went through EXPERT
- Mass tagging of secondary beams
- Measurements focused on A~70 n-deficient isotopes (planned branching ratio measurements in this region were hindered by the CSC RF-Carpet problem)
- First direct mass measurement of ^{69}As, mass of ^{70}Se measured with +/-3 keV → **best achieved mass accuracies sofar**

Highlights S474: Test for the LEB and mass measurements of below ^{100}Sn

- Detector tests for the Low-Energy Branch of the Super-FRS
- Test with very thick targets making optimum use of two-step reactions to increase yields
- Technical difficulties with an essential extraction element in the stopping cell (RF carpet) at the beginning of the experiment → mass measurements could be performed for about 2 shifts only
- First mass measurement of ^{93}Pd **(σ_{prod} ~ 9nb only!)**
  Combined with one-proton decay energy this result helps to resolve the long-standing puzzle of the two-proton decay from the (21+) isomer in 94-Ag.

Highlights S468:
New isotope search below ^{208}Pb

Experiment

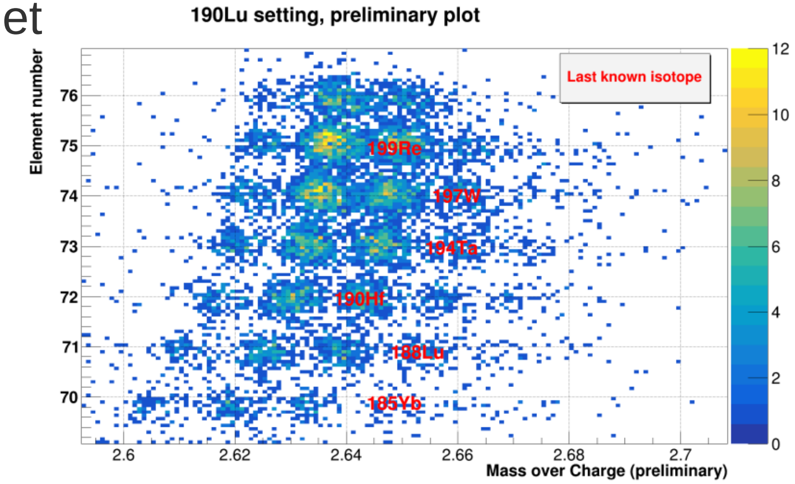
- 1,050 MeV/u ^{208}Pb beam (~5E8/s) on Be target
- Regions of interest: ^{193}W, ^{190}Lu, ^{205}Au
- **FRS:**
  → production, separation, ID, cross sections
- **Ion Catcher**
  → direct mass measurements
- **Active stopper** (Si detectors) and LaBr$_3$
  → *β*-decay half-life measurements

Preliminary results

> 15 new isotopes between $_{68}$Er and $_{76}$Os

> 5 new masses

beta lifetime analysis started



Part of ID plot of ^{190}Lu setting:

➔ in red the last known isotope of this element

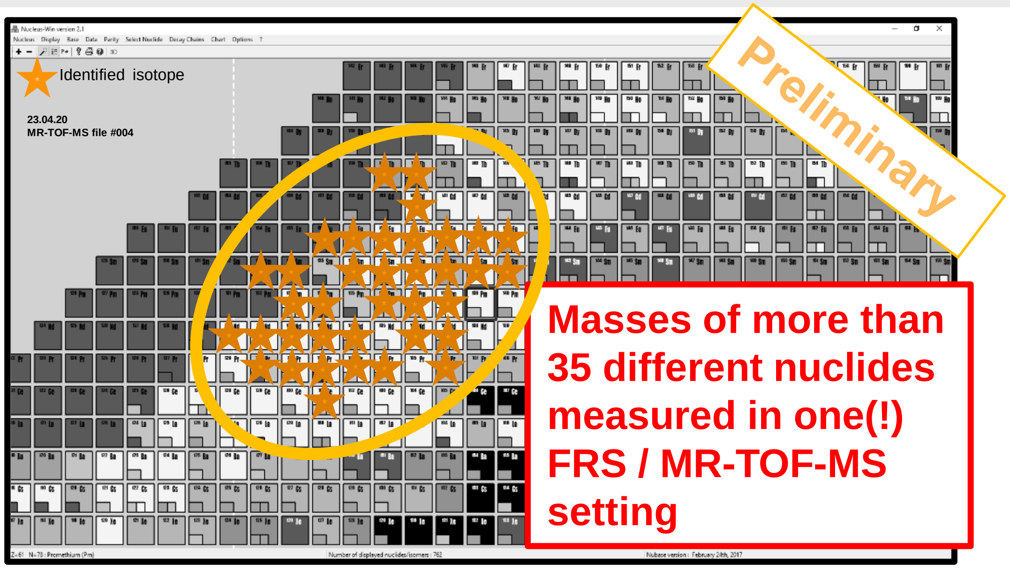
➔ To claim discovery 3 counts are needed

➔ Work ongoing to estimate background

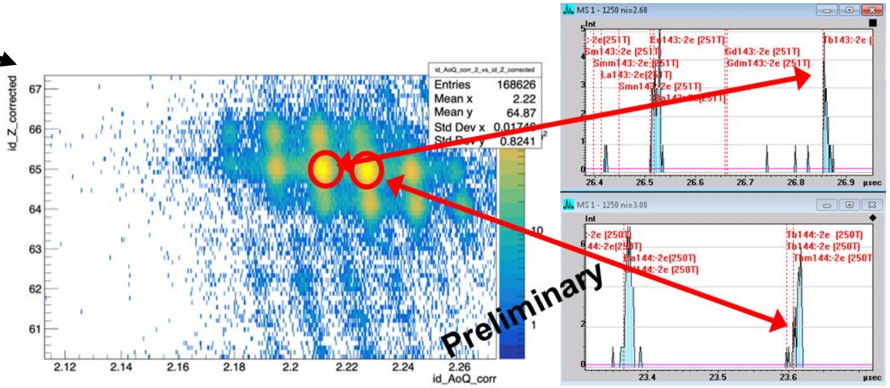
Highlights S482:
Mean range bunching

Experiment

- Ion optical method to stop many different species ***simultaneously*** in an detector
  → efficient data taking
- **Region of interest: n-deficient lanthanides**
- Successful mass tagging of $^{143\text{-}144}$Tb with the MR-TOF-MS



Masses of more than 35 different nuclides measured in one(!) FRS / MR-TOF-MS setting



Preliminary results

> 12 new masses

> 10 improved masses

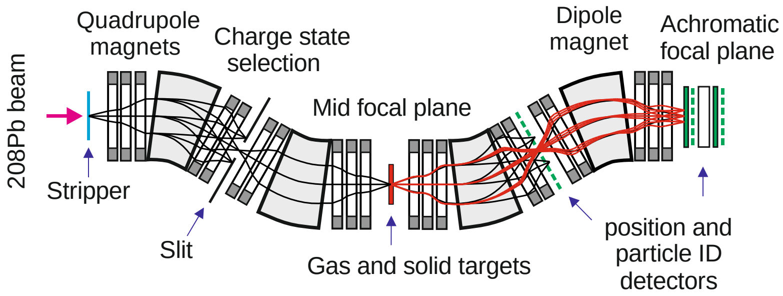
beta lifetime analysis started

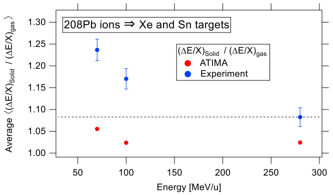
few new isotopes identified (t.b.c.)

Highlights S469: Slowing down of heavy ions in gases and solids

- Accurate energy-loss and charge-state distribution measurements of ^{208}Pb ions in various gases and solids in the energy range 35…280 MeV/u

- **The gas-solid difference according to Bohr-Lindhard theory has been clearly observed at kinetic energies of 100 MeV/u and below**





Preliminary

- The results contribute to a better knowledge of the atomic interaction of ions penetrating matter

- Improved computer codes and more accurate isotope separation will be the direct application

Approved experiments in 2021/22

- S511: FRS developments with beams for NUSTAR
- U316/S479: Test of calorimetric low-temperature detectors (CLTDs) at intermediate ion energies
- S526: Direct mass measurements of heavy N=Z and N=Z-1 nuclides
- S530: Fission isomer studies with the FRS
- S533: Ion-beam therapy with positron emitters
- S484: Hypernuclei
- S490: η′-mesic nuclei

S511: FRS developments with beams for NUSTAR

The NUSTAR Collaboration needs to continue to perform world-wide unique and competetive experiments in FAIR Phase-0 and beyond.

One key is to…

- **…increase the „useful intensity“ for experiments**
  - to optimize coupling SIS-18 and FRS
  - to increase the transmission of secondary beams
  - to further increase the reliability of the FRS
  - to upgrade and develop new detectors and hardware for increased performance (rate, resolution, tracking)
  - to train people on the reliable use of the FRS Standard Equipment
- **… apply the many scientific-technical developments that were performed in recent years**
  - ion optics, detectors, DAQ readout, etc. …
- **…and test them with beams and apply to NUSTAR experiments!**

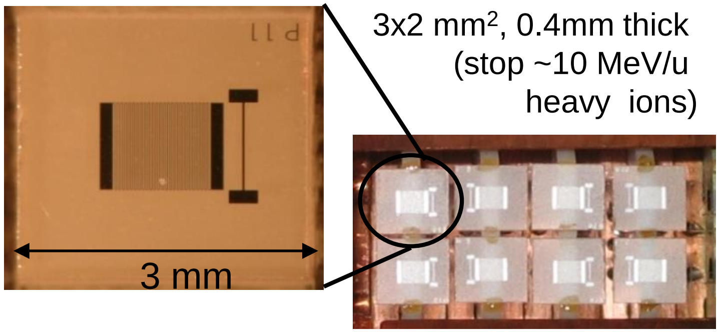
S511: FRS developments with beams for NUSTAR

Performance improvements and R&D work with heavy-ion beams:

- **1) Coupling SIS-18 with FRS: increase of the "useful" primary-beam intensity**
  - a) micro-spill structure: **gain factor ~ 1.3 … 4**, measurement / optimization up to highest SIS-18 intensities
  - b) macro-spill structure: **gain ~ 10…20%**
  - c) further transmission improvements (SIS to FRS target): first quantitative measurements needed
- **2) FRS improvements**
  - a-c) ion optics, improved diagnostics, quantitative measurements (goal: transmission increase for all 3 branches, e.g. main branch: a **gain factor ~ 2.5** is immediately possible)
  - d) standard detectors (for particle identification and beam tracking: Sci-TOF, Music-DE, TPC-XX'YY')
  - e) i) new, radiation-hard detectors for TOF: liquid Cerenkov radiators, multiple read-out PMT's, high rate
  - f) data acquisition (**gain factor of 2…4** expected by block transfer mode)
  - g) mass tagging: redundant ID (confirmation) for light ions (A~30…70), equipment tests (degrader)
- **3) Preparations for high-intensity operation: tests of software and controls for…**
  - increased reliability, quick and reliable recall of settings, integration of simulations, failsafe operation
- **4) Development & training of the NUSTAR Beam Team: dedicated expert team for all expt.'s**
- **5) Detector tests for the Super-FRS**

U316/S479: Test of calorimetric low-temperature detectors (CLTDs)

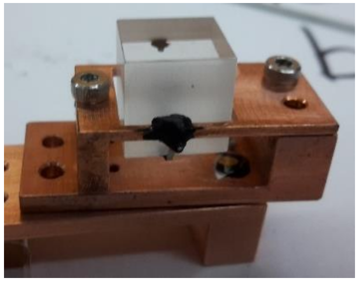
CLTDs for UNILAC energies:



3x2 mm^2, 0.4mm thick (stop ~10 MeV/u heavy ions)

$\Delta E/E \sim 10^{-3}$ even for uranium
→ Mass identification via E/ToF determination

CLTDs for SIS-18 energies:



Saphire crystal,

10x10x10 mm^3, (stop ~150 MeV/u Ni ions)

1. Motivation:

- CLTDs for heavy ions have been tested and applied for UNILAC and low ion energies (P.Egelhof et al.)
- Goal for NUSTAR experiments: development of **large arrays** of CLTDs for UNILAC and SIS energies
- Tests only possible with heavy ion beams

2. Present status:

- Several prototype detectors ready for testing
- Setup can be installed at X7 and at the FRS

3. Beam request:

- At SIS-18 (FRS): very heavy ions (Au/Pb/Bi, U),
  at UNILAC (X7): ditto, and also C
- Parasitic (beam sharing with other experiments possible), energies as available, count rate demands are rather low ($<10^3$ / sec.)

For U316: 27 shifts
For S479: 18 shifts

S526: Direct mass measurements of heavy N=Z and N=Z-1 nuclides

Nuclear forces and isospin symmetry

- Investigate isospin-symmetry breaking forces for heavier nuclei
- Mirror displacement energies (T=1/2) for A>70 for the first time
- Triplet displacement energy (T=1) for A=70 for the first time
- Resolve discrepancy in super-allowed beta decay $\mathcal{F}t$ value for ^{70}Br

P. Baczyk et al., PLB 778 (2018) 178.

J.C. Hardy and I.S. Towner, PRC 91 (2015) 025501.

Neutron-proton (np) interactions and Wigner energy

- Study Wigner effect and np pairing for heavier nuclei

A.S. Lalleman et al., Hyperfine Interact. 132 (2001) 315.

Nuclear structure and isomers

- Region of strong deformation and changing shapes around ^{80}Zr (study separation energies)
- New isomers and isomer studies, e.g. (7^+), (21^+) isomers in ^{94}Ag, predicted high-spin isomer in ^{84}Mo (DESPEC proposal by M. Gorska et al.)

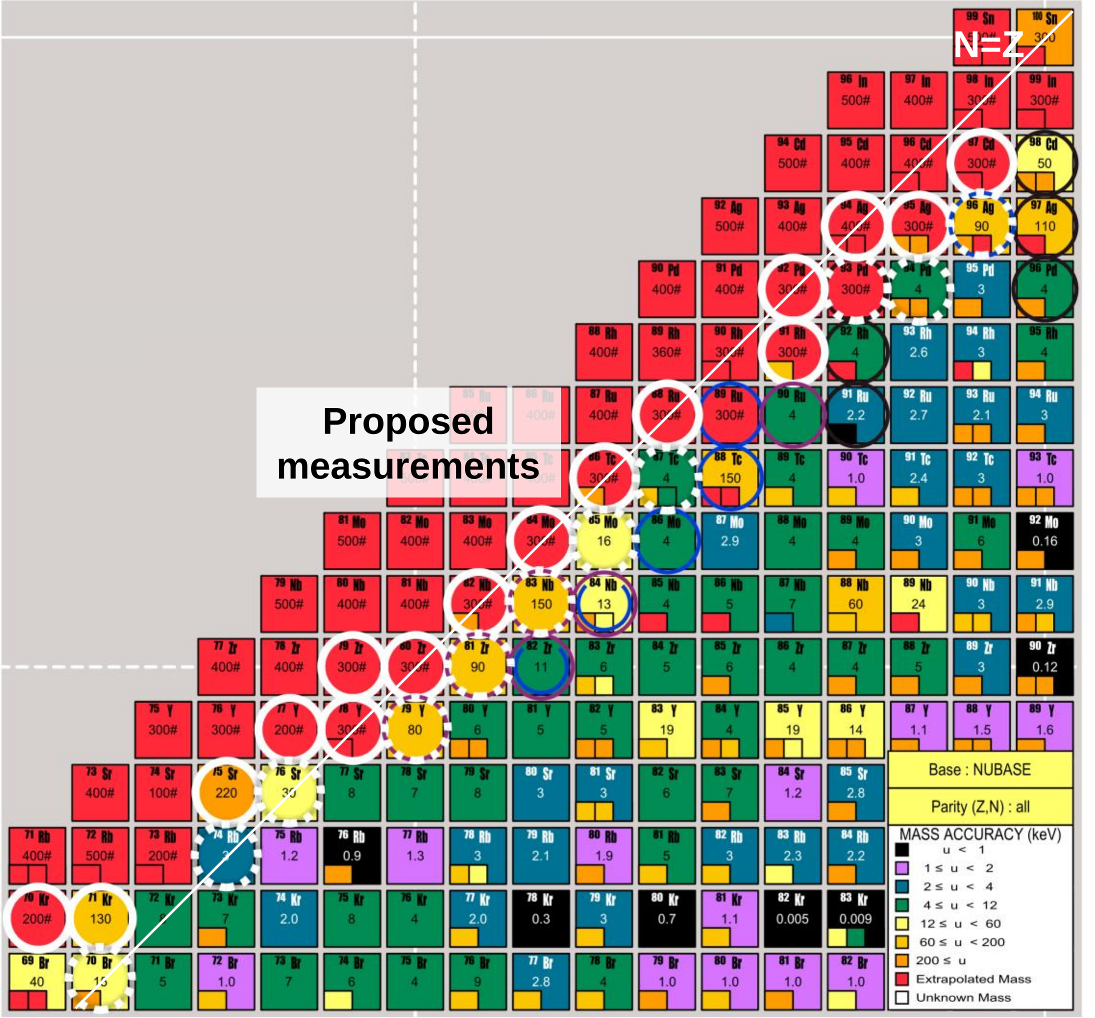
C.J. Lister et al., PRL 59 (1987) 1270.

Nuclear astrophysics

- Uncertainties of rp and νp processes (light curve, abundances)
- Possible formation of Zr-Nb cycle in rp process

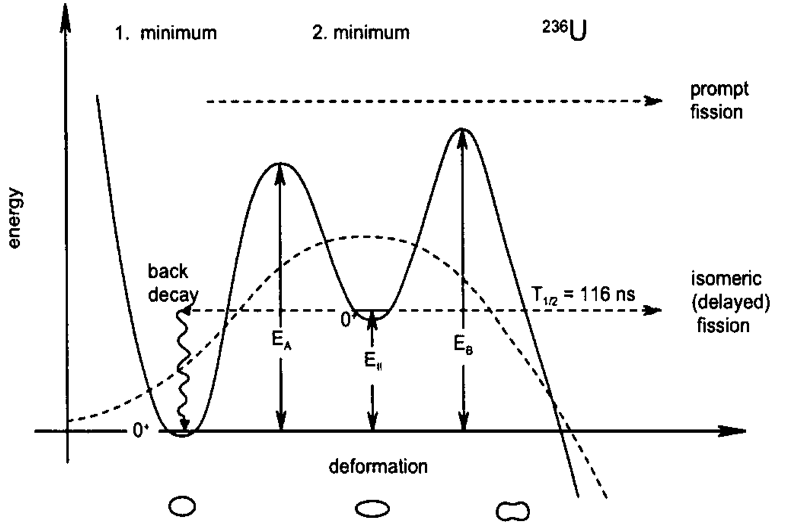
H. Schatz et al., Phys. Rep. 294 (1998) 167.
H. Schatz et al., Astrophys. J. 844 (2017) 139.

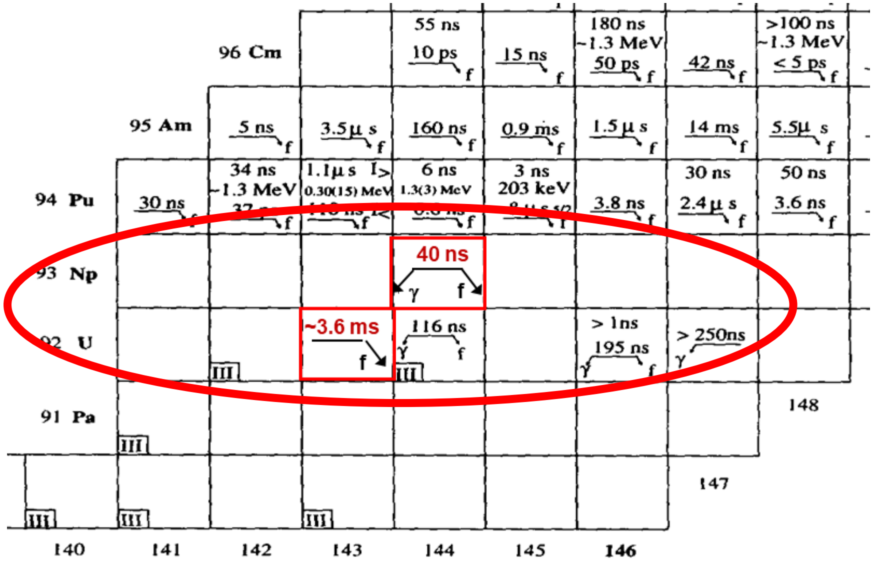
S526: Direct mass measurements of heavy N=Z and N=Z-1 nuclides



- Similar mode as for S474
- Simultaneous measurement of *N*=*Z*, *N*=*Z*+1, and calibrant, or *N*=*Z*-1, *N*=*Z*, and calibrant
- Expected mass uncertainty: 2…30 keV
- Assumed sensitivity limit: 10 events in 1 day
- Experiment also important for the Low-Energy Branch of the Super-FRS (detector development, experiments)

S530:
Fission isomer studies with the FRS





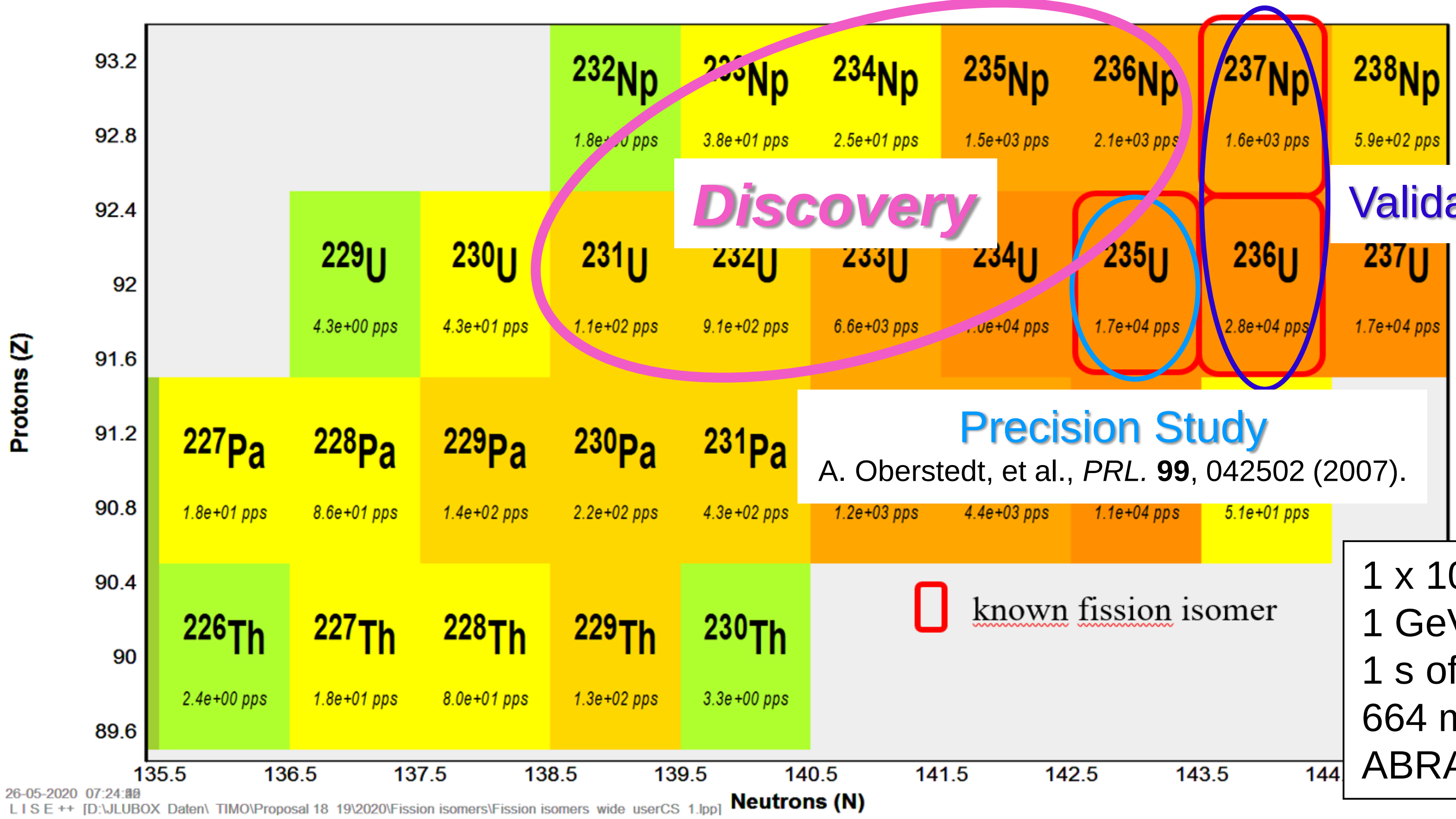
(Superdeformed) second minimum in potential energy surface appears in actinides
→ fission isomers

Ideal testing ground for strongly deformed low-spin nuclei and shell corrections in very heavy systems

Studies in the past by n, p, d, α-induced reaction;
Disadvantages:
1. Huge prompt fission background
2. Low excitation energy and population probability (~ µbarn)
3. Challenging to get targets to study U and Np

H. J. Specht, et al. , *Phys. Lett. B.* **41**, 43–46 (1972).
P. Thirolf, D. Habs, *Prog. Part. Nucl. Phys.* **49**, 325–402 (2002).

S530:
Fission isomer studies with the FRS



Discovery

Validation

Precision Study

A. Oberstedt, et al., *PRL.* **99**, 042502 (2007).

🟥 known fission isomer

Implantation rate in SCI per second

1 x 10^9 ^{238}U / spill
1 GeV/u
1 s off; 9 s on
664 mg / cm² ^{9}Be
ABRABLA

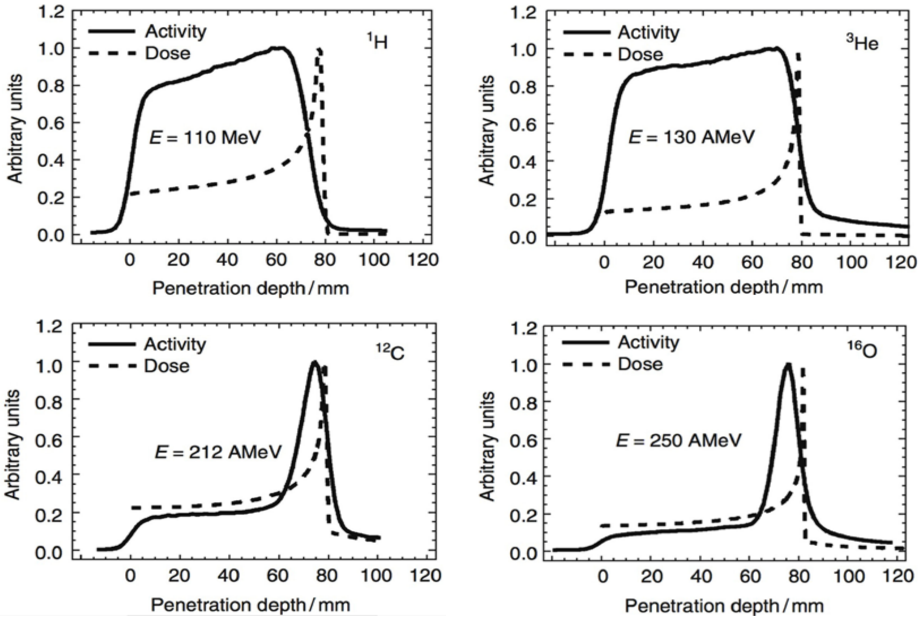
For implantation rate of 1kHz and a very conservative population of 10^{-6} the expected detection rate of fission isomers is:

Fast SCI:	FRS Ion Catcher:	AIDA:
few per minute	1 per hour (1% detection efficiency)	1 per hour (kHz rate capability)

S533: Ion-beam therapy with positron emitters

Limitations of PET imaging with stable beams

- **Non-matching activity and dose distribution**
- **weak PET signal**
  - ➢ PET emitters are produced by projectile and target fragmentation



- **Measured positron emitter activity distribution and irradiation dose distribution**
  - ➢ PMMA target irradiated with ^{1}H, ^{3}He, ^{12}C, and ^{16}O ions
  - ➢ Activity and dose are normalized to their respective maximum

Fiedler et al., In Ion-beam therapy (pp. 527-543). Springer, Berlin, Heidelberg.

A way forward?

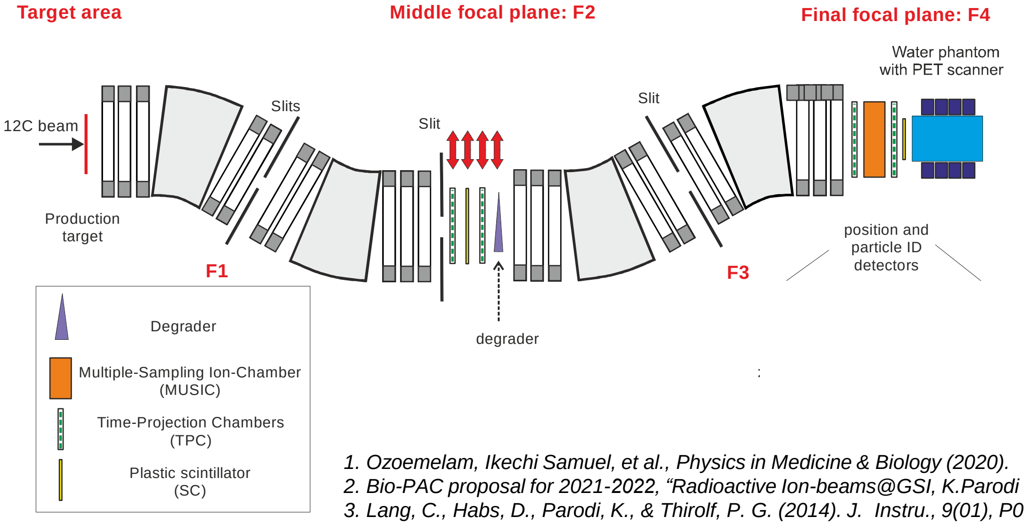
Ion beam therapy using short-lived, positron-emitting isotopes

S533: Ion-beam therapy with positron emitters

Major goals:

1. Range and range straggling in water with PET
2. Stopping power, energy-loss straggling and angular straggling
3. The total interaction and nuclear charge-changing cross-section

- Comparison: PET image vs. distribution measured with FRS event-by-event PID system
- The FRS gives control on the distributions of energy and position using degraders

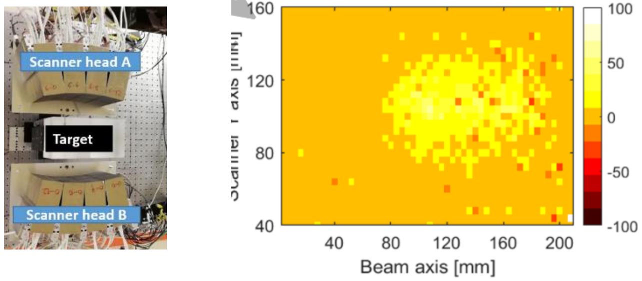


1. *Ozoemelam, Ikechi Samuel, et al., Physics in Medicine & Biology (2020).*
2. *Bio-PAC proposal for 2021-2022, "Radioactive Ion-beams@GSI, K.Parodi et al.*
3. *Lang, C., Habs, D., Parodi, K., & Thirolf, P. G. (2014). J. Instru., 9(01), P01008.*

PET scanner for pilot study (S533)

PET scanner[1] →2 times 52x52 LSO scintillation crystals

P. Dendooven, UG Netherlands & Siemens Healthineers



2D reconstructed PET image of ^{12}N activity
Irradiation of graphite with10^9 protons per pulse

Final BARB detector:

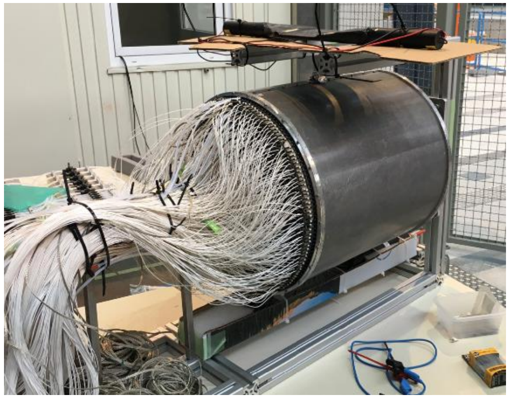
Compton and positron-emission tomography detector under development at LMU, Munich [2,3]

- ➢ Sub-millimeter spatial resolution

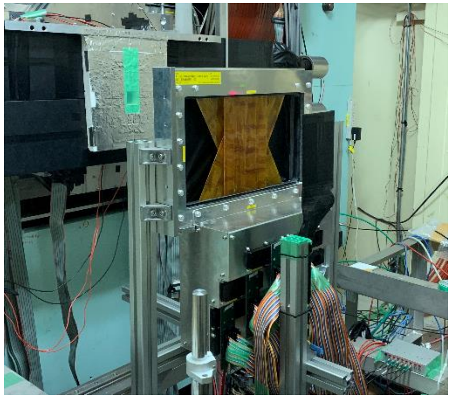
The status of WASA preparation

- Mini drift chamber: DONE
- Superconducting magnet: almost READY for experiments
  - ✓ L-N2 temperature in March 2020
  - ✓ Partially L-He temperature in June 2020
  - ✓ Full cooling at L-He tempretature in August 2020
- Time-of-Flight Barrel Upgrade: in progress, by end of 2020
- Scintillating fiber det.: Mass production completed, Commissioning in progress
- Electronics for fiber detectors: in progress, by end of 2020
- New holding structures: in progress, by Q1 of 2021

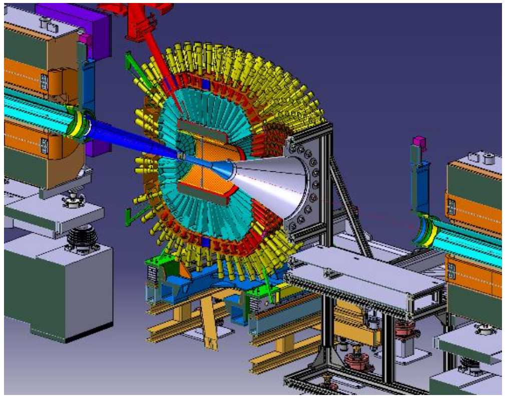
Cryogenic system



Mini drift chamber

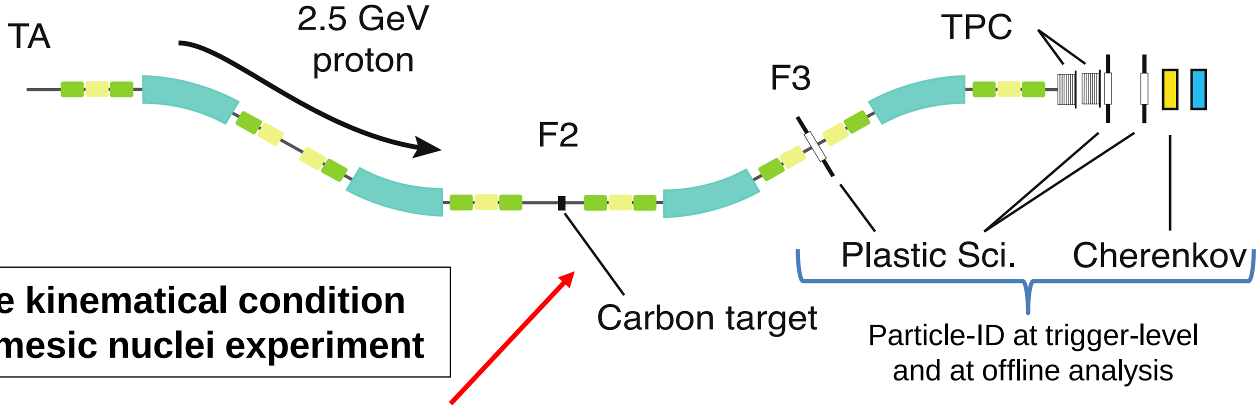


Fiber detector



Design of new holding structure

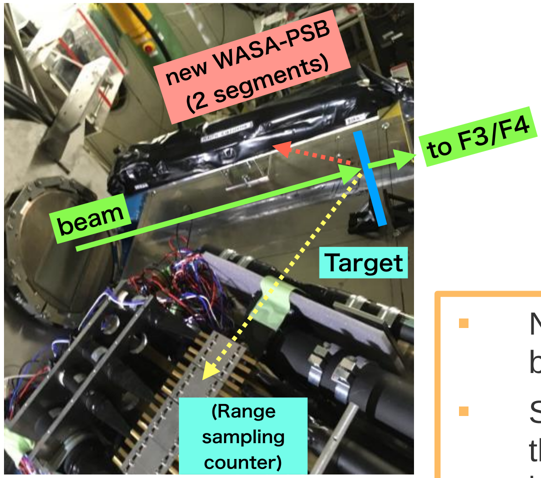
WASA-FRS test experiment with proton beam (June 5-7, 2020)

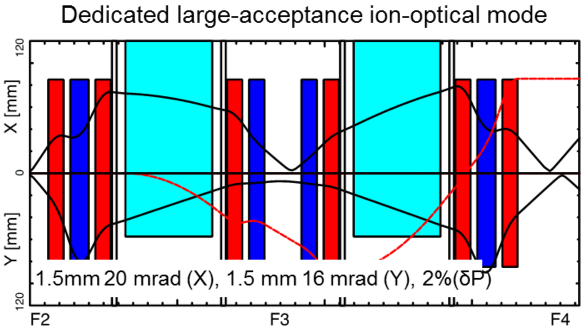


HypHI fiber detector prototype

Same kinematical condition as η’-mesic nuclei experiment

Upgraded WASA-PSB (2 segments)





- New detectors and a dedicated large-acceptance ion-optical mode for WASA@FRS have been successfully tested under realistic kinematical and high-luminosity conditions
- Strong requirement on particle identification in FRS (F3-F4) was achieved, which is crucial for the η’-mesic nuclei experiment: Background reduction of factor 10^2 at Trigger x further factor 10^3 in Offline Analysis reached!
- **Thus, the feasibility of the new experimental concept of forward high-resolution spectroscopy with WASA@FRS (i.e.: FRS in combination with decay-particle detection by WASA) has successfully been demonstrated!**

S484: Hypernuclei

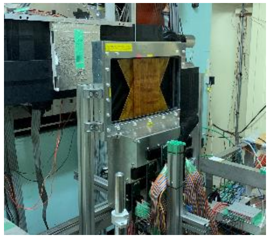
Physics motivations:

- Confirmation of the existence of the **nnΛ bound state** formerly observed by the HypHI experiment at GSI
- Confirmation of the **short life of hypertriton**

The world situation: **very hot topics** in the few-body physics

- nnΛ state
  - ✓ A new experiment performed at the J-Lab in 2019
- Hypertriton
  - ✓ Lifetime measurements by STAR at RHIC and ALICE at LHC
  - ✓ Proposed experiment for lifetime measurement at J-PARC (pilot experiment with $^{4}_{\Lambda}$H was successful)
  - ✓ Proposed experiment at ELPH/Tohoku Univ.
  - ✓ Binding energy by STAR at RHIC (Nature Physics 16, 409–412 (2020))

S484: Hypernuclei

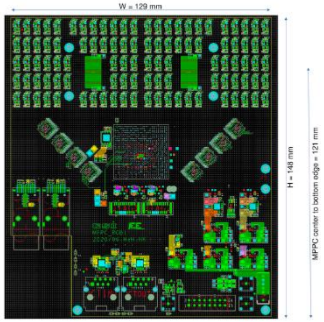


Developments and new facility for WASA-FRS

- Advanced Monte Carlo simulations: RIKEN + CSIC + GSI
- New analysis and machine learning: RIKEN + CSIC
- Scintillating fiber detectors: RIKEN
- Electronics development: GSI + RIKEN
- New computing farm at RIKEN
  - ✓ 1400 CPU cores
  - ✓ 32 GPGPU cards (RTX 2080Ti + Tesla K40, 273910 CUDA cores)
  - ✓ 400 T byte storage

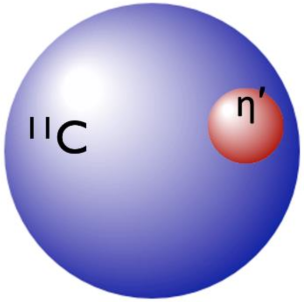
New participating institutions

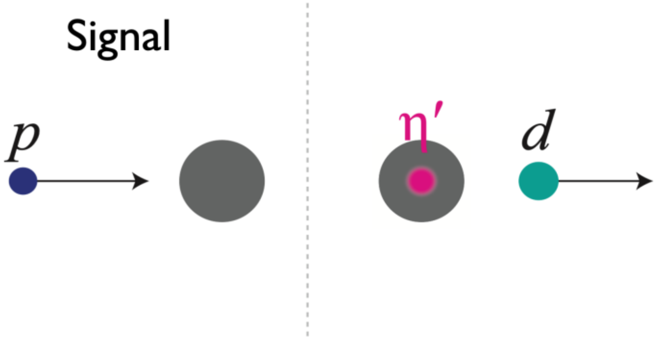
- High Energy Nuclear Physics Laboratory, RIKEN, Japan
  T.R. Saito + 4 staff researchers, 3 postdocs, 3 PhD students
- Hypernuclear Physics Group, Lanzhou University, China
  T.R. Saito + 3 faculty members, 1 master student
- Hypernuclear Physics Group, CSIC, Spain
  C. Rappold + 1 PhD student
- Group of Obertelli, TU Darmstadt, Germany
  A. Obertelli + 1 postdoc

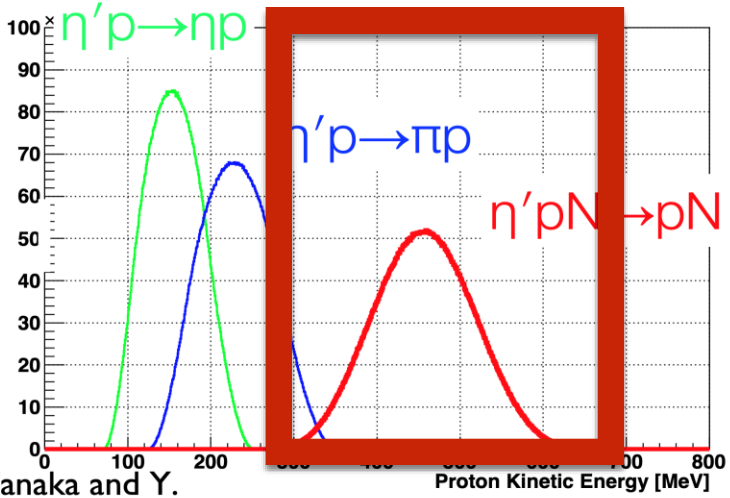


S490: η′-mesic nuclei

Spectroscopy **η′-mesic nuclei** provides information of the strong interaction leading to understanding of **Chiral symmetry and Axial U(1) anomaly**, which is **the origin of large mass of η′**.

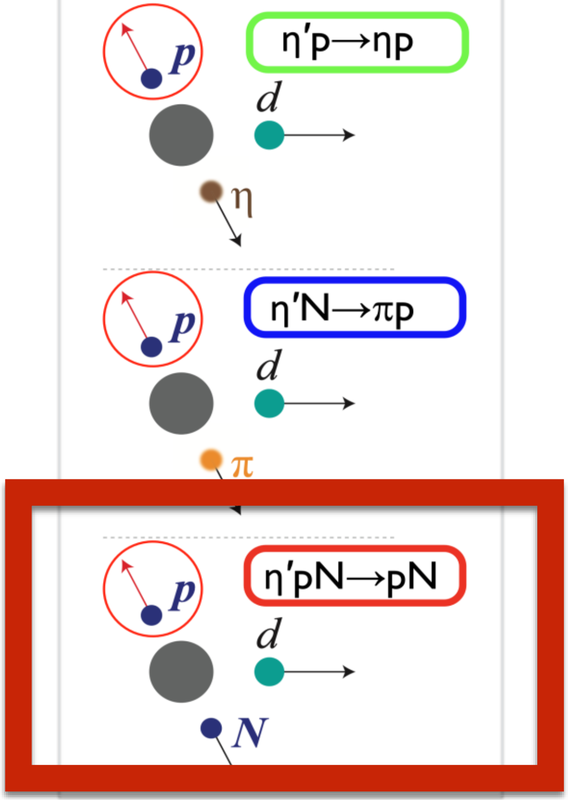




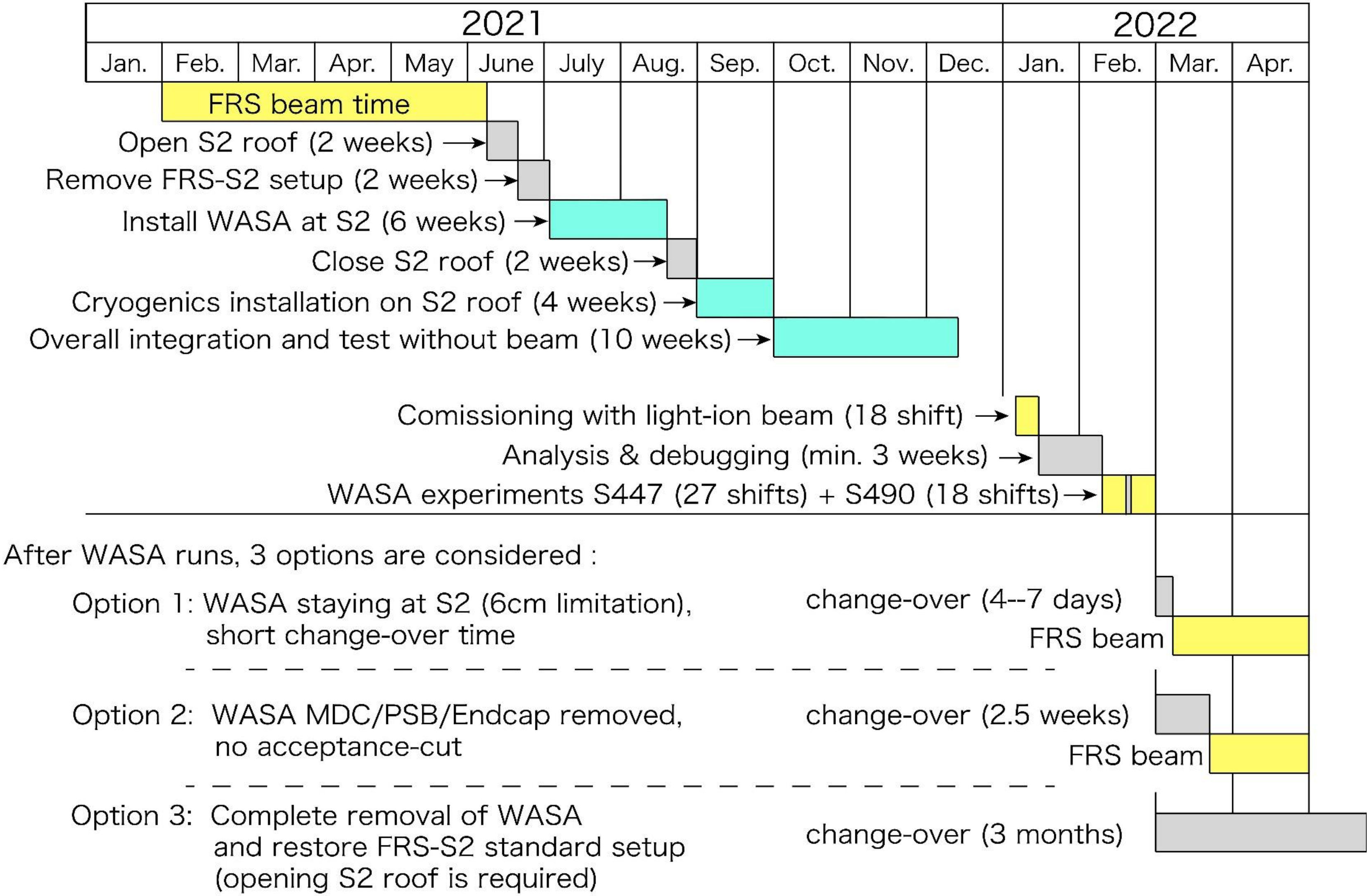


Y.K. Tanaka and Y. Higashi

3 major decay modes of η′-mesic nuclei



WASA:
Installation and Removal Schedule



2021 | 2022

Jan. Feb. Mar. Apr. May June July Aug. Sep. Oct. Nov. Dec. | Jan. Feb. Mar. Apr.

FRS beam time

Open S2 roof (2 weeks) →

Remove FRS-S2 setup (2 weeks) →

Install WASA at S2 (6 weeks) →

Close S2 roof (2 weeks) →

Cryogenics installation on S2 roof (4 weeks) →

Overall integration and test without beam (10 weeks) →

Comissioning with light-ion beam (18 shift) →

Analysis & debugging (min. 3 weeks) →

WASA experiments S447 (27 shifts) + S490 (18 shifts) →

After WASA runs, 3 options are considered :

Option 1: WASA staying at S2 (6cm limitation),
short change-over time

change-over (4--7 days)

FRS beam

Option 2: WASA MDC/PSB/Endcap removed,
no acceptance-cut

change-over (2.5 weeks)

FRS beam

Option 3: Complete removal of WASA
and restore FRS-S2 standard setup
(opening S2 roof is required)

change-over (3 months)

WASA: Removal Options

Option 1:

- ○ Dismount only Fiber detectors => 2 days
- ○ FRS-Sci, TPCs, slit, degrader can be placed in air, for the following experiments. => 2--5 days
- ○ Acceptance is limited by 6 cm diameter of WASA-MDC pipe.

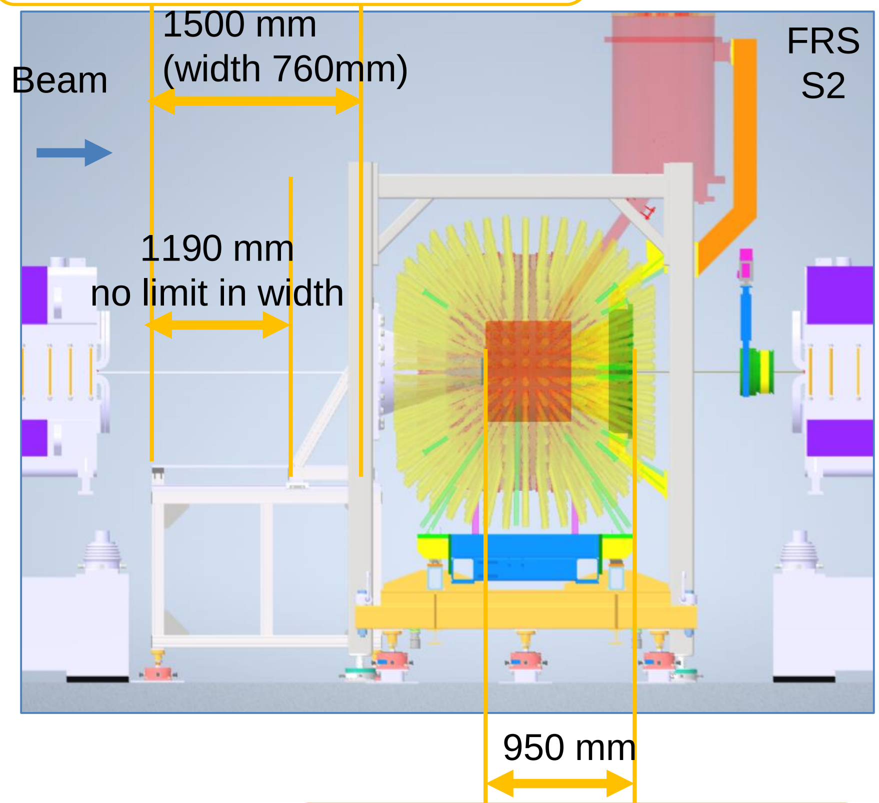
Option 2:

- ○ Dismount Fiber detectors, MDC, PSB, Endcap => 2 weeks
- ○ FRS- Sci, TPCs, slit, degrader can be placed in air, for the following experiments. => 2--5 days
- ○ No cut in acceptance due to WASA.

Option 3:

- ○ Remove whole WASA and install the FRS-standard S2 chamber back (opening roof required) => 3 months

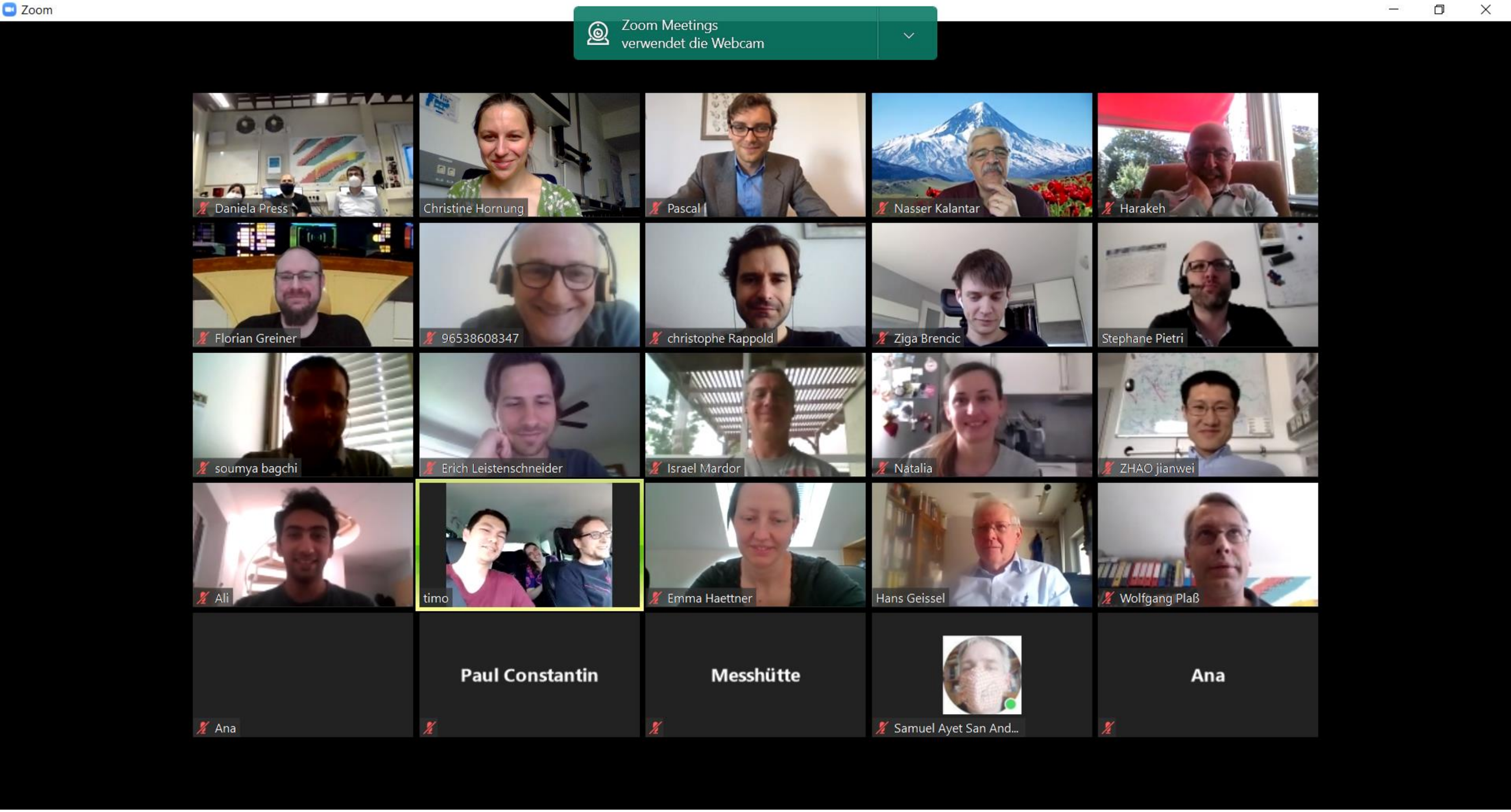
Space to install FRS- Sci, TPCs, slit, degrader (in Option 1 and 2)



With option 1, this section has a limited aperture of φ = 6 cm

With option 2, no limitation

Collaboration photograph „end of the run“ in times of Corona virus


Zoom Meetings
verwendet die Webcam

A great „thank you“ to all collaborators and thank you for your attention !