HELMHOLTZ

RESEARCH FOR
GRAND CHALLENGES

Topic 2
Cosmic Matter in the Laboratory
Highlights

Frank Maas (CML Speaker)
Tetyana Galatyuk (CML Co-Speaker)

Yvonne Leifels (LKII Speaker)

DESY. JÜLICH FORSCHUNGSZENTRUM GSI Helmholtzzentrum für Schwerionenforschung GmbH HI JENA HELMHOLTZ Helmholtz Institute Jena HIM HELMHOLTZ Helmholtz-Institut Mainz HZB Helmholtz Zentrum Berlin HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF Helmholtz-Zentrum Geesthacht Zentrum für Material- und Küstenforschung IPP KIT Karlsruhe Institute of Technology

Our objective:

Creating extreme conditions existing in the Universe with heavy-ion/hadron accelerators

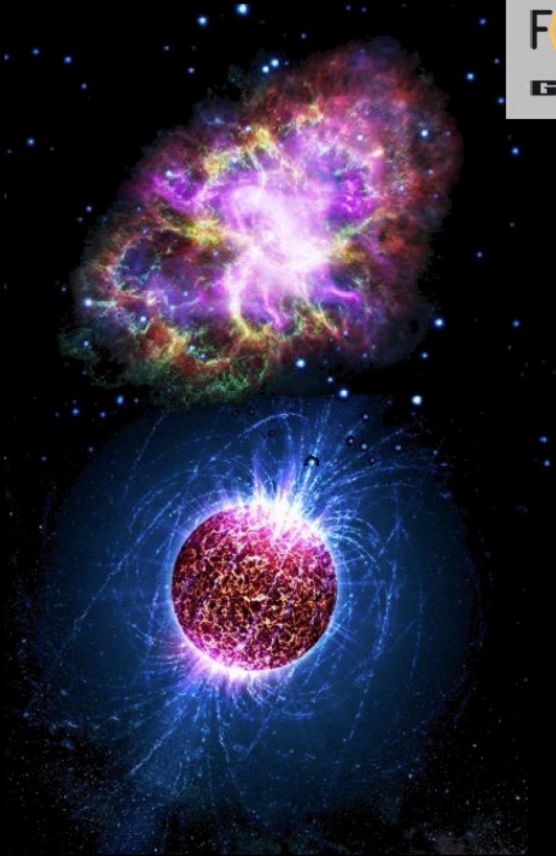
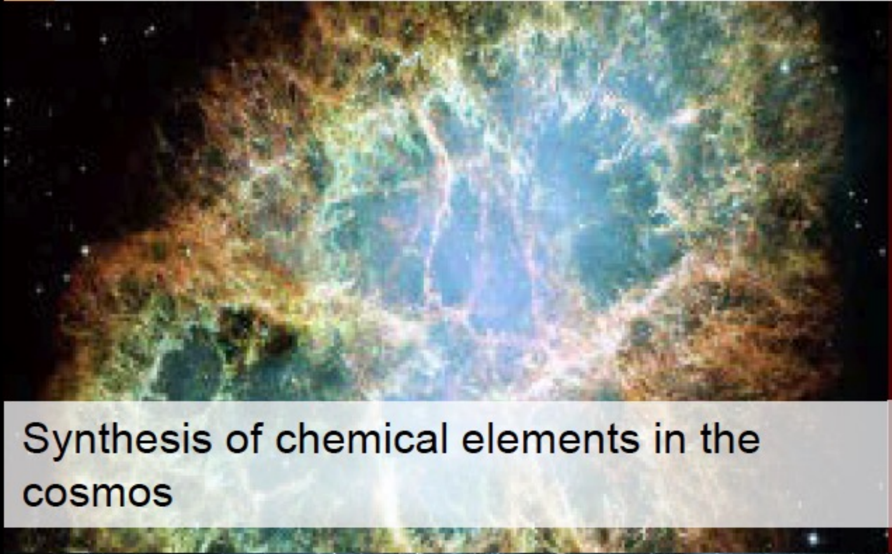
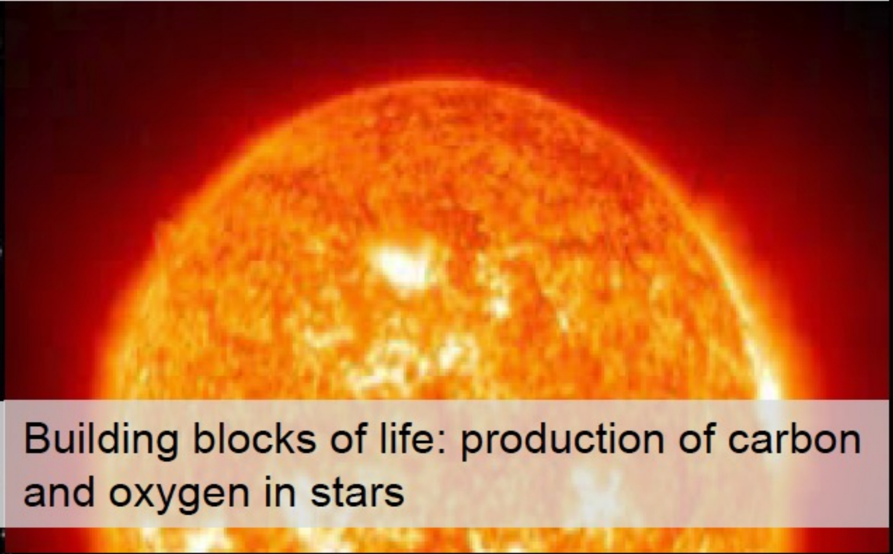


Foto: NASA, ESA, G. Dubner (IAFE, CONICET-University of Buenos Aires) et al.; A. Loll et al.; T. Temim et al.; F. Seward et al.; VLA/NRAO/AUI/NSF; Chandra/CXC; Spitzer/JPL-Caltech; XMM-Newton/ESA; and Hubble/STScI (oben), Penn State University (unten)

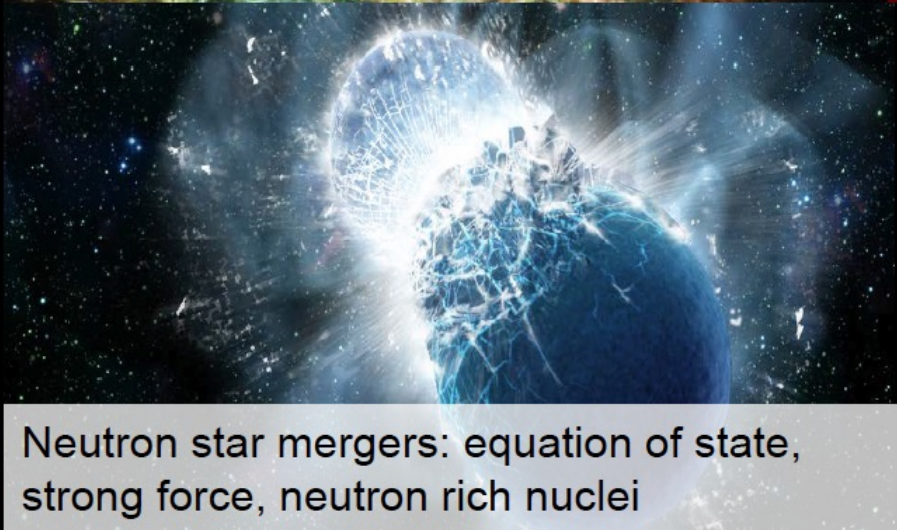
To find answers to fundamental questions about the Universe:
The Universe in the lab …



Synthesis of chemical elements in the cosmos



Building blocks of life: production of carbon and oxygen in stars



Neutron star mergers: equation of state, strong force, neutron rich nuclei

Matter in the interior of Earth and of large planets

Cosmic Matter in the Laboratory within MU

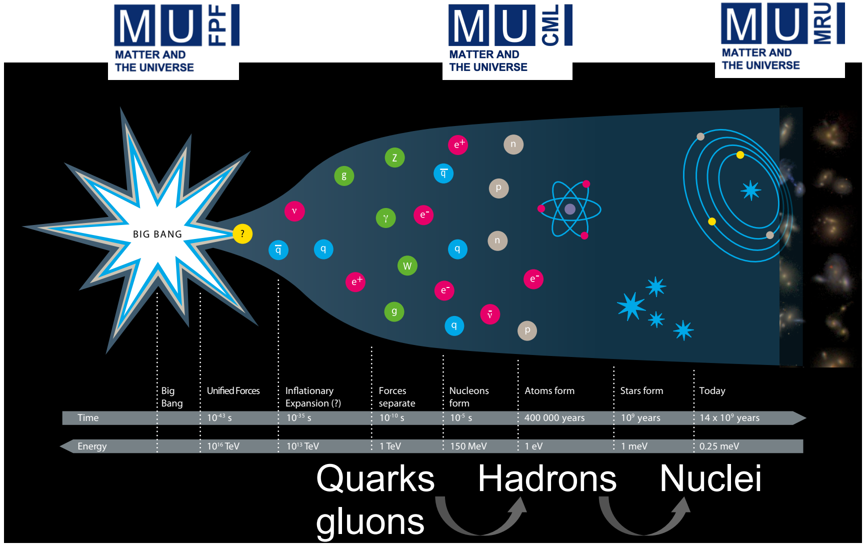
MATTER AND THE UNIVERSE CML

Mission and objectives

Key contribution to the Helmholtz-Mission:

Emergence of complex phenomena in strong interaction

Role of the strong interaction in the evolution of our universe



Mission

- Unravel the properties of hadrons; access and understand the QCD spectrum
- Explore strongly interacting systems under extreme conditions of temperature, density, isospin

Strategy

- Study cosmic matter in the laboratory
- Use primary and secondary ion beams from (anti-)proton to Uranium
- Apply forefront technologies

Strong link to MT MATTER AND TECHNOLOGIES

Uniqueness

- Relativistic ion beams of highest intensities
- Storage rings for cooled (secondary) beams
- Novel experimental instrumentation

User facilities and instruments available for FAIR Phase 0

MATTER AND THE UNIVERSE

MU ion facilities and experimental setups

Nuclear structure, nuclear reactions, and superheavy elements

UNILAC p to U beams up to 11.4 MeV/u

ESR, Fragment Separator FRS

SIS18 all ions up to 2 GeV/u

Properties of hadrons and their excitation spectrum

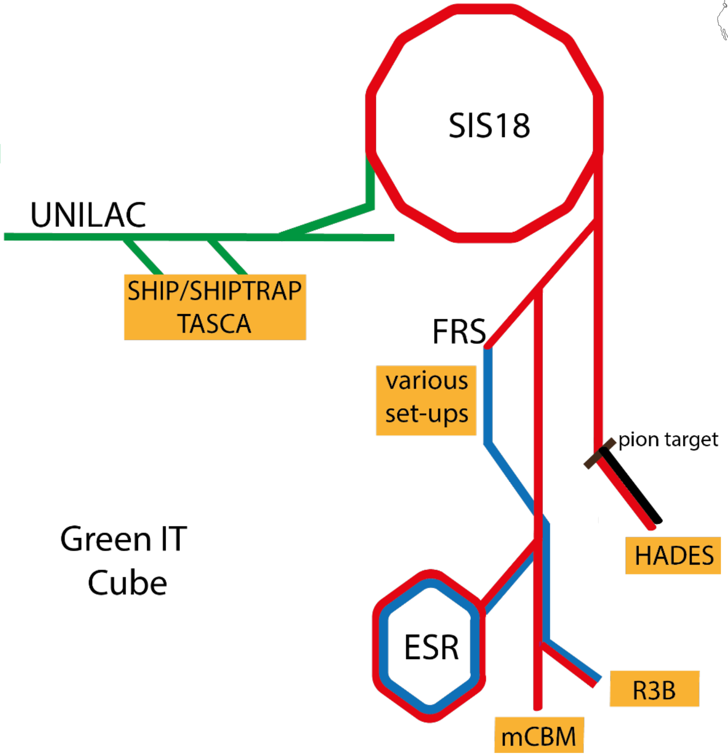
SIS18 π, p beams up to 4.5 GeV

QCD phase structure and properties of QCD matter

SIS18 heavy-ion beams up to 1 GeV/u

Scientific high-performance computing

GSI, HIM, FZ Jülich, KIT



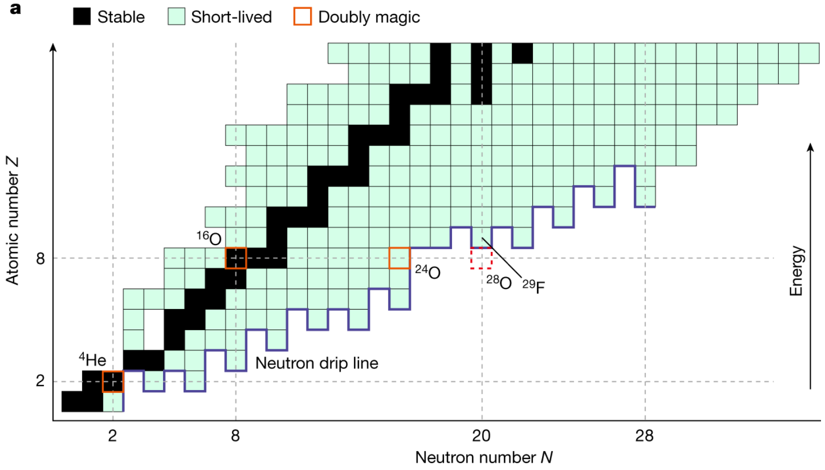
See Yvonne Leifels "Outlook on PoF V"

FAIR Phase 0 outside campus:
LHC / CERN
AD / CERN
BEPCII / China
GANIL / France
COSY / Germany
MAMI / Germany
TRIGA / Germany
RIKEN / Japan
CEBAF / USA
RHIC / USA

First observation of ^{28}O

Extremely neutron rich, doubly magic

Nature, 620, pages 965–970 (August 30, 2023)



- ^{28}O of special interest: Z=8, N=20, double magic
- Observed through their decay in ^{24}O plus 4 neutrons
- Four-body decay shows resonant structure
- Not a closed shell nucleus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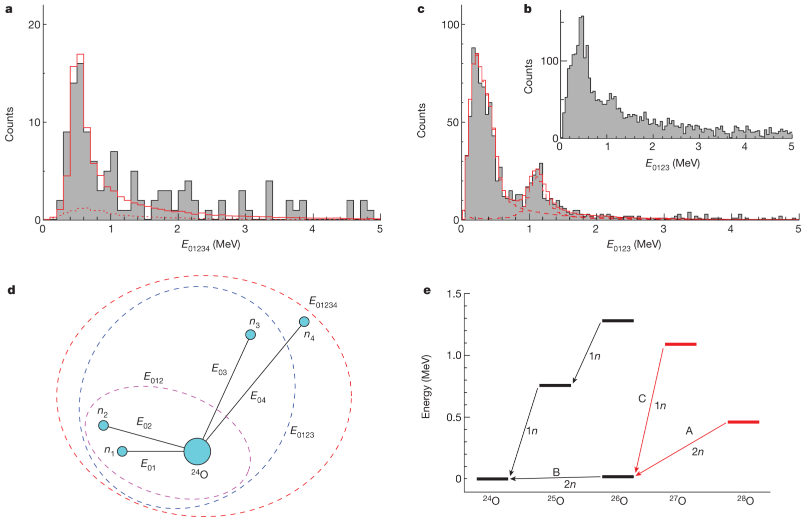
Home > Wissen > Physik > Forscher stellen Sauerstoff-28 her: Das Isotop reagiert anders als erwartet

Kernphysik

Doch nicht so magisch

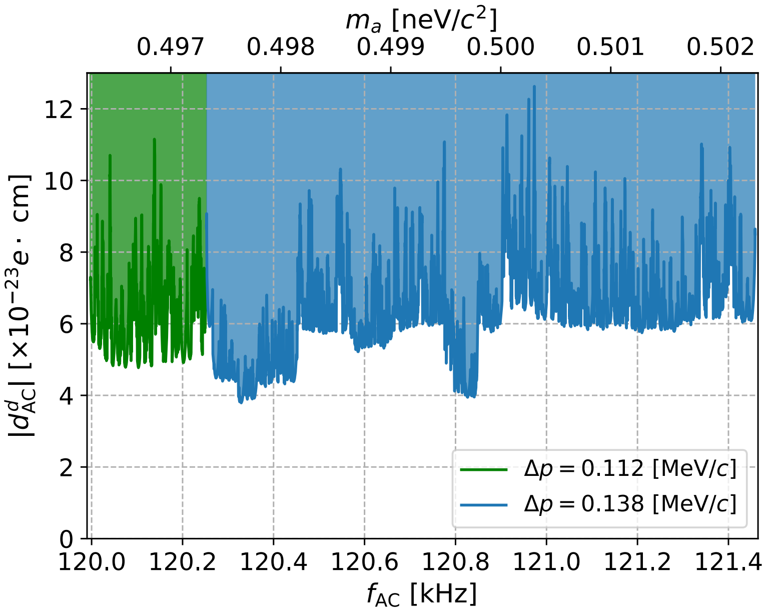
8. September 2023, 16:43 Uhr | Lesezeit: 3 min



First Search for Axion-Like Particles in a Storage Ring Using a Polarized Deuteron Beam

Limits for an ALPs signal

see Jörg Pretz "Axion Searches at COSY"

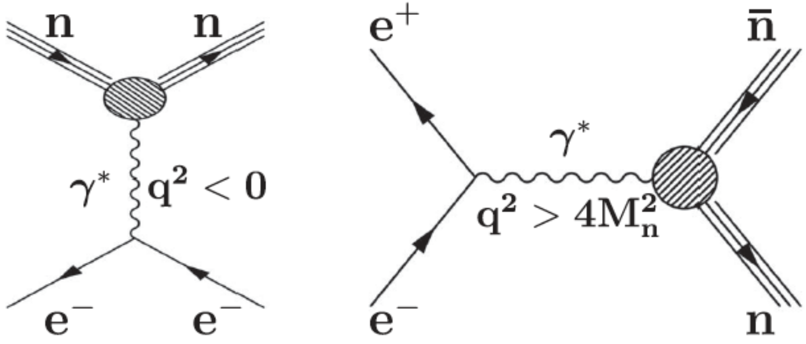


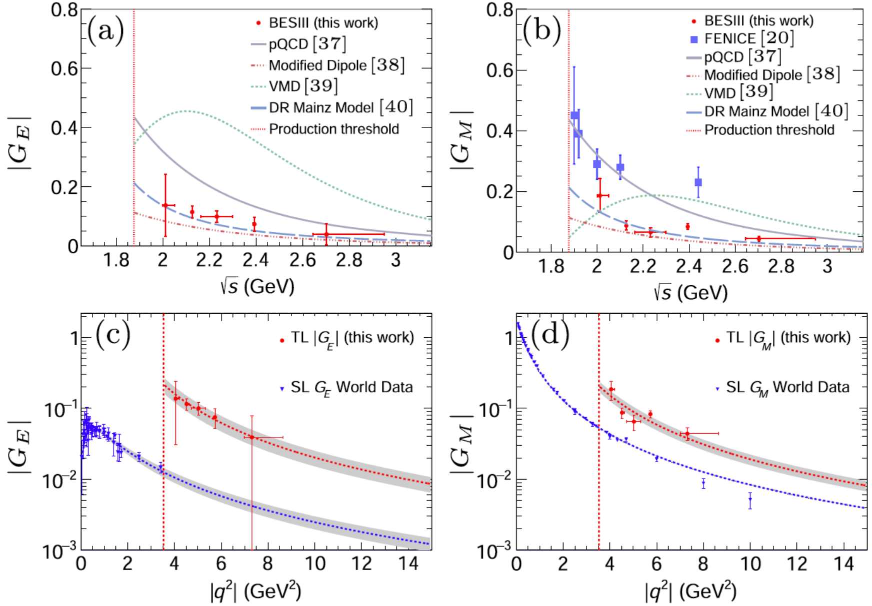
Based on the notion that the **local dark-matter field of axions** or axion-like particles (ALPs) in our Galaxy **induces oscillating couplings to the spins of nucleons** and nuclei (via the electric dipole moment of the latter and/or the paramagnetic axion-wind effect), we have established the feasibility of a new method to search for ALPs in storage rings.

Published in Physical Review X

Measurements of the Electric and Magnetic Form Factors of the Neutron for Timelike Momentum Transfer

First measurement for positive momentum transfer (annihilation region)





- First measurement of Neutron form factors for positive Q^2 (annihilation reactions)
- Accuracy comparable to data from negative Q^2 (electron scattering data)

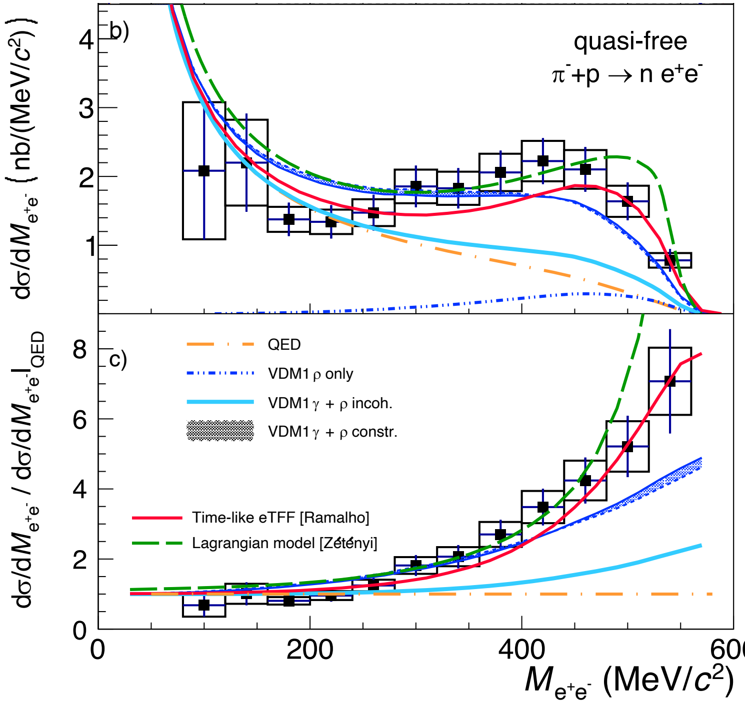
[BESIII Collaboration], PRL 130, 151905 (2023)
Nature Phys. 17 (2021) 11, 1200-1204

Massive virtual photon emission from N* resonances

- Dominance of the $N^*(1520)$ resonance at $\sqrt{s} = 1.49\ \text{GeV}$
  - $\pi^- p \rightarrow n + \pi^- + \pi^+$
    Included in PWA (Bonn-Gatchina) to provide partial wave decomposition
  - $\pi^- p \rightarrow n + e^- + e^+$
    Probe baryon resonance – nucleon transition
- Important input to calculations of the emissivity

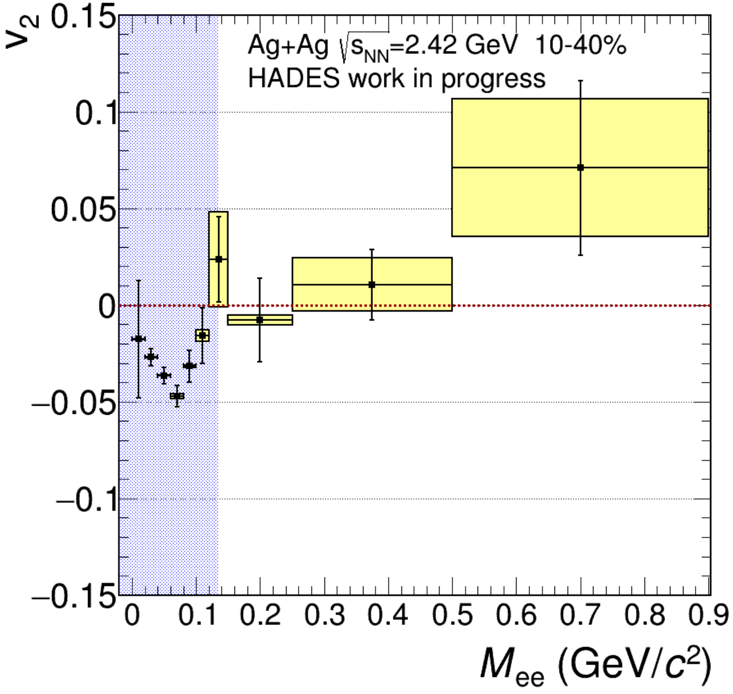
Rapp, van Hees; arXiv:1411.4612

[HADES] arXiv:2205.15914 [nucl-ex]



Elliptic flow of inclusive e^+e^- Ag+Ag $\sqrt{s_{NN}} = 2.42\ GeV$

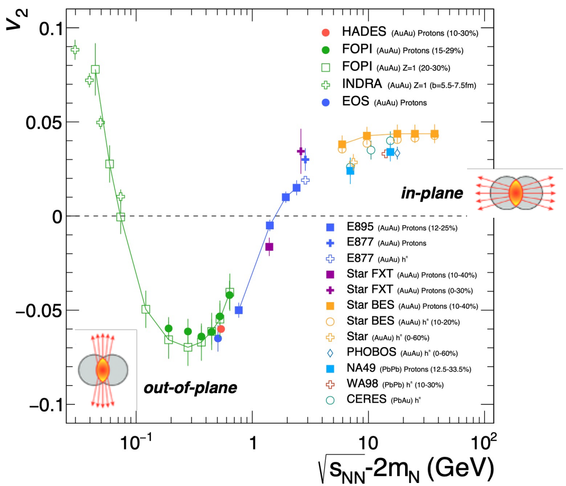
HADES, Quark Matter 2023 Highlight

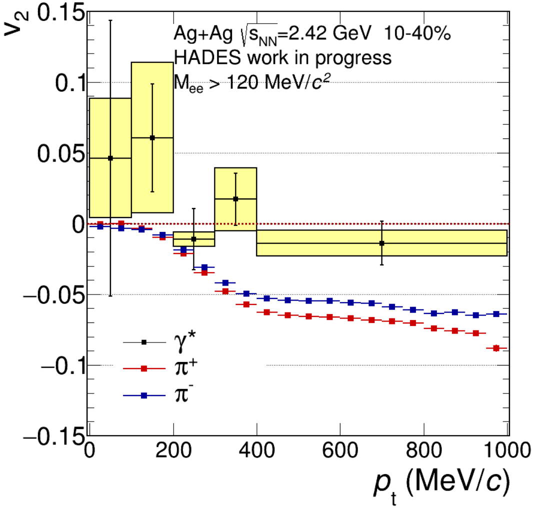


M_{e+e-}< 150 MeV/c^2 dominated by π^0-Dalitz decay → negative v_2 consistent with charged pions

v_2 consistently around zero for M_{e+e-}> 150 MeV/c^2 , seen in centrality, rapidity and p_T
→ Dileptons sensitive to early hot/dense phase

HADES, EPJA 59 (2023) 4, 80

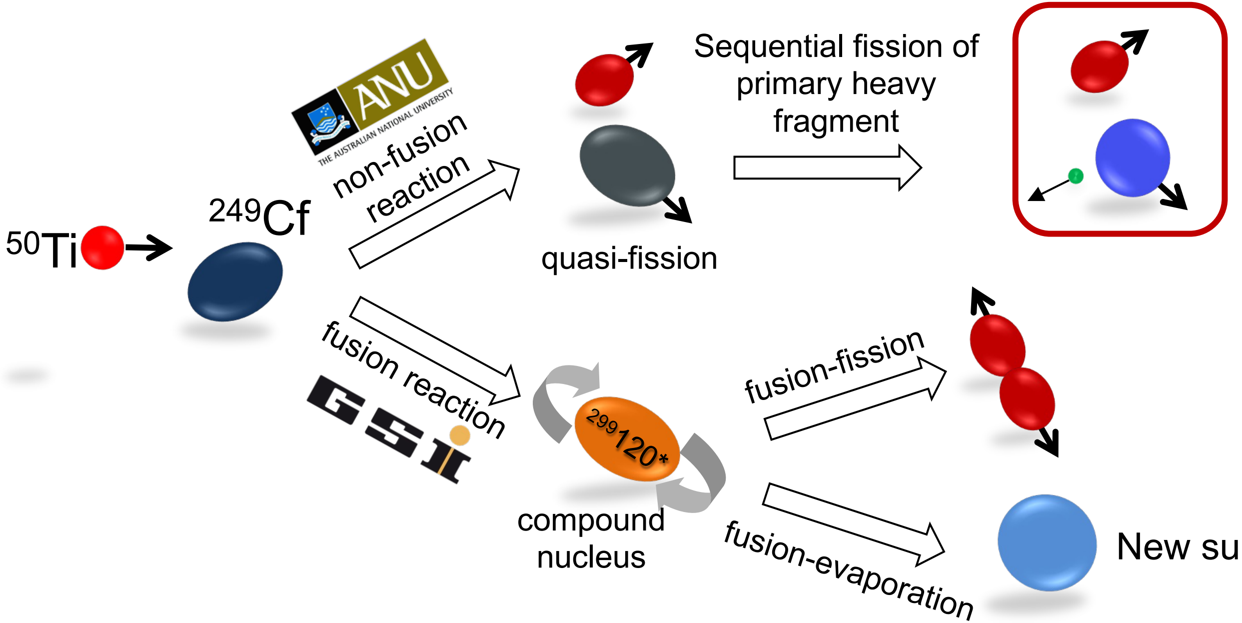




See Behruz Kardan "Decoding the EOS of neutron star-like matter via flow…"

Studies of promising nuclear reactions to synthesize new superheavy elements

Elucidating the influence of closed shells on dynamics of reactions leading to superheavy nuclei



Primary light fragment
Secondary heavy fragment (A~208)
Secondary light "fragment"

D.Y. Jeung *et al.*, PLB 837 (2023) 137641

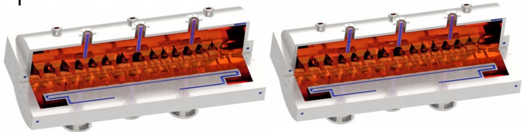
Study of non-fusion reactions at ANU: three-body reaction outcomes need to be considered!
New work accompanies:

- Element 120 search at ***TASCA***: J. Khuyagbaatar *et al.*, PRC 102 (2020) 064602
- Non-fusion studies at ***TASCA***: A. Di Nitto *et al.*, PLB 784 (2018) 199

HElmholtz LInear Accelerator Development at the HI Mainz

HIM

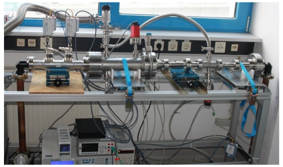
MATTER AND THE UNIVERSE

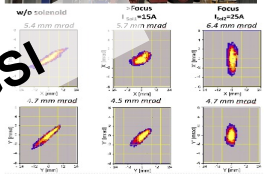


Advanced APF-IH-DTL (*HGF-Innov. Pool*)

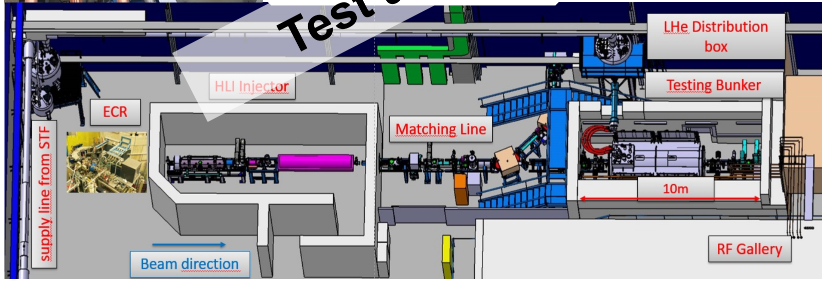
Basic HELIAC approach in preparation: ready 2028
CM1 (PoF3) & CM2 (PoF4) &CM3 (BMBF)

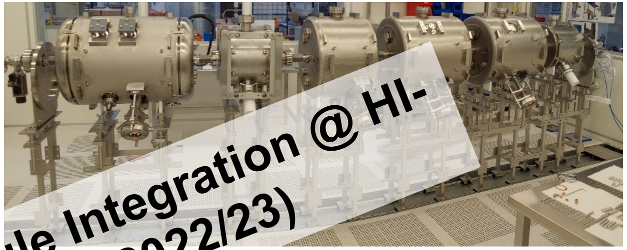
Link2UNILAC:
Beam Line magnets
(on stock)





Test area @GSI





Cryomodule Integration @ HI-Mainz (2022/23)

Theory: Spherical kilonova AT2017gfo

(em counterpart of neutron star merger GW170817)

- Detailed analysis of kilonova spectra
  - fitting of spectral lines and blackbody

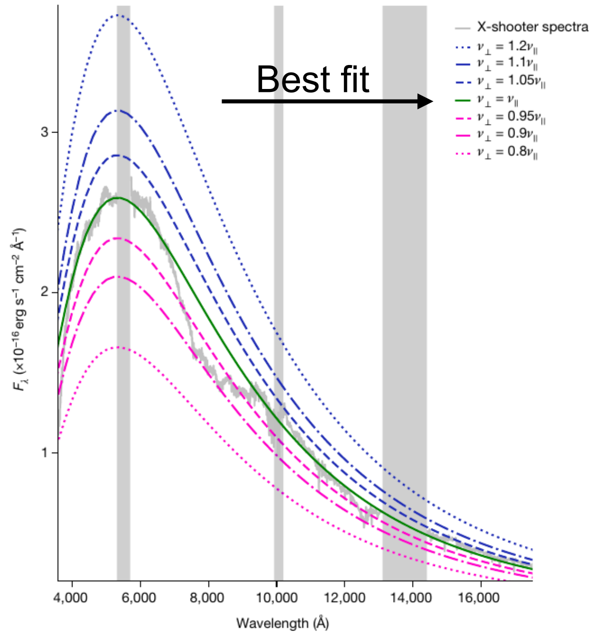
  → expansion velocities in different directions of explosion

  → point to **high degree of sphericity of merger outflow**

- Either coincidence or additional energy injection (no obvious robust mechanism)
  → constrains merger models

- Yields independent distance measure (via Stefan-Boltzmann fit)
  → best measured distance of GW170817 so far (45.5±0.6) Mpc

- Potential for measuring Hubble constant (recall current tension between cosmic microwave background and Type Ia supernovae measurements)



Sneppen, Watson, Bauswein, Just, *et al.*, **Nature** 614, 436 (2023)

See Vimal Vijayan "Impact of pions on BNS mergers"

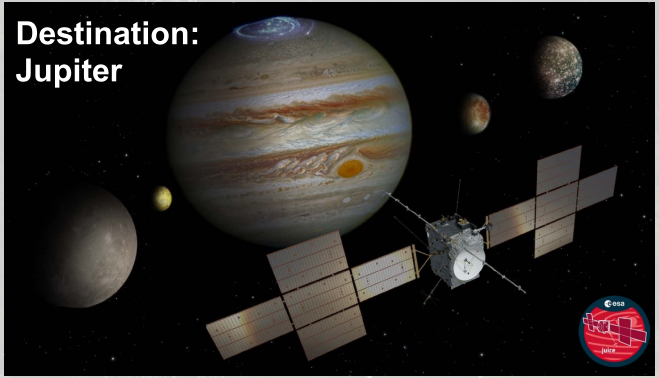
See Oliver Just "**Using simulations …**"

PADI-XII goes to space with JUICE

PADI-XII (ASIC):
Ultrafast **P**re**A**mplifier–**D**iscr**i**minator
Application **S**pecific **I**ntegrated **C**ircuit

designed at **EEL**, **DTL** and **ISS** **(Institute for Space Science, Magurele / Romania)** for the **CBM-TOF** experiment

Front-end electronics
Particle **E**nvironment **P**ackage
PEP/JDC instrument

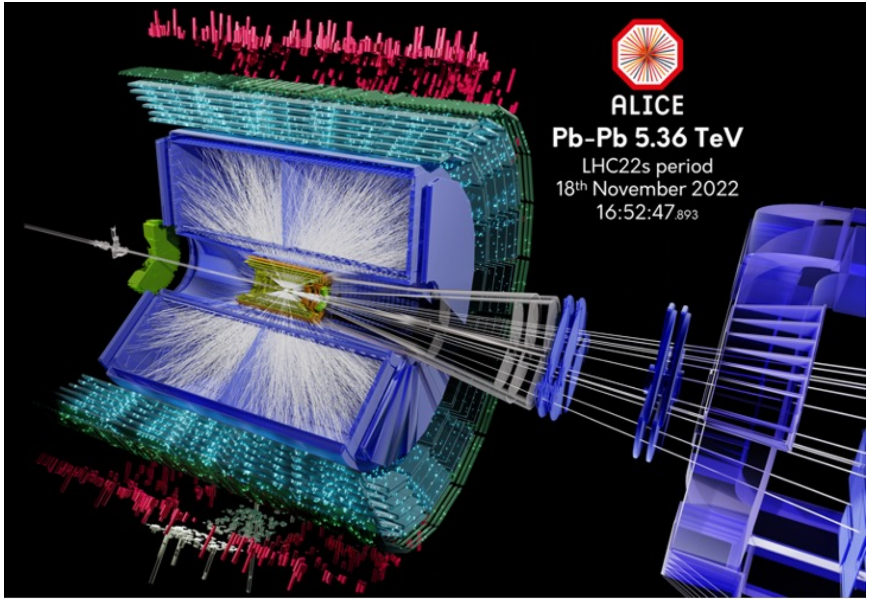


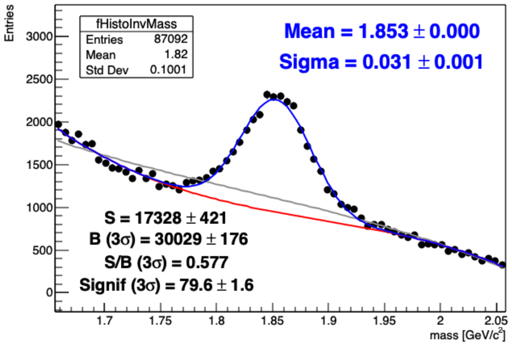
Particle spectrometer to study Jupiter's moons Ganymede, Callisto, Europa and Io, and Jupiter's magnetosphere

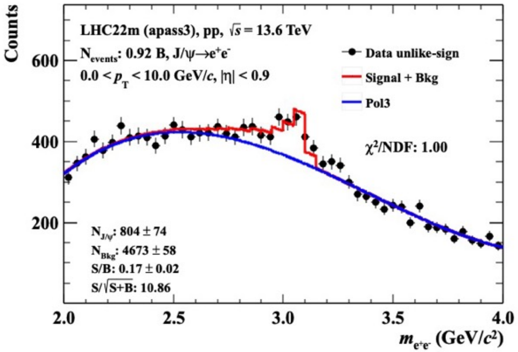
Launched 14. Apr. 2023

ALICE at LHC in Run 3

- Intensive pp data taking at √s = 13.6 TeV:
  - interaction rate 3kHz to 1 MHz
  - 15 pb^{-1} integrated luminosity
  - Pb-Pb test run





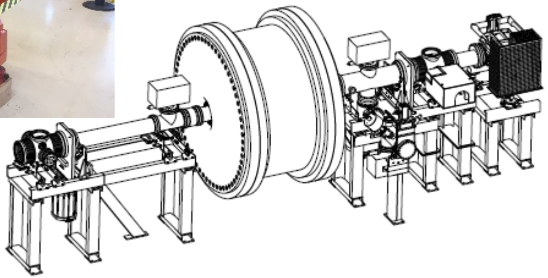


Ongoing:

- TPC calibration
- Parameterization of the specific energy loss
- QA from physics signals: D^0 (left fig.) and J/ψ (right fig.)

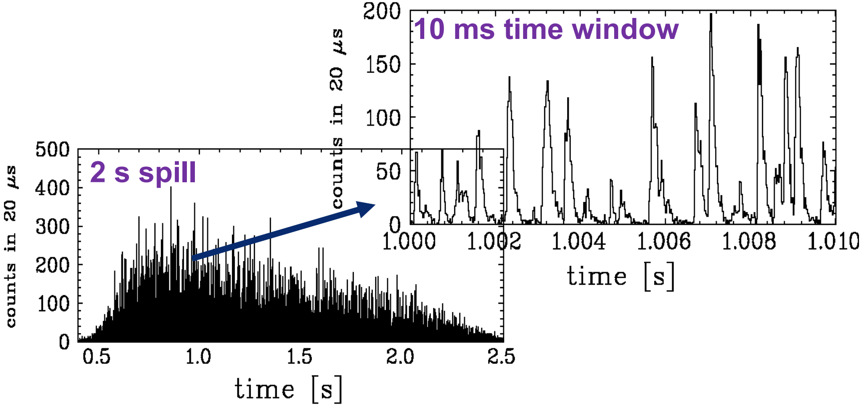
MU accelerator facilities

Spill smoothing cavity for SIS18



Slow extraction of a synchrotron beam is a complex process

- prevention of beam losses
- large span of extraction times (0.2-20 s)
- large difference between vertical and horizontal emittance
- momentum dependence of extraction parameters
- microspill structure problem for high rate experiments



Spill smoothing by rf bunching

- Tune ripple by synchrotron motion and chromaticity
- VHF spill cavity under development
- Demonstration of spill smoothing at AGS, BNL in different operation modes.
- Installation of the test cavity in shut down 2023 completed.
- High shunt impedance limits the use of the test cavity and probably also the beam intensity

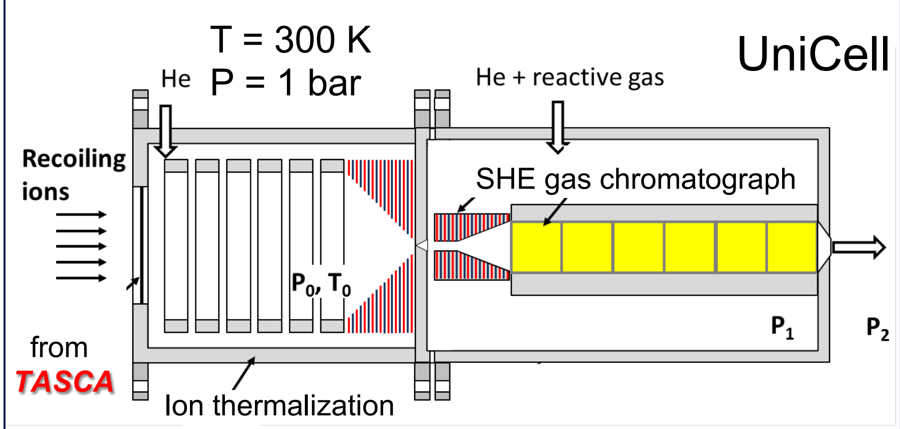
Speeding up SHE chemistry to isotopes with $T_{1/2}$ < 100 ms

UniCell: A new universal buffer gas stopping cell

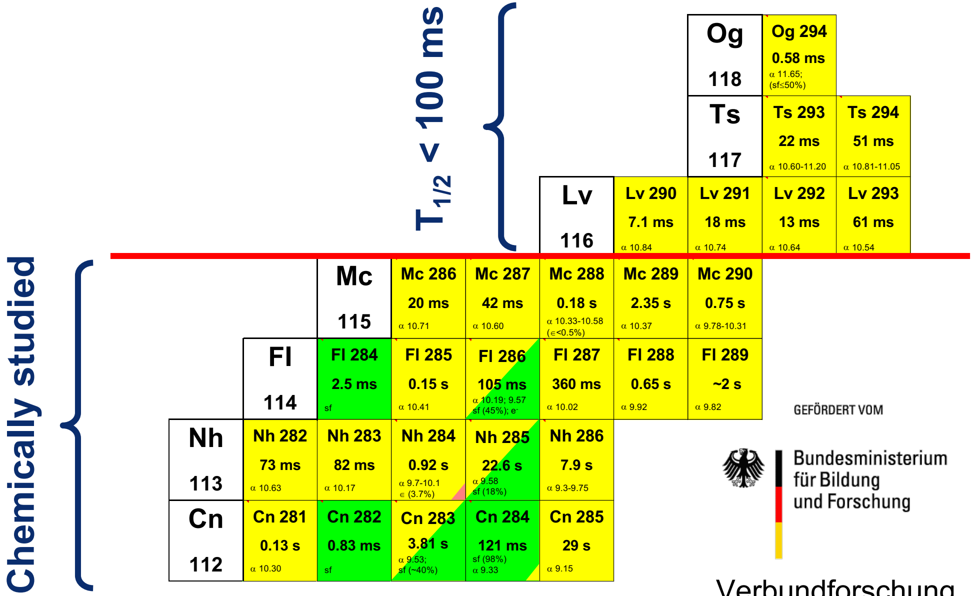
SHE Chemistry

FAIR Phase 0 Research Program

- Allows coupling of fast chemistry setups to TASCA to allow chemical studies of elements Z>115
  - Efficiency ~100%
  - Extraction time < 10 ms (simulated)



Concept: V. Varentsov, A. Yakushev; NIM A 940 (2019) 206



GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

Verbundforschung

GSI MU Computing facilities

Green-IT cube hosts a Digital Open Laboratory

Providing advanced computing capabilities to support the MU, MML and MT research programs

Compute

- CPU: ~660 server, ~54.000 cores
- GPU: 400 AMD Radeon Mi100 GPUs

Storage

- ~ 60 PByte high-performance online storage

Leading ”Green” Data Center Technology

5.5 M€ EU grant in 2022 to expand the Green-IT cube installations by two more floors

- Goal: further strengthen research and collaboration with industry within the FAIR Digital Open Lab (“Reallabor”)
- Open innovation approach to collaborate with industry and other companies

G. Otto/GSI

- High impact results from FAIR Phase 0
- FAIR Phase 0 instrumental on the way to FAIR
- Technical preparations for the next big step ongoing
- CML goes FAIR

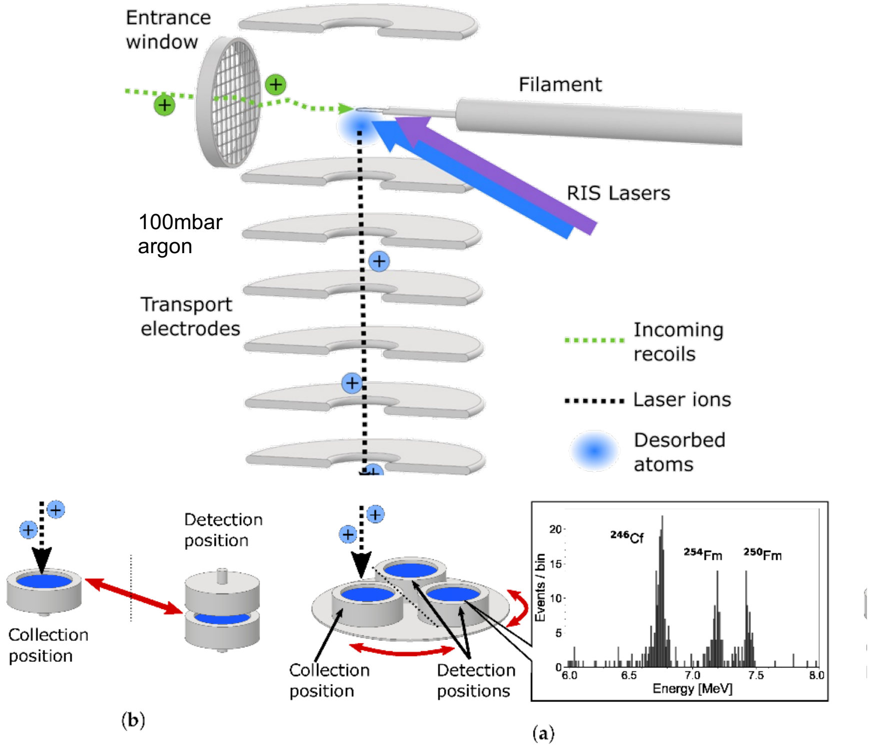
Photo: C. Betz

Thank you for your attention!

Backup

Detector Developments for Laser Spectroscopy

Extending the reach towards heavy elements



H. Backe et al. Eur. Phys. J. D, 45 (1) (2007), 99
J. Warbinek et al., Atoms 10(2) 41 (2022)

RADRIS method for (super)heavy element laser spectroscopy :

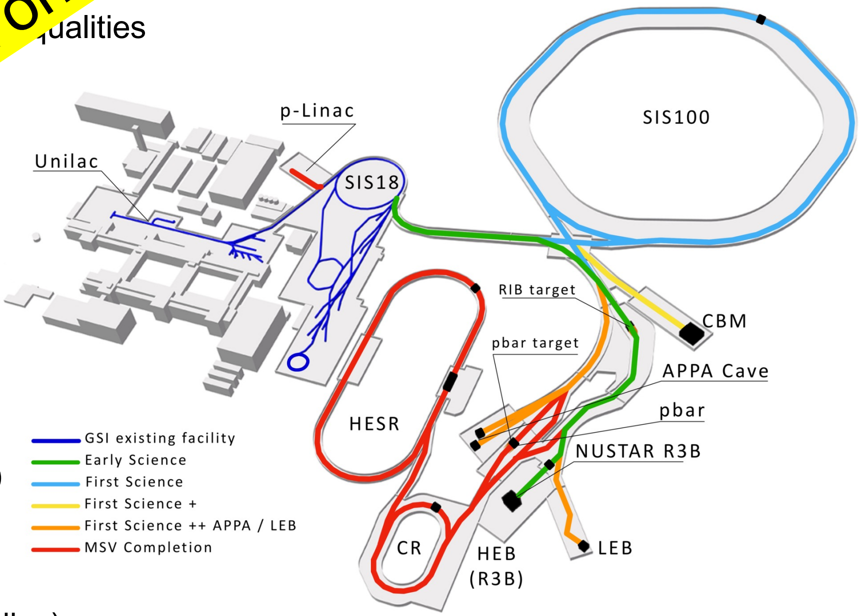
- two-step laser ionization of atoms
- lowest production rates require high efficiency and low background
- detect laser ions by characteristic (alpha) decay
- use of movable detectors increased efficiency and enabled laser spectroscopy of long-lived rare isotopes such as ^{254}Fm ($t_{1/2}$=3.2 h)

Cosmic Matter in the Laboratory

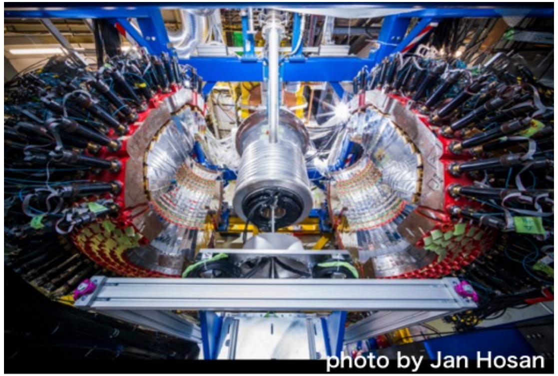
FAIR accelerator complex

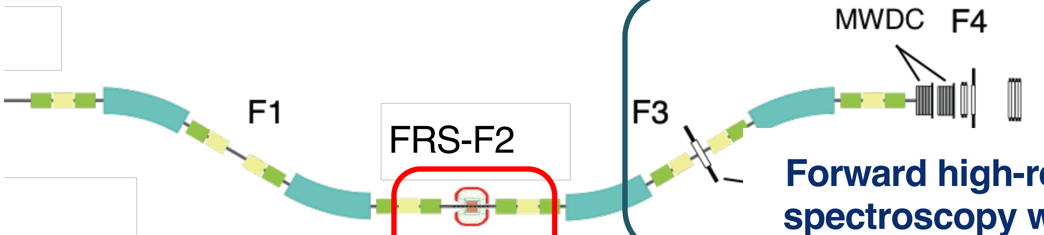
See Yvonne Leifels “Outlook on PoF 5”

- 2027 Early Science program (SIS18 beam into the S-FRS)
  - exotic nuclei available at higher qualities
- 2028 First Science/ First Science+ program (SIS100 beam will be available in the S-FRS CBM)
  - higher energies/intensities
  - more exotic nuclei accessible
- In-house experimental program focus on the available exp facilities at GSI/FAIR and
  - facilities at the Mainz and the JGU Mainz (TRIGA, MESA…)
  - participation in ALICE at LHC
  - in addition to complementary activities at other laboratories, e.g. RIKEN, TRIUMF, participation in JUNO (solar neutrino studies)



Application of AI-methods in Data Analysis of WASA-FRS Experiments





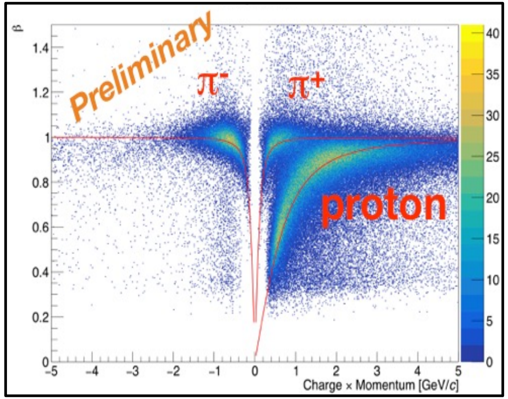
Forward high-resolution spectroscopy with FRS

Decay particle measurement

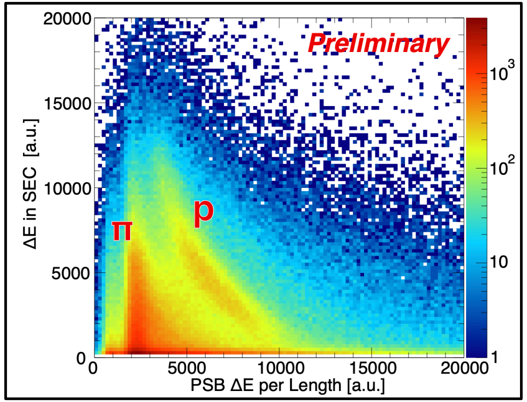
WASA

WASA+FRS combined analysis is ongoing

Achieved WASA Particle ID with Momentum vs β (left) and E vs ΔE (right)



Y. K. Tanaka et al., Acta Phys. Pol. B Proc. Suppl.16, 4-A27 (2023)



Development of Track Finder with Graph Neural Network

Development of machine learning analyses with graph neural network for the WASA-FRS experiment

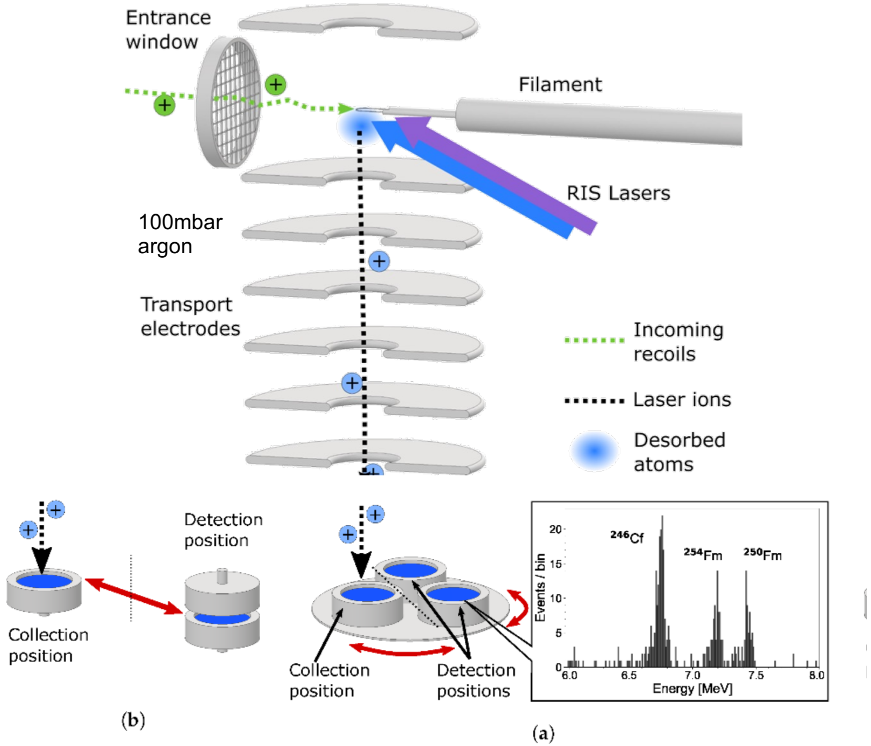
H. Ekawa[1], W. Dou[1,2], Y. Gao[1,3,4], Y. He[1,5], A. Kasagi[1,6], E. Liu[1,3,4], A. Muneem[1,7], M. Nakagawa[1], C. Rappold[8], N. Saito[1], T. R. Saito[1,9,5], M. Taki[10], Y. K. Tanaka[1], H. Wang[1], and J. Yoshida[1,11]

1 High Energy Nuclear Physics Laboratory, Cluster for Pioneering Research, RIKEN, Wako, Japan.
2 Department of Physics, Saitama University, Saitama, Japan.
3 Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China.
4 University of Chinese Academy of Sciences, Beijing, China.
5 School of Nuclear Science and Technology, Lanzhou University, Lanzhou, China.
6 Graduate School of Engineering, Gifu University, Gifu, Japan.
7 Faculty of Engineering Sciences, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Topi, Pakistan.
8 Instituto de Estructura de la Materia, Consejo Superior de Investigaciones Científicas (CSIC), Madrid, Spain.
9 GSI Helmholtz Center for Heavy Ion Research, Darmstadt, Germany.
10 Graduate School of Artificial Intelligence and Science, Rikkyo University, Tokyo, Japan.
11 Department of Physics, Tohoku University, Sendai, Japan.

H. Ekawa et al., Accepted in EPJA (2023 April)

Detector Developments for Laser Spectroscopy

Extending the reach towards heavy elements



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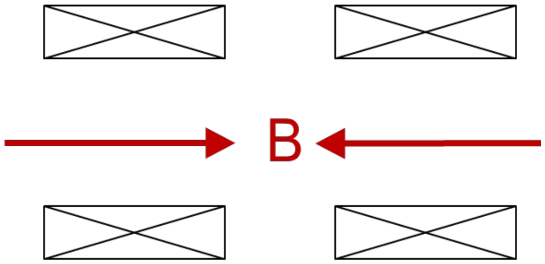
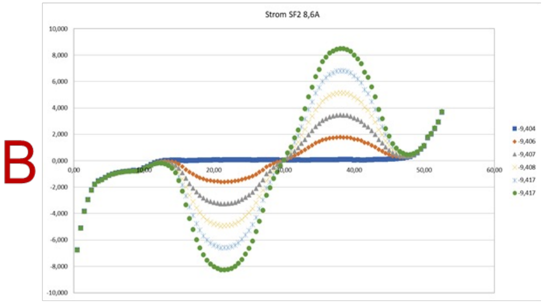
FAIR Forschung NRW (IKP Jülich)
A new method to induce hyperpolarization

MU-CML
MATTER AND THE UNIVERSE

Sona Coils





<u>Patent:</u> (Deutsche Patentanmeldung 102022213860.0)

“A method and an apparatus to produce polarized atoms, molecules and their ions”

<u>Possible Applications</u>

1.) New types of polarized ions sources for accelerators

A polarized $^3He^+$ source will be tested at COSY in Sep. 2023

2.) Polarized fuel for fusion reactors

First test to polarize an intense deuterium beam in Oct. 2023

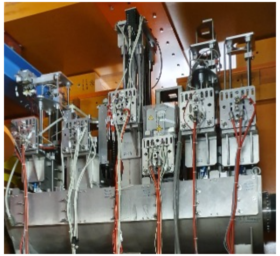
3.) Polarized molecular D_2 beams

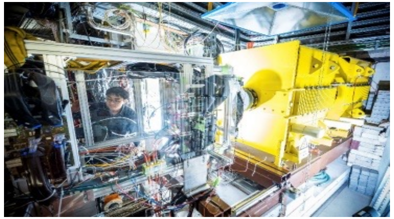
Collab. with Uni. Swansea / Accumulation and storage as pol. ice

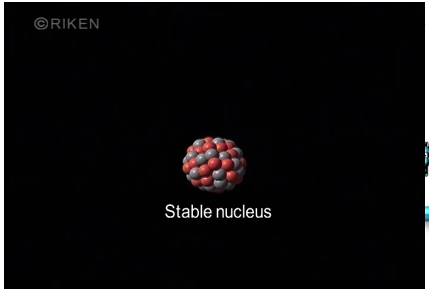
4.) Under discussion: Medical tracer, new type of MRI, ….

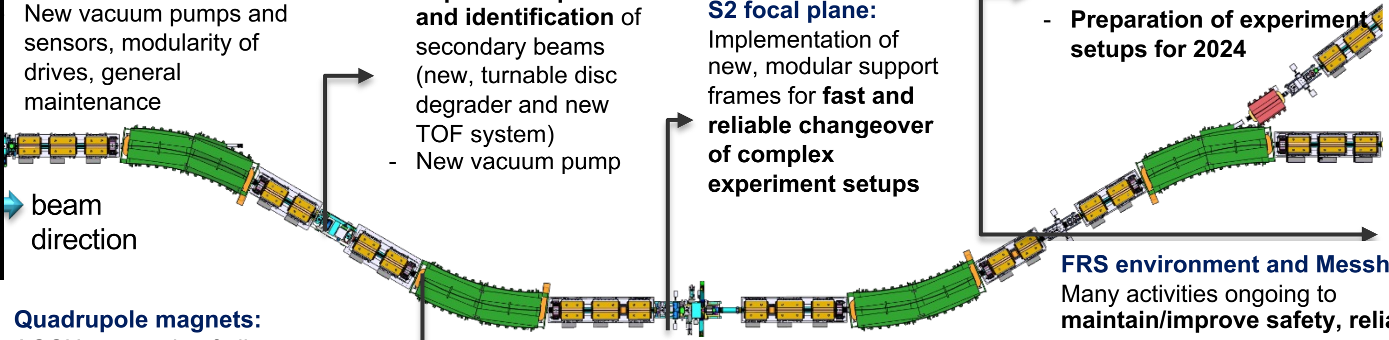
Fragmentseparator

Separation and identification of exotic ions









beam direction

Target Area:
- **Preparation for complete remote handling**
  New vacuum pumps and sensors, modularity of drives, general maintenance

S1 focal plane:
- **Improved separation and identification** of secondary beams (new, turnable disc degrader and new TOF system)
- New vacuum pump

S2 focal plane:
Implementation of new, modular support frames for **fast and reliable changeover of complex experiment setups**

S4 focal plane
- Preparation of detectors for test run in Nov. 2023
- **Preparation of experiment setups for 2024**

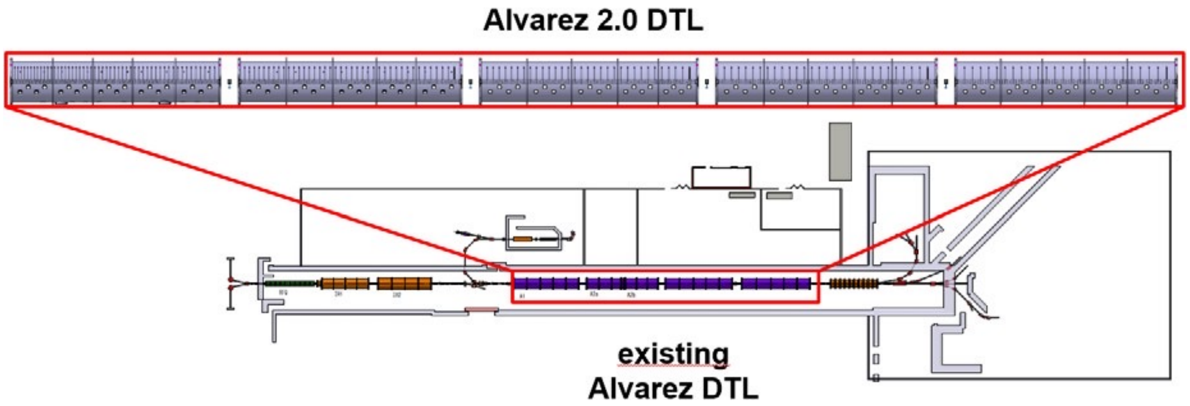
Quadrupole magnets:
ACCU - upgrade of all power supplies (in order to **stay compatible with FAIR control system**)

Steppermotors and insertions:
64-channel COSYLAB system available; installation in 2024

FRS environment and Messhütte:
Many activities ongoing to **maintain/improve safety, reliability** of all technical areas and sub-systems
DAQ: Upgrade to higher rate capability ongoing

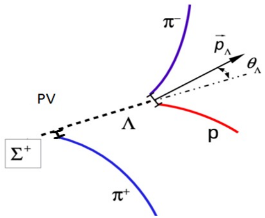
MU accelerator facilities

UNILAC post stripper upgrade



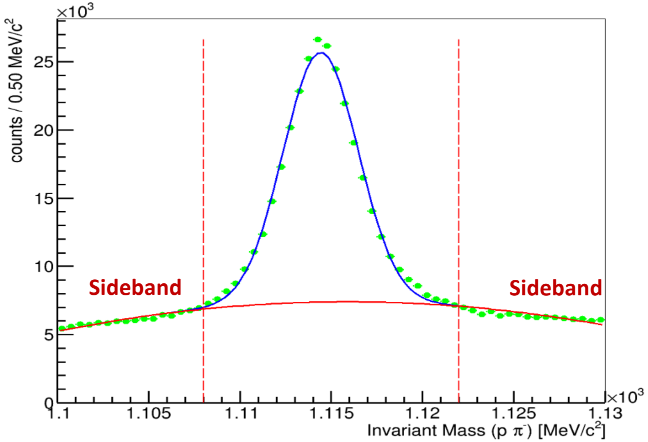
- Replacement of old drift tube linac DTL
  - intensity requirements of FAIR
  - reducing operation risk
- Recent highlight
  - all tanks for 1st section are ready for delivery

Σ(1385) reconstruction p+p 4.5 GeV



Study Dalitz decays of Λ(1520)/Σ(1385) → Λe^+e^- allow for first measurement of hyperon form factors in time-like region

Λ selection enhanced by Machine Learning



Breit-Wigner + background fit:

- $M_{\Sigma(1385)}$ = 1378.17 +/- 0.40 MeV/c^2
- $\Gamma_{\Sigma(1385)}$ = 28.042±0.99 MeV/c^2