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FRIB, RIBF@RIKEN and SPIRAL2 long-term plan

Alexandre Obertelli, TU Darmstadt

KhUK meeting
December 9th-10th, 2021

Nuclear physics with radioactive beams

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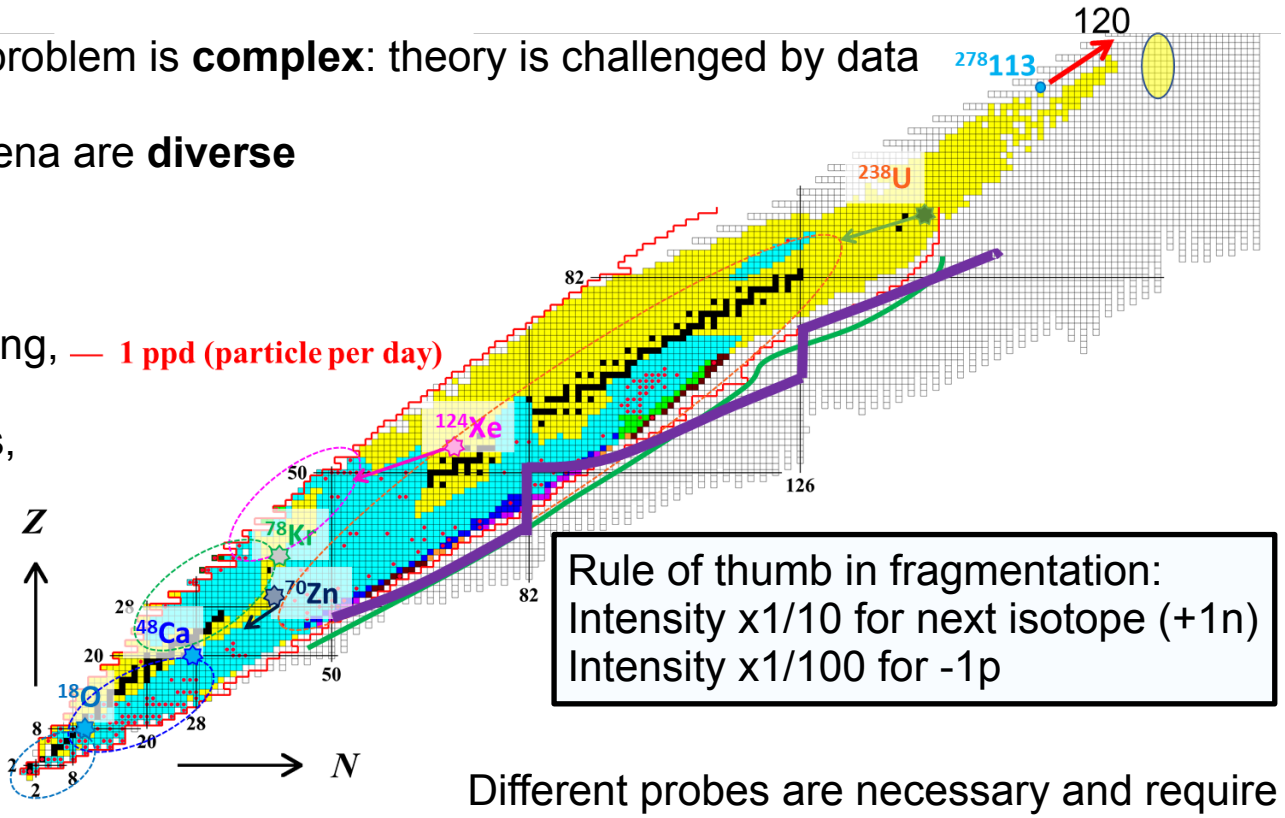
The exploration nuclear structure as a function of mass, isospin and binding energy requires dedicated Radioactive Isotope Beam (RIB) facilities

The nuclear many-body problem is **complex**: theory is challenged by data

Nuclear physics phenomena are **diverse**
- shell structure,
- halos, neutron skins,
- shapes,
- correlations and clustering,
- collective states,
- astrophysical processes,
- reactions,...



Rule of thumb in fragmentation:
Intensity x1/10 for next isotope (+1n)
Intensity x1/100 for -1p

Different probes are necessary and require **different beam intensities and energies**

The evolution of RIB facilities worldwide

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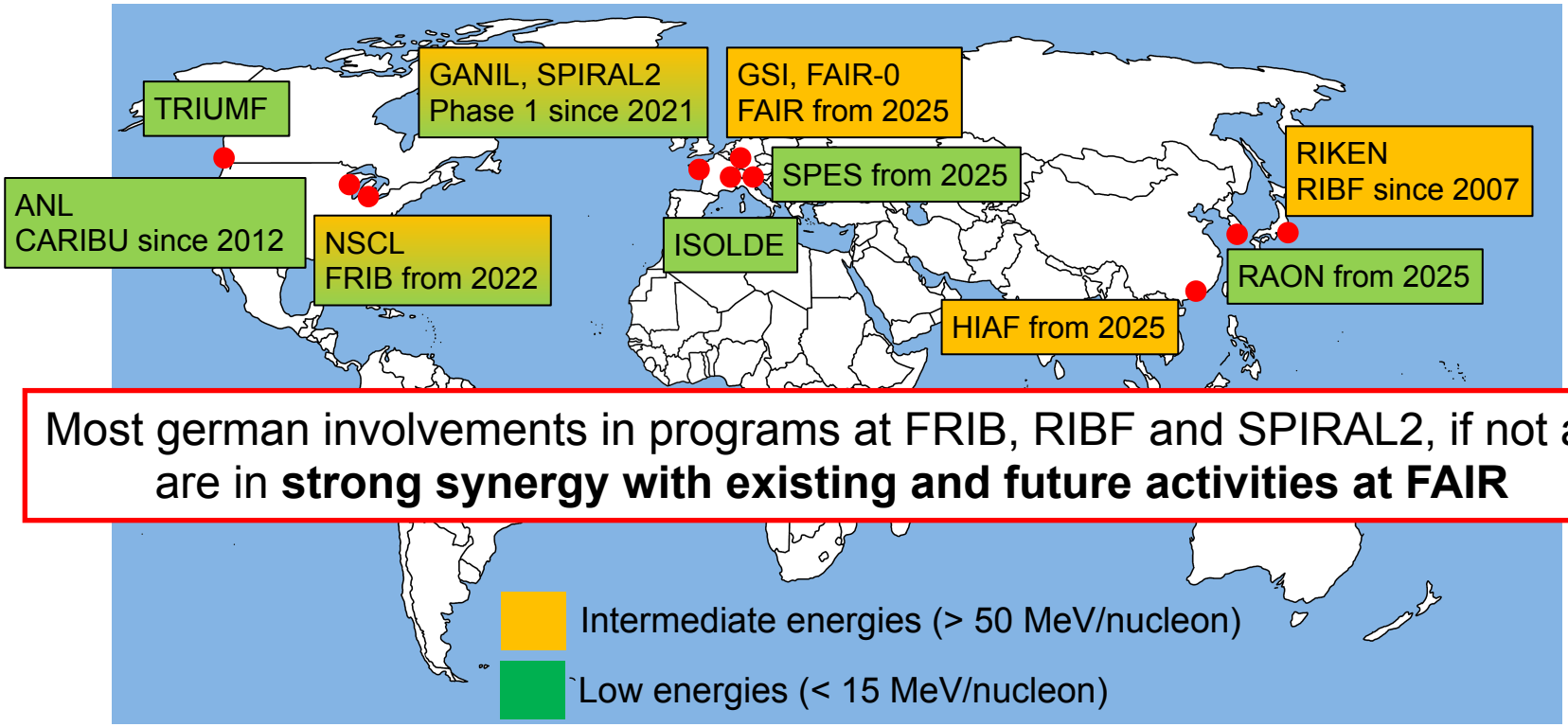
1980s: first generation RIB facilities
Early 2000s: plans for new generation facilities
Since **2007**: Radioactive Isotope Beam Factory of RIKEN (Japan)
2020s (now): new generation facilities coming online



Most german involvements in programs at FRIB, RIBF and SPIRAL2, if not all, are in **strong synergy with existing and future activities at FAIR**

The Radioactive Isotope Beam Factory, RIKEN

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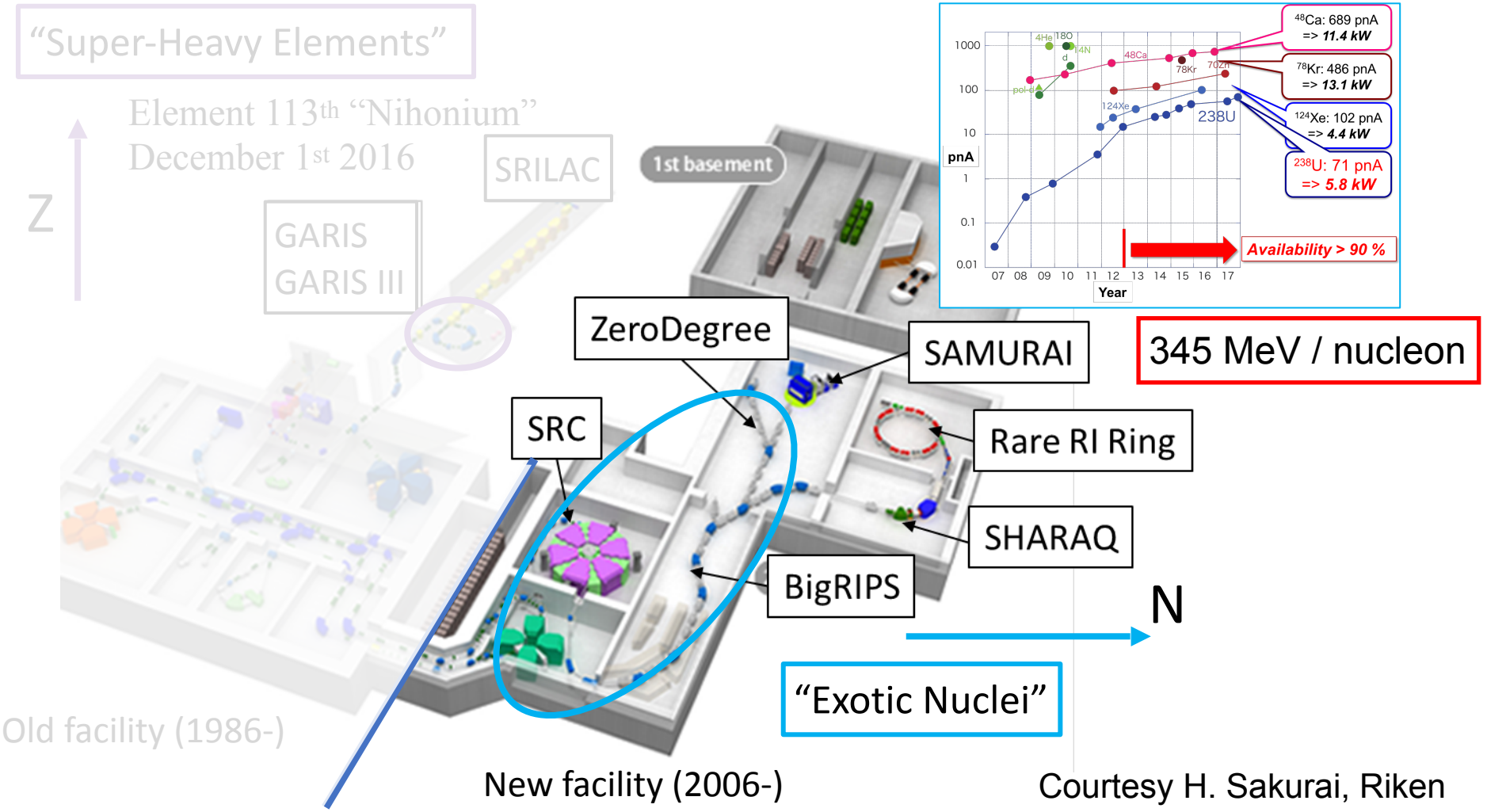

Courtesy H. Sakurai, Riken

Highlights of 2021 (Director's cut)

Courtesy H. Sakurai, Riken

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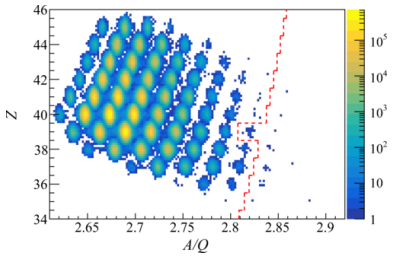
New Isotopes:

Observation of new neutron-rich isotopes
^{101}Br, ^{102}Kr, ^{105,106}Rb, ^{108}Sr, ^{110,111}Y, ^{114}Zr, ^{117}Nb (PRC)



Shell Evolution :

Shape Changes in the Mirror Nuc
^{70}Kr and ^{70}Se (PRL)

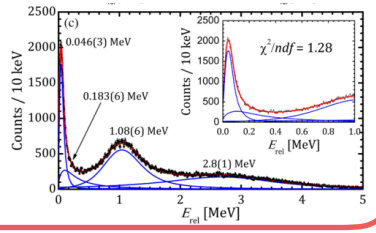
Pairing Forces Govern Population of Doubly Magic ^{54}Ca from Direct Reactions (PRL)

β decay of neutron deficient ^{60}Ge and ^{62}Ge nuclei (PRC)

Three-quasiparticle isomers in ^{159,161}Pm (PRC/L)

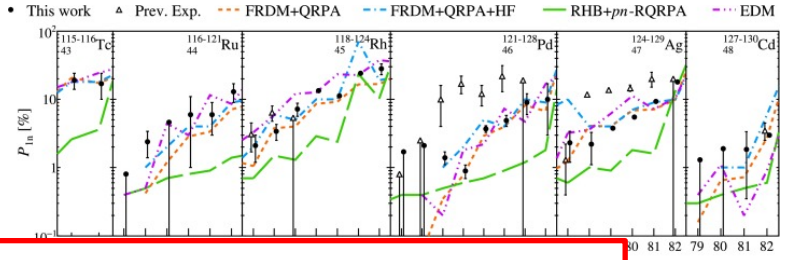
Neutron correlation:

Quasi-free Neutron Knockout Reaction for invariant-mass spectroscopy of ^{16}B (PRL)



r-process nucleo-synthesis:

beta-delayed neutron emission of r-process nuclei at the N=82 shell closure (PLB)



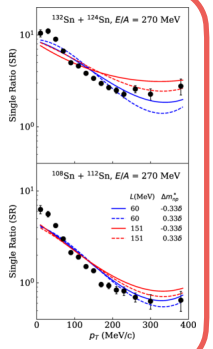
2/3 with contribution from German institutions

er:

Probing the Symmetry Energy with the Spectral Pion Ratio (PRL)

Symmetry energy investigation with pion production (PLB, highly cited paper)

Rapidity distrib. of Z=1 isotopes (PLB)



Mass measurement in the HE and SHE region:

First high-precision direct determination of the atomic mass of a superheavy nuclide(PRC)

$^{206, 207g, m}$Ra using an alpha-TOF detector (PRC)

HICARI
HIgh-resolution Cluster Array at the RIBF

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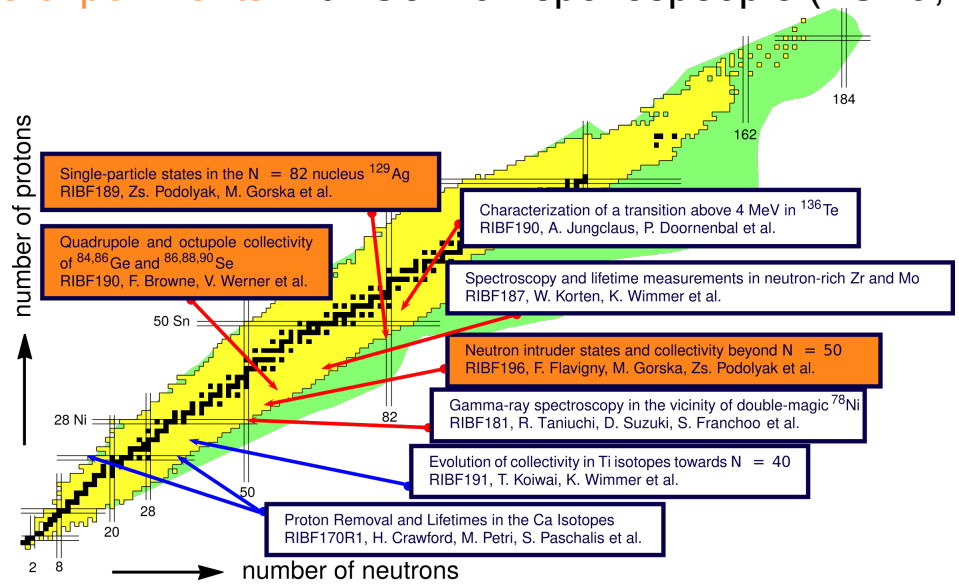
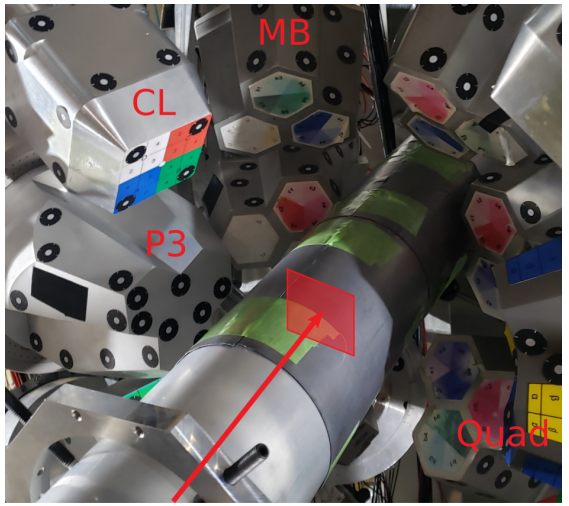
Strong connection with HISPEC/NUSTAR

International hybrid HPGe array with German key contributions:
- 8 Miniball clusters (TUDa, U Köln, GSI)
- mechanical support and frame (U Köln)
- expert support for installation at RIKEN (U Köln)

Resolving power significantly improved, broad physics program
3 experiments with German spokespeople (TUDa, GSI)



Courtesy K. Wimmer, GSI



spokespersons: P. Doornenbal and K. Wimmer
funding: JSPS KAKENHI, RIKEN, RCNP

New: lifetime measurements with solid active targets to explore collectivity in islands of Inversion and shell closures in exotic nuclei

At RIBF first, then at FAIR

K. Wimmer, GSI
ERC CoG, LISA

European Research Council
Established by the European Commission

Correlation studies at SAMURAI, SFB1245

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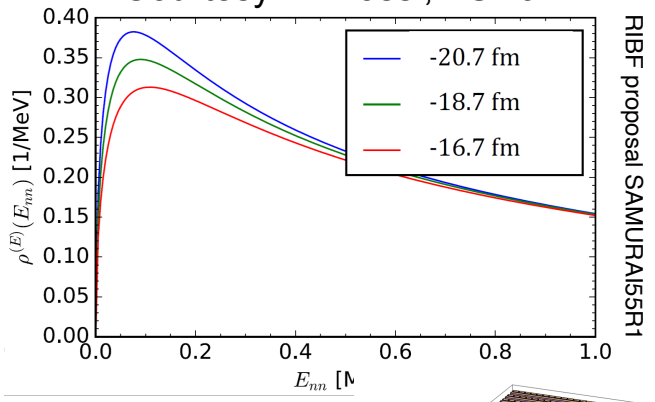
Strong connection with R3B/NUSTAR

Multi-neutron correlations at the dripline
(PIs: T. Aumann, D. Rossi, TUDa)

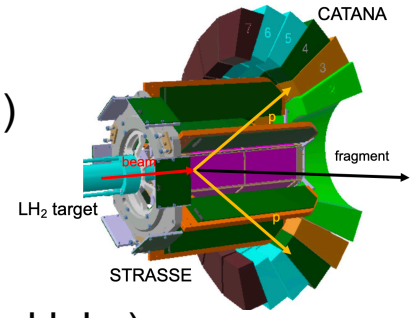
- Search for tetraneutron via ^{8}He(p,pα)4n (performed in 2017, submitted to publication)
- NN-scattering length via ^{6}He(p,pα)2n (accepted, TUDa)
- NN correlations in the ^{26}O g.-s. decay (accepted, TUDa)
- development of ***HIME***, high-granularity neutron detector

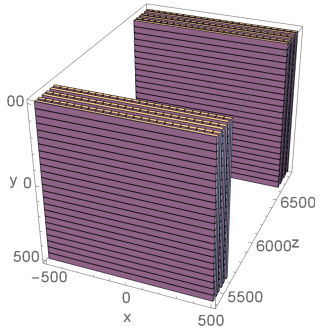
Courtesy D. Rossi, TUDa



Structure of neutron-rich nuclei via direct reactions
(PIs: A. Obertelli, H. Liu, TUDa)

- Evidence of second 0^{+} state in ^{54}Ca (accepted, TUDa)
- Momentum distribution of deeply-bound nucleons (accepted, TUDa)
- development of ***STRASSE***, a Si tracker + LH2 target (collaboration with GSI/FAIR, TUM + other international labs)





FAIR GSI TUM STRASSE Alexander von Humboldt Stiftung/Foundation

Funded by DFG SFB 1245

Mass measurements and isomer research

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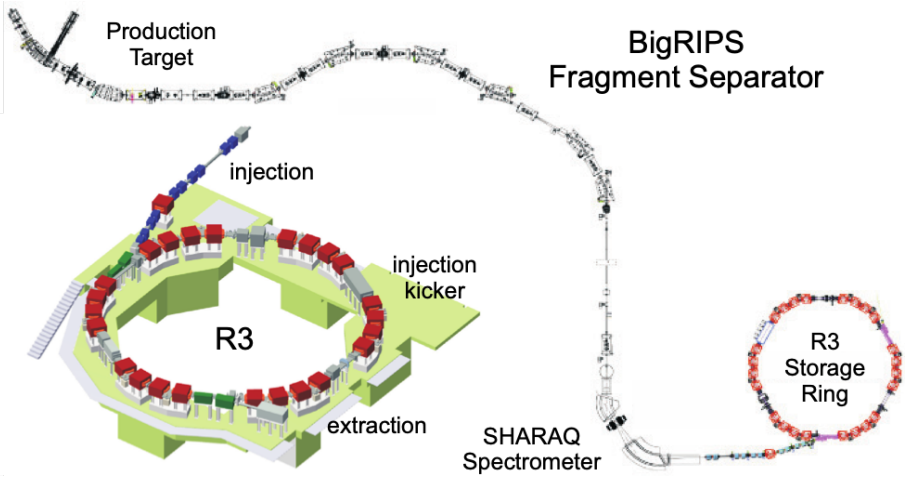
Mass measurement of r-process nuclei at BigRIPS + R3 ring



- Single-particle sensitivity, pre-selection in BigRIPS
- GSI and MPIK groups contribute with expertise in non-destructive in-ring particle detectors
- First experiments in 2018

Isomer research at the KISS facility (KEK project on RIKEN site)

- KISS: production of heavy neutron-rich nuclei close the the r-process path via multi-nucleon transfer at low energy
- Short-term: several proposals submitted to the RIKEN NP-PAC
- Longer term: participation in KISS-II upgrade
- Synergy with low-energy branch program at GSI/FAIR.

Courtesy Y. Litvinov, GSI

The RIBF long-range plan

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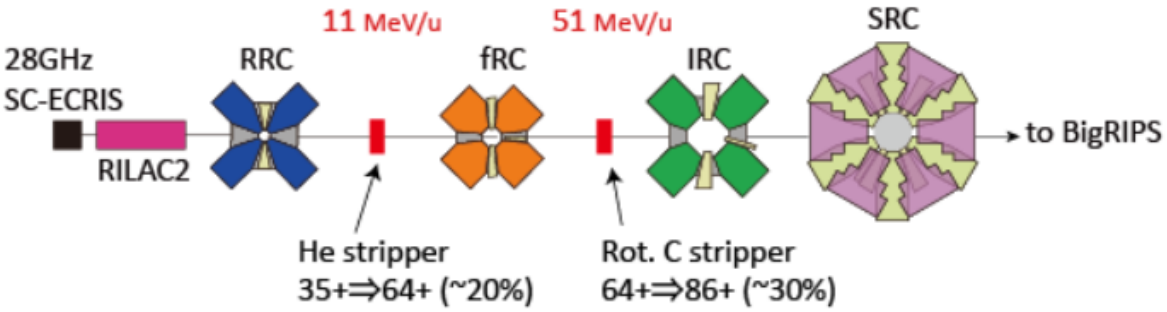
Present Acceleration Scheme

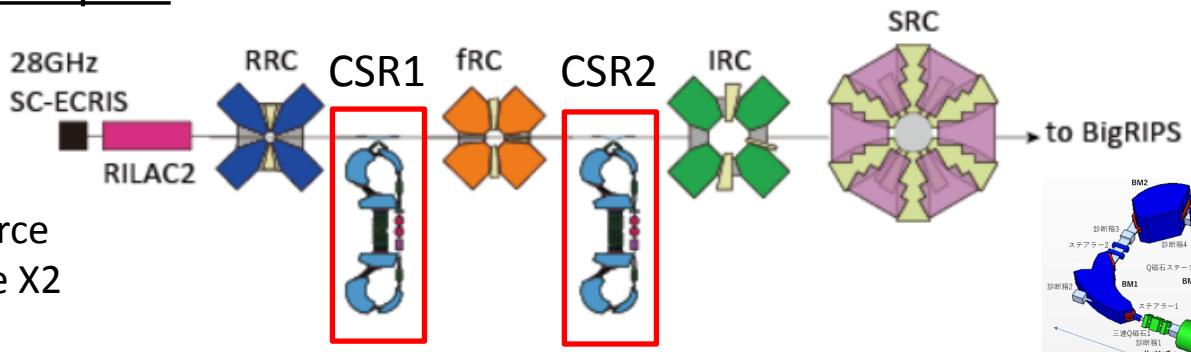


100 pnA

x20

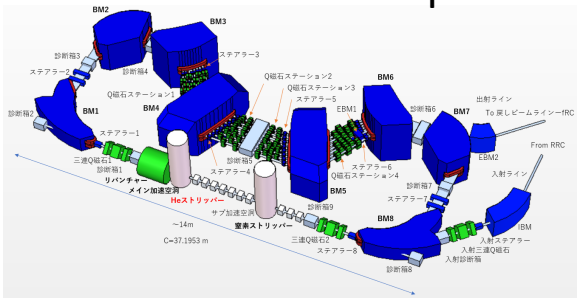
Large loss at the strippers : transmission efficiency is about 6%

Upgrade plan



2000 pnA

Ion-source upgrade X2



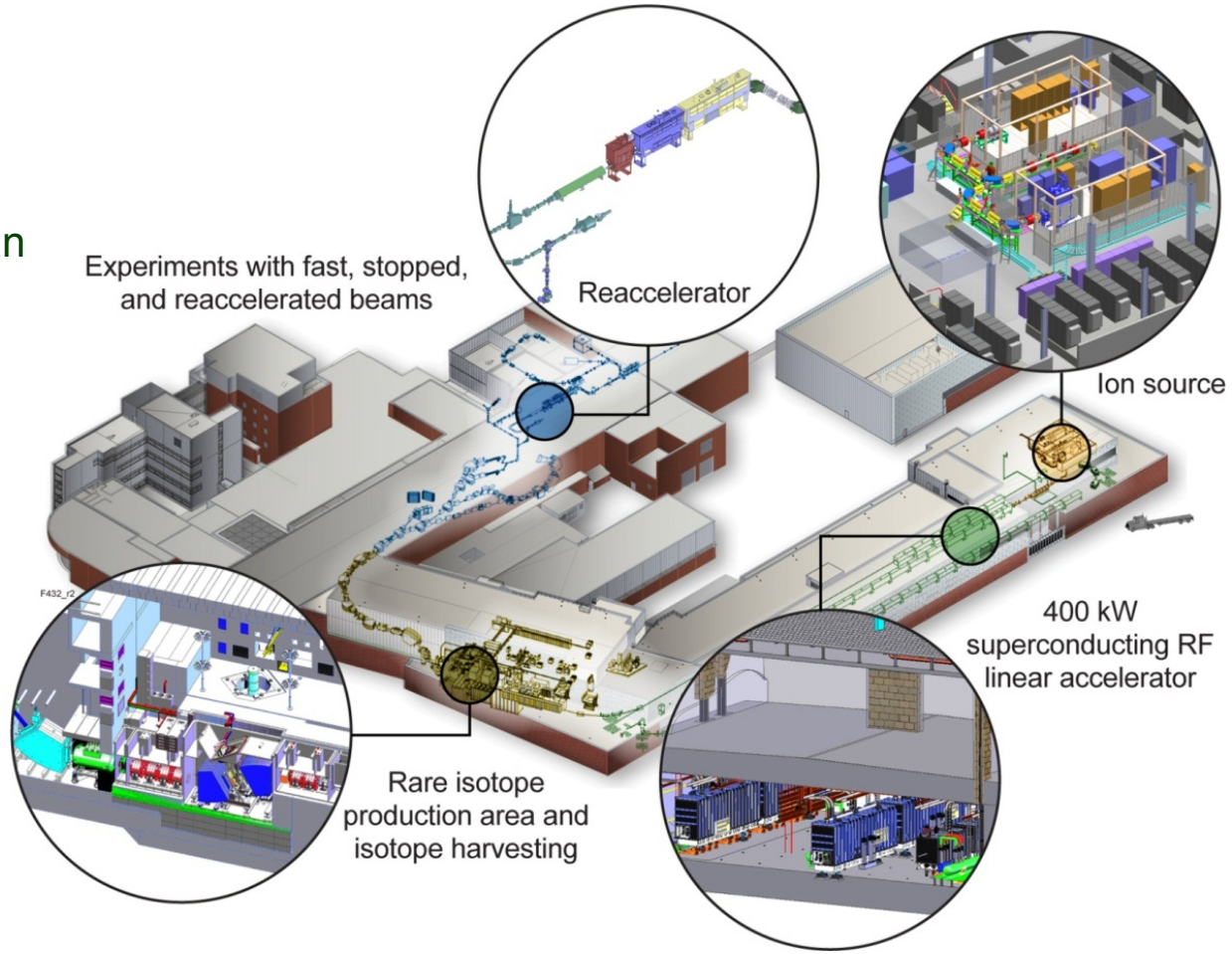
Charge Stripper Rings : beam recycling technology to increase transmission efficiency by a factor of 10

Requesting the construction budget now

Courtesy H. Sakurai, Riken

Facility for Rare Isotope Beams

- Funded by DOE Office of Science Office of Nuclear Physics, Michigan State University and State of Michigan
- Key Feature is **400 kW beam power** (5 x10^{13} ^{238}U/s)
- Primary beams accelerated to **200 MeV/n**. Facility sized for future upgrade to 400 MeV/n (upgrade not funded).
- Separation of isotopes in-flight
  - Fast development time for any isotope
  - Suited for all elements and short half-lives
  - Fast, stopped, and reaccelerated beams



Courtesy A. Gade, MSU, FRIB

FRIB Technical Construction 2014 – 2021
Beam Commissioned through the Entire Accelerator in 2021

Milestones	Date
DOE and MSU cooperative agreement	Jun 2009 ✔
CD-1: preferred alternatives decided	Sep 2010 ✔
CD-2/CD-3a: performance baseline, start of civil construction & long lead procurement	Aug 2013 ✔
CD-3b: start of technical construction	Aug 2014 ✔
FRIB linac construction completion	May 2021 ✔
Planned project construction completion	Jan 2022

FRIB PAC1 met in August 2021 and recommended experiments for early FRIB Science

FRIB user operation anticipated to commence in Spring 2022

- FRIB linac includes the front end and 46 superconducting RF cryomodules
  - Electron Cyclotron Resonance (ECR) ions source, Radio Frequency Quadrupole (RFQ)
  - 324 SRF cavities; 69 SC solenoids
  - Beam velocity β from 0.041 to 0.53
- Liquid helium for 2 K, 4 K operations
- Liquid lithium for charge stripping

FRIB Estimated Rates Available Online

Select the PAC number or ultimate yield

- ○ PAC One
- ○ PAC Two
- ◉ Ultimate FRIB yields

Enter values for A and Z

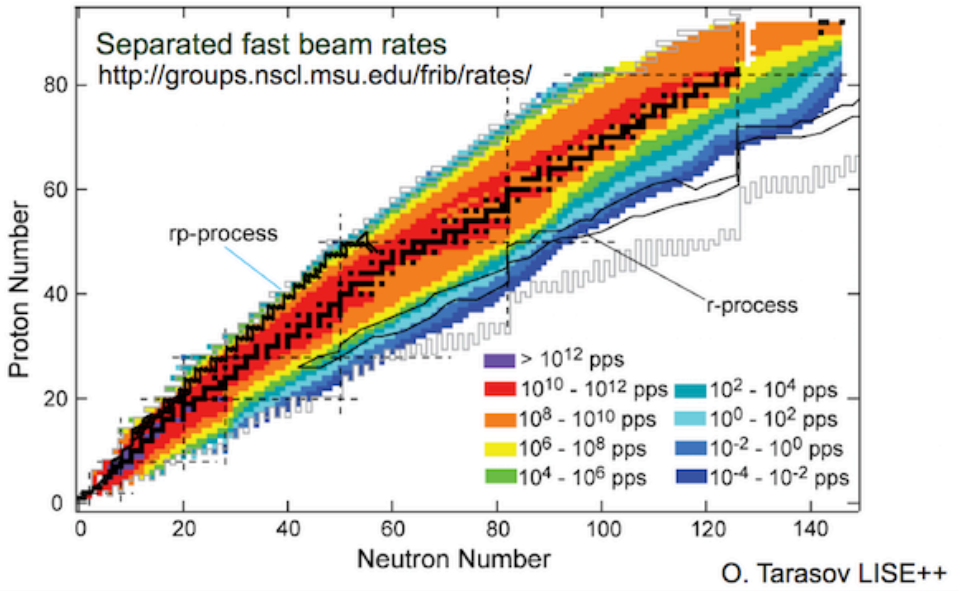
A	79	
Z	29	
N	50	
	Cu	
$T_{1/2}$	1.880e-1	sec
	Calculate Yield	

Beam

AZ	238U_fission	
Energy	203	MeV/u

Fragment

Energy	175.5	MeV/u
B_ρ (Q=Z)	5.435	Tm
Fast beam rate	4.72e+2	pps
Stopped beam rate	2.08e+2	pps
Reaccelerated beam rate	4.42e+1	pps



A comparison to RIBF, RIKEN:
RIBF today: ^{79}Cu @ 200 MeV/n: 40 pps, ultimate FRIB: ^{79}Cu @ 175 MeV/n: 472 pps

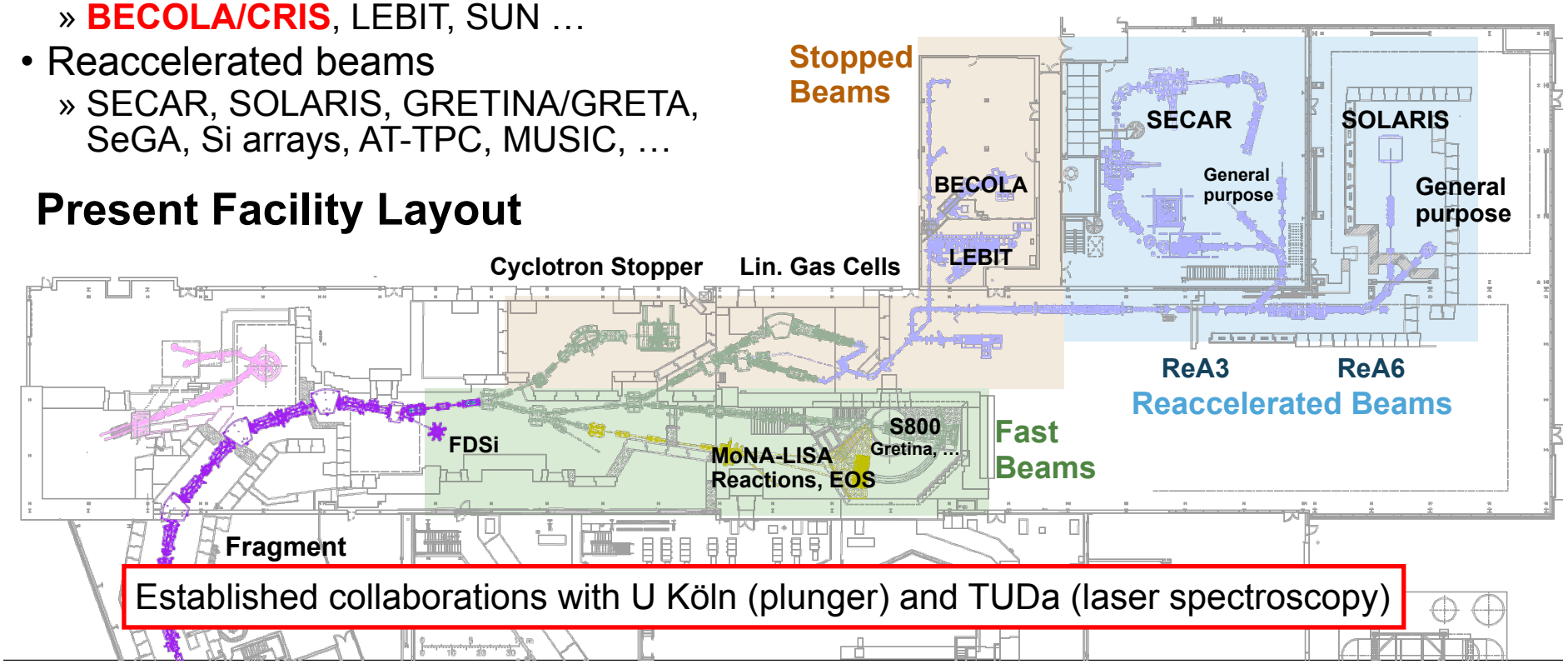
Scaled from R. Taniuchi et al., Nature 569 (2019)

FRIB Has Fast, Stopped, and Reaccelerated Beams

- Enables science with fast, stopped, and reaccelerated beams from projectile fragmentation – world-unique feature of FRIB

  - Fast beams
    - » Experiments with **S800**, GRETINA/GRETA, HiRA, CAESAR, FDSi, MoNA-LISA and others
  - Stopped beams
    - » **BECOLA/CRIS**, LEBIT, SUN …
  - Reaccelerated beams
    - » SECAR, SOLARIS, GRETINA/GRETA, SeGA, Si arrays, AT-TPC, MUSIC, …

Present Facility Layout



Established collaborations with U Köln (plunger) and TUDa (laser spectroscopy)

FDSi: FRIB Decay Station Initiator

BECOLA: hyperfine structure at NSCL/FRIB

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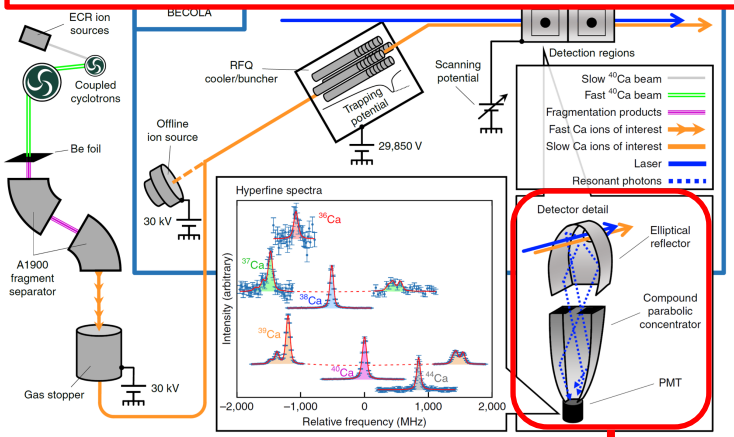
Strong connection with LASPEC/NUSTAR

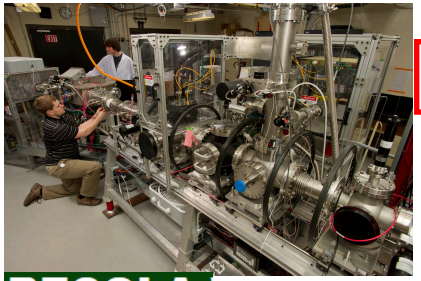


BECOLA is the first (still the only) **collinear laser spectroscopy** setup at an in-flight facility.

- Complementary to ISOL facilities, like ISOLDE
- Operating conditions similar to LASPEC@FAIR
- No fast switching between isotopes, requires additional calibration measures [PRA 103, 032806 (2021)]

Highlights: $^{53\text{-}54}$Fe [PRL 117, 252501 (2016)], $^{36\text{-}39}$Ca [Nat. Phys. 15, 432(2019)], ^{54}Ni [PRL 127, 182503(2021)], ^{55,56}Ni, ^{40}Sc, ^{32}Si [to be published]

Optical detection developed for LASPEC@FAIR, first on-line application at BECOLA



BEam COoler and LAser spectroscopy facility

https://groups.nscl.msu.edu/becola/

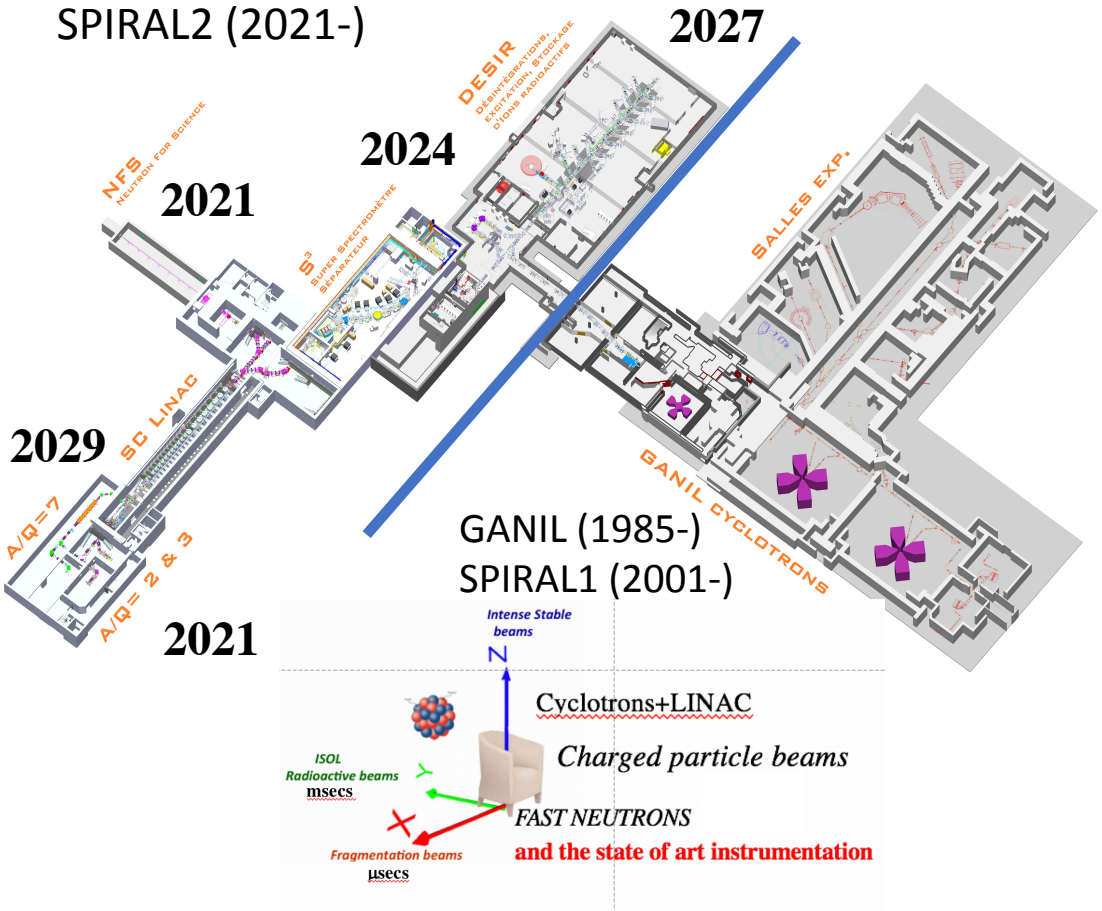
Courtesy W. Nörtershaüser, TU Darmstadt

Future: Proposals for Ti, Fe, Ni (neutron-rich) Combination with Resonance Ionization Spectroscopy (CRIS): Al, Th

In parallel: Operation of the LASPEC Beamline at ANL in **FAIR Phase 0** until 2025

Funded by DFG SFB 1245

GANIL / SPIRAL2



16 Meuros investment of Germany to SPIRAL 2

GANIL:
- fragmentation (100 MeV/n)
- ISOL (SPIRAL1, up to 10 MeV/n)

German participation to AGATA campaigns at GANIL (2015-2021) (GSI, TUDa, U Köln)

SPIRAL 2:
- LINAC
- 40 MeV deuteron, 5 mA

Phase 1 (funded):
- Neutron For Science (NFS)
- heavy-ion beams (S3)

Collaboration with GSI and U Mainz for heavy-element program

Phase 2 (not funded, in discussion):
- reaccelerated fission fragments
- ISOL

SPIRAL2 Linac / NFS: routine operation in 2021

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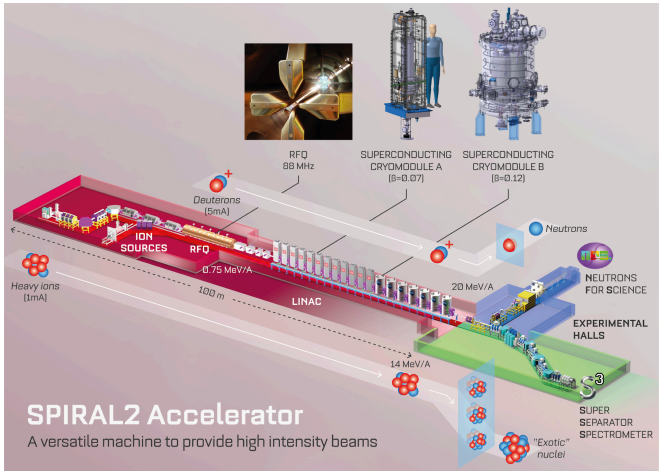
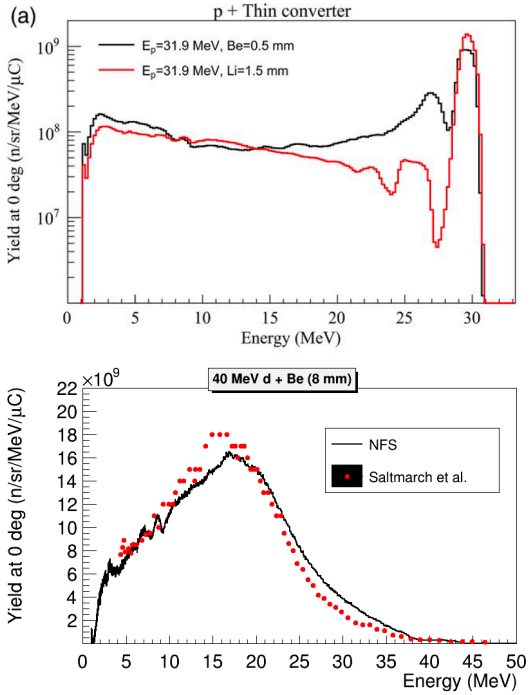
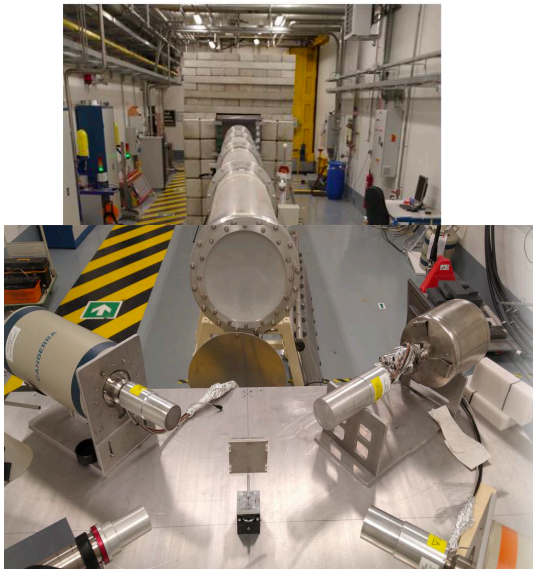
Courtesy N. Alahari, GANIL/SPIRAL2







- *40 MeV 5mA deuteron beam pulsed (1/100) beam to produce neutrons beams*
- *Continuous and quasi-mono-energetic radioactive neutron beams*
- *Highest Intensity in the world (1 to 40 MeV)*
- *Reactions for material science, reactors, methods of production of radioisotopes, fission, biology …*
- *All PAC approved experiments for 2021 successfully run.*

Summary and outlook

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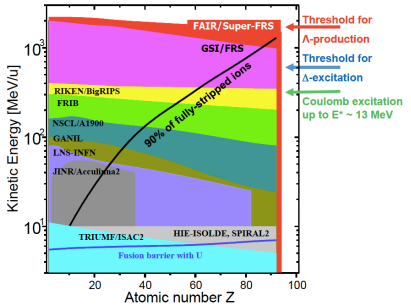
• RIBF is since 2007 the facility that produces the most exotic nuclei at ~ 200-250 MeV/n. After GSI/FAIR, it is the intermediate-energy facility with the strongest German involvement.

• FRIB will compete strongly with RIBF from 2022. German groups are involved in key nuclear-structure experimental programs.

• Many complementarities with FAIR. Parts of FAIR-related detectors have been used at an early stage at RIBF (ex. Neuland), NSCL (ex. optical detection), GANIL (ex. AGATA).

	RIBF	FRIB	FAIR
Primary ^{238}U intensity	100 pnA (today) (upgrade:~2000 pnA)	8000 pnA (full FRIB)	100 pnA (SIS100, U^{28+})
Primary beam energy	345 MeV / n	200 MeV/n (to be updated to 400 MeV/n)	400 - 2000 GeV/n



• GANIL / SPIRAL2 offers a variety of beams, while ongoing developments focus on low energy and heavy elements.

• SPIRAL2 Linac in operation at nominal parameters since 2021. 2021-2040: NFS, S3 and DESIR programs. Long term perspectives of GANIL / SPIRAL2 with re-accelerated radioactive isotopes under discussion.