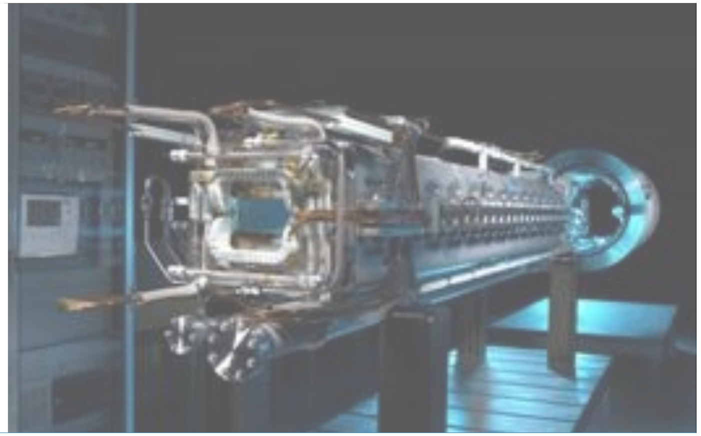


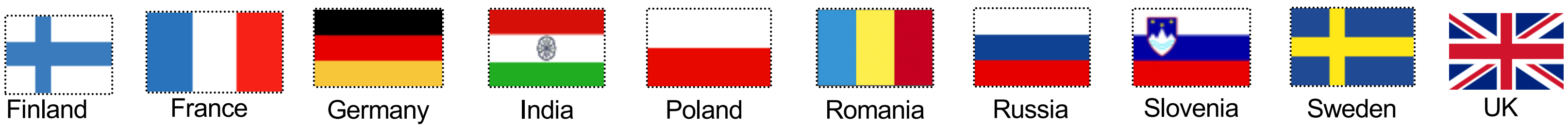


NUSTAR Collaboration Report

Wolfram Korten
IRFU - CEA Paris-Saclay

Joint ECE-ECSG Meeting

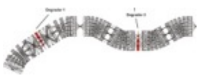
Darmstadt, November 4-5, 2019



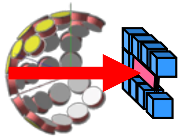
FAIR

The NUSTAR experiments

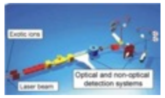
Super-FRS



HISPEC/ DESPEC

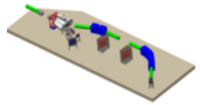


LASPEC

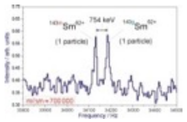


MATS

R3B

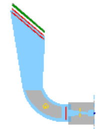


ILIMA



SHE

ELISE



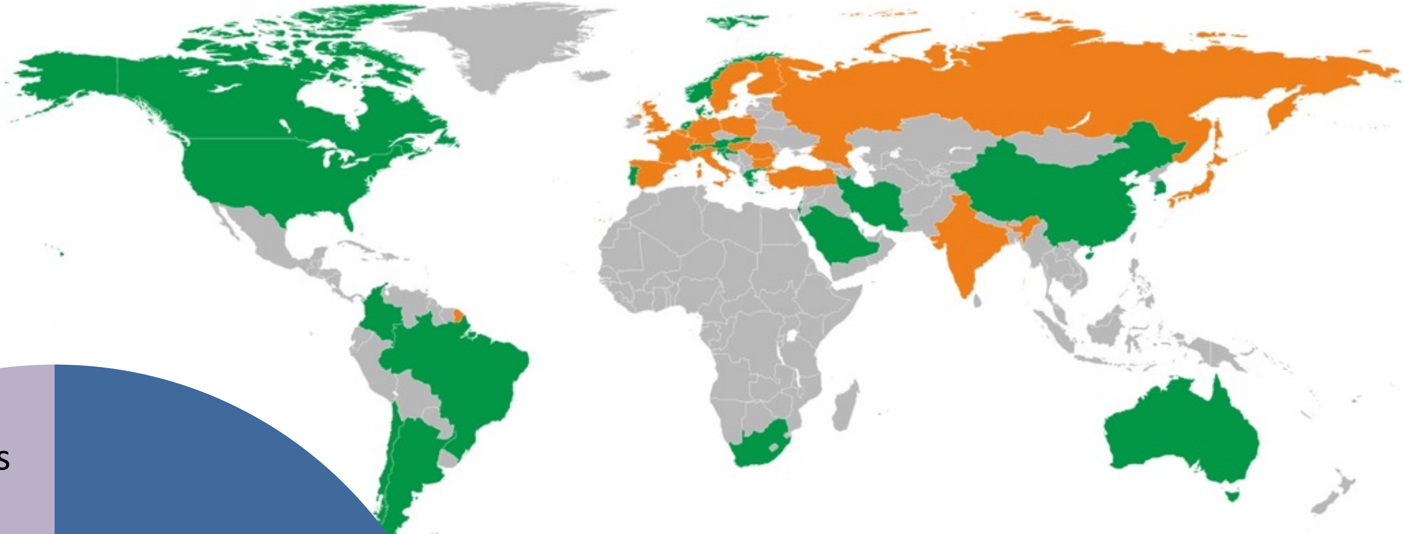
EXL

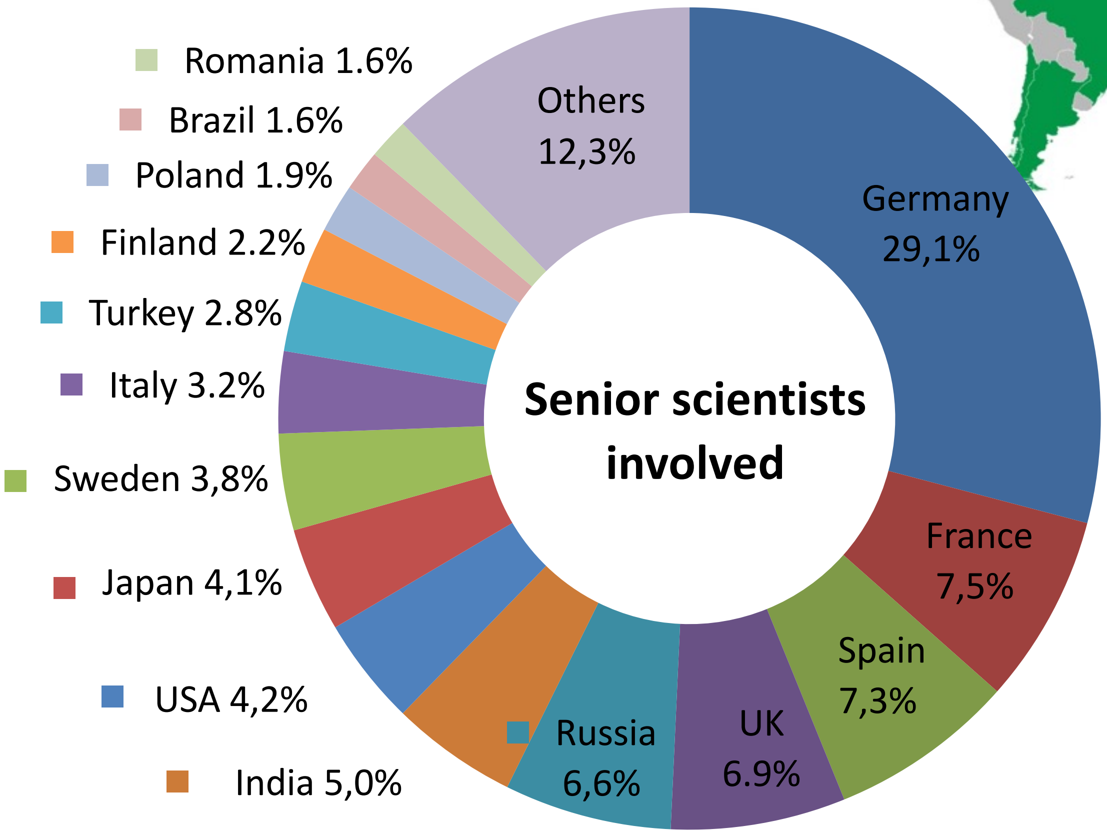
	Super-FRS	HISPEC/DESPEC	LASPEC	MATS	R3B	ILIMA	SHE	ELISe	EXL
Masses		Q-values, isomers		dressed ions, highest precision	unbound nuclei	bare ions, mapping study	precision mass of SHEs		
Half-lives	ps...ns-range	ground state and isomers µs...s			resonance width, decay up to 100ns	bare ions, ms…years	µs...days		
Matter radii	interaction x-section				interaction cross sections				matter densitiy distribution
Charge radii	charge-changing cross sections		mean square radii		charge-changing cross sections			charge density distribution	
Single-particle structure	high resolution, angular momentum	high-resolution particle and γ-ray spectroscopy	magnetic moments, nucl. spins	evolution of shell str., pairing int., valence nucl.	quasi-free knockout, short-range & tensor correlations	evolution of shell closures, pairing corr.	shell structure of SHEs		low momentum transfers
Collective behavior		electromagnetic transition strength	quadrupole moments	halo structure	dipole response, fission	changes in deformation		electromagnetic transition strength	monopole resonance
EoS					polarizability, neutron skin			neutron skin	neutron skin, compressibility
Exotic Systems	bound mesons, hypernuclei, nucleon resonances	rare and exotic e.m. and particle decays			n-rich hypernuclei	exotic decay modes			

NUSTAR - The Project

PSP code	**Super-FRS**	RIB production, separation, and identification
1.2.2	**HISPEC/ DESPEC**	In-beam γ-spectroscopy at low and intermediate energy, n-decay, high-resolution γ-, β-, α-, p-, spectroscopy
1.2.3	**MATS**	In-trap mass measurements and decay studies
1.2.4	**LaSpec**	Laser spectroscopy
1.2.5	**R^{3}B**	Kinematical complete reactions with relativistic radioactive beams
1.2.6	**ILIMA**	Large-scale scans of mass and lifetimes of nuclei in ground and isomeric states
1.2.10	**Super-FRS**	High-resolution spectrometer experiments **(see talk by T. Grahn)**
1.2.11	**SHE**	Synthesis and study of super-heavy elements

The NUSTAR collaboration





- 800 registered “interested” scientists in the NUSTAR data-base from **39 countries and more than 180 institutes**

Secured funding and expression of interest in funding (September 2018): **from 19 countries** (incl. 9 FAIR partner countries)

Update in progress for new MoU

- Sharing of running costs

NUSTAR organisation

NUSTAR Collaboration

NUSTAR Council (NC)

Institutes (secured financial/manpower contribution)

Collaboration Committee (CC)

NUSTAR Experiments

(representatives of the 10 exp. collaborations)

Board of Representatives (BR)

(Five members elected by Council and TC/RC ex officio)

Chair: NUSTAR Spokesperson

Technical Board (TB)

Chair: Technical Coordinator

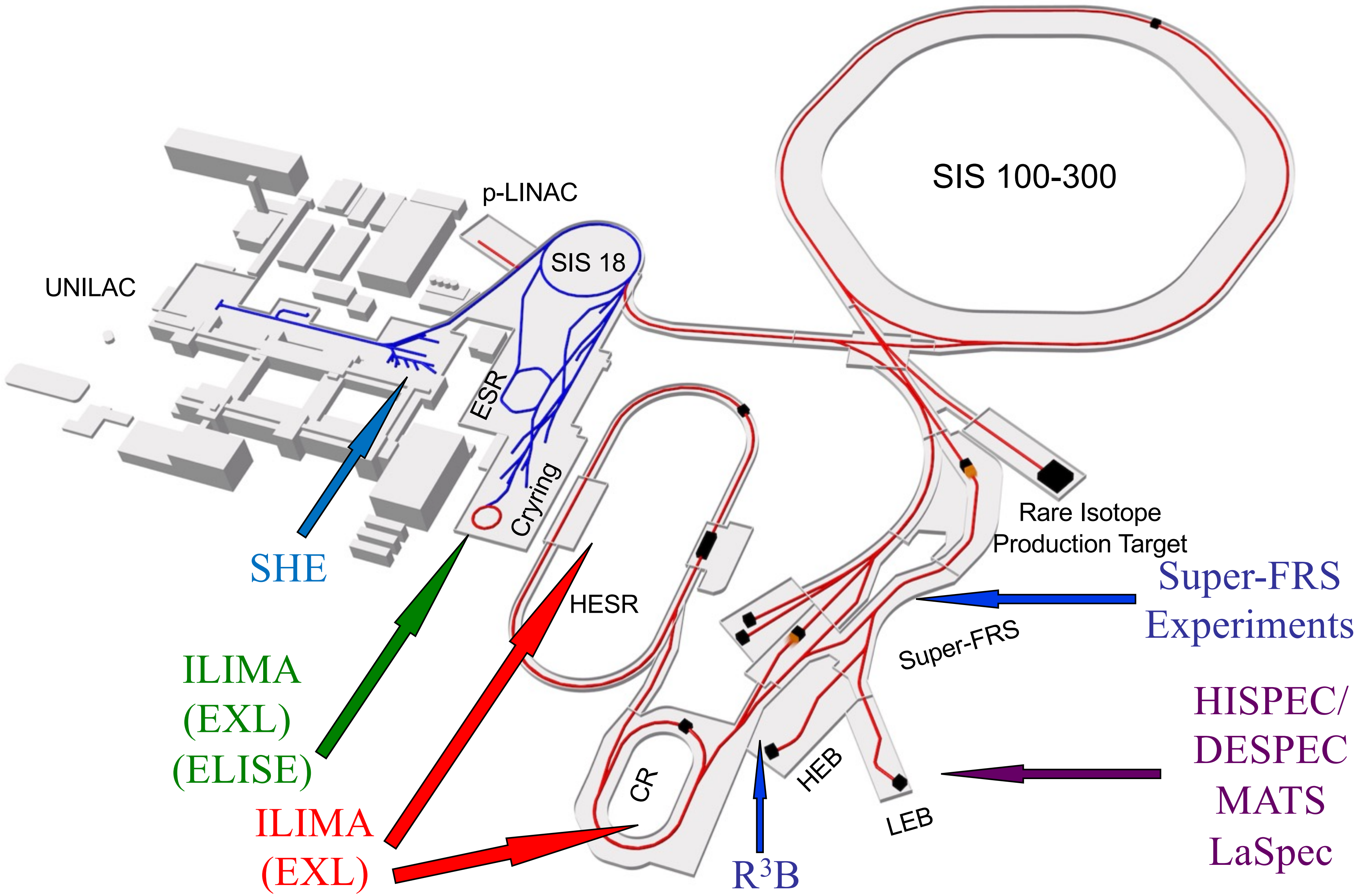
Resource Board (RB)

Chair: Resource Coordinator

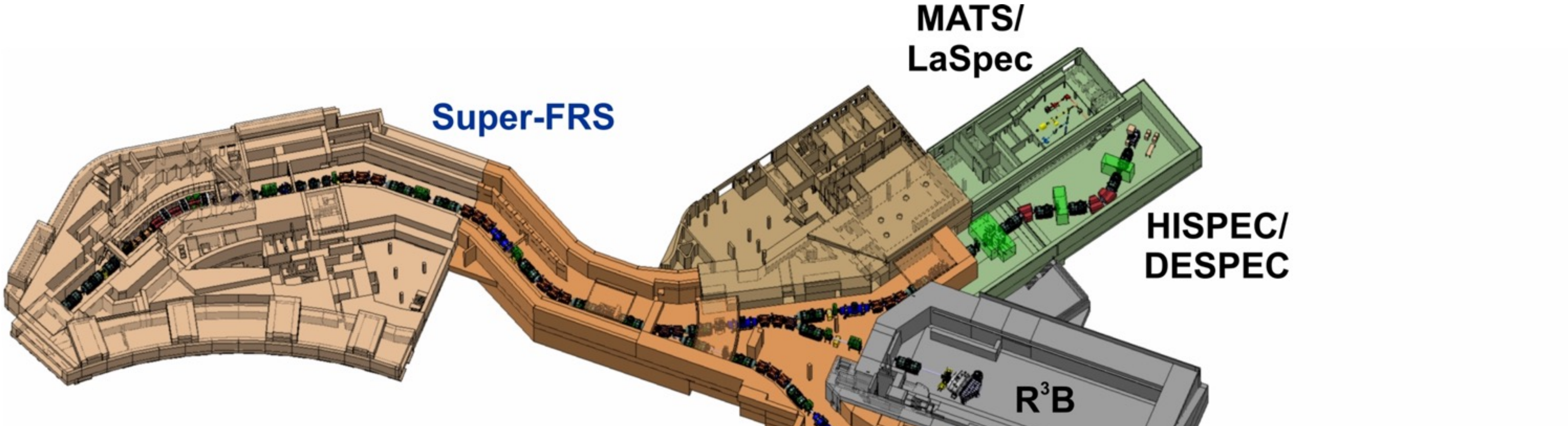
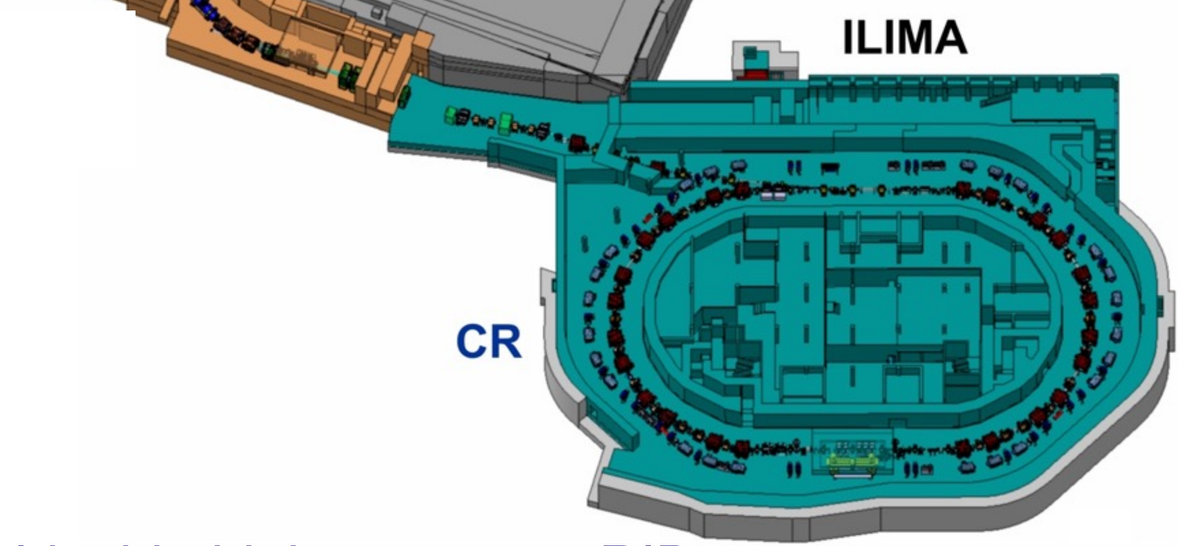
New MoU for Construction

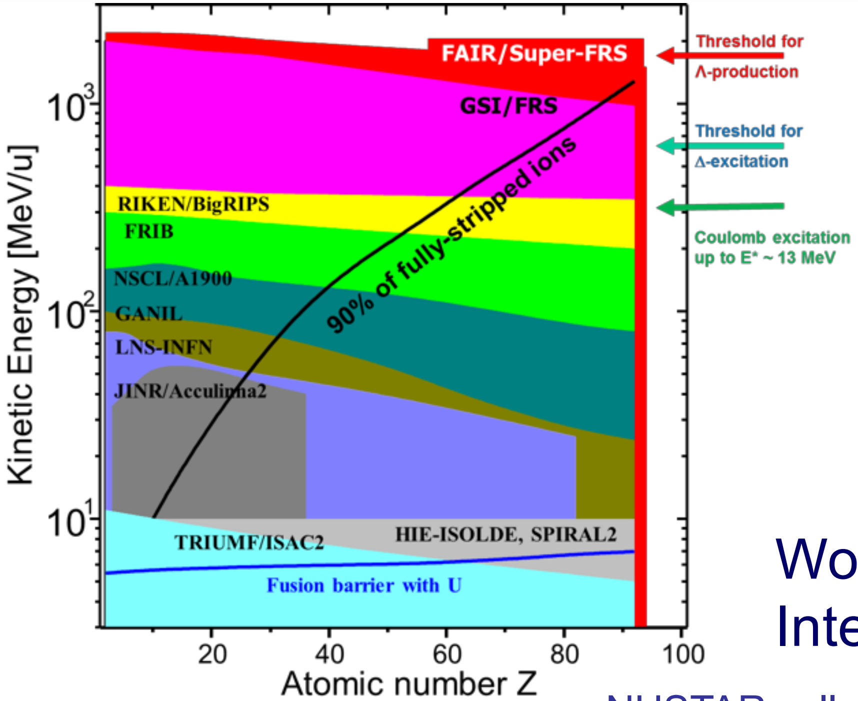
- General Conditions for Experiments
  - Draft version submitted to FAIR management in February 2018
  - Slightly modified version (April 2018) sent to AFC for discussion
  - Approved at the AFC meeting in May 2019
- MoU
  - Similar structure of the MoU for all FAIR experiments
    - NUSTAR MoU compared to the one from CBM and PANDA:
    - Slightly re-structure document (new ordering of articles)
    - Adapt annexes if needed
  - MoU for CBM presented as blueprint at the last FAIR-RRB meeting
  - Updating NUSTAR organizational structures and procedures
  - Presentation to NUSTAR Council in March 2020
  - NUSTAR Common Fund of ~1M€ (see presentation by A. Herlert)

FAIR start version and NUSTAR experiments



The Super-FRS facility for NUSTAR@FAIR

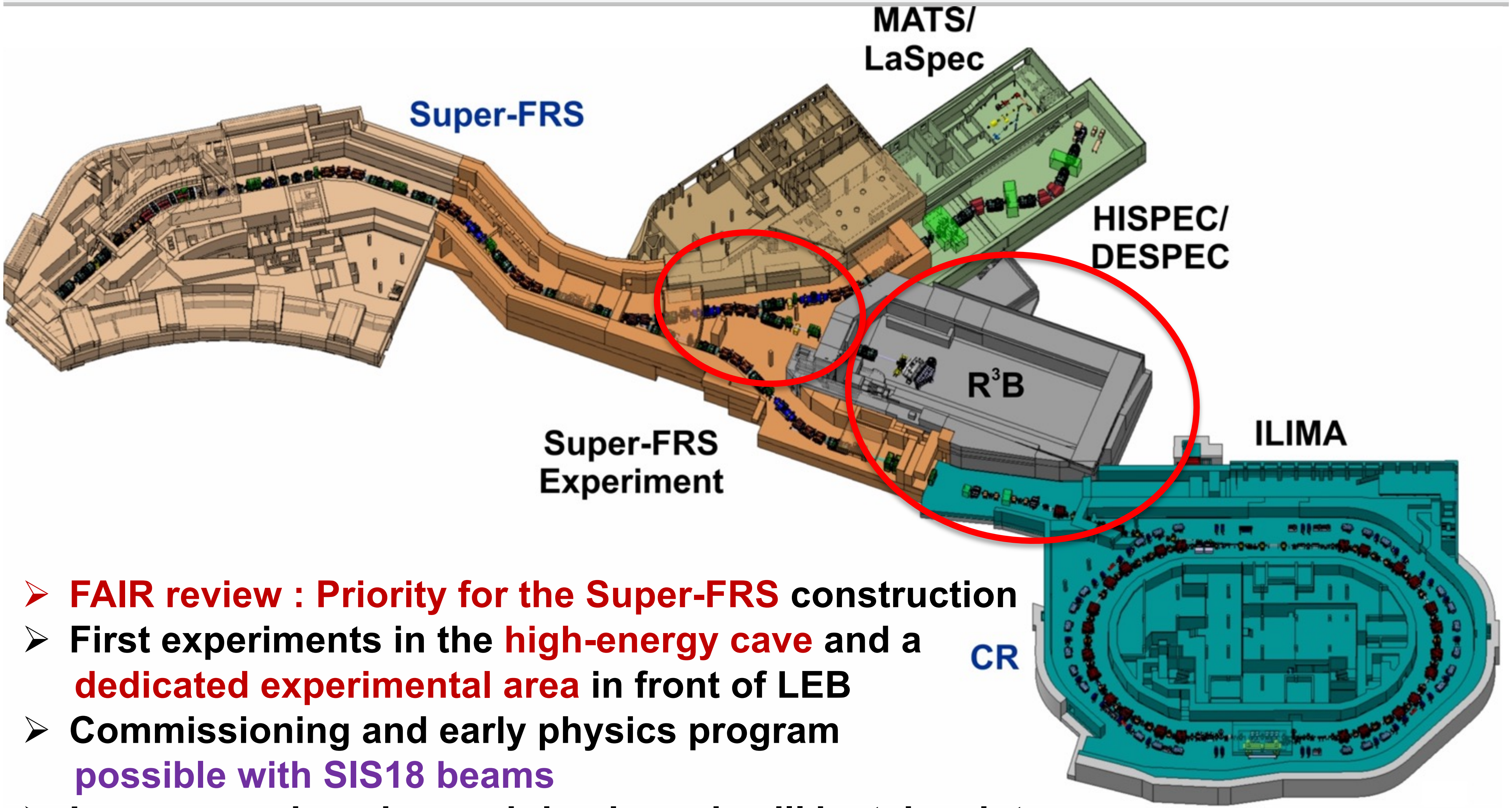





World-wide highest energy RIB

Intensity gain of up to 10^3 compared to GSI

NUSTAR Early Start Version



- FAIR review : Priority for the Super-FRS construction
- First experiments in the high-energy cave and a dedicated experimental area in front of LEB
- Commissioning and early physics program possible with SIS18 beams
- Low-energy buncher and ring branch will be taken into operation consecutively (but should not be further delayed)
- Continue NUSTAR program at FRS beyond 2025, in particular using ESR and Cryring

The NUSTAR road towards FAIR MSV

Facility	U beam intensity/spill at production target	Luminosity [fb^{-1}]
Today at GSI with **FRS** (Phase 0)	1...2x10^9	~0,1
Super-FRS with upgraded **SIS18**	5x10^9	~1
Commissioning phase **SIS100**	2x10^{10}	~5
Full final intensity with **SIS100**	4x10^{11}	100

Phase 0	→	**Day-1**	→	**Full MSV**
preparation	→	**discovery**	→	**detailed studies**
• **0.1 fb^{-1}**	→	**2-5 fb^{-1}**	→	**100 fb^{-1}**
• (near) stability	→	exotic	→	very exotic nuclei

News from the NUSTAR experiments

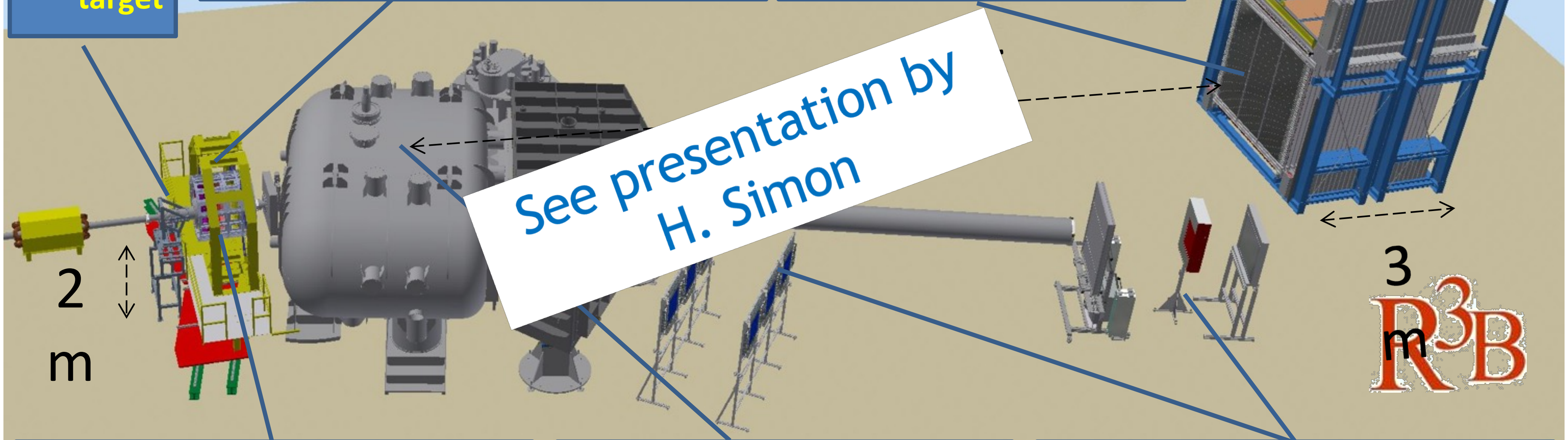
R3B set-up in a nutshell

Complete kinematics, fixed target experiment to study **R**eactions with **R**elativistic **R**adioactive **B**eams with high acceptance, resolution and efficiency

CALIFA
2528 detection units
CsI(Tl)-LAAPD/ LaBr/LaCl-PMT
1.3 m^3 and 2.5 Tm

NeuLAND
250x250 cm^2
3000 BC408 + 6000
PMTs ; 32 tons

LH_2
target



L3T (DSSSD)
18 det.ladders (6+12)
Strip pich 50mm
912 ASICS 116736 channels

GLAD
Large aper. 80x100 cm
5 Tm ; 3,5 x7x4 m
50 Tons

Tracking detectors
Silicon/ Plastics
Fibers 80x80 cm^2, 500 μm
Plastics walls 120x80 cm^2

R^3B schedule and phase-0 experiments

2019 runs

- **Only primary beams** (^{12}C, ^{16}O, ^{124}Sn)
- Microspill structure (eng. Run)

Equipment commissioning

- First operation of GLAD
- Gamma detection tests with CALIFA Demonstrator
- Large size fiber detectors (astrophysics, more to come

Experiments

S454 Heil **(2019)**

- Studying the astrophysical reaction rate of $^{12}C(\alpha,\gamma)$ O via Coulomb dissociation of ^{16}O into He and ^{12}C

S473 Aumann **(2019)**

- Constraining energy-density functionals and the density-dependence of the symmetry energy

2020 runs

- Secondary fragments FRS
- Heavier beams (^{40}Ar, ^{238}U)

Equipment commissioning and physics program

- LH2 target
- CALIFA (24-90º polar)
  - (p,2p) initial
- Gas Tracking detectors (SOFIA)
  - fission studies

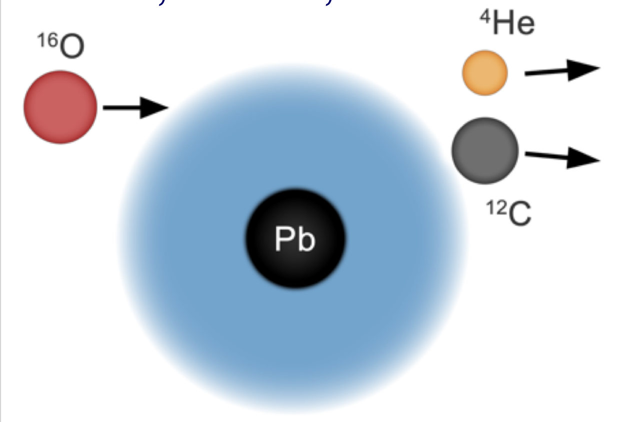
2021 and beyond

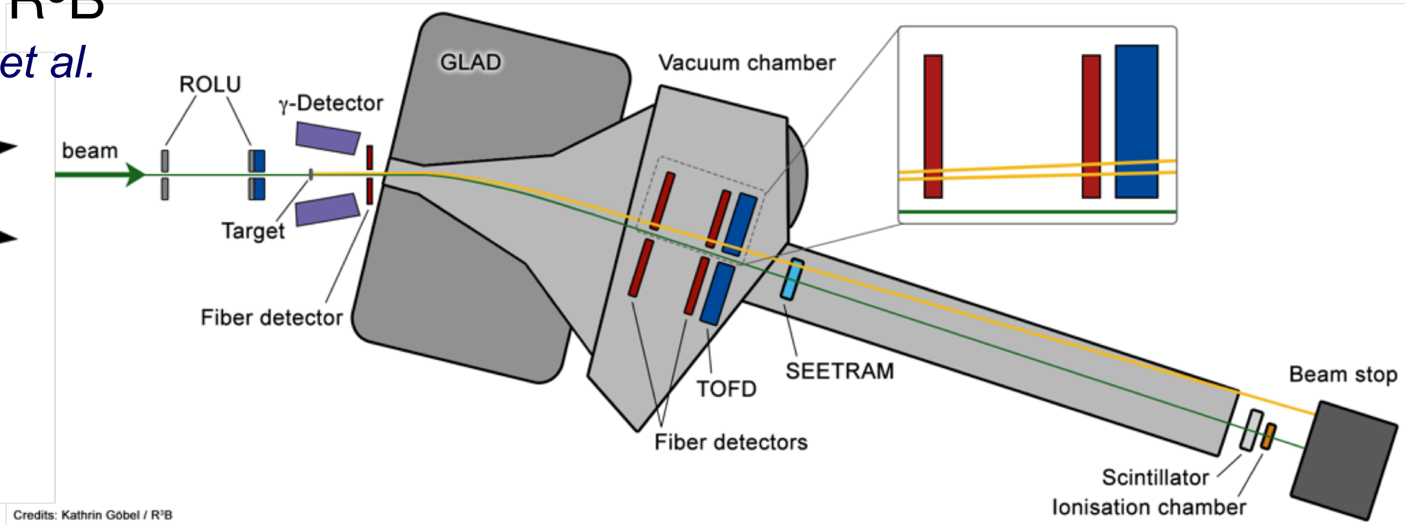
- Si tracker
  - e.g. Sorlin et al., (p,2p) at full performance)
- NeuLAND upgrade to 15(30) double planes
  - EOS, 4n correlations
- CALIFA with front cap
  - (p,2p) (p,pn) at full performance
- Proton Arm Spectrometer (PAS)
  - proton rich nuclei
- Active Target ACTAF (charge distributions)
- TPC
- …

First R^{3}B experiment: Coulomb dissociation of ^{16}O

First (γ,α) experiment at R^{3}B

K. Göbel, M. Heil, R. Reifarth et al.





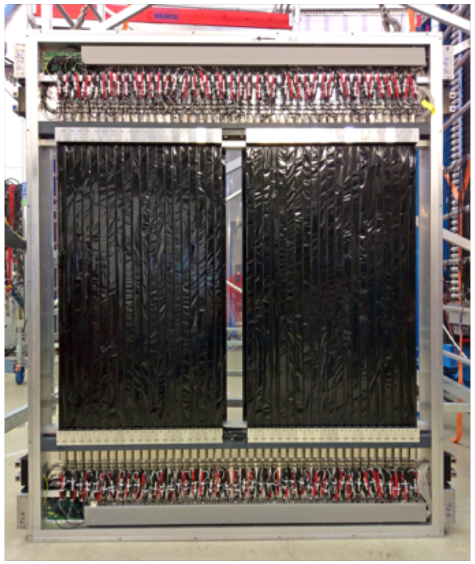
Advantages:

- high intensity (stable) ^{16}O (10^9 s^{-1})
- large number of virtual photons
- large (γ,α) cross section
- High speed tracking (several MHz) with two particles

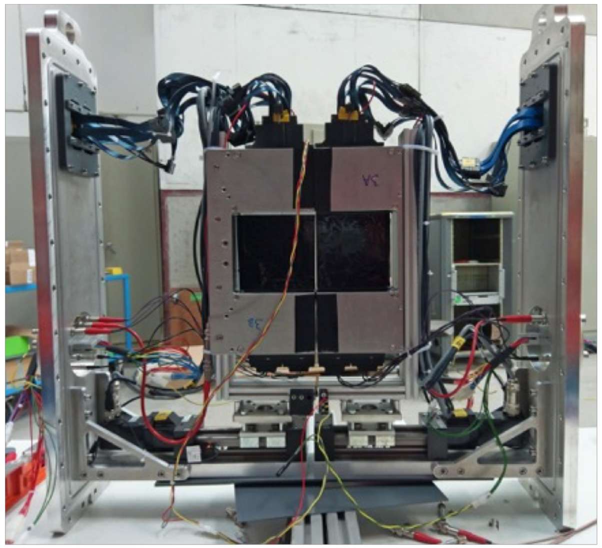
➢ Direct comparison to direct measurements using E1 data, proof of principle via R-Matrix decomposition.

➢ CD studies with E1/E2, proof of principle

ToF wall

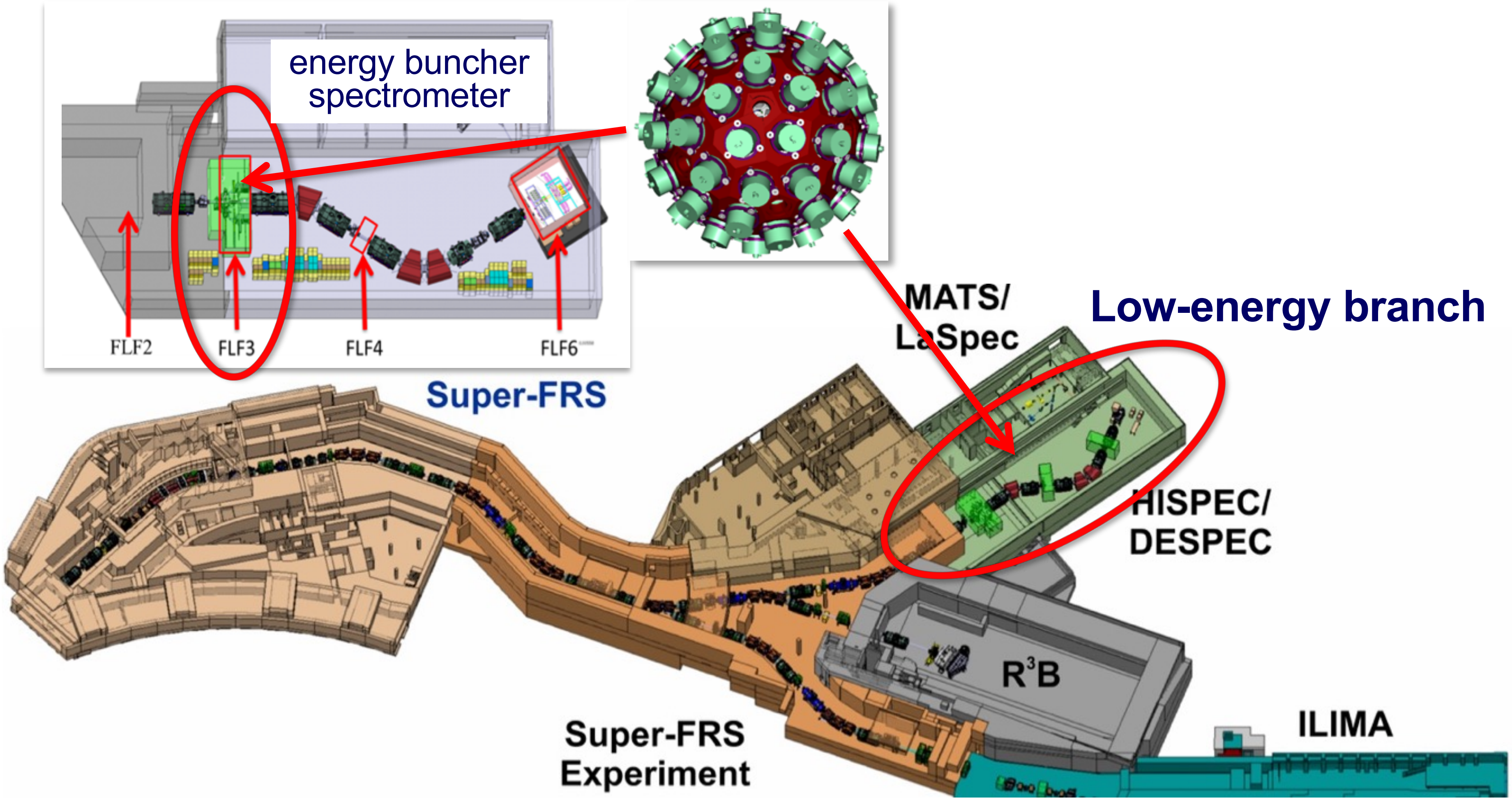


Fiber detectors

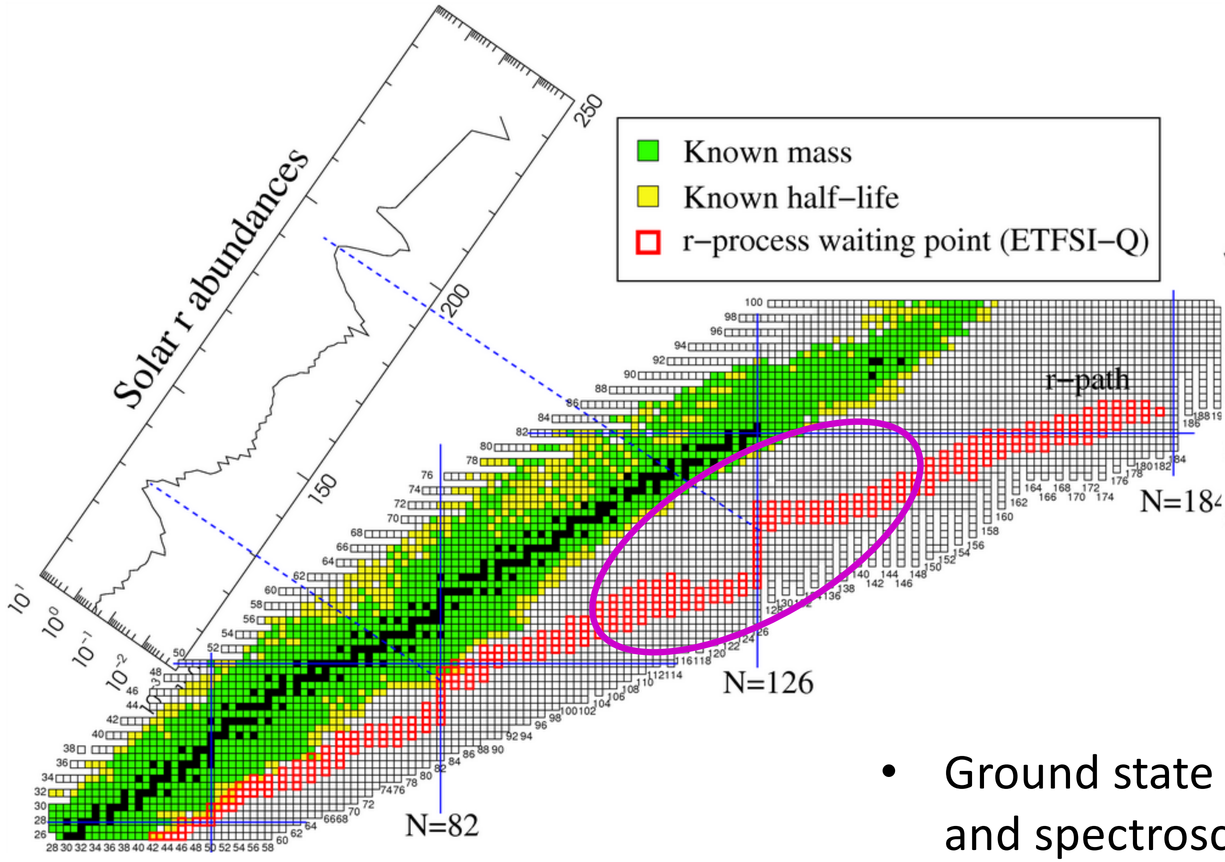


HISPEC/DESPEC in the low-energy branch

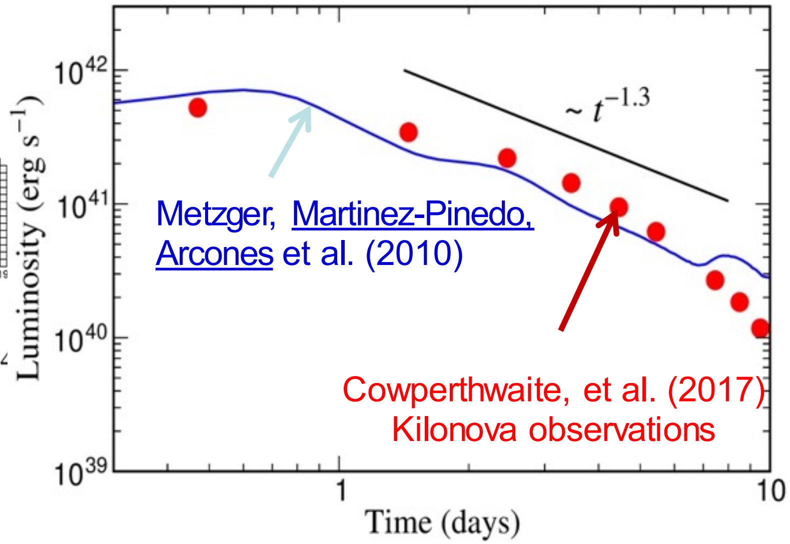
High-resolution in-flight gamma-ray spectroscopy using **AGATA** following secondary nuclear reactions induced by radioactive ion beams from **E~100 MeV/u to 1 GeV/u**



New isotopes and their properties
Joint DeSpec and Super FRS experiments



Electromagnetic “Kilonova” Signal from GW170817



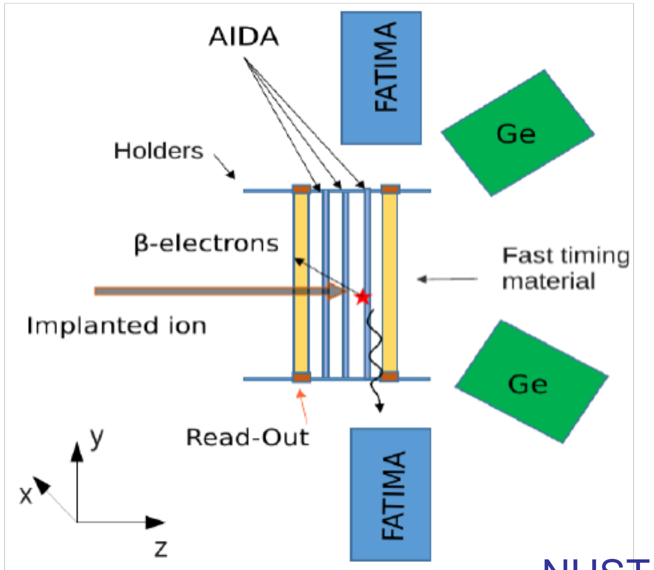
- Ground state properties (halflife, masses, radii) and spectroscopic studies (β-decay, isomers)
- First spectroscopic information for the nucleosynthesis of heavy nuclei
  (for RIB yields as low as one ion per hour)
- Evolution of the shell structure and exotic nuclear shapes near the limits of nuclear existence

DESPEC in FAIR Phase-0 (2019-21)

Spectroscopy & lifetimes of neutron-rich nuclei close to N=126

S452: The Oblate-Prolate Shape Transition around A~190 (2020)
S460: Investigation of 220-*A*-230 Po-Fr nuclei lying in the south-east frontier of the *A*~225 island of octupole deformation (2020)
S468: Search for new neutron-rich isotopes and exploratory studies in the element range from Tb to Re (2020; in collaboration with Super-FRS experiments)
S450: Study of *N*=126 nuclei: isomeric and beta decays in ^{202}Os and ^{203}Ir (2021)

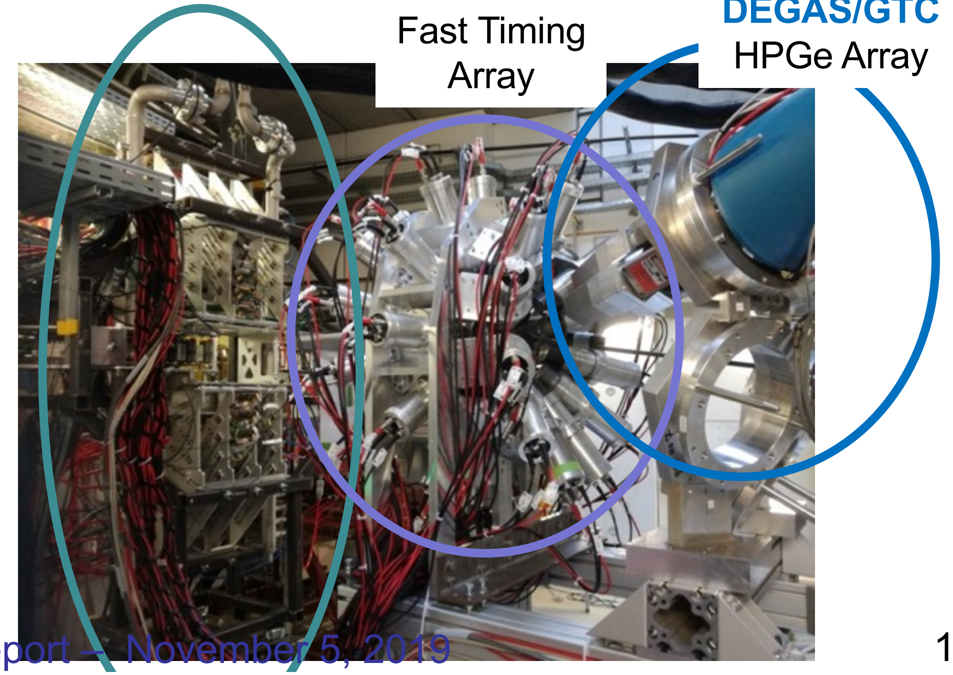
DESPEC PHASE-0 INSTALLED AND UNDERGOING COMMISSIONING (in-house and outside GSI)



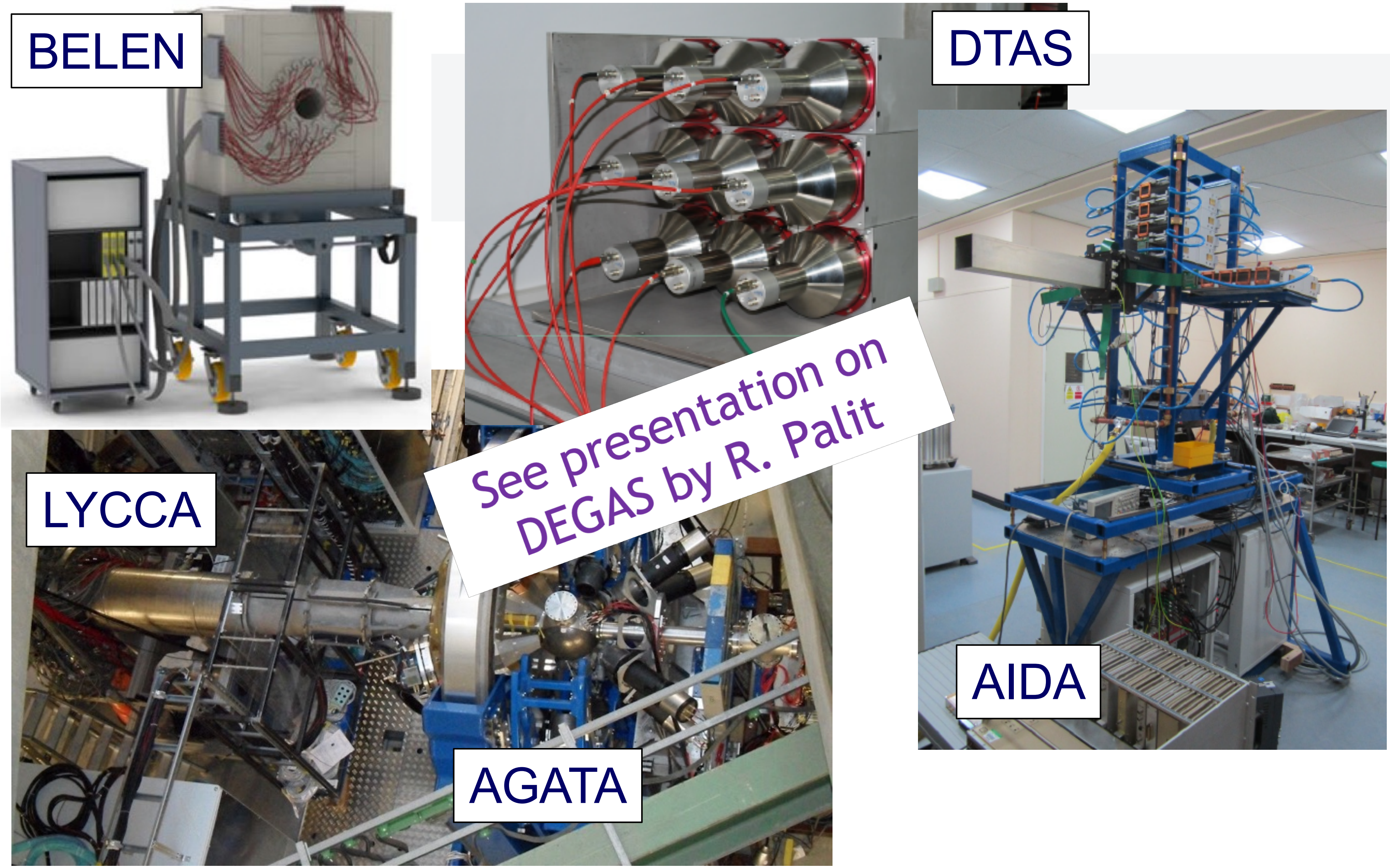
AIDA
implantation and decay detector

FATIMA
Fast Timing Array

DEGAS/GTC
HPGe Array



DeSpec Instrumentation ready for operation

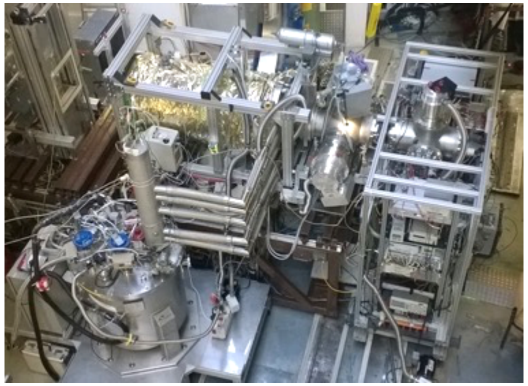


Super-FRS Experiment Collaboration

High-resolution spectrometer experiments at the border line of nuclear, atomic and hadron physics

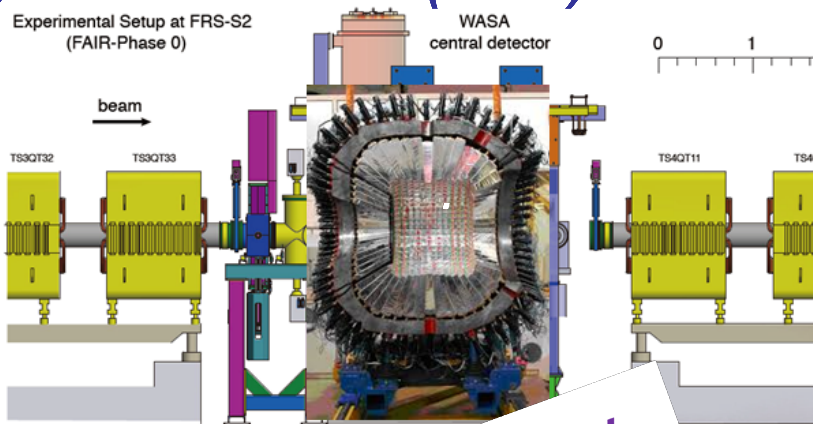
(Super-)FRS as multiple-stage magnetic system (separator, analyser, spectrometer, energy buncher) combined with ancillary detectors, e.g. with:

FRS Ion Catcher (2020)

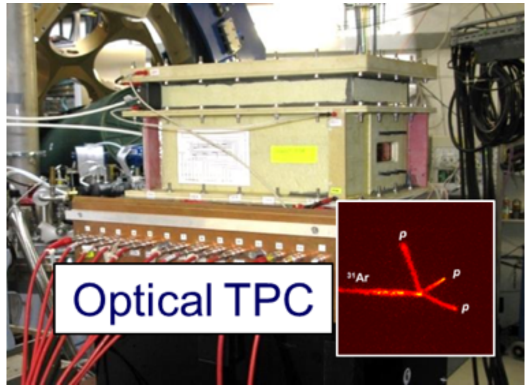


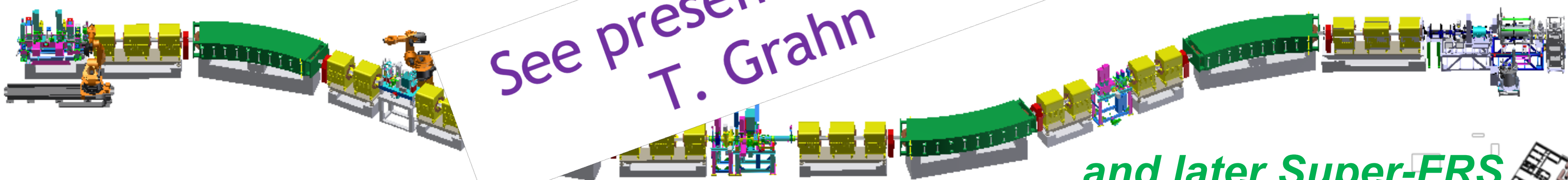
→ Cryogenic Stopping Cell

WASA (2021)



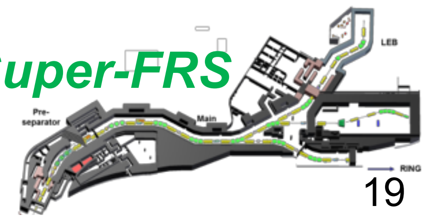
EXPERT (2022)





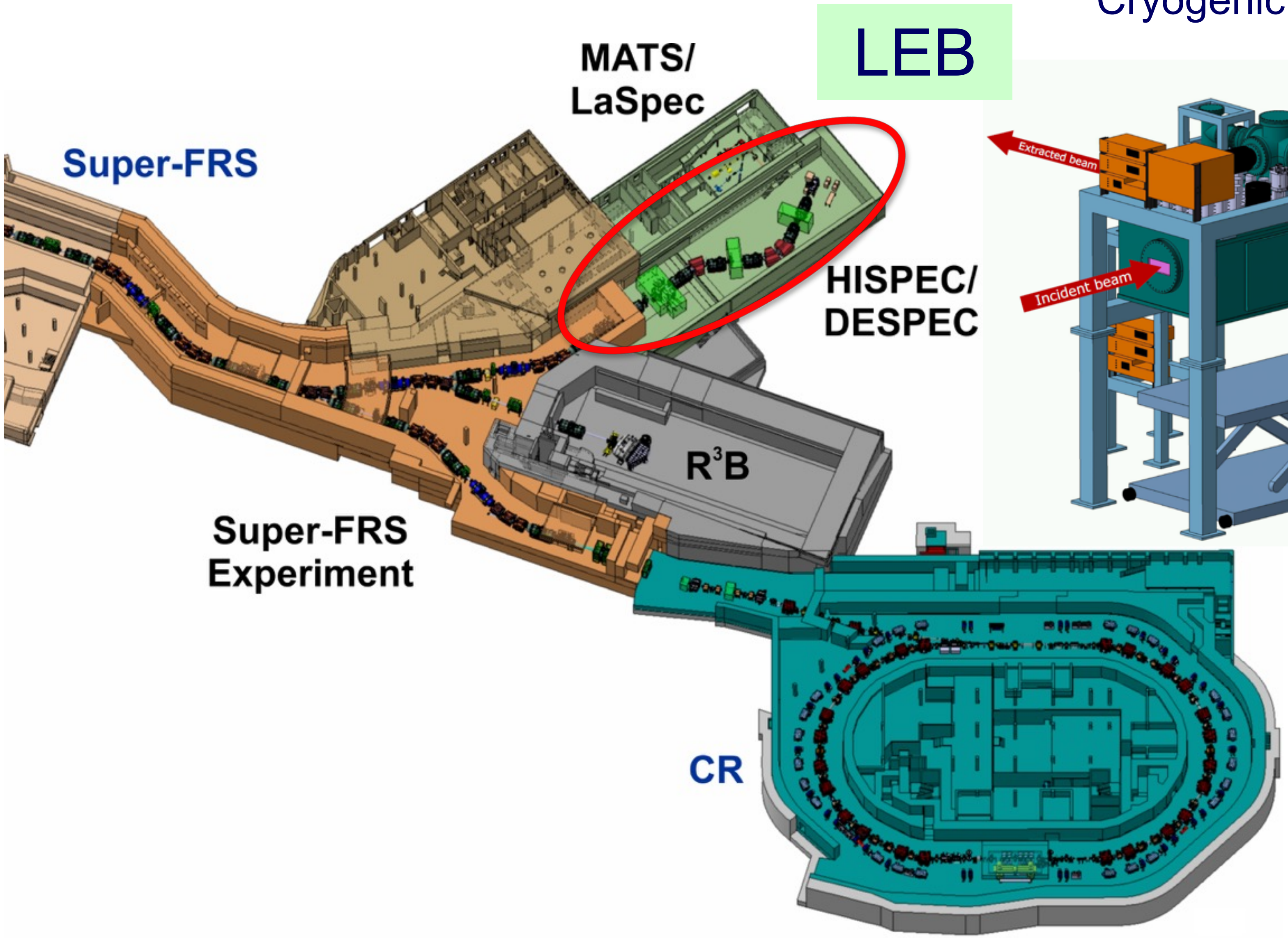
See presentation by T. Grahn

...and later Super-FRS

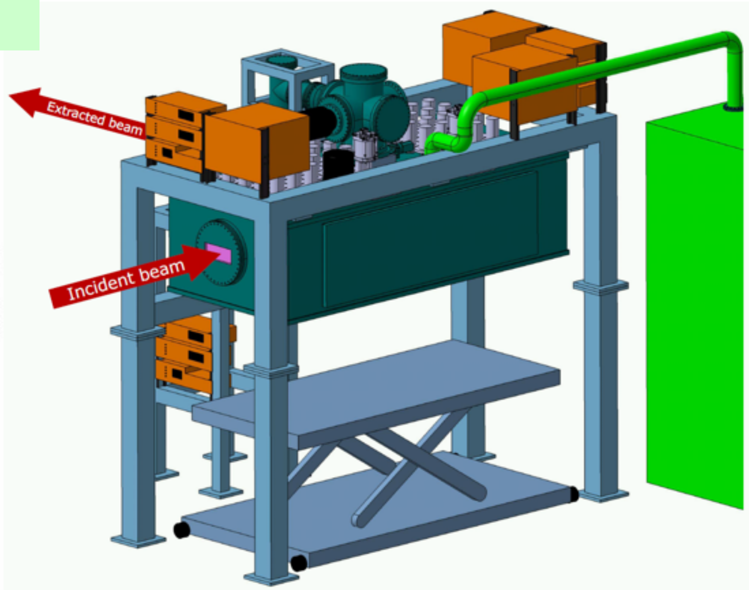


Definition of Day-1 configuration, including funding, in progress

The Super-FRS Low-Energy Branch

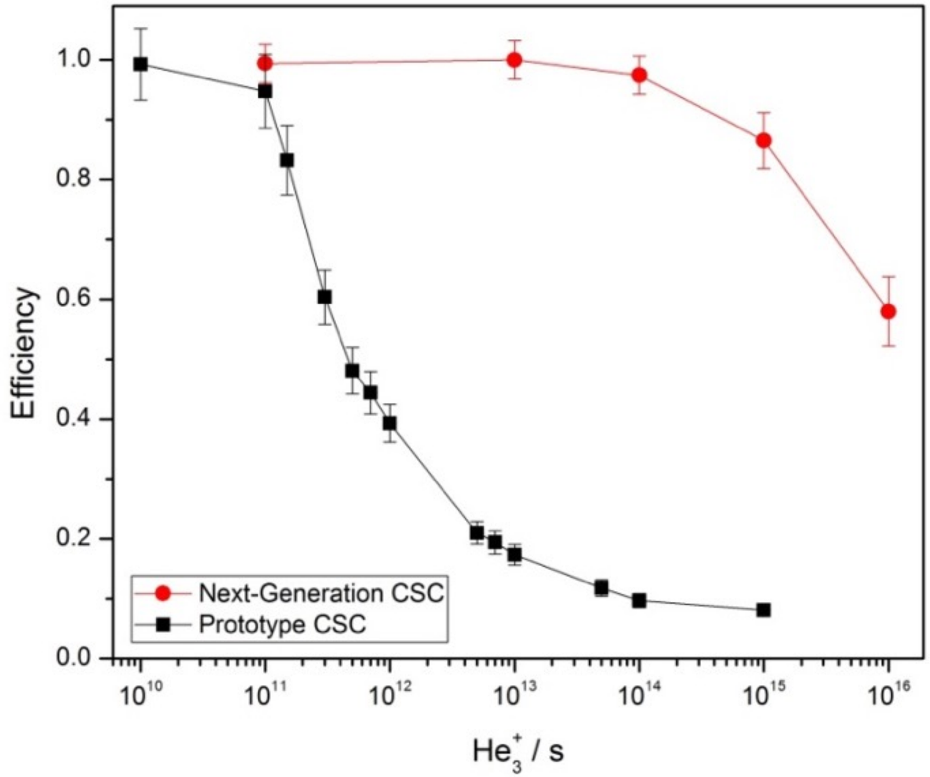


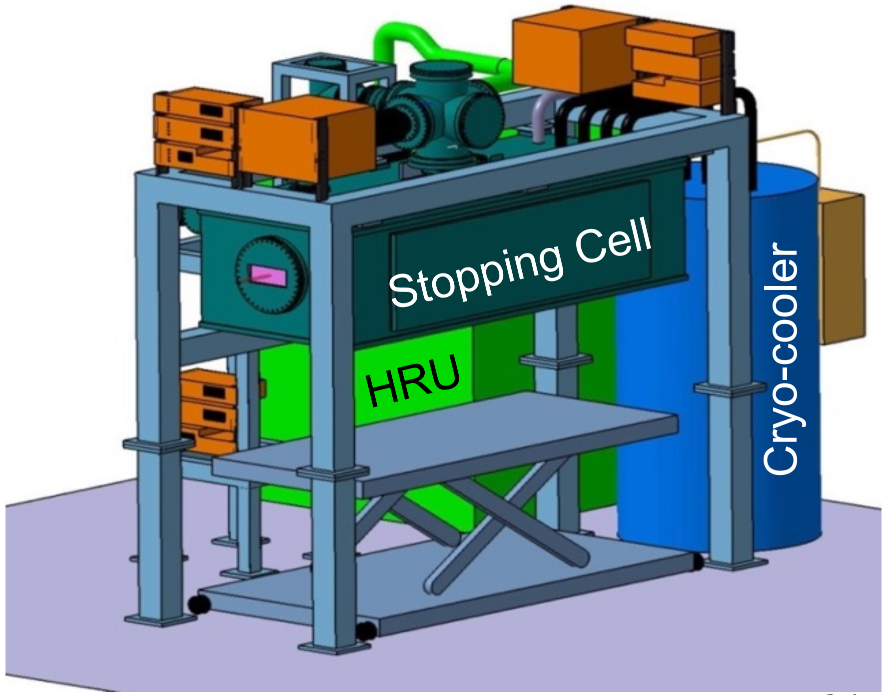
Cryogenic Stopping Cell



The Cryogenic Stopping Cell for the LEB

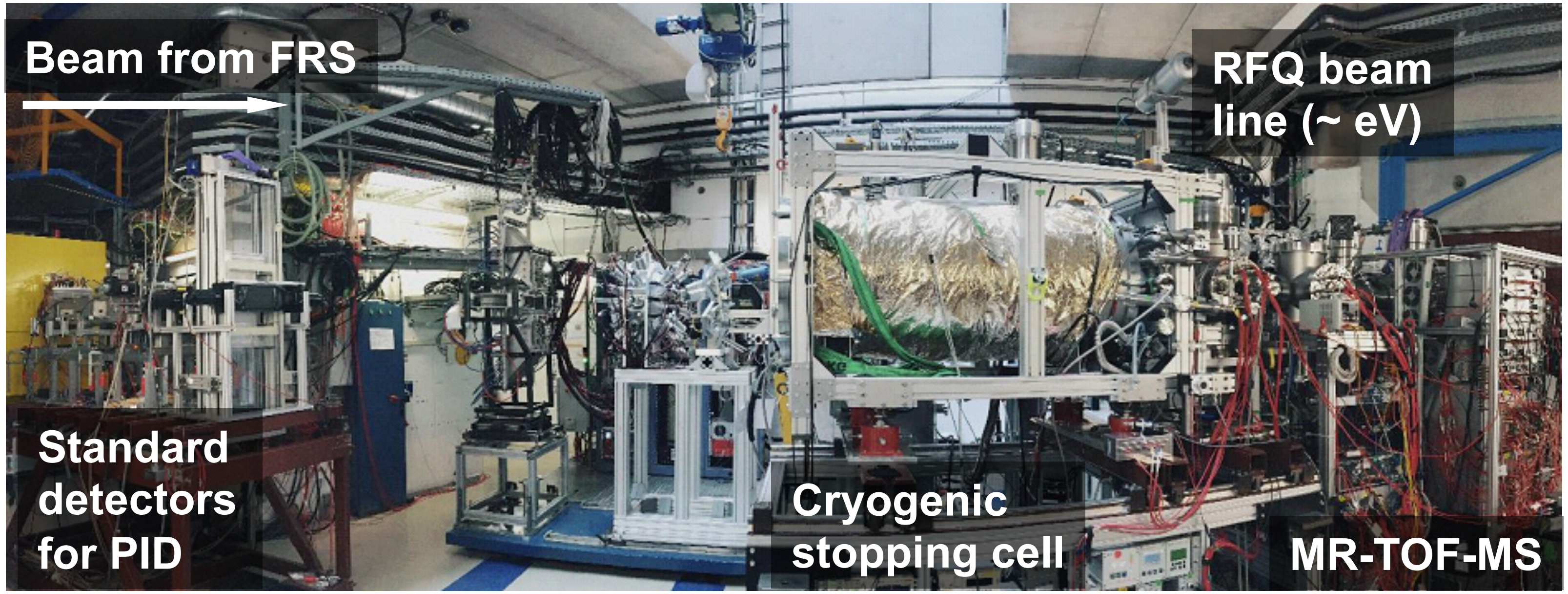
	Prototype CSC	Design Goals LEB CSC
Areal density (He)	6 mg/cm^2	20…40 mg/cm^2
Extraction time	25 ms	5…10 ms
Rate capability	10^4/s	10^7/s



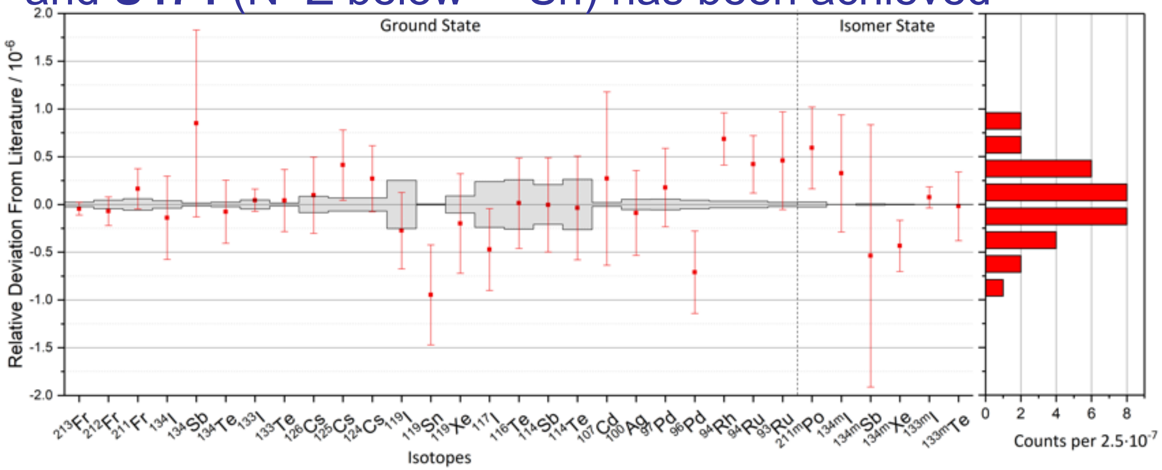


T. Dickel et al., NIMB 376 (2015) 216

FRS Ion Catcher: Proof-of-principle for FAIR Phase-0



Mass measurement performance required for **S468** (isotope search) and **S474** (N=Z below ^{100}Sn) has been achieved

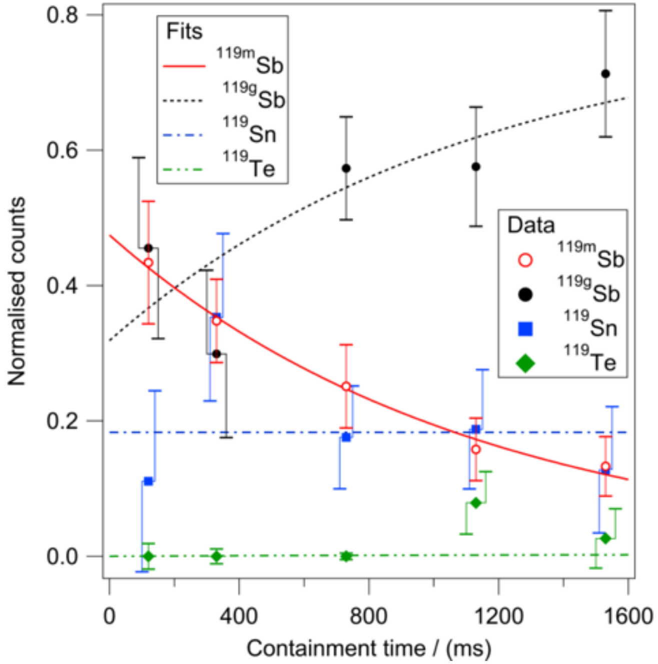


S. Ayet et al, *PRC* 99 (2019) 064313

- Mass resolving power > 400,000
- Mass accuracy down to 6×10^{-8}
- Resolution of ground states and low-lying isomers
- Measurement of nuclides with
  - sub-µbarn cross sections
  - down to 17.9 ms half-life
  - down to 11 events only

FRS Ion Catcher: Proof-of-principle for FAIR Phase-0

S472 (β-delayed neutron branching): Simultaneous measurement of mass, half-life and branching ratio for ^{119m2}Sb



Excitation energy: (2799 ± 30) keV

Half life:

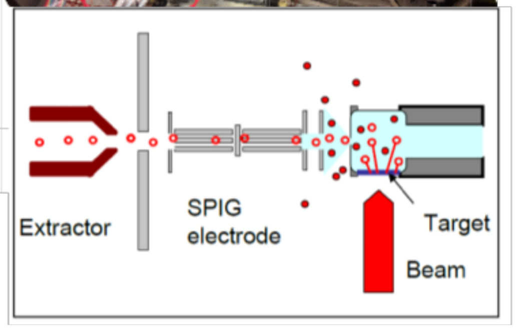
Measured	Literature
(776 ± 181) ms	(859 ± 90) ms

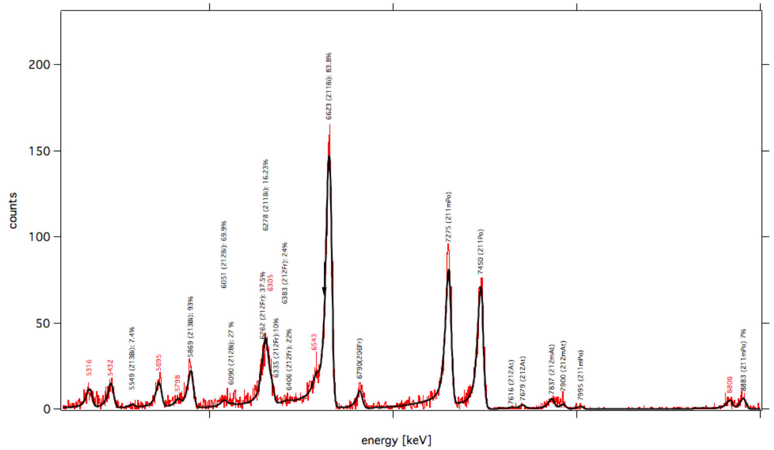
Branching ratios:

γ	β-	β+
1	0	0

I. Miskun et al., *EPJA* 55 (2019) 148

S475 (multi-nucleon transfer): MNT experiment at IGISOL / Jyväskylä





α-Spectroscopy for ^{136}Xe (945 MeV) + ^{209}Bi

T. Dickel, A. Kankainen et al.

MATS – Programme for Phase-0 and Day-1

FAIR phase 0:

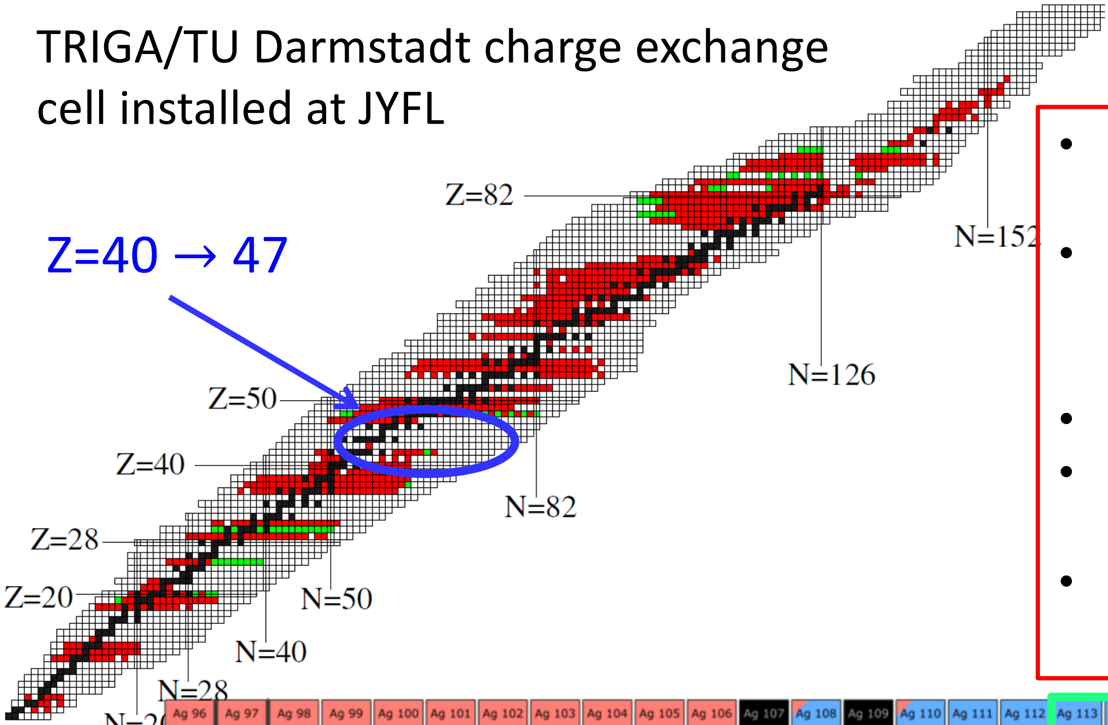
- operation of MATS prototype TRIGA-TRAP at TRIGA Mainz for technical and methodical developments:
  - single–ion mass spectrometry with cryogenic trapping systems
  - optimization of novel phase-imaging technique (PI-ICR) for short-lived nuclides and low-lying isomers
- construction of RFQ system at JYFL
- on-line experiments at different laboratories within the collaboration: ISOLTRAP, JYFLTRAP, SHIPTRAP ...

FAIR phase 1:

- Experiments on neutron-rich nuclides relevant for 3rd r-process peak
- Experiments on selected neutron-rich isotopes, e.g. Zr isotopes

LaSpec Phase-0 and Day 1 program on refractory elements

TRIGA/TU Darmstadt charge exchange cell installed at JYFL

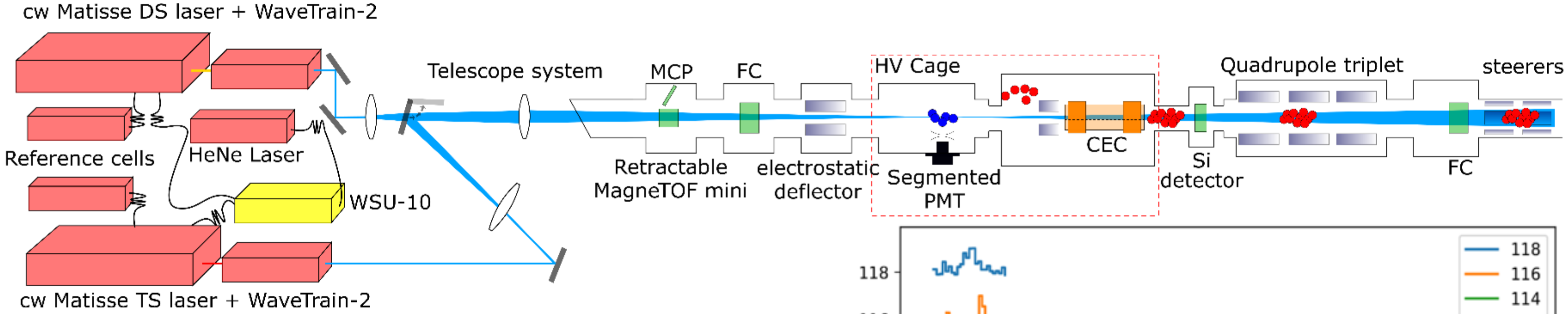


Phase 0 at JYFL and CARIBU

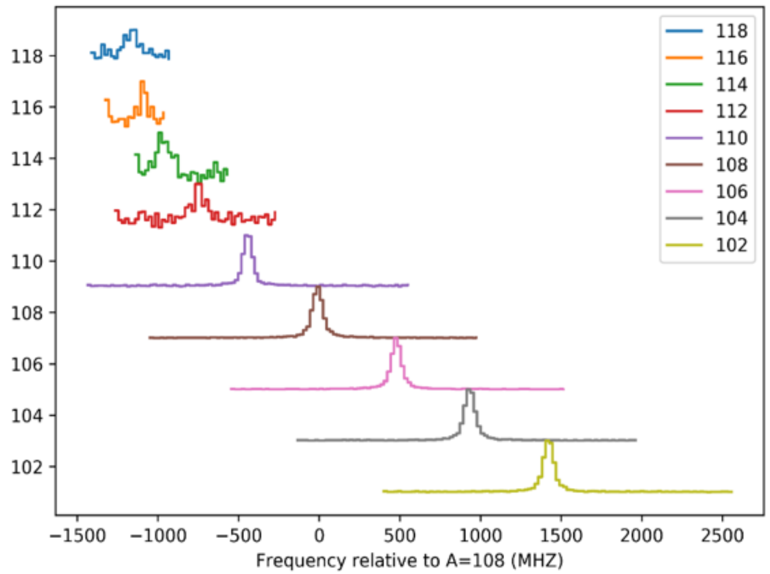
- Spectroscopy on $^{113-121}$Ag (2018) at JYFL (green)
- Fission yield predictions (yellow, JYFL) assuming >5000 ions/s needed for collinear laser spectroscopy on atoms
- Zr, Nb, Mo (red) from JYFL
- CRIS developments lead to 1-2 isotopes further (not shown)
- Phase 1 at LaSPEC aiming at, eg ^{106}Zr and beyond!

Optical spectroscopy enters the transitional region

Collaboration between JYFL, Liverpool, Manchester, GANIL, ISOLDE and TU Darmstadt. First optical spectroscopy of radioactive isotopes of Pd; neutron-rich region; transitional elements challenging to produce at ISOL facilities.

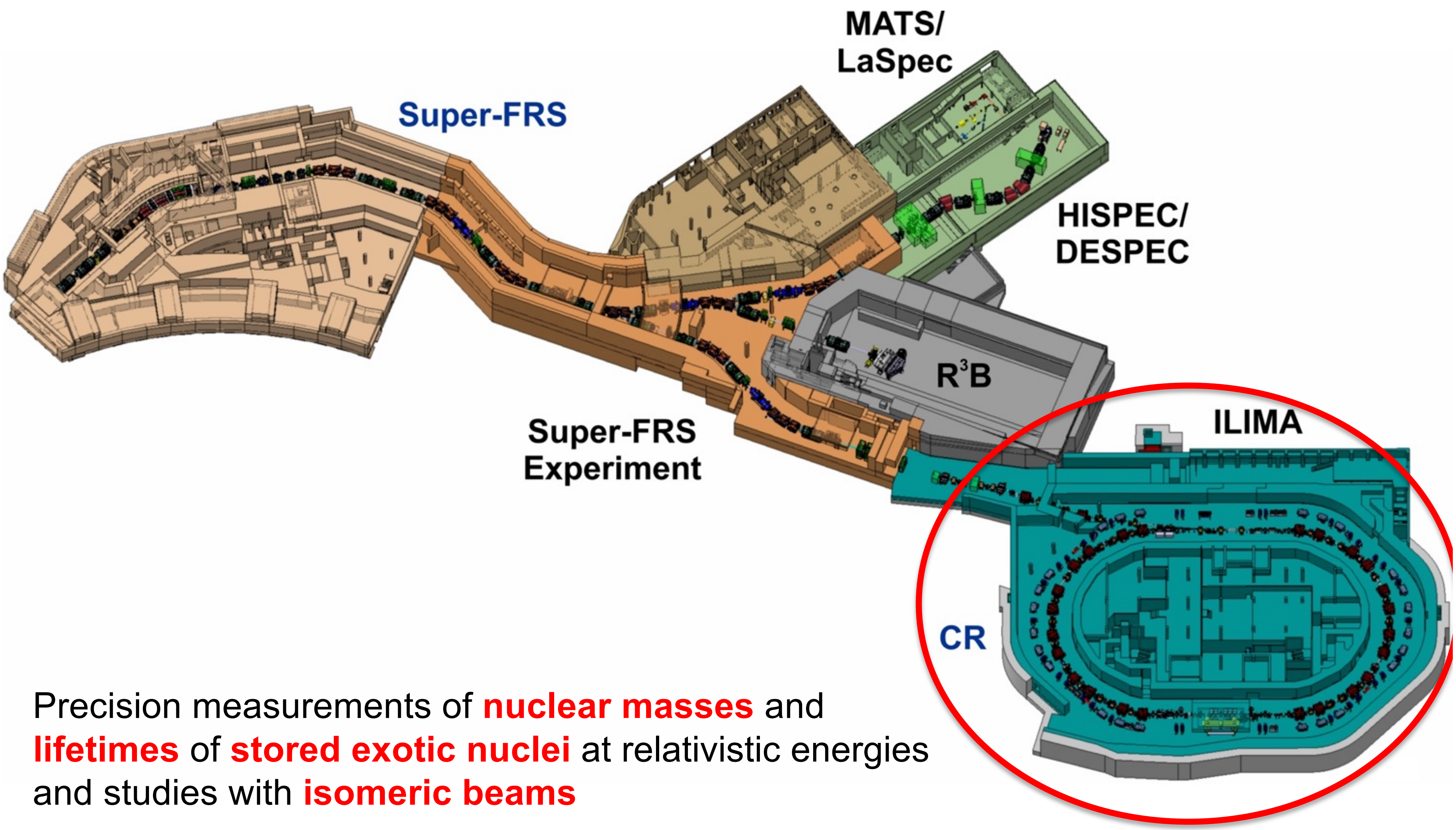


- Open questions regarding the origin and character of deformation changes
- Preliminary data obtained for odd-A isotopes ^{113,115}Pd
- Offline, different optical transitions tested
- Further from stability expected at FAIR



Optical resonance fluorescence spectra of even-A isotopes of Pd

ILIMA in the Collector Ring (CR)
Isomeric beams, Lifetimes and Masses



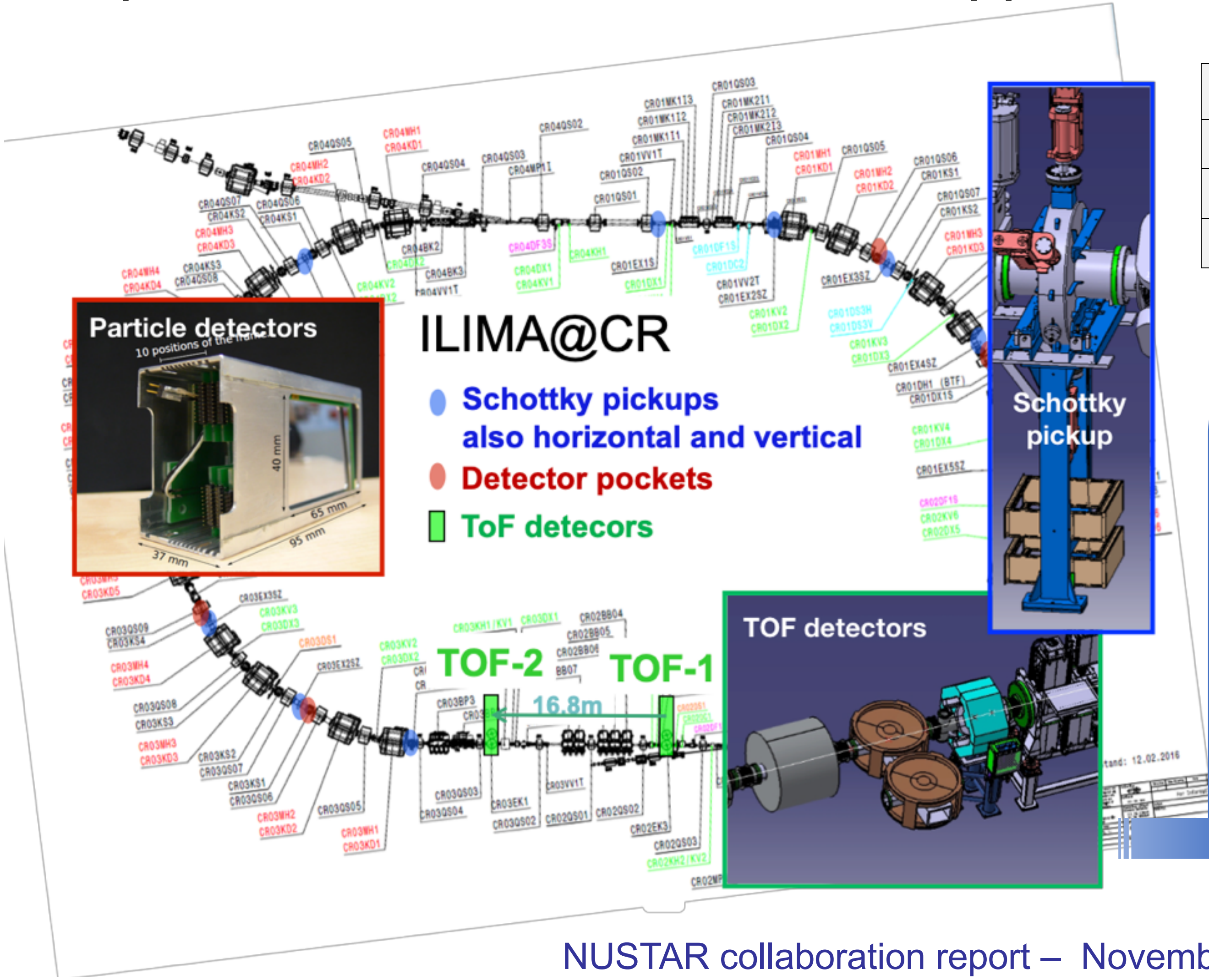
Precision measurements of **nuclear masses** and **lifetimes** of **stored exotic nuclei** at relativistic energies and studies with **isomeric beams**

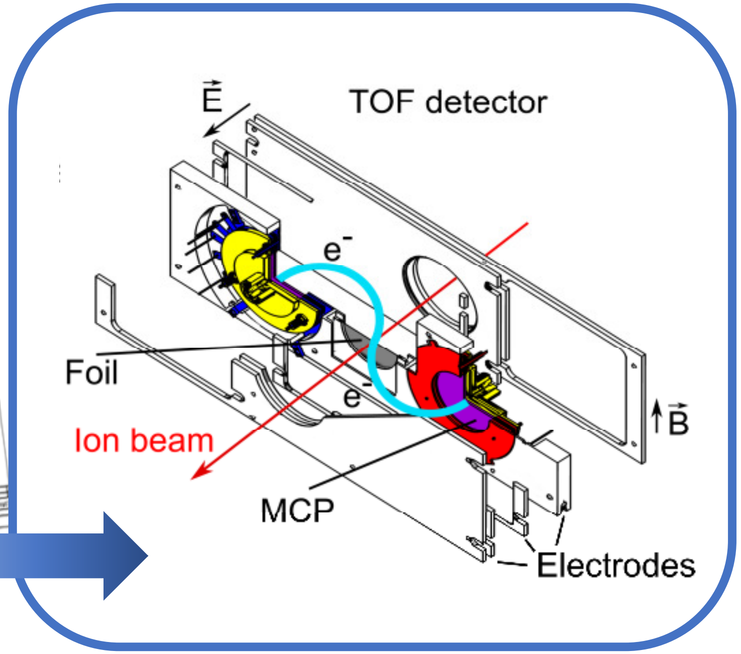
Recent news from ILIMA at the ESR

- All TDRs approved
- Specifications of TOF detector approved

Nustar Experiments	Document Type:	Document Number
FAIR GSI	**Detailed Specification**	F-DS-NUE-en-DC_0003

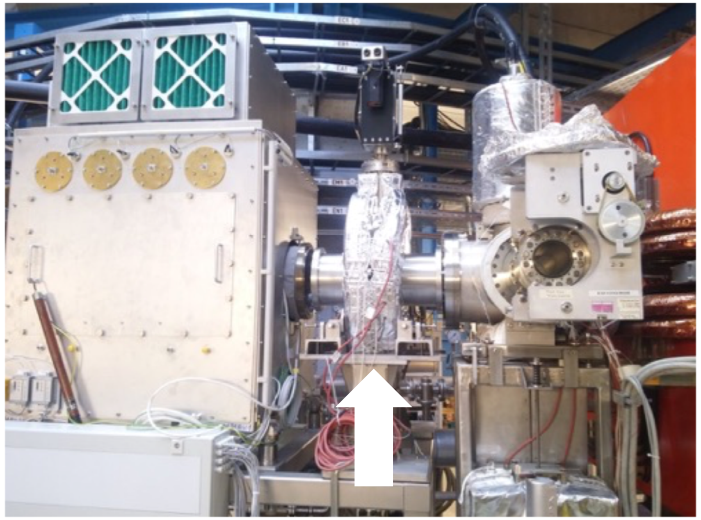
Document Title	**Dual Time-of-Flight detector system for ILIMA** **Detailed Specification**
Description	Specification for in-kind contract
Division/ Organization	ILIMA/NUSTAR/FAIR
Field of application	Isochronous Mass Spectrometry



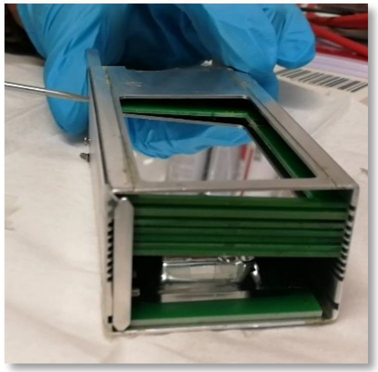


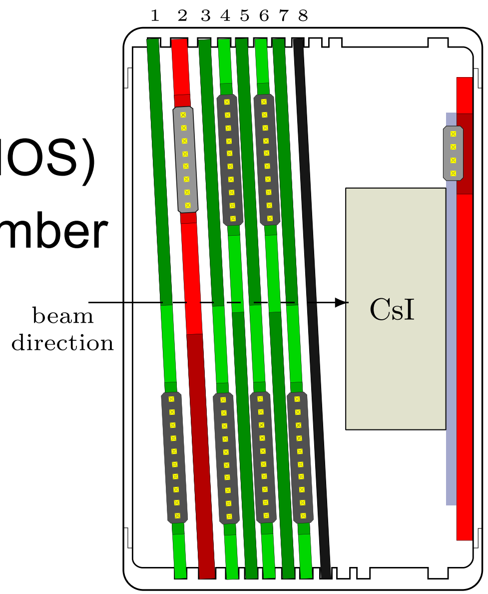
ILIMA Phase-0 program: ^{205}Tl bound-state beta decay

- New prototype Schottky detector installed in ESR
  - Variable resonance frequency: 408-416 MHz
  - Variable Q value: approx. 500-3000
  - High sensitivity

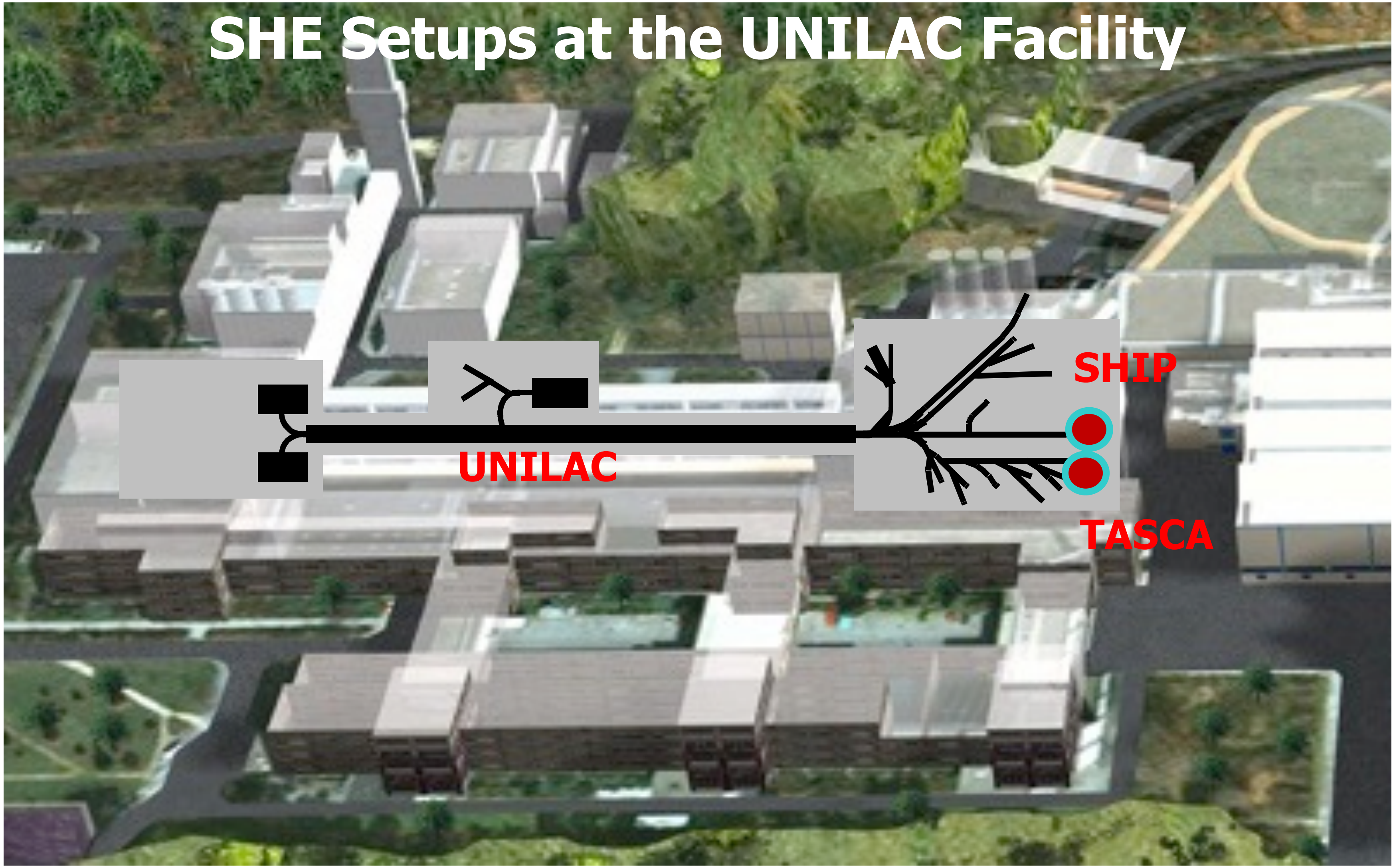


- Specifications of new Schottky detector for CR completed
- Heavy-ion detector
  - Si-CsI telescope (CsISiPHOS) installed in ESR pocket chamber





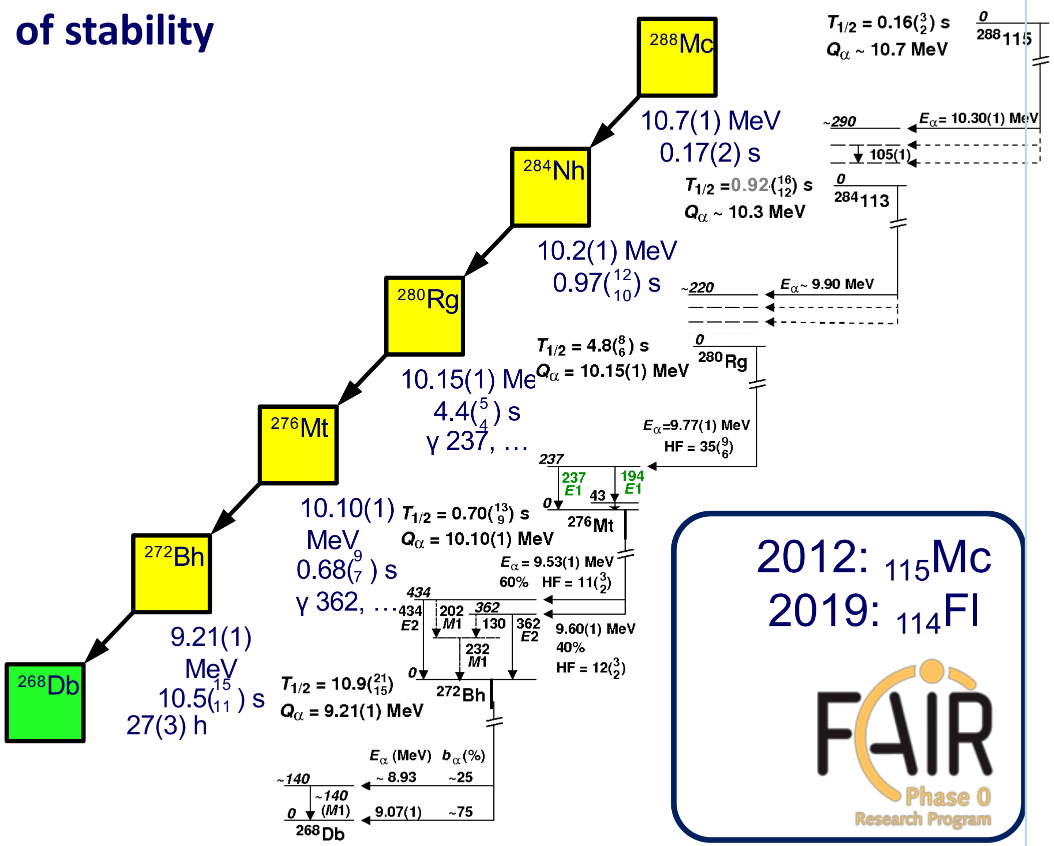
Superheavy element research at NUSTAR and FAIR/GSI



Recent highlights from the SHE collaboration

First nuclear structure information on the island of stability

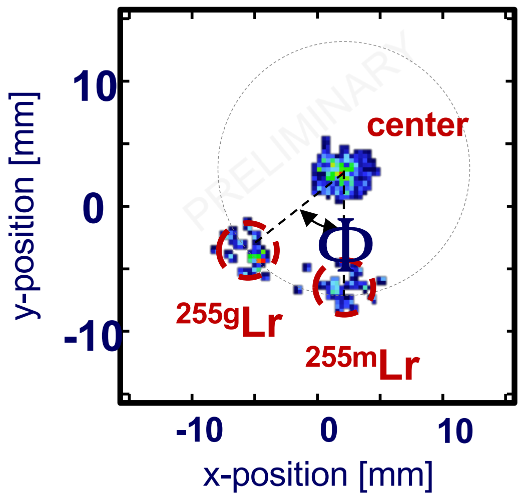
~100 chains
Dubna, **GSI, LBNL**

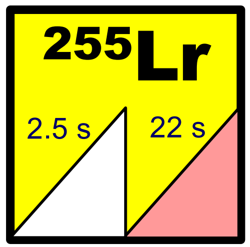


2012: $_{115}$Mc
2019: $_{114}$Fl

High precision direct mass measurements

- Two-week beamtime campaign in summer 2018
- new or improved mass values for ^{251,251m,254,254m}No and ^{254,254m,255m,255,256}Lr
- pinned down nuclear isomers with supreme resolving power of novel PI-ICR technique
- ^{257g,m}Rf (Z=104) measurement at a rate of about 1 event per day





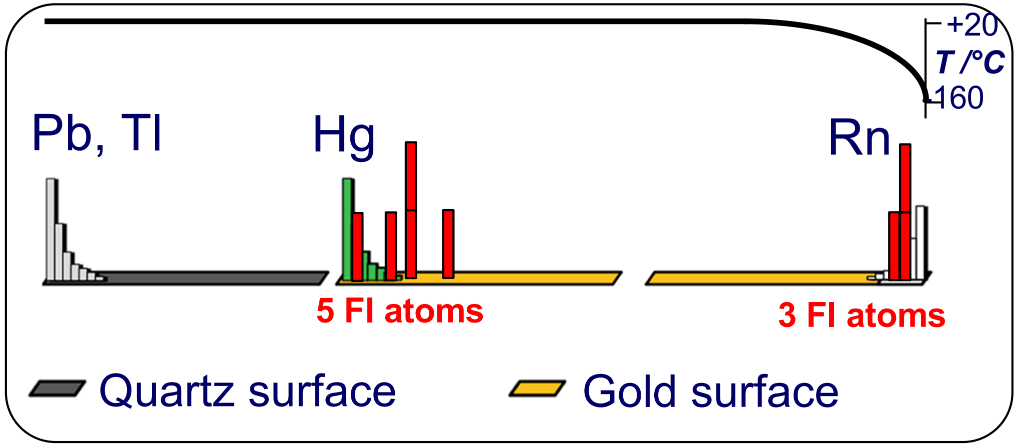
- **35 keV isomer resolved**

D. Rudolph et al., PRL 2013; J.M. Gates et al., PRC 2015
D. Rudolph et al., in preparation

O. Kaleja, F. Giacoppo et al. (SHIPTRAP collaboration)

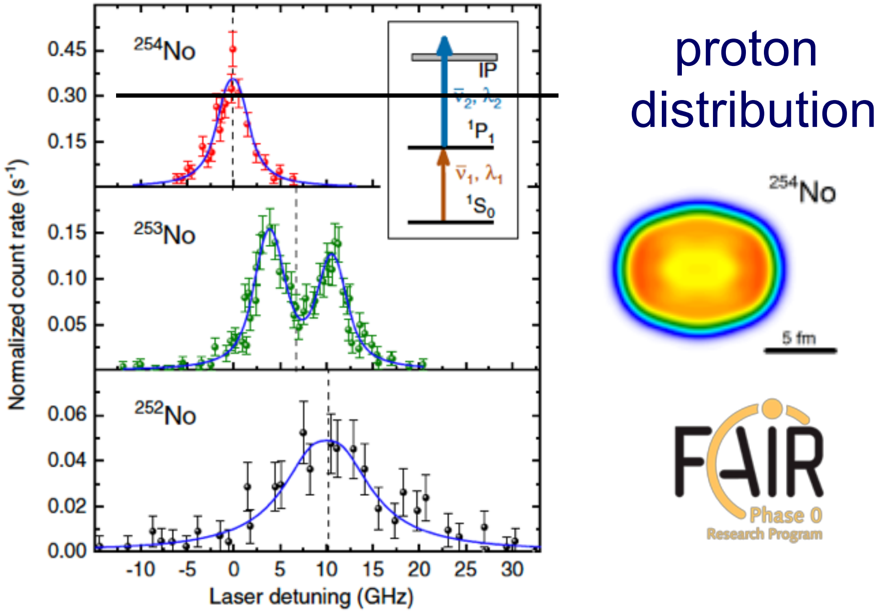
Chemical study of element 114, flerovium

- Heaviest element studied chemically
- Three beam-time campaigns (2009-2015)
- 8 decay chains from 2.5 months UNILAC beamtime
- Studies of interaction of Fl atoms with Au surface reveal Fl to be a noble, volatile metal. Binds strongly at grain boundaries, but not otherwise



Exp.: A. Yakushev, L. Lens et al. (***TASCA*** collaboration)
Theory: V. Pershina et al., and also others

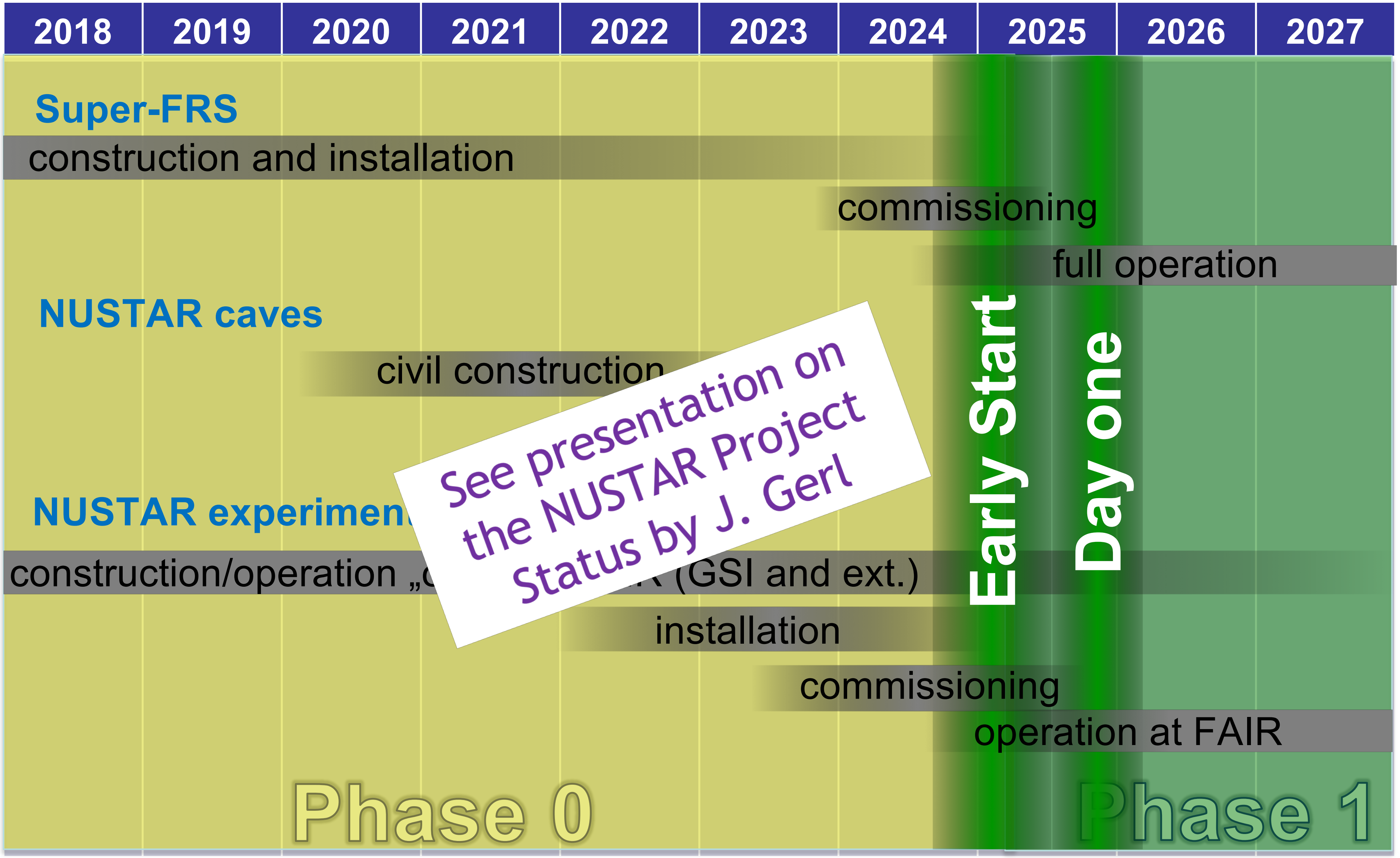
Laser spectroscopy yields information about the size and shape of No isotopes



- Diff. nuclear charge radii and nuclear moments
- Good agreement with nuclear DFT calculations

M. Laatiaoui *et al.*, Nature 538, 495 (2016)
S. Raeder et al., Phys. Rev. Lett. 120 (2018) 232503

Towards NUSTAR Day-1



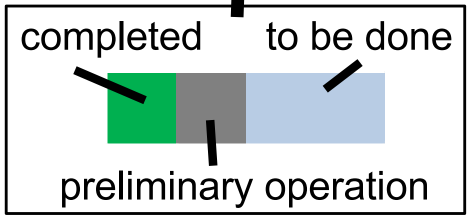
NUSTAR funding and management

	NUSTAR sub-system	TDR	Cost [k€ 2005]	Funding	Construction	Date completion	Test/ Commissioning
Day 1	LEB infrastr.		1,806			06/2023	
	HISPEC/DESPEC		10,817			03/2024	
	MATS		[illegible]			08/2024	
	LaSpec		[illegible]			05/2021	
	R3B		[illegible]			03/2023	
	ILIMA		[illegible]			12/2023	
		83% *value weighted*	…,936	94% *secured*	56% *value weighted*		
Change since report 2019-I		--	--	--	+1%		

See presentation on NUSTAR Finances and Project Management by A. Herlert

NUSTAR experiments and main components

average value weighted with investment/cost



- Three TDRs are under evaluation by the ECE.
- Final four TDRs are still under preparation for Day-1 (3 R3B, LEB).
- No components are on the critical path.
- Increased manpower resources will be required to keep the schedule.

Conclusions

- Most **NUSTAR** equipment is already ready for experiments and being commissioned at GSI or elsewhere
- Very few critical items (will be discussed in the following talks)
- All **NUSTAR** experiments will be ready with their principal equipment for **Day-1 experiments**, that is as soon as
  - **first beams from the Super-FRS will become available**
- **NUSTAR** will be **world-wide competitive** due to the unique properties of the **accelerators** (energy, intensity), the **Super-FRS** (transmission, rejection, resolution), the **storage rings** and other **new instrumentation**