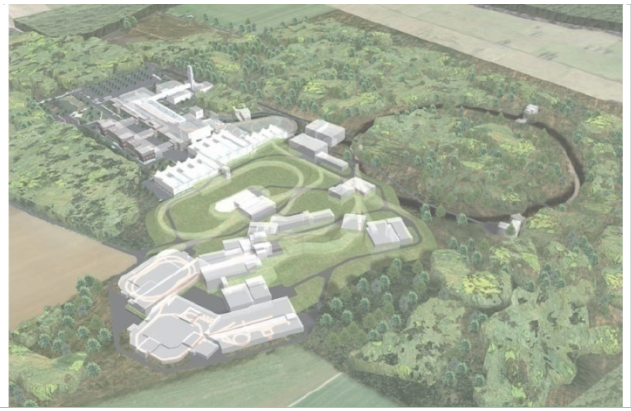
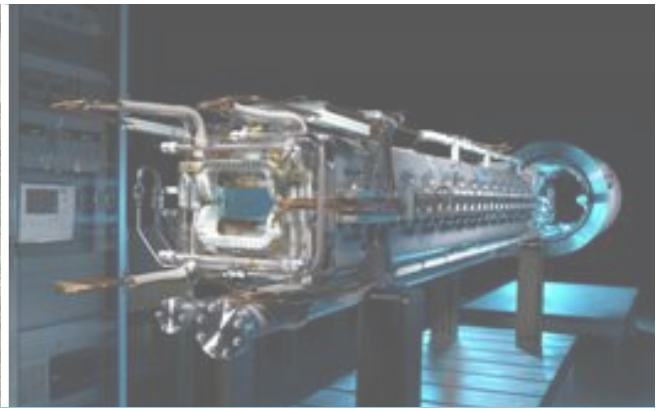



Exploring the extremes with NUSTAR @ FAIR

Nasser Kalantar-Nayestanaki
KVI-CART/University of Groningen

NUSTAR Annual Meeting

Darmstadt, Germany, March 3, 2016

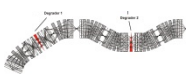
Finland France Germany India Poland Romania Russia Slovenia Sweden UK

FAIR

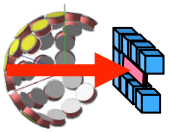
Reminder of the Physics

Complementarity of NUSTAR experiments

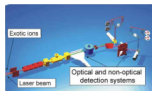
Super-FRS



HISPEC/ DESPEC

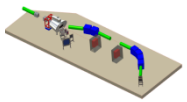


LASPEC

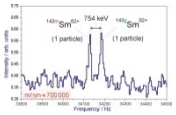


MATS

R3B



ILIMA



SHE

ELISE

EXL

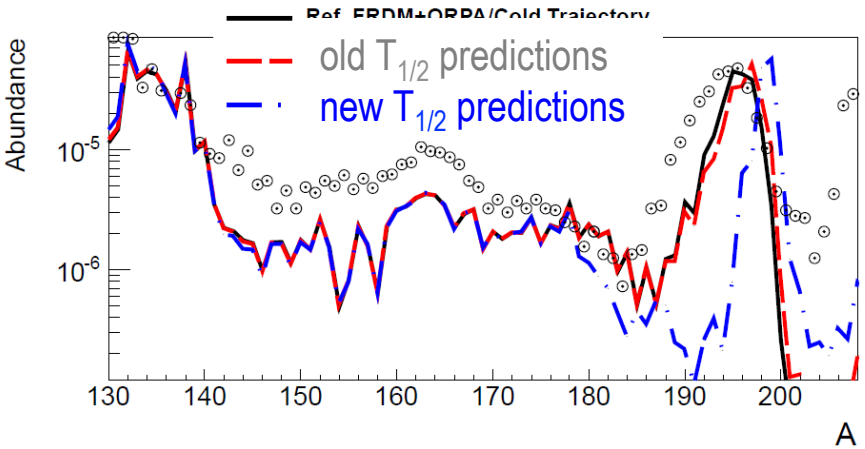
	Super-FRS	HISPEC/DESPEC	LASPEC	MATS	R3B	ILIMA	SHE	ELISe	EXL
Masses		Q-values, isomers		dressed ions, highest precision	unbound nuclei	bare ions, mapping study	precision mass of SHEs		
Half-lives	ps...ns-range	dressed ions, µs...s			resonance width, decay up to 100ns	bare ions, ms…years	µs...days		
Matter radii	interaction x-section				interaction x-section				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 and tensor	evolution of shell closures, pairing corr.	shell structure of SHEs		low momentum transfers
Collective behavior		electromag. transitions	quadrupole moments	halo structure	dipole response	changes in deformation		electromag. transitions	monopole resonance
EoS					polarizability, neutron skin			neutron skin ➔	neturon skin, Compressibility
Exotic Systems	bound mesons, hypernuclei, nucleon res.								

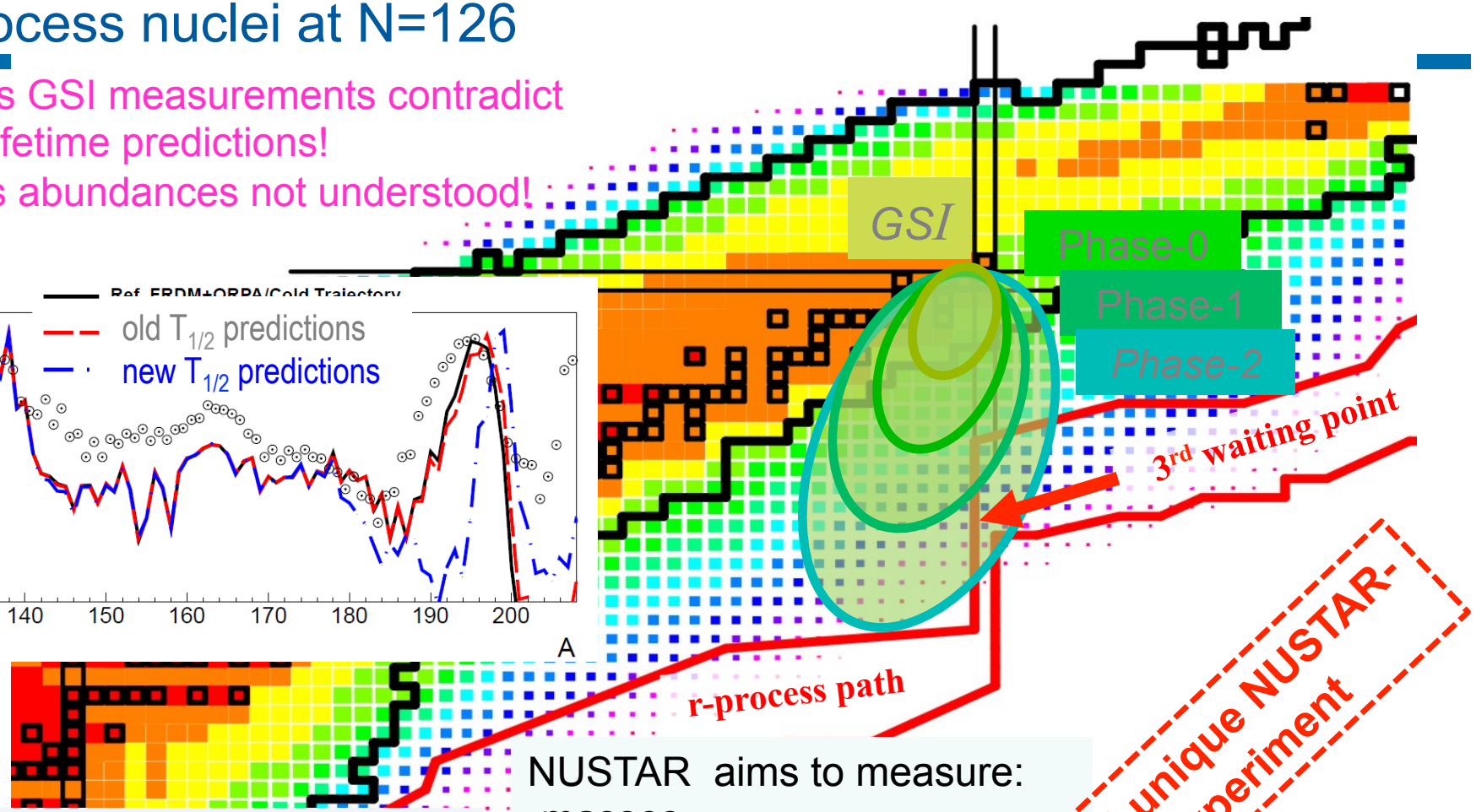
What are the highlights of MSV Phase 1 program?

- Understanding the 3rd r-process peak by means of comprehensive measurements of masses, lifetimes, neutron branchings, dipole strength, and level structure along the N=126 isotones;
- Equation of State (EoS) of asymmetric matter by means of measuring the dipole polarizability and neutron skin thicknesses of tin isotopes with N larger than 82 (in combination with the results of the first highlight);
- Exotic hypernuclei with very large N/Z asymmetry.

Phase 1 Physics with HISPEC/DESPEC:
r-process nuclei at N=126

Previous GSI measurements contradict earlier lifetime predictions!
→ Mass abundances not understood!





Mass abundances depend on the detailed structure of N=126 nuclei around the 3rd r-process waiting point

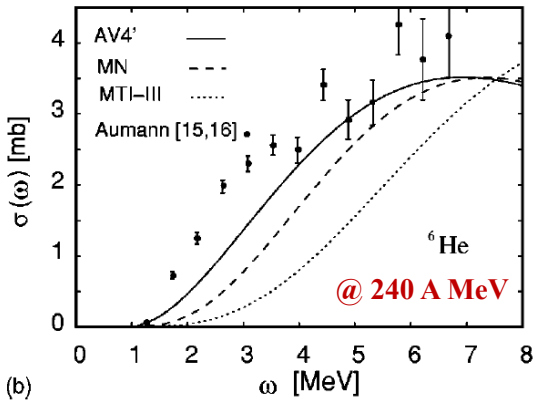
NUSTAR aims to measure:
- masses
- β-lifetimes
- neutron-branchings
- strength distributions
- level structure

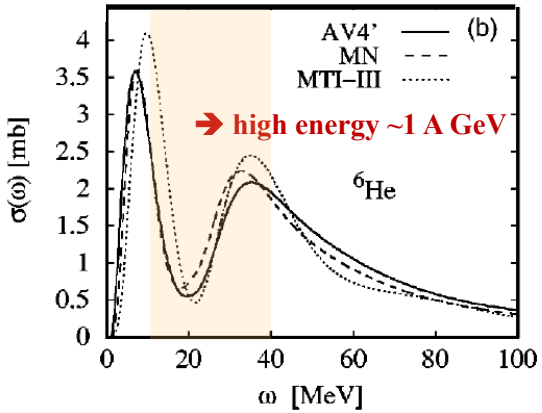
Important unique NUSTAR-LEB experiment

Phase 1 Physics with R3B setup:

Dipole strength Distributions in heavy neutron-rich nuclei

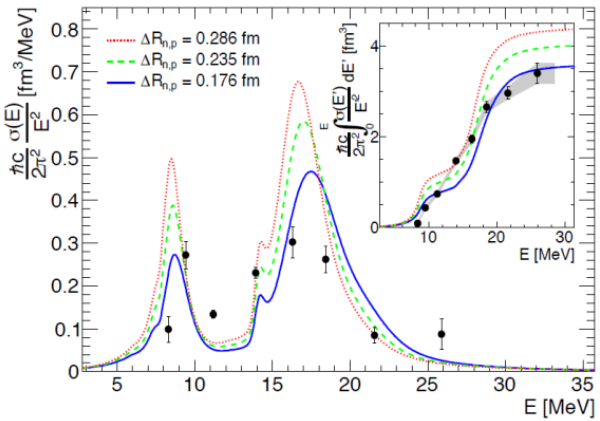
- core vs. neutron skins & halos → density / asymmetry





S. Bacca et al.
PRL **89** (2002) 052502
PRC **69** (2004) 057001

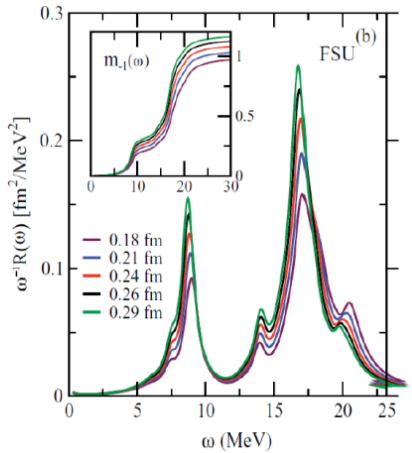
- access to EoS (e.g. neutron star) & low lying E1 strength (r-process)



$$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma(E)}{E^2}dE$$

D. Rossi et al.
PRL **111** (2013) 242503

skin thickness ^{68}**Ni**
0.175(21) fm



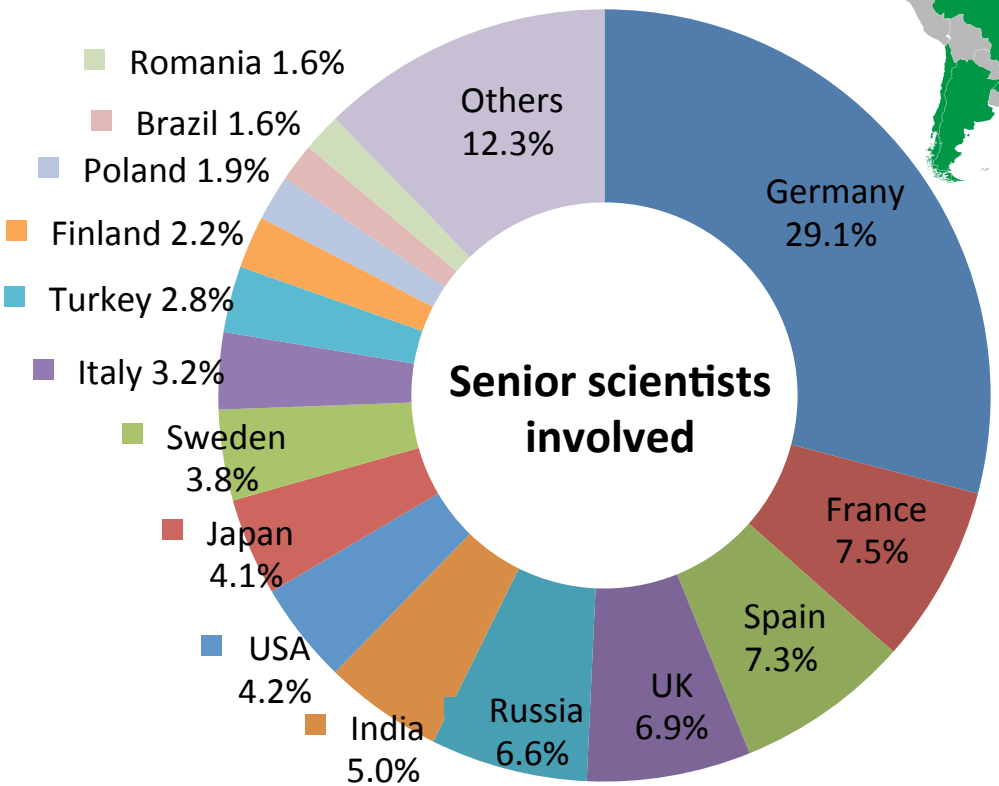
Pb chain & N=126 isotones

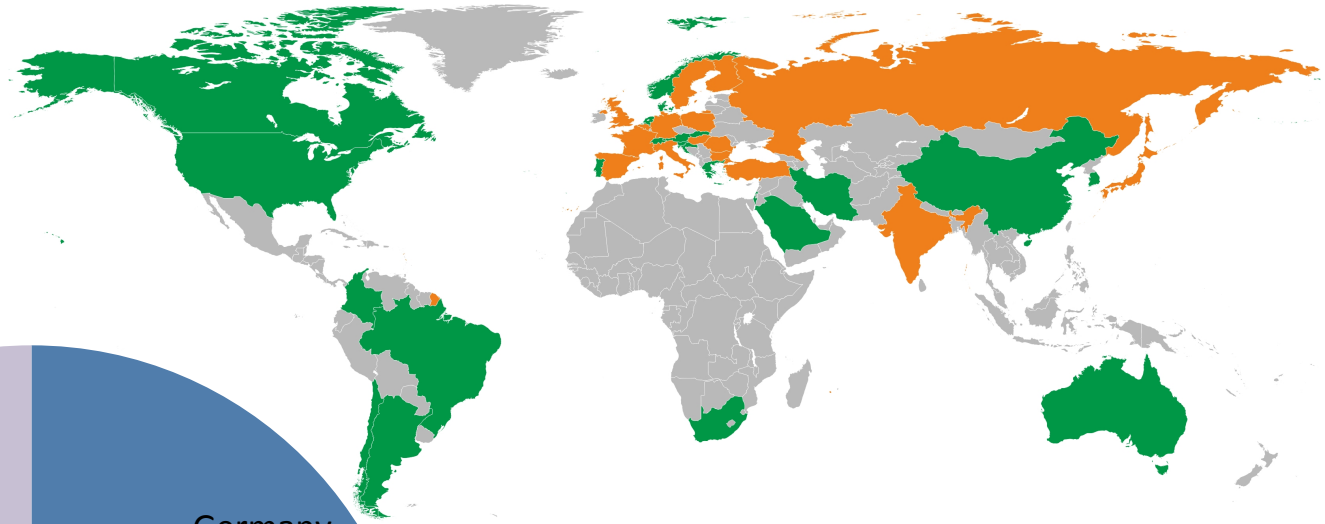
~1 A GeV →
bare ions
Fragment identification

J. Piekarewicz, PRC **83** (2011) 034319

NUSTAR collaboration

NUSTAR Collaboration





> 800 registered "interested" scientists in NUSTAR data base

39 countries

more than 180 institutes

Secured funding and expression of interest in funding (status: January 2016)

16 countries (incl. 9 FAIR partner countries)

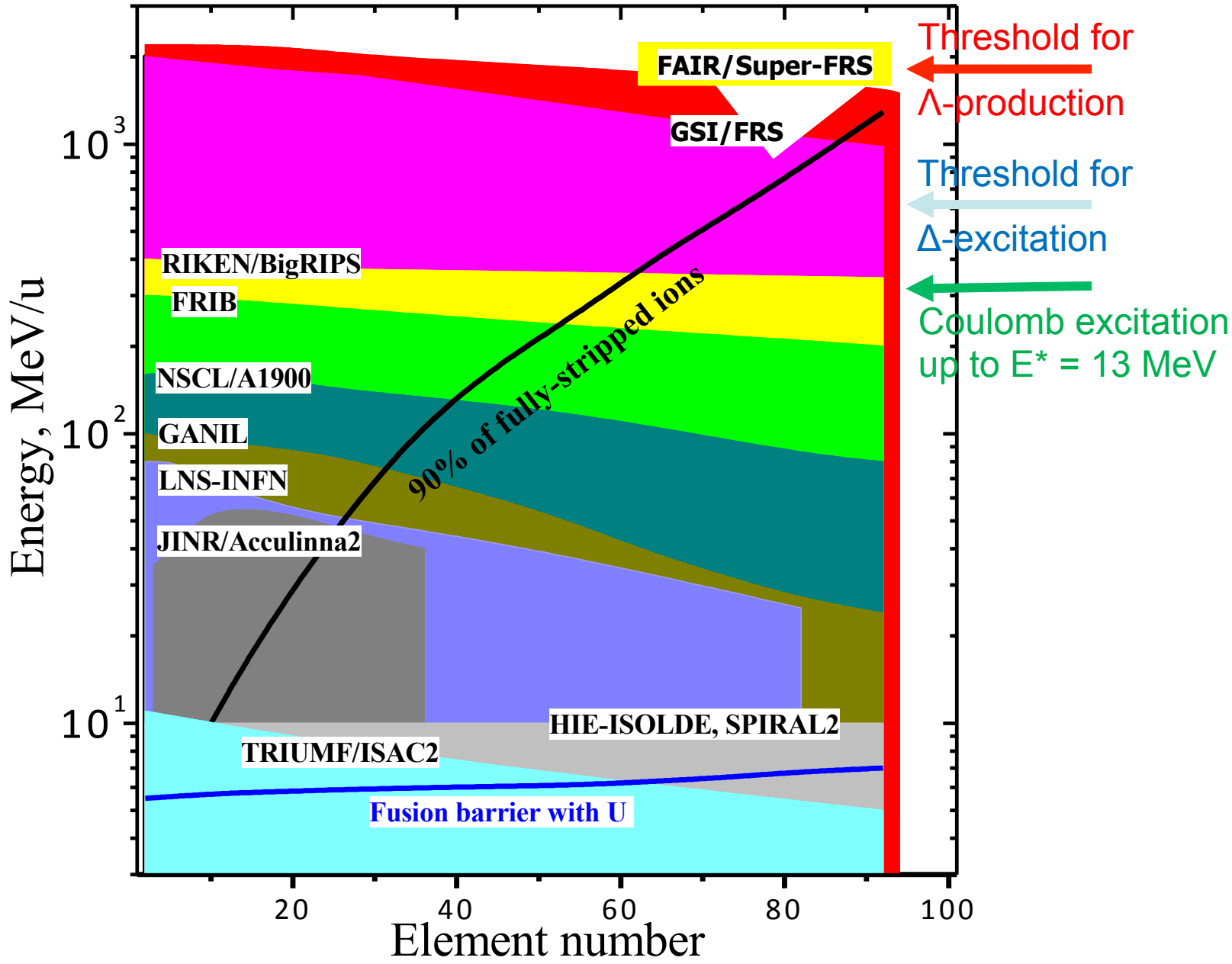
NUSTAR - The Project 1.2

	Super-FRS	RIB production, separation, and identification
PSP	**Experiment**	**Description**
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^3B**	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
1.2.11	**SHE**	Synthesis and study of super-heavy elements
1.2.8	**ELISe(*)**	Elastic, inelastic, and quasi-free e^--A scattering
1.2.9	**EXL(*)**	Light-ion scattering reactions in inverse kinematics

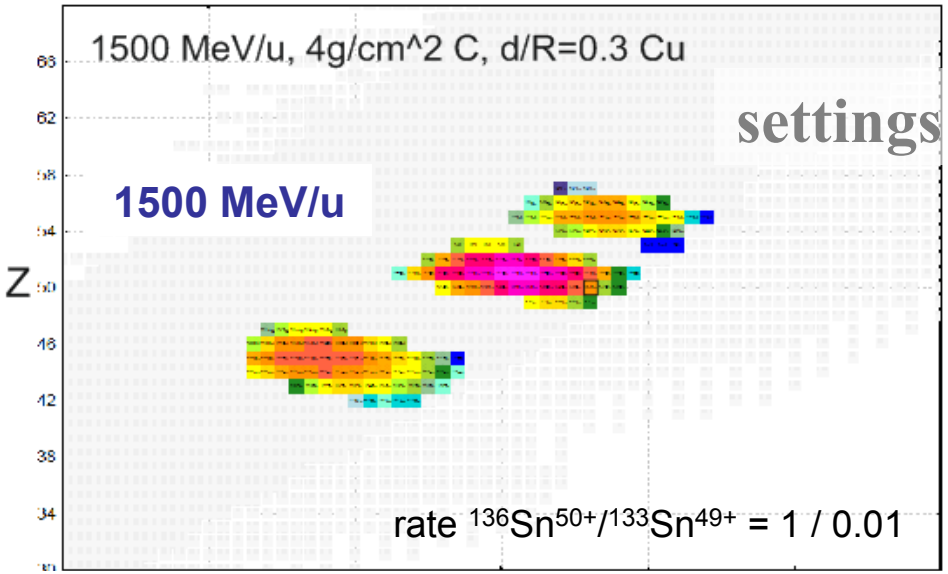
(*) NESR required – alternative/intermediate “operation” within MSV under discussion.
SHE physics case to be evaluated by ECE.

“PARTS” needed

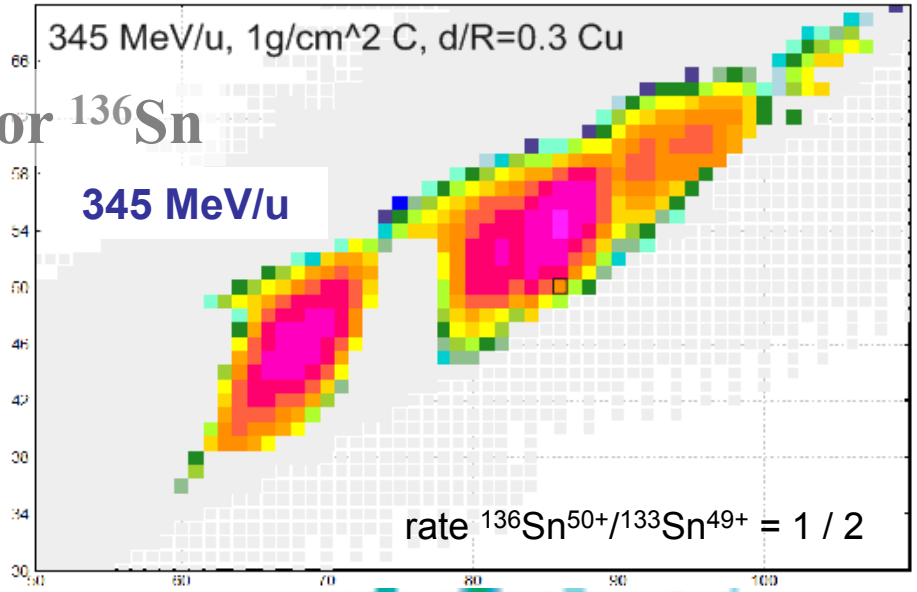
RARE-ISOTOPE BEAM FACILITIES



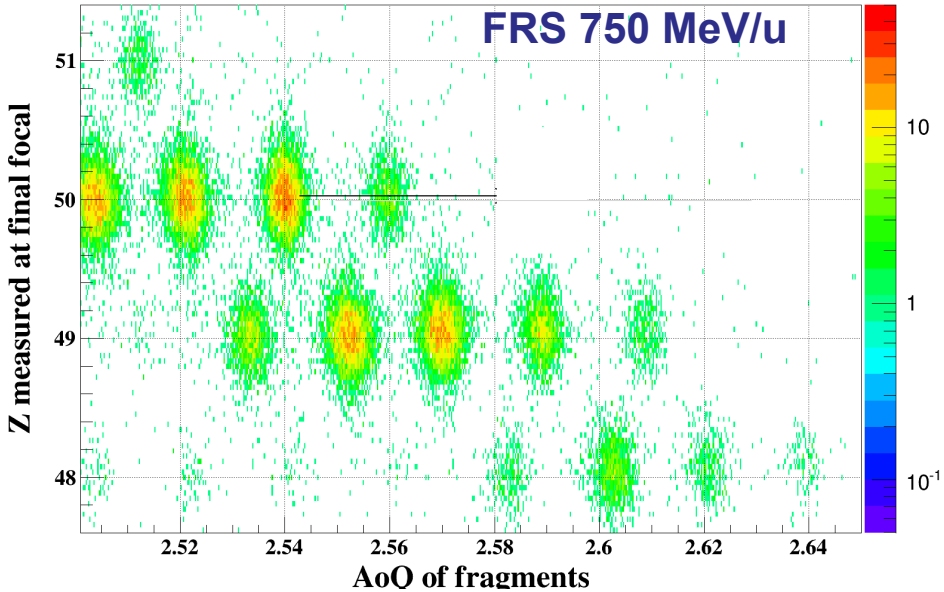
Charge-separation capability for different Energies

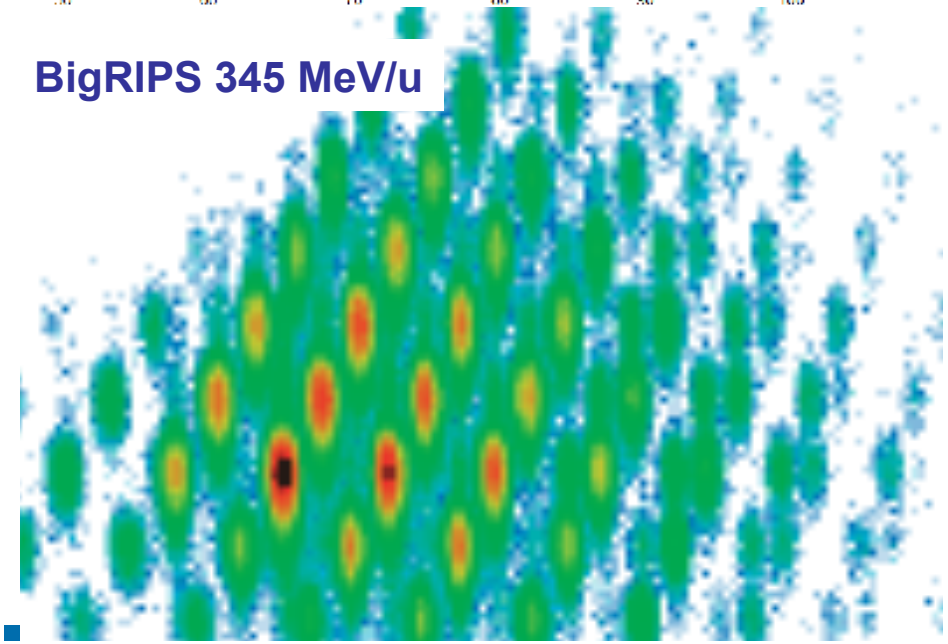


settings for ^{136}Sn

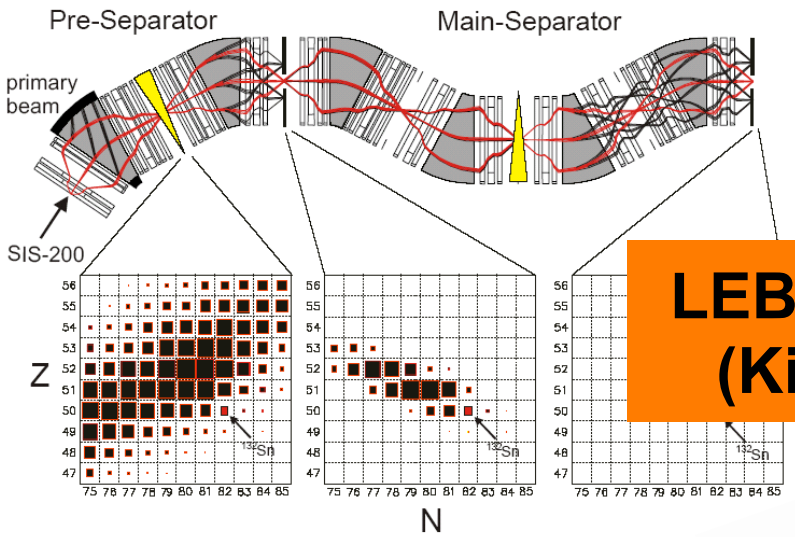


Setting in the Sn region, FRS

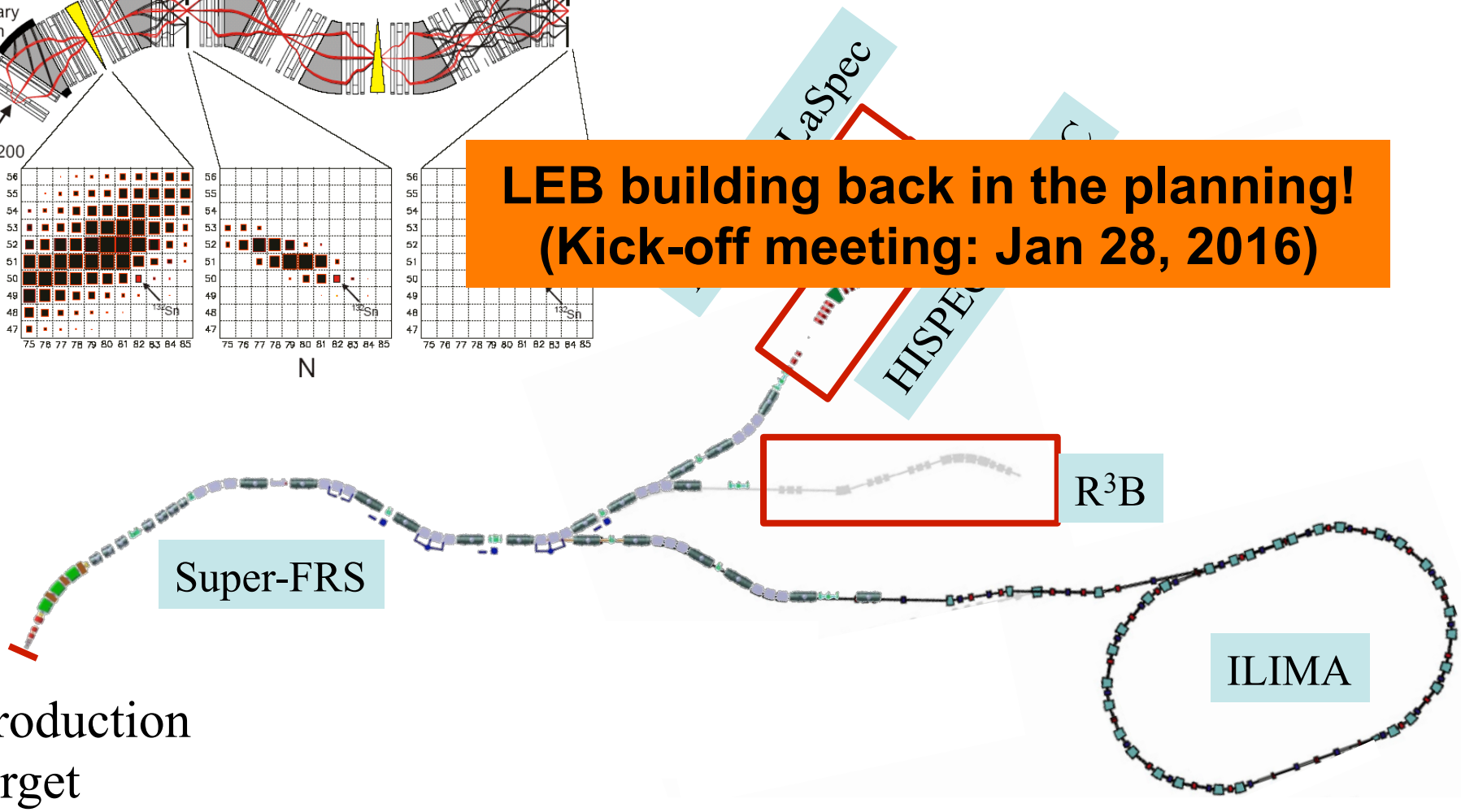




NUSTAR experimental areas, ESSENTIAL to run!



LEB building back in the planning!
(Kick-off meeting: Jan 28, 2016)



Rich program due to approximately 2000 h beam time for NUSTAR experiments per year!

SIS100 essential!

Facility	U beam intensity/spill at production target
previously at GSI	$1...2 \times 10^9$
after the SIS18 upgrade at GSI	8×10^9
commissioning phase SIS100	2×10^{10}
final full intensity with **SIS100**	3×10^{11}

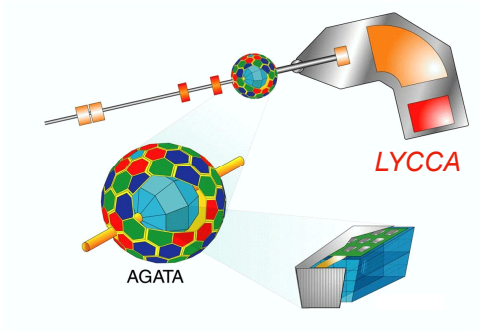
- High energies for unique separation and unique experiments
- Competitive intensities throughout the periodic table

Detector Systems
Status R&D and Construction

HISPEC/DESPEC - foreseen instrumentation

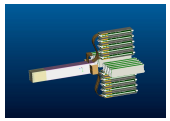
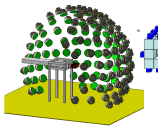
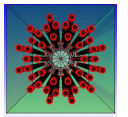
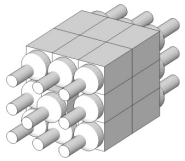
HISPEC

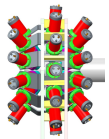
- AGATA gamma-tracking spectrometer
- LYCCA heavy-ion calorimeter with ToF capability
- Plunger nuclear level lifetime measurements
- MINOS Proton target
- NEDA Neutron detector array
- HYDE light charged-particle array



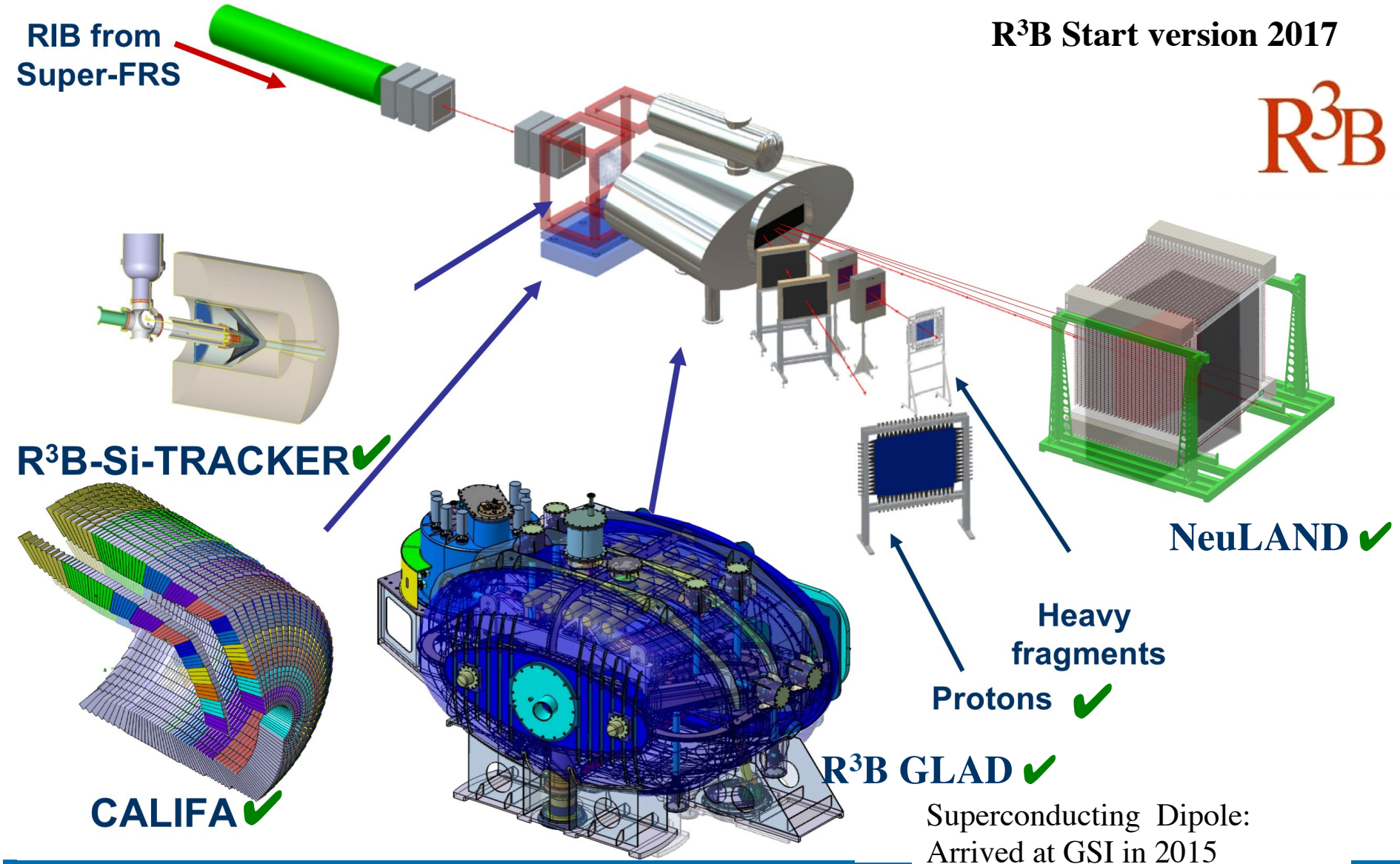
DESPEC

- AIDA active implantation device
- MONSTER neutron ToF array
- BELEN neutron detection array
- DTAS Decay Total Absorption Spectrometer
- DEGAS Ge Array gamma spectrometer
- FATIMA Fast TIMing Array



Reactions with Relativistic Radioactive Beams R^{3}B



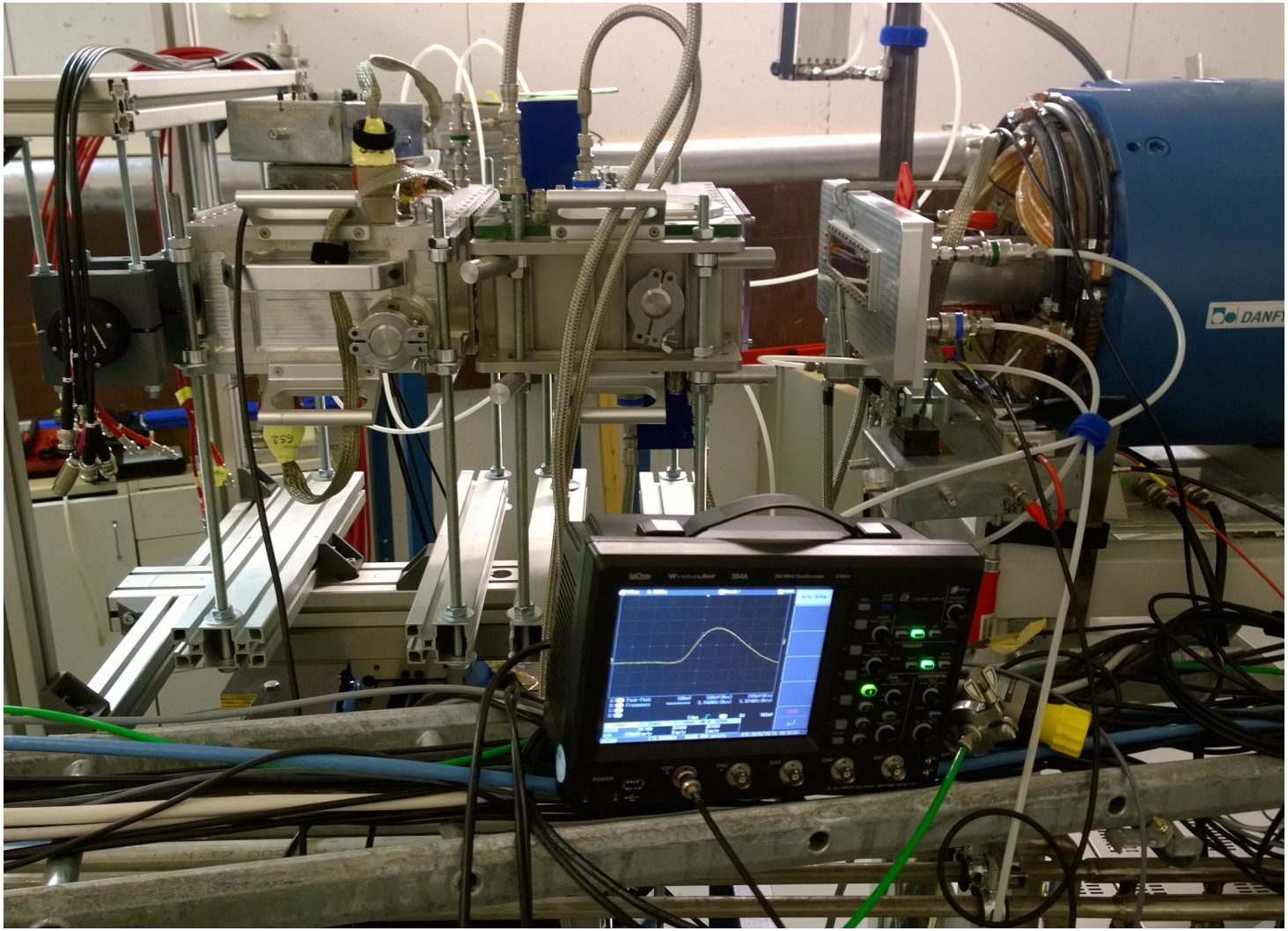
Superconducting Dipole:
Arrived at GSI in 2015
Construction by CEA Saclay

GLAD magnet (Saclay)

GLAD magnet (November 2015, GSI)

GLAD magnet (November 2015, GSI)

GEM-TPC at JYFL beam-line

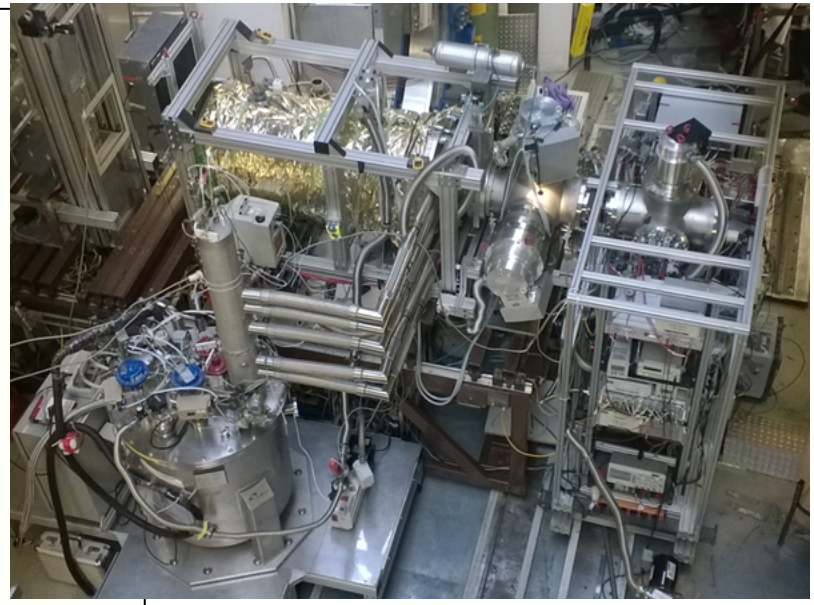


Stopping cell for the LEB

Successfull on-line test of the prototype of the cryogenic stopping cell (CSC) at the FRS Ion Catcher 2014 (analysis in 2015)

Results:

- First thermalization and extraction of ^{238}U fission products produced at 1000 MeV/u
- Systematic investigation of the rate capability of the CSC
- Operation of the CSC and the multiple-reflection time-of-flight mass spectrometer as mass tagger for the fragment separator ID



Collaboration

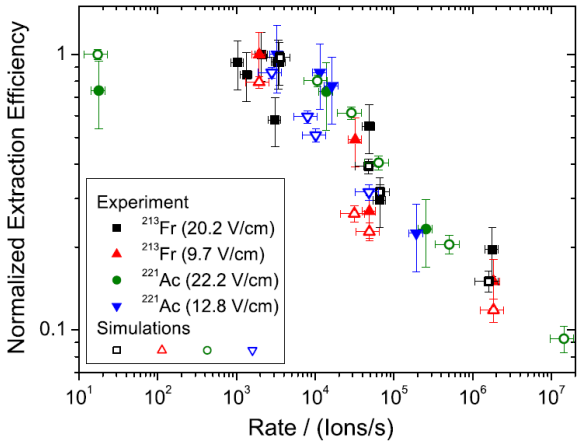
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

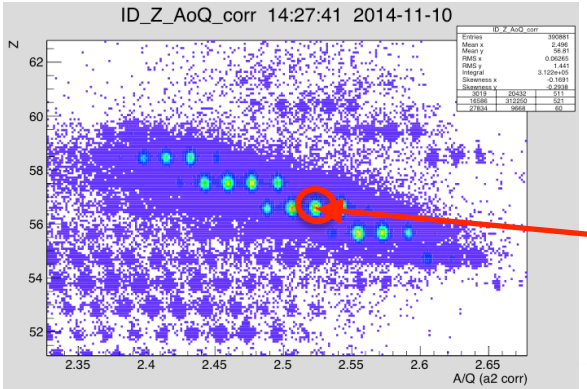
Kernfysisch Versneller Instituut

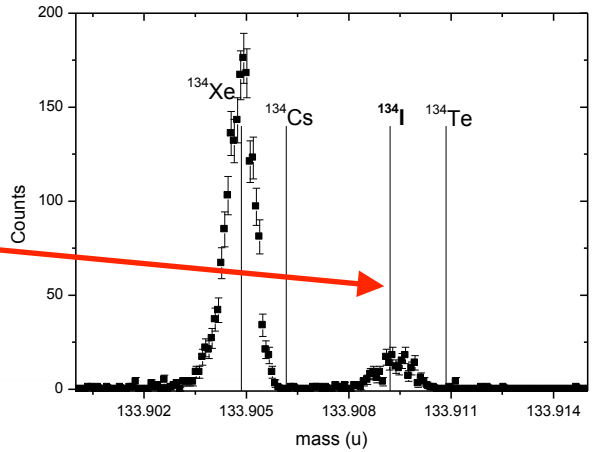
university of groningen

GSI

UNIVERSITY OF JYVÄSKYLÄ





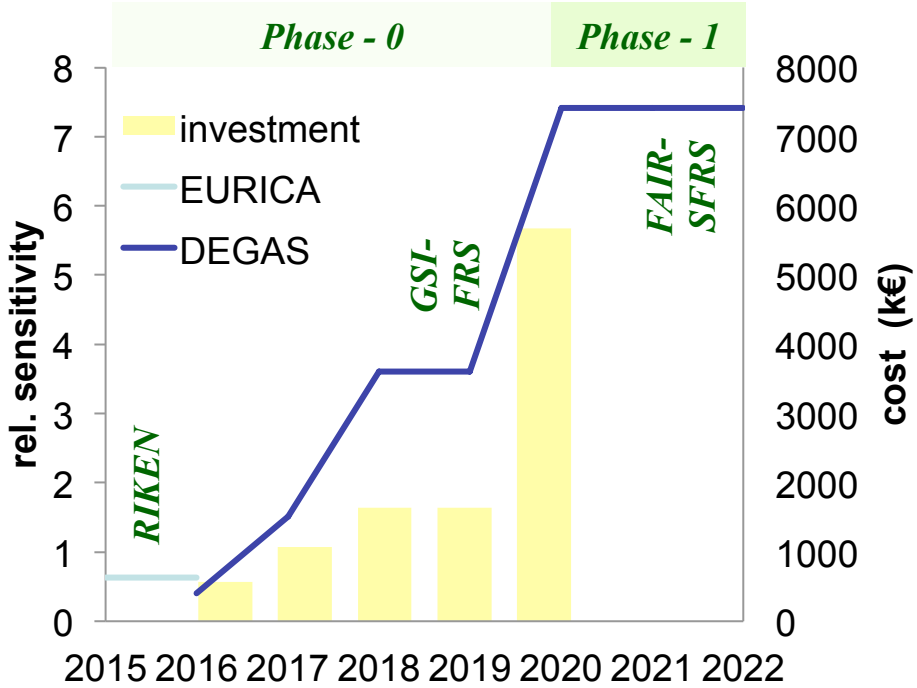


Definition of NUSTAR experiment phases

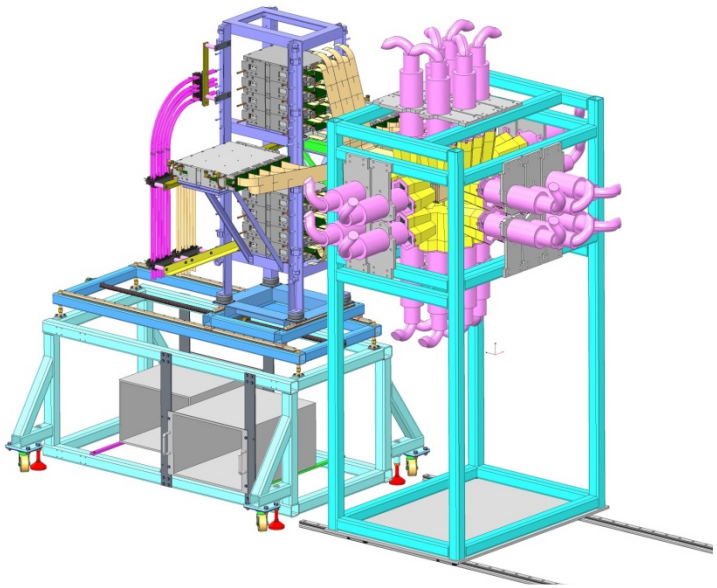
- **Phase 0**
  - R&D and experiments to be carried out with present facilities and FAIR/ NUSTAR equipment
- **Phase 1**
  - Core detectors and subsystems completed
  - First measurements with FAIR/Super-FRS beams
    - **Carry out experiments with highest visibility as part of the core program and within the FAIR MSV**
- **Phase 2**
  - FAIR evolving towards full power
  - Completion of experiments within MSV
    - **Essentially the full program of MSV can be performed**
- **Phase 3**
  - Moderate projects, which have been initiated on the way (outside MSV) can be included (e.g. experiments related to return line for rings)
- **Phase 4**
  - Major new investments and upgrades for all experiments

Funding and TDRs

Work packages and funding: DEGAS array



DEGAS array



- The predecessor of DEGAS, namely EURICA is running currently in RIKEN.
- An intermediate version is planned for experiments at GSI from 2017 onwards.
- The full version shall be available once FAIR is operational.
- The course of construction is mainly determined by the availability of funding.

Funding

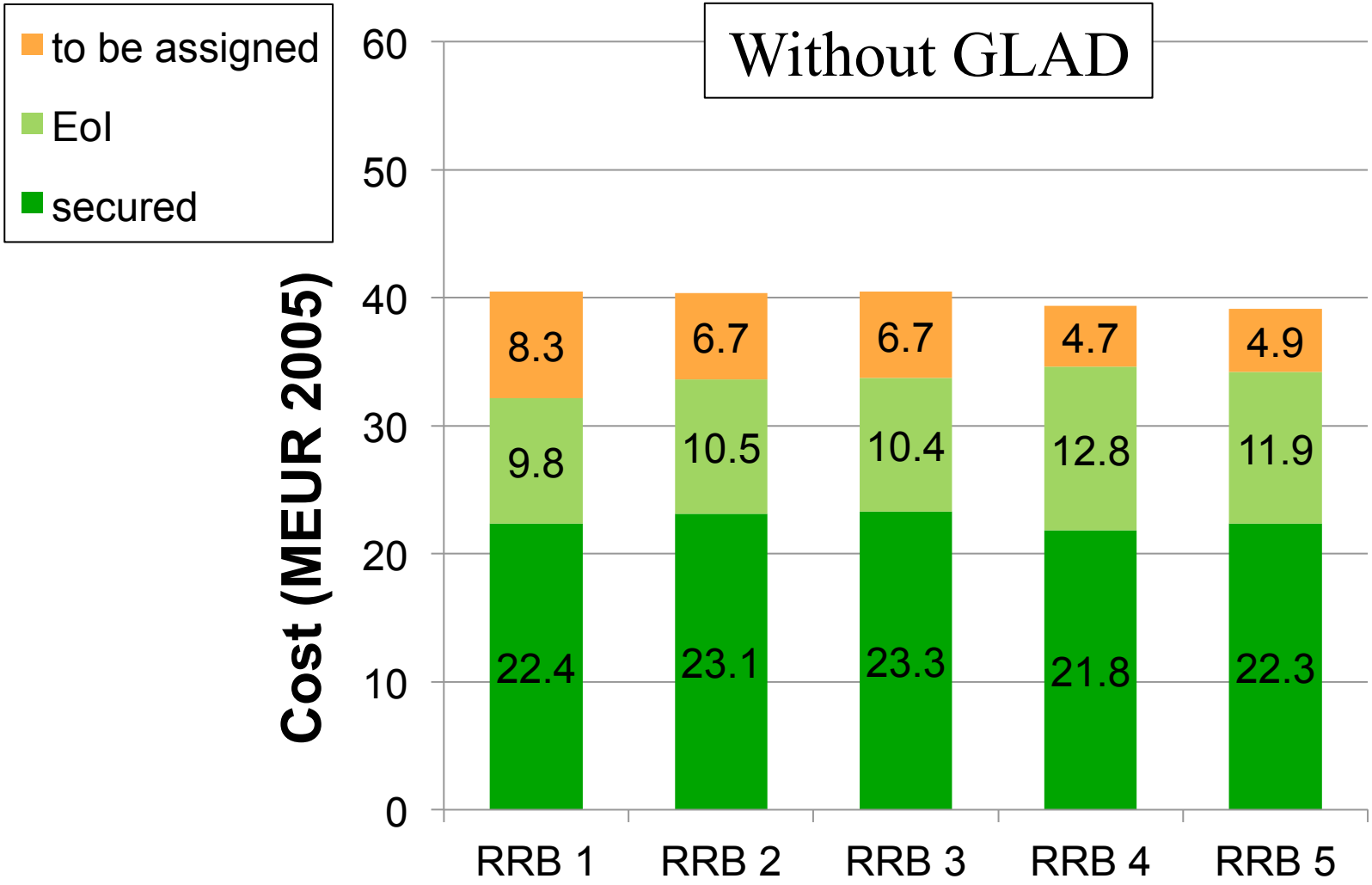
UPDATE

Not needed ... I will show the det

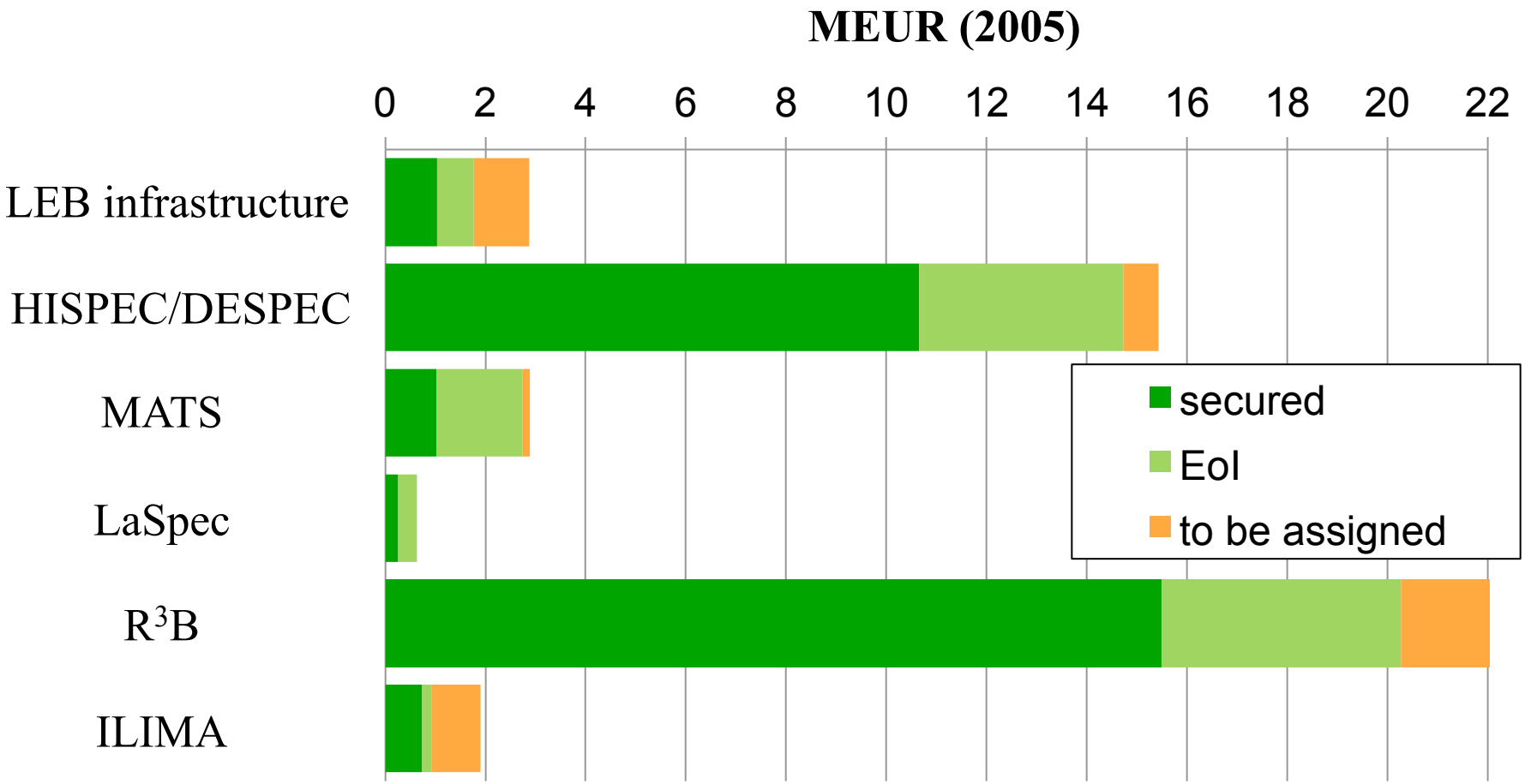
Status experiment funding (NUSTAR) - January 12, 2015							
PSP code	Experiment/Project	Prices (KEUR in 2[illegible])					
		Estimated cost	Secured amount	Expected FA[illegible]	Amount spe[illegible]	EoI	To be assigned
1.2.1	LEB Super-FRS	3050	8[illegible]				
1.2.2	HISPEC/DESPEC	15773	73[illegible]				
1.2.3	MATS	2893	795	206	760	1804	87
1.2.4	LaSpec	640	144	0	144	496	0
1.2.5	R3B	21961	15400	1039	12460	3828	1696
1.2.6	ILIMA	1902	740	0	0	212	950
	Sum	**46219**	**25287**	**3429**	**16800**	**12789**	**4718**

	NUSTAR		**54.7%**	**7.4%**	**36.3%**	**27.7%**	**10.2%**
1.2.1	LEB Super-FRS		29.0%	0.0%	0.0%	29.0%	42.0%
1.2.2	HISPEC/DESPEC		46.4%	13.8%	21.8%	35.3%	4.5%
1.2.3	MATS		27.5%	7.1%	26.3%	62.4%	3.0%
1.2.4	LaSpec		22.5%	0.0%	22.5%	77.5%	0.0%
1.2.5	R3B		70.1%	4.7%	56.7%	17.4%	7.7%
1.2.6	ILIMA		38.9%	0.0%	0.0%	11.1%	49.9%

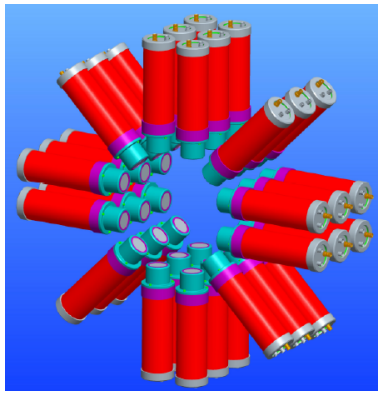
Evolution of NUSTAR project funding (RRBs)



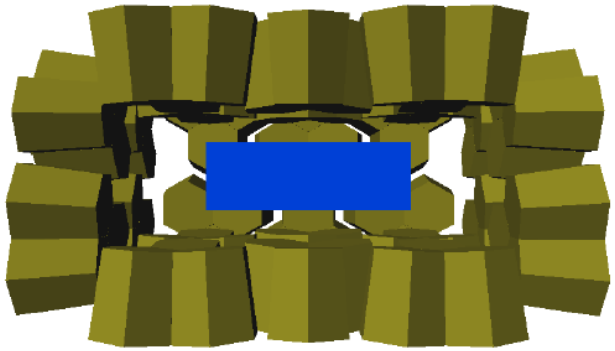
Status of NUSTAR experiment funding



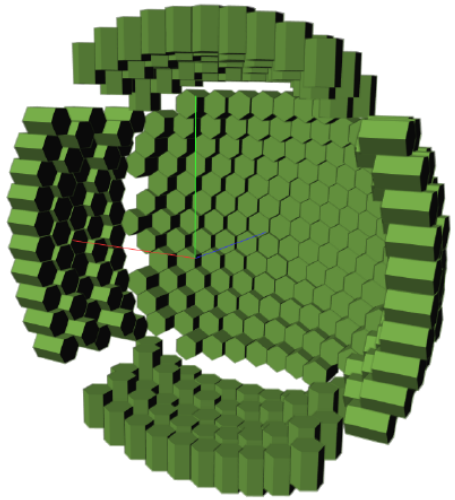
TDRs approved (6th and 7th ECE meeting)



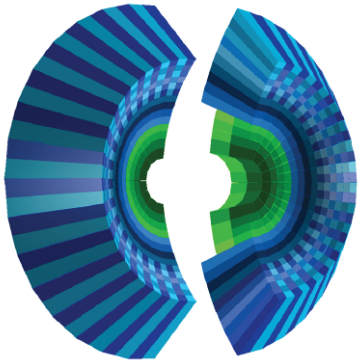
FATIMA
(fast timing array)



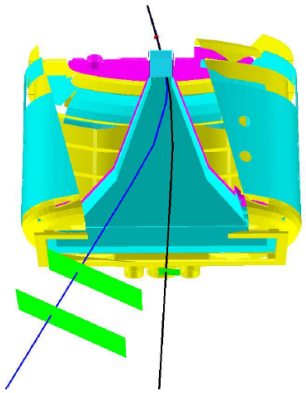
DEGAS
(DESPEC Germanium Array Spectrometer)



NEDA
(Neutron detector array for HISPEC)

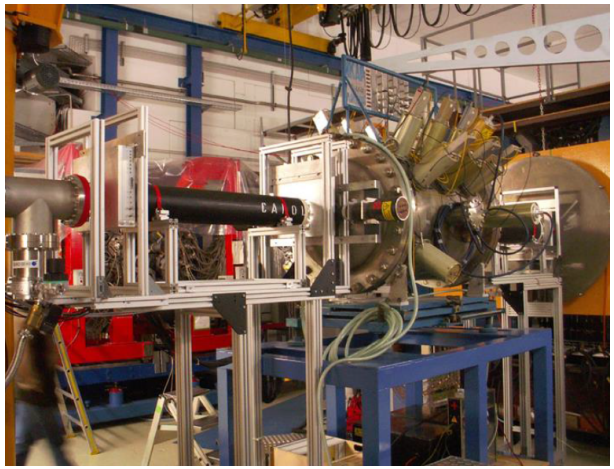


CALIFA
forward endcap



R3B tracking detectors

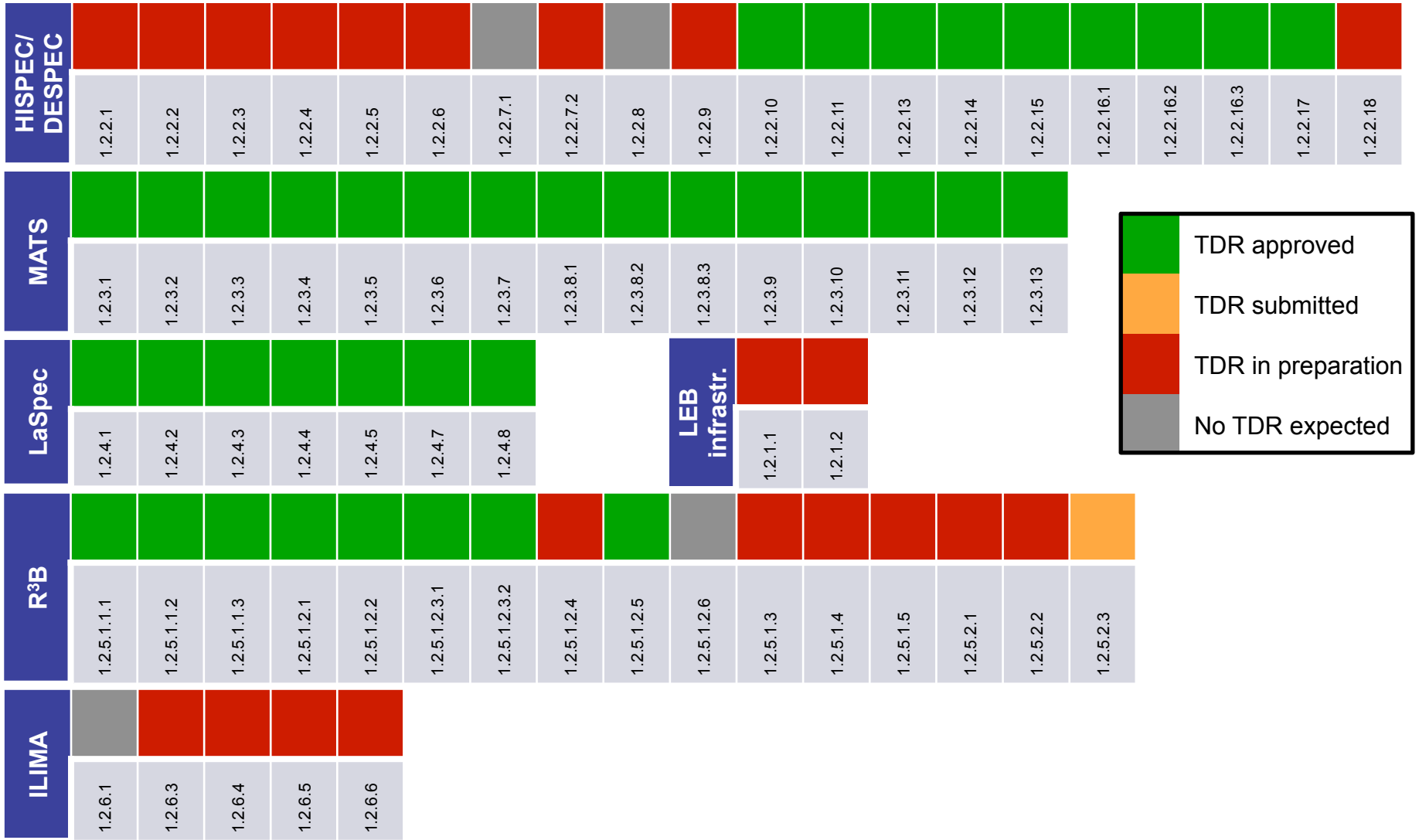
TDRs under evaluation (submitted)



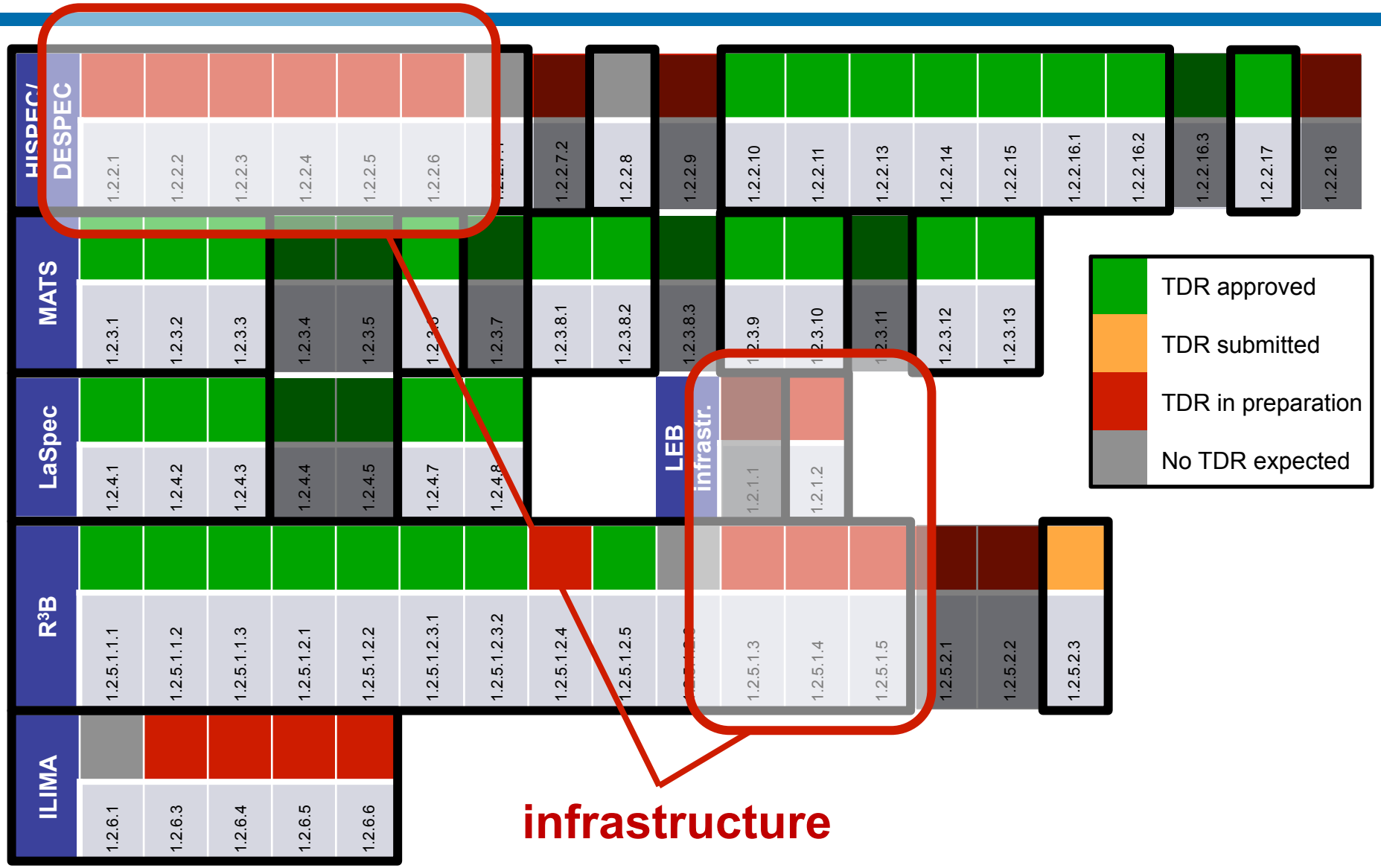
ACTAR
(Active target for the R^3B experiment)
submitted September 2015

Next ECE meeting in summer 2016

NUSTAR work packages (61 with TDR)



NUSTAR work packages (Phase 1 (day-1) experiments)



Status Technical Design Reports (34 TDRs)

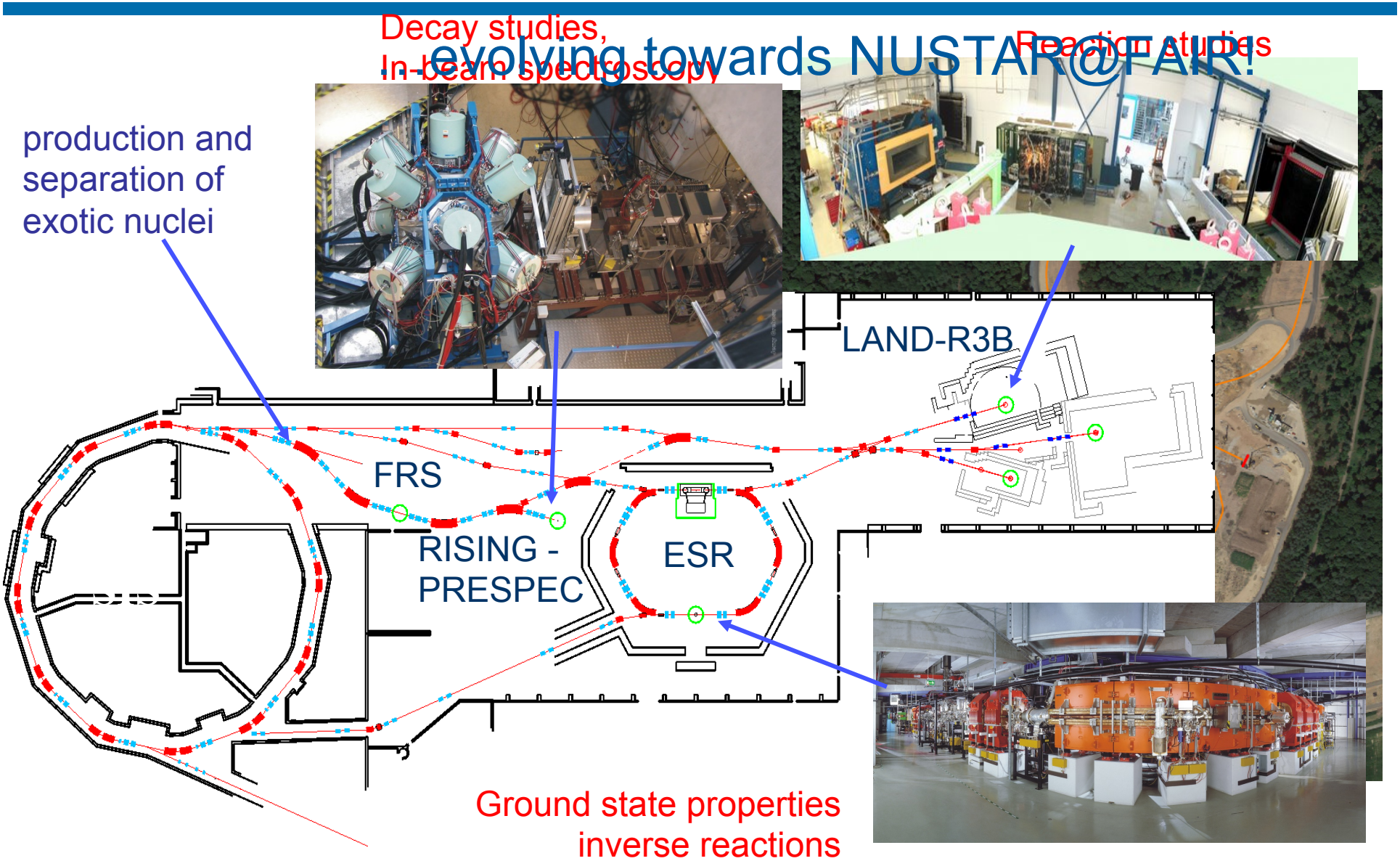
- Approved TDRs (16):
  - HISPEC/DESPEC (9) (LYCCA, Plunger, AIDA, BELEN, MONSTER, DTAS, DEGAS, FATIMA, NEDA)
  - MATS + LaSpec (1) (all subsystems – except LD-RIS: no action)
  - R^3B (6) (Multiplet, NeuLAND, CALIFA-barrel, CALIFA forward endcap, GLAD, tracking detectors)
- Submitted (1):
  - R^3B (1) (Active target)

TDRs expected (17) (submission profile – January 2016)						
2015	2016				2017	2018
	Q1	Q2	Q3	Q4		
0	8	1	4	4	0	0

Strategy

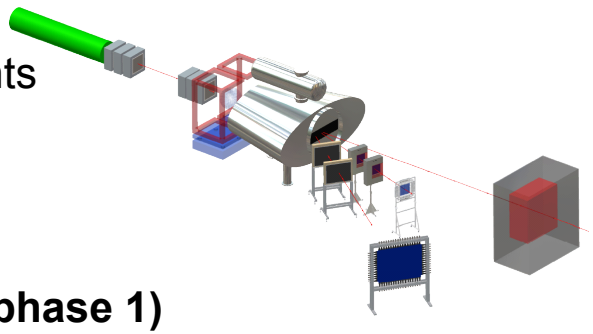
Phase 1

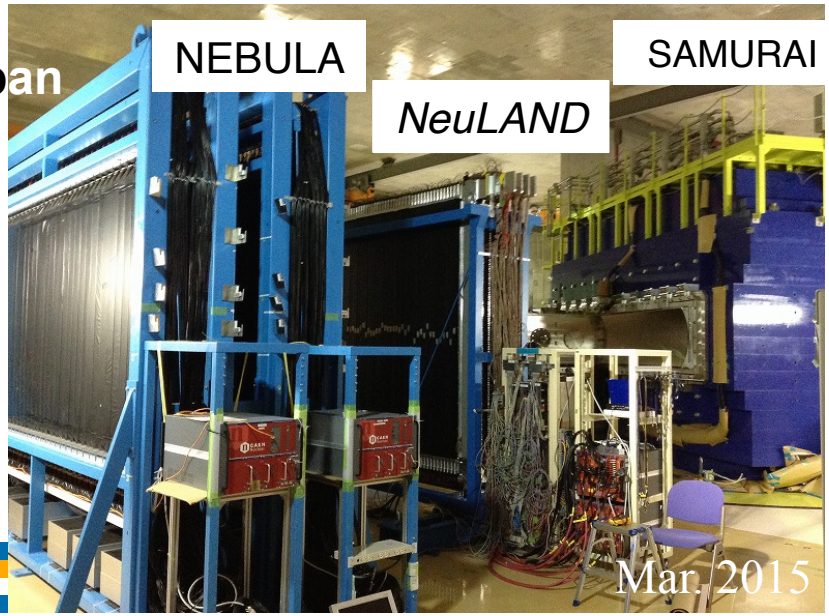
evolving towards NUSTAR@FAIR!



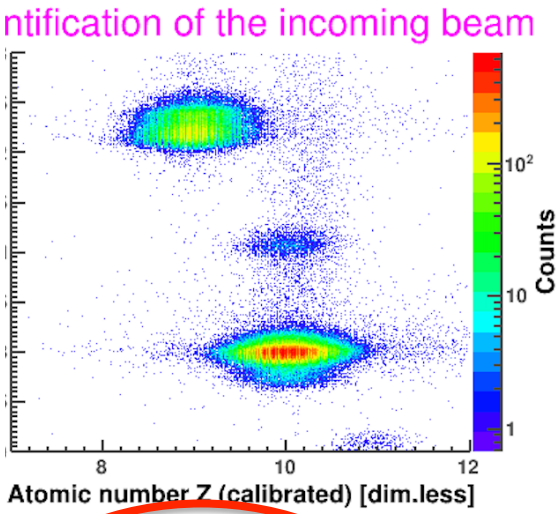
Schedule and first experiments

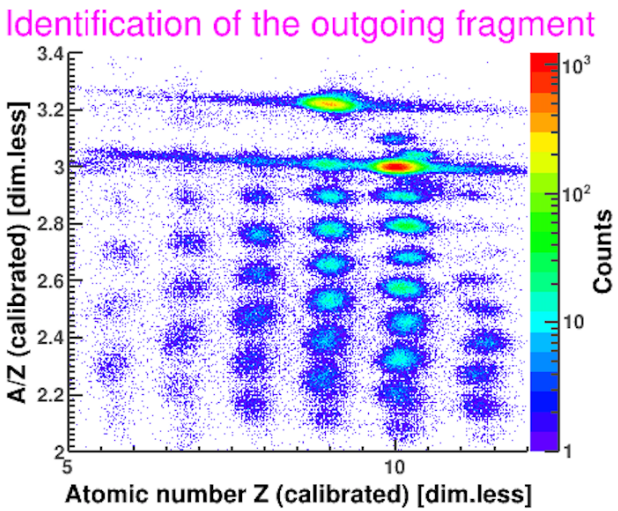
2013	Installation of infrastructure in Cave C for GLAD (He cryo-system, power supply)
	Delivery and installation of superconducting dipole GLAD (Q4/2015-onward)
2014	Installation of 20% detectors NeuLAND and CALIFA
	Commissioning run in Q3/2014, Move Neuland to Japan
2015/16	Construction and installation of detector components
2015/16	Commissioning and physics run with some components
2017/18	Commissioning of full R3B setup (Cave C)
2018-202x	Physics runs at GSI (Cave C) **(phase 0)**
202x-202x+1	Move to High-Energy Branch building
202x+1 →	Commissioning and first experiments at Super-FRS **(phase 1)**

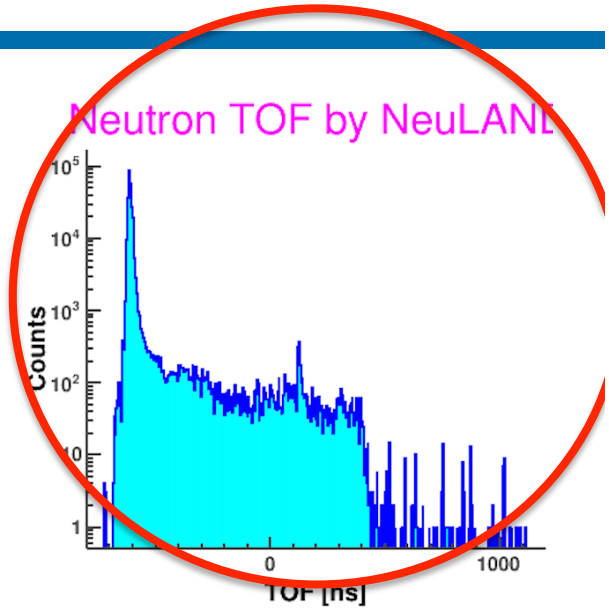


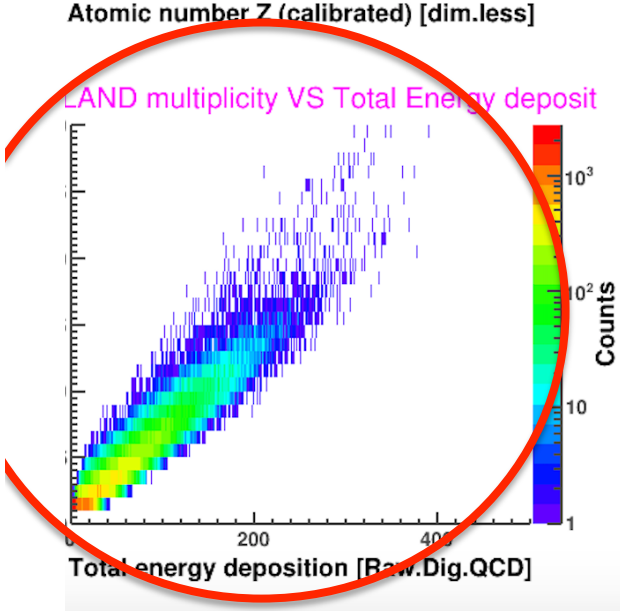


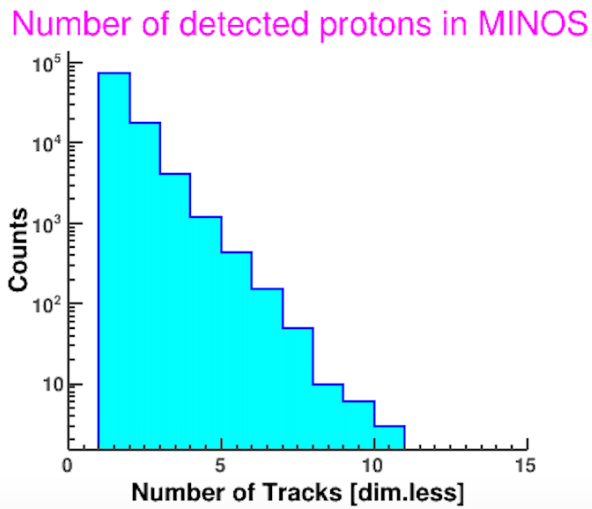
Recent results from RIKEN

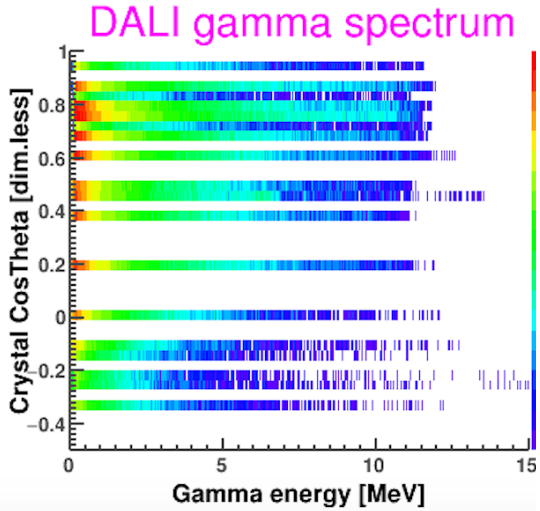






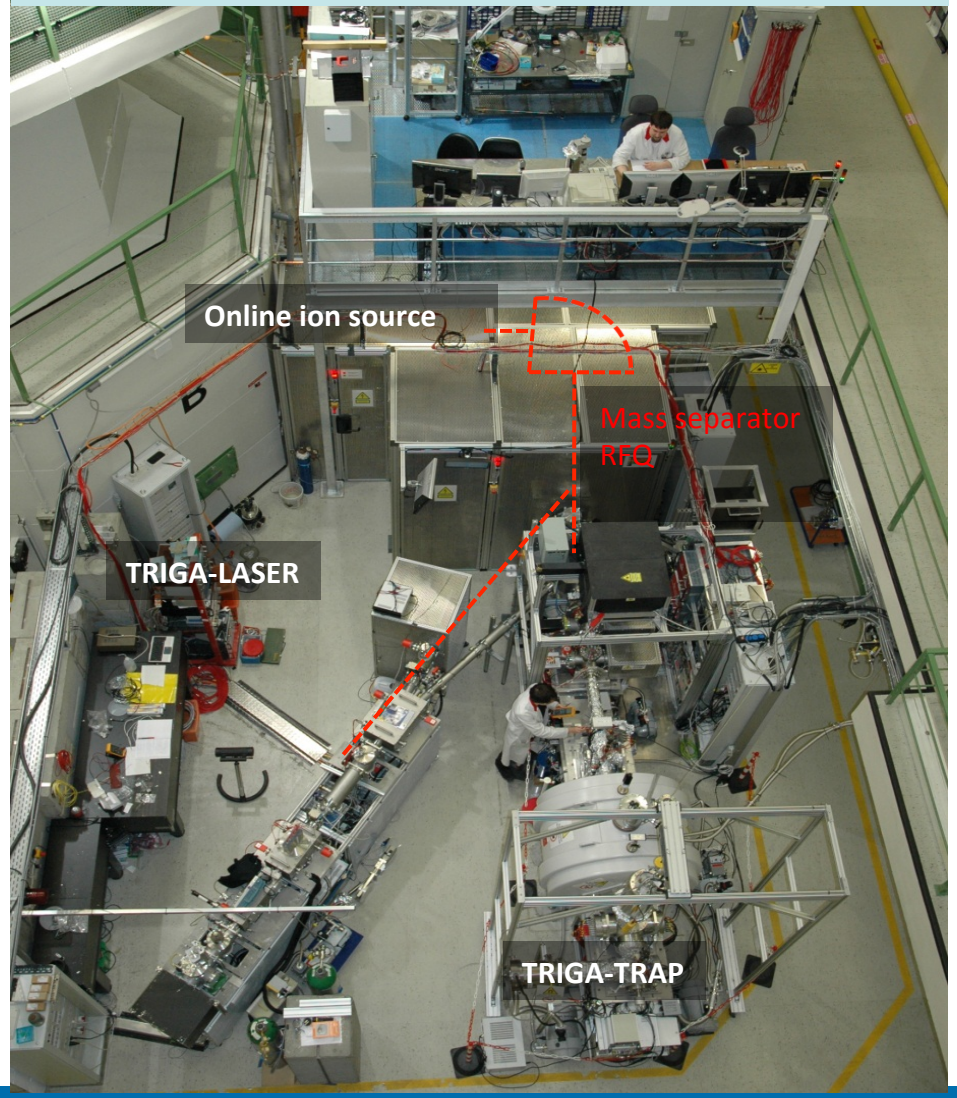


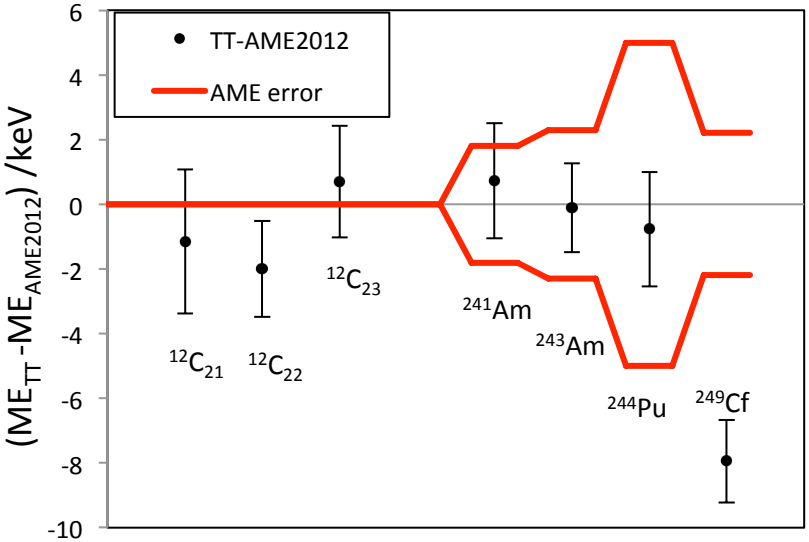




Mass Measurements at TRIGA-TRAP in 2013
Phase 0 of MATS

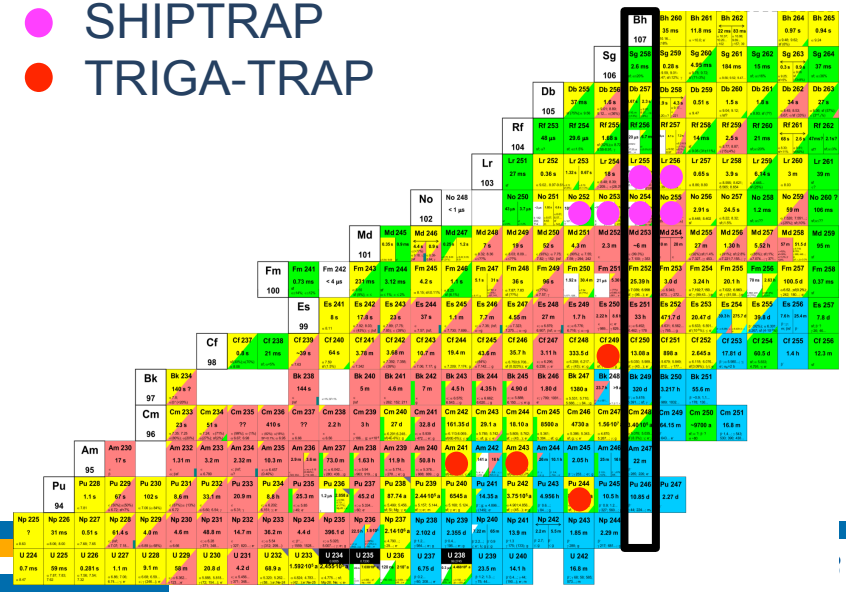
project start @ TRIGA: 01/2008
start data taking: 05/2009





N=152

- SHIPTRAP
- TRIGA-TRAP



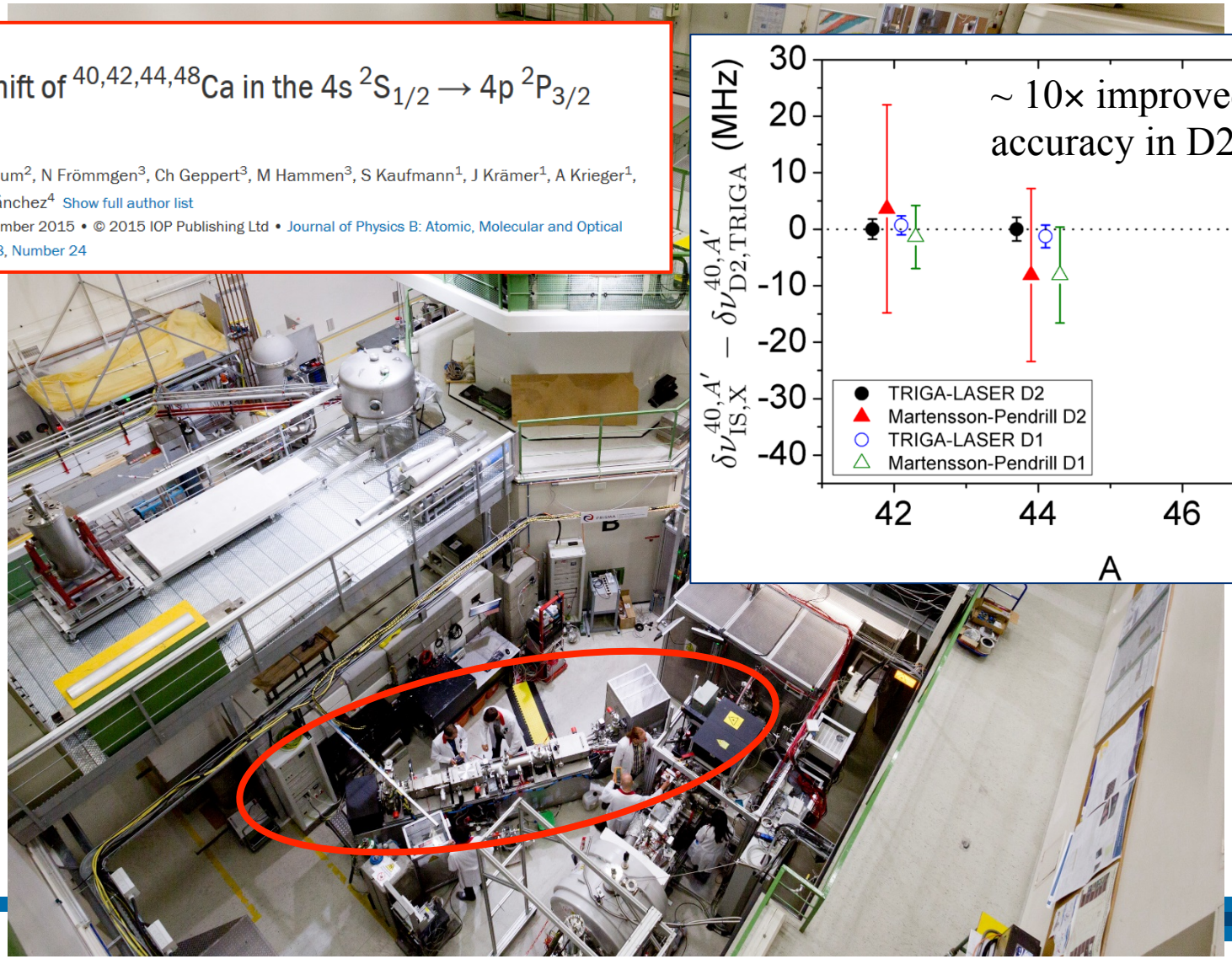
First Physics Results at the LASPEC Prototype

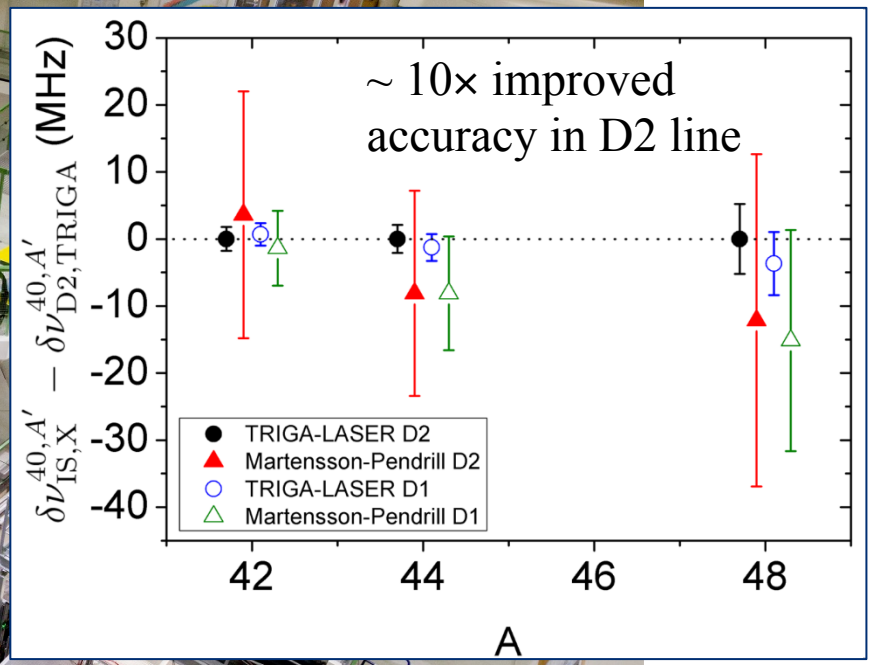
PAPER

Isotope shift of ^{40,42,44,48}Ca in the 4s $^2S_{1/2} \rightarrow$ 4p $^2P_{3/2}$ transition

C Gorges[1], K Blaum[2], N Frömmgen[3], Ch Geppert[3], M Hammen[3], S Kaufmann[1], J Krämer[1], A Krieger[1], R Neugart[2], R Sánchez[4] Show full author list

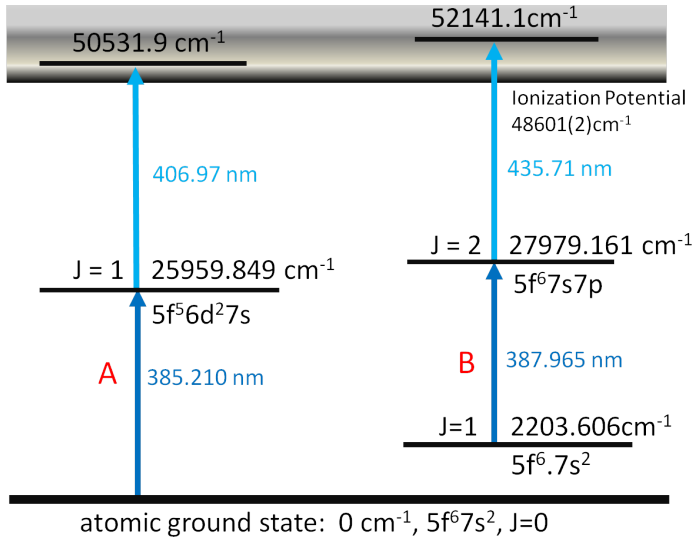
Published 13 November 2015 • © 2015 IOP Publishing Ltd • Journal of Physics B: Atomic, Molecular and Optical Physics, Volume 48, Number 24





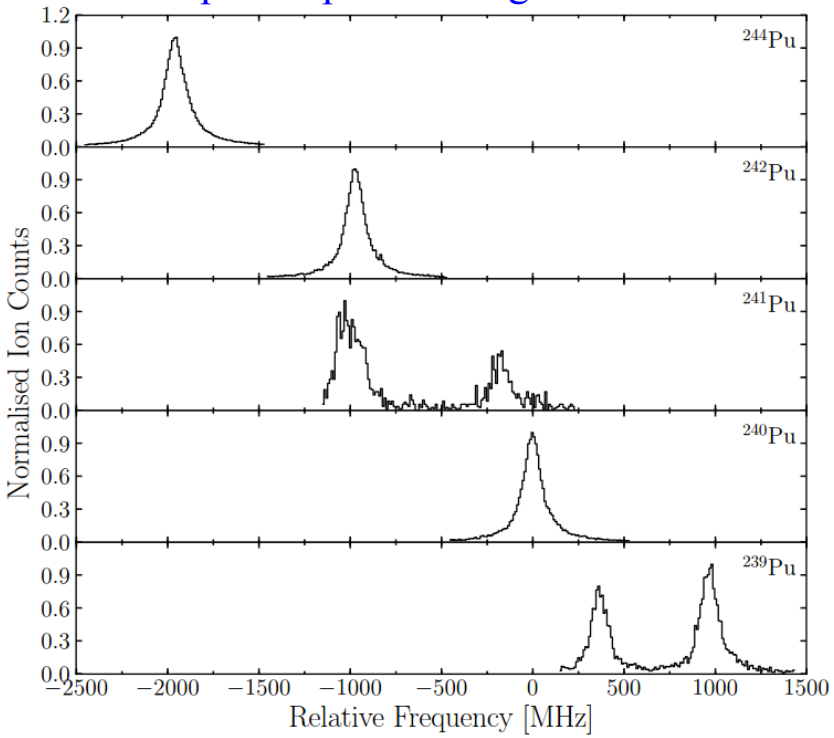
High-resolution laser spectroscopy of long-lived Pu isotopes

Resonance Ionization Mass Spectrometry (RIMS) of Pu isotopes using an injection-locked Ti:sapphire laser was performed in Mainz. The laser provides narrow bandwidth (~20 MHz) pulsed laser light and may be used in the future at LASPEC .

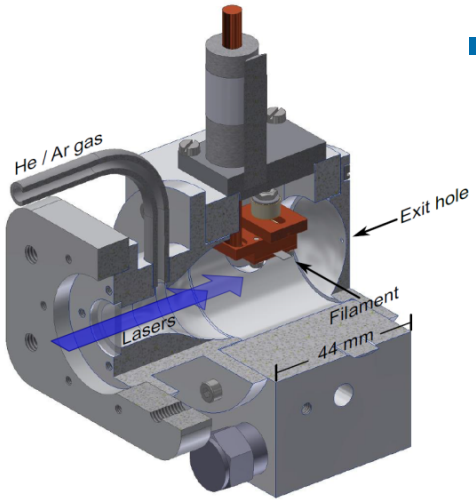


V. Sonnenschein, PhD thesis, University of Jyväskylä (2015)

Optical spectra using transition A

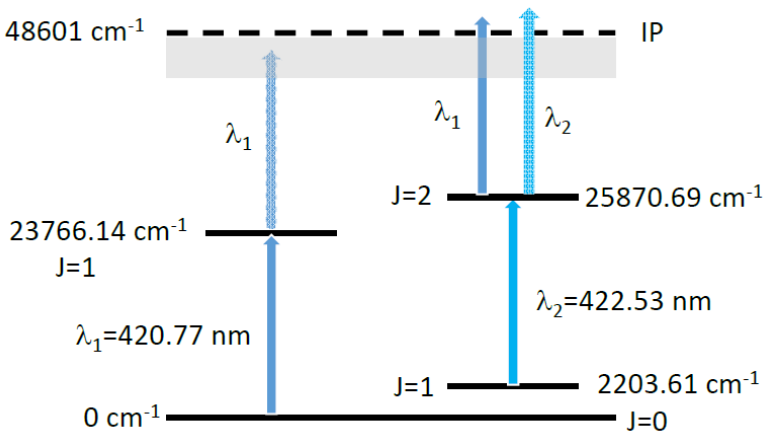


Collinear laser spectroscopy of Pu at JYFL

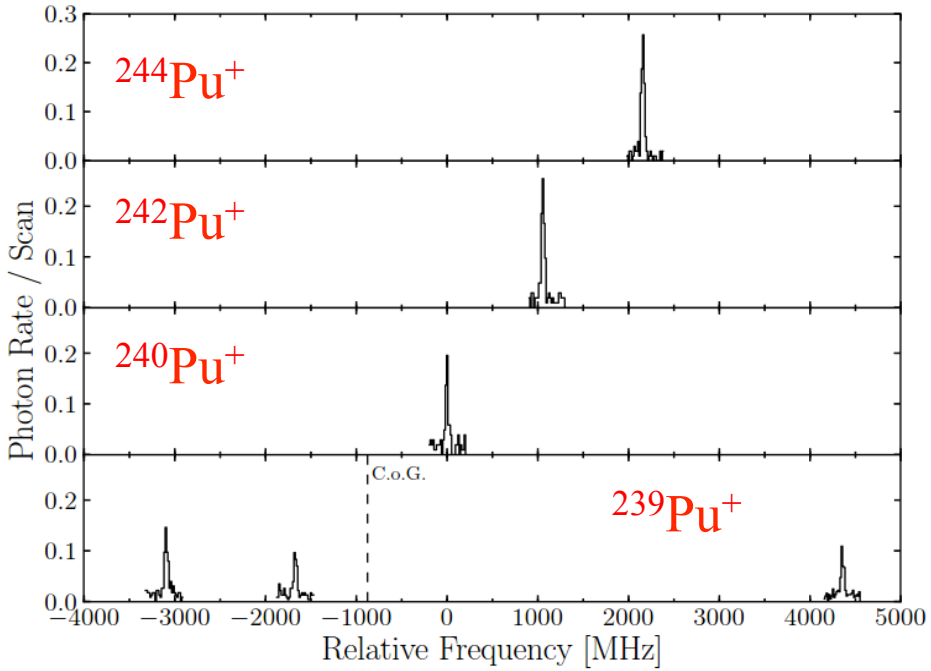


In parallel, Pu isotopes were sent on tantalum substrates to JYFL. Evaporated atoms were laser-ionized and extracted from the gas cell. Bunched beams were delivered to the collinear laser beam line. High resolution spectroscopy was performed on the ion and results compared with the RIMS method.

Laser ionization scheme



$8F_{1/2}$ (0 cm^{-1}) → $6P_{1/2}$ (27523.61 cm^{-1})



Pu is the heaviest element studied to date with the collinear method!

HISPEC/DESPEC

Nuclear Instruments and Methods in Physics Research A 803 (2015) 36–46

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A decay total absorption spectrometer for DESPEC at FAIR

J.L. Tain [a,*], A. Algora [a], J. Agramunt [a], V. Guadilla [a], M.D. Jordan [a], A. Montaner-Pizá [a], B. Rubio [a], E. Valencia [a], D. Cano-Ott [b], W. Gelletly [c], T. Martinez [b], E. Mendoza [b], Zs. Podolyák [c], P. Regan [c], J. Simpson [d], A.J. Smith [e], J. Strachan [d]

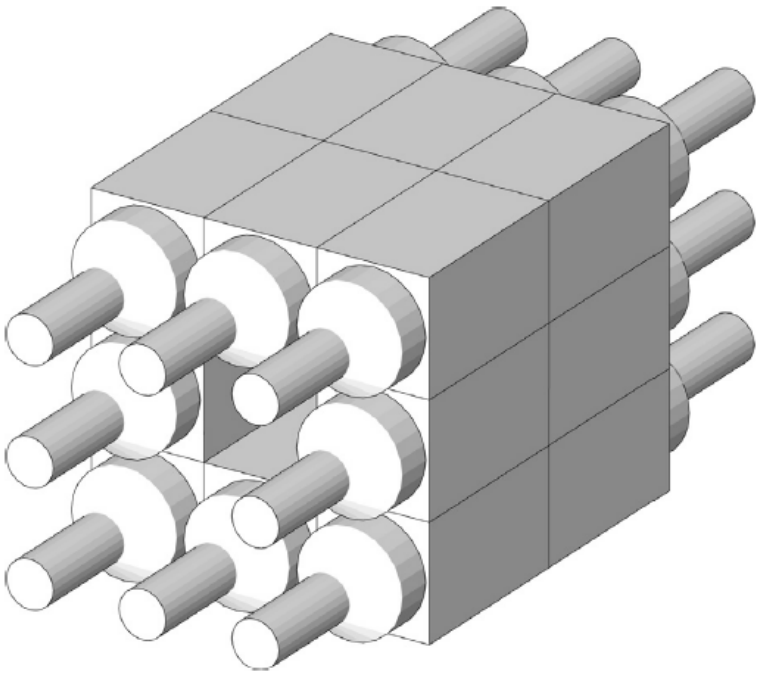


Fig. 1. Arrangement of 16 NaI(Tl) modules consisting of a 15 × 15 × 25 cm^3 cry... coupled to a 5 in. photomultiplier tube.

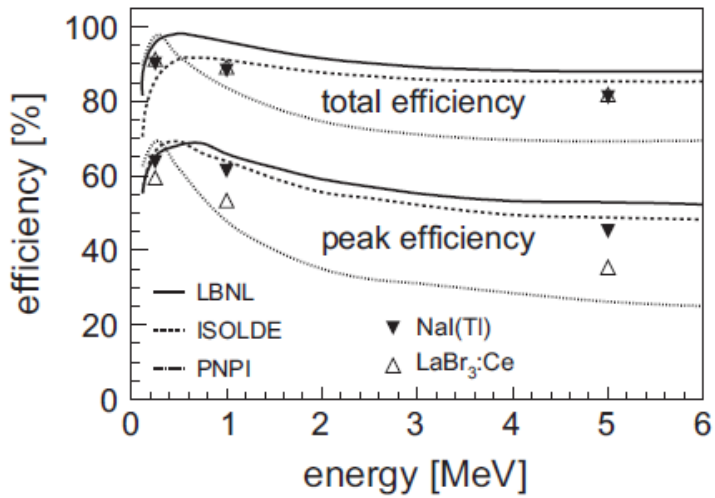


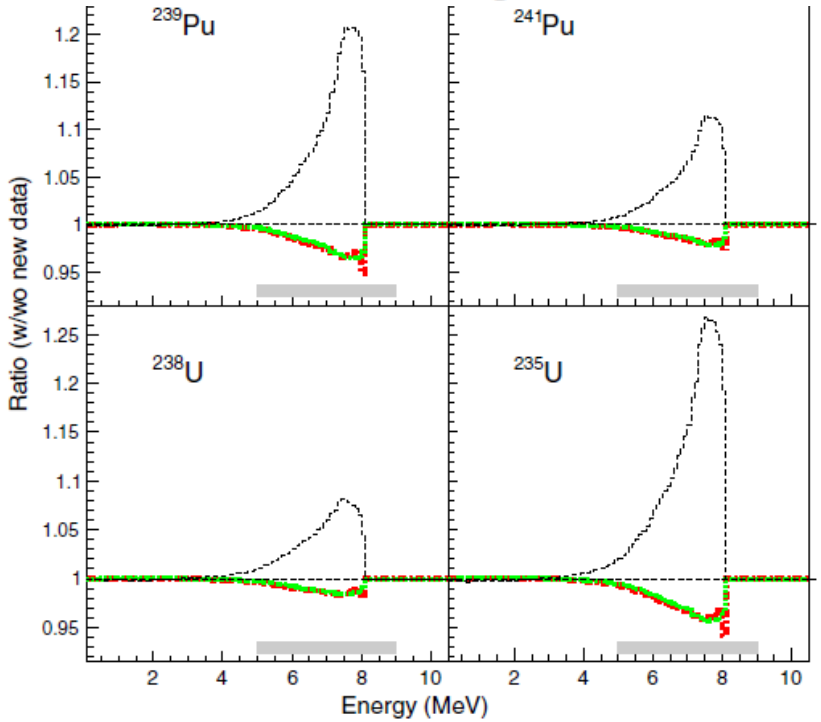
Fig. 11. Comparison of Monte Carlo simulated total and peak efficiencies. NaI(Tl) option (filled triangle), $LaBr_3$:Ce option (open triangle), LBNL spectrometer [33] (continuous line), ISOLDE spectrometer [34] (dashed line), and PNPI spectrometer [19] (dotted line).

PRL 115, 102503 (2015) PHYSICAL REVIEW LETTERS week ending 4 SEPTEMBER 2015

Total Absorption Spectroscopy Study of ^{92}Rb Decay: A Major Contributor to Reactor Antineutrino Spectrum Shape

A.-A. Zakari-Issoufou,[1] M. Fallot,[1] A. Porta,[1,*] A. Algora,[2,3] J. L. Tain,[2] E. Valencia,[2] S. Rice,[4] V. M Bui,[1] S. Cormon,[1]

The antineutrino spectra measured in recent experiments at reactors are inconsistent with calculatior based on the conversion of integral beta spectra recorded at the ILL reactor. ^{92}Rb makes the dominar contribution to the reactor antineutrino spectrum in the 5–8 MeV range but its decay properties are i question. We have studied ^{92}Rb decay with total absorption spectroscopy. Previously unobserved be feeding was seen in the 4.5–5.5 region and the GS to GS feeding was found to be 87.5(25)%. The impact c the reactor antineutrino spectra calculated with the summation method is shown and discussed.



DTAS at Jyväskylä

Enhanced γ-Ray Emission from Neutron Unbound States Populated in β Decay

J. L. Tain,[1,*] E. Valencia,[1] A. Algora,[1] J. Agramunt,[1] B. Rubio,[1] S. Rice,[2] W. Gelletly,[2] P. Regan,[2] A.-A. Zakari-Issoufou,[3]

magnitude in the photon strength to neutron strength ratio. An increase in the photon strength function of such magnitude for very neutron-rich nuclei, if it proves to be correct, leads to a similar increase in the (n, γ) cross section that would have an impact on r process abundance calculations.

DTAS experiment

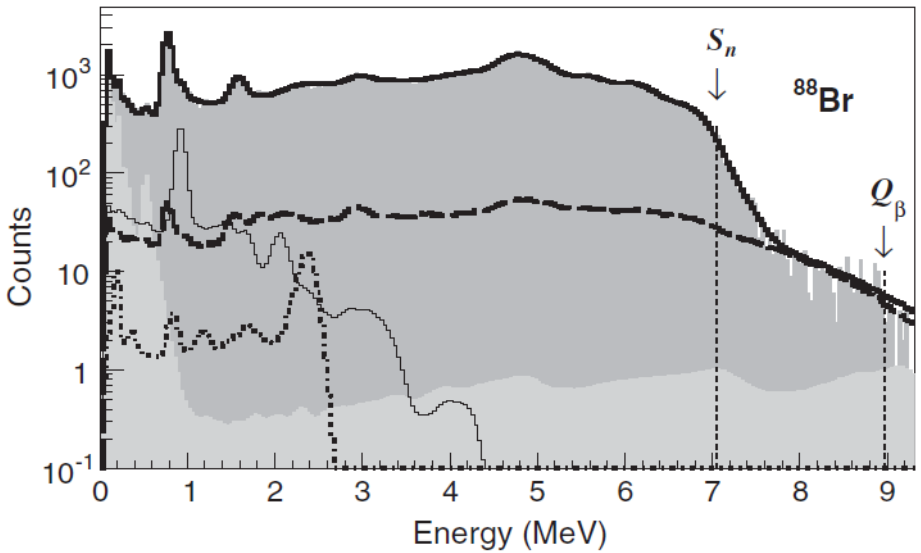


FIG. 1. Relevant histograms for ^{88}Br: parent decay (dark gray filled), daughter decay (dot-dashed line), summing pileup (dashed line), β-delayed neutron decay (light gray filled), accidental contamination (thin continuous line), and reconstructed spectrum (thick continuous line).

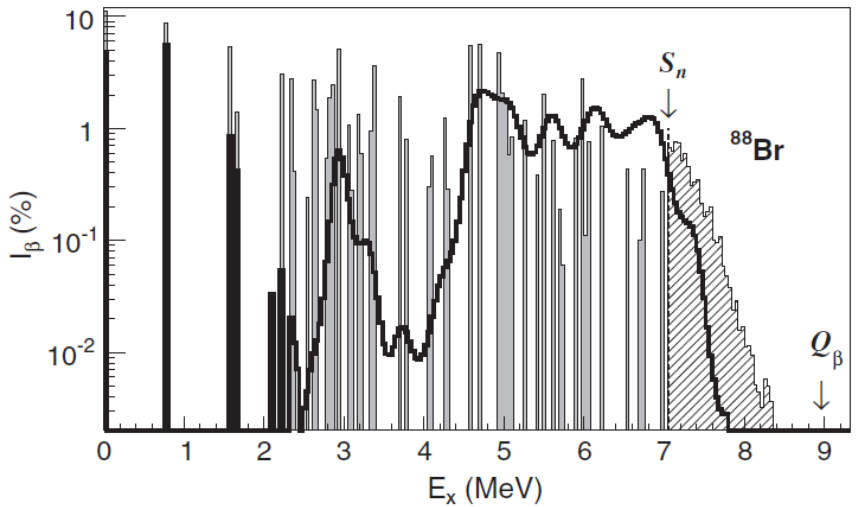


FIG. 2. Beta intensity distributions for ^{88}Br: TAGS result (continuous line), high-resolution γ spectroscopy (light gray filled histogram), and from β-delayed neutron emission (hatched area).

DESPEC fast-timing

RIKEN

2^+ lifetimes in ^{104,106}Zr

F. Browne et al., Phys. Lett. B 750 (2015) 448

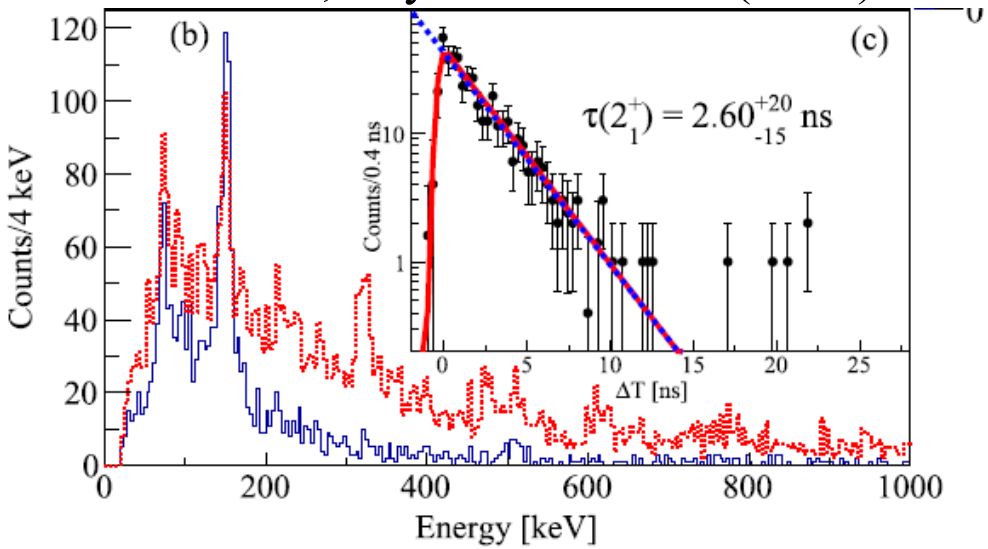
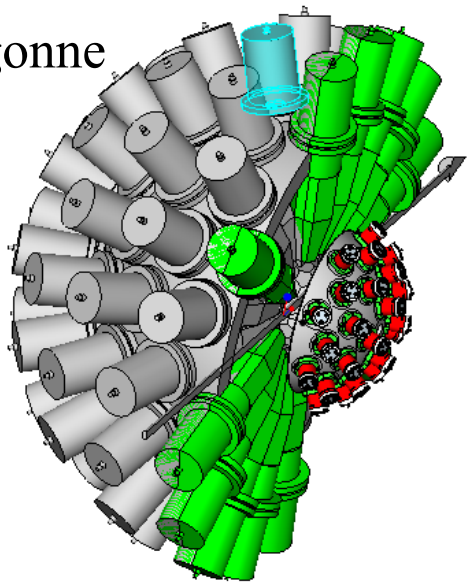


Fig. 2. (Colour online.) (a) Energy–time-difference matrix observed in coincidence with β^- detected within 0.3 s of an ^{106}Y implantation. (b) The γ-ray energy spectrum of the delayed (solid blue) and prompt (dashed red) components of the matrix. (c) Background subtracted time difference spectrum for the $2_1^+ \rightarrow 0_{g.s.}^+$ transition. (See text for details of the fits.)

Argonne



Commissioning of the system (including EDAQ) was done:
Argonne National Laboratory (Dec. 2015-Jan. 2016)
(Gammasphere coupled to FATIMA detectors)

Super-FRS Experiment work packages

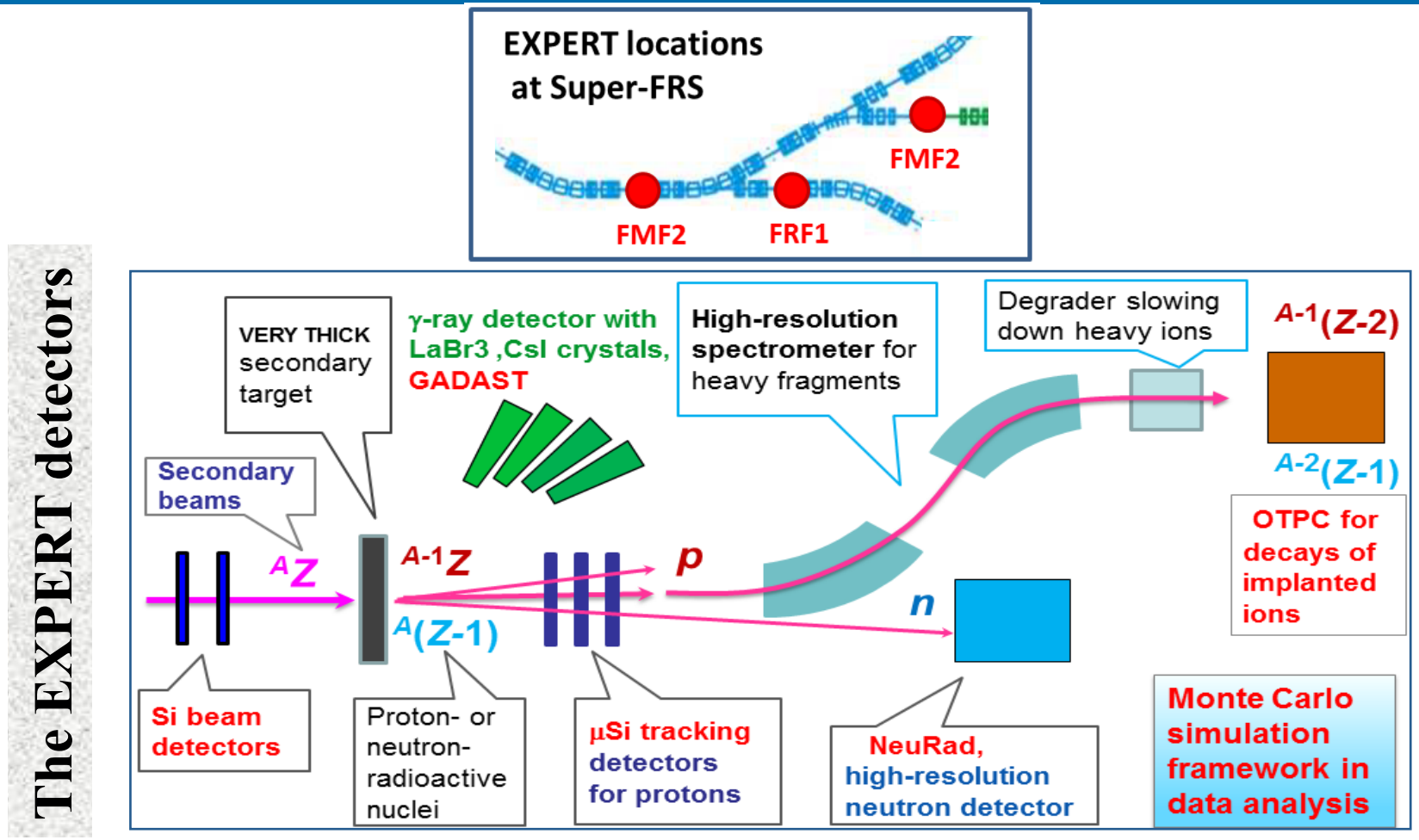
The Super-FRS Collaboration plans to realize the following systems for spectrometer experiments:

PSP code	Description	Responsible person
1.2.10	Super-FRS Experiments	Isao Tanihata (RCNP Osaka, Japan)
1.2.10.1	Infrastructure, DAQ, ancillary systems	Stephane Pietri (GSI, Germany)
1.2.10.2	Cylindrical Detector System (CDS)	Kenta Itahashi (RIKEN, Japan)
1.2.10.3	Pion detection system	Take Saito (GSI, Germany)
1.2.10.4	Liquid hydrogen target	Ritu Kanungo (Univ. Halifax, Canada)
1.2.10.5	Tensor force detection system and chamber	Hooi Jin Ong (RCNP Osaka, Japan)
1.2.10.6	Ice target	Hooi Jin Ong (RCNP Osaka, Japan)
1.2.10.7	EXPERT	Ivan Mukha (GSI, Germany)

Status: Jan. 2016

*N.B. The structural details of the work packages, their technical realisation and costs are still under discussion. Most of these projects will be funded from **fresh external funding** sources (e.g., Japan, Canada) and the extra contributions from members is under discussion.*

EXPERT: EXotic Particle Emission and Radioactivity by Tracking (for in-flight radioactive decay, spectroscopy, etc.)

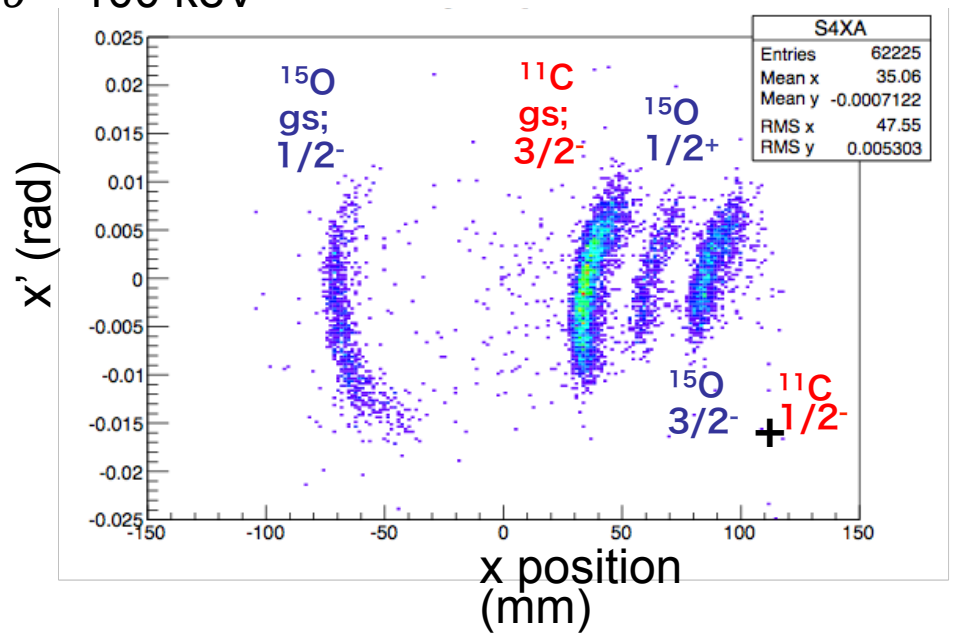


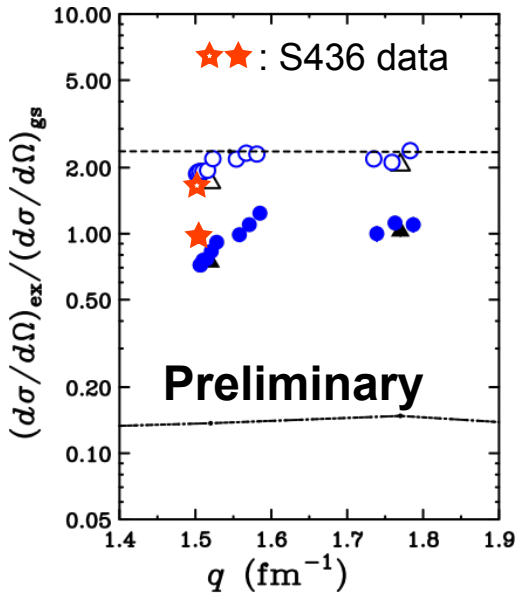
- First results of the EXPERT pilot experiment at FRS have been published in Phys. Rev. Lett. **115** (2015). More to come!
- The TDR on the EXPERT detectors is close to be completed.

Tensor forces

Pilot experiment: $^{16}O(p,d)$ at forward angle with proton beam at 400, 600, 900, 1200 MeV/u using FRS as a spectrometer

sufficient missing mass resolution
$\sigma \sim 100$ keV





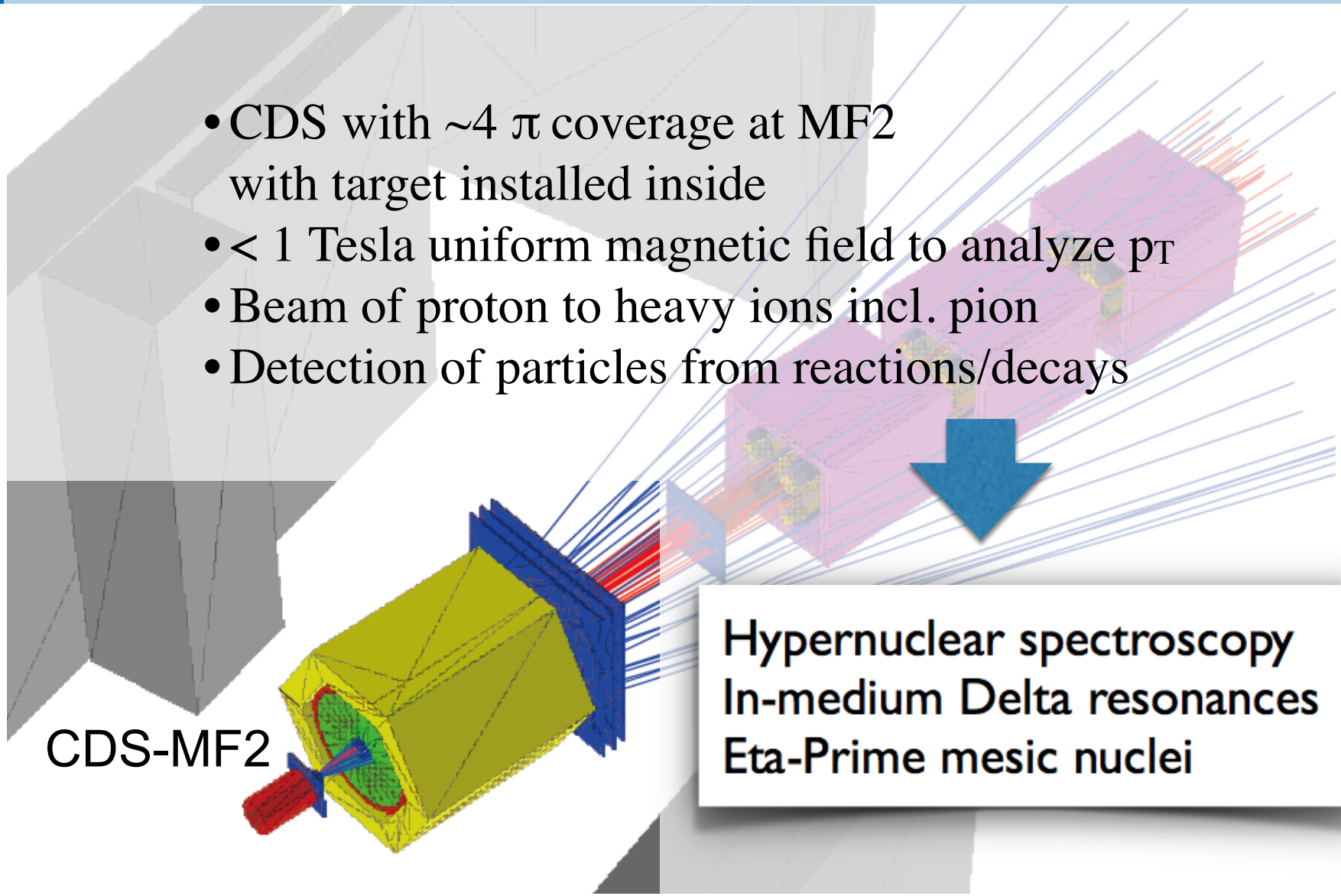
H.J. Ong et al., PLB 725, 277(2013)
C.L. Guo et al., in preparation

Results at 400 MeV/u consistent with Osaka data

- Data analysis is in progress.
- (p,dp) and (p,dn) 400 MeV/u on ^{12}C, ^{16}O target successfully performed in Osaka; similar experiments are planned at Super-FRS.

Cylindrical Detector System at SuperFRS/MF2

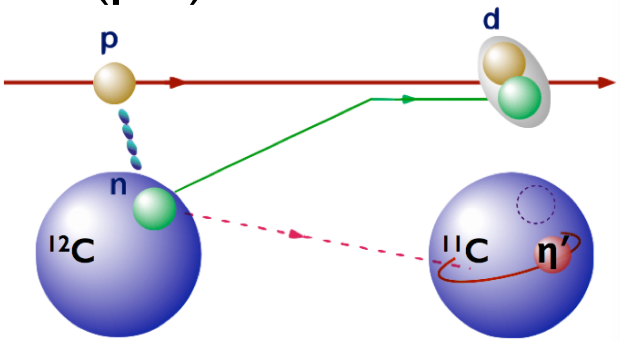
- CDS with ~4 π coverage at MF2 with target installed inside
- < 1 Tesla uniform magnetic field to analyze p_T
- Beam of proton to heavy ions incl. pion
- Detection of particles from reactions/decays



Hypernuclear spectroscopy
In-medium Delta resonances
Eta-Prime mesic nuclei

Eta-prime in inclusive measurement of $^{12}C(p,d)$ reaction

$^{12}C(p,d)$ $T_d = 2.5$ GeV

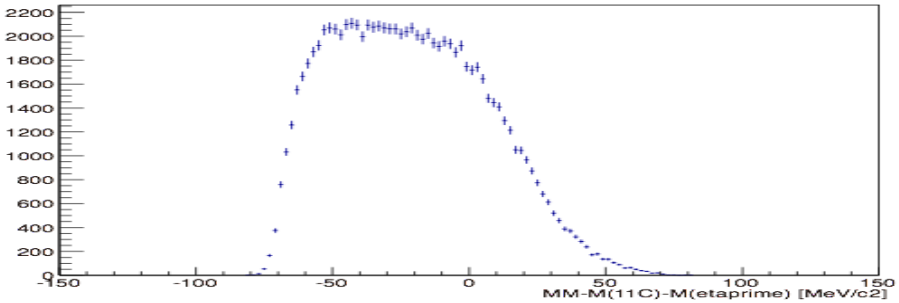


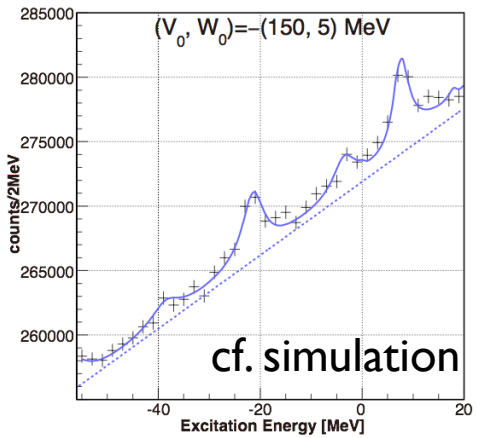
- Search for η′ meson bound states in ^{11}C by missing mass spectroscopy at GSI/FAIR
- Just finished first physics run for inclusive (*p*,*d*)
- PID was perfect
- Successfully accumulated <u>targeted statistics</u> with good resolution ~ 2 MeV/c^2
- Letter paper is in preparation

preliminary
run864

~ 1 % of statistics for an FRS setting. Acceptance uncorrected

counts / 2 [MeV/c^2]



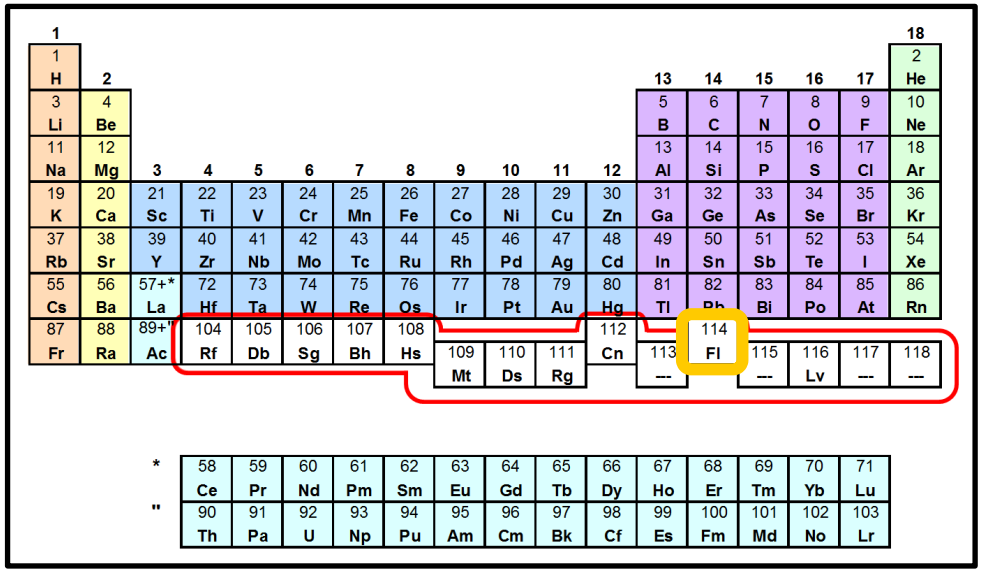


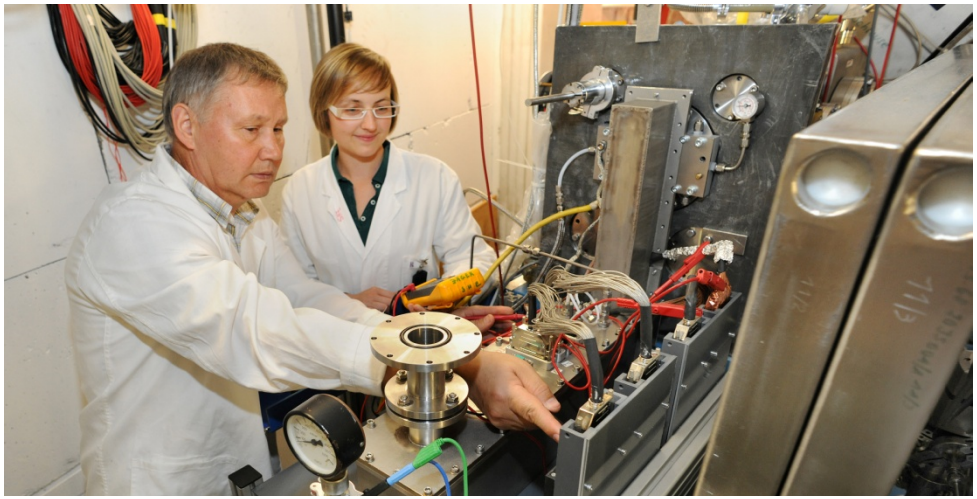
PRiME

UNILAC experiments at TASCA (SHE Chemistry): Measuring Chemical properties of Flerovium (Z=114)

Bundesministerium für Bildung und Forschung

Verbund-forschung





A. Yakushev (Spokesperson) and L. Lens with experimental setup in **TASCA** cave X8

Status in the published literature:

2010 (PSI/Dubna): Three atoms observed

→ noble gas-like behavior inferred

Several additional Dubna experiments failed to observe flerovium

2014 (TUM/GSI): Two atoms observed

→ noble metallic behavior inferred

New, improved TASCA experiments:

Run 1 (Fall 2014)

Duration: 12 days

Beam dose: ~$2.8 \cdot 10^{18}$

2 decay chains from Fl/Cn observed.

Run 2 (Aug.-Oct. 2015),

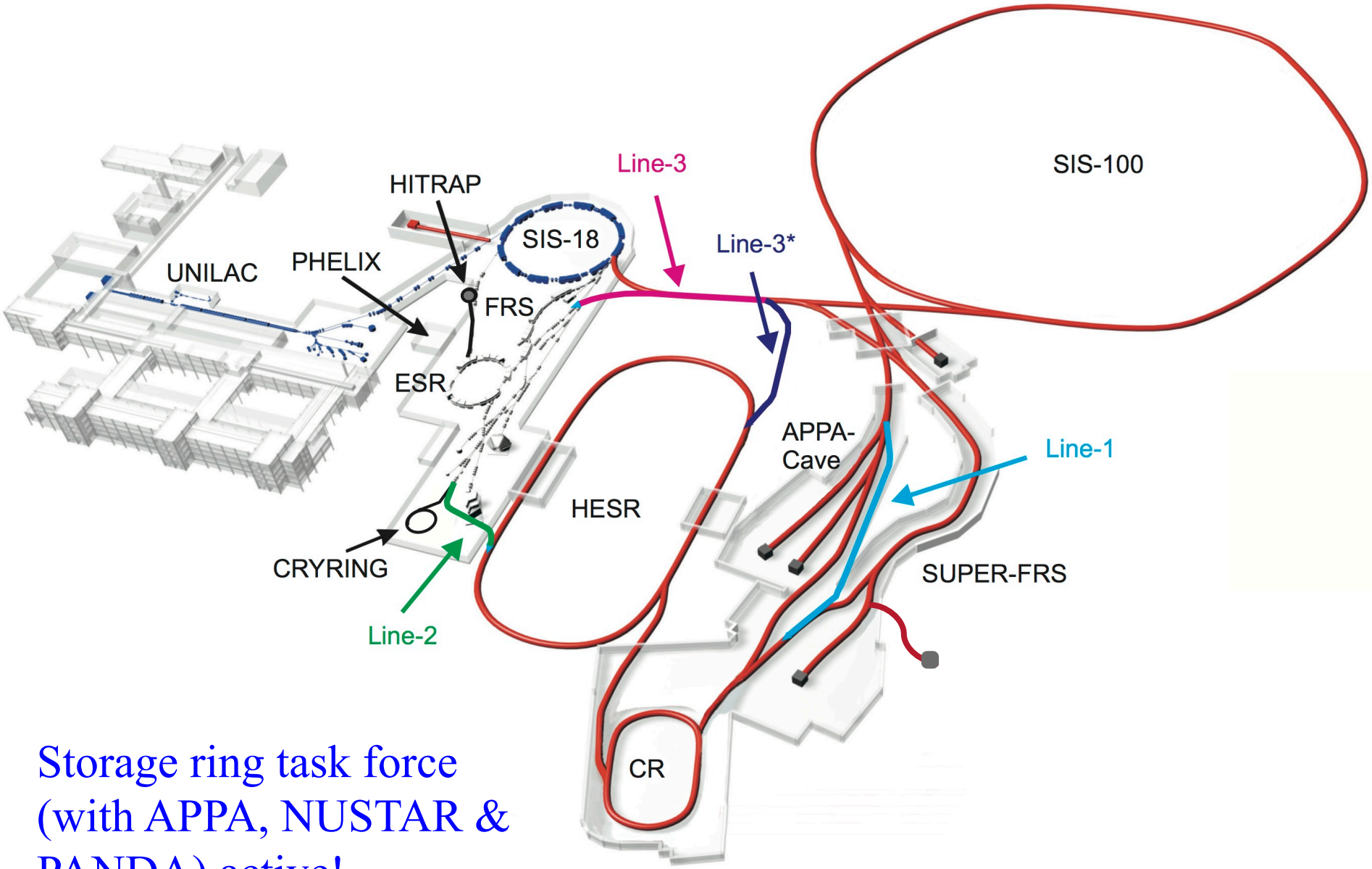
Duration (main beam) 31 days

Beam dose: ~$6 \cdot 10^{18}$

7 decay chains from Fl/Cn observed.

Data are under final evaluation.

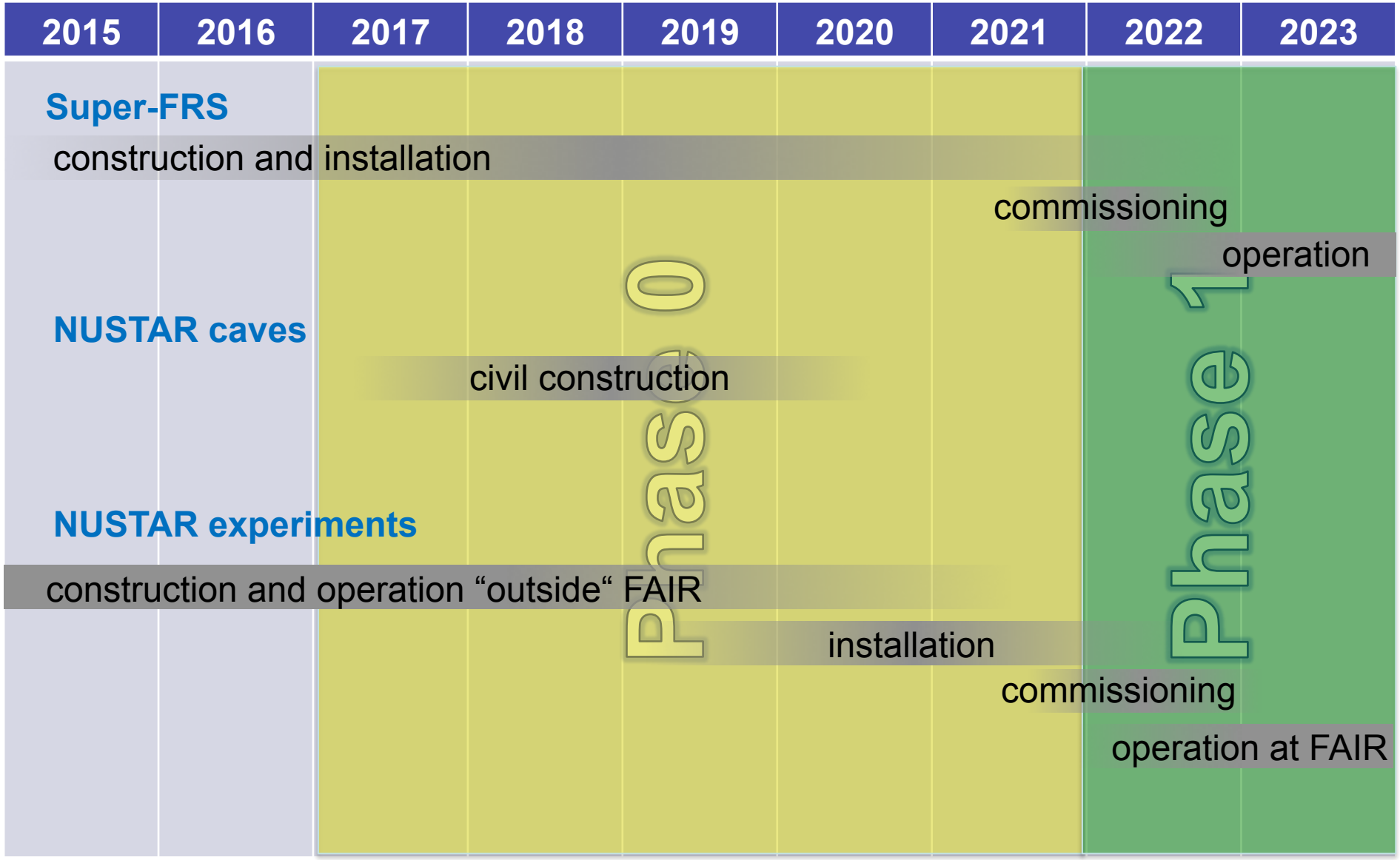
Transfer line to HESR/ESR/CRYRING



Storage ring task force (with APPA, NUSTAR & PANDA) active!

Timeline

Scenario for phase 0 and phase 1 operation



Thank you!