Physics behind the NuSTAR project

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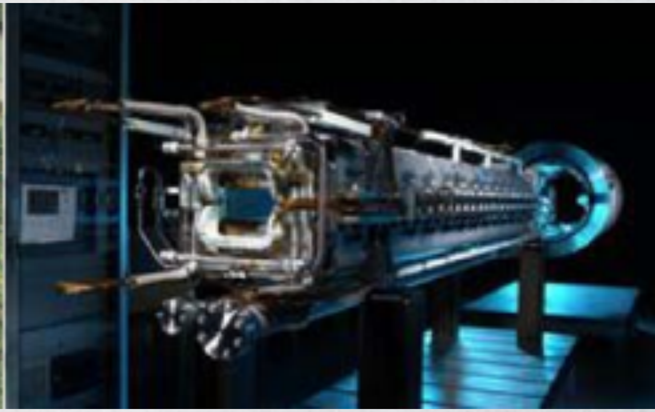
National Superconducting Cyclotron Laboratory

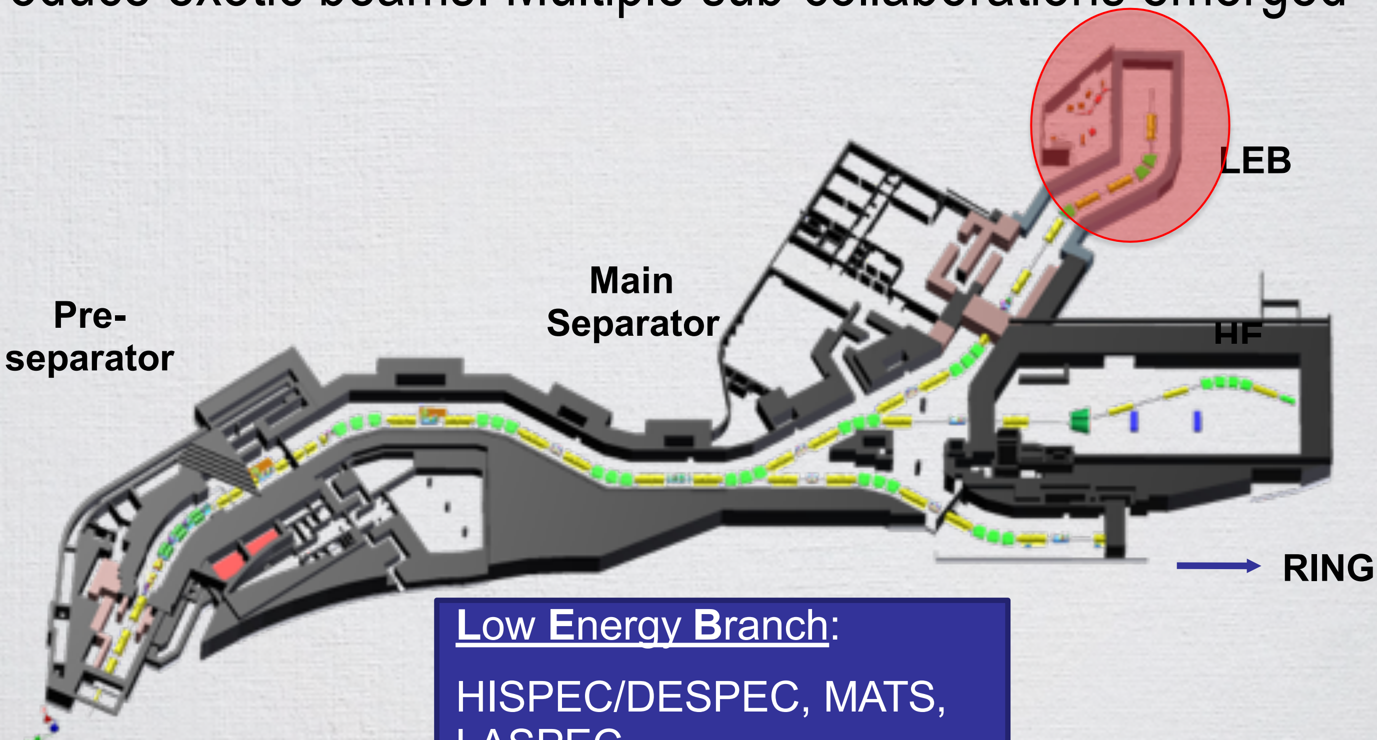




NuSTAR (Nuclear Structure Astrophysics and Reactions) is a story of success

Scientists got together in an effort to study nuclear structure, dynamics and astrophysics at different energy ranges

The main common point of the collaboration is the super FRS as a way to produce exotic beams. Multiple sub-collaborations emerged



<u>L</u>ow <u>E</u>nergy <u>B</u>ranch:

HISPEC/DESPEC, MATS, LASPEC

What are the questions that NUSTAR wants to answer

How are complex nuclei built from their basic constituents?

– *What is the effective nucleon-nucleon interaction and how does QCD constrain its parameters?*
– *How does the three-nucleon force modify the picture?*

How does the effective nuclear force depend on varying proton-to-neutron ratios?

– *What is the isospin dependence of the spin-orbit force?*
– *How does shell structure change far from stability?*
– *How does the role of N-N correlations in nuclei and nuclear matter change with isospin?*

How to explain collective phenomena from individual motion?

– *What are the phases, relevant degrees of freedom, and symmetries of the nuclear many-body system?*

What are the limits of existence of nuclei?

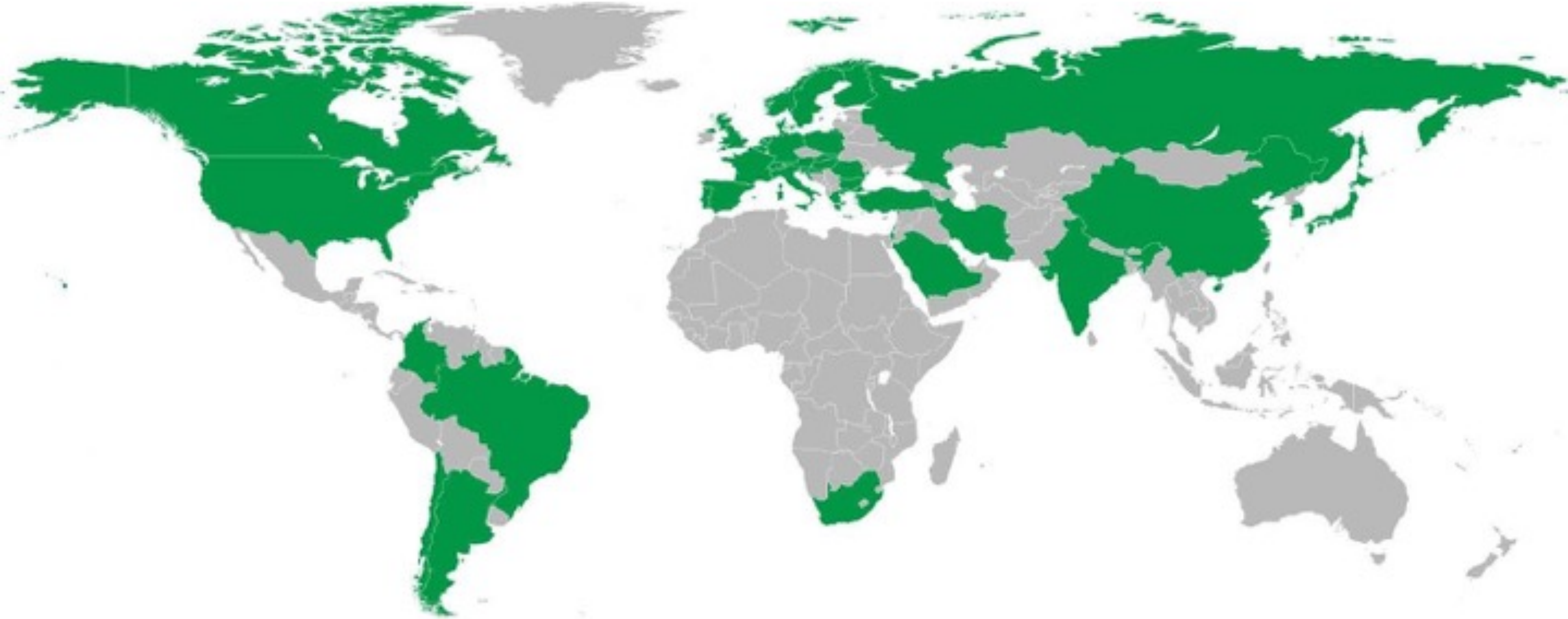
– *Where are the proton and neutron drip lines situated?*
– *What are the heaviest elements?*

How does the equation of state of nuclear matter change with neutron-to-proton asymmetry?

– *How large is the symmetry energy and its density dependence?*
– *What are the properties of neutron-rich matter?*

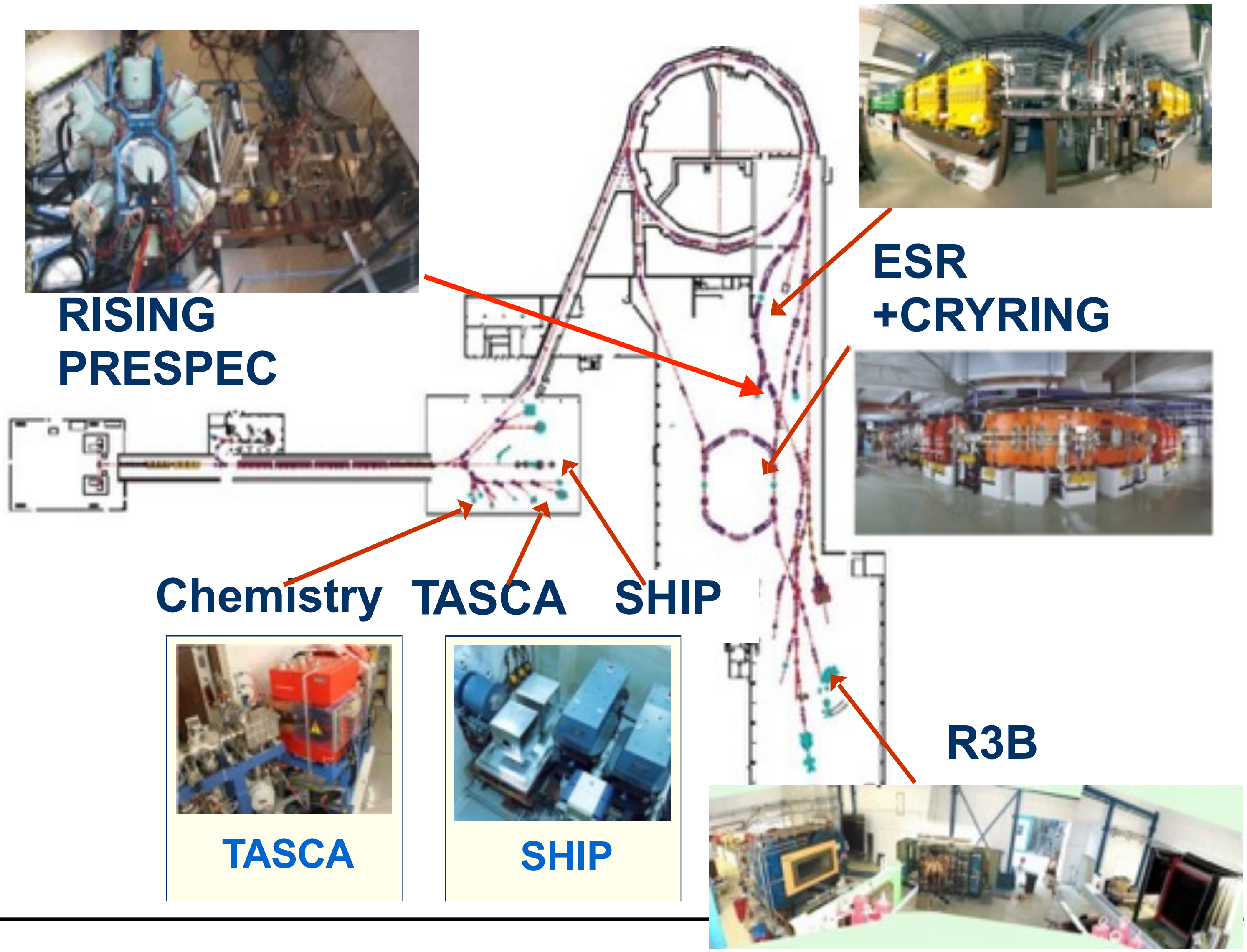
Which nuclei are relevant for astrophysical processes, what are their properties and what is their impact on nucleosynthesis modeling?

NUSTAR Collaboration

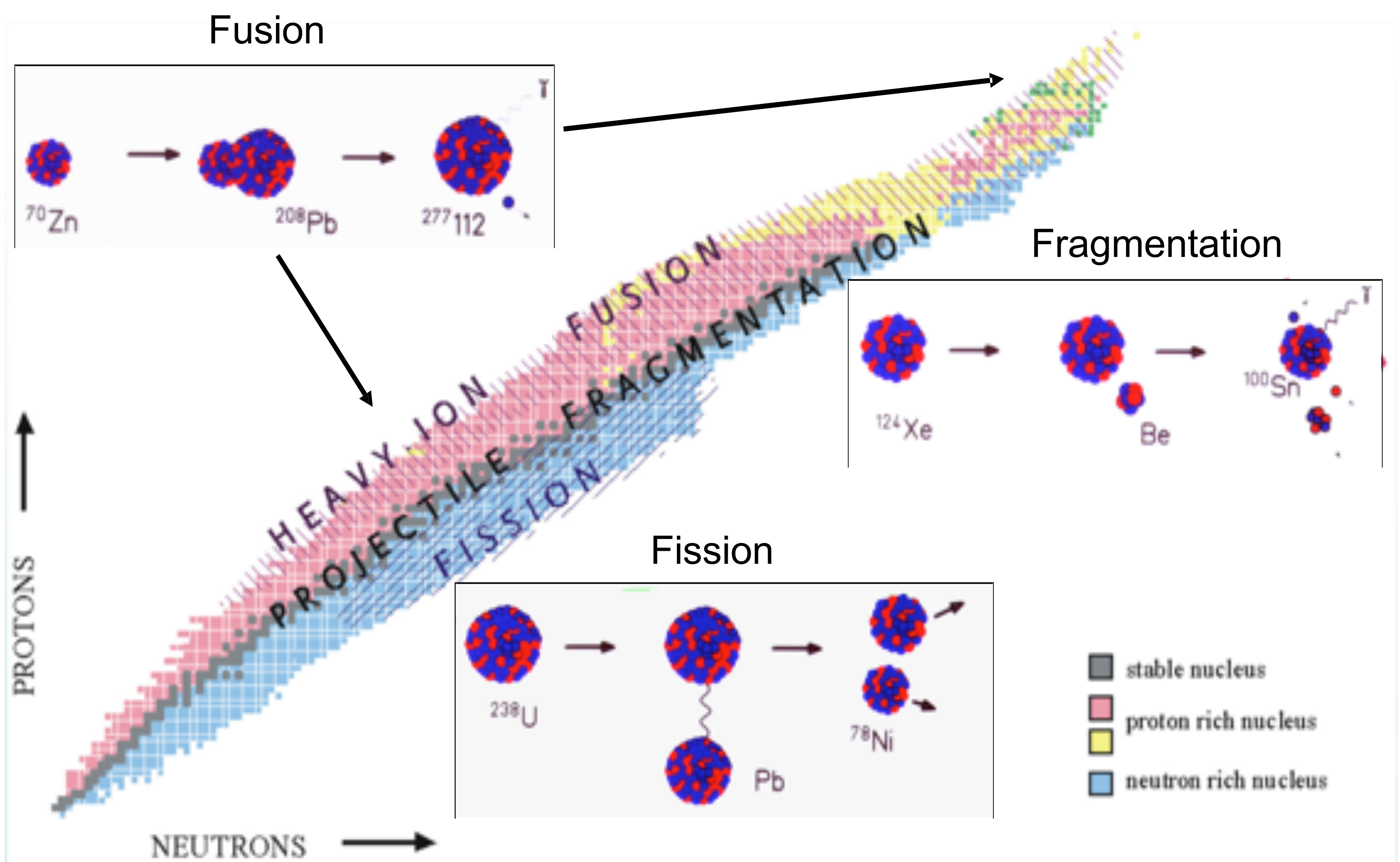


>800 registered NUSTAR members
39 countries
>180 institutes

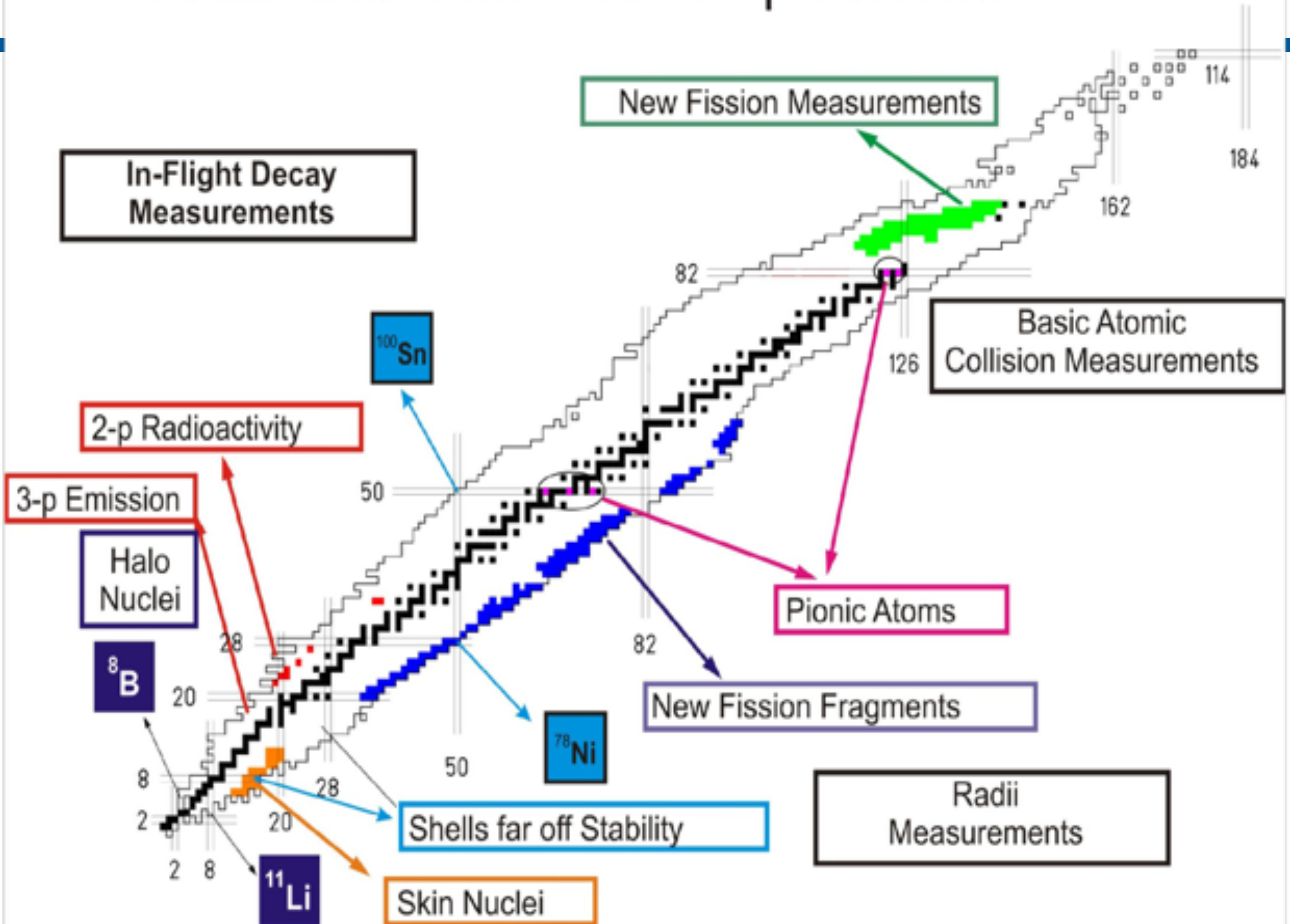
NUSTAR is based on previous success at GSI



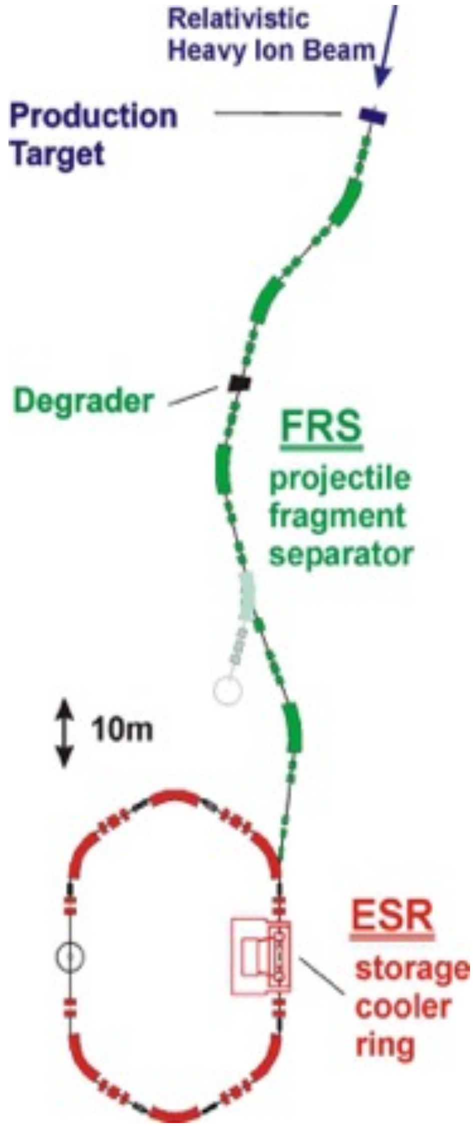
Production Reactions at FRS



Landmarks from FRS Experiments



Storage-ring mass spectrometry at FRS-ESR



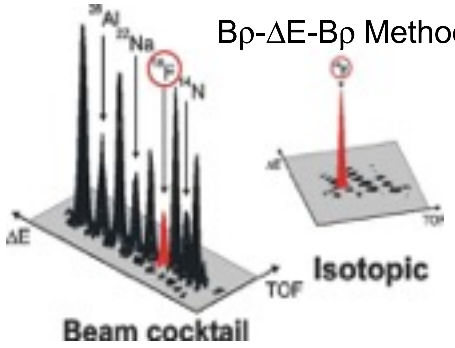
Production:

* Primary beams: H.....U, 100...1000MeV/u
* Reaction mechanisms: Projectile fragmentation, ED and fission
* Yields: ~ 10^5/s.... 10^{-5}/s (=1/day)
* Ionic charge states: bare, H-, He-, Li-like

Separation:

Bρ-Analysis

Bρ-ΔE-Bρ Method

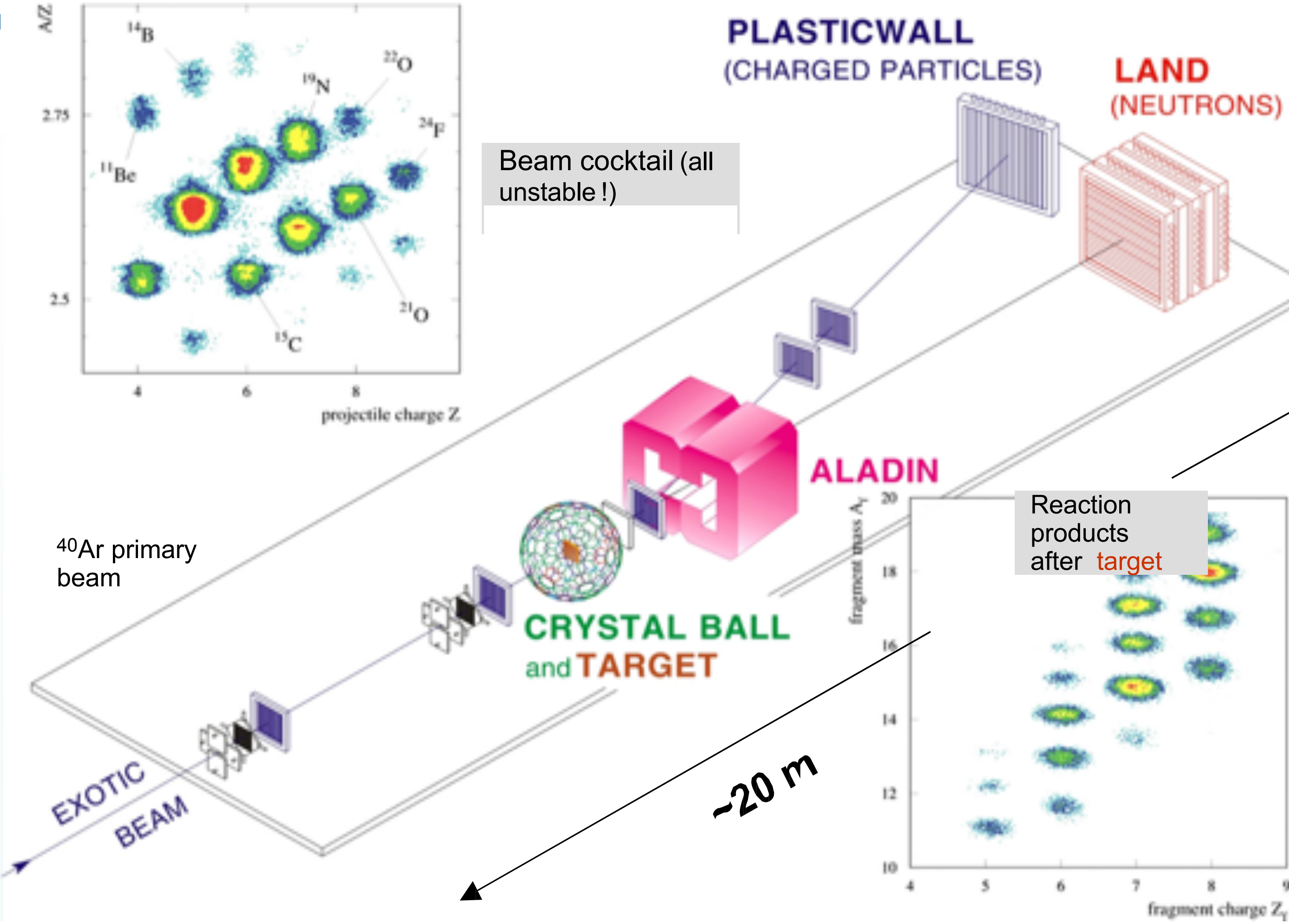


Storage:

* Fast injection (bunch length ~400ns)
* Storage times: minutes .... hours

Mass resolving power $m/\Delta m_{FWHM}$	1-2 $\cdot 10^6$
Mass accuracy	~ 30 keV
Accessible half-lives	> 1 s
Sensitivity	single ions

R3B: Kinematical complete experiments



$$m^* - M = \sum_{i<j} \frac{E_i E_j - m_i m_j c^4 - \mathbf{p}_i \mathbf{p}_j c^2}{M c^4}$$

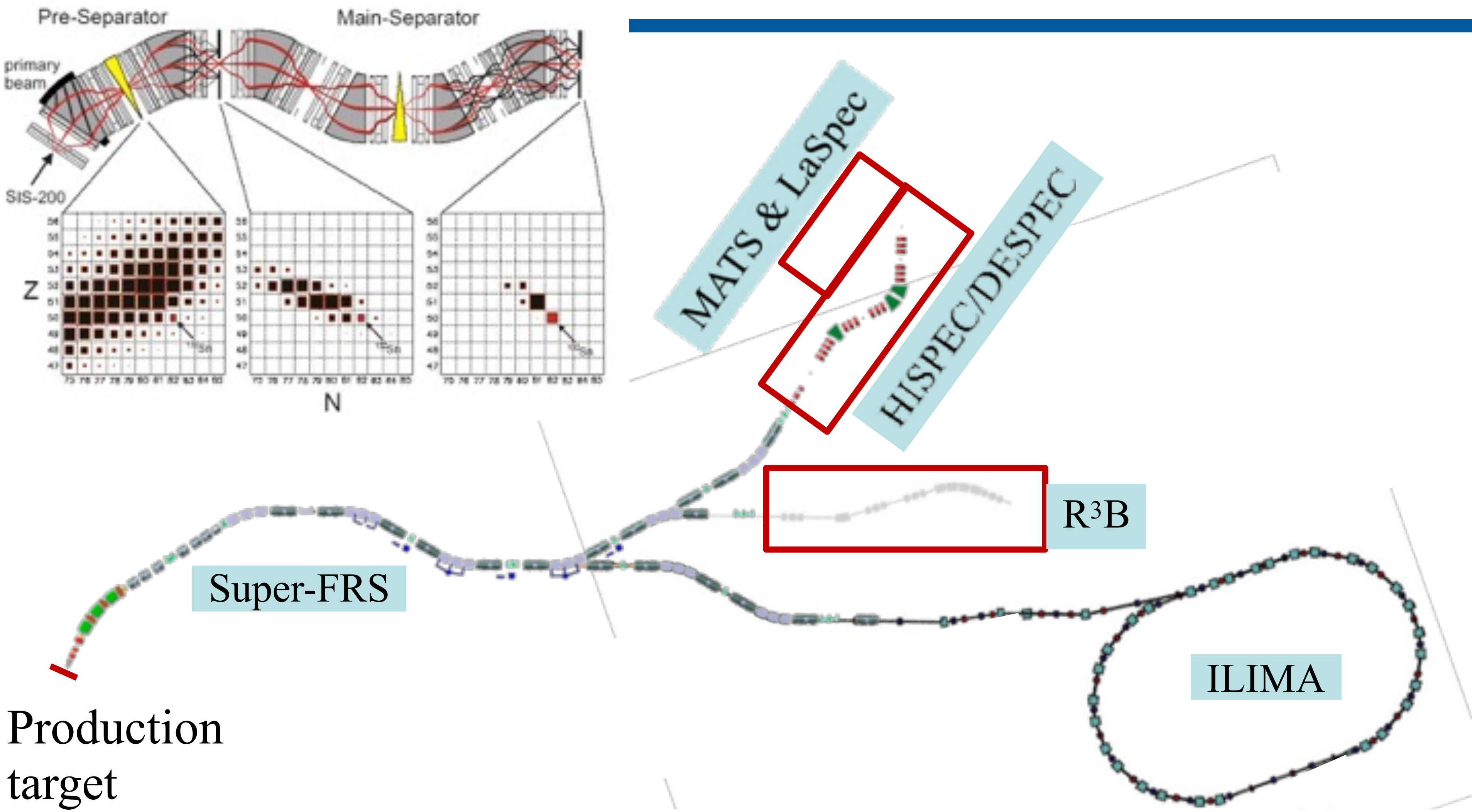
$$M = \sum m_i$$

NUSTAR - The Project

Super-FRS	RIB production, separation, and identification
HISPEC/ DESPEC	In-beam γ-spectroscopy at low and intermediate energy, n-decay, high- resolution γ-, β-, α-, p-, spectroscopy
MATS	In-trap mass measurements and decay studies
LaSpec	Laser spectroscopy
R^3B	Kinematical complete reactions with relativistic radioactive beams
ILIMA	Large-scale scans of mass and lifetimes of nuclei in ground and isomeric states
Super-FRS	High-resolution spectrometer experiments
SHE	Synthesis and study of super-heavy elements
ELISe(*)	Elastic, inelastic, and quasi-free e^--A scattering
EXL(*)	Light-ion scattering reactions in inverse kinematics

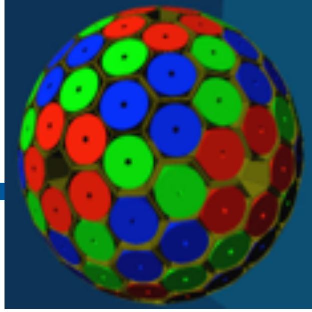
(*) NESR required – alternative/intermediate “operation” within MSV under discussion.
SHE physics case is being evaluated by ECE.

NUSTAR experimental areas



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

LEB : HiSpec and DeSpec



HiSpec project

Nuclear reactions with radioactive beams

at intermediate energies from the S-FRS
at Coulomb barrier energies with further deceleration

single step Coulomb excitations
fragmentation reactions
inelastic scattering
transfer reactions
fusion evaporation reactions

transition probabilities
single particle spectroscopic factors
high spin states, etc.

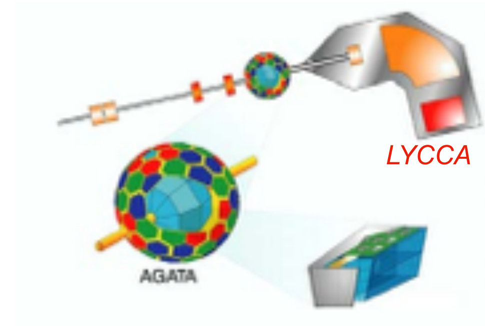
DeSpec concept

- Deep implantation of the ions in a highly pixellated active stopper -> correlation of ion to its subsequent beta decay.
- Neutron and high resolution gamma-ray detectors in a compact arrangement around the active stopper in a highly flexible and modular geometry will be at the heart of this set-up.
- Complementary measurements
  - Total Absorption Gamma technique
  - measurements of nuclear g-factors and quadrupole moments
  - level half lives .

HISPEC/DESPEC - foreseen instrumentation

HISPEC

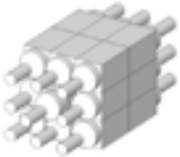
- AGATA gamma-tracking spectrometer
- LYCCA heavy-ion calorimeter with ToF capability
- Plunger nuclear level lifetime measurements
- MINOS Proton target
- NEDA Neutron detector array
- HYDE light charged-particle array

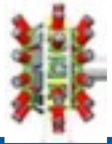


DESPEC

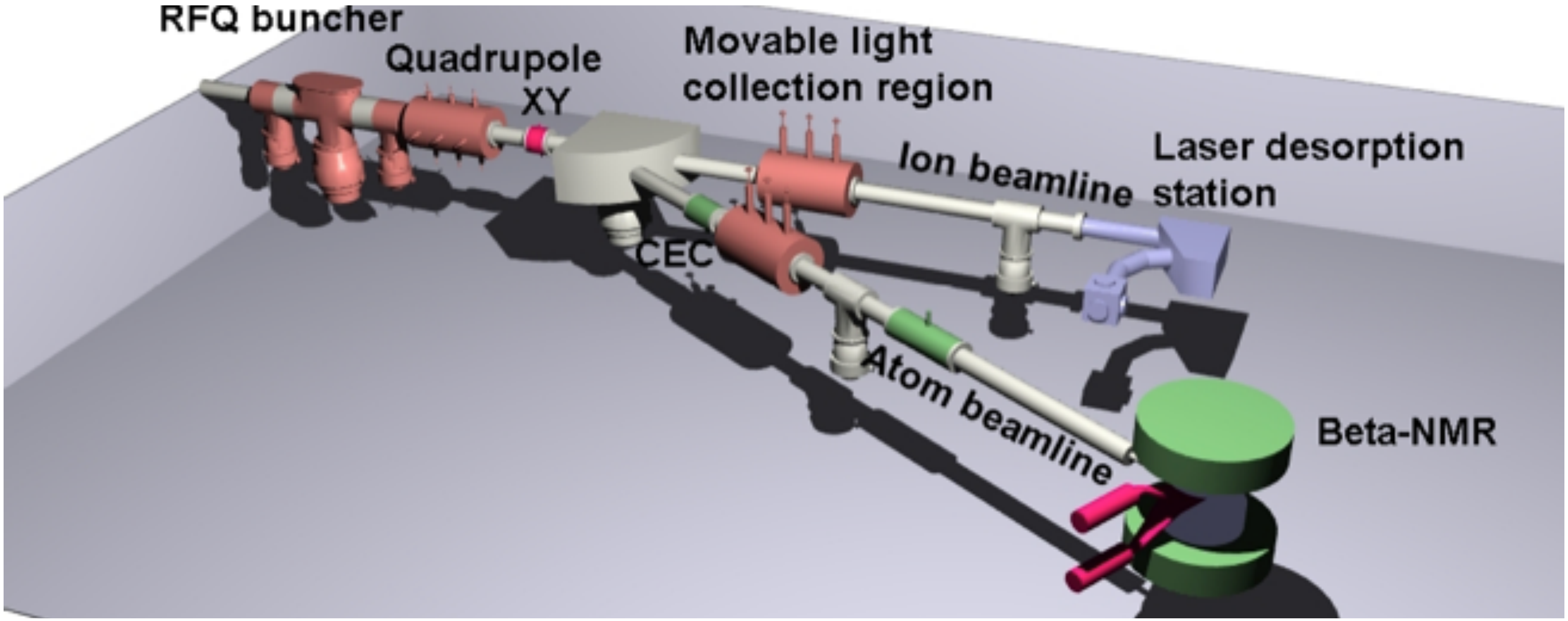
- AIDA active implantation device
- MONSTER neutron ToF array
- BELEN neutron detection array
- DTAS Decay Total Absorption Spectrometer
- DEGAS Ge Array gamma spectrometer
- FATIMA Fast TIMing Array



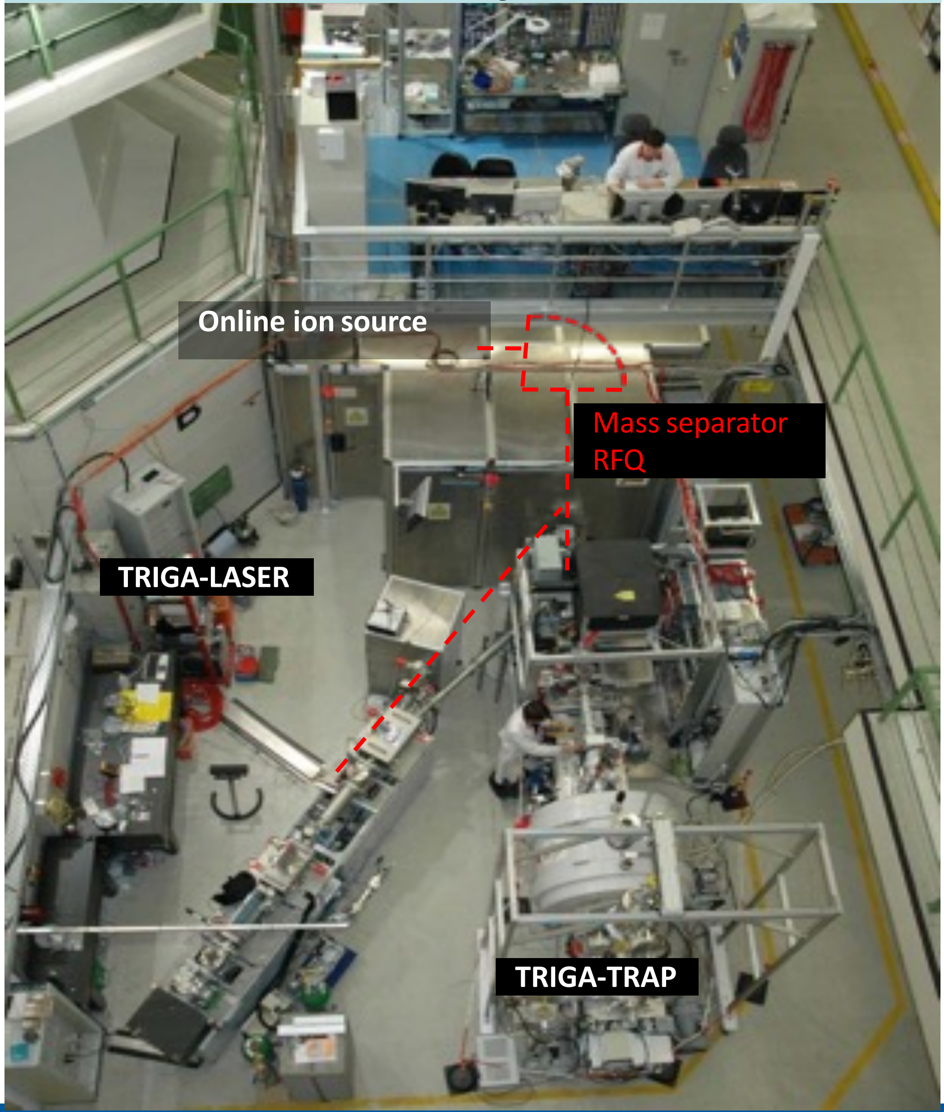


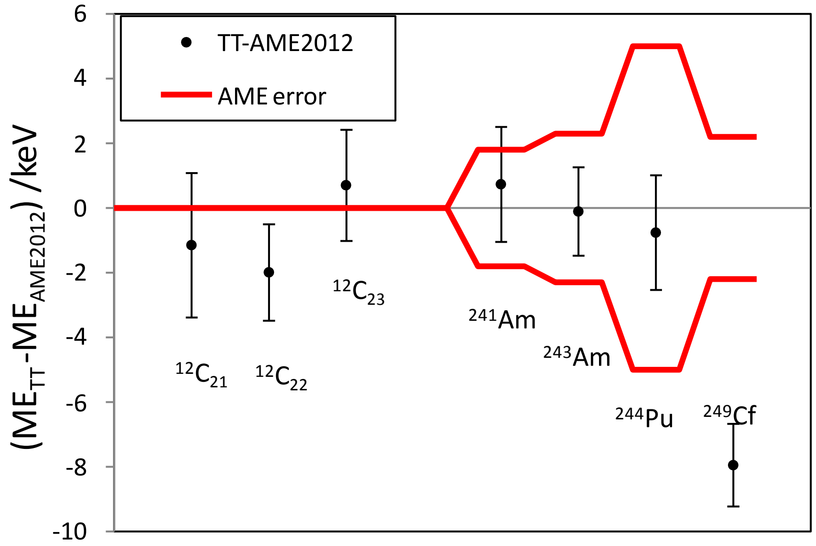
LaSpec

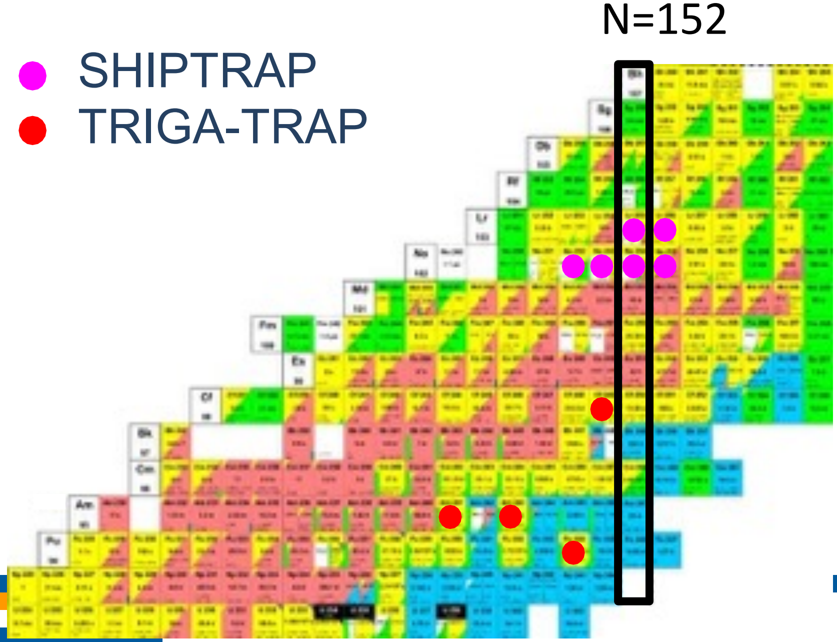


Laser Spectroscopy of Short-Lived Nuclei at FAIR's Low Energy Branch
laser spectroscopy of the stopped, cooled, and bunched radioactive species with fluorescence, resonance ionization and polarization based spectroscopic techniques.
Model-independent isotopic and isomeric nuclear spin, magnetic dipole moments, electric quadrupole moments and changes in mean square charge radii
provides an unparalleled opportunity to study the most exotic, and short-lived, nuclear species to the limits of nuclear stability

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





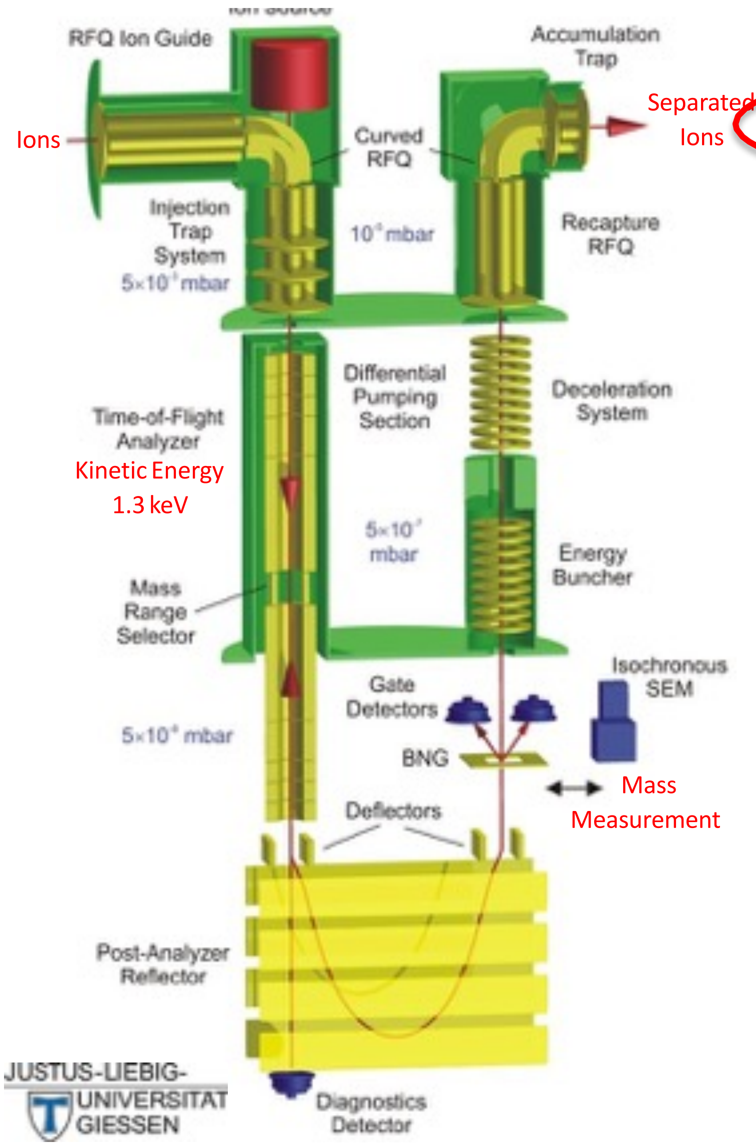


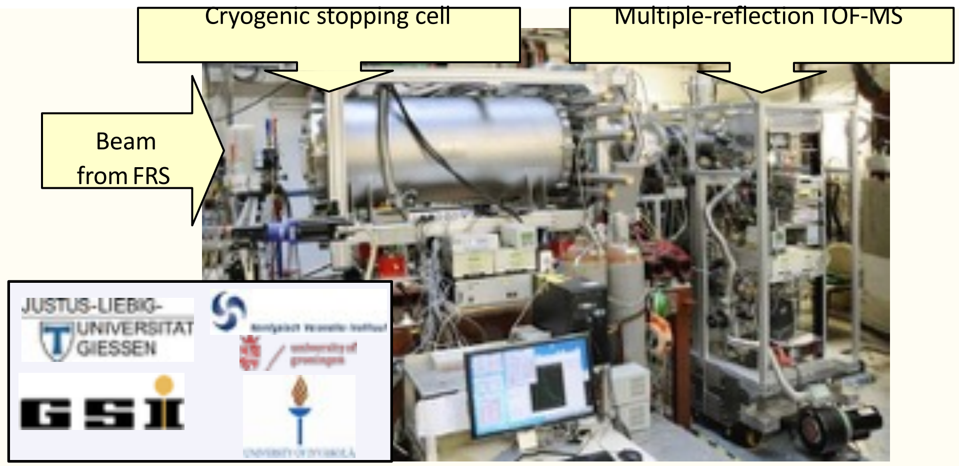
(-> MATS TDR 2.5, pp. 46)

Mass spectrometer (direct mass measurements, broadband diagnostics) and isobar separator

Features world-wide unique performance characteristics:

- Mass resolving power: up to 600,000
- Mass measurement accuracy: down to 10^{-7}
- Measurement duration: ~ few ms
- Repetition frequency: up to 400 Hz
- Transmission efficiency: > 50%
- Ion capacity: up to 10^6 ions/s





Commissioned online at the FRS Ion Catcher in 2012

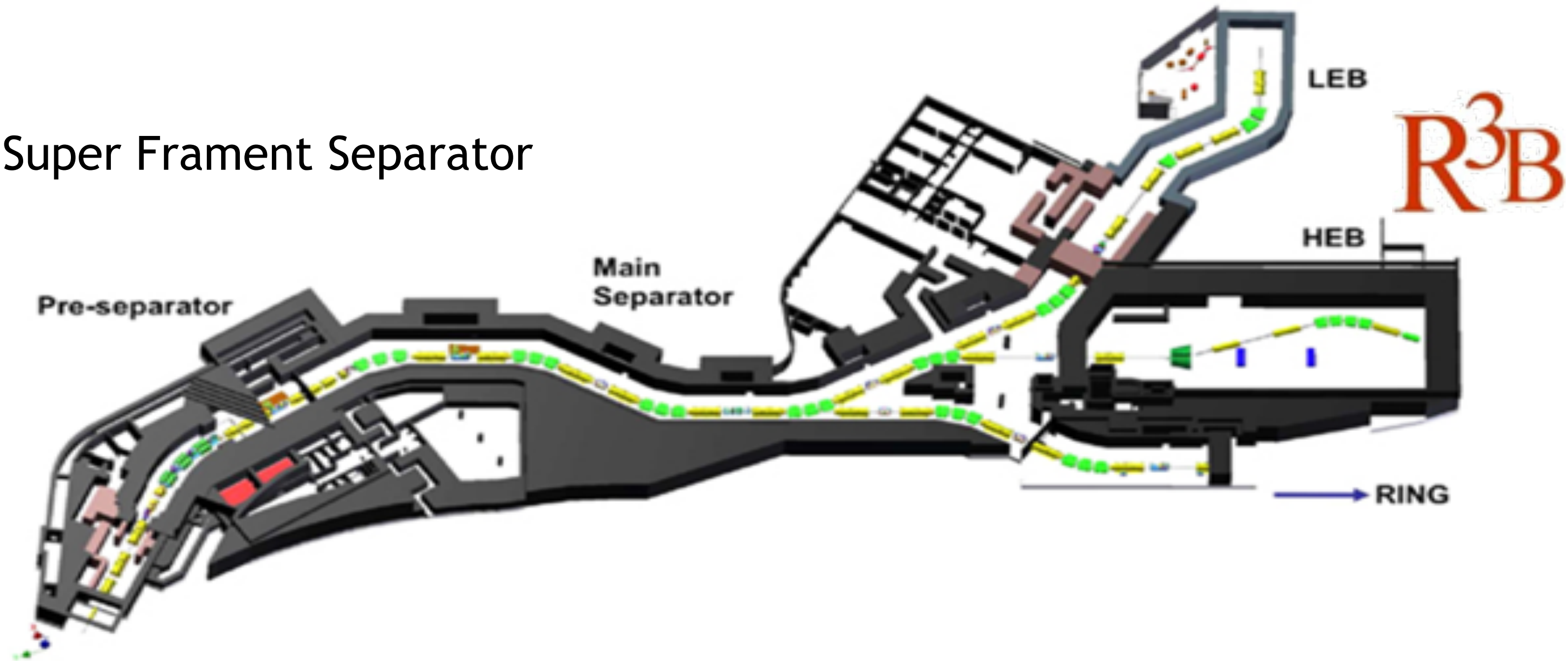
- First direct mass measurements of ^{211}Po and ^{211}Rn, ^{213}Rn ($T_{1/2}$ = 19.5 ms!)
- Characterization of stopping cell performance: MR-TOF-MS ideal diagnostics tool for stopping cells

Future work: Implement recapture system / operation as (ultra-)high resolution mass separator

W.R. Plaß et al., NIM B 266 (2008) 4560
W.R. Plaß et al., Int. J. Mass Spectrom. 394 (2013) 134

Reactions with Relativistic Radioactive Beams R3B

Super Frament Separator



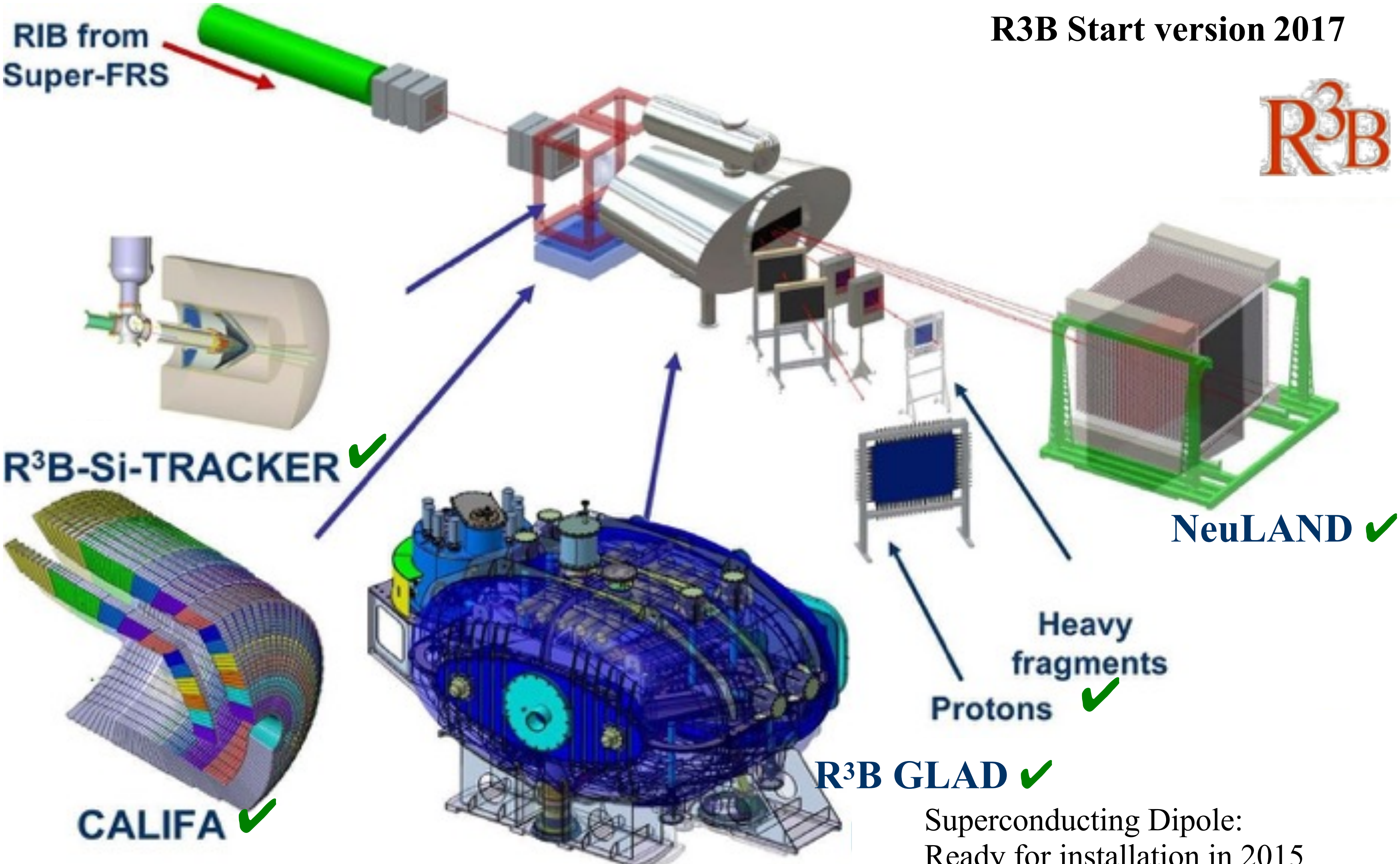
Reactions with Relativistic Radioactive Beams

→Secondary beams at 700 A.MeV
→Fixed target reactions
→Large Acceptance Dipole Magnet
→Very performant detectors: beam, fragment, gamma, Light charge particles and neutrons

Versatile program

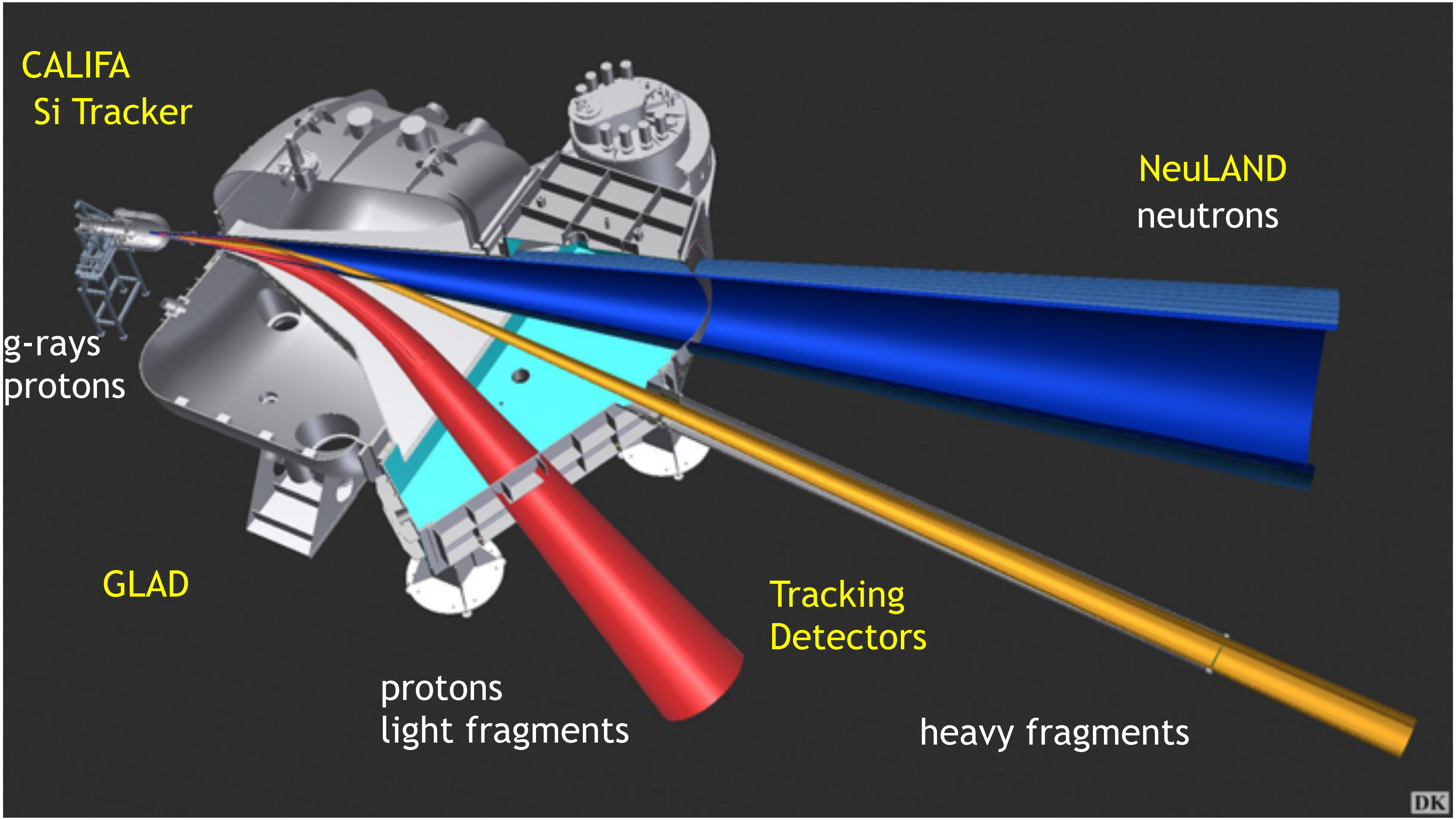
→ NN correlations and the nuclear force
→ nuclear structure far from stability
→nuclear dynamics: fission
→ EoS for high-density neutron-rich matter
→ in-medium excitation of baryon resonances
→strange matter: hypernuclei

Reactions with Relativistic Radioactive Beams R³B



Superconducting Dipole:
Ready for installation in 2015
Construction by CEA Saclay

R^{3}B Layout

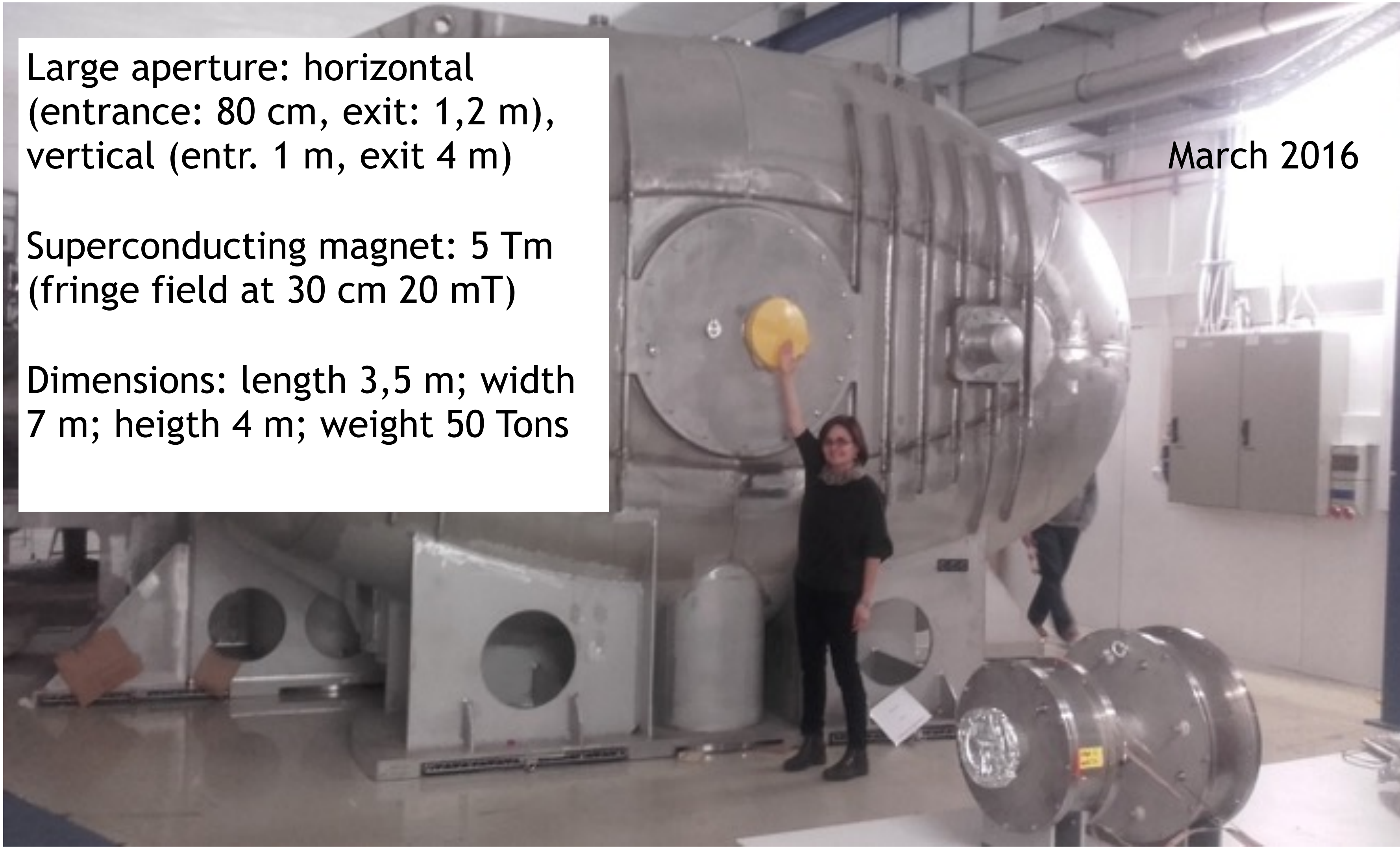

CALIFA
Si Tracker
NeuLAND
neutrons
g-rays
protons
GLAD
Tracking
Detectors
protons
light fragments
heavy fragments
DK

GLAD

Large aperture: horizontal (entrance: 80 cm, exit: 1,2 m), vertical (entr. 1 m, exit 4 m)

Superconducting magnet: 5 Tm (fringe field at 30 cm 20 mT)

Dimensions: length 3,5 m; width 7 m; heigth 4 m; weight 50 Tons



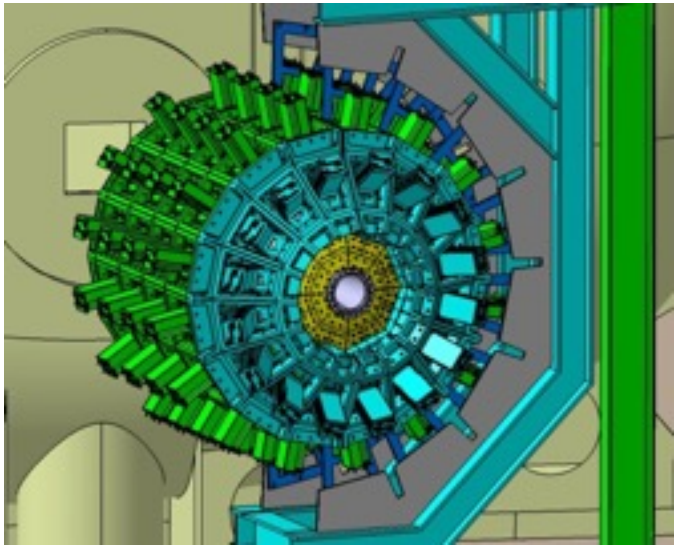
March 2016

CALIFA

Calo.

Spect.

Photo Peak Eff.	40% (up to Eγ=15 MeV projectile frame)
Calorimeter for HE LCP	200-700 MeV in lab system
ΔE/E	~5-6% (FWHM at Eg=1 MeV) , ~ 3% forward
LCP resolution	~2% (stopped particles), ~ 5% (punch through)



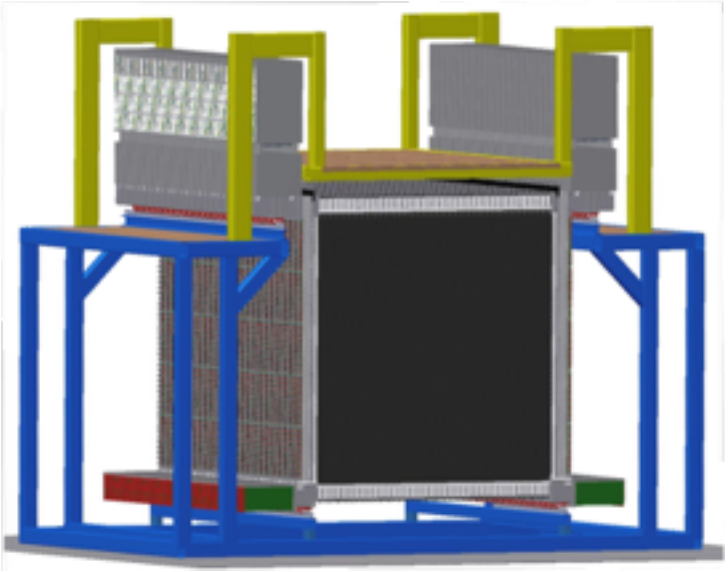
Design recently finalised

major funding from:

- -USC IEM, Uvigo Spain
- -ULund, Chalmers Sweden
- -TUM, TUD Germany
- -Dubna Russia

NeuLAND

Efficiency 0.2-1.0 GeV n	**> 90%**
Multi-hit	Up to 5 n
Invariant mass resolution	ΔE < 20 keV at 100 keV above threshold

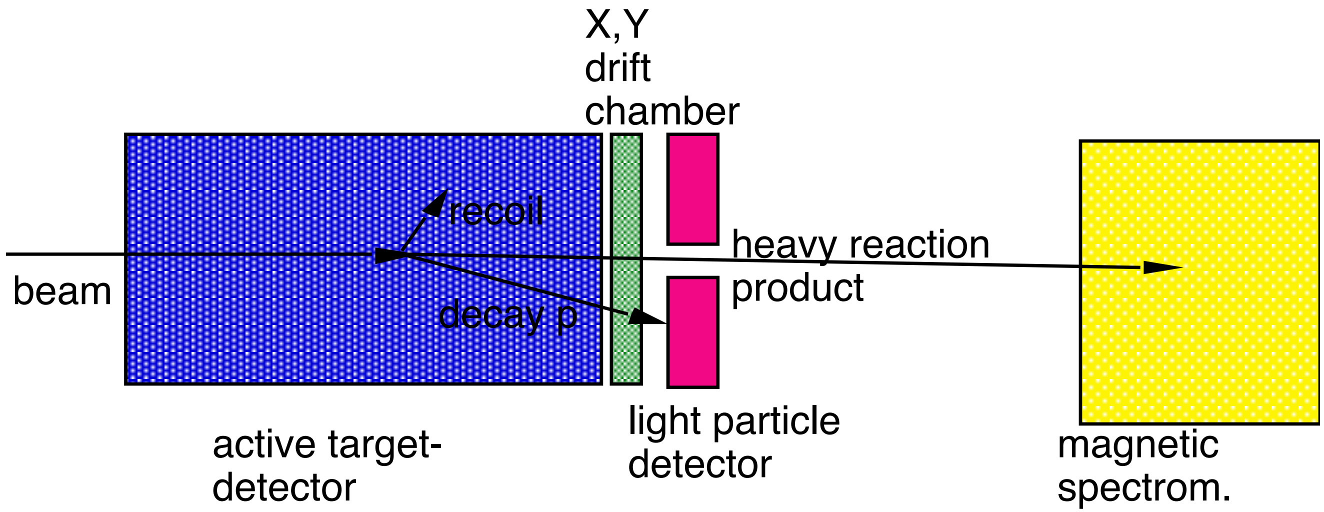


- full active detector
- face size 250x250 cm^2
- active depth 300 cm
- 3000 scintillator bars + 6000 PMTs
- 32 tons
- $\sigma_{x,y,z} \approx$ 3cm and σ_t < 150 ps

major funding from:

- GSI Darmstadt, TU Darmstadt. Univ. Frankfurt, Univ. Köln
- PNPI St. Petersburg

Active Target



⇒ advantage:

- low threshold
- high detection efficiency (rel. thick target)

⇒ well suited as alternative technique to EXL for:

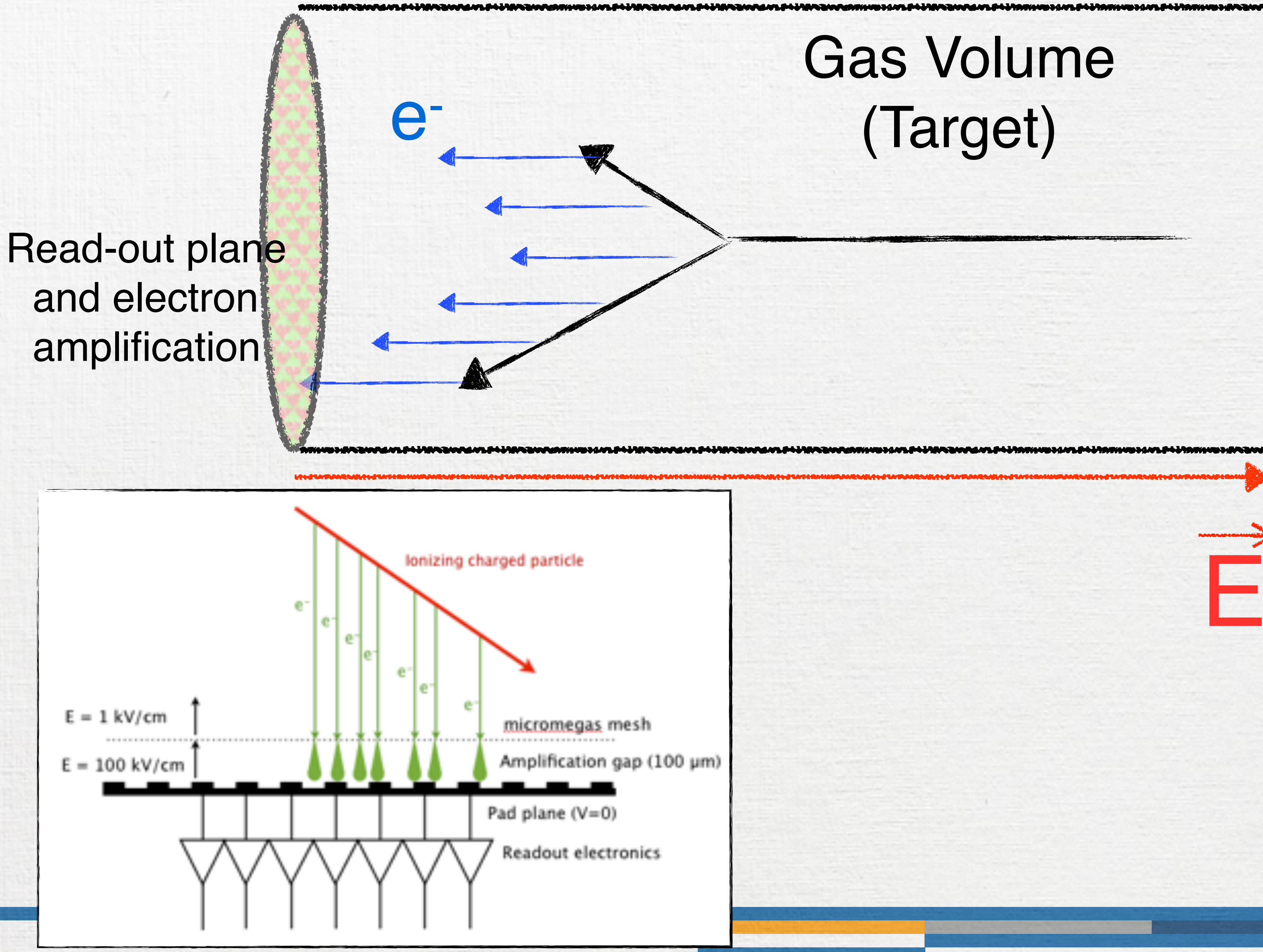
- short lifetimes (T ≤ 1 sec)
- low RIB intensities (≤ 10^5 sec^{-1})

TDR submitted 2015 in review

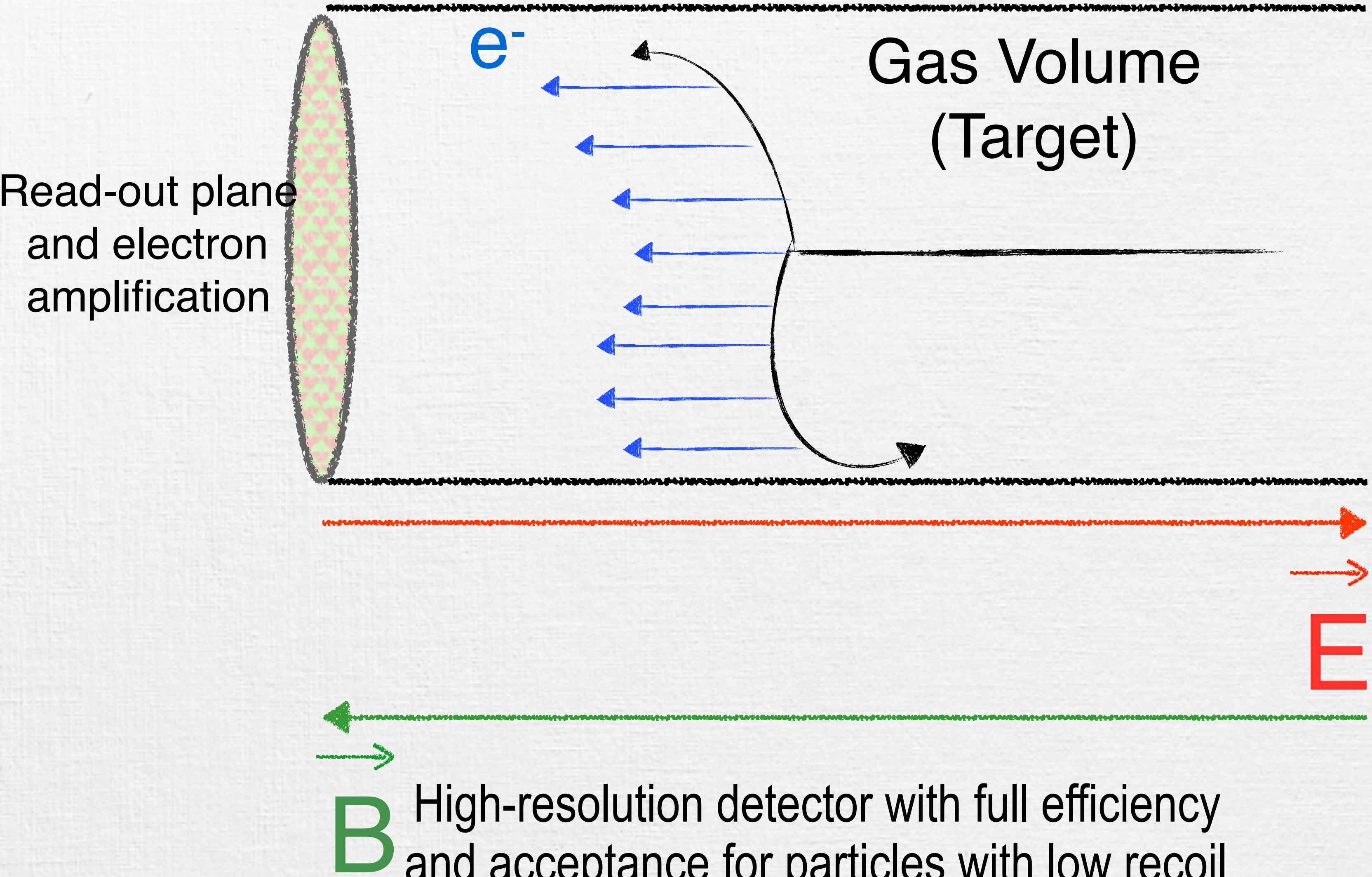
Feasibility study 2014 and 2016
(Ni and Xe)

For 2018
Prototype ready
- (α,αγ) → need a part of CALIFA
- proto elastic → new set up

Active Targets for reactions with radioactive beams

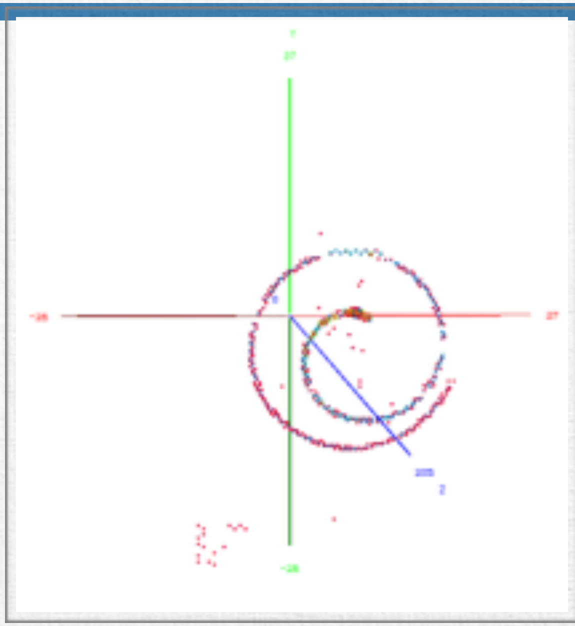


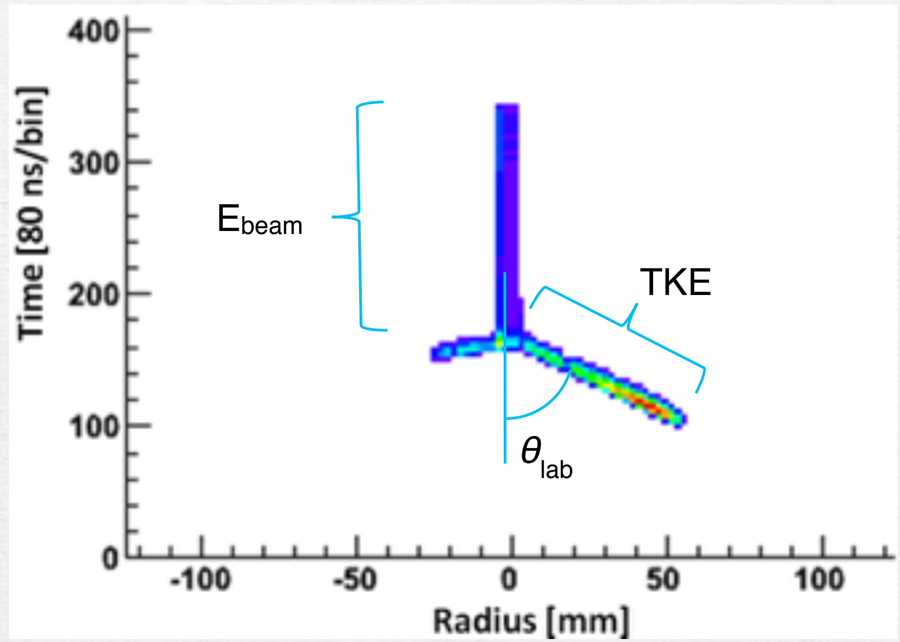
Active Targets for reactions with radioactive beams



High-resolution detector with full efficiency and acceptance for particles with low recoil energy

What we measure





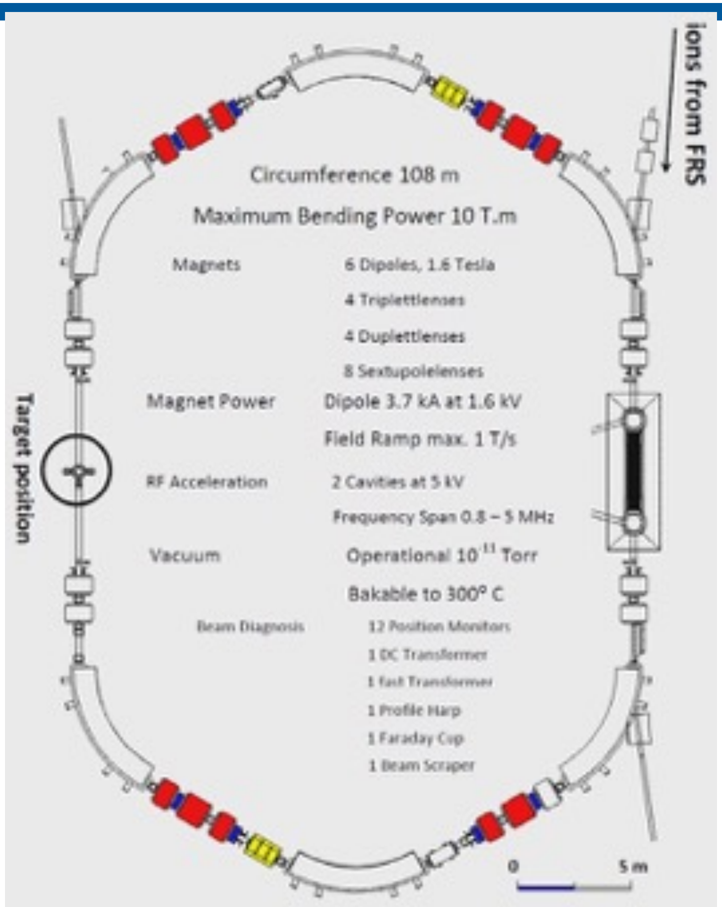
- Angle
  - Tracks
- Energy
  - E_{beam} - position
  - $E_{products}$ - Bragg curve
- Cross Sections (angle, energy)

Beyond MSV: NUSTAR program at “NESR”

Experiments with stored, electron cooled ion beams
- **World-wide unique**
- **Conceptionally new experiments**

ILIMA
- electron cooled beams needed for
  - higher precision and separation (ground and isomeric states)
  - time-resolved studies (unique decay modes, e.g. bound beta decay)
  - studies with pure isomeric beams

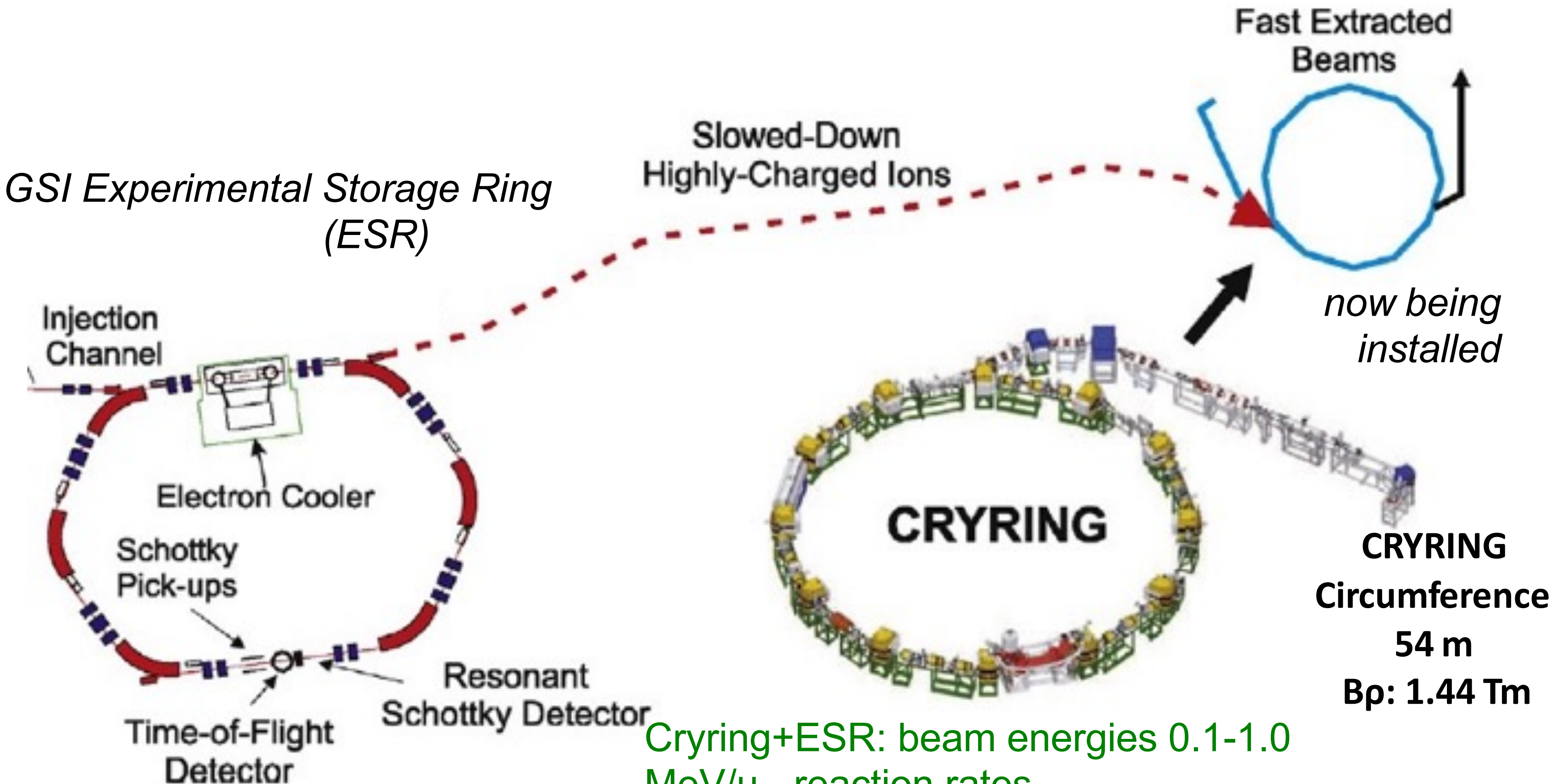
ELISe
- Elastic and inelastic electron scattering on RIBs



EXL: Elastic and inelastic scattering, reaction with low-momentum transfer
- matter distributions, monopole resonances, capture reactions, charge exchange reactions, transfer, knock-out

  (n-skins, compressibility, GT-strength, shell evolution, nucl. astrophysics reactions)

Possibility to prepare <100 keV bare ions

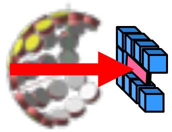


Cryring+ESR: beam energies 0.1-1.0 MeV/u - reaction rates measurements in the Gamow window of the **rp-process**

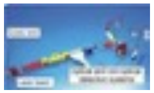
Complementarity of NUSTAR experiments

Super-FRS

HISPEC/ DESPEC

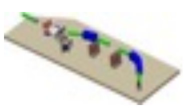


LASPEC

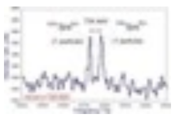


MATS

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.								

Uniqueness of FRS, Super-FRS

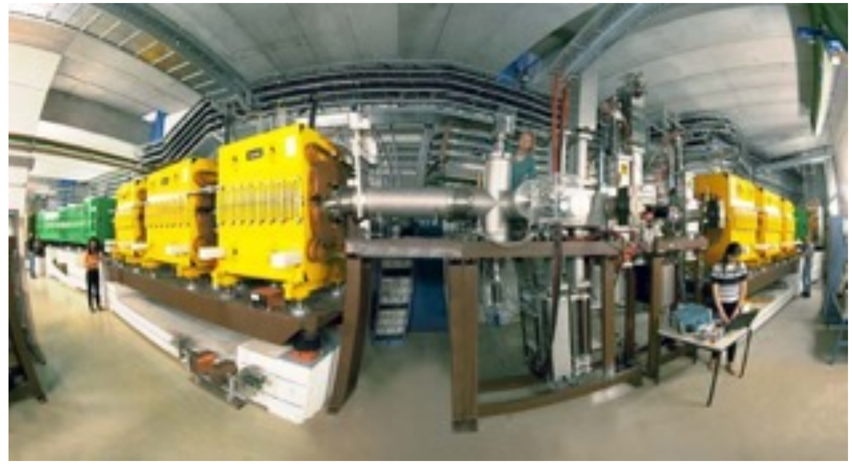
- Universal beams: ions of all elements up to uranium
- Beam energies 100...2000 MeV/u
- Spectrometer with high momentum resolution (dp/p~1E-4)
- Flexible ion-optical multiple-mode/multiple-stage operation (isotope separation, dispersion-matched stages, spectrometer modes)

Transition from FRS → Super-FRS

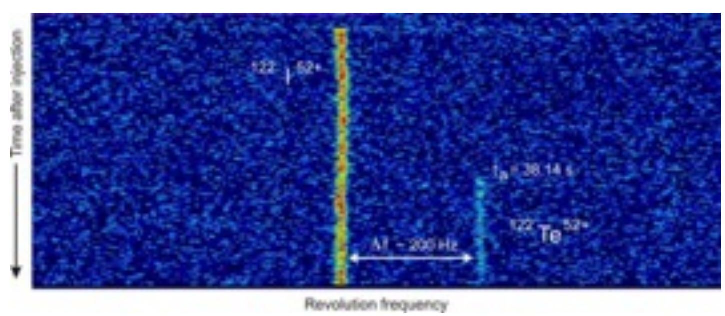
- 100 x higher primary-beam intensity
- 10 x higher transmission for projectile fragments and fission products
- higher ion-optical flexibility: multiple-stage operation/separation/measurements
- full transmission to the three branches (LEB, HEB, RB)
- new instrumentation at all branches: high-resolution spectrometer and ISOL-type experiments (MATS, LaSPEC) at LEB, R3B at HEB, CR at RB

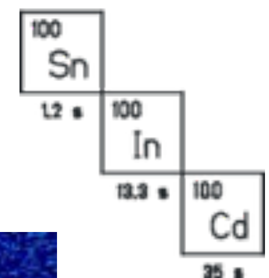
Selectivity and Sensitivity

- Highest selectivity
  - FRS: 1:10[13]
  - Super-FRS: < 1:10[17]



- Ultimate sensitivity
  - FRS: spectroscopy with 1 atom/day
  - ESR: mass and decay measurements with 1 single atom





$T_{1/2} = (0.94\ ^{+0.54}_{-0.27})$ s

$Q_\beta = (3.4\ ^{+0.7}_{-0.3})$ MeV

$\sigma = 11$ pb

(7 atoms)

R. Schneider et al. Z. Phys. (1995)

What is NUSTAR unique in?

World-wide unique synchrotron-based RIB production for:

- High-intensity High-energy Radioactive Beams (≤1.5 GeV/u)
  - Efficient production, separation, transmission and detection aided by Lorentz boost, use of thick targets
  - Access to the **heaviest nuclei** without charge-state ambiguities
  - Many reactions/observables only accessible with high beam energies
- High-intensity in Storage rings
  - Mass measurements and beam preparation/manipulation
  - Isomeric beams
  - Novel experimental tools (beyond MSV/with CRYRING, ESR and HESR)

Combined with:

- Wide range of state-of-the-art instrumentation
- Strong evolution from existing programs
  - **Almost all NUSTAR FAIR experiments could start in 2017/2018**

Overview

- NUSTAR has an excellent science case.
- The case will still be valid in 202x for NUSTAR/Super-FRS@FAIR.
- The situation for LEB building seems to be resolved.
- The critical path is the readiness of Super-FRS.
- The NUSTAR equipment/end stations will be ready well in time for Super-FRS beams.
- NUSTAR has an intermediate plan, and pursues an evolutionary approach: perform unique and exciting pilot experiments at GSI with the available new equipment for FAIR (phase 0).
- Storage-ring activities exhibit world-unique features and must be strengthened.

Acknowledgements

NUSTAR collaboration
Special thanks to
N. Kalantar, C. Scheidenberger and D. Cortina