Nuclear Structure and Astrophysics @ FAIR

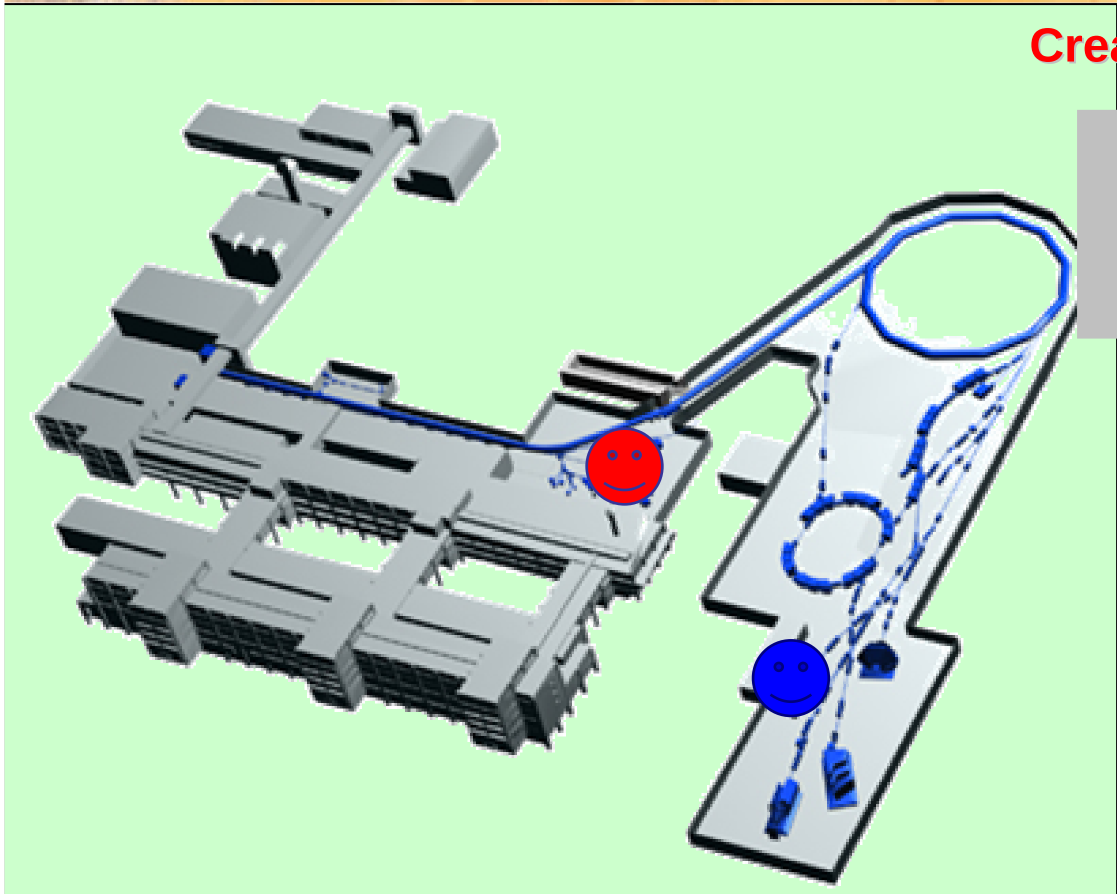
- **FAIR – outline of the facility**
- **GSI – today**
  - **Superheavy Elements**
  - **Nuclear structure and Astrophysics at the FRS**
- **NUSTAR**
  - ***NUclear STructure, Astrophysics and Reactions***

Helmholtz International Summer School
"NUCLEAR THEORY AND ASTROPHYSICAL APPLICATIONS"
Dieter Ackermann, GSI Darmstadt and University of Mainz

Part 1

FAIR
- outline of the facility

GSI today.....



Creation of six new chemical element

107 **Bh** Bohrium	108 **Hs** Hassium	109 **Mt** Meitnerium	110 **Ds** Darmstadtium	111 **Rg** Roentgenium	112 **112**

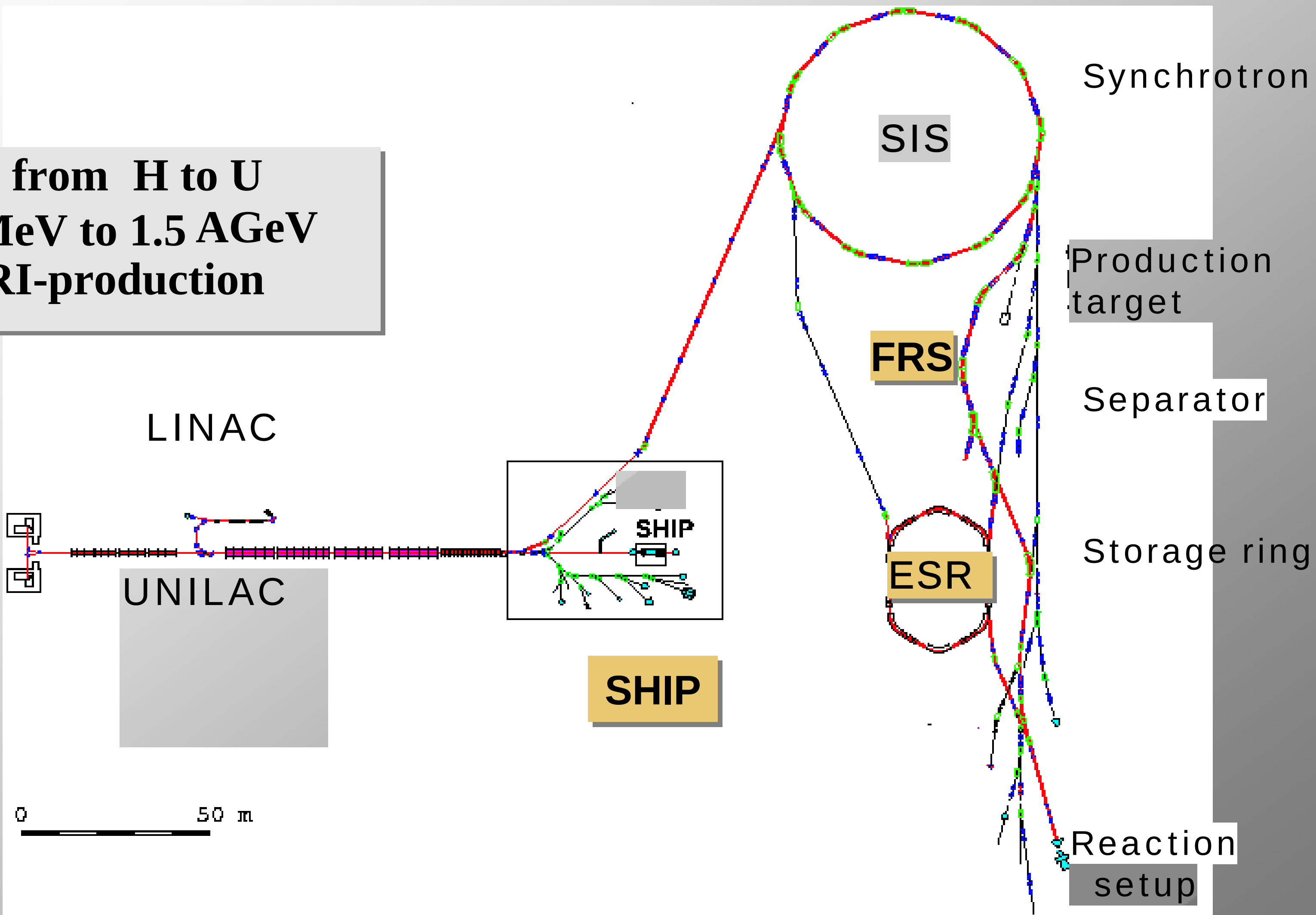
Tumor therapy with heavy ions
over 200 patients successfully treated
HICAT: a new facility to treat up to 1000 patients / year

- plasma physics

supported by a worldwide unique accelerator facility for heavy-ion beams

The present GSI Accelerators and the GSI RI Facility

Ions from H to U
5 AMeV to 1.5 AGeV
for RI-production



Quo vadis GSI?

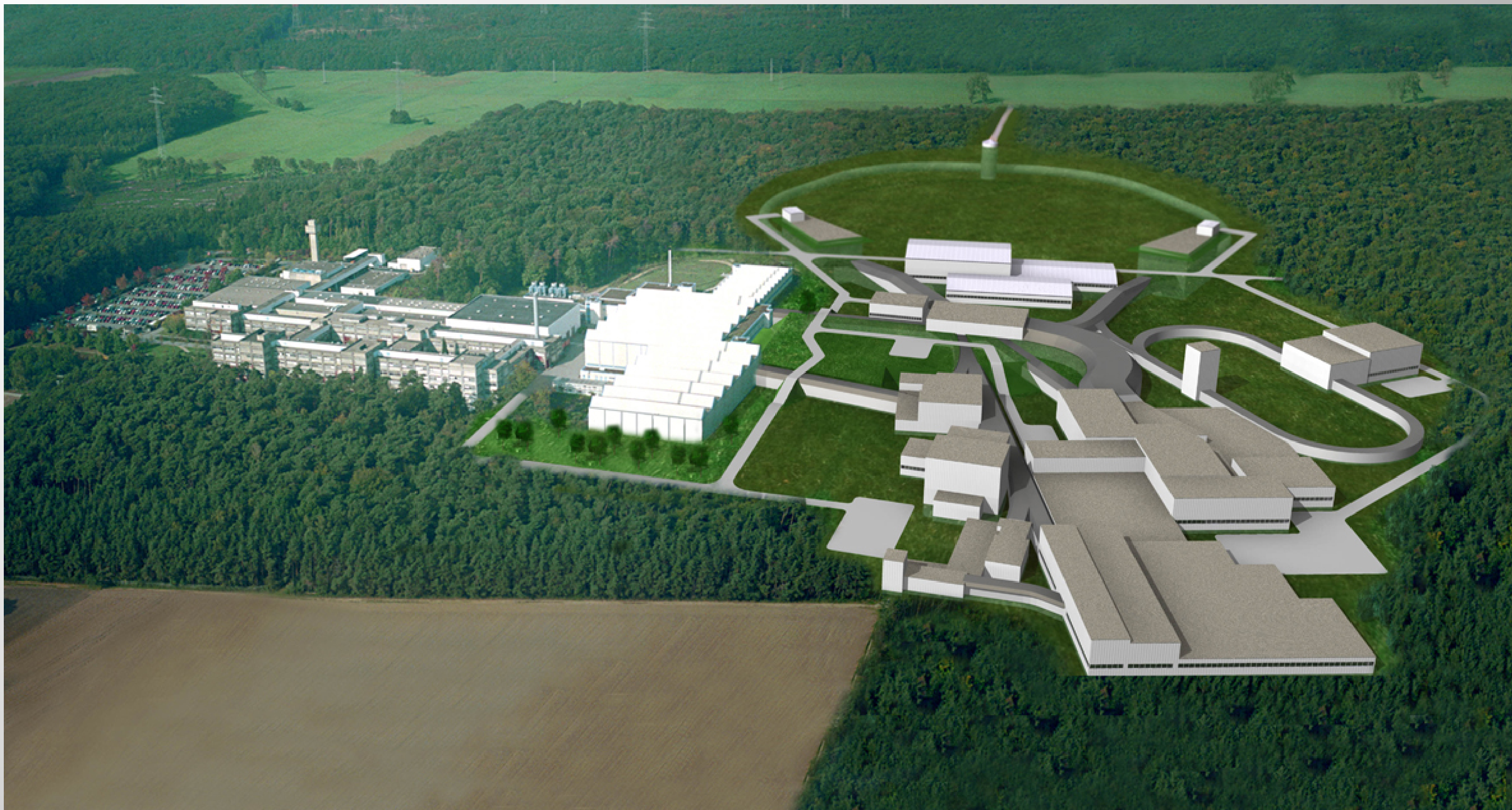
Address questions connected to strong interactions in many-body systems:

- structure and properties of rare, short lived nuclei. How were the elements created?
- quark-gluon structure of hadronic matter: Where from is the mass coming?
- ultra-strong electromagnetic field in atoms

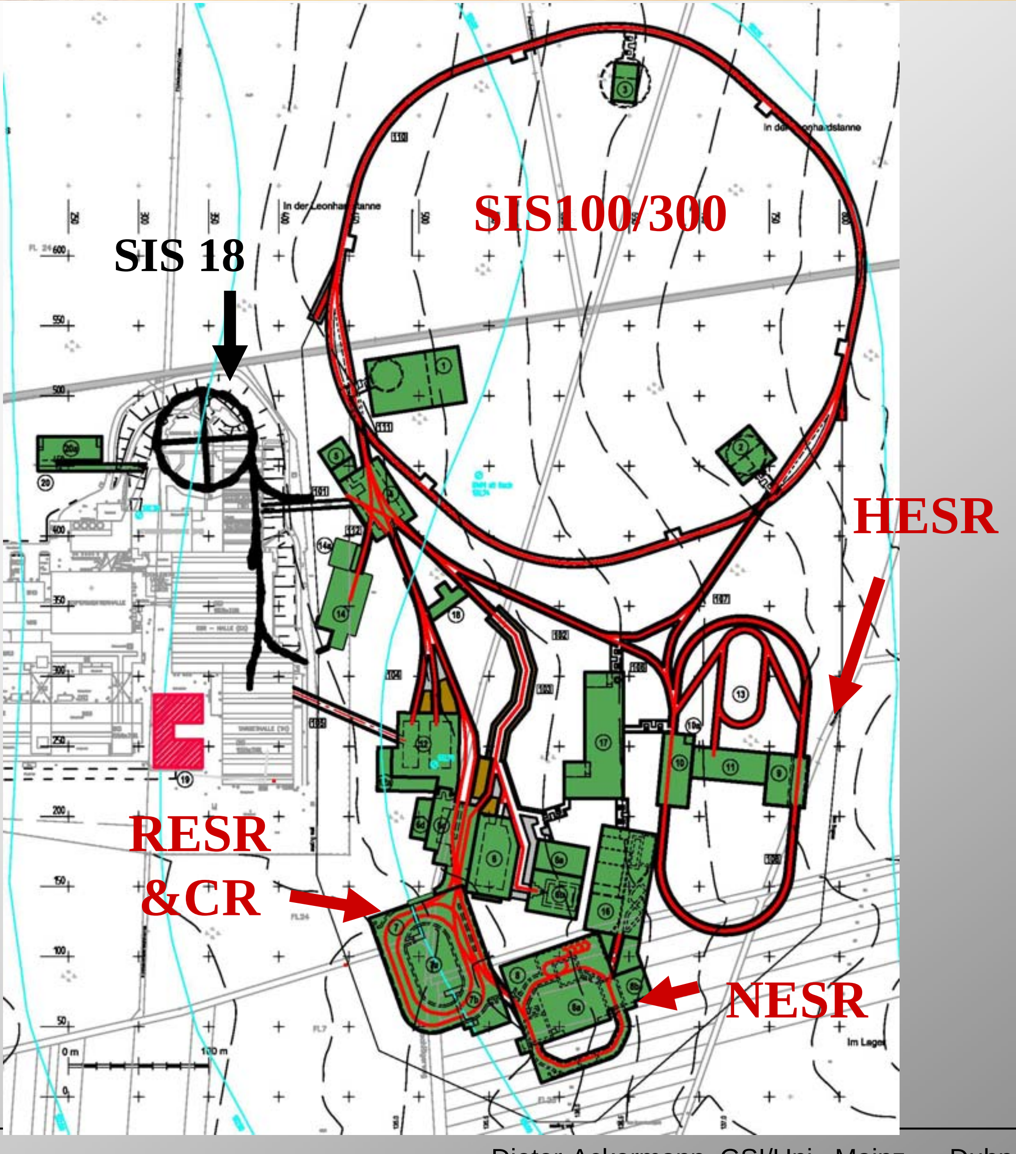
New requests:

- higher energies and intensities
- diversify the available beam species: RIB's and Antiprotons

FAIR



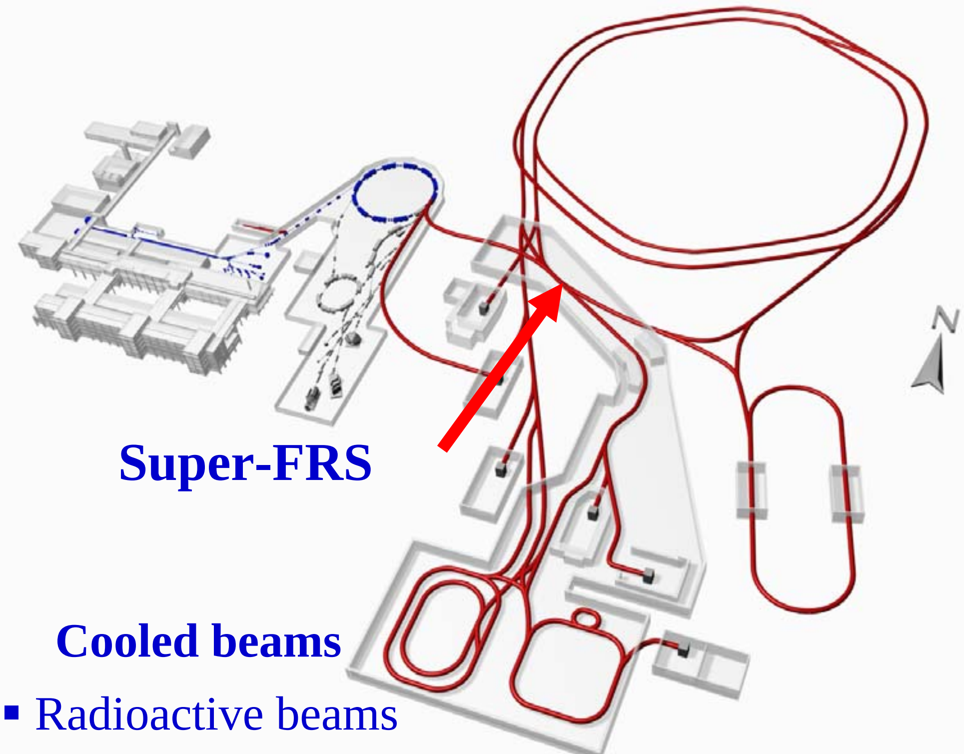
The Facility



Key features

- ✓ Highest beam intensities and energies
- ✓ Brilliant beams
- ✓ Cooled beams
- ✓ Fast cycling superconducting magnets
- ✓ Parallel operation of up to four different scientific programs

FAIR in numbers….



Cooled beams

- Radioactive beams
- e^- – A (or Antiproton-A) collider
- 10^{11} stored and cooled 0.8 - 14.5 GeV antiprotons
- Decelerated HCI (4 MeV/u) and antiprotons (30 MeV/c)

Primary beams (SIS 100)

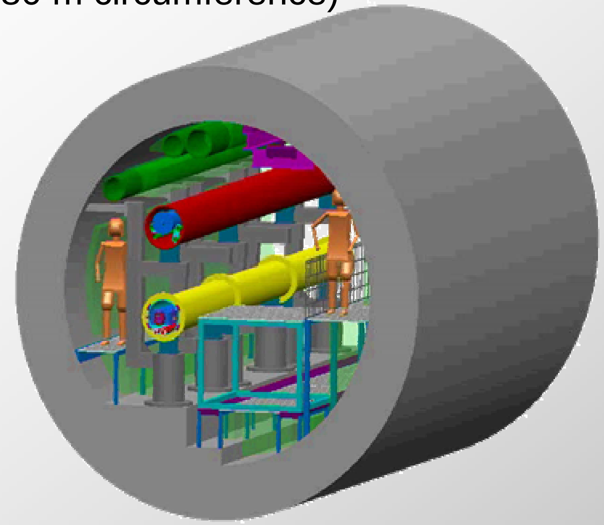
- $^{238}U^{28+}$: 10^{12}/s; 0.4-2.7 GeV/u;
- Intensity: 100-1000 over the present one
- protons: 2.5×10^{13}/ in 5 s at 29 GeV
- 2×10^9/s $^{238}U^{73+}$ up to 35 GeV/u
- 34 GeV/u U^{92+}, 100 s spill
- up to 90 GeV protons

Secondary beams

- broad range of radioactive beams up to 1.5 - 2 GeV/u;
- up to factor 10 000 in intensity over present
- Antiprotons 0.03 - 30 GeV

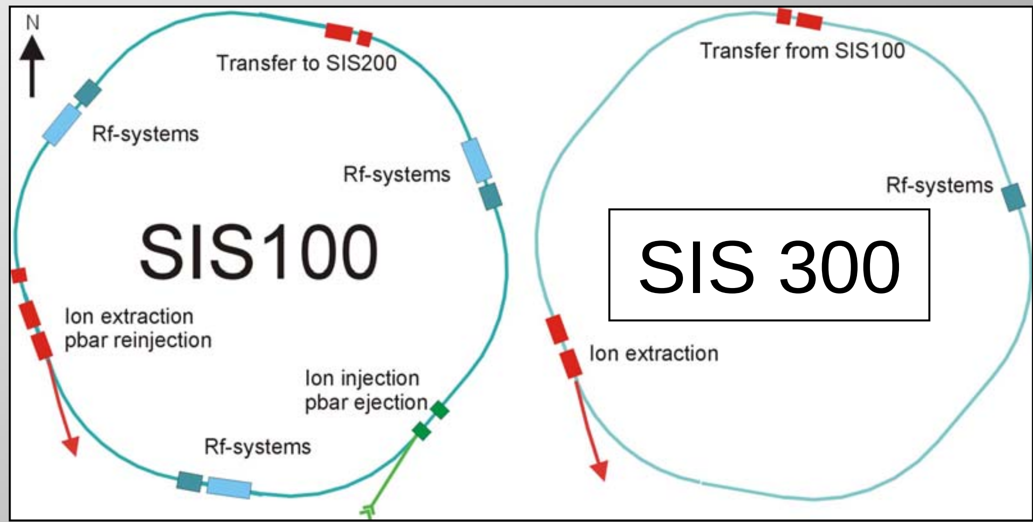
SIS 100/300

Two synchrotrons in one tunnel (1080 m circumference)

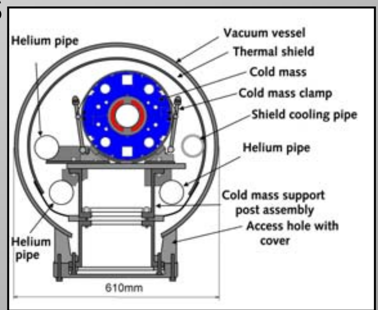


Booster and compressor (50 ns)

Stretcher (slow extraction) and high energy ring (34 GeV/u)



R&D program in rapidly cycling superconducting magnets



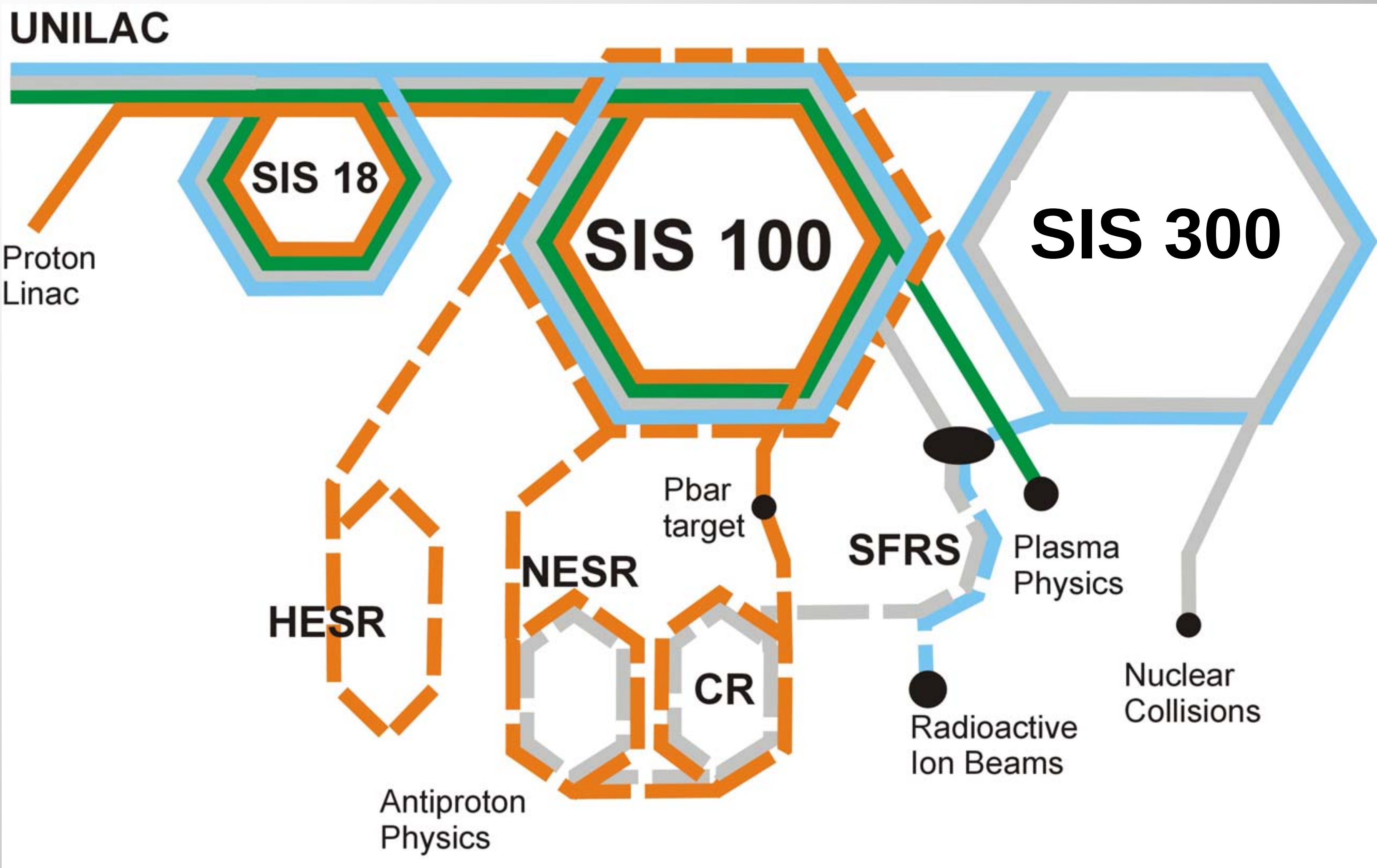
Nuclotron dipole magnet:
B=2T, dB/dt=4T/s

RHIC type dipole magnet:
→ B=4T 6T, dB/dt=1T/s

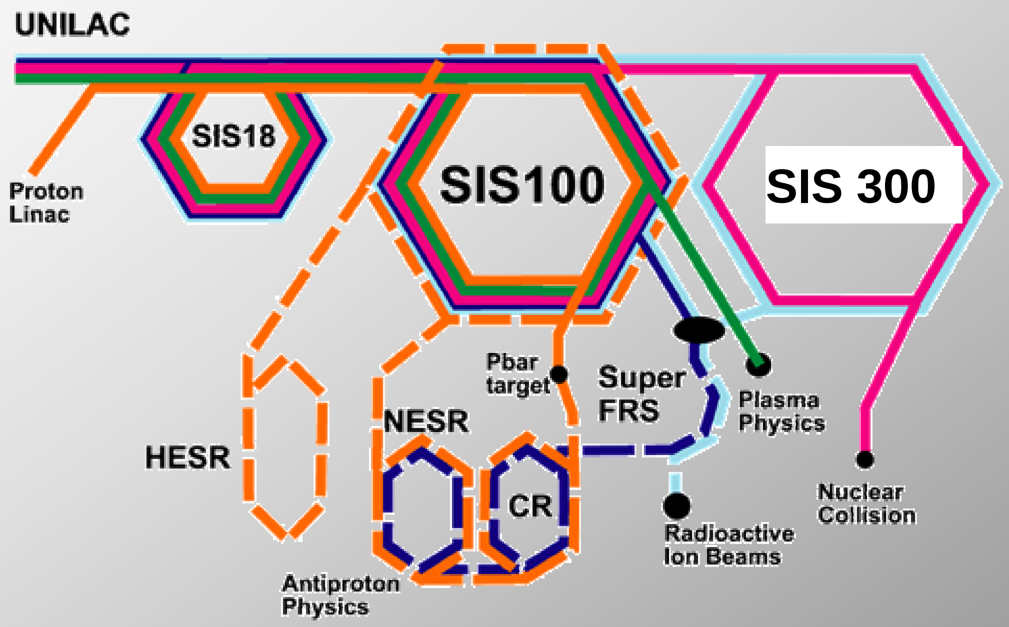
Space charge limit ~A/q^2

- $U^{73+} \rightarrow U^{28+}$ gain of a factor 6.8 in beam in tensity
- Short cycle ~ 1 s
- p = 1 x 10^{-12} mbar

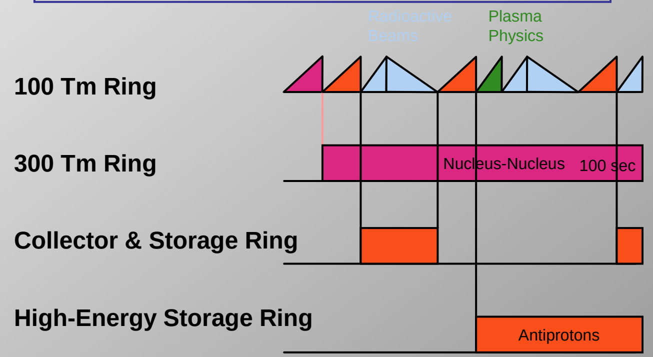
Operation scenario



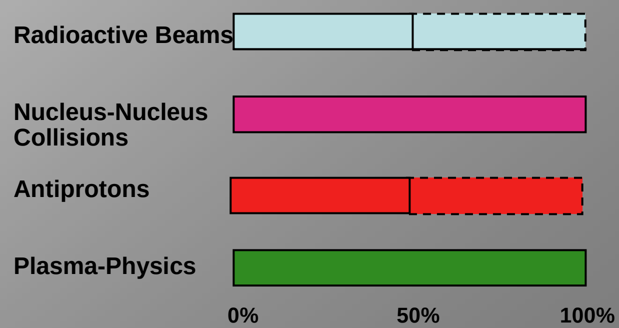
Parallel Operation



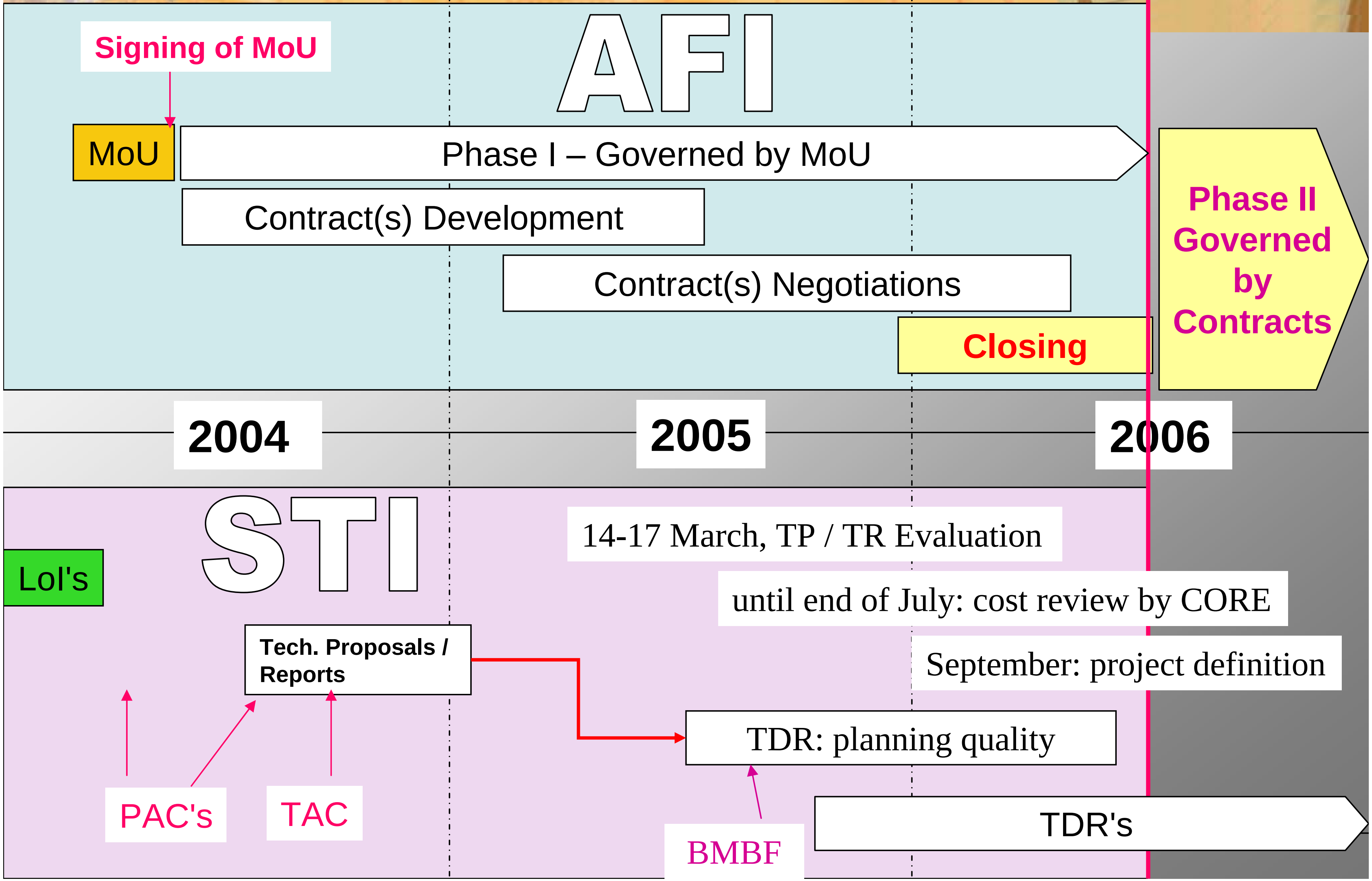
Duty-Cycles of the Accelerator Rings



Duty-Cycles of the Physics Programs



FAIR's International Working Groups



Next Steps

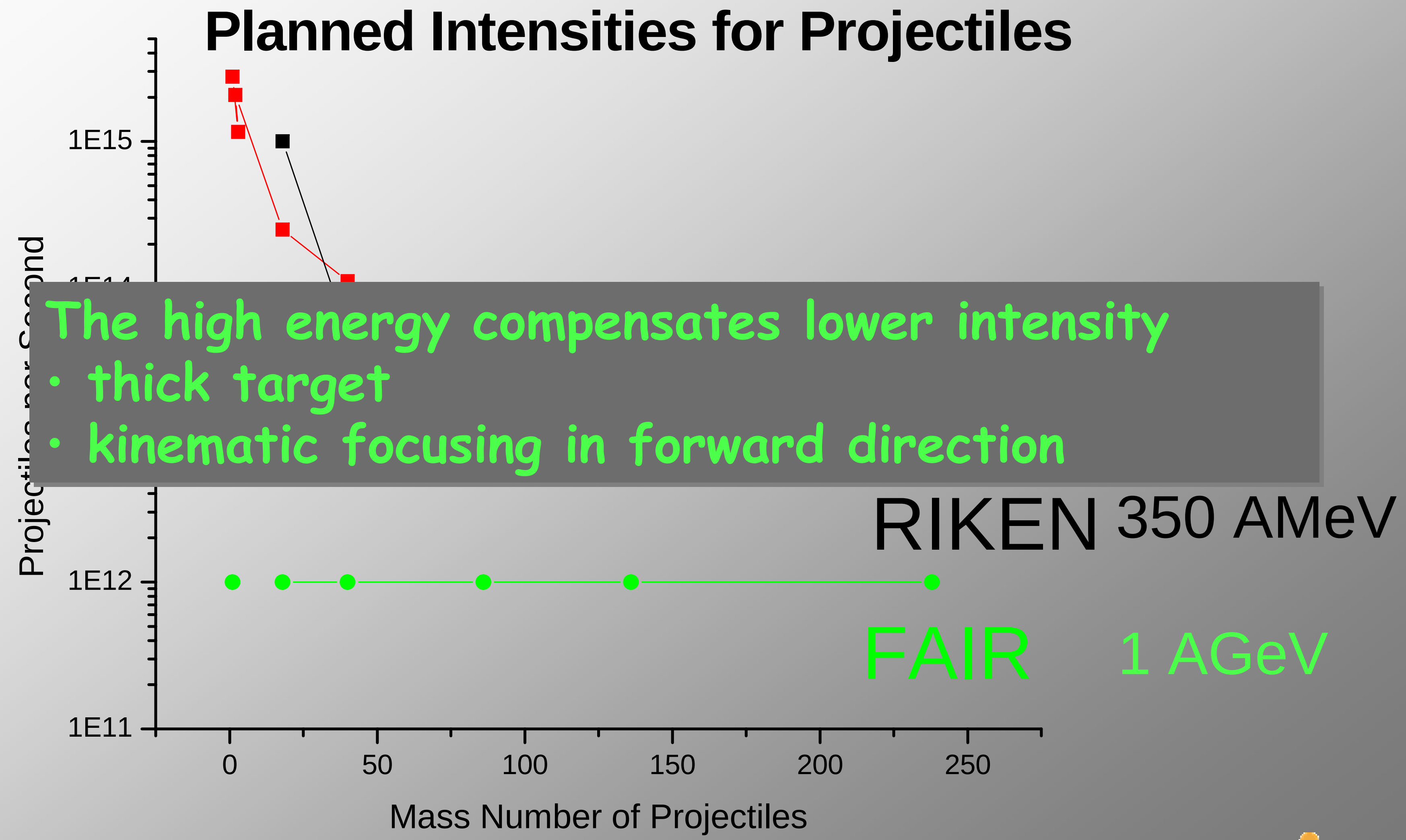
2005: Determination of the Legal Structure of FAIR GmbH, draft of FAIR contract

Summer of 2006: Contract on FAIR signed by Member States, followed by **FAIR construction Start**

2006 to 2010 Technical Design Reports (TDR) for the sub systems

2011 - 2014: Commissioning of FAIR

Next-Generation Secondary Nuclear Beam Facilities



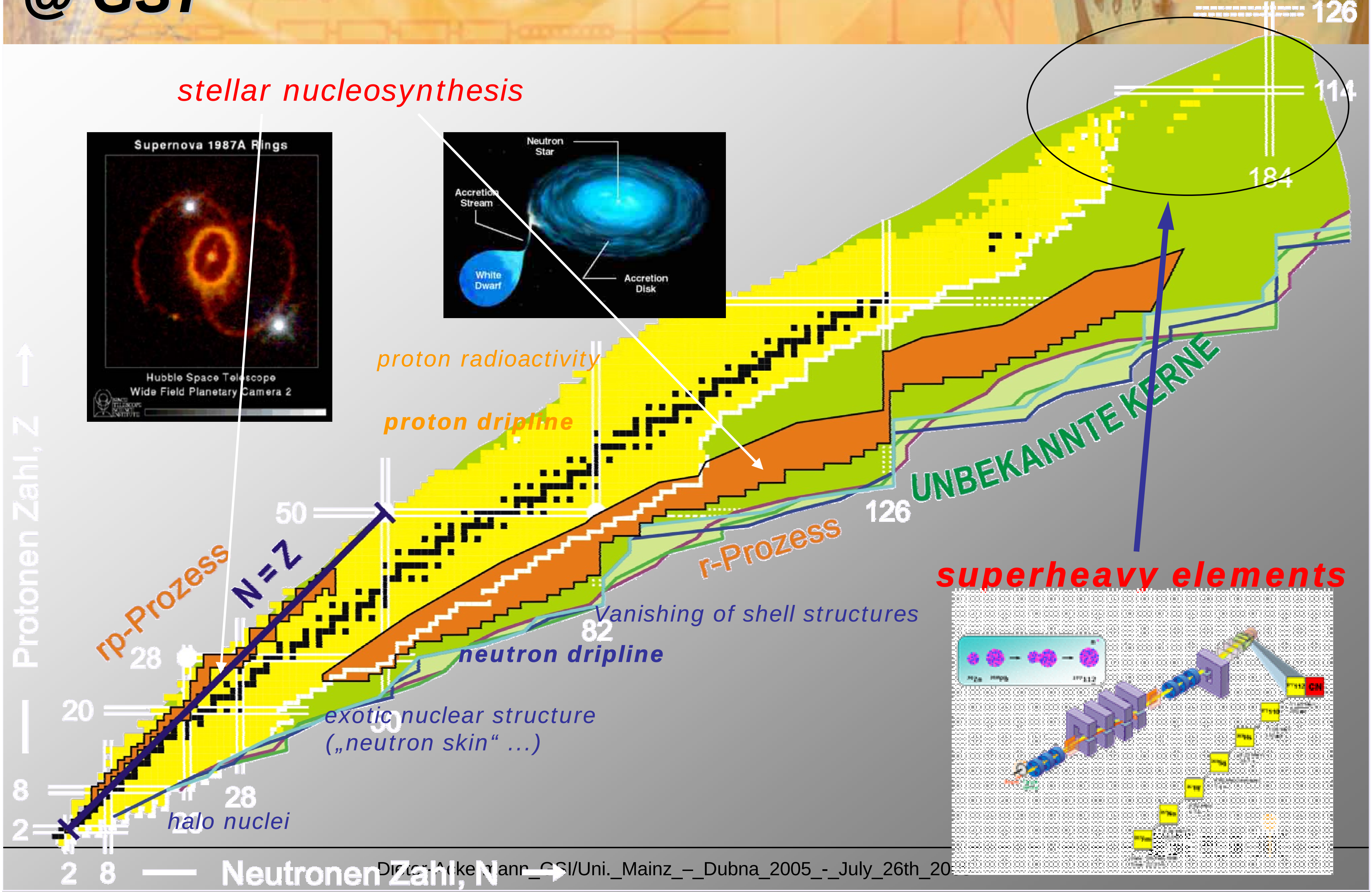
The high energy compensates lower intensity
- thick target
- kinematic focusing in forward direction

Part 2

GSI

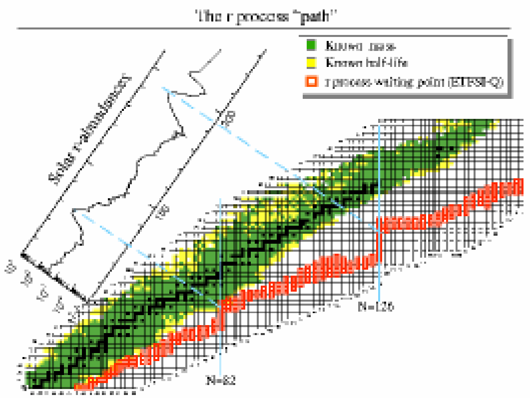
present

Nuclear Structure and Astrophysics @ GSI



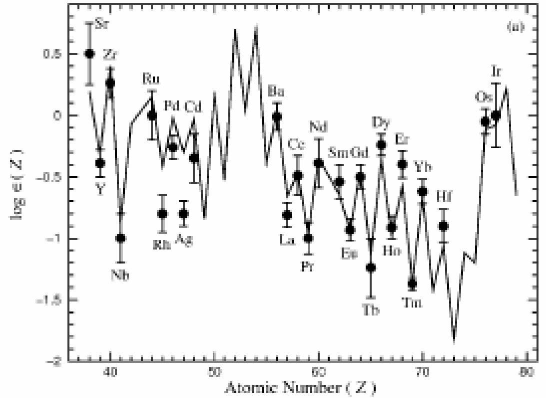
R-process: Path and Abundances

R-process paths



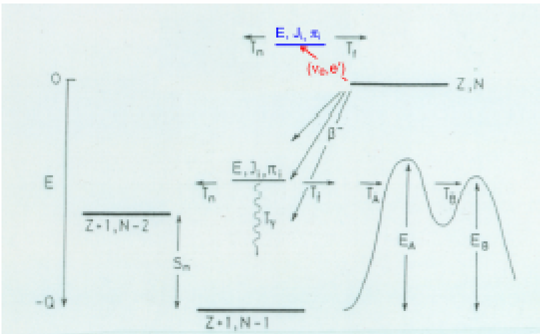
neutronrich nuclei

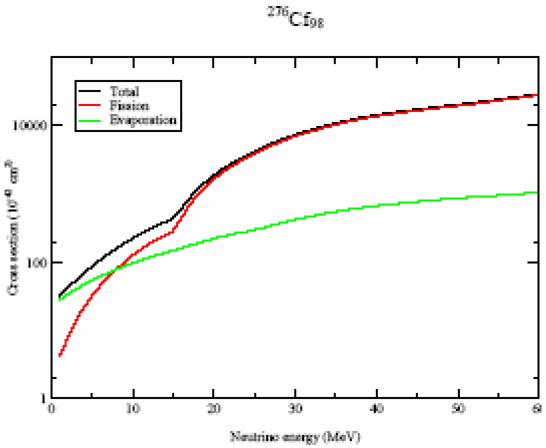
Abundances in metalpoor stars



- peaks at $A \sim 90$ and 130
- fission? neutrinos?

Neutrino induced fission for r-process



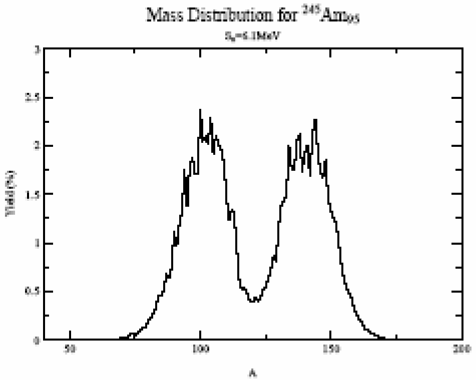


- Competition between neutron decay and fission.
- Fission relatively enhanced with increasing neutrino energy.

R-process fission fragment distributions.

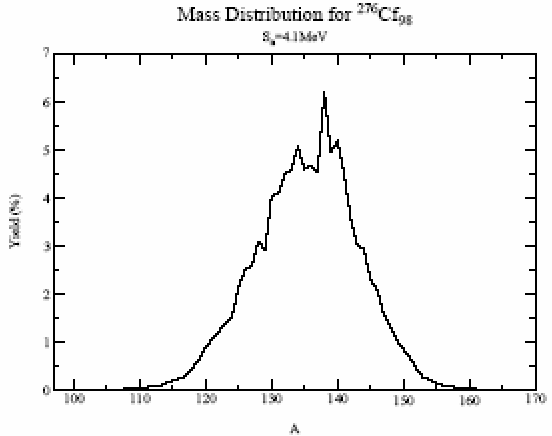
A. Kelić, K.-H. Schmidt, N. Zinner

^{245}Am, decay to stability



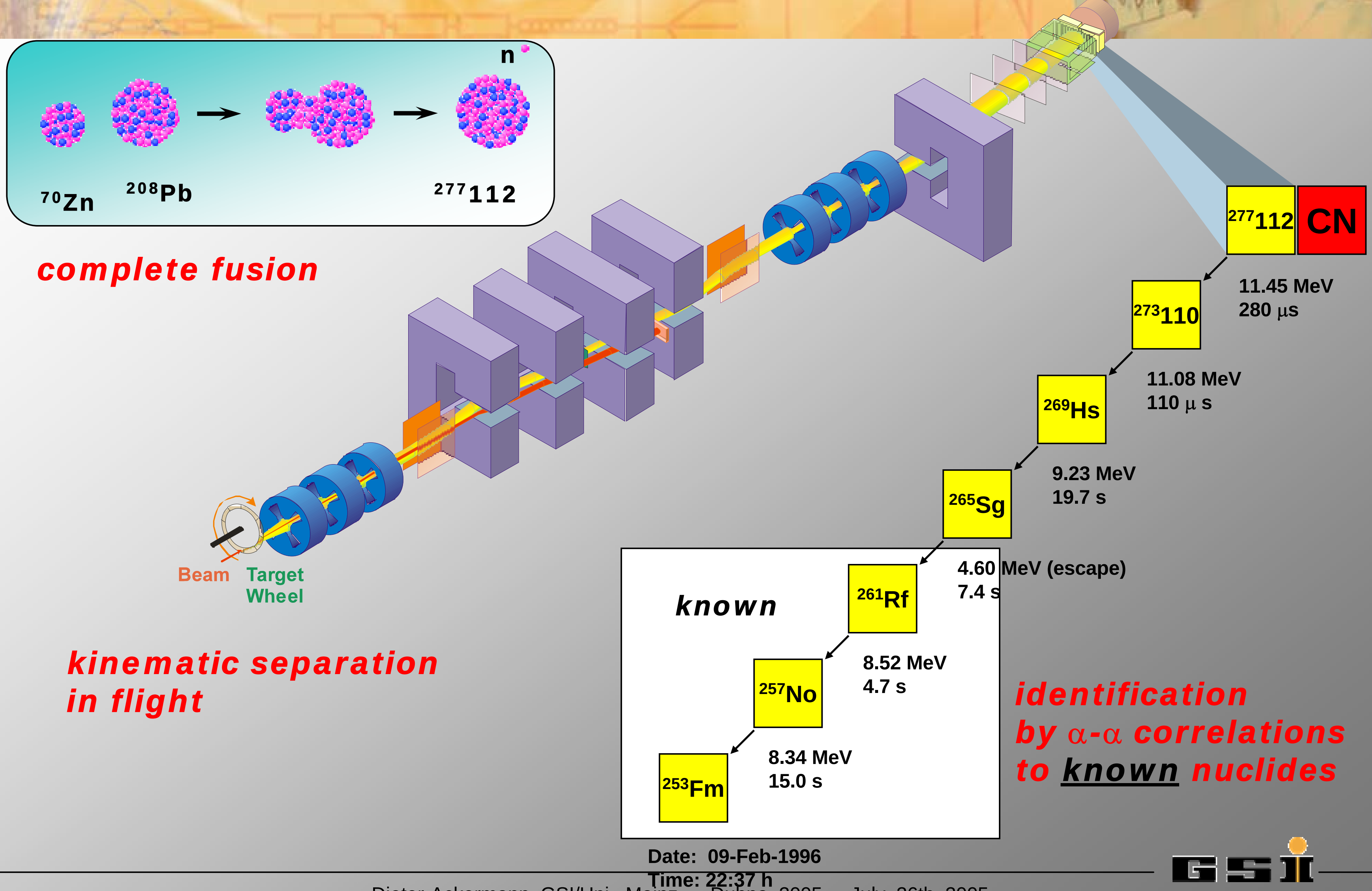
Fission fragment distribution

^{296}Cf, on r-process path



Fission fragment distribution

In-flight Separation at low Energies and Identification with SHIP



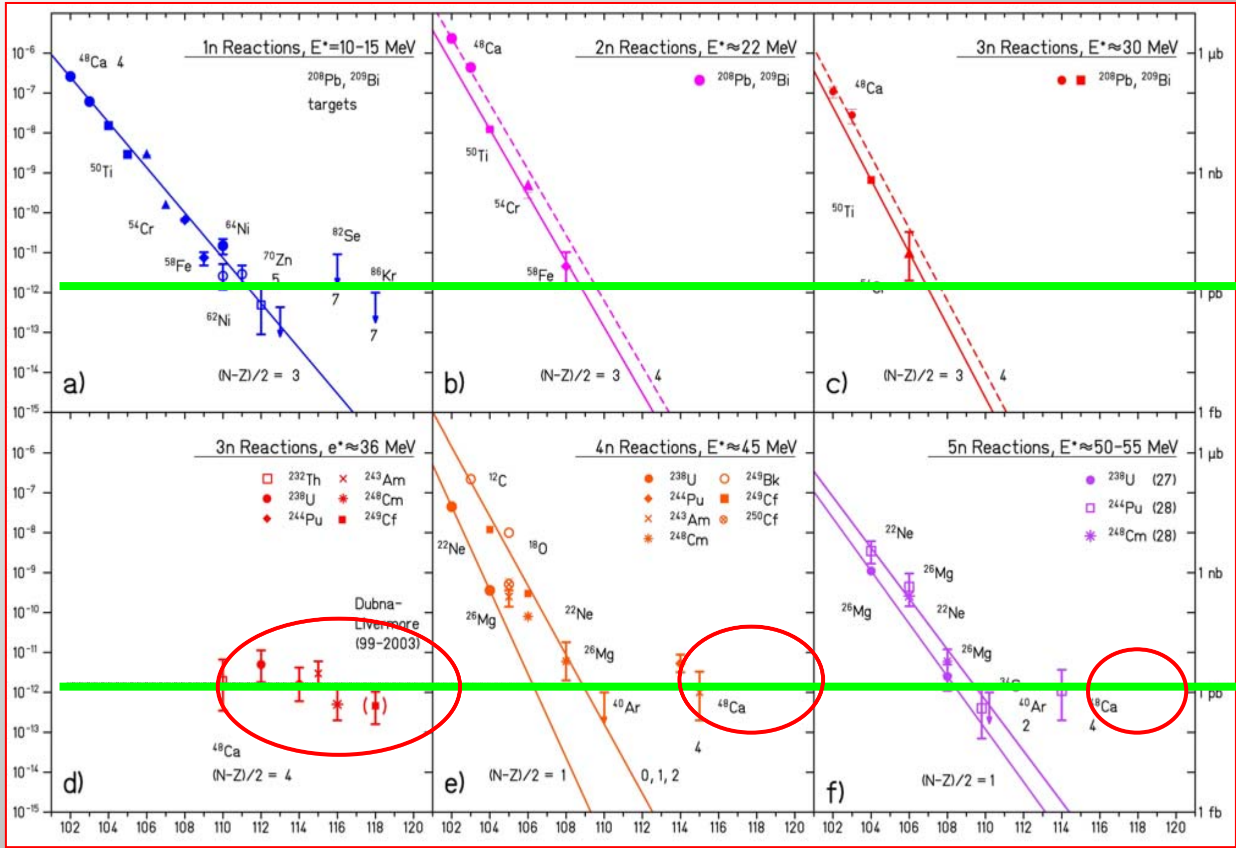
SHE - Cross Section Systematics

cold fusion (GSI)
→ based on
Pb and Bi targets

hot fusion (JINR)
→ based on
actinide targets

1 pb

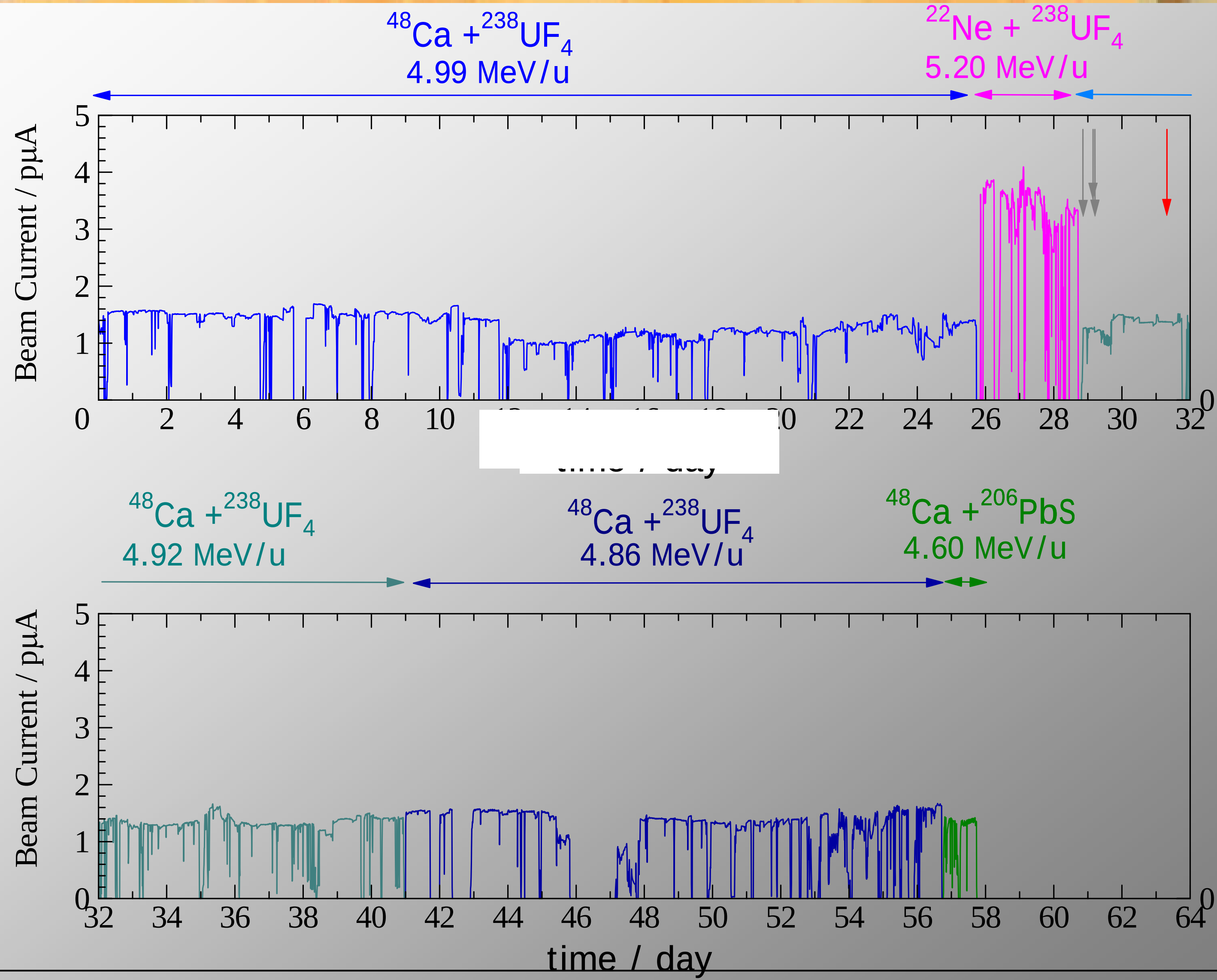
1 pb



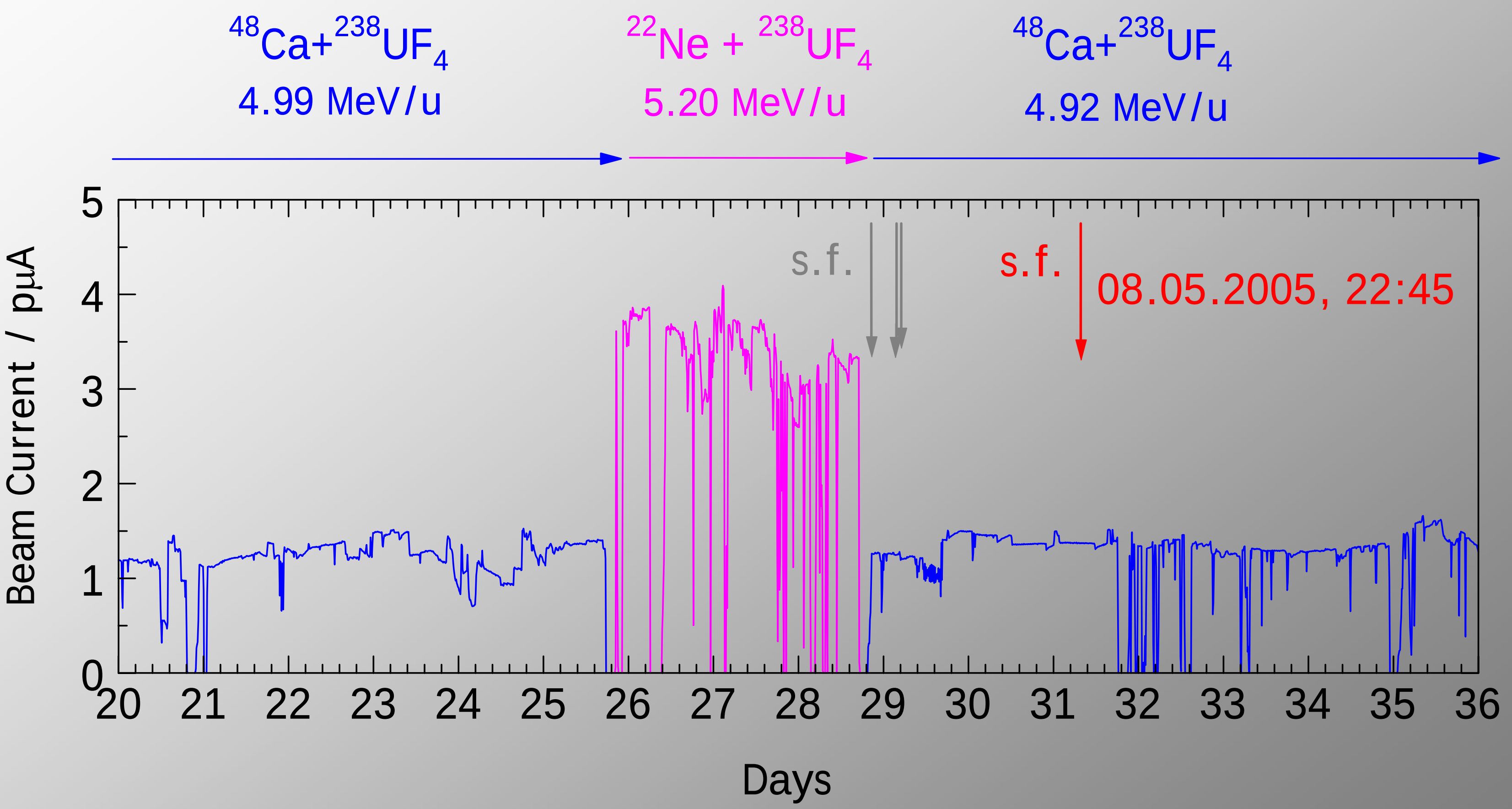
surprisingly high cross-sections (0.5 – 5 pb) for the synthesis of spherical SHE

Experiment at SHIP

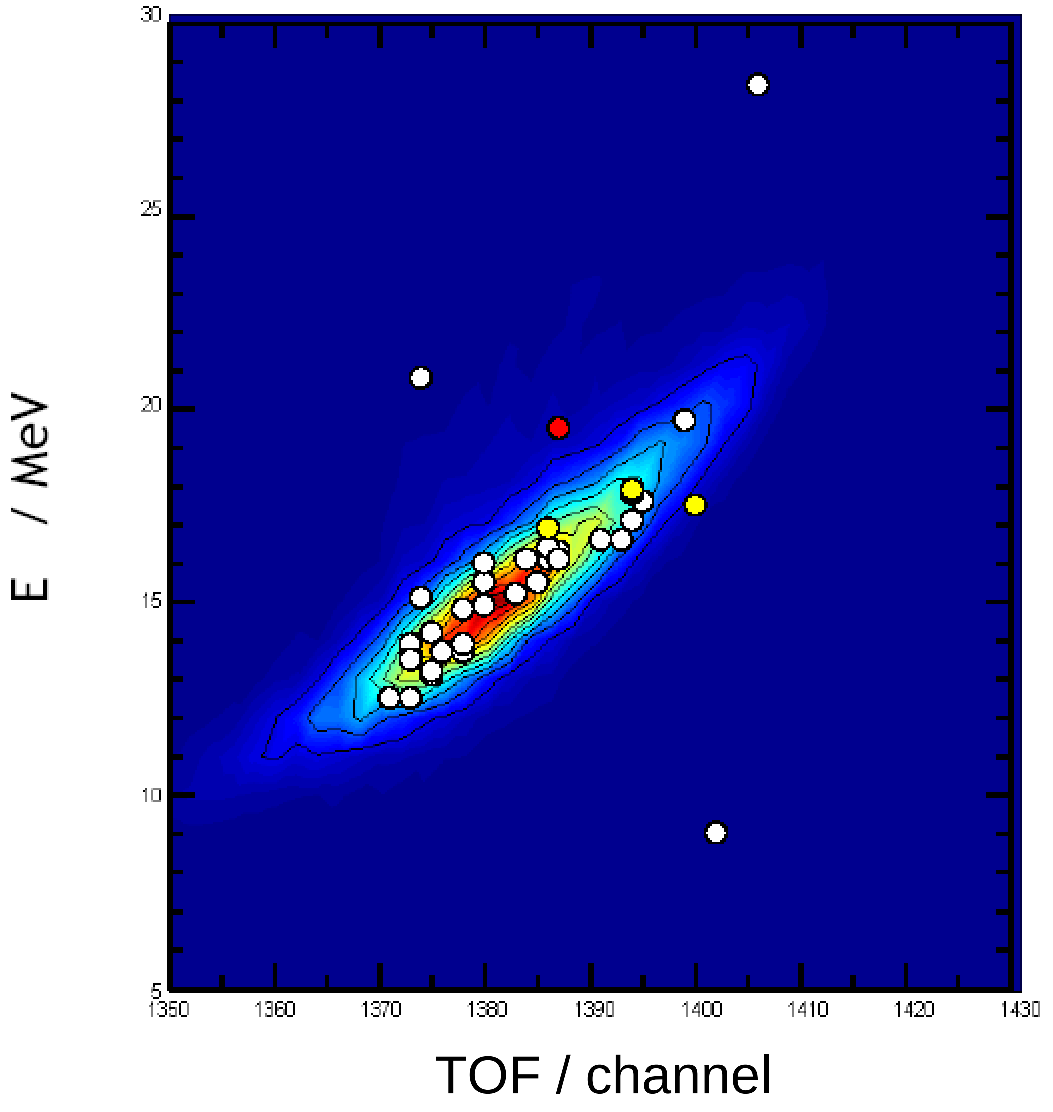
April 6 – June 9, 2005

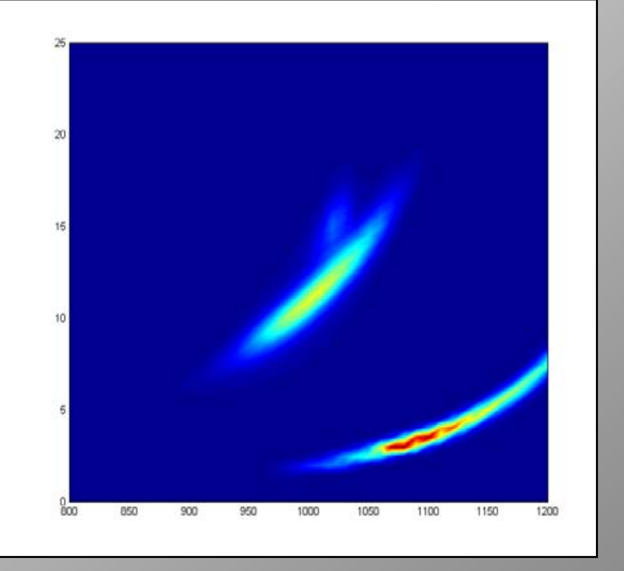


Observed spontaneous fission events



Energy versus time-of-flight plots





$^{48}Ca + ^{206}PbS$

$^{48}Ca + ^{238}UF_4$

$^{48}Ca + ^{238}U \rightarrow ^{286-x}112 + xn$ at DGFRS and SHIP

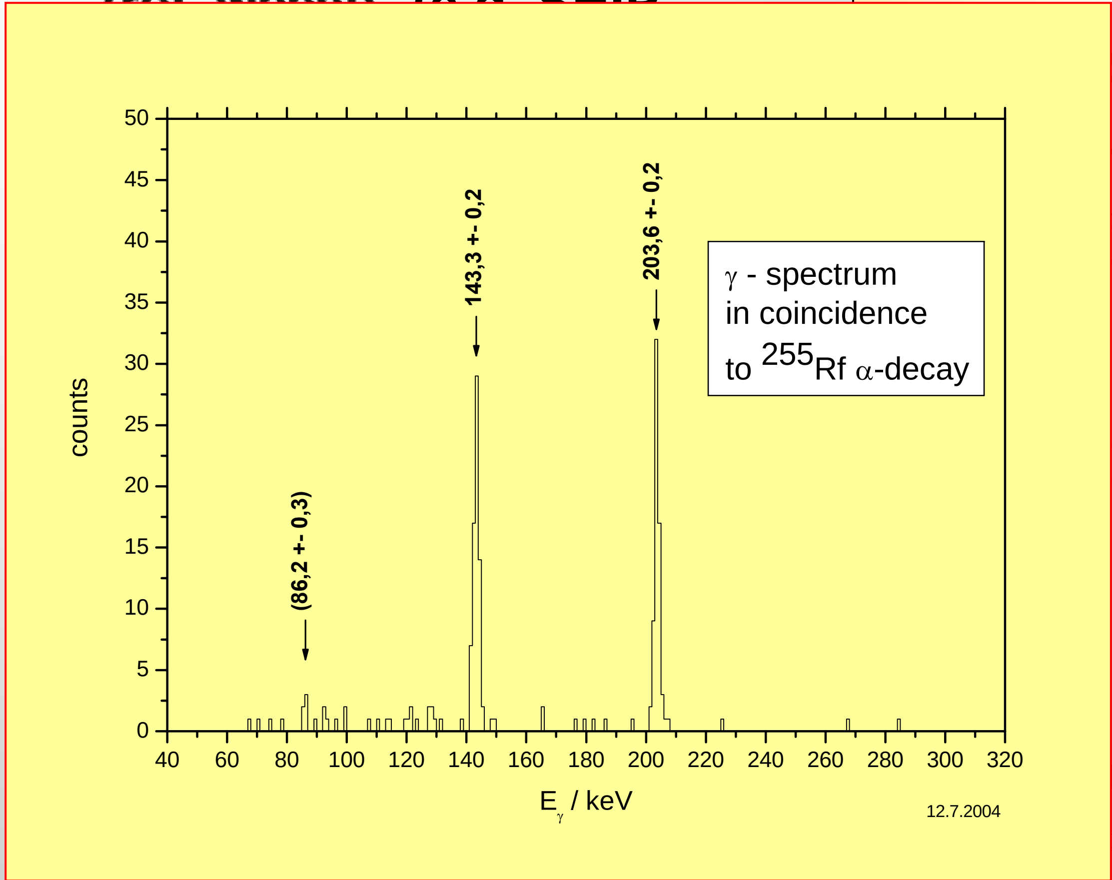
E*/MeV	dose/10^{19}	events	$T_{1/2}$ (parent)	x	σ/pb (1 ev. limits)
31.4	0.58	1 (ER−[α]−sf)*	(3.4 s)	3	0.5 +1.2 −0.4
32.0	0.7	0	--		< 0.8
35.0	0.71	2 (ER−[α]−sf) 3 (ER− α −sf) 1 (ER−4α−sf)	(1.4 s) 2.7 s 6.1 s	3	2.5 +1.8 −1.1
34.5	1.0	1 (ER − sf)	5.2 s	?	0.7 +1.6 −0.6
39.8	0.52	1 (ER − sf)	0.14 ms	4	0.6 +1.6 −0.5
37.0	1.2	0	--		< 0.6

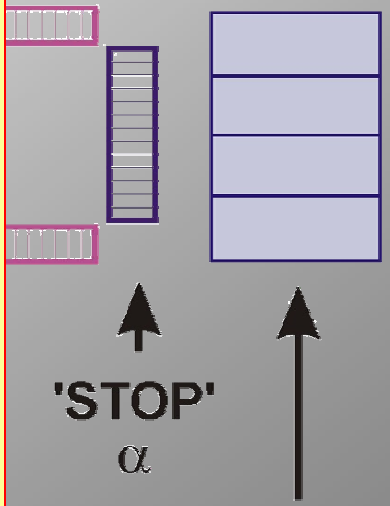
* Dubna work: $T_{1/2}(^{279}Ds) = 0.18$ s, $b_{sf} = 0.9$

ER-α-γ Spectroscopy after Separtion

Target Separator

- *highly efficient*
- *clean*
- *…ure information for SHE*
- *…ners → hint in ^{270}Ds*





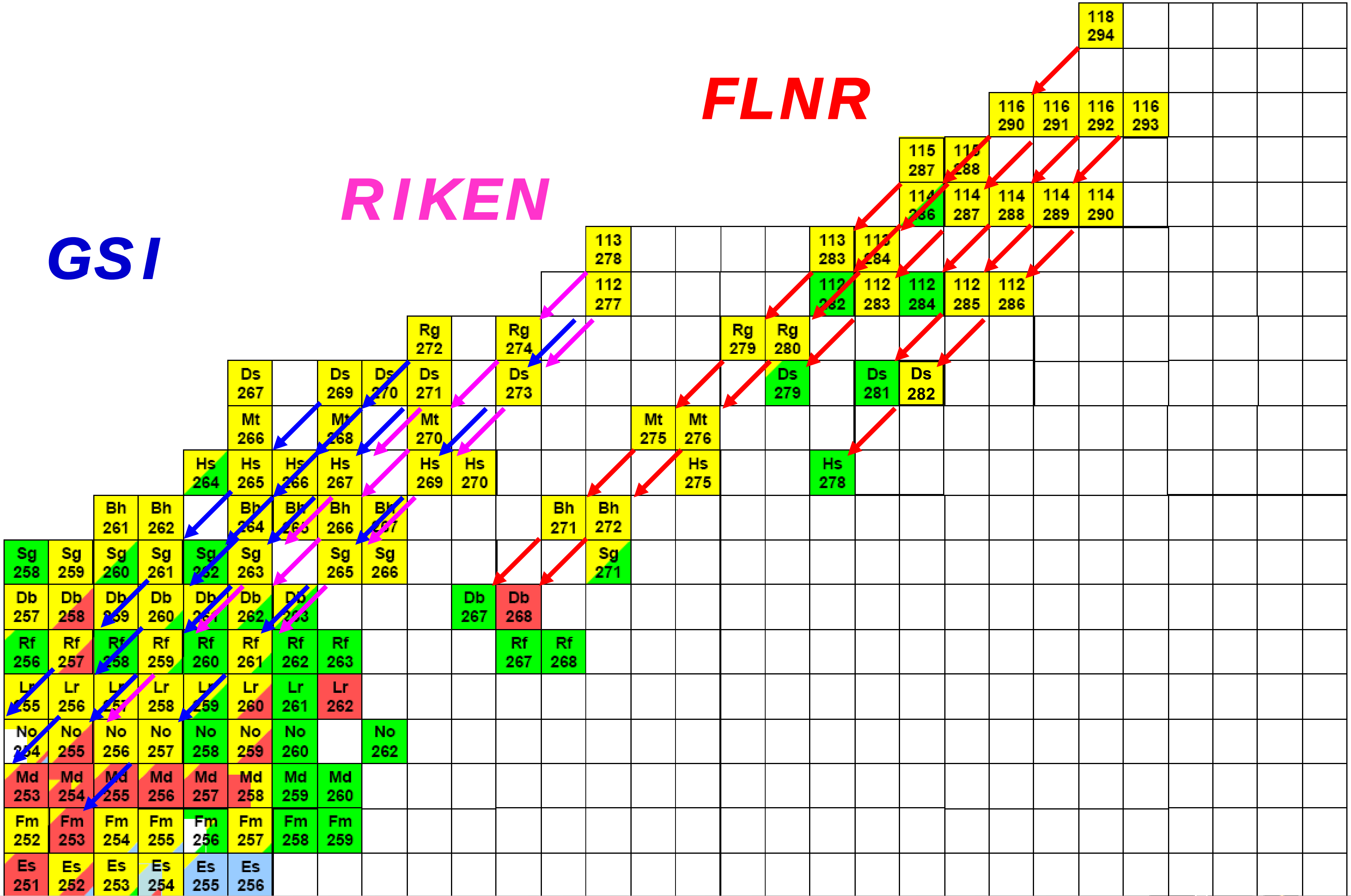
high eff.
ε ≈ 15%

'STOP'
α

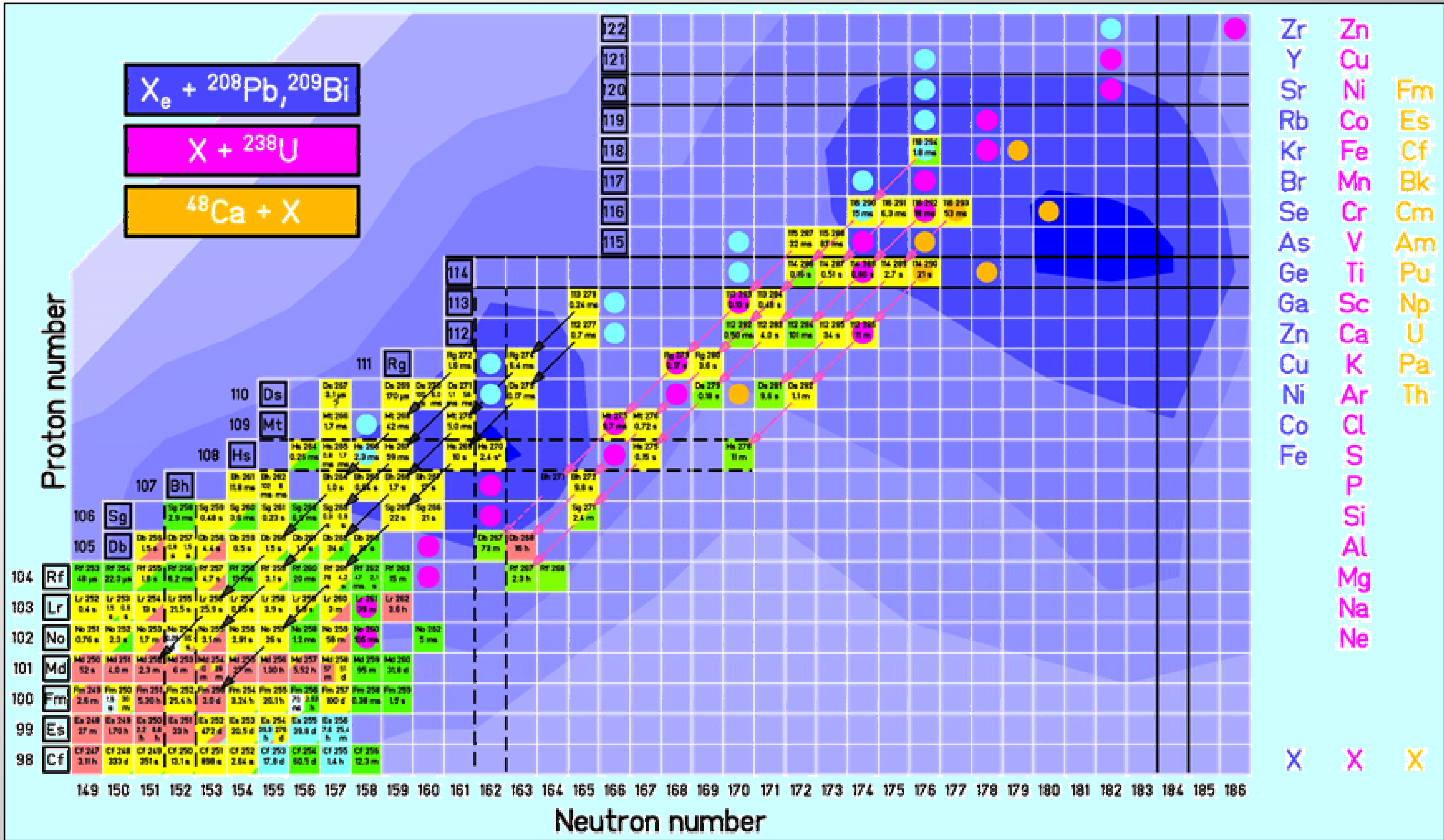
γ - ray
(segmented)

SHE Synthesis

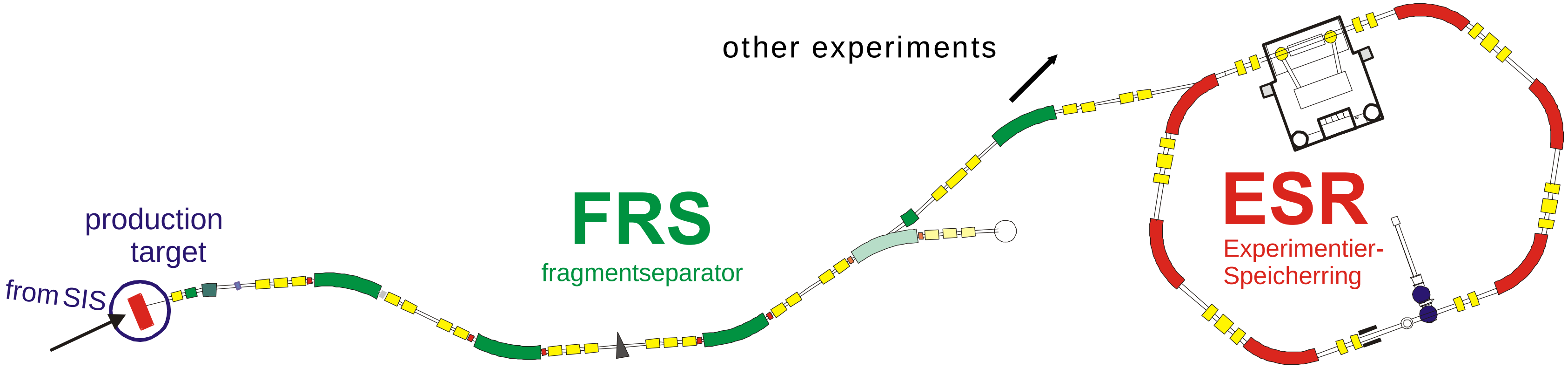
Dubna – RIKEN - GSI



Reactions to be studied, overview

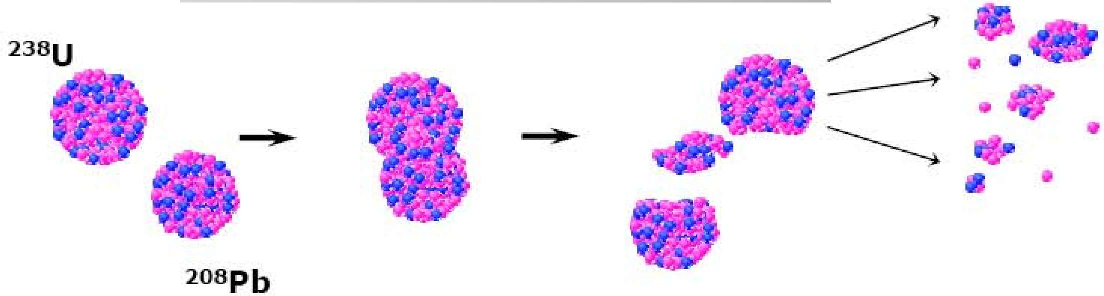


Radioactive Beams from the FRS

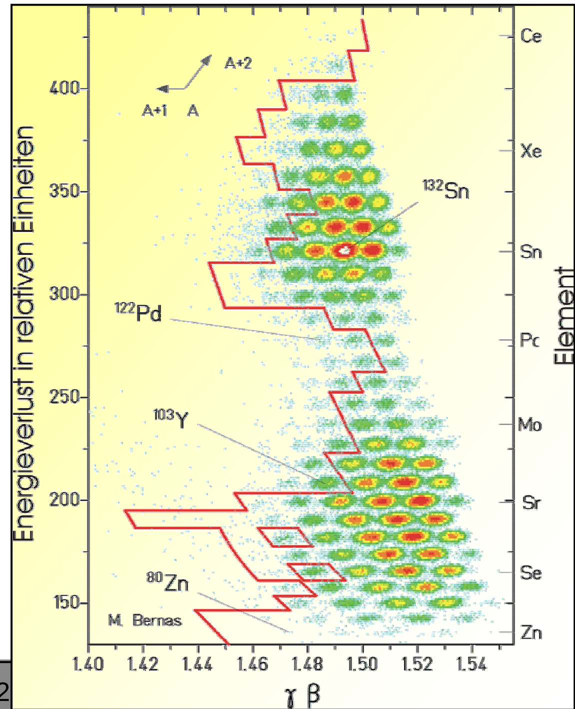


kinematic separation
+
energy loss → ***separation of a single isotope***

1. Projectile fragmentation

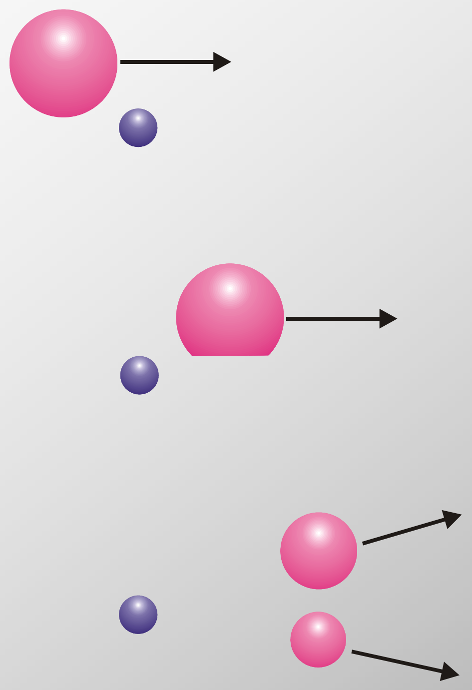


2. Projectile fission



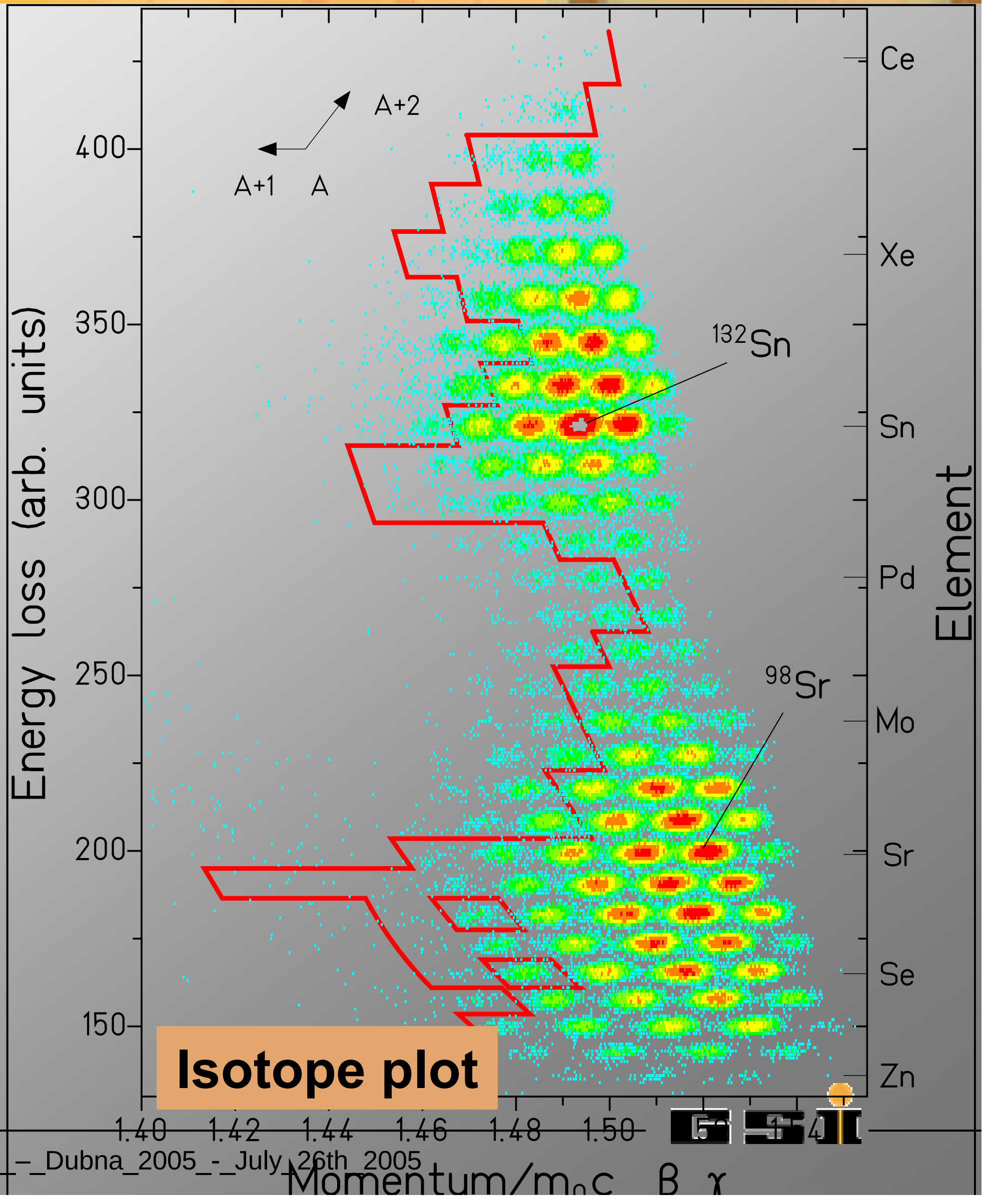
Radioactive Beams from Fission of relativistic ^{238}U

^{238}U at 1 A GeV on Be target

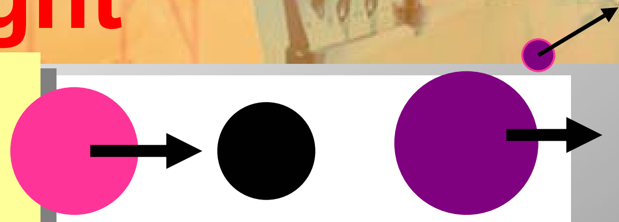


- **Access to n-rich nuclei**
- **high energy**

M. Bernas et al. Phys. Lett. B331(1994)331



Separation and Identification of Radioactive Beams in-Flight



Preservation of reaction kinematics

Fast **Separation time 100 ns**

Sensitive **Single-atoms**

- **Access to the limits of the Nuclear landscape**

Reaction kinematics is used for separation

Coulomb barrier energies:

- **super heavy elements**

  Identification by decay-spectroscopy

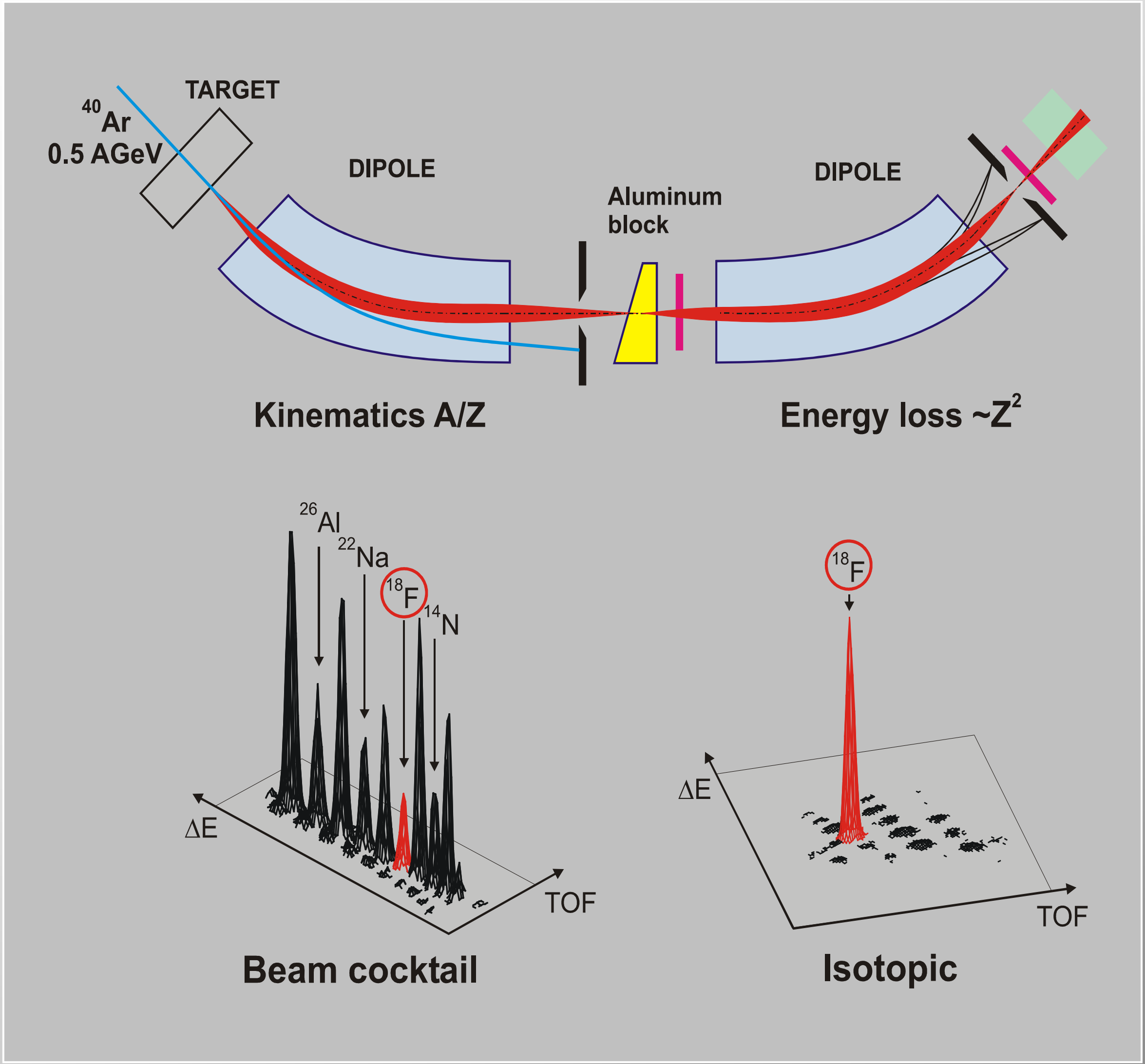
Relativistic energies

- **drip line nuclei**

  A, Z identification in-flight with:
  magnetic spectrometer, time-of-flight, and energy loss

GSI

In-flight Separation at relativistic Energies with the FRS



Transmutation of the projectile beam by

- **Fragmentation**
- **Fission in flight**

➢ **n-rich nuclides**

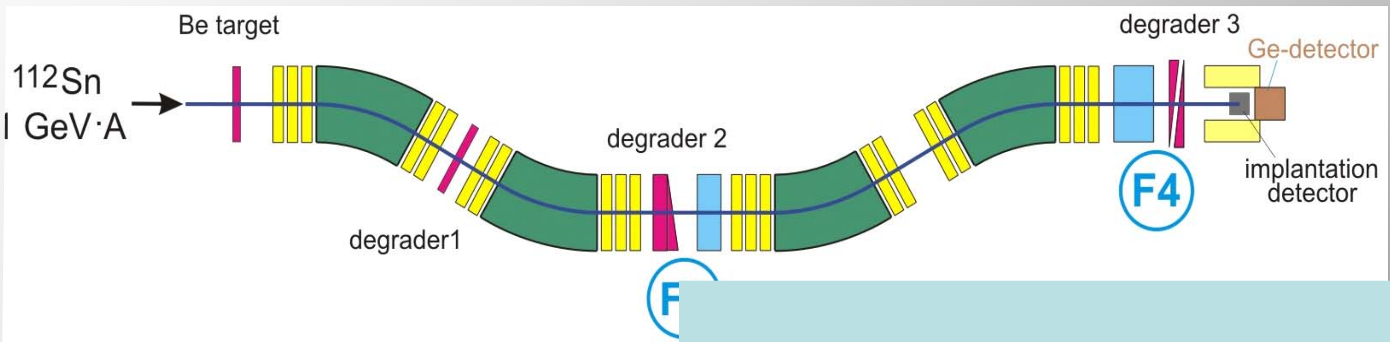
Preservation of projectile velocity and beam quality

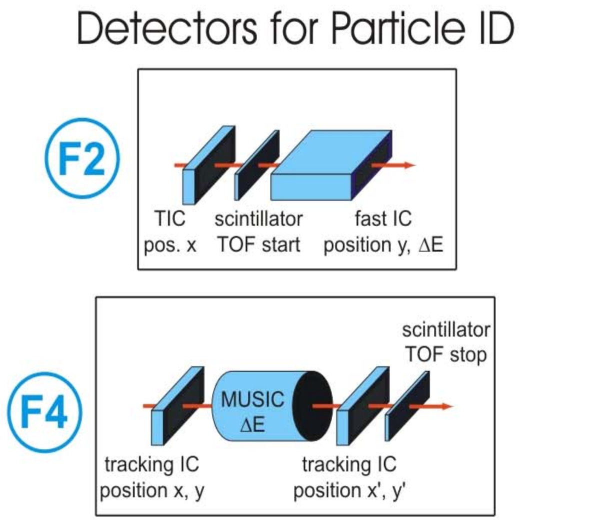
✓**Injection into separators and beam lines with high efficiency**

✓**Separation time << µs**

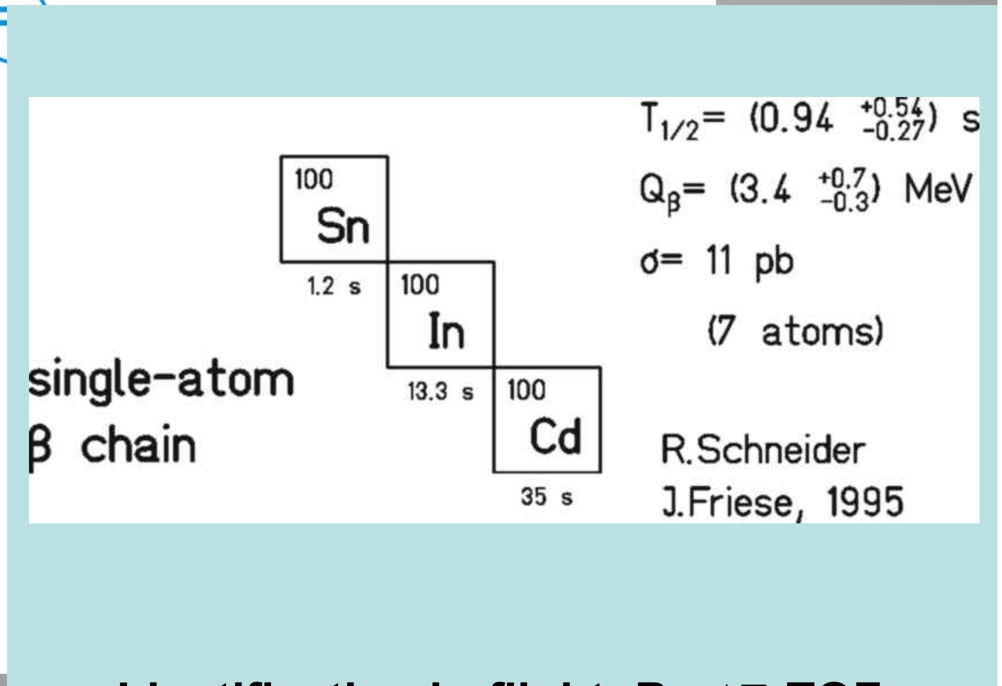
H. Geissel et al., Nucl. Instr. Meth. 161(1979) 65

Discovery of the Doubly Magic Nucleus ^{100}Sn



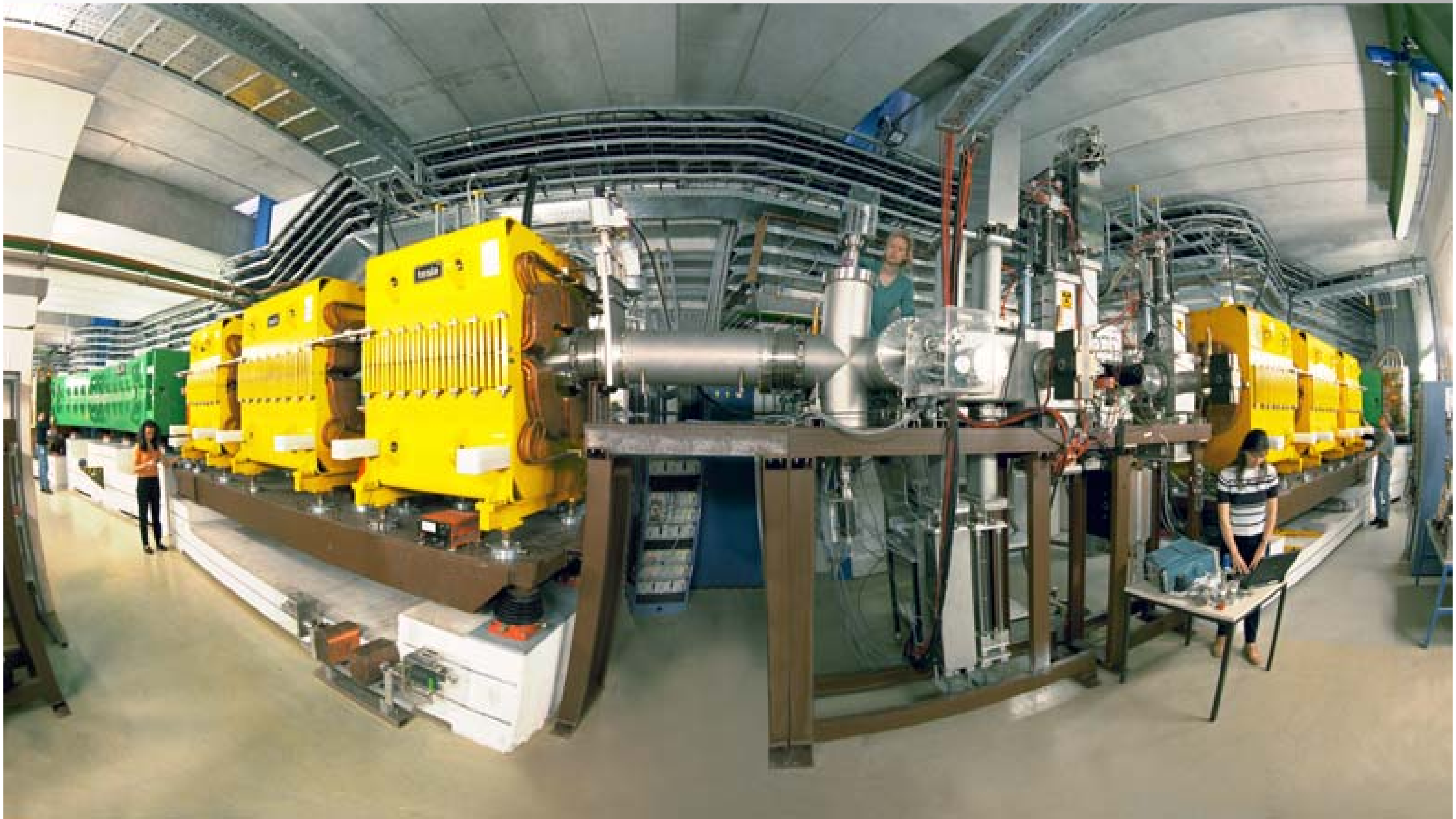


A. Stolz (TUM)



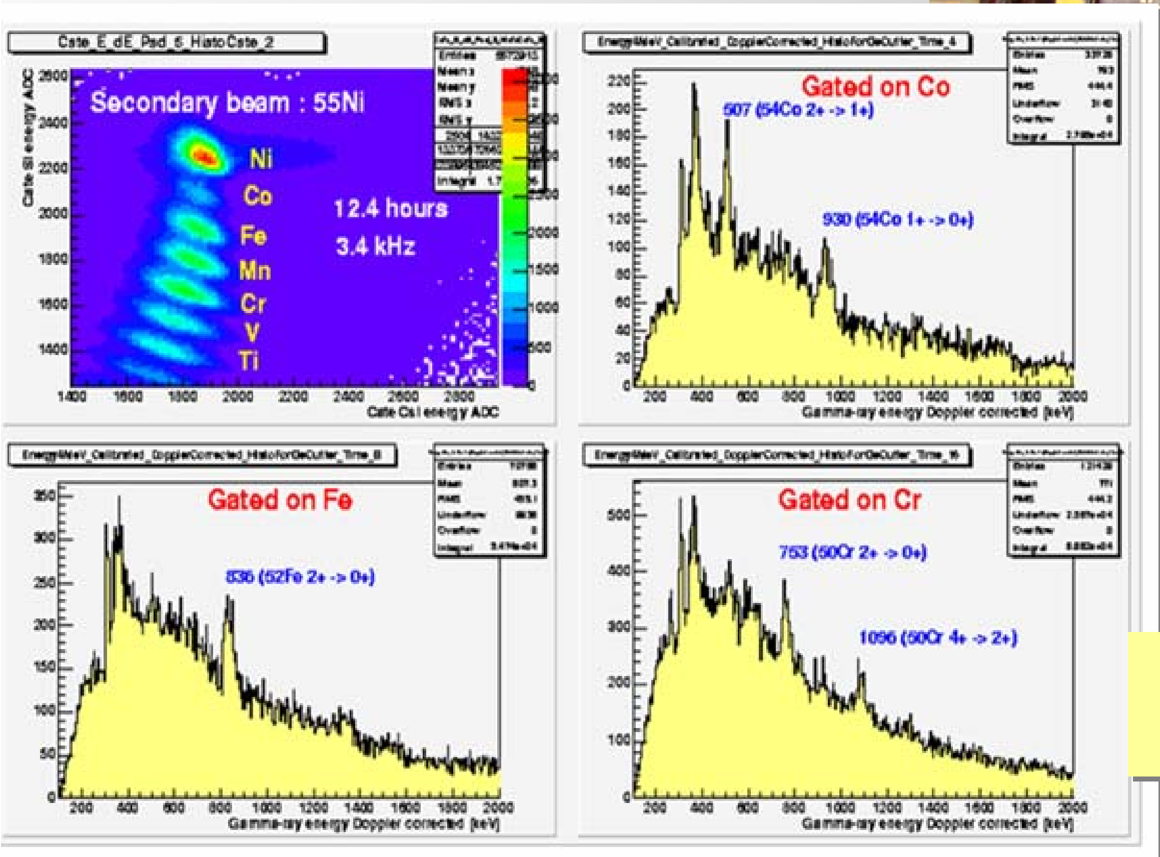
Identification in-flight: Bρ-ΔE-TOF

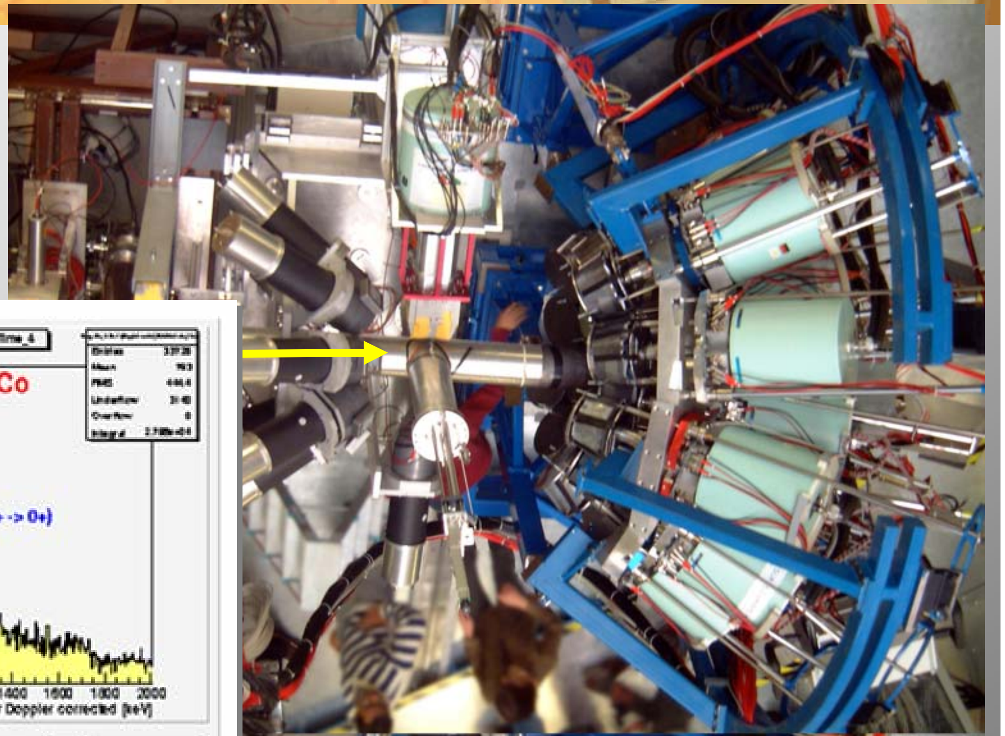
FRS Midplane Photo with Fish-Eye Lens



In-Beam γ-Spectroscopy with RISING J.Jolie

170 MeV/u ^{55}Ni
beam from FRS
on secondary target





RISING setup behind FRS
Collaboration of 38 institutes)

Major program 2005-2009

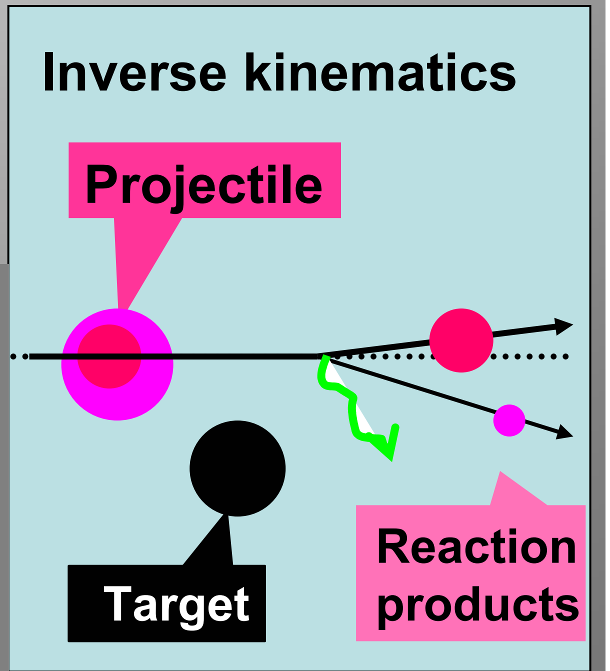
Inverse Kinematics

Reactions with in-flight separated energetic beams of radioactive nuclei

Nucleus of interest is the Projectile

complete kinematics ==> look into the nucleus

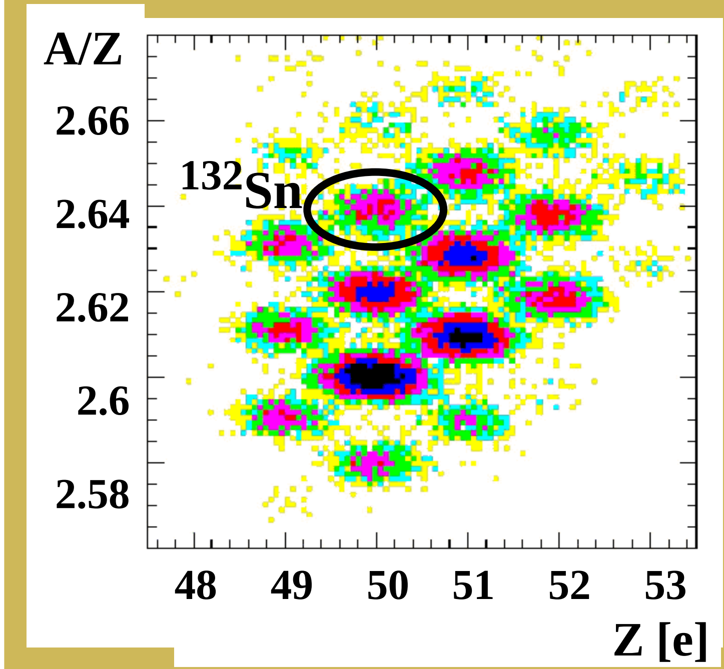
➢ ***reaction studies with 1 - 10000 projectiles s^{-1}***



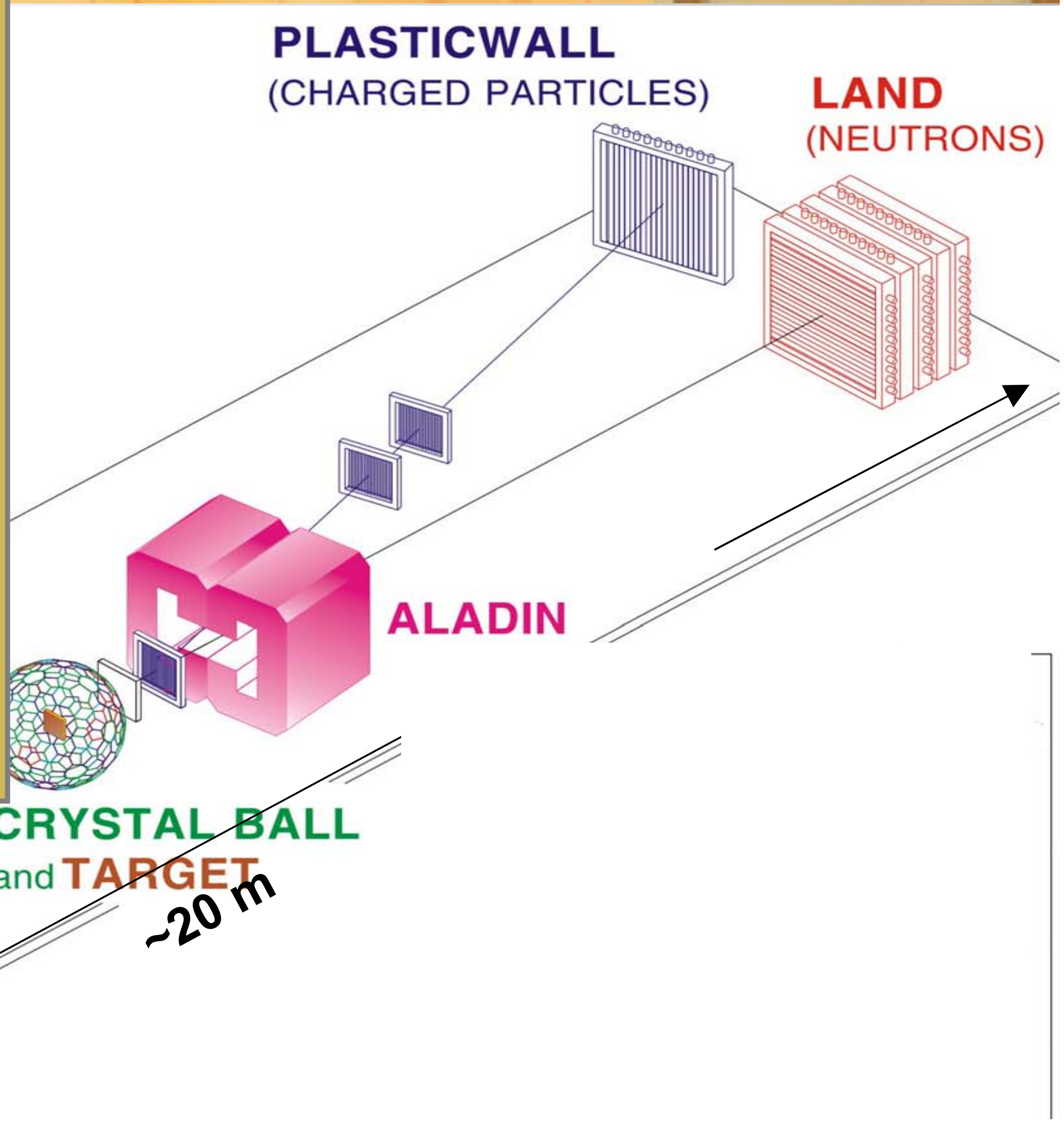
New insights into nuclear structure

- **matter distributions ➔ neutron halo**
- **Nuclear response ➔ giant resonances**

LAND-ALADIN Setup for Reaction Studies in reversed Kinematics



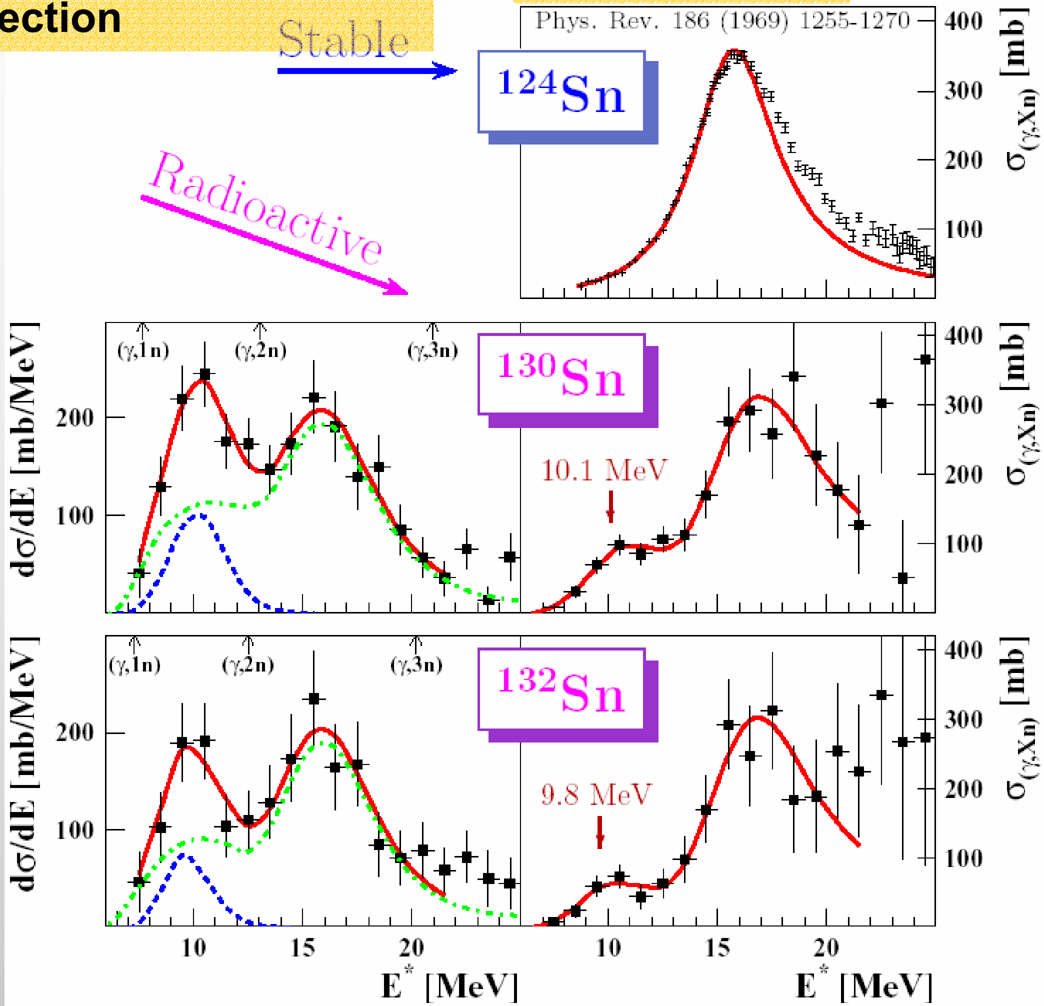
Beam cocktail from FRS: ^{238}U fission fragments



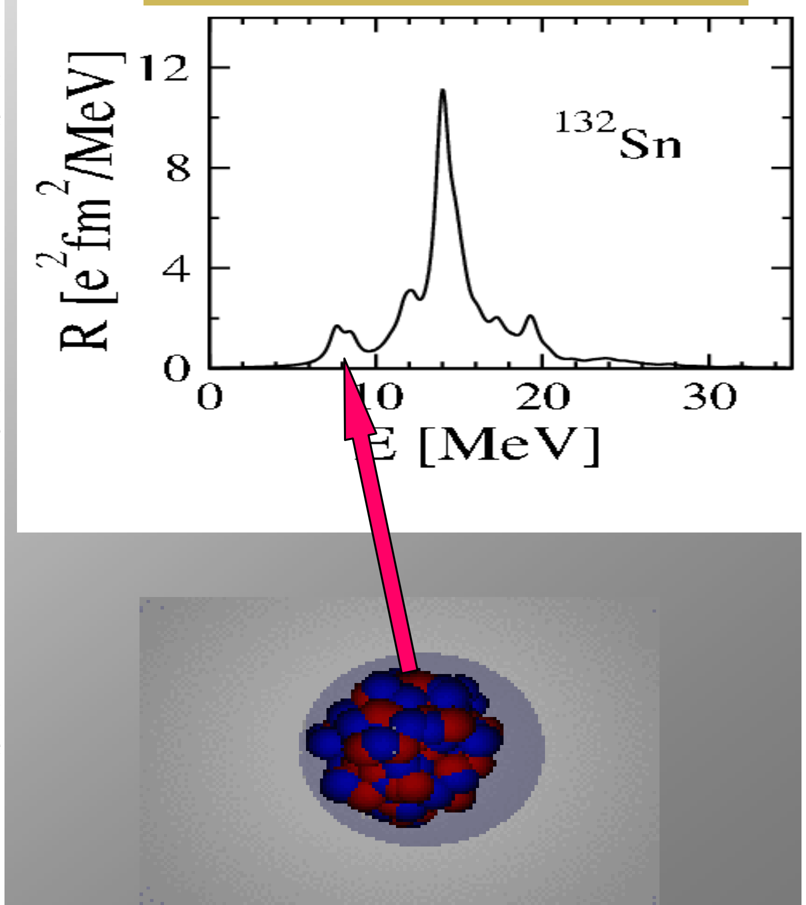
Dipole Strength in Neutron-rich Sn isotopes

Electromagnetic-excitation cross section

Photo-neutron cross section



Prediction: Relativistic Mean Field (N. Paar et al.)



P. Adrich et al. 2005

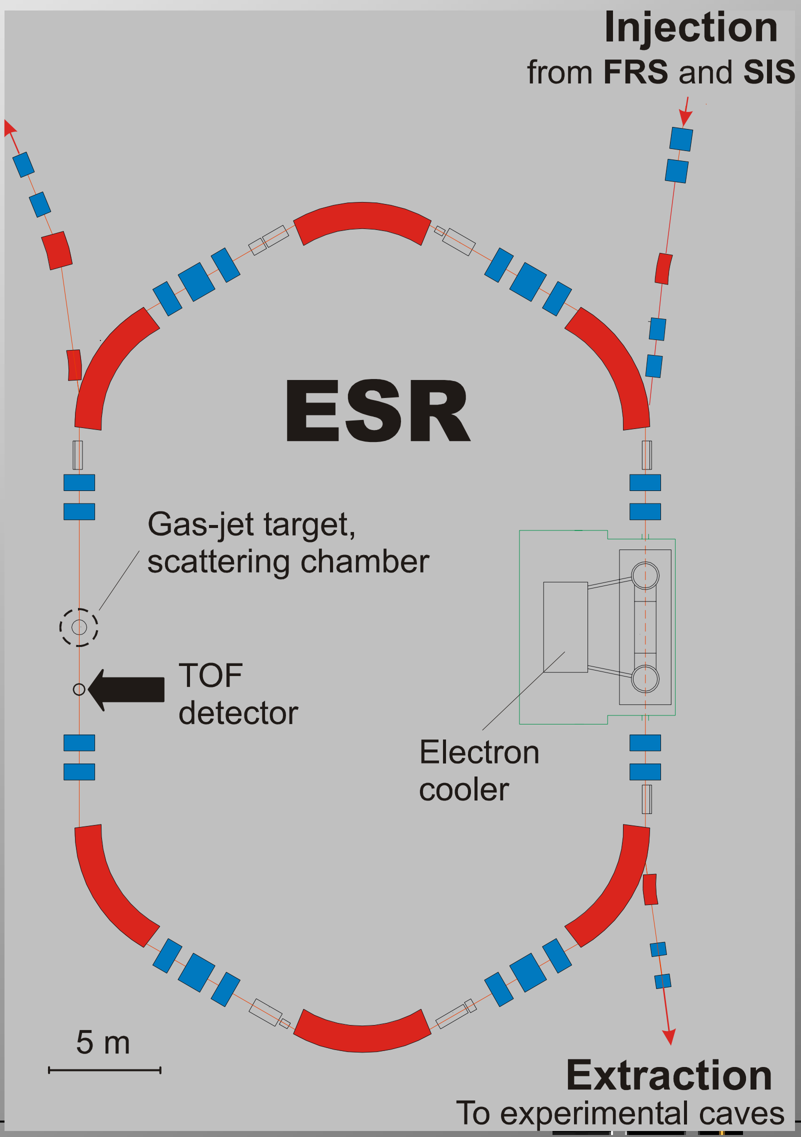
Storage and Cooling: The Experimental Storage Ring ESR

Storage of

- exotic atoms (bare, H, He-like)
- radioactive nuclei
- ➢ conditions like in space

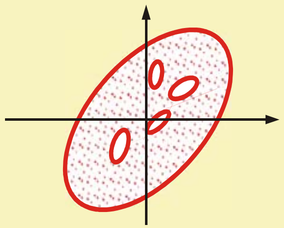
Electron cooling

- small velocity spread (10^{-6})
- ➢ precision experiments

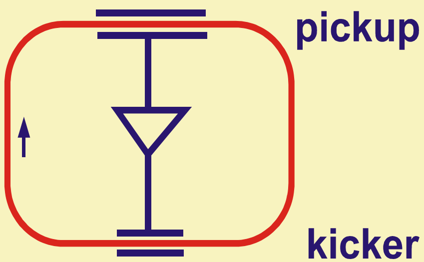


Beam cooling in a Storage Ring

Stochastic cooling: drive "bubbles" out of phasespace

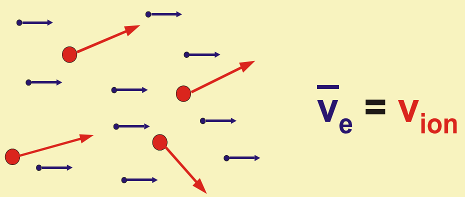


Density fluctuations in phasespace

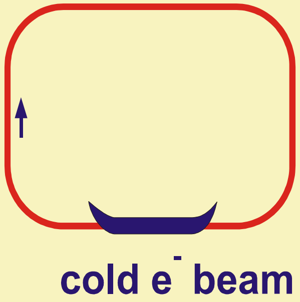


Van der Meer 72

Electron cooling: mix hot ion beam with cold electron beam (heat exchange)

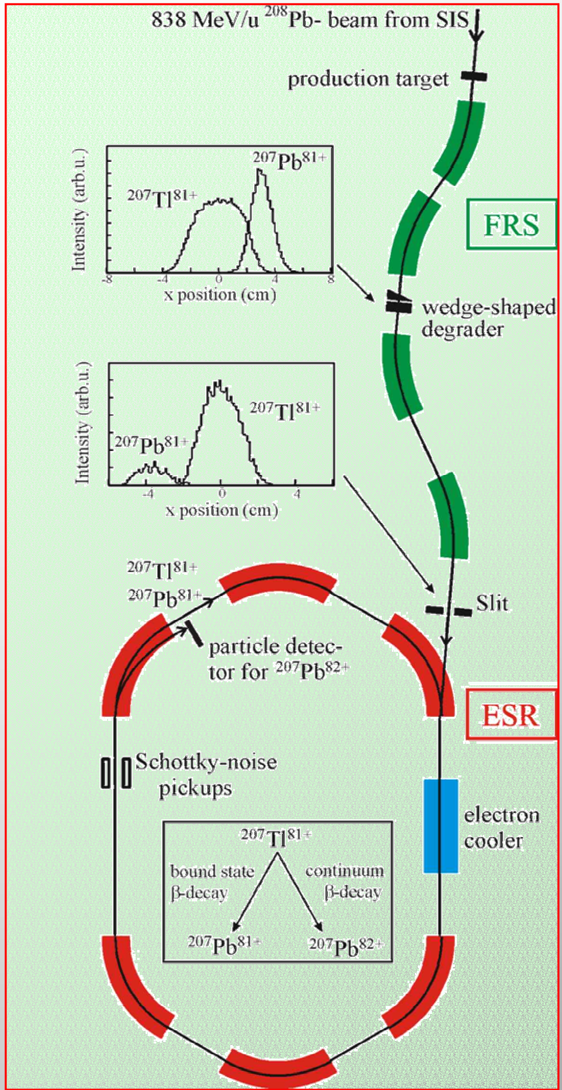


Heat exchange
cold electrons - hot ions



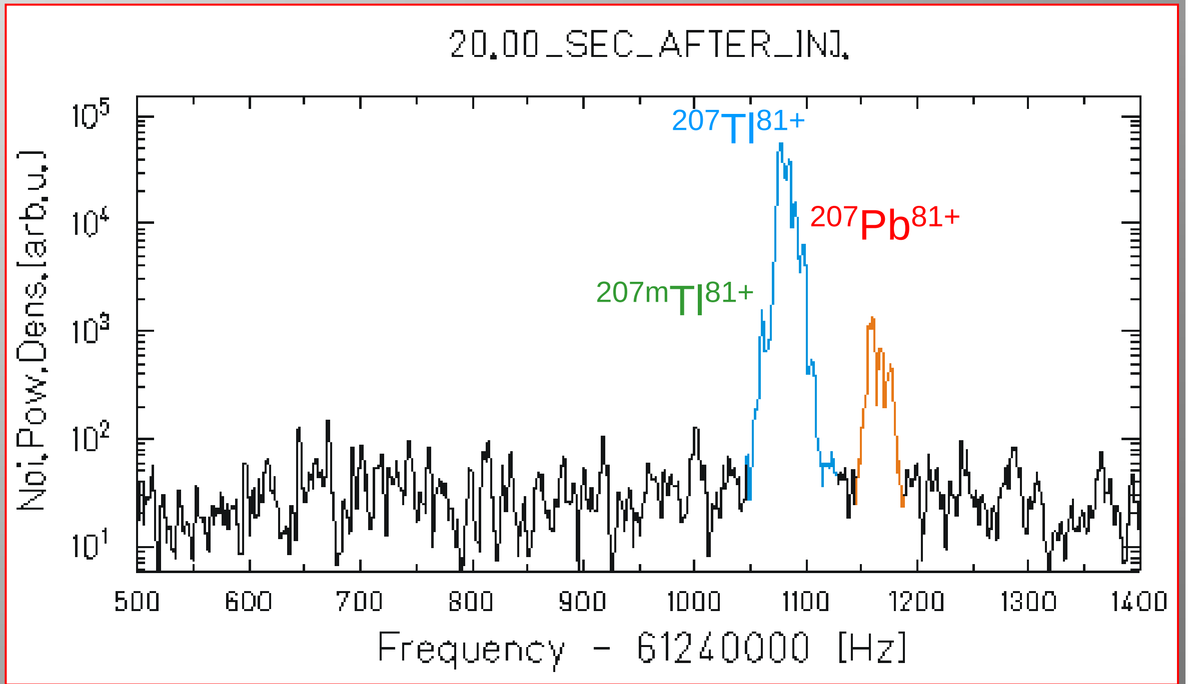
Budker 66

Stellar Processes observed in ESR
Bound-State Beta Decay of $^{207}Tl^{81+}$



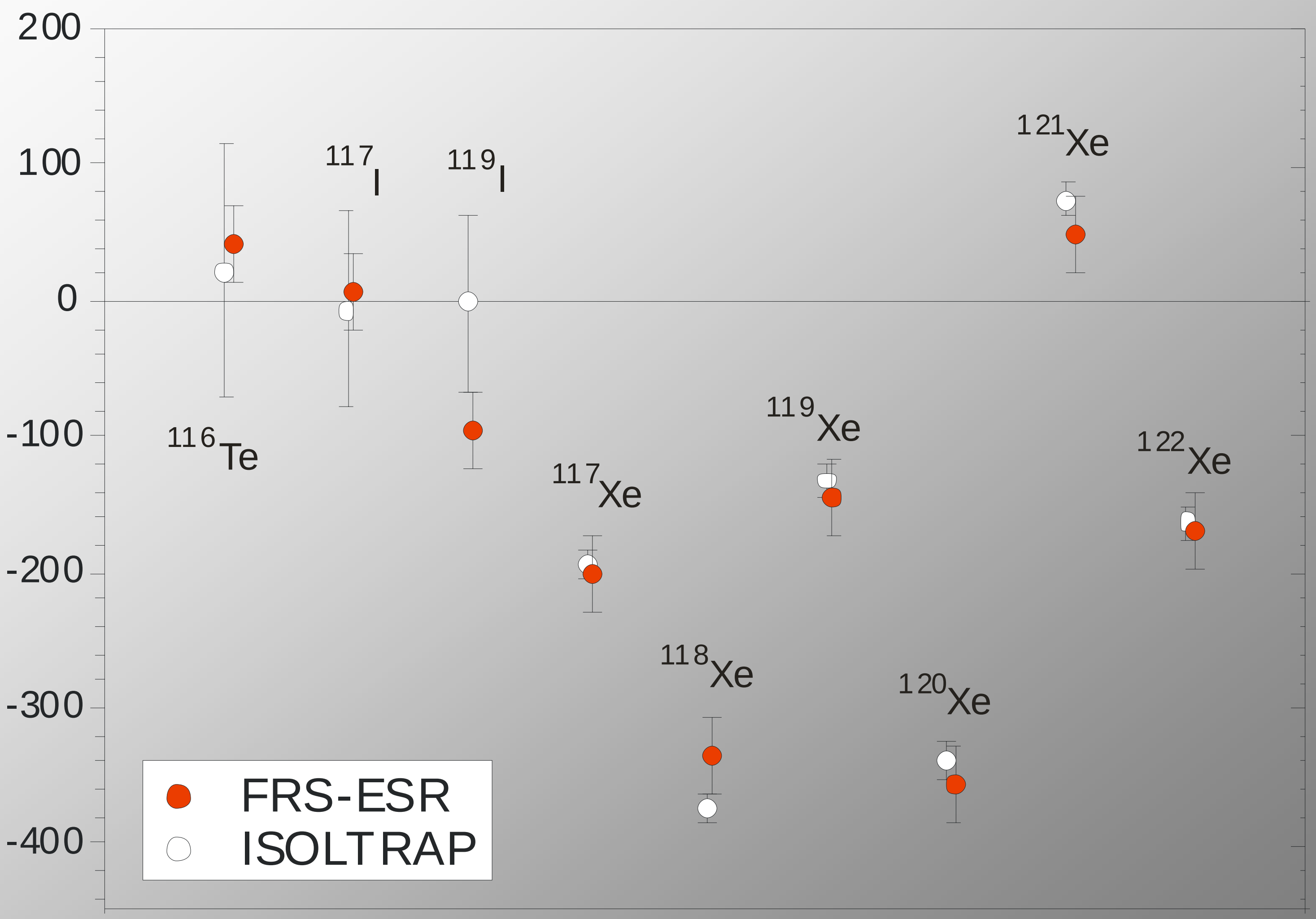
Pecularities:

- New decay mode
- Mono-isotopic separation of bare $^{207}Tl^{81+}$
- Stochastic cooling and electron cooling

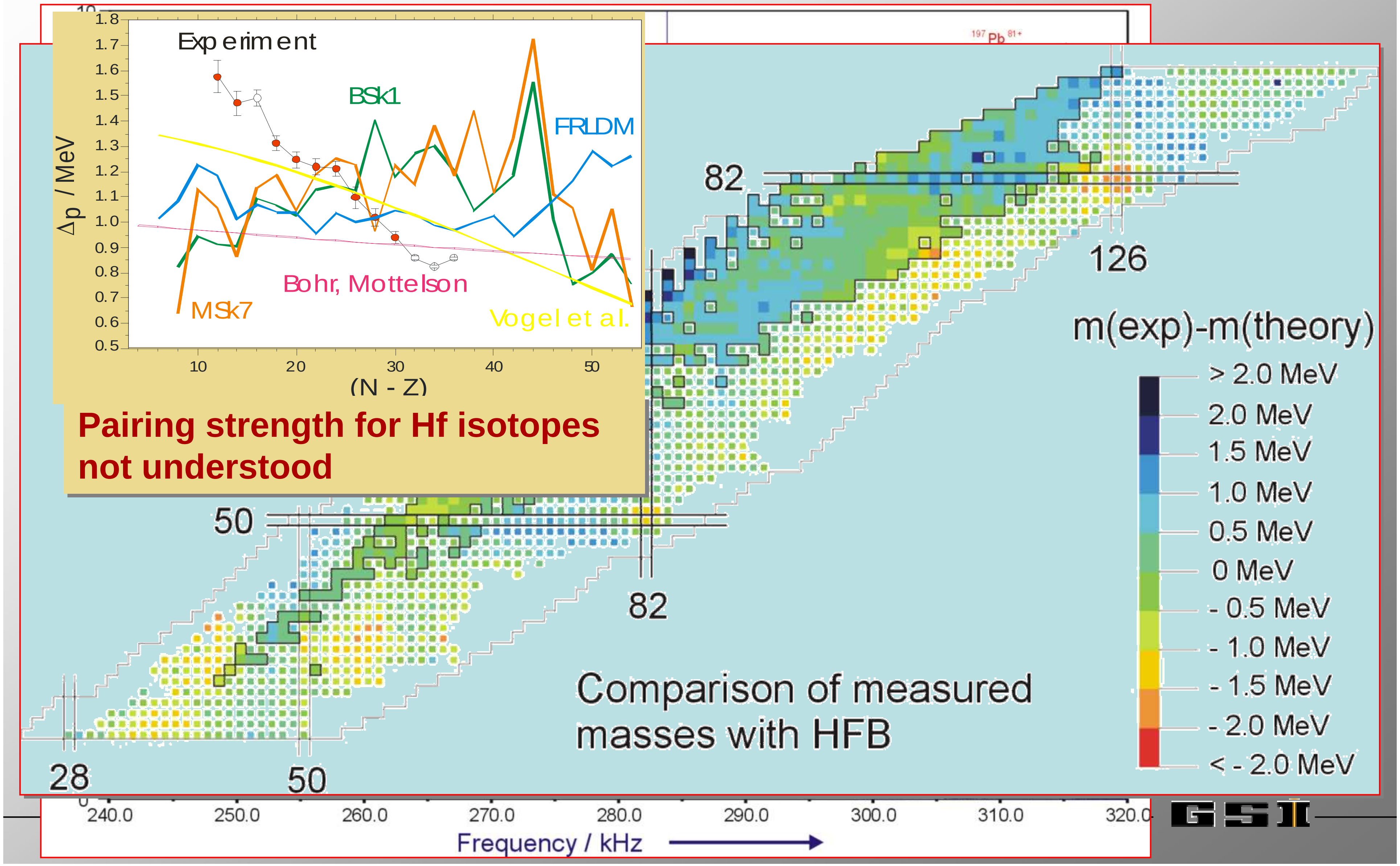


Masses: Comparison of ESR and ISOLTRAP

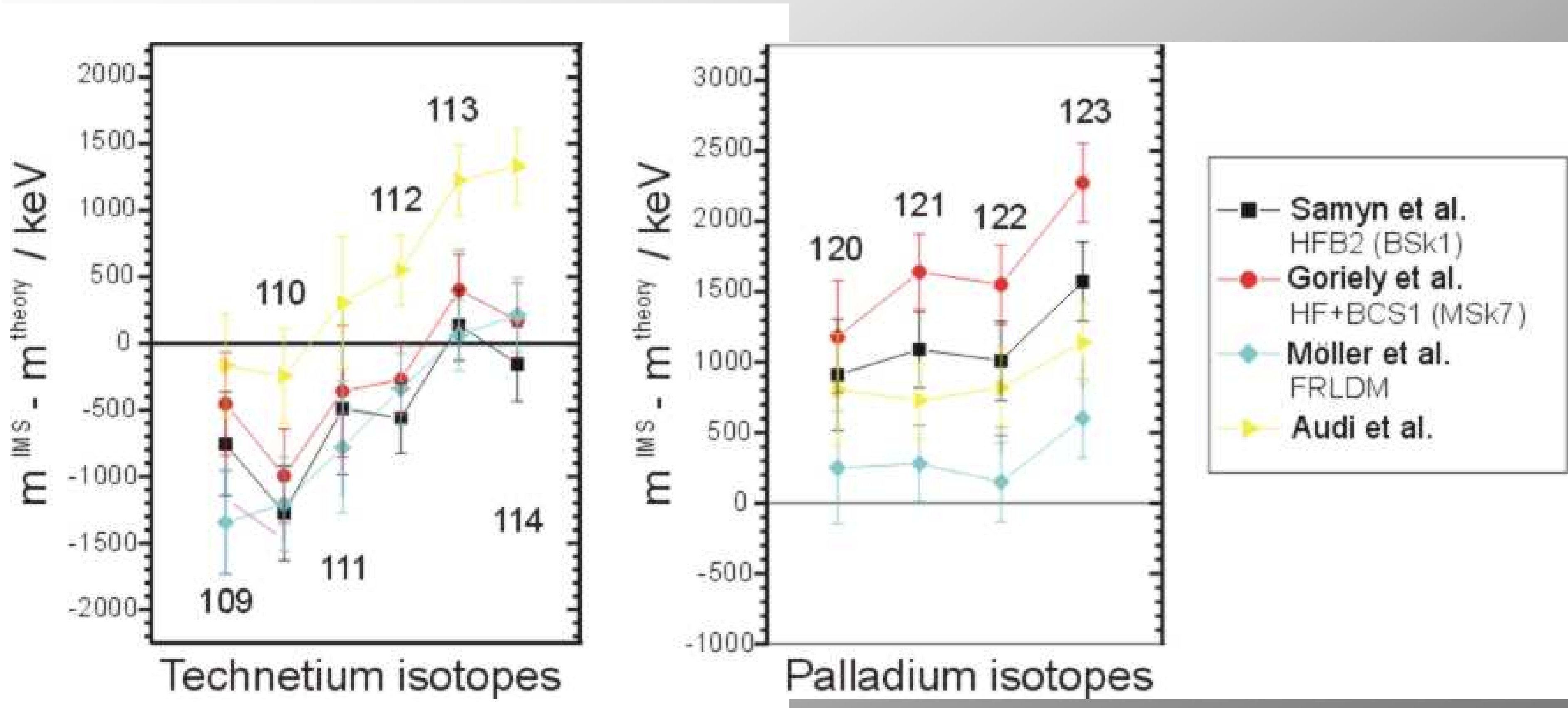
J. Aysto



Direct Mass Measurements in the Storage Ring

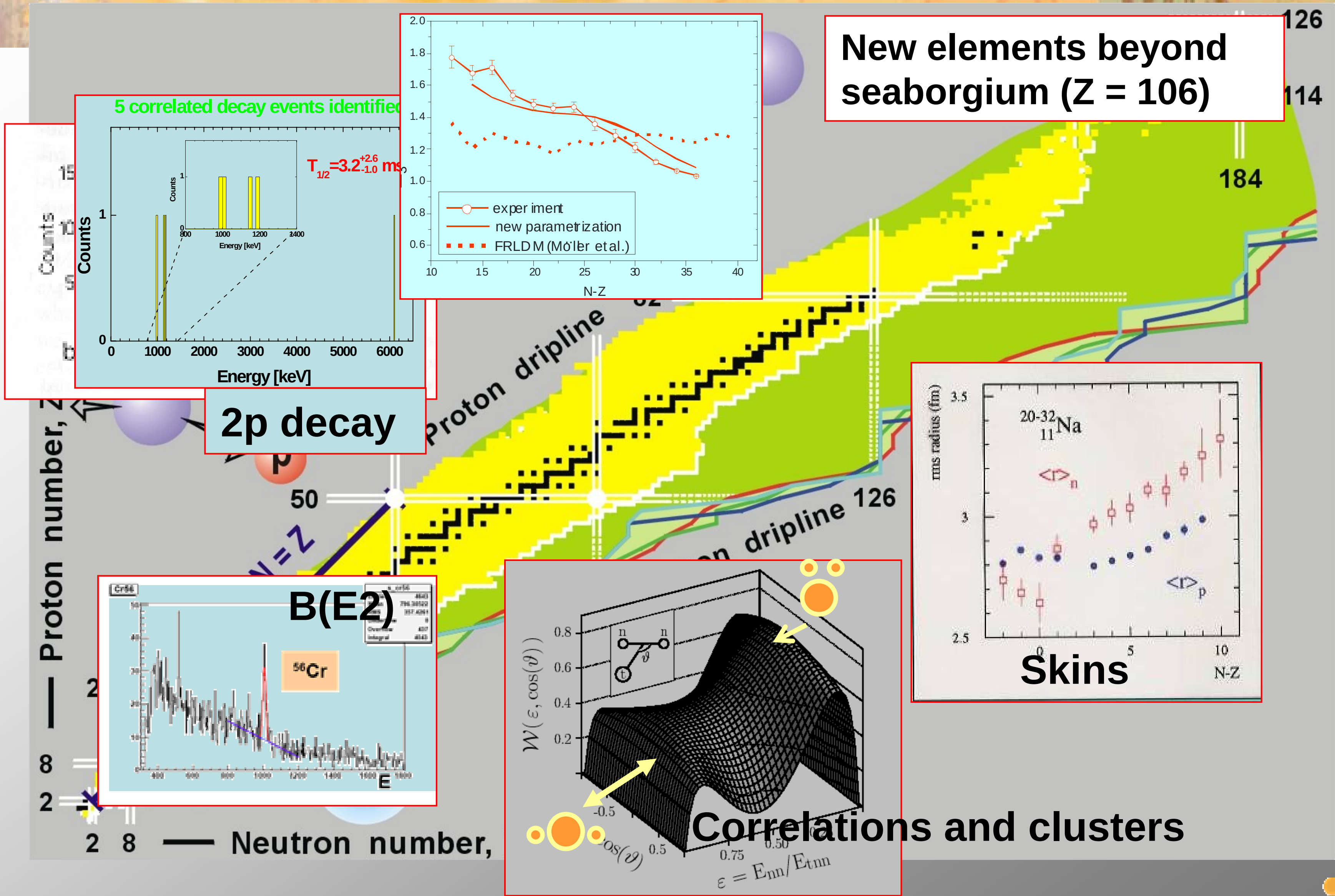


Preliminary Results of Isochronouos Mass Spectroscopy of Fission Fragments



S.A. Litvinov, M. Matos

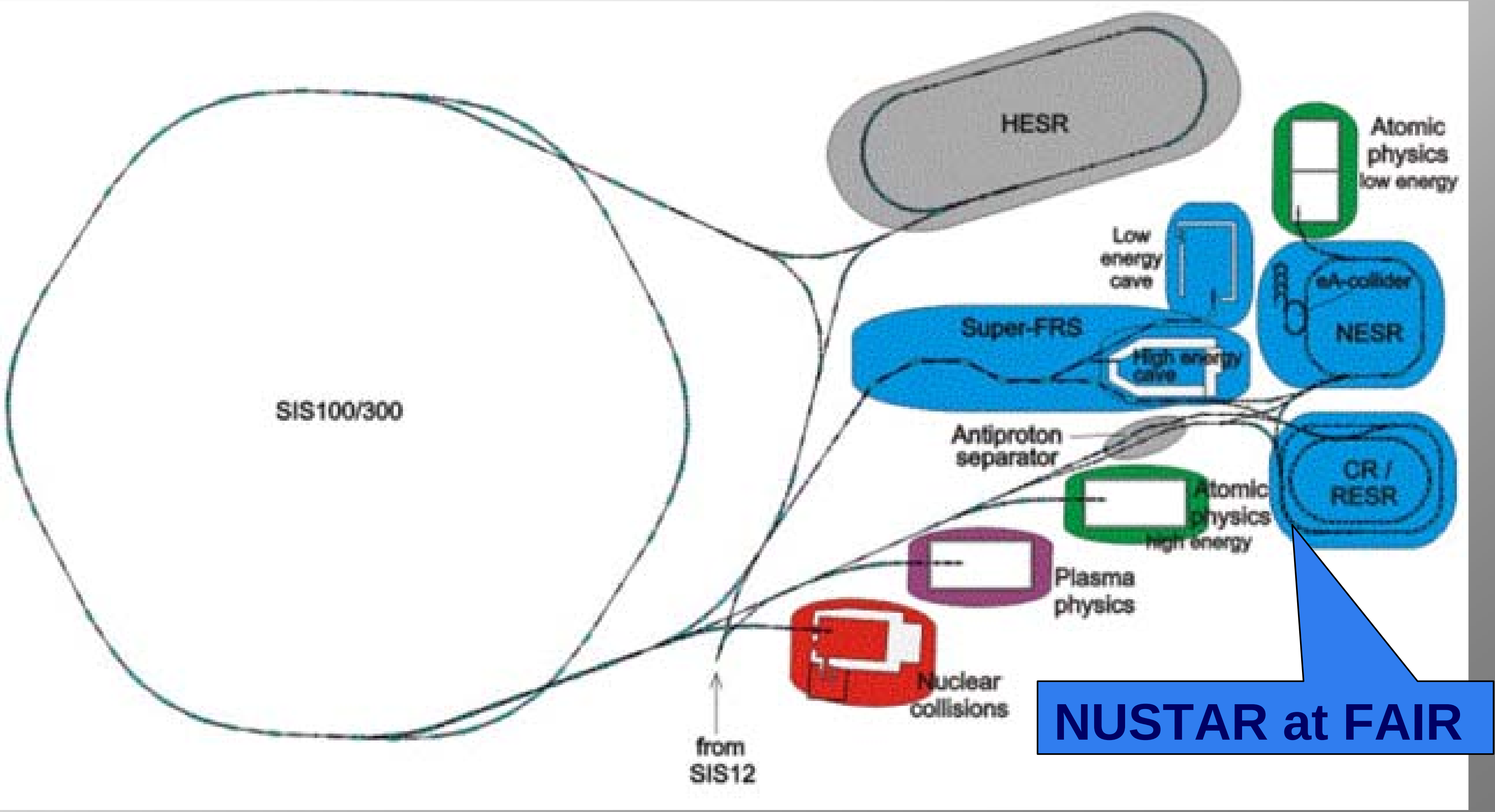
Highlights and Discoveries



Part 3

NUSTAR @ FAIR

NUSTAR at the FAIR
Facility for Antiproton and Ion Research



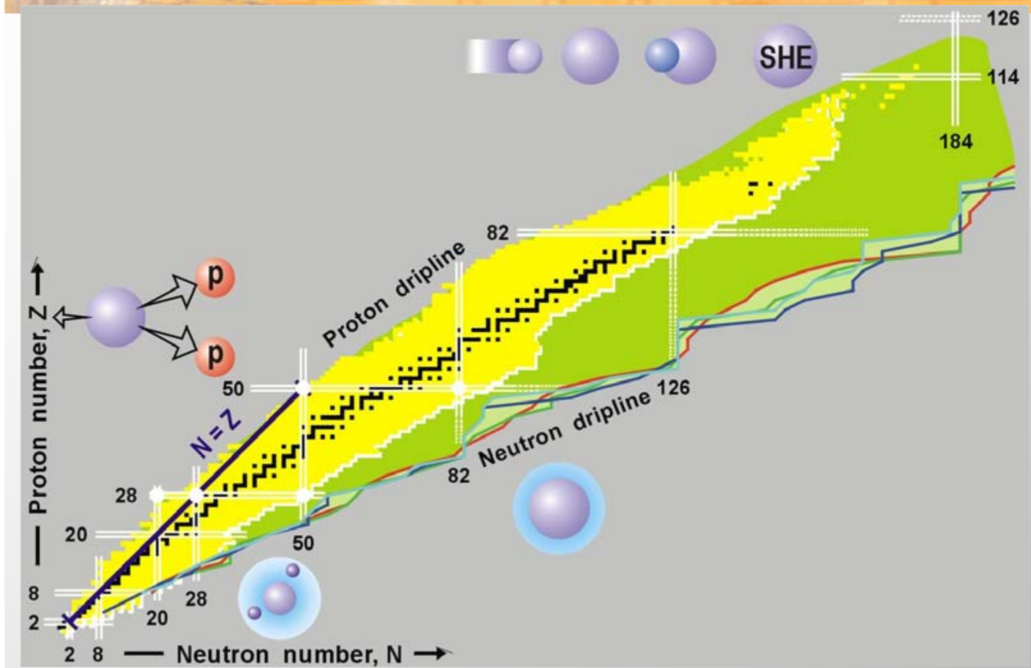
New basic Instrumental Developments

Beam production
by fission of relativistic projectiles

- Separation in-flight
- Reactions with radioactive beams in reversed kinematics
- Storage and cooling of radioactive nuclei

These techniques use single atoms,
ideally suited for nuclei at the limits of
stability (low production rates)

NUSTAR: NUclear STructure Astrophysics and Reactions



- Proton-neutron asymmetric matter
- Loosely bound nucleons
- Correlations
- Large proton numbers

↓

New phenomena:

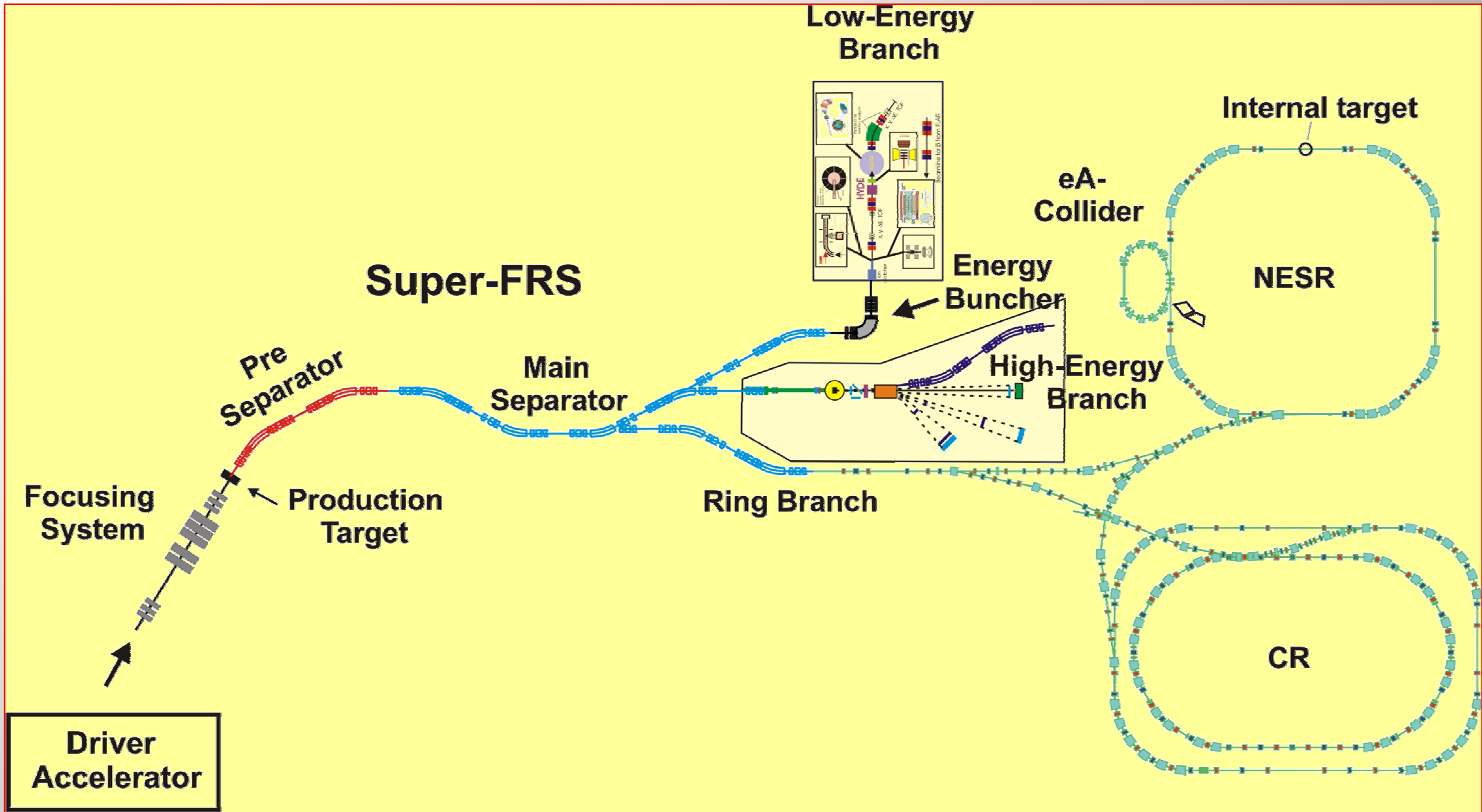
- New decay modes
- New shells
- Neutron skins and halos
- Super heavy elements

- Decay studies
- Reactions in reversed kinematics
- Precision experiments in a storage-ring

➢Medium dependence of Nucleon-nucleon interaction

GSI Proposal 2002

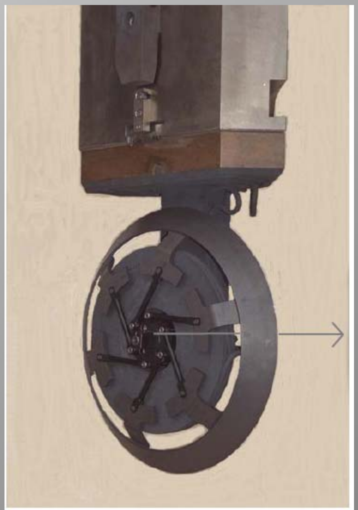
The NUSTAR Rare-Isotope Facility with SuperFRS



High-Power Production Target
(Concept for a Rotating Target Wheel)

Facility	Beam	Total Beam Power P [kW]	Graphite Target Thickness [g cm^{-2}]	Deposited Power ΔP [kW]	Specific Power $\Delta P/M$ [kW/g]
Super-FRS	all ions	< 38	4 - 8	< 12	< 0.15
PSI	P	1000	10.8	54	0.18
RIKEN/BigRIPS	all ions	< 100	1	< 20	0.81
SPIRAL-II	D	200	~ 0.8	200	~ 0.25

Target E at PSI



Key parameters:

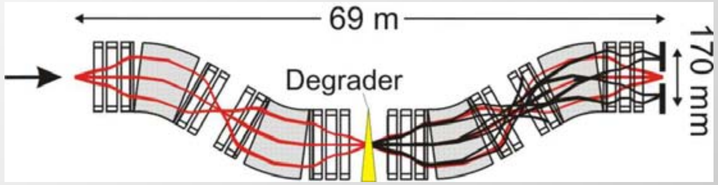
- radiation cooled
- continuous reliable operation (≈ 1 year)
- safe handling concepts needed (plug system, vertical access)

Milestones:

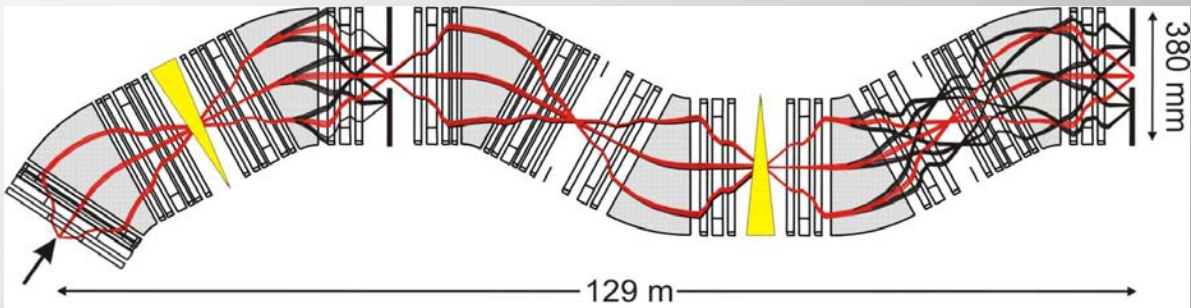
- M6-1: Concept for rotating target wheel, 12/2006*

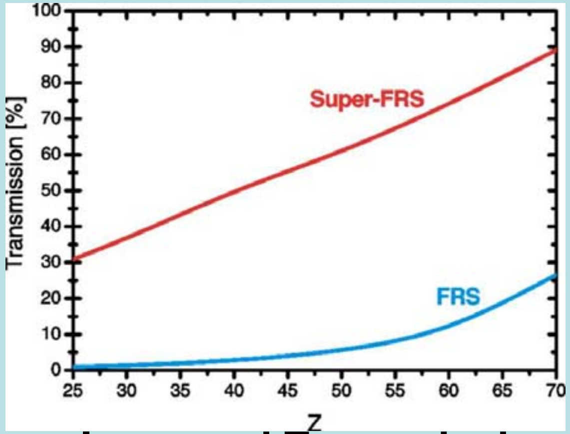
Comparison of FRS with Super-FRS

FRS

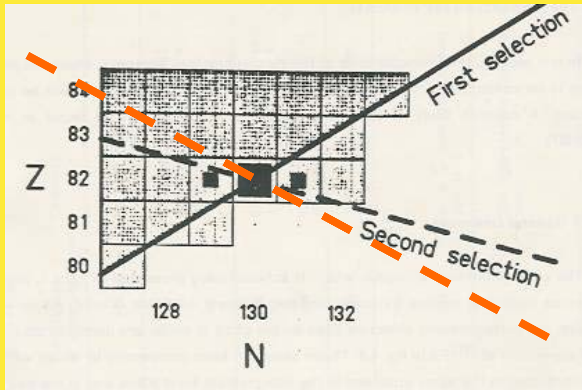


Super-FRS





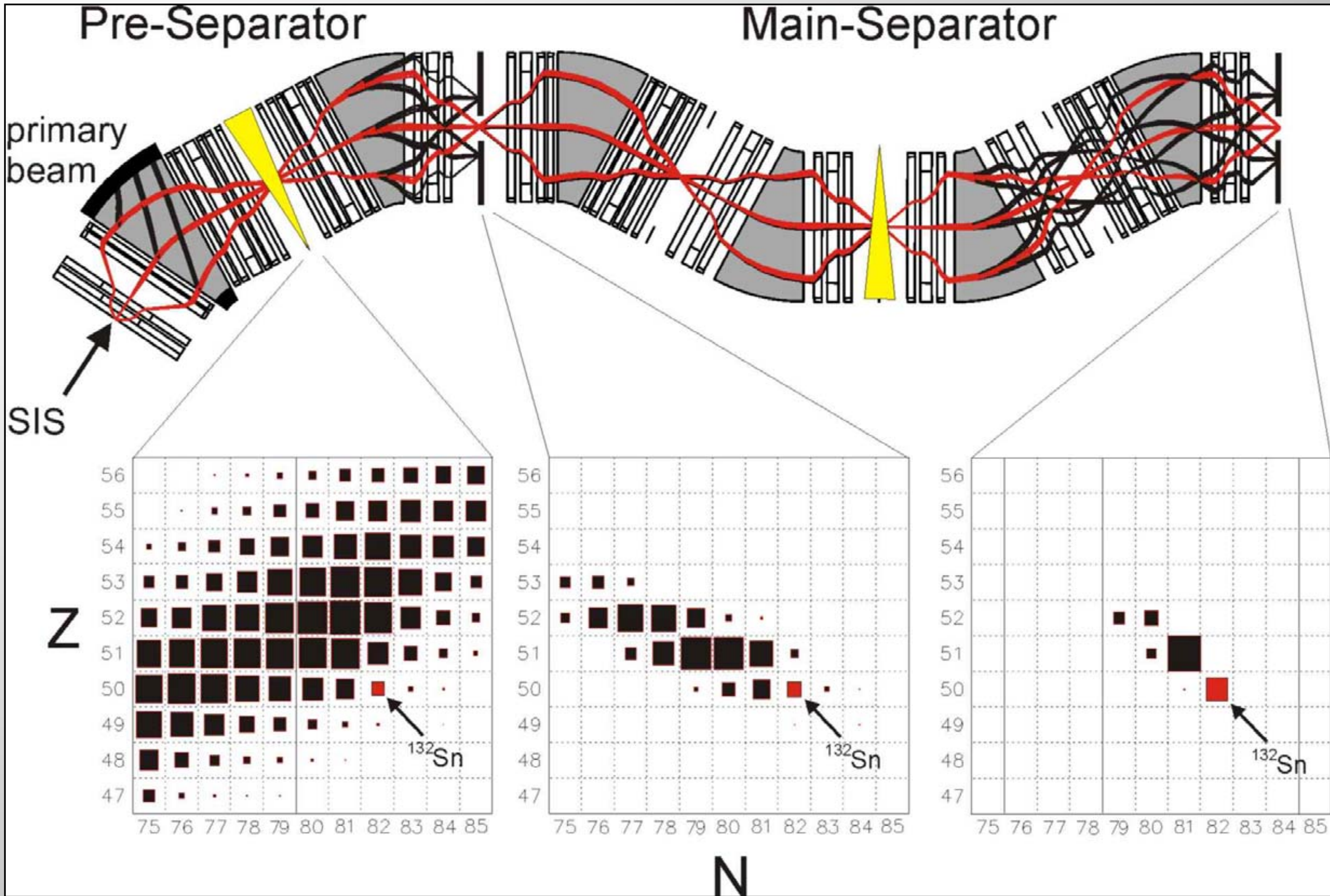
Improved Transmission for fission fragments



Energy-loss selection is energy dependent

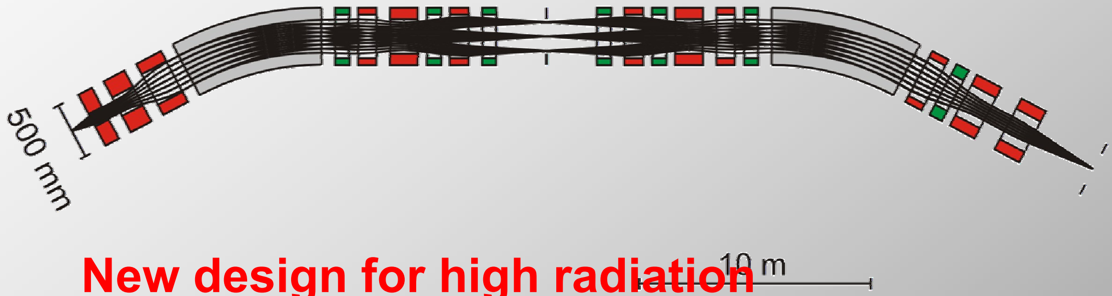
	$B\rho_{max}$	$\Delta p/p$	$\Delta\Phi_x$, $\Delta\Phi_y$	resolving power	gain factor ^{19}C	gain factor ^{132}Sn
FRS	18 Tm	1.0 %	± 13, ±13 mrad	1500	1	1
Super-FRS	20 Tm	2.5 %	±40, ±20 mrad	1500	5	10
				including primary rate	250	20 000

Layout and Separation Properties



Pre-Separator Optical Design

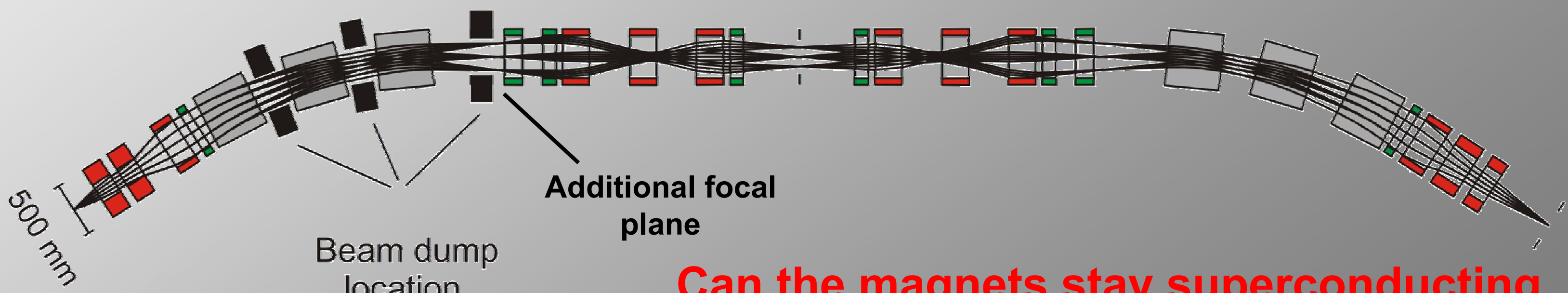
Previous



Previously	Presently
1x 28° dipole	3x 11° dipoles
1 focal plane (Degrader)	3 focal planes (Degrader + BD)
L_{Path} = 43 m	L_{path} = 69 m

New design for high radiation

Splitted-Dipole Design



Can the magnets stay superconducting after the target and beam dumps?

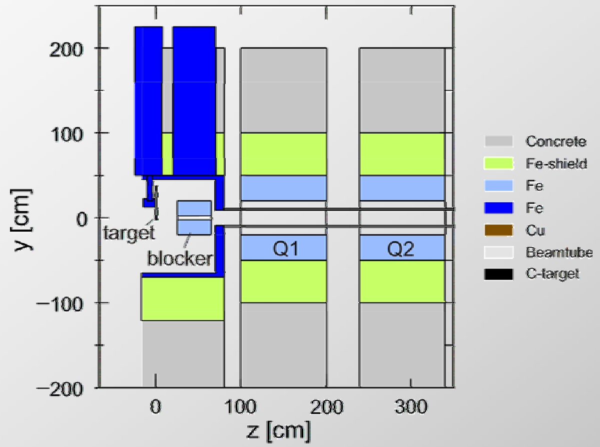
H. Geissel, M. Winkler

Radiation – Resistent Large - Aperture Quadrupole Magnet

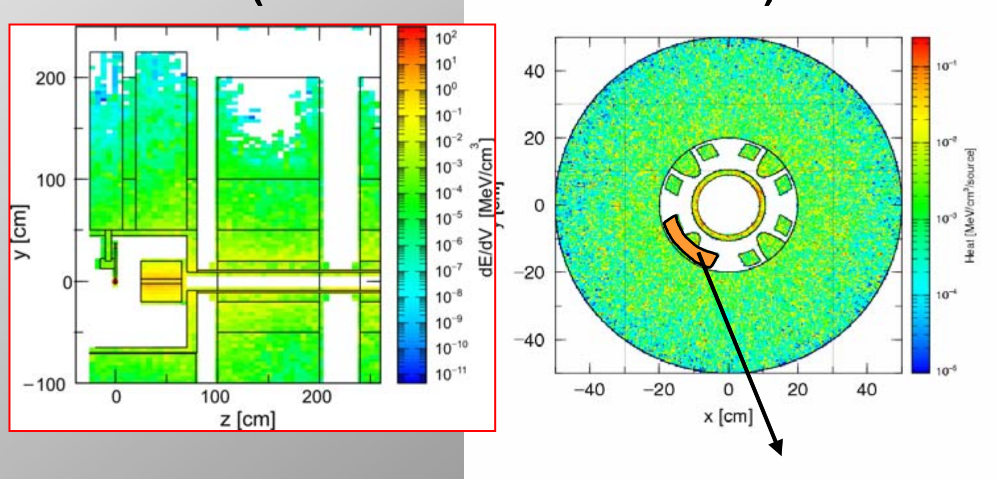
TECHNISCHE UNIVERSITÄT DRESDEN

BABCOCK NOELL NUCLEAR GmbH

Geometry at target area



Energy deposition distribution (calculated with PHITS)



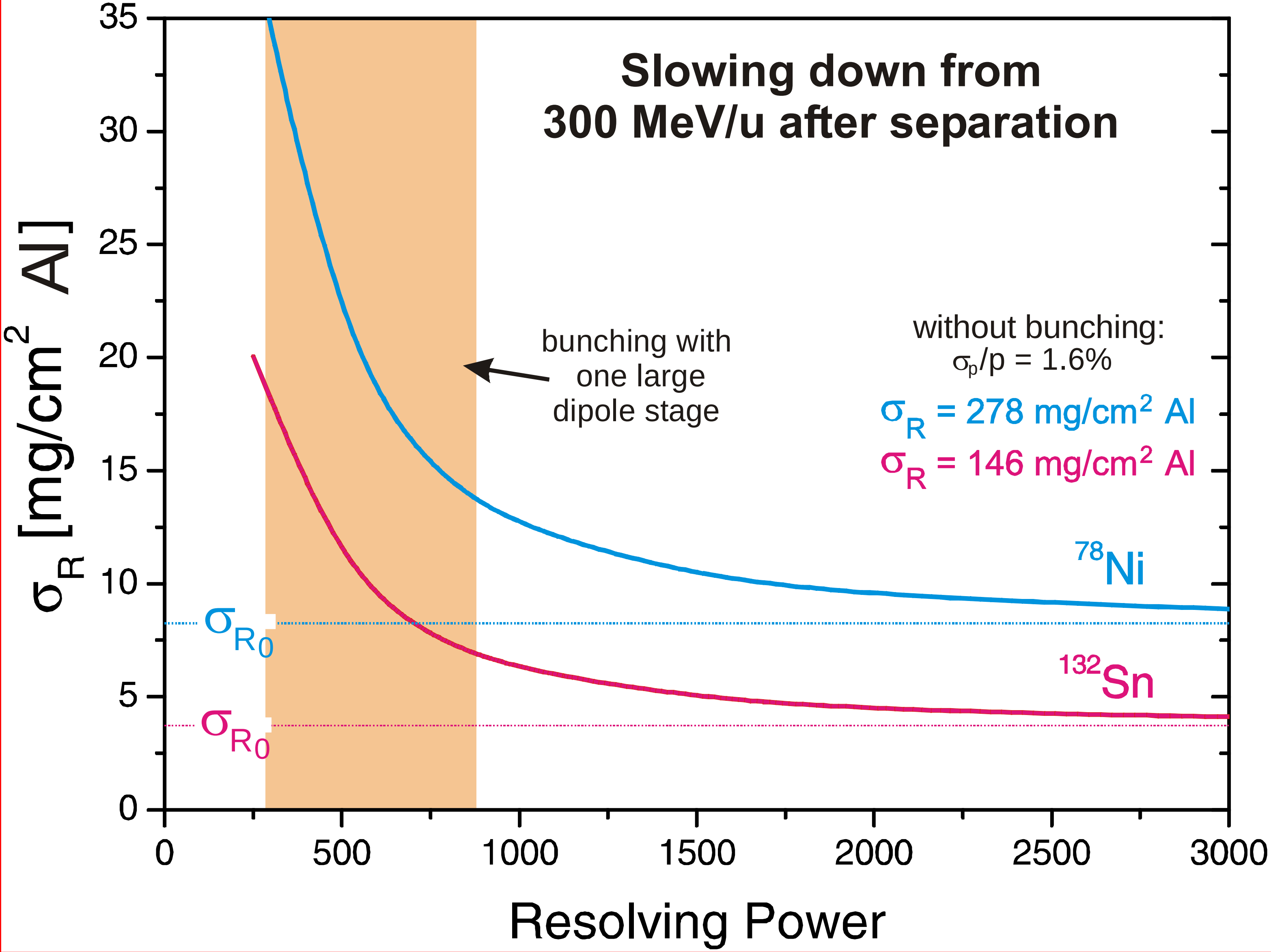
<ΔE> / M = 0.46 mJ/g

(quench limit: 2-3 mJ/g)

Milestones:

- M7-1: Decision on insulating material, 10/2005*
- M7-2: Delivery of model coil, 9/2006*
- M7-3: Design and test for Surveying and alignment system ready, 4/2007*
- M7-4: Prototype Magnet delivered, 12/2007*

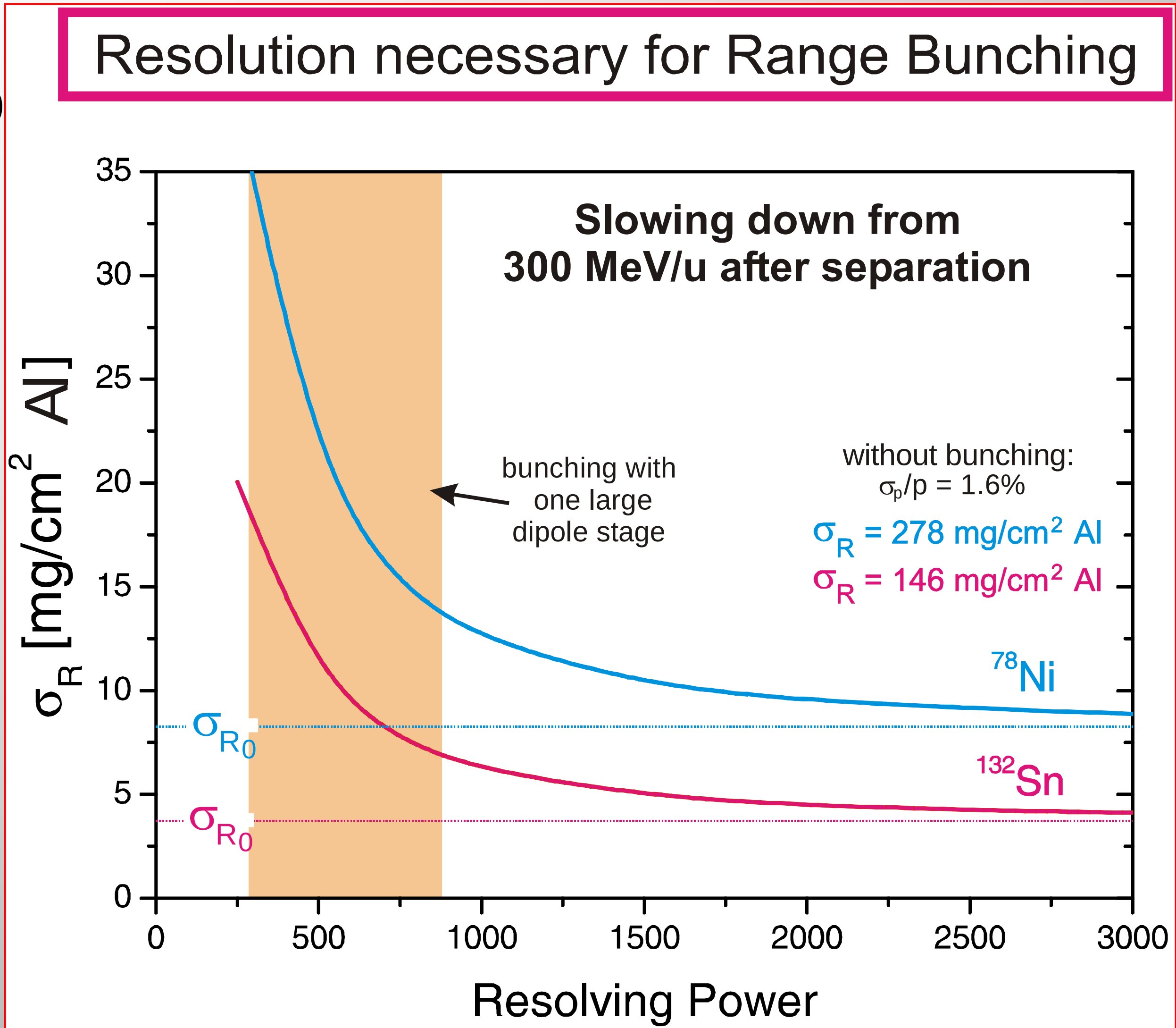
Resolution necessary for Range Bunching



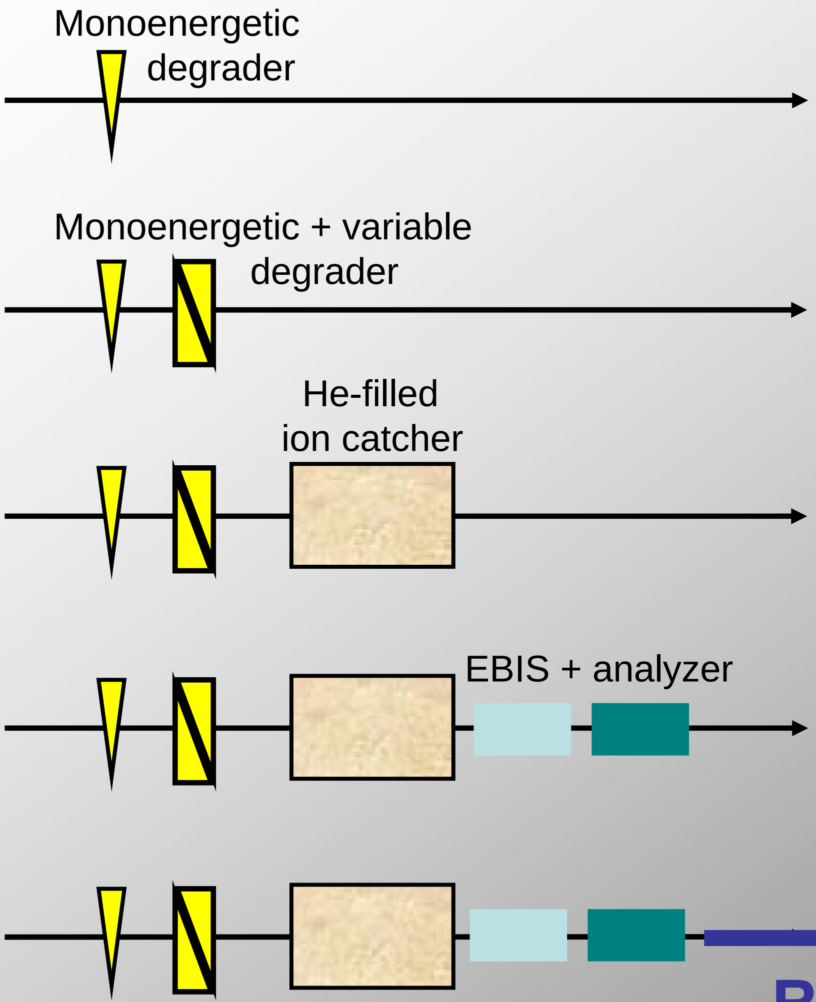
Energy buncher: Principle and Ion-optical Layout

Princip

Layou



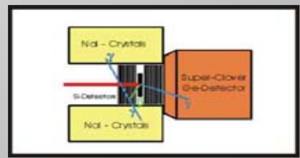
Experimental Opportunities and Instrumentation



Slow beams
(500...10 MeV/u)

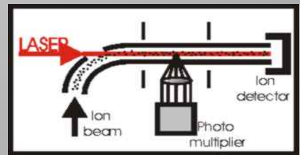
in-beam γ-ray spectroscopy

Stopped beams
(~ 25meV)



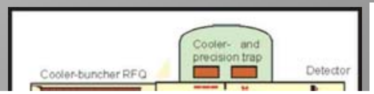
α, β, γ -decay spectroscopy

ISOL-type beams
(~10...100 keV)

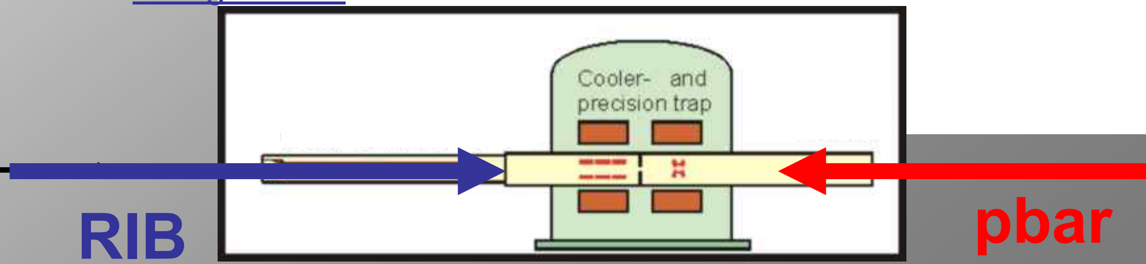


LASER spectroscopy

Highly-
charged ions



in-trap ex-

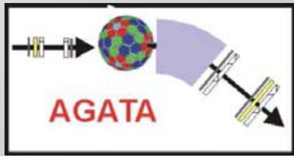


Unique feature: RIBs and pbar at (almost) the same place

Experimental opportunities and instrumentation

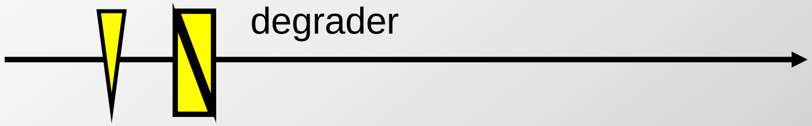
Monoenergetic degrader

Slow beams (500...10 MeV/u)

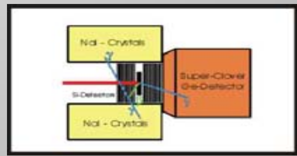


in-beam γ-ray spectroscopy

Monoenergetic + variable degrader

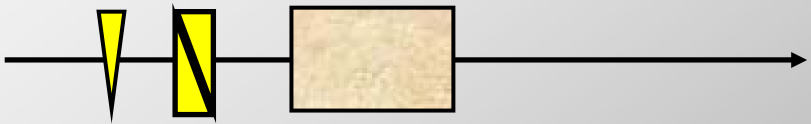


Stopped beams (~ 25meV)

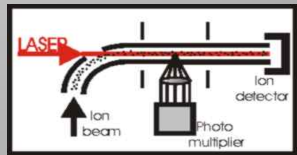


α, β, γ -decay spectroscopy

He-filled ion catcher

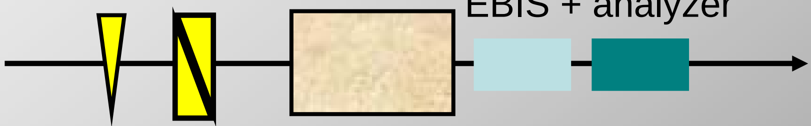


ISOL-type beams (~10...100 keV)

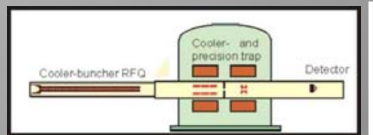


LASER spectroscopy

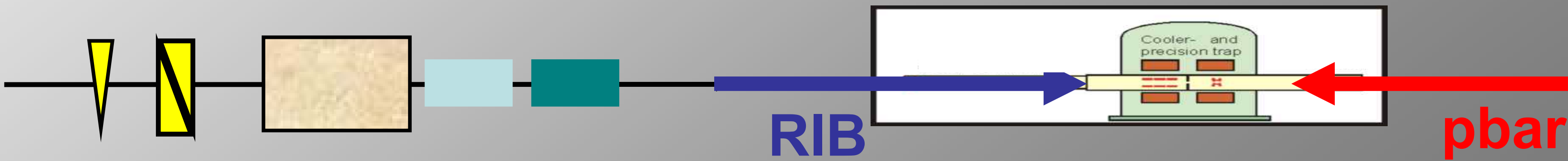
EBIS + analyzer



Highly-charged ions

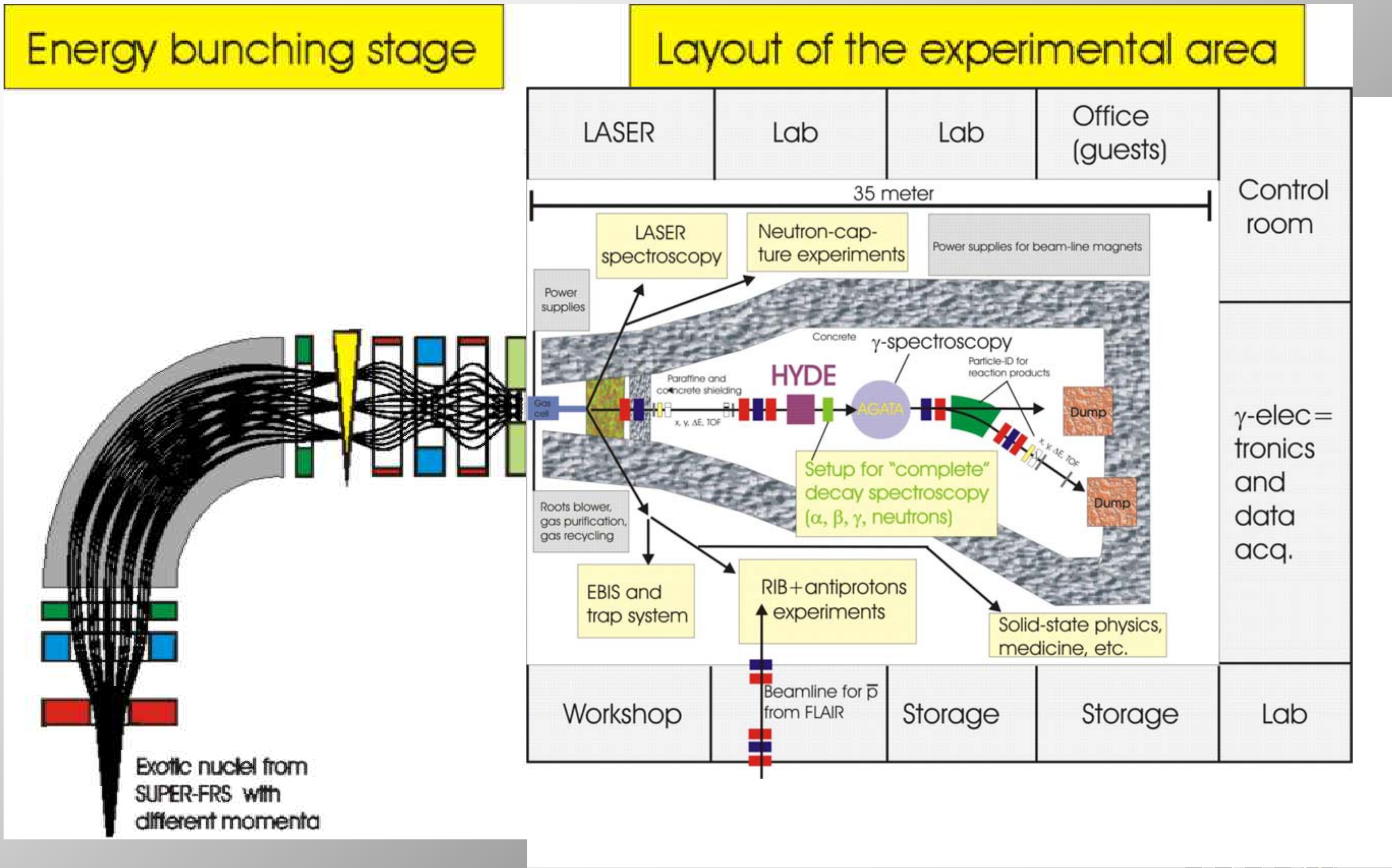


in-trap ex-periments

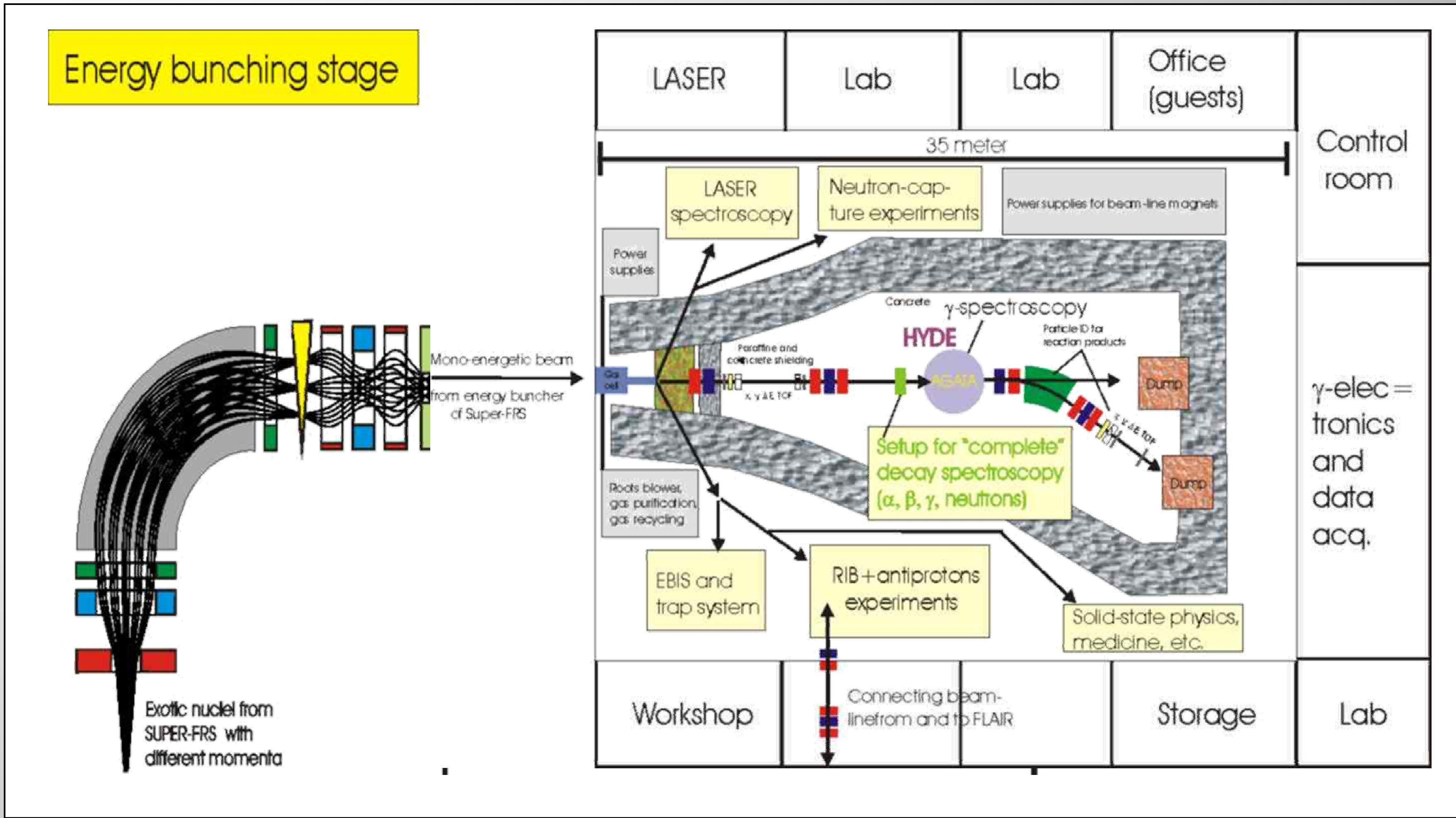


Unique feature: RIBs and pbar at (almost) the same place

The Low-Energy Branch



Experimental Area at the Low-Energy Branch of the Super-FRS



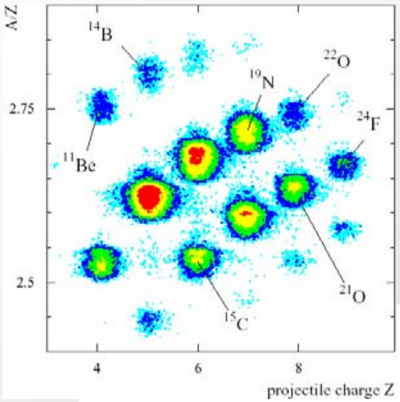
The high-energy branch

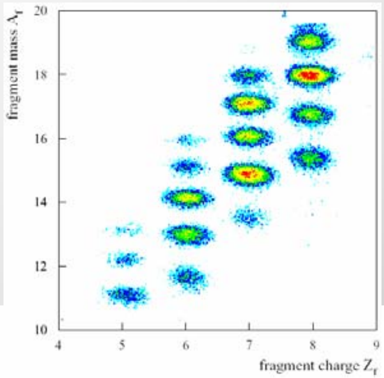
Reactions with high-energy radioactive beams:

- Knockout reaction: shell structure, valence-nucleon wave function in light nuclei
- Quasi-free scattering
- Total absorption measurement: nuclear radii, for heavy nuclei (one ion/s)
- Spallation reactions: neutron sources, production of radioactive beams, astrophysics
- Projectile fragmentation

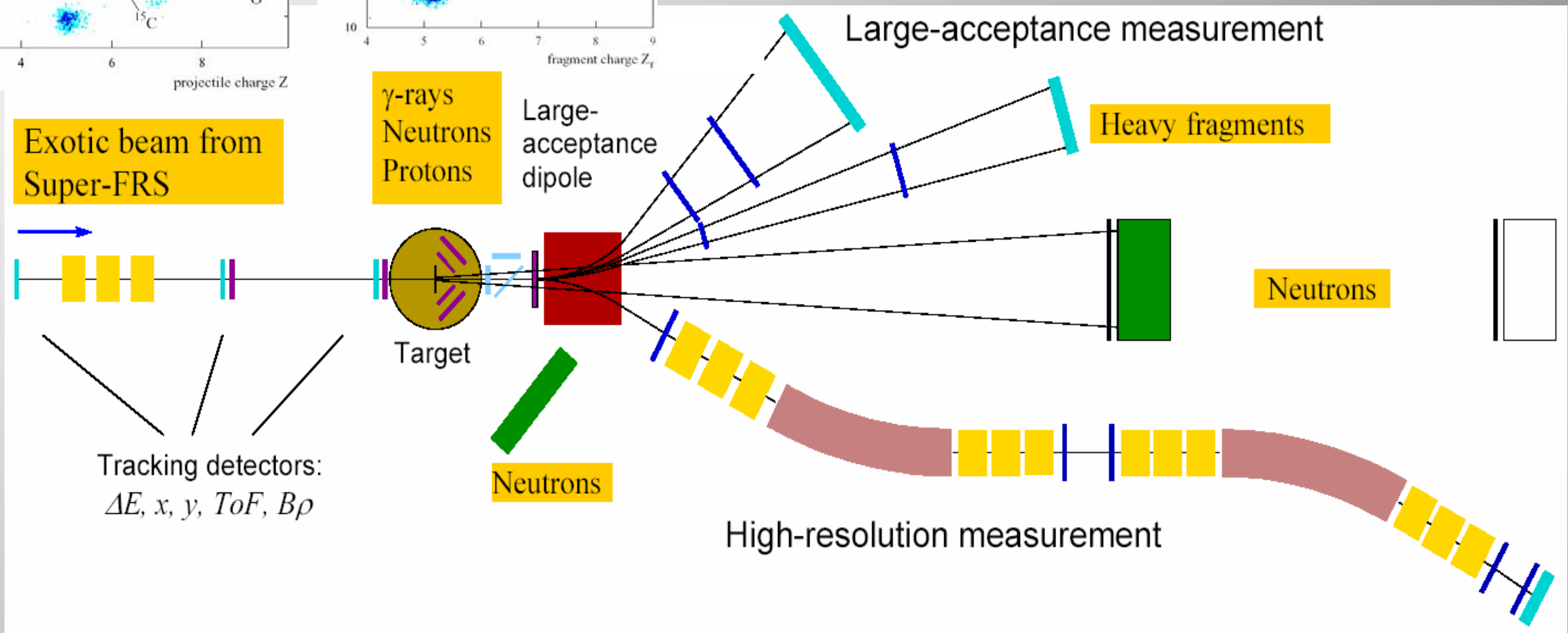
Kinematically complete measurements using a large variety of γ and particle detectors and a high resolution magnetic spectrometer

Physics with Radioactive Ion Beams: The SFRS high-energy branch

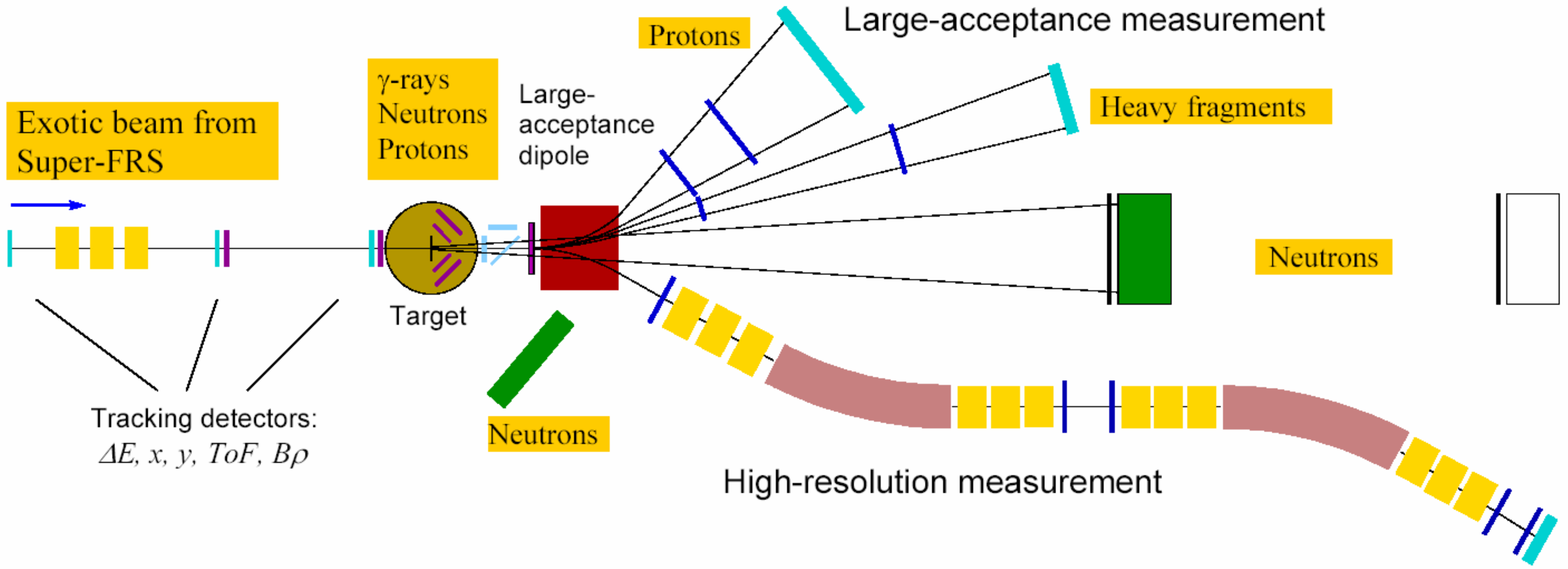




Projectile fragmentation



Reactions with Relativistic Radioactive Beams



- identification and beam "cooling" (tracking and momentum measurement, Dp/p ~10-4)
- exclusive measurement of the final state:
- - identification and momentum analysis of fragments
- (large acceptance mode: Dp/p~10-3, high-resolution mode: Dp/p~10-4)
- - coincident measurement of neutrons, protons, gamma-rays, light recoil particles
- applicable to a wide class of reactions

New Methods and Concepts

Storage Rings

•Precision experiments

•New access to structure

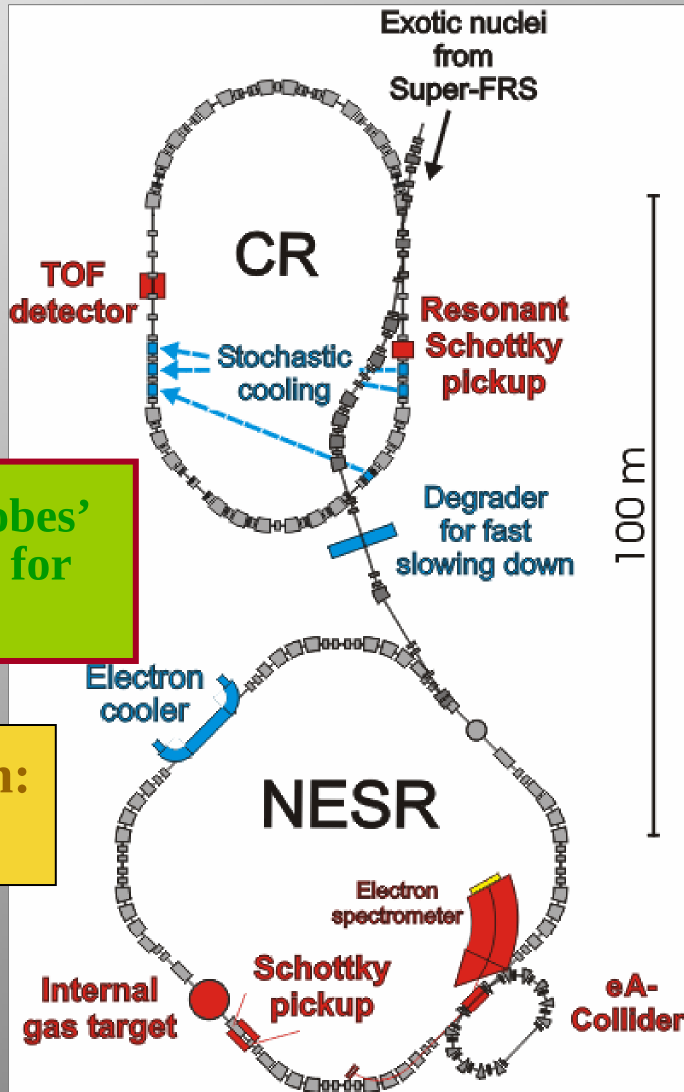
- **Light hadron (p,d,He..) scattering**
  - ➔ *internal-target experiments*

'Standard probes' not available for RI so far

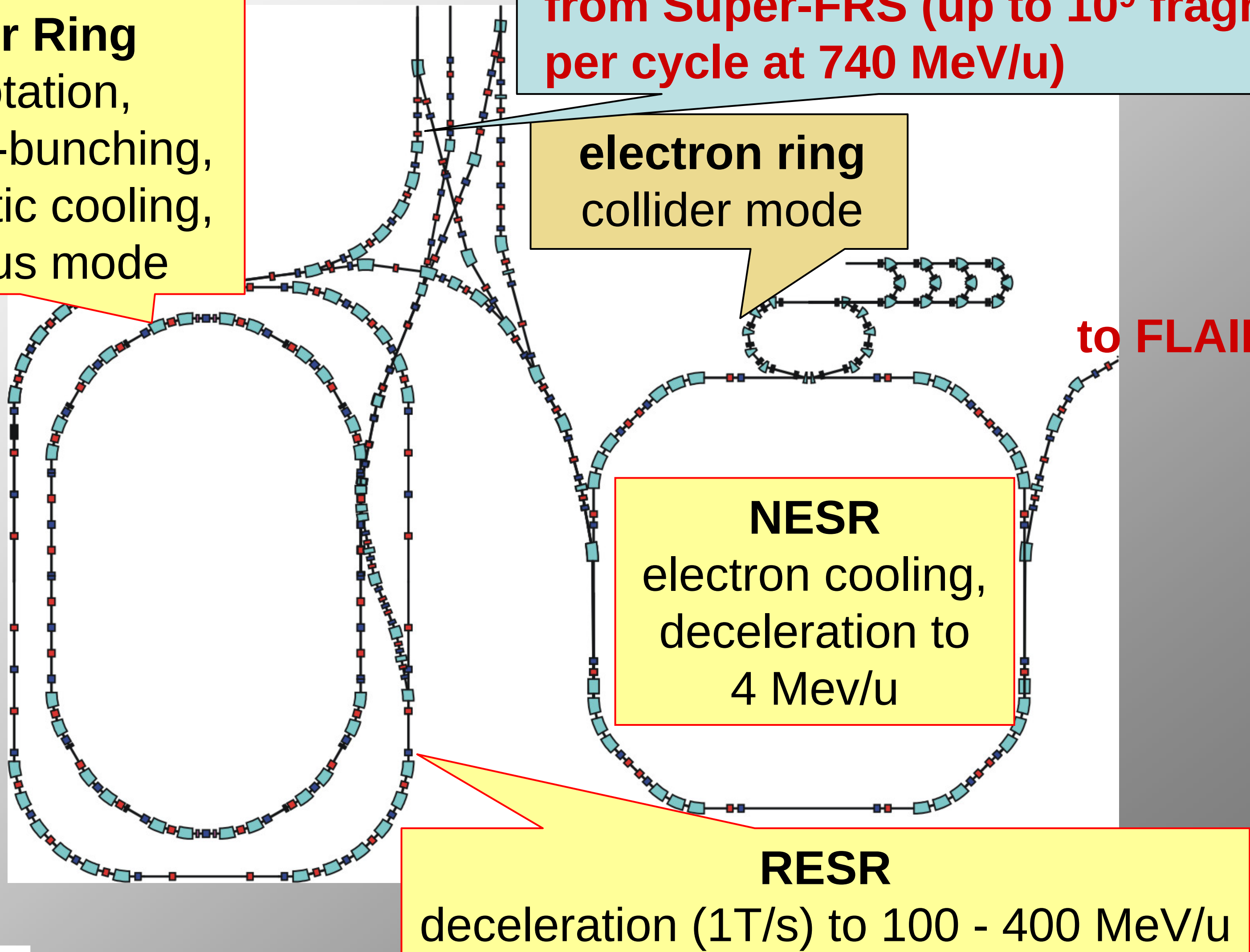
- **Electron scattering**
  - ➔ *Electron-Ion Collider*
  - idea born at Dubna

First generation: charge radii

- **Rapid transfer + fast cooling**
  - ➔ Shortest-lived isotopes



The Storage Rings



H. Weick,

Physics with Radioactive Ion Beams

The Ring Branch: CR and NESR

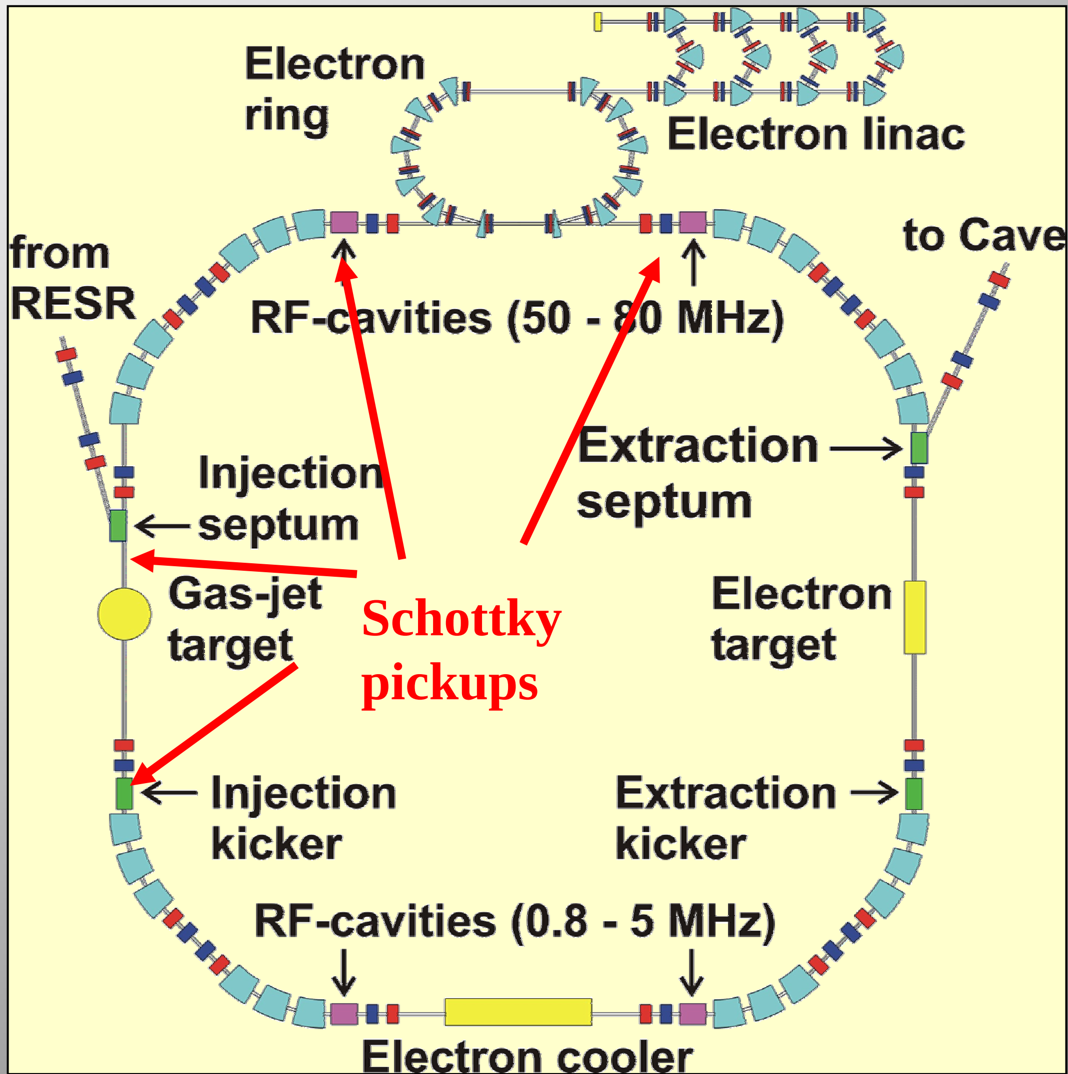
- **mapping of large area of unknown masses**
- **life time of HCI**
- **pure isomeric beams**

Method: precise measurements of the revolution time in ring

$$df/f = -\gamma_t^{-2}\, d(m/q) / (m/q) + + (1- \gamma^2/ \gamma_t^2)dv/v$$

$$\Delta v/v = \gamma^{-2}(\Delta p/p)$$

- Schottky Mass Spectr.
- Isochronous Mass Spectr.

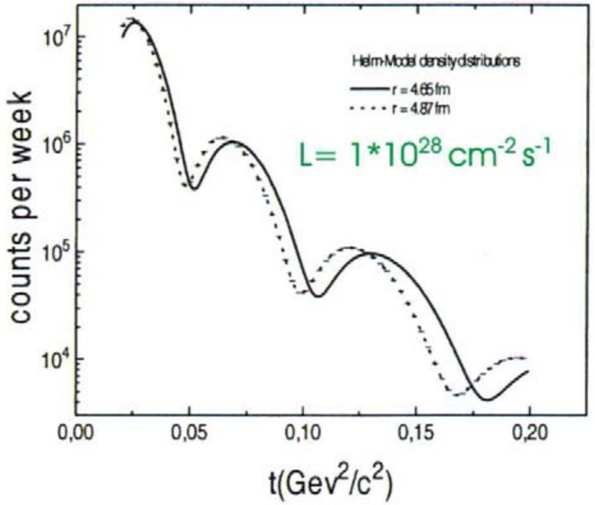


Precision Experiments in Storage and Collider Rings

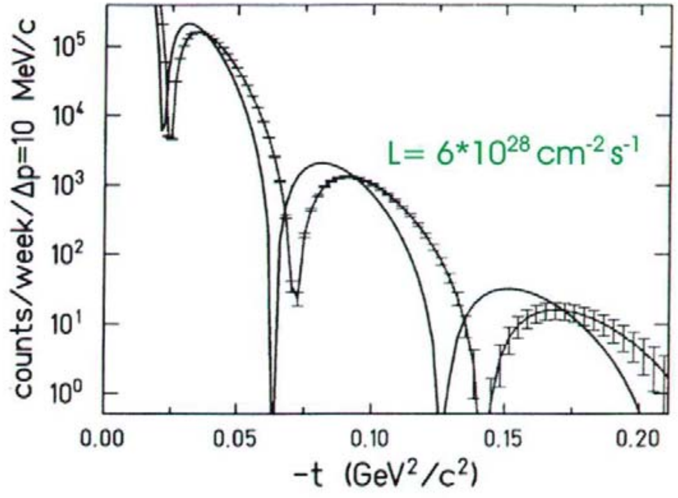
Example:

Elastic scattering of bare ^{132}Sn nuclei ......

...off protons in NESR



...off electrons in e-A-Mini-collider



....yields * nuclear matter distributions

* charge distributions

Hadron scattering with thin targets at high resolution

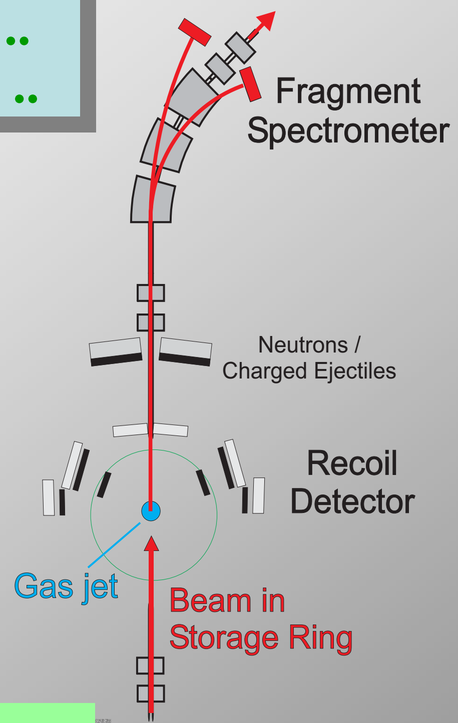
Elastic (p,p) …
Inelastic (p,p'), (α,α') ...
Charge exchange: (p,n), (^{3}He,t) ..
Quasifree (p,pn), (p,2p), (p, pα) ..

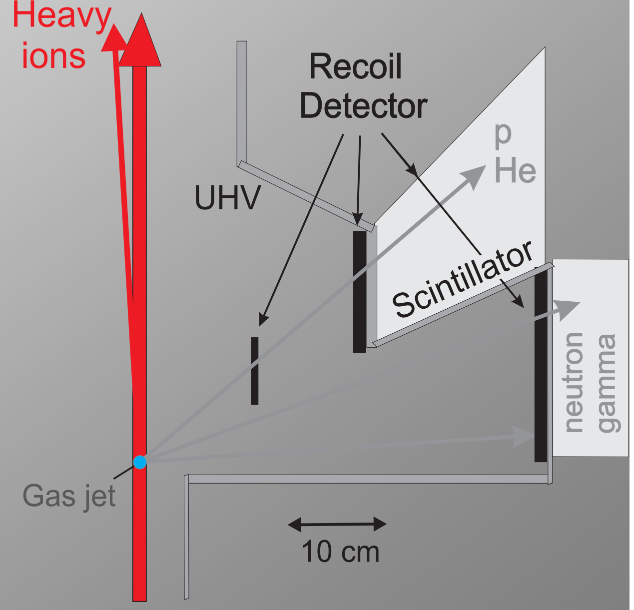
Reversed kinematics:

Form factors from
<u>low energy/momentum</u>
recoils

Thin (gaseous) targets,
new detector concepts,
e.g. UHV in-ring det.
…… ……. ….

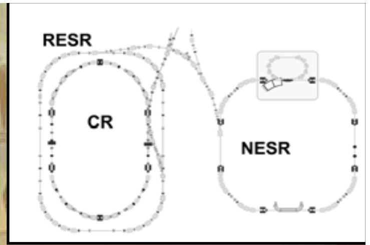
complete kinematics , decay
product coincibdences
suppression of phys. bgr.
…………





Target thickness 10^{13}-10^{15} cm^{-2}

Electron Scattering



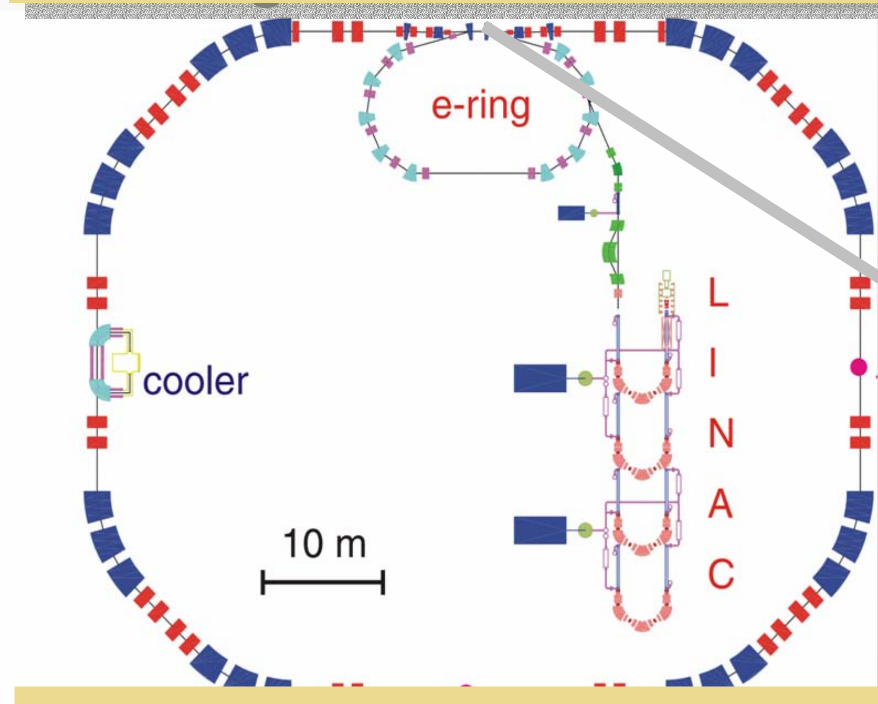
- Pointlike particle
- Pure electromagnetic probe
  - ⇒ formfactors F(q)
  - ⇒ elastic scattering
- F(q) transition formfactors
  - ⇒ high selectivity to certain multipolarities
  - ⇒ inelastic scattering
- Large recoil velocities
  - ⇒ full identification (Z,A) complete kinematics
- Bare ions (no atomic bg.)

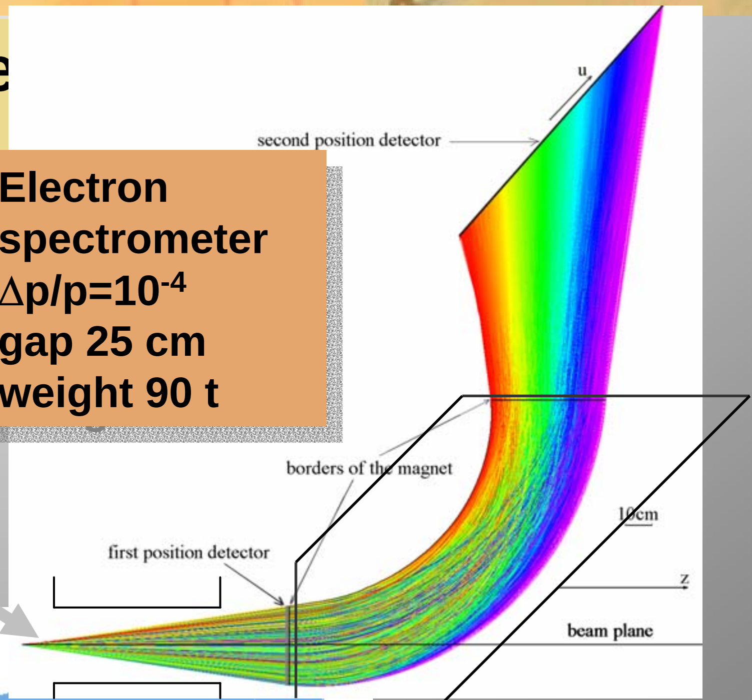
Physics goals

- Charge distribution of exotic nuclei (radius, diffuseness, higher moments...) req. luminosity: > 10^{24} cm^{-2} s^{-1}
- Selective electromagnetic excitation plus spectroscopy, fission, ... studies. Full identification of electric & magnetic multipolarities and of the final state (*new* collective *soft* modes) req. luminosity: about 10^{28} cm^{-2} s^{-1}
- Quasi-free scattering (single-particle structure) req. luminosity: about 10^{29} cm^{-2} s^{-1}

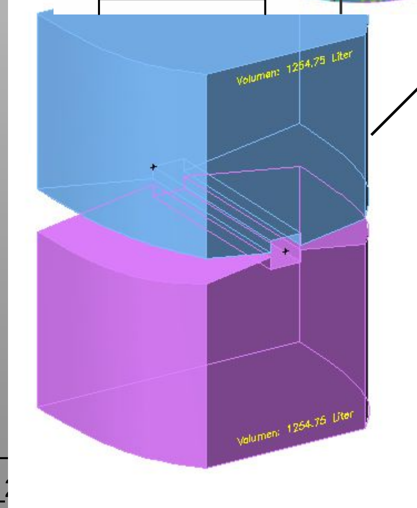
The Electron-Ion (eA) Collider

Electrons, a new probe for structure investigations of unstable nuclei





Electron spectrometer
$\Delta p/p=10^{-4}$
gap 25 cm
weight 90 t



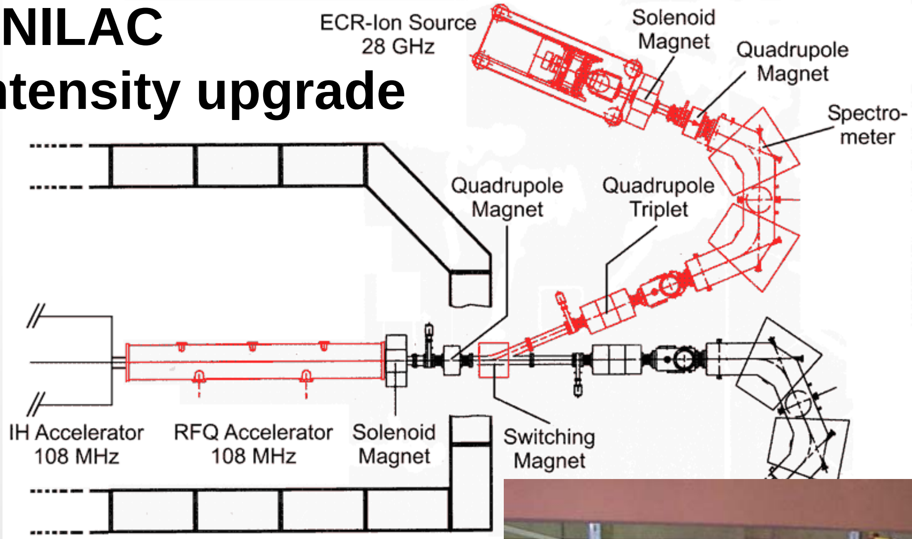
JINR: UHV detectors

Idea and first common studies from JINR (Oganessian, Meshkov, TerAkopian)

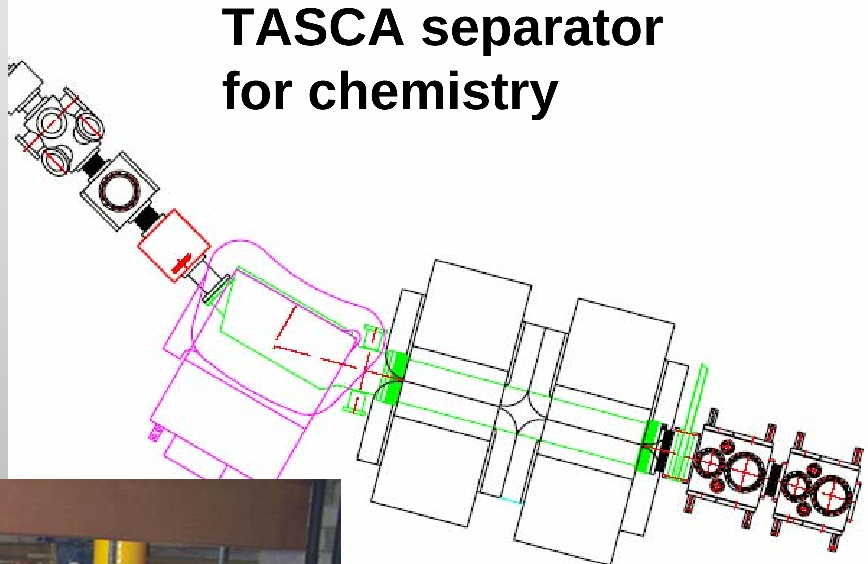
H. Simon

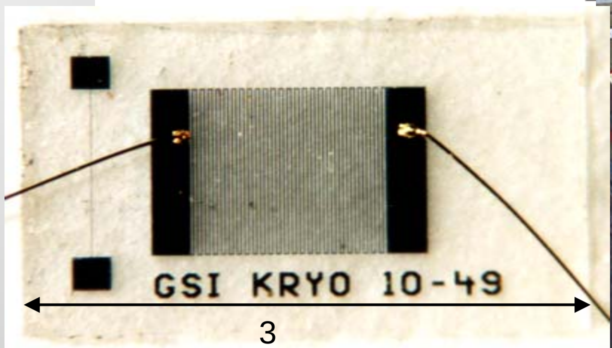
Future of SHE

UNILAC intensity upgrade

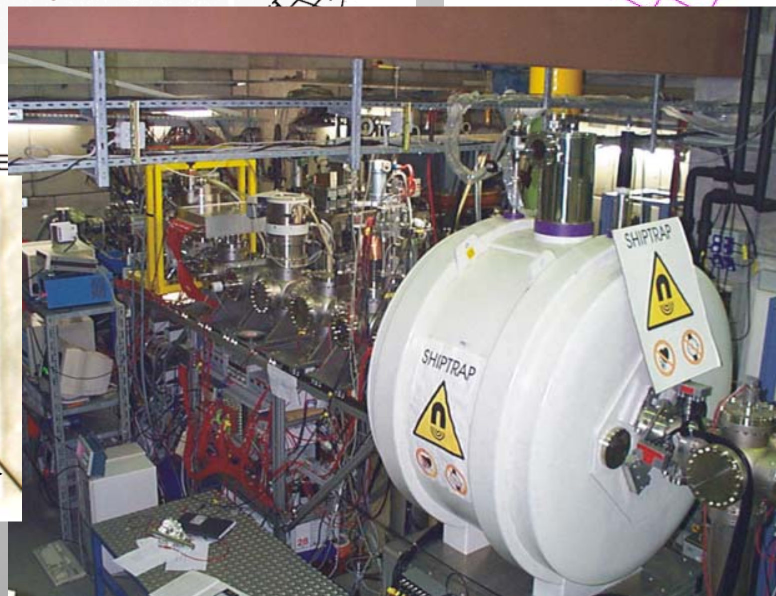


TASCA separator for chemistry

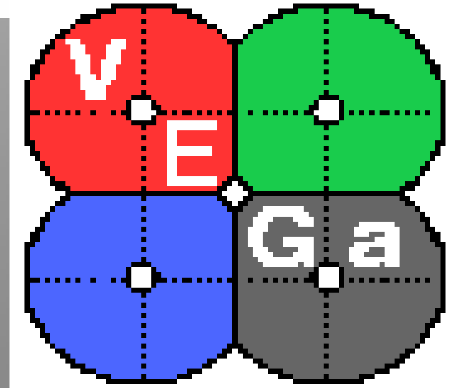




Calorimeter mass detemination

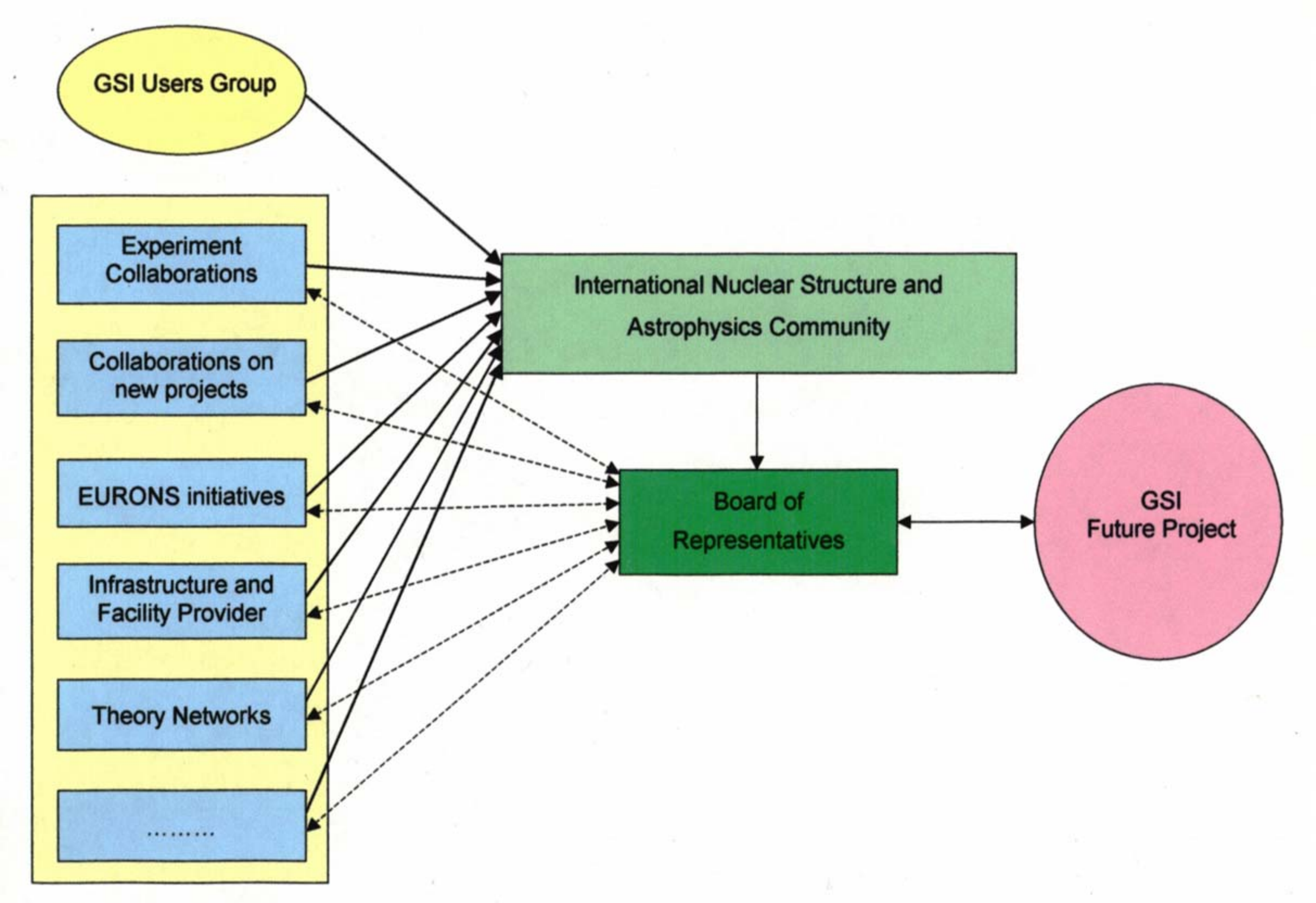


SHIPTRAP atomic physics



γ-spectroskopy

NUSTAR - Organisation



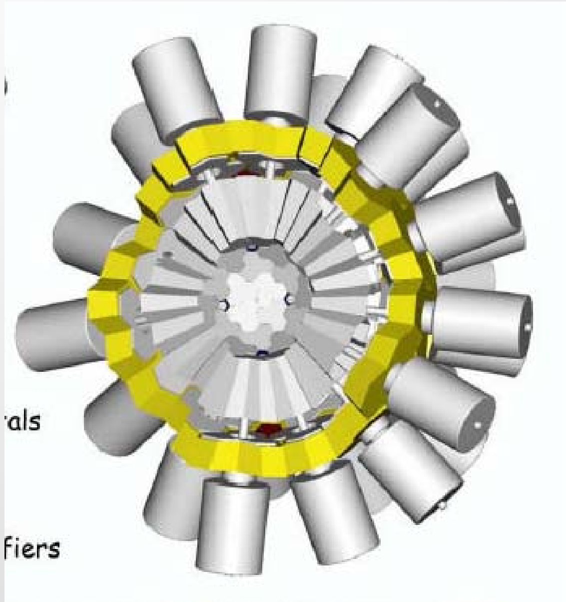
In Summary

- FAIR –
  - versatile facility for nuclear structure, astrophysics (hadron-, atomic, plasma phsyics ...)

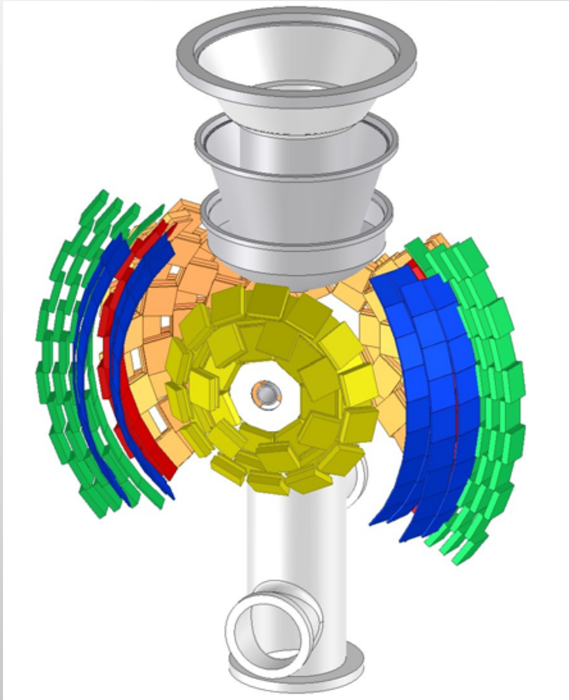
- GSI today – a few examples
  - Superheavy Elements
  - Nuclear structure and Astrophysics at the FRS

- NUSTAR @ FAIR
  - ***NU**clear **ST**ructure, **A**strophysics and **R**eactions*
  - *will provide new oprtunities and insights exploiting new concepts and methods*

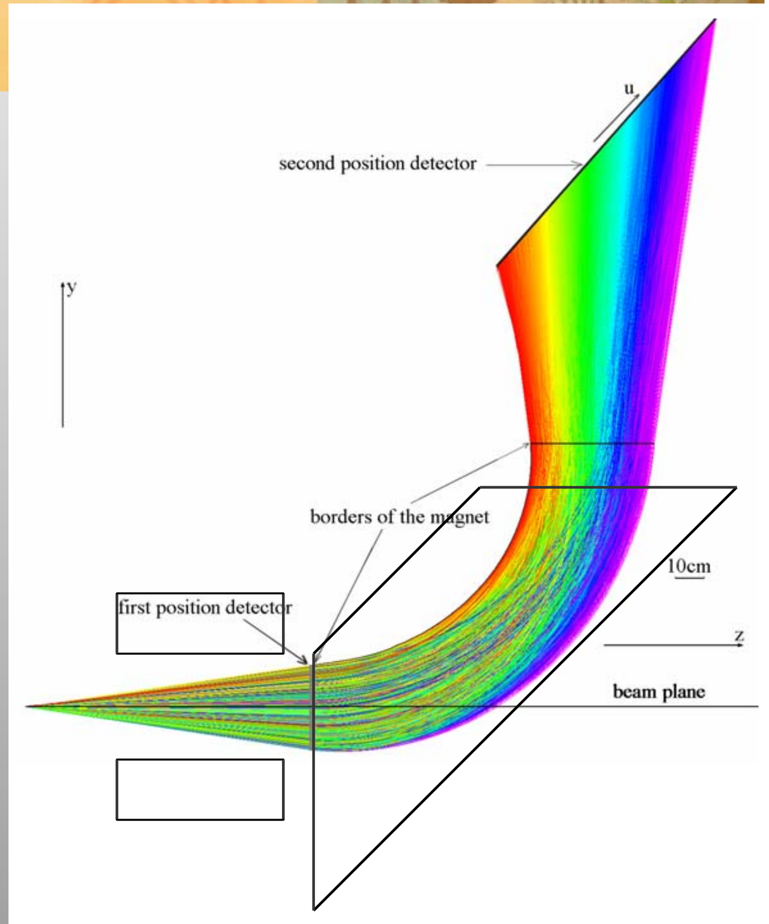
New Techniques, New Probes



AGATA
in-beam spectroscopy



EXL
light hadron scattering



ELISe
electron scattering

New Insights

into the Structure of the Nucleus

Letters of Intent for NUSTAR

Low Energy Branch

HISPEC	High-resolution in-flight gamma-ray spectroscopy	C. Scheidenberger (GSI) Z. Podolyak	(U.Surrey)
DESPEC	Decay spectroscopy with Implanted Ion Beams	B. Rubio	(CSIC Valencia)
MATS	Precision measurements of very short-lived nuclei using an advanced trapping system for highly-charged ions	K. Blaum	(U.Mainz)
LASPEC	LASER spectroscopy for the study of nuclear properties	P. Campbell	(U.Manchester)
NCAP	Neutron capture measurements	M. Heil	(FZ Karlsruhe)
Exo+pbar	Antiprotonic radioactive nuclides	M. Wada	(RIKEN)

High-Energy Branch

R³B	A universal setup for kinematically complete measurements of reactions with relativistic radioactive beams	T. Aumann	(GSI)

Ring Branch

ILIMA	Study of isomeric beams, lifetimes and masses	Y. Novikov	(NPI St.Petersburg)
EXL	Exotic nuclei studied in light-ion induced reactions at the NESR storage ring	M. Chartier	(U.Liverpool)
ELISE	Electron-ion scattering in a storage ring (e-A collider)	H. Simon	(GSI)
pbar-A	Antiproton-ion collider: measurement of neutron and proton rms radii of stable and radioactive nuclei	P. Kienle	(TU Munich)
PIONIC	Spectroscopy of pionic atoms with unstable nuclei	K. Itahashi	(RIKEN)

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