New generation of measurements and model developments on nuclide production in spallation reactions

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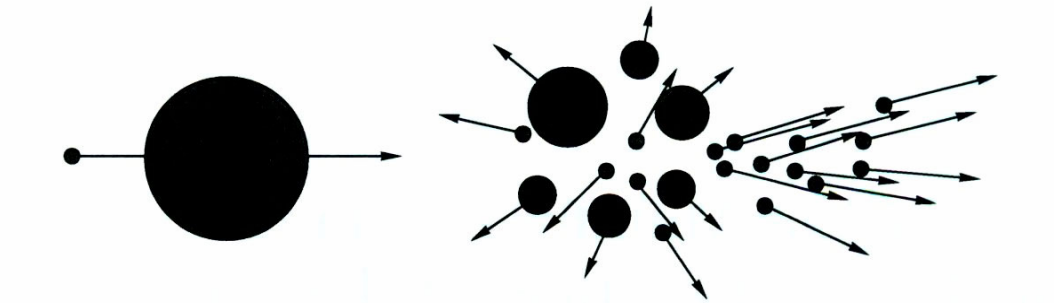
Spallation reaction:

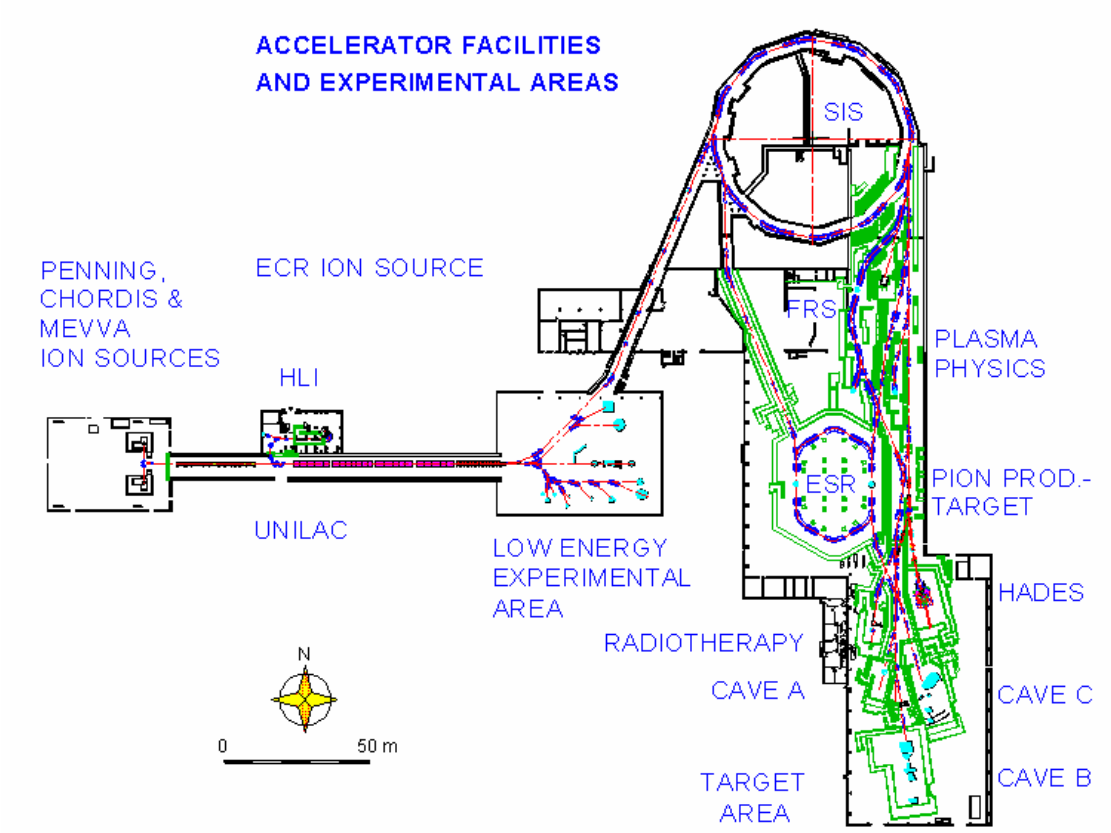
Violent collision of nucleons with heavy nuclei,
exploited e.g. for production of neutrons or exotic nuclei.



Interest for studying nuclide production in spallation:

- **Spallation target in general**
- **ADS (transmutation of nuclear waste)**
  HINDAS (FP5), EUROTRANS (FP6)
- **EURISOL (ISOL-based secondary-beam facility)**
  EURISOL_DS (FP6)
- **Astrophysics (reactions of cosmic rays with matter)**

Installations of GSI

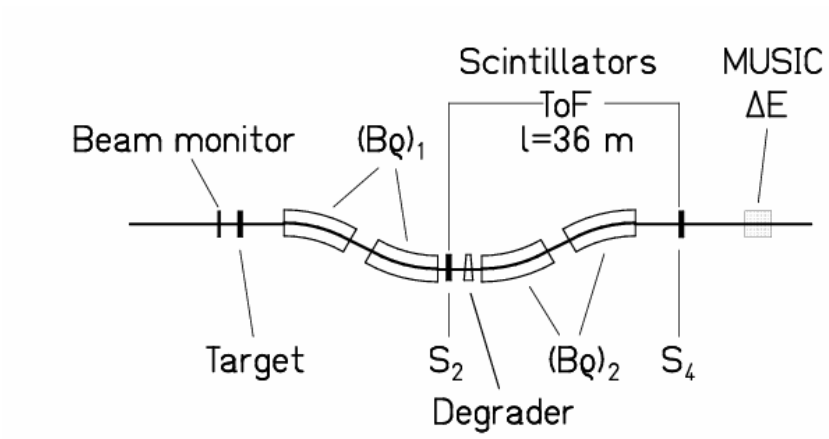


Facility for basic and applied research with heavy ions.

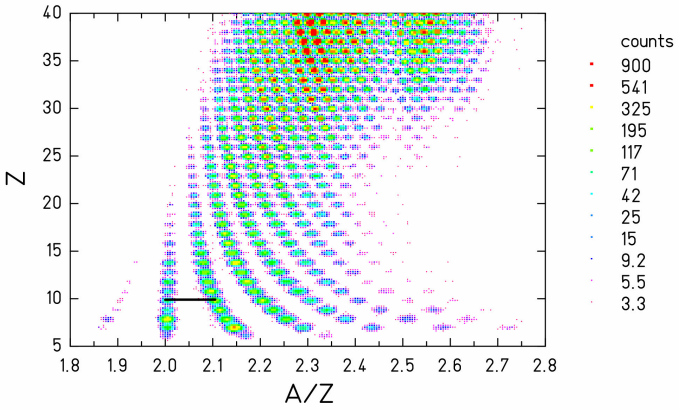
Beams of all stable nuclides up to 1-2 *A* GeV.

Magnetic spectrometers, storage ring, ...

The fragment separator: nuclide identification in-flight



Fragment separator



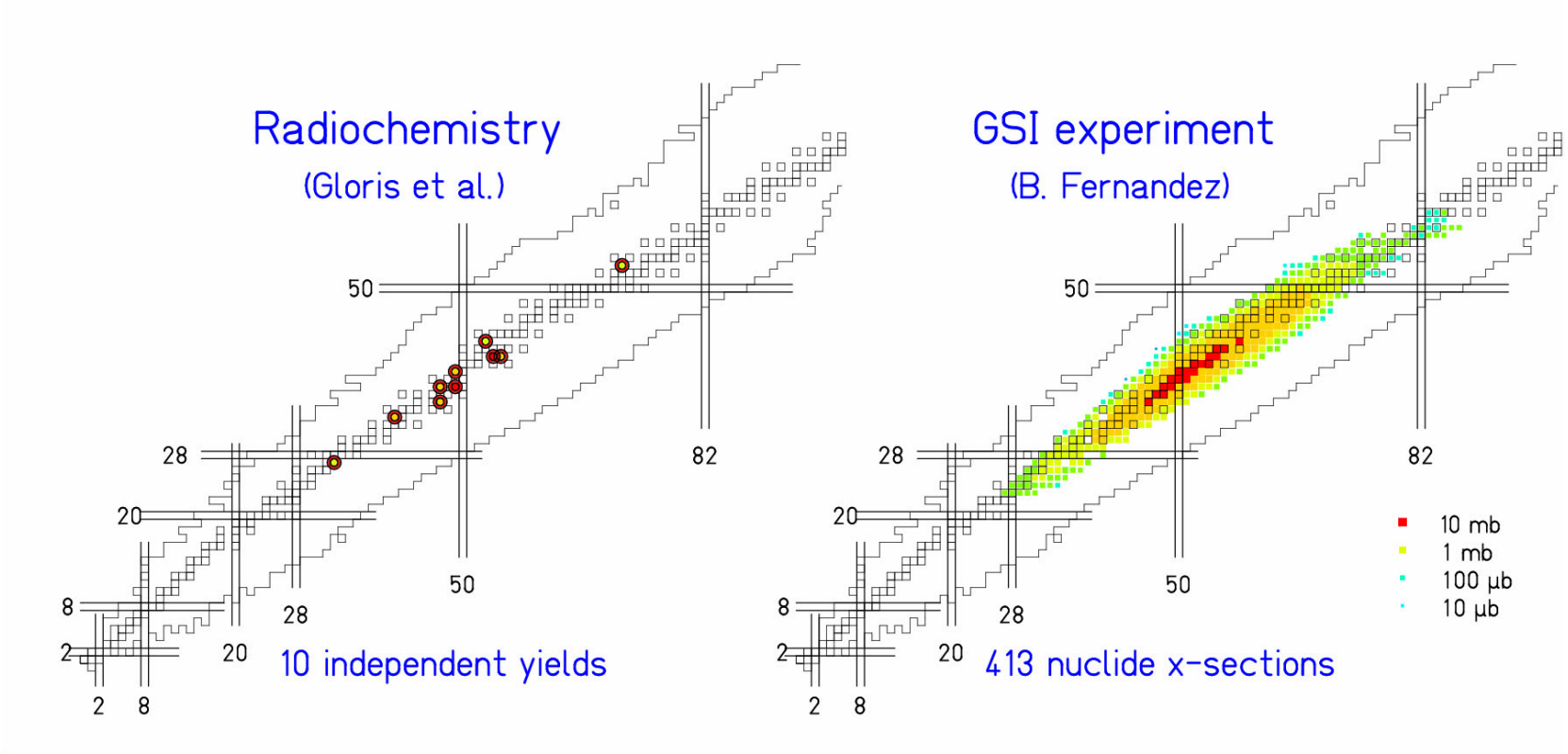
Identification pattern

^{238}U (1 A GeV) + ^{1}H

M. V. Ricciardi

Experimental progress by inverse-kinematics method

Example: Fission of lead induced by ≈ 500 MeV protons



protons (553 MeV) on lead

^{208}Pb (500 A MeV) on hydrogen

Common experimental effort of an international collaboration

CEA Saclay (France)
A. Boudard, M. Combet, J.-E. Ducret, B. Fernandez, E. Le Gentil, K. Kezzar, R. Legrain, S. Leray, S. Pietri, C. Villagrasa, C. Volant, W. Wlazlo

CEN Bordeaux-Gradignan (France)
S. Czajkowski, J.-P. Dufour, D. Karamanis, M. Pravikoff

IPN Orsay (France)
L. Audouin, C. O. Bacri, M. Bernas, L. Ferrant, A. Lafriak, B. Mustapha, P. Napolitani, F. Rejmund, C. Stephan, J. Taieb, Tassan-Got,

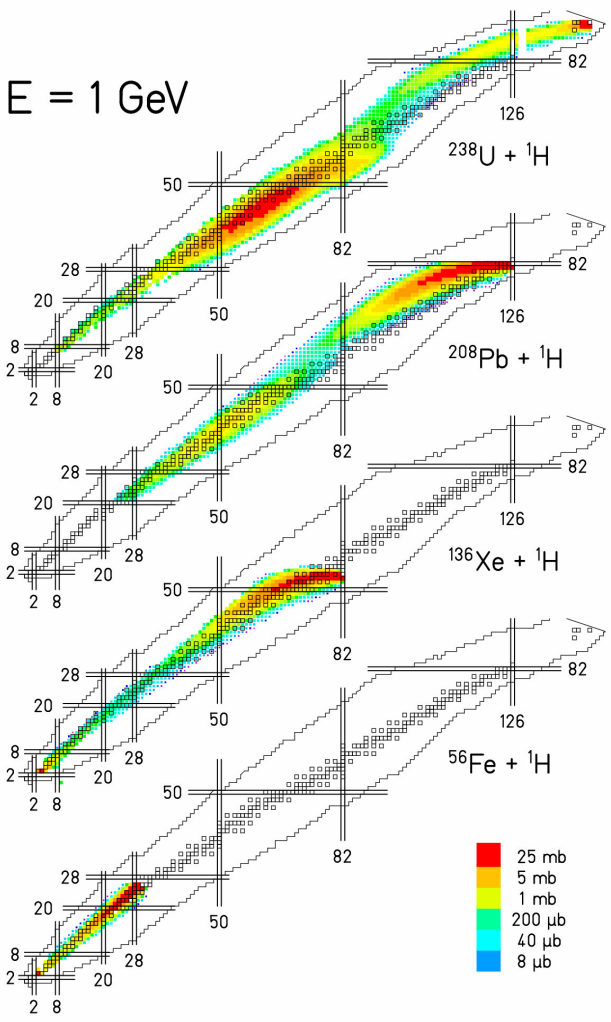
University of Santiago de Compostela (Spain)
J. Benlliure, E. Casarejos, M. Fernandez, T. Kurtukian, J. Pereira, D. Perez

GSI Darmstadt (Germany)
P. Armbruster, T. Aumann, A. Bacquias, T. Enqvist, L. Giot, A. Heinz, K. Helariutta, V. Henzl, D. Henzlova, H. Johansson, A. Junghans, B. Jurado, A. Kelic, A. Le Fevre, J. Lukasiak, S. Lukic, W. F. J. Müller, R. Pleskac, M. V. Ricciardi, K.-H. Schmidt, C. Schmitt, C. Schwarz, C. Sfienti, H. Simon, K. Sümmerer, W. Trautmann, F. Vives, O. Yordanov,

Others:
M. Böhmer, J. J. Connell, T. Fästermann, J. S. George, R. Gernhäuser, F. Hamache, R. Krücken, R. A. Mewaldt, M. Wiedenbeck, N. Yanasak, ,

34 Publications (see http://ww.gsi.de/charms/publica.htm)

Systematic survey on production of heavy nuclides



Full coverage of all residues

Systematic overview on

- spallation-evaporation residues
- spallation-fission residues
- LCP and IMF production

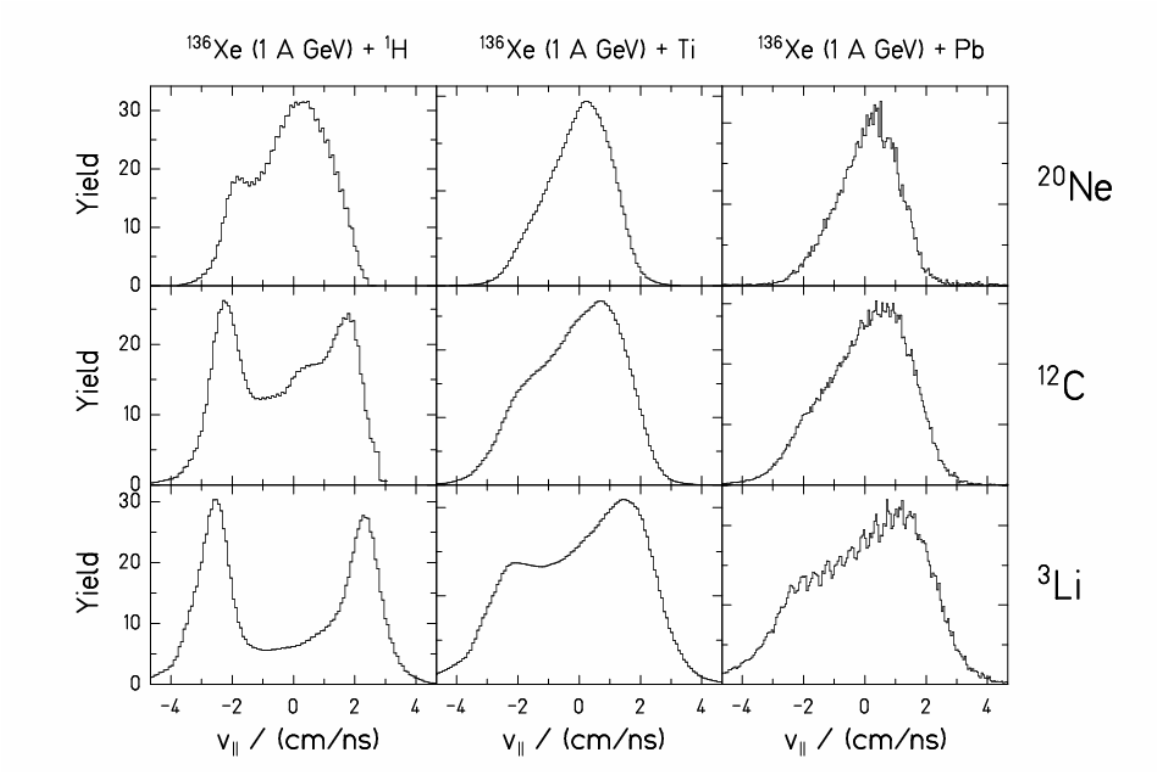
projectile	target	energy in projectile frame
^{238}U	p, d	1 GeV, 2 GeV
^{208}Pb	p, d	0.5 to 2
^{197}Au	p	0.8 GeV
^{136}Xe	p, d	0.2 to 1 GeV
^{56}Fe	p, d	0.3 to 1.5 GeV

Data available: www.gsi.de/charms/data.htm

Analysis partly still in progress, see following talks:

C. Paradela, E. Casarejos

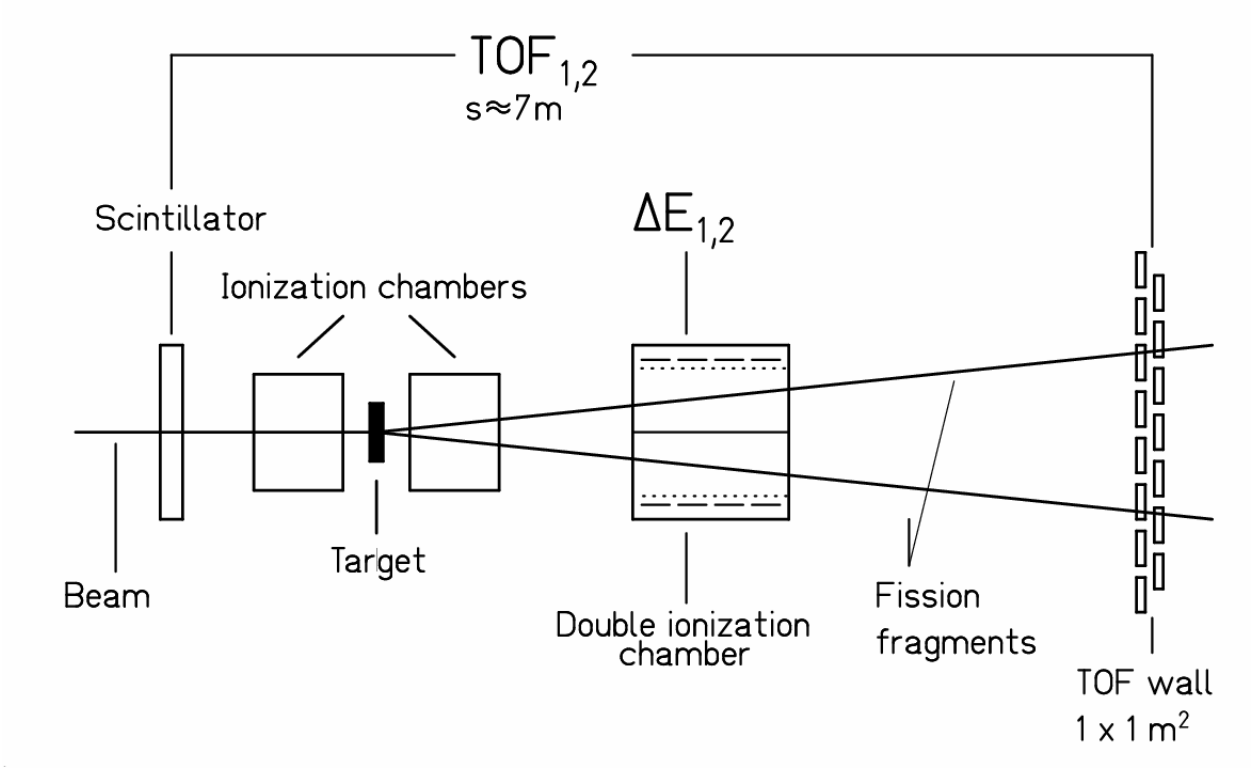
Distributions of longitudinal velocities



P. Napolitani,
D. Henzlova

Signatures of binary decay (double-humped distributions) and multifragmentation (single-humped distributions), producing the same nuclides with different weights.

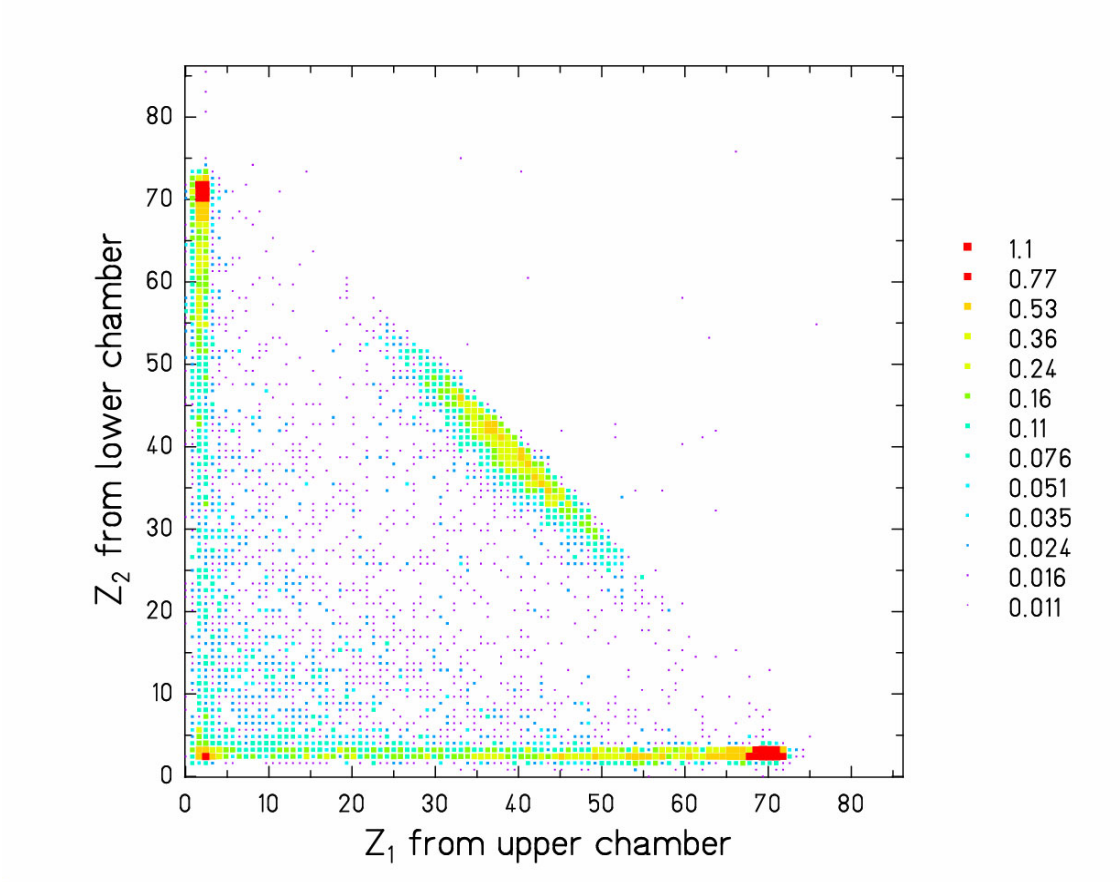
Total fission cross sections



Full-acceptance detector set-up with active target.

(EURATOM fellowship FISA, R. Pleskac)

Identification of both fission fragments



^{208}Pb (500 A MeV) + ^{1}H

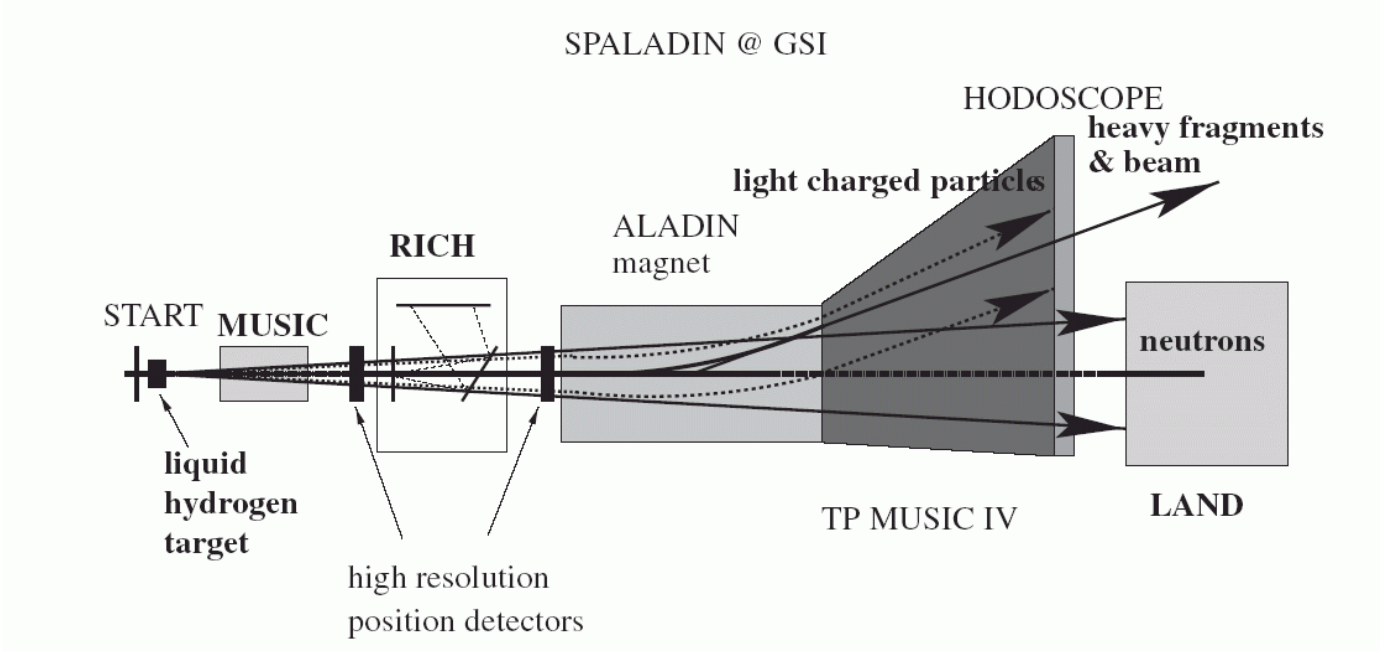
Results on total fission cross sections

reaction	**full-acceptance set up**	FRS	Prokofiev [1]	Kotov et al. [2]
^{208}Pb+^{1}H 500 MeV	**146±7**	232±33 [3]	112	
^{208}Pb+^{2}H 1000 MeV	**203±9**			
^{238}U+^{1}H 545 MeV	**1490±100**		1360	1491±78
^{238}U+^{1}H 935 MeV	**1550±100**	1530±200 [4]	1270	1489±64

(For the values given in green, the energies deviate slightly.)

1 A. V. Prokofiev, Nucl. Instrum. Methods **A 463**, 557 (2001).
2 A. A. Kotov et al., Phys. Rev. **C 74**, 034605 (2006).
3 B. Fernandez et al., Nucl. Phys. **A 747**, 227 (2005).
4 M. Bernas et al., Nucl. Phys. **A 725**, 213 (2003).

SPALADIN: LCP in coincidence with heavy residues



- High angular acceptance
- Low mass resolution

Aim: separate cascade from evaporation phase, dedicated talk by J. E. Ducret

Development of the ABRABLA code (ABRA + ABLA)

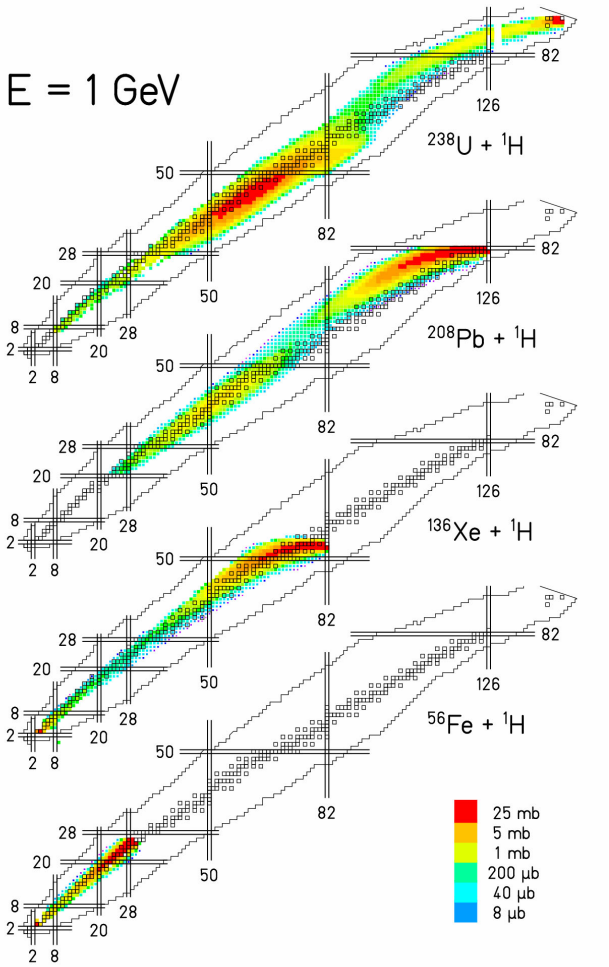
Not all relevant targets (resp. projectiles) can be measured over the whole energy range. The development of realistic models is necessary.

The ABLA code (→ ABLA07) has been improved on the following subjects:

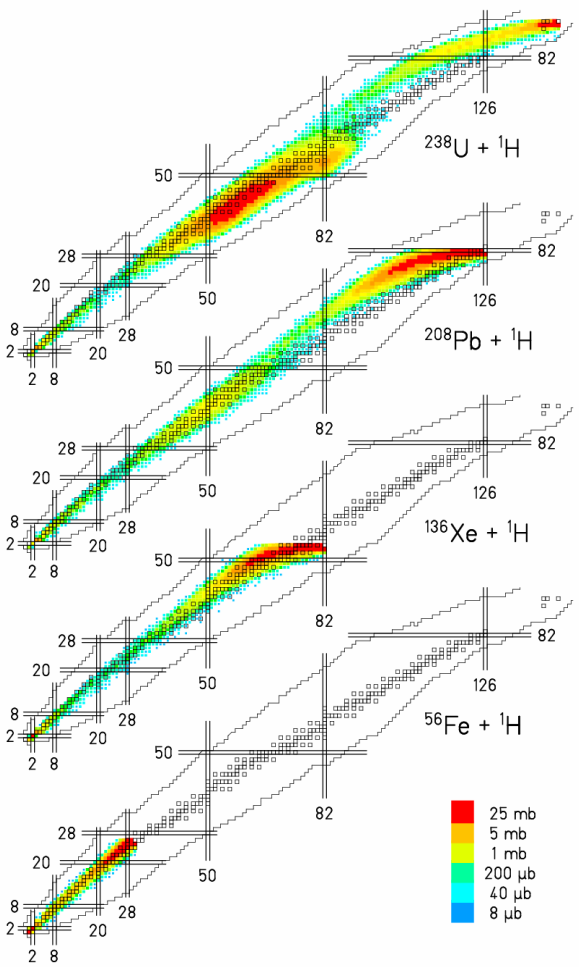
- **Extension of evaporation to heavier masses**
  Coulomb barriers from Bass nuclear potential (no adjustable parameter).
  Gap between LCPs and fission is filled. (Compare GEMINI, GEM)
- **Multifragmentation**
  Simultaneous break-up if E*/A>3MeV, sizes of fragments follow power law.
  (Compare SMM)
- **Fission**
  Improvements in fission dynamics and structural effects.

A. Kelic, M. V. Ricciardi

Benchmark of ABRABLA07: Spallation with 1 GeV protons

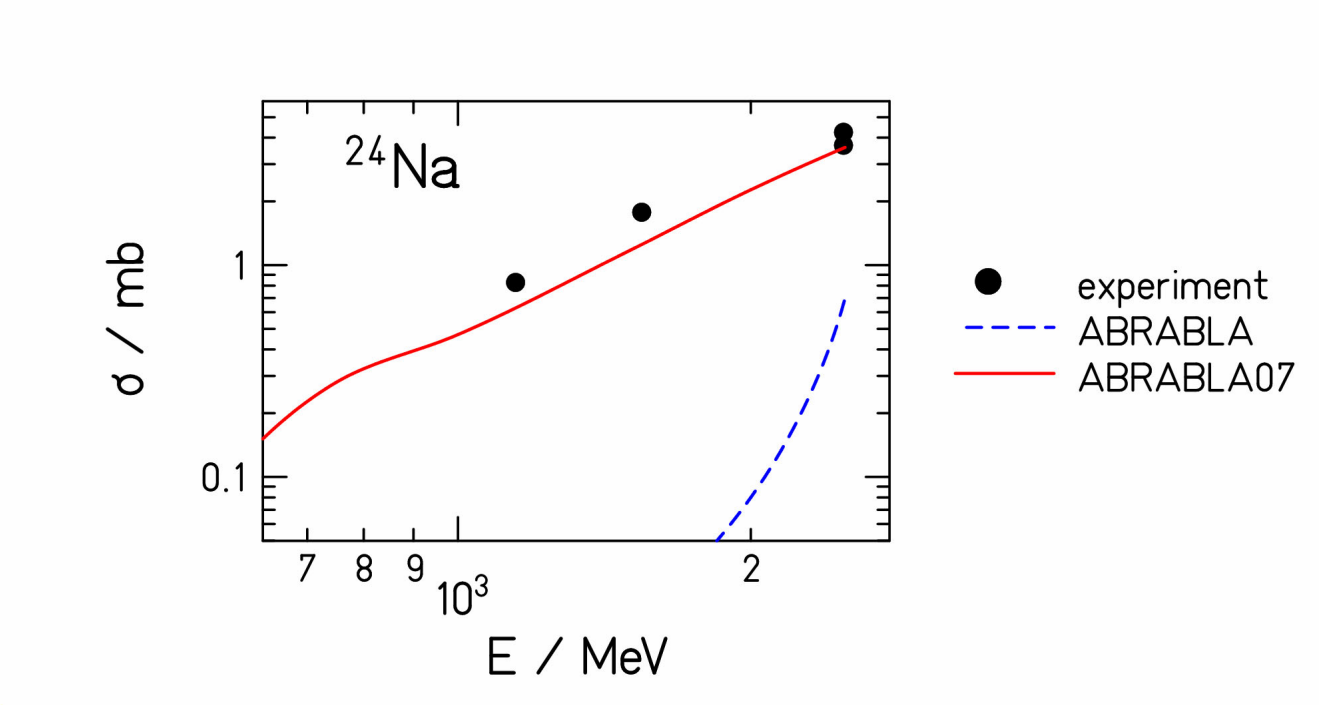


Experiment (FRS)



ABRABLA07

Benchmark of ABLA07: Threshold behaviour of IMFs



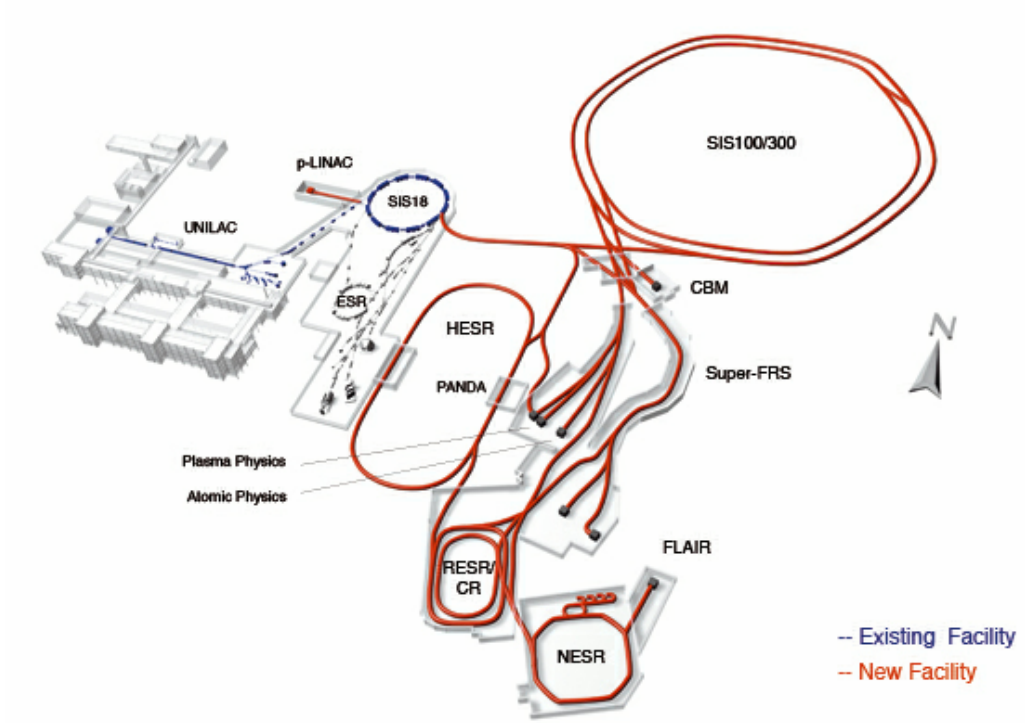
Production of ^{24}Na in the reaction ^{209}Bi + ^{1}H.

Experiment: Direct-kinematics experiment (Titarenko et al. NIM A562 (2006) 801)

Improvement of IMF production in ABLA07
by binary decay and multifragmentation.

The FAIR project of GSI

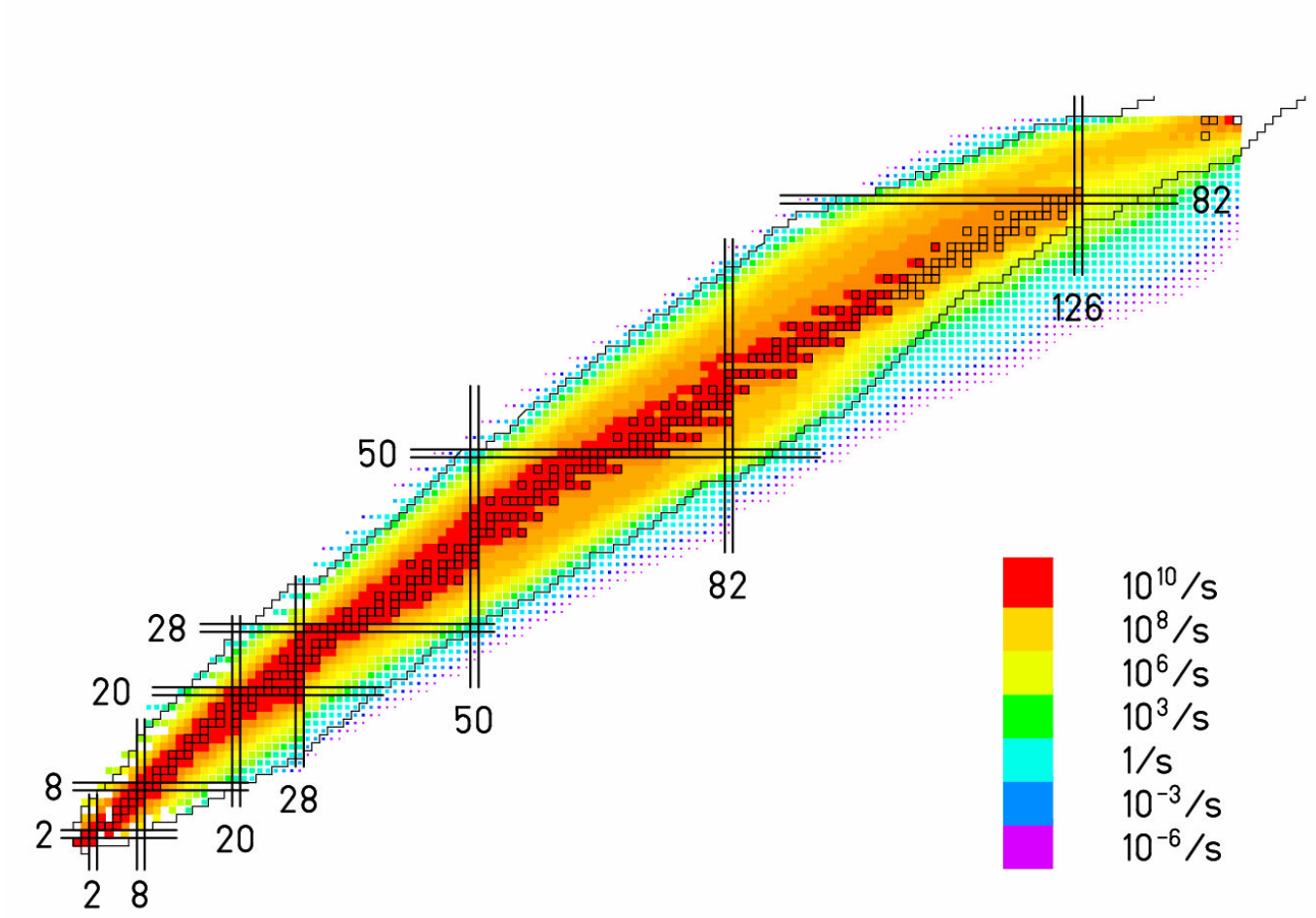
FAIR is dedicated to **research with ion and antiproton beams** on the **properties of matter in the dimensions of atoms, nuclei and sub-nuclear particles**.



Improvements for nuclear-data measurements:

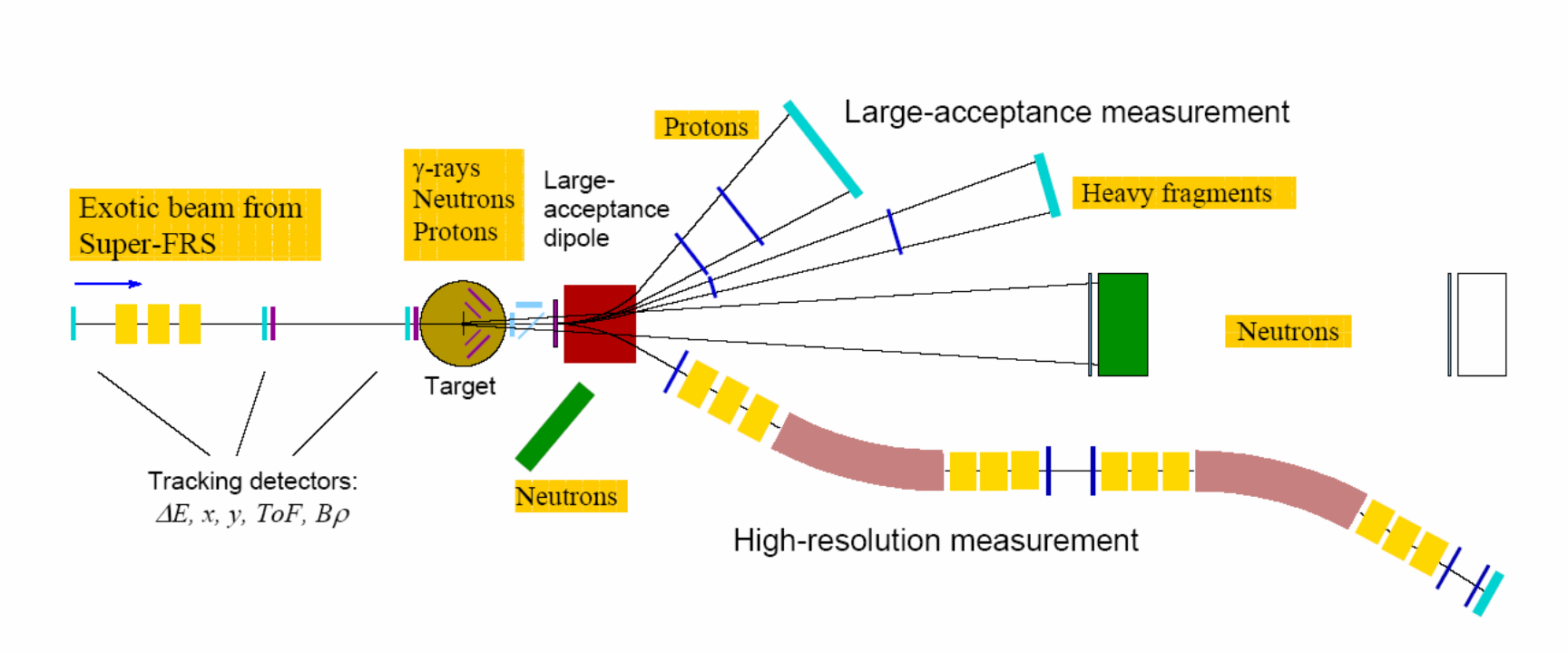
- Primary beams with higher intensities and higher energies.
- Extended variety of secondary beams.
- Powerful magnetic spectrometers, storage rings, colliders.

Estimated intensities of secondary beams at FAIR



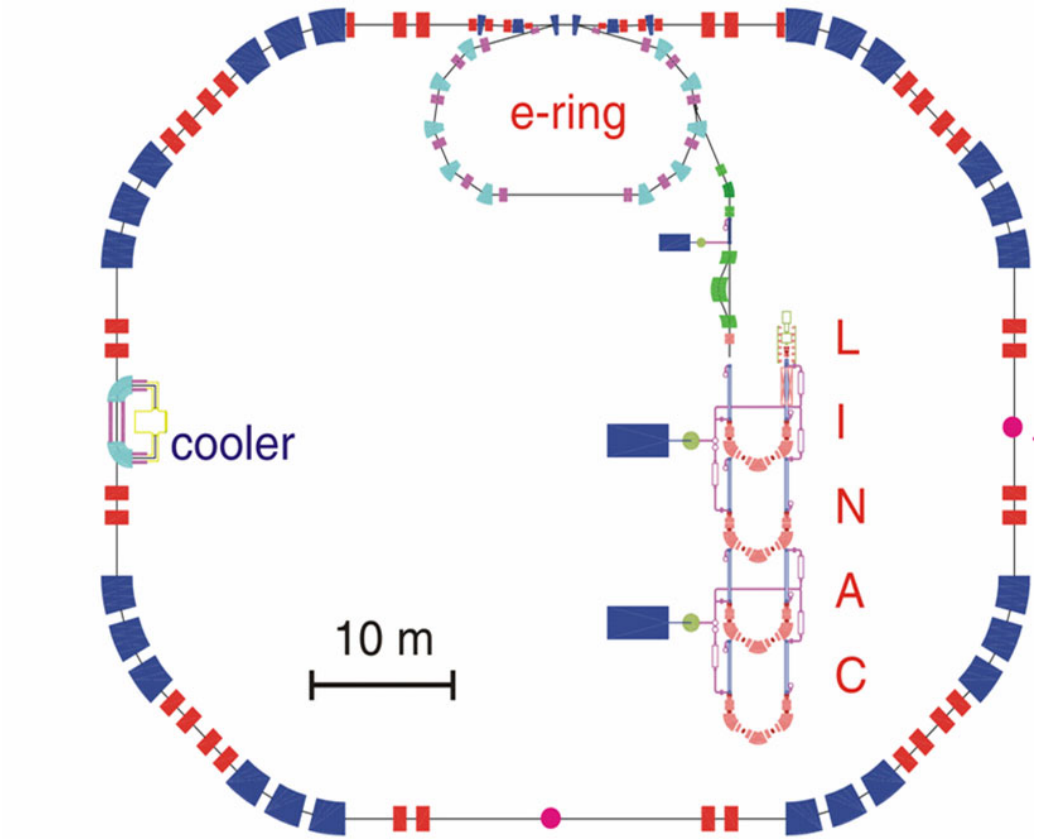
Excellent conditions for experiments on properties of exotic nuclei.

R^3B, part of the FAIR project of GSI
(Reaction studies with Relativistic Radioactive Beams)



Experimental complex with large-acceptance and high-resolution magnetic spectrometers.

ELISe: Electron-Ion collider, part of the FAIR project of GSI



Equipped with

- e-spectrometer
- fission detection system

→ First time that fission-fragment yields, resolved in Z and A, will be measured for specific systems (stable and radioactive) and well-defined excitation energies!

Excitation by tagged photons (inelastic electron scattering).

Summary

In a common effort, a French-Spanish-German collaboration is producing a set of high-quality data on spallation reactions at the GSI facility using

the FRS as a high-resolution spectrometer,
a large-acceptance fission set-up and
the large-acceptance SPALADIN set-up.

Extensive set of high-quality data used as a basis for improvements of codes:
INCL4.4 – advanced description of the collision stage (Cugnon, Boudard).
ABLA07 – consistent description of all deexcitation processes of a thermalized system (fission, evaporation of nucleons / LCPs / IMFs, multifragmentation).

The new accelerator facility FAIR will be an outstanding instrument for research on the properties of matter in the dimensions of atoms, nuclei and sub-nuclear particles with ion and antiproton beams.

It will also provide excellent conditions for research on nuclear data.