Reactions with Relativistic Radioactive Beams

Roy Lemmon
CCLRC Daresbury Laboratory

The high-energy branch of the Super-FRS:

A universal setup for kinematical complete measurements of

Reactions with Relativistic Radioactive Beams

Broad Scientific Themes of R3B

Single-Particle and Shell Structure

Collective Excitations

Equation of State

••• of Asymmetric Nuclei and Nucleonic Matter

The method: Scattering experiments with radioactive nuclei at high energy

heavy-ion inelastic (elm) scattering

peripheral and mid-central reactions

light ion induced scattering

•••

Merits of using high beam energies:

- luminosity gain: maximum transmission of secondary beams, use of thick targets
- high efficiency and full-solid angle acceptance due to kinematical forward focusing
- quantitative description of reaction mechanisms
- fully stripped ions even for heavy nuclei

→ compensating low beam intensities

→ experiments possible for very exotic nuclei with low production rates (down to ~1 ion/sec)

Broad Physics Programme

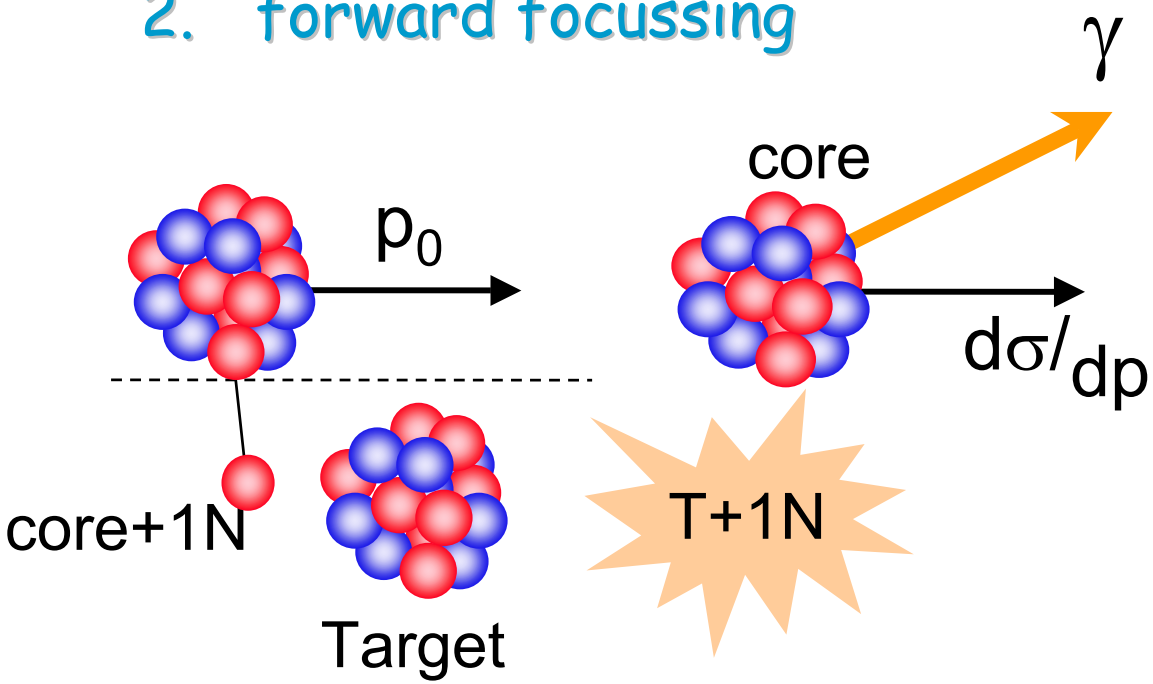
Reaction type	Type of Experiment
One-nucleon removal	Shell structure, valence-nucleon wave function, many-particle decay channels, unbound states, nuclear resonances beyond the drip lines
Quasi-free hadronic scattering	Single-particle spectral functions, shell-occupation probabilities, nucleon-nucleon correlations, cluster structures, in-medium properties
Total-absorption measurements	Nuclear matter radii, halo and skin structures
Elastic proton scattering	Nuclear matter densities, halo and skin structures
Heavy-ion induced electromagnetic excitation	Low-lying transition strength, single-particle structure, astrophysical S factor, soft coherent modes, low-lying resonances in the continuum, giant dipole (quadrupole) strength
Charge-exchange reactions	Gamow-Teller strength, soft excitation modes, spin-dipole resonance, neutron skin thickness
Projectile fragmentation, multi-fragmentation, collective flow	Equation-of-state, in-medium properties, thermal instabilities, structural phenomena in excited nuclei, γ-spectroscopy of exotic nuclei
Fission	Shell structure, dynamical properties
Spallation	Reaction mechanism, astrophysics, applications: nuclear waste transmutation, neutron spallation sources

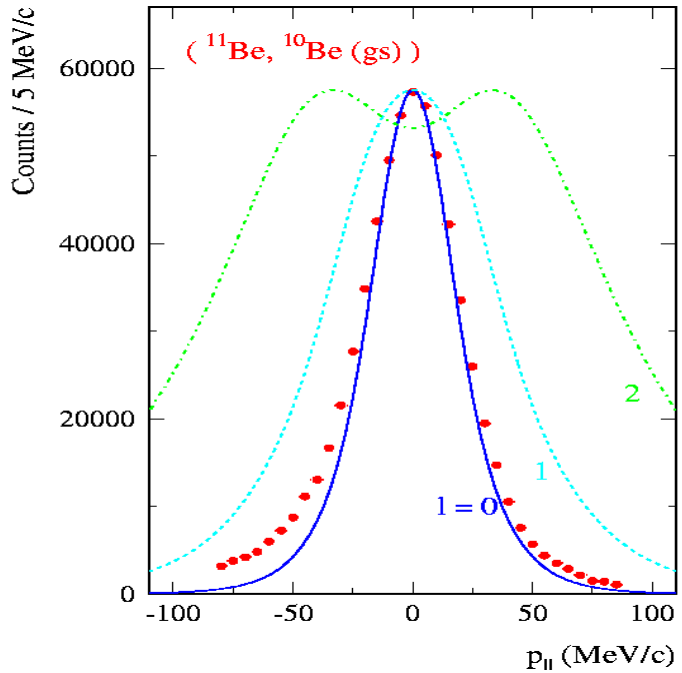
Broad Physics Programme

Reaction type	Type of Experiment
One-nucleon removal	Shell structure, valence-nucleon wave function, many-particle decay channels, unbound states, nuclear resonances beyond the drip lines
Quasi-free hadronic scattering	Single-particle spectral functions, shell-occupation probabilities, nucleon-nucleon correlations, cluster structures, in-medium properties
Total-absorption measurements	Nuclear matter radii, halo and skin structures
Elastic proton scattering	Nuclear matter densities, halo and skin structures
Heavy-ion induced electromagnetic excitation	Low-lying transition strength, single-particle structure, astrophysical S factor, soft coherent modes, low-lying resonances in the continuum, giant dipole (quadrupole) strength
Charge-exchange reactions	Gamow-Teller strength, soft excitation modes, spin-dipole resonance, neutron skin thickness
Projectile fragmentation, multi-fragmentation, collective flow	Equation-of-state, in-medium properties, thermal instabilities, structural phenomena in excited nuclei, γ-spectroscopy of exotic nuclei
Fission	Shell structure, dynamical properties
Spallation	Reaction mechanism, astrophysics, applications: nuclear waste transmutation, neutron spallation sources

One-Neutron Removal Reaction in Inverse Kinematics

1. σ_{-1n} ~ 10-100mb, ρ_s ~ 100 mg/cm2
2. forward focussing



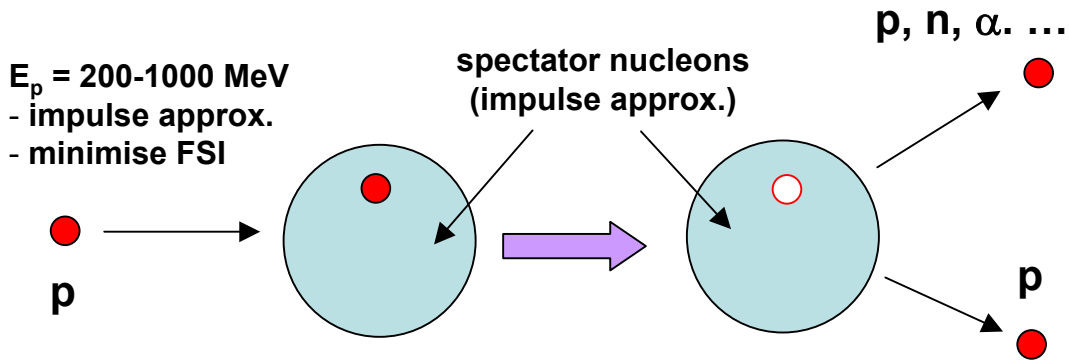


$\gamma \Rightarrow E^x_{core}$ $d\sigma/dp \Rightarrow \lambda_n$ $\sigma_{-1n}(J^\pi_{core}) \Rightarrow C^2S$

REVIEW: Hansen, Tostevin, Ann. Rev. Nucl. Part. Sci. (2003)

Quasifree Hadronic Scattering

Separation energies and momentum distributions of nucleons in nuclei :
Separation energy spectra give levels
Angular correlation spectra give l-values



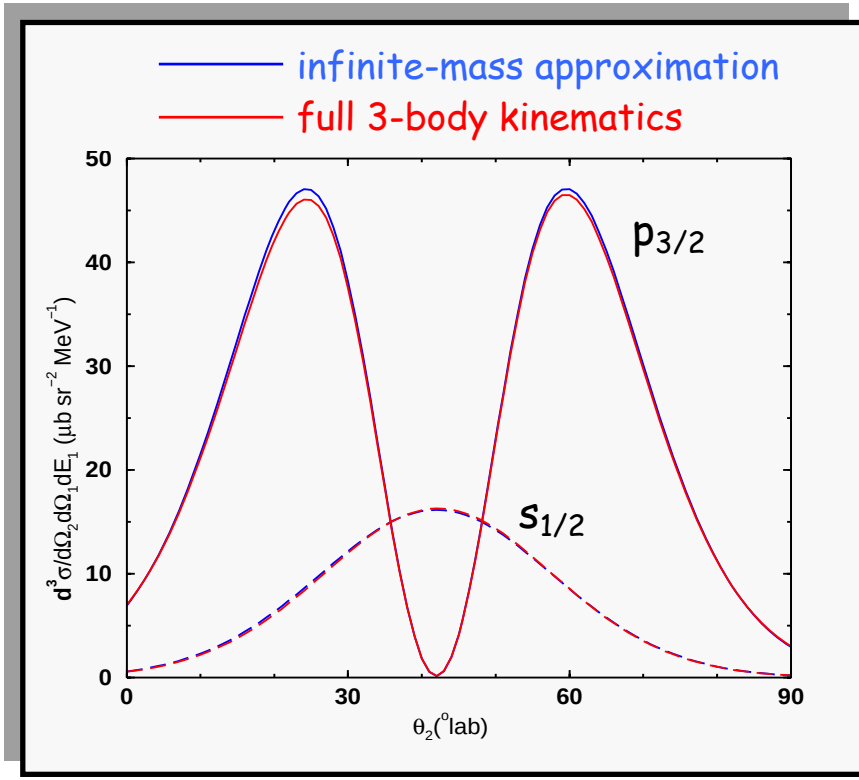
Can probe valence *and* deeply-bound nucleons
Simple picture is modified by nuclear medium :
distortion of distributions, absorption etc.

DWIA :

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_2} = \underbrace{S_p F_k}_{\text{spectroscopic factor}} \underbrace{\frac{d\bar{\sigma}_{pp}}{d\Omega}\left(E_0, \theta, P_{eff}\right)}_{\text{free n-n cross-section}} \underbrace{G(\mathbf{k}_3)}_{\text{distorted proton momentum distribution}}$$

- **Single particle structure in nuclei**
- **Long- and short-range correlations in nuclei**
- **Density and isospin dependence of in-medium n-n interaction**
- **Modification of meson and nucleon properties in nuclear medium**

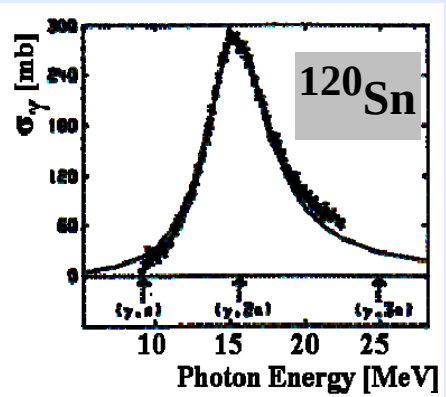
Calculations: Surrey Theory Group

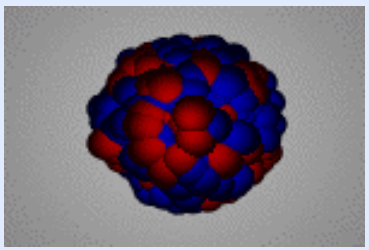


The Dipole Response of Neutron-Rich Nuclei

Stable nuclei:

100% of the E1 strength absorbed into the **Giant Dipole Resonance** (GDR)



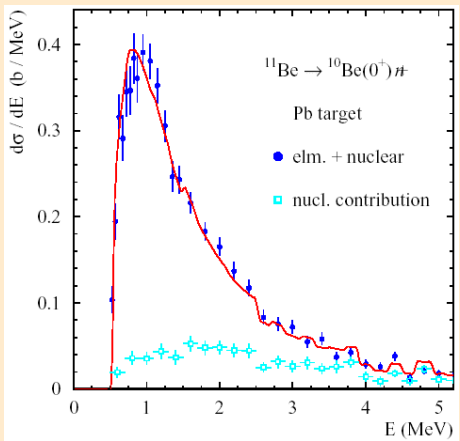


Neutron-Proton asymmetric nuclei: low-lying dipole strength

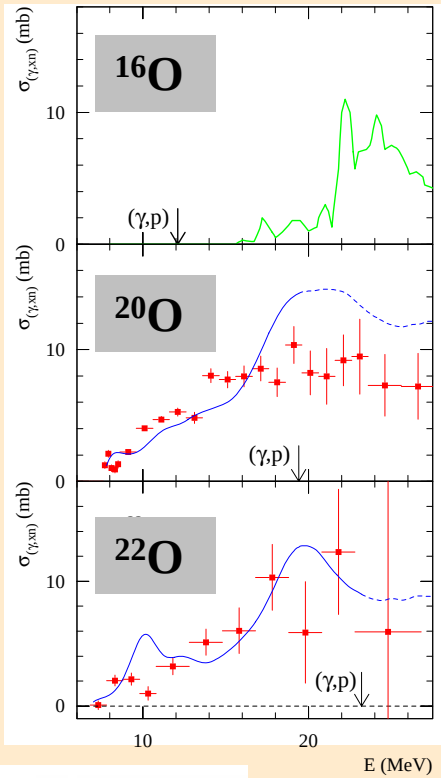
! threshold strength

non-resonant transitions

The one-neutron Halo ^{11}Be



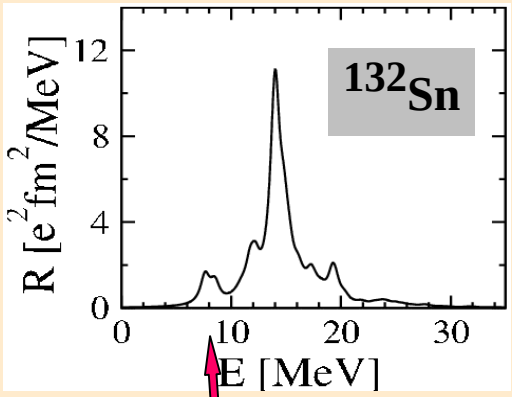
! strong fragmentation



? new collective soft dipole mode

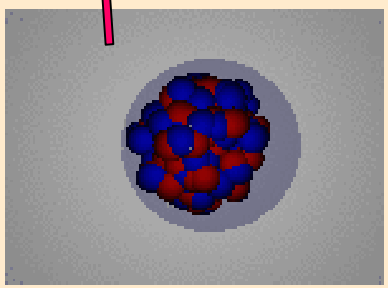
(Pygmy resonance)

Prediction: RMF (N. Paar et al.)

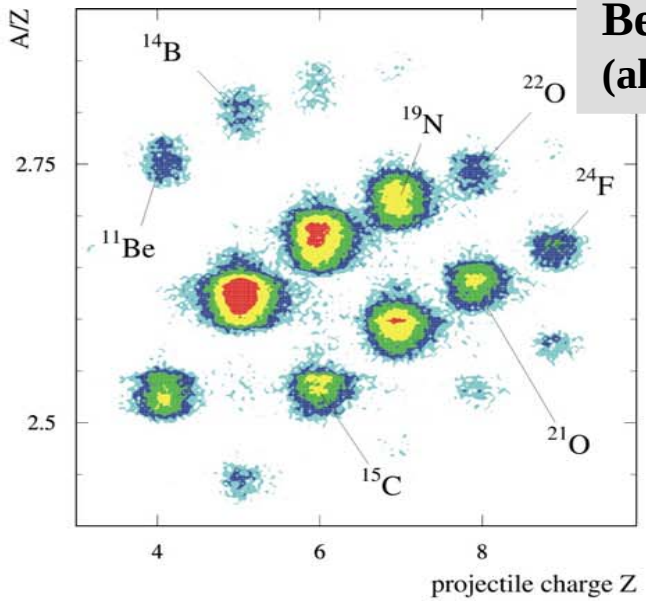


spectroscopic tool:

$$\frac{d\sigma}{dE^*}(I_c^\pi) = (\frac{16\pi^3}{9\hbar c})N_{E1}(E^*)\sum_{nlj} C^2S(I_c^\pi, n\ell j) \times \sum_m |\langle \boldsymbol{q}|(Ze/A)rY_m^1|\phi_{n\ell j}(r)\rangle|^2.$$



LAND/ALADIN Reaction Setup



Beam cocktail (all unstable !)

(^{40}Ar primary beam)

PLASTICWALL (CHARGED PARTICLES)

ToF, ΔE

LAND (NEUTRONS)

ToF, x, y, z

Charged fragments

tracking → Bρ ~ A/Qβγ

Photons

projectile tracking

ALADIN

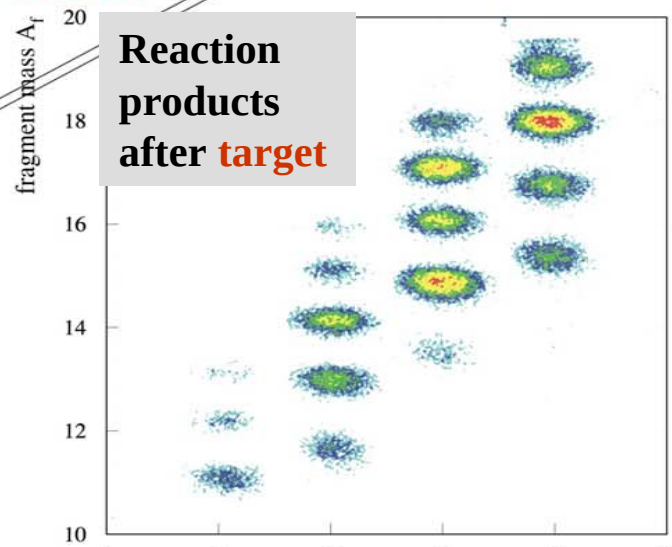
^{20}O beam

CRYSTAL BALL and TARGET

~20 m

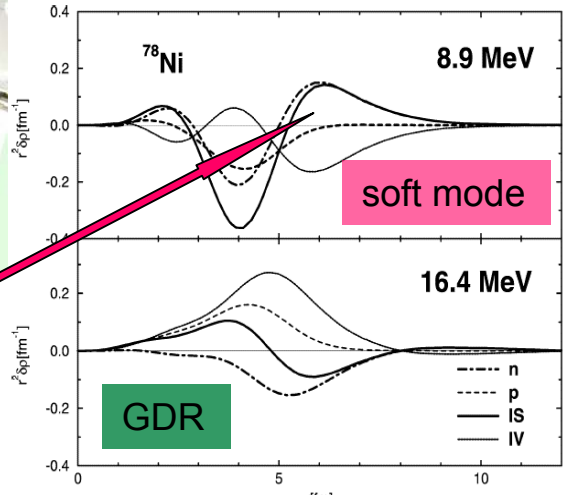
EXOTIC BEAM

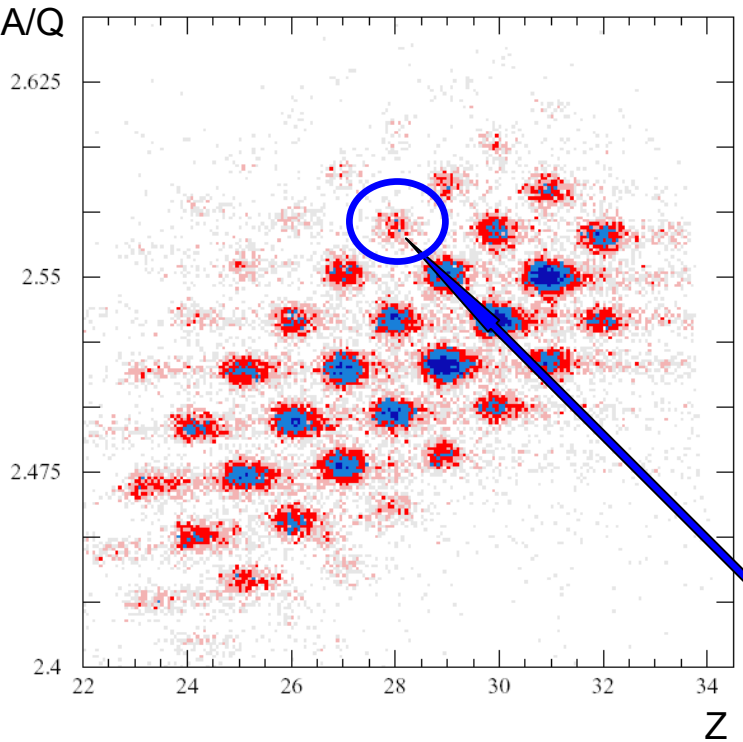
Reaction products after target

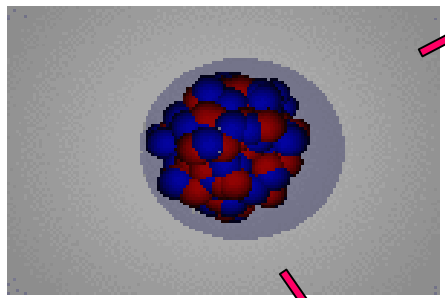


First LAND experiment in Cave C in April/May 2005: Search for the collective soft dipole mode in n-rich Ni isotopes

Relativistic mean field calculations: Vretenar et al.



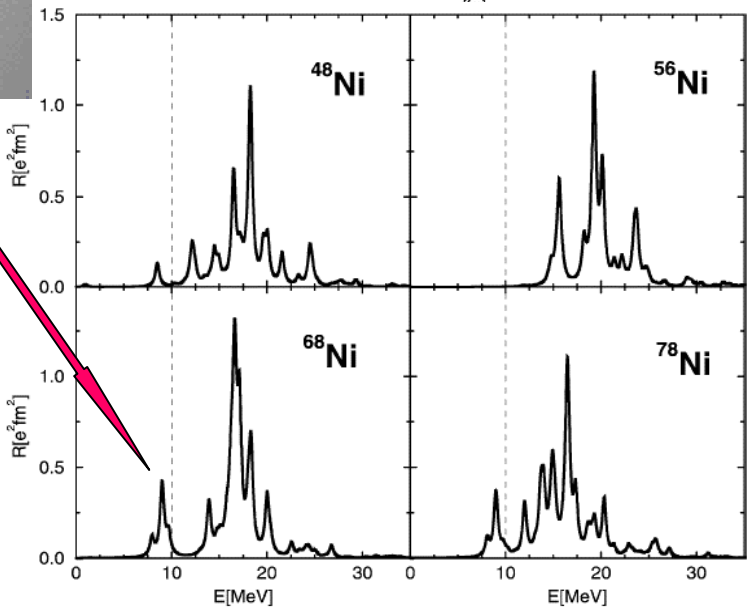




Mixed secondary beam in Cave C

^{72}Ni @500 MeV/u

(~20 ions/sec)



Evolution of LAND/ALADIN to R3B …

New Dedicated LAND-ALADIN Setup in Cave C
First experiments made 2005 …
R3B is continuous upgrade of this setup before final move to FAIR area

Already substantial UK involvement – present focus on QFS programme:

- Participation by UK groups in first LAND/ALADIN experiment in Cave C, April/May 2005
  - n-rich Ni isotopes: collective soft dipole modes, one-nucleon removal reactions
- One-nucleon removal reactions part of first experiment: proton target, QFS
  - being analysed in Liverpool by S. Paschalis (PhD student)
- Initial Experiment of QFS Programme Approved. Will run late 2006 / early 2007
  - Spokesperson: R. Lemmon (Daresbury)
- Prototype Si μ-strip detectors/readout bought by UK for target recoil detector. To be installed for initial QFS experiment
  - Liverpool, Birmingham, Surrey and Daresbury groups
- Substantial theoretical involvement by Surrey theory group in QFS programme

Also large involvement of UK groups in Active Target Projects:

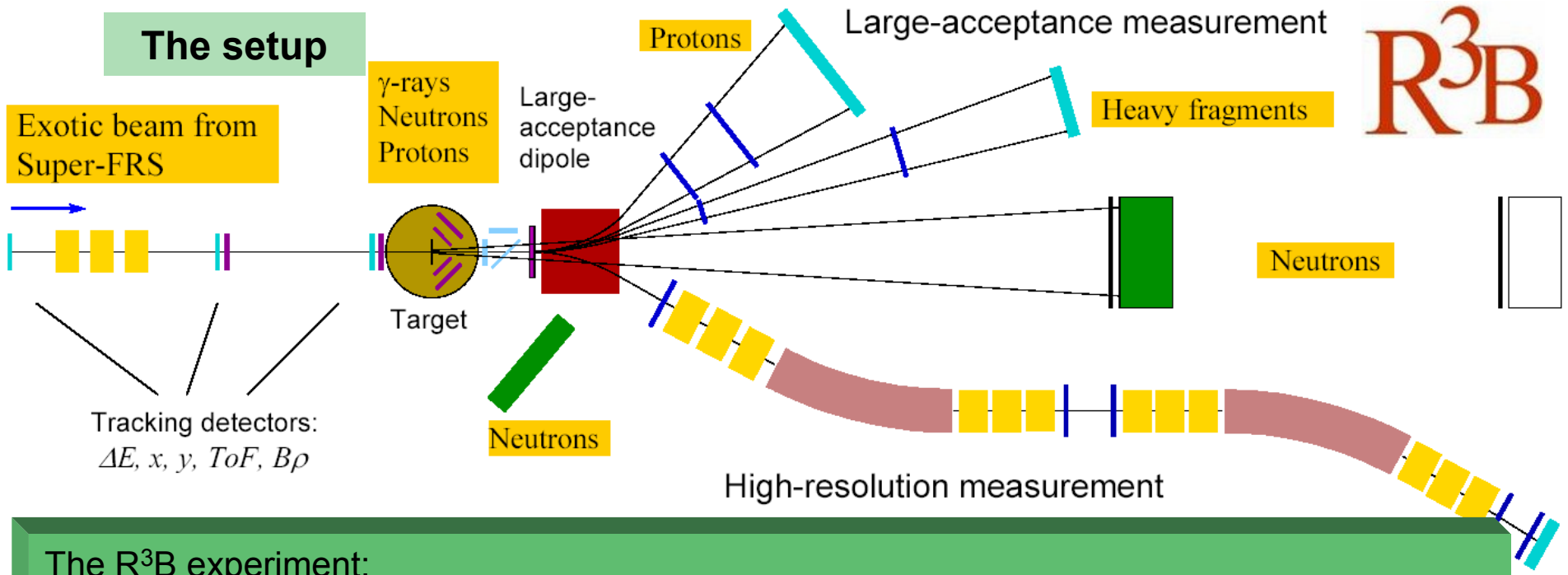
- ACTAR of JRA EURONS 6th Framework: R&D in simulation, readout chambers, ASIC/FEE/DAQ
- Liverpool, Birmingham, Daresbury
- B. Fernandez-Dominguez (postdoc - Liverpool)
- Experiments with prototype MAYA at GANIL

Physics output from now to FAIR Day One and beyond …

The high-energy branch of the Super-FRS:

A universal setup for kinematical complete measurements of

Reactions with Relativistic Radioactive Beams



The R^{3}B experiment:

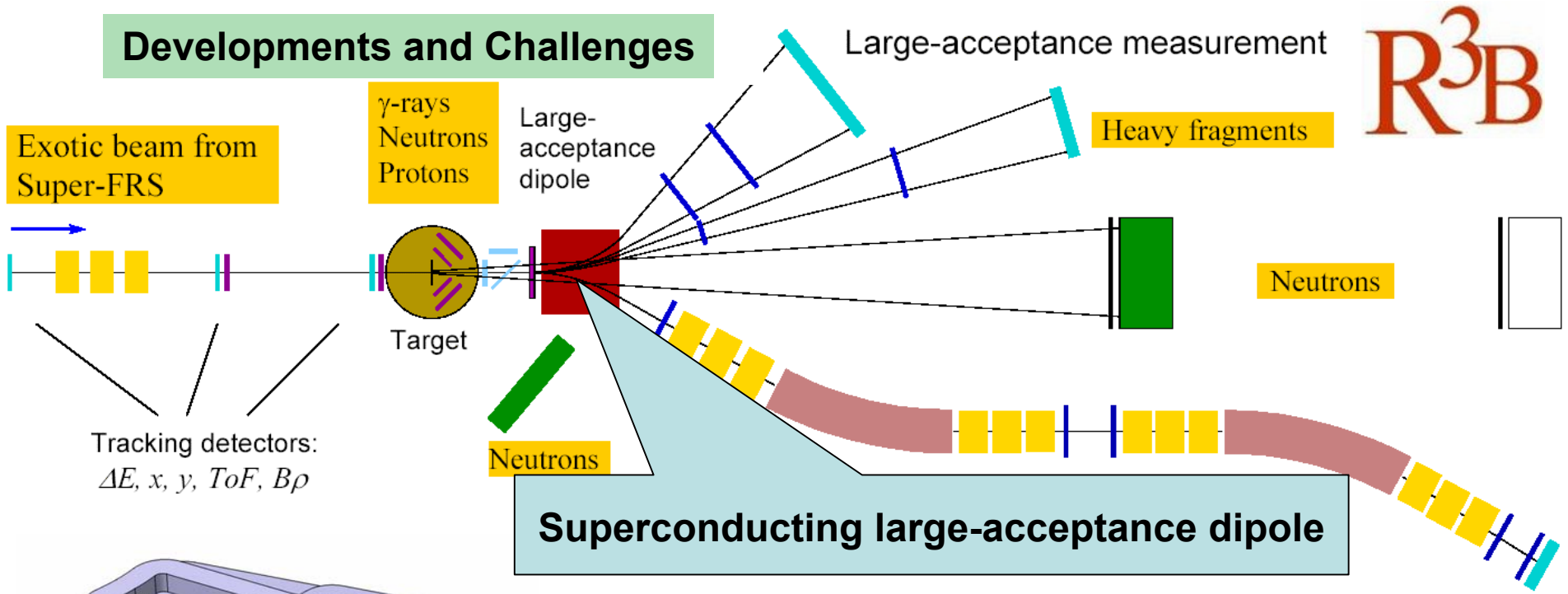
- identification and beam "cooling" (tracking and momentum measurement, $\Delta p/p \sim 10^{-4}$)
- exclusive measurement of the final state:
  - identification and momentum analysis of fragments
    (large acceptance mode: $\Delta p/p \sim 10^{-3}$, high-resolution mode: $\Delta p/p \sim 10^{-4}$)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

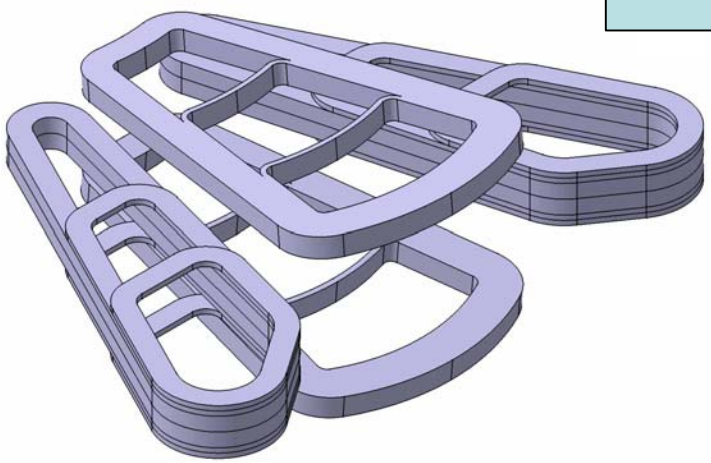
The high-energy branch of the Super-FRS:

A universal setup for kinematical complete measurements of

Reactions with Relativistic Radioactive Beams

Developments and Challenges





High field integral (5 Tm) → <u>high beam energies</u>

Active shielding → dipolar field, low fringe fields

Large acceptance → full-acceptance measurements

Superconducting coils → low operation cost

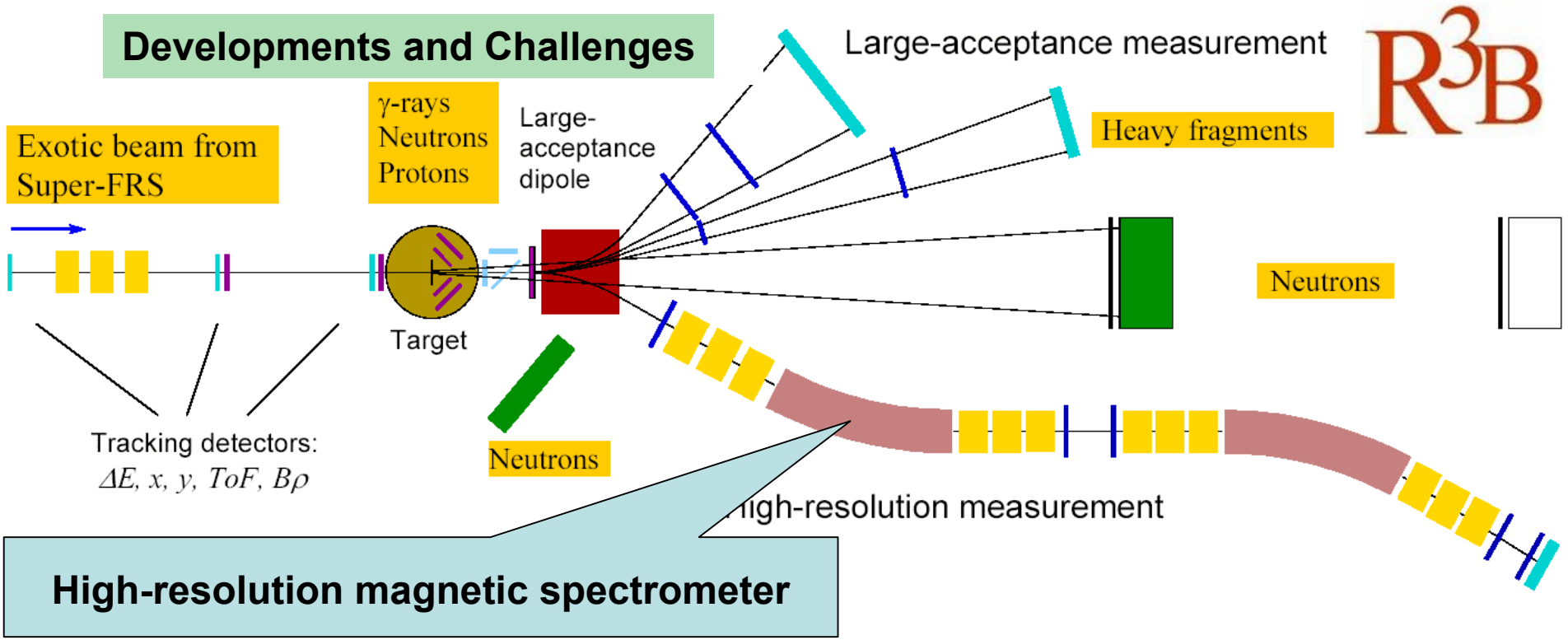
18° bend for 15 Tm beams (~1 GeV/u ^{132}Sn)

The high-energy branch of the Super-FRS:

A universal setup for kinematical complete measurements of

Reactions with Relativistic Radioactive Beams

Developments and Challenges



High-resolution magnetic spectrometer

Design goals:

momentum resolution $\Delta p/p \sim 10^{-4}$
dispersion matching? or <u>tracking</u>

acceptance: ≥ Super-FRS

Initial design close to Super-FRS

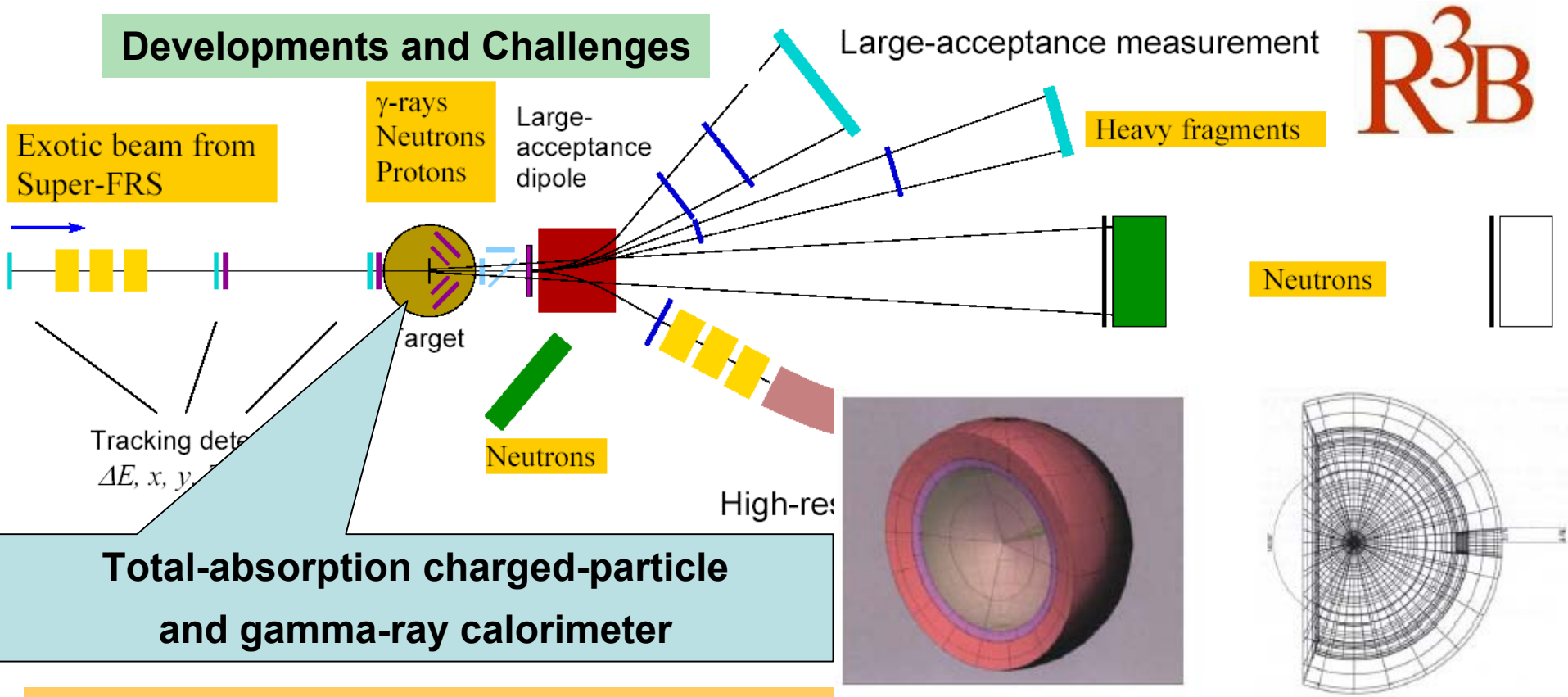
Possible involvement of Cockroft Accelerator Institute ?

The high-energy branch of the Super-FRS:

A universal setup for kinematical complete measurements of

Reactions with Relativistic Radioactive Beams

Developments and Challenges



Total-absorption charged-particle and gamma-ray calorimeter

High efficiency for high-energy γ (~15 MeV lab)

High γ-sum energy efficiency

Good resolution (~2% including Doppler broadening)

Calorimeter for high-energy protons

common development phase for EXL, R3B, DESPEC

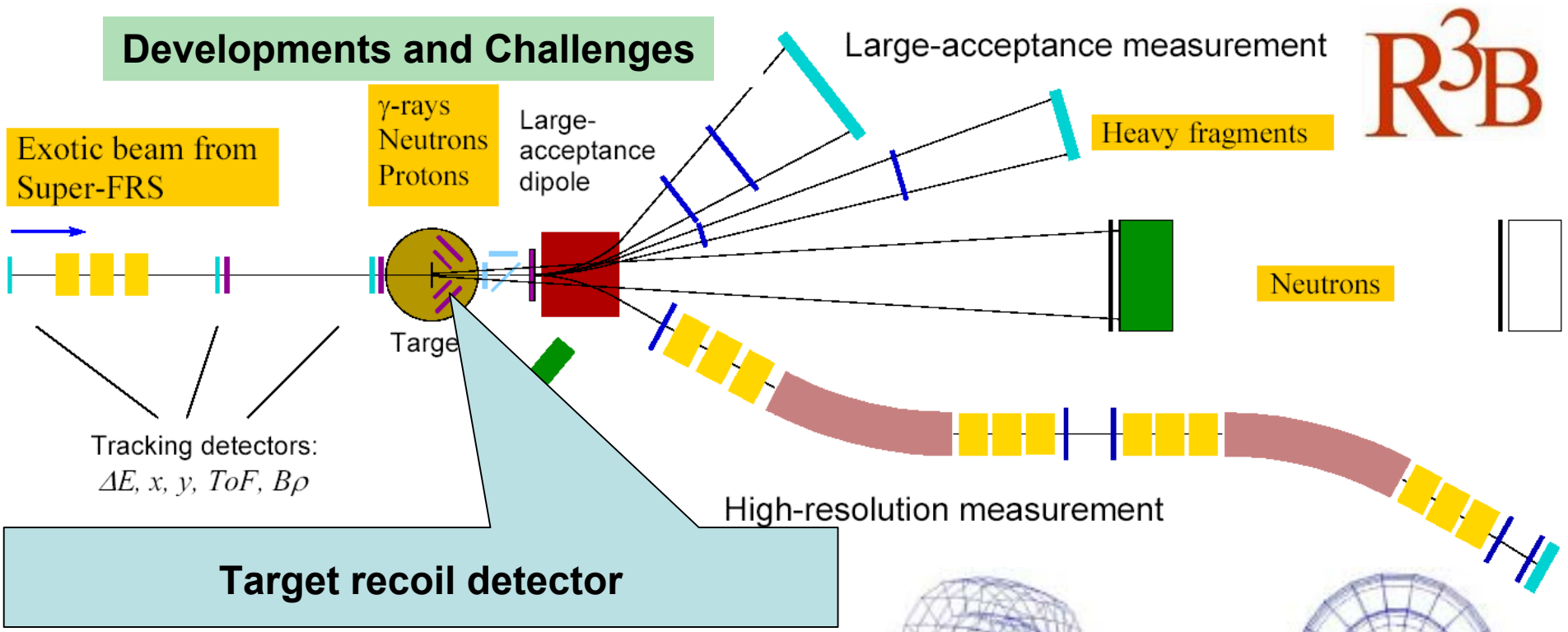
possible solution: cooled NaI or CsI, very high granularity (~ 10.000)

The high-energy branch of the Super-FRS:

A universal setup for kinematical complete measurements of

Reactions with Relativistic Radioactive Beams

Developments and Challenges



measurement of recoiling protons after (in)-elastic scattering or quasi-free knockout

determination of angles by two layers of Si-strip detectors

total energy measurement using the γ calorimeter

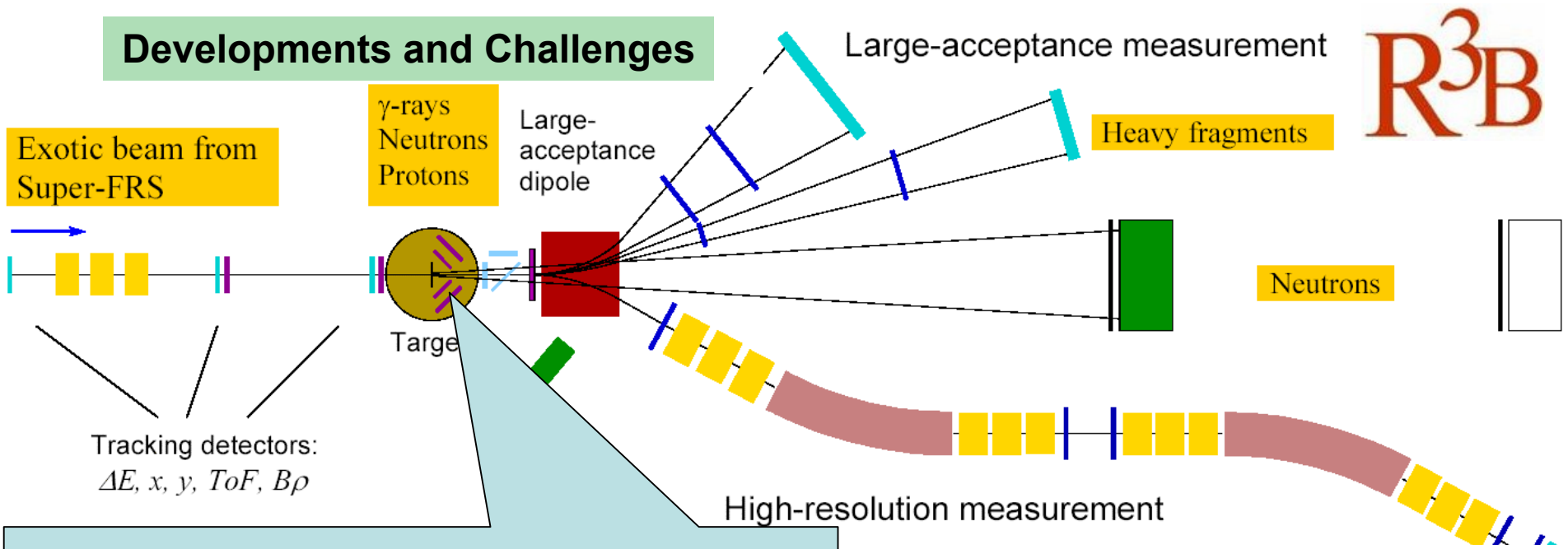
for (p,n) reactions: low-energy n detector (plastic scintillator)

The high-energy branch of the Super-FRS:

A universal setup for kinematical complete measurements of

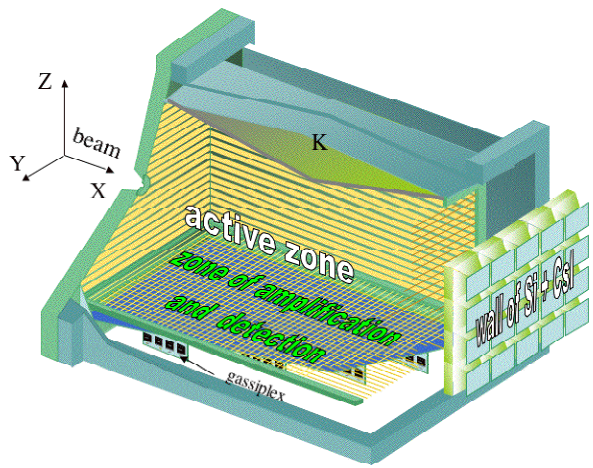
Reactions with Relativistic Radioactive Beams

Developments and Challenges



Alternatively: Active Target

measurement of recoils in reactions with low-momentum transfer



Complementarity with EXL: See talk of M. Chartier

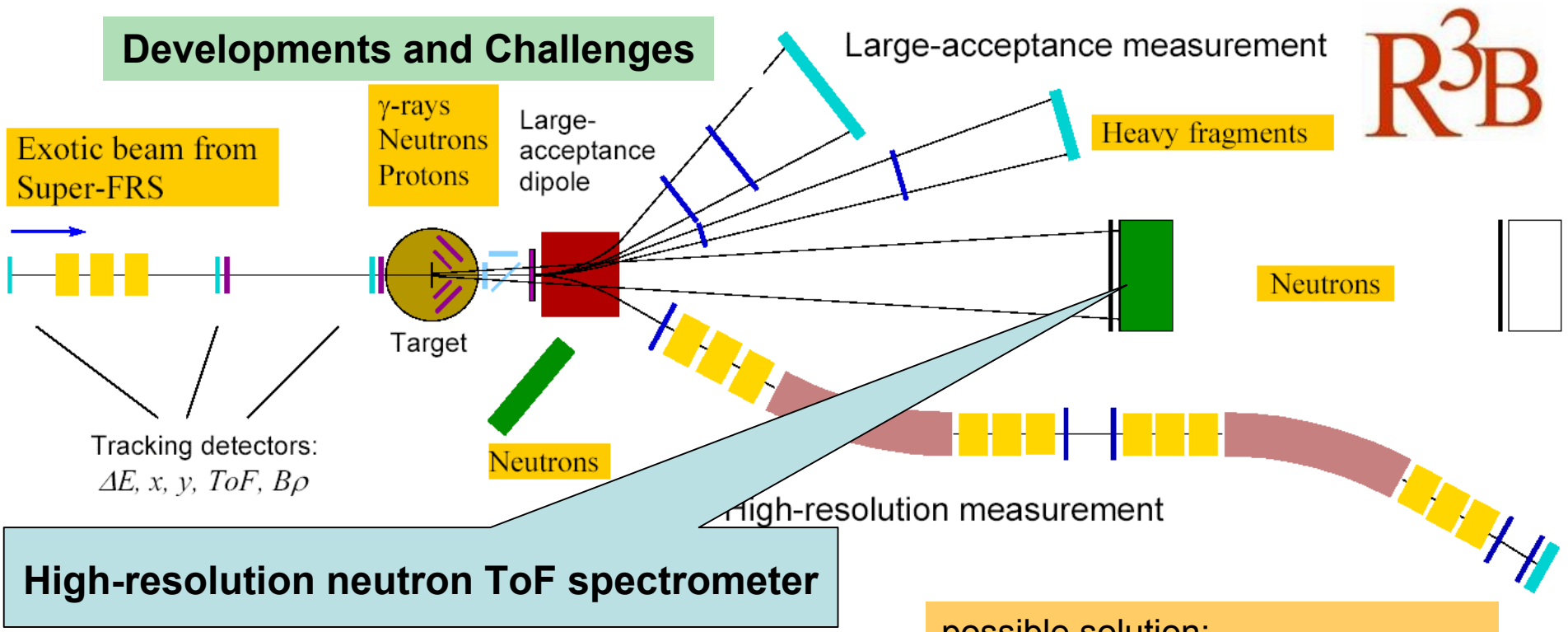
R&D supported by ACTAR JRA of EURONS 6th Framework – substantial involvement of UK groups

The high-energy branch of the Super-FRS:

A universal setup for kinematical complete measurements of

Reactions with Relativistic Radioactive Beams

Developments and Challenges



High-resolution neutron ToF spectrometer

goal: improvement in time- and position resolution by a factor of three compared to LAND

→ improved resolution in excitation energy

→ improved multi-hit recognition

possible solution:

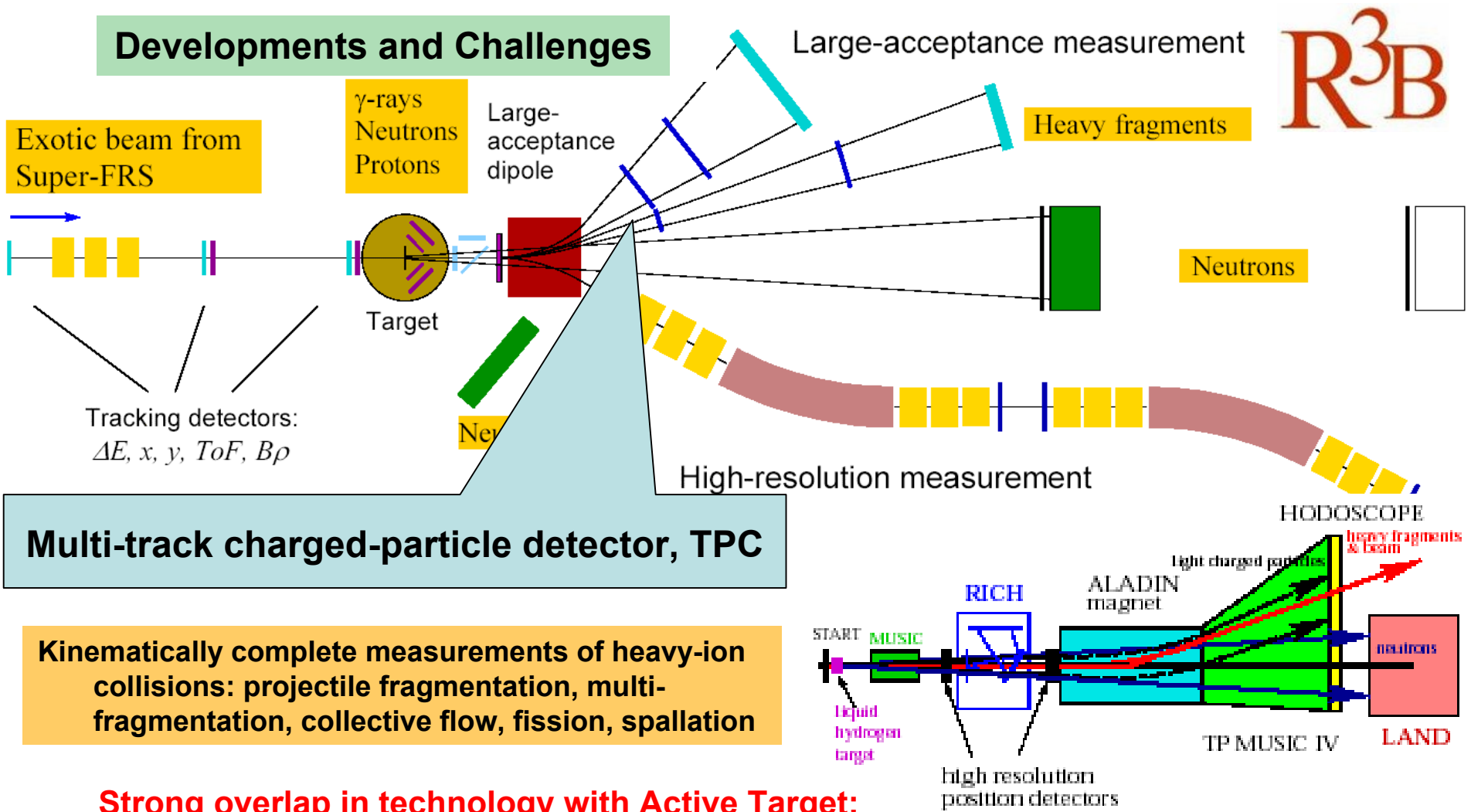
converter plus detection of charged particles using RPCs

The high-energy branch of the Super-FRS:

A universal setup for kinematical complete measurements of

Reactions with Relativistic Radioactive Beams

Developments and Challenges



Multi-track charged-particle detector, TPC

Kinematically complete measurements of heavy-ion collisions: projectile fragmentation, multi-fragmentation, collective flow, fission, spallation

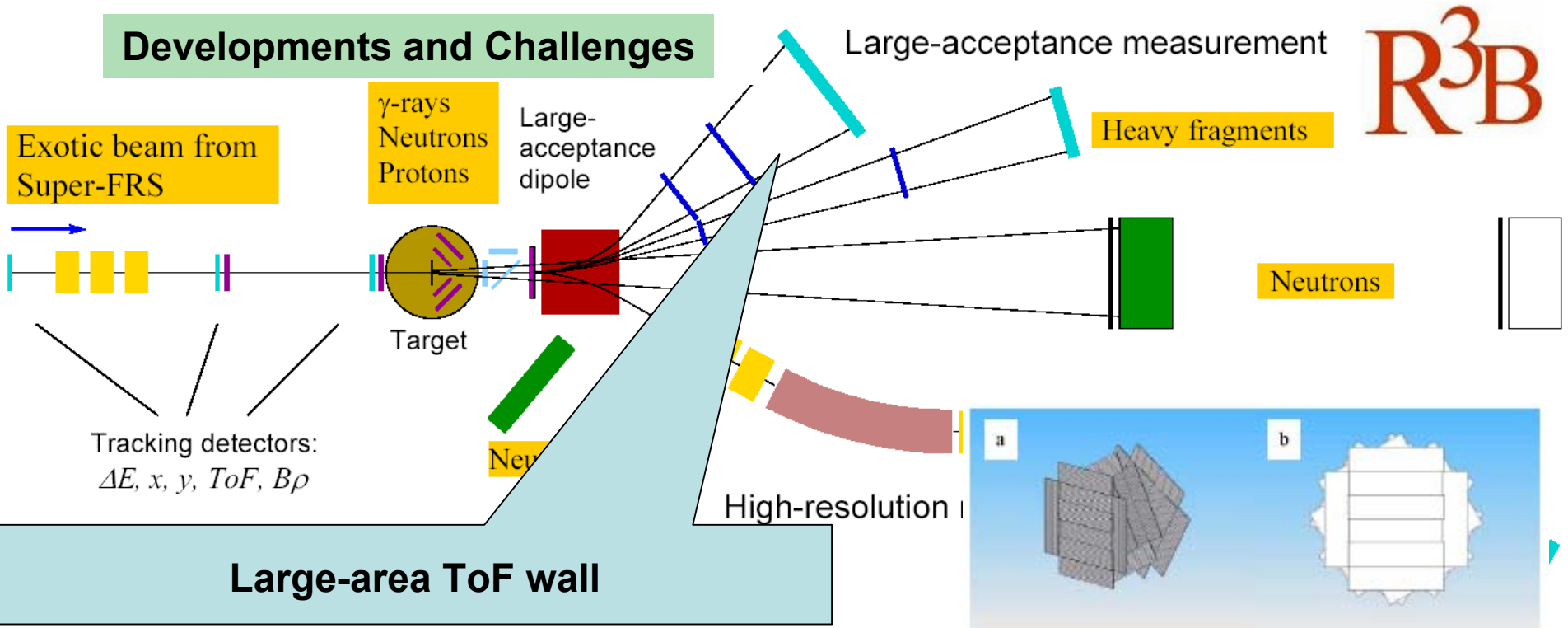
Strong overlap in technology with Active Target: readout chambers (GEMs, μMegas), ASICs, FEE/DAQ, …

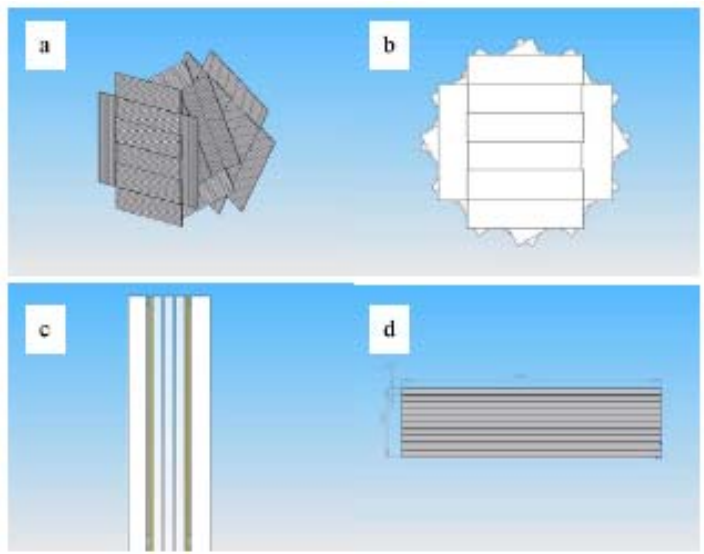
The high-energy branch of the Super-FRS:

A universal setup for kinematical complete measurements of

Reactions with Relativistic Radioactive Beams

Developments and Challenges





Large-area ToF wall

kinematical complete measurement of spallation reactions and fission

high-resolution ToF measurement of charged particles

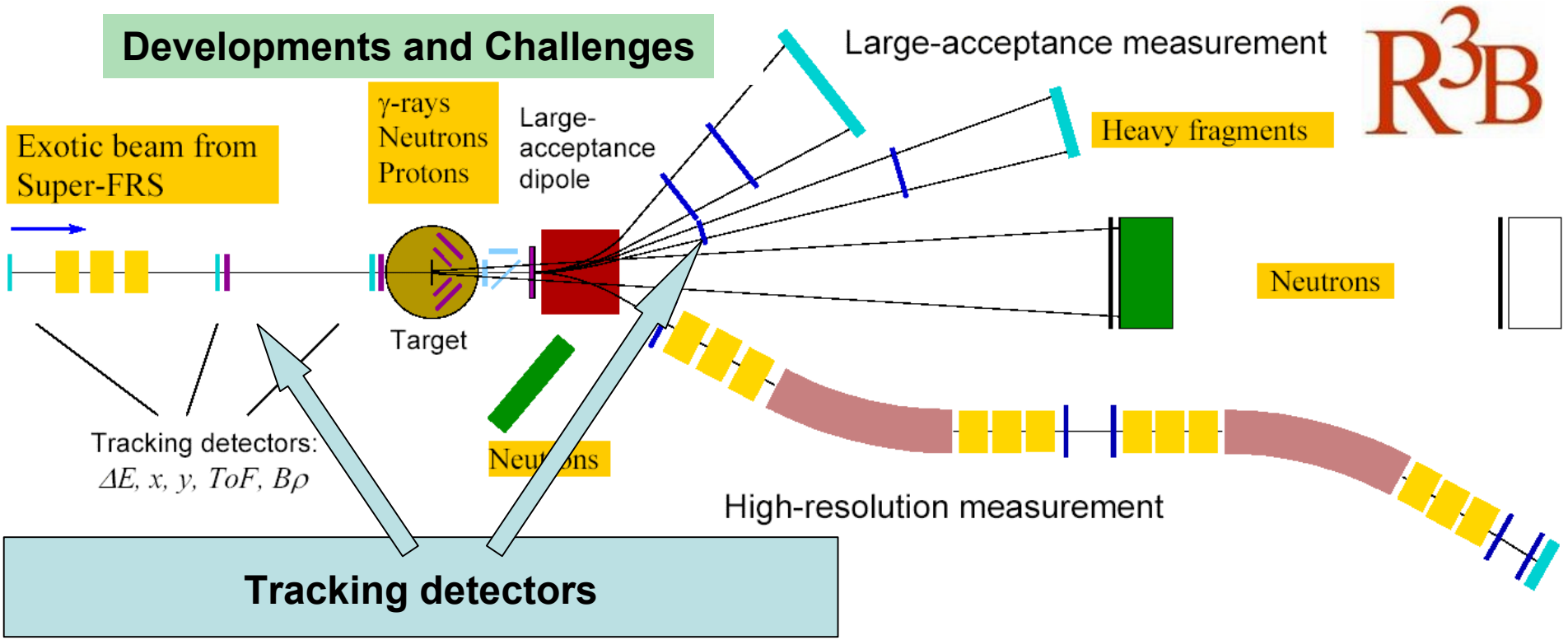
RPC based detection principle considered

The high-energy branch of the Super-FRS:

A universal setup for kinematical complete measurements of

Reactions with Relativistic Radioactive Beams

Developments and Challenges



Diamond detectors

Si-strip detectors

Low-mass tracking detectors

Drift chambers

Momentum Resolution

tracking through dipole field: 4 position measurements

momentum resolution limited by straggling in detectors

detector thickness 200 μm (σ_x=50 μm) → $\Delta B\rho/B\rho \sim 0.8\times10^{-3}$

50 μm (σ_x=15 μm) → $\Delta B\rho/B\rho \sim 0.4\times10^{-3}$

The high-energy branch of the Super-FRS:

A universal setup for kinematical complete measurements of

Reactions with Relativistic Radioactive Beams

Summary

Key features of the experimental approach

- capable to accept the maximum beam energy (max rigidity of Super-FRS: 20Tm)

  max transmission for fission products (max intensity)
- and full emittance: 'individual cooling' (tracking and momentum measurement, $\Delta p/p \sim 10^{-4}$)
- access to short-lived nuclei (flight path ~μs)
- use of thick targets (~ g/cm^2) → luminosity gain
- kinematical complete measurement
- full-solid angle measurement plus high detection efficiency
- quantitative description of reaction mechanisms
- fully stripped ions even for heavy nuclei
- large cross sections for many reactions (e.g. elm excitation ~1 b, knockout ~100 mb)

→ **compensating low beam intensities**

→ **experiments possible for very exotic and short-lived nuclei** (even with low rates, ~1 ion/sec)

Collaboration

The R^{3}B Collaboration

Aarhus, Denmark, University of Aarhus
D.V. Fedorov, H.O.U. Fynbo, A.S. Jensen, K.-H. Langanke, K. Riisager

Argonne, USA, Argonne National Laboratory
J. Nolen

Bergen, Norway, University of Bergen
J.S. Vaagen

Birmingham, UK, University of Birmingham
M. Freer

Caen, France, GANIL
D. Boilley, C.E. Demonchy, W. Mittig, P. Roussel-Chomaz, H. Savajols

T. Aumann, F. Becke
M. Gorska, V. Henzl, J.
T. Neff, M.V. Ricciardi,

A. Algora,

Dresden, Germany, Forschungszentrum Rossendorf
E. Grosse, A. Wagner

Dubna, Russia, Joint Institute for Nuclear Research
S.N. Ershov, L. Grigorenko

East Lansing, USA, NSCL, MSU
B. Sherrill

Gatchina, Russia, Petersburg Nuclear Physics Institute, P
A. Khanzadeev

Giessen, Germany, Justus-Liebig-Universität
H. Lenske, M. Winkler

Gif sur Yvette, France, DAPNIA, CEA Saclay
N. Alamanos, A. Boudard, J.-E. Ducret, B. Gastineau, E. Le Gentil, V. Lap
E. Pollacco, C. Volant

Göteborg, Sweden, Chalmers University of Technology
H. Johansson, B. Jonson, M. Meister, G. Nyman, M. Zhukov

Guildford, UK, University of Surrey
J. Al Khalili, W. Catford, W. Gelletly, R. Johnson, M. Oi, Z. Podolyak, P. Regan, P. Stevenson, I. Thompson, J. Tostevin, P. Walker

Heidelberg, Germany, Max-Planck-Institut
Heiko Scheit

Keele, UK, University of Keele
M. Bentley

Köln, Germany, Universität zu Köln
P. Reiter

Kolkata, Saha Institute of Nuclear Physics, India
U. Datta Pramanik

Krakow, Poland, Jagellonski University
P. Adrich, M. Kajetanowicz, A. Klimkiewicz, K. Korcyl, R. Kulessa

Krakow, IFJ PAN Krakow
A. Maj

Liverpool, UK, University of Liverpool
M. Chartier, P. Nolan

Lyon, IPN Lyon, France
Ch. Schmitt

Madrid, Spain, Instituto de Estructura de la Materia, CSIC
M.J.G. Borge, L.M. Fraile, E. Garrido, O. Tengblad

g Universität

anchester

stitute

ssian Academy of Sciences

mental Research

München, Germany, TU München
M. Böhmer, T. Faestermann, J. Friese, R. Gernhäuser, T. Kröll, R. Krücken

Obninsk, Russia, IPPE Obninsk
A. Ignatyuk

Orsay, France, IN2P3/IPN Orsay
Ch.-O. Bacri, Y. Blumenfeld, E. Khan, F. Rejmund, J.A. Scarpaci

Paisley, UK, University of Paisly
R. Chapman, M. Labiche, X. Liang, K. Spohr

Pyhäsalmi, Finland, CUPP project
T. Enqvist

RIKEN, Japan
R. Kanungo

Santiago de Compostela, Spain, Univers. of SdC
J. Benlliure, D. Cortina-Gil, I. Duran

Valencia, Spain, CSIC-University
B. Rubio, J.L. Tain

Yale University, USA
A. Heinz

York, UK, University of York
Ch. Barton

Spokesperson: T. Aumann E-Mail: t.aumann@gsi.de
Deputy: B. Jonson E-Mail: bjn@fy.chalmers.se

Management Board
Spokesperson: T. Aumann (GSI)
Deputy: B. Johnson (Chalmers)
Chair of Technical Board: R. Lemmon (Daresbury)

~150 people

49 institutes

19 countries

Slides after this are not part of the talk