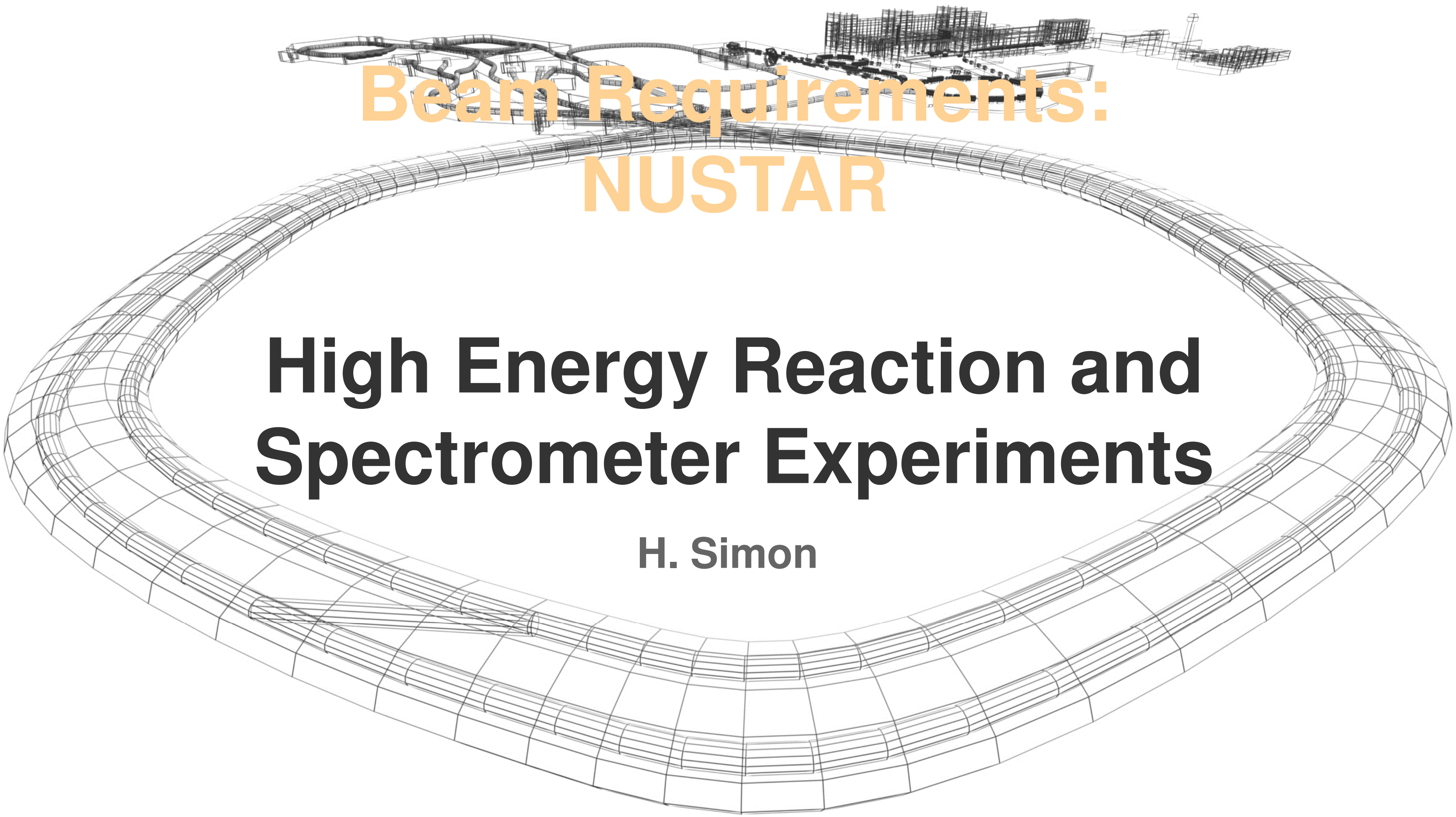
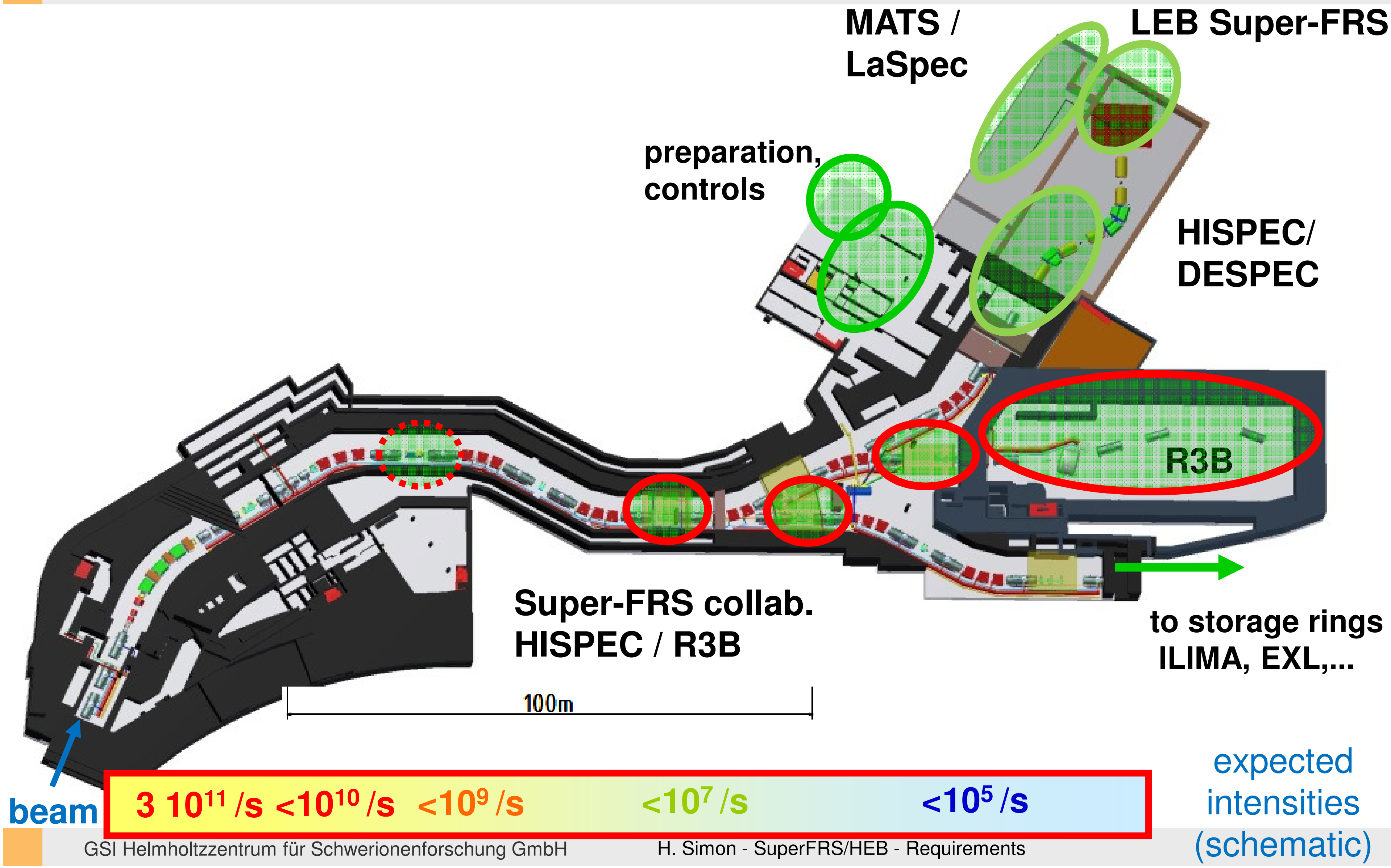


# Beam Requirements: NUSTAR

## High Energy Reaction and Spectrometer Experiments

H. Simon

# Experiment locations



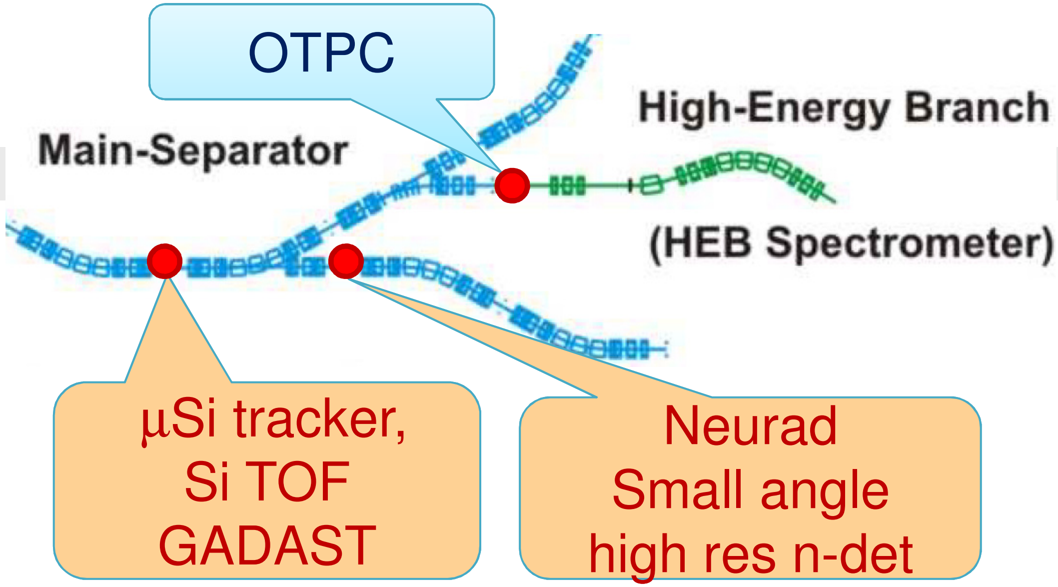
# The Super-FRS Experiments physics topics

- Rare isotope search experiments (Pietri, Jokinen, Plaß et al.)
- Atomic collision experiments (Purushothaman, Geissel et al.)
- Mesonic atoms and in-medium effects (Itahashi, Weick et al.)
- Exotic hypernuclei and their properties (Saito, Nociforo et al.)
- Exploration of tensor force (Ong,Terashima, Toki, et al.)
- Delta resonances probing nuclear structure (Benlliure, Lenske et al.)
- Nuclear radii and momentum distributions (Kanungo, Prochazka et al.)
- Exotic radioactivity modes (Fomichev, Pfützner, Mukha et al.)
- Low-q experiments with Active Target (Egelhof et al.)
- Low energy reactions (Heinz, Winfield et al.)

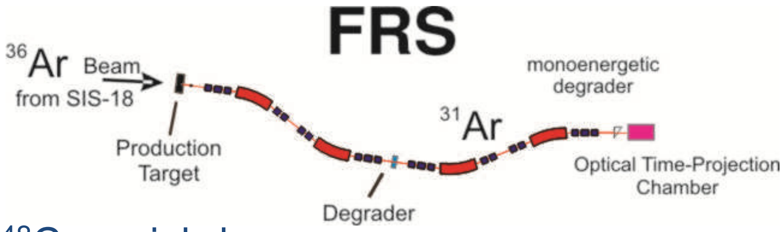
Ideas currently being worked out
Selected examples with specific requirements will be shown …

# EXPERT
# (**EXotic** Particle Emission and Radioactivity by **Tracking**)

I. Mukha




Experiment@FRS→ Super-FRS carried out at the main separator

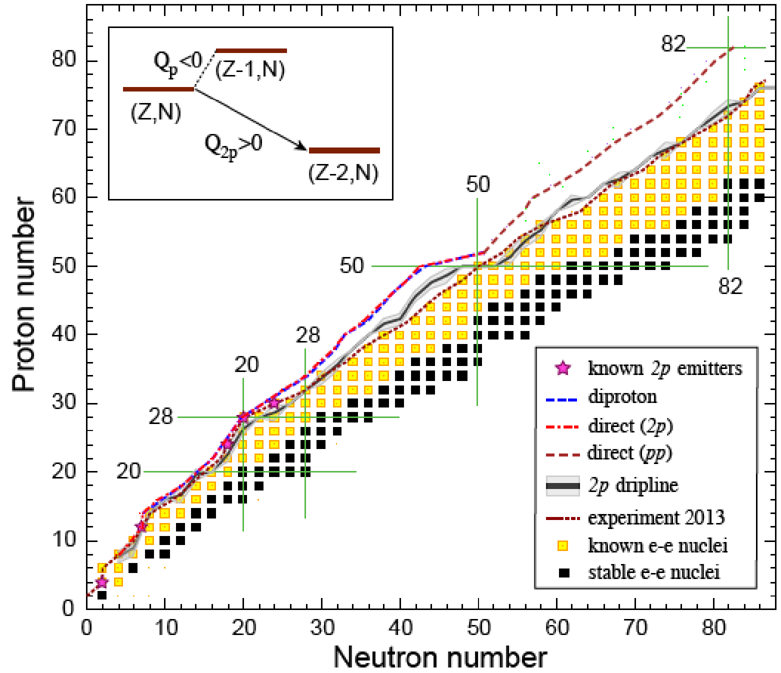



$^{48}$Ca n-rich !

**Two-proton radioactivity e.g. $^{34}$Ca, $^{26}$S**
**Four-proton decay e.g. $^{21}$Si**

**β-delayed 3-proton decays, e.g. $^{27}$S (S414)**

**Low-energy proton / neutron resonances in e.g. $^{73}$Rb, $^{69}$Br / $^{7}$H, $^{16}$Be**




**Competiveness through instrumentation ➔**
**All beams from heavy to light beneficial**
**Energies: a few 100 A MeV**

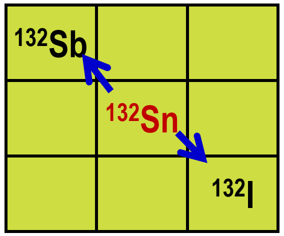


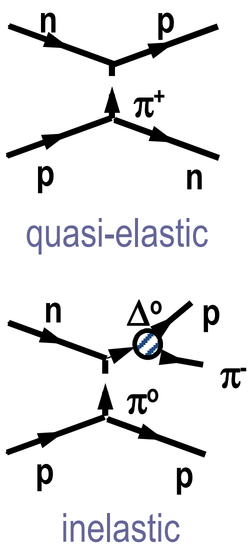
2p landcape: Phys. Rev. Lett. 110, 222501 (2013) + Erratum

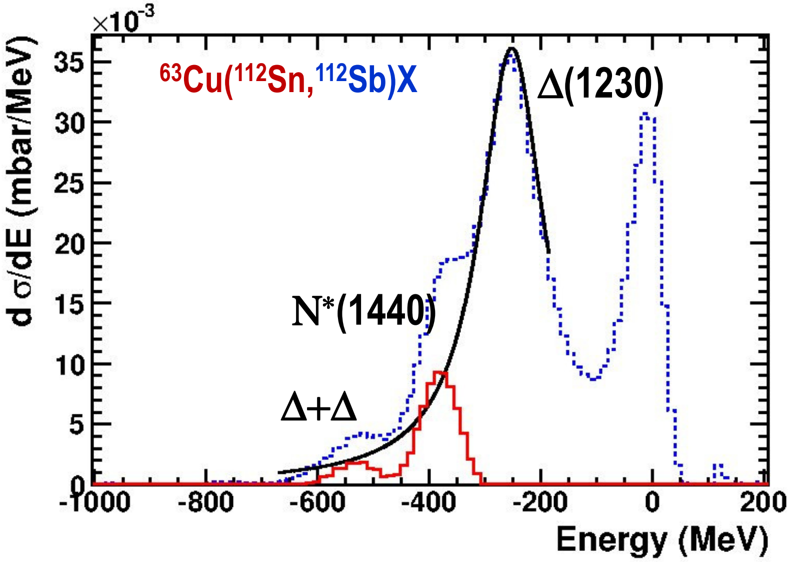
# Nucleon resonances in asymmetric nuclear matter

José Benlliure

## Isobaric charge exchange reactions.




momentum recoil induced by pion emission

**Relativistic neutron-rich projectiles (inverse kinematics)**

**High-resolving power spectrometer**

## Physics case.

- ✓ In-medium baryon resonances.
- ✓ Role of nucleon excitations in compact and massive neutron stars.
- ✓ Constraining the symmetry energy $\sigma(n,p)/\sigma(pn)$
- ✓ The puzzling nature of the Roper resonance.

➔ medium to heavy beams
1.2 - 2 A GeV ~$10^8$/s

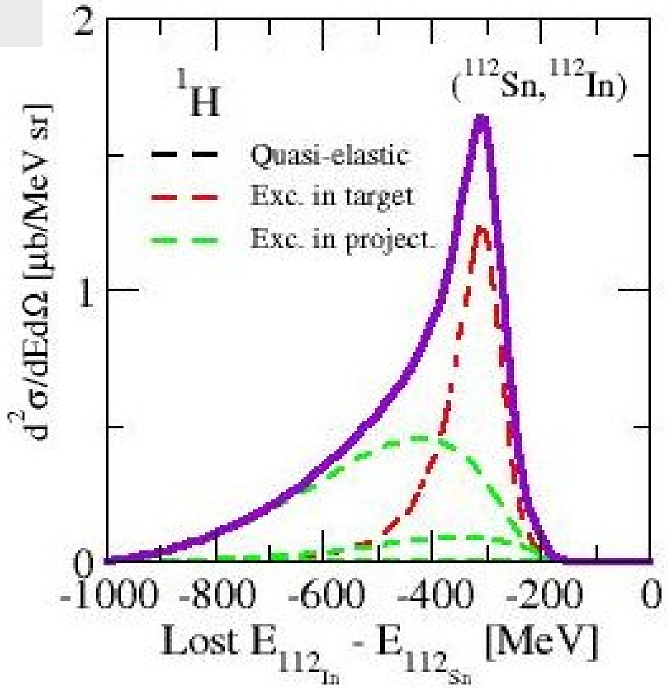
# Nucleon resonances in asymmetric nuclear matter

José Benlliure

## First pilot experiment at the FRS (2011).

✓ The in-medium excitation of baryon resonances in isobaric charge-exchange reactions was proved.

✓ These inclusive measurements provide limited information of the properties of the excited resonances.




## Proposal for a new experiment at the FRS (2018).

✓ Exclusive measurements measuring in coincidence the pion emission will allow a complete characterization of the baryon resonances.

✓ Such an experiment could be performed with the same experimental setup proposed for the investigation of hyper-nuclei.

➔ medium to heavy beams
1.2 – 2 A GeV ~$10^8$/s

## A dedicated experimental program at the SuperFRS.

✓ Final experiments taking advantage of the full capabilities of FAIR and the SuperFRS to investigate the excitation of baryon resonances in very exotic systems (medium to heavy)

Neutron-rich projectiles (inverse kinematics)

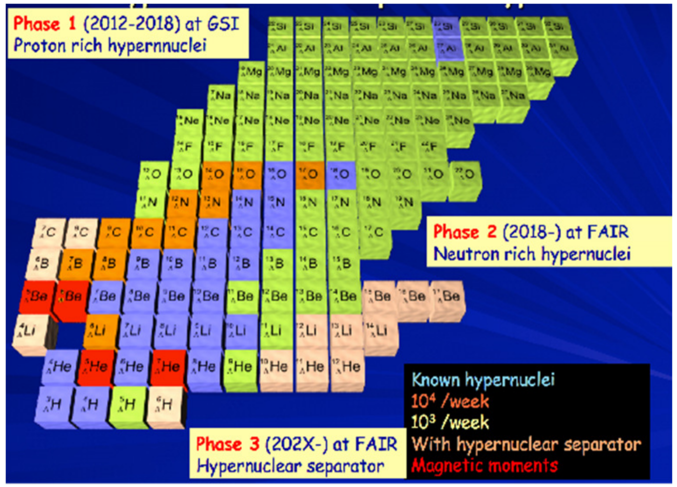
# Hypernuclei @ FRS

T. Saito

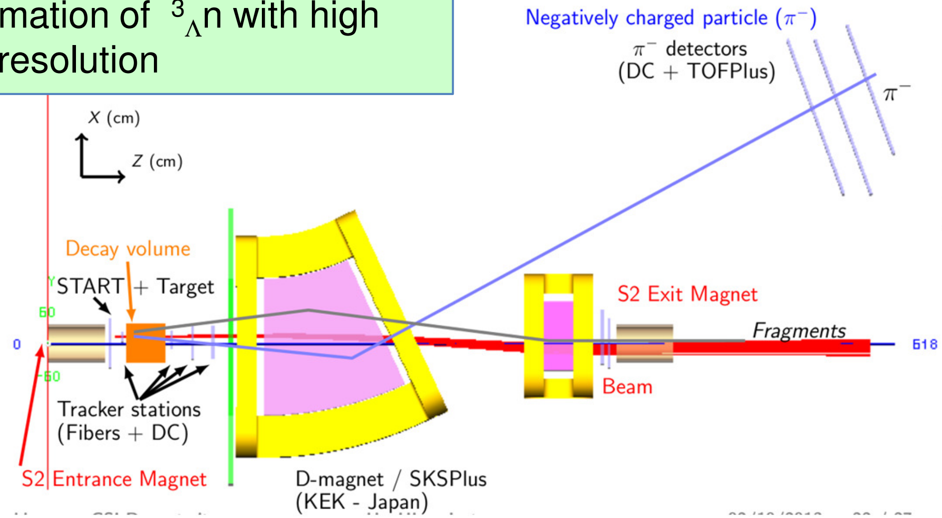
- Hypernuclear spectroscopy with peripheral collisions of heavy ion beams
  - **Possible only at GSI (Ebeam > 1.6 A GeV, e.g. $^6$Li, $^9$C,… mainly light, ~$10^6$/s)**

  c.f. Relativistic heavy ion collisions at RHIC and LHC: only up to 3-body hypernuclei

Observe
- $^4{}_\Lambda$H -> $^4$He + $\pi^-$ (exclusive)
  Proof of principle
  Lifetime measurement
- $^3{}_\Lambda$n -> d + $\pi^-$ (inclusive)
  Confirmation of $^3{}_\Lambda$n with high mass resolution




Beams from first half of the (main) separator

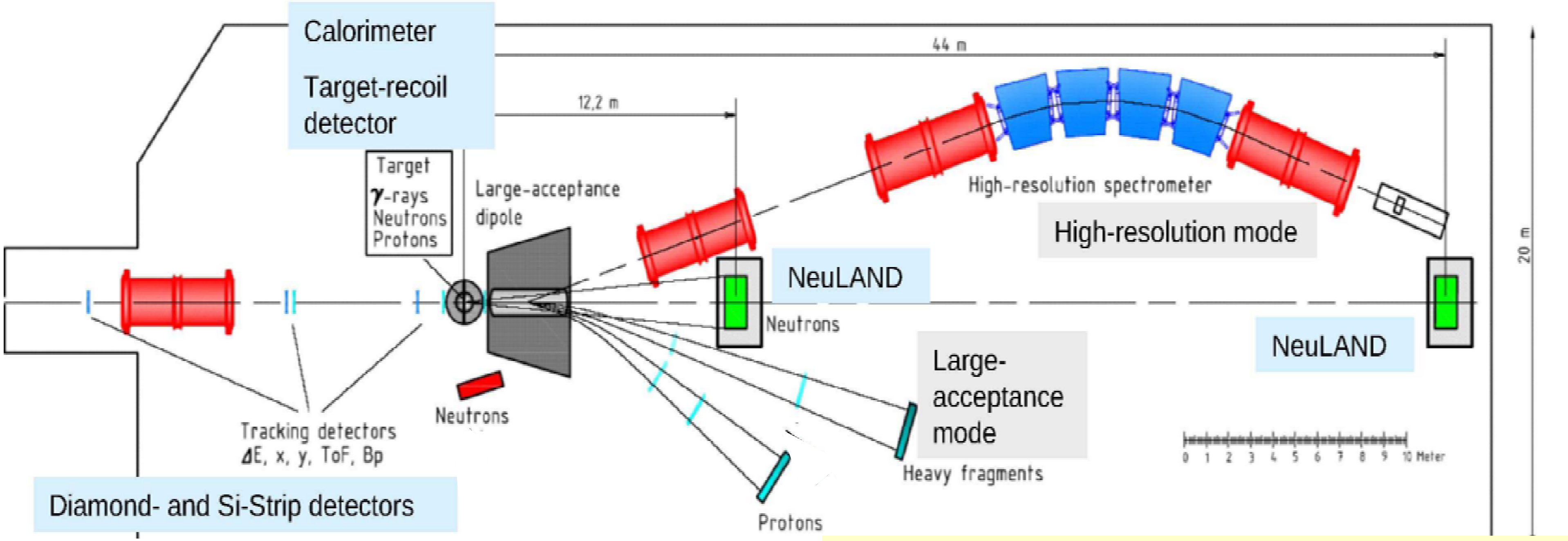



Decay residues to
Second half of FRS, Super-FRS
**High resolution spectrometer**

**$\pi$ measurements mid focus of the (main) separator**

# Reactions with Relativistic Radioactive Beams
# - A versatile and flexible setup

T. Aumann



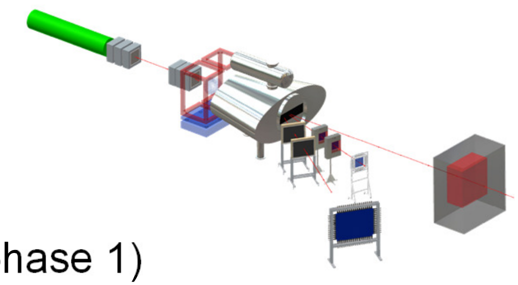

- High energy branch of the SuperFRS
  Beam energies: ~ 100 A MeV – 1 A GeV
- Overdetermined Measurement
  - Kinematically Complete
  - Target Calorimetry
  - Target Recoil Protons/Neutrons
- Incoming beam tracking
  - secondary beam emmittance

**Objectives:**

- Reaction Studies
- Nuclear Astrophysics
- Structure of (exotic) Nuclei
- Neutron-rich Matter

# Schedule and first experiments

| | |
|---|---|
| 2014 | Installation of 20% detectors NeuLAND and CALIFA<br>Commissioning run in Q3/2014 |
| 2015/16 | Construction and installation of detector components |
| 2017/18 | Commissioning of full R3B setup (Cave C) |
| 2018-202x | Physics runs at GSI (Cave C) (phase 0) |
| 202x-202x+1 | Move to High-Energy Branch building |
| 202x+1 → | Commissioning and first experiments at Super-FRS (phase 1) |



**Experiments will make use of uniqueness of R$^3$B:**

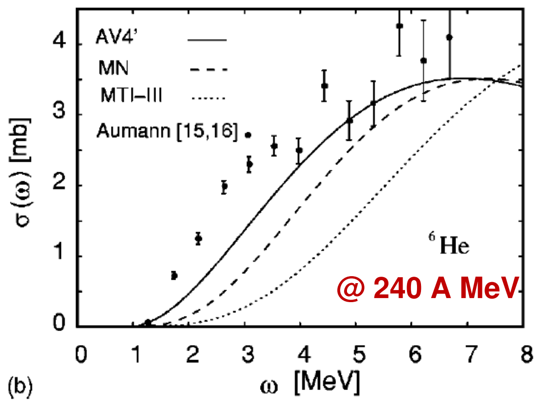
- Reactions at high beam energies up to 1 GeV/nucleon
- Tracking and identification capability even for the heaviest ions
- Multi-neutron tracking capability, high-efficiency calorimeter

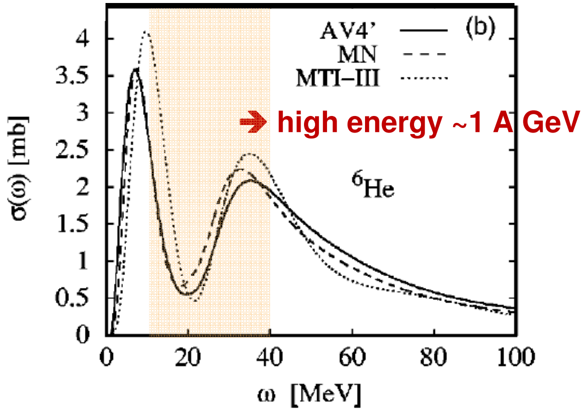
→ **Experiments possible for the first time:**

- 4 neutron decays beyond the drip-line and for heavier n-rich isotopes (still light)
- Kinematically complete measurements of quasi-free nucleon knockout reactions
- Electric dipole and quadrupole response of Sn nuclei beyond N=82, and of neutron-rich Pb isotopes & N=126 (polarizability, symm. E)
- fission barriers from (p,2p) reactions (→ r-process) (heavy)

# Physics with R3B setup:
# e.g. Dipole strength Distributions in heavy neutron-rich nuclei

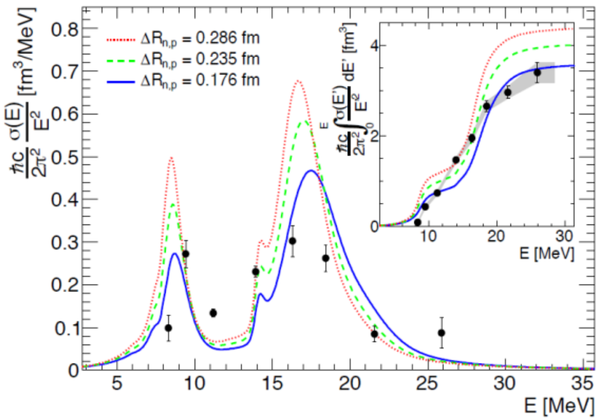
- core vs. neutron skins & halos → density / asymmetry → (light beam, high energy)




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

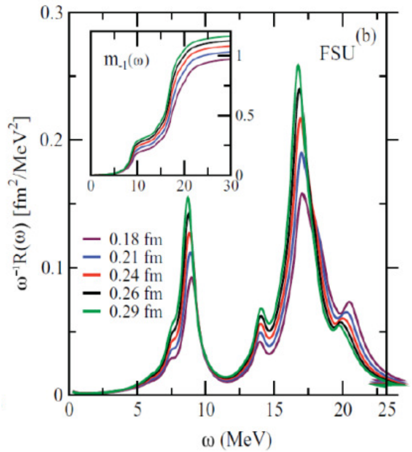
- access to EoS (e.g. neutron star) & low lying E1 (r-process) → (heavy beam, high energy)




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

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

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

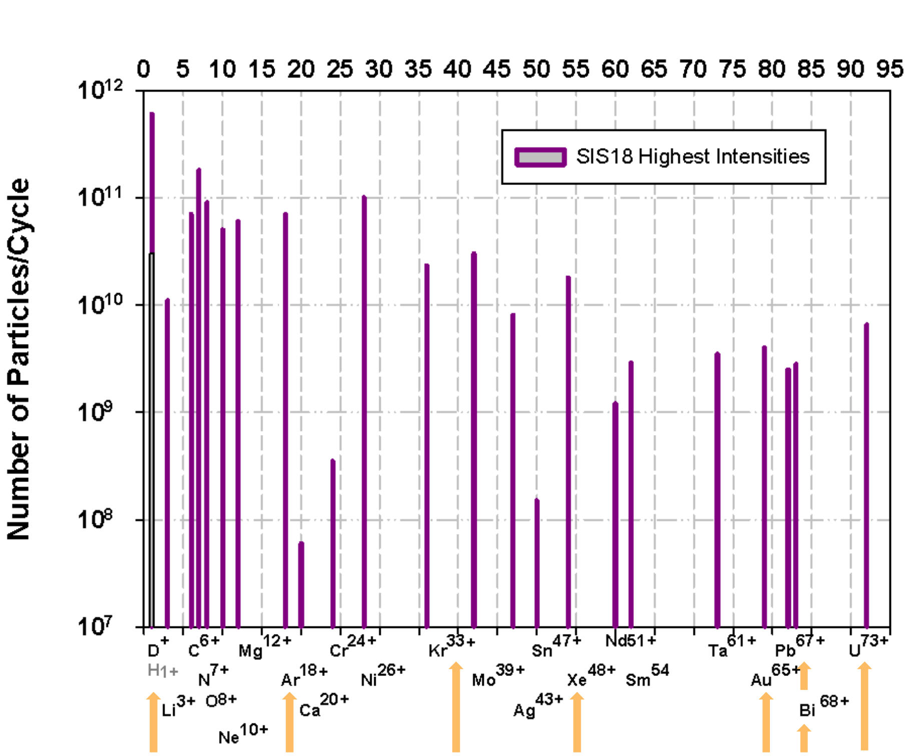


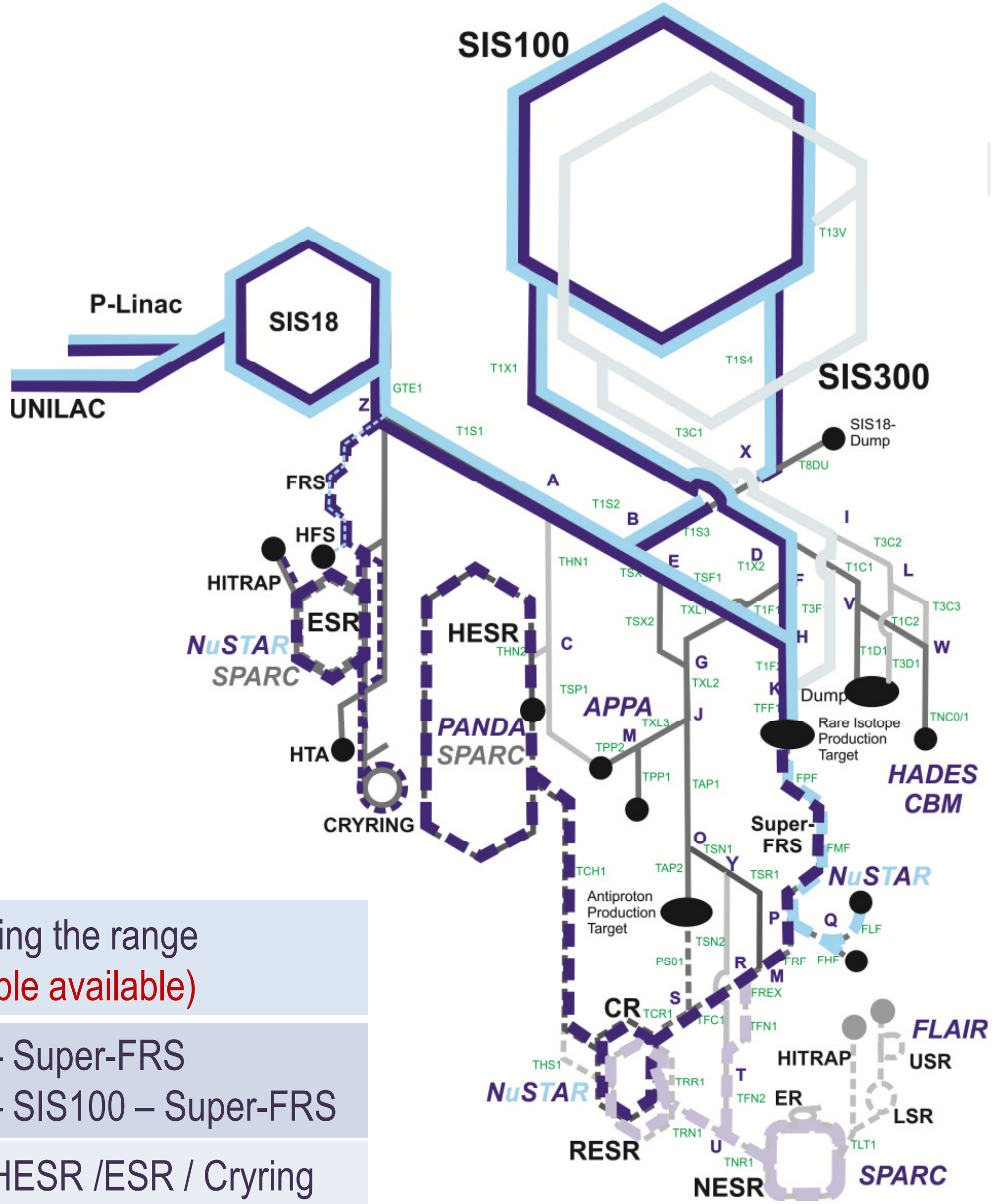

**Pb chain & N=126 isotones**

**~1 A GeV** →
bare ions
Fragment identification

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

# Favorable Beam Options



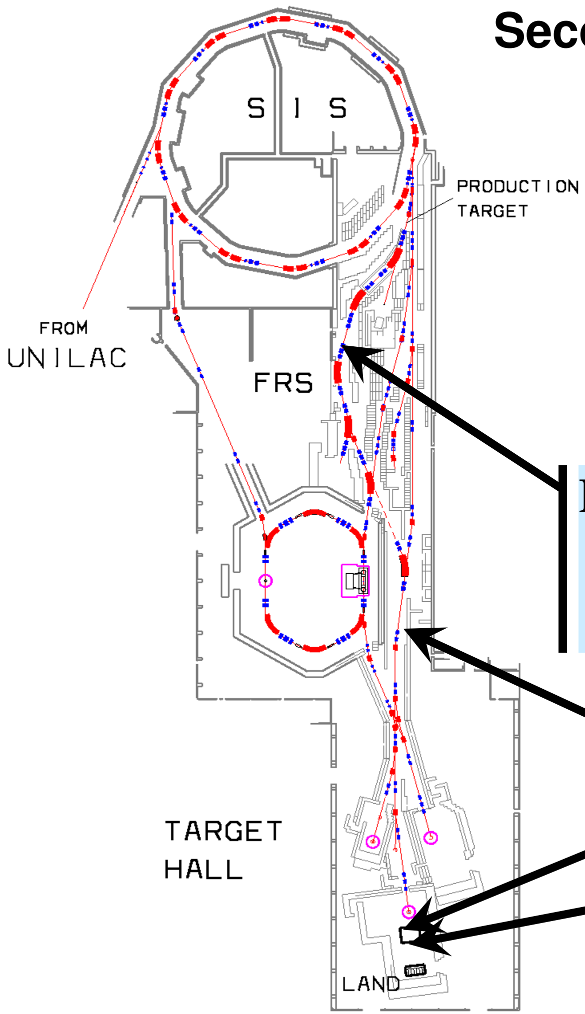




| | |
|---|---|
| Optimal production of RIBs from a multitude of primary beams | From H to U covering the range (coversion/yield table available) |
| Versatile operation modes for enhanced parallel beam usage | UNILAC – SIS18 – Super-FRS<br>UNILAC – SIS18 – SIS100 – Super-FRS |
| Fast beam tuning and switching between NUSTAR experiments | LEB / HEB / CR / HESR /ESR / Cryring (information from experiments for opt.) |

# **Continous Beam ID** is integral part of experiments
## Eg.: $^{132}$Sn PDR studies @ FRS/ALADIN-LAND

**Primary:** $3 \cdot 10^{8}$ $^{238}$U/spill @550 A MeV

**Secondary (mixed): 50 ions $^{132}$Sn/spill**

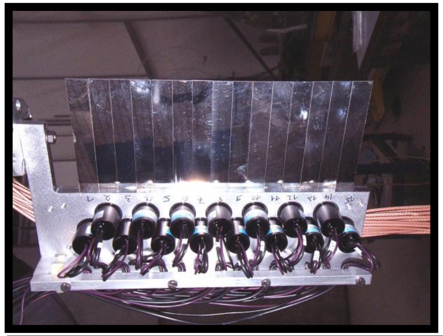


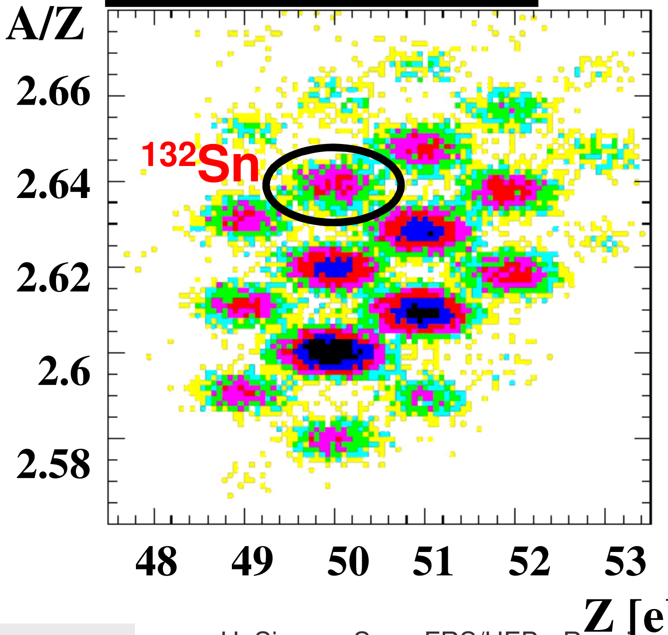

$$\frac{A}{Z} = \frac{m_u c}{e} \frac{B\rho}{\beta\gamma}$$

**Bρ** – from position at middle focal plane of the FRS

**β** – from TOF

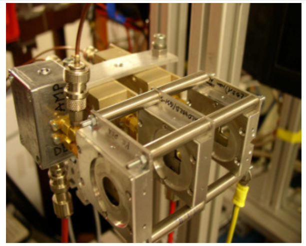
**Z** – from ΔE

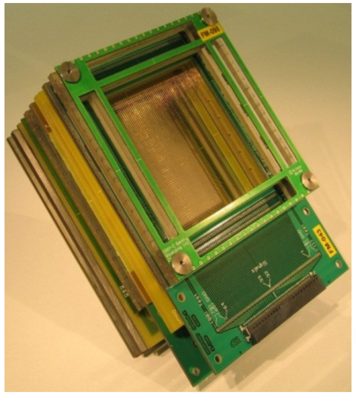




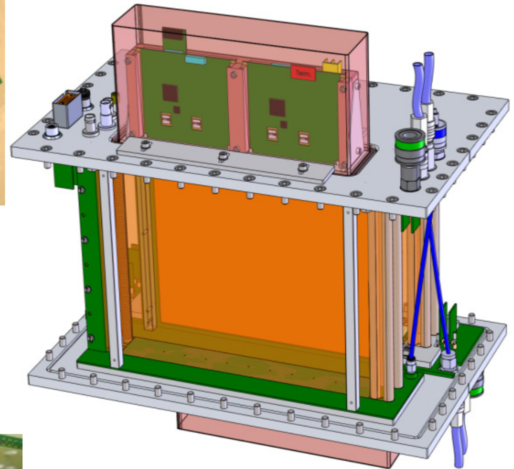
# Intended Tracking capabilities @ Super-FRS

C. Nociforo

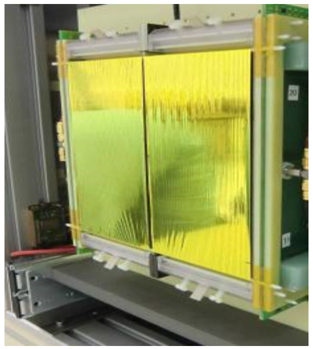


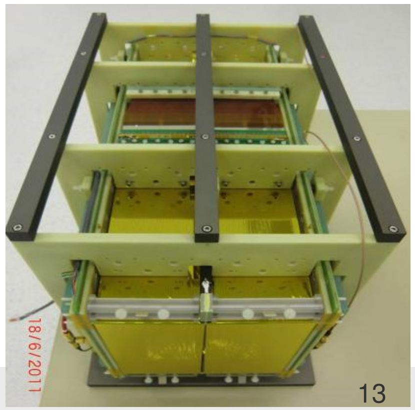


- Detectors for
  - beam diagnostics & particle identification
  - fast & slow extracted beams
- Resolutions required
  - Position $\sigma_{x,y}$~ 1 mm
  - Timing $\sigma_t$ ~ 50 ps
  - Energy loss $\sigma_{\Delta E}$~ 0.2-1%



- Major challenges
  - Radiation hardness (diagnostics on target & machine safety)
  - Particle rates 1/day ...$10^9$/s (main-separator)
  - Typ. 1-10 MHz
  - Dynamic range H...U, 100...1500 A MeV
- Tracking is optimized
  vs. optical resolution





# Rate limitations / Spill structure (online monitoring can be provided)

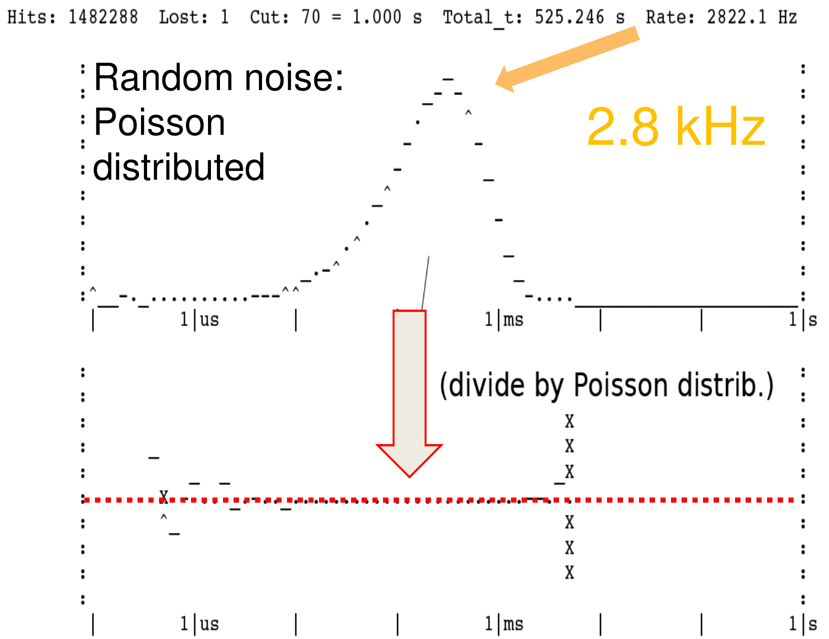
H.T. Johansson /NUSTAR EDAQ WG

- Different classes of (hard) limitations
  - Dose limits ➔ radiation hard design
  - Detector limits charge collection ➔ segmentation & opt. spill structure

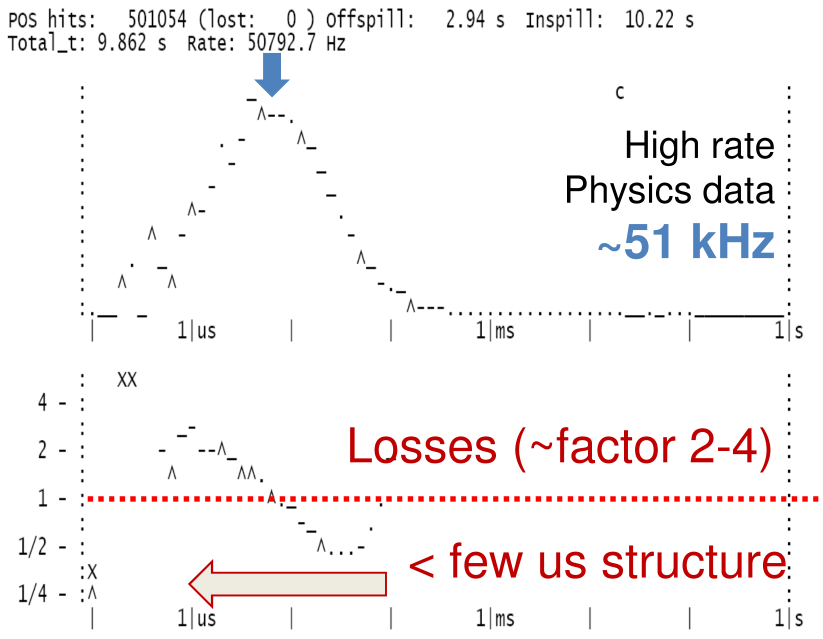
  & continous readout in frontends & selecting a region of interest

  ➔ only short (~1..10us) structures harm

Optimum Performance only with truely random spill structure !




Time between two hits on start detector




Time between two hits on start detector

# Summary

- Intense Primary beams (~100 MeV/u - maximum energy) are needed from light ions to uranium (with preference for optimization toward heavy beams)
  - optimized production scenarios can be provided
  - & proton beams with intensities only ~$10^{9..10}$/s e.g. for η′ mesic nuclei search

- Parallel Operation will be of importance (typical running times of one week, with parasitic startup commissioning of experiments)

- Machine Protection concept for experiments is highly desireable For mixed beams, focussing capabilities gated by selected isotopes in the secondary beam are required (➔ feedback of „experimental“ data into controls framework)

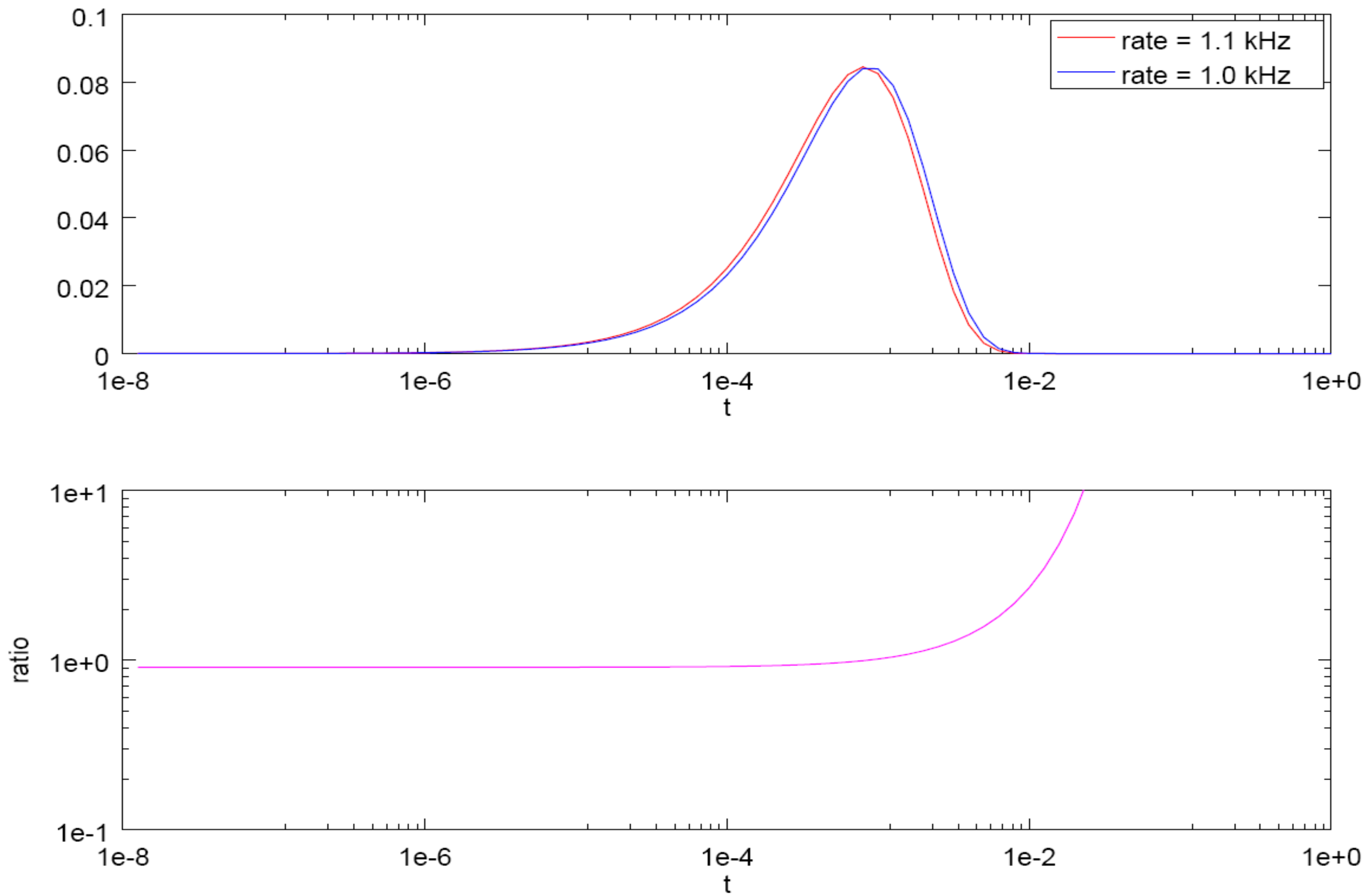
- Slow extraction (~1-10s) with a momentum spread +-5 $10^{-4}$ (for high res spectroscopy) is desired. For highly collimated experiments, e.g. atomic collisions @ Super-FRS the extraction angle variation should be limited

- All resulting beam parameters & geometry will be later discussed by Helmut Weick:

➔ Time structure of the extracted beam directly affects the performance of the experiments.
  - Microstructures on a time scale ~>10us might be tolerated
  - Microstructures below ~10us cause real pileup in detectors and electronic chain and severely reduces the amount of usable beam.


SDMS
Irfu cea
E. ZANON SPA
SCHIO (VI) - ITALIA
ASG

# Poisson vs. Rate artefacts



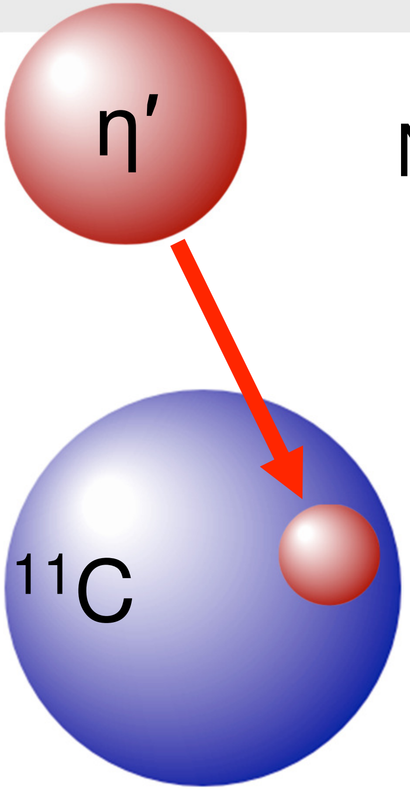
# NUSTAR: The ‚Experiment' comprises several facilities

| | |
|---|---|
| **Super-FRS** | RIB production and identification |
| **DESPEC** | $\gamma$-, $\beta$-, $\alpha$-, p-, n-decay spectroscopy |
| **HISPEC** | in-beam $\gamma$ spectroscopy at low/intermediate energy |
| **ILIMA** | masses and lifetimes of nuclei in ground and isomeric states |
| **LASPEC** | Laser spectroscopy |
| **MATS** | in-trap mass measurements and decay studies |
| **R³B** | kinematically complete reactions at high beam energy |
| **ELISE** | elastic, inelastic, and quasi-free e—A scattering |
| **EXL** | light-ion scattering reactions in inverse kinematics |
| **Super-FRS physics** | high-resolution spectrometer experiment |
| **Superheavy elements** | synthesis, nuclear structure, atomic physics, chemistry experiments with elements $Z \geq 104$ |

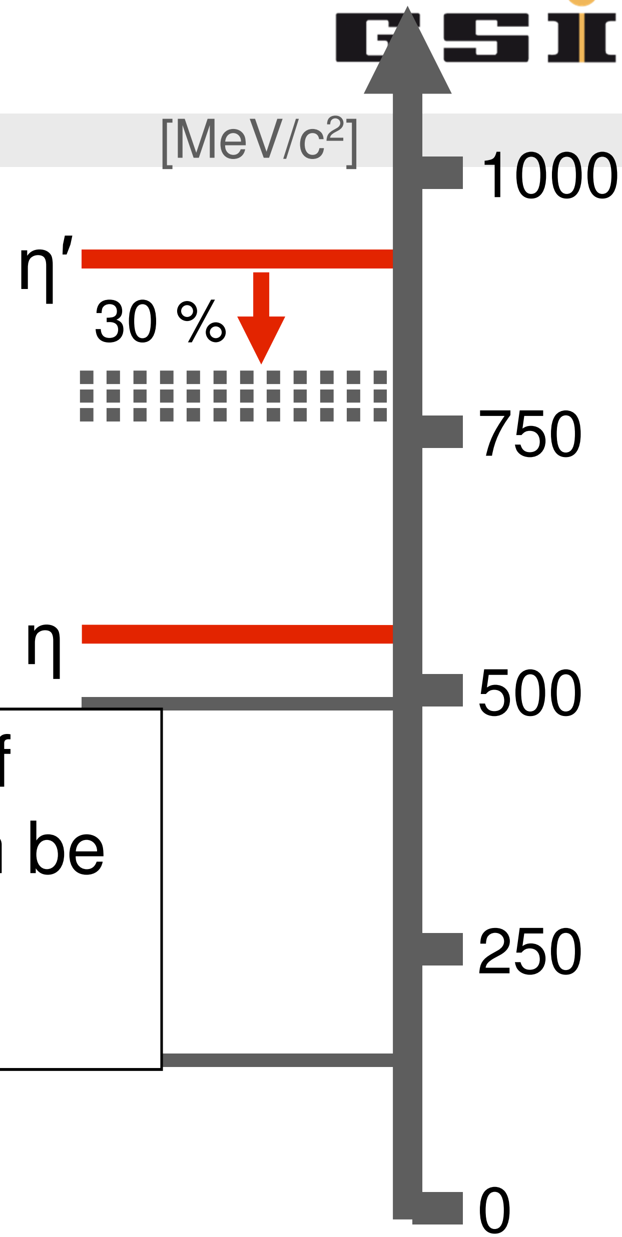
## The Approach

Complementary measurements leading to consistent answers

# η′ mesic nuclei search



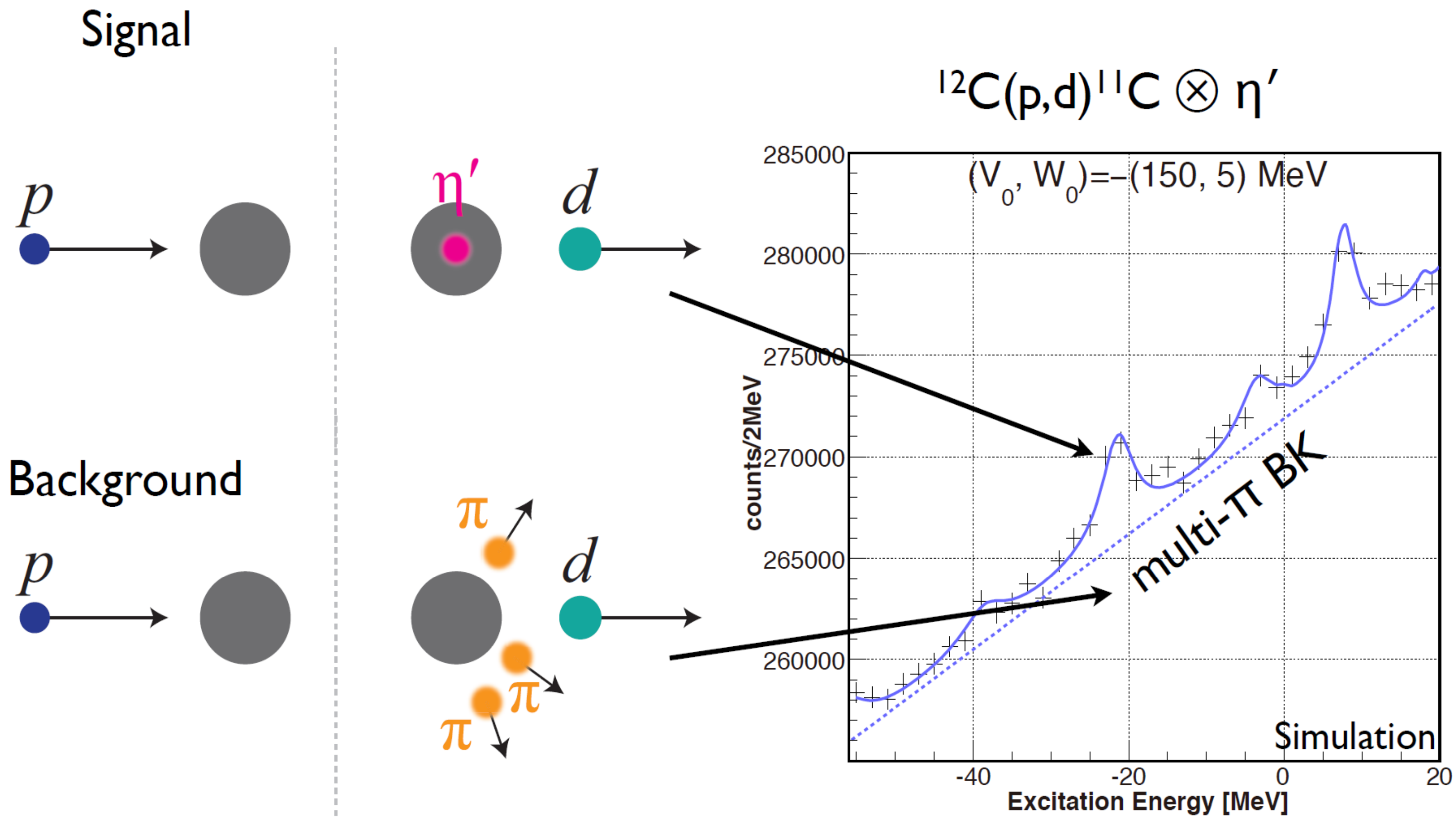

Naive estimation shows 30% reduction of $|m_{\eta'}-m_{\eta}|$




Q. Mass shift of ~ 150 MeV/c$^2$ can be observed in experiment?

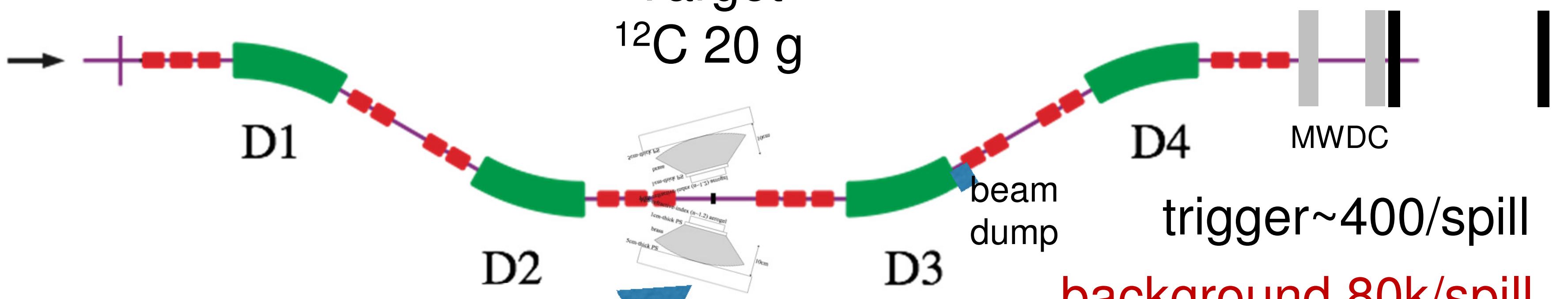
Jido, Nagahiro, Hirenzaki, PRC85(2012)032201(R)

# Background in Inclusive Measurement at GSI



# Exclusive measurements, proton beam & pion detection

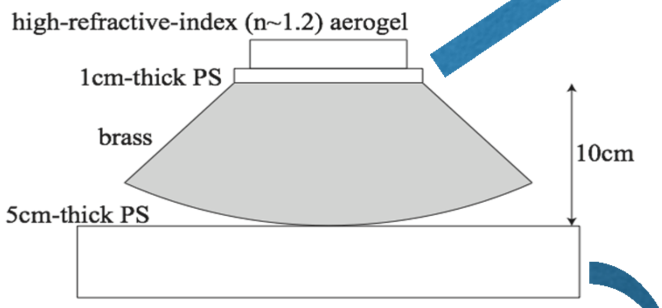
Target
$^{12}C$ 20 g

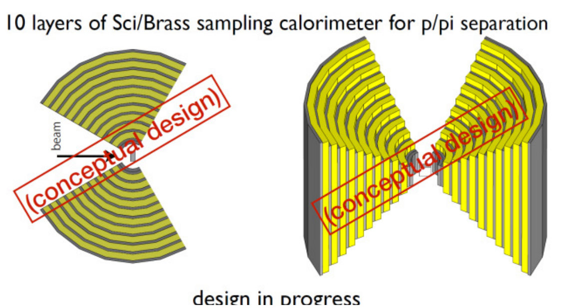



trigger~400/spill

background 80k/spill

prototype (p, π) det.



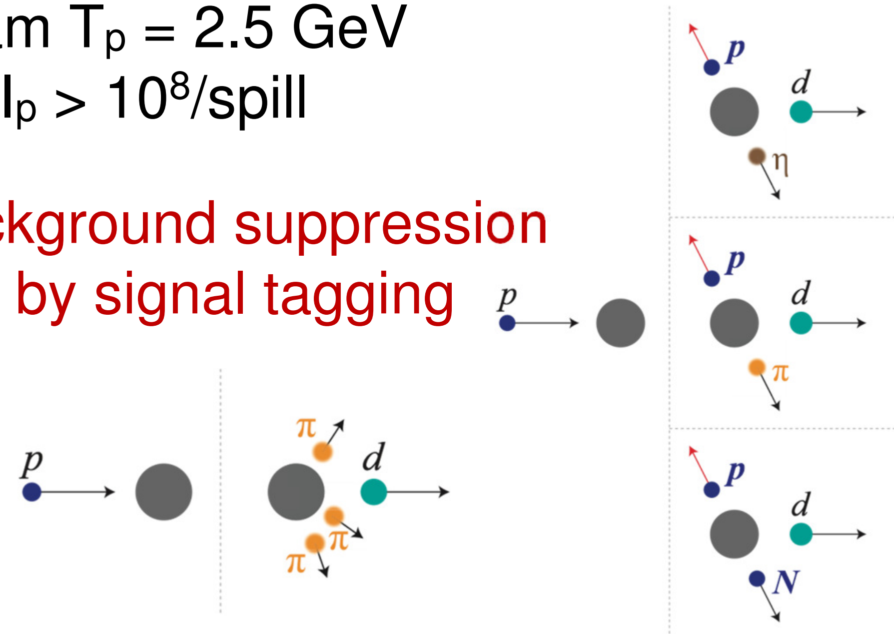




final

Beam $T_p$ = 2.5 GeV

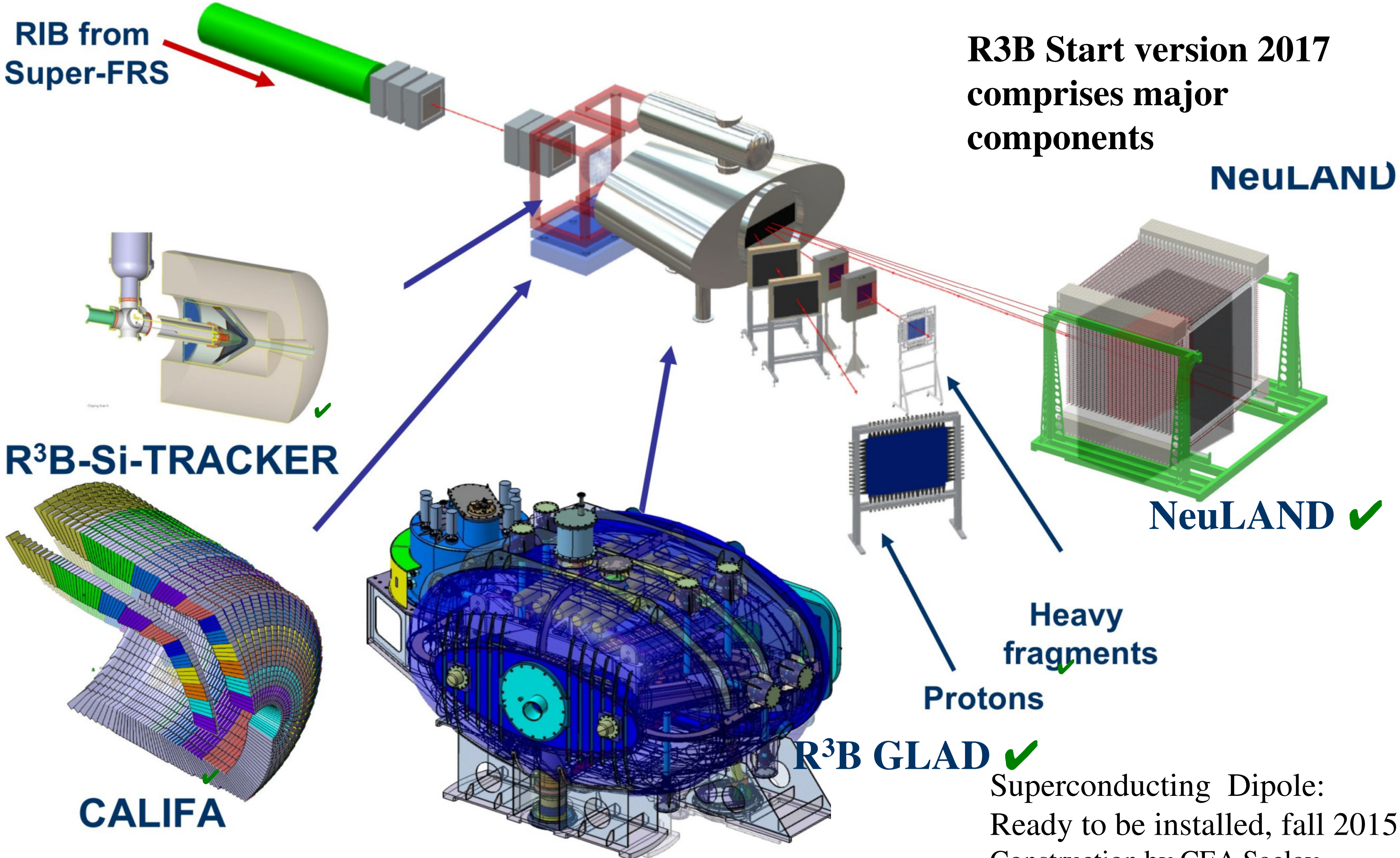
$I_p > 10^8$/spill

Background suppression by signal tagging



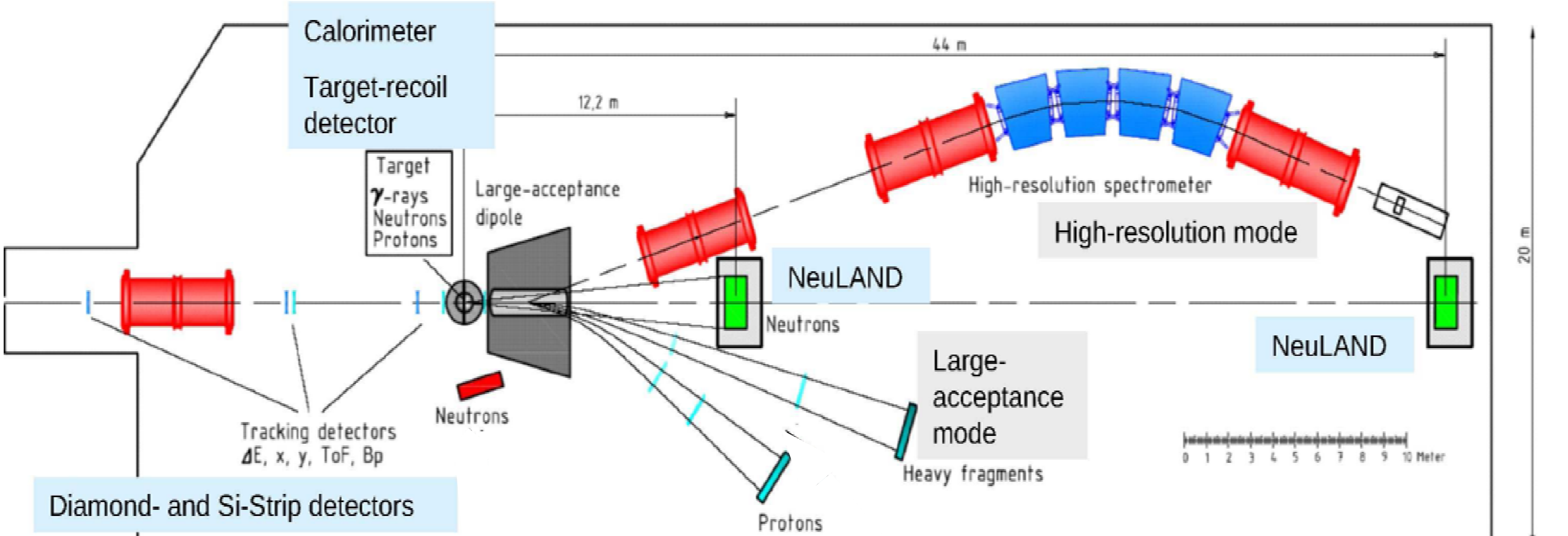
# Reactions with Relativistic Radioactive Beams R$^3$B

R3B Start version 2017 comprises major components




Superconducting Dipole:
Ready to be installed, fall 2015
Construction by CEA Saclay

# Reactions with Relativistic Radioactive Beams
## - A versatile and flexible setup



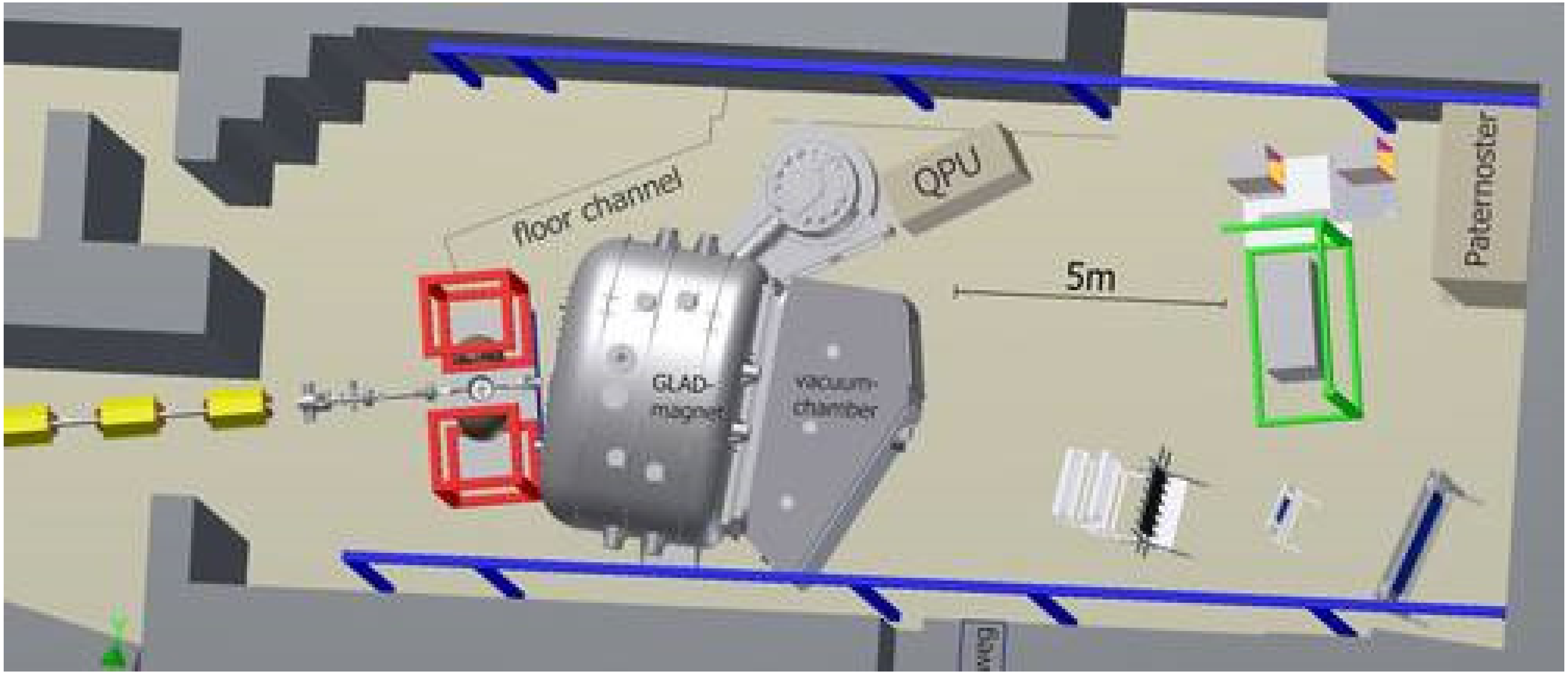

**Major Components:**

- Large Acceptance Dipole (GLAD)
- Neutron ToF Spectrometer (NeuLAND)
- Target Calorimeter and Recoil Detector (CALIFA + Si Tracker)
- Beam Tracking system

**Additional Systems:**

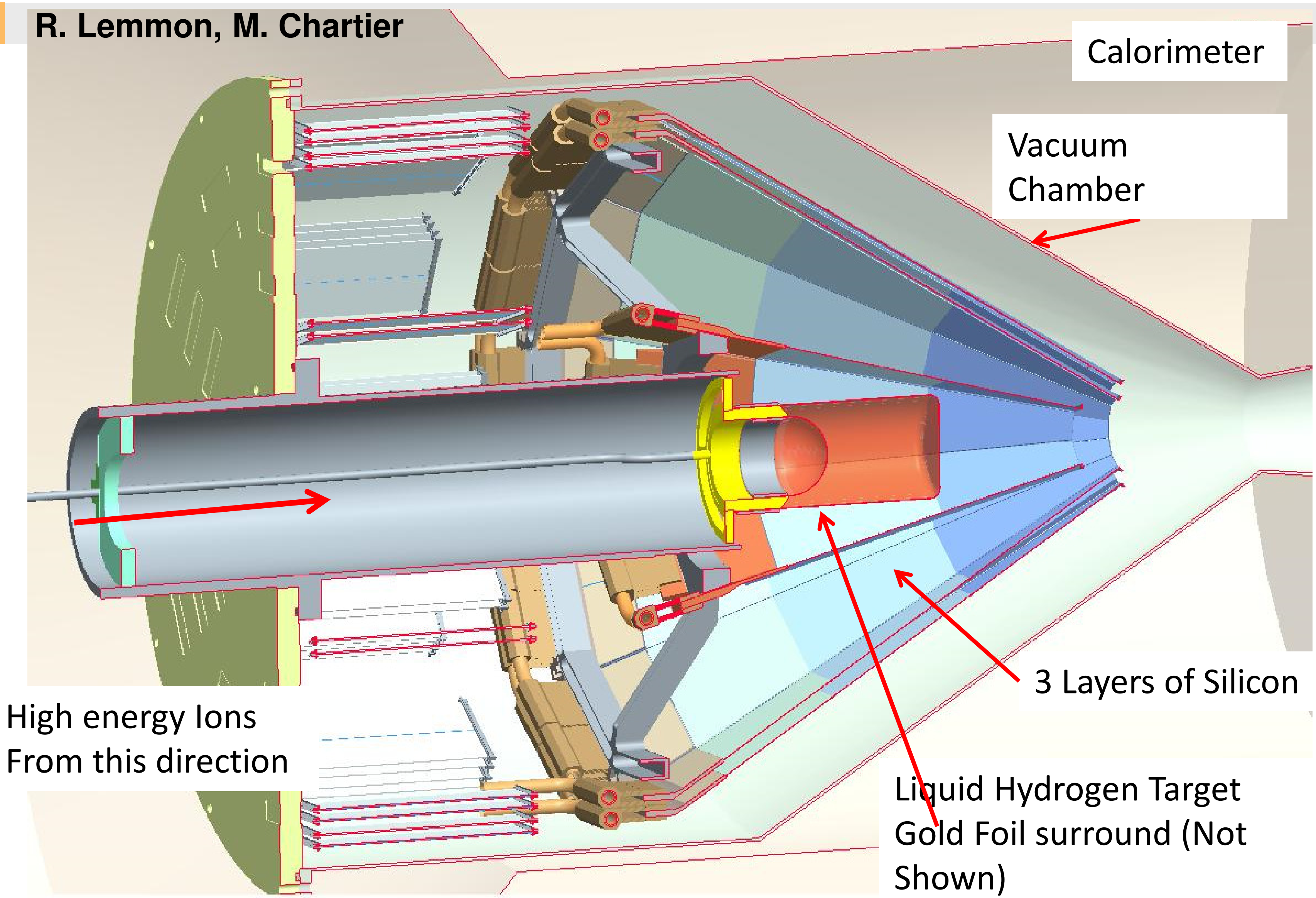
- High Resolution Spectrometer
- Active Target
- Low-energy Neutron Detector

# GLAD @ Cave-C


floor channel
QPU
GLAD-
magnet
vacuum-
chamber
5m
Paternoster

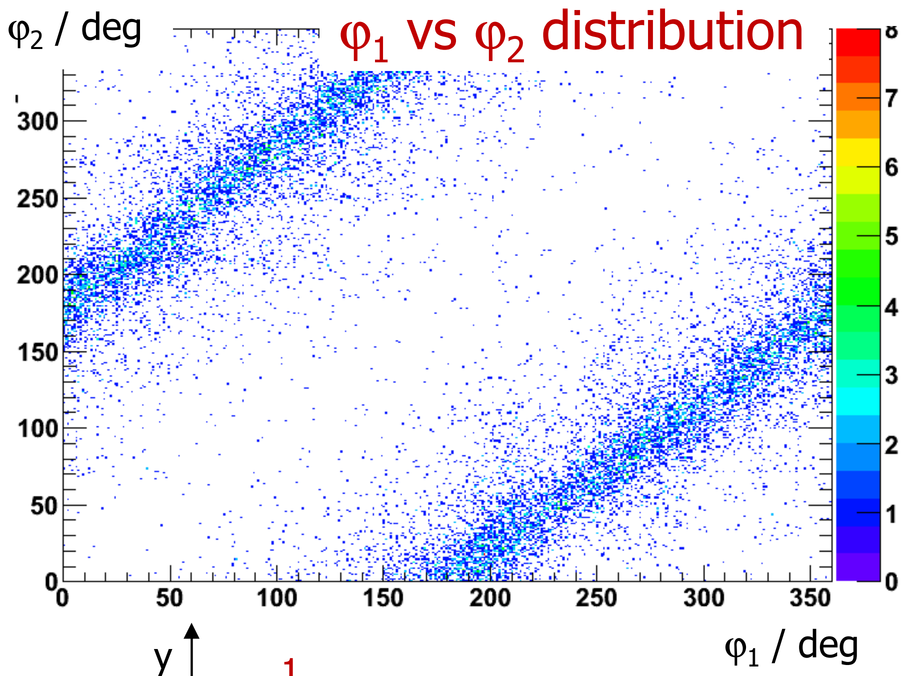
# R3B Si Tracker

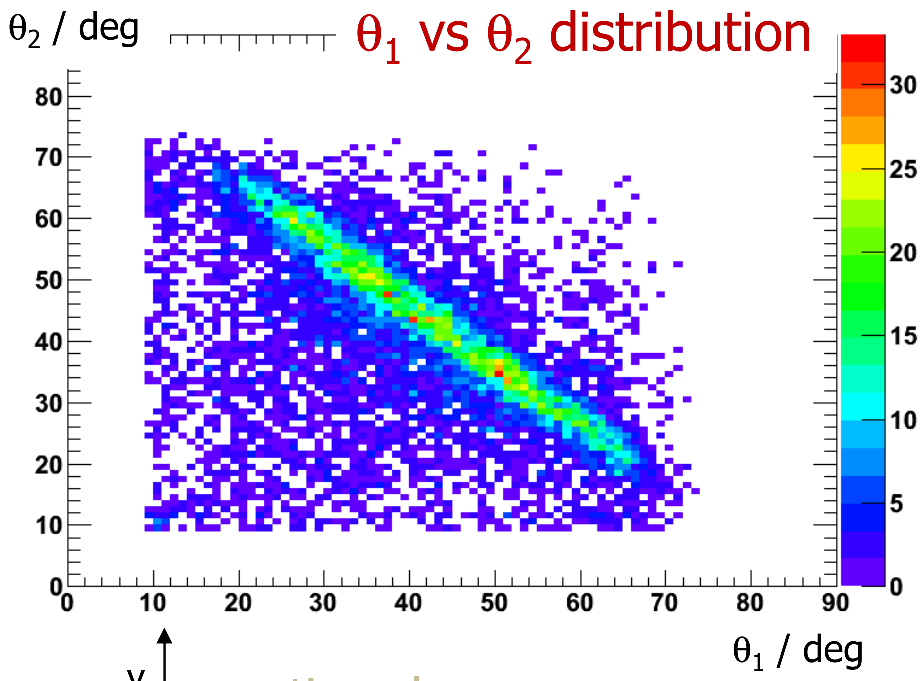
R. Lemmon, M. Chartier

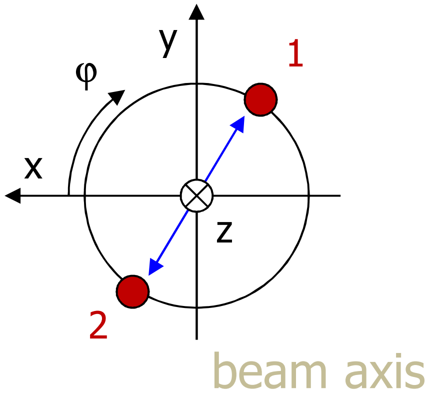


# Target Recoil Detection

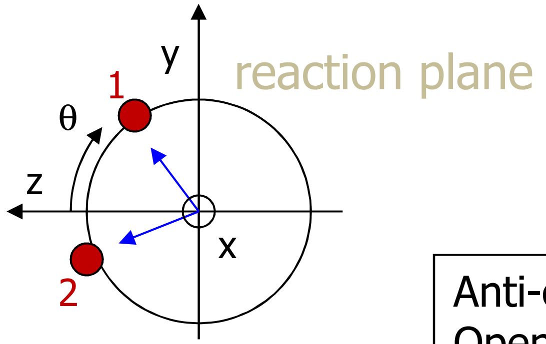
Data: F. Wamers $^{17}Ne(p,2p)$ @ 500MeV/u, $CH_2$




Correlation in $\varphi$:
$\Delta\varphi = 180°$



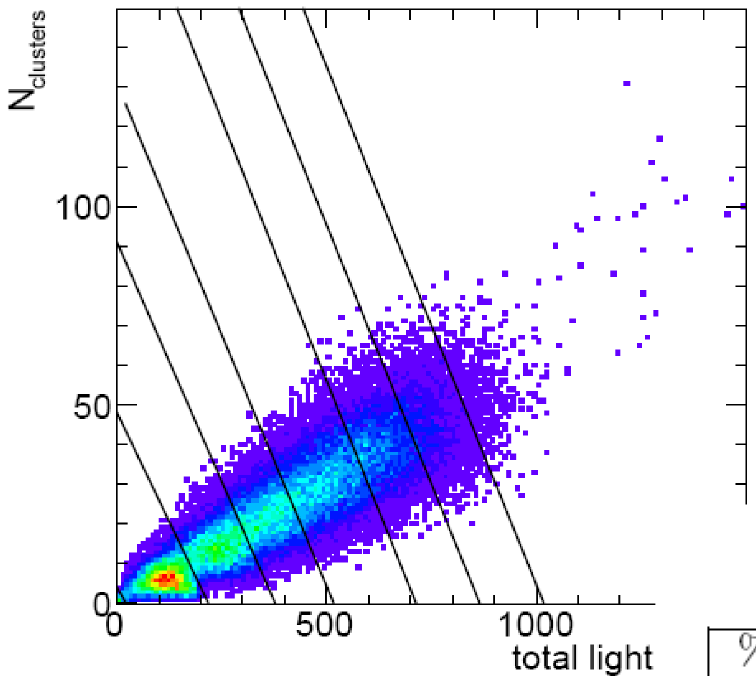

Anti-correl. in $\theta$:
Opening angle ≈ 83°

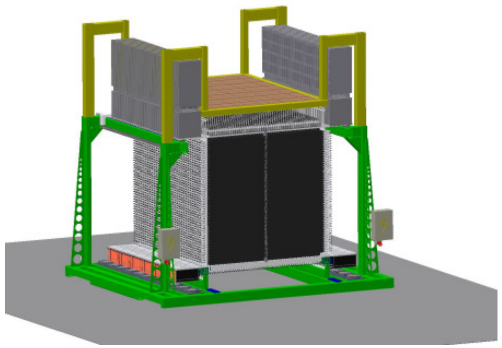
➔ Clear signature for (p,2p) reactions

# Novel Neutron Detector: NeuLAND

K. Boretzky

Fully active neutron detector based on scintillators (calorimetry & tracking)

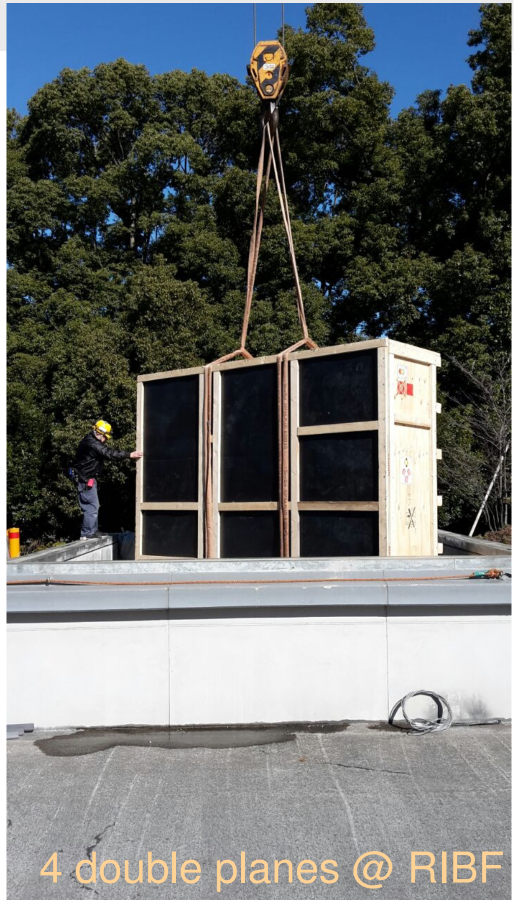


| | % | 1000 MeV generated 1n | 2n | 3n | 4n | 5n |
|---|---|---|---|---|---|---|
| detected | 1n | **89** | 12 | 1 | 0 | 0 |
| | 2n | 7 | **78** | 23 | 3 | 0 |
| | 3n | 0 | 8 | **63** | 26 | 5 |
| | 4n | 0 | 0 | 12 | **63** | 40 |
| | 5n | 0 | 0 | 0 | 7 | **46** |
| | 6n | 0 | 0 | 0 | 0 | 8 |

**Previously < 50%**

**Previously <5% !**




30 double planes
2 x 50 paddles each
5 x 5 x 250 cm³
RP408 / R8619ASSY

FPGA TDC readout

# Incredients for the $^{7}$H case

- t + n + n + n + n

PHYSICAL REVIEW C 77, 054317 (2008)

**Strong dineutron correlation in $^{8}$He and $^{18}$C**

K. Hagino,[1] N. Takahashi,[1] and H. Sagawa[2]

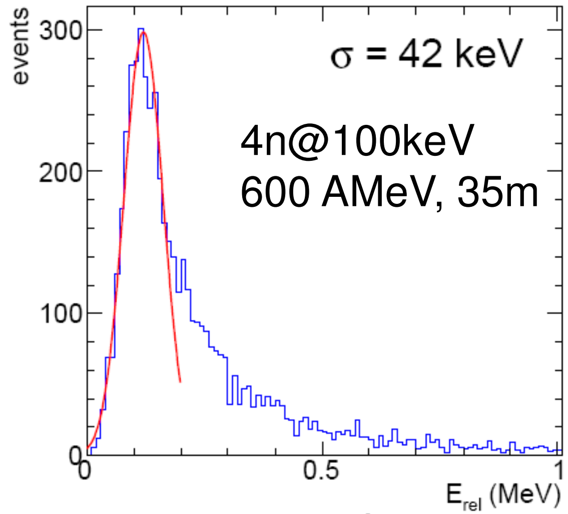
Core +4n (HFB)

PHYSICAL REVIEW C **80**, 021304(R) (2009)

**Di-neutron correlations in $^{7}$H**

S. Aoyama[1] and N. Itagaki[2]

Core +4n
AMD selected snapshots

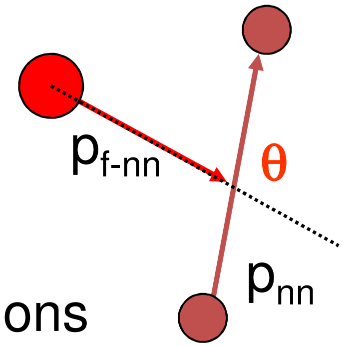



NeuLAND Simul.

- t + 2n + 2n

$^{11}$Li - α → $^{7}$H + 2n + 2n
$^{8}$He – p → $^{7}$H + 2n + 2n

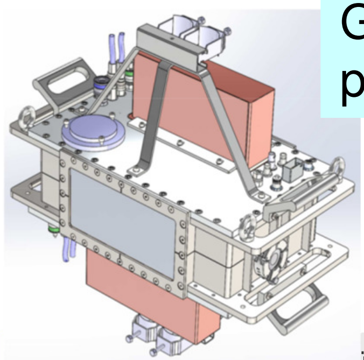
→ Analysis of three body correlations

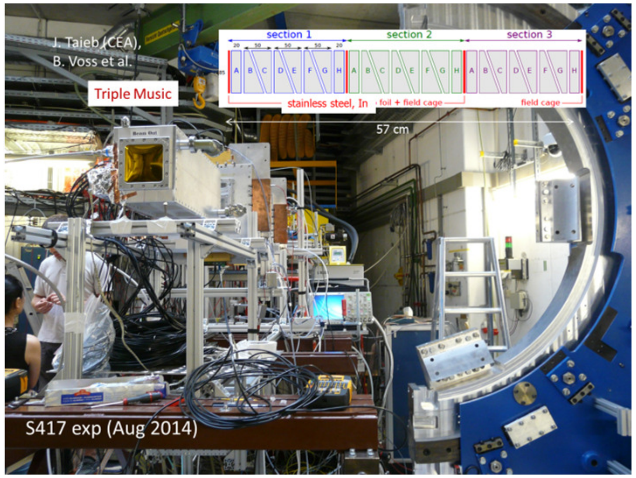


# Beam Diagnostics

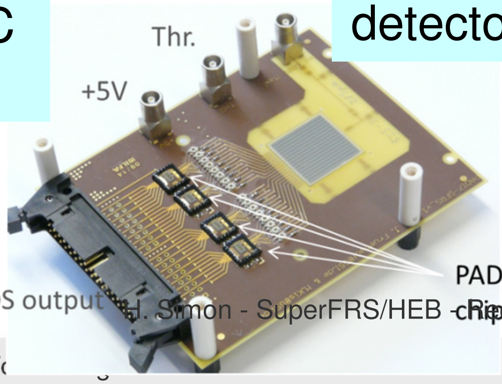
C. Nociforo, RBEE, RBDL

- Full isotope identification (x, y, x', y', DE and TOF)
- Operation modes: fast- and slow-extracted beams
- Special devices (slits, degrader, secondary target, ...)
- Controls → machine safety
- DAQ (in-kind GSI / Sweden)
- Various detector systems
  - ➢ GEM-TPC (Finnish in-kind) Test @ GSI 10/2014
  - ➢ SEM-GRID & ladder system (Finnish in-kind) "
  - ➢ Silicon detectors (EoI Russia) Test @ GSI 08/2014
  - ➢ Diamond detectors (EoI Finland) "
  - ➢ MUSIC detectors (EoI Finland) Test @ GSI 10/2014
- Various test beam-times at FRS/Cave C

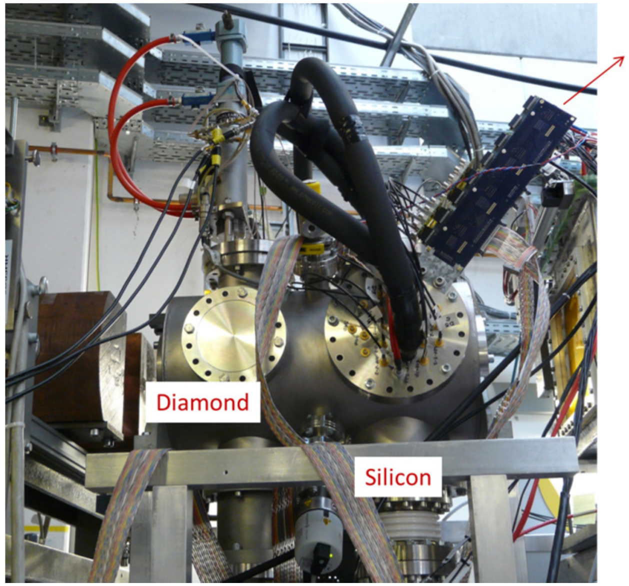





GEM TPC prototype

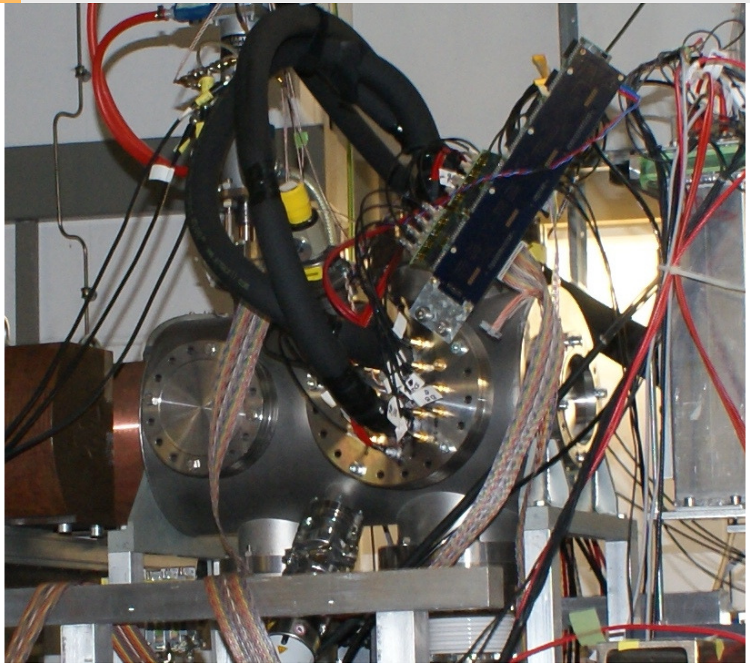


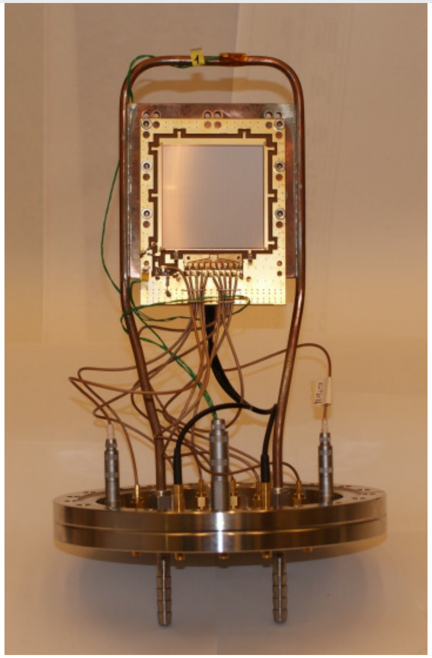

Diamond strip detector

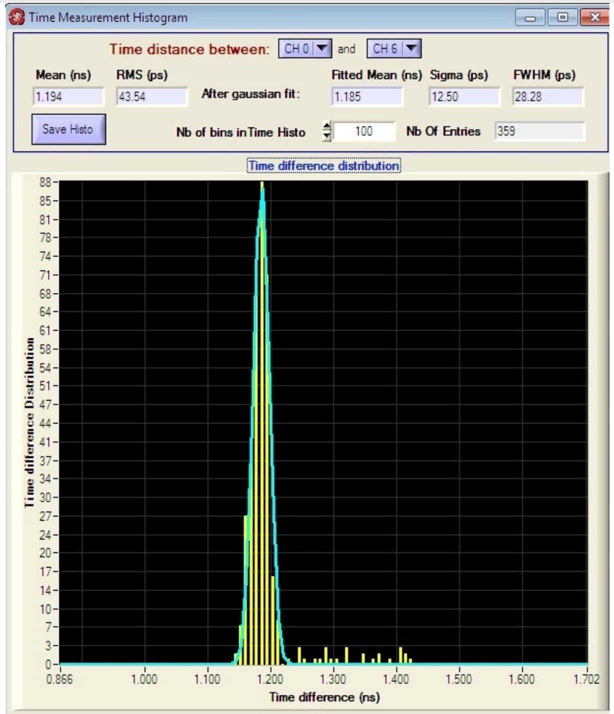


# Si detectors for Super-FRS TOF diagnostics

V. Eremin, RBDL








- Two beam tests at GSI in 2012 with $^{238}$U@370 MeV/u and $^{197}$Au@750 MeV/u
- Beam test in JINR in 2014, Dubna with $^{40}$Ar@40 MeV/u
- Beam test at GSI in August 2014 with $^{197}$Au@1 GeV/u

- Full-size strip detectors tested
- Low and high intensity irradiation
- Heavy irradiation with a dose equivalent up to 1-2 years of Super-FRS operation
- Functionality is confirmed
- TOF resolution up to 13 ps ($\sigma$), required 50 ps

*Potential In-Kind contribution of PTI, St. Petersburg, Russia*

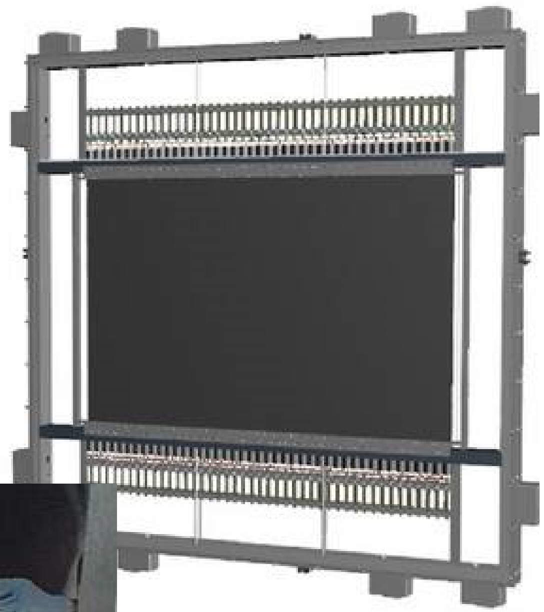
# $R^3B$: Time-of-flight detector prototyping

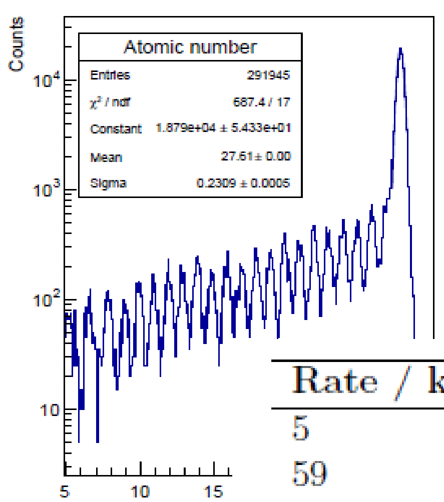
M. Heil, RBEE

## Performance goals:

- Time resolution $\sigma_t/t$ = 2E-4
  (⇔ $\sigma_t$ =20 ps for 20 m flight path at 1 *A*GeV)
- Energy resolution $\sigma_E/E$ = 1%
- High-counting rate capabilities (~1 MHz)
- Large dynamic range (up to Pb-U).
- **FPGA based TDC** readout (ΔE via ToT Techniques)

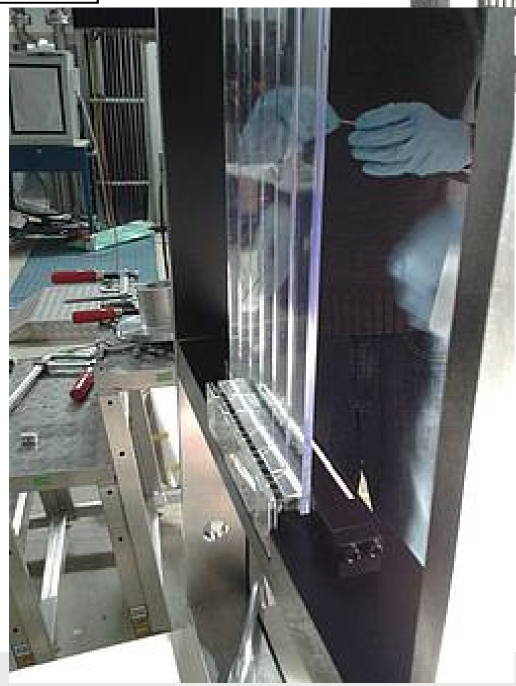
Detector layout





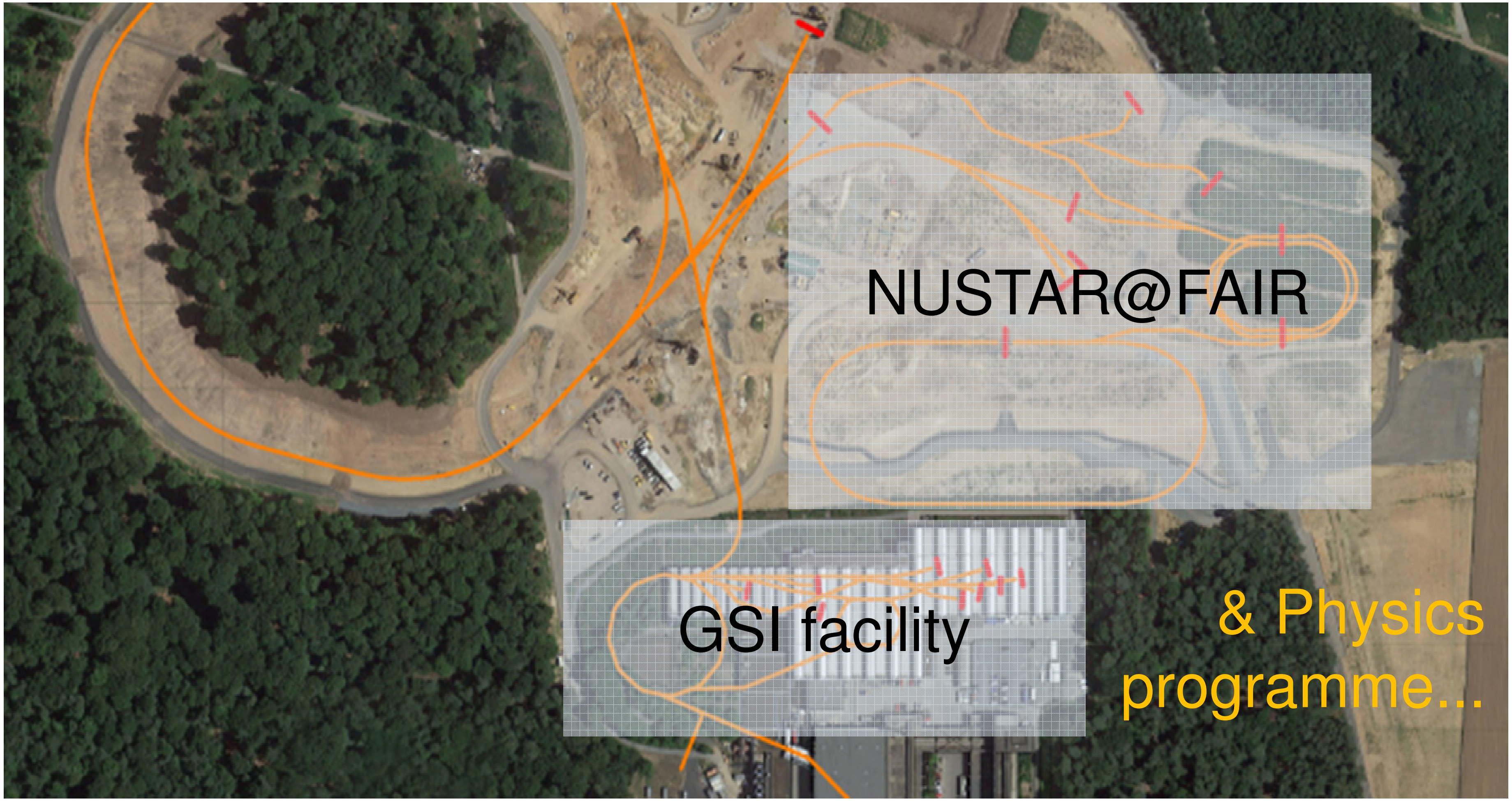

Excellent time and energy resolution at high rates

| Rate / kHz | $\sigma_t$ / ps | $\sigma_t^{det}$ / ps |
|---|---|---|
| 5 | 41 | 14 |
| 59 | 41 | 14 |
| 375 | 45 | 16 |
| 1000 | 64 | 23 |



Prototype studies @ Cave-C 08/2014 10/2014

# Areal view of the combined facility



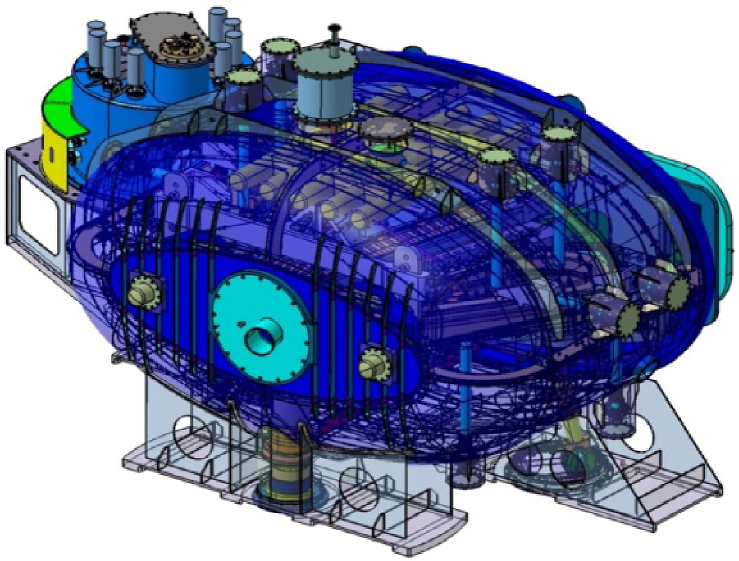
# Large-acceptance superconducting dipole magnet GLAD

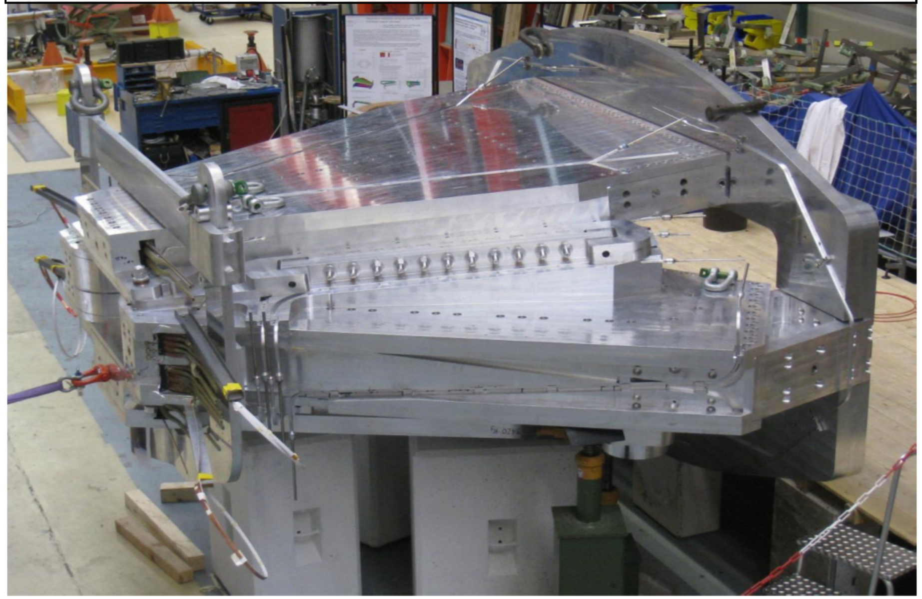
**Magnet parameters:**

- Large vertical gap ± 80 mrad
- High integrated field of 4.8 Tm
- Fringe field at the target position less than 20 mT
- Operational temperature 4.6 K
- The overall size of the conical cryostat: 3.5 m long, 3.8 m high and 7 m wide.

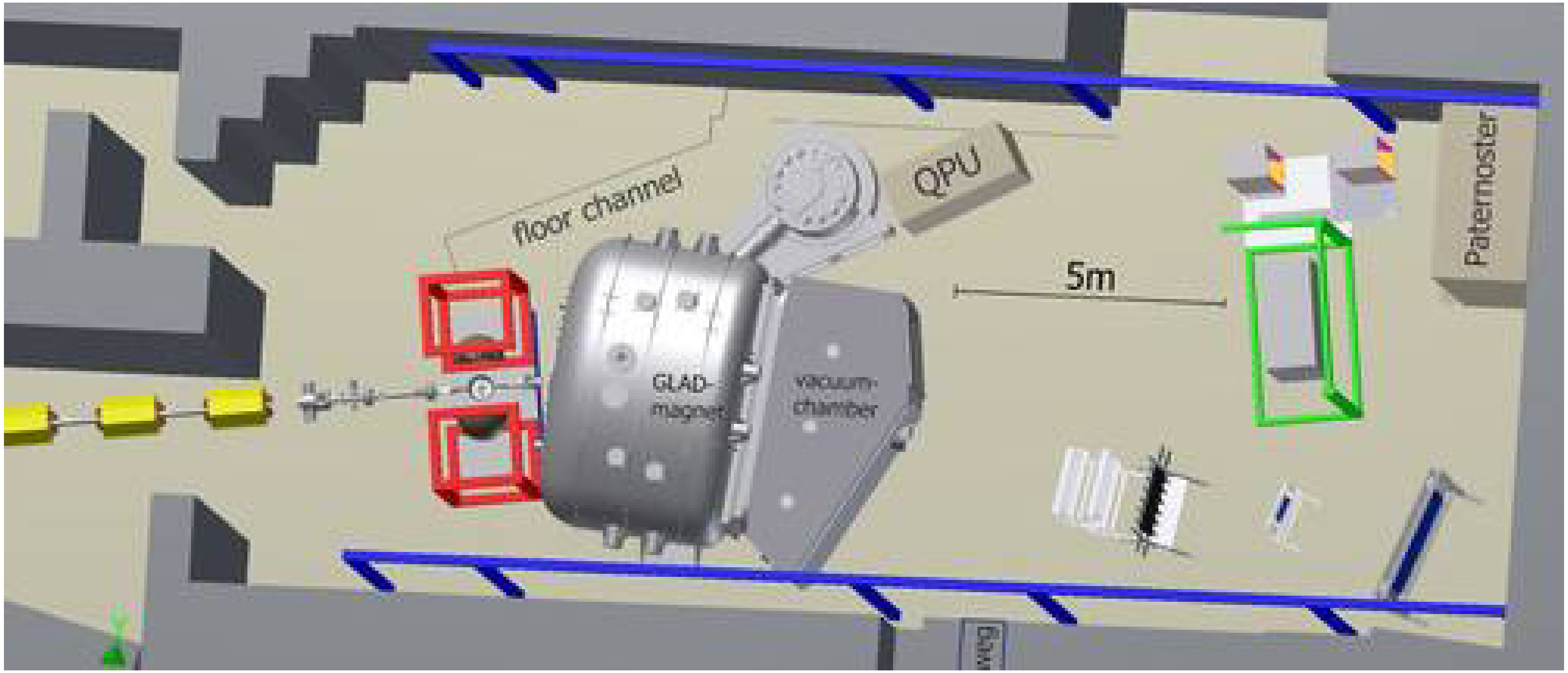
**Challenging Magnet design:**

- Collaboration CEA Saclay/GSI
- Tilted coils, ironless design
- Correction Coils
- Lightweight design
- Indirect coil cooling
- Thermosyphon cryo distribution





# Test Setup@Cave-C – Next steps



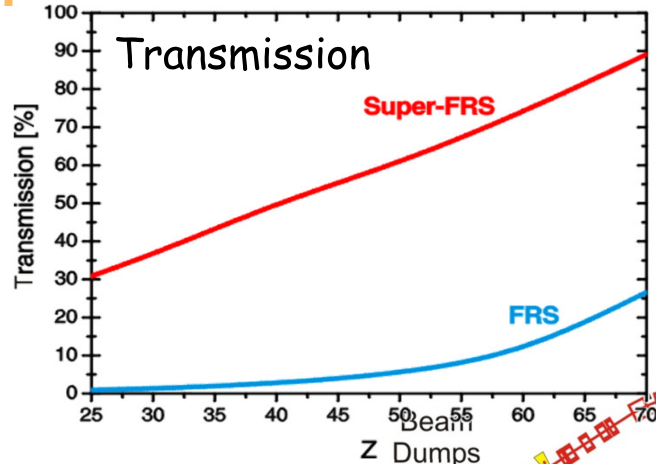

- Experiment campaign 2014
- Preparations for GLAD installation
- Full integration test and potential later runs in Cave-C
- Move fully commissioned systems to FAIR high energy Cave

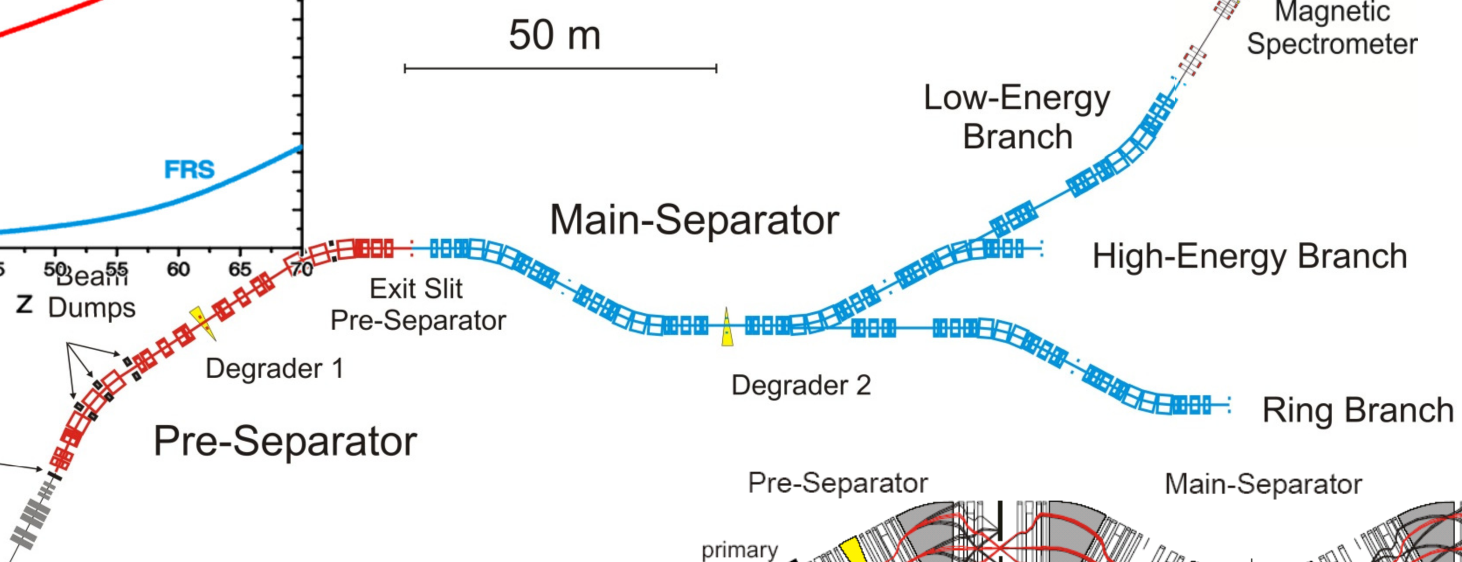
# Definition of NUSTAR experiment phases

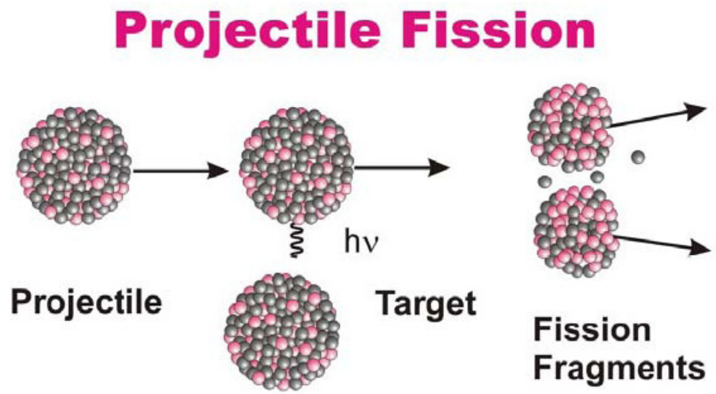
- **Phase 0 ( 2018- )**
  - R&D and experiments to be carried out with present facilities <u>and</u> FAIR/NUSTAR equipment
- **Phase 1 ( 2022 - )**
  - Core detectors and subsystems completed
  - First measurements with FAIR/Super-FRS beams
  - ➢ **Carry out experiments with highest visibility as part of the core program and within the FAIR MSV**
- **Phase 2**
  - FAIR evolving towards full power
  - Completion of experiments within MSV
  - ➢ **Essentially the full program of MSV can be performed**
- **Phase 3**
  - Moderate projects, which have been initiated on the way (outside MSV) can be included (e.g. experiments related to return line for rings)
- **Phase 4**
  - Major new investments and upgrades for all experiments

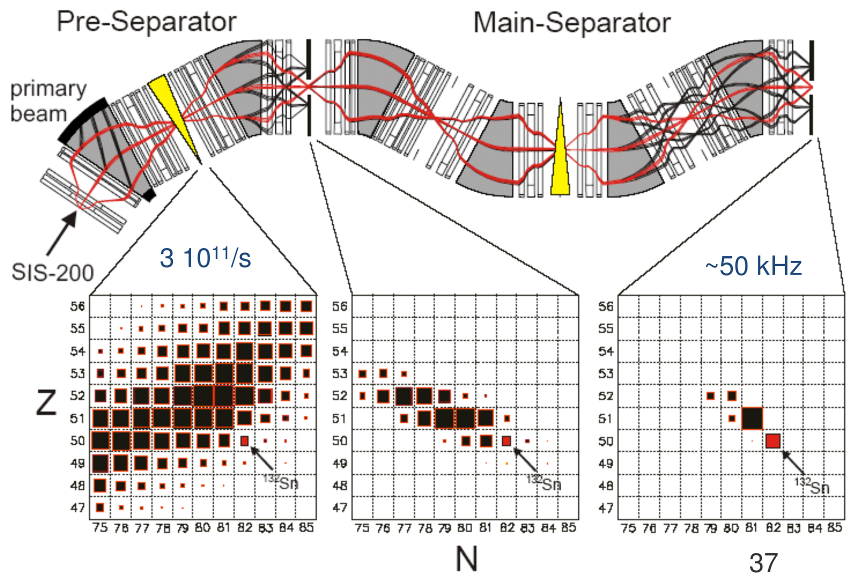
# Superconducting FRagment Separator

- Apertures (~400mm) fully illuminated
- Resolution requirement ~ $10^{-3}$
  achromatic system limited by matter !



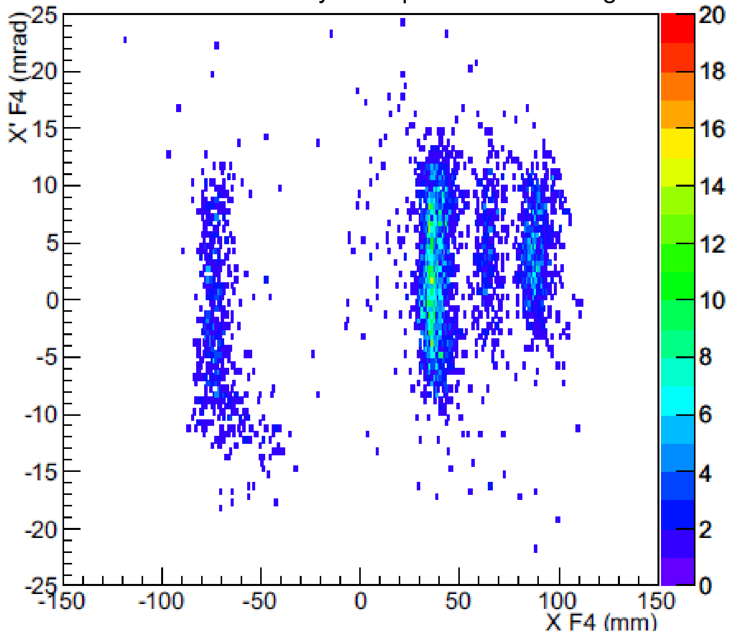



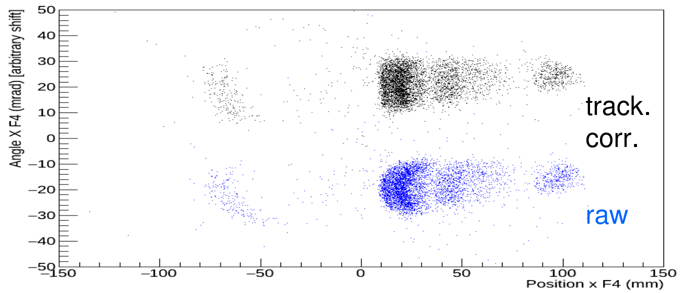



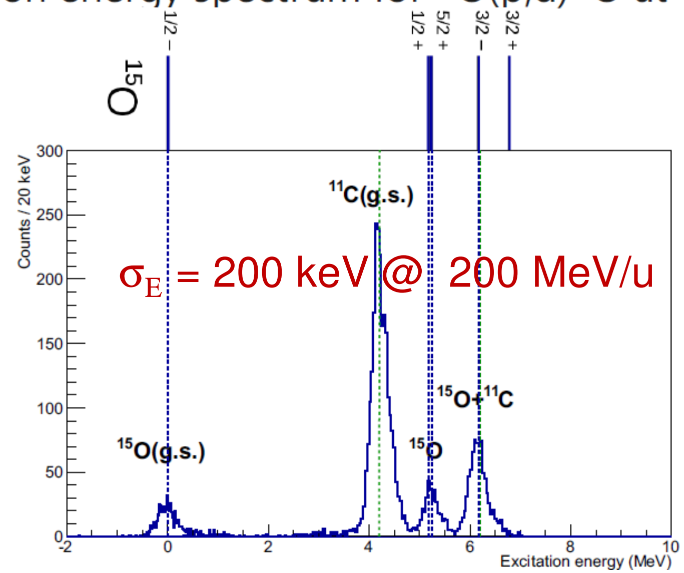
# High Resolution Spectrometer
## - recent example

Example from recent FRS experiment:
correct aberrations by sextupoles and tracking




Excitation energy spectrum for $^{16}O(p,d)^{15}O$ at 400 Mev/u




**R ~ 2000** (via tracking)

**Problems at higher energies (intensities) and with heavier nuclei**