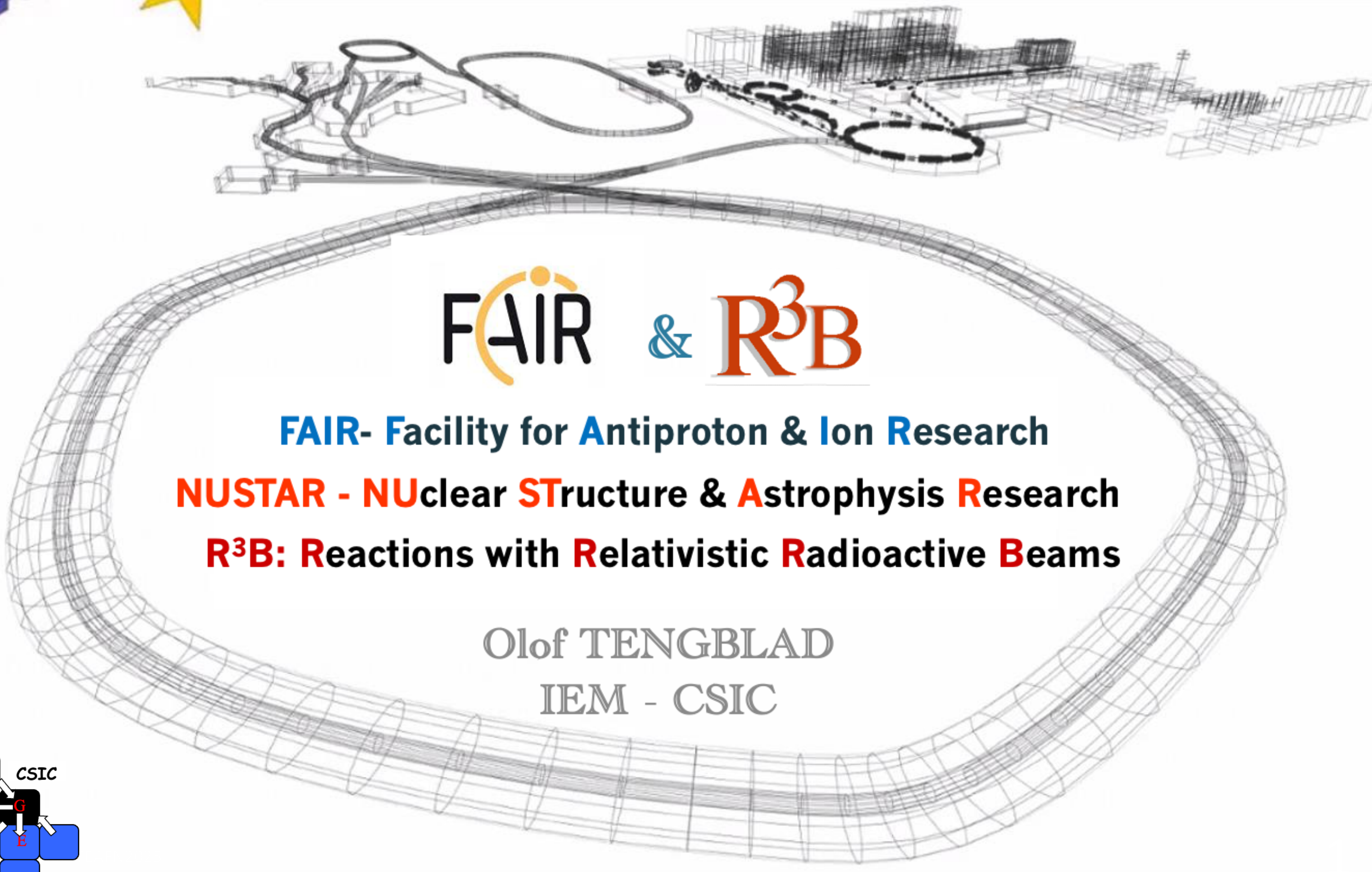


FAIR & R³B

FAIR- Facility for Antiproton & Ion Research

NUSTAR - NUclear STructure & Astrophysis Research

R^3B: Reactions with Relativistic Radioactive Beams

Olof TENGBLAD

IEM - CSIC

The Universe in the Laboratory

FAIR- Facility for Antiproton & Ion Research

https://fair-center.eu/

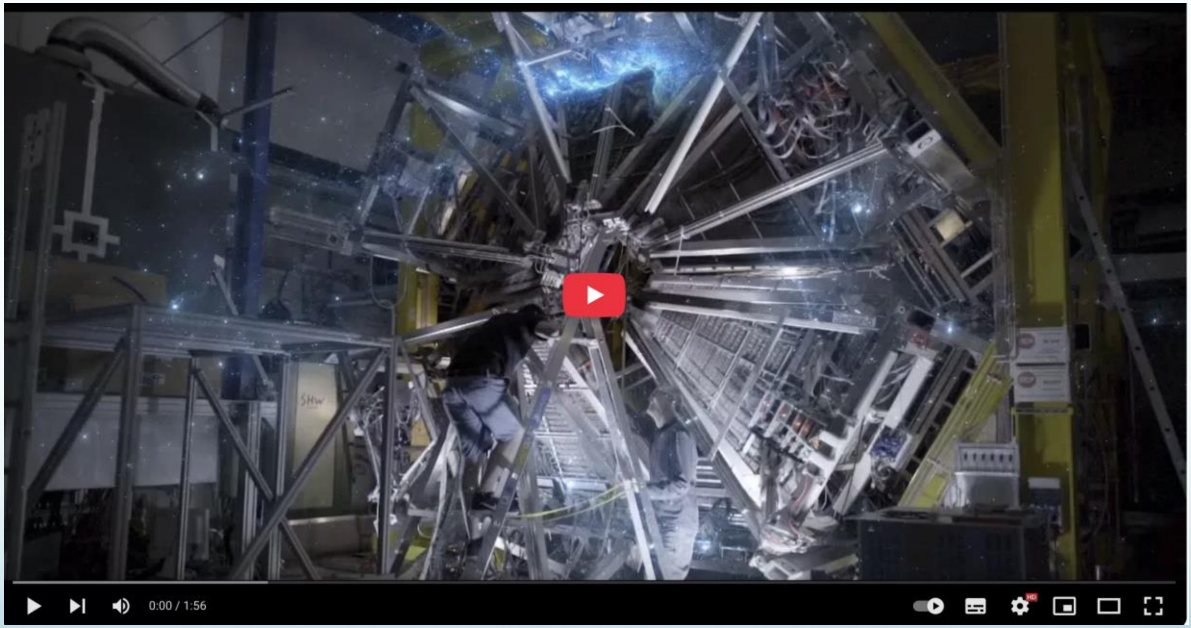
FAIR - The Universe in the Laboratory

Youtube movies

FAIR - The Universe in the Laboratory

https://www.youtube.com/watch?v=kbvK5AGg8oM

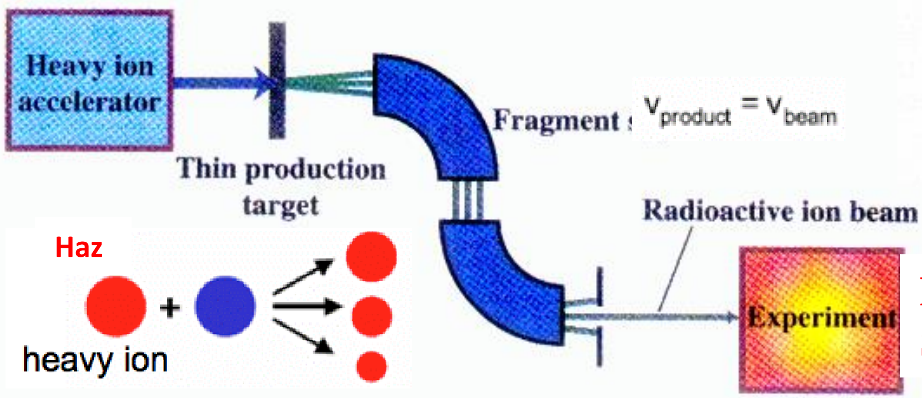
https://www.youtube.com/watch?v=wTCkZdeqI8I

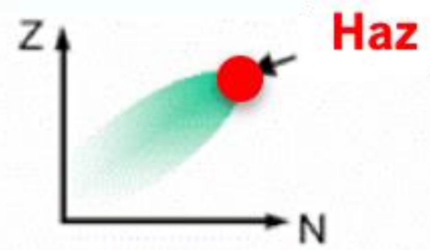


NUSTAR https://fair-center.eu/user/experiments/nustar/documents/technical-design-reports

Radioactive Beam Production

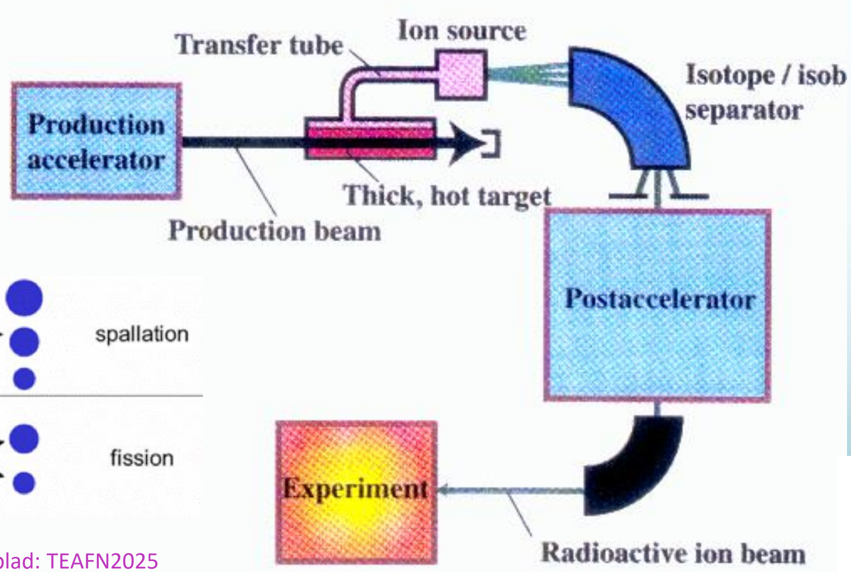
Beam Fragmentation

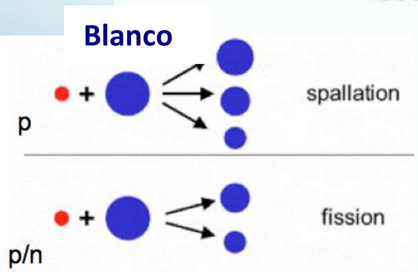


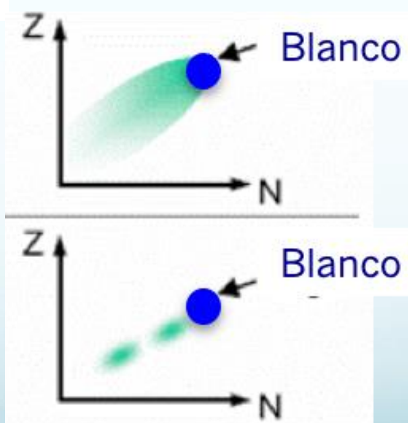


High energy, large variety of species, Short half-lives (μs), cocktail beam

ISOL – Isotope Separation On Line



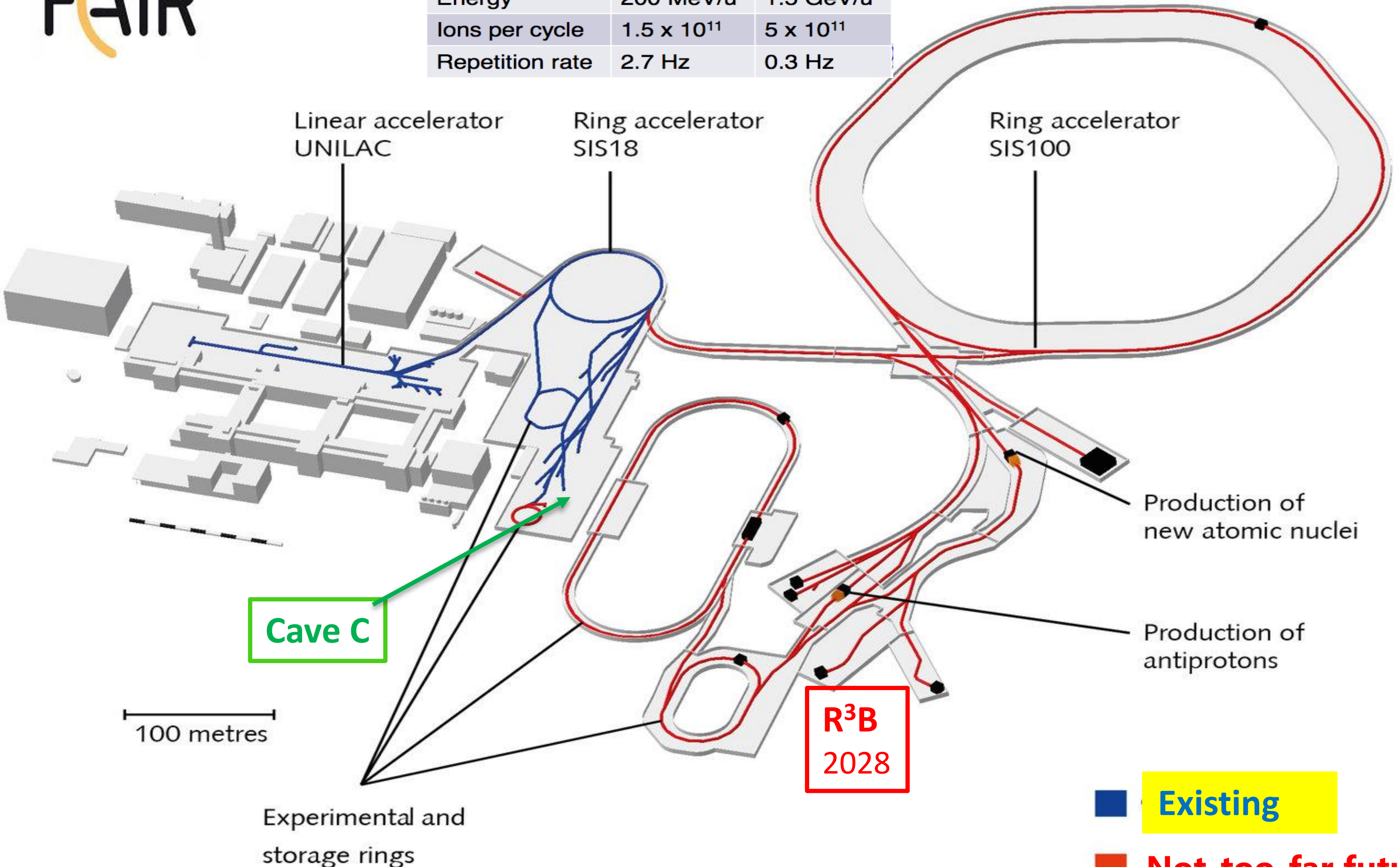




Variable energy, high intensity, good beam qualities

FAIR (2028)	2 GeV
GSI	1 GeV
GANIL	50 MeV
SPIRAL	10 MeV
HIE – ISOLDE	
ISOLDE	0.06 MeV

Design parameters U^{28+}	SIS18	SIS100
Energy	200 MeV/u	1.5 GeV/u
Ions per cycle	1.5×10^{11}	5×10^{11}
Repetition rate	2.7 Hz	0.3 Hz



Existing

Not-too-far future

Experiment facilities

The scientific user community of FAIR is organised in experimental collaborations, which are grouped in **4 scientific pillars**:

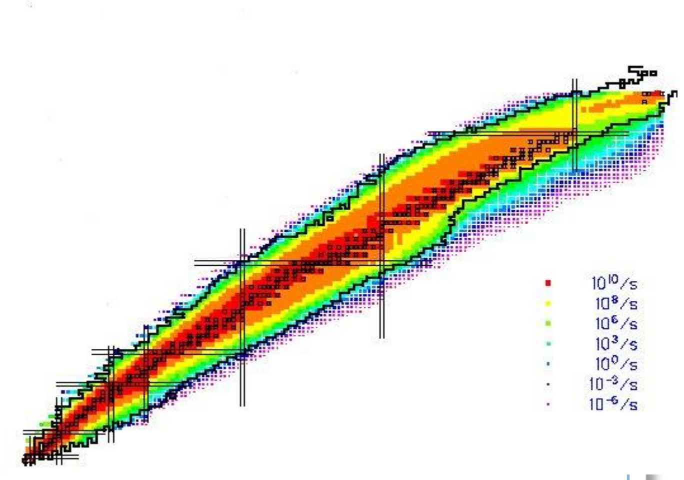
1. APPA - Atomic, Plasma Physics and Applications
   - **BIOMAT** - **Bio**logy and **Mat**erial Science
   - **HED@FAIR** - **H**igh **E**nergy **D**ensity Science at FAIR
   - **SPARC** - **S**tored **P**articles **A**tomic **R**esearch **C**ollaboration

2. CBM - Compressed Baryonic Matter

3. **NUSTAR - Nuclear Structure, Astrophysics and Reactions**
   - **High Eenergy Branch R3B** **2028**
   - **Low Energy Branch HISPEC/DESPEC, MATS, LASPEC** **2032**
   - **Ring Branch ILIMA, ELISe, EXL** **20xx**

4. PANDA - Physics with High Energy Antiprotons
   1. Antiprotons produced by a primary proton beam → High Energy Storage Ring (HESR) → fixed target inside PANDA

NUSTAR:
NUclear Structure, Astrophysics and Reactions



What are the limits for existence of nuclei?

- Where are the proton and neutron drip lines situated?
- Where does the nuclear chart end?

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

- What is the isospin dependence of the spin-orbit force?
- How does shell structure change far away from stability?

How to explain collective phenomena from individual motion?

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

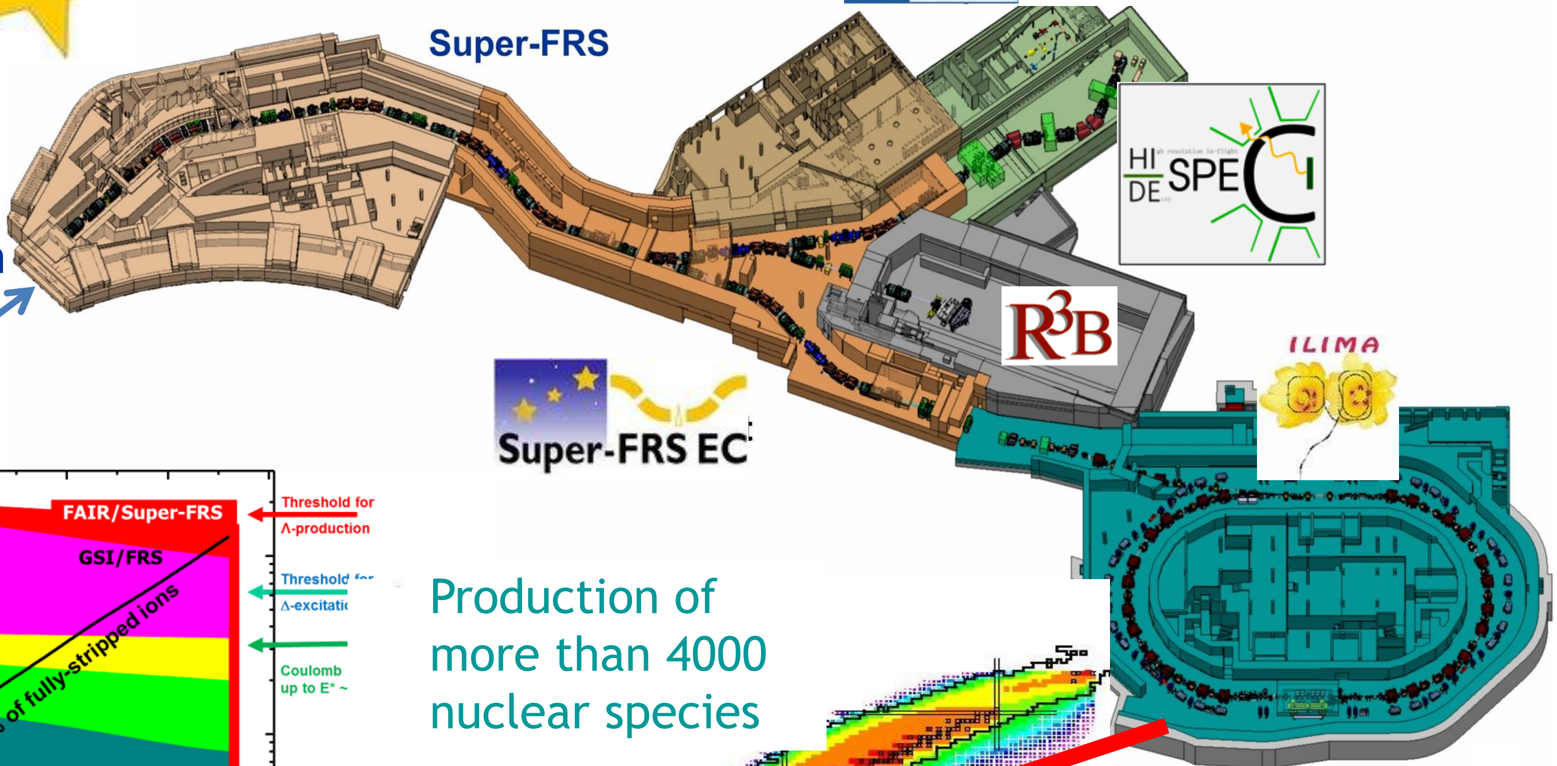
How are complex nuclei built from their basic constituents?

- What is the effective nucleon-nucleon interaction?
- How does QCD constrain its parameters?

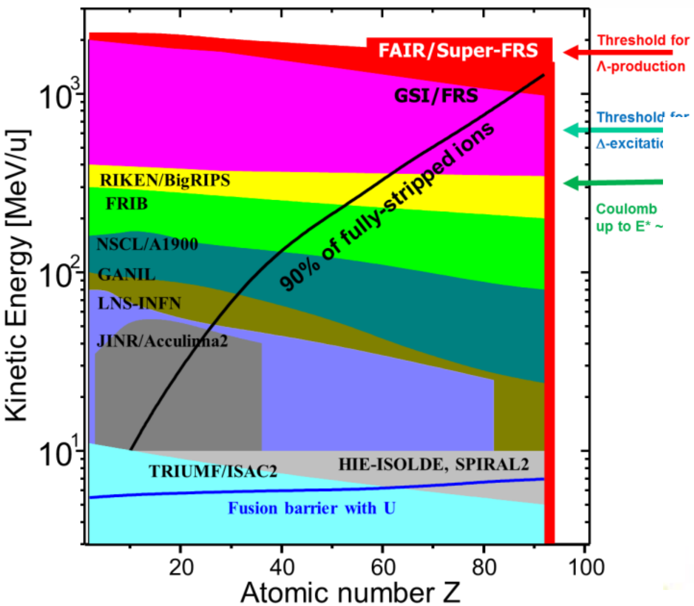
Which are the nuclei relevant for astrophysical processes and their properties?

- What is the origin of the heavy elements?

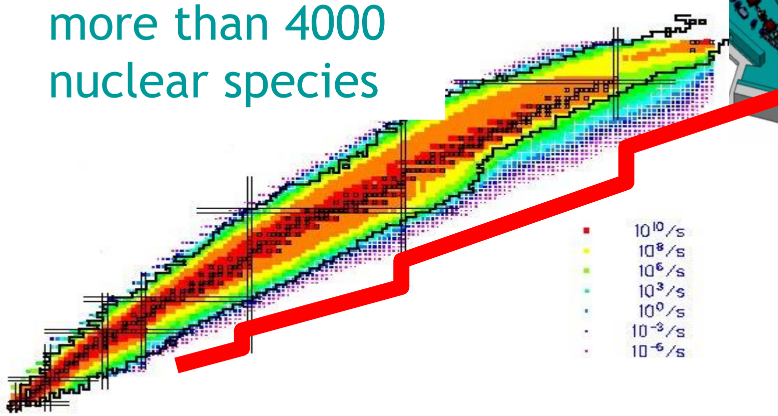
NUclear STructure & Astrophysis Research



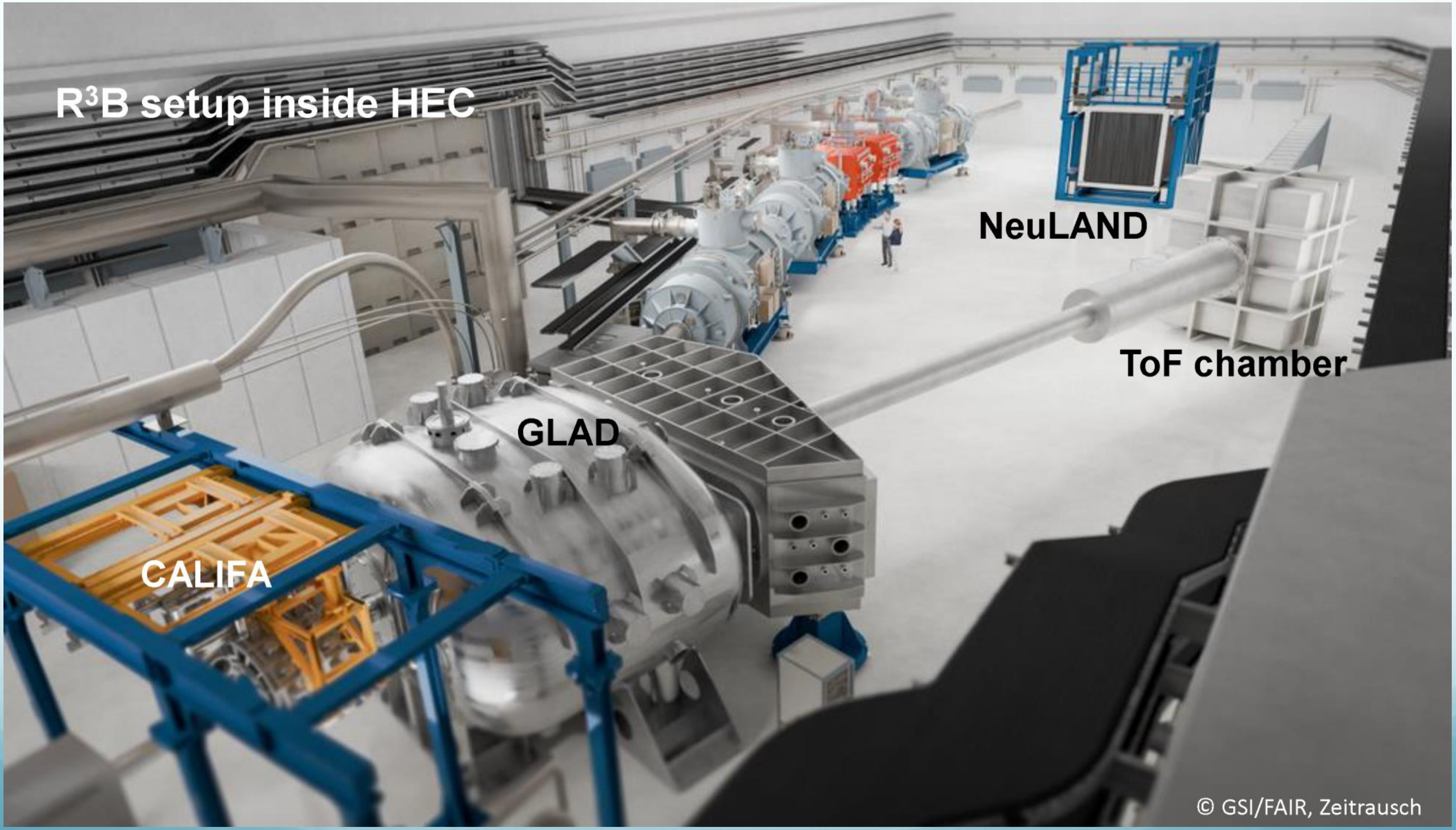
Primary beam from SIS100



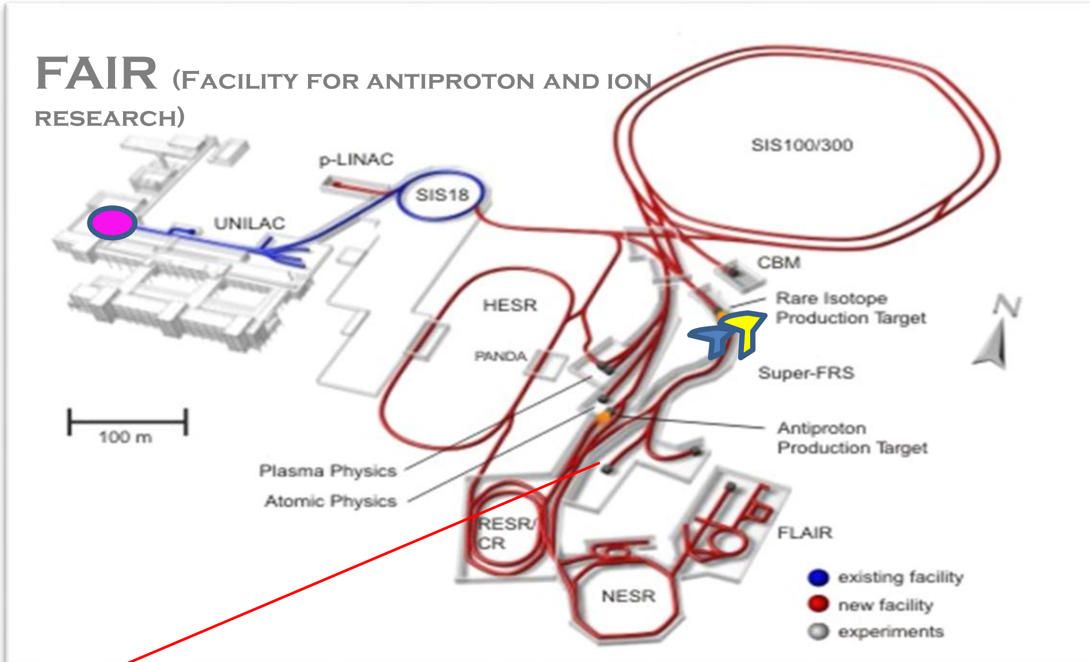
Production of more than 4000 nuclear species



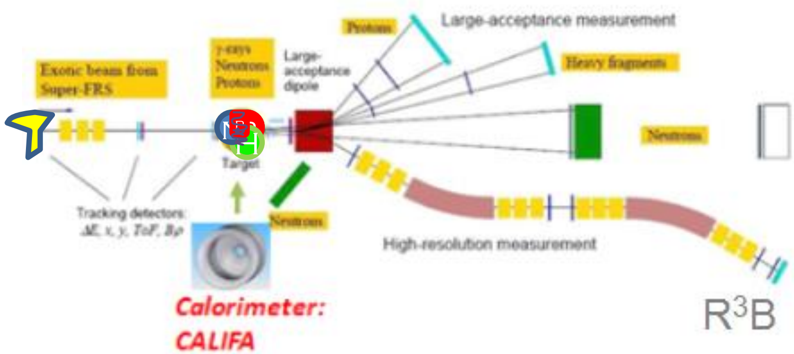
CAD drawing of the new installation in High Energy Cave



How does it work



R³B



1. Accelerated beam impact on Production Target

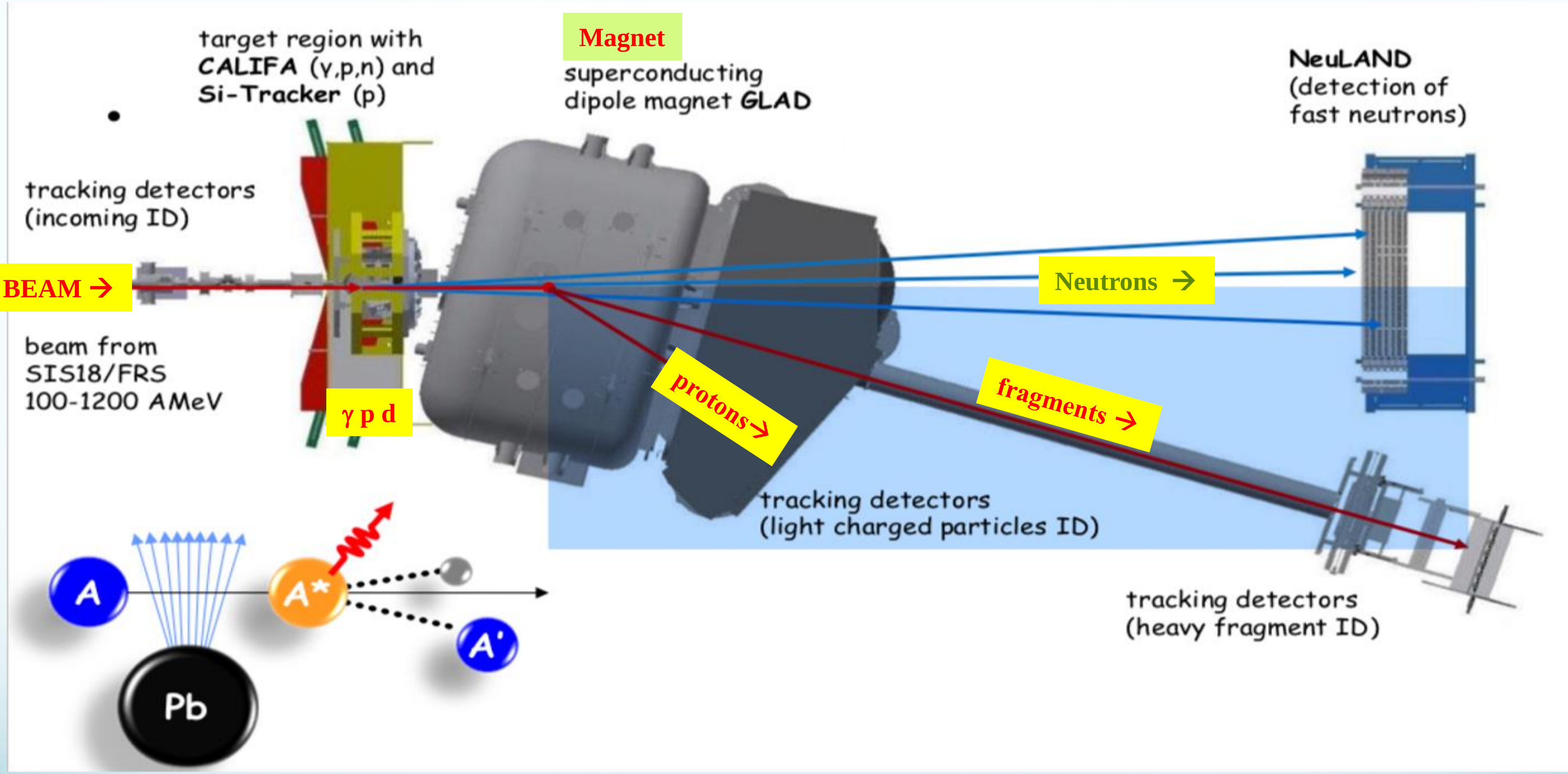
2. Products are separated in SFRS

3. Separated isotopes directed to experiment

4. Isotope of interest impact on Reaction Target

5. Reaction fragments and gammas are detected

R^{3}B: Reactions with Relativistic Radioactive Beams



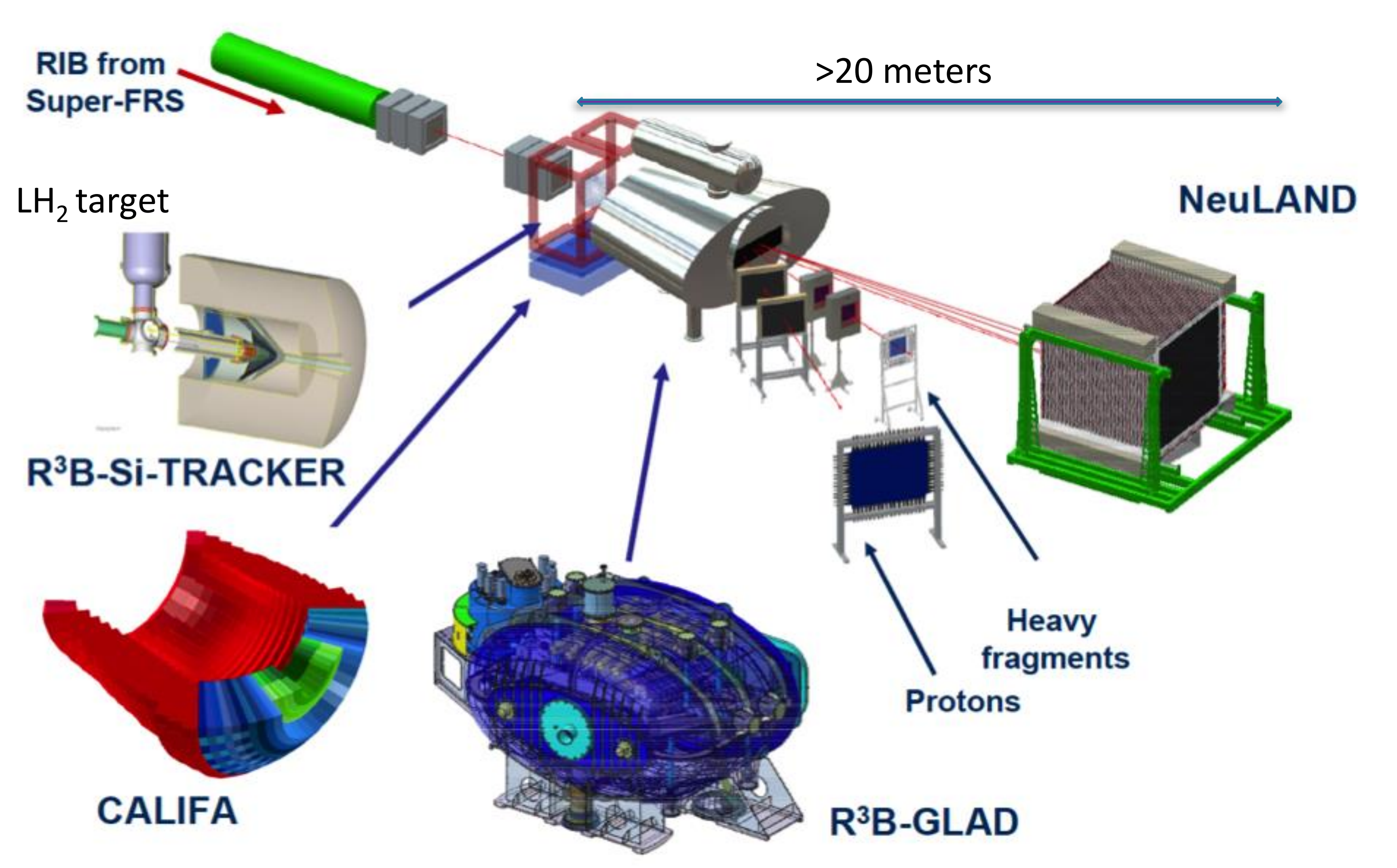
Kinematically complete measurement of reactions with high-energy secondary beams

- **Nuclear Astrophysics**
- **Structure of exotic nuclei**
- **Neutron-rich matter**

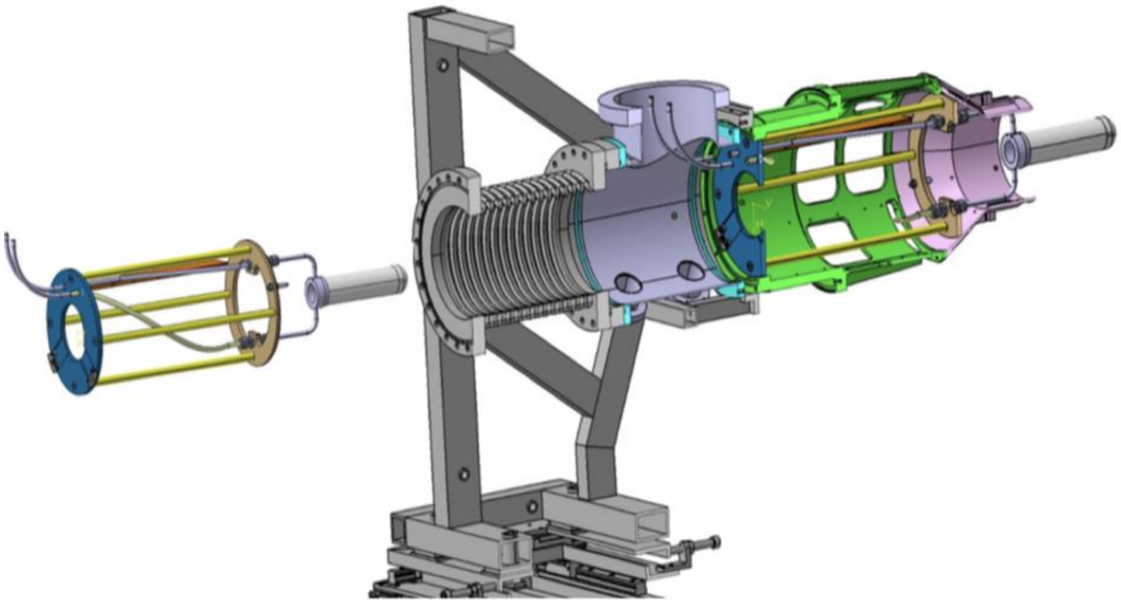
•fixed-target experiment for complete inverse-kinematics reactions with relativistic RIBs ~100 MeV/u – 1.5 GeV/u

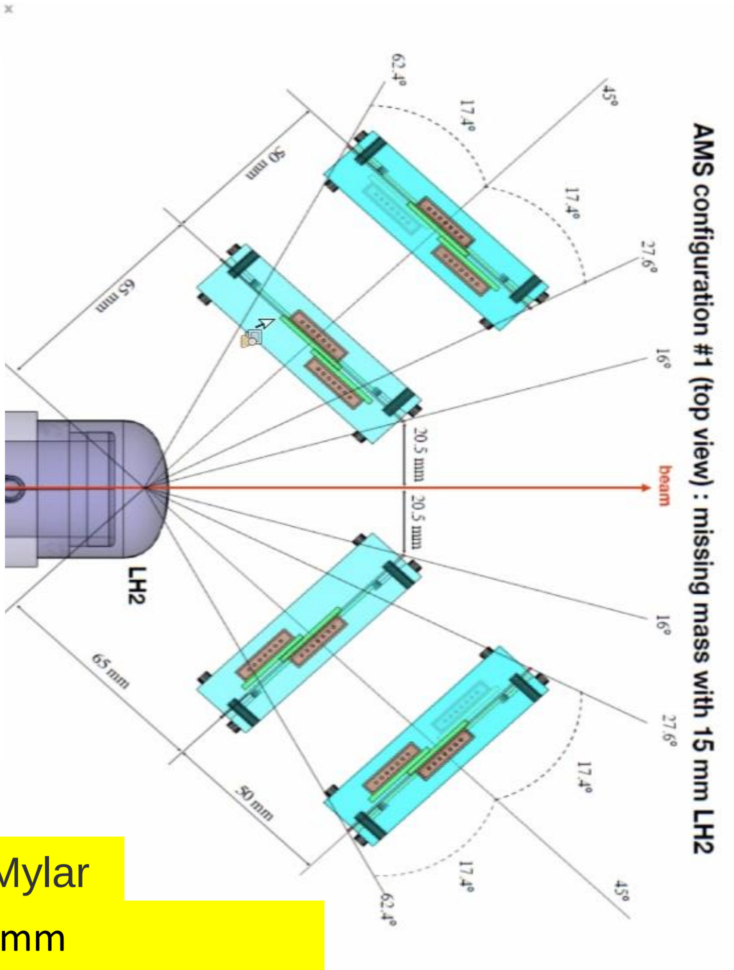
•Experiments with most exotic and short-lived nuclei - exploring the isospin frontier at and beyond the drip-lines

Key instrumentation



LH_2 target with Si-detector



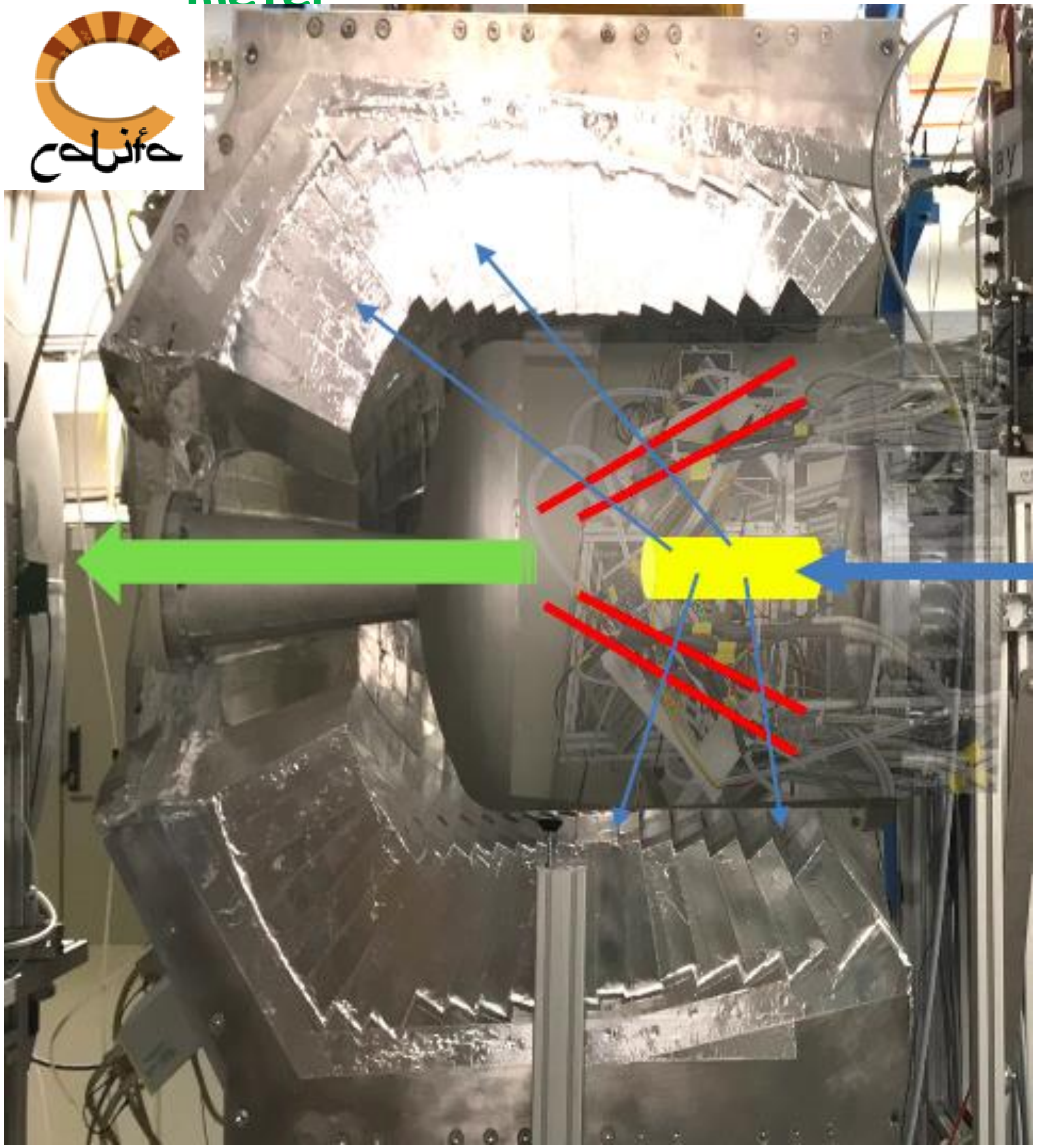


The target cell made of Mylar

Target cell diameter	42 mm
Three target length	15, 50 and 150 mm.

The cryogenic system operates in a **closed loop**.
The target is connected to a storage tank.
The tank is filled with **800 l of hydrogen at room temp**.
After liquefaction **the target hydrogen is at 20.3 K** and **1041 mbar**.

Reaction chamber: LH_2-target, p-tracker, γ-spec-calori-meter



Identify and track recoils emmitted at large angles

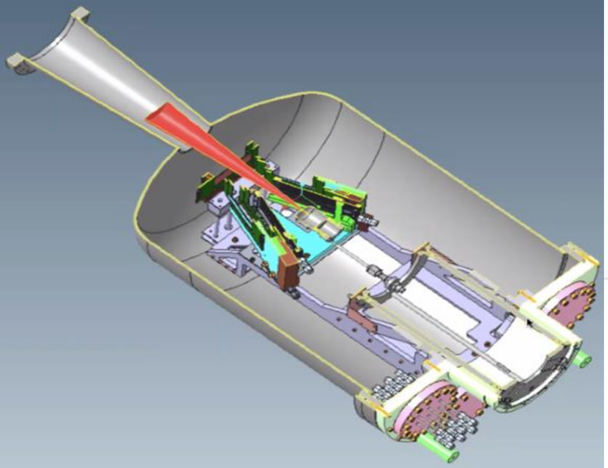
- **High angular resolution (better than 1 mrad) → very high segmentation**
- **Low noise level → detection of MIP**
- **Multi-layer sensors 50-100 μm for 1st layer → minimize multiple scattering or shadow γ rays**
- **Low threshold 25 KeV**
- **Multi-hit capability**

Further:

- **Closed geometry around the extended target→ 4p vertex reconstruction**
- **Spark protection against ionising particles hit**
- **Operate in the proximity of strong magnetic fields and vacuum**

Dedicated electronics

I+D para p-tracker → **flexible pixelated Si-boards**

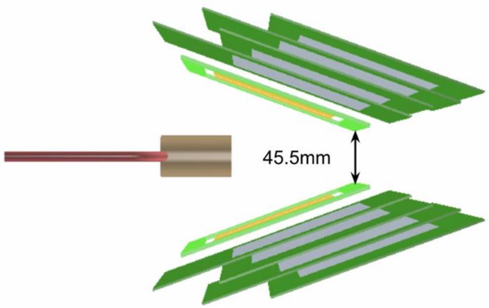


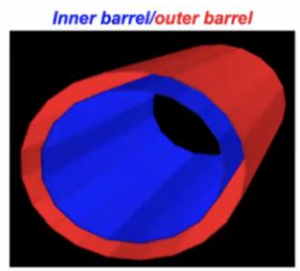
Optional future upgrade

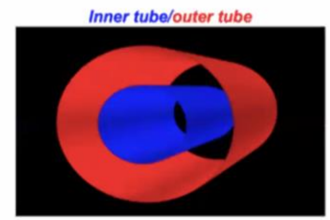
Modular conical arrangement using ALPIDE modules (recently designed by AMBER collaboration at CERN)

Barrel geometry based on ALPIDE modules optimised for thickness (ongoing R&D by AMBER and **NUSTAR** collaboration)

Cylinder with fully flexible, ultra thin pixel sensors for inner layer (current R&D phase by ALICE collaboration)







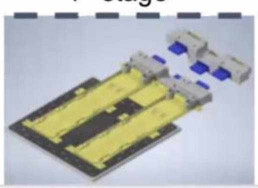
present

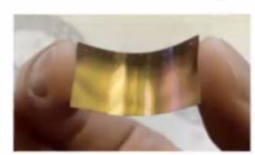
2024/25
Immediate goal
1st stage

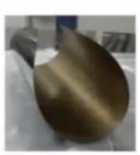
2026/27
intermediate goal
2nd stage

2028/30
final goal
3rd stage

flexible boards







Hybrid γ/p spectrometer/calorimeter

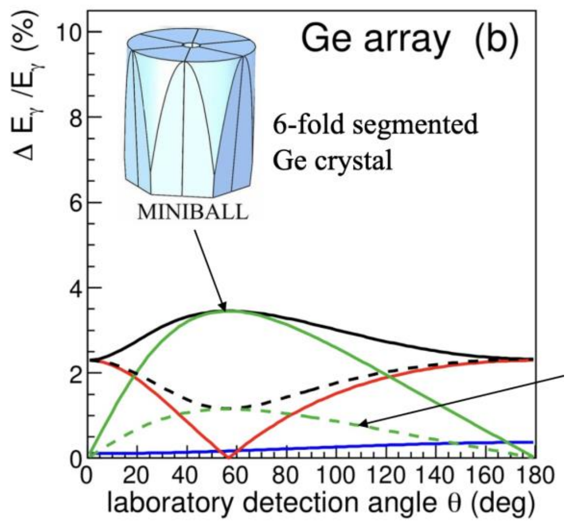
Univ. Santiago de Compostela

Grupo de Física Nuclear Experimental

TUDa - TUM – Lund

From the talks yesterday we learned

Design constrins

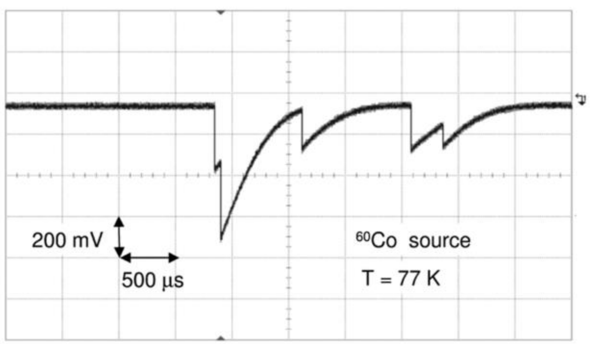


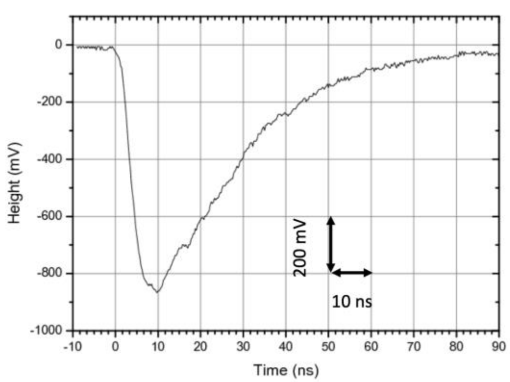
A. Jungclaus

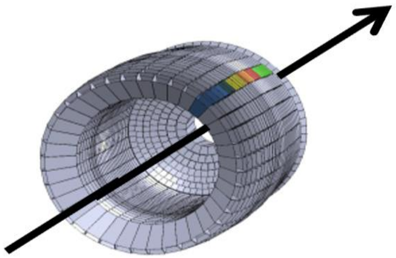
R^3B $\beta > 80\%$ c
the intrinsic resolution not so important.
→ we can go for scintillator
Doppler broadening → high segmentation

B. Olaizola

Scintillators are fast (CsI 420ns) but some are faster ($LaBr_3$ 18ns!)
→ Forward endcap $LaBr_3$ to avoid the pile-up



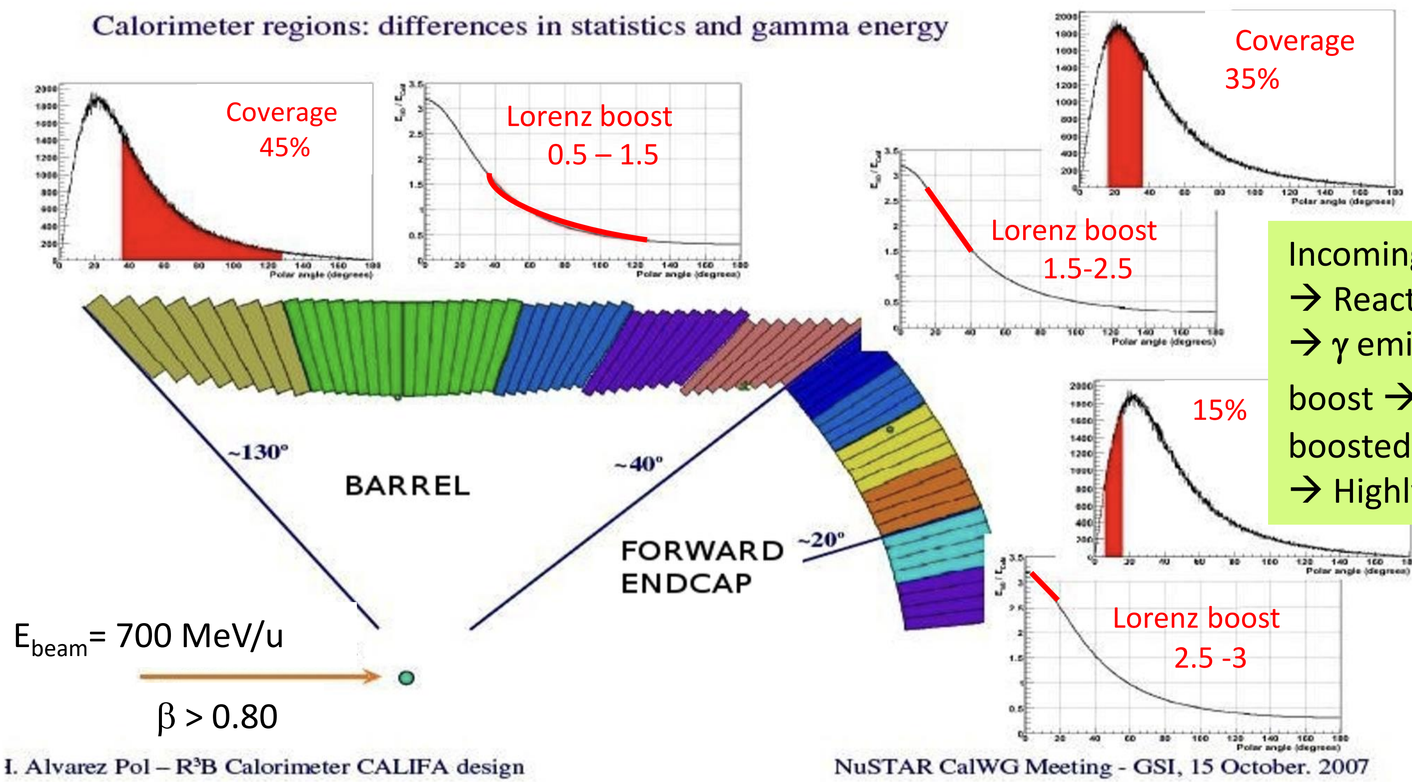




Detect γ (50 keV – 25 MeV) with energy resolution < 5%)

Barrel: Region from ~40° up to 130° in polar angles

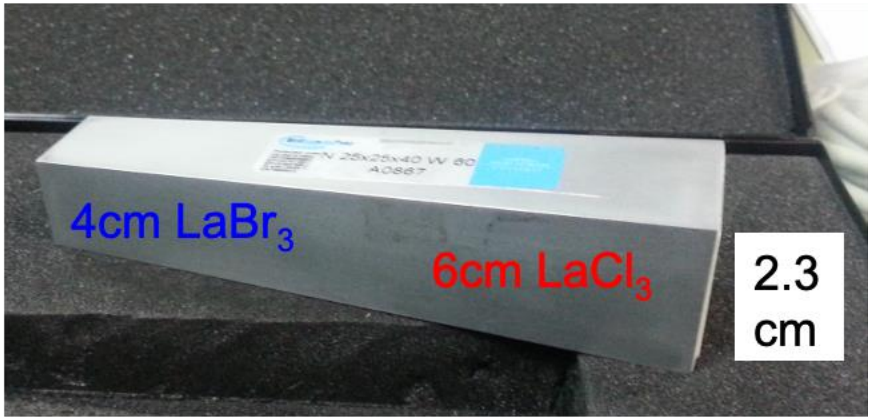
Forward endcap: From ~ 7° up to ~40°



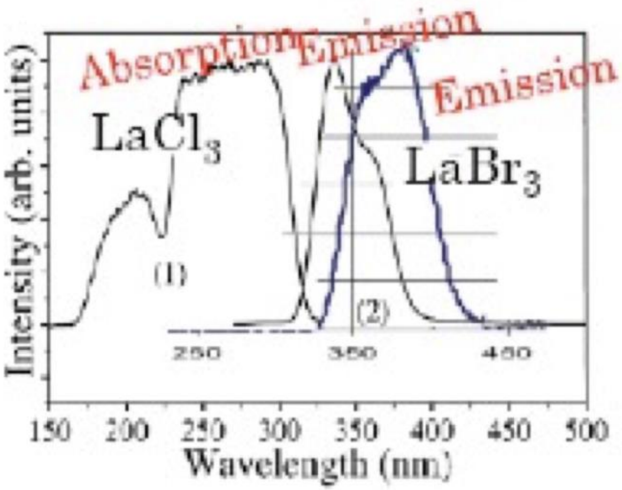
Incoming beam **@ 85% of c**
→ Reaction very much forward
→ γ emitted in flight → Lorenz boost → at small angles γ boosted up to 3x
→ Highly segmented

I+D de un centellador con dos cristales distintos con una única salida electrónico → Phoswich de $LaBr_3(Ce)$ + $LaCl_3(Ce)$

1,9 cm



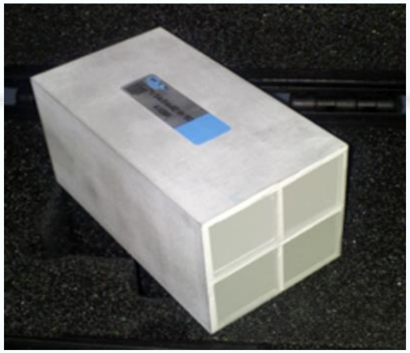
2.3 cm



Materials	Energy Resolution (at 662 keV) (%)	Light yield (photons/ keV γ)	Decay time (ns)	$\lambda_{emision}$
$LaBr_3$	2.9	63	16	380 nm
$LaCl_3$	3.8	49	28	350 nm

Segundo cristal transparente para la luz del primero

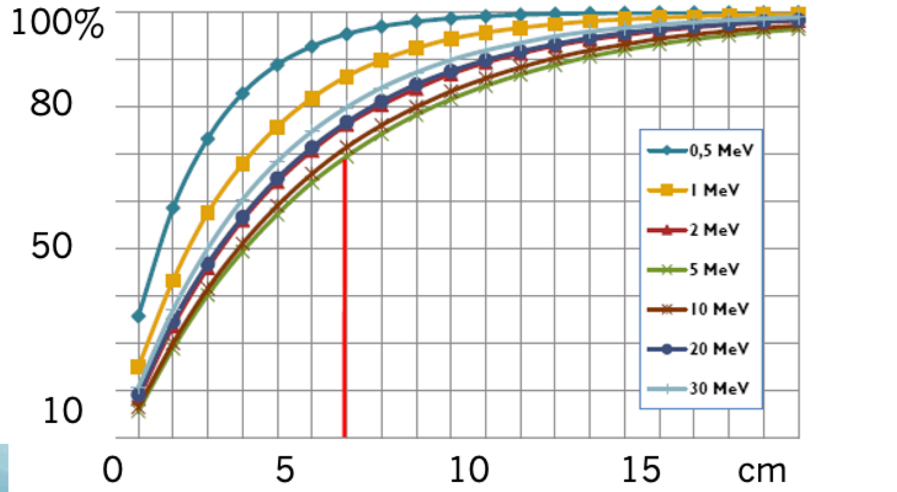
gammas in Phoswich



Question to be answered:
- Depth of first interaction
- **Depth @ 90% photopeak efficiency**
- How many neighbouring crystals are being hit?

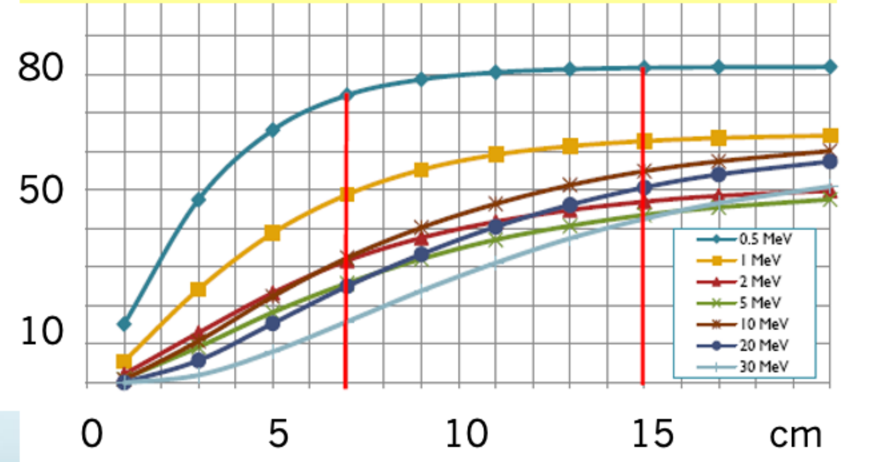
Simulation codes
- SRIM --- GEANT4 --- MCNPX Monte Carlo N-Particle eXtended code

First hit



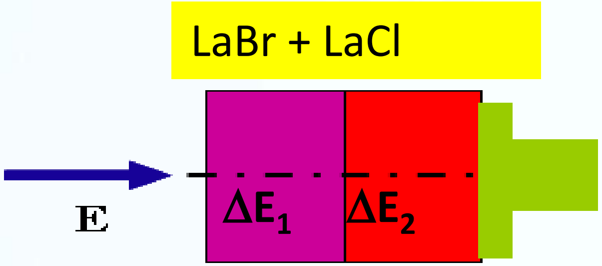
@7 cm 70 % of incident beam is detected

Photopeak efficiency vs crystal length



>15 cm has NO influence efficiency

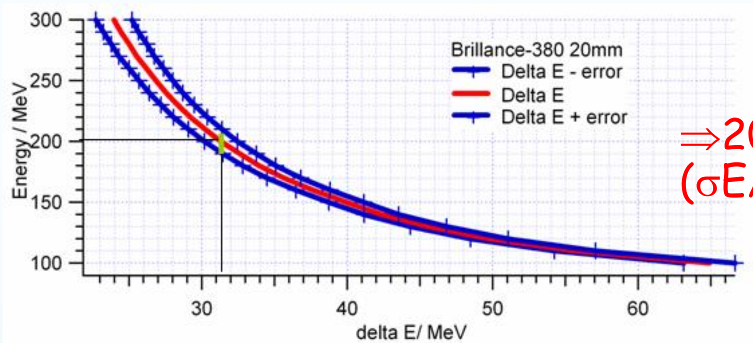
PROTONS in Phoswich: ΔE+ E



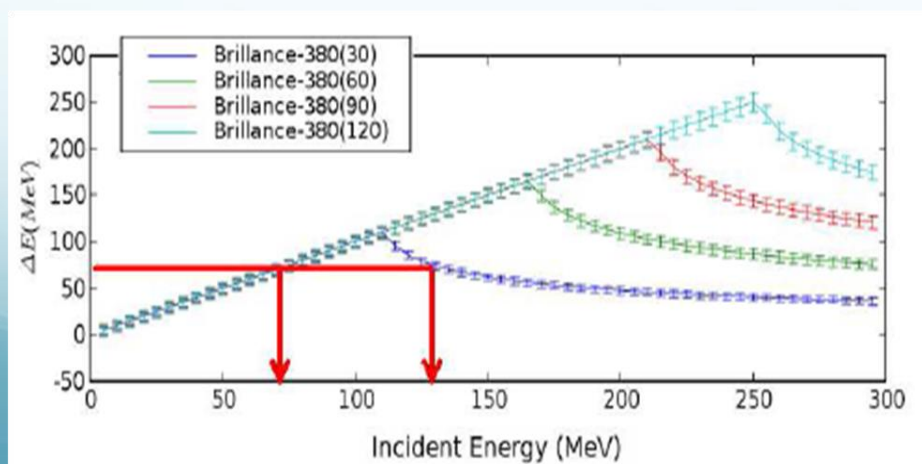
$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\log\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2\right]$$

$$E = f(\Delta E_1) + g(\Delta E_2)$$

Ep= 200MeV → 20 mm LaBr → ΔE = 31 ± 1 MeV



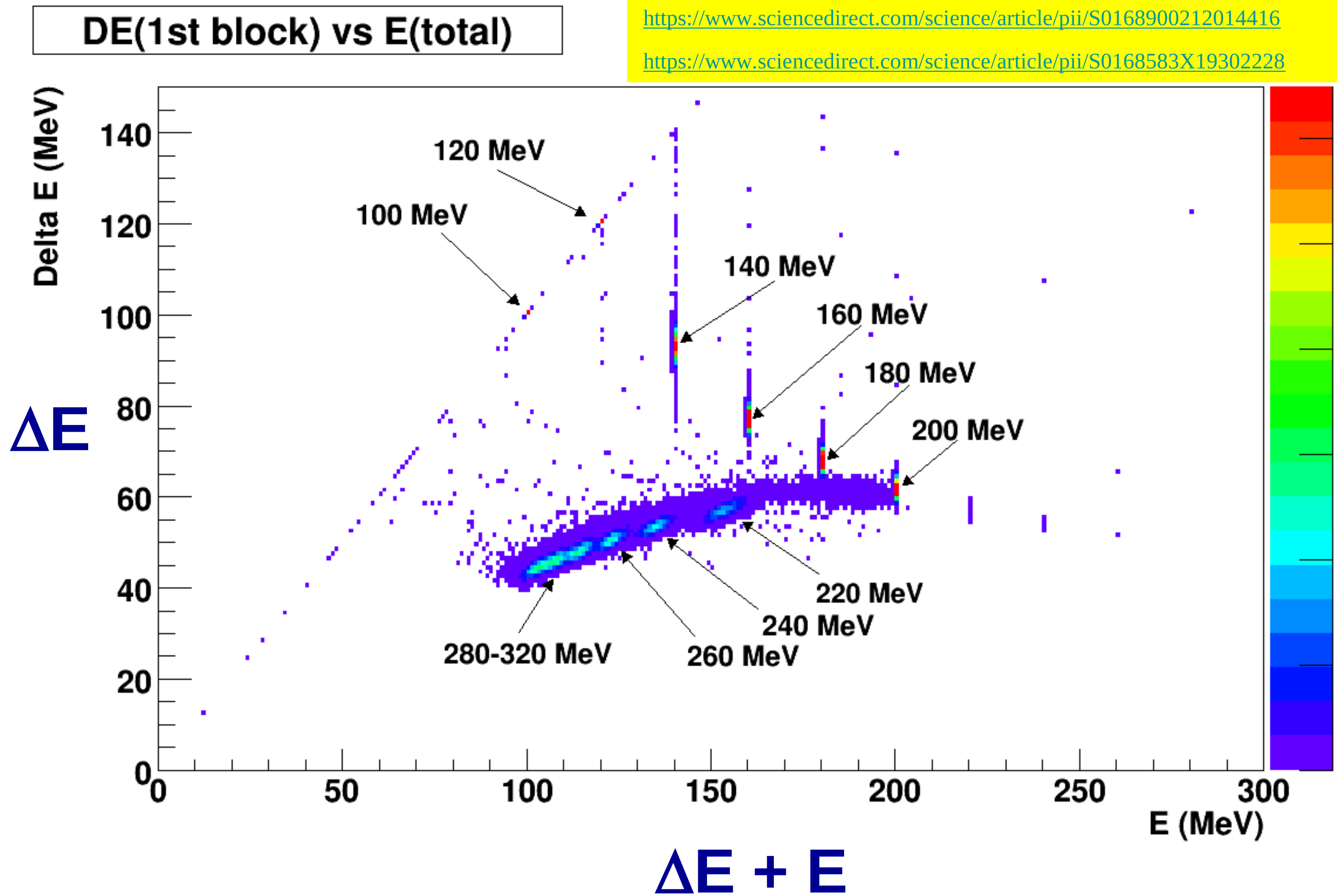
⇒200±10MeV
(σE/E=5%)



- **Protons: two ΔE-detectors one can determine the full proton energy with a resolution of <5%.**
- **Gammas: Second detector placed to solve the ambiguity on the signal**

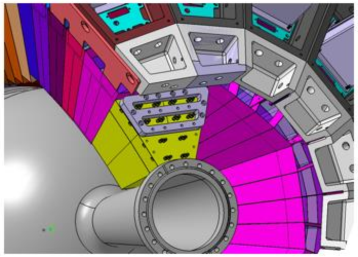
PROTONS in Phoswich: ΔE vs ΔE+ E

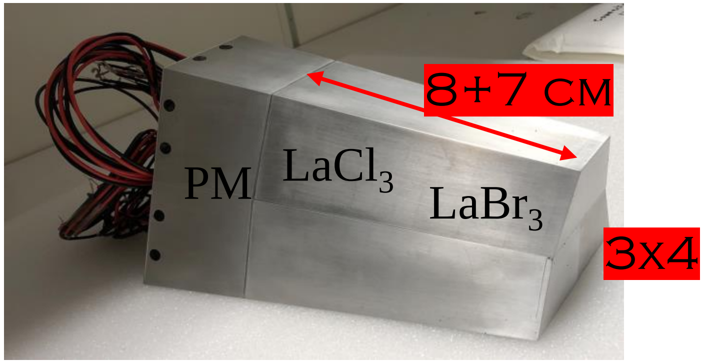
https://www.sciencedirect.com/science/article/pii/S0168900212014416
https://www.sciencedirect.com/science/article/pii/S0168583X19302228

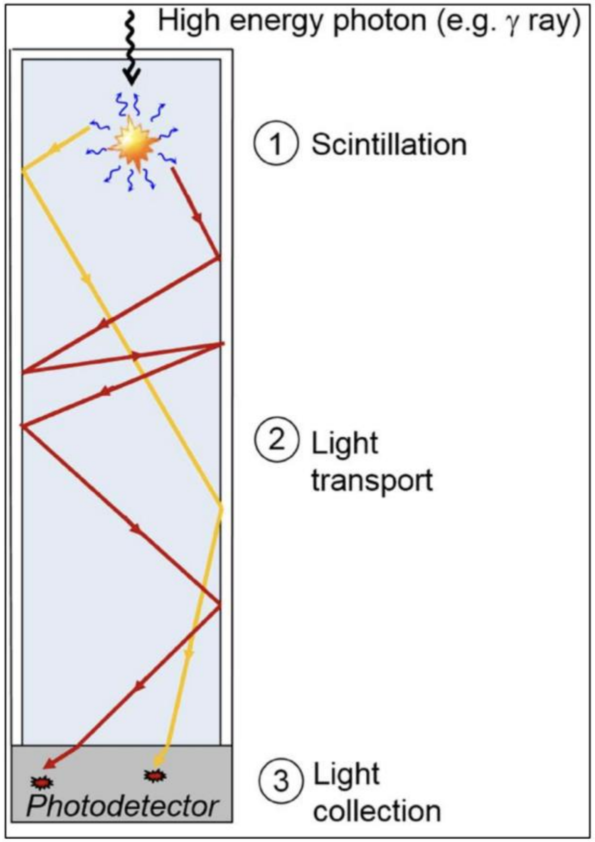


Endcap still in R&D!

As explained by Bruno
long funny shaped crystals
→ non-linear response
This is in CsI mitigated by LAPPING
In LaBr not easy…







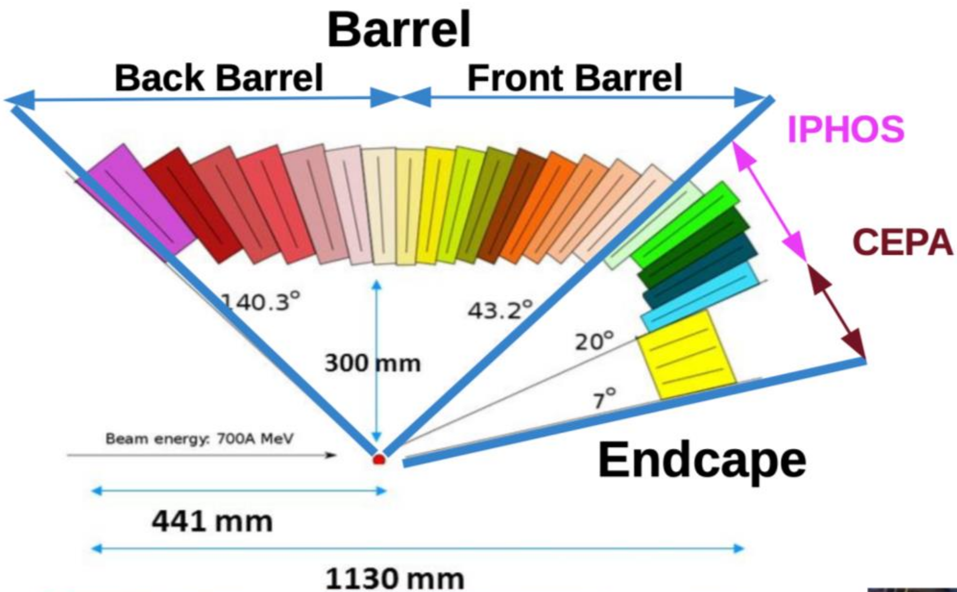
https://iopscience.iop.org/article/10.1088/1742-6596/1667/1/012006

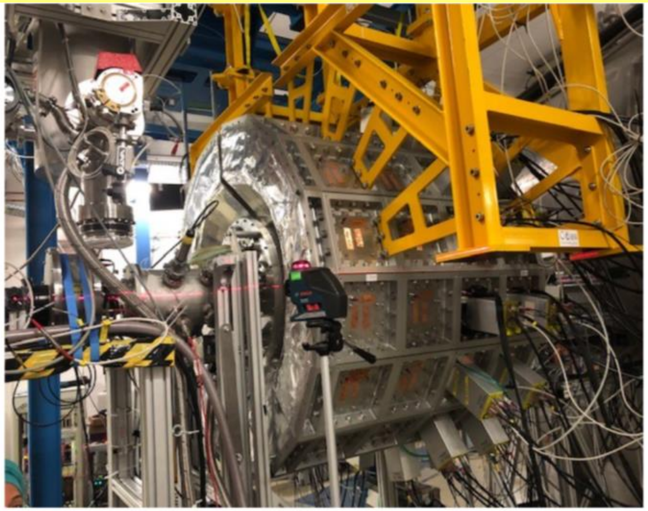
CALIFA barrel and forward endcap (gamma/particle calorimeter)

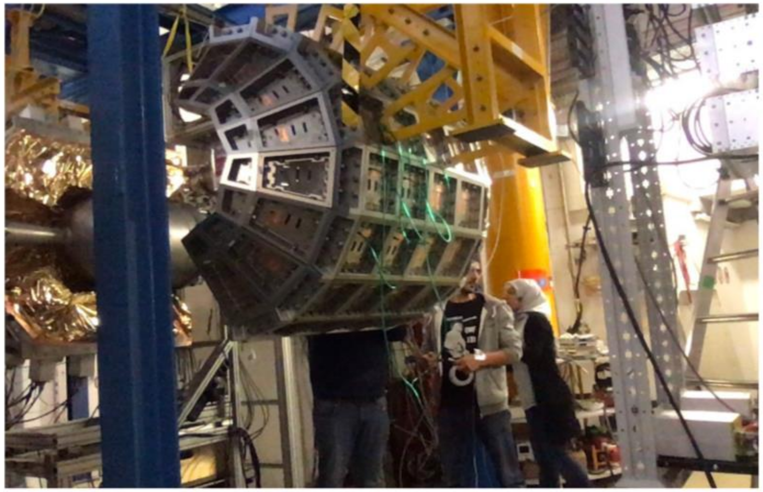
CALIFA: Highly segmented
Thick detection volume
Inner radius 50cm

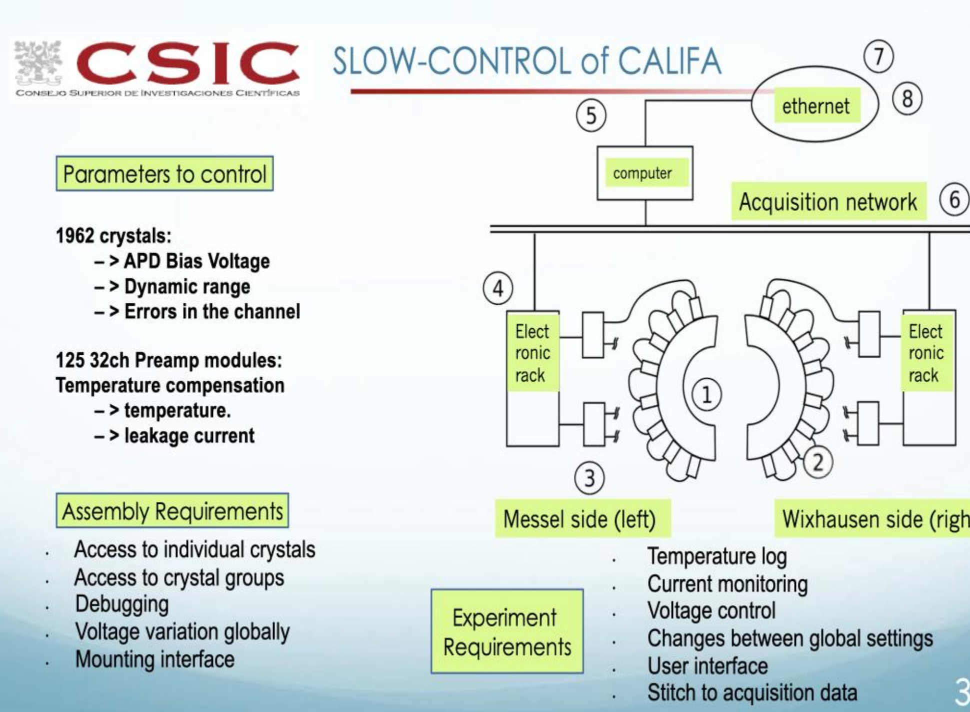
Barrel: Crystal length 15-20 cm
1952 crystals = 2 Ton

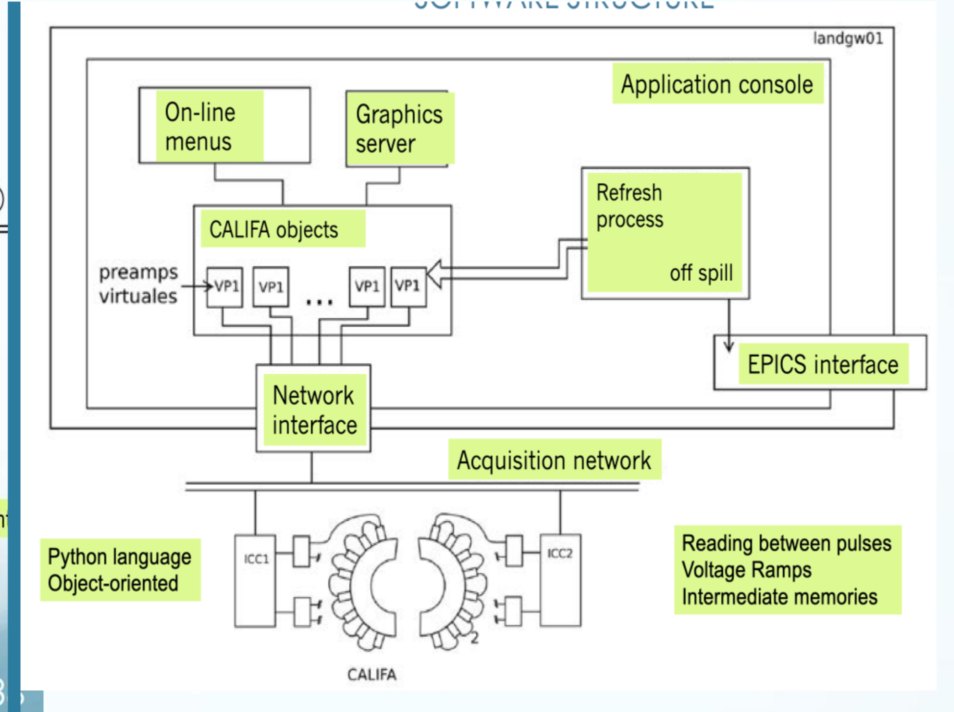
EndCap: 680 crystals = 1 Ton

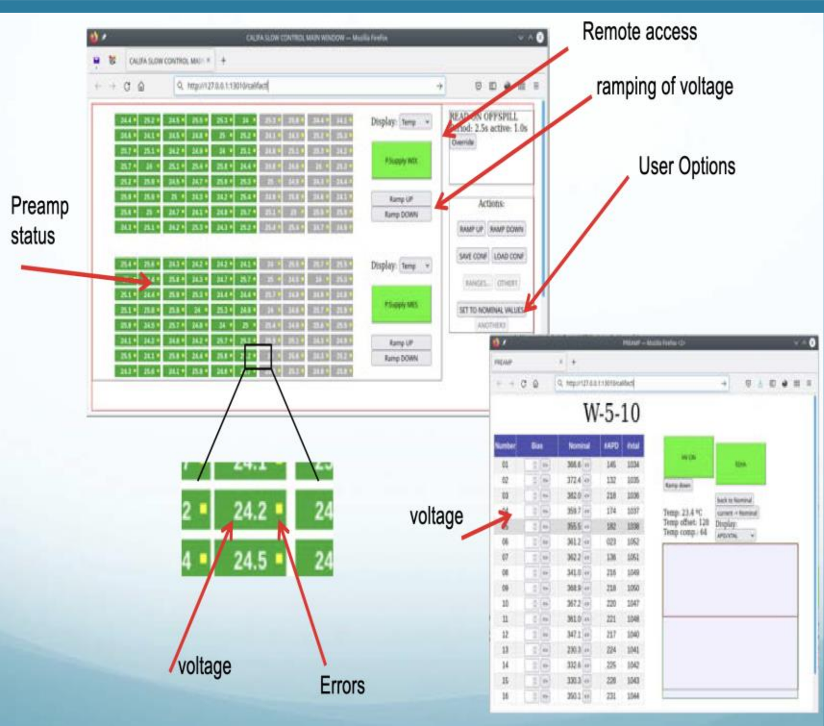


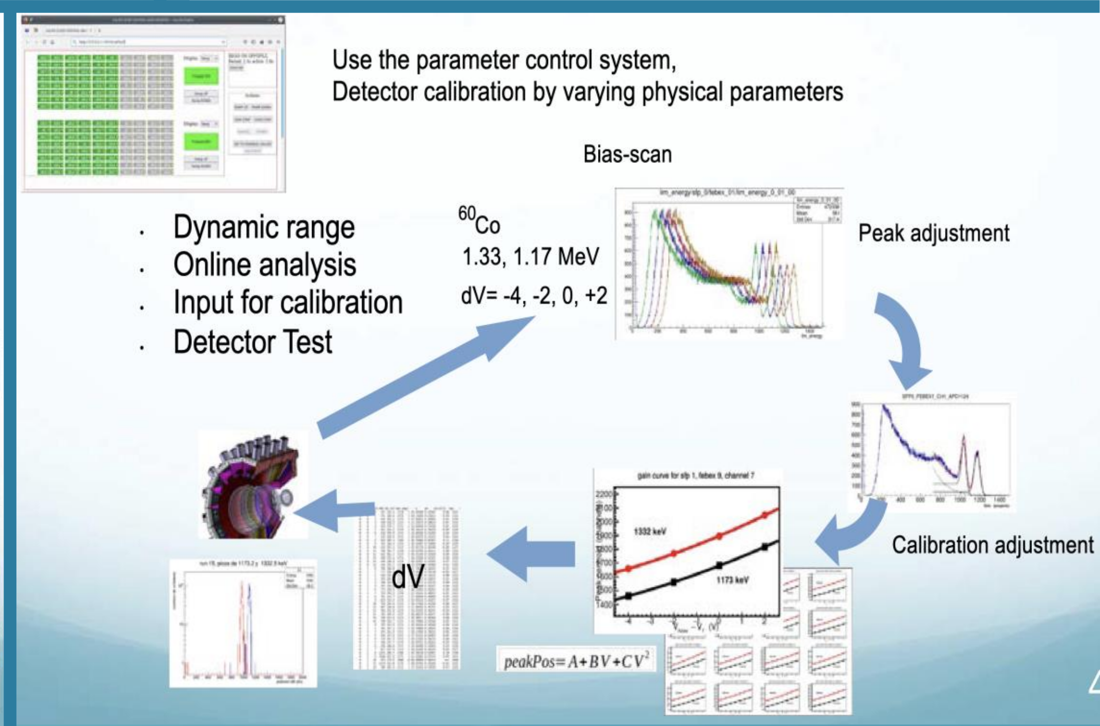





CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
SLOW-CONTROL of CALIFA
Parameters to control
1962 crystals:
–> APD Bias Voltage
–> Dynamic range
–> Errors in the channel
125 32ch Preamp modules:
Temperature compensation
–> temperature.
–> leakage current
Assembly Requirements
Access to individual crystals
Access to crystal groups
Debugging
Voltage variation globally
Mounting interface
ethernet
computer
Acquisition network
Electronic rack
Electronic rack
Messel side (left)
Wixhausen side (righ
Experiment Requirements
Temperature log
Current monitoring
Voltage control
Changes between global settings
User interface
Stitch to acquisition data


landgw01
Application console
On-line menus
Graphics server
CALIFA objects
Refresh process
off spill
preamps virtuales
VP1
VP1
VP1
VP1
EPICS interface
Network interface
Acquisition network
ICC1
ICC2
CALIFA
Python language
Object-oriented
Reading between pulses
Voltage Ramps
Intermediate memories


Remote access
ramping of voltage
User Options
Preamp status
voltage
Errors
voltage
24.2
24.5
W-5-10

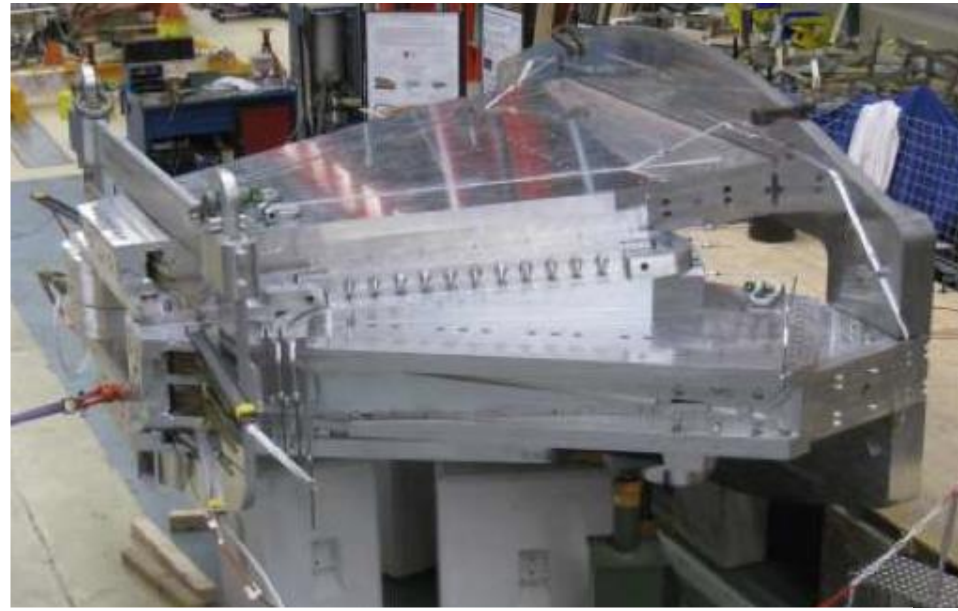

Use the parameter control system,
Detector calibration by varying physical parameters
Bias-scan
Dynamic range
Online analysis
Input for calibration
Detector Test
60Co
1.33, 1.17 MeV
dV= -4, -2, 0, +2
Peak adjustment
Calibration adjustment
dV
1332 keV
1173 keV
peakPos=A+BV+CV2

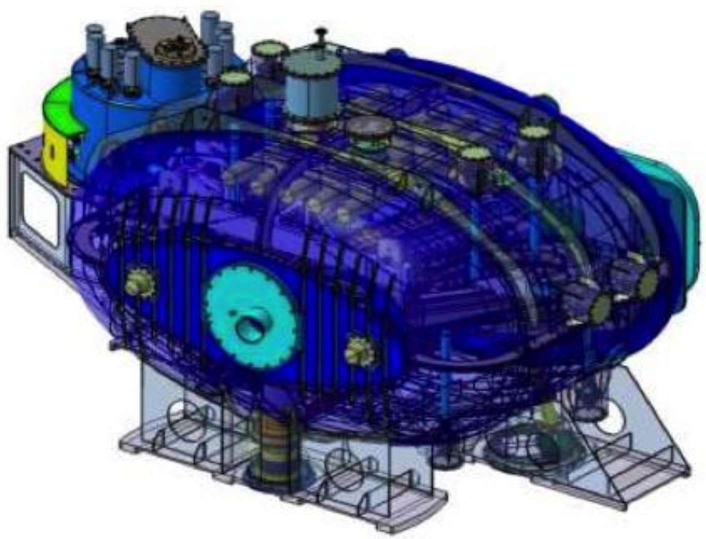
GLAD - Large-Acceptance superconductingDipole magnet

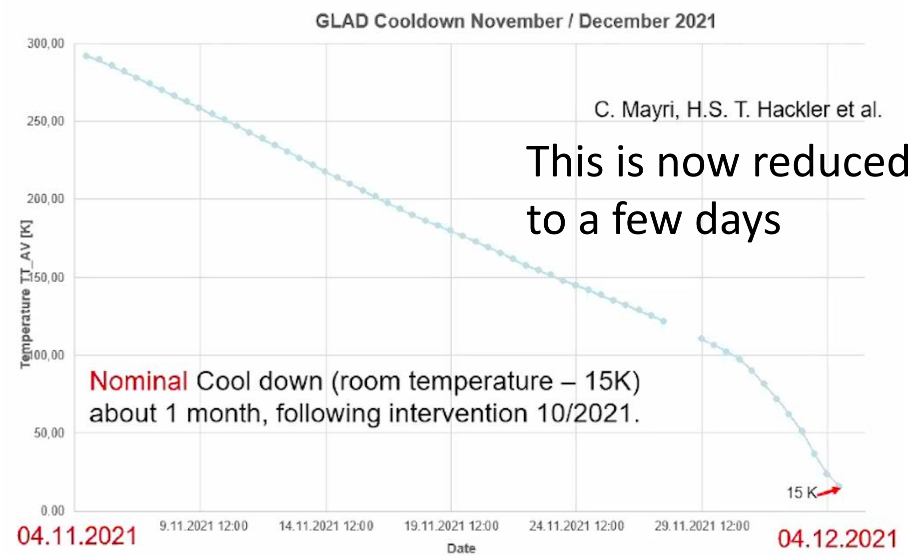
https://www.gsi.de/work/forschung/nustarenna/nustarenna_divisions/kernreaktionen/r3b_project_group/glad

Magnet parameters: Weight: 50 t

- 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.



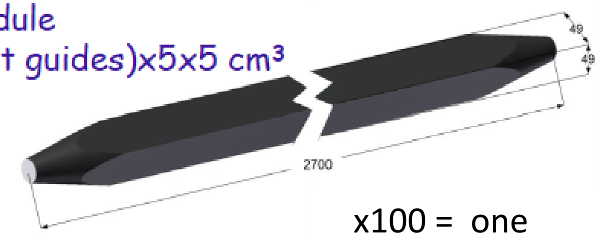




NeuLAND - High-resolution neutron ToF spectrometer

https://www.gsi.de/work/forschung/nustarenna/nustarenna_divisions/kernreaktionen/r3b_project_group/neuland

NeuLAND submodule
250(270 incl. light guides)x5x5 cm³

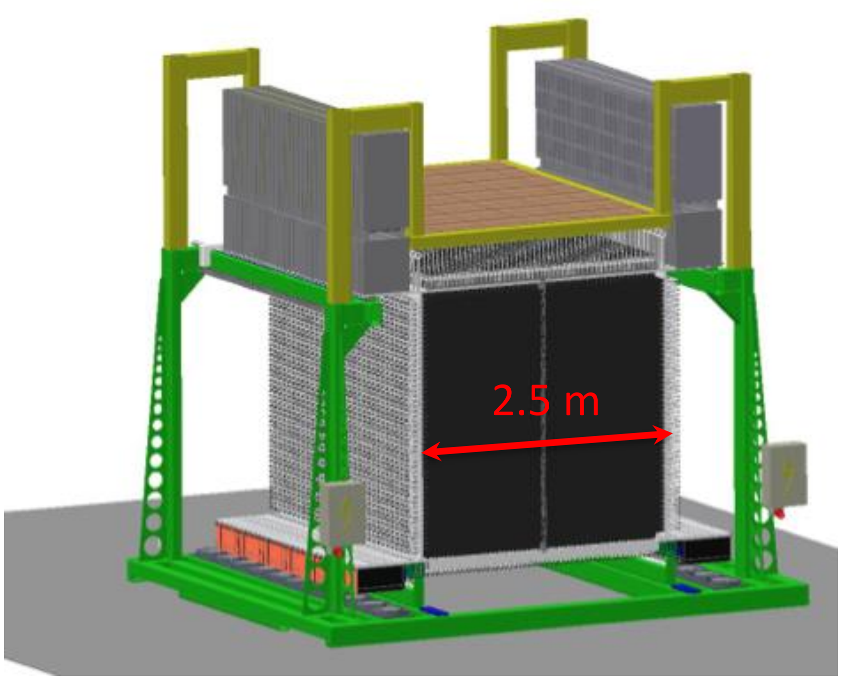


x100 = one double-plane

NeuLAND detector parameters:

- full active detector using RP/BC408
- face size 2.50x2.50 m^2
- active depth 3m (30 double-planes)
- 3000 scintillator bars
- 6000 PM / readout channels (both ends)
- 32 tons

2024: 17 DP installed



NeuLAND design goals:

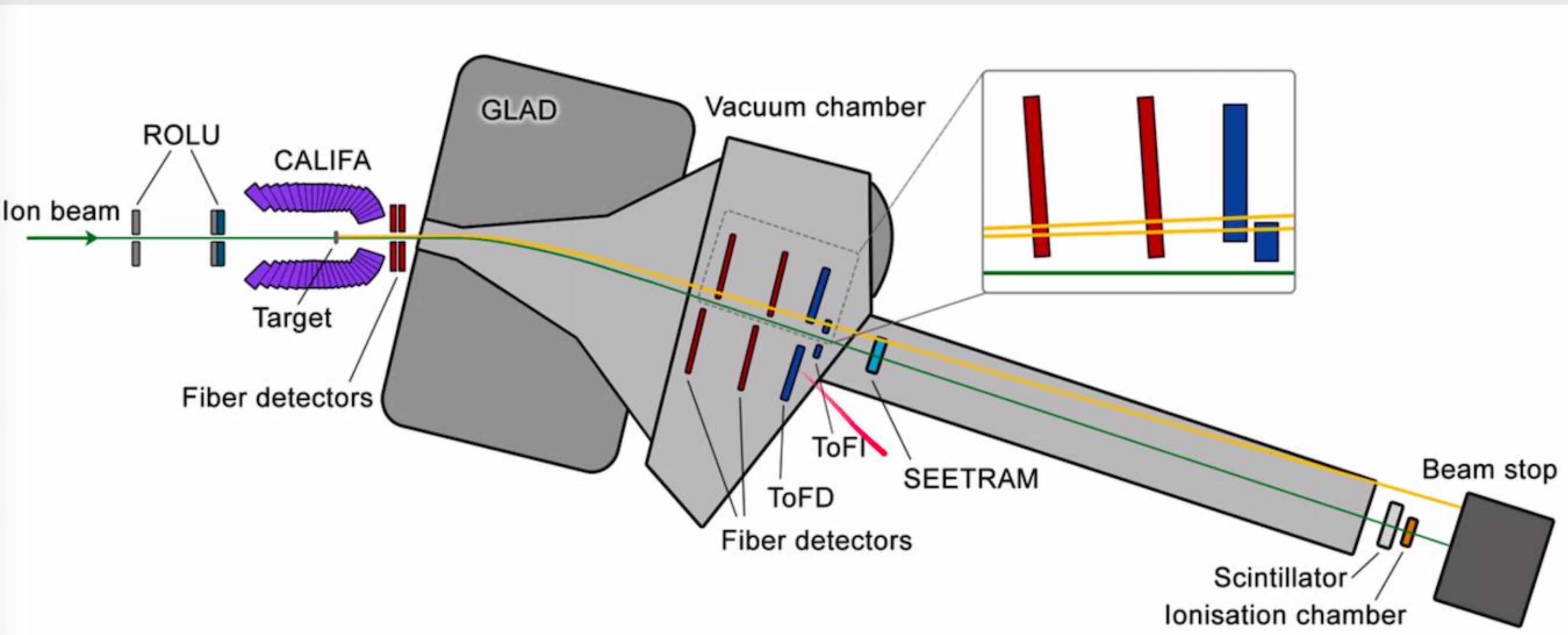
- >90% efficiency for 0.2-1.0 GeV neutrons
- Multi-hit capability for up to 5n
- invariant-mass resolution:
  NeuLAND to target distance 35 m
  ΔE < 20 keV at 300 keV

https://www.sciencedirect.com/science/article/pii/S0168900221006860?via%3Dihub

For full kinematic reconstruction & reaction channel ID we need to know

- Energy loss → Nuclear charge Z
- Time of Flight → Mass identification
- Trajectory → Momentum

for incoming and outgoing fragments, beam, gammas



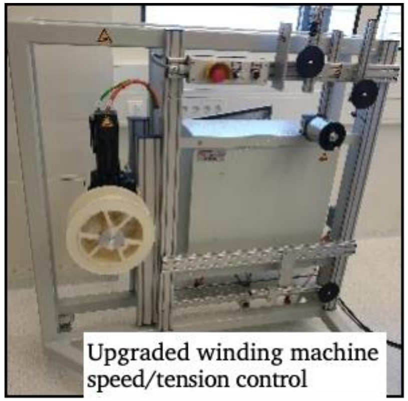
R3B tracking system

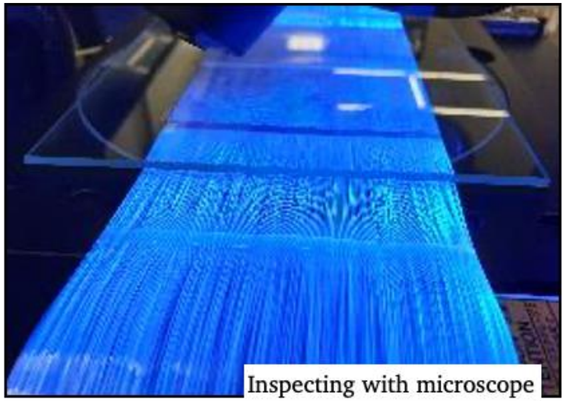
Scintillating Fiber Tracker

4d Tracking at High Rate with High Dynamic Range

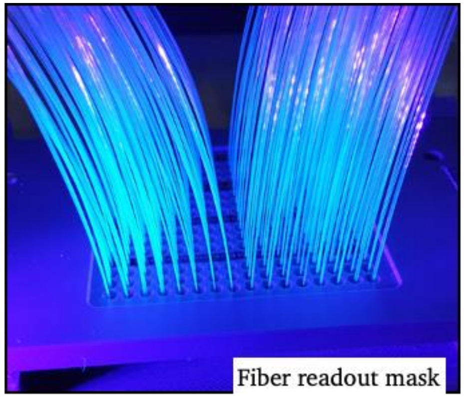
C. Caesar and D. Savran

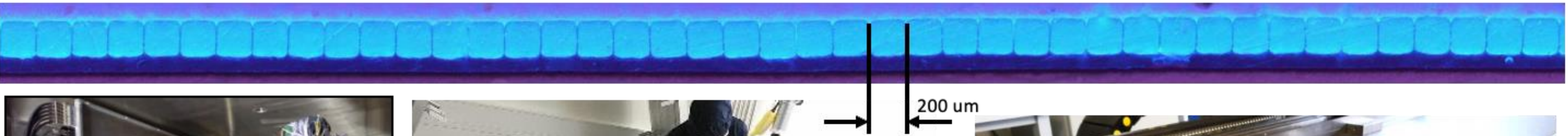
Square fibers 0.2x0.2 mm^2
Number of fibers ~ 10^4 fibers
→ 60 μm resolution

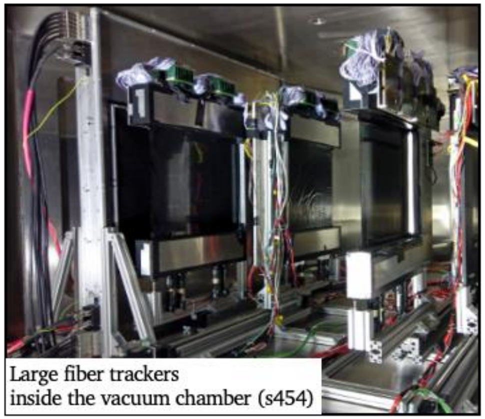

Upgraded winding machine speed/tension control


Inspecting with microscope

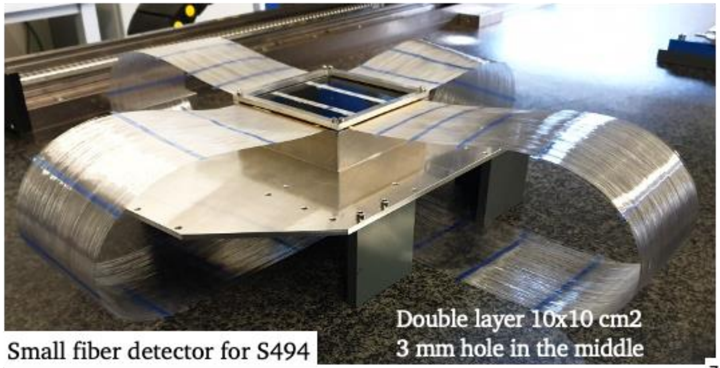

New infrastructure for sorting fibres into a mask


Fiber readout mask




Large fiber trackers inside the vacuum chamber (s454)

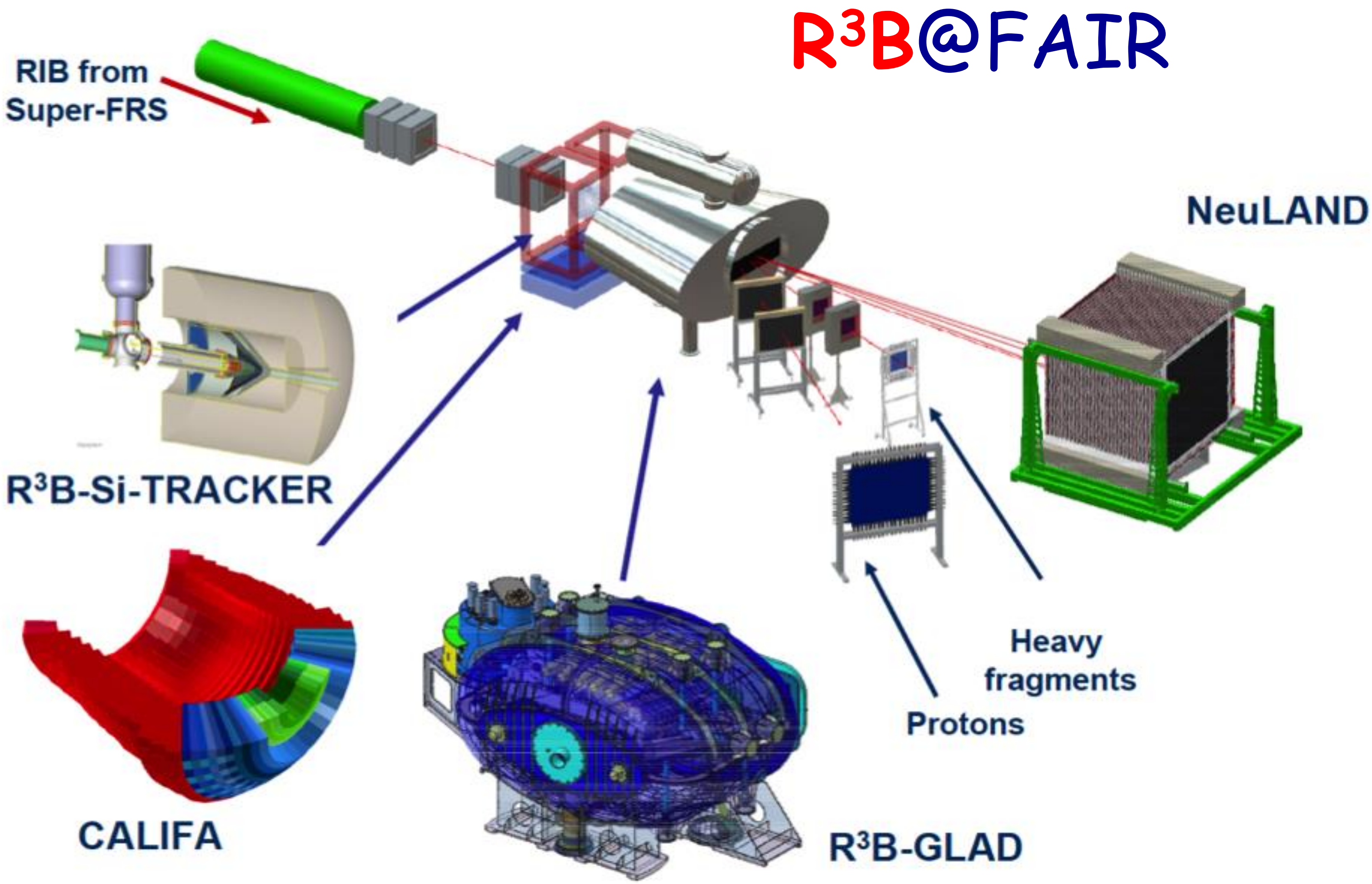

Manufacturing process


Small fiber detector for S494

Double layer 10x10 cm2
3 mm hole in the middle

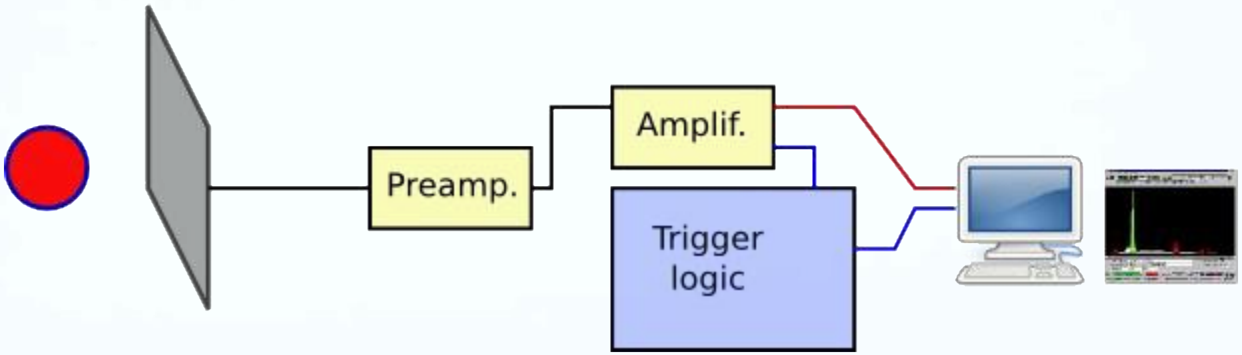
7

Many detectors, big distance, each with individual electronics and DAQ → But should work synchronized

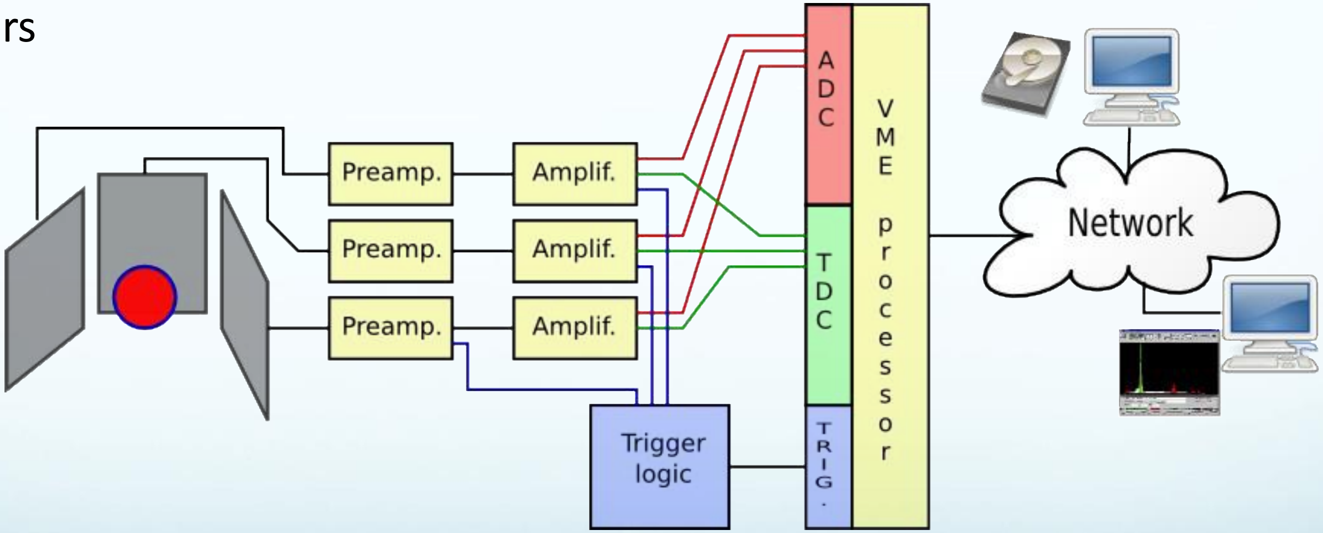


General outline of electronics and DAQ

1 detector
1 channel



several detectors
Many channels



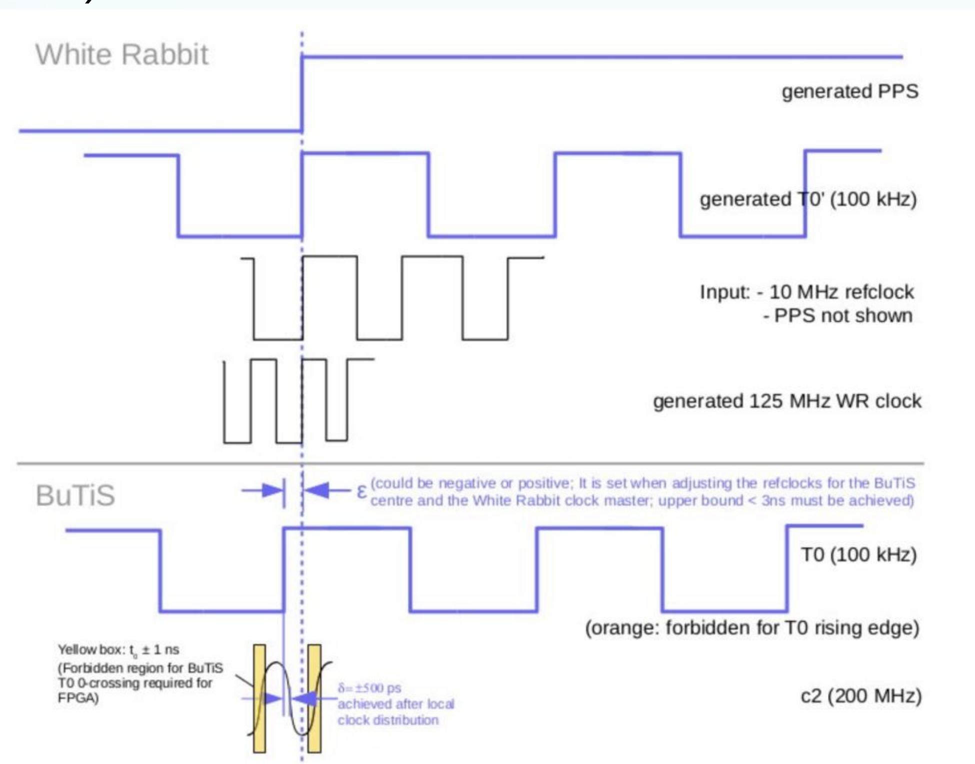
Many detectors many channels + many systems → how to synchronize

Synchronization and Coincidences to build event by event data →. GSI-FAIR wide Time reference:

The R3B experiment is composed by several separate detector components that are **spatially extended**, **running independent DAQ → stitch together in MAIN-DAQ**

For the **coincidence timing** at R3B we have to be in time-correlation with all the **detector-systems**, with **FRS** and with the **Machine timing** of GSI-FAIR

Bunch Timing System **(BuTiS)** distribute high precision clock train (100 kHz ident pulse, 10 MHz sine).



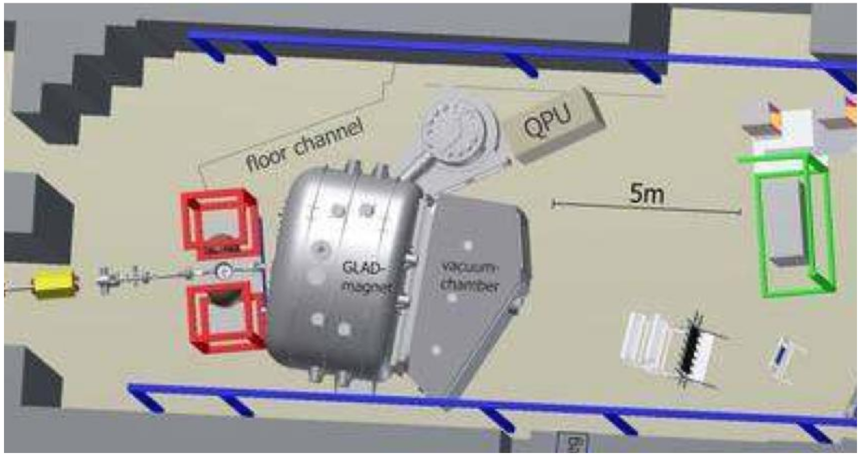
The distributed data acquisition system run in a time-synchronized distributed environment based on **BuTiS** **and** **White Rabbit** with timestamps of pico-second precision and 100 ps/km accuracy.

White Rabbit is a fully deterministic Ethernet-based network for general purpose data transfer and synchronization. It can synchronize over 1000 nodes with **sub-ns accuracy** over fiber lengths of **up to 10 km.**

Individual detector triggers are stitched together event by event in the MAIN DAQ before storage.

R3B Summary:
Schedule and first experiments @ GSI in Cave C

2020 **50% NeuLAND and 50% CALIFA & Si-Tracker + tracking detector prototypes**
Liquid Hydrogen target (LH_2)



2019-25 Physics runs at GSI (Cave C) (phase 0)

2026 - 2027 Move to HEC- cave @FAIR

2028 1st R3B-NUSTAR experiment @FAIR

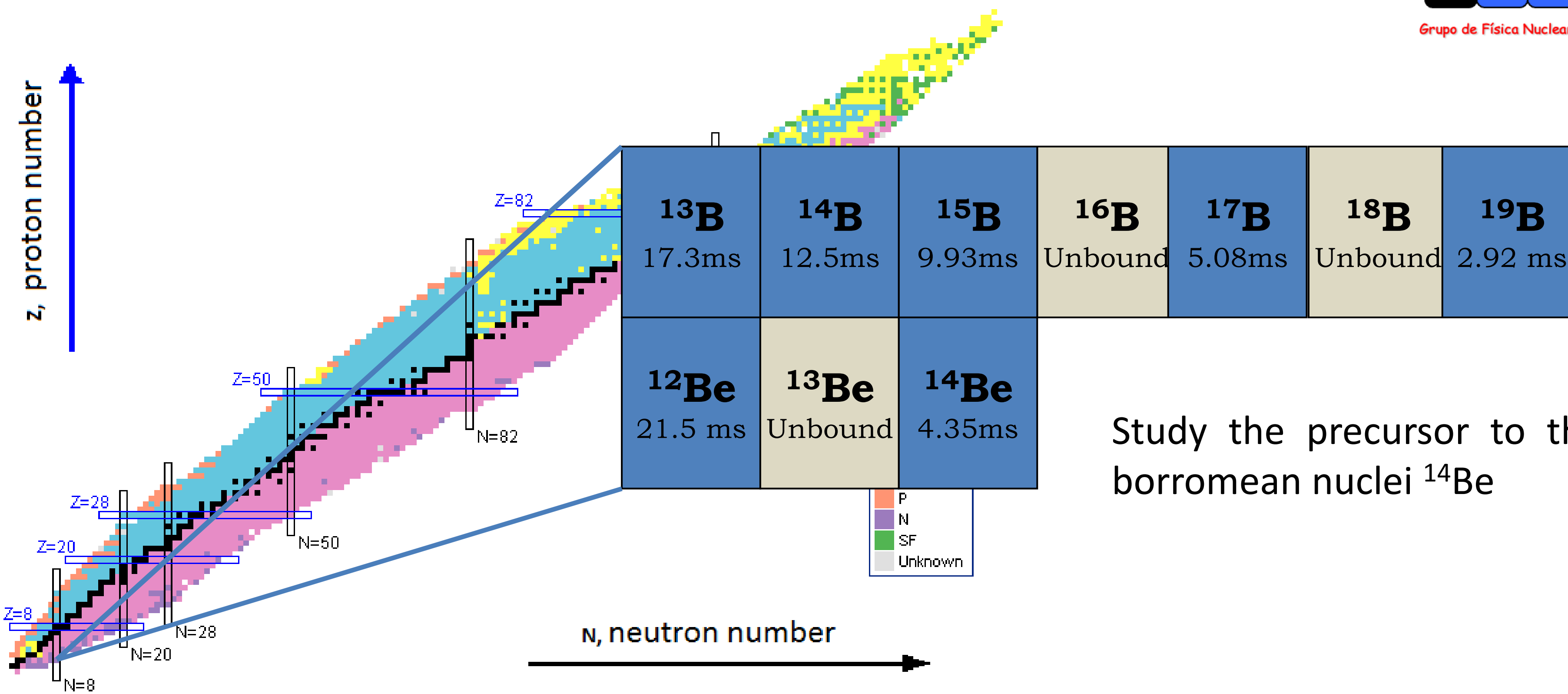
Experiments will make use of uniqueness of R3B:
- Reactions at high beam energies up to 1 GeV/u
- Tracking and identification capability for the heaviest ions
- Multi-neutron tracking capability, high-efficiency calorimeter

Experiments possible for the first time:
- 4 neutron decays beyond the drip-line and for heavier n-rich isotopes
- 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 (polarizability, symmetry energy)
- Fission barriers from (p,2p) reactions (→ r-process)

An example: S393 experiment

Study of light neutron-rich nuclei using kinematically complete measurements in inverse kinematics @ GSI

quasi-free scattering: $^{14}B(p,2p)^{13}Be$

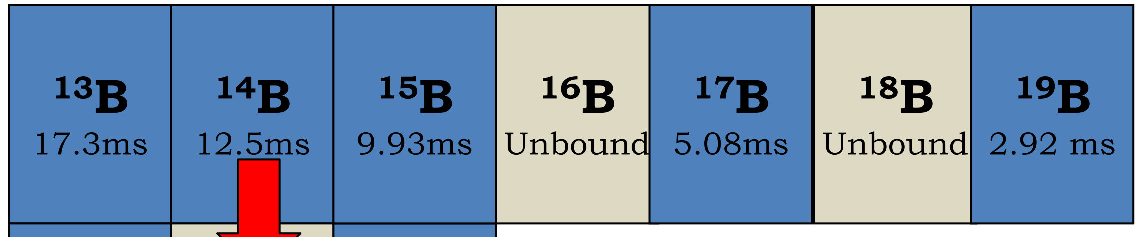


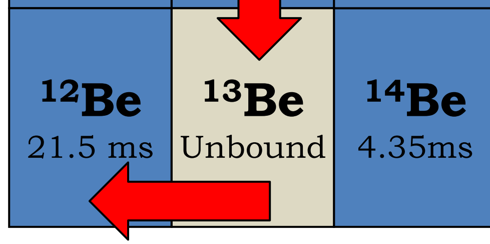
Study the precursor to the borromean nuclei ^{14}Be

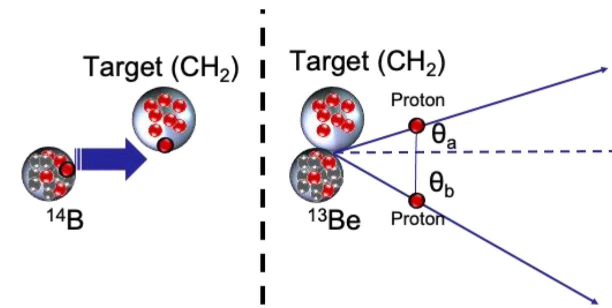
https://fnexp.iem.csic.es/reports/PhD_Theses/PhD-G_Ribeiro-2015.pdf

Quasi-Free Scattering: Knockout reaction

$^{14}B(p,2p)^{13}Be$





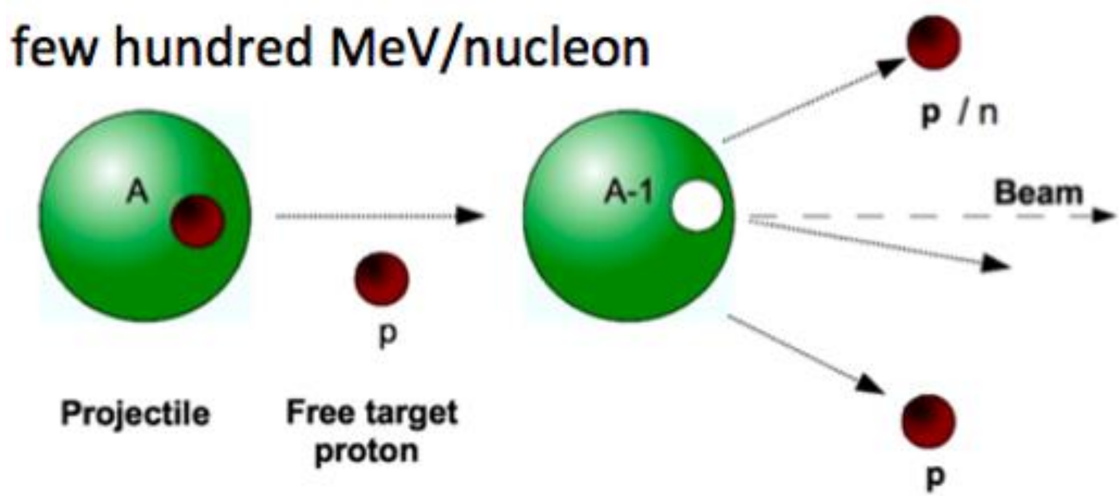


- Direct Reaction: quick and direct **from initial to final states without intermediate compound state**.

- If both outgoing particles have the same masses, in the lab system:

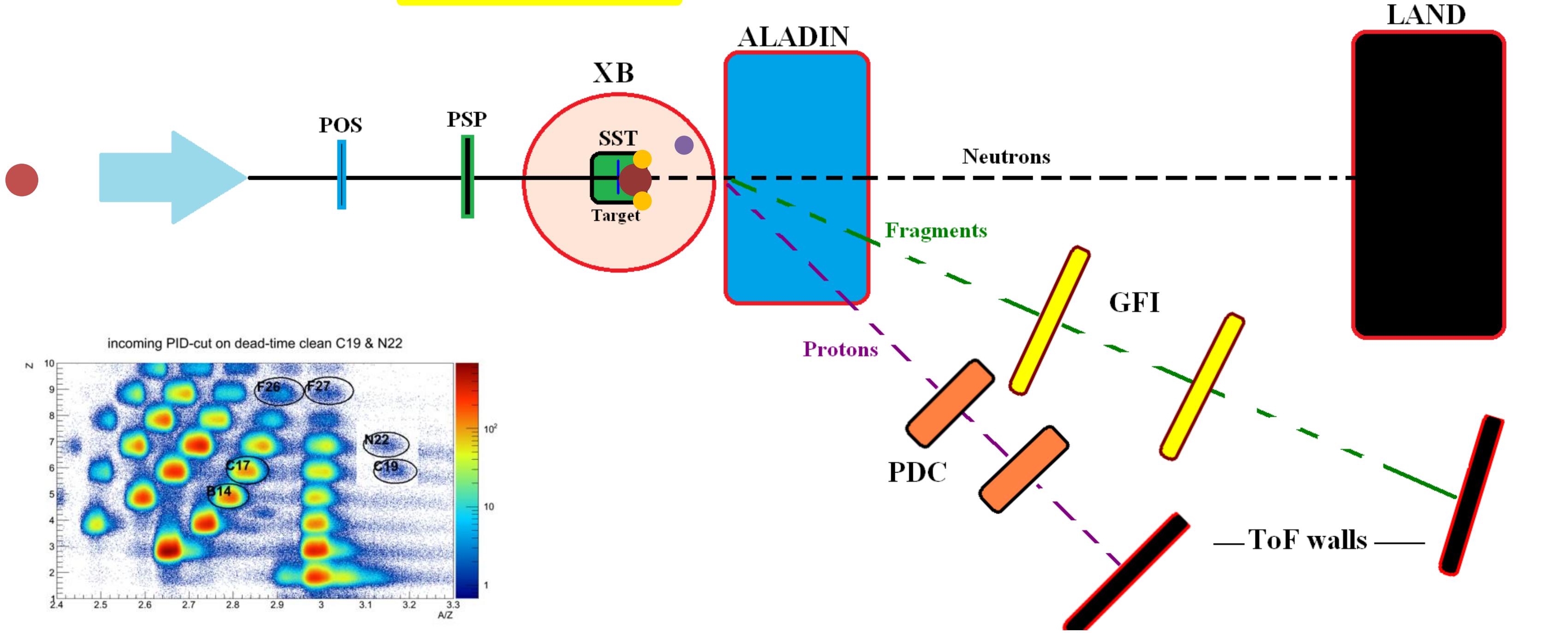
$$\theta_A + \theta_B \simeq 81^\circ$$

(p,2p), (p,np)



Experiment:Cave C

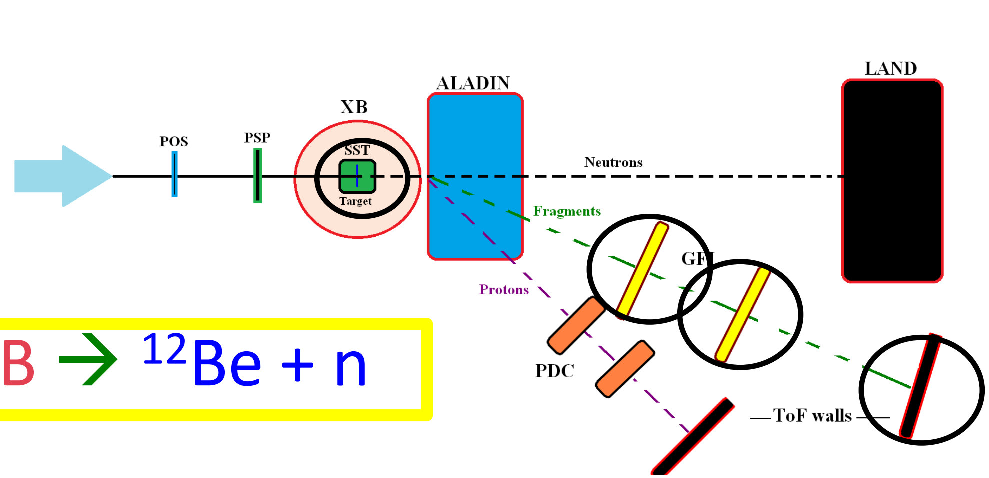
$^{14}B(p,2p)^{13}Be$



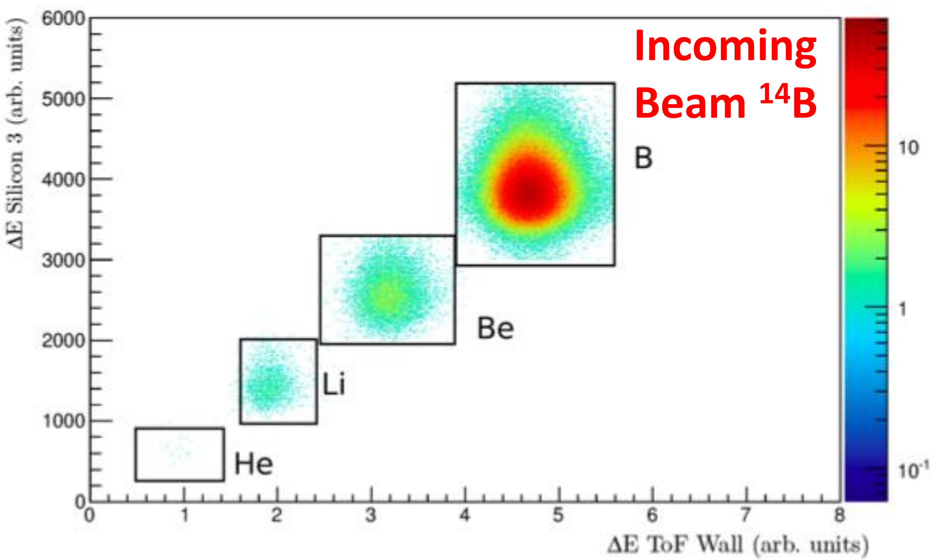
Primary beam	$^{40}Ar^{11+}$ @ 490 MeV/u
Intensity	$6{\cdot}10^{10}$ ions/spill.
Production target	Be 4 mg/cm^2
Reaction target	**H, C, empty**

Reaction channel Idenitifcation

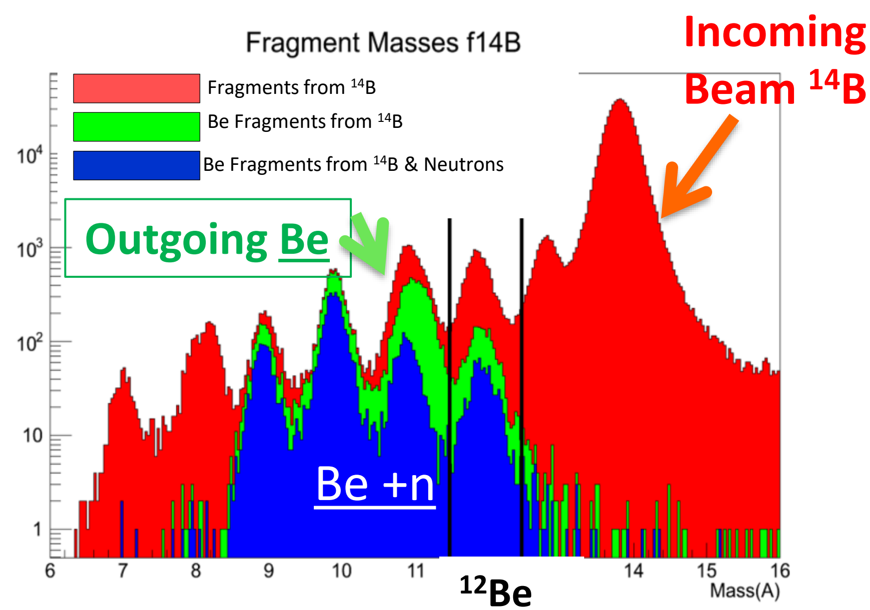
- Energy loss in the ToFW after the target → Identify the element after the reaction.
- Identify the isotope from the ALADIN position deviation and beta of the fragment.



$^{14}B \rightarrow {}^{12}Be + n$

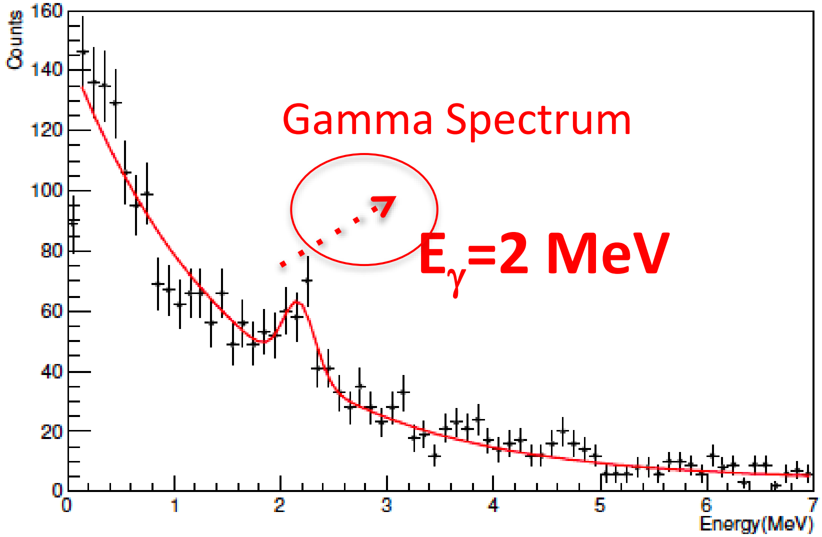


Charge identification from energy loss

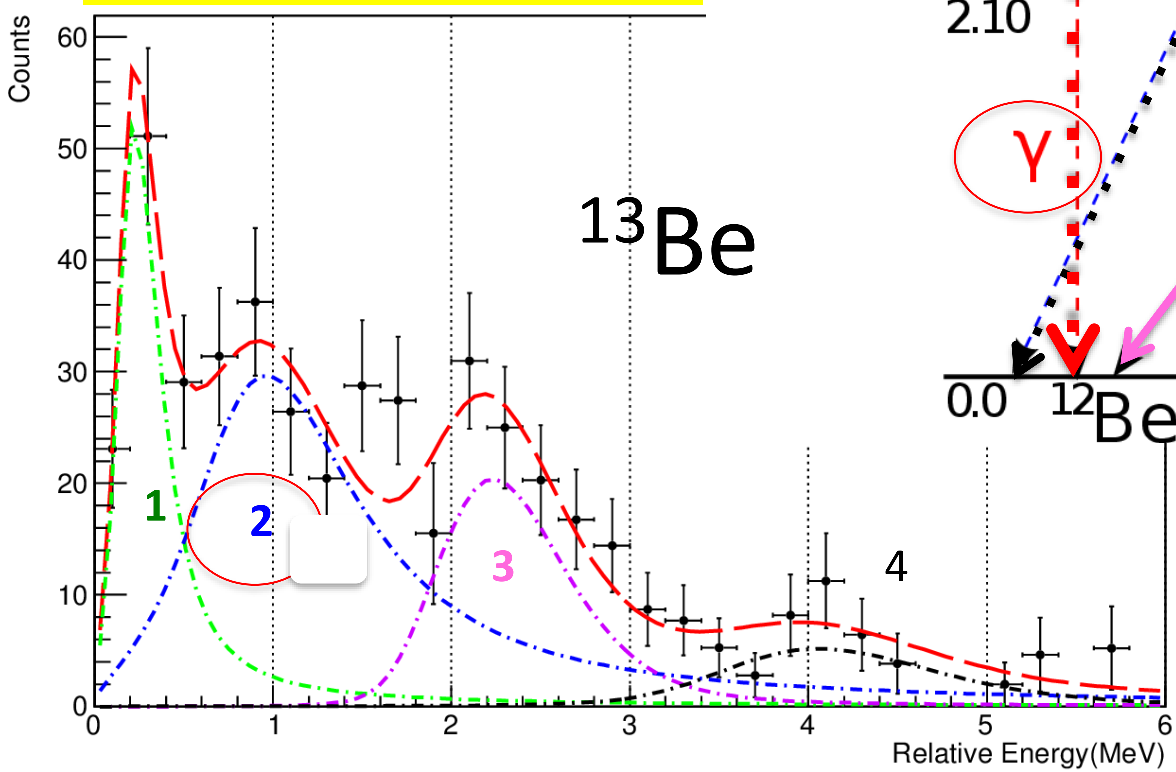


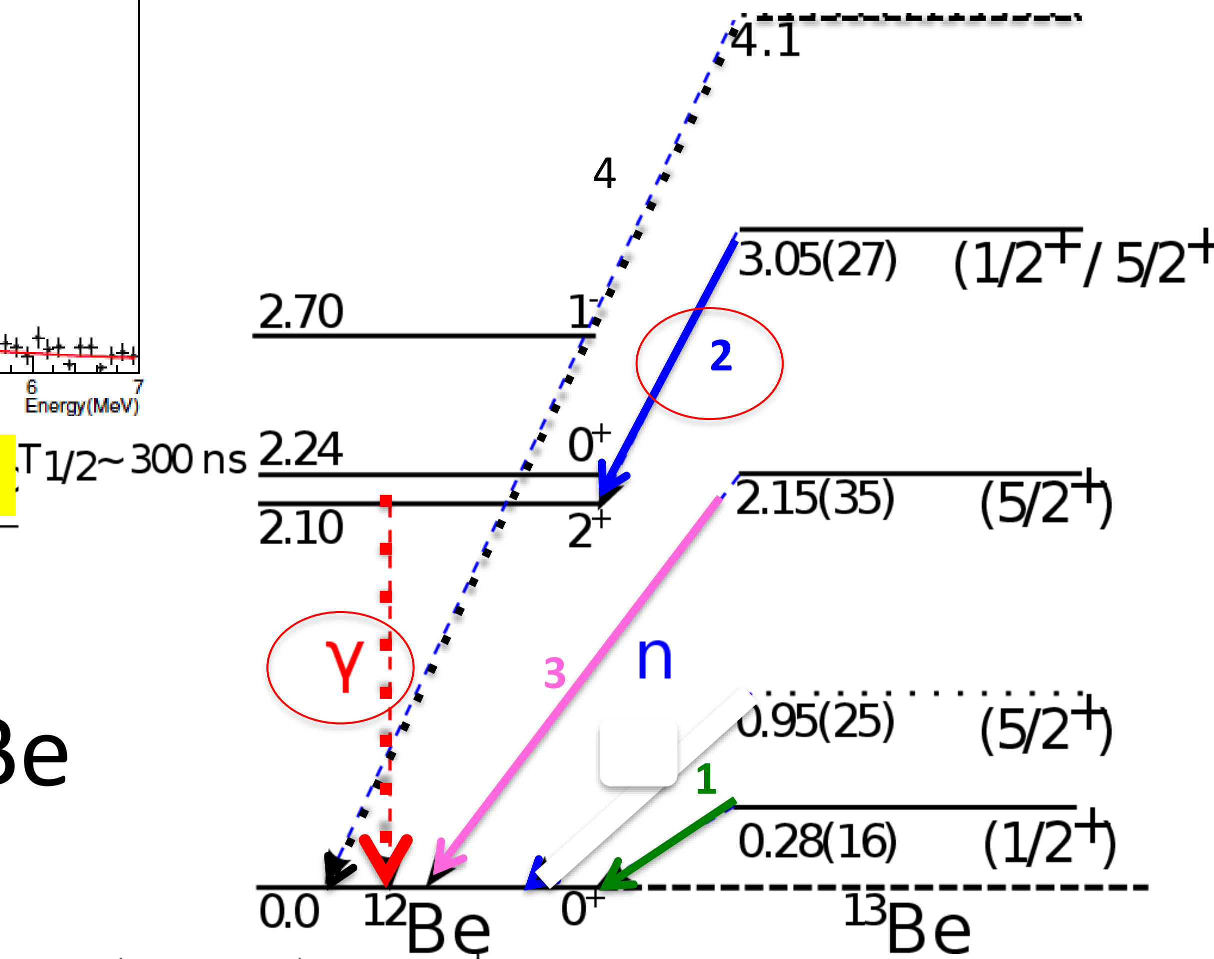
Mass identification from ToF tracking

https://journals.aps.org/prc/abstract/10.1103/PhysRevC.98.024603



Relative Energy of ^{12}Be + n:





Experimentos de NUSTAR: pensar y recordar!

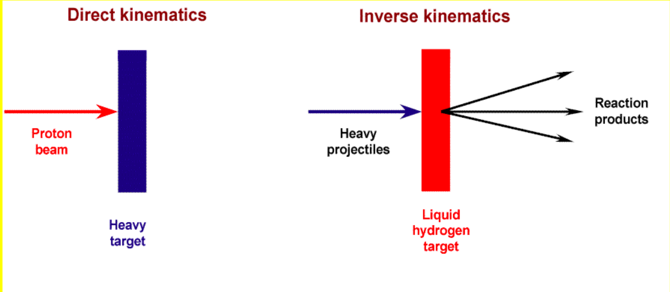
Acrónimos: **FAIR** **NUSTAR** **SFRS** **R3B**

Que método de producción se usa en experimentos de NUSTAR?

Cual es el **haz primario**, y de que origen normalmente?
Cual es el blanco de **Producción?**

Cual es el **haz secundario**? Cual es el blanco de **Reacción?**
Por que usamos **varios blancos** de reacción en el mismo experimento?

Por que cinemática inversa?



Que significa cinemática completa?

Como se selecciona el canal de reacción de interés del experimento?

Como se determina la carga, masa, la energía, el momento,
no olvides la importancia de medir las: γ & **neutrónes**!

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Member List

	Affiliation	Name
CAN	Saint Mary University	**Kanungo, Rituparna**
	Members: 1	
DEU	Extreme Matter Institute	**Savran, Deniz**
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		Silva, Joel
DEU	GSI Darmstadt	*Aumann, Thomas*
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		Movsesyan, Alina
		Schrock, Philipp
		Simon, Haik
		Boretzky, Konstanze
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		Heil, Michael
		Kelic-Heil, Aleksandra
		Kiselev, Oleg
		Kurz, Nikolaus
		Körper, Daniel
		Pietri, Stephane
		Plag, Ralf
		Rossi, Dominic
		Wamers, Felix
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		Geissel, Hans
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		Göbel, Kathrin
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		Kahlbow, Julian
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		Scheit, Heiko
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		Törnqvist, Hans

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		Kröll, Thorsten
		Fernández Martínez, Guillermo
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		Ilieva, Stoyanka
		Rhee, Han-Bum
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		Klenze, Philipp
		Le Bleis, Tudi
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		Korten, Wolfram
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		Tassan-Got, Laurent
		Yan, Yiman
FRA	Université Paris Sud	*Audouin, Laurent*
	Members: 0	
GBR	STFC Daresbury Laboratory	**Lemmon, Roy**
	Members: 7	Borri, Marcello
		Grant, Alan
		Kogimtzis, Moschos
		Labiche, Marc
		Lazarus, Ian
		Pucknell, Victor
GBR	University of Birmingham	**Freer, Martin**
	Members: 1	
GBR	University of Edinburgh	**Woods, Phil**
	Members: 4	Davinson, Thomas
		Estrade, Alfredo
		Lederer, Claudia
GBR	University of Liverpool	**Chartier, Marielle**
	Members: 5	Lindsay, Scott
		Powell, William
		Thornhill, Jim
		Wells, David
GBR	University of Surrey	**Catford, Wilton**
	Members: 1	
HRV	RBI Zagreb	**Gasparic, Igor**
	Members: 2	Basrak, Zoran
HUN	ATOMKI Debrecen	Elekes, Zoltan
	Members: 2	**Krasznahorkay, Attila**
HUN	Eötvös Lóránd Univers	**Horváth, Ákos**
	Members: 1	
LTU	University of Vilnius	**Deltuva, Arnoldas**
	Members: 1	
NLD	KVI-CART	**Kalantar-Nayestanaki, Nasser**
	Members: 3	Harakeh, Muhsin
		Rigollet, Catherine
PRT	Instituto Superior Tecnic	**Crespo, Raquel**
	Members: 1	
PRT	Nuclear Physics Center, U	**Galaviz Redondo, Daniel**
	Members: 3	Henriques, Ana
		Teubig, Pamela
ROU	Institute of Space Scienc	**Haiduc, Maria**
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RUS	JINR Dubna	**Fomichev, Andrey**
	Members: 5	Bezbakh, Andrey
		Golovkov, Mikhail
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RUS	NRC Kurchatov Institute M	**Chulkov, Leonid**
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		Nikolskii, Evgenii
		Volkov, Vasily
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		Dobrovolsky, Alexander
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		Gruzinsky, Nikolay
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		Khanzadeev, Alexey
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		Kozlenko, Nikolai
		Krivshich, Anatoly
		Kuznetsov, Viacheslav
		Maev, Evgeny
		Maisuzenko, Dmitrii
		Orishchin, Evgeny
		Sarantsev, Victor
		Uvarov, Lev
		Vikhrov, Vladimir
		Zhdanov, Andrey
SVN	Josef Stefan Institut Lju	**Vencelj, Matjaz**
	Members: 1	
SWE	Chalmers University of Te	**Nilsson, Thomas**
	Members: 6	Johansson, Håkan
		Jonson, Björn
		Thies, Ronja
		Heinz, Andreas
		Lindberg, Simon
SWE	Lund University	**Cederkall, Joakim**
	Members: 4	Avdeichikov, Vladimir
		Fahlander, Claes
		Golubev, Pavel
USA	Texas A&M University-Comm	**Bertulani, Carlos**
	Members: 1	

Explanation
Name in italic indicates member with different main affiliation

250	Members
40	Institutes
15	Countries

Spokesperson: Lola Cortina IFIC
Technical Director 2014-24: O. Tengblad IEM

R3B España

IFIC — INSTITUT DE FÍSICA CORPUSCULAR

Lola Cortina
Pepe Benlliure
Enrique Nacher

Hector Alvarez Pol
Diego Gonzales

GENP — Grupo Experimental de Núcleos y Partículas
Univ. Santiago de Compostela

UNIVERSIDADE DA CORUÑA

Saúl Beceiro Novo
Jose Luis Rodriguez Sanchez

Enrique Casarejos
Carlos Parrilla

CIMA — UNIVERSIDAD DE VIGO

IEM CSIC — Grupo de Física Nuclear Experimental

Olof Tengblad
María Borge
Christoph Rappold