



107° Congresso Nazionale

13-17 Settembre 2021

Sezione 1: Fisica nucleare e subnucleare

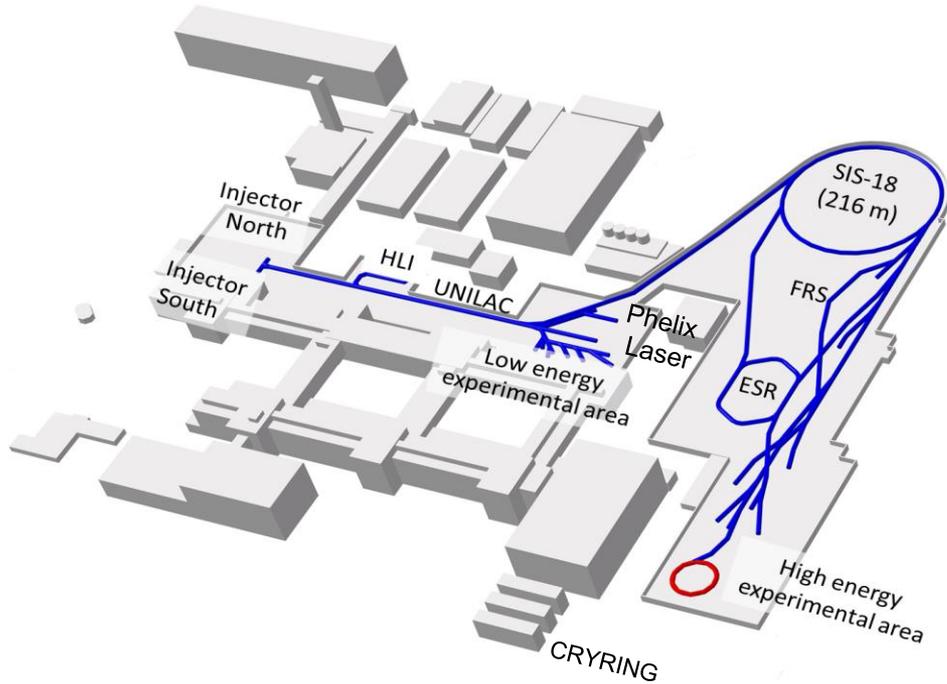
Esperimenti e prospettive nei laboratori di Fisica Nucleare:

Le attività di Fisica Nucleare presso i
laboratori GSI/FAIR

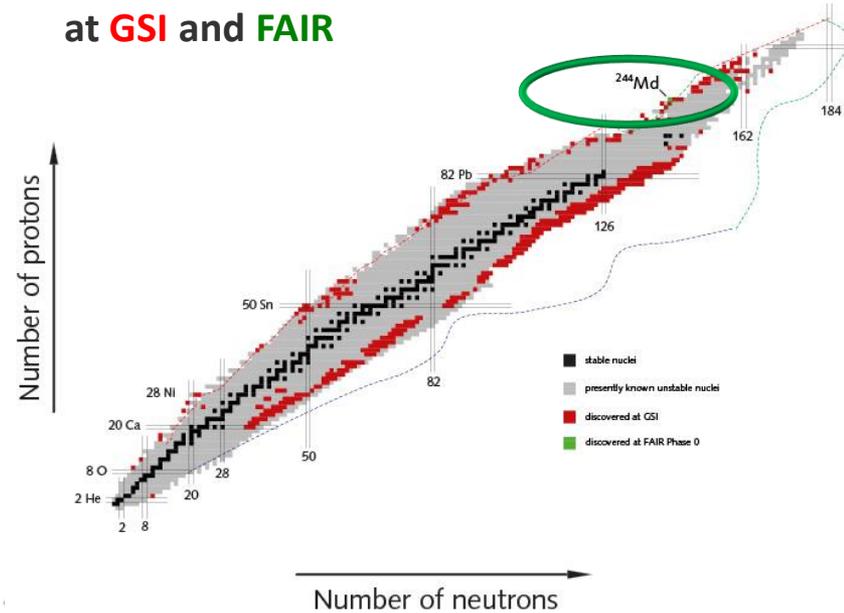
P. Russotto

INFN-Laboratori Nazionali del Sud

GSI – Almost 50 Years of Scientific and Technical Competence



Isotopes discovered at **GSI** and **FAIR**

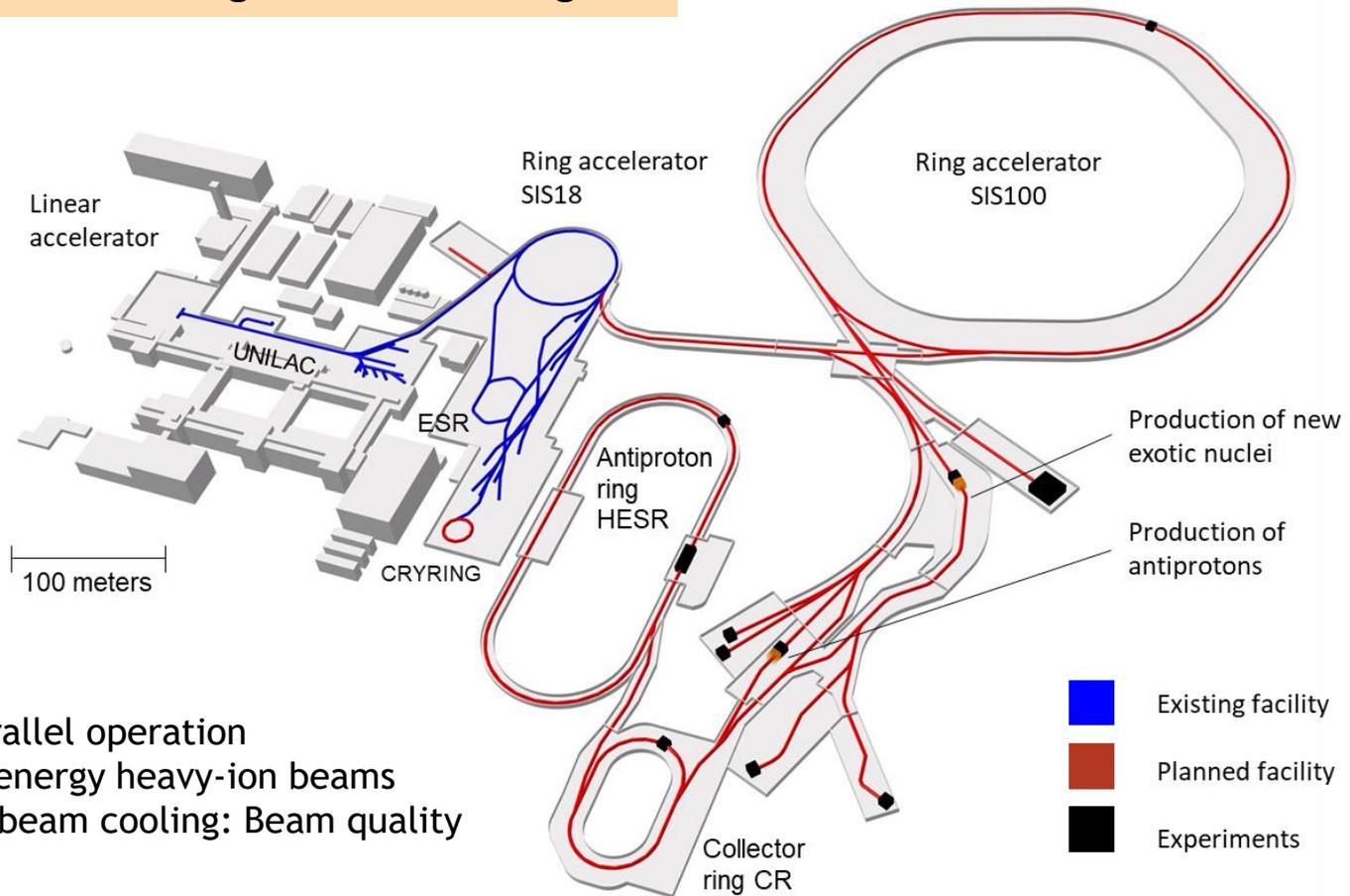


One of reference laboratory for nuclear physics in Europe, one of the top heavy-ion accelerator facilities in the world

- New chemical elements
- Hundreds of new isotopes
- New decay modes

FAIR – The Facility

- **Intensity gain:** x 100 – 1000
- **Antimatter:** antiproton beams
- **Precision:** System of storage and cooler rings



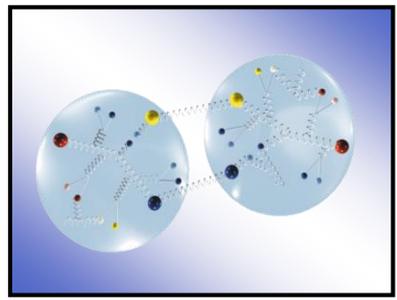
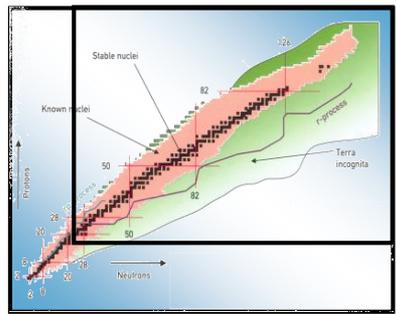
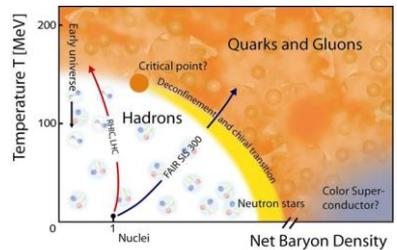
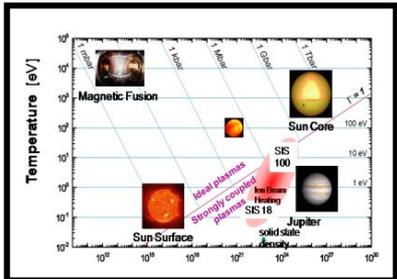
Unique features:

- Flexibility and parallel operation
- **Intense** and high-energy heavy-ion beams
- Storage rings and beam cooling: Beam quality

The FAIR science: four pillars

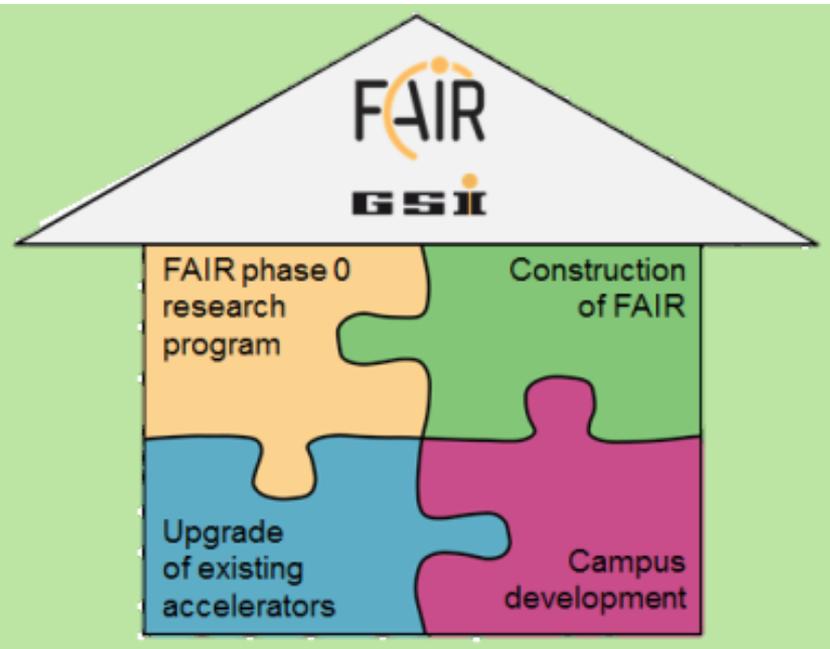


atomic physics, biophysics,
plasma physics, material research **APPA**



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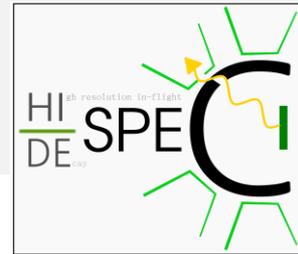
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Now: FAIR Phase-0:
Goal: 3 months of beam time/year until start of FAIR operation

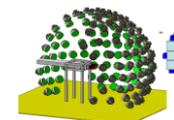
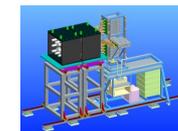
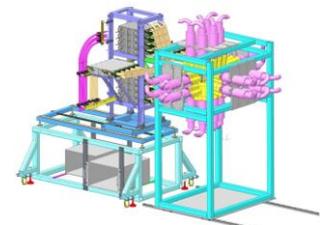
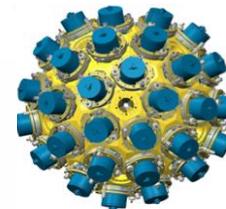
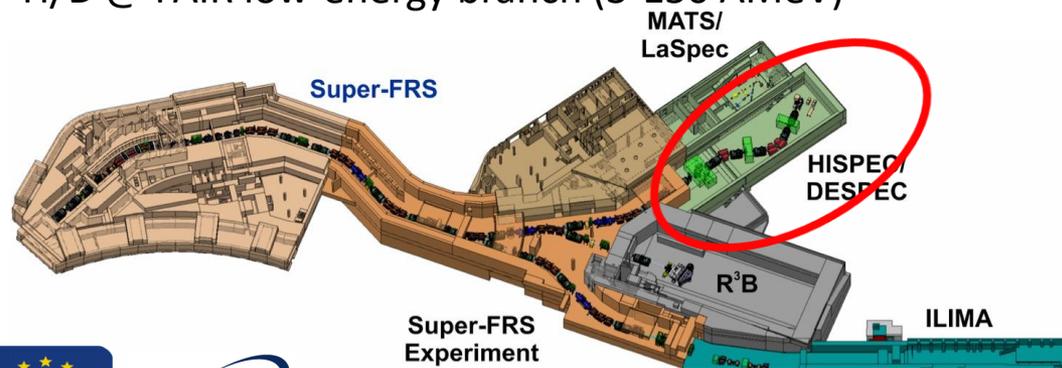
HISPEC (High-resolution in flight spectroscopy)

DESPEC (Decay spectroscopy)



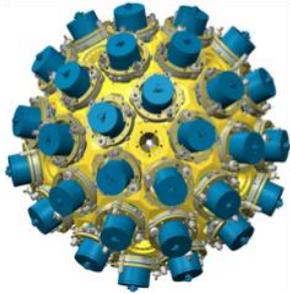
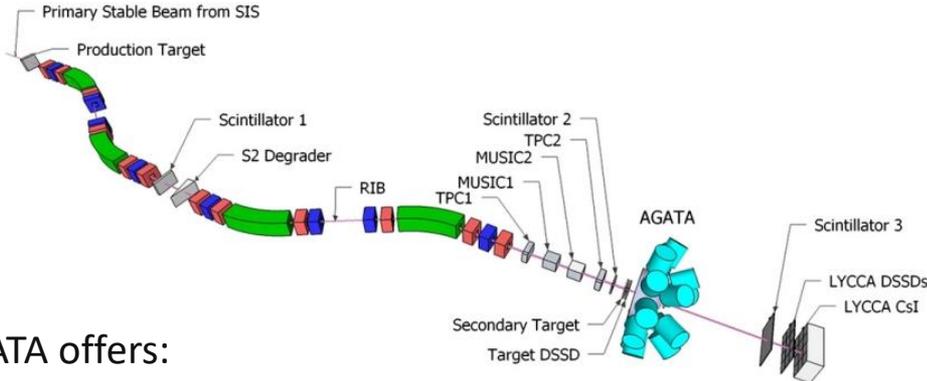
- Spectroscopic studies both in-beam (HISPEC) and with stopped ions (DESPEC):
Dual complementary approach
- Evolution of the shell structure and exotic nuclear shapes of very short-lived nuclei not available at ISOL facility...in **uncharted nuclear territory**
- Spectroscopic information for the **nucleosynthesis of heavy nuclei**
- **Highest sensitivity** to achieve decay information from beam yields as low as one ion per hour
- Primary focus on **GSI-FAIR uniqueness around $N \sim 126$** nuclei, BUT aims to provide **competitive data** on key nuclei in lighter regions: around ^{100}Sn and ^{132}Sn , rare earth nuclei, ...
- **Large suite of detectors** organized in campaigns
- More than 200 researchers (≈ 25 Italians, including G. Benzoni (INFN-Mi) as Spokesperson)

H/D @ FAIR low-energy branch (3-150 AMeV)



HISPEC-DESPEC experiment @GSI-FAIR

HISPEC-DESPEC revolves around the core instrument: AGATA



AGATA offers:

- high γ -ray efficiency
 - excellent peak-to-total ratio
 - unprecedented position resolution due to its fine segmentation combined with pulse-shape analysis techniques.
-
- studies of excited states in nuclei which can be produced only with very low rates giving access to very exotic species,
 - investigation of non-yrast states at excitation energies of up to 30 MeV and excitations built on isomeric states,
 - lifetime measurements using novel high-velocity Doppler-shift techniques,
 - analysis of γ - γ coincidences for the elaboration of complex excitation schemes

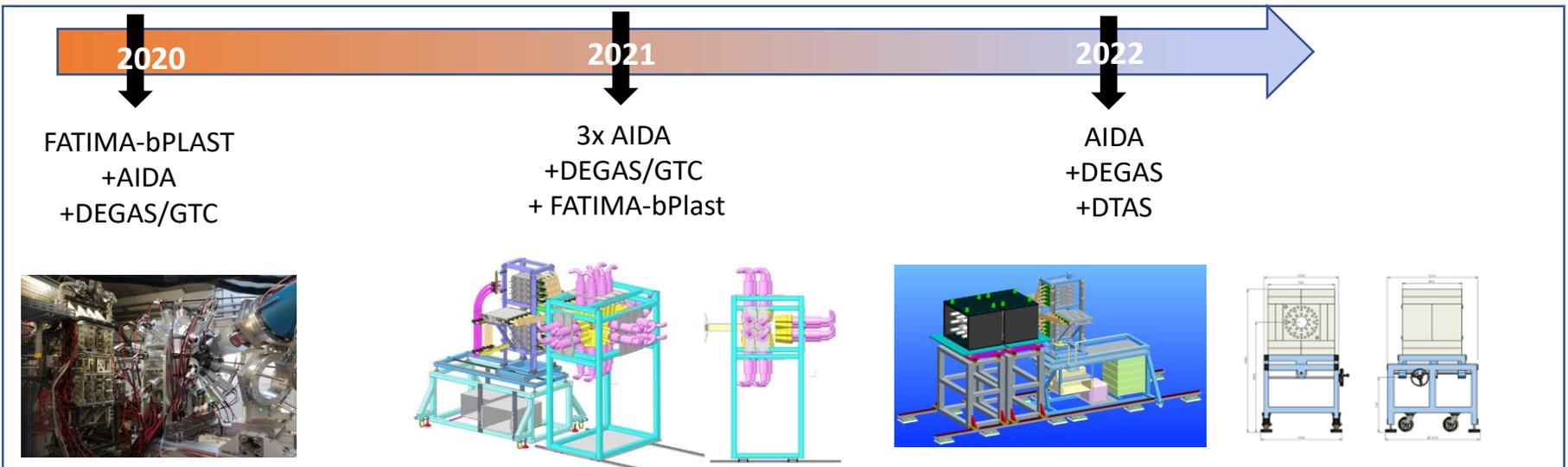
Physics opportunities with the Advanced Gamma Tracking Array: AGATA (Eur. Phys. J. A (2020) 56:137)



DESPEC: Decay SPEctroscopy

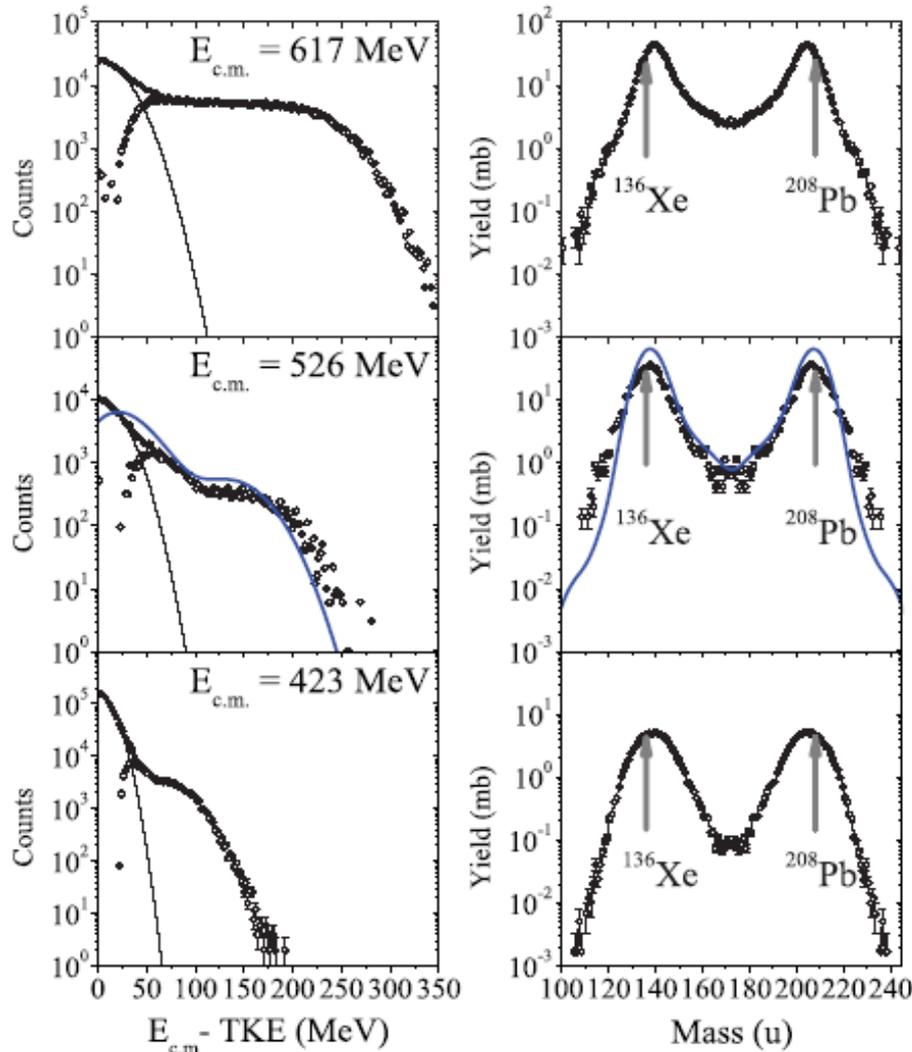
A very large suite of detectors:

- AIDA: highly segmented active stopper based on Si-strip detectors with a position resolution on the millimetre scale for implantations as well as for subsequent β decays or emitted charged particles such as α or protons.
- FATIMA: FAST TIMing Array for DESPEC at FAIR, 36 LaBr₃(Ce) scintillators, lifetimes of excited nuclear states via the method of delayed coincidence electronic fast timing + bPLAST, beta-plastic detectors surrounding the Si decay station, for time reference.
- Belen: BEta deLAYed Neutron detector, based on ³He prop. counter after neutron moderation
- DEGAS: DESPEC Germanium Array Spectrometer, HPGe-Cluster array
- DTAS: Decay Total Absorption Spectrometer, segmented NaI(Tl)/LaBr₃(Ce) scintillators

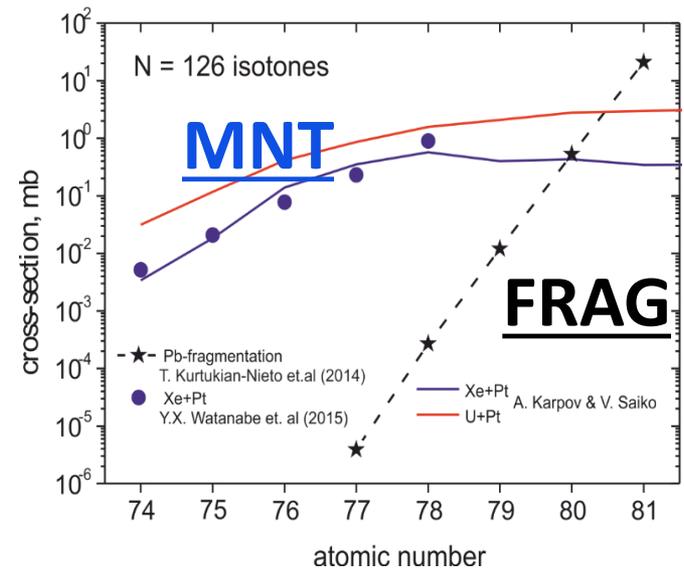


FORTE: Fission, Other Reactions and Terra incognita Exploration

$^{136}\text{Xe} + ^{208}\text{Pb}$ @ Dubna



Production of neutron-rich N=126 isotones

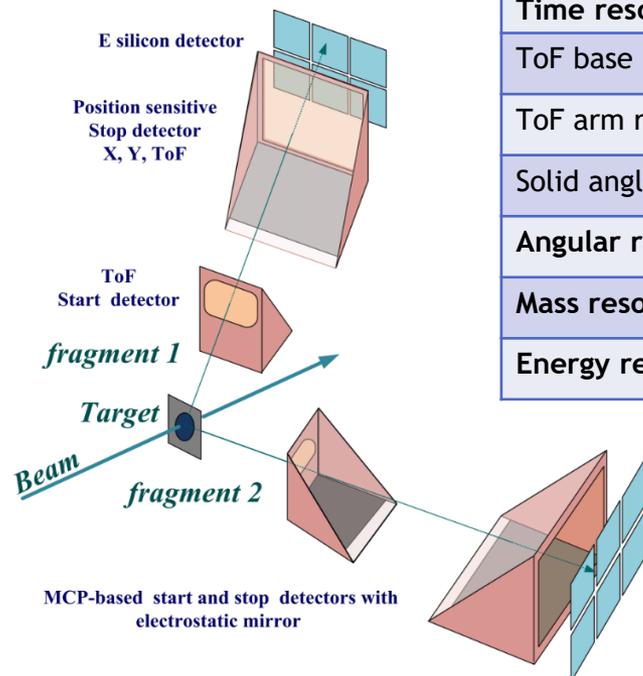


LOI U325: Multi-Nucleon Transfer Reactions at GSI: In-depth broadband reaction studies with complementary methods, paving the way towards the production and study of the terra incognita on the nuclear chart T. Dickel (GSI), E. Vardaci (UNINA)

FORTE: Fission, Other Reactions and Terra incognita Exploration

- Use of complementary methods to detect products of multinucleon transfer reactions
- Study of the reaction kinematics and energetics
- Use of the many beams available (^{48}Ca , ^{68}Ni , ^{136}Xe , ^{208}Pb , ^{238}U)
- Build new dedicated equipment (Target module, TOF spectrometer upgrade, Cryogenic Stopping cells, low energy beam transport, separation and cooling, MR-TOF-MS system)

Double Arm TOF-E



| | |
|------------------------|--------------|
| Time resolution | 150-180 ps |
| ToF base | 10-30 cm |
| ToF arm rotation range | 15° -165° |
| Solid angle | 100 -200 msr |
| Angular resolution | 0.3° |
| Mass resolution | 2-4 u |
| Energy resolution | 1% |

Measured parameters:

- ToF, X, Y, Energy of each fragment

Extracted parameters:

- Velocity, Energy, Angles

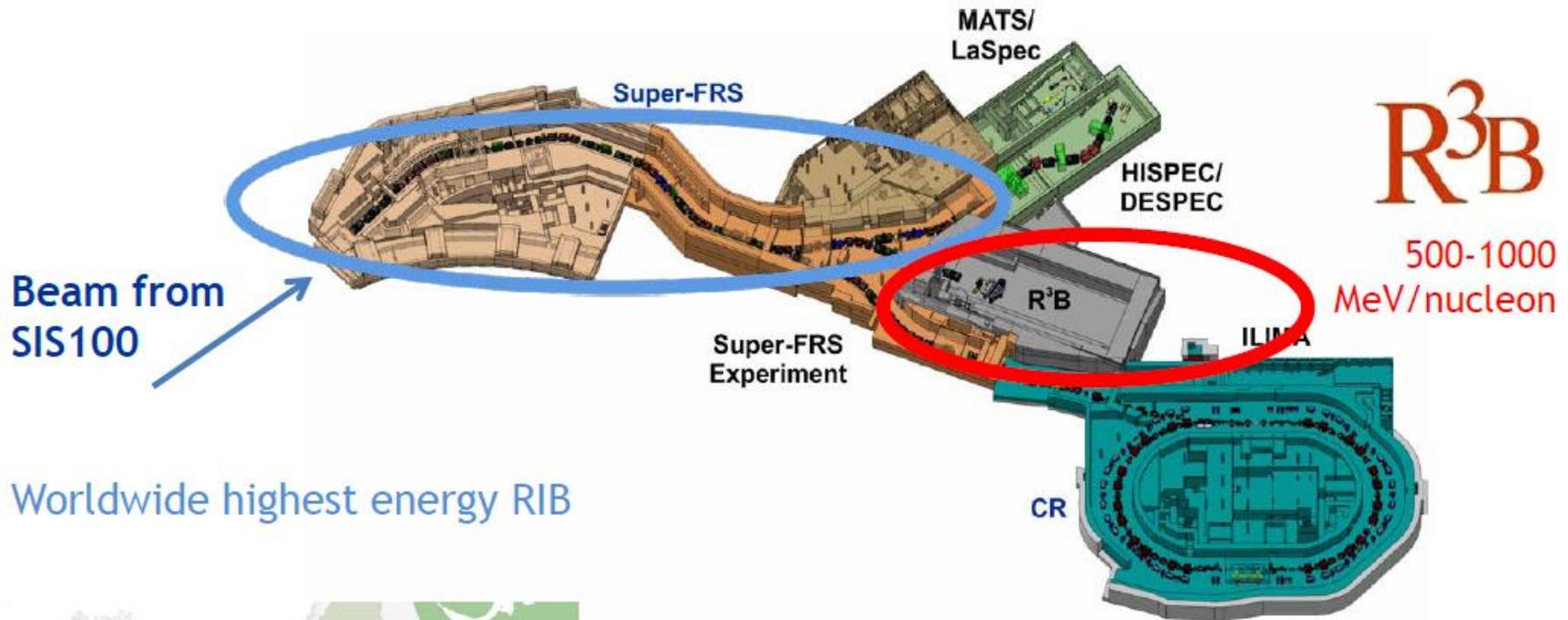
Computed parameters :

- Masses and TKE

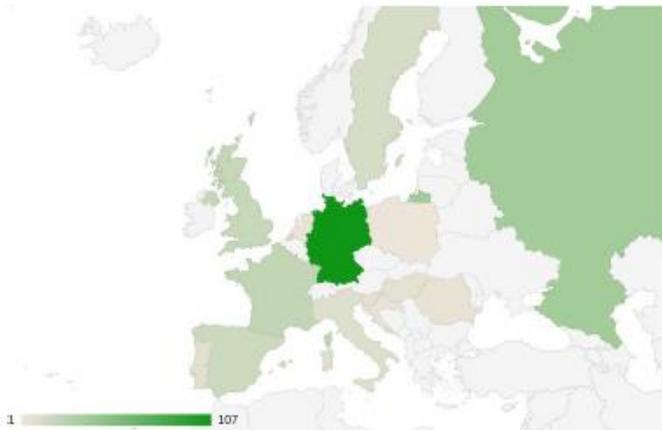
- Measurement of the *primary mass* of the TLF and PLF
- Mass distribution vs. different degrees of energy dissipation (TKEL)
- Effect of Q_{gg} values on the secondary mass distribution (after neutron evaporation)

R3B collaboration

Reaction Relativistic
Radioactive Beams



Worldwide highest energy RIB



To study reactions with high-energy secondary beams exploring static and dynamic properties of nuclei far off stability

More than 200 scientists
22 countries

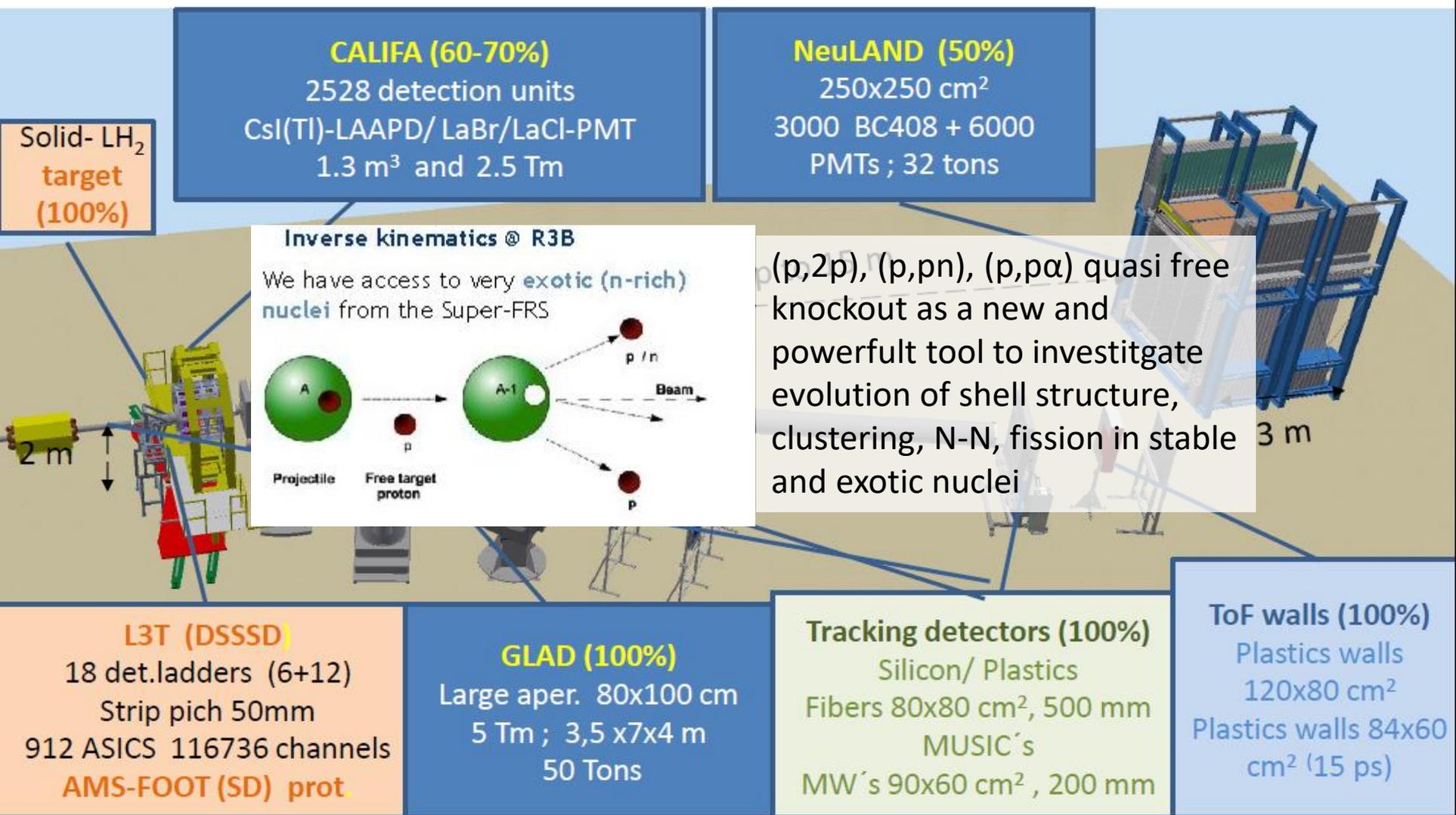
See R3B on www.gsi.de for more

The R3B set-up

a versatile experimental setup with unprecedented:

efficiency, acceptance, and resolution

for kinematical complete measurements of reactions with high-energy radioactive beams



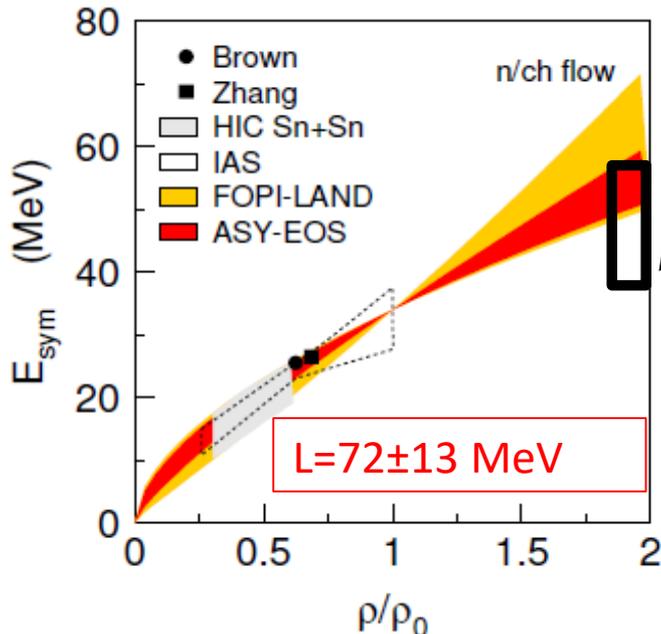
R3B (huge) physics program

Just an overview on 2021-2022 running experiments

- ❖ Fission investigated with relativistic-radioactive beams and the advanced SOFIA@R3B setup (J. Tajeb, P. Benlliure, D. Muecher)
- ❖ Constraining energy-density functionals and the density-dependence of the symmetry energy by measurements of accurate cross sections with large acceptance at R3B (T. Aumann, A. Horvat)
- ❖ Coulomb Dissociation of ^{16}O into ^{12}C and ^4He (K. Gobel, M. Heil, R. Reifhart)
- ❖ First characterization of Short-Range Correlations in exotic nuclei at R3B (A. Corsi)

ASY-EOS exp. @ GSI (2011) Au+Au @ 400 A MeV

-  P. Russotto et al., Phys. Lett. B 697 (2011)
-  P. Russotto et al., PRC 94, 034608 (2016)



ASY-EOS II. @ GSI (2023?)
Au+Au @ 400, 600, 800, 1000 A MeV

Measurements of v_{2n}/v_{2p} (thanks to NeuLAND) elliptic flows ratio excitation function for a precise determination of slope L and curvature K_{Sym} of the symmetry energy towards 2 rho region, the density region relevant for determining M-R relation of a canonical neutron star

Zhang & Li, $E_{\text{sym}}(2\rho_0) = 47 \pm 10$ MeV from NS radius, max. mass, tidal polarizability EPJA 55 39 (2019)

$R_{1.4} = 12.6 \pm 0.7$ km (ASY-EOS) $R_{1.4} = 12.7 \pm 1.1$ km (NICER)



FragmentatiOn Of Target (FOOT) collaboration

Focused on the measurement of nuclear fragmentation X-section for Particle Therapy and radioprotection in space

Nagoya, GSI, Aachen, Strasbourg

Bologna, Frascati, Milano, Napoli, Perugia, Pavia, Pisa, Roma1, Roma2, Torino, Trento

People: ~70 researcher, ~38 FTE

Data taking @ GSI, HIT



<https://web.infn.it/f00t/index.php/en/>

| Phys | Beam | Target | Energy (MeV/u) | kinematic |
|-------------------|---|----------------------------------|----------------|-----------|
| Target Frag. (PT) | ^{12}C , ^{16}O | C, C_2H_4 , PMMA | 200 | inverse |
| Beam Frag. (PT) | ^4He , ^{12}C , ^{16}O | C, C_2H_4 , PMMA | 250-350 | direct |
| Rad. Prot. Space | ^4He , ^{12}C , ^{16}O | C, C_2H_4 , PMMA | 700 | direct |

Cross sections on C,O,H extracted from C, C_2H_4 , PMMA targets

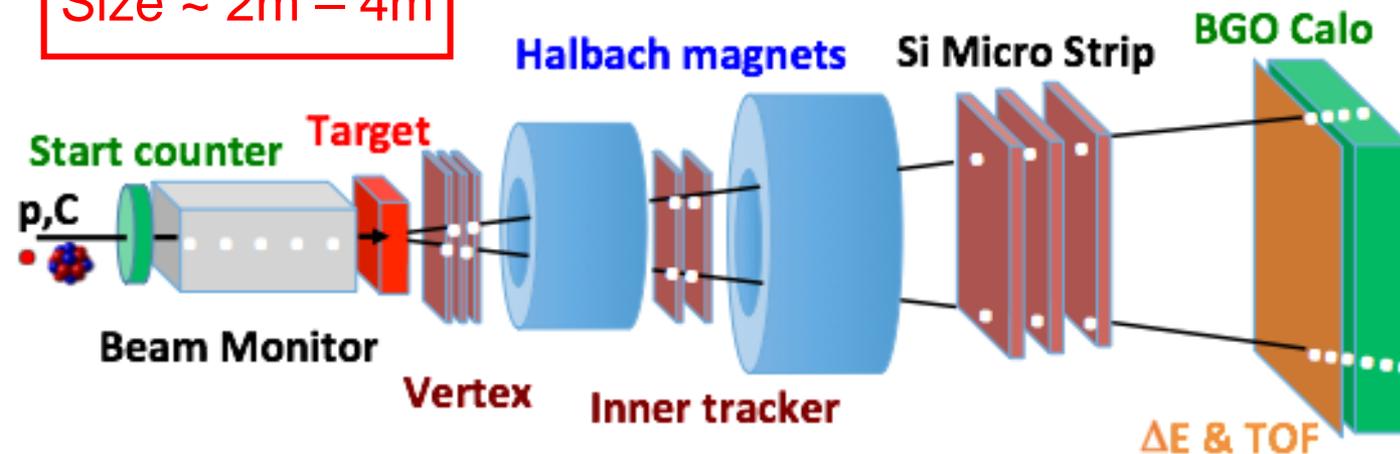
In case of enlargement of the “core” physics program the detector can be used as baseline for future upgrade in view of extending physics program



The FOOT electronic setup



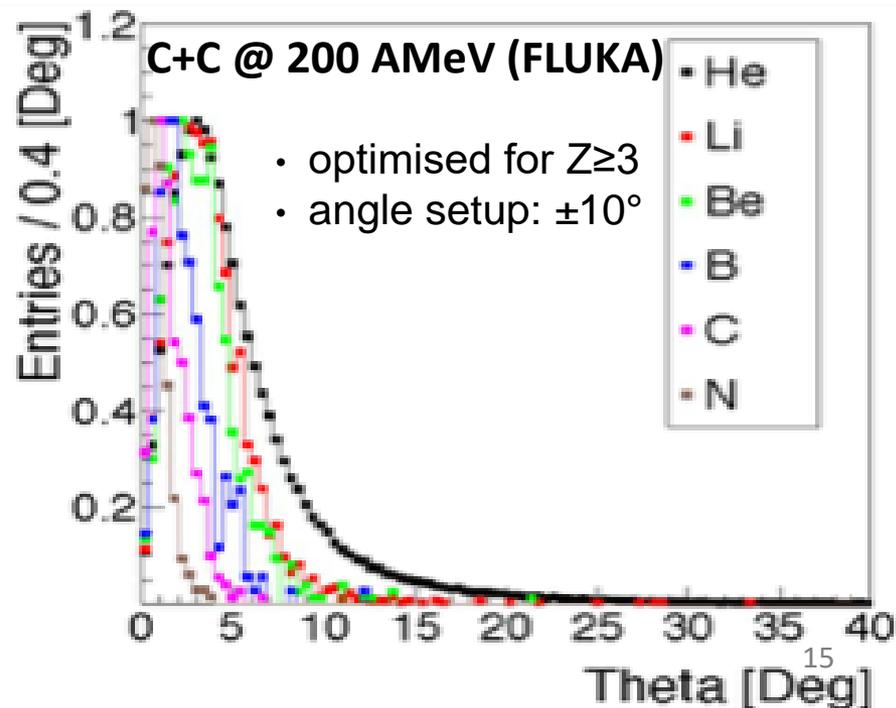
Size ~ 2m – 4m



Performances on ^{12}C at 200 MeV/u

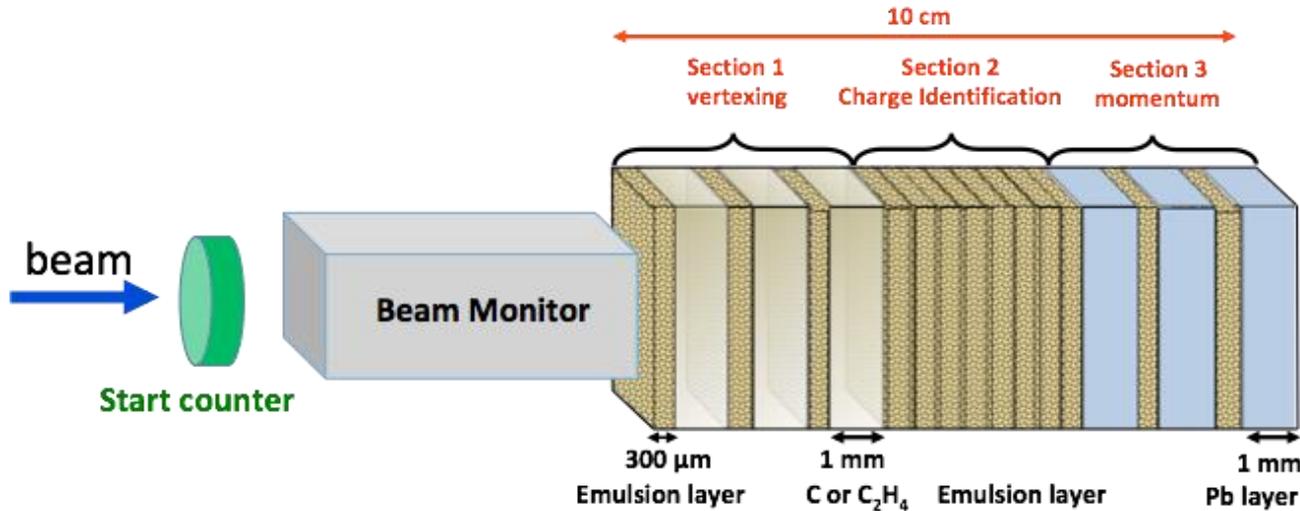
- $\Delta p/p \sim 3\%$
- $\Delta_{\text{TOF}} < 70\text{ps}$
- $\Delta E_{\text{kin}}/E_{\text{kin}} < 2\%$
- $\Delta(dE)/dE \sim 2\%$

| Sub-detector | Main characteristics |
|---------------|--|
| Start counter | plastic scintillator 250 μm |
| Beam monitor | drift chamber (12 layers of wires) |
| Target | C, C ₂ H ₄ , PMMA (2 mm) |
| Vertex | 4 layers silicon pixel (20x20 μm) |
| Magnet | 2 permanent dipoles (1 T) |
| Inner tracker | 2 layers silicon pixel (20x20 μm) |
| Outer tracker | 3 layers silicon strip (125 μm pitch) |
| Scintillator | 2 layers of 20 bars (2x40x0.3 cm) |
| Calorimeter | 360 BGO crystals (2x2x24 cm) |





The FOOT emulsion setup



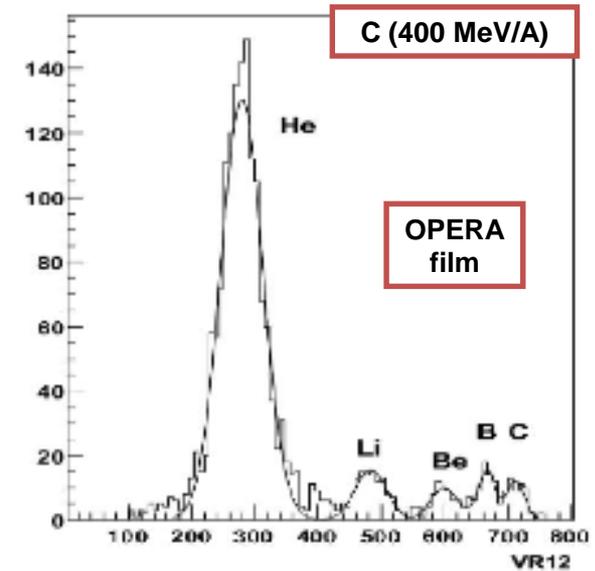
- optimised for light ($Z \leq 3$) fragments
- less than 1m: can be easily movable to fit the space limitations from experimental and treatment rooms
- angle setup: $\pm 75^\circ$

Two complementary setups

- main reason: required angular precision of few mrad hard to achieve with an apparatus of limited size
- lower mass fragments ($Z < 3$) can be emitted within a wider angular aperture wrt heavier nuclei

Main characteristics

- both target and detector integrated in a very compact setup
- accurate reconstruction of the interactions inside the target (sub-micrometric resolution)
- fragment charge assessed with an efficiency $> 99\%$
- automated scanning system technique: very fast and with wide angular acceptances





CONCLUSIONS

- **A lot of interesting physics at GSI/FAIR is going on...and is going to take place in near future!**

Many thanks to:

- **G. Benzoni (INFN-MI), S. Leoni (INFN-MI), D. Napoli (INFN-LNL) for HISPEC/DESPEC (GAMMA exp.)**
 - **E. Vardaci (INFN-NA) for FORTE**
 - **G. Politi, S. Pirrone (INFN-CT) for R3B**
 - **V. Patera (INFN-Roma1) for FOOT**