

A journey through the beam diagnostics of the Super-FRS

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Contents



Origin of the project

Part 1 - Beam diagnostics for Early Science
 primary beam & RIBs

Part 2 - Detectors developments for First Science+ and beyond

Acknowledgement

Origin



In 2001, GSI, together with a large international science community, prepared a Conceptual Design Report for a major new international Facility for Antiproton and Ion Research (FAIR) at Darmstadt (Germany).

Following an in-depth evaluation of the German Wissenschaftsrat, conditional approval for construction of FAIR was given in 2003. The approval was contingent upon the condition of international participation and contribution of 25% of total construction cost by the international partners.

H. Geissel et al., The Super-FRS project at GSI, NIM B 204(2003)71

In 2006, the International Steering Committee for FAIR (ISC), comprising the partner states Austria, China, Finland, France, Germany, Great Britain, Greece, India, Italy, Romania, Russia, Slovenia, Spain and Sweden, agreed to the scientific case and accelerator infrastructure as outlined in the FAIR Baseline Technical Report (FBTR). This central document provided the technical description, cost, schedule, organizational and management structure and assessment of risk for the FAIR project.



On October 17th, 2007, the ISC decided on the realization of the FAIR Start Version without delay according to secure funds. Based on the proposals of the Scientific and Technical Issue Working Group together with the experiment collaborations the scope of the project first phase, FAIR Start Version, was worked out and defined. Already in the Start Version a unique unprecedented infrastructure for Nuclear- Atomic-, Astrophysics and high density plasma physics will be available that opens new fields in research.

M. Winkler et al., The status of the Super-FRS in-flight facility at FAIR, NIM B 266(2008)4183

In parallel to the preparatory activities for FAIR research and development for the accelerators and experimental facilities has advanced considerably. A series of Technical Design Reports (TDR), summarizing the actual system design, the status of R&D of key components, and technical aspects of realization for the FAIR accelerators have been composed, based on the ISC resolution and Technical Advisory Committee recommendations.

Super-FRS TDR



Based on experience and successful experimental program at the FRS

- Multi-stage separation (high resolution spectrometer)
- Multi-branch system serving experimental areas and storage-rings

Technical Design Report (version submitted on April 24th 2008)

H. Geissel, M. Winkler, H. Weick, K.-H. Behr, G. Münzenberg, H. Simon, K. Sümmerer, B. Achenbach, D. Acker, D. Ackermann, T. Aumann, J. Äystö, R. Baer, M. Berz, D. Boutin, C. Brandau, A. Brünle, P. Dendooven, G. Fehrenbacher, E. Floch, M. Gleim, W. Hüller, H. Iwase, A. Kalimov, C. Karagiannis, M. Kauschke, A. Kelic, B. Kindler, G. Klappich, E. Kozlova, A. Kratz, T. Kubo, N. Kurz, K. Kusaka, H. Leibrock, J. Lettry, S. Litvinov, Y. Litvinov, B. Lommel, S. Manikonda, A. Marbs, G. Moritz, C. Mühle, C. Nociforo, J. A. Nolen, H. Penttilä, W. Plass, Z. Podolyak, A. Prochazka, I. Pschorn, T. Radon, H. Ramakers, J. Saren, G. Savard, C. Scheidenberger, P. Schnizer, M. Schwickert, B.M. Sherrill, B. Sitar, A. Stafinak, R. Stieglitz, M. Svedentsov, N.A. Tahir, An. Tauschwitz, O. Tarasov, M. Tomut, P. Vobly, H. Welker, R. Wilfinger, Ch. Will, J.S. Winfield, Y. Xiang, M. Yavor, A. Yoshida, A.F. Zeller.

The TDR was complemented by the FAIR Costbook on accelerators and associated man power – FAIR Start Version and Phase B, Version 5.0 (June 2008), providing information on project costs based on FY 2005 prices. Furthermore, relevant legal documents between the FAIR partners were compiled in the FAIR Baseline Administrative Report.

Beam diagnostics (TDR 2008)



Based on the operating experience gained at the FRS:

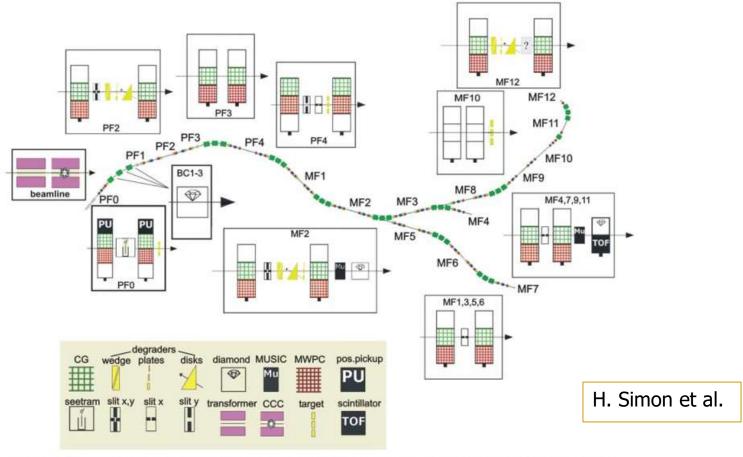
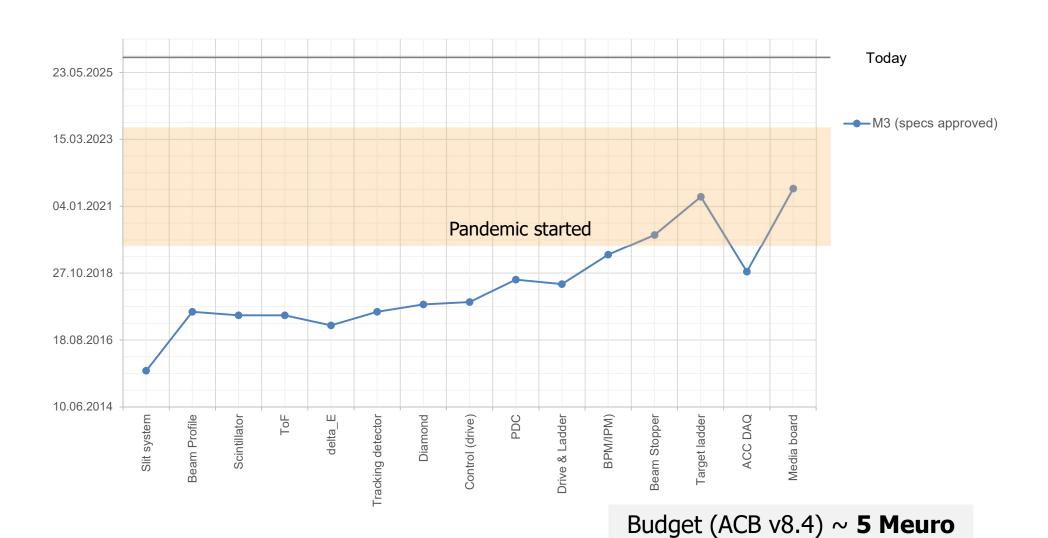


Figure 2.4-78: Detector systems and their positions in the Super-FRS. The particular areas and setups

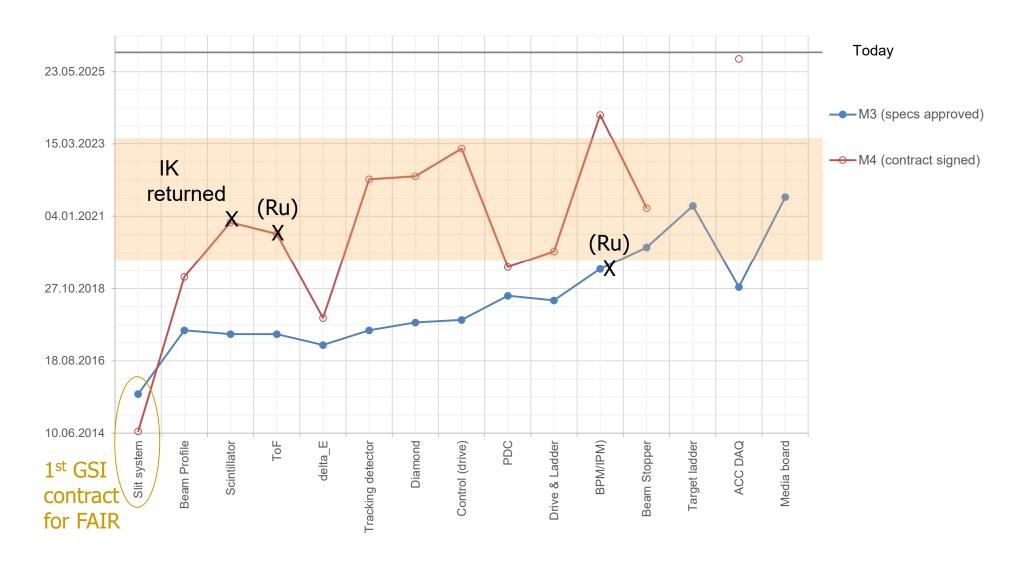
"Specs" mission





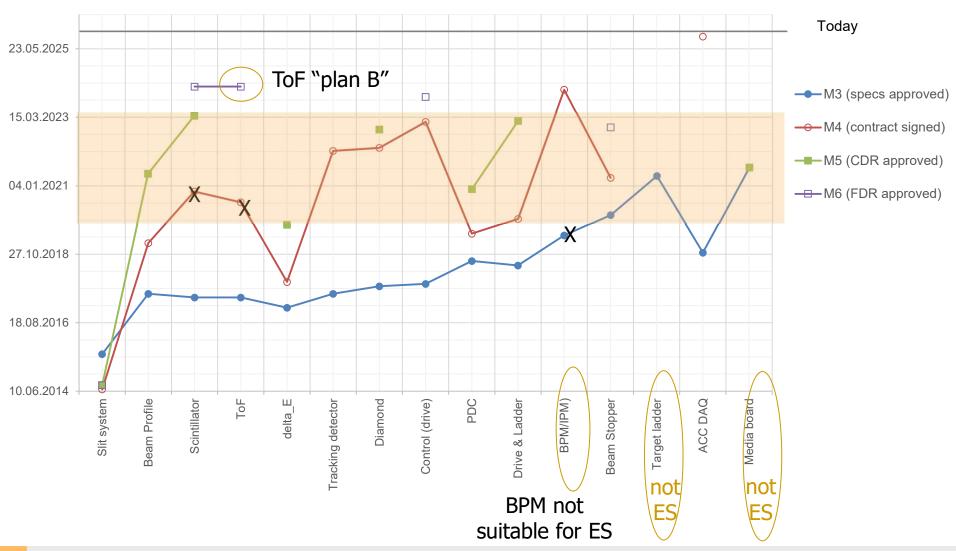
Contract/tender phase





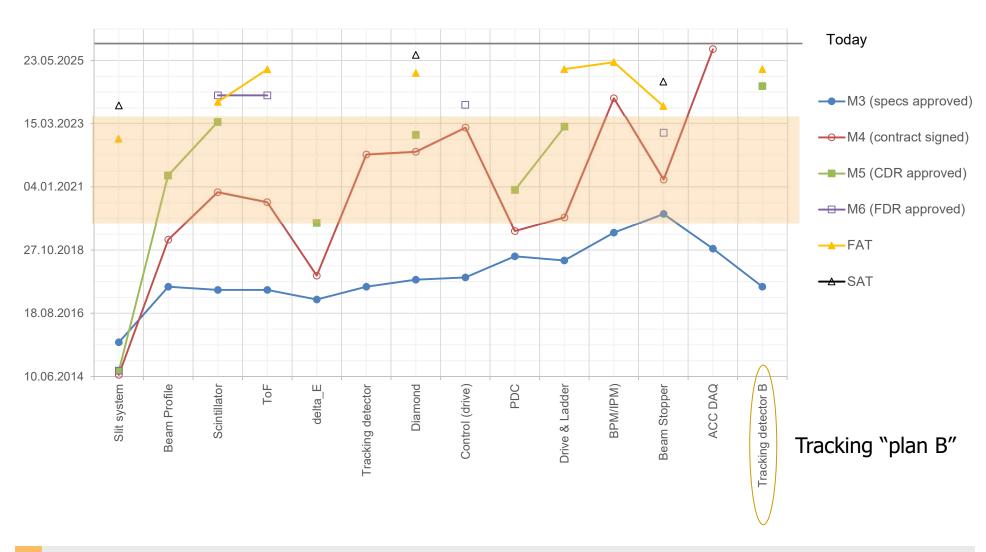
Design phase





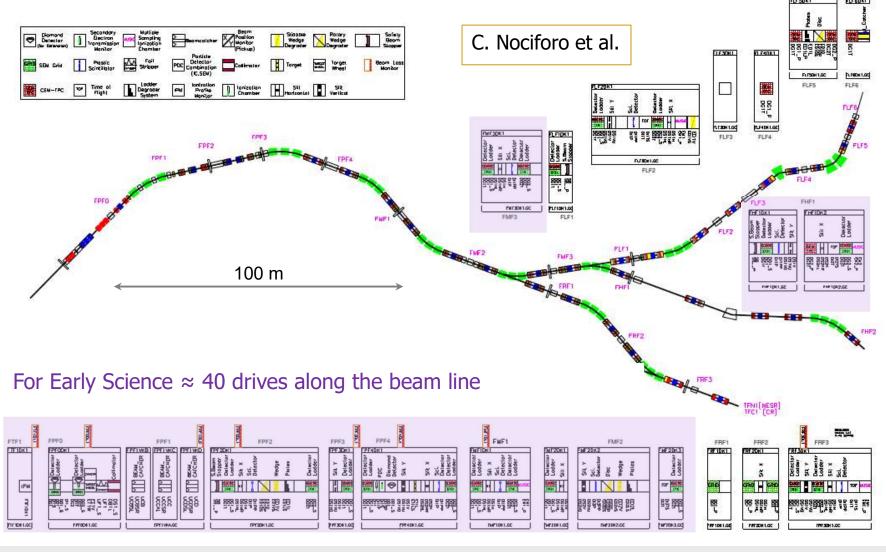
FAT/SAT phase





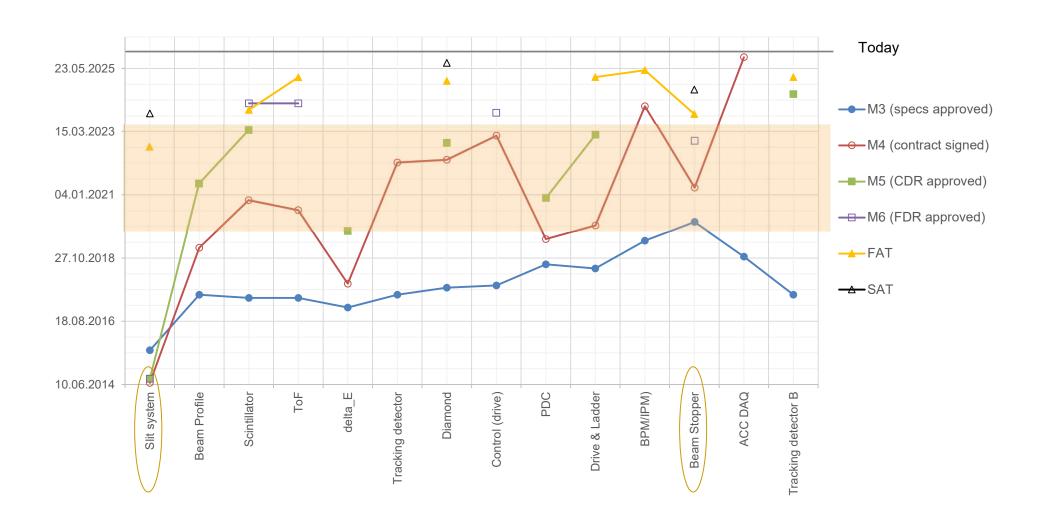
Beam diagnostics (2023)





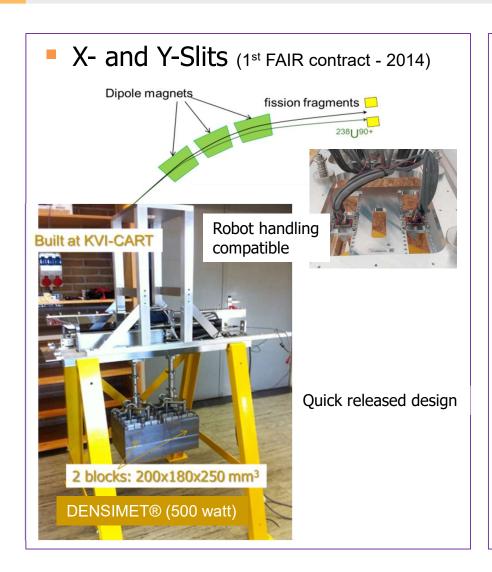
FAT/SAT phase

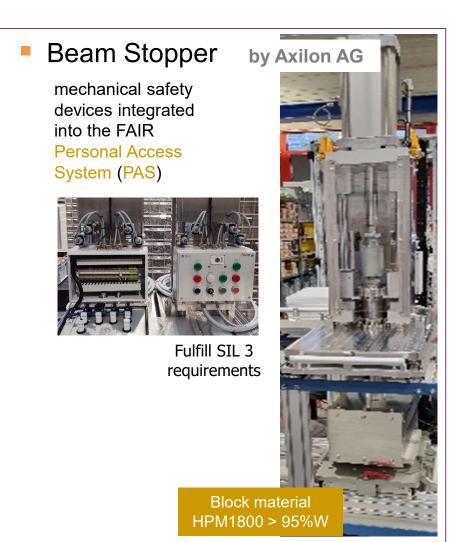




"Passive" insertions delivered

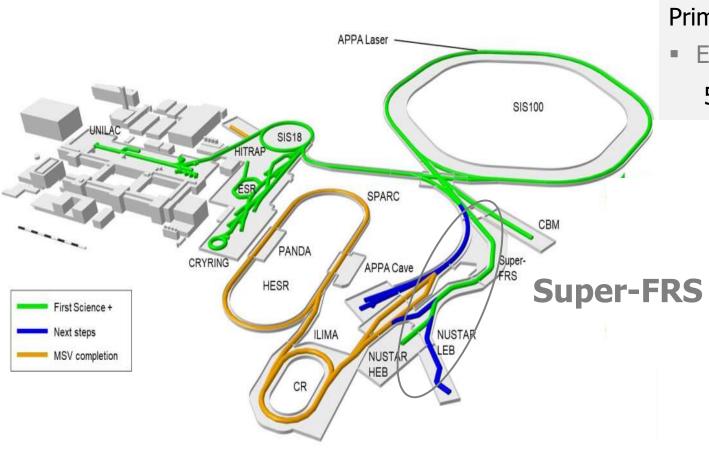






The FAIR NUSTAR in-flight facility





Primary Beams

Early Science (SIS18)
 5x10⁹ ²³⁸U/spill

Main operation requirements

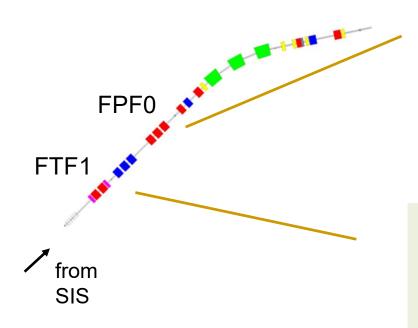


- Setting up and adjusting the separator can be done at a low rate for almost any detector system.
- The main design goal is to get an easy to maintain, reliable system.
- An online monitoring has to be performed, especially in the target and beam catcher areas.
- Any deviation of the primary beam from its nominal position should lead immediately to an inter-lock condition.
- The main challenge is to cope with the very high intensities and background radiation; the design of the detector systems should allow extended periods of operation without hands-on maintenance.

Beam diagnostics at the target



- used to set up and tune the separator
- it must provide the necessary measures for machine protection and monitoring



FPF0DK1 (target chamber)

- Beam profile monitor (2xSEM grids)
- Intensity monitor (PDC)
- Camera

FTF1DK1

Ionization Profile Monitor (2xIPM)
 non destructive devices

Beam intensities at different locations are to be stored also to normalize measured rates in order to extract production **cross sections**.

Particle Detector Combination (PDC) FAIR == i



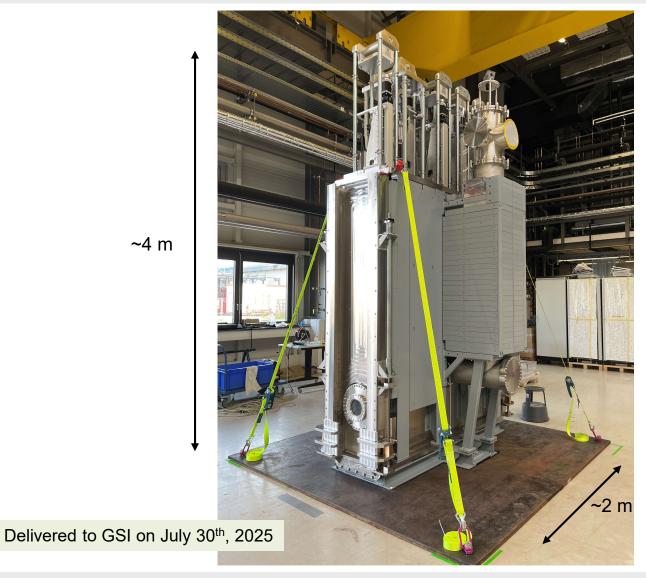
pcCVD-DD selected as reference counting detector up to few MHz overlapping with IC/SEM monitor because of the high-radiation level at Super-FRS target area

- **PDC-FPF0** (<10¹¹ ions/s)
 - ✓ radiation hardness
 - S. Schlemme et al., *Diam. Relat. Mater.* 99 (2019) 107536
 - M. Alfonsi et al., JINST 19 (2024) C05009
 - √ efficiency
 - F. Schirru et al., *JINST* 15 (2020) C04040
 - DD/SEETRAM mounted on 1st and 3rd plugs
 - IC on middle plug (not for ES)

PDC-FPF4 (<10⁹ ions/s) • IC/SEETRAM on two independent vertical pneumatic drives DD assigned to a separate drive (not for ES)

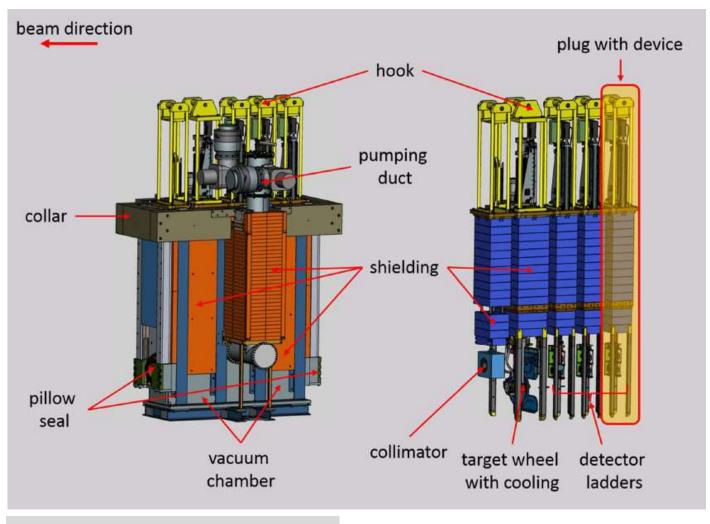
Target station at Testing Hall





Target station: 3D model





Designed by M.F.Lindemulder (KVI)

Plug and Ladder





Fantini, January 2025

Plug ~ 2 ton



Fantini, May 2025

Cabling



Cables and connectors at the plug are non exchangeable

Inner components



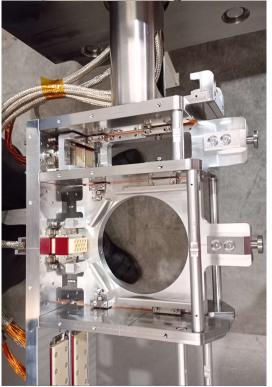




SEETRAM (highest intensity)

Ionization chamber (mid-high intensity)





- each detector is attachable/removable by a manipulator via its own sub-frame
- electrical connections are established using self-aligned connectors with ceramic carriers equipped with pins
- **3.7 m** kapton cables from the multipin connector up to the feed-throughs

Detector replacement possible only **1 time per year**

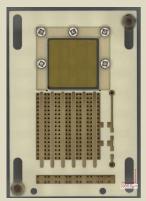
FAT (July 2025)

pcCVD-DD prototype



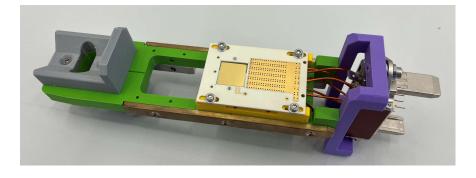
E6_PC622-10 20 x 20 x 0.313 mm³ (308-318um)





- metallisation 100nm Au
- guard ring outer dimension 18 x 18 mm²
- 5 strips 17.0 x 3.3 mm²
- gaps inside guard ring 100um

Mock-up of the sub-frame built for testing at HIT (Dec 2024)

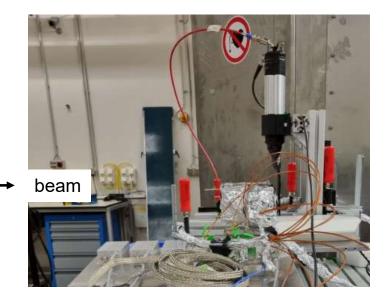


Custom-made DD multipin ceramic connector

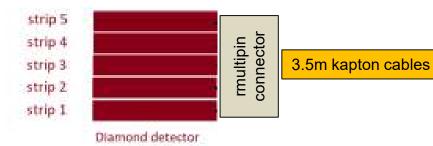


Experimental setup at HIT





Each coaxial cable has the inner conductor and the outer shield separated and soldered on two neighboring pins.



SCI DD

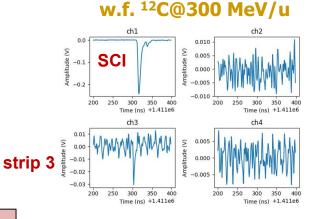
tallianter

beam

148.8

64.5





5x 1-stage amp. (DBA4/R or Mini-Circuits)

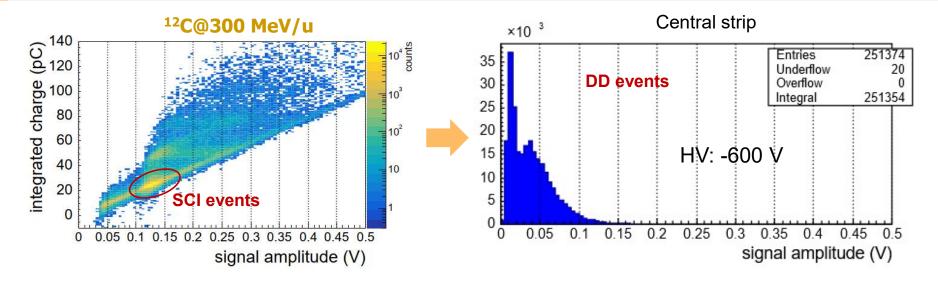
Oscill.

LED + Scaler

Dec 2024: run in "therapy" mode @2 MHz rate

Test results





Central strip

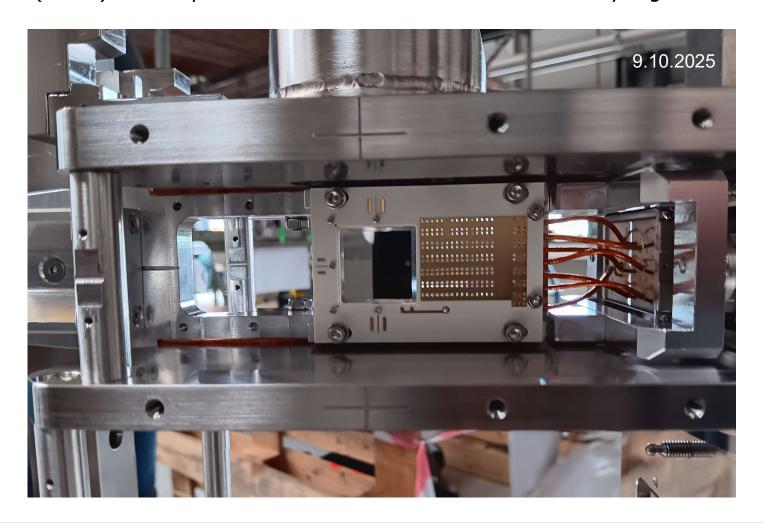
w.f. analysis of 3 strips with \emptyset 6 mm collimator (S/N < 10, high noise):

- \checkmark ε_{strip 3} **≈60%** at S > 20mV, N will be smaller for operation in vacuum
- √ double-strip events negligible (S < 10mV)
 </p>

Plug1



II-VI (25x25) mm² strip diamond detector mounted and horizontally aligned on Ladder 1



1st alpha source test at FPF0DK1



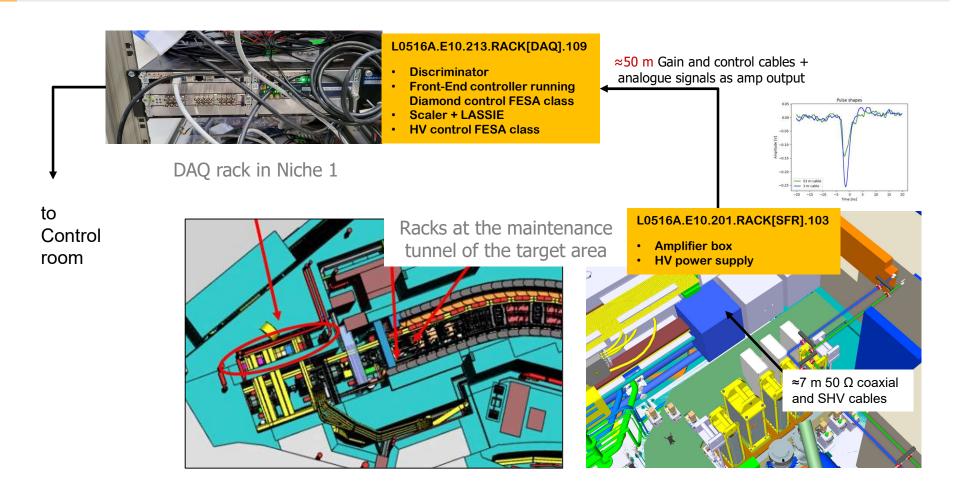
 V_{MAX} -945 V bias (I_{MAX} 0.1 – 0.2 uA) at p = 3 x 10⁻⁵ mbar

10.10.2025

- all connected strips show comparable alpha signals (thr -20mV), central strip more noisy (-25 mV)
- guard ring influenced by low frequency noise (thr -40mV)
- signals not visibly affected by high leakage current at the highest bias
- capacitive coupling is visible in all channels with opposite polarity and amplitude (<10%)
- some signal ringing after the alpha signals delayed by 100ns is visible in all channels (not present in the lab test)

Outer components





New Amplifier Box to cover larger dynamic range (≥70 dB from C to U)

Diamond system at FPF0



 Final counting diamond detectors designed to be operated in a harsh environment are ready to be installed at the Super-FRS target chamber.

1st plug: pcCVD-DD 3rd plug: scCVD-DD (25x25 mm²) (7x7 mm²)

- Greenstreams (M. Kumm et al.) customized electronics developed for the readout of analogue the strip signals and for a not accessible area is under test
 - multi preamplifiers with different gains and switches remotely operable
 - ≥70 dB of total input signal dynamic range
 - able to operate with primary beams up to U



 It will be included into the FAIR control system (FESA classes) allowing to calibrate of the Super-FRS IC/SEM monitors during the Super-FRS operation.







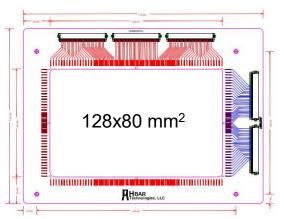
SEM prototypes were tested with POLAND single-wire readout.

GSI (2024)



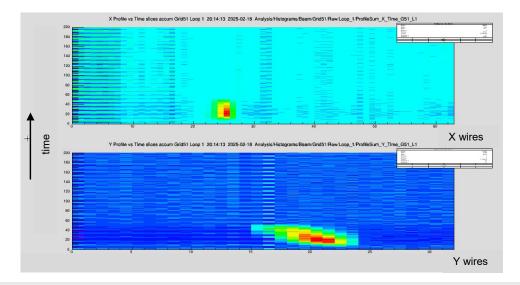
SEM profile monitors





SEM by Hbar Technology LLD (w conn.)

Ag beam in Cave C (Feb 2025)



POLAND board (32 chs)

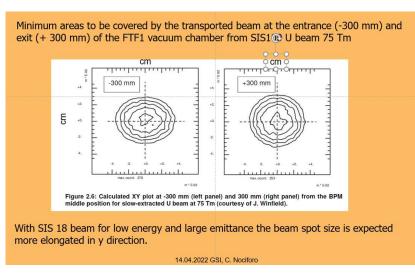


S. Löchner et al.

Super-FRS focusing system



J.S. Winfield et al., Ion-optical developments tailored for experiments with the Super-FRS at FAIR, NIM B 491(2021)38



XY plot simulated at the BPM Diagnostics Box

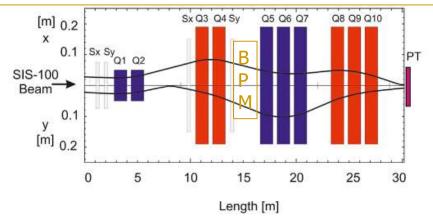


Fig. 2. Ion-optical elements for the Super-FRS focusing system in front of the production target (PT). The main task of the cascaded quadrupole magnets is to focus the projectile beam from SIS-100 or directly also from SIS-18 on the production target. Red colored quadrupoles are x-focusing, blue-colored quadrupoles are focusing in y direction. Horizontal (Sx) and vertical (Sy) steerers are used to correct angles and positions in case of misalignment. The ion beam will enter on the left hand side, which is the usual convention in ion-optics. The emittance of $\epsilon_x = 25~\pi$ mm mrad and $\epsilon_y = 10~\pi$ mm mrad are chosen to reflect the transverse emittance of the beamline. The achromatic beam spot on the production target can have a width of $x_{PT} = 1~\text{mm}$ and a height of $y_{PT} = 2~\text{mm}$ for slow-extraction.

The space available was only for 1 Diagnostic Box, to be included into the machine protection for the fast-extracted beams and, then assigned as **BPM**.

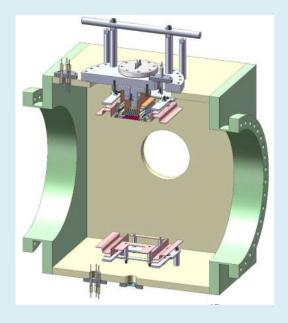
Super-FRS IPM

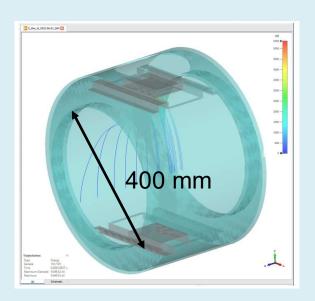


The delay of the FAIR-Russia BPM contract and the decision to postpone the construction of the Ring Branch lead to look for a different solution.

In 2022, T. Giacomini was asked for designing of a large IPM detector to be installed at the focusing system of Super-FRS.

3D model (2023)





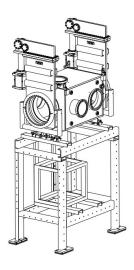
Simulations by T. Giacomini (2023)

First vacuum test



FTF1DK1

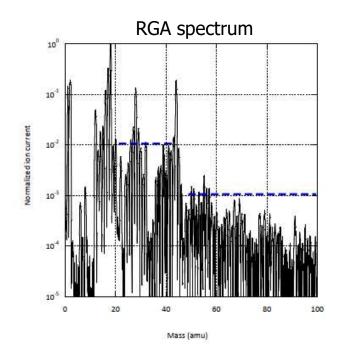
Vacuum chamber shipped to GSI on Dec 2024



3D model by R. J. Simillon (GSI)

SAT setup at VAC lab (Jan 2025)





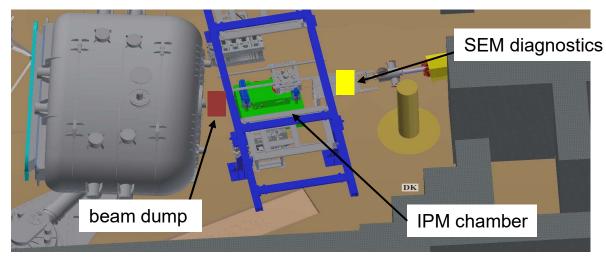
S. Purushothaman et al.

It was needed to clean the chamber at GSI for the first IPM test

SFRS IPM tests in Cave C



7-9 Feb 2025, Ag primary beam E_{SIS}=0.4 GeV/u up to 10⁸ ions/s



courtesy of D. Körper

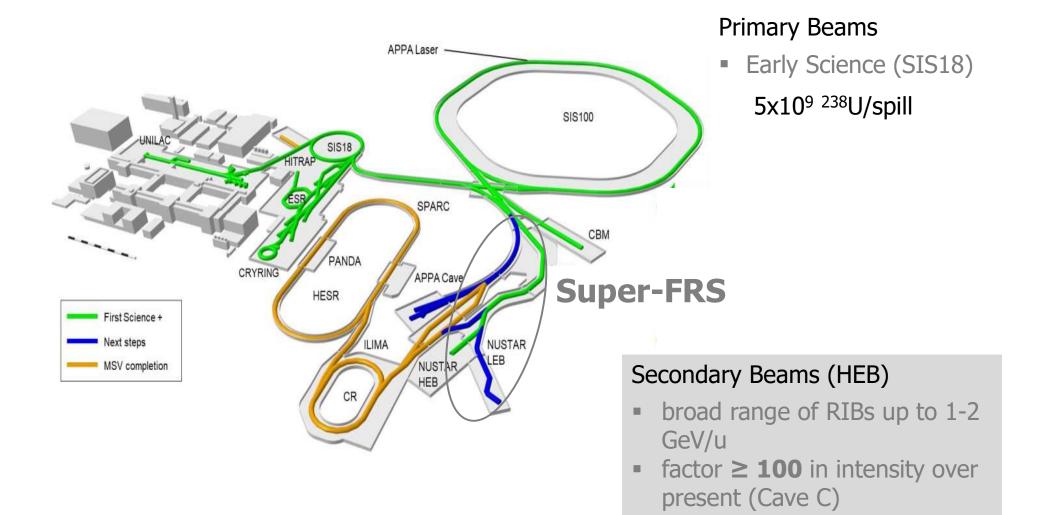
1-2 Jul 2025, U primary beam E_{SIS}=0.3-0.9 GeV/u up to 10⁹ ions/s

Both tests helped to debug the electronics and the setup.

Despite the high intensity, the measured beam profile was not so clear because of too much residual gas.

The new NUSTAR in-flight facility

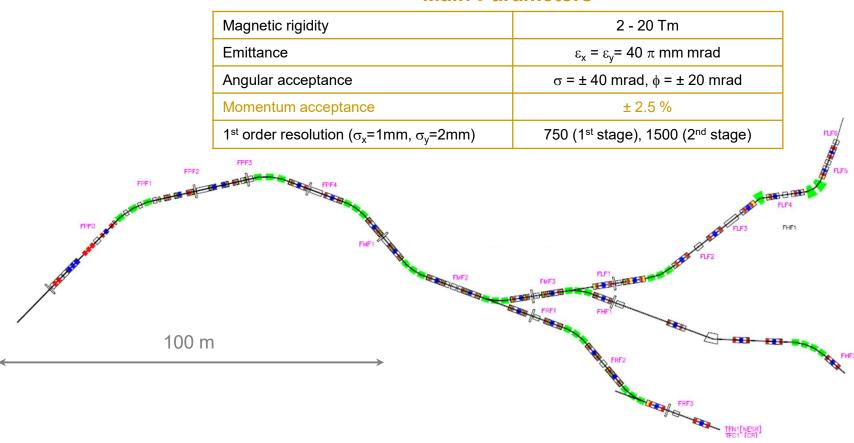




Super-FRS layout



Main Parameters

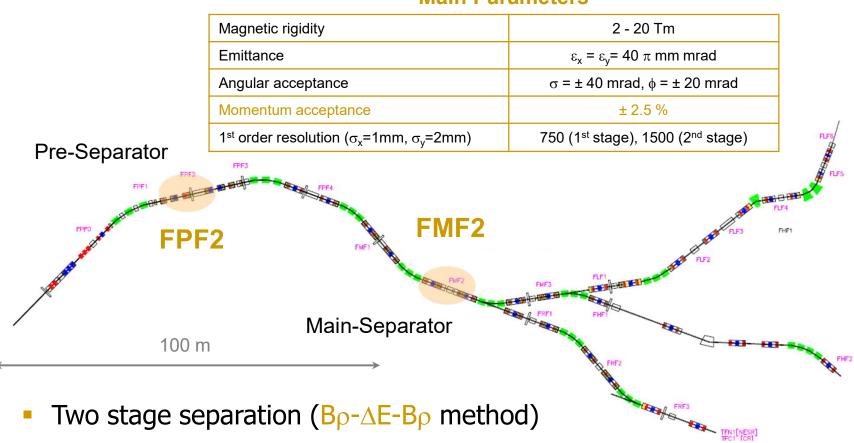


M. Winkler et al., *NIM B* 266 (2008) 4183

Super-FRS layout



Main Parameters

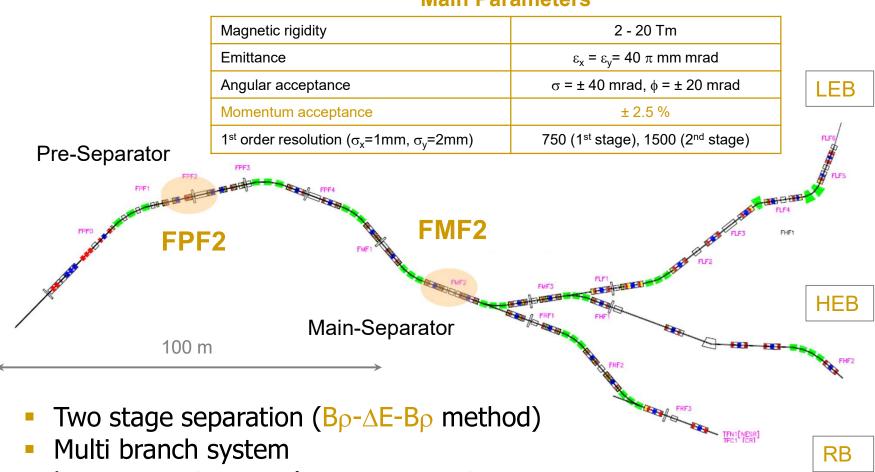


M. Winkler et al., NIM B 266 (2008) 4183

Super-FRS layout



Main Parameters



- Large acceptance using s.c. magnets
- Handling concept for high radiation area

M. Winkler et al., NIM B 266 (2008) 4183

Bρ-**ToF**-Δ**E** method

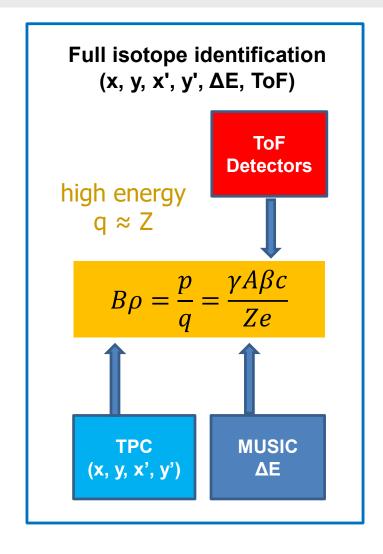


For almost all **NUSTAR** experiments, the separator is to be treated as the first part of the experimental setup.

The beam particles entering the different branches have to be identified and their longitudinal and transverse momentum components should be known.

In-flight **PID** event-by-event requirements:

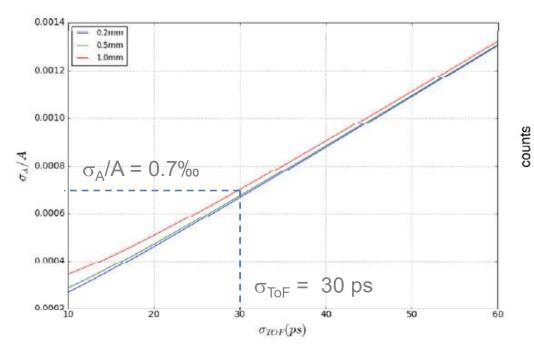
Bρ ToF ΔE $\Delta x \sim 1 \text{mm} \qquad \Delta T < 100 \text{ps} \qquad \sigma_E \sim 1\%$

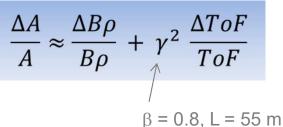


Requirement on A/q separation

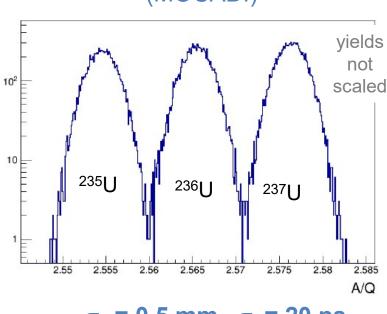


Clean full isotope identification on event-by-event basis









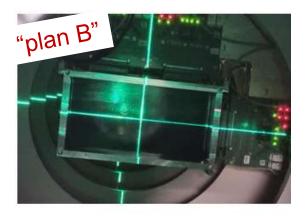
 σ_x = 0.5 mm, σ_t = 20 ps

C. Nociforo, 2014 JINST 9 C01022

PID detectors

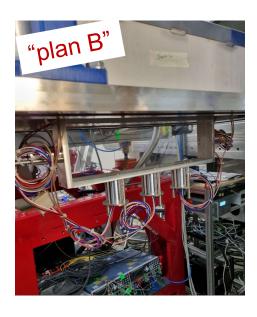


Βρ



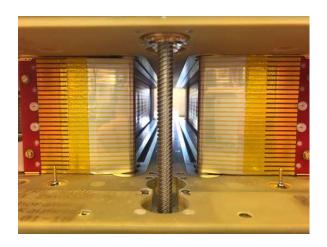
X and Y layers of fiber SCSF-78J (Kururay) 0.5 mm square area coupled to MPPC S13552 by Hamamatsu and read out by ROB3 – FPGA TDC with ToT (σ = 200 ps).

ToF



Non-segmented EJ-230 (400x100x1) mm³ size coupled to H14211-210 Hamamatsu PMT read out by SFRS-PEAKS1 and TAMEX4 (σ =10 ps).

 ΔE



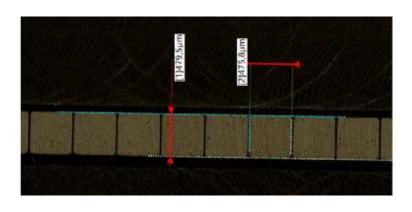
lonization chamber with two field cages separated by a strip foil and segmented anodes coupled to Mesytec preamplifier MUPR-18 and digitizer MDPP32-D.

"Plan B" for commissioning and ES

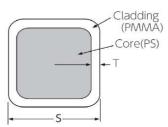
Scintillating fiber prototype



Layer of 128 fiber SCSF-78J (Kururay) 0.5 mm square



- large area (400x150) mm²
- very homogeneous thickness
- assembly done in-house
- SiPM photosensors



Cladding Thickness: T=2% of S Numerical Aperture: NA=0.55 Trapping Efficiency: 4.2%

MDPP ROB3

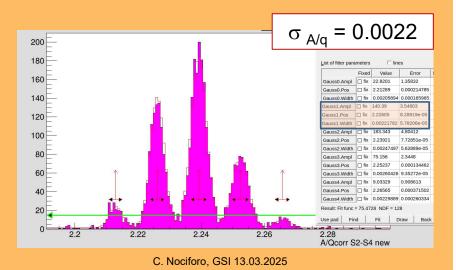


Fibers coupled to ToT (σ = 200 ps)

MPPC S13552 by Hamamatsu and read by ROB3 -FPGA TDC with

Effect of 1 layer of 0.5 mm on A/q resolution

Isotopes around Z = 76 produced at FRS via $1 \text{ GeV/u}^{238}\text{U} + \text{Be/Nb} (1032/223 \text{ mg/cm}^2)$

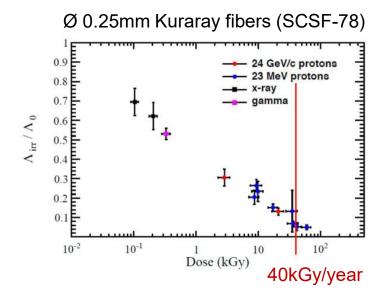


Long term plans (beyond 2028)



For later FS and MSV phase system with higher rate capability (with SIS100 we can expect factor 5...10 higher intensities than SIS18) is needed.

- at PS (remote handling) not rate capability, rather radiation-resistance issues



https://arxiv.org/abs/1710.08325

- VMM3a is rated at 100 krad (≈1 kSv), in the tunnel 5 Sv/h, i.e. 1000 hours of operation.

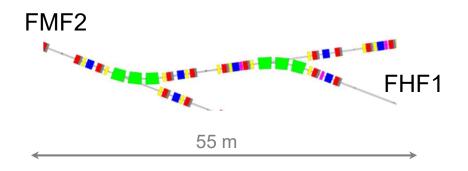
ToF - Plastic Scintillator



In-house design started after the withdrawal of the in-kind Swedish contract in 2019 and the closure of the FAIR contracts with Russia in 2022.



The plastics scintillator design was optimized for Time-of-Flight measurements between FMF2 and FHF1.



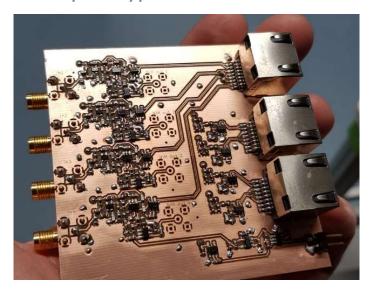
Two First of Series (FoS) already built and successfully tested

For the procurement of the remaining drives of the Super-FRS Plastic Scintillator detectors a FAIR tender is assigned to PREVAC.

Analogue fast processing electronics

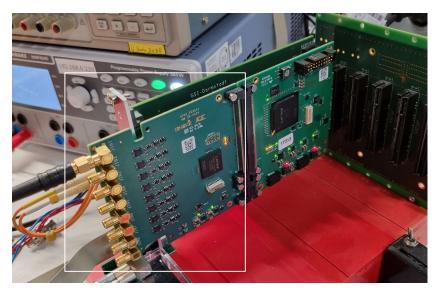


4-ch prototype tested in 2023-2024



Design by M. Wiebusch (GSI-EE)

8-ch SFRS-PEAKS1 tested in 2025

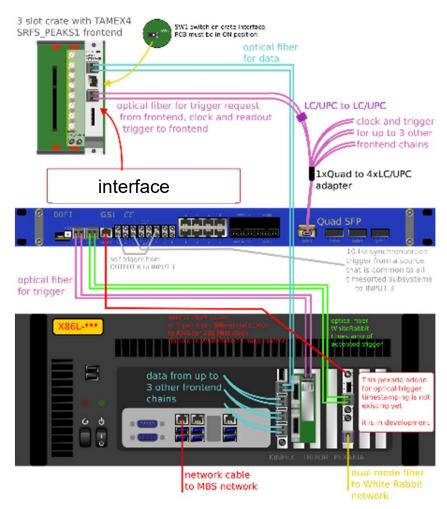


For rising time up to 1-2 ns, both have $ToT = t_{leading} - t_{trailing}$ capability

The final board equipped with integrated attenuation/amplification stage provides additionally the "Energy" signals for the walk correction.

DAQ configuration





courtesy of M. Reese (GSI-EE)

The DAQ is fully MBS compatible.

The TDC clock coming from the new EXPLODER is distributed over the QUAD SFP to the TAMEX4 cards. It accepts the trigger #1 and #3 if the system is not in dead-time and generates the accepted trigger, which is also sent to the TRIXOR trigger module in the PC.

The PC X86L, located at the service tunnel generates an interrupt after an adjustable dead time (conversion time) and the MBS starts the readout process through the optical fibers from the KNIPEX card to the crate interface. After the readout the MBS tells to TRIXOR to release the dead-time.

The synchronization with the other detectors is done via White Rabbit network.

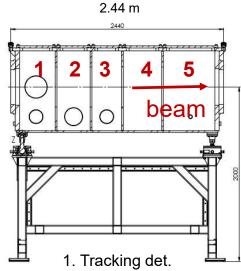
Focal plane chamber





- 2 First of Series (FoS) Super-FRS diagnostic chambers delivered in 2023
 - FMF1DK1 suitable for preassembly and detector tests

FMF1DK1 commissioning



- 2. X-slit
- 3. ToF det.
- 4. Tracking det.
- 5. MUSIC det.

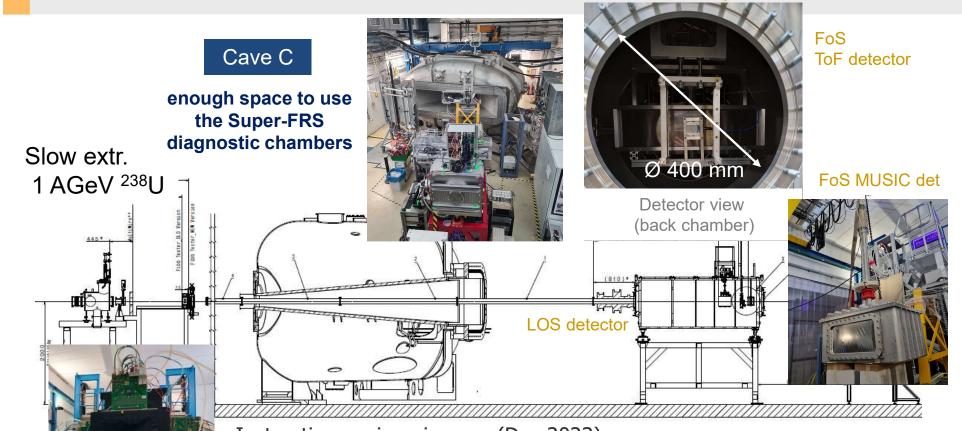
It allowed to performed the first in-beam tests of

- 2x FoS SFRS Scintillating Fibers
- 1x FoS SFRS Plastic Scintillators
- 1x FoS SFRS MUSIC

with **U**, **C**, **Ag** SIS18 beams at **0.5-1 AGeV** delivered to Cave C.

Beam test in 2023





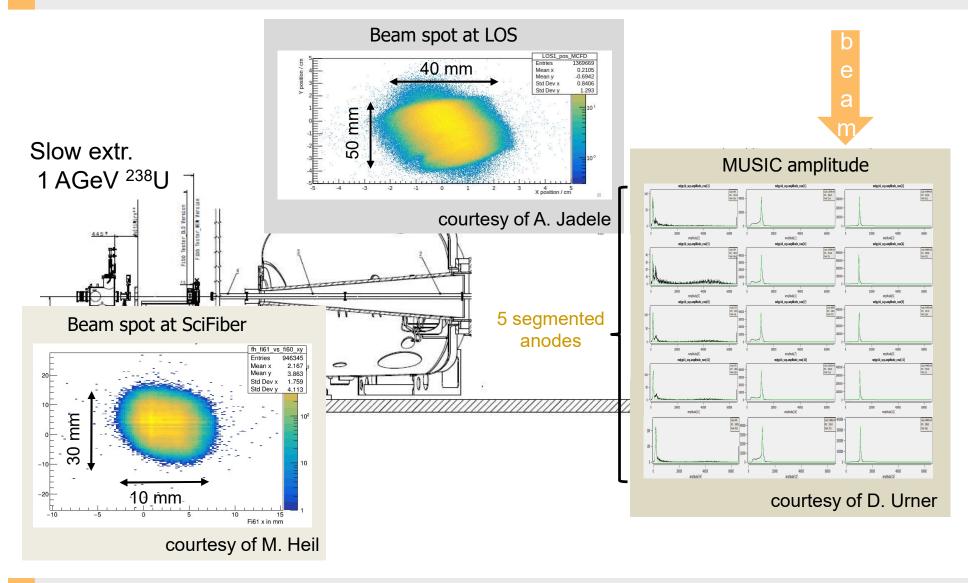
2 x SciFiber detectors

Instructive engineering run (Dec 2023):

- ✓ First operation of the SFRS diagnostic chamber
- ✓ **First** run of full size SFRS prototypes (SCI, MUSIC, SciFiber det.)
- ✓ First training of the SFRS diagnostics team and estimate of focal plane commissioning w/wo beam

Beam test in 2023

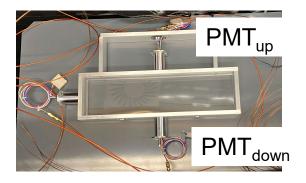




Resolution - U ions



$$\Delta T = t_{PMT up} - t_{PMT down}$$



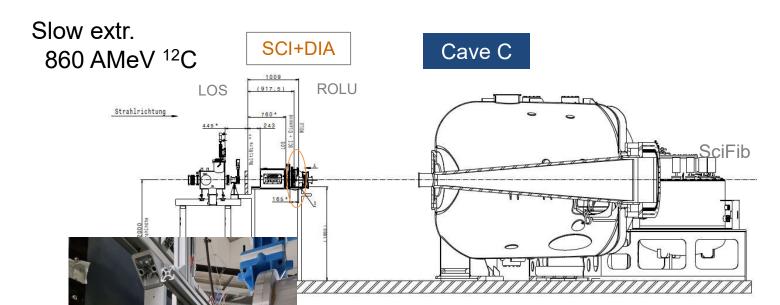
Results for hit multiplicity = 1

 $\sigma_{\rm t} \approx 20~{\rm ps}$

for U beams is within the specs

Cave C setup - 2024





Diamond active area $\approx 1 \text{mm}^2$

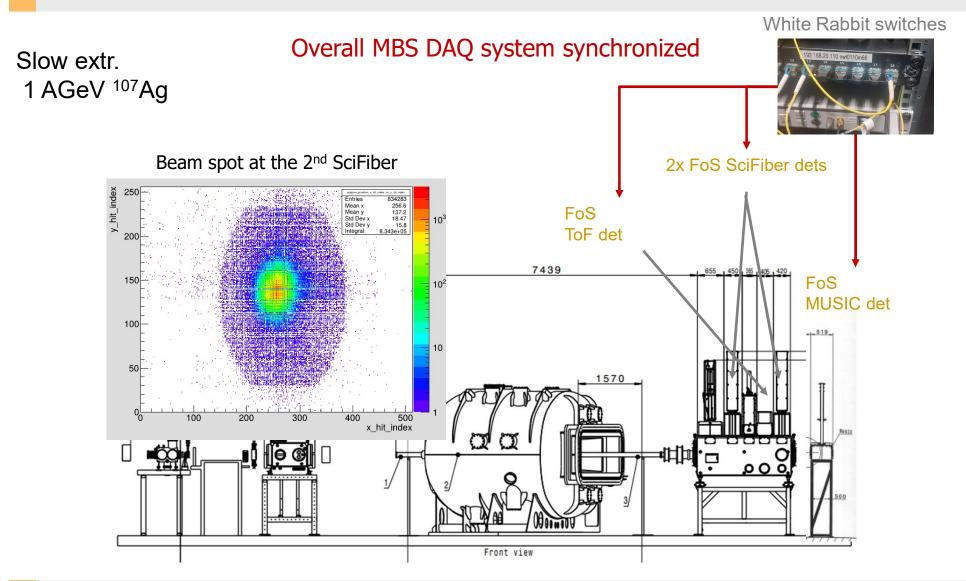


4x4mm² size ~480um thickness, Al electrodes

 $\sigma_{\rm t}$ < 50 ps

for C beam up to 150 kHz







Slow extr. 1 AGeV ¹⁰⁷Ag

Overall MBS DAQ system synchronized

X SciFib vs dE MUSIC Beam spot at the 2nd SciFiber y_hit_index 3000 dE MUSIC 500 x_hit_index $\sigma \approx 1.7\%$ over 5-anode average Front view

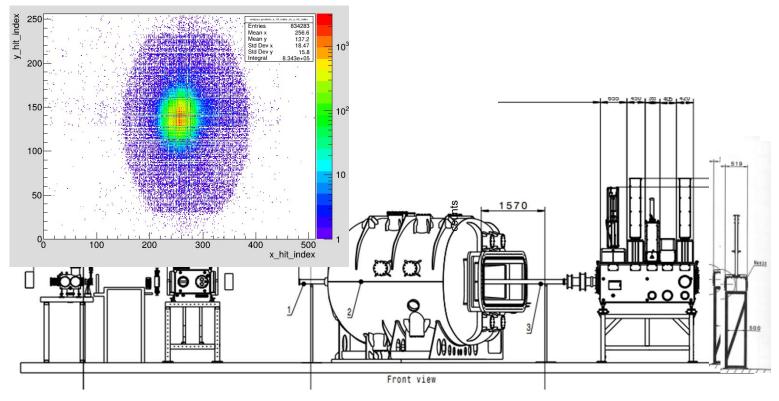


Slow extr. 1 AGeV ¹⁰⁷Ag

Overall MBS DAQ system synchronized

X SciFiber vs ΔT

Beam spot at the 2nd SciFiber

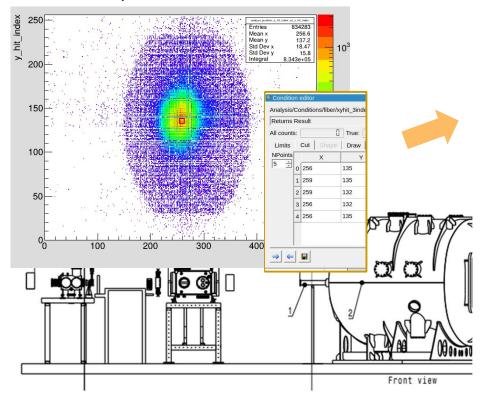




Slow extr. 1 AGeV ¹⁰⁷Ag after gating on position

SCI ToT vs ΔT

Beam spot at the 2nd SciFiber



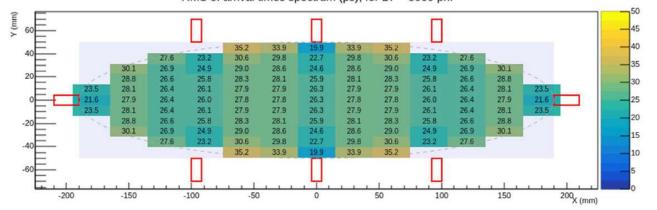
SCI ΔT

ToF detector



EJ-230 Plastic Scintillators 400x100 mm² read by 8 PMT

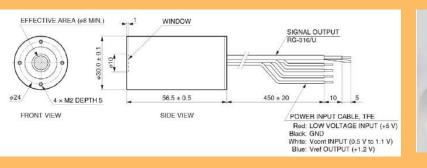
RMS of arrival times spectrum (ps), for LY = 8000 ph.



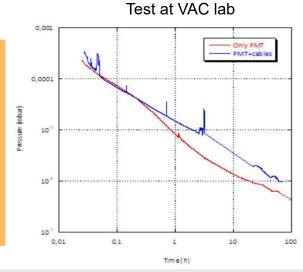


GEANT4 sim. (U ions) by M. Alfonsi

H14211-210 Hamamatsu PMT



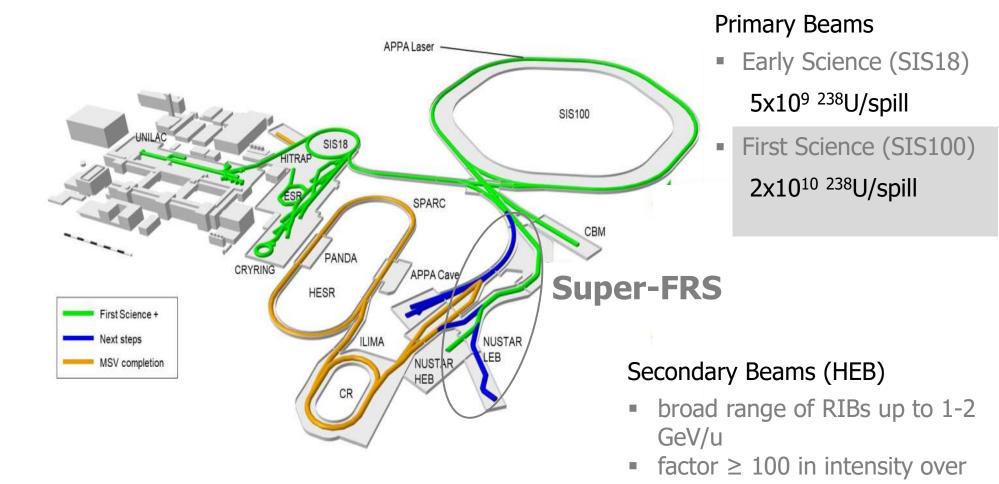




The new NUSTAR in-flight facility



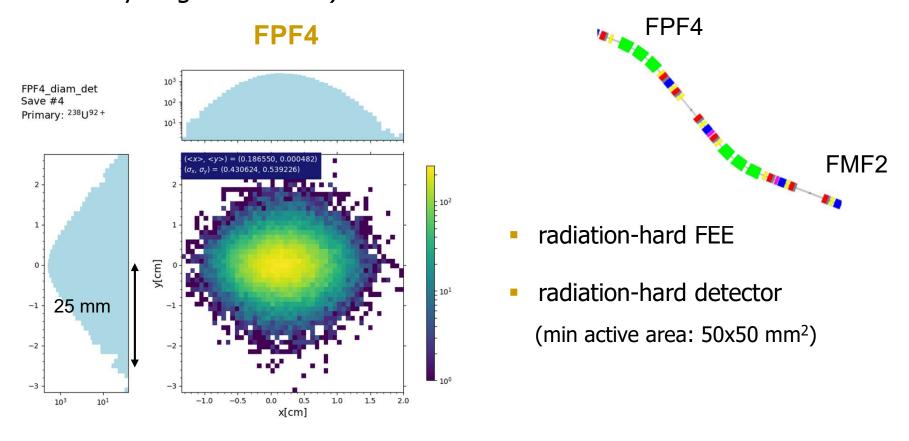
present (Cave C)



FPF4 requirements



Timing/position detector at FPF4 detector will be needed (e.g. case of secondary targets at FMF2).



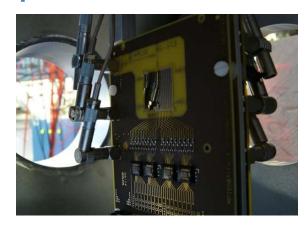
Simulations by E. Kazantseva

Previous studies

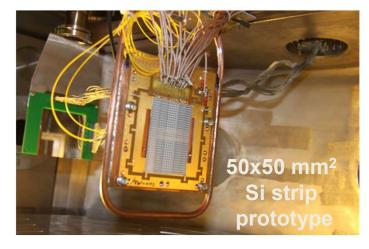


- ToF resolution (σ_t = 20 ps for U), activity < 1 kGy/year
 - → ToF silicon/diamond strip detectors arranged in planar geometry, use of pico-seconds electronics (PADI+VFTX)

2 x pcCVD -DD 20x20x0.3 mm³



F. Schirru et al., J. Phys. D: Appl. Phys. 49 (2016) 215105



V. Eremin et al., NIM A 796 (2015) 158

- Radiation tolerance
 - → CVD-DD as counting particle detector up to few MHz, calibration device for beam intensity monitors (PDC)

S. Schlemme et al., *Diam. Relat. Mater.* 99 (2019) 107536

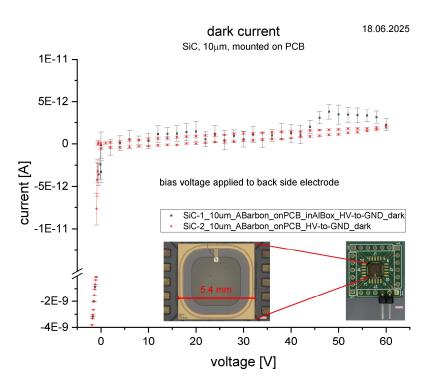
M. Alfonsi et al., *JINST* 19 (2024) C05009

SiC characterization at DTL



p-n junction SiC detectors (10 um)

Detectors were provided by S. Tudisco (LNS-INFN, Catania)



α not stopped

SiC in-beam test at GSI (July 2025)



- 1x scCVD-DD 3x3x0.110 ($dE_{loss} \approx 700-1000 \text{ MeV}$)
- 2x SiC 3.4x3.4x0.001 mm ($dE_{loss} \approx 55-80 \text{ MeV}$)
- all detectors connected to Bias-T w/o amplification
- w.f. collected with osc. (2GHz, 20 GS/s) triggering on scCVD-DD channel (thr: 5 mV)



spectra w/o baseline correction, 100 w.f. (5% of data)

Summary and perspectives



- Large active area detectors required because of the larger phase space of the Super-FRS (≈2 higher of FRS) were designed for Early Science operation at FAIR.
- Unique components having challenging technological functionalities were successfully tested with beam in Cave C thanks to an intense work of the Super-FRS beam diagnostic team in 2023-2025.
- In parallel to the procurements and installations for the Super-FRS commissioning, R&D is carried on radiation-resistant detectors (diamond, SiC) for First Science and beyond

such that the Super-FRS will be well suited to nuclear experiments at the forefront of science.

Acknowledgment



M. Alfonsi, F. Amjad, S. Althoff, C.-H. Behr, C. Bellachioma, A. Bergmann, C. Betz, T. Blatz, P. Boutachkov, A. Brünle, C. Caesar, D. Chokheli, M. Czogalik, M. Faul, P. Forck, J. Frühauf, J. A. Galvis Tarquino, P. Garcia Gil, M. Gleim, D. Grünberg, R. Haseitl, E. Heattner, M. Heil, R. Hettrich, T. Hoffmann, K. Höhne, C. Karagiannis, E. Kazantseva, M. Kis, O. Kiselev, K. Koch, D. Körper, E. Kozlova, R. Knöbel, A. Kratz, J. Kurdal, N. Kurichiyanil, N. Kurz, D. Liebert, S. Liebert, S. Löchner, R. Lonsing, R. R. Mändl, H. Marcocelli, I. Mukha, A. Prochazka, I. Pschorn, S. Purushothaman, M. Reese, A. Reiter, M. V. Ricciardi, M. Salinas Rodriguez, D. Savran, H. Schaffner, C. Schlör, F. Schirru, S. Schlemme, C. J. Schmidt, M.-M. Schmidt, P. Schwarz, M. Schwickert, H. Simon, R. Singh, C. Subhasis, K. Sümmerer, P. M. Suherman, B. Szczepanczyk, Y. Tanaka, M. Träger, S. Udrea, D. Urner, S. Utz, R. Visinka, B. Voss, B. Walasek-Höhne, H. Weick, M. Wiebusch, P. Wieczorek, M. Winkler

Special thanks



I am indebted to **Nik Kurz** with whom I worked at GSI continuously for more than 20 years





... and the BD team, especially my deputy Joshua Galvis Tarquino, for the last 5 intense working years.