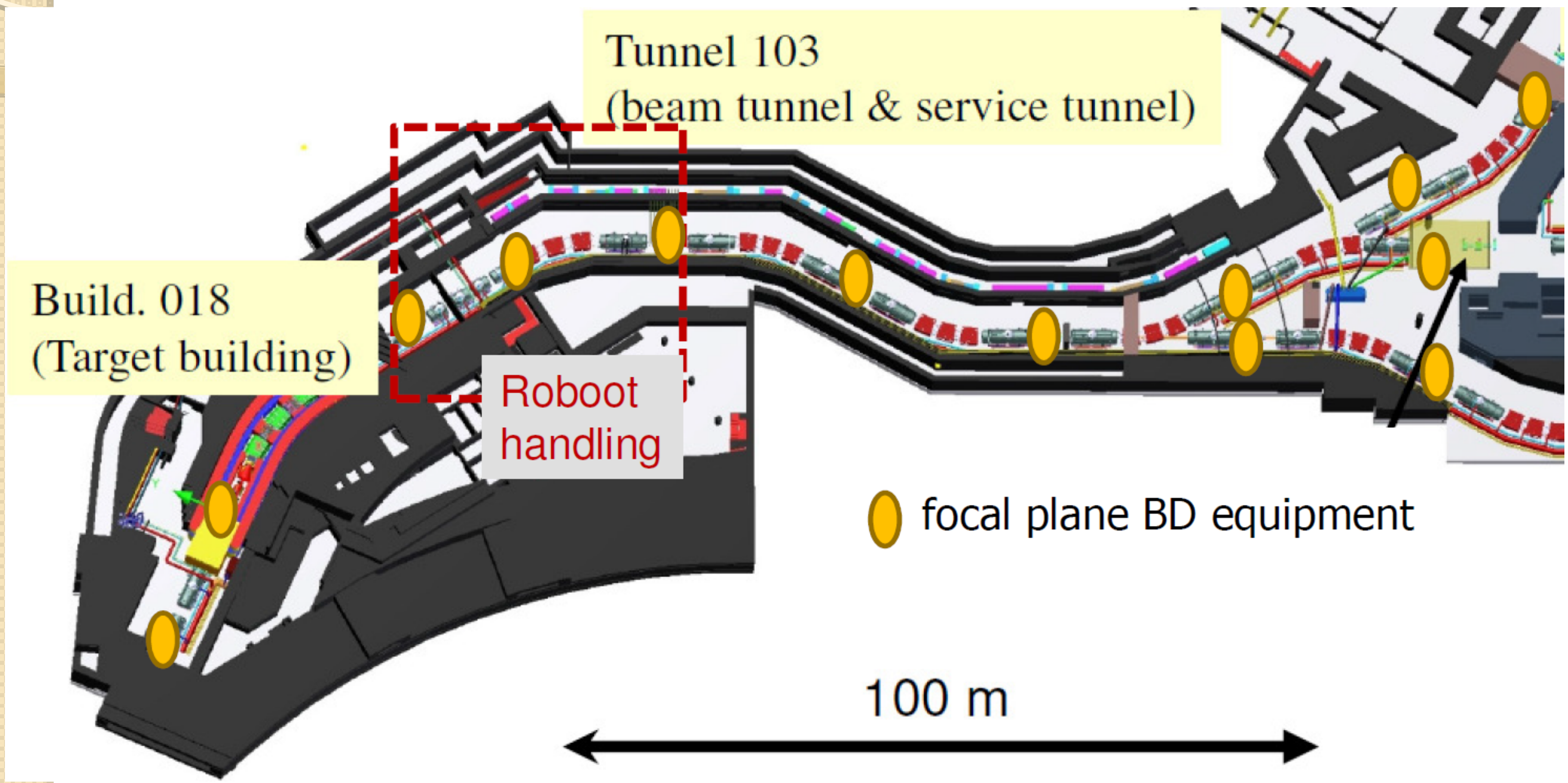
Super-FRS detectors (with emphasis on silicon)

Oleg Kiselev
GSI Darmstadt

Projectile Fragment Experts' Workshop, 30.08-01.09.2016, MSU, USA

Super-FRS with beam diagnostics

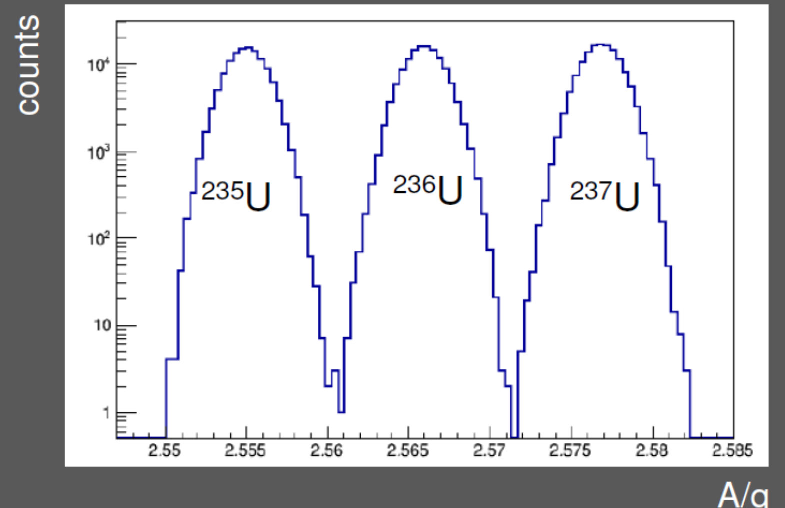


Requirements to the PID detectors

- **Clean full PID on event-by-event basis**

  → momentum tagging $\Delta x \sim 1mm$
  → ToF measurements $\Delta ToF \sim 100ps$ (FWHM)
  → charge resolution $\Delta Z \sim 0.2e$

$\sigma_x = 0.5mm$
$\sigma_t = 20ps$



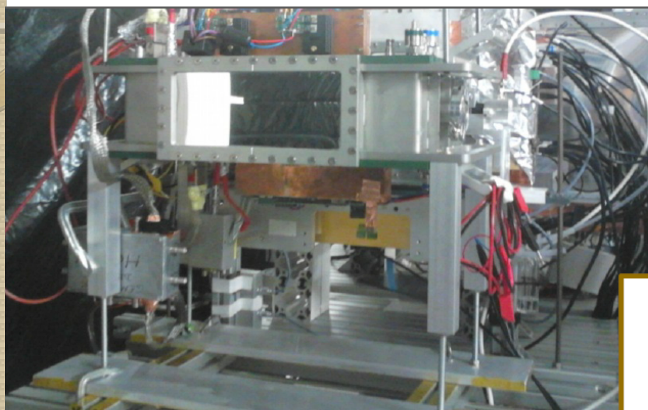
Monte Carlo simulations (MOCADI)

Yields not scaled

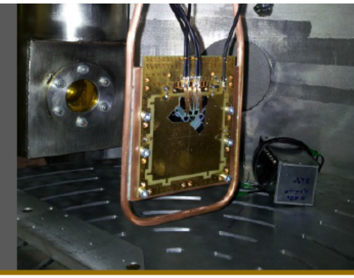
- **Increasing intensity of produced radioactive beams** requires detecting system with high-rate capability

C. Nociforo, NUSTAR Week 2015

Particle detectors for Super-FRS



Twin GEM-TPC
(x, y)
Partner:
Helsinki IP

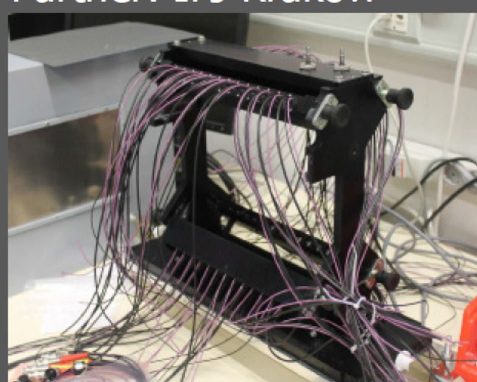


Silicon
(ToF, ΔE)
Partner:
IOFFE PTI St. Petersburg

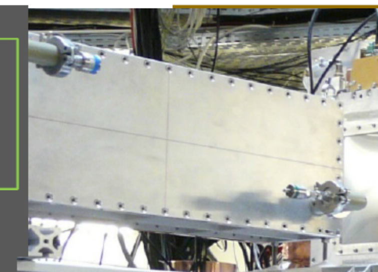
$Z \leftarrow -dE/dx = \mathrm{f}(Z, \beta)$ atomic number

$A/Q = \dfrac{B\rho}{\gamma\beta m_u}$ $Z \neq Q$ charge state

Segmented plastic scintillator (ToF)
Partner: IFJ Krakow



Bρ – ToF – ΔE method



Triple MUSIC
(ΔE)
Partners: CEA, Helsinki IP

Other diagnostics (ToF, intensity, x, y)

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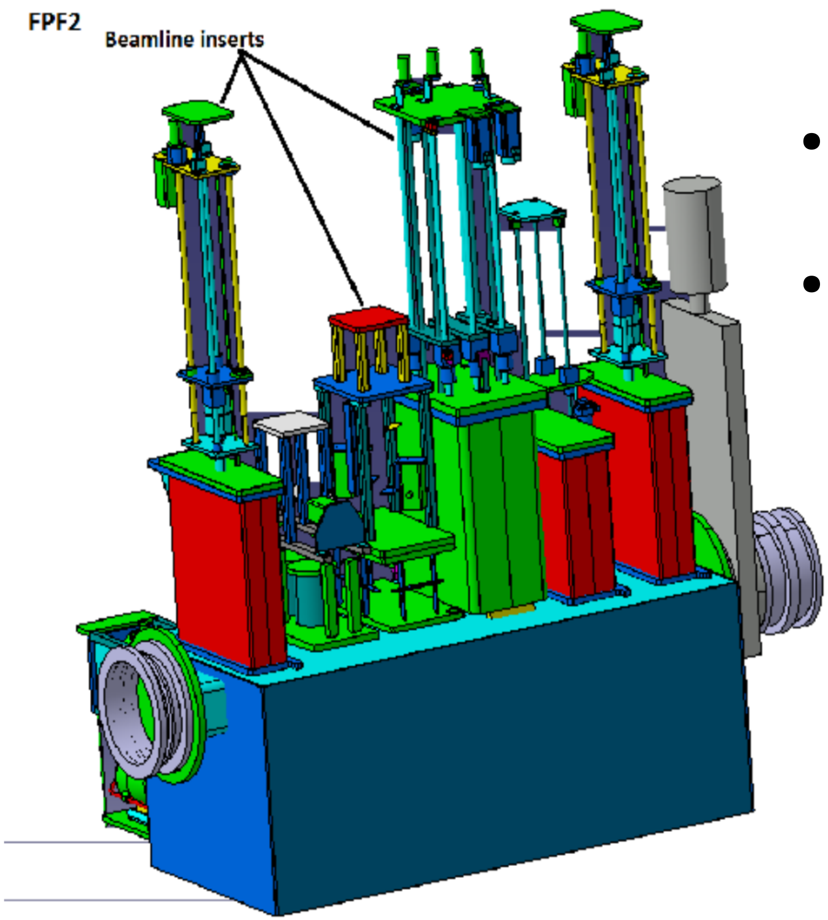
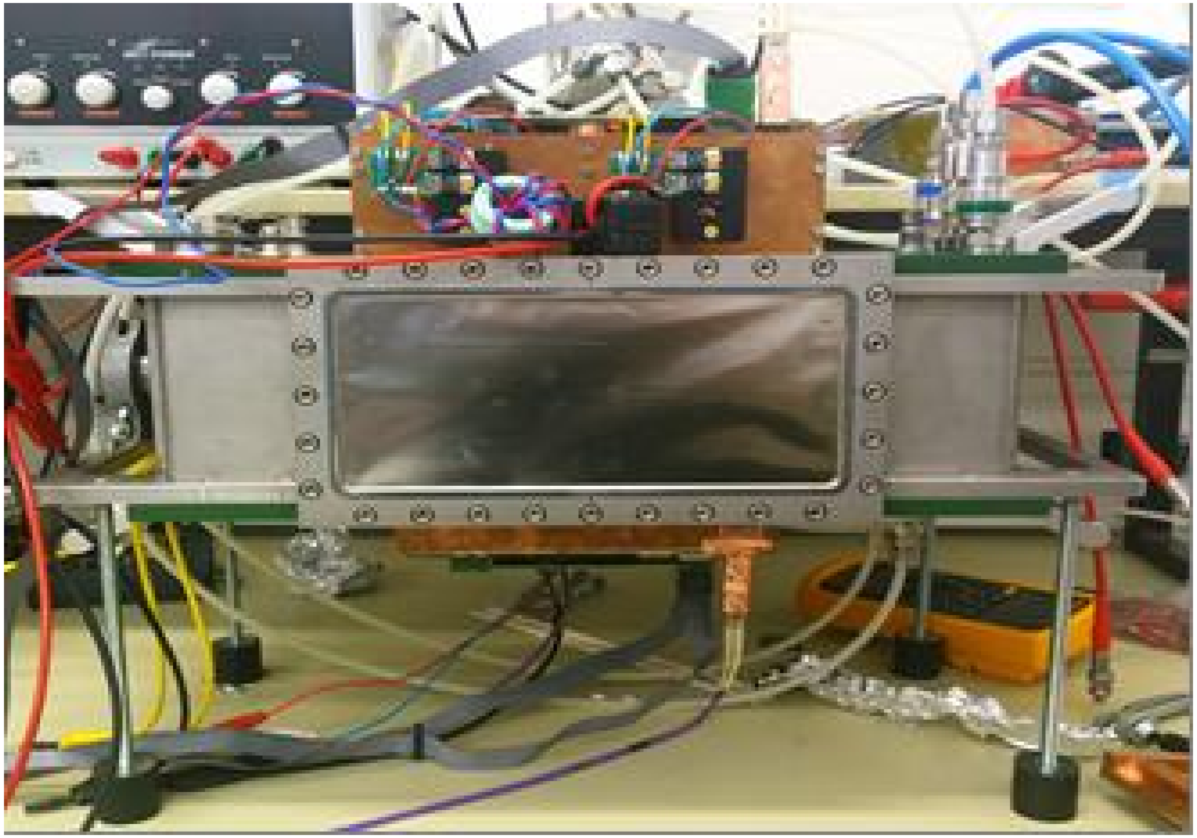
Mounting and handling of the detectors at Super-FRS



- In preseparator – only robot handling
- In main separator – only standard ports and connections

Twin GEM-TPC

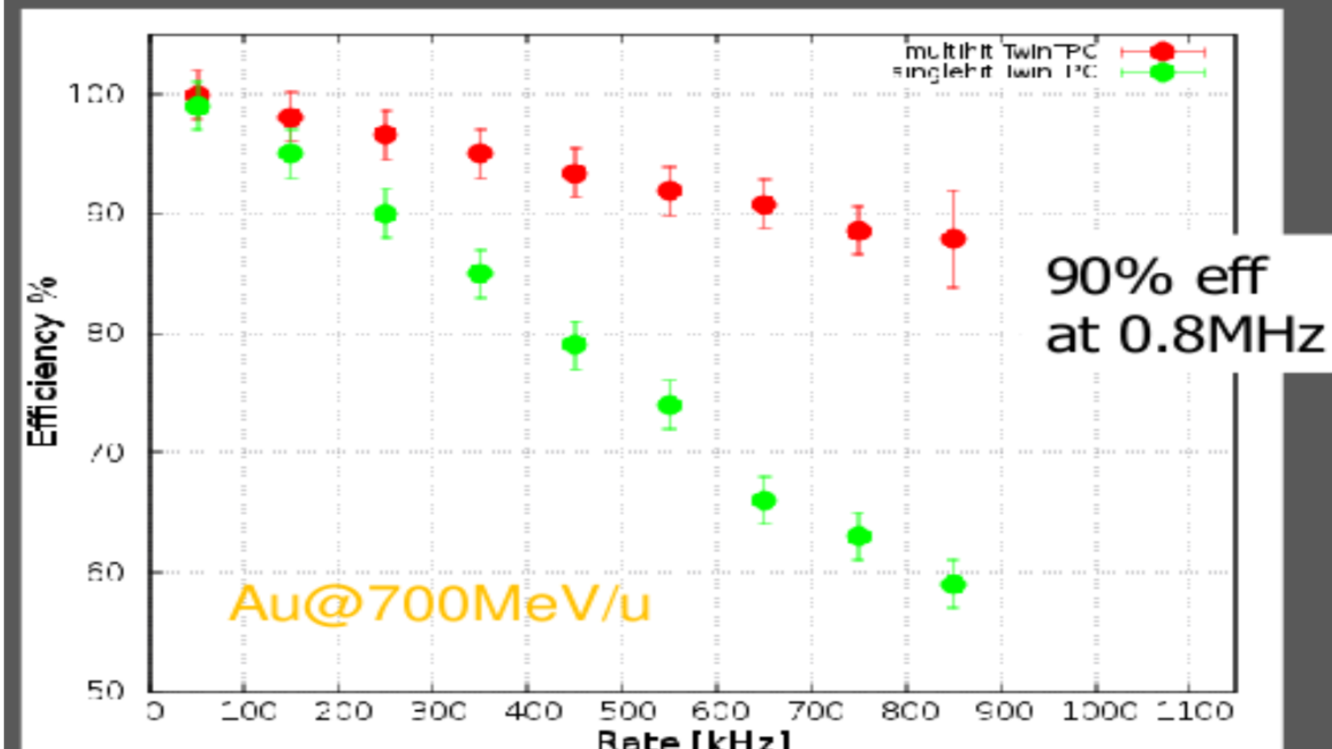


Coordinate Measurement
Size 200x70x30 mm
Ar/CO_2 gas, 1 bar

GEMEX readout for the coordinates, position resolution – 100-150 µm

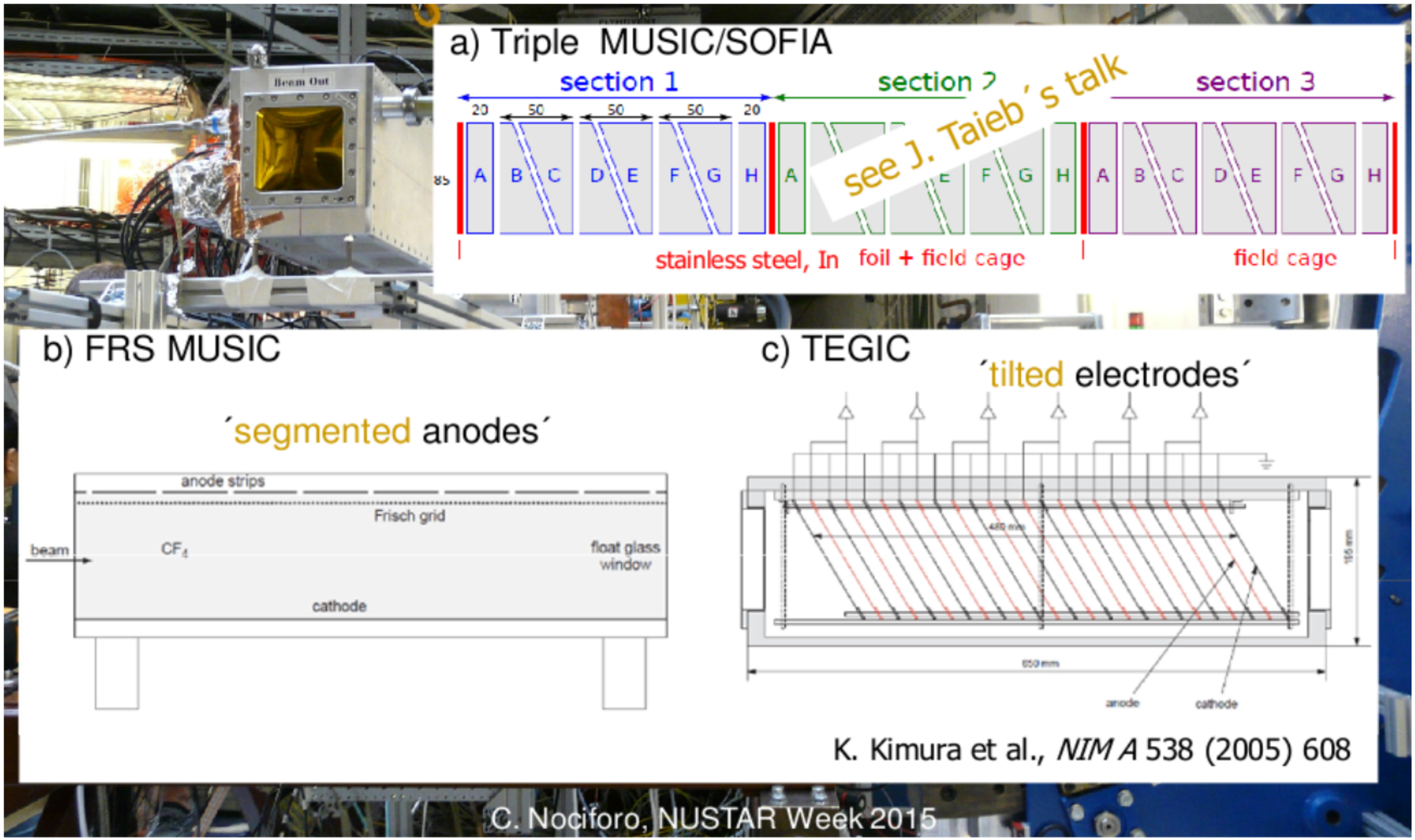
Twin GEM-TPC

- Delay line, multi-hit TDC (V1290) readout



A. Prochazka et al., *GSI report* (2014)

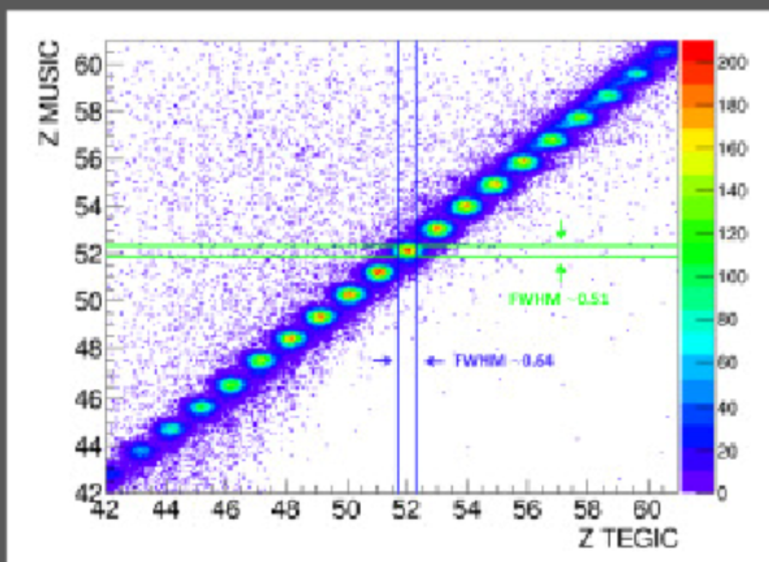
MUSIC for energy loss measurement

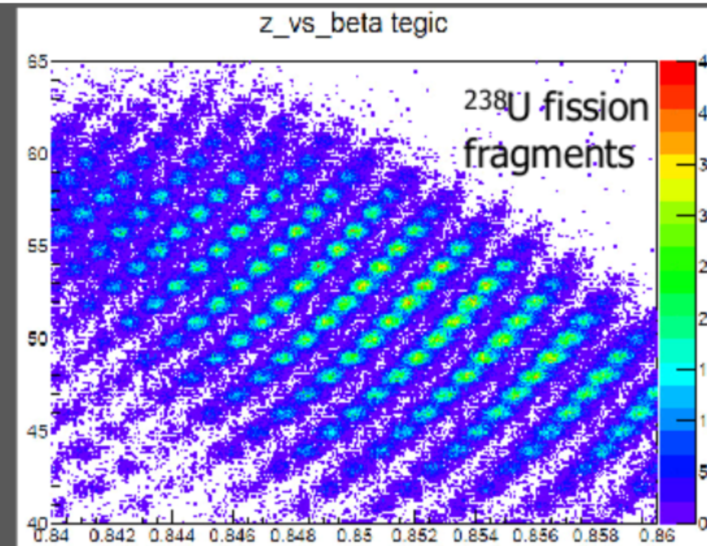


Comparison of TUM vs TEGIC prototype

March 2014

- anodes: 30° tilted and ´segmented´
- P10 gas at 1 atm
- readout FEBEX3a (ADC pipeline)





- Z resolution comparison in the Sn region at 700 MeV/u

$\Delta Z_{TUM} \sim 0.8\ \Delta Z_{TEGIC}$

S. Maurus, R. Gernhäuser et al., *GSI report* (2014)

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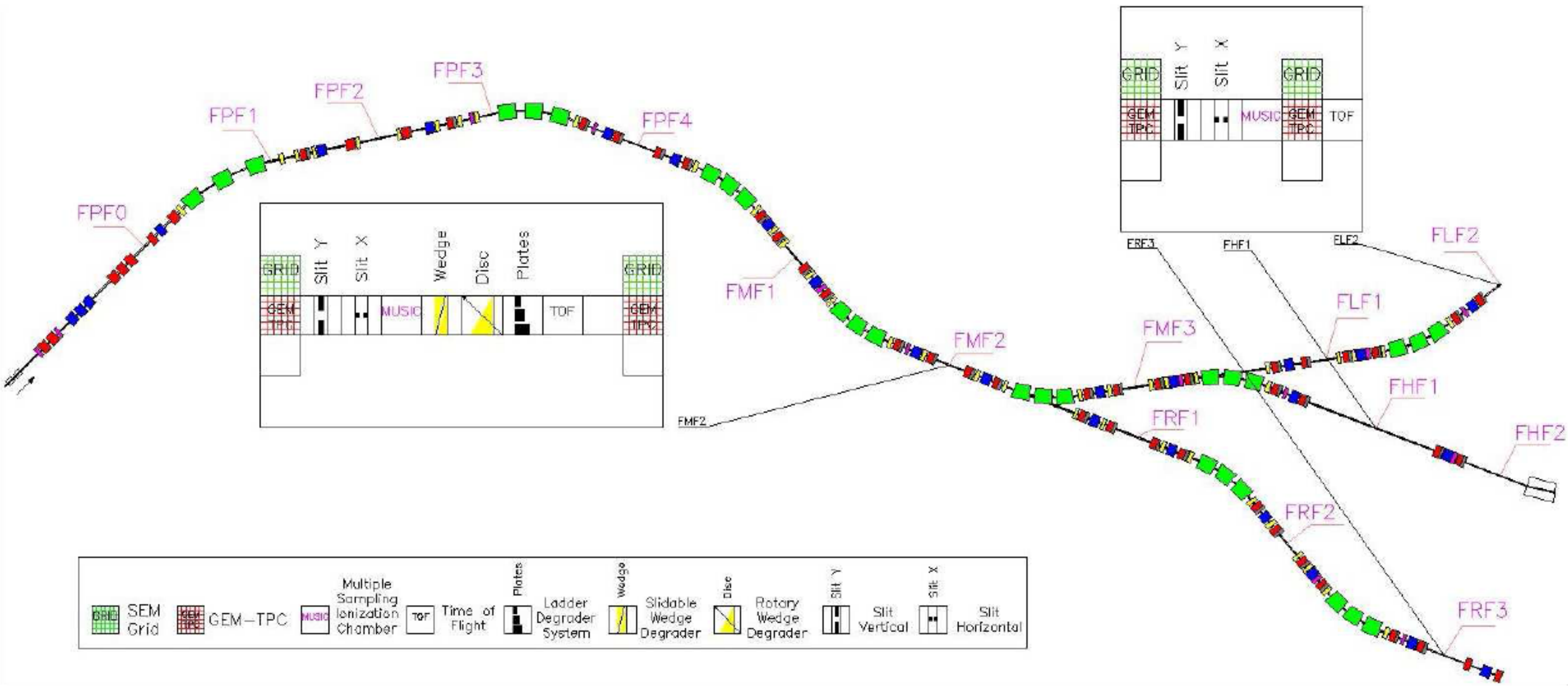
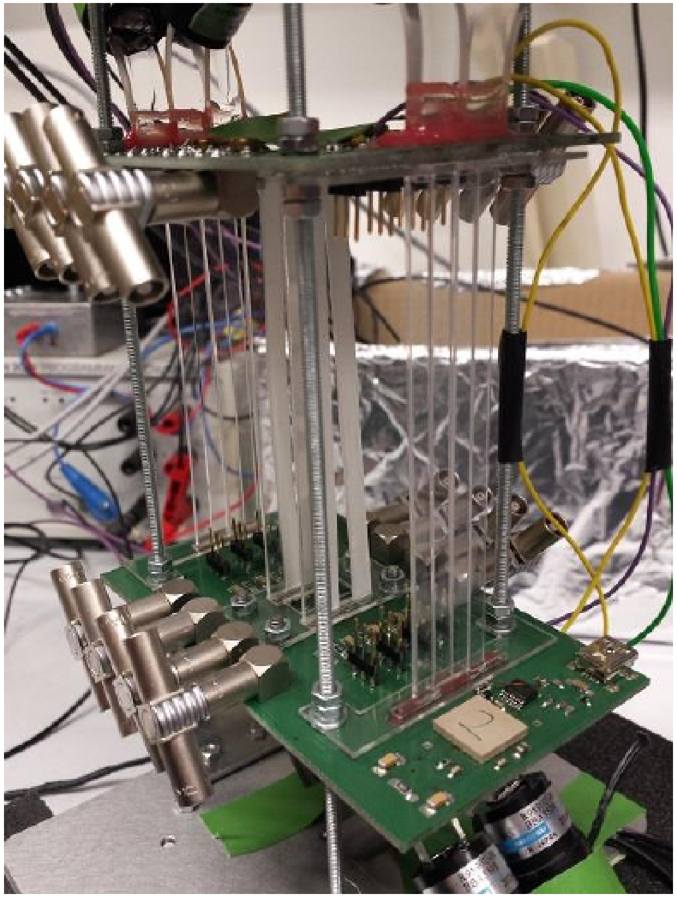
TOF measurement at Super-FRS



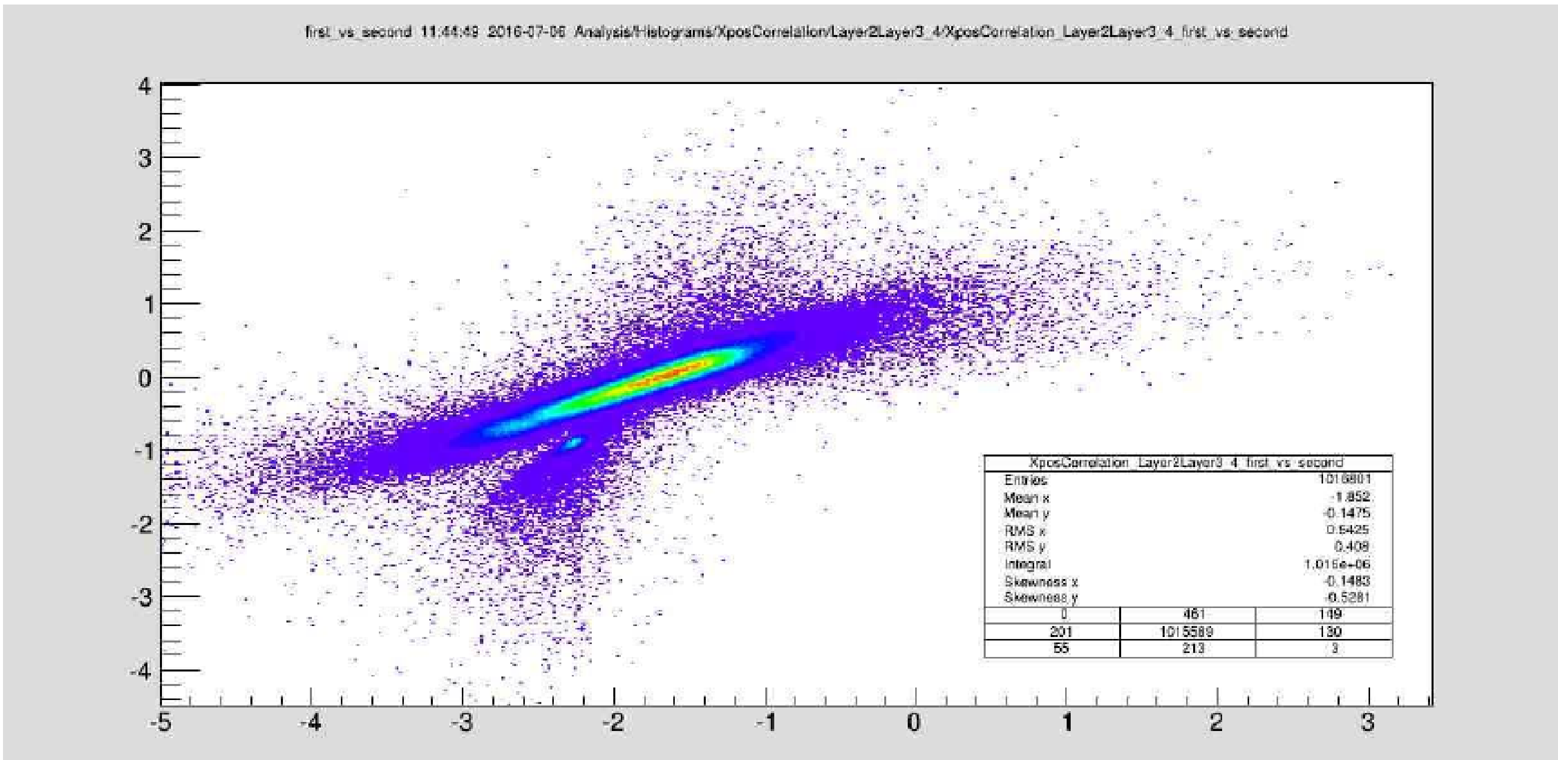
- TOF stations FMF2, FLF2, FHF1, FRF3
- Ion rate up to 50 kHz per cm^2
- Time resolution – 20-35 ps (σ)

TOF scintillator detector



- 51 strips, 4.4 mm wide
- BC420 scintillator
- PMT Hamamatsu R9880U-01
- Time resolution ~70 ps
- Development on the basis of existing detectors at FRS
- Higher segmentation to reduce an occupancy
- Faster electronics
- Detector for a Low Energy Branch (HISPEC/DESPEC)

TOF scintillator detector



First tests at GSI with Xe @ 600 MeV
Data analysis in progress

Motivation: Cherenkov Radiation

Cherenkov radiation (ChR) – is an electromagnetic radiation emitted when a charged particle passes through a medium at a velocity greater than the phase velocity of light in that medium: $v > c/n$ is emitted at a specific angle ϑ_C with respect to the strait-line trajectory (or to velocity direction).

Cherenkov angle: $$\theta_C = \arccos\frac{c}{nv} = \arccos\frac{1}{\beta n}$$

The number of Cherenkov photons created at threshold velocity $\beta = 1/n$

$$\Delta N_{Ch.p} = \frac{2\pi}{137} z^2 \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{n(\lambda)^2 \beta_0^2}\right) \frac{d\lambda}{\lambda^2} \Delta x$$ (including energy loss in the radiator)

Altapova V.R., Bogdanov O.V., Pivovarov Yu.L.,
NIM B 256 (2009) pp.109-113

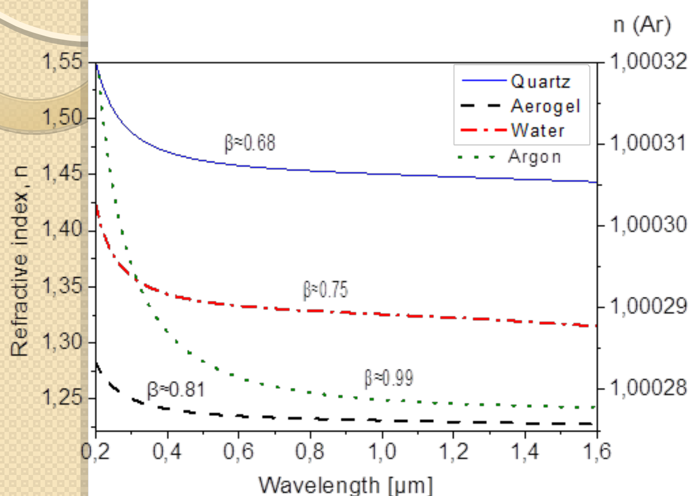
Cherenkov light is a prompt event and therefore ideal for timing

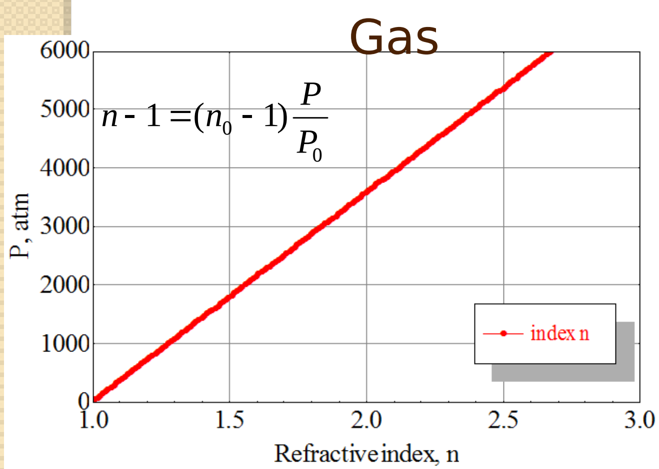
At Super FRS @ FAIR:

heavy ions at E=100 MeV/u÷1.5 GeV/u → β=0.4295 ÷ 0.9237

Required material with high reftactive index n!

Material for Cherenkov Radiator: Solid, Liquid or Gas?





Pro

Solid:

- Manufacture with difference dimensions
- High transmission of Cherenkov photons: (> 90% for SiO_2) in UV range

Liquid:

- High number of Cherenkov photons
- easy to refresh via circulation to prevent degradation of the performance
- operation under room temperature
- low cost

Gas:

- High number of Cherenkov photons
- easy to refresh via circulation to prevent degradation of the performance
- Small energy loss

Contra

Solid:

- Particle rate resistance, Cooling system required

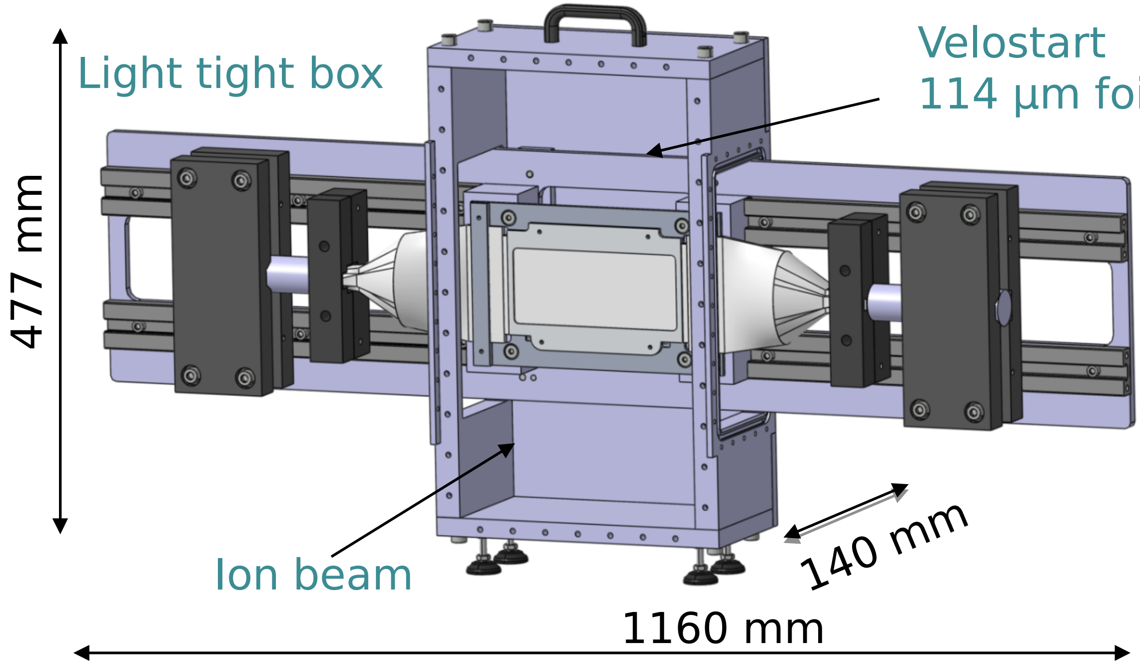
Liquid:

- With > n increases toxicity, presence of color centers and viscosity

Gas:

- very low refractive index: $n_{typ.}$=1.0003 (β≈0.99)
- Pressure dependency of n

Prototype Design



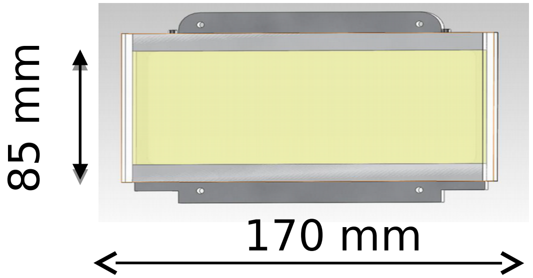
Iodine Naphthalene ($C_{10}H_7I$):

n_D =1.7001 @ 589 nm

ρ=1,738 g/cm^3

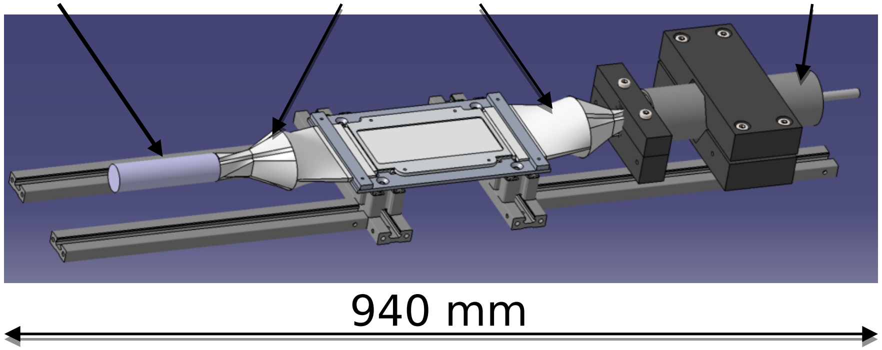
ρ_A = 347 mg/cm^2

Cuvette with Iodine Naphthalene

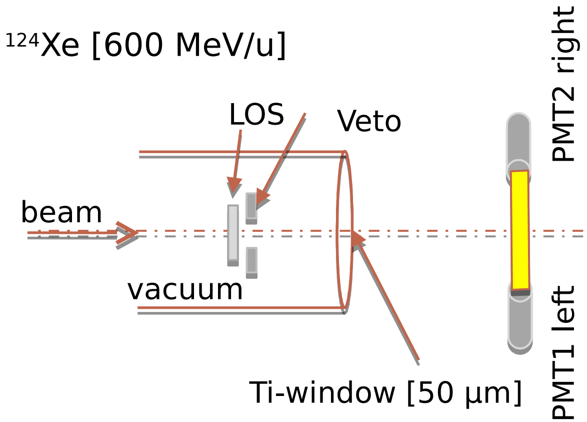


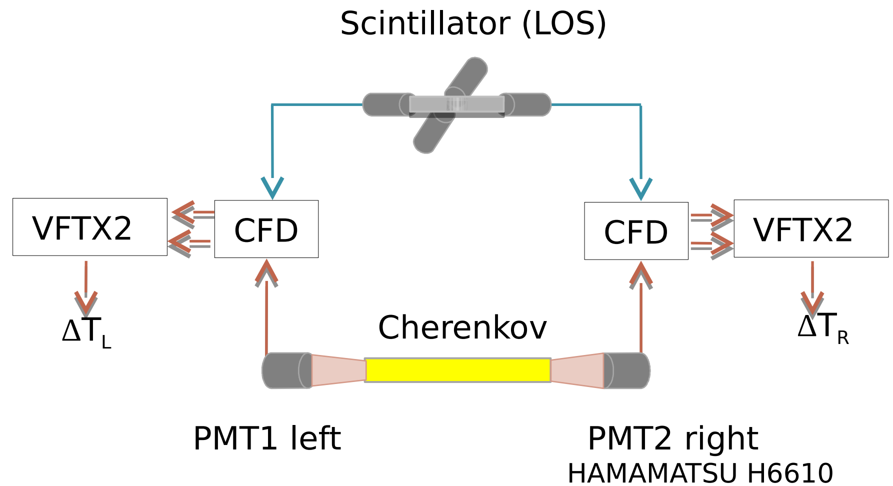
Coating: 0.15 µm of Al

PMT 1 Light guides PMT 2

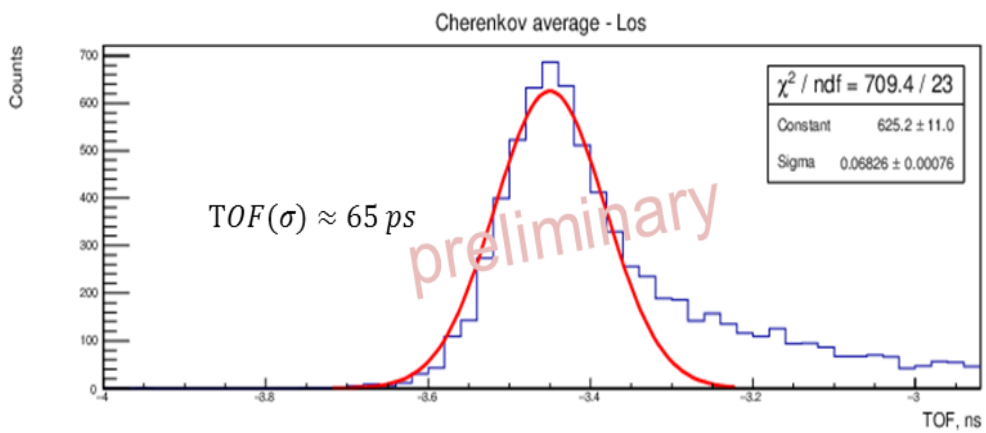


TOF Measurements with ^{124}Xe ions





Time-of-Flight spectra



$$\Delta T_{LOS} = \frac{T_{up} + Tdo_{wn}}{2} - \frac{T_{left} + Tri_{ght}}{2}$$

$$< T_{LOS} >= \frac{T_{up} + Tdo_{wn} + T_{left} + Tri_{ght}}{4}$$

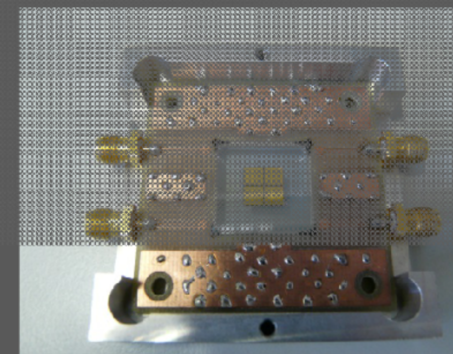
$$\Delta T_{Ch} = \frac{\Delta T_L + \Delta T_R}{2} - < T_{LOS} >$$

Diamond detectors for TOF

February 2014

First test of (E6) pcCVD-DD samples at ACCULINNA separator with 40.5 MeV/u ^{40}Ar beam

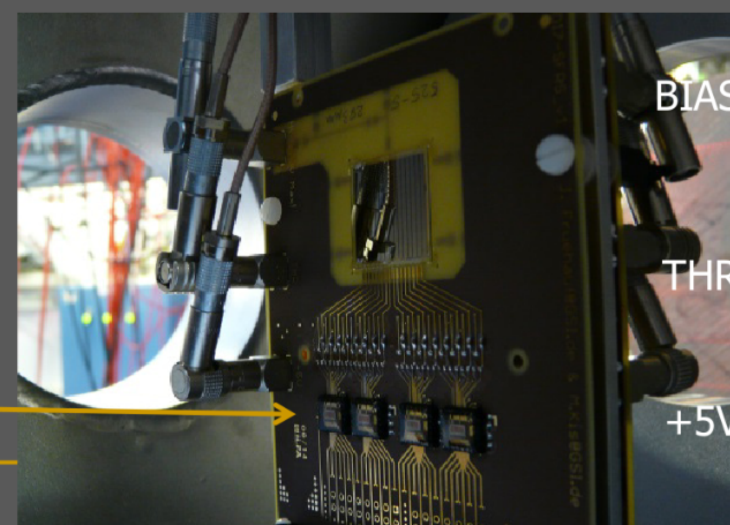
- 4 Al contacts, ΔE~20-600 MeV (DBA amp, V_{in} < 50 mV)
- total rate 10^{11} ions/cm^2 , test with α particles



August 2014

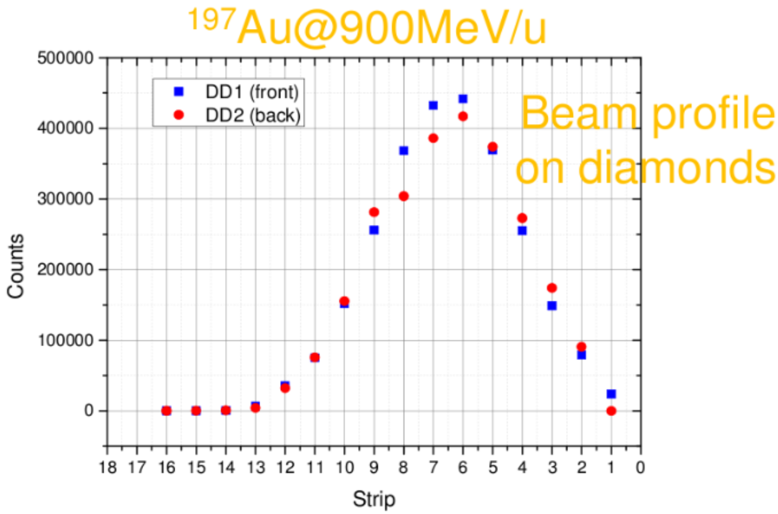
First ToF measurements at FRS with 900 MeV/u ^{197}Au beam with (E6) pcCVD-DD 20x20x0.3 mm^3

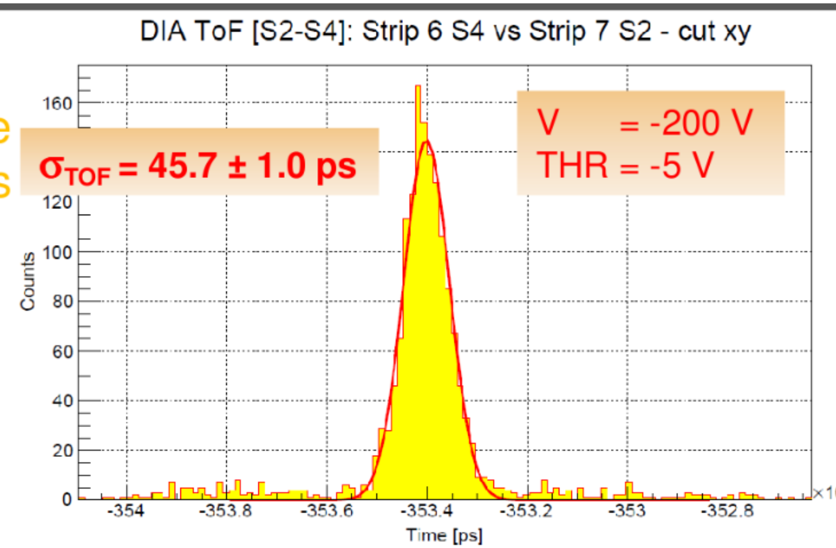
- 16-strip design: (1x18) mm^2 each (0.15 mm gap), C = 4.3 pF/strip
- metallization: 50nm/100nm (Cr/Au) by photolithography (GSI-DL)
- PADI7, gain ~250, 4x4chs



C. Nociforo, NUSTAR Week 2015

Diamond detectors for TOF





S2-S4 Detector resolution

F. Schirru et al. , *GSI report (2014)*

$$\sigma_{DD} = \sqrt{\sigma_{ToF}{}^2 - \sigma_j{}^2} = \sqrt{(45.7)^2 - (15)^2} = 43.2 \text{ ps}$$

$\sigma_{intr,DD1}$=25 ps

$\sigma_{intr,DD2}$=35 ps

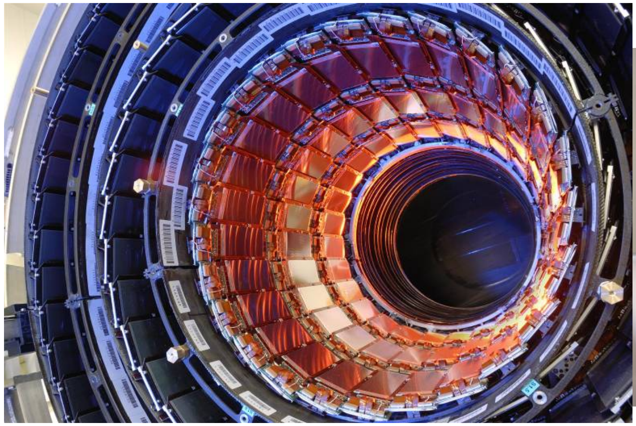
Measured PADI/VFTX intrinsic time resolution: 15 ps (σ)

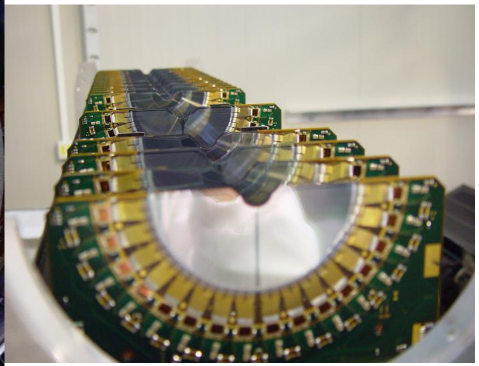
C. Nociforo, NUSTAR Week 2015

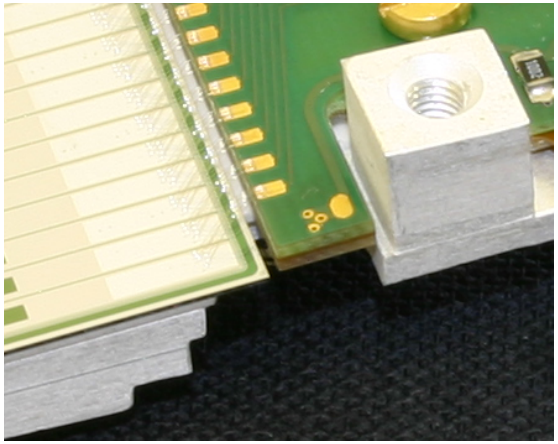
Si detectors in High Energy Physics

- FNAL. D0 & CDF
- BNL. STAR & PHENIX
- LHC. CMS, ATLAS, LHCb, ALICE
- AMS + other astrophysical experiments

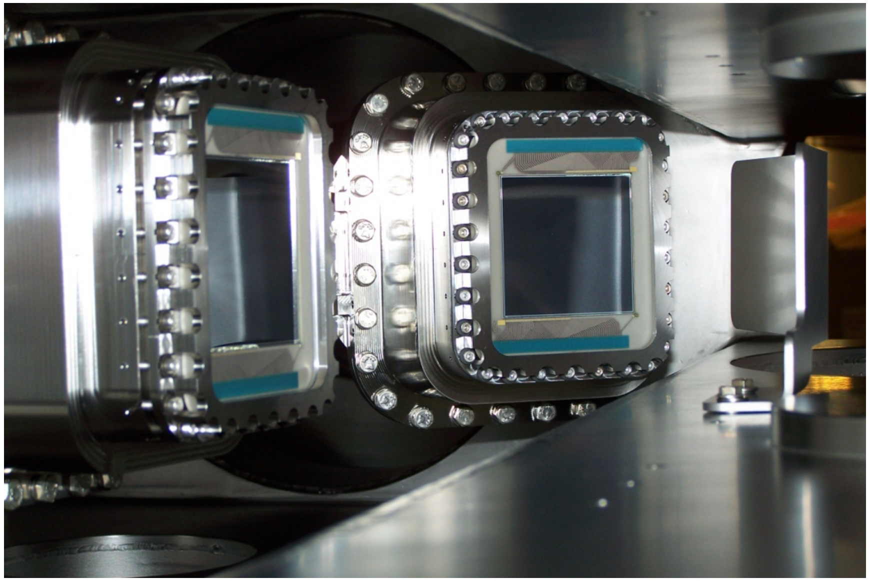
Driving force of almost all Si detector developments

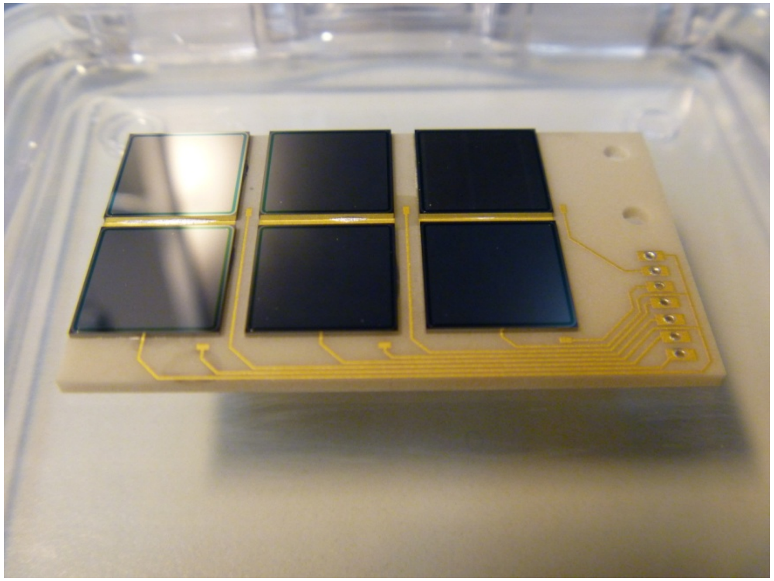






“Special” applications of Si detectors in nuclear physics



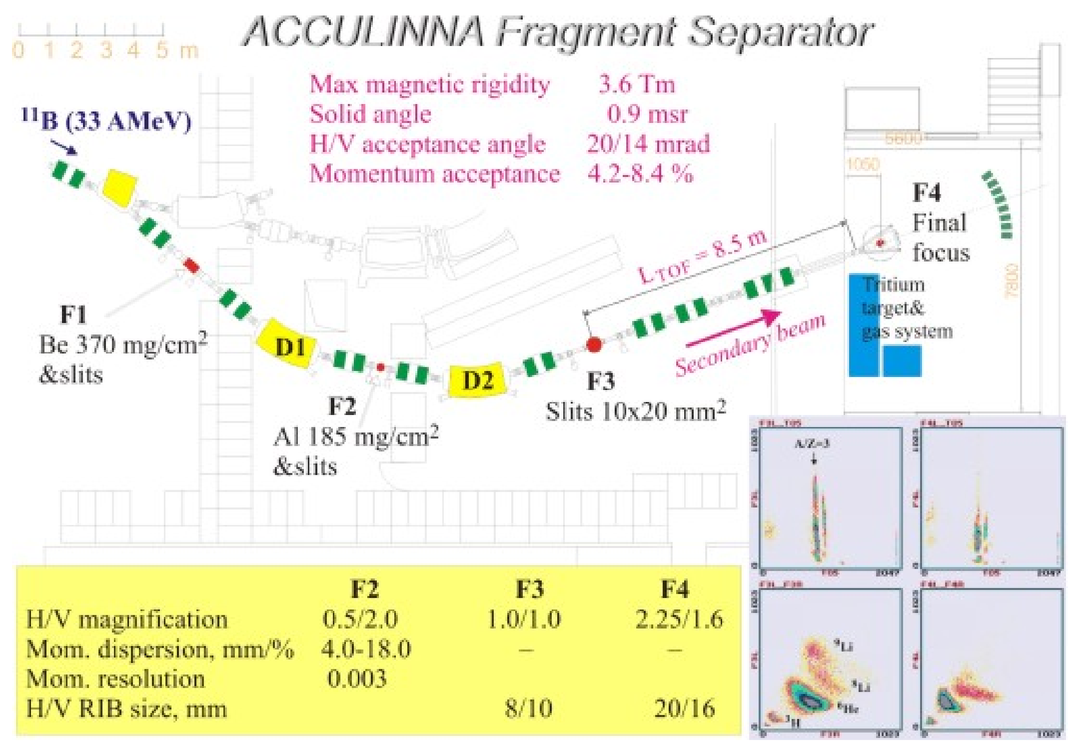


- Typically less precise position measurement – 0.1 - 1 mm instead of 10 – 50 μm
- Precise energy loss measurement – up to 0.5%
- Much higher dynamic range – up to 1000 MIPs
- Less event rate
- Time measurement

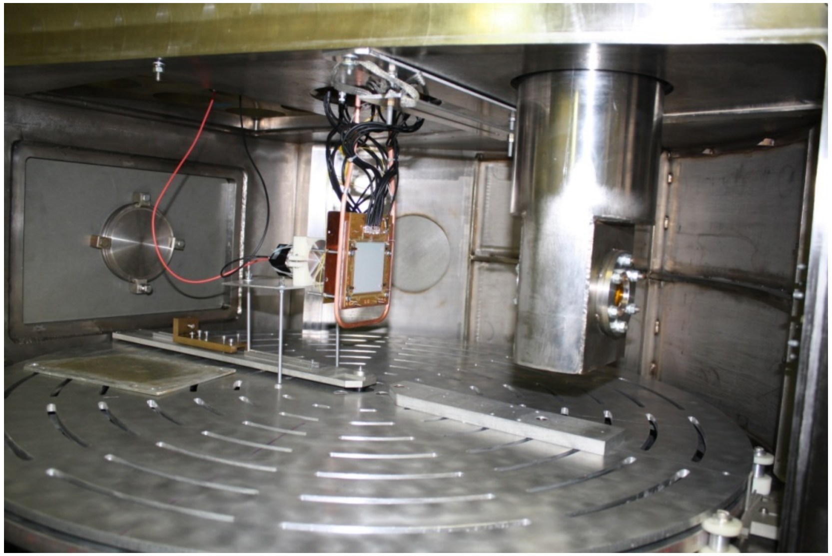
Beam tests of Si TOF detectors at JINR

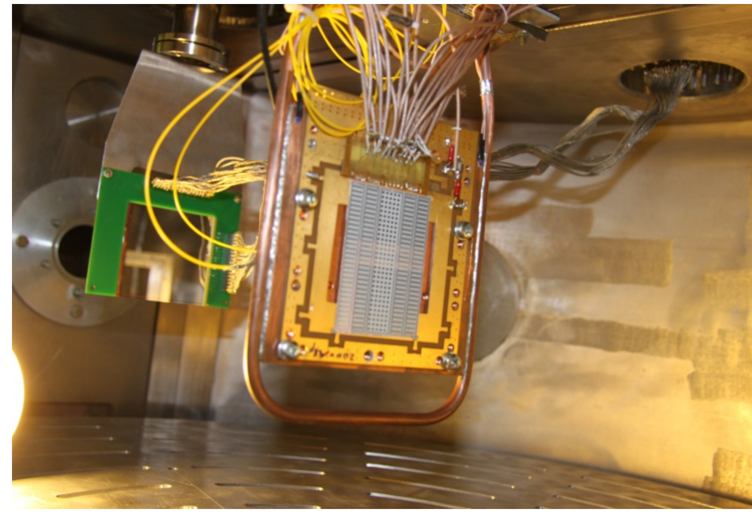
- Test of time resolution with fast electronics
- Check performance change under heavy irradiation
- Compare Si detectors with different topology

^{40}Ar @ 40.5 MeV/u
^{32}S @ 50 MeV/u
Intensity – up to 2*10^{9}/s



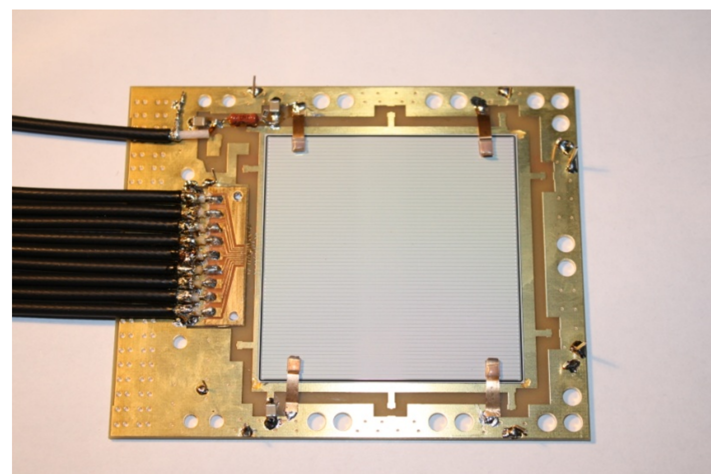
Experimental setup at JINR



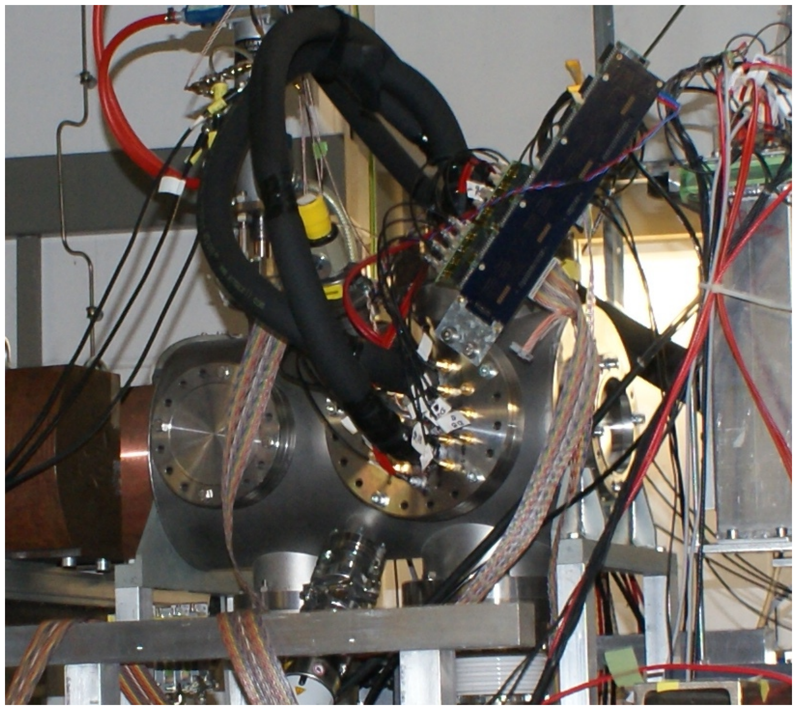


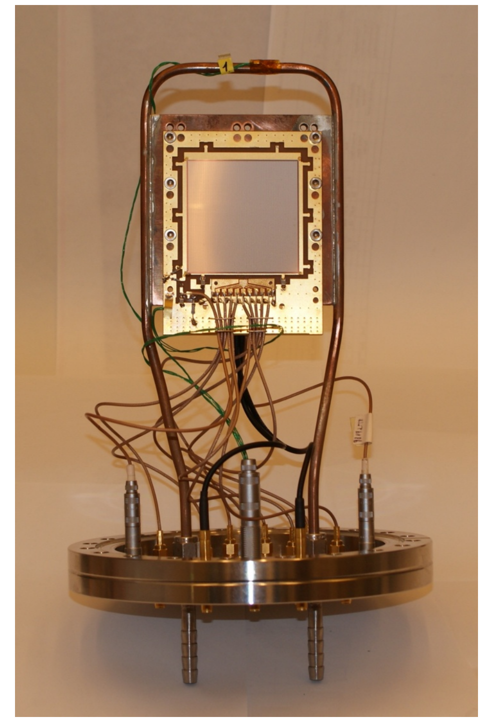
- ACCULINA fragment separator after U400 cyclotron
- Scattering chamber/final focal place F4
- Trigger scintillator + MWPC (beam tracking)
- Full-size (40 cm^2) Si detector tested
- Accumulated dose – up $6*10^{12}$ ions/cm^2

Si detectors made in St. Petersburg, Russia



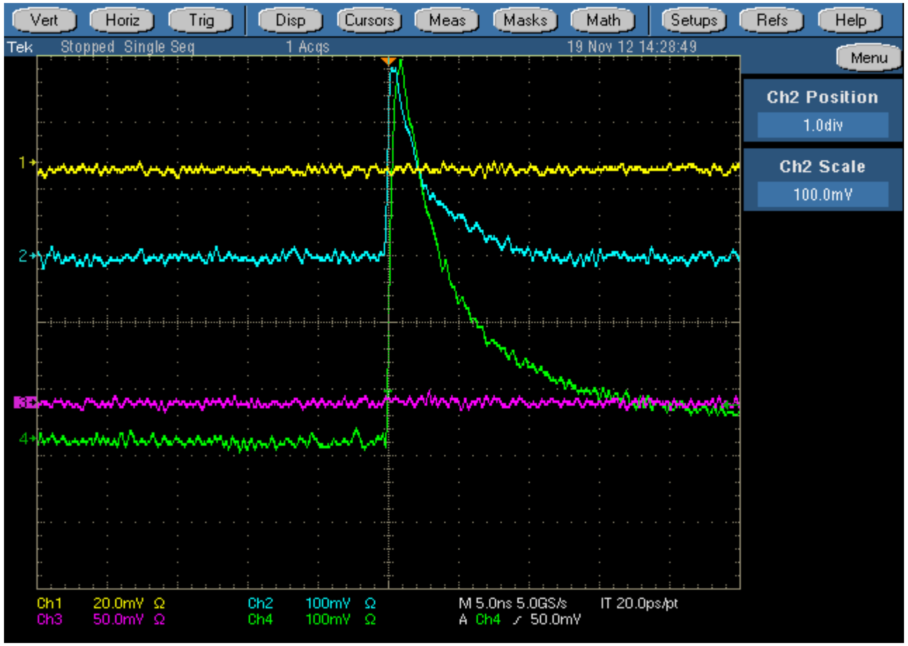
Experimental setup at GSI





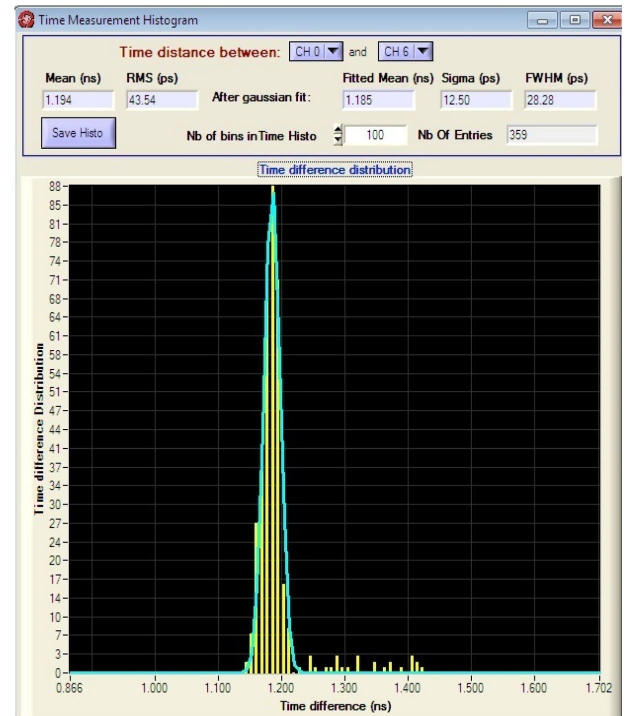
- S4 focal area of FRS
- ^{197}Au @ 1 GeV/u beam
- DAQ 1: Fast current amplifiers/discriminators + FPGA TDC
- DAQ 2: Waveform digitizers (3.2 Gs/s and 5 Gs/s)

Example of the signal shapes



- Signals from U, Au ions can be digitized without amplification
- Digitized signals hold all information – amplitude, charge, timing
- Sampling should be very fast – 3-10 Gs/s due to a fast rise time (0.3 – 1 ns)

Time resolution with the fast digitizers

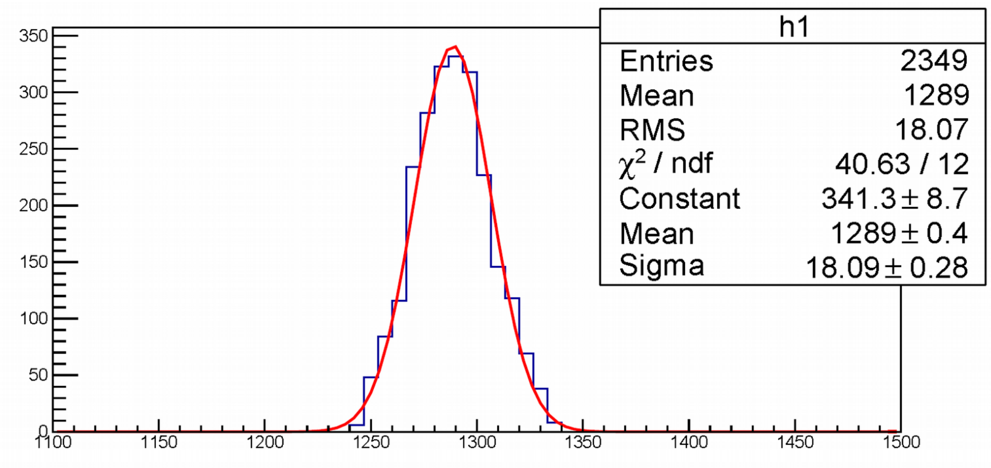


- CAEN 5742, DRS4 chips inside, 12 bit ADCs
- CAEN 5743, SAMLONG chips inside, 12 bit ADCs
- Digitised waveforms - ΔE, pile-up rejection possible
- Spline fitting, CFD method for time determination
- **ΔT (TOF) = 13 ps (σ)**

Event rate < 5 kHz

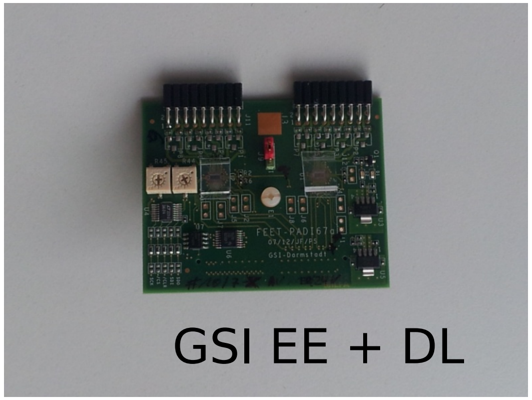
O. Kiselev at al., GSI Scientific Report 2014 (2015) 137

Time resolution with PADI/VFTX2

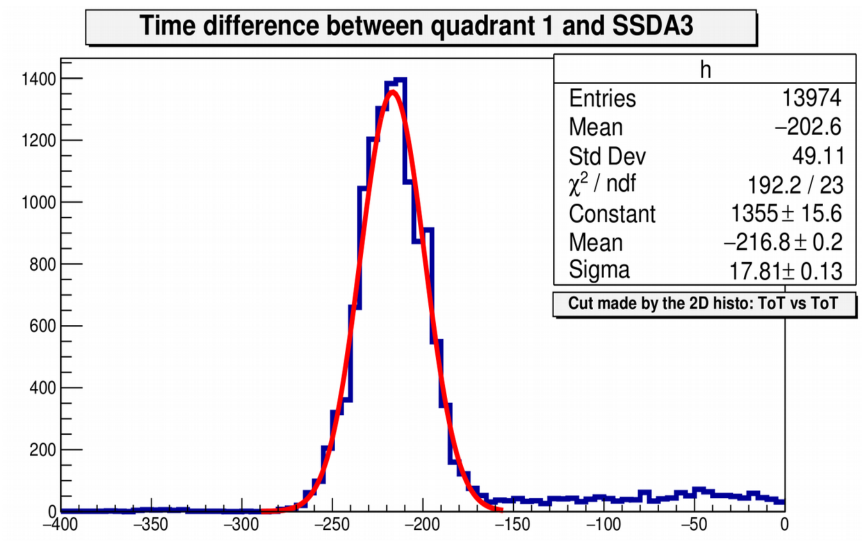


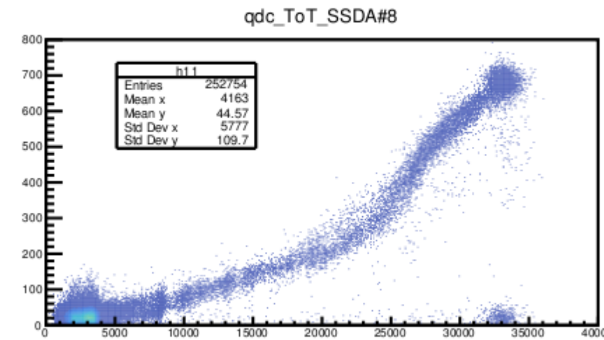
U beam @ 1 GeV
GSI, FRS, Aug. 2014

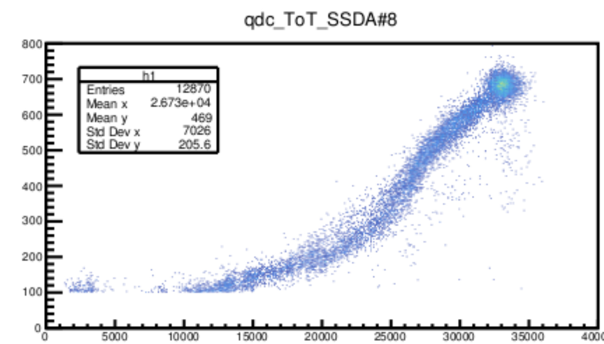
- PADI current amplifier/discriminator
  (10-15 ps internal resolution)
- VFTX2 FPGA TDC – 28 channels, 7 ps resolution, up to 1 MHz/channel
- Leading edge method with ToT measurement
- **ΔT (TOF) = 18-20 ps (σ)**
- Only possible method for high event rates

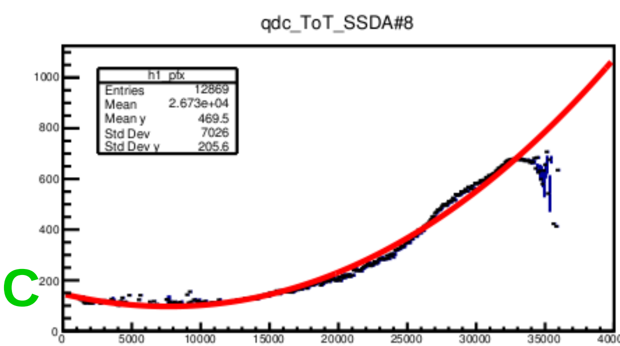


Time resolution with PADI/VFTX2







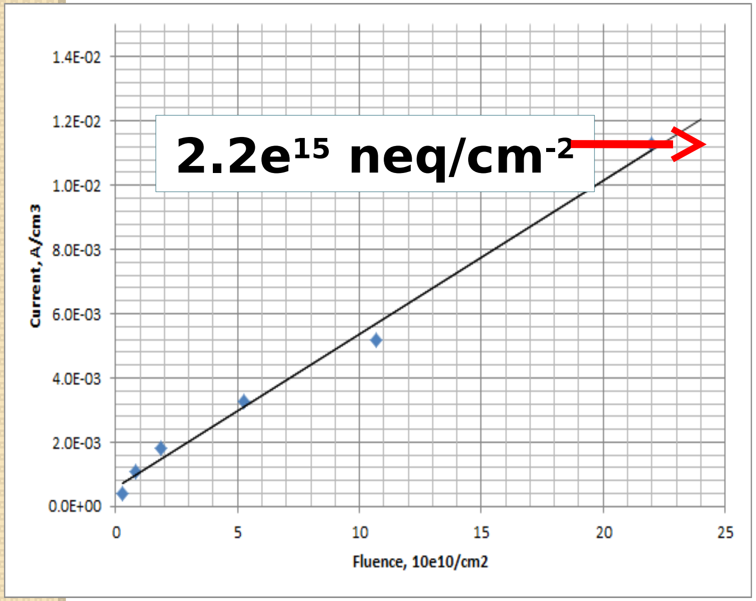


Xe beam @ 600 MeV
GSI, Cave C, June 2016

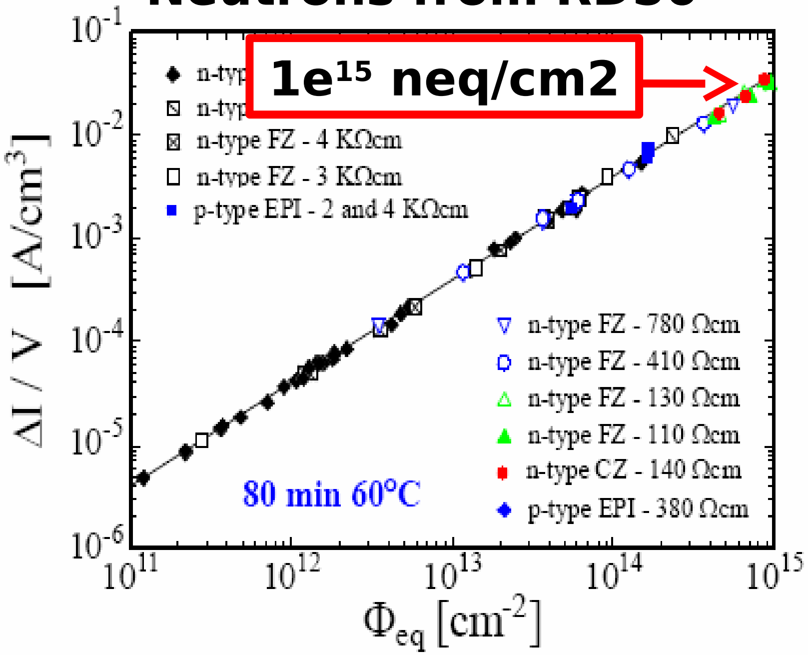
Time resolution for Ar, Xe, Au, U beams down to 17 ps
ToT useful for walk correction
Energy measurement in addition to MUSIC
Position resolution ~1 mm (strip size)

Current generation in Si P-i-N detector at 300K, irradiated by Ar

Ar ions, experiment



Neutrons from RD50



300 K

α(ions) = dI/V dF = $1.1e^{-2}/22*10e^{10}$ = $5e^{-14}$ A/cm

α(neutrons) = dI/V dF = $4e^{-17}$ A/cm

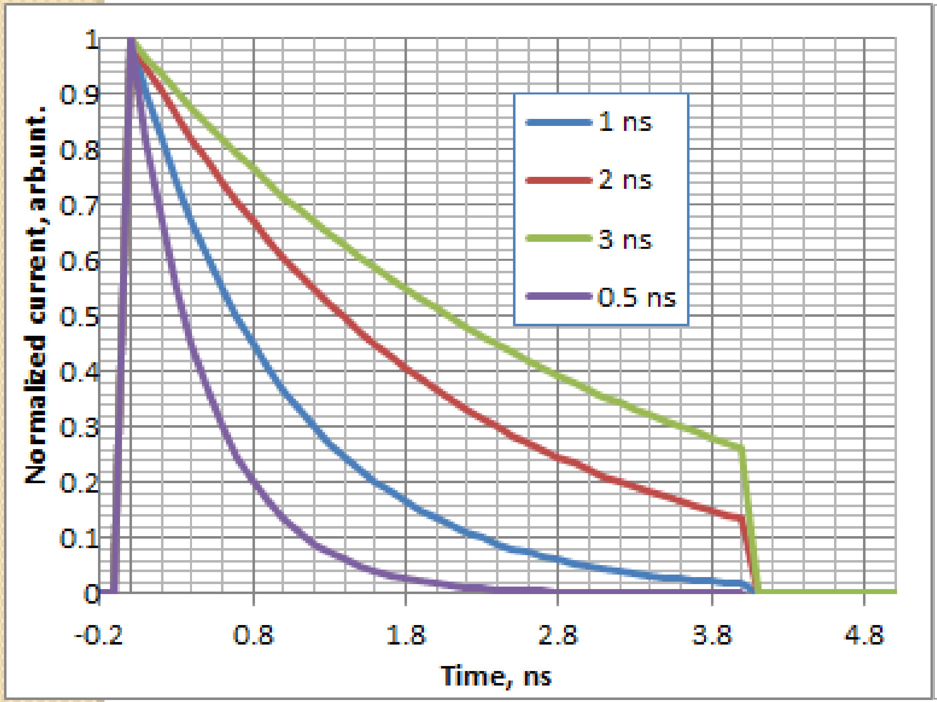
$1e^{12}$ ions /cm² >>>>>> $1e^{15}$ neq/cm²

250 K

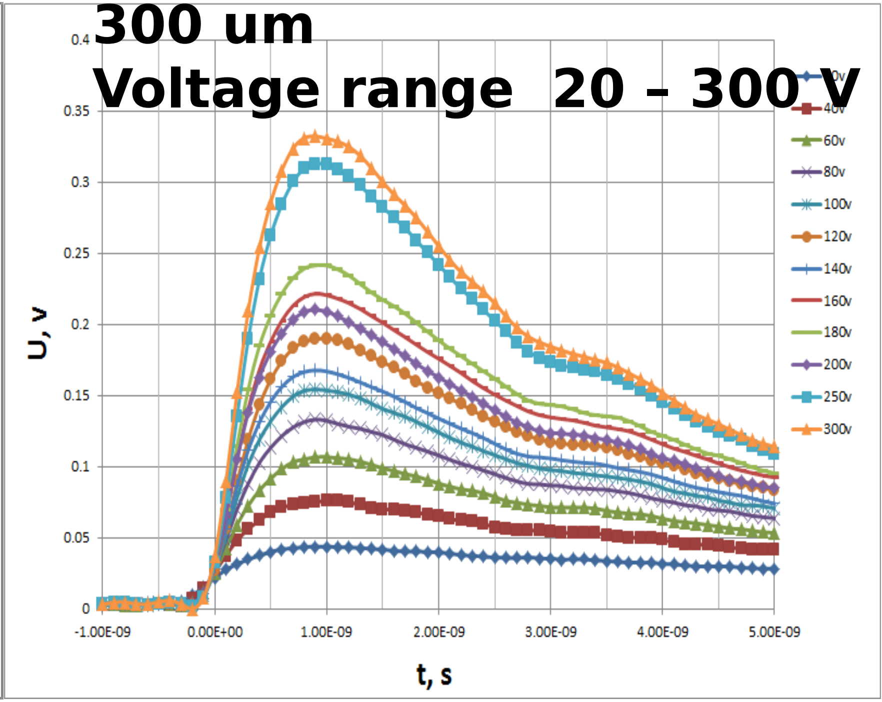
α(ions) = 1.5 e^{-15} A/cm
Strip (50 mm²) ion fluence $1e^{12}$ cm^{-2}
Current < 10 μA
Negligible noise

Calculation of the signal amplitude

Simulated current pulses at different trapping time



Rising edge of current pulses
^{197}Au, E = 920 MeV/u
Detector thickness - 300 um
Voltage range 20 – 300 V



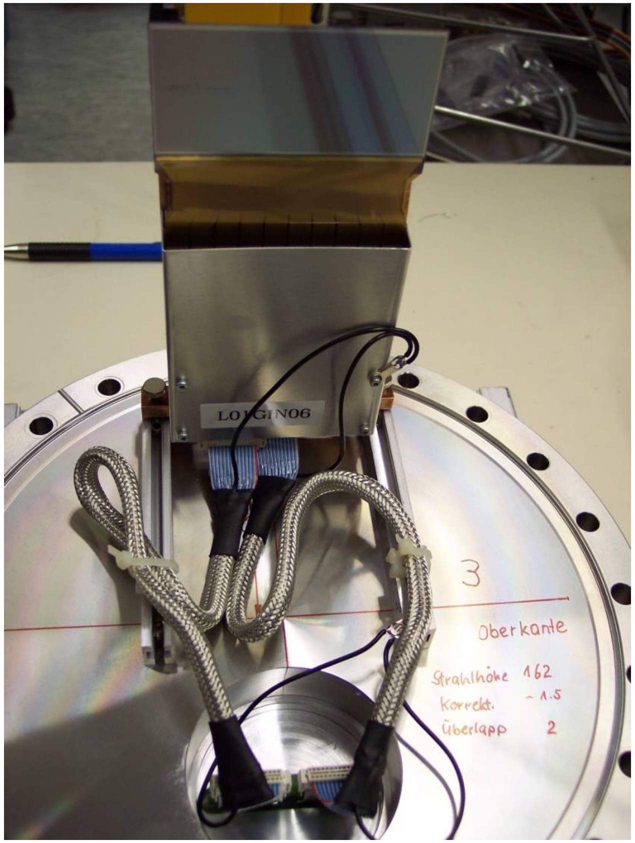
Amplitude of the peak current I_p
I_p at 1e^{12} ions/cm^2 = 1 - Tr/Ttr = 1 - 1ns/5ns = 0.8 (1ns – time of reaching maximum)

After 2.2*10^{11} ions/cm^2 10% degradation – reasonable agreement

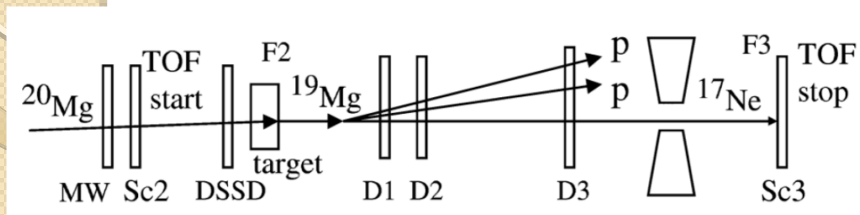
Si microstrip detectors for tracking of the fast ions and protons

- DSSDs, area 28 cm^2, 300 µm, 100 µm strip pitch
- Energy resolution ~ 1%
- Dynamic range – from p to Fe
- Very low energy dissipation of FE electronics (VAHDR9 ASICs, IDEAS) - work in vacuum without active cooling
- 1024 channels, multiplexed readout (event rate up to 10 kHz

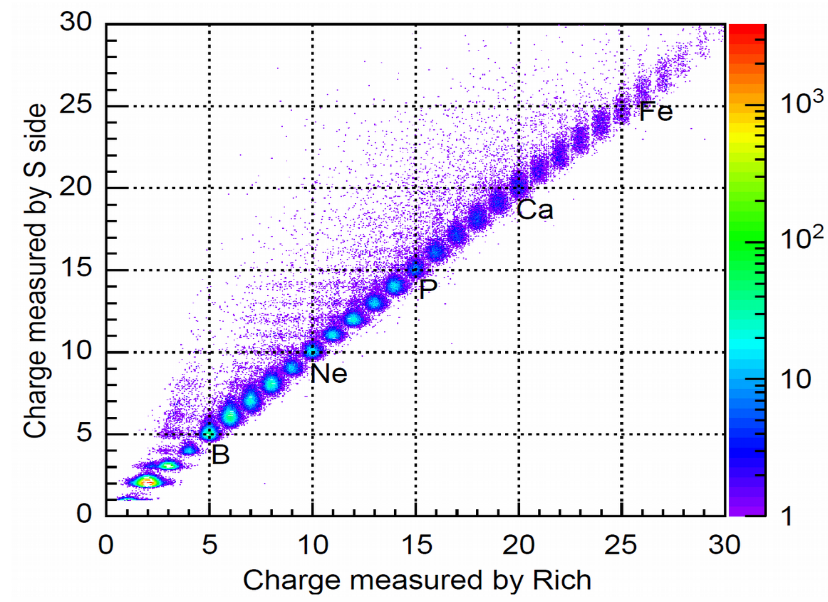
  per detector)
- ***Position resolution ~40 µm for protons, ~15 µm for ions***



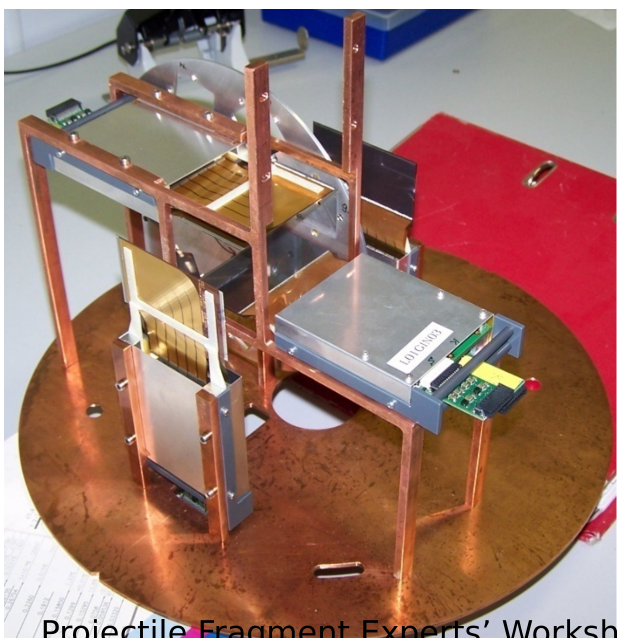
Precise tracking + spectroscopy



S271, S388 experiments at FRS, tracking of ions + protons
I. Mukha et al., PRL 99, 182501 (2007)
I. Mukha et al., PRL 115, 202501 (2015)

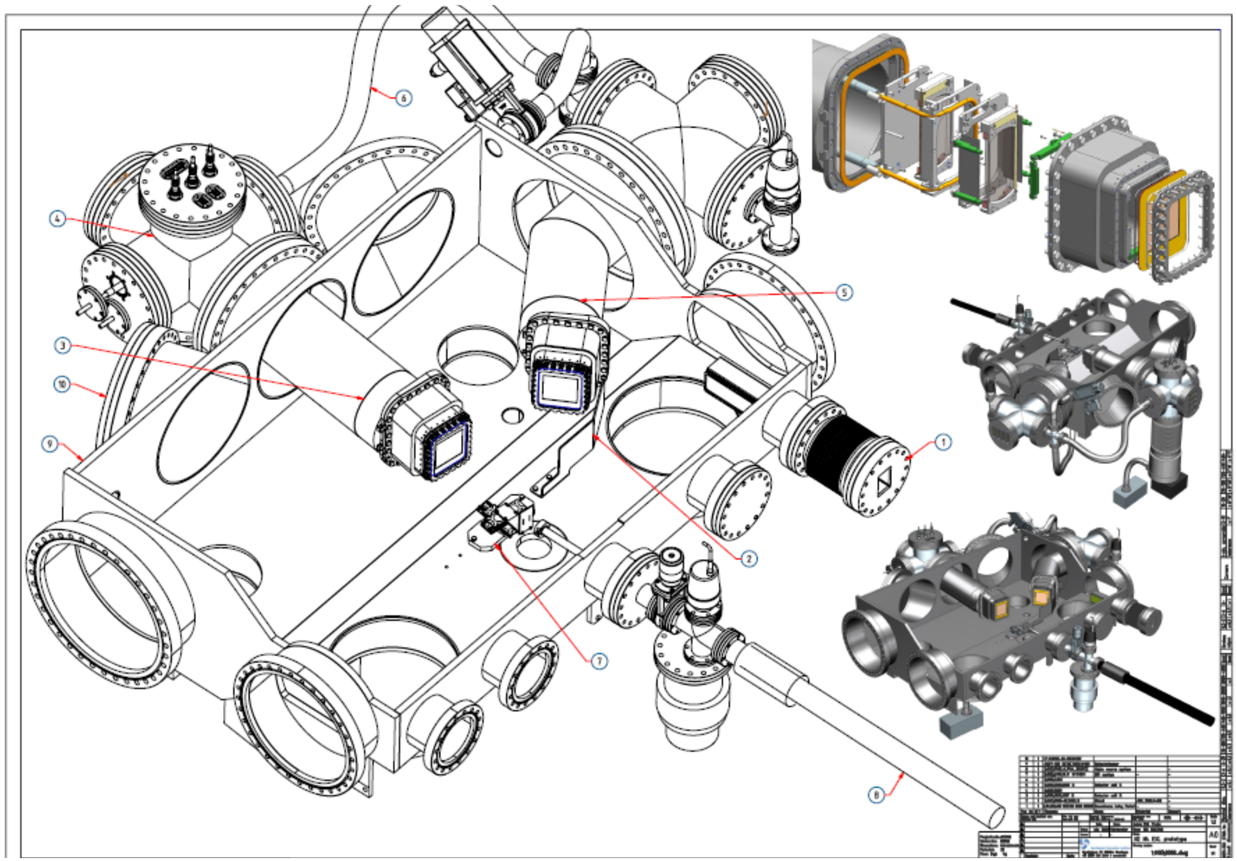


Si – RICH correllation (AMS data)



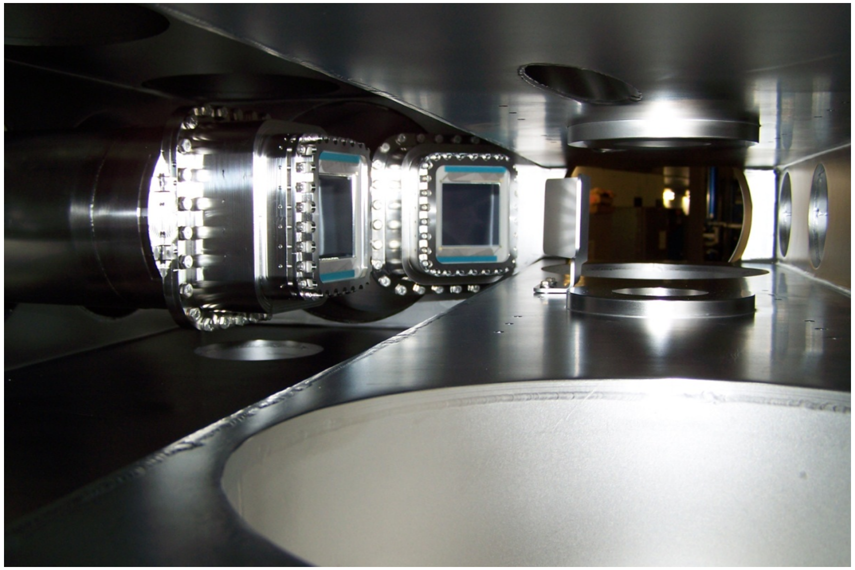
- C, P, Ne + p tracking and identification
- ***Key to success*** of 2p-radioactivity and QFS experiments

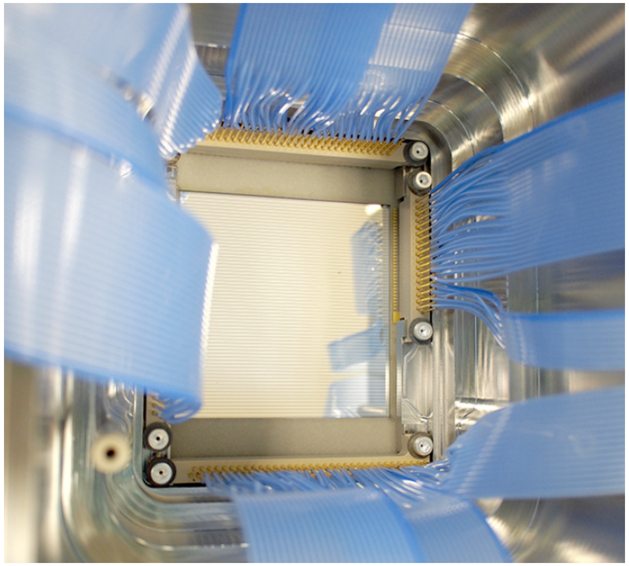
Tracking and spectroscopy for the storage ring experiments



- R&D and first experiments within EXL@FAIR project
- Successfully used in ^{56}Ni(p,p), ^{58}Ni(α,α') experiment at GSI

Si detectors in UHV

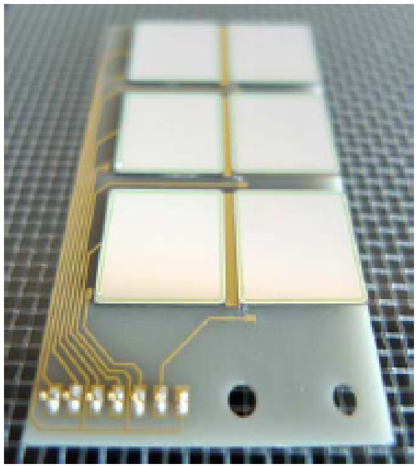


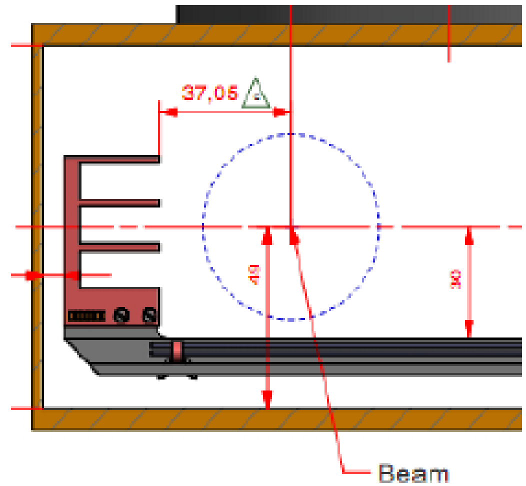


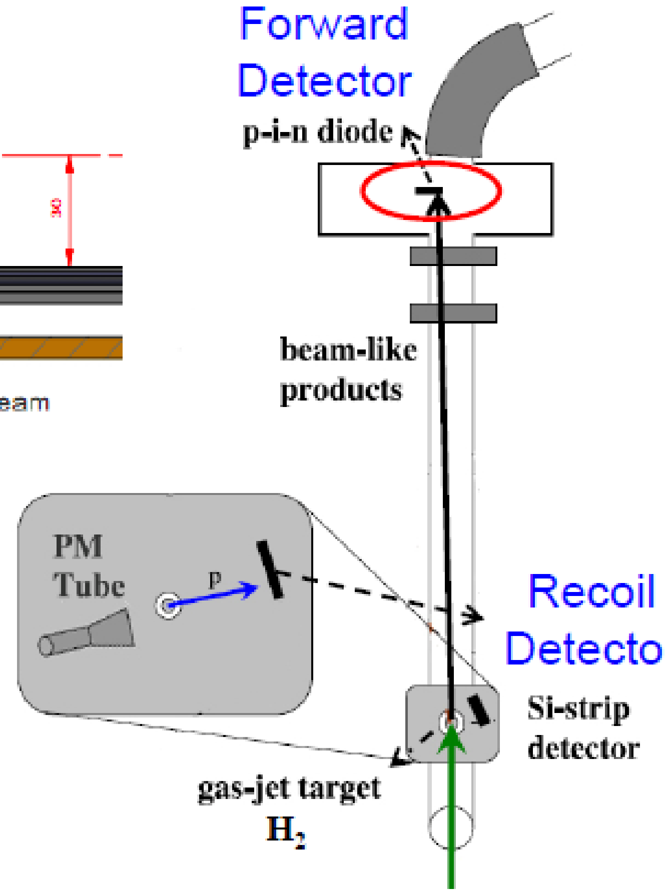
- *First experiment worldwide having Si DSSDs as a window between UHV (10^{-10} – 10^{-11} mbar) and auxiliary vacuum (10^{-7} mbar)*
- *Active cooling of the Si(Li) detectors during backing of the storage ring and the experiment itself*
- *Many other technical challenges - step motors inside UHV, power-fail protected power system*
- *DSSDs with 192 strips, very thin (60 nm) entrance window, made in St. Petersburg, Russia*
- *Energy resolution – 25 keV (for 5.5 MeV α-particles)*

O. Kiselev, Physica Scripta, T166 (2015)014004

Tagging detector in UHV







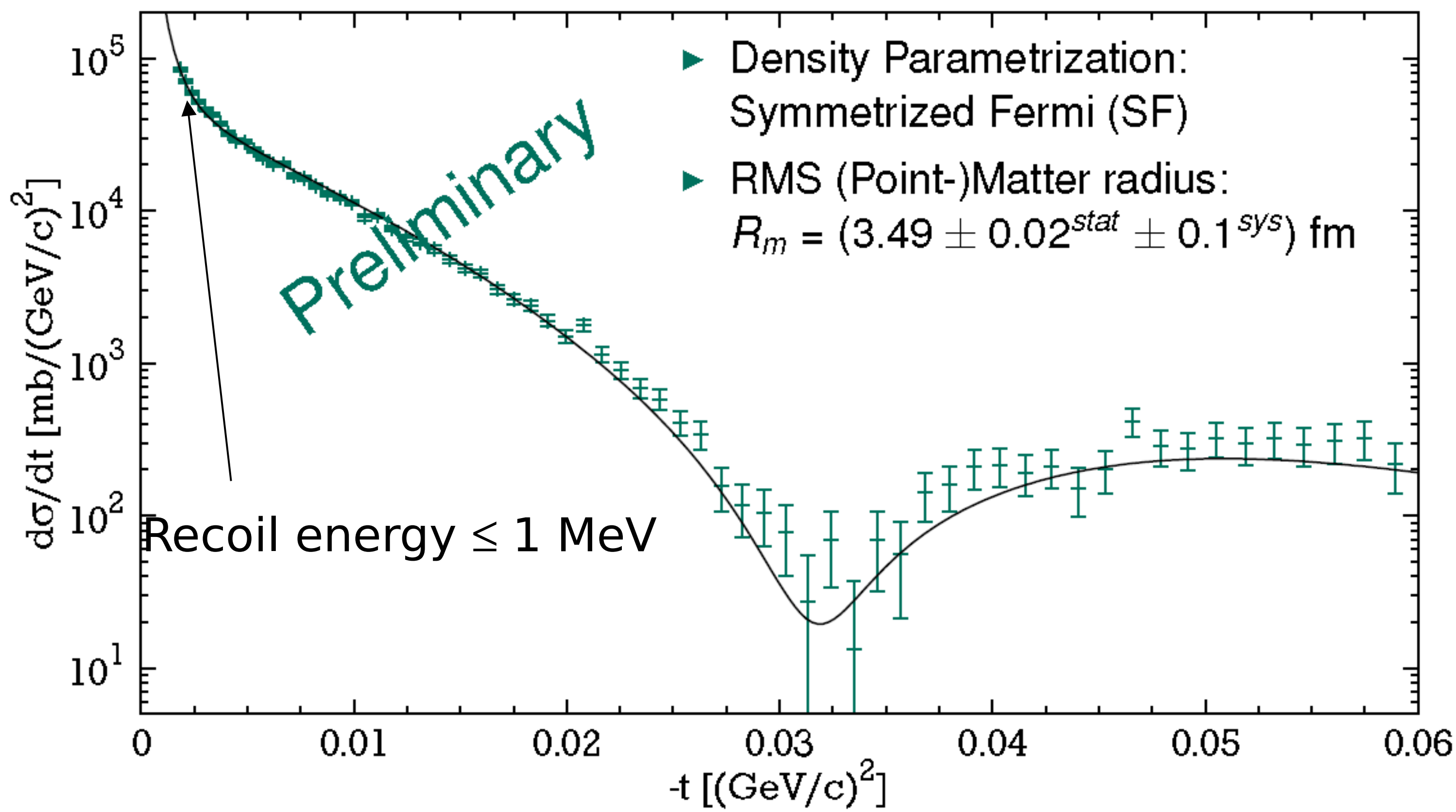
- Forward detector before the first dipole, detection of beam like reaction products in coincidence with recoils.
- 6 PIN diodes (1 x 1 cm²) on AlN PCB, directly in the UHV
- Small dead edge, could be very close to the beam
- Baked at 250° C

M. Mutterer, Physica Scripta, T166 (2015)014053

Elastic cross section measured with a help of Si detectors

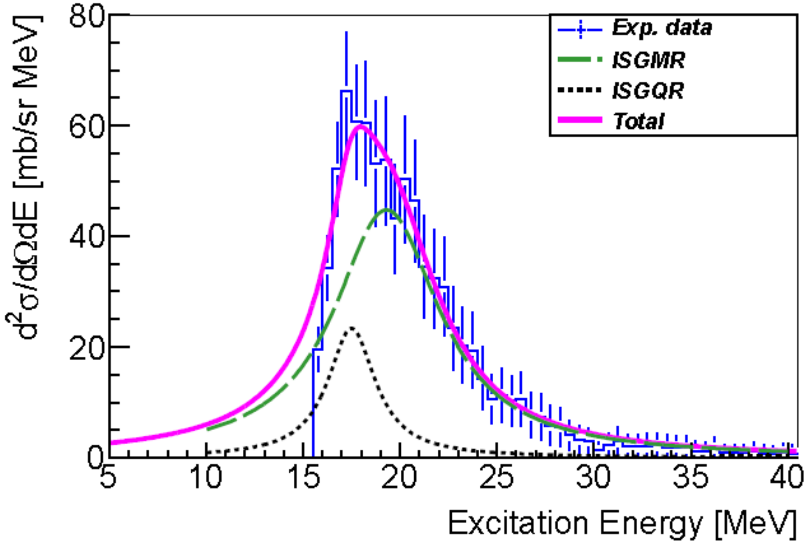
Preliminary results: ^{56}Ni(p,p)^{56}Ni at 400 MeV/u
Cross section fitted with
Glauber multiple-scattering theory

M. von Schmidt, TUD

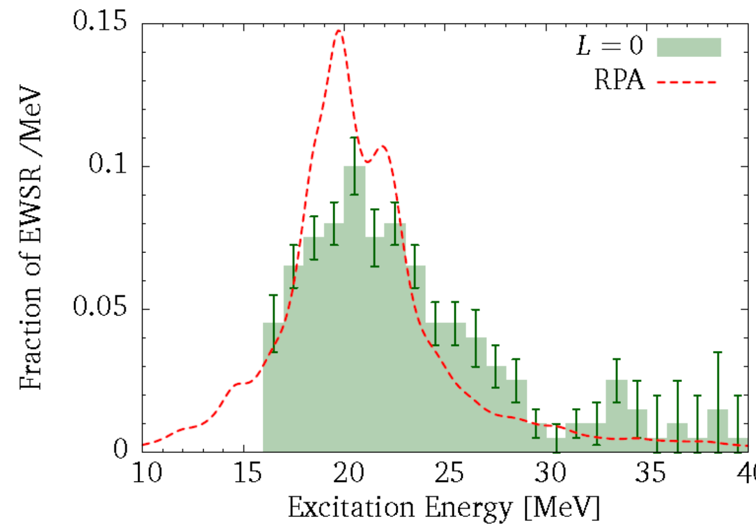


Inelastic cross section measured with a help of Si detectors

^{58}Ni(α,α') at 100 MeV/u, feasibility study for ISGMR J.C. Zamora, TUD



Double-differential cross section

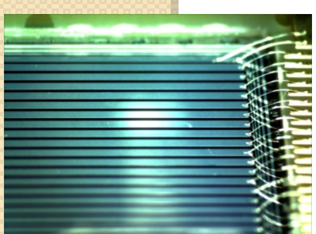


Fraction of the EWSR for the monopole contribution. Histogram are the Coefficients of the energy bins fit. RPA calculation with the Skyrme interaction Sko'.

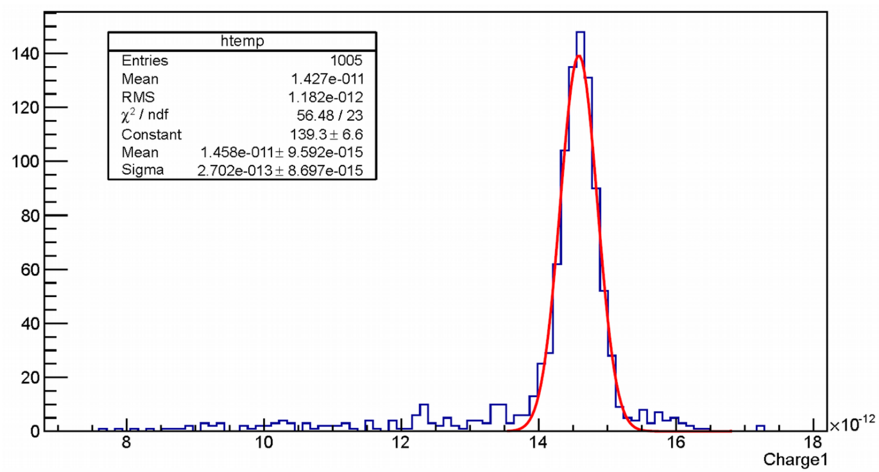
Reference	m_1/m_0 [MeV]	$\sqrt{m_3/m_1}$ [MeV]	Width$_{\mathrm{rms}}$ [MeV]	EWSR [%]
this work[1]	21.1(5)	21.6(6)	3.0(5)	53(8)
this work[2]	$21.4^{+0.5}_{-0.6}$	$21.9^{+0.8}_{-1.1}$	$3.4^{+0.5}_{-0.6}$	79^{+12}_{-11}
this work[3]	$21.5^{+0.8}_{-0.9}$	22.3(1.0)	3.5(6)	106(12)
RPA	20.04	21.20	3.24	109
[119]	$20.30^{+1.69}_{-0.14}$	$21.48^{+3.01}_{-0.32}$	$4.25^{+0.69}_{-0.23}$	74^{+22}_{-12}
[65]	$19.20^{+0.44}_{-0.19}$	$20.81^{+0.90}_{-0.28}$	$4.89^{+1.05}_{-0.31}$	85^{+13}_{-10}
[4]	$19.9^{+0.7}_{-0.8}$	-	-	92^{+4}_{-3}

Conclusions

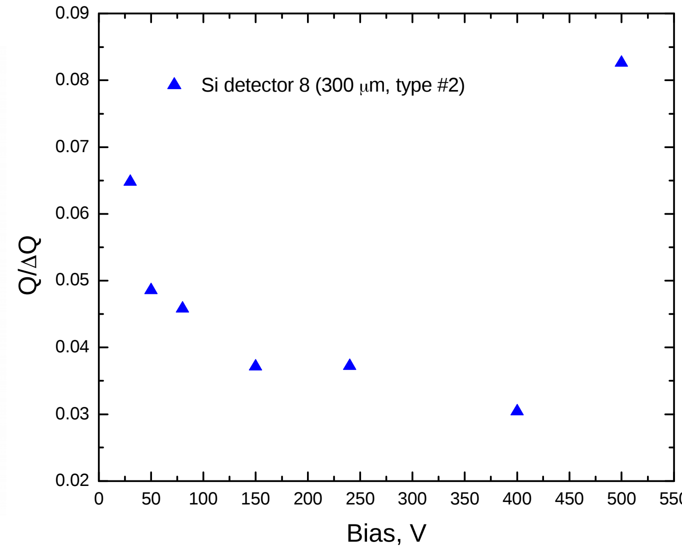
- Super-FRS diagnostics and experiments require precise position, energy and time measurements at high rates
- Detectors for all kind of diagnostics are on the way; feasibility tests are successful
- Si detectors are especially interesting as they are kind of universal devices delivering all information needed – energy loss, position and timing
- Detector development for Super-FRS/FAIR might be useful for other RIB facilities – at MSU, JINR, RIKEN, Ganil



Energy resolution for heavy ions



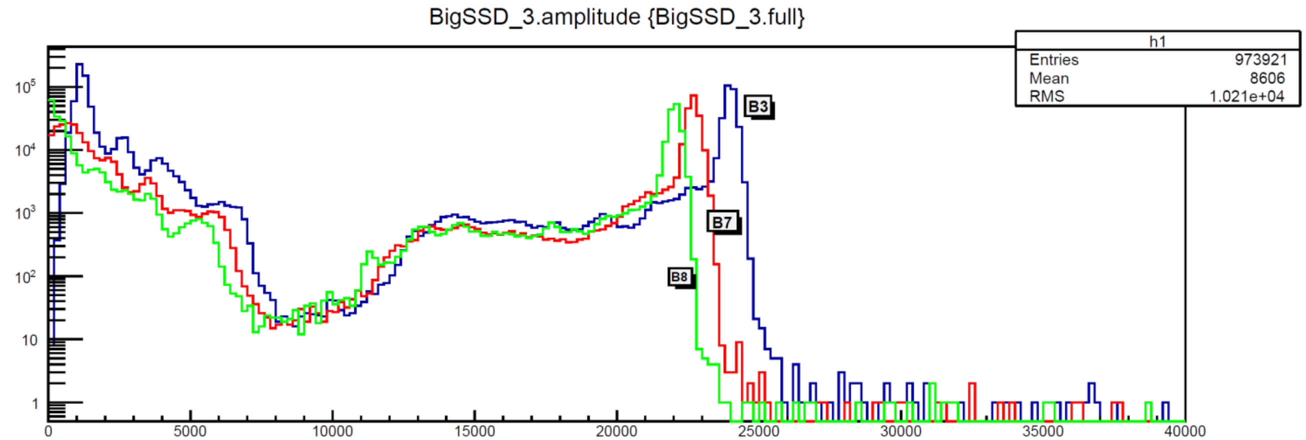
Beam - ^{40}Ar @ 40.5 MeV/u
$\Delta E/E$ = 1.9%

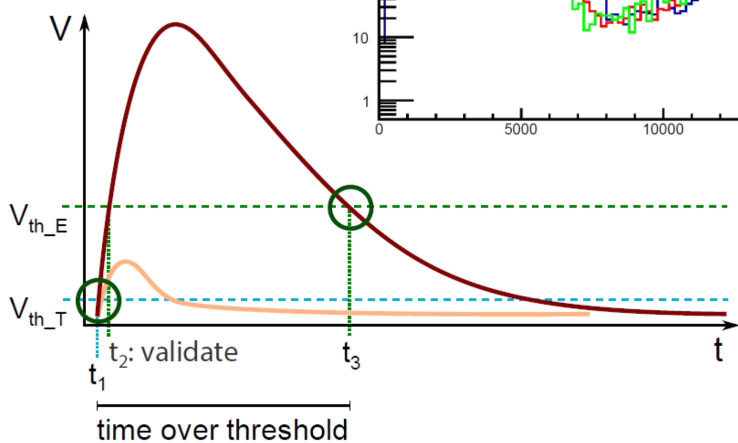


Beam - ^{197}Au @ 750 MeV/u
$\Delta E/E$ = 2.7%

- Contribution of beam itself ~0.5%
- Si detectors can be used for charge ID of heavy and light ions
- **But – under heavy irradiation the energy resolution degrades**

Energy loss via Time-over-Threshold





PADI + VFTX2 electronics

- Indirect energy measurement, non-linear
- Direct use for a „time walk“ correction
- Resolution – 3-10%