Si detectors for NUSTAR

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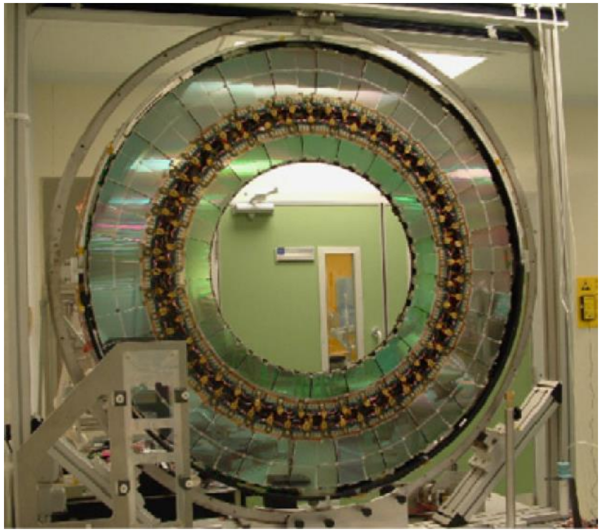
GSI Darmstadt,

for EXL, R3B, HISPEC/DESPEC collaborations and EXPERT/SFRS project

Typical applications of Si detectors

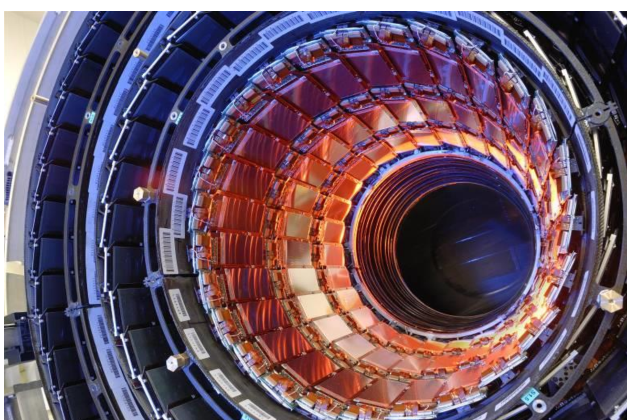
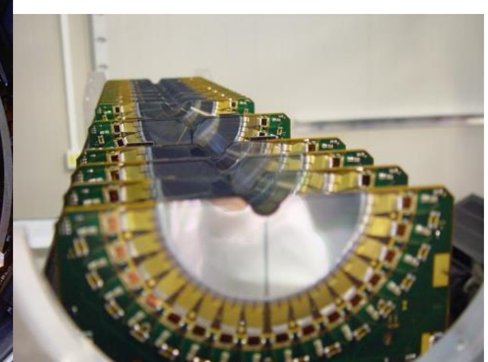
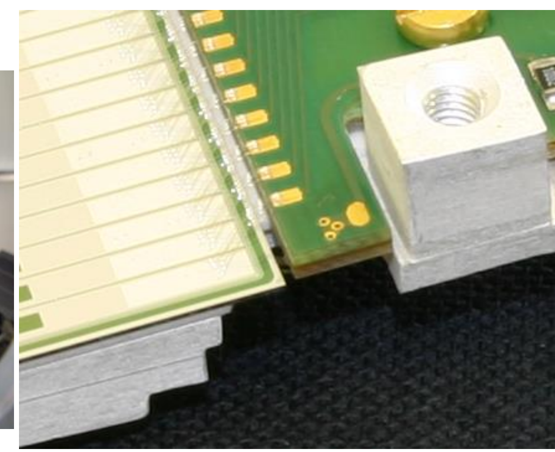
- Energy loss measurements.
  Range - from γ-particles/photons to heavy ions.
  In connection to a charge sensitive preamplifier per active strip/pad/pixel and precise (10-14 bit) ADC.
- Position measurements. Also widely used, same range.
  In connection to a charge sensitive preamplifier per active strip/pad/pixel and less precise (4-8 bit) ADC.
- Time measurements.
  Less used application,
  for charged particles from protons to heavy ions.
  In connection to a current amplifier per active strip/pad and a fast digitizer or a precise TDC.



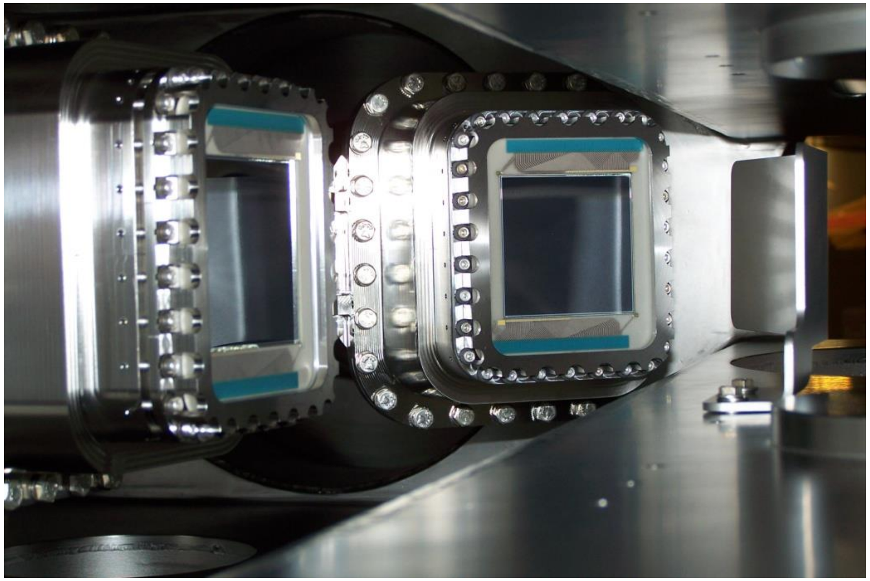
Si trackers in High Energy Physics

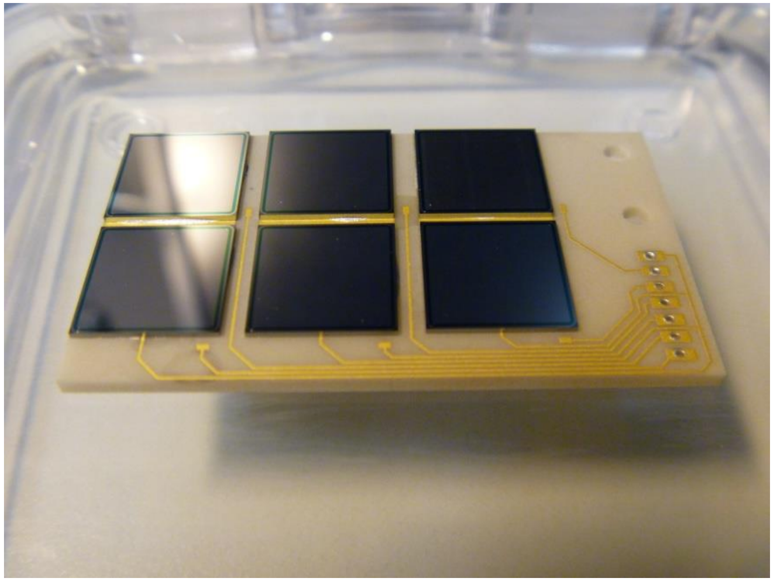
- FNAL. D0 & CDF
- BNL. STAR & PHENIX
- LHC. CMS, ATLAS, LHCb, ALICE
- AMS + other astrophysical experiments

Driving force of almost all Si detector developments

“Special” application of Si detectors in nuclear physics

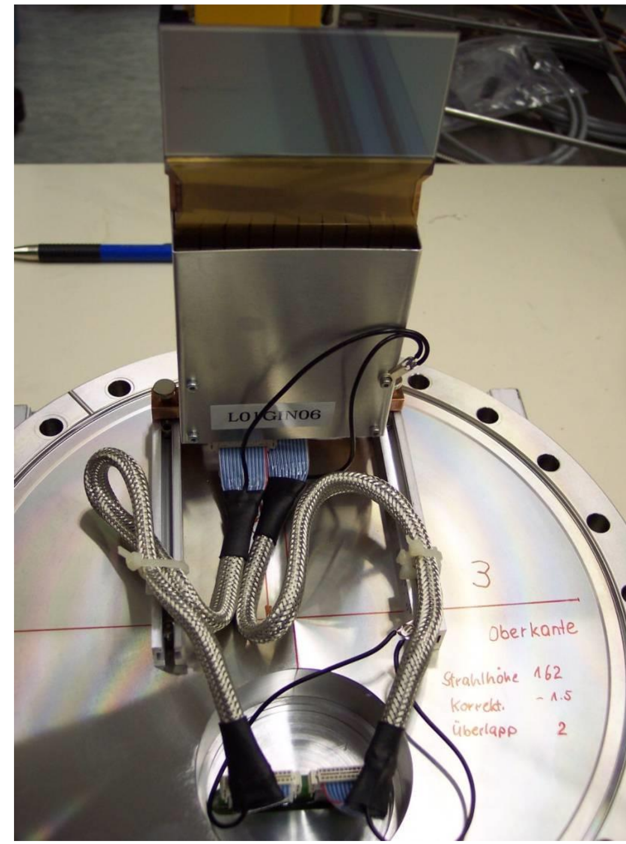




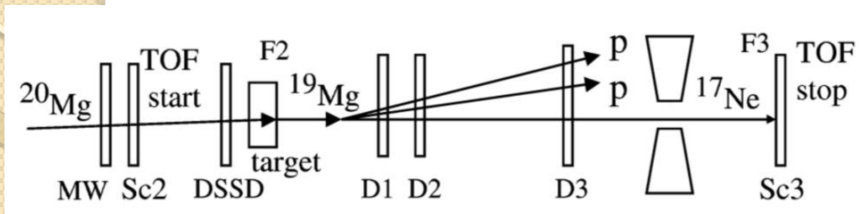
- Less precise position measurement – 0.1 - 1 mm instead of 10 – 50 μm
- Precise energy loss measurement – up to 0.5%
- Much higher dynamic range – up to 1000 MIPs
- Less event rate
- Time measurement

Si microstrip detectors for tracking of the fast ions and protons

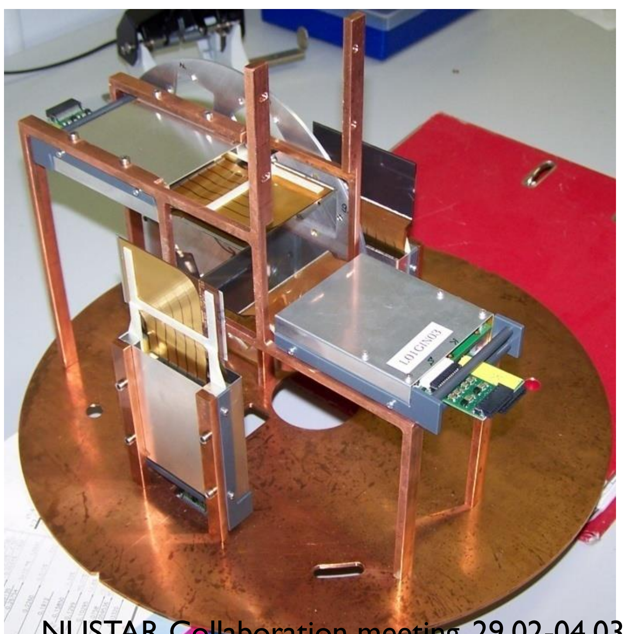
- DSSDs, area 28 cm^2, 300 μm,   100 μm strip pitch
- Energy resolution ~ 1%
- Dynamic range – from p to Fe
- Very low energy dissipation of FE electronics (VAHDR9 ASICs, IDEAS) - work in vacuum without active cooling
- 1024 channels, multiplexed readout
- ***Position resolution ~40 μm for protons, ~15 μm for ions***

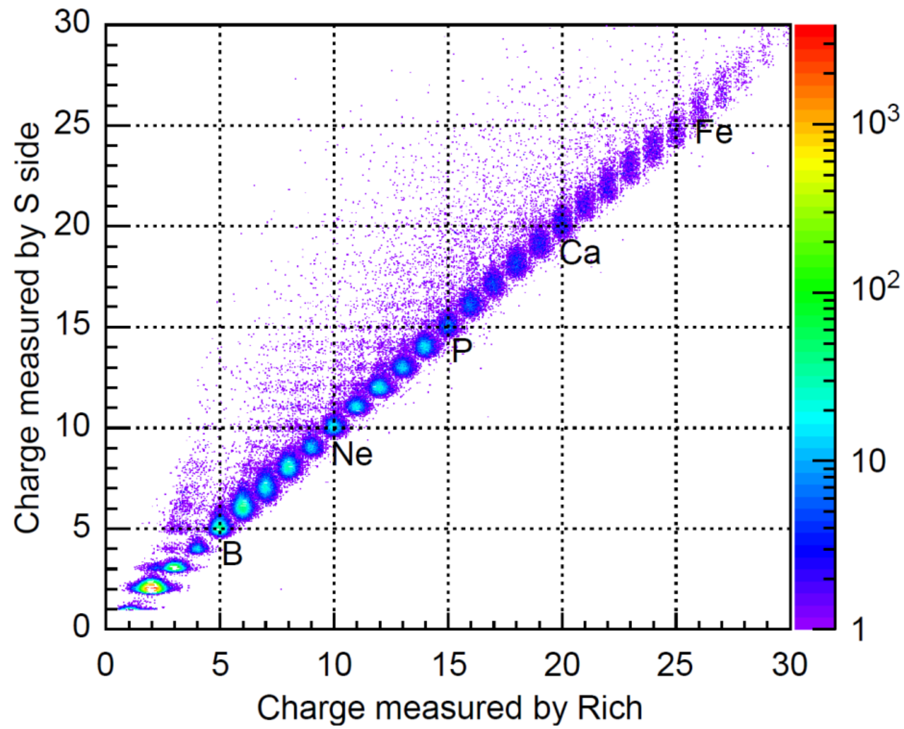


Precise tracking + spectroscopy



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)

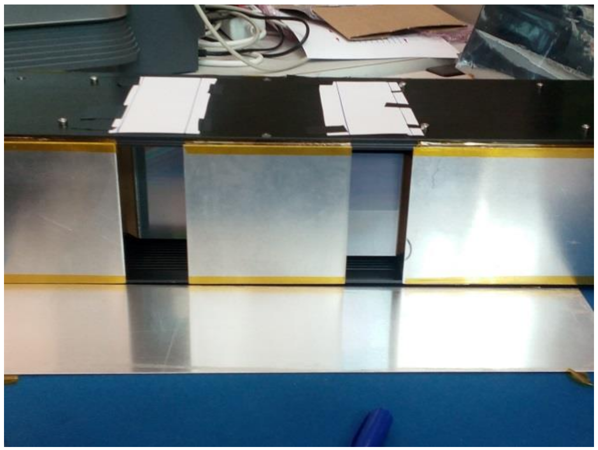




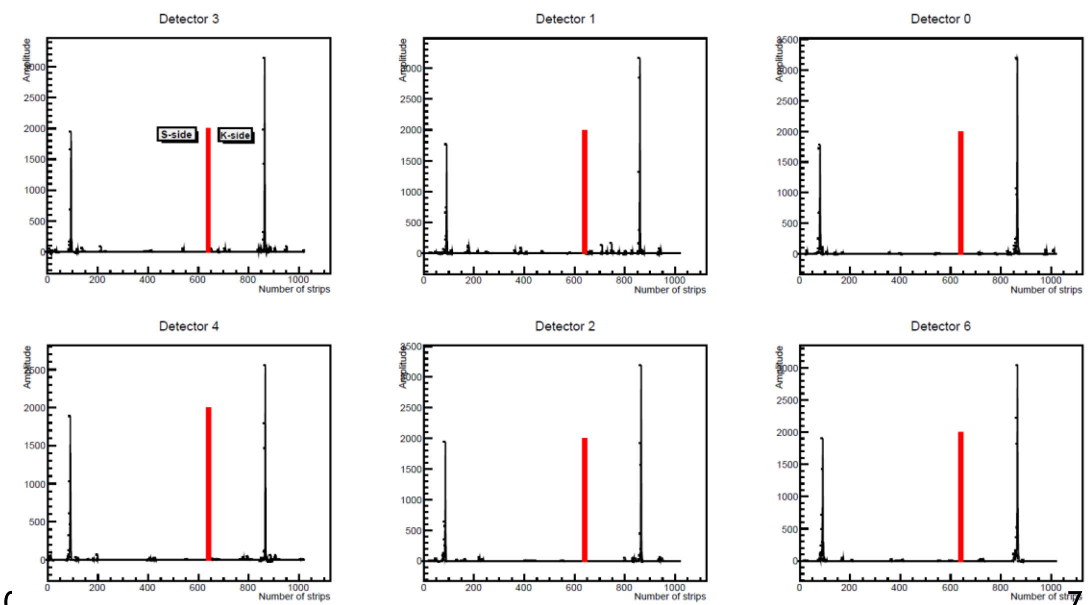
Si – RICH correllation (AMS data)

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

System test with fast protons and ions at CERN



- Together with DAMPE collaboration
- Protons and ^{40}Ar @ 30 GeV/c
- 6 DSSDs measured at once
- Test of the tracking algorithms



R3B - standard detectors for heavy-ion tracking

X1

- 5 x 5 cm^2
- 140/300 um thick
- 16 strips on the front, read out on both ends (position)
- Cathode on the back

=> 33 channels each

X5.1

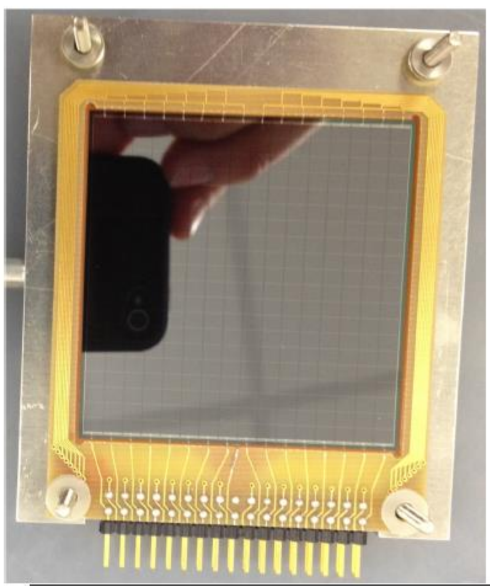
- 10 x 10 cm^2
- 200 um thick
- 32 strips on the front and the back, read out on both ends (position)

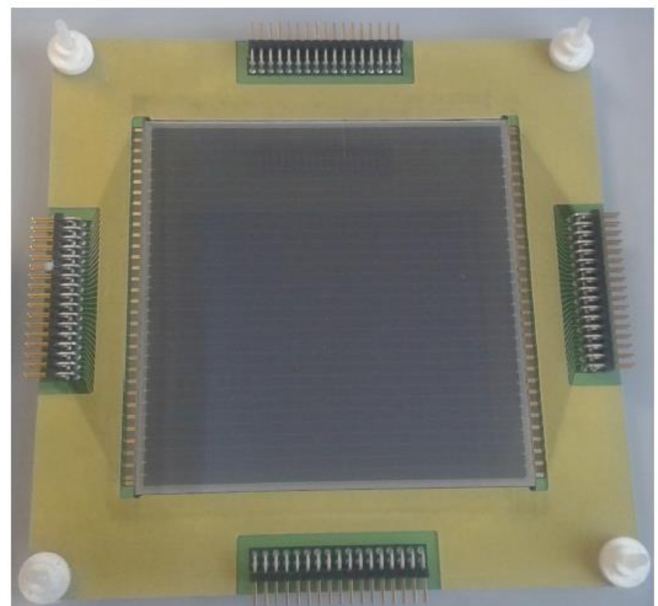
=> 128 channels

X5.2

- 10 x 10 cm^2
- 200 um thick
- 32 strips on the front and the back, read out between the strips (position)

=> 128 channels

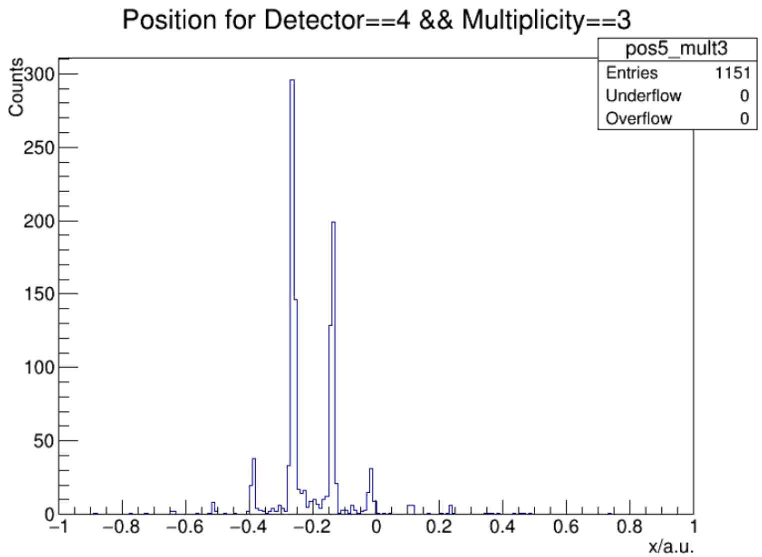




I. Syndikus, D. Rossi, TUD

R3B - standard detectors for heavy-ion tracking

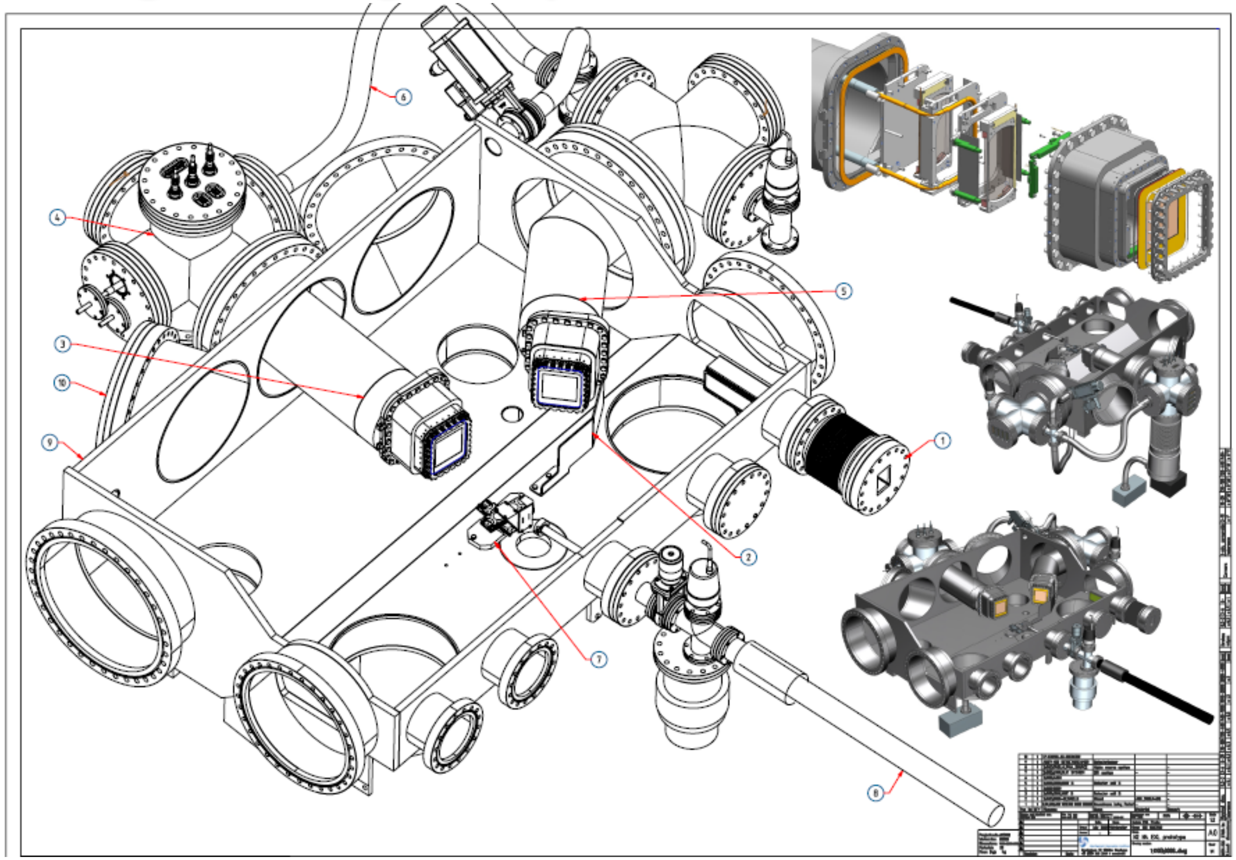
I. Syndikus,
D. Rossi, TUD



- Mesytec preamplifiers
- FEBEX digitizers
- MBS/NDAQ readout

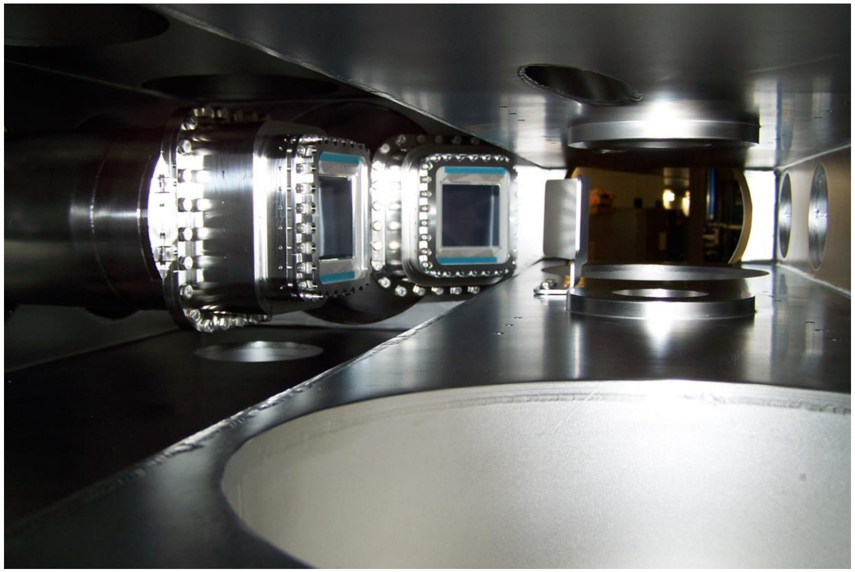
- R3BROOT environment for unpacking/analysis
- FEBEX Multihit Readout implemented
- **System check – beam test in June 2016**

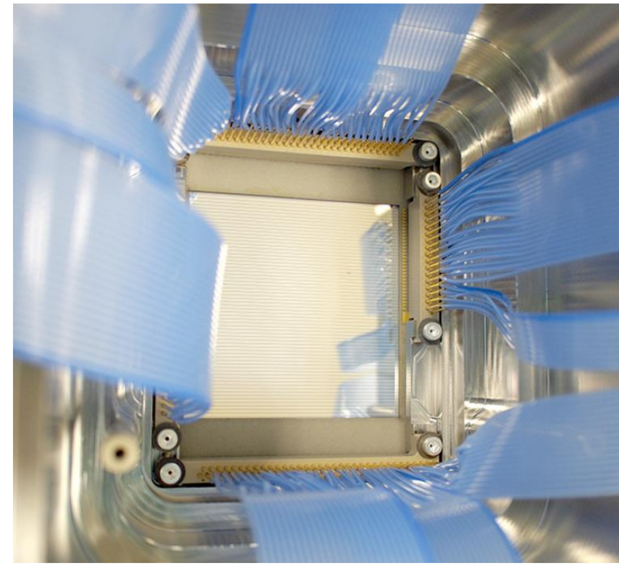
Tracking and spectroscopy for the storage ring experiments



- 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

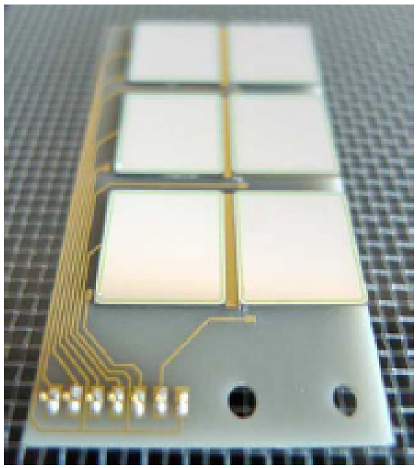


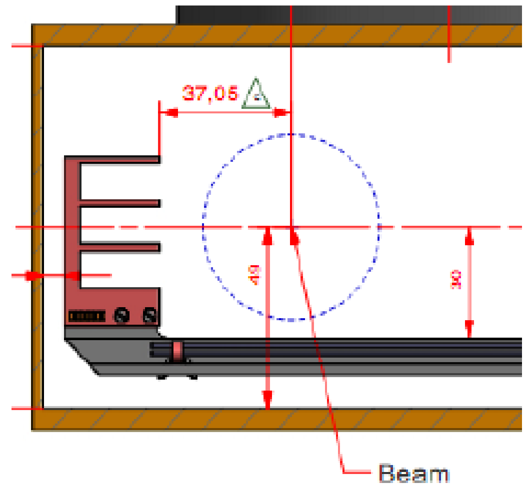


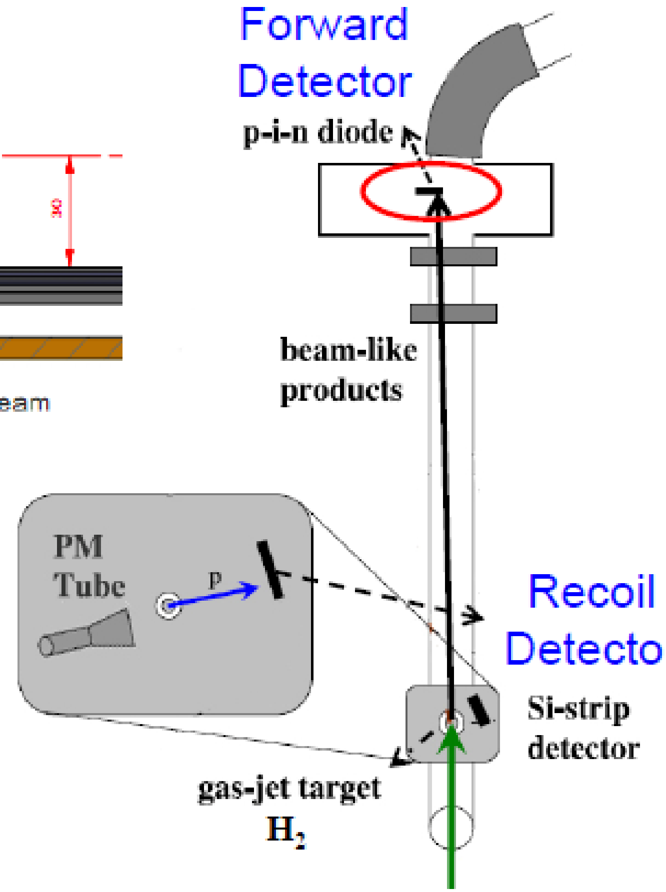
- *First experiment worldwide having Si DSSDs as a window between UHV (10^{-10} – 10^{-11} mbar) and auxiliary vacuum (10^{-7} mbar)*
- *Active cooling of the Si(Li) detectors during backing of the storage ring and the experiment itself*
- *Many other technical challenges - step motors inside UHV, power-fail 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







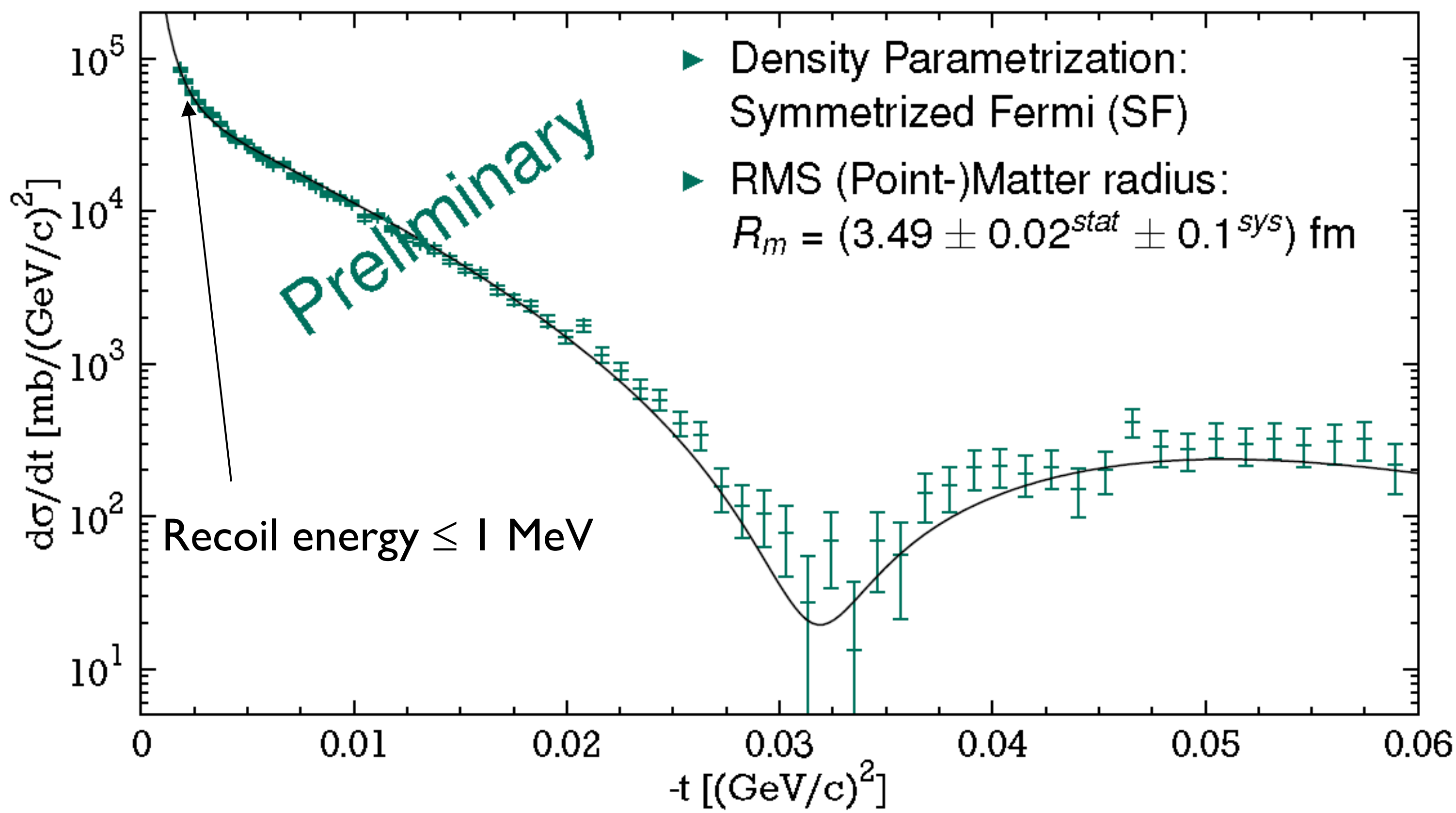
- Forward detector before the first dipole, detection of beam like reaction products in coincidence with recoils.
- 6 PIN diodes (1 x 1 cm²) on AlN PCB, directly in the UHV
- Small dead edge, could be very close to the beam
- Baked at 250° C

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

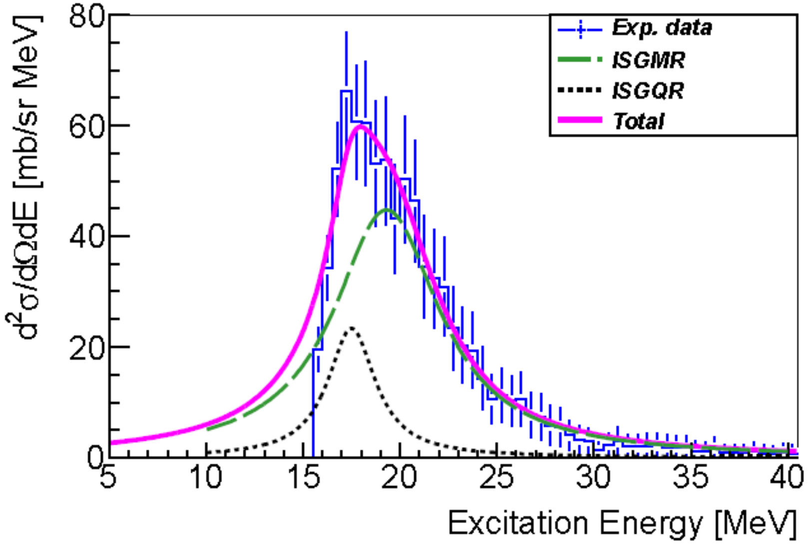
M. von Schmidt, TUD



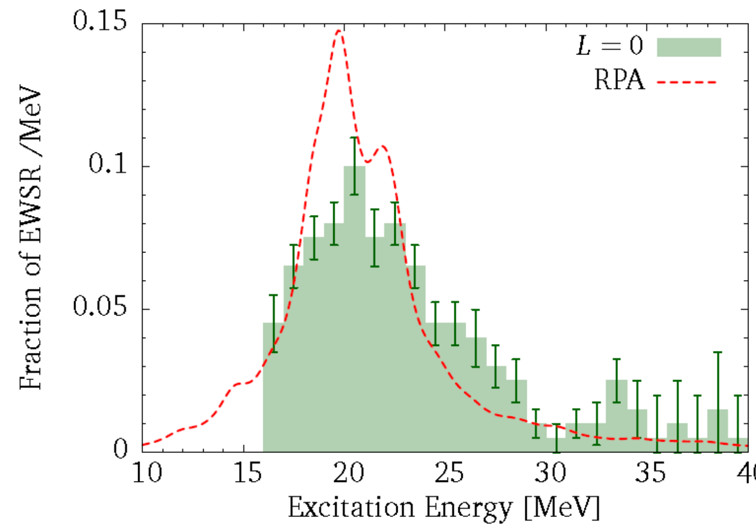
Inelastic cross section measured with a help of Si detectors

^{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$_{rms}$ [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}

Fast timing with double sided Si strip detector

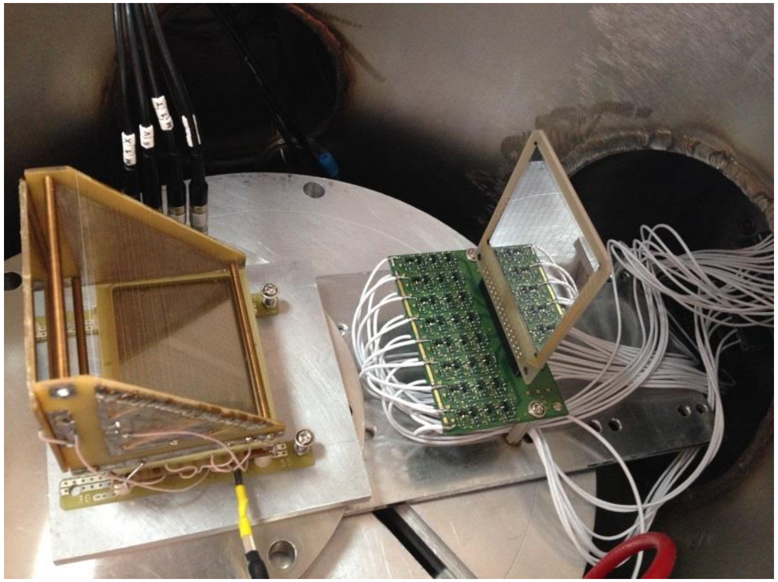
Akhil Jhingan , Inter University Accelerator Centre

RIB-experiments after slowing down to Coulomb barrier

Ideal beam tracking detector:

- ✓ large area tracking system
- ✓ Energy resolution $\Delta E/E < 1\%$
- ✓ Position resolution ~ 1 mm
- ✓ Time resolution ≤ 100 ps

MCP DSSSD



double-sided silicon-strip detectors

- active area 50x50 mm^2
- thickness 40 μm
- 16 x 16 strips (3.125 mm)
- manufactured by MICRON

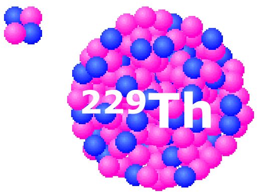
Courtesy of H.-J.Wollersheim

Fast timing with double sided Si strip detector

Akhil Jhingan , Inter University Accelerator Centre

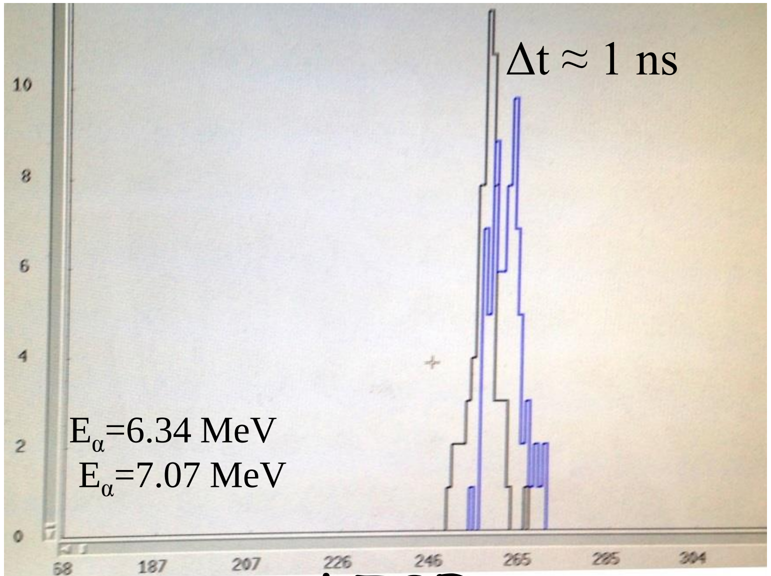
Energy measurement with Mesytec:

Energy resolution ΔE = 300 keV



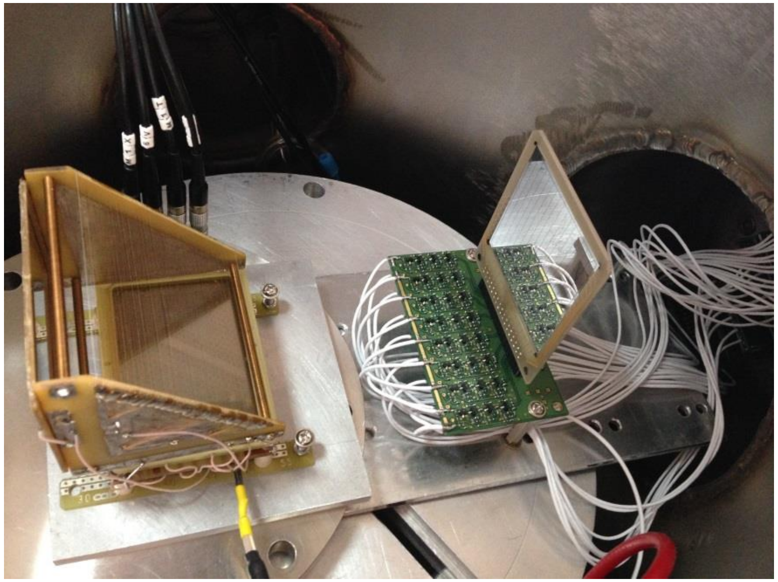
Time measurement with 16-ch. fast timing preamplifier (IUAC):

pulse height 15 mV
noise 5 mV
rise time 5 ns



energy gated TOF spectra:

MCP DSSSD



Courtesy of H.-J.Wollersheim

Fast timing with double sided Si strip detector

Akhil Jhingan , Inter University Accelerator Centre

Energy measurement with Mesytec:

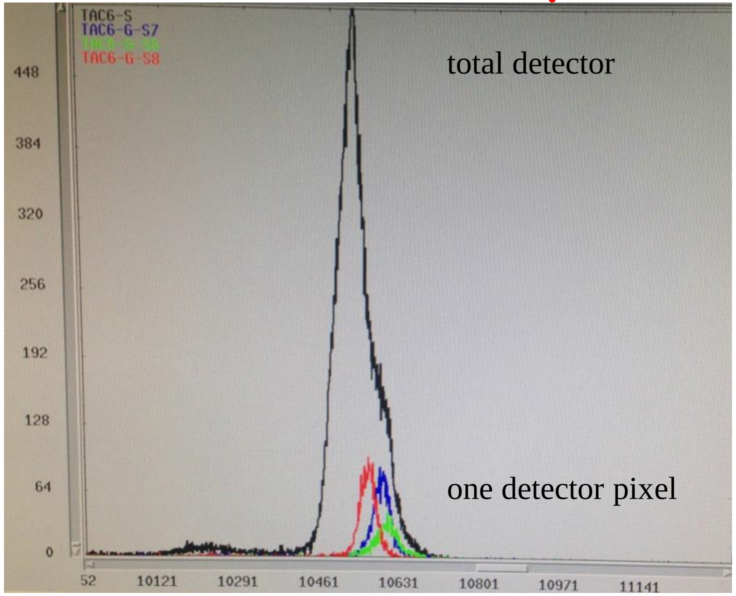
Energy resolution $\Delta E/E$ = 1.5%

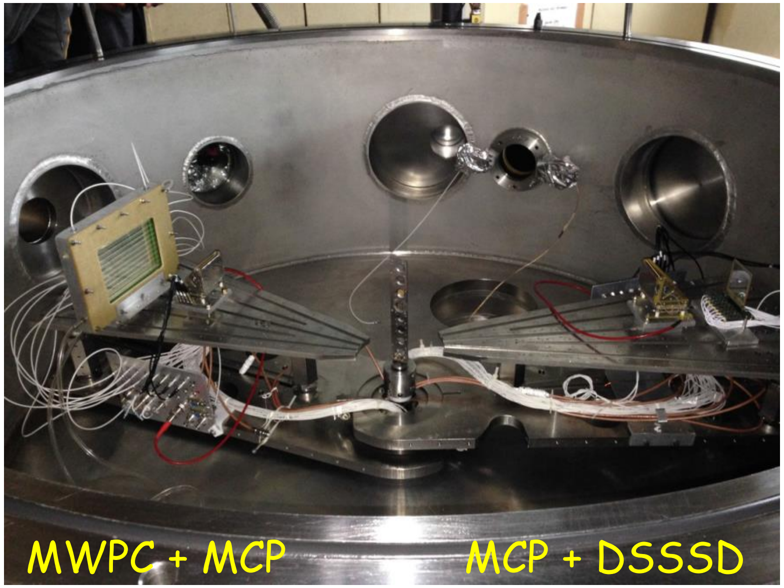
IUAC experiment :
^{28}Si $\rightarrow$ ^{197}Au $_{(0.2mg/cm^2)}$ at 122 MeV

Time measurement with 16-ch. fast timing preamplifier (IUAC):

pulse height 300 mV
rise time 6.3 ns

Time resolution 200 ps for one of the 256 detector pixels

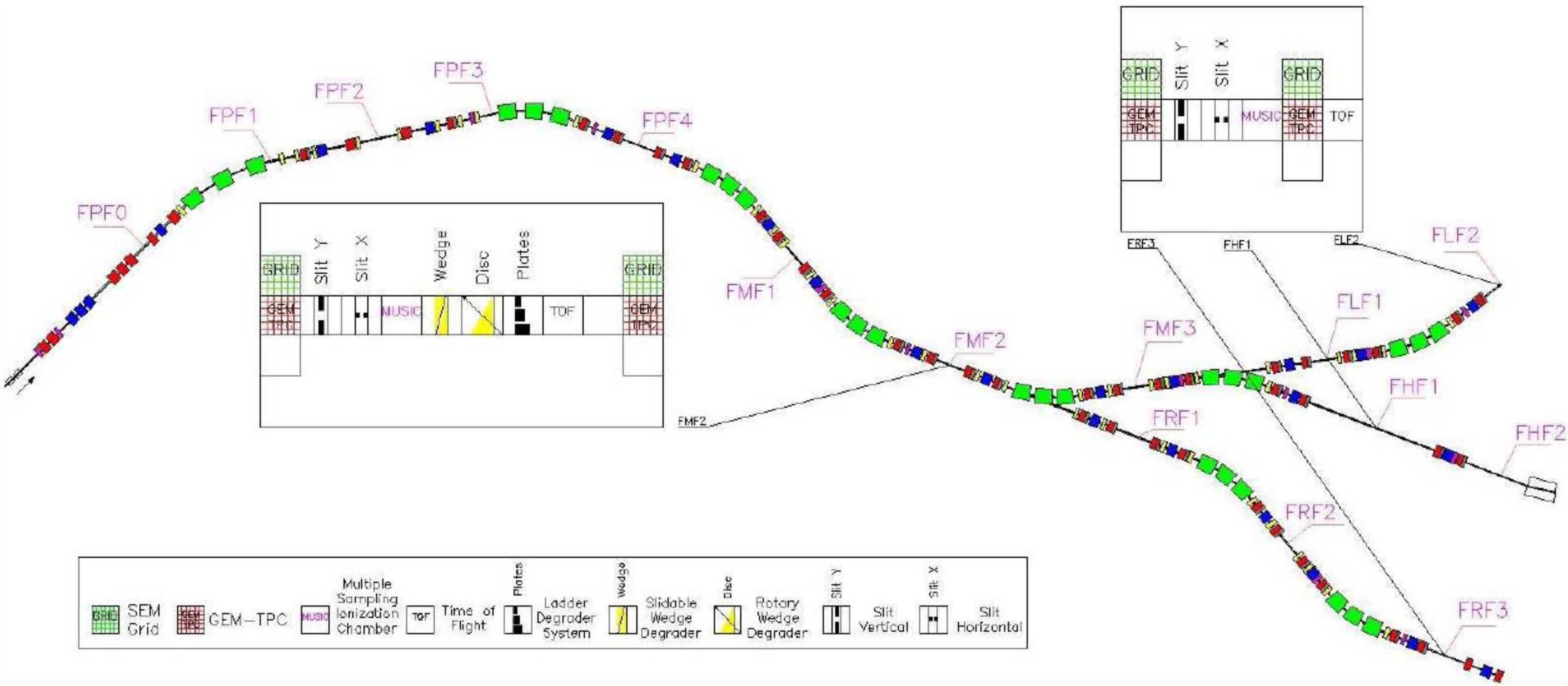




TOF between MCP and DSSSD

Courtesy of H.-J.Wollersheim

TOF measurement with Si detectors for SFRS

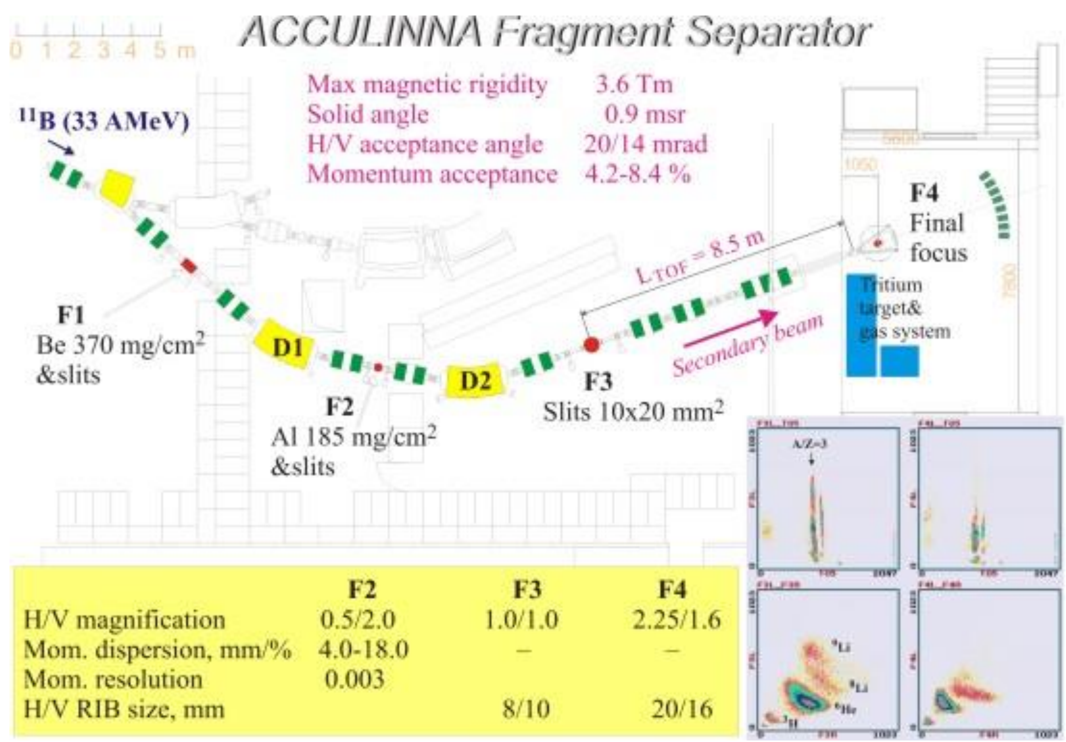


- TOF stations FMF2, FLF2, FHF1, FRF3
- Ion rate $<5*10^4$ s^{-1} per cm^2
- Time resolution – 20-35 ps (σ)

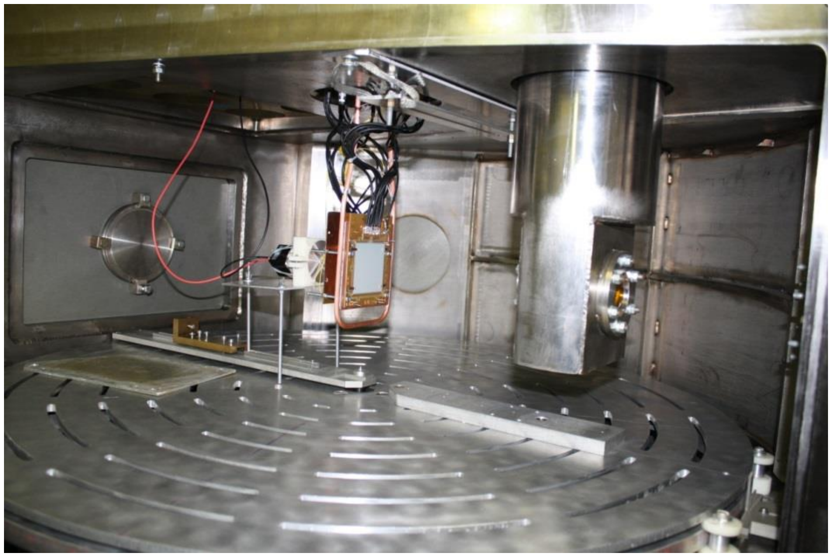
Beam tests in JINR

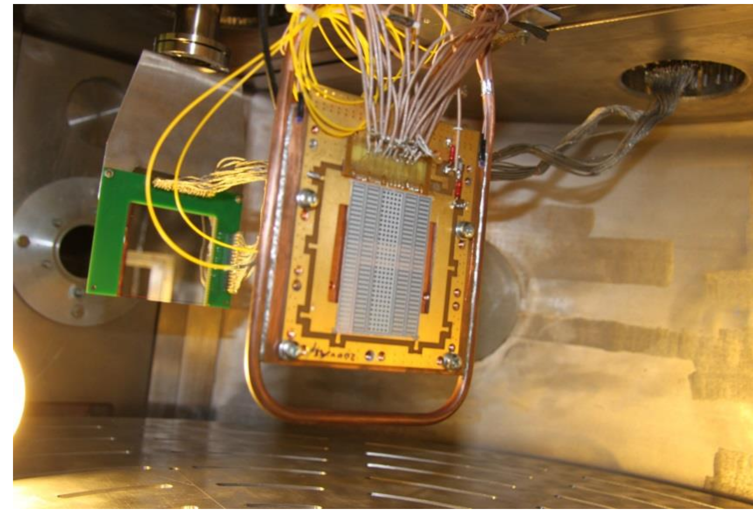
- Test of time resolution with fast electronics
- Check performance change under heavy irradiation
- Compare Si detectors with different topology

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



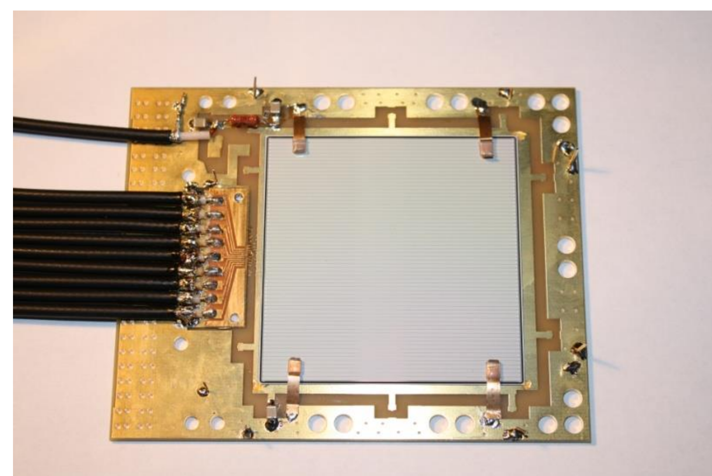
Experimental setup at JINR



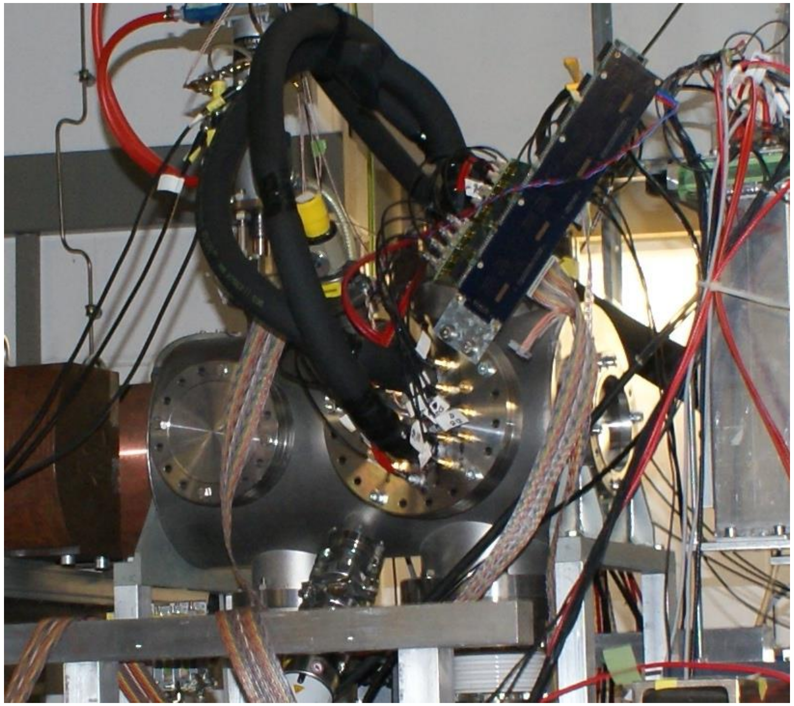


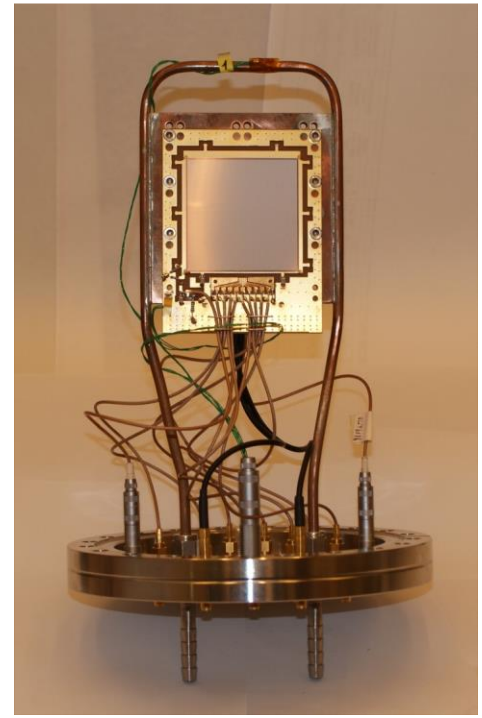
- ACCULINA fragment separator after U400 cyclotron
- Scattering chamber/final focal place F4
- Trigger scintillator + MWPC (beam tracking)
- Full-size (40 cm^2) Si detector tested
- Accumulated dose – up 6*10^{12} ions/cm^2

Si detectors made in St. Petersburg, Russia



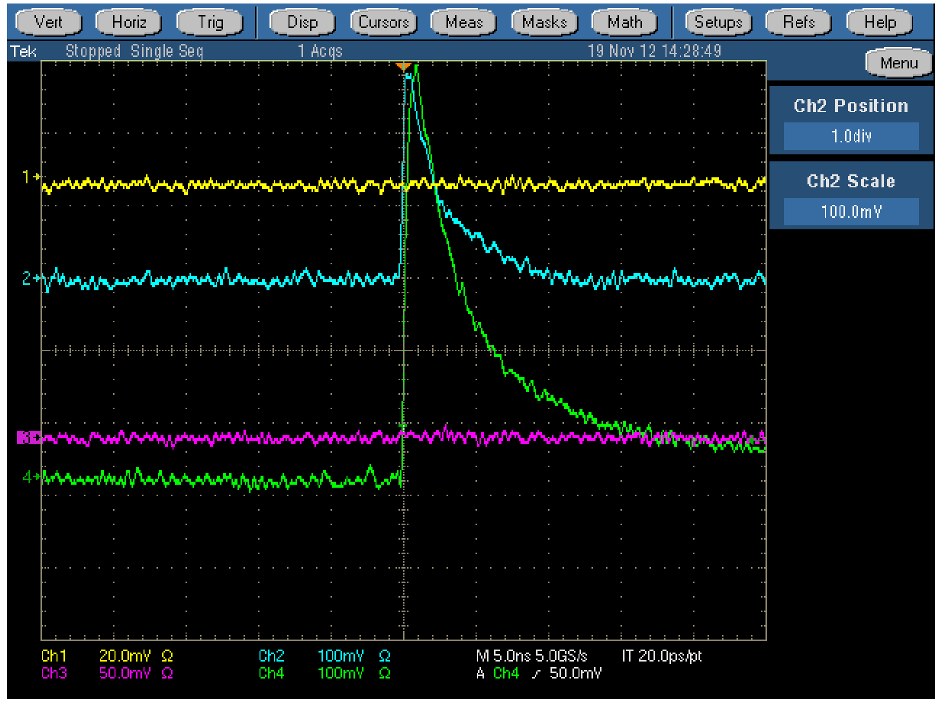
Experimental setup at GSI





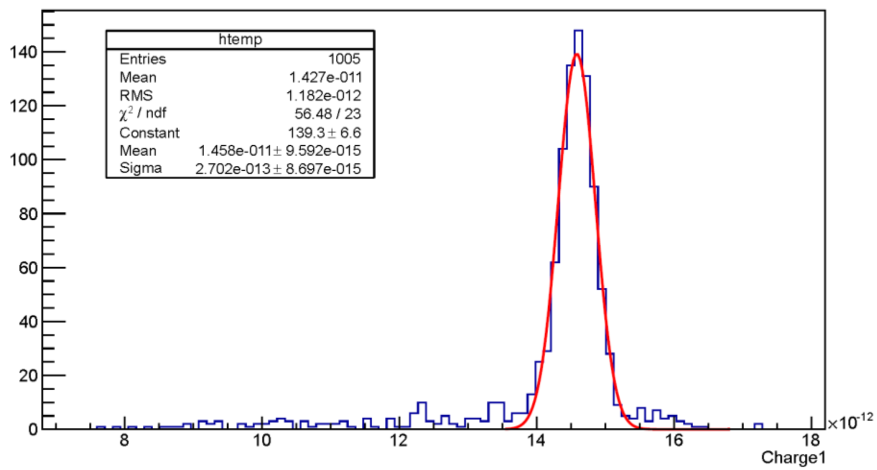
- S4 focal area of FRS
- ^{197}Au @ 1 GeV/u beam
- DAQ 1: Fast current amplifiers/discriminators + TDC
- DAQ 2: Waveform digitizers (3.2 Gs/s and 5 Gs/s)

Example of the signal shapes

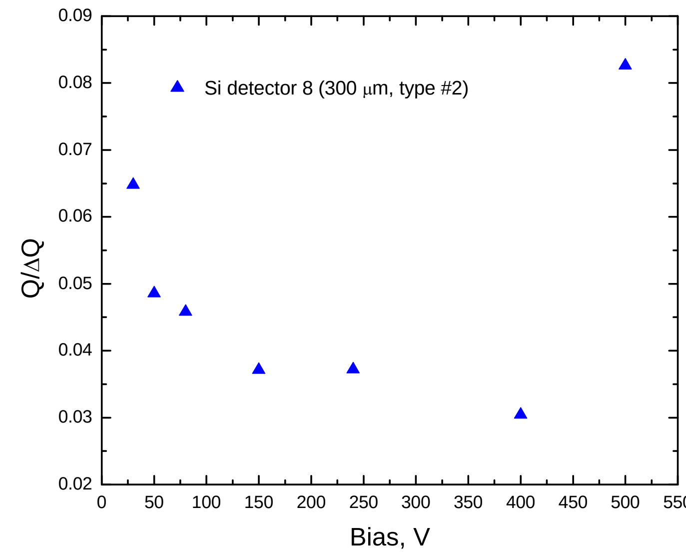


- Signals from U, Au ions can be digitized without amplification
- Digitized signals hold all information – amplitude, charge, timing
- Sampling should be very fast – 3-5 Gs/s due to a fast rise time (0.3 – 1 ns)

Energy resolution for heavy ions



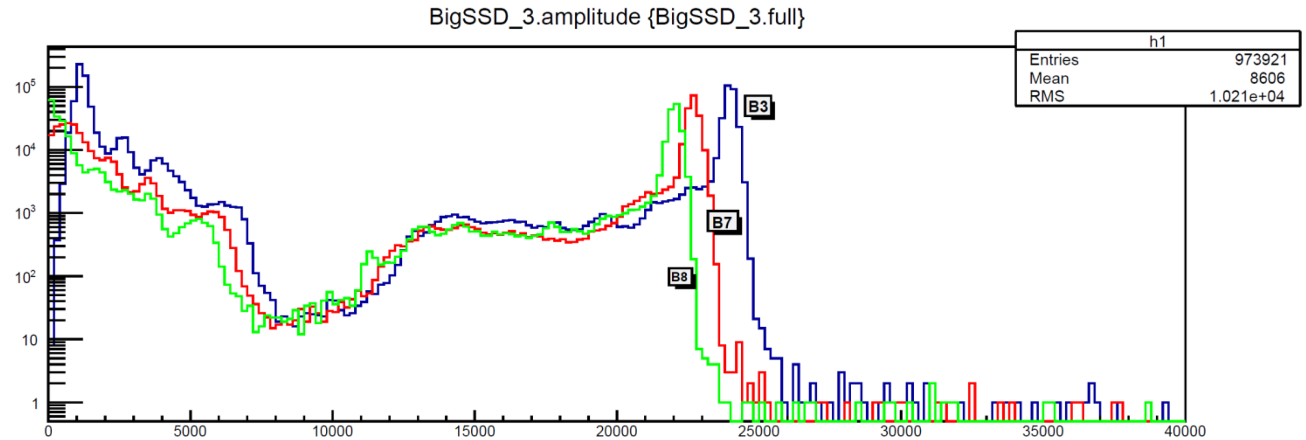
Beam - ^{40}Ar @ 40.5 MeV/u
$\Delta E/E$ = 1.9%

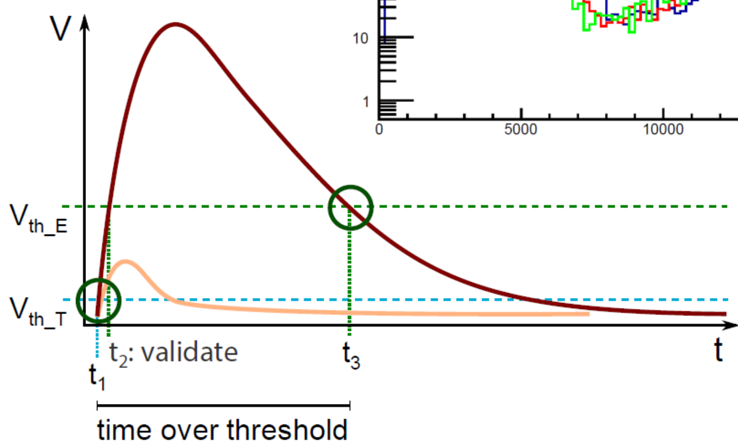


Beam - ^{197}Au @ 750 MeV/u
$\Delta E/E$ = 2.7%

- 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

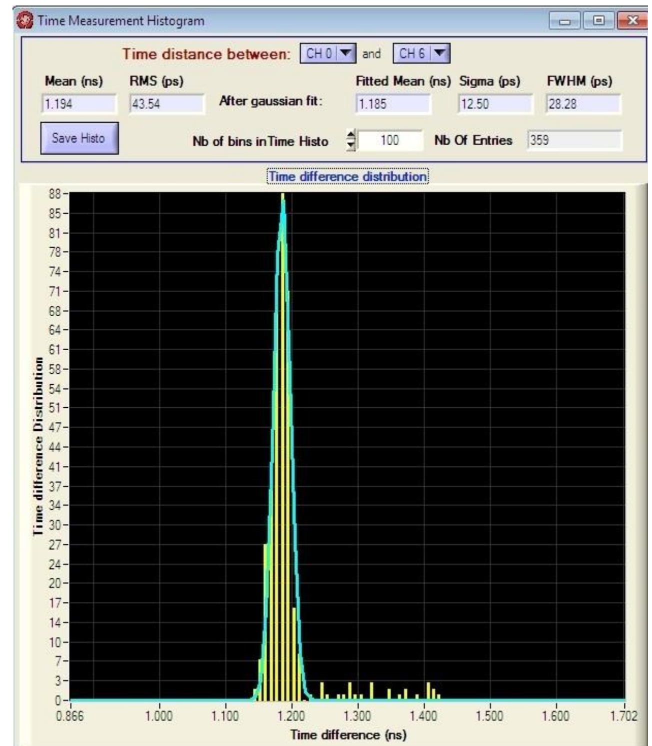




PADI + VFTX2 electronics

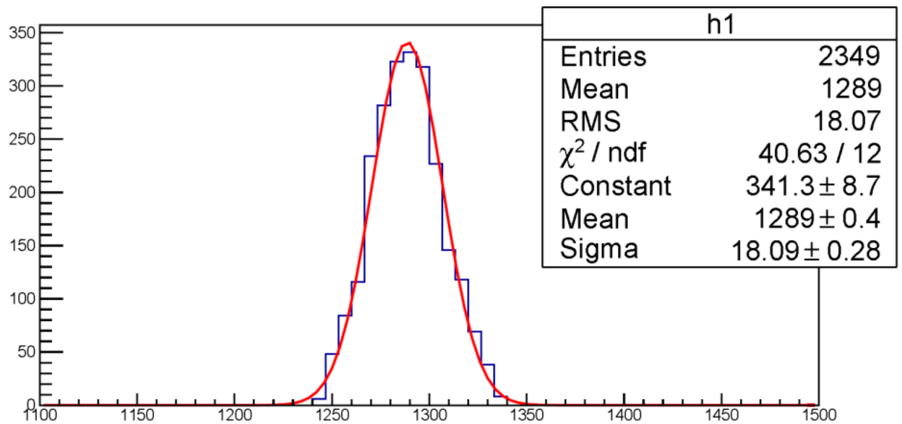
- Indirect energy measurement, non-linear
- Direct use for a „time walk“ correction
- Resolution – 3-10%

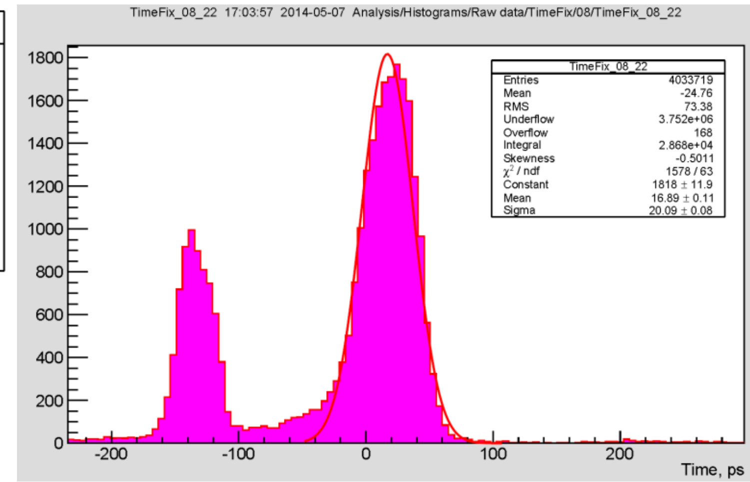
Time resolution with the fast digitizers



- DRS4 (PSI development) chip inside, 12 bit ADCs
- Digitised waveforms $\Rightarrow$ ΔE also possible
- Spline fitting, CFD method for time determination
- ΔT (TOF) $\leq$ 13 ps (σ)! *O. Kiselev at al., GSI Scientific Report 2014 (2015) 137*

Time resolution with PADI preamplifier

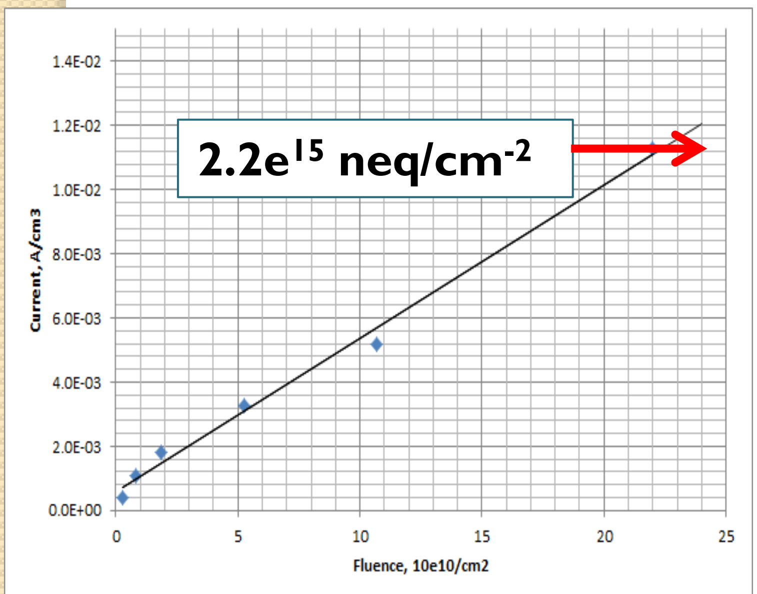




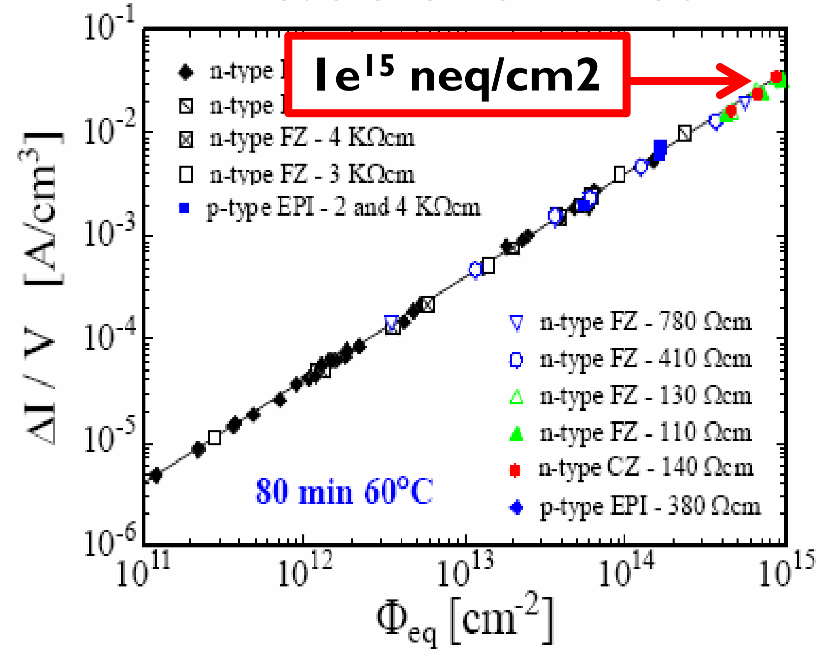
- PADI current amplifier/discriminator + VFTX2 TDC (~15 ps internal resolution, up to 10^6 events per channel)
- One VME module – 28 channels
- Leading edge method with amplitude correction
- **ΔT (TOF) ≤ 25 ps (σ)**
- Only possible method for high event rates

Current generation rate 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 /cm^2 >>>>> 1e^{15} neq/cm^2

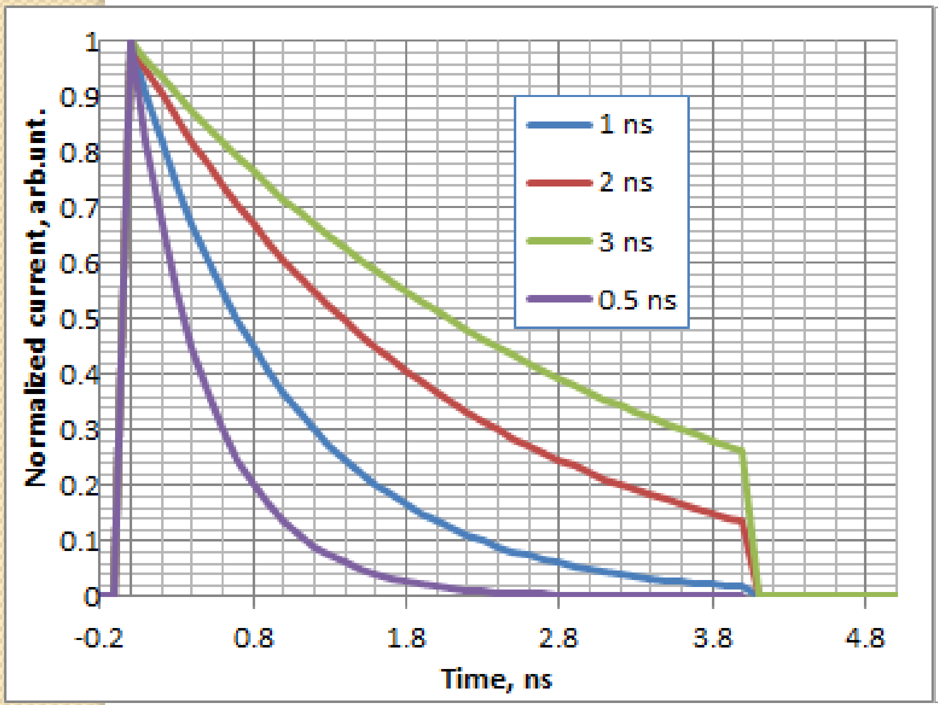
250 K

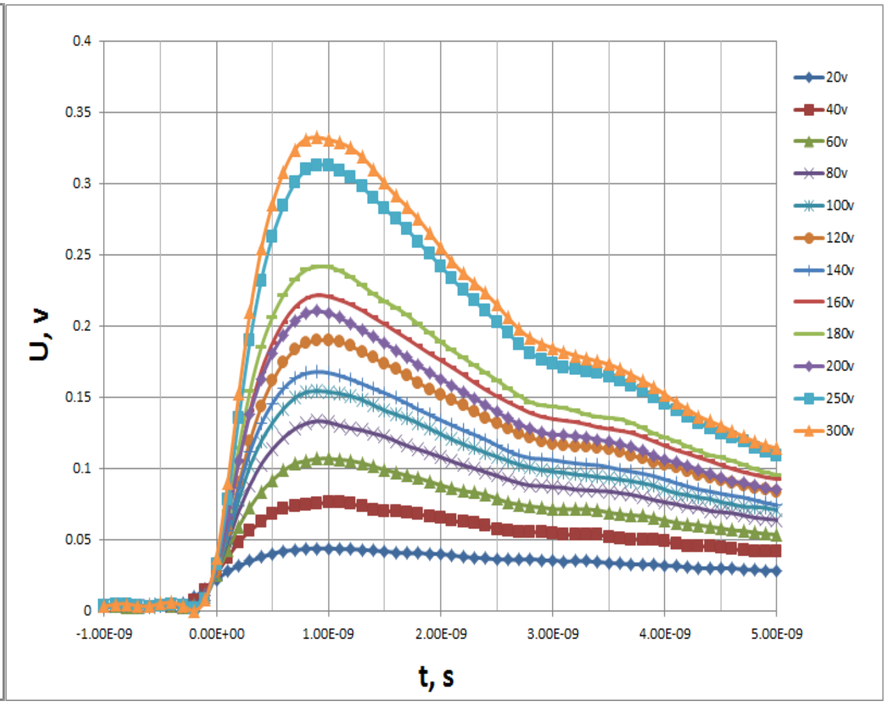
α(ions) = 1.5 e^{-15} A/cm
Strip (50 mm^2) ion fluence 1e^{12} cm^{-2}
Current < 10 μA
Negligible noise

The signal amplitude estimation

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

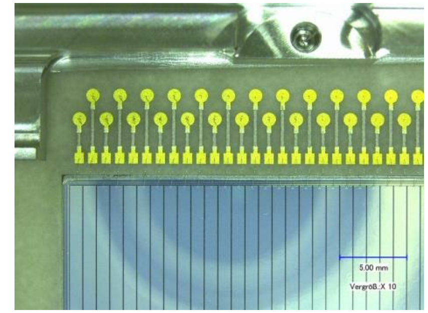




Amplitude of the peak current I_p
I_p at 1e^{12} ions/cm^2 = 1 - Tr/Ttr = 1 - 1ns/5ns = 0.8
(1ns – time of reaching maximum)

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

Conclusions



- Si detectors widely used in HEP; successfully used in nuclear physics experiments with exotic ions
- Kind of universal devices delivering all information needed – energy loss, position and timing
- All these observables can be obtained with precision on the same or even better level then alternative approaches (scintillator, MCP, IC, MWPC)
- Si detectors are planned to be intensively used for the coming experiments within NUSTAR/FAIR