Pico-second resolution timing measurements

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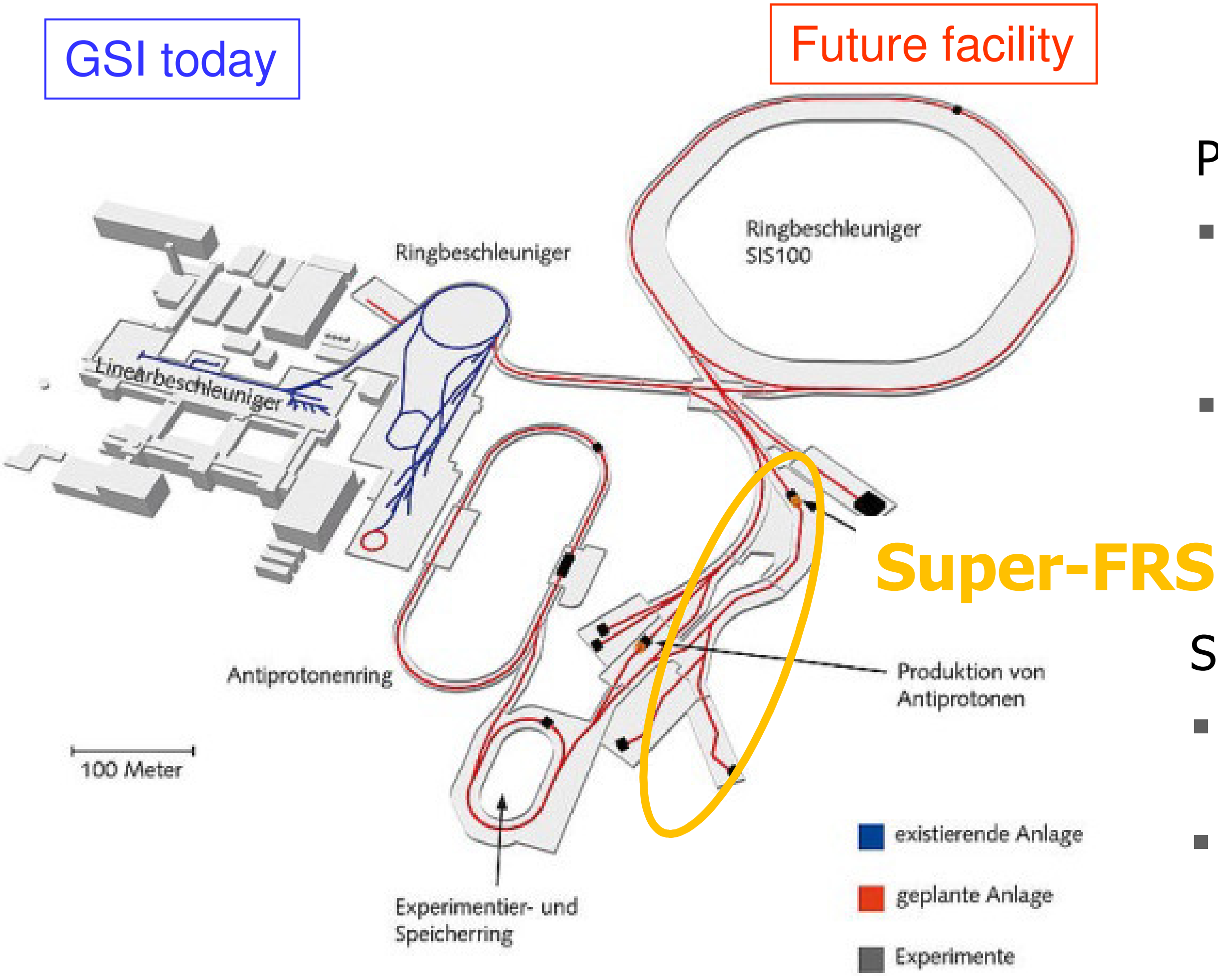
- Introduction to the Super-FRS at FAIR:
  RIB production and separation method

- In-flight particle identification (PID) of relativistic heavy ions at Super-FRS: ToF requirements & developments

- In-beam tests of focal plane ToF detector prototypes:
  - diamond (pcCVD) & silicon material properties
  - electronics role
  - irradiation and damages

The NUSTAR facility at FAIR



Primary Beams

- $5x10^{11}$ $^{238}U^{28+}$ (pulsed)
  $3.5x10^{11}$ $^{238}U^{28+}$ (DC)
  @1.5 GeV/u
- factor **100** in intensity over present

Secondary Beams

- broad range of RIBs up to 1-2 GeV/u
- up to factor **10000** in intensity over present

In-flight PID

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

atomic number

$$A/Q = \frac{B\rho}{\gamma\beta m_u}$$

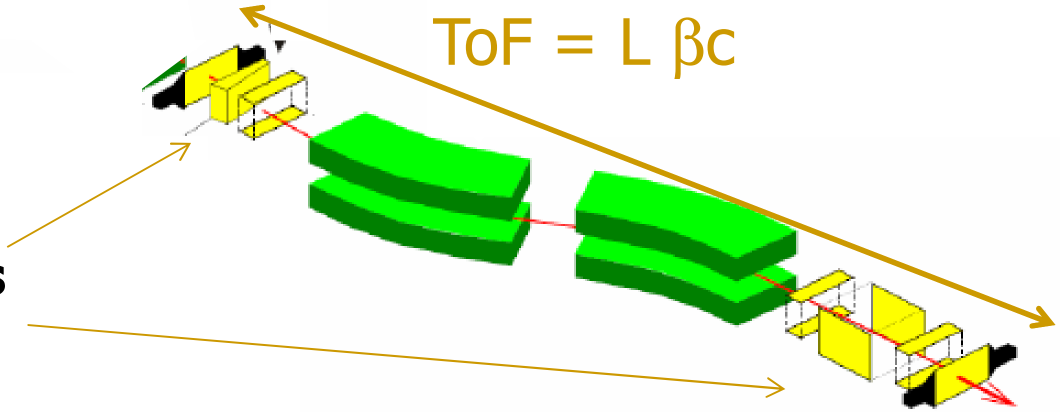
Z ≠ Q charge state

Bρ – ToF – ΔE method

$$A = \frac{T_{\mathrm{KE}}}{(\gamma - 1)\, m_u}$$

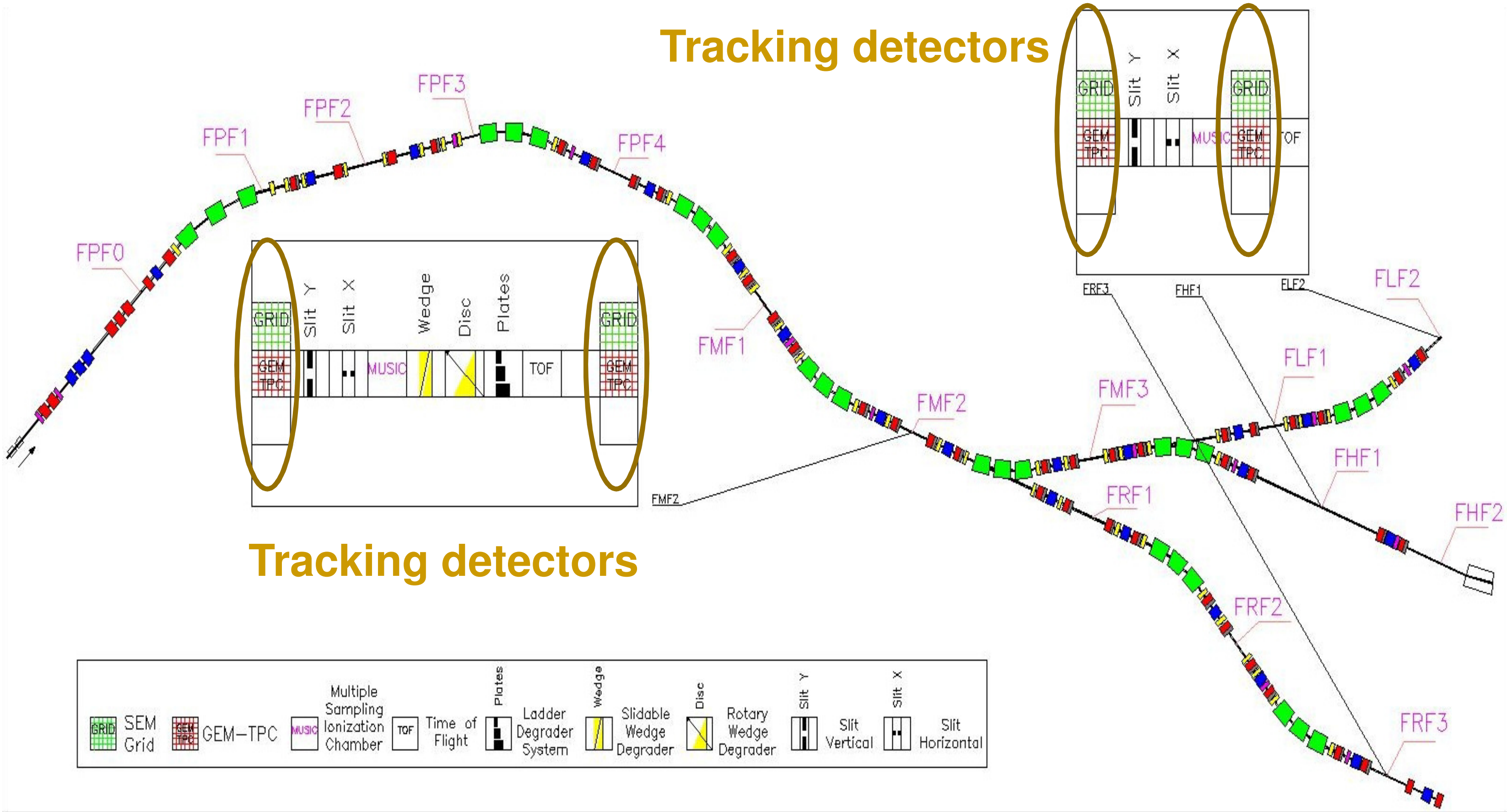
mass number, T_{KE} kinetic energy

$$Q = \frac{A}{A/Q}$$



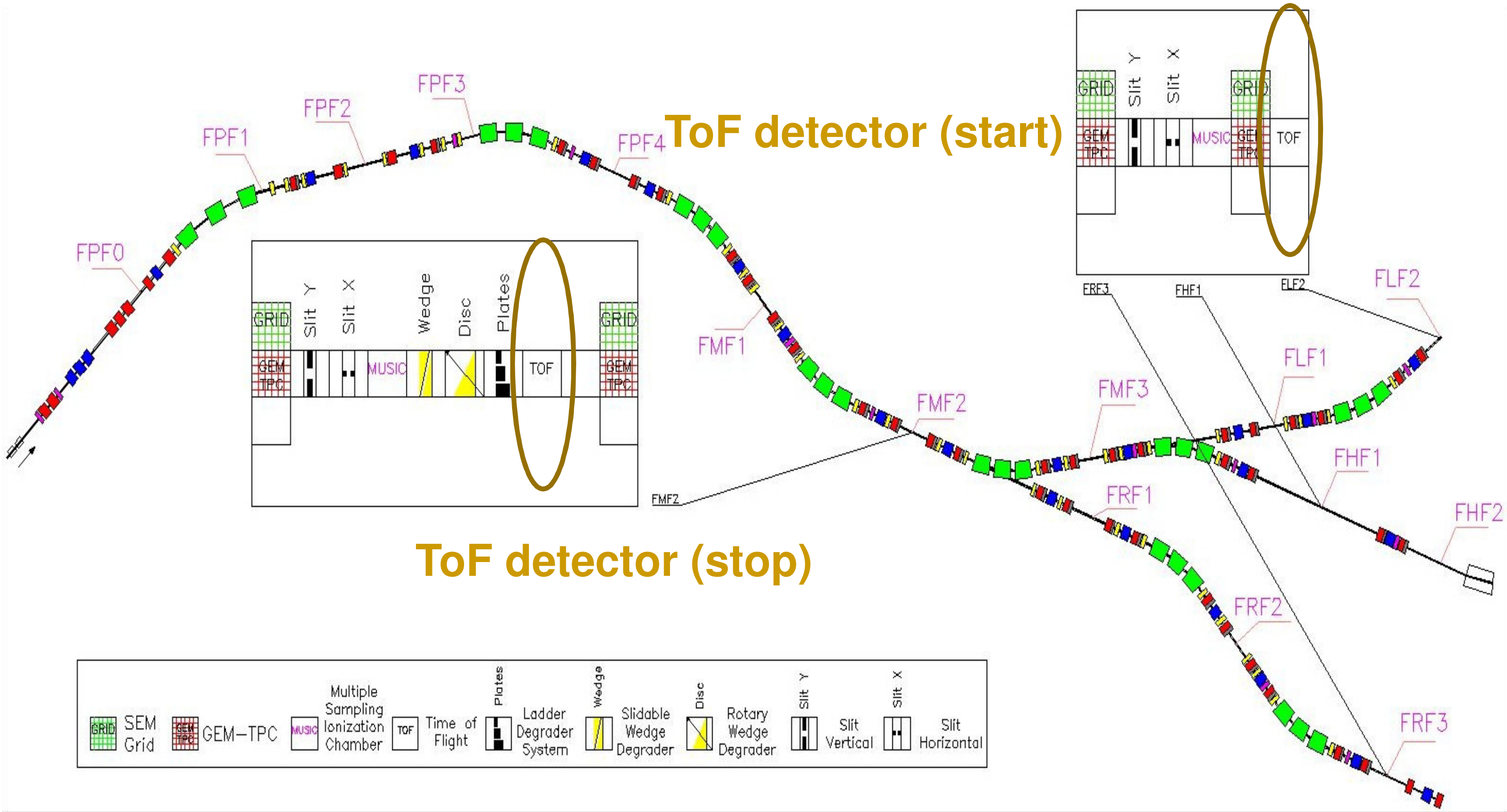
Detectors

Super-FRS layout



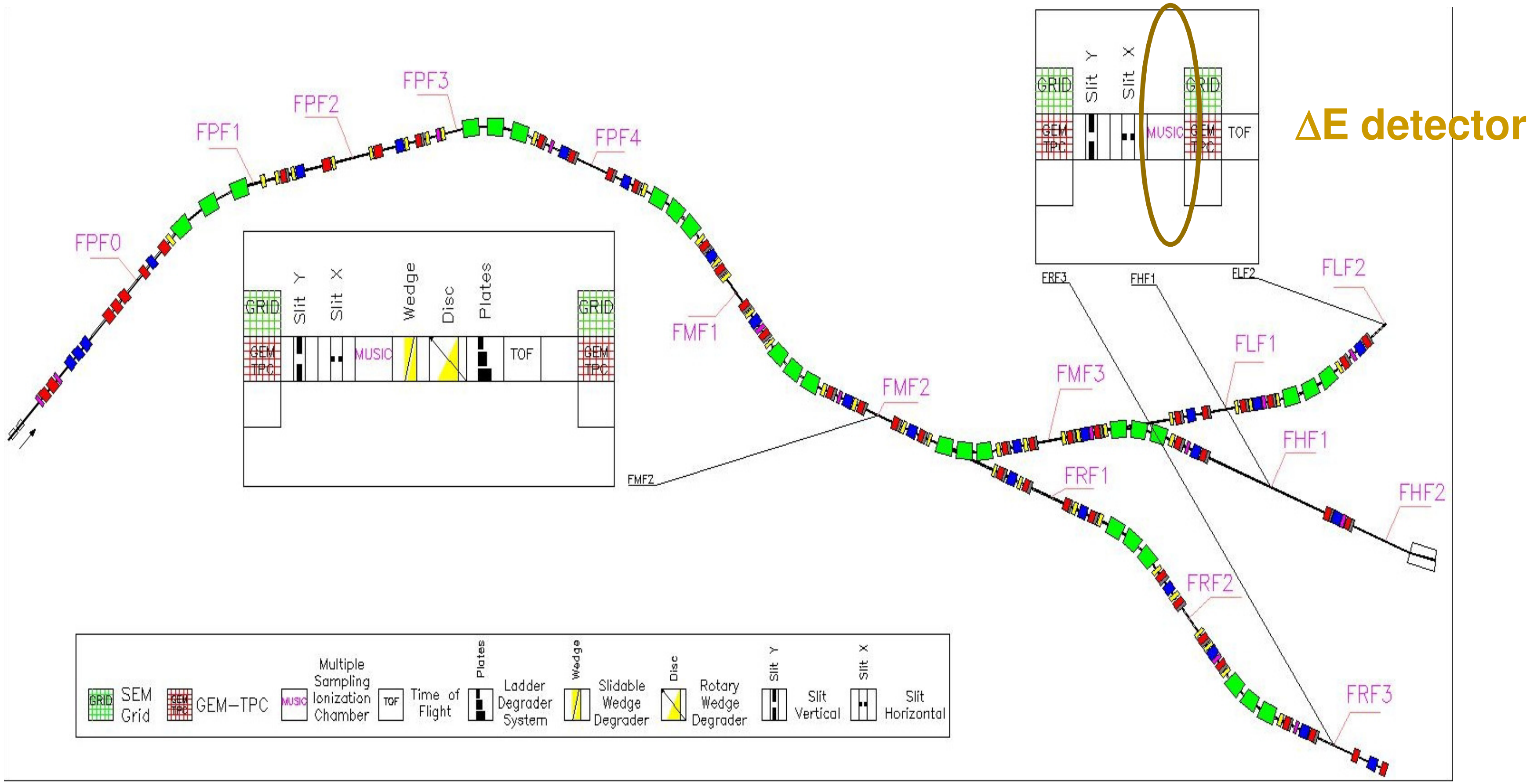
Intensity 10^{11}/s $<10^{10}$/s $<10^{9}$/s $<10^{7}$/s $<10^{5}$/s

Super-FRS layout



Intensity	10^{11}/s	<10^{10} /s	<10^{9} /s	<10^{7} /s	<10^{5} /s

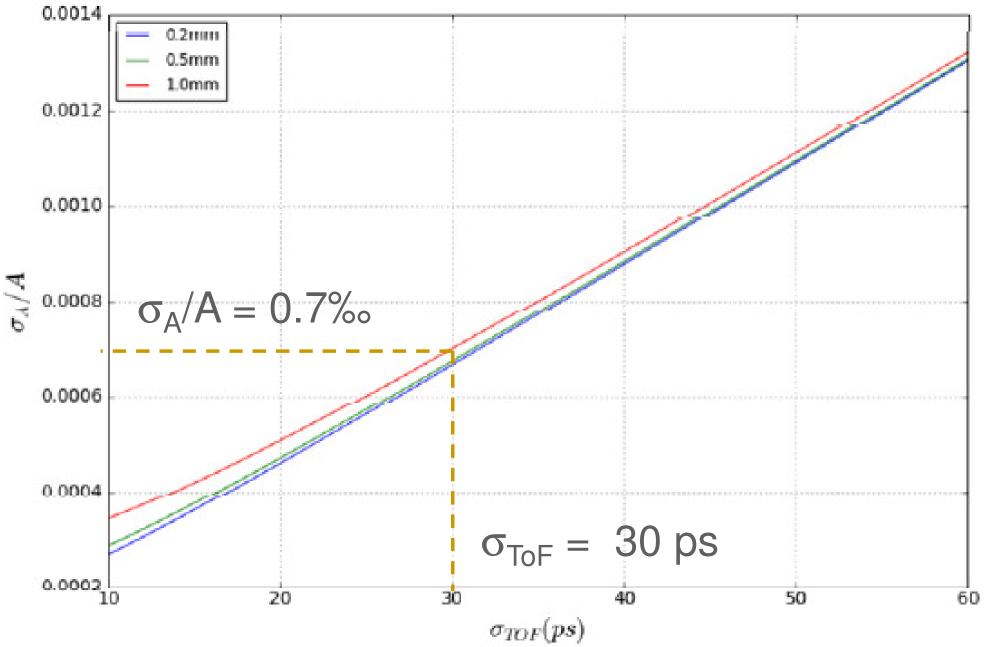
Super-FRS layout



Intensity 10^{11}/s $<10^{10}$/s $<10^{9}$/s $<10^{7}$/s $<10^{5}$/s

Requirements on A/q separation

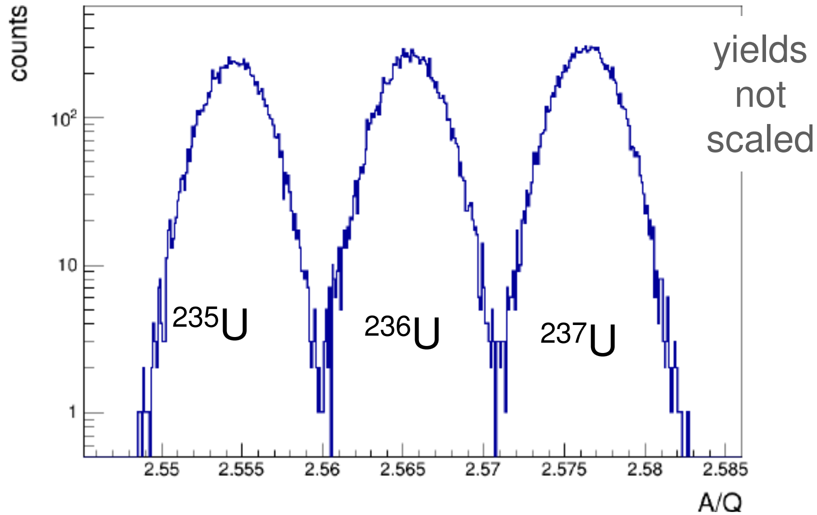
- Clean full isotope identification on event-by-event basis



$$\frac{\Delta A}{A} \approx \frac{\Delta B\rho}{B\rho} + \gamma^2 \frac{\Delta ToF}{ToF}$$

β = 0.8, L = 55 m

Monte Carlo simulations (MOCADI)



σ_x = 0.5 mm, σ_t = 20 ps

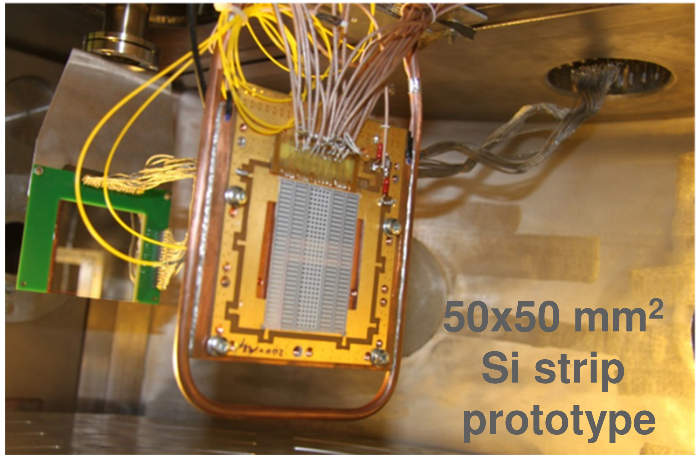
C. Nociforo, NUSPIN 2017

ToF detector requirements

- homogeneous and large-area material (total 70000 mm^2)
- start/stop fast (triggering) signals

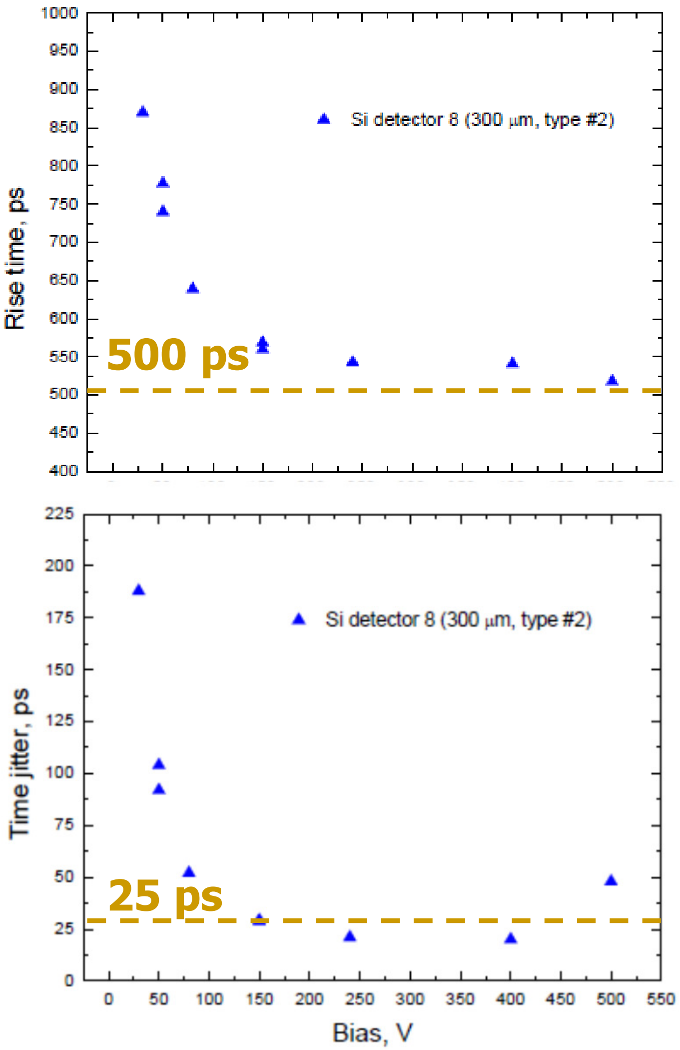
→ ToF silicon/diamond strip detectors arranged in planar geometry

  - total channels (strips): 1400 chs
  - timing resolution (full): σ_t < 35 ps, σ_t = 20 ps for U
  - rate capability: 0.5 kHz/mm^2 , < 15 kHz/strip
  - activity: < 1 kGy/year
  - FEE-sensor distance: > 550 mm
  - readout: FPGA, e-link interface
  - full remote control
  - timestamping



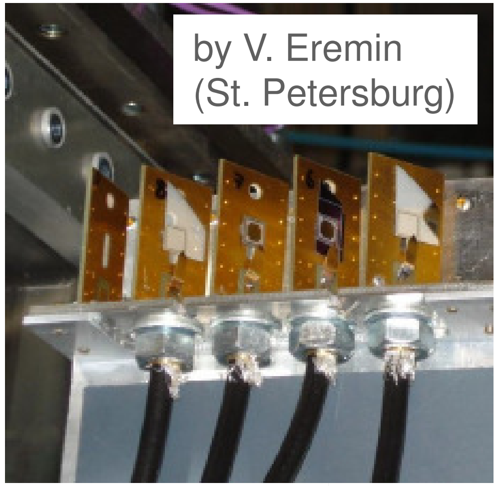
Silicon time properties

^{197}Au @750MeV/u

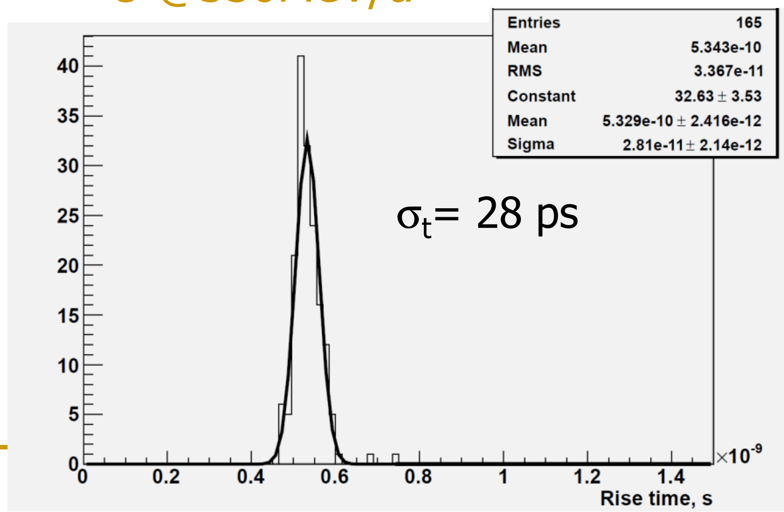


- matched to Si-strip capacity (ρ= 10 kOhm cm)
- digital waveform sampled (2GHz bandwidth scope)
- time jitter ~ 20 ps

Si samples

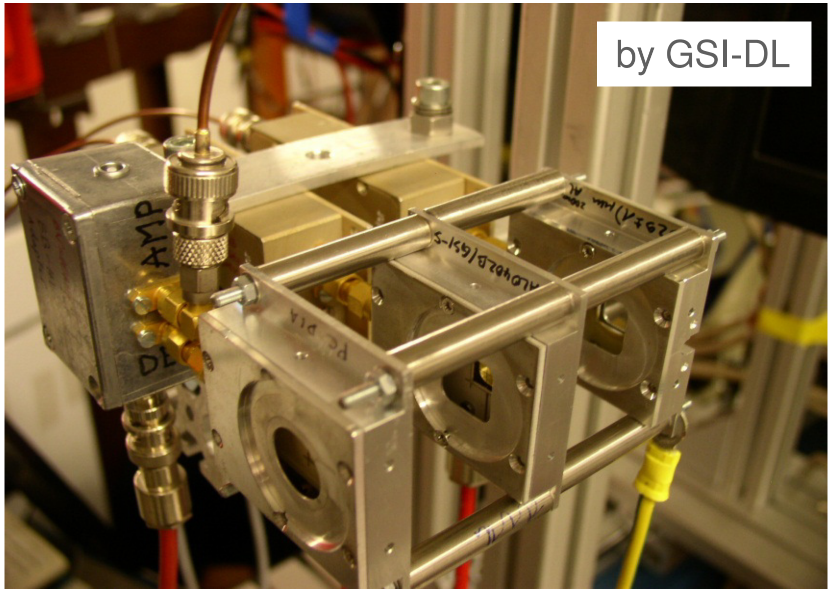


^{238}U @350MeV/u



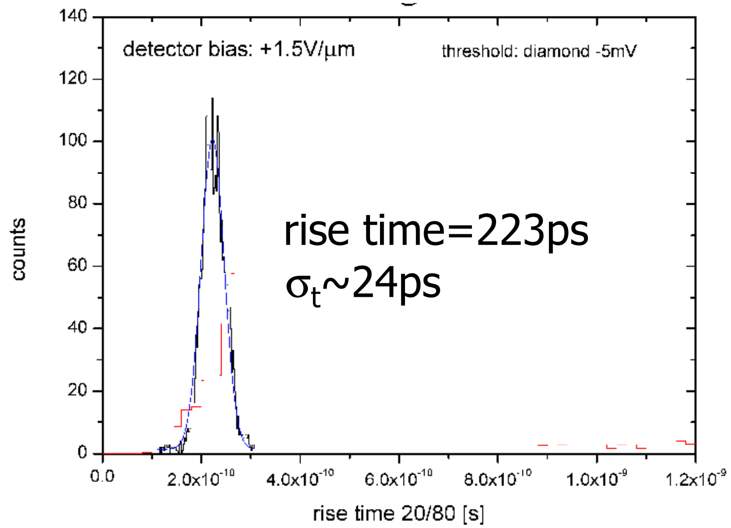
Diamond time properties

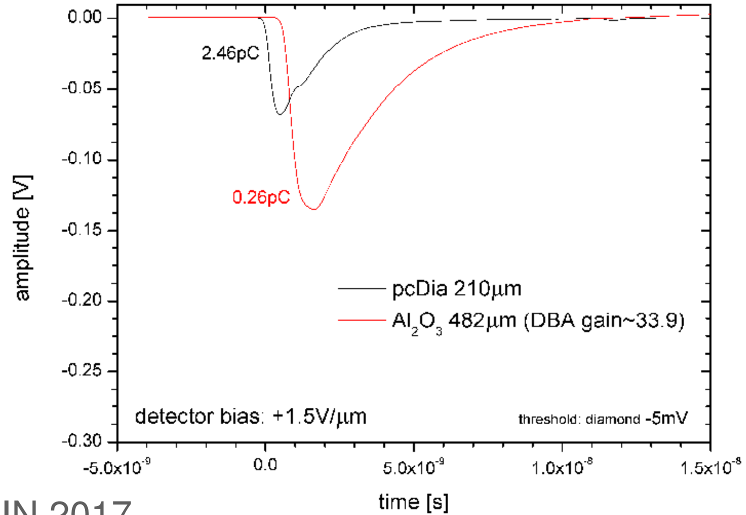
pcCVD -DD **10x10x0.2 1 mm^3**



- digital waveform sampled
  (20 GS/s scope)
- small charge collection Q=2.46pC

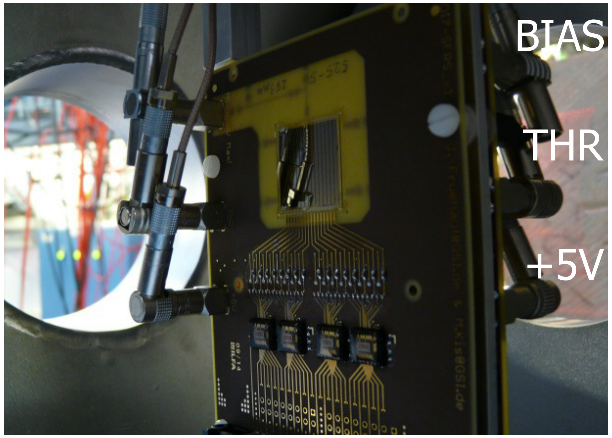
^{238}U @350MeV/u

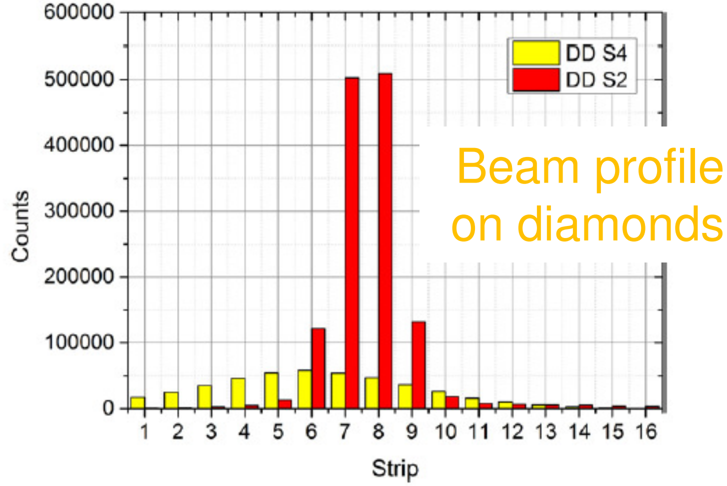




ToF measurements at FRS

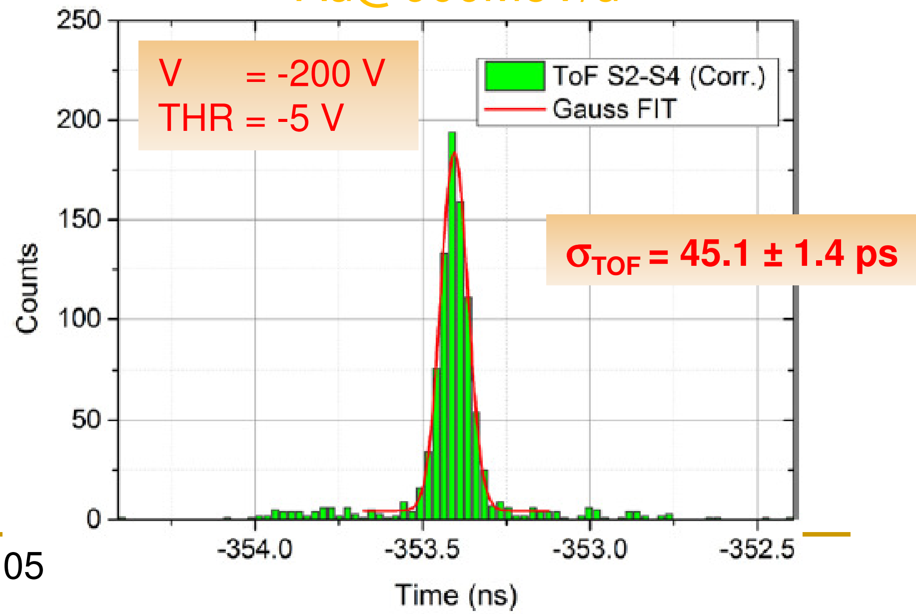
2 x ***pcCVD -DD*** **20x20x0.3 mm³**





- 16-strip design: (1x18) mm² each (0.15 mm gap), C = 4.3 pF/strip
- metallization: 50nm/100nm (Cr/Au) by photolithography (GSI-DL)
- PADI7 4x4chs

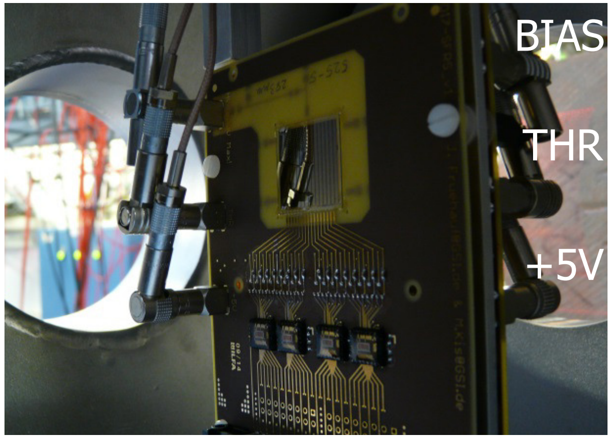
^{197}Au@900MeV/u



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

ToF measurements at FRS

2 x ***pcCVD -DD* 20x20x0.3 mm³**



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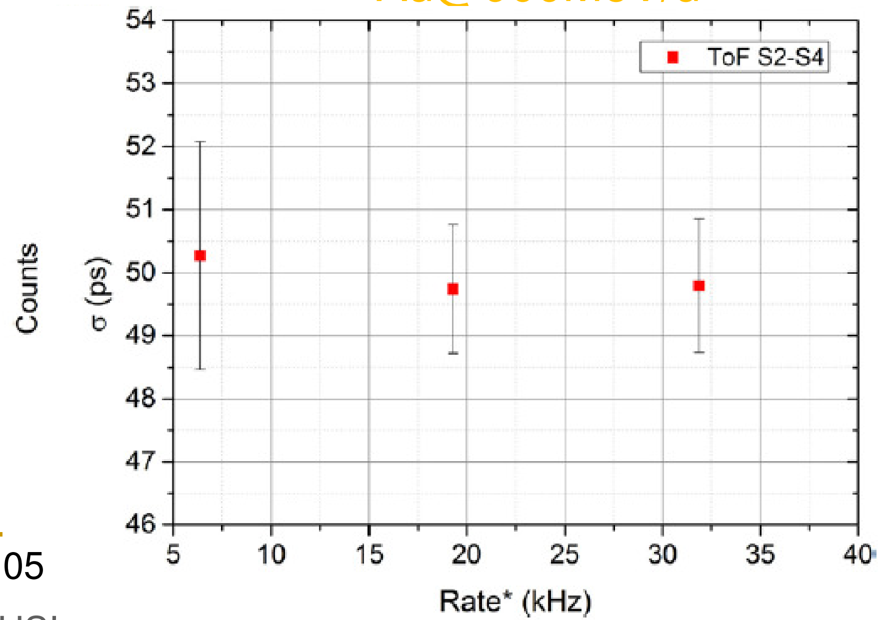
- metallization: 50nm/100nm (Cr/Au) by photolithography (GSI-DL)
- PADI7 4x4chs

- no rate dependence observed

^{197}Au@900MeV/u



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

σ_{DD} contribution

S2-S4 Detector resolution

$$\sigma_{DD} = \sqrt{\sigma_{ToF}^2 - \sigma_j^2} = \sqrt{(45.1)^2 - (15)^2} = 42.5 \text{ ps}$$

$\sigma_{DD1} \sim 25$ ps

$\sigma_{DD2} \sim 35$ ps

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

- **VFTX** (28 chs) VME FPGA TDC
  - LVDS inputs
  - 200 MHz clock (external & internal)
  - $\sigma_t < 10$ ps

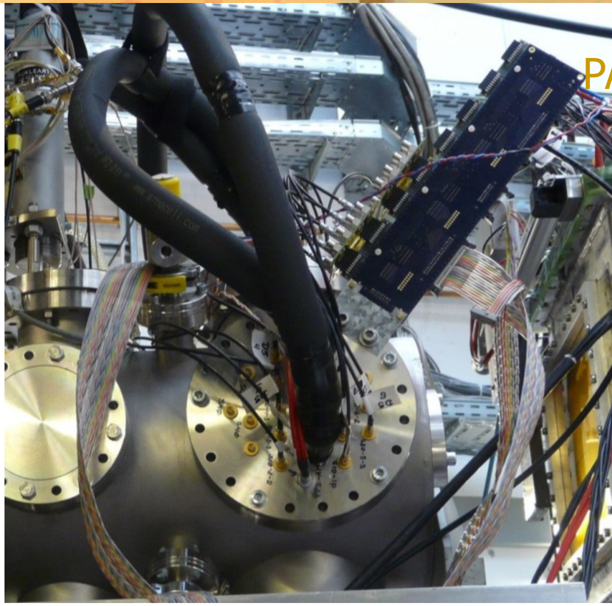
(https://www.gsi.de/fileadmin/EE/Module/Dokumente/vftx1_8.pdf)

- **PADI** ASIC 180 nm CMOS
  - rise time < 500 ps
  - 30 fC <Q< 2000 fC
  - $\sigma_{tE} < 15$ ps
  - LVDS digital outputs
  - 350 MHz bandwidth
  - gain 250

(M. Ciobanu et al., IEEE Transactions on Nuclear Science, vol.58, no. 4, p. 2073, Aug. 2011)

Silicon in-beam tests

- detectors cooled (T= -20°C) and overbiased for good timing
- ToF between one strip and small pad measured by PADI6 + VFTX



^{197}Au@900MeV/u

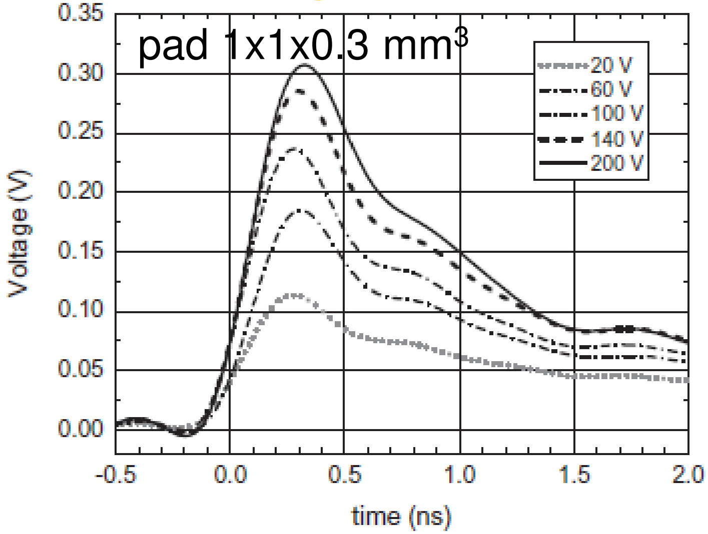
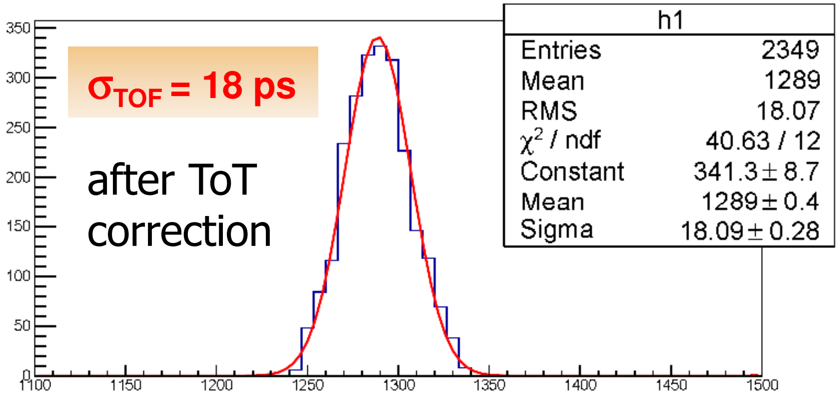


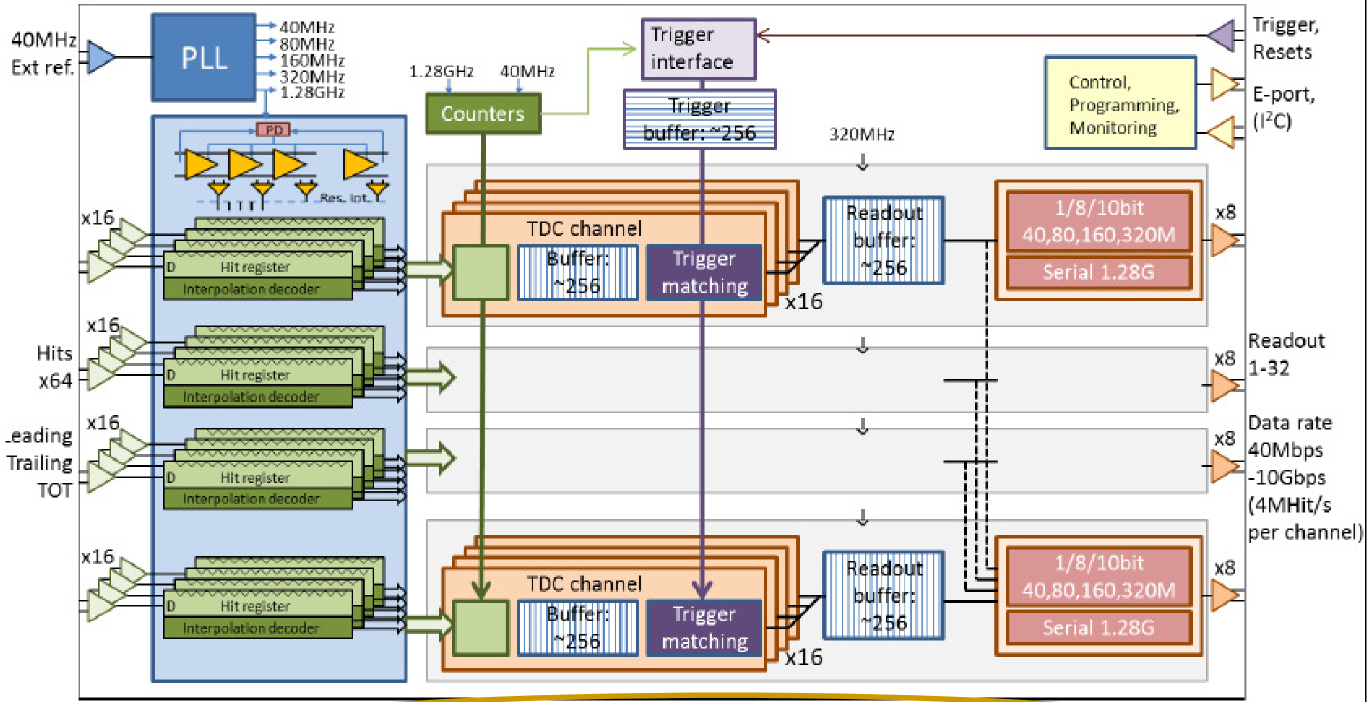
Fig. 2. Current response of the pad detector at different bias voltages.



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

TDC architecture in 65 nm

picoTDC Architecture

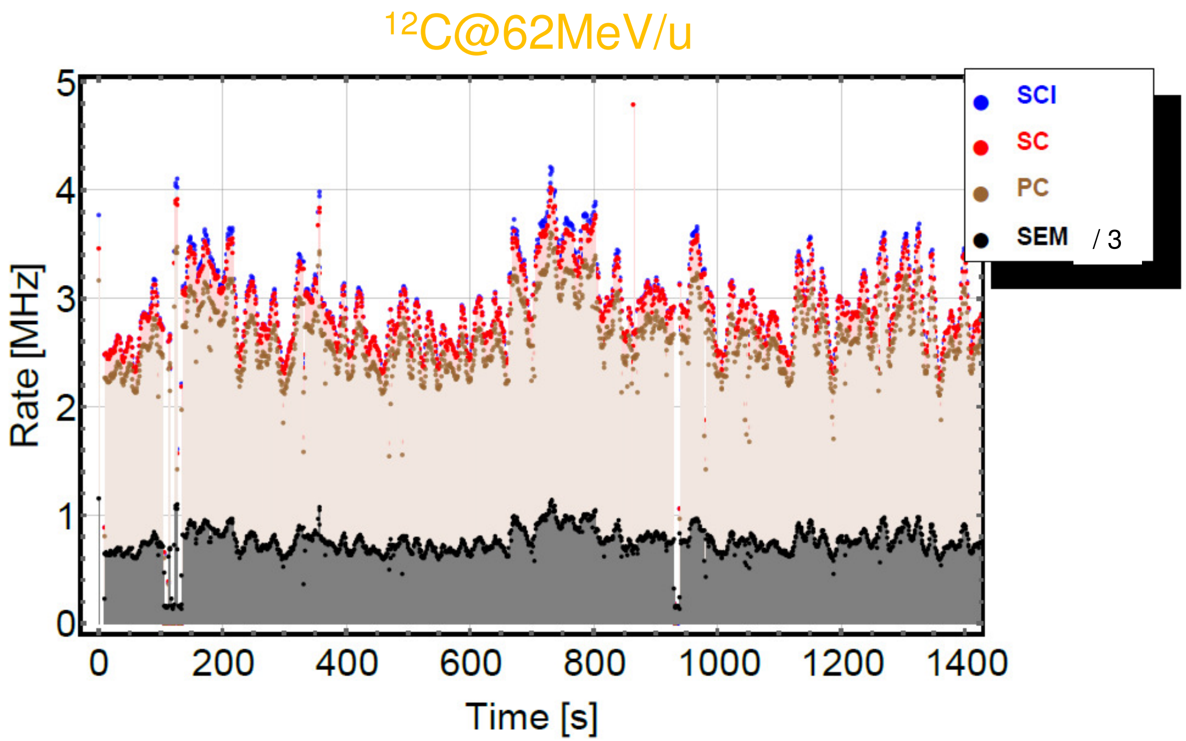


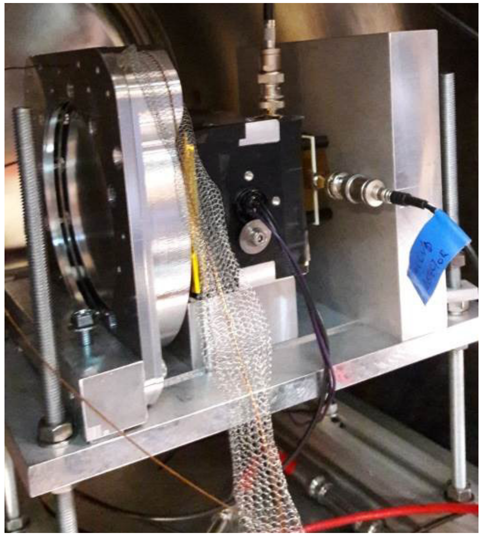
64 channels, 3ps or 12ps time binning, 100us dynamic range

64 channels, 3ps: ~1W; 64 channels, 12ps: ~0.5W; 32 channels, 12ps: ~0.3W

Comparison diamond vs scintillator

Calibration of SEM monitor vs **scCVD-DD 3.23x3.23x0.16 mm^3** and **pcCVD-DD 18x18x0.3 mm^3** tested with broadband current sensitive amplifiers (DBA (P. Moritz, GSI), PA-20 (M. Jastrzab, IFJ Cracow)

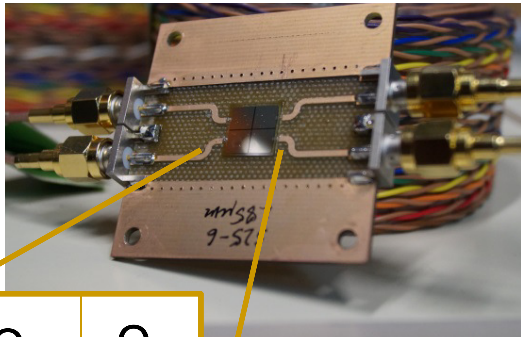


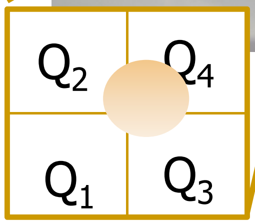


- collimator Ø 2.5mm
- SEM monitor Ø 100 mm
- plastics SCI 100x100x0.25 mm^3

Irradiation tests at LNS-INFN, 2016

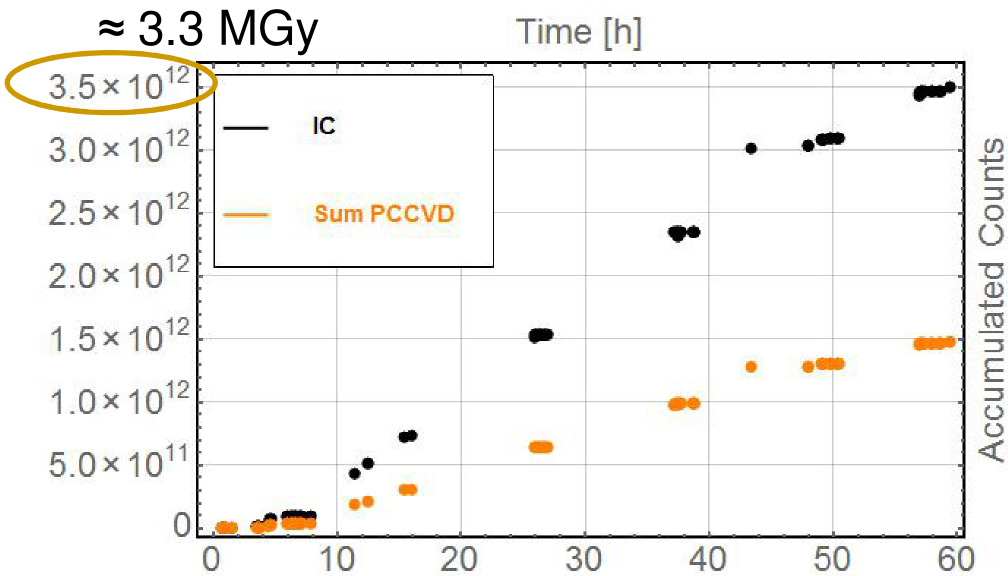
Series of irradiation of **10^7 $^{12}C/mm^2$ s** followed by data taking via digital scope (10 GS/s) at low rate to monitor the time resolution and CCE of **pcCVD-DD (10x10x0.3 mm^3)** and **scCVD-DD (2x2x0.09 mm^3)**





collimated beam

^{12}C@62MeV/u



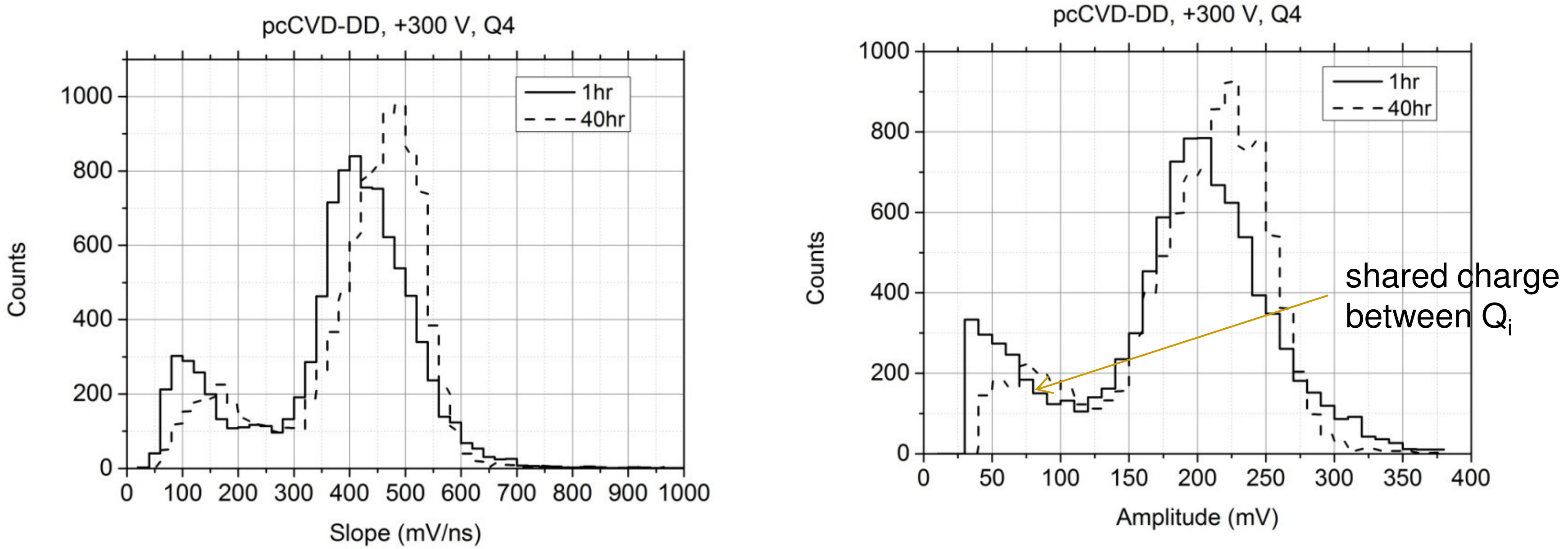
$E_{loss} \approx 36$ MeV
(comparable to ^{40}Ar@2GeV/u)

- discrepancy due to pile-up in diamond signals

Digital waveform analysis (pcCVD-DD)

^{12}C@62MeV/u

V = 300 V
THR = -30 mV



- no degradation of the signal observed at the end of the irradiation

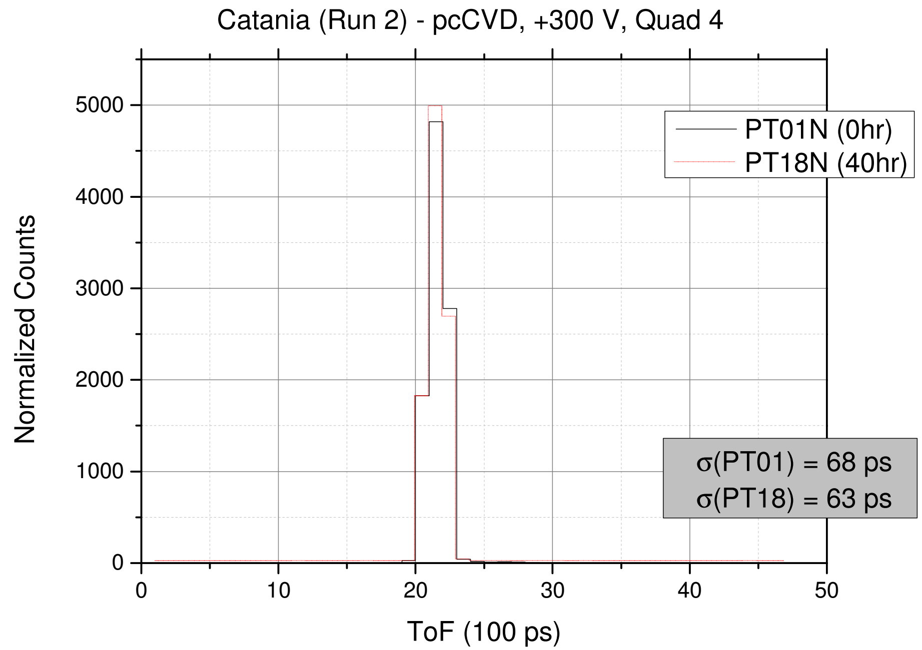
C. Nociforo et al., EPJ Web Conf. 117 (2016) 10007

Digital waveform analysis (pcCVD-DD)

ToF: Q_4 pcCVD-DD & scCVD-DD

^{12}C@62MeV/u

V = 300 V
THR = -30 mV



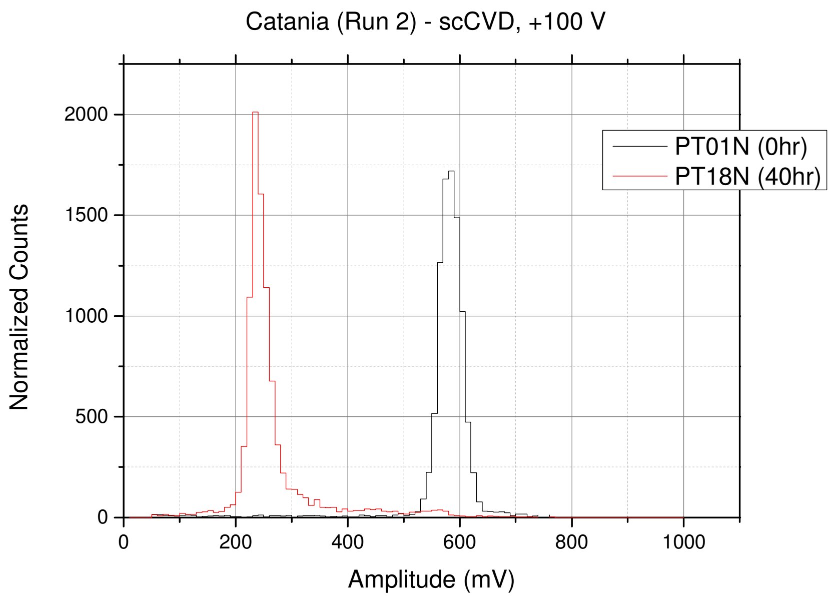
- no change in the measured ToF at the end of the irradiation

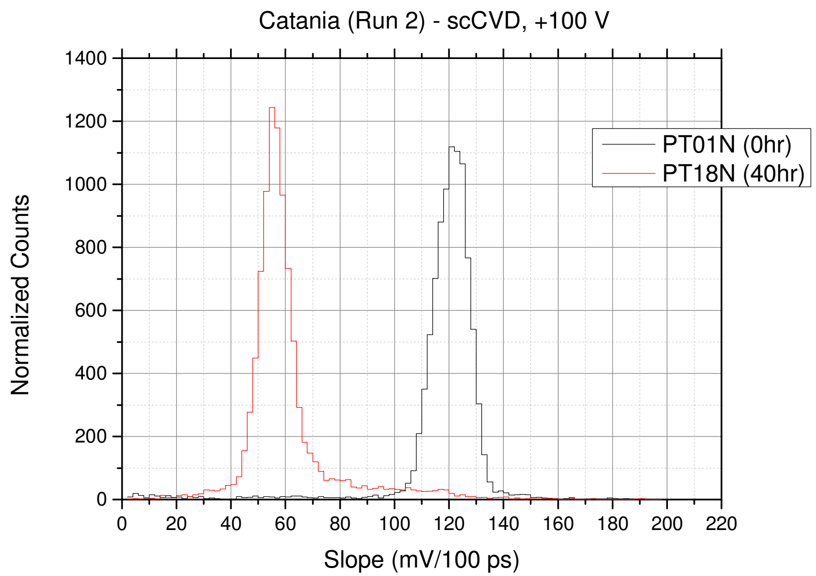
C. Nociforo et al., EPJ Web Conf. 117 (2016) 10007

Digital waveform analysis (scCVD-DD)

V = 100 V
Thr = -30 mV

^{12}C@62MeV/u



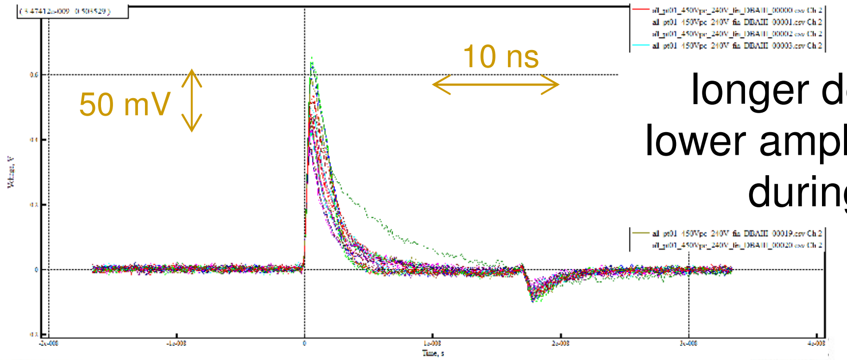


x scale to be multiplied by 10 and dimensions written as mV/ns

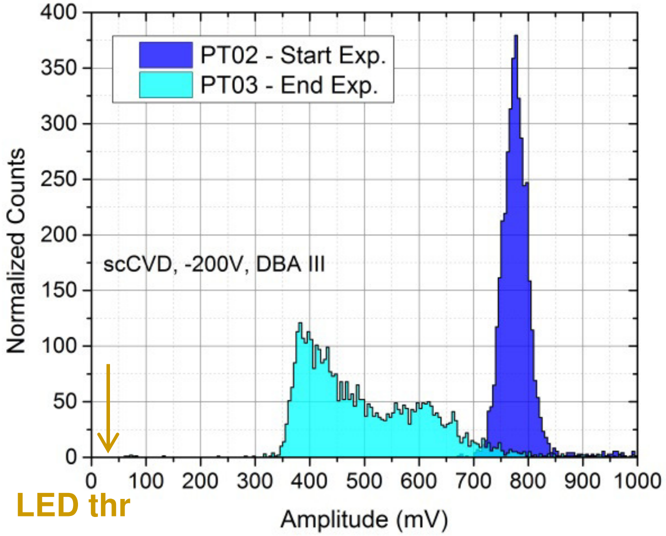
- shift observed after about 12 hours of irradiation, kept constant until the end

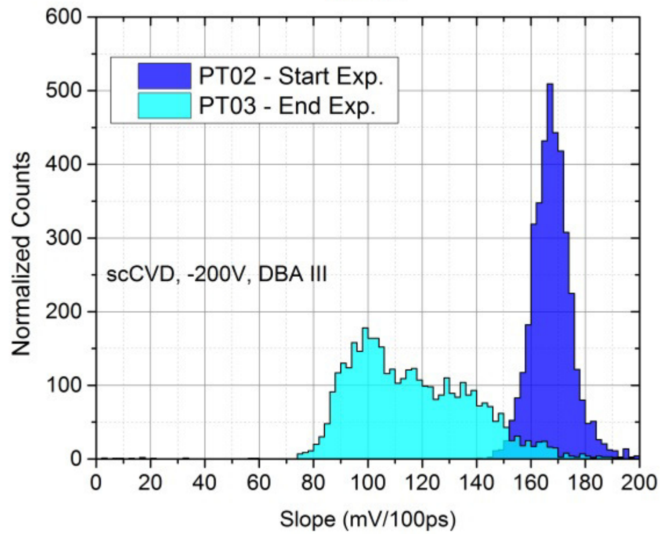
Damage effects (scCVD-DD)

$^{12}C@62MeV/u$



longer decay time and lower amplitude, appearing during irradiation





- final amplitude distribution is well above threshold

Summary

To obtain a clean PID at Super-FRS:

- ToF detectors with timing resolution σ_t ~ 20 ps are required

  → in-beam tests of silicon and diamond strip detectors 0.3 mm thick (^{197}Au@900 MeV/u) show that by using pico-seconds electronics the required time performance is achievable

  → irradiation test results (^{12}C@62MeV/u) indicate pcCVD diamonds as superior material for application in high radiation level environment.

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