A hydrogen-filled TPC as an active target for a proton-radius measurement at CERN

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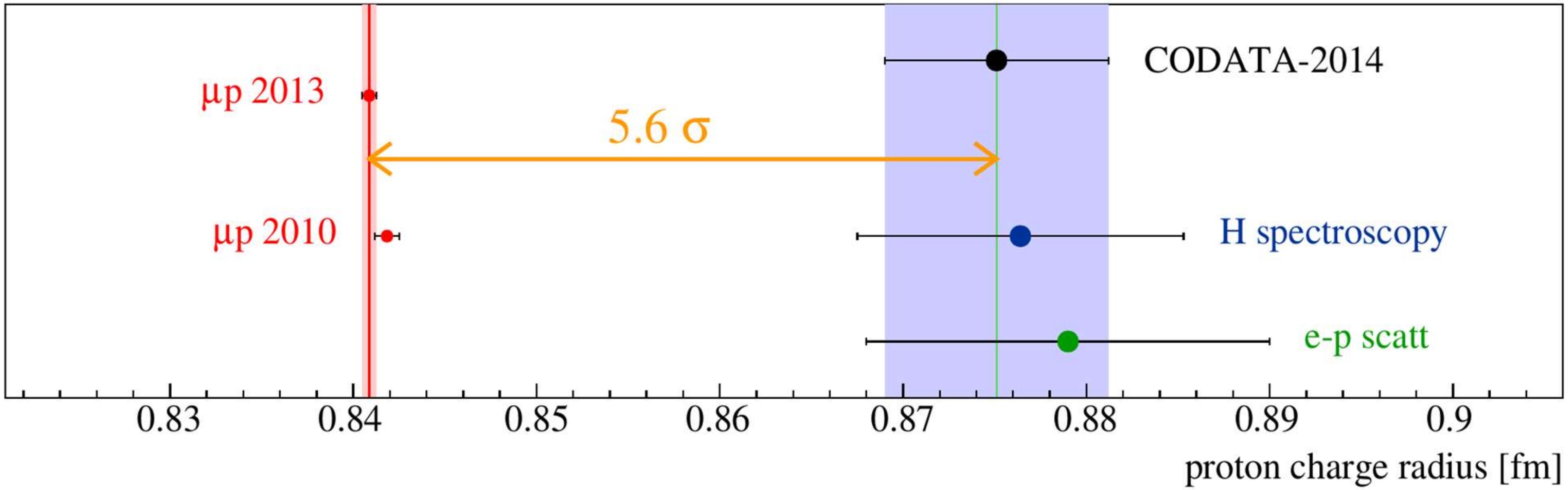
Proton radius puzzel



J. J. Krauth et al., 2017 [arXiv:1706.00696]

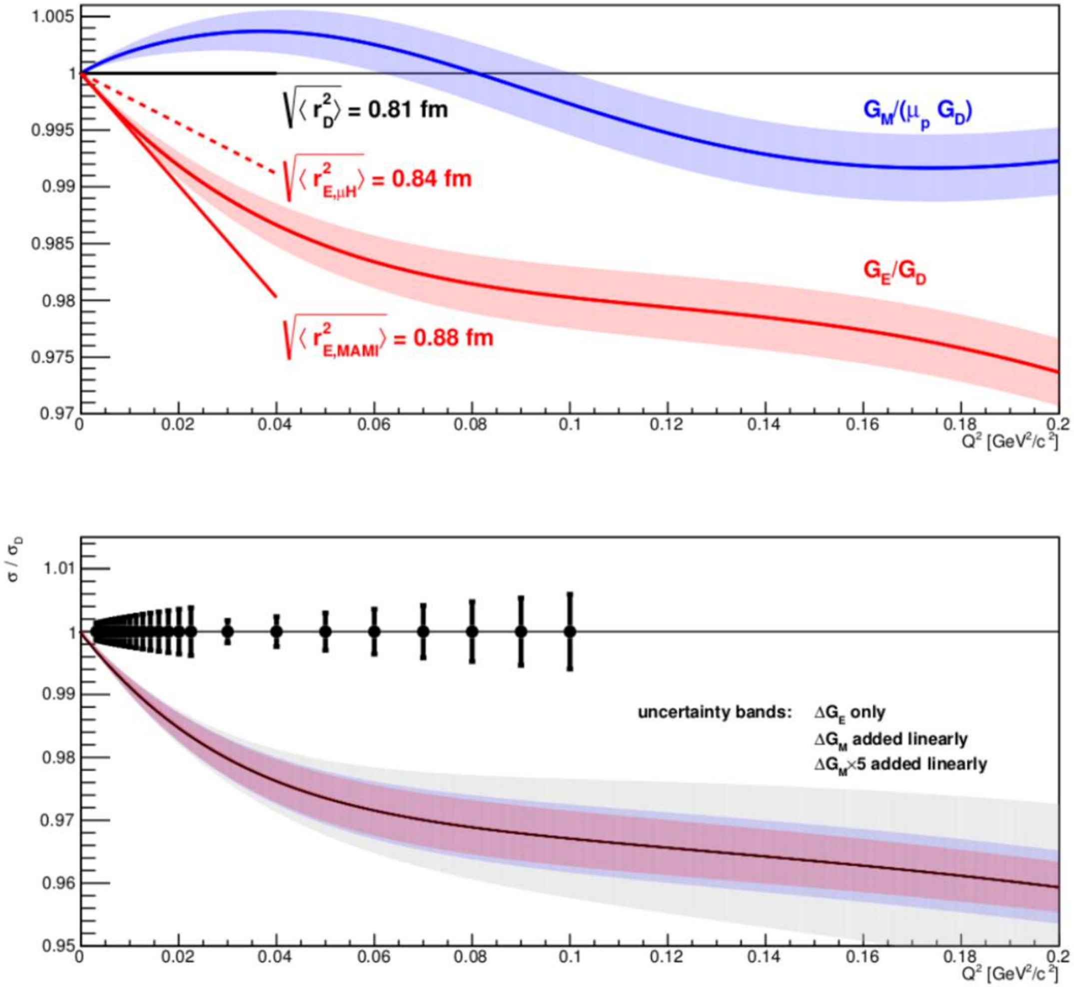
- CODATA: ep-scattering, H- and D-spectroscopy
- Too large discrepancy
- Proton radius is an important value for nuclear and particle physics

New Letter of Intent

CERN-SPSC-2019-003 / SPSC-I-250
14/01/2019

A New QCD facility at the M2 beam line of the CERN SPS: COMPASS++/AMBER

Slope of the form factor vs radius



Smaller (as for e-p scattering) QCD radiative corrections

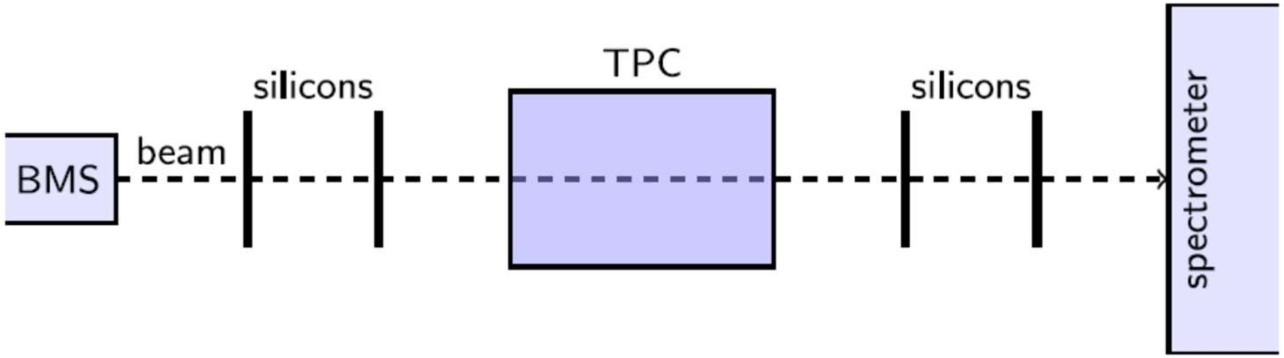
Proton radius measurement at CERN

General idea: measure the proton form factor slope using the high-energy muon beam on a high-pressure hydrogen target

In a one-year measurement, we estimate to achieve a precision of ~0.01fm on the proton radius, thus contribute to resolve the proton radius puzzle between

0.84 fm (muonic hydrogen laser spectroscopy)

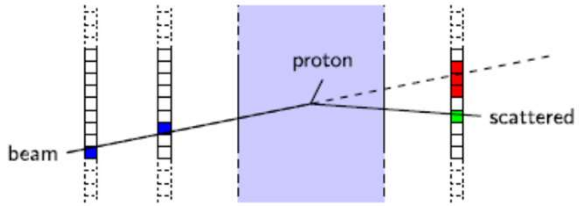
0.88 fm (electron scattering)



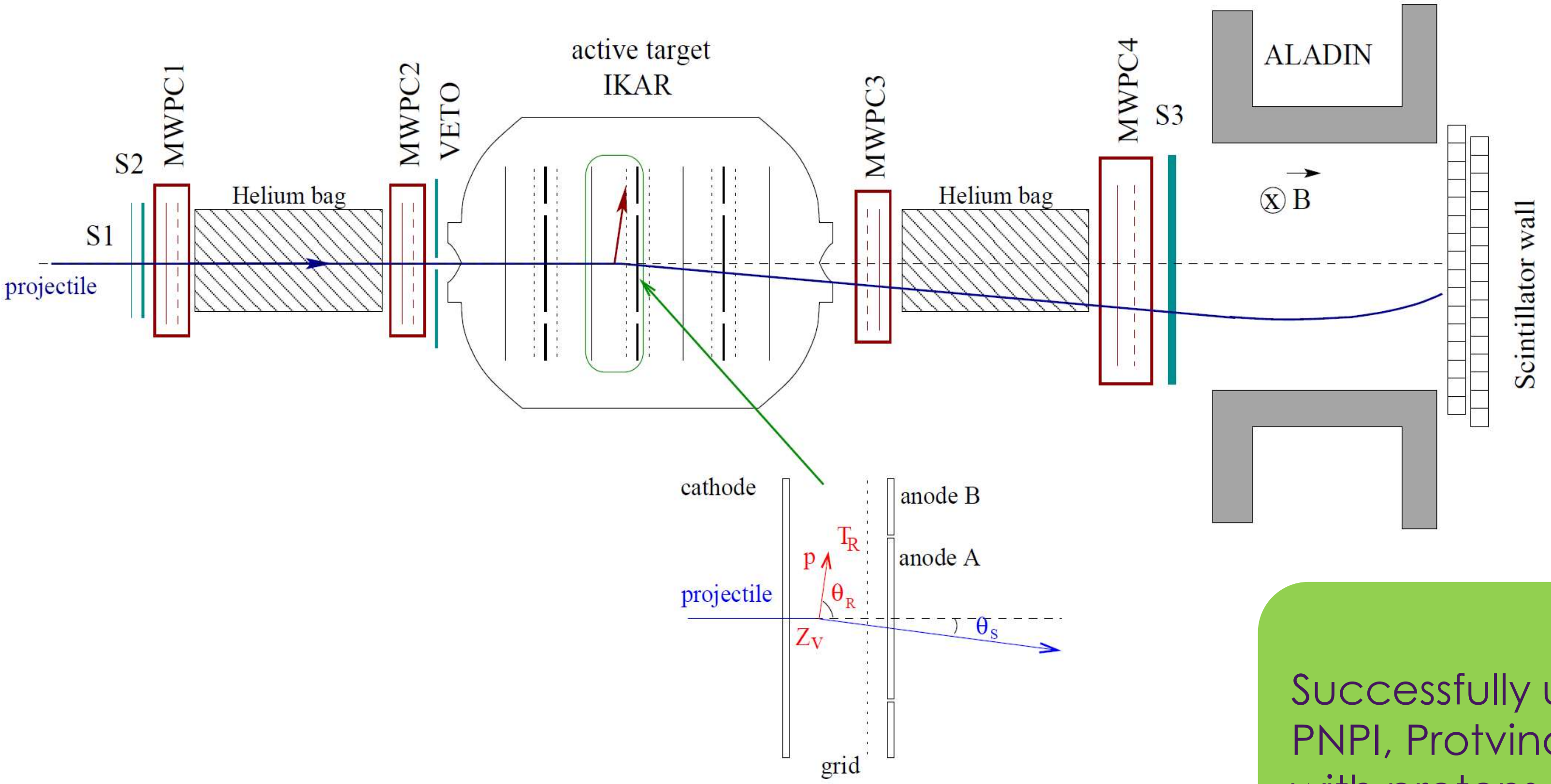
trigger concepts under study:

triggerless readout (for 2e6…2e7/s)

kink trigger (for Q^2 >3e-4)



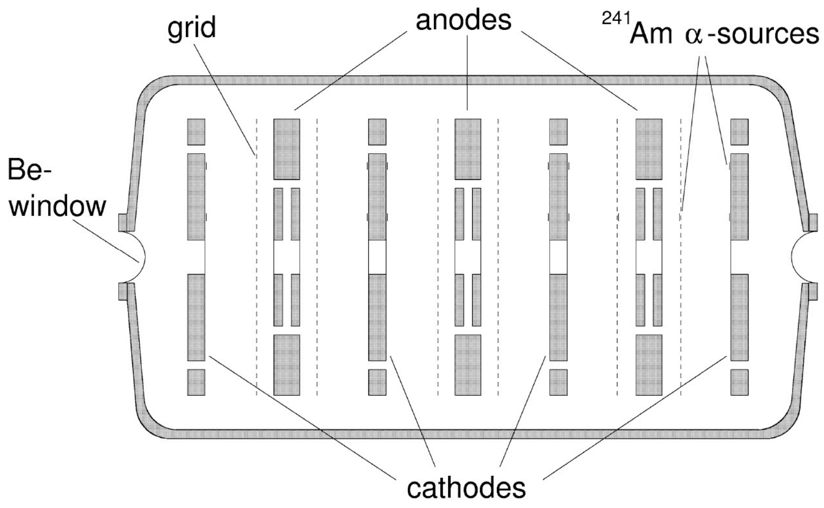
Setup with ionization chamber IKAR

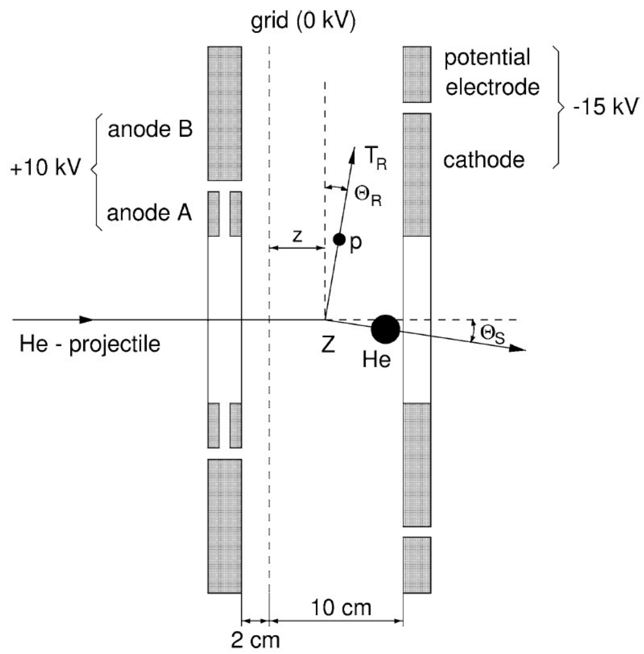


"Classical" ionization chamber, built at PNPI
Pressure up to 10 bar
Diameter of inner anodes – 20 cm, of outer – 40 cm
Normally filled with pure H_2 but D_2, He are also possible
6 independent detection modules in the same gas volume

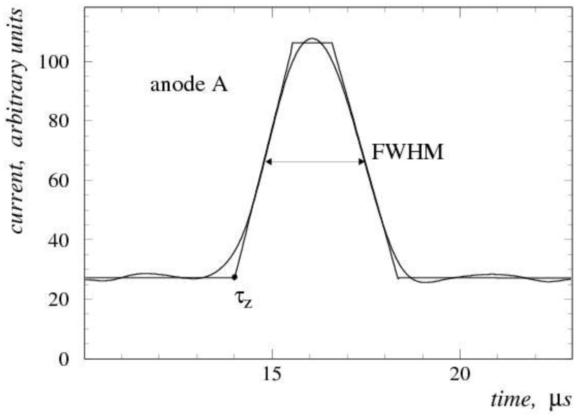
Successfully used at PNPI, Protvino, CERN with protons and at GSI with radioactive ions

Active target IKAR





- Electrodes out of Al, 140 μm
- Be windows, 0.5 mm
- Energy and time of drift measured by FADCs
- Energy resolution – 35-40 keV
- Energy threshold <100 keV
- Dynamic range for protons – 5.2 MeV



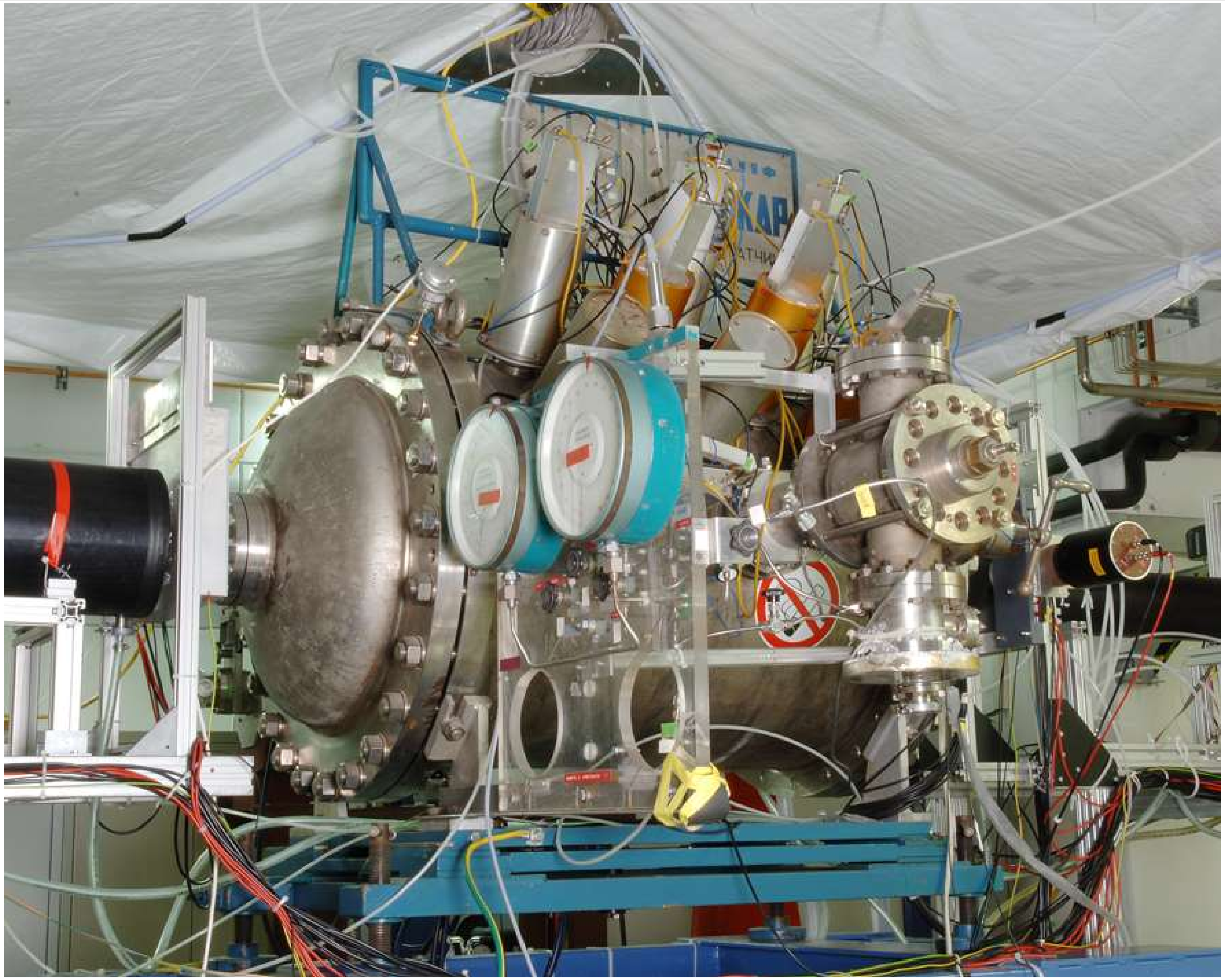
Pulse shape analysis

integral - recoil energy T_R

risetime - recoil angle Θ_R $(\delta\Theta_{R\ FWHM} < 0.6°)$

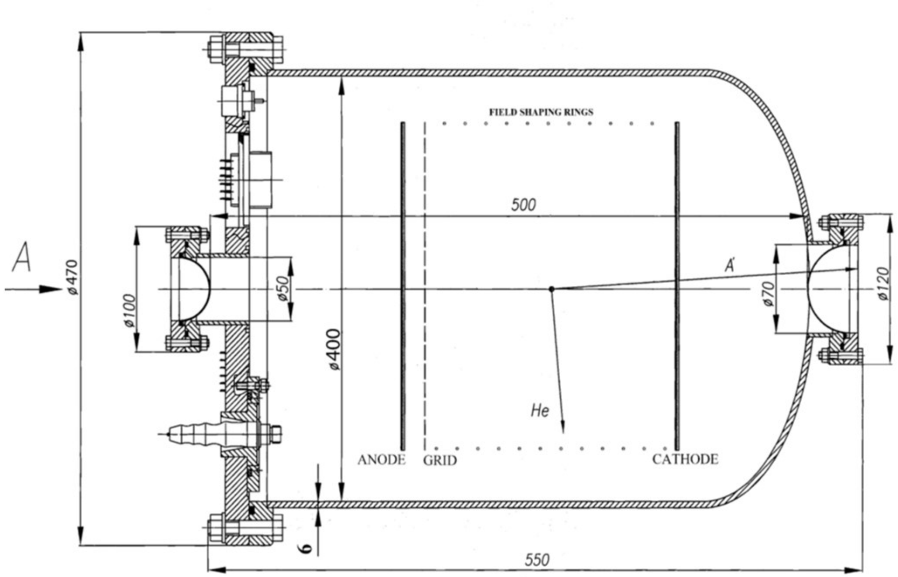
start - vertex point Z_V $(\delta z_{FWHM} < 110\ \mu m)$

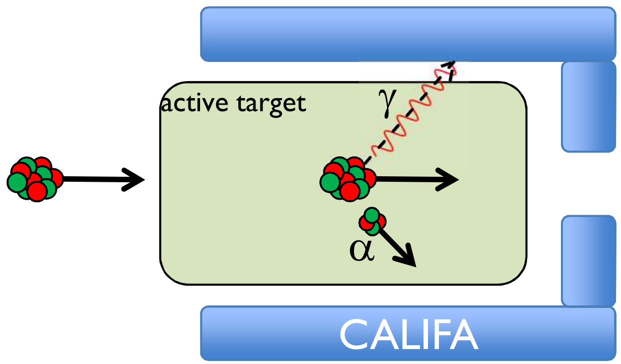
IKAR in Cave C



Active chamber ACTAF2 inside R3B calorimeter CALIFA

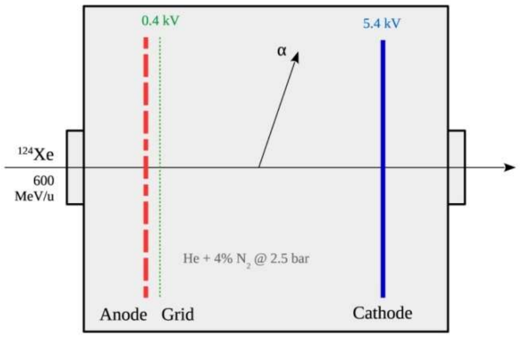
- Investigation of low-lying dipole strength in inelastic α scattering
- Experiments on stable nuclei show significant difference to (γ,γ‘)
- Extension to unstable nuclei in inverse kinematics
- He gas

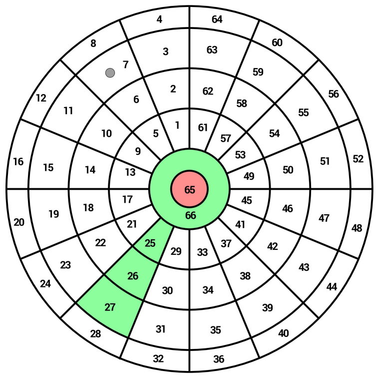


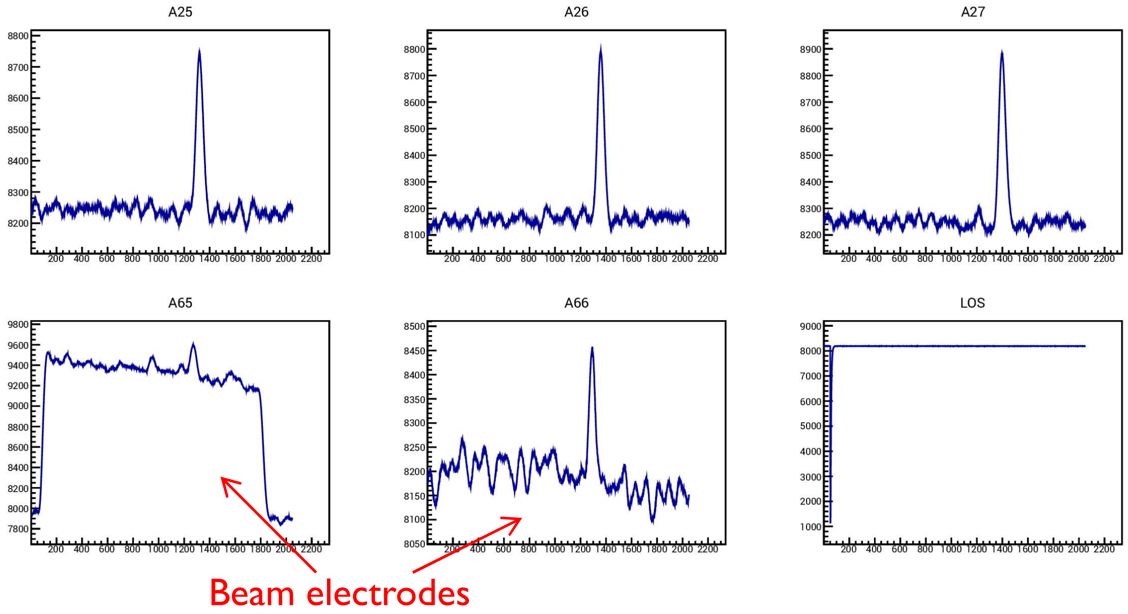


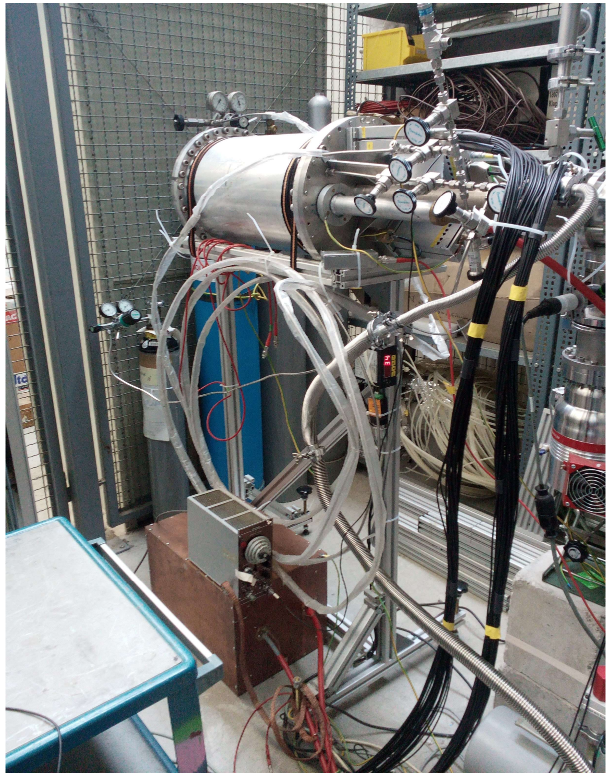
- Coincident determination of excitation and decay energy
- Allows selection of decay channel
- Clean separation of E1 excitation in (α,α‘γ) experiments

^{124}Xe(α,α') measurement with ACTAF2

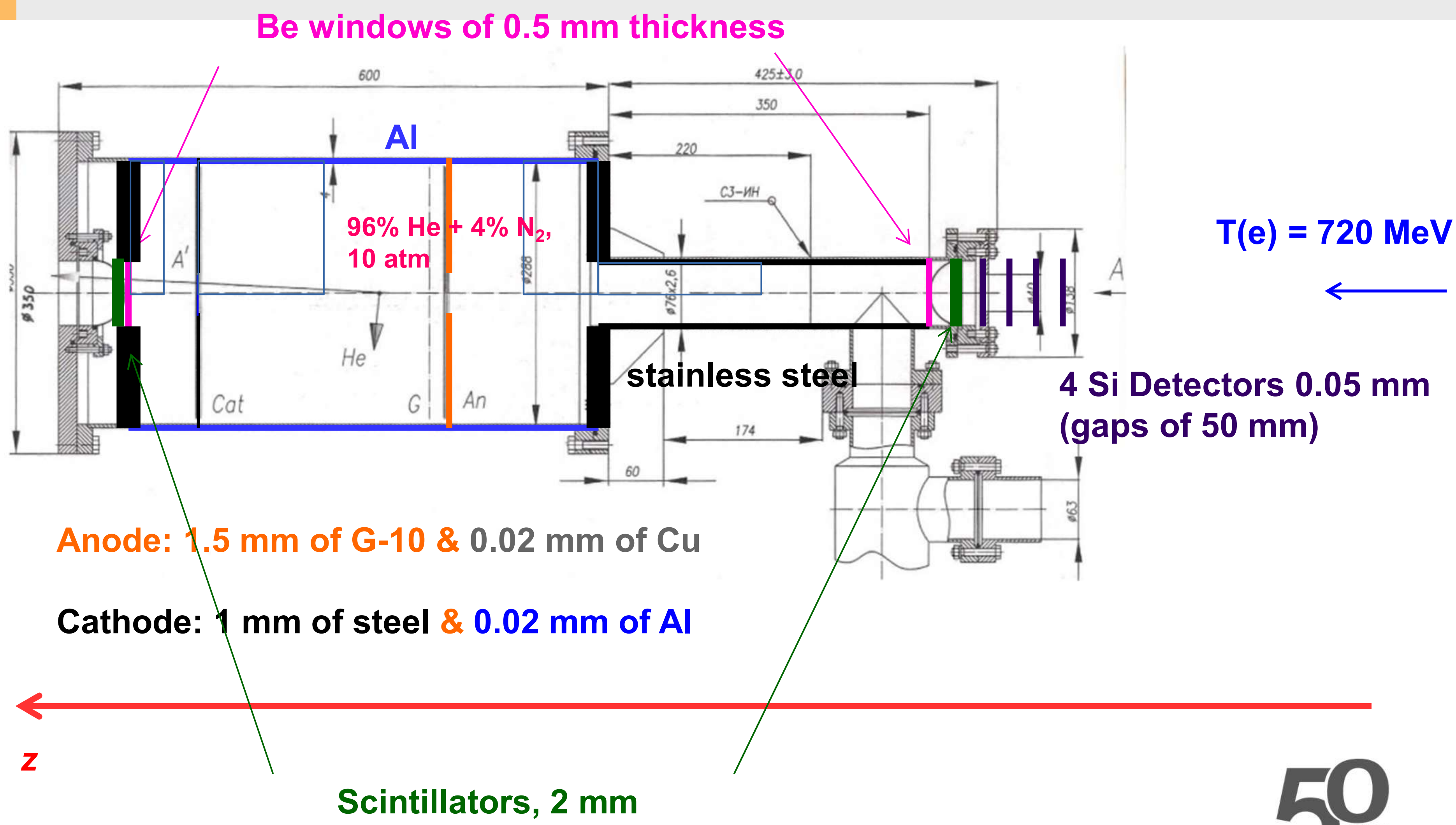






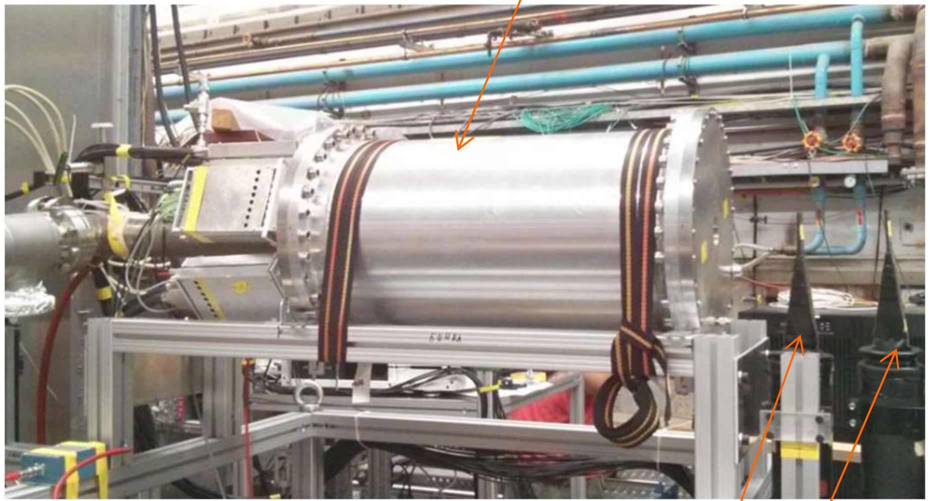


R3B ACTAF2 prototype – beam test at MAMI, 2017



Experimental conditions at MAMI

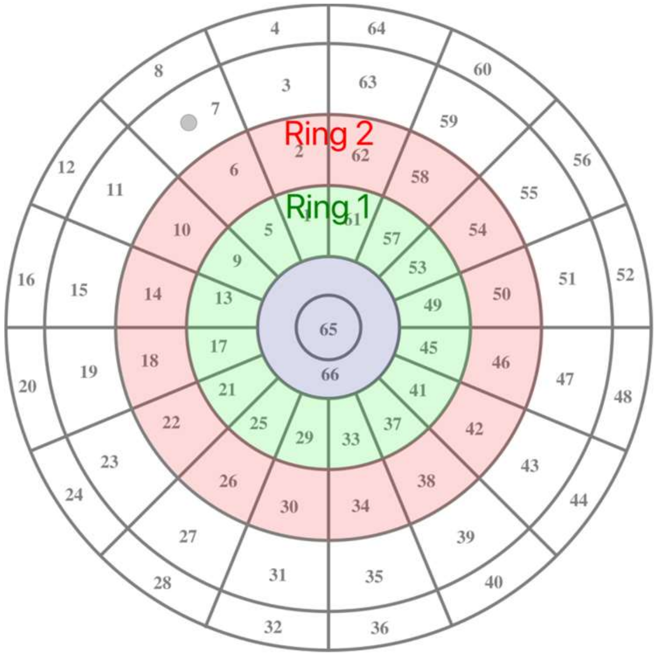
ACTAF2 prototype



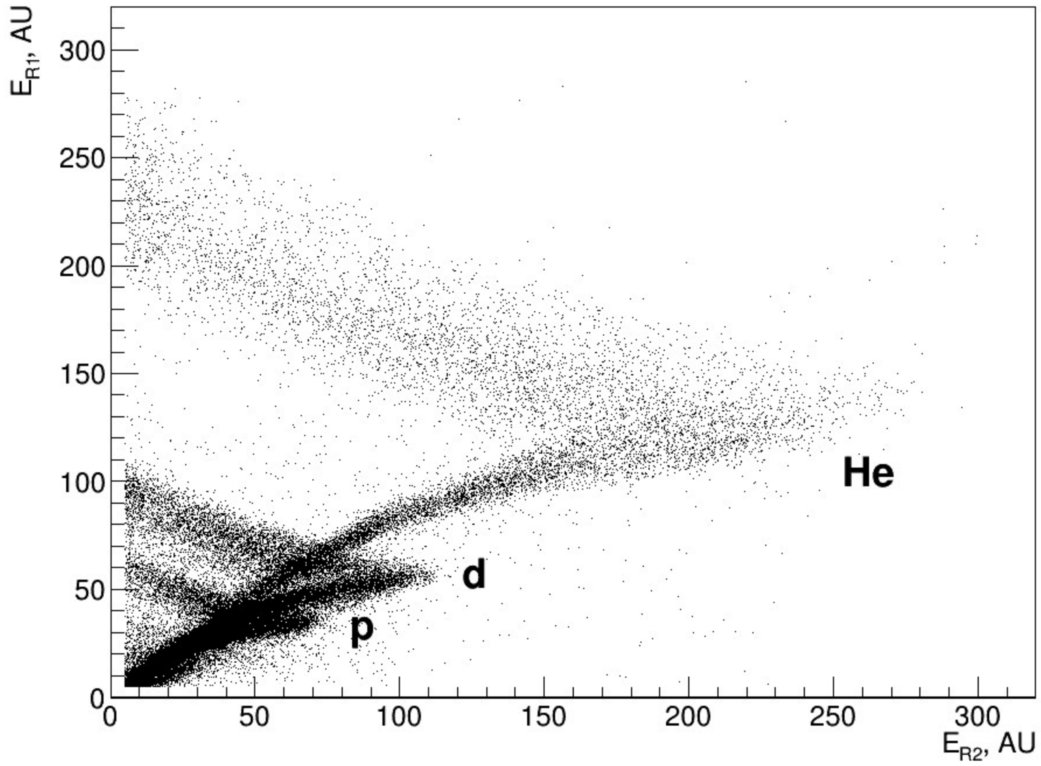
Scintillation counters

	Test run	Main experiment
Gas	$He+4\%N_2$	clean H_2
Pressure	10/5 bar	20/4 bar
Intensity	$1.6x10^6$	$2x10^6$

E-p scattering, energy correlations



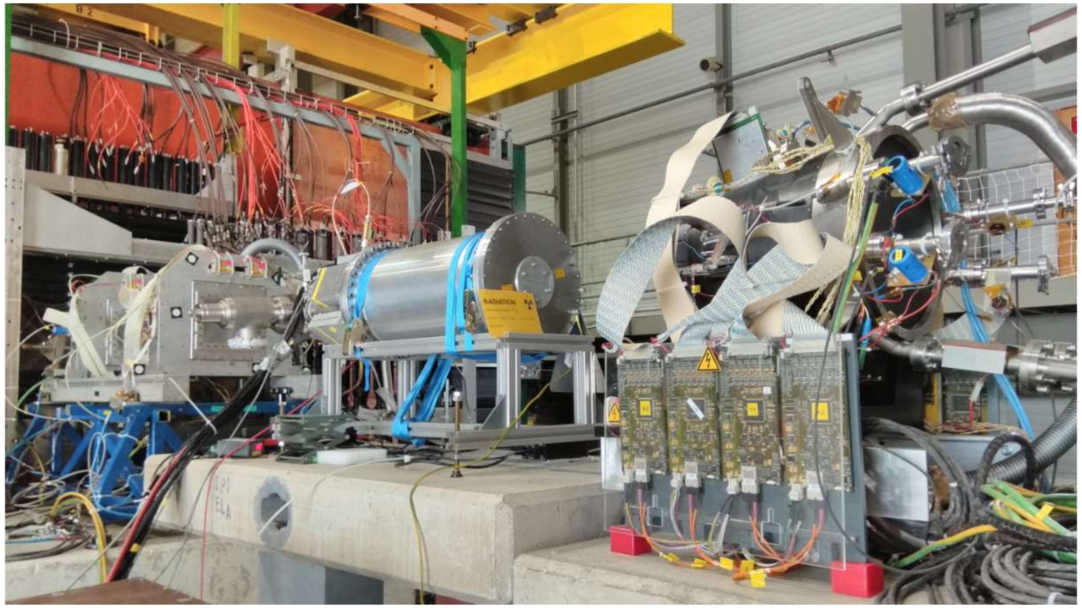
Energies on anode rings 1 and 2

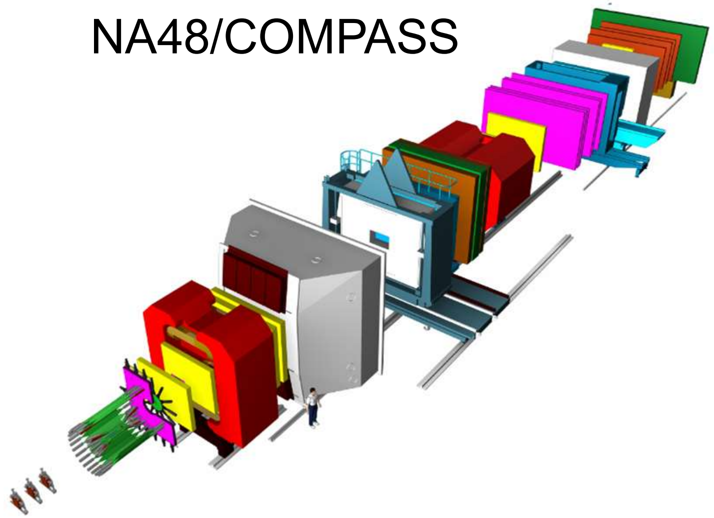


1 AU = 22 keV

Energies correspond to those calculated by SRIM

Proton radius measurement via μ-p scattering





Test run May 2018

Si microstrip detectors for tracking

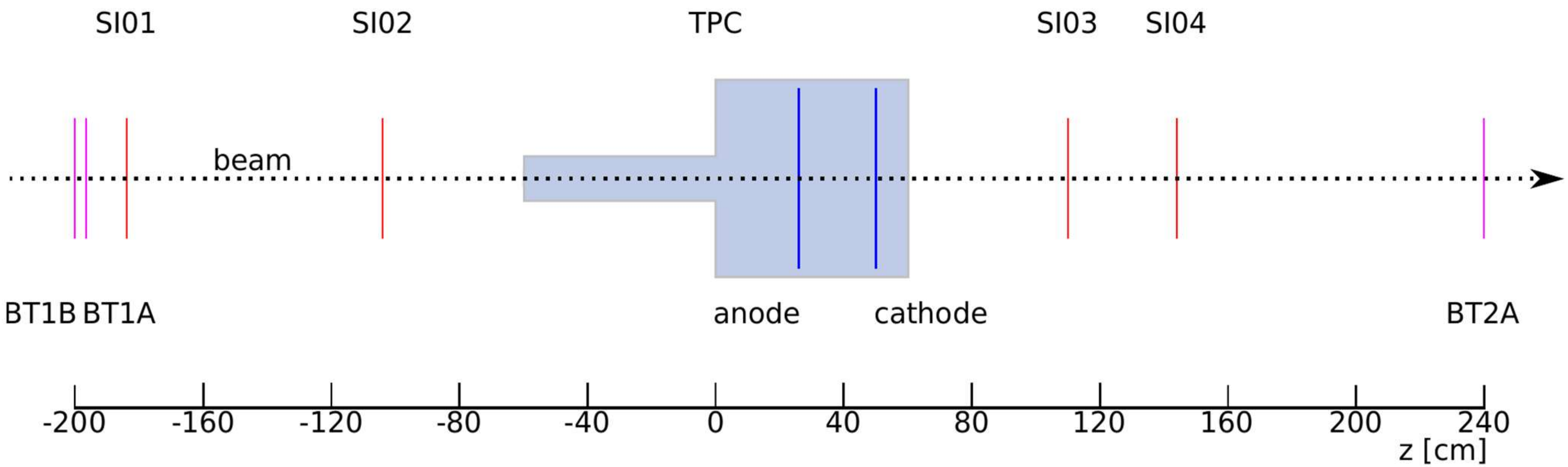
Rate – up to 2 MHz

E_μ = 190 GeV

Wide beam (RMS ≈ 20 cm)

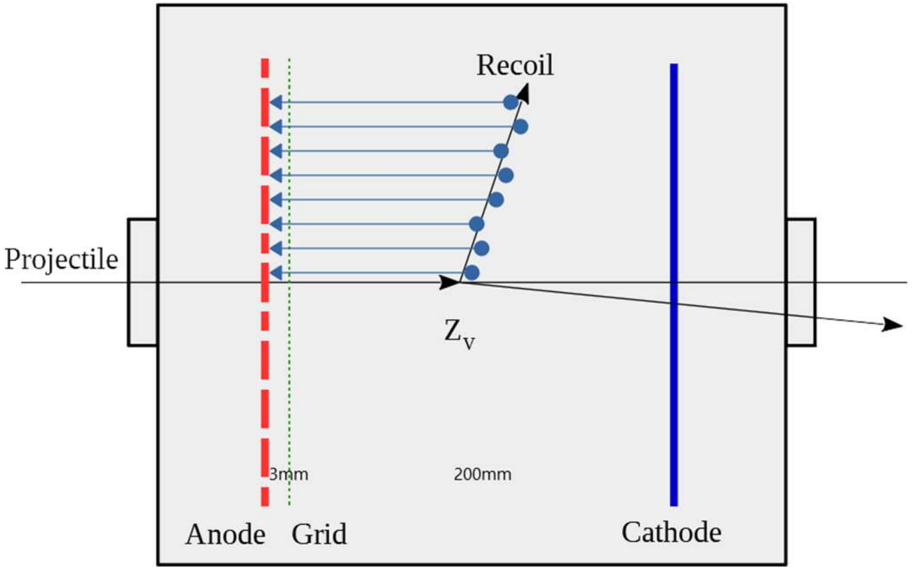
Duty cycle: ~20% (spill — 5 s)

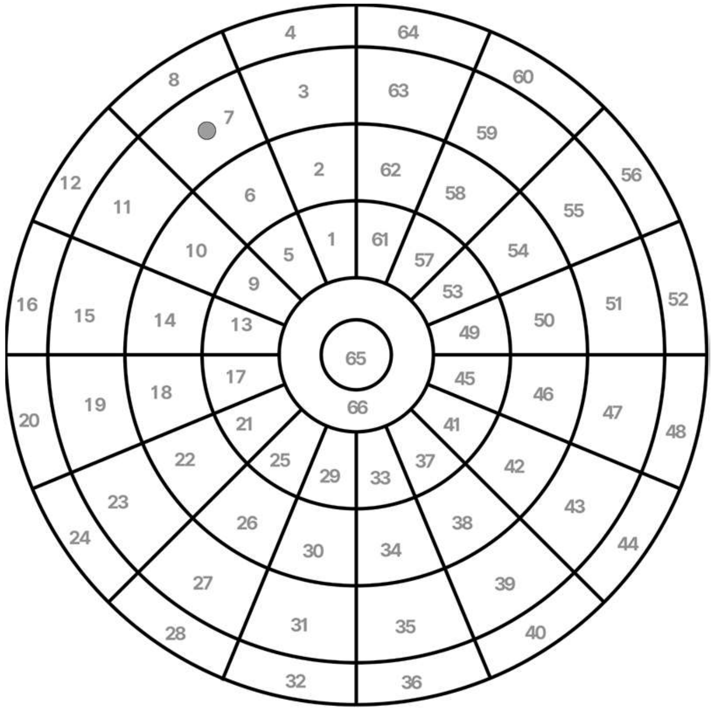
Scheme of test run, CERN, April-May 2018



- Active target D = 200 mm (TPC)
- Scintillators (BT) 64x48 mm ×3
- Si microstrip detectors (SI) 70x40 mm ×4

Test TPC structure



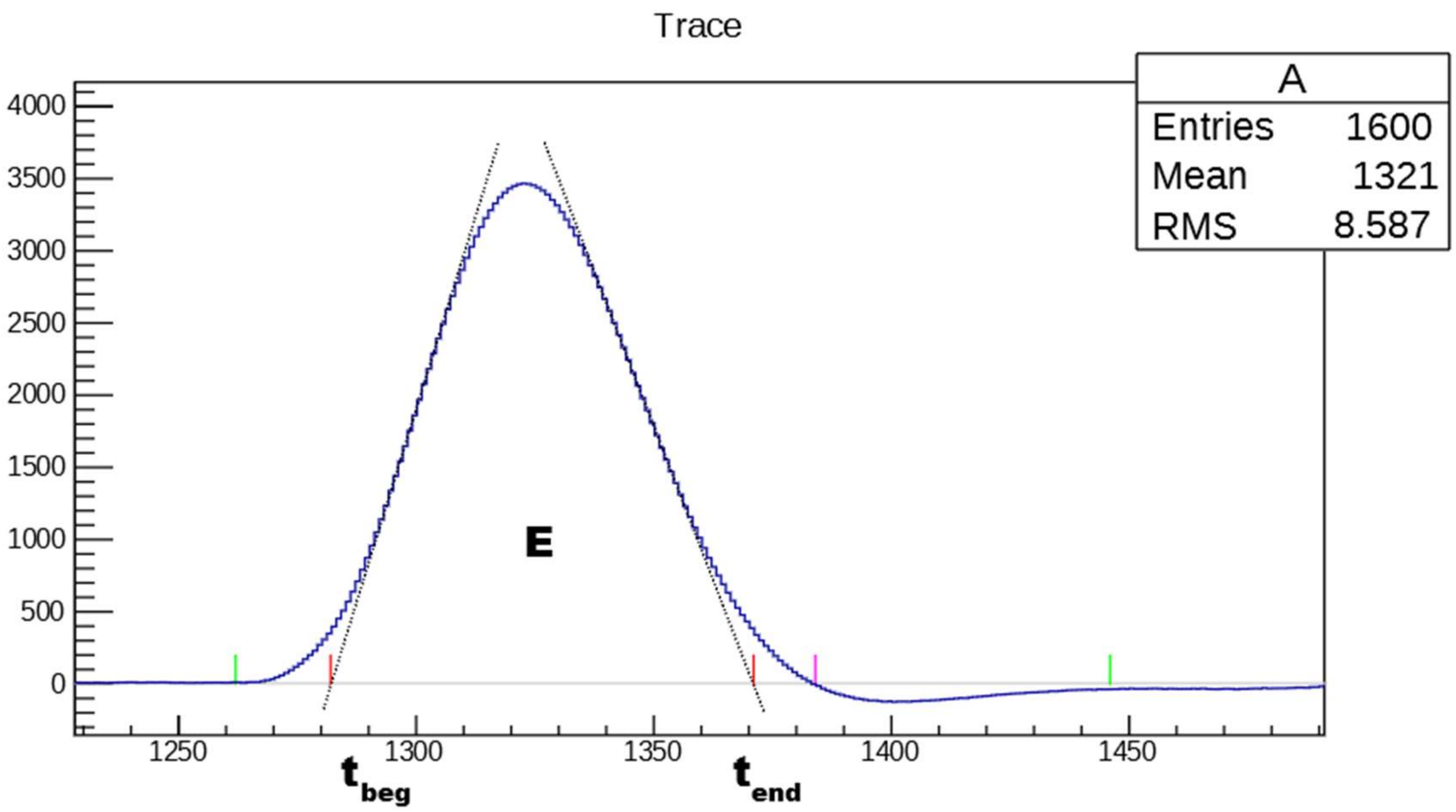


- Gas: H_2 (purity 6.0)
- p = 1, 4, 8 bar
- L_{CG} = 220 mm
- V_C = 18 kV
- V_G = 1 kV
- t_{CG} ≈ 60 μs

FADC

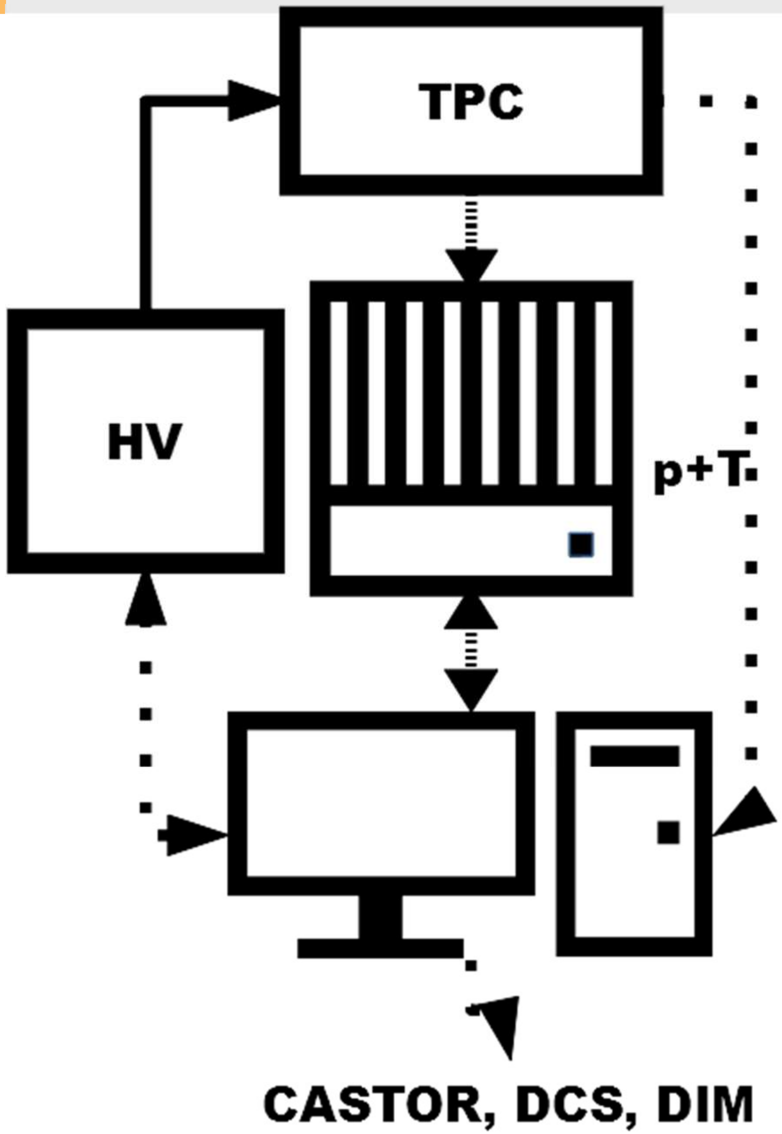
- Struck SIS3316 VME FADC
- 14 bit @250 MHz (we use at 25 MHz)
- 16 channels
- Range: -2,5 – +2,5 V
- Modes: triggering or self-triggering
- Clock PLL lock
- Reading of raw ADC values or 2/4/8 points averaging
- Energy thr.: 300/200 keV (moving window averaging)
- Reading window: 108 μs
- Determination of amplitude, integral and time of the signals possible within the FPGA

Waveforms



- Waveforms have all information about the noise and signal
- Energy/integral, time of signal, pile-up can be extracted

TPC DAQ



TPC

Preamplifiers/amplifiers

VME crate

RIO4 (LynxOS, MBS)

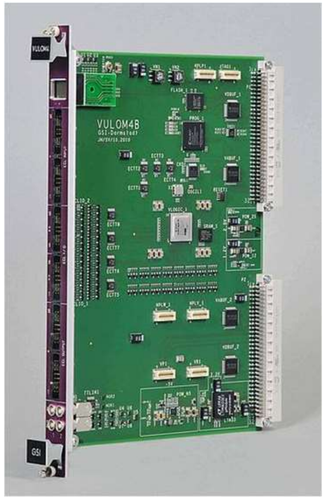
FPGA logic module VULOM (BM, trigger)

5× FADC

Linux X86 PC

- LynxOS boot
- Slow control (HV, p, T)
- HDD → CASTOR
- DIM, DCS (EPICS)

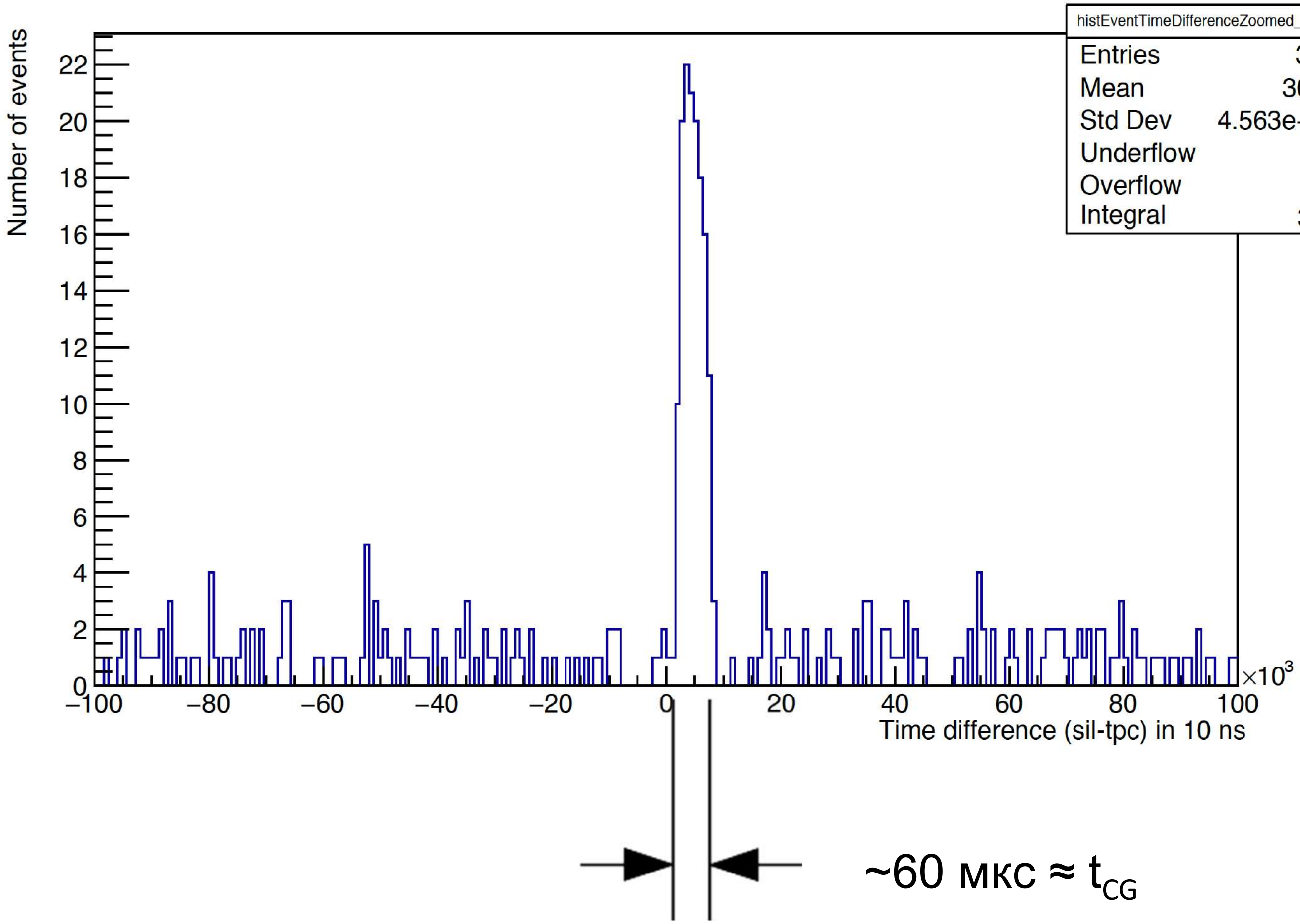
Timestamp/event syncronisation



- 32 bit «watch/clock» @100 MHz
- Sending to any device and saving of the timestamps
- Si DAQ – linear interpolation between the timestamps
- Offline time stamps matching between Si and TPC events

VULOM4B - logic module with FPGA, our firmware

Events syncronyzed



- Timestamp sync – TPC and Si DAQ
- Files recorded independently, processed and sync offline

Count rate

Detector	TPC	S*	S_e	Si*
Mean	16 HZ	64 kHz	640 kHz	22 kHz
Max	46 Hz	370 kHz	3.7 MHz	43 kHz

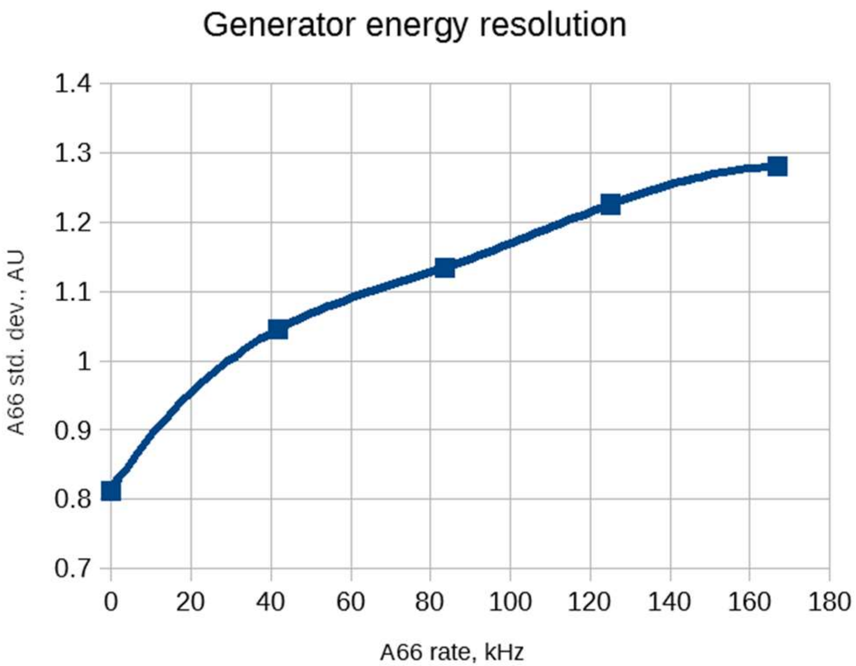
Events total: 4 600 000

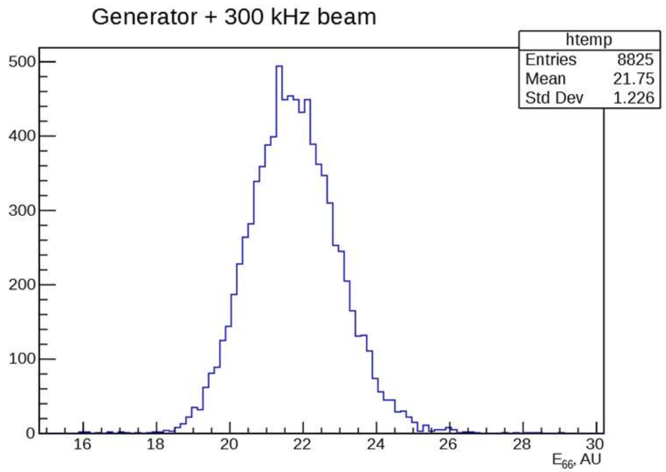
With thr. 300 keV: 1 100 000 With thr. 200 keV: 3 500 000

8 bar: 4 290 000 4 bar: 310 000

- * area - 10% of full anode area of TPC
- TPC is self-triggering, with independent DAQ

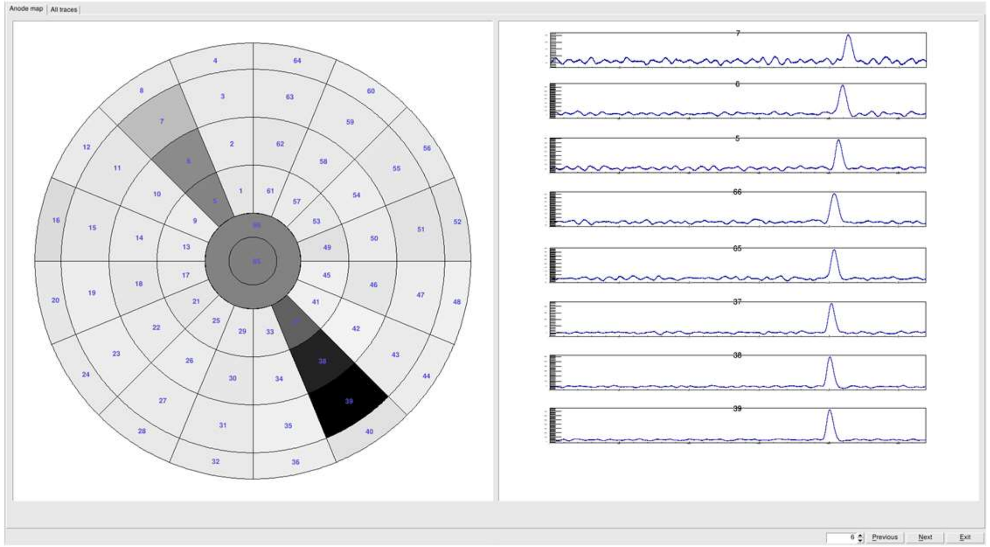
TPC energy resolution vs beam rate





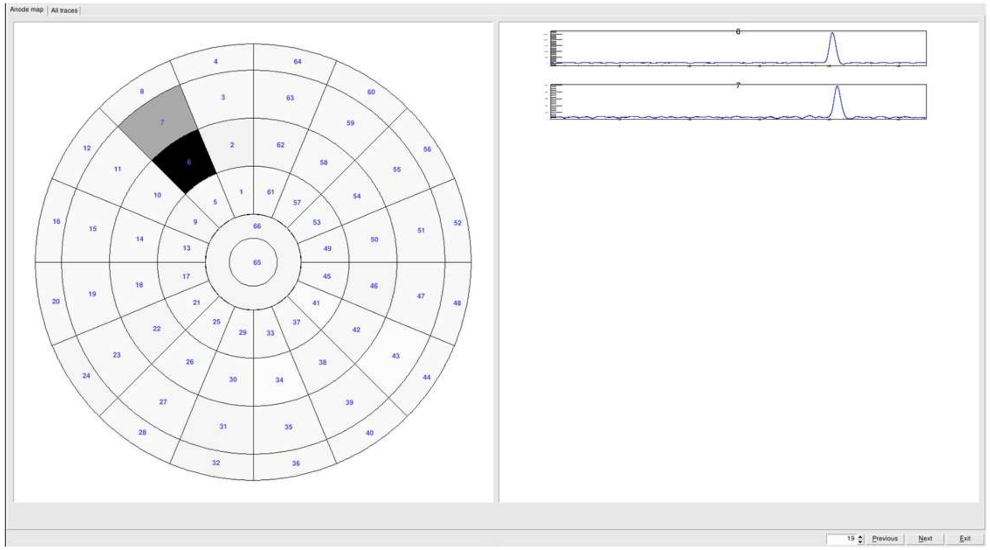
- Test pulses injected to all anodes at the same time
- Measured vs beam intensity

Gas quality control



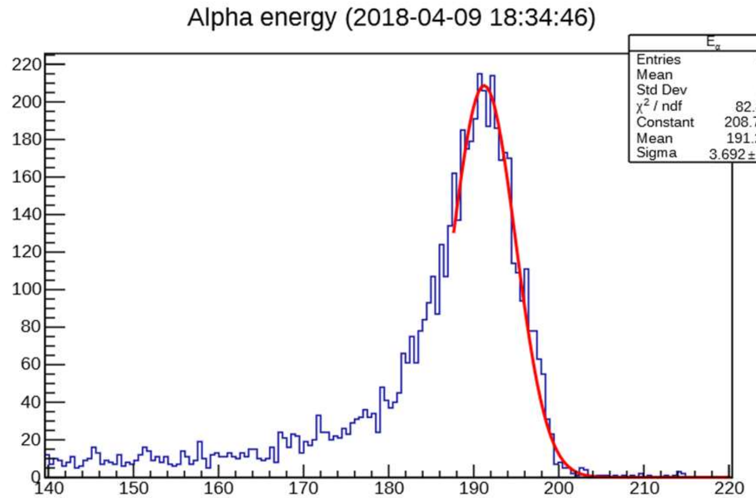
He, 1 bar

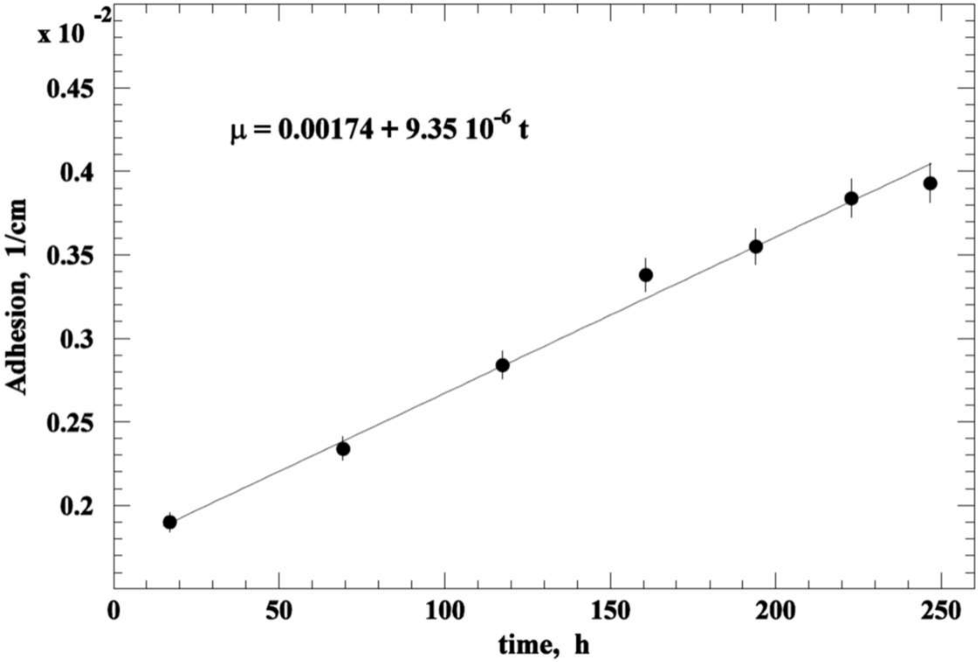
^{241}Am source on the cathode
Readout in the same way as physical events



H_2, 8 bar

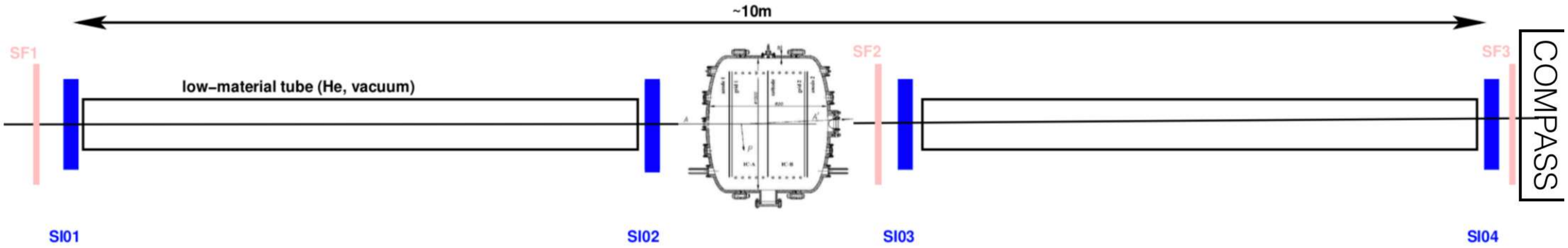
Gas quality check during each experiment





- α-spectrum measured several times per day
- Shift of the maximum ~1%/day (~1 ppm O_2)
- Refilling – once per week
- No gas purification or circulation

Main experiment at CERN

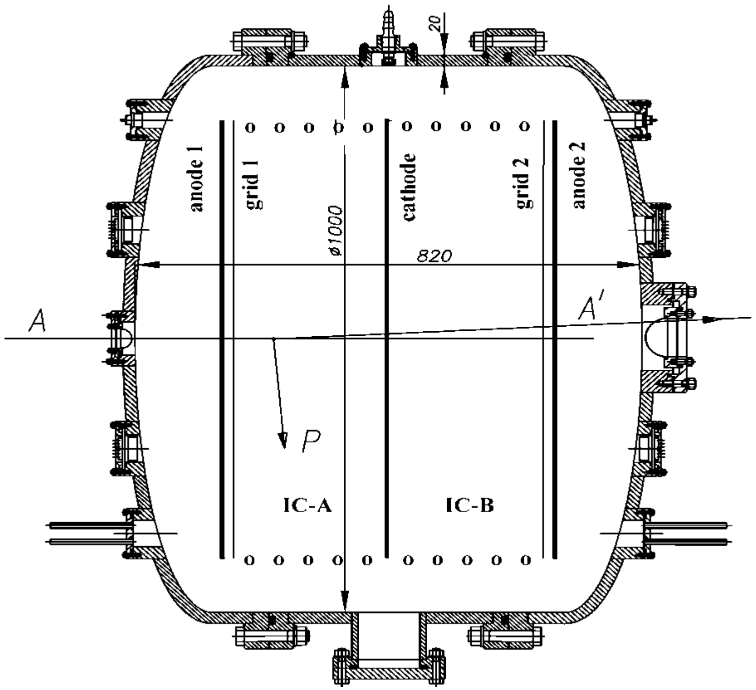


- Beam size: $\sigma \approx 8$ mm
- Energy: 100 GeV
- Scattering angles (μ) 0.3–2 mrad ($Q^2 = 0.001–0.04\ GeV^2/c^2$)
- Base: 5 м — scattering 1.5 – 10 mm
- Si detectors $\Delta x < 10\ \mu m$ ($\Delta\theta < 2\ \mu rad$ at 5 m)

- New fast electronics fro the Si detectors
- Scattering trigger («kink trigger» — SciFi detector)

- **New active target: diameter — 800 мм, 20 bar H_2**
- Beam intensity: $2\cdot10^6$ μ/s — 1 year running time (2022 г.)

Large ionisation chamber



- 820 mm long
- Inner diameter 1000 mm
- Total volume 600 liters
- Weight is 2000 kg
- Internal surfaces electrically polished
- Gas pressure up to 20 bar, tested up to 25 bar
- Spherical Be windows for the beam
- HV up to 80 kV

GSI-TUM application for EU ATTRACT grant made

- μ-p elastic scattering for proton radius measurement
- Proton-ion elastic scattering
- Charge-exchange reactions

Summary

- Application of ionization chamber without gas amplification as an active target for the elastic proton scattering at the intermediate energies is very powerful method to study the nuclear matter distribution of stable and exotic nuclei
- Many light exotic nuclei like $^{6,8}He$, ^{11}Li, ^{8}B, $^{12,14}Be$, $^{15,16,17}C$ and many stable nuclei (from p to Pb) are measured
- New active targets will allow measurement with the heavy beams like ^{132}Sn, elastic, inelastic scattering and charge-exchange reactions
- Similar techniques can be used for e-p and μ-p experiments aiming the measurement of the proton radius with high precision
- Main option for the readout of the signals – free-running FADC
- Waveform offline analysis possible due to relative low event rate