Proton radius measurement in the A2 hall

Vahe Sokhoyan

Mainz, 15.01.2018

MAMI
MAINZER MIKROTRON

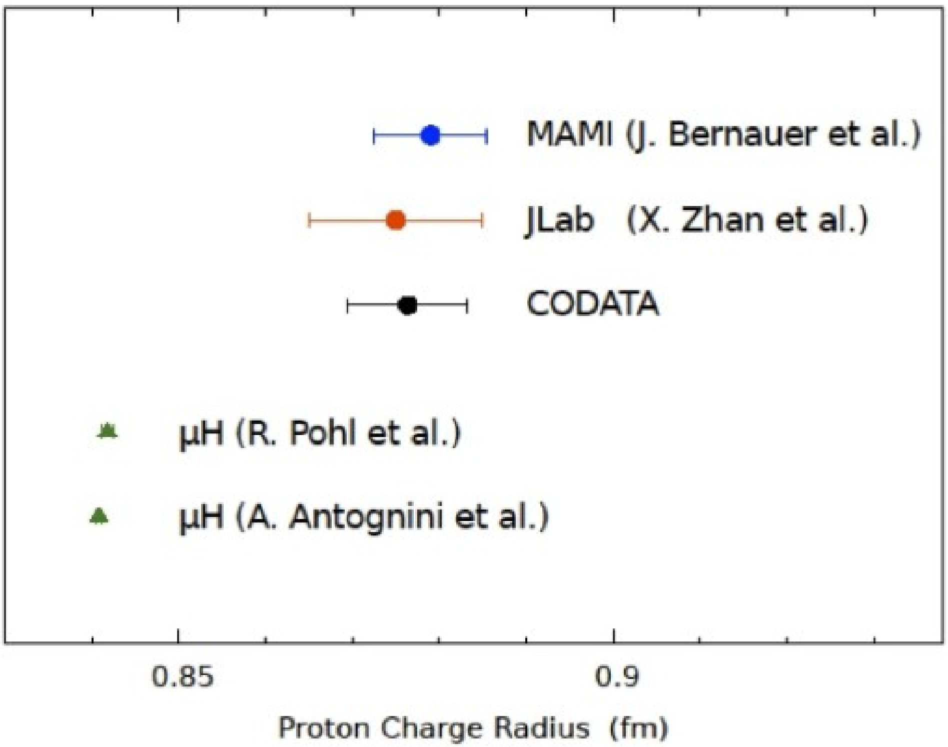
SFB 1044
THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL

Institut für
Kernphysik

JG|U
JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

Motivation

Main motivation: Understanding the proton radius puzzle



Significant difference between results of muonic hydrogen experiments (CREMA Collaboration, PSI) and CODATA value

- Electron scattering: validity of the Q^2 range and choice of the fitting function?
- Hadronic corrections not sufficient to explain the differences?
- Exotic particle coupling differently to electrons and muons?

More than a comparison of two numbers:

- Inconsistencies between atomic measurements
- In a more general consideration: differences between electronic and muonic systems (besides one of the recent electronic hydrogen results)
- Differences observed for the deuteron, but not for helium isotopes
- The solution will not come from a single experiment!

Scattering experiments

Worldwide program of scattering experiments:

- A1 Collaboration in Mainz: Initial State Radiation (ISR) experiments
  Accessing Q^2 below values defined by the experimental kinematics:
  $R_{pE} = 0.810 \pm 0.035$ (stat) ± 0.074 (syst) fm *(M. Mihovilovič et al., Phys.Lett. B771, 194 (2017))*
  Further experiments reaching $Q^2 = 10^{-4}$ GeV^2 with improved systematics planned.

- PRad experiment at JLab:
  Electron scattering on a hydrogen gas jet target studied in combination with a forward calorimeter, access to $Q^2 = 10^{-4}$ GeV^2.

- MUSE Collaboration: preparing for a simultaneous measurement of the absolute cross-sections for the *ep* and *μp* elastic scattering at low momentum transfer.
  The electron-muon universality will be tested in the context of the measurement of the proton radius.

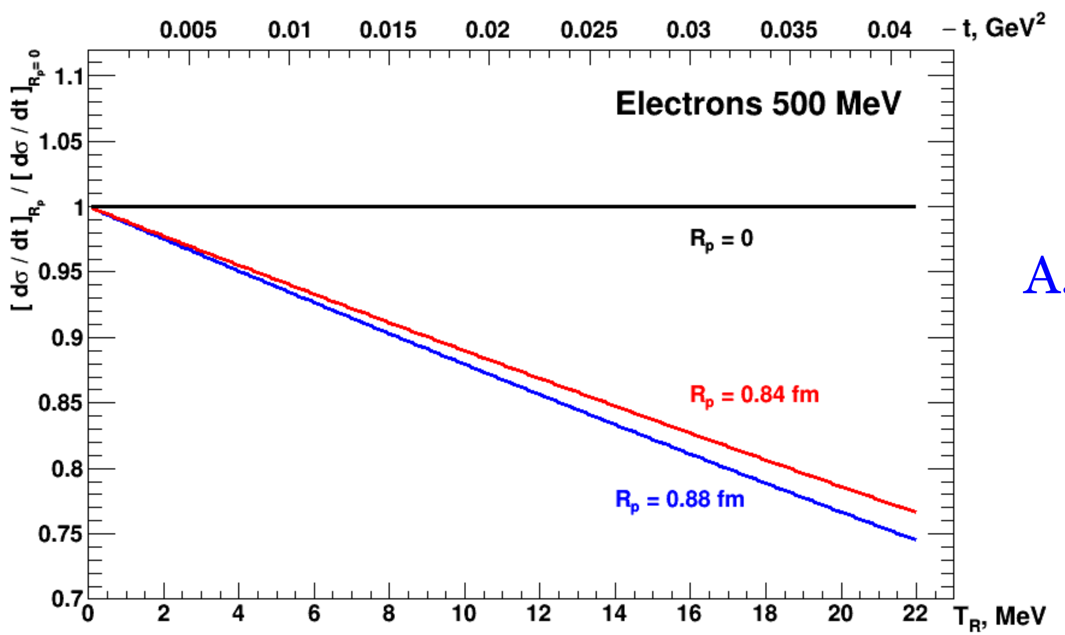
- New experiments at MAMI (A2 Hall): Accessing proton radius with dilepton photoproduction at with a Hydrogen Time Projection Chamber combined with Forward tracking detector (IKAR-M).

Motivation

Innovative approach to the measurement of the proton radius

- Simultaneous detection of the scattered electron and recoil proton
- Lower radiative corrections
- Low transfer momentum region: 0.002 – 0.02 (0.04) GeV^2
- High resolution in Q^2 (~100 resolved points)
- Absolute measurements of dσ/dt accuracy on a level of ~0.2%

Completely different systematics compared to other experiments



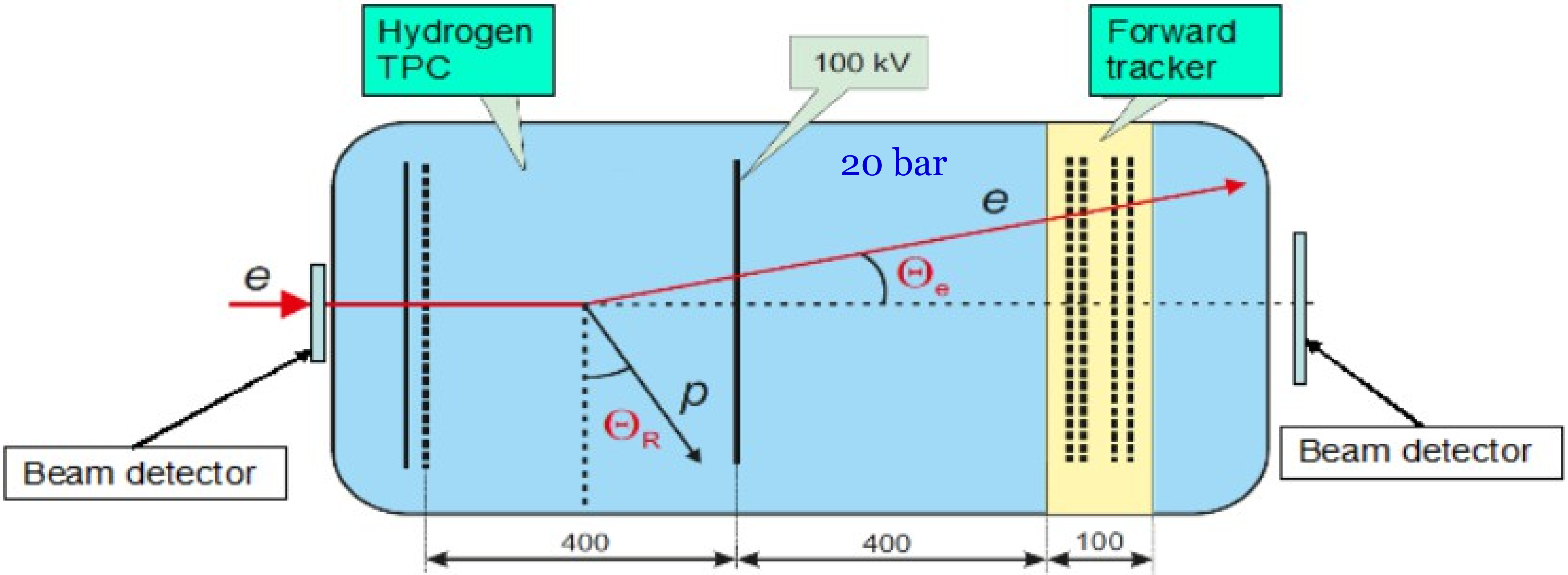
A. Vorobyov (PNPI)

Difference between R_p=0.84 fm and R_p=0.88 fm: ~1.3% at Q^2 = 0.02 GeV^2

IKAR-M detector

New-generation experiments with a completely different systematics:

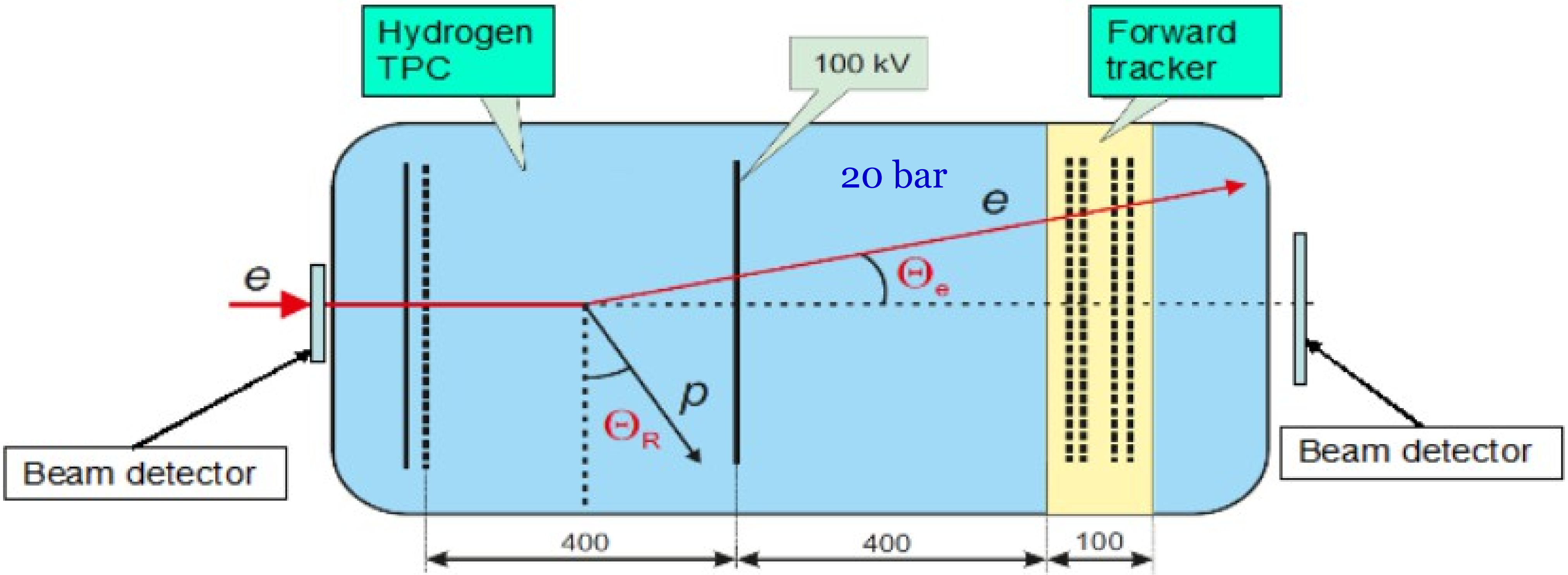
- Electron scattering with detection of both recoil proton and scattered electron
- Dilepton photoproduction (proton radius measurement, lepton universality test)



TPC&FT at MAMI beam will open avenue for various experiments:

- Experiments with electron and photon beams in A2 with accurate detection of charged particles (including recoil fragments)
- Hydrogen, deuterium, helium gas filling possible
- Longer term: transfer of technology to experiments at MESA accelerator e.g. for complementary measurement of the nucleon scalar polarizabilities (in addition to the A2 program)

IKAR-M detector



Measured quantities:

Recoil energy T_R

Recoil angle Θ_R

Vertex Z coordinate

E scattering angle Θ_e

$$-t = \frac{4\varepsilon_e^2 \sin^2 \frac{\vartheta}{2}}{1 + \frac{2\varepsilon_e}{M}\sin^2 \frac{\vartheta}{2}}$$

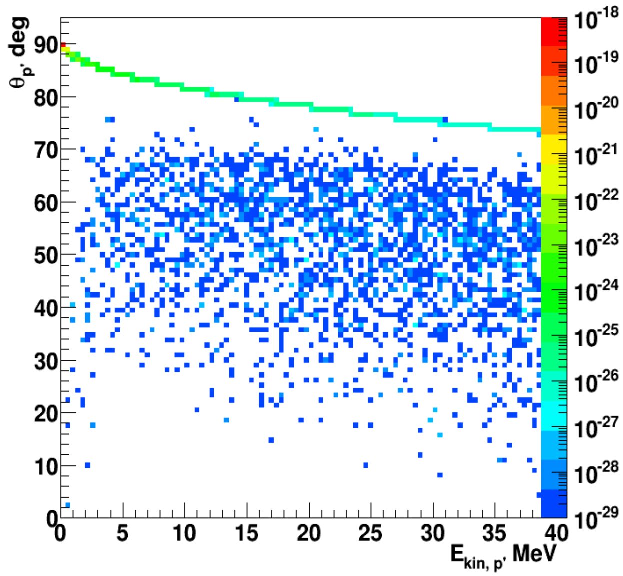
$$-t = 2MT_R$$

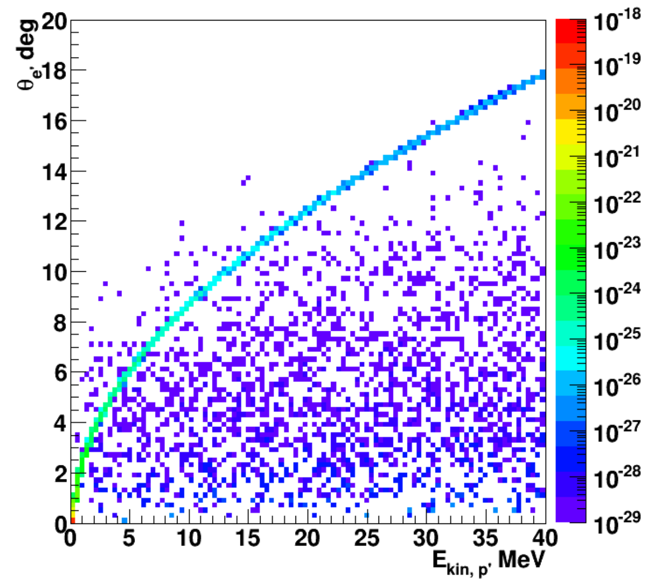
Gas pressure (bar)	4, 20
Drift distance, (mm)	300± 0.1
σ_z (μm)	150
σ_{T_p} (keV)	60
σ_{θ_p} (mrad)	10-15
$\sigma_{x/y/z}$ tracker (z TPC) (μm)	30/30/150
σ_t TPC/ tracker (ns)	40/5
θ_{max} (°)	32

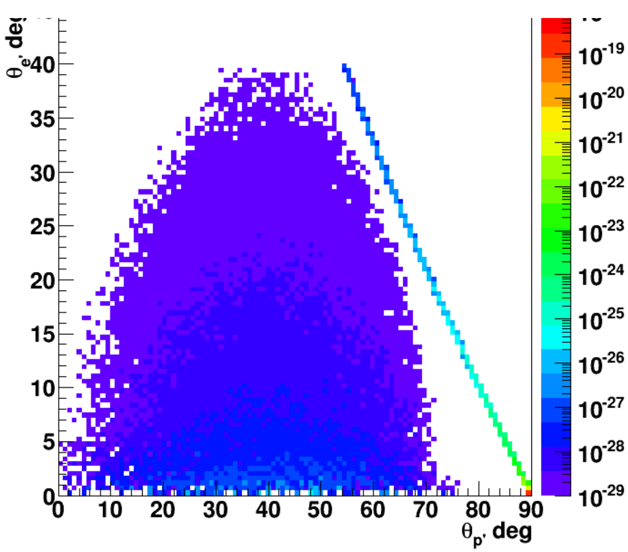
H_2 4 bar: $T_R \leq 4$ MeV

H_2 20 bar: $T_R \leq 10$ MeV

Background suppression





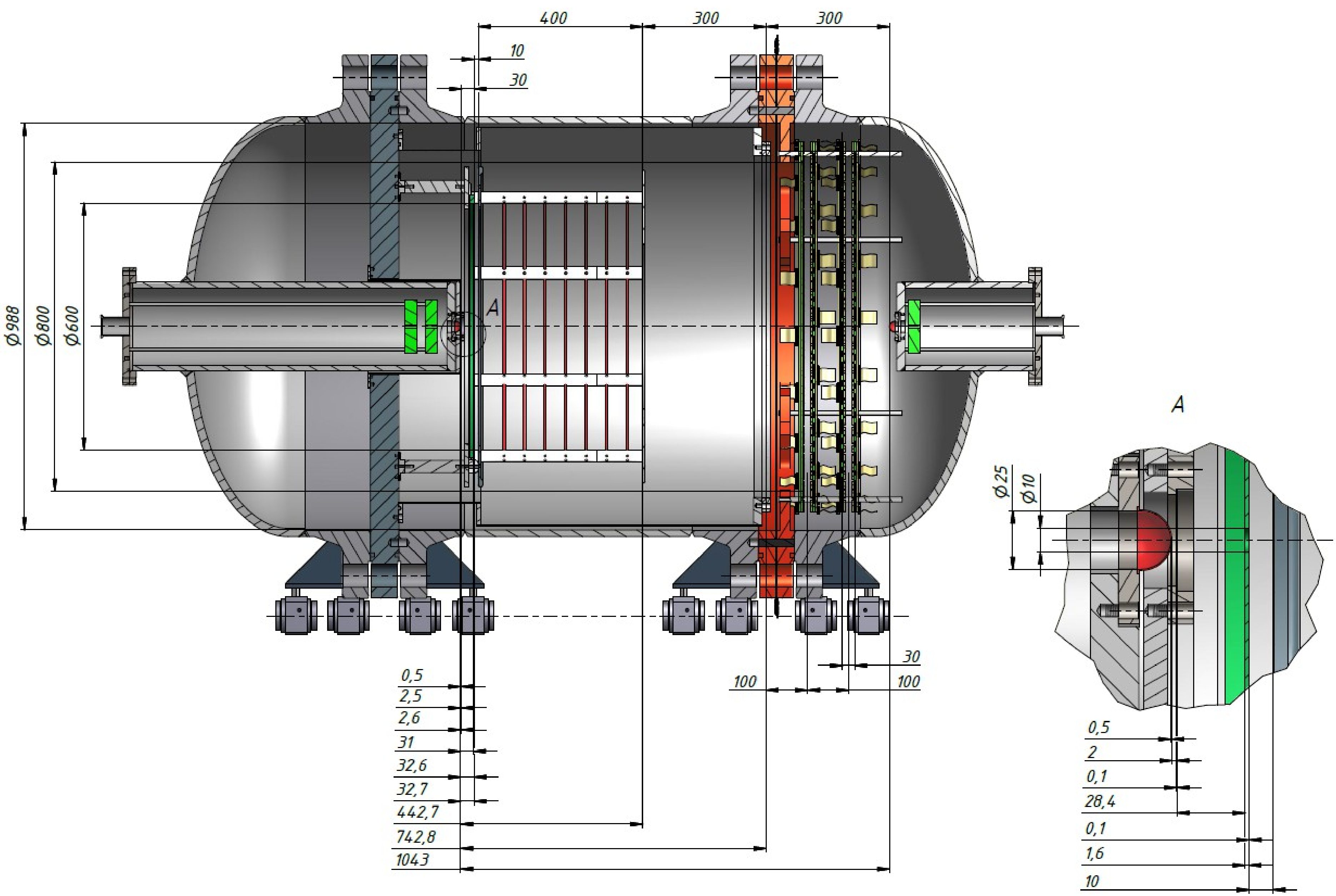


A. Vorobyov (PNPI)

<u>Background suppression:</u>

Correlations: $(\Theta_e;T_R)$, $(\theta_R;\ T_R)$, and $(\theta_e;\ \theta_R)$ plots calculated for the elastic ep scattering and for the background reaction $ep \rightarrow ep\pi^0$ for $\varepsilon_e = 900$ MeV

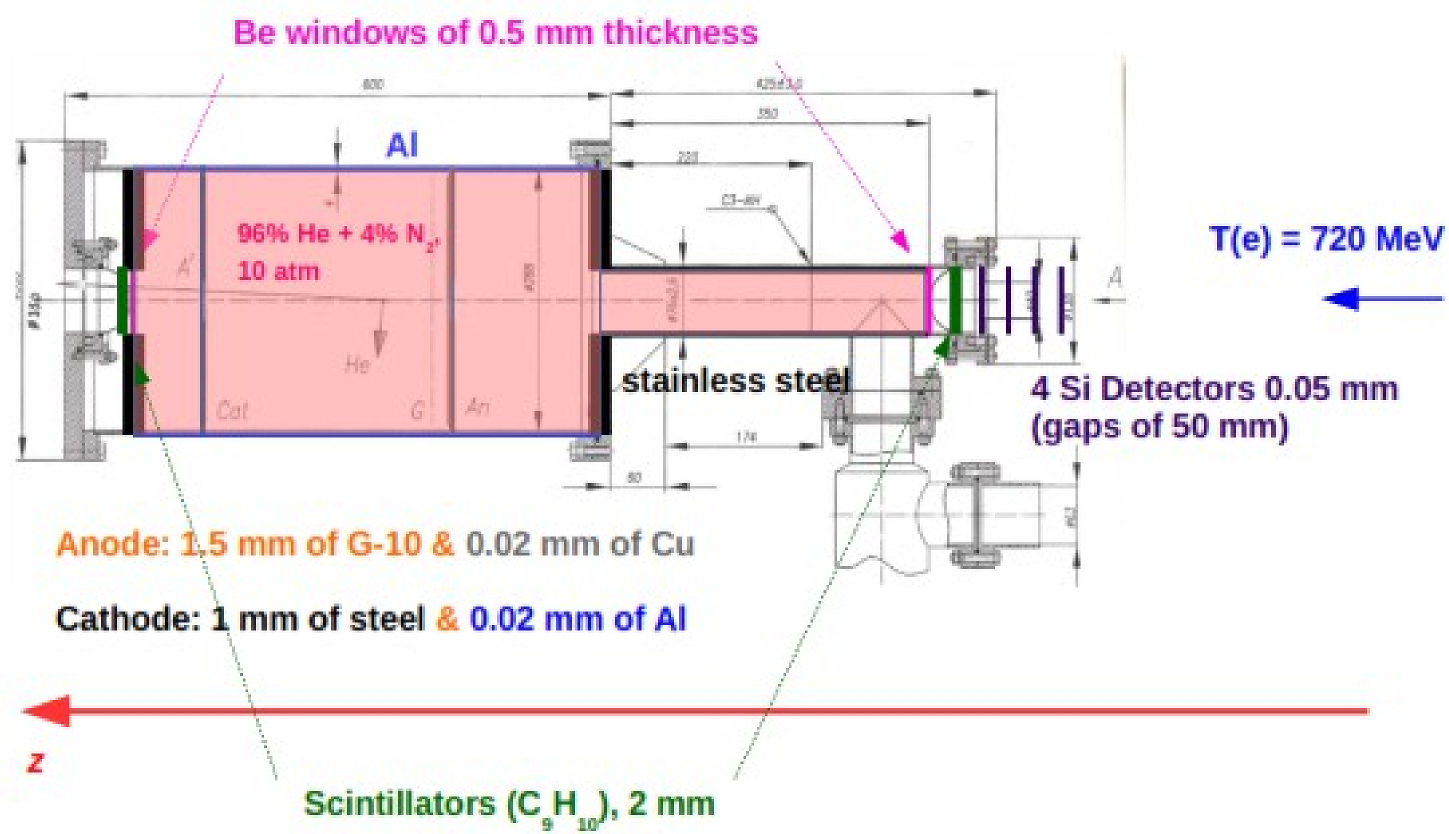
IKAR-M detector (tentative design)



Systematic errors

1	Drift velocity, W1	0.01%
2	High Voltage, HV	0.01%
3	Temperature, K	0.015 %
4	Pressure, P	0.01%
5	H_2 density , ρ_p	0.025 %
6	Target length, L_{tag}	0.02 %
7	Number of protons in target, N_p	0.045 %
8	Number of beam electrons, N_e	0.05 %
9	Detection efficiency	0.05 %
10	Electron beam energy, ε_e	0.02 %
11	Electron scattering angle, θ_e	0.02 %
12	t-scale calibration, T_R relative	0.04 %
13	t-scale calibration, T_R absolute	0.08 %
	dσ/dt , relative	0.1%
	dσ/dt , absolute	0.2%

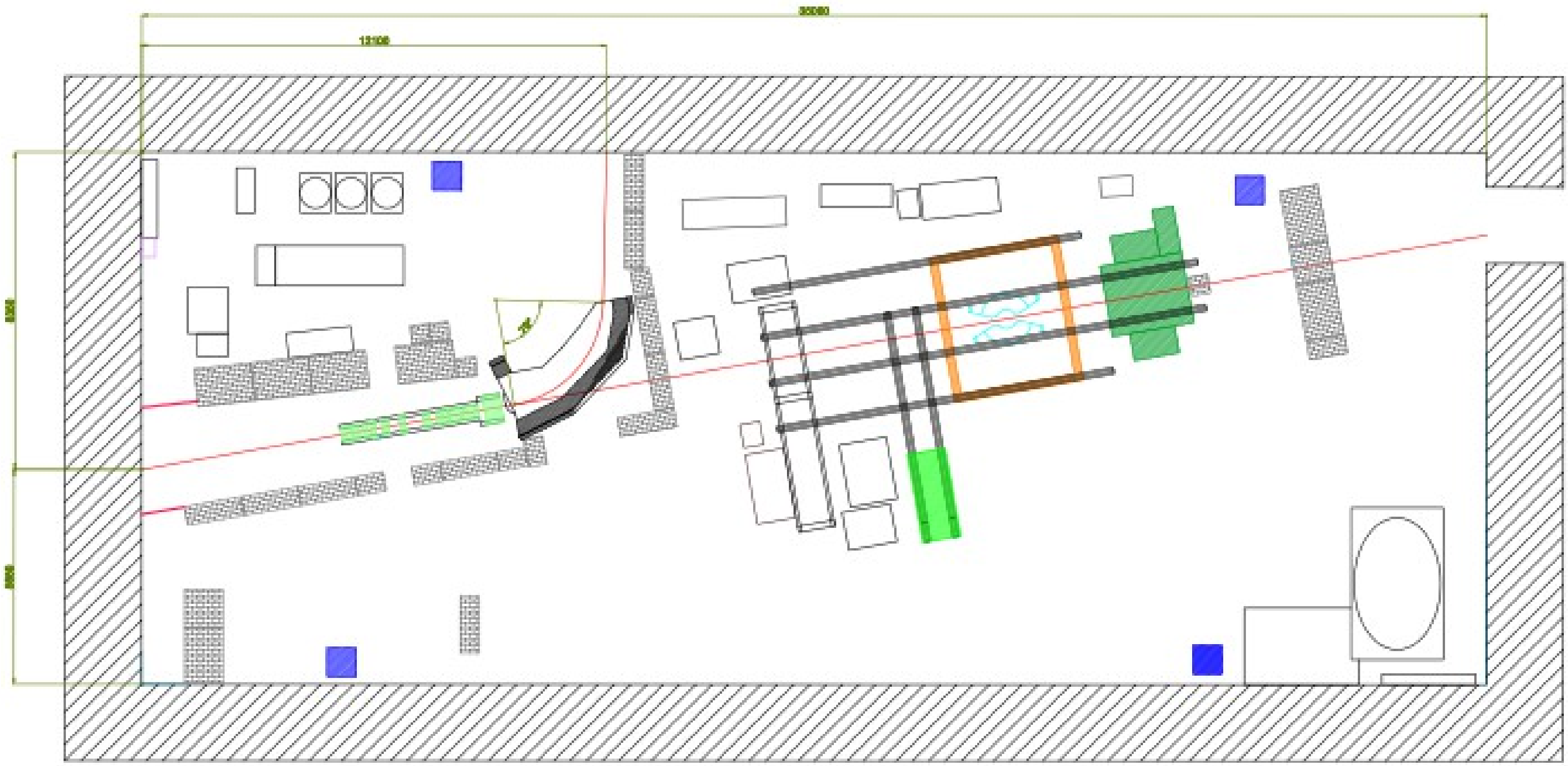
Test setup and beam monitoring system



Determination of the optimal run conditions for the main experiment:

- Study of the background created by the electron beam at the intensity of 2×10^6 e/sec
- Measurement of the flux of charged particles created by the electron beam in the forward direction (covered by the FT detector).
- Development and test of a prototype for a beam monitoring system
- Measurement of the parameters of the low-intensity electron beam at 2×10^6 e/sec, $\sim10^4$ e/sec, and $\sim10^3$ e/sec

Beamline construction



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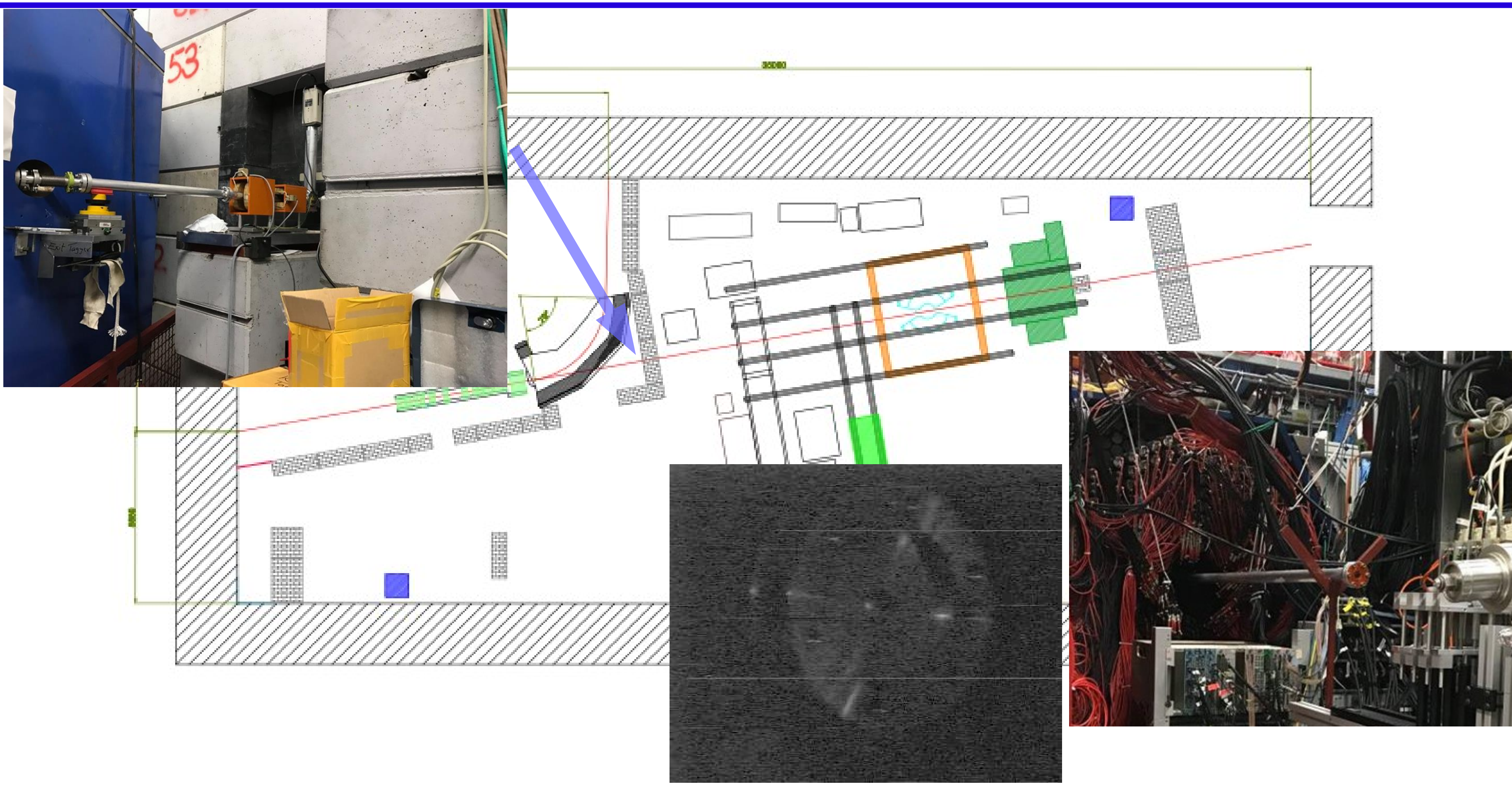
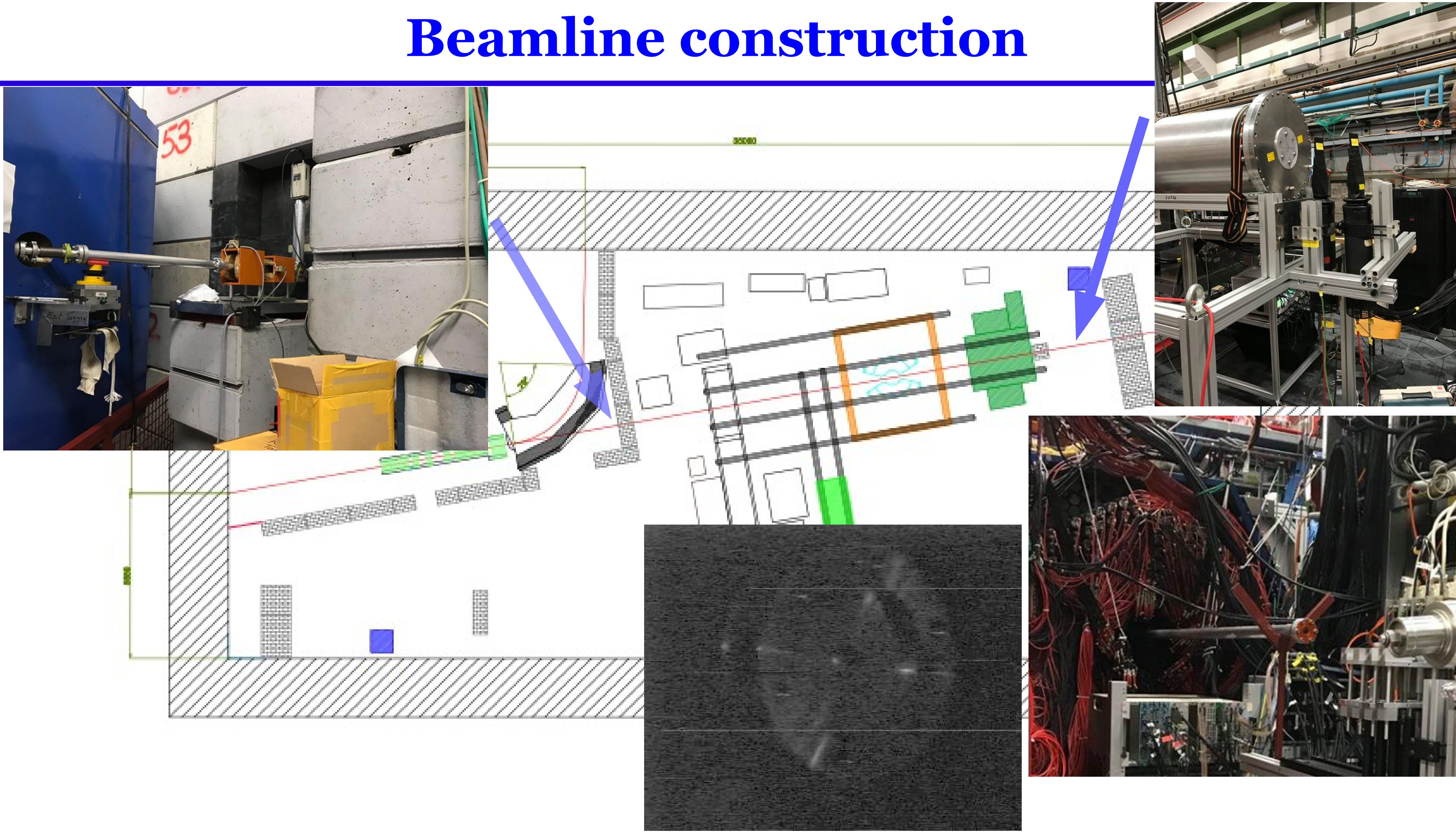


- One horizontal and one vertical steering magnets before tagger wall, luminescent screens for steering, ionization chamber connected to the interlock (M. Dehn)

Beamline construction



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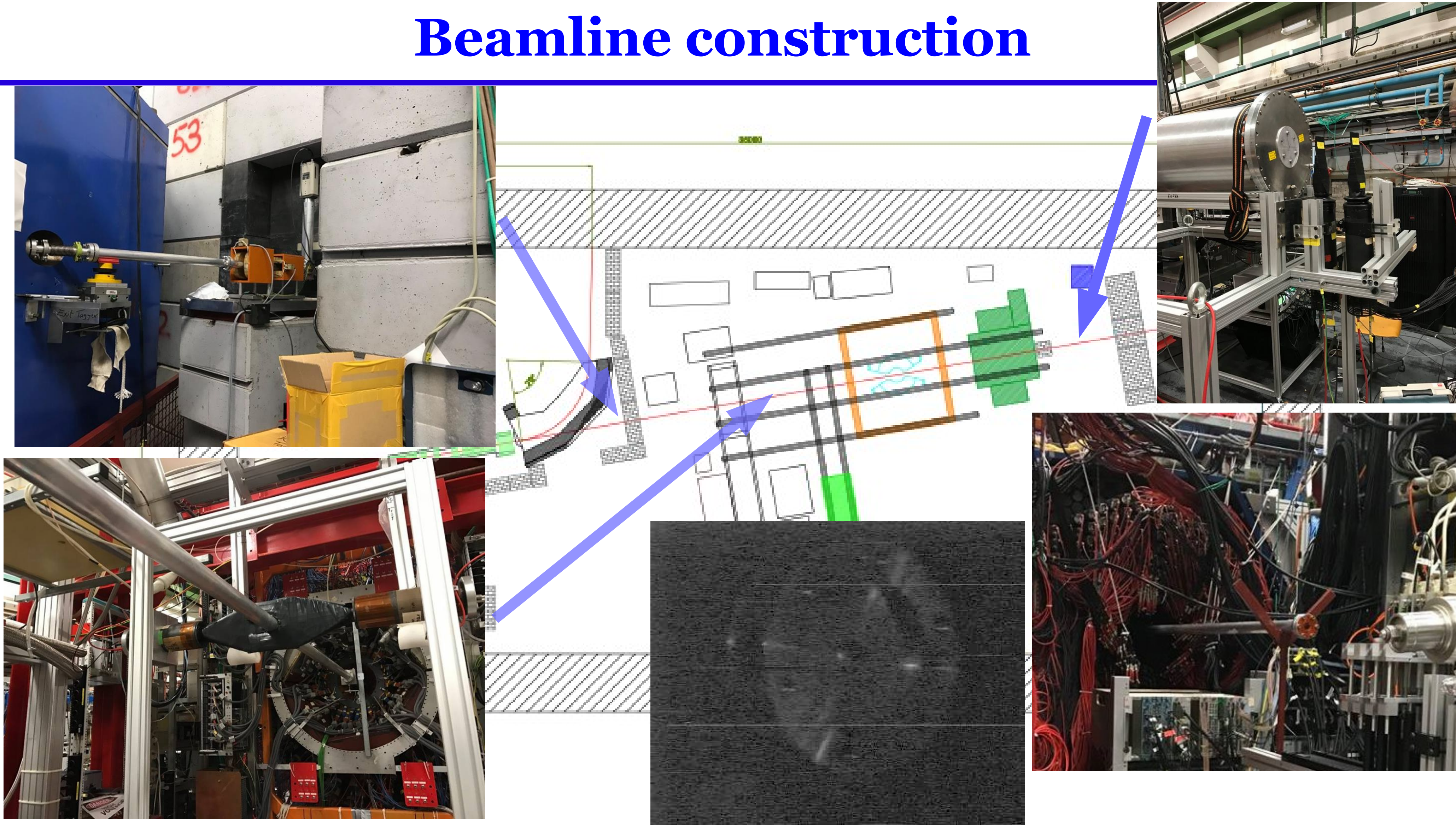
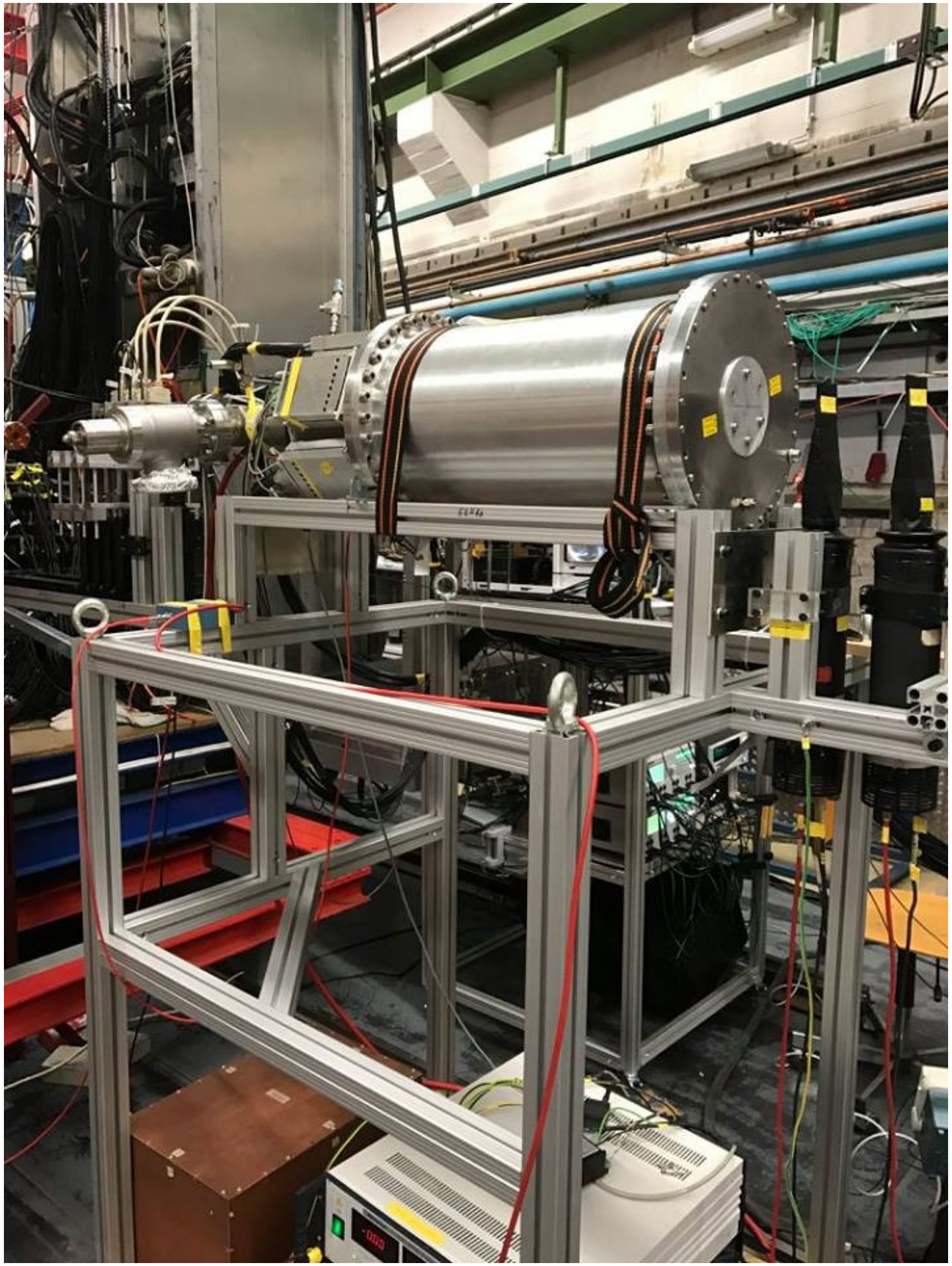


- One horizontal and one vertical steering magnets before tagger wall, luminescent screens for steering, ionization chamber connected to the interlock (M. Dehn)
- Beam scintillators (M. Biroth, O. Kiselev, P. Drexler)
- Beam telescope (F. Wauters, A. Tyukin, M. Zimmermann, N. Berger)
- PIZZA detector (P. Drexler, A. Inglessi, O. Kiselev)
- Scintillator counters before Crystal Ball (M. Biroth)

Test setup



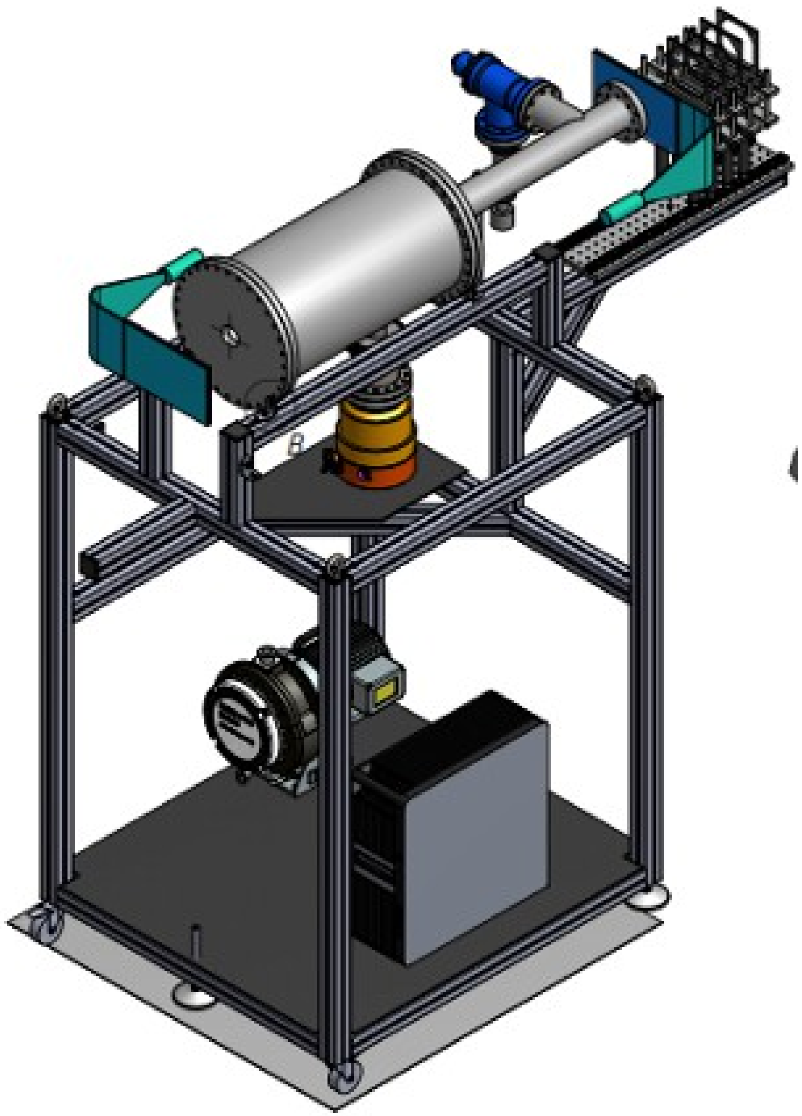
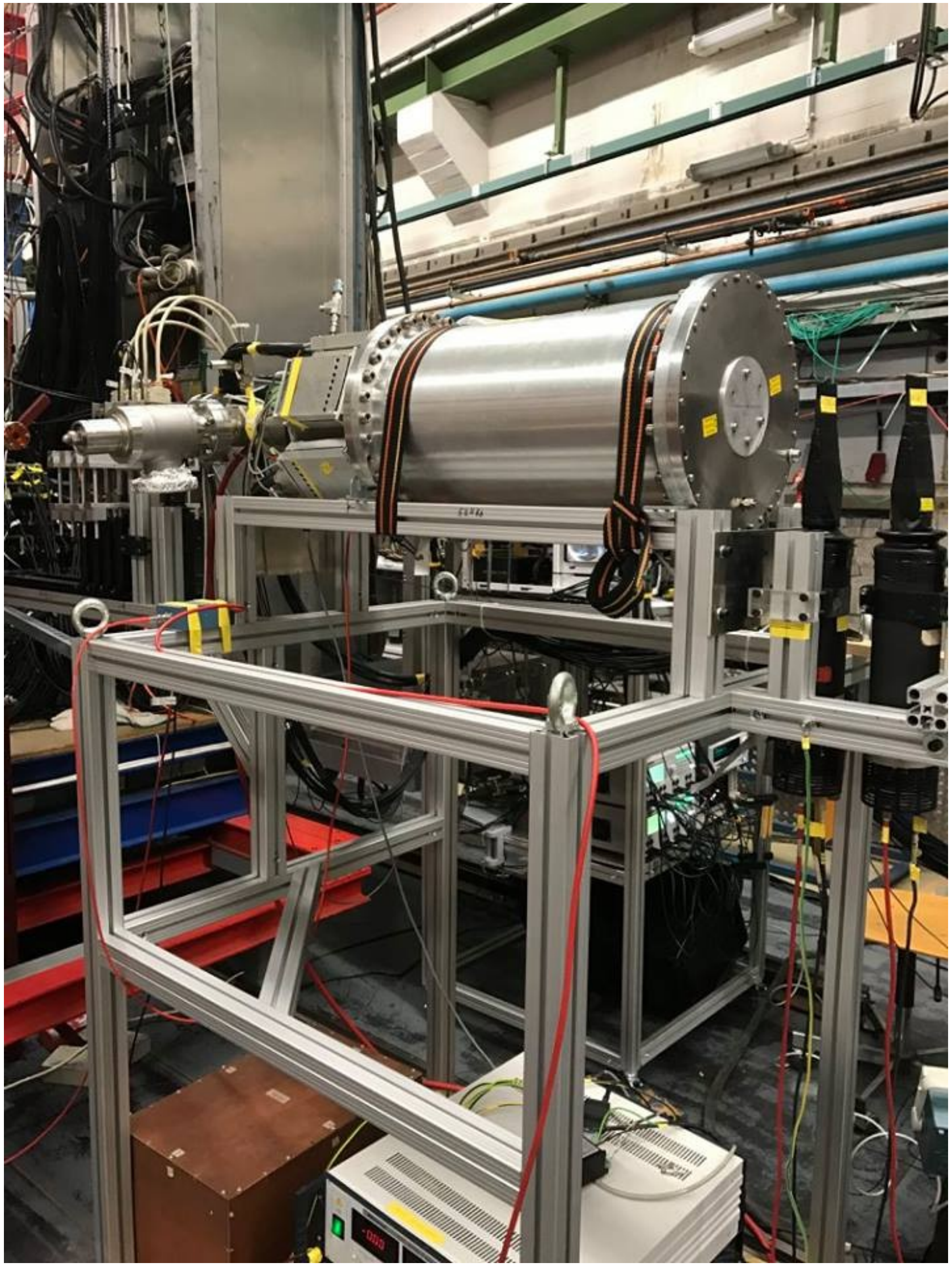


Figure from Marat Vznuzdaev (PNPI)

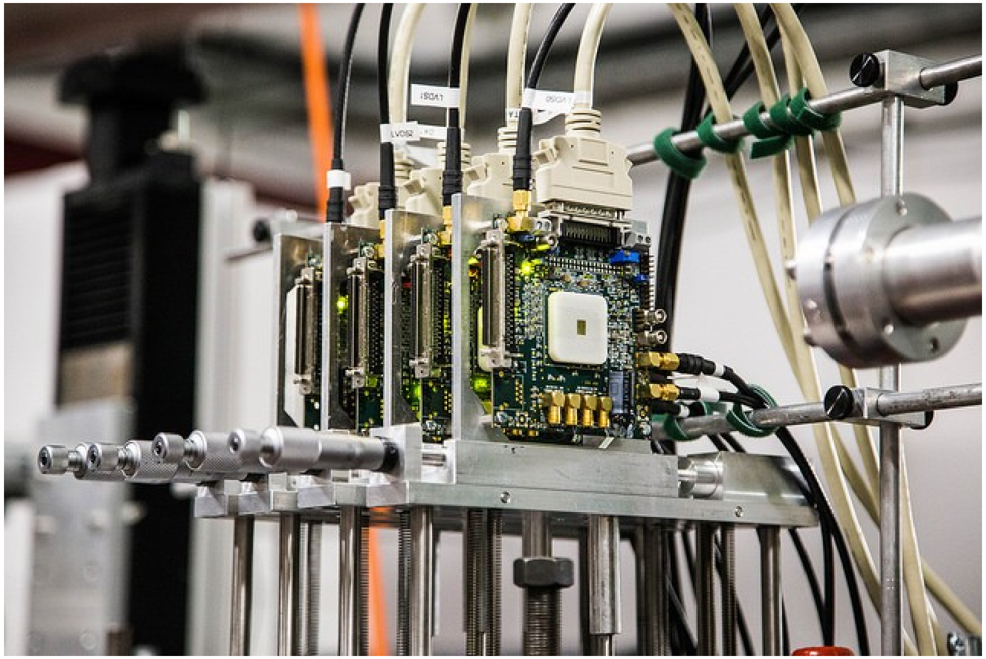
Test setup



- TPC mounted on the electron beamline Helium + 4.3% Nitrogen at 10 bar

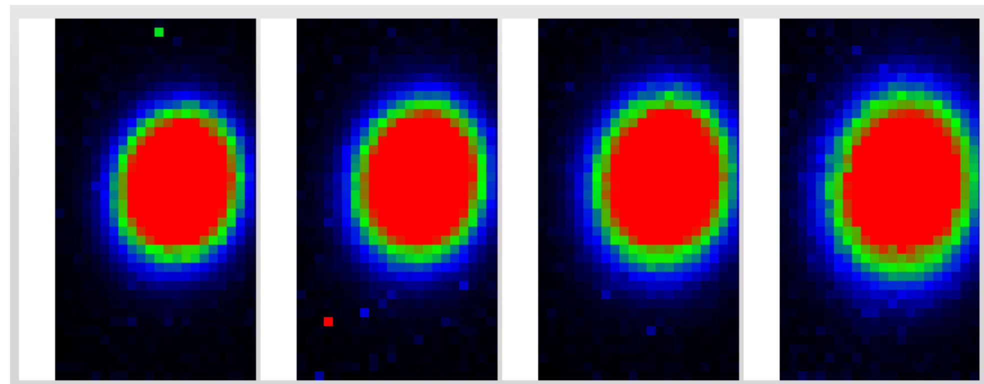
- Upstream and downstream scintillator counters (2mm thick, 55x55 mm) + 4-layer pixel detector (HV-MAPS, 3x3 mm)

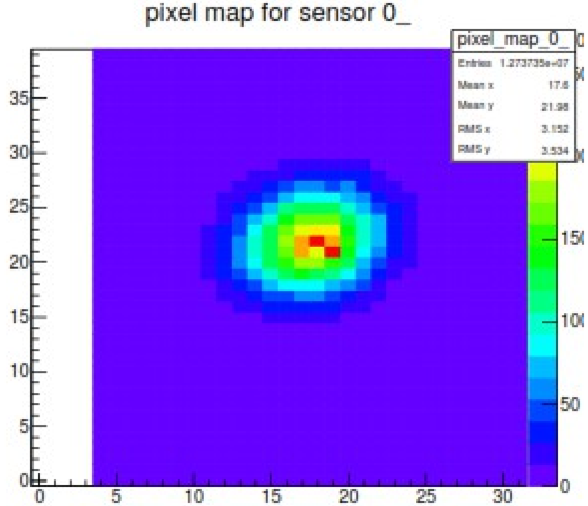
Test setup and beam monitoring system

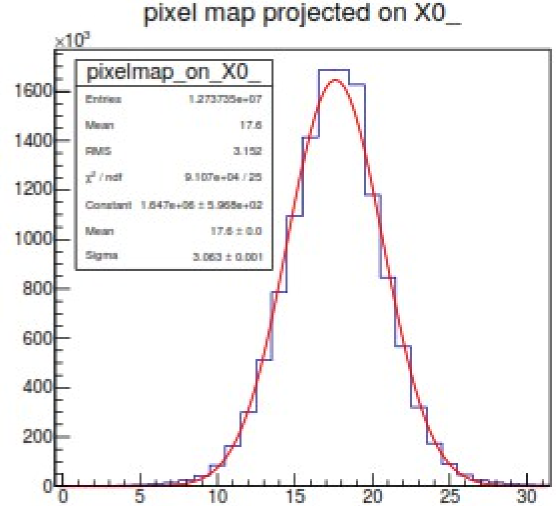


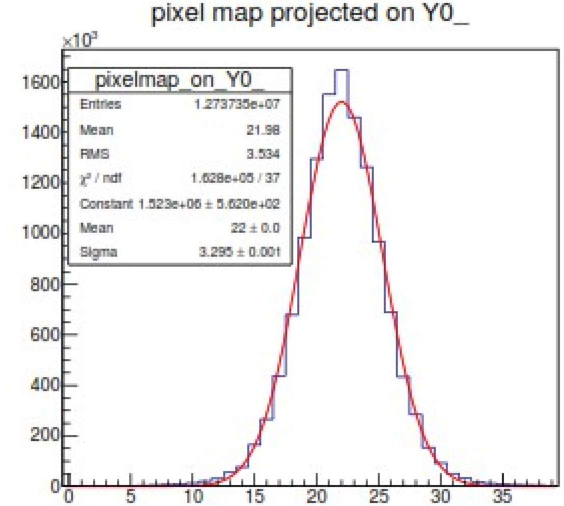
4-layer HV-MAPS pixel detector (3x3 mm)

Monitoring the beam position, reconstruction of electron tracks, and determination of the electron flux



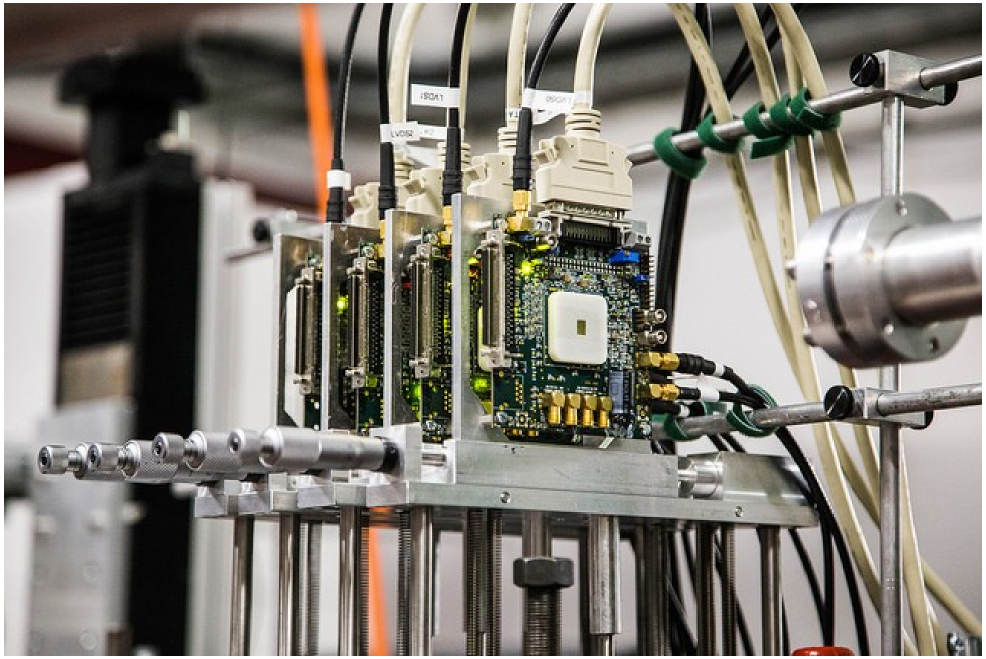






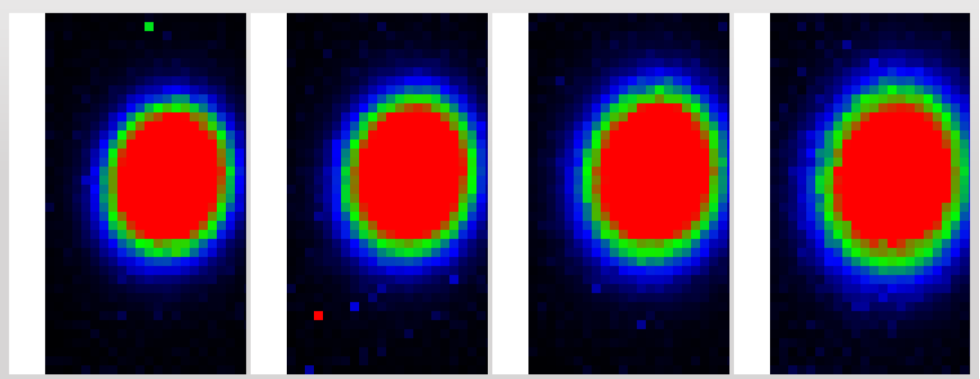
Alexey Tyukin, Frederik Wauters (KPH)

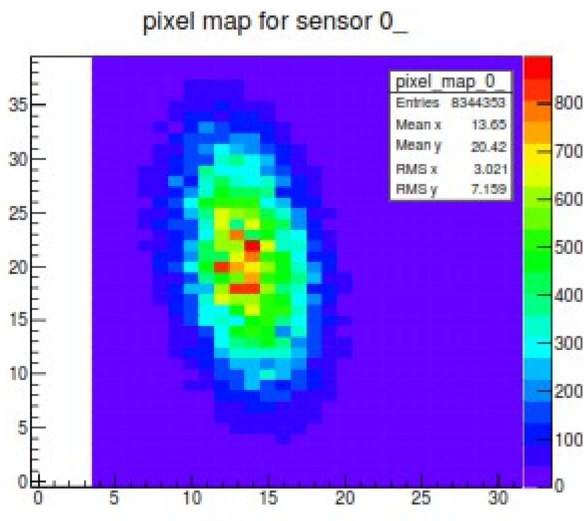
Test setup and beam monitoring system

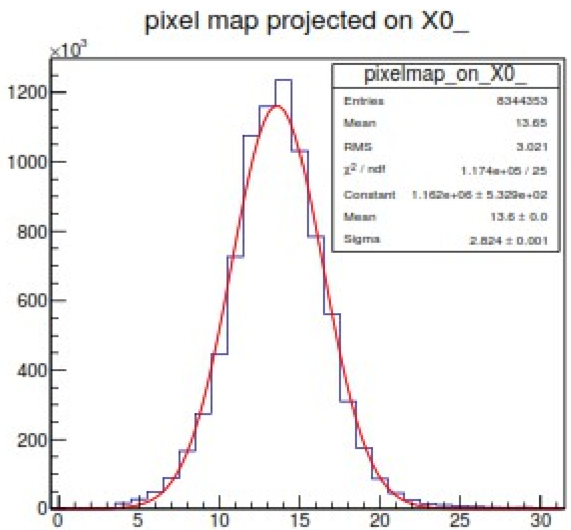


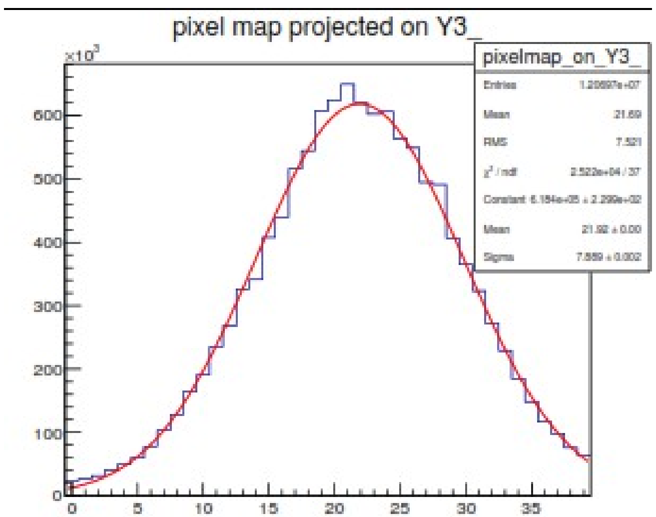
4-layer HV-MAPS pixel detector (3x3 mm)

Monitoring the beam position, reconstruction of electron tracks, and determination of the electron flux



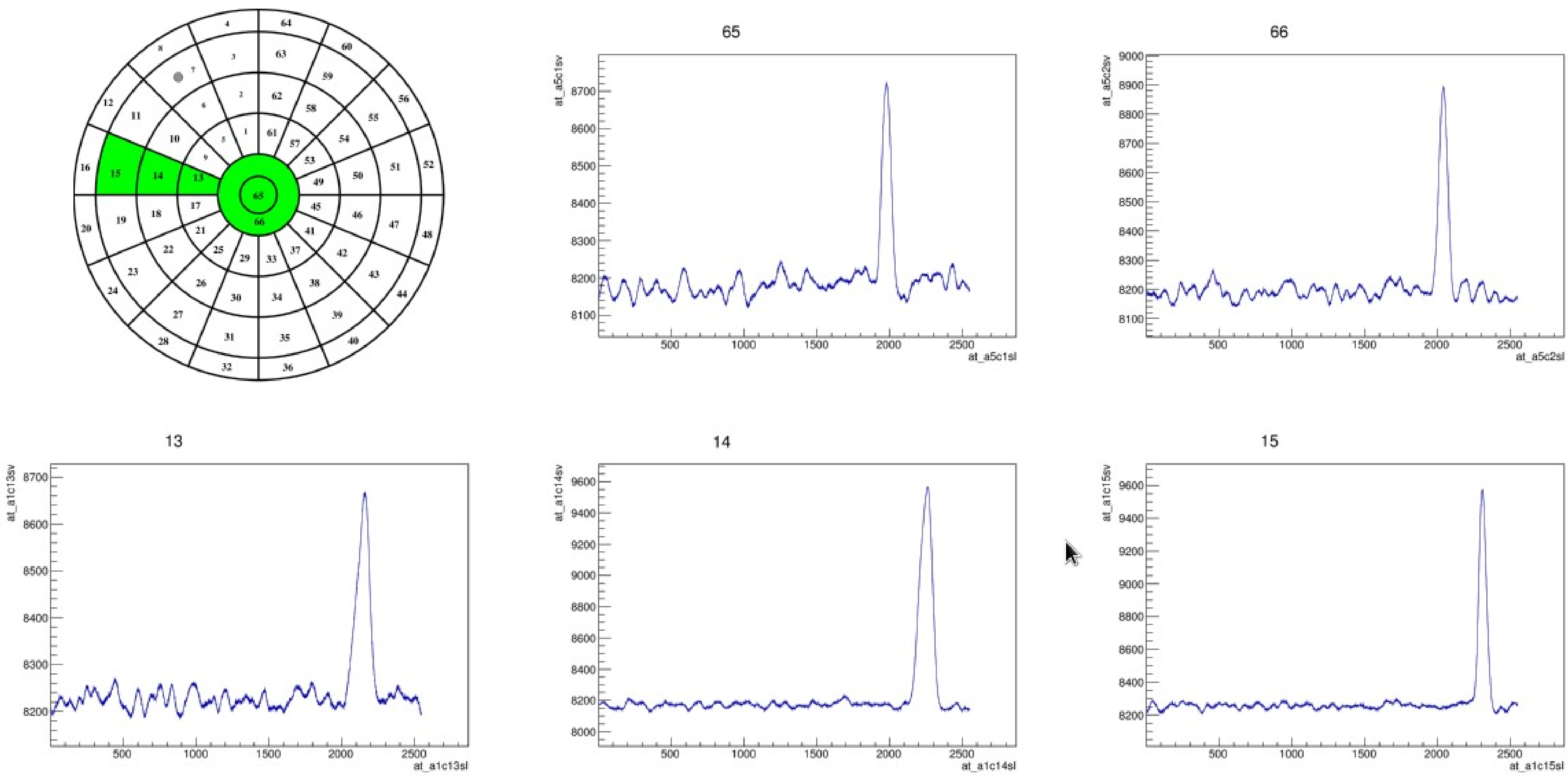






Beam defocused due to high rates

Example recoil track in the TPC

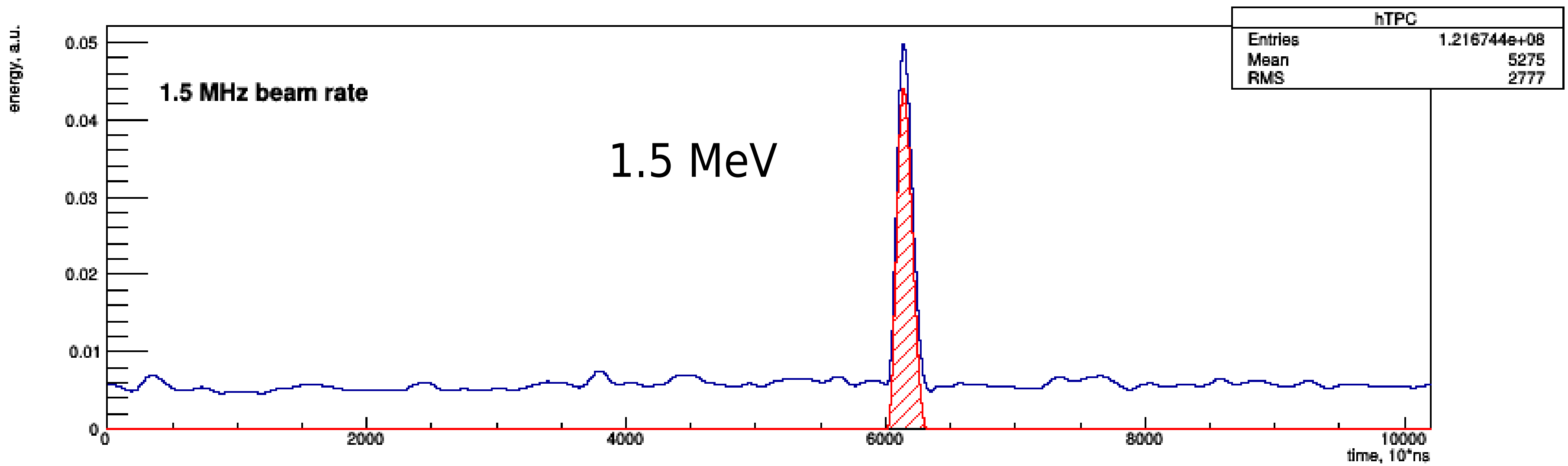


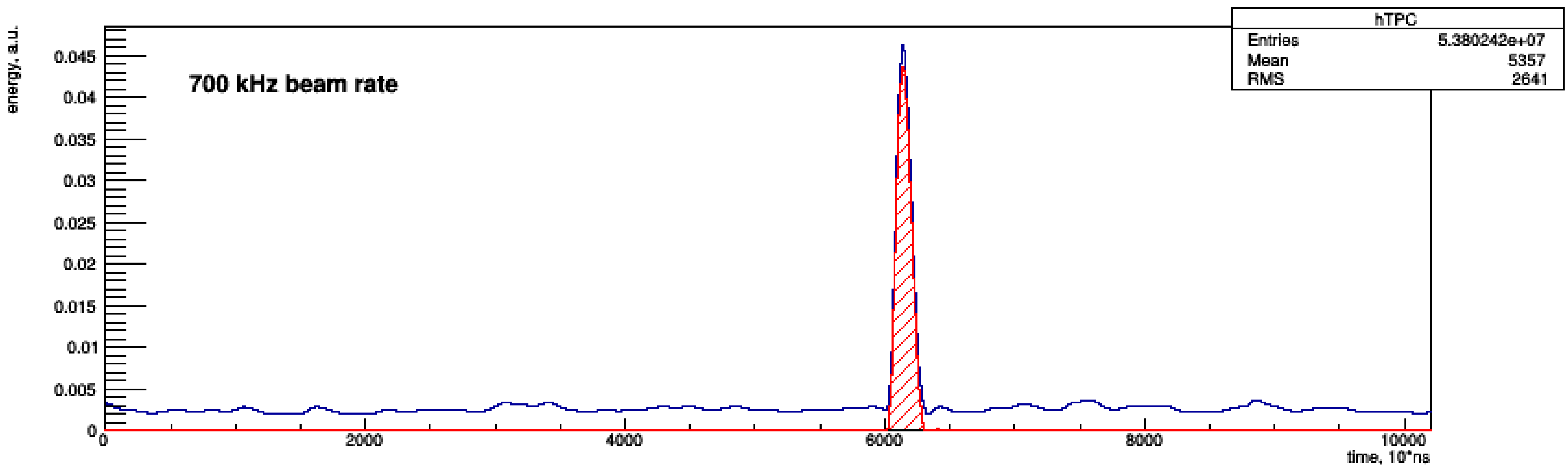
Signals in the TPC clearly identified!

Alexander Inglessi, PNPI

Beam ionization noise in the TPC

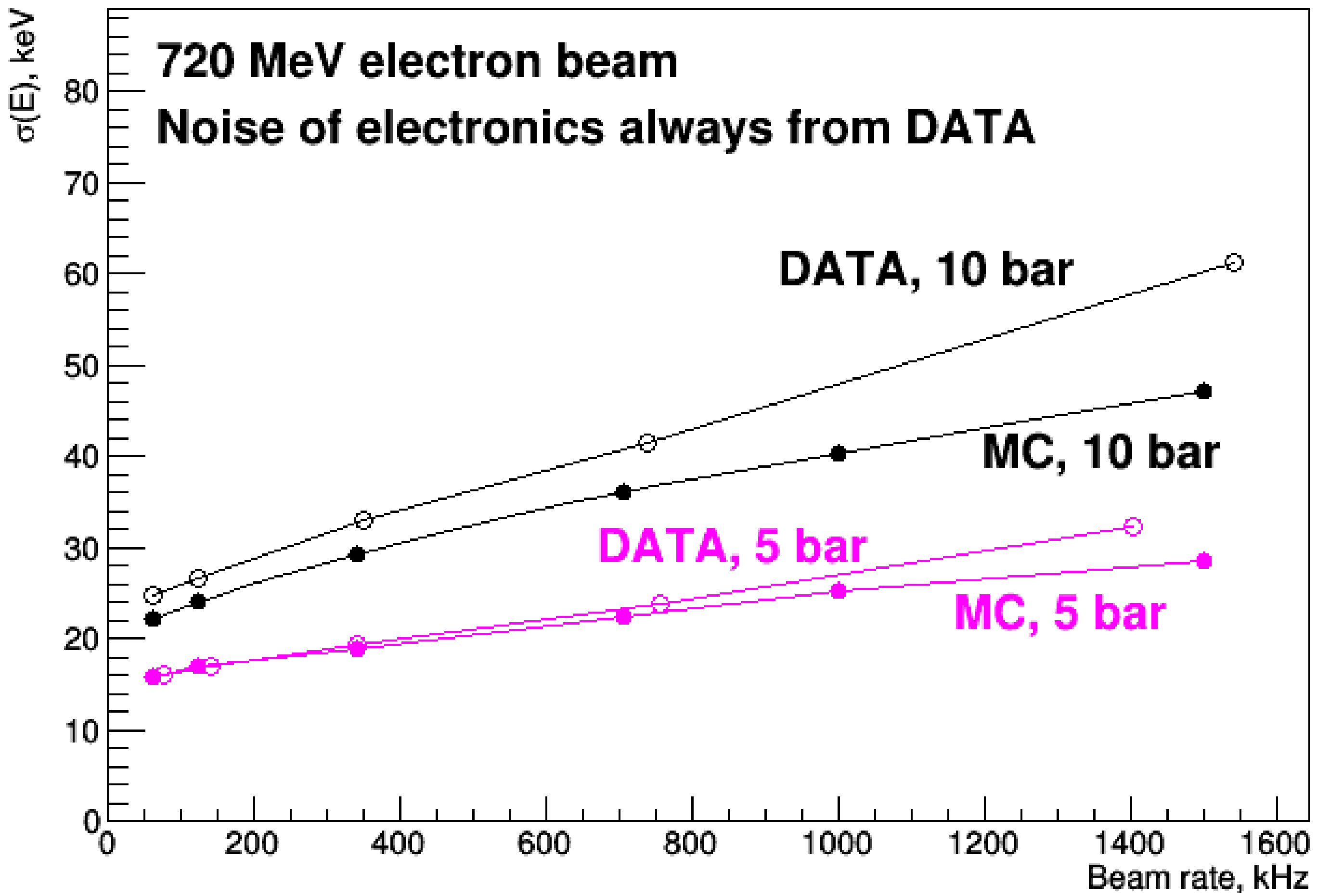
Central pad





(Alexey Dzyuba, Alexey Vorobyov, PNPI)

Noise from the electron beam

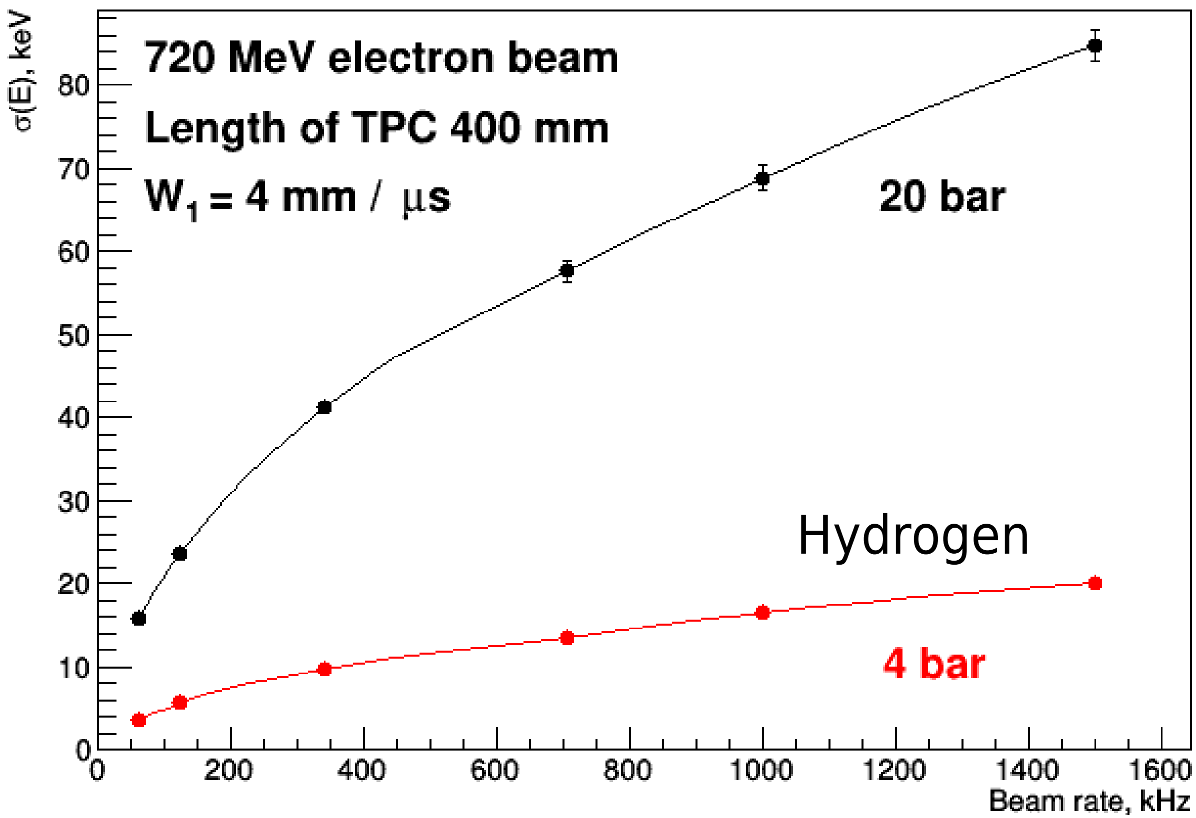


- The beam noise is nearly proportional to the gas pressure
- Measurements are in reasonable agreement with MC
- The beam noise in hydrogen is expected to be smaller than that in the He+4%N_2 mixture by ~ 20%

(Alexey Dzyuba, Alexey Vorobyov, PNPI)

Noise from the electron beam (predictions)

Beam ionization noise at the central pad



Expected TPC energy resolution in the main experiment at 2 MHz beam rate

90 keV at the central pad, 20-30 keV at the other pads at 20 bar
30 keV at the central pad, 20-30 keV at the other pads at 4 bar

(Alexey Dzyuba, Alexey Vorobyov, PNPI)

Main conclusions from the test run

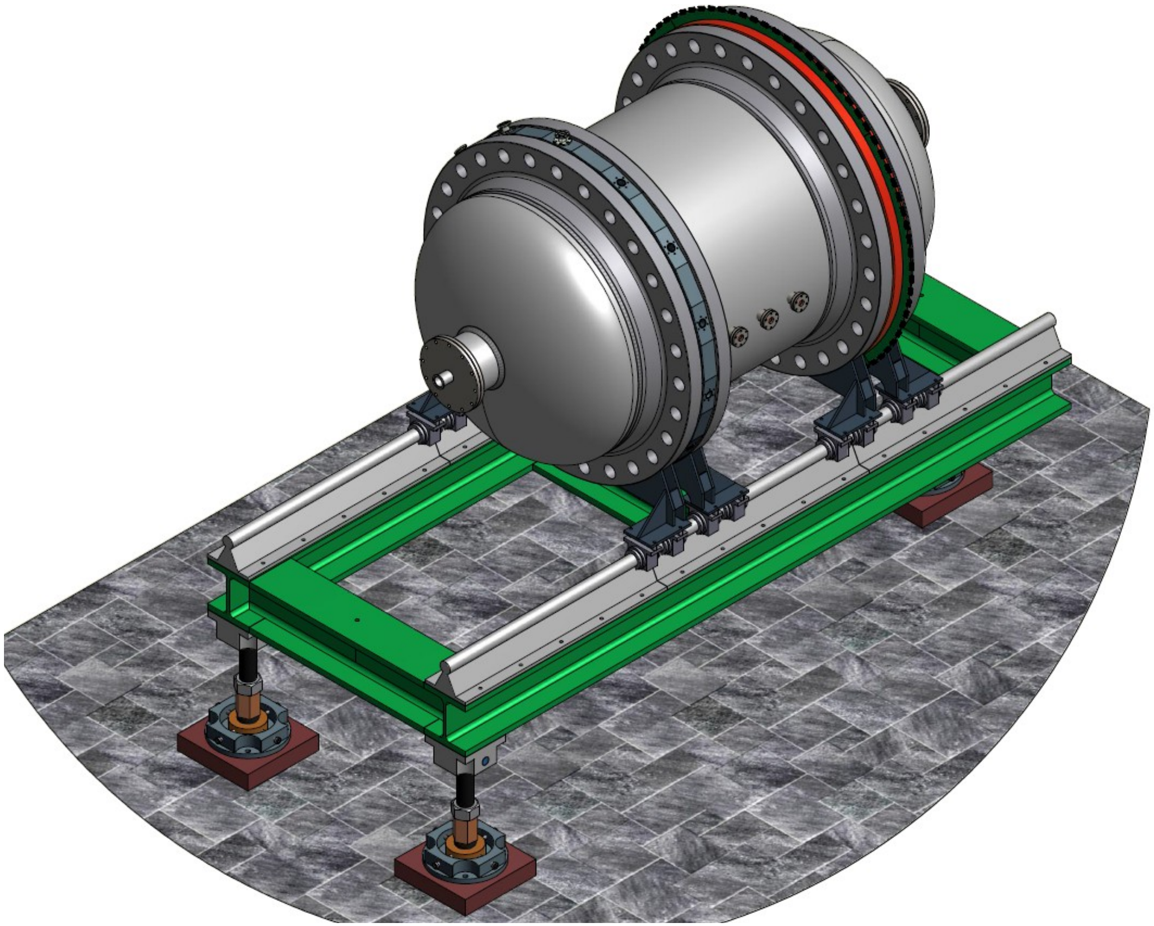
- MAMI electron beam has reasonable quality for this experiment
- The beam ionization noise in the central pad is in reasonable agreement with Monte Carlo simulation

Self triggering mode:
Any signal in the anode exceeding 300 keV
Rates:

- ~4 Hz including ~ 1Hz from elastic *e*He scattering at 10 bar with 1.6 MHz beam
- Very low background in TPC except the central pad
- The low background allows to use TPC in the self-triggering mode

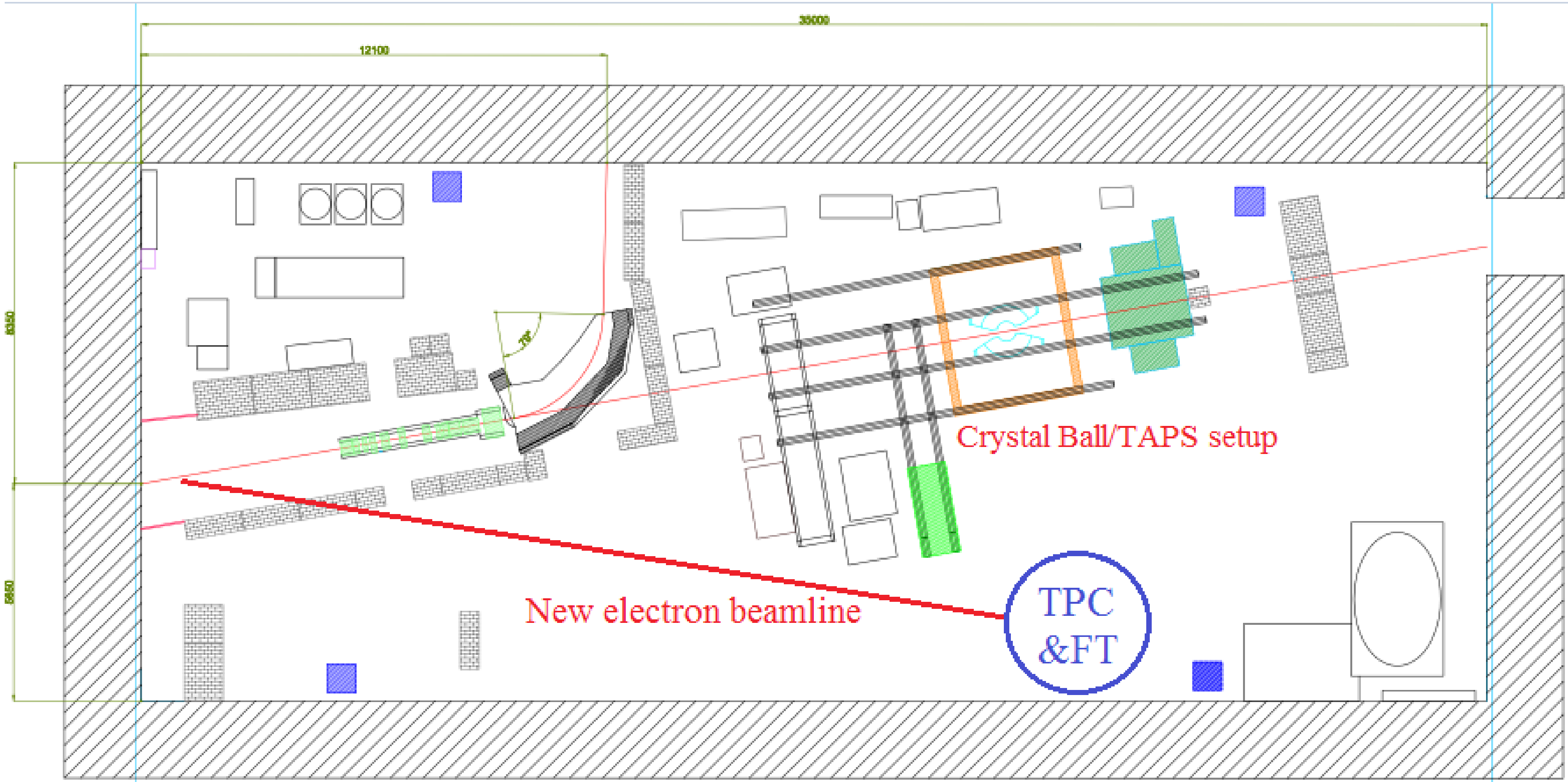
(Alexey Dzyuba, Alexey Vorobyov, PNPI)

IKAR-M experiment in the A2 Hall



- Total area required: 3 x 3 m
- How can the detector be used in the A2 Hall?
- How would it be possible to combine the plans of the A2 Collaboration with the proposed experiments?

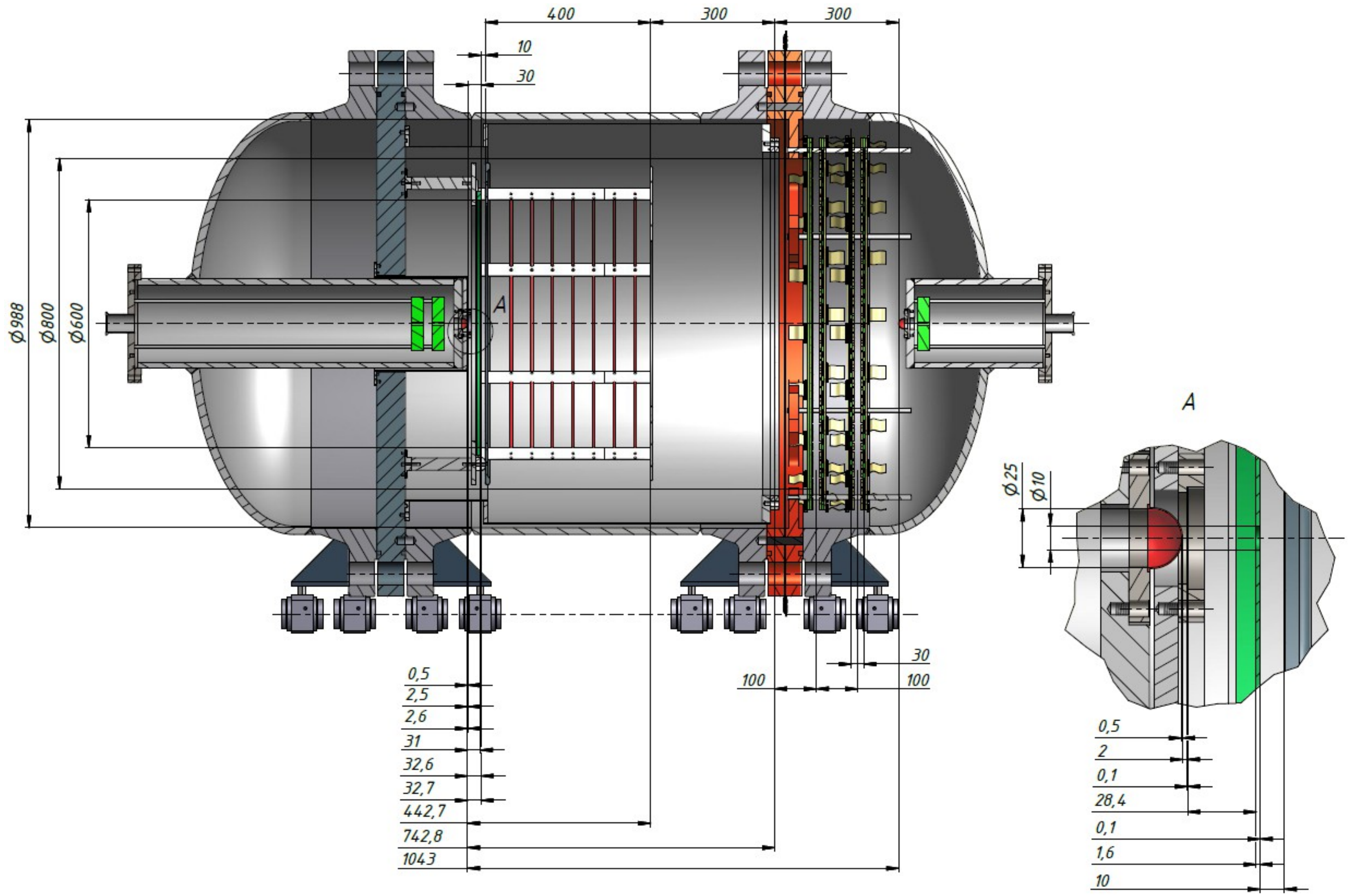
Next: New electron beamline in A2



Construction of a new electron beamline in A2

- Distance ~20 m: additional dipole magnet, 3-4 quadrupole magnets, beam monitors
- Multilayer beam monitoring system for the TPC (HV-MAPS), beam scintillators
- Full support from the MAMI group + KPH Workshops

IKAR-M detector (tentative design)



Construction of the IKAR-M by the PNPI group

In coordination with groups at KPH, GSI, …

➔ Matching with KPH infrastructure

Agreement between KPH and PNPI (2017-2020)

Official agreement signed between KPH (Mainz) and PNPI (Gatchina)

Contribution of the KPH group:

- Construction of a dedicated electron beamline (calculations and hardware production) + technical service
- Preparation of a beam monitoring system and integration of this system into the TPC&FT readout system
- Simulations and data analysis

Contribution of the PNPI group:

- Design and construction of a high pressure (20 bar) hydrogen TPC combined with a forward tracker for scattered electrons
- Transportation of these detectors from PNPI to KPH Mainz
- Simulations, DAQ, data analysis

Practical steps

- Two Letters of Intent (LOI) were presented to the MAMI PAC (2016) and full proposal was considered by PAC in 2017. PAC recommended to proceed with the full program and and to work out final details for the main experiment.

Funding:

KPH:
- Submitted a DFG application within the DFG-RSF Call (2019-2021)
  - Module Eigene Stelle (Temporary position for principal investigators)
  - 2 PhD positions (Beamline construction and preparation of the beam monitoring detector system)
  - Requested support for the construction of the new beamline and beam detectors

PNPI:
- Submitted an application to RSF within the DFG-RSF Call (2019-2021)
- Personnel costs and preparation of DAQ
- Additionally, PNPI invests ~500 kEUR in the construction of the IKAR-M detector (core funding)
- Working group of 8 people at PNPI

Working groups and infrastructure

Current composition of the working groups:

KPH: Patrik Adlarson, Marco Dehn, Peter Drexler, Andreas Thomas, Frederik Wauters, V.S., Achim Denig, Michael Ostrick, Niklaus Berger, Oleksandr Kostikov

PNPI: Alexey A. Vorobyov, Alexander Vasilyev, Petr Kravtsov, Marat Vznuzdaev, Kuzma Ivshin, Alexander Solovyev, Ivan Solovyev, Alexey Dzyuba, Evgeny Maev, Alexander Inglessi, Gennady Petrov

GSI: Peter Egelhof, Oleg Kiselev

College of William and Mary: Keith Griffioen, Timothy Hayward

New collaborators are highly welcome!

PRES: Proton Radius from Electron Scattering (!?)

Summary and Outlook

Preparation of experiments with the IKAR-M (TPC&FT) in the A2 Hall:

- Contribution to understanding the proton radius puzzle
- Innovative approach with detection of both recoil proton and scattered electron
- Experiments possible with electron or photon beams and light nuclei

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- Successful test run: high quality electron beam in the A2 Hall and very low background contamination in the TPC

➡ TPC operation feasible with an electron beam in the A2 Hall

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Next:
- ➔ Construction of a new electron beamline in the A2 Hall (KPH)
- ➔ Construction of the beam monitoring detector system for IKAR-M (KPH&PNPI)
- ➔ Construction of the IKAR-M detector (PNPI)
- ➔ First test with a complete setup in 2019, main experiment in 2020

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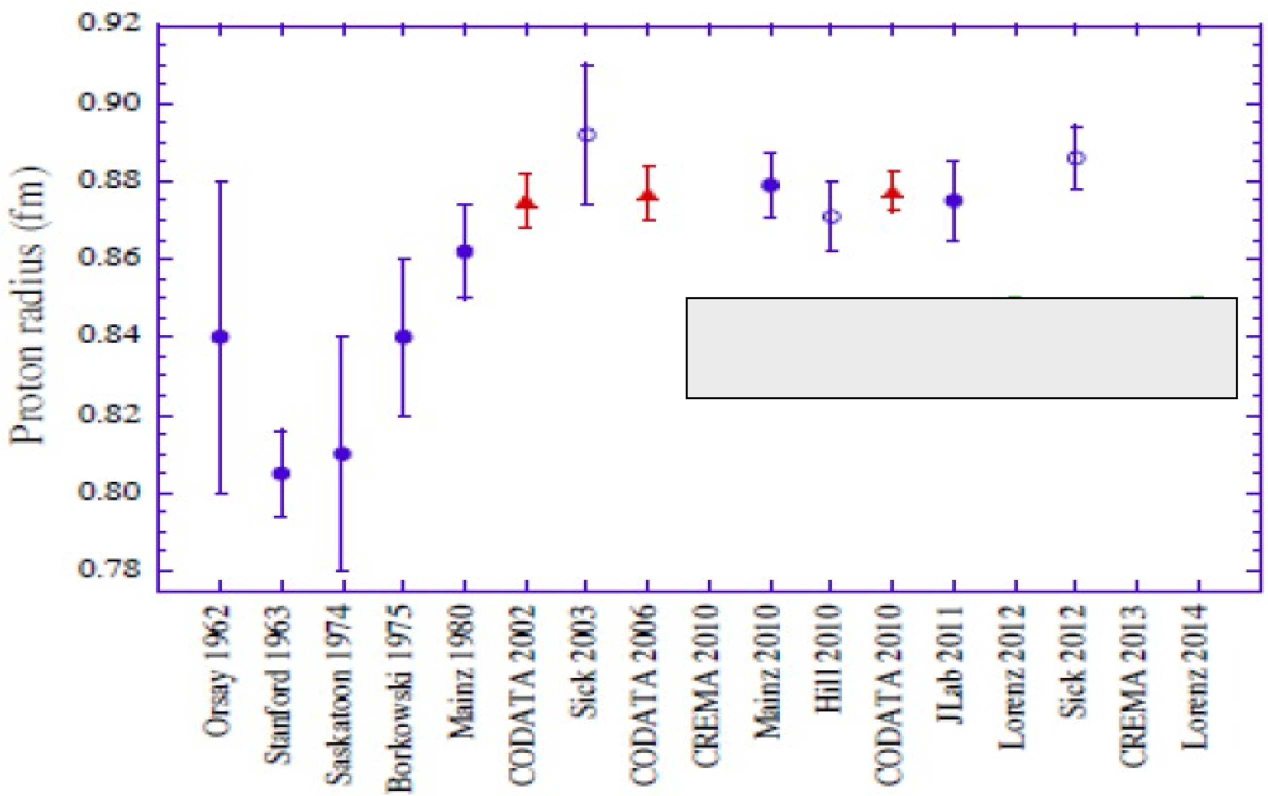
Thank you for your attention!

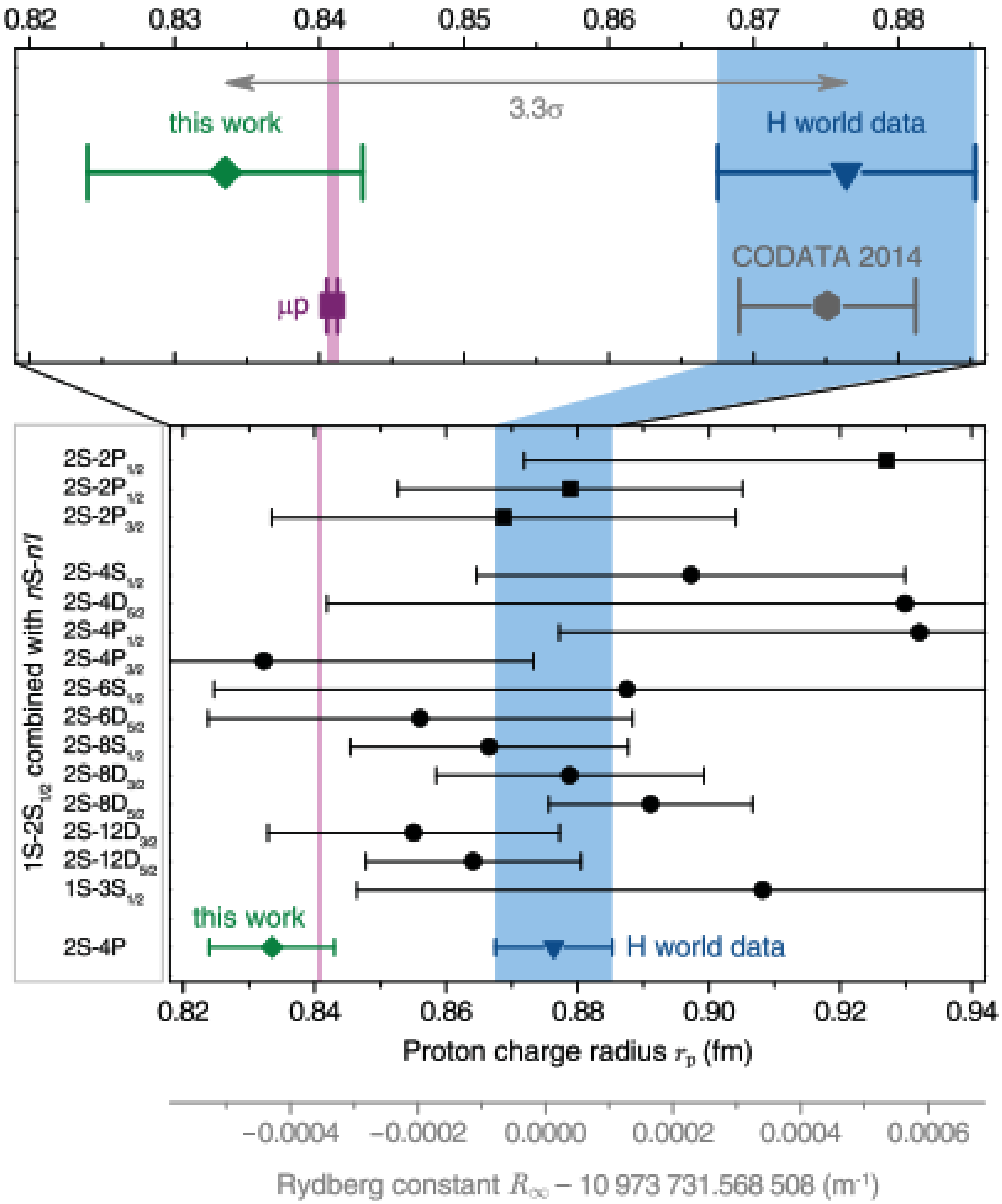
Backup

Proton radius from ep-scattering
1962-2014



- Electron-proton scattering:
  1. $r_p = 0.879(8)$ **fm**, *Mainz, A1 Collaboration, 2010*
  2. $r_p = 0.875(10)$ **fm**, *JLab, Zhan et al, 2011*

- CODATA: $r_p = 0.877\ 5\ (51)$ **fm** *2010*



0.82
0.83
0.84
0.85
0.86
0.87
0.88
3.3σ
this work
H world data
CODATA 2014
μp
1S-2S1/2 combined with nS-n′l′
2S-2P1/2
2S-2P1/2
2S-2P3/2
2S-4S1/2
2S-4D5/2
2S-4P1/2
2S-4P3/2
2S-6S1/2
2S-6D5/2
2S-8S1/2
2S-8D3/2
2S-8D5/2
2S-12D3/2
2S-12D5/2
1S-3S1/2
this work
2S-4P
H world data
0.82
0.84
0.86
0.88
0.90
0.92
0.94
Proton charge radius rp (fm)
−0.0004
−0.0002
0.0000
0.0002
0.0004
0.0006
Rydberg constant R∞ − 10 973 731.568 508 (m⁻¹)

Patrik Adlarson

CREMA deuteron charge radius

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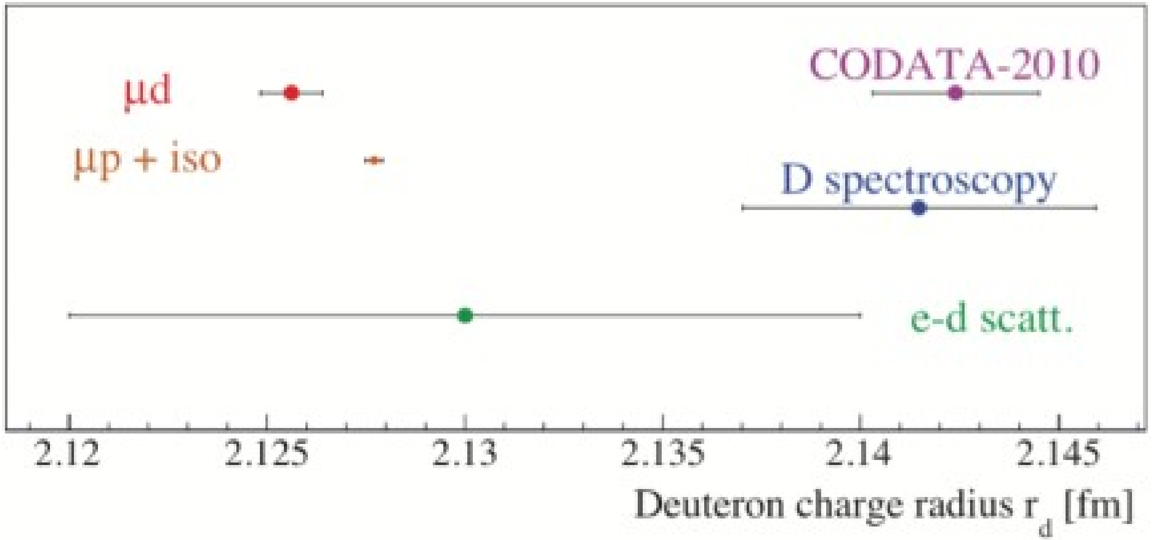


Randolf Pohl et al. CREMA collaboration. Science, 353(6300):669, August 2016.

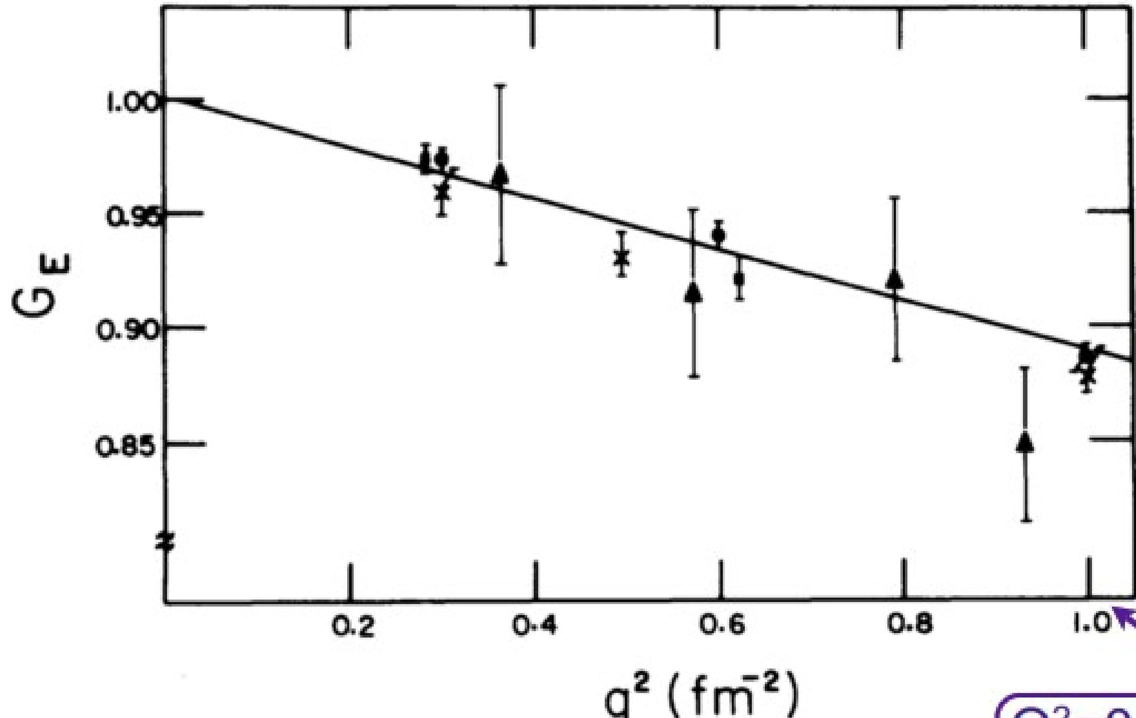
Very recently CREMA made their muonic deuterium official. Two ways to extract the deuteron radius. Both favor low deuteron radius

Similar discrepancy compared to e-deuteron, 7.5σ, only 2.6σ off when taking the muonic proton + isotope shift

Charge radius puzzle became charge radii puzzle

Keith Griffioen

Low Q^2 G_E in 1974



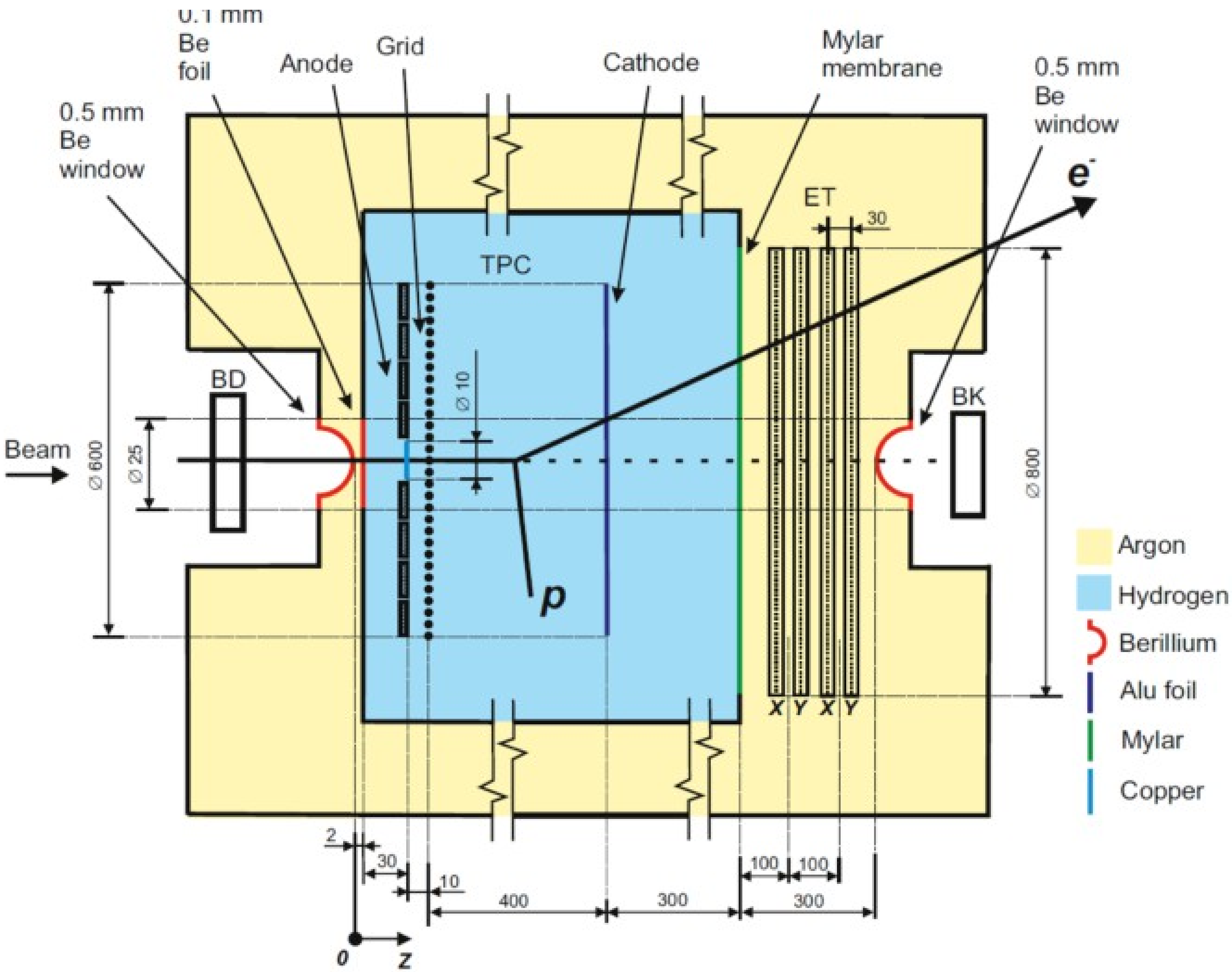
r_E = 0.810(40) fm

Q^2=0.0389 GeV^2

Fit to $G_E(Q^2)=a_0+a_1Q^2+a_2Q^4$
Saskatoon 1974

Murphy PRC9(74)2125

Backup



A. Vorobyov (PNPI)

Backup

The ep elastic scattering cross sections are given by the following expression:

$$\frac{d\sigma}{dt} = \frac{\pi\alpha^2}{t^2}\left\{G_E^2\left[\frac{\left(4M + t/\varepsilon_e\right)^2}{4M^2 - t} + \frac{t}{\varepsilon_e^2}\right] - \frac{t}{4M^2} G_M^2\left[\frac{\left(4M + t/\varepsilon_e\right)^2}{4M^2 - t} - \frac{t}{\varepsilon_e^2}\right]\right\} \quad (1)$$

where $t = -Q^2$, $\alpha = 1/137$, ε_e - initial electron energy, M – proton mass, G_E – electric form factor and G_M – magnetic form factor.

At low Q^2 the form factors can be represented by the expansions:

$$\frac{G(Q^2)}{G(0)} = 1 - \frac{1}{6}\langle R_p^2\rangle Q^2 + \frac{1}{120}\langle R_p^4\rangle Q^4 - \ldots, \quad (2)$$

The electric proton radius R_{pE} can be measured by measuring the slope of the electric form factor G_E as Q^2 goes to 0:

$$R_{pE}^2 = \left.\frac{-6 \cdot dG_E(Q^2)}{dQ^2}\right|_{Q^2 \to 0} \quad (3)$$

Backup

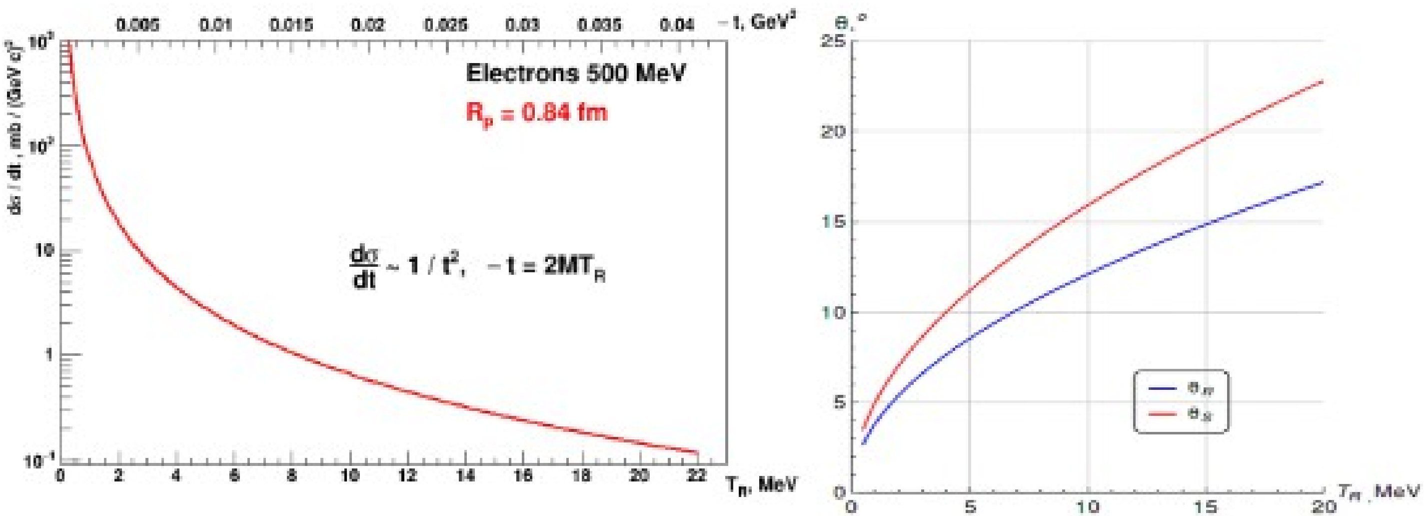


Figure 2: Left panel: differential cross section of the ep elastic scattering calculated for ε = 500 MeV with electric and magnetic form factors represented by expansion Eq. 2. Right panel: Scattering electron and recoil proton angles as function of the recoil proton energy.

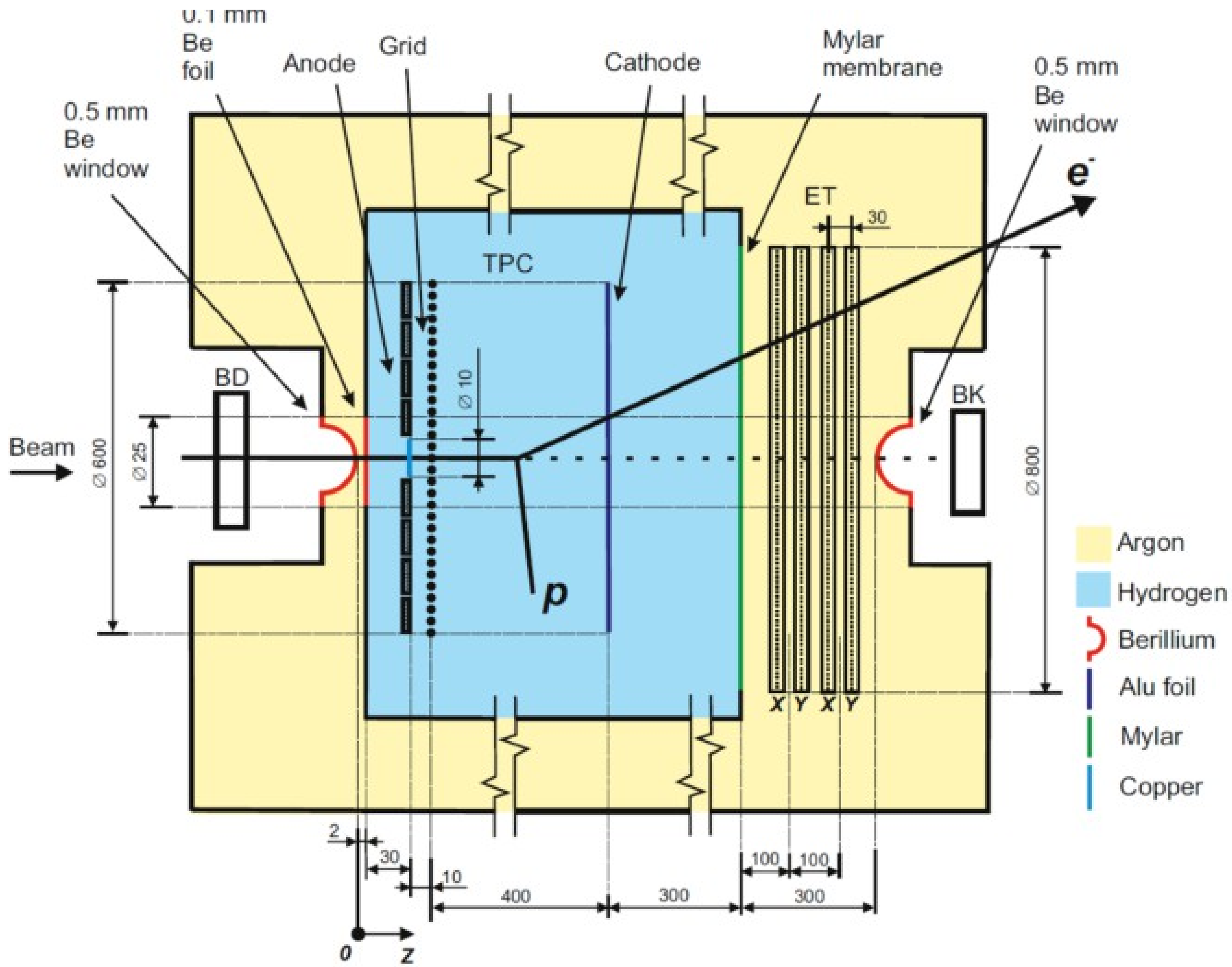
The ep elastic scattering differential cross section is given by the following expression:

$$\frac{d\sigma}{dt} = \frac{\pi\alpha^2}{t^2}\left\{G_E^2\left[\frac{(4M+t/\varepsilon)^2}{4M^2-t}+\frac{t}{\varepsilon^2}\right]-\frac{t}{4M^2}G_M^2\left[\frac{(4M+t/\varepsilon)^2}{4M^2-t}-\frac{t}{\varepsilon^2}\right]\right\}, \qquad (1)$$

where $t = -Q^2$, $\alpha = (137)^{-1}$ – fine structure constant, ε – initial electron energy, M – proton mass, G_E and G_M -– proton electric and magnetic form factors. At the low Q^2, the form factors can be represented by the expansions

$$\frac{G_{E,M}(Q^2)}{G_{E,M}(0)} = 1 - \frac{\langle r^2_{pE,M}\rangle}{6}Q^2 + \mathcal{O}(Q^4), \qquad (2)$$

Backup



A. Vorobyov (PNPI)

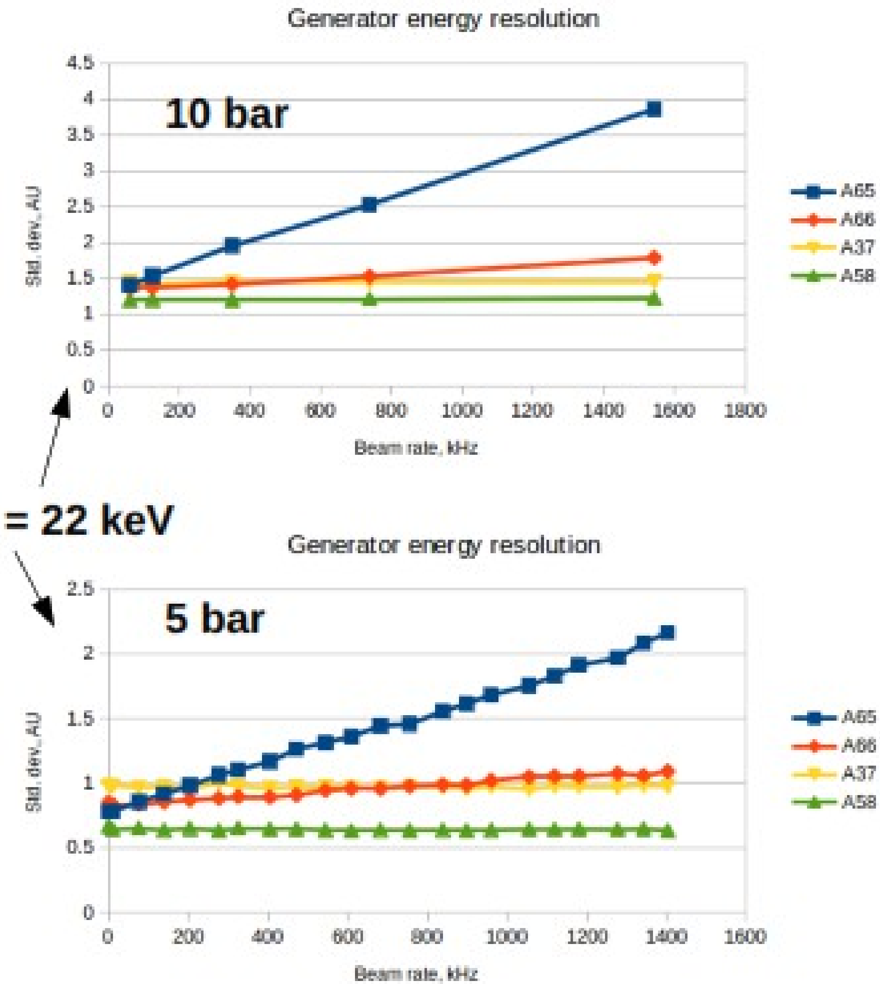
Measured pulse generator resolution

– Sizeble effect only for centrlal anode (A65);

– Visible effect for the second ring (A66);

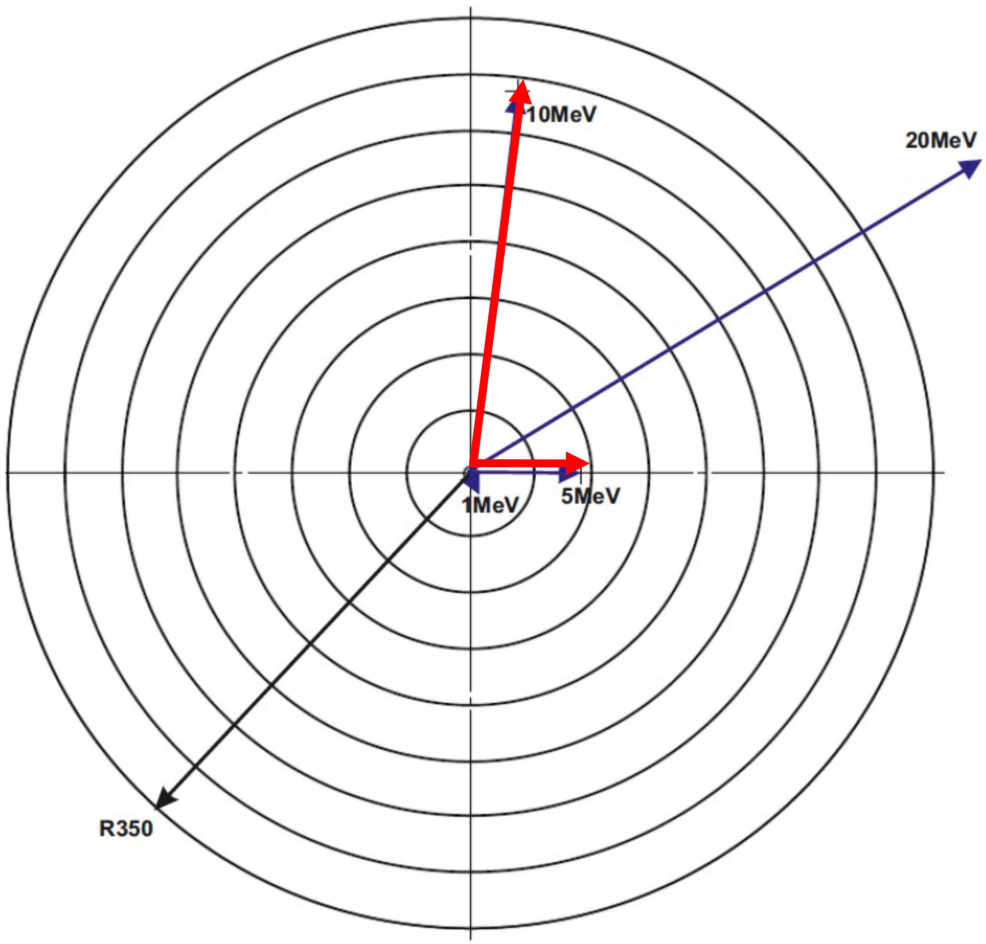
– Practically no effects in the other channels (A37 / A58).

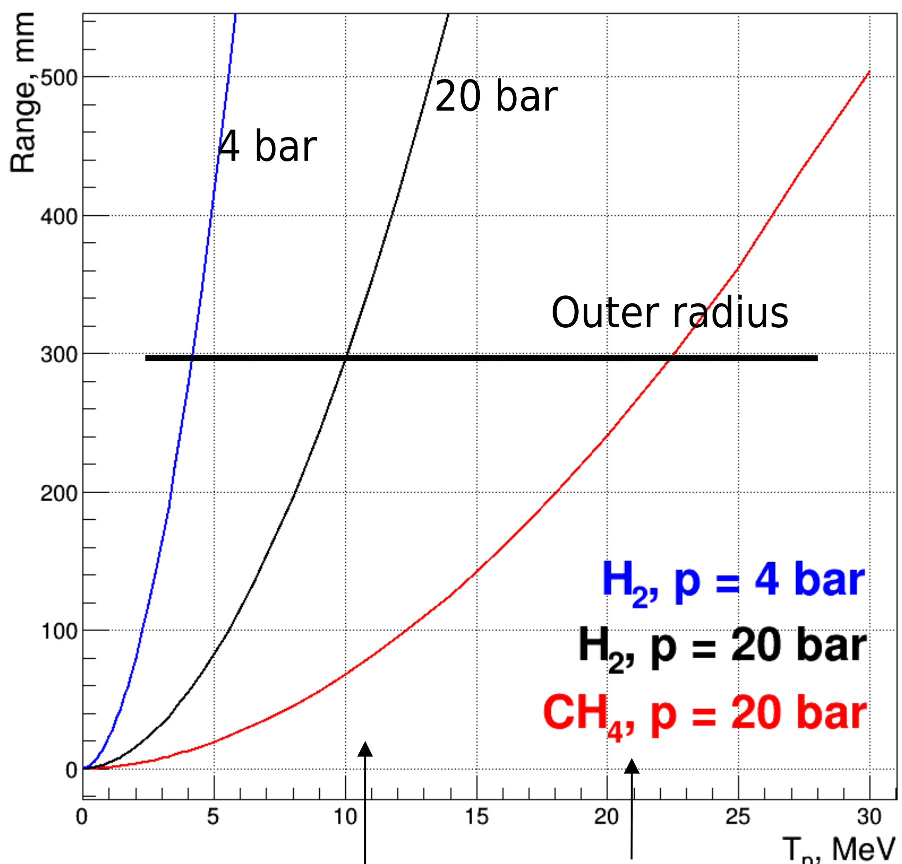
1 AU = 22 keV



TPC gas fillings

H_2 4 bar	$T_R \le 4$ MeV
H_2 20 bar	$T_R \le 10$ MeV
CH_4	$T_R \le 22$ MeV





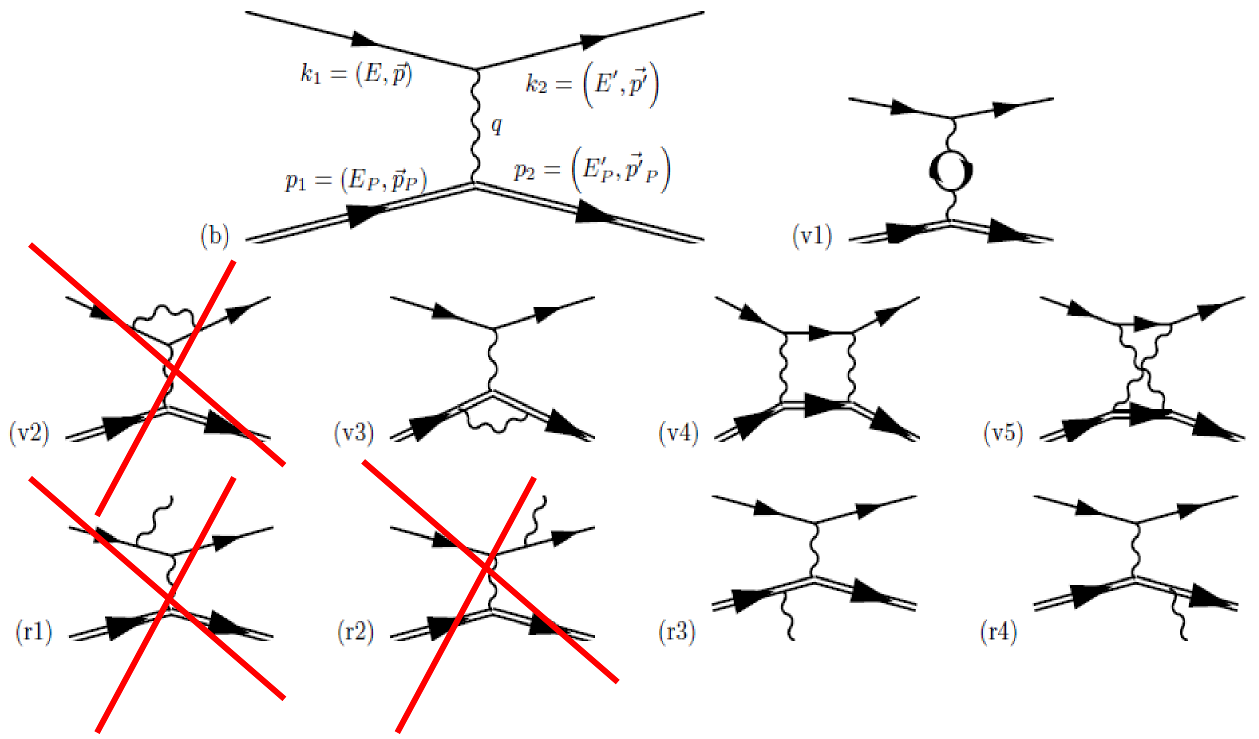
$Q^2 = 0.02$ GeV^2

$Q^2 = 0.04$ GeV^2

TPC anode structure: 10 mm in diameter disc surrounded by 7 rings

Radiative corrections

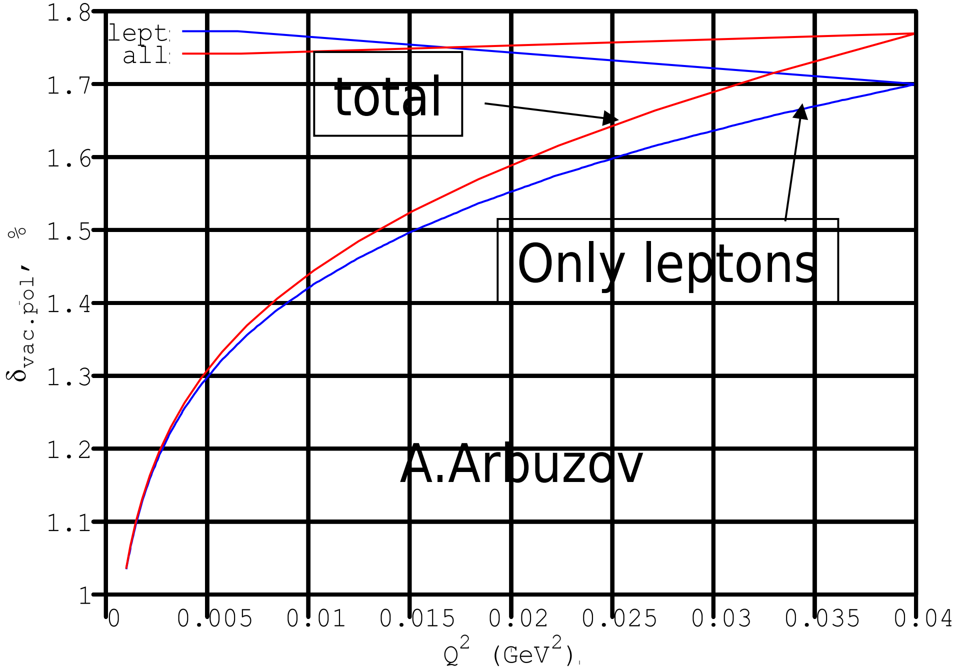
$$\left(\frac{d\sigma}{d\Omega}\right)_1 = \left(\frac{d\sigma}{d\Omega}\right)_0 (1+\delta).$$

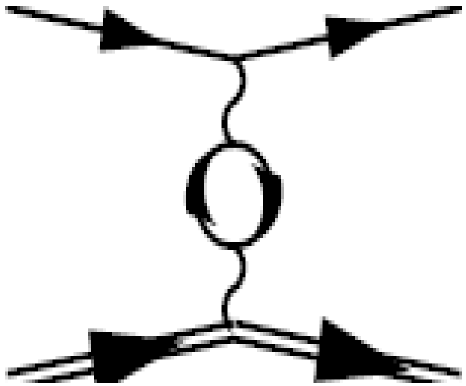


Diagrams v2, r1,r2 are self-cancelling in the recoil method.
The other RC are small and can be calculated to ≤ 0.1% precision.

Absolute measurement of dσ/dt with 0.2% precision
gives a control for the level of introduced radiative corrections.

Vacuum polarization is the largest RC in this method





Q^2=0.022 GeV^2

δ_{VP} =1.61546((28)%

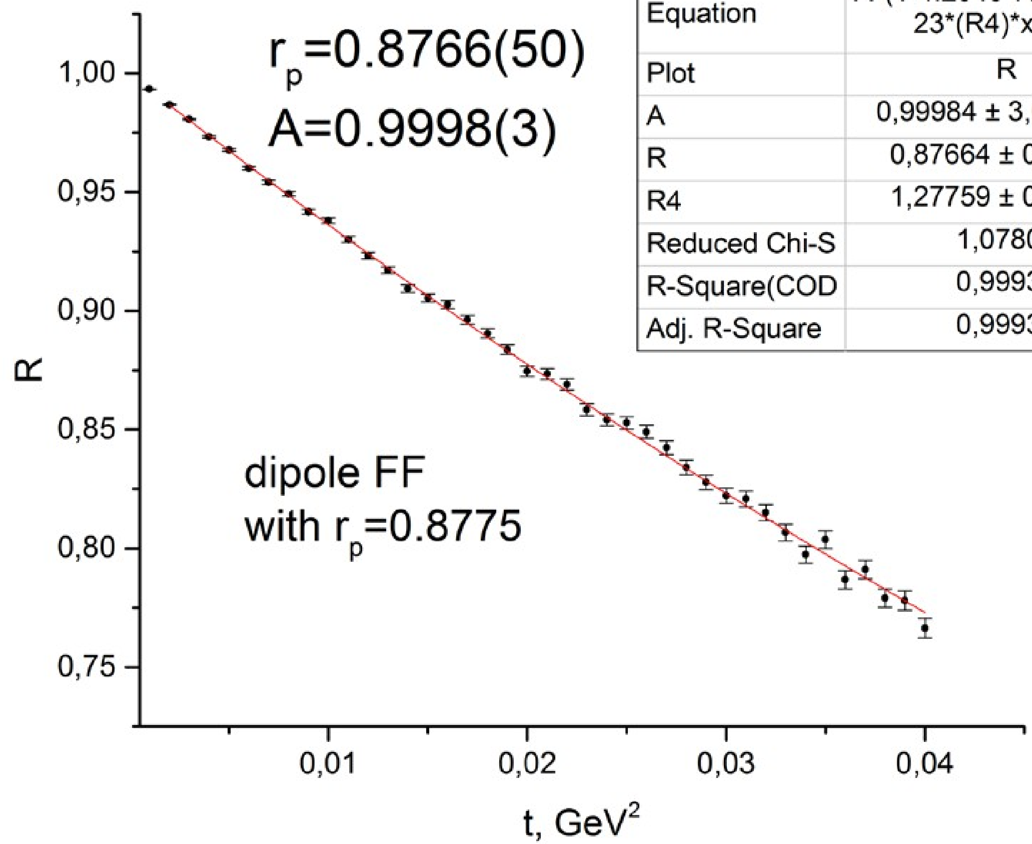
The other corrections will be calculated with the Novosibirsk ESEPP generator

Statistics

45 days 33x10^6 events

$$\frac{G(Q^2)}{G(0)} = 1 - \frac{1}{6}\langle R_p^2\rangle Q^2 + \frac{1}{120}\langle R_p^4\rangle Q^4 - \ldots,$$

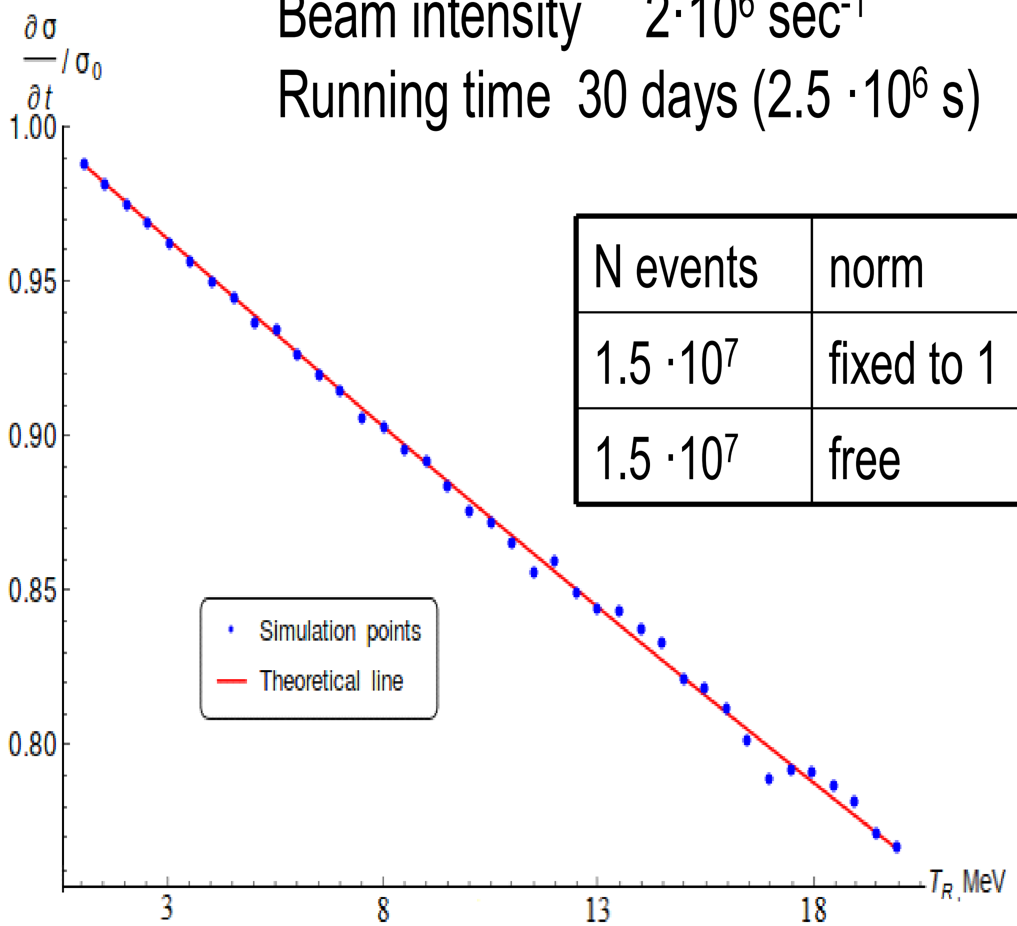
Model	polinFF (User)
Equation	A*(1-4.2943*R^2*x+5.5323*(R4)*x^2)^2
Plot	R
A	0,99984 ± 3,0008E-4
R	0,87664 ± 0,00495
R4	1,27759 ± 0,22675
Reduced Chi-S	1,07804
R-Square(COD	0,99939
Adj. R-Square	0,99936



Rp ± 0.005 fm

Statistical accuracy

Target thickness = $3.6 \cdot 10^{22}$ p/cm^2
P =20bar L =35cm
Beam intensity $2 \cdot 10^6$ sec^{-1}
Running time 30 days ($2.5 \cdot 10^6$ s)



N events	norm	t-scale	σ(Rp)
$1.5 \cdot 10^7$	fixed to 1	fixed	± 0.002 fm
$1.5 \cdot 10^7$	free	fixed	± 0.003 fm

A. Vorobyov (PNPI)

Run conditions and acquired data

- The main run: 10 bar pressure, electron beam intensity ~ 1.4 MHz (counted by the upstream scintillator): ~100 hours, acquired ~2000 files. ~2.5×10^6 events (total)

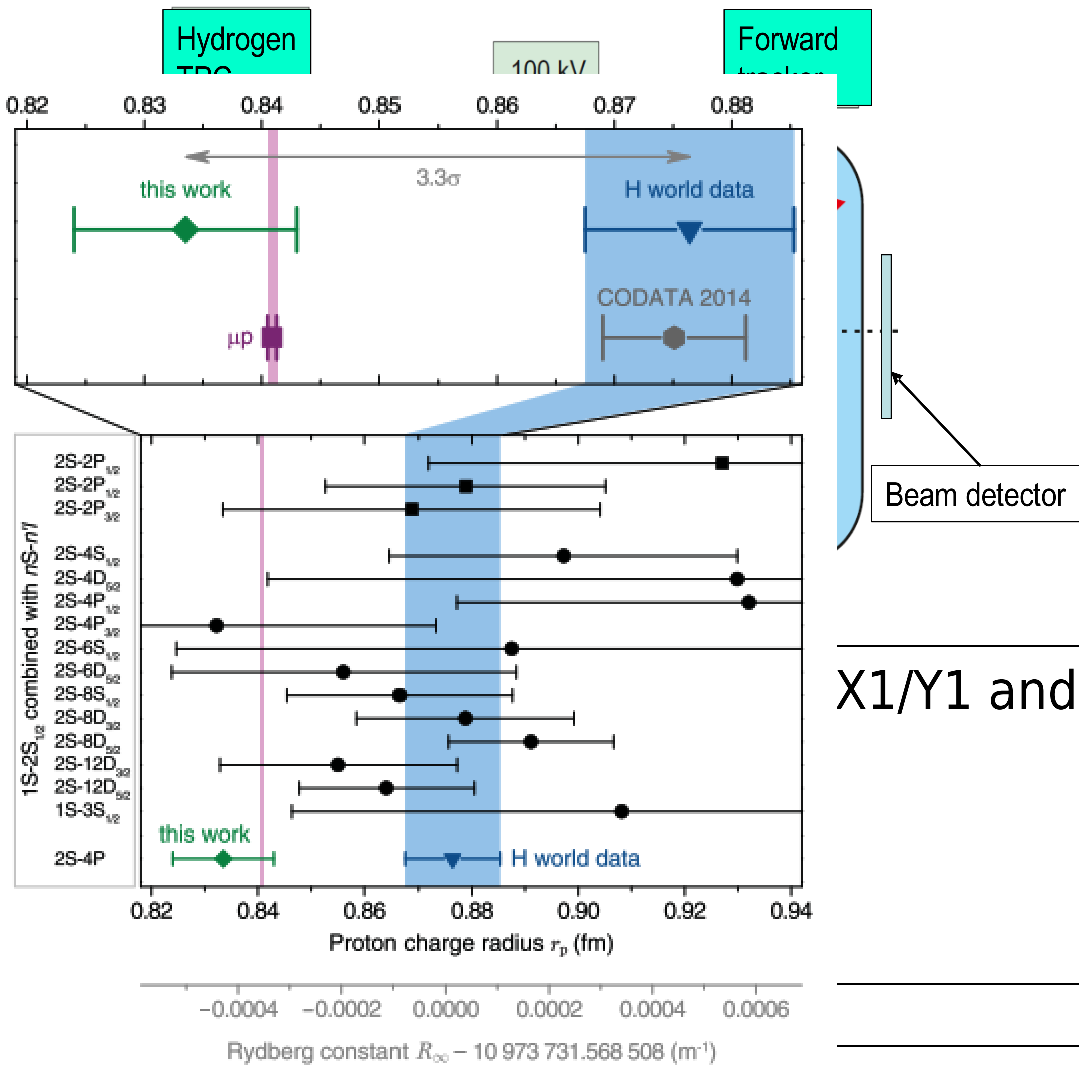
- Low intensity tests: (130kHz, 90files) and (300kHz, 150 files)

In the end of the experiment: the gas pressure in the TPC was decreased down to 5bar (HV on cathode ~9kV), beam intensity ~ 1.35 MHz, ~35 hours were collected ~ 350 files,~ 4×10^6 events (total)

See the talk of A. Dzyuba for further details and results

Data:
- ~2.1 TB from the TPC and scintillators and 3.7 TB from the pixel telecsope
- Stored at GSI at two different locations and will be copied to the machines in Mainz in the near future
- Analysis and simulation steps to be discussed (Patrik Adlarson, Alexey Dzyuba, Timothy Hayward, Alexander Inglessi, V.S.)

Forward Tracker



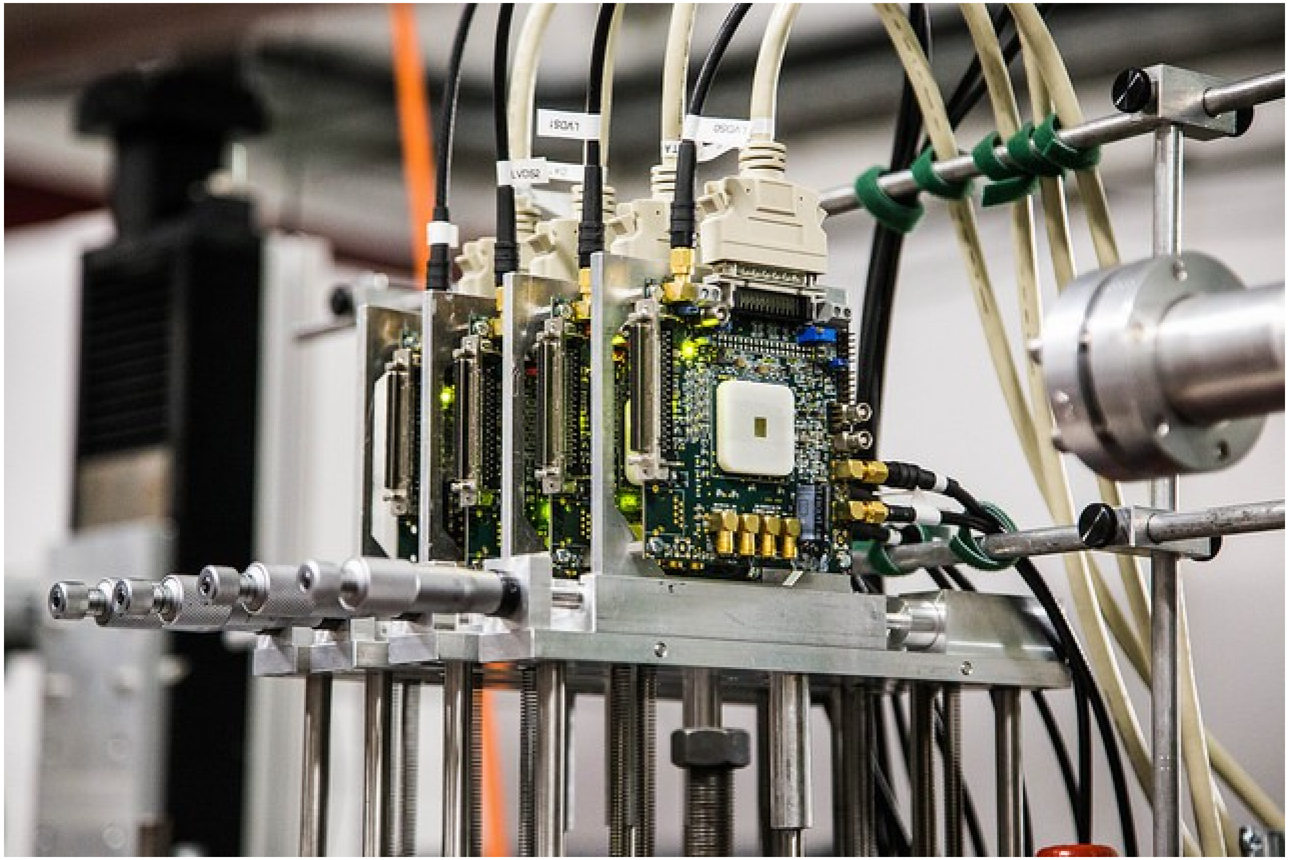
Bear

T

X1/Y1 and X2/Y2.

Linear scale with 0.02 % absolute precision

Prototype for the beam monitoring system

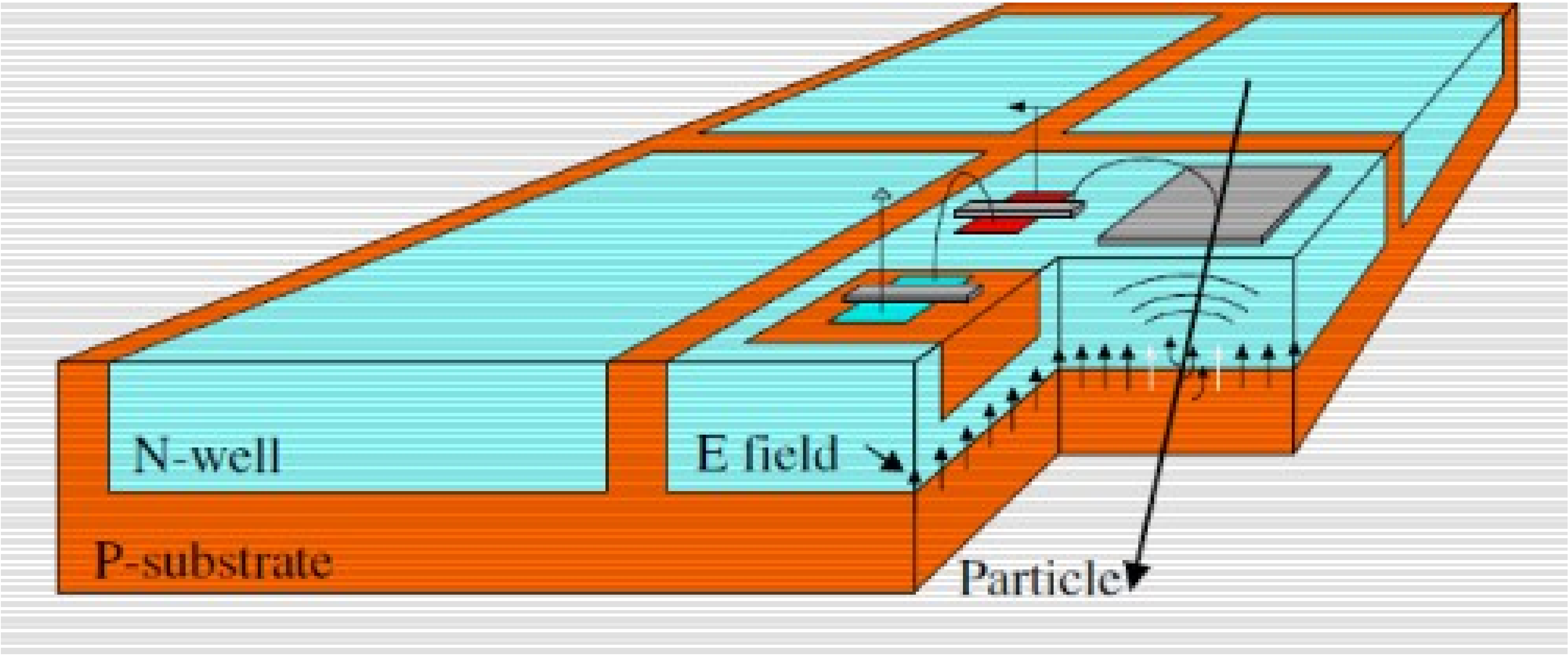


Mupix 7:

- 32 x 40 pixels of 103 um x 80 um
- 62.5 MHz timestaps
- 1.25 Gb/s readout to FPGA
- Track based alignment to better than 5 um
- 99 % efficiency per plane

(Frederik Wauters, Mainz)

Backup



Backup (Patrik Adlarson)

Bethe–Heitler (BH) process

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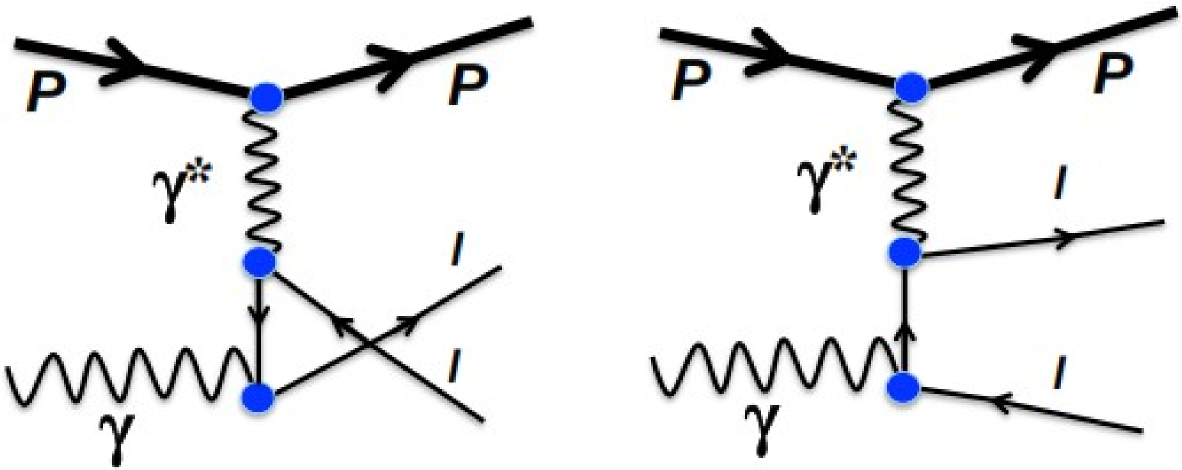

$$\frac{d\sigma^{BH}}{dt\,dM_{ll}^2} = \frac{\alpha^3}{(s-M_p^2)^2}\cdot\frac{4\beta}{t^2(M_{ll}^2-t)^4}\cdot\frac{1}{1+\tau}\times\left[C_E G_{E_p}^2 + C_M \tau G_{M_p}^2\right]$$

Invariant mass sq lepton pair

Proton mom transfer

Proton form factors

Backup (Patrik Adlarson)

Bethe–Heitler $d\sigma/dE\gamma$

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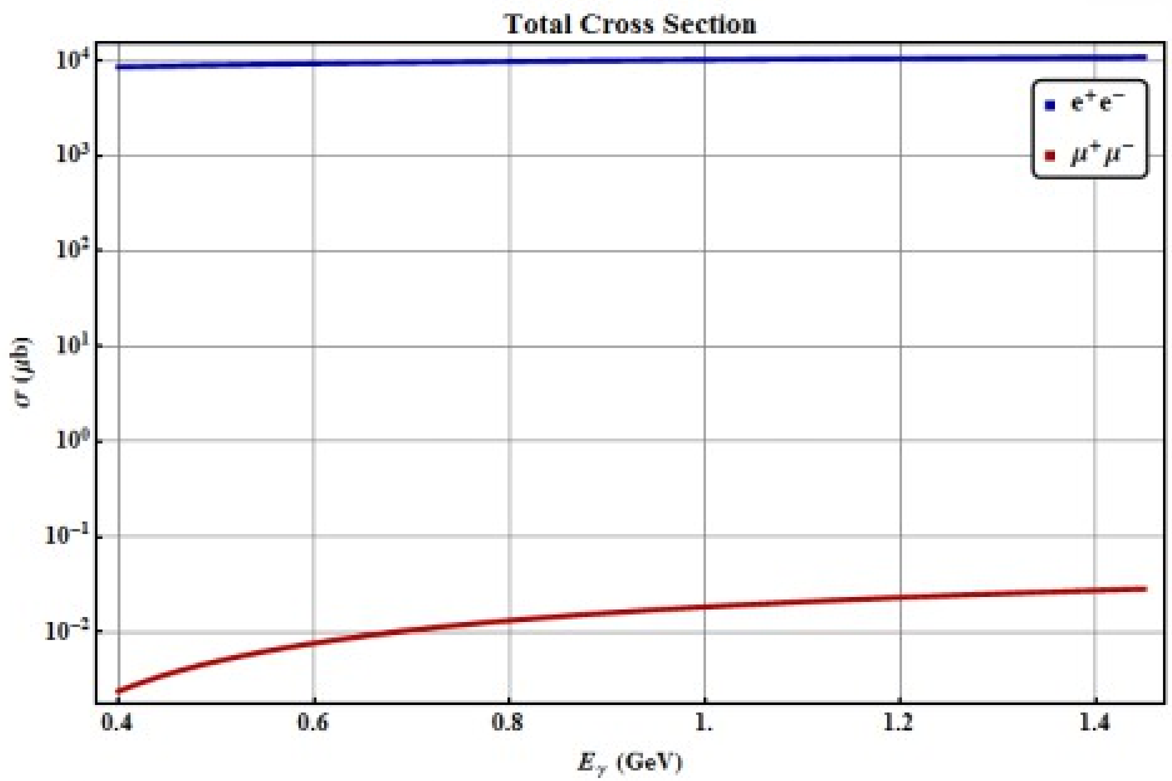

BH-ee (blue) and BH-μμ (red) cross section as function of beam energy

Dimuon cross section increases more for increasing beam energies

Backup (Patrik Adlarson)

Bethe–Heitler (BH) process

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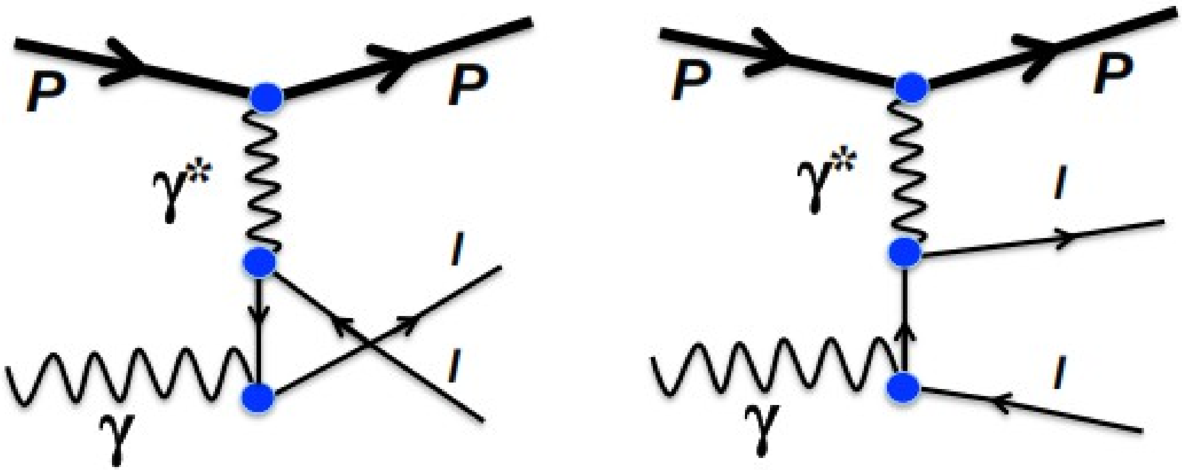

$$\frac{d\sigma^{BH}}{dt\,dM_{ll}^2} = \frac{\alpha^3}{(s-M_p^2)^2} \cdot \frac{4\beta}{t^2(M_{ll}^2 - t)^4} \cdot \frac{1}{1+\tau} \times \left[C_E G_{E_p}^2 + C_M \tau G_{M_p}^2\right]$$

Invariant mass sq lepton pair

Proton mom transfer

Proton form factors

Backup

		Syst. Error %	comment
1	Drift velocity, W1	0.01	
2	High Voltage, HV	0.01	
3	Pressure, P	0.01	
4	Temperature, K	0.015	
5	H_2 density , ρ_p	0.025	Sum of errors 3 and 4
6	Target length, L_{targ}	0.02	
7	Number of protons in target, N_p	0.045	Sum of errors 5 and 6
8	Number of beam electrons, N_e	0.05	
9	Detection efficiency	0.05	
10	Electron beam energy, ε_e	0.02	
11	Electron scattering angle, θ_e	0.02	
12	t-scale calibration, T_R relative	0.04	Follows from error 11
13	t-scale calibration, T_R absolute	0.08	Follows from the sum of errors 11 and 10
	$d\sigma/dt$, relative	0.1	0.08 % from error 12
	$d\sigma/dt$, absolute	0.2	0.16 % from err.13 plus errors 7,8, and 9

Backup

MAMI Specifications

Beam energy	500 MeV, 720 MeV
Energy spread	< 20 keV (1σ)
Energy shift	< 20 keV (1σ)
Absolute energy	±< 150 keV (1 σ)

Electron Beam Specifications

Beam intensity (main run)	2x10^6 e^-/sec
Beam intensity for calibration	10^4 e^-/sec and 10^3 e^-/sec
Beam divergency	≤ 0.5 mrad
Beam size	minimal at given divergence

Beam Time Request

Test run in 2017	~ 2 weeks
First physics run in 2018	~ one month