TPC test: installation and first results

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Mainz, 25.09.2017

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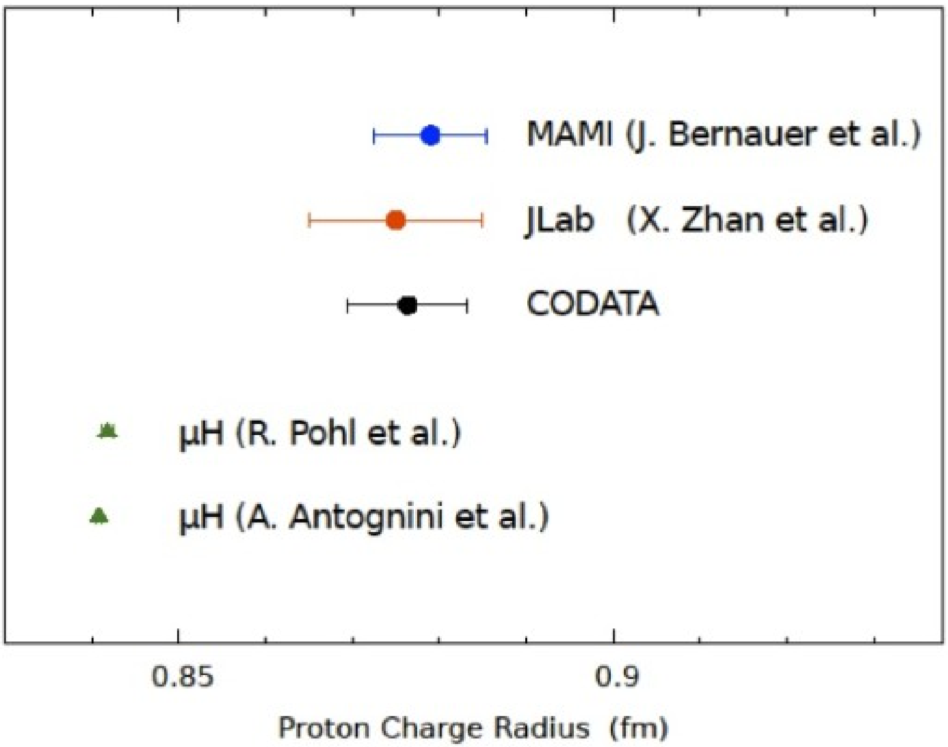
Motivation

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
- 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) $\pm$ 0.074 (syst) fm *(M. Mihovilovič et al., arXiv:1612.06707, 2016)*
  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.

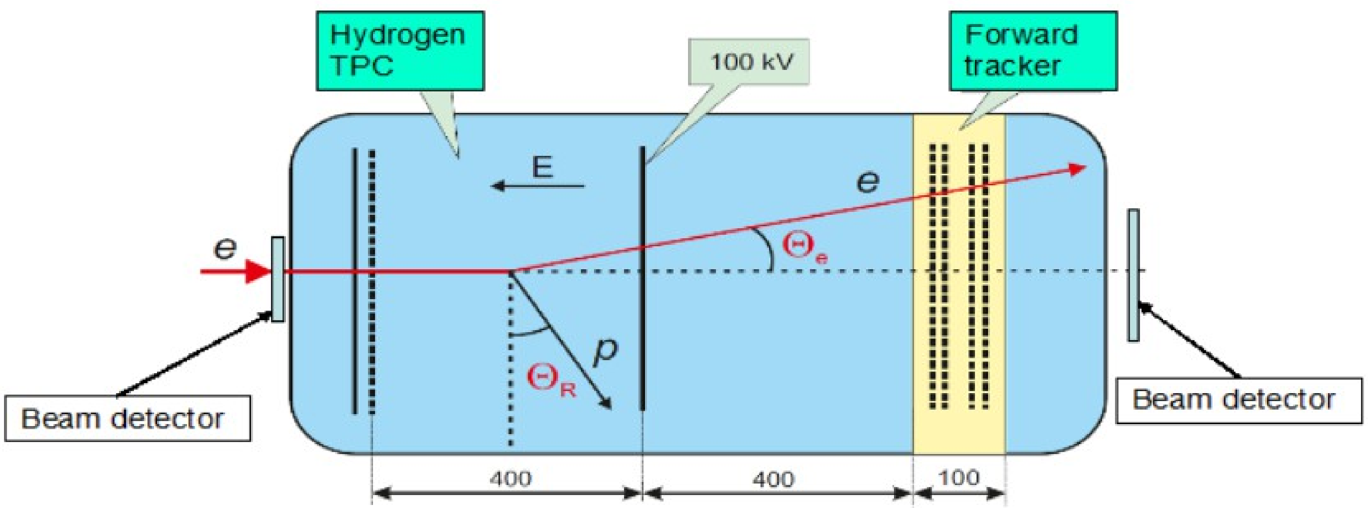
- New experiments at MAMI (A2 Hall): Accessing proton radius with dilepton photoproduction with a Hydrogen Time Projection Chamber combined with Forward tracking detector (IKAR-M).

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 – 0.04 GeV^2
- High resolution in Q^2 (~100 resolved points)
- Absolute measurements of $d\sigma/dt$ accuracy on a level of ~0.2%

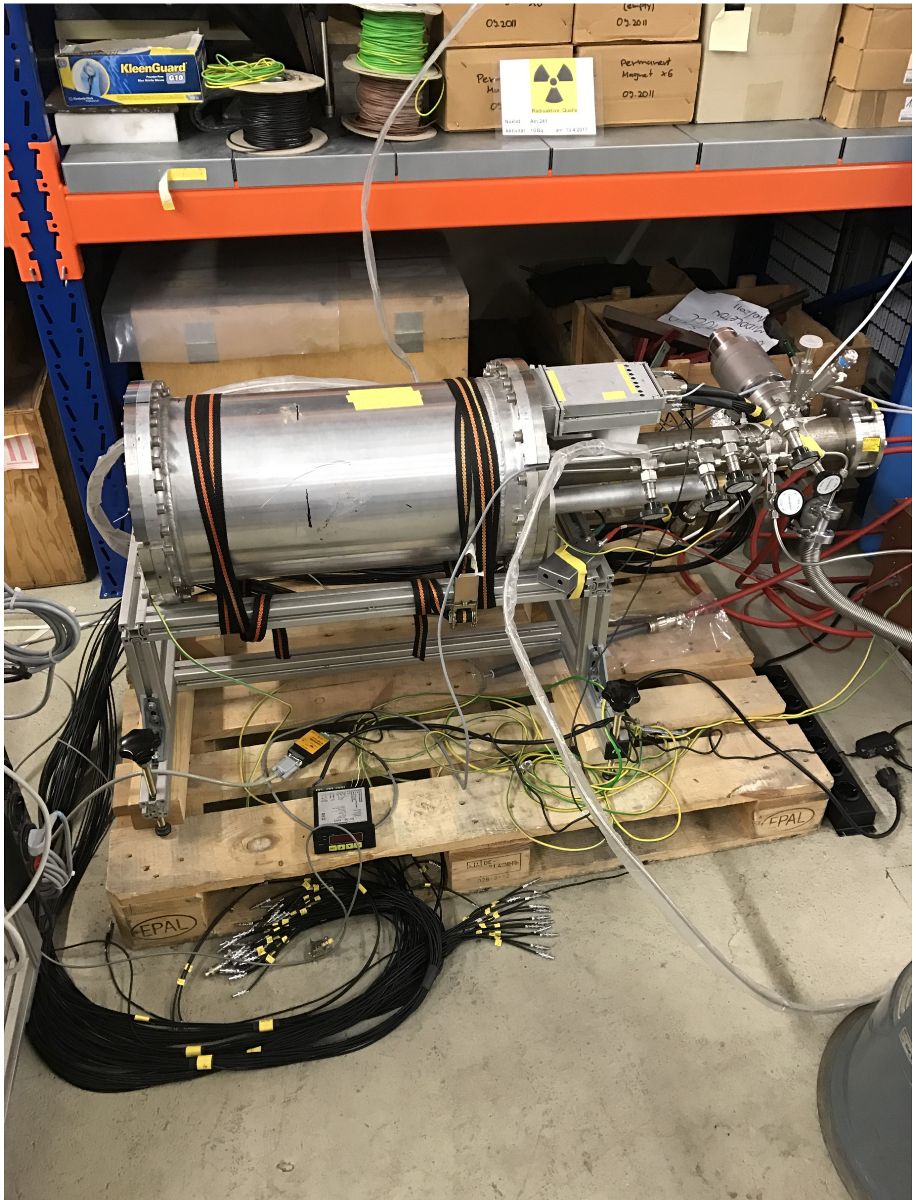
Completely different systematics compared to other experiments



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

- Dilepton photoproduction (proton radius measurement, lepton universality test)
- 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

Test runs in the A2 Hall (August/September 2017)



Main goals:

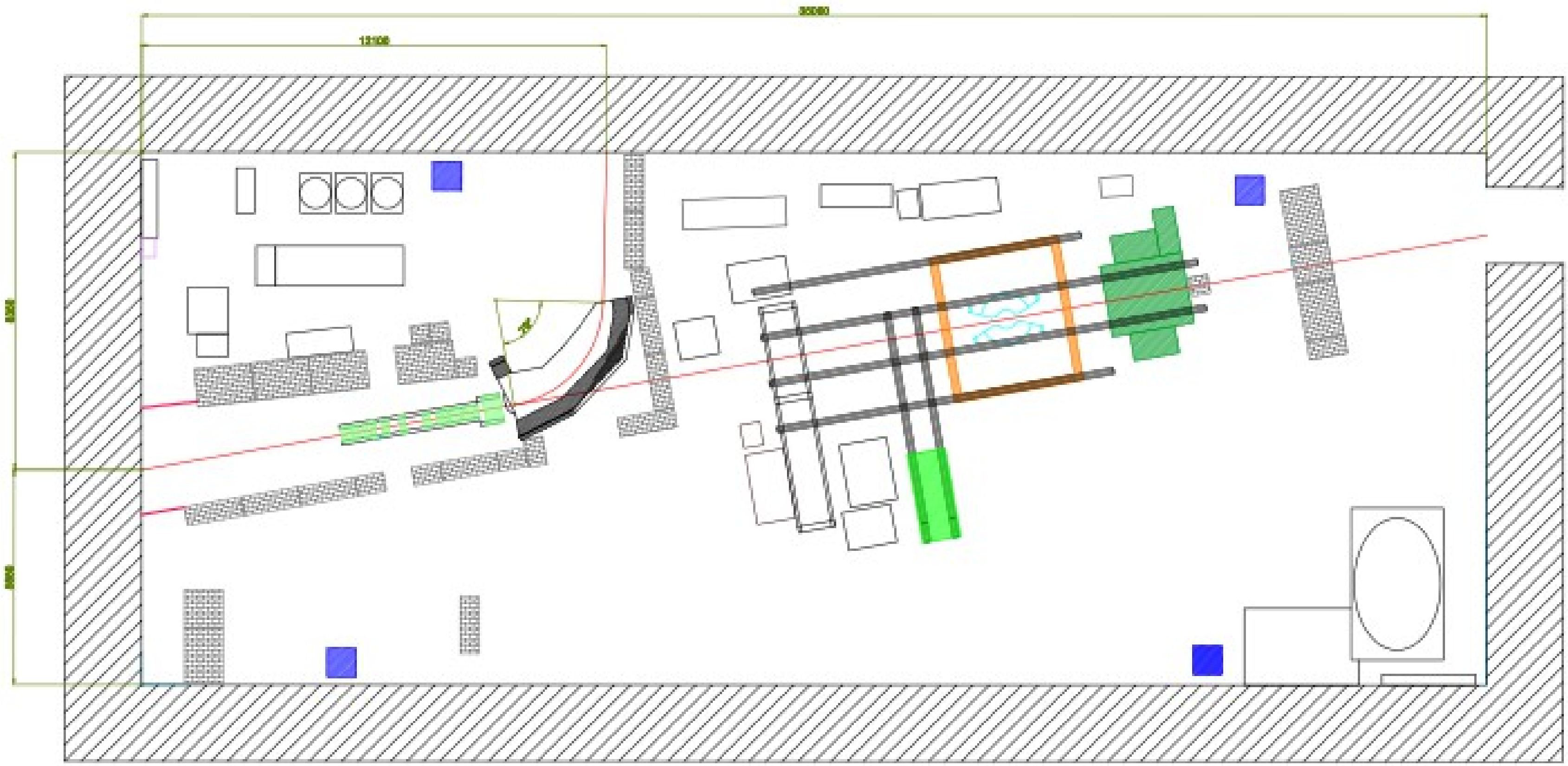
Studies with a test TPC for preparation of the main experiment (2018 – 2020 + …)

- Handling of electron beam in the A2 Hall
- Performance of the TPC in the electron beam
- Testing and development of beam monitoring elements (beam telescope, beam scintillators)
- Many other aspects are studied (e.g. safety issues, additional monitoring systems)

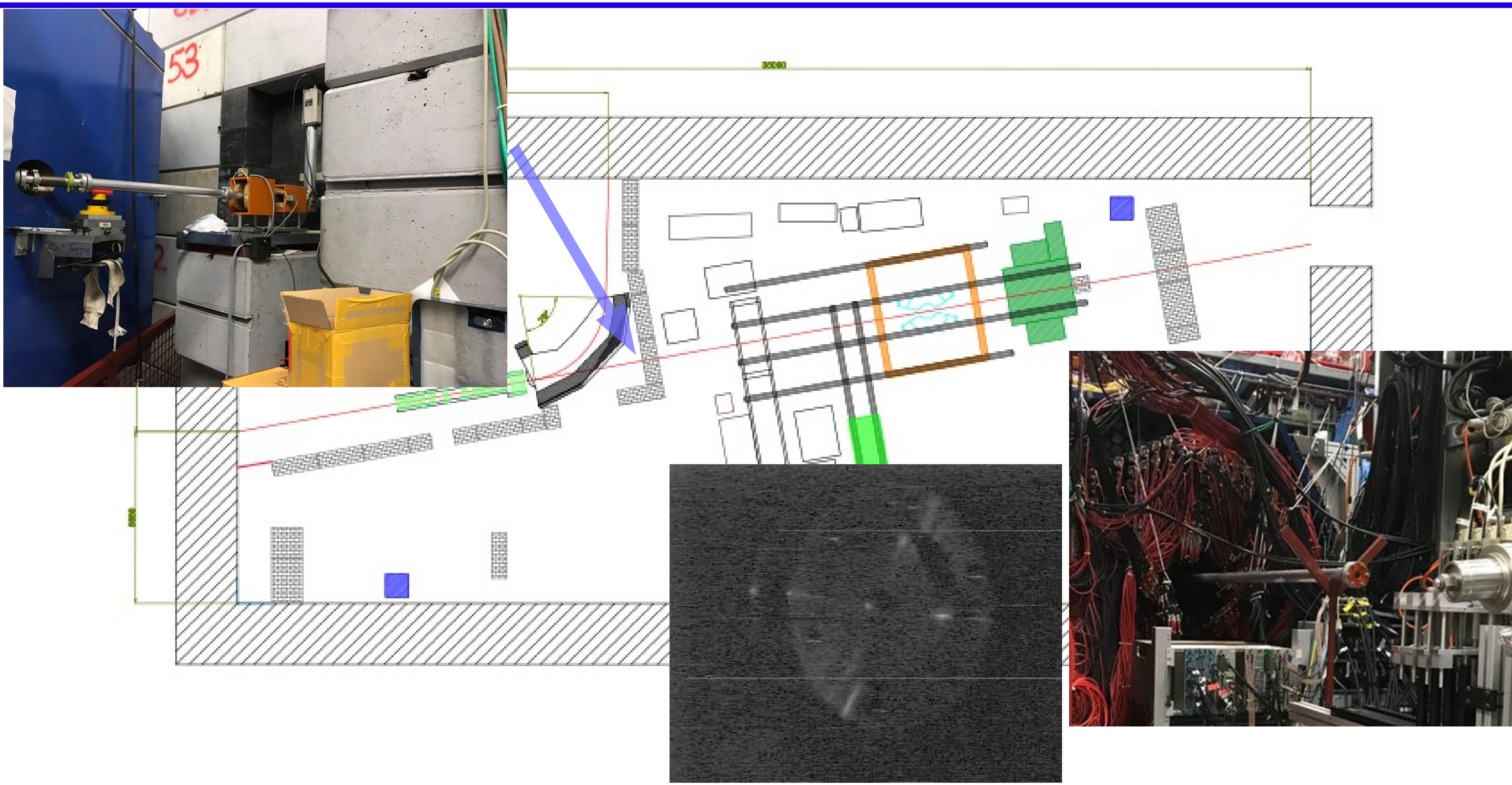
→ Testing electron beam: 08.08.2017-09.08.2017
→ Main part of the tests: 15.08.2017 – 04.09.2017 (with short breaks)

Smooth running of MAMI (as planned) during the test runs.

Beamline construction

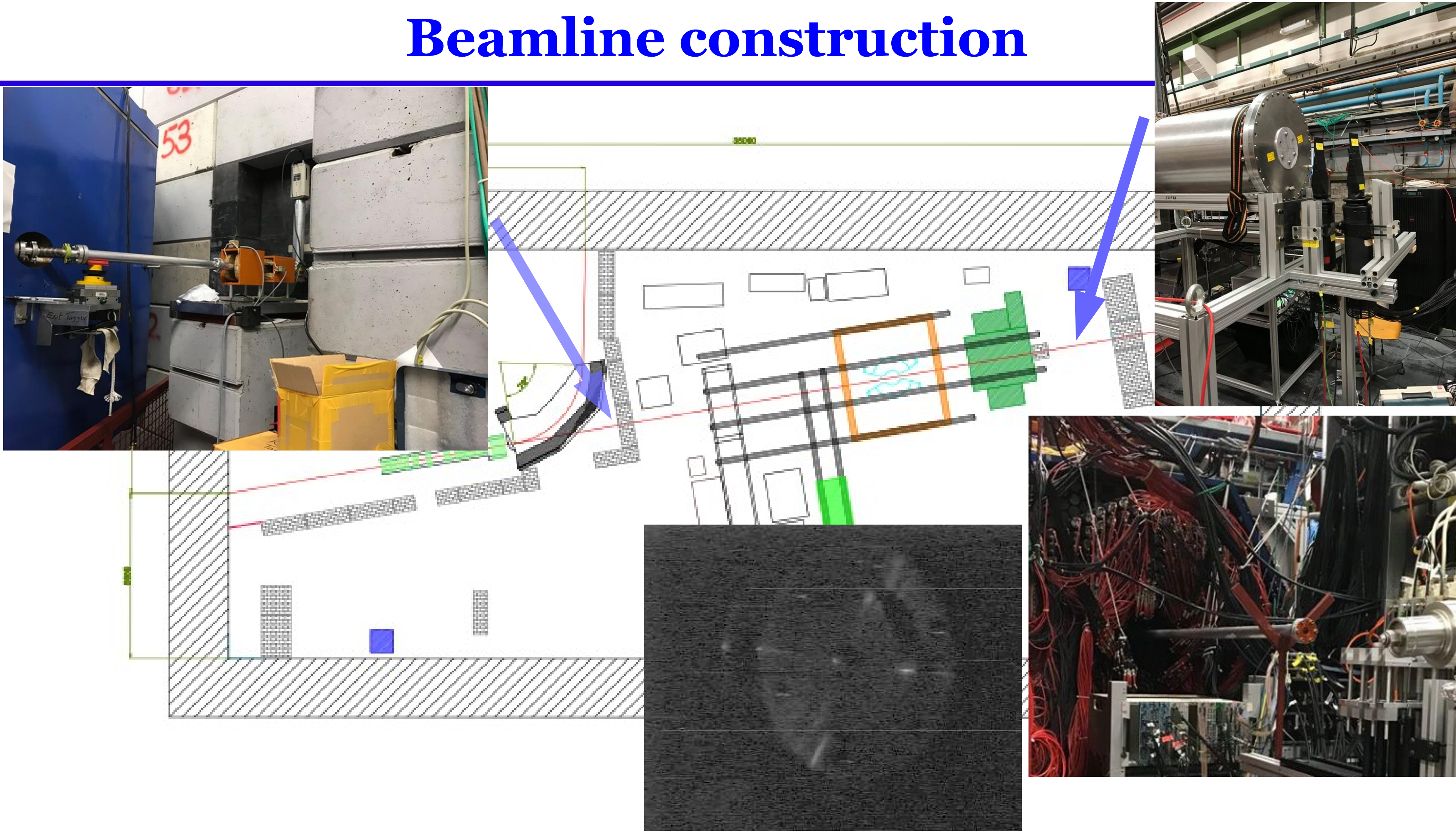


Beamline construction



- 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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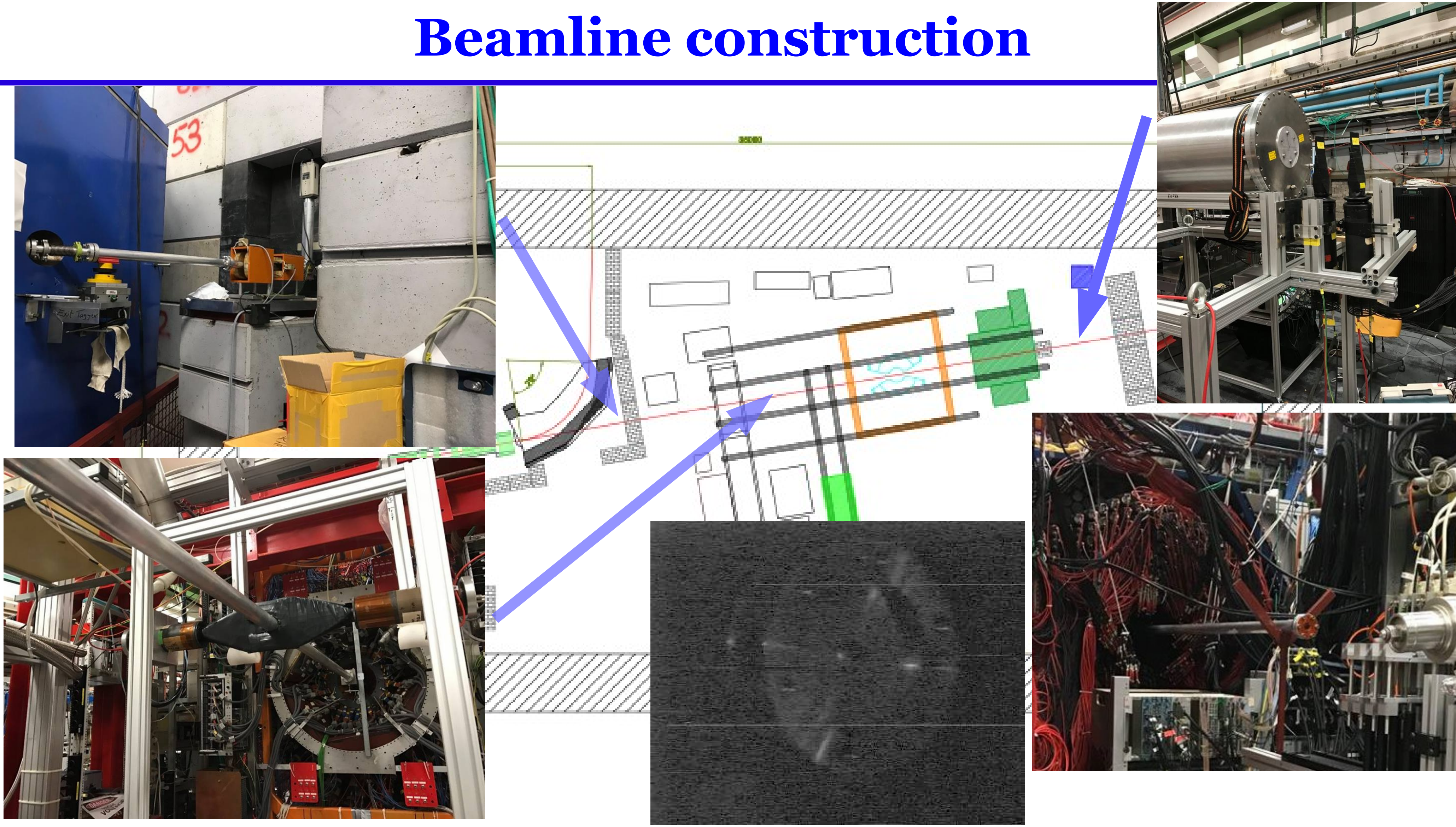
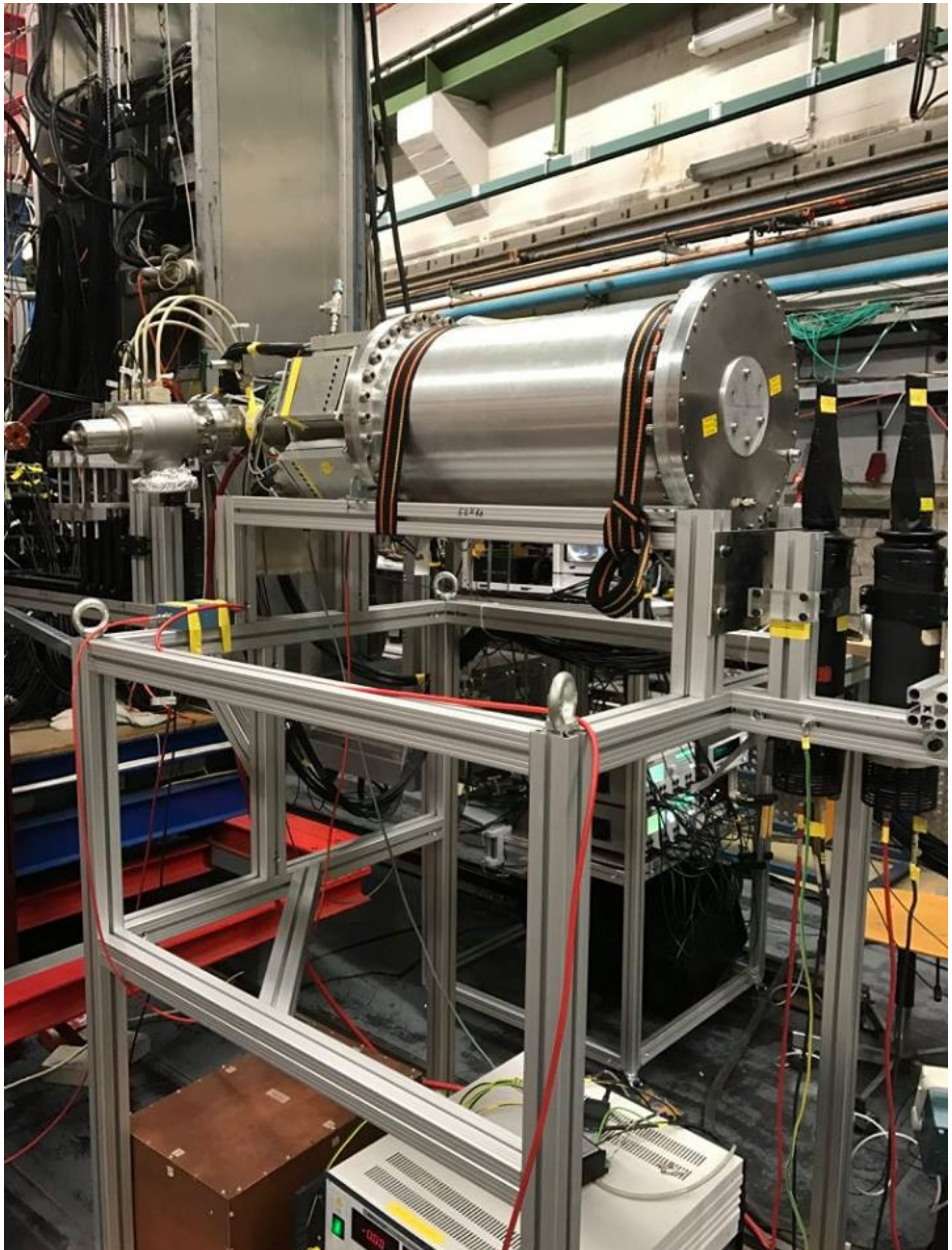


- One horizontal and one vertical steering magnets before tagger wall, luminescent screens for steering, ionization chamber connected to the interlock (M. Dehn)
- Beam scintillators (M. Biroth, O. Kiselev, P. Drexler)
- Beam telescope (F. Wauters, A. Tyukin, M. Zimmermann, N. Berger)
- PIZZA detector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

Test setup



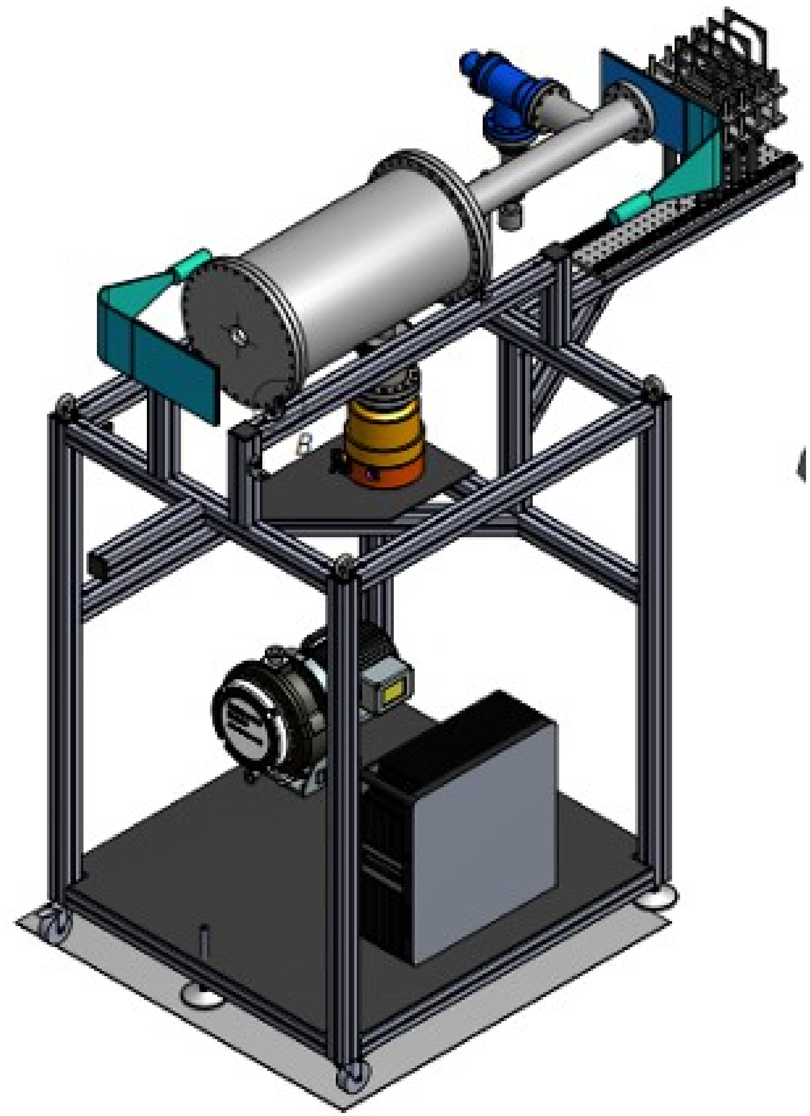
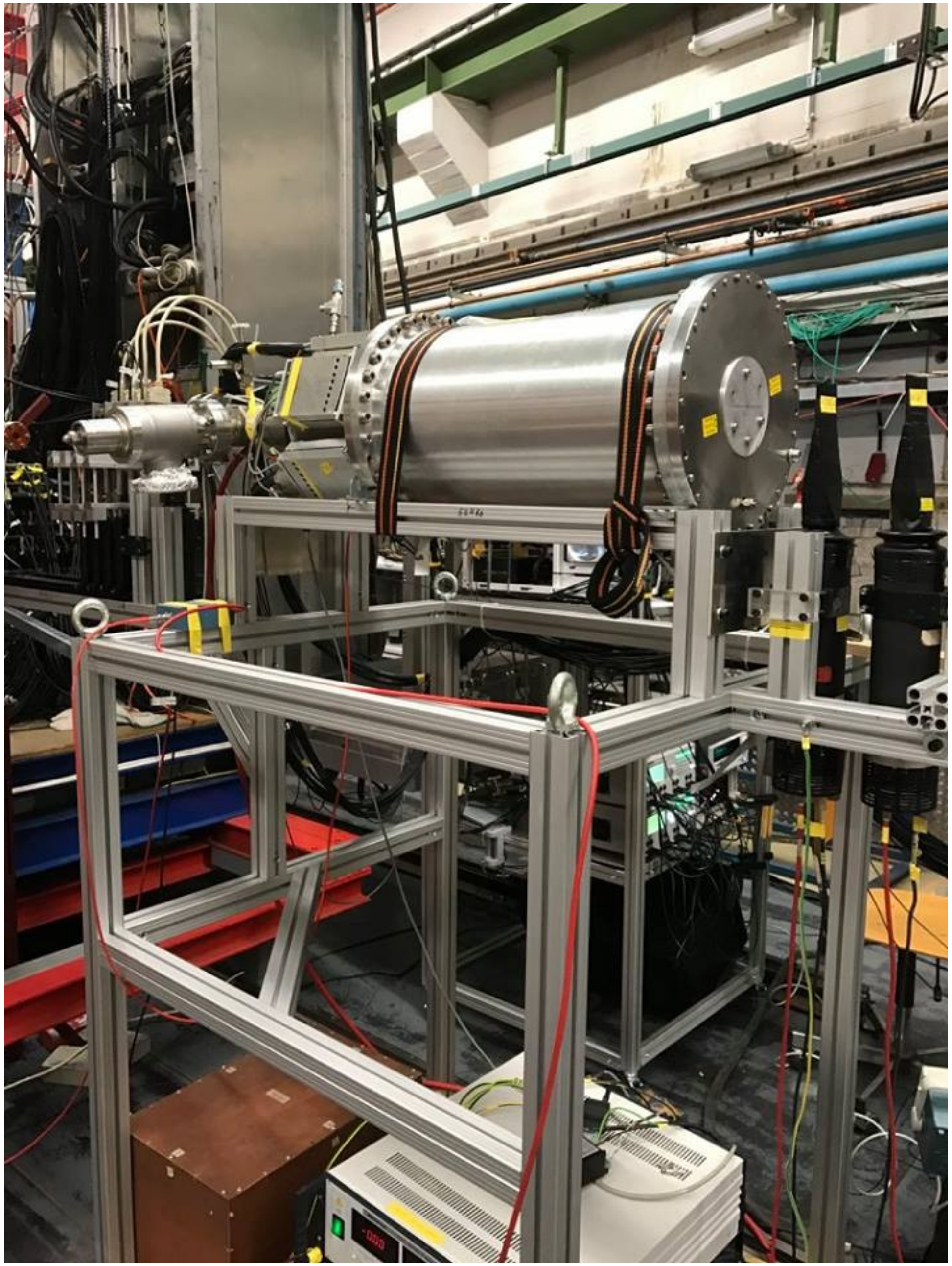


Figure from Marat Vznuzdaev (PNPI)

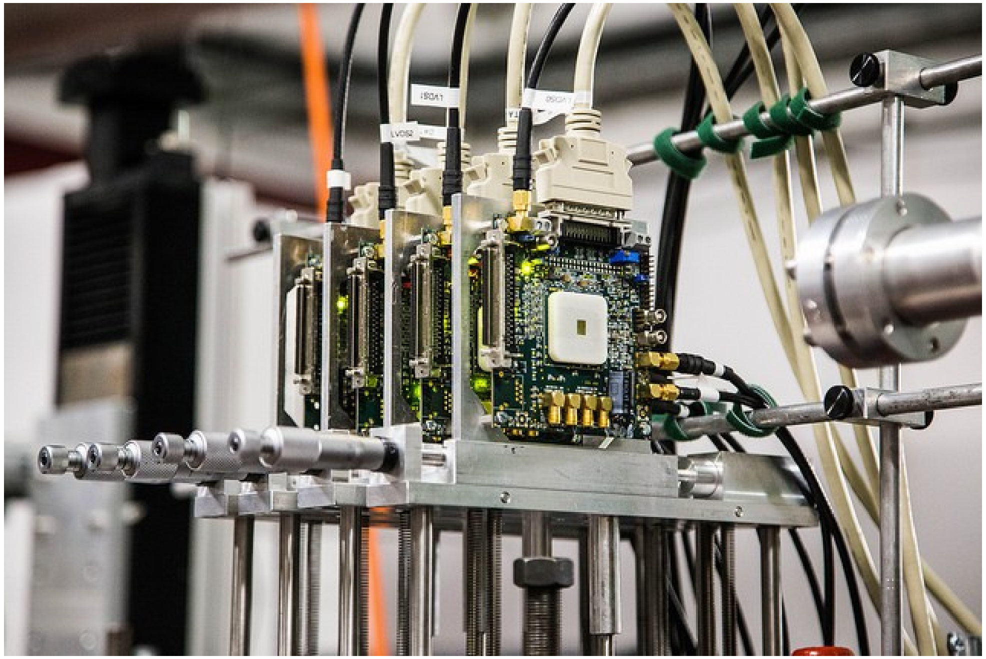
Test setup



- 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)

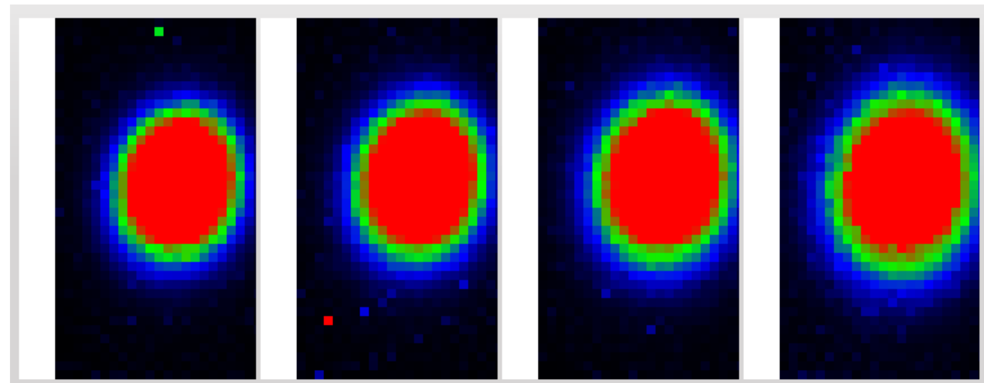
See the talk of Alexey Dzyuba

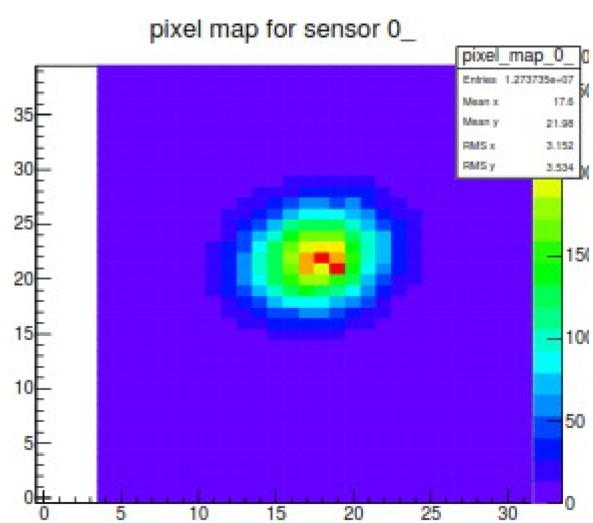
Test setup and beam monitoring system

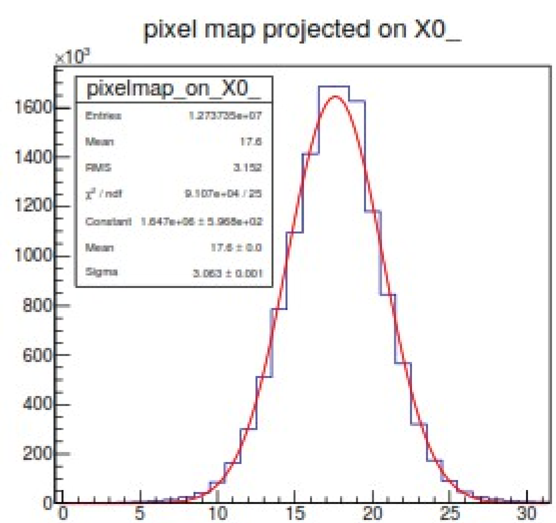


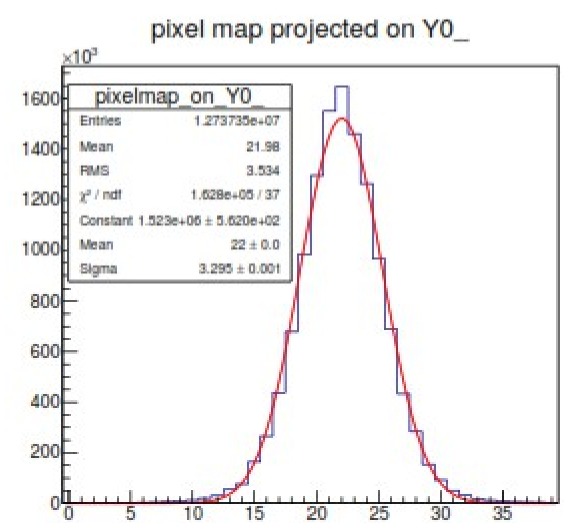
4-layer HV-MAPS pixel detector (3x3 mm)

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



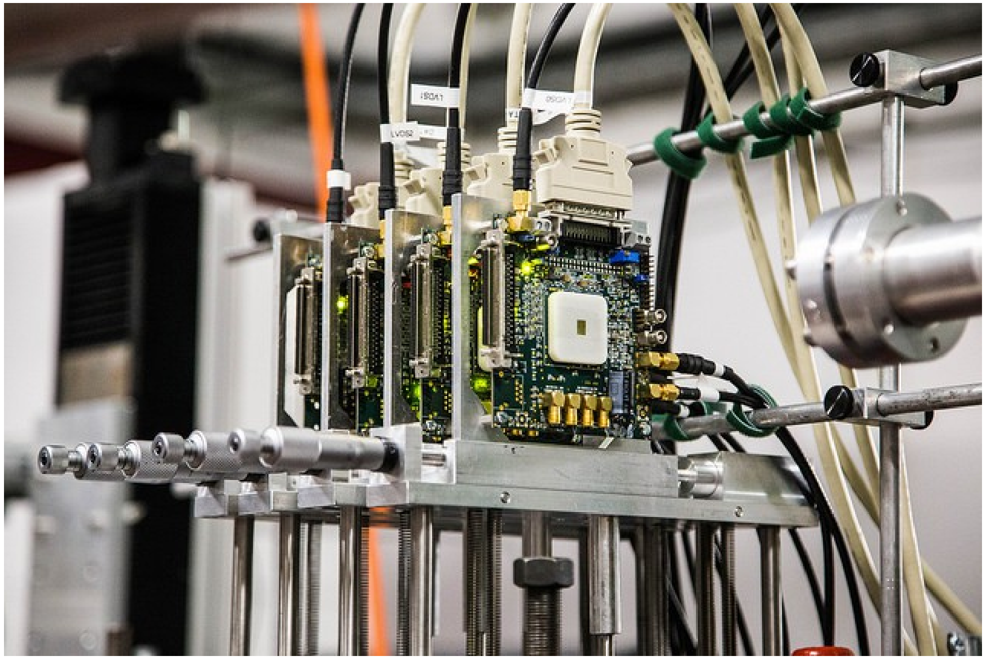






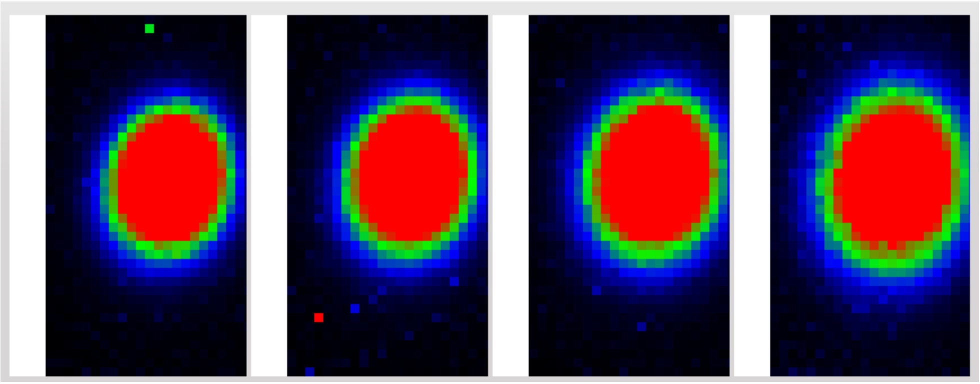
Figures from Aleyey Tyukin (PNPI)

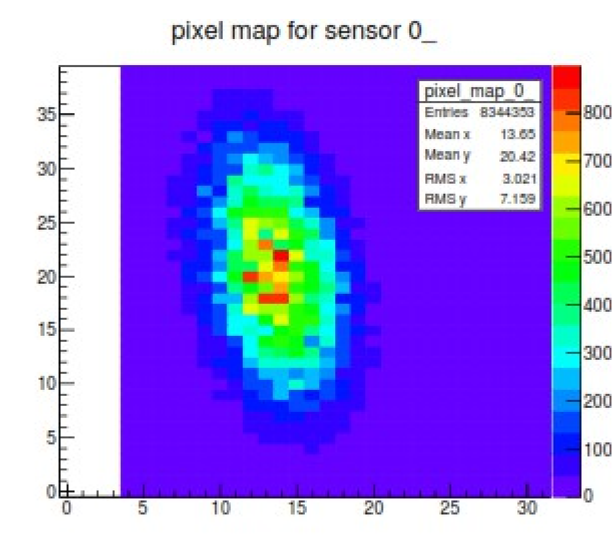
Test setup and beam monitoring system

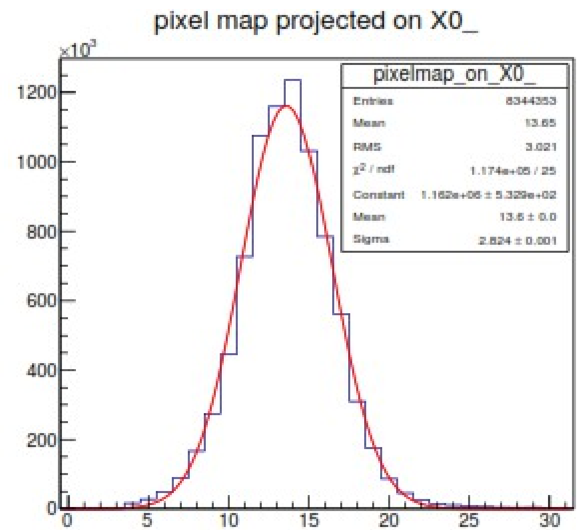


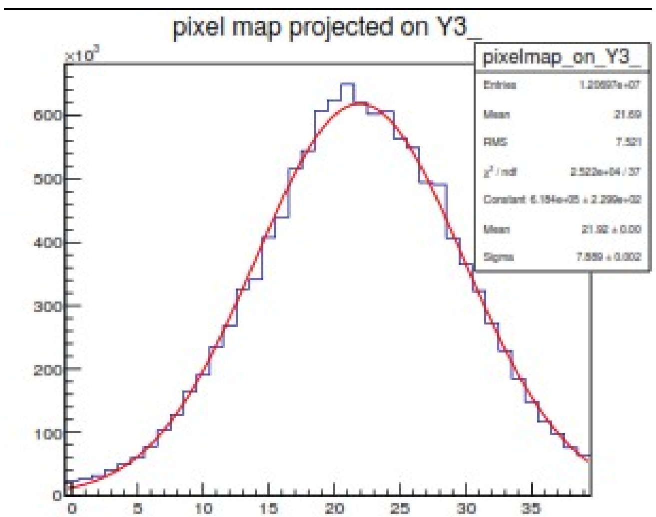
4-layer HV-MAPS pixel detector (3x3 mm)

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









Beam defocused due to high rates

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. ~$2.5x10^6$ events (total)

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

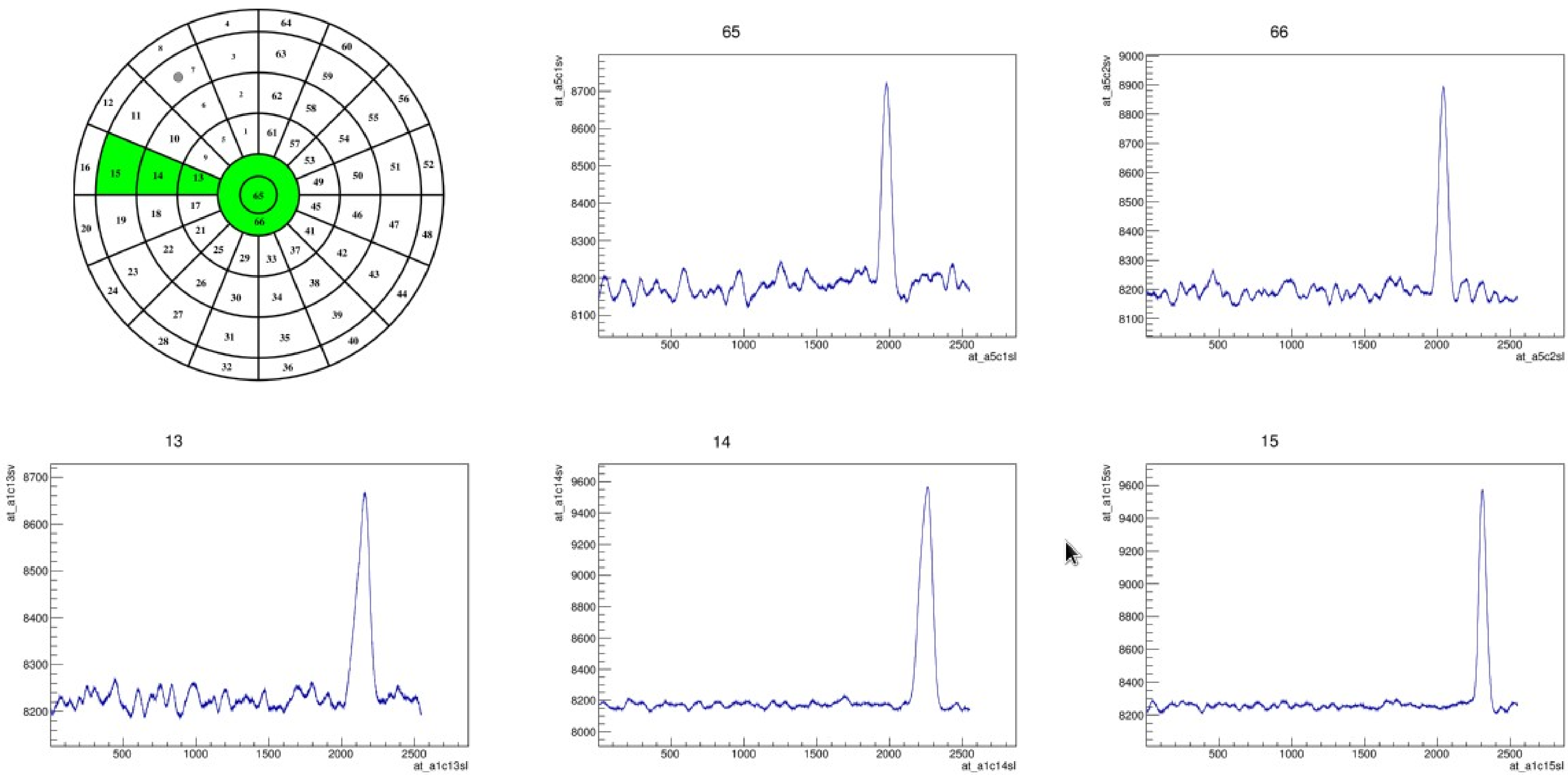
In the end of the experiment: the gas pressure in the TPC was decreased down to 5bar (HV on cathode ~9kV), beam intensity ~ 1.35 MHz, ~35 hours were collected ~ 350 files,~ $4x10^6$ events (total)

<u>See the talk of A. Dzyuba for further details and results</u>

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.)

Example recoil track in the TPC



Signals in the TPC clearly identified!

Alexander Inglessi, PNPI

Safety aspects

Problems and solutions:

- Possible X-ray emission in the TPC:

➔ Interlock system organized using a pressure sensor, turns HV off if the pressure drops below 90% of the nominal pressure in the TPC

Be windows:

- Covered with metallic caps, open only during operation in the hall

- Gas filling: helium + nitrogen (3-4%) (can be simulated reasonably well: work of Alexey Dzyuba, PNPI)

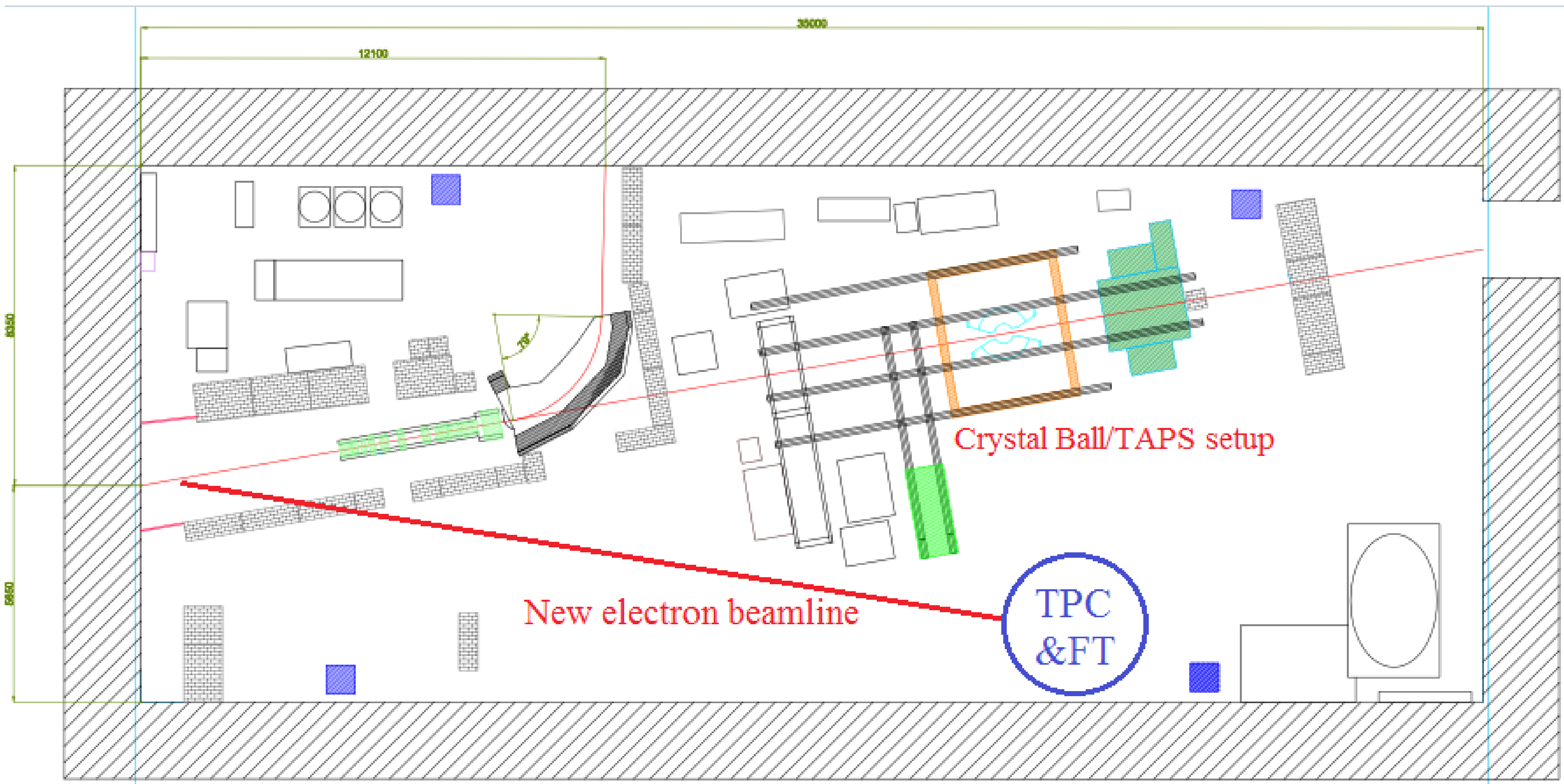
Electron beam (radiation):

➔ Upgrade of the photon beam dump (second layer of lead is installed)

➔ Diagnostic pulses with low repetition rate

➔ Additional beam monitoring (ionization chamber in the interlock, scintillators around beam pipe before Crystal Ball, PIZZA, beam scintillators, pixel detectors)

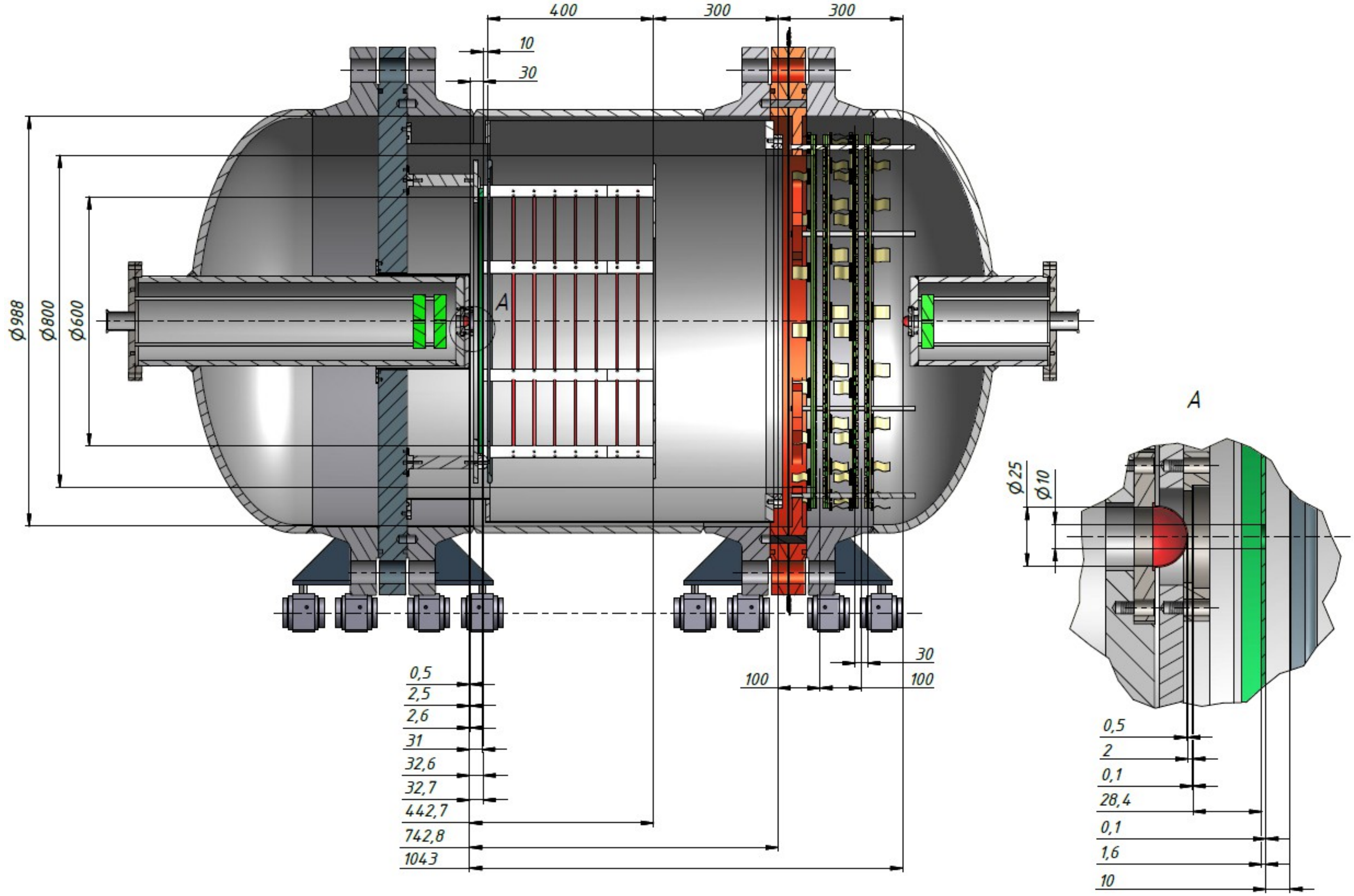
Next: New electron beamline in A2



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)
- Full support from the MAMI group + KPH Workshops

IKAR-M detector (tentative design)



<u>Construction of the IKAR-M by the PNPI group</u>

In coordination with groups at KPH, GSI, …

- Safety issues to be understood/solved

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

Experiments with the IKAR-M (TPC&FT) in the A2 Hall:

- Successful test run in August/September
- Electron beam line mounted and operation continuously monitored
- Tested functionality of various detector and beamline components (beam scintillators, beam monitoring scintillators (mounted before CB), pixel detectors)
- TPC operation feasible with the electron in the A2 Hall (for further details → talk of Alexey Dzyuba)

- Construction of the main TPC (IKAR-M) by the PNPI group in coordination with KPH
- Safety aspects need to be understood
- Construction of a dedicated electron beamline in the A2 Hall

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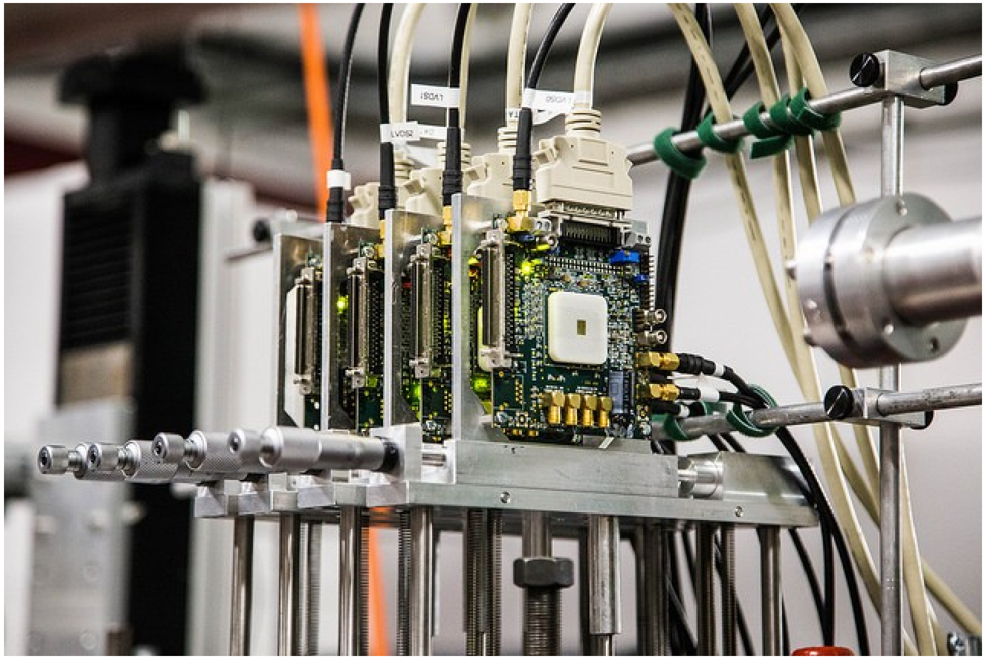
Thank you for your attention!

Backup

Test setup and beam monitoring system



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

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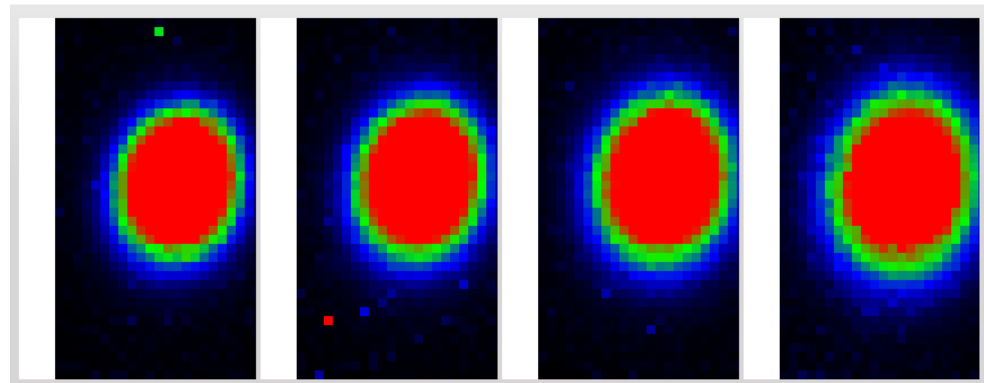
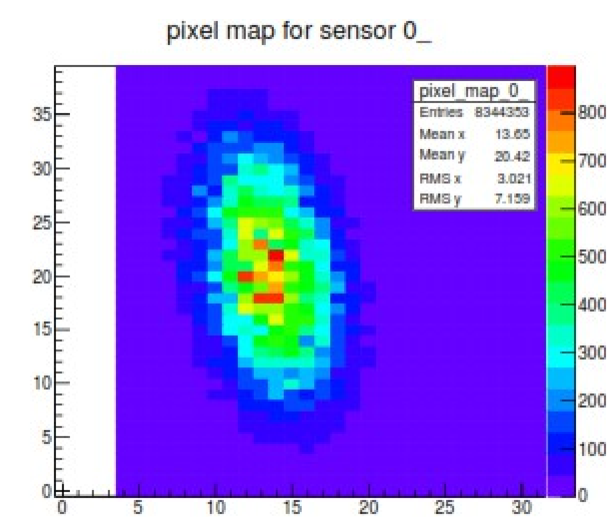
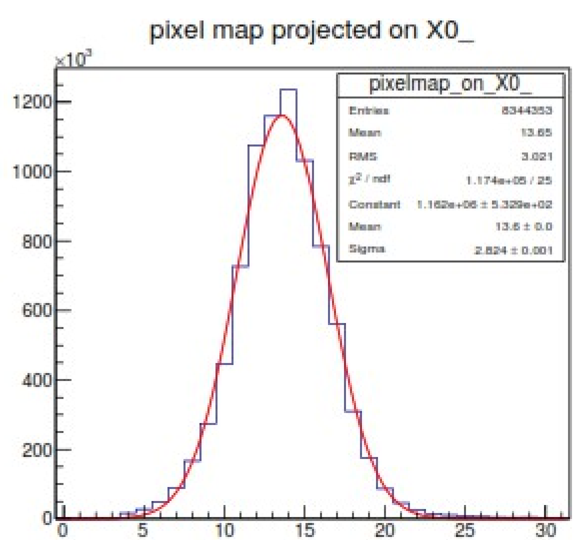
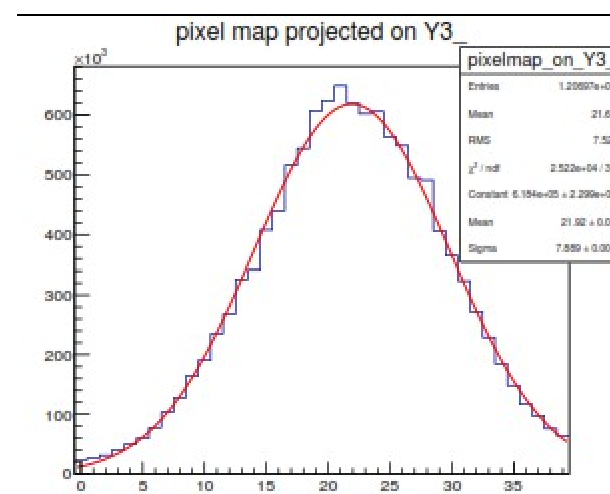








Beam defocused due to high rates

Practical steps

- Two Letters of Intent (LOI) were presented to the MAMI PAC (2016). Planning and preparation of new experiments was supported by the PAC and the preparation of full proposals was encouraged.

Funding:

KPH:

- Submitted a DFG application within the DFG-RFBR Call (2018-2020)
- 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 RFBR within the DFG-RFBR Call (2018-2020)
- PNPI invests ~500 kEUR in the construction of the IKAR-M detector (core funding)
- Working group of 8 people at PNPI

Agreement between KPH and PNPI (2017-2020)

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

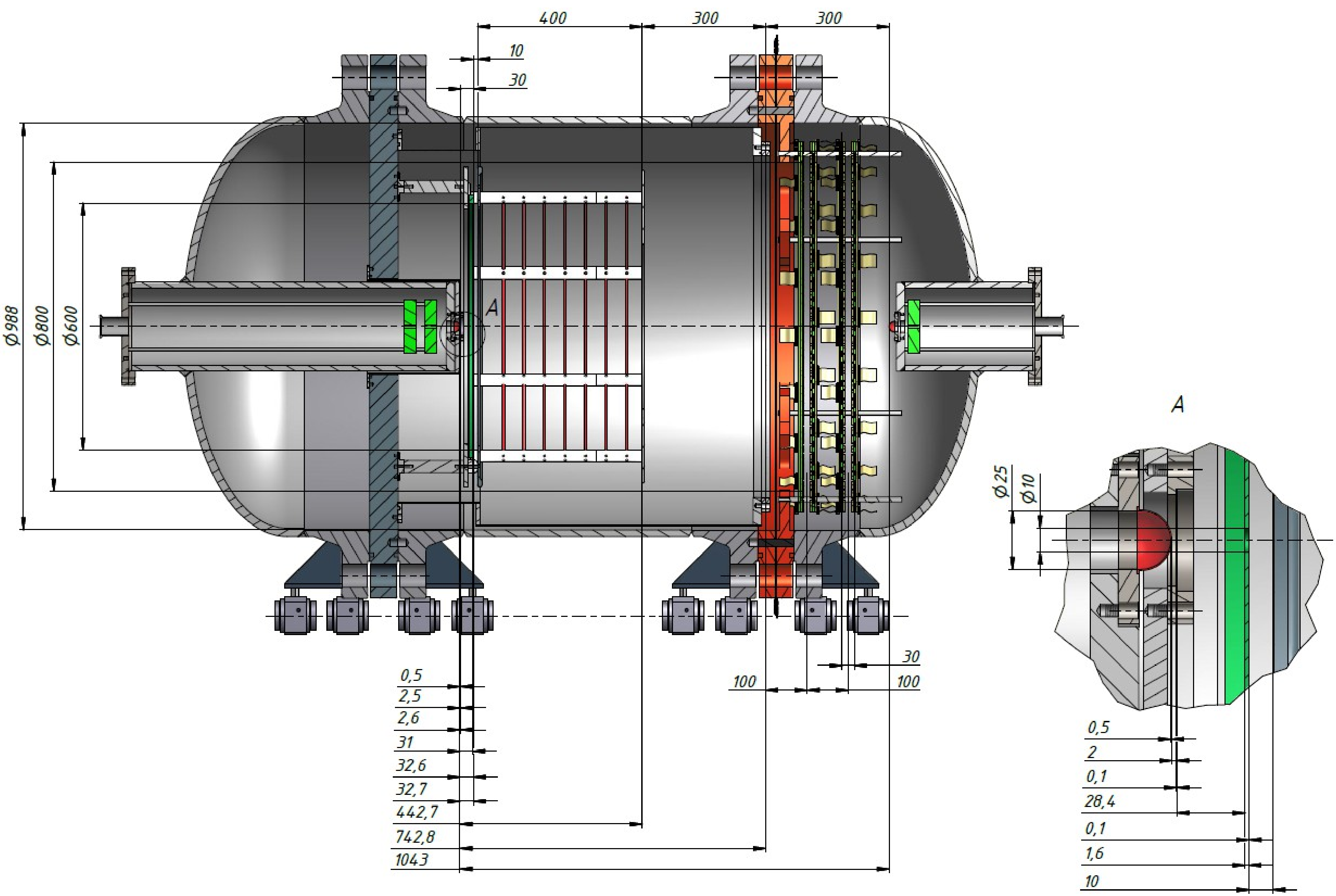
Contribution of the KPH group:

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

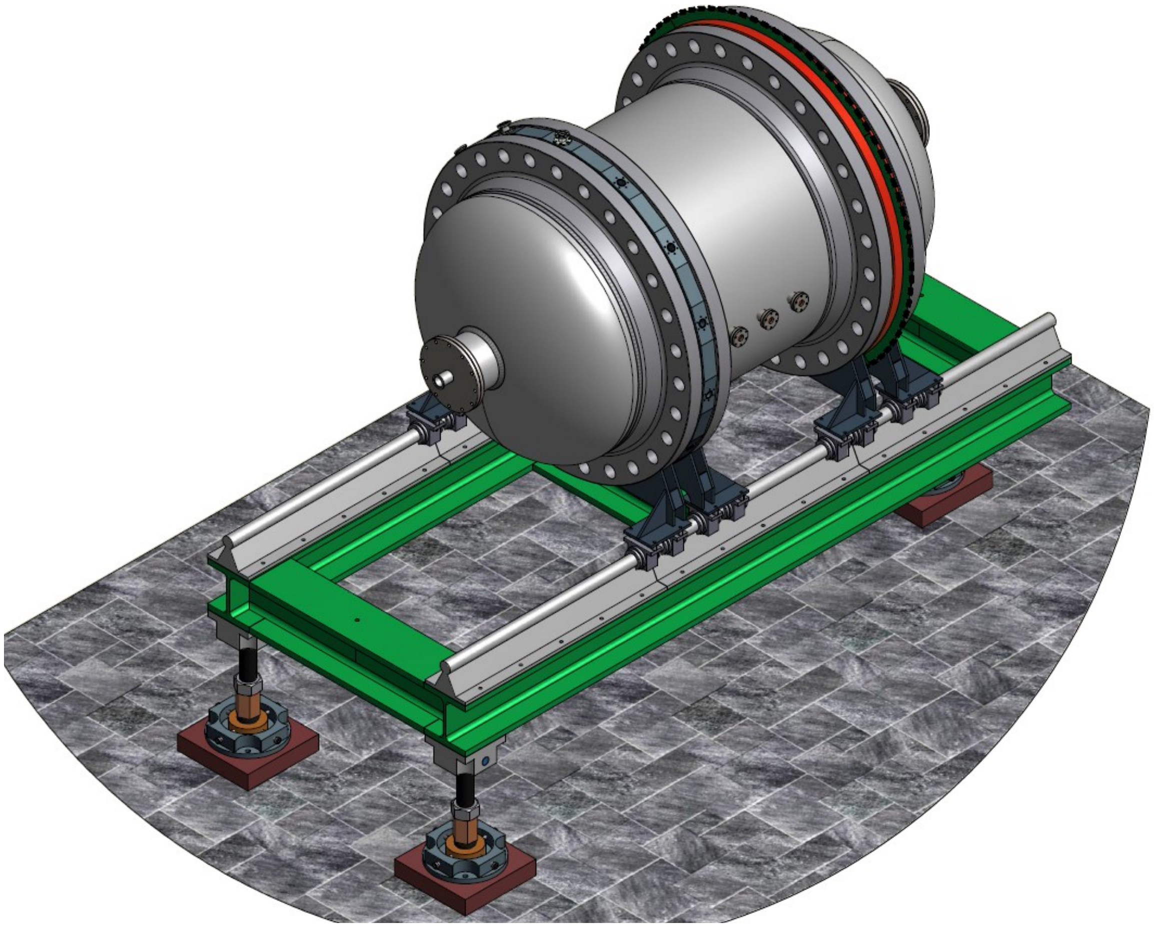
Contribution of the PNPI group:

- 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

IKAR-M detector (tentative design)



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?

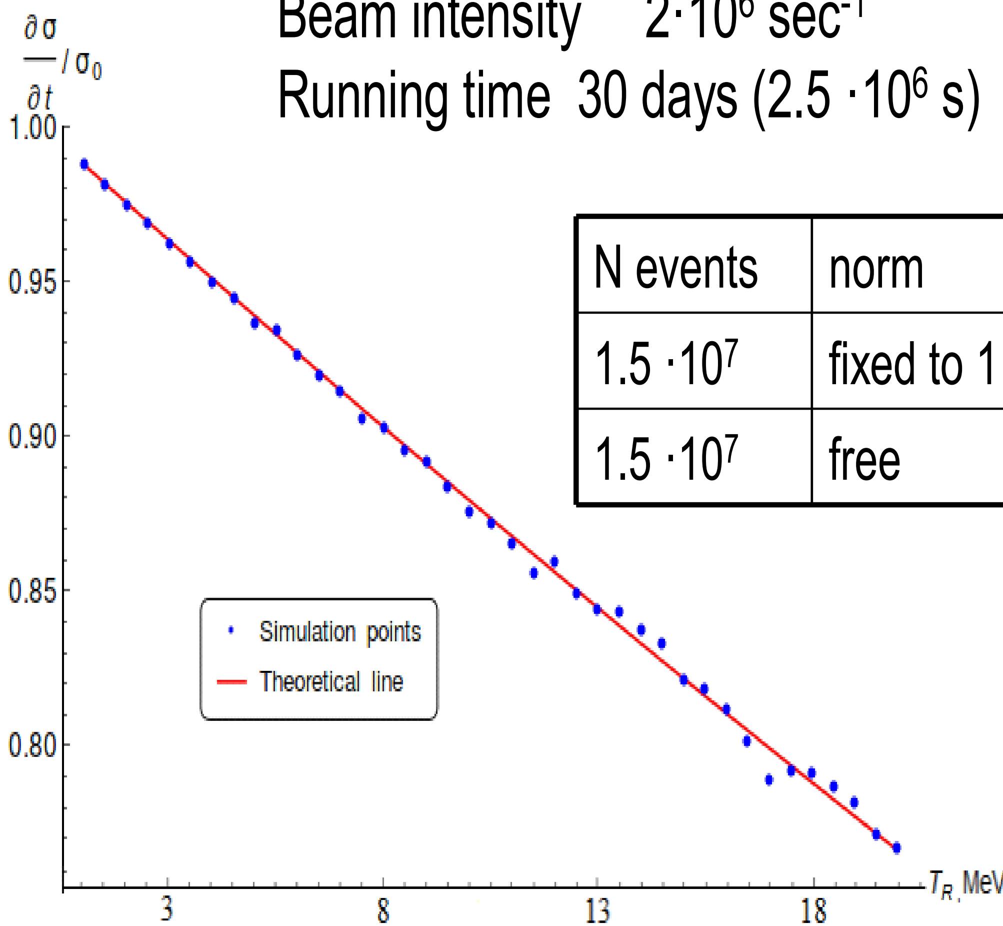
Statistical accuracy

Target thickness = $3.6 \cdot 10^{22}$ p/cm^2

P =20bar L =35cm

Beam intensity $2 \cdot 10^6$ sec^{-1}

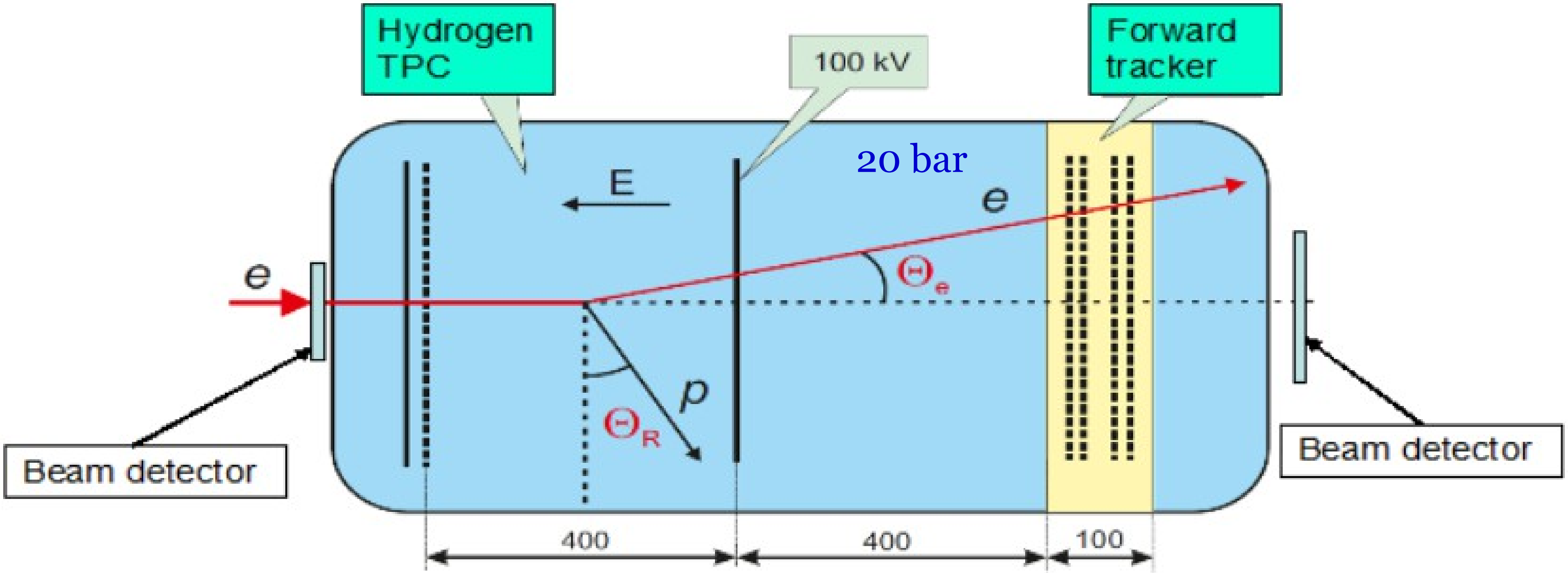
Running time 30 days ($2.5 \cdot 10^6$ s)



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)

IKAR-M detector



Measured quantities:

Recoil energy T_R

Recoil angle Θ_R

Vertex Z coordinate

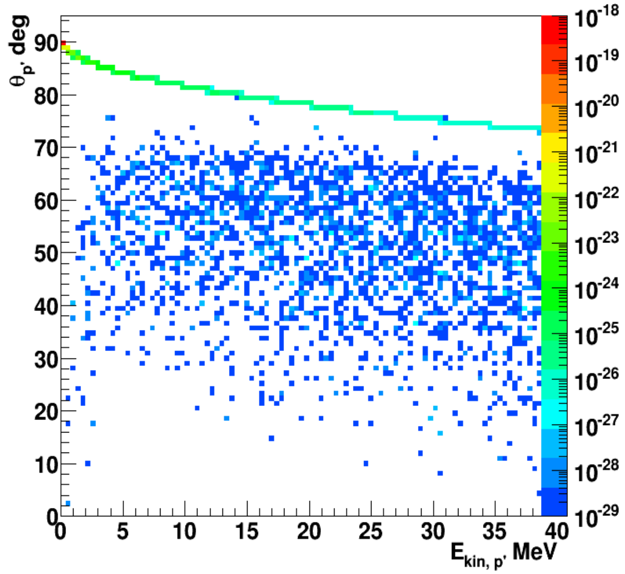
E scattering angle Θ_e

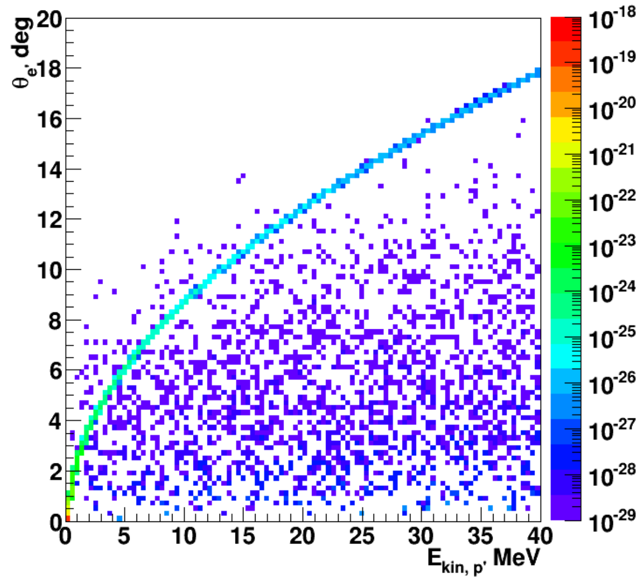
$$-t = \frac{4\varepsilon_e^2 \sin^2\frac{\vartheta}{2}}{1+\frac{2\varepsilon_e}{M}\sin^2\frac{\vartheta}{2}}$$

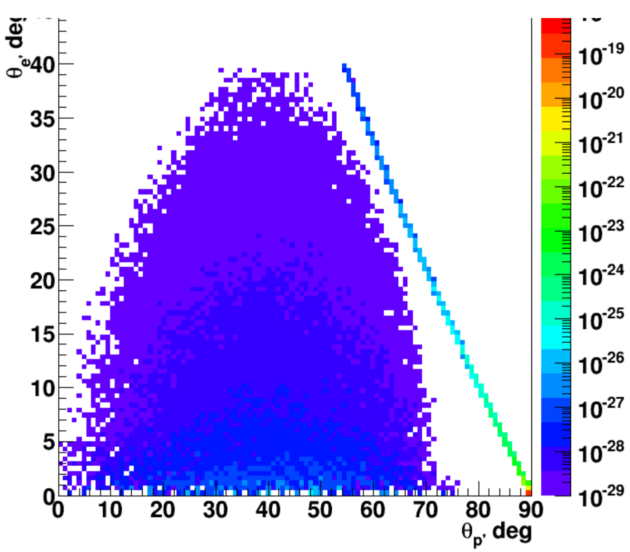
$$-t = 2MT_R$$

Gas	H_2, D_2, He_3, He_4, CH_4
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

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 $ep \to ep\pi^0$ for ε_e = 900 MeV

Patrik Adlarson

CREMA deuteron charge radius

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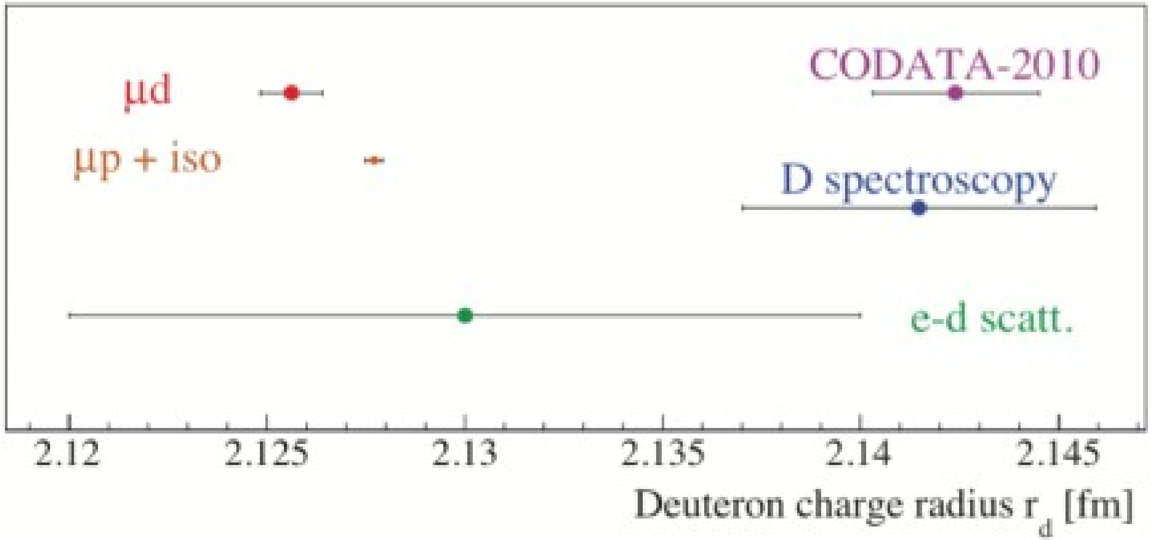


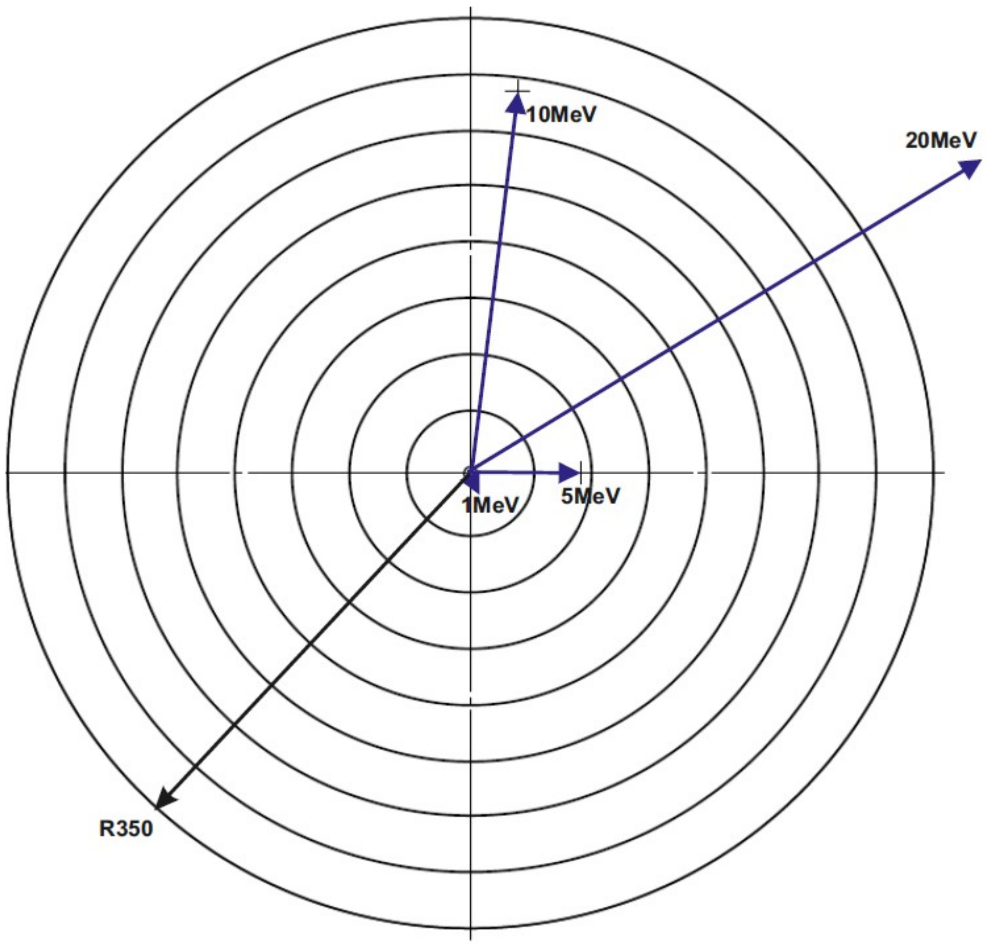
Randolf Pohl et al. CREMA collaboration. Science, 353(6300):669, August 2016.

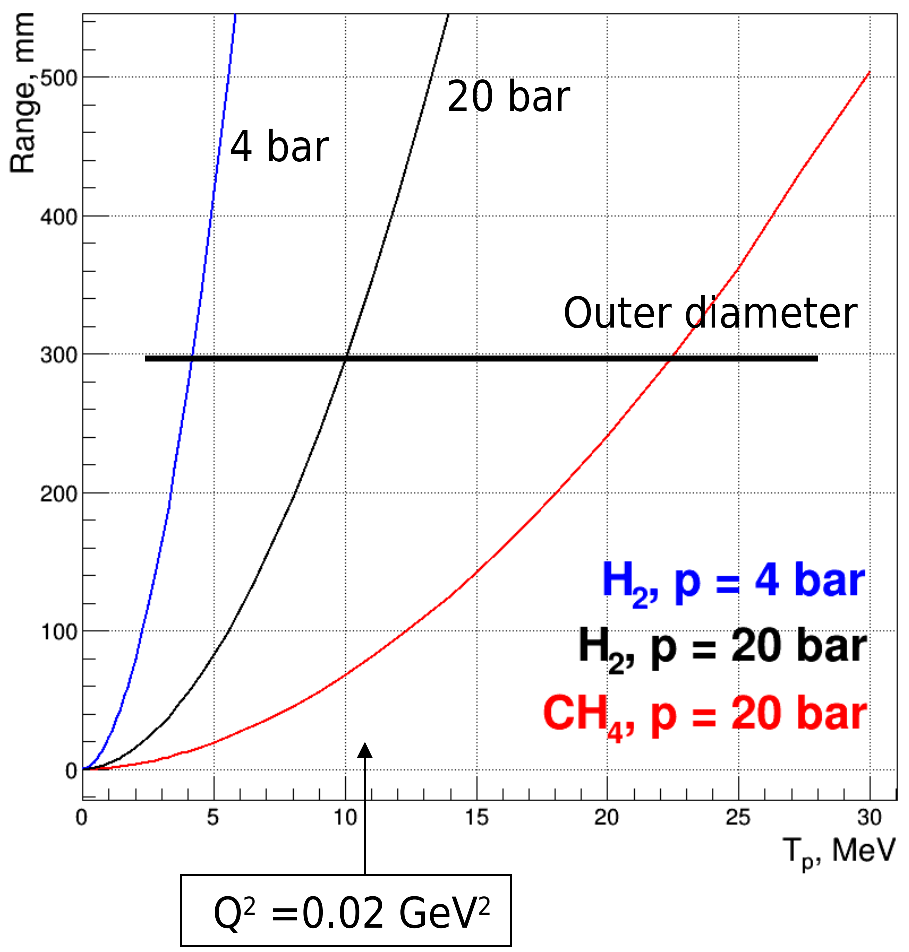
Very recently CREMA made their muonic deuterium official. Two ways to extract the deuteron radius. Both favor low deuteron radius

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

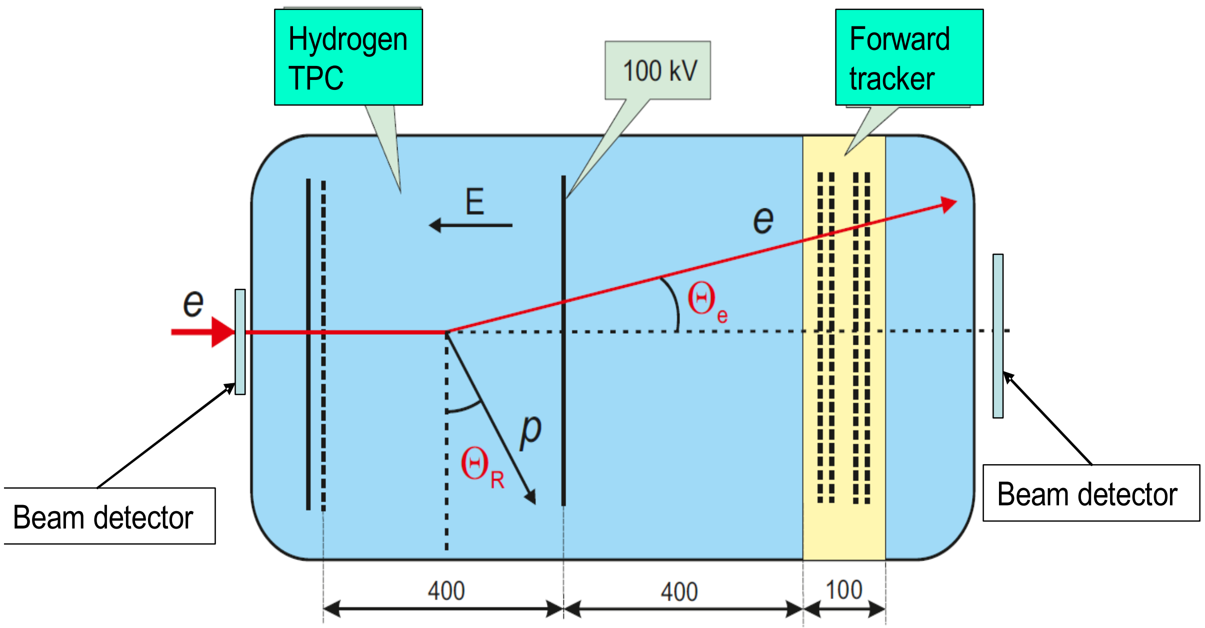
Hydrogen Time Projection Chamber





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

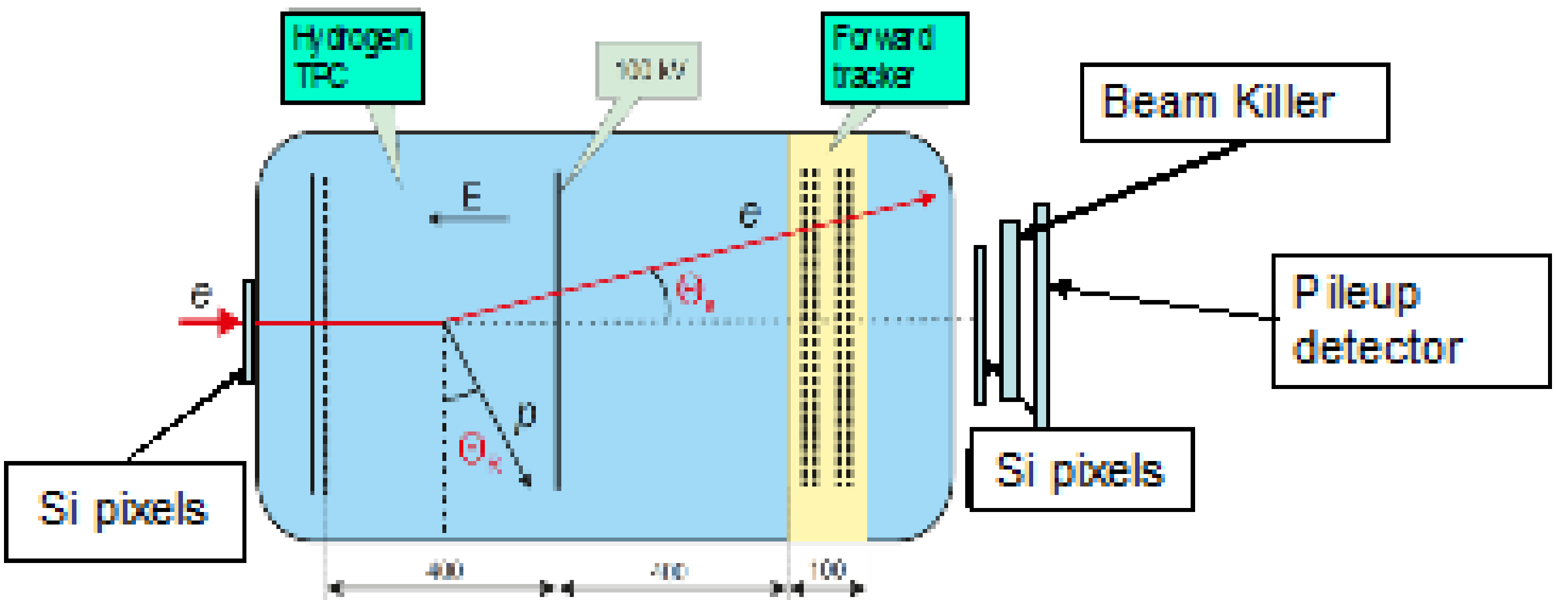
Forward Tracker



Two pairs of Cathode Strip Chambers X1/Y1 and X2/Y2.
Size: 600mm x 600 mm.
Strip width: 2mm.
Spatial resolution: 30 µm.
Time resolution : 5 ns.

Linear scale with 0.02 % absolute precision

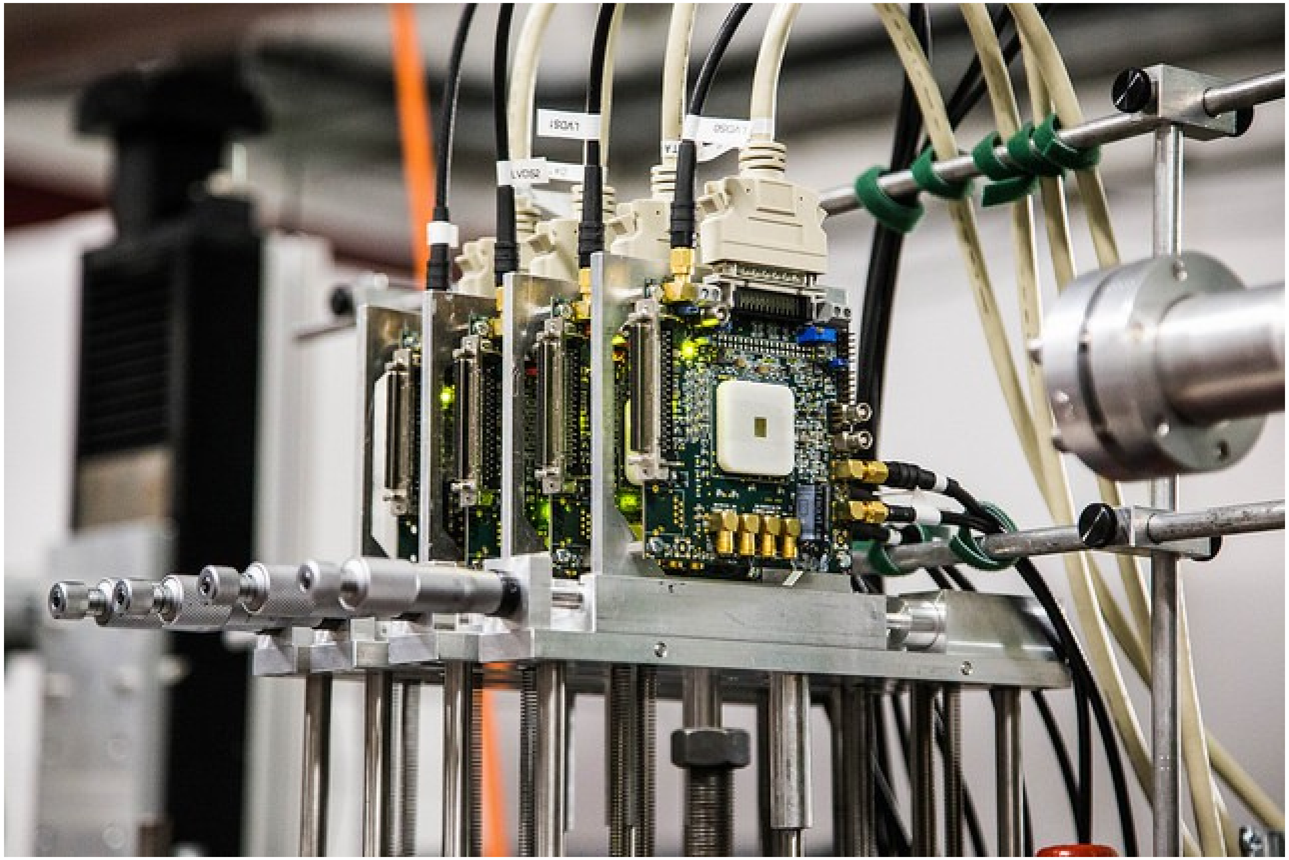
Beam Detectors



Si-pixels 3x3 mm: Input trajectory $\sigma_X = \sigma_Y = 30\ \mu m$ Time resolution 10 ns
Beam Killer: SC counter 1 ns resolution
Pileup detector: SC counter 0.1 ns resolution

Beam intensity 2 x 10^6 electrons/sec

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

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.

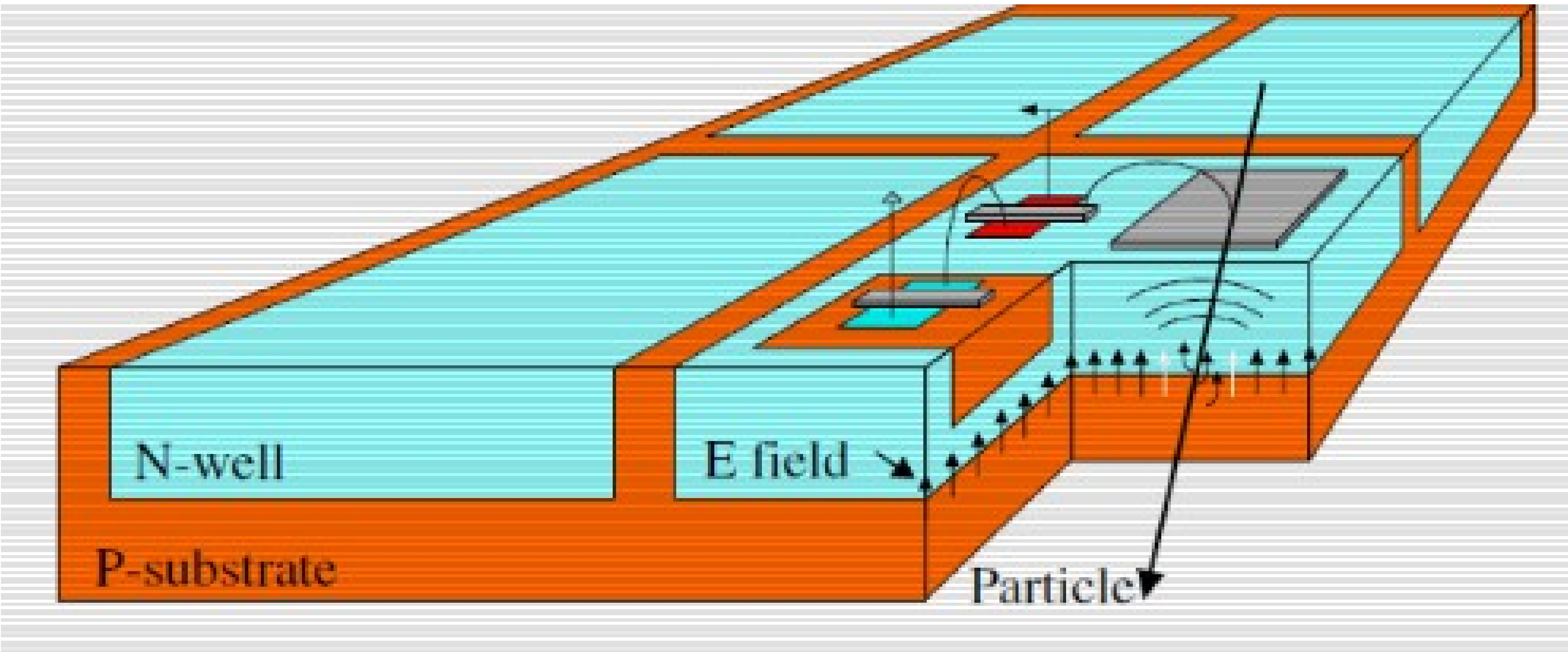
At low Q^2 the form factors can be represented by the expansions:

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

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



Backup (Patrik Adlarson)

Bethe–Heitler (BH) process

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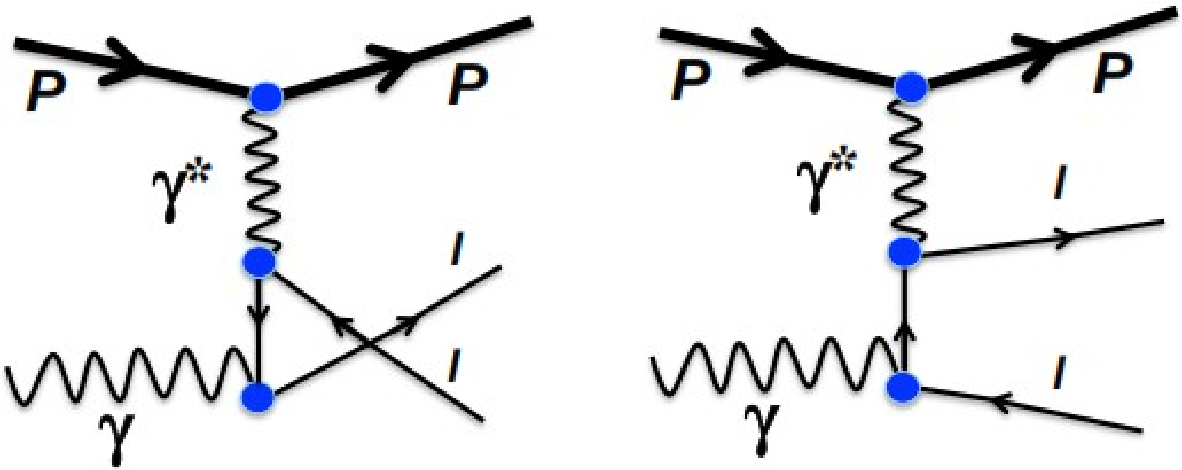

$$\frac{d\sigma^{BH}}{dt\,dM_{ll}^2} = \frac{\alpha^3}{(s-M_p^2)^2}\cdot\frac{4\beta}{t^2(M_{ll}^2-t)^4}\cdot\frac{1}{1+\tau}\times\left[C_E G_{E_p}^2 + C_M \tau G_{M_p}^2\right]$$

Invariant mass sq lepton pair

Proton mom transfer

Proton form factors

Backup (Patrik Adlarson)

Bethe–Heitler dσ/dEγ

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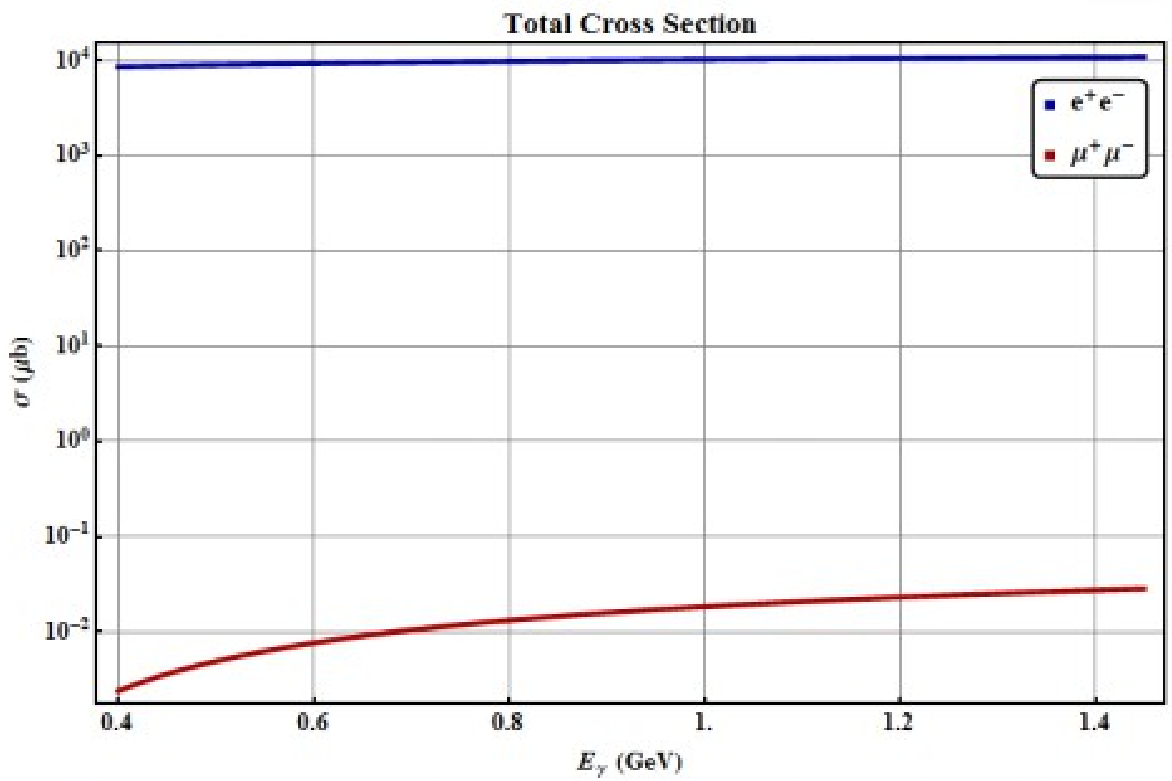

BH-ee (blue) and BH-μμ (red) cross section as function of beam energy

Dimuon cross section increases more for increasing beam energies

Backup (Patrik Adlarson)

Bethe–Heitler (BH) process

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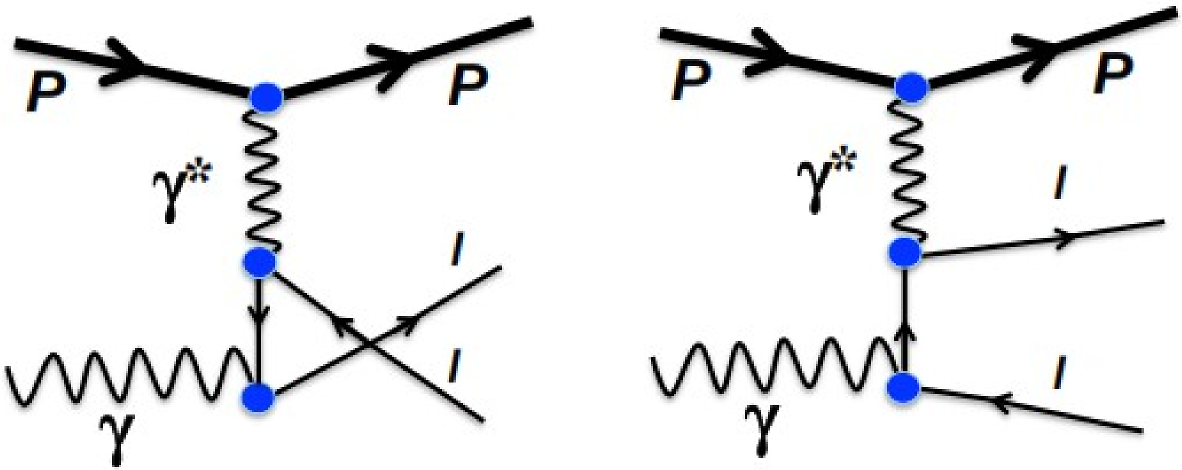


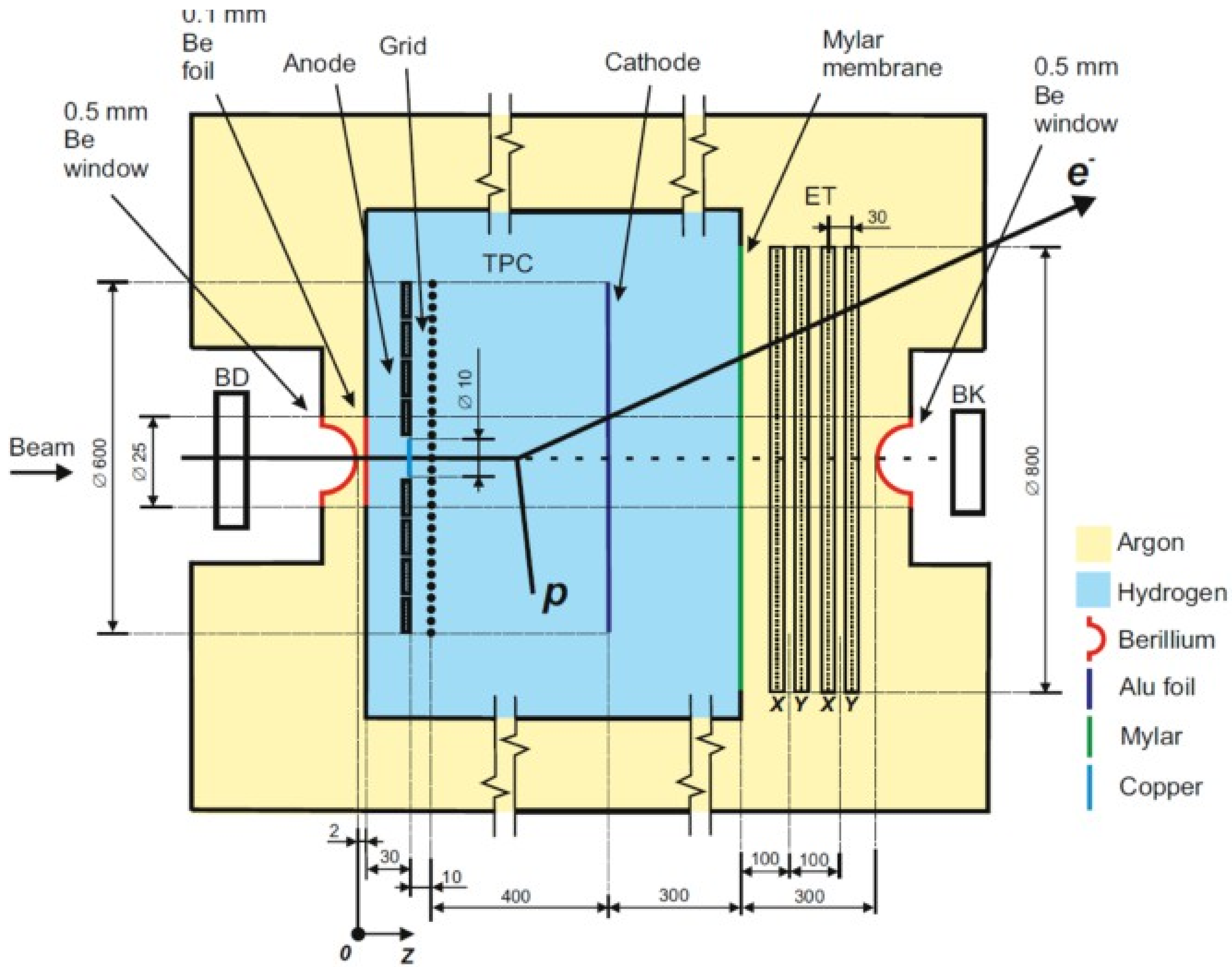
$$\frac{d\sigma^{BH}}{dt\,dM_{ll}^2} = \frac{\alpha^3}{(s-M_p^2)^2}\cdot\frac{4\beta}{t^2(M_{ll}^2-t)^4}\cdot\frac{1}{1+\tau}\times\left[C_E G_{E_p}^2 + C_M \tau G_{M_p}^2\right]$$

Invariant mass sq lepton pair

Proton mom transfer

Proton form factors

Backup



A. Vorobyov (PNPI)

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)

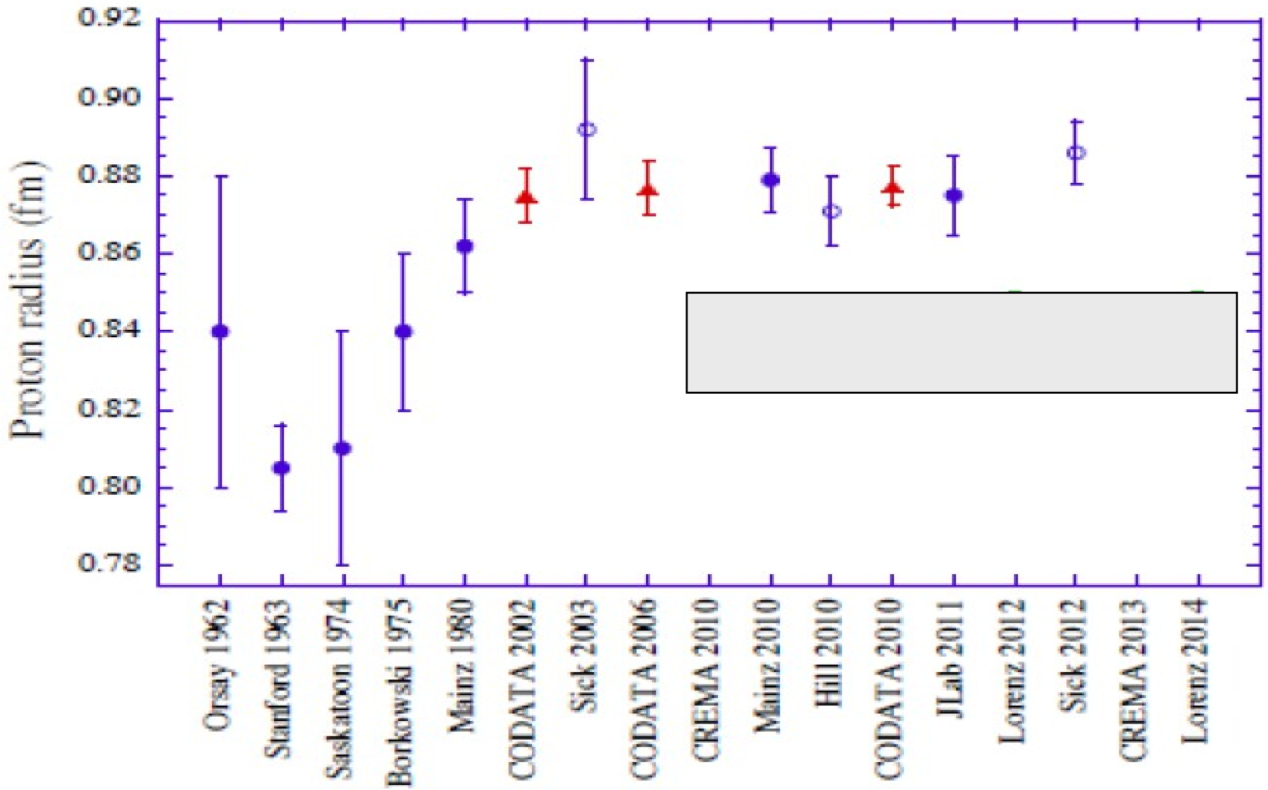
Electron Beam Specifications

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

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*

Radiative corrections

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