

# Electron Scattering Experiments in Mainz



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*U Mainz*

April 2026

“It would be great if you could give a presentation on **proton form-factor** and charge radius measurements **at Mainz: past, current status, and future.**”

Vlad

## Introduction

- Pioneering experiments in Mainz

## Current Status

- Continuation of experiments with MAMI in Mainz

## Future

- New experiments with MESA in Mainz

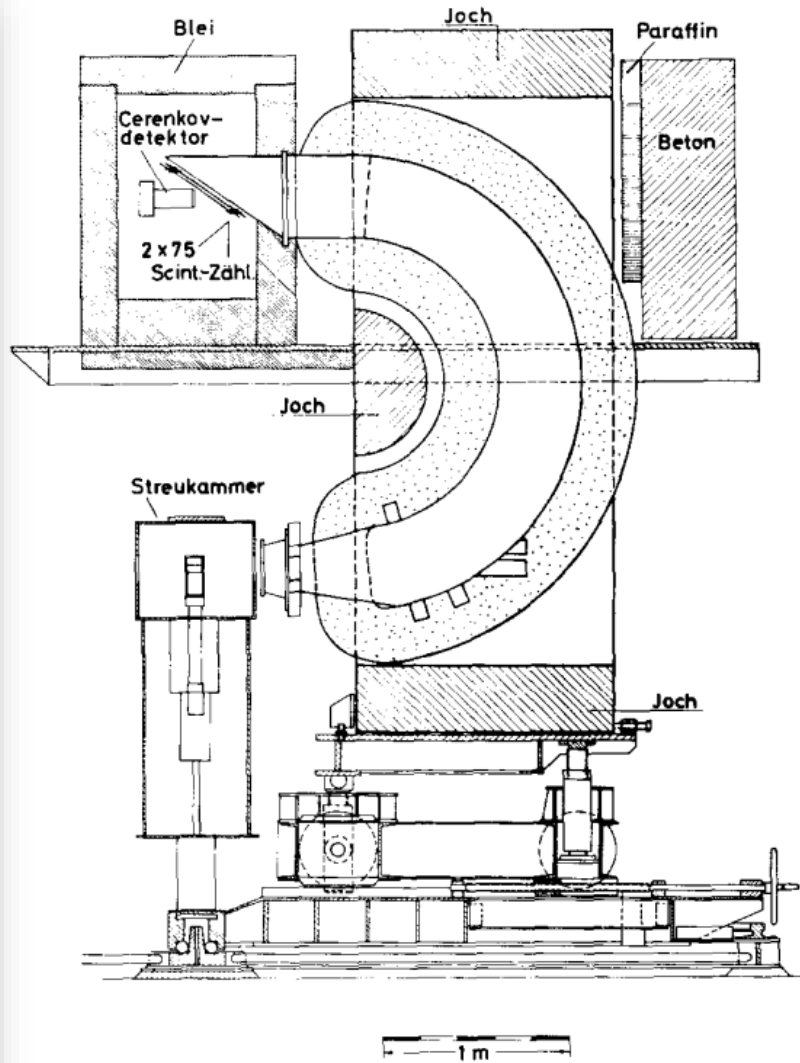
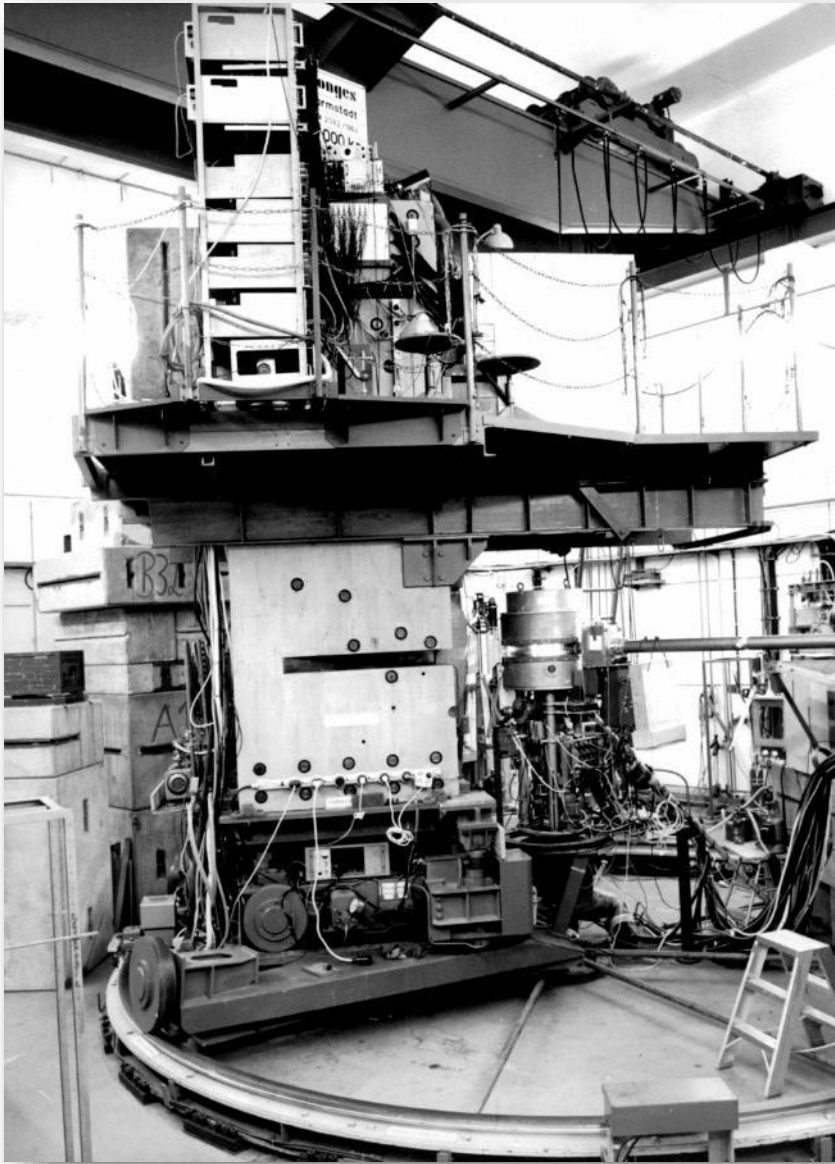
**Disclaimer: No new analyses or simulations since NREC 2024**

**See also talk by Sören Schlimme at NREC 2024**  
→ My talk provides an overview of **instrumentation**

# Electron Scattering Spectrometers

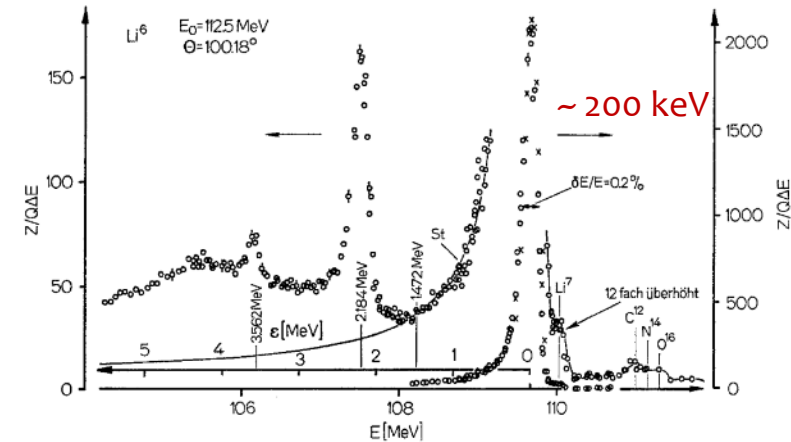


# The 180° Spectrometer at the Mainz 300-MeV Linac



Magnetoptische Daten  
 (für Abstand Target-Jochkante  
 $l_0 = 78 \text{ cm}$ )  
 Effektiver Ablenkwinkel  
 max. Winkelakzeptanz  
 Impulsakzeptanz  
 Abstand Bildebene-Jochkante  
 Neigung Bildebene-Sollbahn  
 Dispersion  $D = (\delta x/r_0)/(\delta p/p)$   
 (auf Sollbahn)  
 Auflösungsvermögen  $R = \delta p/p$   
 (Strahlfleckhöhe = 1 mm)

$\alpha = 180^\circ 14''$   
 $\Omega = 6 \times 10^{-3} \text{ sr}$   
 $\Delta p/p = 7\%$   
 $l = (67,3 \pm 0,5) \text{ cm}$   
 $\varepsilon = 34^\circ 40''$   
 $D = 4,1$   
 $R = 3-4 \times 10^{-4}$



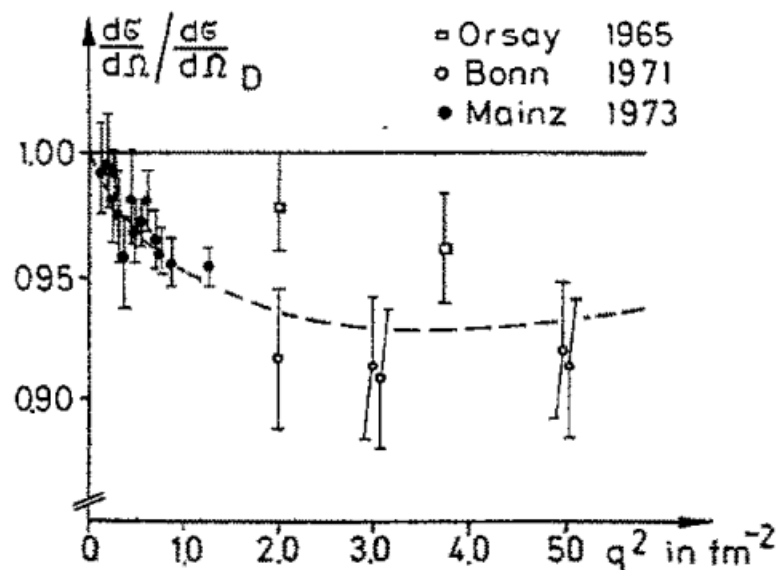
Momentum acceptance  $\Delta p/p = 7\%$   
 Momentum resolution  $= 3 \times 10^{-4}$   
 Accepted solid angle  $\Delta\Omega = 6 \text{ msr}$

[H. Ehrenberg, NIM 105, 253 (1972)]

[R. Neuhausen, Z. Physik 220, 456 (1969)]

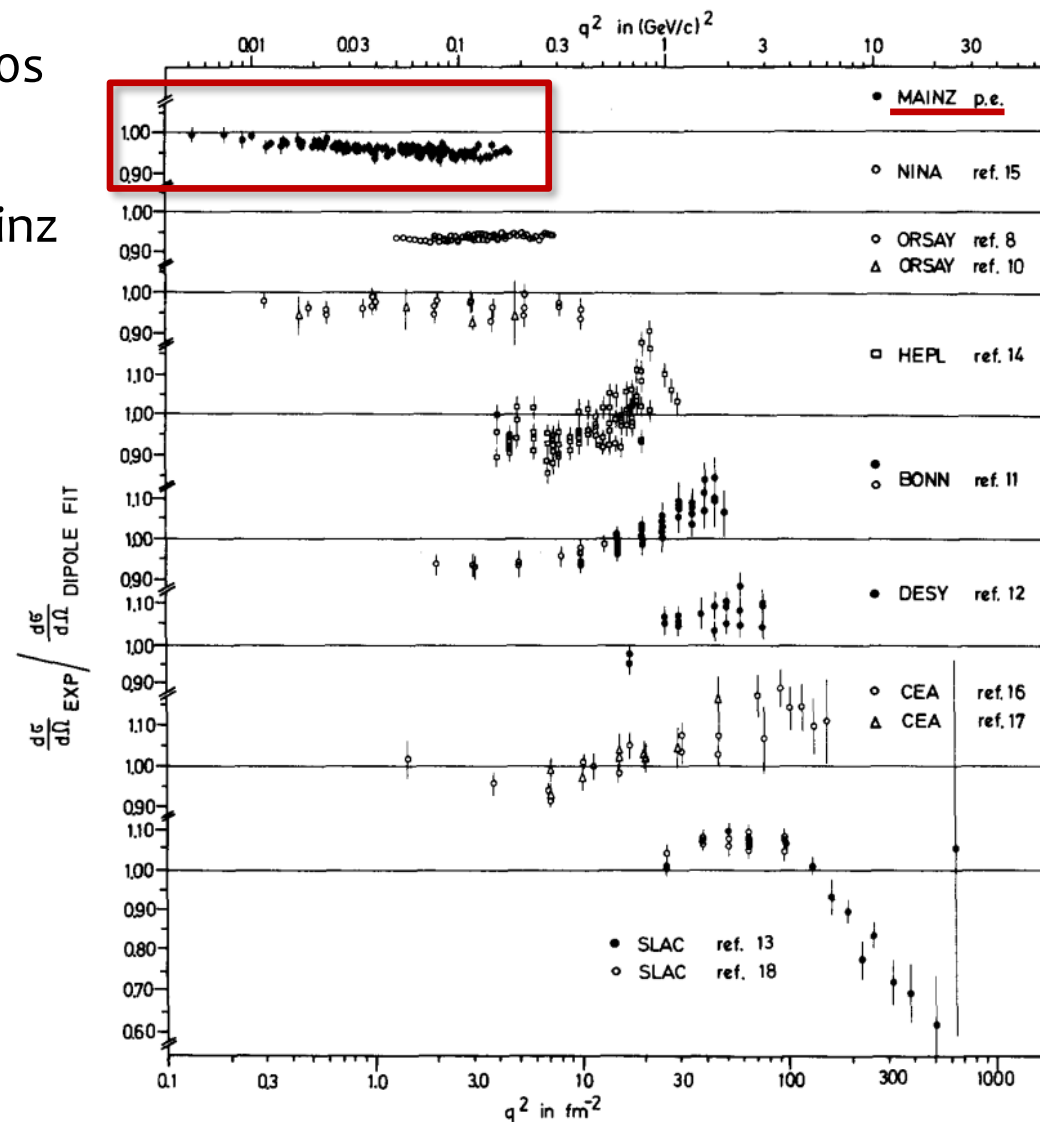
# Pioneering Electron Scattering Experiments in Mainz

- Deviations from the dipole fit were known since the 1970s
- Mainz data dominating the proton radius extraction
- Initiating > 50 years of form factor measurements in Mainz



[F. Borkowski et al., Nucl. Phys. A222, 269 (1975)]

$$r_E = \sqrt{\langle r_E^2 \rangle} = 0.88(3) \text{ fm}$$



[F. Borkowski et al., Nucl. Phys. B93, 461 (1975)]

# MAMI and the A1 Spectrometers



# The Mainz Microtron MAMI

## MAMI-B:

3 Race Track Microtrons

$E_0 = 180 \dots 883 \text{ MeV}$

Energy spread  $\Delta E = 13 \text{ keV}$

Energy stability  $\Delta E = 100 \text{ keV}$

(long-term drifts over 1 week)

$\varepsilon_x = 9 \mu\text{m mrad}$ ,  $\varepsilon_y = 0.5 \mu\text{m mrad}$

Beam current max.  $100 \mu\text{A c.w.}$

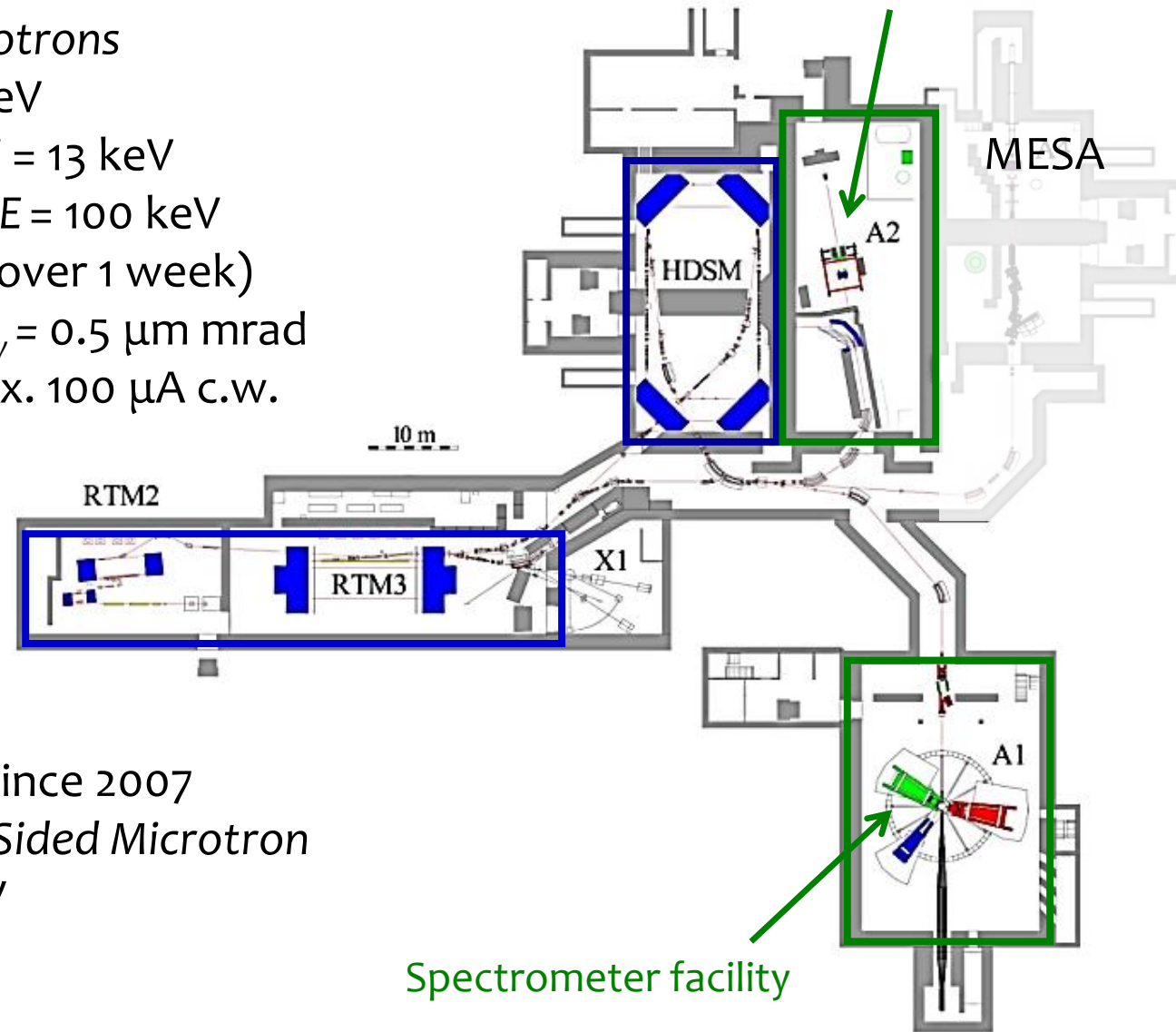
## MAMI-C:

Additional stage since 2007

Harmonic Double-Sided Microtron

$E_0$  up to  $1604 \text{ MeV}$

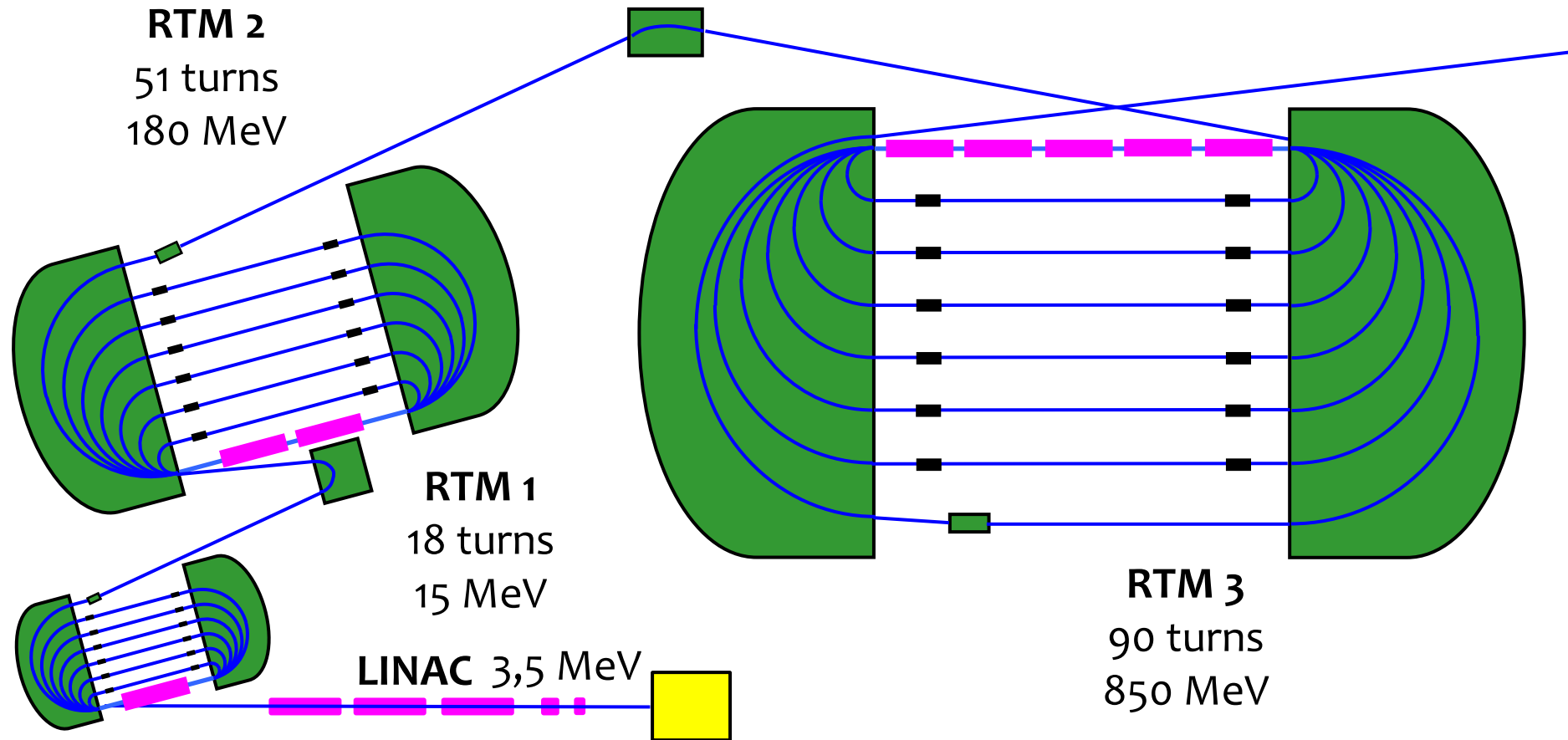
Photon beam and experiments



Spectrometer facility

# Race-Track Microtrons (RTM 1 – 3)

Cascade of 3 RTMs with each 2 magnets and 1 linac with RF acceleration

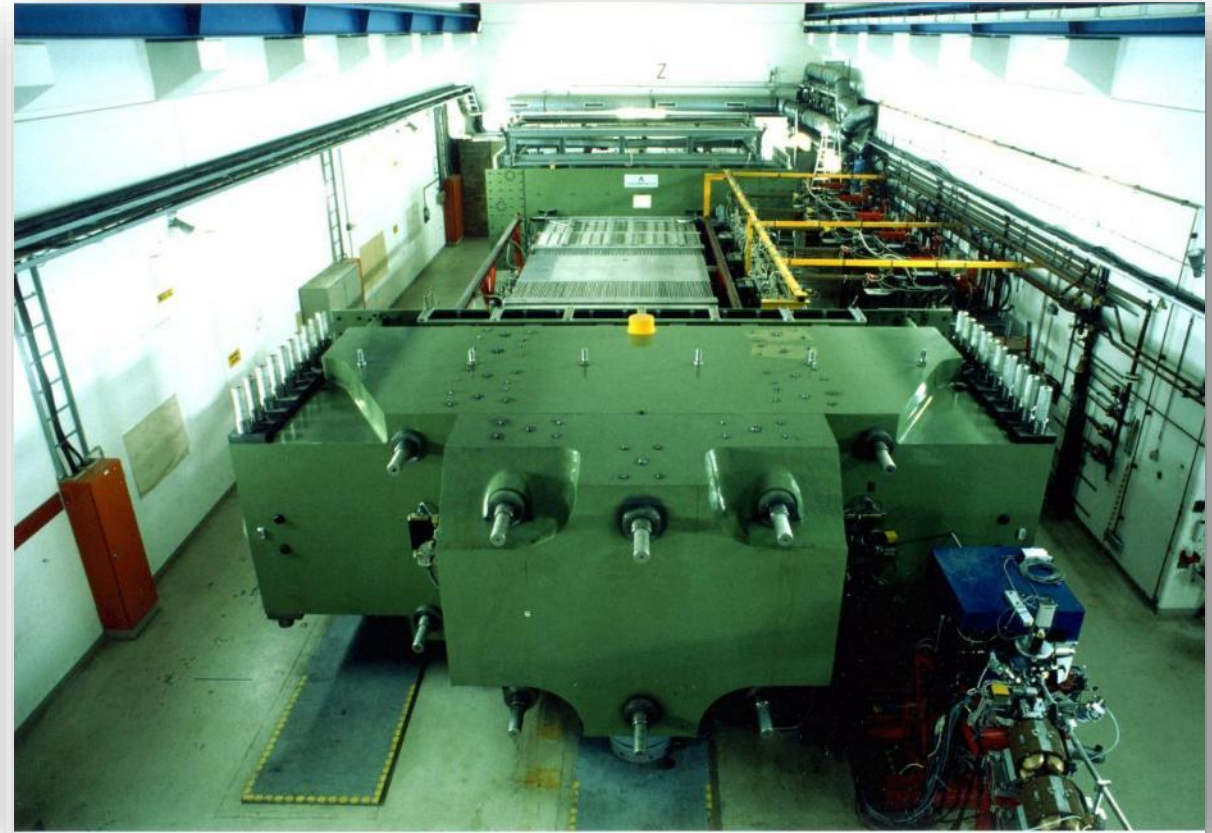


**RTM3: single pass energy gain 7.5 MeV x 90 turns = 675 MeV total energy gain**  
with only 163 kW RF power for 67.5 kW of beam power at 100 mA

# MAMI-B (RTM1 – 3)

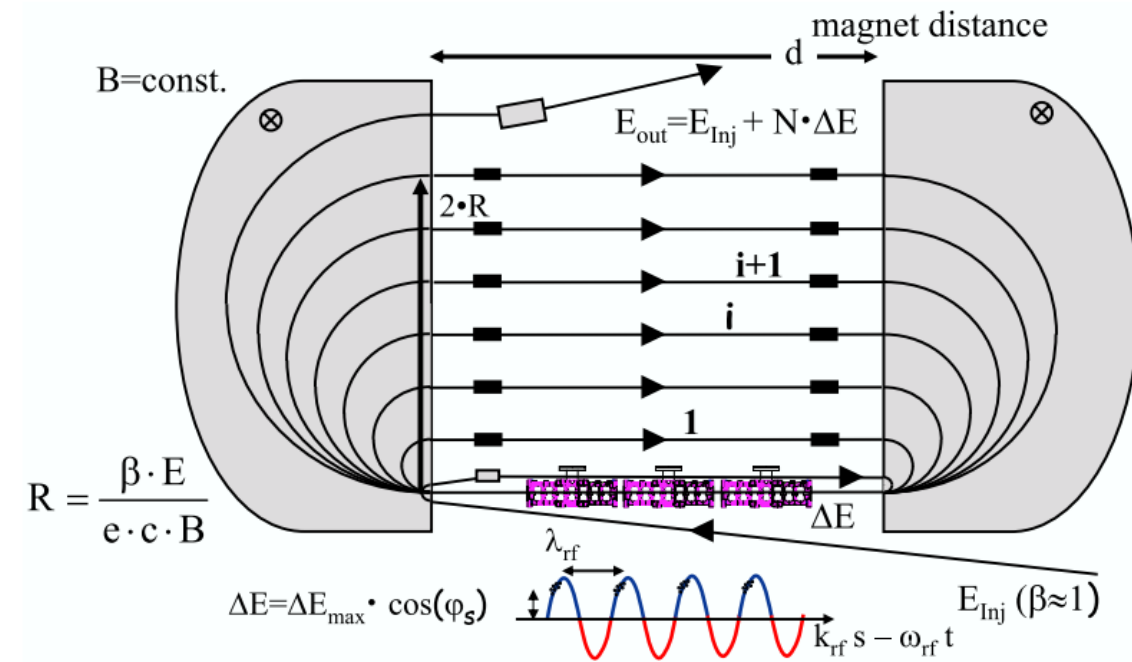


**RTM1 and RTM2**



**RTM3**

# RTM Operation Parameters



		Injector	RTM1	RTM2	RTM3
<b>General</b>					
injection / extraction energy (total)	[GeV]	0.511 / $3.97 \cdot 10^{-3}$	$3.97 / 14.86 \cdot 10^{-3}$	$14.86 / 180 \cdot 10^{-3}$	0.180 / 0.855
number of turns		–	18	51	90
total power consumption	[kW]	92	92	220	650
<b>Rf-System</b>					
energy resp. energy gain / turn	[MeV]	3.5	0.599	3.24	7.50
frequency	[GHz]	2.4495	2.4495	2.4495	2.4495
linac length (electrically)	[m]	4.93	0.80	3.55	8.87
number of sections / klystrons		3 / 1	1 / 1	2 / 2	5 / 5
power dissipation / beam power	[kW]	33.2 / 0.35	7.9 / 1.1	48.4 / 16.6	102.5 / 67.5
power consumption	[kW]	90	90	180	450
<b>Magnet-System</b>					
flux density (within the gap)	[T]	–	0.1026	0.5550	1.2842
gap height	[cm]	–	6	7	10
min./max. deflection radius	[m]	–	0.129-0.482	0.089-1.083	0.467-2.216
iron / copper weight of the magnets	[t]	–	4 / 0.2	90 / 2.3	900 / 11.6
number of corrector magnets		40	72	204	360
number of quadrupoles and solenoids		20	2	4	4
power consumption	[kW]	2	2	40	200
<b>Beam-Parameters</b>					
energy spread ( $1\sigma$ )	[keV]	1.2	1.2	2.8	13
norm. emittance hor. / vert. ( $1\sigma$ )	$[\pi \cdot 10^{-6} \text{ m}]$	0.05 / 0.04	0.07 / 0.07	0.25 / 0.13	13 / 0.84
standard-energies for experiments				180MeV	195-855MeV in steps of 15MeV

- Commercially available microwave components for 2.45 GHz  
 $\rightarrow \lambda_{RF} = c / 2.45 \text{ GHz} \approx 12 \text{ cm} \rightarrow t = 1 / 2.45 \text{ GHz} \approx 0.4 \text{ ns}$  bunch structure
- Dynamic-resonance condition** for path length increase from turn to turn:  
 $L_{i+1} - L_i = 2\pi\Delta R = n \cdot \lambda_{RF} \rightarrow 2\Delta R \approx 4 \text{ cm}$
- Fulfilled by setting the **energy gain per turn** to:  
 $\Delta E = ecB / 2\pi \cdot n \cdot \lambda_{RF} = 7.5 \text{ MeV}$  for RTM3 field
- Large number of turns** to reach GeV energies

[A. Jankowiak, Eur. Phys. J. A 28, s01, 149 (2006)]

Large number of standard energies allows for many overlapping kinematic settings

# A1 Spectrometer Facility at MAMI

## Focusing spectrometers:

- 3 high-resolution  $\Delta p/p \sim 10^{-4}$  spectrometers (SpekA,B,C)
- 1 short-orbit spectrometer (KAOS, since 2008)

## SpekA:

Momentum resolution:

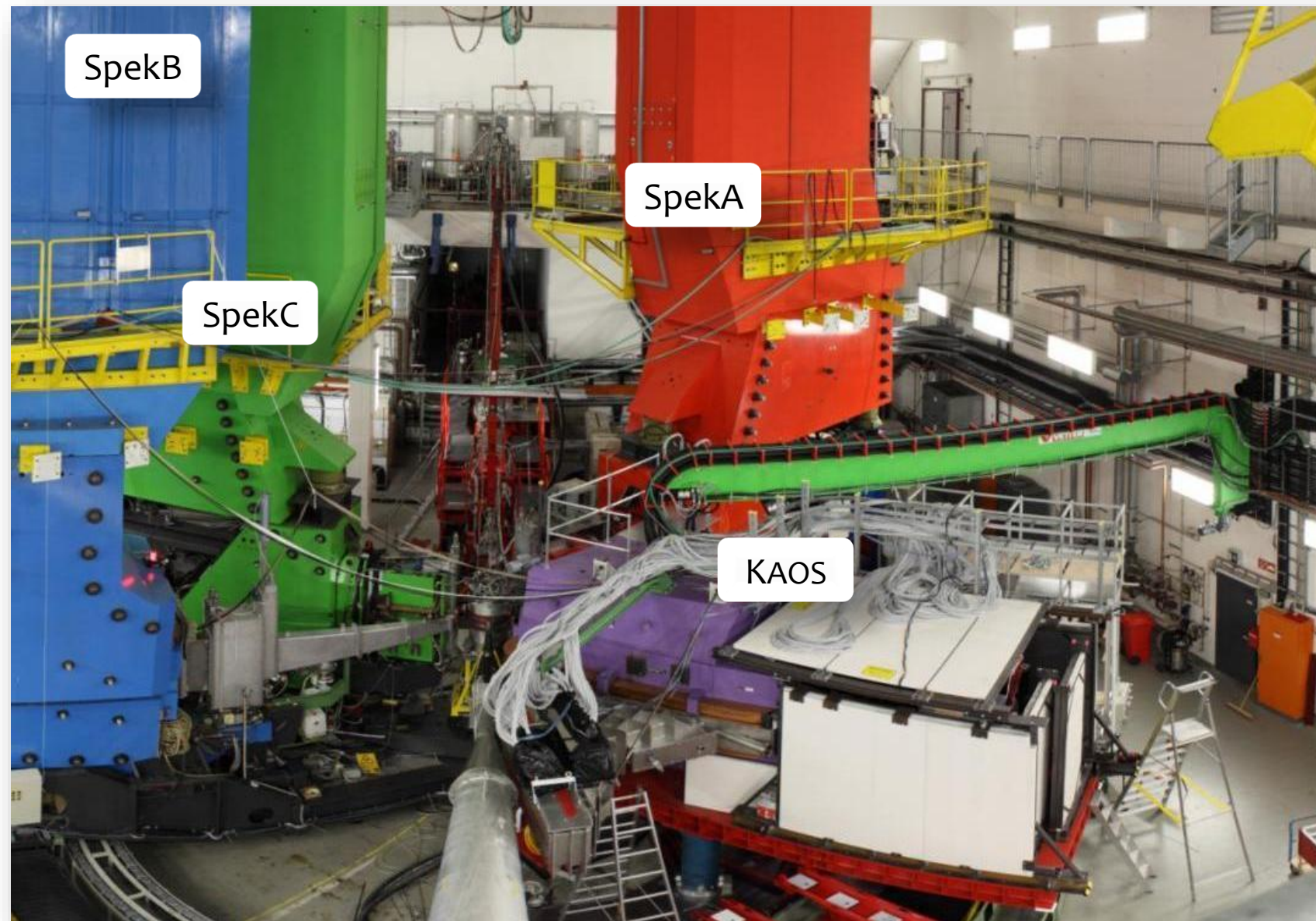
$$\delta p/p < 10^{-4}$$

Momentum acceptance:

$$\Delta p/p = 20\%$$

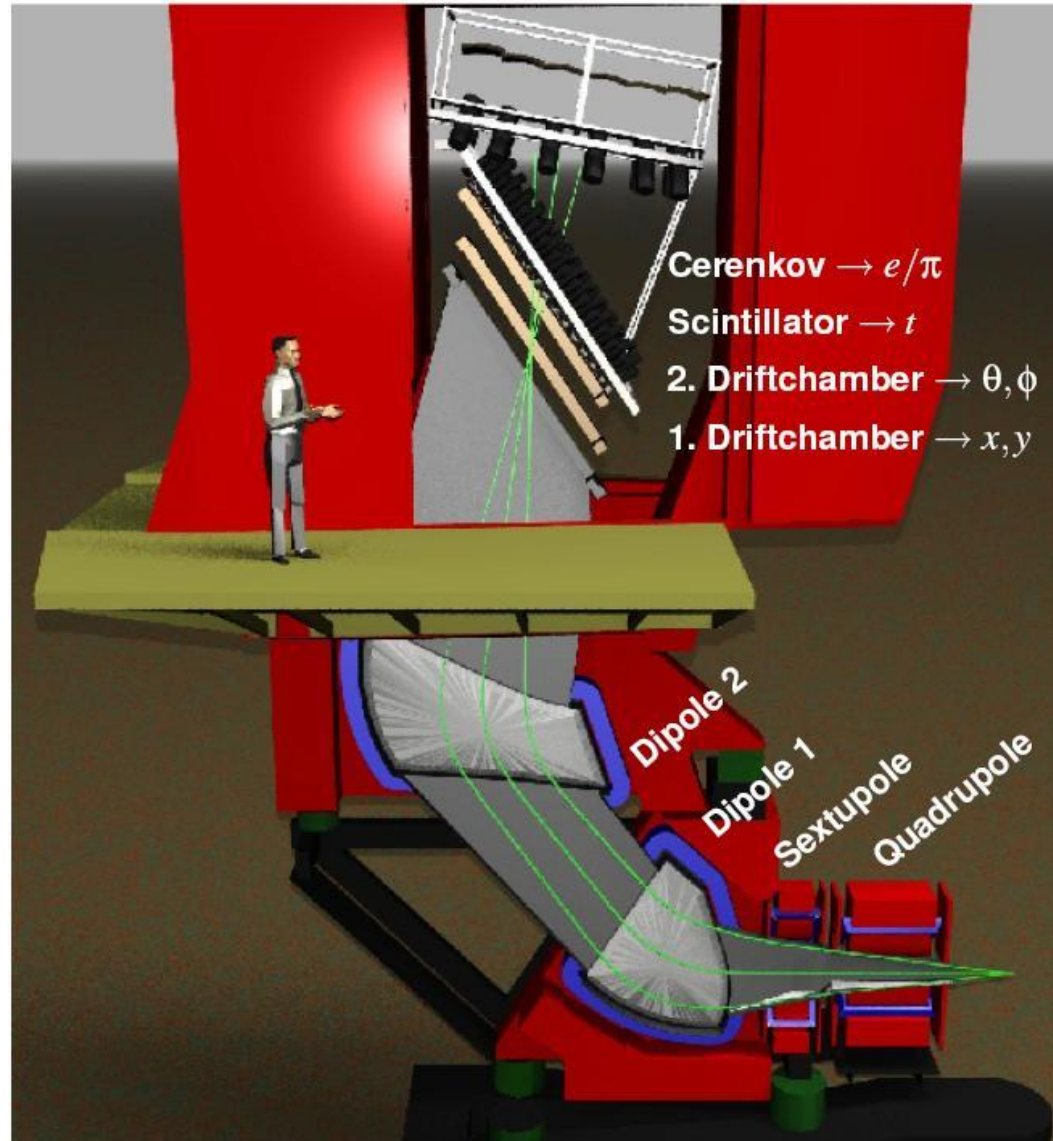
Accepted solid angle:

$$\begin{aligned}\Delta\Omega &= 11.5^\circ \times 8.0^\circ \\ &= 28 \text{ msr}\end{aligned}$$



# Magnet Optics for the QSDD Design (SpekA and SpekC)

Resolving power of 21,000  
for beam spot size of 0.5 mm



## Sophisticated design:

- Intermediate image ( $y|\phi_0$ ) before D2
- Sextupole to correct ( $x|\theta_0^2$ ) and ( $x|\phi_0^2$ )
- ( $y|y_0$ ) small for long target acceptance
- Focal plane angle  $\Psi = 45^\circ$  matched to vertical drift chambers

## Pole contour corrections:

- D1: 5<sup>th</sup> order polynomial (entry)
- D2: 4<sup>th</sup> order & 7<sup>th</sup> order polynomial (entry/exit)

Spectrometer	A	B	C
Configuration	QSDD	D	QSDD
Focussing properties			
dispersive plane	pt → pt	pt → pt	pt → pt
nondispersive plane	→ pt	pt → pt	→ pt
Maximum momentum [MeV/c]	735	870	551
Solid angle [msr]	28	5.6	28
Angular range			
minimum angle	18°	7°	18°
maximum angle	160°	62°	160°
Momentum acceptance [%]	20	15	25
Angular acceptance			
dispersive plane [mrad]	±70	±70	±70
nondispersive plane [mrad]	±100	±20	±100
long-target acceptance [mm]	50	50	50
Angle of focal plane	45°	47°	45°
Length of focal plane [m]	1.80	1.80	1.60
Length of trajectory [m]	10.75	12.03	8.53
Dispersion (central) [cm/%]	5.77	8.22	4.52
Magnification (central)	0.53	0.85	0.51
Dispersion / Magnification [cm/%]	10.83	9.64	8.81
Momentum resolution	$10^{-4}$	$10^{-4}$	$10^{-4}$
angular resolution at target [mrad]	≤3	≤3	≤3
position resolution at target [mm]	3–5	1	3–5

[K.I. Blomqvist et al., Nucl. Inst. Meth. A 403 (1998)]

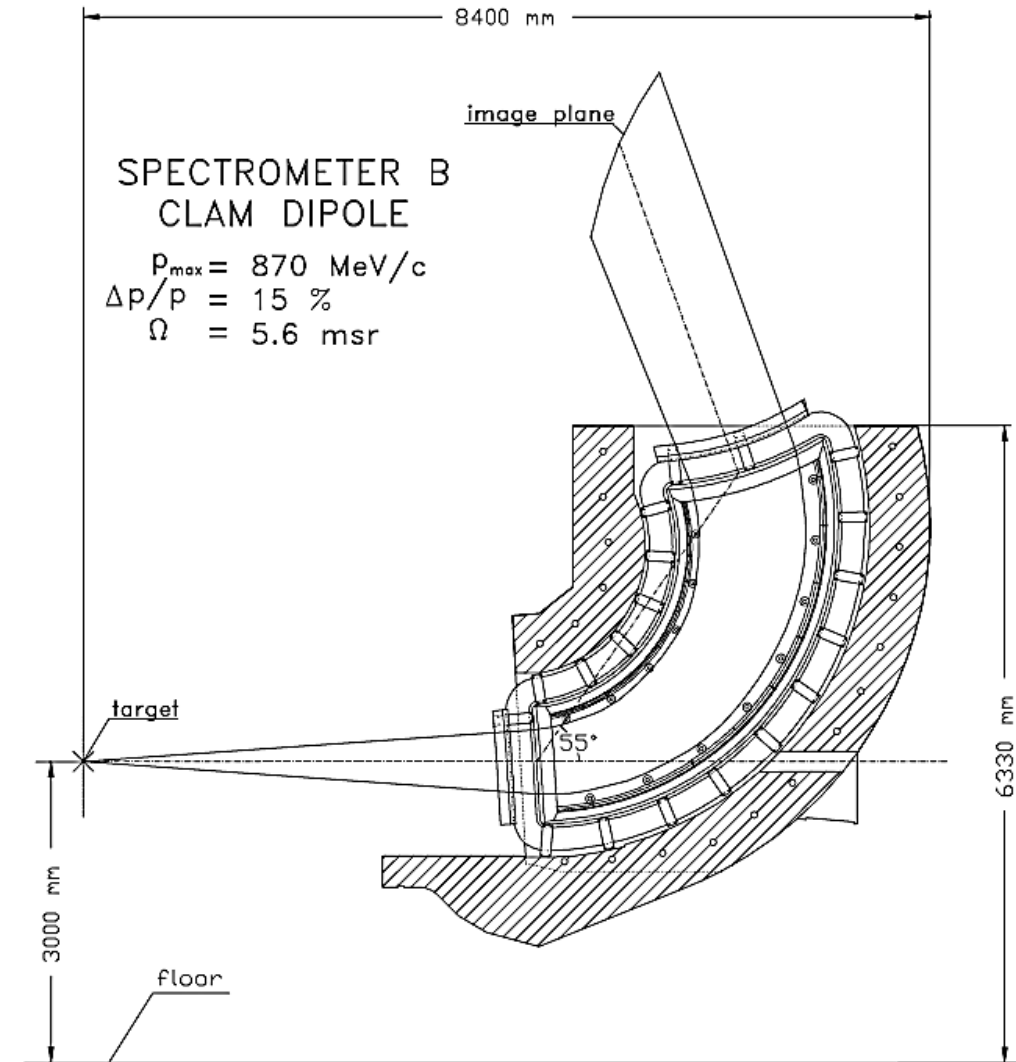
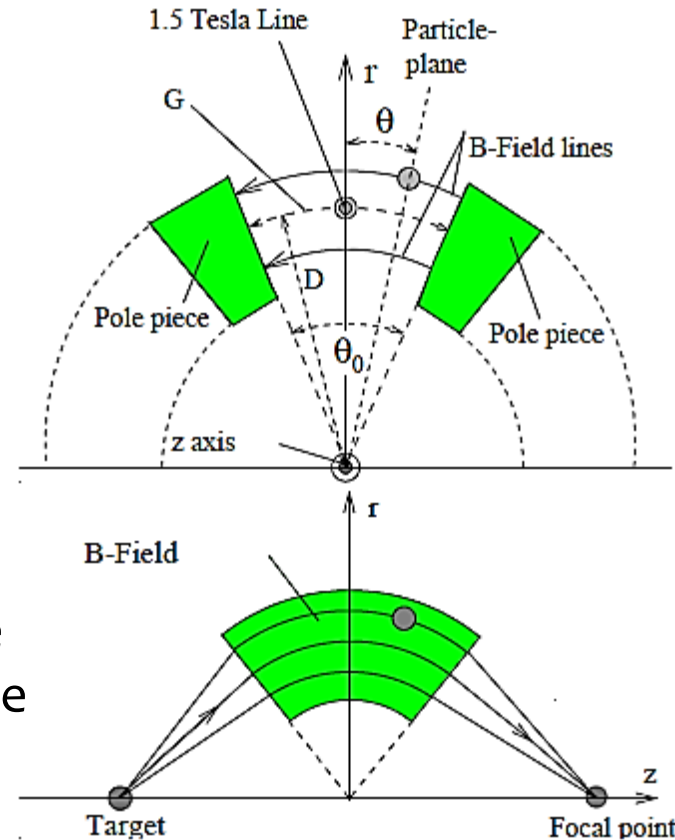
# Magnet Optics for the Clam-Shell Design (SpekB)

## Advantages:

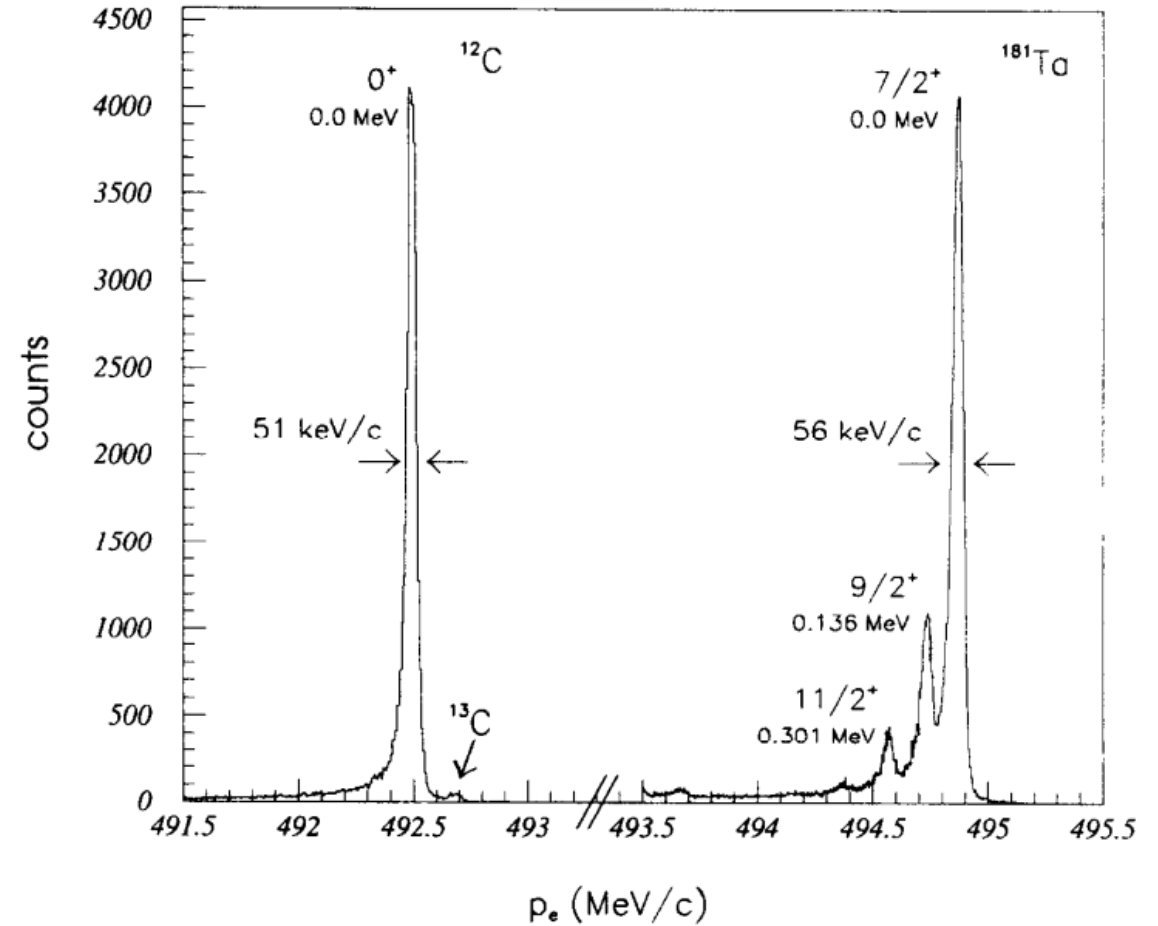
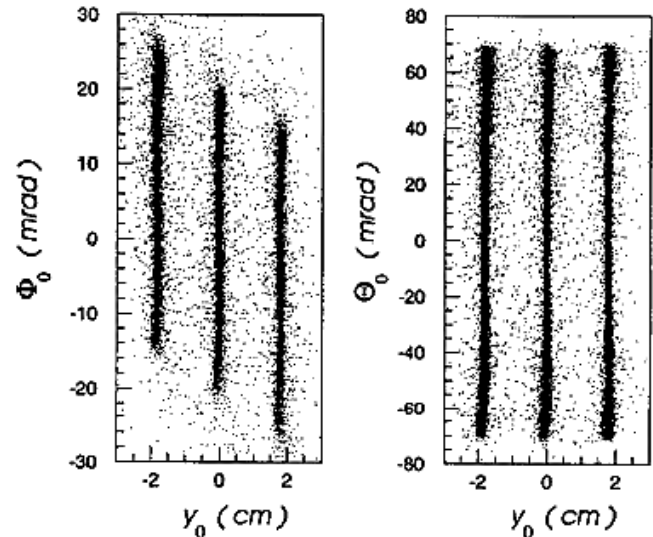
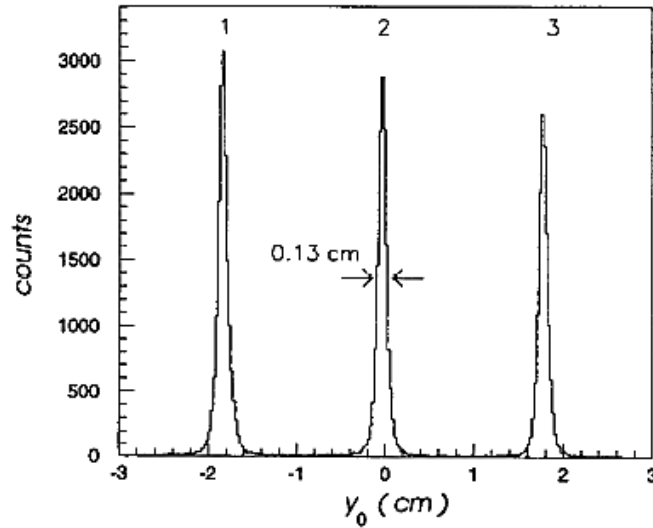
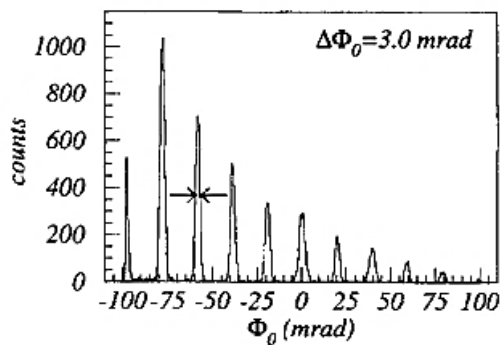
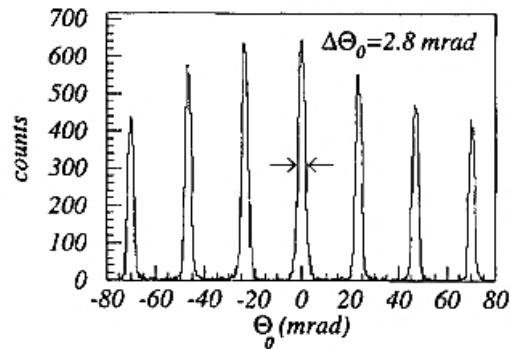
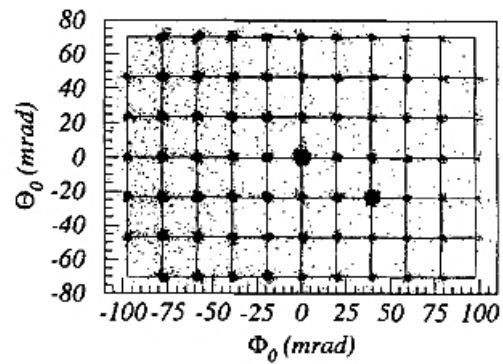
- Double-focusing with **one magnet only**
- Compact design
- **High maximum momentum**
- **Small minimum angle**
- Out-of-Plane capability
- High vertex resolution

## Disadvantages:

- Small solid angle acceptance
- Small momentum acceptance



# Spectrometer Performance



$\delta p \sim 50$  keV/c FWHM at  $p \sim 500$  MeV/c

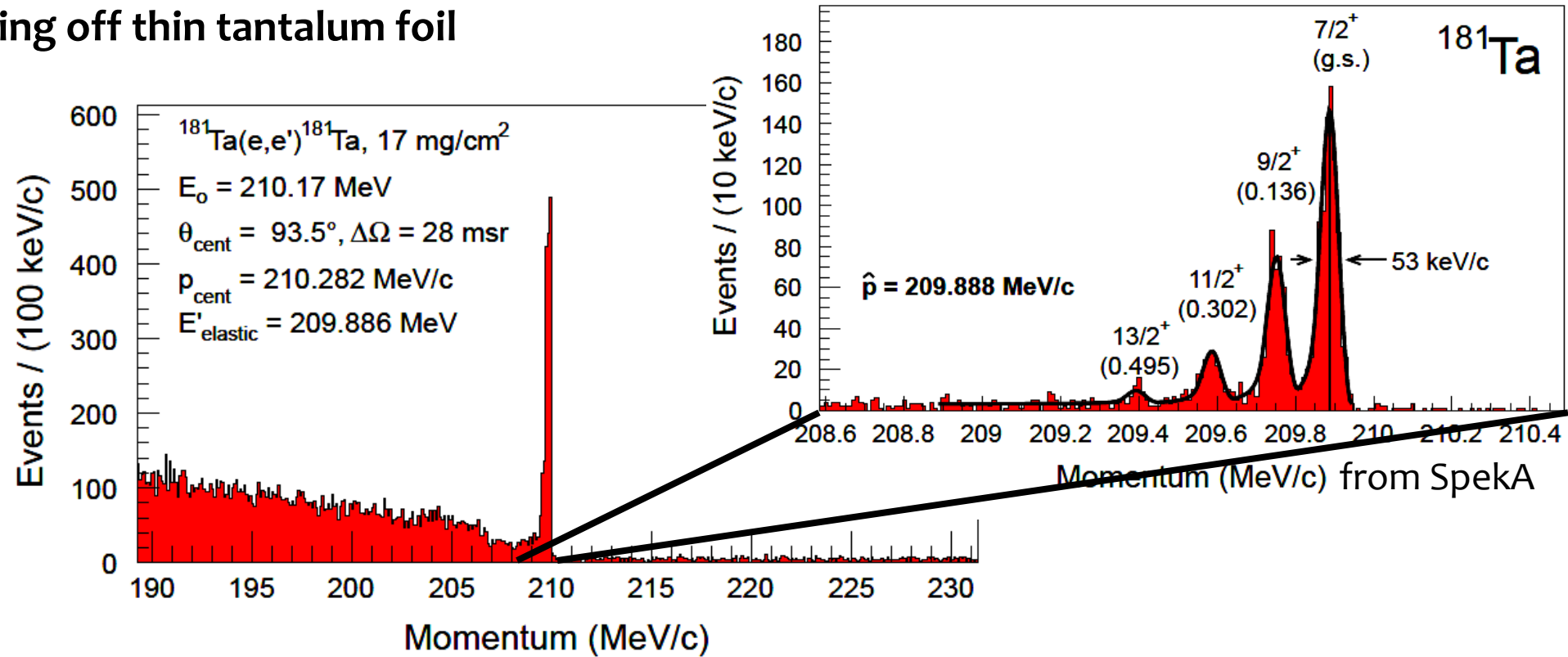
Target angles from SpekA

Vertex position from SpekB

[K.I. Blomqvist et al., Nucl. Inst. Meth. A 403 (1998)]

# Absolute Momentum Calibration

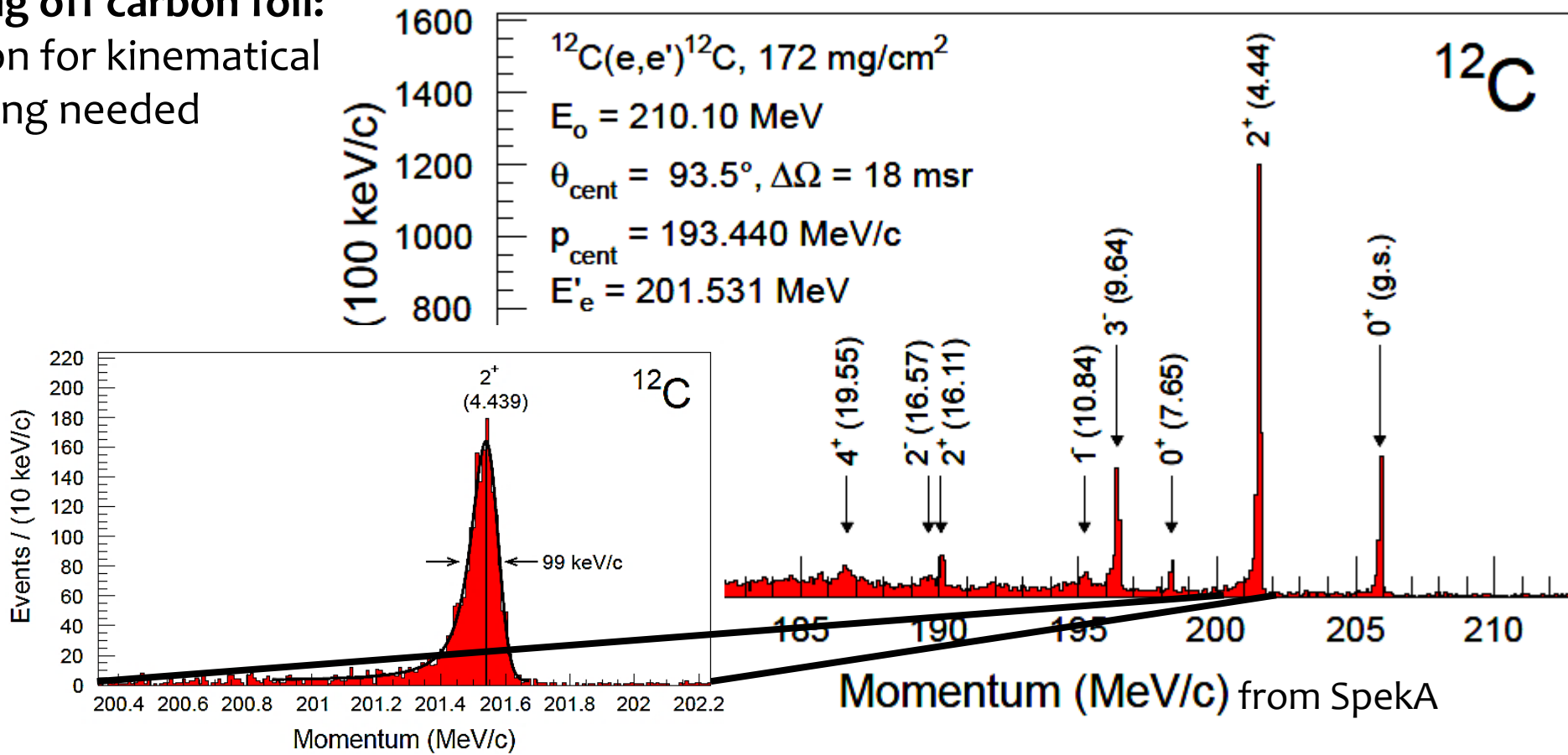
## Scattering off thin tantalum foil



- Elastic peak FWHM of 53 keV/c  $\rightarrow \delta p/p \sim 2 \cdot 10^{-4}$
- Beam energy **absolute accuracy**  $\delta p_{\text{beam}} = \pm 160$  keV/c  $\rightarrow \delta E/E \sim 7 \cdot 10^{-4}$
- Repeated calibrations at different momenta revealed  $\delta p_{\text{syst}} \sim 5$  keV/c

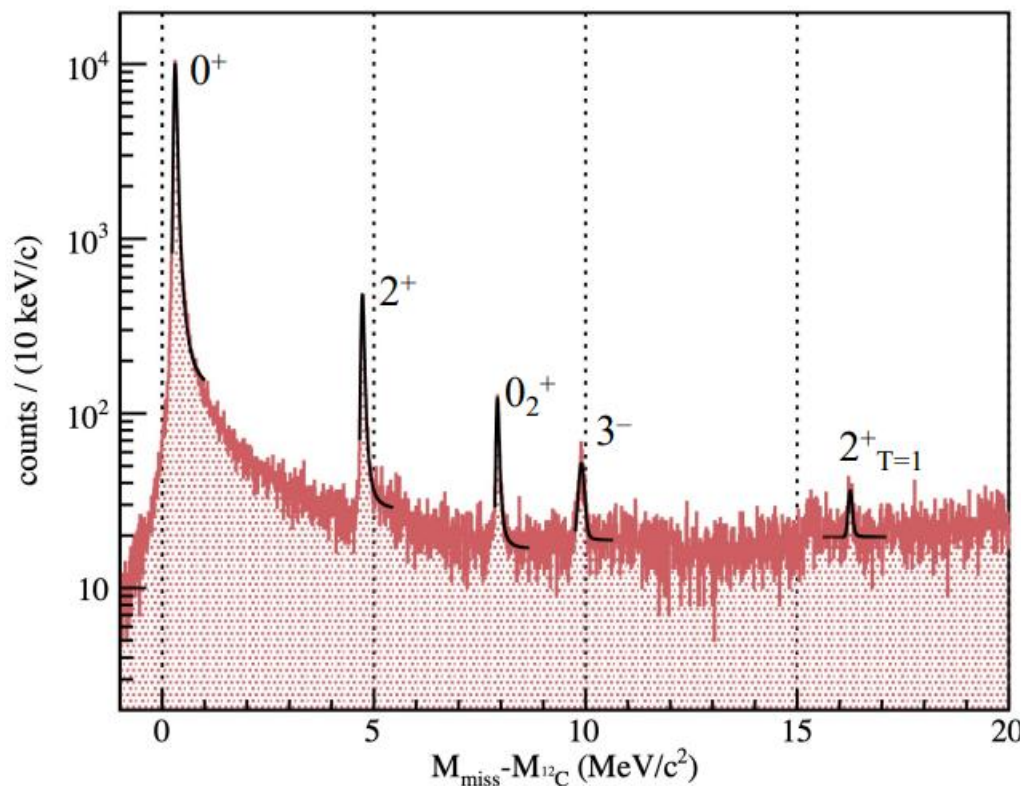
# Relative Momentum Calibration

Scattering off carbon foil:  
Correction for kinematical  
broadening needed



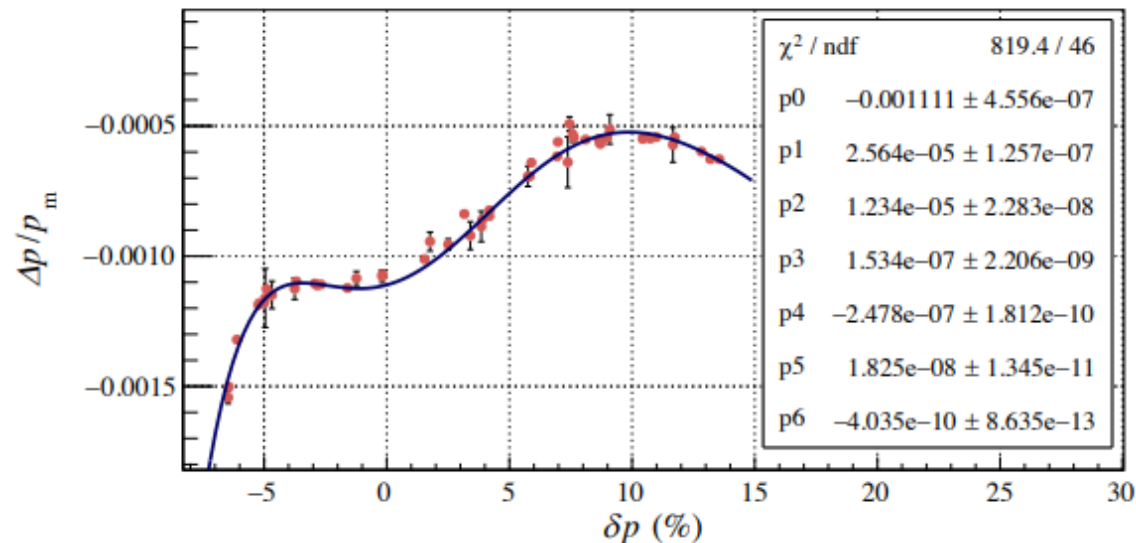
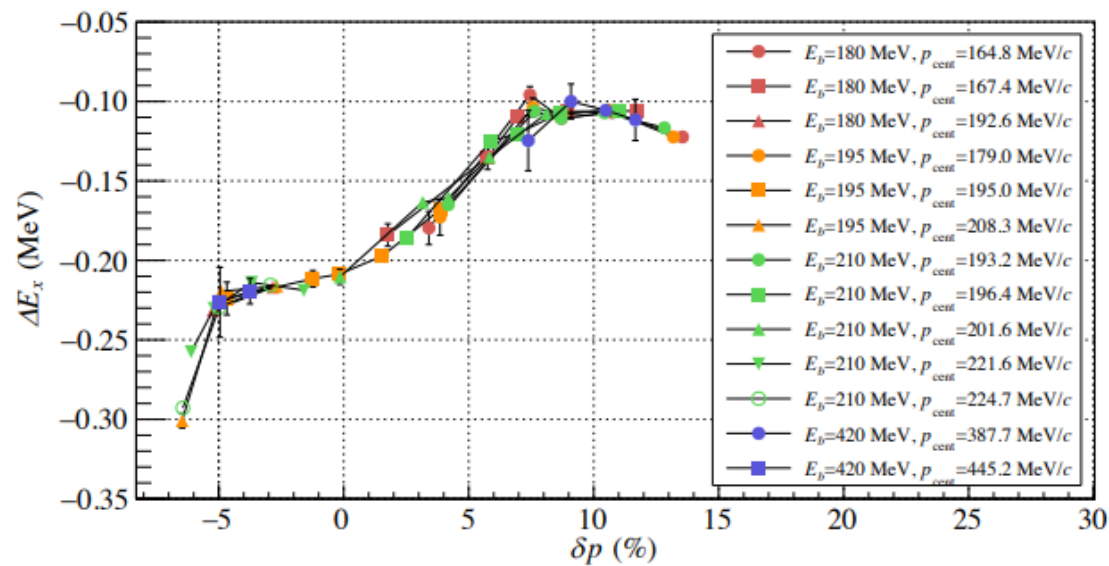
Distribution of excited states for **relative calibration** of momentum

# Systematic Study of Focal-Plane Non-Linearity

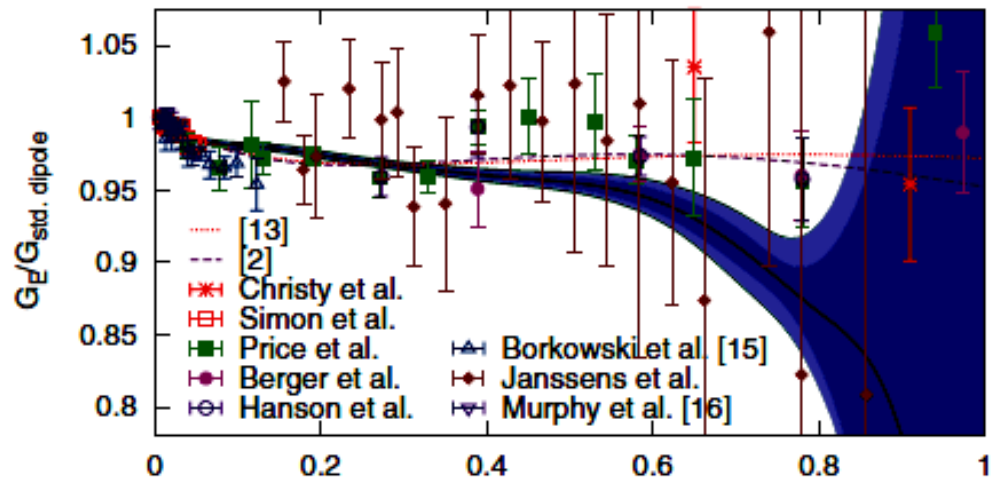
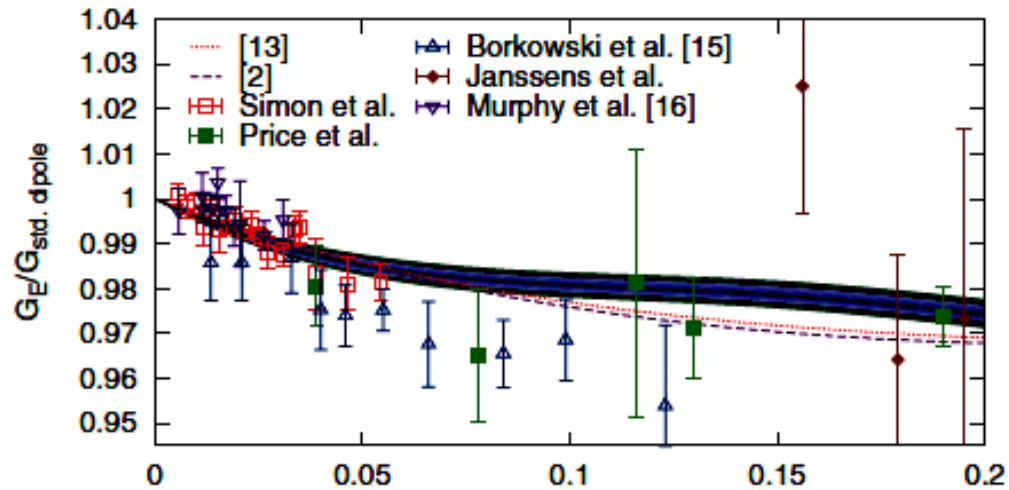


- 13 kinematic settings measured
- Multiple peaks fitted in each setting
- 6<sup>th</sup> order polynomial correction function  
 $p = (1 + p') \times p_{\text{cent}} \times (1 + \delta p)$

**Deviation of  $\Delta p \sim 2 \text{ keV}/c$  revealed**

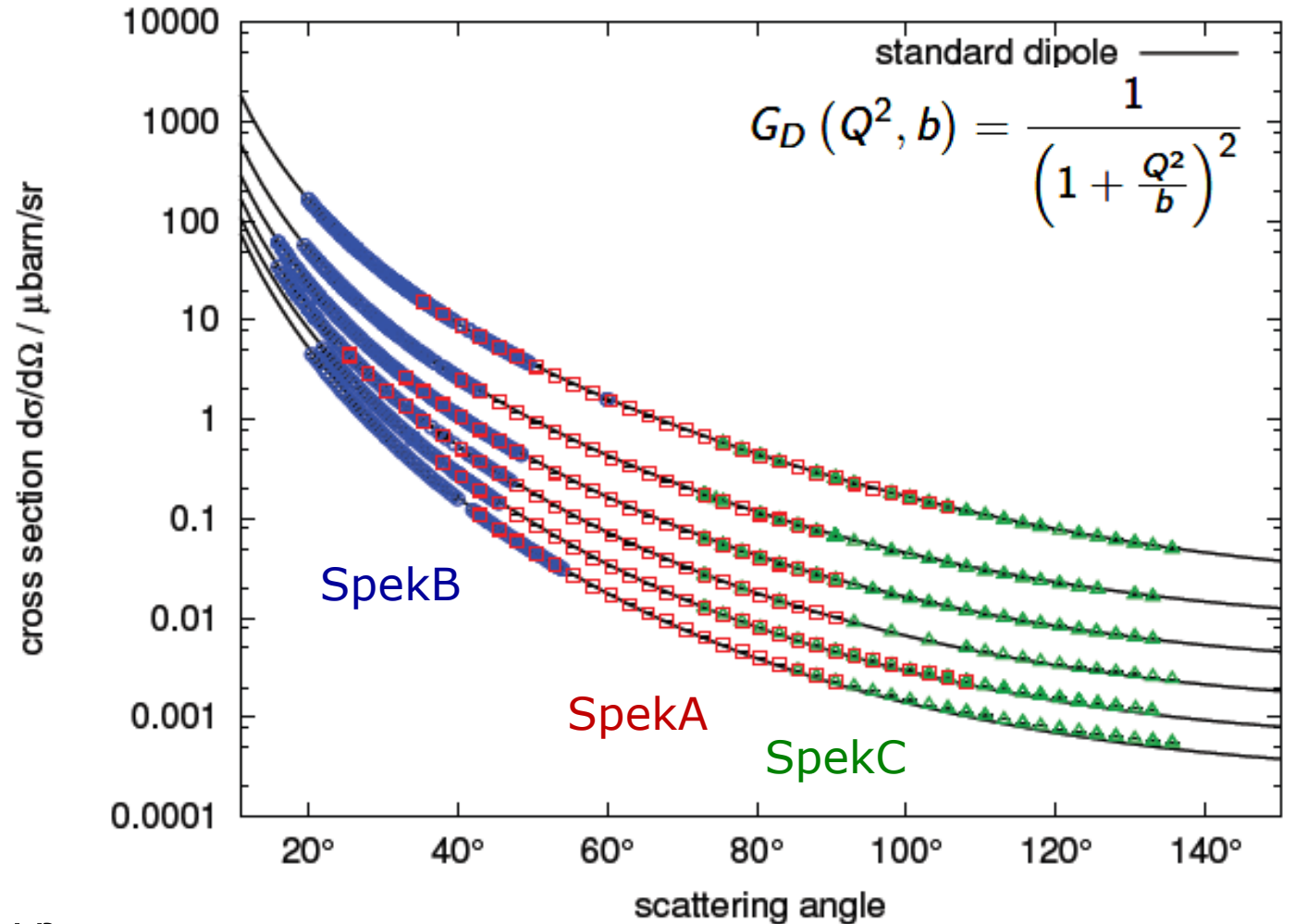


# Form Factor Measurements with A1 Spectrometers



- 1422 data points between  $Q^2 = 0.004 - 1 \text{ GeV}^2$
- Statistical errors below 0.2 %

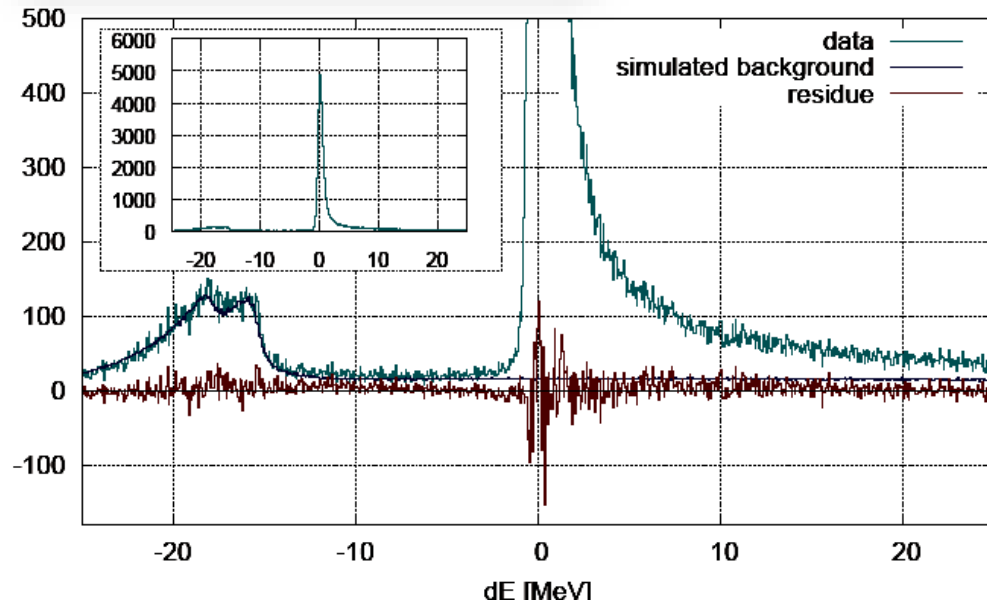
[J.C. Bernauer et al. (A1 Collab.), PRL 105, 242001 (2010)]



$$\langle r^2 \rangle = -\frac{6}{G(0)} \cdot \left. \frac{dG}{dQ^2} \right|_{Q^2=0} \quad \boxed{r_E = \sqrt{\langle r_E^2 \rangle} = 0.879(8) \text{ fm}}$$

# A Windowless Gas-Jet Target

## Liquid hydrogen target:



- Subtraction of **cell window contribution**

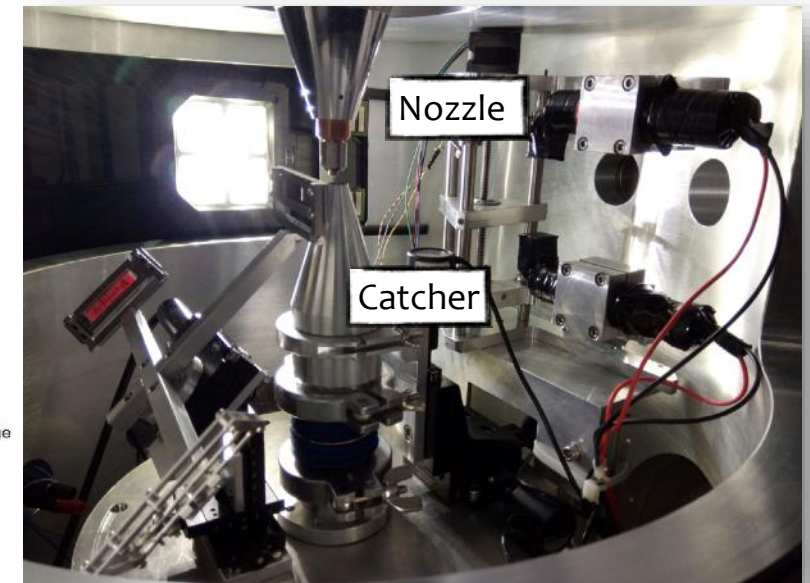
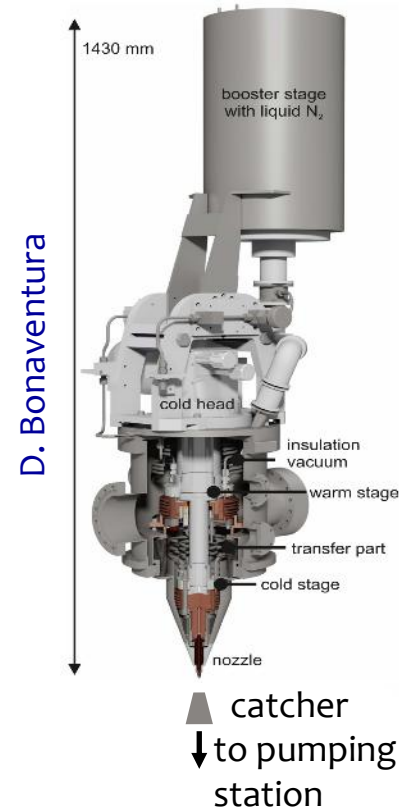
## Gas-jet target:

- Windowless, thin, point-like jet target
- Operated with **hydrogen** and argon



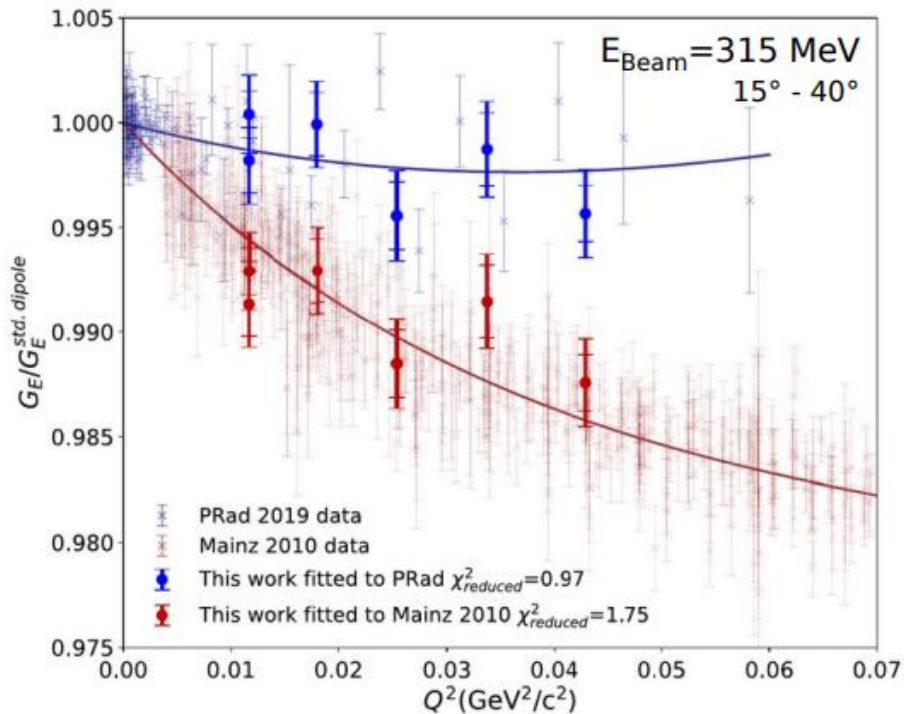
Argon gas jet

P. Brand



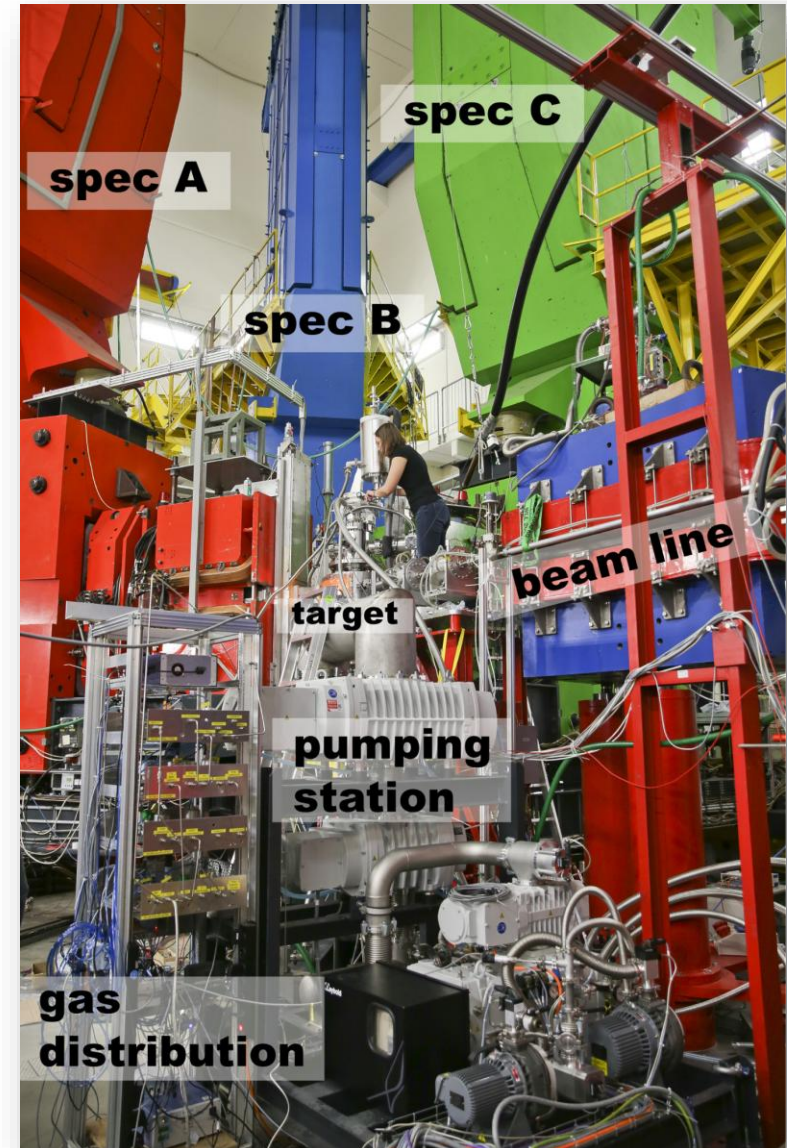
[S. Schlimme *et al.*, NIM A 1013, 165668 (2021)]

# Form Factor Measurements with Gas-Jet Target



- Statistically limited because of low target density
- **One beam energy only**
- **No absolute normalization**
- Compatible with PRAD data and liquid hydrogen data

[Y. Wang et al., PRC 106 , 044610 (2022)]

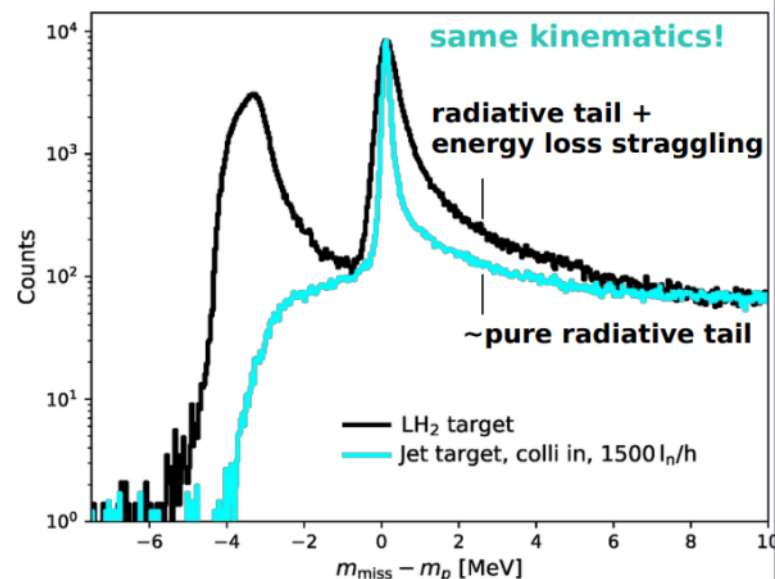
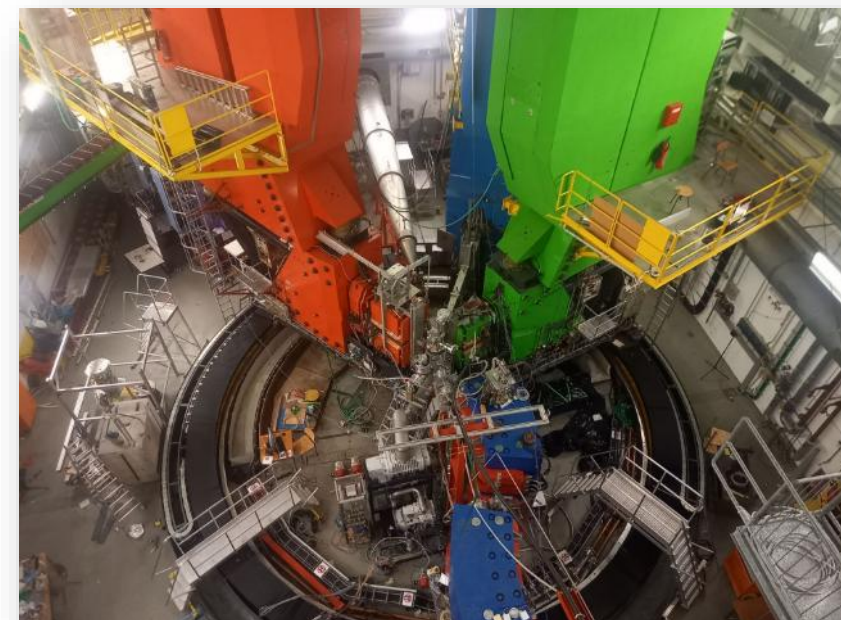


# New Form Factor Measurement with Gas-Jet Target

Beamtime April 21 – May 11, 2026

- Gas-jet target in filament mode operation
  - Suppressed residual gas background
  - Increased luminosity
- Refurbished beam halo blocker
  - Suppressed beam halo electron background

Main goal: reducing remaining background



Gas target nozzle



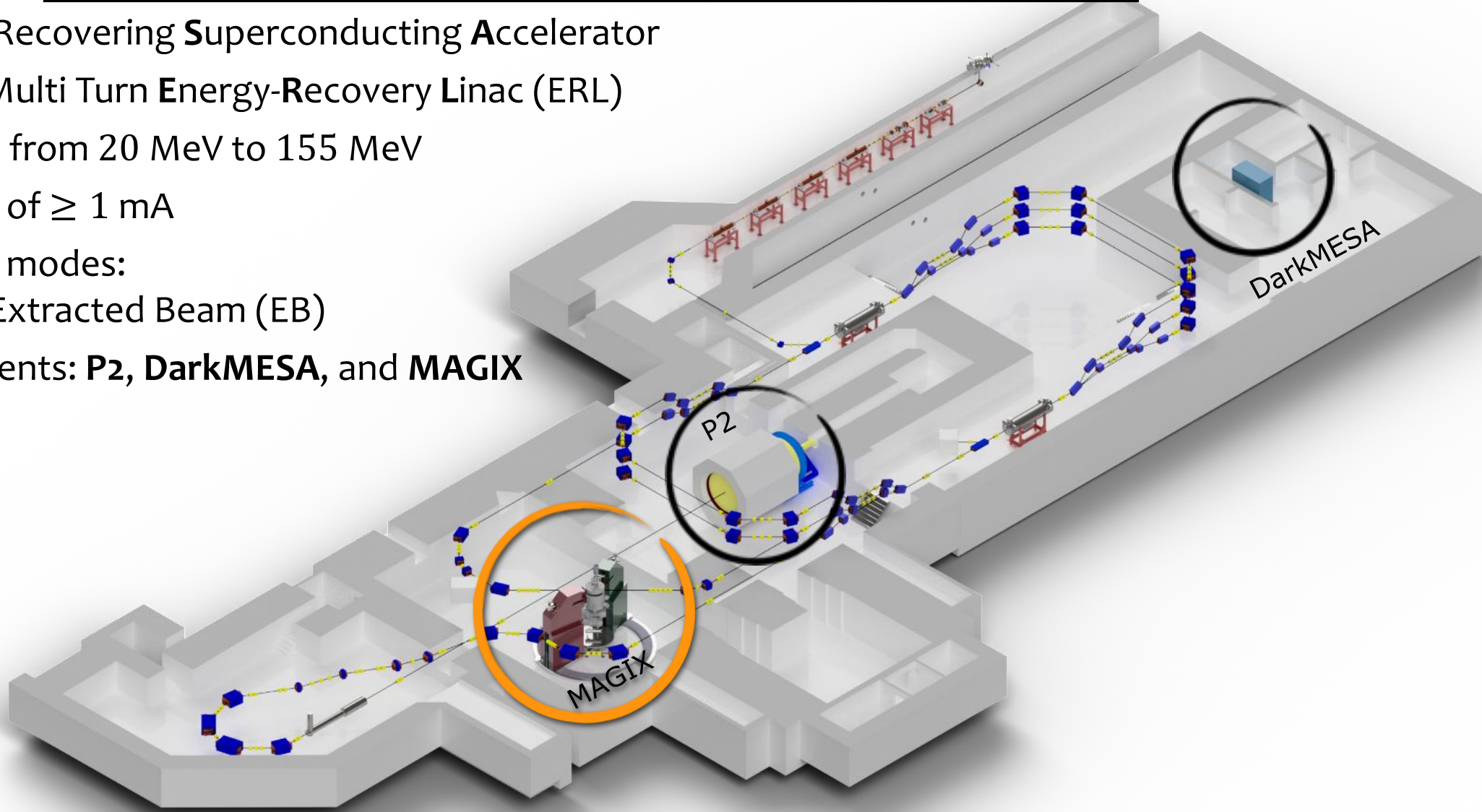
Beam halo blocker



# MESA and the MAGIX Spectrometers

# The Low-Energy Electron Accelerator MESA

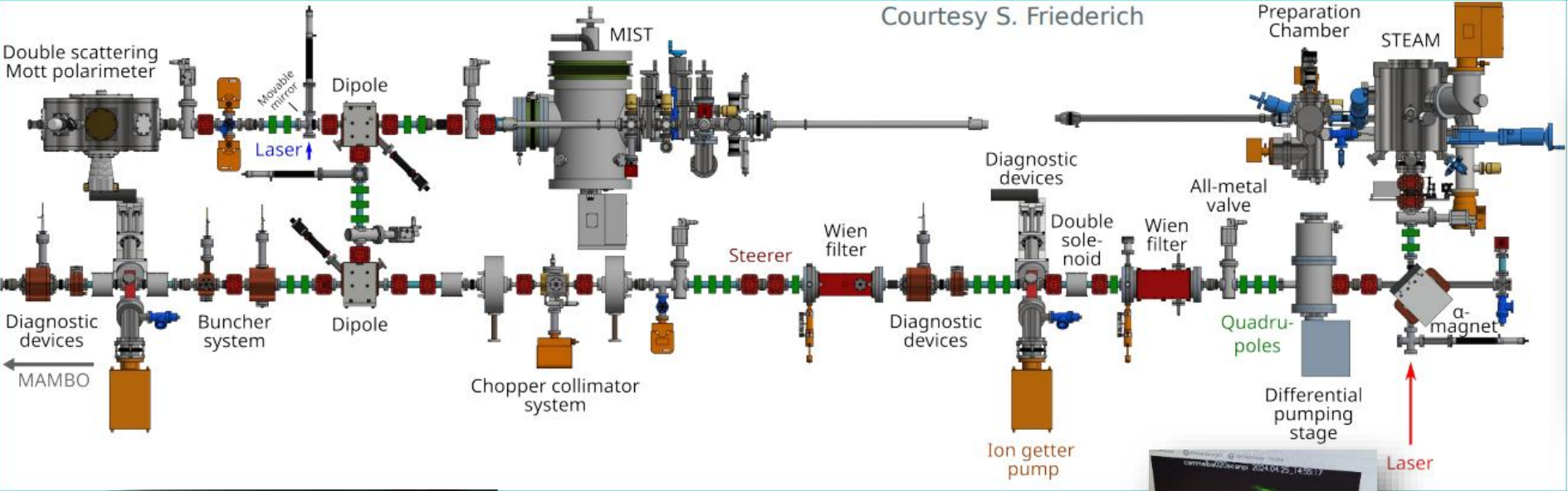
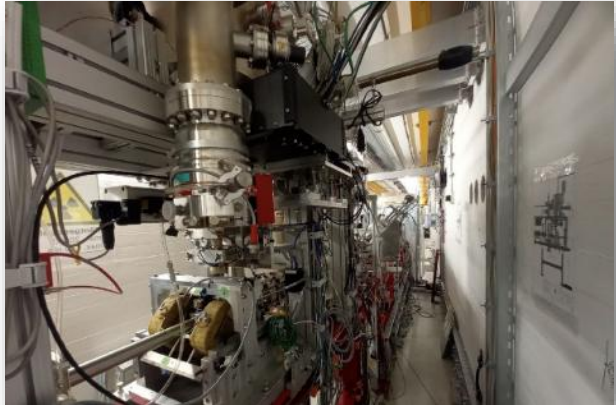
- **M**ainz **E**nergy-Recovering **S**uperconducting **A**ccelerator
- Double-sided Multi Turn **E**nergy-Recovery **L**inac (ERL)
- Beam energies from 20 MeV to 155 MeV
- Beam currents of  $\geq 1$  mA
- Two operation modes:  
ERL and Extracted Beam (EB)
- Three experiments: **P2**, **DarkMESA**, and **MAGIX**



# MESA Source and Beam Preparation System

Courtesy S. Friederich

STEAM



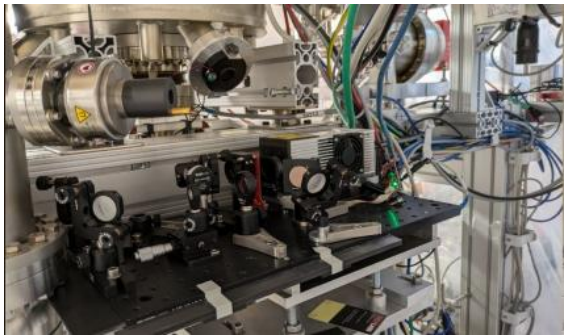
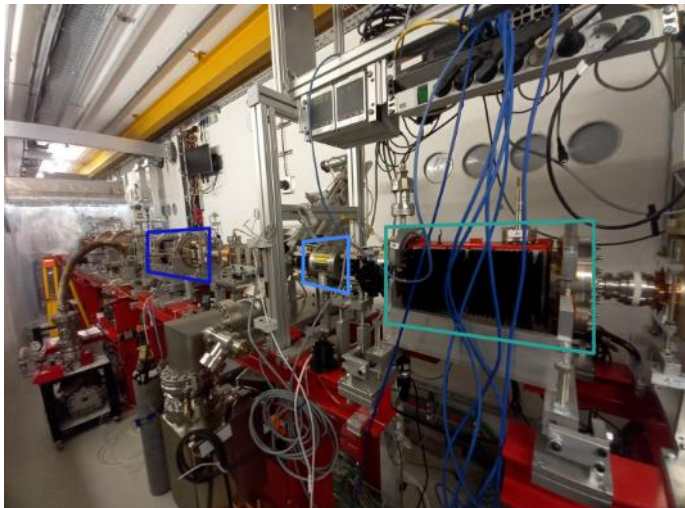
Chopper and collimator

Wien filter and solenoid



First beam

Laser system



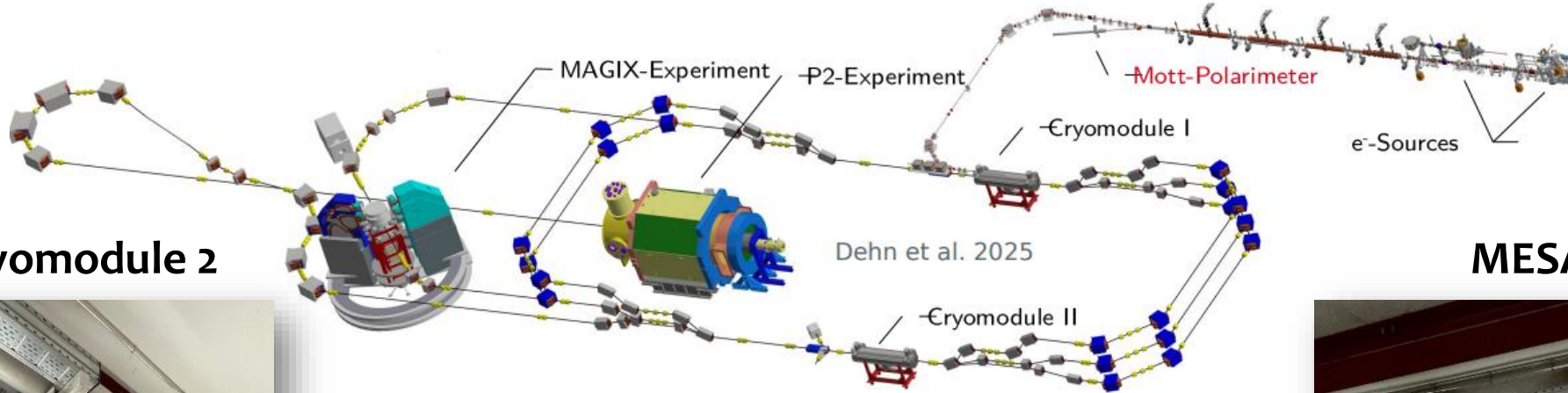
# MESA Linac



**Pre-  
accelerator  
MAMBO**



# MESA Enhanced ELBE Cryomodules



MESA cryomodule 2

MESA cryomodule 1

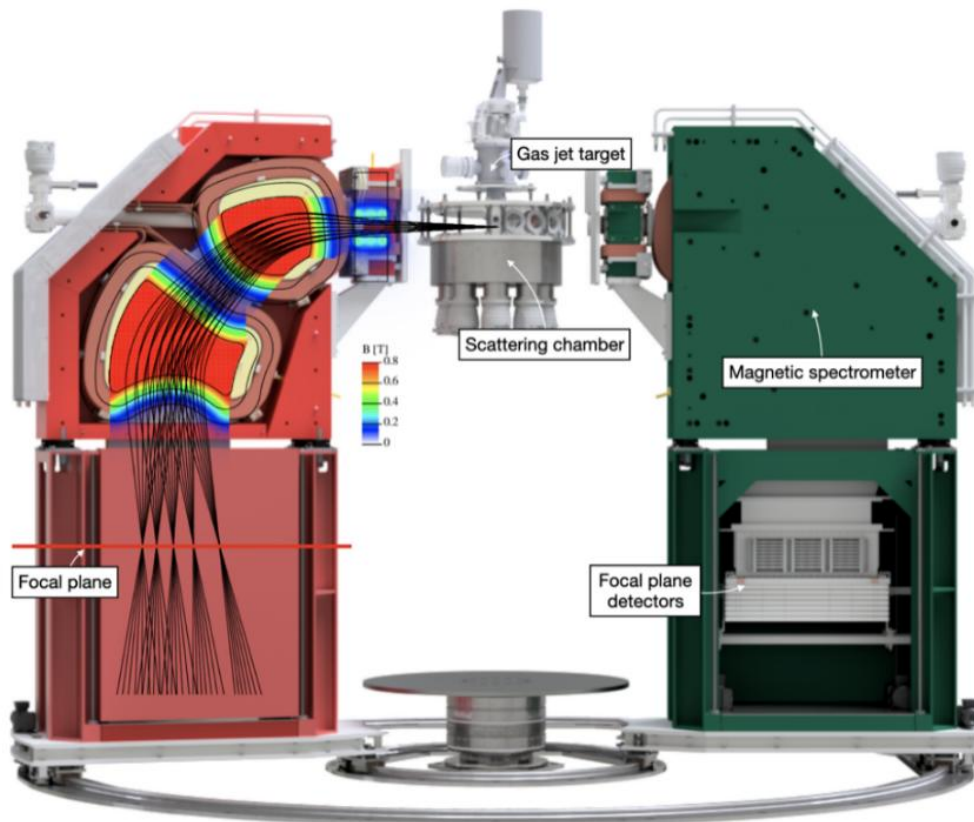
- 2 XFEL cavities tested and installed
- Girders under construction



# MAinz Gas Internal eXperiment MAGIX

Operation of a high-intensity ERL beam in conjunction with internal target

- A novel technique in nuclear and particle physics
- Measurement of low momenta particles with high accuracy
- Competitive luminosities at very low target thicknesses



# Magnet Optics for the QDD Design

## Requirements:

- Momentum resolution:

$$\frac{\delta p}{p} < 10^{-4}$$

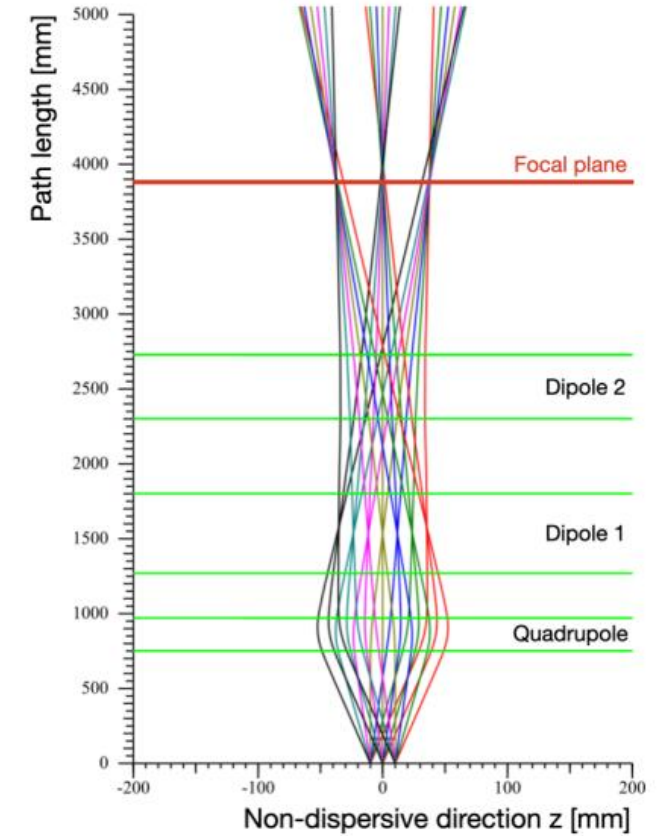
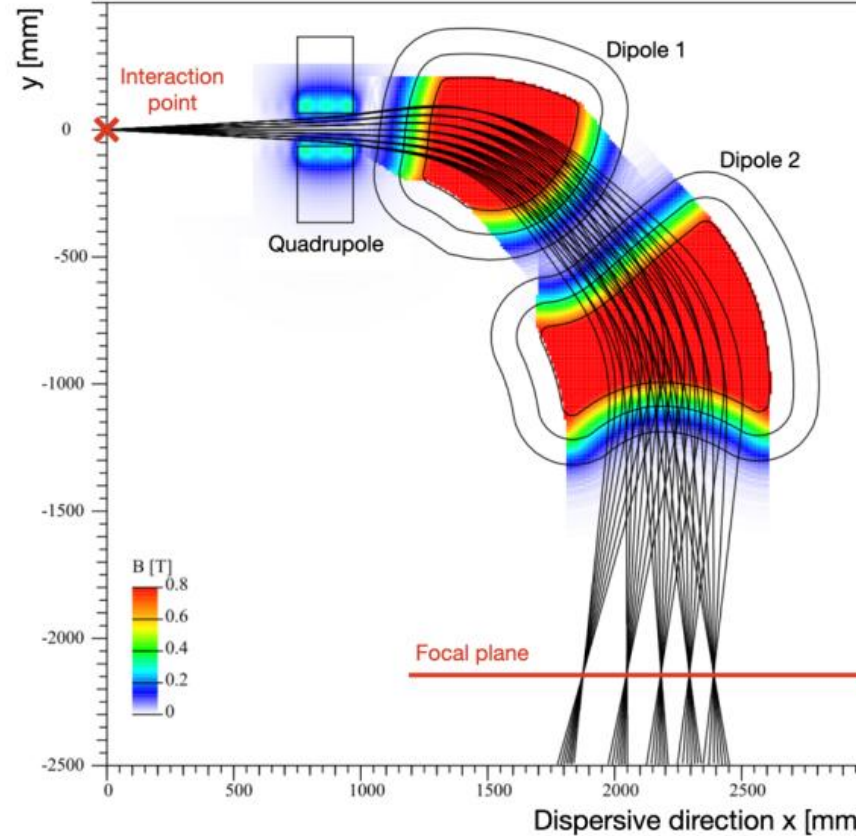
- Angular resolution:

$$\delta\theta < 0.05^\circ$$

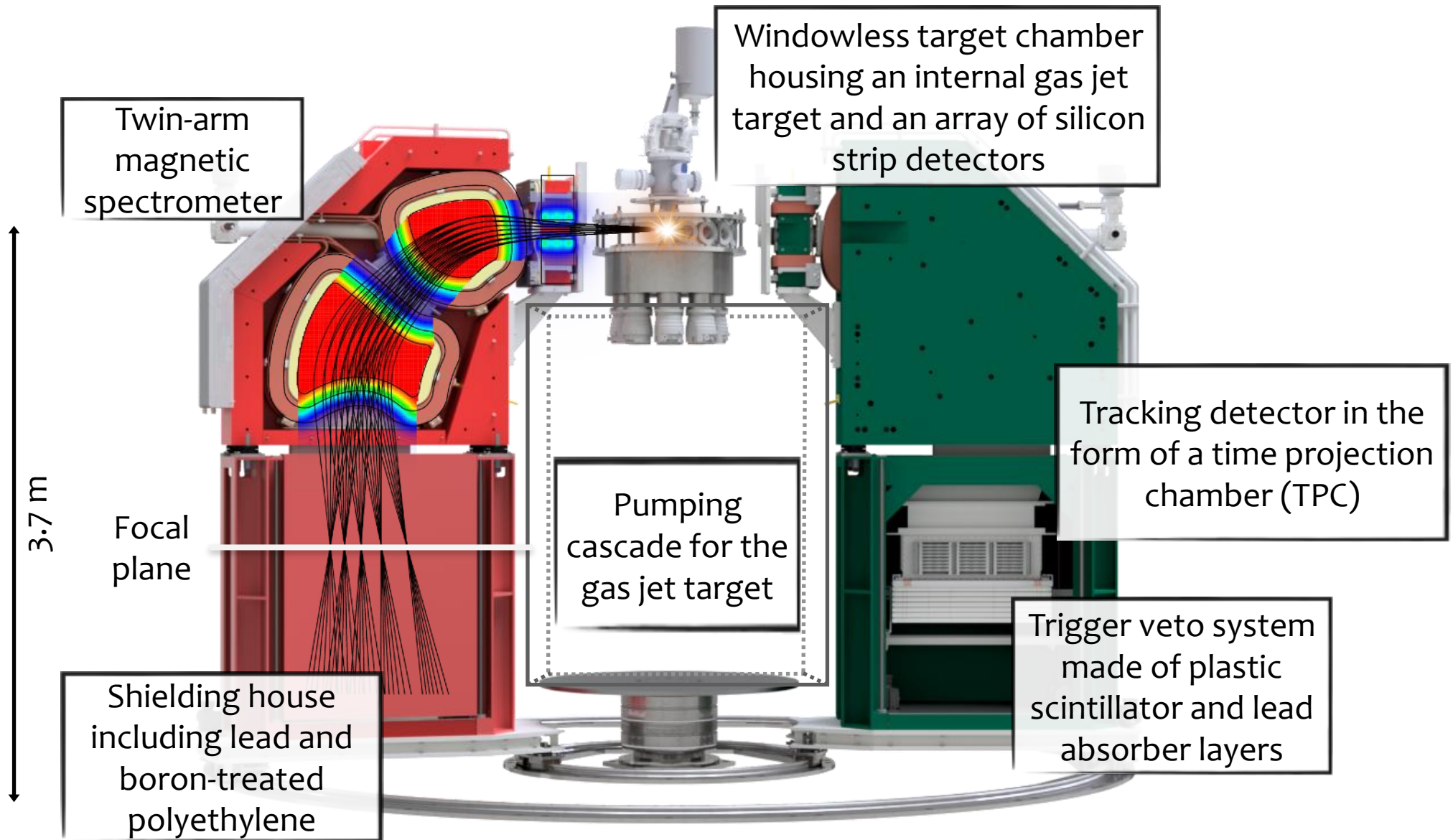
- Precision cross section measurements with two identical spectrometers (**STAR** and **PORT**)

## First-order matrix:

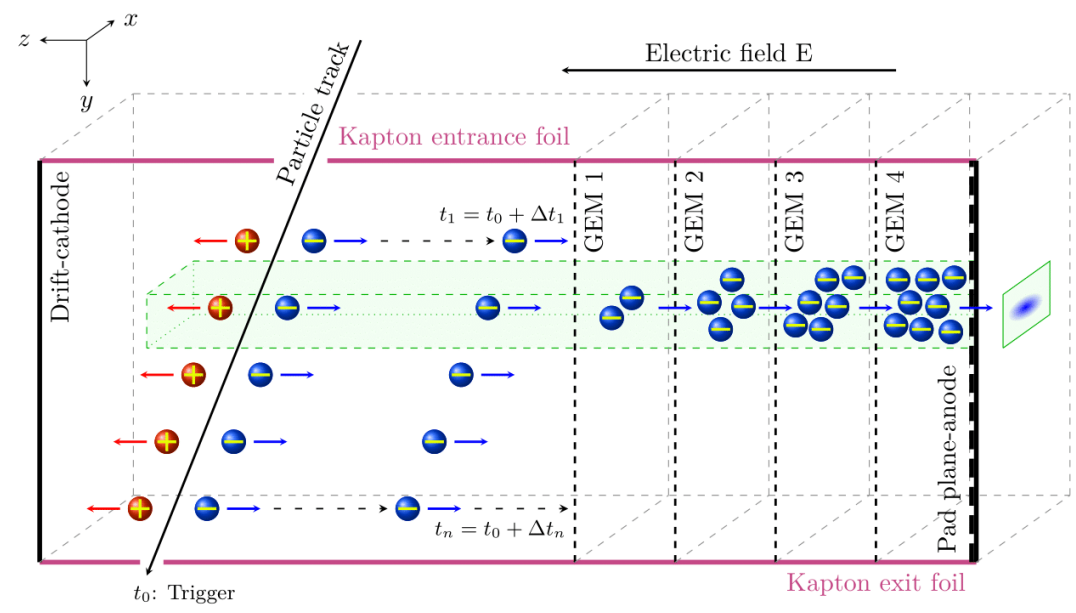
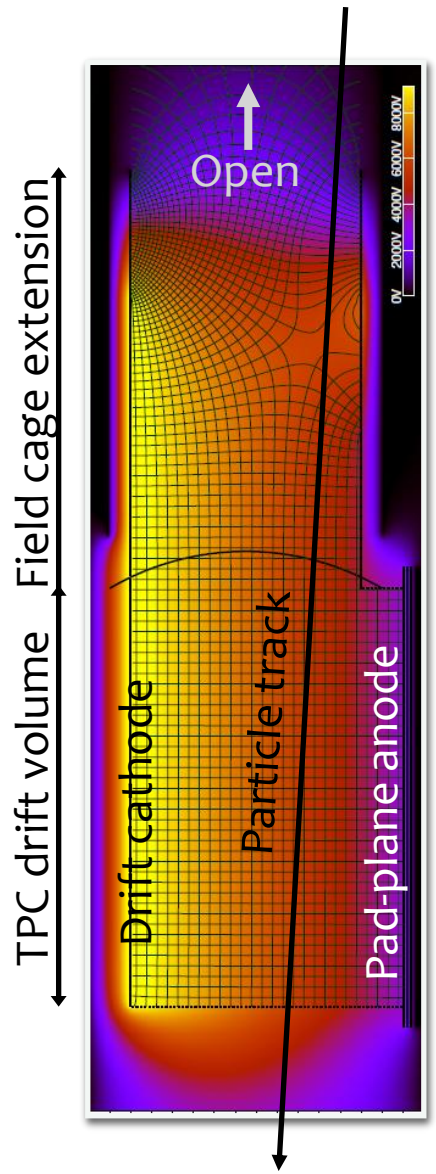
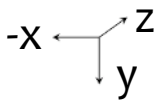
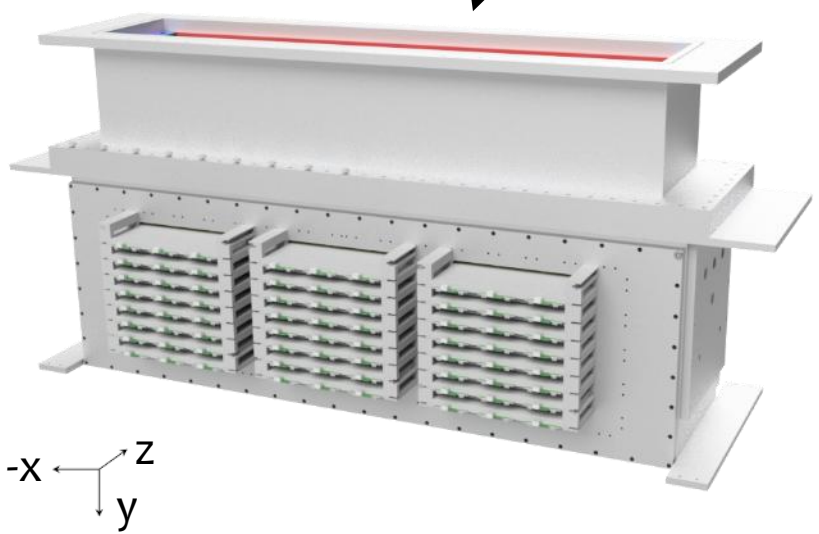
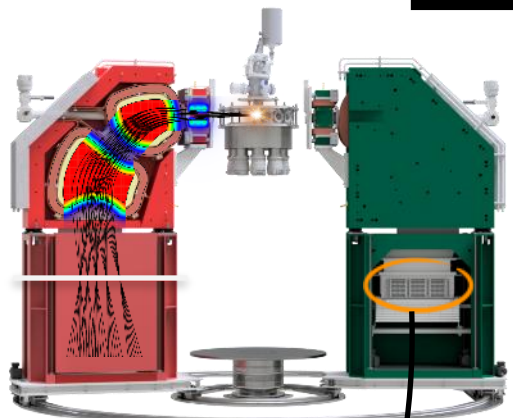
- Point-to-point focus in dispersive direction ( $x|\theta_0$ ) = 0
- Nearly point-to-point focus in non-dispersive direction ( $y|\phi_0$ ) = 0
- Magnification  $M_x \sim -0.5$
- Dispersion  $D \sim 5.5 \text{ MeV/cm}$
- Angular range:  $15^\circ - 165^\circ$
- Momentum range:  $3 - 282 \text{ MeV}/c$
- Accepted solid angle:  $\Delta\Omega = 6 \text{ msr}$



# MAGIX Subsystems

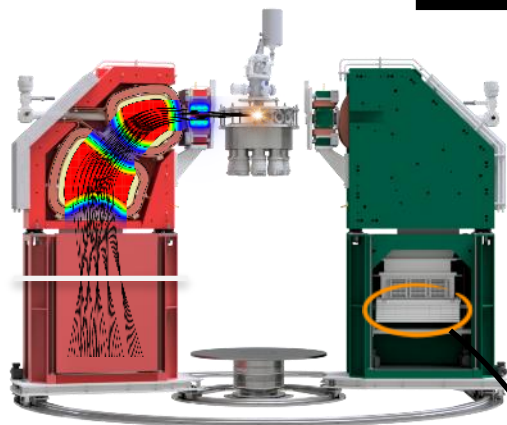


# The MAGIX Time Projection Chamber (TPC)

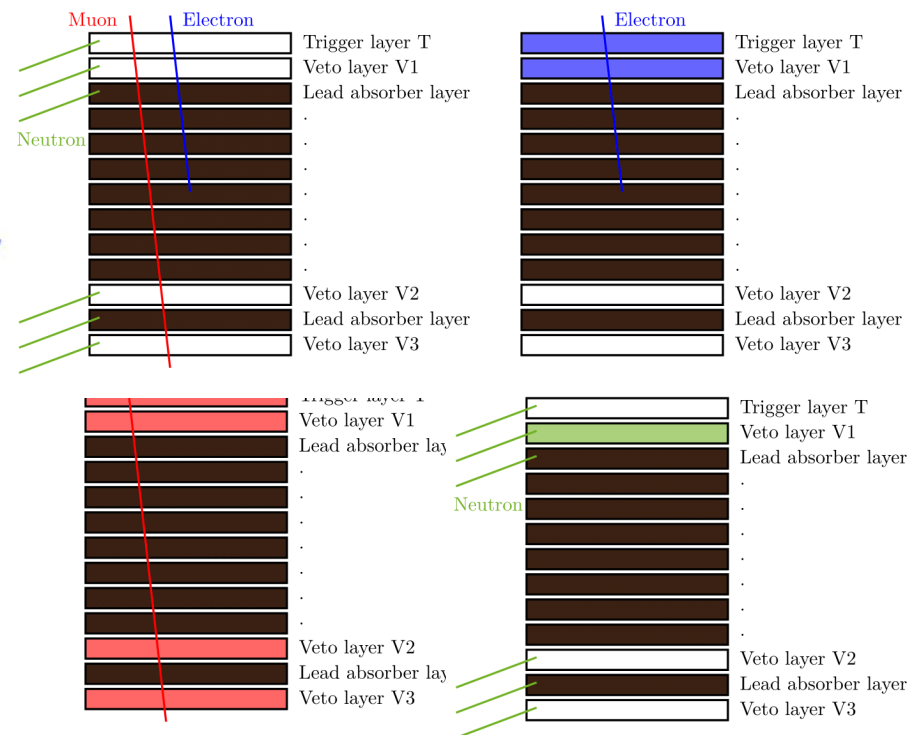
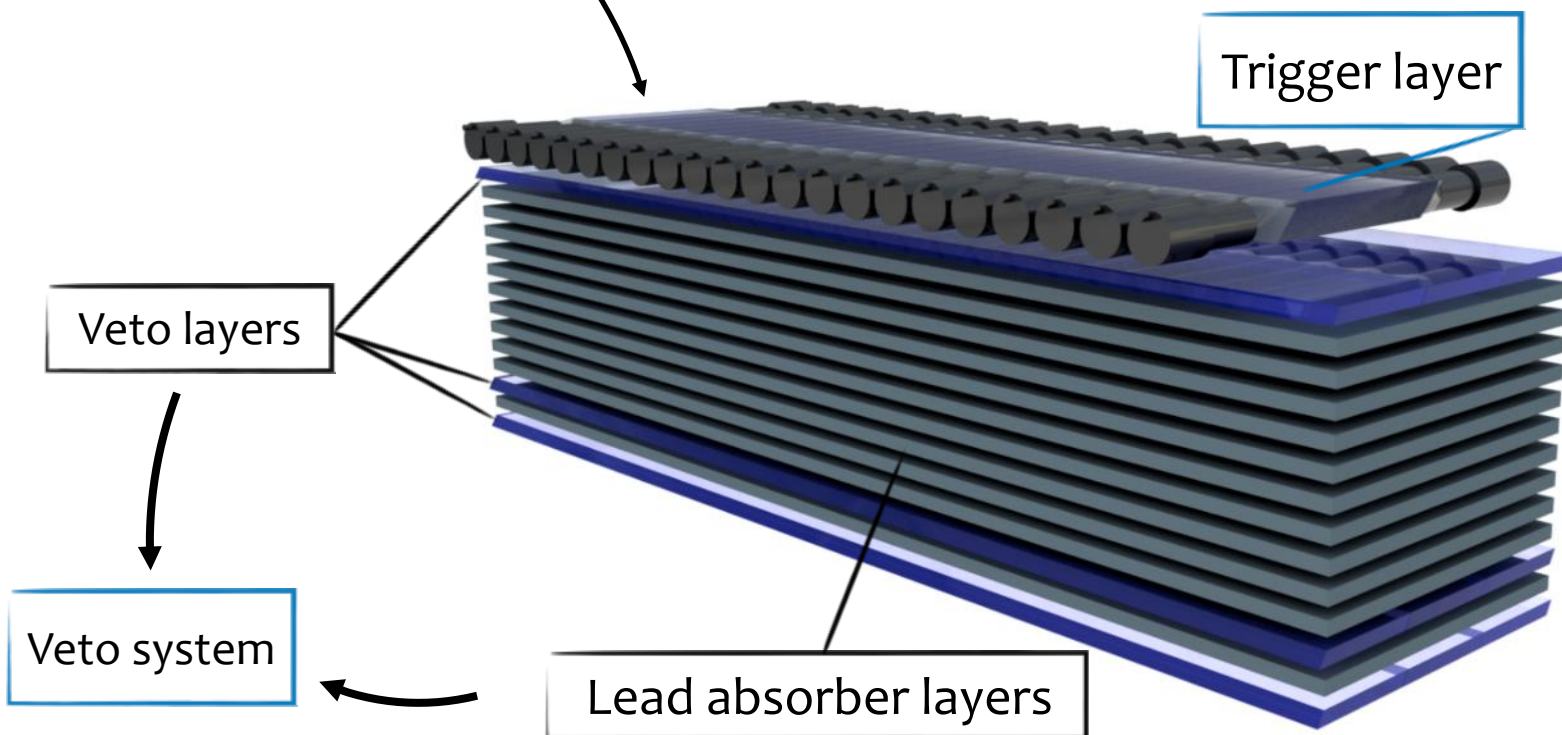


- TPC based on 4 Gas Electron Multipliers (GEMs)
- Segmented readout at pad-plane anode
- Track reconstruction by pad plane plus drift time
- Expected accuracy in focal plane coordinates:  
 $\delta x = 100 \mu\text{m}$  and  $\delta \theta = 3.5 \text{ mrad}$
- Open field cage to minimize the material budget

# The MAGIX Trigger Veto System (TVS)



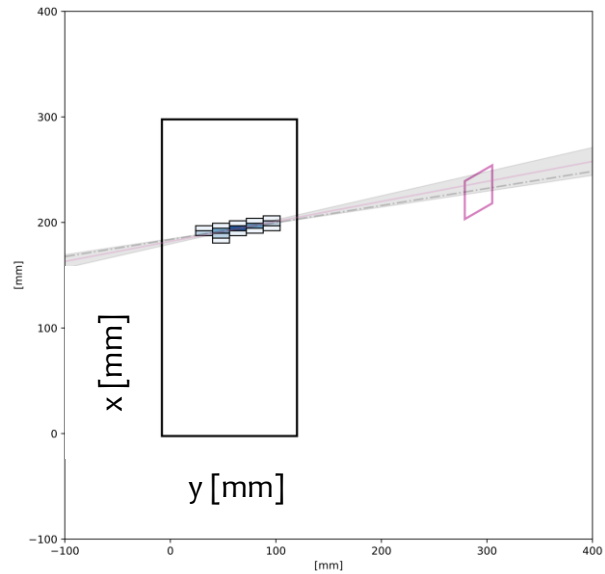
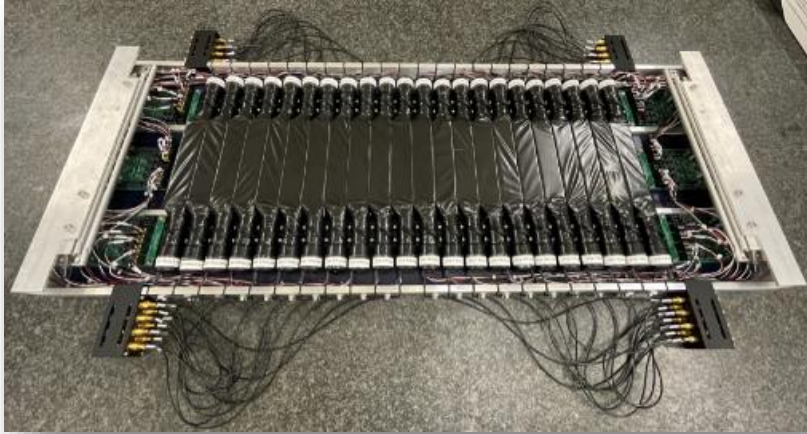
- Triggering and PID in one modular system
- Segmented trigger layer of plastic scintillators read out by 2 PMTs each
- Several veto layers of plastic scintillators read out by SiPMs
- Several passive lead absorber layers in between



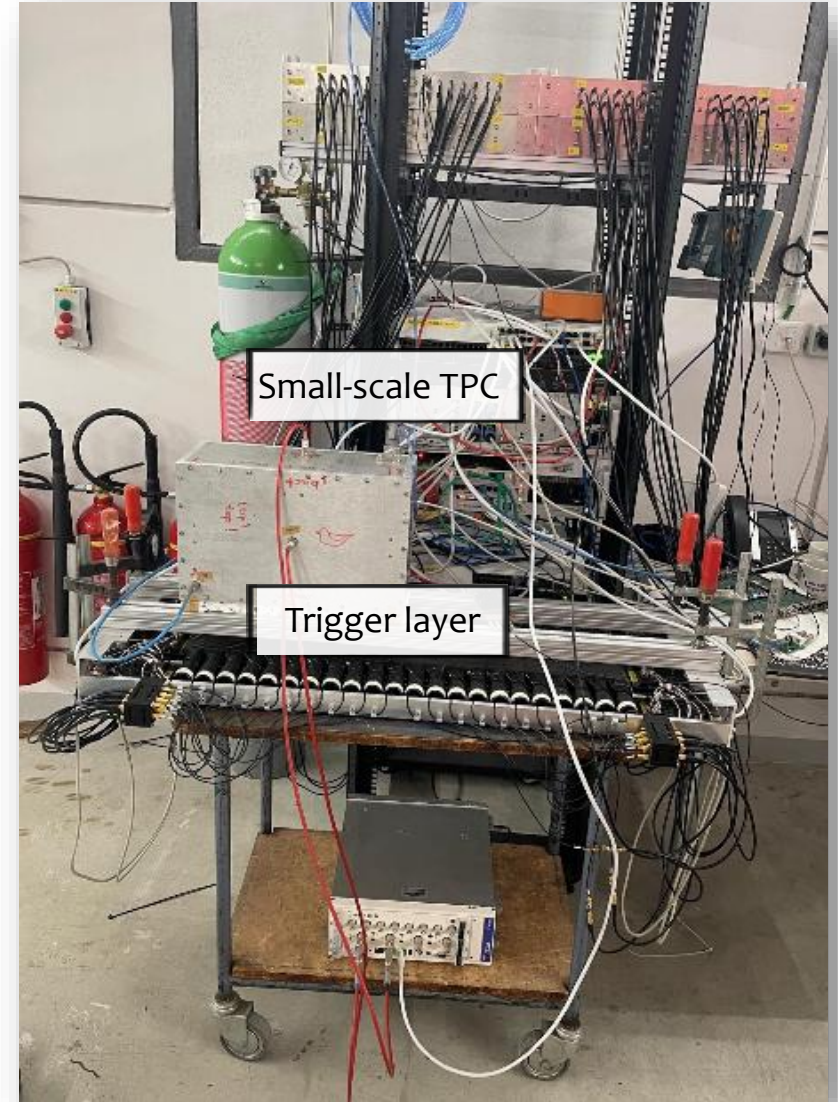
# Status of MAGIX Subsystems

## Detectors:

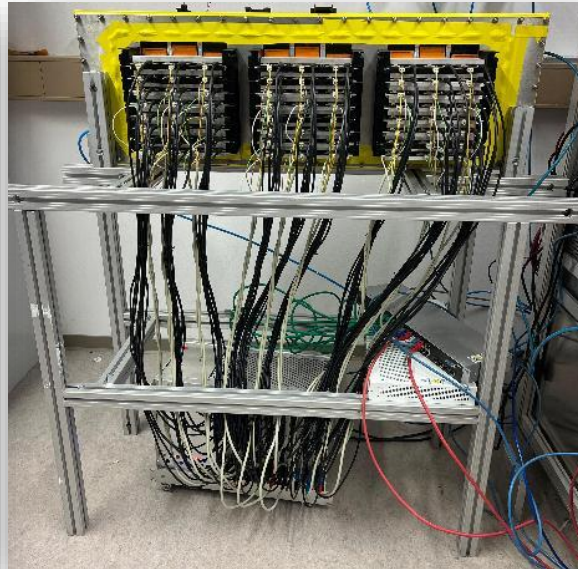
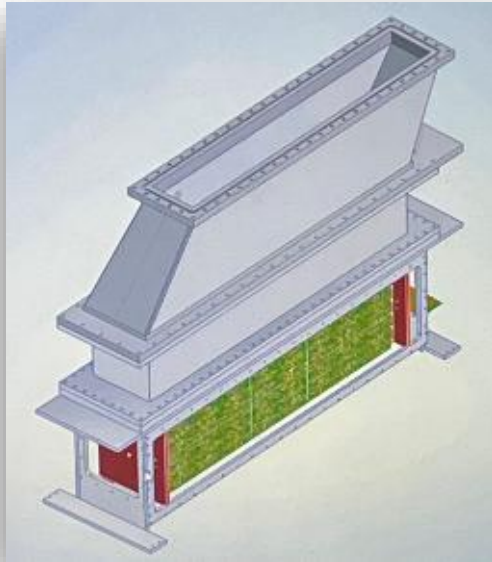
### Trigger layer



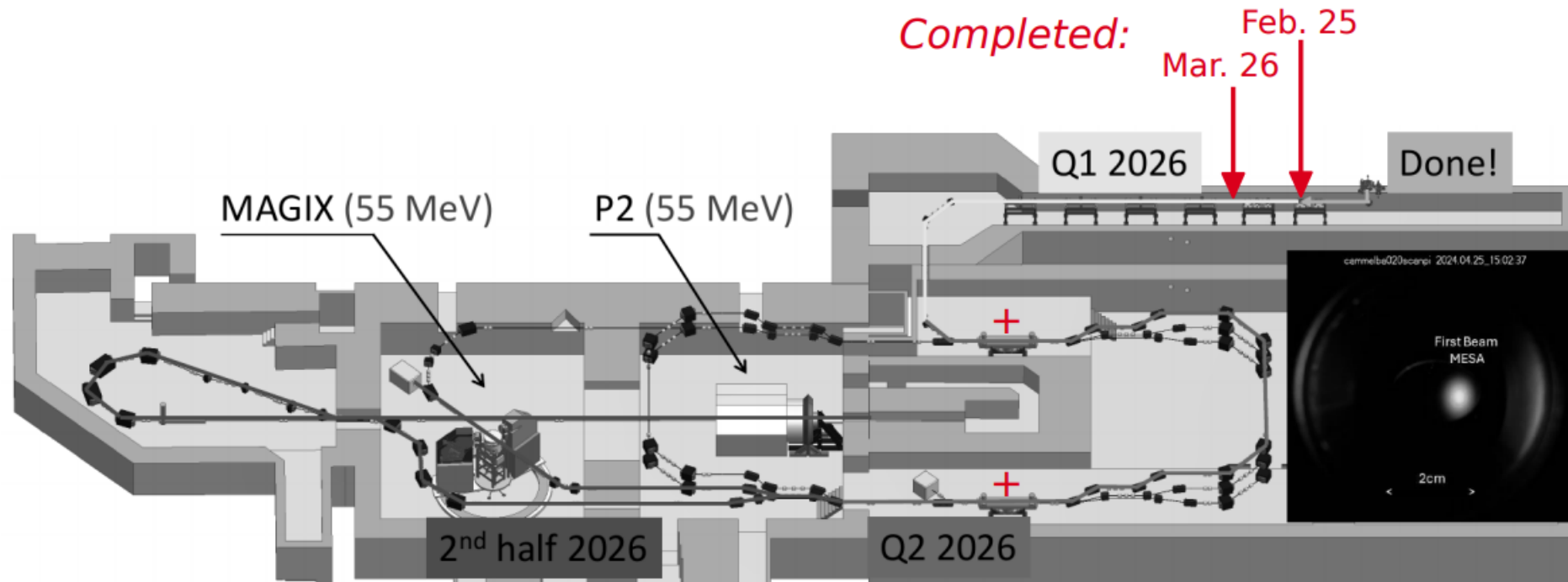
### Combination of trigger with TPC



### TPC



# MESA Commissioning Schedule



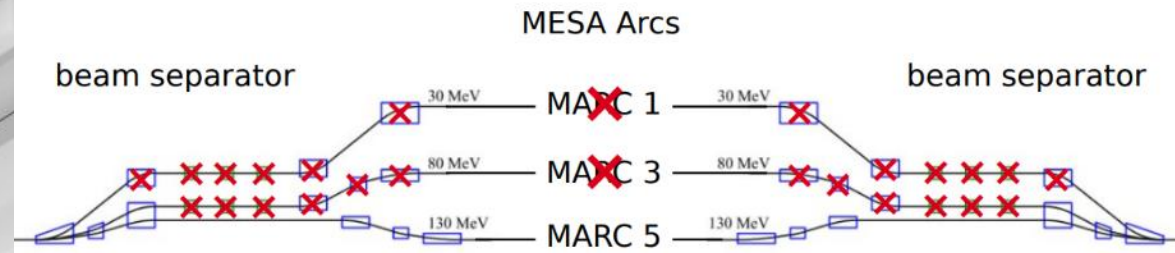
- **Staged approach:**

- June 2027: first MESA beam at 55 MeV, unpolarized, 1  $\mu$ A
- September 2027: first extracted beam to MAGIX
- November 2027: first extracted beam to P2

# MESA First Stage Operation

Significant simplification for  
55 MeV (EB) possible

MARCO  
MARC1  
MARC2  
MARC3  
MARC4  
MARC5  
MAGIX-ARC  
P2-ARC

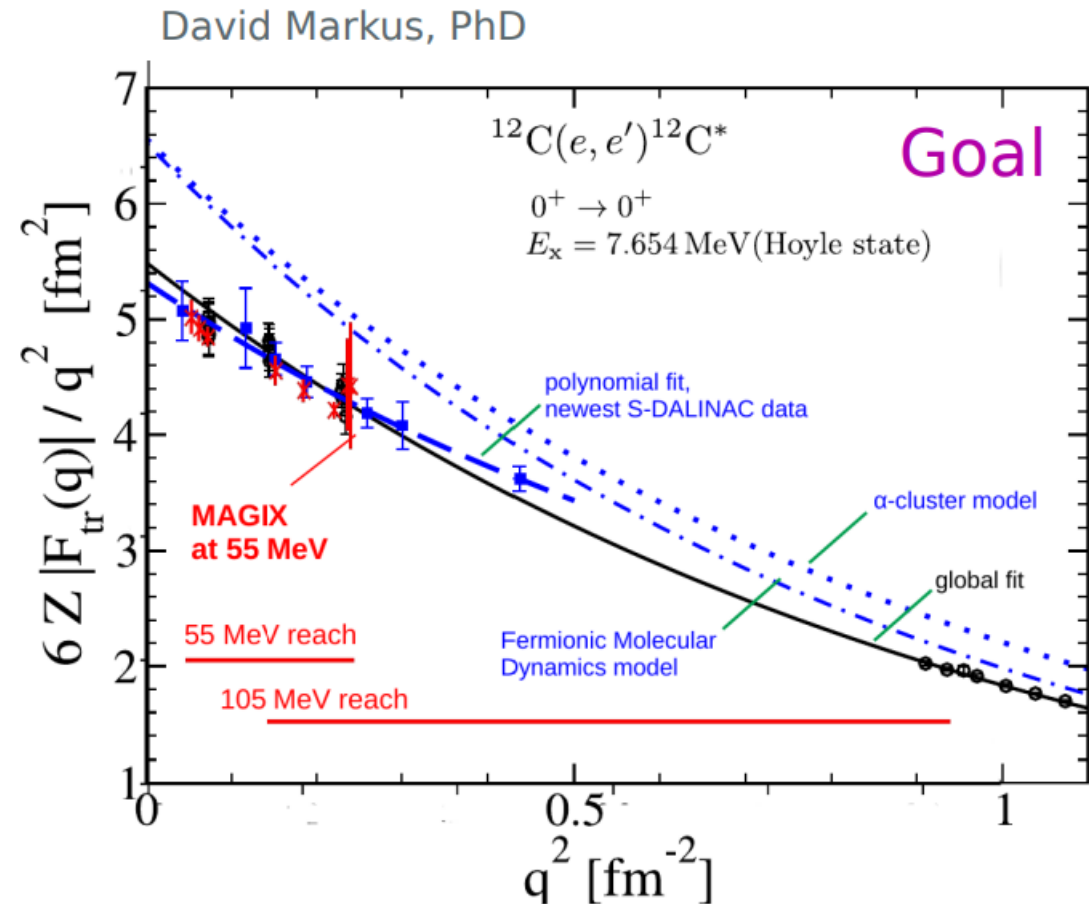


- No energy-recovery mode
- No recirculation
- Low beam availability
- Limited beam control

# Consequences for MAGIX Operation

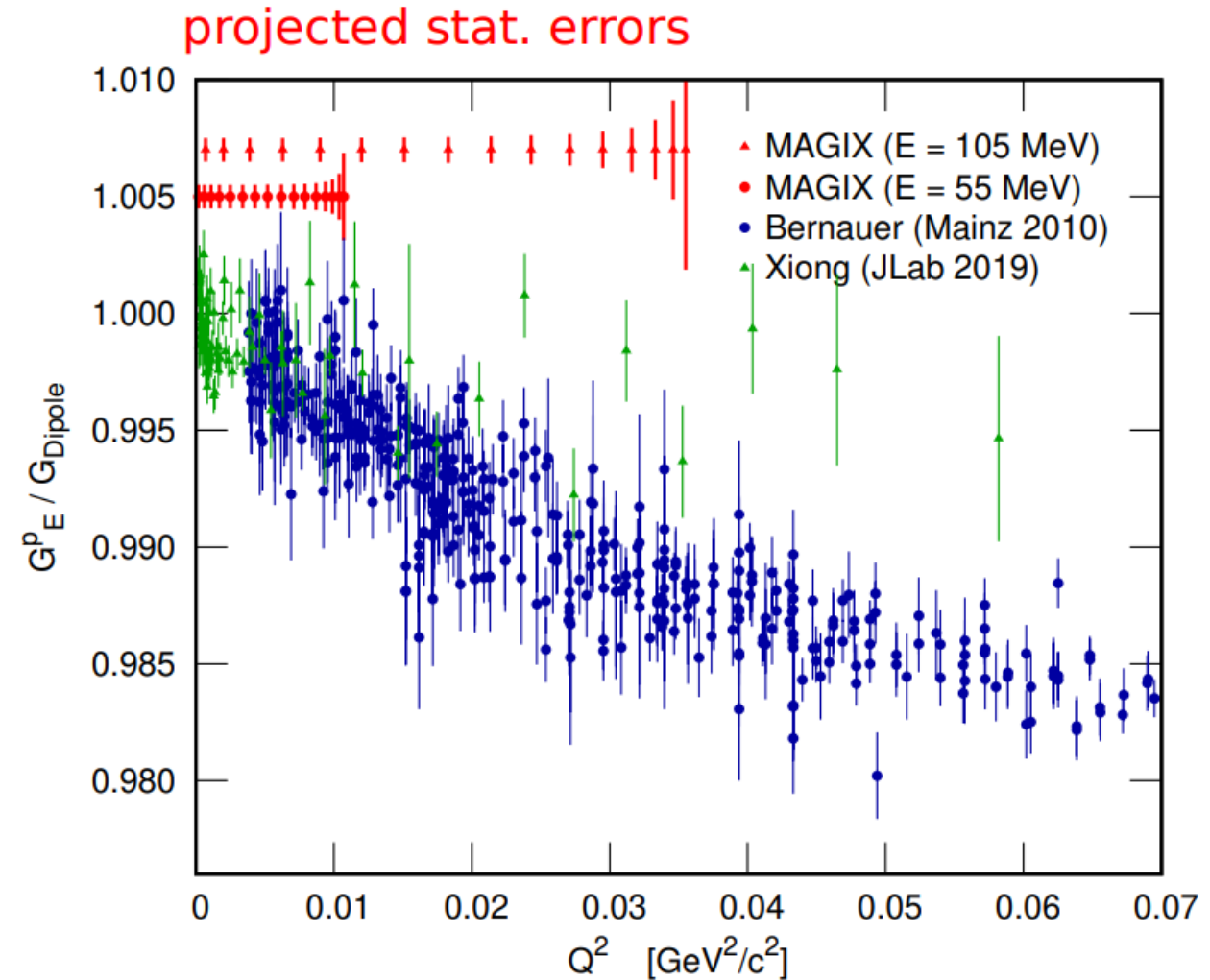
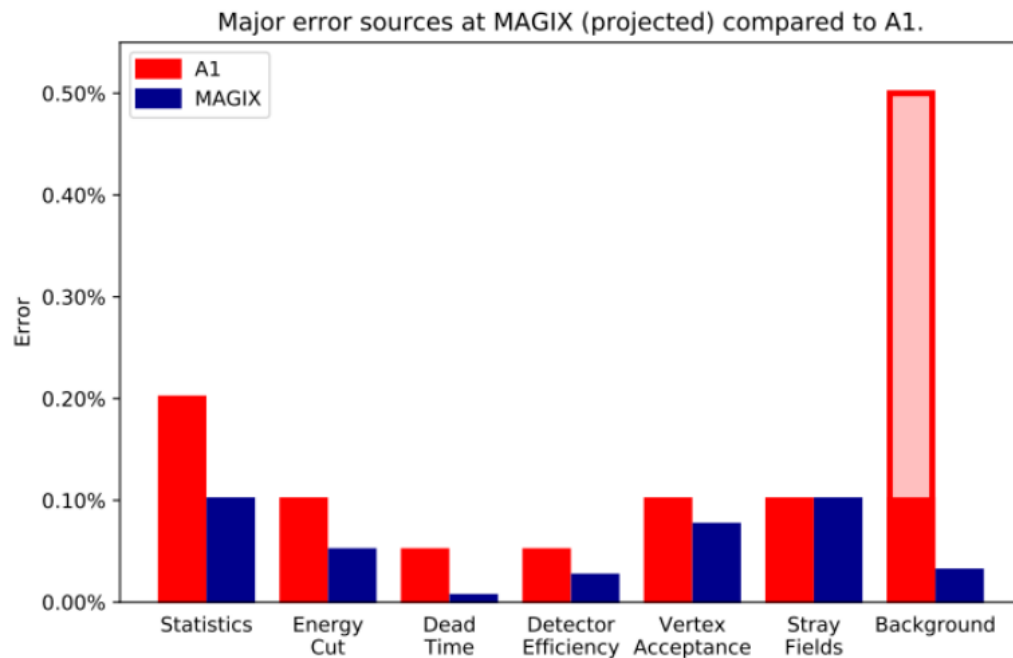
- **No energy-recovery mode** → No gas-jet target
  - Solid state target: Simpler handling
  - Luminosity independent of hit position
  - Reduced instrumentation demands
- **No recirculation** → No FF separation etc.
  - Reduced experimental complexity
- **Low beam availability** → Need for short experiments
  - More time for analysis
- **Limited beam control**

- **First experiment** :  $^{12}\text{C}$  Hoyle state transition form factor measurement at low  $Q^2$



# Projection of $G_E$ Form Factor Measurements

- 55 MeV beam energy
- Unpolarized measurement
- $Q^2$  coverage from  $10^{-5}$  to  $10^{-2}$  GeV<sup>2</sup>
- Dominated by systematic error



## Electron scattering experiments in Mainz:

- Continuation of **experiments with MAMI**
- Preparation of **experiments with MESA**
  - Building upon a newly constructed low-energy accelerator
  - Building upon a newly constructed high-precision spectrometer setup

Operation of a gas-jet target in combination with  
high-intensity beams and high-resolution spectrometers