Future Perspectives for Electron Scattering Experiments with MESA

"Particle accelerators are among the most useful tools for research in nuclear physics and in high-energy particle physics […] Fundamental questions can be asked of nature, and answered by experiments […]. The field of high-energy particle physics is on the threshold of a significant breakthrough in our understanding of the particles of nature and the origins of the nuclear force."

[Stanley Livingston, *Particle Accelerators: A Brief History*, Harvard University Press, Cambridge, Mass. (1969)]

Patrick Achenbach

JGU Mainz

July 2026

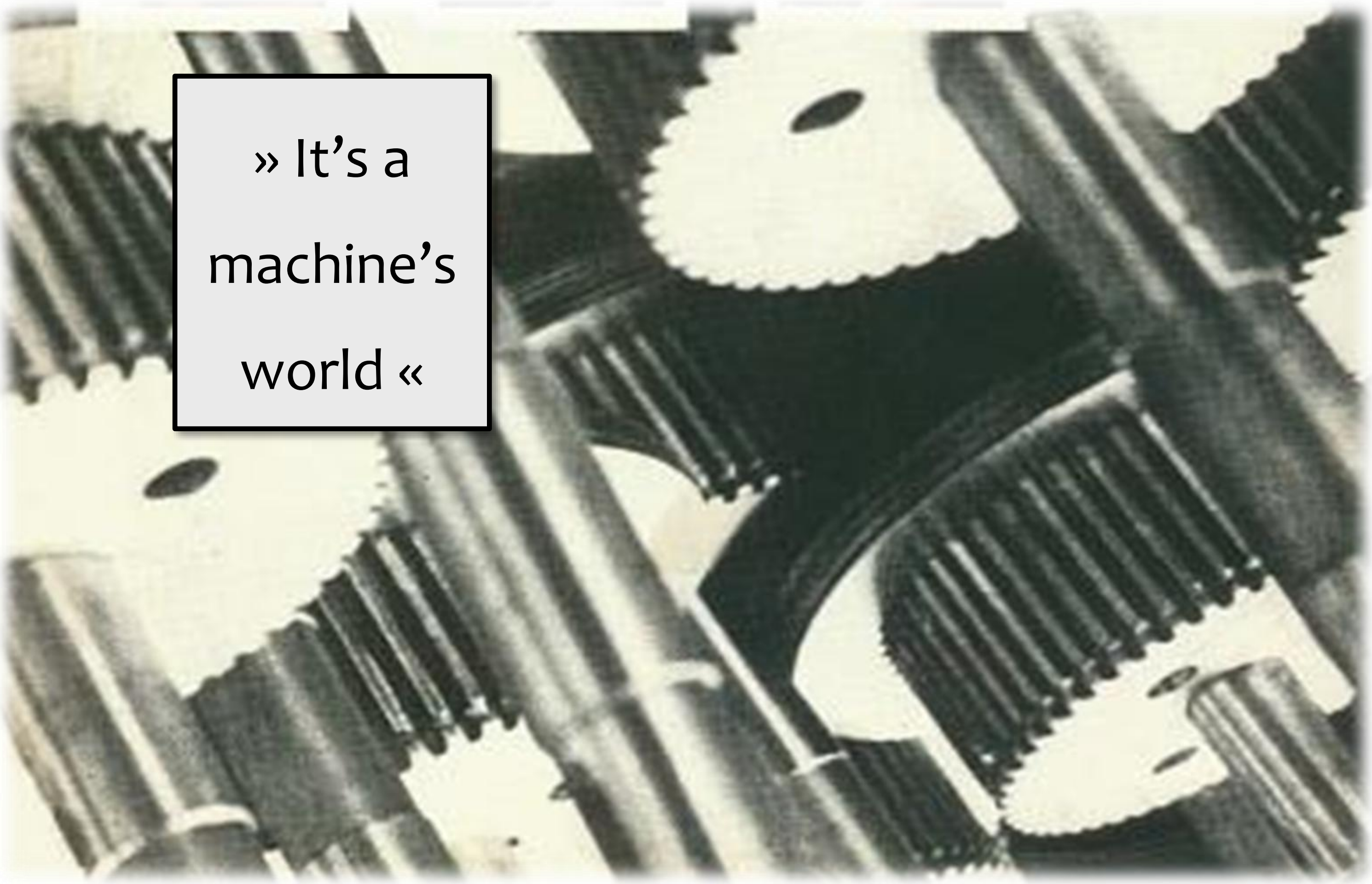
» It’s a Machine’s World «

Short History of Electron Scattering Experiments in Mainz

- **Mainz University Electron Linac**
  - Pioneering Experiments
- **Mainz Microtron** (MAMI)
  - Experiments by the A1, A2, A3 and A4 Collaborations

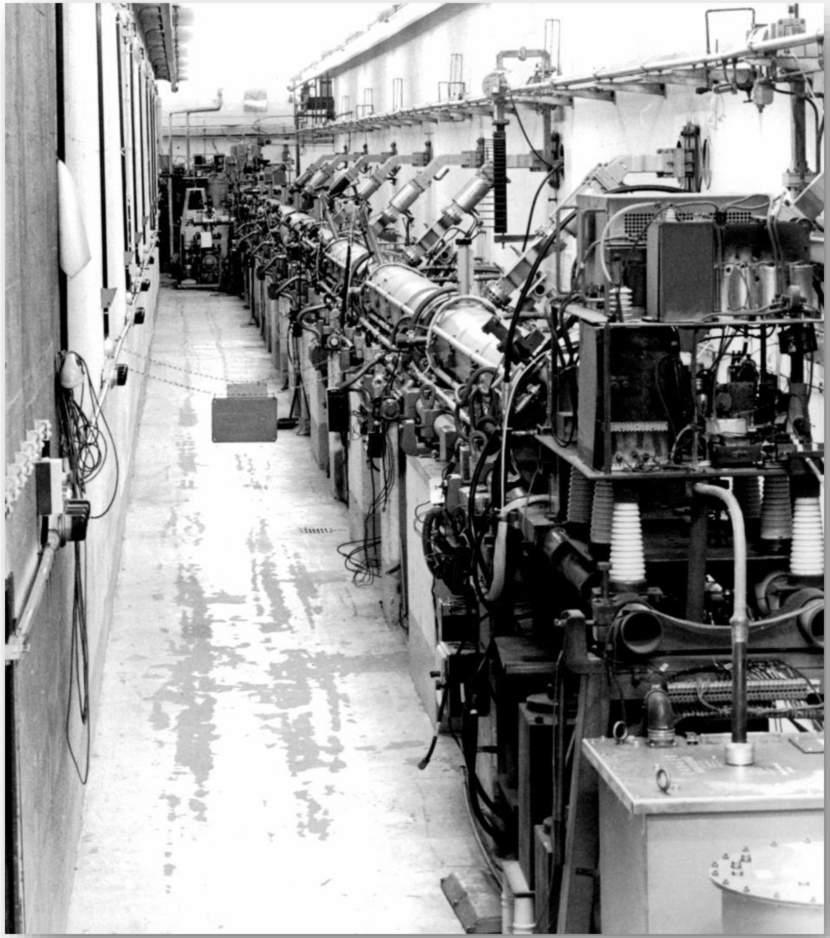
Future of Electron Scattering Experiments in Mainz

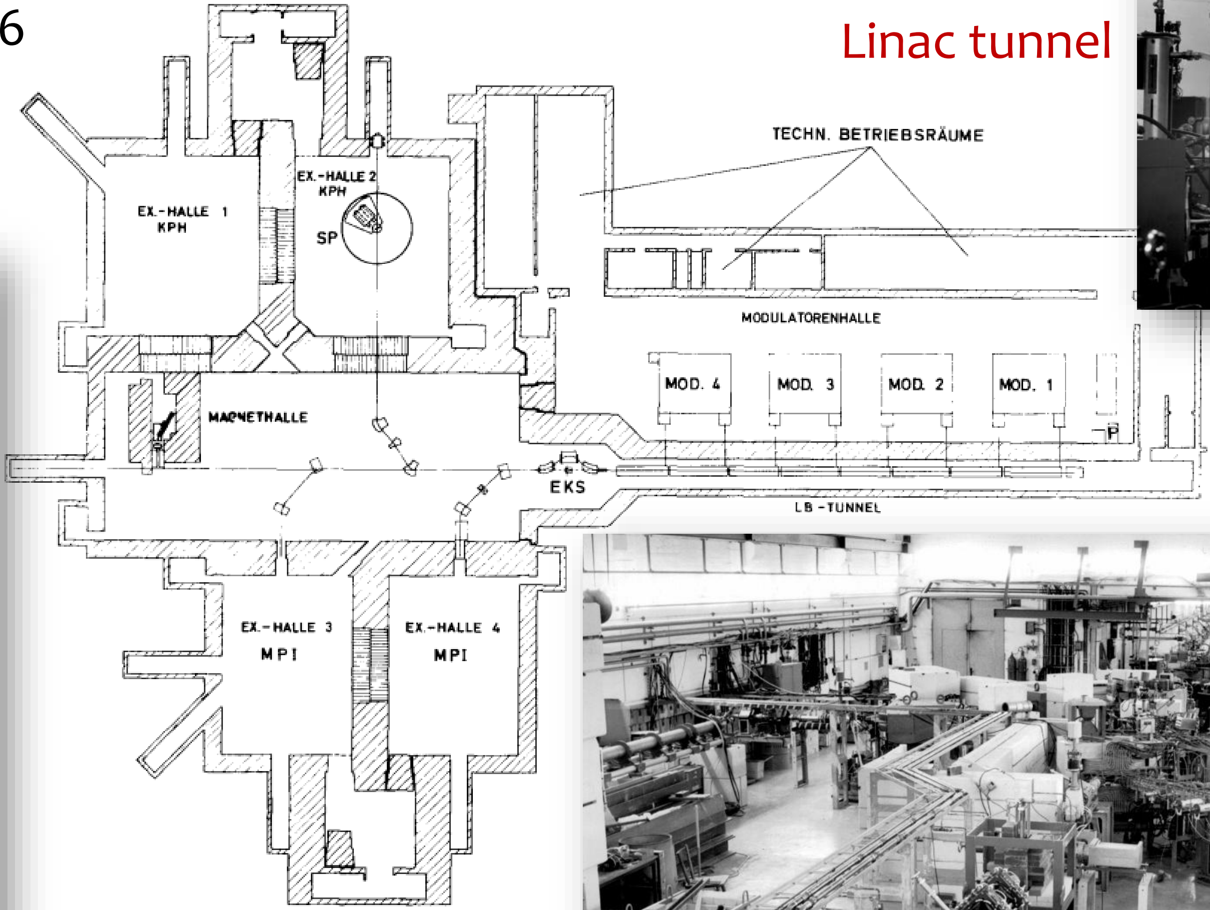
- **Mainz Energy-Recovering Superconducting Accelerator** (MESA)
  - Experiments by the MAGIX and P2 Collaborations


» It’s a machine’s world «

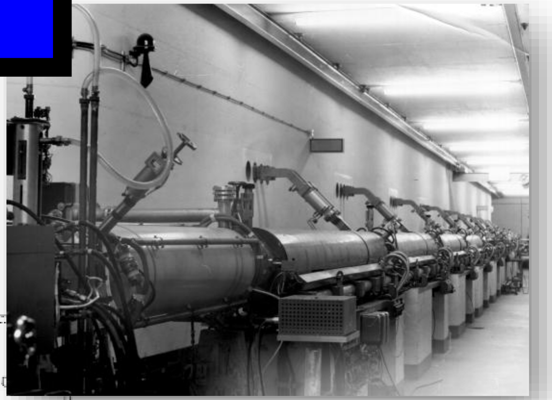
The Mainz Electron Linac

- Installed & commissioned 1964–66
- 320 MeV, 80–300 MeV beamlines
- Experiments 1968–1989





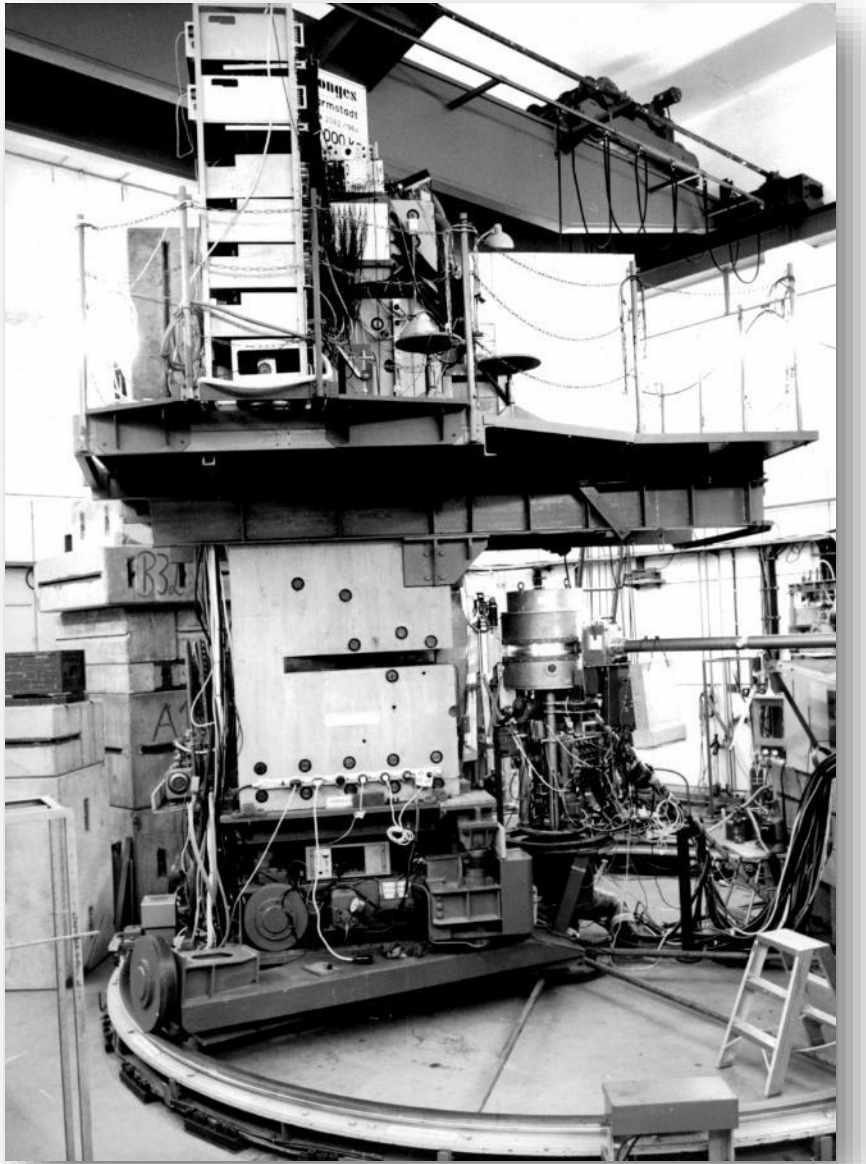
Linac tunnel

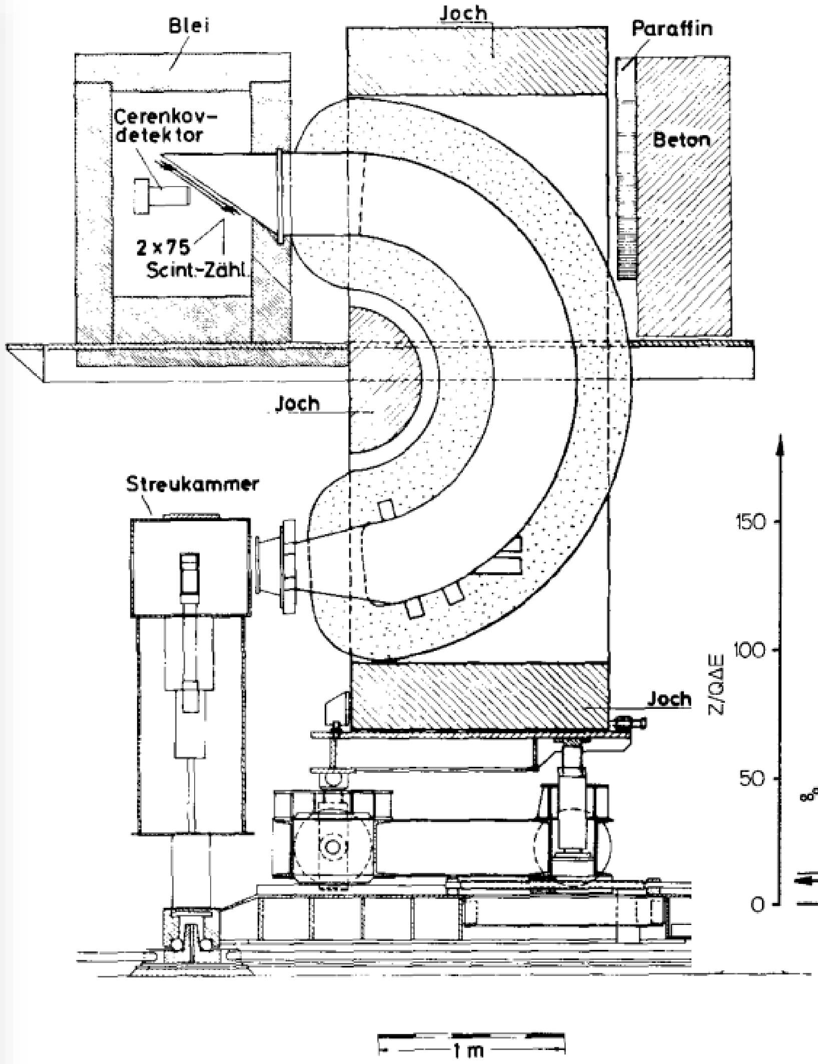


Linac tunnel

Magnet hall, later known as tagger hall

The 180° Spectrometer at the Mainz Electron Linac

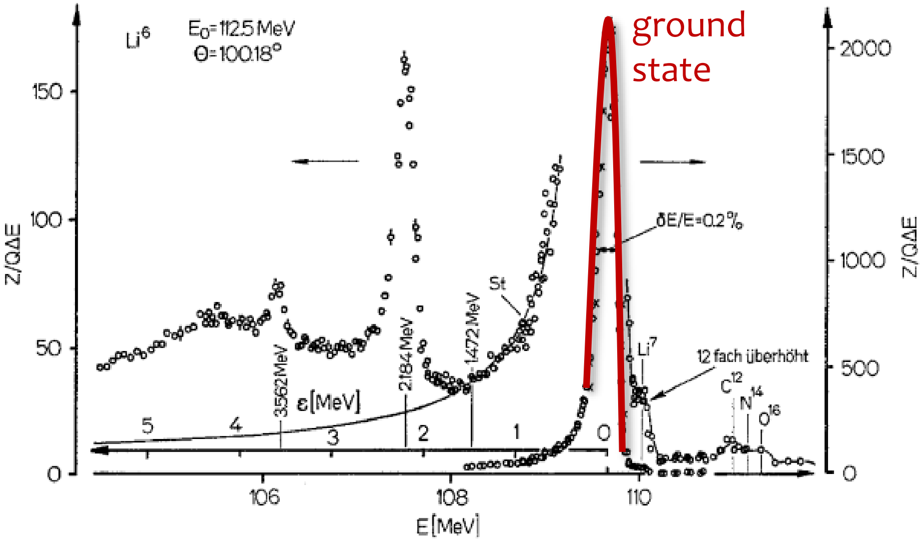




[H. Ehrenberg, NIM 105, 253 (1972)]

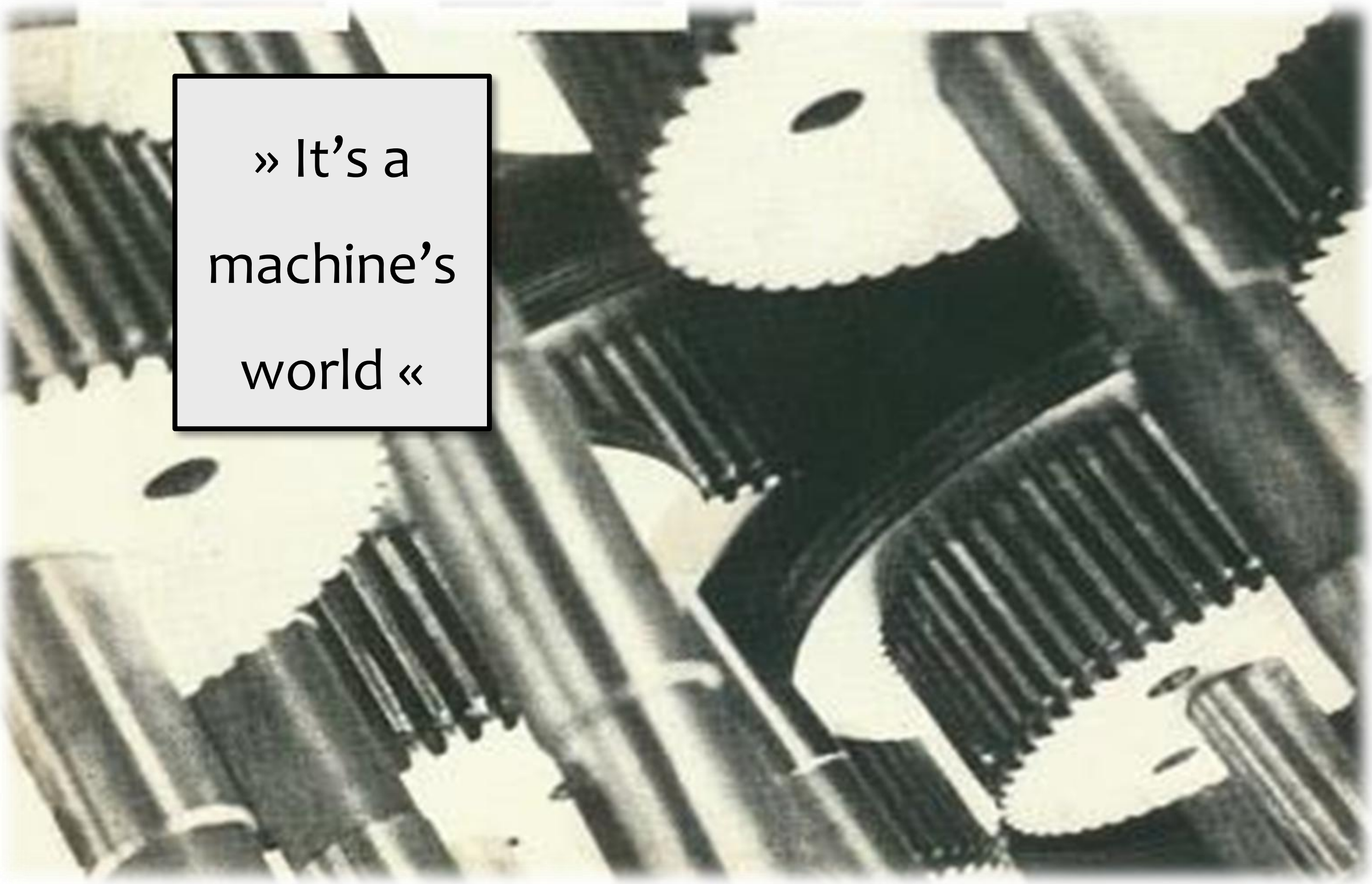
Momentum acceptance $\Delta p/p$ = 7%
Momentum resolution = 3 x 10^{-4}
Accepted solid angle $\Delta\Omega$ = 6 msr

^{6}Li electro-excitation spectrum:



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

MAMI and Experiments



The Mainz Microtron MAMI

MAMI-A:

1983–87: *Van-De-Graaff +*
2 *Race Track Microtrons*
E_0 = 183 MeV

MAMI-B:

Since 1990: Linac + 3 *Race Track Microtrons*
E_0 = 180 … 883 MeV
Energy spread ΔE = 13 keV
Energy stability ΔE = 100 keV
(long-term drifts over 1 week)
ε_x = 9 µm mrad, ε_y = 0.5 µm mrad
Beam current max. 100 µA c.w.

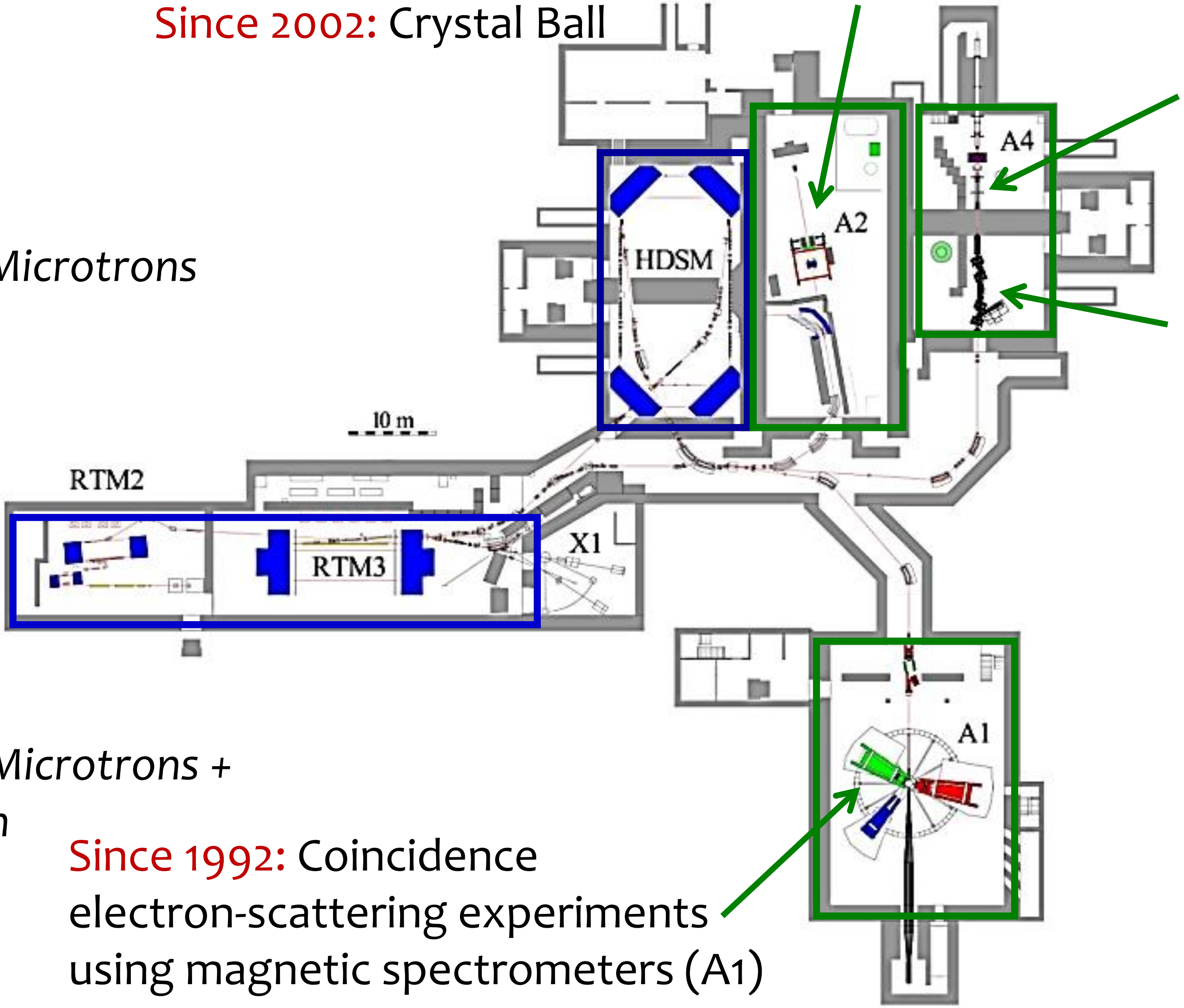
MAMI-C:

Since 2007: Linac + 3 *Race Track Microtrons* +
Harmonic Double-Sided Microtron
E_0 up to 1604 MeV

Since 1991: Photon beam experiments (A2)
Since 2002: Crystal Ball

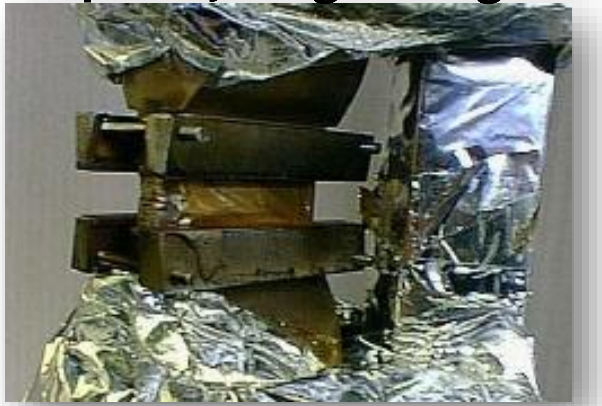
2000–12: Parity violating electron scattering experiments (A4)

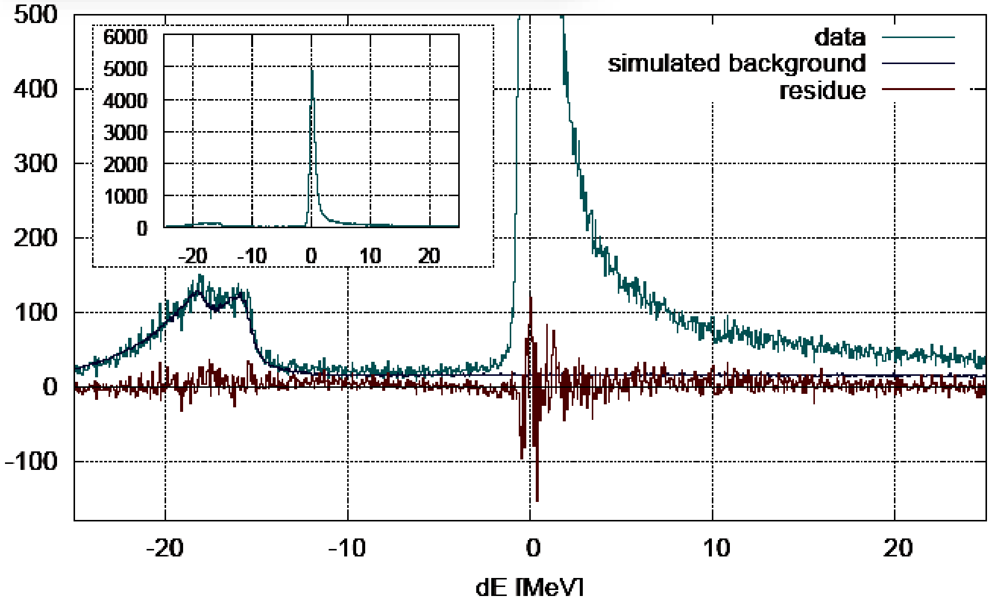
1992–95: Polarized electron beam experiments (A3)



Since 1992: Coincidence electron-scattering experiments using magnetic spectrometers (A1)

Liquid hydrogen target:





- Subtraction of **cell window contribution**

Gas-jet target:

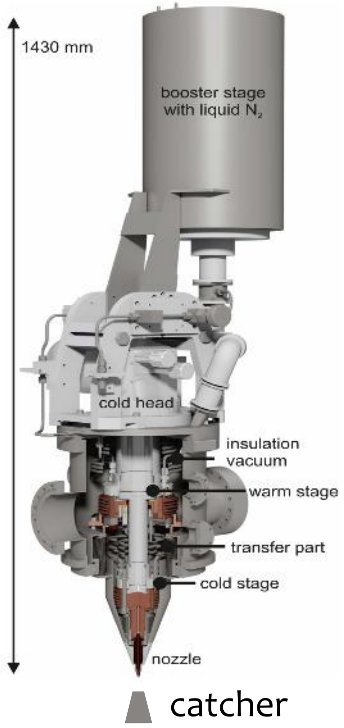
- **Windowless, thin, point-like** jet target
- Operated with **hydrogen** and argon

Ultimate precision in elastic scattering

P. Brand

Argon gas jet

D. Bonaventura

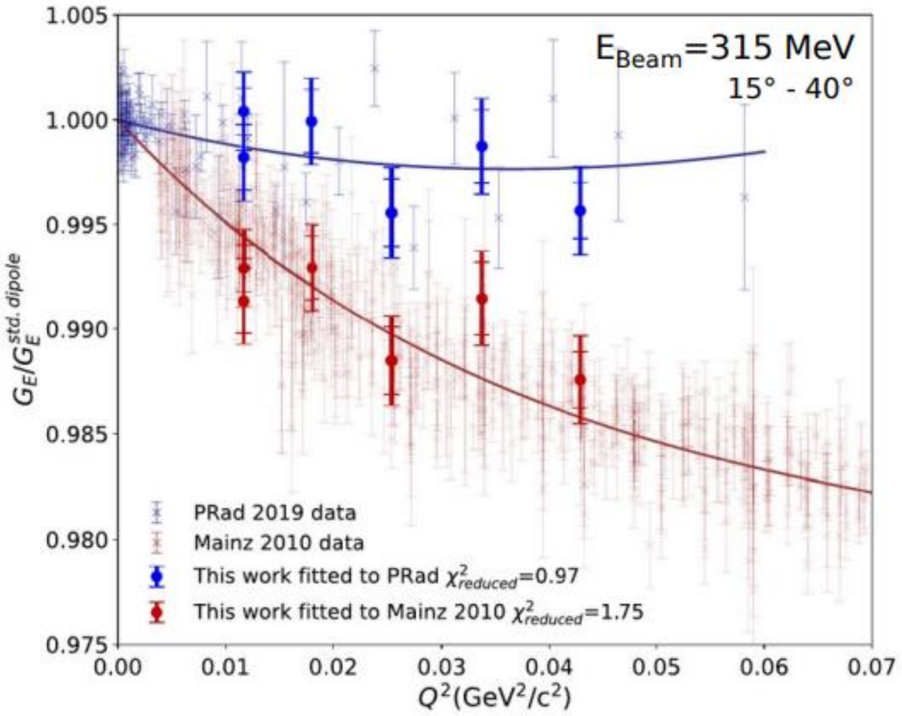


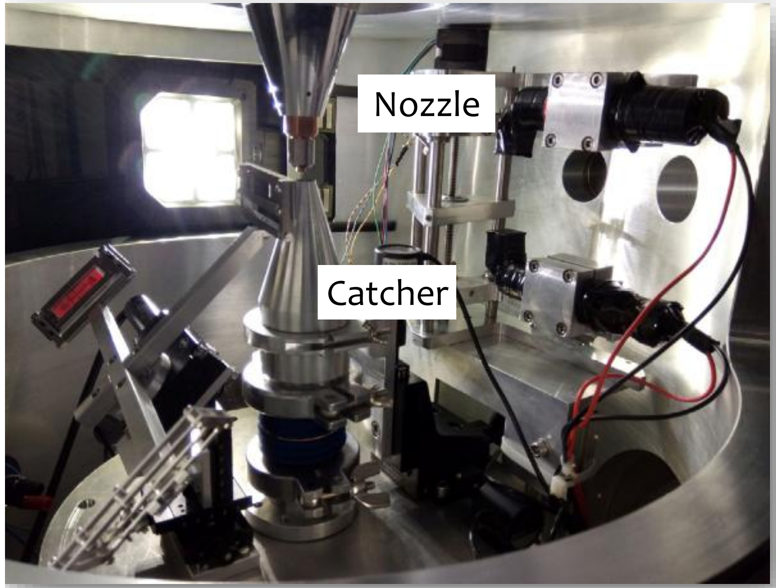
catcher
to pumping station

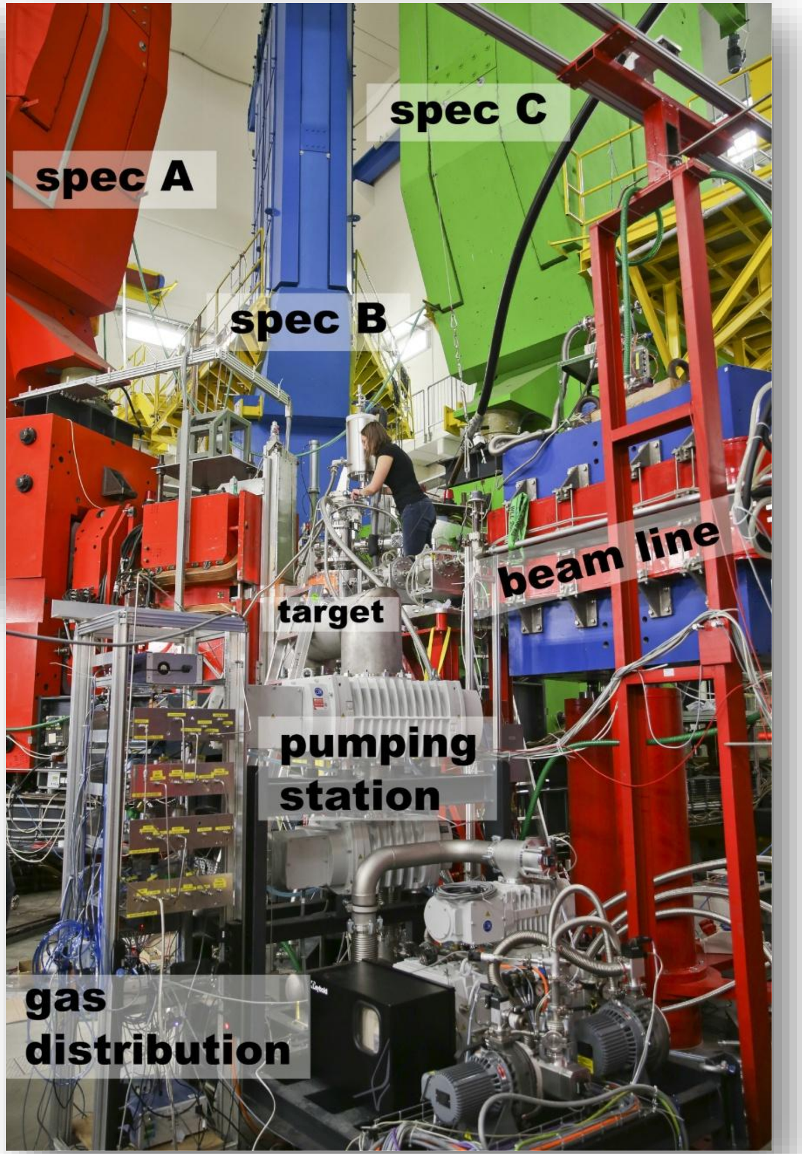
- Windowless design
- Supersonic gas jet
- Gas density $O(10^{19}/cm^2)$
- H_2, ^4He, O_2, …, Ar
- Luminosity $O(10^{35}\ cm^{-2}\ s^{-1})$ at gas thickness of $10^{19}/cm^2$

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

Proton Electric Form Factor Measurement







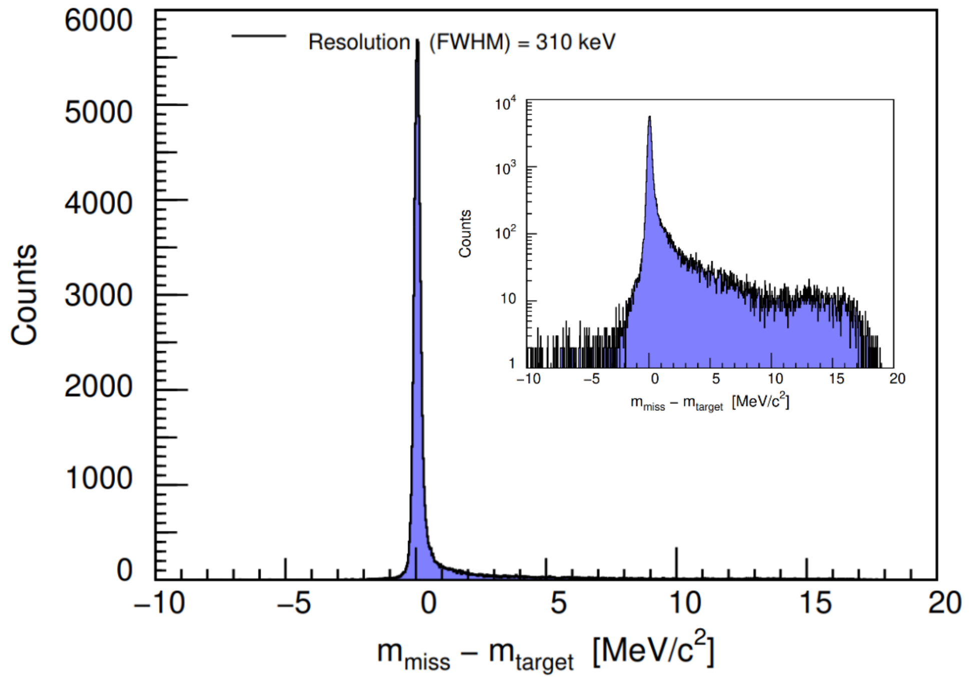
- **Statistically limited** because of low target density
- One beam energy only
- No absolute normalization
- Compatible with PRAD 2019 data and Mainz 2010 data

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

Hydrogen Gas-Jet Target in Filament Mode

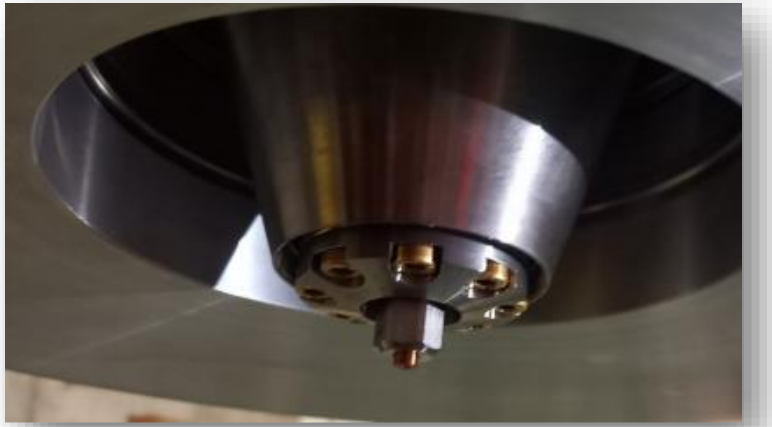
Latest beamtime June 2026

- Hydrogen target in filament mode operation
- Signal/background ratio > 10^3

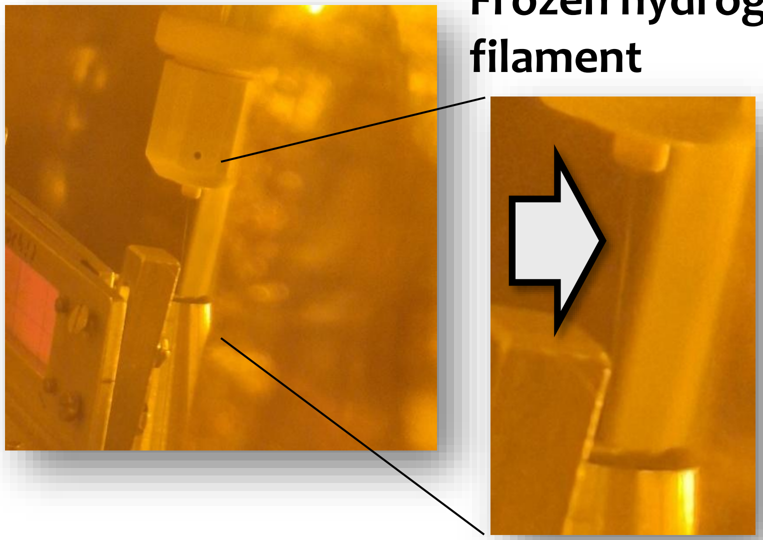


Operation of this target will be continued at MESA

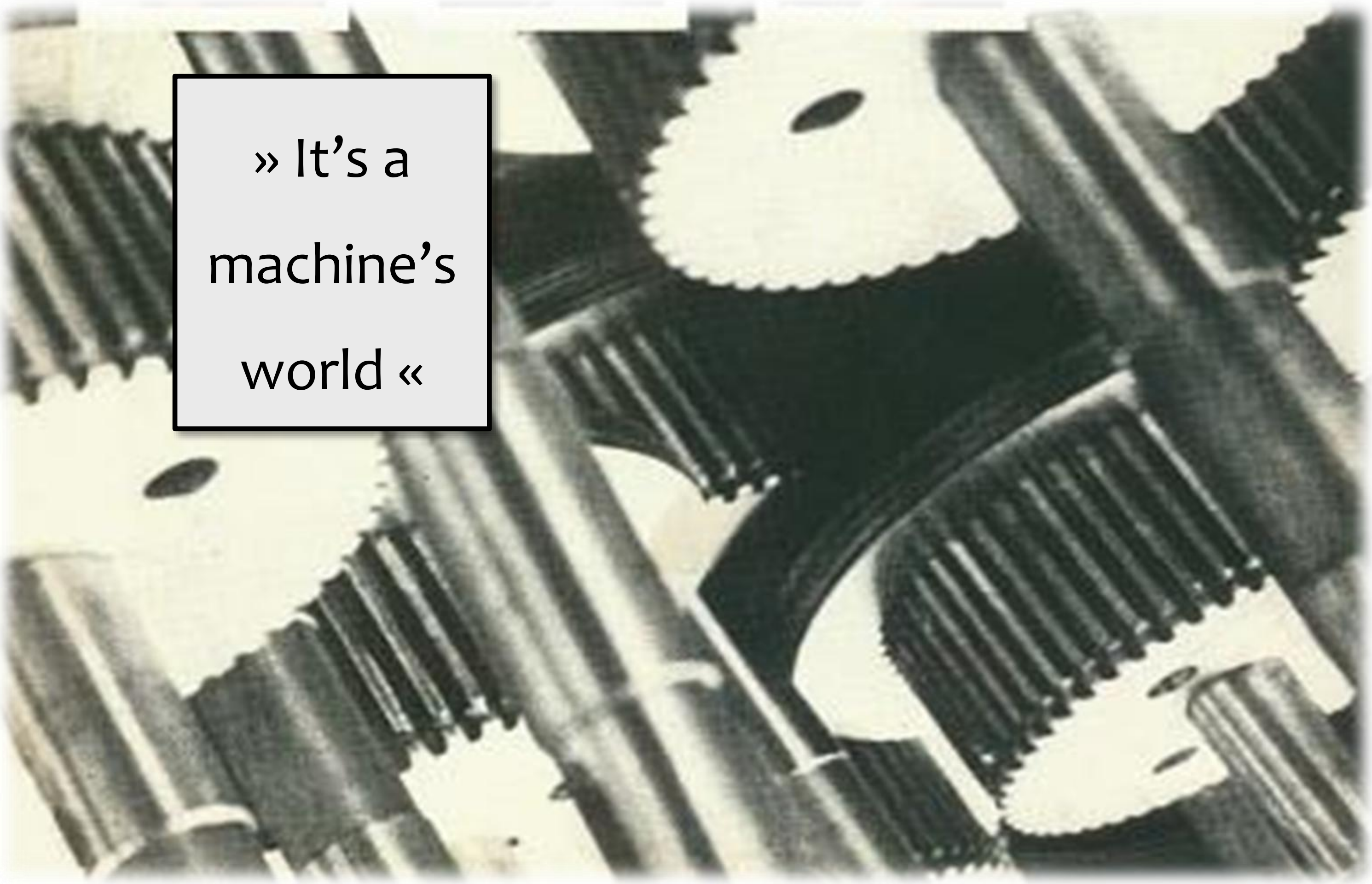
Target nozzle with 20 μm diameter



Frozen hydrogen filament

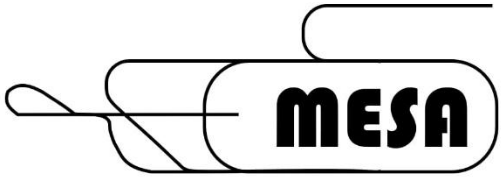


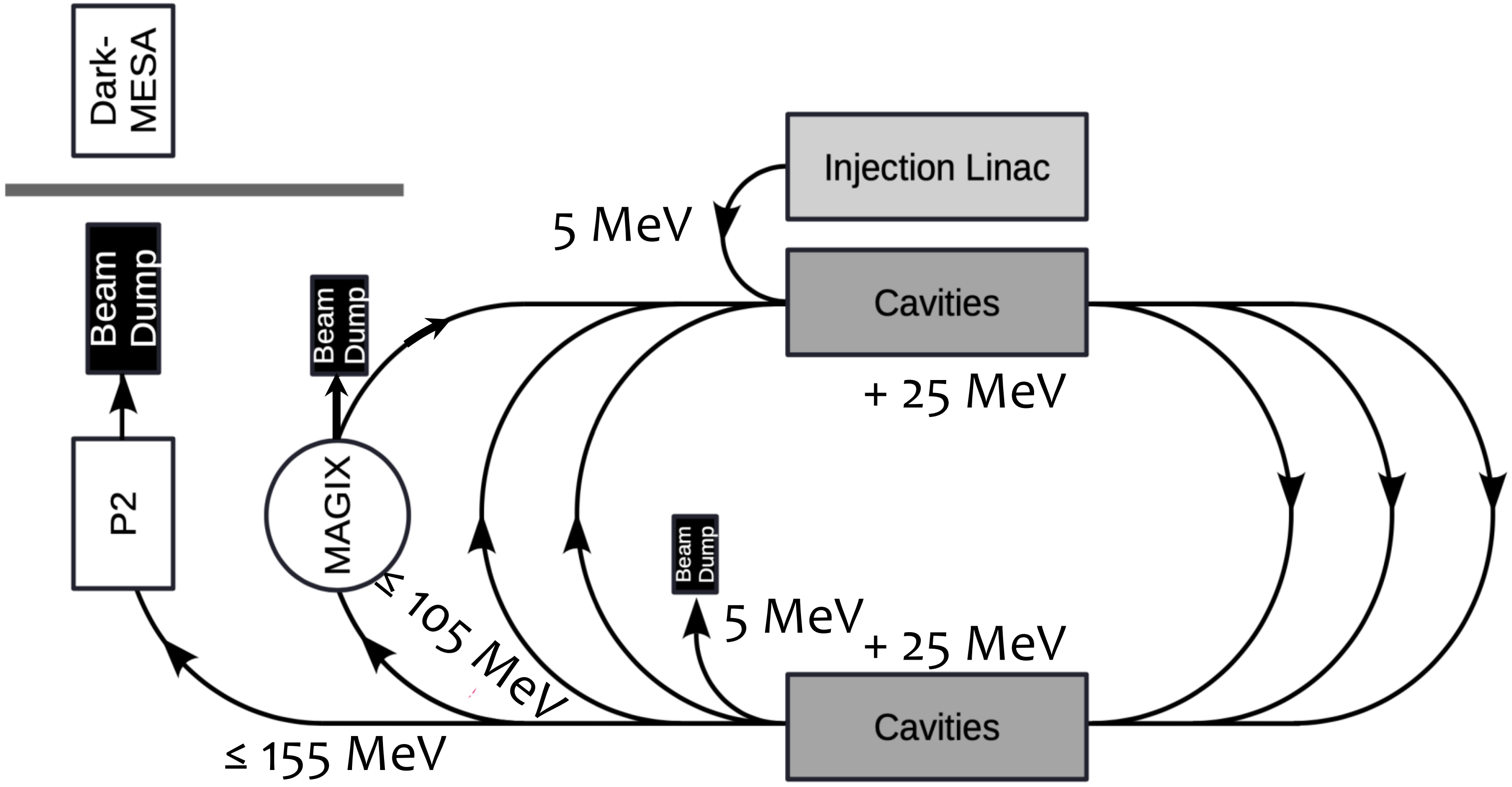
MESA



The Low-Energy Electron Accelerator MESA

- **M**ainz **E**nergy-Recovering **S**uperconducting **A**ccelerator
- Double-sided Multi Turn **E**nergy-**R**ecovery **L**inac (ERL)
- ERL operation mode:
  – E_0 = 20 MeV to 105 MeV
  – Currents of ≥ 1 mA (unpolarized)
- **E**xtracted **B**eam (EB) mode:
  – E_0 up to 155 MeV
  – Currents of 150 µA (polarized)
- Three experiments:
  P2, DarkMESA, and **MAGIX**

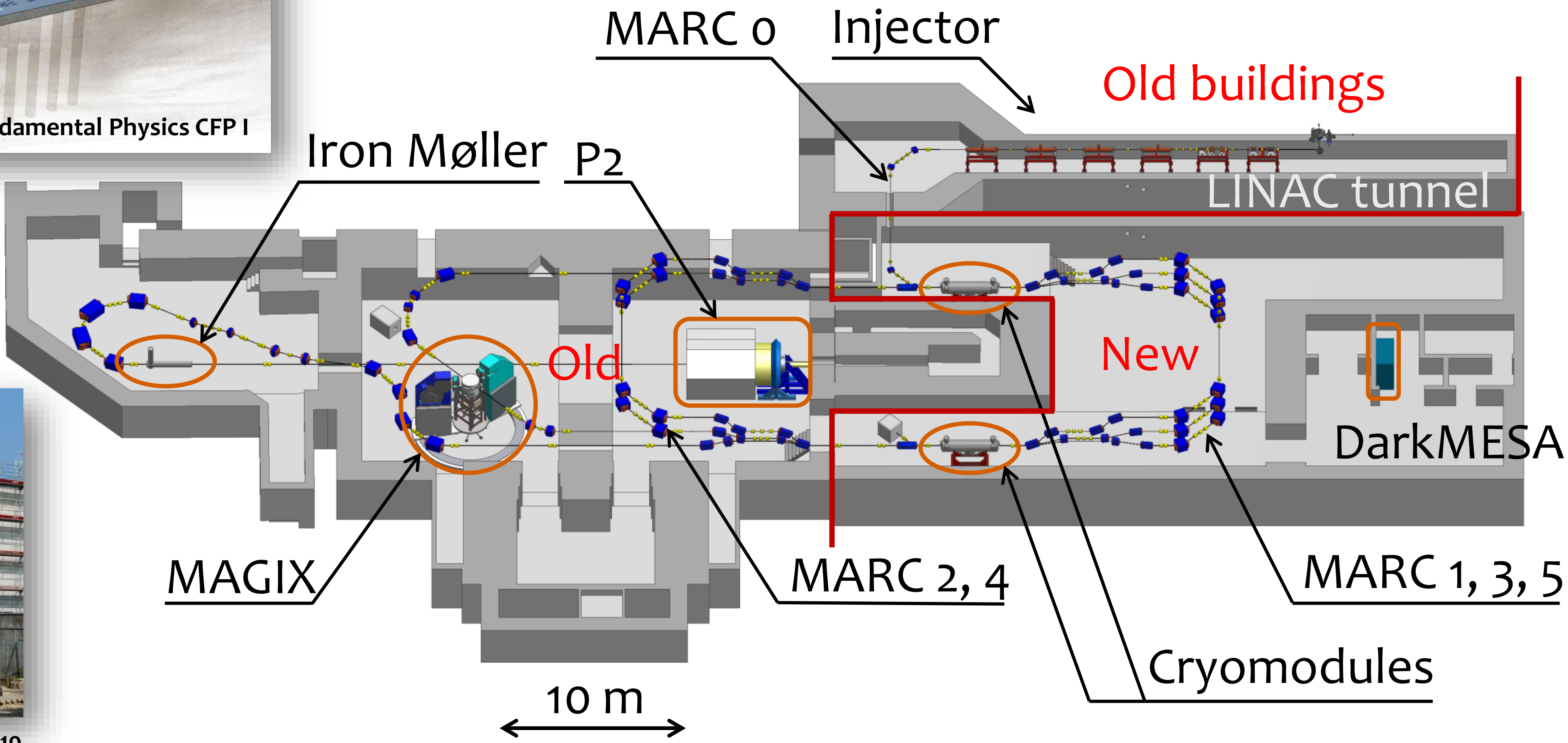




MESA Integration and Infrastructure

Centre for Fundamental Physics CFP I

- 1 MESA arc (MARC) from injection linac
- 5 MARCs inside MESA main hall
- 2 Beamlines to experiments



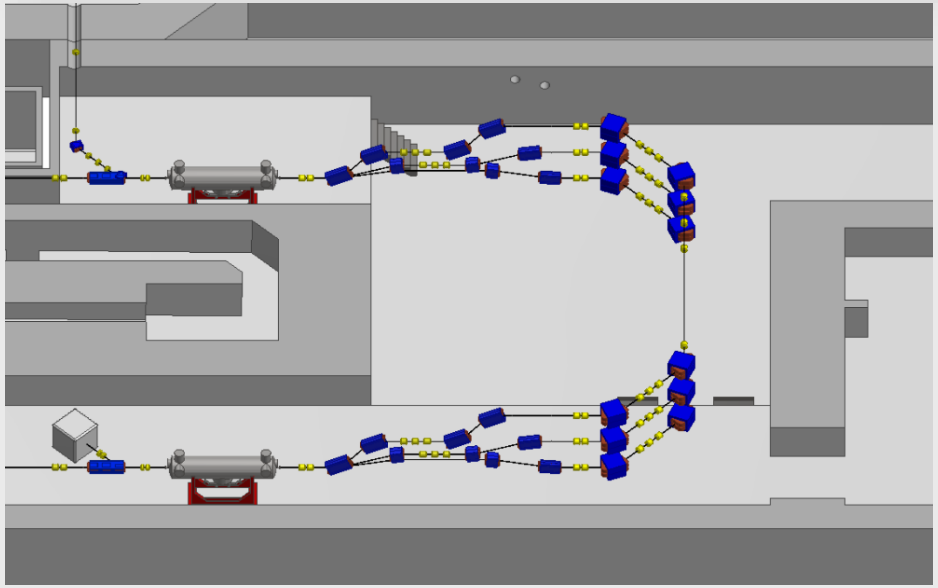
New workshop and storage buildings in 2019

Civil Construction

05/2020

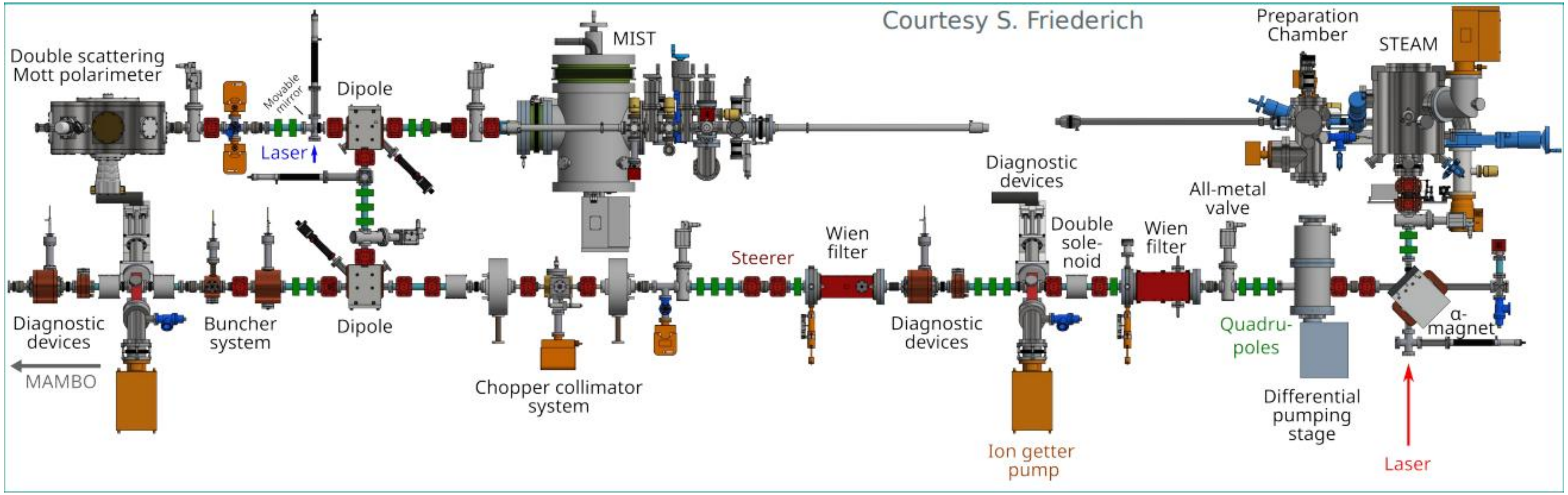
CFP1

11/2024



MESA main hall

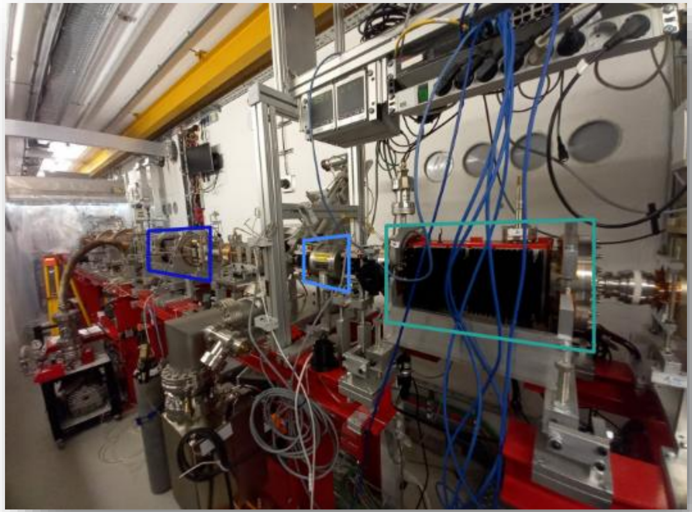
MESA Source and Beam Preparation System



STEAM

Chopper and collimator

Wien filter and solenoid

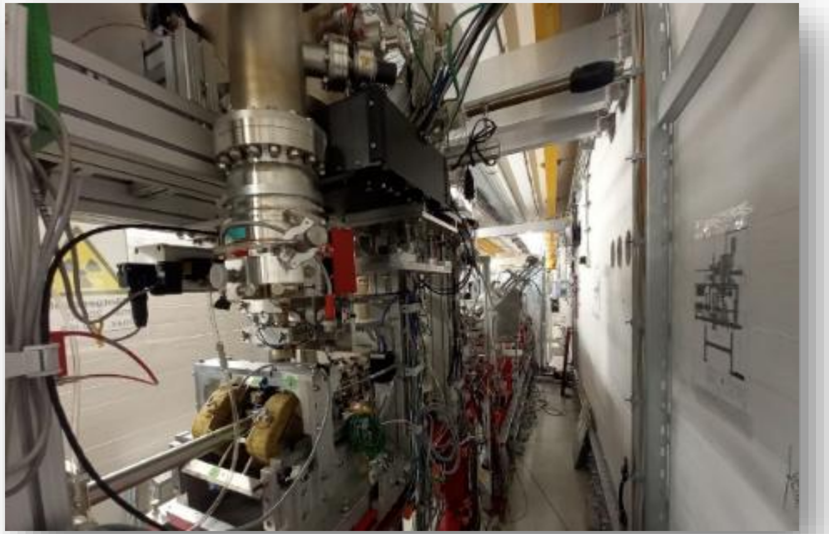


Laser system

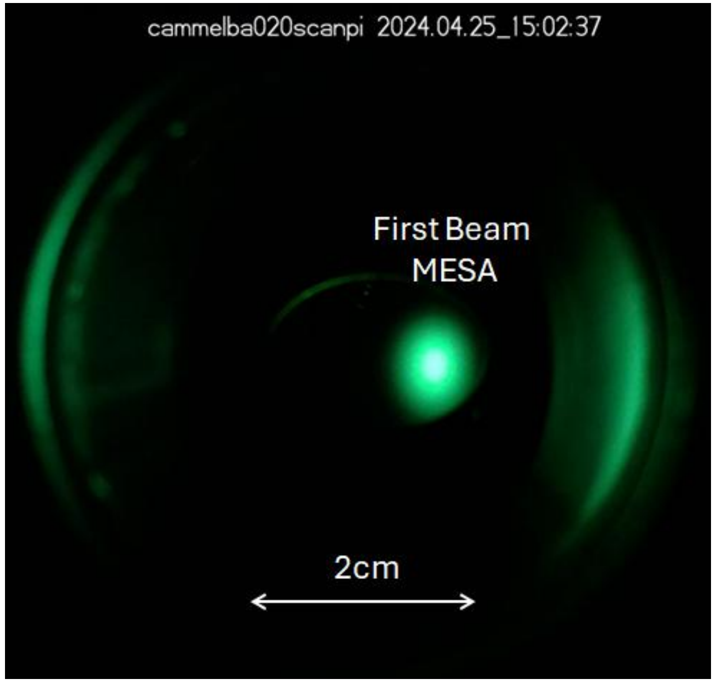
First Beam From STEAM to MELBA

Small Thermalized Electron Source at Mainz

STEAM	Photoemission GaAs
Pulsed	1.3 GHz
Current	150 µA, 85% polarized
E_{kin}	100 keV
E_{acc}	2.5 MV/m
ε_{rms}	$\leq$ 1 mm mrad



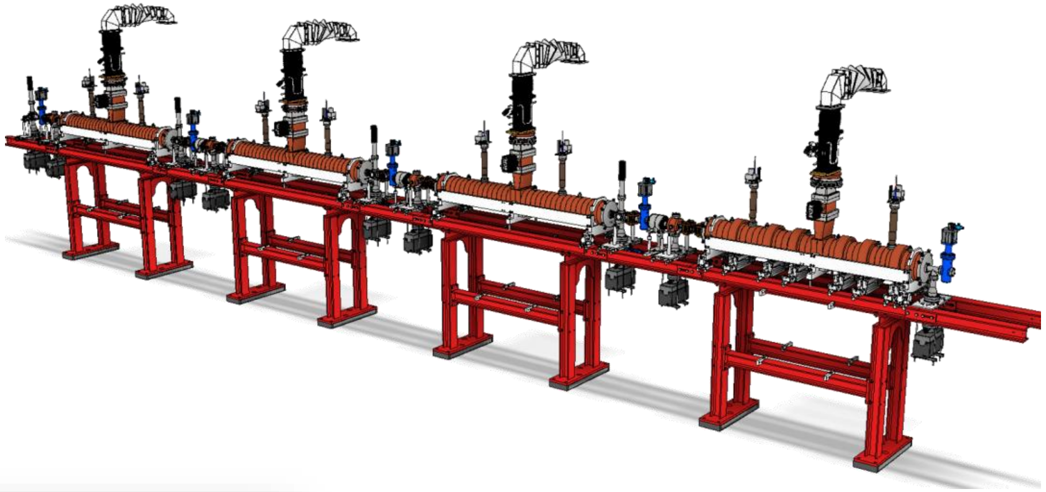
MESA Low Energy Beam Apparatus

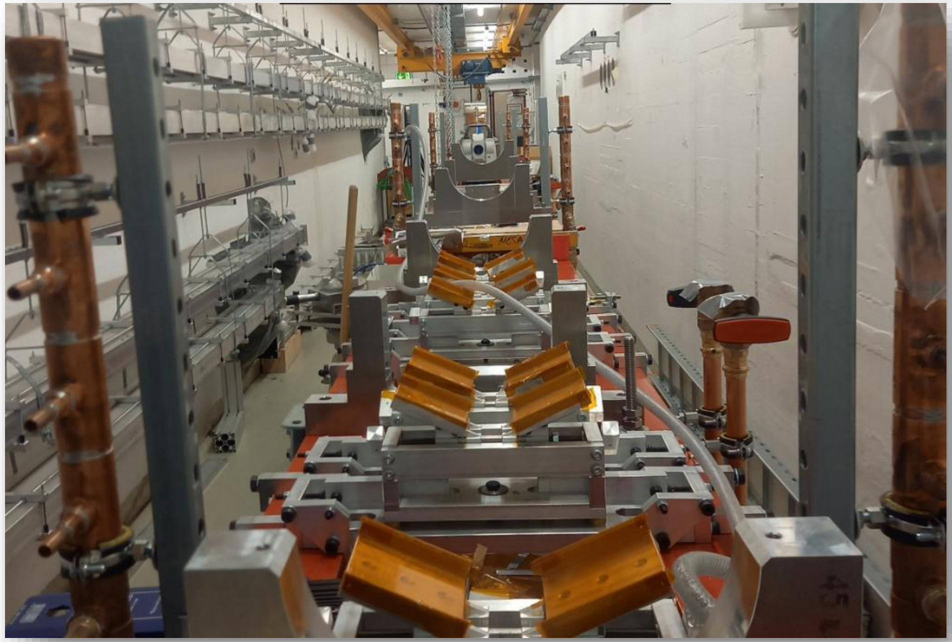


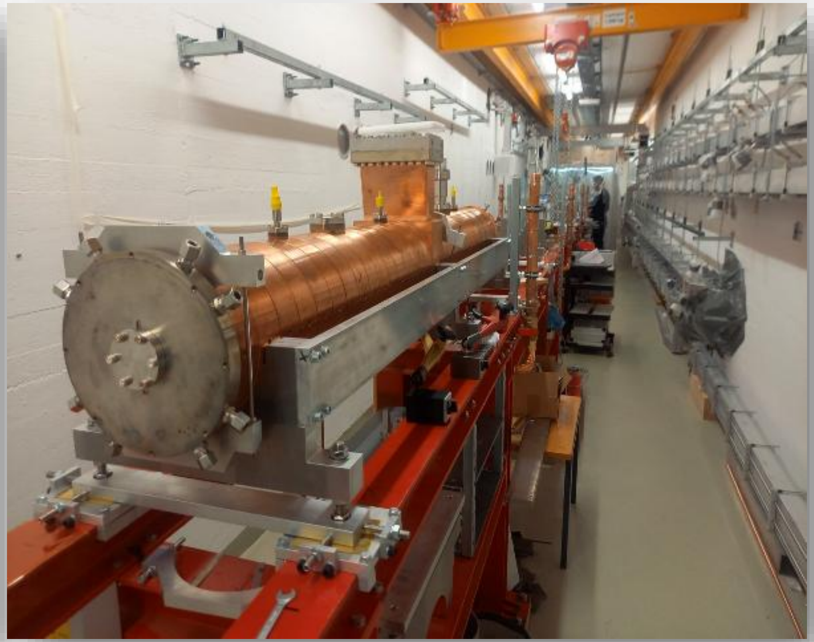
- 10 mA beam current transported in MELBA test stand (07/2019)
- **100 keV beam energy (04/2024)**
- Emittance goal achieved

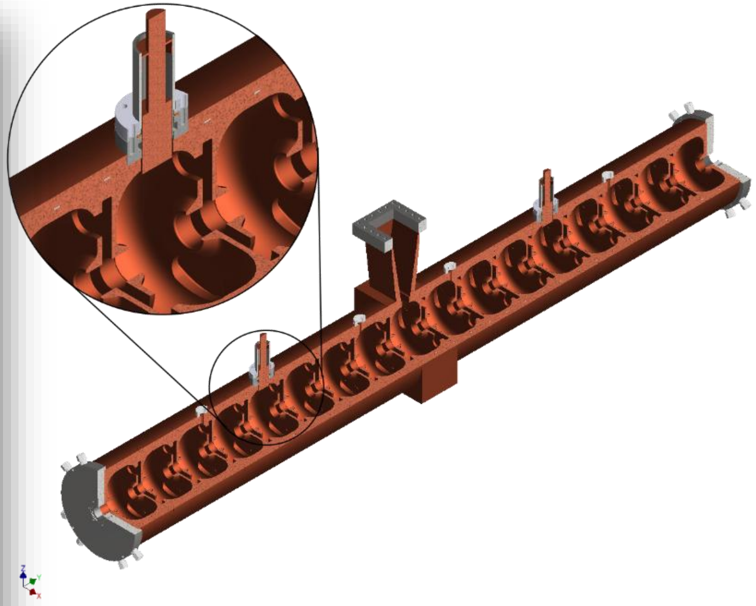
Milli-Ampere Booster

- Design up-scaled from MAMI 2.45 GHz to MESA 1.3 GHz
- Normal-conducting, bi-periodical $^{\pi}/_{2}$-structures
- MAMBO comprises 4 structures:
  1x graded ß ($\Delta E = 1.15$ MeV), 3x ß=1 ($\Delta E = 1.25$ MeV)
- $Q_0 = 2.1 \cdot 10^5$









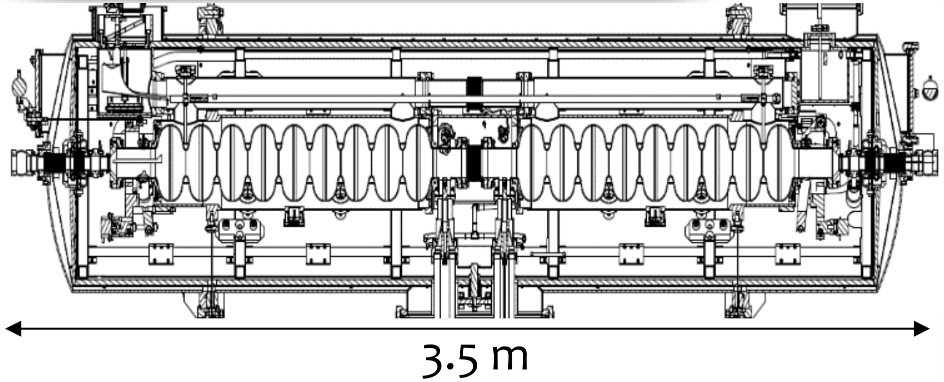
MESA Enhanced ELBE Cryomodules

MESA cryomodule 2

2x Superconducting RF modules

- ELBE-Rossendorf type
- 2 XFEL cavities each
- 25 MeV energy gain
- Site Acceptance Test completed in 2020
- < 40 W thermal loss at 2 K
- Installed within MESA since 12/2024

MESA cryomodule 1



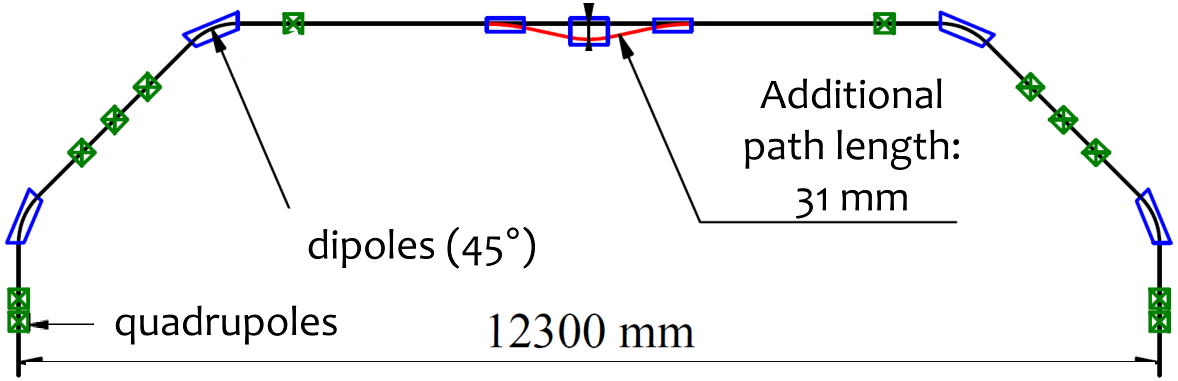
Magnetic Lattice

107 Dipoles:

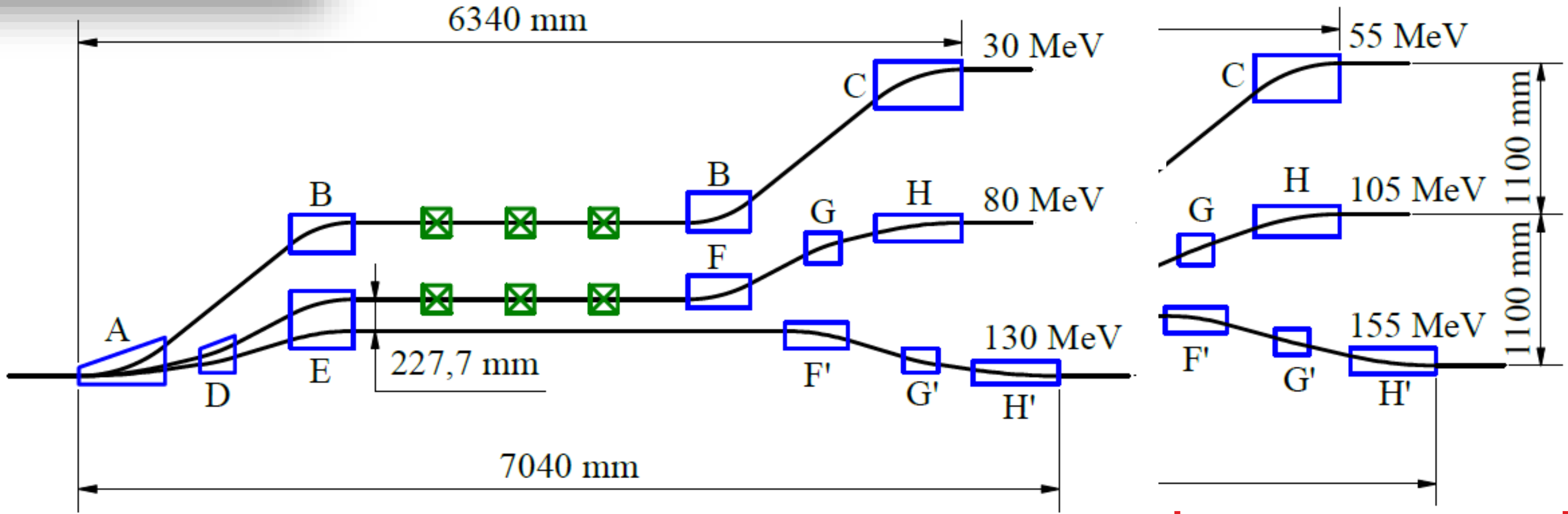
- 20 MARC 45° dipoles
- 18 chicane dipoles
- 45 beam separation dipoles
- 6 MAGIX beamline
- 12 P2 beamline

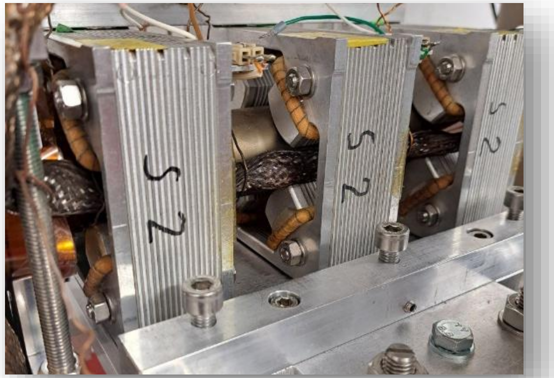
207 Quadrupoles

- 22 MELBA (100 keV)
- 20 MAMBO/MARC0 (5 MeV)
- 165 main accelerator (155 MeV)



MARC design with chicane





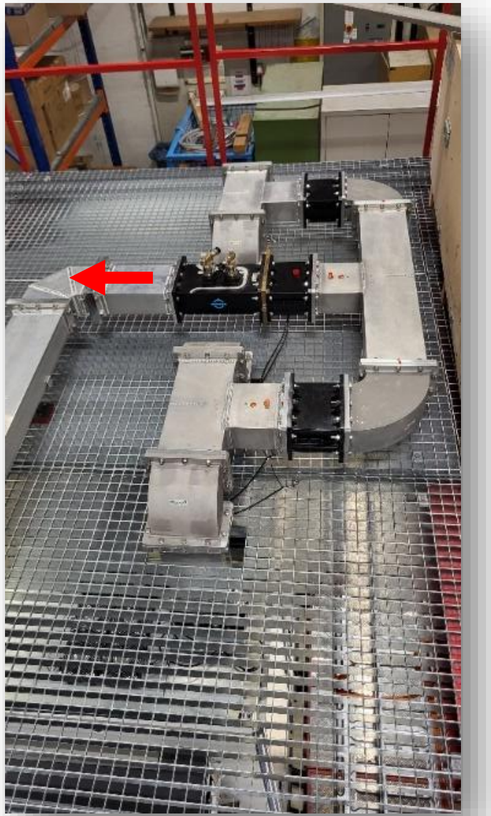
Beam separation

between cryomodules   to/from experiments

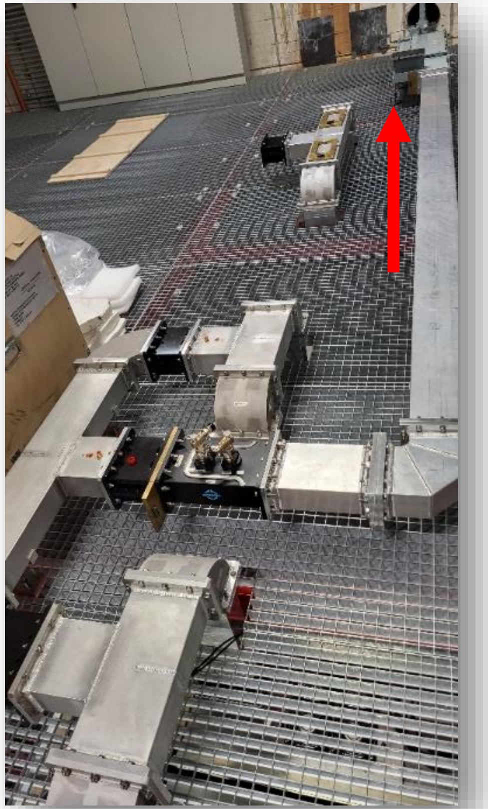
RF Infrastructure

20-kW 1300-MHz control unit and power supply

17 modules of 20-kW 1300-MHz solid state amplifiers

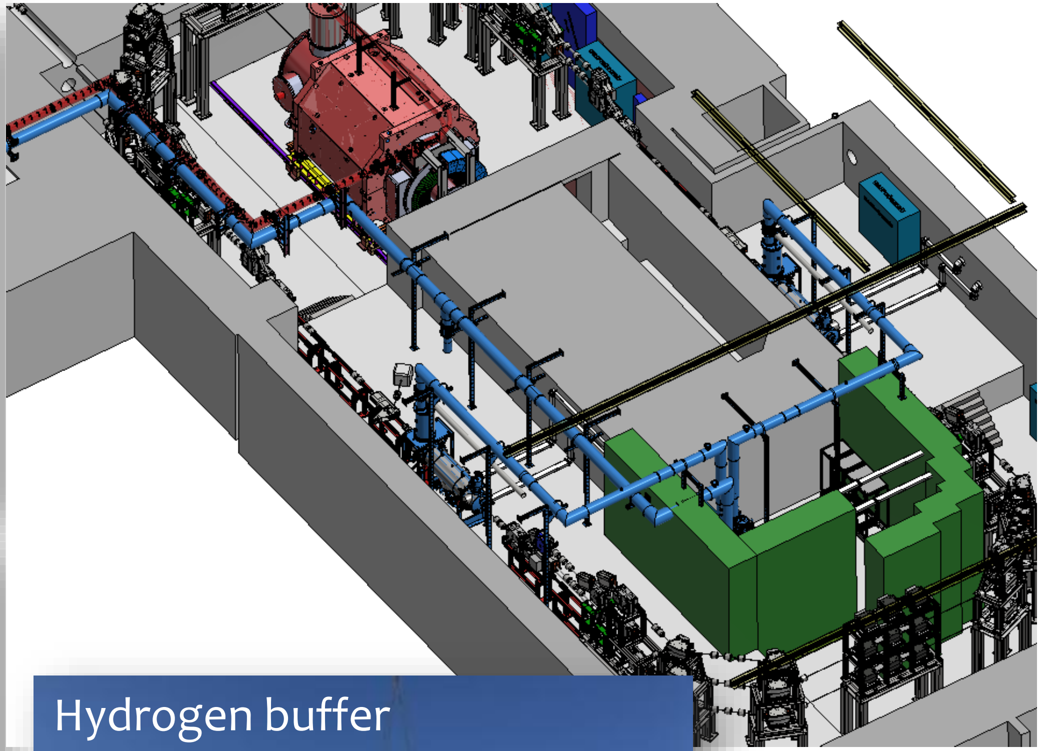


4x20-kW combined for MAMBO-1

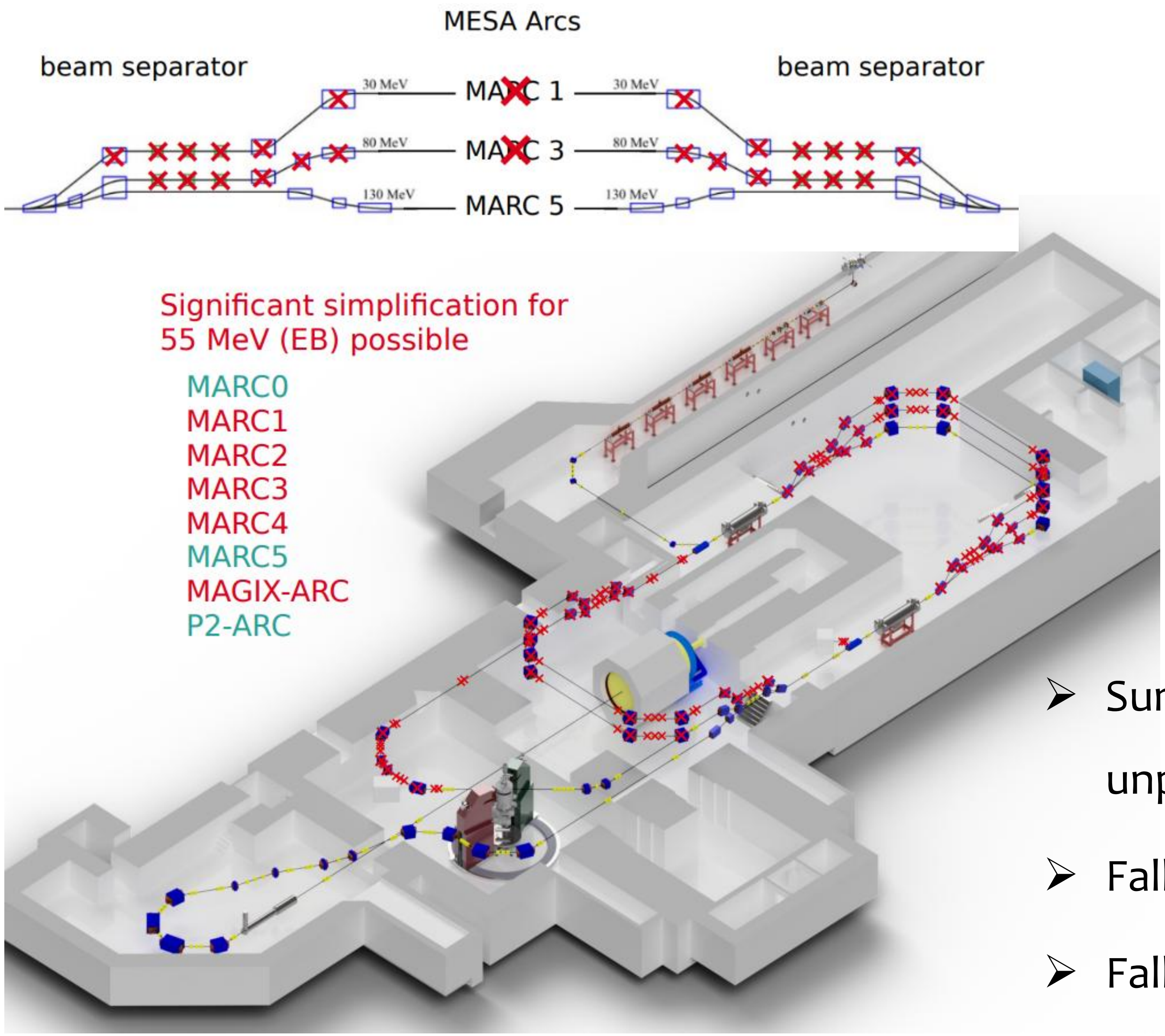


Waveguides

Cryogenic Infrastructure



Staged Approach for MESA Operation

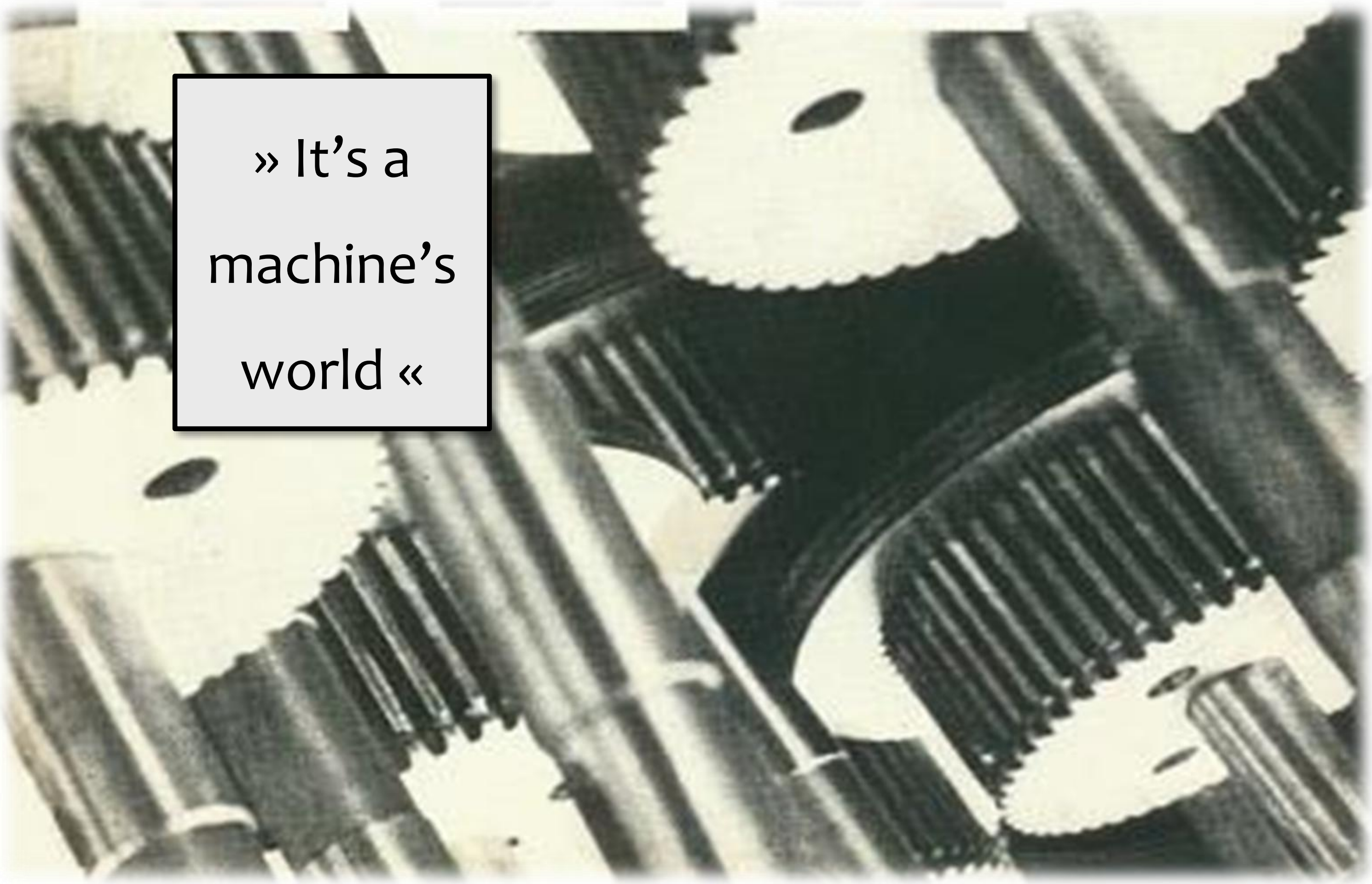


First stage:

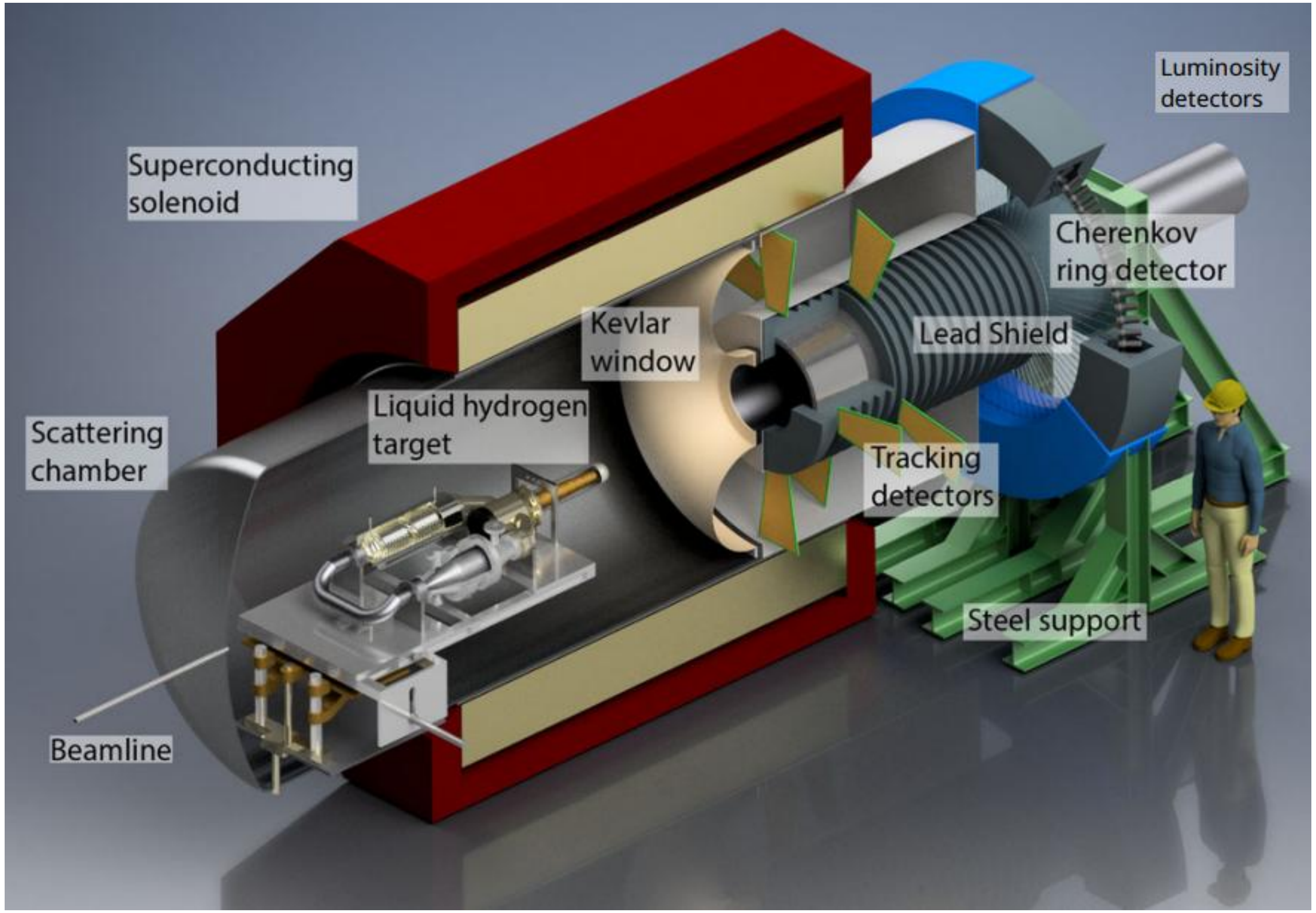
- No energy-recovery mode
- No recirculation
- Low beam availability
- Limited beam control

- Summer 2027: First MESA beam with 55 MeV, unpolarized, 1 μA
- Fall 2027: First extracted beam to MAGIX
- Fall 2027: First extracted beam to P2

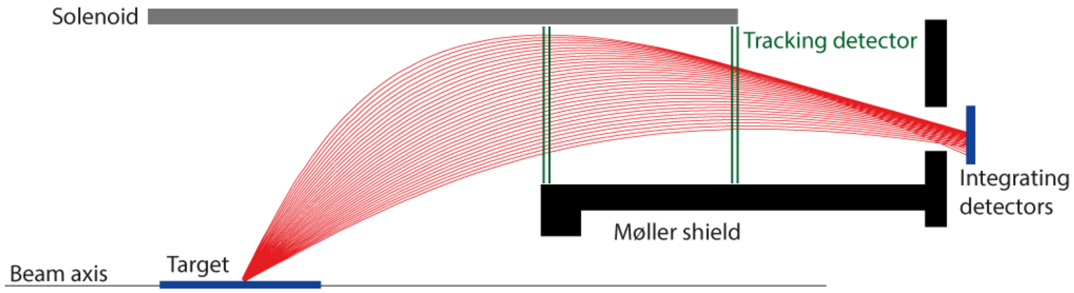
MESA Experiments



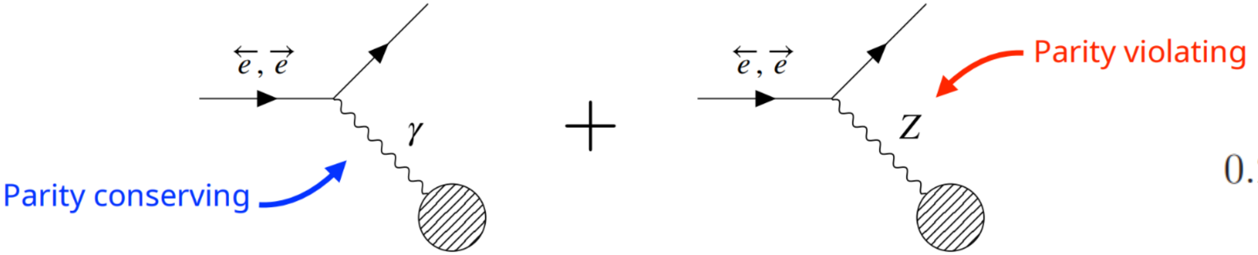
P2: External Beam Solenoid Spectrometer



- Extracted beam: E = 155 MeV, I = 150 µA
- Targets: lH_2, ^{12}C, ^{208}Pb
- **Superconducting solenoid** spectrometer
- Full azimuthal acceptance
- Central scattering angle = 35°
- **Tracking detectors** (HV-MAPS)
- **Integrating Cherenkov detectors**
- Air Cherenkov luminosity monitor
- Rapid helicity flip (100 – 1000 Hz)



Weinberg Angle Measurement

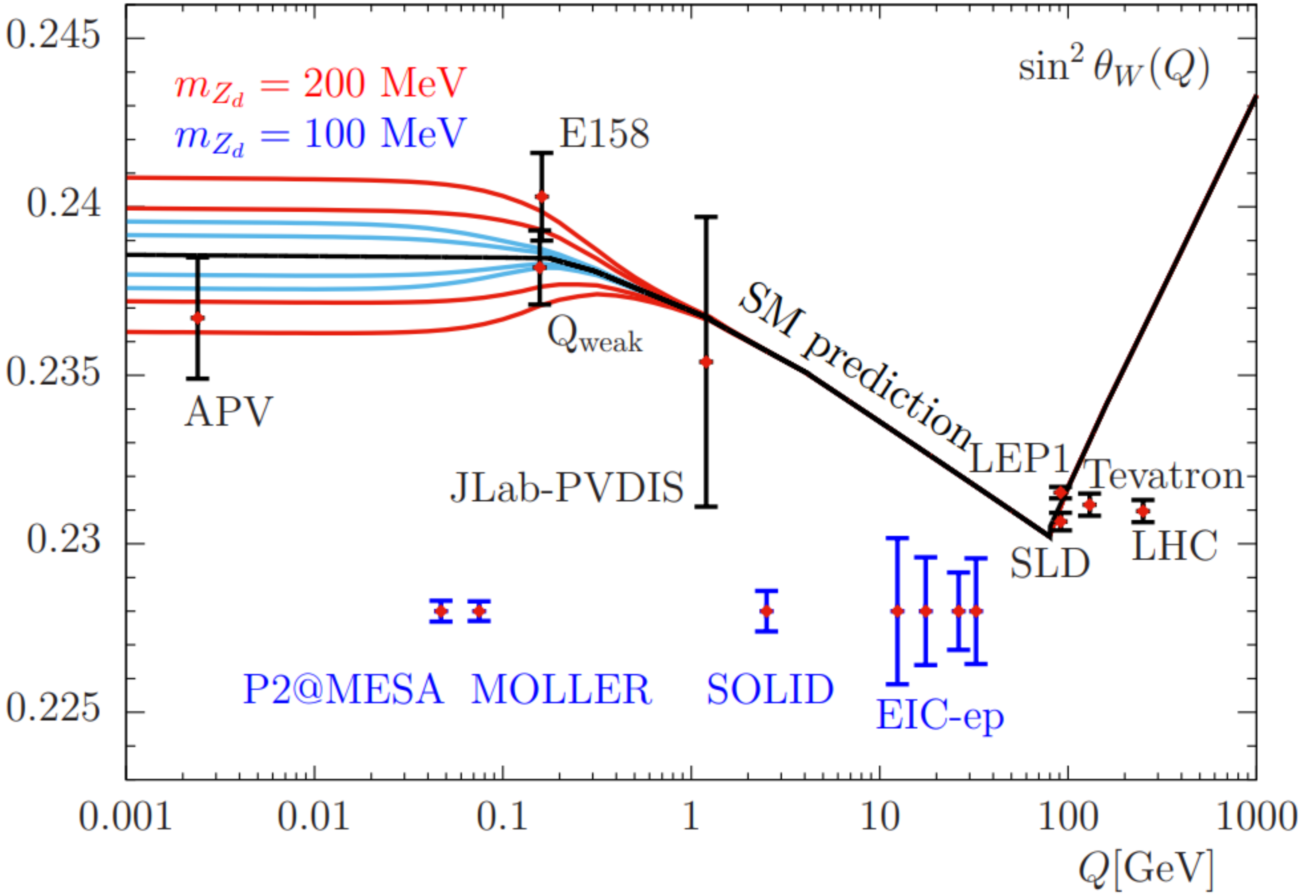


- Parity-violating interference between γ and Z exchange:

$$A_{PV} = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[Q_W^p - F(E, Q^2) \right]$$

$$Q_W^p = 1 - 4\sin^2\theta_W$$

- Precision test of the Standard Model
- P2 precision goal: 40 ppb ± 0.57 ppb
  $\delta\sin^2\theta_W \sim 0.0003$ (0.15% on θ_W)
- > 10 000 hours of beam time
  with high-power hydrogen target
- Sensitivity for BSM physics up to 50 TeV

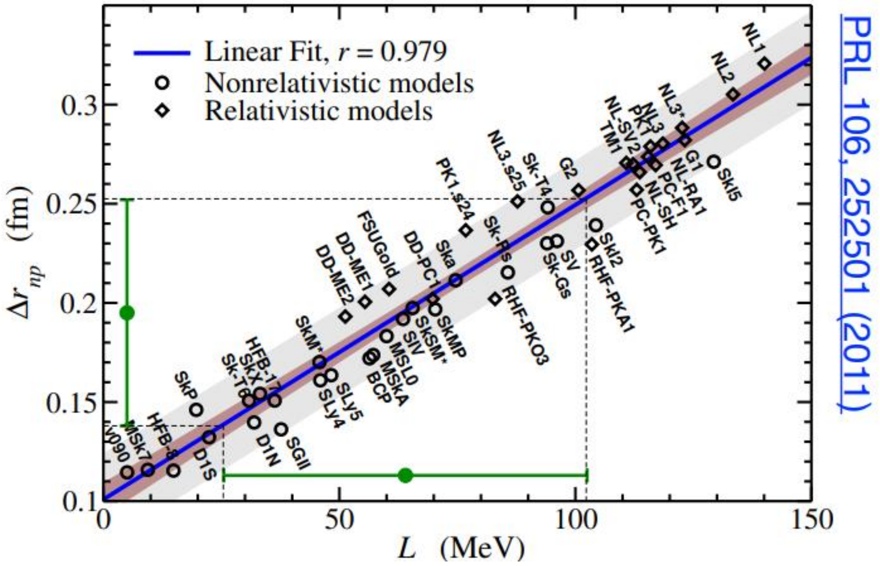


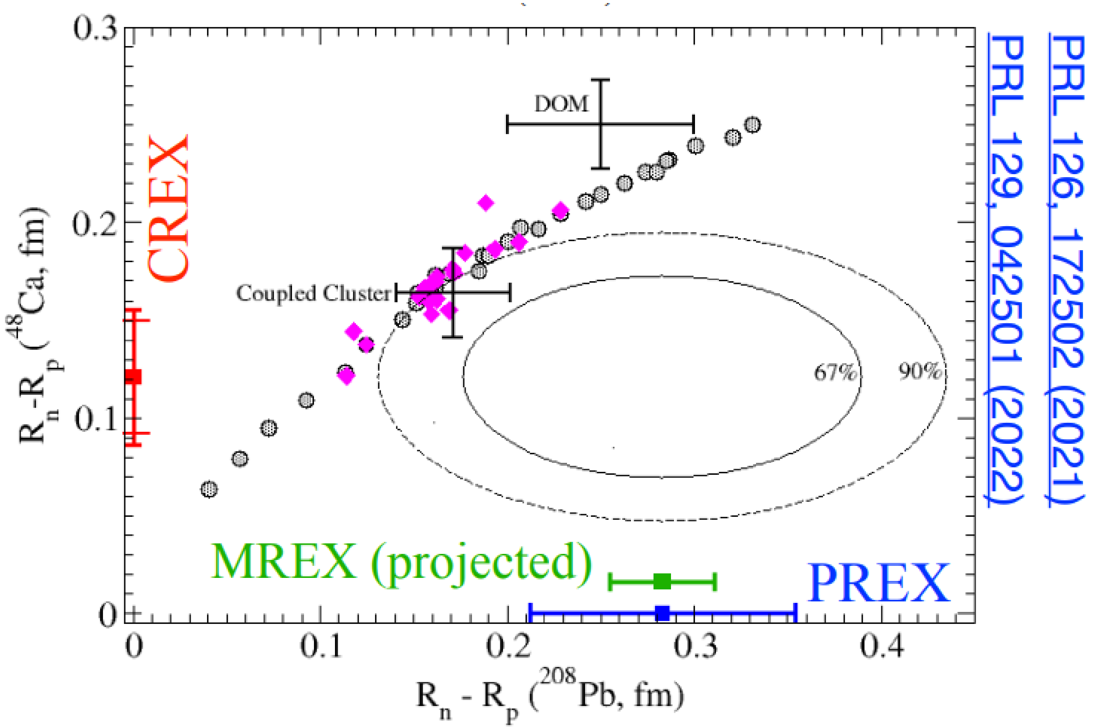
$$A_{PV} = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_C(Q^2)}$$

F_W dominated by neutrons

F_C dominated by protons

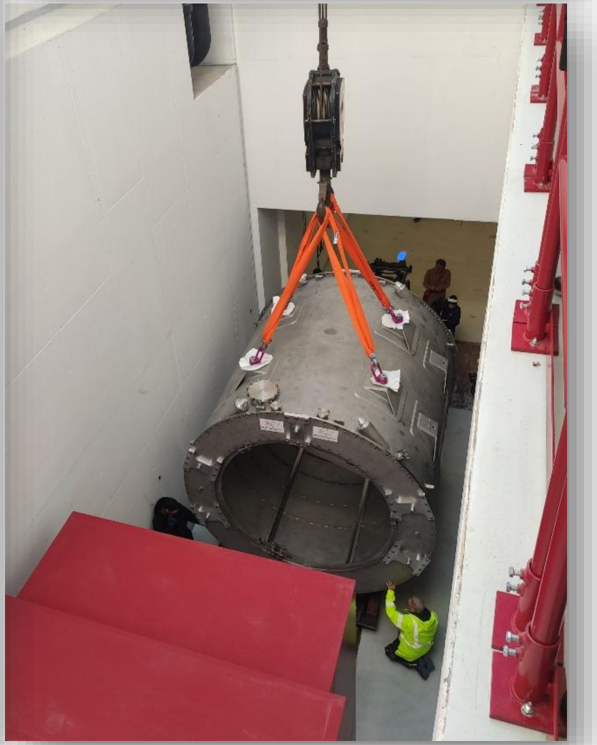
- RMS neutron radius of ^{208}Pb from F_W at low Q^2
- **Neutron skin** $\Delta r_{np} = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$ PREX/CREX puzzle
- **Nuclear Equation-of-State:**
  Slope L of symmetry energy correlated with Δr_{np}



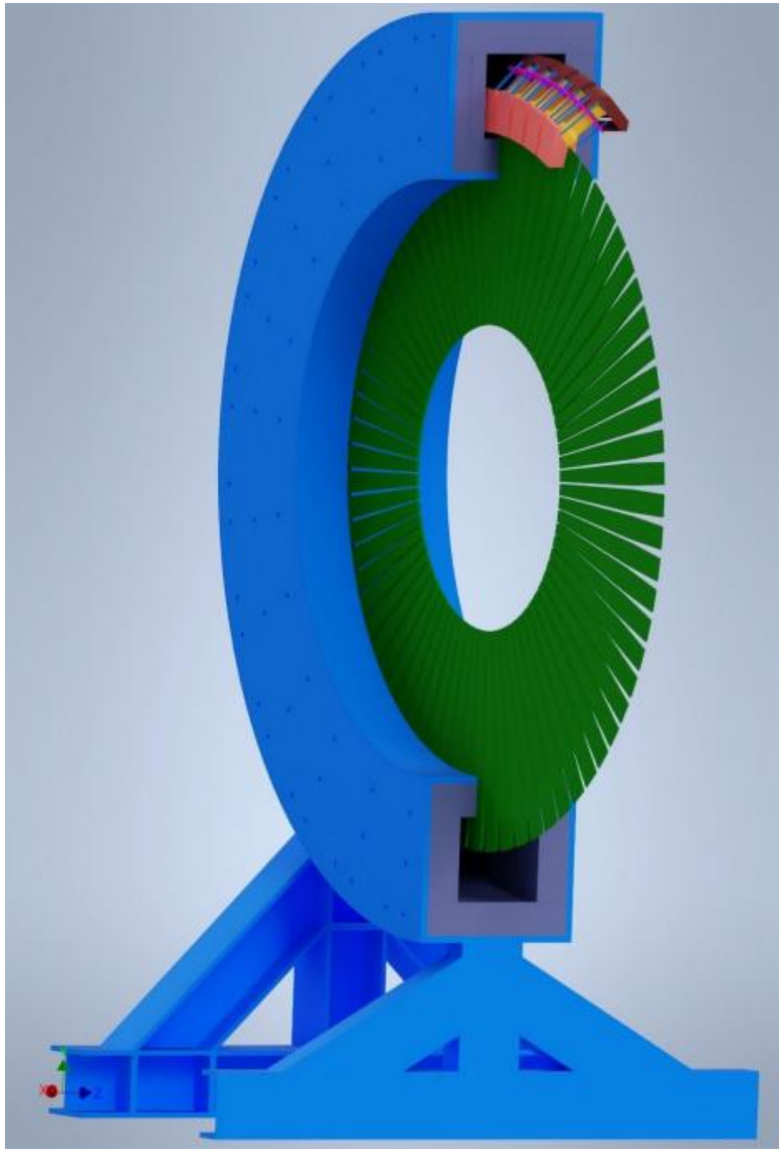


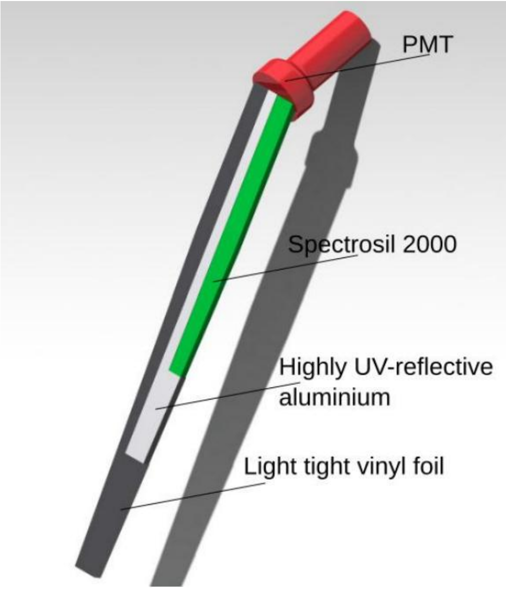
MREX:
1.440 h beam time with a ^{208}Pb target

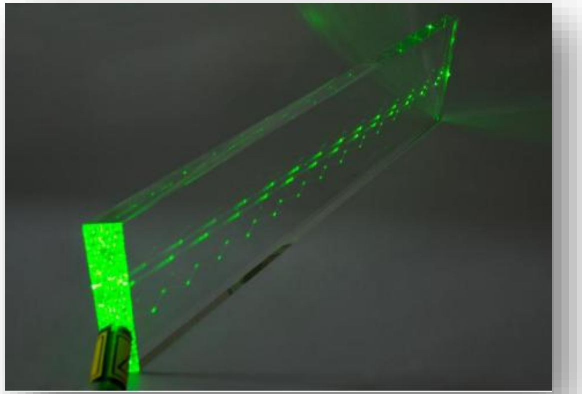
Delivery of the P2 Solenoid



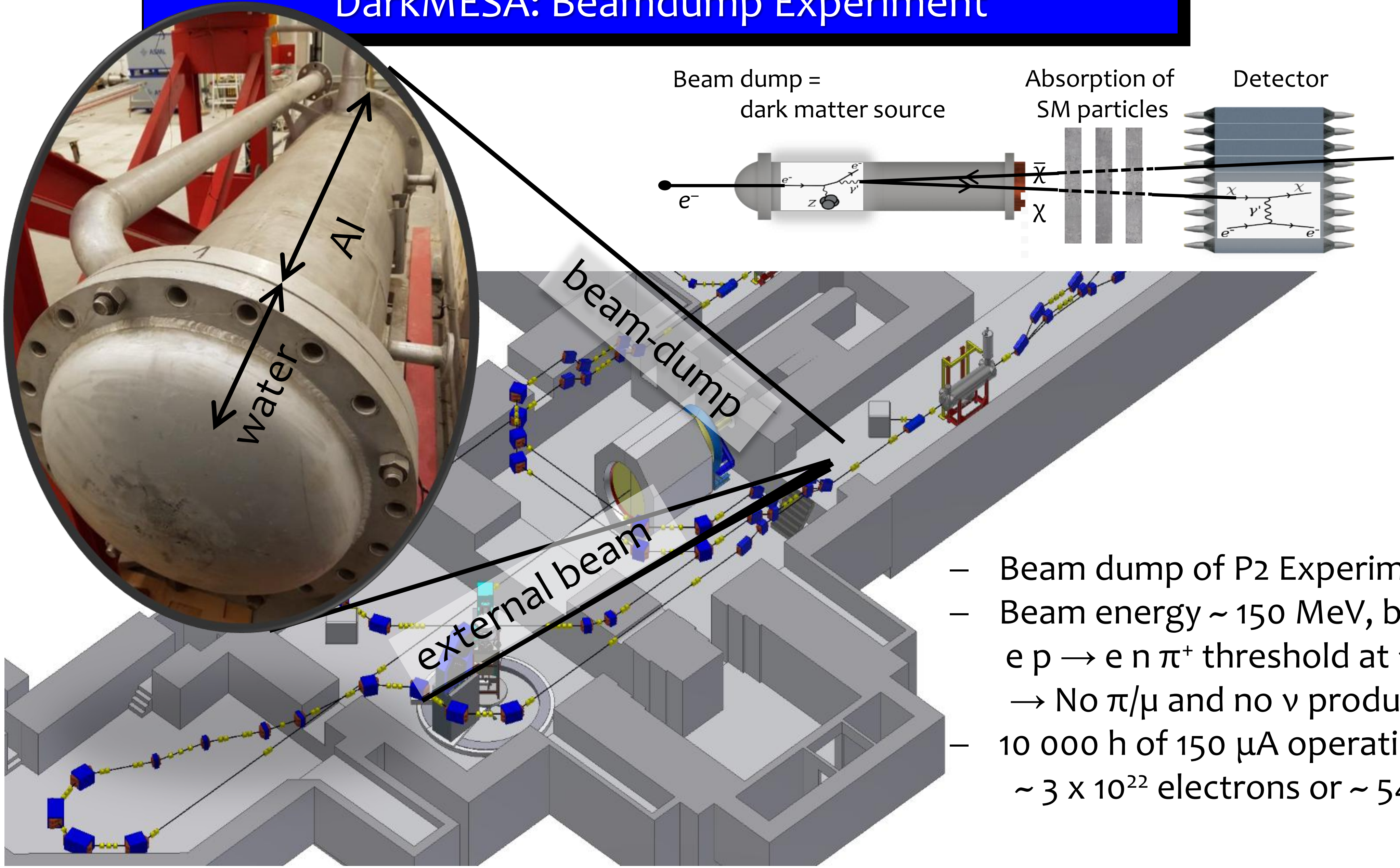
P2 Cherenkov Detectors







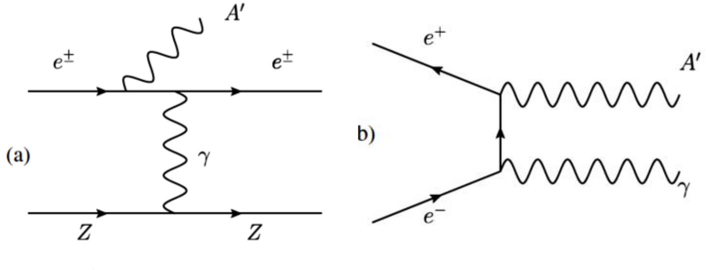
DarkMESA: Beamdump Experiment

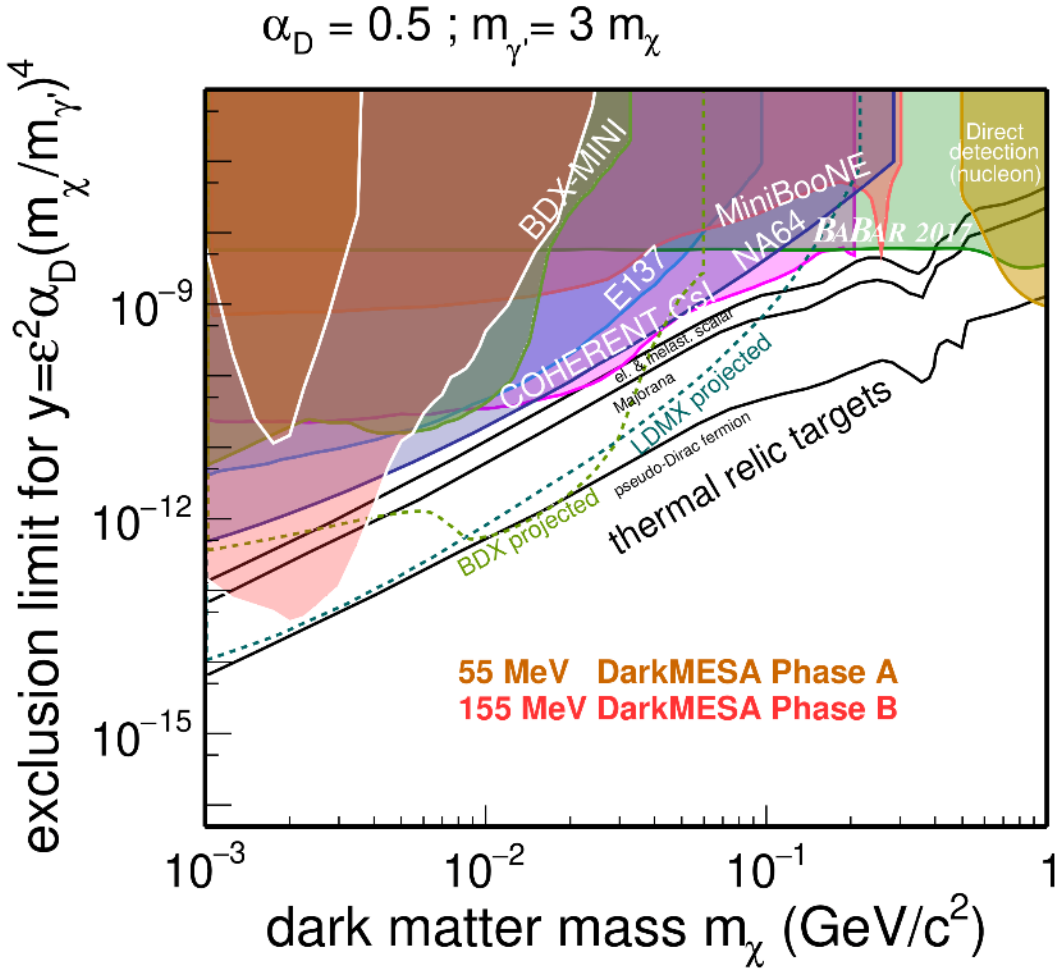


- Beam dump of P2 Experiment
- Beam energy ~ 150 MeV, but
  e p → e n π^+ threshold at 152 MeV
  → No π/μ and no ν production
- 10 000 h of 150 µA operation:
  ~ 3 x 10^{22} electrons or ~ 5400 C

	Detector	Run Time	EOT
Phase A	Prototype	2,200 h	$7.42 \cdot 10^{21}$
Phase B	PbF_2 + SF5	6,600 h	$2.23 \cdot 10^{22}$

– Assumptions:
  - Detection threshold 10 MeV (electron recoil)
  - Detector efficiency 95%
  - Confidence level 90%
  - No backgrounds
– Production processes:
  - Bremsstrahlung-like production $e^{\pm}N \rightarrow e^{\pm}NX$
  - Resonant in-flight positron annihilation on atomic electrons $e^{+}e^{-} \rightarrow X \rightarrow \chi\chi$





MAGIX: MAinz Gas Internal eXperiment

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

- Spectroscopy of low momenta particles with high accuracy
- Competitive luminosities at very low target thicknesses

First experiment with MAGIX

- **No energy-recovery mode** → No internal target

  → Solid state target with simpler operation

  → Reduced instrumentation demands

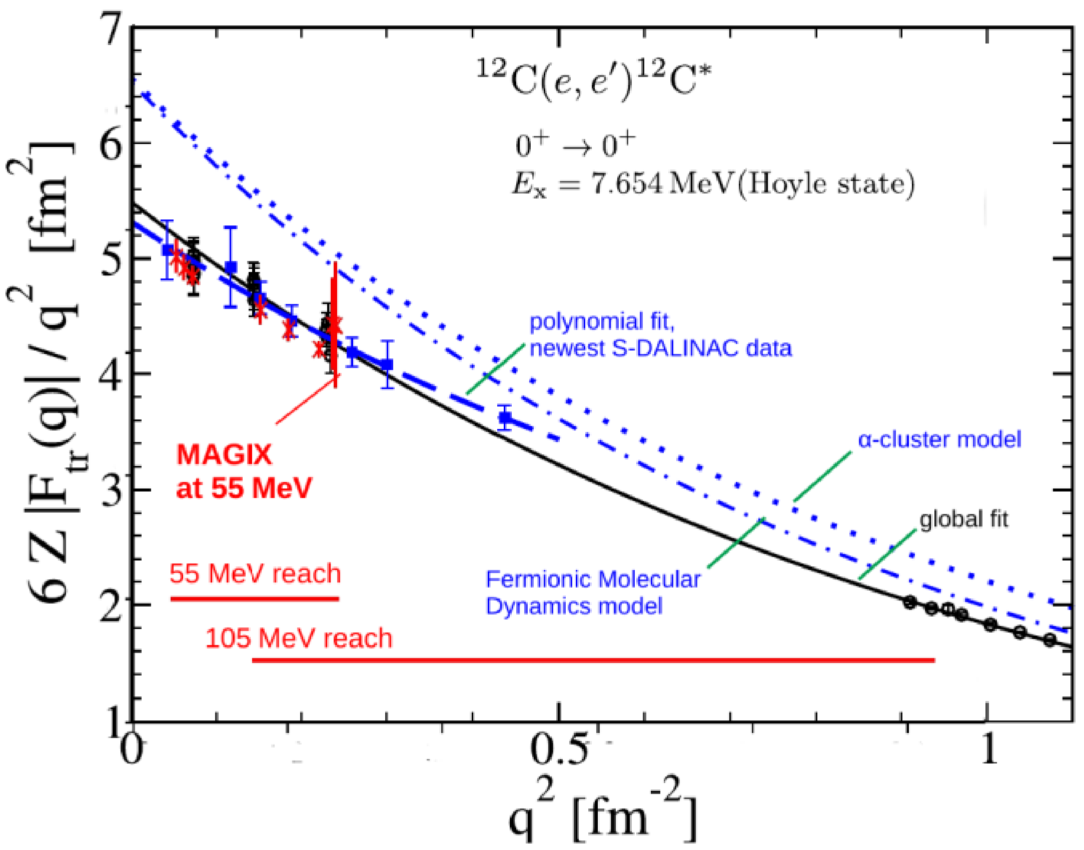
- **No recirculation** → Fixed beam energy

  → Reduced experimental complexity

- **Low beam availability** → Need for short experiments

- **Limited beam control**

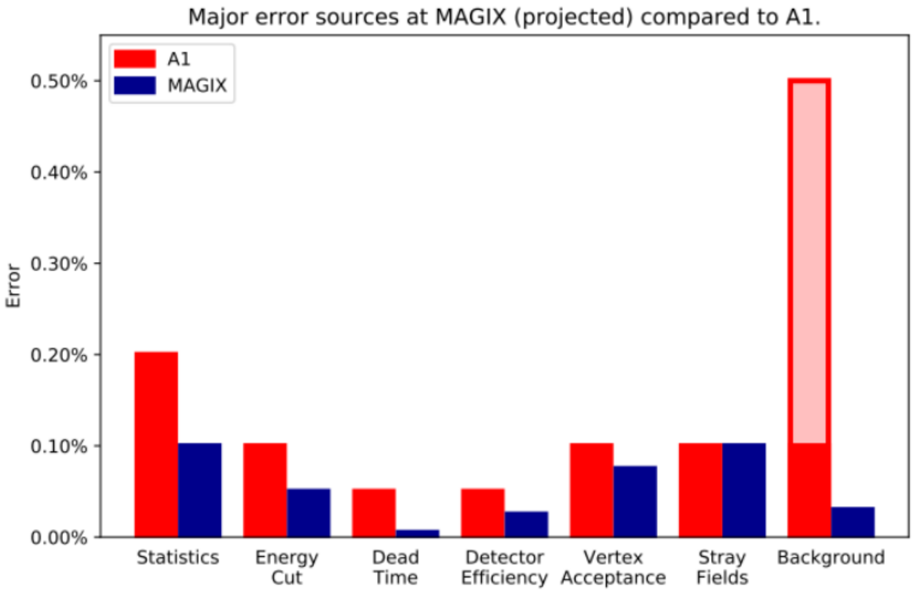
^{12}C Hoyle state transition form factor at low Q^2

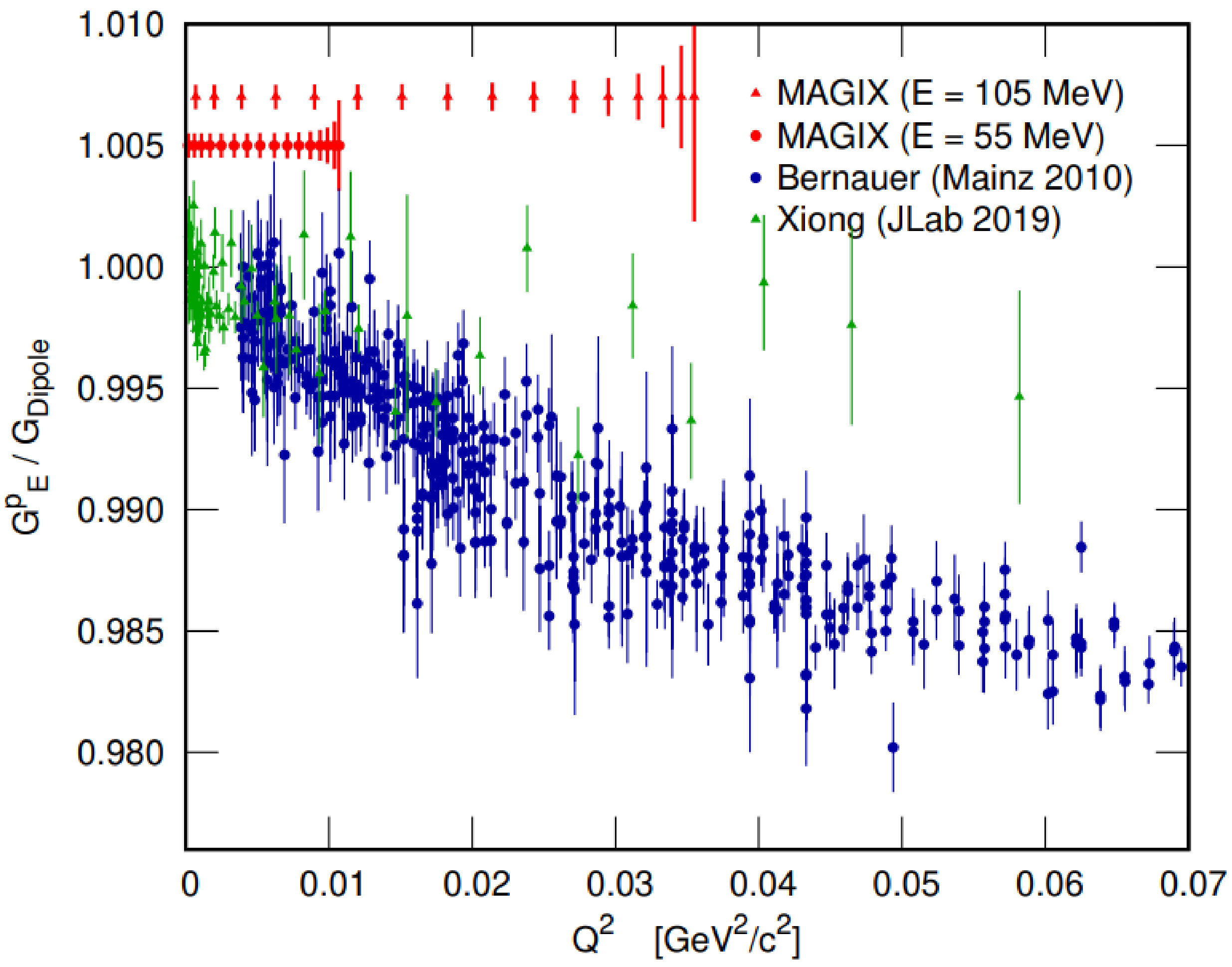


Proton Electric Form Factor Measurement

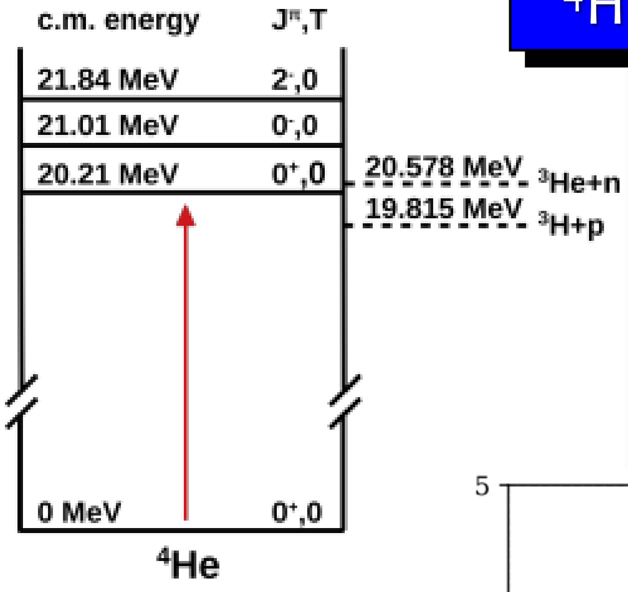
Internal target setup:

- **55 MeV** beam energy
- Unpolarized measurement
- Q^2 coverage from 10^{-5} to 10^{-2} GeV^2
- Systematic error sources:





^{4}He Monopole Transition Form Factor Measurement

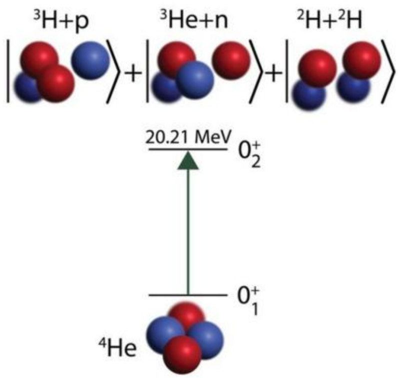


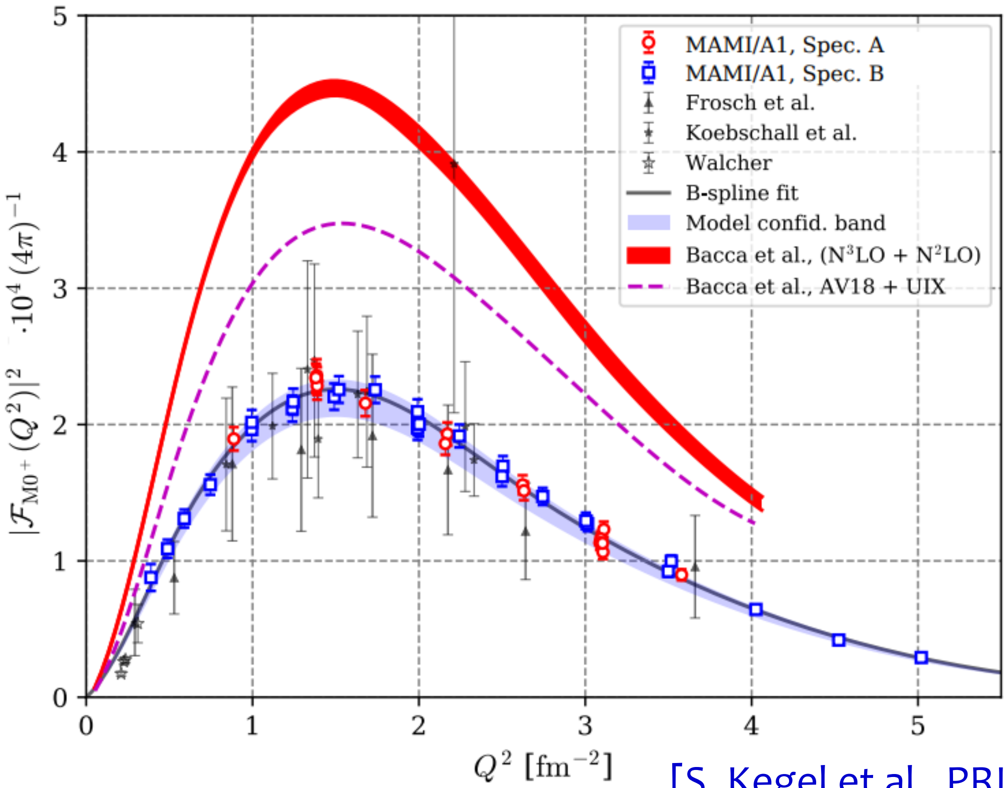
^{4}He ground state to 0_2^+ resonance state transition at low Q^2

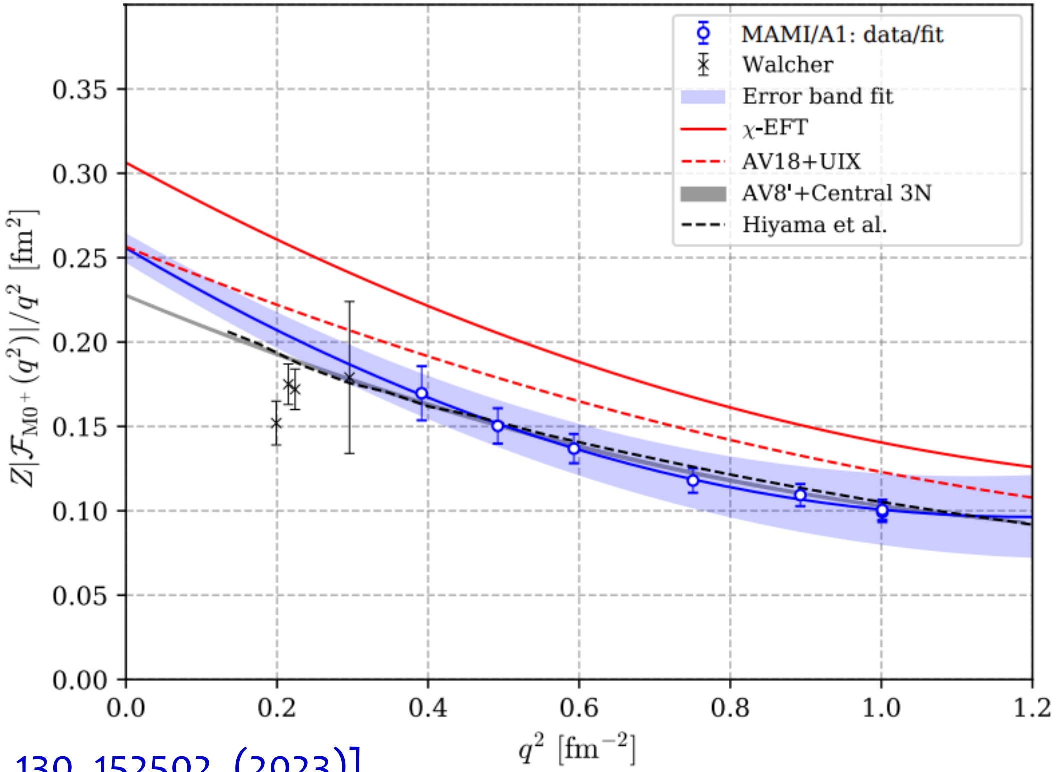
- Continuation of MAMI measurements
- A low-energy puzzle for nuclear forces?
- Sensitivity to 3N forces

	$\langle r^2 \rangle_{tr}$ [fm^2]	$\mathcal{R}_{tr}$ [fm]
Experiment	1.53 ± 0.05	4.56 ± 0.15
Theory (AV8'+ central 3N)	1.36 ± 0.01	4.01 ± 0.05
Theory (AV18+UIX)	1.54 ± 0.01	3.77 ± 0.08
Theory (χEFT)	1.83 ± 0.01	3.97 ± 0.05

Binary clusters:

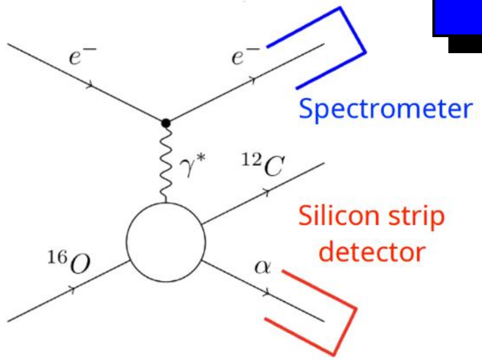






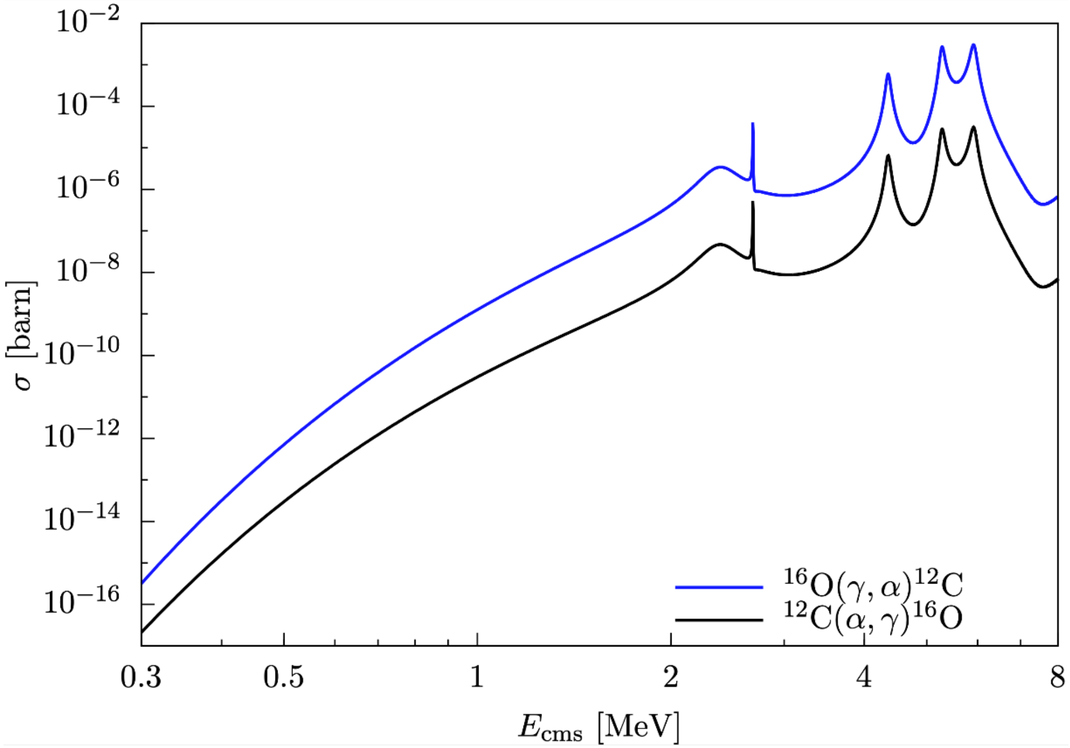
[S. Kegel et al., PRL 130, 152502, (2023)]

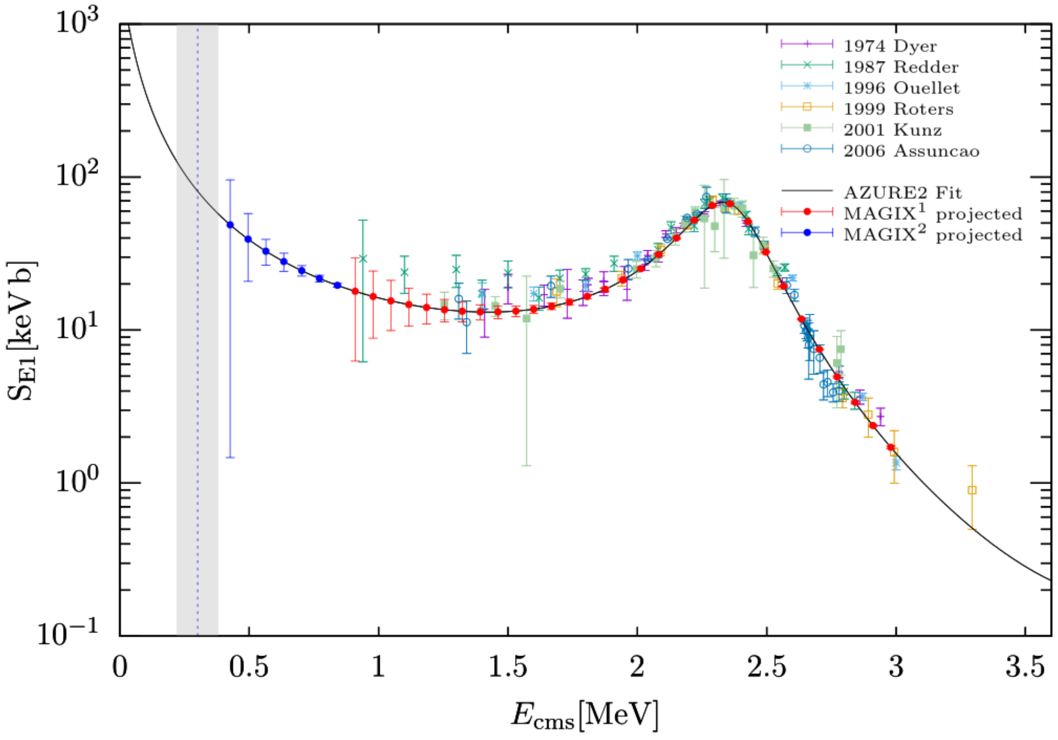
^{16}O Photo-Dissociation Cross Section Measurement



- Photo-dissociation cross section ^{16}O(e,$e'\alpha$)^{12}C
- Time-reversal of radiative capture ^{12}C(α,γ)^{16}O
- Determines ^{12}C/^{16}O ratio, influences nucleosynthesis
- Extraction of S-factor for near Gamow peak
- Benchmark calculations from cluster EFT

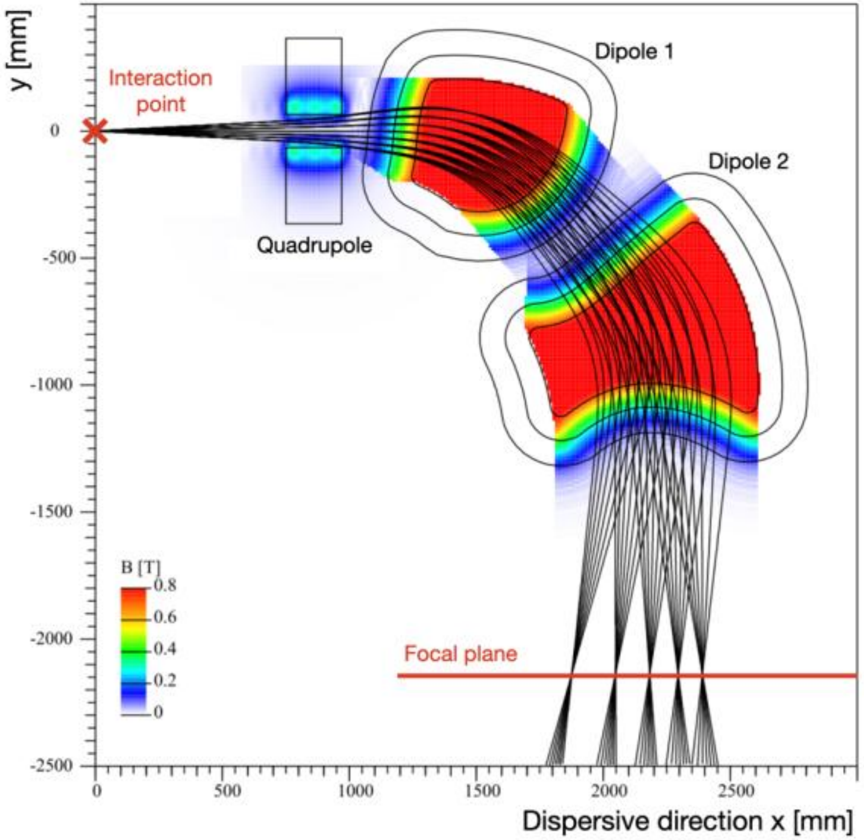
Between 1 MeV, and point of helium burning at 0.3 MeV, cross section drops by ~ six orders of magnitude

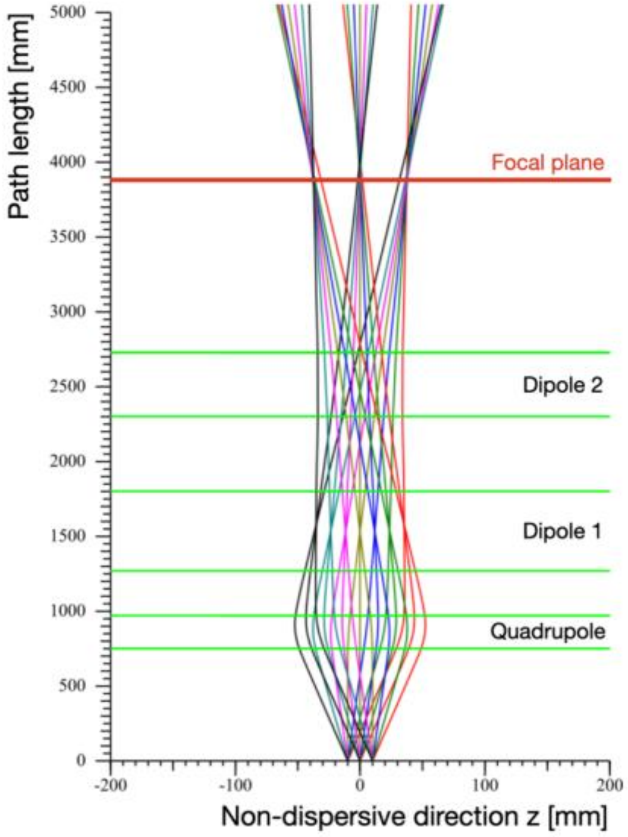




Requirements:

- Momentum resolution:
  $$\frac{\delta p}{p} < 10^{-4}$$
- Angular resolution:
  $$\delta\theta \ < \ 0.05°$$
- Precision cross section measurements with two identical spectrometers (**STAR** and **PORT**)



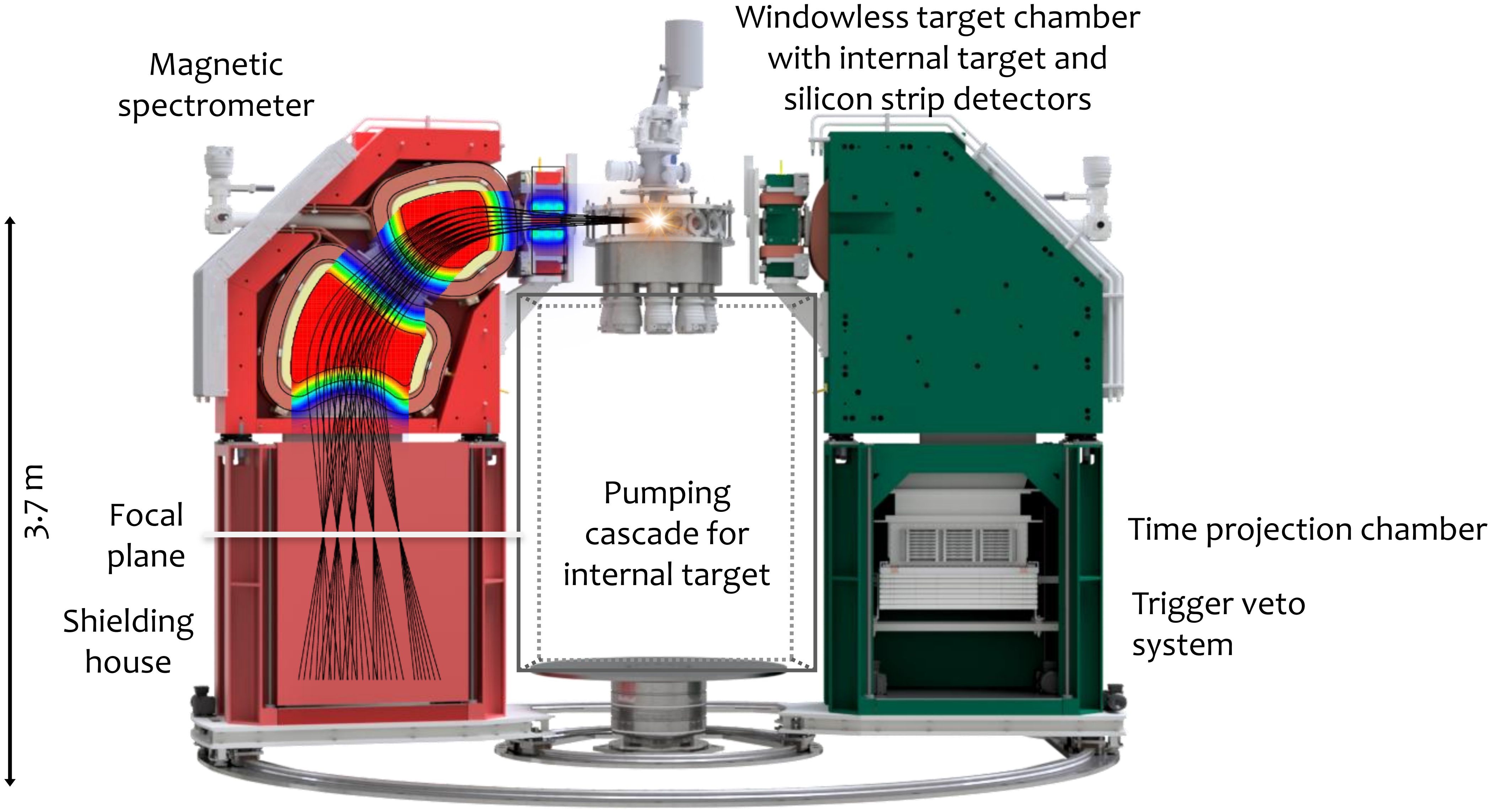


First-order matrix:

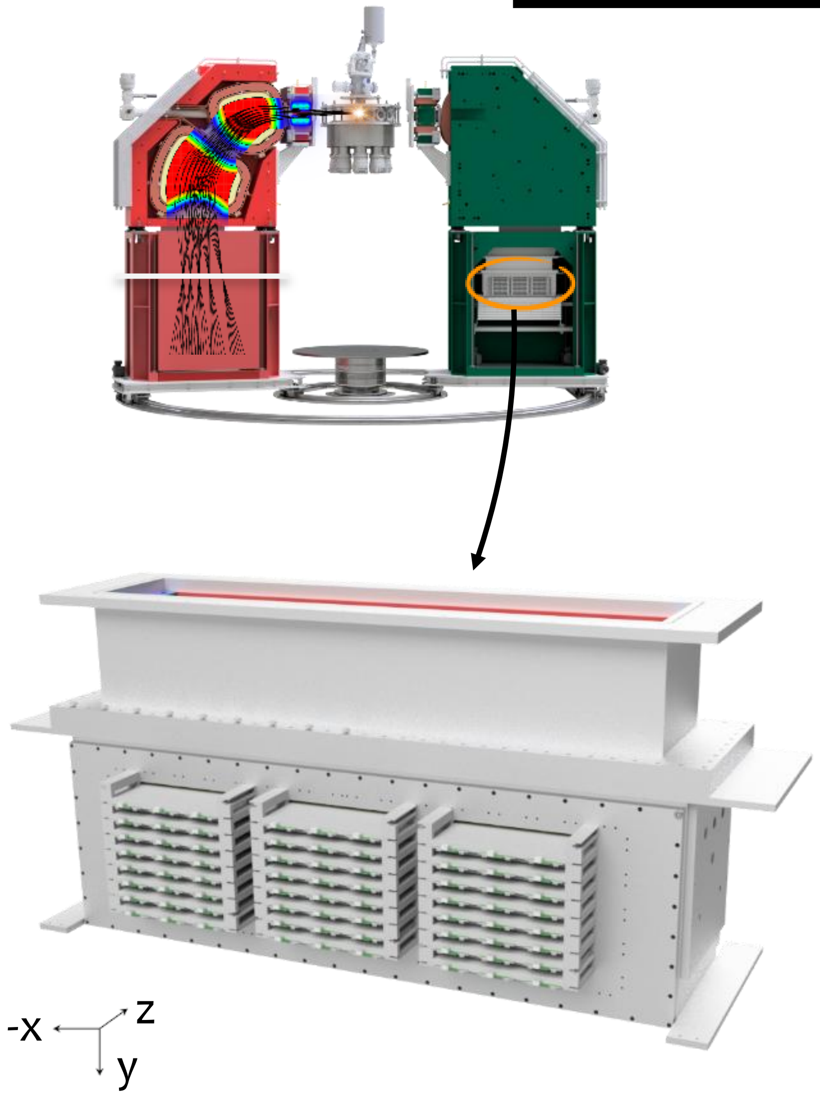
- Point-to-point focus in dispersive direction $(x|\theta_0) = 0$
- Nearly point-to-point focus in non-dispersive direction $(y|\phi_0) = 0$
- Magnification $M_x \sim -0.5$
- Dispersion $D \sim 5.5$ MeV/cm

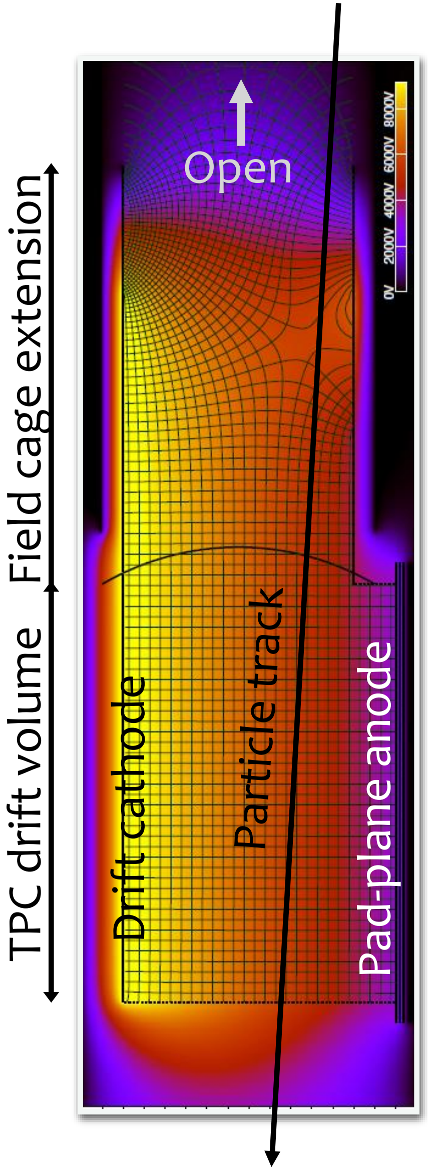
- Angular range: 15° – 165°
- Momentum range: 3 – 282 MeV/c
- Accepted solid angle: $\Delta\Omega$ = 6 msr

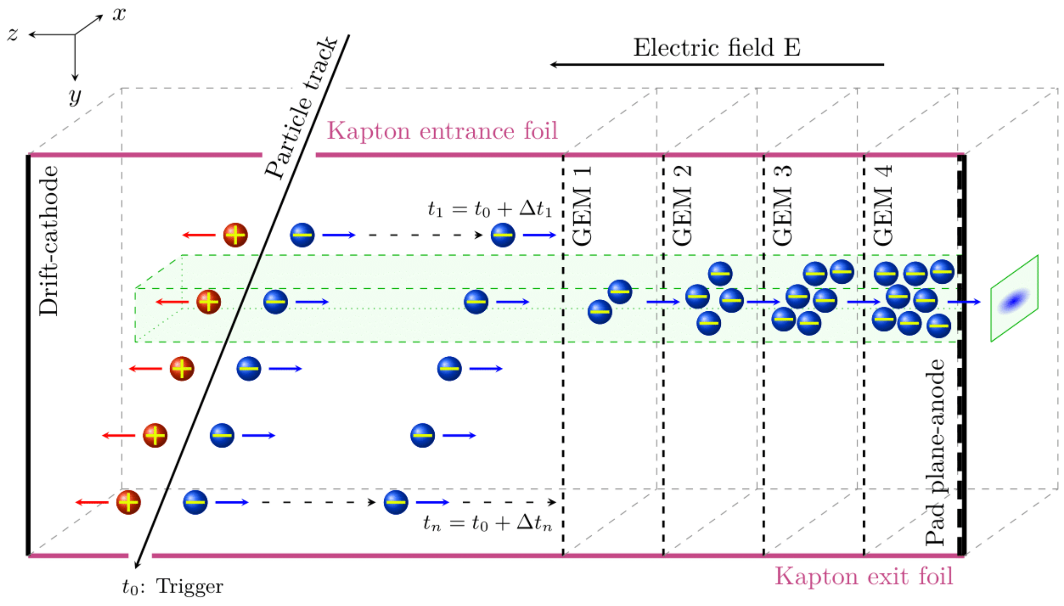
MAGIX Subsystems



The MAGIX Time Projection Chamber (TPC)



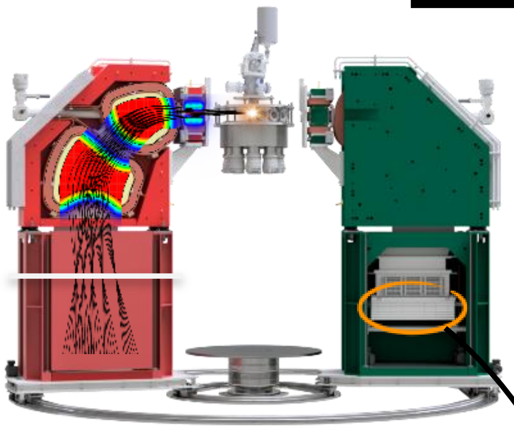


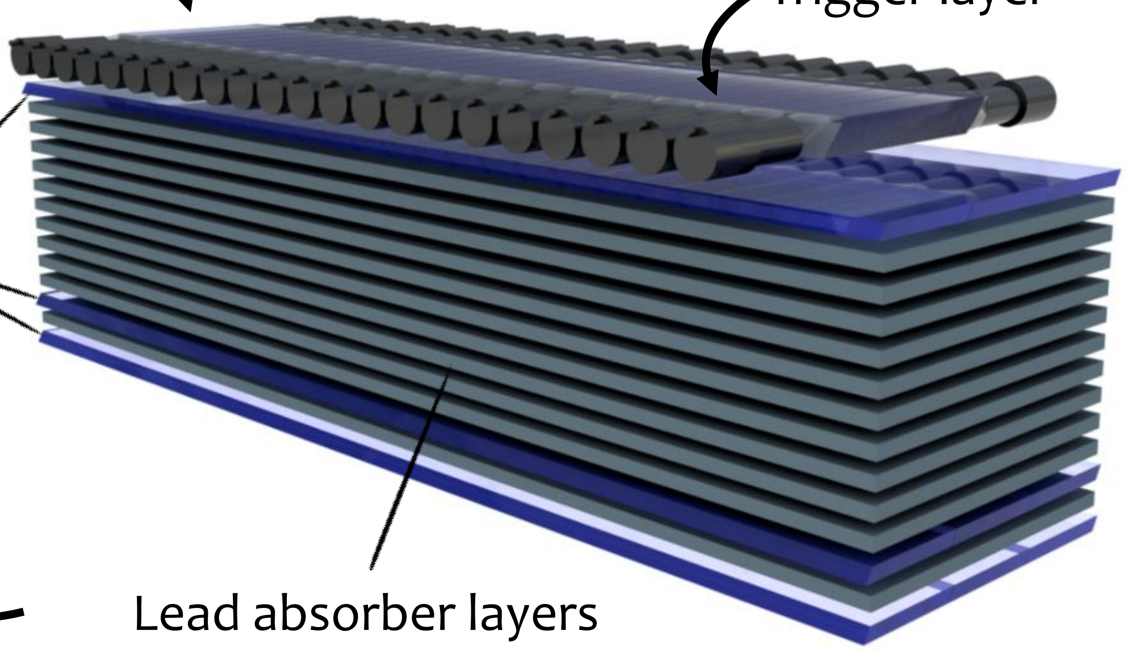


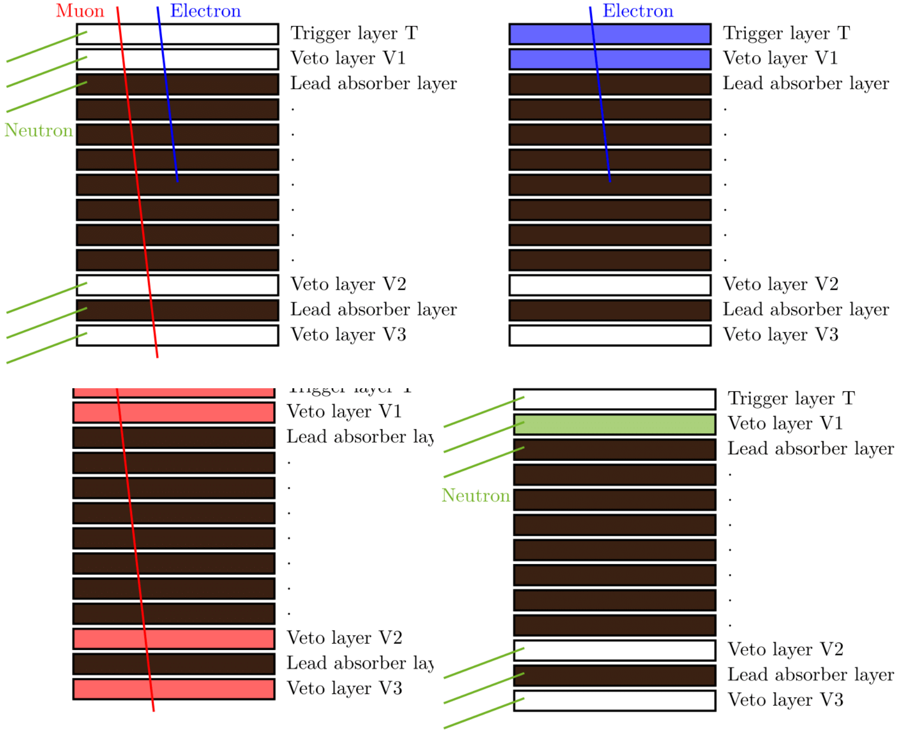
- TPC based on 4 Gas Electron Multipliers (GEMs)
- Segmented readout at pad-plane anode
- Track reconstruction by pad plane plus drift time
- Expected accuracy in focal plane coordinates: $\delta x = 100\ \mu\text{m}$ and $\delta\theta = 3.5$ mrad
- Open field cage to minimize the material budget

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



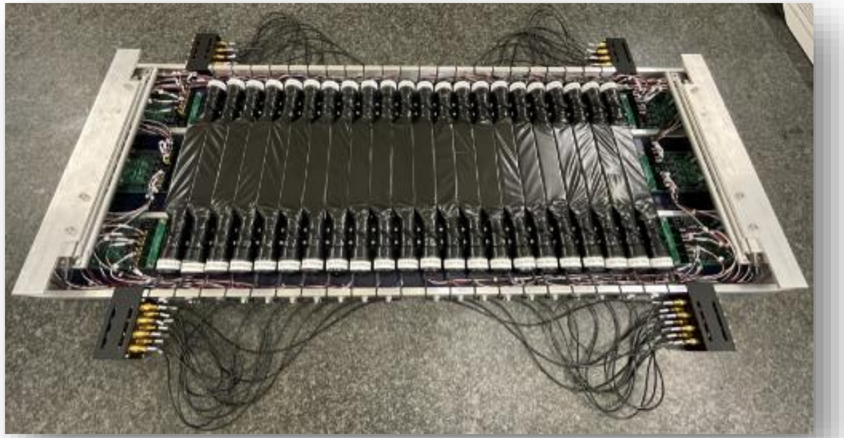


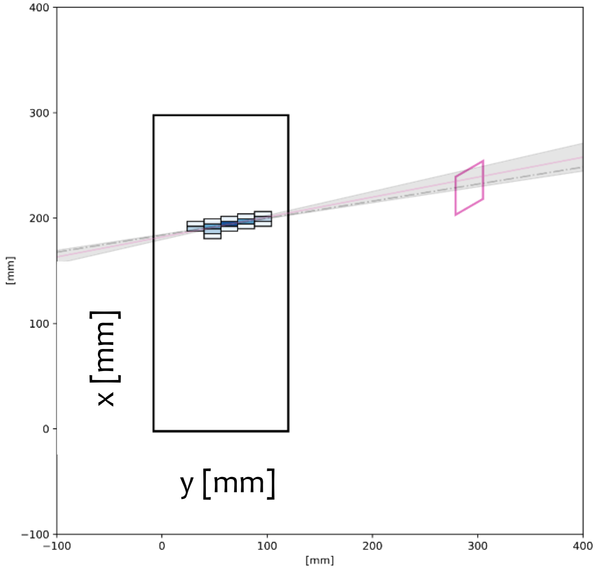


Status of MAGIX Subsystems

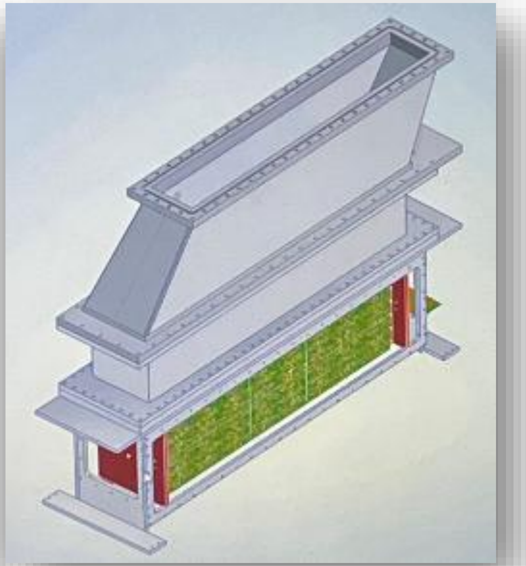
Detectors:

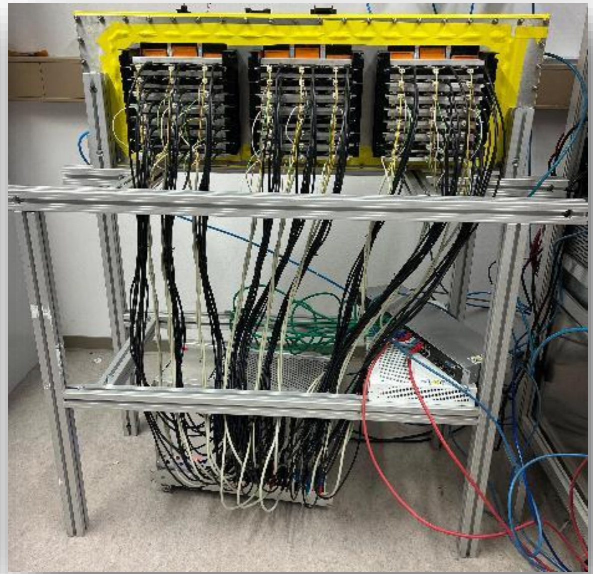
Trigger layer



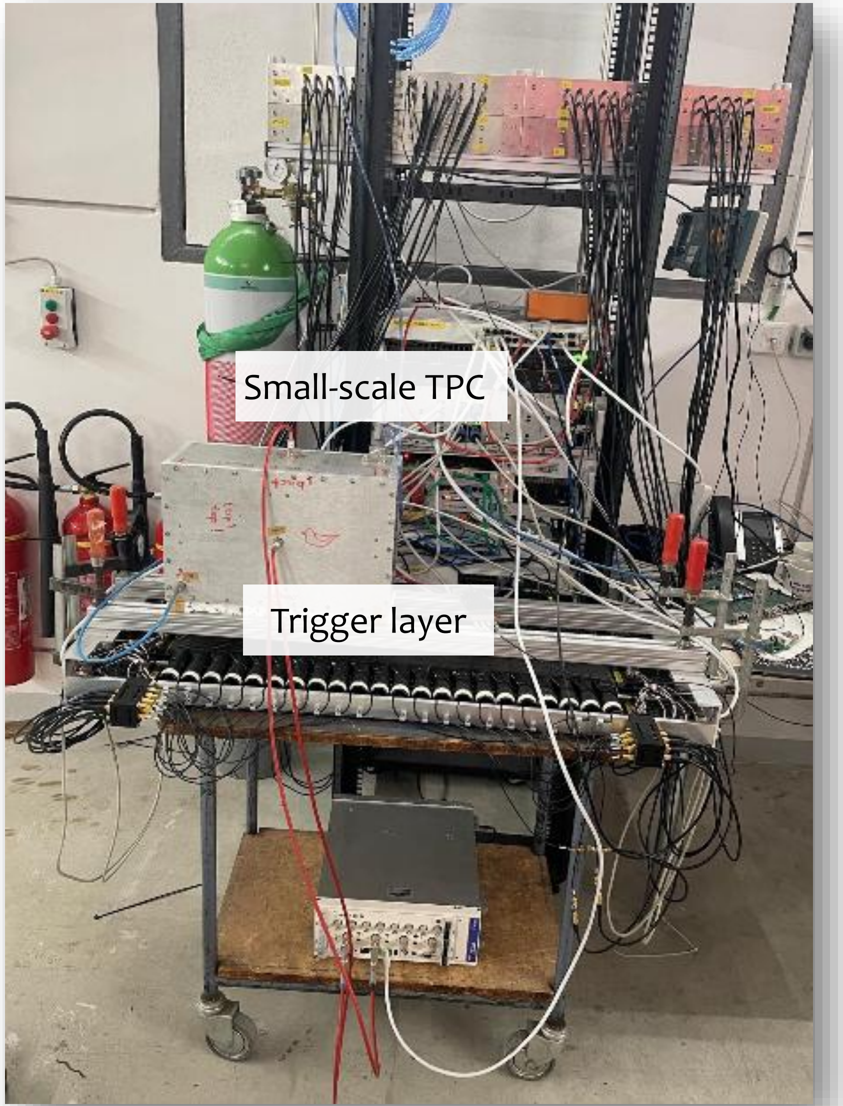


TPC

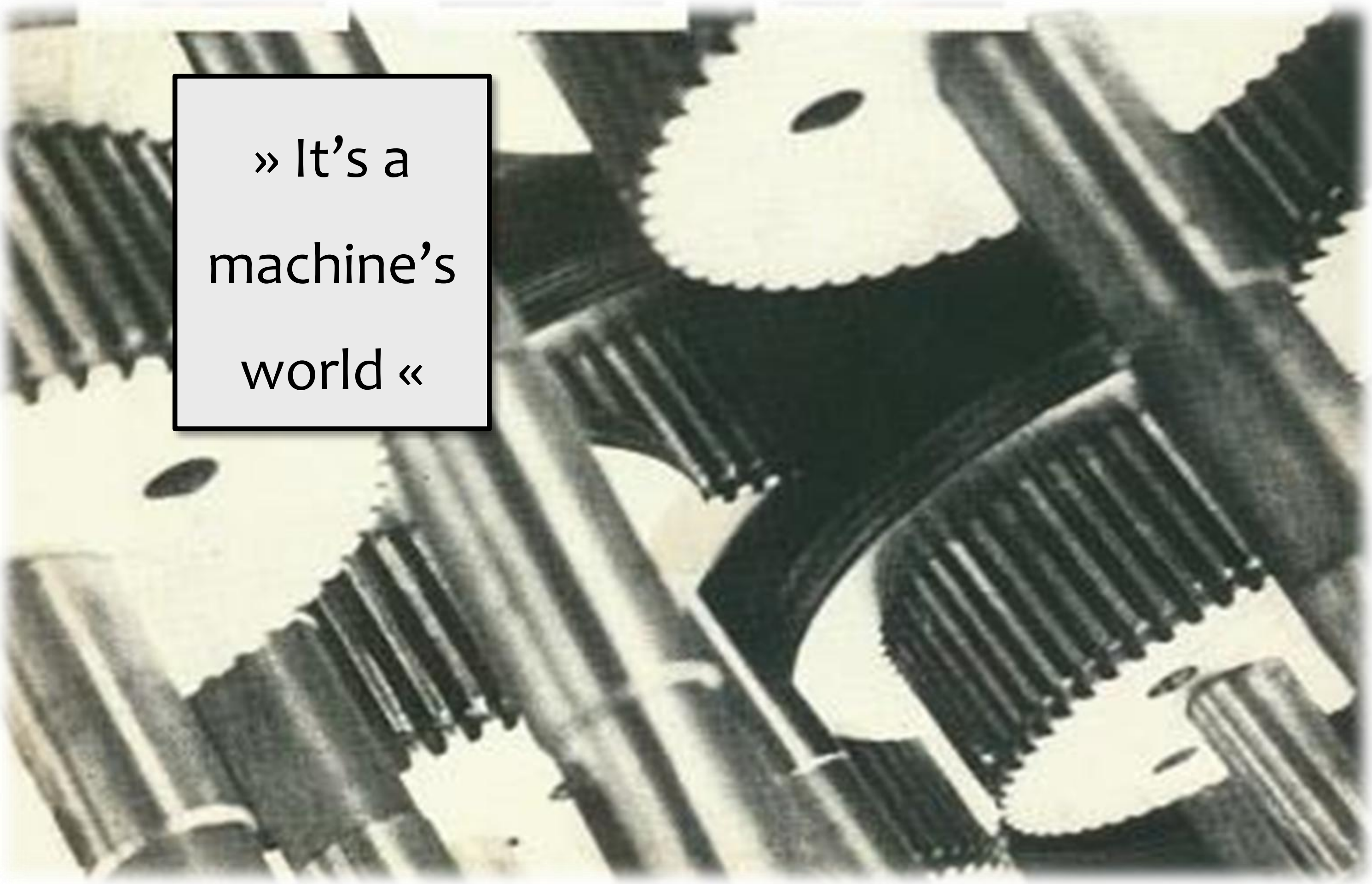




Combination of trigger with TPC



Backmatter



Electron scattering experiments in Mainz:

- Continuation of **experiments with MAMI**
- Preparation of **experiments with MESA**

Precision electroweak physics

- Tests of the Standard Model
- Weak form factors and neutrons skins

Light dark matter searches

Nucleon/nuclear structure

- Proton form factors
- Few-body systems
- Astrophysically relevant cross sections