The MESA Facility in Mainz.

Mirco Christmann

for the MAGIX Collaboration

NSTAR 2026 - 15th International Workshop on the Physics of Excited Nucleons

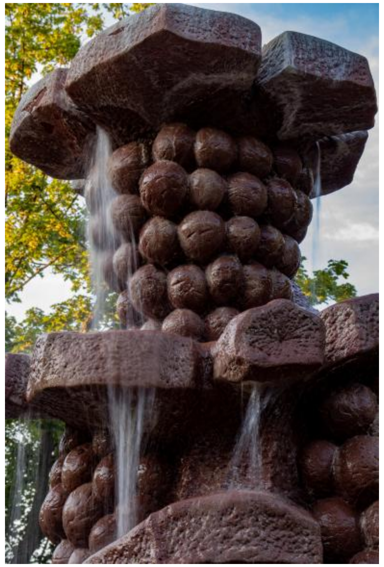
7th - 11th September 2026, Seville, Spain

Mainz – Wine, Carnival, the Rhine…

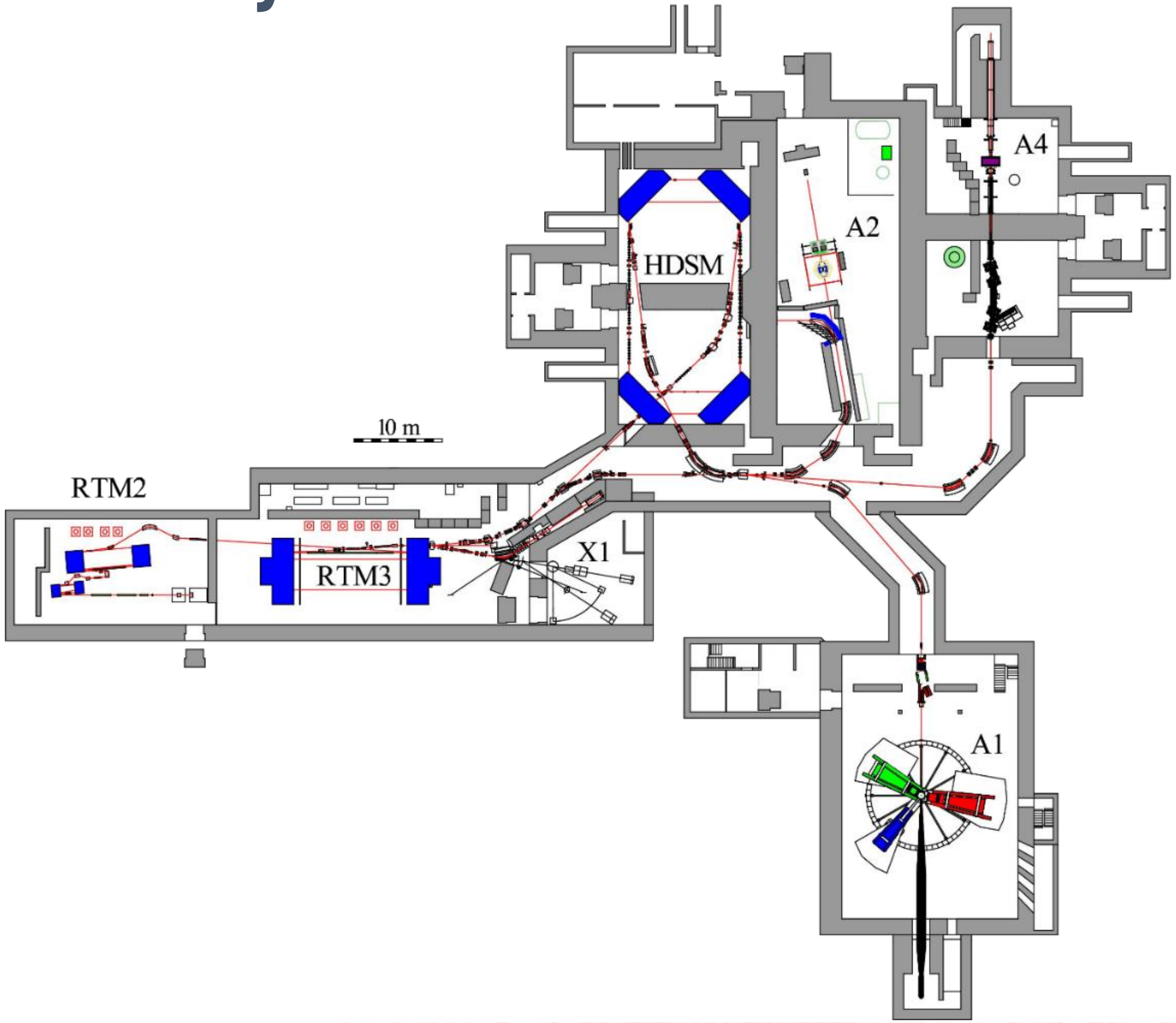
bistummainz.de

mainz-tourismus.com

rheinhessen.de: Laubenheimer Klosterberg



… and Nuclear Physics.



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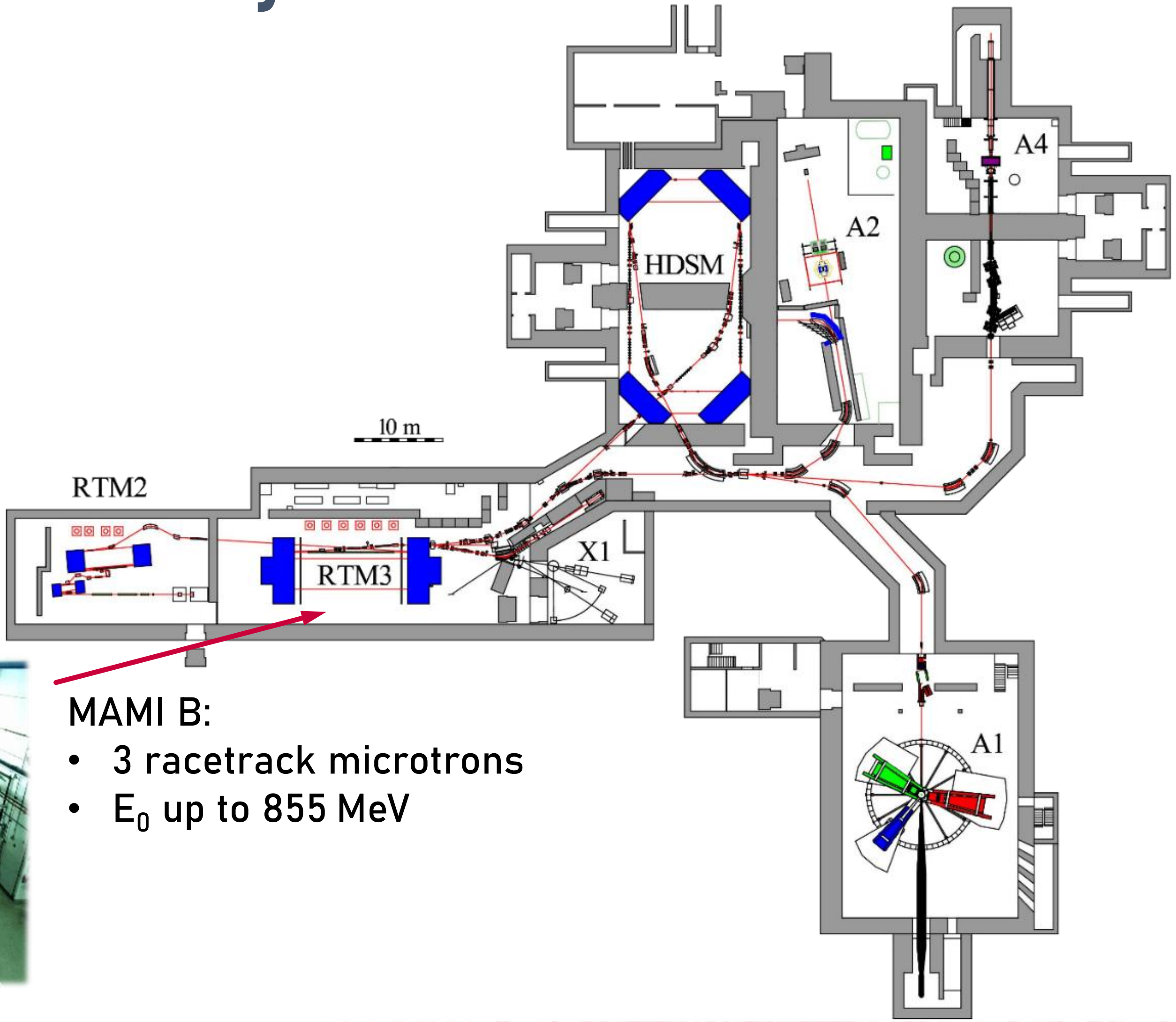
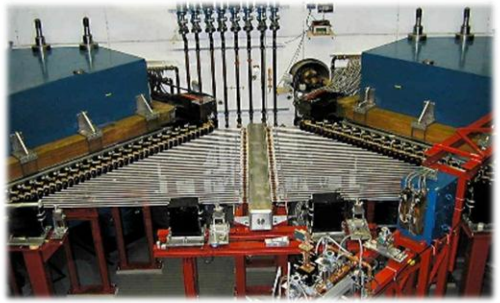
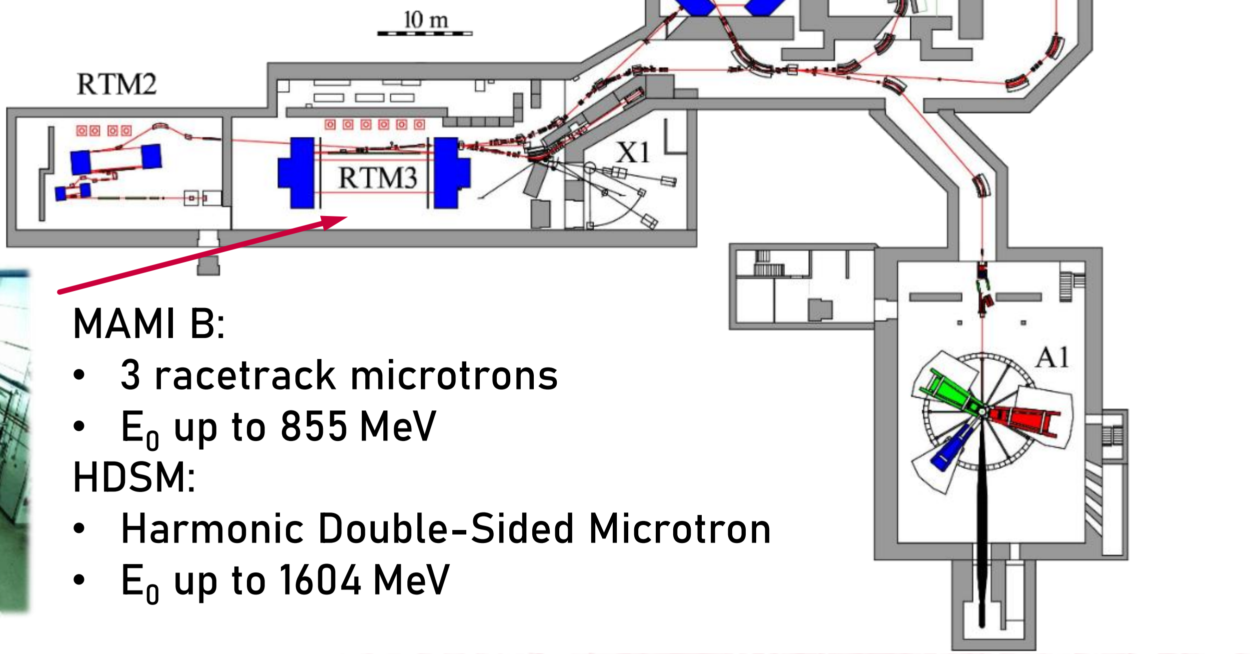


MAMI B:

- 3 racetrack microtrons
- E_0 up to 855 MeV

… and Nuclear Physics.

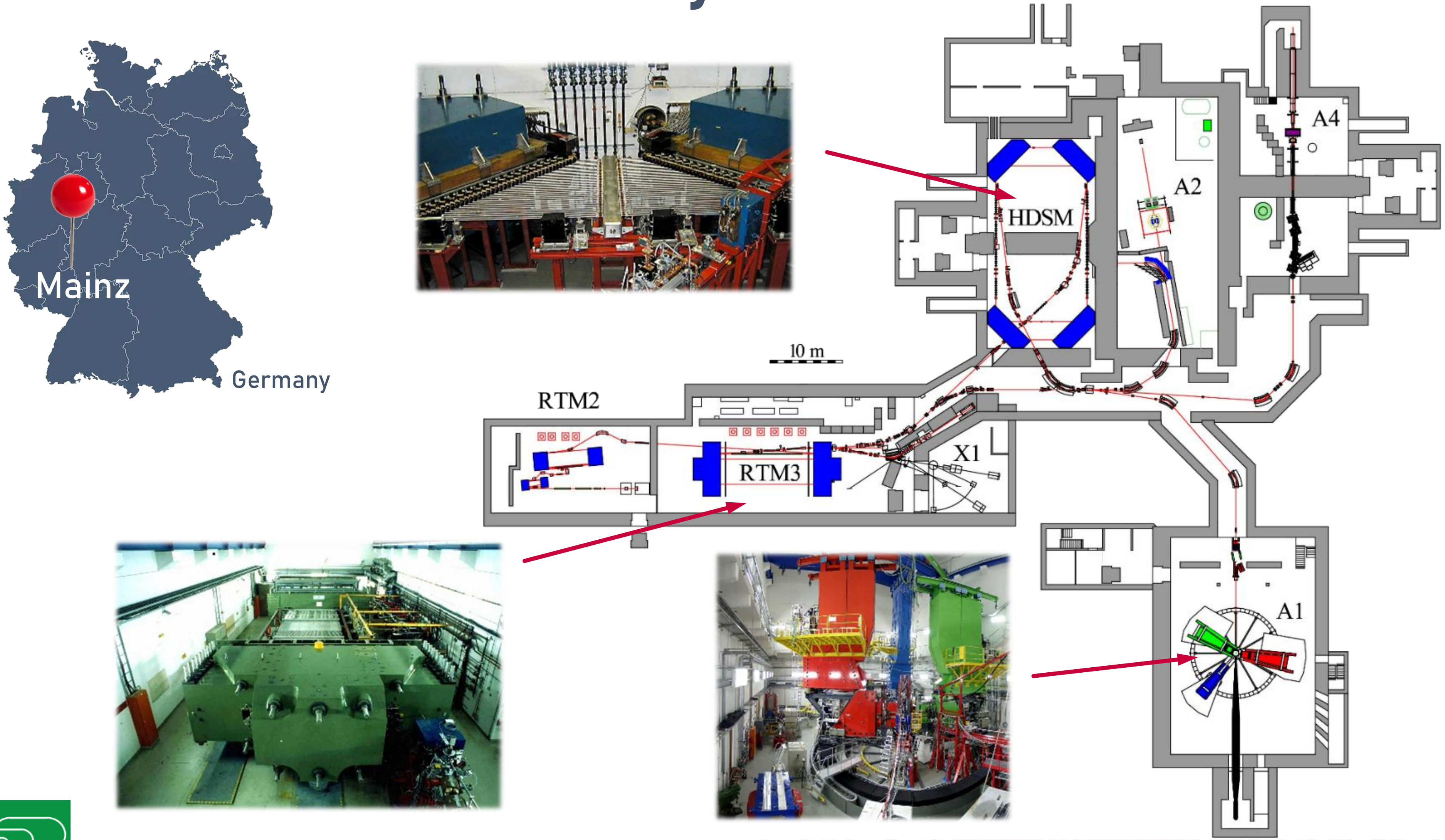




MAMI B:
- 3 racetrack microtrons
- E_0 up to 855 MeV

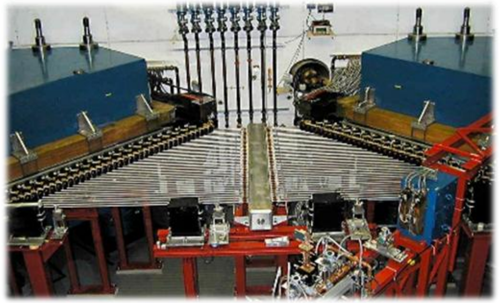
HDSM:
- Harmonic Double-Sided Microtron
- E_0 up to 1604 MeV

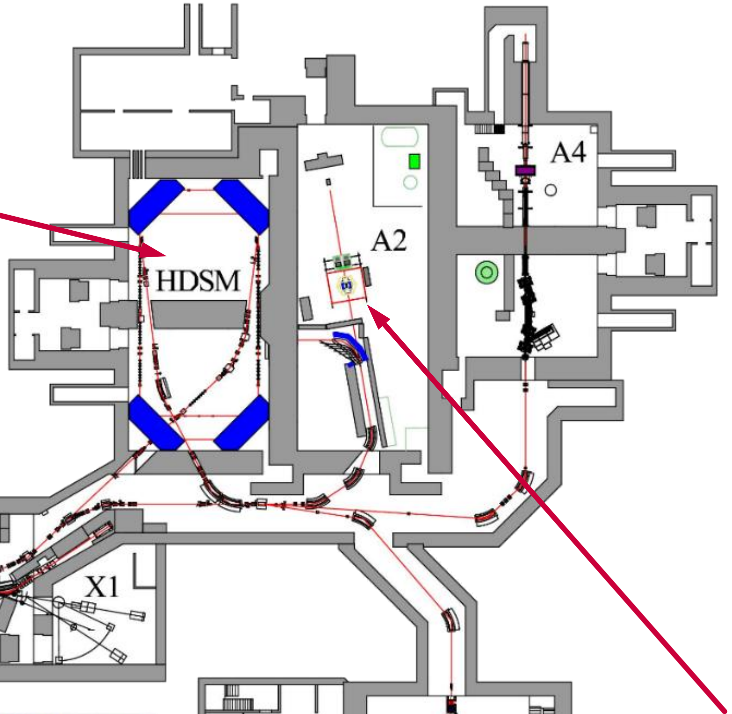
… and Nuclear Physics.

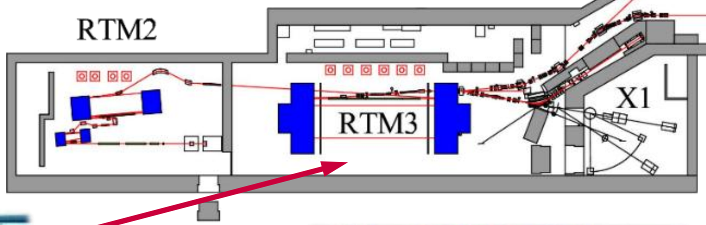


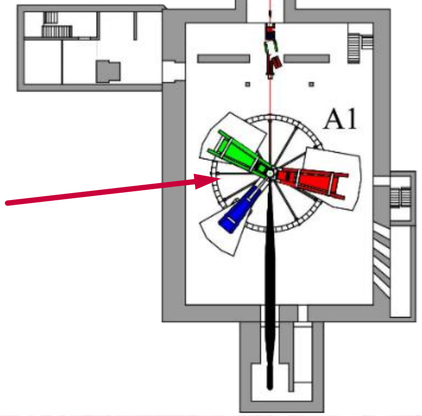
A1 – **High-resolution electron scattering**
A2 – **Real-photon physics**

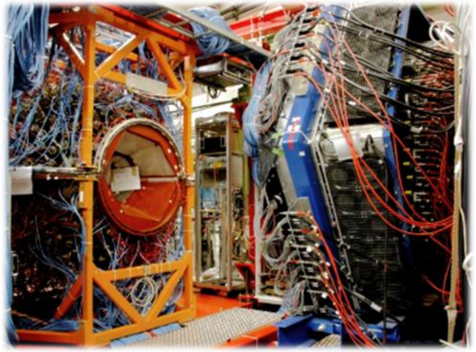
… and Nuclear Physics.





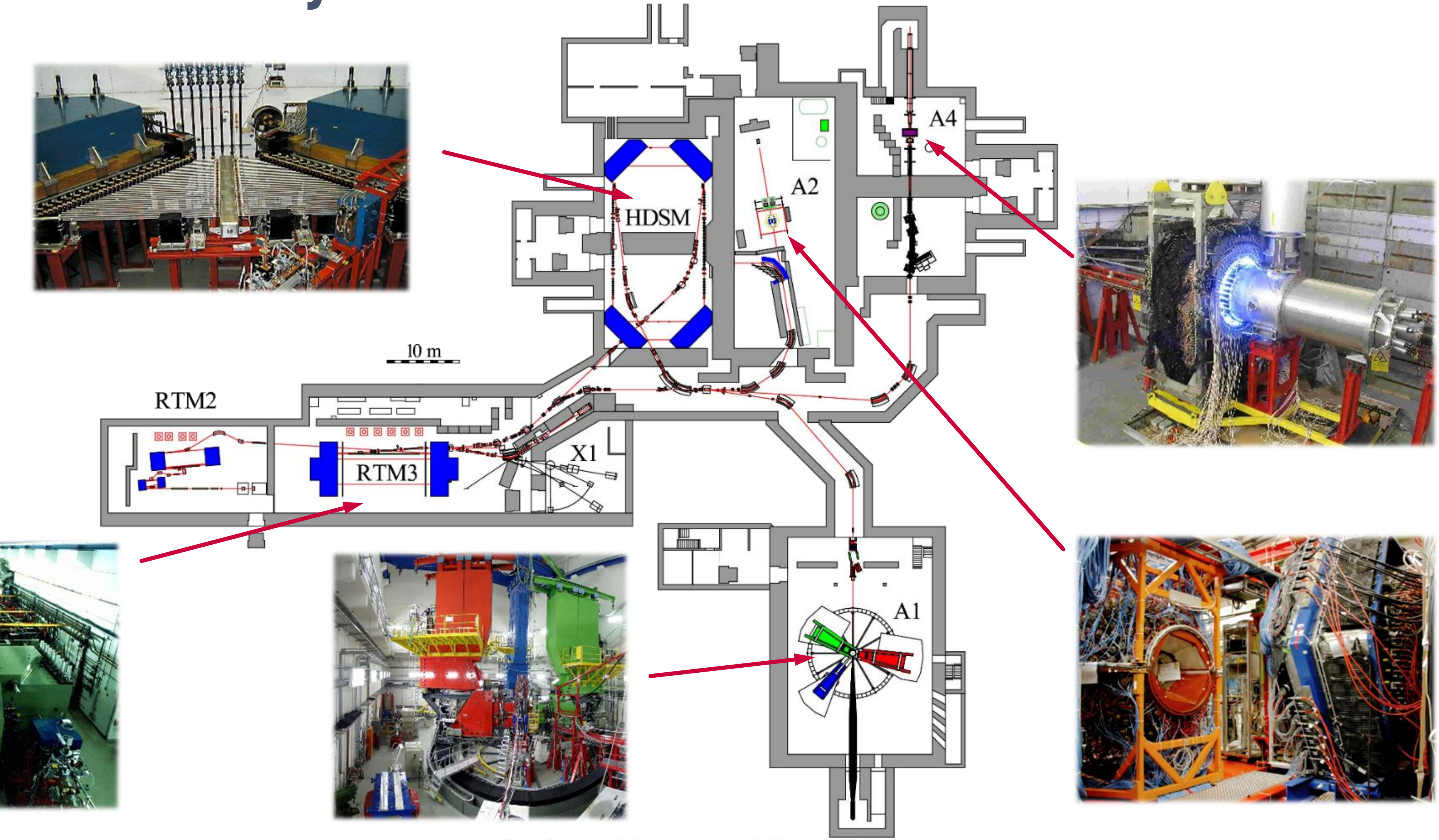






A1 – High-resolution electron scattering
A2 – Real-photon physics
A4 – Parity-violation & nucleon structure

… and Nuclear Physics.



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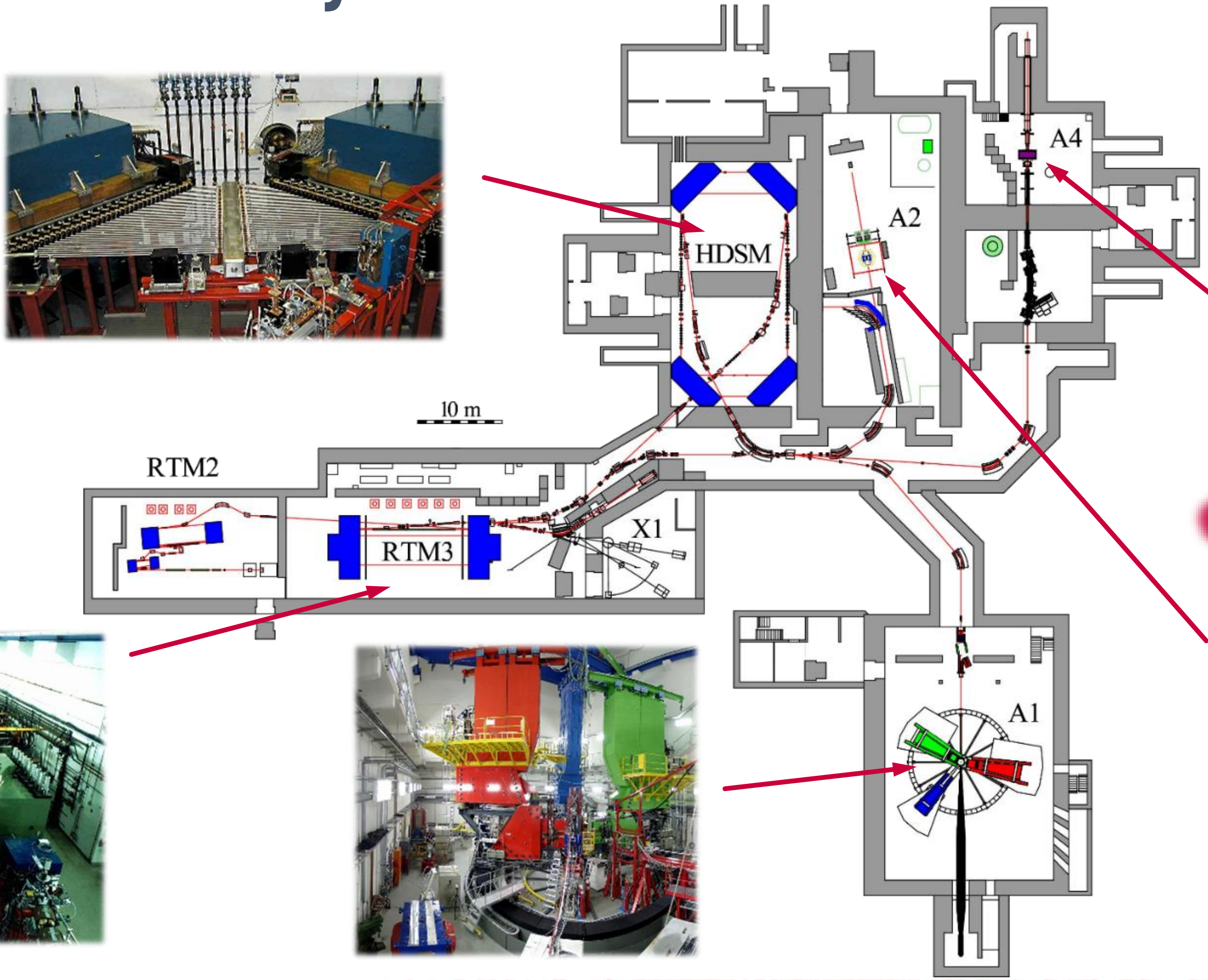

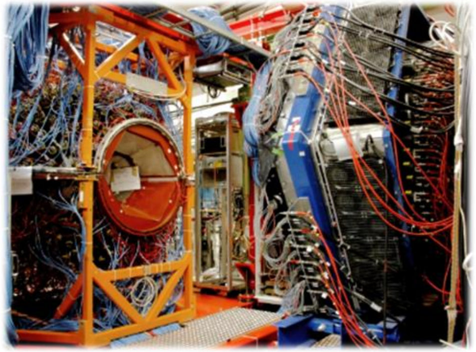

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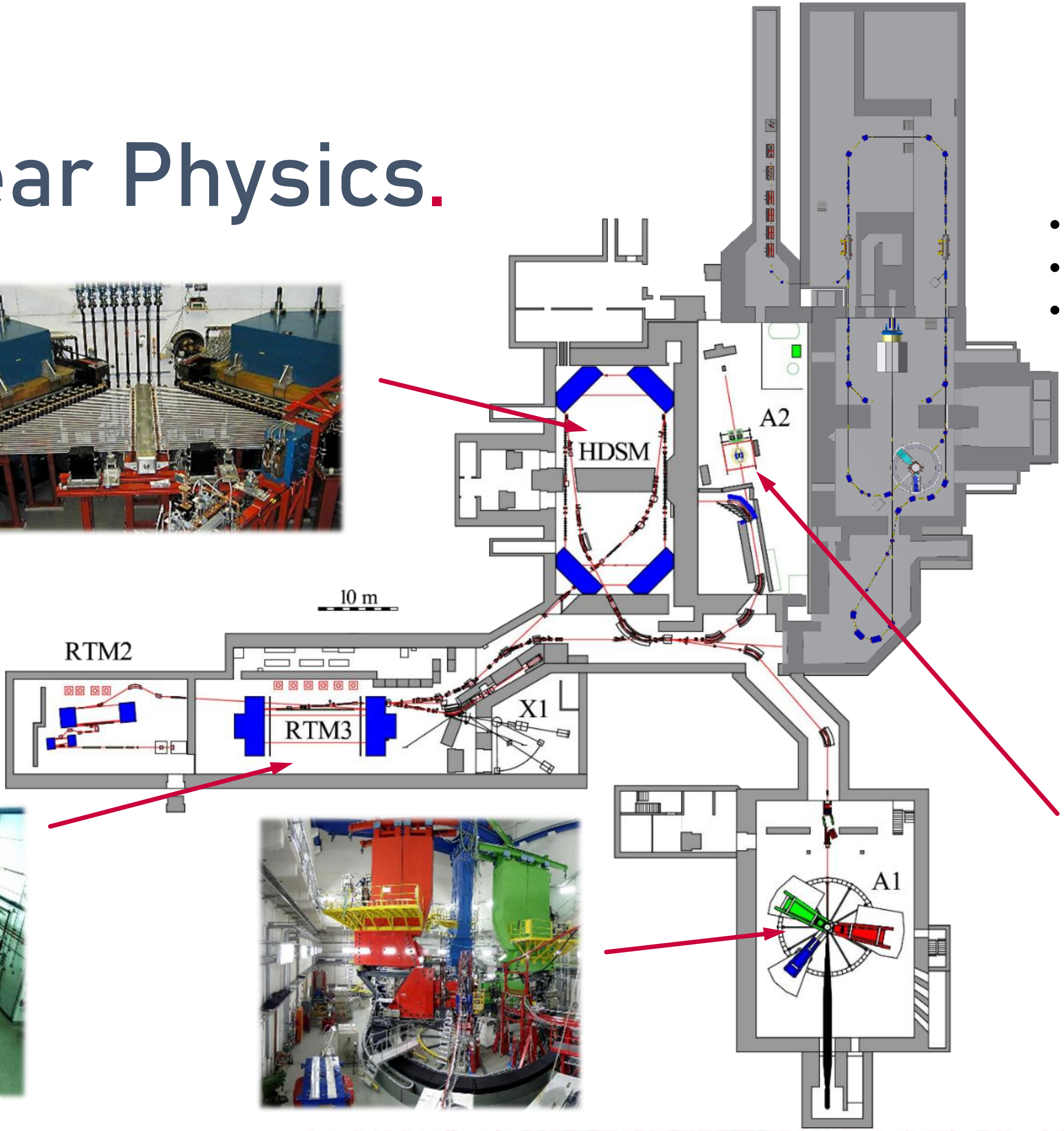
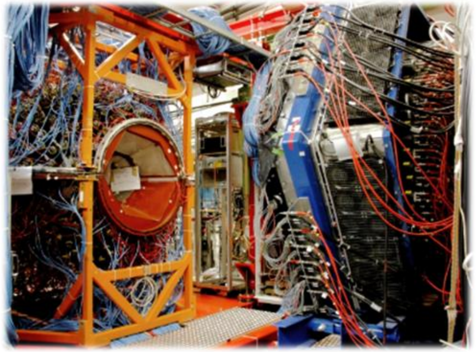
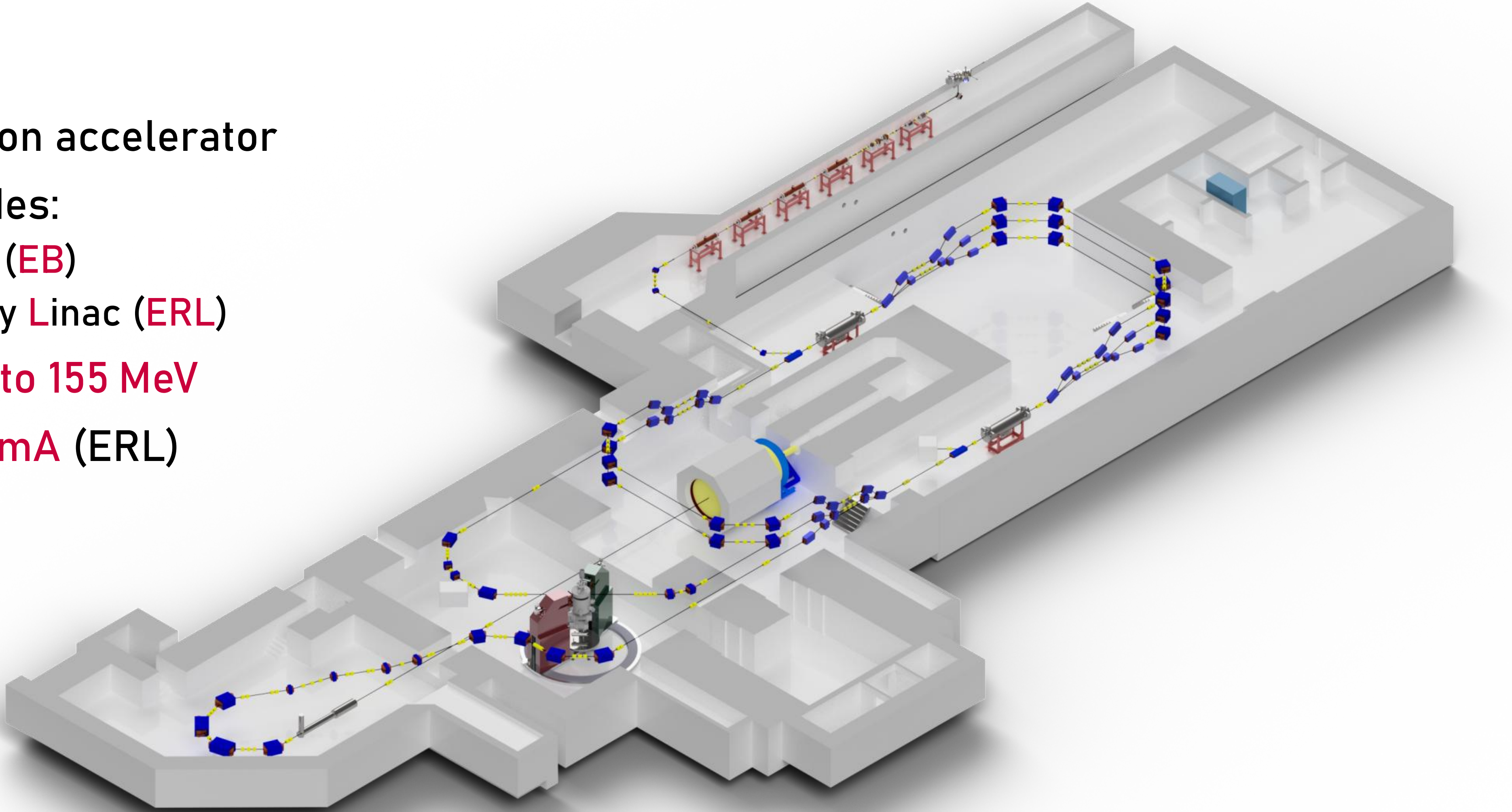




- Existing halls cleared
- Additional halls
- A4 beam dump reused

The Mainz Energy-recovering Superconducting Accelerator.

- Low-energy electron accelerator
- Two operating modes:
  - Extracted Beam (EB)
  - Energy-Recovery Linac (ERL)
- Beam energies up to 155 MeV
- Beam currents $\geq 1\,\mathrm{mA}$ (ERL)



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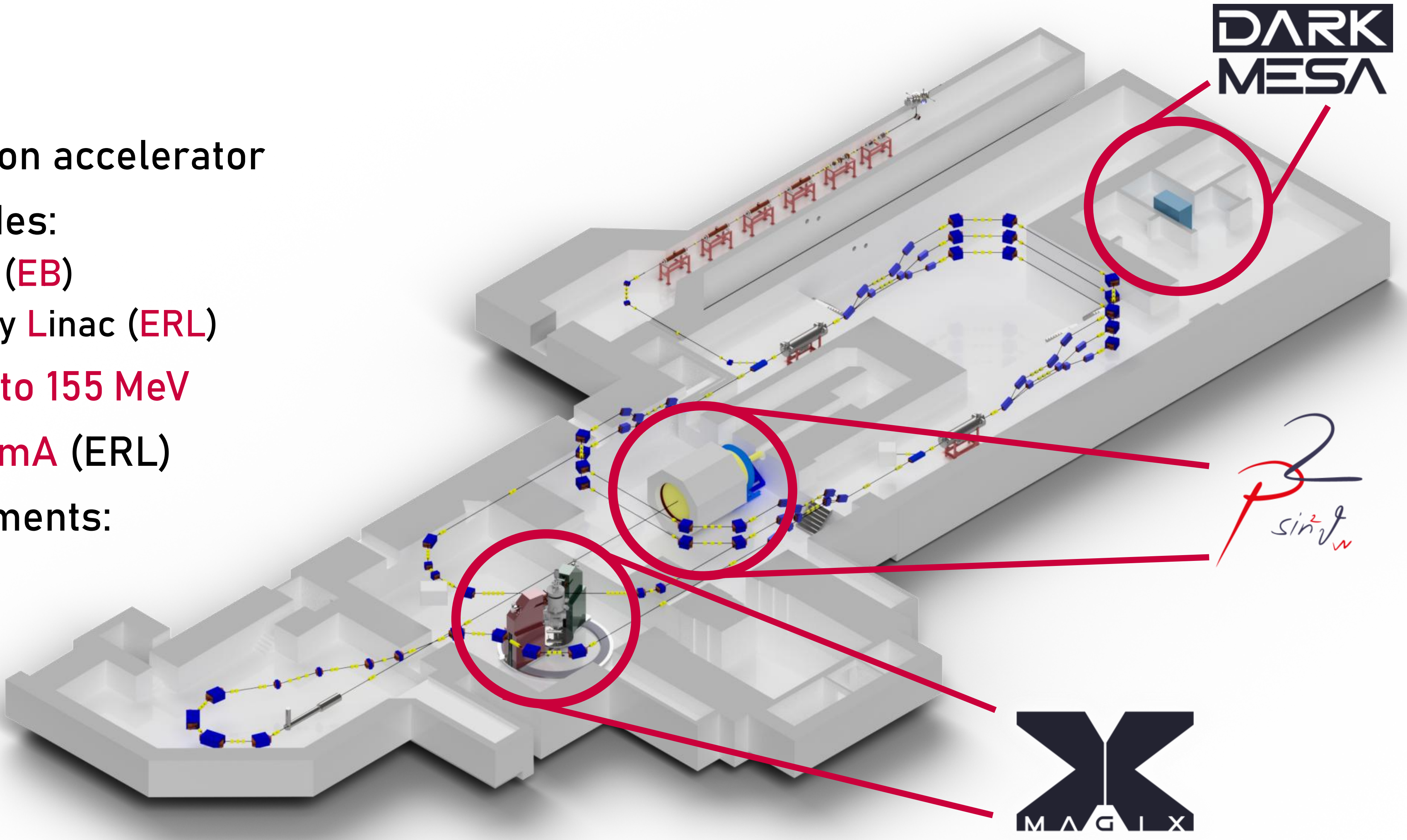
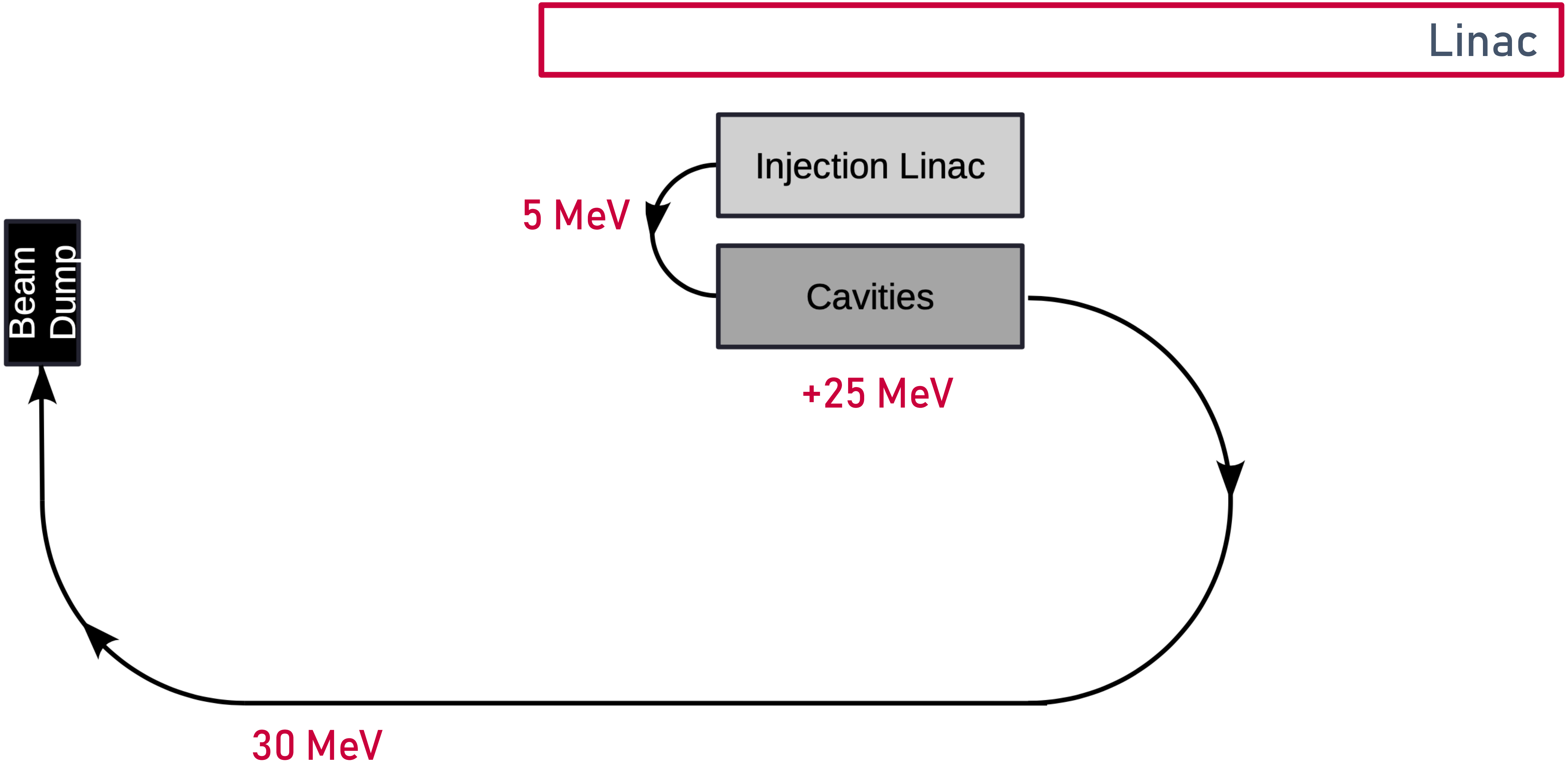
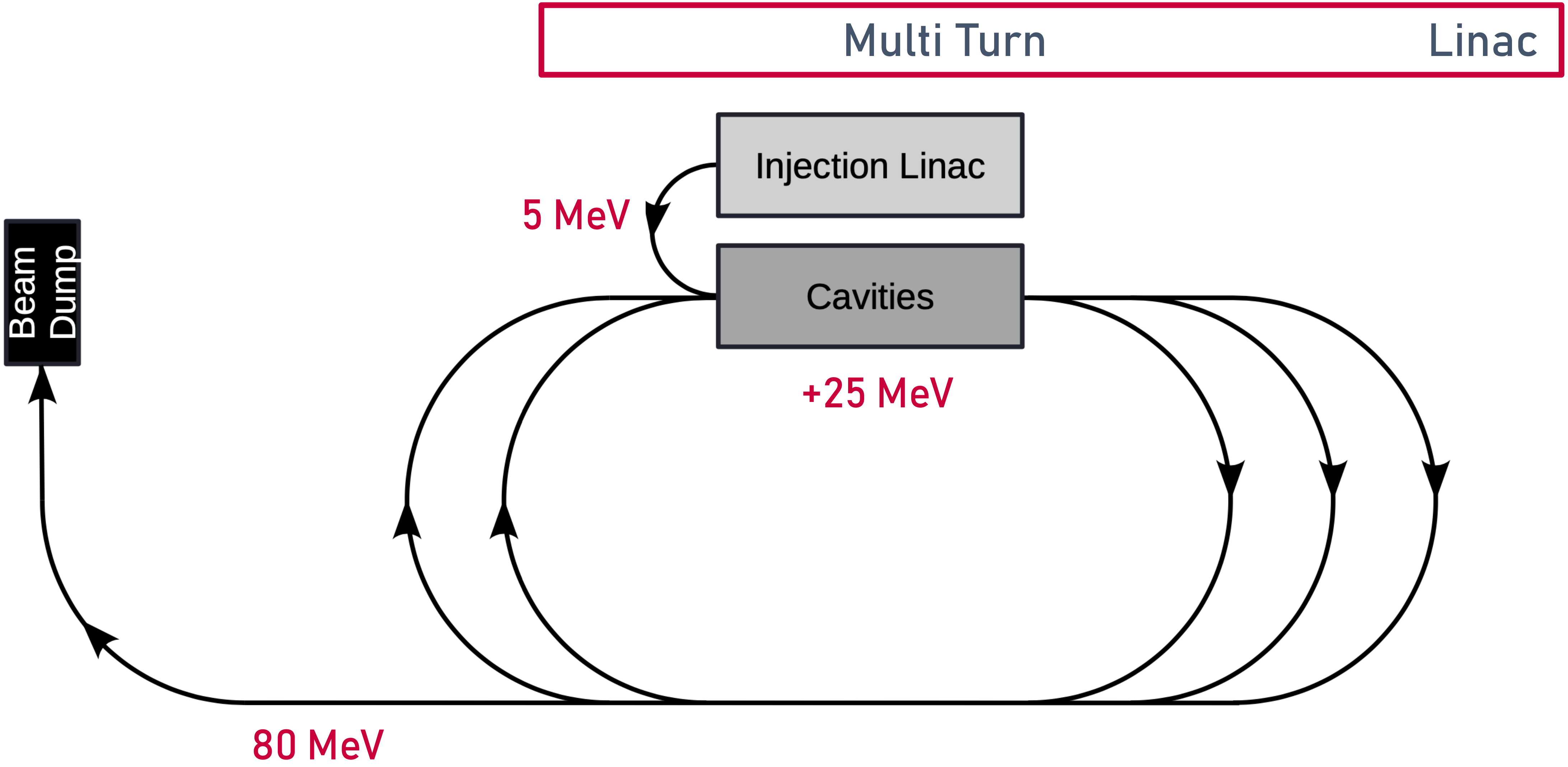
- Beam currents $\geq$ 1 mA (ERL)
- Three main experiments:
  - MAGIX
  - P2
  - DarkMESA



MESA, step by step. (1/6)

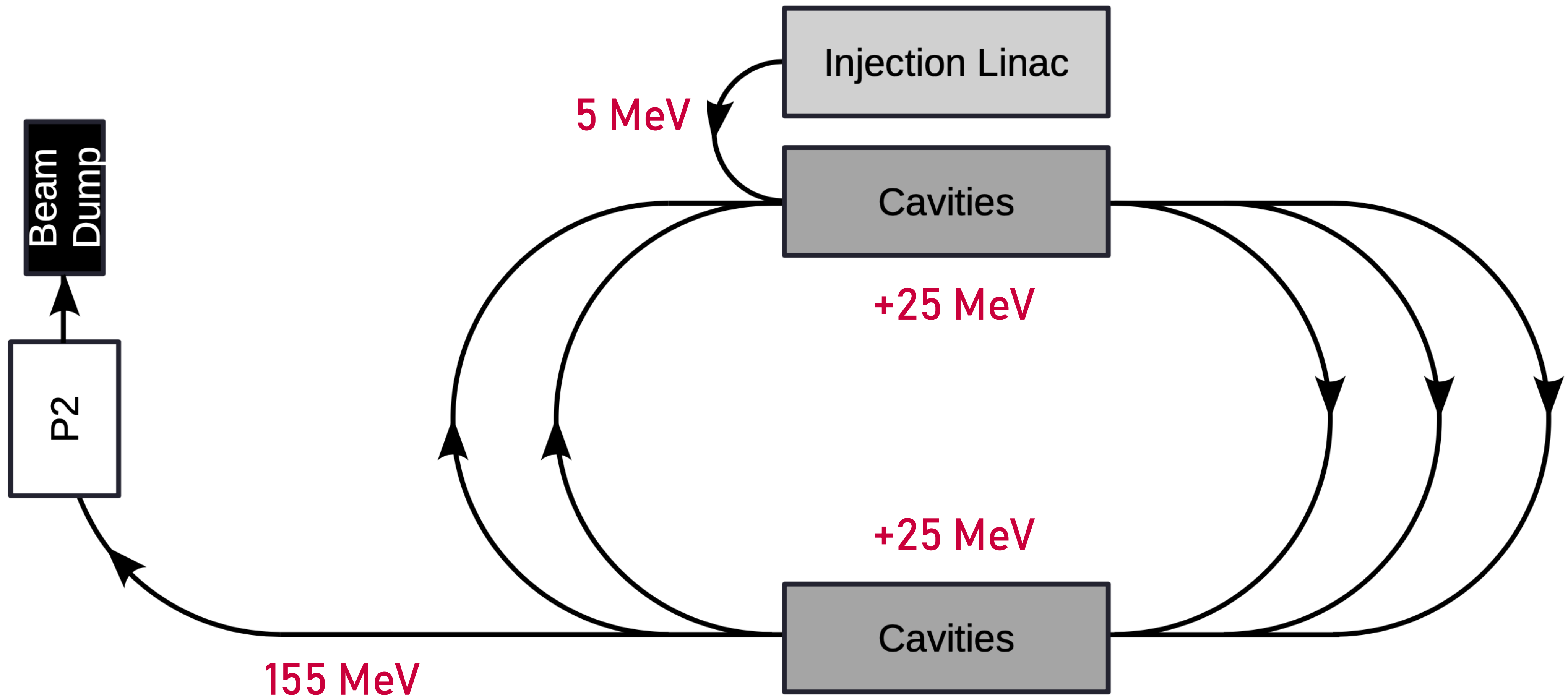


MESA, step by step. (2/6)



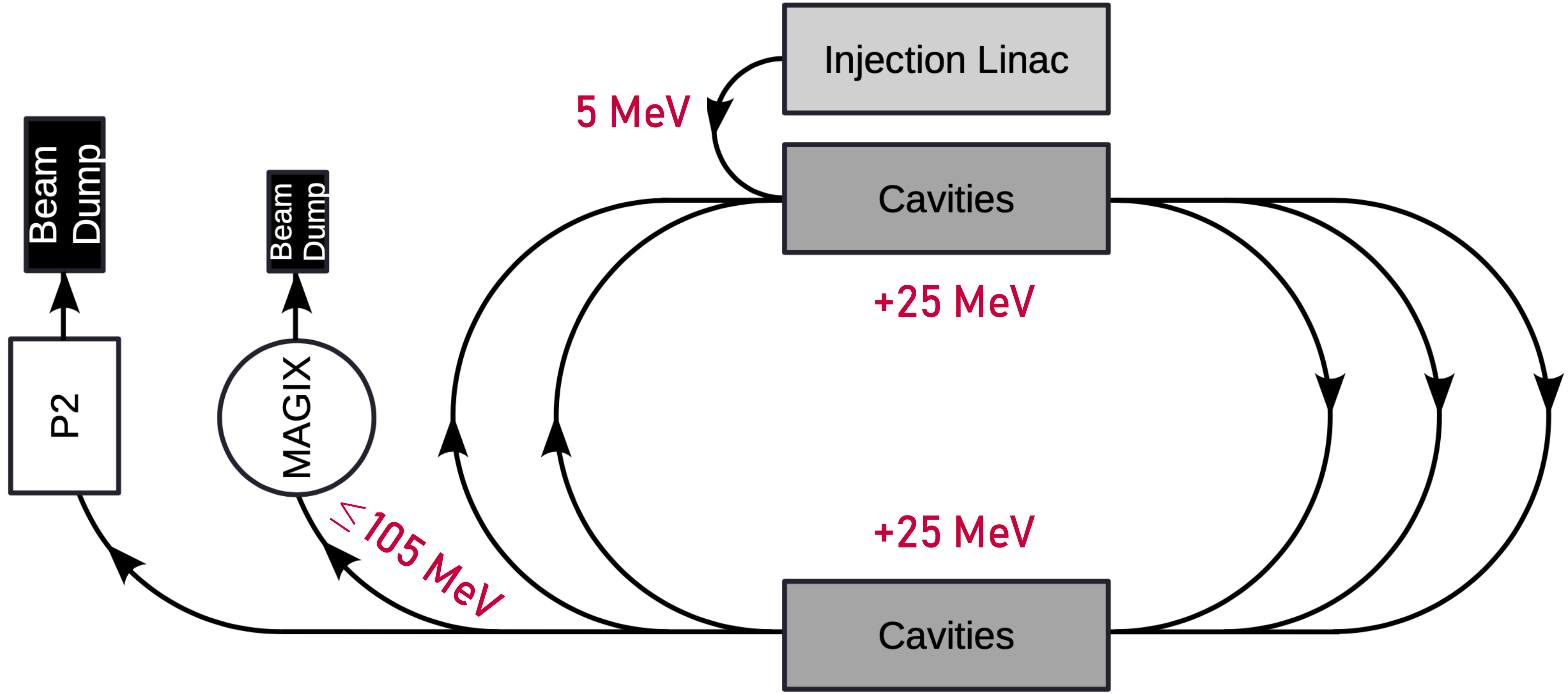
MESA, step by step. (3/6)

Double-sided Multi Turn Linac



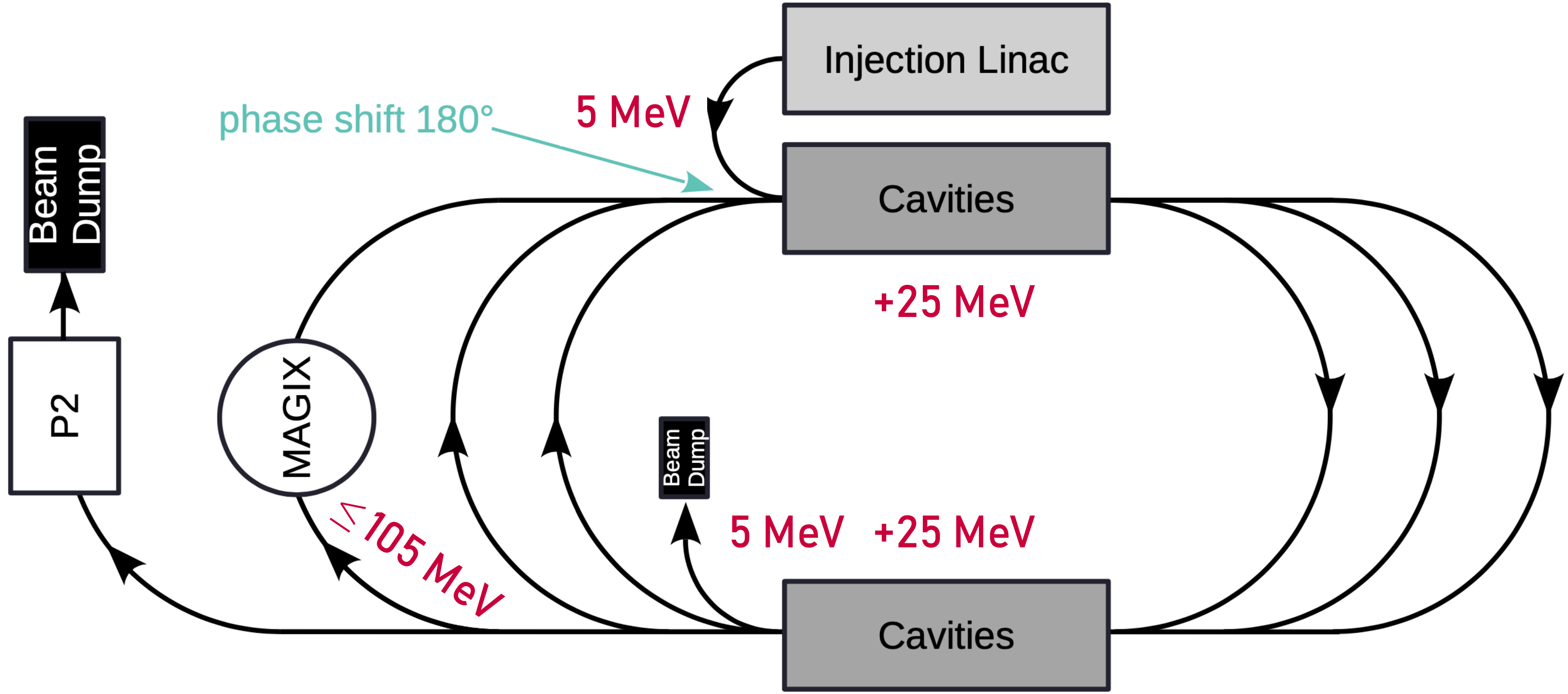
MESA, step by step. (4/6)

Double-sided Multi Turn Linac



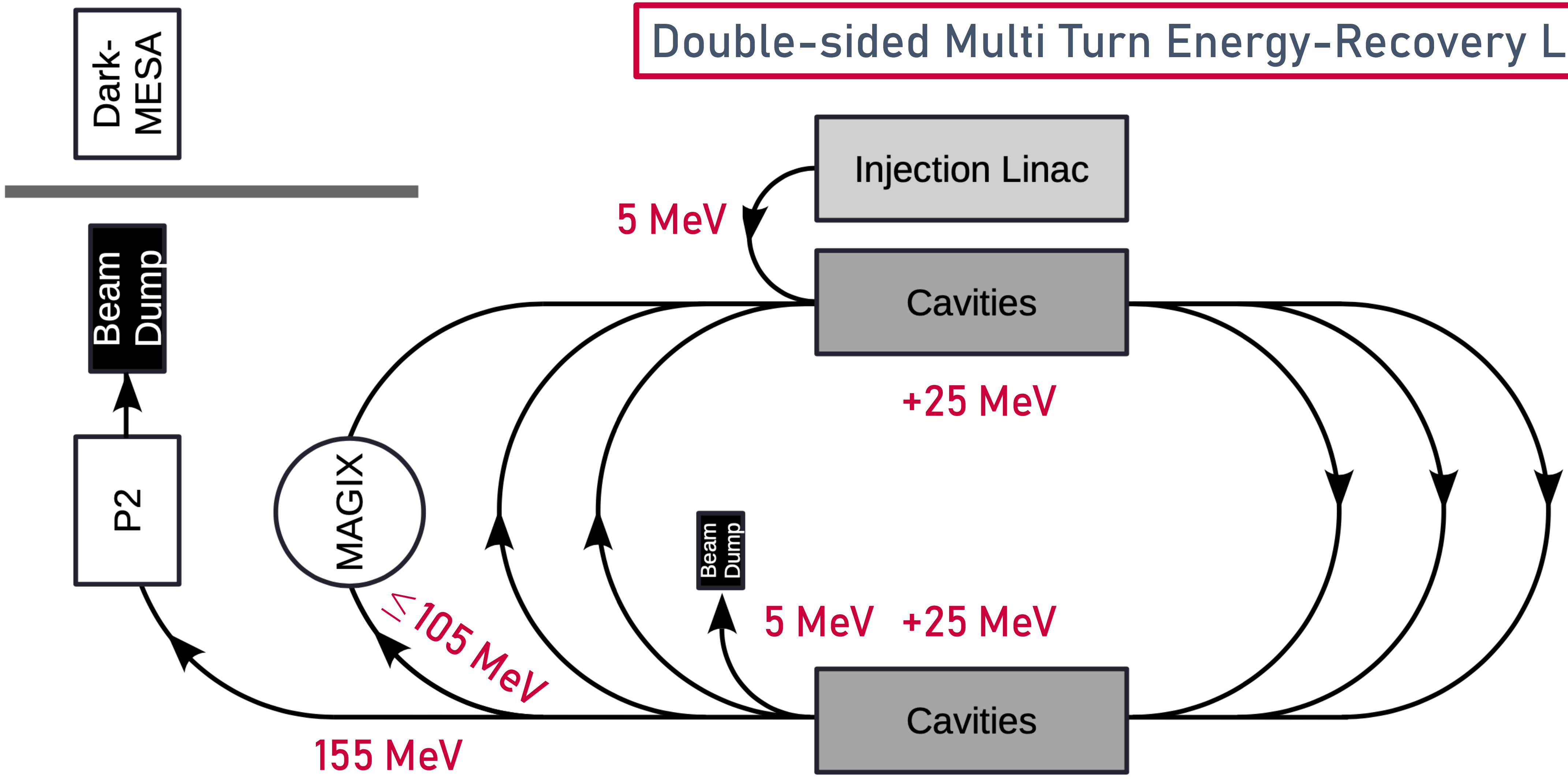
MESA, step by step. (5/6)

Double-sided Multi Turn Energy-Recovery Linac

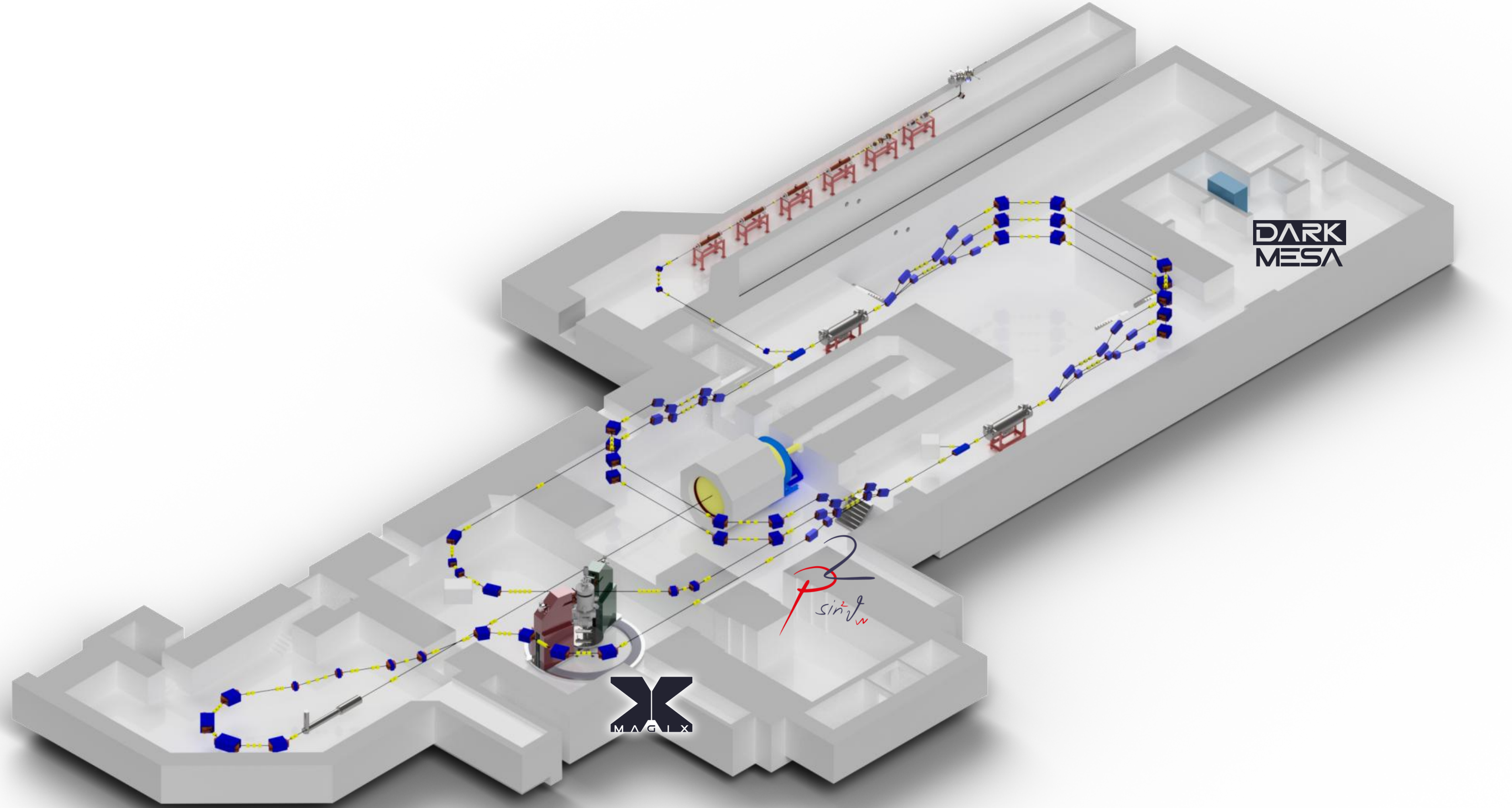


MESA, step by step. (6/6)

Double-sided Multi Turn Energy-Recovery Linac



MESA – Status & Impressions.



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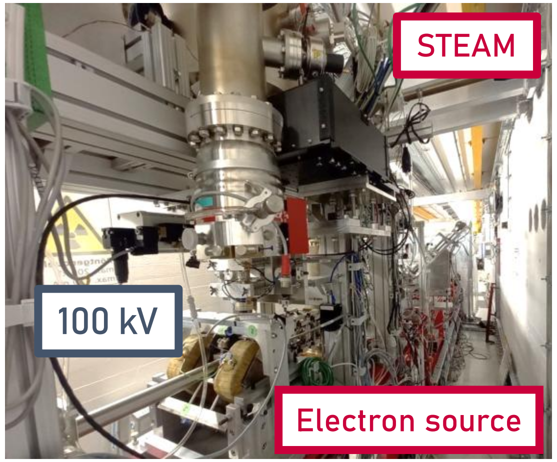
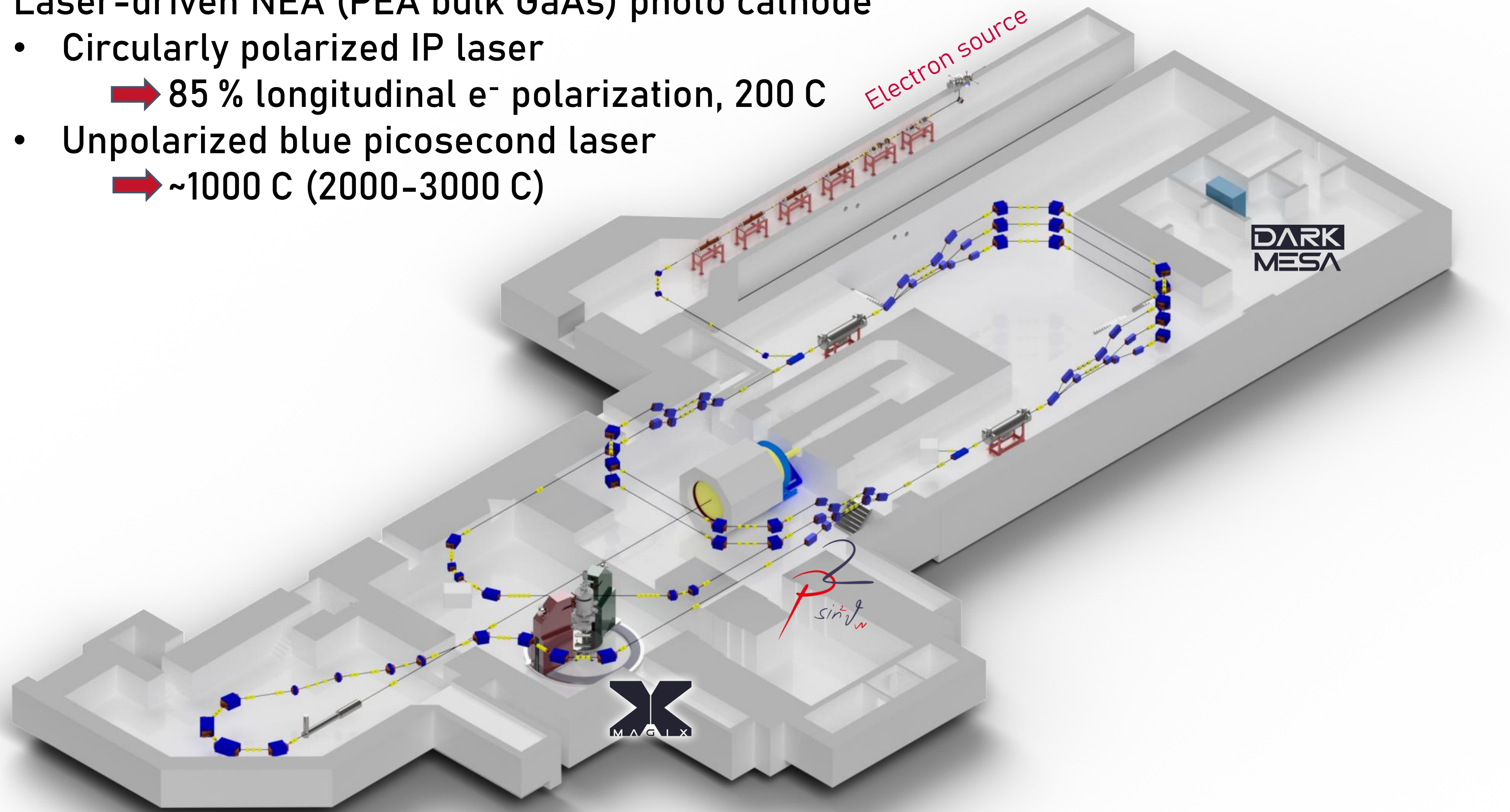


Laser-driven NEA (PEA bulk GaAs) photo cathode

- Circularly polarized IP laser
  - ➡ 85 % longitudinal e⁻ polarization, 200 C
- Unpolarized blue picosecond laser
  - ➡ ~1000 C (2000-3000 C)



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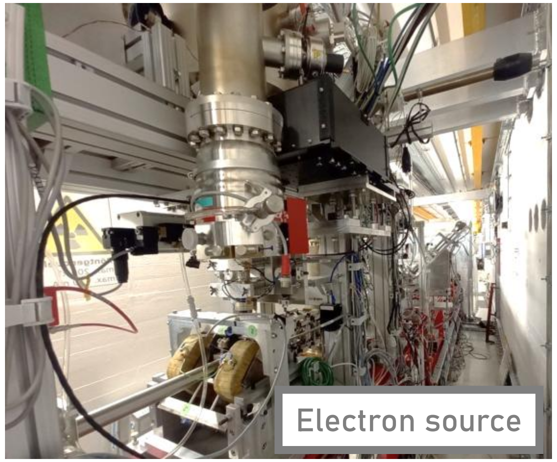
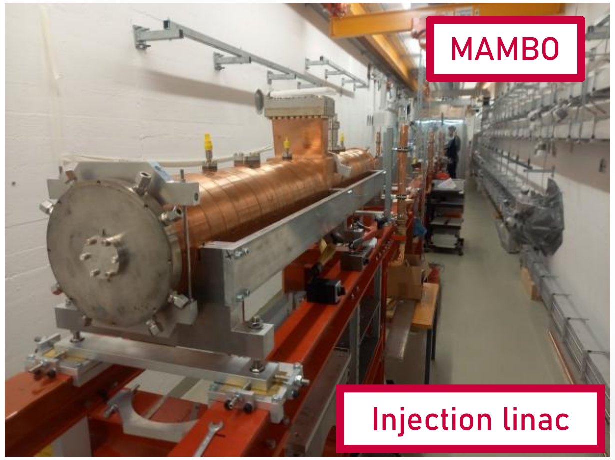
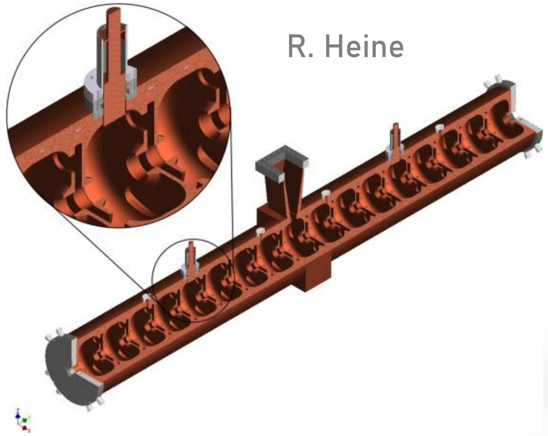
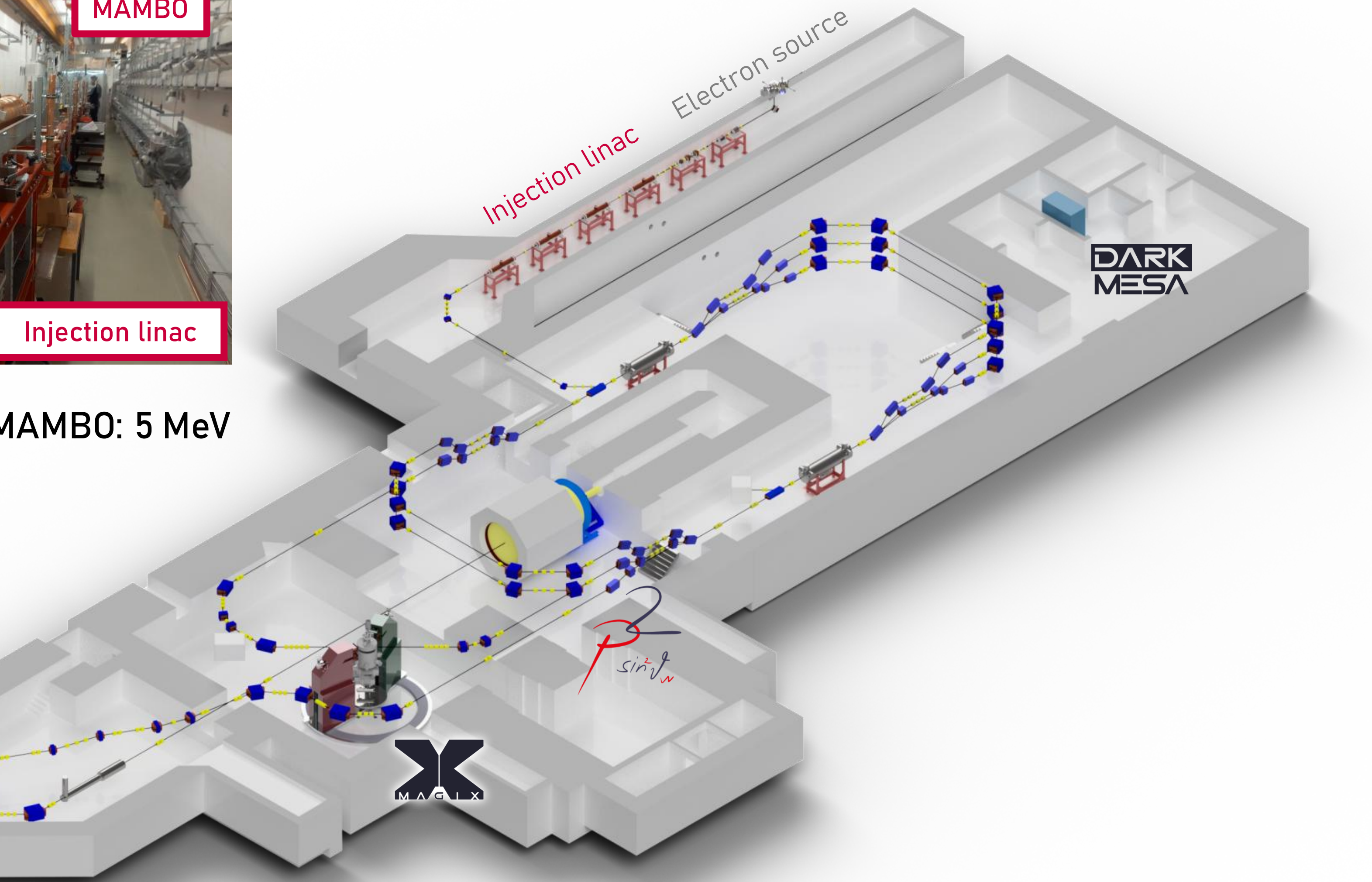






Pre-accelerator MAMBO: 5 MeV



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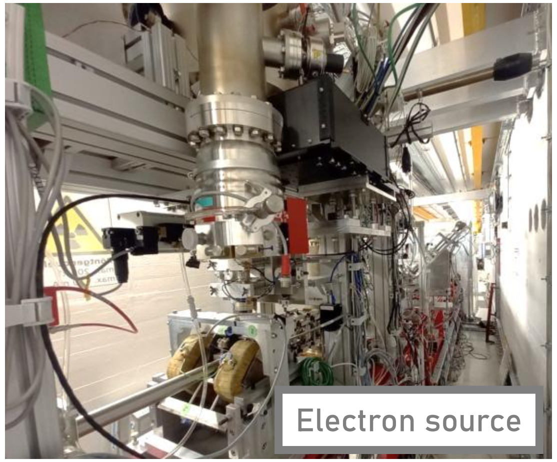
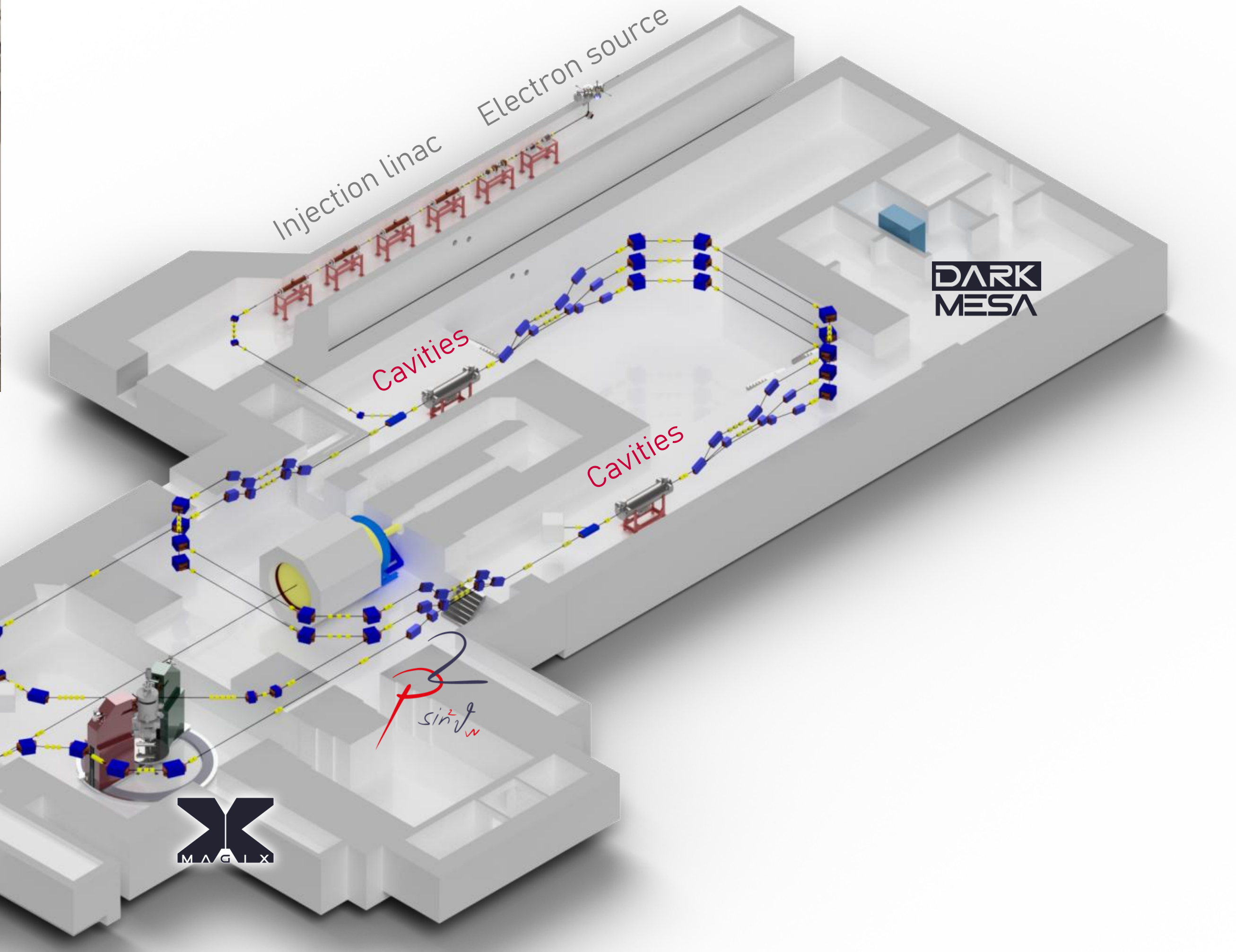


MESA enhanced ELBE cryomodule

- 2 XFEL cavities
- Tested and installed within MESA

f_0 = 1.3 GHz



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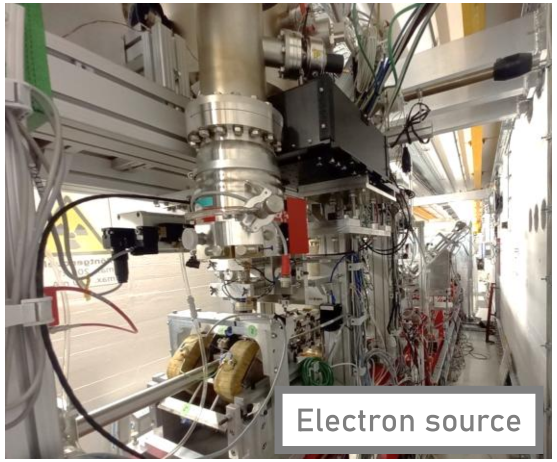
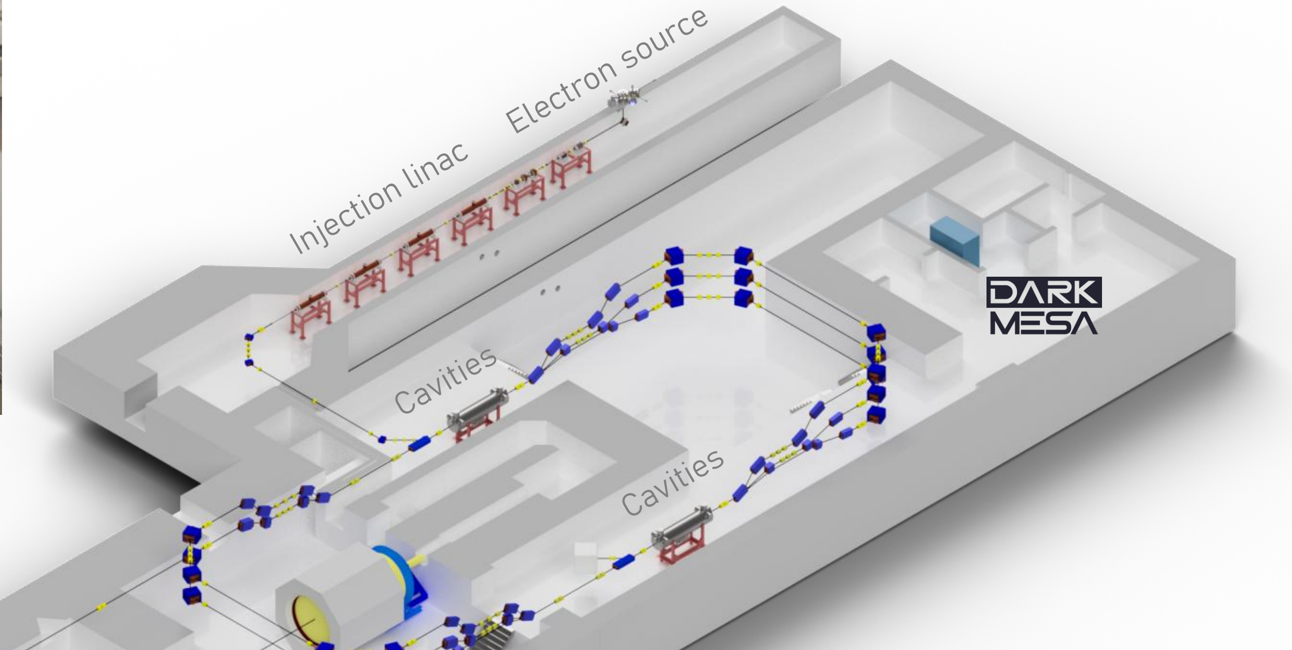
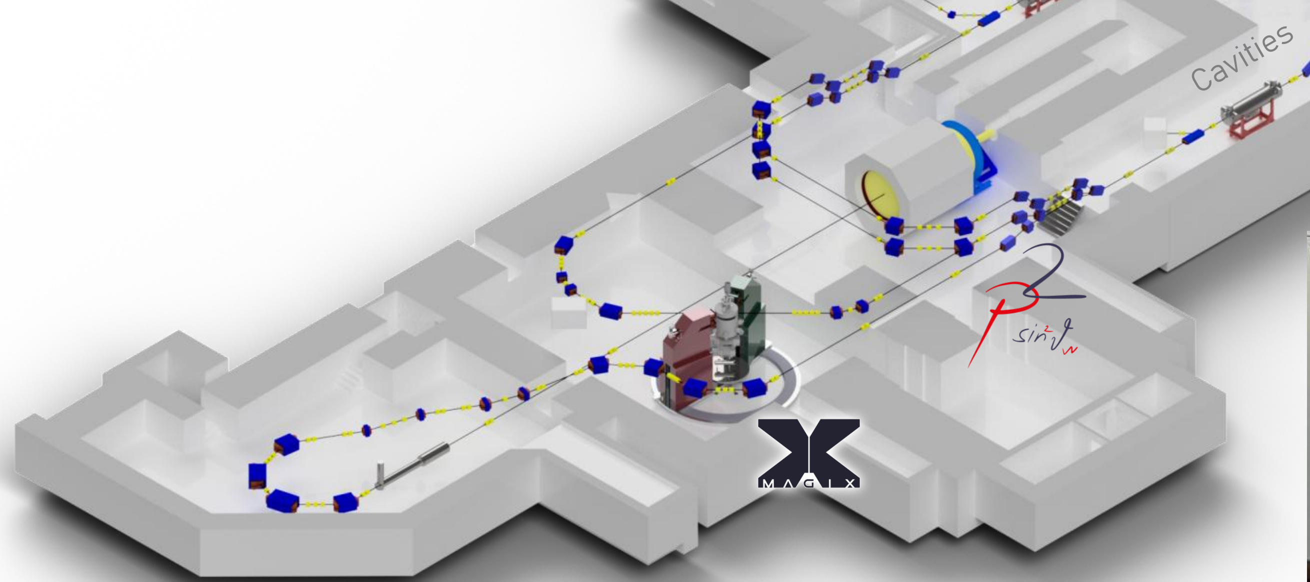

Electron source


Injection linac

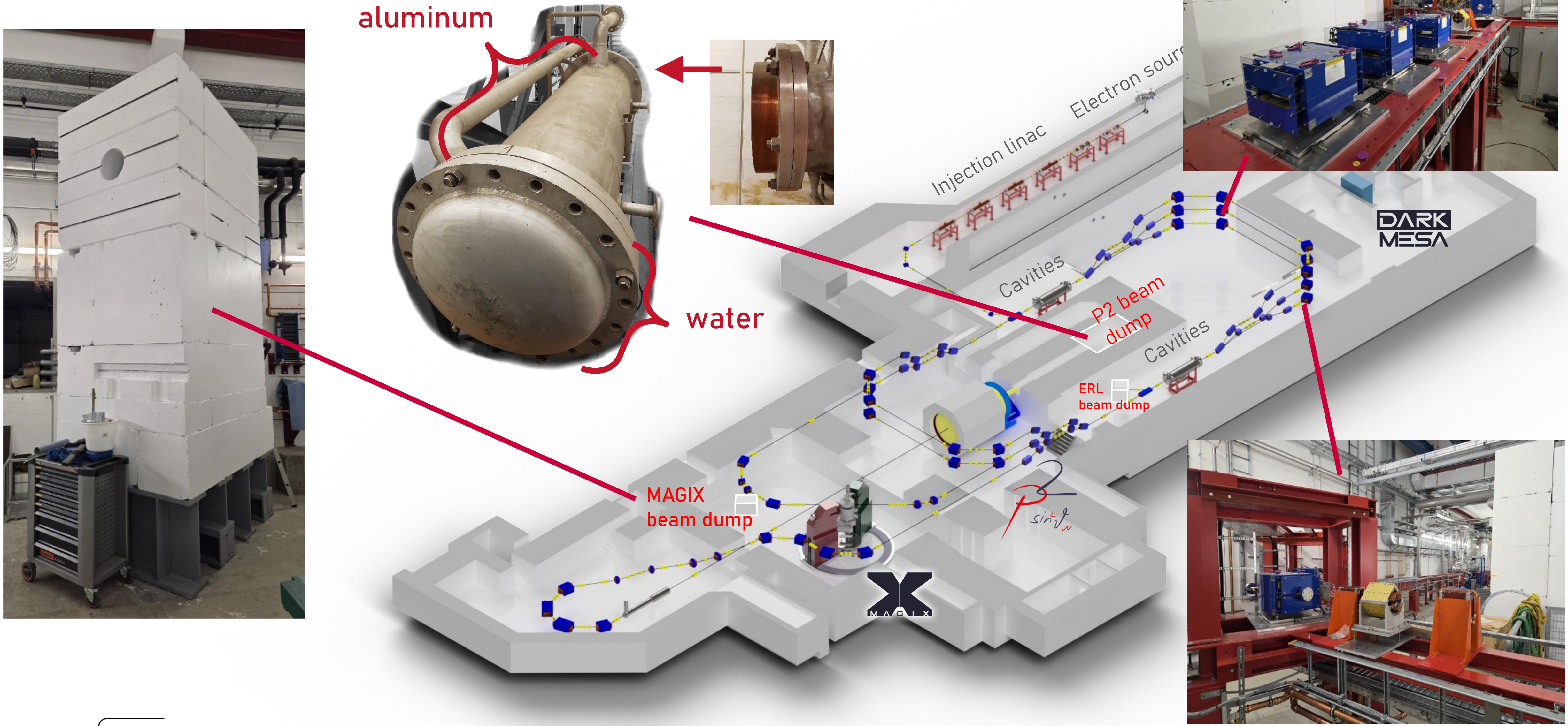

Cavities/ Cryomodule

MESA first beam

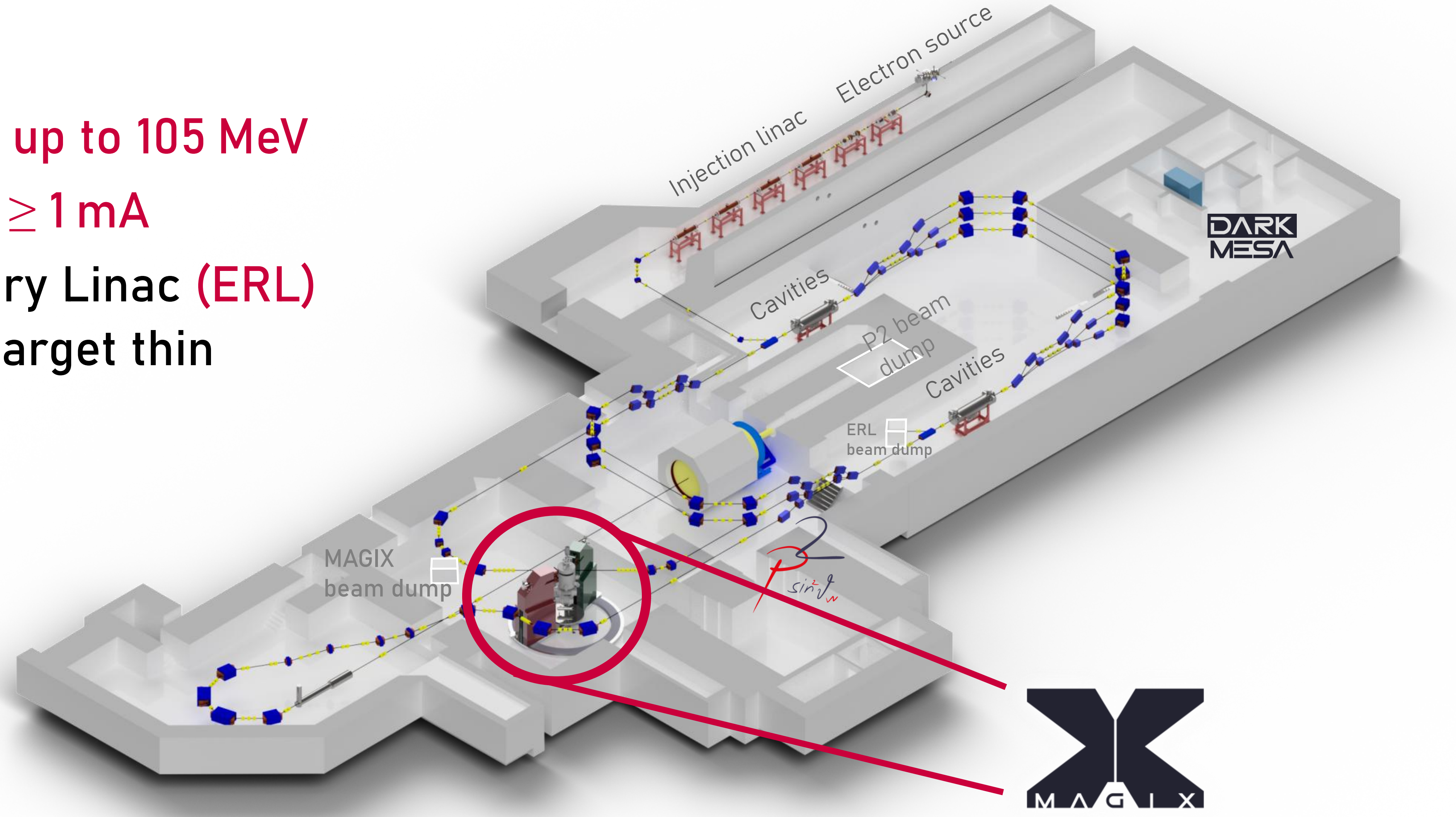
f_0 = 1.3 GHz

MESA – Status & Impressions.



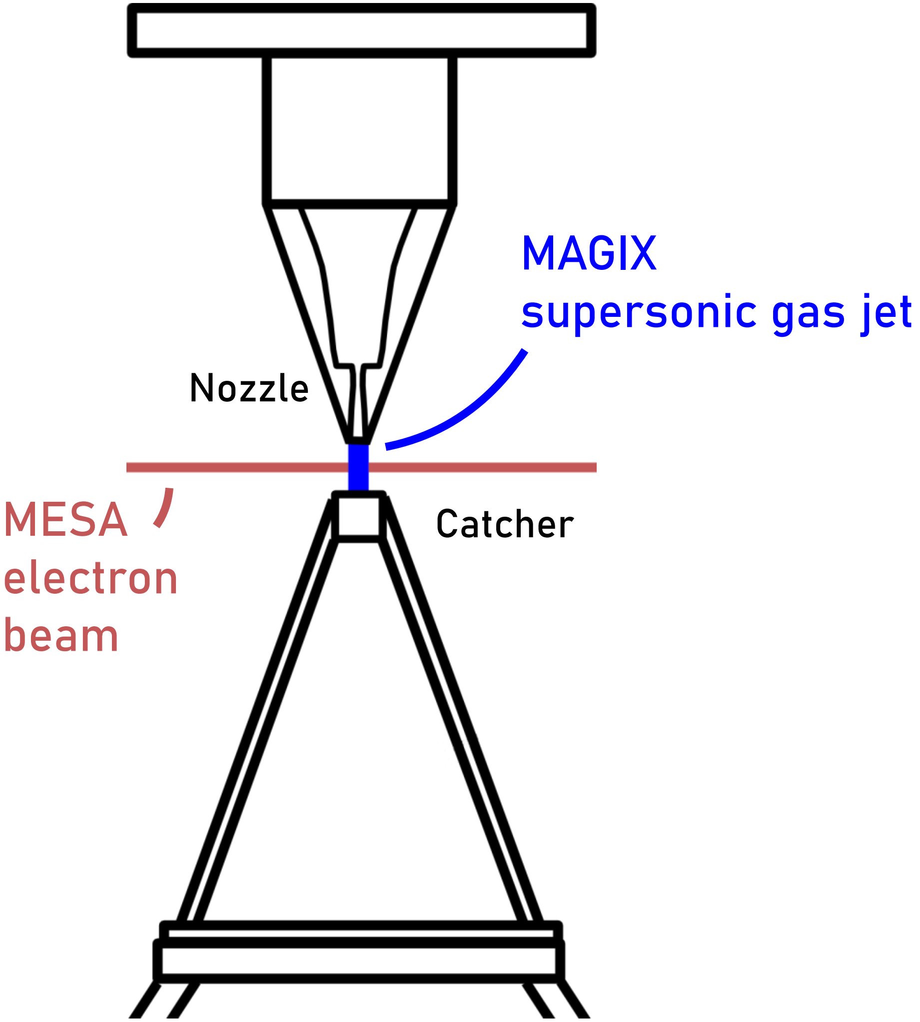
MAGIX - MAinz Gas Injection EXperiment.

- Beam energies up to 105 MeV
- Beam currents $\geq 1\,\mathrm{mA}$
- Energy-Recovery Linac (ERL)
  ➡ Keep the target thin



MAGIX – Gas Jet Target.

- Windowless gas jet target
- Operated with gases from hydrogen up to xenon
- Typical value for hydrogen operation: 40 K and 40 l/min
- Target thickness: $\geq 10^{18}$ atoms/cm^2
  ➡ Luminosity: 10^{35} cm^{-2}s^{-1}



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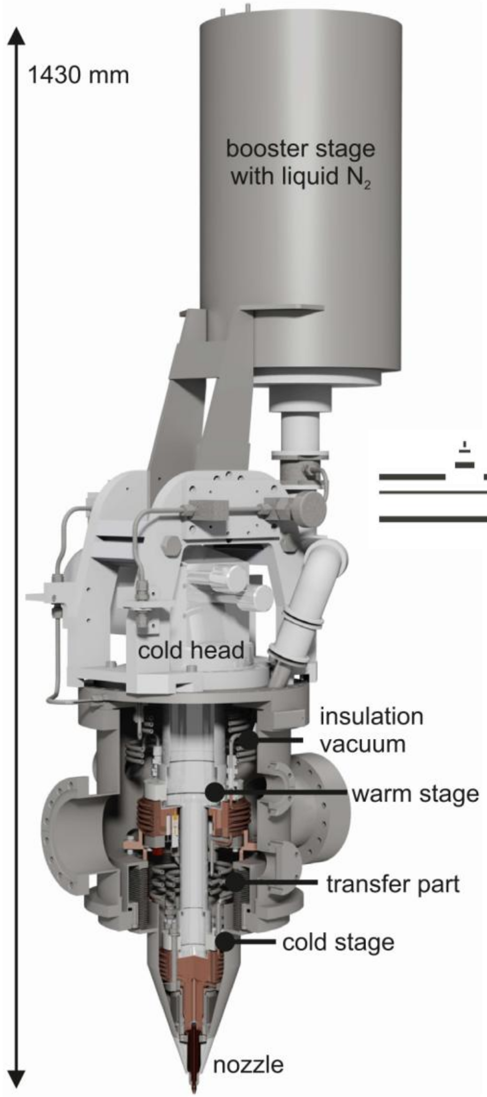
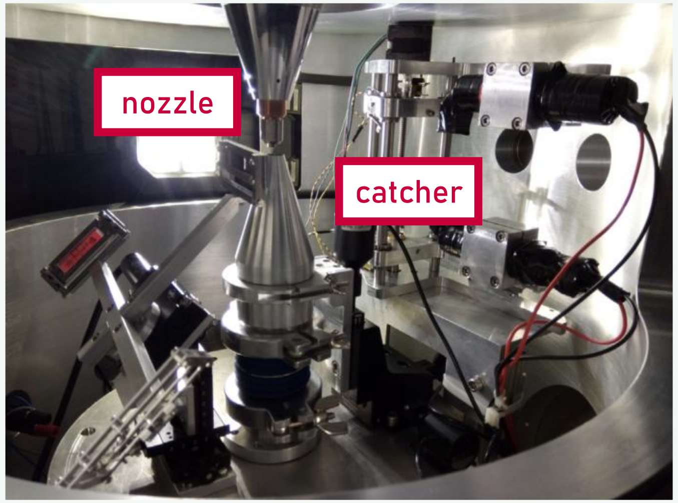


D. Bonaventura

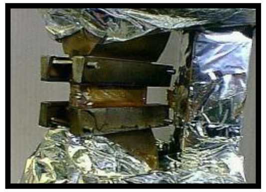
P. Brand



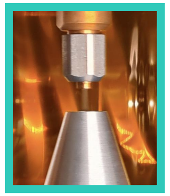
S. Schlimme *et al.*, 10.1016/j.nima.2021.165668

MAGIX – Gas Jet Target.

- Gas jet target successfully operated at A1 several times

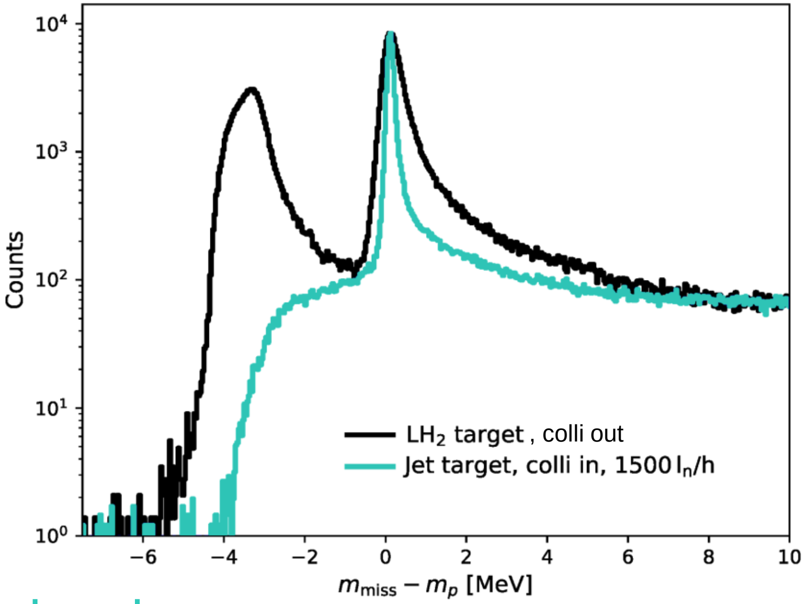


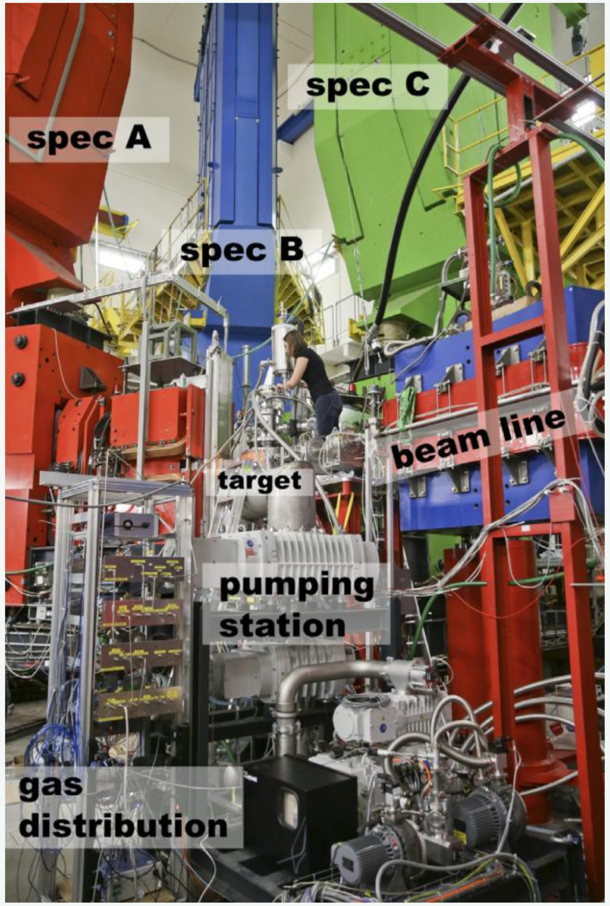
LH_2 target



H_2 gas jet target

S. Schlimme *et al.*, 10.1016/j.nima.2021.165668





S. Schlimme *et al.*, 10.1016/j.nima.2021.165668

- Background drastically reduced
- Sharper elastic peak

MAGIX – Gas Jet Target.

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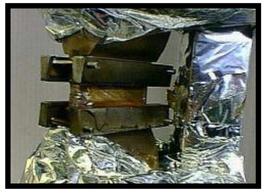
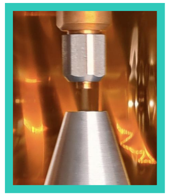
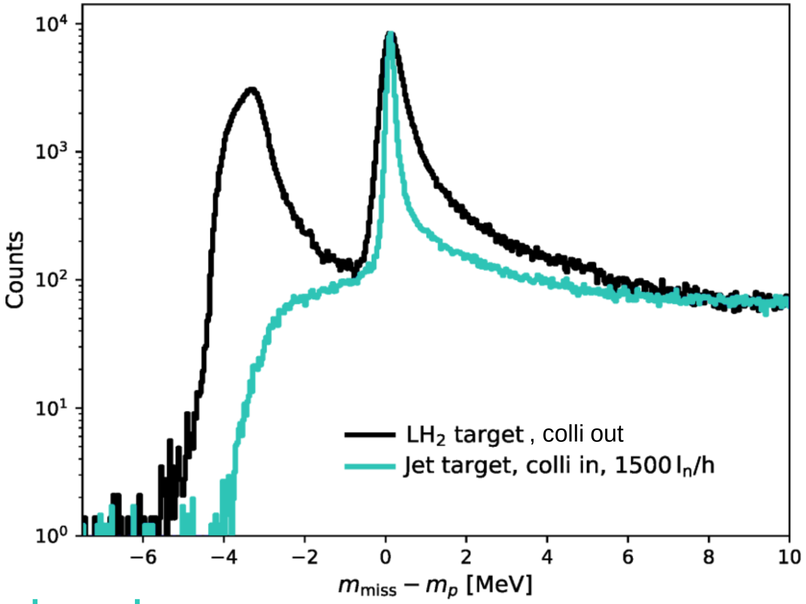


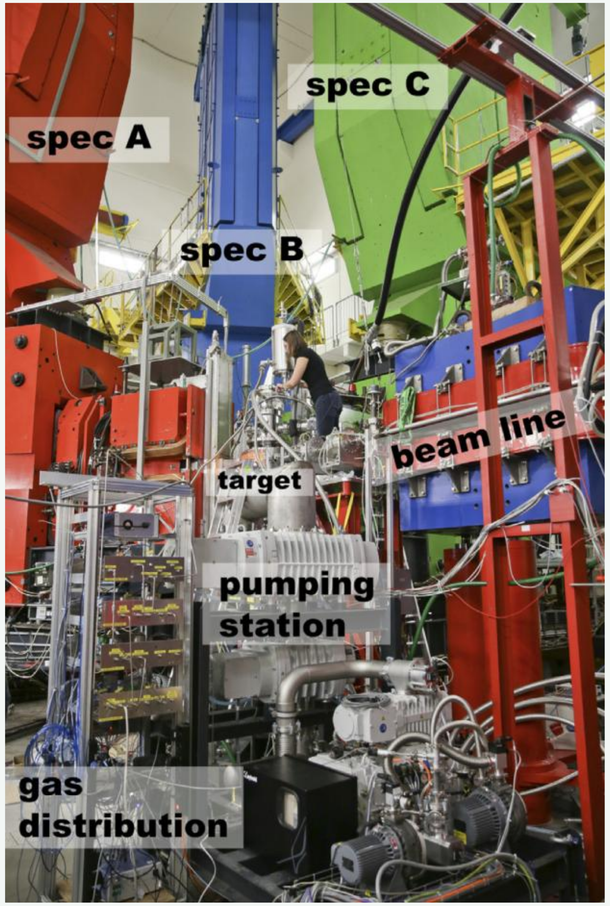
LH$_2$ target



H$_2$ gas jet target

S. Schlimme *et al.*, 10.1016/j.nima.2021.165668





S. Schlimme *et al.* ,10.1016/j.nima.2021.165668

- Background drastically reduced
- Sharper elastic peak

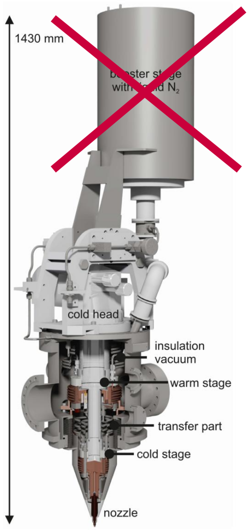
Can we do better?

MAGIX – Filament Target?

- New Münster approach: „Filament target“
- Minor changes:
  - Cartridge for gas purification
  - Aperture nozzle
  - Add. particle filter
- Possible benefits:
  - Lower flowrate
  - Better vacuum
  - Enhanced cooling
  - Higher target thickness

Target	MAGIX gas jet	Filament
Flow rate	40 l/min	160 ml/min
Vacuum	10^{-1} mbar	10^{-4} mbar
Thickness	10^{18} atoms/cm²	$4.5\cdot10^{19}$ atoms/cm²
Nozzle	de Laval 200 µm	Aperture 10 µm

D. Bonaventura



WWU MÜNSTER

L. Deda

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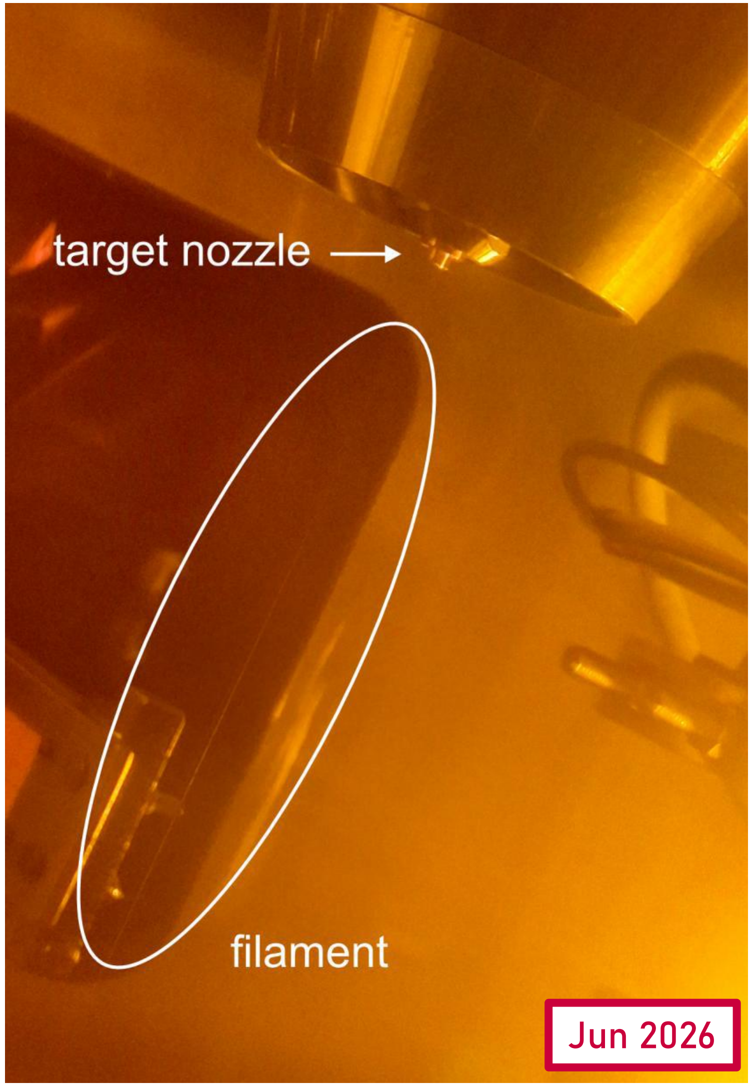
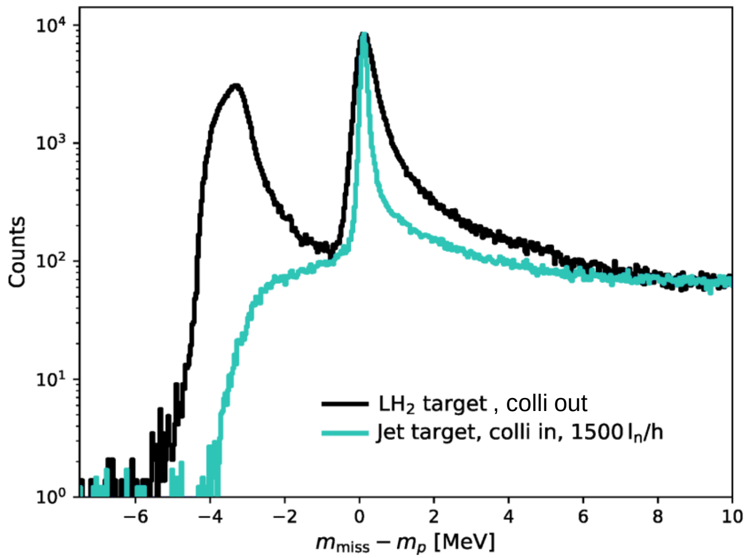


J. Froning

MAGIX – Filament Target.

- Hydrogen filament (Jun 26)
- Operation condition: 1.2 bar and 16 K
- Catcher and nozzle further away from electron beam
- Highly background-suppressed measurement
- Promissing Argon filament beam time (Aug 26)



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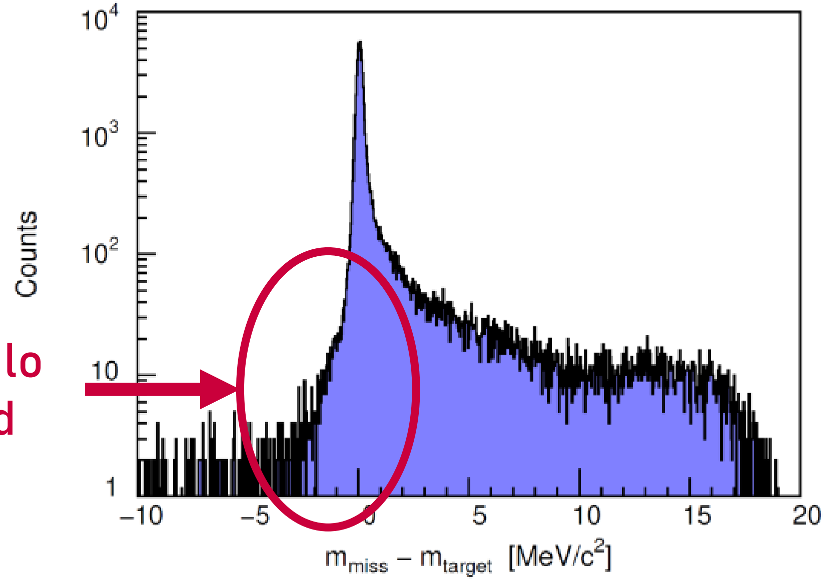
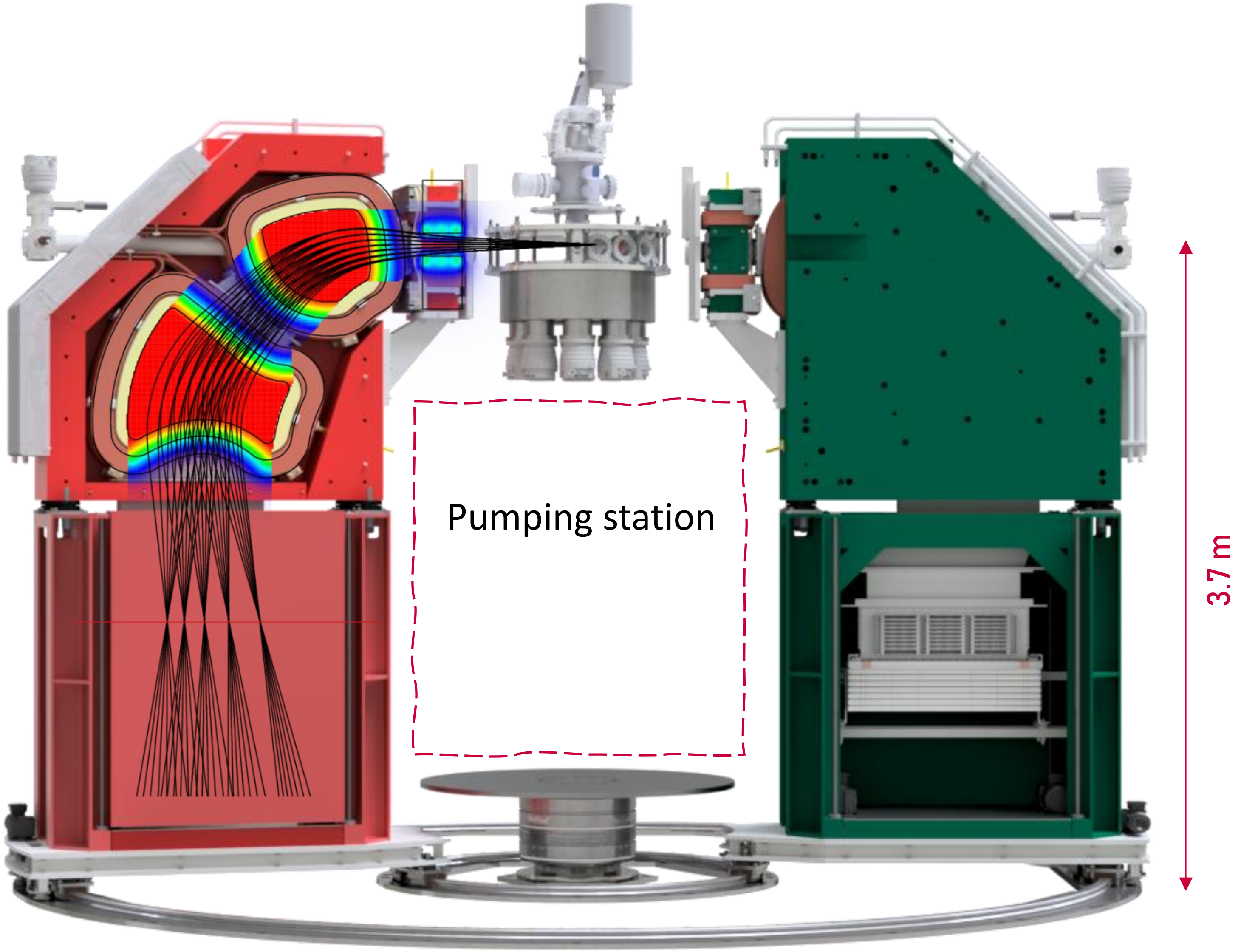


H. Merkel

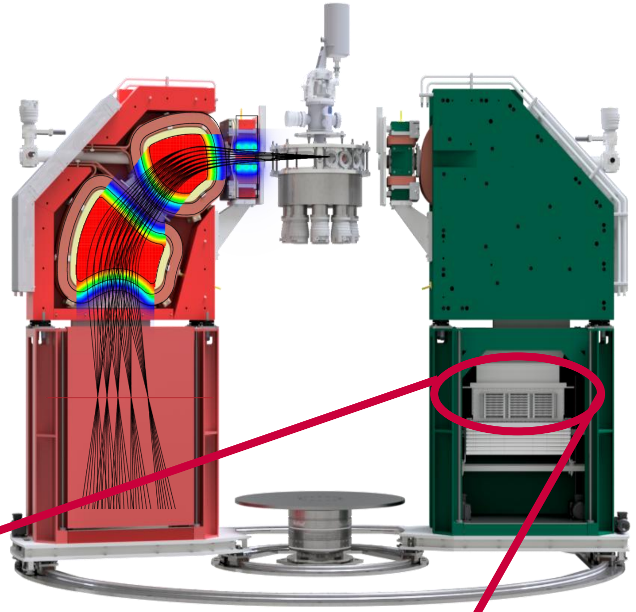
MAGIX – Setup Overview.

- Windowless scattering chamber
- Twin-arm magnetic spectrometer
  - ➡ 15-165°
  - ➡ 3-282 MeV/c
  - ➡ 6 msr
- Tracking detectors
  - ➡ $\Delta p/p < 1\cdot10^{-4}$
- Trigger veto system

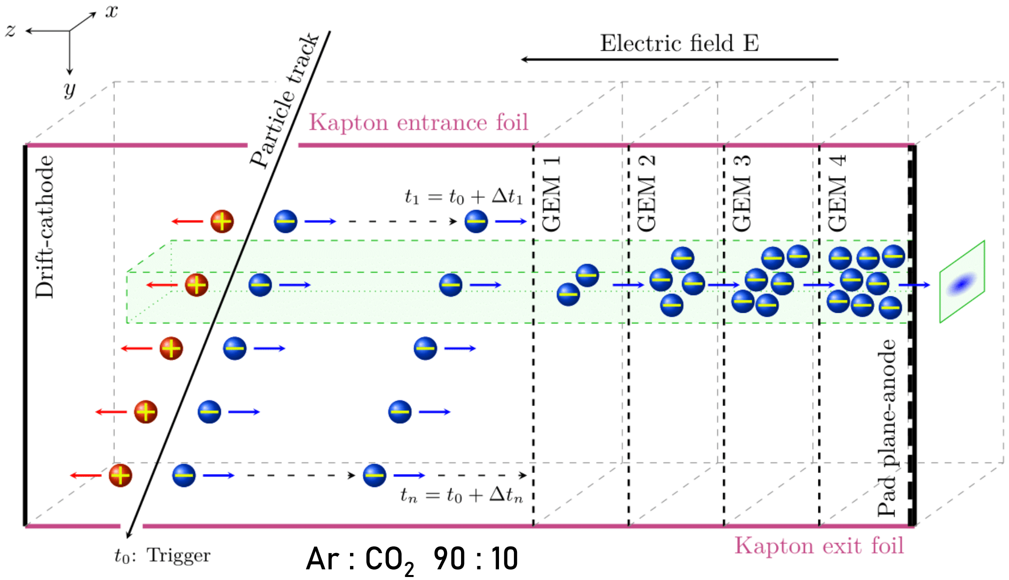
Minimal material budget



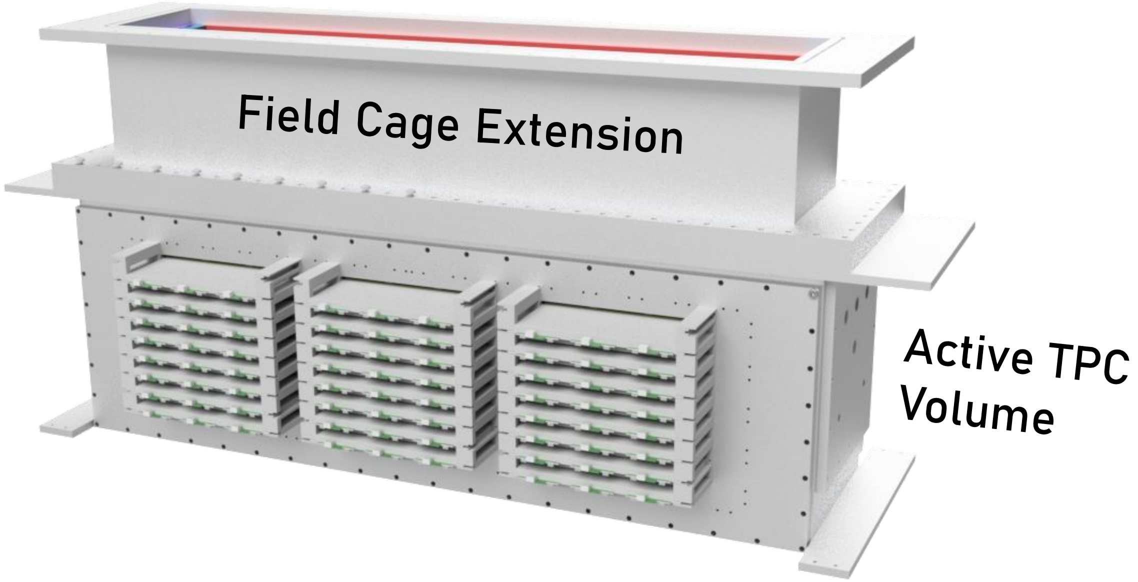
MAGIX – Time Projection Chamber.



- Gas Electron Multiplier (GEM) stack and pad plane anode
- 3D Track reconstruction
- Δx = 100 µm and $\Delta\theta$ = 3.5 mrad

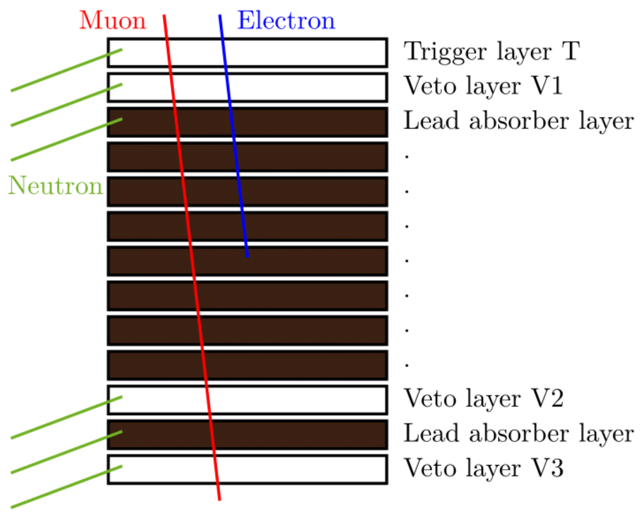


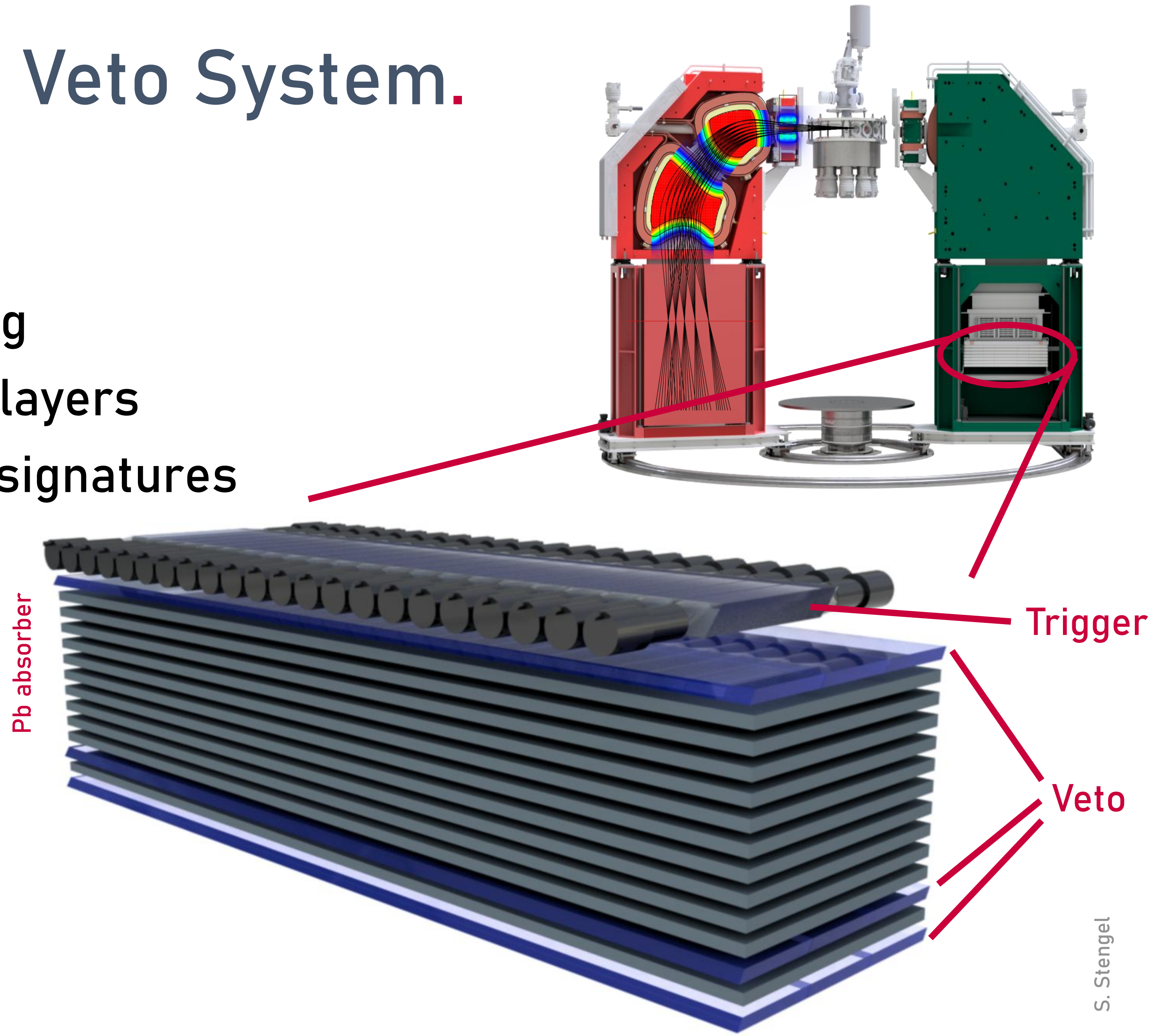
Ar : CO_2 90 : 10



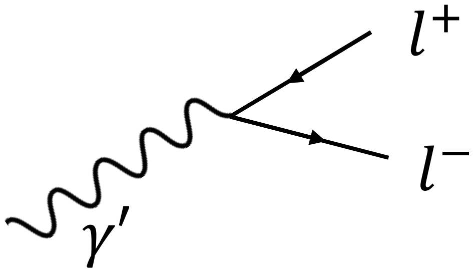
MAGIX – Trigger and Veto System.

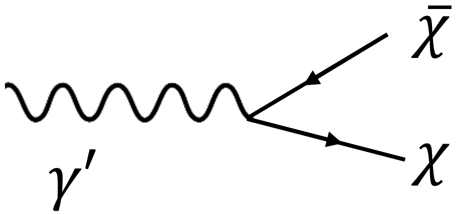
- System for PID and triggering
- Segmented trigger and veto layers
- PID via distinct trigger-veto signatures
- Flexible drawer system



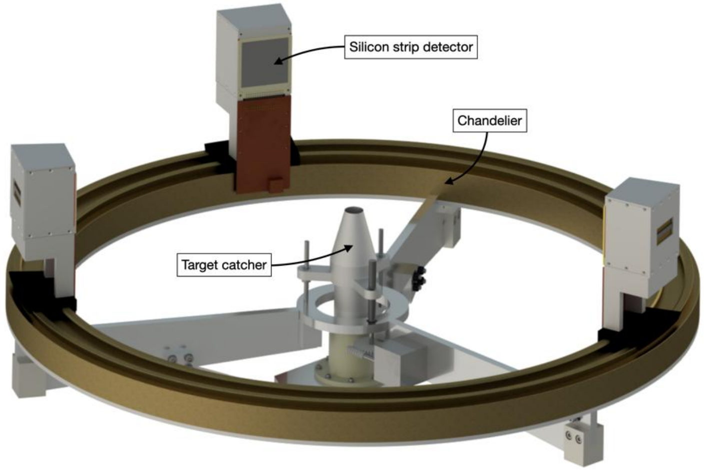


MAGIX – Physics Programme.





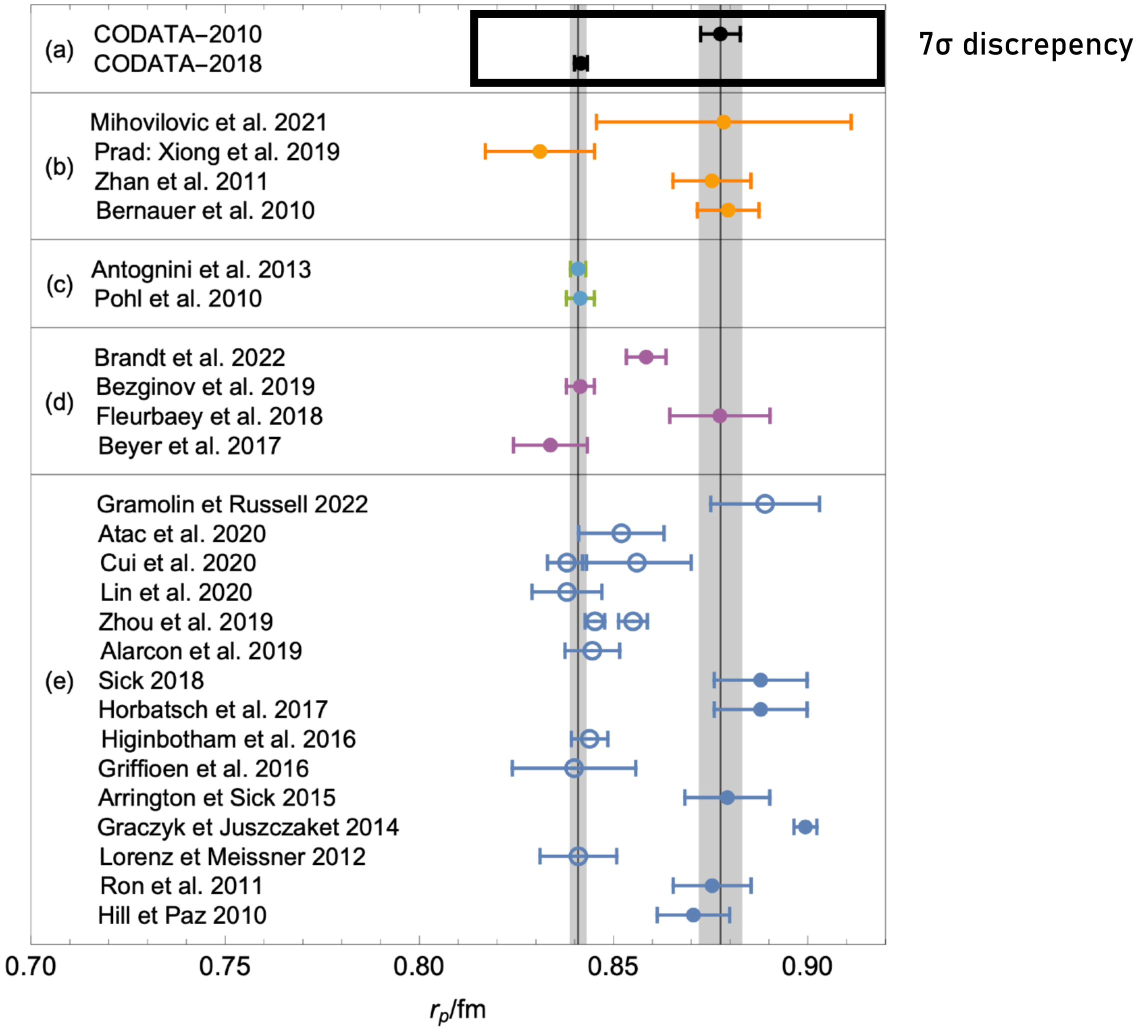
- **Dark photon searches**
  - ➡ Visible decay to e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$
  - ➡ Invisible decay into DM pairs (if $m_{\gamma'} > 2m_\chi$)
- **Astrophysics**
  - ➡ Astrophysical S-Factor of the reaction $^{12}C(\alpha,\gamma)^{16}O$
- **Few body physics**
  - ➡ Transition form factor of ^4He
- **Nuclear physics**
  - ➡ Electromagnetic form factors of the proton



Proton Radius at MAGIX?

- Proton radius puzzle – new physics?
- Inconsistent results with different measurement techniques
- More precise measurements needed

T. Walcher, 10.48550/arXiv.2304.07035



S. Stengel

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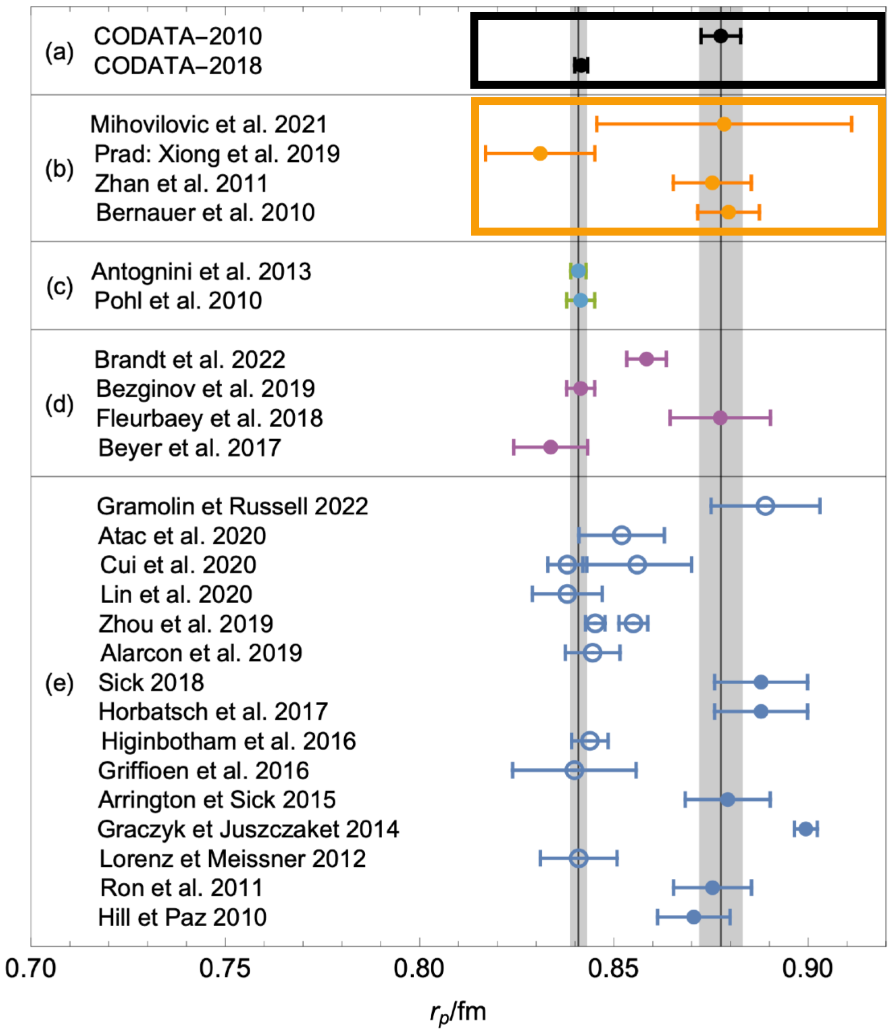
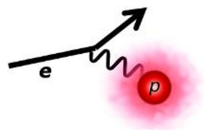


7σ discrepency

e⁻ scattering



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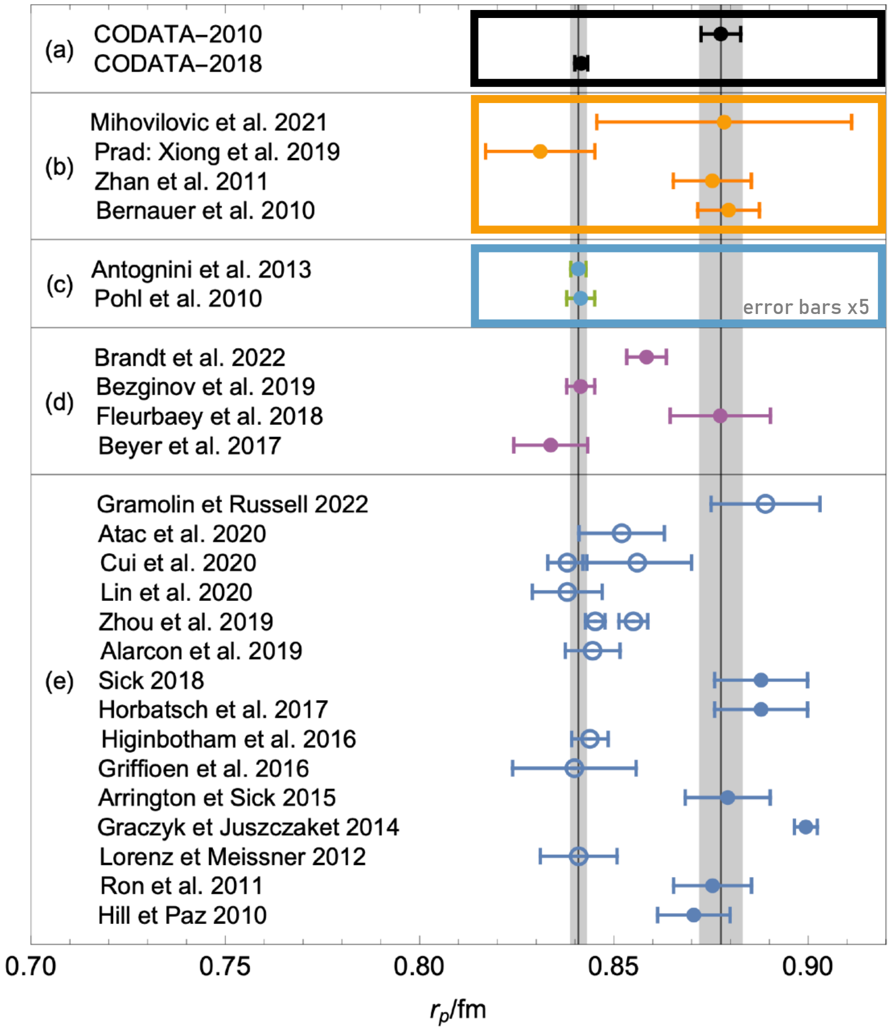

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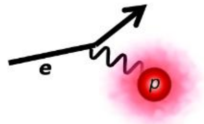
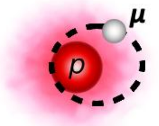


Muonic hydrogen spectroscopy



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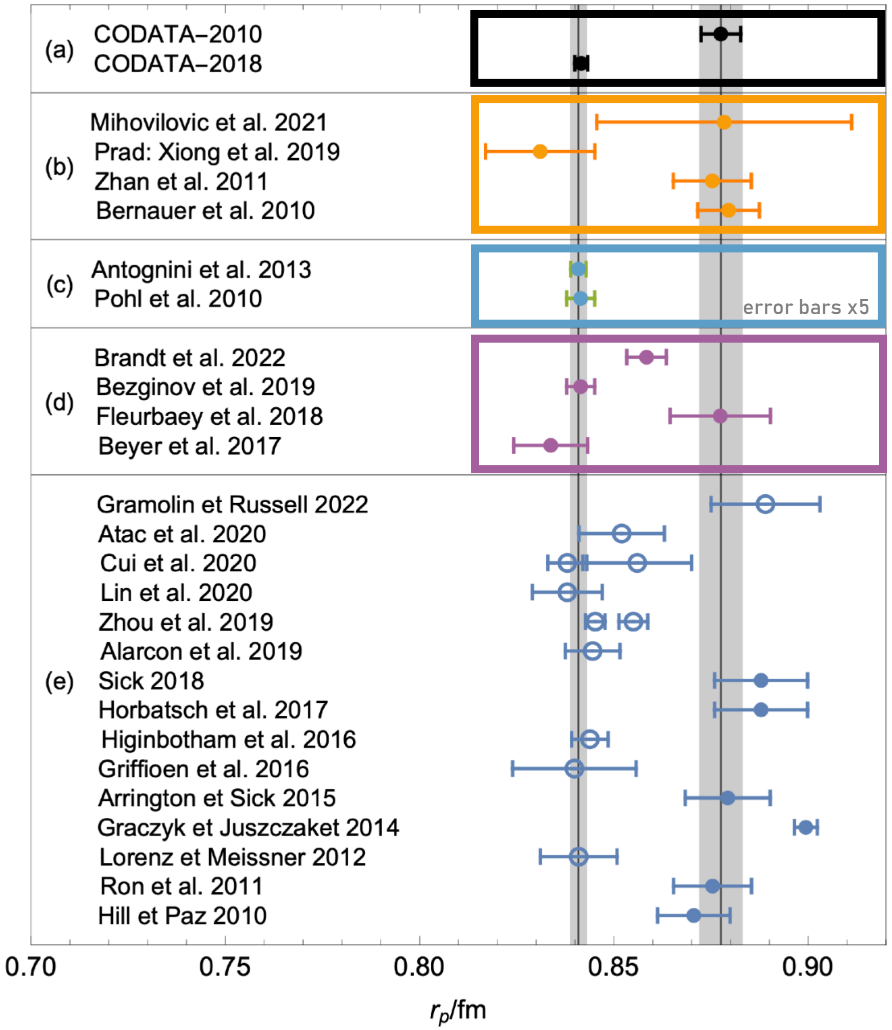

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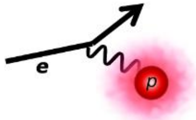

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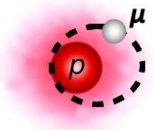
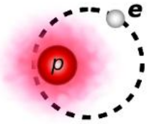


Electronic hydrogen spectroscopy



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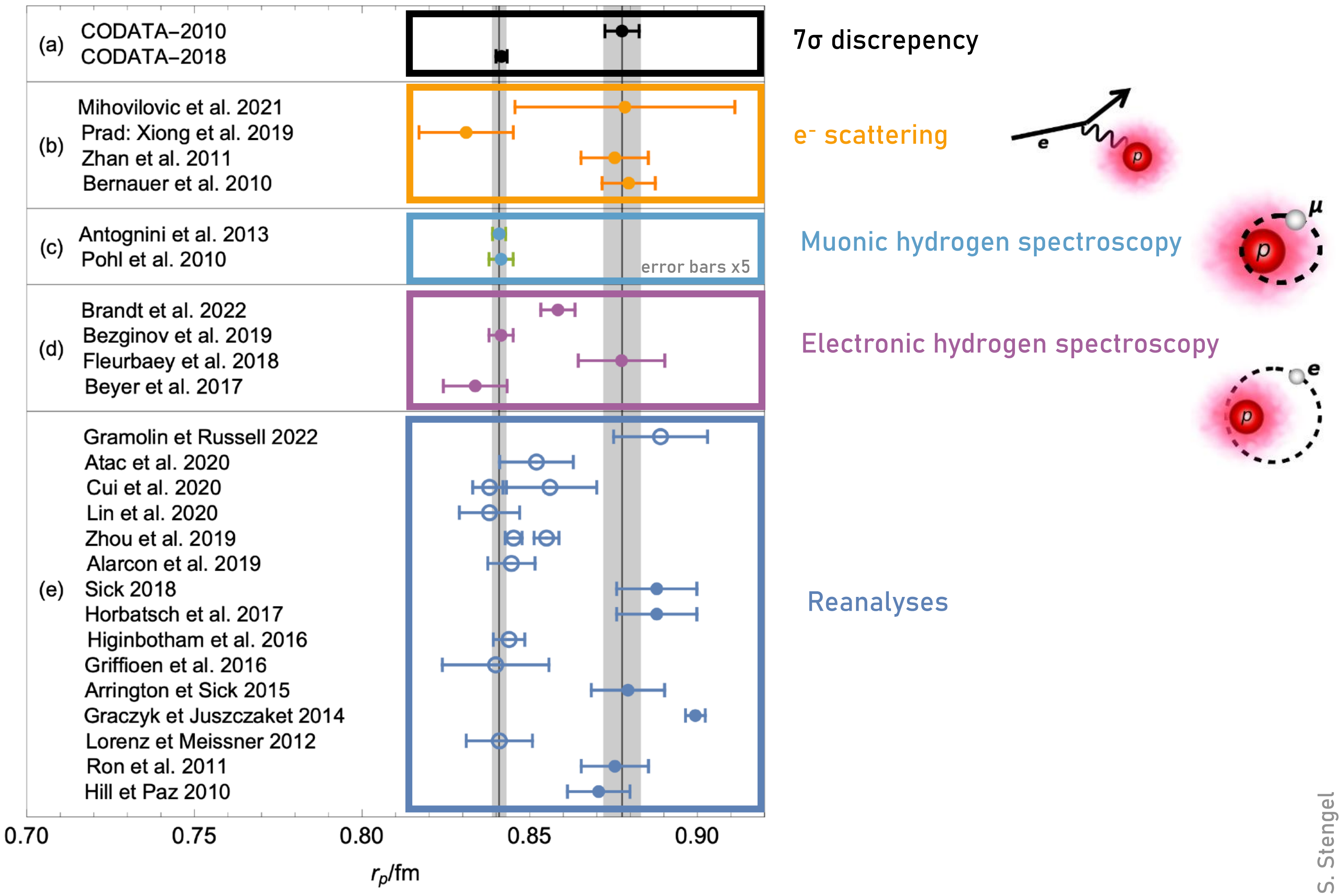

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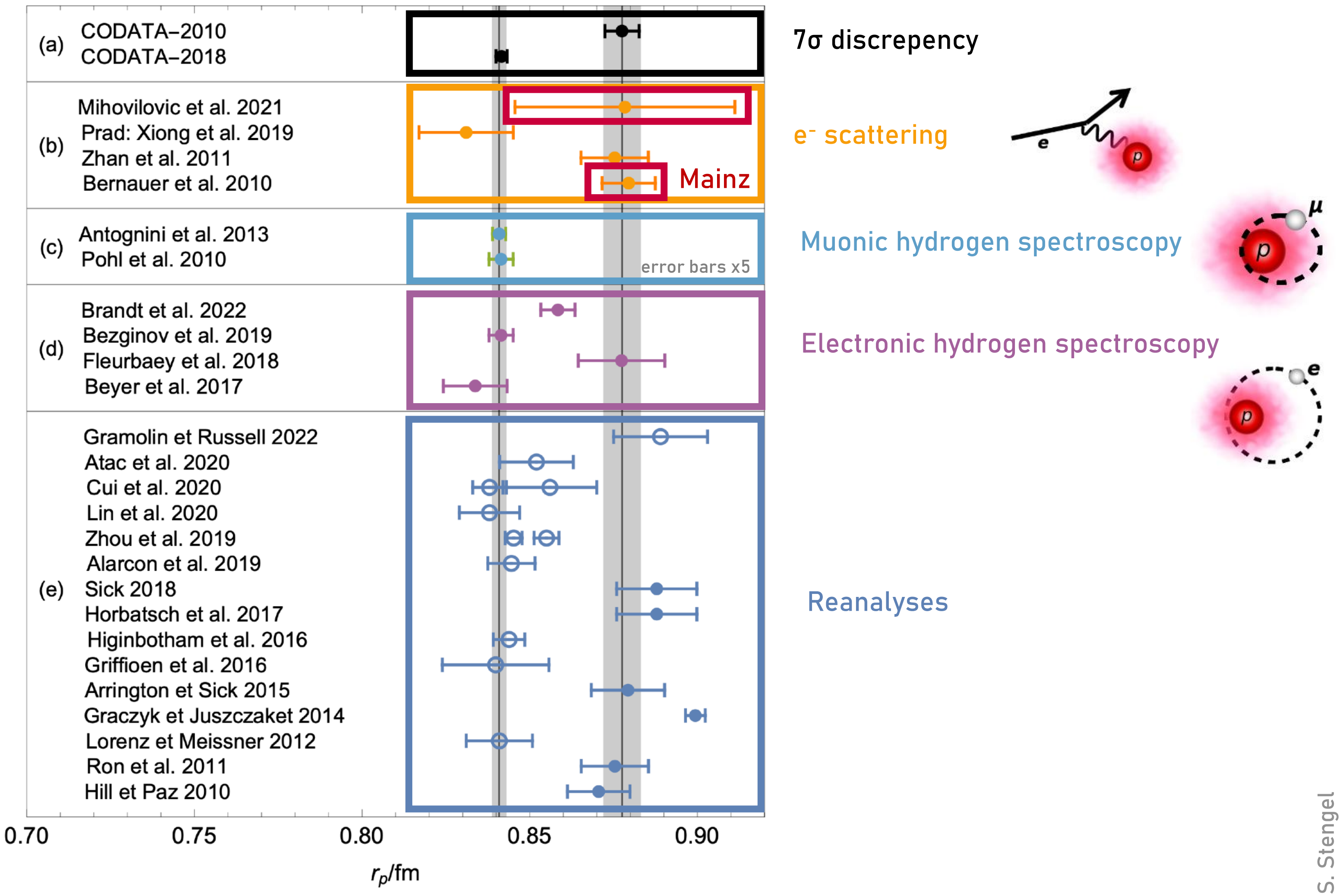
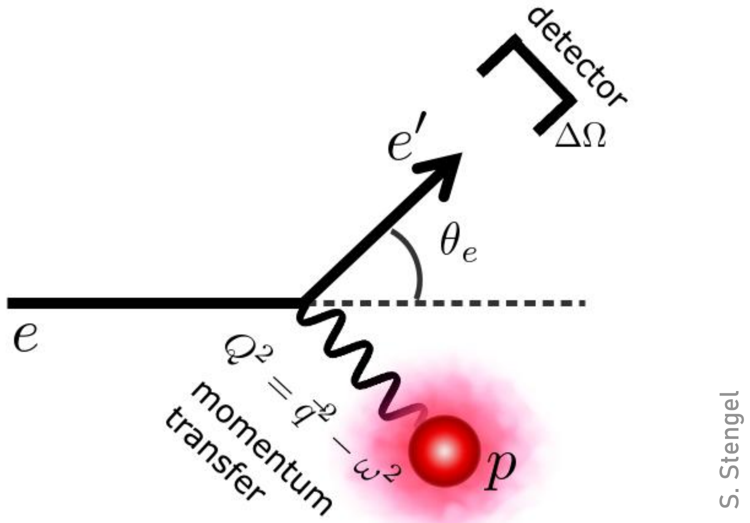


S. Stengel

Proton Radius at MAGIX.

- Elastic scattering off a proton:

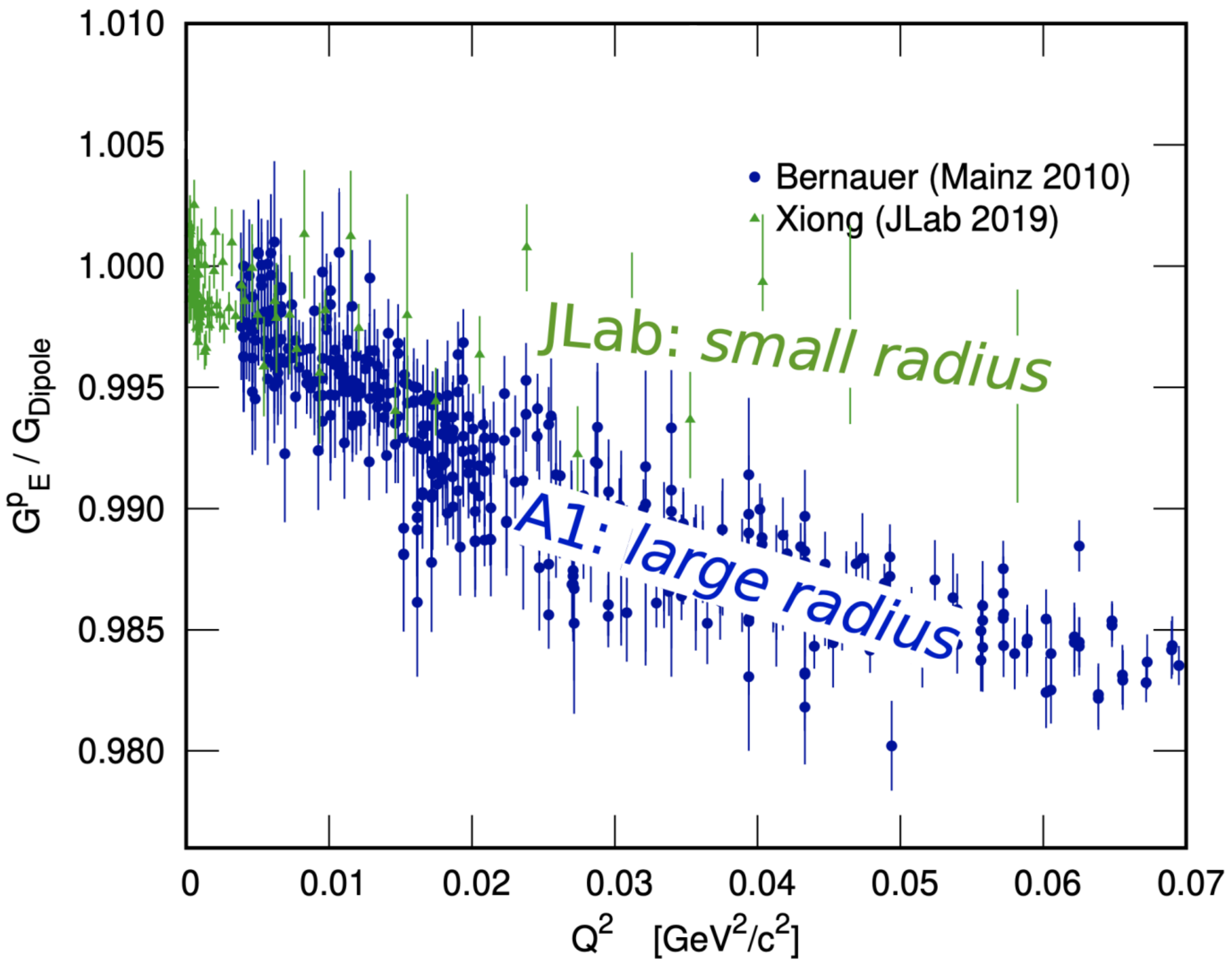
$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right) = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{Mott}} \cdot \frac{1}{(1+\tau)}\left[G_E^2(Q^2) + \frac{\tau}{\epsilon} G_M^2(Q^2)\right]$$



- Extraction of form factors through Rosenbluth separation: Measurement for different beam energies (E) and angles (θ_e) at fixed Q^2
- Slope of G_E at Q^2=0 gives proton radius:

$$\langle r_E^2 \rangle = -6\hbar^2 \left.\frac{\mathrm{d}G_E}{\mathrm{d}Q^2}\right|_{Q^2=0}$$

Proton Radius at MAGIX.



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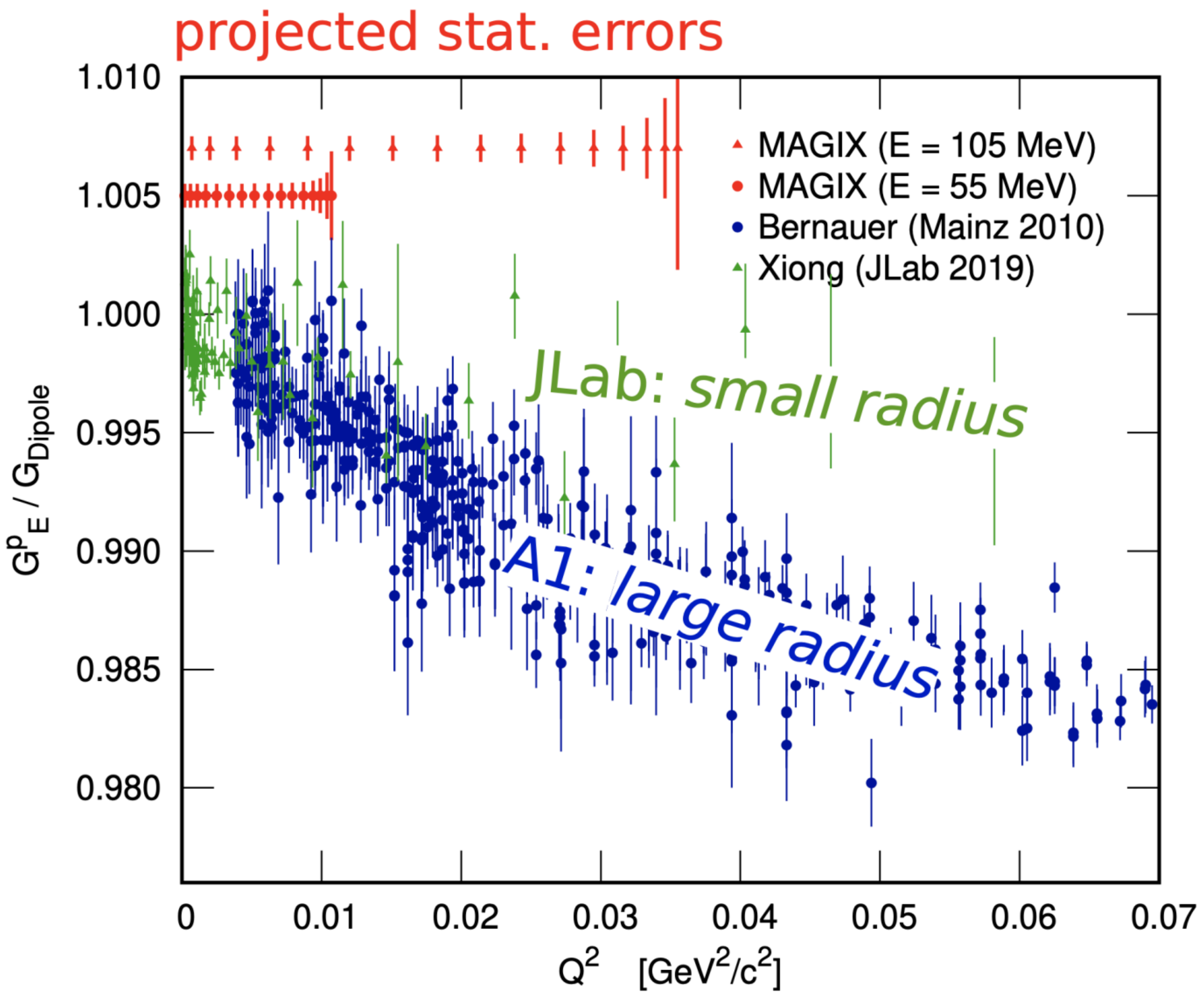
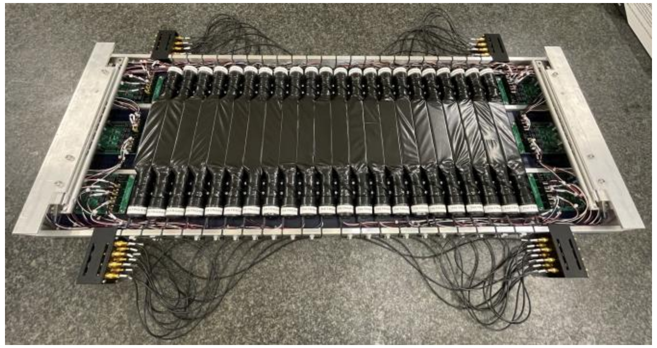
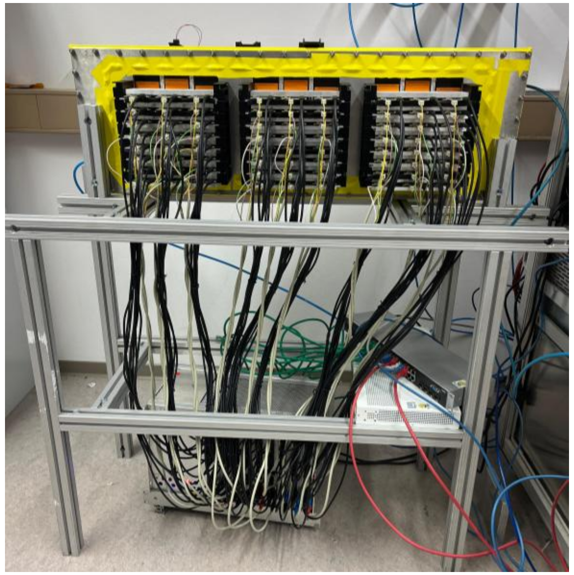


MAGIX – Status & Impressions.



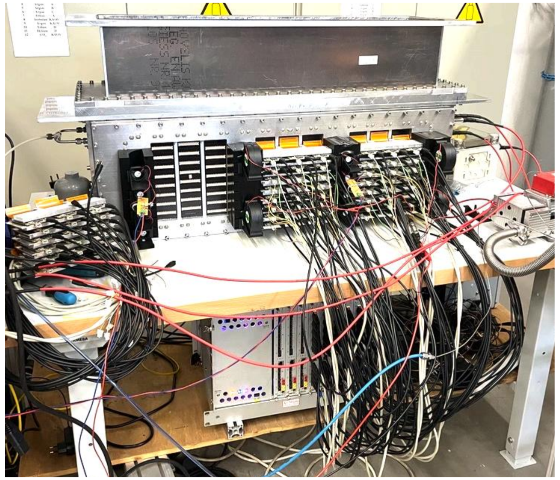
Trigger

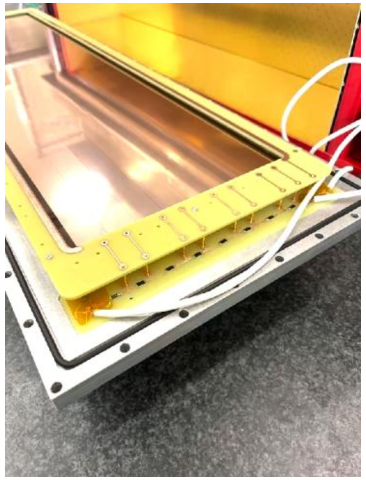
Veto drawers



TPC

MAGIX – Status & Impressions.


L. Bister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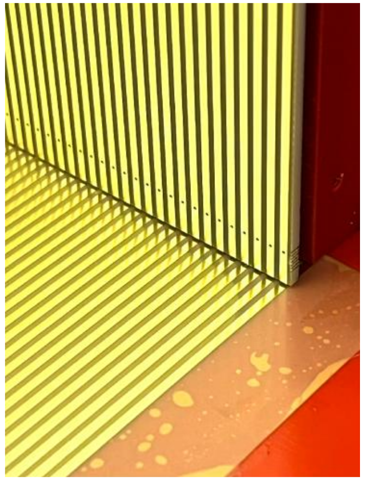
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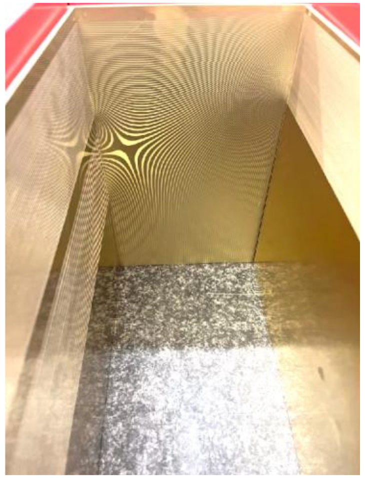
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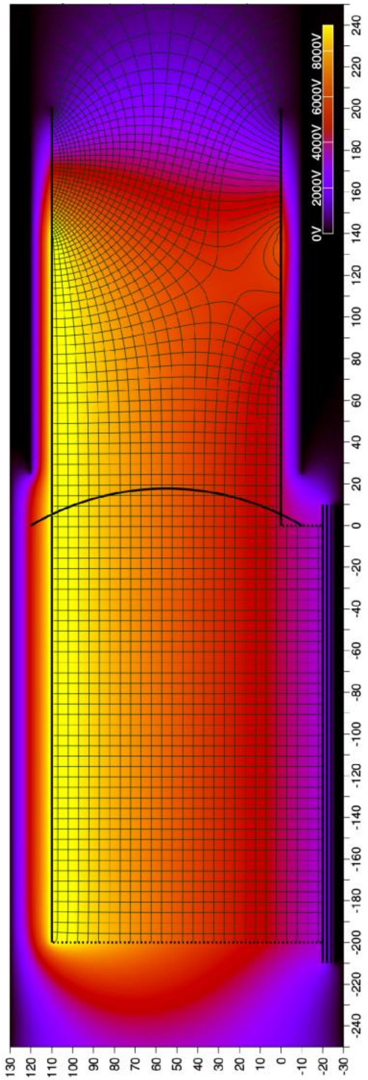
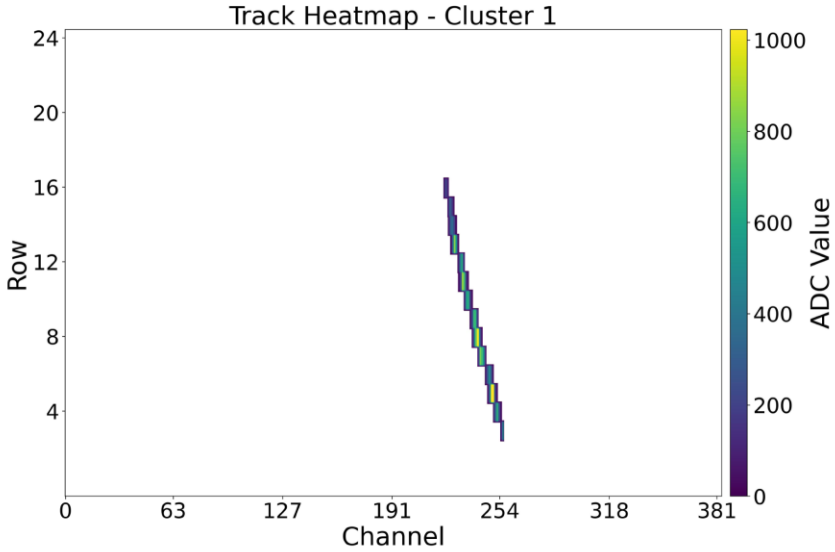


H. Merkel



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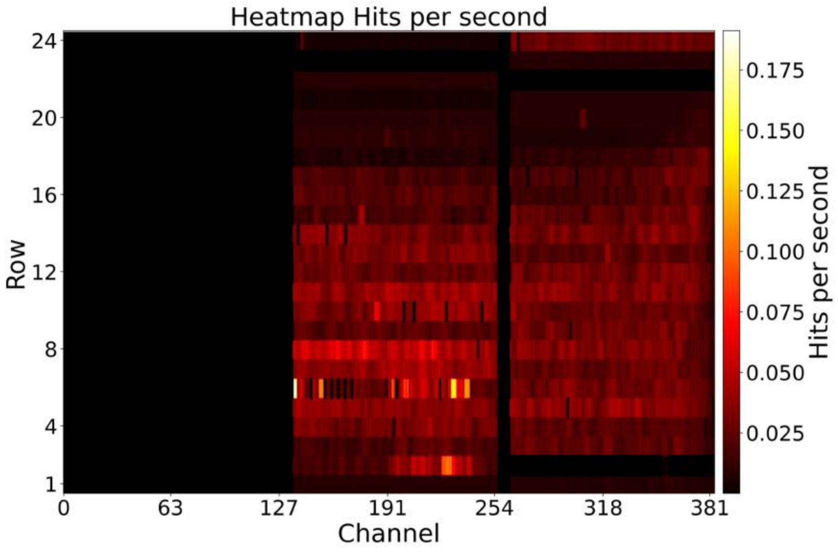
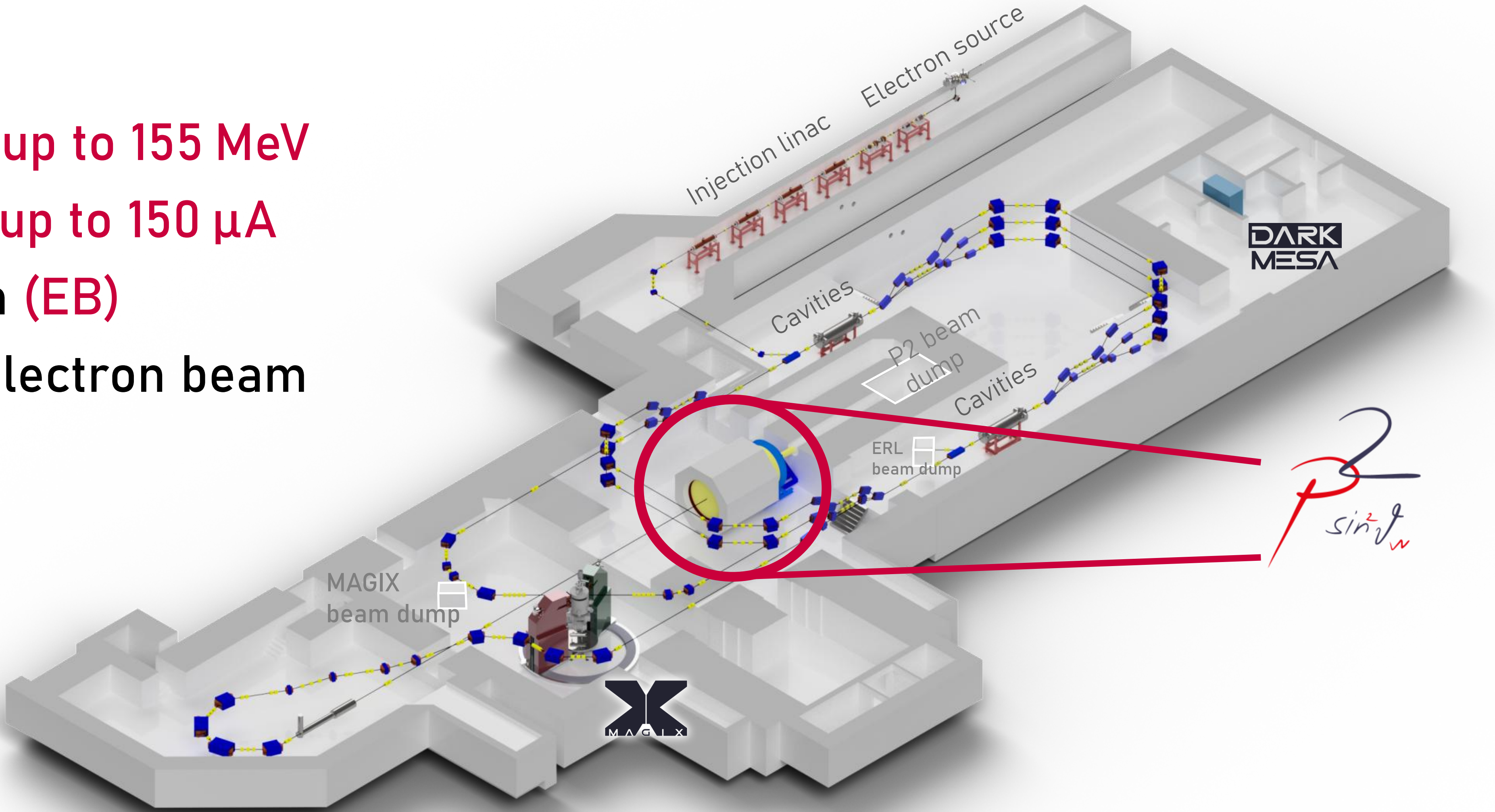


L. Bister

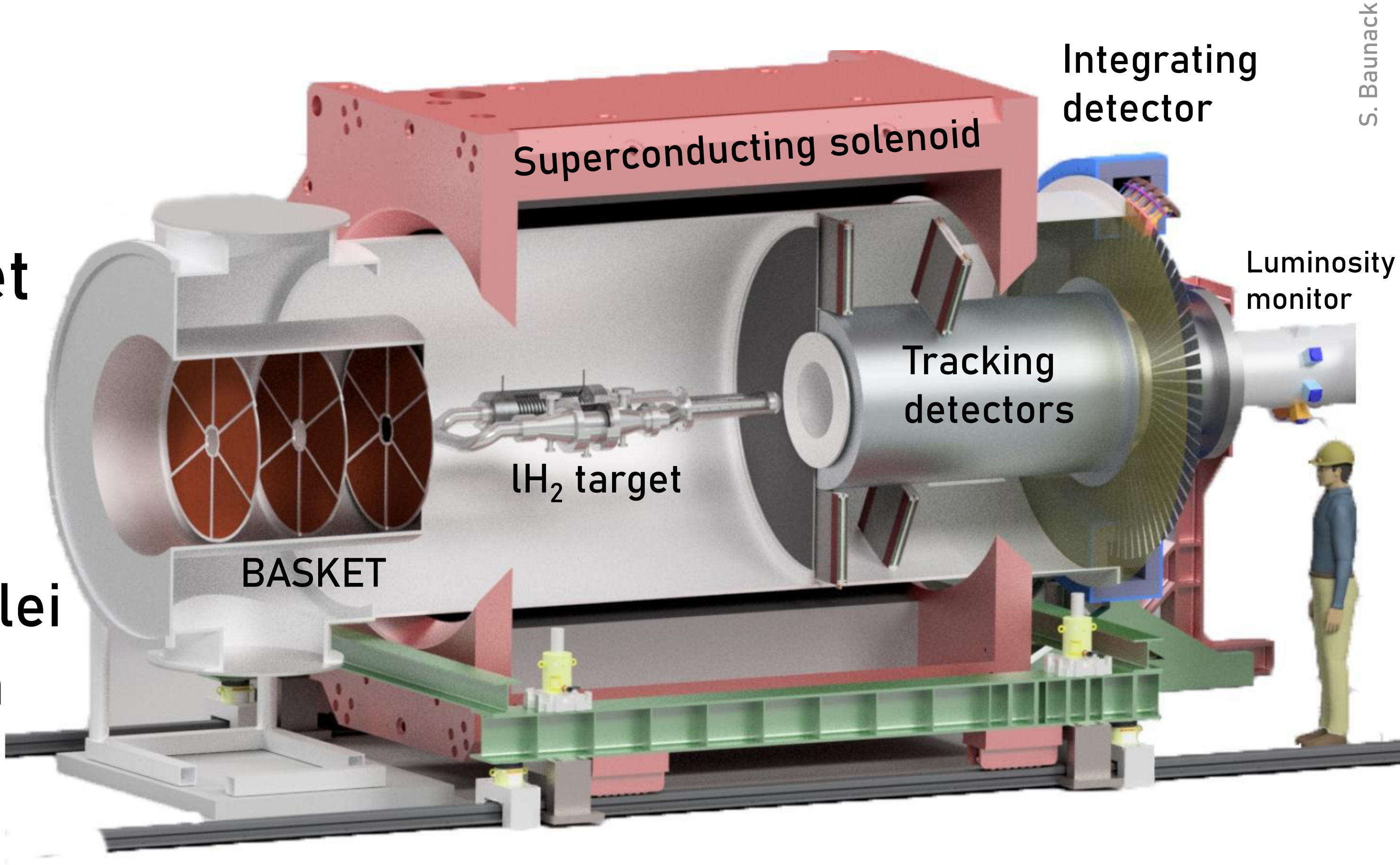
The P2 Experiment.

- Beam energies up to 155 MeV
- Beam currents up to 150 µA
- Extracted Beam (EB)
- 85% polarized electron beam



P2 – Overview.

- Solenoid spectrometer
- 60 cm long liquid H_2 target
- Physics programme
  - ➡ Axial and strange form factors of the proton
  - ➡ Neutron skin of heavy nuclei
  - ➡ Weak charge of the proton
  - ➡ Search for new physics



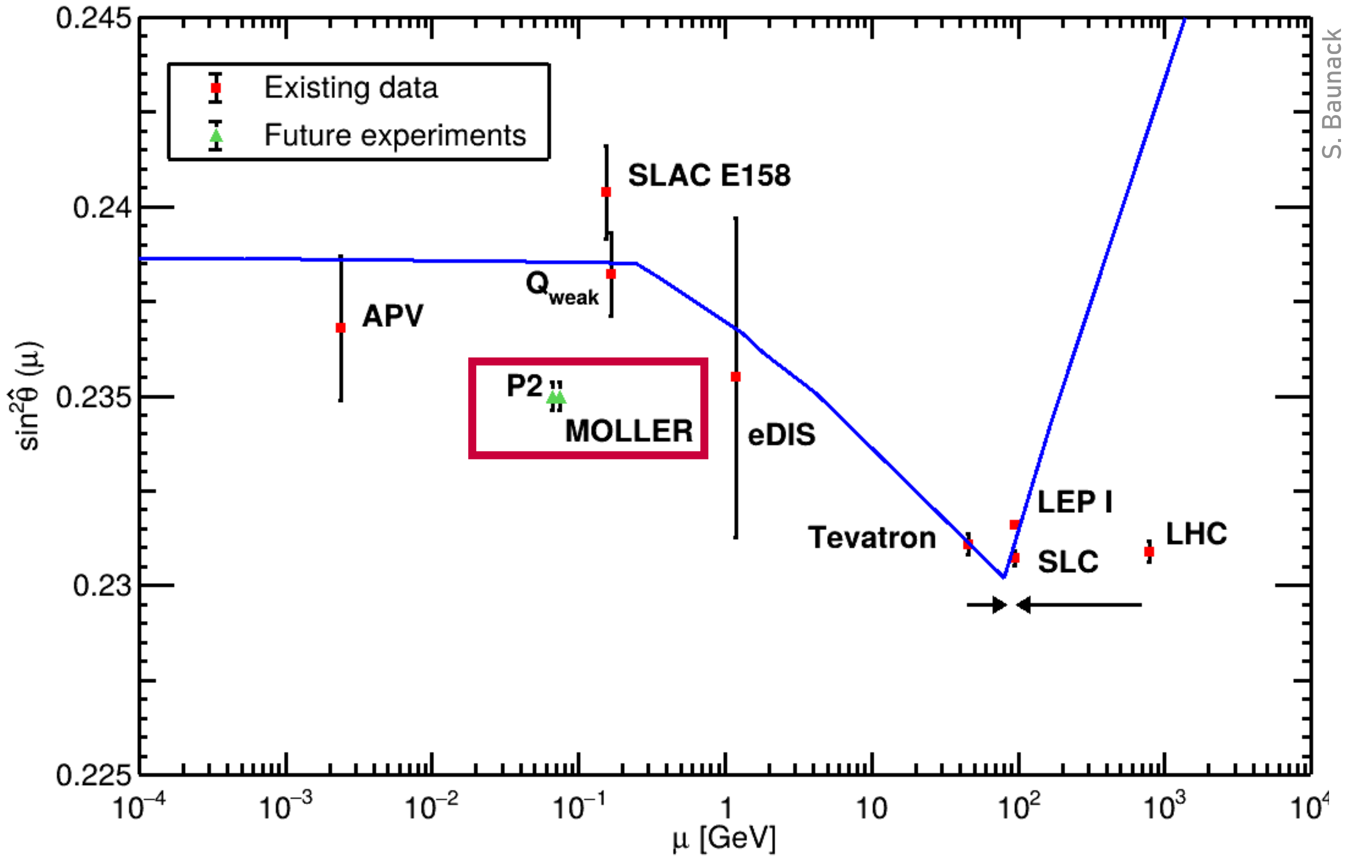
P2 – Weak Charge of the Proton.

- Parity violating asymmetry in elastic e-p-scattering

$$A_{LR}^{exp} = \frac{\sigma(\vec{e}p) - \sigma(\overleftarrow{e}p)}{\sigma(\vec{e}p) + \sigma(\overleftarrow{e}p)}$$
$$= -P\,\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(p) - F(Q^2)\right)$$

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

- Measure $\sin^2\theta_W$ with 0.15 % precision at $Q^2 = 4.5\cdot10^{-3}$ GeV²
- New Physics? Dark Z-Boson?
- Backward angle measurement



10,000 h data taking

D. Becker *et al.*, 10.1140/epja/i2018-12611-6
S. Baunack – 8th MAGIX Collaboration Meeting 2026

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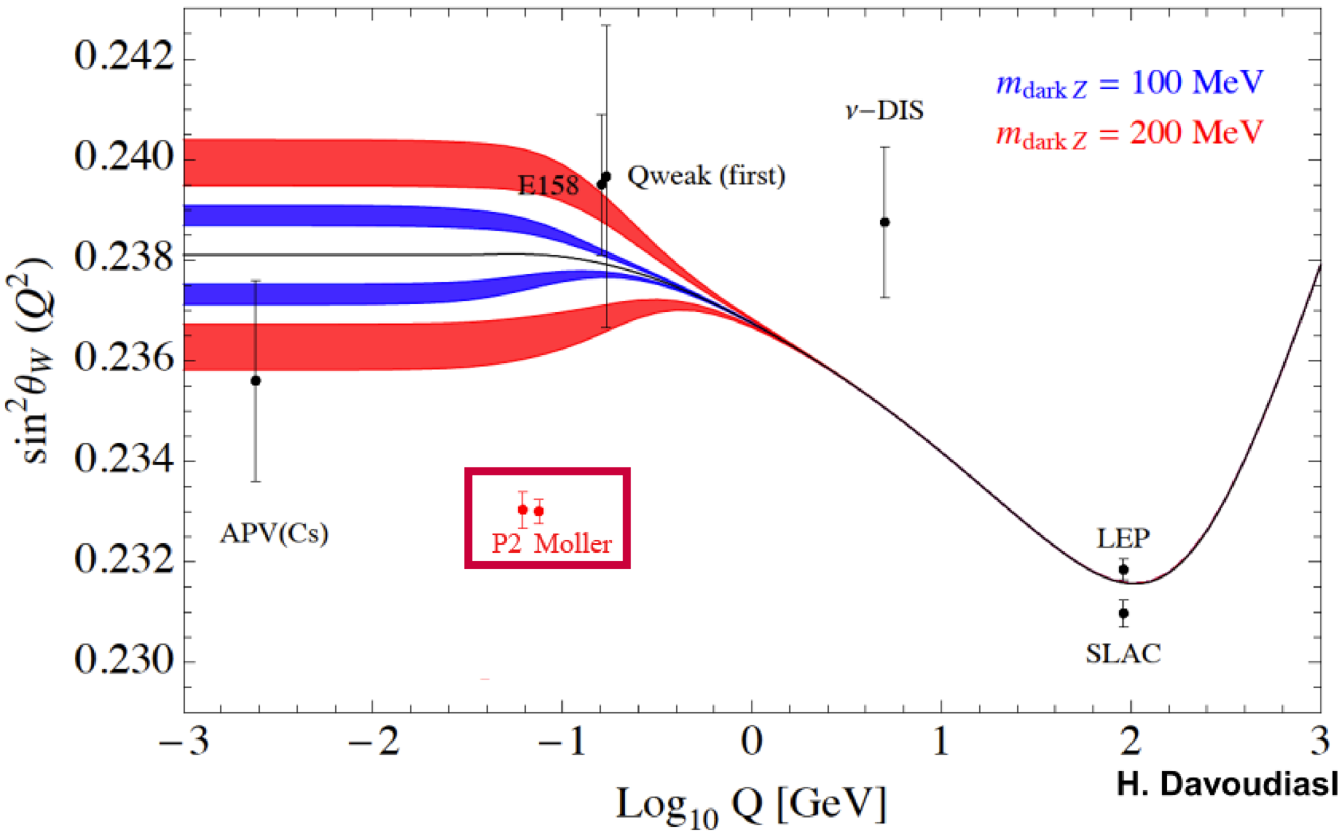

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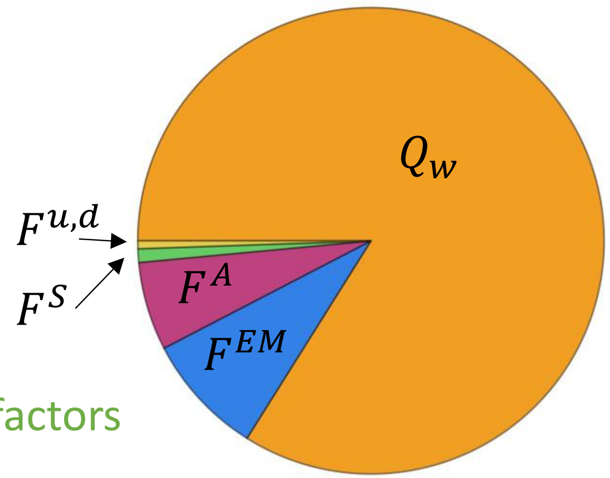
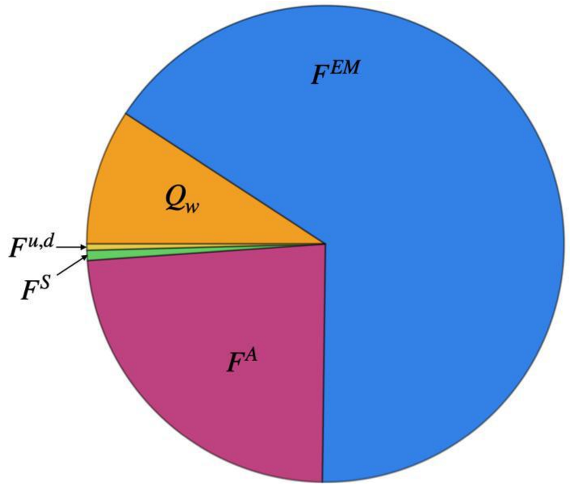
Hadron form factors

- Measure $\sin^2\theta_W$ with 0.15 % precision at $Q^2 = 4.5 \cdot 10^{-3}$ GeV²
- New Physics? Dark Z-Boson?
- Backward angle measurement

Contributions to A_{PV}



Forward angle



Backward angle

A backward-angle measurement reduces the hadronic contribution to the uncertainty of the forward-angle measurement.

D. Becker *et al.*, 10.1140/epja/i2018-12611-6
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P2 – Status & Impressions.

Nov 2024

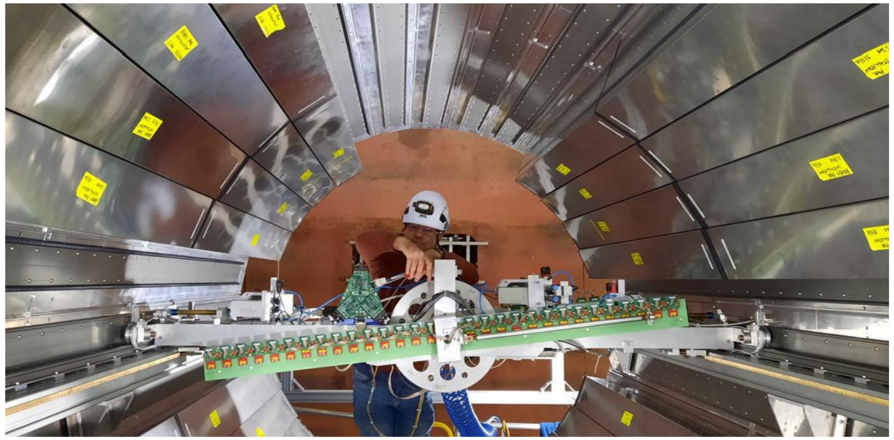
- Solenoid delivery
- Vacuum chamber delivery
- 90 m³ hydrogen tank delivery
- Field mapping with CERN magnet group in Nov 2026

- Superconducting Magnet (NbTi)
- FOPI yoke
- Operating Temperature < 6 K
- Maximum field of 0.7 T
- Outer Diameter 3.3 m
- Length 4 m

June 2025

Aug 2026

Feb 2025



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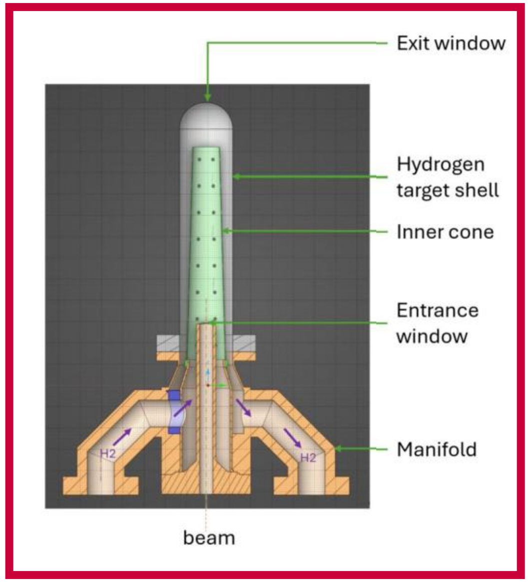
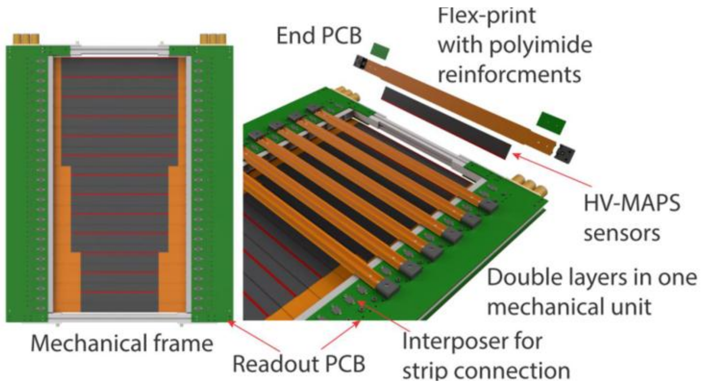
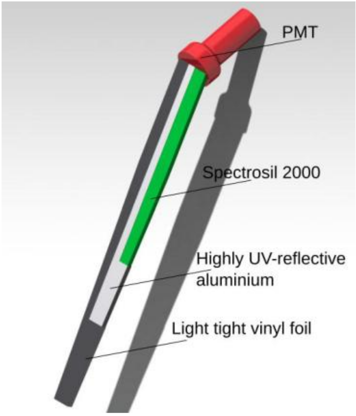
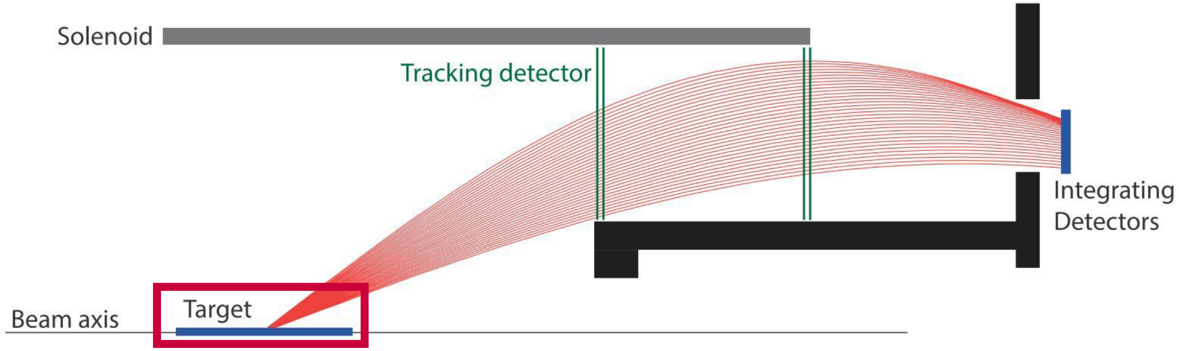
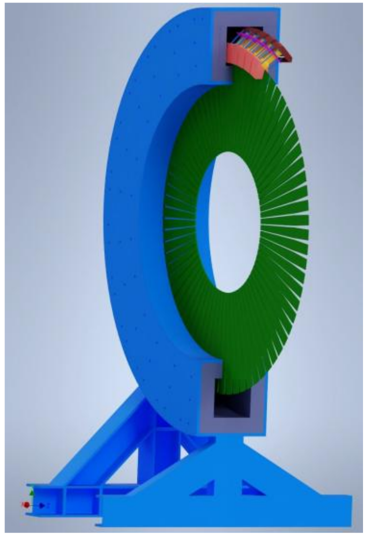




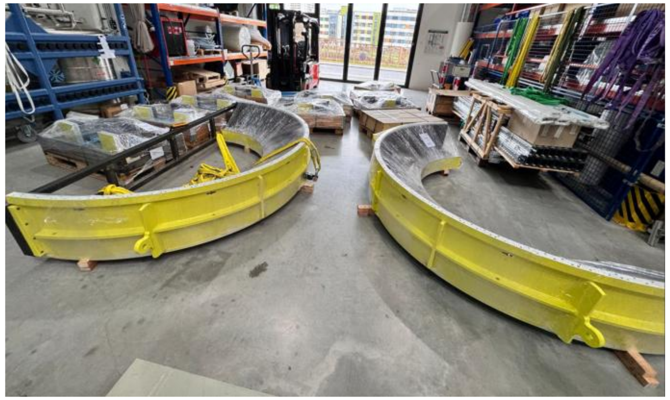


- Target installation in July 2027
- Manufacturing and assembly ongoing
- Integrating detectors ready in early 2027





Detector shielding and holding structure



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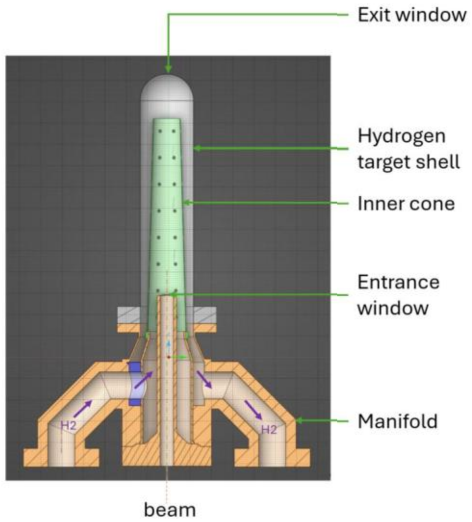

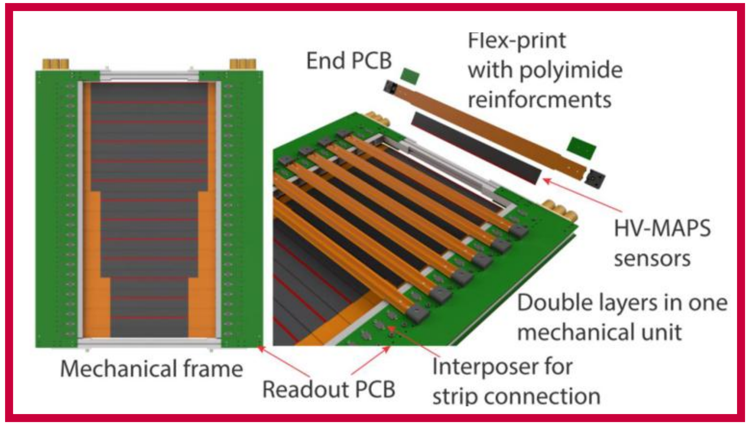

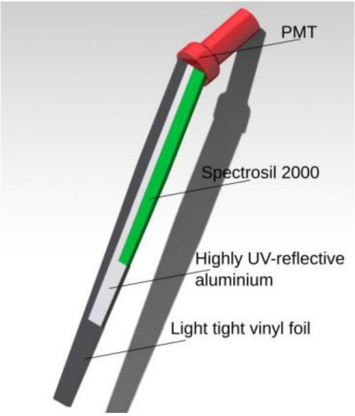

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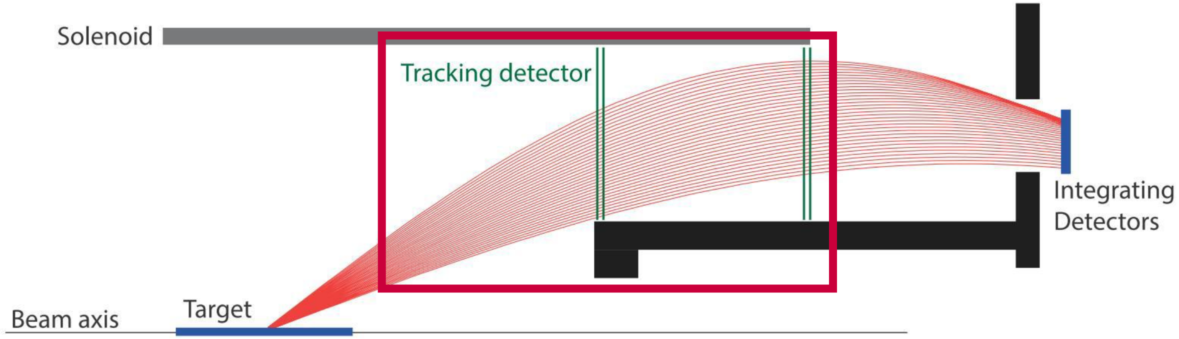

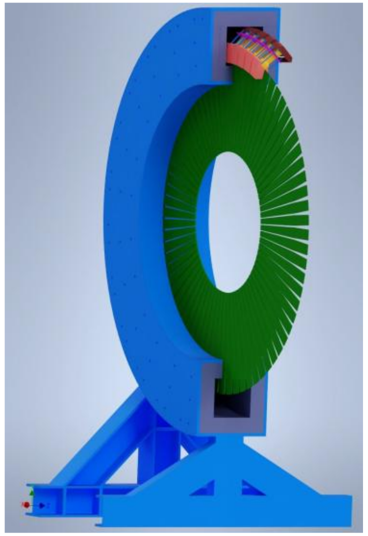

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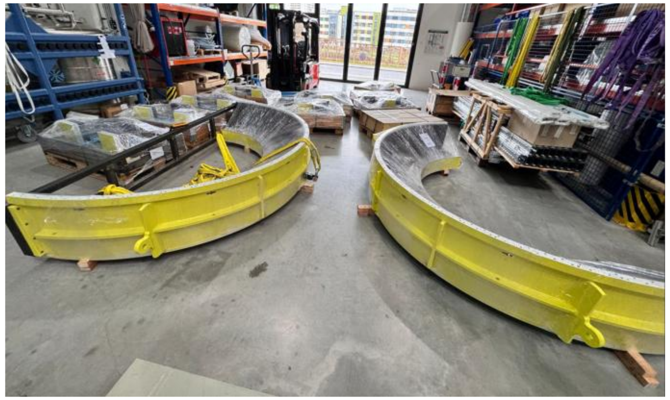

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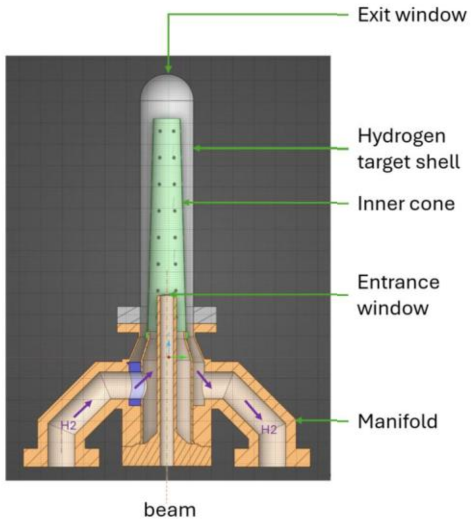

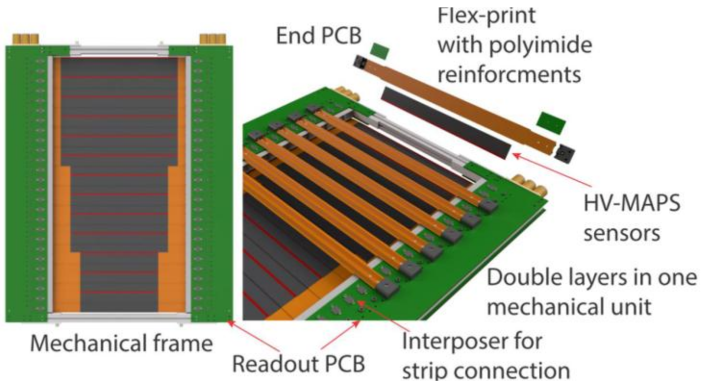

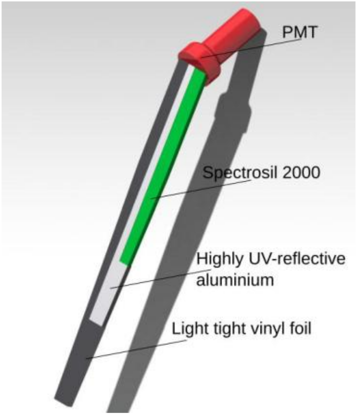

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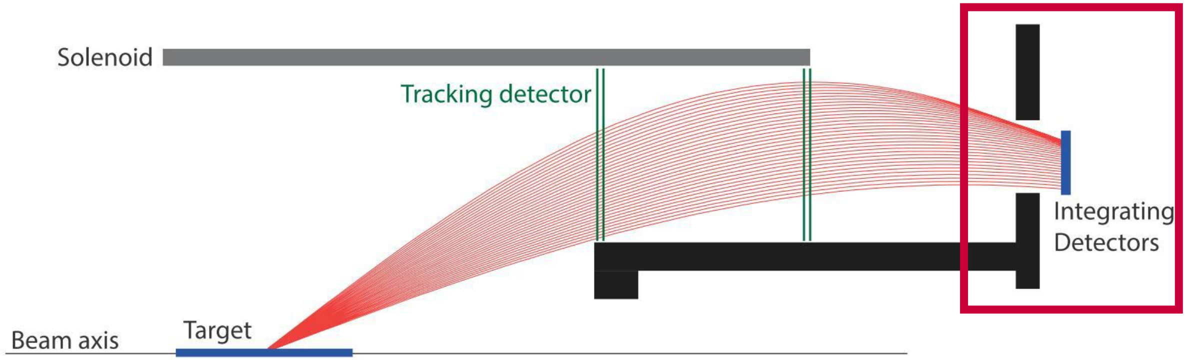

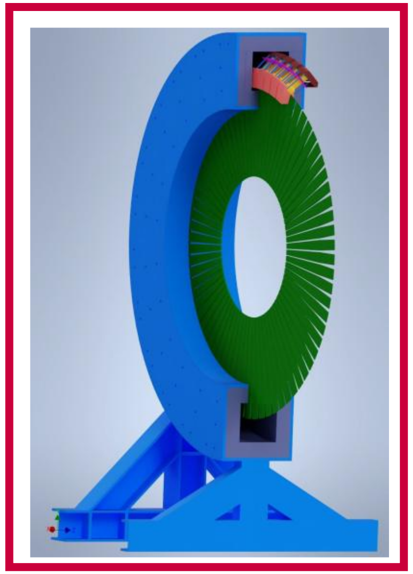

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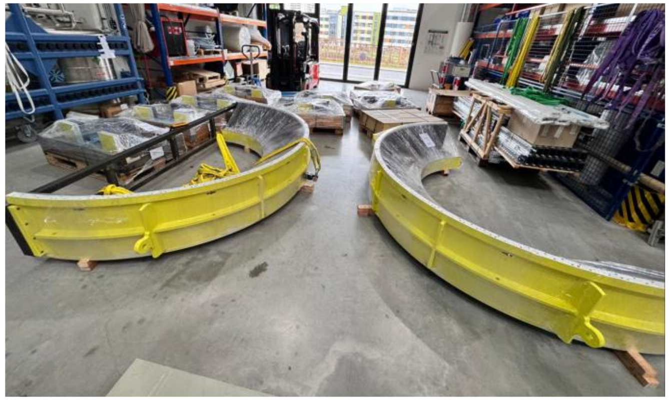

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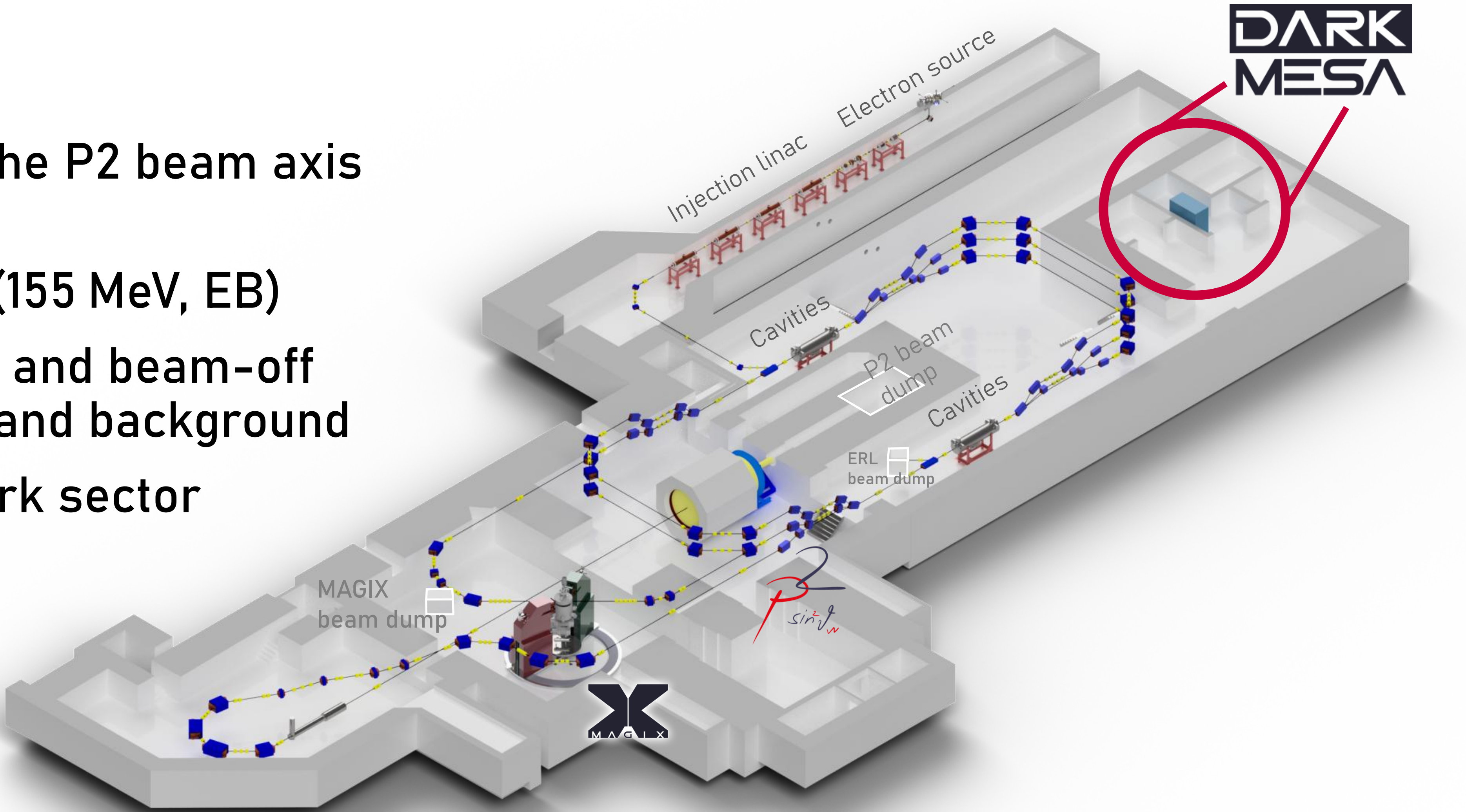
DarkMESA – A parasitic beam dump experiment.

- Located along the P2 beam axis extension
- Parasitic to P2 (155 MeV, EB)
- MESA beam-on and beam-off runs for signal and background
- Dedicated to dark sector searches

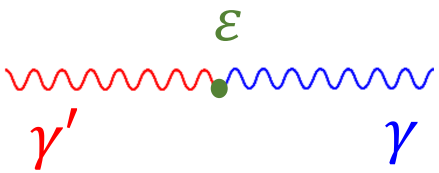


Hidden (Dark) Sector.

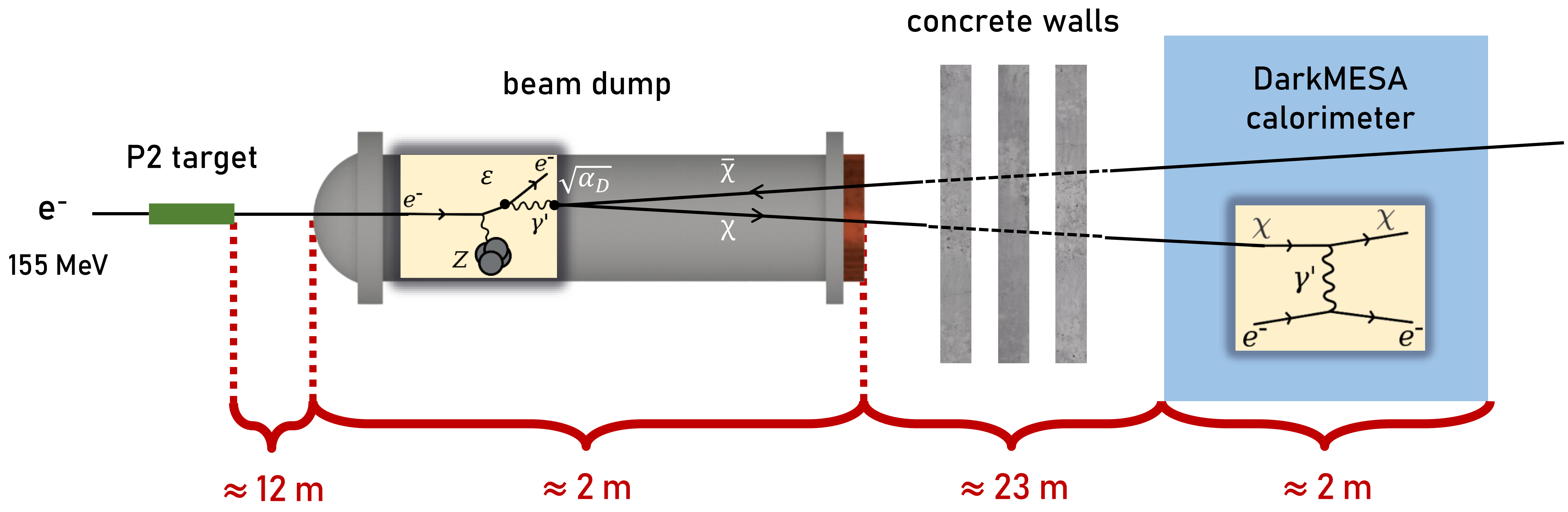
- Standard Model incomplete (astrophysical observations)
- No beyond SM particles found yet
- Hidden sector particles without SM interactions
- But interaction through portals is possible (vector, Higgs, neutrino)

➡ e.g., coupling via kinetic mixing:

$$\mathcal{L}_{\mathrm{mix}} = -\frac{\varepsilon}{2} F_{\mu\nu}^{\mathrm{QED}} F_{\mathrm{dark}}^{\mu\nu}$$



Experimental Concept.

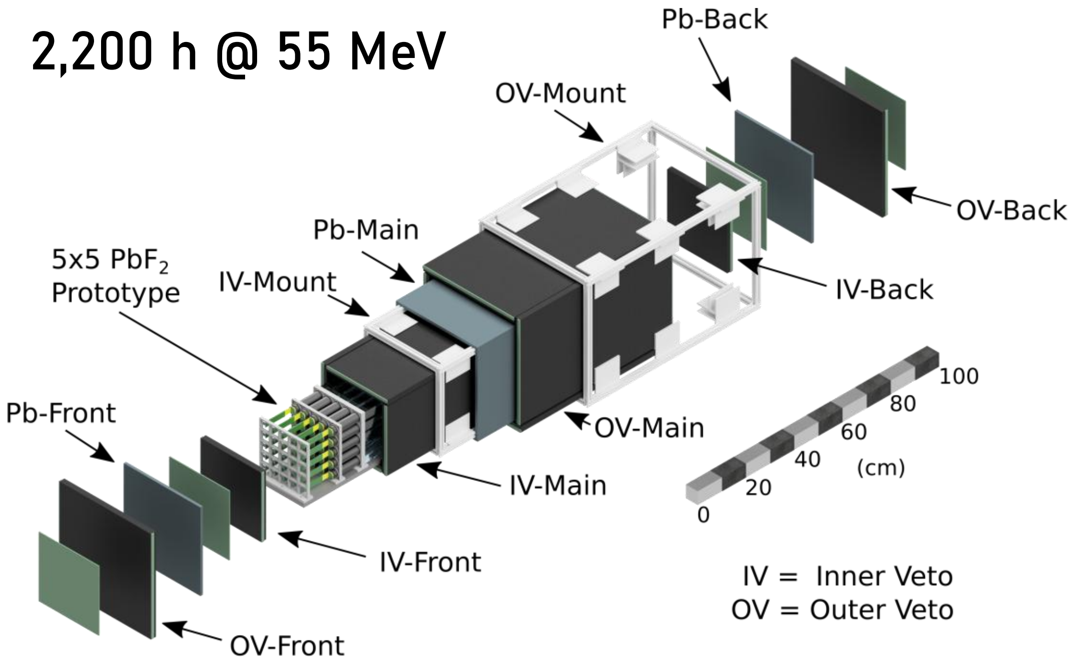


Testing ground for DM production at $\boxed{m_{\gamma'} < 140\ \text{MeV}}$

Proposed Phase A and B.

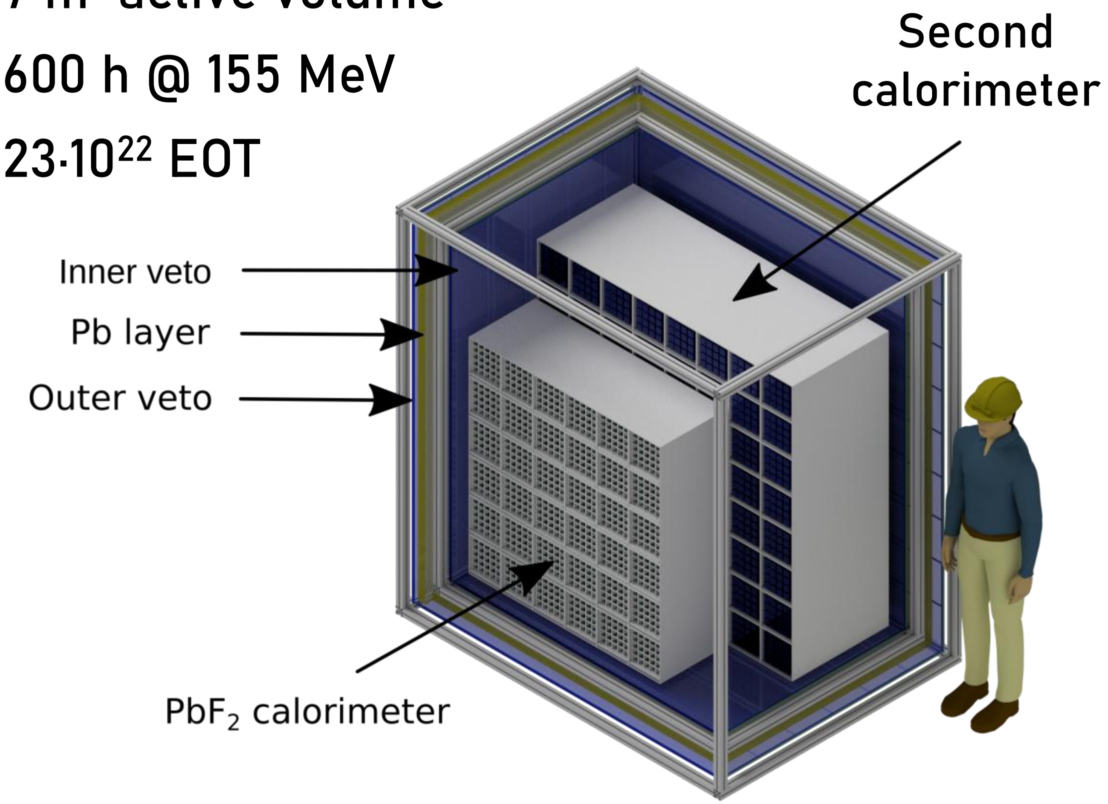
Phase A

- One PbF_2 module (5×5 crystals)
- 0.004 m^3 active volume
- 2,200 h @ 55 MeV



Phase B

- 36 PbF_2 modules + second wall
- 0.7 m^3 active volume
- 6,600 h @ 155 MeV
- $2.23 \cdot 10^{22}$ EOT

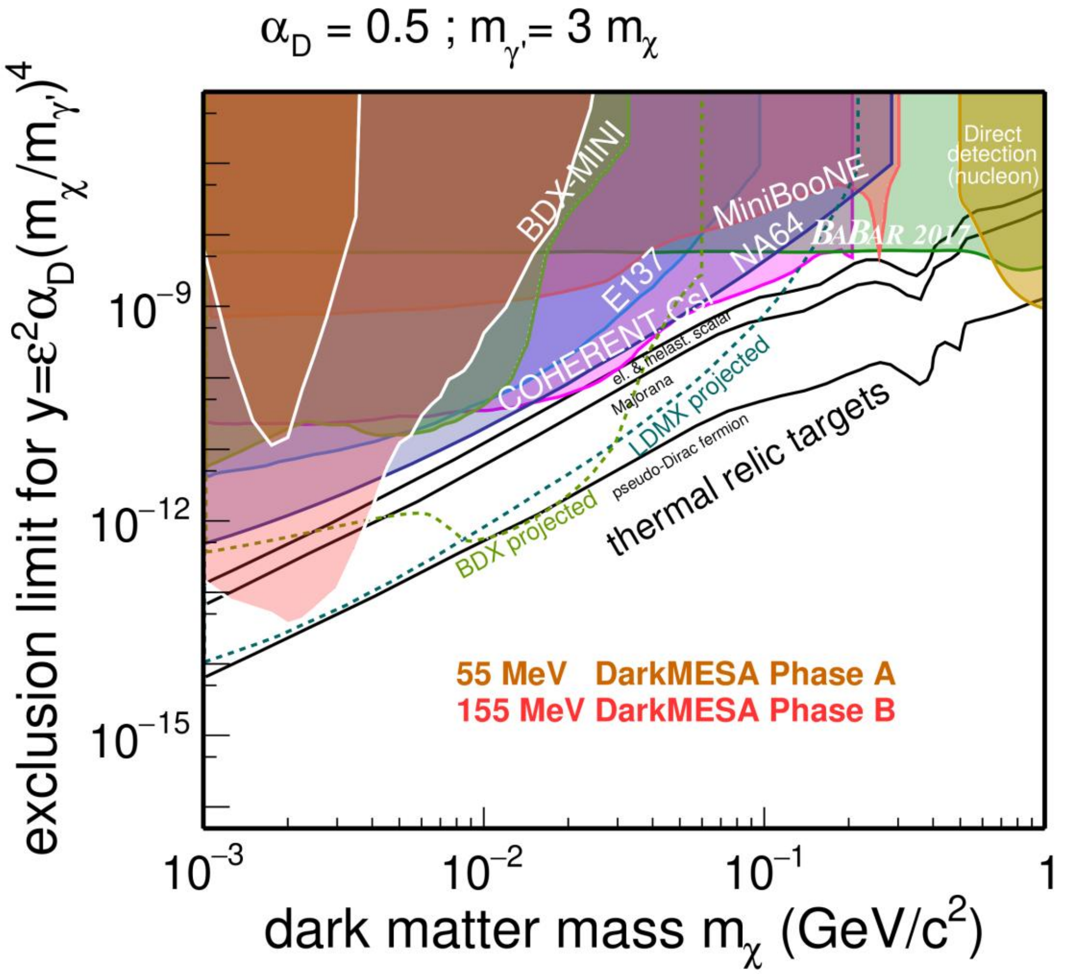


DarkMESA Exclusion Limits.

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

- Additional assumptions:
  - Detection threshold 10 MeV (electron recoil)
  - Detector efficiency 95%
  - Confidence level 90%
  - No backgrounds
- Positron annihilation on e^- of the beam-dump

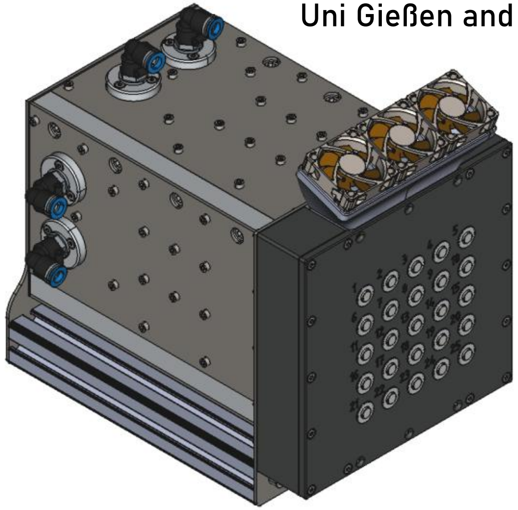
$$e^+ + e^- \rightarrow \gamma'$$
$$e^+ + e^- \rightarrow \gamma + \gamma'$$

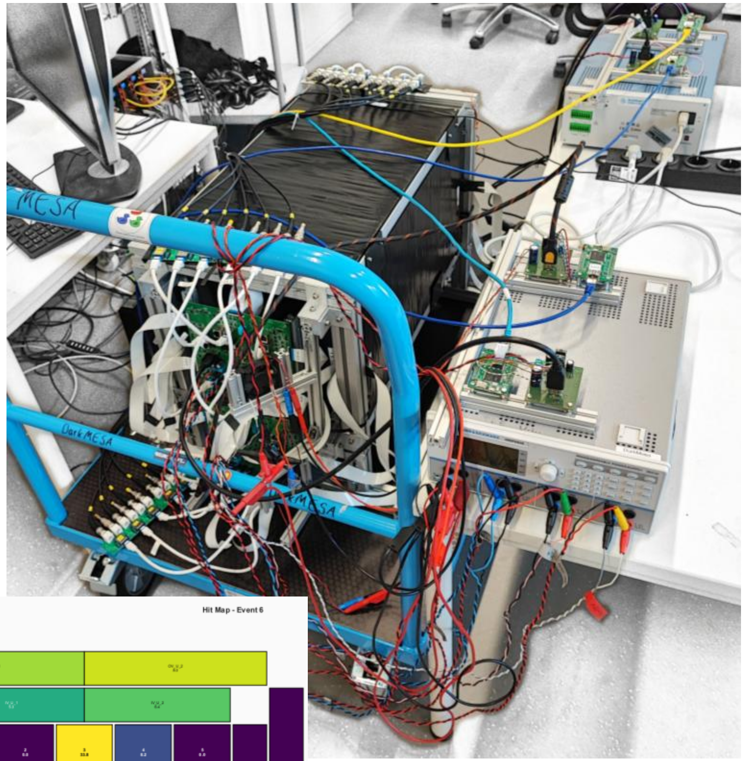


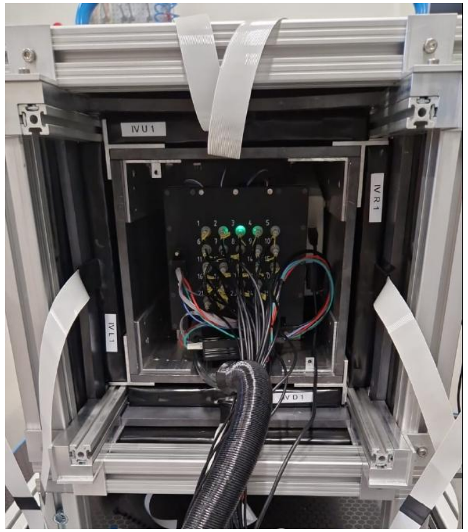
DarkMESA – Status & Impressions.

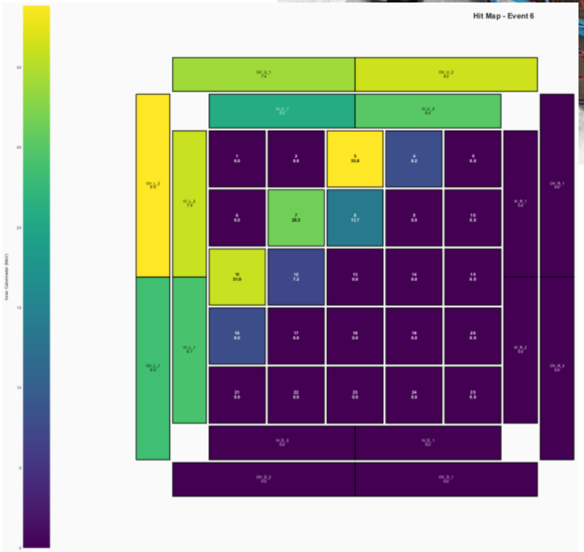
- PWO prototype calorimeter & Phase A veto system
- 99.8 % veto efficiency *

Co-operation with
Uni Gießen and CRYTUR





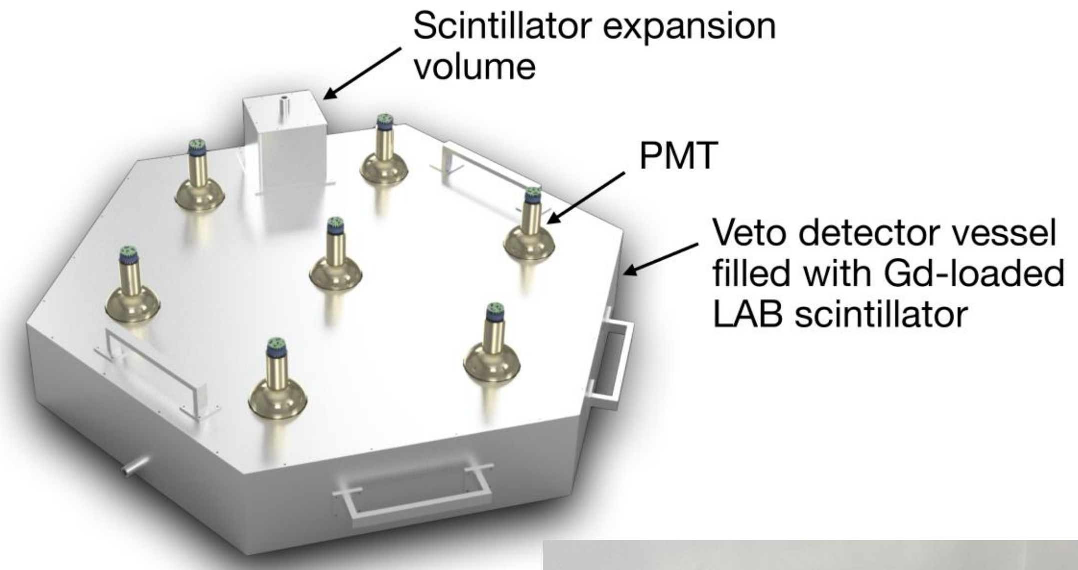


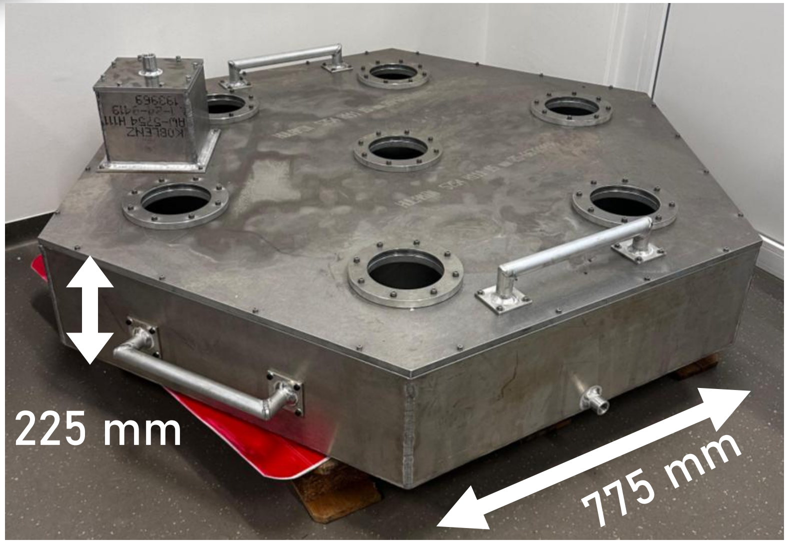


*with outer calo layer & multiplicity cut

DarkMESA – Status & Impressions.

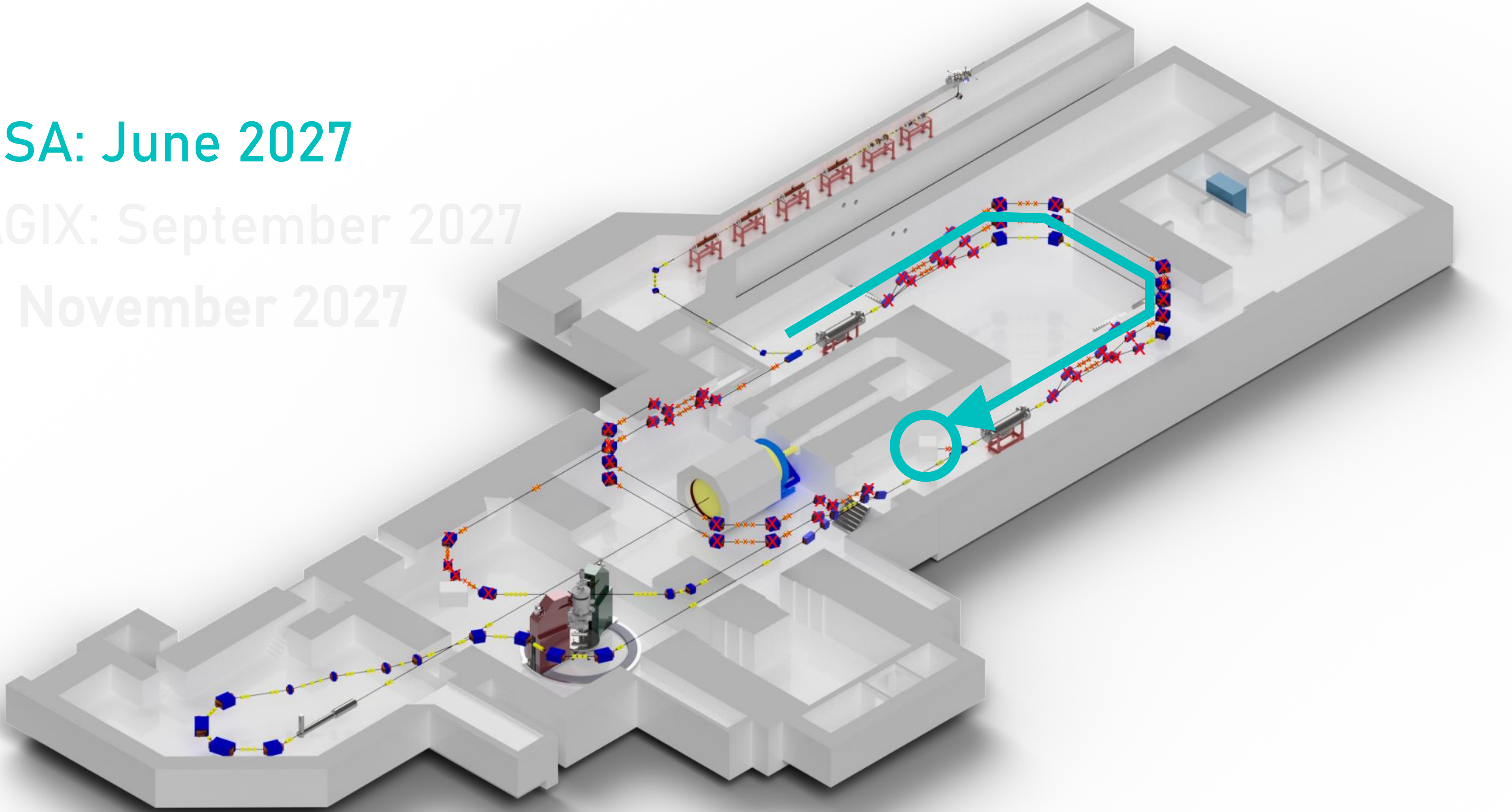
- PWO prototype calorimeter & Phase A veto system
- 99.8 % veto efficiency *
- Additional detector & veto system studies in co-operation with NuDoubt^{++}





MESA Facility timeline.

- First beam MESA: June 2027
- First beam MAGIX: September 2027
- First beam P2: November 2027



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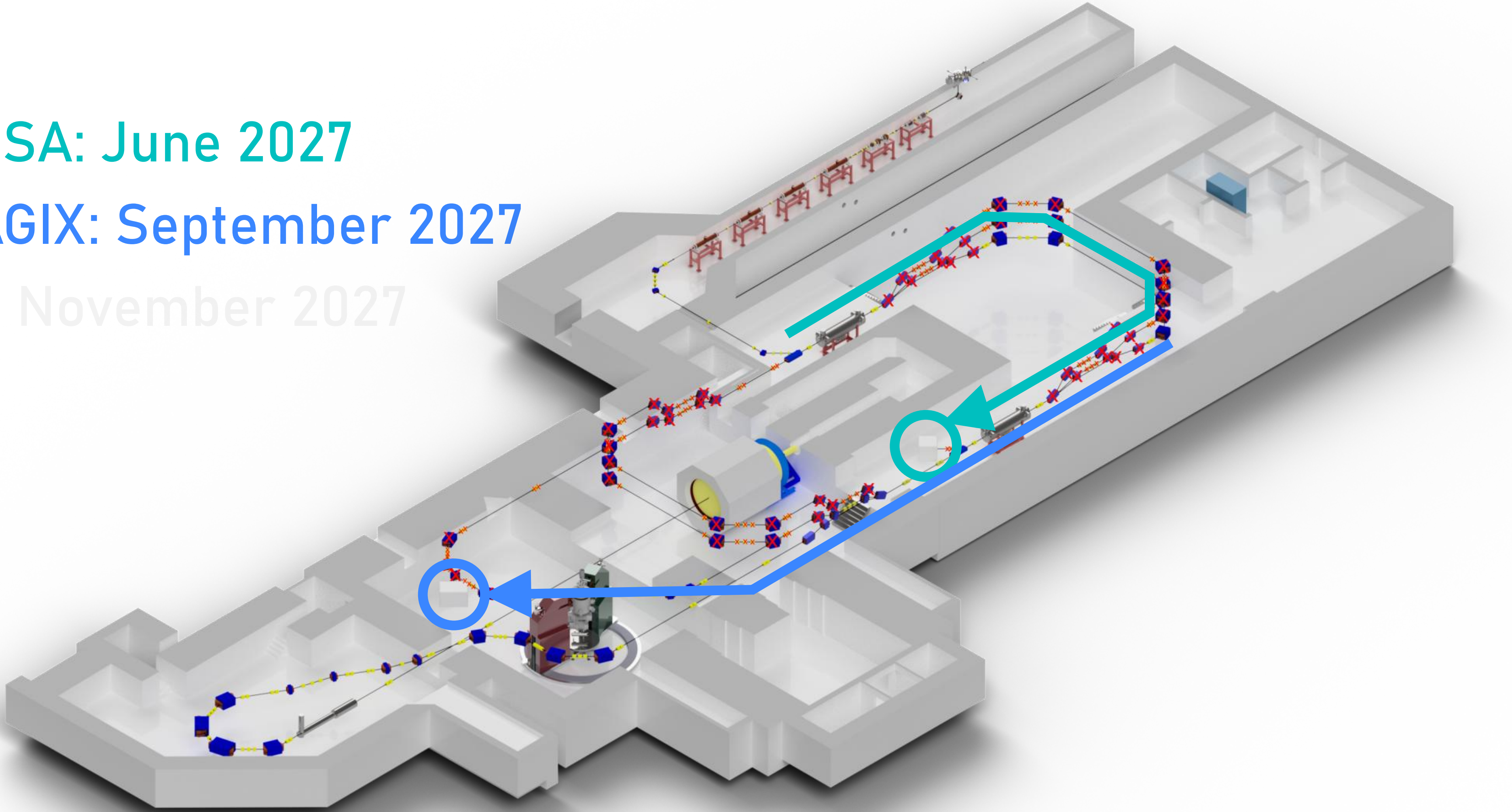

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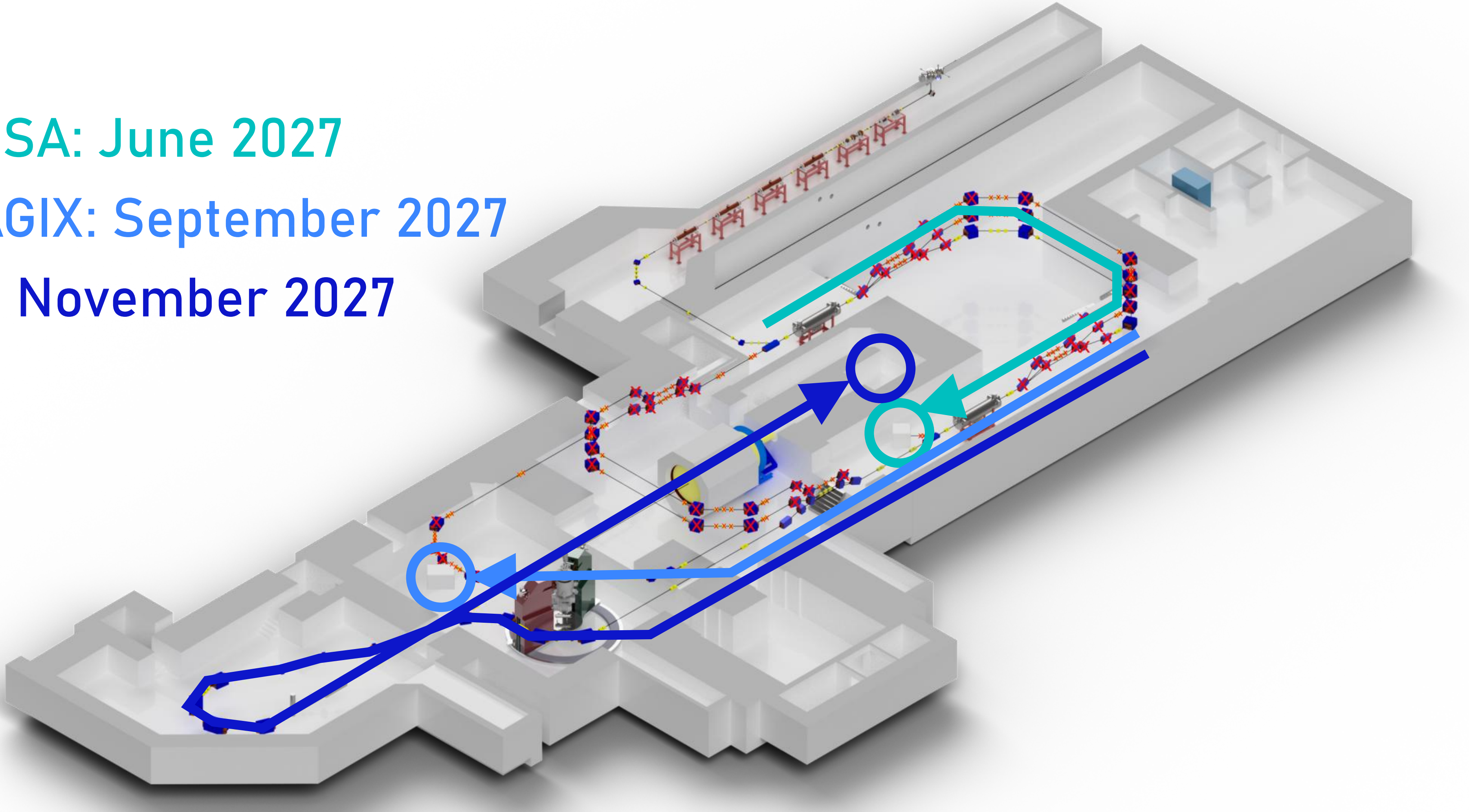
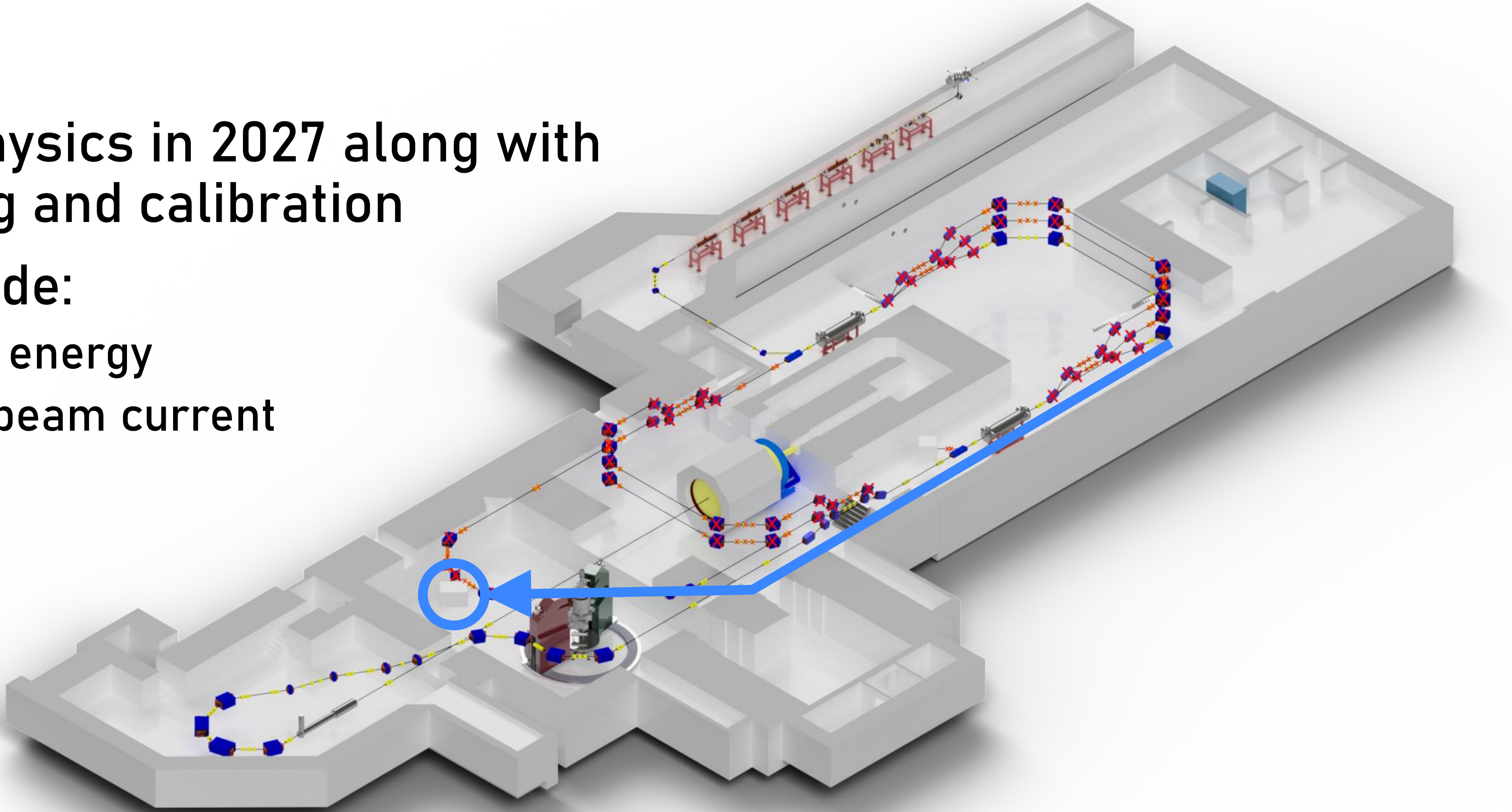


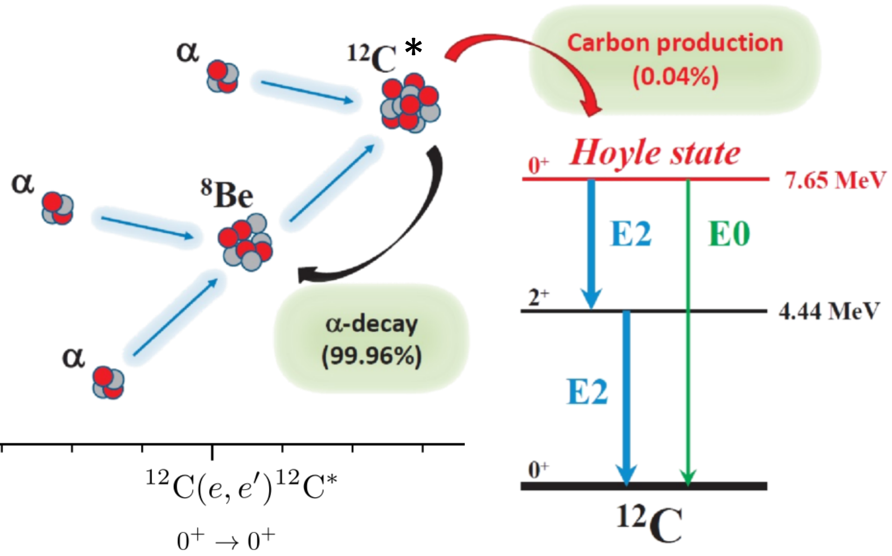
Hoyle state measurement @ MAGIX.

- First MAGIX physics in 2027 along with commissioning and calibration
- MESA's EB mode:
  - 55 MeV beam energy
  - At least 1 µA beam current

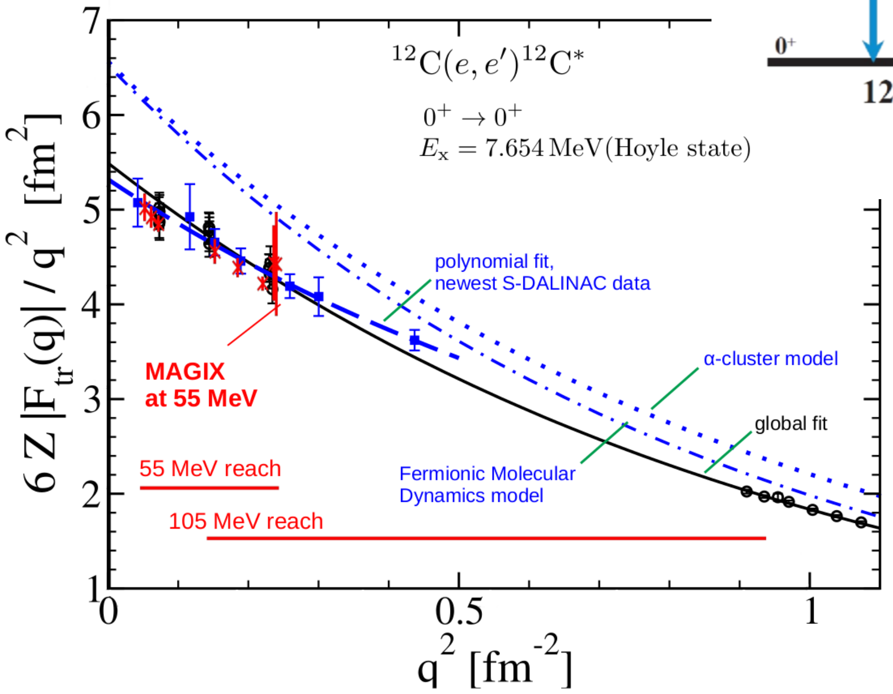


Hoyle state measurement @ MAGIX.

- First MAGIX physics in 2027 along with commissioning and calibration
- MESA's EB mode:
  - 55 MeV beam energy
  - At least 1 μA beam current
- Inelastic e^- scattering on ^{12}C target
- Measure E0 transition form factor
- Probe α-cluster structure of ^{12}C



T.K. Eriksen *et al.*, 10.7566/JPSCP.14.020404

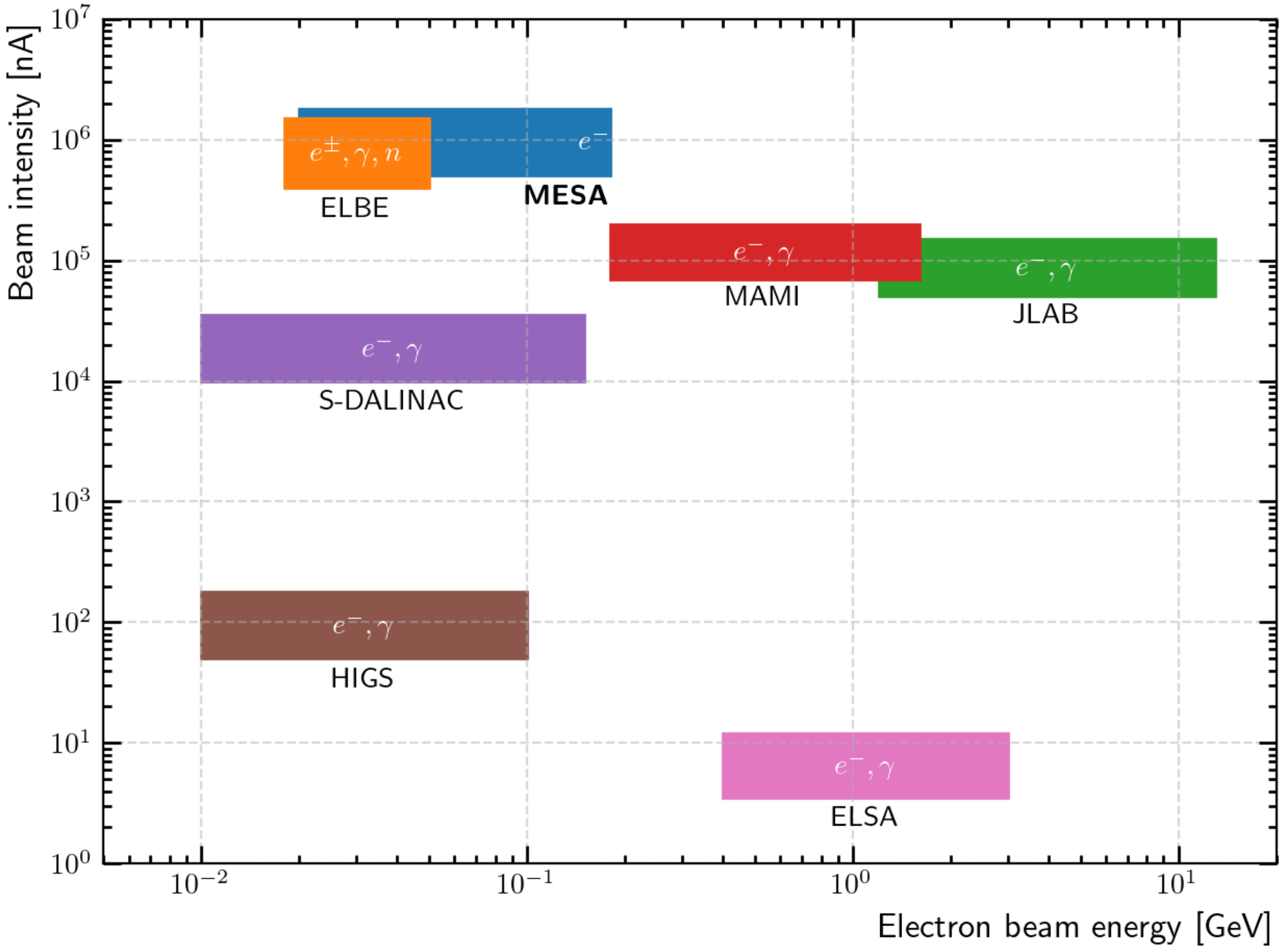


D. Markus

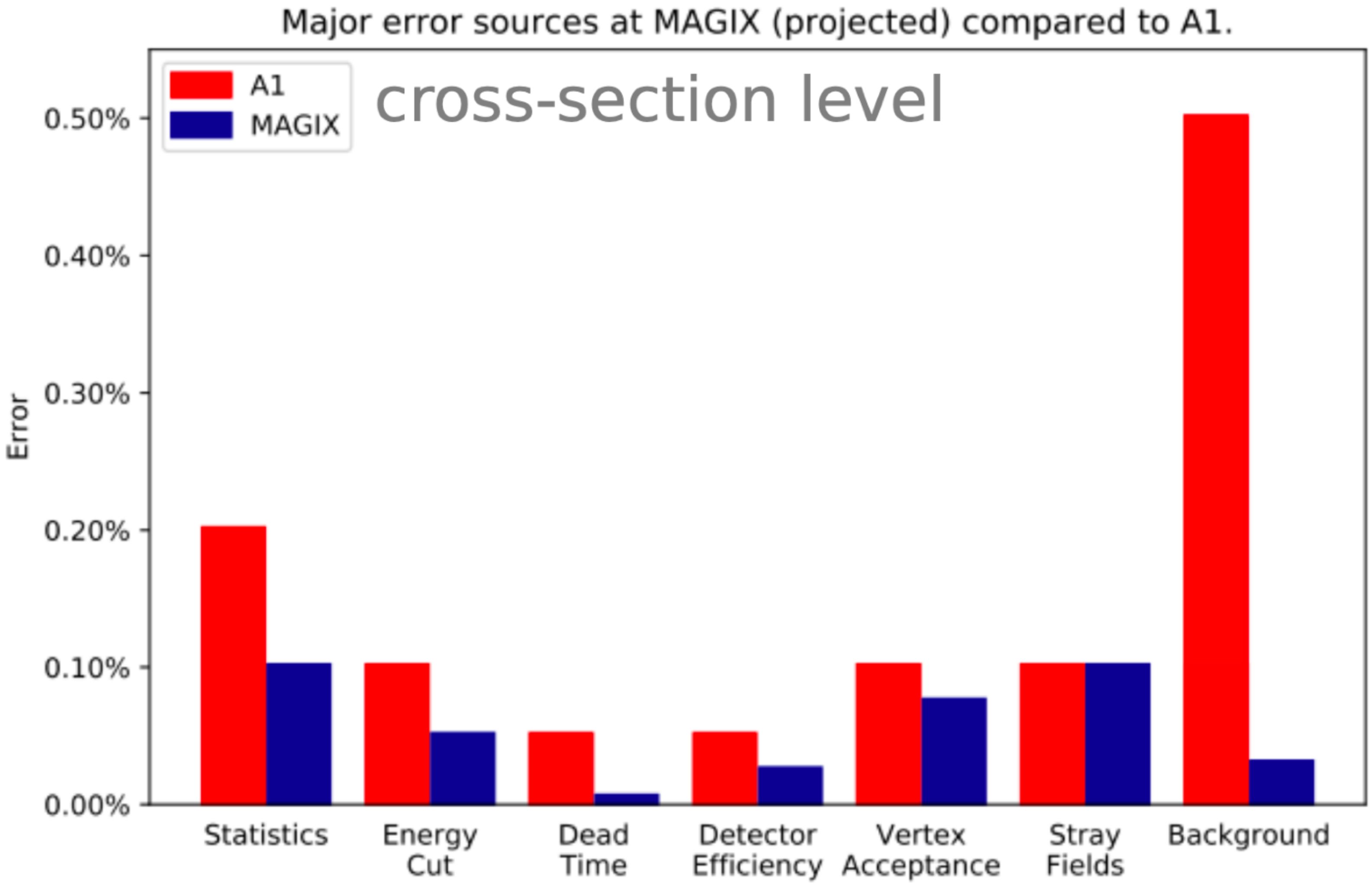
Thank you for your attention!

Backup.

Comparison of Beam Intensities.



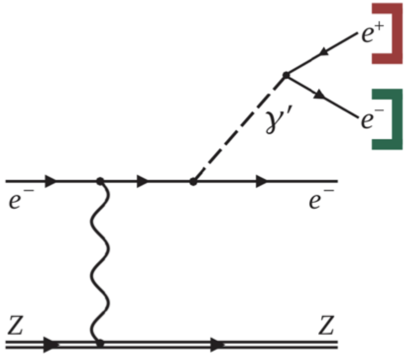
Error reduction at MAGIX.

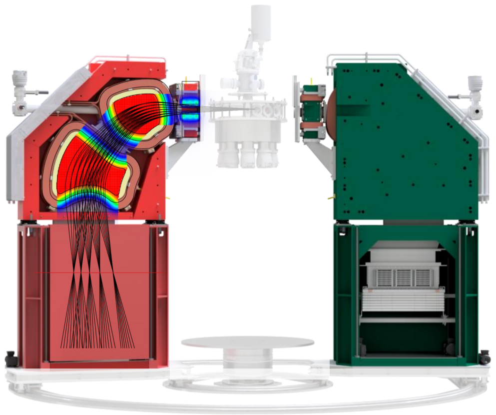


S. Schlimme

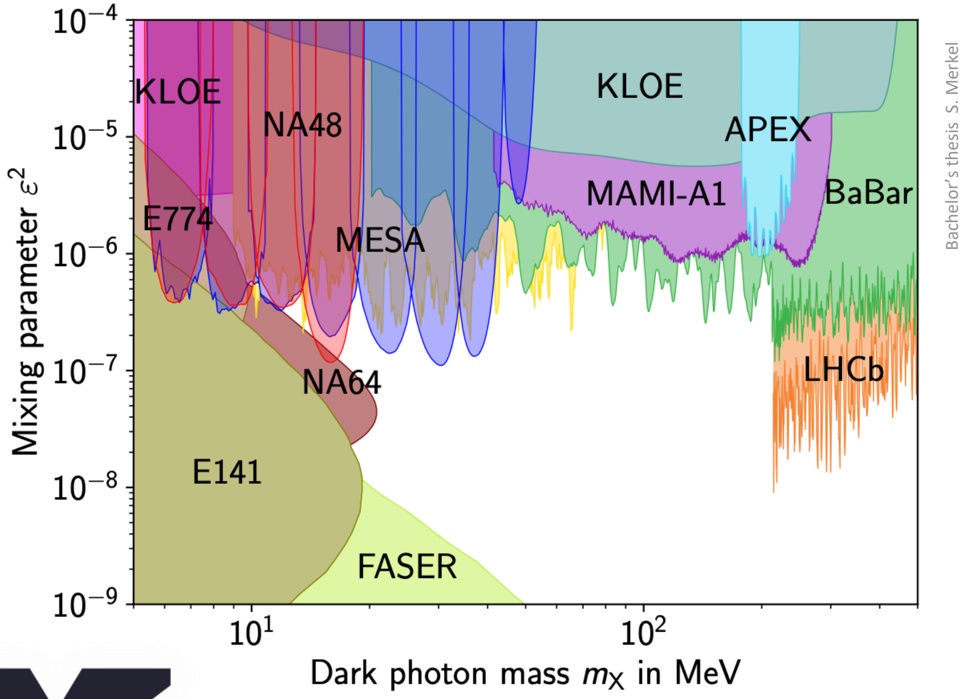
MAGIX – Dark Photon.

Visible decay

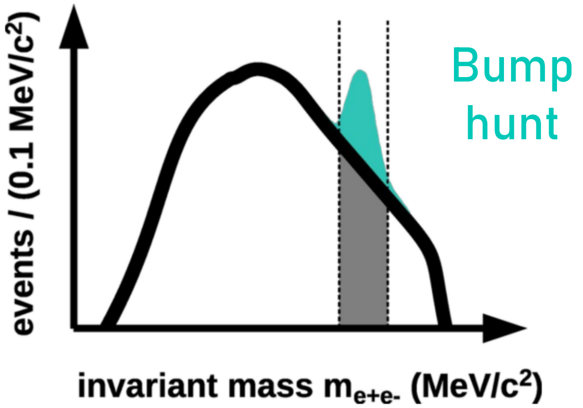




Coincidence measurement between both spectrometers

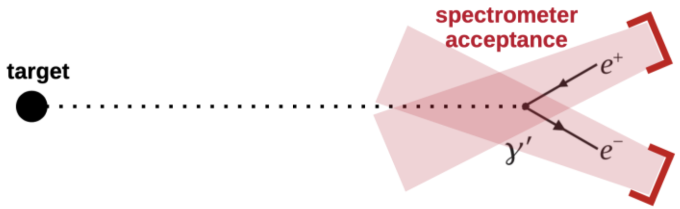


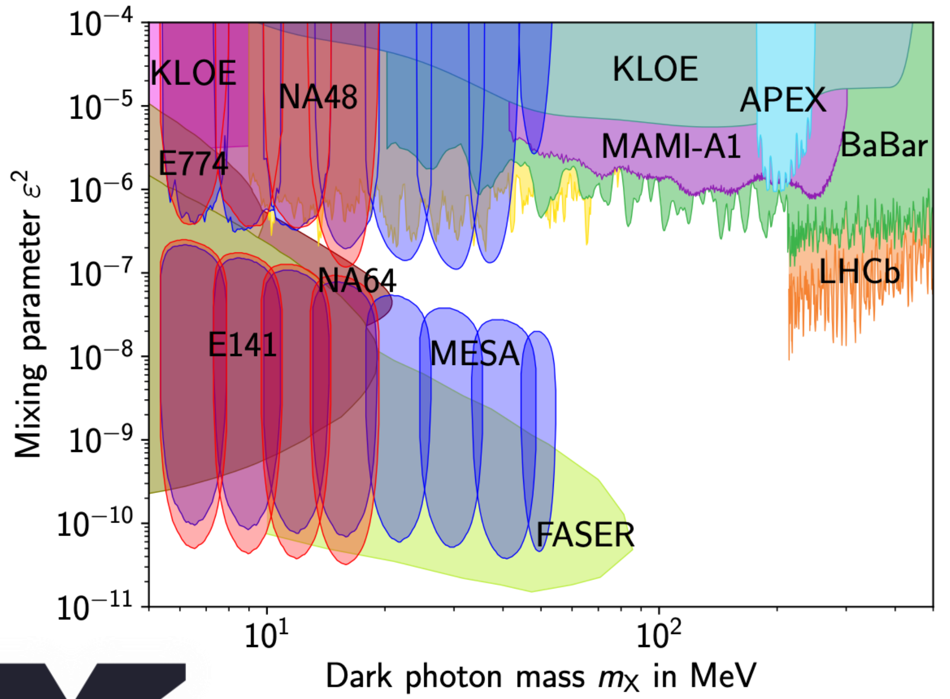
- 100 µA beam current and beam energies of 55 MeV and 105 MeV
- ^{181}Ta solid target
- 2 weeks per run



MAGIX – Dark Photon.

Visible decay & displaced vertex





Bachelor's thesis S. Merkel

e.g.

$$\boxed{l_{\text{decay}}} \approx 1.5\,\text{mm}\left(\frac{E_{\text{beam}}}{55\,\text{MeV}}\right)\cdot\left(\frac{10^{-4}}{\boxed{\varepsilon}}\right)^2\cdot\left(\frac{17\,\text{MeV}/c^2}{m_{\gamma'}}\right)^2$$

- 100 µA beam current and beam energies of 55 MeV and 105 MeV
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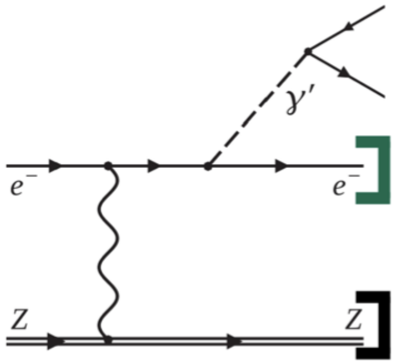
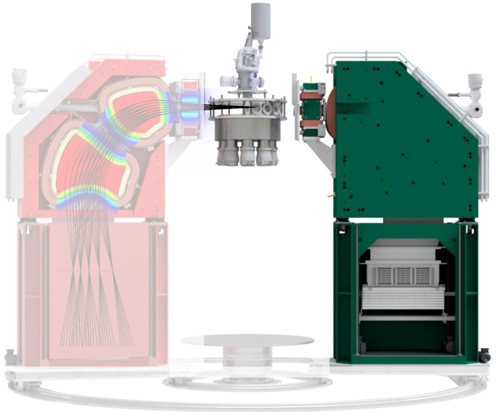
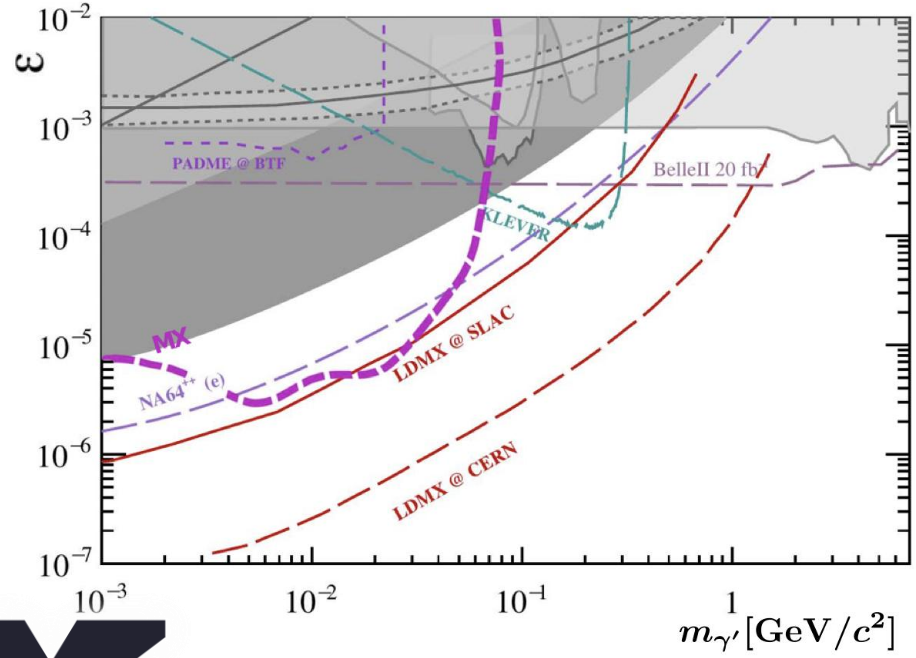
MAGIX – Dark Photon.

Invisible decay

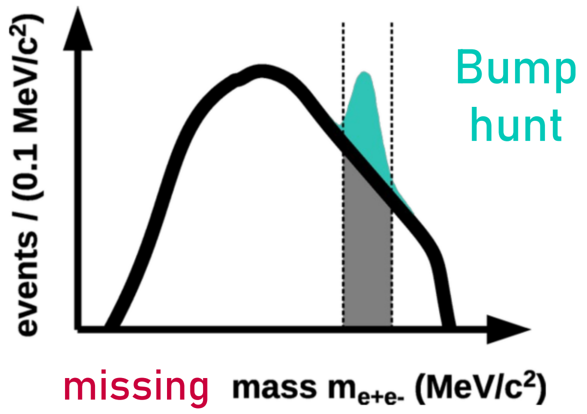




+



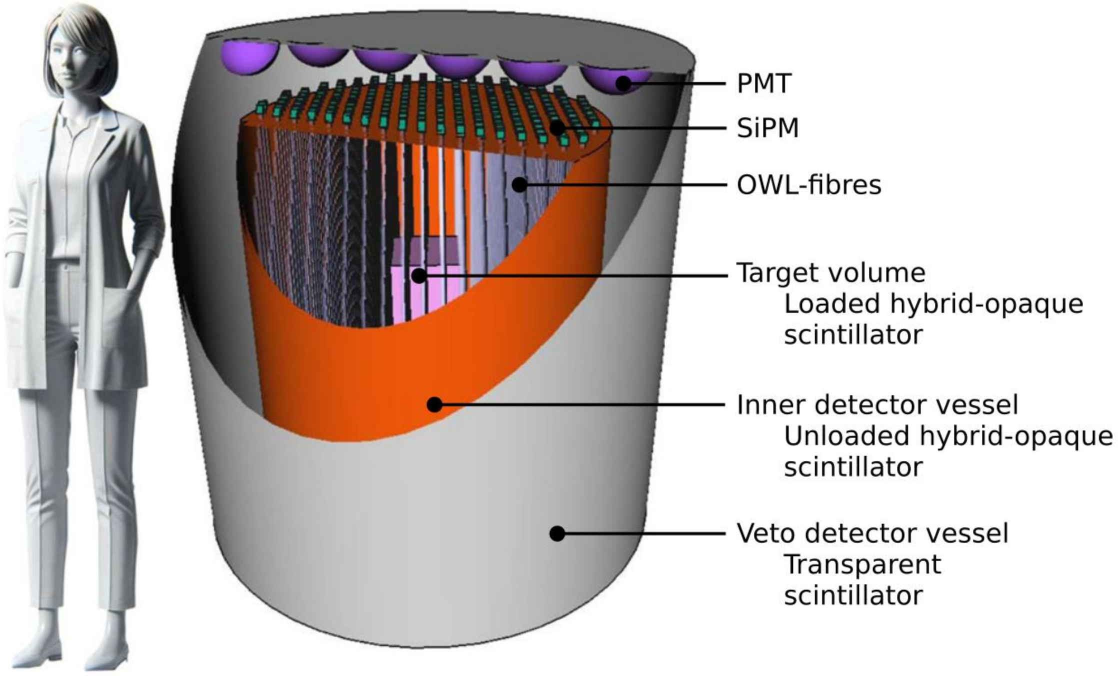
Coincidence measurement between one spectrometer and the silicon strip detectors



Liquid Scintillator – NuDoubt++.

Liquid Scintillator – NuDoubt^{++}.

- Search for double beta plus decays
- 1 m³ demonstrator



[1] Boehles et al., arXiv:2407.05999v3 [hep-ex]

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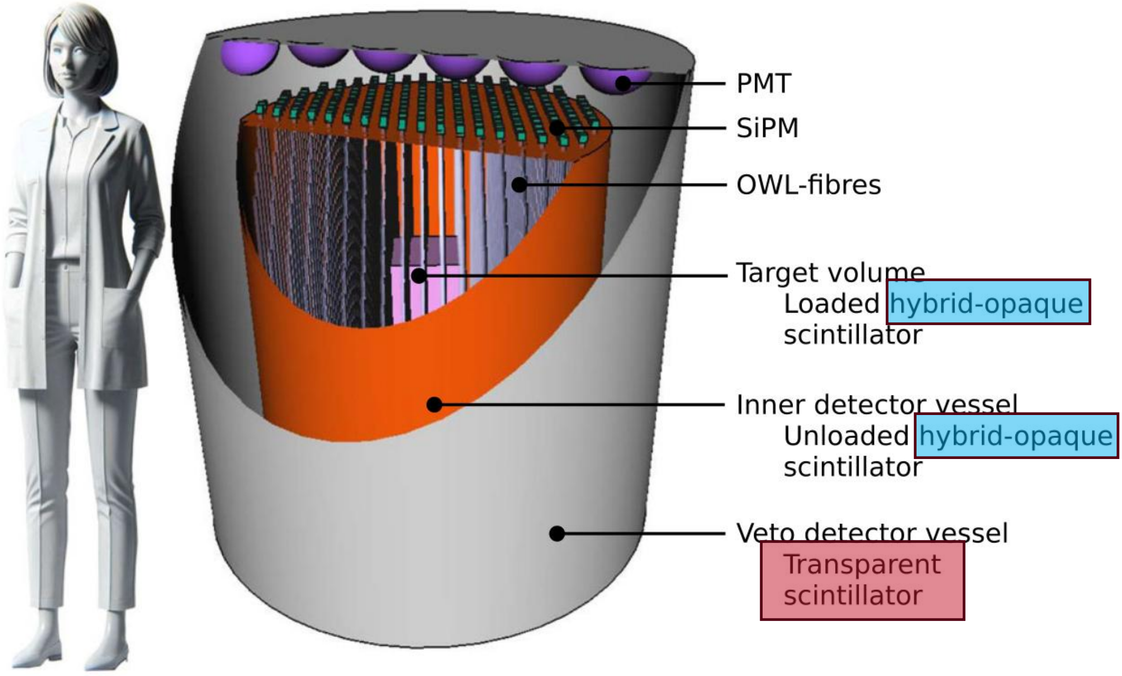
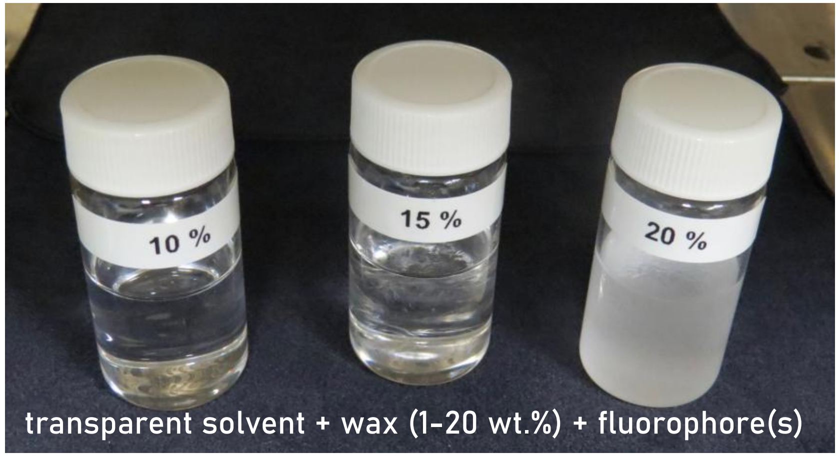
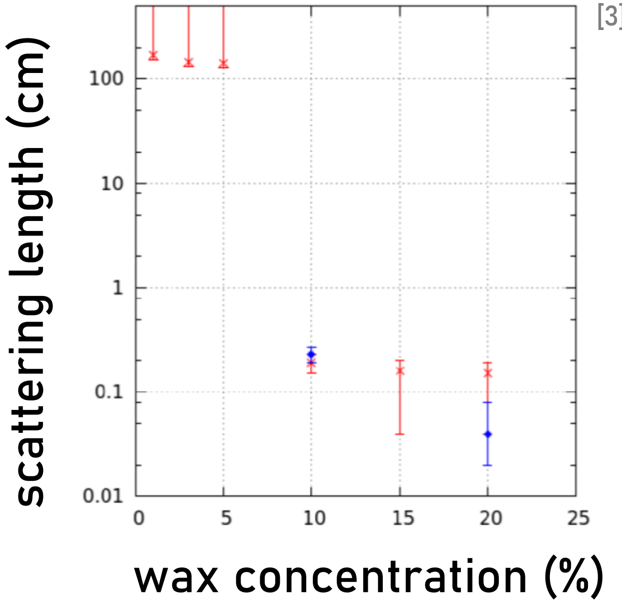


[1] Boehles et al., arXiv:2407.05999v3 [hep-ex]

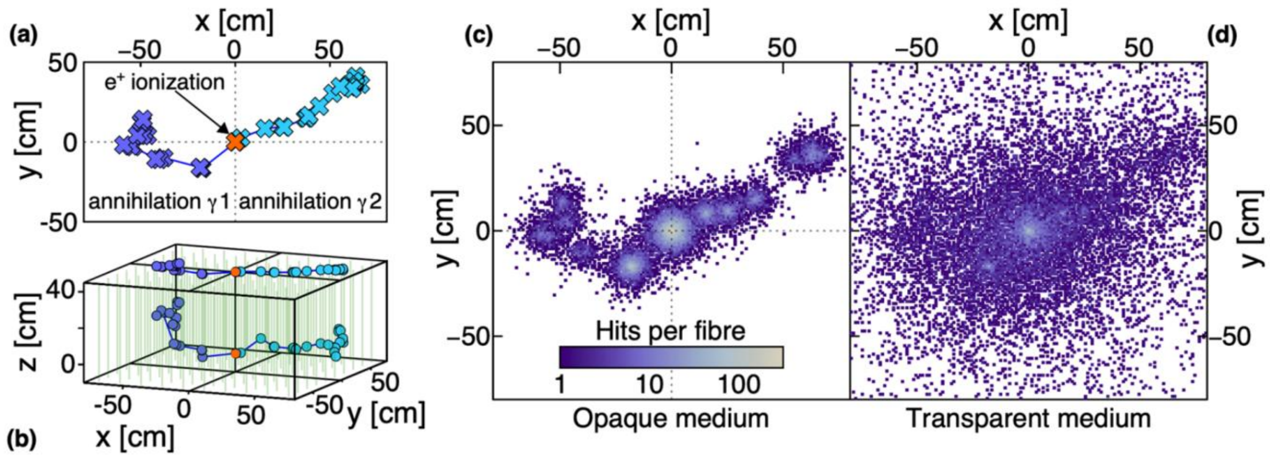
Opaque Liquid Scintillator.



[2]



[3]



[4]

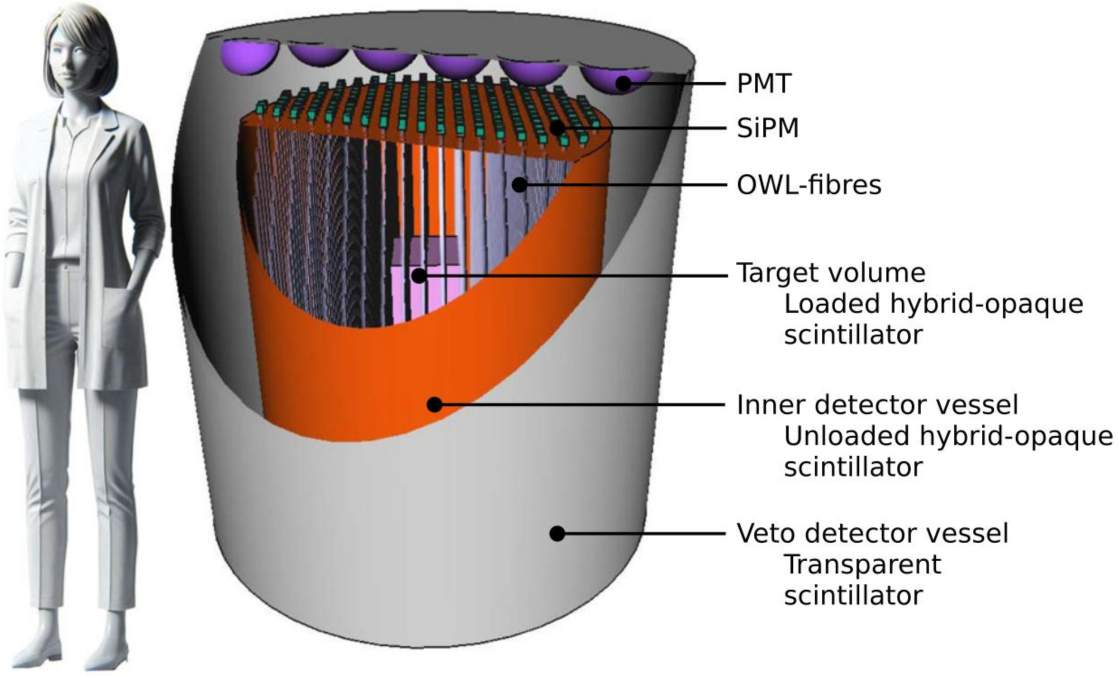
confined light

washed out

[2] JINST 14, P11007 (2019); Patent applications EP 25 195 873.2 & EP 25 195 874.
[3] LiquidO Collaboration, Comm. Phys. 4, 273 (2021)
[4] C. Buck, B. Gramlich, S. Schoppmann, JINST 14, P11007 (2019)

Liquid Scintillator – NuDoubt++

- Search for double beta plus decays
- 1 m³ demonstrator
- Hybrid-opaque liquid scintillator
  - ➡ Cherenkov and scintillation light
  - ➡ Particle dependent ratio
- Particle track information
- Lower threshold possible (~MeV)



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Liquid Scintillator – NuDoubt++

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- Hybrid-opaque liquid scintillator
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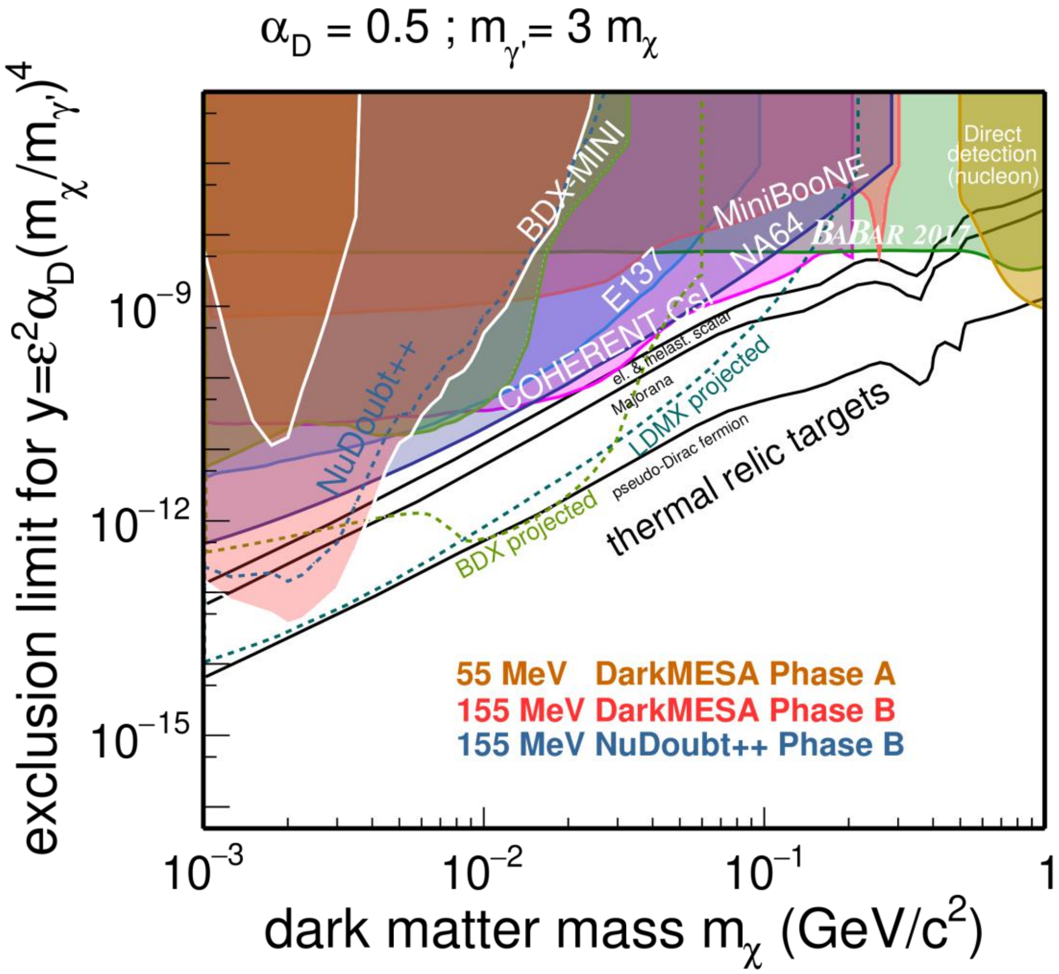
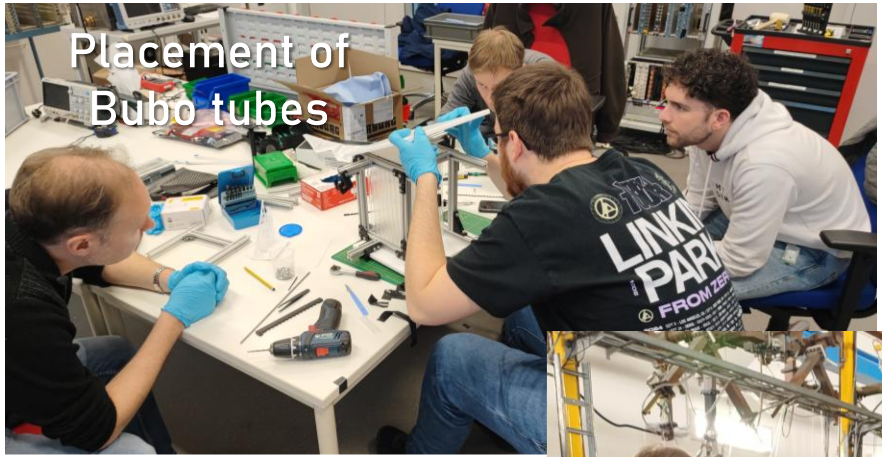
  - ➡ Particle dependent ratio
- Particle track information
- Lower threshold possible (~MeV)
- First projection of NuDoubt++@DarkMESA

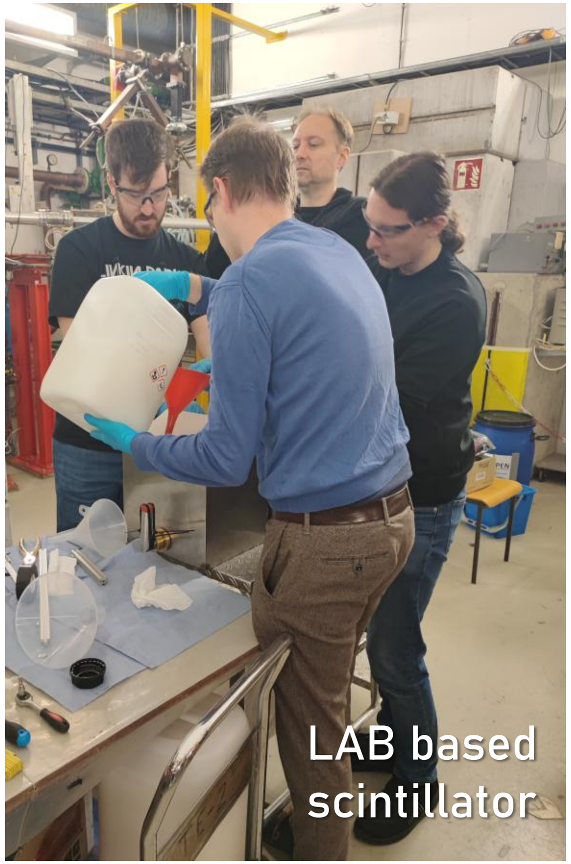


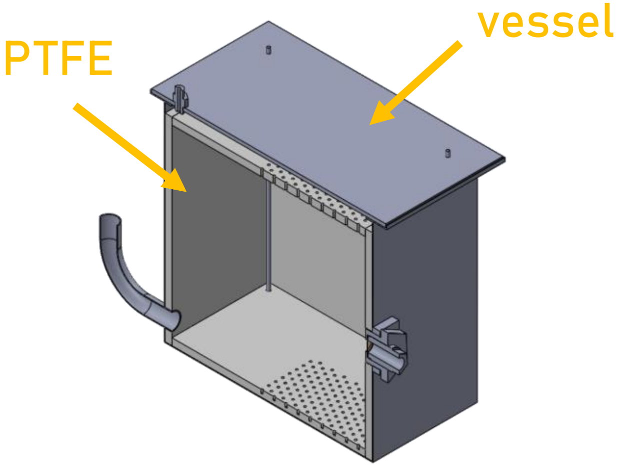
DARK MESA

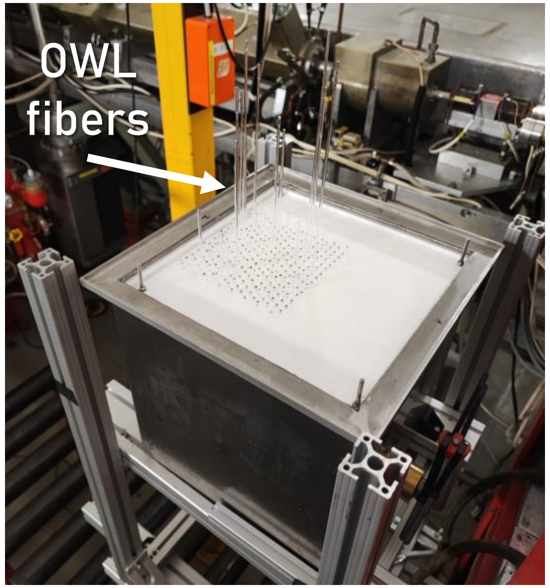
NuDoubt^{++}@DarkMESA – Detector.



Beamtime preparation
November 2025



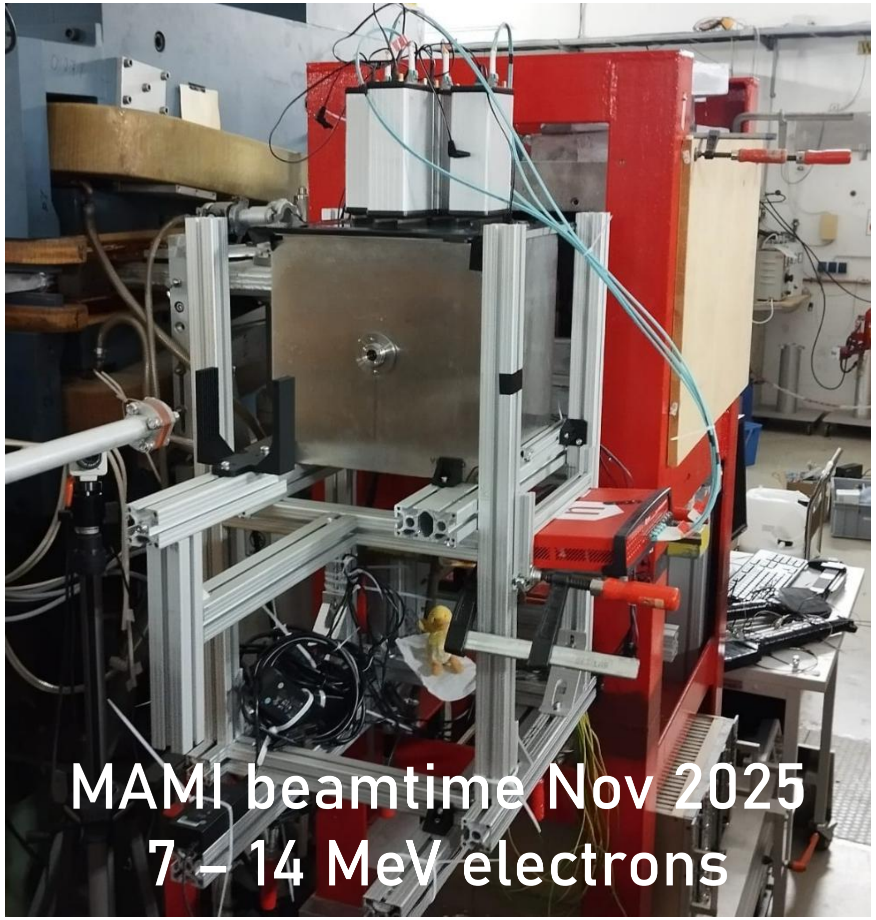


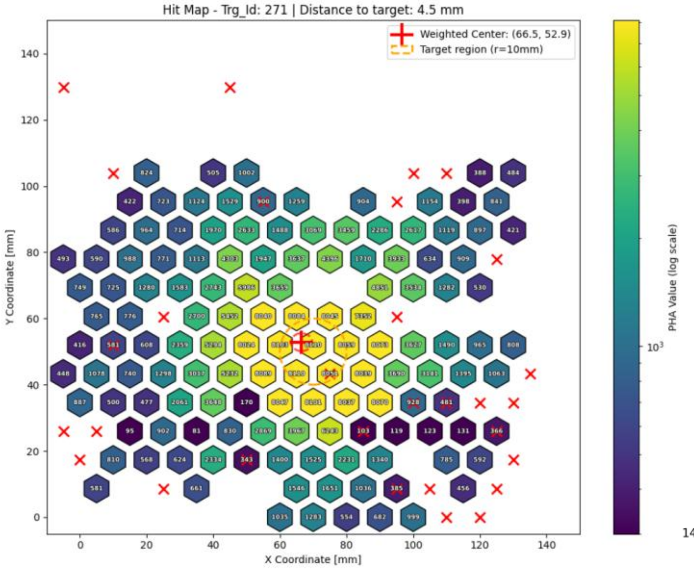


MSc thesis J. Pätschke

NuDoubt^{++}@DarkMESA – Detector.

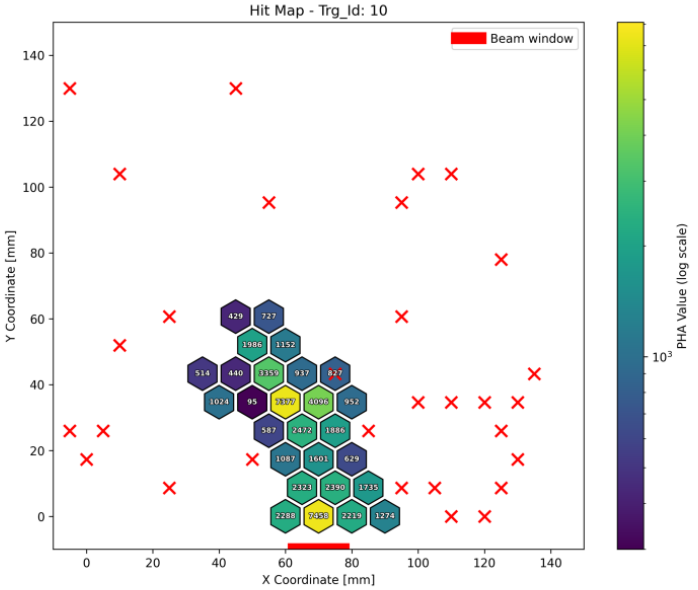
CAEN Front-End Readout System (FERS)





cosmic particle

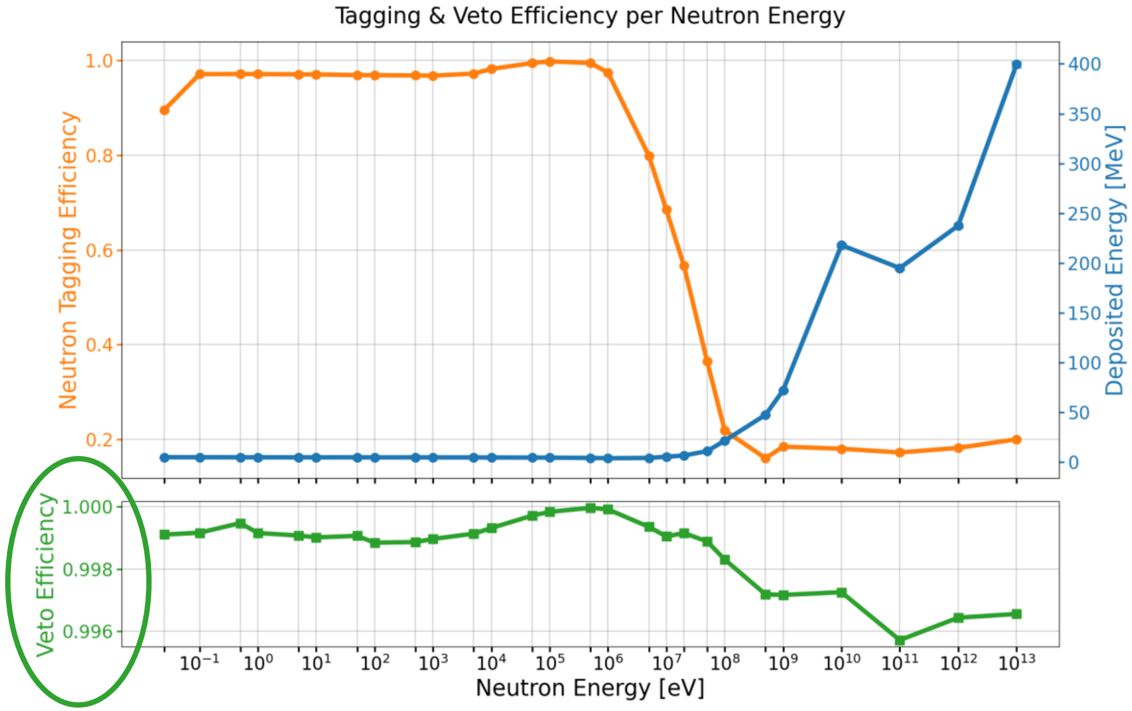
beam electron



→ Proof of concept

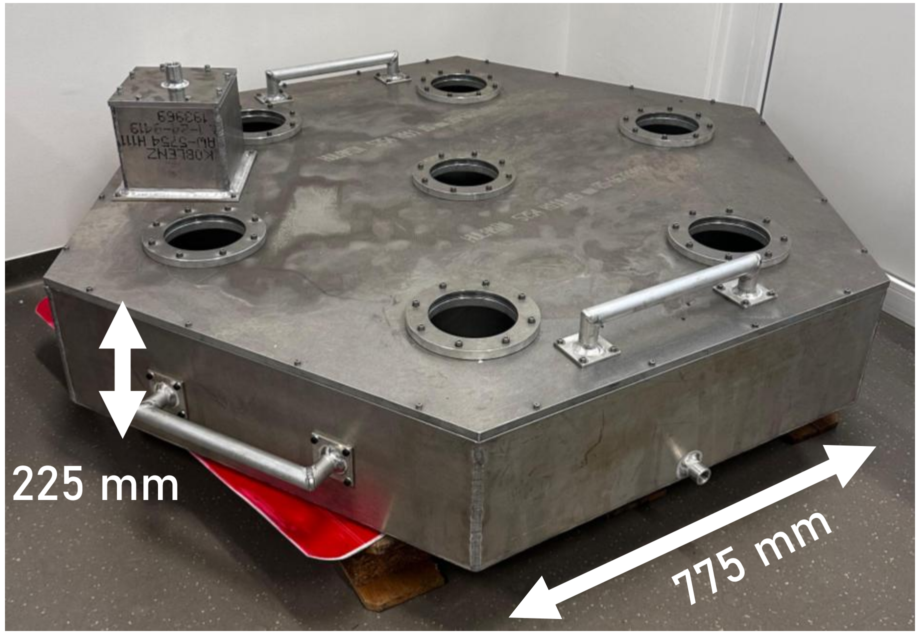
MSc thesis J. Pätschke

NuDoubt++@DarkMESA – Veto.



thermal neutrons high-energy (fast) neutrons

- Gd-loaded liquid scintillator
- Simulation studies
- Readout: seven 5“ PMTs
- Measurements will start soon



MSc thesis M. Kontogoulas