Nuclear Physics towards 2050:
Experiments with Electron Beams

- Electron Beams for Nuclear Physics
- Personal View on Perspectives for Nuclear Physics

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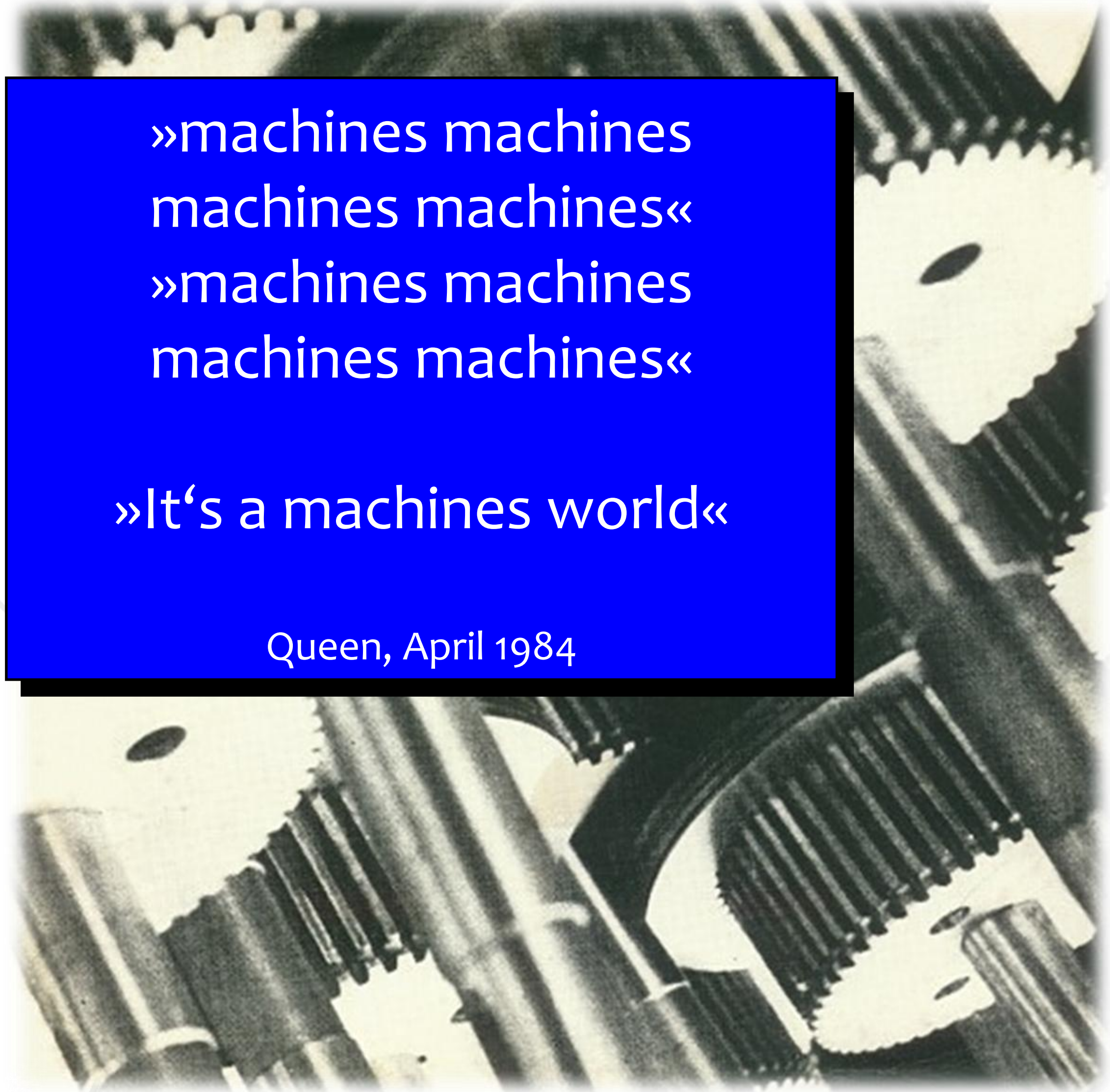
April 2026

Machines (Or Back to Humans)



»machines machines
machines machines«
»machines machines
machines machines«

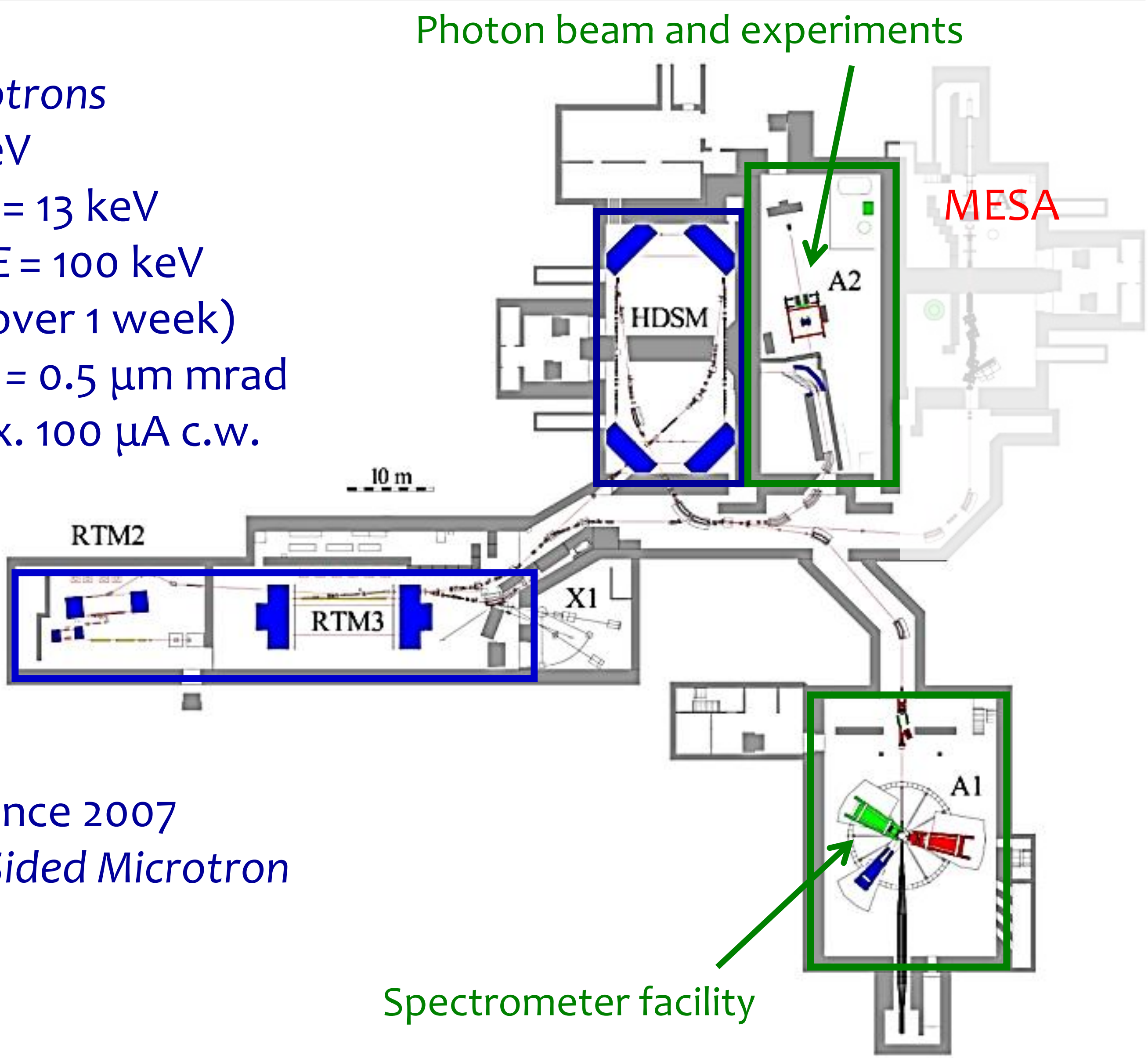
»It‘s a machines world«

Queen, April 1984

The Mainz Microtron MAMI

MAMI-B:

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.

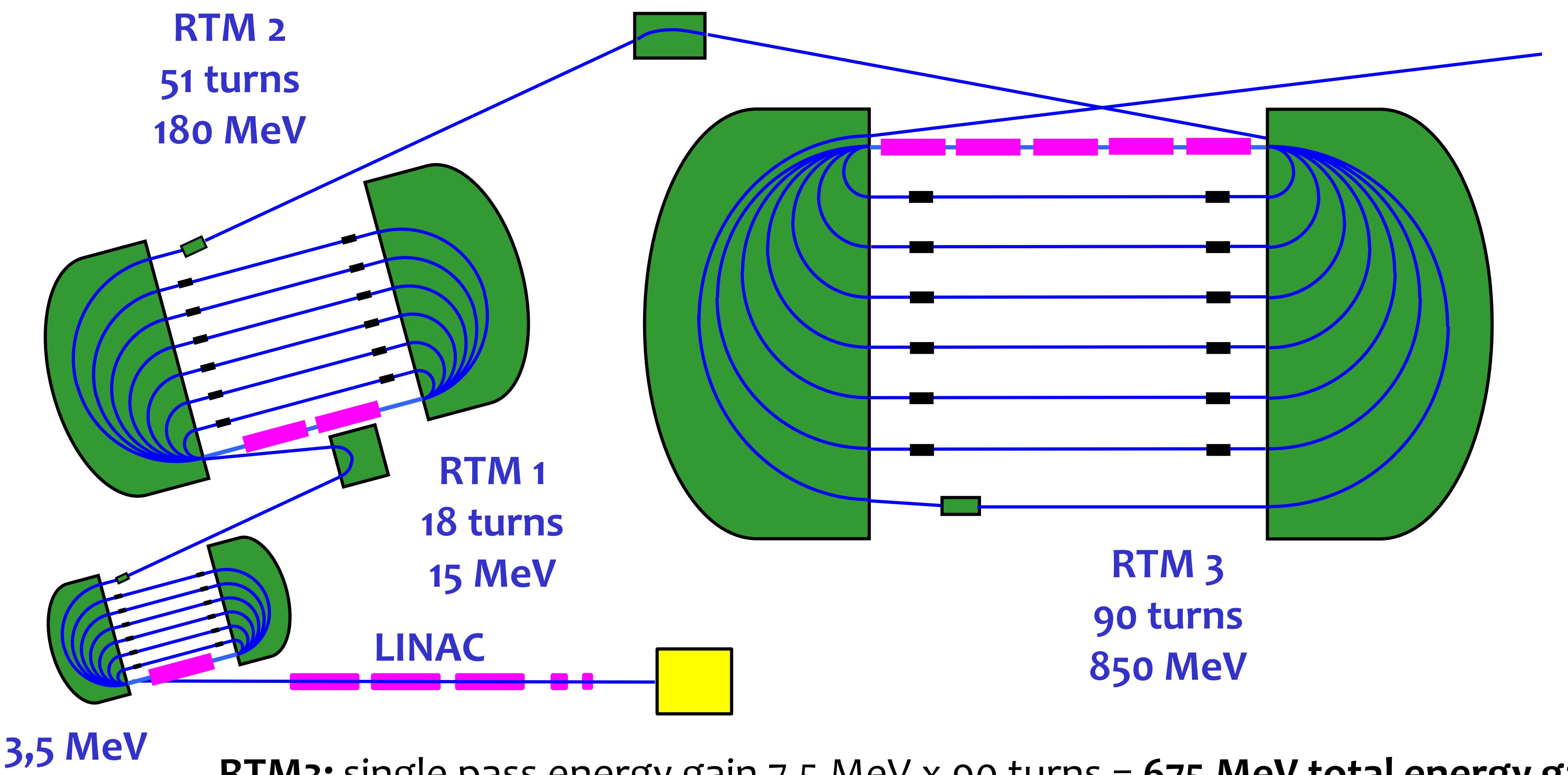


MAMI-C:

Additional stage since 2007
Harmonic Double-Sided Microtron
E_0 up to 1604 MeV

Race-Track Microtrons (RTM 1 – 3)

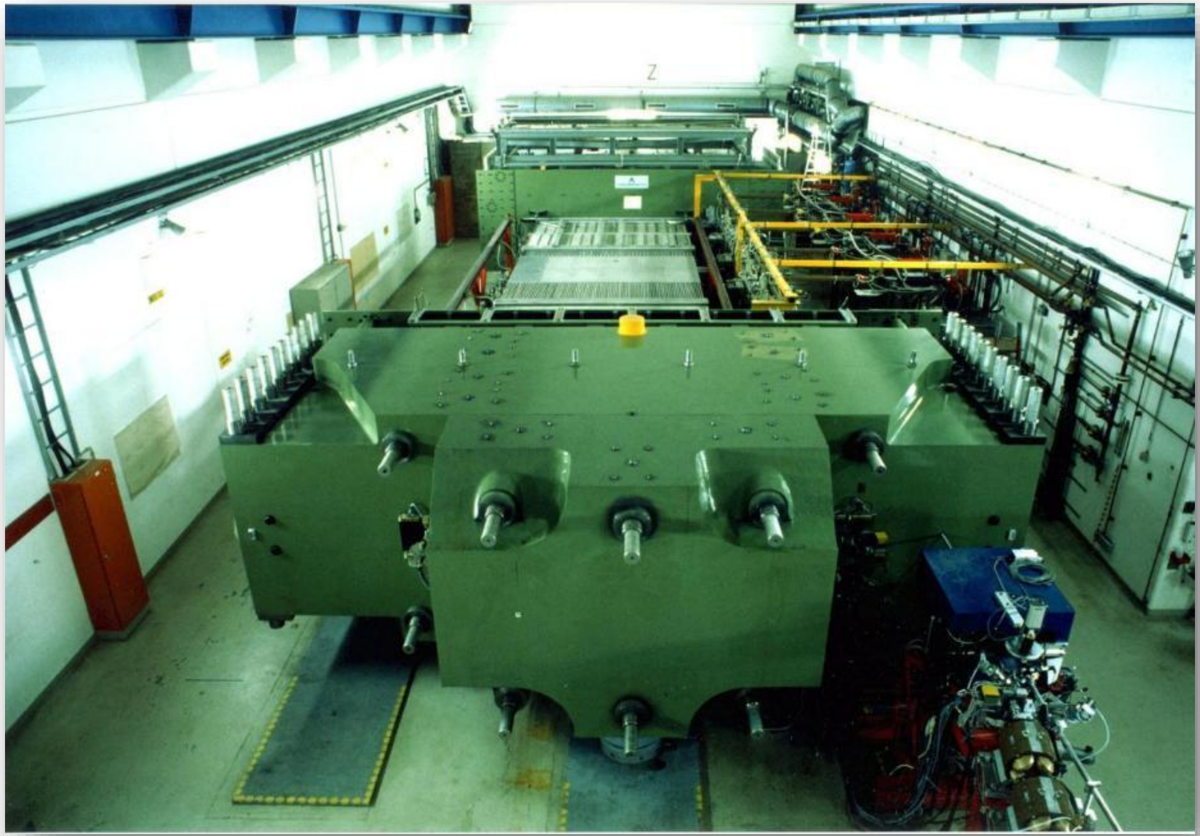
Cascade of 3 RTMs with each 2 magnets and 1 linac with RF acceleration



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

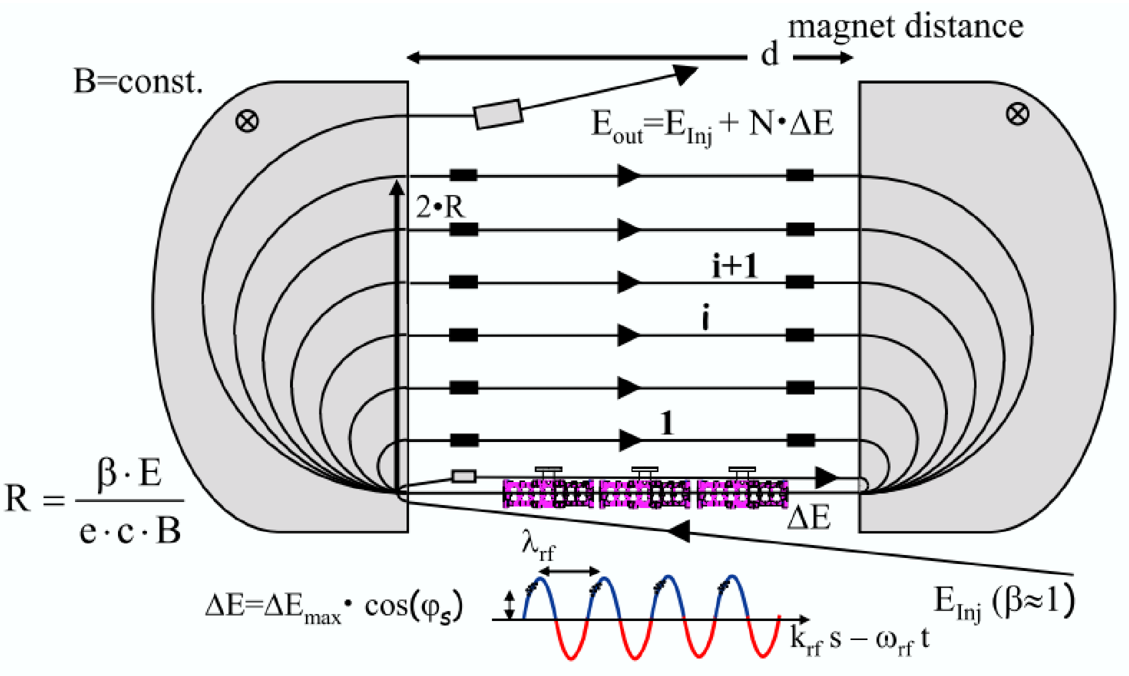
MAMI-B (RTM1 – 3)

RTM1 and RTM2 for 180 MeV beam energy



RTM3 for maximum 885 MeV beam energy

RTM Operation Parameters



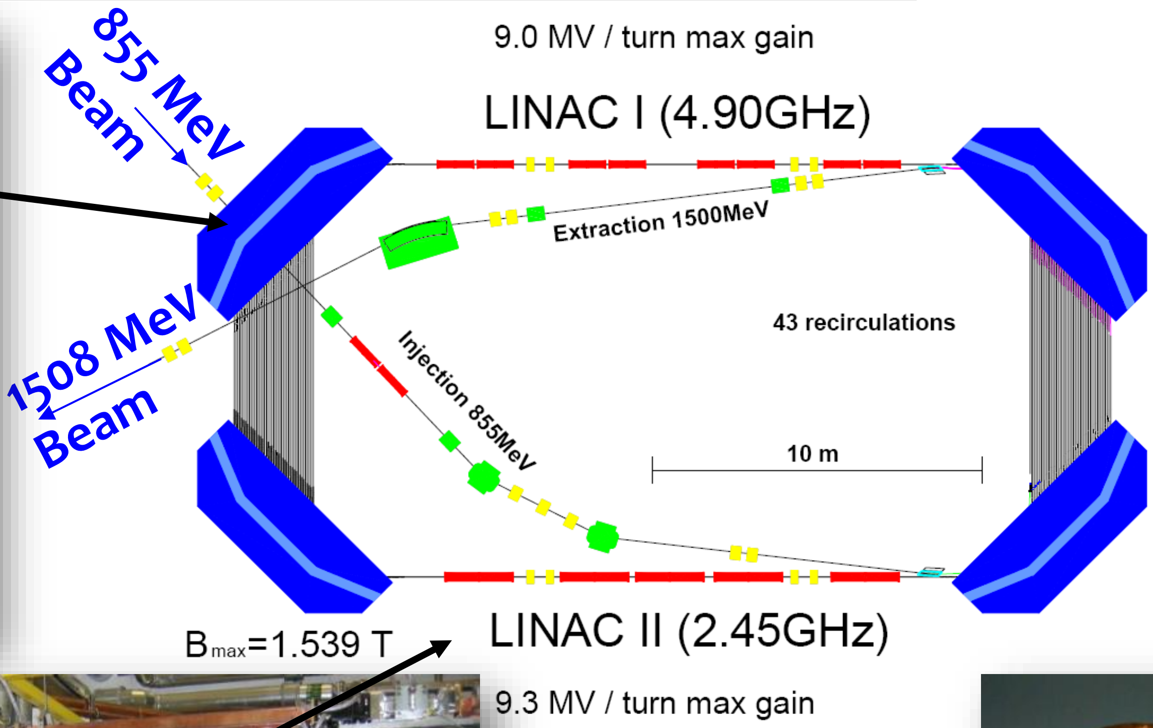
		Injector	RTM1	RTM2	RTM3
General					
injection / extraction energy (total)	[GeV]	$0.511/3.97 \cdot 10^{-3}$	$3.97/14.86 \cdot 10^{-3}$	$14.86/180 \cdot 10^{-3}$	0.180 / 0.855
number of turns		–	18	51	90
total power consumption	[kW]	92	92	220	650
Rf-System					
energy resp. energy gain / turn	[MeV]	3.5	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
Magnet-System					
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 weigth 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
Beam-Parameters					
energy spread (1σ)	[keV]	1.2	1.2	2.8	13
norm. emittance hor. / vert. (1σ)	$[\pi \cdot 10^{-6}$ 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

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

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

Large number of standard energies allows for many different kinematic settings

Harmonic Double Sided Microtron (HDSM)



Installation 2002 – 6

Linac II

Resonators for 2.45 and 4.90 GHz:

[K.-H. Kaiser et al., Nucl. Instr. Meth. A 593 (2008) 159]

A1 Spectrometer Facility at MAMI

Focusing spectrometers:

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

SpekA:

Momentum resolution:

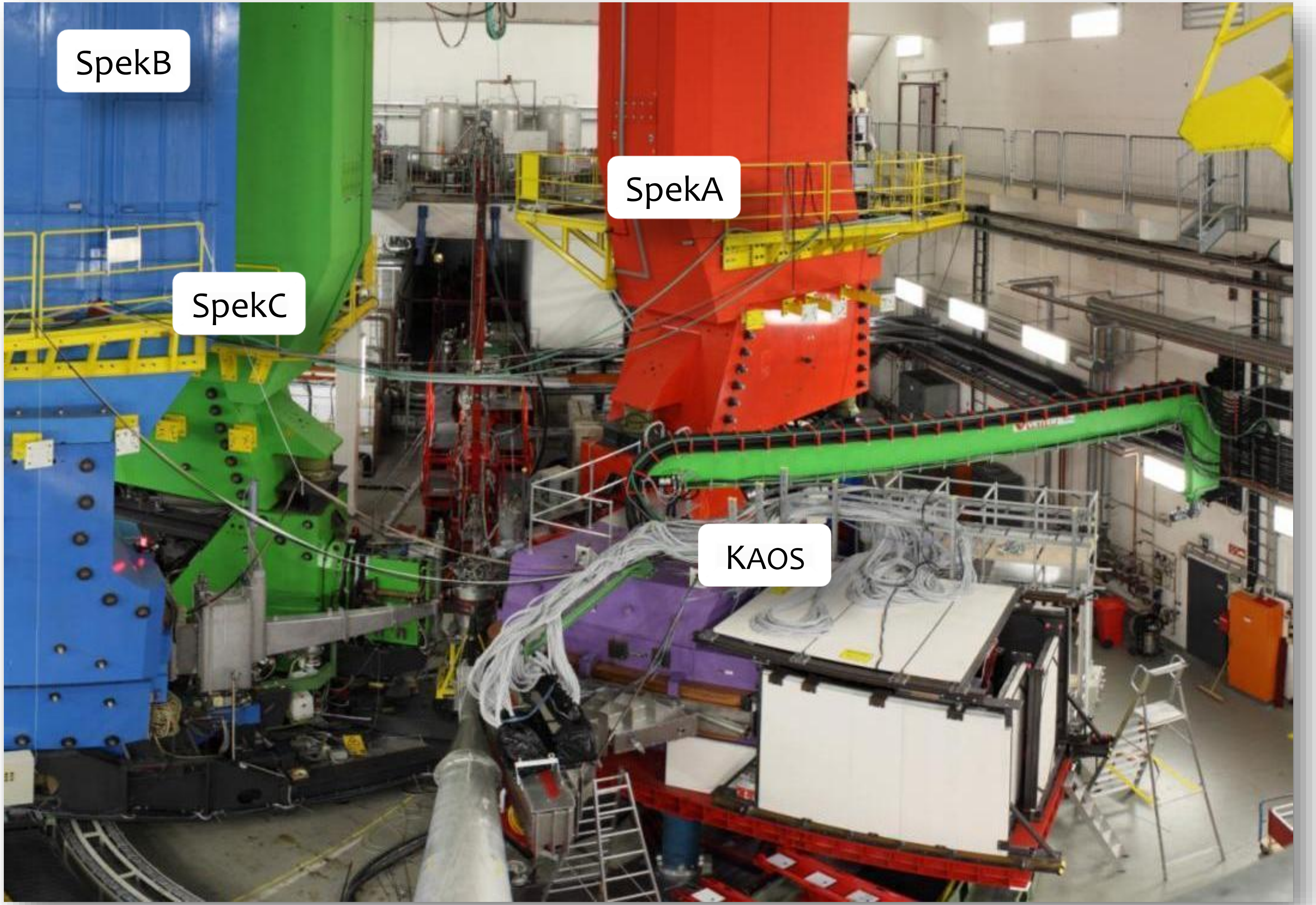
$$\delta p/p < 10^{-4}$$

Momentum acceptance:

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

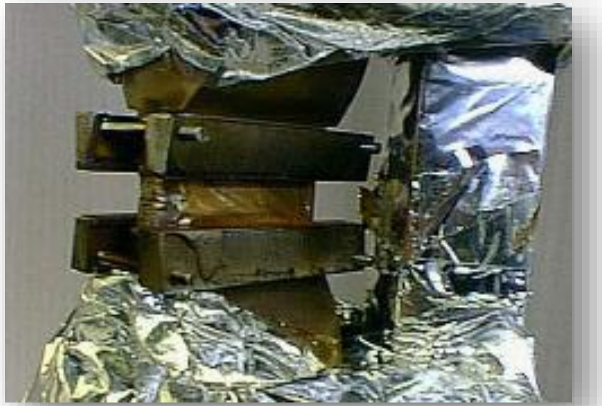
Accepted solid angle:

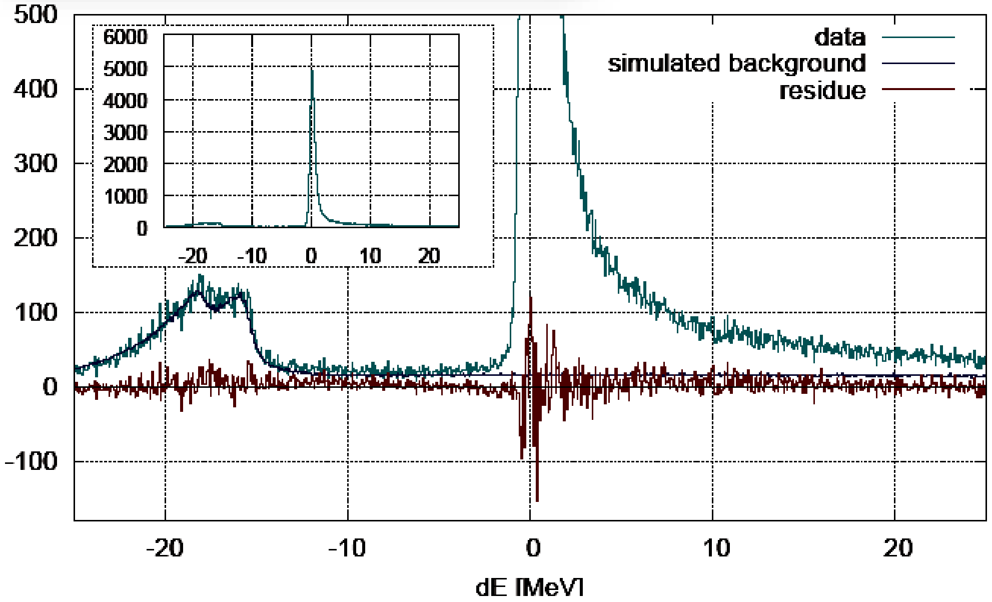
$$\begin{aligned}\Delta\Omega &= 11.5^\circ \times 8.0^\circ \\ &= 28\,\mathrm{msr}\end{aligned}$$



Novel Windowless Gas-Jet Target(s)

Liquid hydrogen target:





- Subtraction of cell window contribution

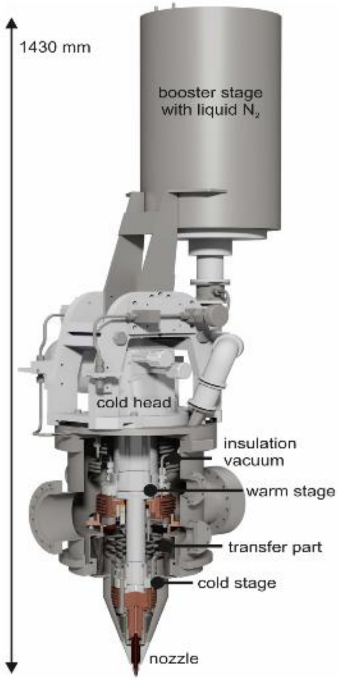
Gas-jet target:

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

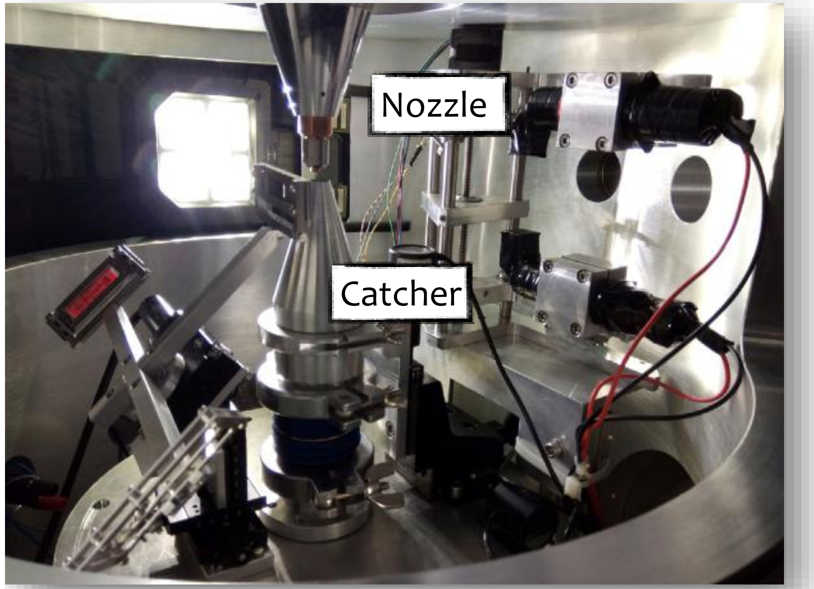
P. Brand

Argon gas jet

D. Bonaventura



catcher
to pumping station

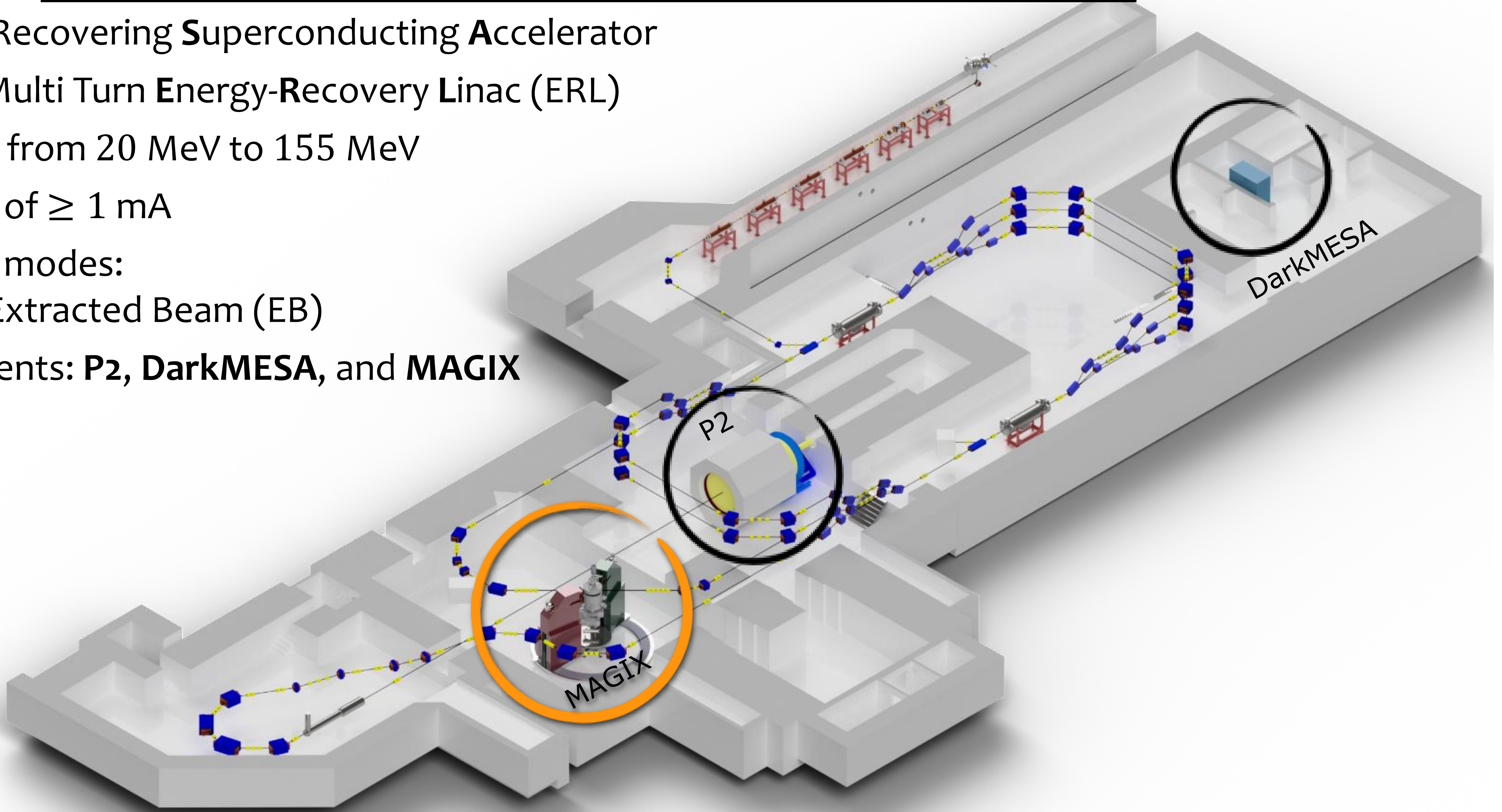


[S. Schlimme *et al.*, NIM A 1013, 165668 (2021)]

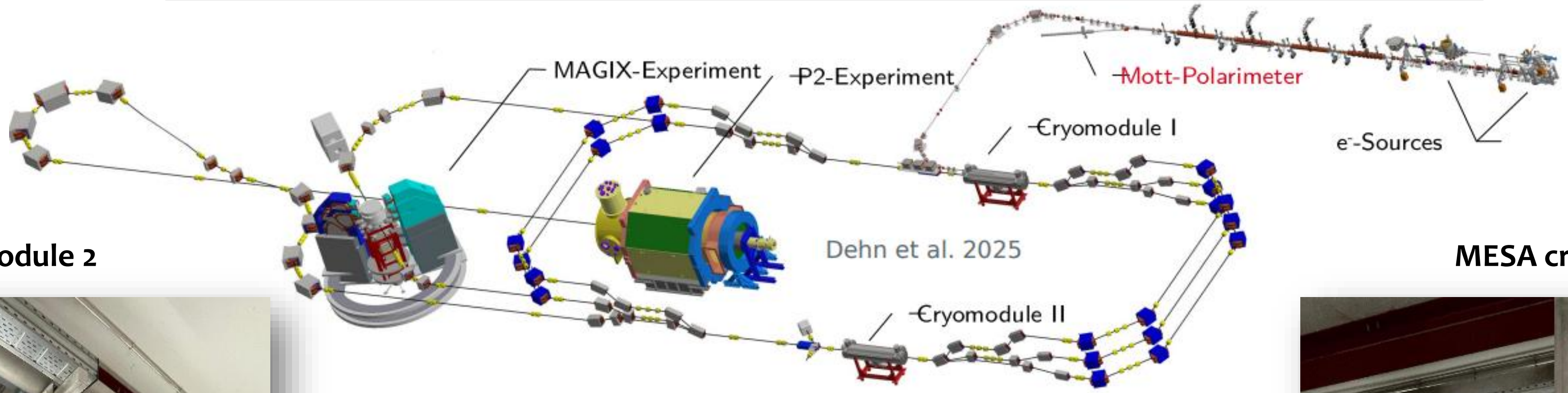
MESA and the MAGIX Spectrometers

The Low-Energy Electron Accelerator MESA

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



Superconducting Accelerating Sections



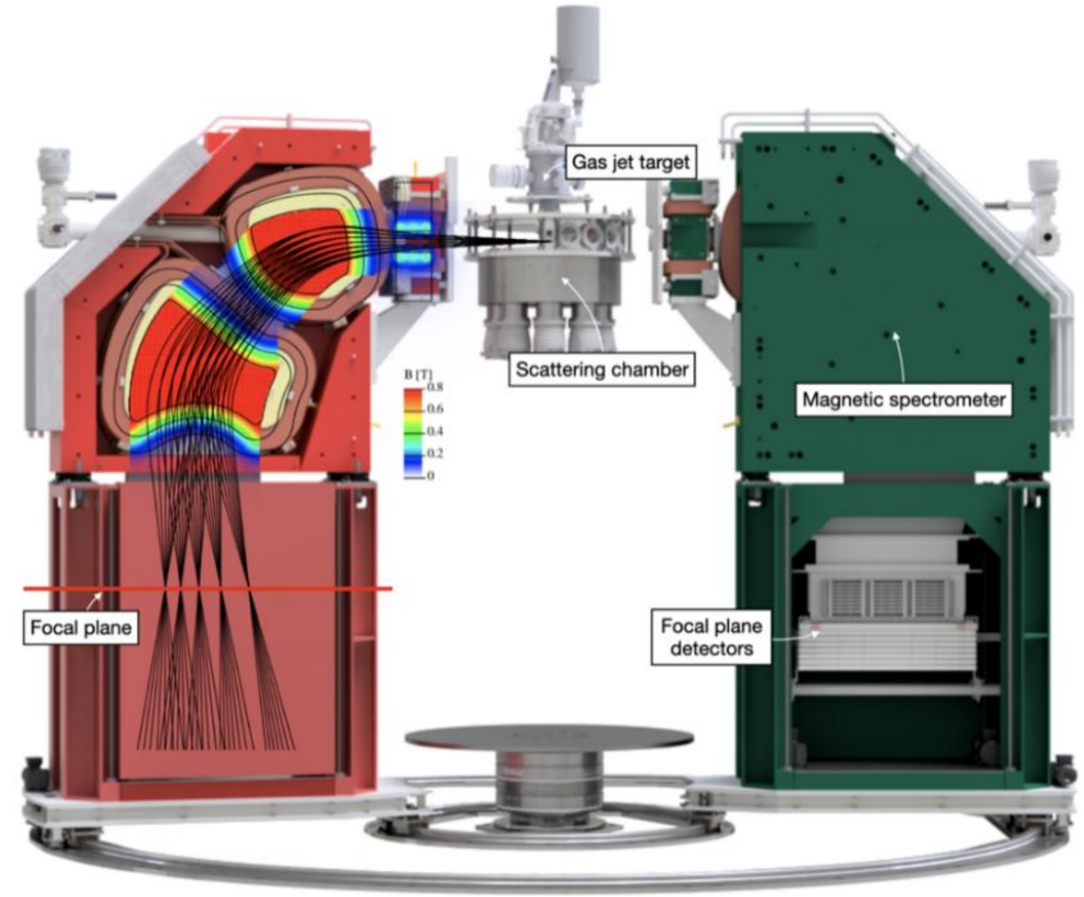
MESA cryomodule 2

MESA cryomodule 1

MAinz Gas Internal eXperiment MAGIX

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

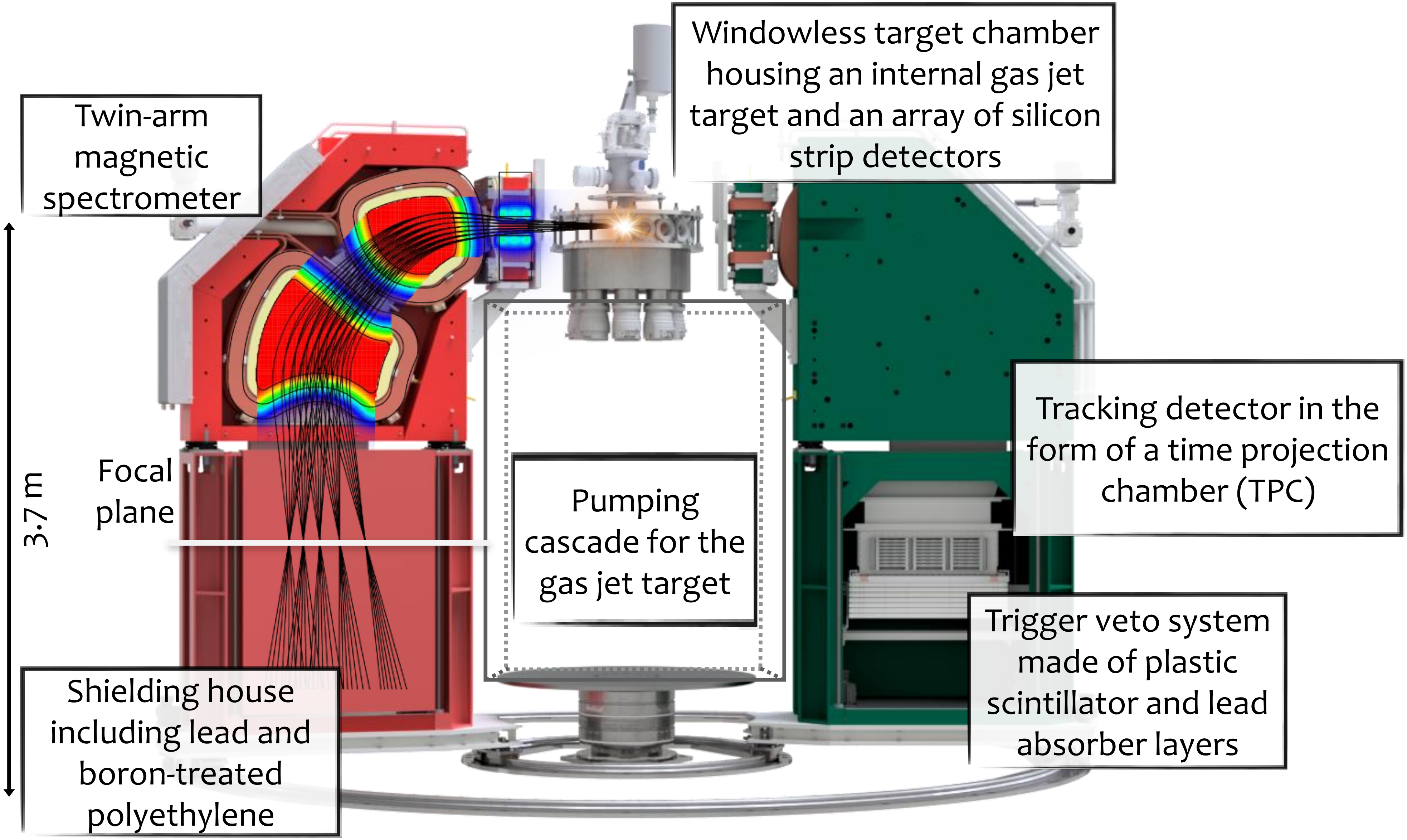
- A novel technique in nuclear and particle physics
- Measurement of low momenta particles with high accuracy
- Competitive luminosities at very low target thicknesses



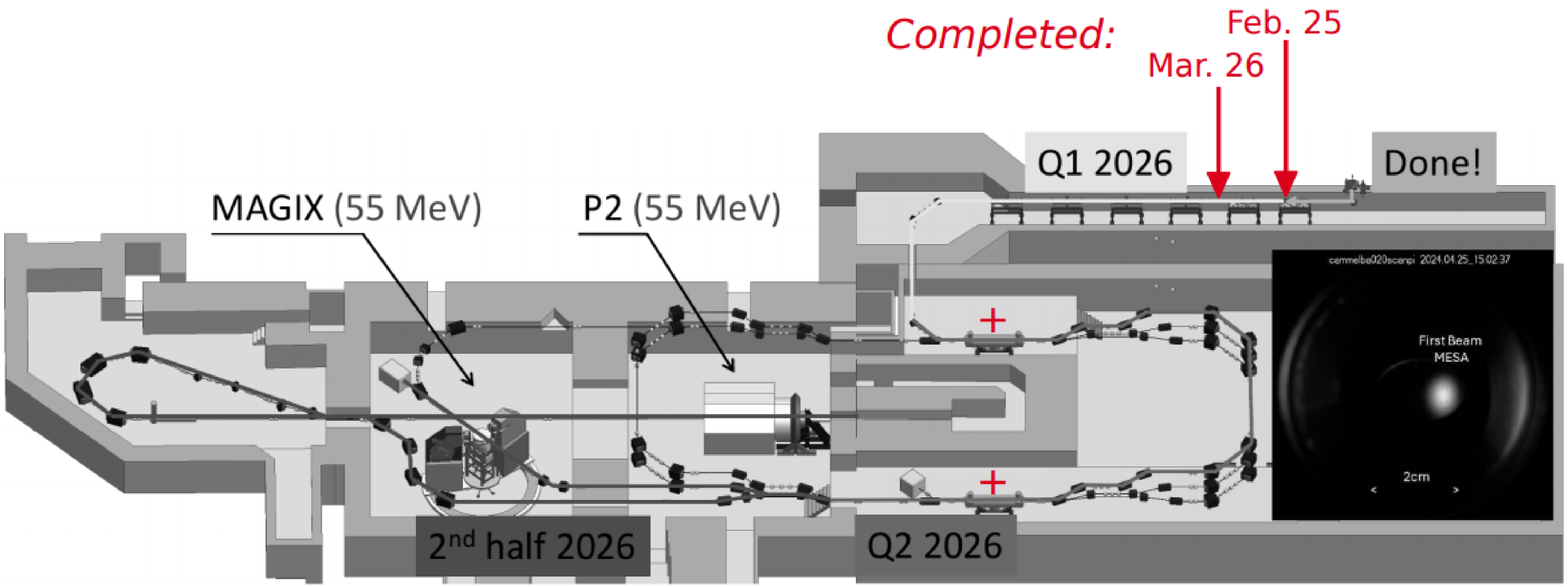
MAGIX Twin Spectrometers

Requirements:

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



MESA Commissioning Schedule

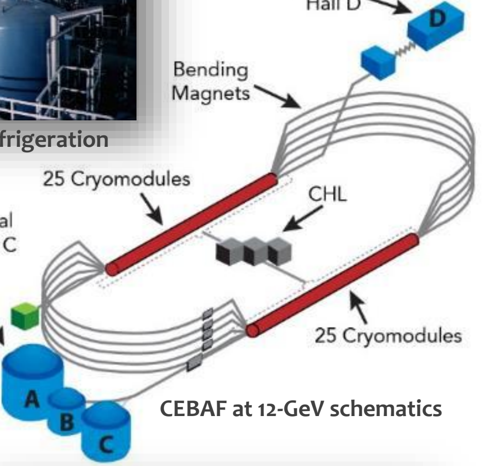


- **Staged approach:**
  - June **2027: first MESA beam at 55 MeV,** unpolarized, 1 µA
  - September 2027: first extracted beam to MAGIX
  - November 2027: first extracted beam to P2

Jefferson Lab Operating the 12-GeV CEBAF

Superconducting niobium radiofrequency cavities

Cryogenic refrigeration plant



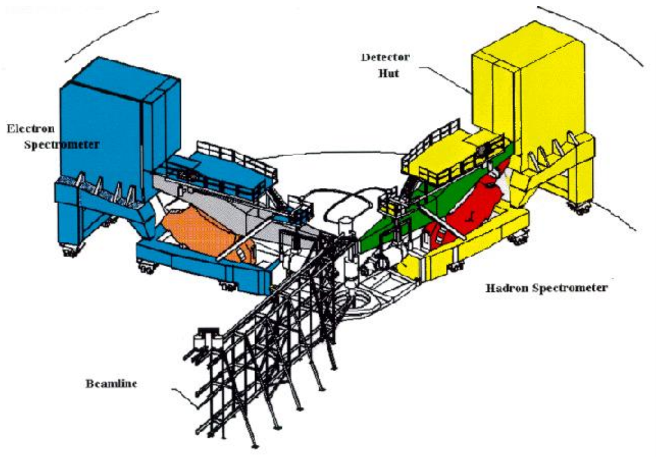
CEBAF at 12-GeV schematics

Cryomodules in the accelerator tunnel

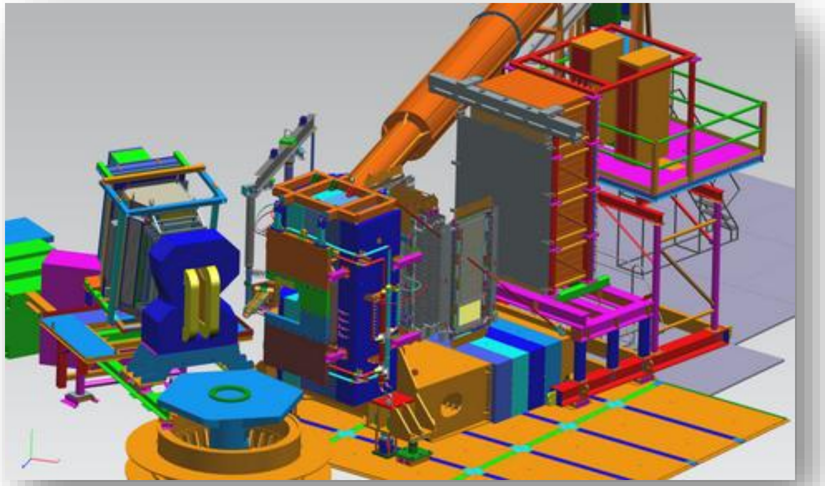
Recirculation arcs

Large Number of Instruments in Halls A, B, and C

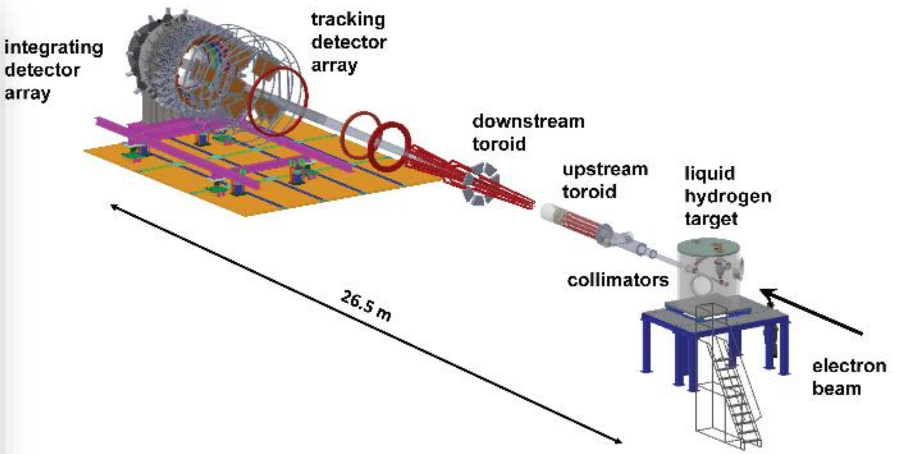
L+R HRS **Hall A**



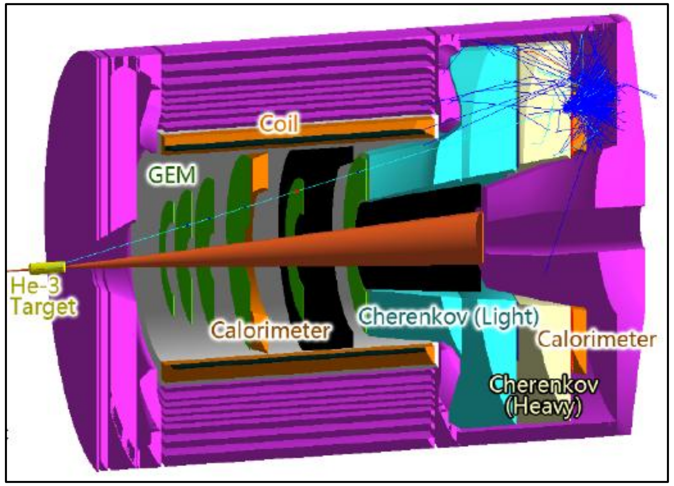
BigBite & SBS **Hall A**



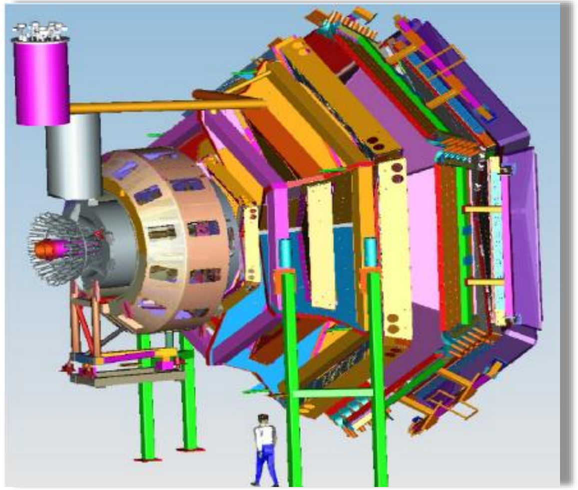
MOLLER **To come in Hall A**



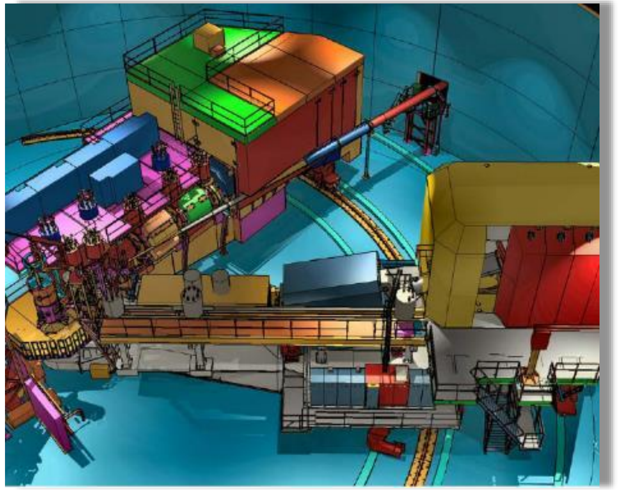
SOLID **Proposed in Hall A**



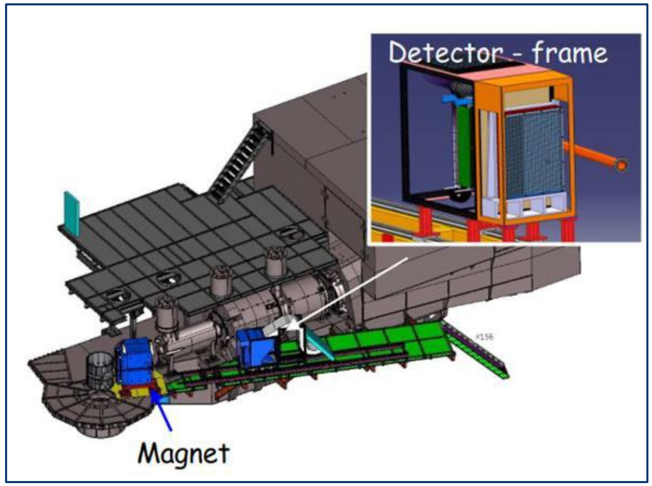
CLAS12 **Hall B**



HMS & SHMS **Hall C**



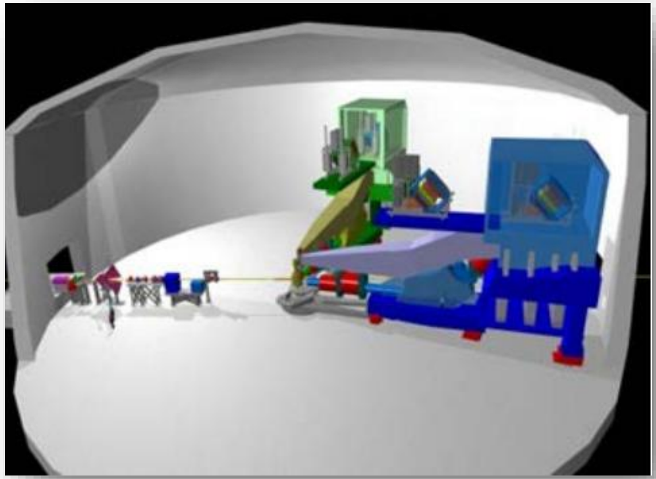
NPS **Hall C**

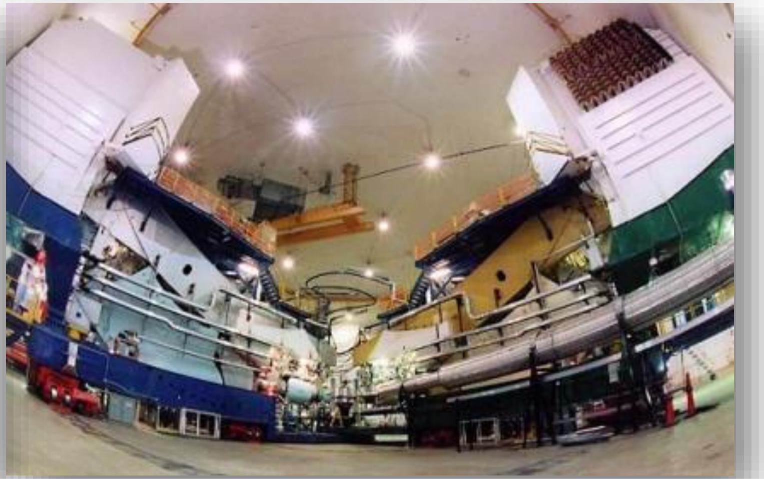


Hall A

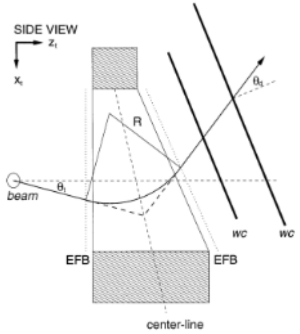
Hall A: High-Resolution QQDQ Spectrometers

- Two spectrometers: **Right and Left HRS**
  - $\delta p/p = 10^{-4}$, $\delta\theta$ = 2 mrad
  - Angular range $\theta = 12.5° – 150°$
  - Dipole septa to access $\theta < 12.5°$
  - Max. p = 4.2 GeV/c (left), 3.2 GeV/c (right)
  - $\Delta p/p$ = 10%, $\Delta\Omega$ = 6 msr
- Luminosity up to 10^{39} cm^{-2} s^{-1}

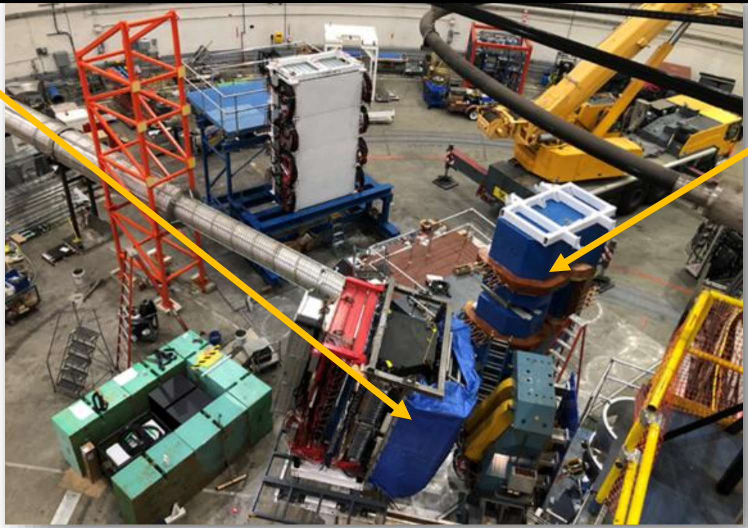




Hall A: BigBite and SuperBigBite Spectrometers

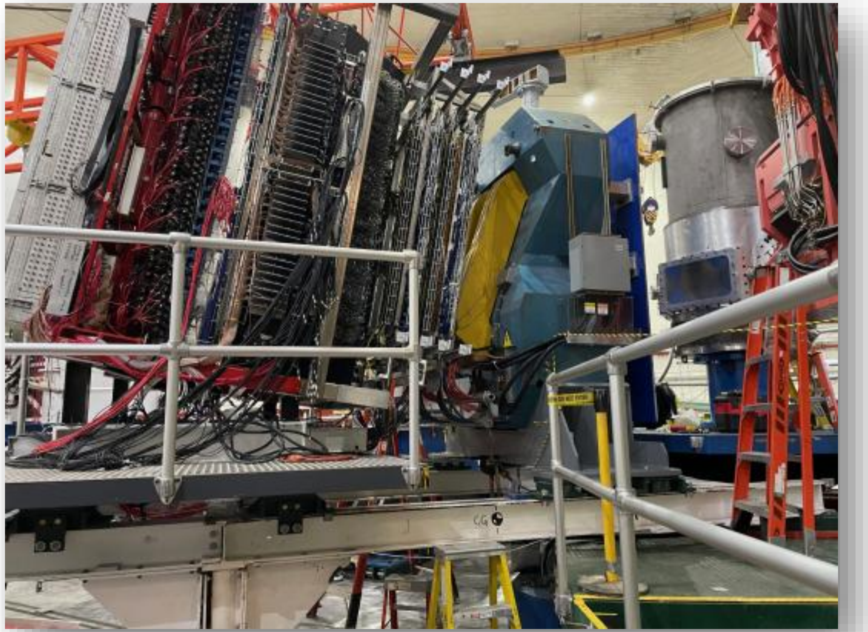


- **BigBite** Spectrometer
  - Indexed dipole magnet
  - $\delta p/p$ = 1–2% , $\delta\Theta$ < 1 mrad
  - $\Delta p/p$ = 80% , $\Delta\Omega$ = 75 msr



- **SuperBigBite** Spectrometer
  - Dipole magnet, 1.7 T-m
  - $\delta p/p$ = 1% at 8 GeV/c
  - $\Delta\Omega$ = 70 msr
  - Proton/neutron separation

BB magnet and detector:



Non-focusing spectrometers with **large dipole magnets** near the target to maximize solid angle

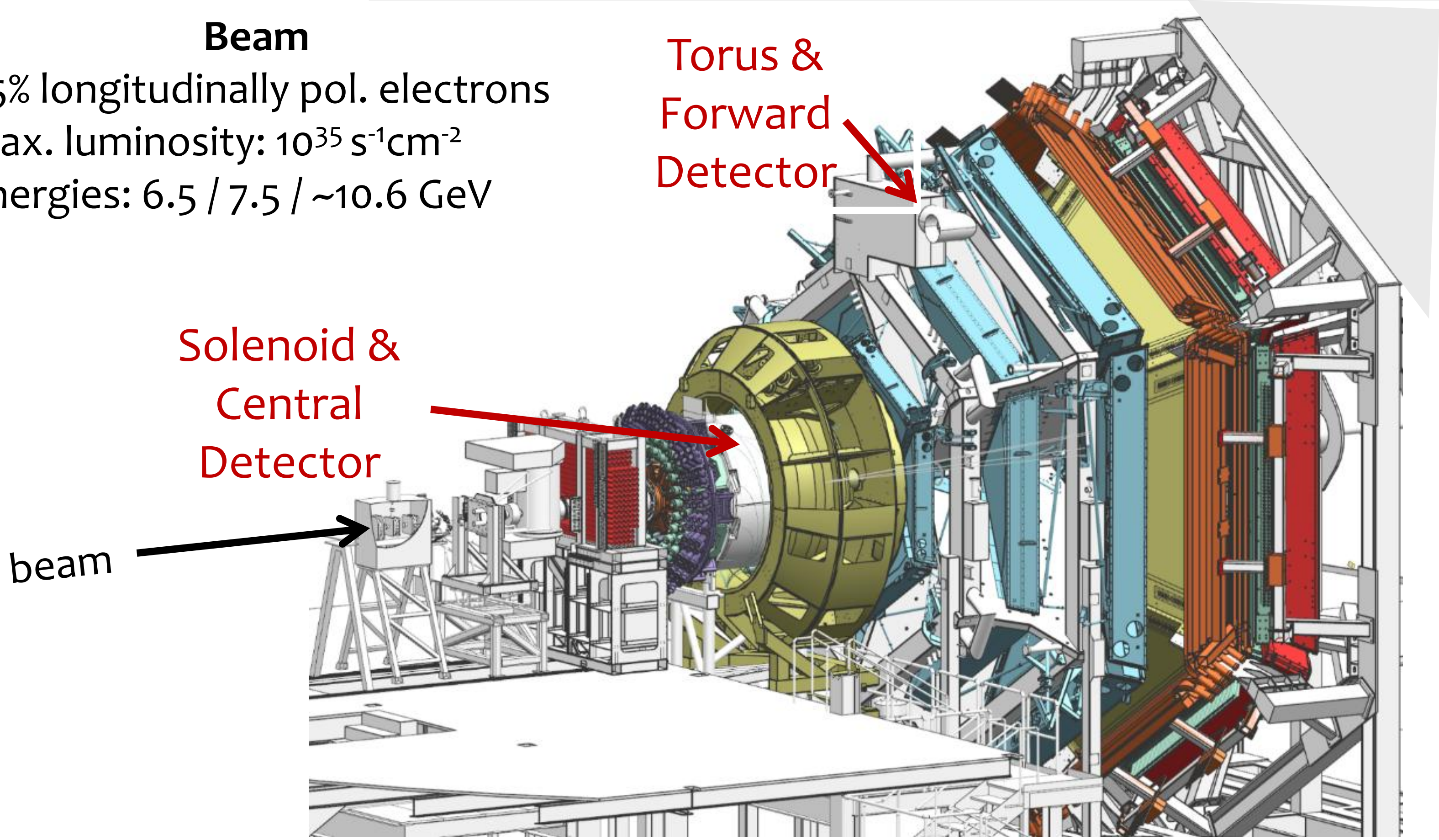
View along downstream beamline with SBS left:

Hall B

Hall B: The CLAS12 Spectrometer for 12 GeV

Beam

- 85% longitudinally pol. electrons
- Max. luminosity: 10^{35} $s^{-1}cm^{-2}$
- Energies: 6.5 / 7.5 / ~10.6 GeV

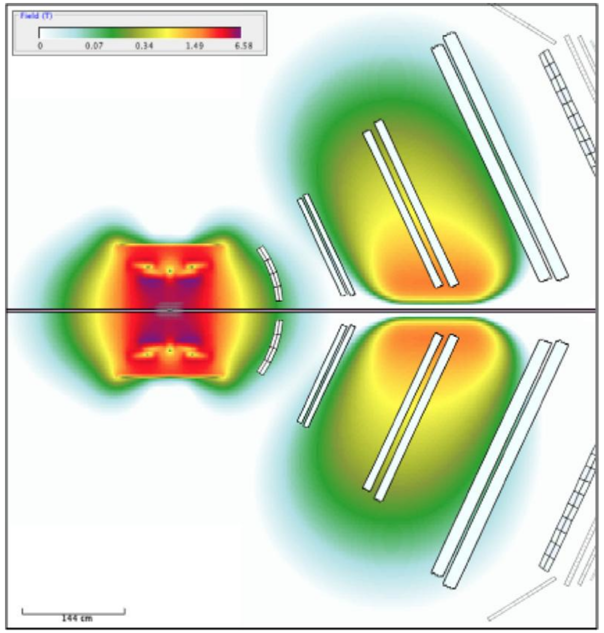


[V.D. Burkert et al., Nucl. Inst. and Meth. A 959, 163419 (2020)]

Targets (org. by Run Groups)

- Proton (RG-A/K)
- Deuteron (RG-B)
- Nuclei (RG-M/D/E)
- Long. pol. NH_3/ND_3 (RG-C)

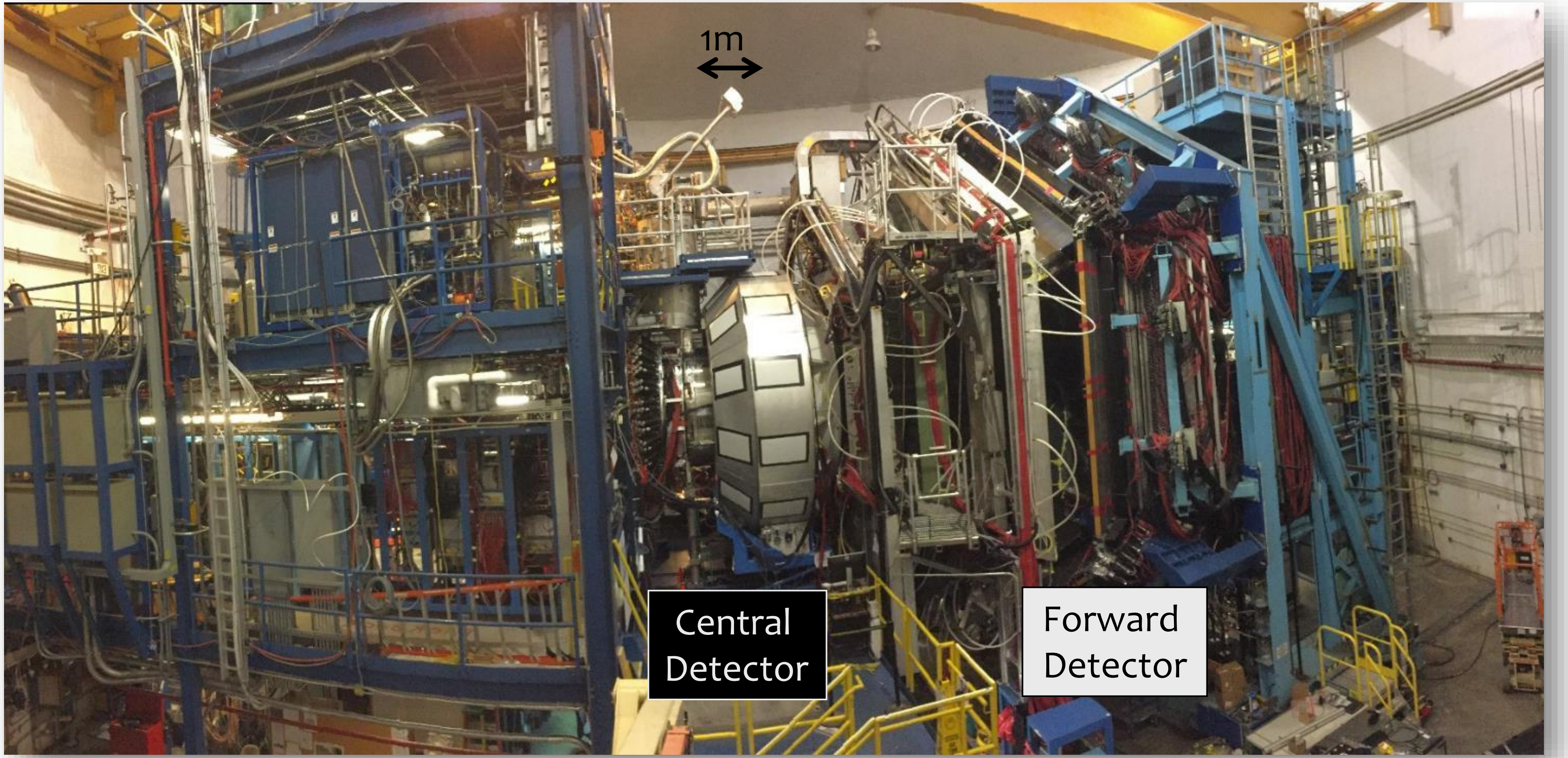
Magnetic Field



Large-acceptance multi-purpose spectrometer

Hall B: Side View of the CLAS12 Spectrometer

Electron beam



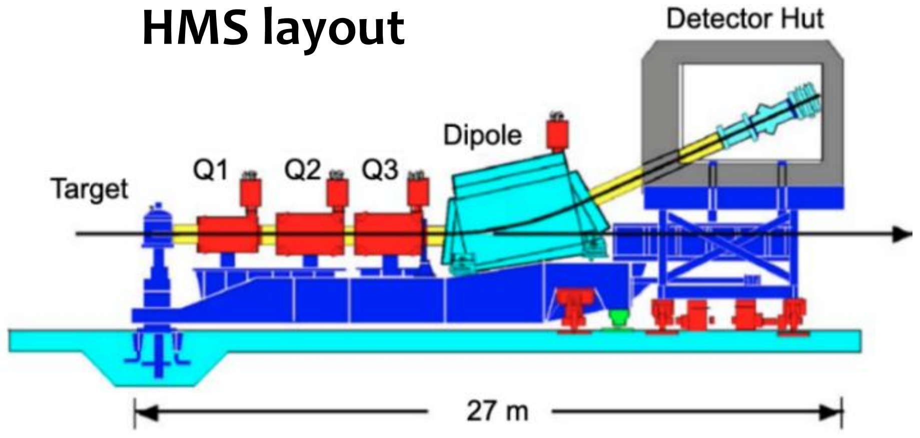
Hall C

Hall C: Small Acceptance Spectrometers for High Luminosity

High-Momentum Spectrometer (HMS)

- Momenta: up to 6 GeV/c, acceptance exceeding 10%
- Horizontal angular range: 10.5° to 90°
- Four superconducting magnets, three of them focusing quadrupoles in a vertically focusing–defocusing–focusing configuration followed by a dipole with a vertical bend of 25°
- Momentum resolution: 1–1.5 $\times 10^{-3}$
- Angular acceptance: ±32 mrad in-plane, ±85 mrad out-of-plane
- Angular resolutions: ~ 1 mrad
- Track length from target to detector hut: ~ 25 m

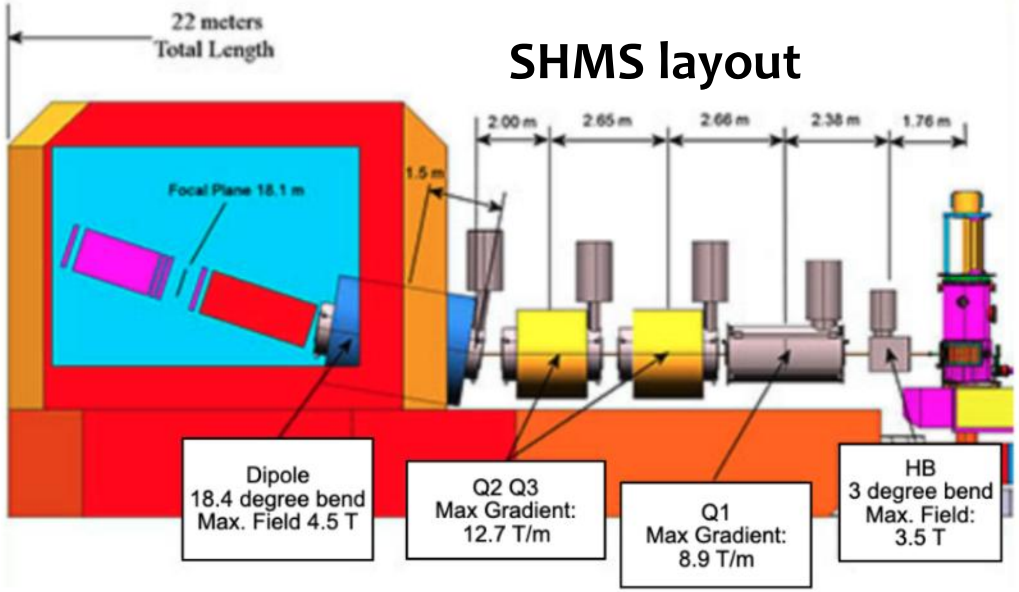
HMS layout



Super-High-Momentum Spectrometer (SHMS)

Parameter	HMS Design	SHMS Design
Range of Central Momentum	0.4 to 7.4 GeV/c	2 to 11 GeV/c
Momentum Acceptance δ	$\pm 10\%$	-10% to $+22\%$
Momentum Resolution	0.1% – 0.15%	0.03% – 0.08%
Scattering Angle Range	10.5 to 90 degrees	5.5 to 40 degrees
Horizontal Angle Acceptance	±32 mrad	±18 mrad
Vertical Angle Acceptance	±85 mrad	±50 mrad
Solid Angle Acceptance	8.1 msr	>4 msr
Horizontal Angle Resolution	0.8 mrad	0.5 – 1.2 mrad
Vertical Angle Resolution	1.0 mrad	0.3 – 1.1 mrad
Target resolution (ytar)	0.3 cm	0.1 - 0.3 cm
Maximum Event Rate	2 kHz	10 kHz
Max. Flux within Acceptance	~5 MHz	~5 MHz

SHMS layout



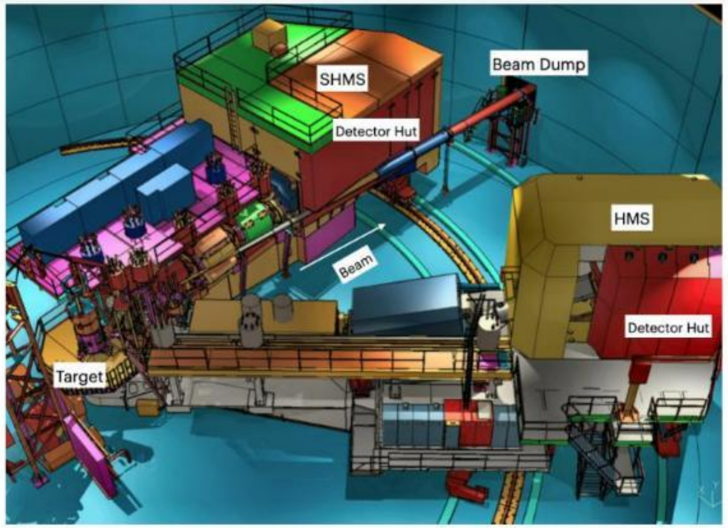
Hall C: HMS and Super-HMS Spectrometers

SHMS

View from downstream beamline with SHMS on the right and HMS on the left

HMS

SHMS at minimum forward angles HMS to the right:



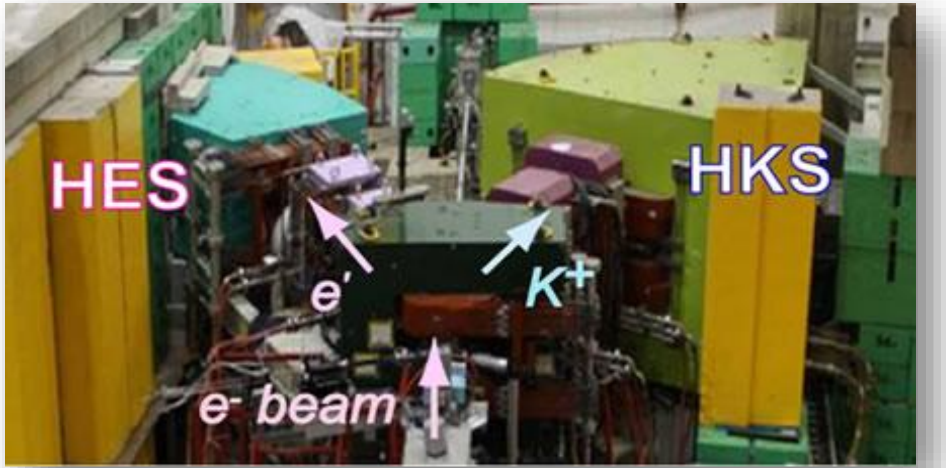
Small-acceptance spectrometers for high luminosity and high momenta

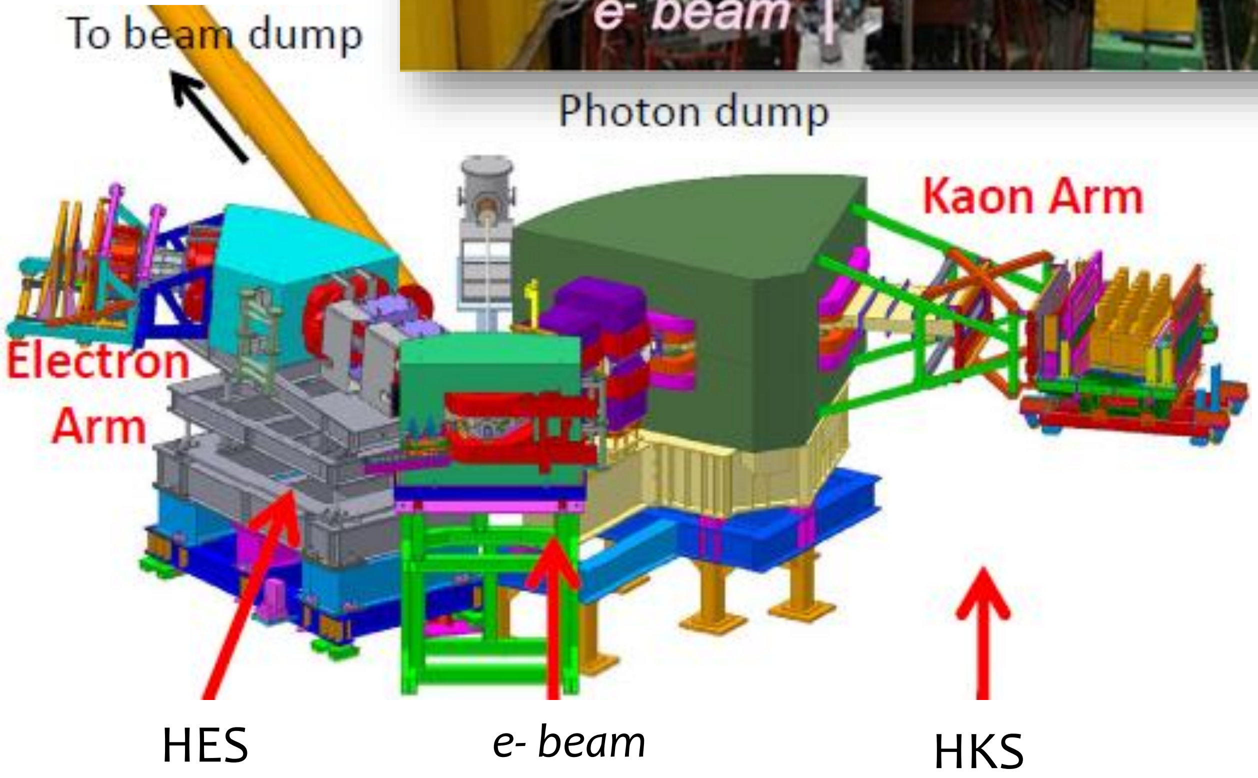
Hall C: HKS/HES Spectrometers

	Updated
Experimental Hall	Hall-C
Beam Energy [/(GeV)]	2.240
Electron spectrometer	HES
Bending direction	Horizontal
Central momentum [/(GeV/c)]	0.74
Kaon spectrometer	HKS
Bending direction	Horizontal
Central momentum [/(GeV/c)]	1.20

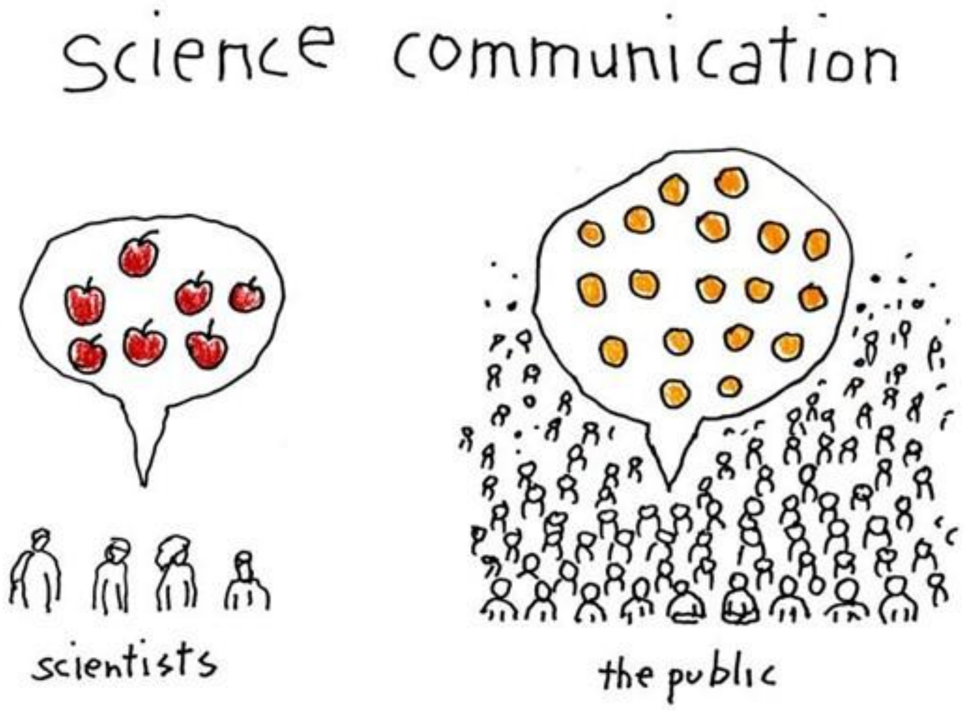
Beam	Energy E_e [/(GeV)]	2.240
	Energy stability $\Delta E_e/E_e$	3×10^{-5}
PCS + HES	Central momentum P_e [/(GeV/c)]	0.744
	Central angle $\theta_{e,e'}$ [/(deg)]	8
	Solid angle $\Delta\Omega_{e'}$ [/(msr)]	3.4
	Momentum resolution $\Delta P_{e'}/P_{e'}$	4.4×10^{-4}
PCS + HKS	Central momentum P_K [/(GeV/c)]	1.200
	Central angle θ_K [/(deg)]	15
	Solid angle $\Delta\Omega_K$ [/(msr)]	8.3
	Momentum resolution $\Delta P_K/P_K$	2.9×10^{-4}

HKS: Dedicated small-orbit spectrometer for hypernuclei electro-production:



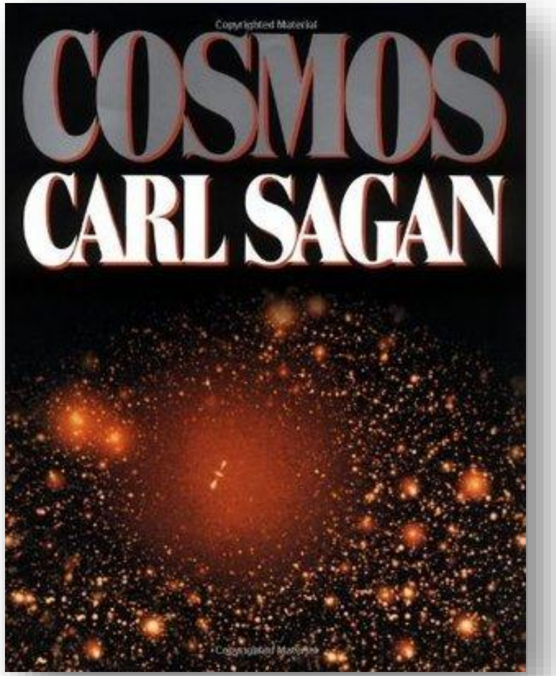


Perspectives for Nuclear Physics



Roles of Researchers are Changing

- **Publishing the results of a measurements is not finishing the job!**
- **Students and young researchers** must become aware of other roles
  - Need to be able to **communicate their science**
  - Need to be able to **explain their research to a non-specialist**
  - Need to be able to **simplify their science**
  - Need to put their **science into a broader perspective**



- **Quoting Carl Sagan:**
  - *"the public is far more intelligent than it is has generally been given credit for"*
  - *"the deepest scientific questions on the nature and origin of the world excite the interests and passions of an enormous number of people"*

Nuclear Physics Towards 2050

The future of our science depends on how it is practiced today

- Need for good **science communication**
- Need for international **exchange and collaboration**
- Need for motivating and engaging **young researchers**
- Need for **connections between subfields**

Example:

International Leading Research Program (PI: Tokyo University)