Detector R&D: low-energy facilities

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ECFA detector R&D roadmap, February 22nd , 2021

Perimeter

The following reports on detector R&D for particle-physics-related programs at **low-energy facilities**.
It is based on a non-exhaustive survey, from literature and from inputs from the community.

The following contains:

- X-ray and UV measurements for **precision atomic physics** (QED, QCD)
  Example of facilities: PSI,GSI/FAIR, KEK
  Inputs from P. Indelicato, M. Trassinelli (LKB, France)

- **Antimatter** precision experiments @ ELENA
  Inputs from M. Döser (CERN)

- **EDM** studies, small scale experiments (not at accelerators) and future JEDI experiment at COSY
  Inputs from M. Tarbutt (Imperial college, UK)

- **Neutron** physics @ ESS
  Inputs from F. Ott (CEA, France) and slides from R. Hall-Wilton (ESS)

It excludes:

- nuclear physics (beyond scope)
- DM searches and neutrino experiments (covered by others)

Precision atomic physics

Measured quantity: X rays
Physics case:

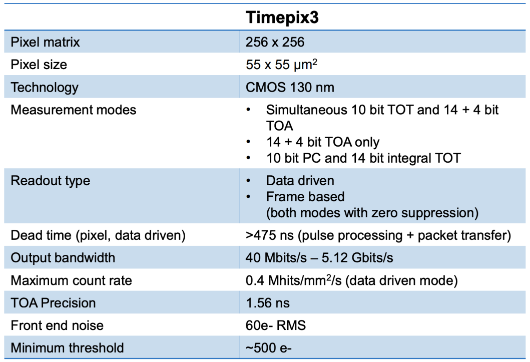
- QED in extreme electric fields (ex. spectroscopy of H-like heavy ions at storage ring @ GSI/FAIR)
- Exotic atoms for QED and QCD-related studies (ex. PSI, KEK, ELENA)

Requirements: better energy and time resolutions, linearity / calibration, less sensitive to surrounding noise.

At accelerators, an identified need is a X-ray detector sensitive to position, with good energy resolution and timing for coincidences, with about 1 keV threshold.

Example of existing system: https://advacam.com/advapix based on the Timepix3 (CERN). ***Limitations:*** not sensitive to photons below 4-5 keV because of sensitivity to noise environment and better resolution wished.

Knowledge Transfer
technology Accelerating Innovation



	Timepix3
Pixel matrix	256 x 256
Pixel size	55 x 55 μm^2
Technology	CMOS 130 nm
Measurement modes	• Simultaneous 10 bit TOT and 14 + 4 bit TOA • 14 + 4 bit TOA only • 10 bit PC and 14 bit integral TOT
Readout type	• Data driven • Frame based (both modes with zero suppression)
Dead time (pixel, data driven)	>475 ns (pulse processing + packet transfer)
Output bandwidth	40 Mbits/s – 5.12 Gbits/s
Maximum count rate	0.4 Mhits/mm^2/s (data driven mode)
TOA Precision	1.56 ns
Front end noise	60e- RMS
Minimum threshold	~500 e-

Microcalorimeters

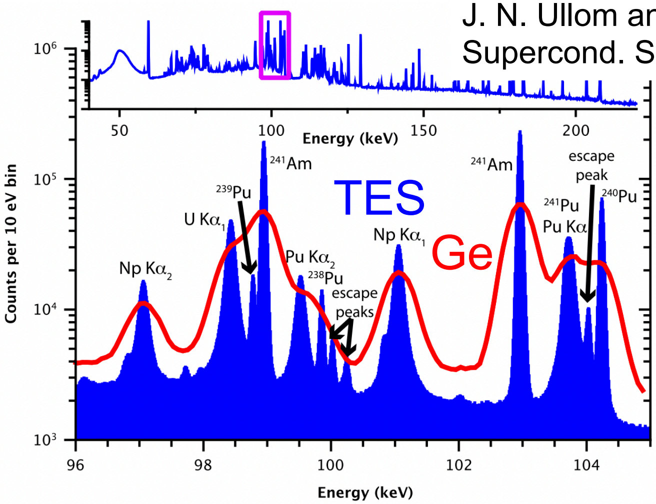
State of the art (X rays): superconducting transition edge sensors (TES) for micro-calorimeters (from 10 mK to 2 K)

Measured quantity: temperature rise after X ray adsorption

Resolutions of micro-calorimeters:

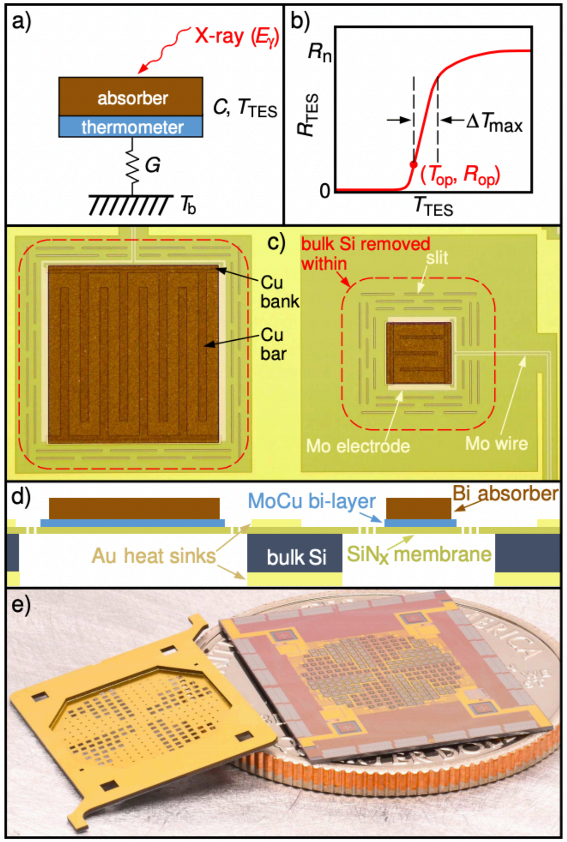
- **Energy** (sigma): 2.5 eV @ 6 keV, 1.0 eV @ 500 eV
 (to be compared to 150 eV @ 6 keV for Ge semiconductor)
- **Time constants are long (decay of 50 μs to > 100 ms)**

Rates: state of the art about 100 Hz / pixel



J. N. Ullom and D. A. Bennett, Supercond. Sci. Technol. 28, 084003 (2015)

Principle of TES & micro-calorimeter



W. B. Doriese et al., Rev. Sci. Instrum. 88, 053108 (2017)

R&D directions for TES / microcalorimeters

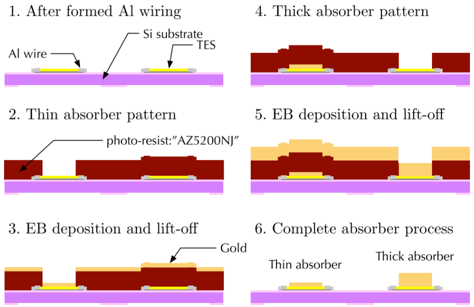
- Increase active surface: arrays of **> 10,000 channels** (State of the art: about 1000 pixels)
  Dale Li *et al.,* Jour. Low. Tempo. Phys. 193, 1287 (2018)

- improved energy resolution down to **1 eV at 5 keV**

$$\Delta E \propto \sqrt{k_B T^2 C}$$

Low C, low T better for resolution but decreases dynamic range
⇒ Optimisation of detection range and resolution

Hybrid detectors are proposed as solution (different absorber thicknesses for an accessible range from 50 eV and 15 keV)
T. Hayashi et al., Jour. Low Temp. Phys. 199, 908 (2020)



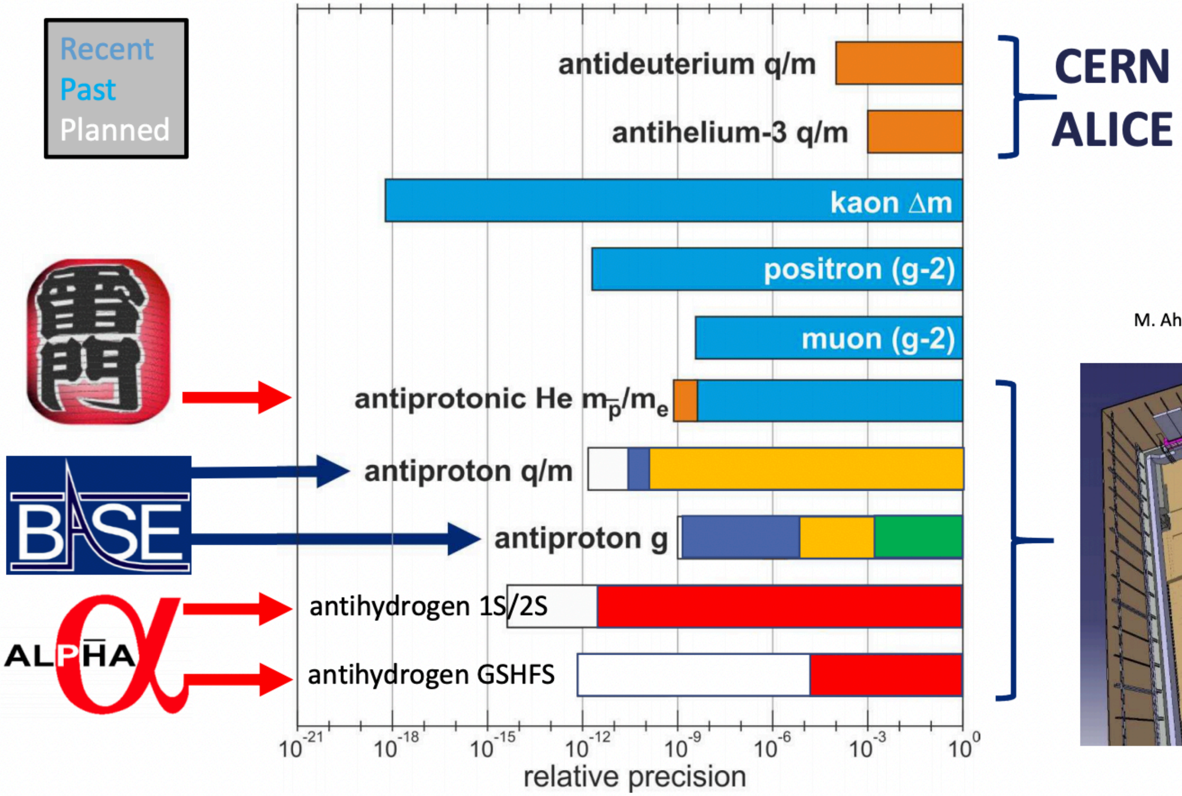
- Faster detectors: **recovery time to be improved to few 10 μs** by thermal conductance optimisation
  80 μs = 3 eV FWHM @ 1.5 keV, J. P. Hays-Wehle et al., J. Low Temp. Phys. 184, 492 (2016)
  Count rate can then be improved to > 1000 cps/pixel

- **Time resolution < 100 ns** for coincidence measurements at accelerators

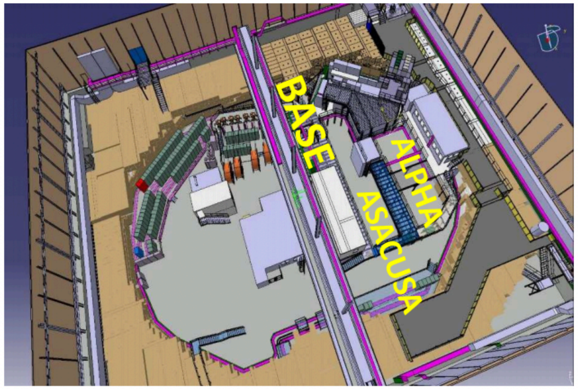
Other improvements directions:
Low energy tailing in spectrum / not critical but still to be understood
Count rate optimization by filter windows @ LCLS II, USA: C. J. Titus et al., Jour. Low Temp. Phys. 199, 1038 (2020)
Calibration methods: D. T. Becker et al., IEEE 66, 2355 (2019)

ELENA at CERN

CPT tests based on particle/antiparticle comparisons



R.S. Van Dyck et al., Phys. Rev. Lett. **59**, 26 (1987).
B. Schwinghenheuer, et al., Phys. Rev. Lett. 74, 4376 (1995).
H. Dehmelt et al., Phys. Rev. Lett. **83**, 4694 (1999).
G. W. Bennett et al., Phys. Rev. D **73**, 072003 (2006).
M. Hori et al., Nature **475**, 485 (2011).
G. Gabriesle et al., PRL **82**, 3199(1999).
J. DiSciacca et al., PRL **110**, 130801 (2013).
S. Ulmer et al., Nature **524**, 196-200 (2015).
ALICE Collaboration, Nature Physics **11**, 811–814 (2015).
M. Hori et al., Science **354**, 610 (2016).
H. Nagahama et al., Nat. Comm. **8**, 14084 (2017).
M. Ahmadi et al., Nature **541**, 506 (2017).
M. Ahmadi et al., Nature **586**, doi:10.1038/s41586-018-0017 (2018).

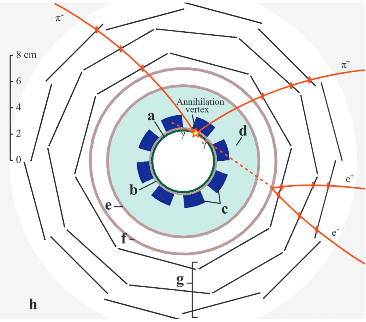


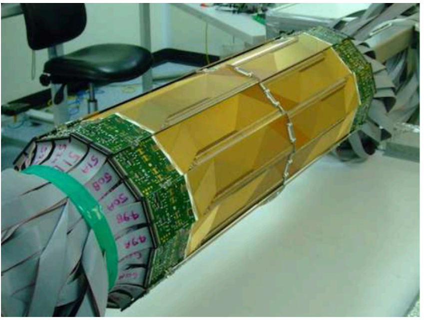
Courtesy: S. Ulmer, RIKEN, CERN

Overview of detection at ELENA at CERN

Antihydrogen and gravity experiments at ELENA, so far, the main difficulty has been in the creation of the anti-atoms and manipulation. Detectors are needed to tag and track annihilation vertices. So far *existing* technologies suffice.

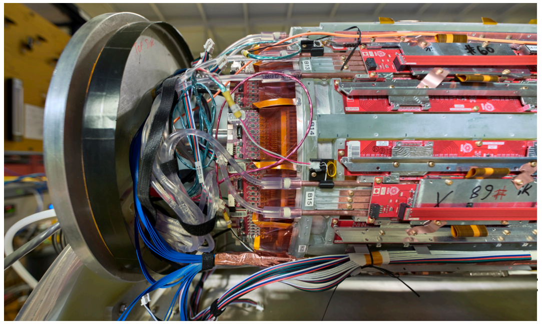
- need for moderate position resolution (down to 500 μm, with one exception: AEGIS requires 1-micron resolution (emulsion) for Moire interferometer.
- low rates (from 1 Hz to about 10k events in 30 ms in total)





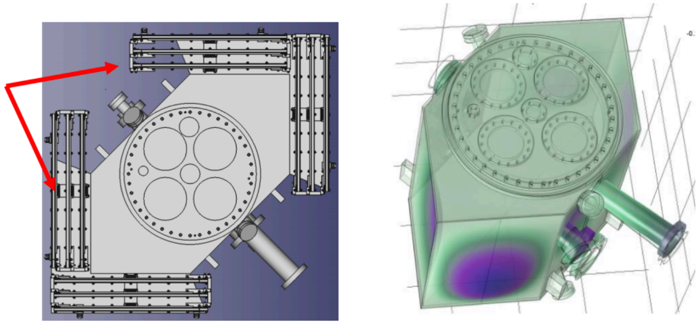
Silicon tracker of ALPHA (3 layers) for pion tracking and vertexing
G. B. Andresen et al., NIMA 684, 73 (2012)

radial (wire amplification) TPC



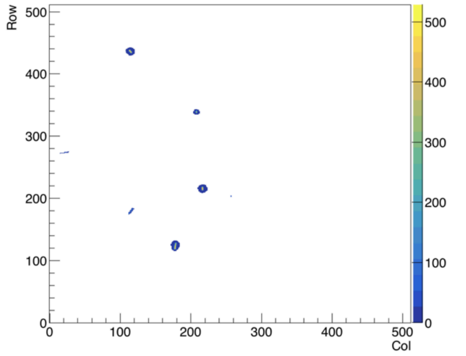
ALPHA-G radial TPC
@copyright by CERN

Micromegas detection plans (tracker)



GBAR free fall chamber design
SPSC, GBAR status report 2020

TIMEPIX3



Position detector for antiproton-nucleus annihilations, **ASACUSA**, SPSC-P307 (2019)

CPT violation at ELENA with BASE

- charge-over-mass of the antiproton at the ppt level and magnetic moment of the antiproton at the ppb level
S. Ulmer et al., Nature 524 (2015), C. Smorra et al., Nature 550 (2017)

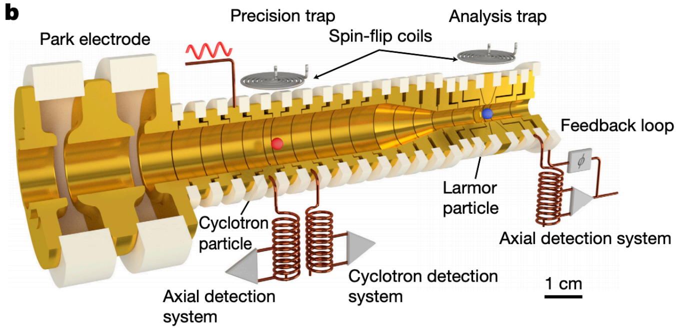
- high precision frequency measurements from **non-destructive high-Q detection after charge induction on electrodes** (very specific and beyond the scope of the ECFA initiative)

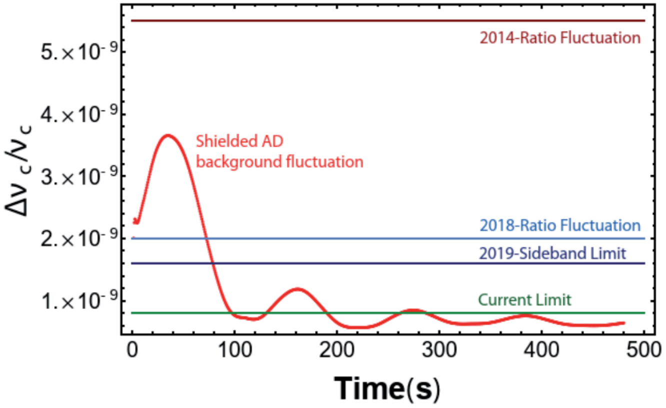
Main current limitation: **AD noise**

« In AD-off mode [BASE] reach[es] meanwhile a shot-to-shot frequency fluctuation of 0.8 p.p.b.. Different effects, such as temperature and pressure fluctuations, as well as fluctuations imposed by boiling cryoliquids, contribute to the current 0.8 p.p.b. limit. »

SPSC-P363 (2019), Future program of the BASE experiment at the AD of CERN

C. Smorra et al., Nature 550, 371 (2017)





Solutions to reduce EM noise are:

- **Self-shielding superconducting coil**
G. Gabrielse and J. Tan, J. App. Phys. 63, 5143 (1988), J. A. Devlin et al., Phys. Rev. Appl. 12, 044012 (2019)

- **Move** away (antiprotons) to a reduced-noise laboratory: STEP-BASE project, Ch. Smorra
https://antimatter.physik.uni-mainz.de/

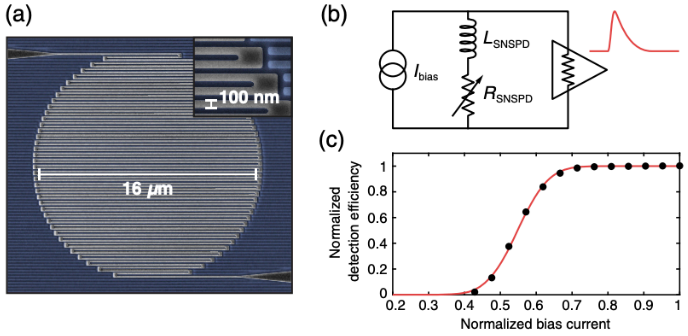
Future perspectives at ELENA

Beyond the state of the art at ELENA, on may foresee:

- in-trap photon spectroscopy (X, optical, IR, microwave), e.g., to replace destructive methods in ALPHA

- single photon counting
 e.g., **SNSPD**: few ps timing resolution, high rates, compact, operative at few K
Improvements: larger arrays, sensitivity range, energy resolution ?

- long term: **high-resolution missing mass** from annihilation at rest; in-vacuum tracking of charged particles and neutral pion detection.



Superconducting nanowire single-photon detector
E. E. Wollman et al., J. Astron. Telesc. Instrm. Syst. 7 (2021).

with the corresponding challenges:

- **lowering of EM noise and active shielding** is (and will be) a limitation for a range of measurements

- measurements measurements in **XHV** (10^{-15} mbar and lower), cryogenic electronics

- detection inside superconducting magnet bore (several Tesla): **compactness** required

Permanent Electric Dipole (EDM) measurements

- an EDM is a direct sign of a T violation and therefore CP

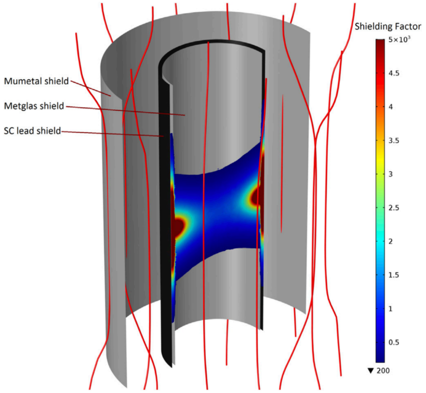
$$H = -(\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E})$$

$$|\Delta\omega| = \frac{|dE|}{\hbar J}$$

frequency shift of two adjacent magnetic sub levels

- In small-scale experiments, importance of **magnetic shield at the level of nT/cm,** e.g., Superconducting lead shield, nEDM

$$d_{false} = \frac{\mu \Delta B}{E}$$

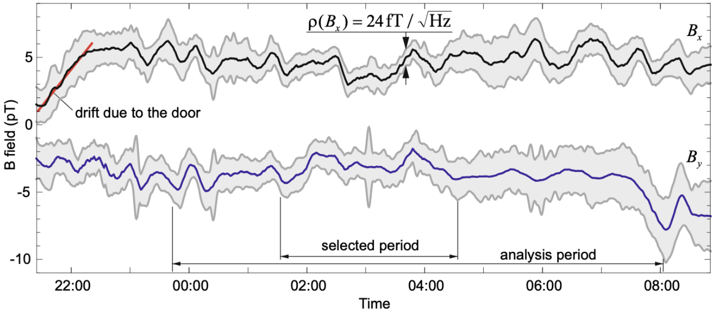


S. Slutsky et al., NIMA 862, 36 (2017)

- **Magnetic field measurements** are necessary out the chamber for determining the entering flux and, if possible, inside the chamber close to the measurement location

Optically pumped magnetometers (OPM) are among the most sensitive magnetic field sensors known today. Atomic spin polarisation is created by optical pumping. Its change by the interaction with the magnetic field is measured by optical means. **Sensitivity**: 50 fT / Hz$^{1/2}$

Small-scale EDM experiments suffer mostly from B-field related systematics.



G. Bison et al., Optics Express 26, 17350 (2018)

EDM review: T. E. Chupp et al., Rev. Mod. Phys. 91, 015001 (2019)

Deuteron EDM search at COSY

Storage ring experiments are seen as the future state-of-the-art for precision EDM measurements with charge particles since systematic uncertainties can be better controlled in principle. The interaction of the EDM with an external strong electric field will provoke a small vertical polarisation from the axial polarisation imposed to the beam.

$$\frac{d\vec{s}}{dt} = \vec{s} \times (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}) \qquad \Delta P_V = P\frac{\omega_{EDM}}{\Omega}\sin(\Omega t + \theta_0) \simeq P\omega_{EDM}t$$

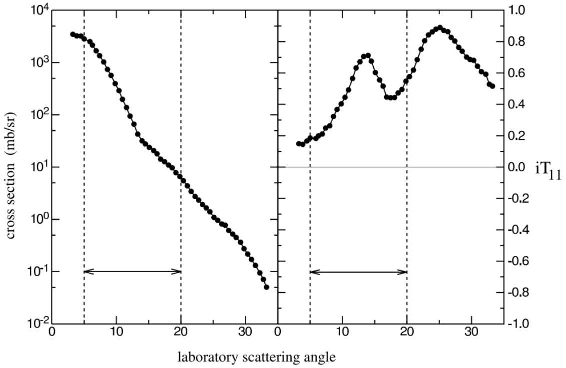
- JeDI collaboration since 2011 towards the deuteron EDM measurement at COSY at a 10^{-29} e.cm level.
- Beam control and optics are the main challenges: (1) COSY, (2) prototype ring (5 years), (3) new ring (10 years)
- detector is a polarimeter (final stage of development) based on Ay measurements from scattering from carbon

vertical beam polarisation
(non zero if EDM)

$$\sigma_{pol} = \sigma_{unpol}(1 + 2\overset{\downarrow}{it_{11}}\underset{\uparrow}{iT_{i11}} + t_{20}T_{20} + \ldots)$$

analysing power

AGS proposal (2008)



Spin-dependent elastic scattering: carbon target is chosen

Deuteron EDM search at COSY

- First measurements (proton) around 2024 (ERC AdGrant P-EDM)
- Polarimeter in final phase of development (several validation beam times already)

F. Müller et al., Hyperfine Interac. 240, 10 (2019), F. Müller et al., JINST 15, P12005 (2020)

Statistical error for EDM

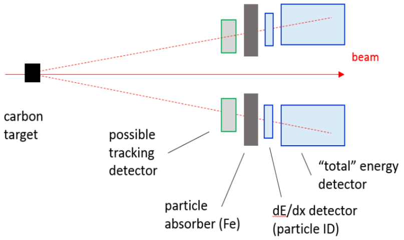
$$\sigma_d = \frac{2\hbar}{PAE_0\sqrt{N_{tot}T_{tot}f\tau_{SCT}}}$$

f: particle detection efficiency, **1.1%**, compatible with a 10^{-29} e.cm level.

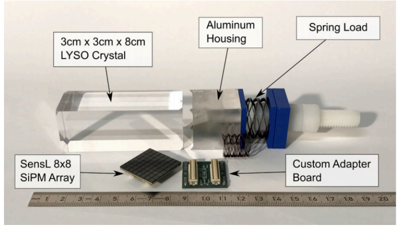
- C target off-beam, enlarged beam at polarimeter, peripheral ions will be measured / lost

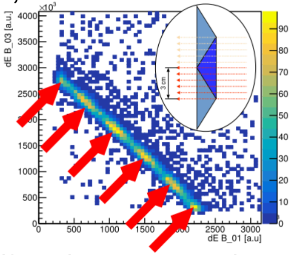
- Detection of scattered particle with LYSO hadron calorimeters with the following requirements:
  - no strong E or B field no to infer with the measurement
  - long time stability and radiation hard
  - compact

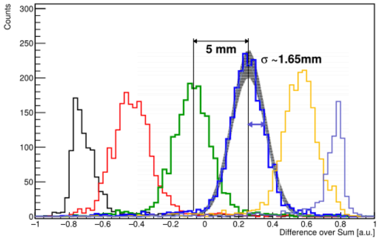
- **All criteria met by recently developed detector,** while possible improvements with tracker (thicker target)



V. Anastassopoulos et al., Rev. Sci. Instrum. 87, 115116 (2019)







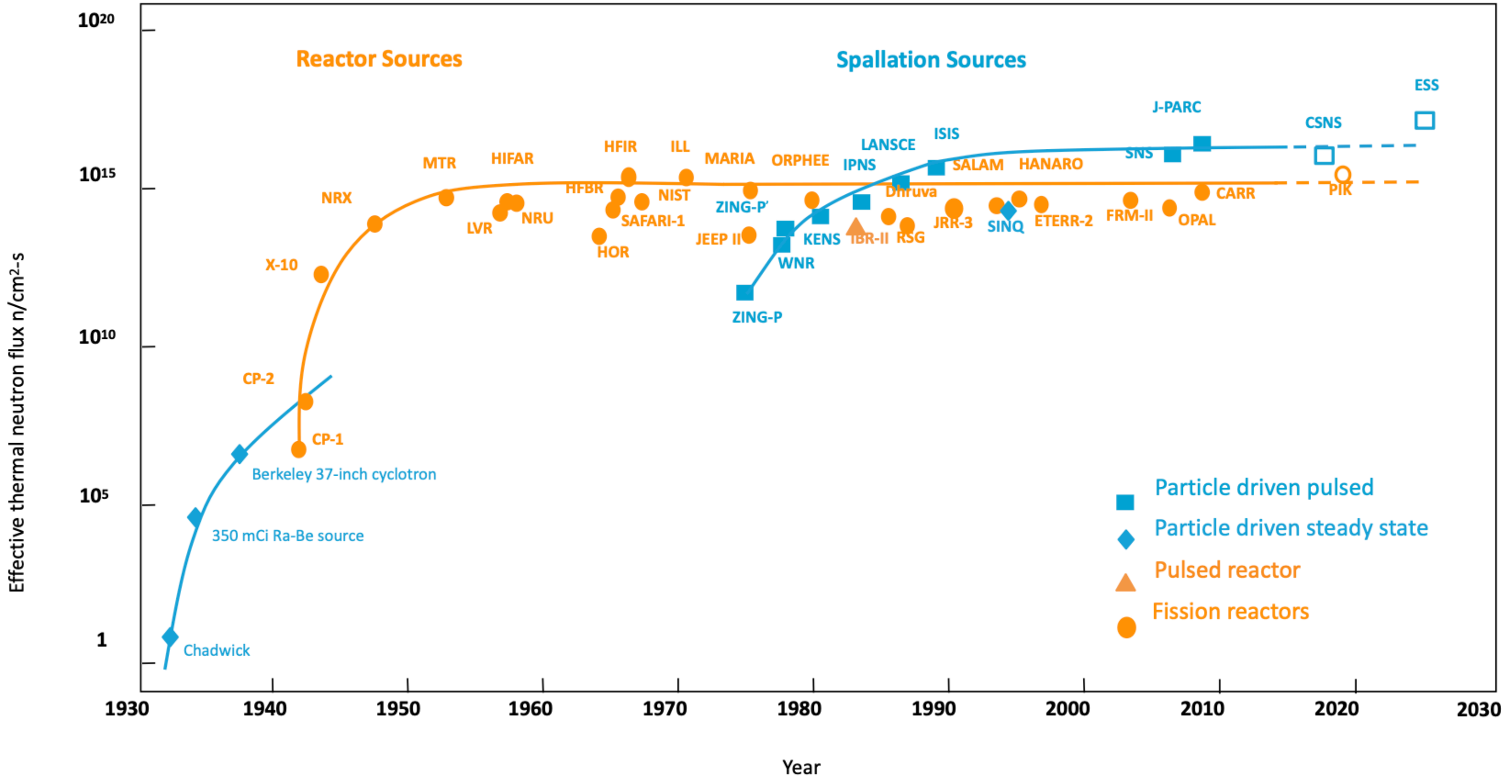
https://www.crystals.saint-gobain.com/sites/imdf.crystals.com/files/documents/lyso-material-data-sheet_1.pdf

Neutron physics at ESS

ESS (European Spalation Source) is the European forefront of neutron science, starting operation in 2025

Brightness increased by a factor 30 compared to the existing state of the art, improved resolutions are required

^{3}He scarcity to be addressed: new technologies were investigated

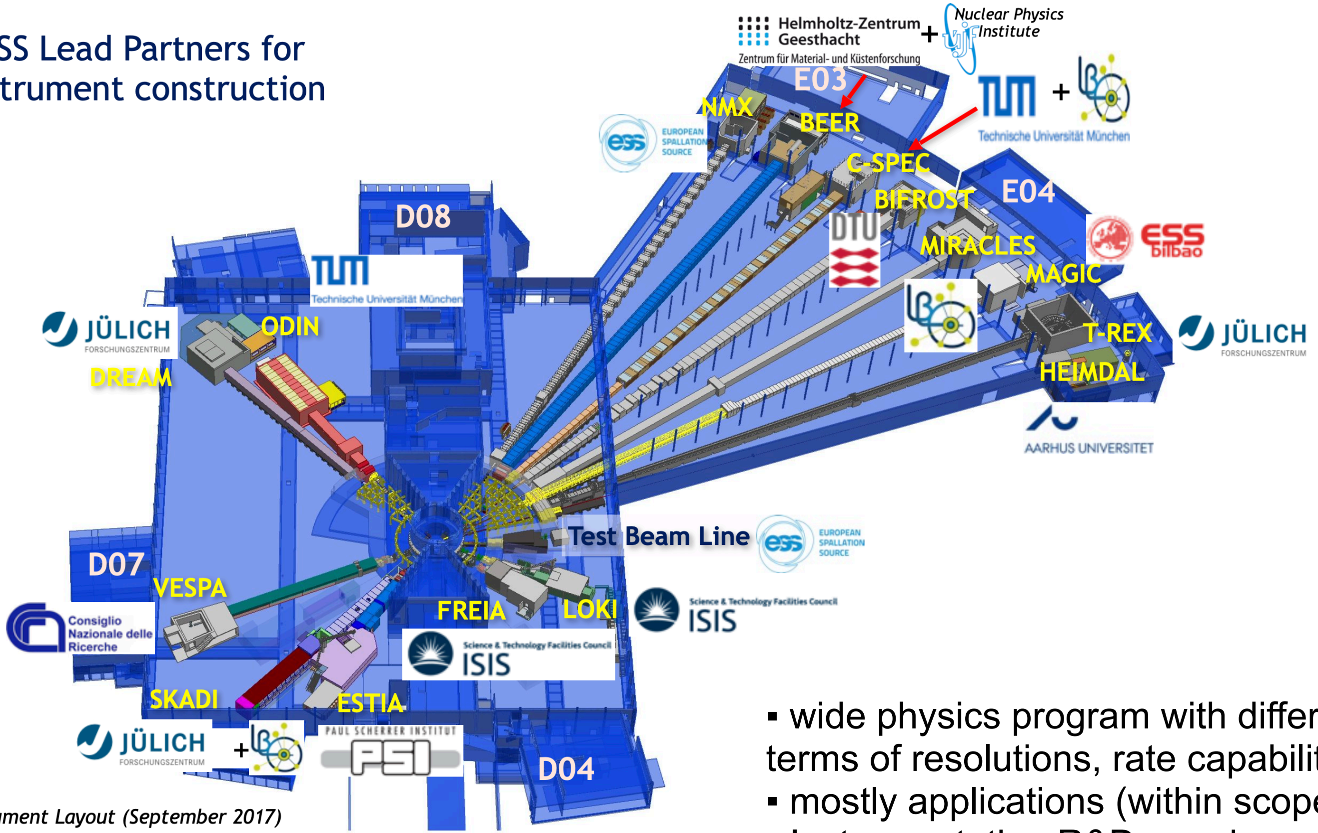


5 MW accelerator capability

Updates from Neutron Scattering, K. Skold and D. L. Price, ads., Academic Press, 1986

From CERN Detector Seminar by R. Hall-Wilton, head of ESS detector group (Dec. 2020), https://indico.cern.ch/event/979864/

Neutron physics at ESS



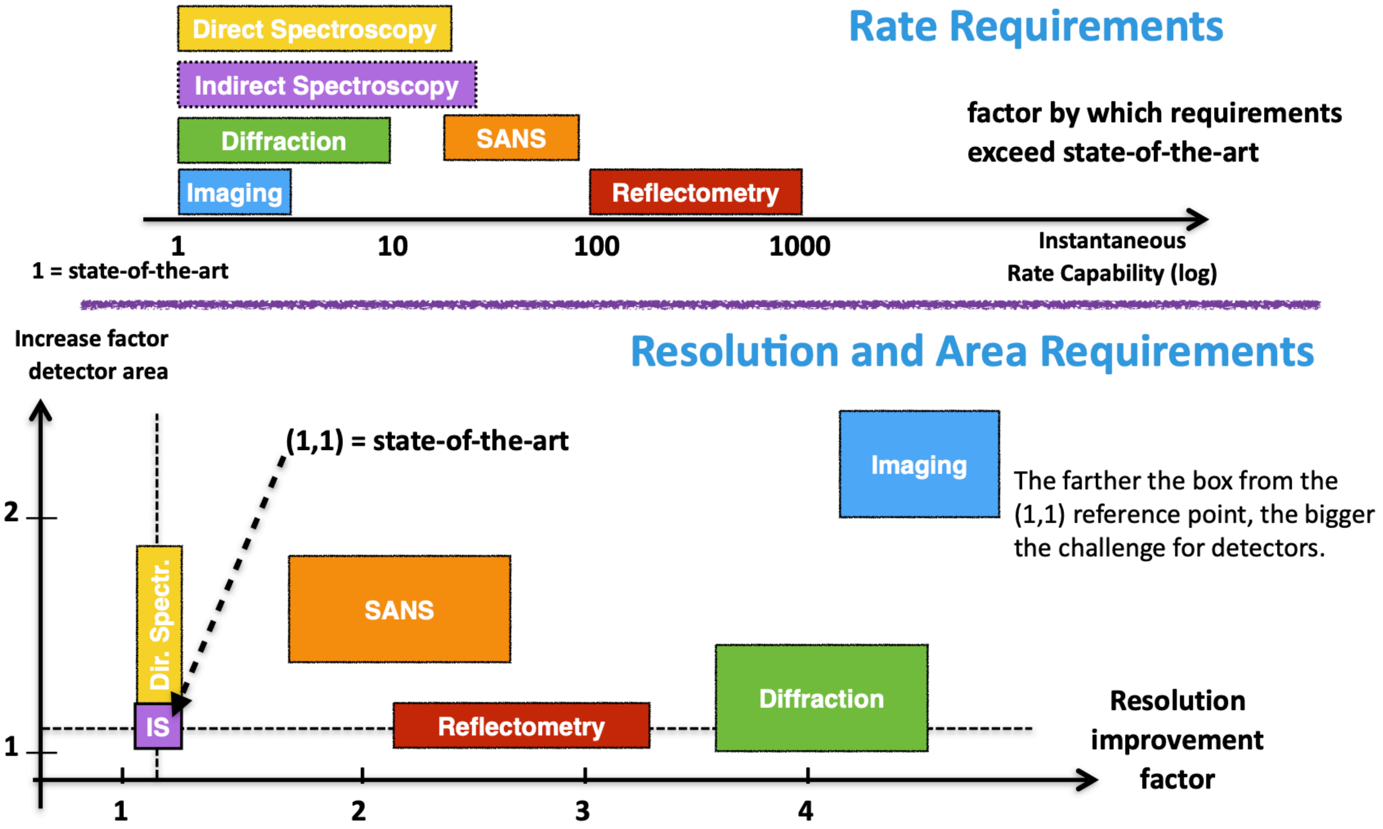
ESS Instrument Layout (September 2017)

- wide physics program with different needs in terms of resolutions, rate capabilities, geometry…
- mostly applications (within scope of ECFA ?)
- Instrumentation R&D ongoing

Taken from CERN Detector Seminar by R. Hall-Wilton (Dec. 2020), https://indico.cern.ch/event/979864/

Neutron physics at ESS

(SANS: small angle neutron scattering)

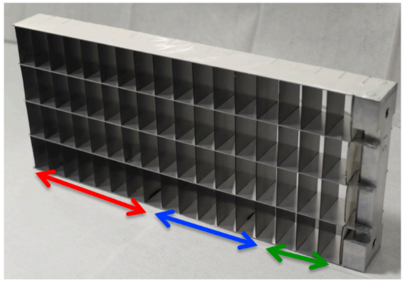


The farther the box from the (1,1) reference point, the bigger the challenge for detectors.

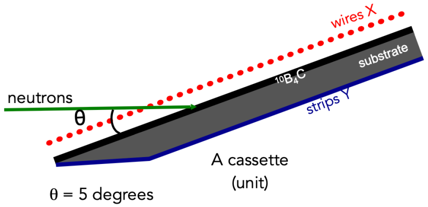
From CERN Detector Seminar by R. Hall-Wilton (Dec. 2020), https://indico.cern.ch/event/979864/

Neutron physics at ESS

- New requirements for better resolution (position and time) rate capabilities, lower background, larger area/ lower costs

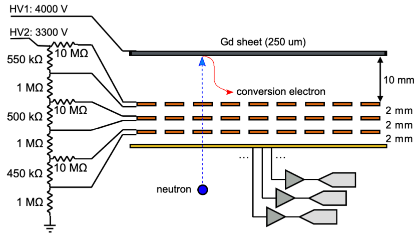


- **Multi-grid detector** development: M. Anastasopoulos et al., JINST 12, P04030 (2017)
  - technological difficulty: deposition of micrometrical layers of ^{10}B
  - Solved with $^{10}B_4C$ at ESS thin films workshop
  - multi-gas cell detectors (proportional gas chambers) for nuclear recoils
  - efficiencies comparable to ^{3}He detectors
  - **position resolution** is size of the cell (2.2x2.2x1.1 cm^3)



- **Multi-blade detectors** for reflectrometry

Requirements: « high » rates (10 kHz/mm2) and millimetric position resolution
Limitations: re-scattering, efficiency vs position resolution
F. Piscitelli et al, Journal of Instrumentation13 P05009 (2018)
G. Mauri et al., Proc. Royal Society A474 (2018) 20180266



- **Gd-deposited MPGD** detectors

D. Pfeiffer et al., JINST 11, P05011 (2016), development in collaboration with RD51
Dedicated workshop at CERN in 2015: https://indico.cern.ch/event/365380/
Ongoing development based on GEM, VMM3 + SRS readout
Requirements are:
- position resolution of few 100 microns
- several m^2 detector, high rates

Improvements in efficiency from **amplification optimisation, Gd enrichment** (11% @ 30 kHz)

Summary

- **High resolution X-ray measurements**: further development of the micro **calorimeter and TES technology** in terms of **resolutions** (1 eV @ 5 keV), **detection threshold** (sub-keV) in experimental conditions and **timing** for coincidences < 100 ns (**TF4,TF5,TF7**).

- **Precision physics at ELENA**: the detection is not today a limiting factor

- For a large part of precision measurements, the detection have reached a sensitivity at which the **electromagnetic environment is a limitation**. **Shielding** and low-noise experimental rooms are a priority Ex. BASE and STEP-BASE, GBAR @ ELENA, neutron and atomic EDM search measurements

- **Future in-trap antimatter measurements @ ELENA** (optical, IR, X ray) to be foreseen requiring **single-photon detection** in **cryogenic, XHV and narrow environments** (solenoid bore of few 10-30 cm diameter) (**TF4,TF5,TF7,TF8**)

- **EDM search at COSY** (JeDI): **polarimeter** in finalization. Mature technology. In beam tests ongoing.

- **Neutron detection @ ESS**: requirements for next decades already defined. Ongoing joint R&D and prototypes (ex. BrightnESS program and collaboration with RD51). **Gas detector** developments ongoing and current situation not limiting the physics case for Day 1 experiments at ESS.

Improvements in **efficiency, rate capabilities and resolution** would improve the physics reach but would require further R&D (**TF1, TF7**).