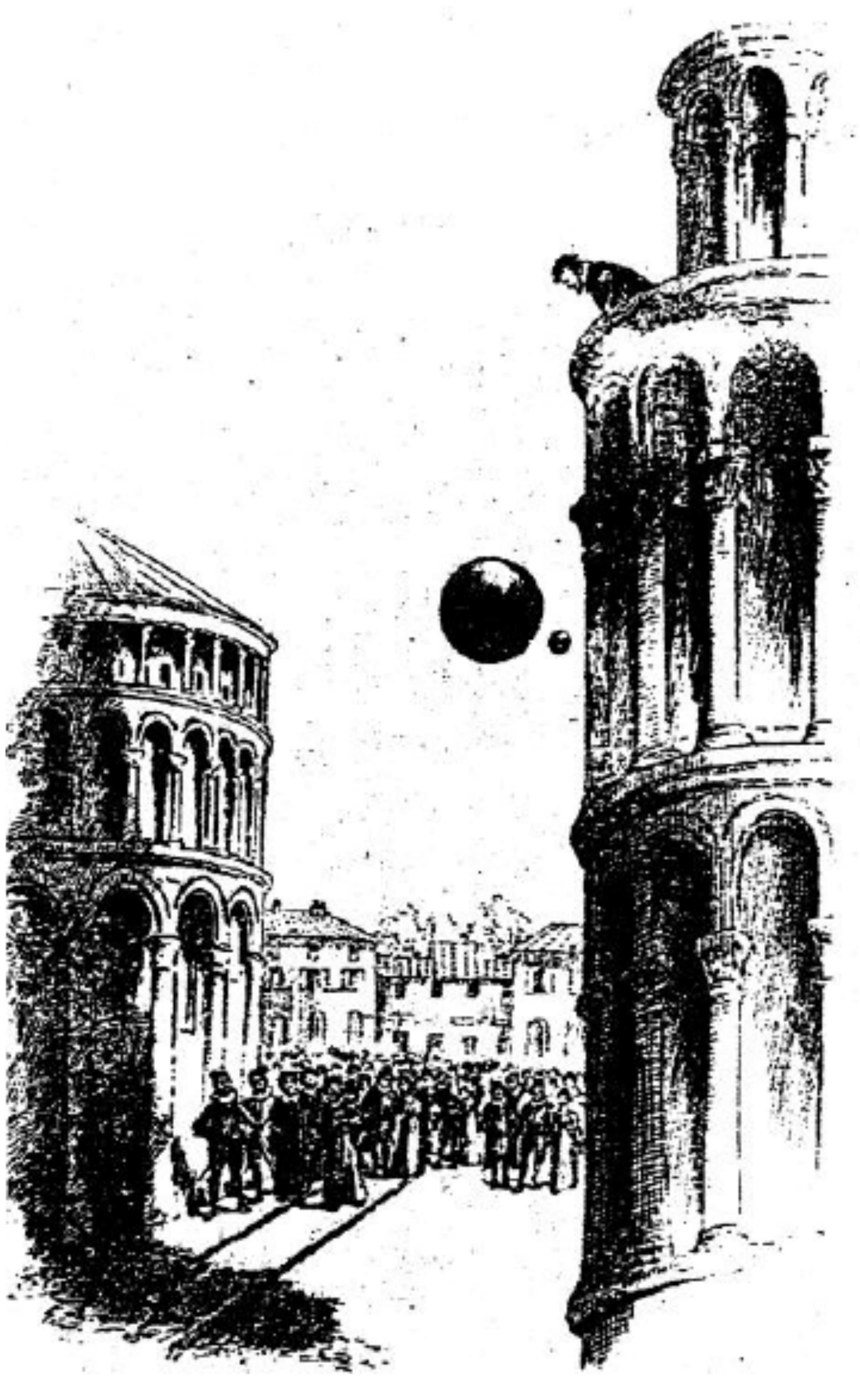


The AEgIS Experiment

Measuring the Gravitational Interaction of Antimatter

Michael Doser / CERN

Liverpool, 12/2/2014

AEgIS Collaboration

CERN, Switzerland

INFN Genova, Italy
INFN Bologna, Italy

Kirchhoff Institute of Physics, Heidelberg, Germany

Max-Planck-Institut für Kernphysik Heidelberg, Germany

INFN, Università degli Studi and Politecnico Milano, Italy

INFN Pavia-Brescia, Italy

INR Moscow, Russia

Université Claude Bernard, Lyon, France

University of Oslo and University of Bergen, Norway

Czech Technical University, Prague, Czech Republic

INFN Padova-Trento, Italy

ETH Zurich, Switzerland

Laboratoire Aimé Cotton, Orsay, France

University College, London, United Kingdom

Stefan Meyer Institut, Vienna, Austria

University of Bern, Switzerland

Motivation

- General relativity is a classical (non quantum) theory;
- EEP violations may appear in some quantum theory
- New quantum scalar and vector fields are allowed in some models (Kaluza Klein ….)

Einstein field: tensor graviton (Spin 2, "Newtonian")

+ Gravi-vector (spin 1)

+ Gravi-scalar (spin 0)

- These fields may mediate interactions violating the equivalence principle

M. Nieto and T. Goldman, Phys. Rep. 205, 5 221-281,(1992)

Scalar: "charge" of particle equal to "charge of antiparticle" : attractive force

Vector: "charge" of particle opposite to "charge of antiparticle": repulsive/attractive force

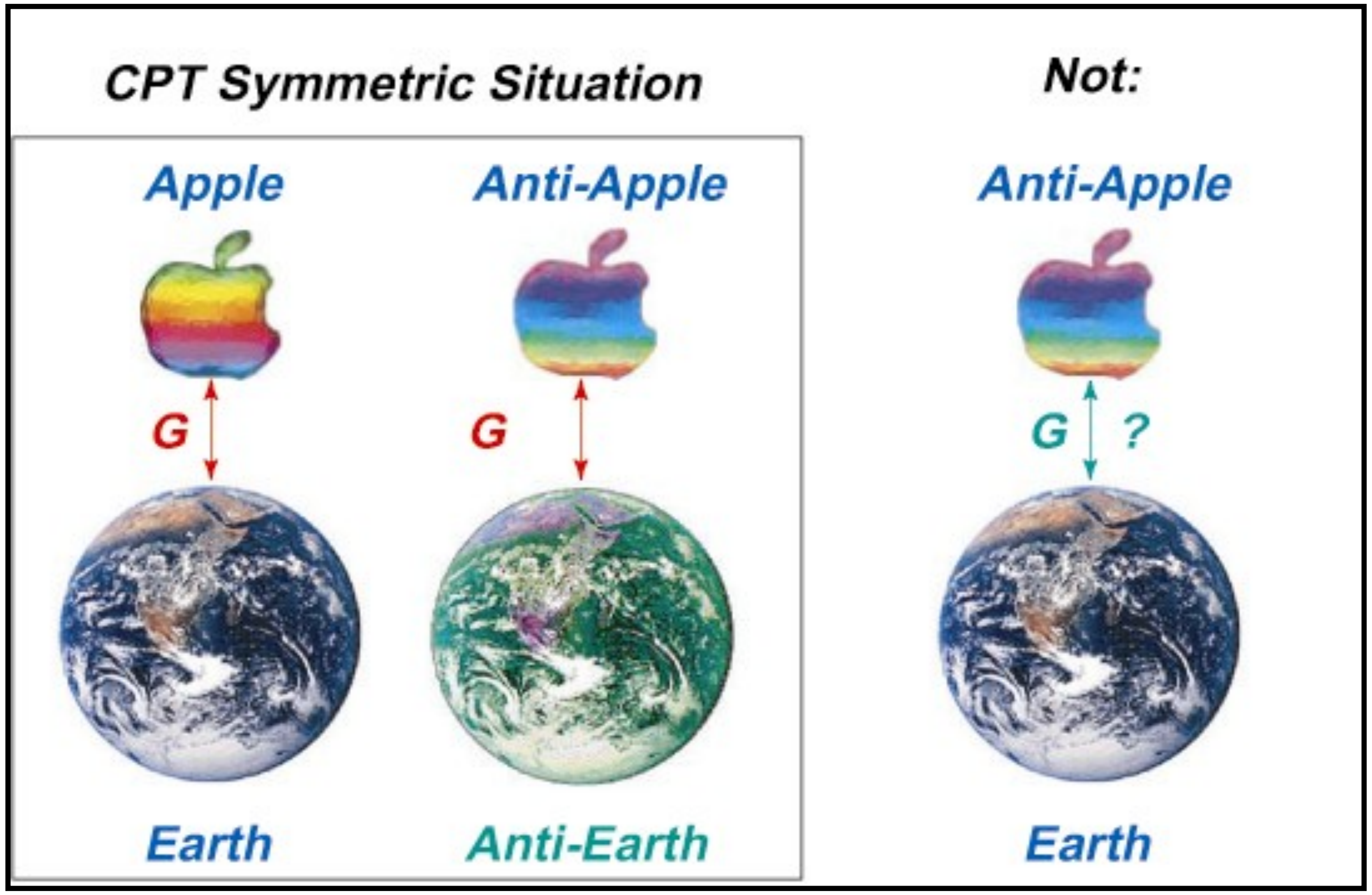
$$V = -\frac{G_\infty}{r} m_1 m_2 \left(1 \mp a\, e^{-r/v} + b\, e^{-r/s} \right)$$

Phys. Rev. D 33 (2475) (1986)

Cancellation effects in matter experiment if a ≈ b and v ≈ s

Motivation

- First direct test of the Weak Equivalence Principle involving antimatter
  - Direct tests so far only for matter systems
  - Validity for antimatter inferred from heavily debated indirect arguments
  - Theory could accommodate differences
    (e. g. through potential including gravivector and graviscalar)



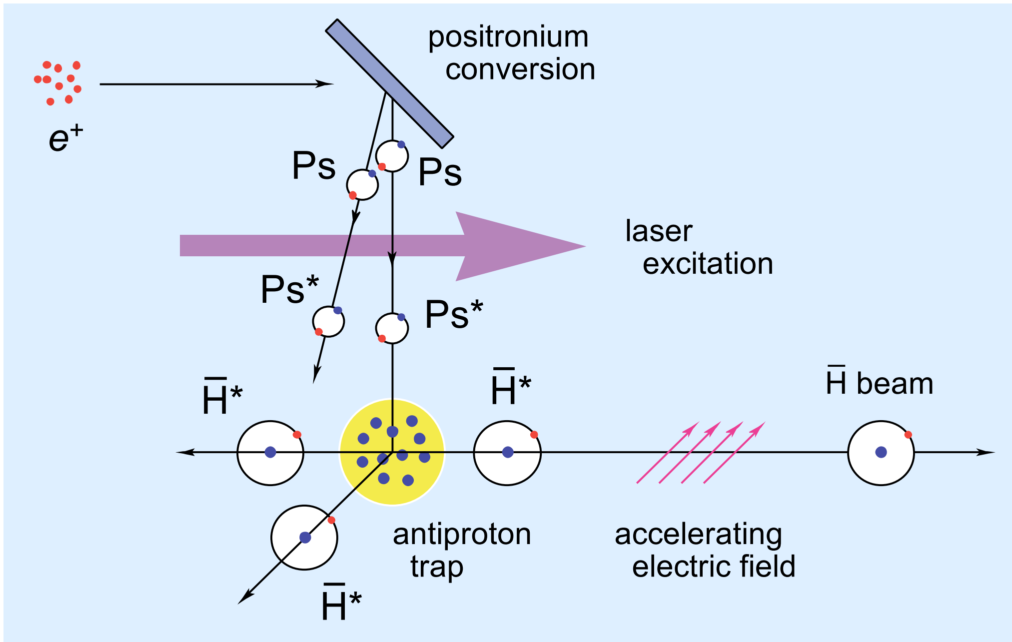
Nieto and Goldman, Phys. Rep. 205, 221 (1991)
Amole et al., Nat. Comm. 4:1785 (2013)

AEgIS Experimental Goal

- Primary goal:
  - Measurement of gravitational acceleration **g** for antihydrogen with 1% accuracy
- Secondary goals:
  - Spectroscopy of antihydrogen
  - Study of Rydberg atoms
  - Positronium physics: formation, excitation, spectroscopy
  - PALS with different materials

Step i) antihydrogen formation

- Charge exchange reaction:



$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$

- cold antiprotons (T~0.1K)
- production of Rydberg positronium
- production of antihydrogen atoms

- Principle demonstrated by ATRAP (Cs* → Ps* → $\bar{H}$*)
  [C. H. Storry *et al.*, Phys. Rev. Lett. **93** (2004) 263401]

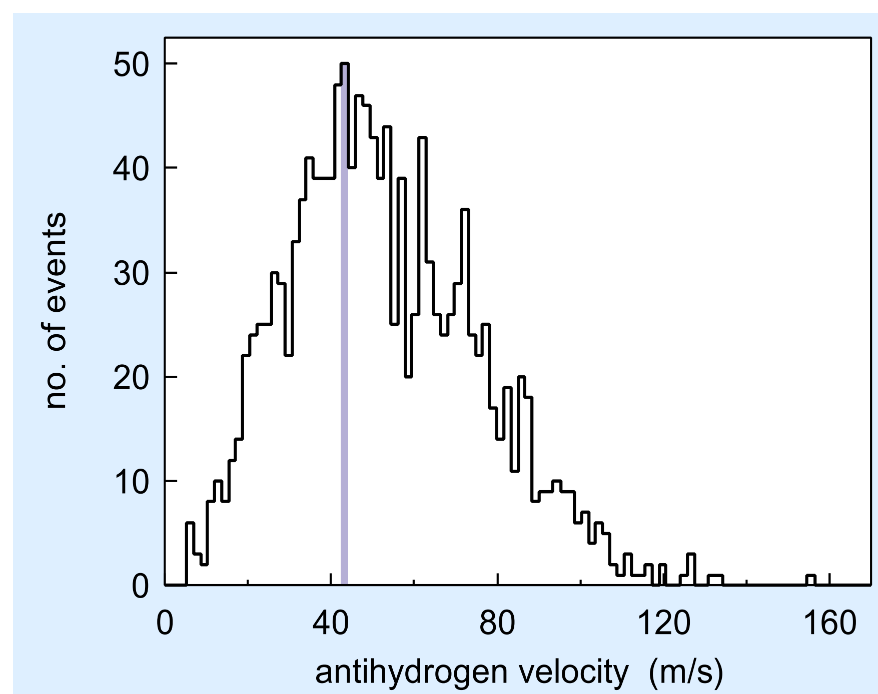
- Advantages:

– Large cross-section: $\sigma \approx a_0 n^4$

– Narrow and well-defined $\bar{H}$ *n*-state distribution

– $\bar{H}$ production from $\bar{p}$ at rest → ultracold $\bar{H}$

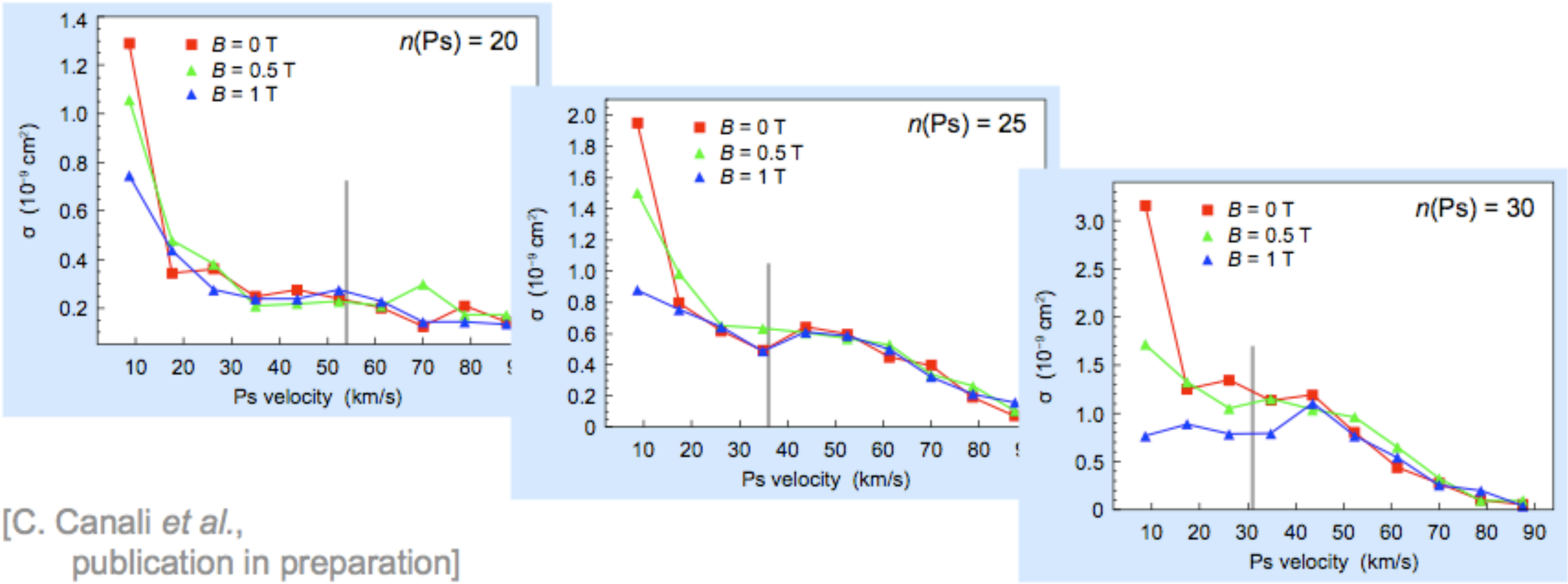
- pulsed production of $\bar{H}$



At *T*(p) = 100mK,
n(Ps) = 35
⇒ *v*(H) ≈ 45 m/s
T(H) ≈ 120mK

Step i) antihydrogen formation

Charge exchange cross-section in magnetic field (CTMC simulations)



[C. Canali *et al.*, publication in preparation]

- Cross-section large, $\sigma \approx 10^{-9}$ cm^2, slightly reduced in weak magnetic field
- "Velocity matching": Cross-section large when

$$\frac{v_{\mathrm{cm}}}{v_{\mathrm{orb}}} \approx 1 \quad \text{where} \quad v_{\mathrm{orb}} = \frac{e^2}{2\hbar n}$$

v = 36 km/s for n(Ps) = 25

$\Rightarrow T_{\mathrm{Ps}} \approx 75$ K

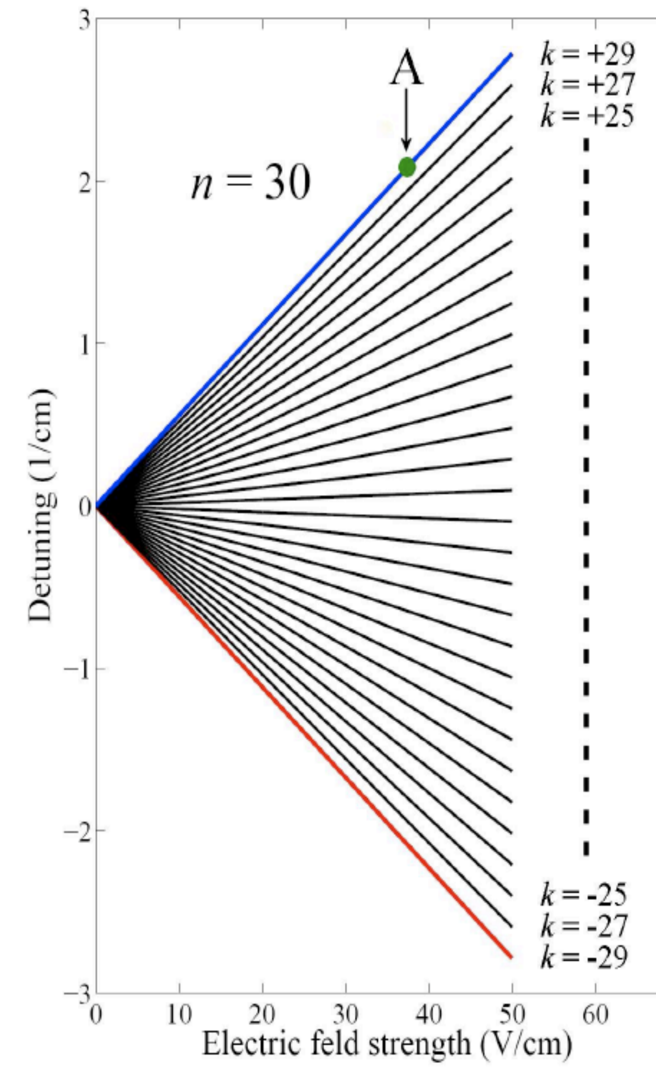
central requirement for Ps production

Step ii) beam formation

- Neutral atoms are not sensitive to static electric and magnetic fields
- Electric field gradients exert force on electric dipoles:

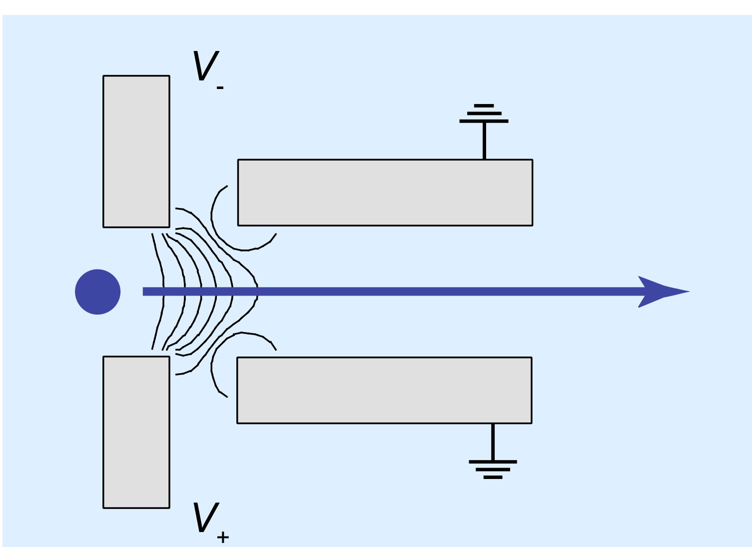
$$E = -\frac{1}{2n^2} + \frac{3}{2}nkF$$

$$Force = -\frac{3}{2}nk\vec{\nabla}F$$



⇒ Rydberg atoms are very sensitive to inhomogeneous electric fields

- Stark deceleration of hydrogen demonstrated
  [E. Vliegen & F. Merkt, J. Phys. B **39** (2006) L241 - ETH Physical Chemistry]

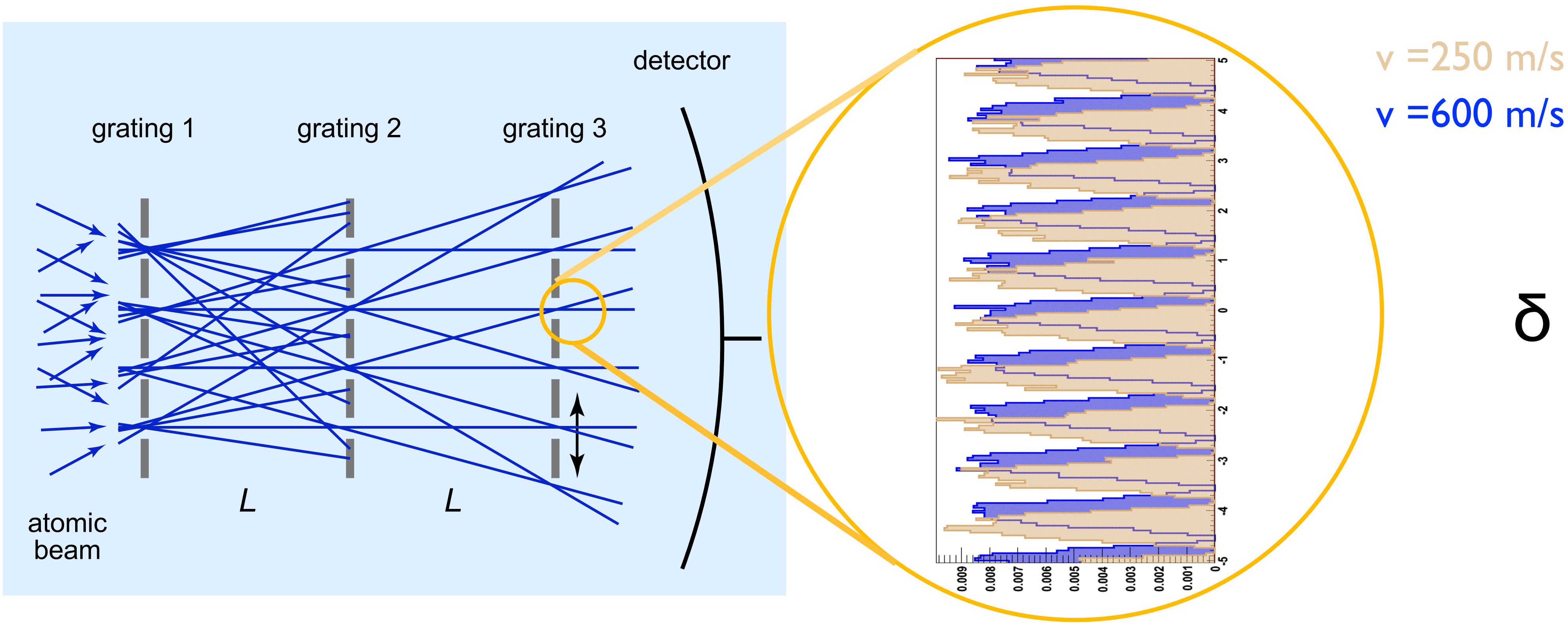


- n = 22,23,24
- Accelerations of up to 2×10^8 m/s^2 achieved
- Hydrogen beam at 700 m/s can be stopped in 5 μs over only 1.8 mm
- ongoing work on Zeeman deceleration, Stark deceleration and trapping of H

Step iii) trajectory measurement

- Classical counterpart of the Mach-Zehnder interferometer
  - Decoherence effects reduced
  - "Self-focusing" effect – beam collimation uncritical

Fringe phase and phase shift identical to Mach-Zehnder interferometer!



$$\delta = \frac{gt^2}{a}$$

- Replace the third grating and detector by position-sensitive detector

  ⇒ Transmission increases by ~ factor 3

- Has been successfully used for a gravity measurement with ordinary matter, $\sigma(g)/g = 2\times10^{-4}$ [M. K. Oberthaler *et al.*, Phys. Rev. A **54** (1996) 3165]

- with 10^5 $\bar{H}$ at 100mK, $\sigma(g)/g$ = 1% (expected) [A. Kellerbauer *et al.*, Phys. Rev. A **54** (1996) 3165]

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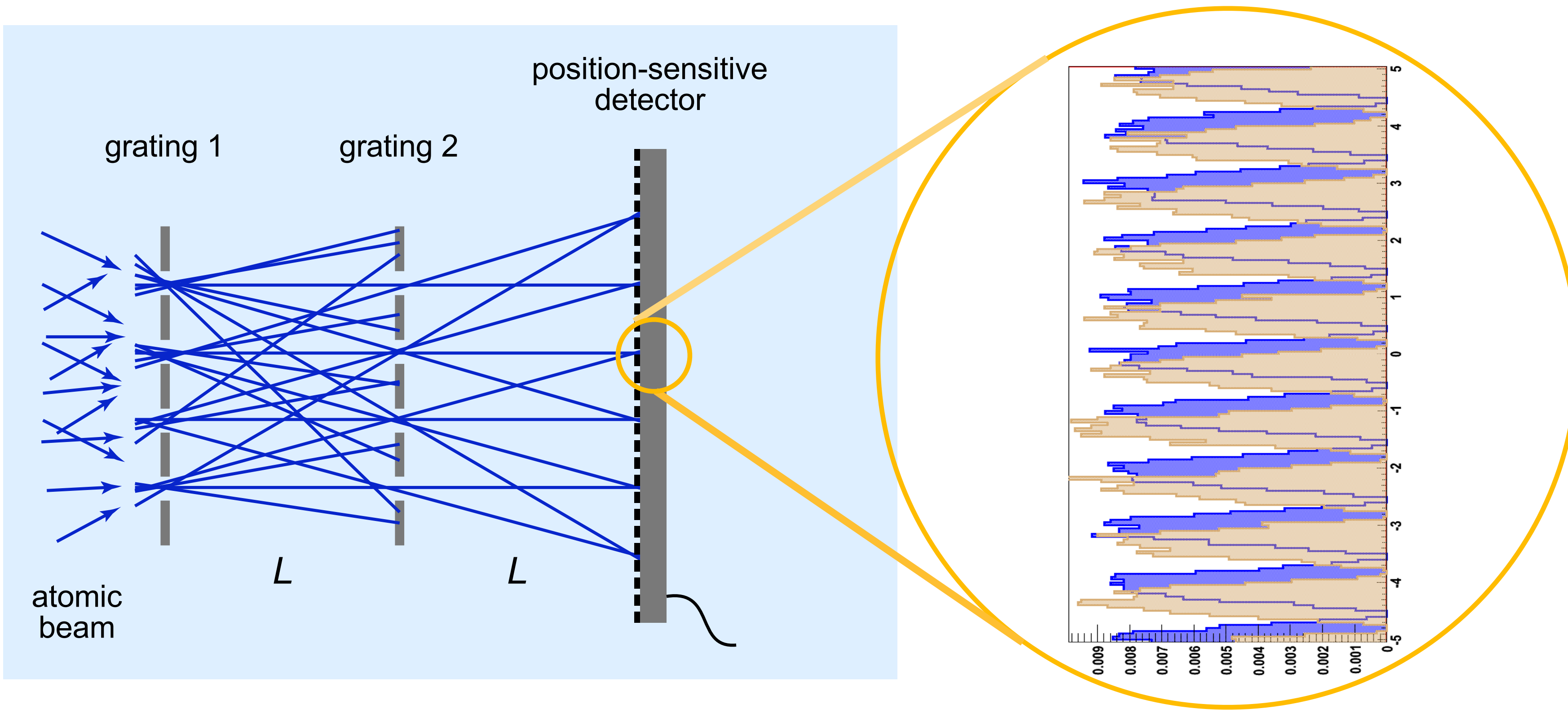


v =250 m/s
v =600 m/s

$$\delta = \frac{gt^2}{a}$$

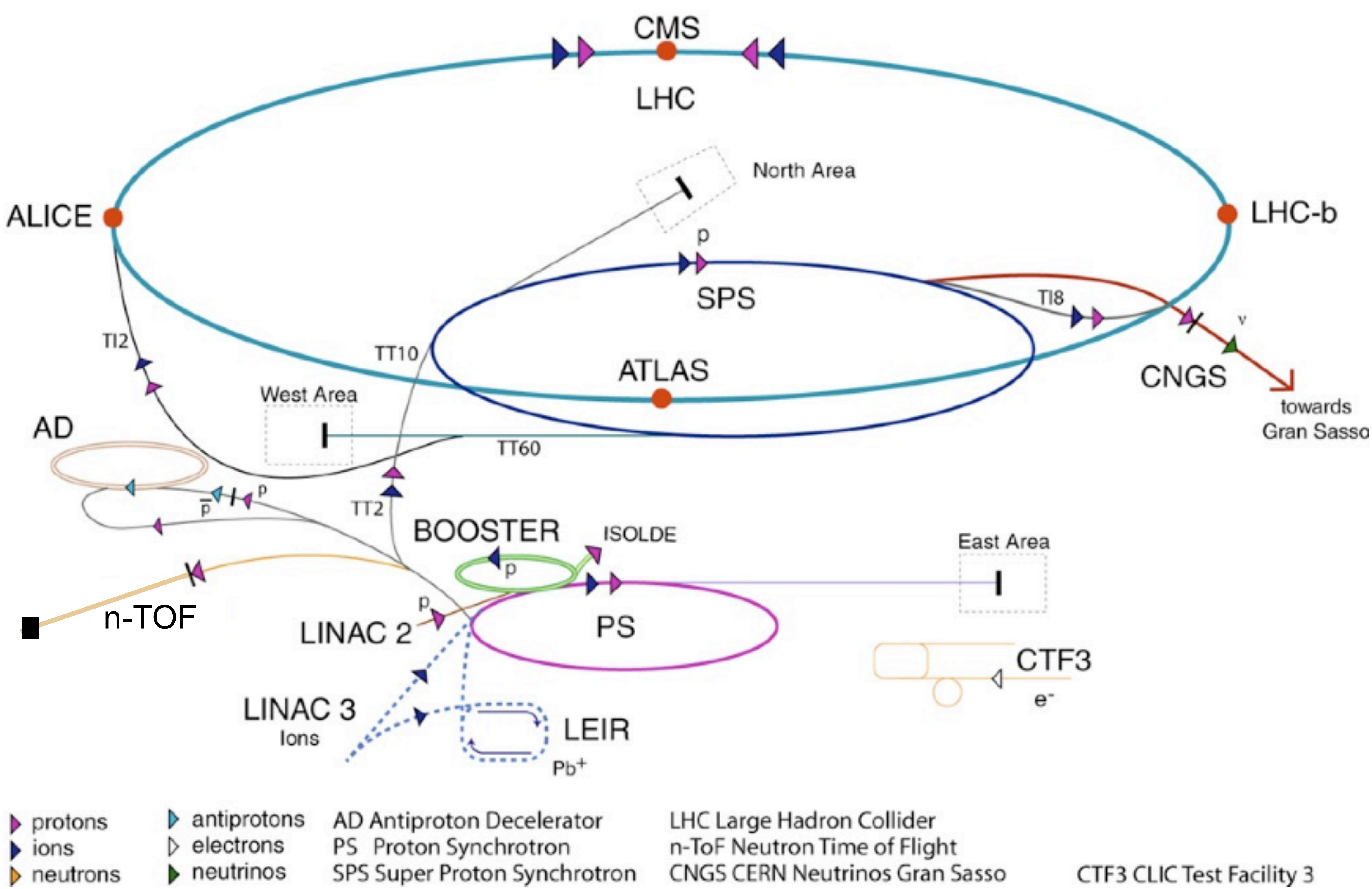
- Replace the third grating and detector by position-sensitive detector

  $\Rightarrow$ Transmission increases by ~ factor 3

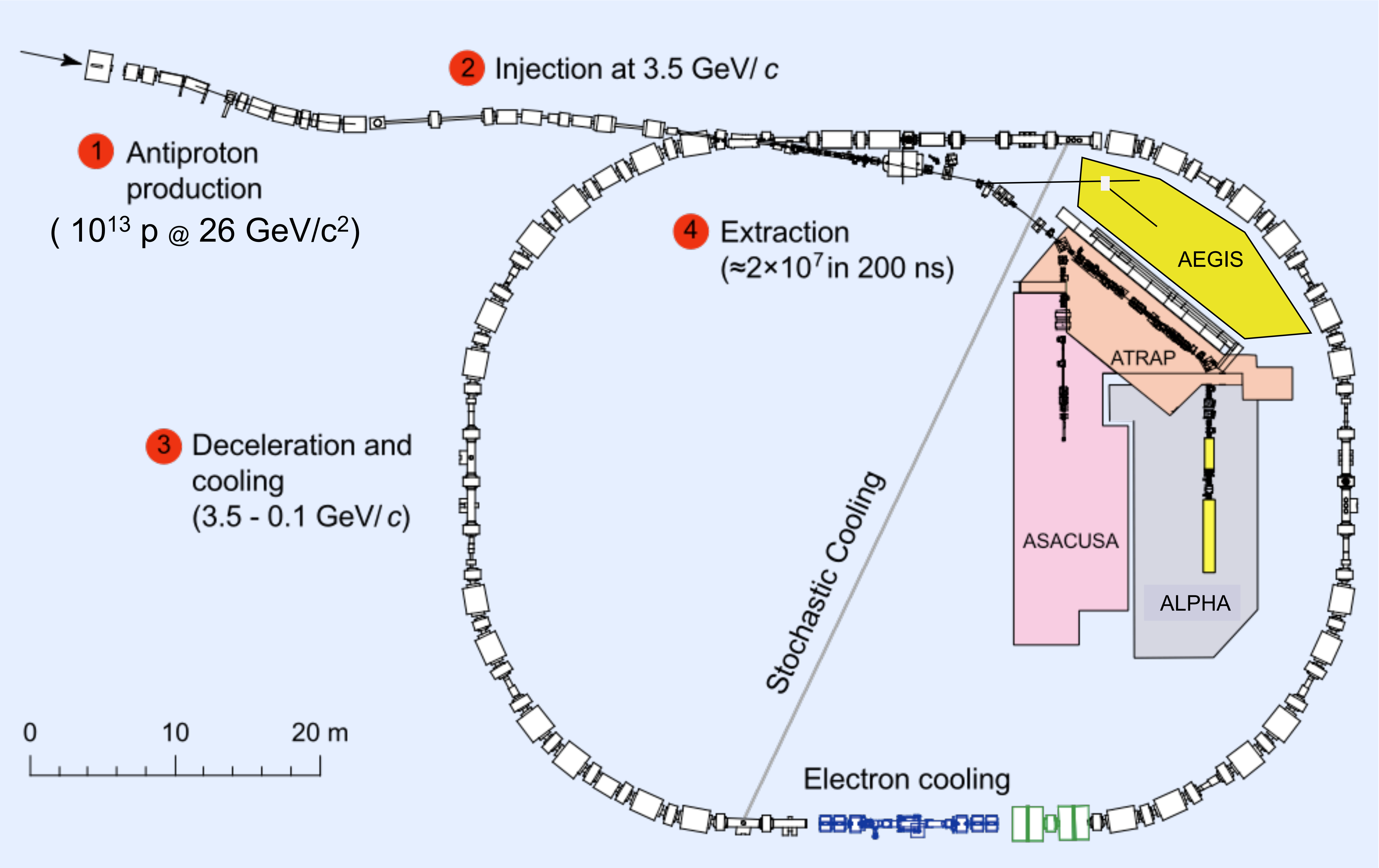
- Has been successfully used for a gravity measurement with ordinary matter, $\sigma(g)/g = 2\times10^{-4}$ [M. K. Oberthaler *et al.*, Phys. Rev. A **54** (1996) 3165]

- with 10^5 $\bar{\mathrm{H}}$ at 100mK, $\sigma(g)/g$ = 1% (expected) [A. Kellerbauer *et al.*, Phys. Rev. A **54** (1996) 3165]

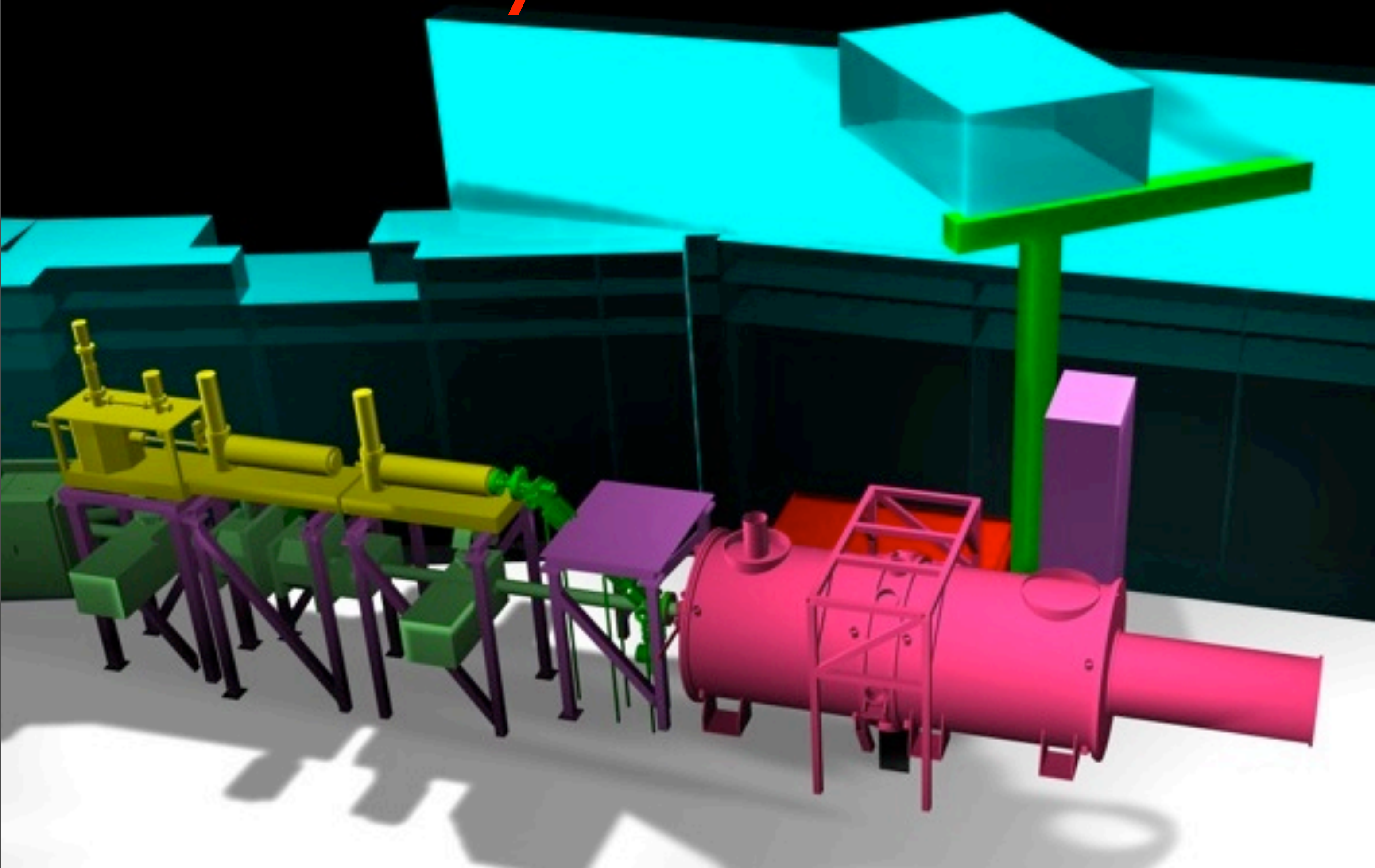
CERN Accelerator Complex

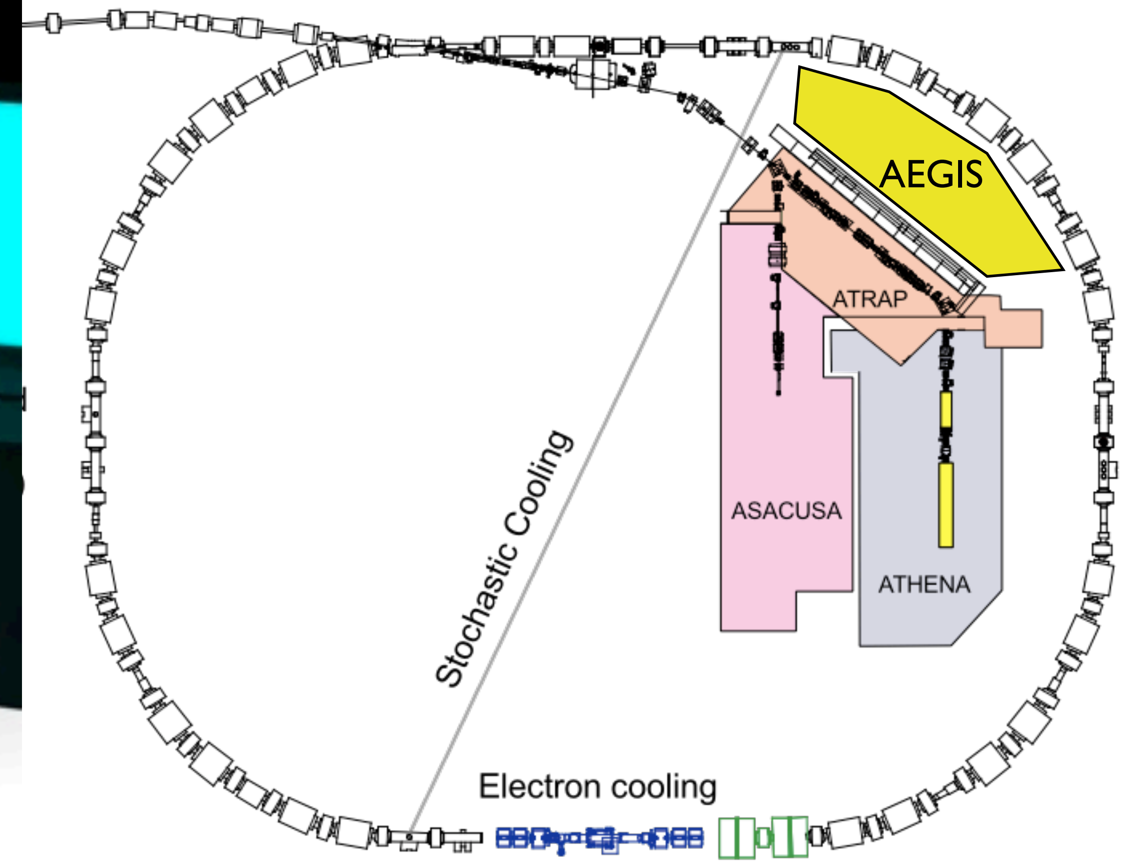


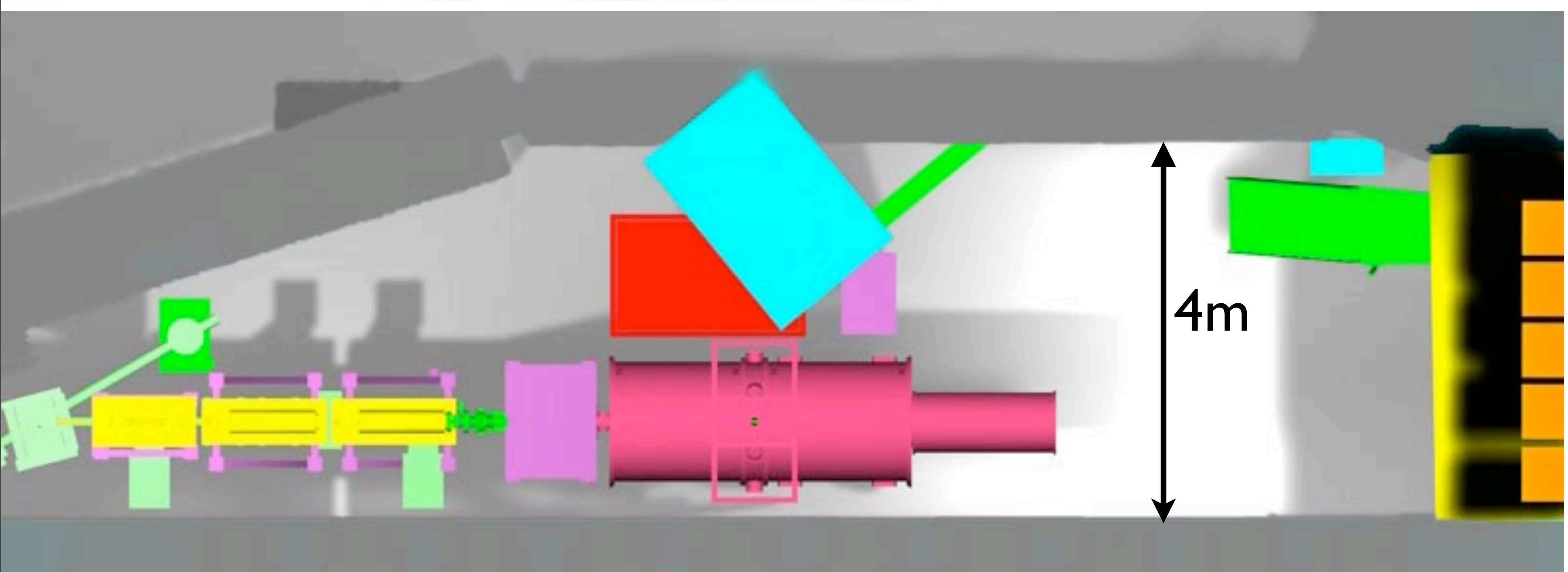
Antiproton decelerator



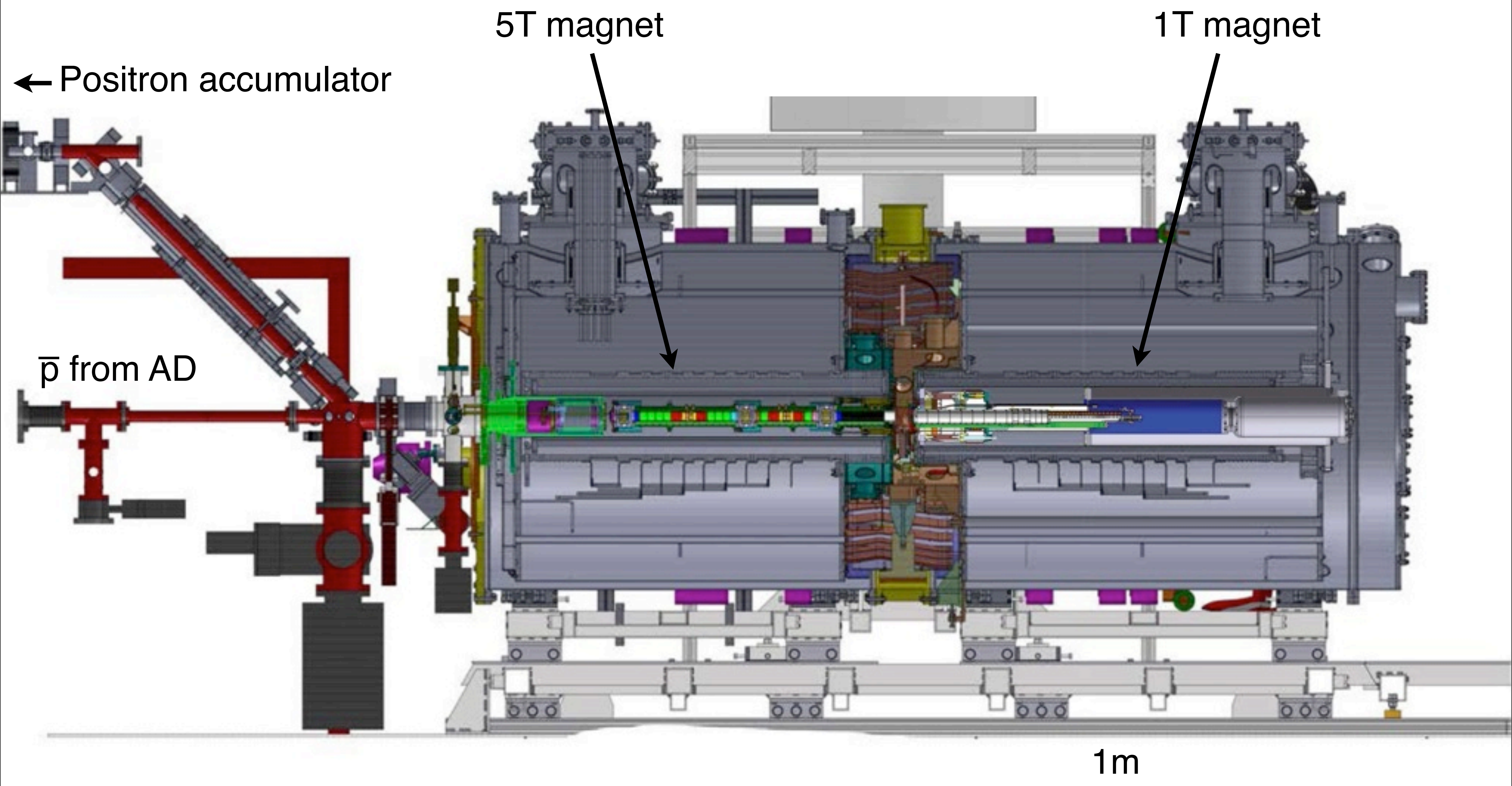
Zone layout



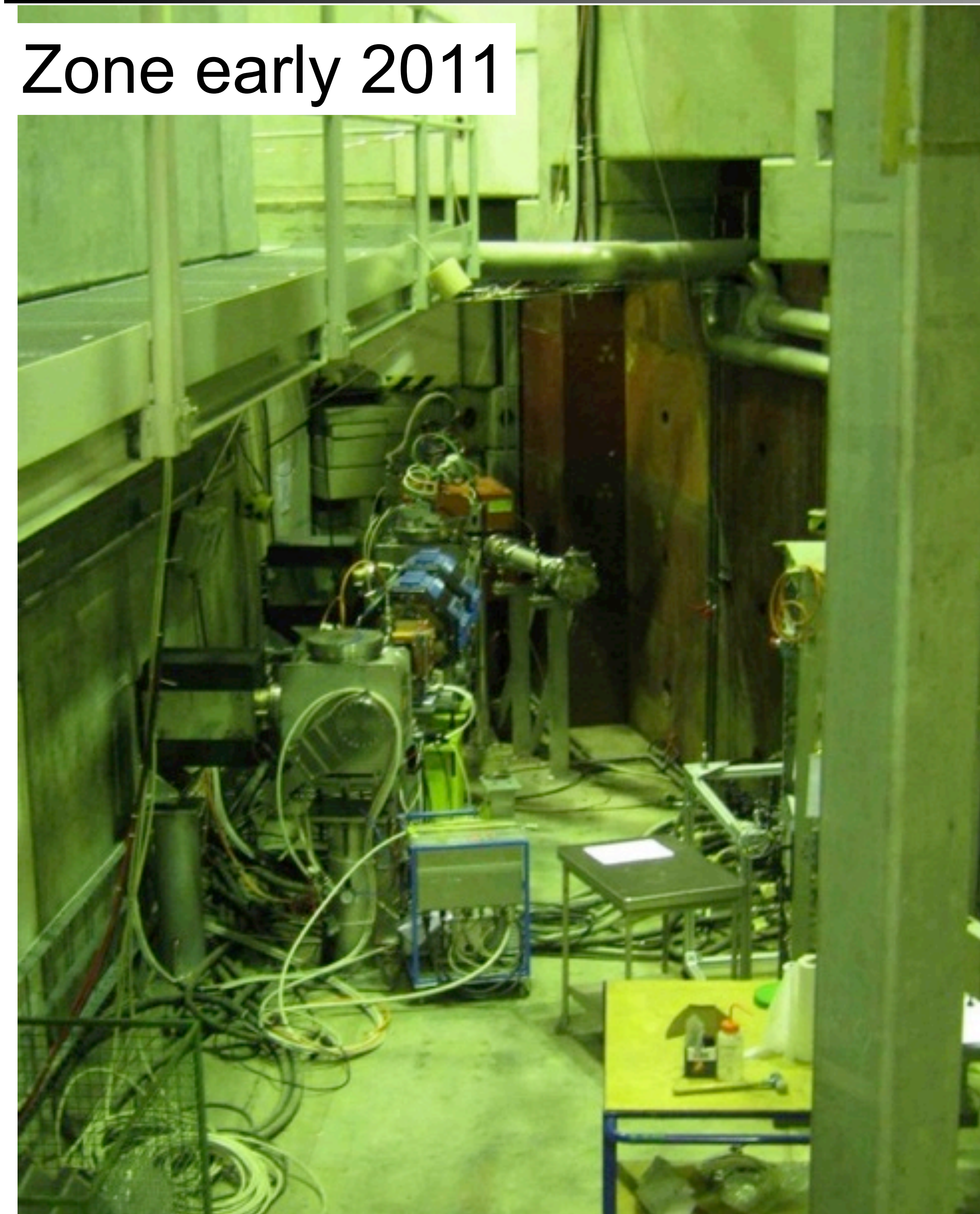

AEGIS
ATRAP
ASACUSA
ATHENA
Stochastic Cooling
Electron cooling


4m

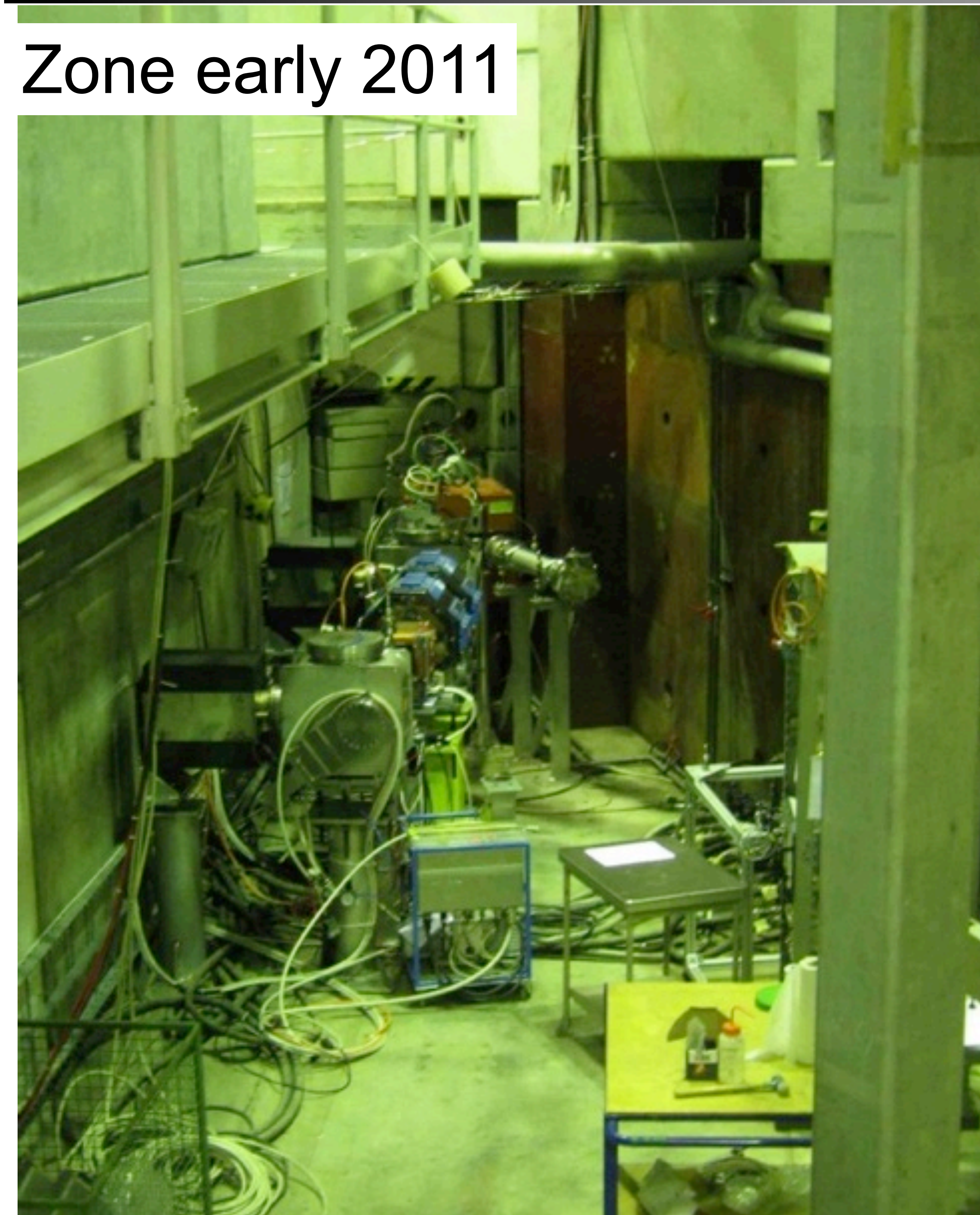
Experimental Apparatus @ CERN

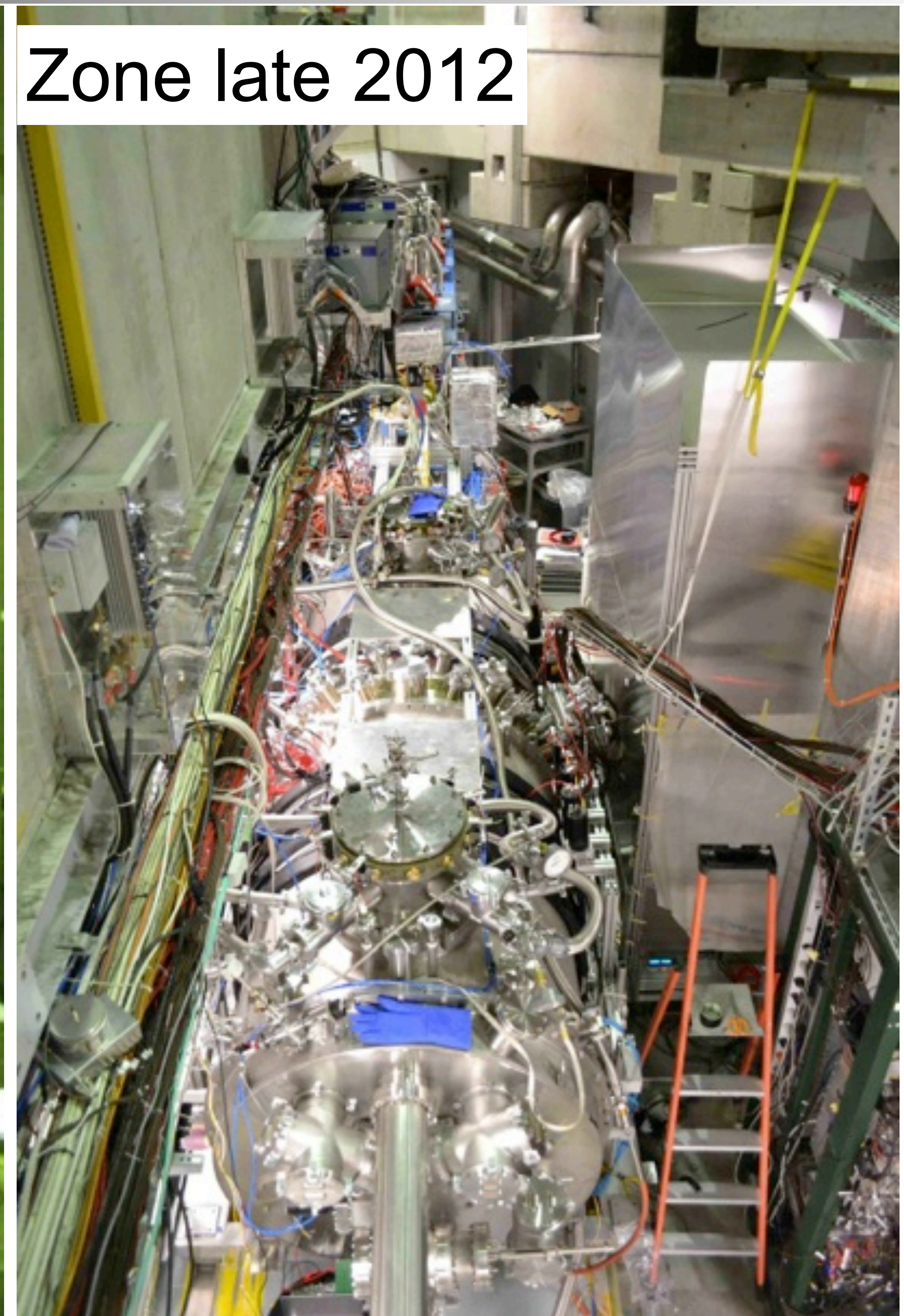


Experimental Installation

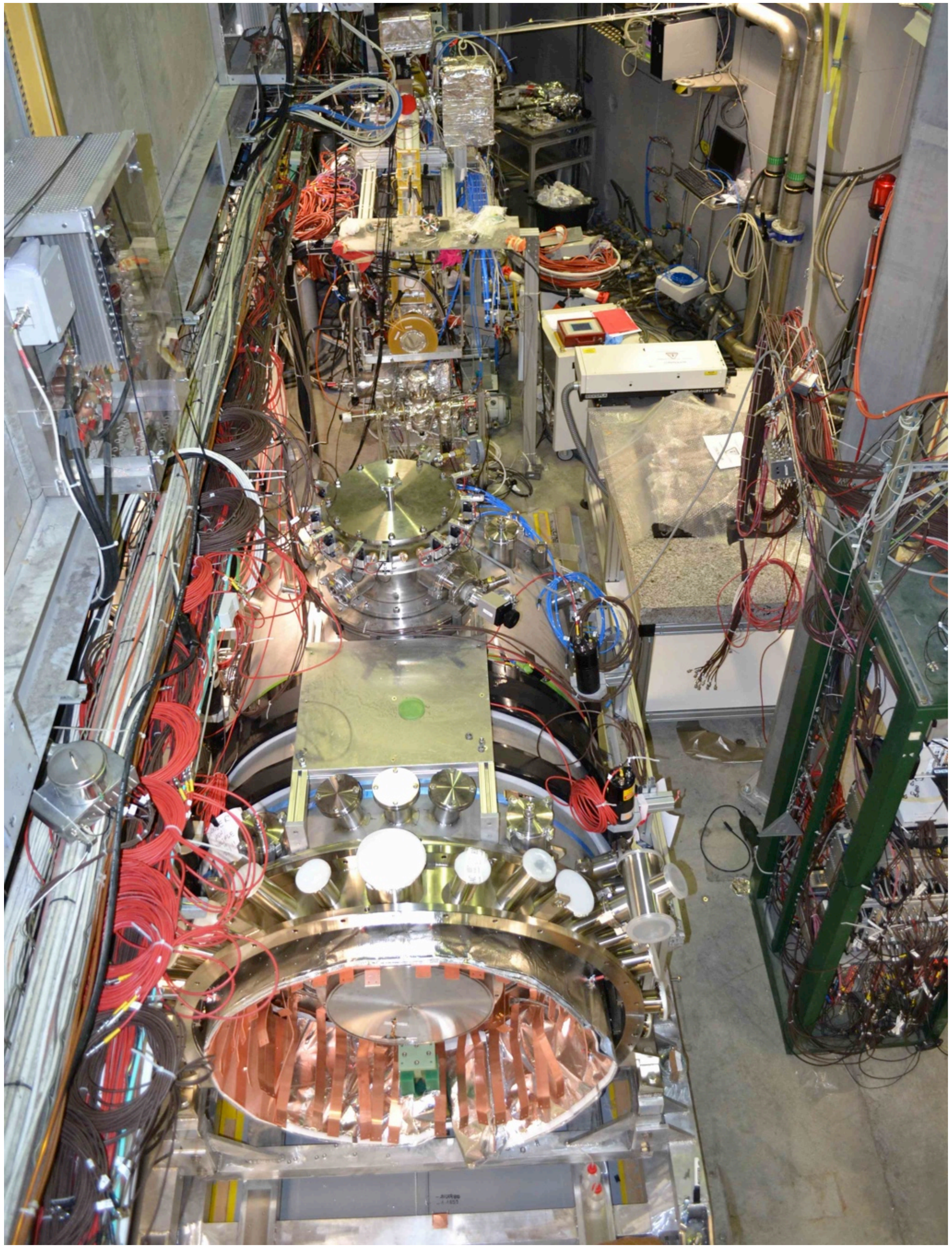


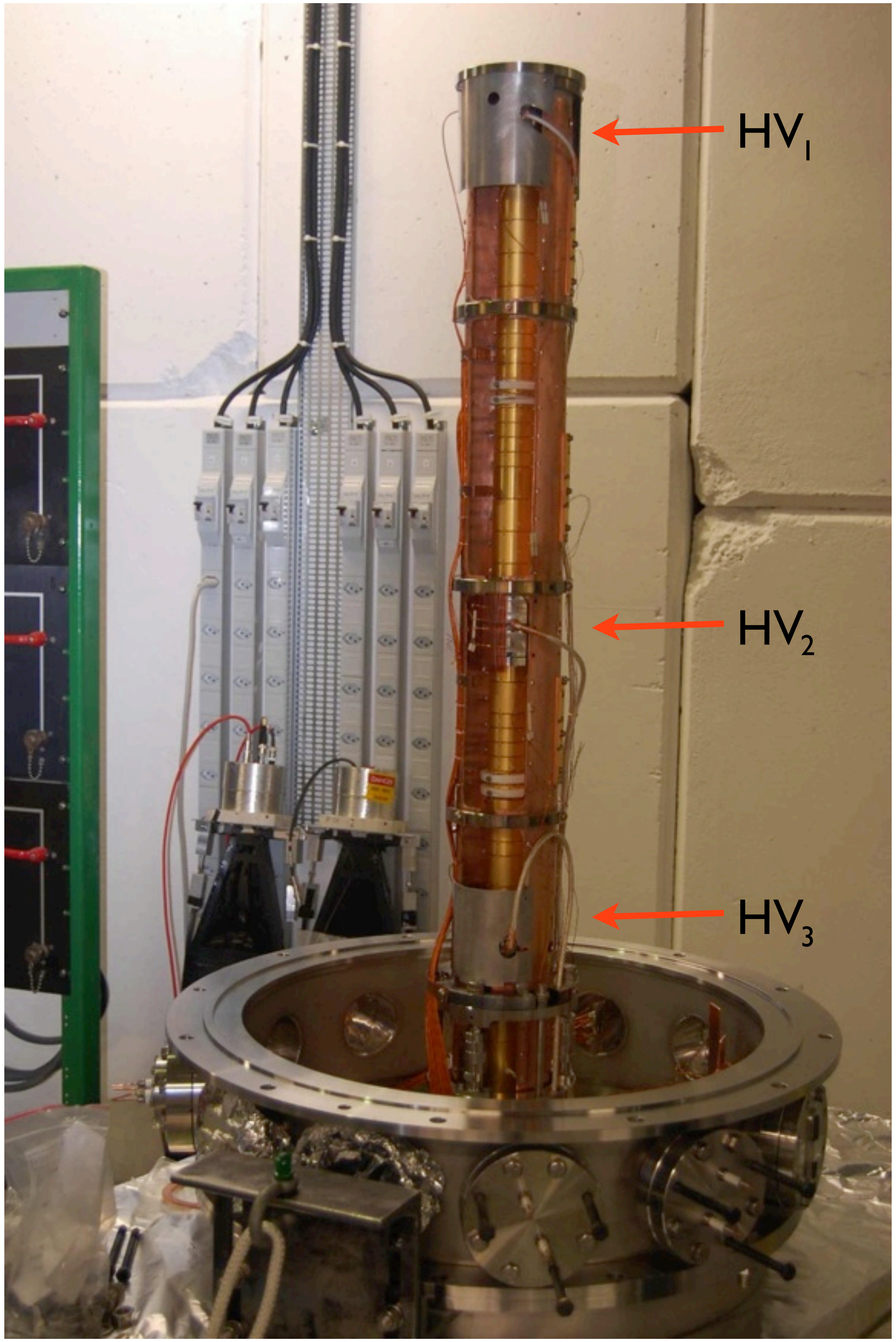
Experimental Installation



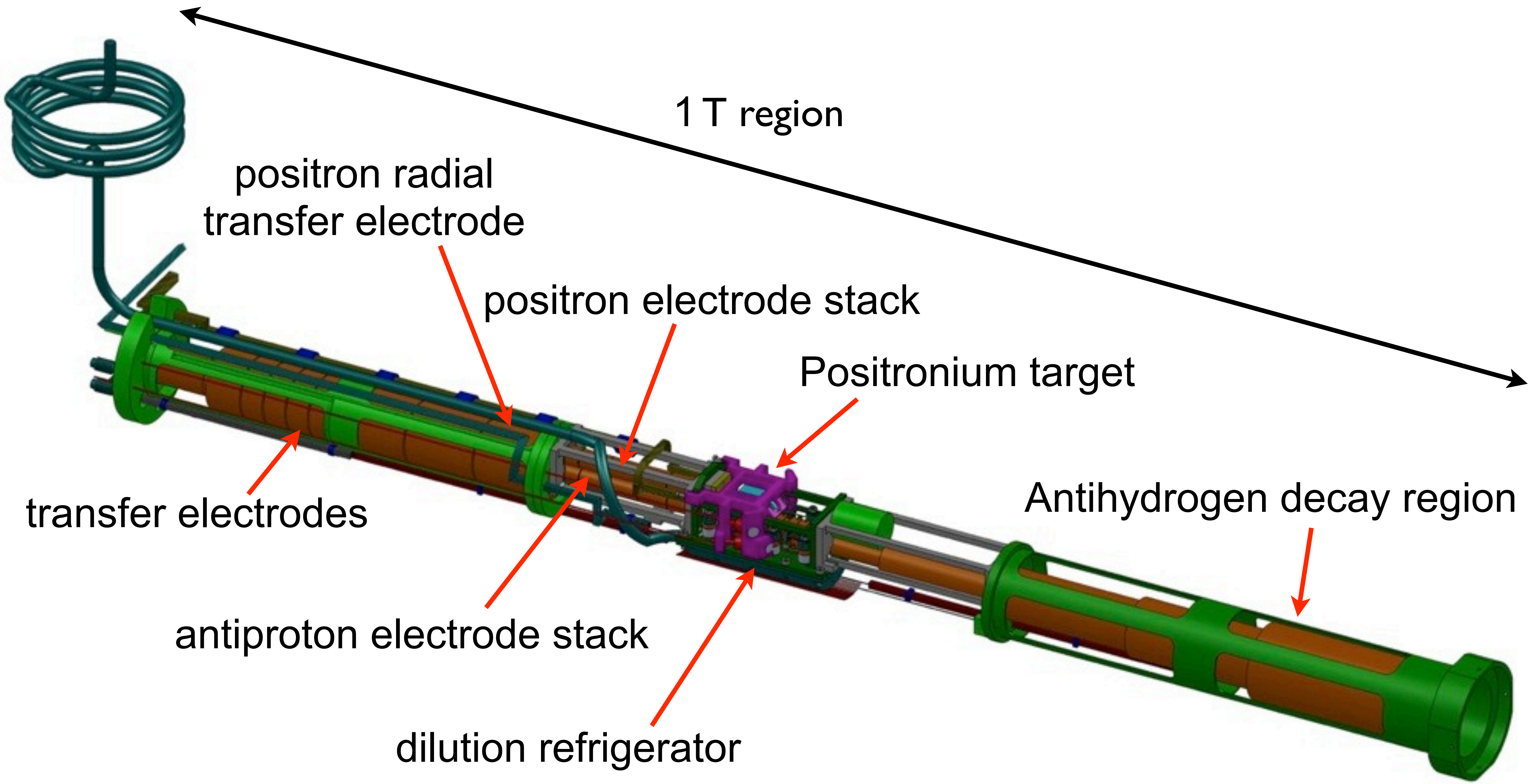


5T magnet and traps

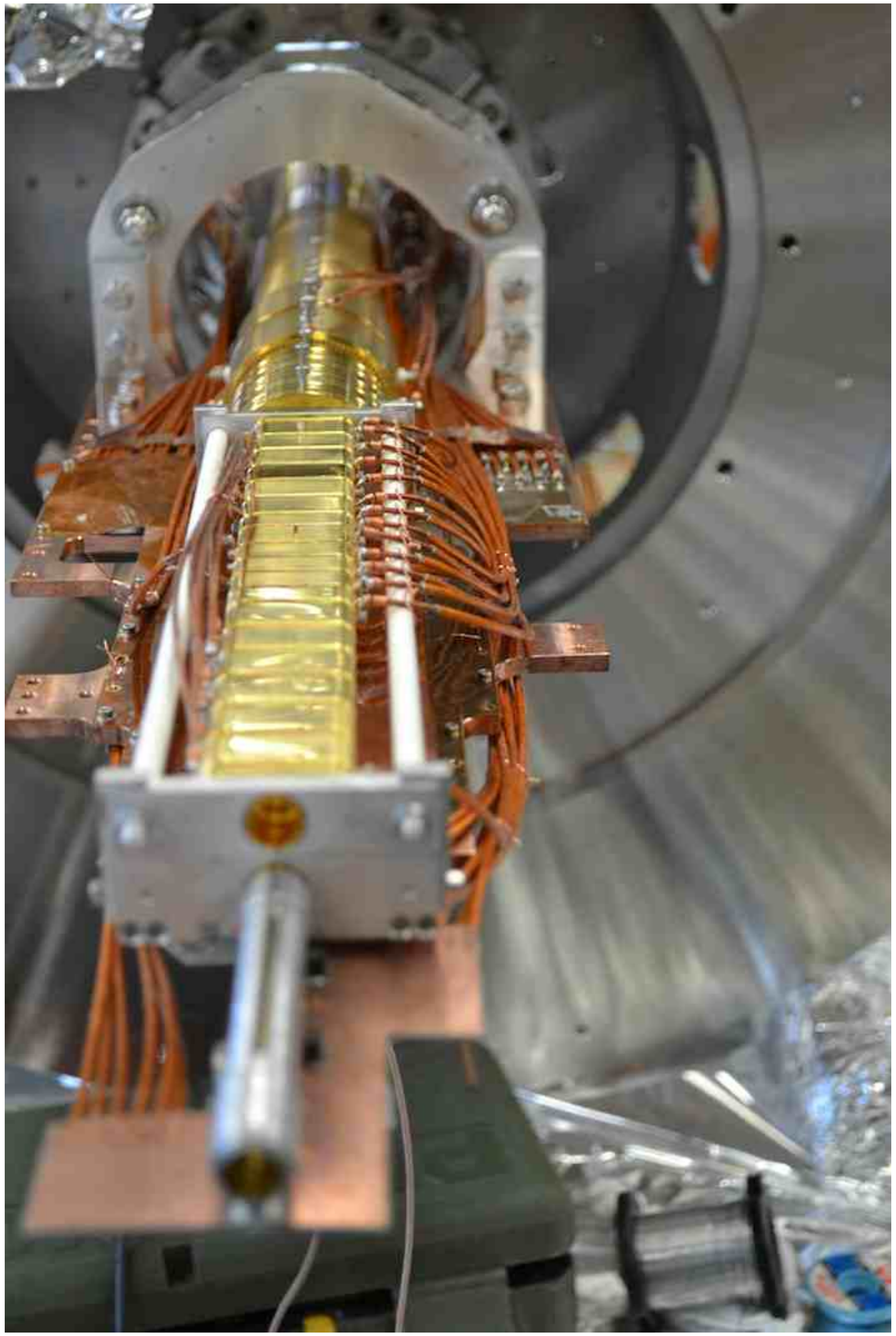


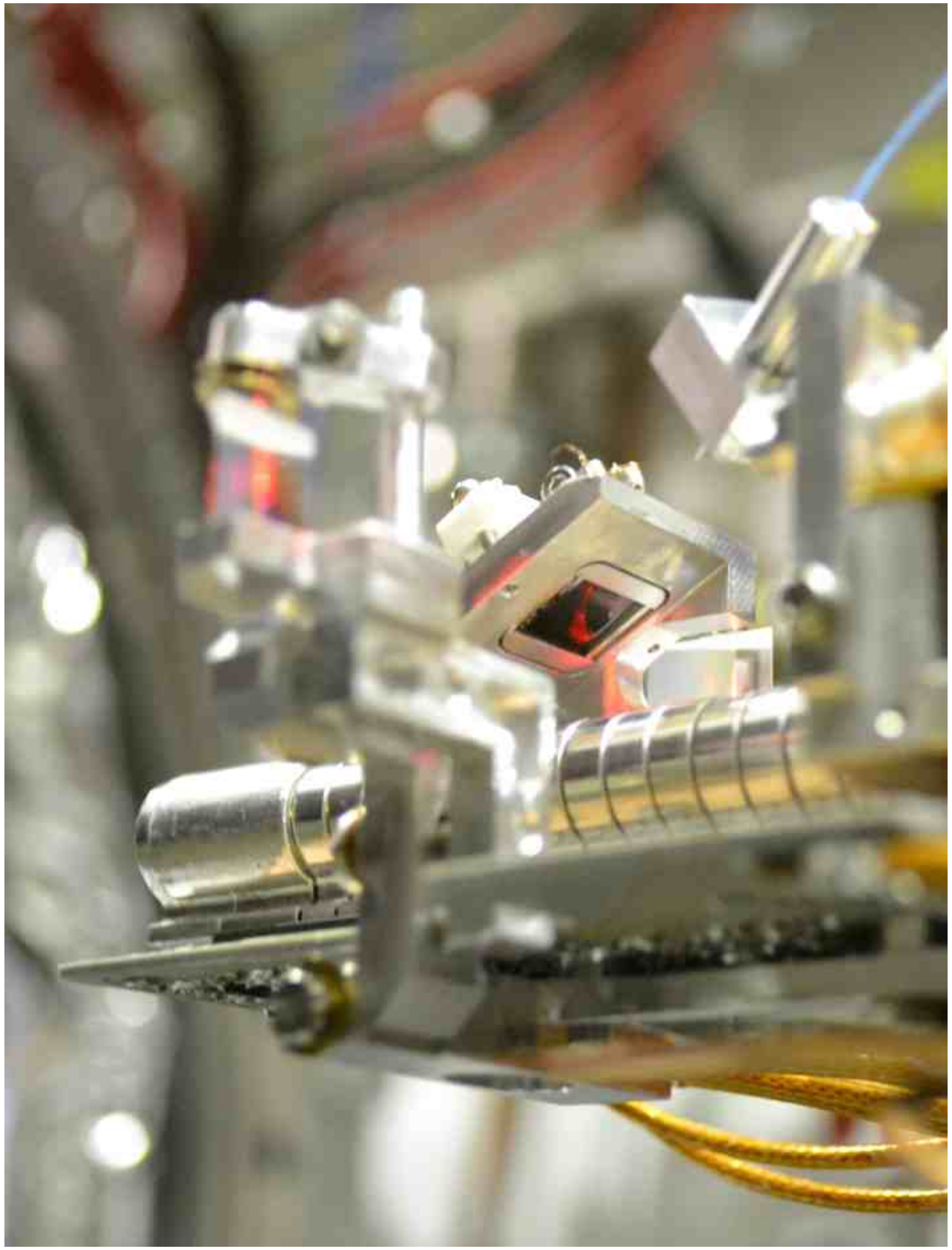


1T Formation Traps: conceptual design

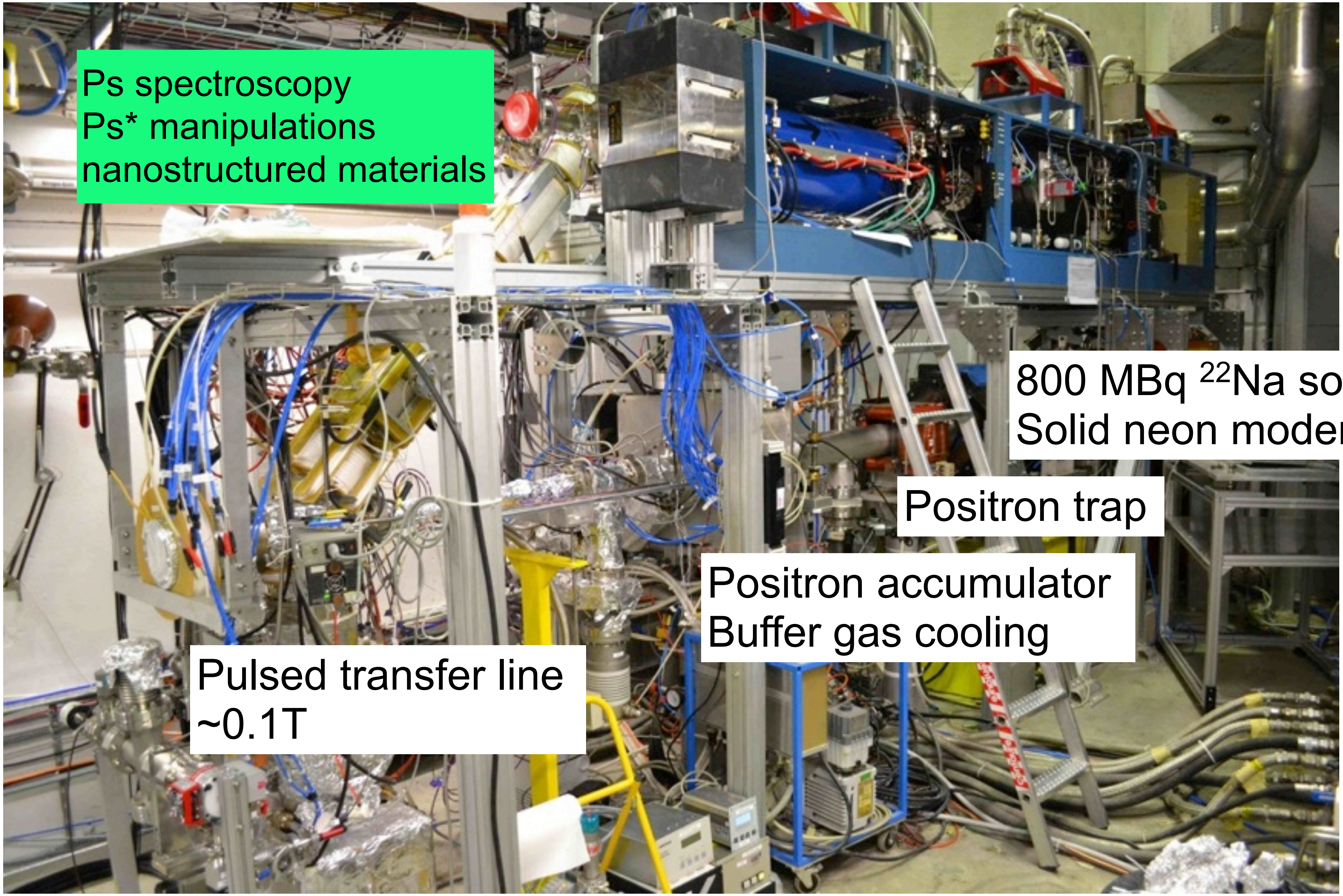


1T Formation Traps





Positron System



Implementing the techniques

Positronium formation

Positronium excitation

Plasma manipulations

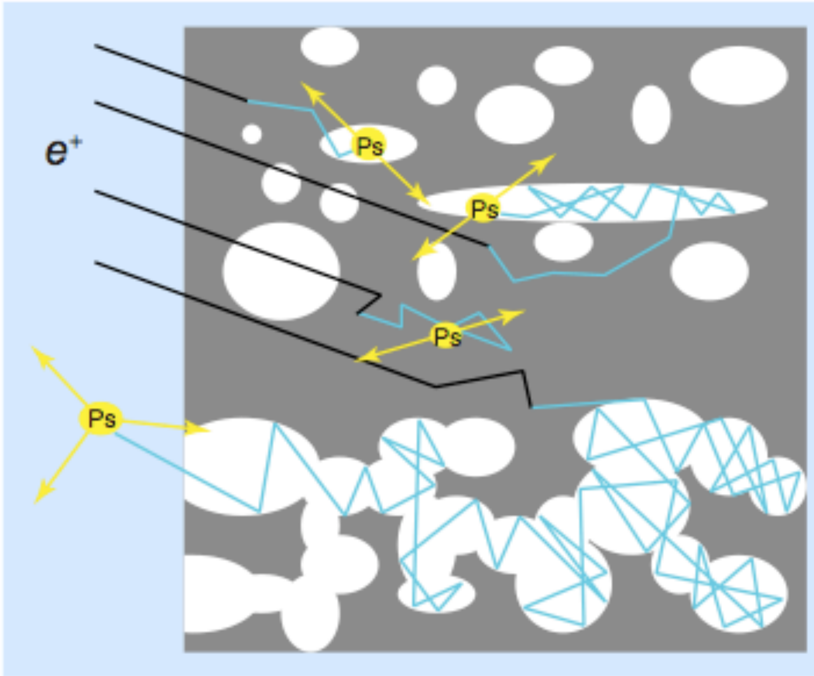
Detection of antihydrogen at the end of the flight tube

Positronium target - parameters

Ps formation in nanoporous insulators:

- Implanted positrons scatter off atoms and electrons, slow to eV in few ns
- Positronium formation by capture of bound electrons or free electron from collisions
- Reduced dielectric strength in defects
  ⇒ accumulation of positronium in voids
- If pores are fully interconnected, (almost) all *ortho*-Ps diffuses out of the film

⇒ High-efficiency positronium converter



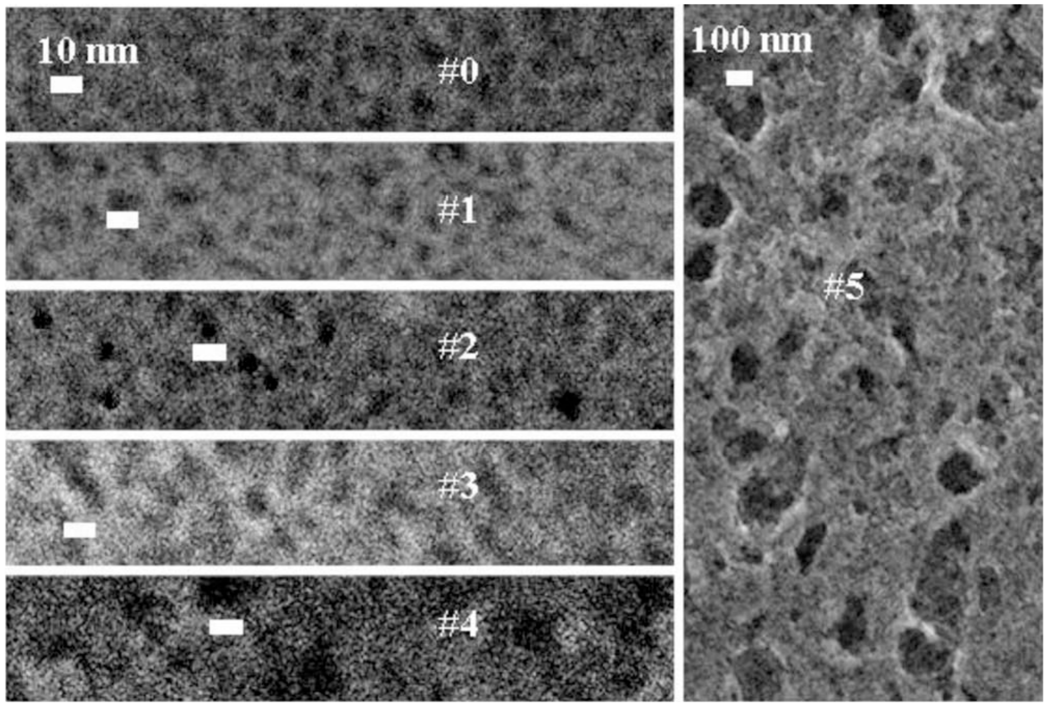
[D. W. Gidley *et al.*, Annu. Rev. Mater. Res. **36** (2006) 49]

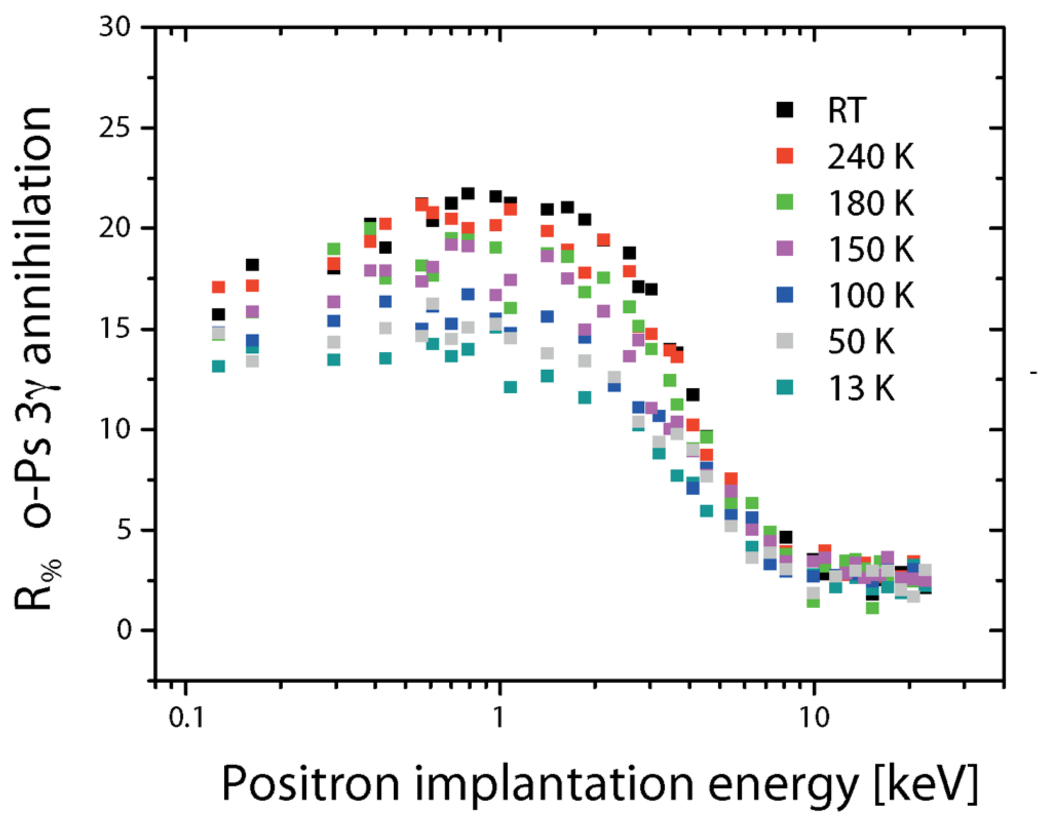
ortho-Ps yield and energy (velocity) distribution depend on

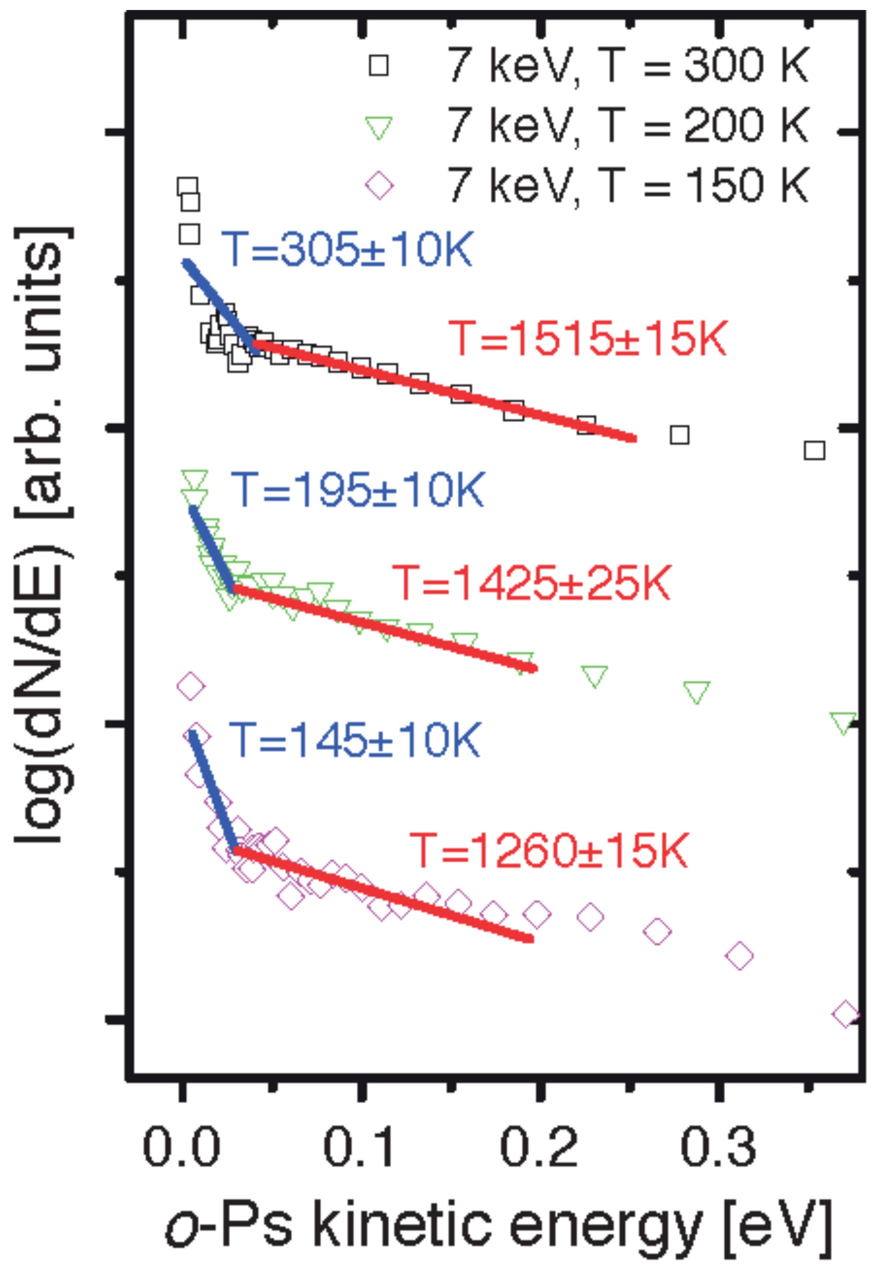
- Converter material
- Implantation depth (energy)
- Target temperature

Positronium target - measurements

ordered nanochannels in silica through electrochemical etching





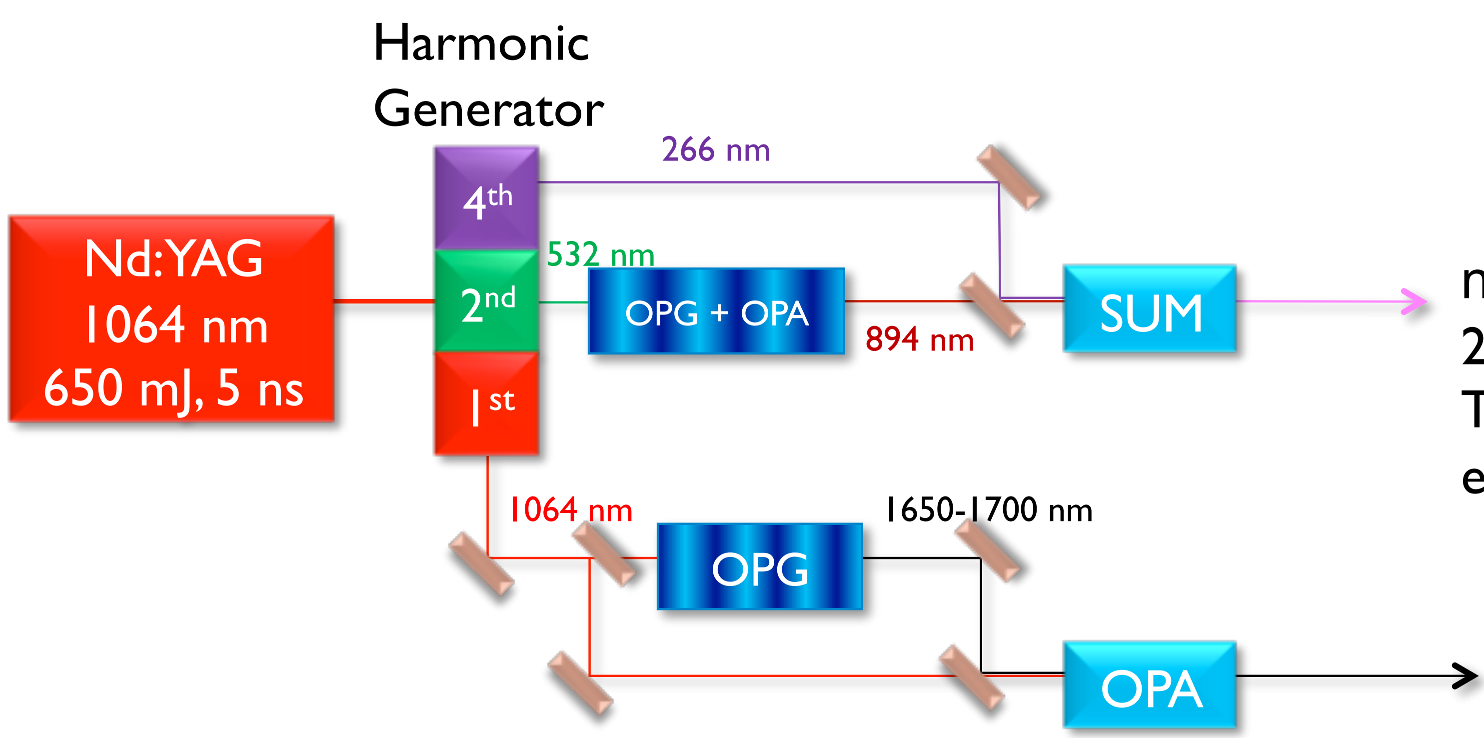


Lasers

Rydberg excitation via a simultaneous two step incoherent process:
1 → 3 → Rydberg (wavelengths: 205 nm and 1650 - 1700 nm)

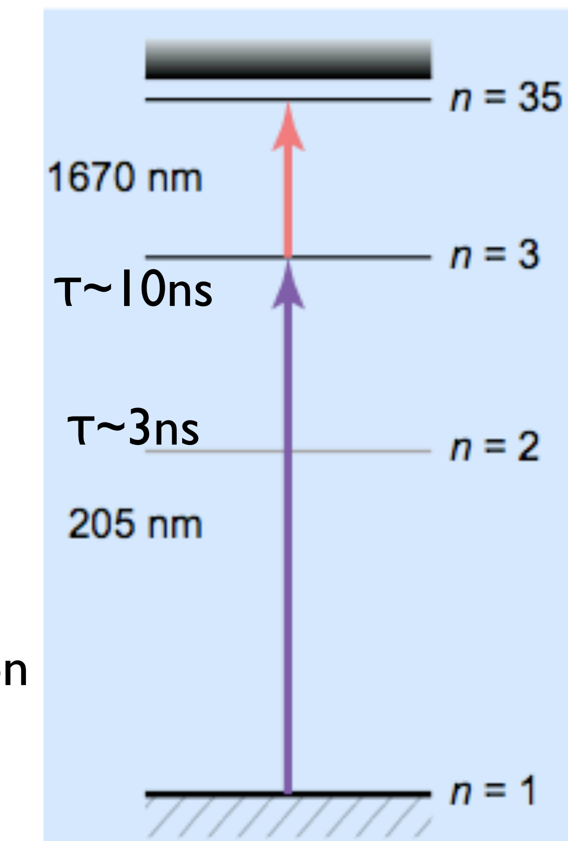
Main effects of level broadening:

- 1 → 3: Doppler effect (~0.04 nm) due to velocity distribution of Ps
- 3 → Rydberg: Motional Stark effect (makes a quasi-continuum from n=17, each level is broadened to many nm) due to Ps movement in a strong **B** field



n=1 → n=3
205 nm
Transition saturation energy: ~2 μJ

n=3 → Rydberg
1650-1700 nm
Transition saturation energy: ~0.2 mJ



Expected excitation efficiency: 30%

Positronium excitation

Doppler broadening:
T=100 K ~ v~10^5 m/s

Motional Stark effect ($\vec{E} = \vec{v} \times \overline{B}$) + linear & quadratic Zeeman splitting:
B=1T ~ sublevels of Rydberg state will be mixed and separated in energy

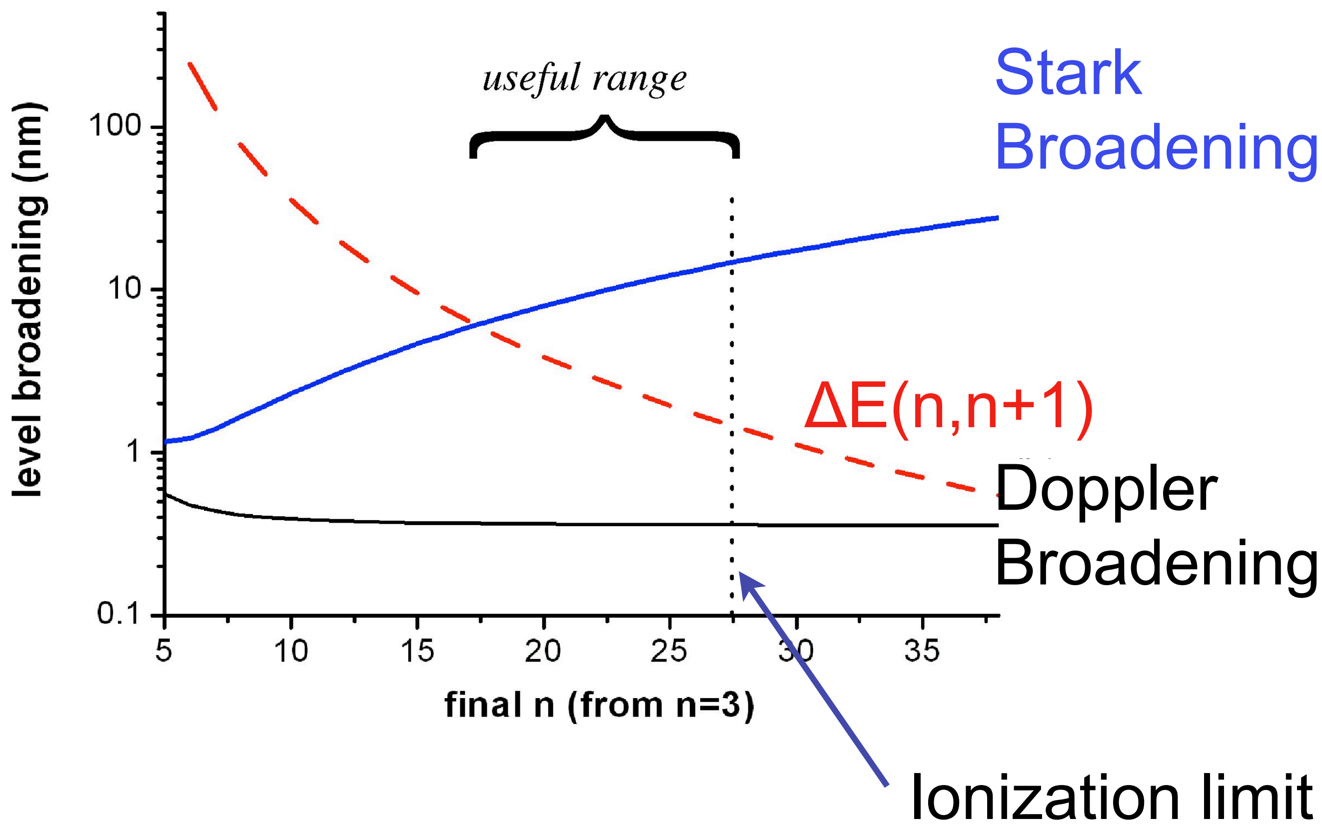
broadening ~ 1THz

Ps excitation model must be tailored (power, bandwidth) to this broad Rydberg level band

Use OPG + OPA (+ frequency summing)

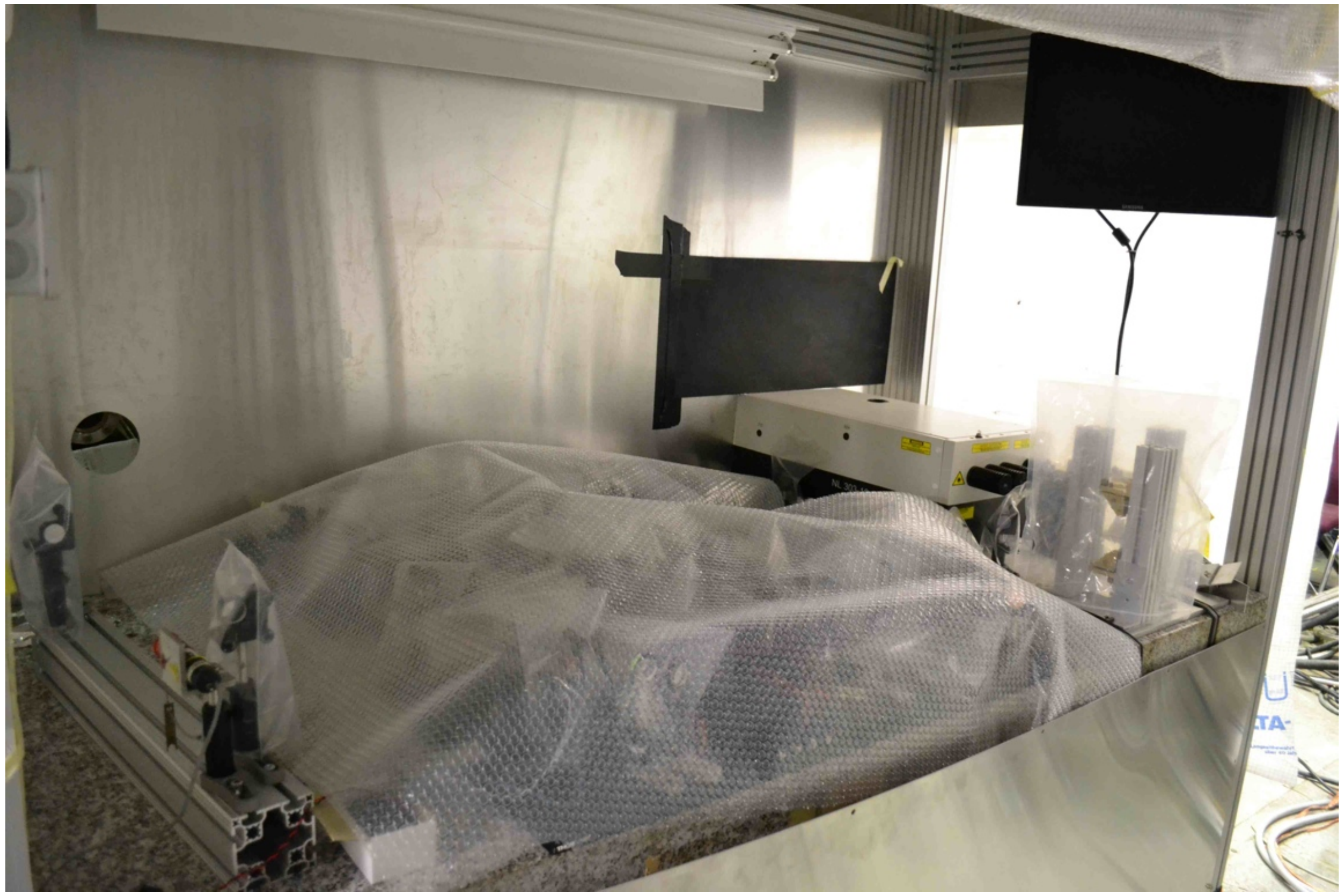
Laser 1: $\Delta\lambda$=0.045nm (=λ_D), >5μJ, τ~4ns

Laser 2: $\Delta\lambda$~1 nm, >60μJ, τ~2ns



Simulation: excitation efficiency = 30%

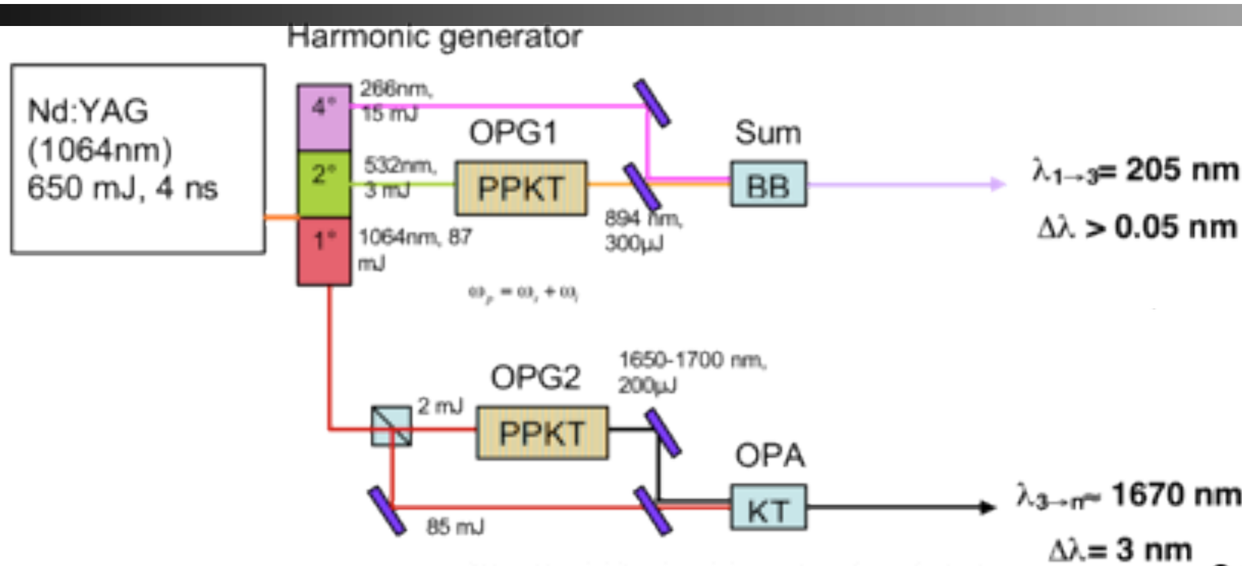
Ps excitation laser system

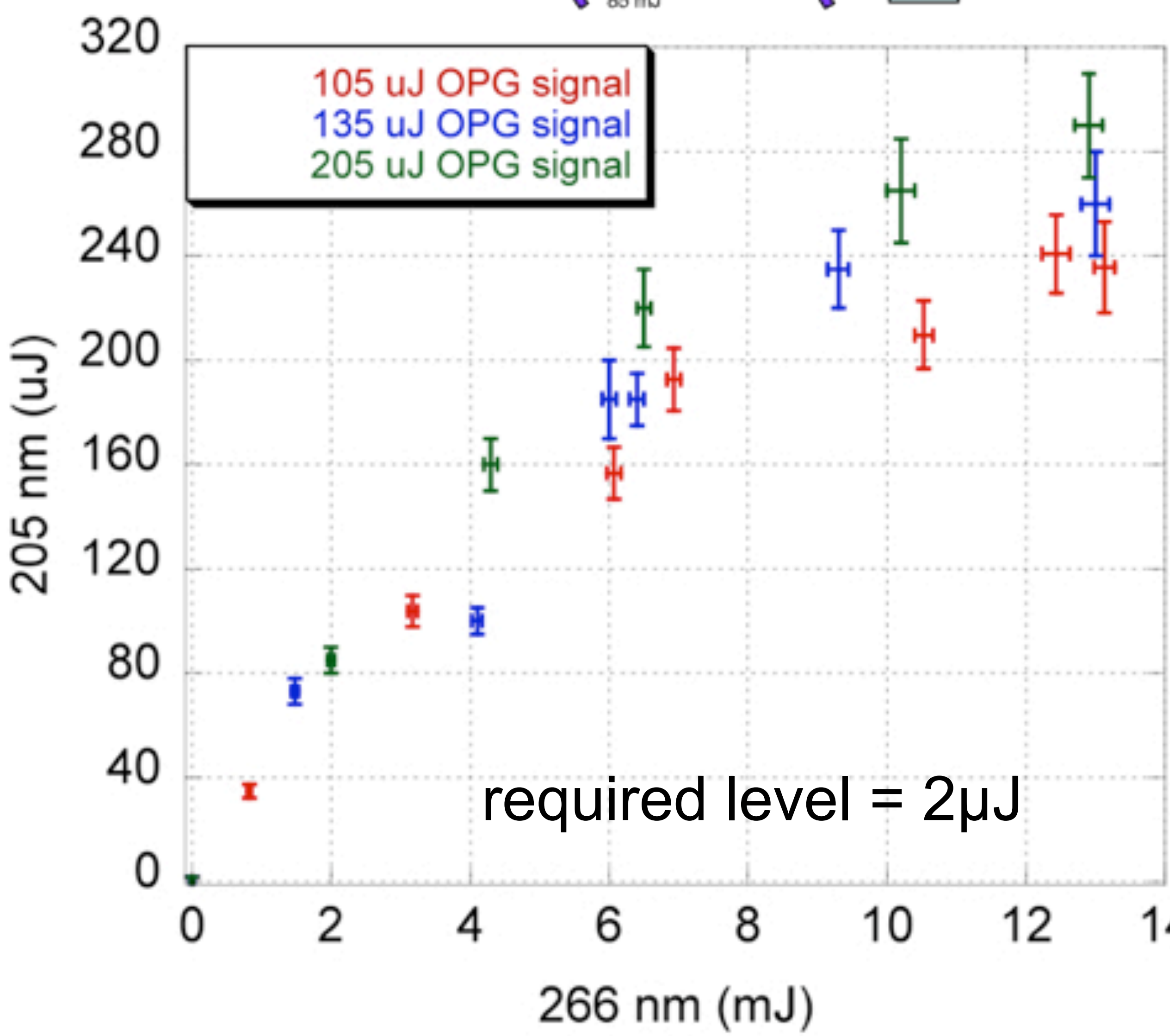


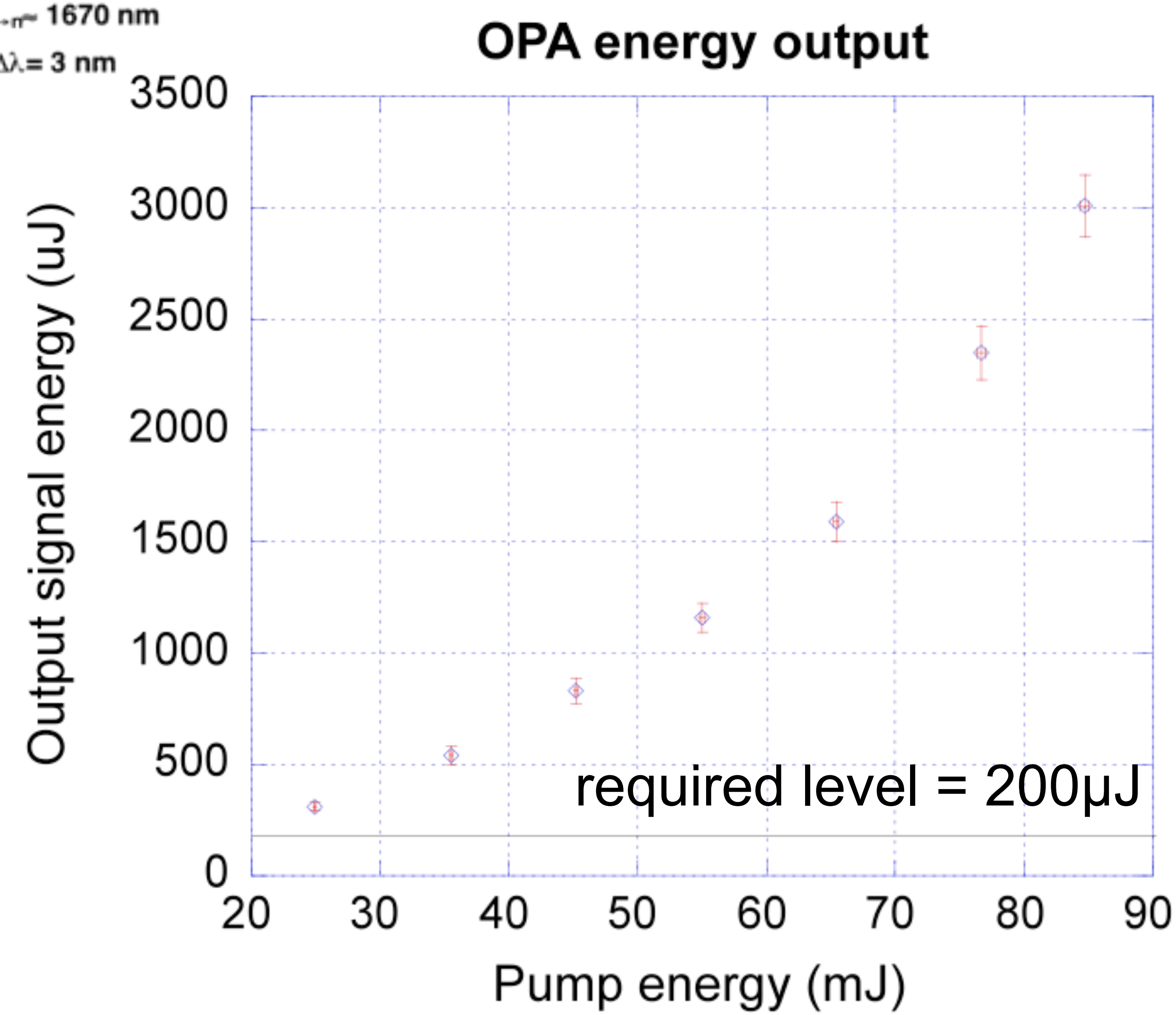
In operation since October 2012, UV power 50% above design value

Second narrow-band dye laser under installation for Ps spectroscopy

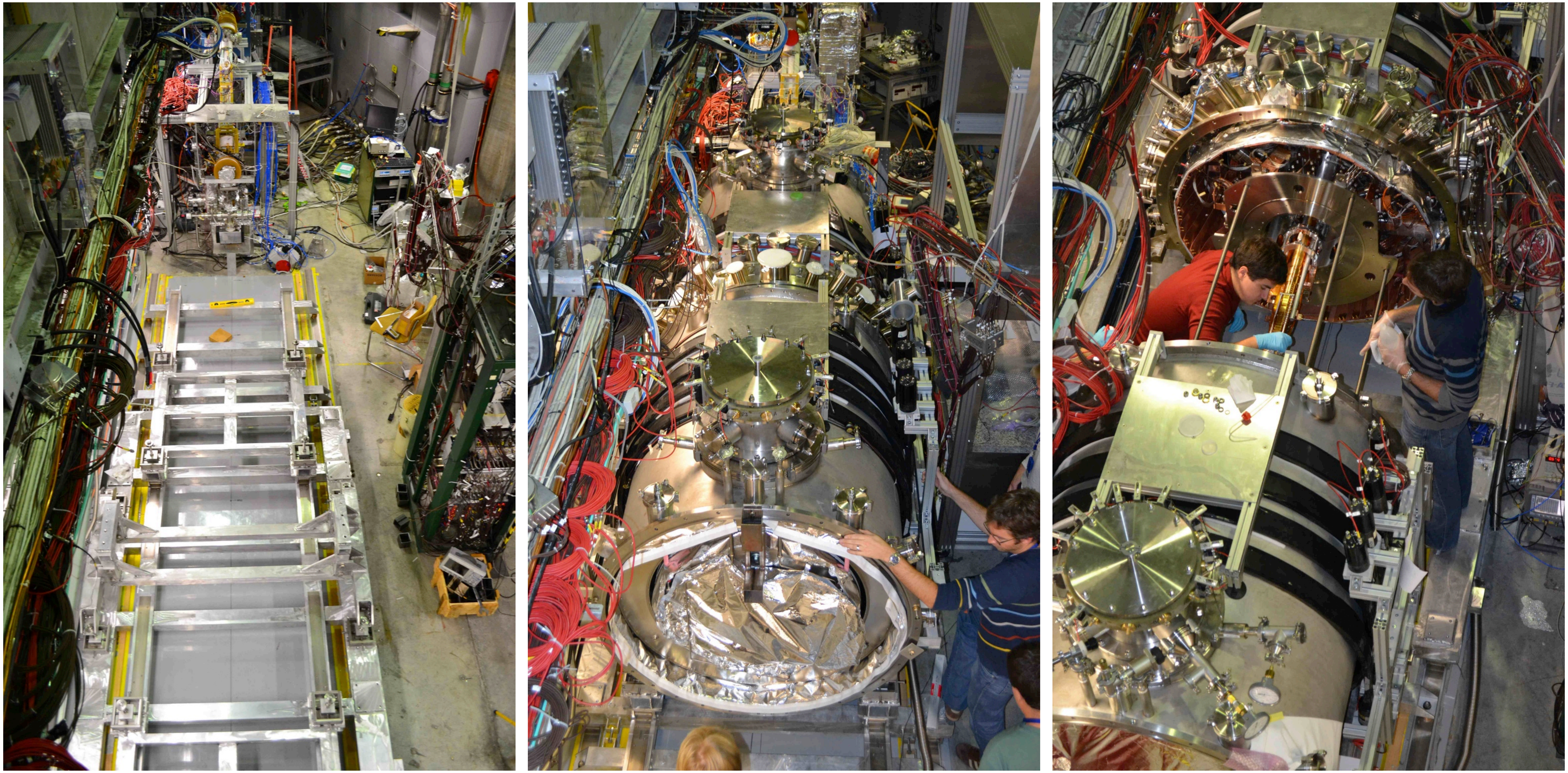
Laser system: power tests







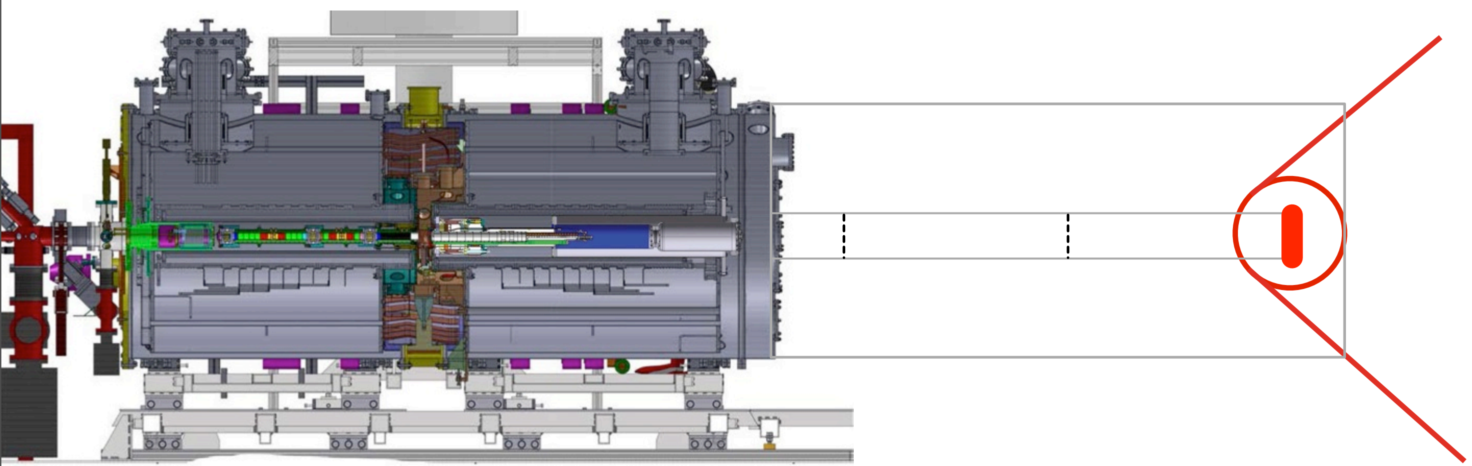
Assembly in 2012



Assembly completed end of November 2012; immediate pump-down and cool-down (10 days) during which commissioning with antiprotons and positrons could take place

Detector Tests: use $\bar{p}$ to test $\bar{H}$ detection

Parasitic tests:



Explore different candidate technologies for the (hybrid) downstream antihydrogen detector

Need:

high spatial resolution (~ 1µm): silicon, emulsion

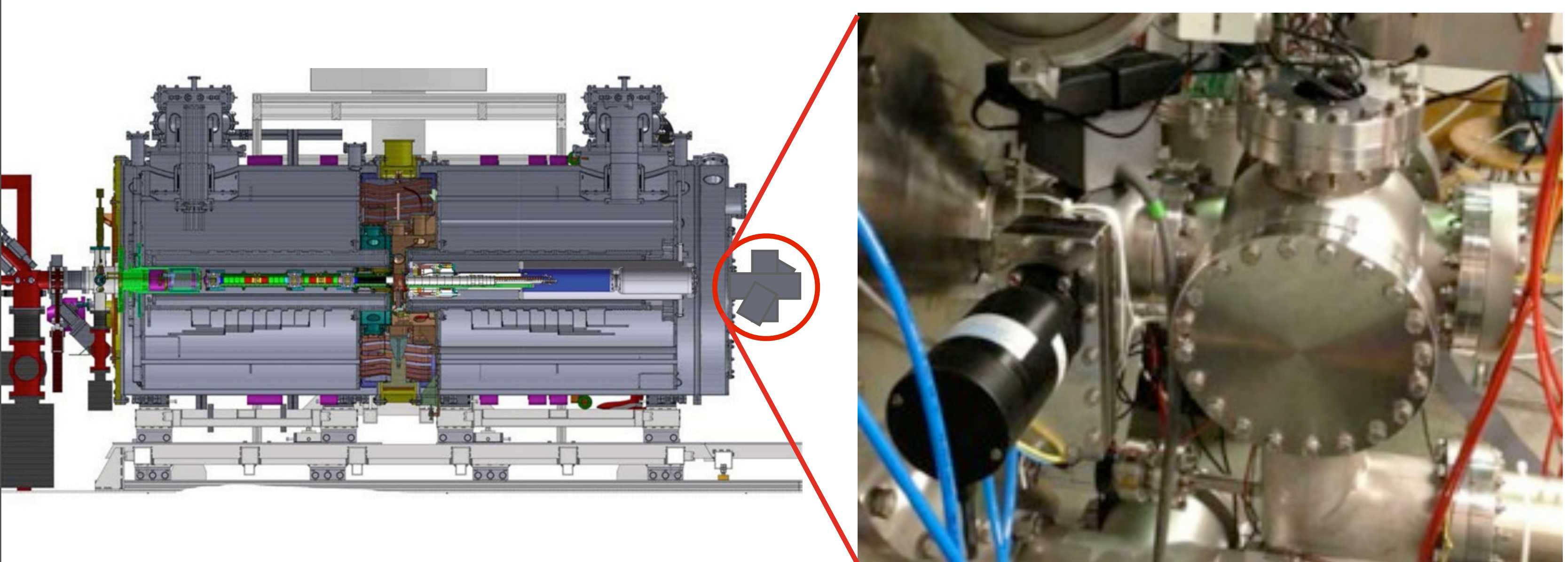
good timing (~ 10 µs): silicon, scintillating fiber tracker

redundancy: 2 trackers, 2 timing detectors

⟶ hybrid detector: Si + emulsion + fibers

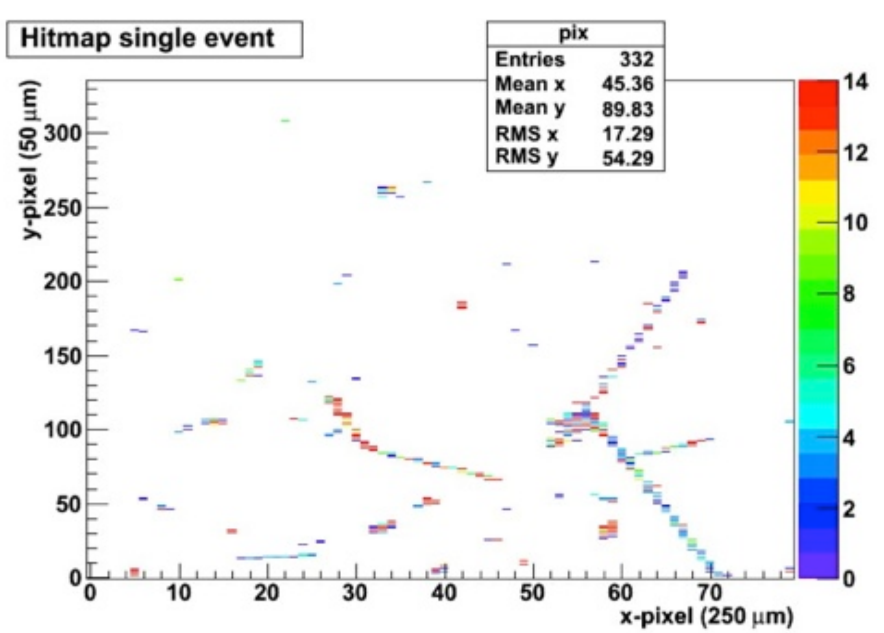
Detector Tests: use $\bar{p}$ to test technologies

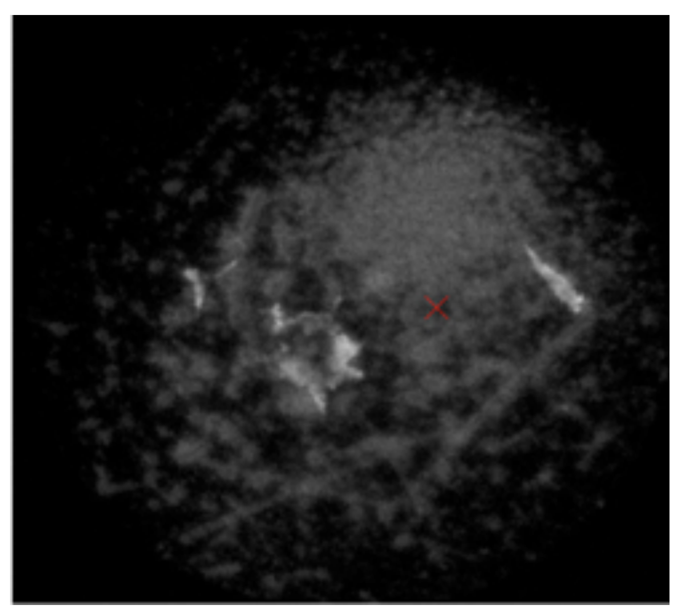
Parasitic tests:

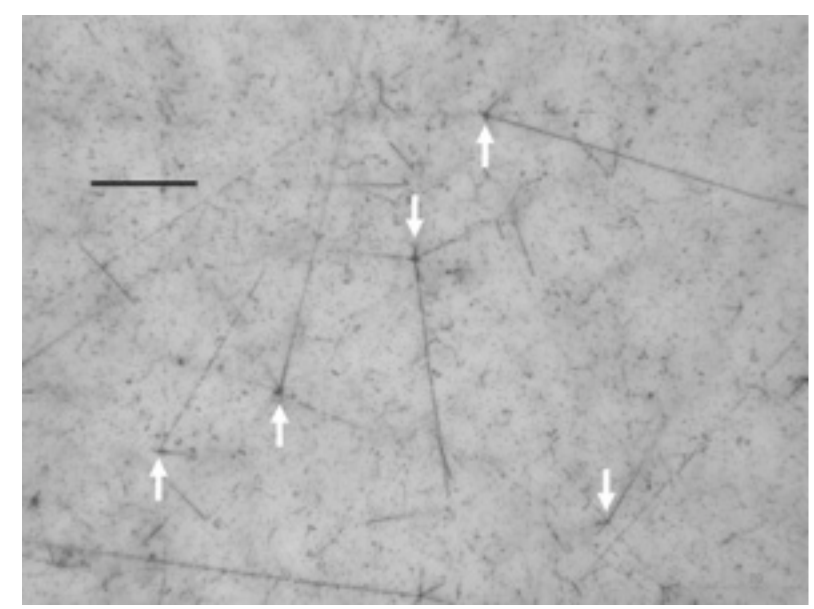


Explore different candidate technologies for the (downstream) antihydrogen detector

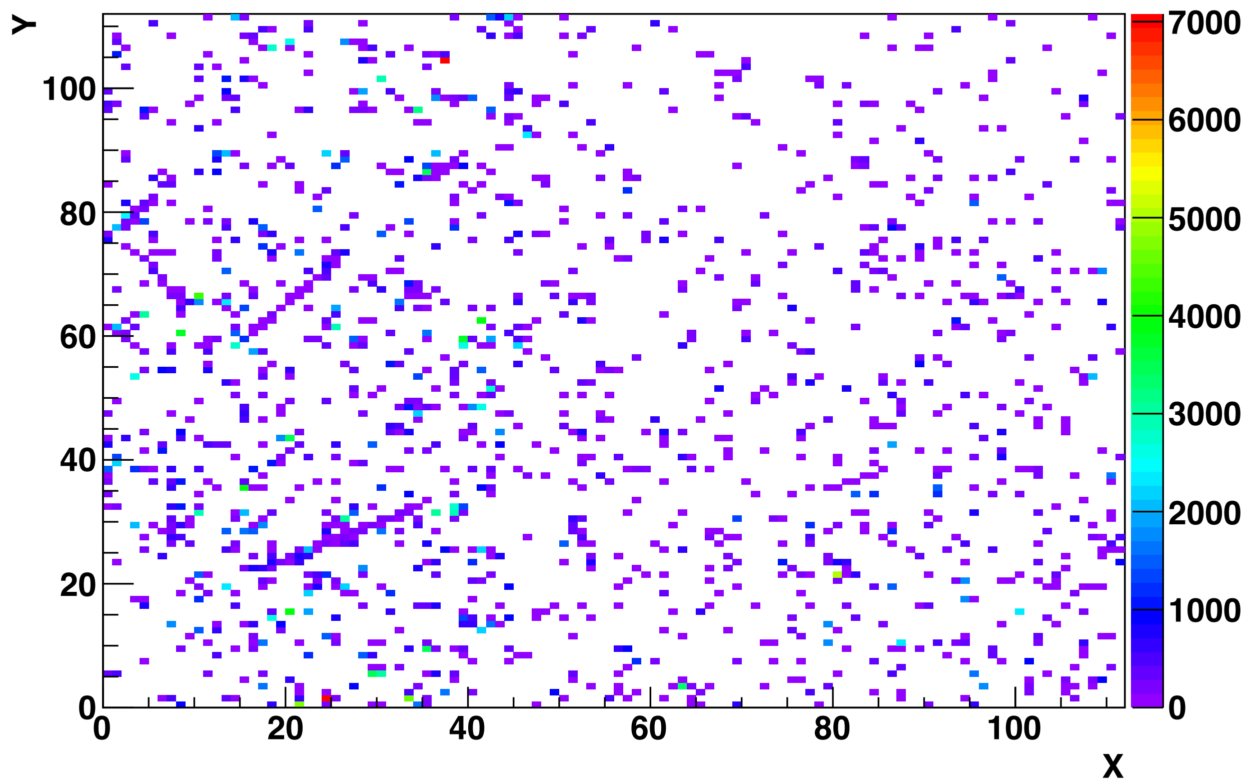
Silicon detectors (strip, pixel)	MCP	Emulsions

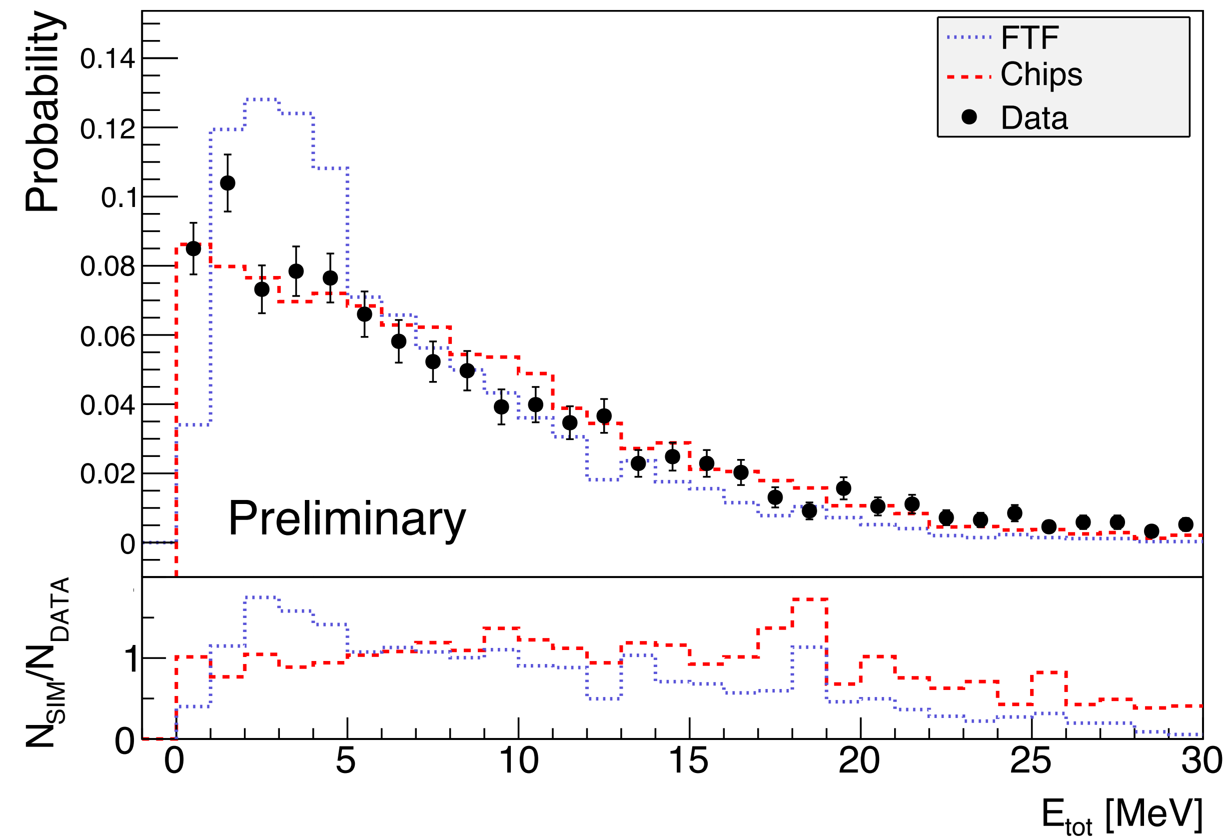






Mimotera Detector

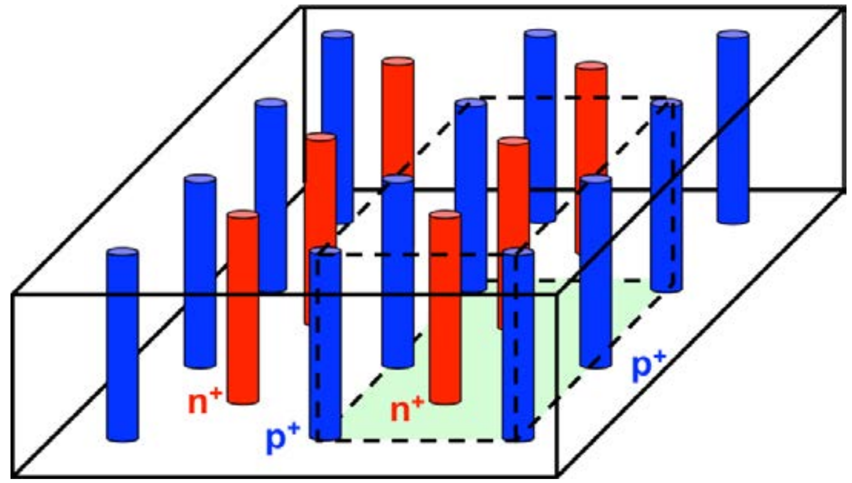


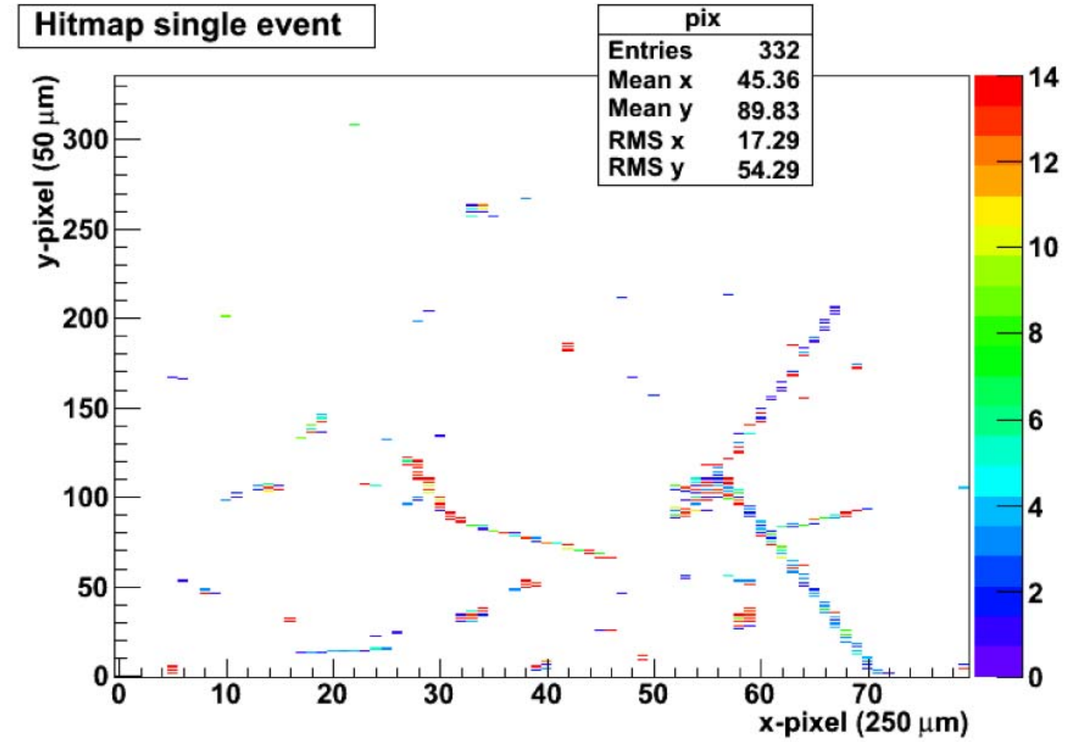


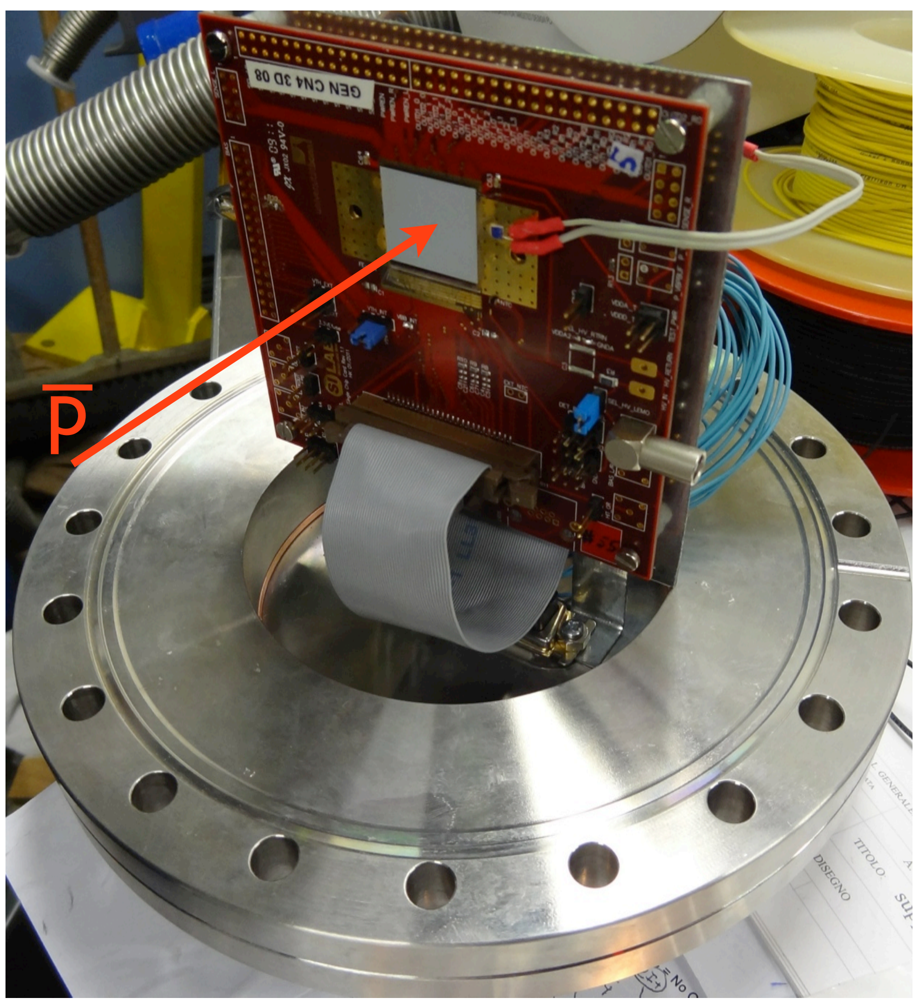
- 112 x 112 silicon pixel detector, 153 µm x 153 µm, 15 µm active depth
- Detailed comparison of data vs simulation
- Test of Monte Carlo treatment of antiproton annihilations at rest in silicon → Publication forthcoming!

Silicon Detectors

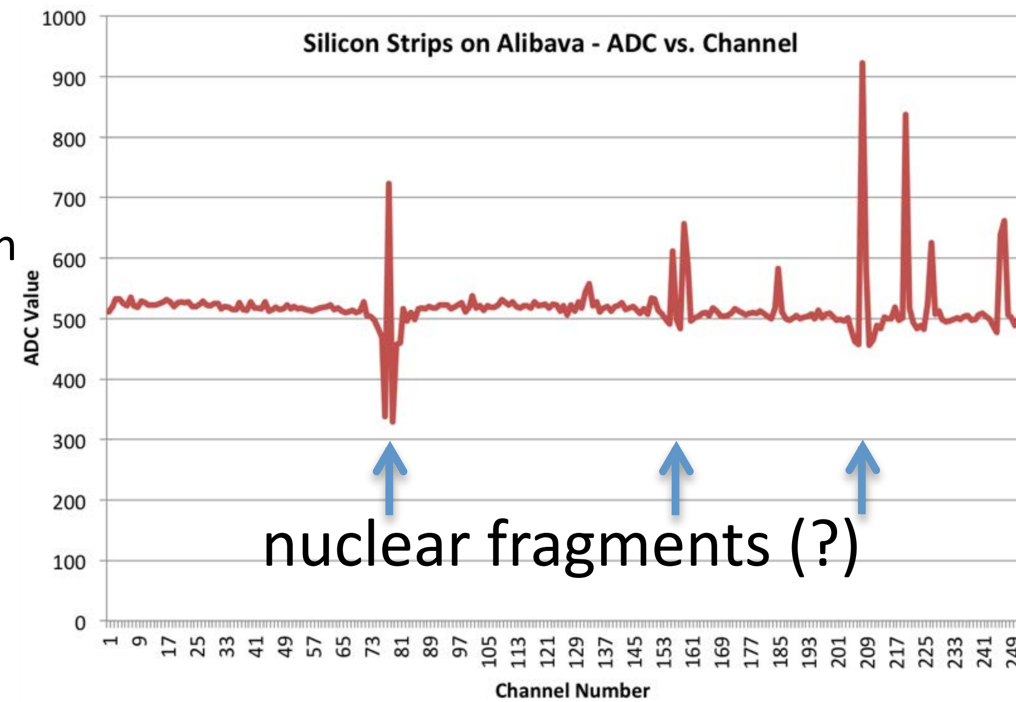
CNM-55-3D pixel sensor bump-bonded to FE-I4 R/O chip designed for the ATLAS Insertable B layer upgrade



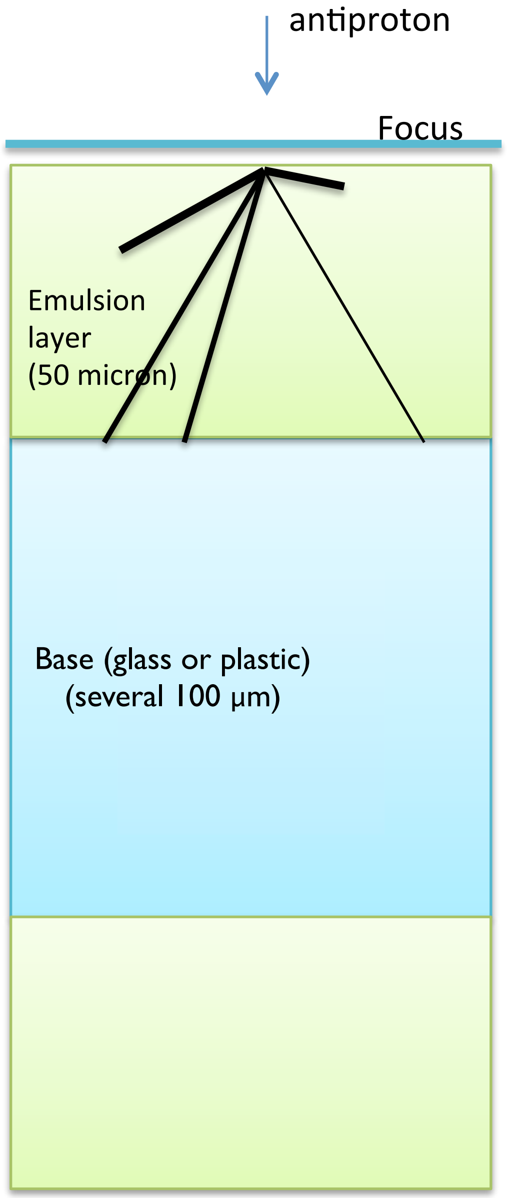




Strip sensors 50 and 80 um pitch
300 um thickness
Beetle based - Alibava readout



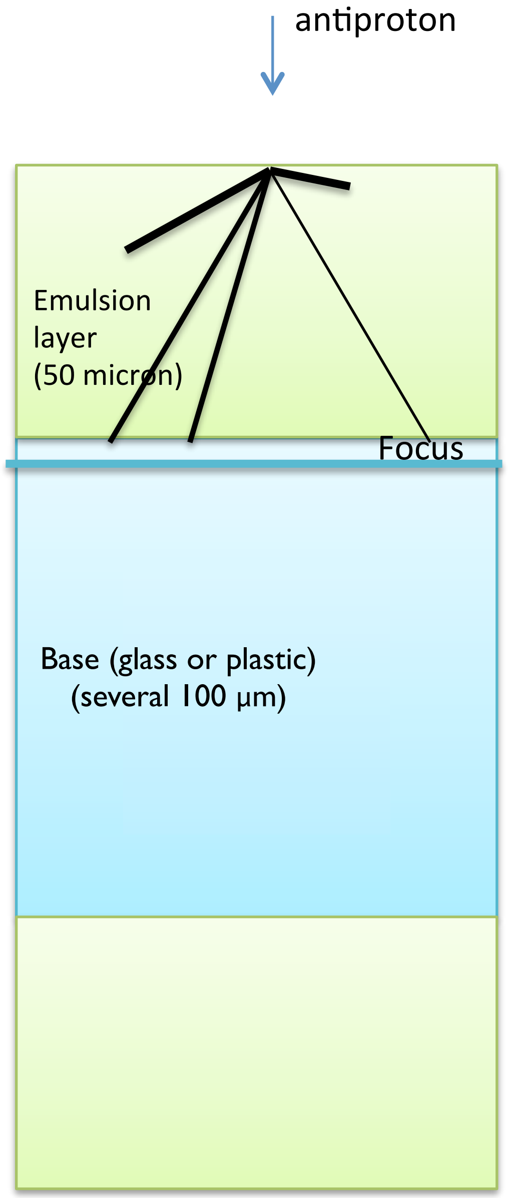
Emulsion tests

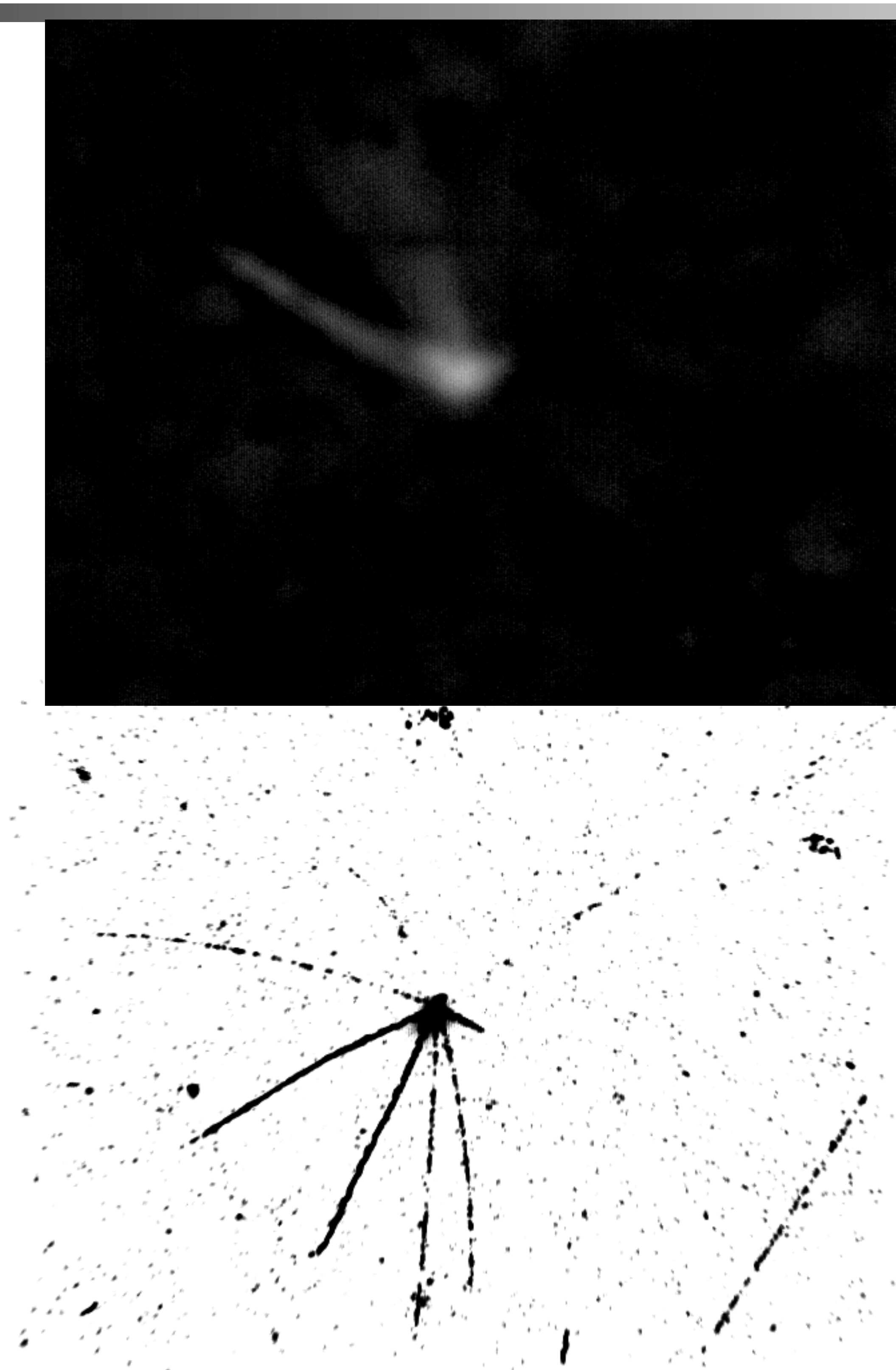


- Exposure of emulsion
- Development in dark room
- Scanning on automated microscopes

→ S. Aghion et al., J. of Instrumentation 8 (2013) P08013

Emulsion tests





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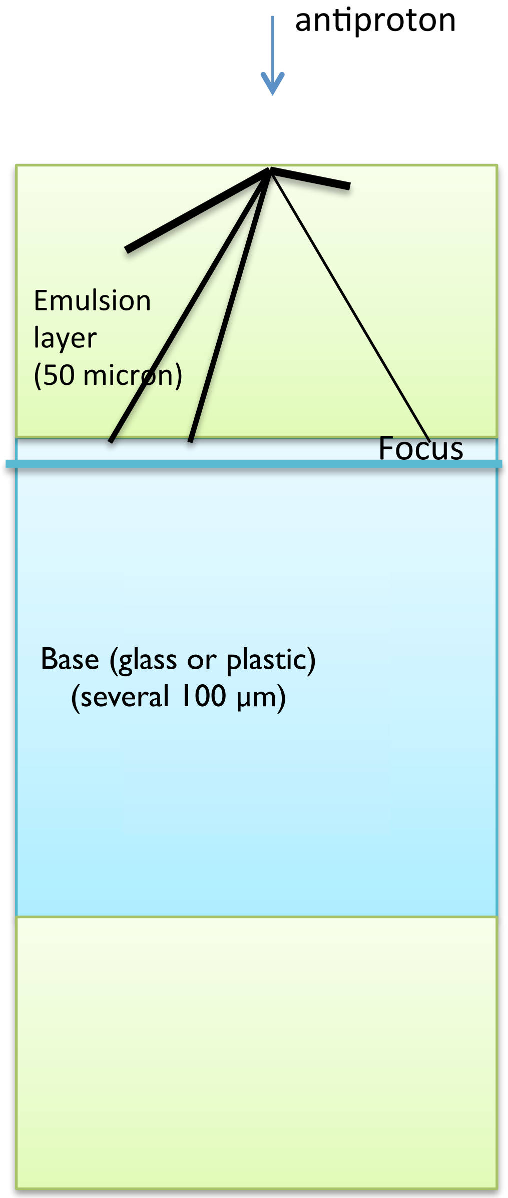
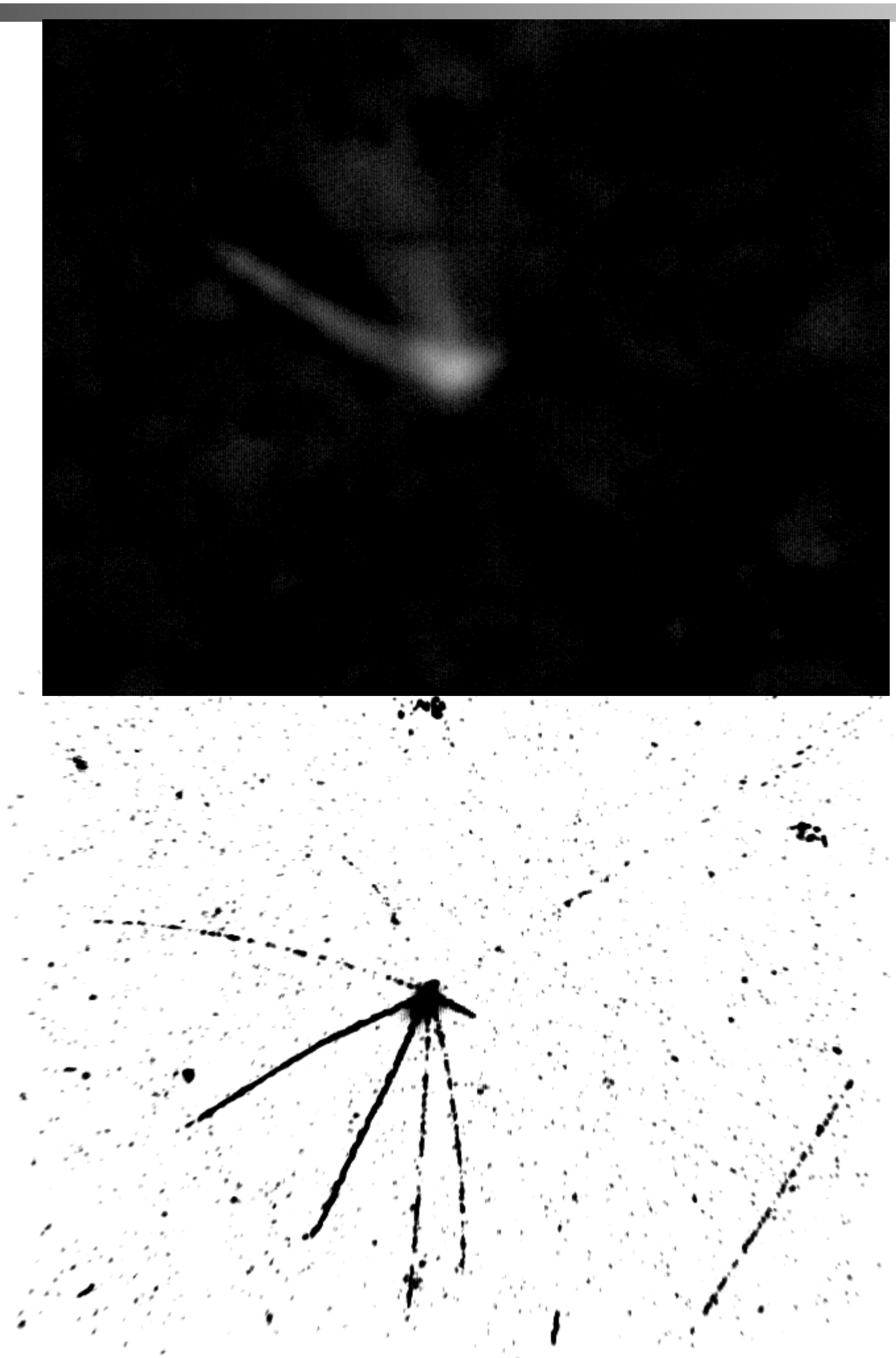
- Development in dark room
- Scanning on automated microscopes

→ S. Aghion et al., J. of Instrumentation 8 (2013) P08013

Emulsion tests





- Exposure of emulsion
- Development in dark room
- Scanning on automated microscopes

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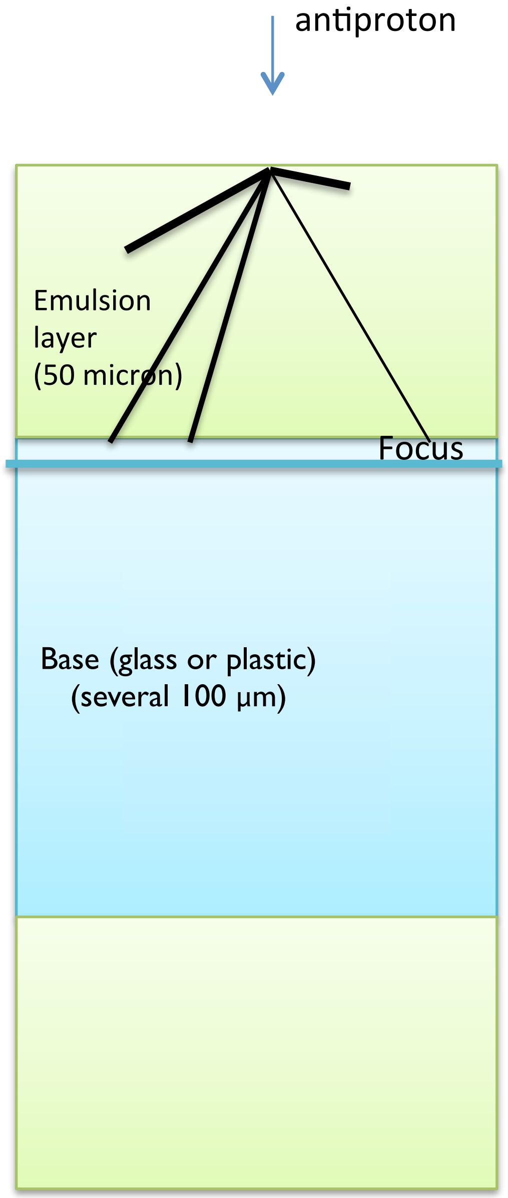

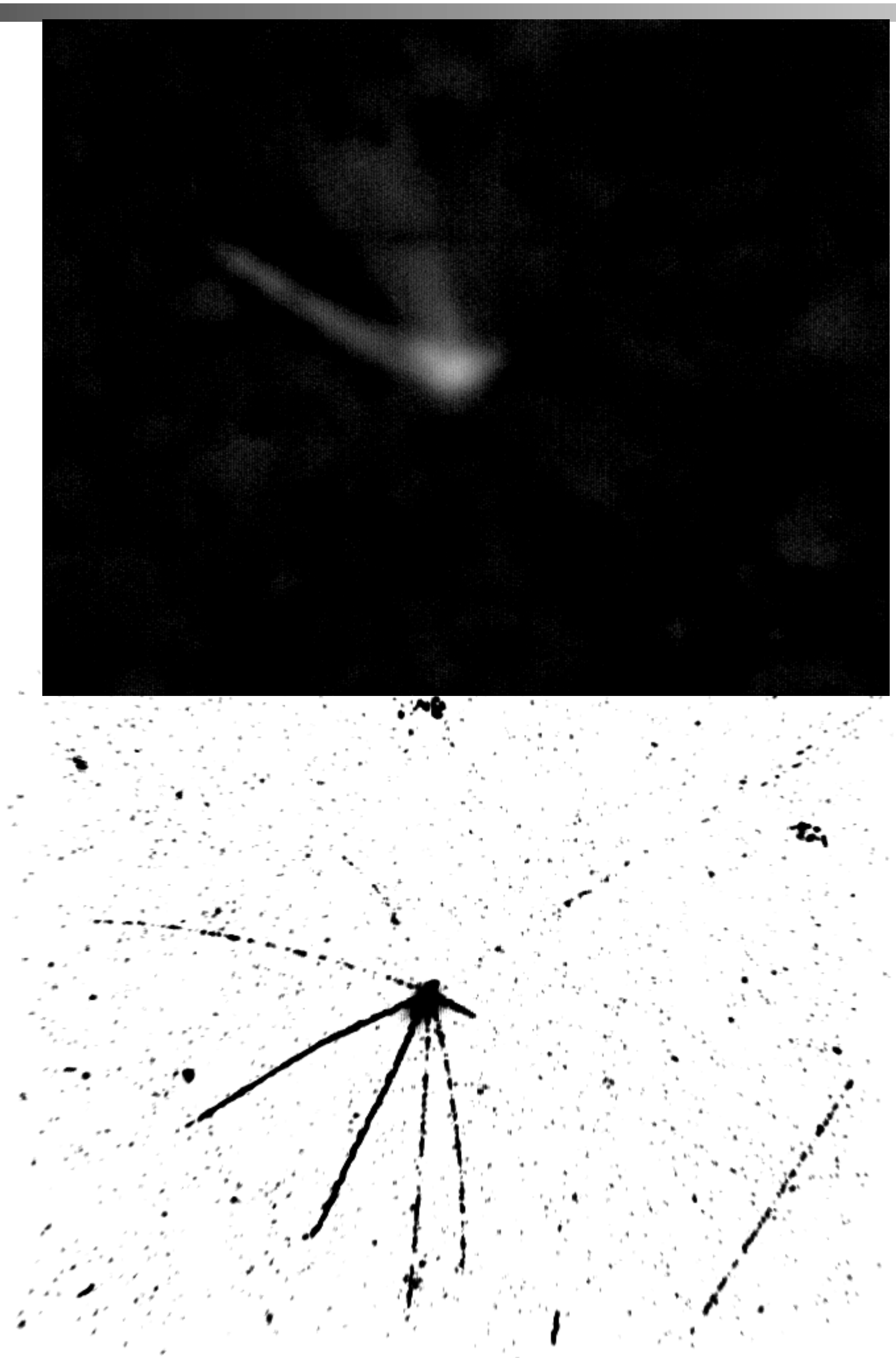

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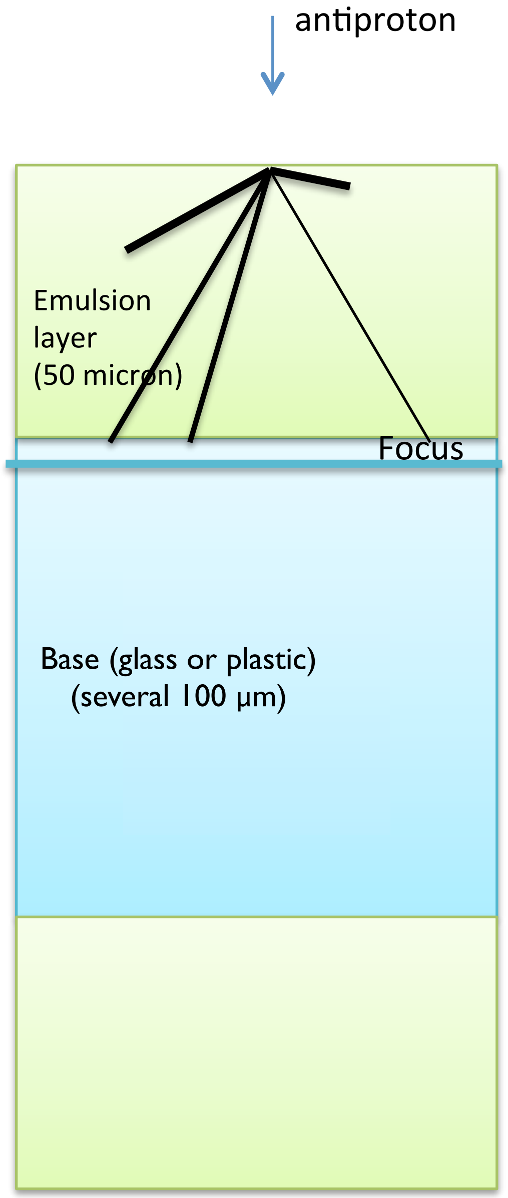

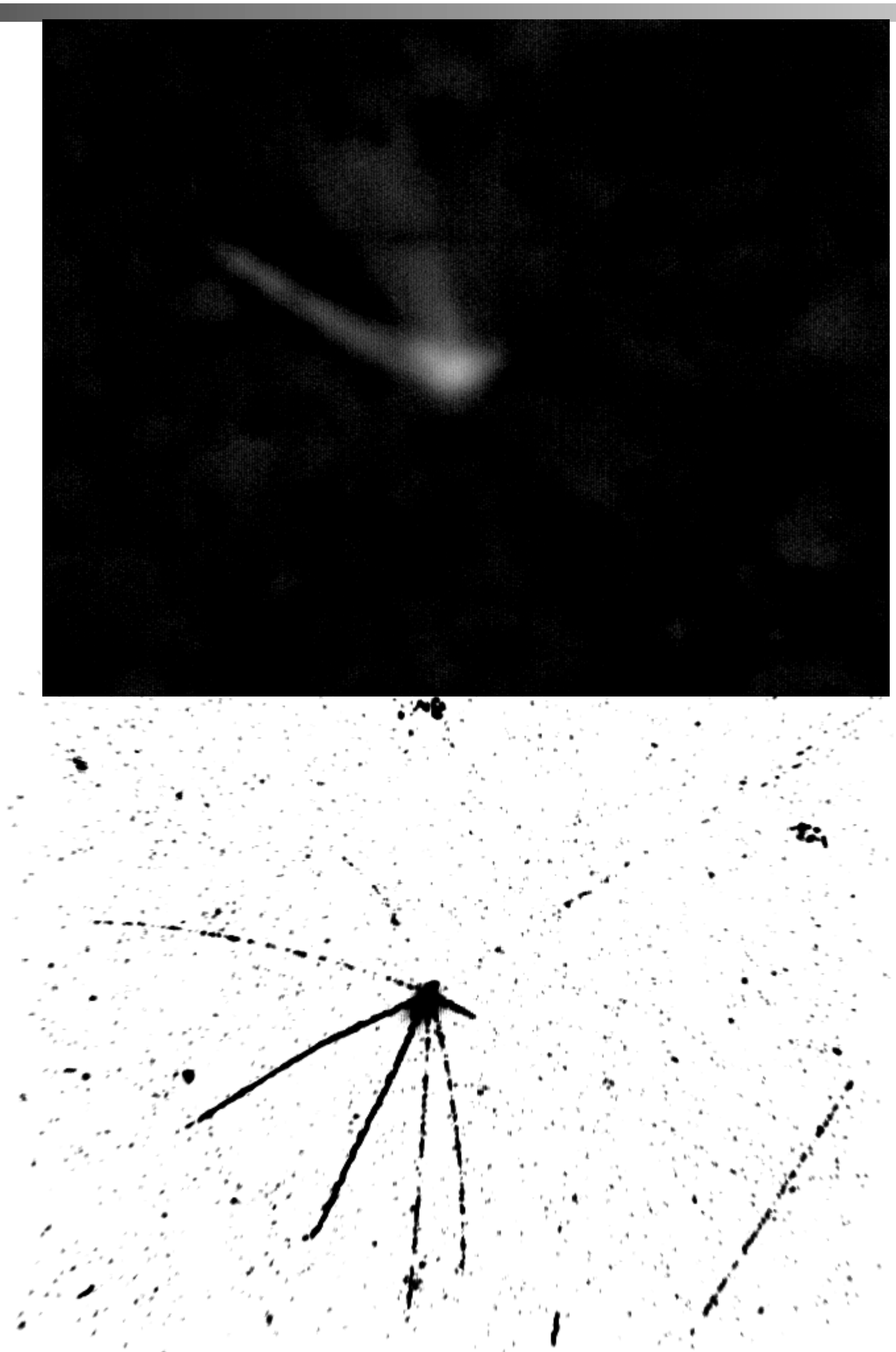

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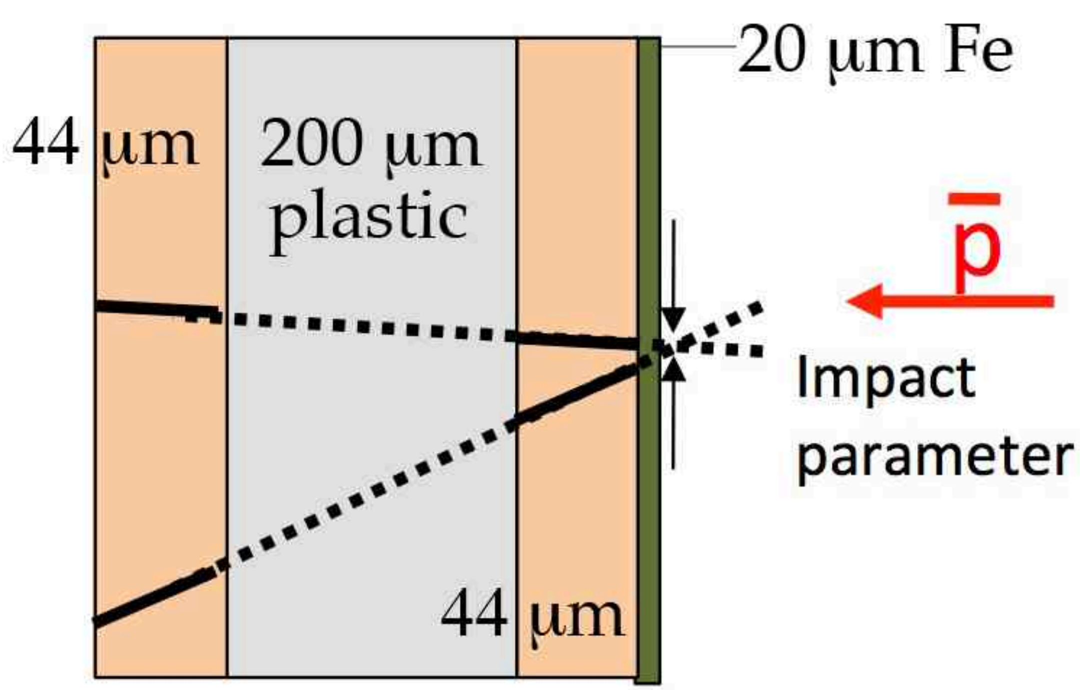
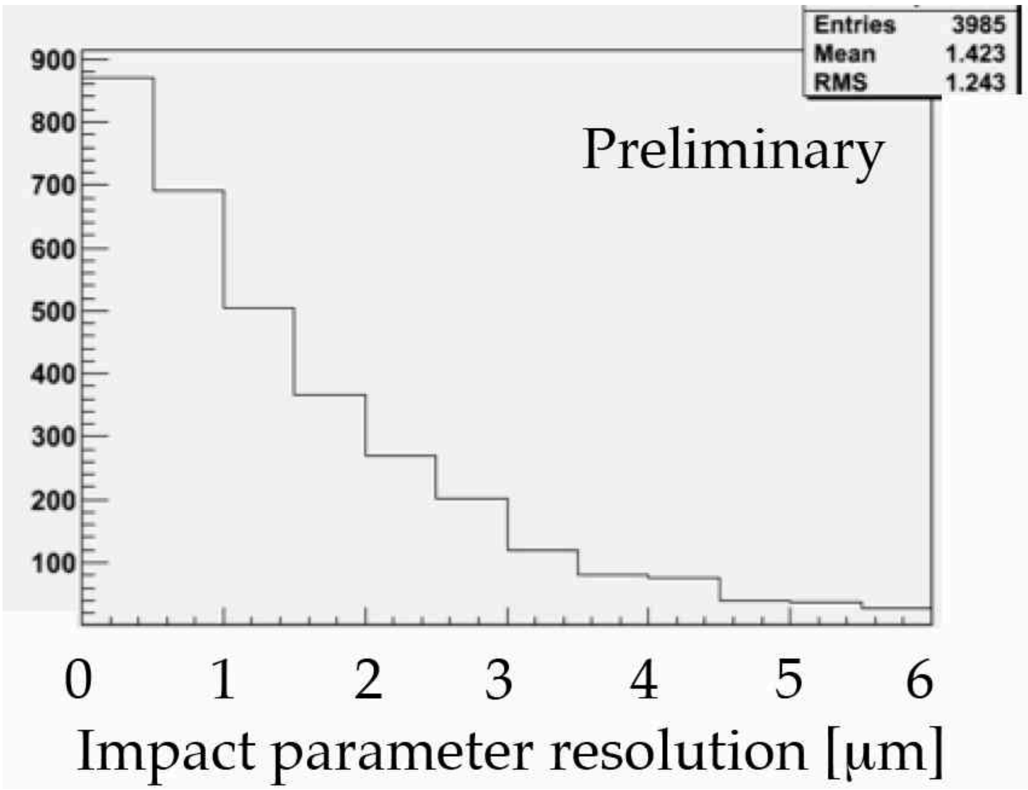
Emulsion: annihilation in thin foils of different composition

- Offline track and vertex finding algorithms
- 1 μm vertex resolution

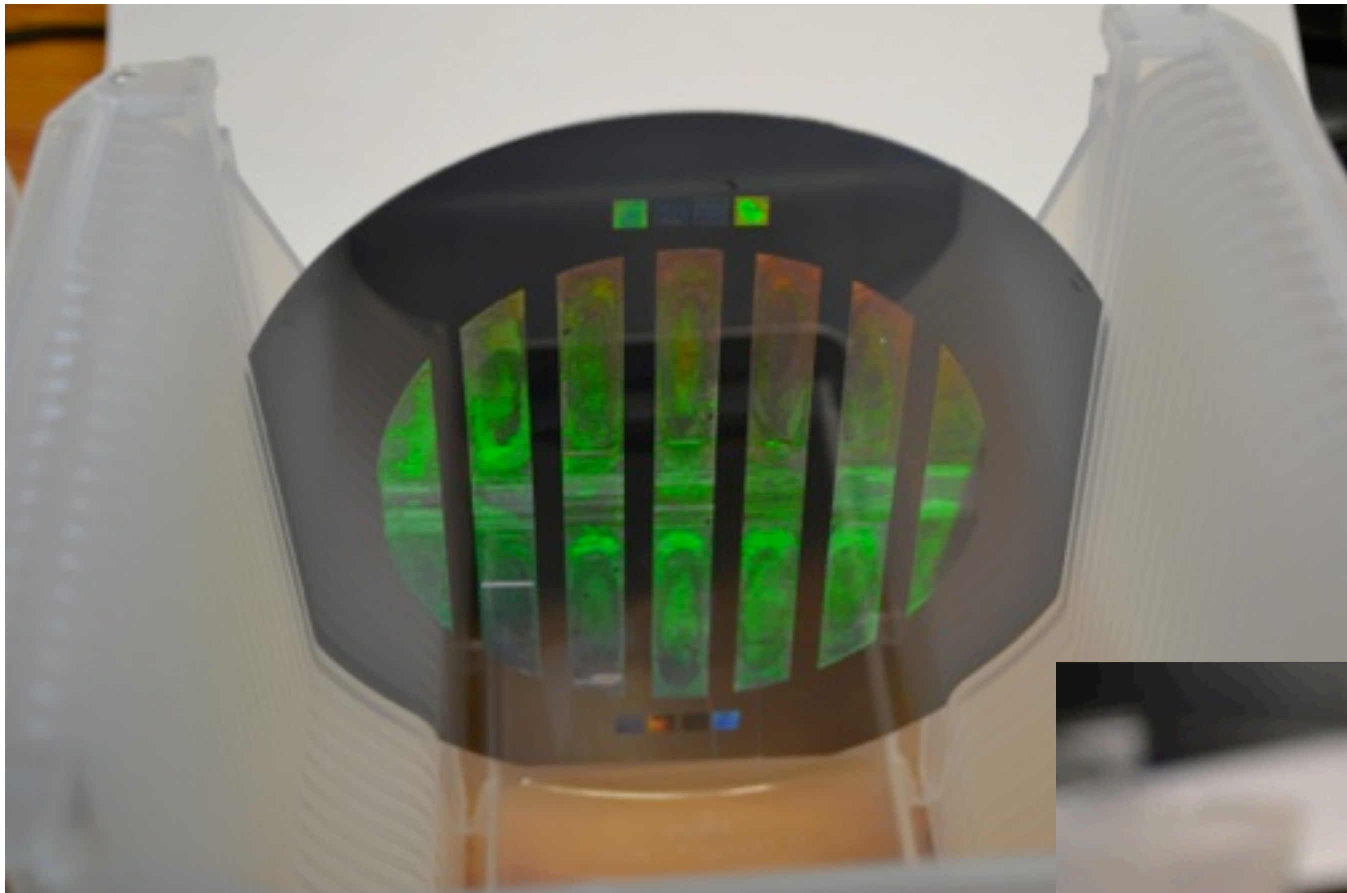




Results on annihilation in Au, Ag, Si, Al, Pb, ... : systematic measurement of fragmentation functions to check systematics for the gravitational measurement ("proton tag")

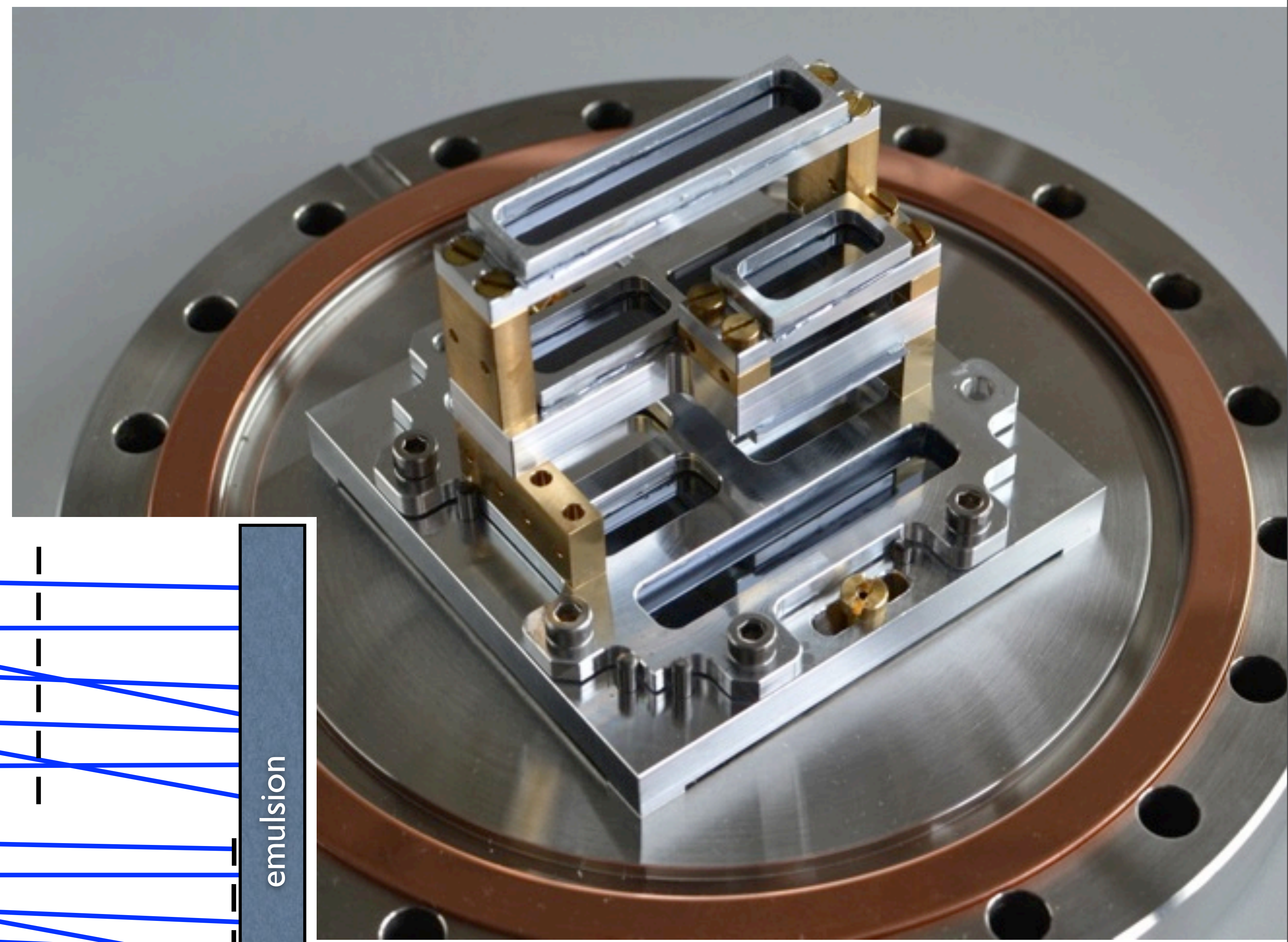
→ further publications on antiproton-induced fragmentation

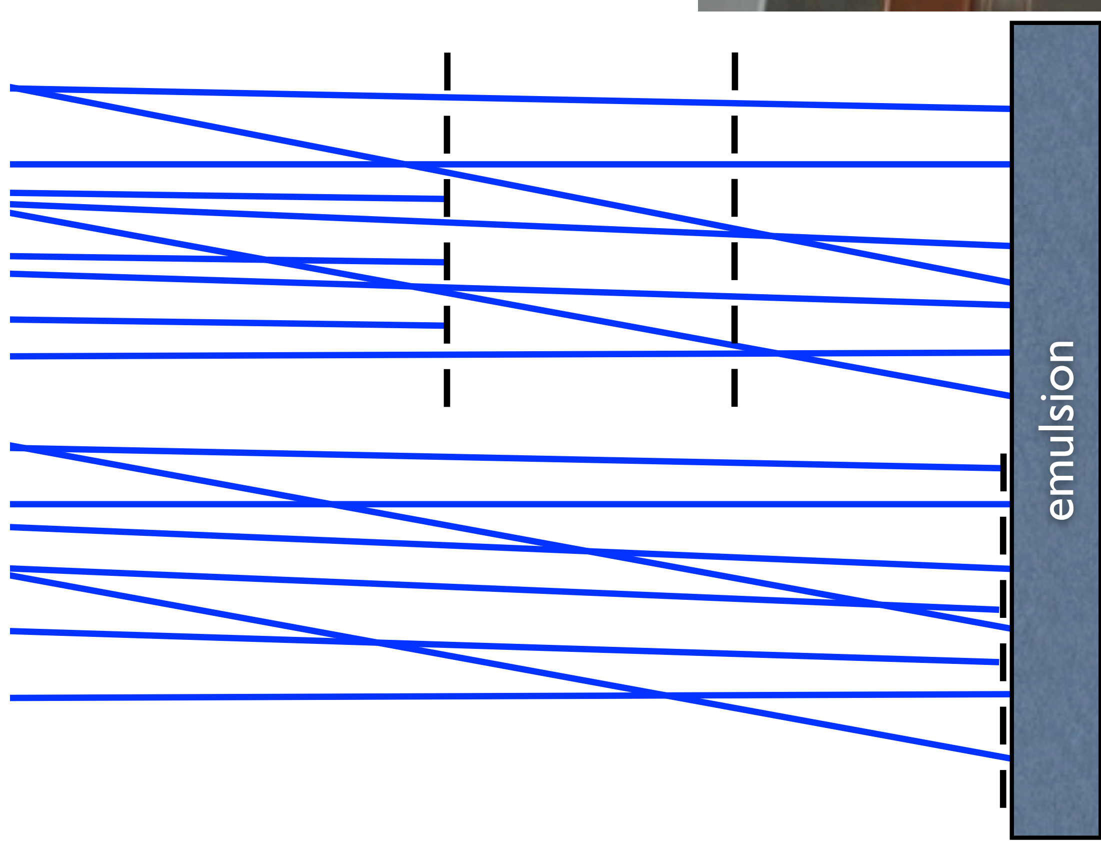
Moiré deflectometer: 6” (full size) grating prototype



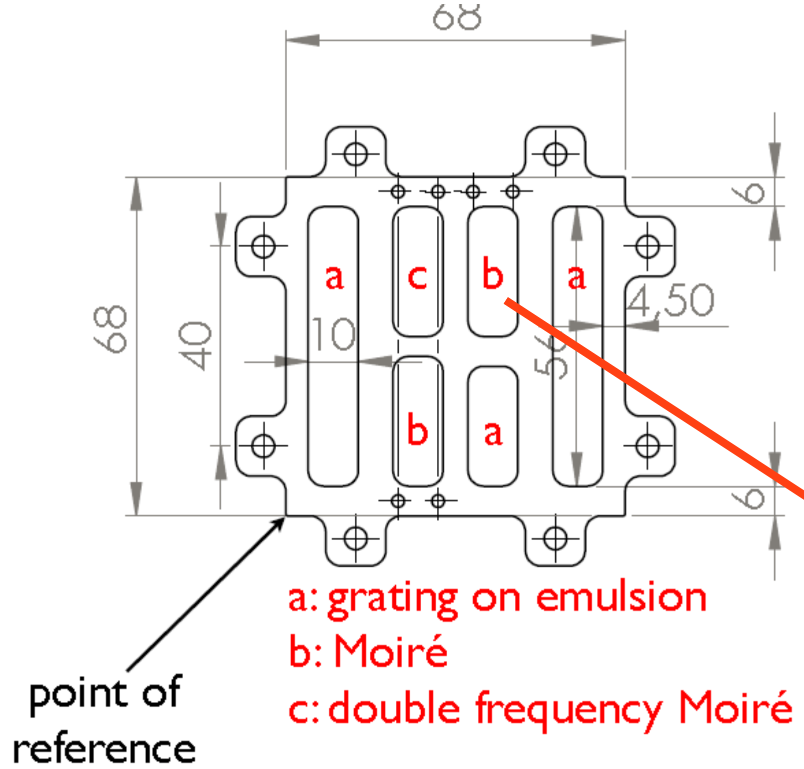
First test of moiré deflectometer

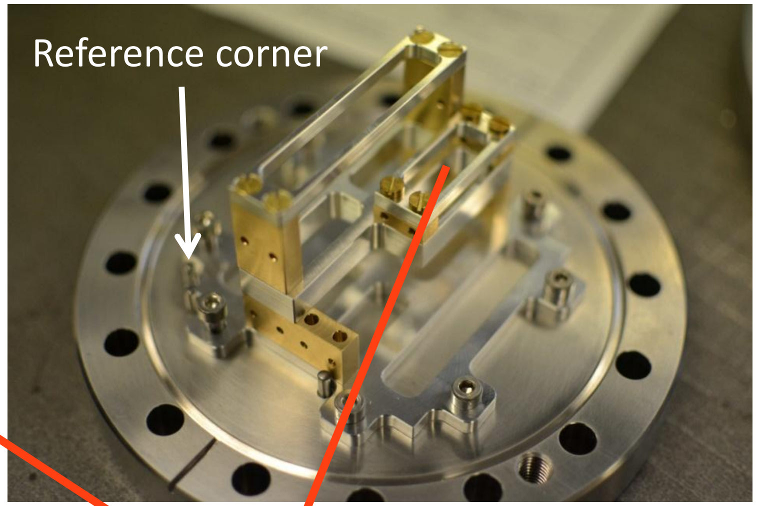
- ~100 keV antiprotons
- 7 hour exposure
- Bare emulsion behind deflectometer





Test of moiré deflectometer with antiprotons

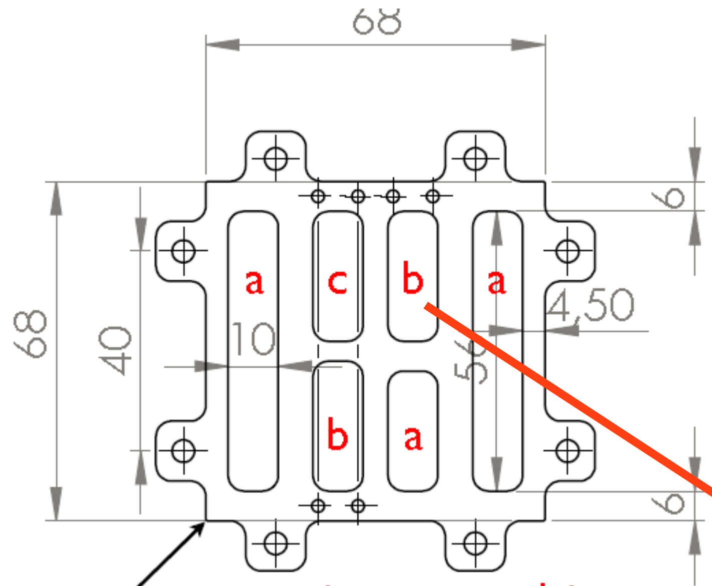




first look at data in zone b)
353 vertices in ~ 1 cm^2

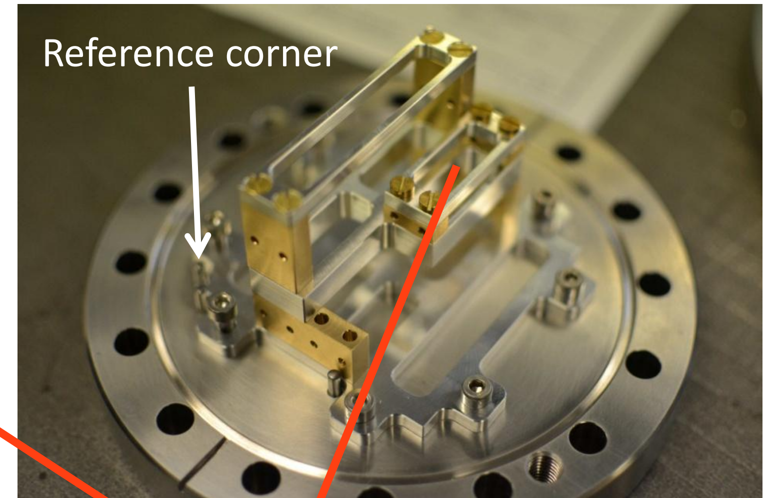
→ Publication submitted

Test of moiré deflectometer with antiprotons



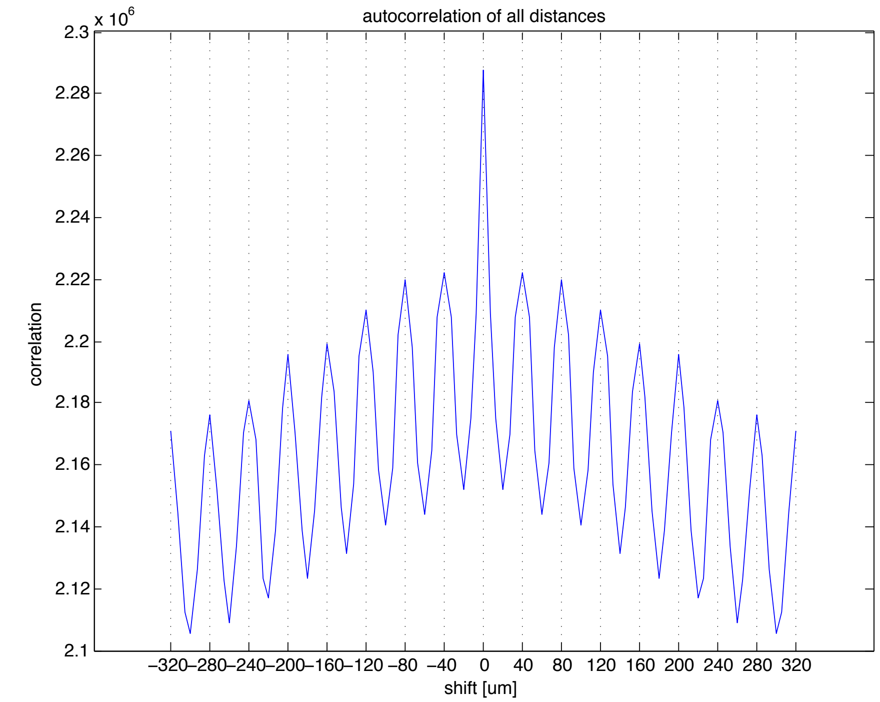
a: grating on emulsion
b: Moiré
c: double frequency Moiré

point of
referen

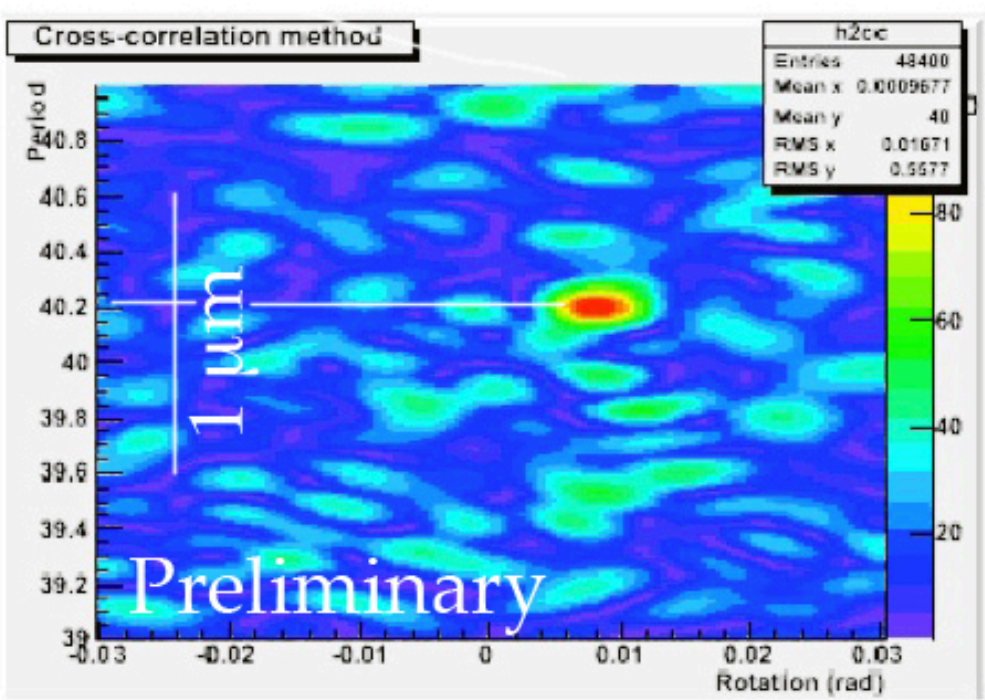


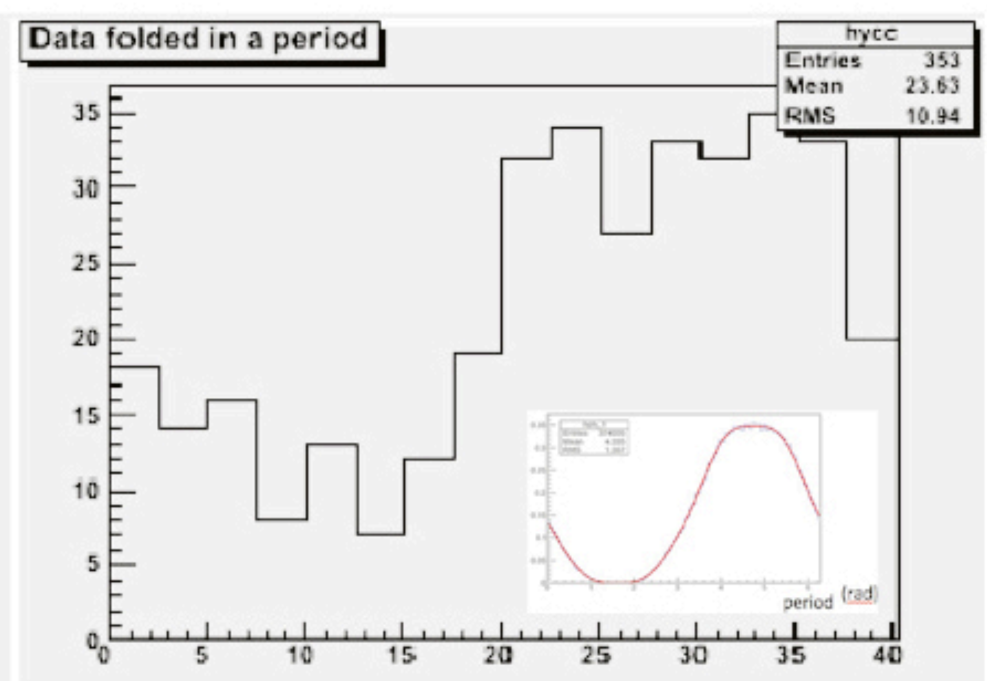
first look at data in zone b)
353 vertices in ~ 1 cm^2

vertex-to-vertex autocorrelation



pitch [µm]





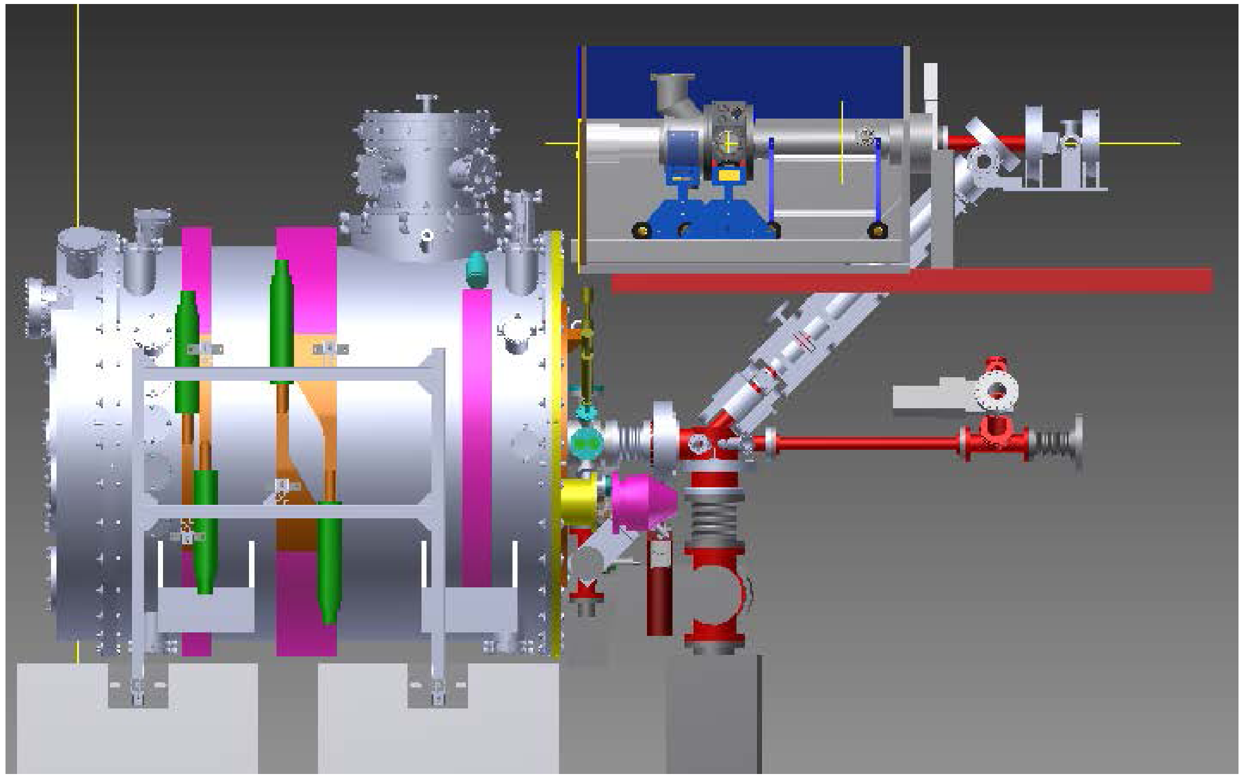
rotation [rad]

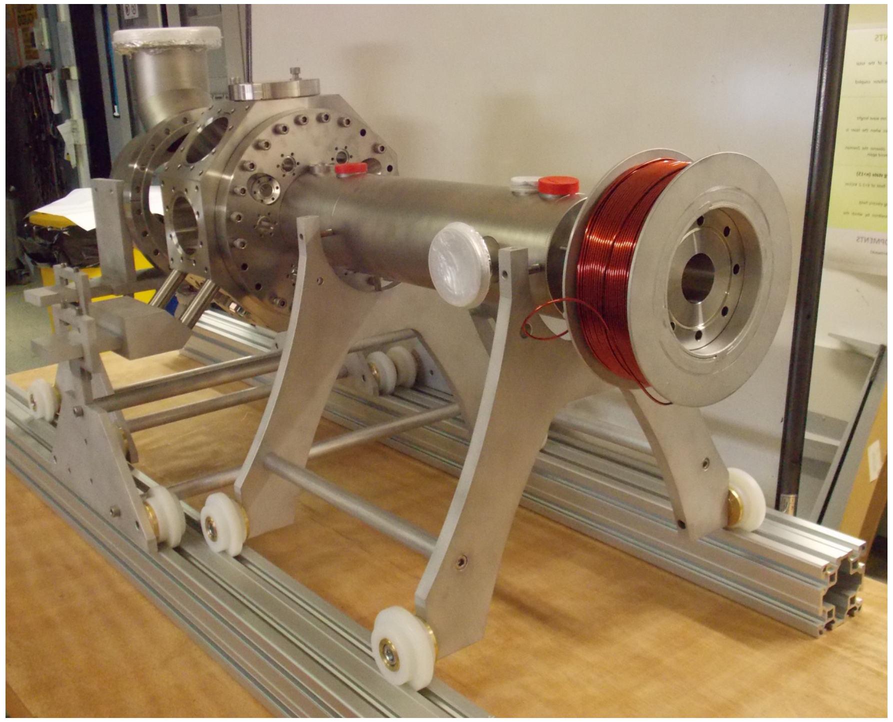
pitch [µm]

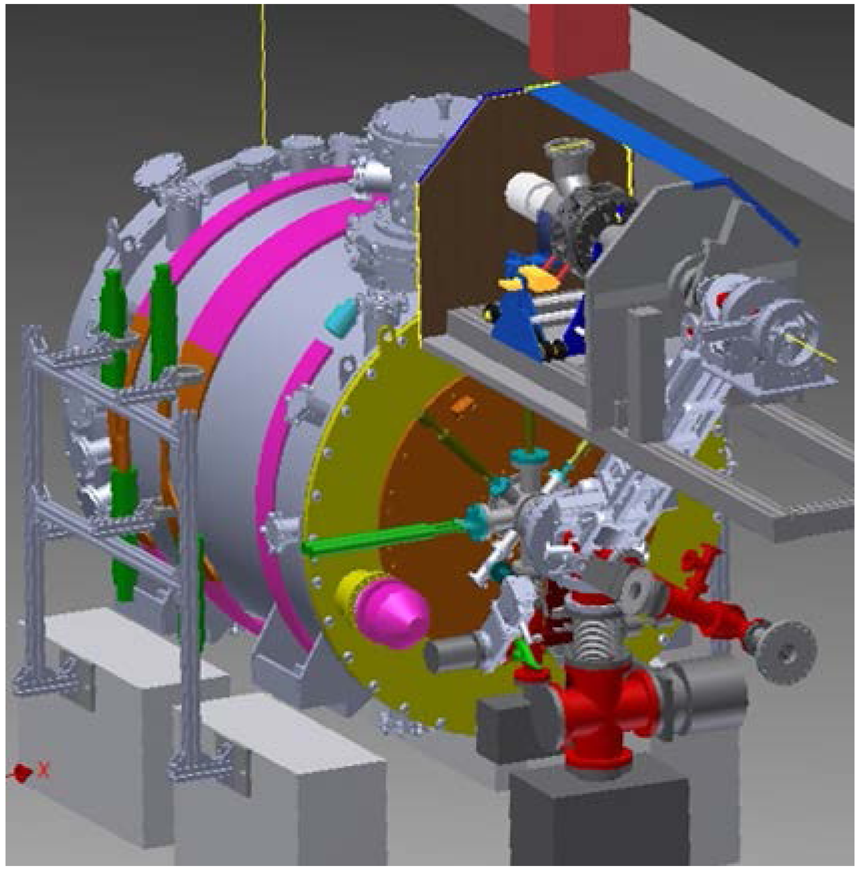
First demonstration of the moiré deflectometer technique with antiprotons!

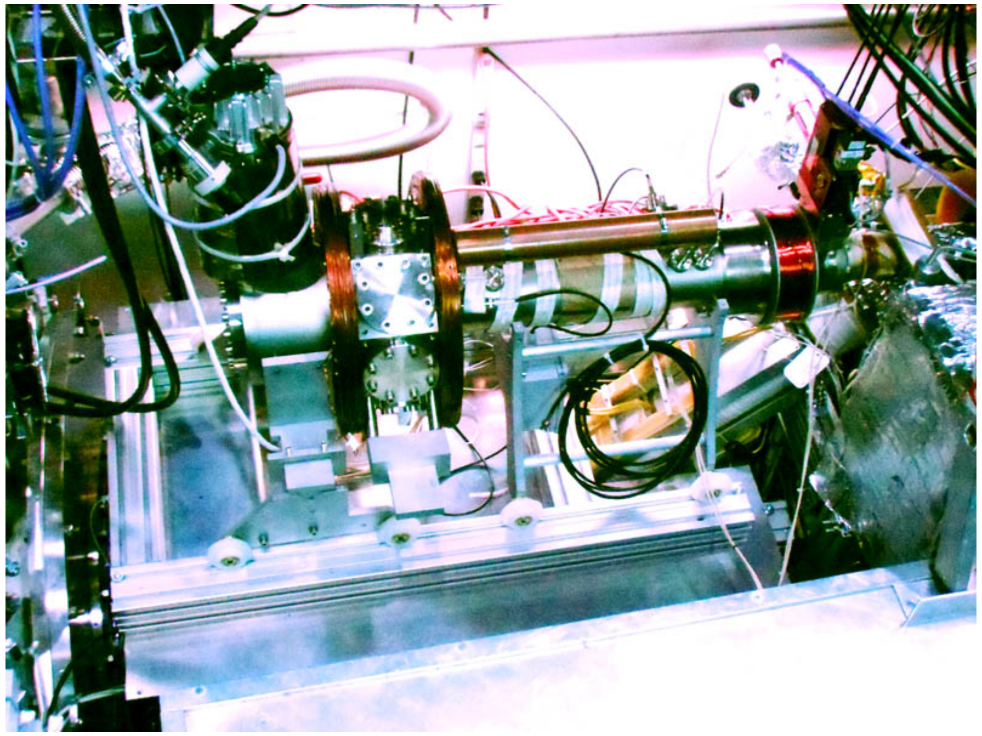
→ Publication submitted

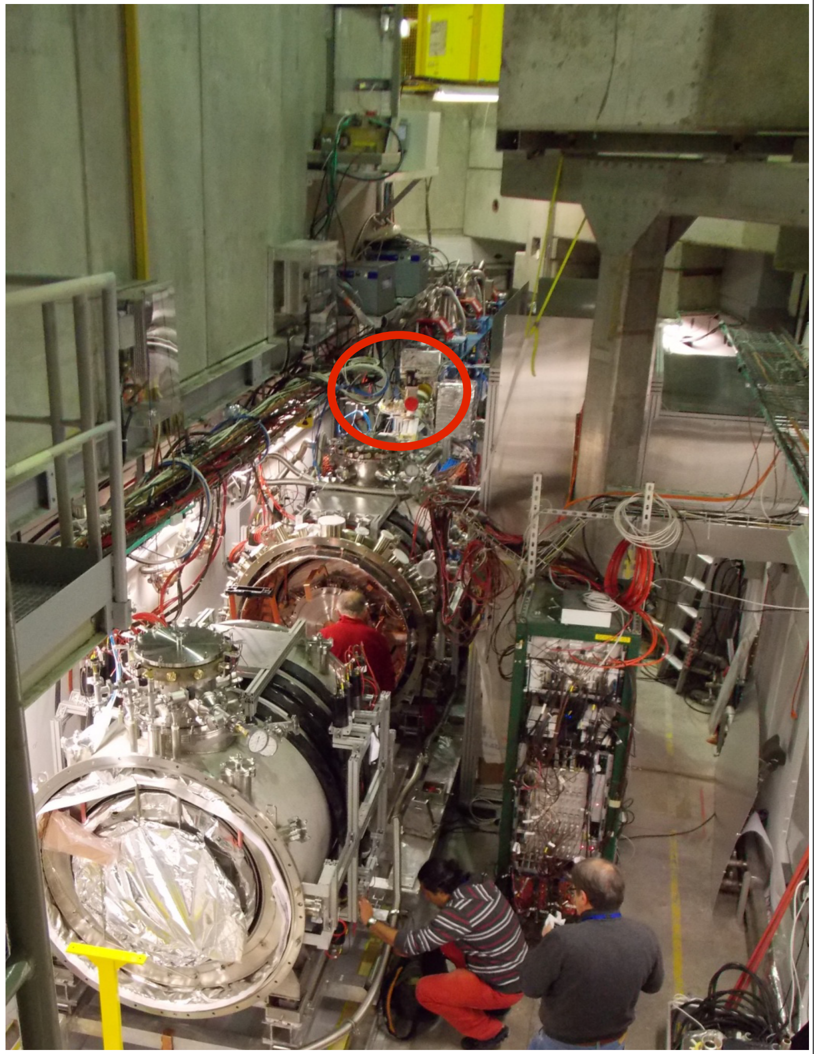
ongoing work: Positronium test station











installed and under commissioning

Conclusions and Outlook

- Installation of base apparatus largely completed and commissioned
- Parasitic measurements essential in converging to an optimal deflectometer/detector layout

- Next steps:
  - install proton source, hydrogen detector, positronium test stand
  - commission Rydberg positronium formation (targets, lasers, atomic physics)
  - work on hydrogen formation/characterization
  - design gravity module, flight tube
  - goal: be ready for antihydrogen formation in autumn 2014

- In parallel:
  - prepare deflectometer, microwave spectrometry, interface, hybrid detector, ...