

**AE $\bar{\text{g}}$ IS / AD-6**  
**Antihydrogen experiment:**  
**Gravity, Interferometry and Spectroscopy**

**Status report for 2014 and  
outlook for 2015/16**

**Michael Doser / CERN**  
**on behalf of the AE $\bar{\text{g}}$ IS collaboration**

# AĒIS collaboration



IPNL, Lyon



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University Bern,  
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CERN, Switzerland



INFN Genova, Italy



MPI-K, Heidelberg,  
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U of Heidelberg,  
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INFN Milano, Italy



Politecnico di Milano,  
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INR, Moscow, Russia



U of Bergen, Norway



University College London, UK



Laboratoire Aimé  
Cotton, Orsay,  
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U of Oslo, Norway



INFN Pavia/Brescia,  
Italy



Czech Technical U,  
Prague, Czech  
Republic



INFN Padova/Trento,  
Italy



ETH Zurich,  
Switzerland

# Topics

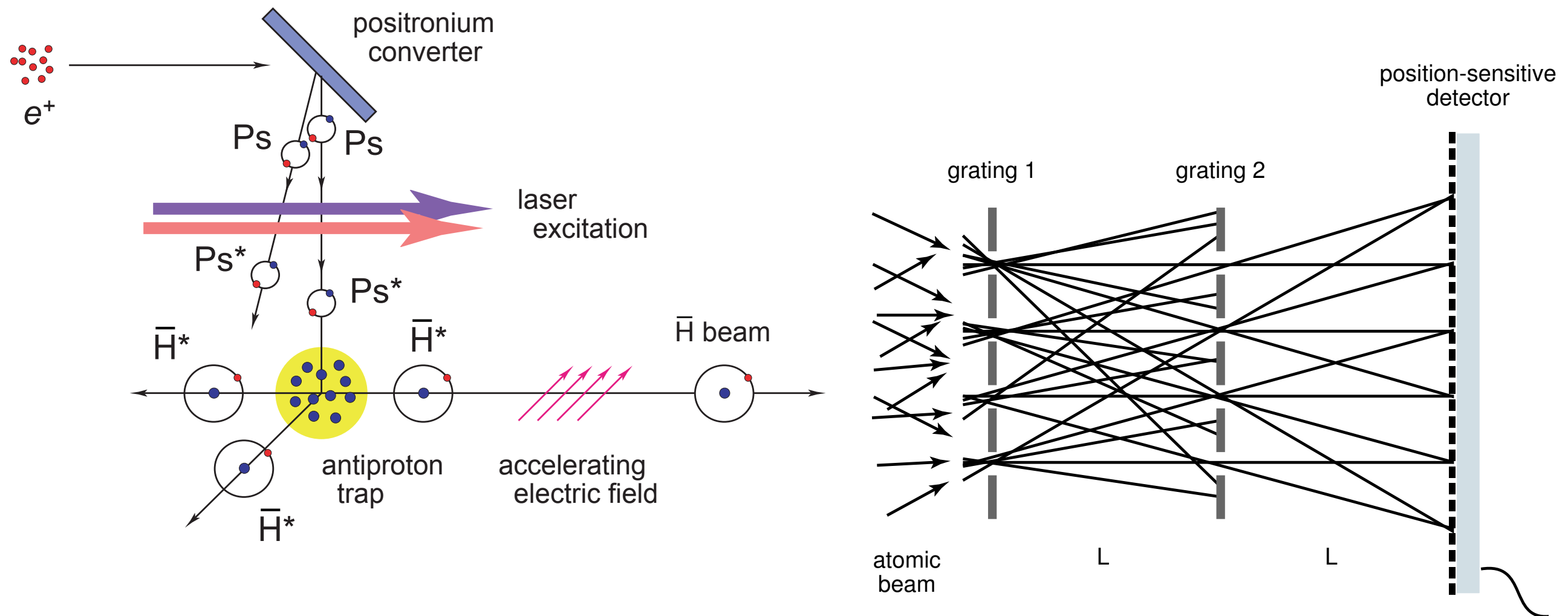
Schematic overview

Work in 2014 (since April) on apparatus

Results of measurements with antiprotons and positrons

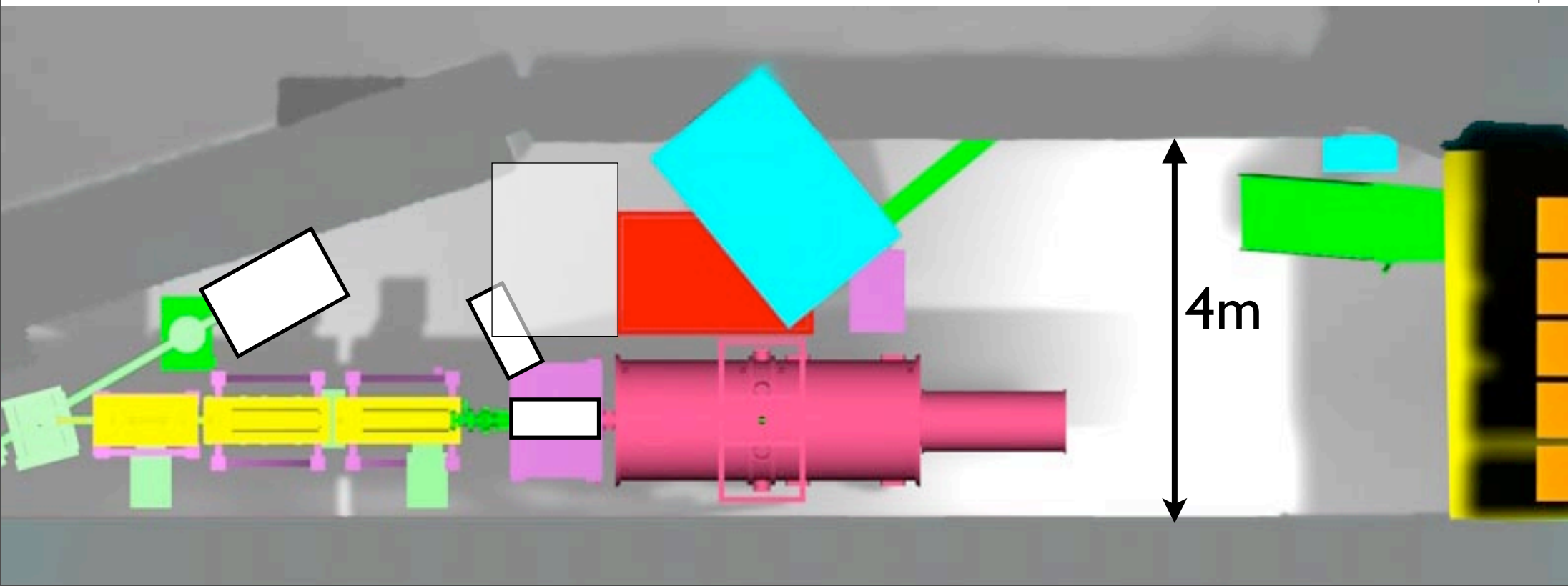
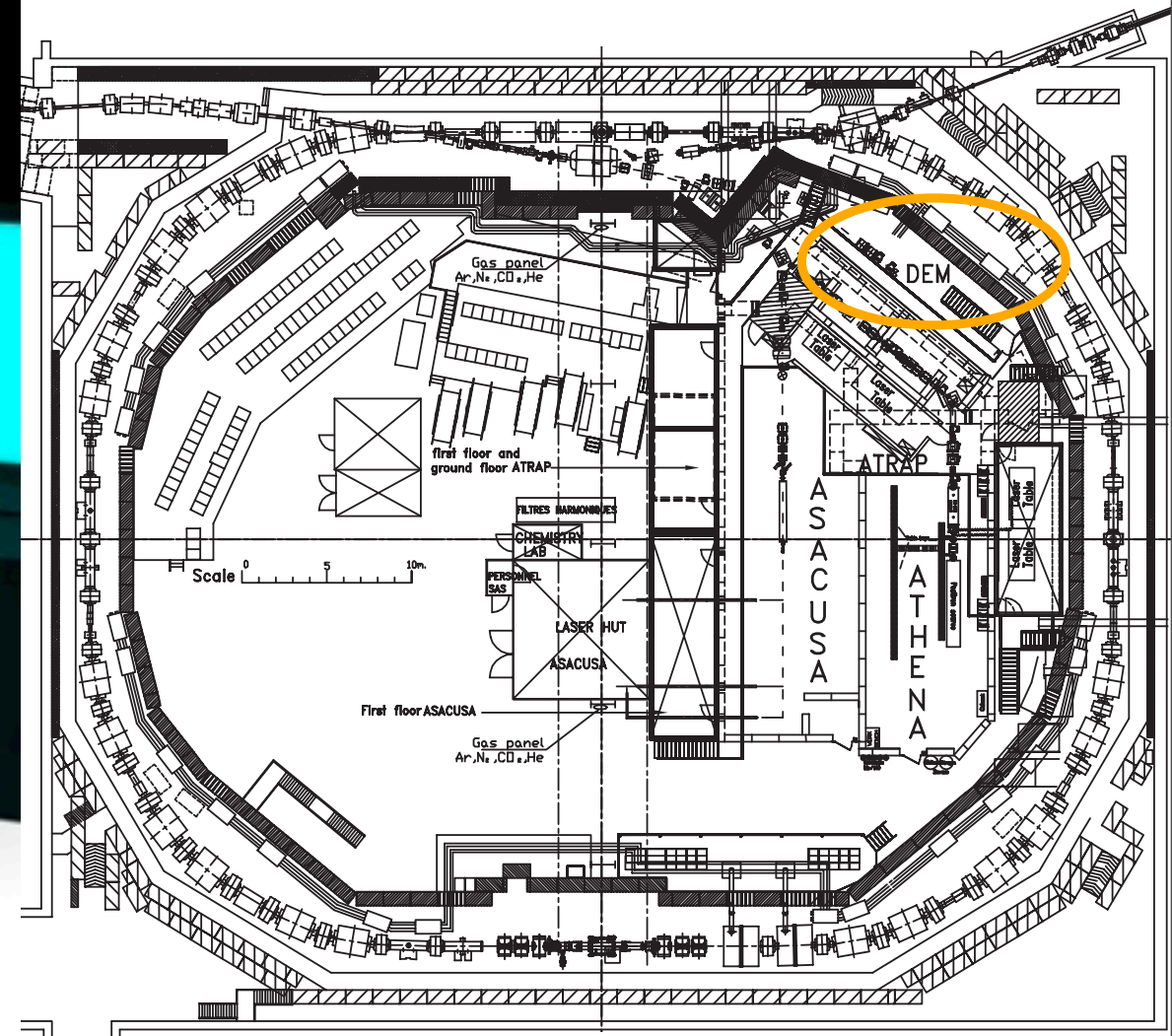
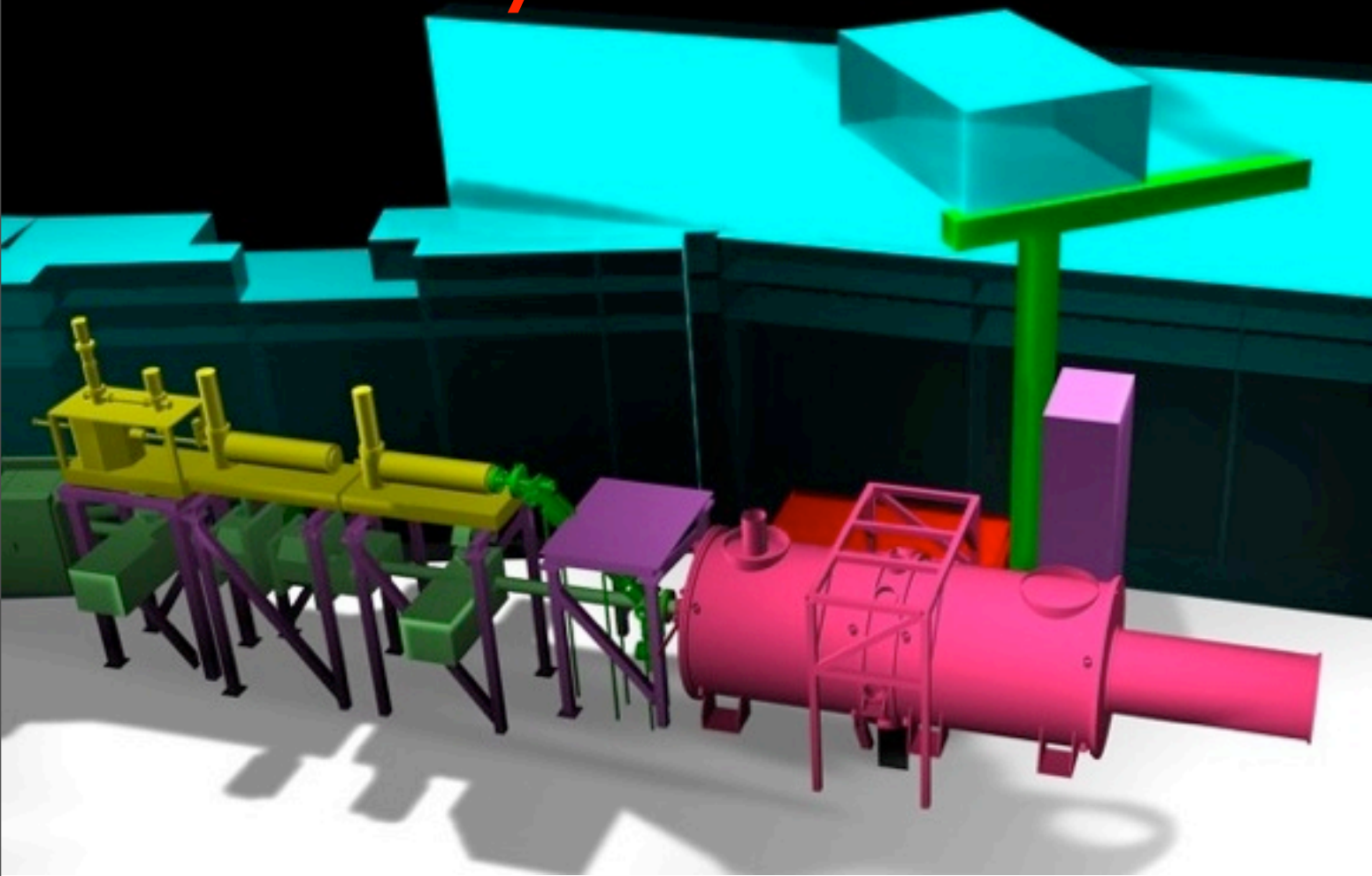
Outlook for 2015 and 2016

# Schematic overview



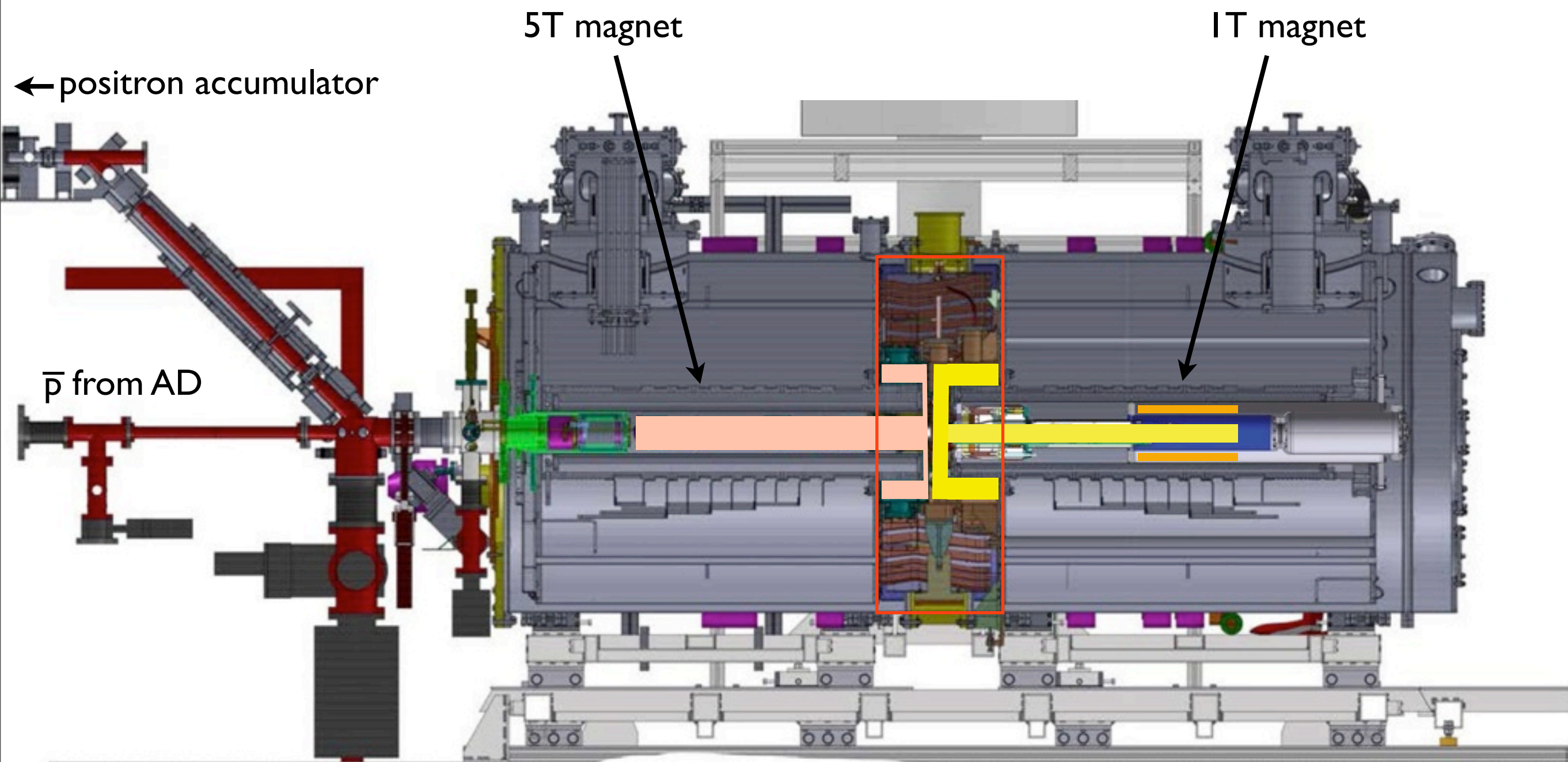
Physics goals: measurement of the gravitational interaction between matter and antimatter,  $\bar{H}$  spectroscopy, ...

# Zone layout



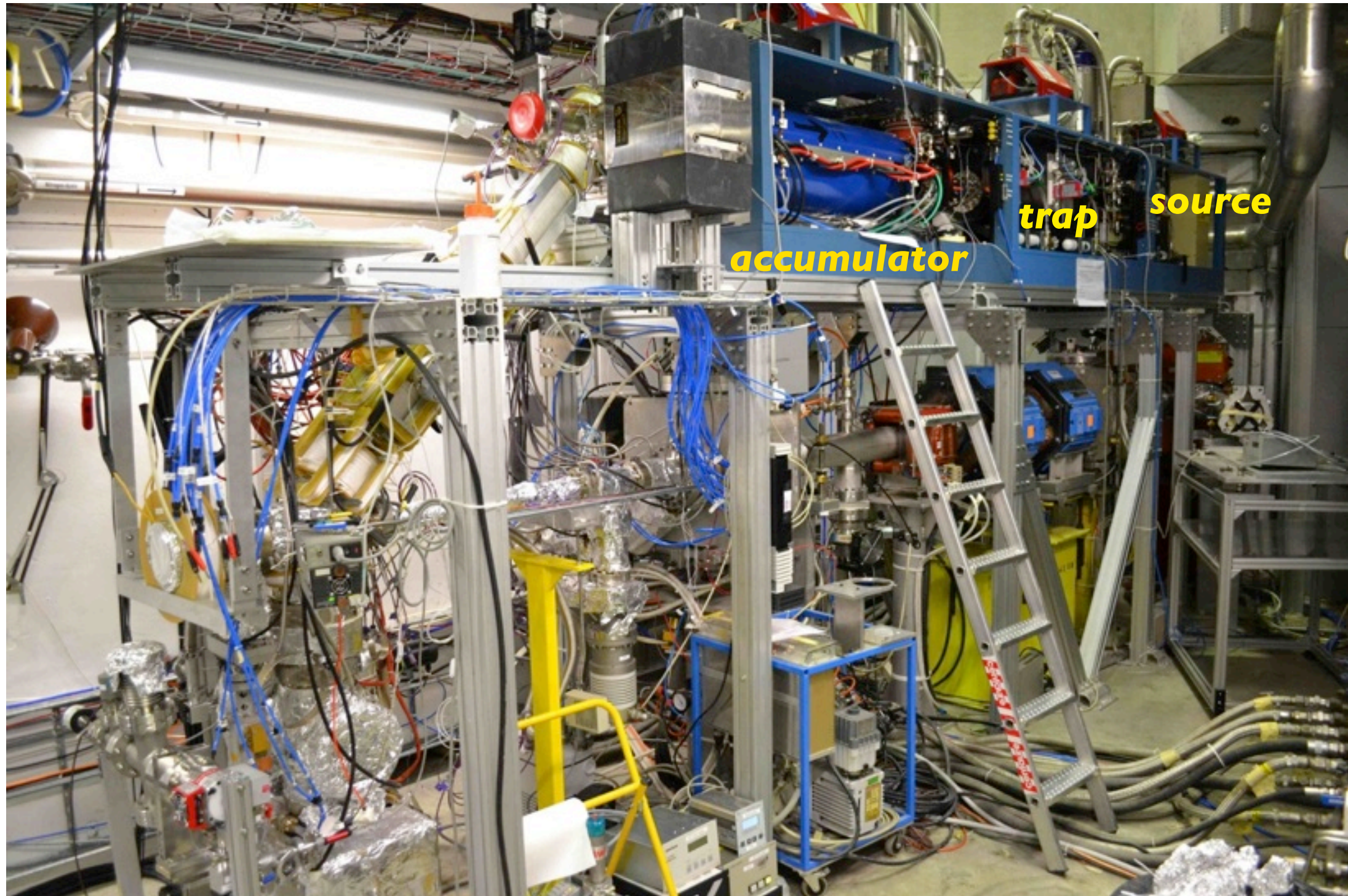


# Central apparatus design





# Positron system

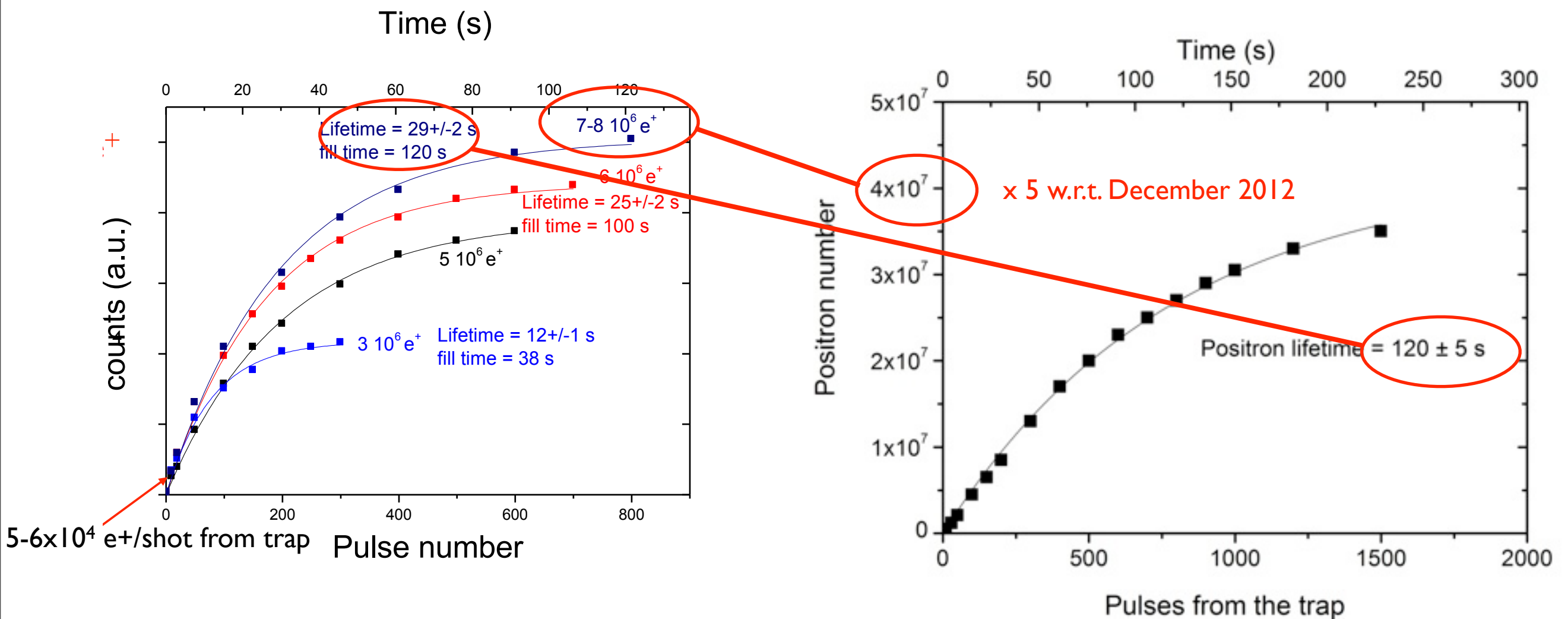


Completed and first operation in October 2012



# Positron system: from Dec 2012 to April 2014

Alignment, magnetic shielding, vacuum, control SW ...

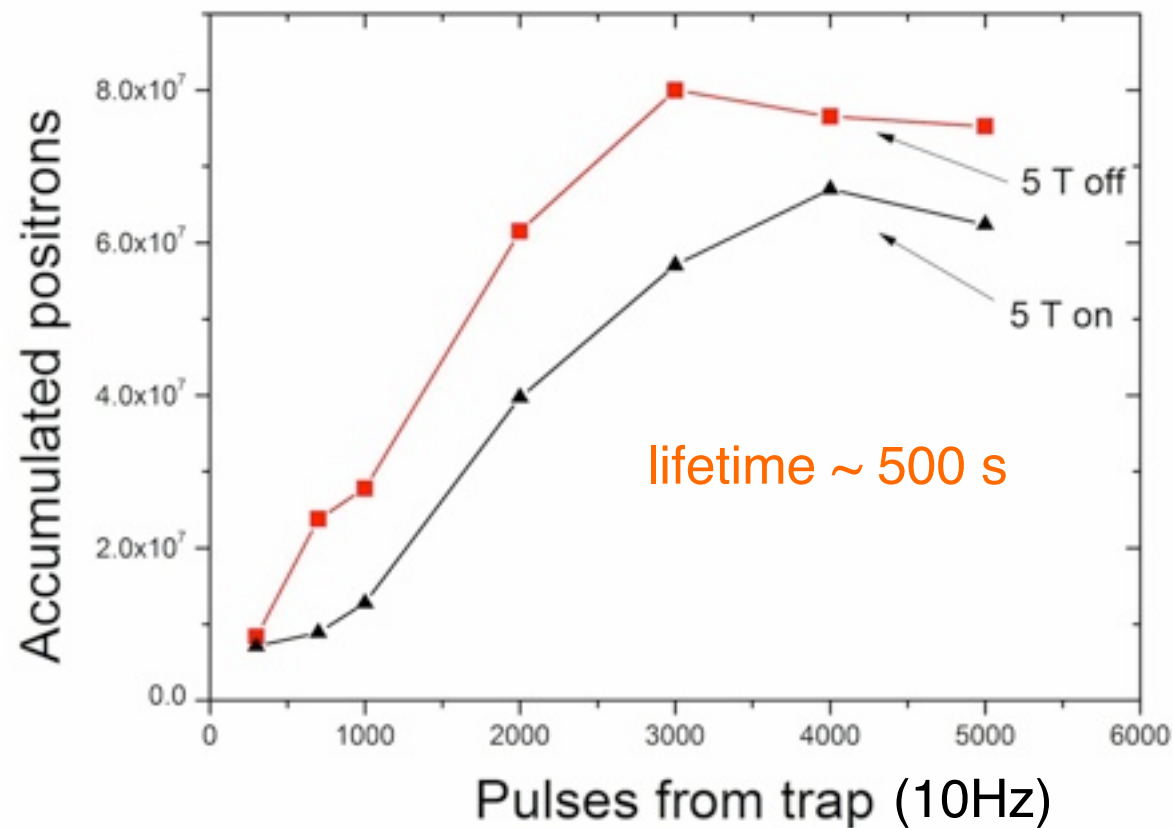


further improvements in rates and lifetimes welcome...

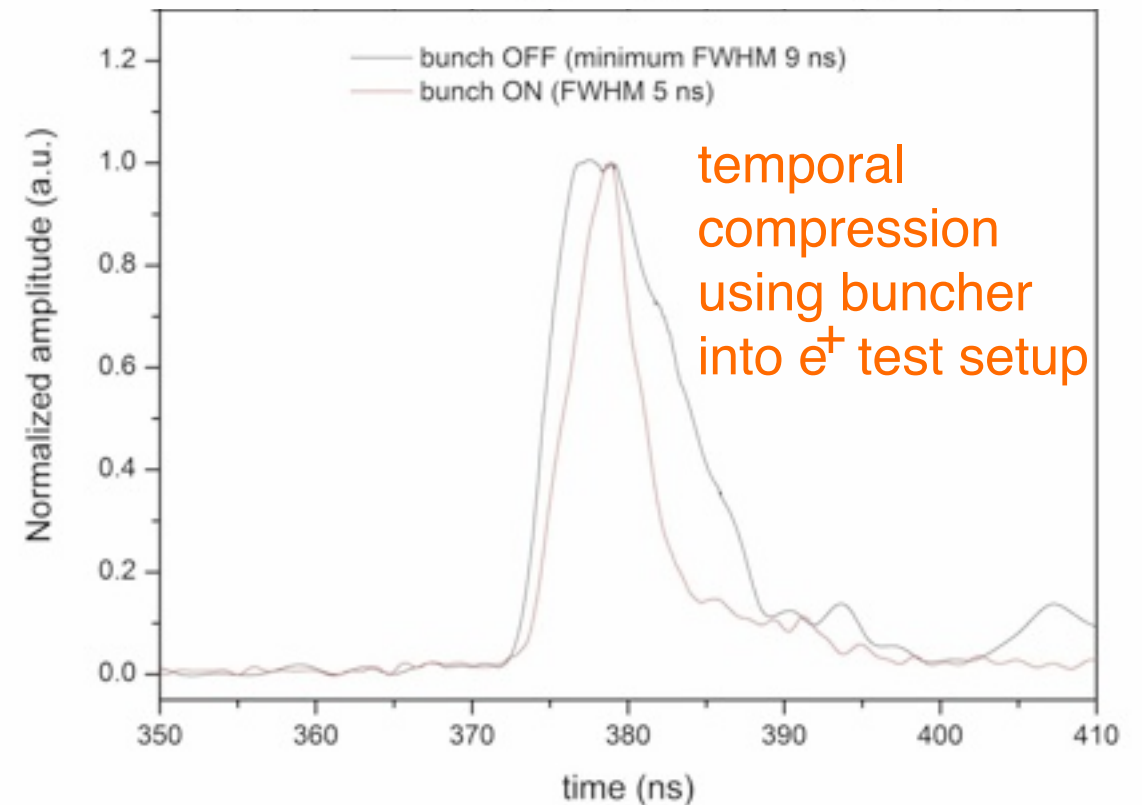
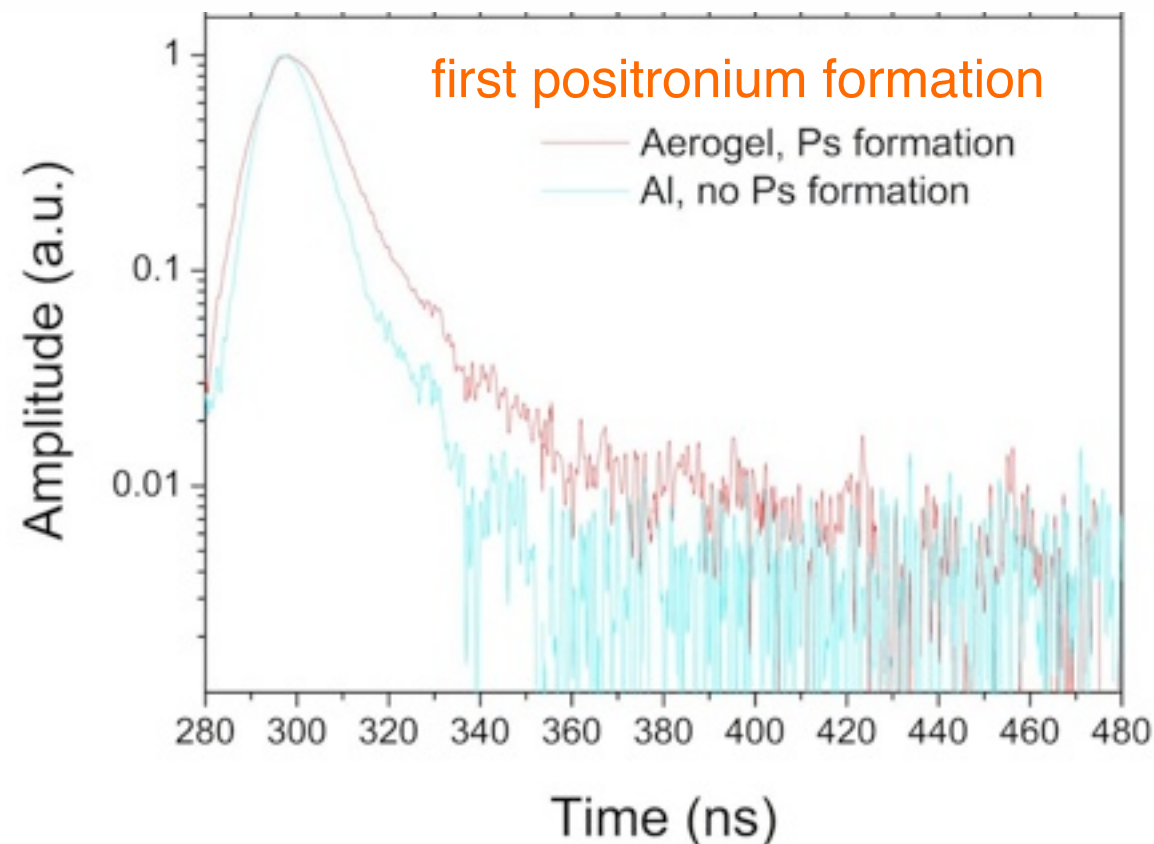
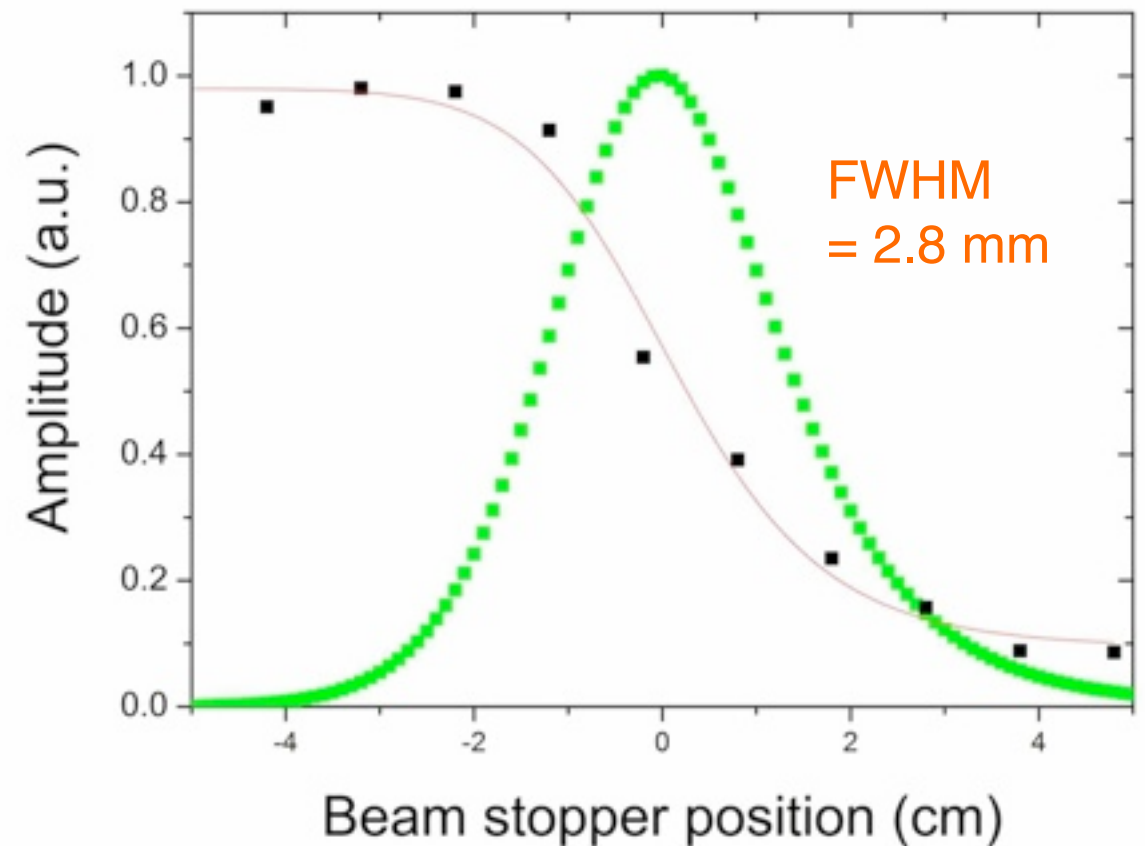


..., alignment, magnetic shielding, vacuum, control SW ...

Accumulated # more than doubled again

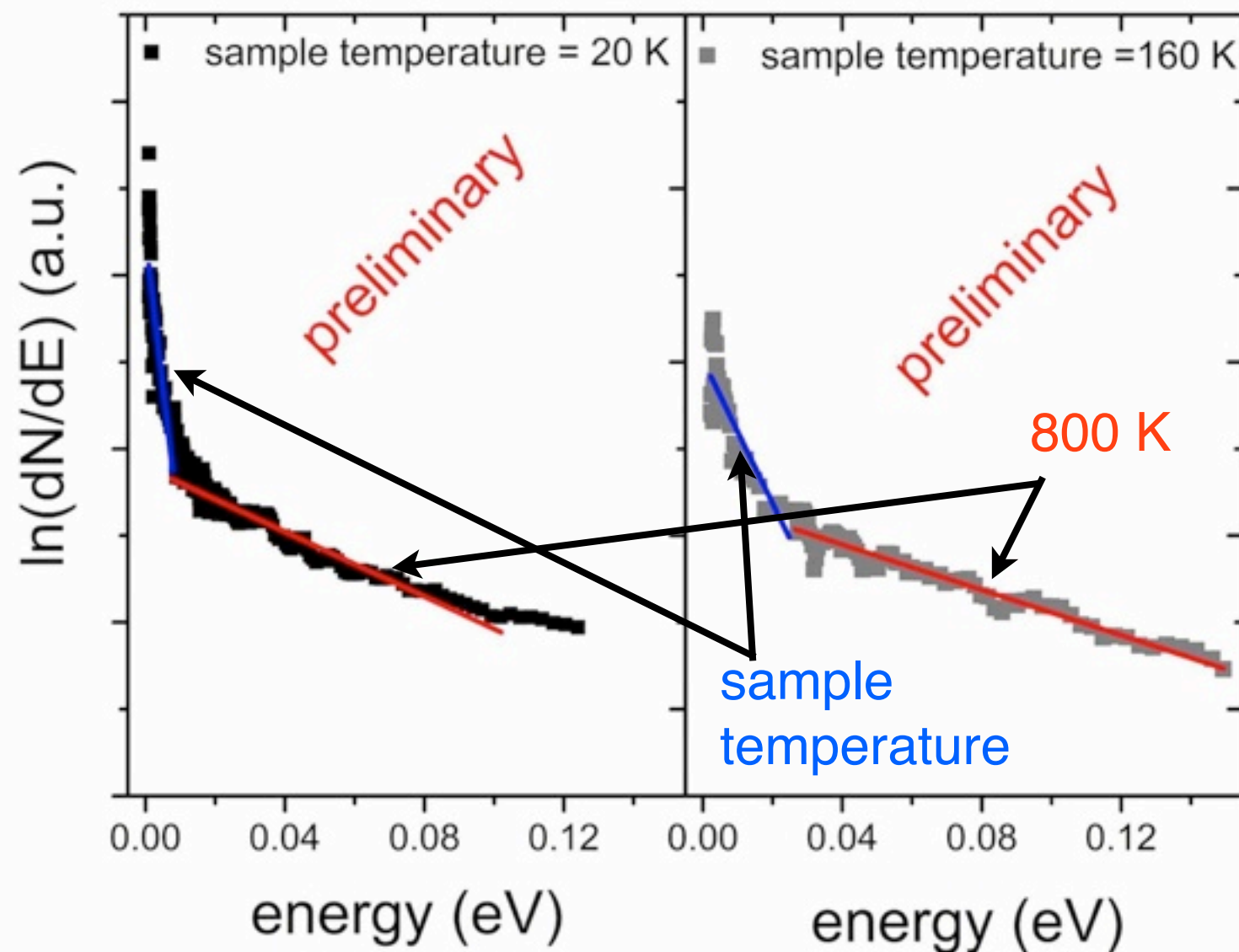


Beam size significantly reduced



# Positronium production tests in NEPOMUC reactor (Nov 2014)

- investigation of thermalization (target at 20K, at 160 K);  
injection at 7kV, nano-channeled silicon (15 nm pore size)

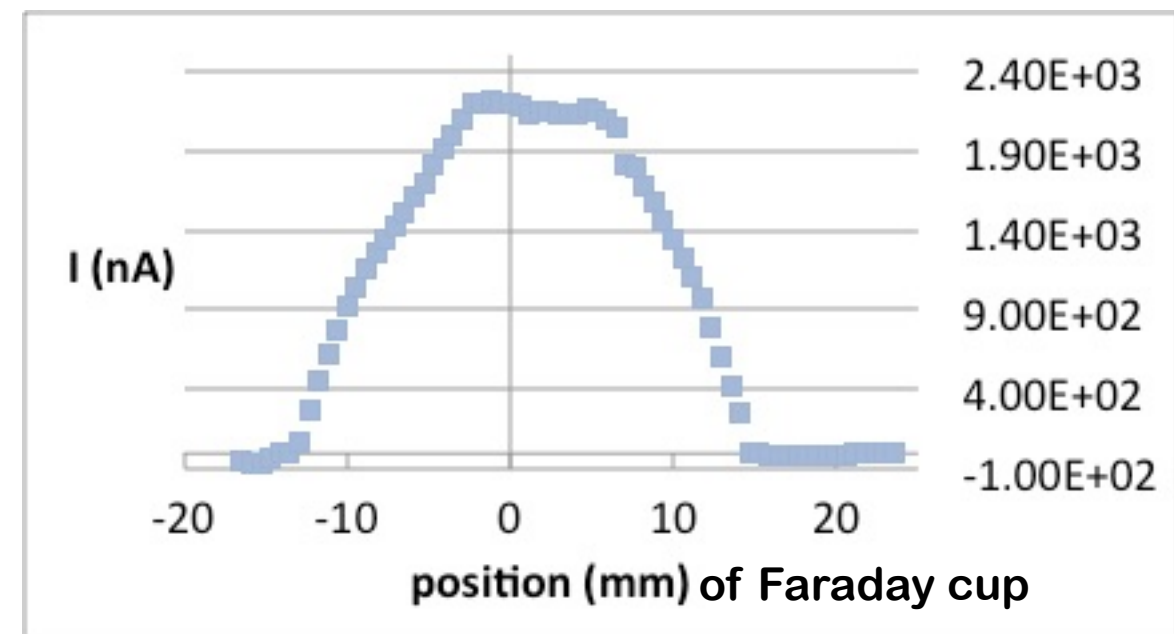
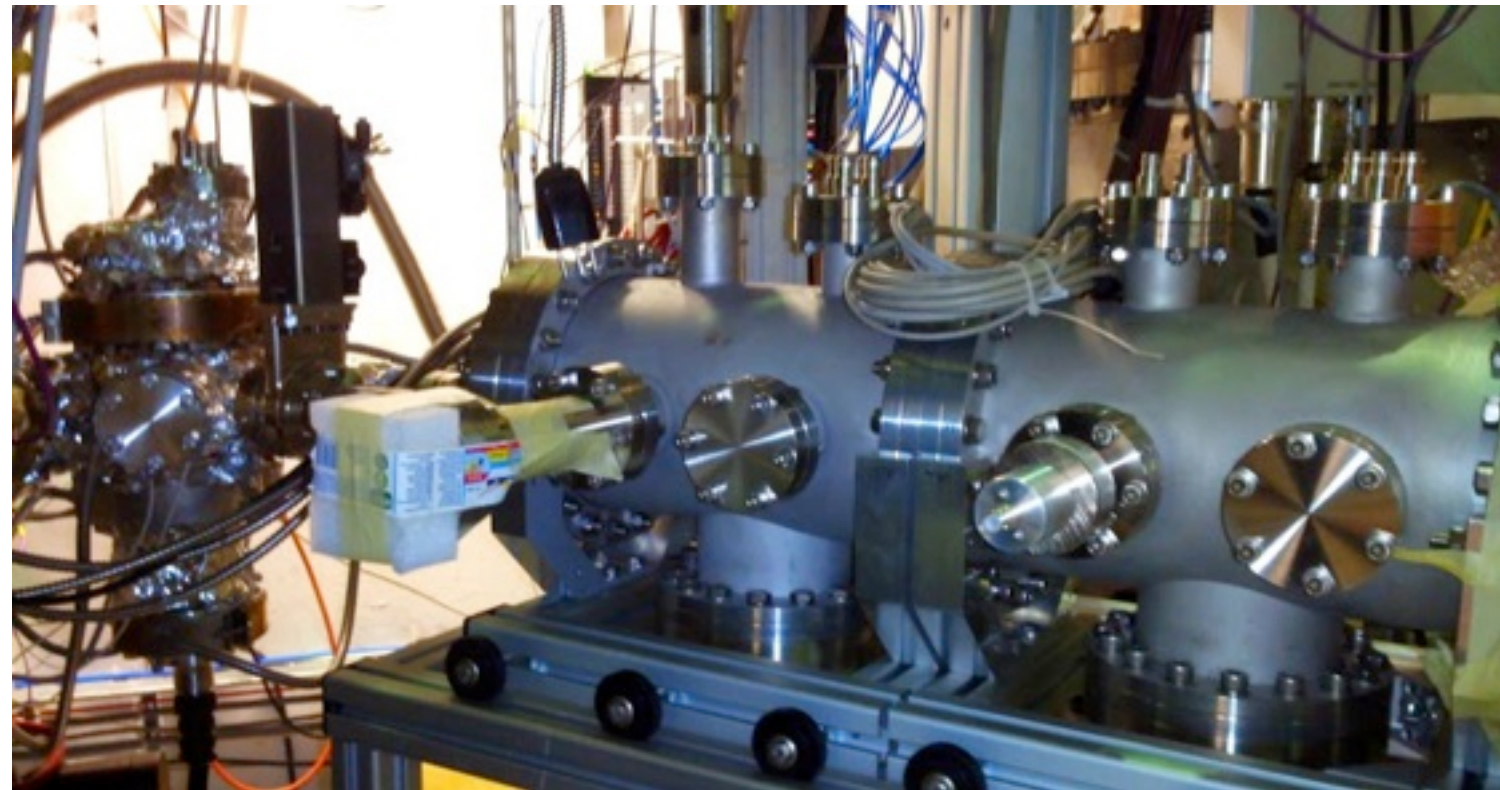
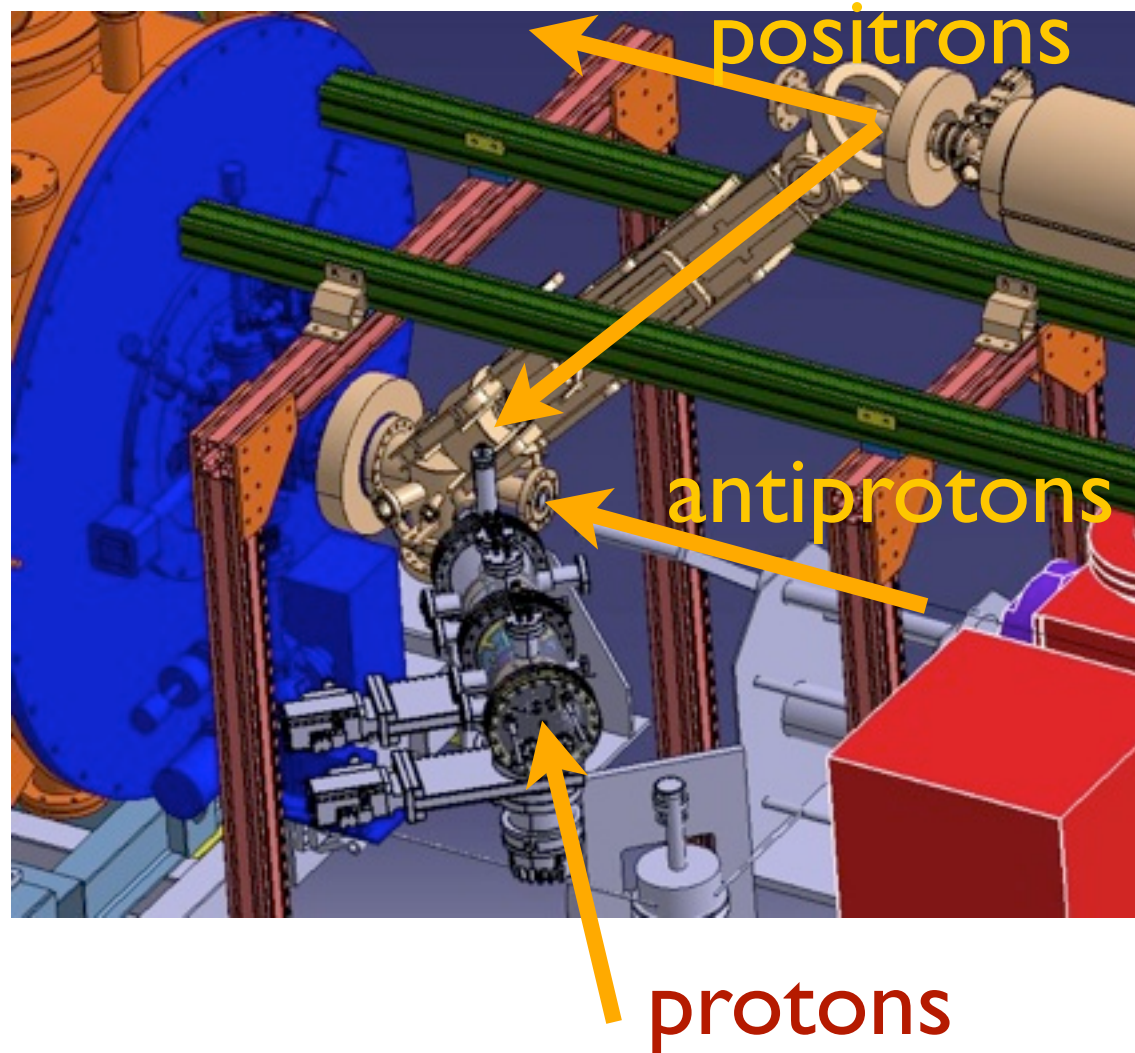
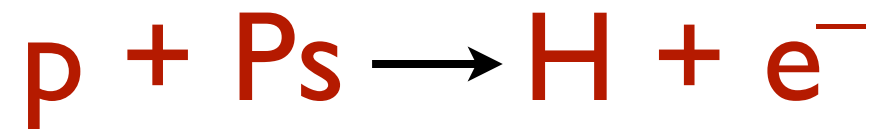


change in low-energy  
slope  $\rightarrow$  reduction of  
Ps temperature

analysis is ongoing to  
determine optimal  
parameters for “cold”  
Ps production



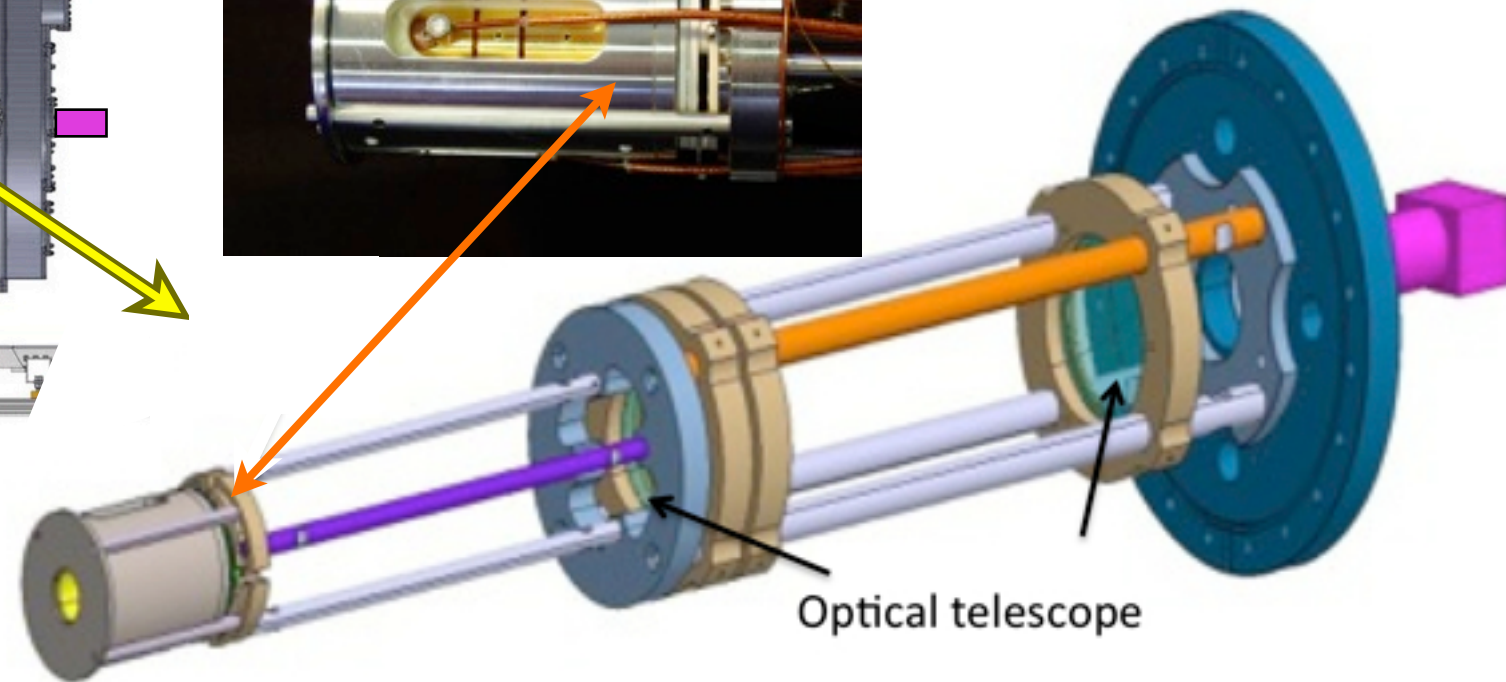
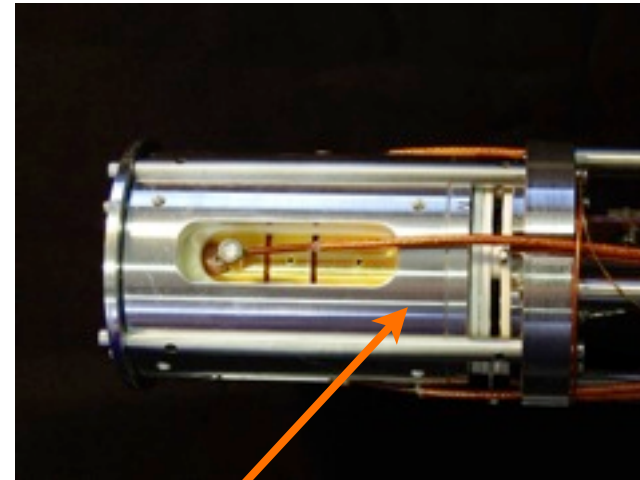
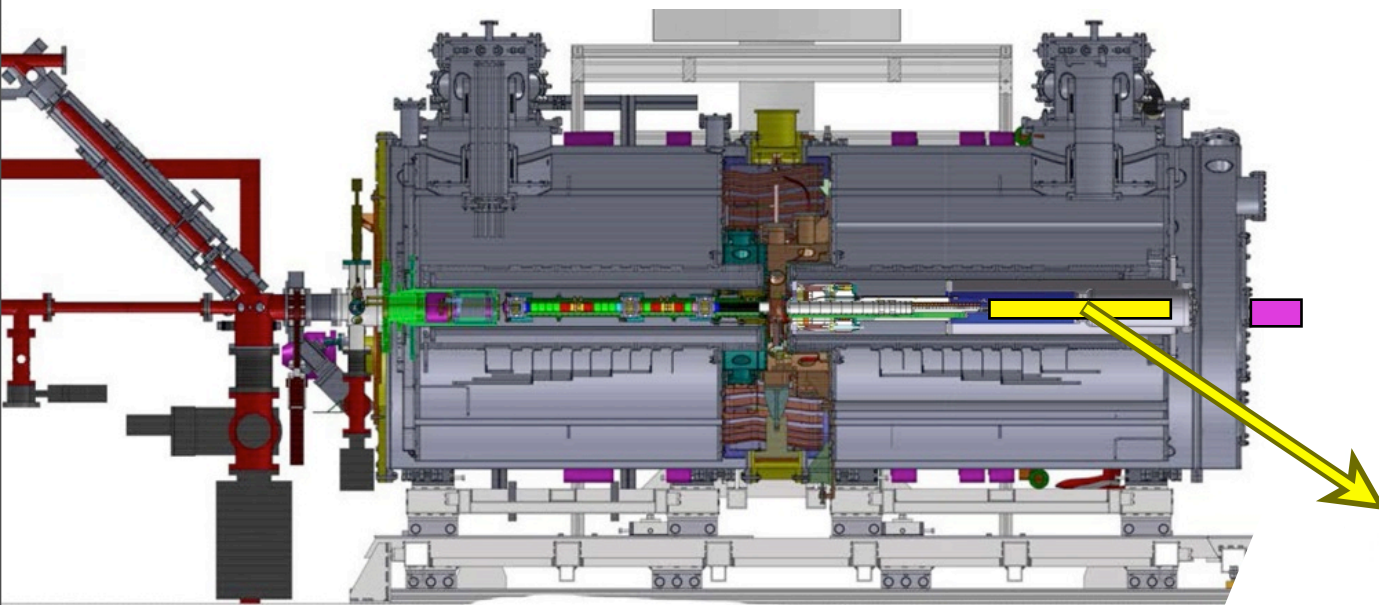
# new equipment: Proton source



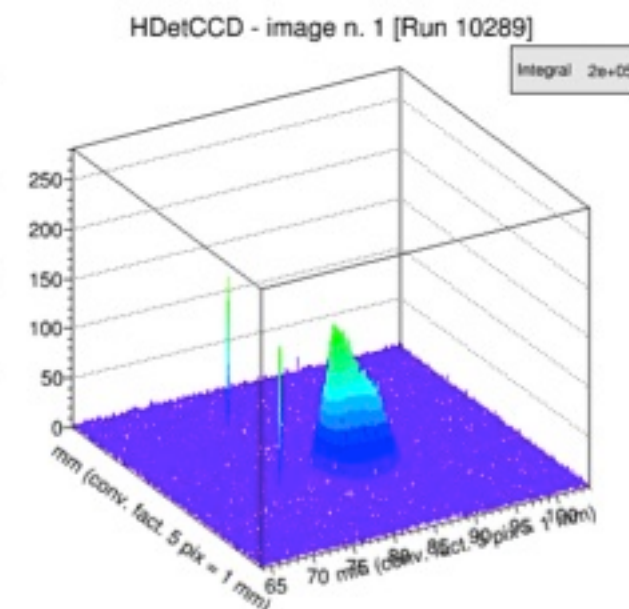
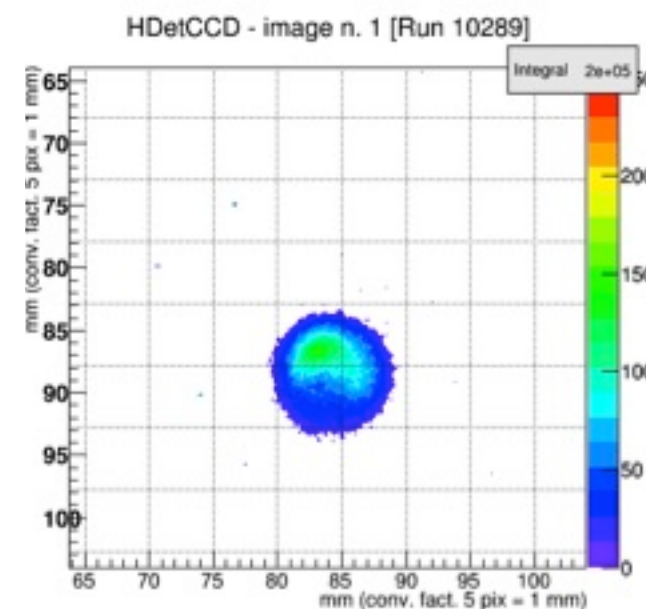
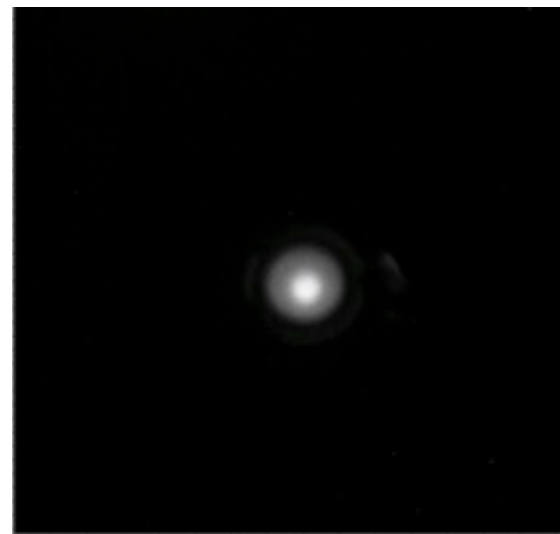
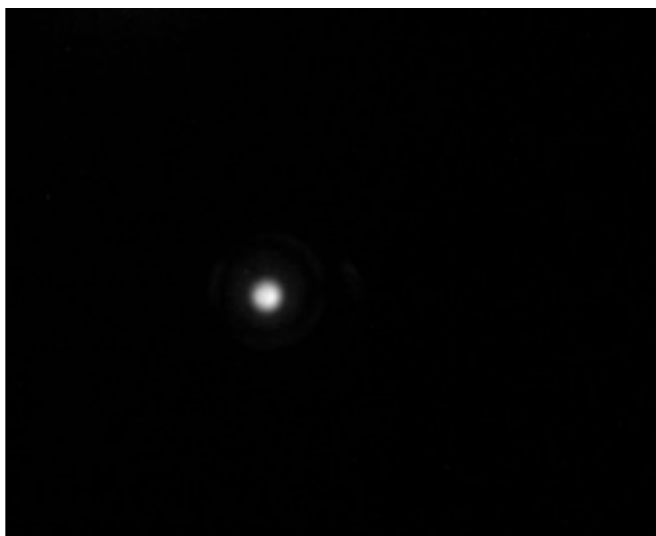
Installed on AEgIS beam line,  
commissioning in-situ started



# new equipment: (Anti)hydrogen detector

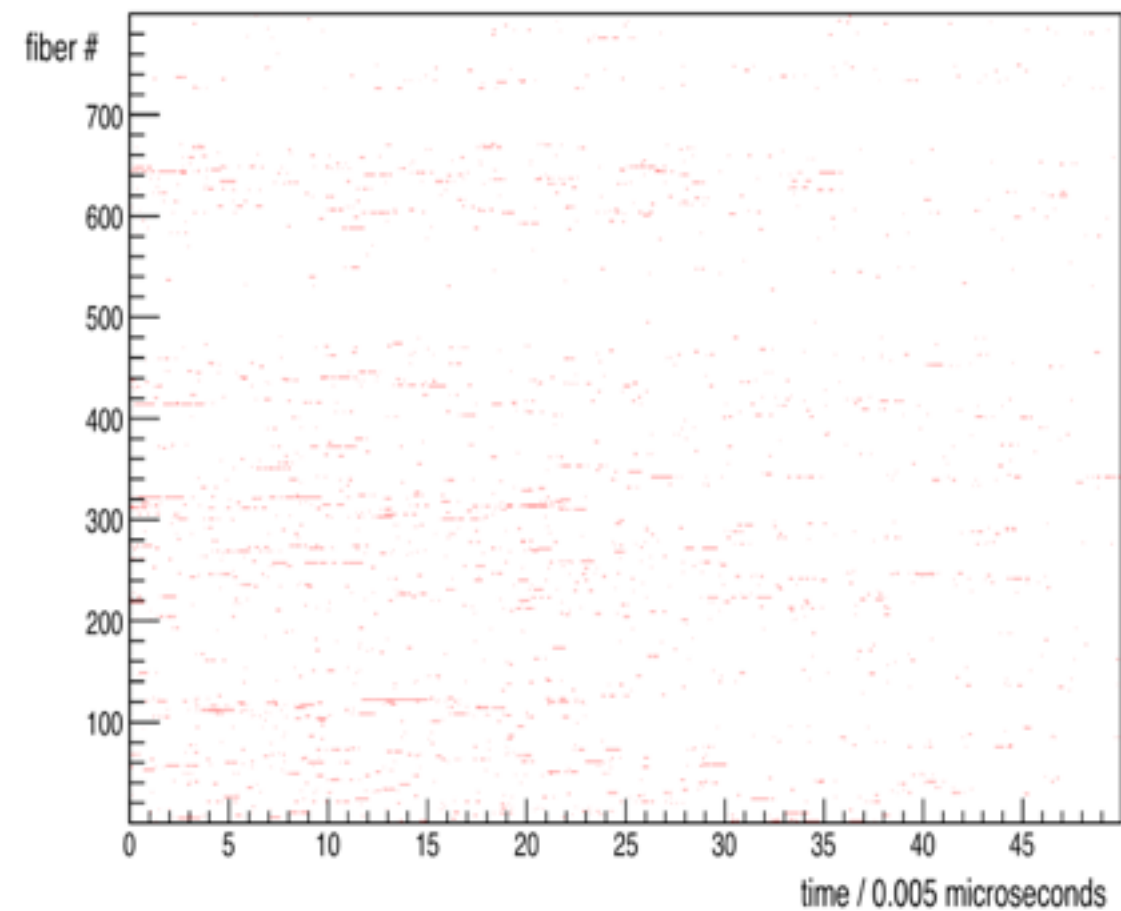
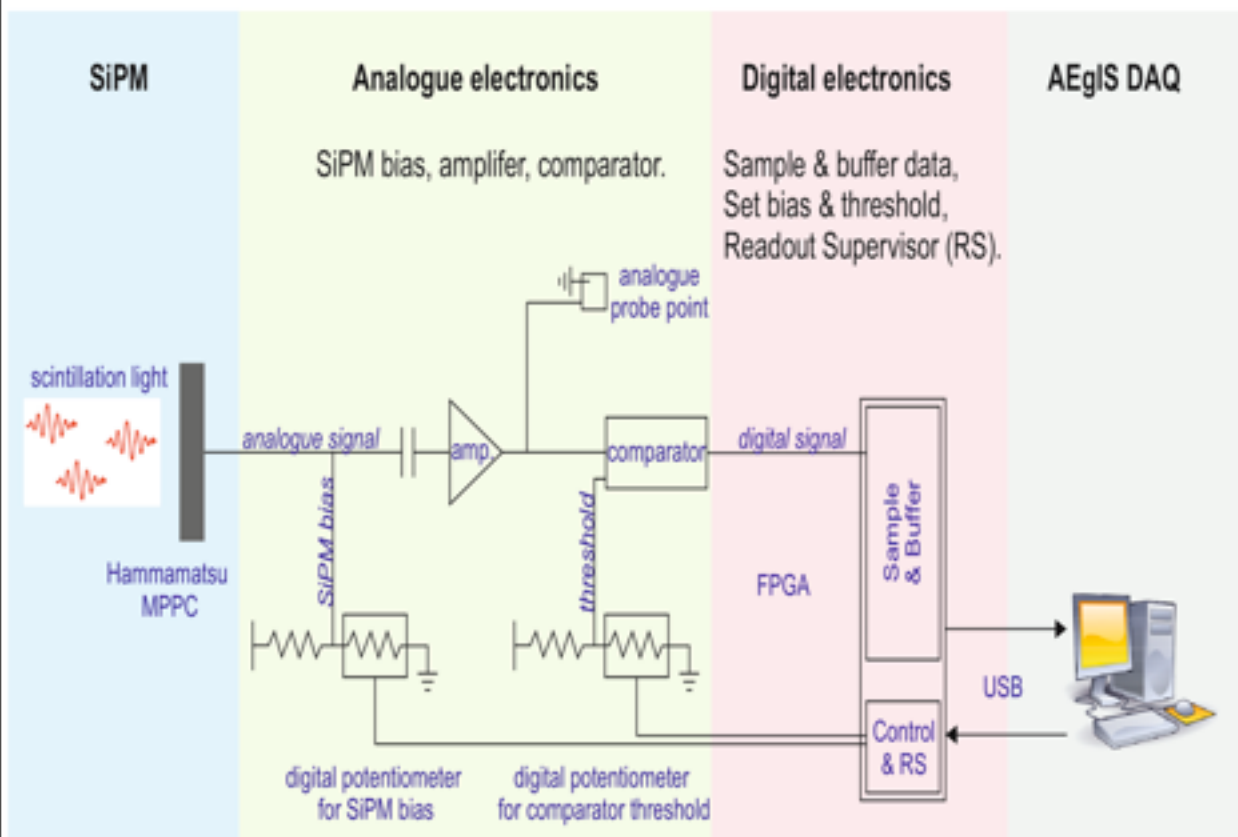
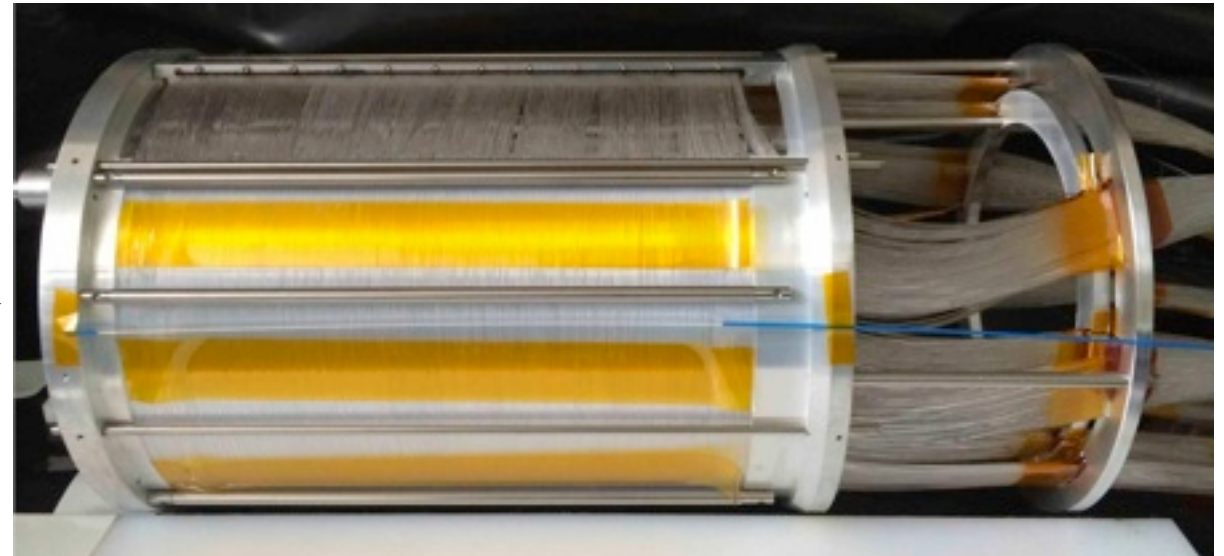
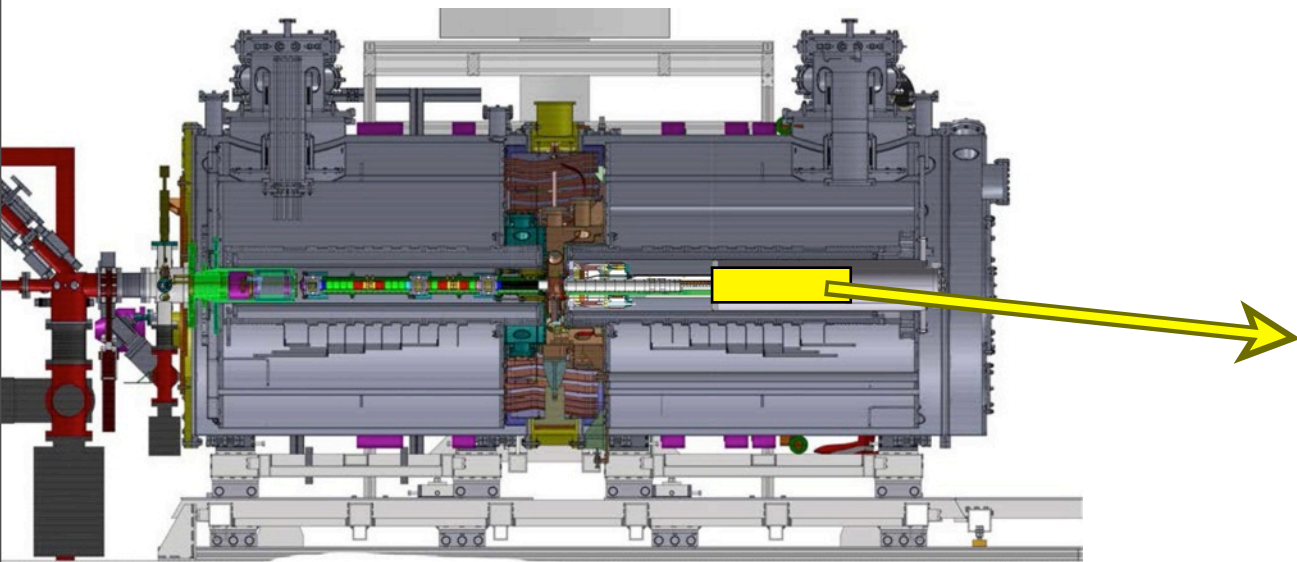


field-ionizing electrodes + MCP /  
Faraday cup + optics + CCD camera



commissioned with electrons, antiprotons, positrons

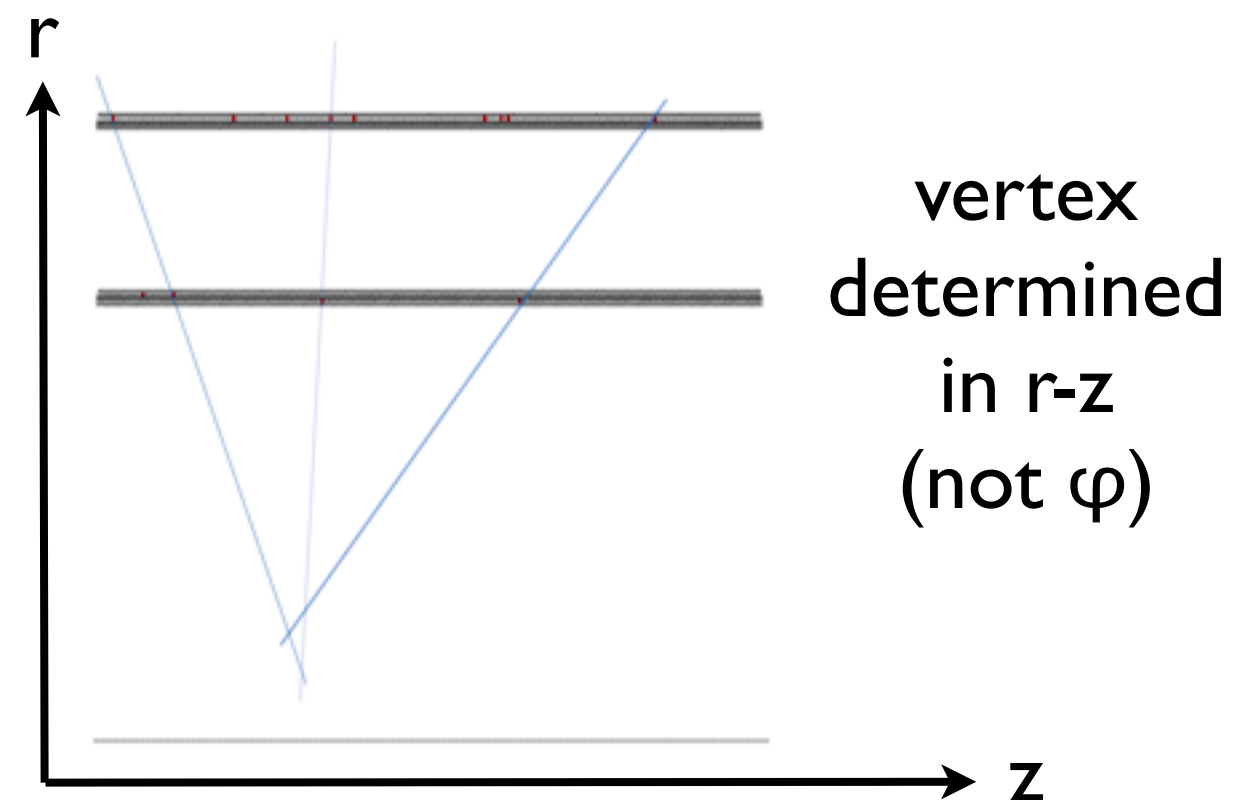
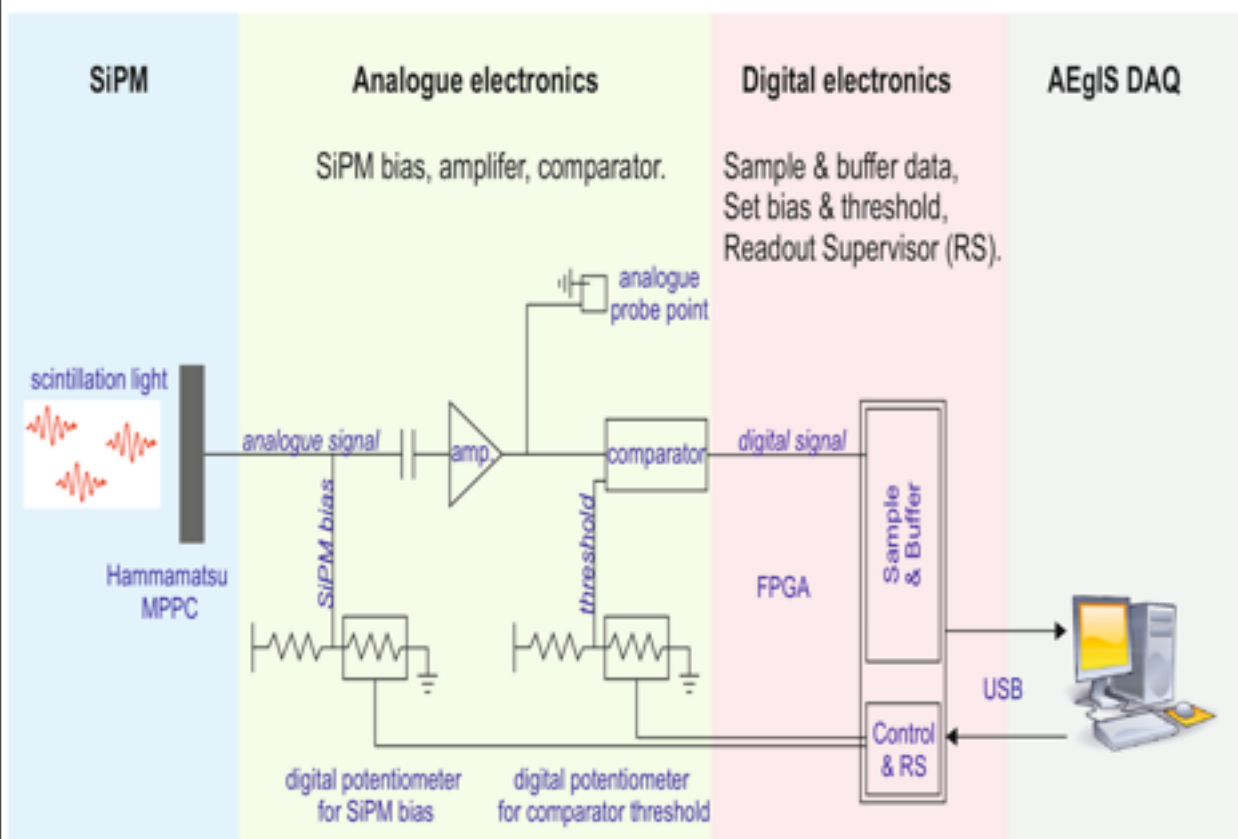
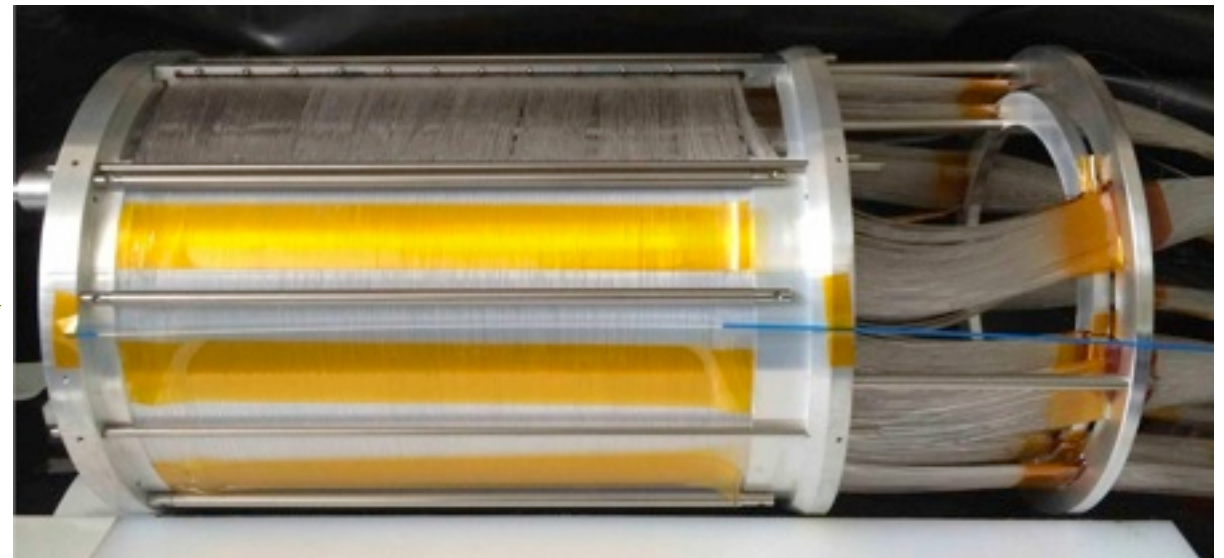
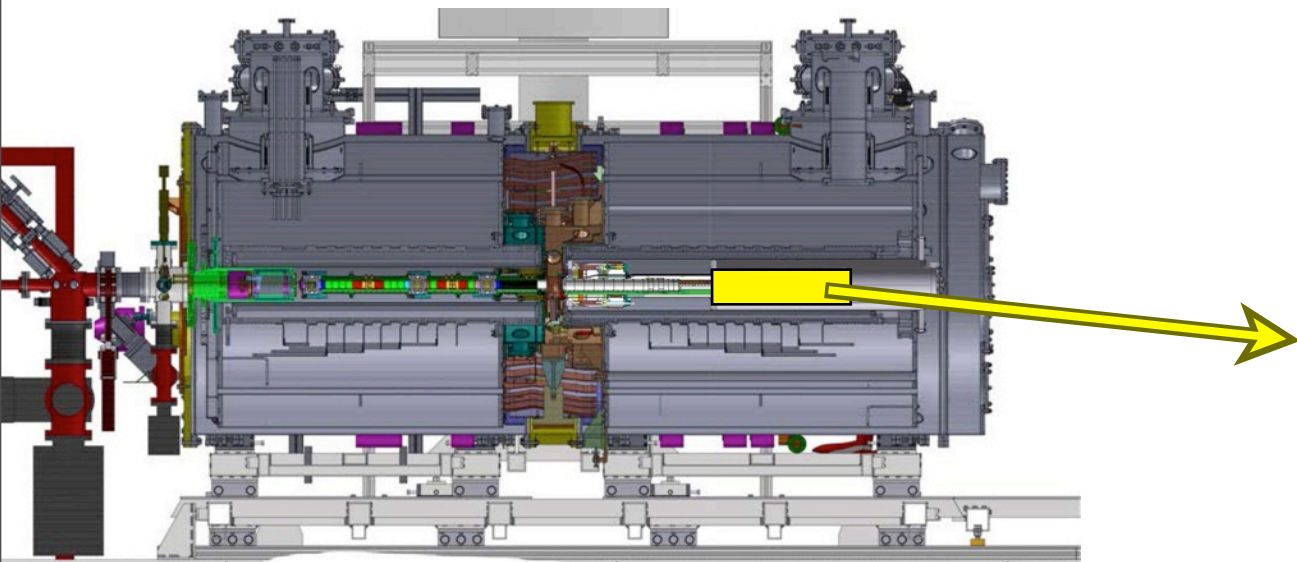
# “new” equipment: central antihydrogen detector



commissioned with antiprotons; analysis of vertexing is in progress



# “new” equipment: central antihydrogen detector



commissioned with antiprotons; analysis of vertexing is in progress



# Antiproton runs: 2014 (Oct - Dec)

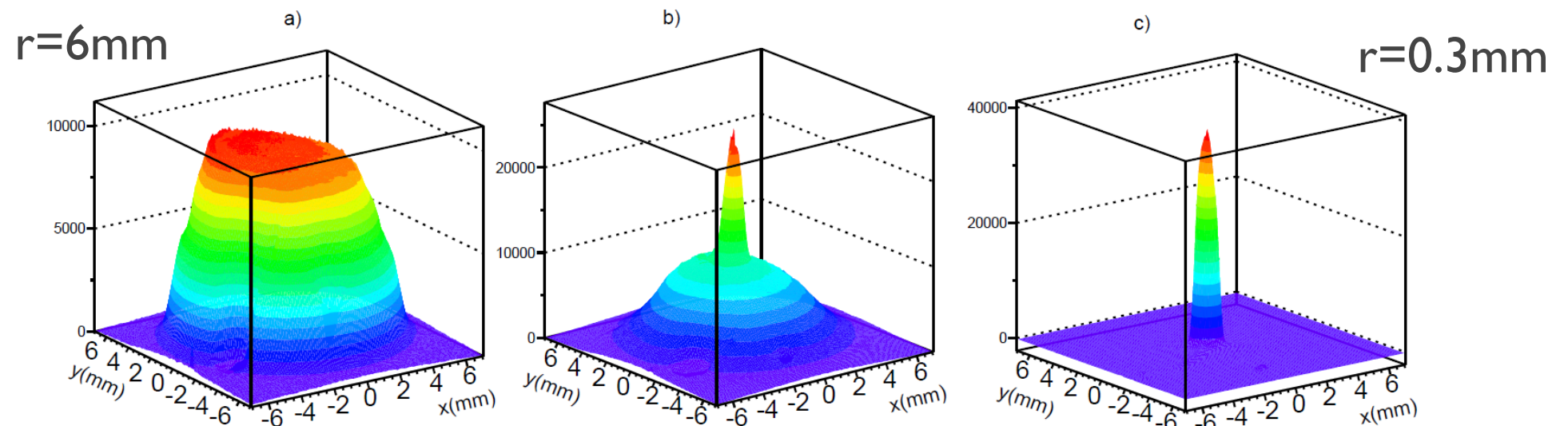
**goal:** implement all steps needed to produce antihydrogen:

cooling in 5T, compression in 5T, transfer into IT, compression in IT, transfer into production trap,

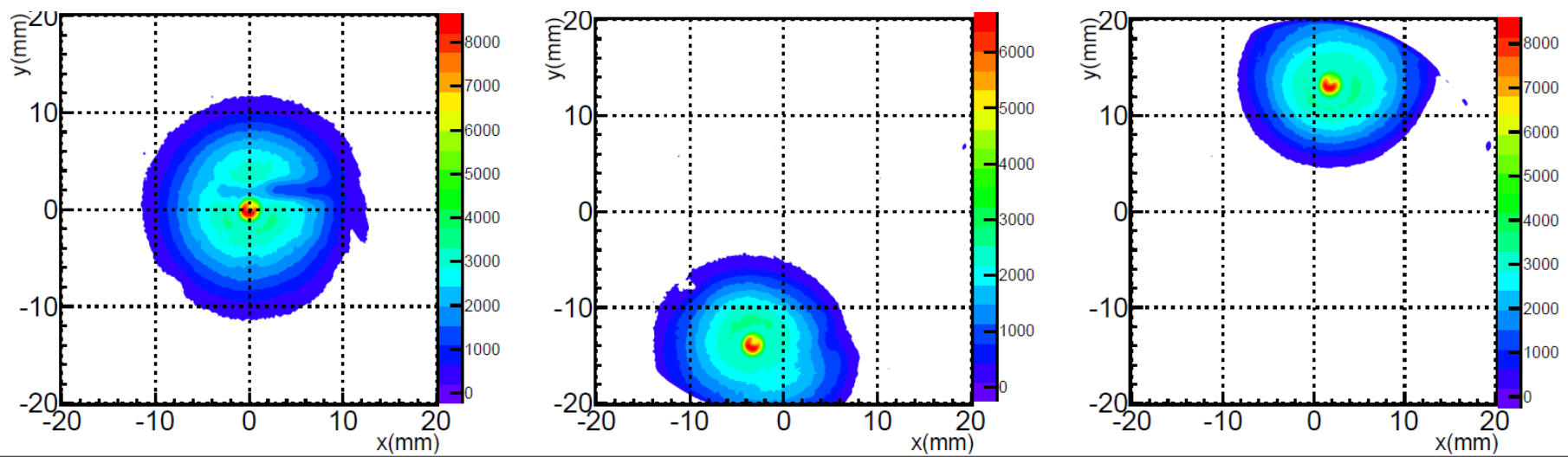
diagnostics, understanding of plasma processes and characteristics

**Electrons:** plasma manipulations already exercised in spring 2014:

rotating wall



diocotron  
excitation

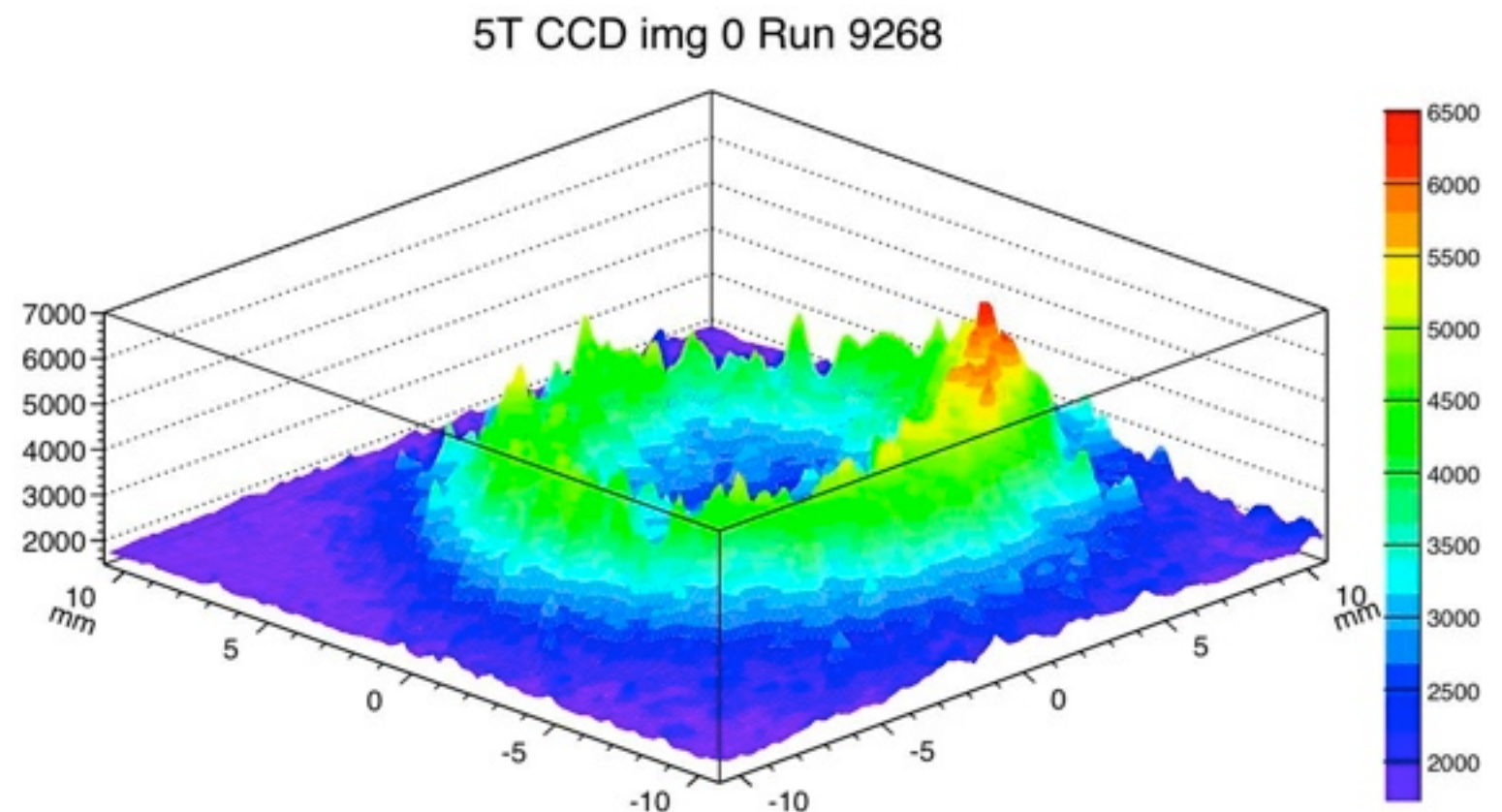


# Direct imaging of antiprotons on MCP (study of interactions between antiprotons and electrons: cooling, compression, ...)

Centrifugal separation observation:

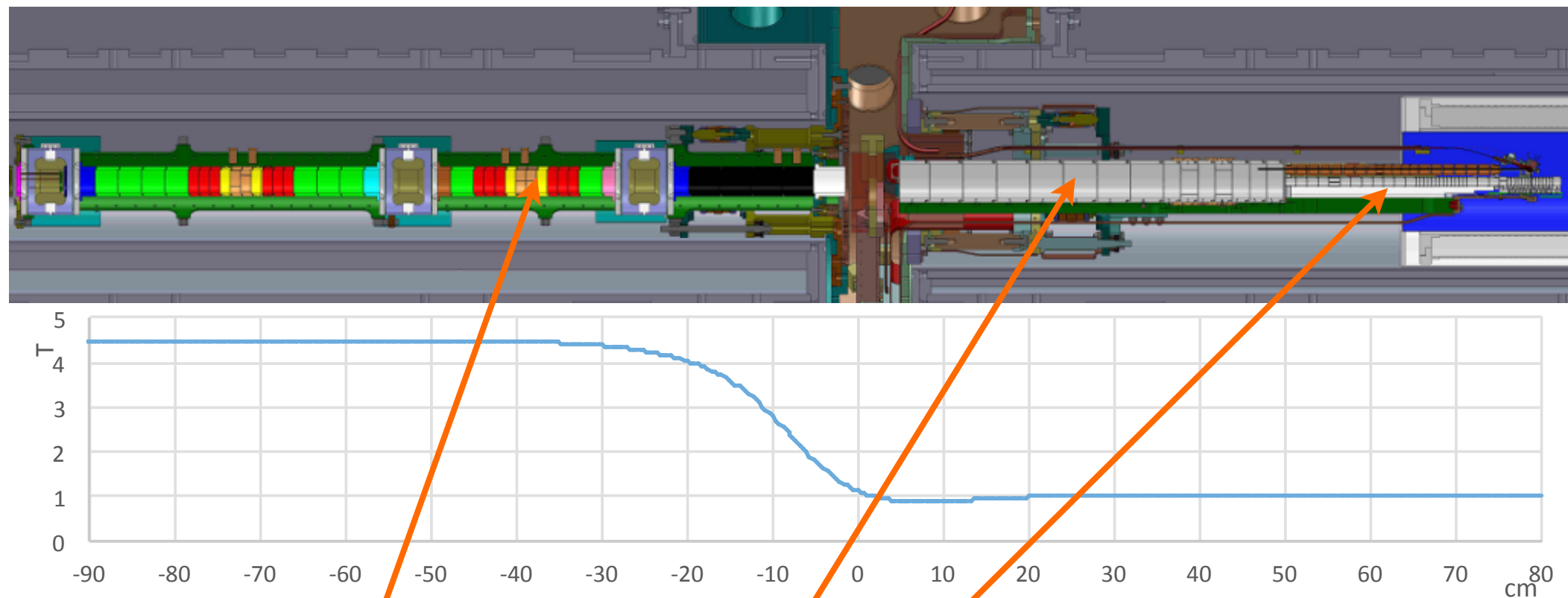
- ⇒ Allows for temperature estimate
- ⇒ from measured  $e^-$  density we estimate  $T_{\min}$  which corresponds to traps' temperature of 10K

$$KT_{\min} = \frac{1}{8\epsilon_0^2} m_p q^2 \left( \frac{nr}{B} \right)^2$$



# Transfer of antiprotons from 5T to 1T trap

## Challenge:



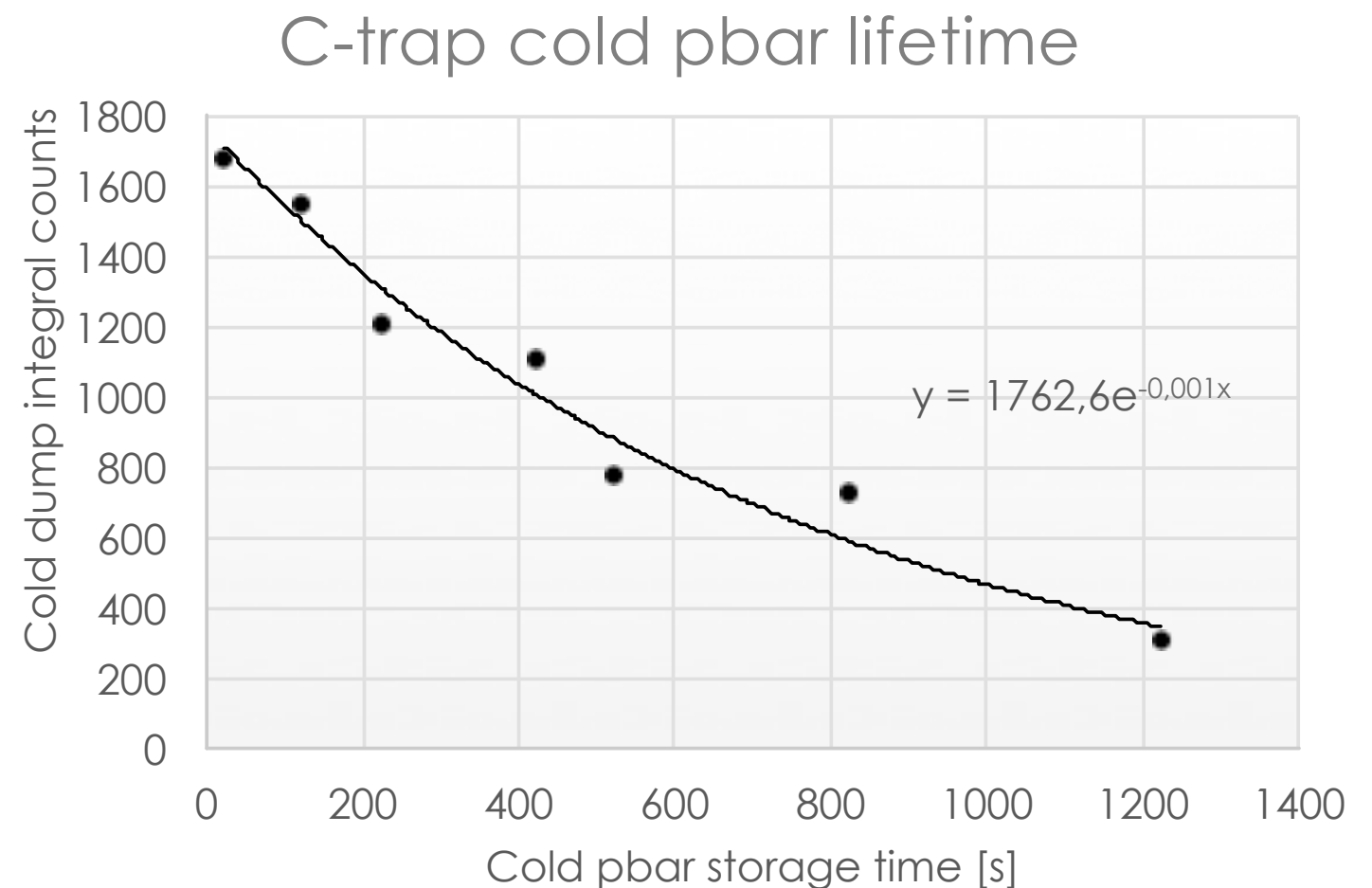
Transfer of antiprotons (with  $e^-$ ) “adiabatically”

- within 5T trap no losses
- from 5T C-trap to 1T large radius trap: no losses after optimization
- transfer to On-axis trap: strongly depends on prior antiproton compression and needs more optimization (  $\leq 60\%$  transfer efficiency)



# Lifetimes of (cold) antiprotons in 5T, 1T region

- 5T Catching trap:  $\tau \approx 1000\text{s}$  (close to the gas flux from the RT region)
- 1T large radius trap: no significant losses observed within 1 hour

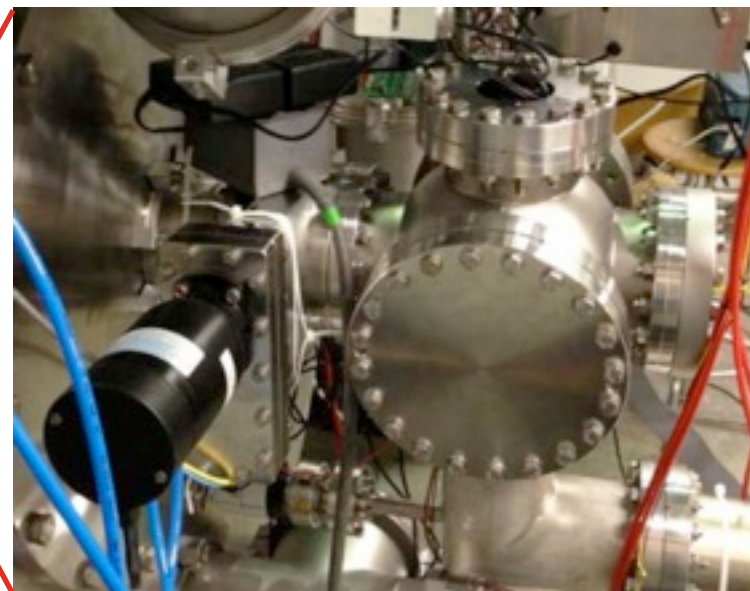
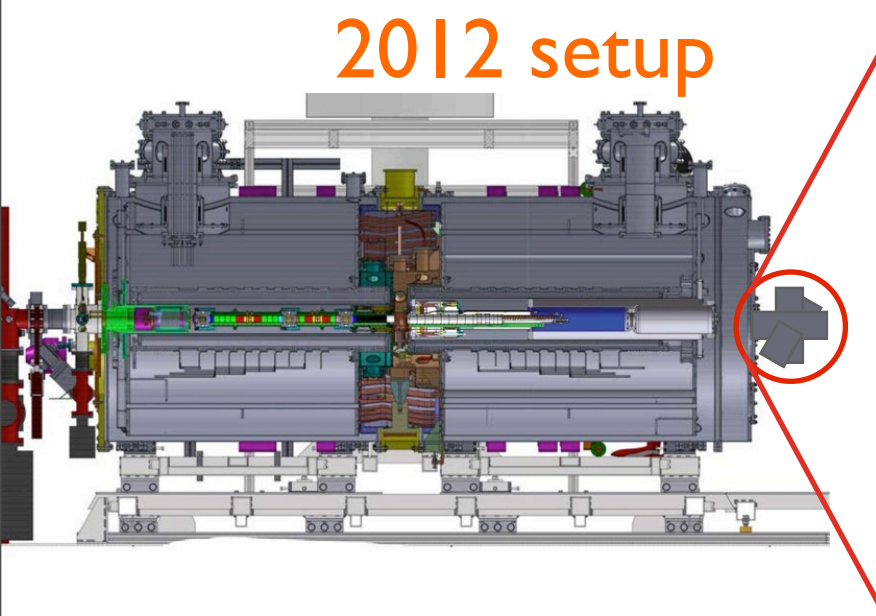
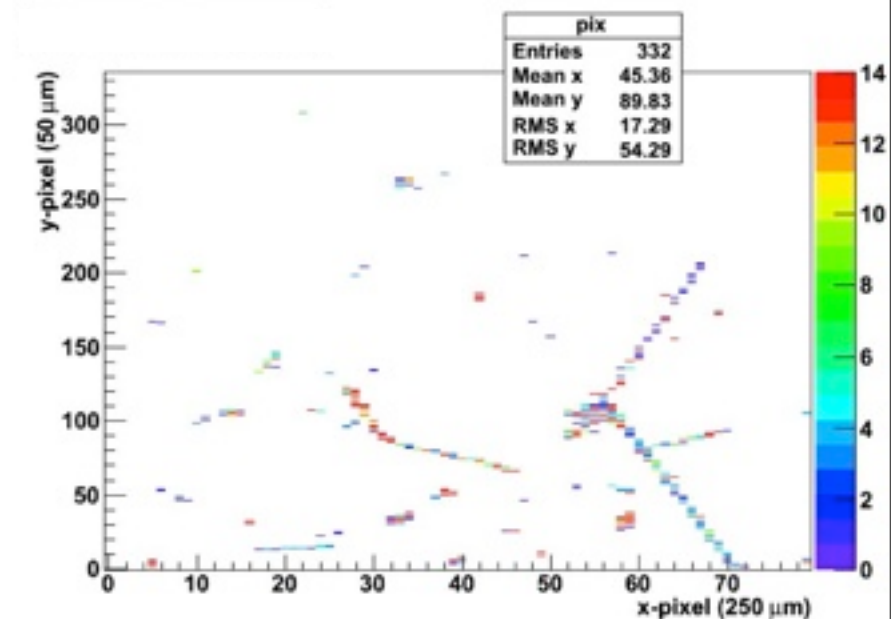
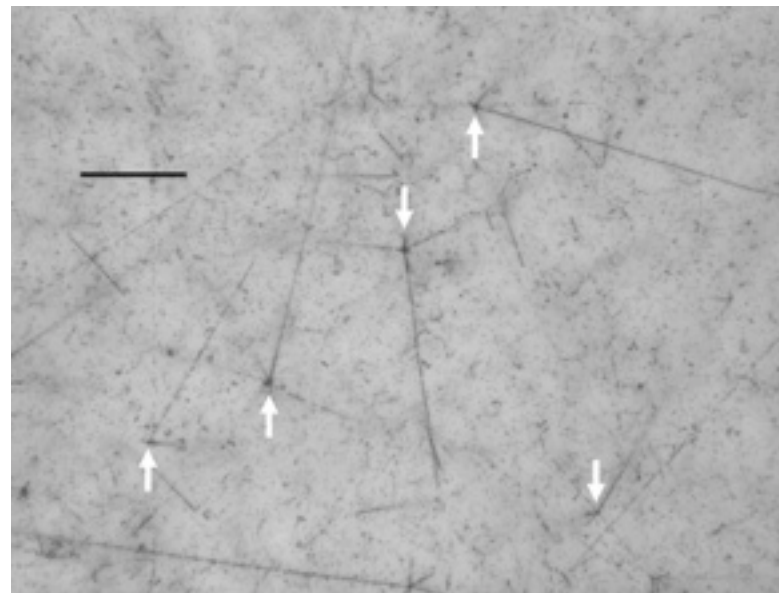
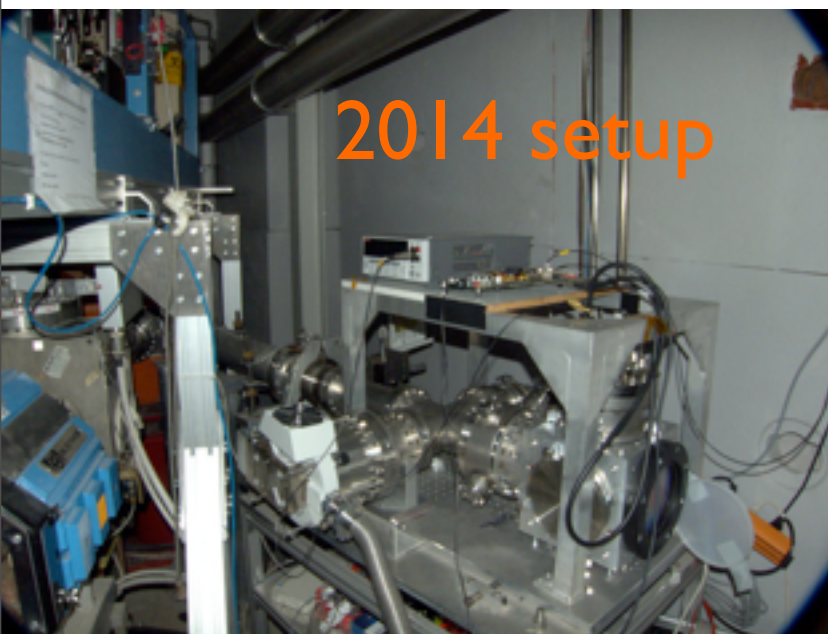


# Antiproton runs: 2014 (and data from Dec. 2012)

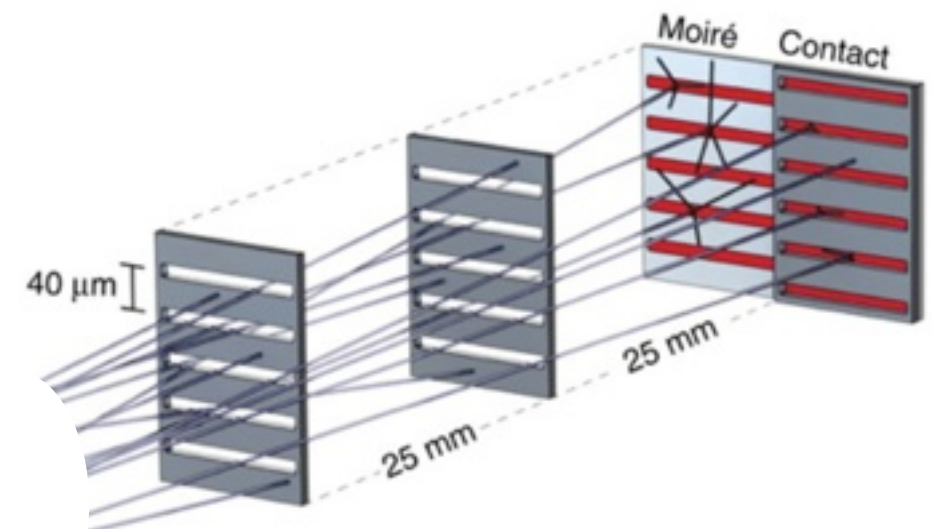
**Parasitic tests:** explore/validate different candidate technologies for the (downstream) antihydrogen detector by annihilating (low energy) antiprotons in the detectors

emulsions

Silicon detector

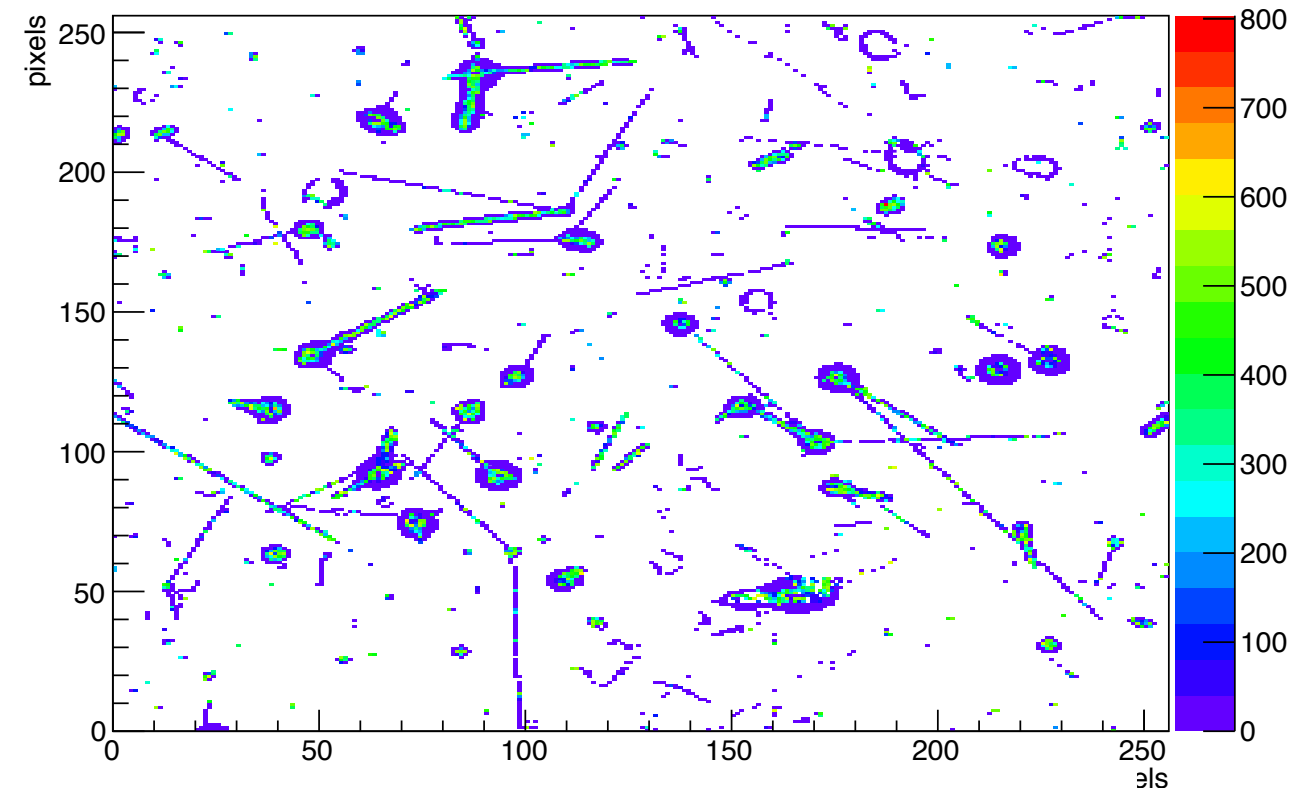
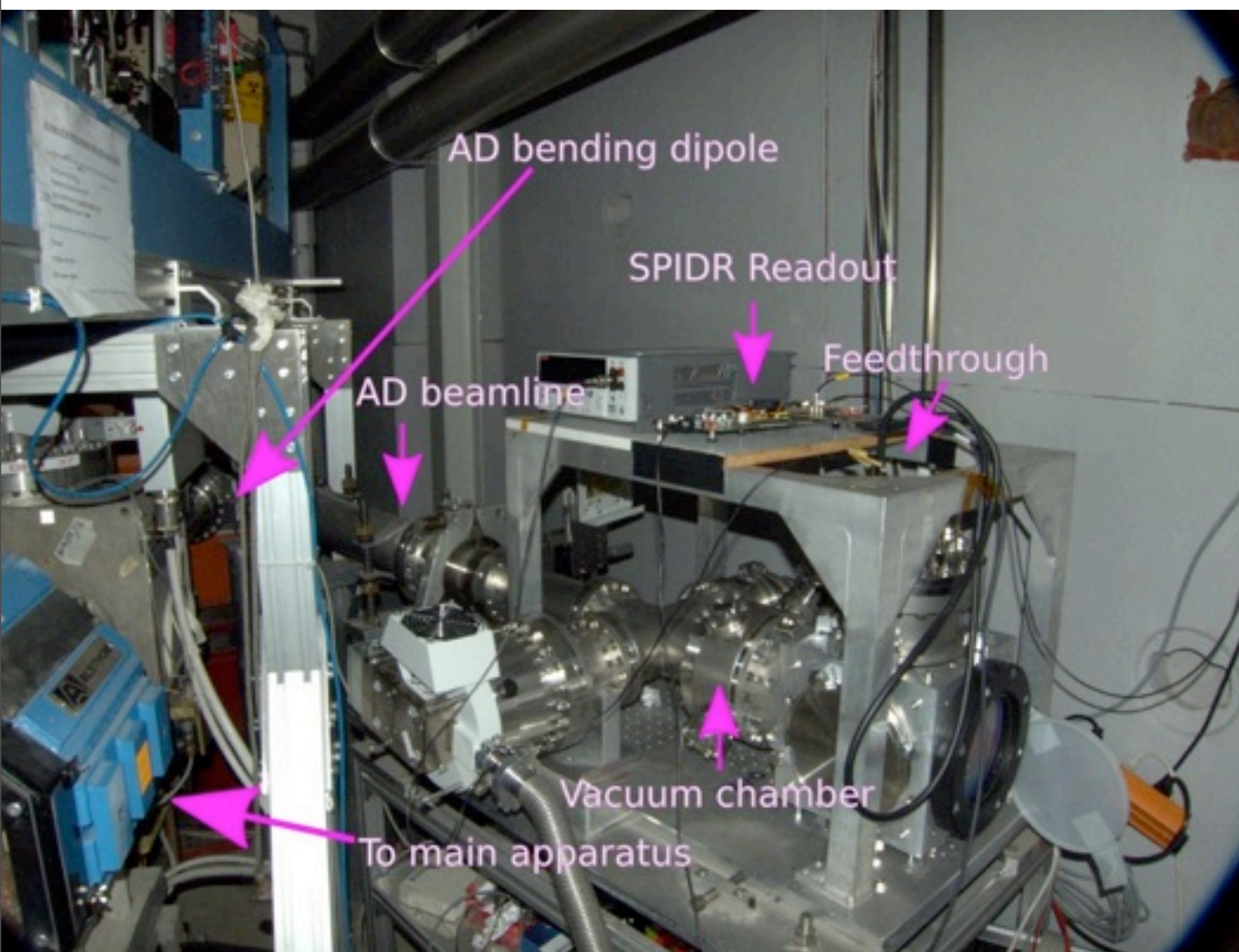


moiré deflectometer

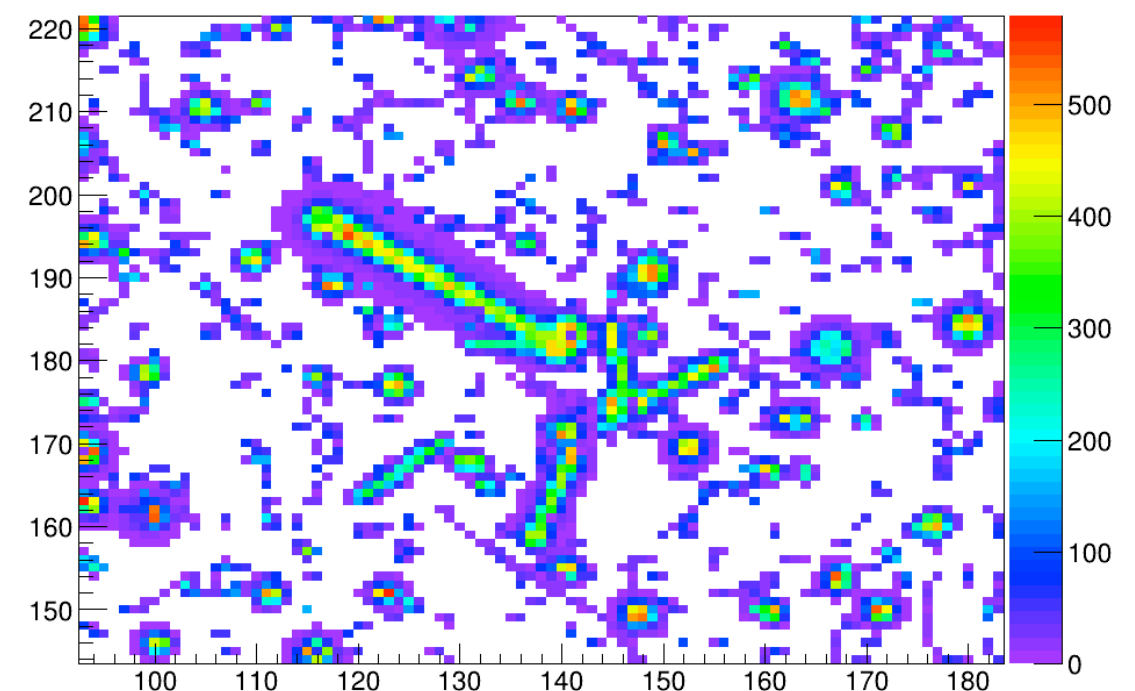




Silicon detectors: Timepix3 (high dynamic range, granularity (55  $\mu\text{m}$ ), time resolution (1.2 ns)) + 300  $\mu\text{m}$  sensor



zoom for another shot (adjacent vertices)



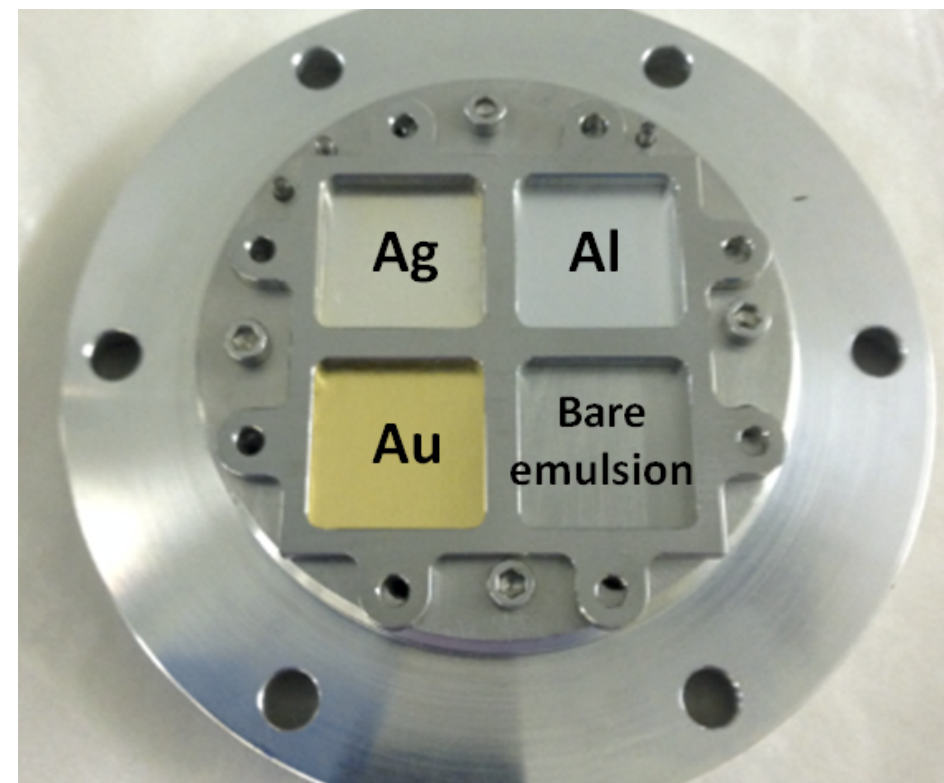
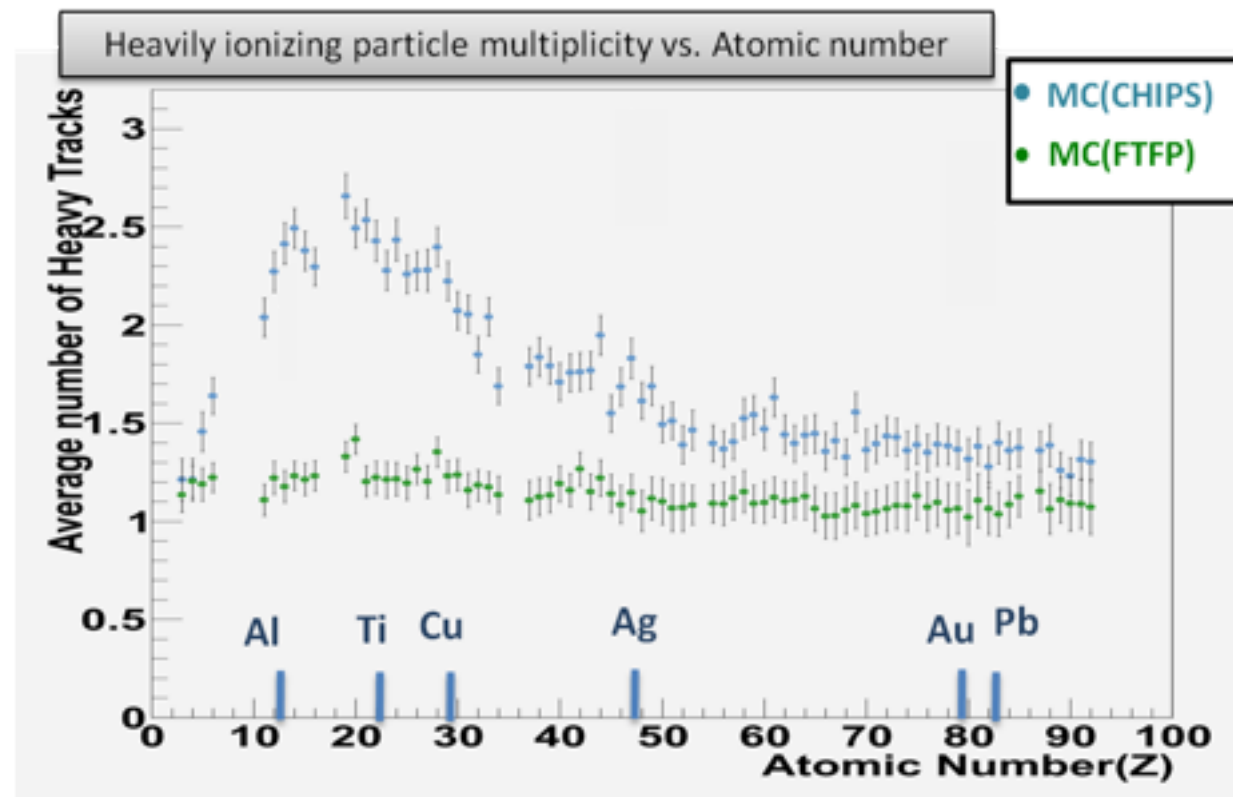
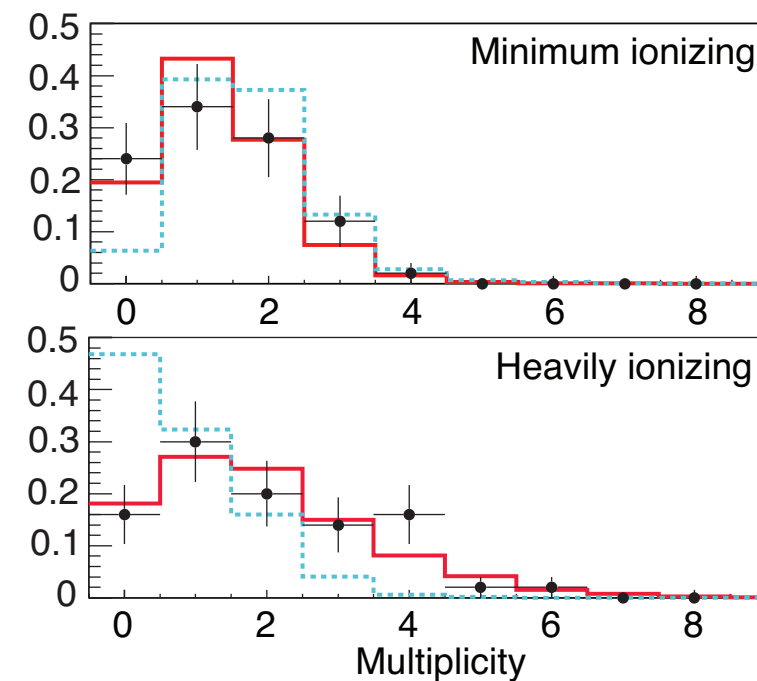
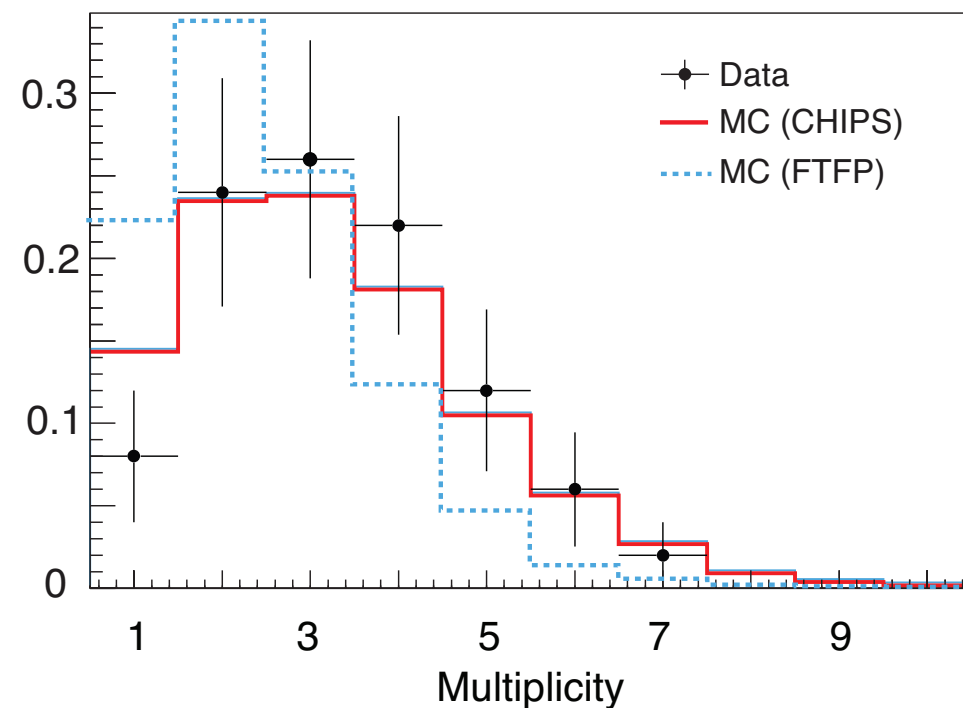
- cluster size, energy deposit
- compare with Geant4 (fragmentation models): fragment ID, range, ...
- improved vertex association to emulsion in hybrid detector ( $\sigma \sim 20 \mu\text{m}$ )



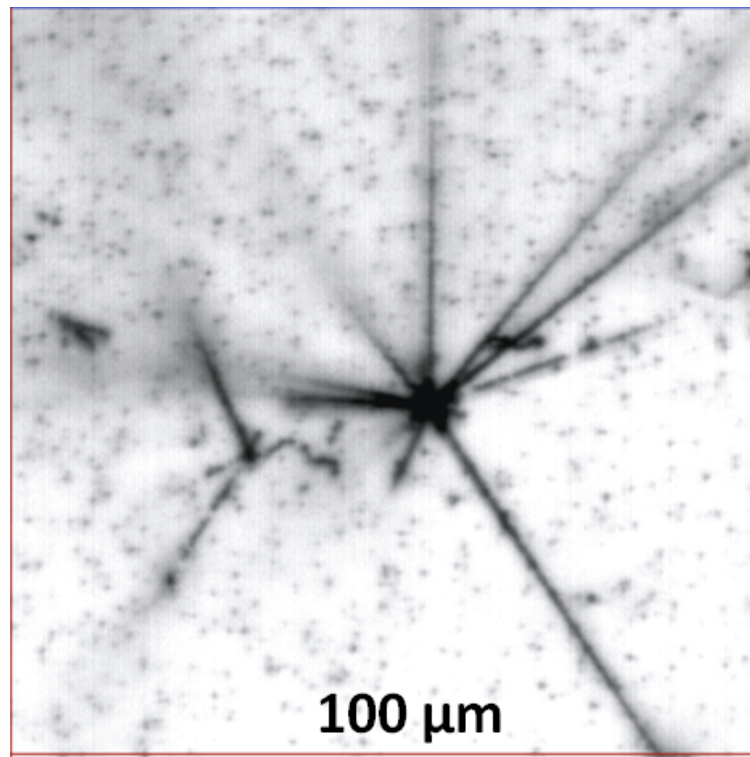
# Emulsion: annihilation in emulsion & in thin foils of different composition

2012 parasitic measurements:

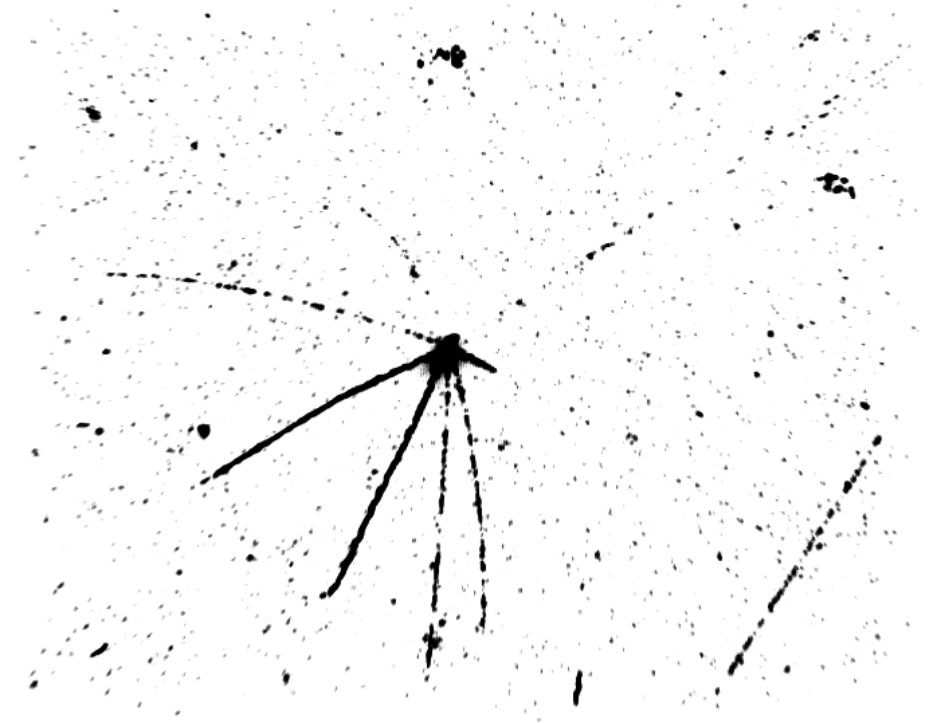
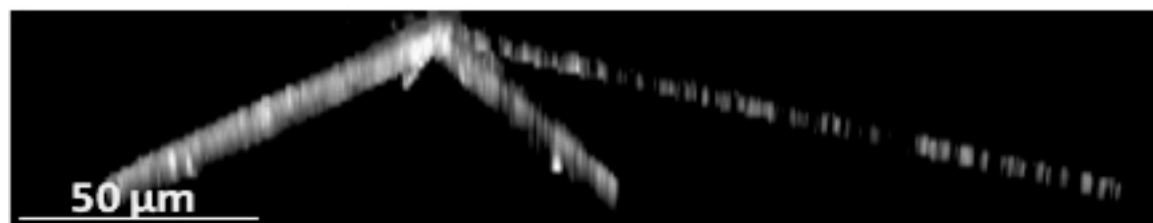
comparison of data (# of strongly ionizing fragments) with Geant4



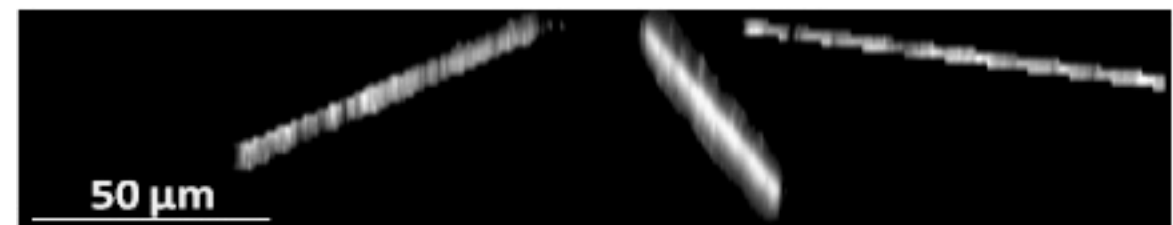
Emulsion: annihilation in emulsion & in thin foils of different composition  
thick emulsion film (300  $\mu\text{m}$ )  $\Rightarrow$  range curves, fragment ID



annihilation in emulsion (side view)



annihilation in Gold (side view)

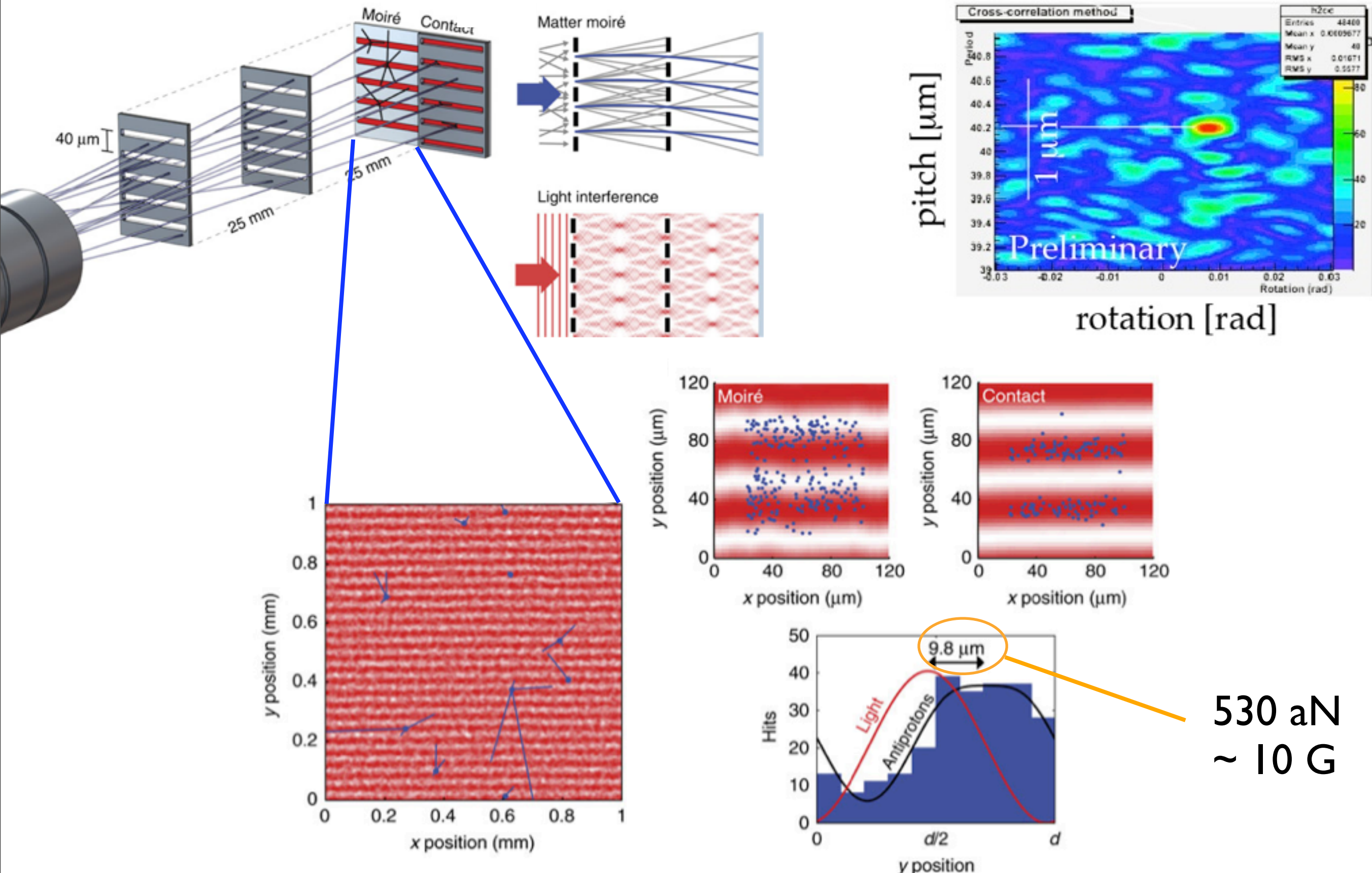


Analysis of different targets (with between 500 and 2000 annihilations per target material) is under way



# Test of moiré deflectometer with antiprotons (2012)

353 vertices in  $\sim 1\text{ cm}^2$



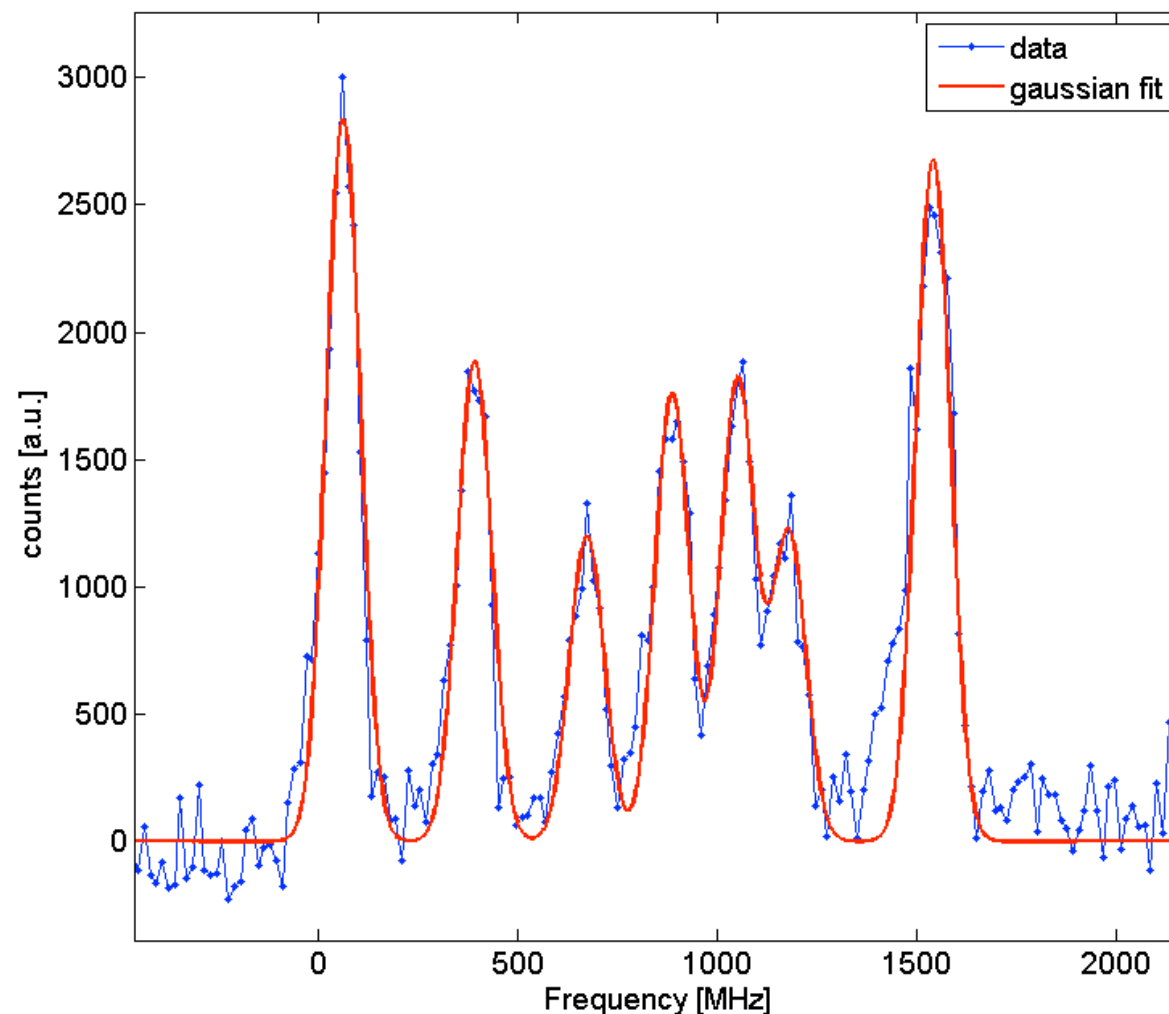
First demonstration of the moiré deflectometer technique with antiprotons

Nature Comm. 5:4538 (2014)



In parallel: work on laser-cooling of anions  
(  $\rightarrow$  sympathetic cooling of antiprotons)

- ongoing work in Heidelberg with  $\text{Os}^-$ ,  $\text{La}^-$
- stable, relatively intense  $\text{La}^-$  source: spectroscopy well advanced



- next: trapping, cooling of  $\text{La}^-$

## Outlook for 2015/2016

next months:

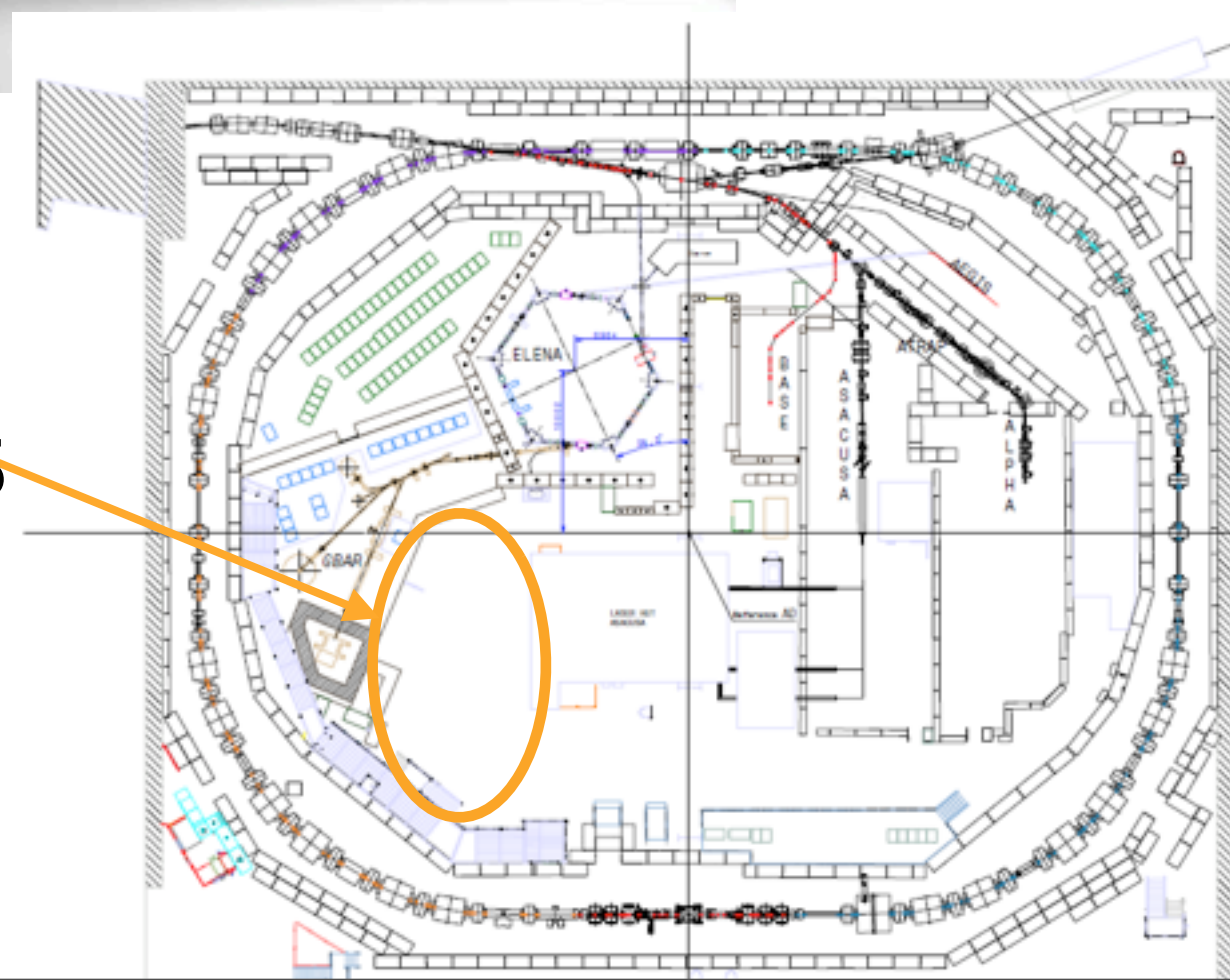
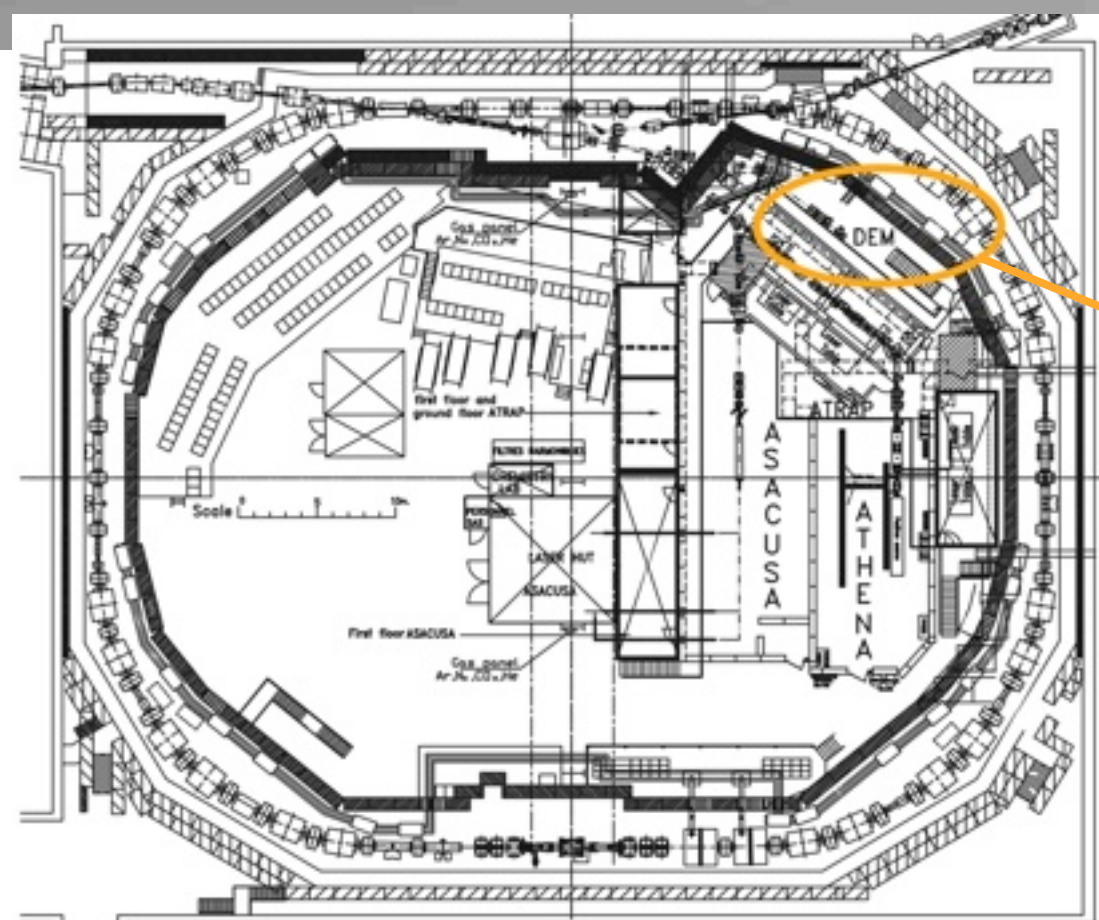
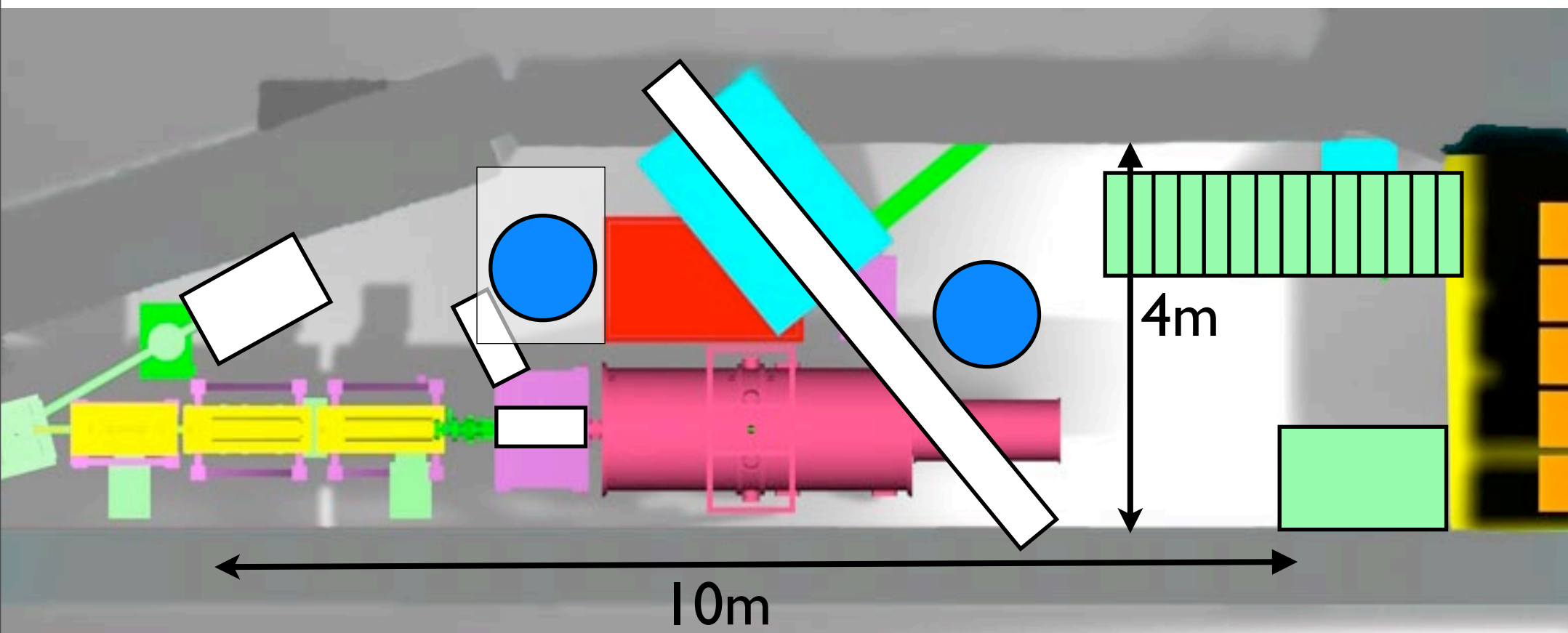
- prepare system for antiprotons (goal: ready in May)
- continue testing/commissioning apparatus with electrons, positrons
- finalize positronium test station commissioning (pulser optimization)
- Ps laser excitation and characterization (main laser, then secondary)
- commission detectors w/ electrons, positrons

remainder of year:

- work toward formation and characterization of Ps, Ps\*
- validate Ps characteristics (test station & in IT magnet)
- Ps spectroscopy (test station)
- work towards pulsed  $\bar{H}$  formation
- design work on downstream module (beyond IT magnet traps)
- R&D work on downstream antihydrogen detector
- R&D work on cooling of antiprotons

goal for 2015: pulsed formation of antihydrogen

## a longer-term issue: Zone layout





## Conclusion and outlook

Apparatus is now at the aimed-for operating point (temperature, vacuum)

Many procedures working, many remain to be commissioned

Work with antiprotons (and electrons, and positrons) extremely valuable in understanding the apparatus and commissioning all the steps required to from antihydrogen (pulsed, beam); now able to use protons as well

Parasitic measurements were very successful - essential information was obtained to design optimal deflectometer+detector layout; will be pursued

We have had several very busy years, and 2015 / 2016 will not be any easier, requiring a sustained effort with the now-existing infrastructure.

beam request for 2015 (& 2016): pro rata share of the antiproton beam

request for 2017 (start of ELENA): move apparatus to new larger zone

End of slides