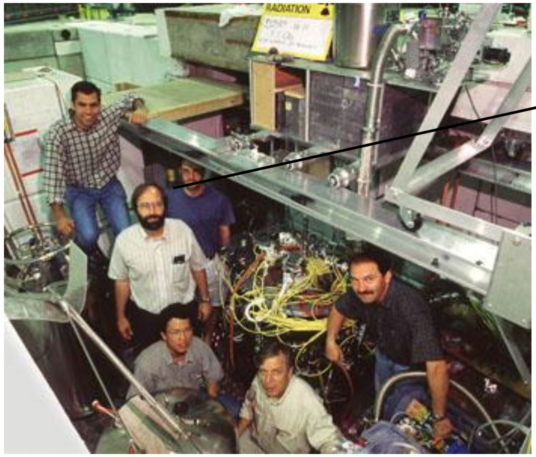
Detectors for Trap Experiments

by
G. Khatri
(ATRAP Experiment, CERN)

Outline

- First trap for antimatter: brief history
- ATRAP Experiment
- Detectors at ATRAP
  - Annihilation (destructive) detectors
  - Alignment/steering detectors
  - ~~Non-destructive (image current based) detectors~~
  - Diagnostics: Imaging (MCP+Phosphor+camera), ~~Counting (FC), Plasma modes (RW)~~
  - Recent and future upgrades
  - ~~.... (e.g. Laser and microwave excitation)~~
- Summary

>30 Years Since We First Trapped and Then Cooled Antiprotons



ATRAP@CERN, year 2000

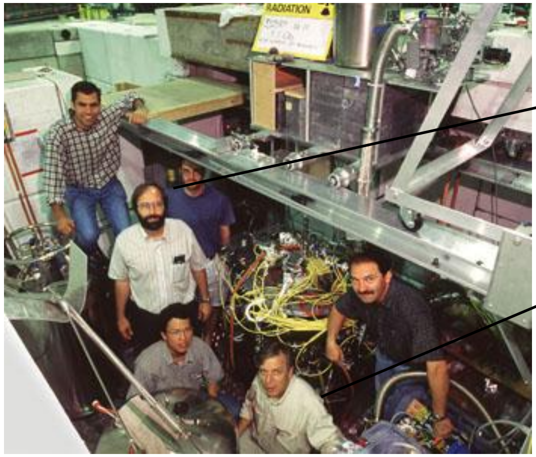
G. Gabrielse (to trap the first anti-protons)

1986 – headed to CERN and trapped the first antiprotons

1986 – proposed making cold antihydrogen from cold antiprotons and positrons
– proposed trapping cold antihydrogen for study (a radical new direction at the time)

-- electron cooling,
-- trapped single antiproton for months
-- nested Penning trap, …

>30 Years Since We First Trapped and Then Cooled Antiprotons



ATRAP@CERN, year 2000

G. Gabrielse (to trap the first anti-protons)

W. Oelert (first “hot” anti-hydrogen)

1986 – headed to CERN and trapped the first antiprotons

1986 – proposed making cold antihydrogen from cold antiprotons and positrons
– proposed trapping cold antihydrogen for study (a radical new direction at the time)

-- electron cooling,
-- trapped single antiproton for months
-- nested Penning trap, …

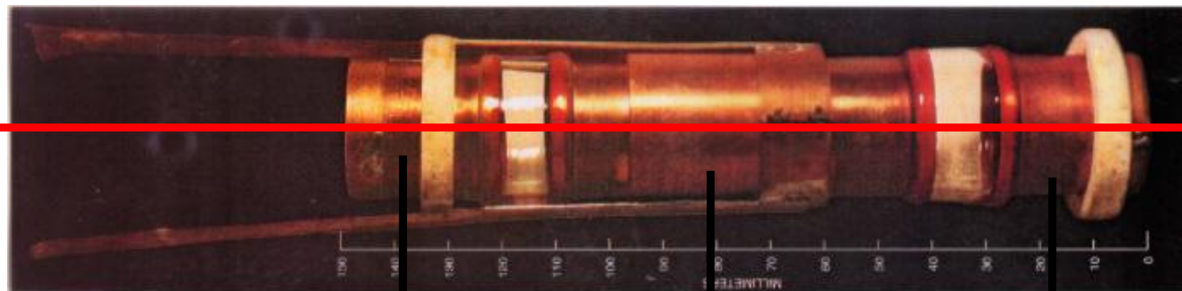
ATRAP@CERN, year 2016

>30 Years Since We First Trapped and Then Cooled Antiprotons

TRAP Collaboration
at CERN's LEAR

1 cm

magnetic
field



21 MeV
antiprotons

−

+

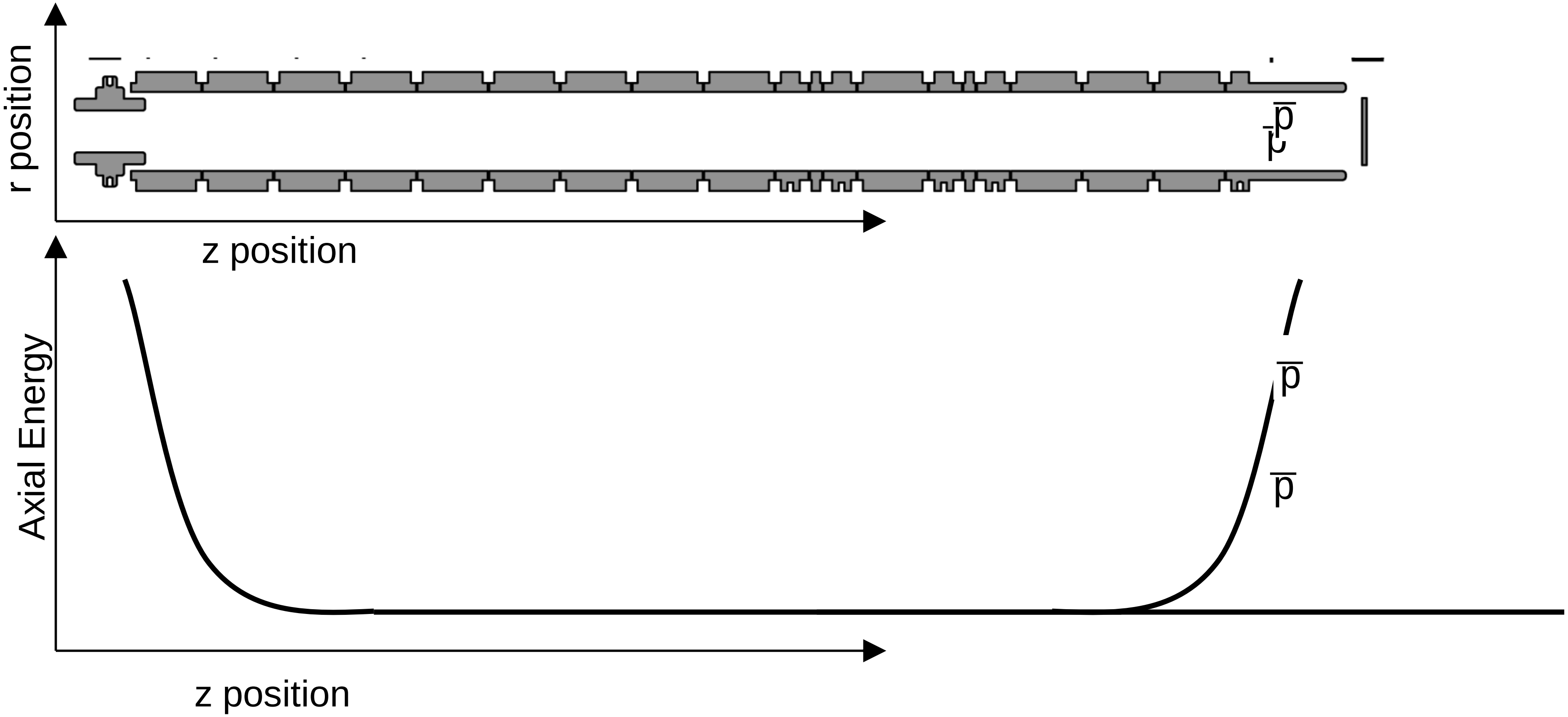
−

10^{-10}
energy
reduction

- **Slow antiprotons in matter**
- **Capture antiprotons in flight**
- **Electron cooling → 4.2 K**
- **5 x 10^{-17} Torr**

Now used by 5 collaborations
at the CERN AD
ATRAP, ALPHA, ASACUSA,
AEGIS, BASE and GBAR

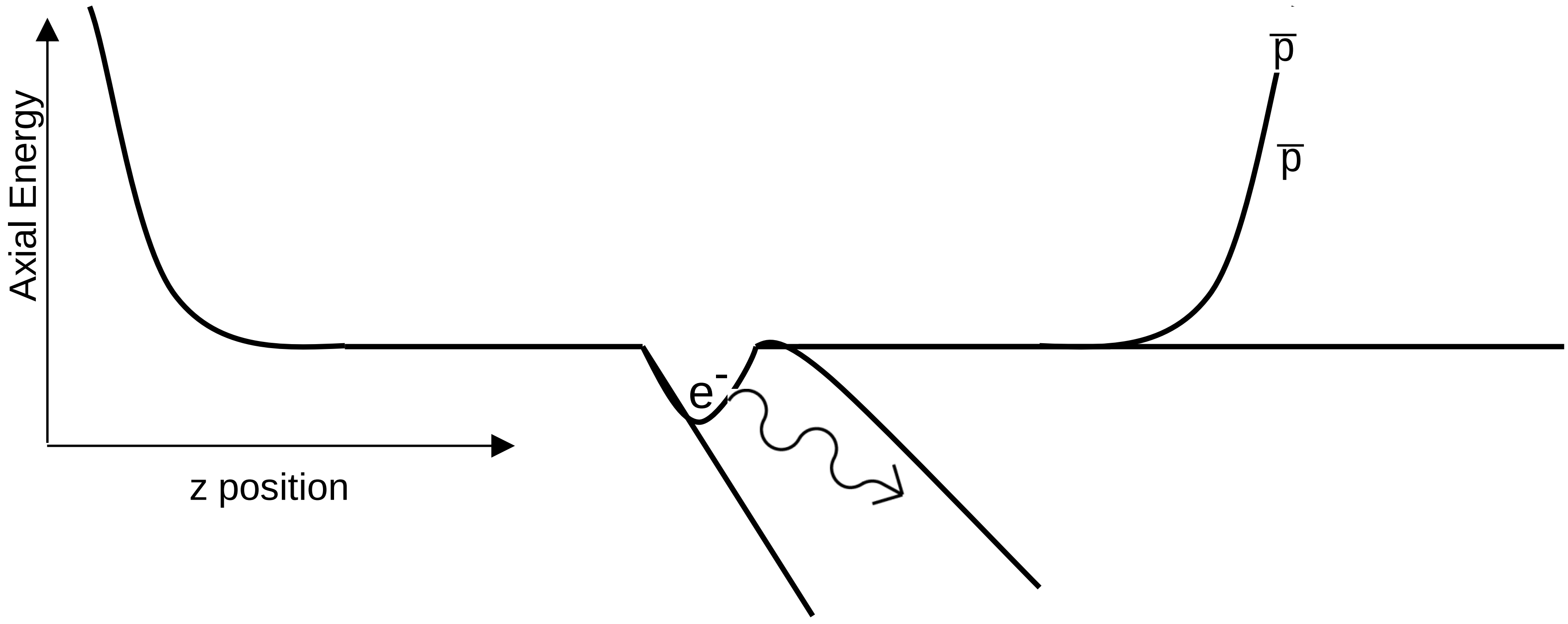
Antiproton Capture – the Movie



"First Capture of Antiprotons in a Penning Trap: A KeV Source",
G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker, T.A. Trainor, H. Kalinowsky, J. Haas, and W. Kells;
Phys. Rev. Lett. 57, 2504 (1986).

Electron-Cooling of Antiprotons – in a Trap

- Antiprotons cool via collisions with electrons
- Electrons radiate away excess energy



"Cooling and Slowing of Trapped Antiprotons Below 100 meV",
G. Gabrielse, X. Fei, L.A. Orozco, R. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor, W. Kells;
Phys. Rev. Lett. 63, 1360 (1989).

Cold Antihydrogen

Proposal to Trap Cold Antihydrogen – 1986

- **Produce cold antihydrogen from cold antiprotons**

  "When antihydrogen is formed in an ion trap, the neutral atoms will no longer be confined and will thus quickly strike the trap electrodes. Resulting annihilations of the positron and antiproton could be monitored. ..."

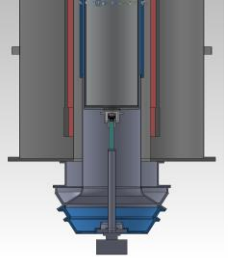
- **Trap cold antihydrogen**
- **Use accurate laser spectroscopy to compare antihydrogen and hydrogen**

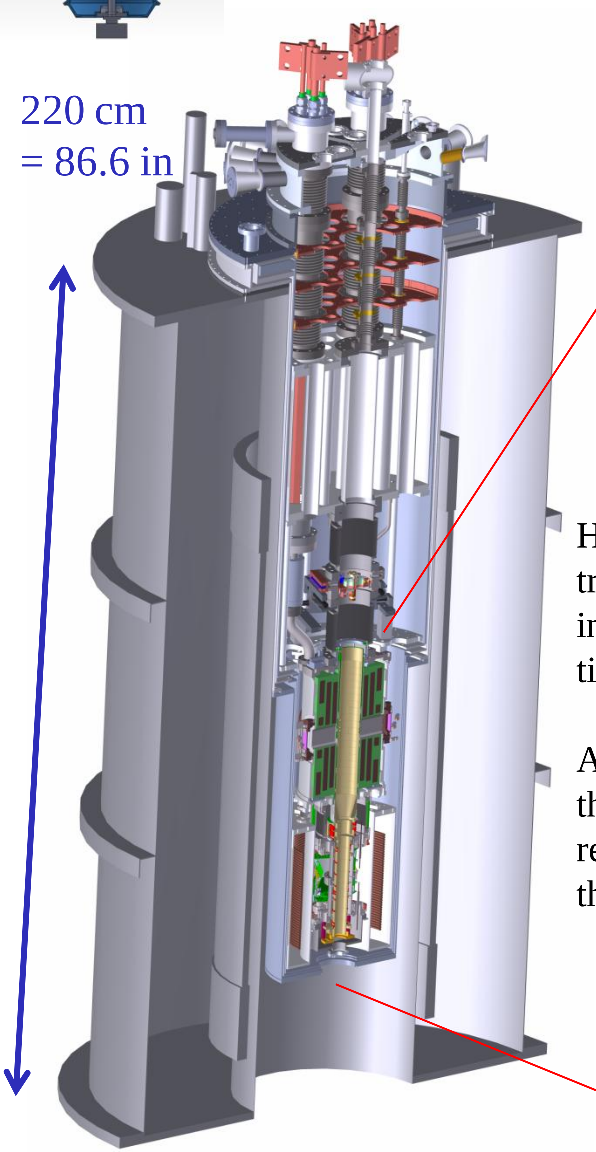
  "For me, the most attractive way ... would be to capture the antihydrogen in a neutral particle trap ... The objective would be to then study the properties of a small number of [antihydrogen] atoms confined in the neutral trap for a long time."

  Gerald Gabrielse, 1986 Erice Lecture (shortly after first pbar trapping)
  In **Fundamental Symmetries**, (P.Bloch, P. Paulopoulos, and R. Klapisch, Eds.) p. 59, Plenum, New York (1987).

(A radical new direction at the time.)

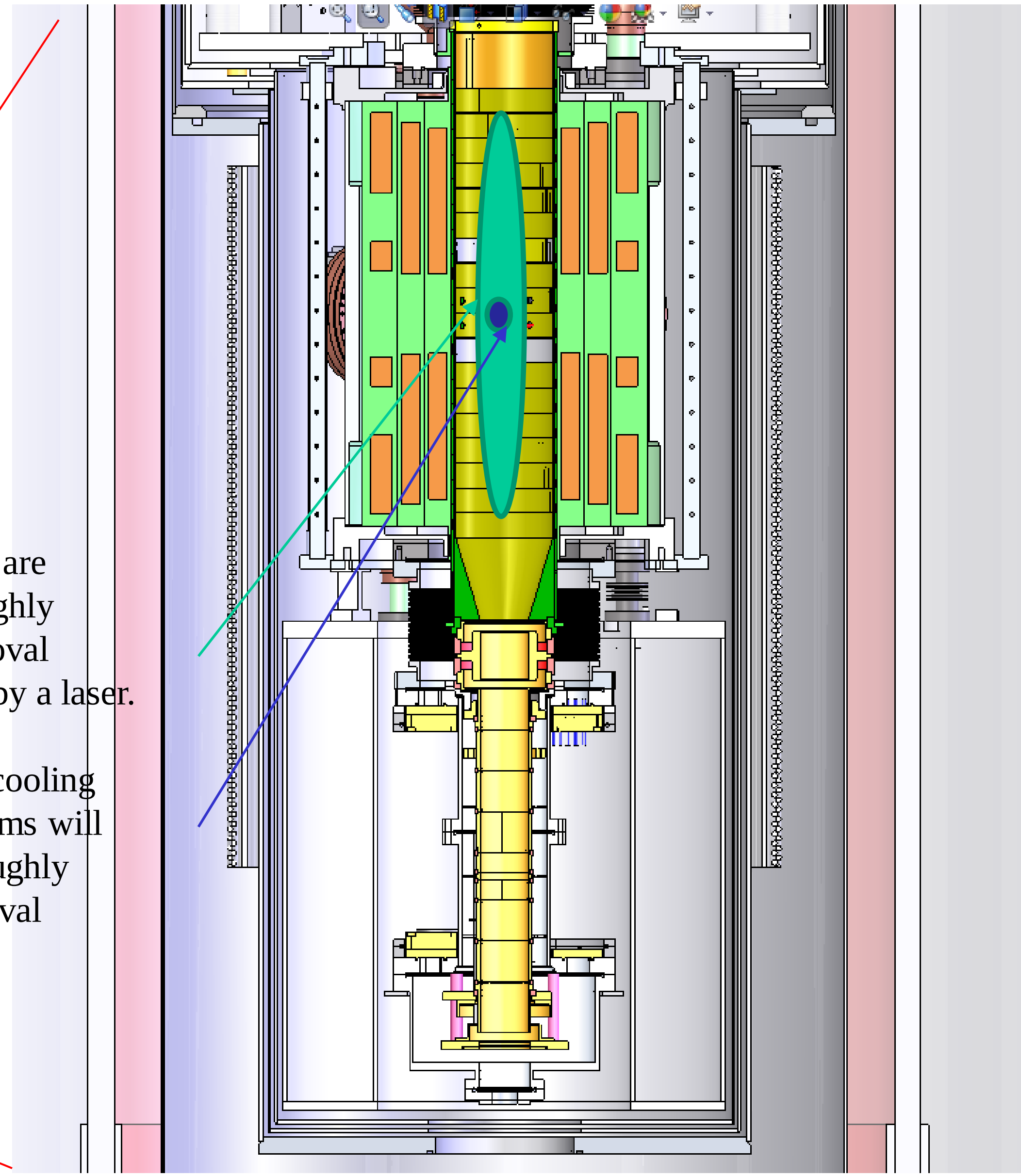
full stack in magnet and insert dewar with fiber detectors



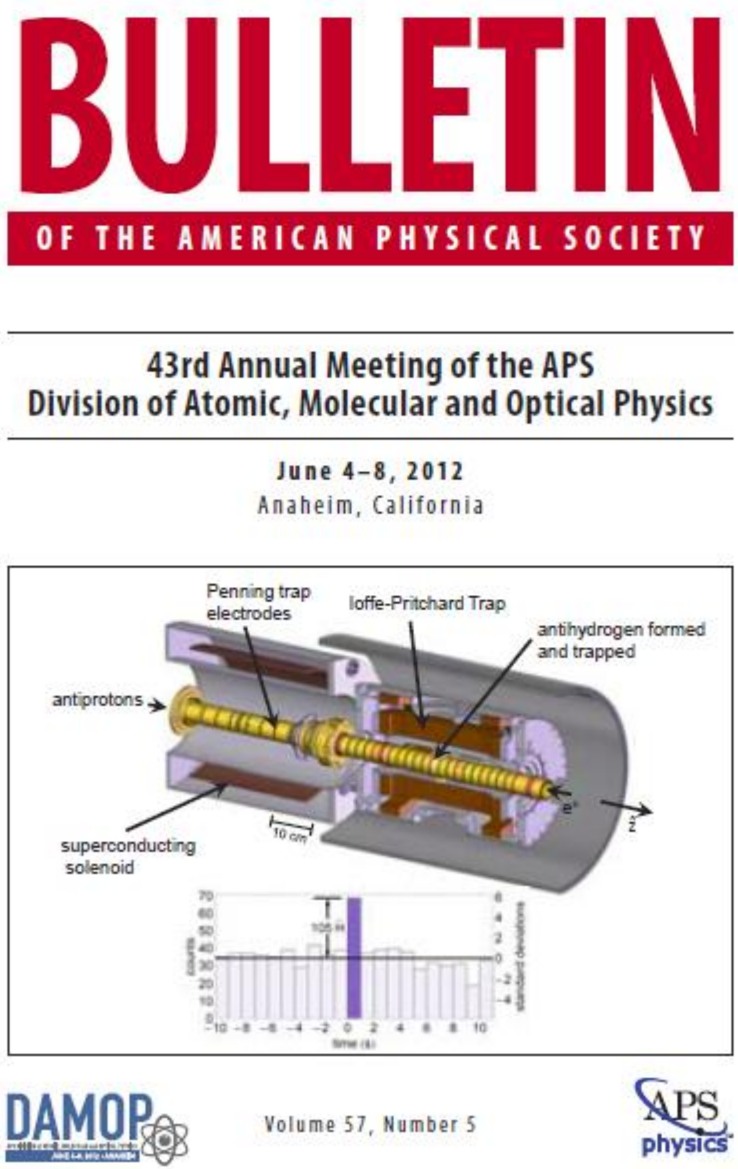


Hbar atoms are trapped roughly in the blue oval till ionized by a laser.

After laser cooling the hbar atoms will reside in roughly the brown oval



Gen. I trap: Most Trapped Hbar Per Trial



5 +/- 1 ground state atoms
simultaneously trapped

Expect more with 2nd generation Ioffe trap

Enough to demonstrate 3-d Lyman alpha laser cooling (with 2nd generation trap)

Need more atoms/trial

ATRAP, “Trapped Antihydrogen in Its Ground State”, Phys. Rev. Lett. **108**, 113002 (2012)

Goals of ATRAP Collab.

- ATRAP wants to produce large number of trapped Hbars in ground state
- Laser cool them (on 3 axis), we have Ly-alpha laser (0.5K to ~10 mK)
- Do precise 1S-2S spectroscopy

Check for updates

Letter Vol. 43, No. 12 / 15 June 2018 / *Optics Letters* 2905

Optics Letters

Lyman-α source for laser cooling antihydrogen

G. Gabrielse,[1,2] B. Glowacz,[3] D. Grzonka,[4] C. D. Hamley,[1] E. A. Hessels,[5] N. Jones,[1] G. Khatri,[1] S. A. Lee,[6] C. Meisenhelder,[1] T. Morrison,[1] E. Nottet,[2] C. Rasor,[6] S. Ronald,[6] T. Skinner,[5] C. H. Storry,[5] E. Tardiff,[1] D. Yost,[6] D. Martinez Zambrano,[2,*] and M. Zielinski[3]

[1]Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
[2]Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA
[3]Faculty of Physics, Astronomy, and Applied Computer Science, Jagiellonian University, 30-059 Krakow, Poland
[4]Forschungzentrum Juelich GmbH, D-52425 Juelich, Germany
[5]Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada
[6]Department of Physics, Colorado State University, Fort Collins, Colorado 80523, USA
*Corresponding author: daniel.mtzz@cern.ch

Received 1 May 2018; accepted 9 May 2018; posted 21 May 2018 (Doc. ID 328396); published 13 June 2018

We present a Lyman-α laser developed for cooling trapped antihydrogen. The system is based on a pulsed Ti:sapphire laser operating at 729 nm that is frequency doubled using an LBO crystal and then frequency tripled in a Kr/Ar gas cell. After frequency conversion, this system produces up to 5.7 μW of average power at the Lyman-α wavelength. This laser is part of the ATRAP experiment at the antiproton decelerator in CERN.

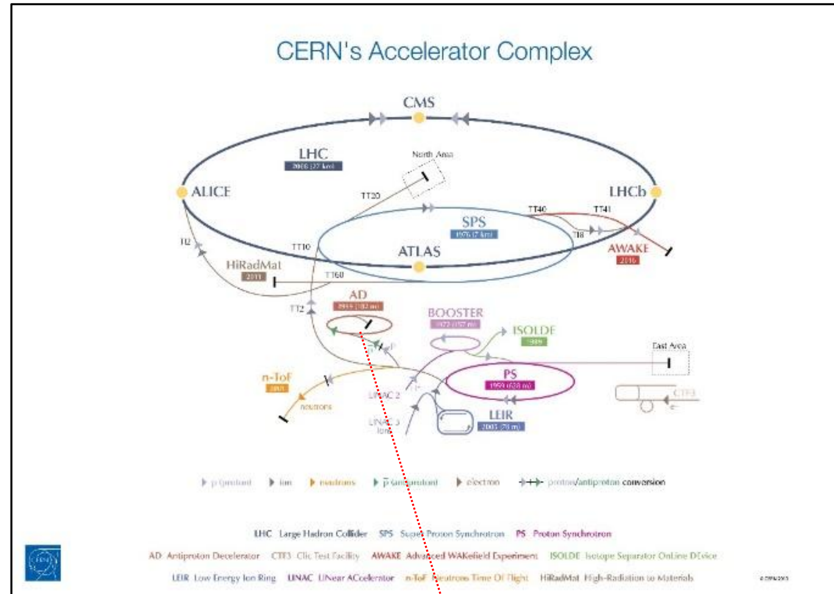
OCIS codes: (020.3320) Laser cooling; (190.2620) Harmonic generation and mixing.

https://doi.org/10.1364/OL.43.002905

precision and decrease leading systematic effects [18,19]. For antimatter gravity studies, higher precision requires the average kinetic energy of the atoms to be less than the change in gravitational potential over a magnetic trap [4,5].

While magnetically trapped hydrogen has previously been cooled through evaporation [20], such methods are not realizable in antihydrogen. With so few atoms, collisions are rare and thermalization rates are prohibitively slow. Instead, there is considerable interest in laser cooling antihydrogen using the 1S-2P transition with Lyman-α (Ly-α) radiation at 121.6 nm [4,21,22–25]. The challenge is that Ly-α lasers are notoriously difficult to build and produce relatively low power. The only demonstration of hydrogen laser cooling reduced the temper-

ATRAP



Antihydrogen Experiments

Precision Measurements with Antiprotons

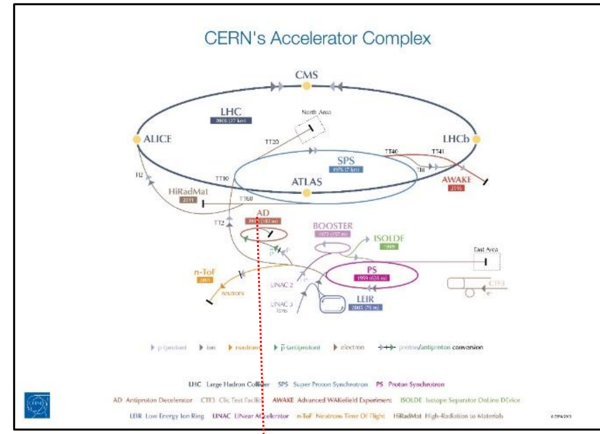
Antiprotons from AD

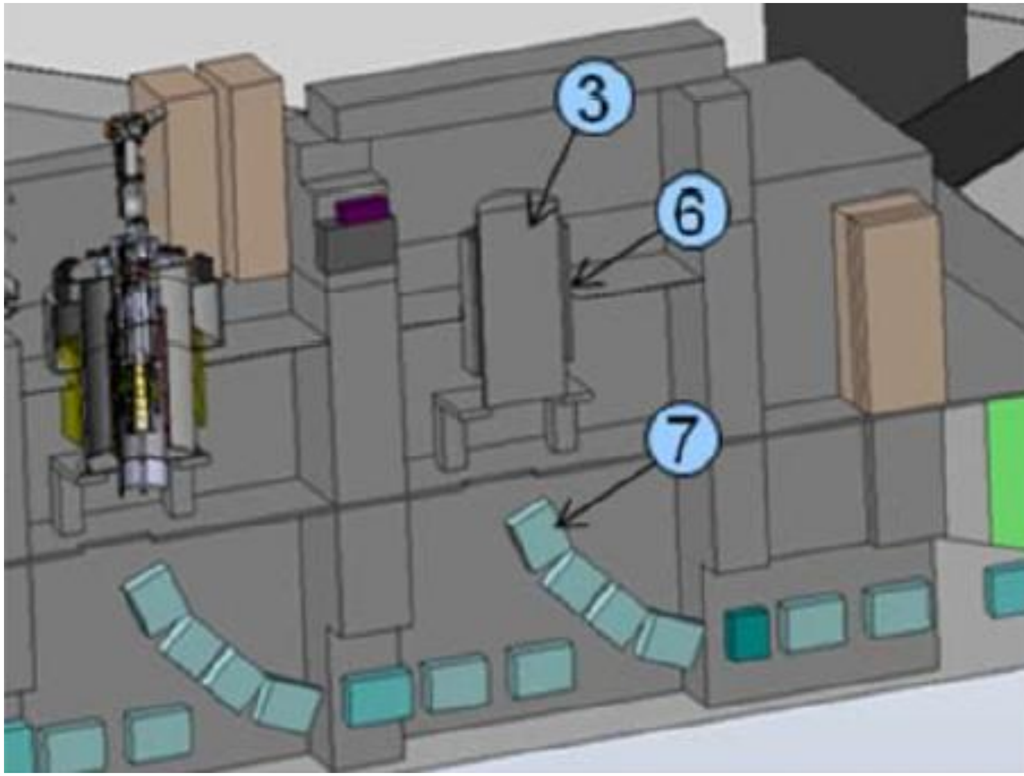
trapped antihydrogen in its ground state
laser cooling
precise laser spectroscopy

680-fold improved measurement of the antiproton magnetic motion

further improved by **BASE** Collab.@CERN

ATRAP





nents

ns

Antiprotons from AD

trapped antihydrogen in its ground state

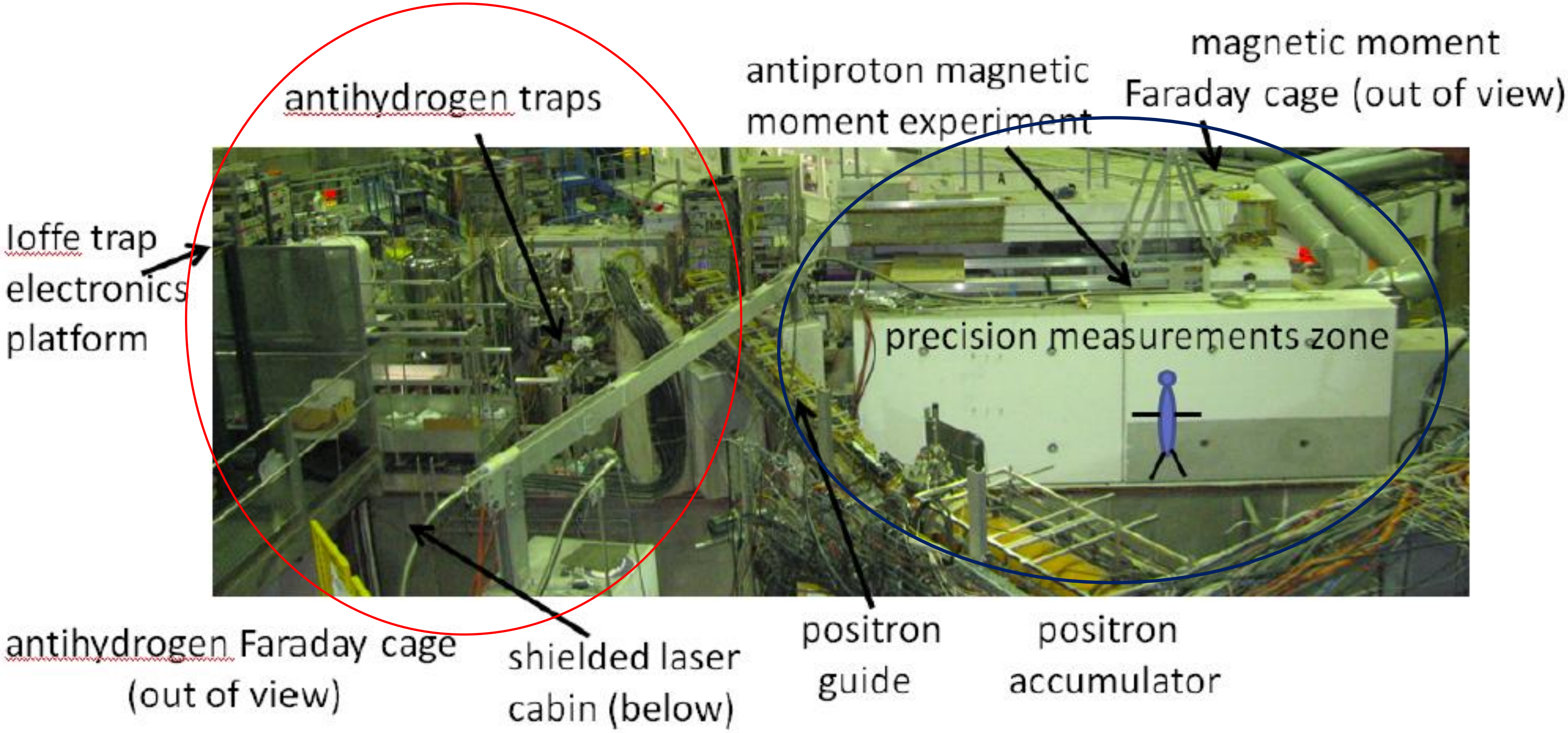
laser cooling

precise laser spectroscopy

680-fold improved measurement of the antiproton magnetic motion

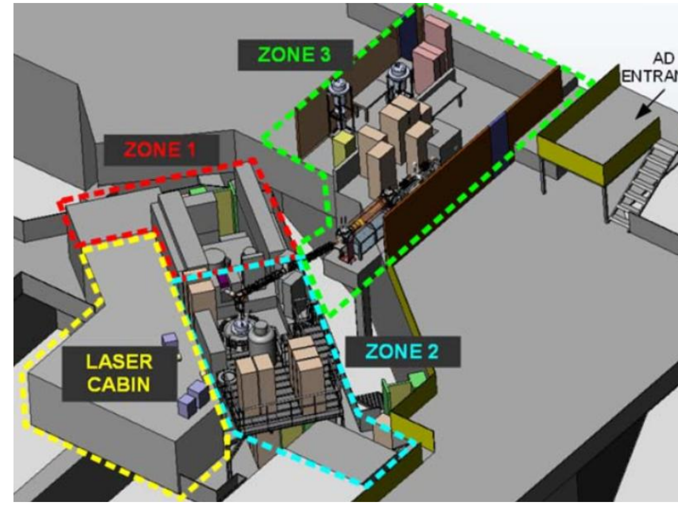
ATRAP

Photos



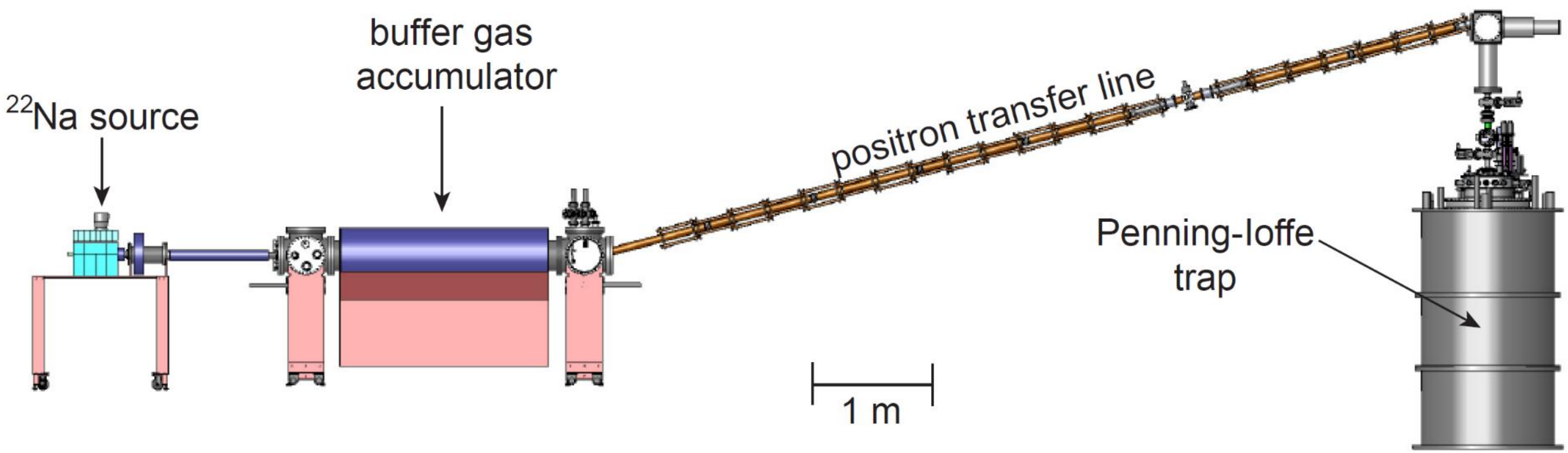
ATRAP Experimental Area

ATRAP



- CERN’s AD provides 5 MeV antiprotons
- positrons from 22Na source,

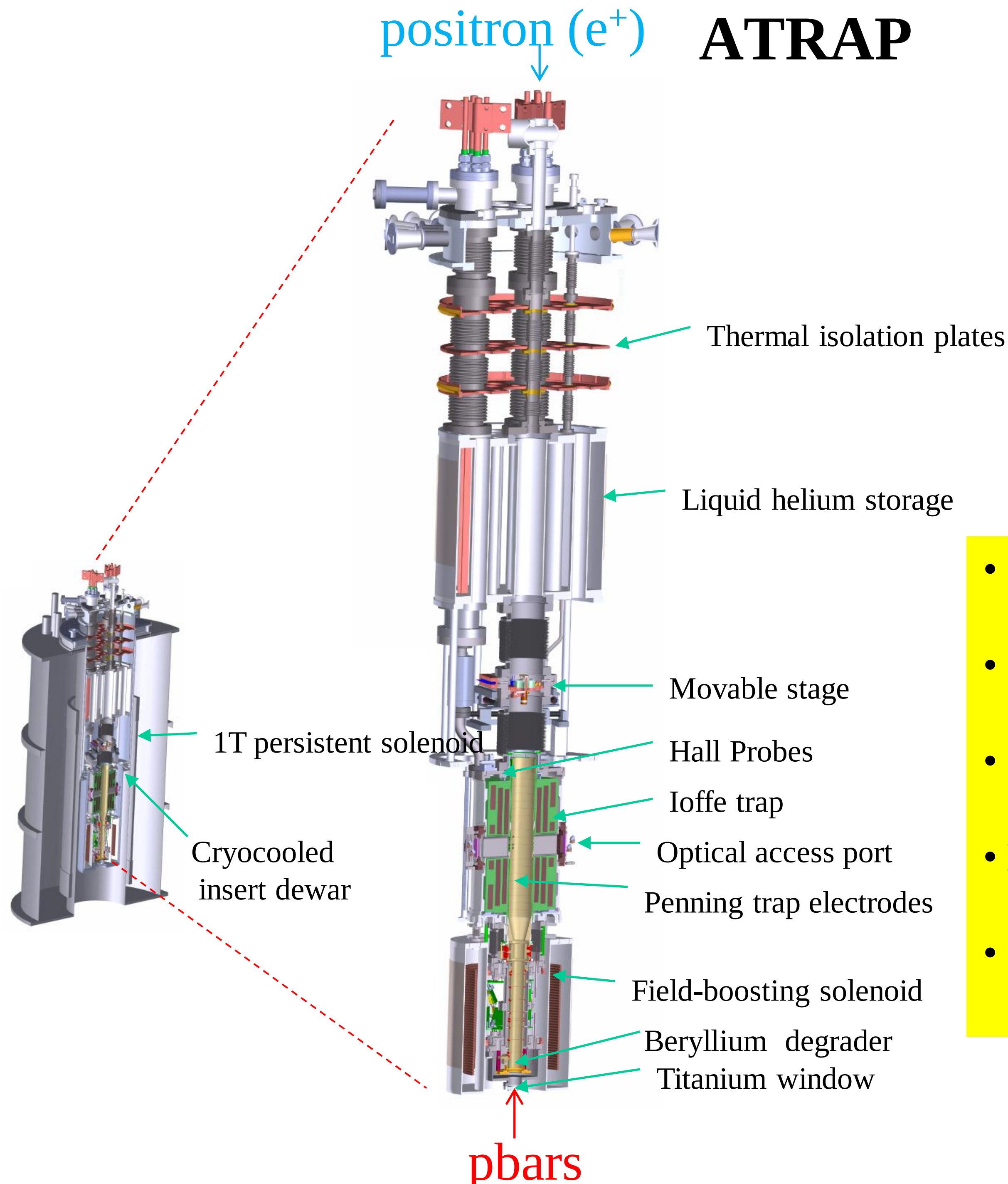
positron (e^+)



pbars

New ^{22}Na source, March 2018

ATRAP



- e- cooling
- 2.7 T boost field (catch more)
- 1K pot (colder)
- Multiple laser paths
- Cs for enhancing Hbar production

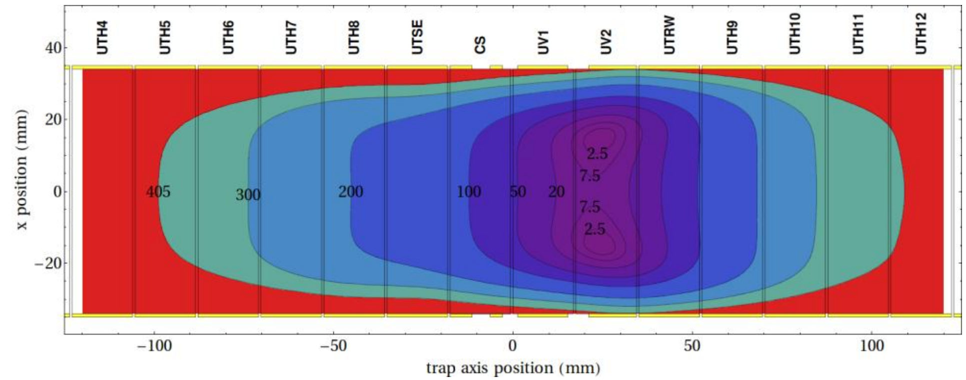
Ioffe Trap

Achieved Magnetic Trap Configurations

Octupole trap operating currents

- 680 A octupole
- 210 A pinch
- 179 A bucking

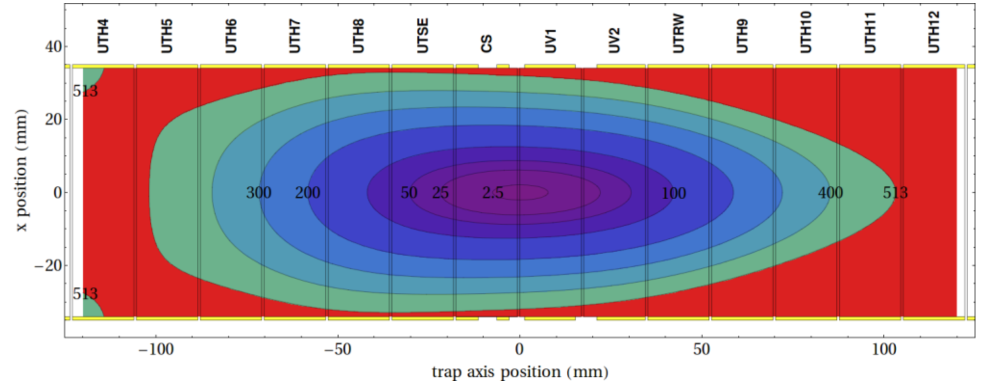
- Generates a trap depth of 405 mK



Quadrupole trap operating currents

- 460 A quadrupole
- 298 A pinch
- -254 A bucking

- Generates a trap depth of 504 mK

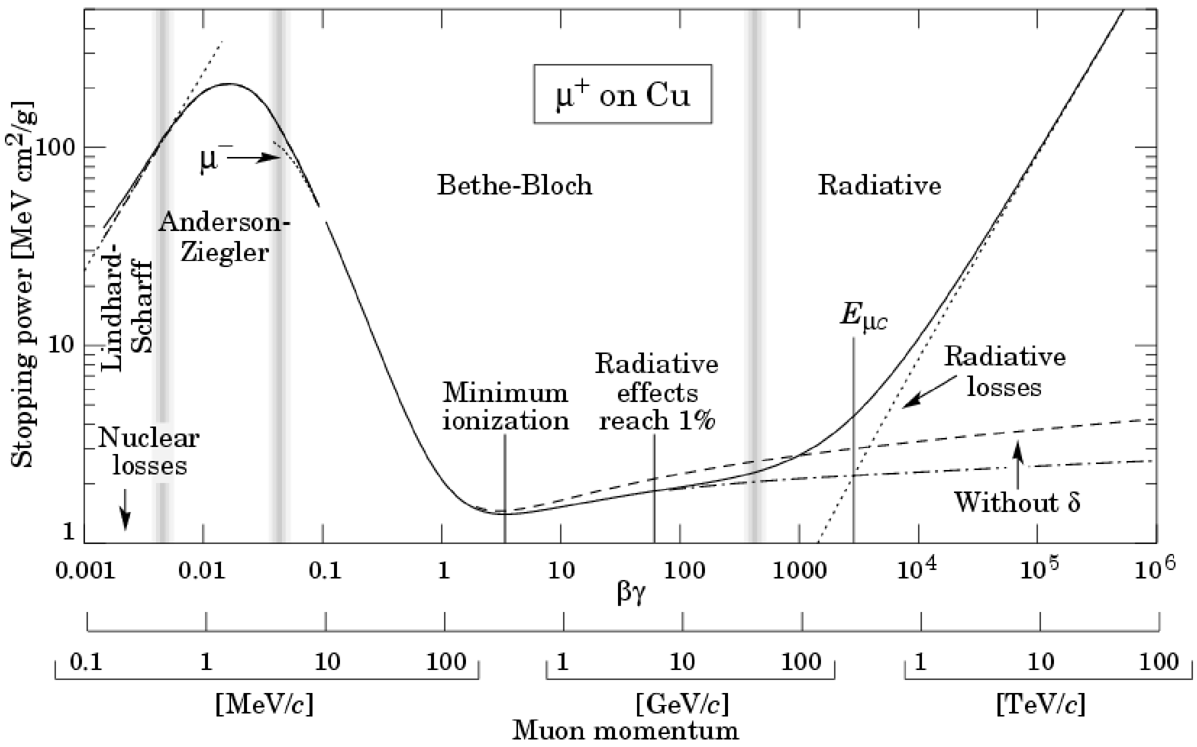


ATRAP Detectors

MIP (Minimum Isonizing Particles)

Energy loss of a particle in matter (Bethe formula)

$$-\frac{dE}{dx} \approx \left(0.307\,\mathrm{MeV\ mol^{-1}\ cm^2}\right)\,\rho\,\frac{Z}{A}\,\frac{z^2}{\beta^2}\left[\ln\frac{2\,m_e\,c^2\,\gamma^2\,\beta^2}{I} - \beta^2\right]. \qquad (2.2)$$

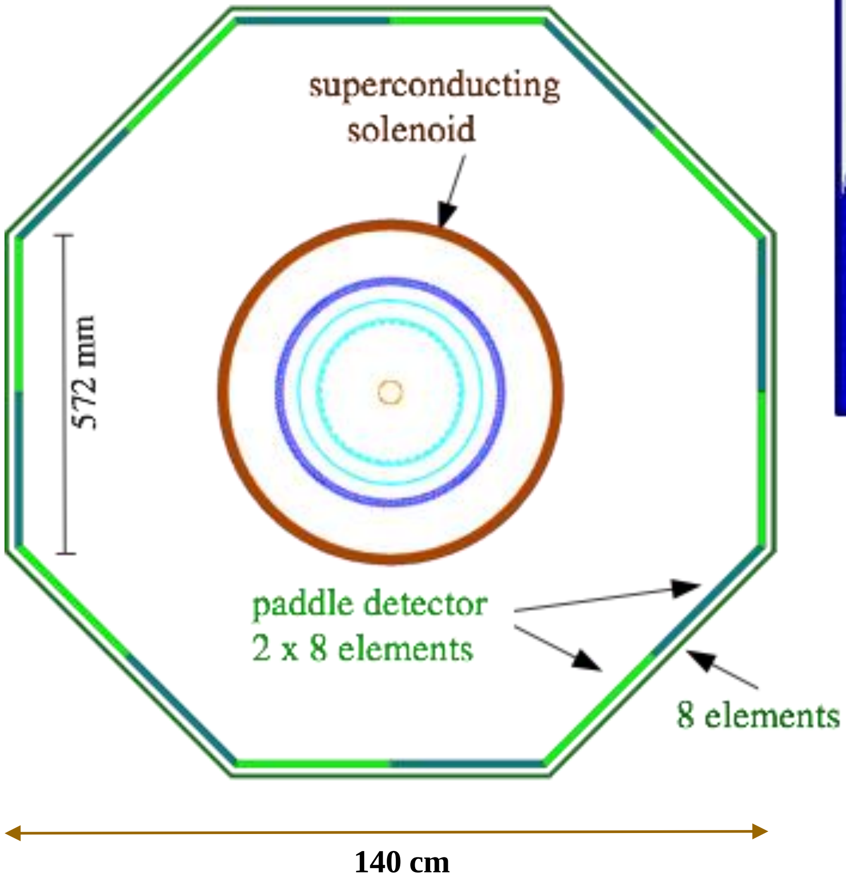


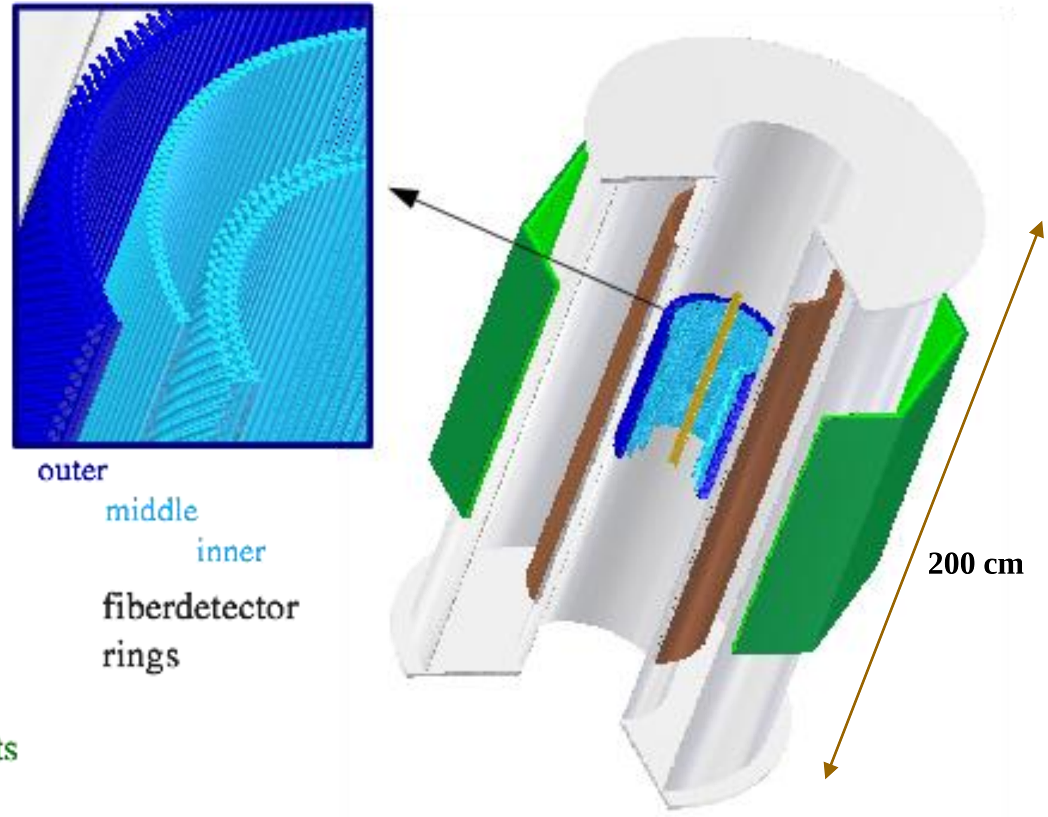
http://aladdin.utef.cvut.cz/ofat/methods/MIPtracking/index.htm

http://www.hephy.at/user/friedl/diss/html/node10.html

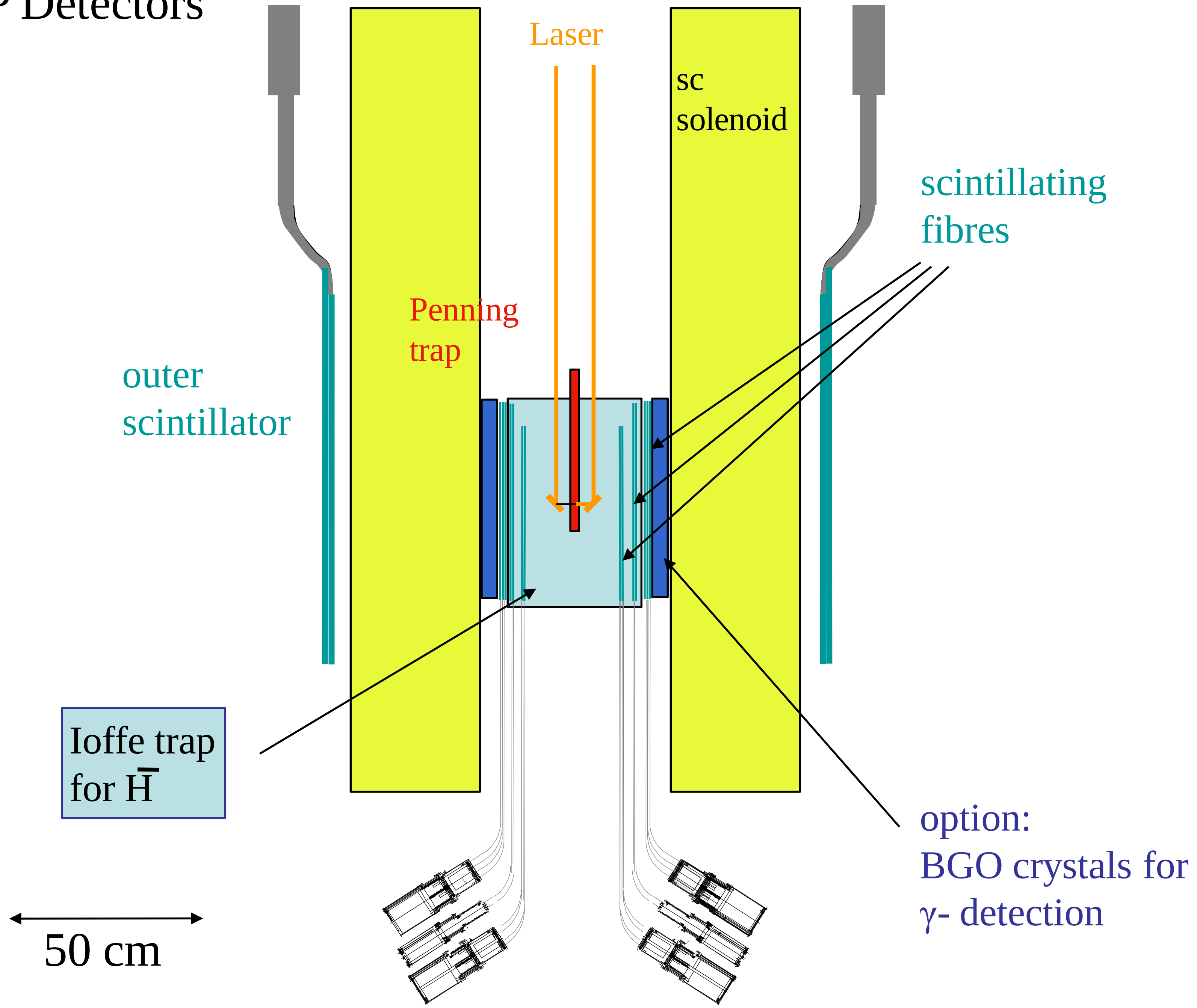
http://webhome.phy.duke.edu/~schol/392/faqs/faq3/node4.html

ATRAP Detectors



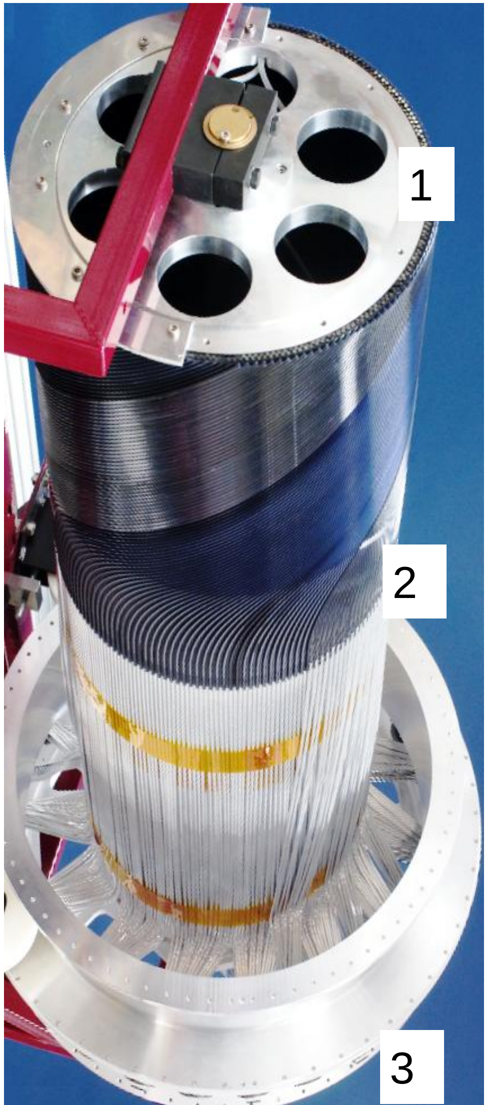


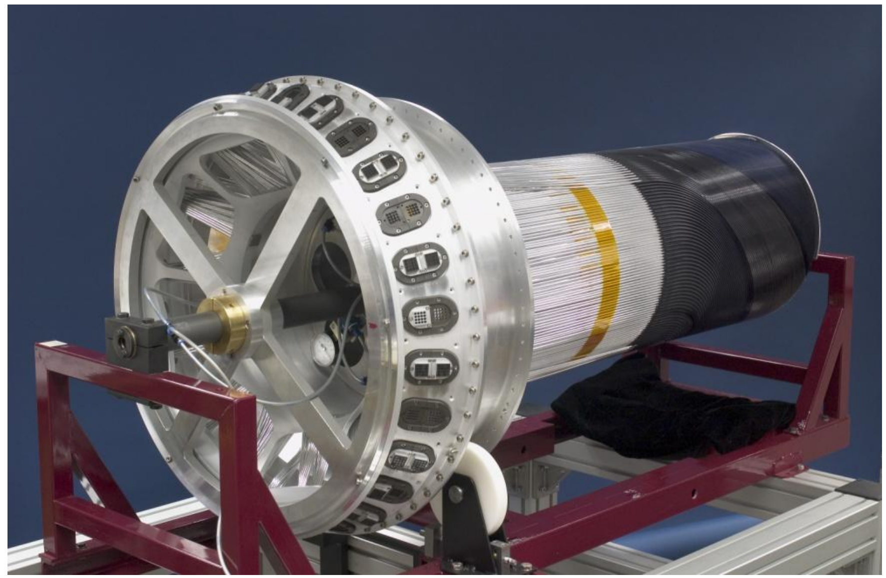
ATRAP Detectors



Installation of
Scintillator paddles

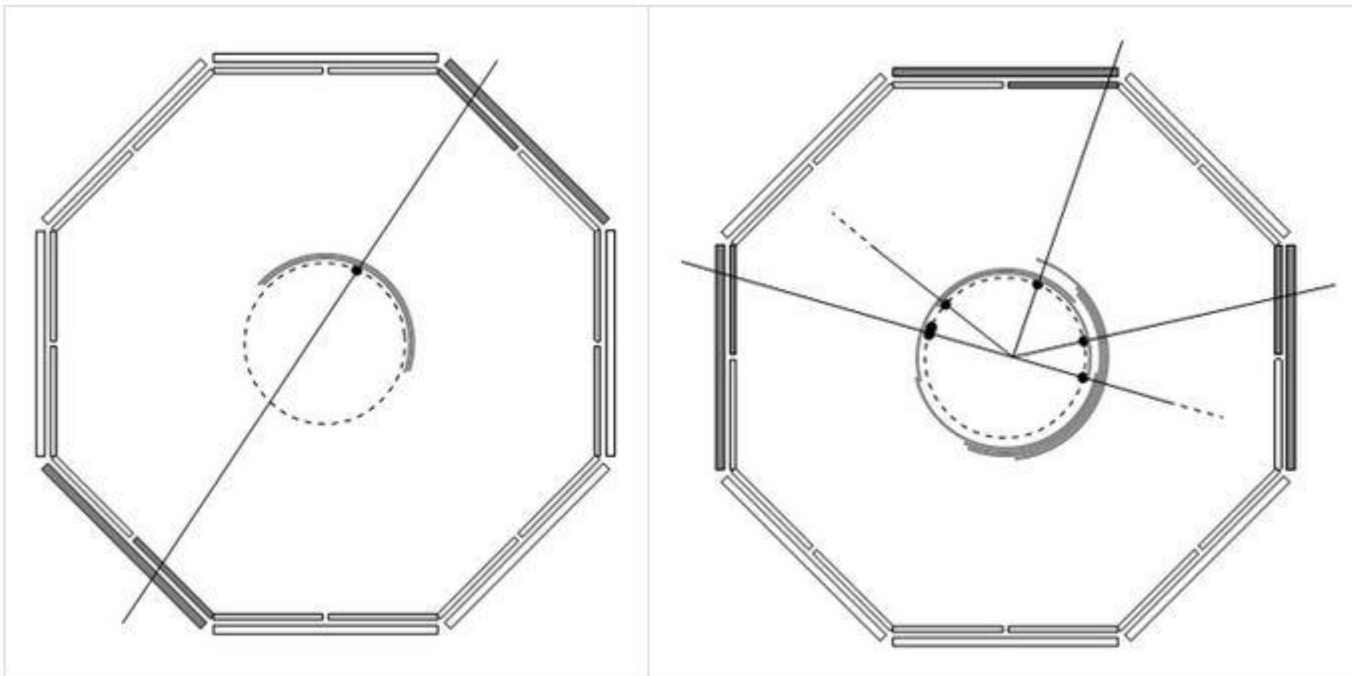
Scintillating fiber detector





Pbar Annihilation vs. background

Hits from actual event
(cosmic and pbar annihilation)



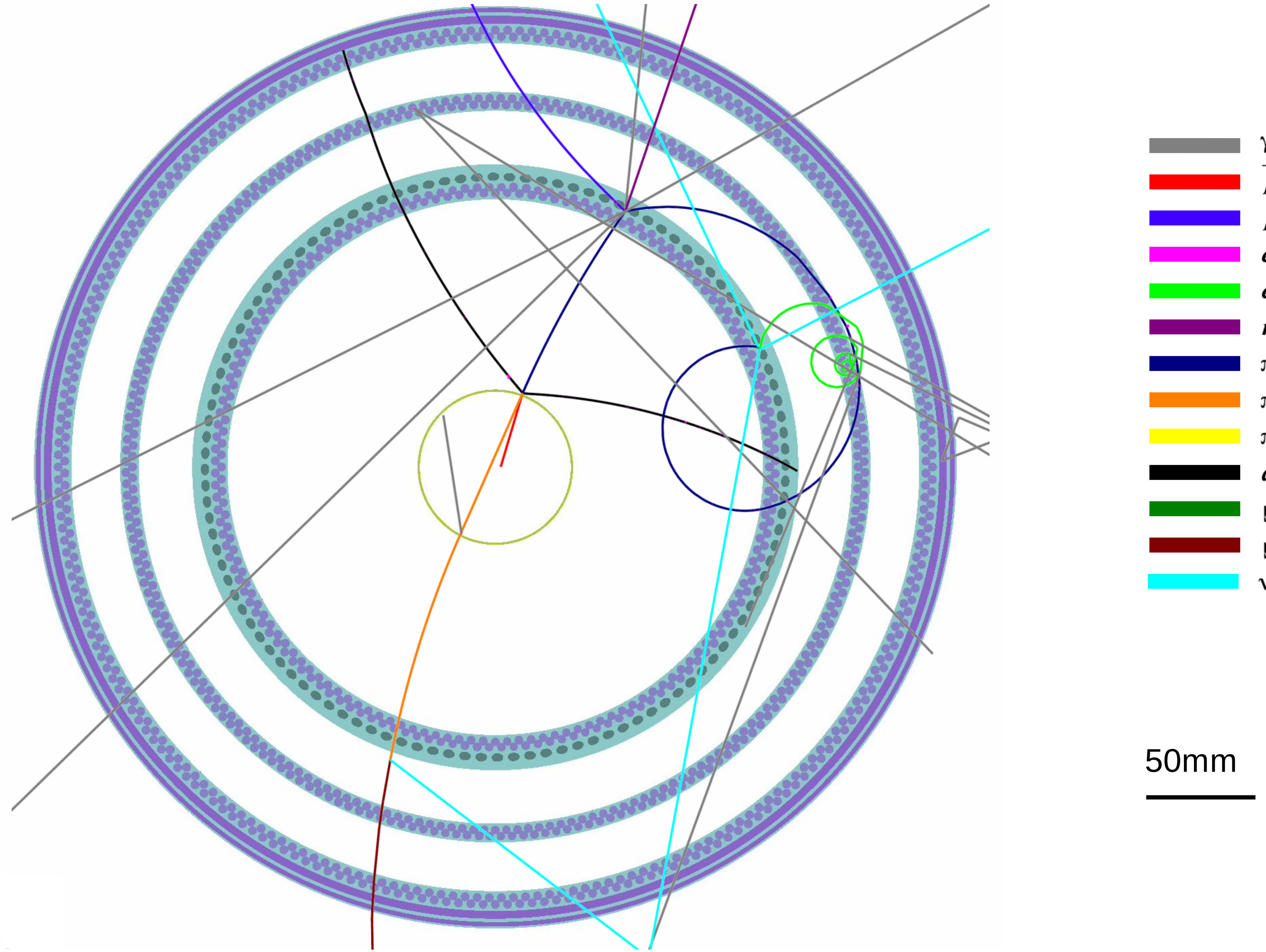
An event that looks like a cosmic.   An event that looks like a pbar.

Analysis Method:

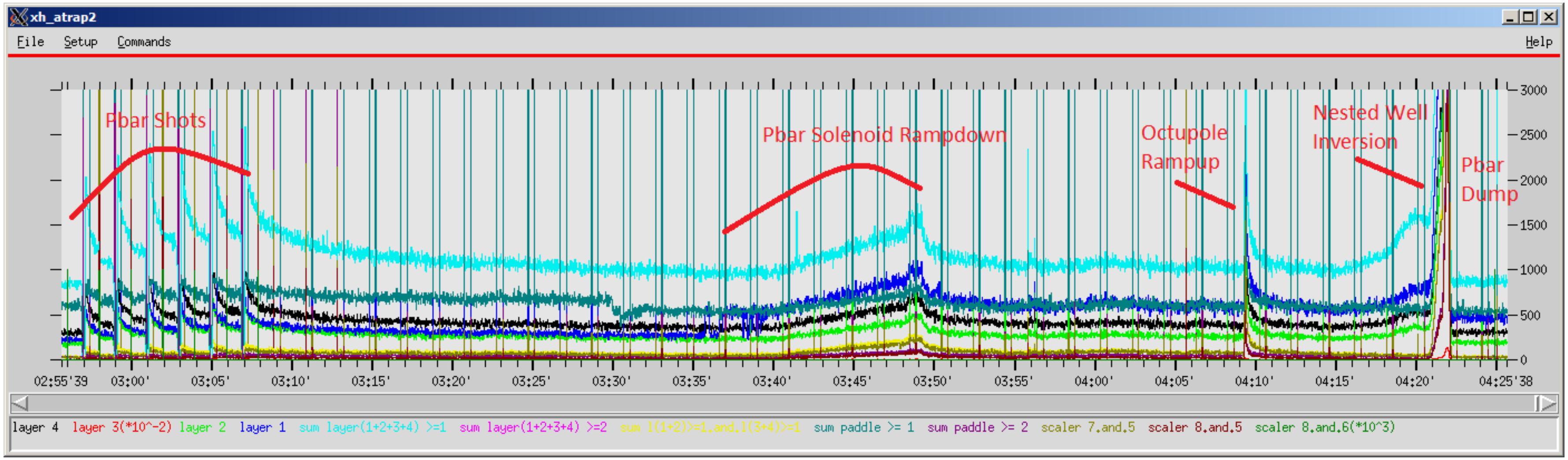
- data with cosmics, with pbar spill
- find probablility distribution based on these two sets of data and decide if an event was from pbar or sosmic

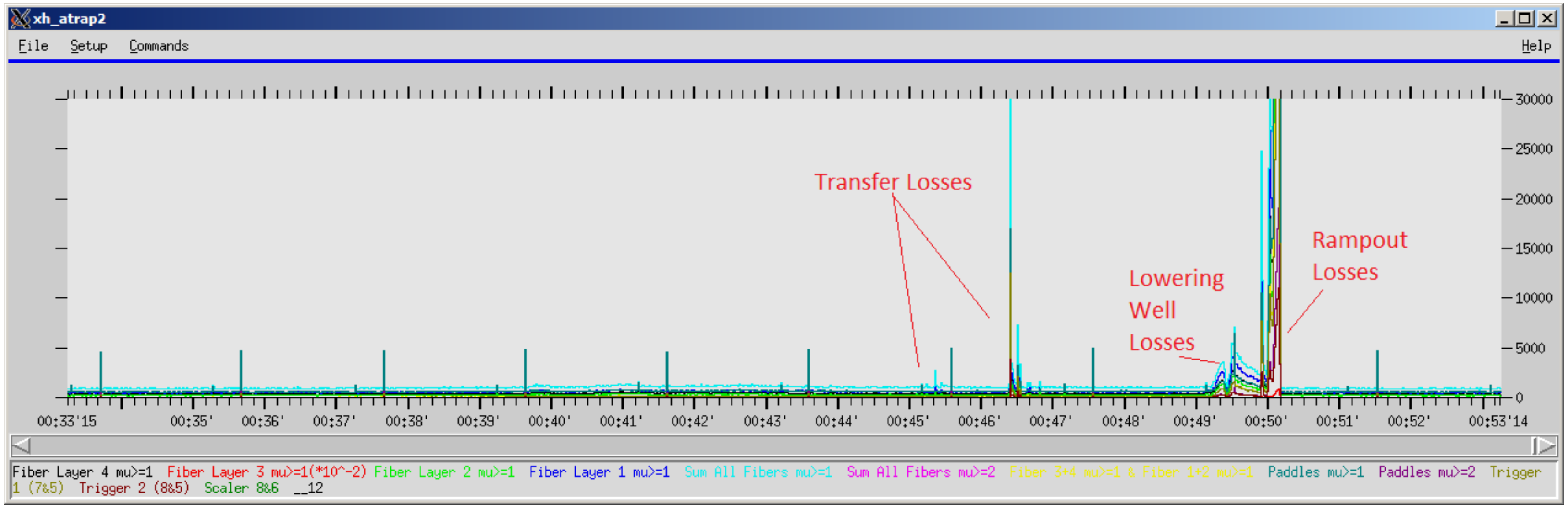
Antiproton Annihilation Event
(generated with GEANT-4)

ATRAP Detectors



Live monitor - detector (scalers)

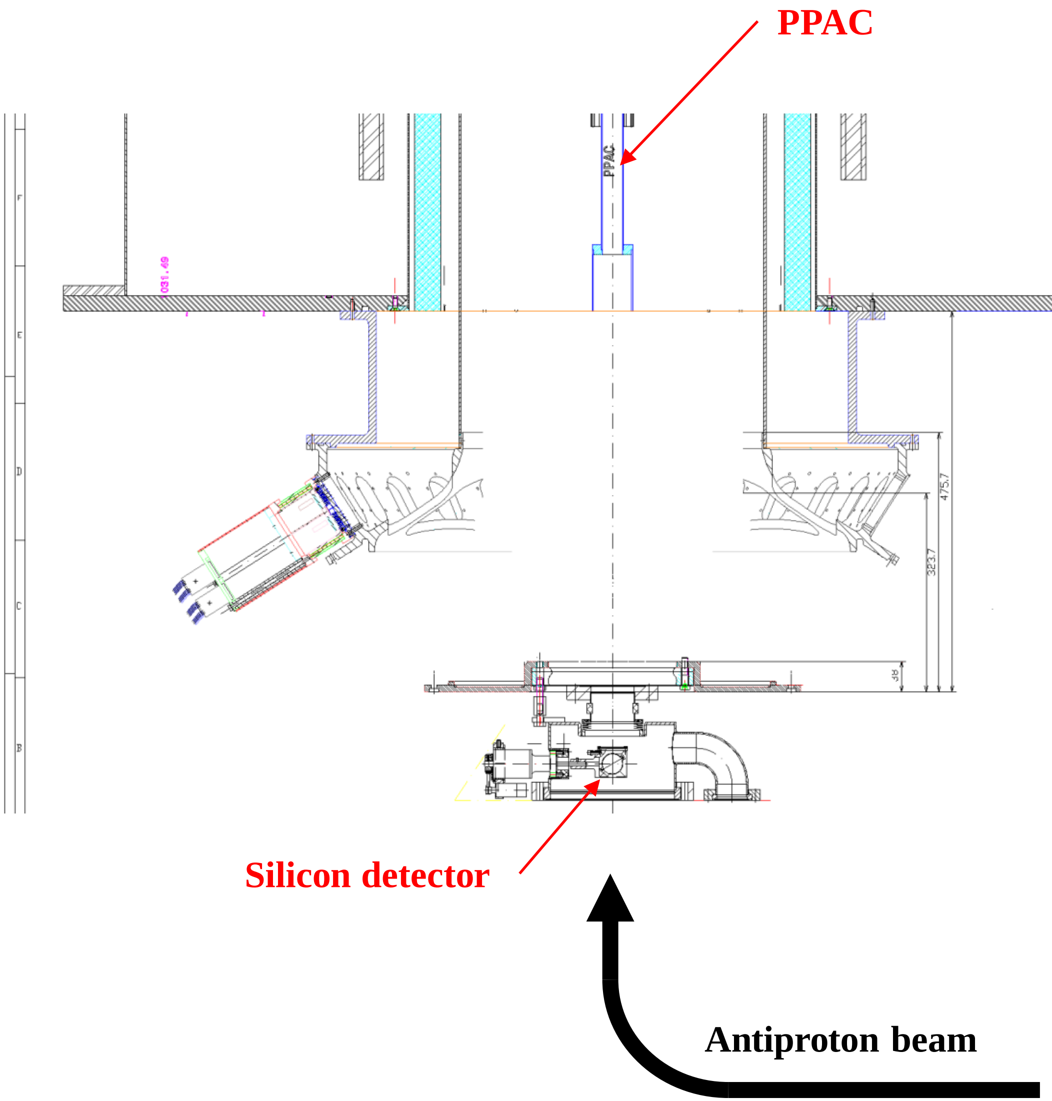




beam alignment/steering detectors

(important to trap on center B lines)

Relative locations of PPAC and Si-detector



PPAC : Parallel Plate Avalanche Counter

PPAC + Energy Tuning gas cell

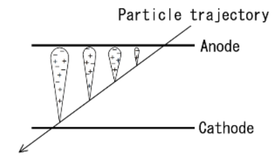
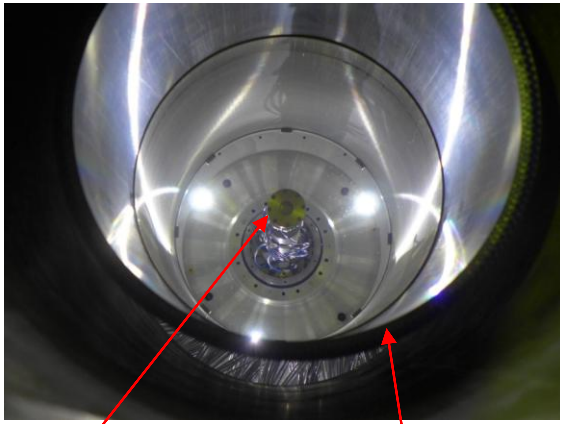
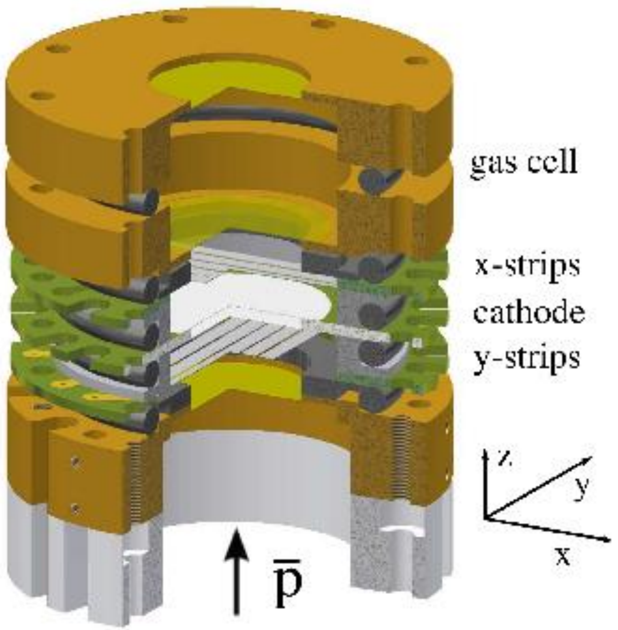


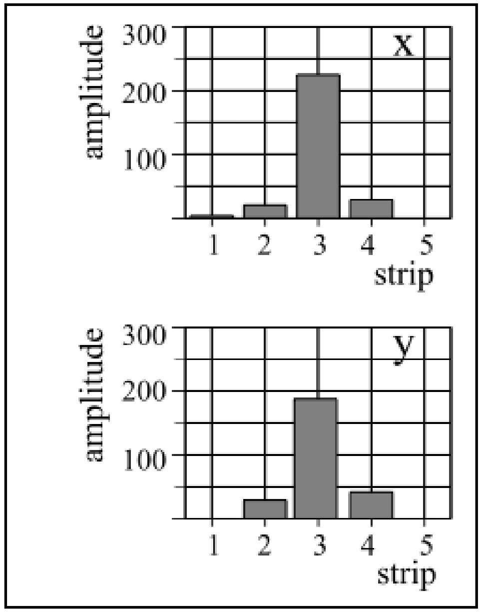
Fig. 1. Operating principles of PPAC.



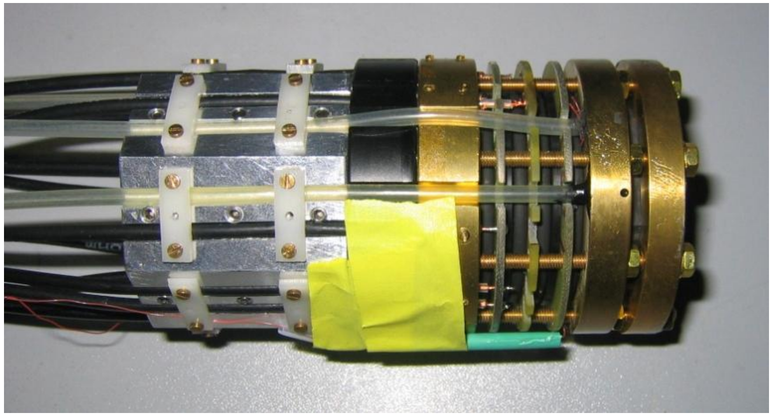
PPAC

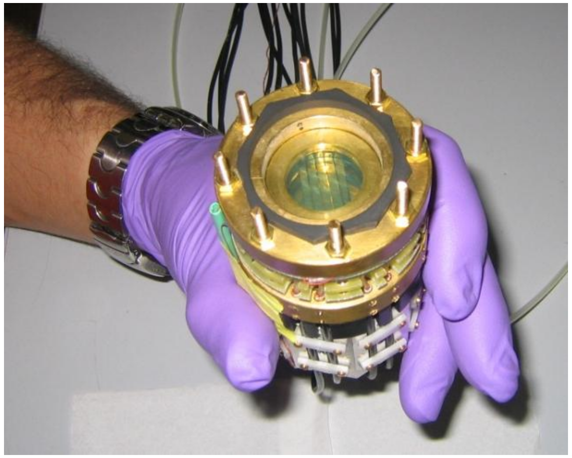
Fiber detectors

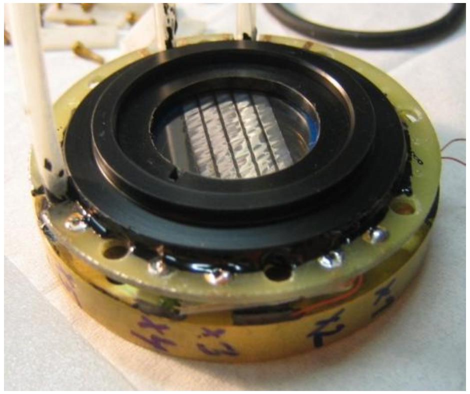




strip width: 2 mm
gap: 0.5 mm



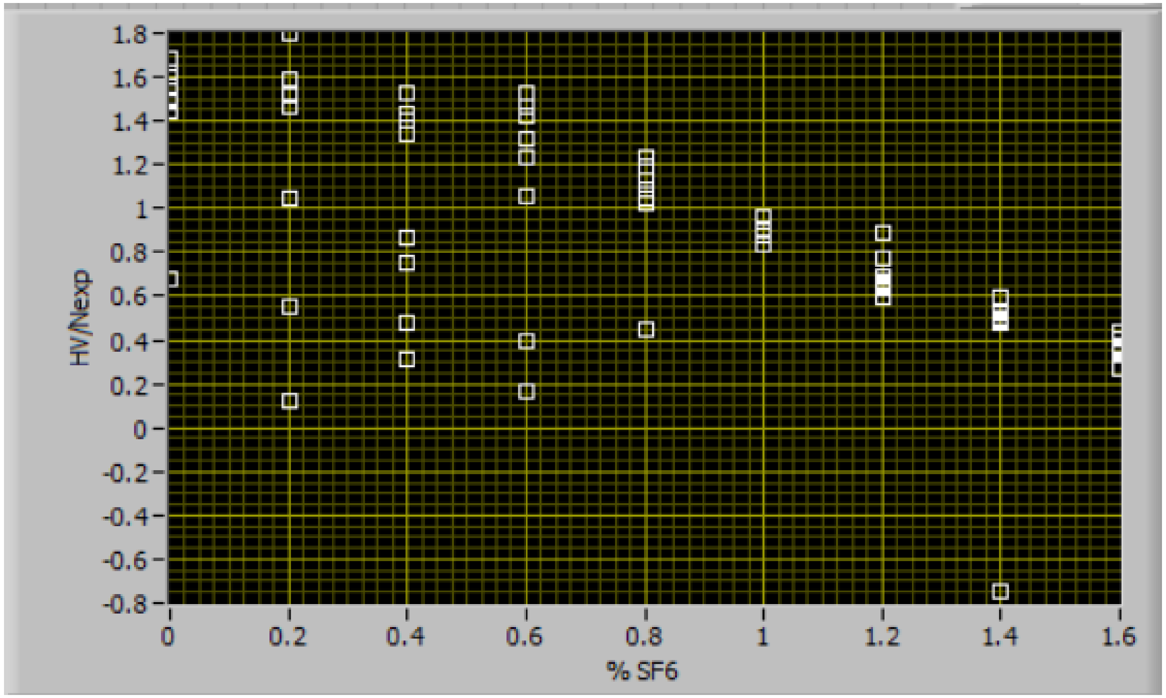




Etune gas mix ratio and # of pbars caught from an AD shot

Gas mixture : He + SF6

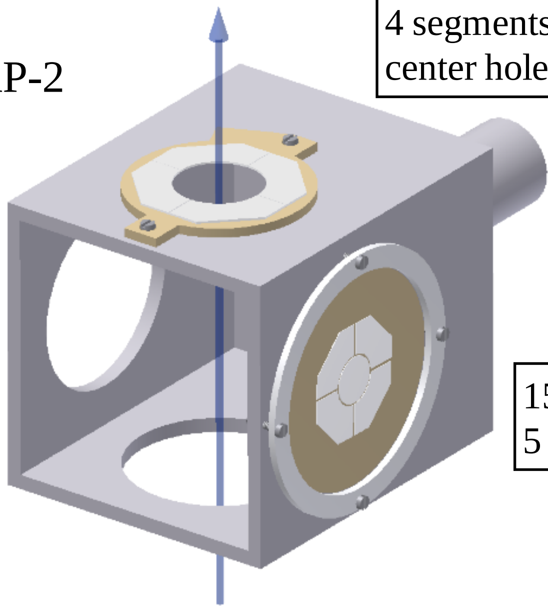
Normalized # of pbars



% of SF6 gas in the gas mixture

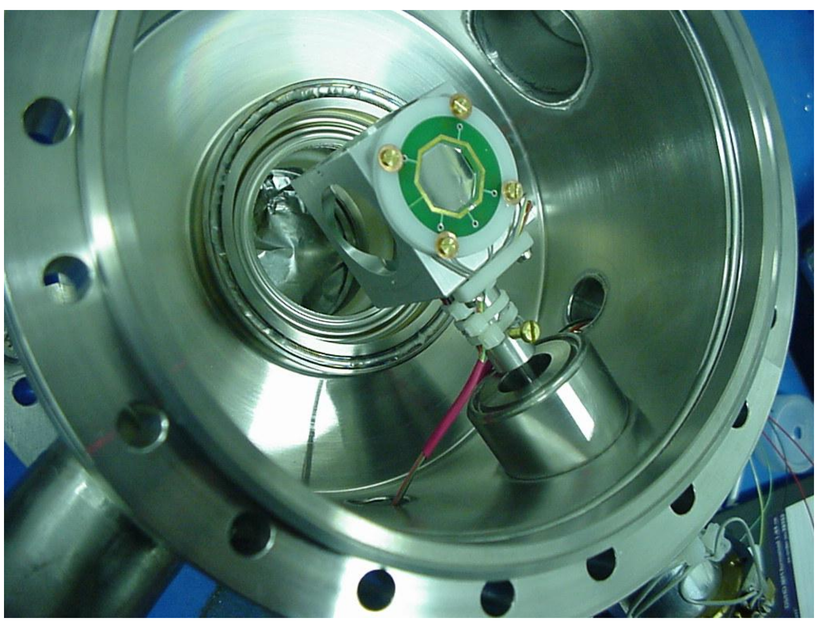
Si-detectors

ATRAP-2



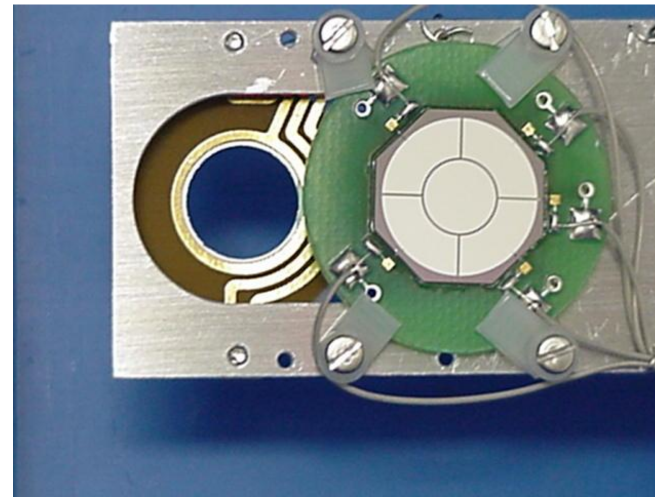
200 μm thick
4 segments
center hole: 12 mm

15 μm thick
5 segments

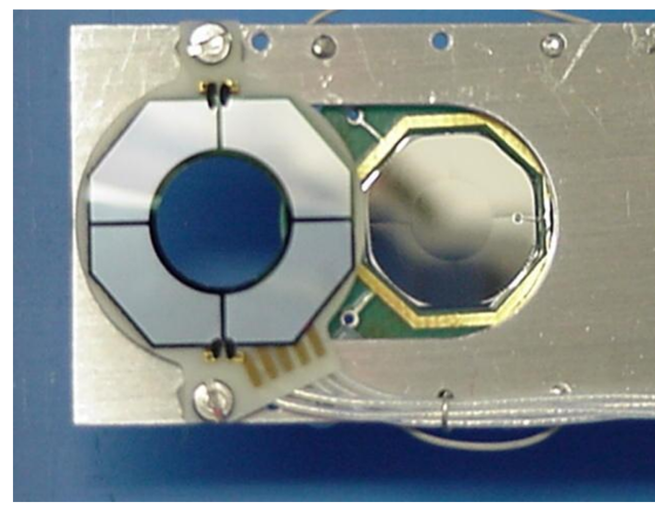


ATRAP-1

front side

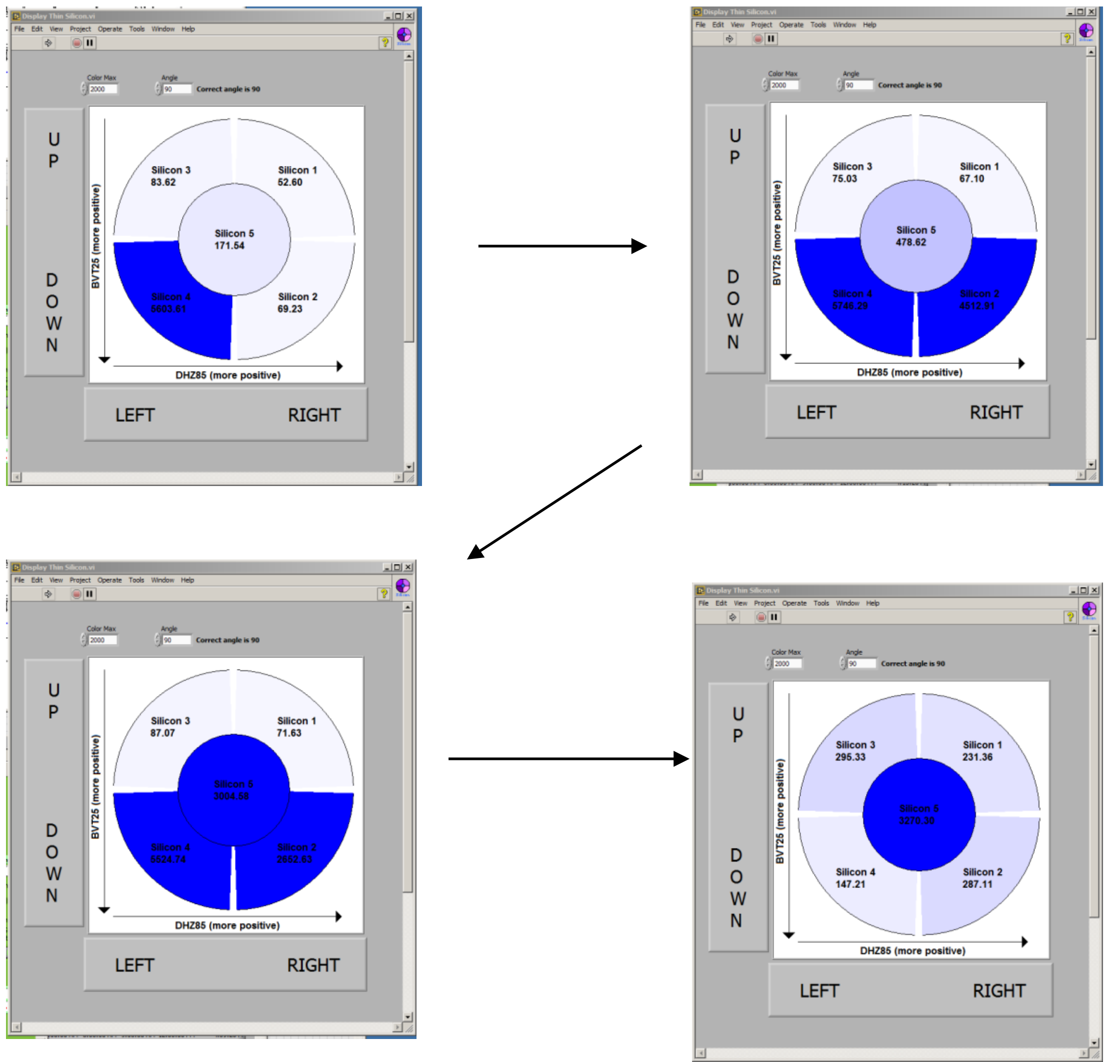


back side

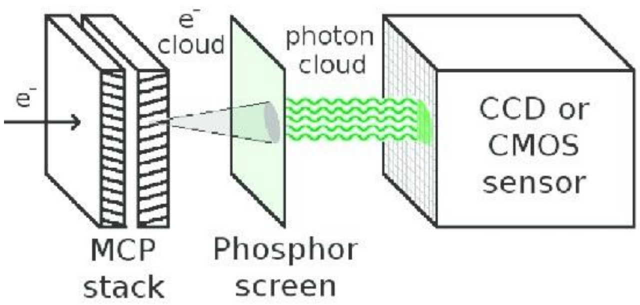


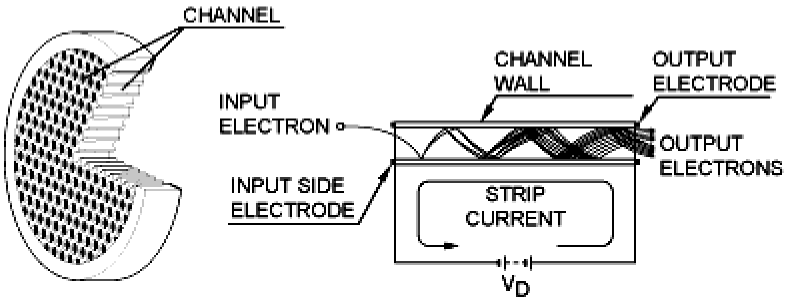
Examples of beam position monitored by Si Detector

Need to know exactly which magnet (current) in beam line to tweak !

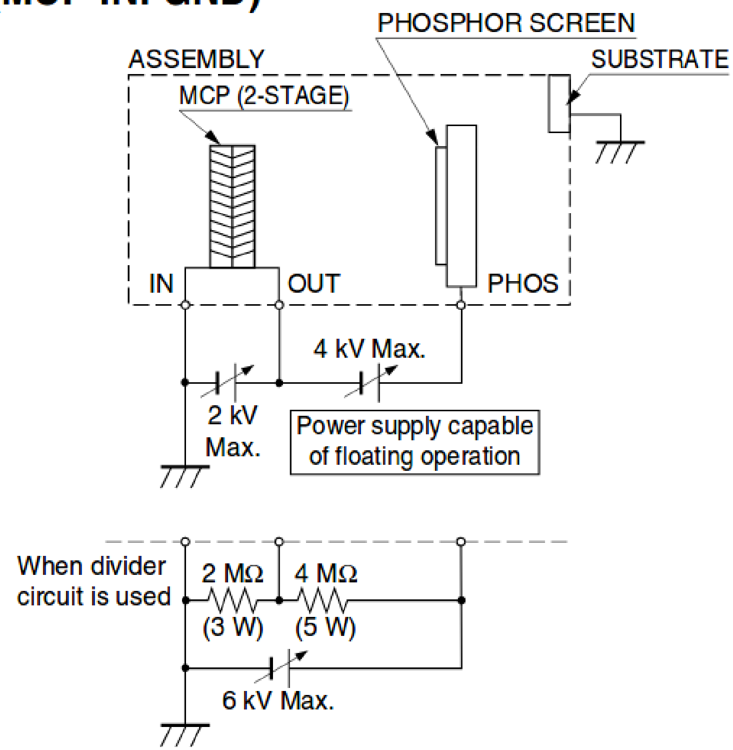


Plasma diagnostics: MCP + Phosphor + Camera





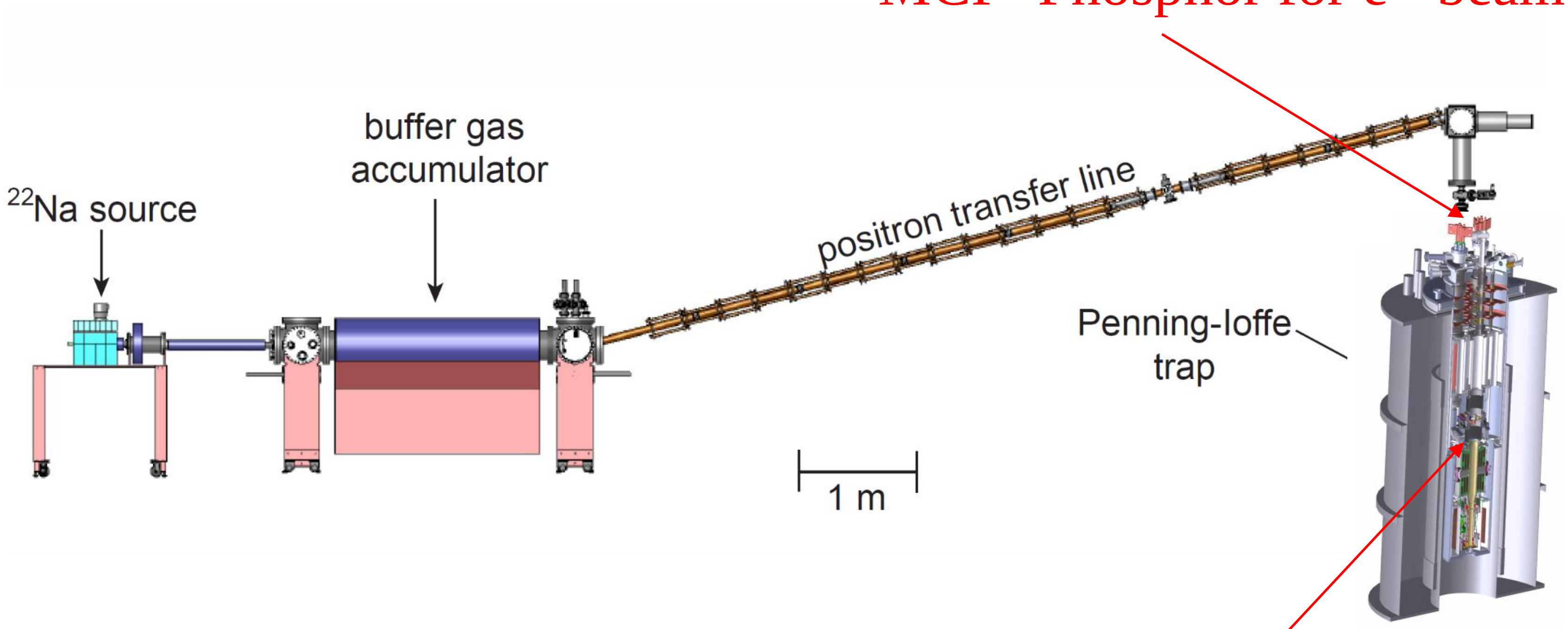
●**Electron or positive ion detection (MCP-IN: GND)**

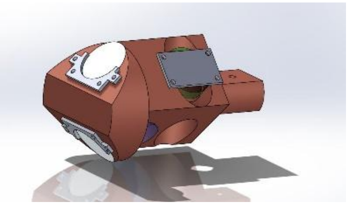


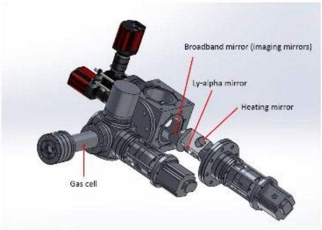
https://www.hamamatsu.com/resources/pdf/etd/MCP_TMCP0002E.pdf

Location of MCP+Phosphor screen

MCP+Phosphor for e+ beam

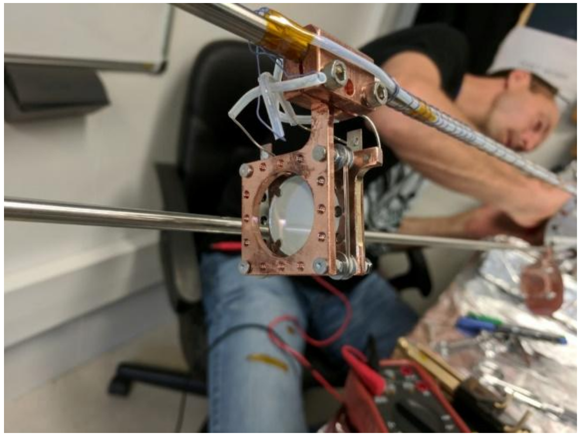






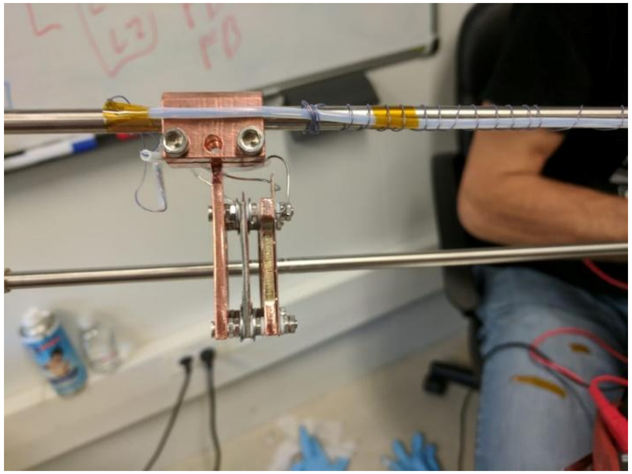
MCP+Phosphor for all species
(plasma imaging)

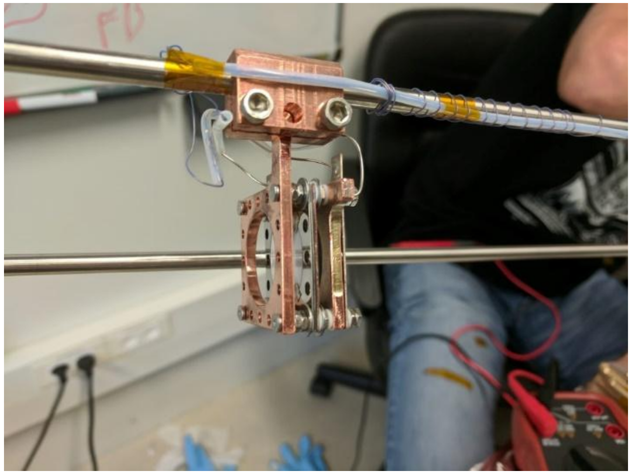
MCP+Phosphor for e+ beam



Crazy ! Mad ! Angry !

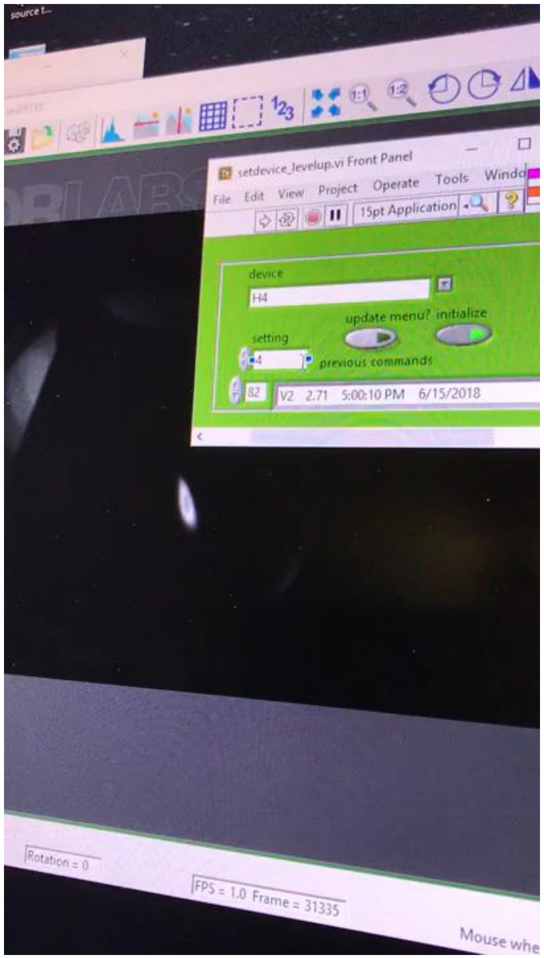
- First time, shorted after few rotations in and out
- Second time the applied HV deflected e+
- Third time managed with shielded co-ax cable for HV bias

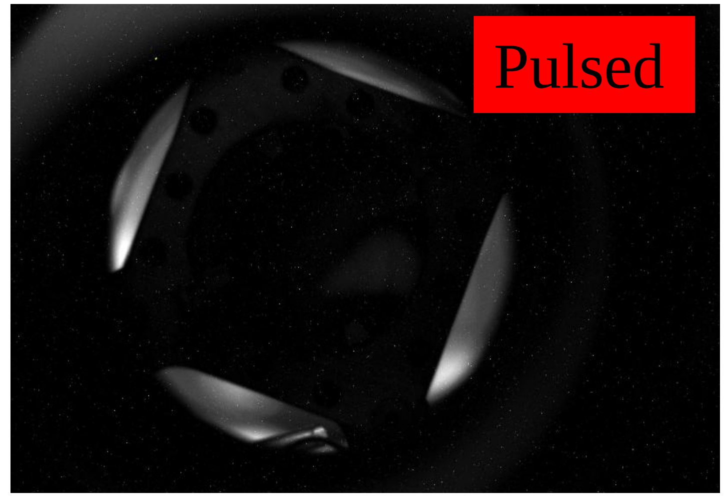


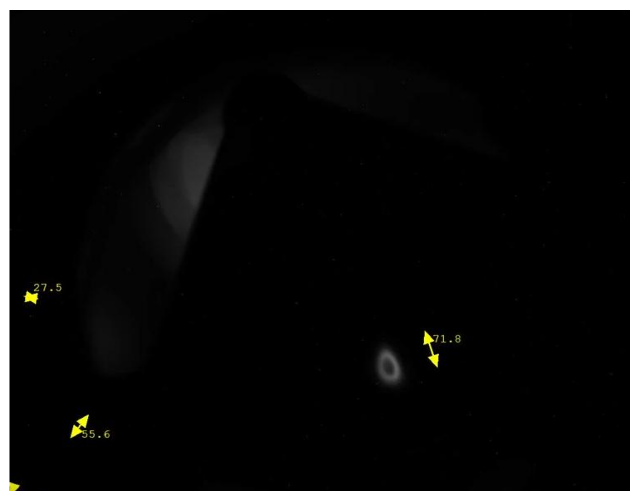


Video: continuous e+ beam

Without accumulation, straight from source

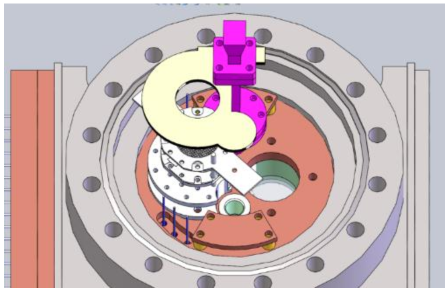




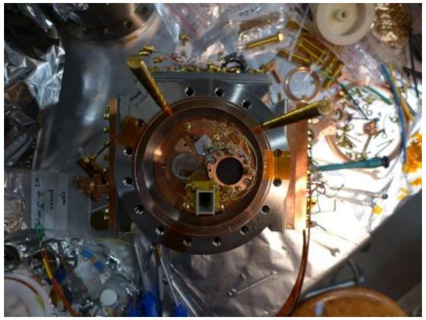


Preserves the ring shape (formed at moderator of frozen neon gas)

MCP+Phosphor for all species



- MCP at Cryogenic temp, in high B field
- Use laser to heat, bring MCP temp >20K to operate



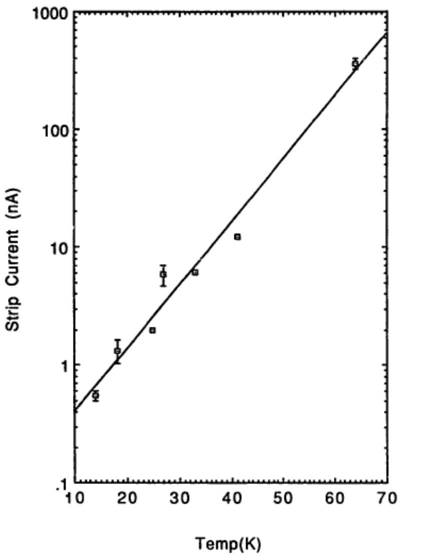
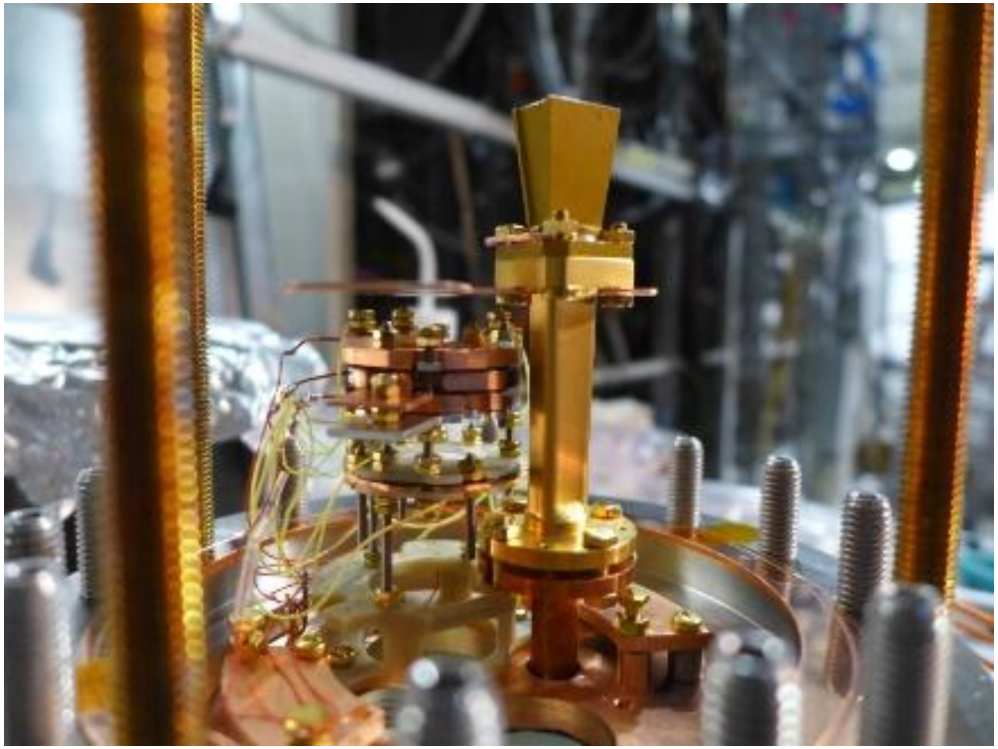


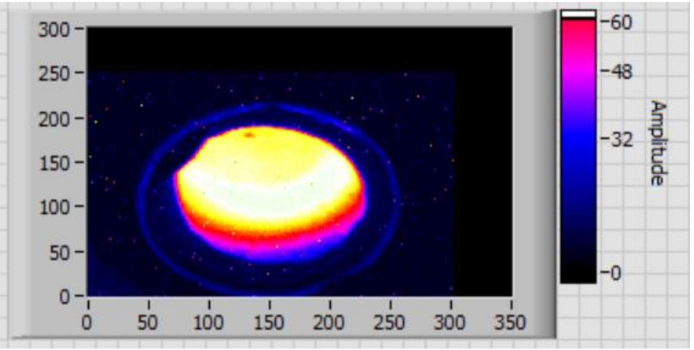
Fig. 4. Variation of strip current with the ambient temperature of the channel plate mounting fixture. The line is the result of a least squares fit, $I_2 = (0.12\ \text{nA}) \exp(T/0.81)$.



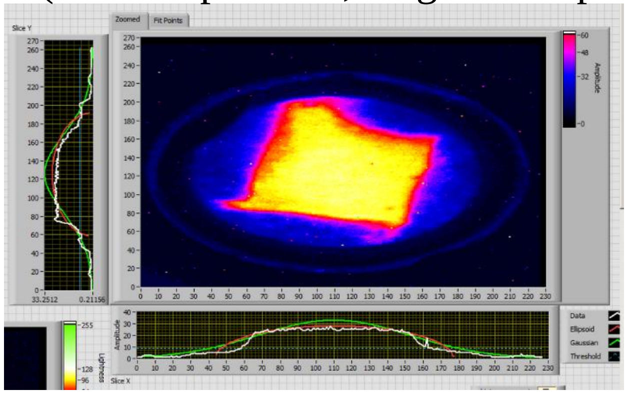
J.A. Scheckei, NIM A320, (1992) 556-561

MCP+Phosphor for all species

e- (no compression)



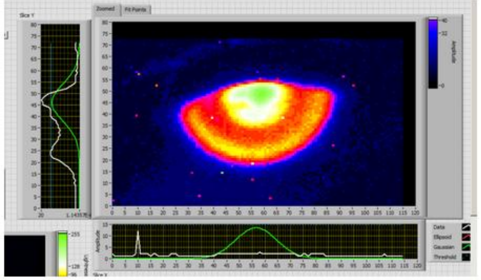
pbar (bad compression, magnetic trap ON)



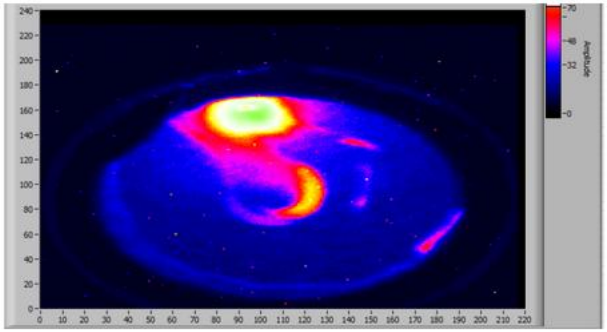
Diameter of phosphor screen: 25mm

Goal is to get sub mm plasma

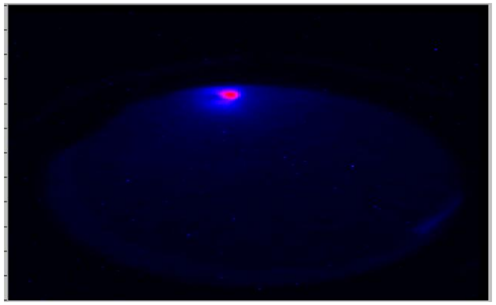
e- (compression)



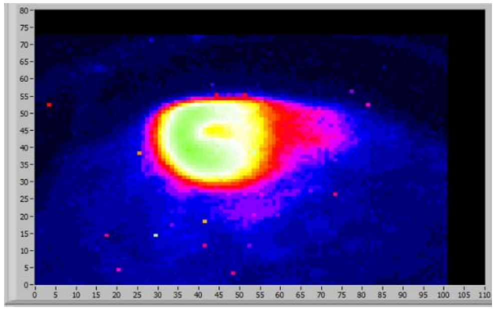
e+ (compression, magnetic trap ON)



e- (compression, less particles)

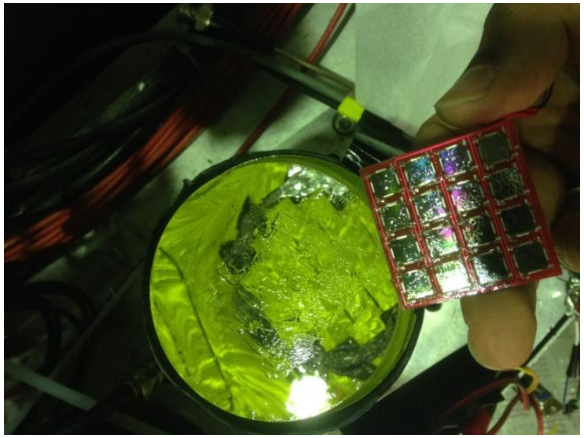


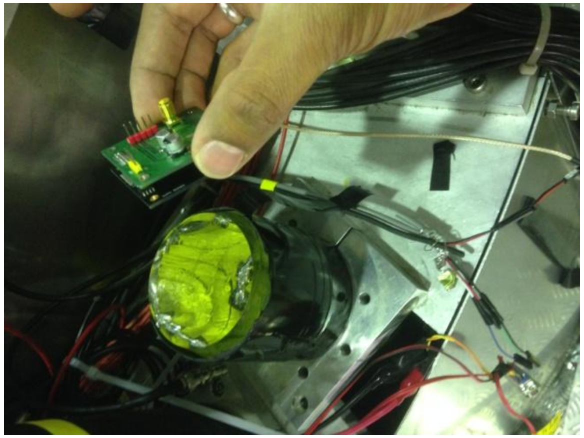
pbar (compression, magnetic trap ON



Recent Upgrades

- **Replaced PMT with SiPM array**
- Magnetic field effect, need shield
- He gas into PMT, causing noise
- Making SiPM array, not straight forward

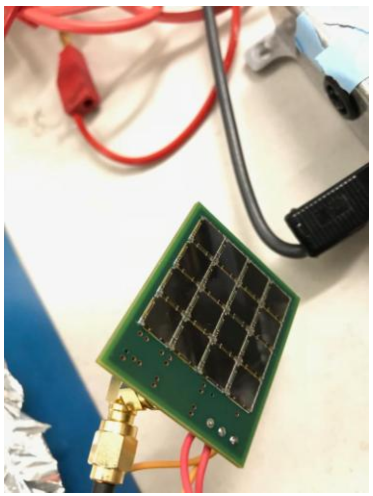




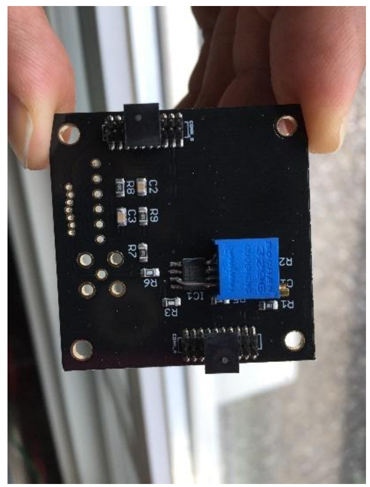
Recent Upgrades

- **SiPM Array (by D. Zambrano, PhD student at ATRAP)**
- Three tests: sum all 16 SiPM output, sum 4 in one, individual readout

array front

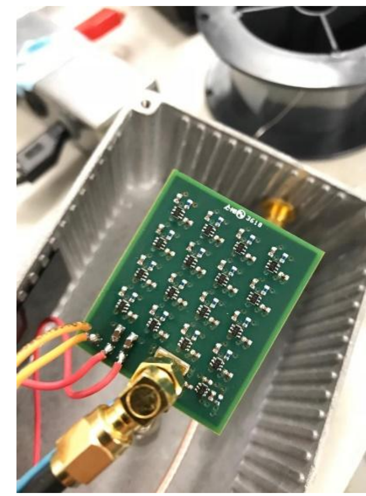


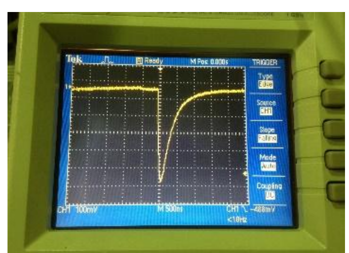
sum all 16 output

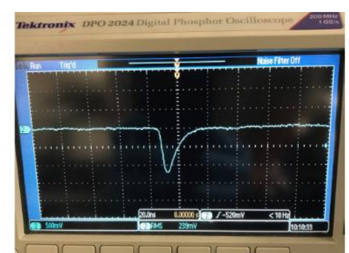


Sum group of 4

readout individually





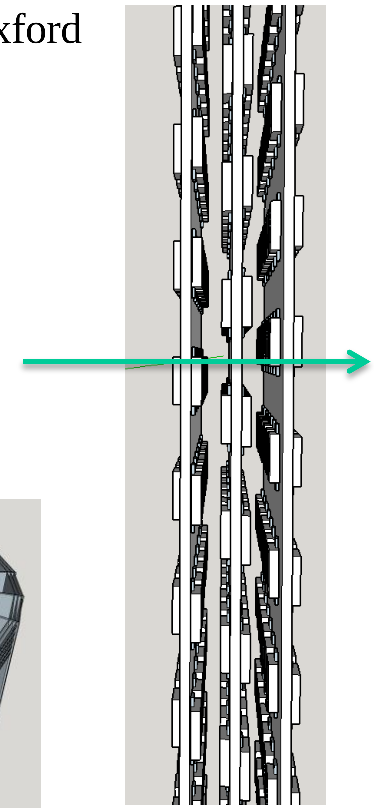


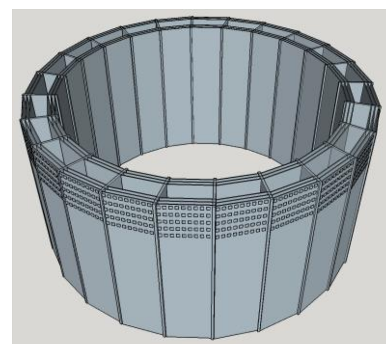
Used AD8000 & AD8003

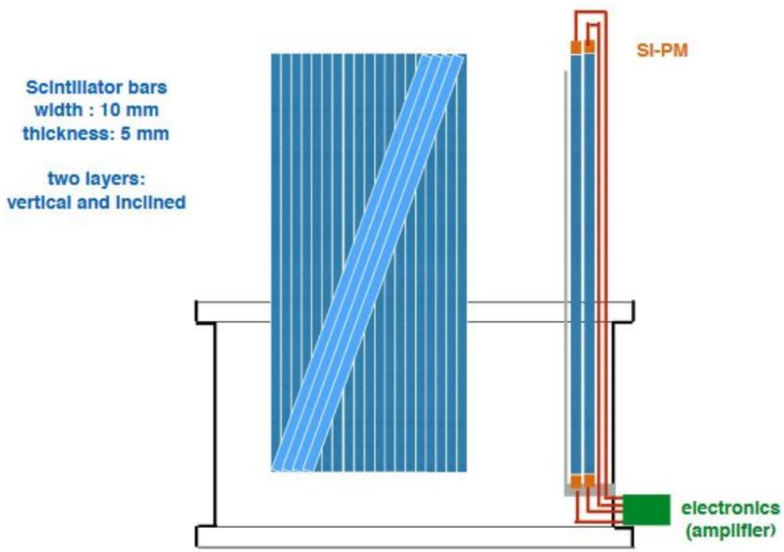
Future Upgrades

Add an additional layer (layers) of detector to be able to get a track and z-resolution
New DAQ based on TRB + PADIWA (from GSI)

by R. Plackett, Uni. Oxford







Thin Scint. strips with SiPM readout on two ends

Silicon PIN Photodiode
(e.g. Vishay VBPW34S),
Cheap solution but advantage of
Silicon technology

Summary

• new plasma diagnostics → better control of our plasmas

• Goal is to simultaneously make large number of trapped Hbars in a single trial, then laser cool them and do precise spectroscopy.

Thank you for your attention !!!

ATRAP Collaboration

G. Gabrielse[1,2], Y. Chen[1,2], N. Jones[1], G. Khatri[1,2], K. Marable[1],
T. Morrison[1], E. Tardiff[1,2], D. Zambrano[2], E. Nottet[2]

[1]Harvard University, Cambridge, MA, USA
[2]Northwestern University, Evanston, IL, USA

E. Hessels, C. Storry, R. Thai
York University, Toronto, Ontario, Canada

S.A. Lee, D. Yost
Colorado State University, Fort Collins, Colorado, USA

B. Glowacz, M. Zielinski
Jagiellonian University

D. Grzonka
Juelich, Germany

ELENA beam profile monitor SEM