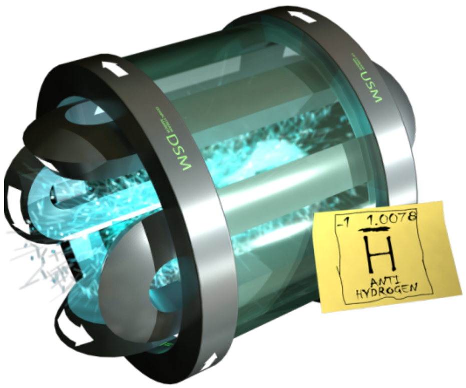
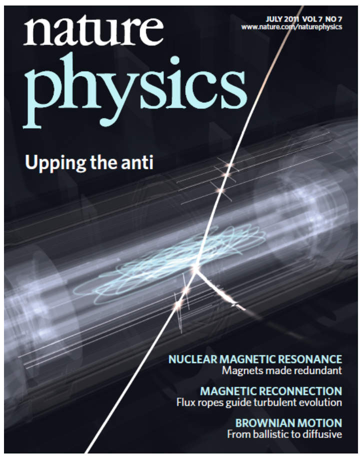
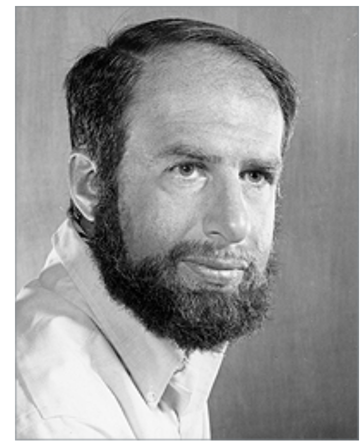



# Cooling and Phase Space Manipulation of Nonneutral Plasmas for Antihydrogen Synthesis

ALPHA

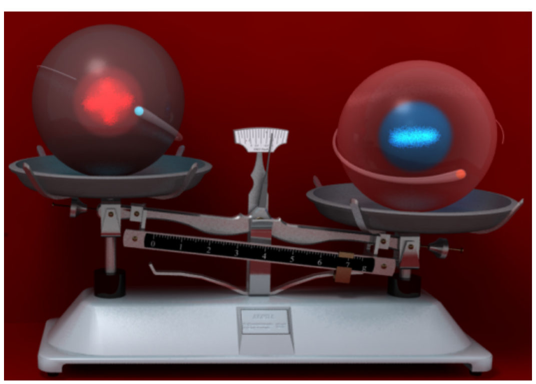



Jonathan Wurtele
U.C. Berkeley and LBNL

ALPHA Collaboration
16 institutions and roughly 40 co-authors

G.B. Andresen, M.D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P.D. Bowe, E. Butler, C.L. Cesar, S. Chapman, M. Charlton
A. Deller, S. Eriksson, L. Evans, J. Fajans, T. Friesen, M.C. Fujiwara, D.R. Gill, A. Gutierrez, J.S. Hangst, W.N. Hardy, R.S. Hayano, M.E. Hayden
A.J. Humphries, R. Hydomako, S. Jonsel, L. Kurchaninov, N. Madsen, S. Menary, P. Nolan, K. Olchanski, A. Olin, A. Povilus, P. Pusa
F. Robicheaux, E. Sarid, D.M. Silveira C. So, R.I. Thompson, D.P. van der Werf, J. S. Wurtele, Y. Yamazaki and A. Zhmoginov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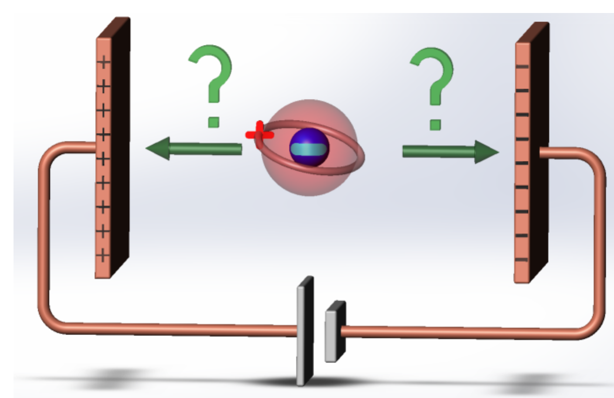
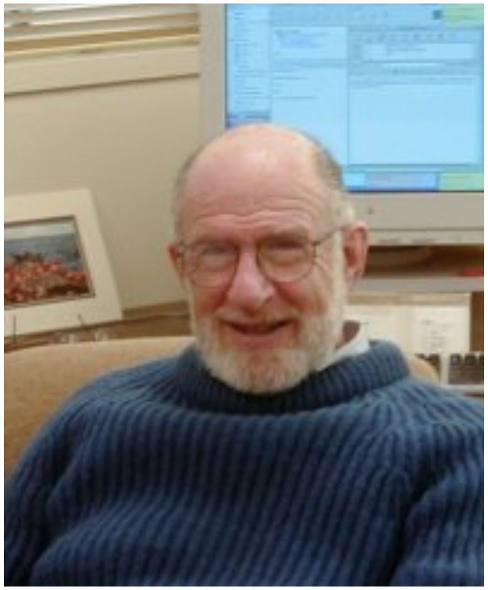
(Accelerator Science)
2011-2012 LBNL LDRD

# The Cooling of Particle Beams

Andrew M. Sessler

*Center for Beam Physics
Lawrence Berkeley Laboratory
Berkeley, CA 94720



**Abstract**. A review is given of the various methods which can be employed for cooling particle beams. These methods include radiation damping, stimulated radiation damping, ionization cooling, stochastic cooling, electron cooling, laser cooling, and laser cooling with beam coupling. Laser cooling has provided beams of the lowest temperatures, namely 1 mK, but only for ions and only for the longitudinal temperature. Recent theoretical work has suggested how laser cooling, with the coupling of beam motion, can be used to reduce the ion beam temperature in all three directions. The majority of this paper is devoted to describing laser cooling and laser cooling with beam coupling.

# Overview

*Goal: Test the foundations of physics through precision Antihydrogen measurements*

*1S-2S spectroscopy*

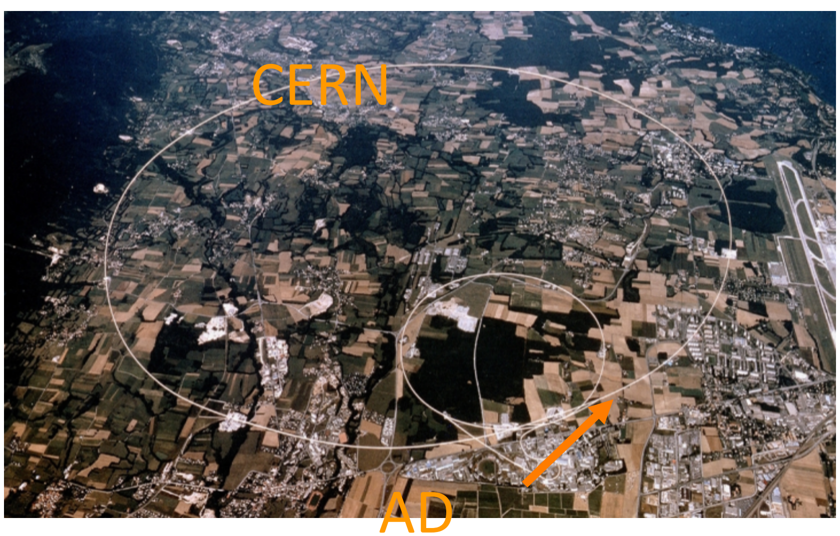
*Hyperfine spectroscopy*

*Charge neutrality*

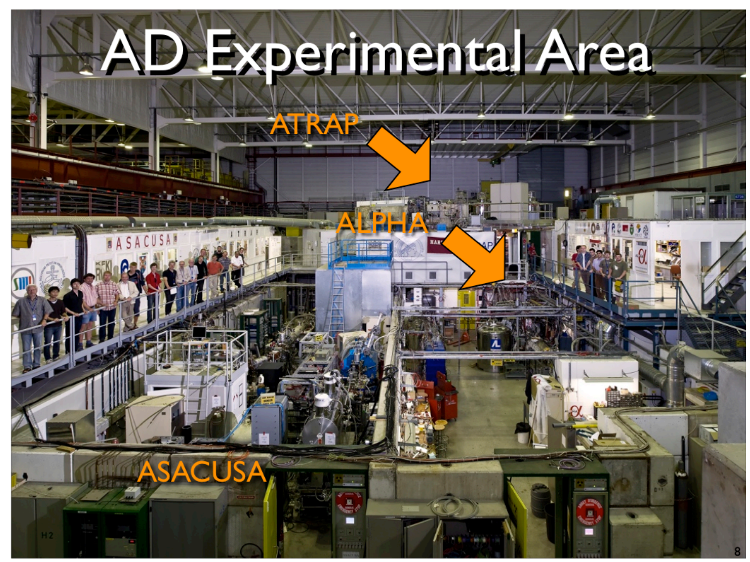
*Gravitational force (Einstein Equivalence Principle)*

The ALPHA Collaboration: *Founded in 2005; 40-50 members 14-15 institutions in 8 countries*

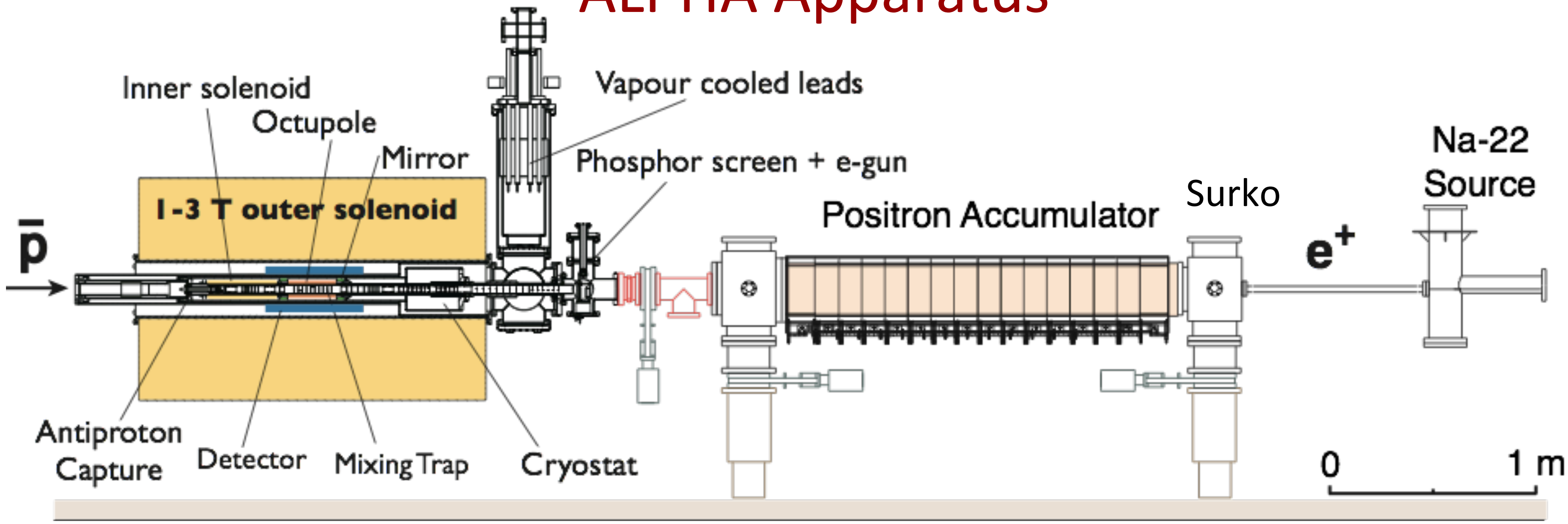
- Experiment at the Antiproton Decelerator (AD) Facility at CERN

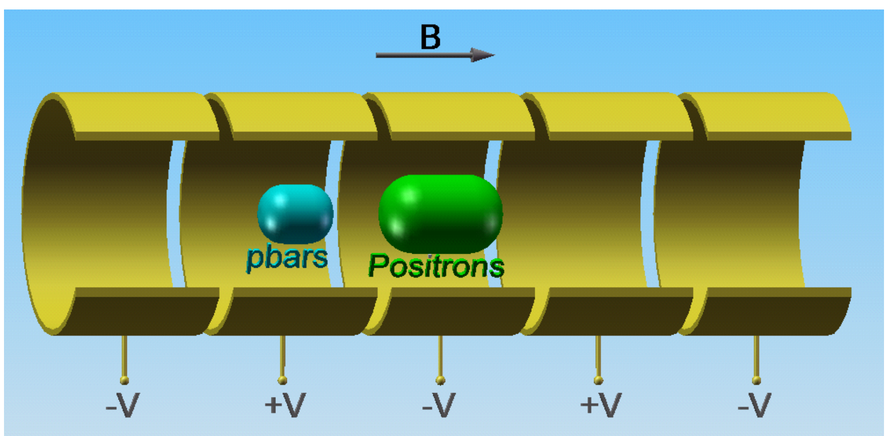



3

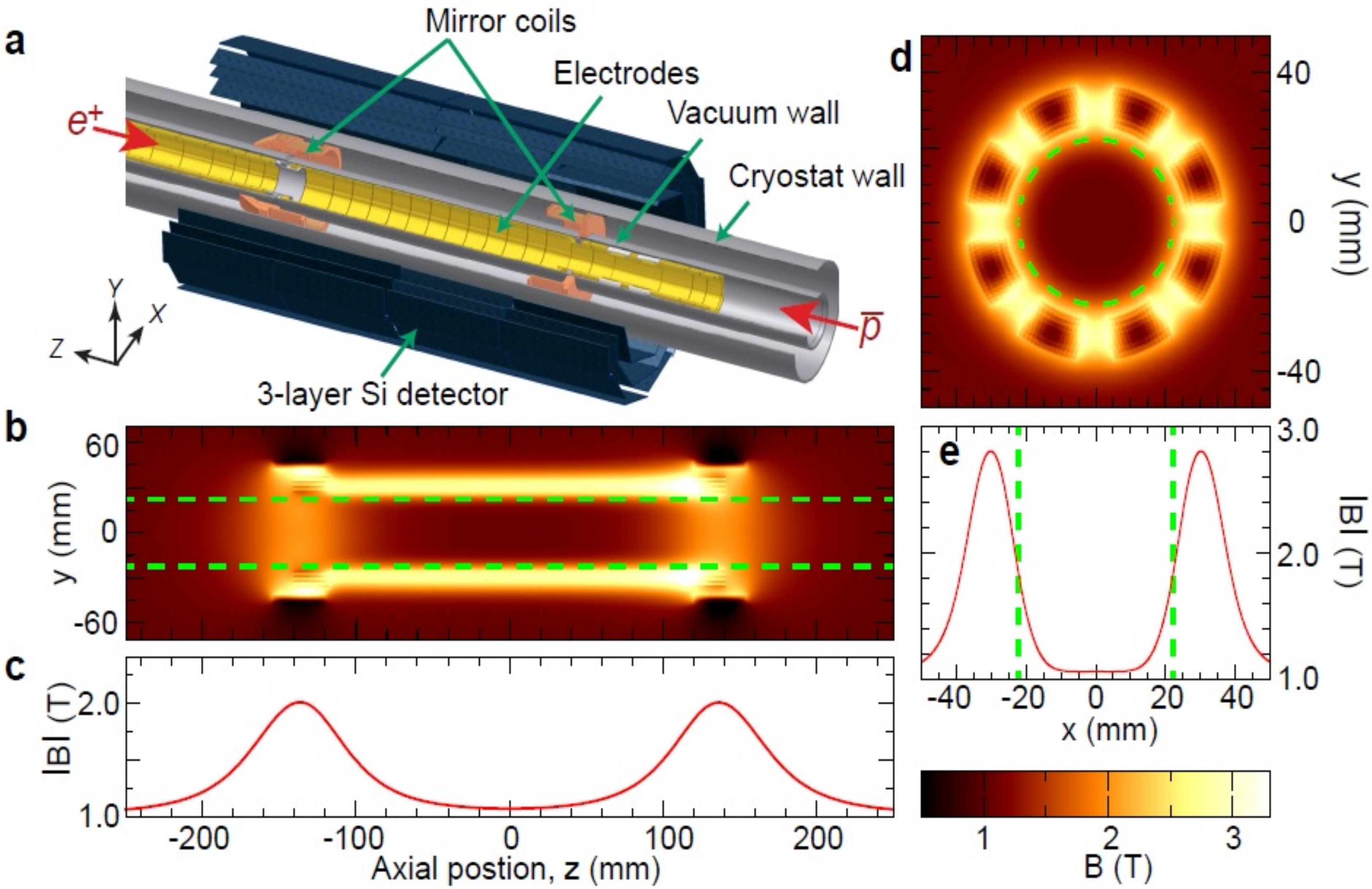


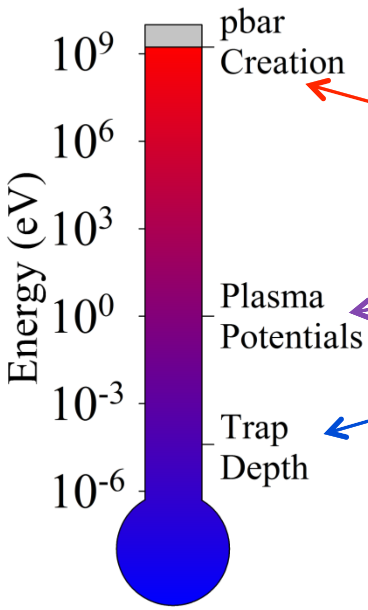
# ALPHA Apparatus




ATRAP apparatus broadly similar.


a
Mirror coils
Electrodes
Vacuum wall
Cryostat wall
e+
p̄
Y
X
Z
3-layer Si detector
b
60
0
-60
y (mm)
c
|B| (T)
2.0
1.0
-200
-100
0
100
200
Axial postion, z (mm)
d
40
0
-40
y (mm)
e
3.0
2.0
1.0
|B| (T)
-40
-20
0
20
40
x (mm)
1
2
3
B (T)




Energy Scales:

Antiproton Creation Energy: 1.7GeV

Self-Potential: 30mV-10V

Trap Depth: 0.5K or 40µeV

$$\frac{\text{Antiproton Creation Energy}}{\text{Trap Depth}} = 10^{14}$$

$$\frac{\text{LHC Energy Increase}}{\text{Free Protons on Creation}} = 10^{8}$$

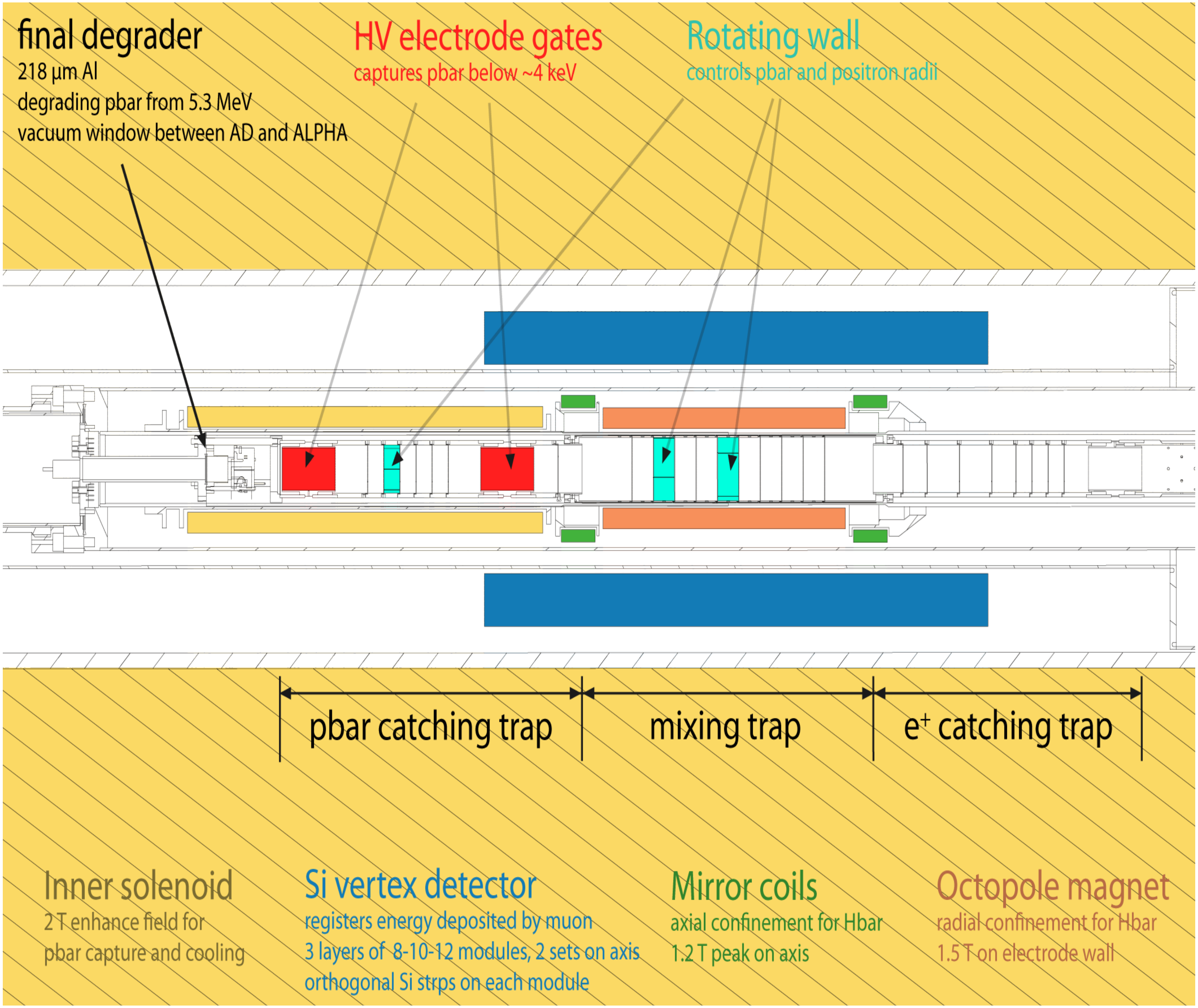
$$\frac{\text{Collective Potential}}{\text{Neutral Trap Depth}} = 10^{3} - 10^{5}$$

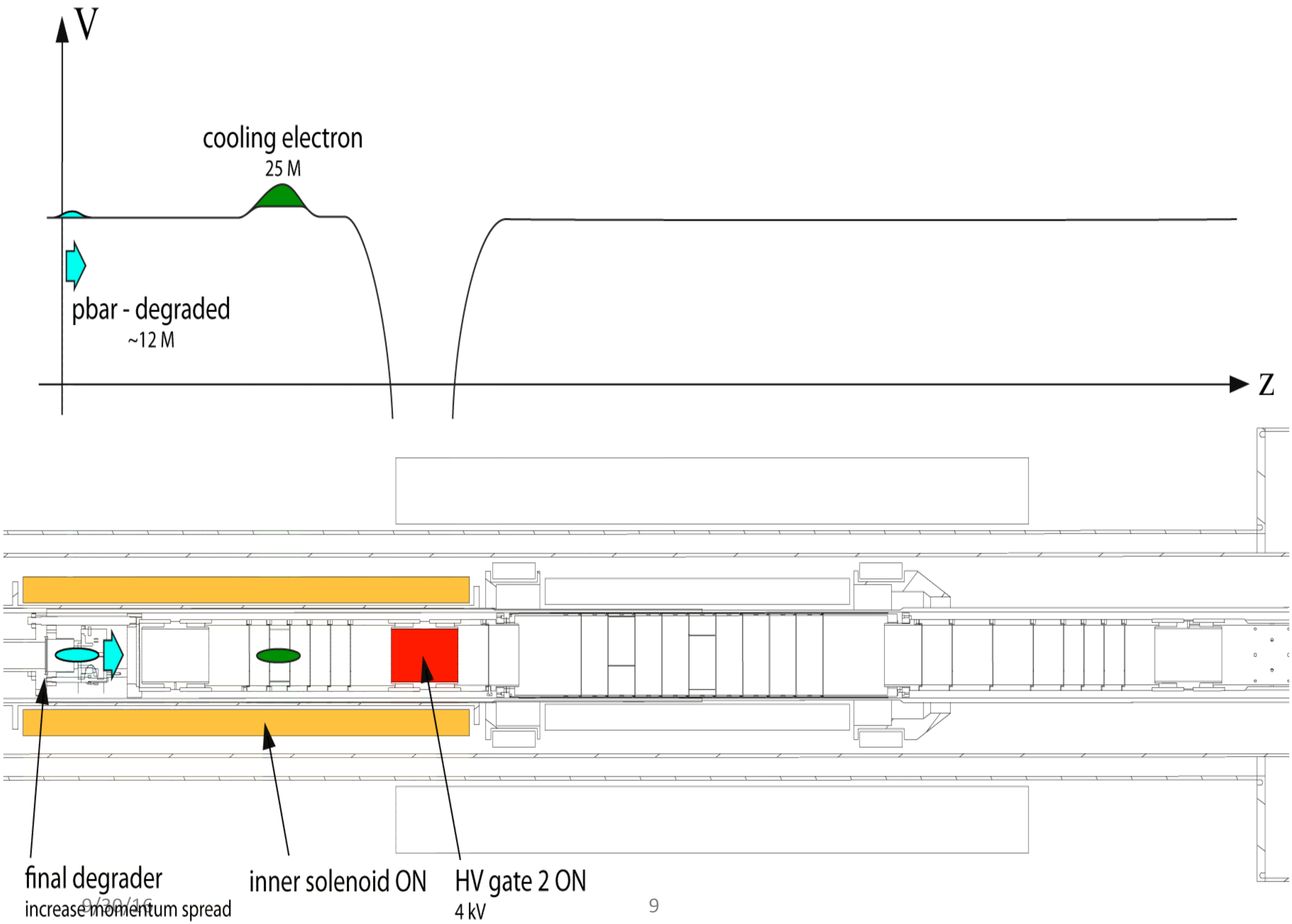
# Phase Space Manipulations

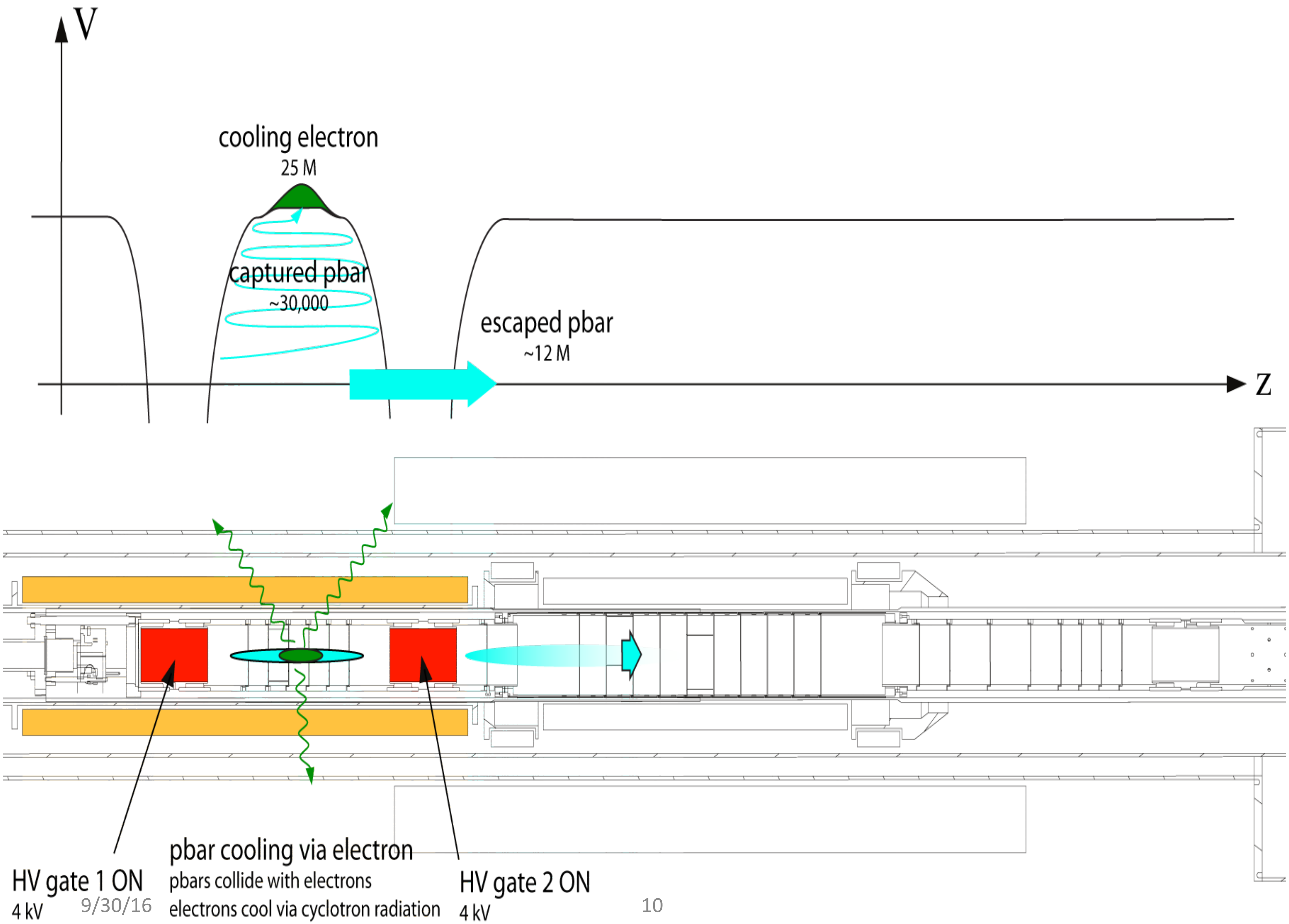
- Radiative Cooling: Electrons and Positrons
- Sympathetic Cooling: antiprotons cool on electrons [ATRAP]
- Evaporative cooling: Prepare low temperature bunches [ALPHA PRL 2010],
- Buffer gas slowing: Surko-style positron trapping.
- Microwave mode excitation: Measure plasma parameters

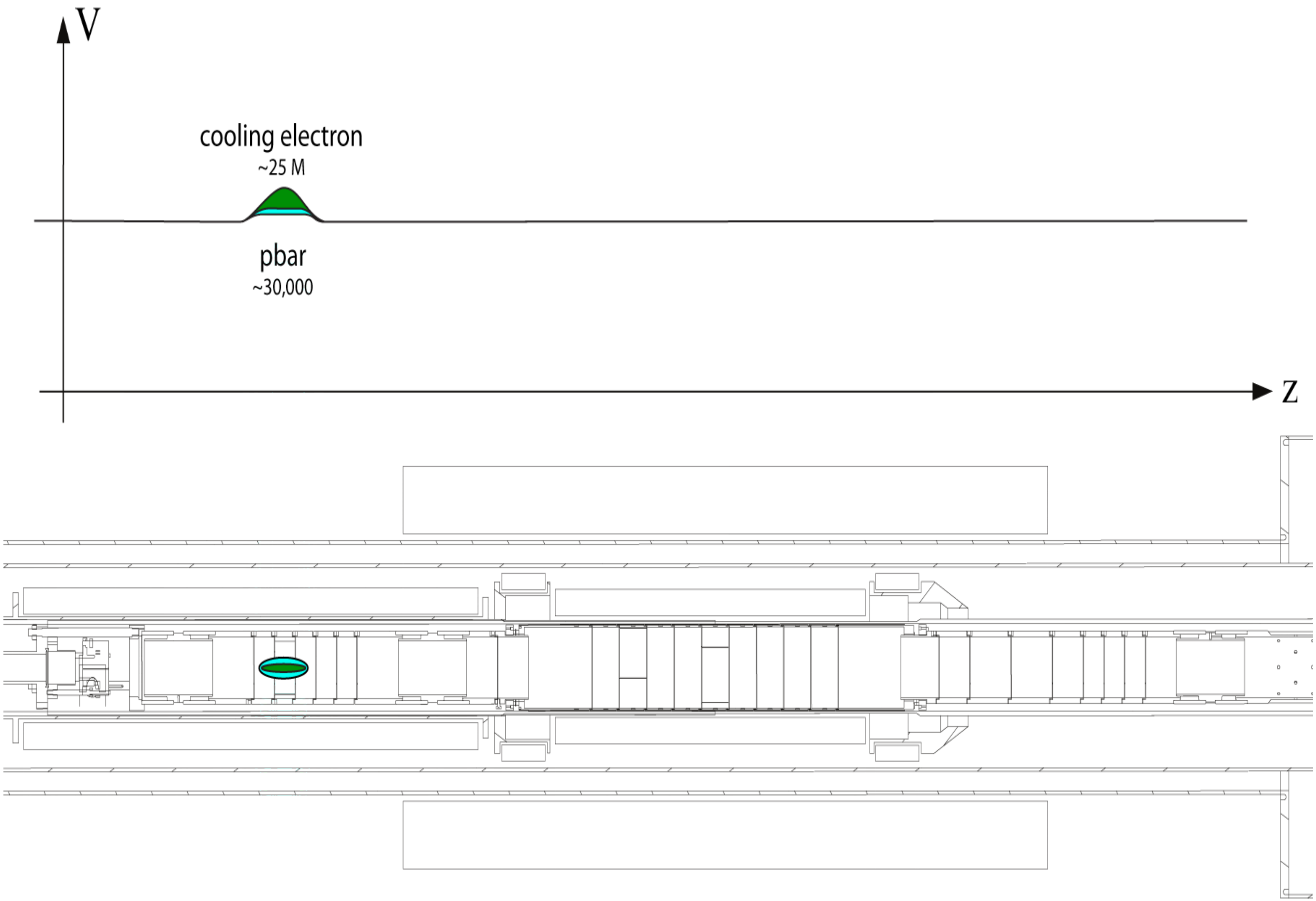
- Species separation (heats): E-kick. Remove electrons from antiproton. Cutting (number reduction).
- Species mixing (heats): Autoresonance used to drive antiprotons into positrons. [ALPHA PoP 2013]
- Rotating wall compression (heats): Apply torque to compress plasma. [ALPHA, PRL 2011] USCD pioneered..

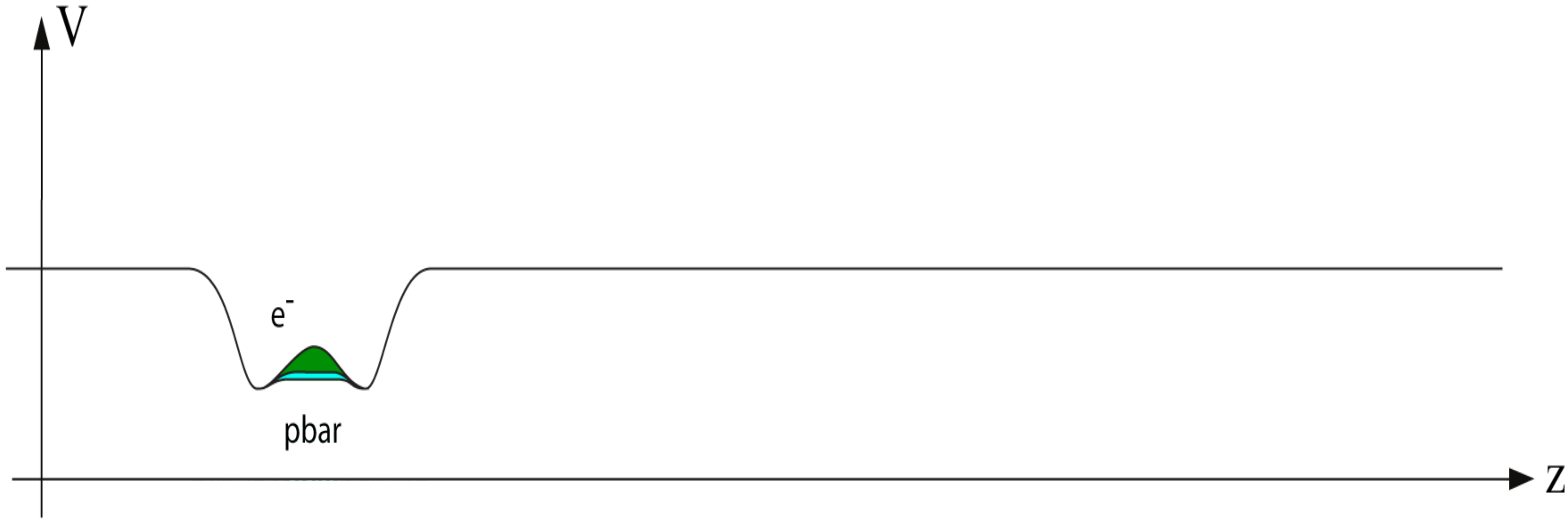
- Cavity-enhanced radiative cooling: CERES experiment underway at Berkeley in Fajans laboratory

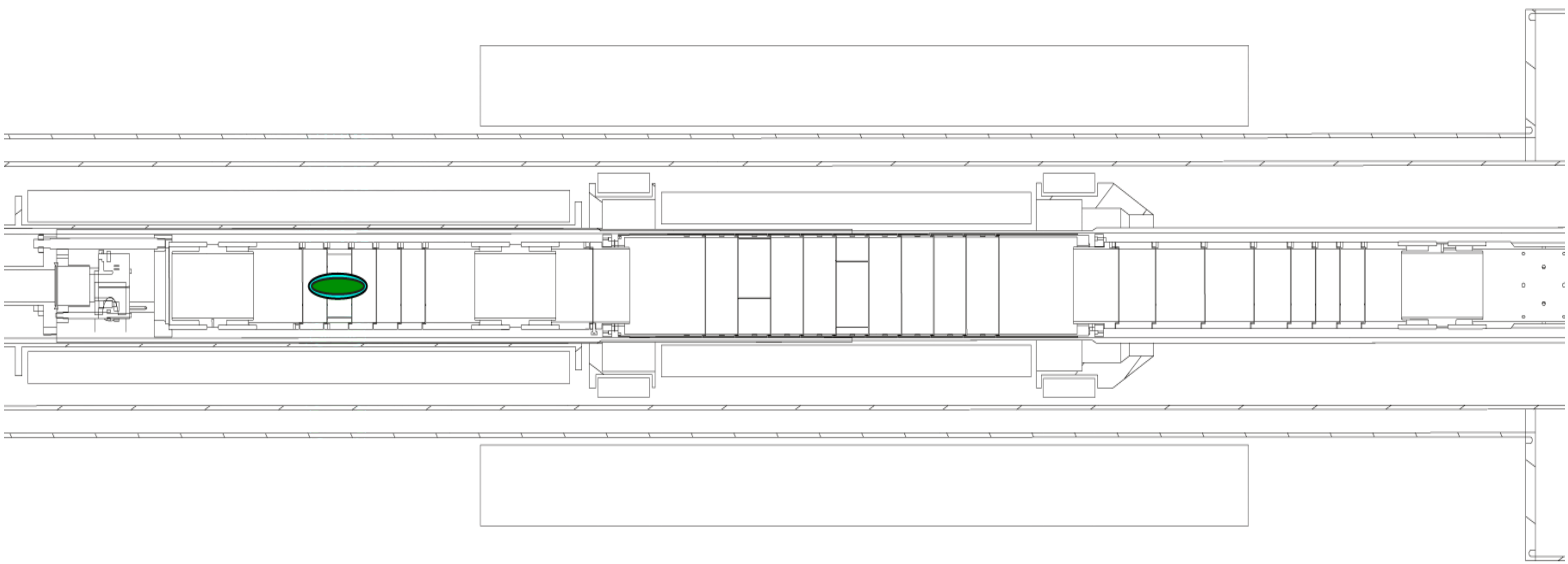

final degrader
218 μm Al
degrading pbar from 5.3 MeV
vacuum window between AD and ALPHA
HV electrode gates
captures pbar below ~4 keV
Rotating wall
controls pbar and positron radii
pbar catching trap
mixing trap
e+ catching trap
Inner solenoid
2 T enhance field for
pbar capture and cooling
Si vertex detector
registers energy deposited by muon
3 layers of 8-10-12 modules, 2 sets on axis
orthogonal Si strps on each module
Mirror coils
axial confinement for Hbar
1.2 T peak on axis
Octopole magnet
radial confinement for Hbar
1.5 T on electrode wall

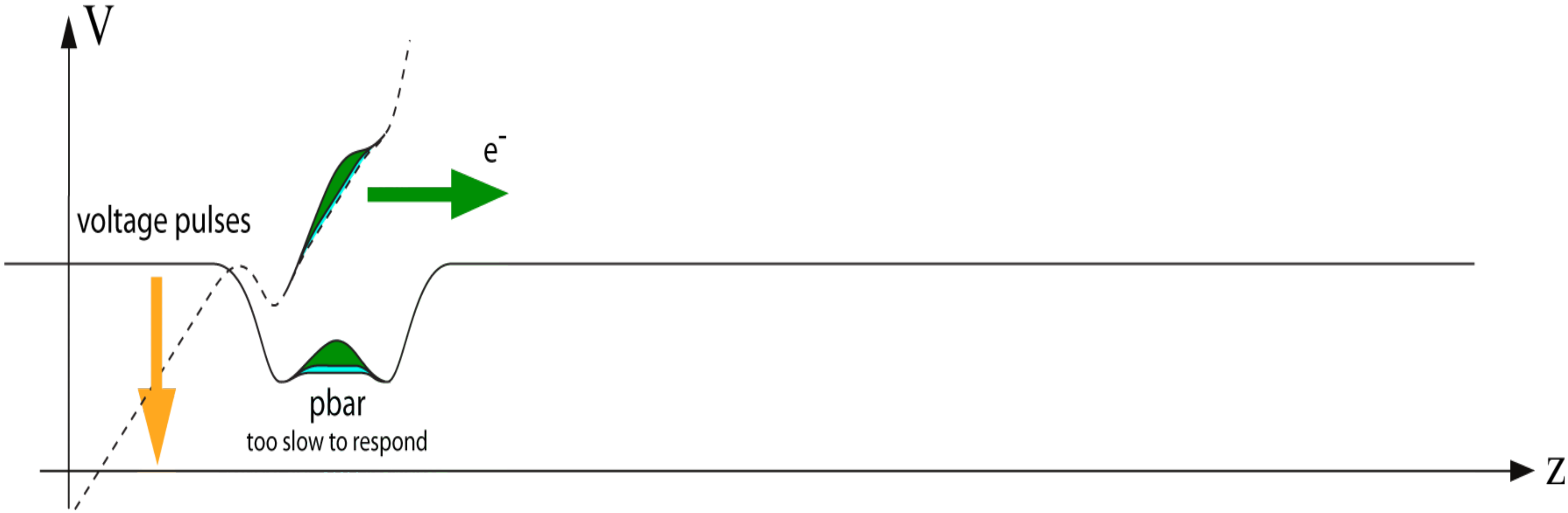

V
cooling electron
25 M
pbar - degraded
~12 M
Z
final degrader
increase momentum spread
inner solenoid ON
HV gate 2 ON
4 kV

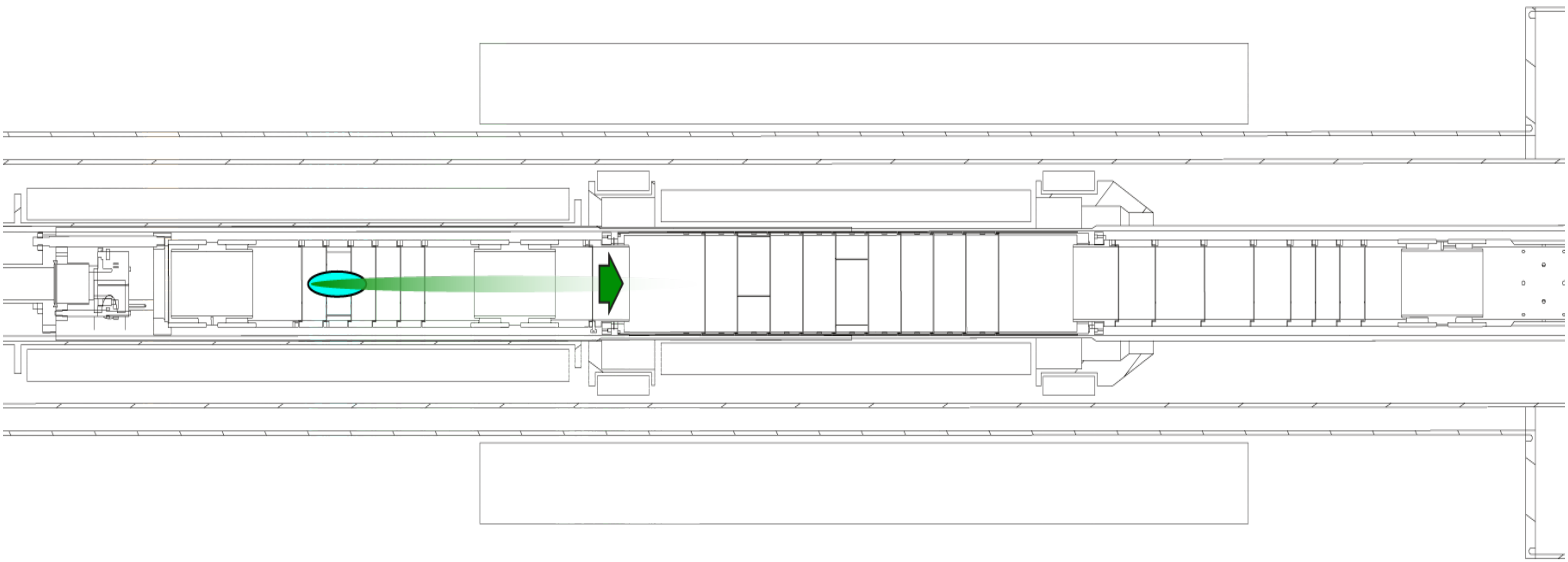

V
cooling electron
25 M
captured pbar
~30,000
escaped pbar
~12 M
Z
pbar cooling via electron
pbars collide with electrons
electrons cool via cyclotron radiation
HV gate 1 ON
4 kV
HV gate 2 ON
4 kV

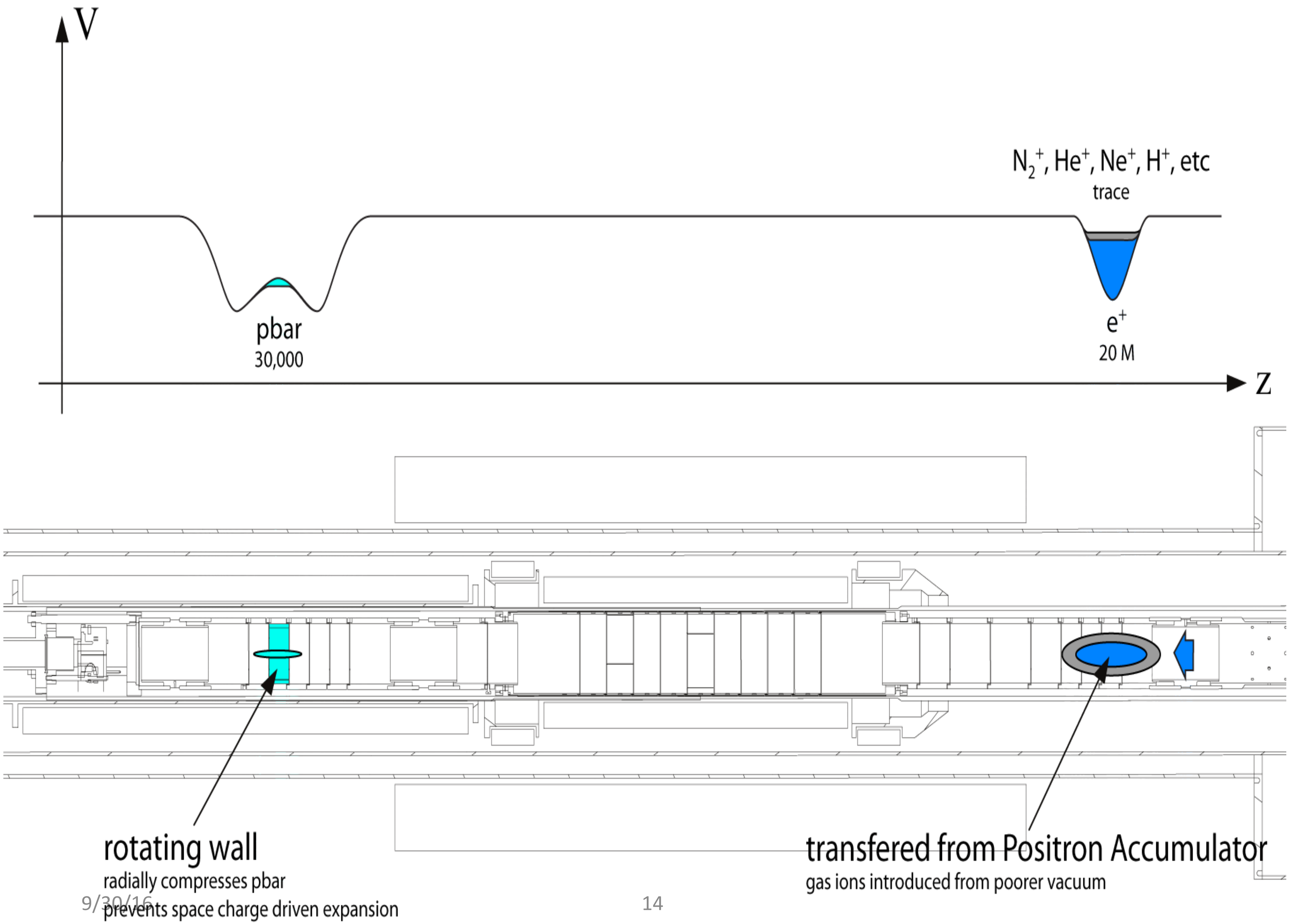

V
cooling electron
~25 M
pbar
~30,000
Z


V
e-
pbar
Z

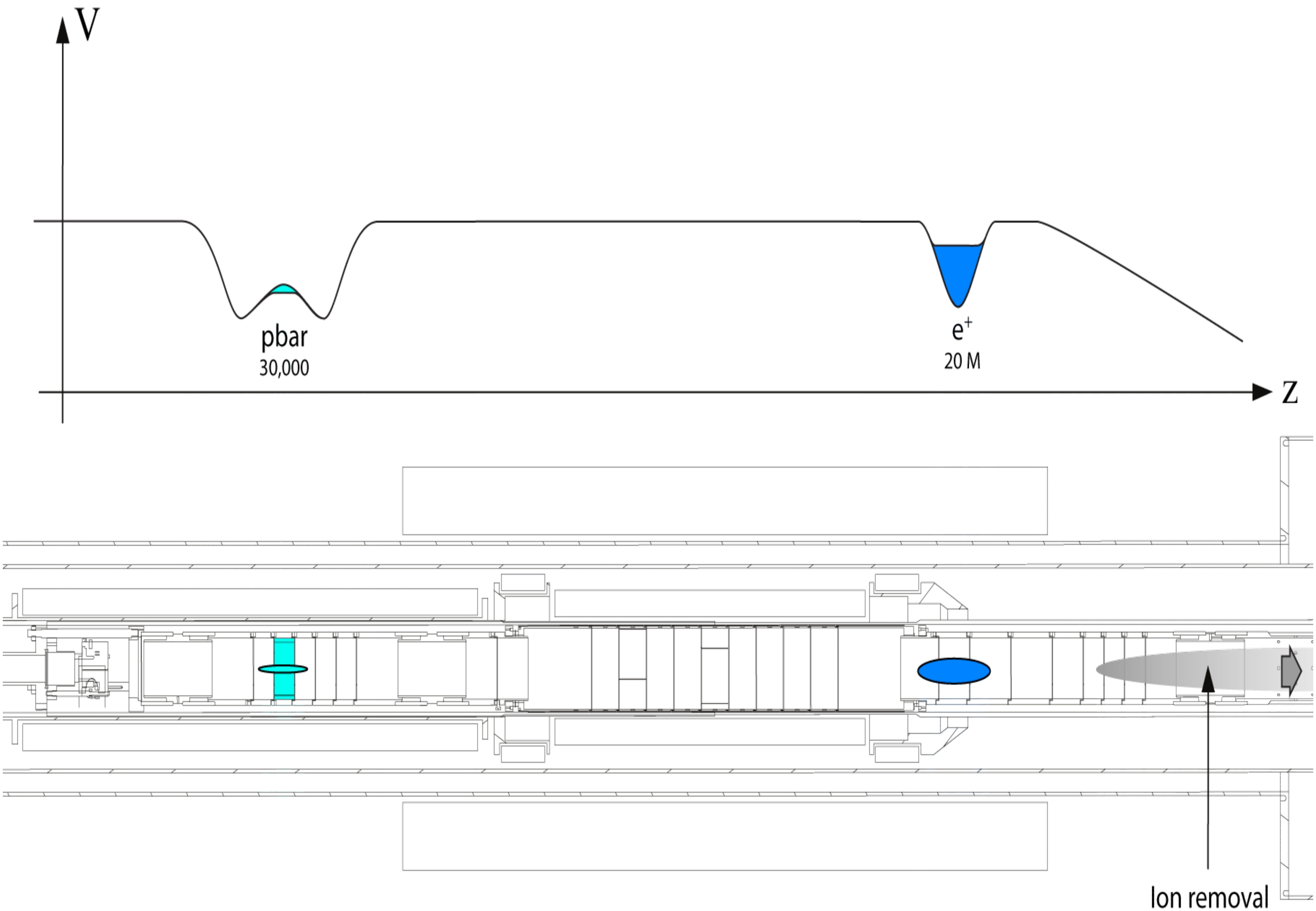


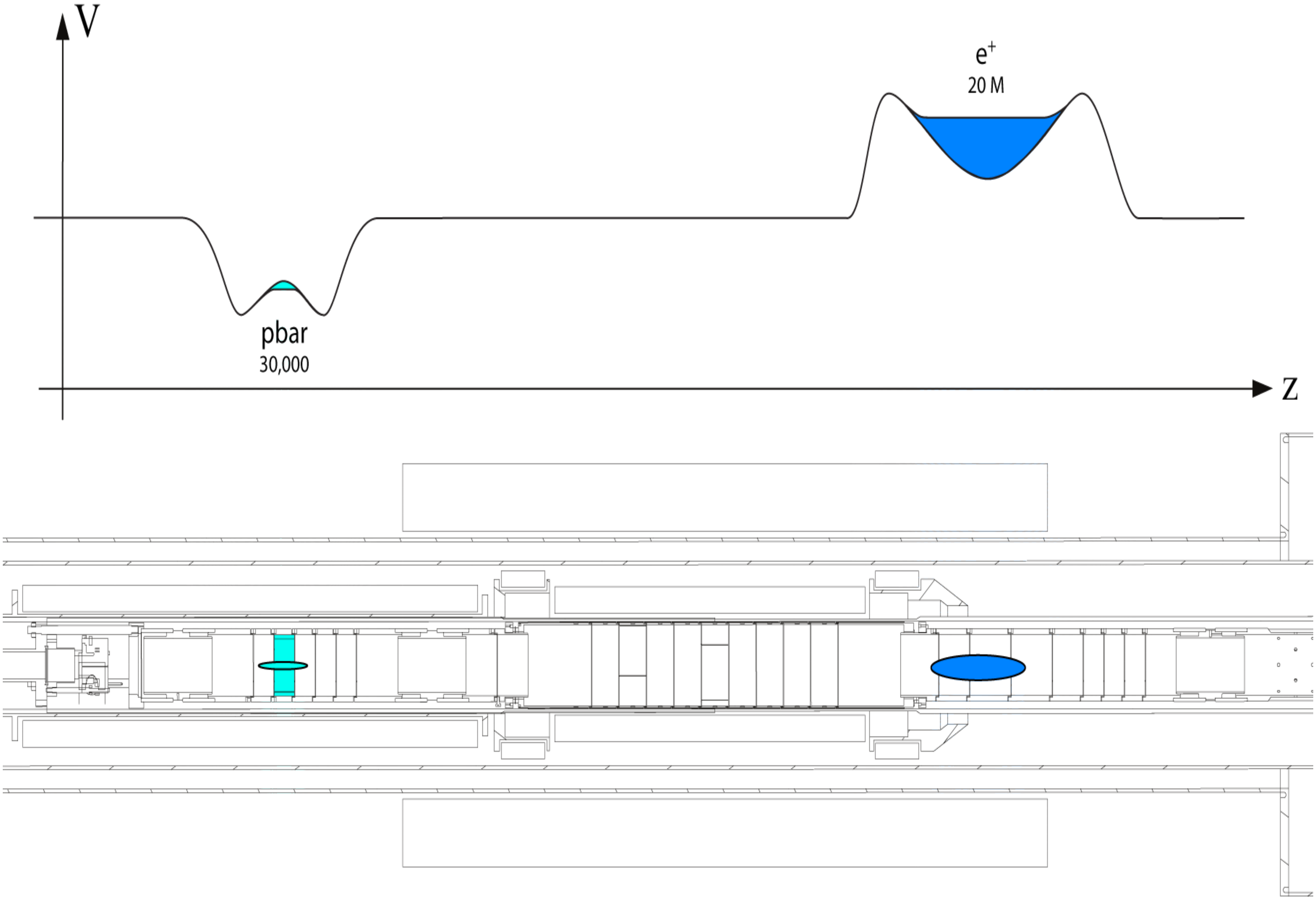

V
e-
voltage pulses
pbar
too slow to respond
Z

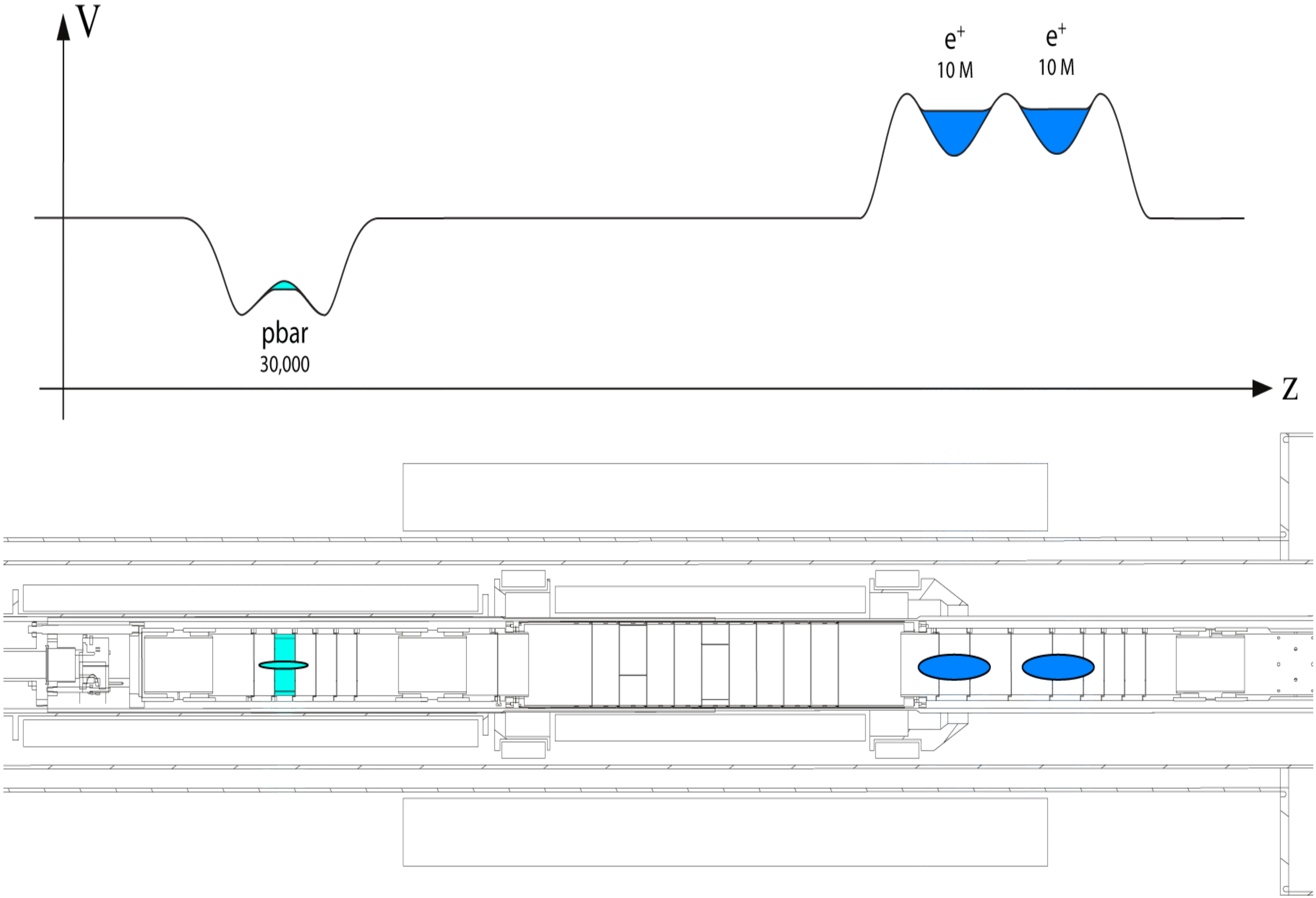


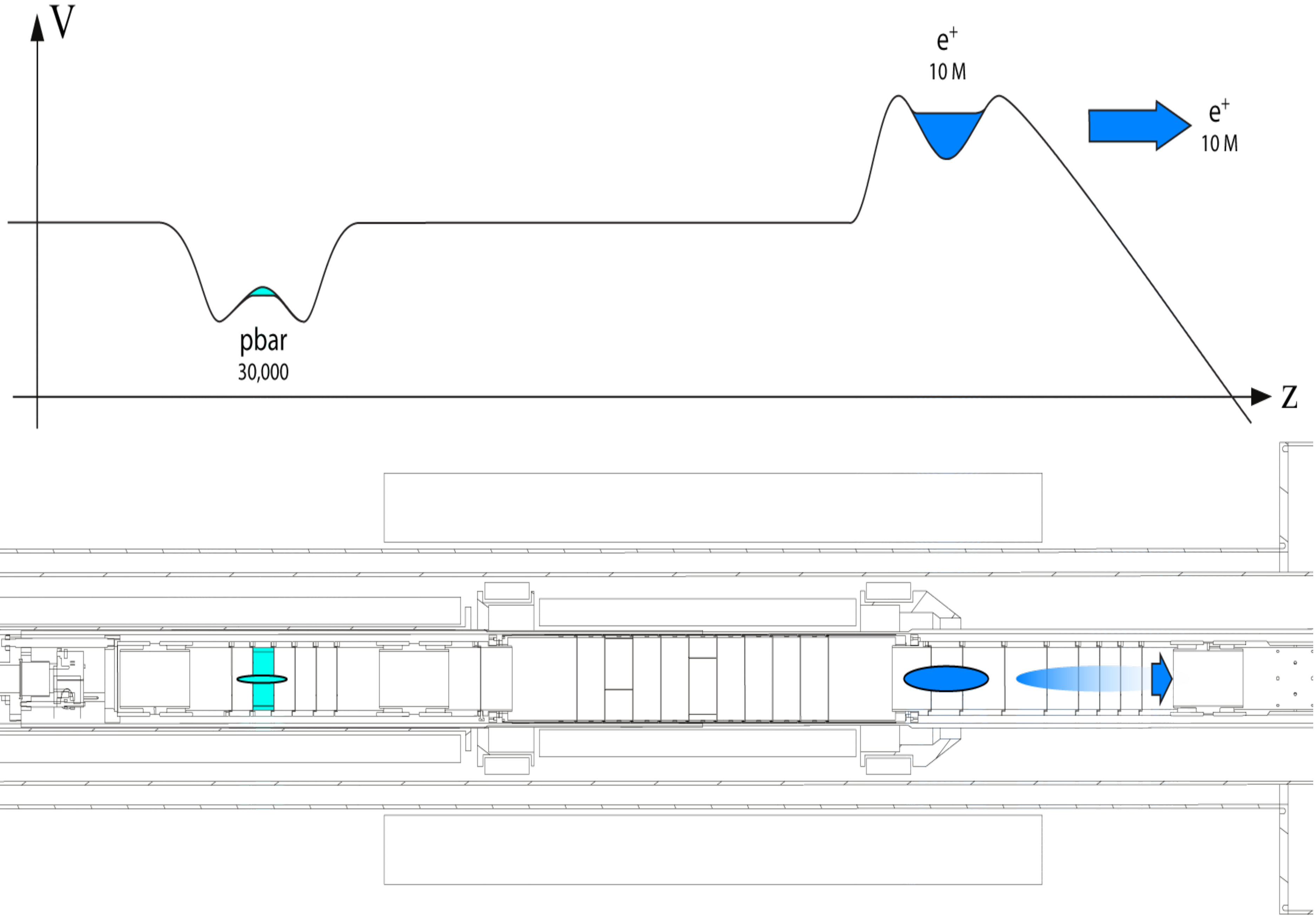


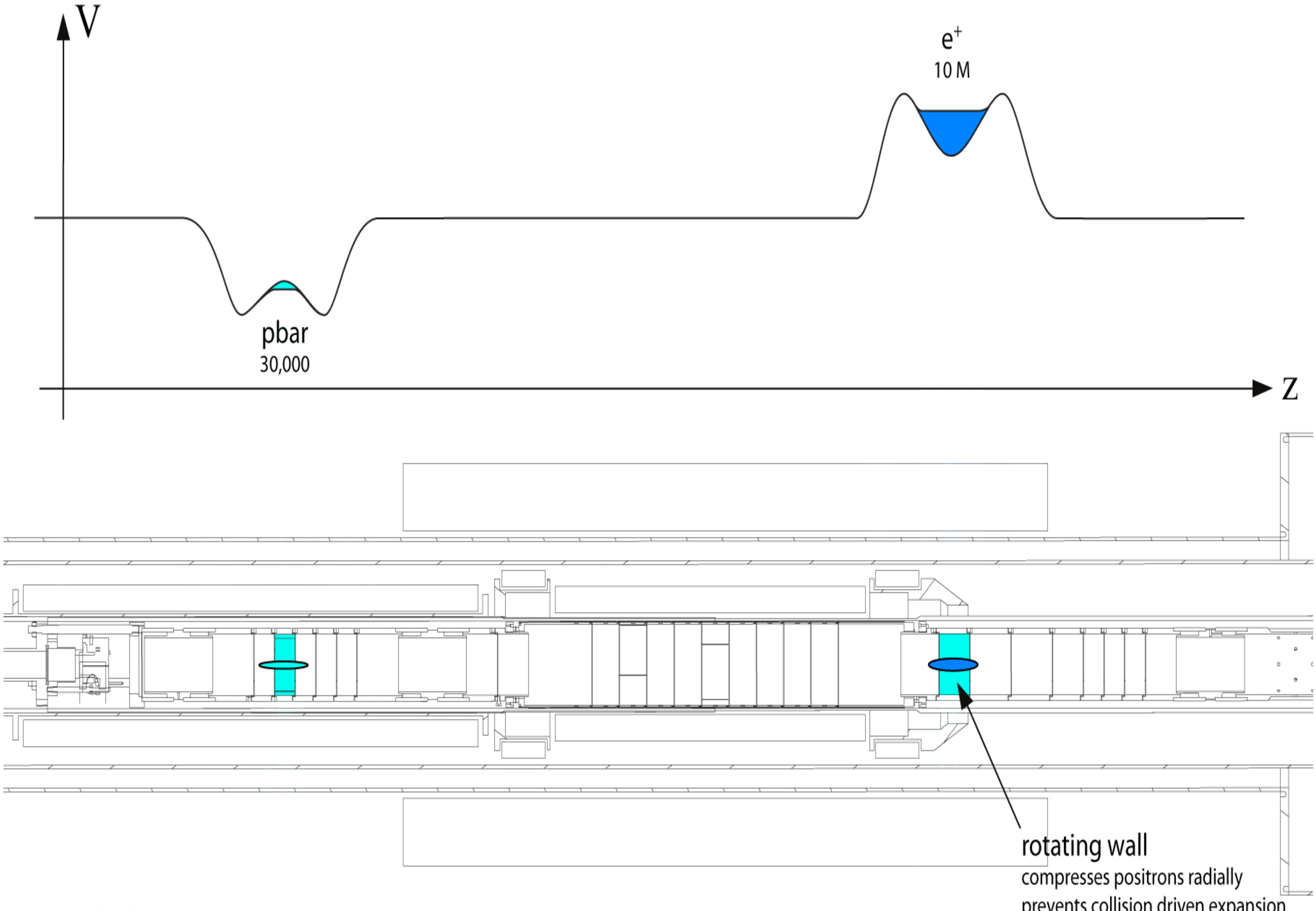
V
$N_2^+$, $He^+$, $Ne^+$, $H^+$, etc
trace
pbar
30,000
$e^+$
20 M
Z
rotating wall
radially compresses pbar
prevents space charge driven expansion
transfered from Positron Accumulator
gas ions introduced from poorer vacuum

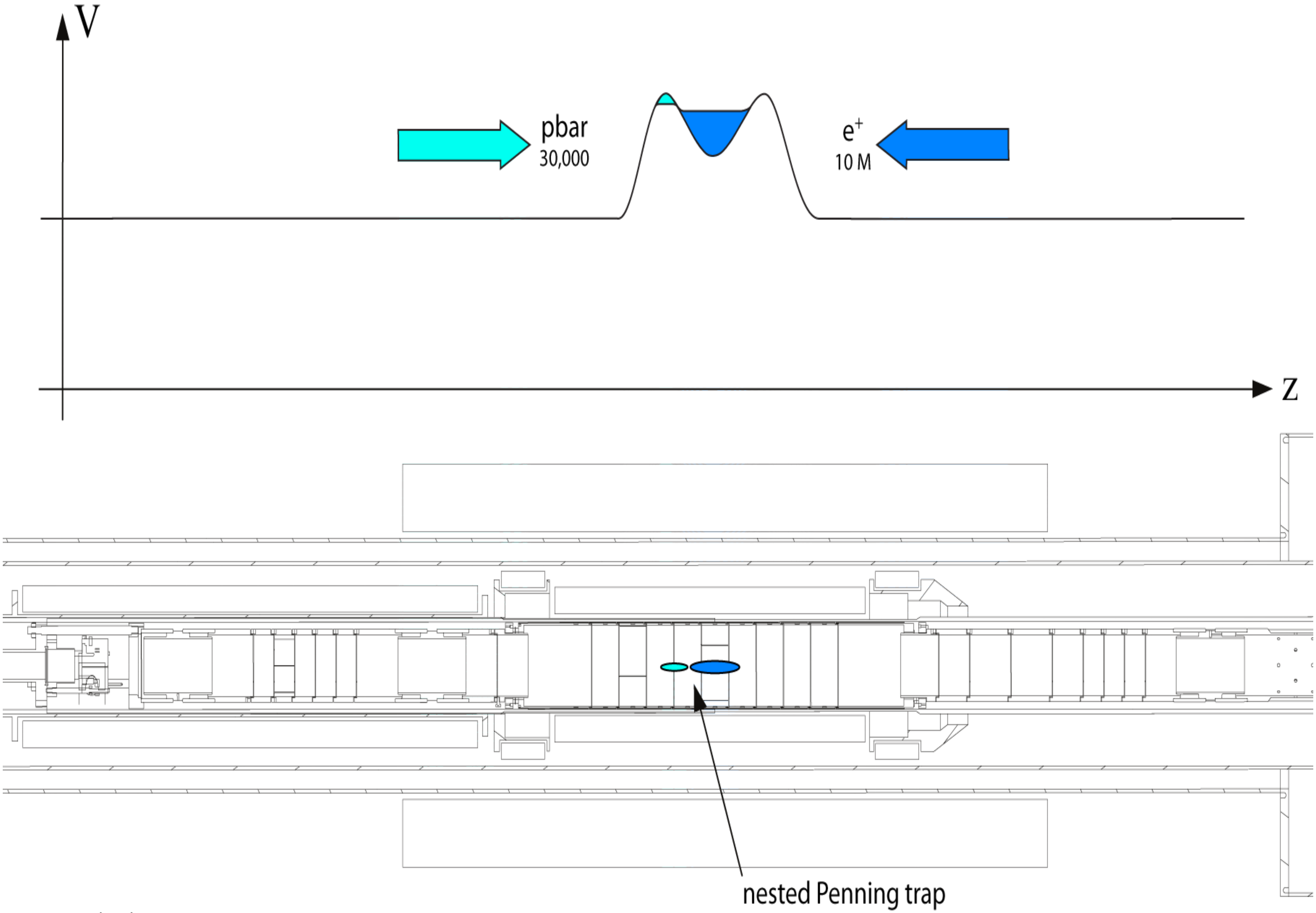

V
pbar
30,000
$e^+$
20 M
Z
Ion removal

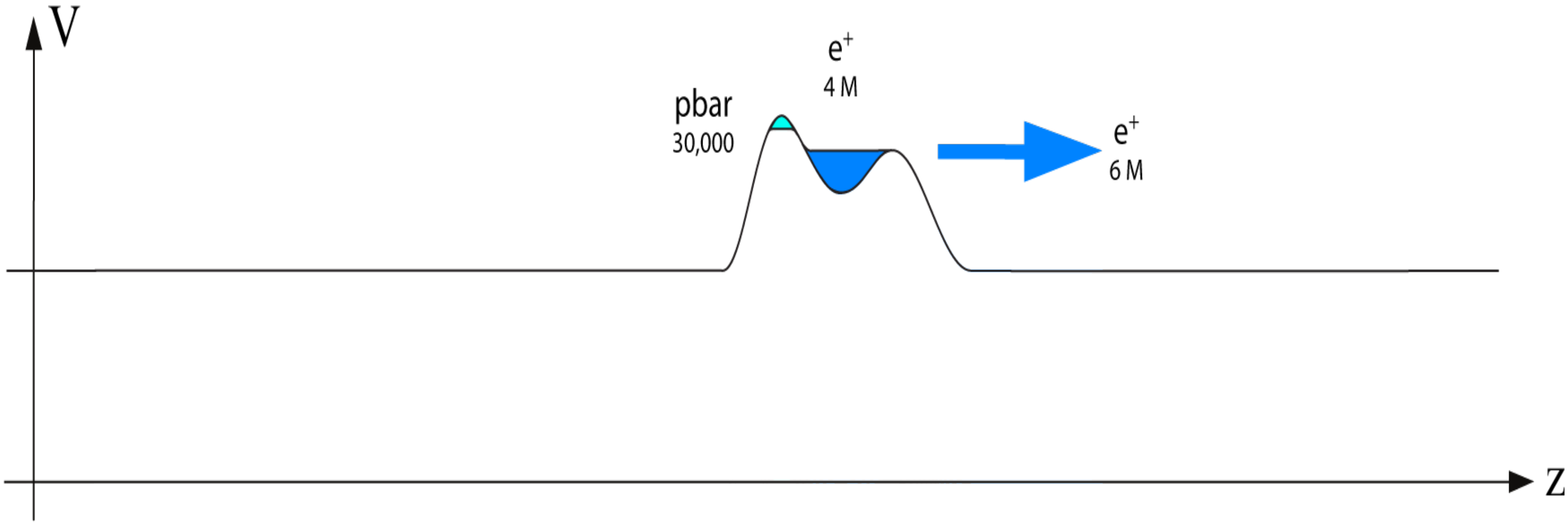

V
e+
20 M
pbar
30,000
Z

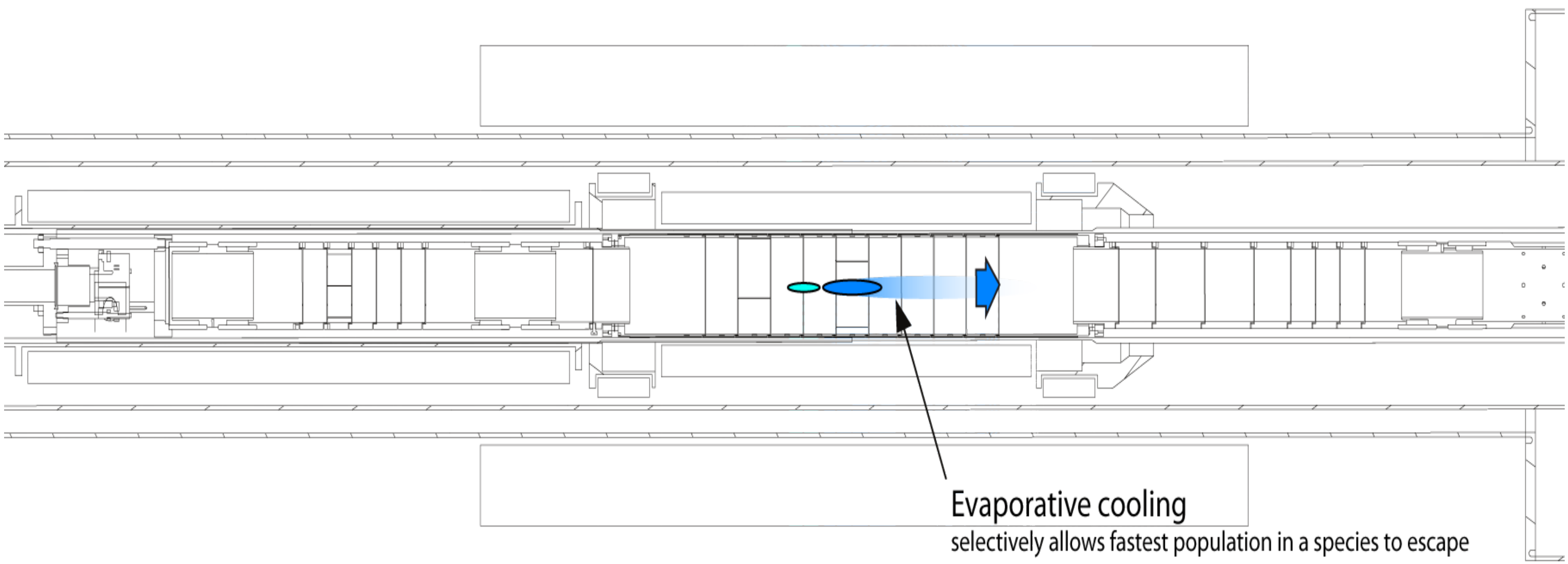

V
e+
10 M
e+
10 M
pbar
30,000
Z


V
e+
10 M
e+
10 M
pbar
30,000
Z


V
e+
10 M
pbar
30,000
Z
rotating wall
compresses positrons radially
prevents collision driven expansion

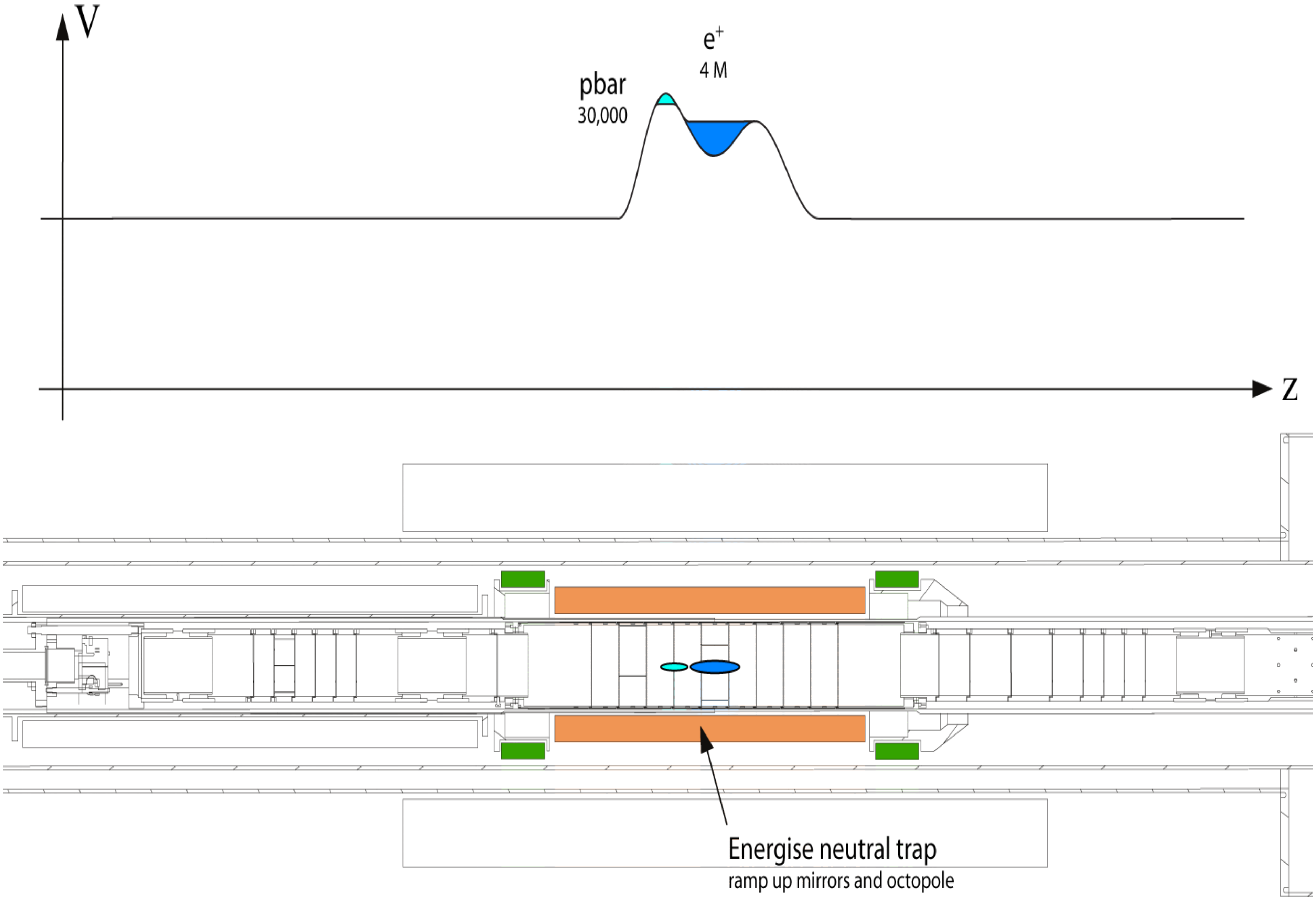

V
pbar
30,000
e+
10 M
Z
nested Penning trap

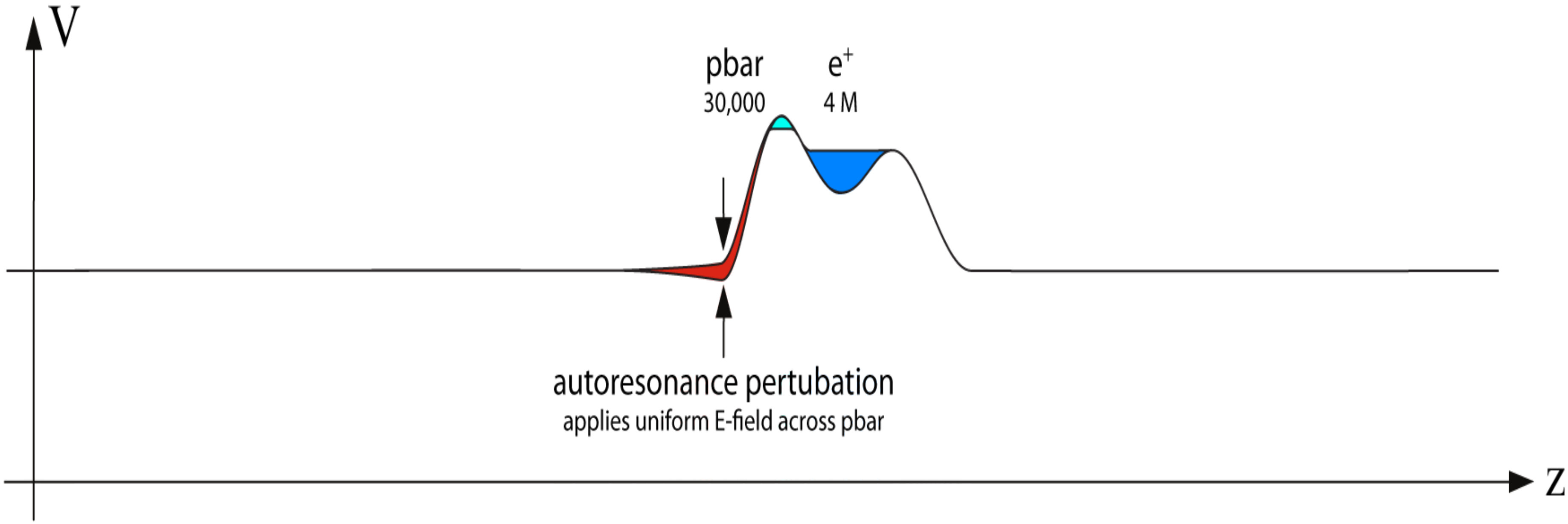


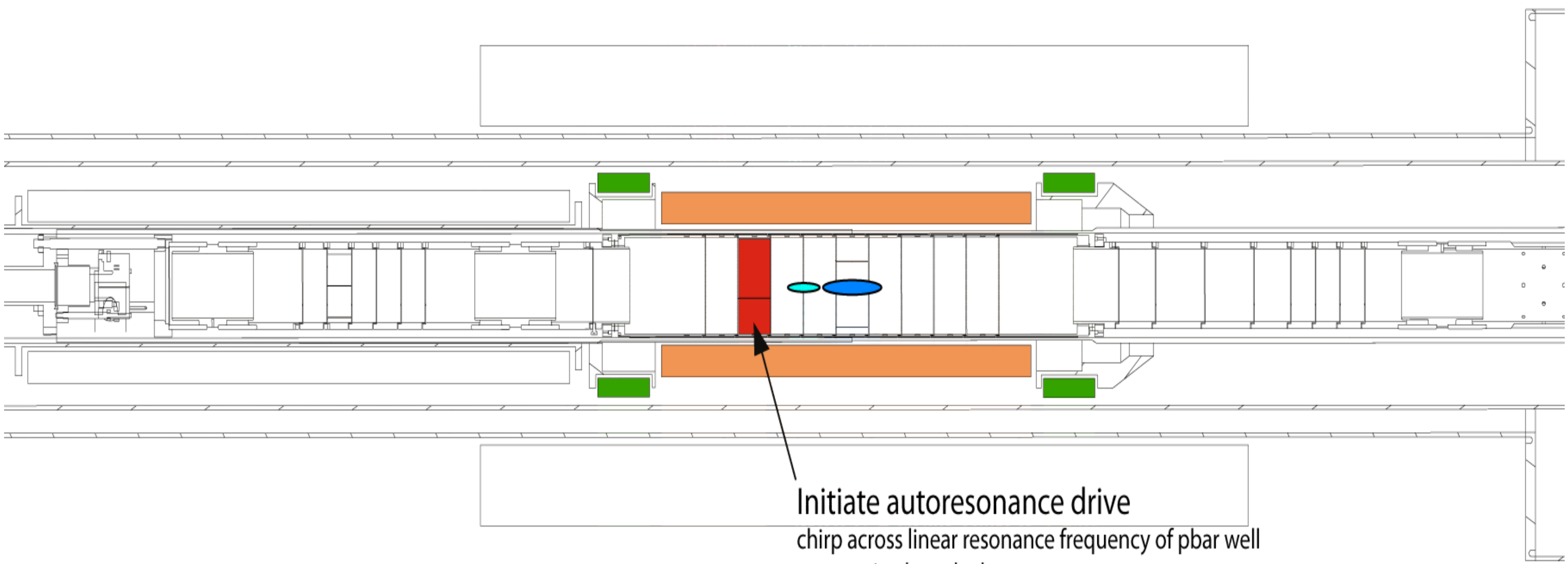



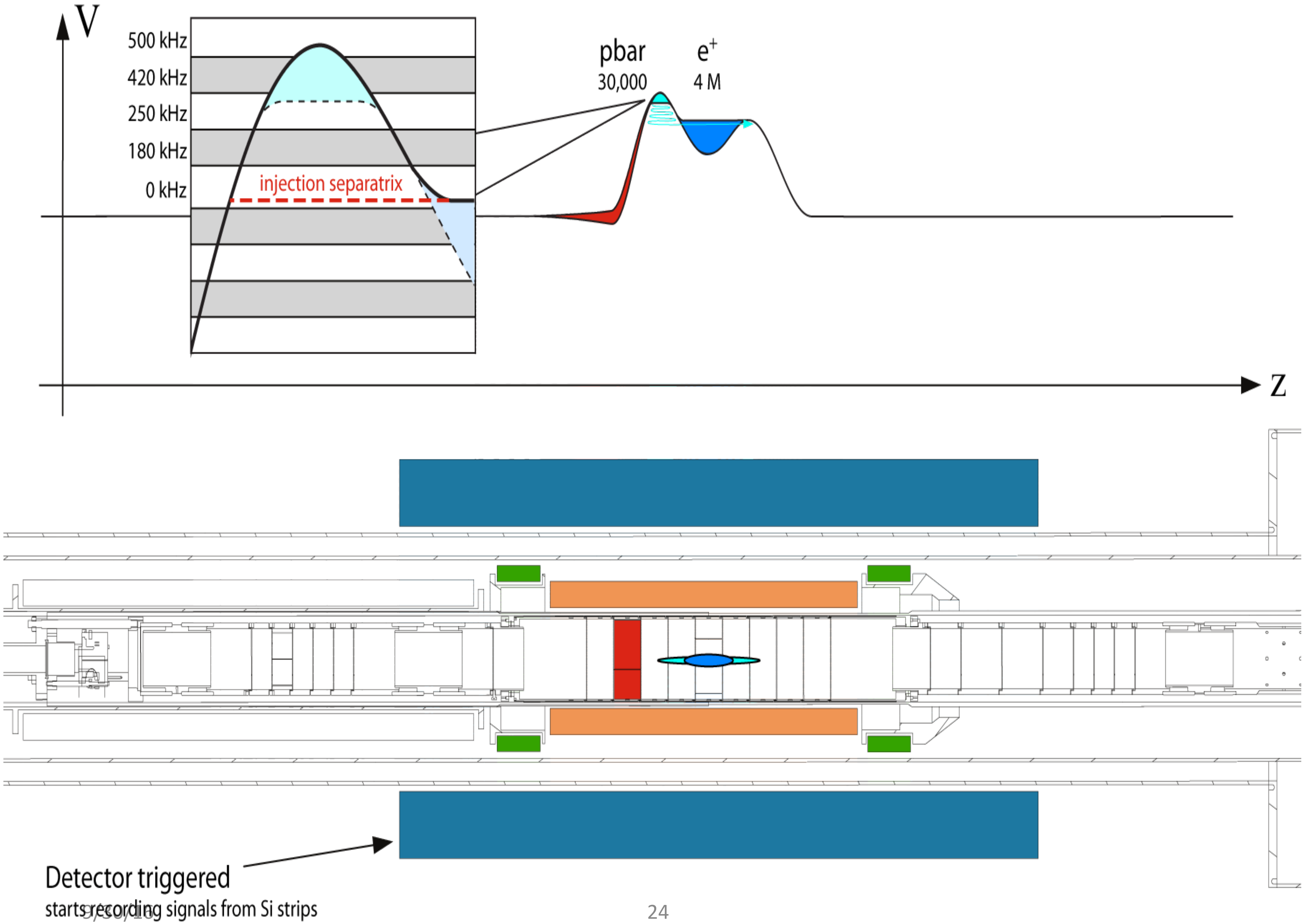
Evaporative cooling

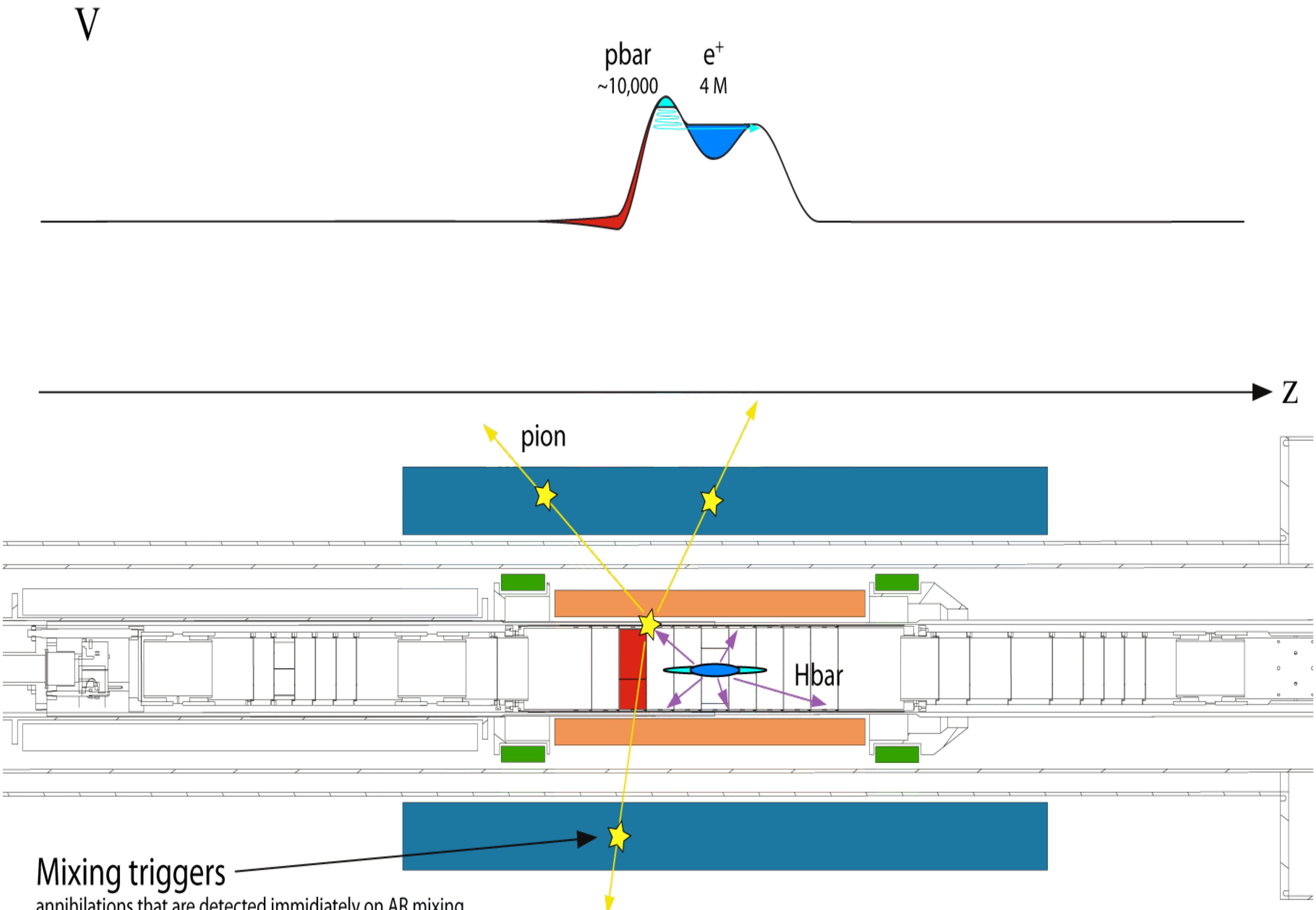
selectively allows fastest population in a species to escape
remaining population re-thermalise to lower temperature


V
e+
4 M
pbar
30,000
Z
Energise neutral trap
ramp up mirrors and octopole

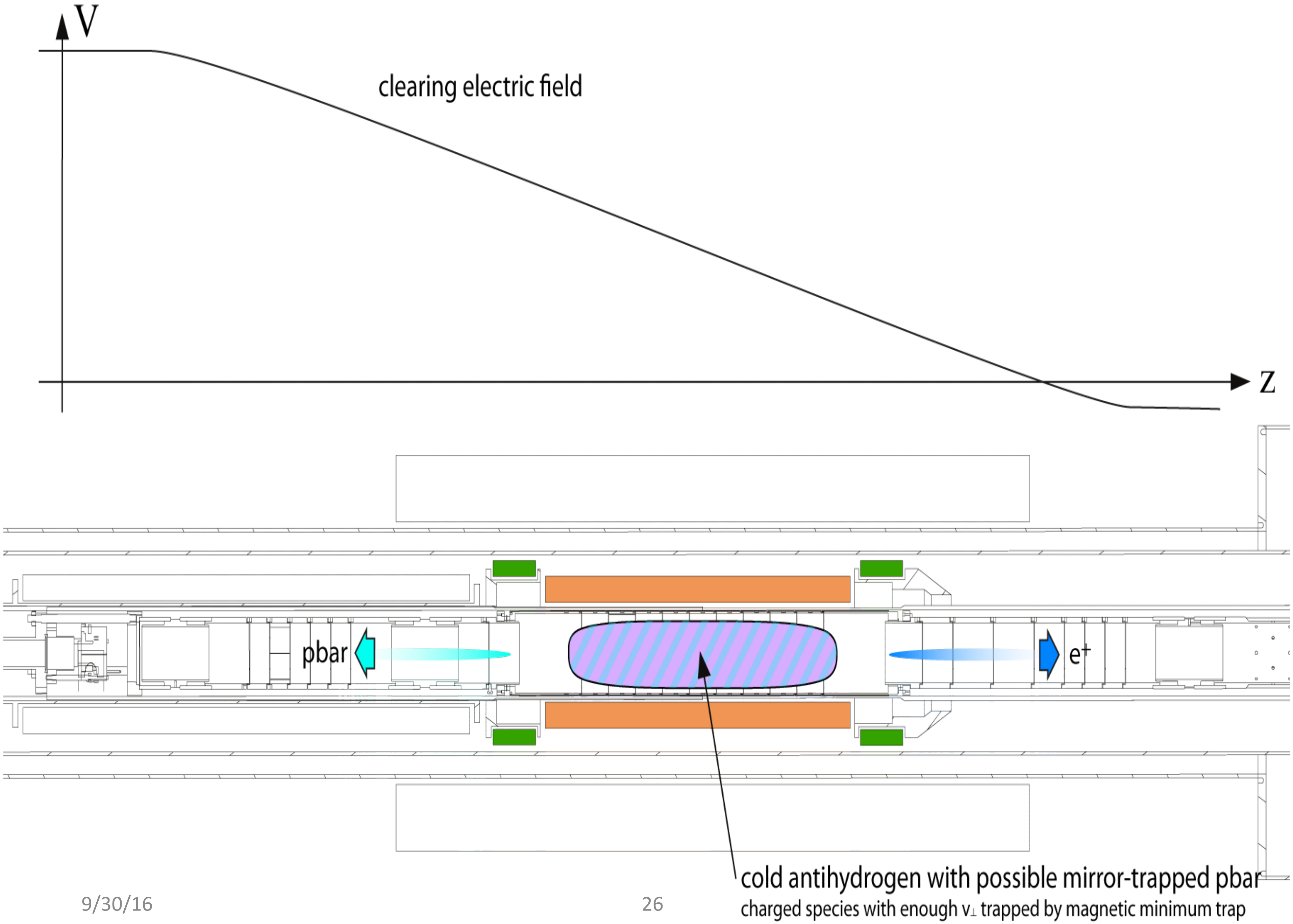

V
pbar
30,000
e+
4 M
autoresonance pertubation
applies uniform E-field across pbar
Z

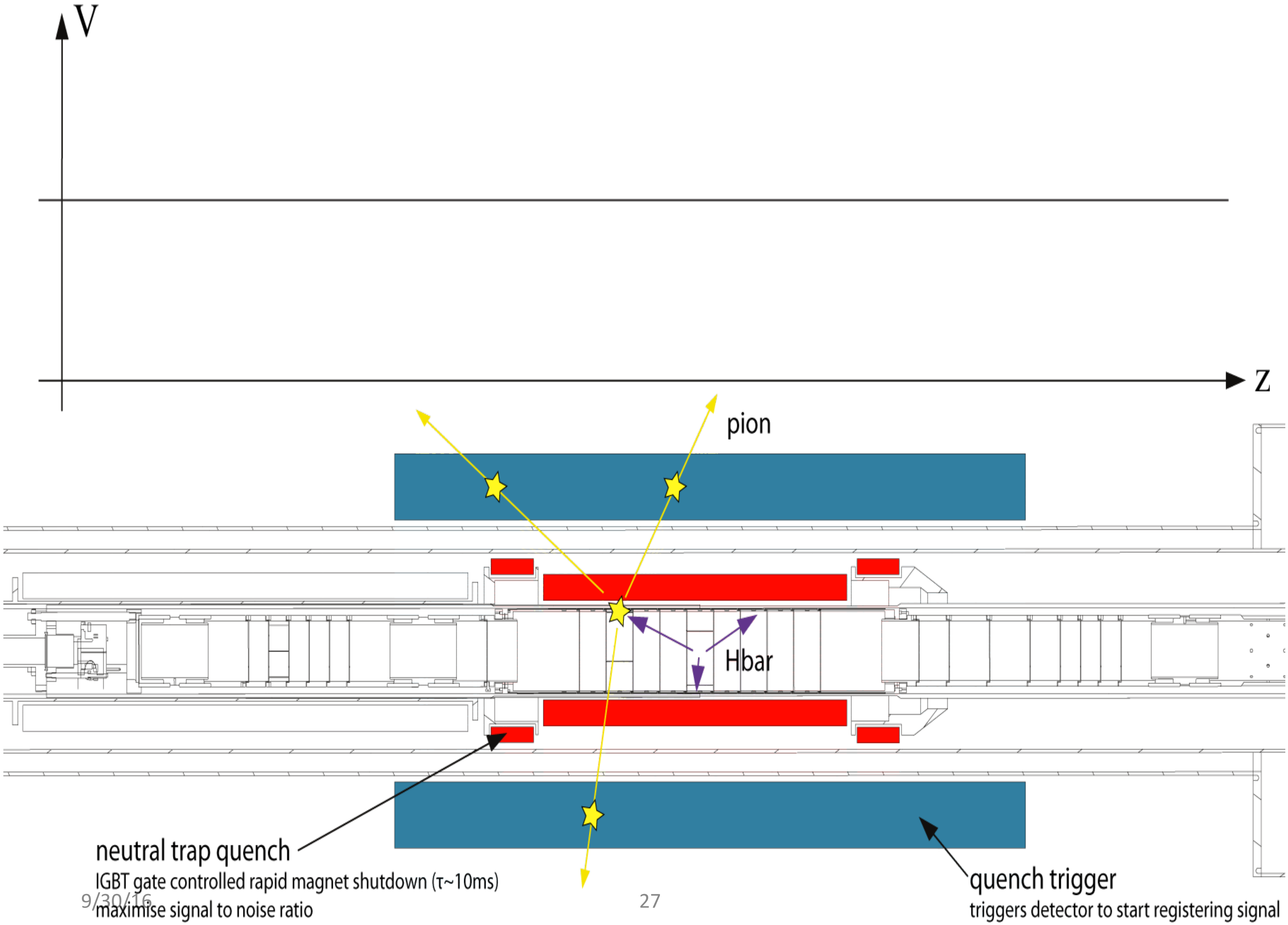

Initiate autoresonance drive
chirp across linear resonance frequency of pbar well
automatic phase-lock


V
500 kHz
420 kHz
250 kHz
180 kHz
0 kHz
injection separatrix
pbar
30,000
$e^+$
4 M
Z
Detector triggered
starts recording signals from Si strips




Mixing triggers
annihilations that are detected immidiately on AR mixing indicates untrapped antihydrogen


V
clearing electric field
Z
pbar
e+
cold antihydrogen with possible mirror-trapped pbar
charged species with enough v⊥ trapped by magnetic minimum trap


V
Z
pion
Hbar
neutral trap quench
IGBT gate controlled rapid magnet shutdown (τ~10ms)
maximise signal to noise ratio
quench trigger
triggers detector to start registering signal

# Phase Space Manipulations of antihydrogen

- Stochastic Acceleration: Bound on antihydrogen charge [proposed NJP 2014. Experiment performed and paper in works, ALPHA 2015]
- Laser Cooling: Future
- Adiabatic Cooling: Future
- Atomic fountain and interferometer: Precision gravity—requires advanced vertical apparatus [PRL, 2014]. Far future.

# Antihydrogen Trapping and Manipulation

LETTER

doi:10.1038/nature09610

## Trapped antihydrogen

G. B. Andresen[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4], P. D. Bowe[1], E. Butler[4], C. L. Cesar[5], S. Chapman[3], M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiwara[8,7], D. R. Gill[8], A. Gutierrez[9], J. S. Hangst[1], W. N. Hardy[9], M. E. Hayden[2], A. J. Humphries[4], R. Hydomako[7], M. J. Jenkins[4], S. Jonsell[10], L. V. Jørgensen[4], L. Kurchaninov[8], N. Madsen[4], S. Menary[11], P. Nolan[12], K. Olchanski[8], A. Olin[8], A. Povilus[3], P. Pusa[12], F. Robicheaux[13], E. Sarid[14], S. Seif el Nasr[9], D. M. Silveira[15], C. So[3], J. W. Storey[8]†, R. I. Thompson[7], D. P. van der Werf[4], J. S. Wurtele[3,6] & Y. Yamazaki[15,16]

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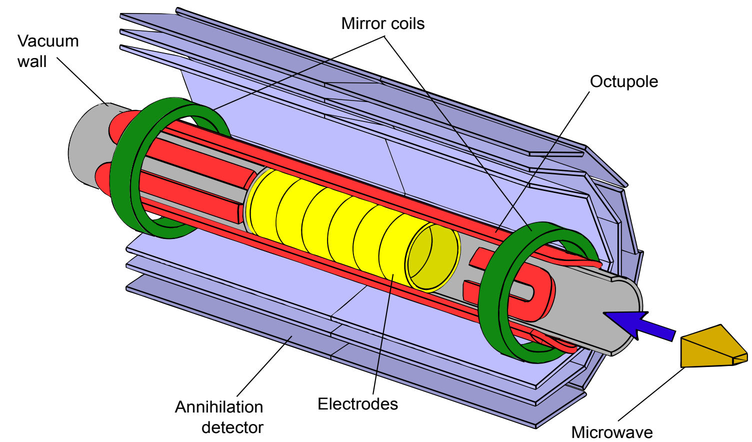
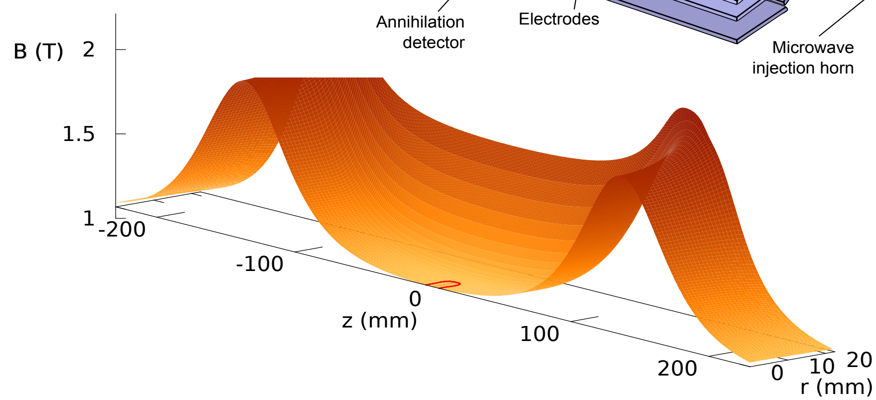
## Confinement of antihydrogen for 1,000 seconds

The ALPHA Collaboration*

Atoms made of a particle and an antiparticle are unstable, usually surviving less than a microsecond. Antihydrogen, made entirely of antiparticles, is believed to be stable, and it is this longevity that holds the promise of precision studies of




LETTER

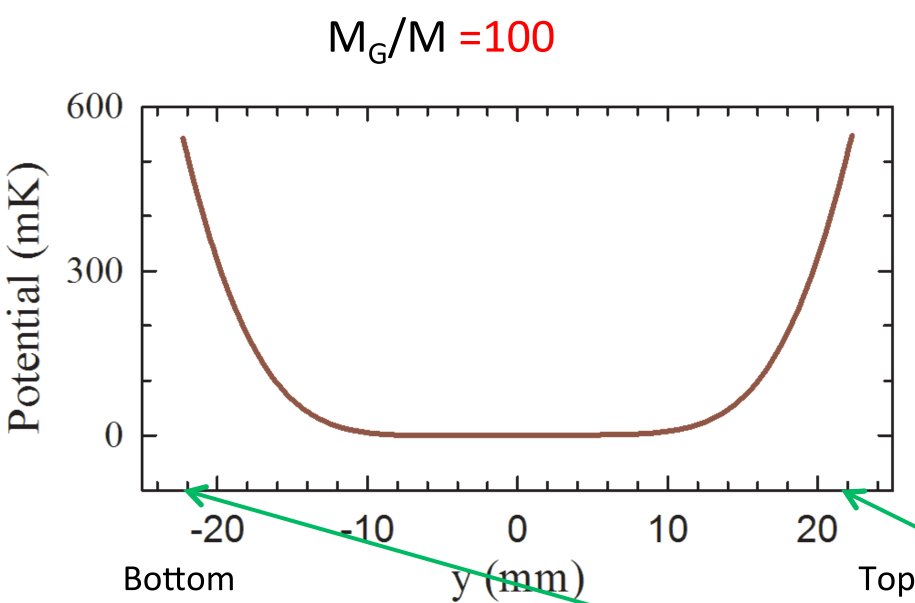
## Resonant quantum transitions in trapped antihydrogen atoms

$$\nu_{\bar{H}}^{hfs} = 1.42 \pm .10\ GHz$$

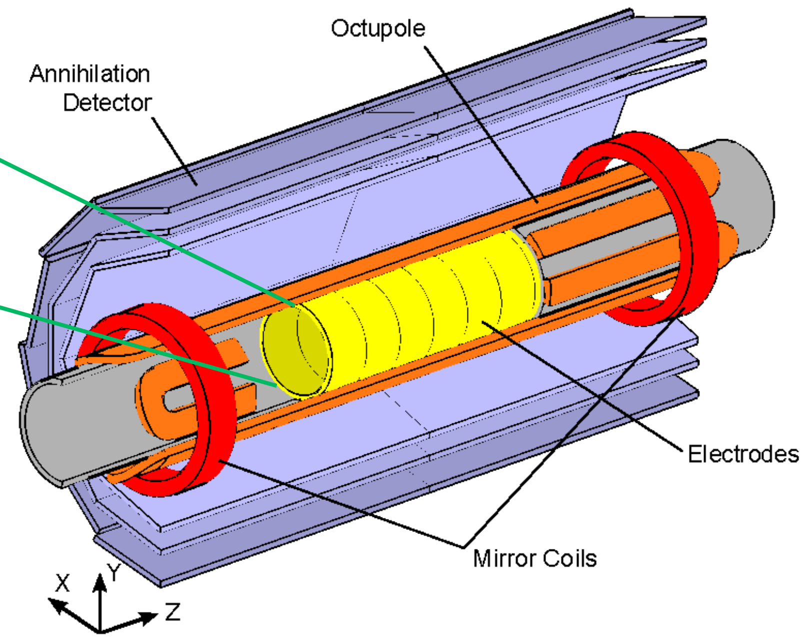
- Positron spin flip measurement
- Shows that it is possible to do physics with few atoms

…would like x10 (or higher) trapping rate and laser cooling

# Effect of Gravity on the Anti-Atom Trapping Well

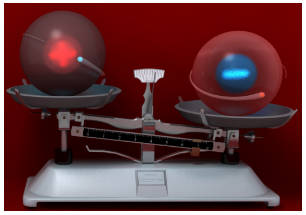



- Bound the ratio of the gravitational mass $M_G$ to the inertial mass of antihydrogen, M.
- “Normal” gravity: $M_G$=M




- Potential includes effect from both the magnet system and gravity.
- The trap diameter is 44.55mm.

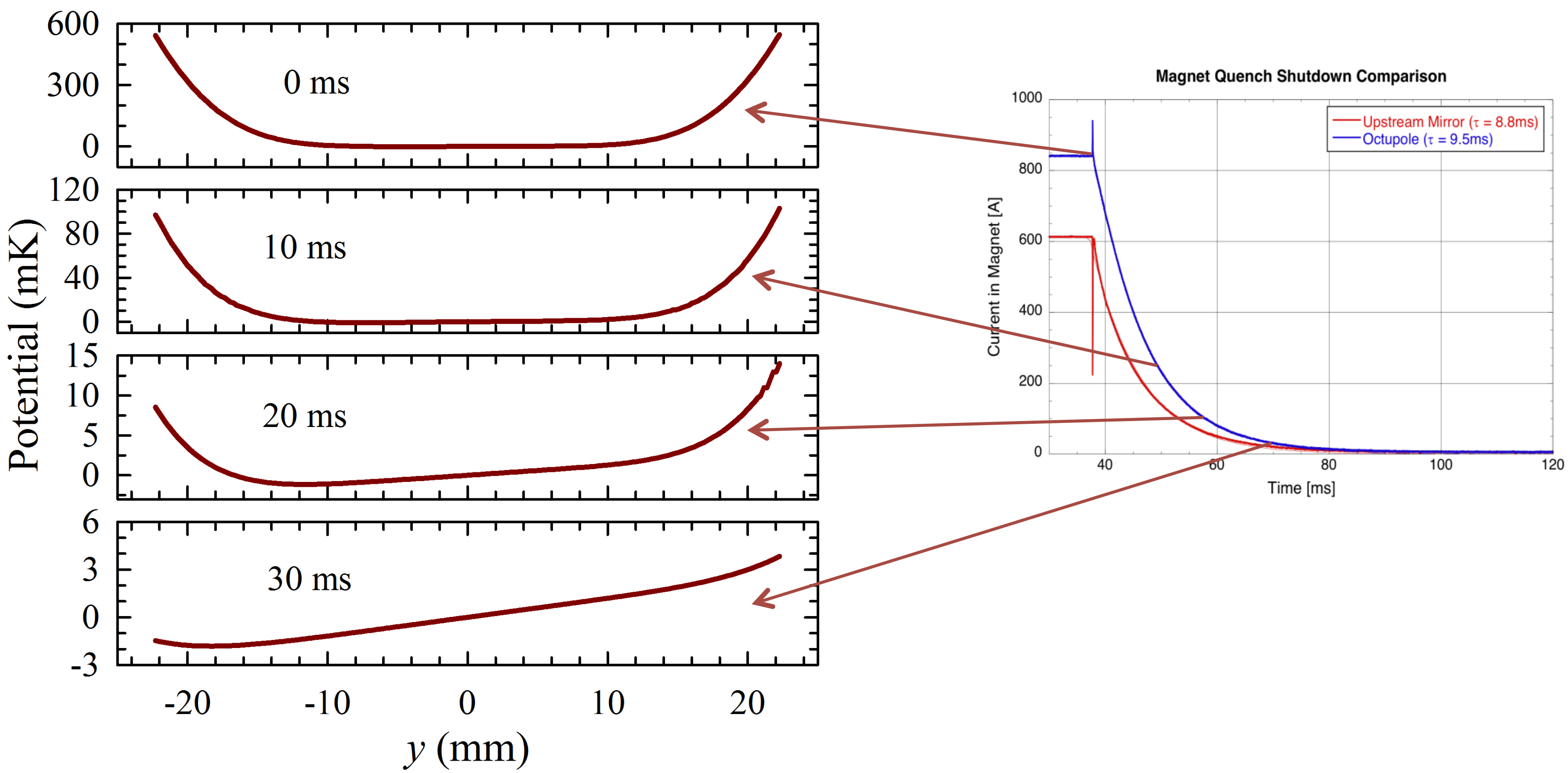
ALPHA, Description and first application of a new technique to measure the gravitational mass of antihydrogen, Nature Comm **4**, 1785 (2013).



# Potential Well After Magnet Shutdown

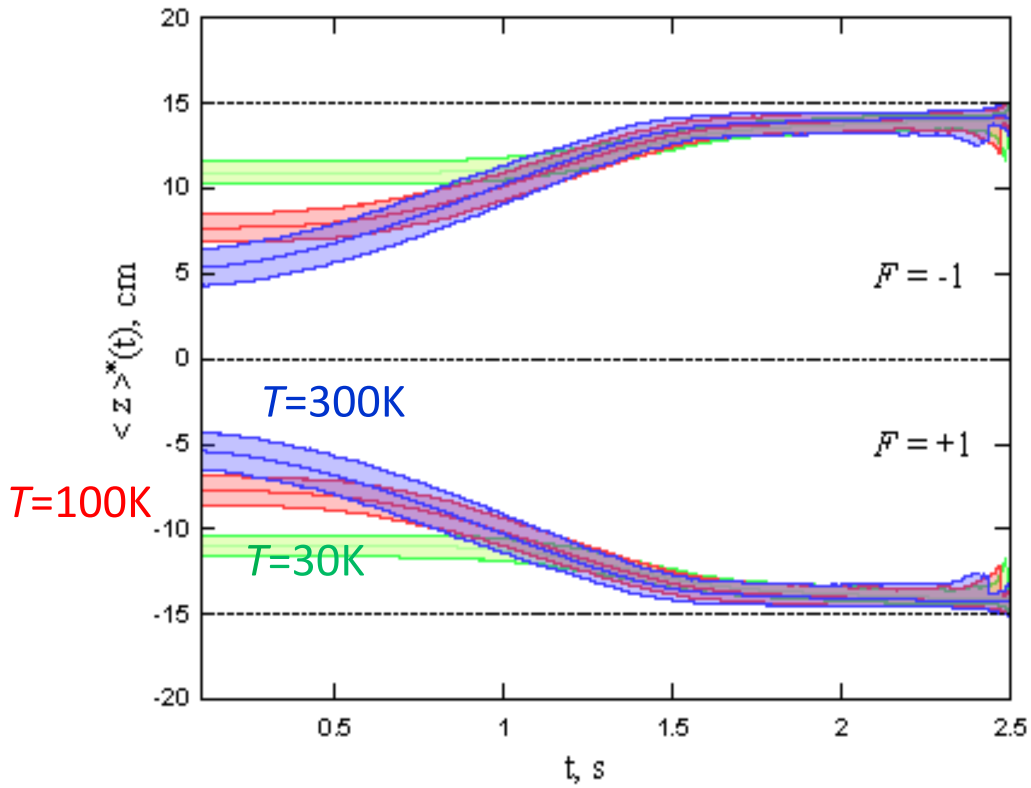
$M_G/M < 110$ (Normal gravity)
$M_G/M > -65$ (Antigravity)
[ALPHA Nature Comm. 2012]

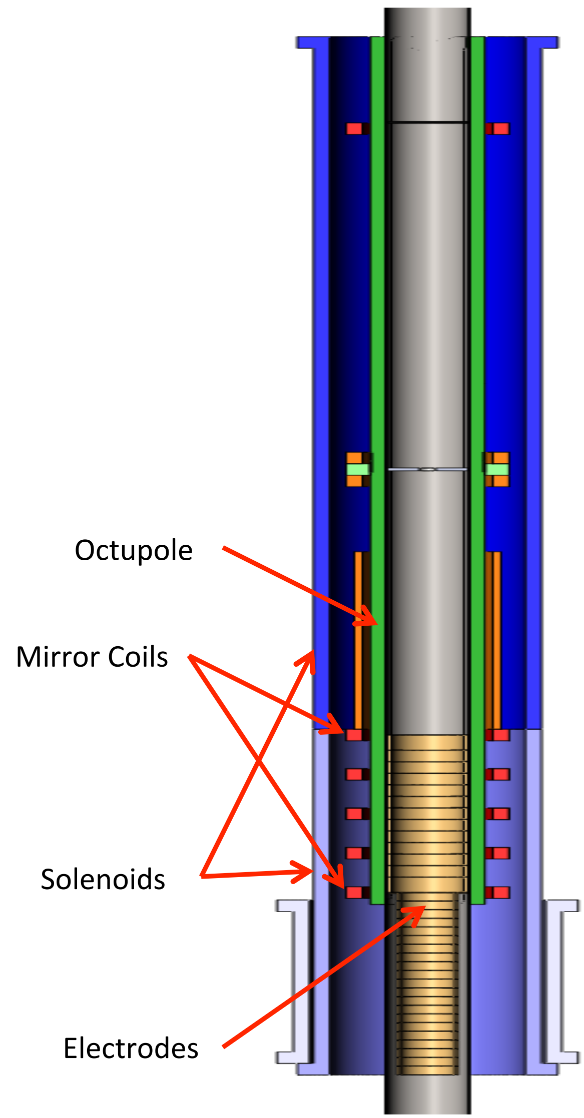
$M_G/M=100$



# Can we do better?

- Much easier in a vertical trap.
  - Laser cooling not necessary, though it helps.
  - Slow down the magnet turnoff by a factor of ten.
  - Turnoff the mirror coils only.
  - 1% measurement possible.



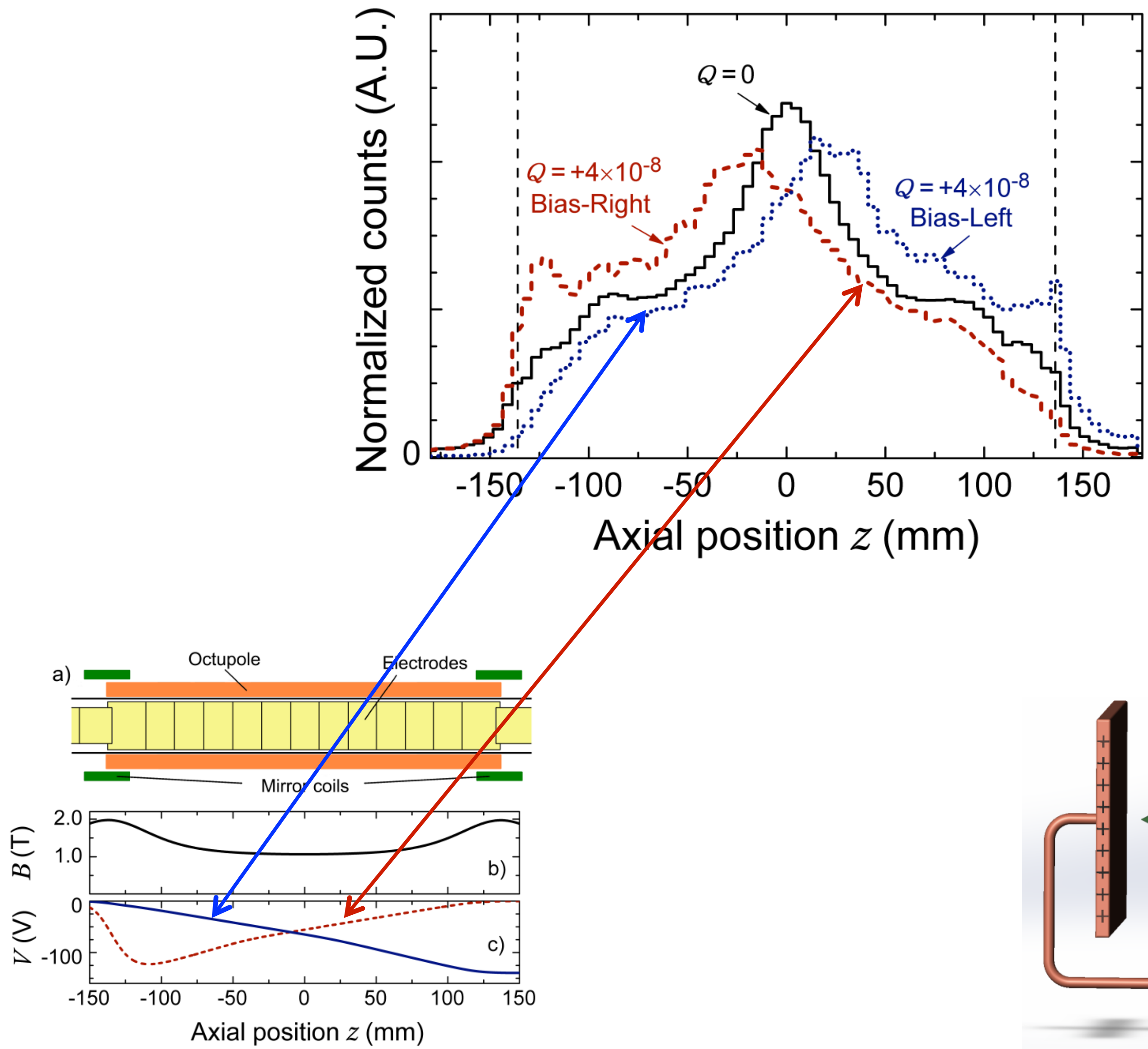

A. Zhmoginov, et al , Class. And Quantum Grav. **30** 205014 (2013).

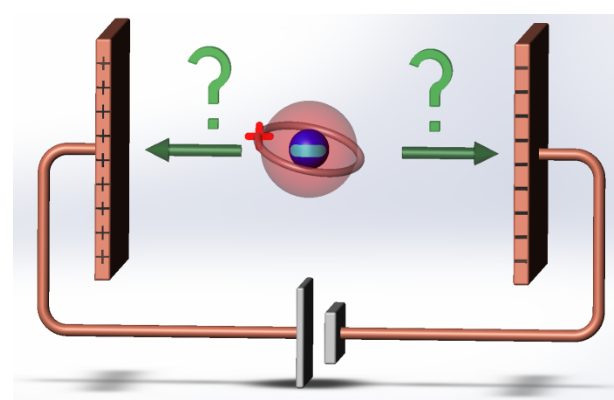
# Antihydrogen Charge

- Normal matter atoms are known to be charge neutral to remarkable precision: on the order of $10^{-21}e$.
- CPT and quantum anomaly cancellation demand that antihydrogen be charge neutral to a similar level.
- How well is the charge of antihydrogen known?
  - Techniques used for normal matter atoms are inapplicable.
  - Only prior limits on antihydrogen are at the $10^{-2}e$ level.
  - Using superposition:
    - Charge of the antiproton is known to $7\times10^{-10}e$.
    - Charge of the positron is known to $2.5\times10^{-8}e$.
    - *Can we be sure that superposition is valid? Almost surely…*

Greenland, P. T. Antimatter, Contemporary Physics 38, 181{203 (1997).

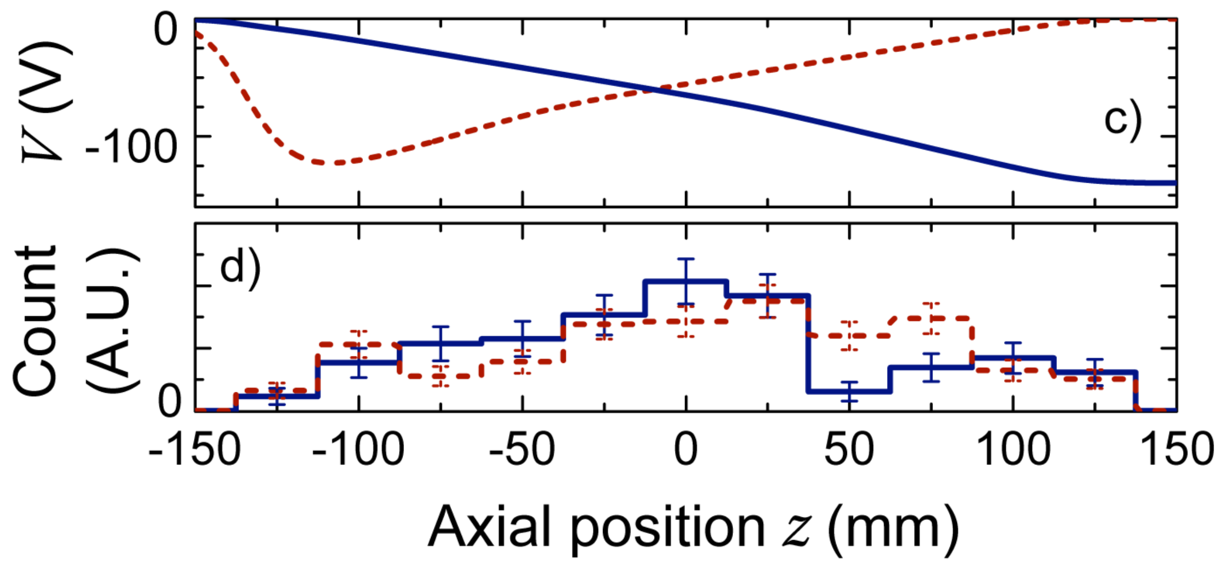
# Anti-Atom Annihilation Position vs. Anti-Atom Charge



# Antihydrogen Charge

- By searching for the deflection of antihydrogen atoms by an electric field, we can set a limit on the antihydrogen charge of $(-1.31.1)10^{-8}e$ (one sigma).

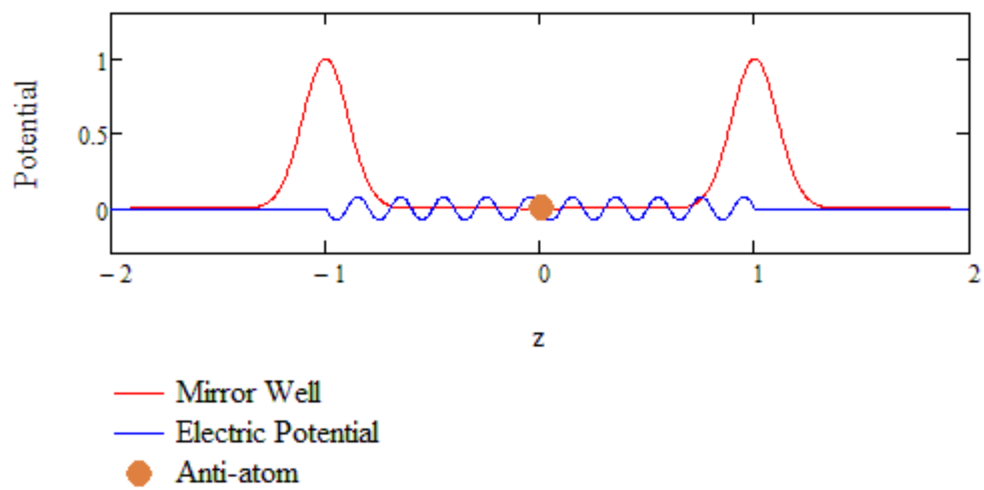



ALPHA, An experimental limit on the charge of antihydrogen, essentially accepted by Nature Comm., (2014).

M. Baquero-Ruiz, W. Bertsche, A.E. Charman, J. Fajans, A. Little, A. Povilus, E. Sarid, D.M. Silveira, C. So, T.D. Tharp, D.P. van der Werf, J.S. Wurtele, Z. Vendeiro, A.I. Zhmoginov

# Improved Antihydrogen Charge Bound Using Stochastic Fields

- Stochastic acceleration (Fermi acceleration) can eject charged anti-atoms from the trap.




- Using stochastic acceleration, we expect that we can determine the charge to the $10^{-12}e$ level.

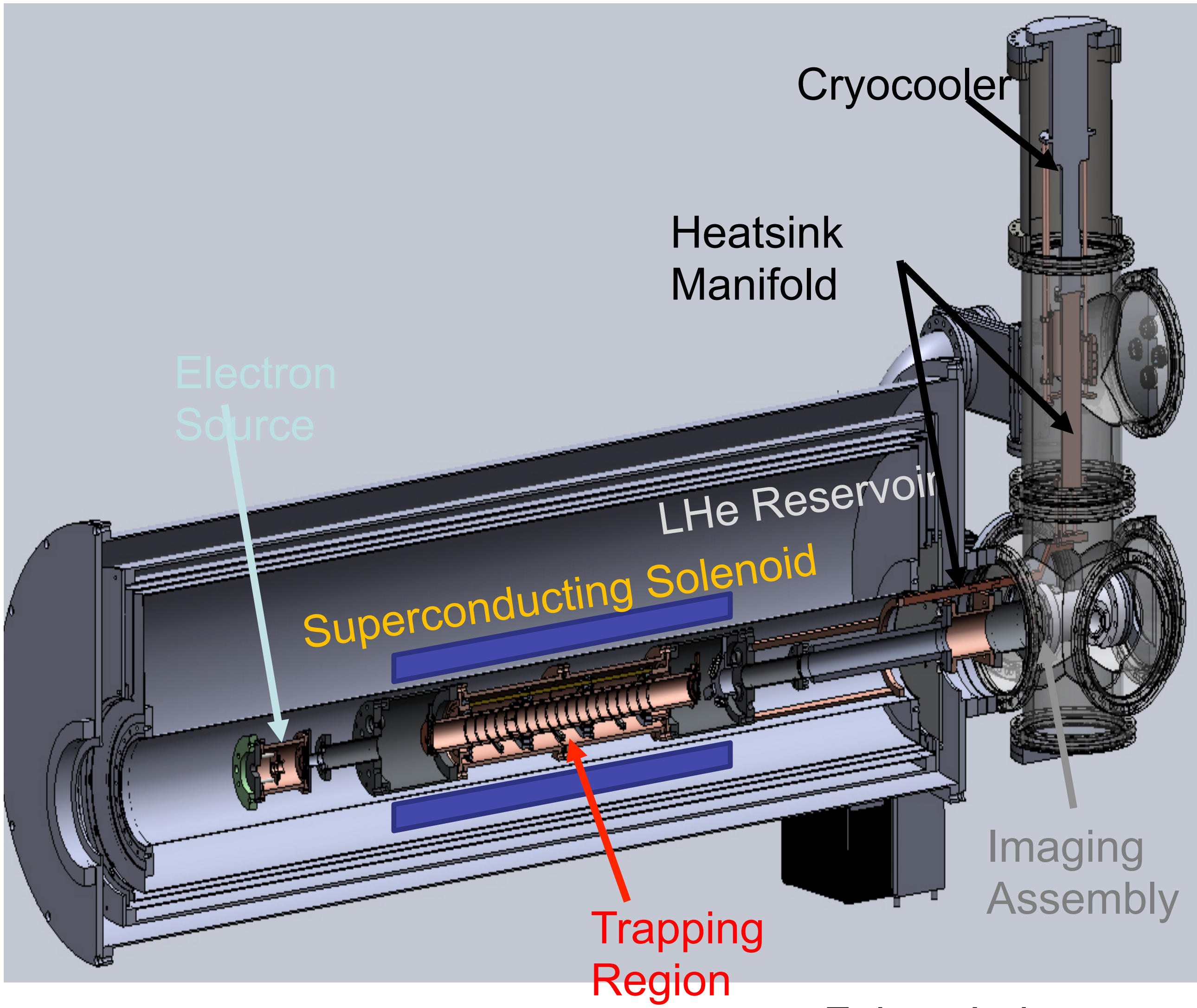
$$\Delta E_{\bar{H}} \sim Qe\Delta\Phi_{kick} N_{kick}^{1/2}$$

$$\Delta E_{\bar{H}} \leq U_{trap}$$

$$Q \leq \frac{U_{trap}}{e\Delta\Phi}\sqrt{\frac{1}{N}}$$

M. Baquero-Ruiz, A.E. Charman, J. Fajans, A. Little, A. Povilus, F. Robicheaux, J.S. Wurtele, A.I. Zhmoginov, Measuring the electric charge of antihydrogen by stochastic acceleration, NJP (2014).

# The Cold Electron Research (CERES) Apparatus at UC Berkeley




- **Cryogenic** (<15K) environment
- **High-Q** (~10000) cavity
- **Strong magnetic field** (0.5 to 6T)
- **Electrostatic confining electrodes**

__**Diagnostics**__:

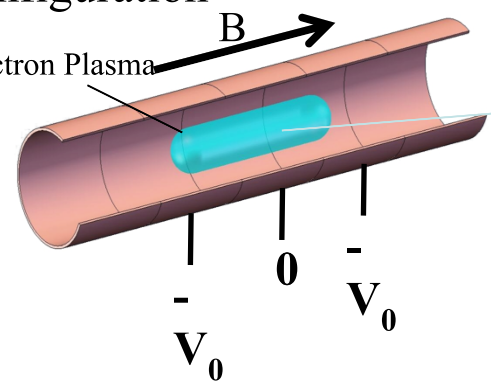
- Low-T (70K) MCP/Phosphor Imaging Assembly
- Current pickups on electrode leads for detection of image motion
- Quiet, Amplified Charge Collectors
- Fast High-Gain Phosphor/ Photodetector

Fajans Lab, courtersy A. Povilus (now @LLNL)

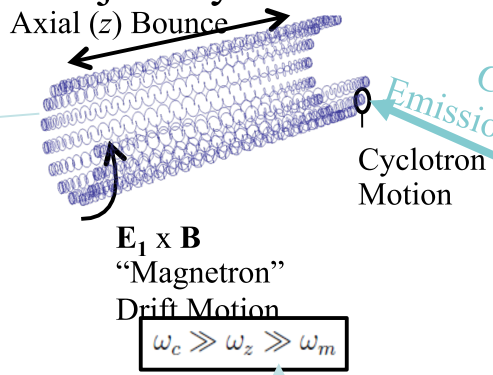
# Cyclotron-Cavity Mode Cooling Scheme

Collaboration of Fajans/Wurtele groups at UCB and W. Hardy group at UBC

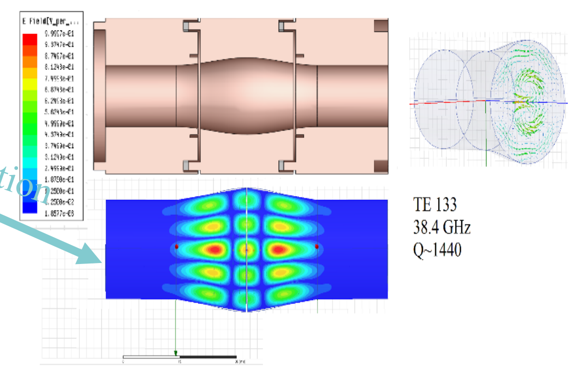
Penning Trap Configuration




Classical Electron Trajectory




Electromagnetic Cavity Modes




Transverse confinement
.1T<B<6T
Axial: $V_{electrode}$ <100V
T: 30000→4K??
N<$10^{10}$/cm$^3$

**<u>Hierarchy of motion:</u>**
Cyclotron: ~30GHz
Axial Bounce: ~10MHz
Drift: ~100kHz
Collision Frequency: ~300kHz

**Radiation is emitted into the cavity as discrete modes:**

- Cyclotron radiation preferentially emits into transverse electric (TE) modes
- Radiation is either attenuated by electrode material or reabsorbed by electrons

# Cavity Enhanced Cooling (Purcell Effect)

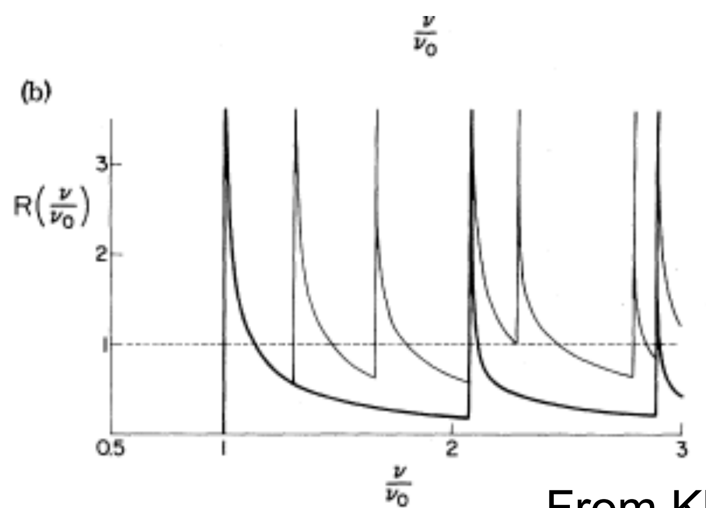
Free Space

$$\frac{1}{\tau_c} = \frac{P_r}{KE} = \frac{e^2a^2 \big/ 6\pi\epsilon_0 c^3}{(1/2)mv^2} = \frac{e^4B^2}{3\pi\epsilon_0 c^3}$$

Ideal Cavity Enhancement:

$$\frac{1}{\tau_{\substack{cavity\\Enhnace}}} \sim \frac{Q}{\tau_c}$$

Calculated Emission Rate for Sparse Mode Density Cavity




From Kleppner, PRL 81

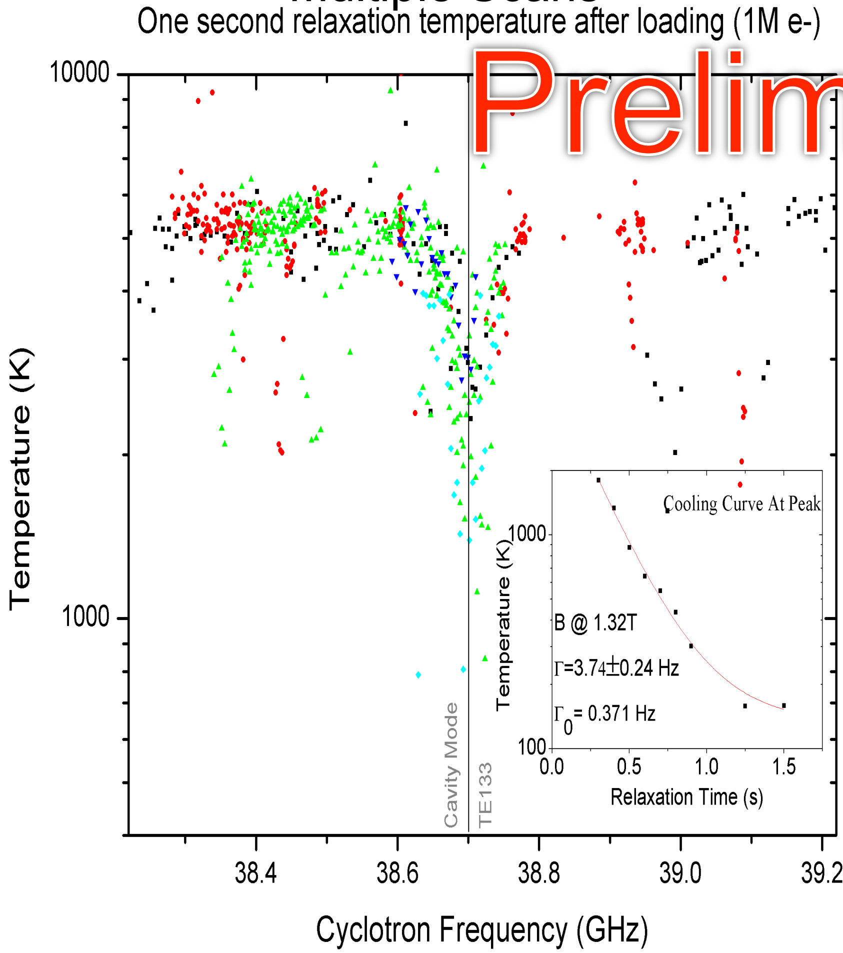
Physics issues:

Geometric enhancement & overlap
Mode separation
Finite longitudinal motion
Large N bottleneck (too many photons)
Plasma to single particle
Quantum to classical?

Alex Povilus. PhD thesis. UC Berkeley, 2015.
Nathan Everts, MS Thesis, UBC.
Eric Hunter, PhD in progress

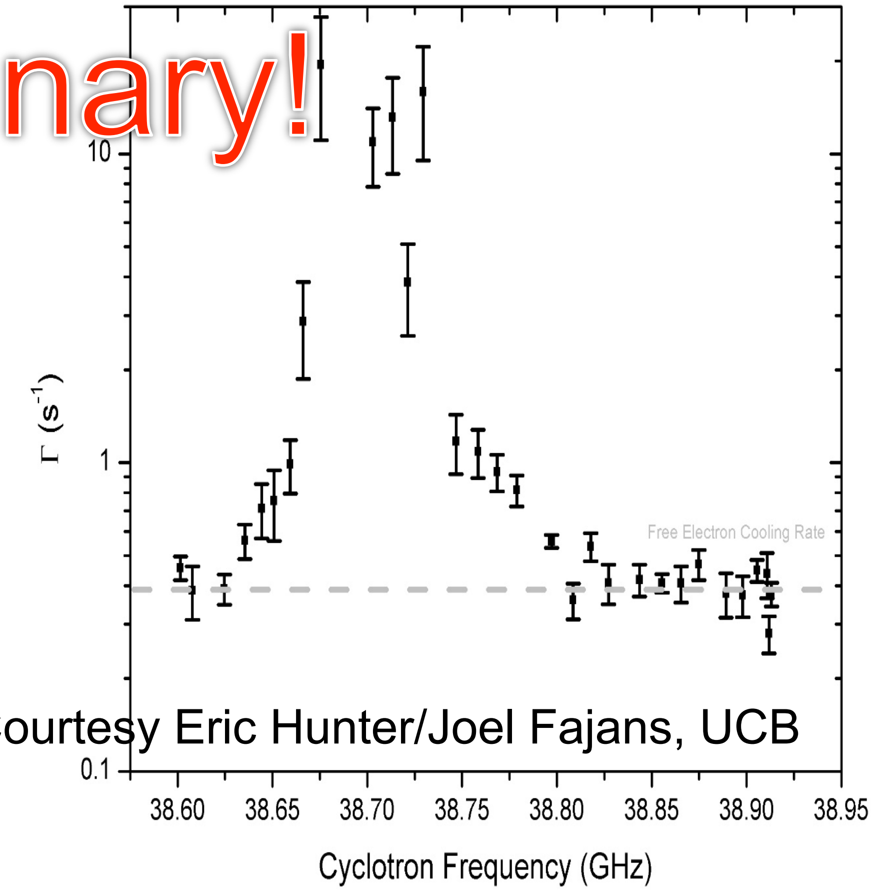
# Demonstrated Enhanced Cooling in Bulge Cavity
# (VERY PRELIMINARY)

Coarse Search for Resonance – Multiple Scans




Scanning Magnetic Field

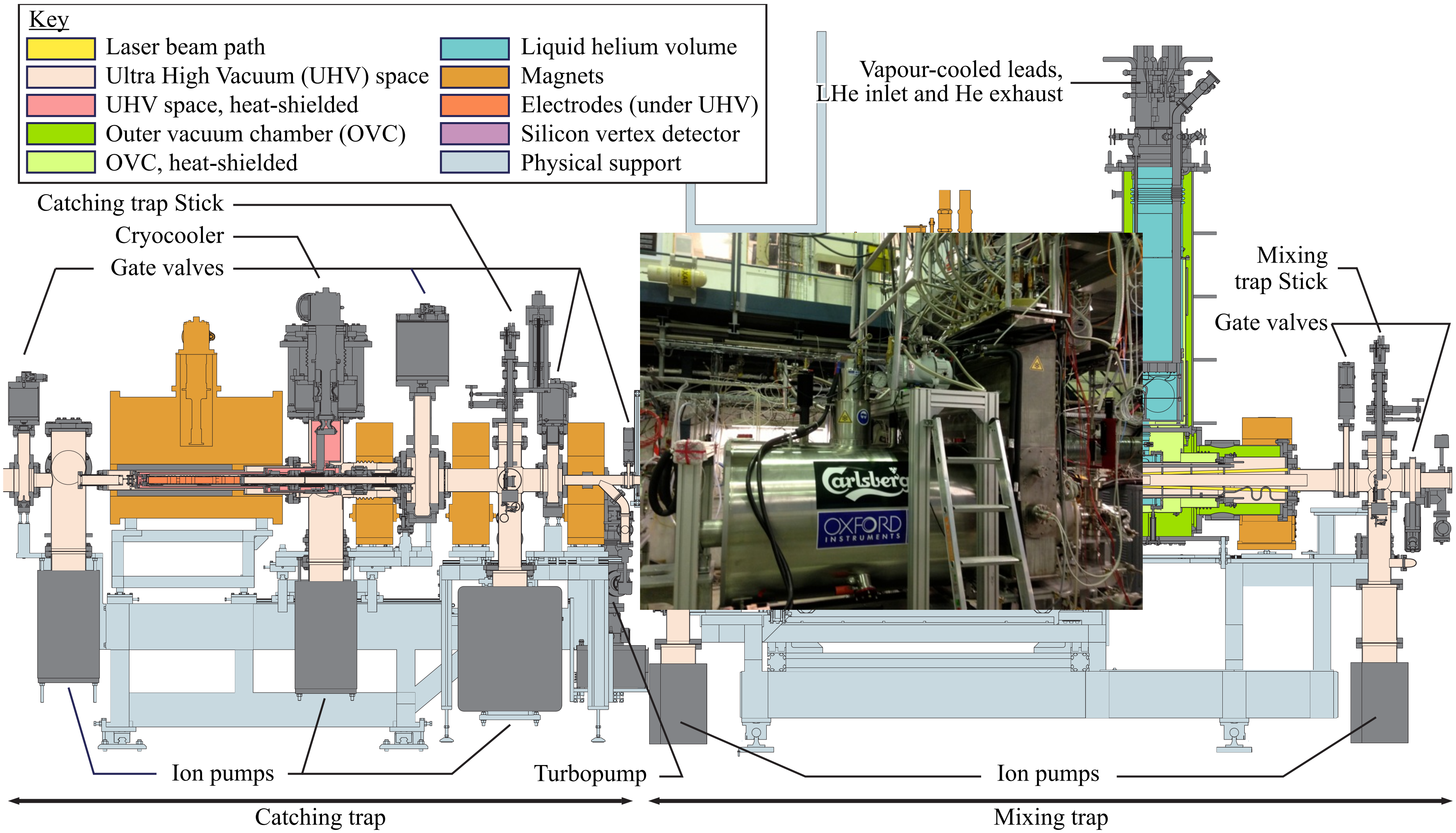
Cooling Rate of Plasma Near TE133




Courtesy Eric Hunter/Joel Fajans, UCB

Set magnetic field and hold plasma for varying relaxation times, measure time constant

# ALPHA-II Apparatus



# On advising students

"Go to Building 47 and find something interesting"

- Students should not have projects too well defined.
- A surprising number of future CEBAF builders and leaders were in Building 47 at that time. (Joe B., Geoff, Swapan. Christoff and Hermann were nearby.)

# Andy on doing physics: Theory with a purpose.

"Don't hide behind mathematics"

"Say it in words. And, a good title helps sell things."

Here are some of Andy's:

- "Optical Guiding";
- "Beam Conditioner";
- "Adiabatic focuser";
- "Two-beam accelerator";

"I'm too smart—I can prove anything!"

- Proof by intimidation
- You have to stand up for yourself

# Andy on doing physics (2)

"Physics is a contact sport"

- Micro-aggressions galore!!! Of an intellectual variety.

After losing a physics argument:

"First you don't believe something, then you don't understand it, then you think you thought of it yourself."

# As LBL Lab Director

"I went downtown and any building I saw painted camouflage brown"

"I took down half the traffic signs."

(try that now!)

"Only the squirrels know this is edible"

(on picking up a berry from the path and consuming it)

"I went to protest at the Soviet consulate"

(On taking an afternoon off)

Andy also moved LBL from its HEP focus to become a fully multi-disciplinary laboratory with a strong environmental focus—that story is for a different forum.

# Andy on Life

"I've had a good run"

"Your achievements scale as the square root of your expectations."

"As with my students, I recommend to my children following my path: have an early family, raise your children to be good people and, also, to have a thirst for knowledge, enjoy the outdoors, travel a lot, save money for later years, but try not to get divorced."

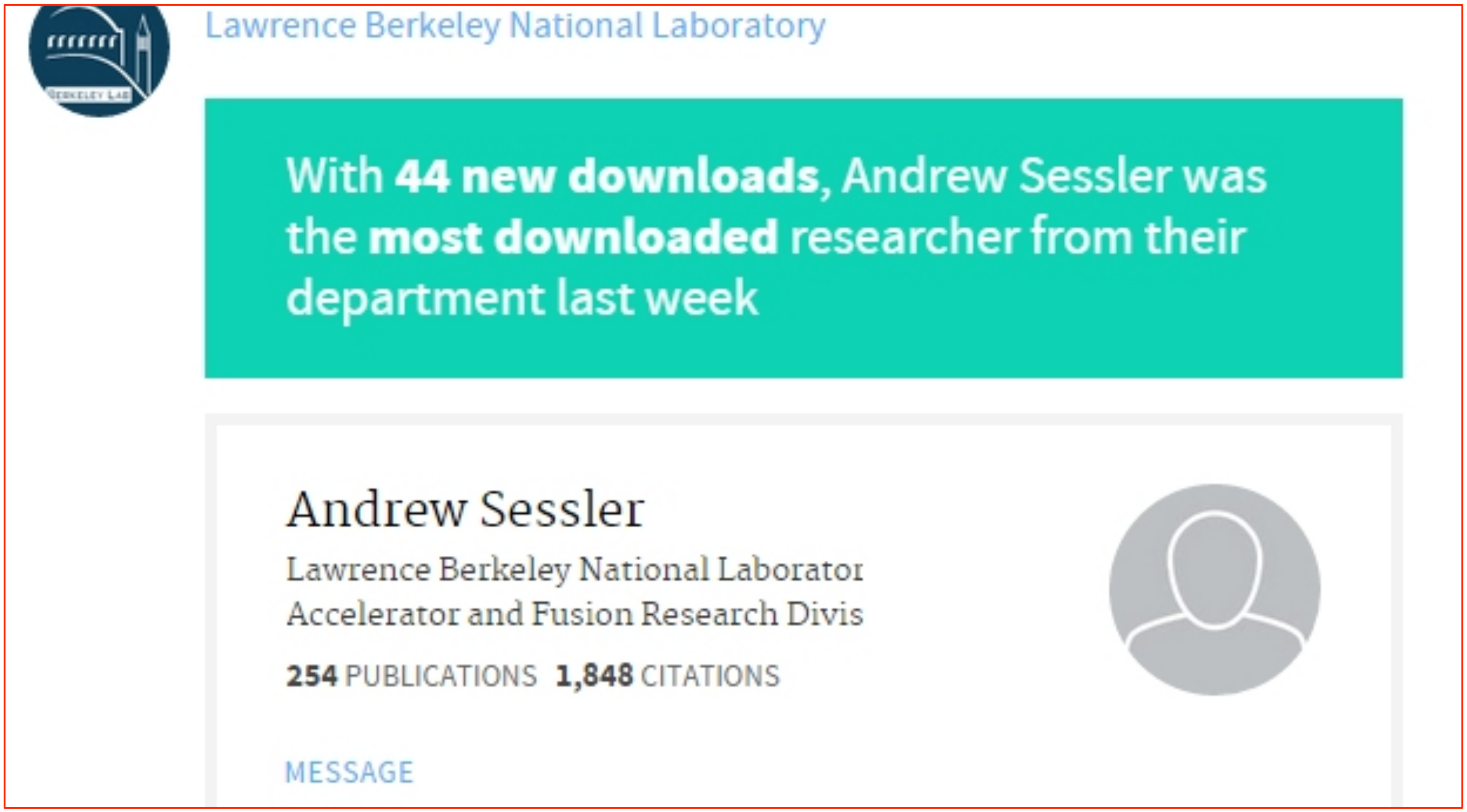
**For a serious biography of Andy's numerous contributions to physics and society see**

http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/sessler-andrew.pdf

Some of Andy's personal comments on life, and most well-known papers are here:

http://raman.physics.berkeley.edu/asessler/Site/Welcome.html

# “There’s never a time not to do physics”

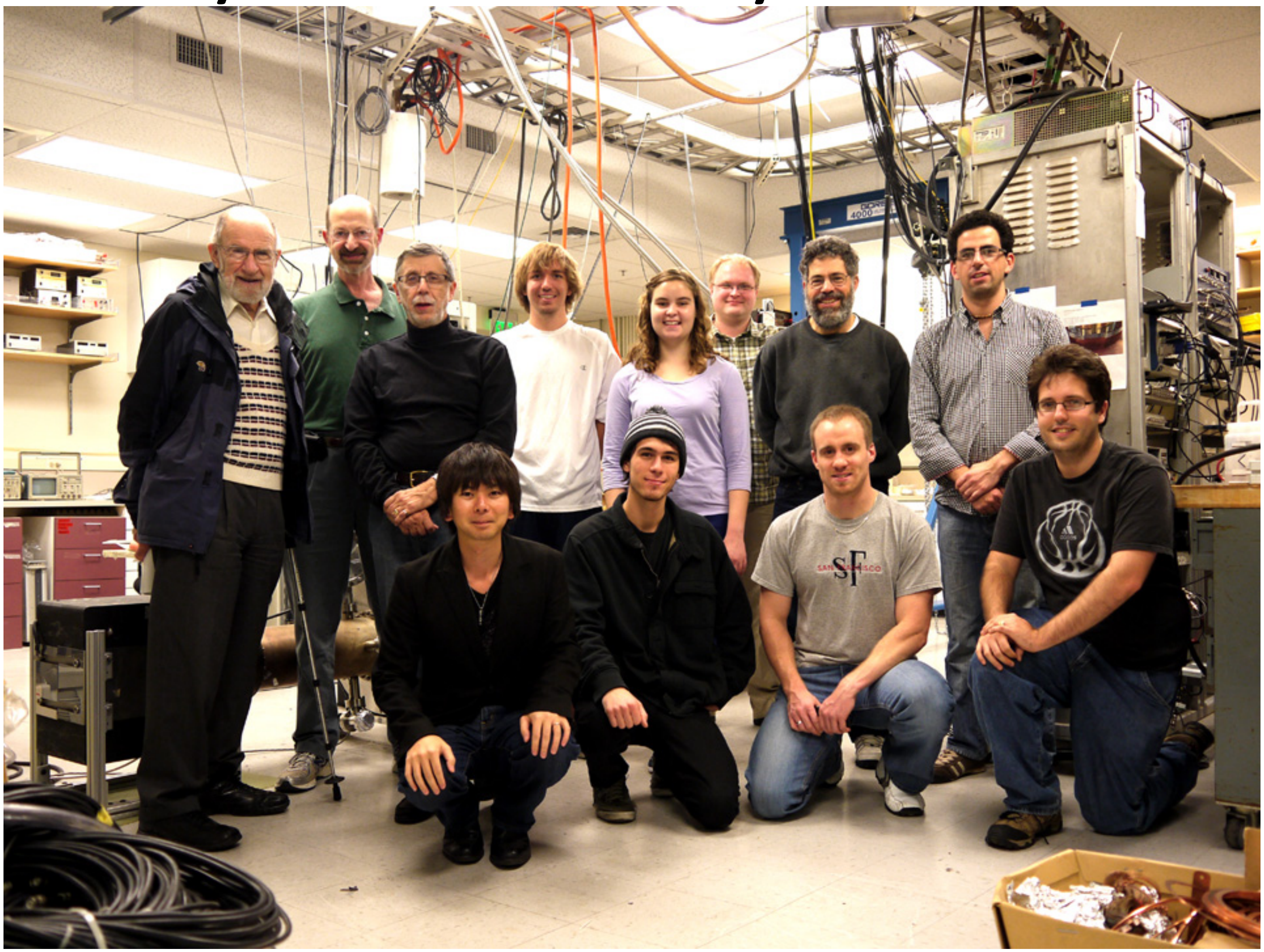



Researchgate 9/2015

# Andy with Berkeley friends

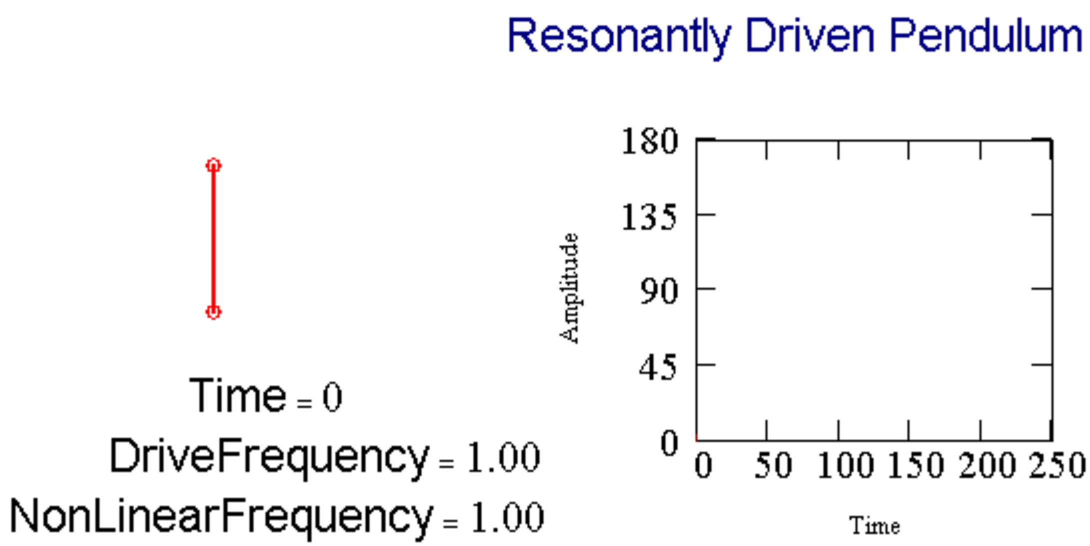




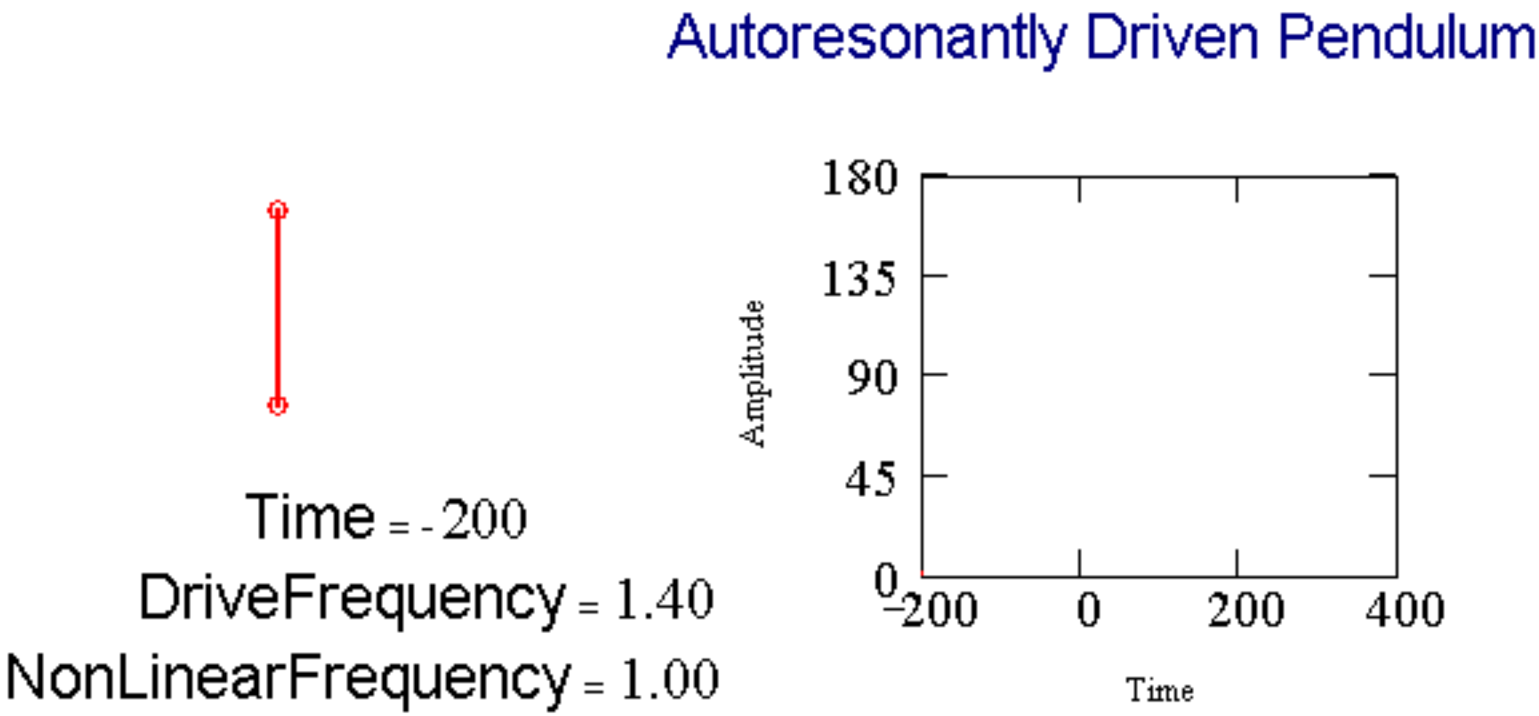


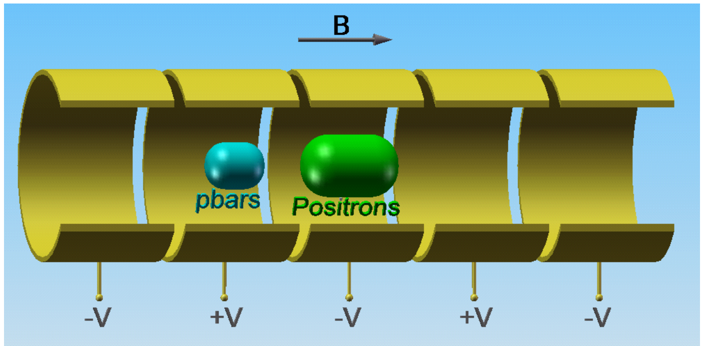
Fajans and Wurtele Groups, Berkeley

# Pendulum with a Fixed Frequency Drive

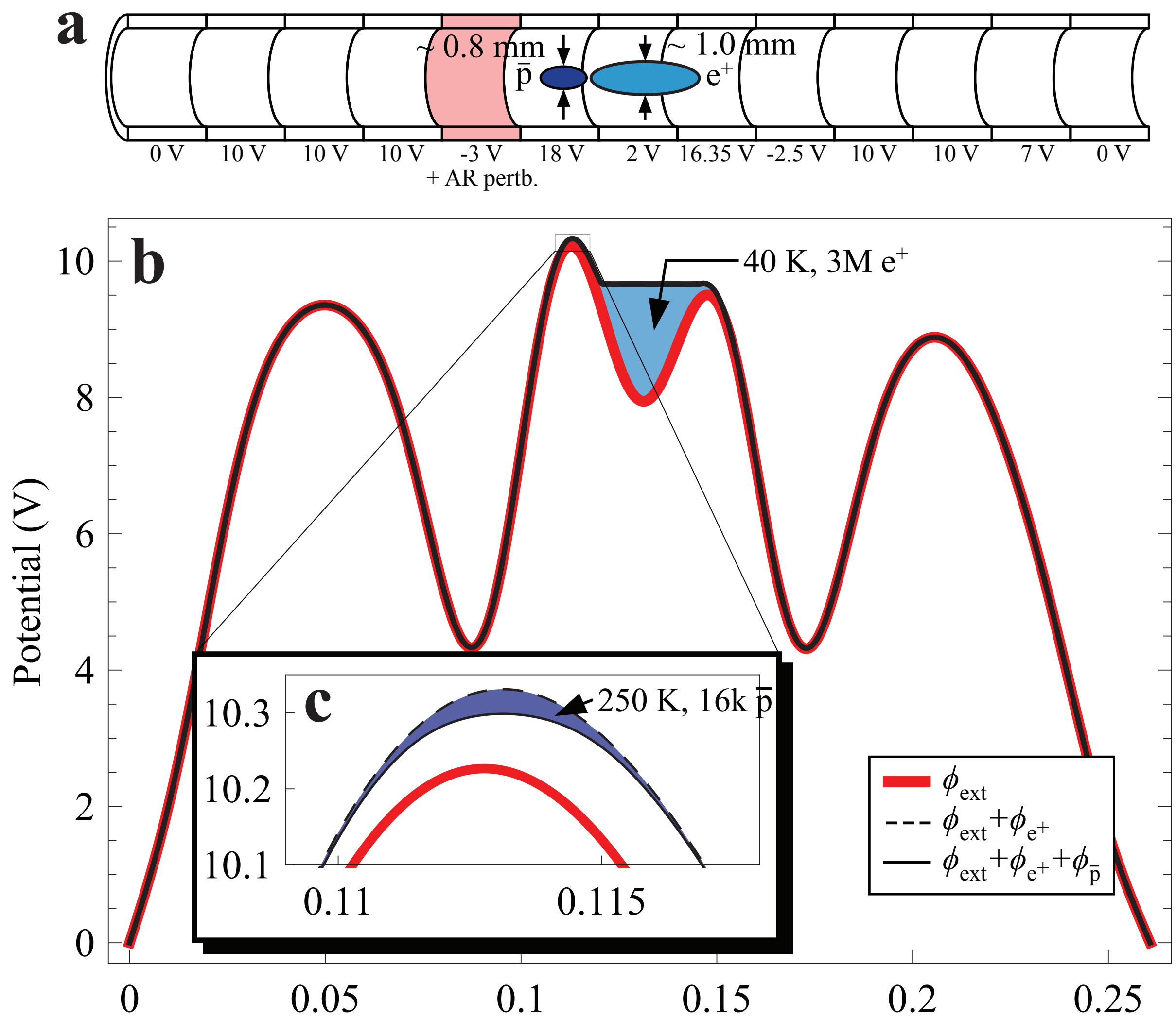


# Pendulum with a Swept Frequency Drive






# Autoresonant mixing

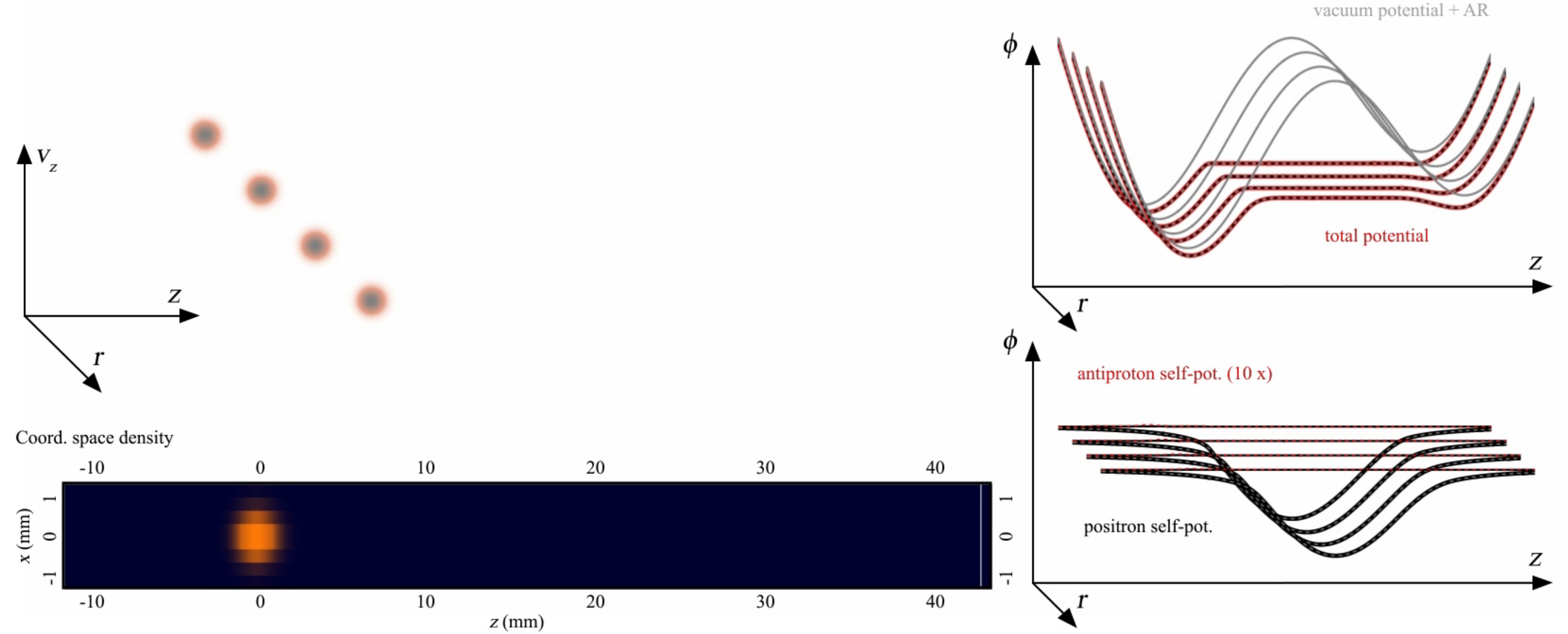


# Autoresonant Mixing of antiprotons

~10,000 antihydrogen created per attempt, ~1 with KE<.5K

C. So, Ph.D. 2014

Antiproton F(z,vz,t) at different radial locations

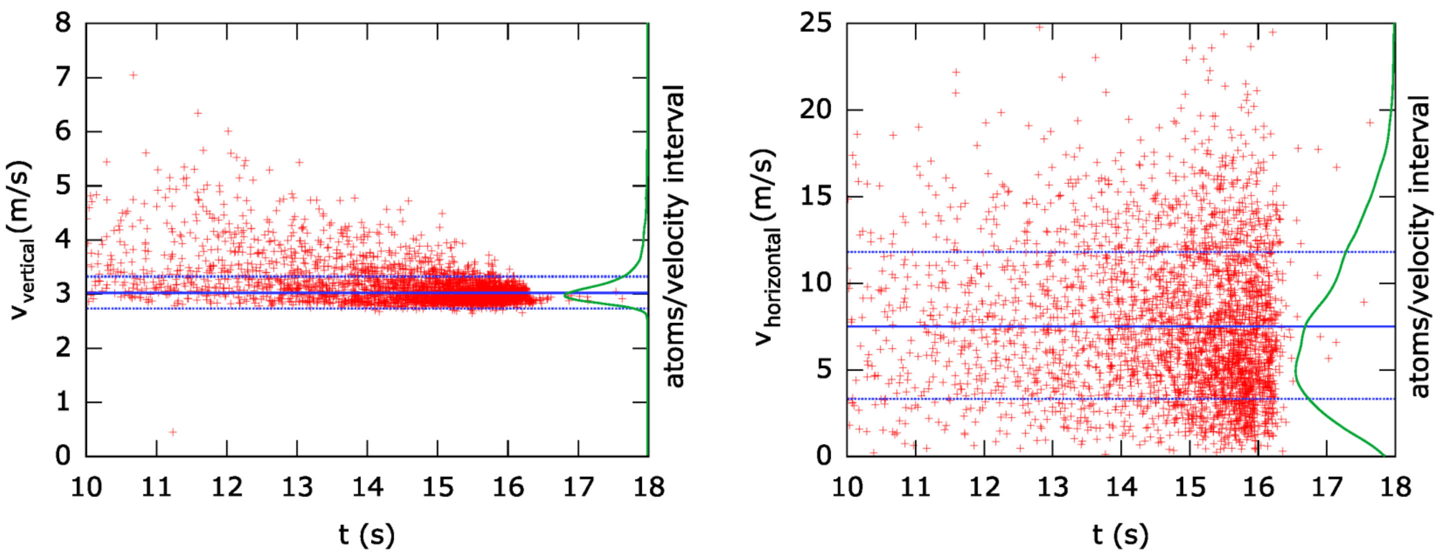




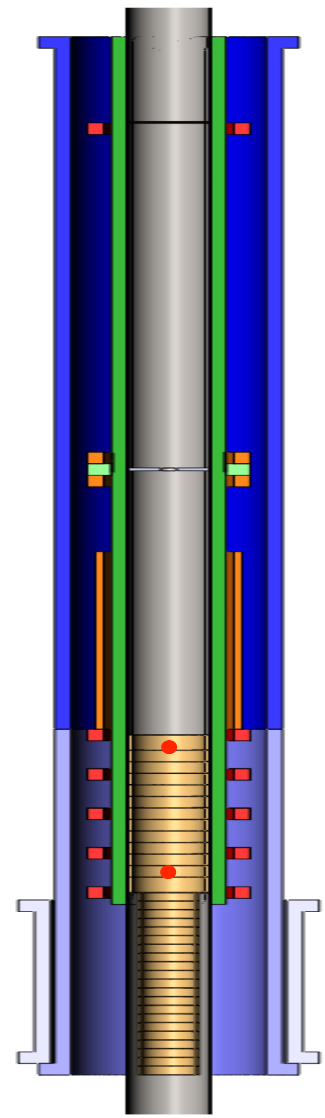
ALPHA, Autoresonant excitation of antiproton plasmas, in press Phys. Rev. Lett., (2011).
I. Barth, L. Friedland, E. Sarid, and A. G. Shagalov, Autoresonant Transition in the Presence of Noise and Self-Fields, Phys. Rev. Lett., 103, 155001 (2009).

# Antihydrogen Fountain

- Let anti-atoms evaporate over a magnetic barrier.
  - Substantial parallel cooling results.




Simulated fountain results

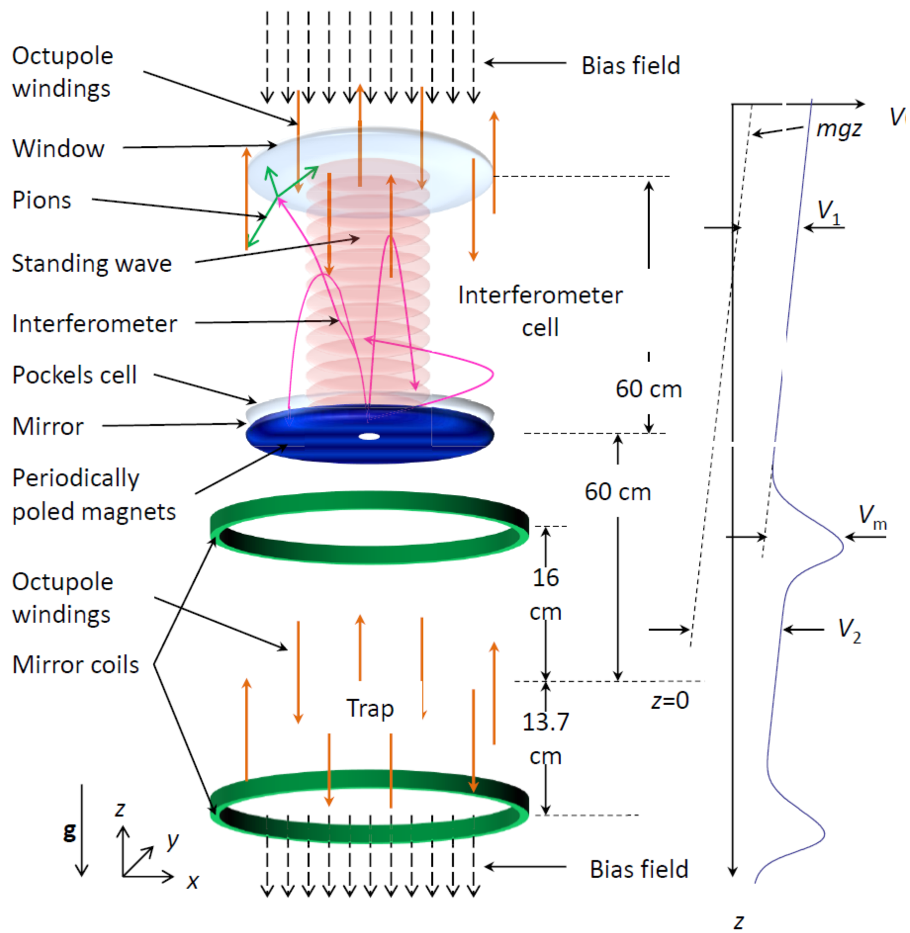


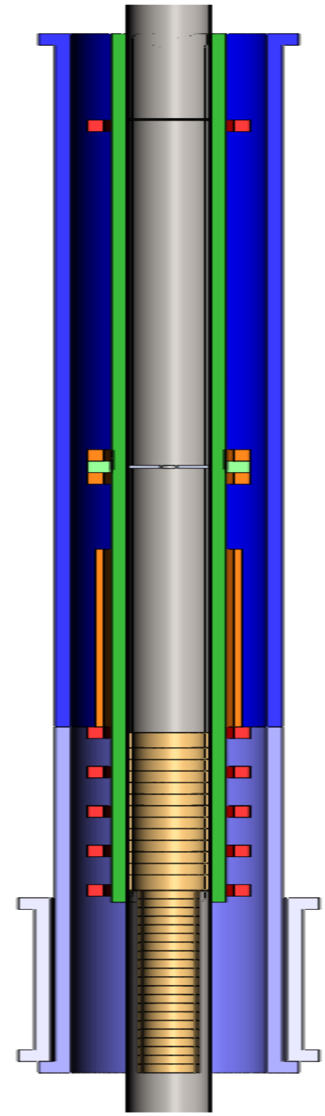
An anti-atom with a velocity of 3m/s upwards will continue upwards 46cm.

A.I. Zhmoginov

# Interferometric Measurements

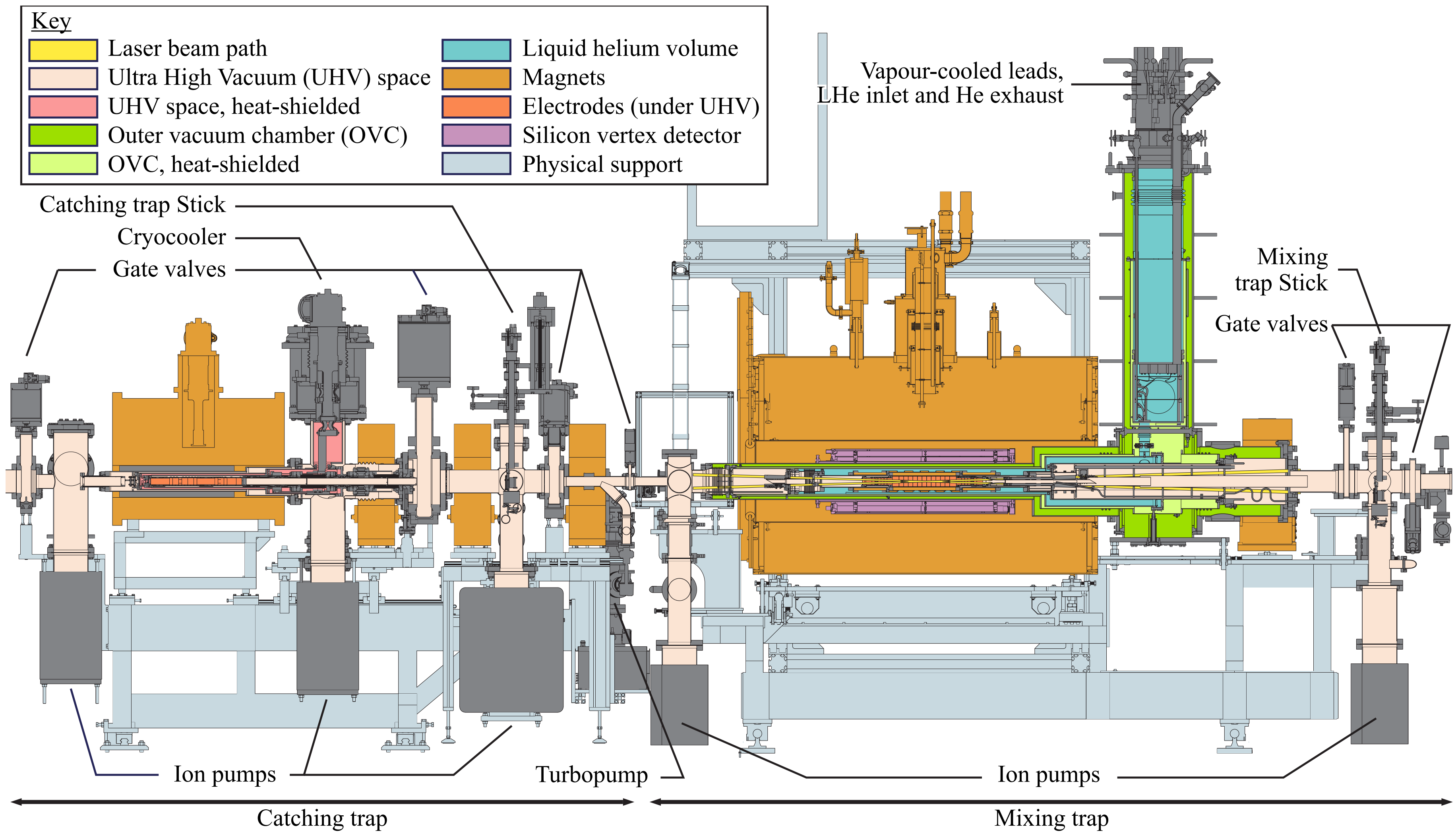
- More accurate gravity measurements can be made with a laser atom interferometer. This is for the far future.
  - Initial results to 1%
  - Eventual result to perhaps 0.0001%.



P. Hamilton, et al ,, Antimatter interferometry for gravity measurements, Phys. Rev. Lett. 112 121102 (2014).

# New ALPHA-II Apparatus

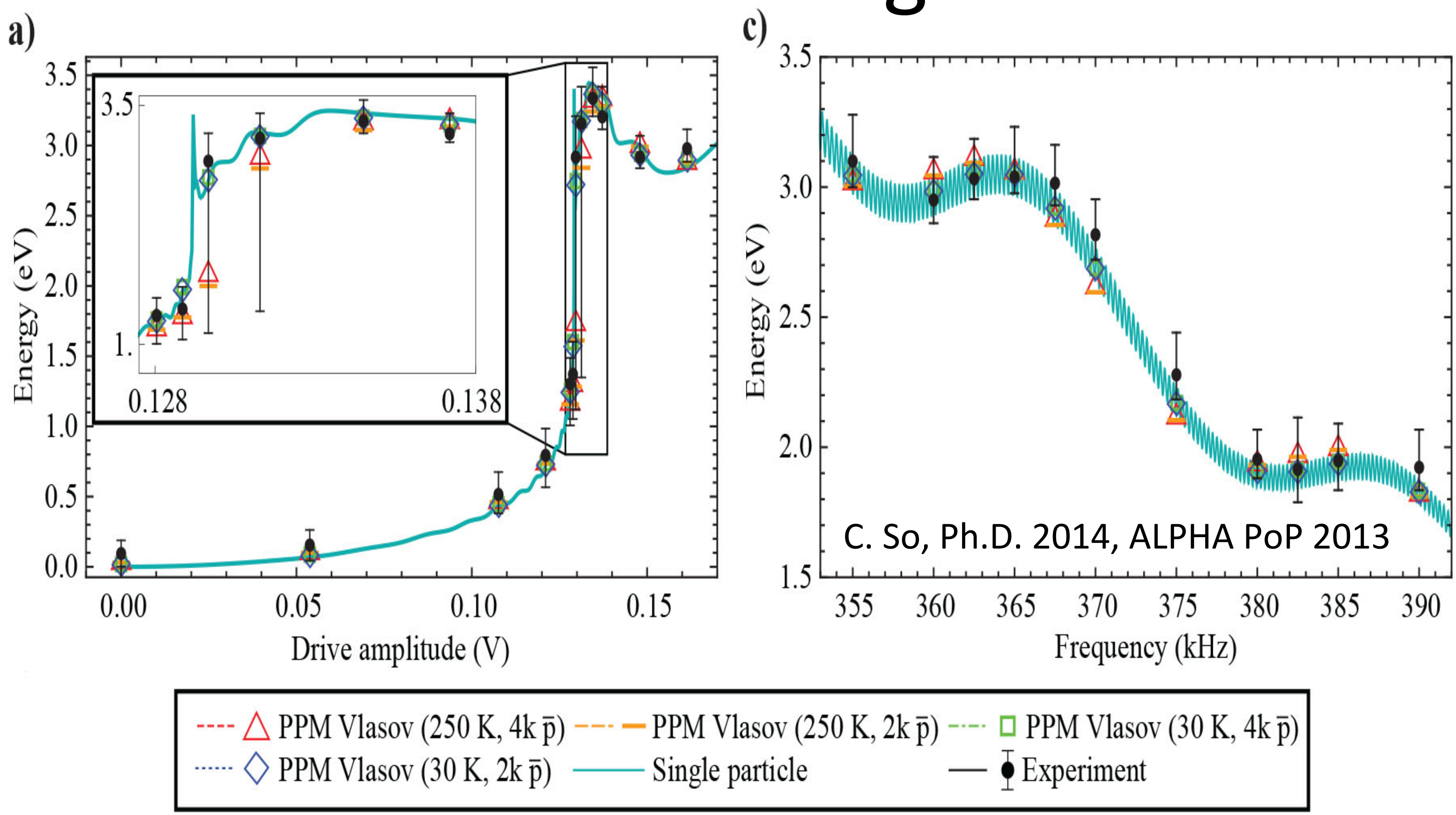


# Technique: Autoresonant Control

- Synchrotron: Vexler, MckMillan, 1945.
- Diocotron modes in nonneutral plasmas
- Nonlinear phase space structures in nonneutral plasmas
- Mixing of antiprotons and positrons
- Spectrometer for residual gas identification.
- Josephson Junction resonators
- Robust laser wakefield accelerator
- Spatio-temporal nonlinear wave control, Raman and Brillouin interactions with plasma gradients
- Many other fluid and wave systems
- Advantage: **Robust** to jitter and parameter uncertainty, threshold behavior, works at low drive power.

Intro: Fajans and Friedland Am. J. Phys. **69**, 1096 (2001).

# Autoresonant mixing simulation



# Antiparticles

1928-1931 - Dirac: Existence of the positron.

P. Dirac

P. Dirac

"A hole, if there were one, would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti-electron."

P. A. M. Dirac, Quantised Singularities in the Electromagnetic Field, Proc. R. Soc. Lond. A **133** p60 (1931).