Generation of Antimatter
Antiprotons and Positrons

Swansea University
Prifysgol Abertawe

Dirk van der Werf

HBAR formation processes using positrons

	Radiative	Three-Body
Reaction	$e^+ + \overline{p} \rightarrow \overline{H} + h\nu$	$e^+ + e^+ + \overline{p} \rightarrow \overline{H} + e^+$
T dependence	$T^{-2/3}$	$T^{-9/2}$
n_{e+} dependence	$\propto n_{e+}$	n_{e+}^2
States	$n < 10$	$n >> 10$
Expected rates	~ 10 Hz	Unknown

J. Stevefelt et al. Phys rev. A 12 (1975) 1246

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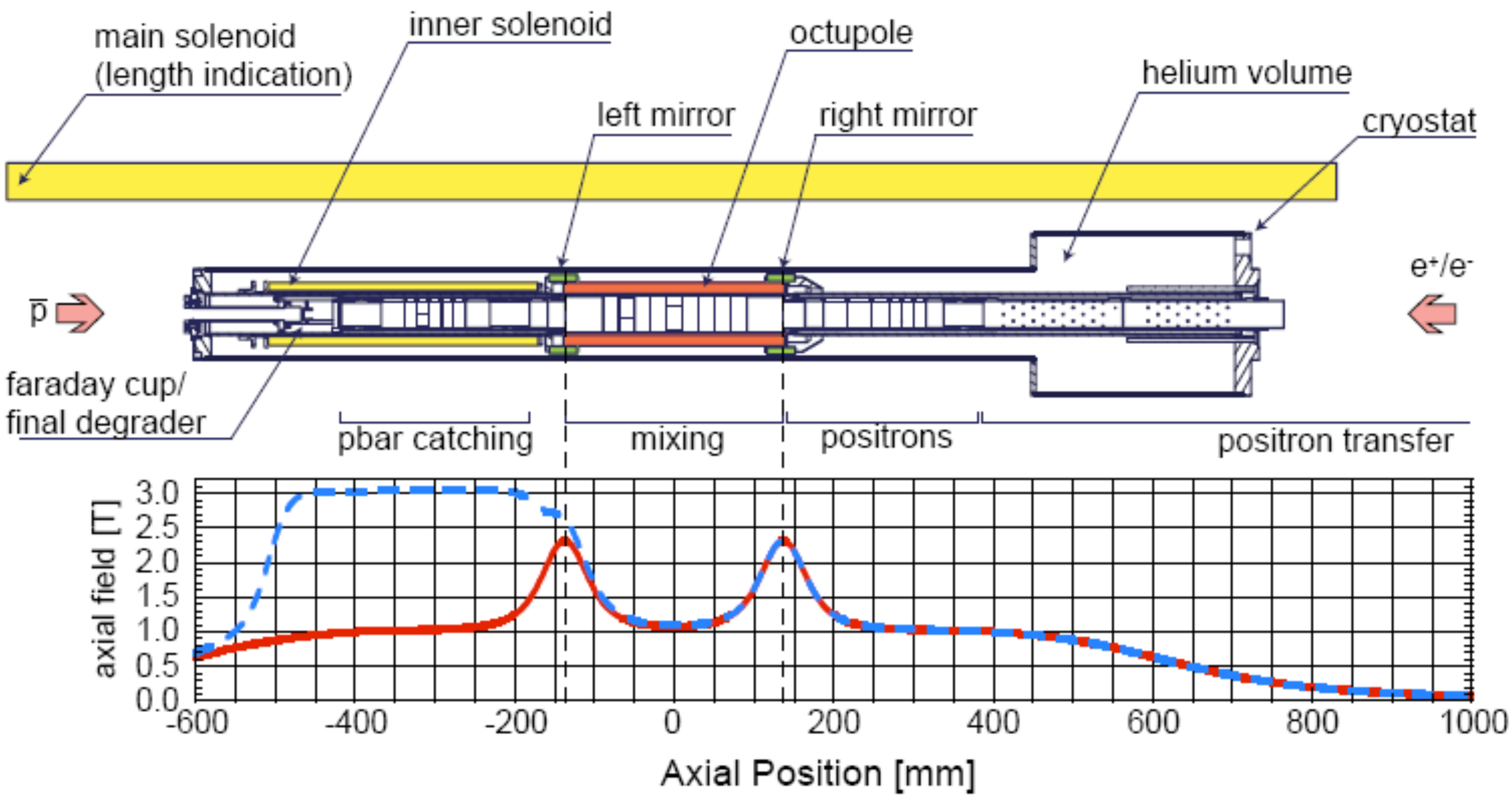
HBAR+ formation processes using positronium

$$\overline{p} + Ps \rightarrow \overline{H} + e^+$$

$$\overline{H} + Ps \rightarrow \overline{H}^+ + e^+$$

J. Walz and T. W. Hänsch
Gen. Relativ. Gravit. **36 (2004)** 561

ALPHA: uses non-neutral plasmas



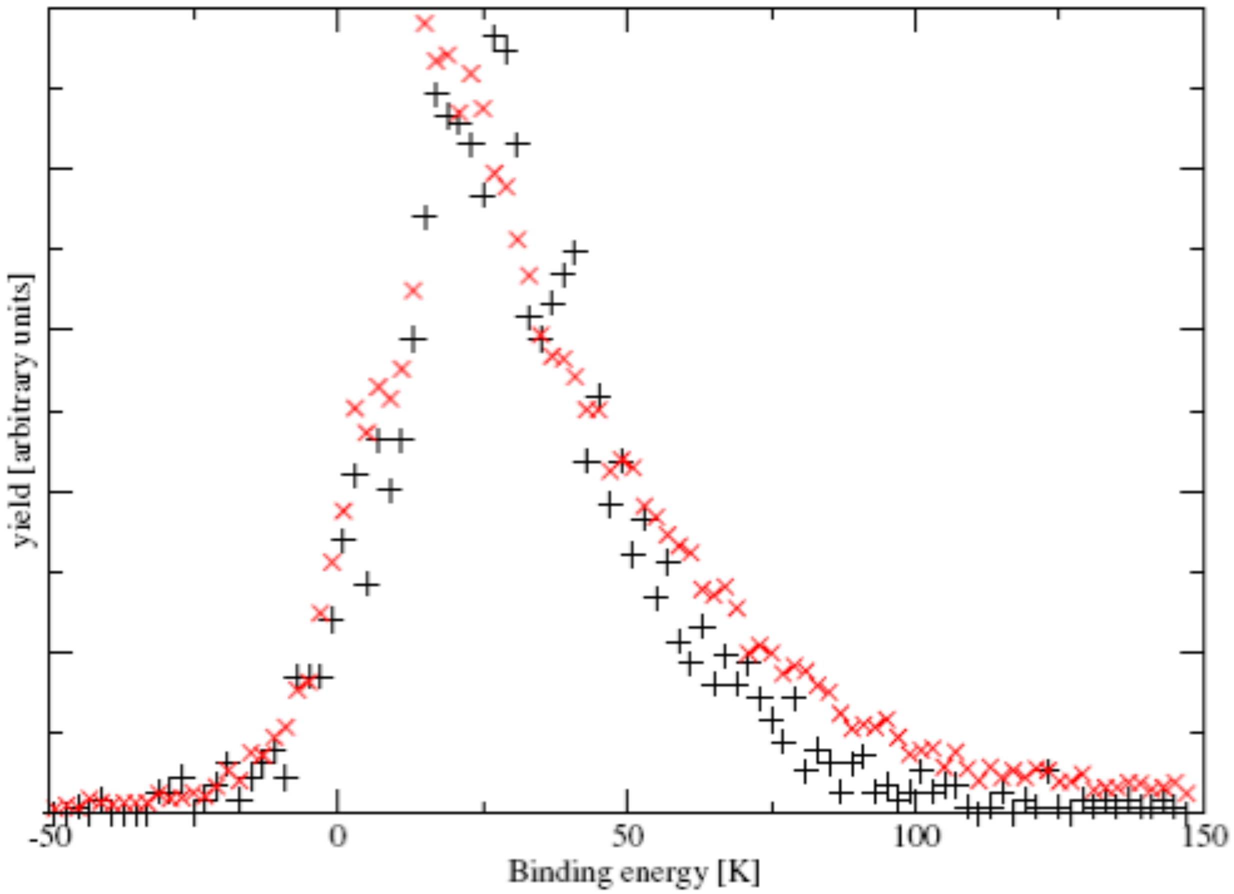
Debye length << particle cloud size

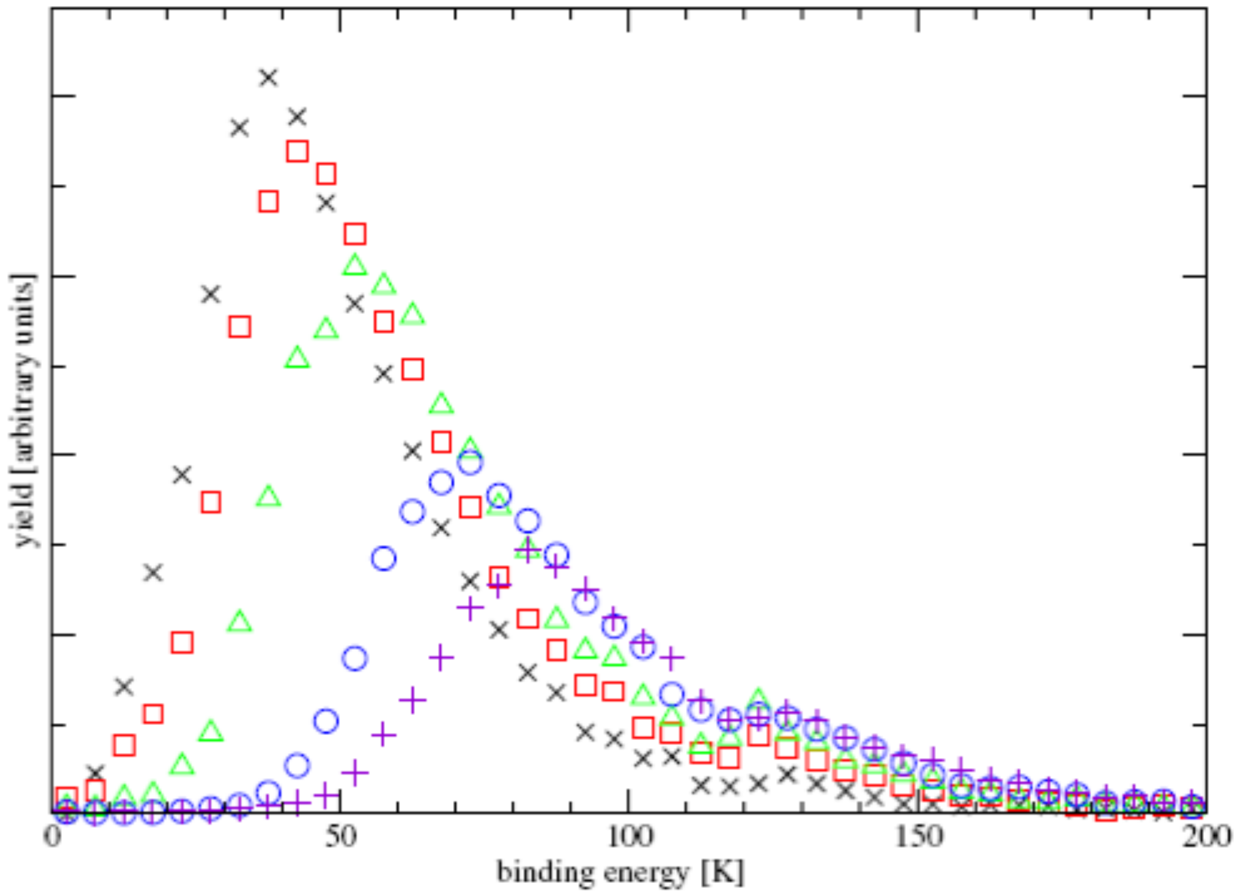
Antihydrogen formed by mixing positrons and antiprotons

Antihydrogen Production: Insights from Simulations

$T_e = 15$ K

Effects of plasma self field on antihydrogen binding energies





Antihydrogen binding energies as the atoms leave the positron plasma

$n_e = 10^{15}$ m^{-3} (x); $n_e = 5 \times 10^{13}$ m^{-3} (+)

Antihydrogen binding energies on detection

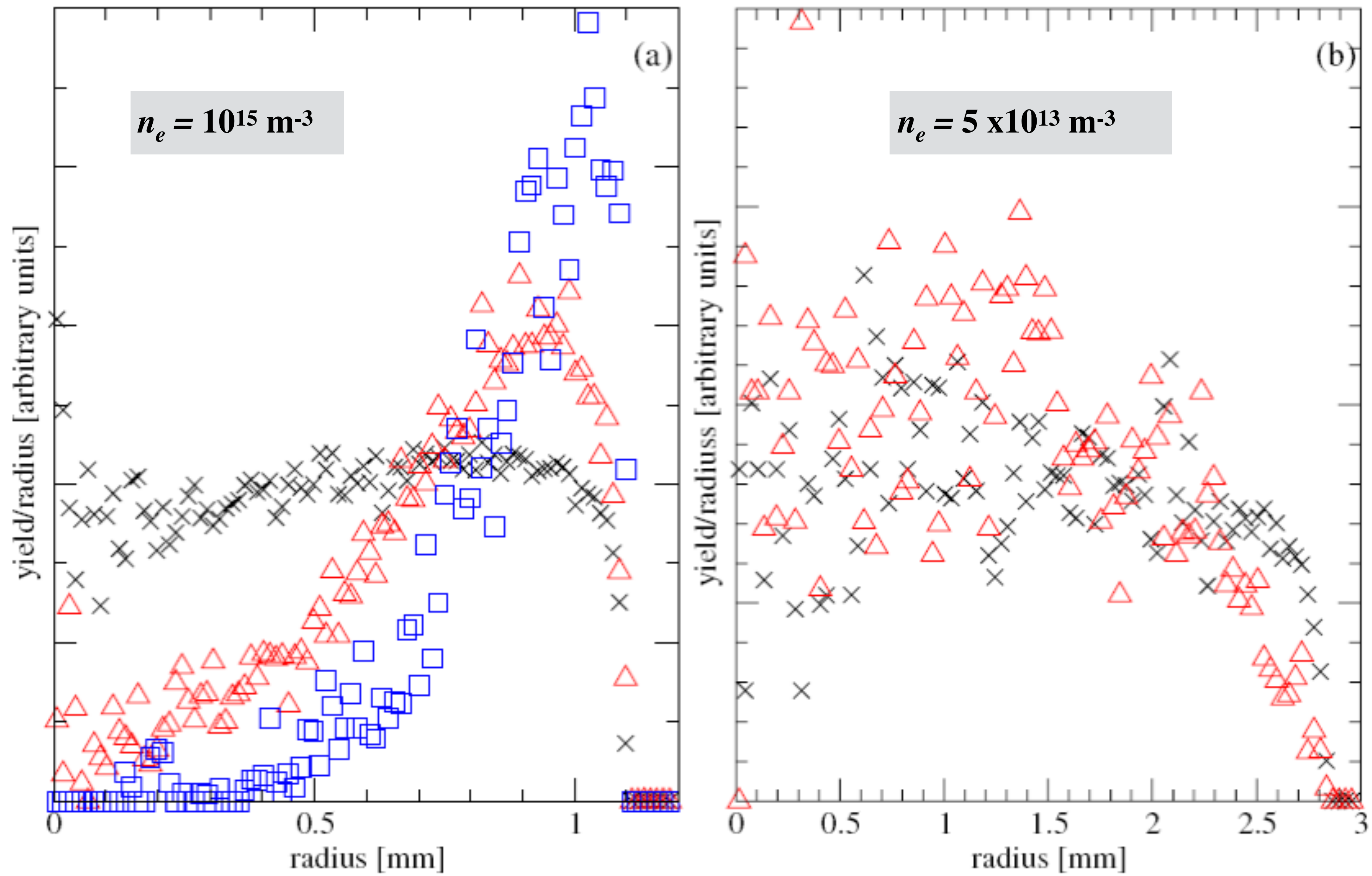
$n_e = 10^{15}$ m^{-3} (+); 5 (○), 2 (Δ) and 1 (□) x 10^{14} m^{-3} and 5 x 10^{13} m^{-3} (x)

S Jonsell, D P van der Werf, M Charlton and F Robicheaux
J. Phys. B: At. Mol. Opt. Phys. 42 (2009) 215002

Antihydrogen Production: Insights from Simulations

Radial distribution of antihydrogen formation positions at different time intervals

$T_e = 15$ K



short (x), medium (Δ) and long (□) times

NB at 10^{15} m^{-3} a "long" time is > 1ms

S Jonsell, D P van der Werf, M Charlton and F Robicheaux
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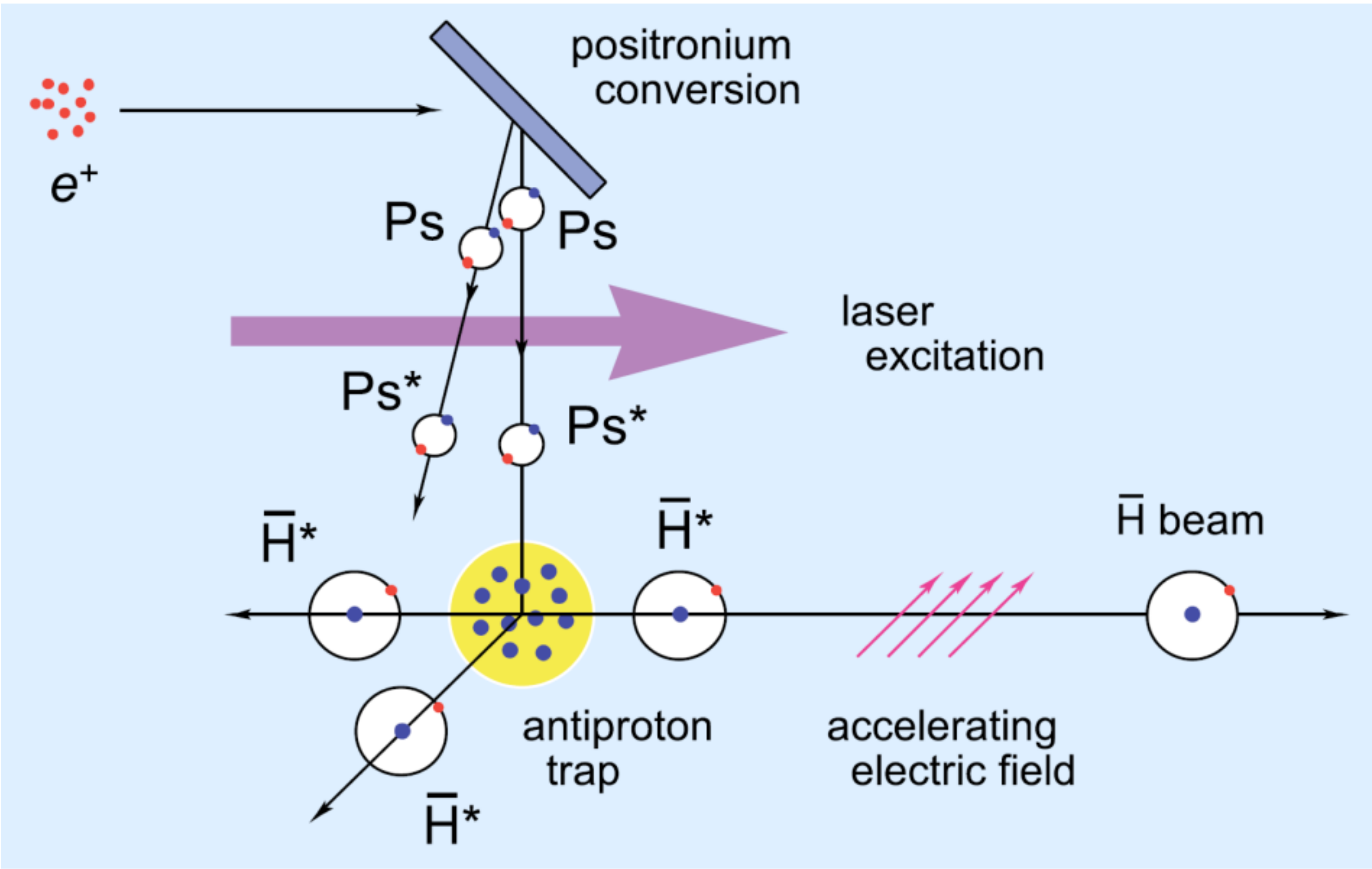
Antihydrogen Production: Formation Processes

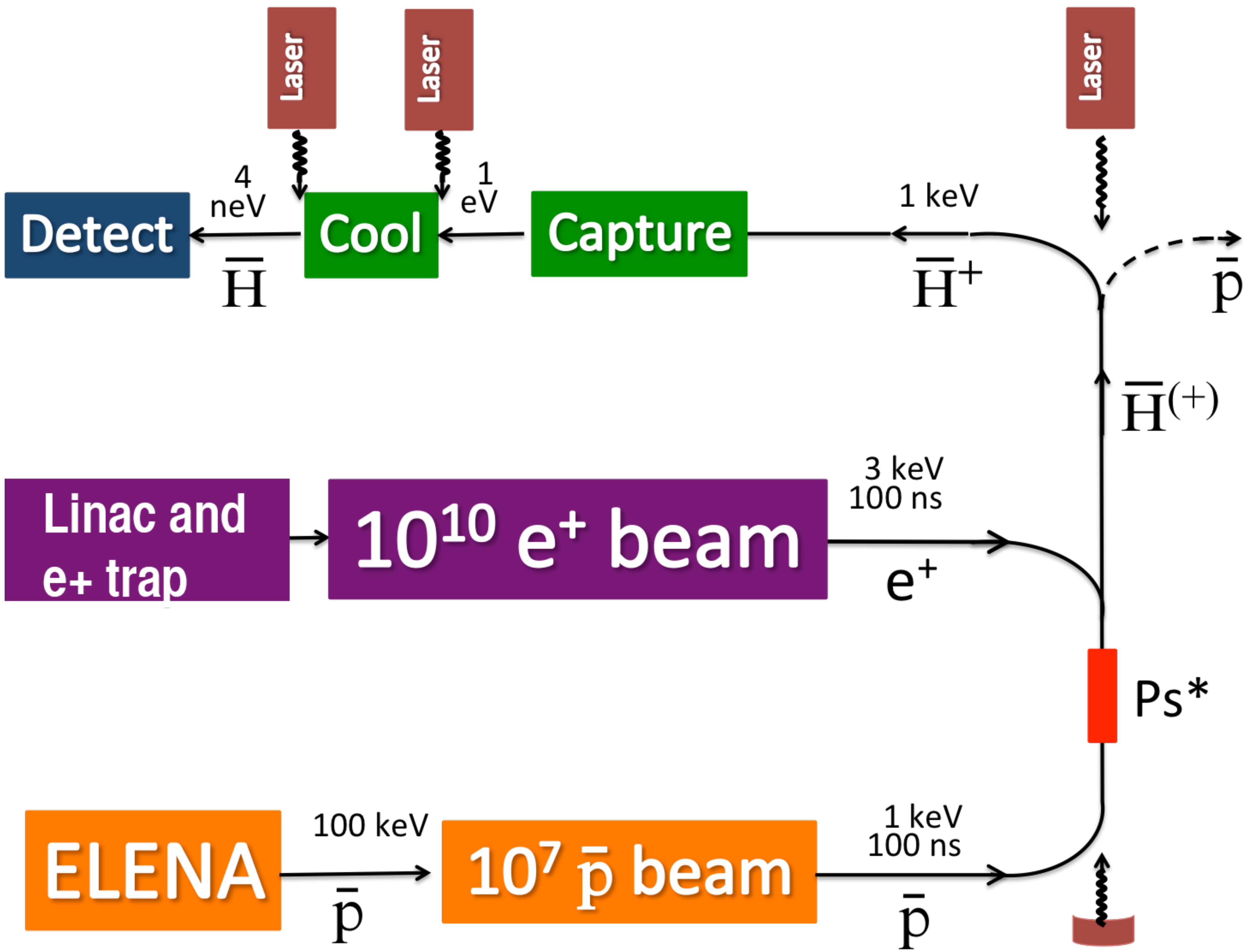
Rydberg Ps can offer dramatic increases in reaction rates – leads to Rydberg antihydrogen

$$\overline{p} + Ps \rightarrow \overline{H} + e+$$



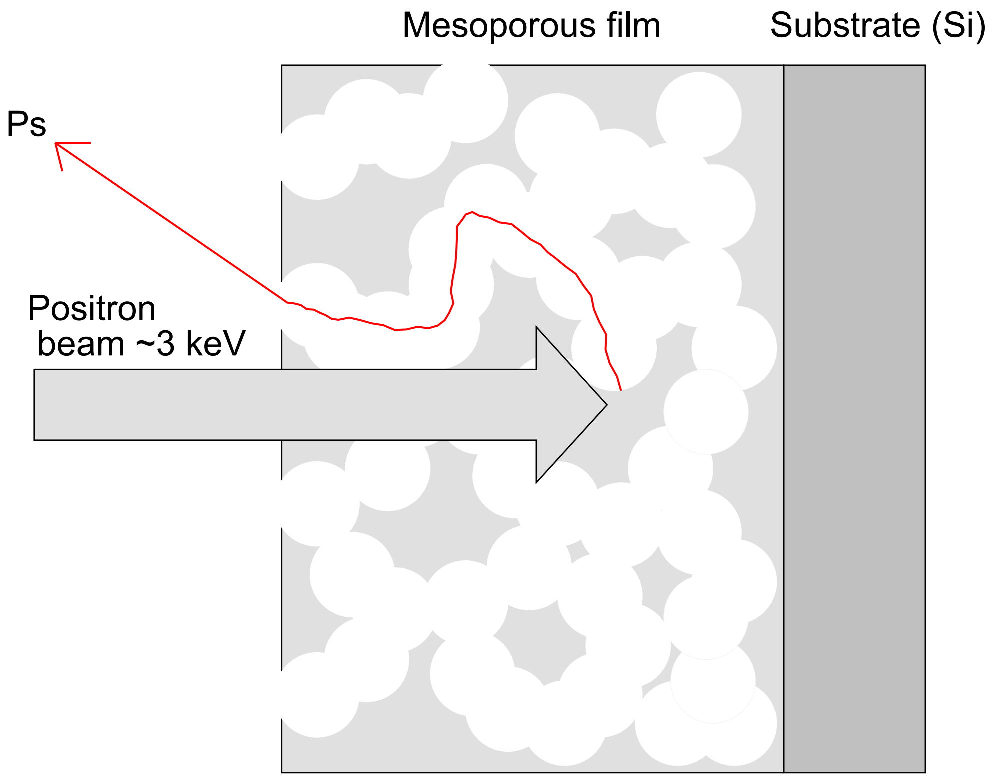
AEgIS Schematic

$\overline{H}^{+}$ formation (GBAR)



Interaction area

- Positrons are converted into positronium
- Part of the Ps atoms will be excited (see later), i. e. laser radiation needs to be introduced
- Antiprotons will "shoot" through the positronium cloud to form $\overline{H}^+$



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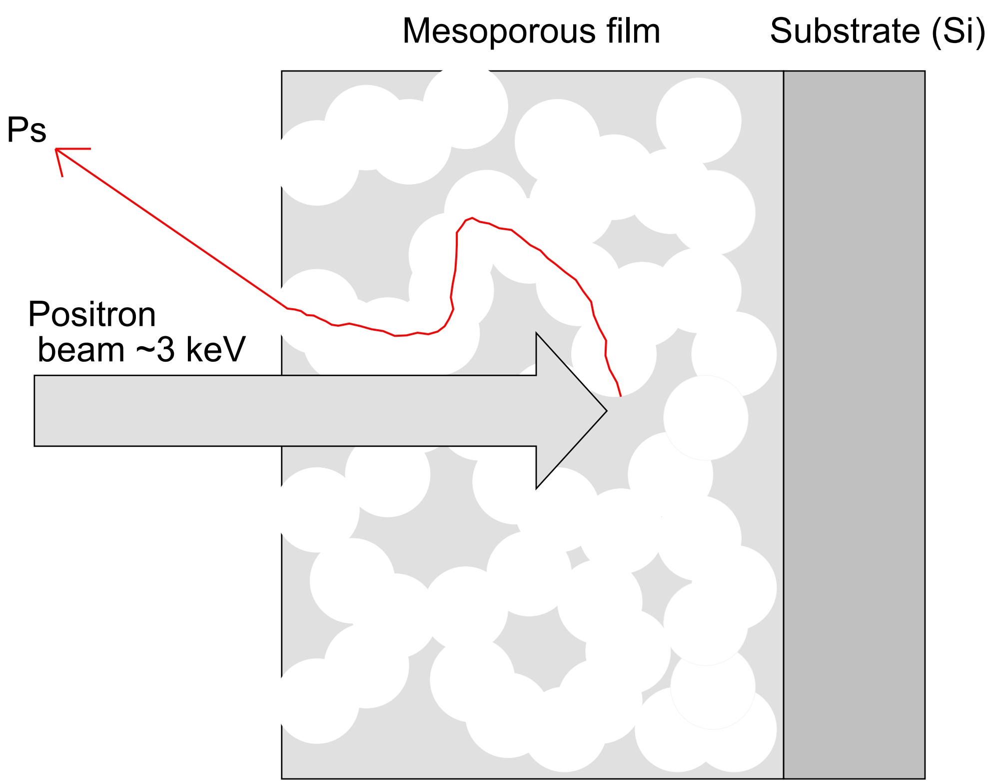

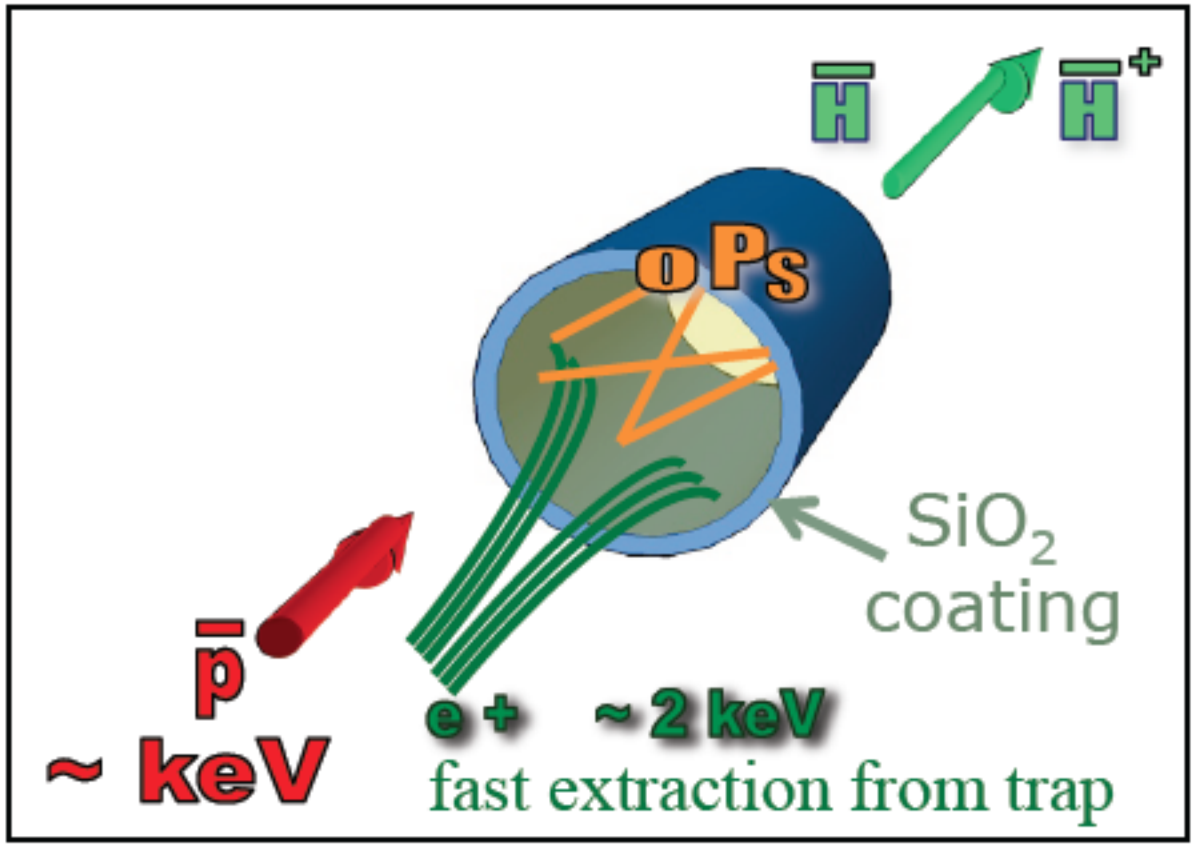

$\overline{H}^+$ formation

$$\overline{p} + Ps \rightarrow \overline{H} + e^+$$

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from GBAR proposal

Positron storage			
Stored positrons			
2.1×10^{10}			
Positronium			
Tube length	Positronium density	Loss fraction from Ps decay	
1 cm	7.4×10^{11} cm^{-3}	0.5	
Antihydrogen positive ions			
Production cross section of the $\overline{H}$ atom	Production cross section of the $\overline{H}^+$ ion	$\overline{H}$ per pulse	$\overline{H}^+$ per pulse
4.4 10^{-16} cm^2	8.8 10^{-15} cm^2	3.9×10^2	0.32

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Antiproton production

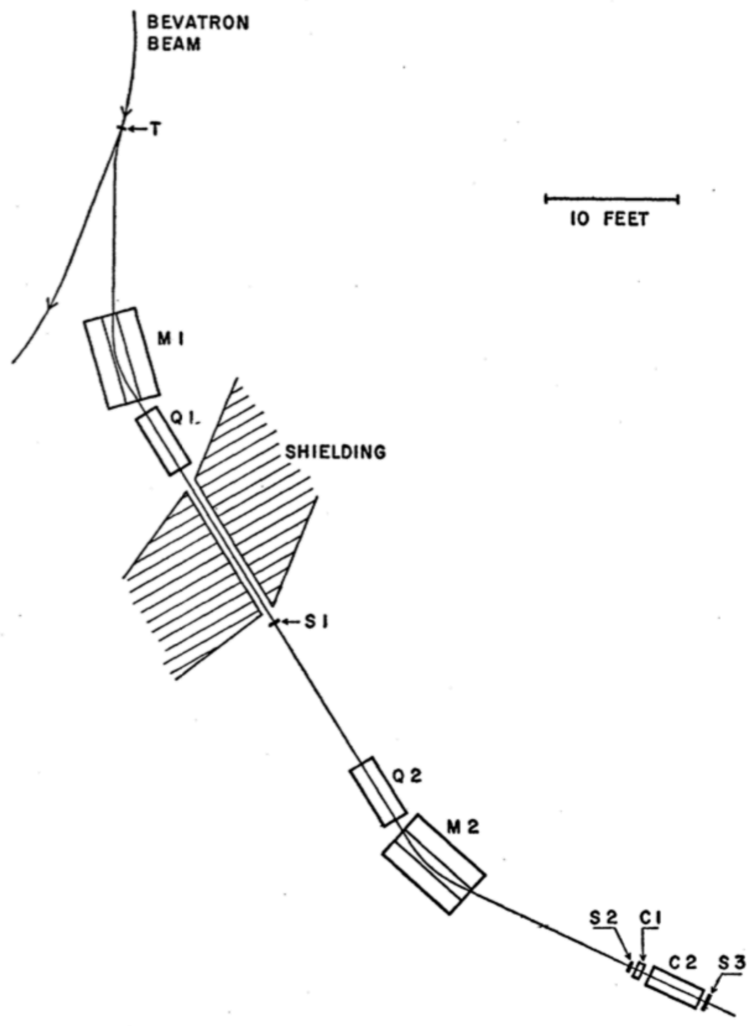
Antiprotons are produced using pair production i.e.:

$$p + N \rightarrow p + N + p + \overline{p}$$

Where N is a nucleon, and the threshold energy of the incoming proton is about 6 GeV.

At CERN, N is an Iridium nucleon

First Observation of antiprotons



O. Chamberlain, E. Segrè, C. Wiegand and T. Ypsilantis
Phys. Rev. **100** (1955) 947

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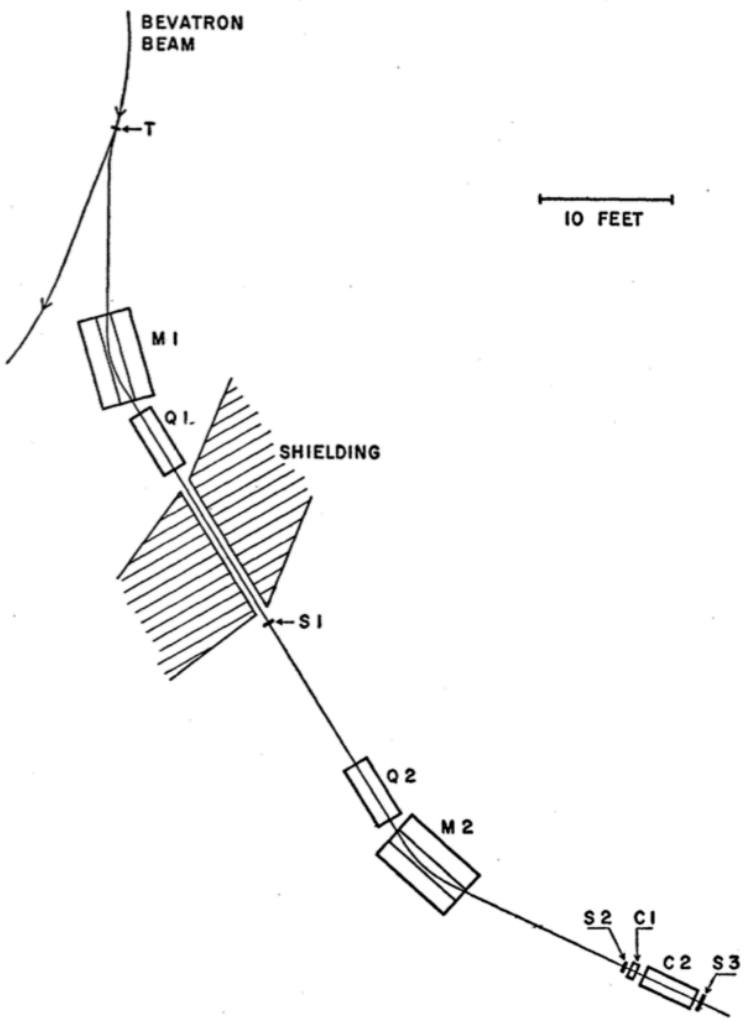

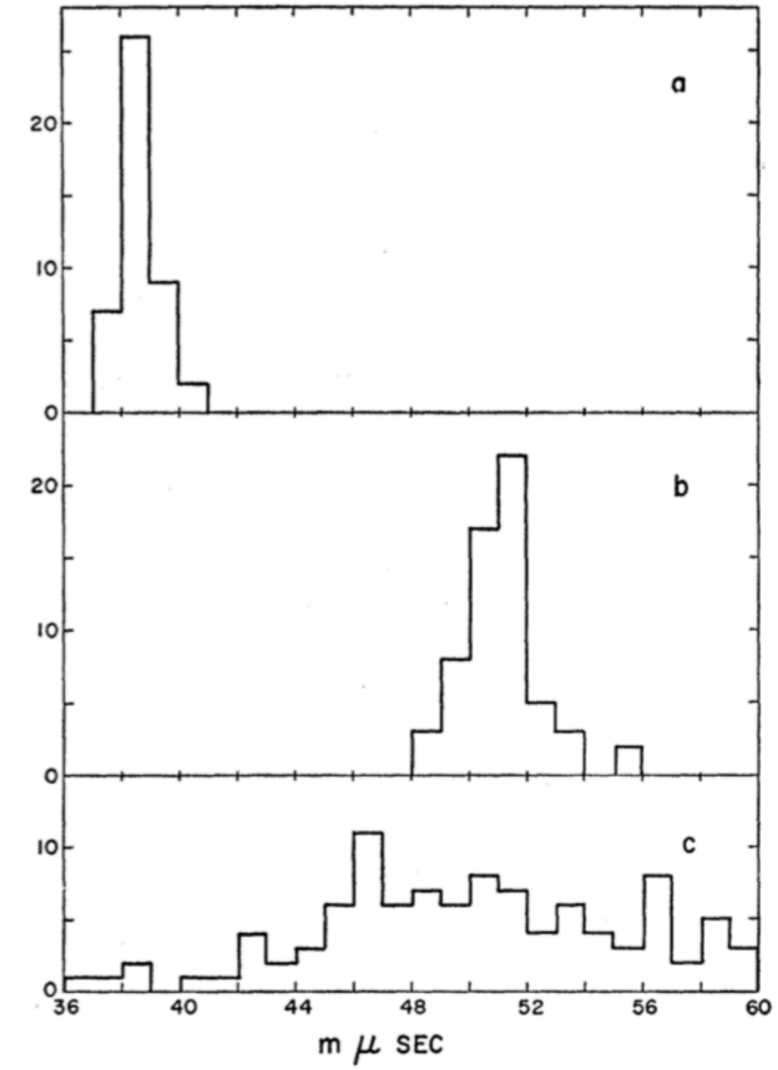

FIG. 3. (a) Histogram of meson flight times used for calibration. (b) Histogram of antiproton flight times. (c) Apparent flight times of a representative group of accidental coincidences. Times of flight are in units of 10^{-9} sec. The ordinates show the number of events in each 10^{-10}-sec intervals.

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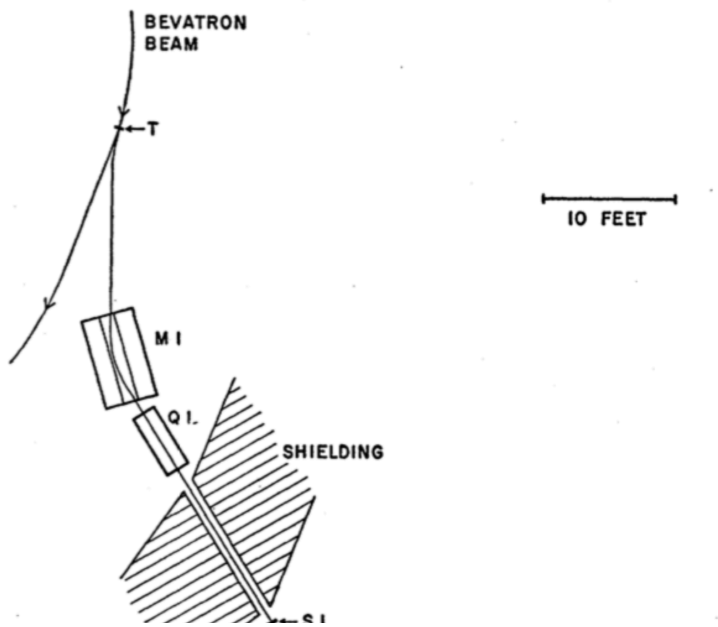

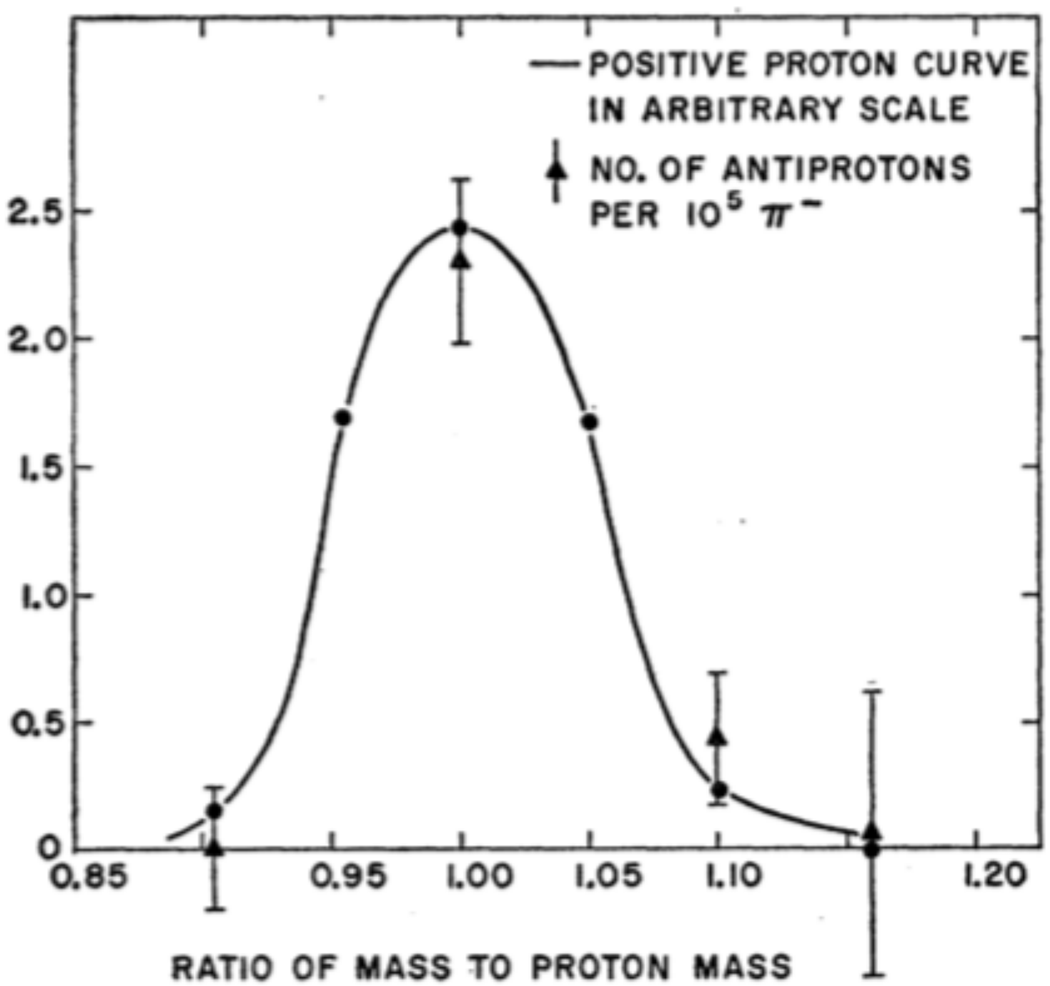

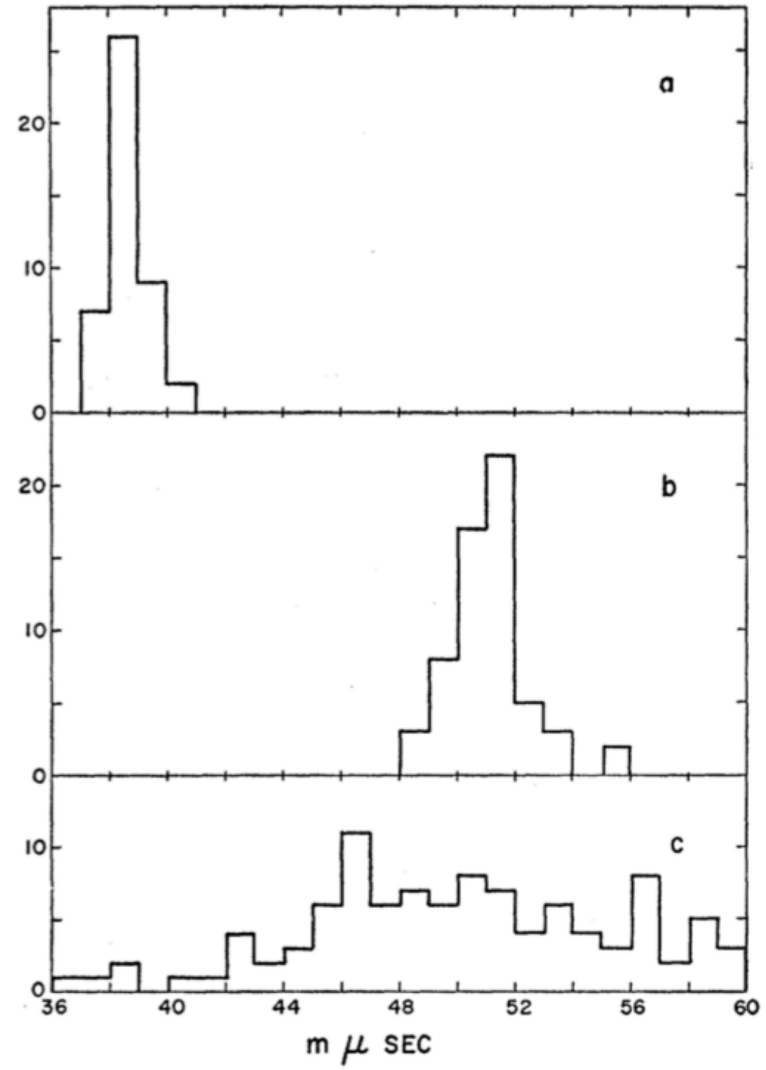

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Magnetic Horn

A DIRECTIVE DEVICE FOR CHARGED PARTICLES AND ITS
USE IN AN ENHANCED NEUTRINO BEAM

BY

S. van der Meer

S. van der Meer CERN 61-7

Magnetic Horn

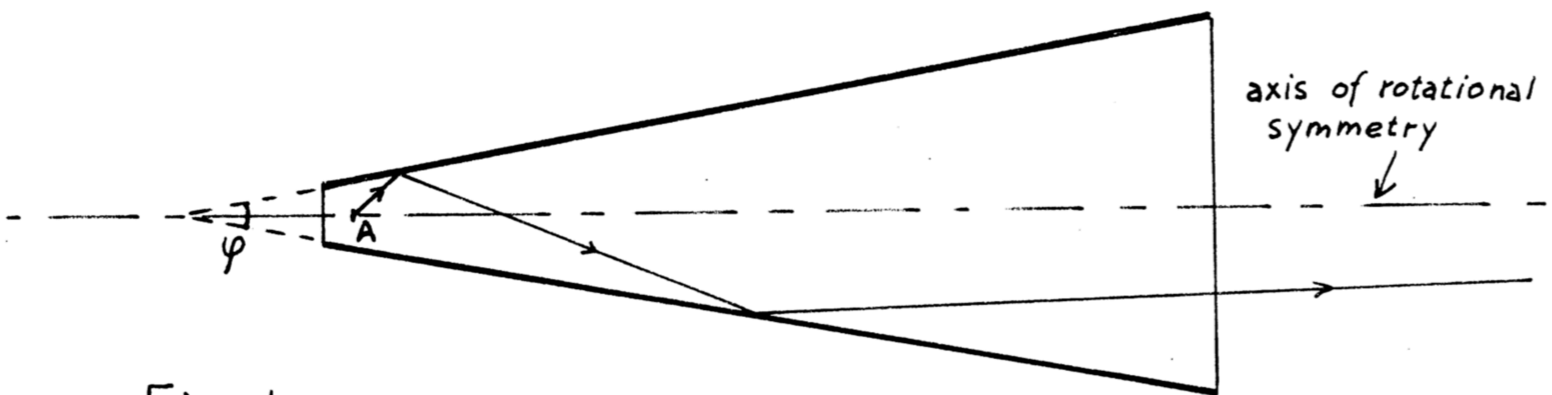

Fig. 1

A DIRECTIVE DEVICE FOR CHARGED PARTICLES AND ITS USE IN AN ENHANCED NEUTRINO BEAM

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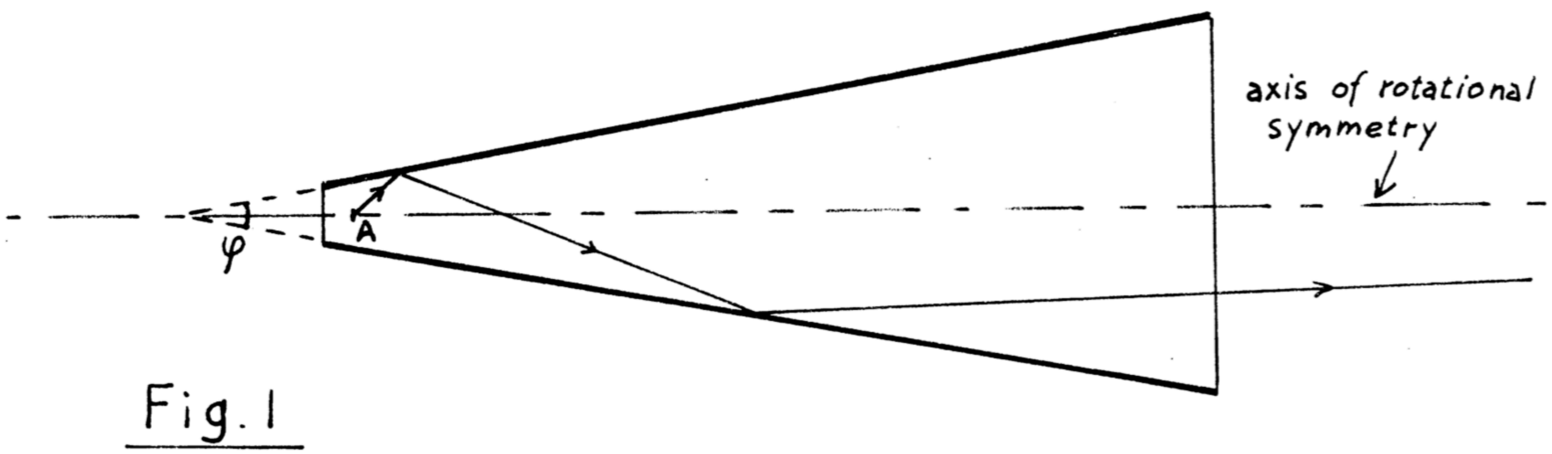

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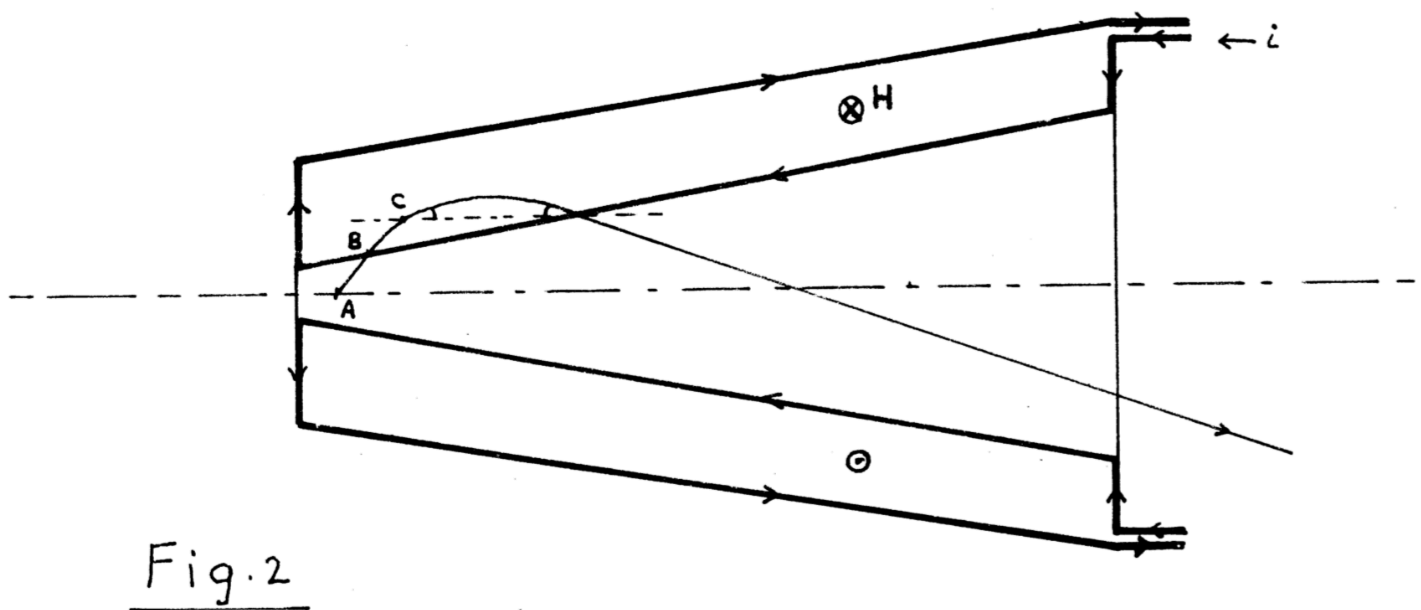

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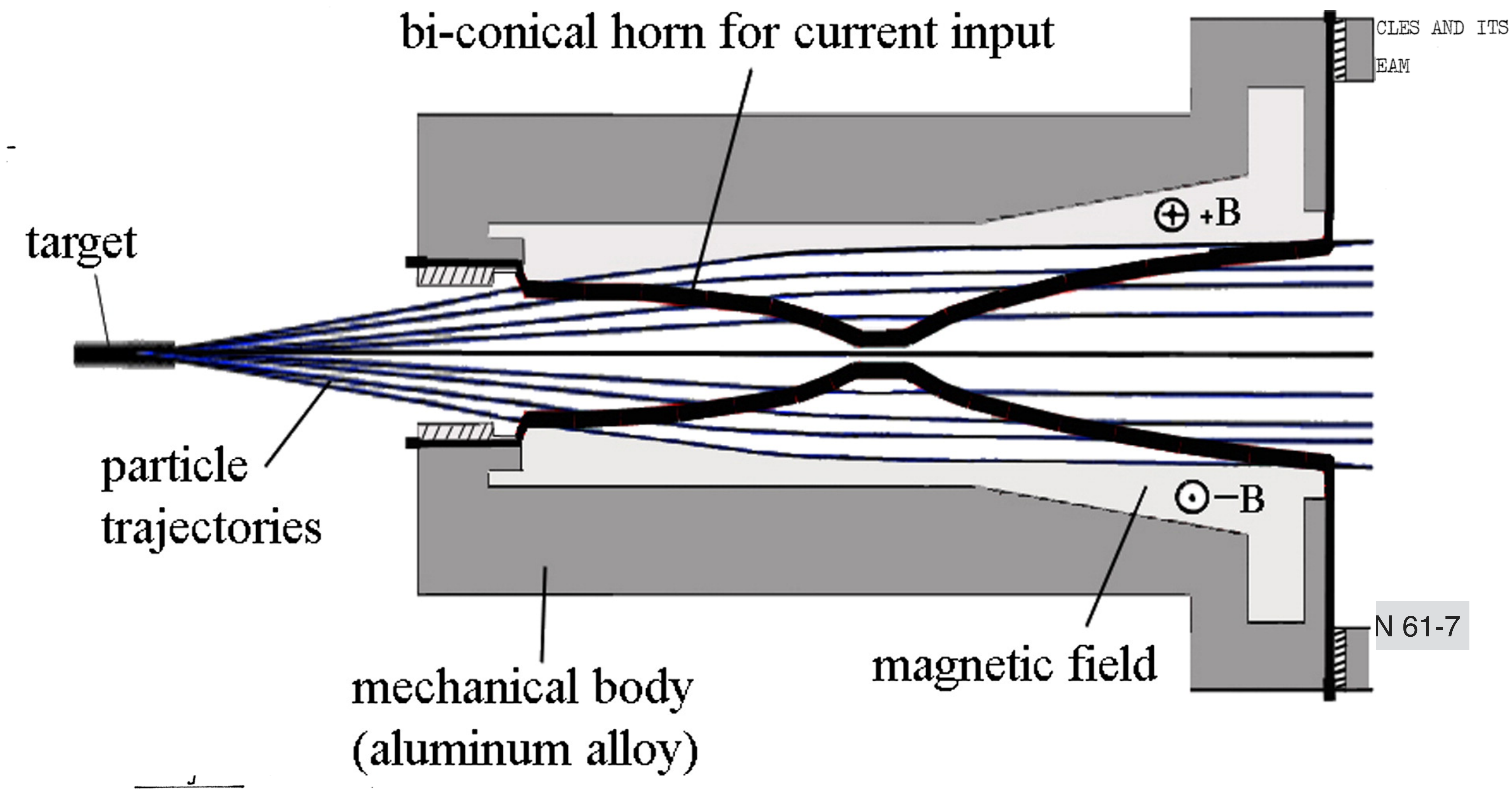


AD source + horn

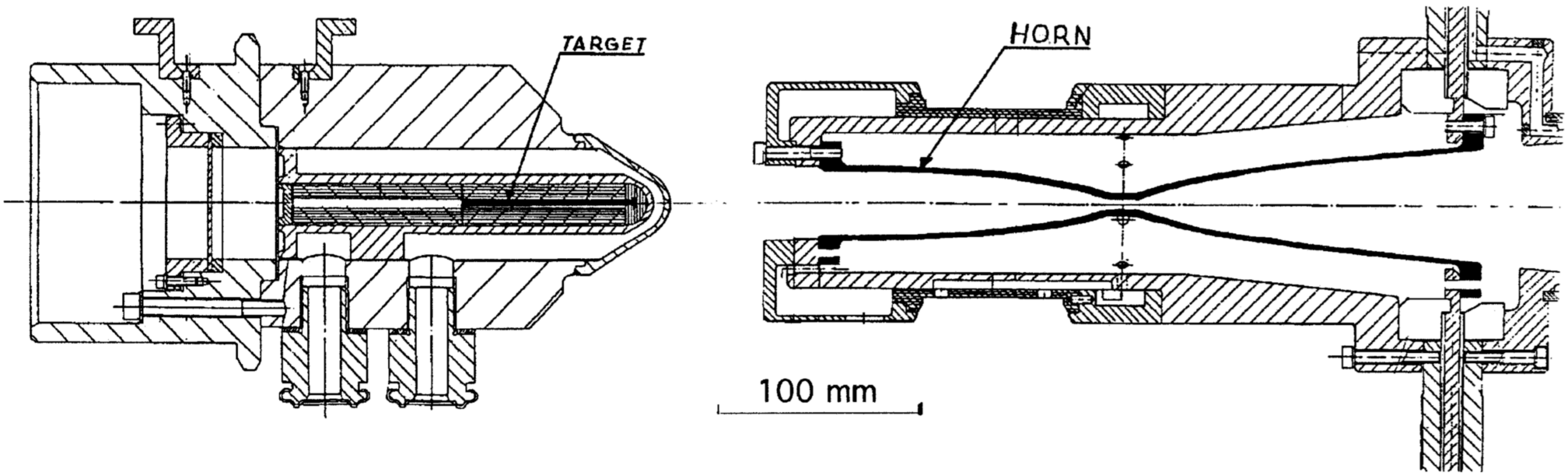
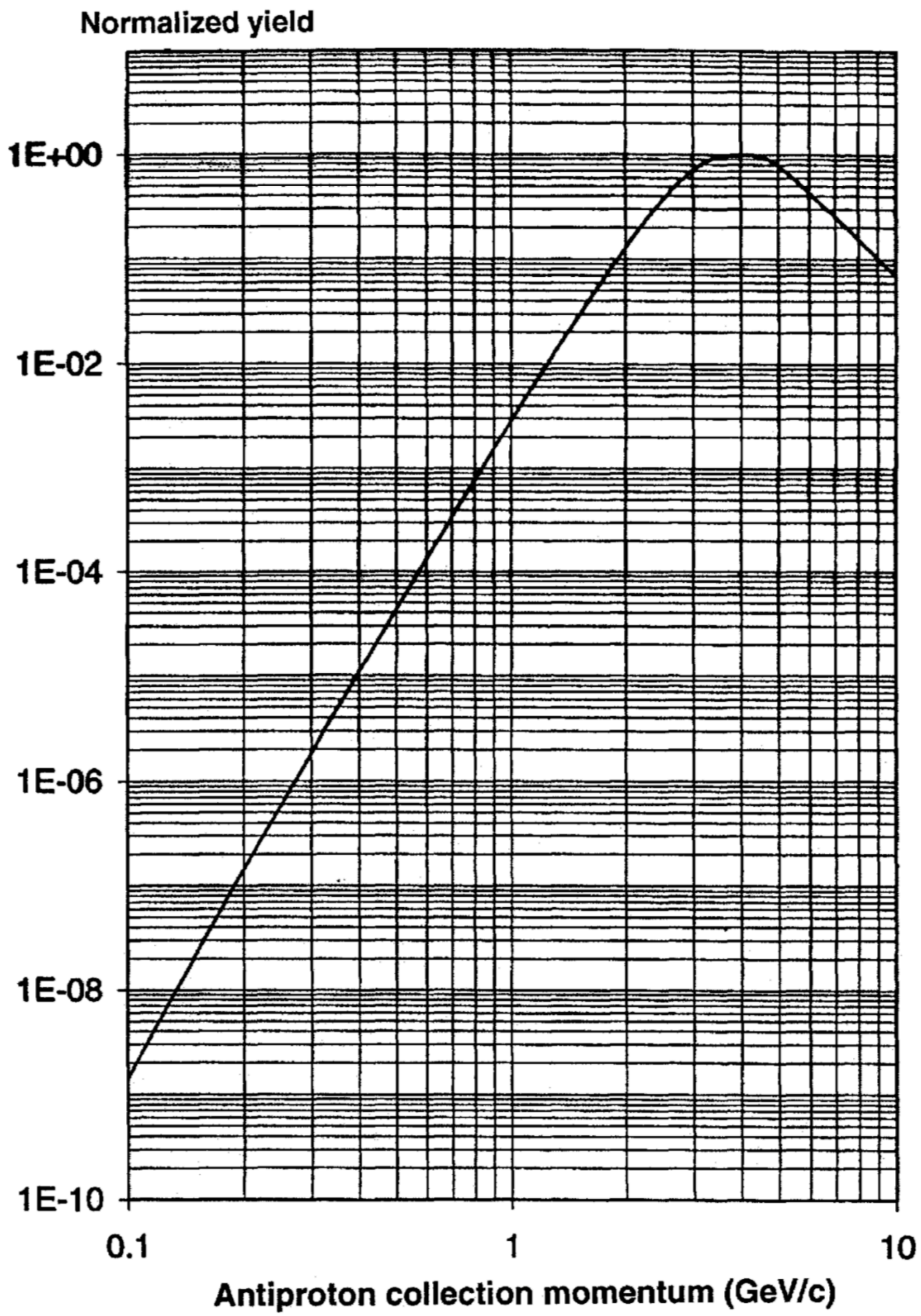


Fig. 1. Target and magnetic horn assembly. The target is a 55 mm long 3 mm diameter iridium rod embedded in graphite. A pulse current of 400 kA is fed into the horn-shaped electrode at the downstream end and creates an azimuthal magnetic field in the region between the horn and the wall of the container.

D. Möhl *Hyperfine Interactions* **109** (1997) 33

Yield for 26 GeV protons



D. Möhl *Hyperfine Interactions* **109** (1997) 33

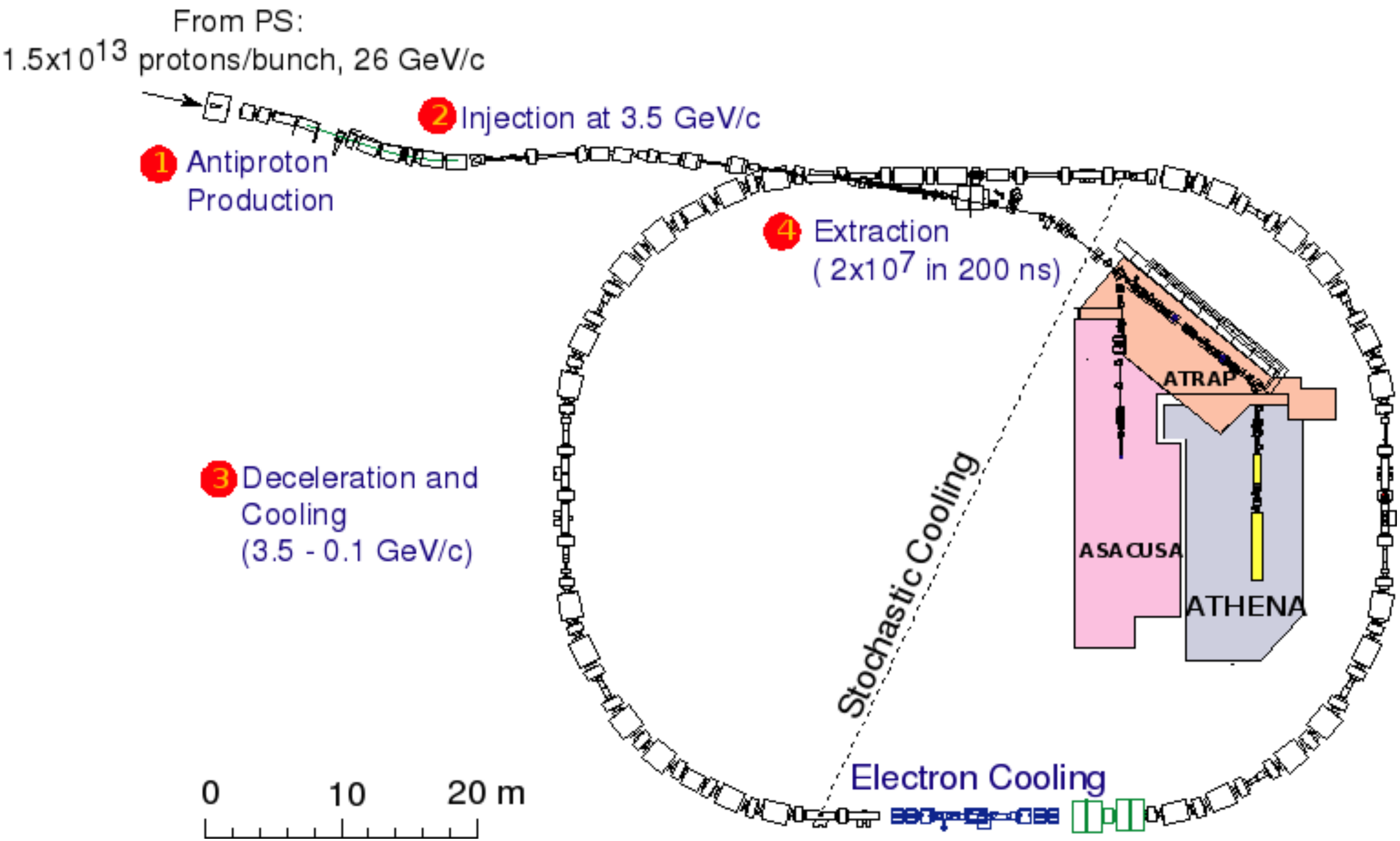
Fermilab vs CERN

Comparison of antiproton sources. In contrast to [9] we take in the Fermilab case a higher intensity production beam thus partly anticipating the upgrade program [9]. For the CERN case we use the measured yield with a magnetic horn.

Machine		CERN AC	Fermilab Debuncher
Production beam momentum (GeV/c)		26	120
Collection momentum (GeV/c)		3.5	9
Production cross-section [(sr×GeV/c)$^{-1}$]		0.013	0.25
Acceptances	A_h (π mm mrad)	200	25
	A_v (π mm mrad)	200	25
	$\Delta p/p$ (10^{-3})	60	40
$\sqrt{A_h \times A_v} \times \Delta p/p$ (π mm mrad)		12×10^3	1×10^3
Yield ($\bar{p}$/p)		3.5×10^{-6}	14×10^{-6}
Protons per pulse		1.5×10^{13}	0.5×10^{13}
Antiprotons per pulse		5×10^7	7×10^7

D. Möhl *Hyperfine Interactions* **109** (1997) 33

AD ring


From PS:
1.5x10^13 protons/bunch, 26 GeV/c
1 Antiproton Production
2 Injection at 3.5 GeV/c
3 Deceleration and Cooling (3.5 - 0.1 GeV/c)
4 Extraction (2x10^7 in 200 ns)
Stochastic Cooling
Electron Cooling
ATRAP
ASACUSA
ATHENA
0
10
20 m

Stochastic cooling

S. van der Meer CERN-ISR-PO-72-31

Stochastic cooling

As is well known, Liouville's theorem predicts that betatron oscillations cannot be damped by the use of electromagnetic fields deflecting the particles. However, this theorem is based on statistics and is only strictly valid either for an infinite number of particles, or for a finite number if no information is available about the position in phase plane of the individual particles. Clearly, if each particle could be separately observed and a correction applied to its orbit, the oscillations could be suppressed. It is also well known to be possible to damp coherent betatron oscillations (where the beam behaves like a single particle) by means of pickup-deflector feedback systems. In the same way, the statistical fluctuations of the average beam position, caused by the finite number of particles, can be detected with pickup electrodes and a corresponding correction applied. In other words, the small fraction of the oscillations that happens to be coherent at any time due to the statistical fluctuations, can be damped.

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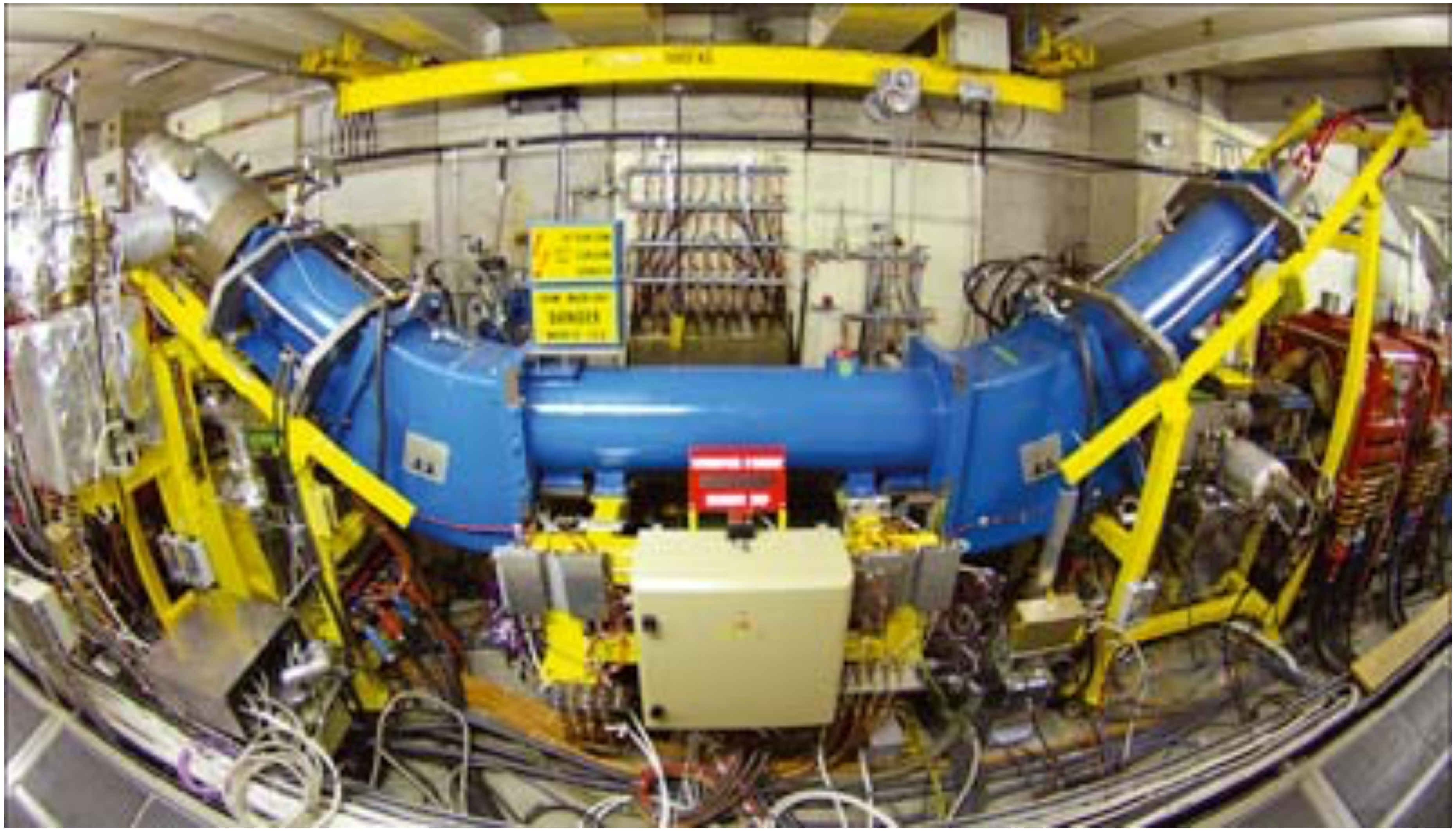
Electron cooling

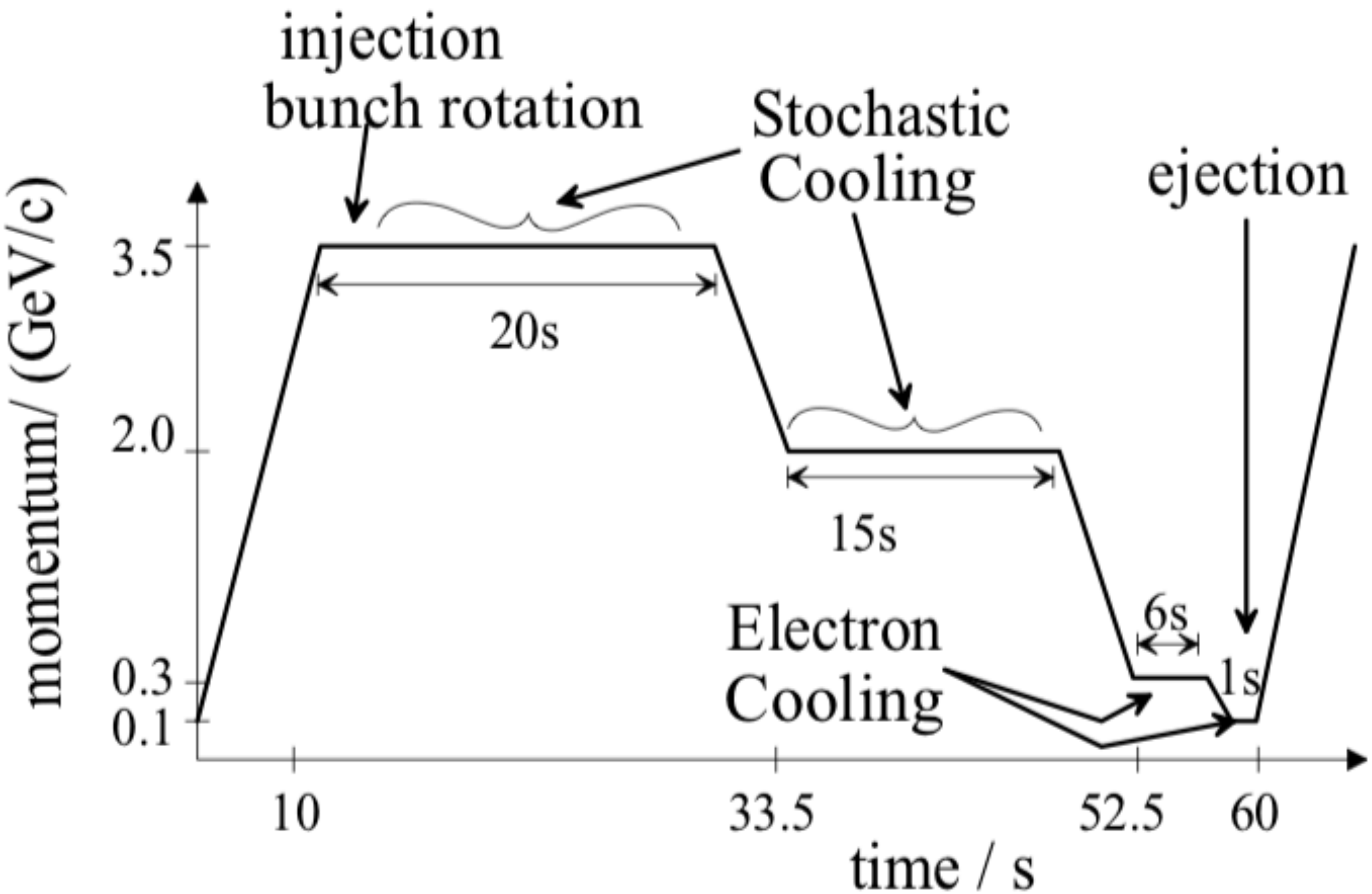
At lower energies de stochastic cooling does not work dat well anymore, so an other method is used: electron cooling.

Here the antiproton beam is merged with electrons and the antiprotons are cooled by collisions with these electrons.



G. I. Budker UDC.62.284.60

Deceleration cycle



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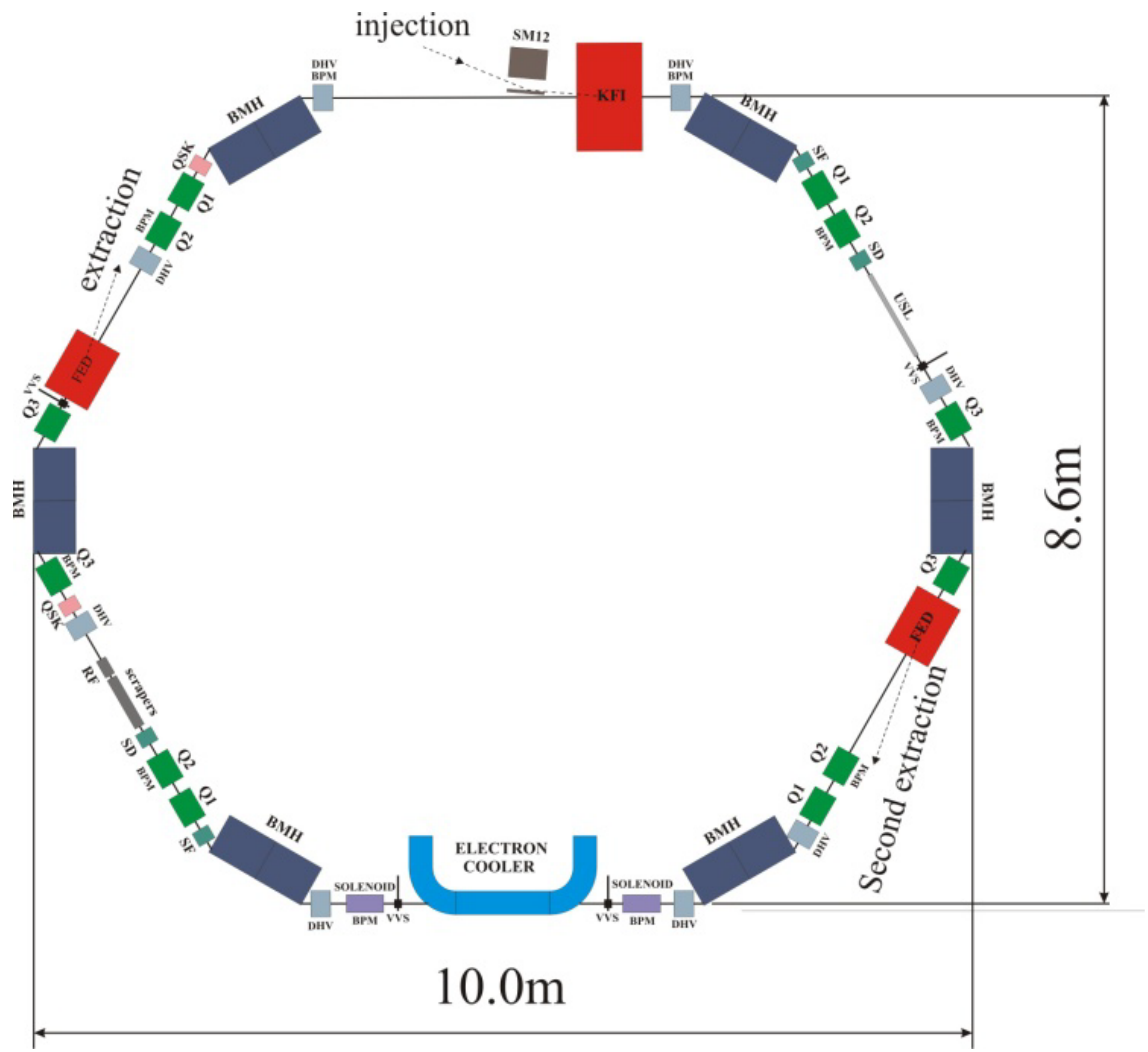

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ALL/MOST OF THE ABOVE
(AT SOME STAGE IN THE PROCEDURES)

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- Strongest possible β^+ source (about 3.5 GBq ^{22}Na in the past, now 2.85 GBq) combined with the most efficient moderator (solid Ne; working efficiency about 5 x 10^{-3}) to produce a beam of a few million positrons per second

$$^{22}\mathrm{Na} \rightarrow ^{22}\mathrm{Ne}^{*} + e^{+} + \nu_e$$

$$^{22}\mathrm{Ne}^{*} \rightarrow ^{22}\mathrm{Ne} + \gamma(1.274\ MeV)$$

- A "CERN/AD-friendly" compact electron linac-based source – should give a beam of around 10^8 per second using pair production:

$$\gamma + \mathrm{nucleus} \rightarrow e^{+} + e^{-} + \mathrm{nucleus}$$

The γ originate from electrons giving of Bremsstrahlung in a tungsten target

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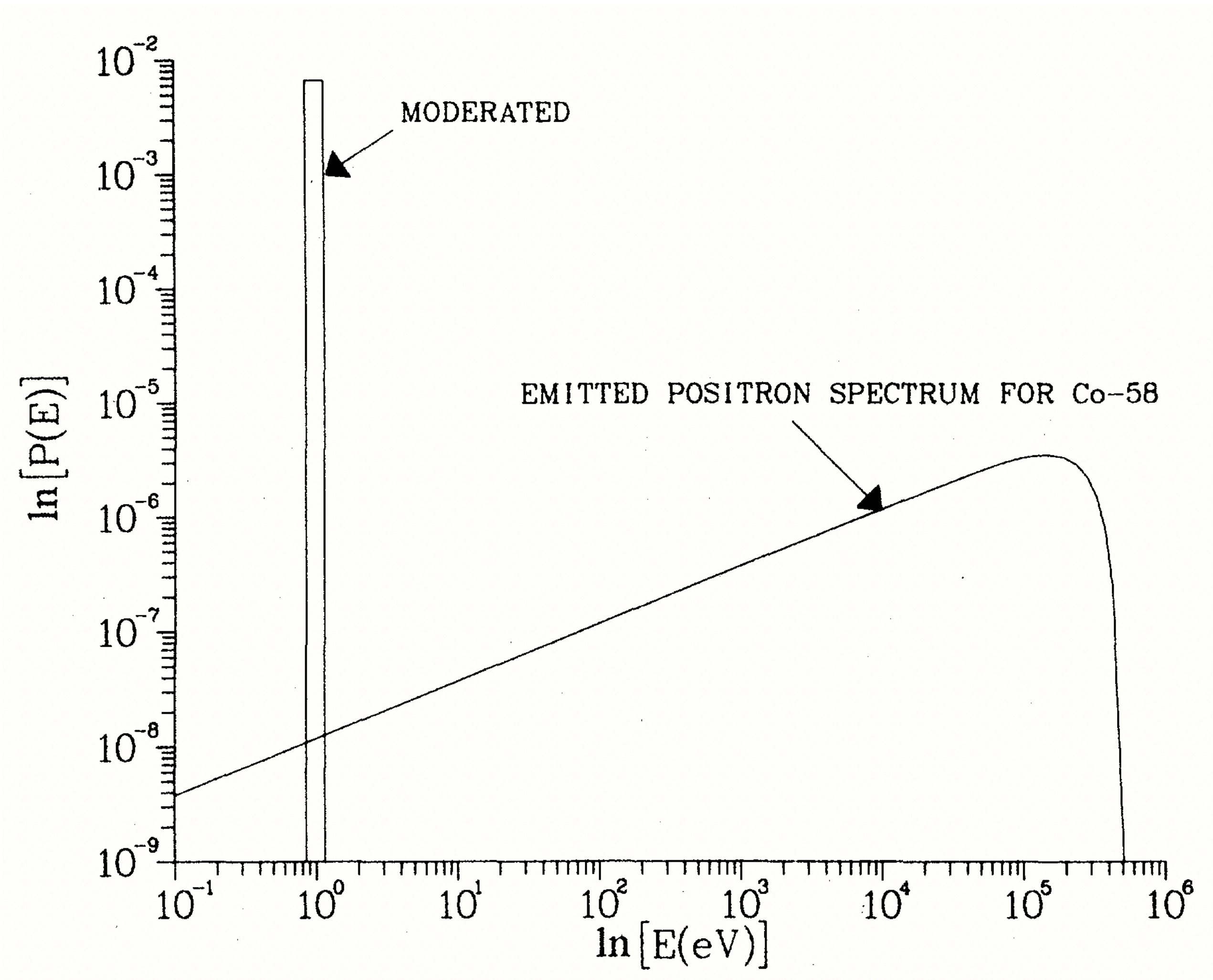
The γ originate from electrons giving of Bremsstrahlung in a tungsten target

Moderation

The kinetic energy of the positrons is quite broad and up to 545 KeV for positrons originating from ^{22}Na and a couple of MeV for LINAC produced positrons

To obtain a mono-energetic positrons beam they need to be moderated, i.e. de positrons loose energy inside a solid and are subsequently emitted into the vacuum.



Typical moderators

Metal: e.g.Tungsten

- Positrons are thermalized by inelastic collisions with electrons and then diffuse to the surface.
- Subsequently they are ejected due to the negative work function of the positron in tungsten.
- The moderated positrons have a narrow energy distribution.
- Max efficiency $\sim 10^{-3}$

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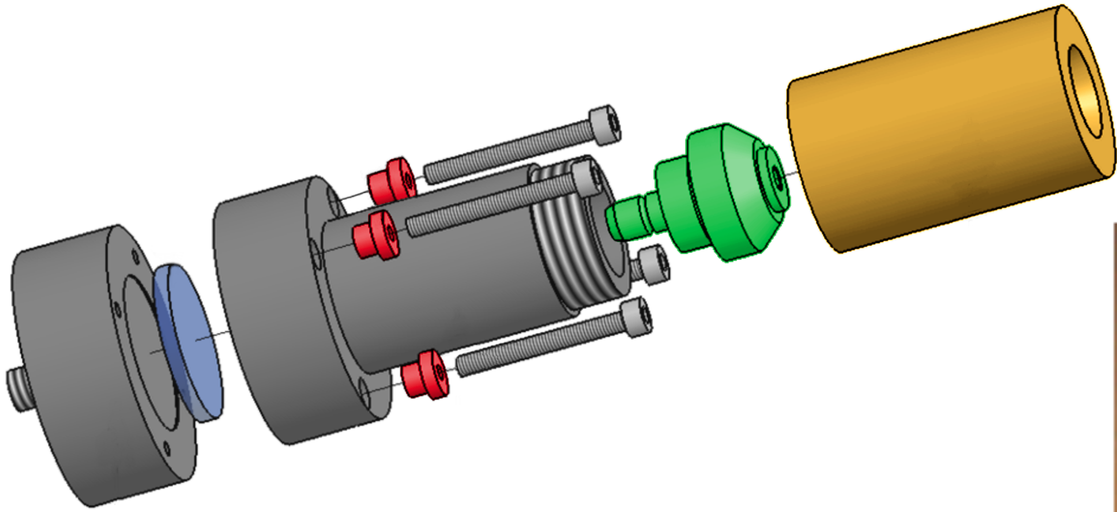
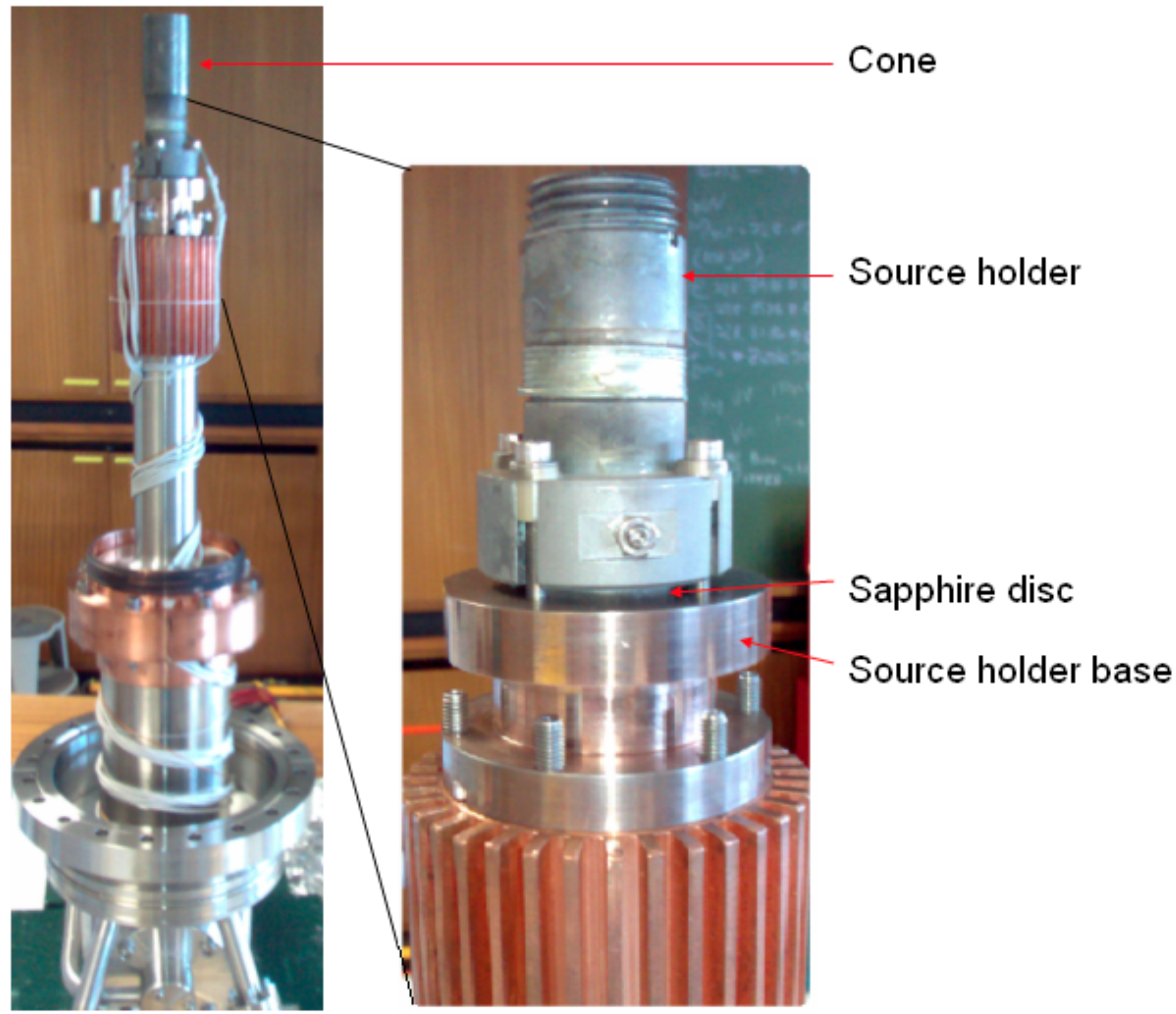
- Positrons are thermalized by inelastic collisions with electrons and then diffuse to the surface.
- Subsequently they are ejected due to the negative work function of the positron in tungsten.
- The moderated positrons have a narrow energy distribution.
- Max efficiency ~ 10^{-3}

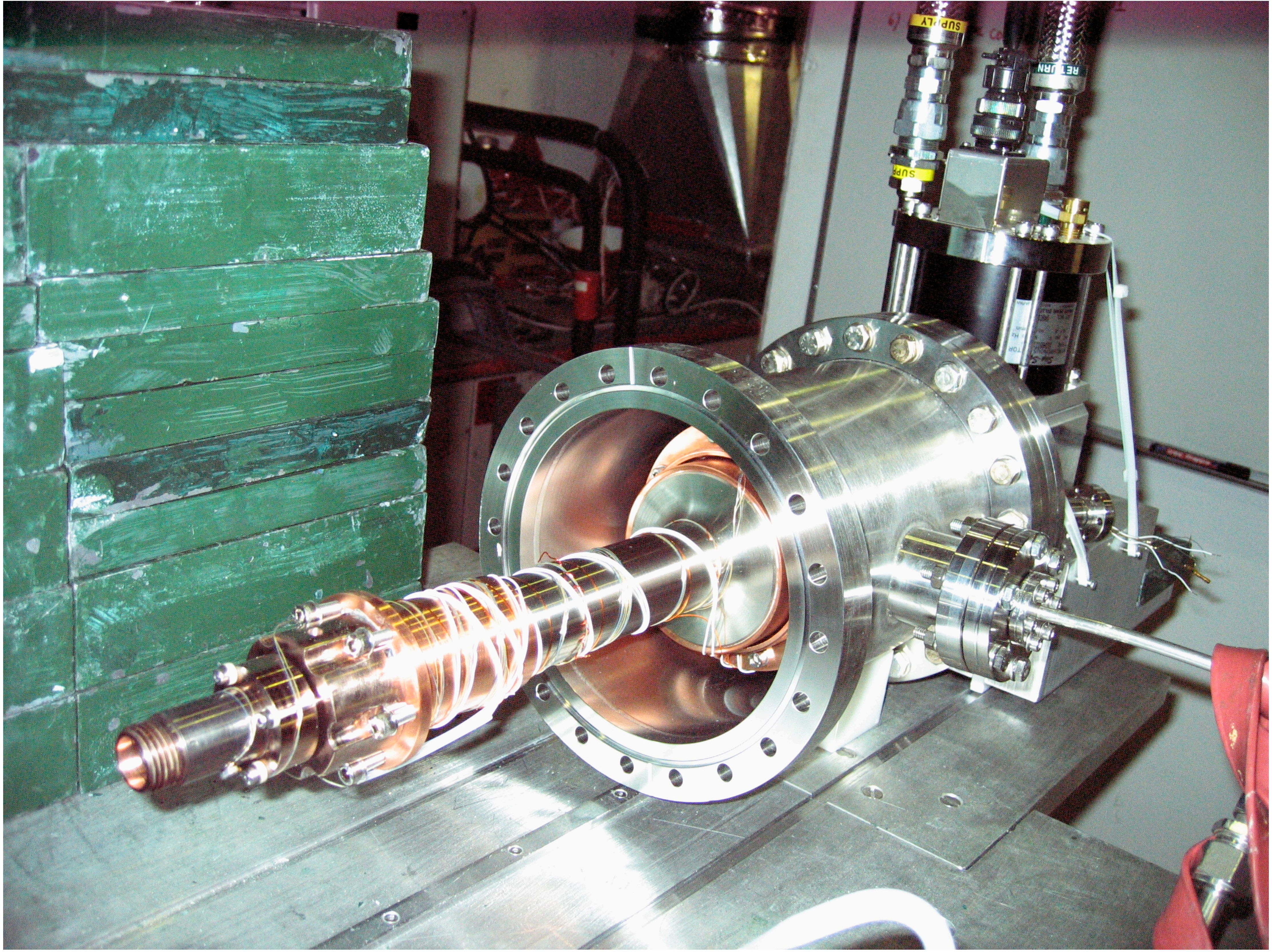
Solid rare gas: e.g. Neon

- Positrons are thermalized by electron-hole excitation until their energy is lower then the bandgap. Thereafter they can only loose energy via the production of acoustic phonons (slow process).
- Rare gases have positive workfunctions for positrons, so only so-called epithermal positrons can escape from the surface.
- The moderated energy distribution ~ 2 eV.
- Max efficiency ~ 10^{-2}

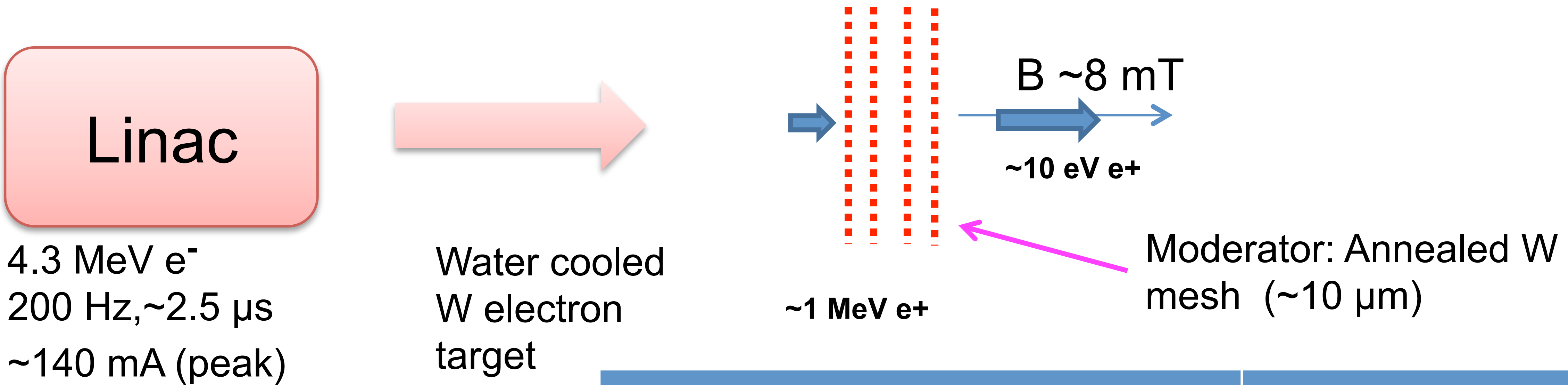
Example source/neon moderator (ALPHA)





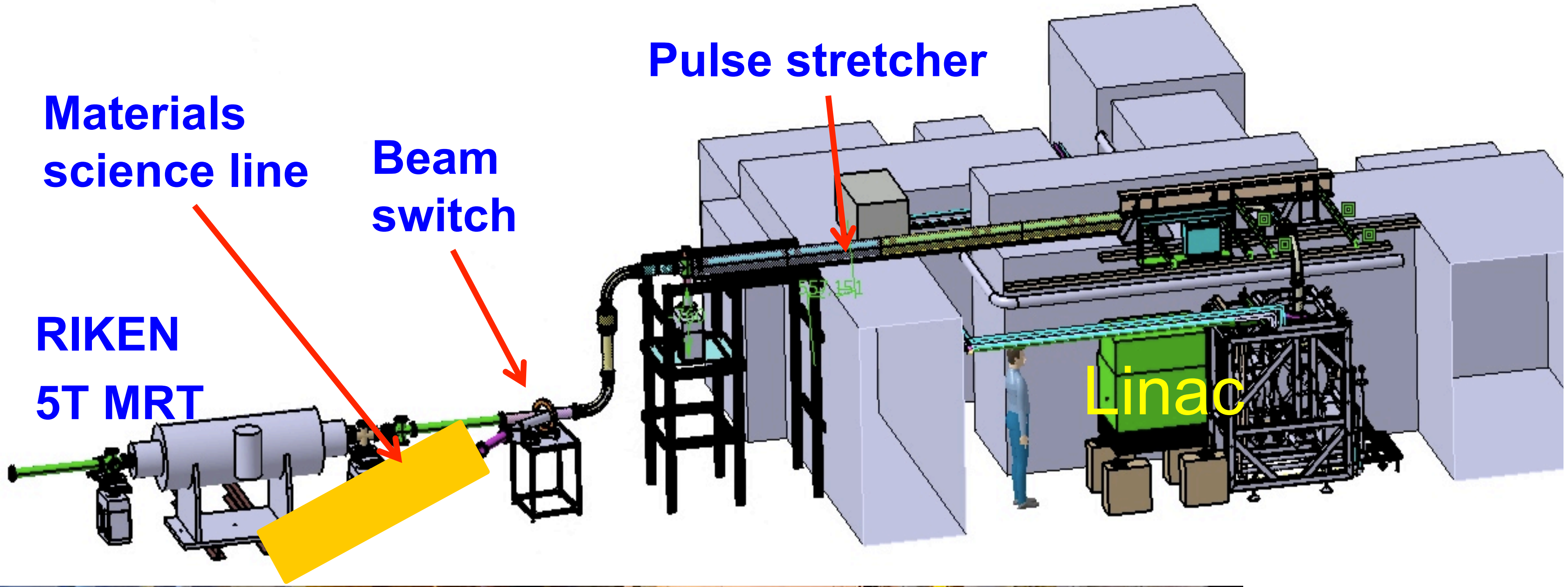


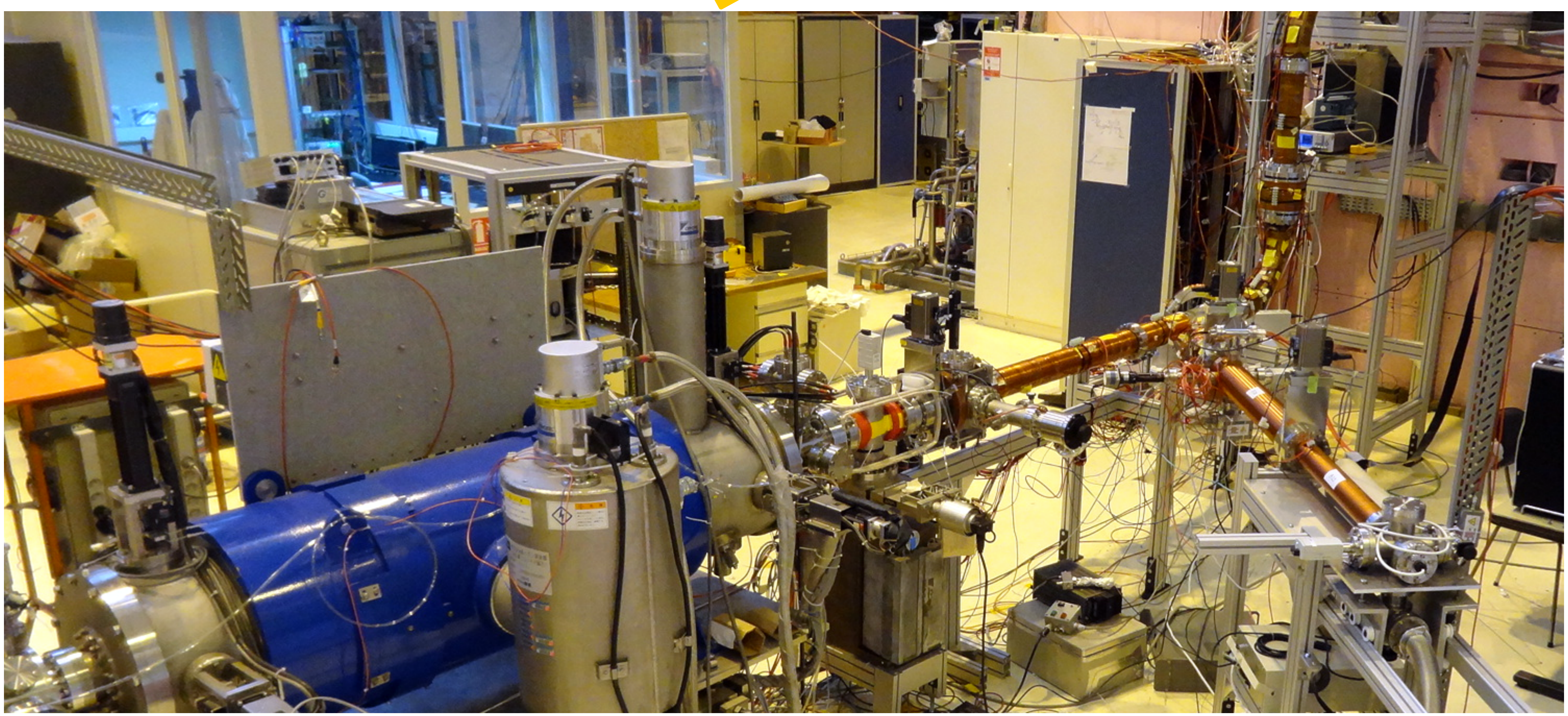
Example Linac (Saclay)



Present slow e^+ rate	$3.2\ 10^6\ s^{-1}$
Extrap. to 10 MeV linac	$4.3\ 10^7\ s^{-1}$
target value	$2.8\ 10^8\ s^{-1}$

Example Linac (Saclay)





Example Linac (GBAR)

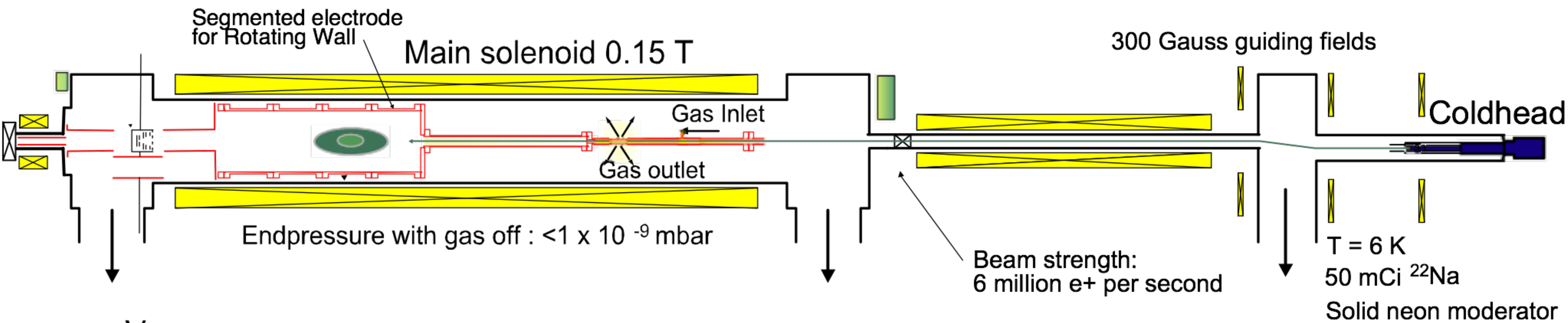
Cavity

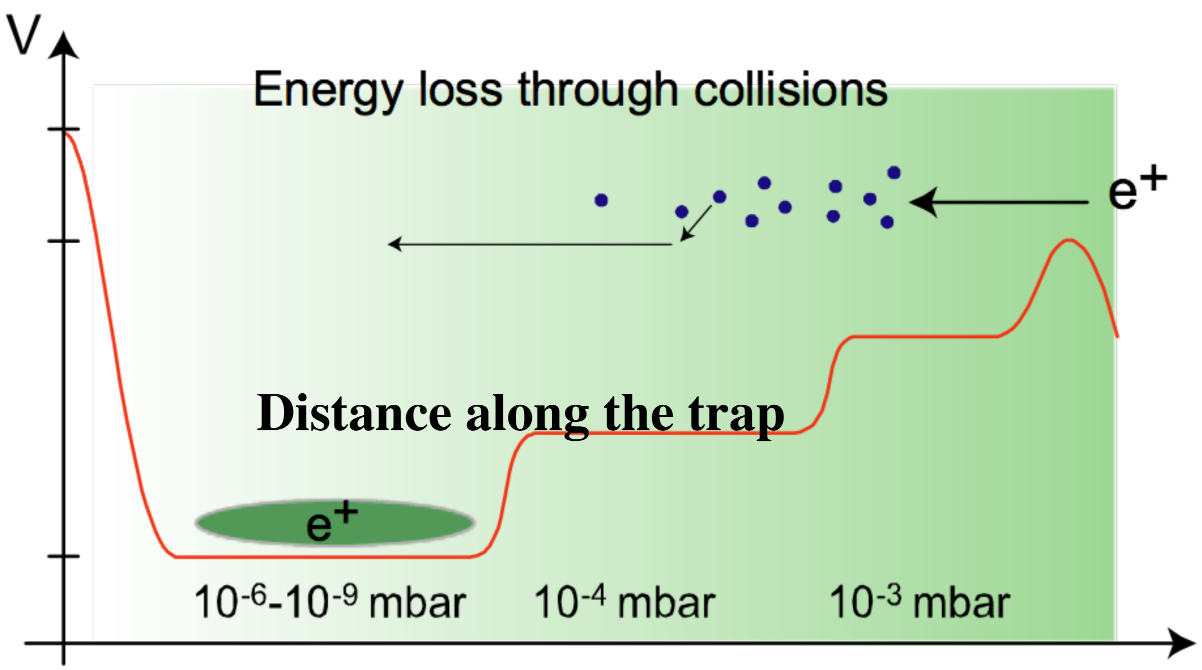
Target + moderator

GBAR bunker

Accumulation: Buffer gas accumulator

Used by ATHENA, ALPHA, AEgIS, ASACUSA and ATRAP





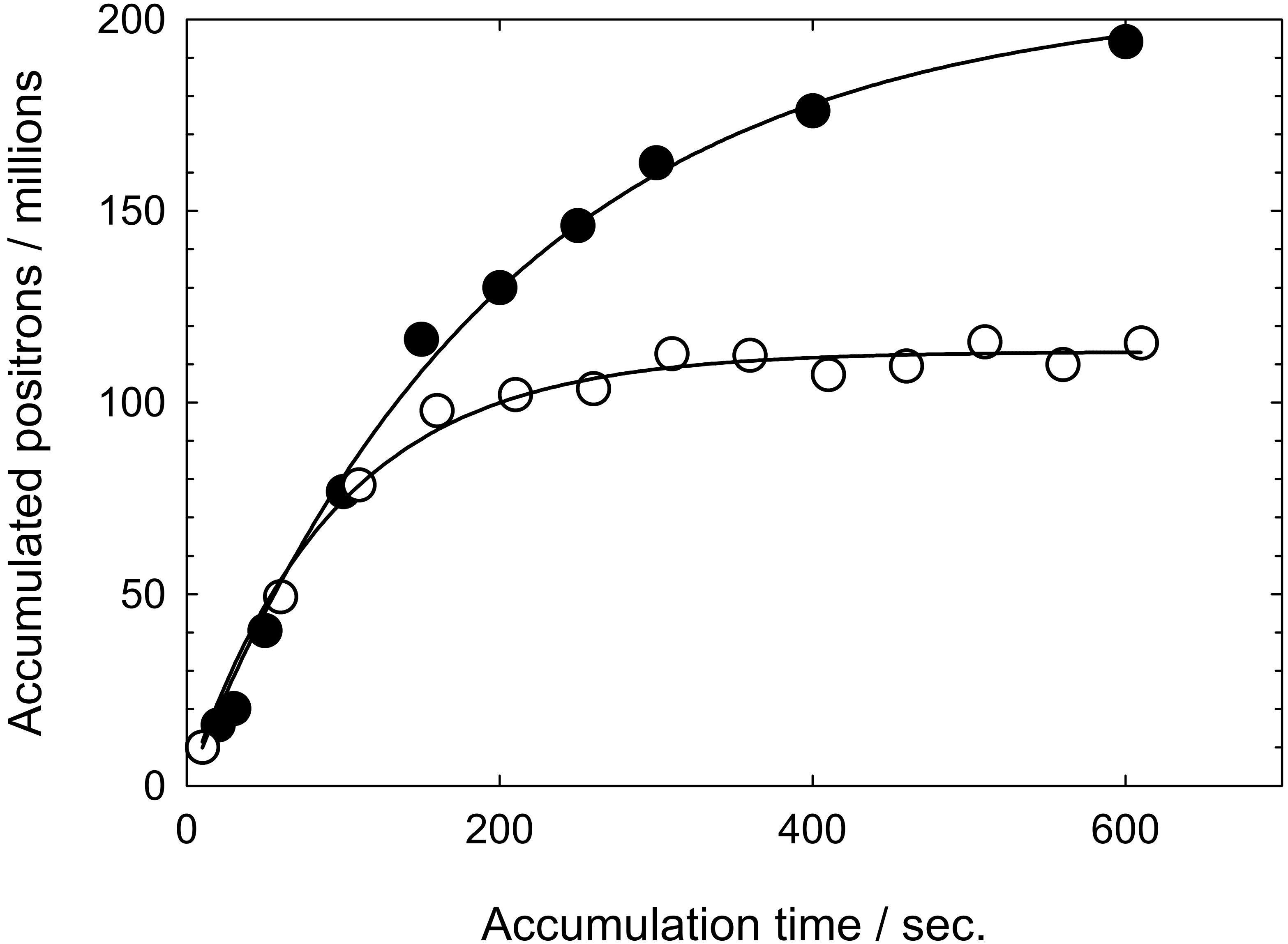
Based upon the industry standard …

{Solid-Ne moderator -plus - UCSD Penning Malmberg buffer gas trap: Surko and co-workers}

$$e^+(E_i) + N_2 \rightarrow e^+(E_f) + N_2^*$$

Accumulation: Buffer gas accumulator

$$N(t) = N(\infty)(1 - e^{-t/\tau}) \qquad N(\infty) = R\tau$$



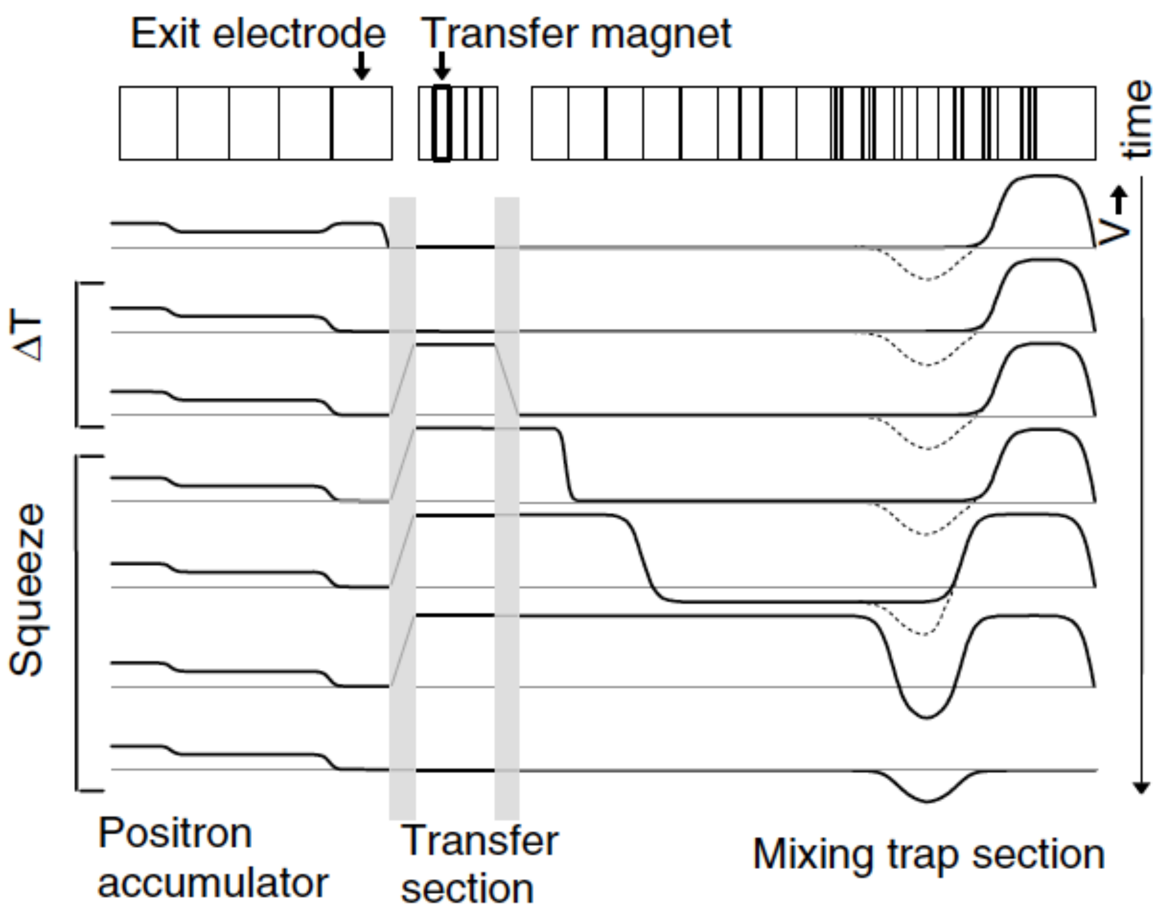
Open circles:
no rotating electric field

Closed circles:
rotating field applied

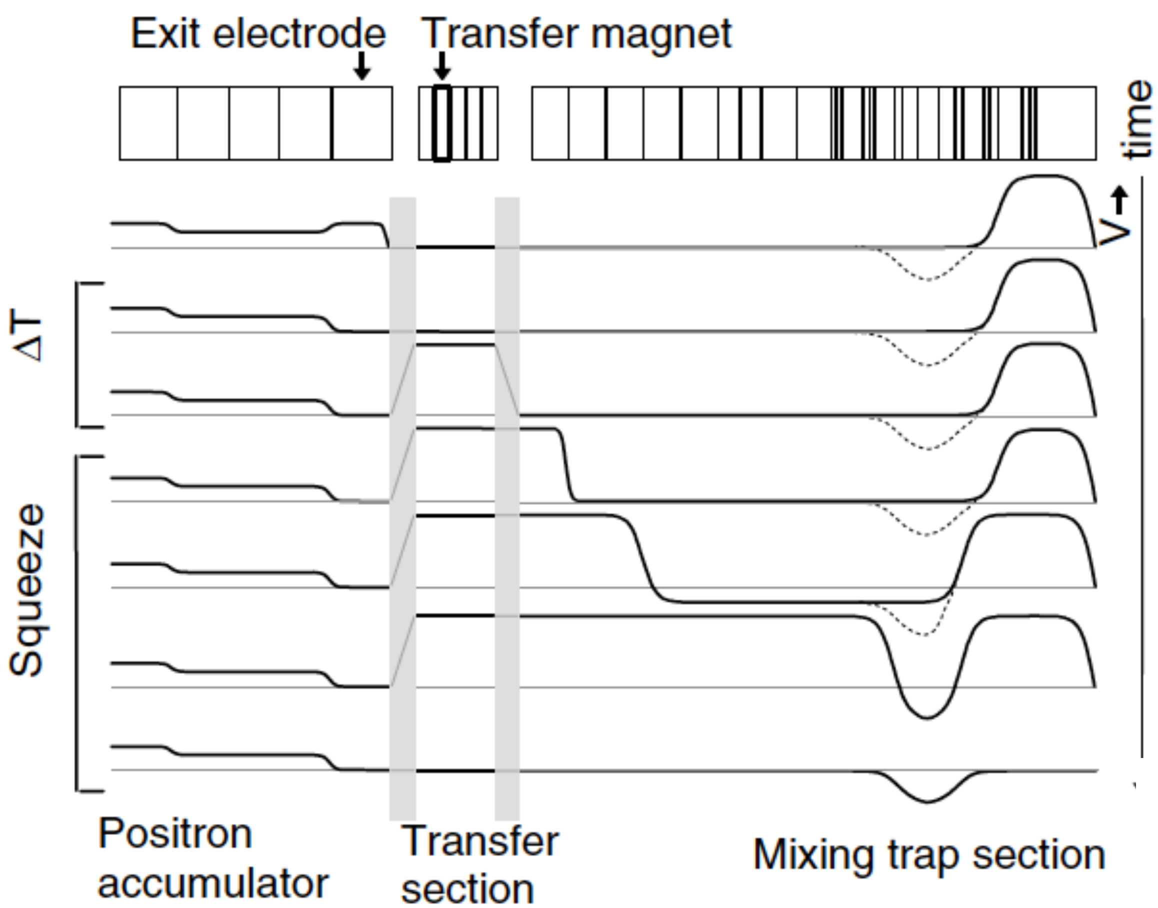
Plasma formed after about 10^{-15} s

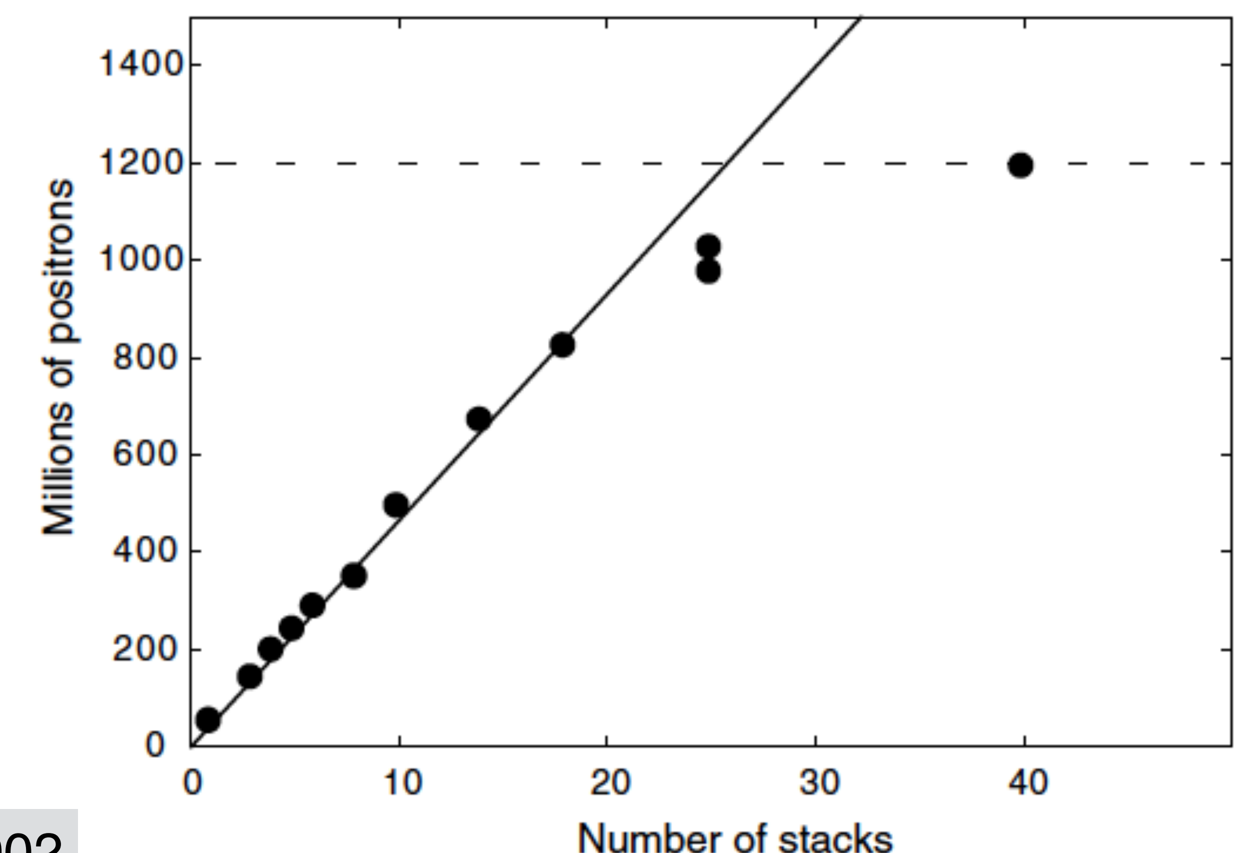
Accumulation: Stacking

Accumulation: Stacking



Accumulation: Stacking



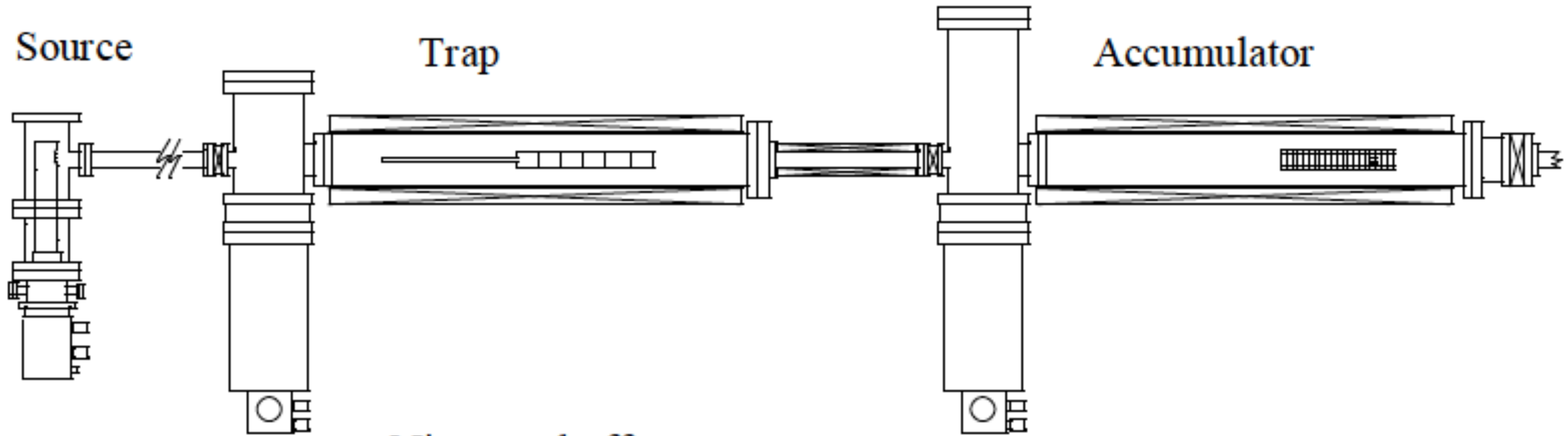


L. V. Jørgensen et al *Phys. Rev. Lett.* **95** (2005) 025002

Commercial available

Experimental methods: positron plasma production

2-stage Surko trap + accumulator



^{22}Na source

Neon moderator

Efficiency ~ 1%

> 10^6 e$^+$/sec

Nitrogen buffer gas

e$^+$ lifetime ~ 2 seconds

Single particle RW compression

efficiency ~ 10%,

2 Hz rep rate

> 150,000 e$^+$/pulse

SF_6 cooling gas (~ 1 x 10^{-7} Torr)

e$^+$ lifetime > 500 seconds

efficiency ~ 80%

Maximum 10^8 e$^+$

Typical 2 x 10^7 e$^+$

Pulse out ~ 10-50 ns FWHM

RSI **77**, 073106 (2006)

This slide - courtesy of DB Cassidy, UCL

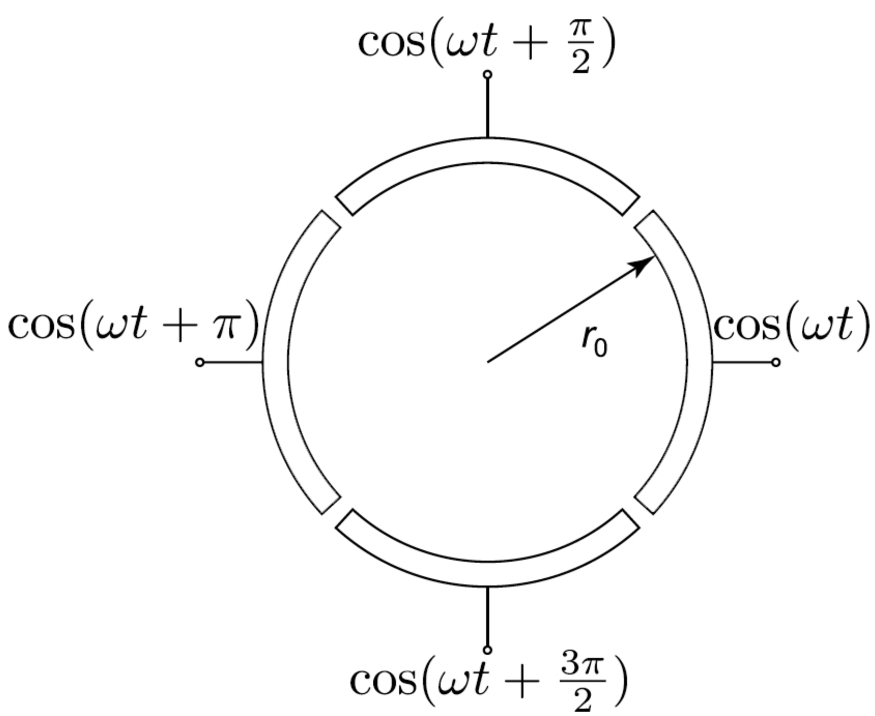
Compression - Rotating Wall

Compression - Rotating Wall

$$\phi = \frac{m}{q}\frac{\omega_z^2}{2}\left(z^2 - \frac{r^2}{2}\right)$$

Compression - Rotating Wall

$$\phi = \frac{m}{q}\frac{\omega_z^2}{2}\left(z^2 - \frac{r^2}{2}\right) \quad + \quad \frac{m}{q} azr\cos(\theta + \omega_r t)$$



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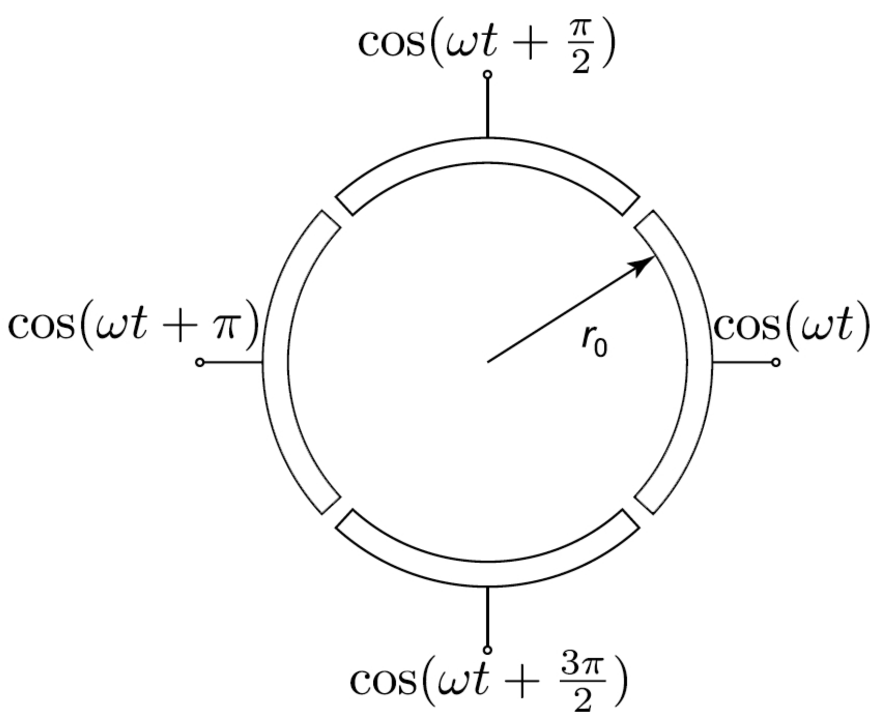
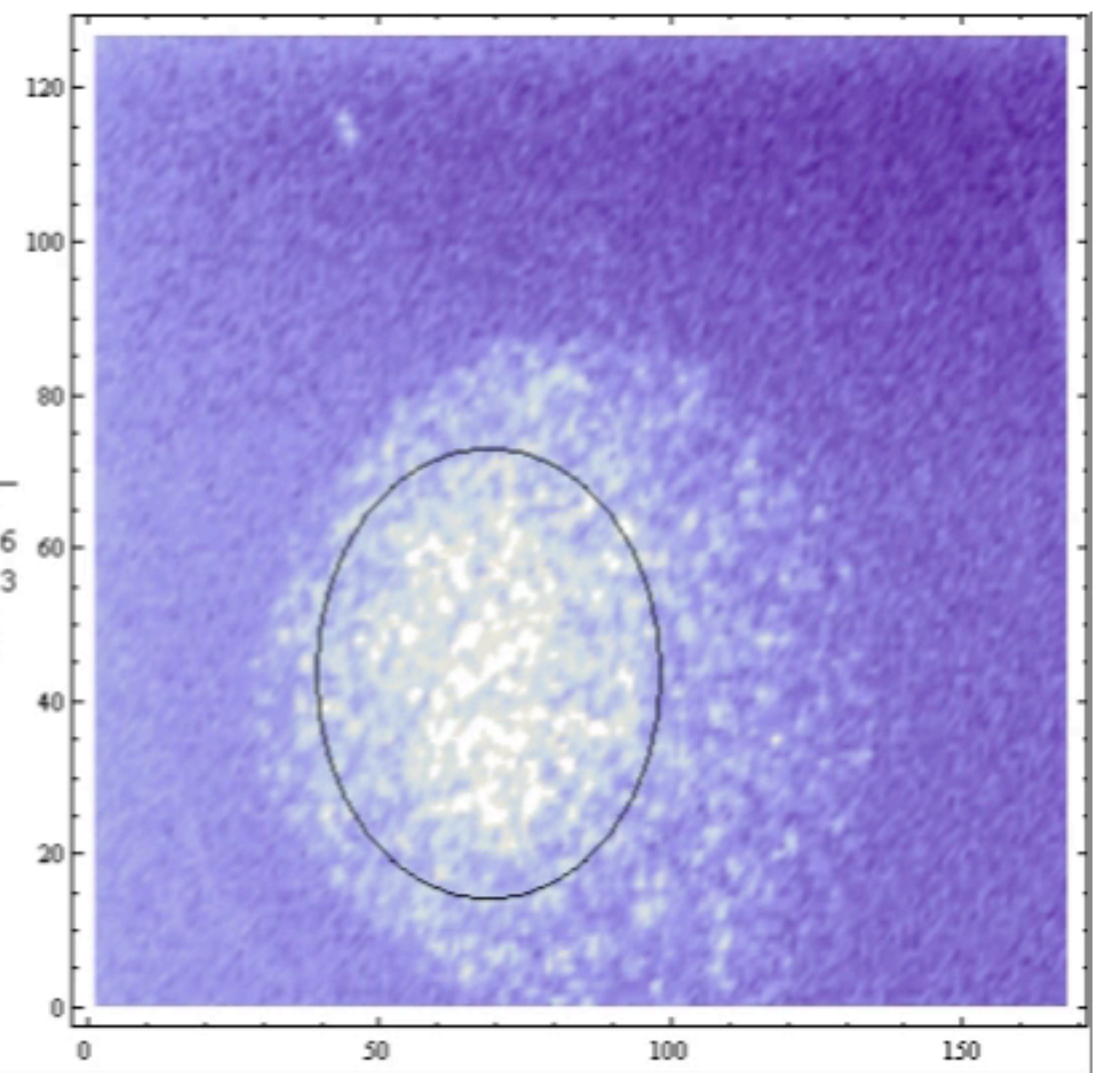


3.000000E-6

	Est.	StdErr
A	531803.	4410.36
x0	68.6667	0.128006
y0	43.3748	0.131493
σ	25.0594	0.12118
B	68.3328	0.23116



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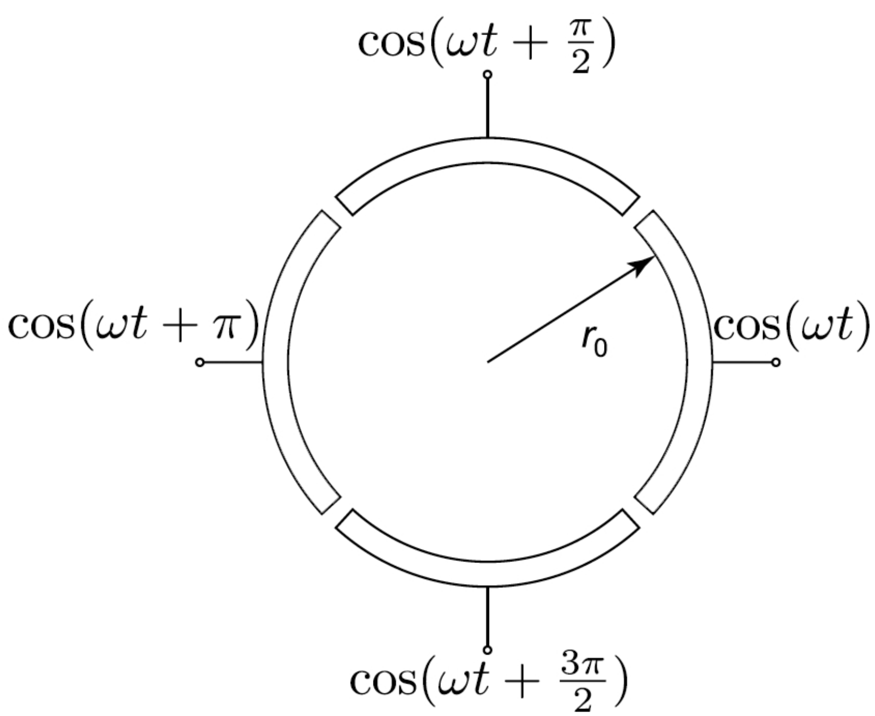

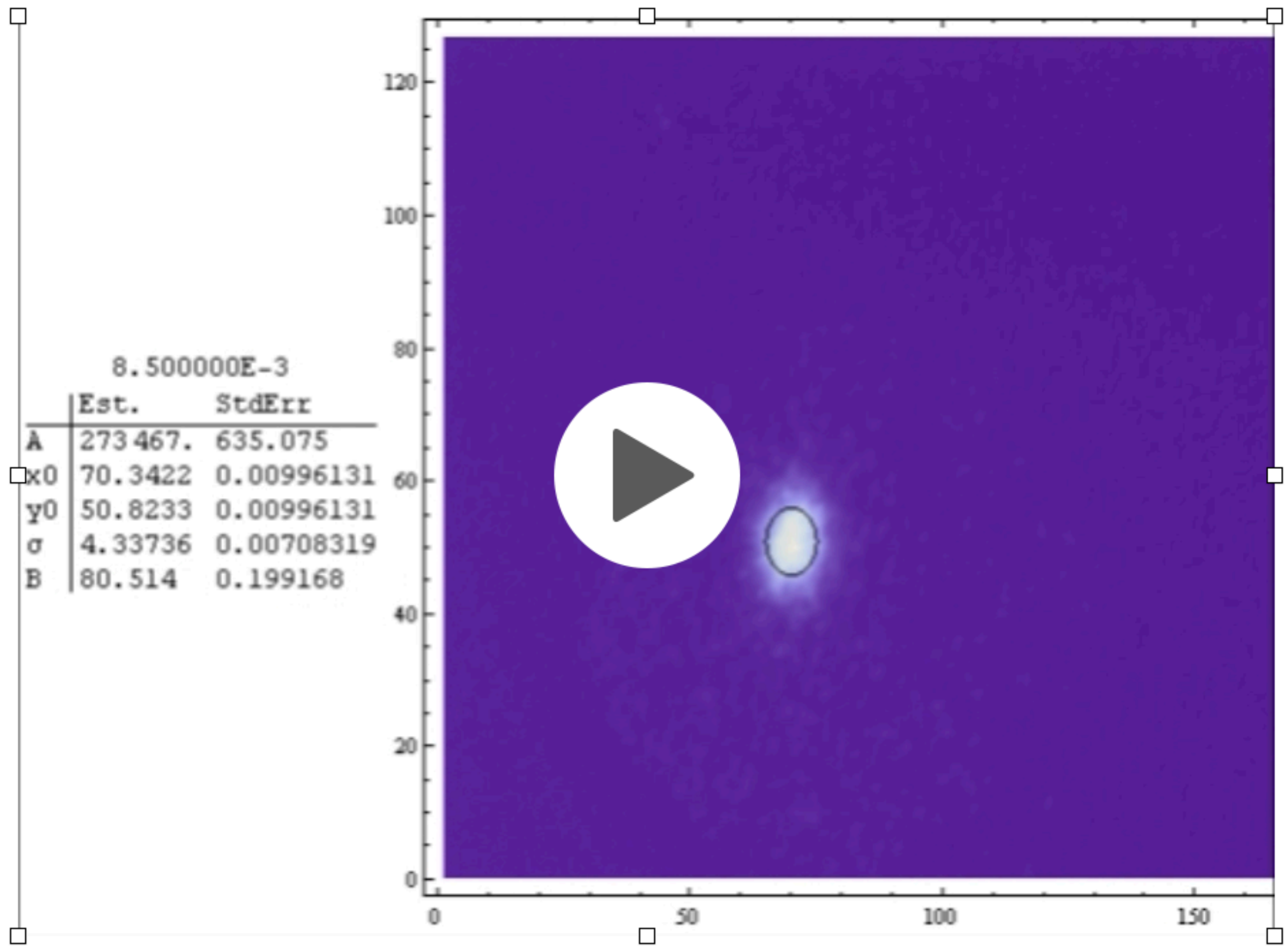

Compression - Rotating Wall

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Debye screening length $$\lambda_D = \left(\frac{kT_e \epsilon_0}{n_q e^2} \right)^{1/2}$$

Compression - Rotating Wall

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- Single particle $\lambda_D >> L$
- Plasma $\lambda_D << L$
- Rarefied Plasma $\lambda_D \sim L$

Ideal Penning trap motions

Charged particle in $\mathbf{B} = B\hat{\mathbf{z}} \rightarrow$ cyclotron orbit around $\hat{\mathbf{z}}$, $\Omega_c = qB/m$

Adding ideal Penning Trap potential

$$\phi = \frac{m}{q}\frac{\omega_z^2}{2}\left(z^2 - \frac{r^2}{2}\right)$$

Three frequencies:

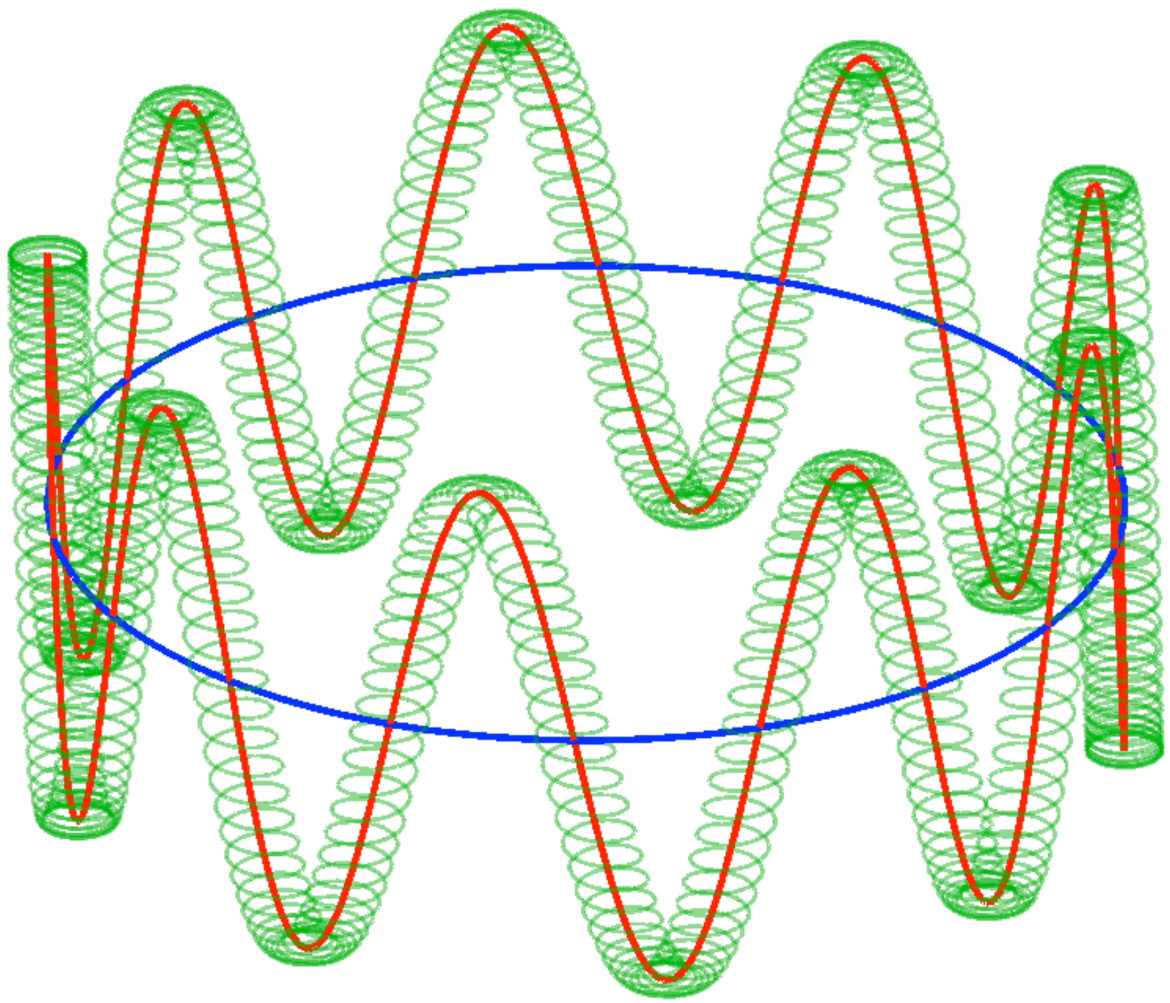
- Axial bounce frequency ω_z

And due to $\mathbf{E} \times \mathbf{B}$

- Modified cyclotron orbit $\Omega_c \rightarrow \omega_+ = \frac{1}{2}\left(\Omega_c + \sqrt{\Omega_c^2 - 2\omega_z^2}\right)$

- Magnetron motion $\omega_- = \frac{1}{2}\left(\Omega_c - \sqrt{\Omega_c^2 - 2\omega_z^2}\right)$

Ideal Penning trap motions

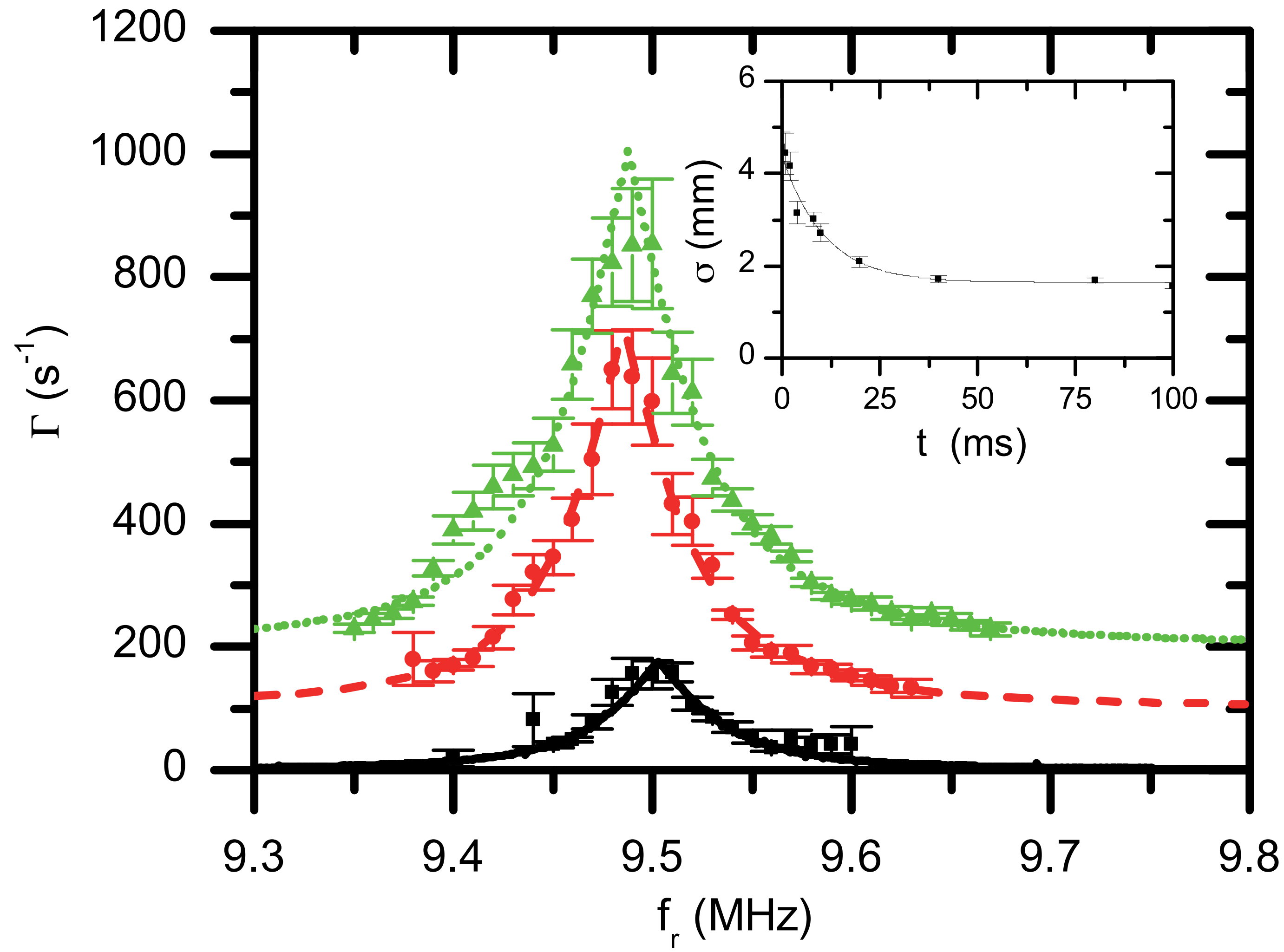


$$\omega_+ \approx 6.6\ \mathrm{Grad\,s^{-1}} \gg \omega_z \approx 60\ \mathrm{Mrad\ s^{-1}} \gg \omega_- \approx 270\ \mathrm{krad\,s^{-1}}$$

Compression Rate

$$\Gamma = \frac{\kappa}{4}\left(1 - \sqrt{\frac{(\omega_r - \omega_0)^2}{\delta^2 + (\omega_r - \omega_0)^2}}\right)$$

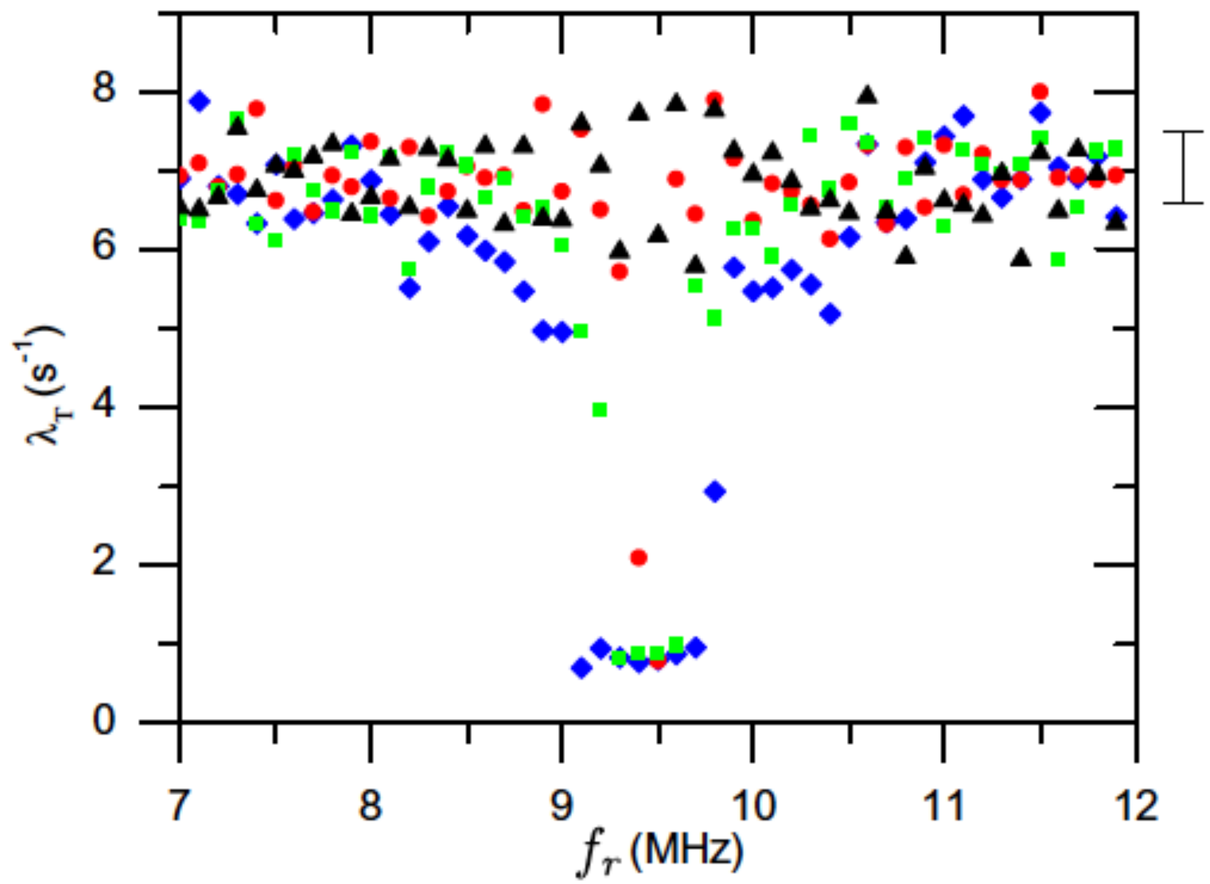
$$\delta = \frac{a}{\sqrt{(\omega_+ - \omega_-)\omega_z}}$$



C.A. Isaac, C.J. Baker, T. Mortensen, D. P. van der Werf and M. Charlton
Phys. Rev. Lett. **107** (2011) 033201

D.P. van der Werf, C. A. Isaac, C. J. Baker, T. Mortensen, S. J. Kerrigan and M. Charlton
New J. Phys. **14** (2012) 075022

Importance of rotating wall for accumulation efficiency

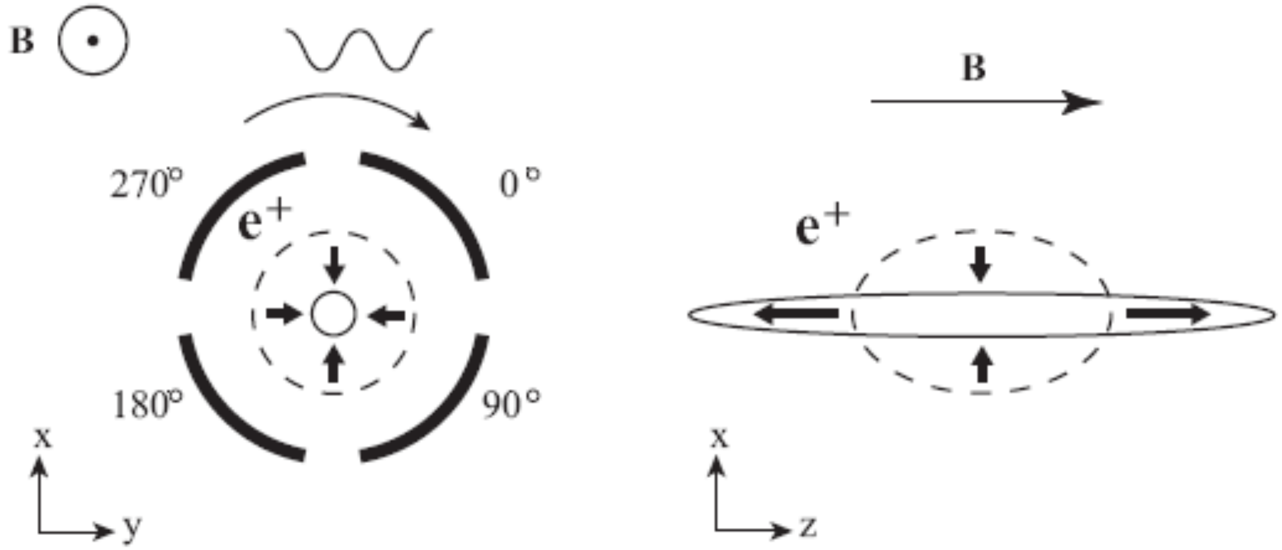


The minimum in λ_T is consistent with the expected annihilation rate.
Thus, the rotating wall eliminates cross field transport

Figure 8. The measured loss rate from the trap with the rotating wall applied during the accumulation cycle as f_r is varied at fixed SF_6 pressure and for various amplitudes: 0 V (▲), 100 mV (●), 500 mV (■) and 1.0 V (◆). The error bar to the right of the figure represents the typical uncertainty around $\lambda_T = 8\,s^{-1}$, whereas the uncertainty for low values of λ_T is roughly the size of the points.

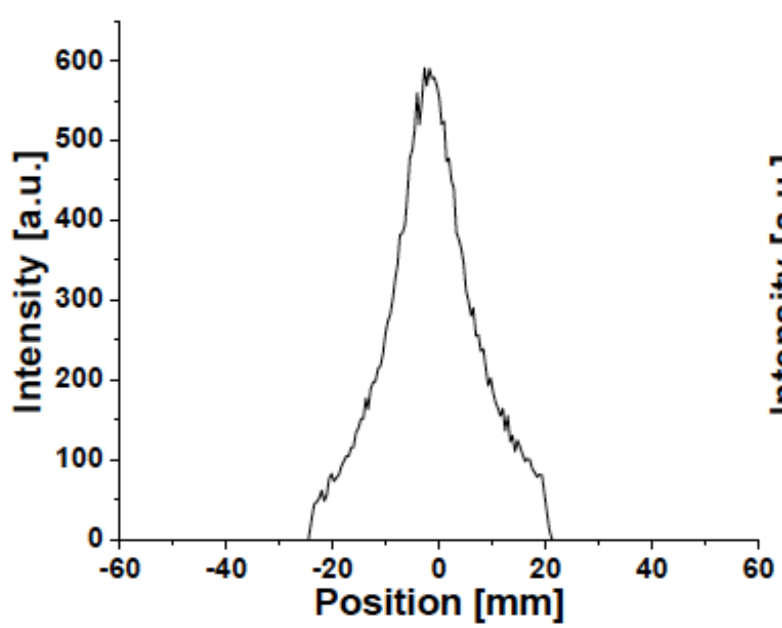
D. P. van der Werf, C. A. Isaac, C. J. Baker, T. Mortensen, S. J. Kerrigan and M. Charlton
New Journal of Physics **14** (2012) 075022

Plasma Regime (ALPHA)

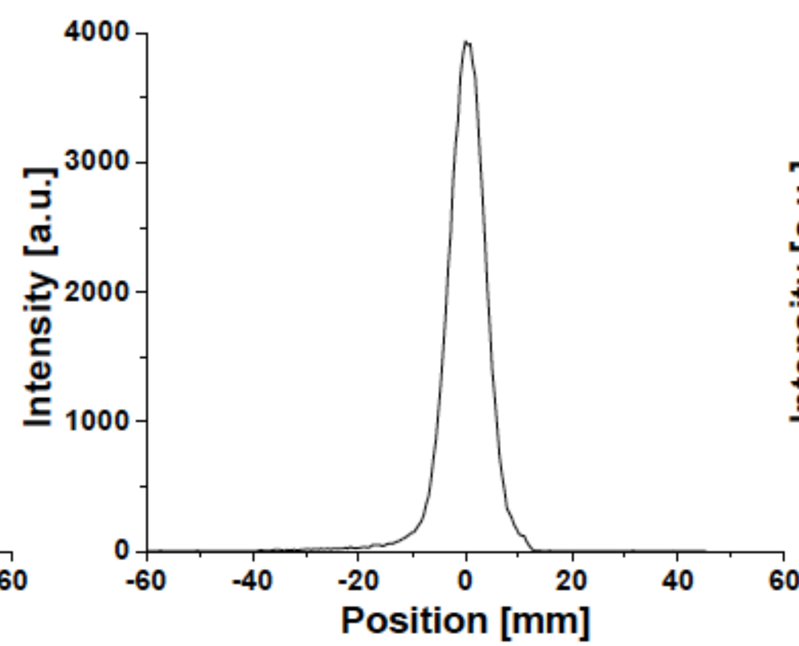


N_2 promotes capture, but an extra cooling gas is needed to maximize compression

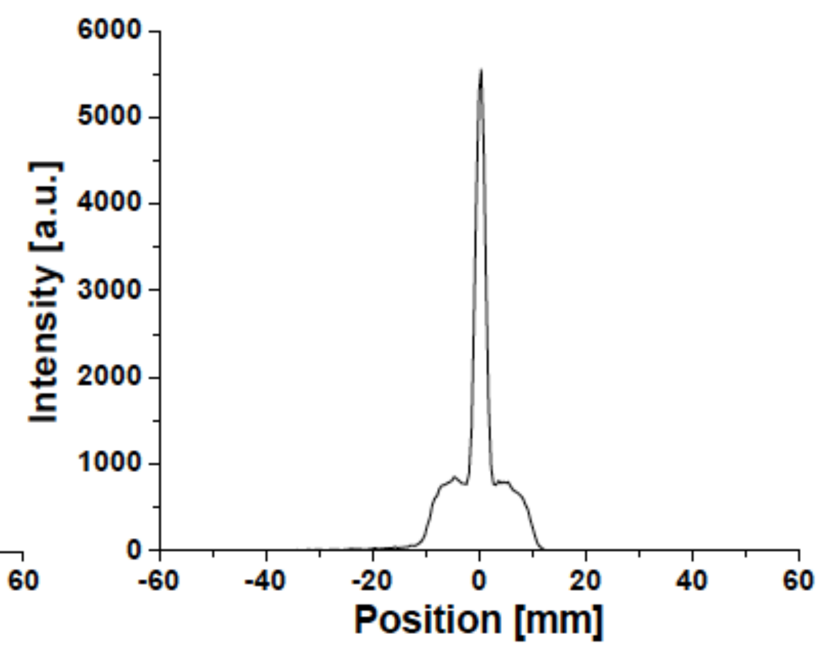
No r.w.



r.w. with N_2

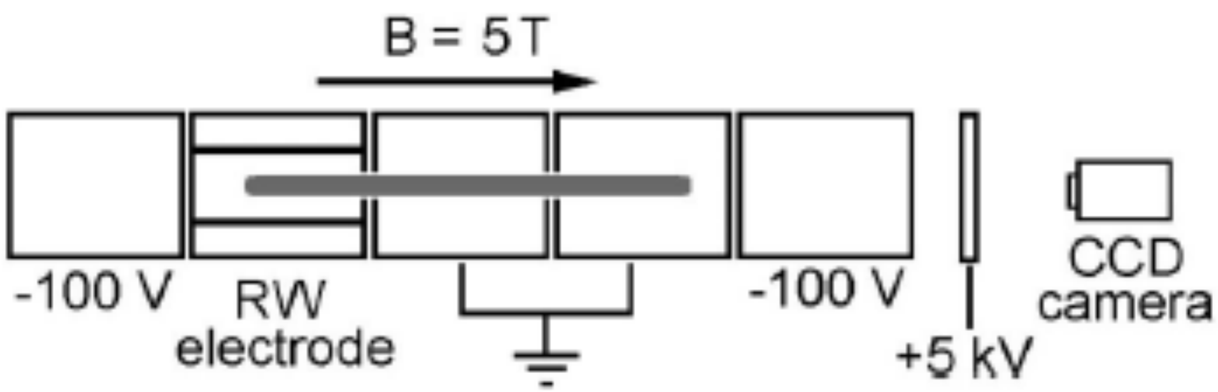


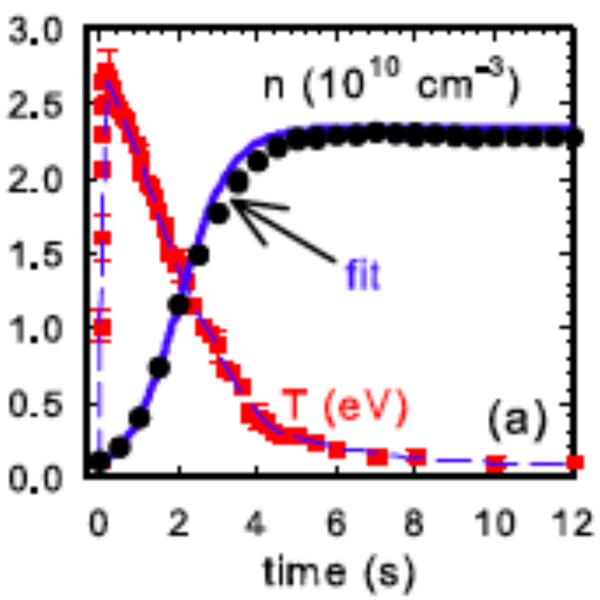
r.w with added cooling gas

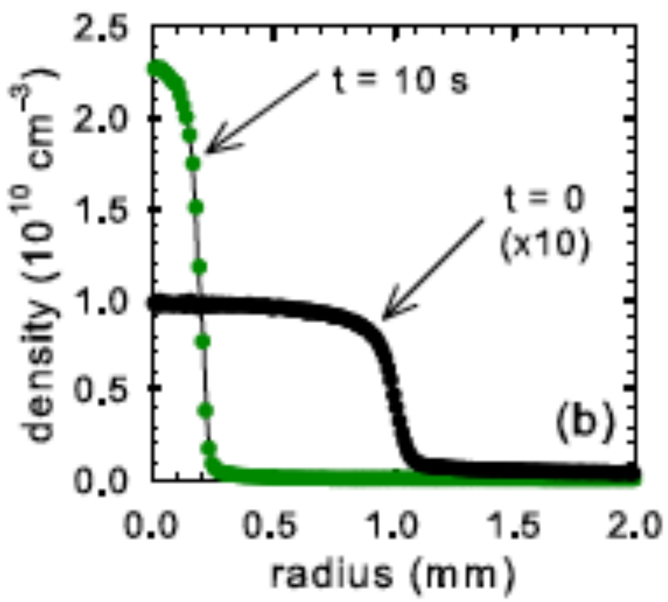


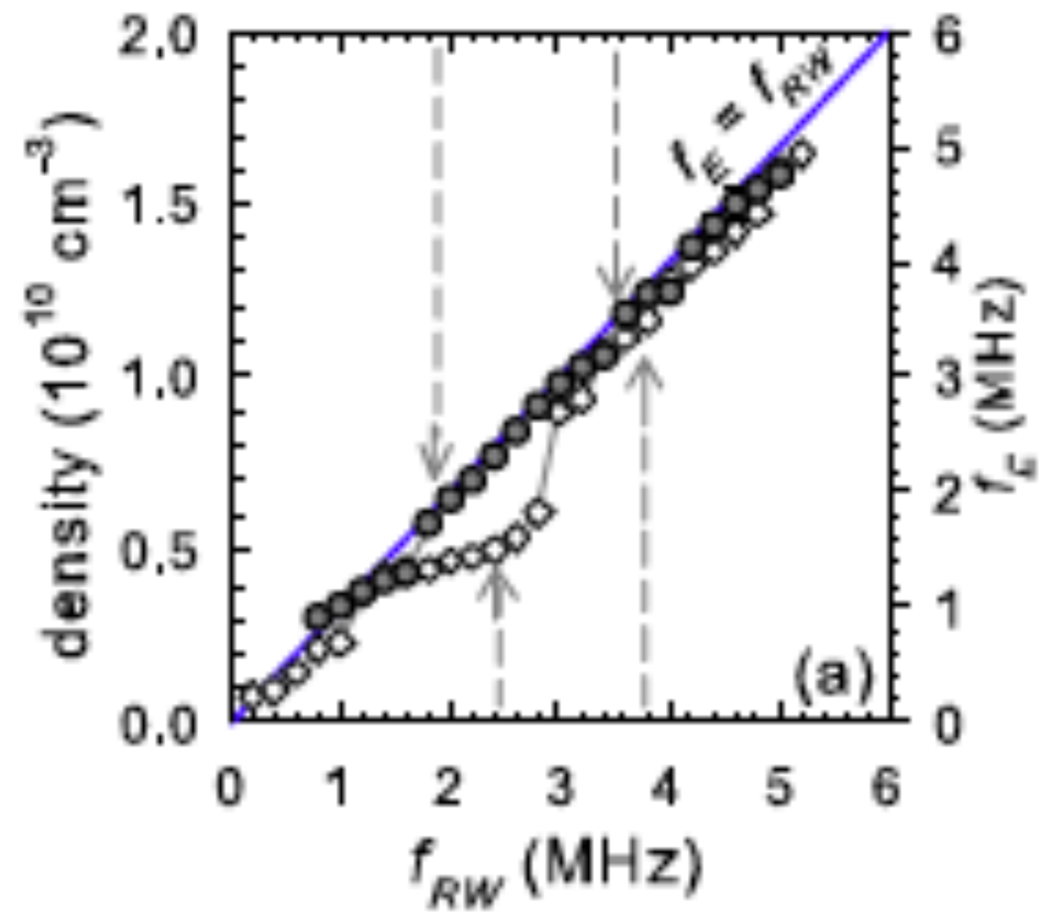
Positron plasma radial Distributions

Plasma Regime (Surko)







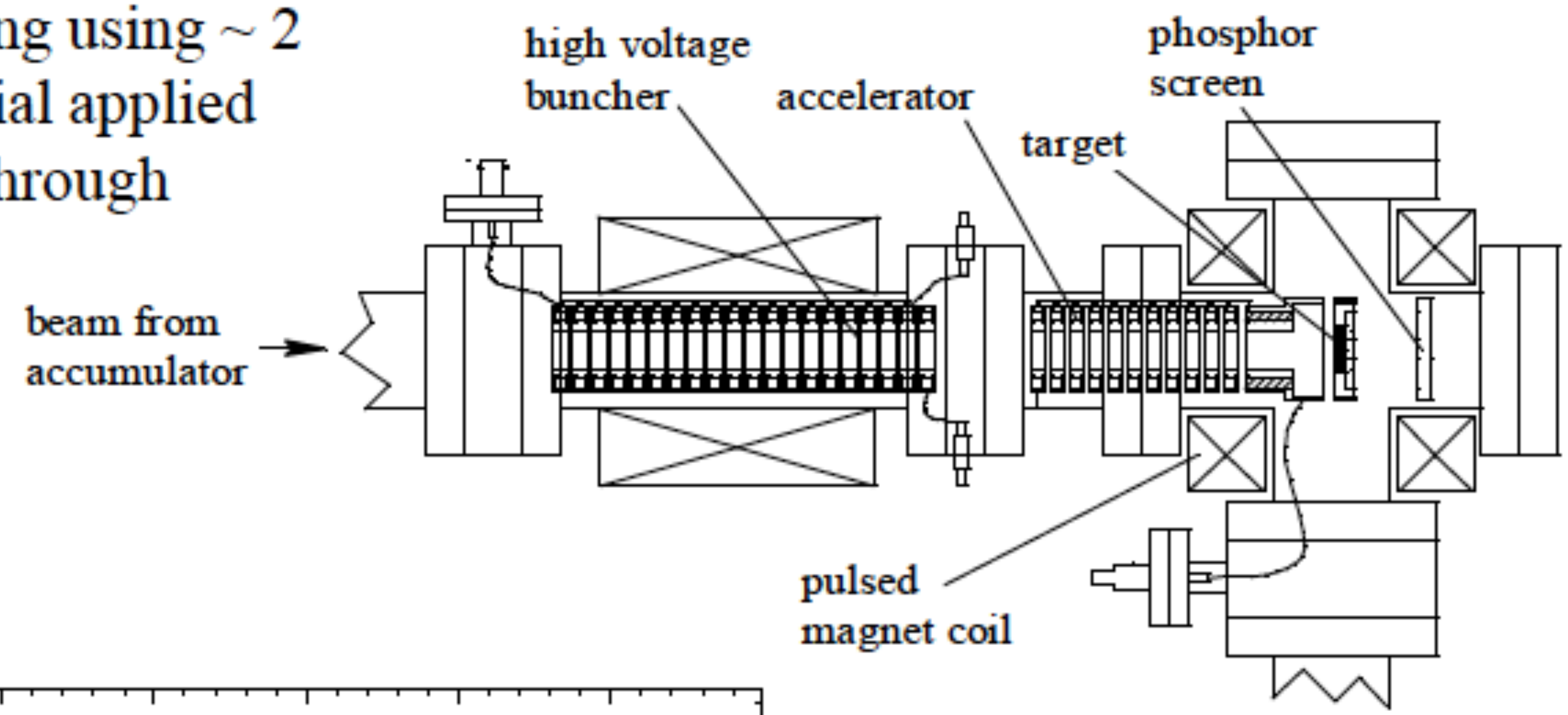


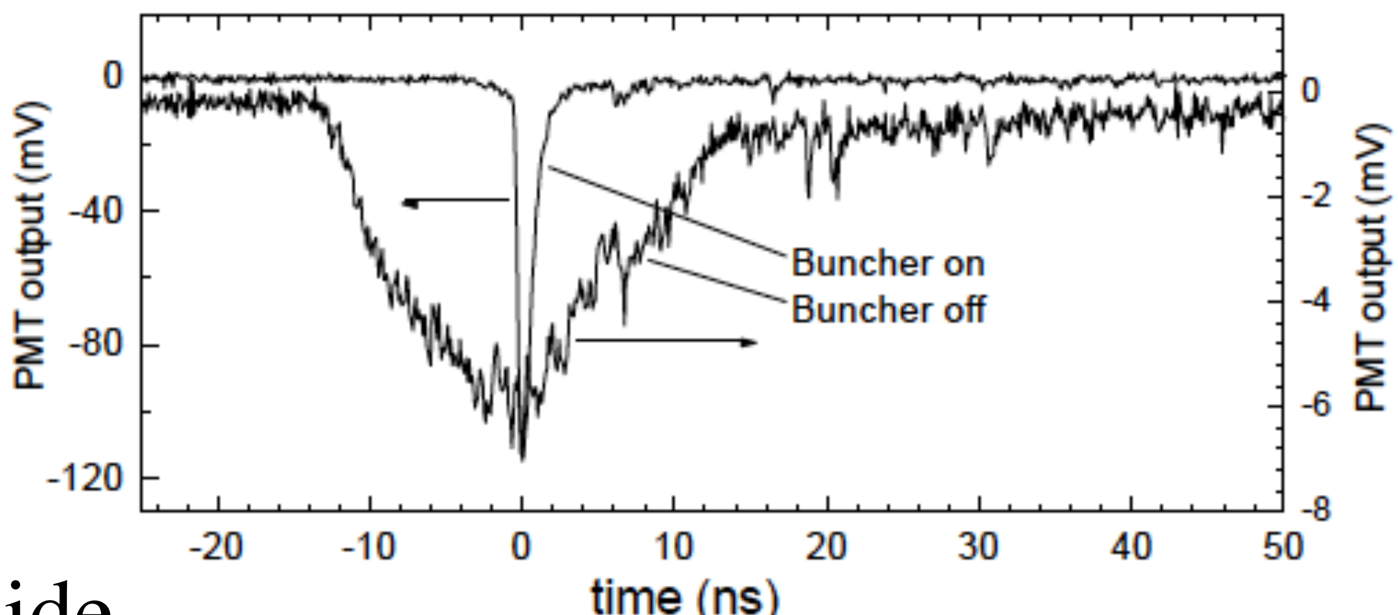
f_{RW} is rotating wall frequency; $f_E = \omega_D/2\pi$

J. R. Danielson, C. M. Surko and T. M. O'Neil
Physical Review Letters 99 (2007) 135005

Time compression

Time compression: Important to sync Ps with pulsed lasers: Electrostatic bunching using ~ 2 kV harmonic potential applied while beam passes through





Creation of ~ 1 ns FWHM pulses routine. No dependence on number of positrons apart from requirement of beam to fit in buncher

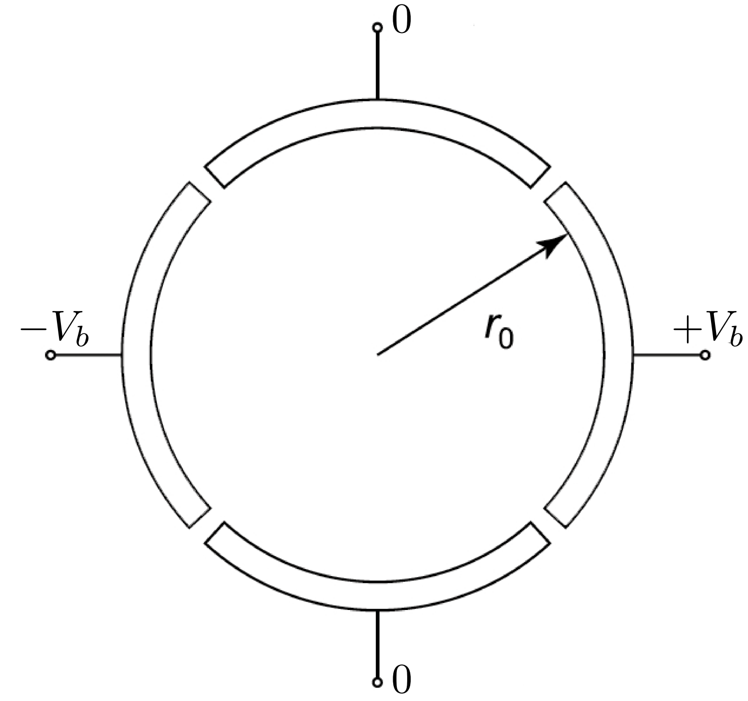
This slide - courtesy of DB Cassidy, UCL

Orbit Manipulation

$$\phi = \frac{m}{q}\frac{\omega_z^2}{2}\left(z^2 - \frac{r^2}{2}\right)$$

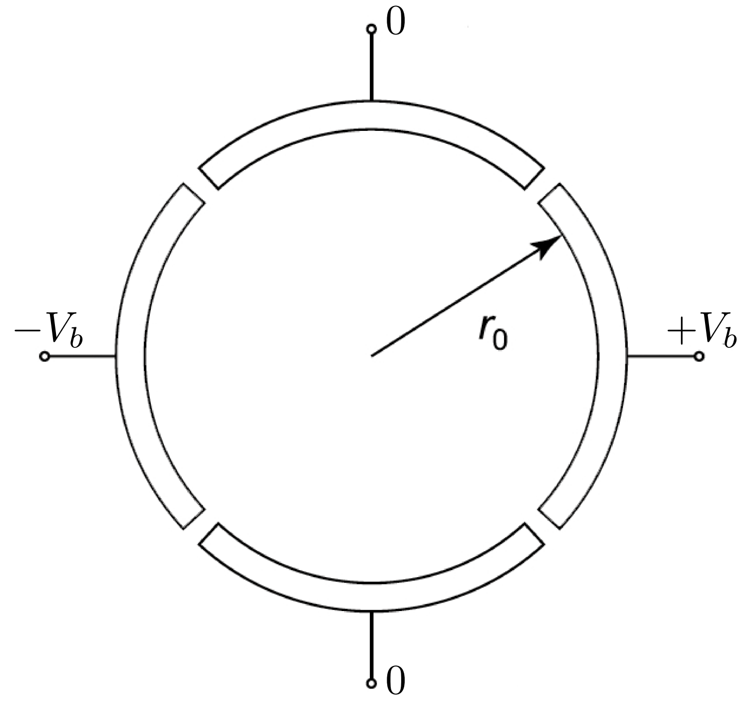
Orbit Manipulation

$$\phi = \frac{m}{q}\frac{\omega_z^2}{2}\left(z^2 - \frac{r^2}{2}\right) \;+\; \frac{m}{q}ax$$



Orbit Manipulation

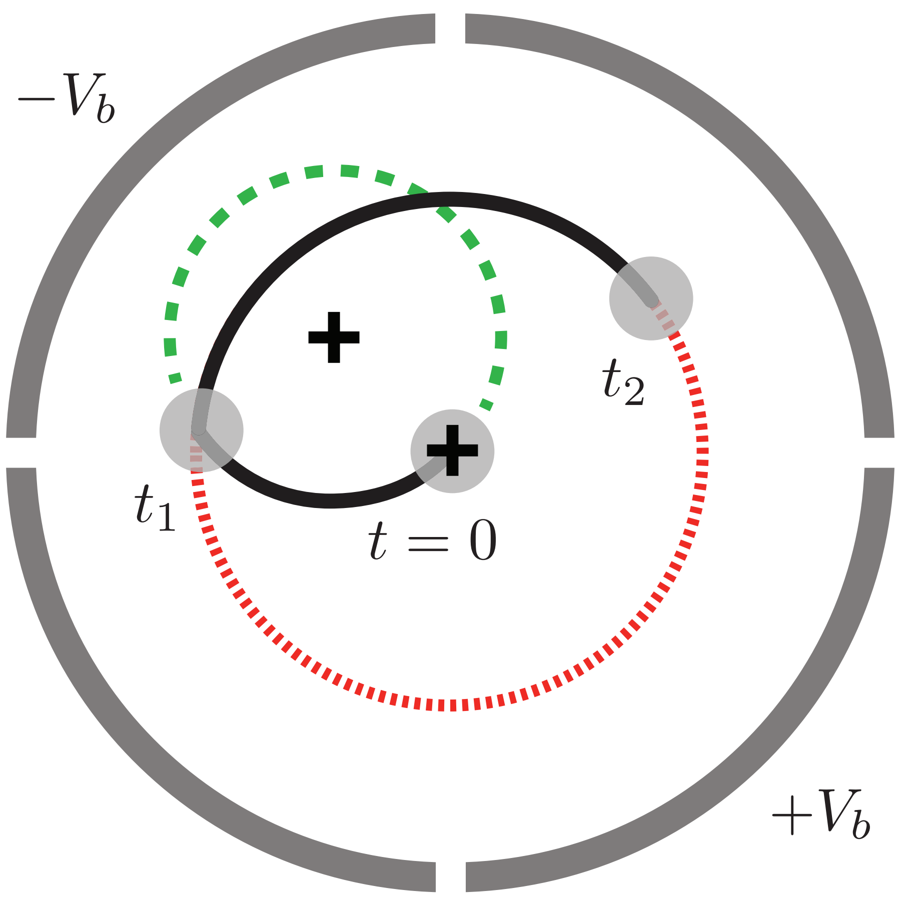
$$\phi = \frac{m}{q}\frac{\omega_z^2}{2}\left(z^2 - \frac{r^2}{2}\right) \quad + \quad \frac{m}{q}ax$$

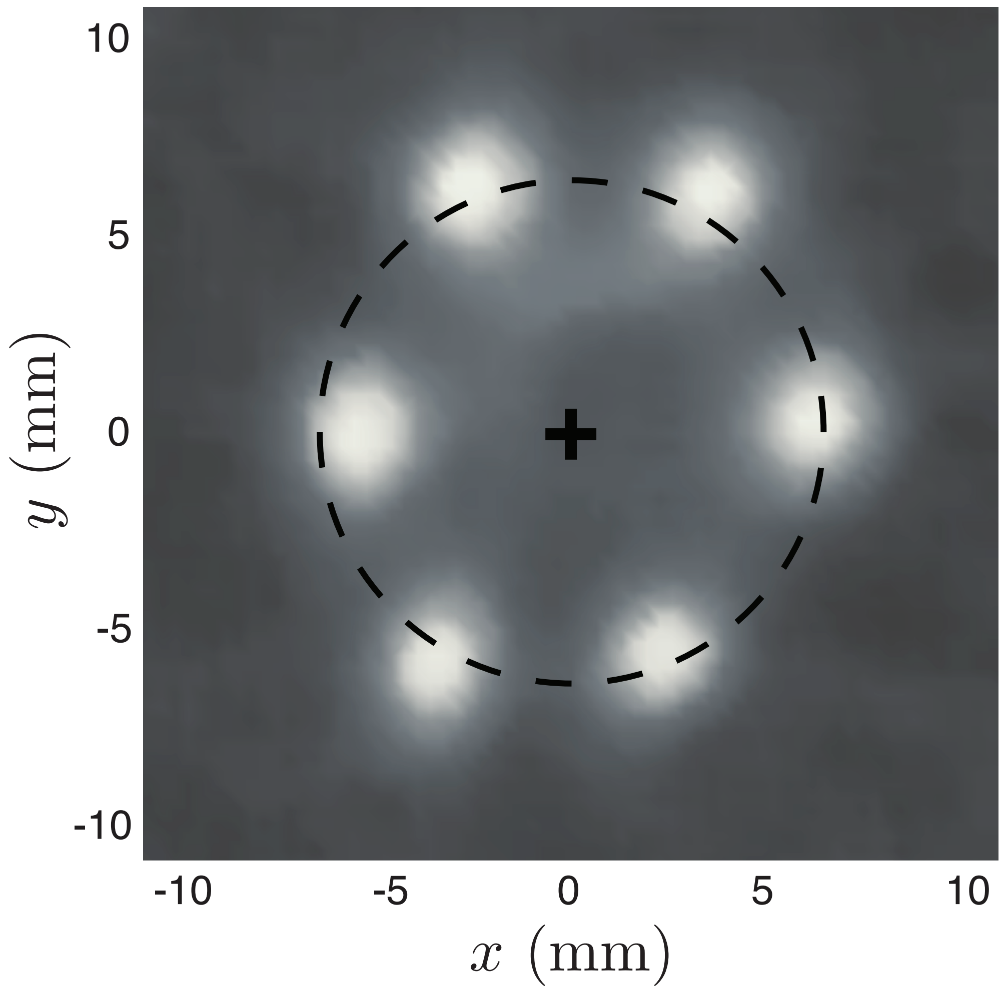


$$\begin{aligned}\phi &= -\frac{m\omega_z^2}{4q}\left(-2z^2 + x^2 + y^2\right) + \frac{m}{q}ax \\ &= -\frac{m\omega_z^2}{4q}\left(-2z^2 + \left(x - \frac{2a}{\omega_z^2}\right)^2 + y^2\right) + \frac{a^2m}{q\omega_z^2}.\end{aligned}$$

Orbit Manipulation

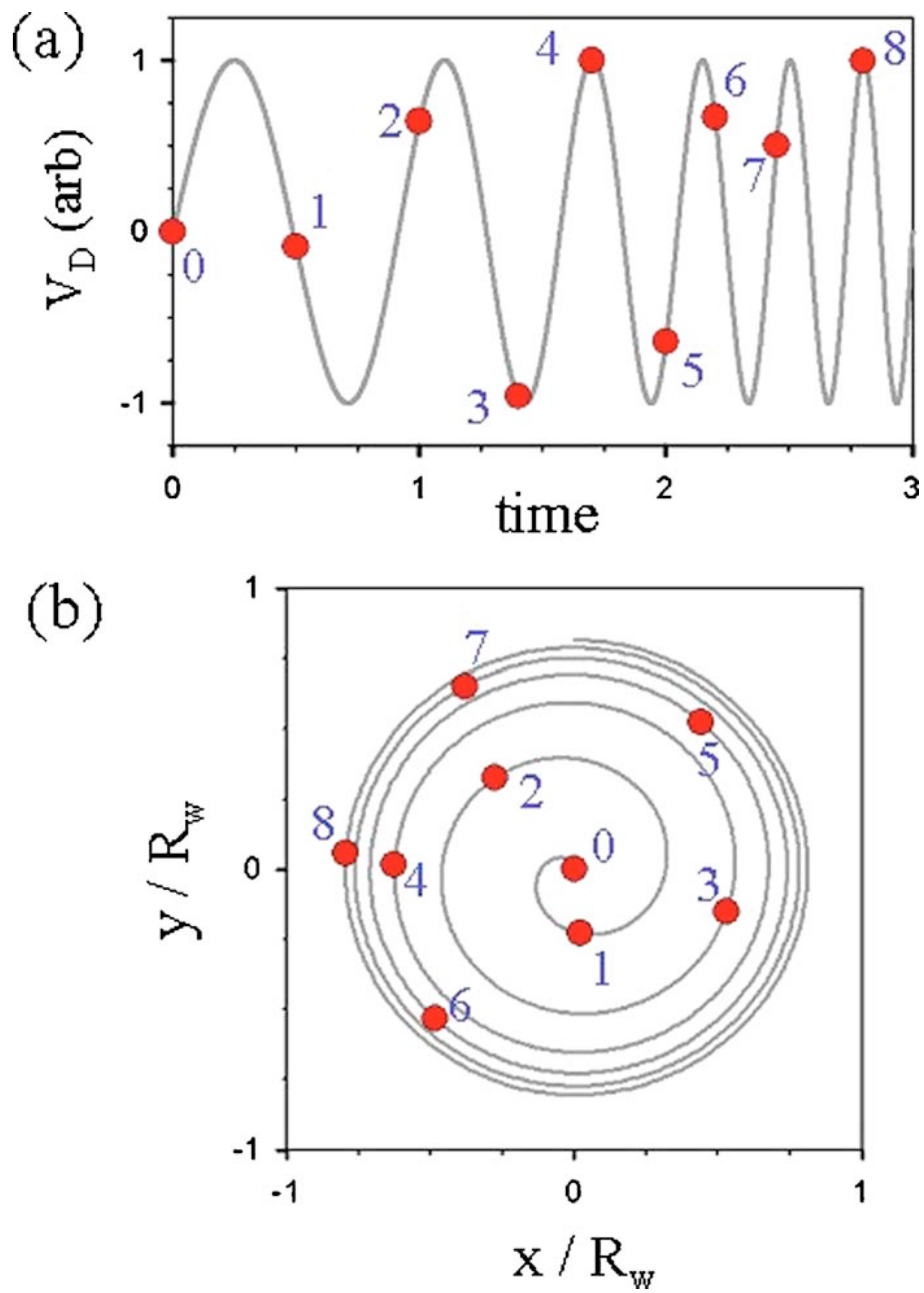
1. Load and compress positrons
2. Bias on for a time t_1
3. Dump at time t_2

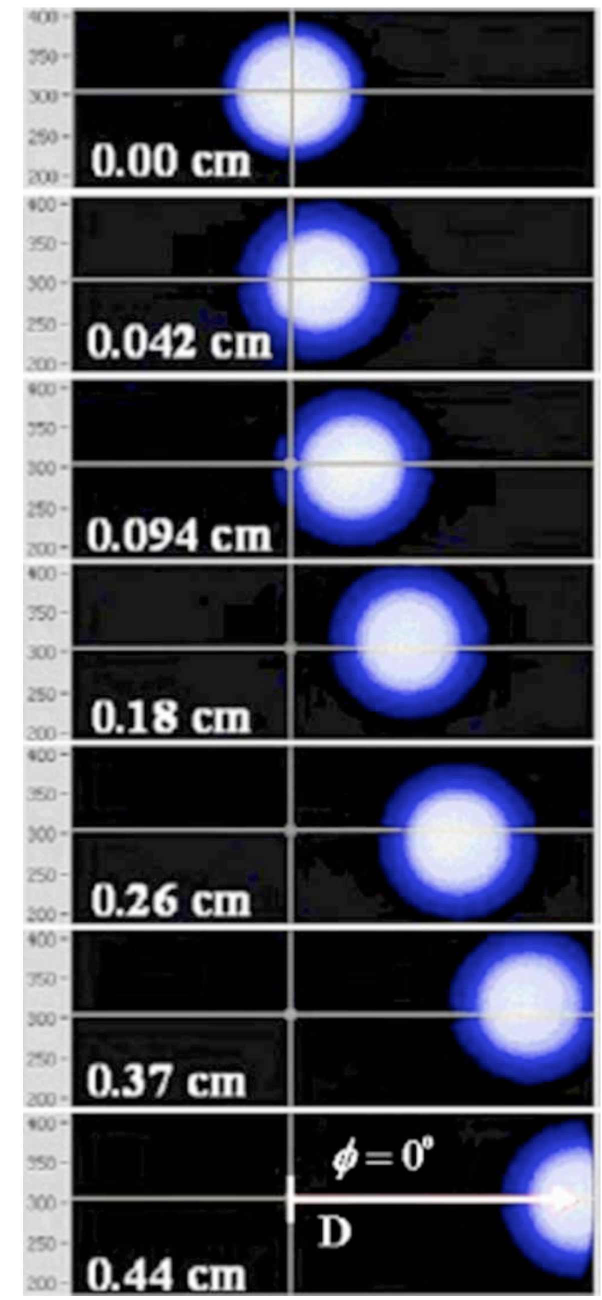




T. Mortensen, A. Deller, C. A. Isaac, D. P. van der Werf, M. Charlton and J. R. Machacek
Physics of Plasmas **20** (2013) 012124

Autoresonant diocotron excitation (plasma)





J. R. Danielson, T. R. Weber, and C. M. Surko
Phys. Plasmas **13** (2006) 123502

Even more positrons: Kelvin Lynn's approach

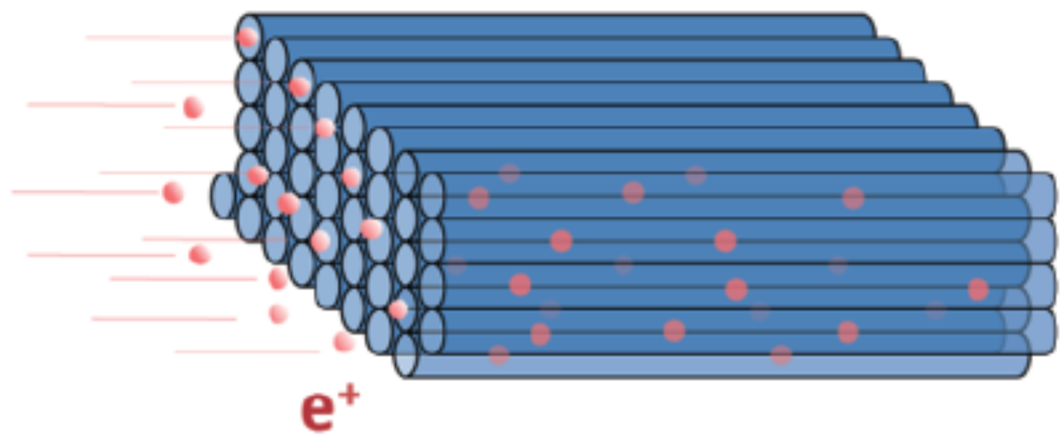
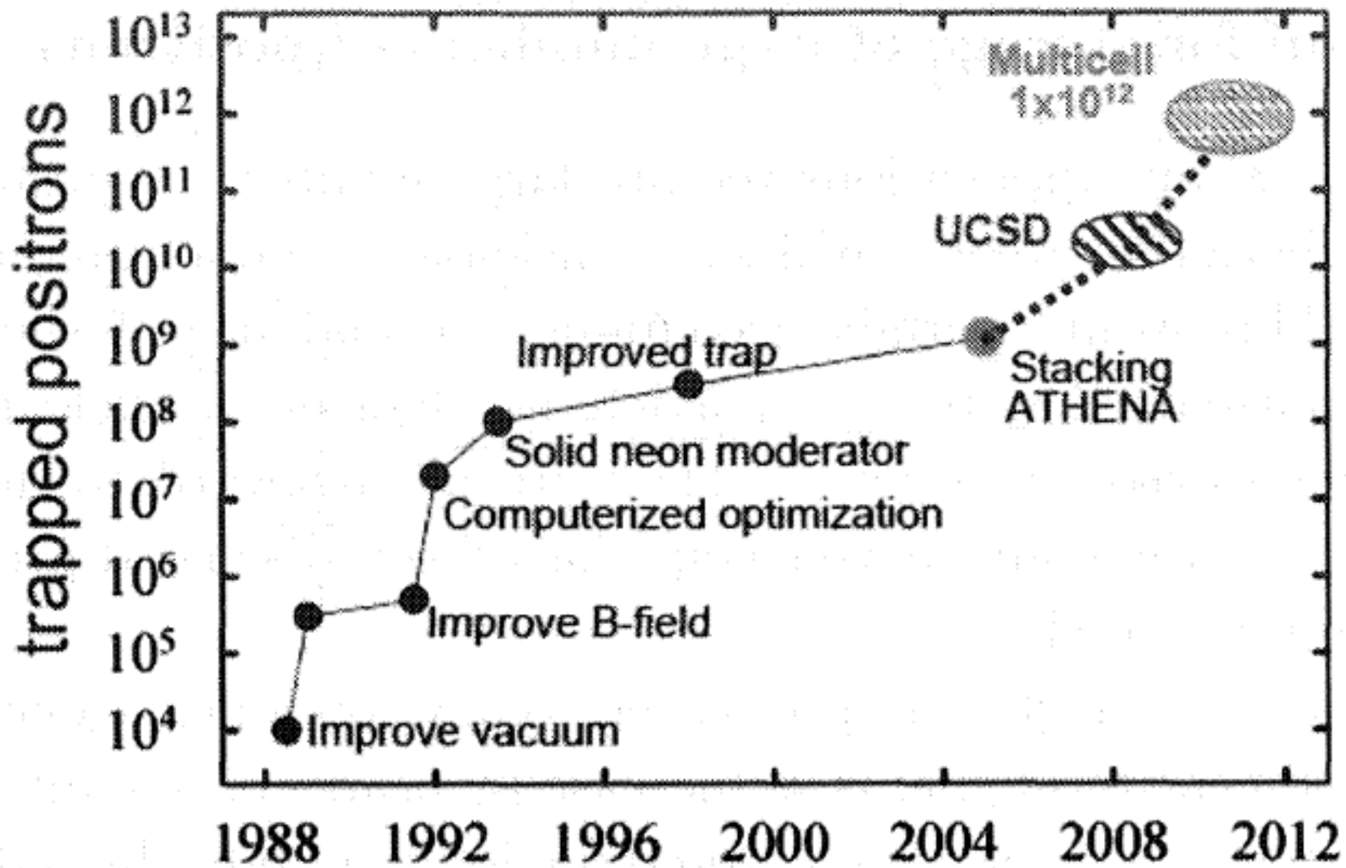
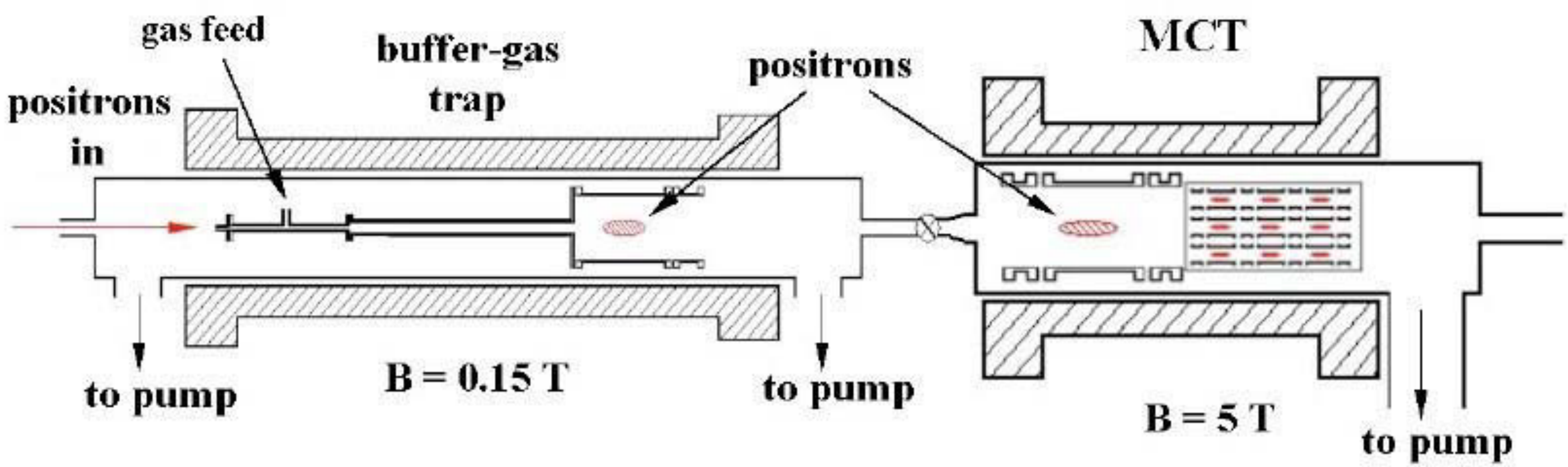


FIG. 1: Schematic configuration of an array of microtraps. The image is not to scale.

A. Narimannezhad, J. Jennings, M. H. Weber, and K. G. Lynn, arXiv:1307.2335

Even more positrons: Cliff Surko's approach





C. M. Surko, J. R. Danielson, and T. R. Weber, *in Physics with Many Positrons*,
R. S. Brusa, A. Dupasquier and A. P. Mills, Jr., eds. (IOS Press, Amserdam, 2010)., pp. 545

Even more positrons: Cliff Surko's approach