Penning trap usages : Antiproton cooling to mass spectroscopy

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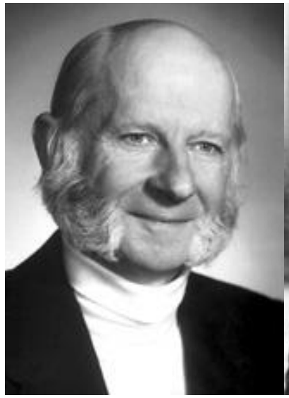
- Simple explanation of charged particle trap
- Basis of penning trap
- Cooling methods in penning trap
- Penning trap at the GBAR experiment
- Precision measurement methods in penning trap
- Usage in Nuclear physics field
- Other issues of penning trap basis

charged particle trap



Nobel Prize in physics at 1989

- Wolfgang Paul and Hans Dehmelt received the Novel Prize for the developing the first ion trap
- Paul trap and Penning trap (named by Dehmelt) were made al most same time.

Based on Earnshaw’s theorem, three-dimensional electro-static potential wall is forbidden to make

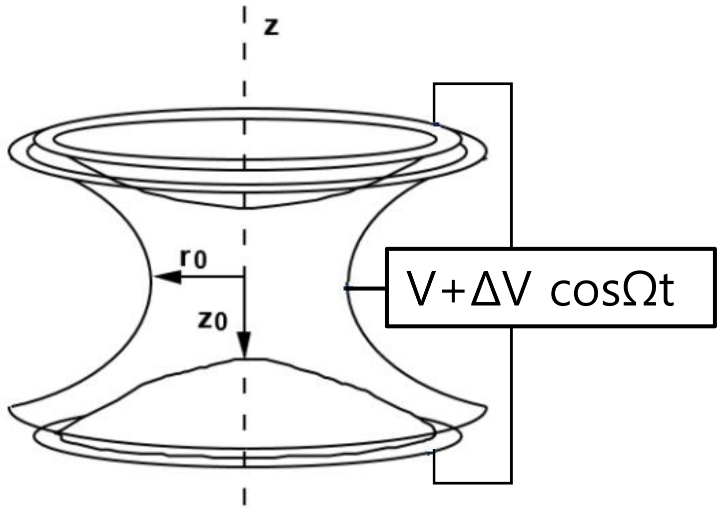
Earnshaw’s theorem

- for point charge, stable stationary equilibrium configuration by the electrostatic interaction is not possible
- $\varphi = Ax^2 + By^2 + Cz^2$: no three-dimensional minimum by
$\nabla^2\varphi =$ (0 Laplace’s equation)

charged particle trap

Principle

- Only possible to make saddle point by electrostatic potential $\varphi = Ar^2 + Bz^2$, $A + B = 0$ (simplest quadratic potential case)
- Three electrodes (two endcap + one ring) of hyperboloid shape for quadratic potential
- Vertical confinement by applying potential



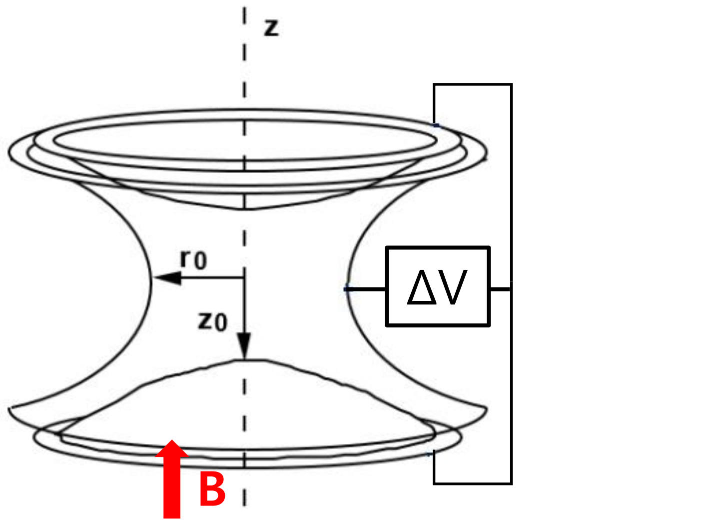
- Additional

- RF field at endcap : Paul trap

: oscillate the electric field between radial and axial direction

- Magnetic field : **Penning trap**

: confinement to plane perpendicular to magnetic field (cyclotron motion)

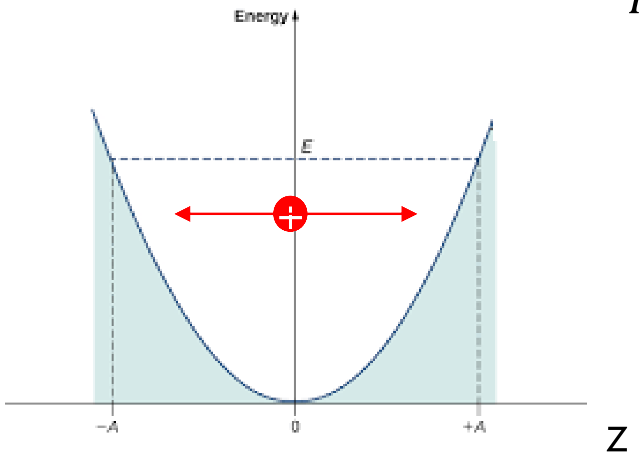


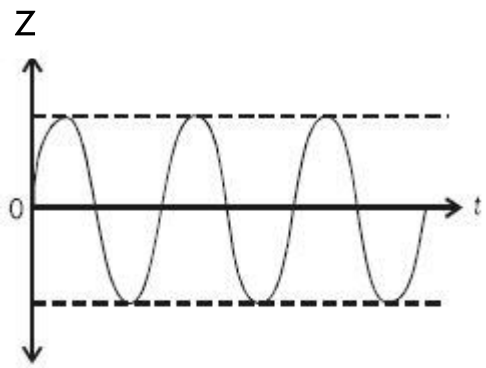
Basis of penning trap

Simple Electromagnetism

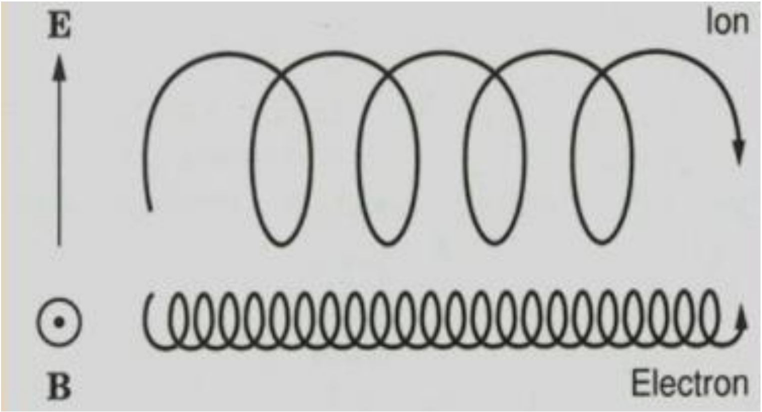
In harmonic potential wall : Periodic motion

$$F_E = -eE = -2kez\, e_z$$

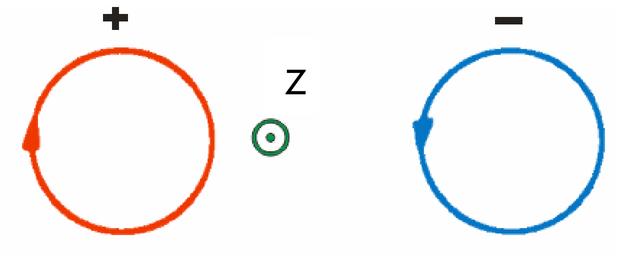




In E x B field : Drift motion

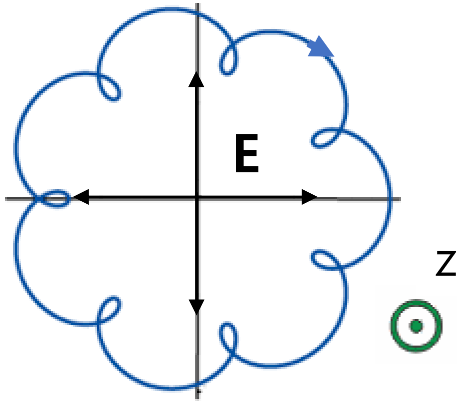


In Magnetic field : Circular periodic motion



$$F_B = ev \times Be_z$$

In E x B Drift radially : Magnetron motion

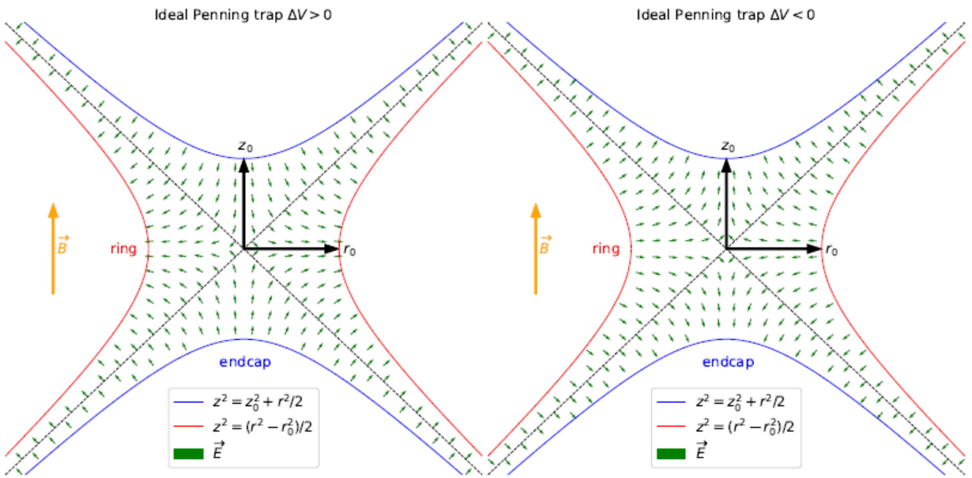


Basis of penning trap

S.Niang, thesis (2021)

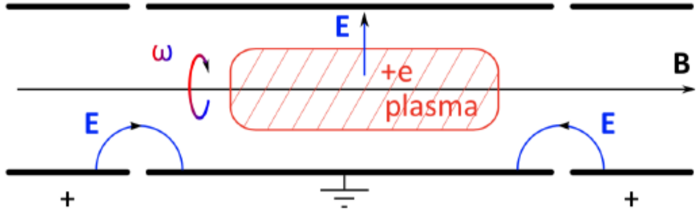
Axial motion

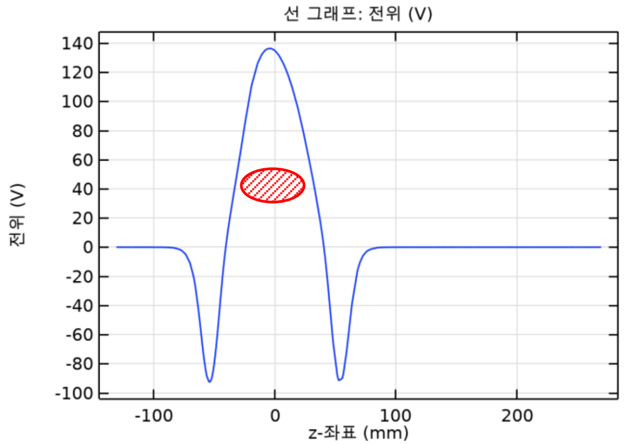
- $F_E = -eE = -e\frac{\Delta V}{L^2}(2ze_z - re_z) \leftarrow \Phi = \frac{\Delta V}{L^2}(2z^2 - r^2) + c$
- $\ddot{z} = \frac{-2e\Delta V}{mL^2} z$
- $z = z_0\cos((w_z)t + \varphi_0)$

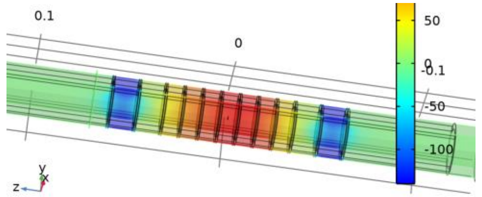


Penning-malmberg trap

- Made of several cylindrical electrodes aligned with magnetic field
- easy access to the trap and easy extraction from the trap
- quadratic potential can be made by several electrodes

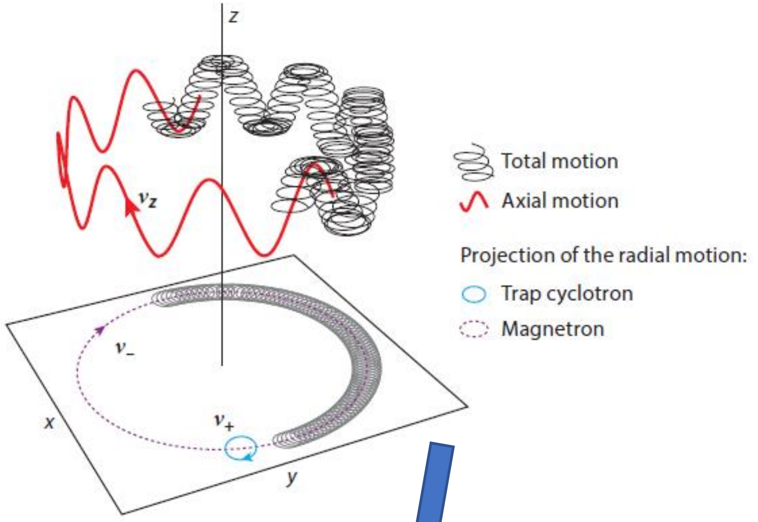






Basis of penning trap

Annu. Rev. Nucl. Part. Sci. 2018. 68:45–74



Motion in penning trap

- $F_E = -eE = -e\frac{\Delta V}{L^2}(2ze_z - re_z), L^2 = z_0^2 + 0.5r_0^2$, - $F_B = -ev \times Be_z$
- $\ddot{u} = \frac{ieB}{m}\dot{u} + \frac{e\Delta V}{L^2}u, (u = x + iy)$
- $u = \alpha \exp(iw_+t) + \beta\exp(iw_-t)$

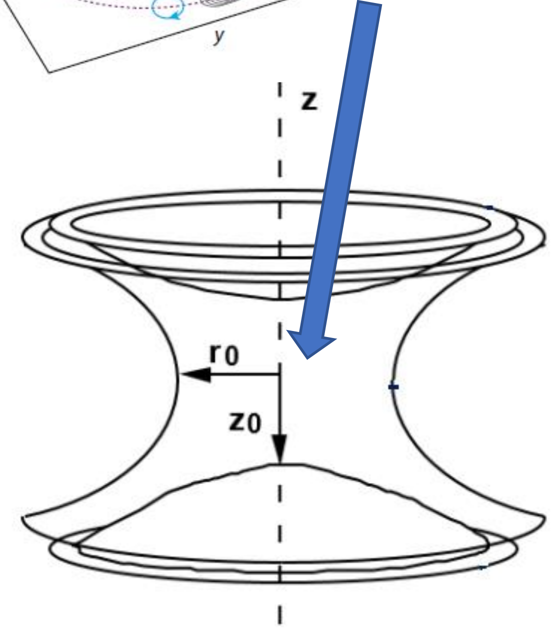
→Axial motion : $\boldsymbol{w_z^2 = \frac{2e\Delta V}{mL^2}}$

→Radial motion : magnetron frequency - $\boldsymbol{w_m (= w_-) \equiv \frac{w_c}{2} - \sqrt{\frac{w_c^2}{4} - \frac{w_z^2}{2}}}$,

modified cyclotron frequency - $\boldsymbol{w_c' (= w_+) \equiv \frac{w_c}{2} + \sqrt{\frac{w_c^2}{4} - \frac{w_z^2}{2}}}$, $\boldsymbol{(w_c = \frac{eB}{m})}$

$w_c^2 = w_m^2 + w_c'^2 + w_z^2, \; w_c = w_c' + w_m$

International Journal of Mass Spectrometry 279 (2009) 107–112



Penning trap usage procedure

- Loading
- Trapping
- **Cooling**
- **Detecting**
- Extracting

- Penning trap is a novel technique to trap charged particle to isolated and stable condition
- Relatively higher accumulation, high efficiency can be achieved.
- In the trapped situation, cooling or non-destructive detection is possible and extraction can be done if required.

Cooling methods in penning trap

- **Radiative cooling :**

(in positron&pbar trap) cyclotron(synchrotron) radiation energy loss by cyclotron motion of charged particle

$$\tau = \frac{3\pi\varepsilon_0 m_e c^3}{q^2 w_c^2}\ , w_c = \frac{qB}{m},$$

→ 3T, ~0.3/s for electron or positron but not efficient for heavier particles

- **Sympathetic cooling :**

(in almost GBAR traps) cooling by simultaneously stored cooled particles (cooled by mutual coulomb interaction)

Cooling methods in penning trap

- **Buffer gas cooling :**

(in Buffer gas trap) widely used for fast cooling, radial expansion expecte d ← Rotating wall technique

- **Laser cooling :**

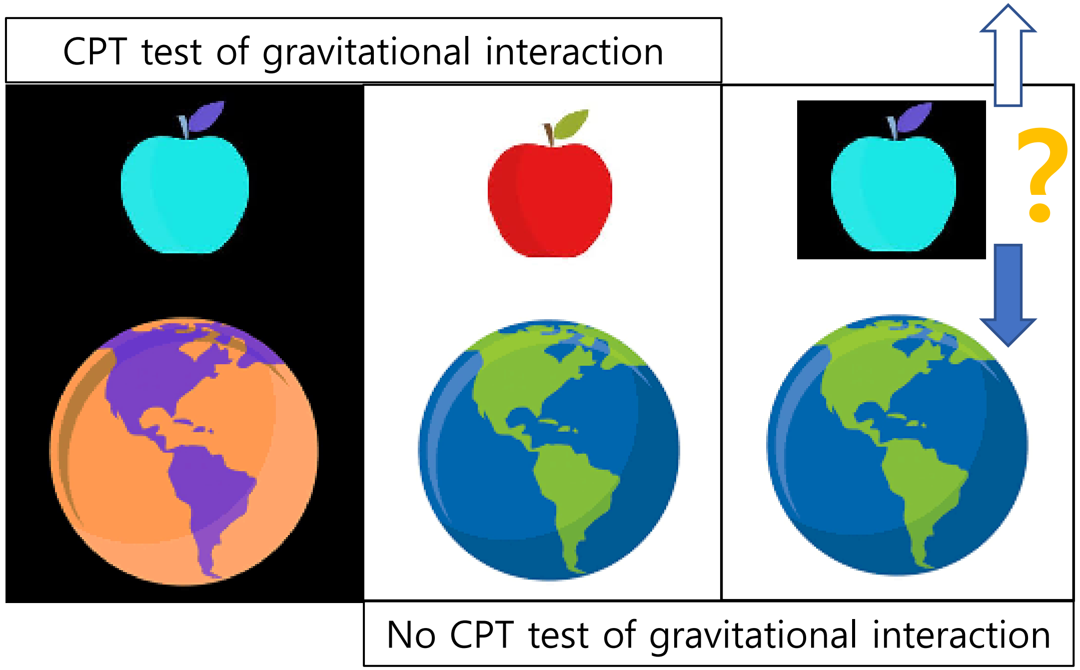
(in capture & precision trap) efficient way for cooling but only few (most alkaline atoms) available

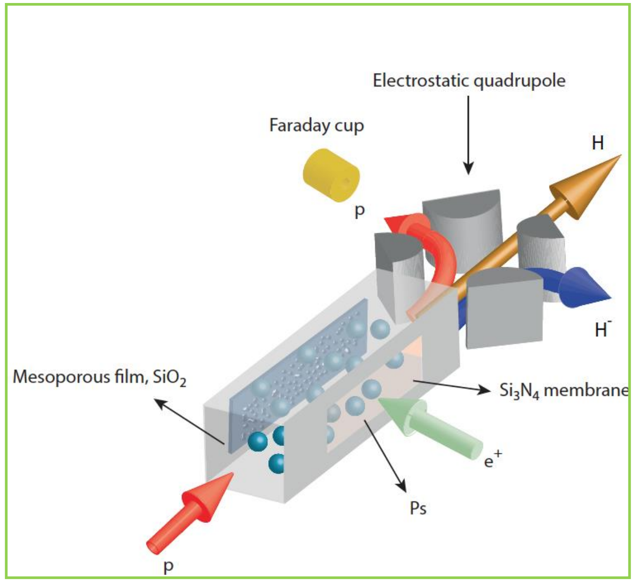
- **Resistive cooling :**

connect external RLC circuit to dissipate energy ($\tau = \frac{md^2}{Rq^2}$) and cooling of e nvironment required

- **Evaporative cooling :** Remove energetic particles by reducing potential wall ← useful for single ion trapping.

GBAR experiment



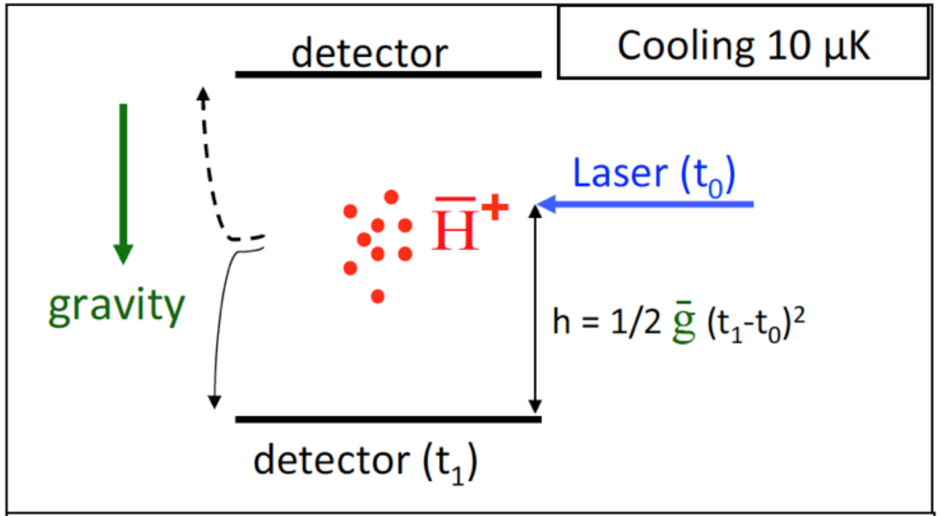


Gravitational Behavior At Rest

- Gravitational Behaviour of Antihydrogen at Rest (GBAR) experiment aims direct measurement of the gravitational acceleration of antihydrogen at terrestrial gravitational field by a classical freefall test.
- Double charge exchange process between antiproton beam and dense positronium cloud
- $\bar{p} + Ps \rightarrow \bar{H} + e^{-}$
- $\bar{H} + Ps \rightarrow \bar{H}^{+} + e^{-}$
- Cooling antihydrogen ion down to 10uK range (ultra-cold) with Be^{+} to get extremely slow velocity.
- After dropping (by photodetachement laser) one positron, let the ultra-cold antihydrogen freefalls

penning trap at GBAR experiment

- Measurement of the gravitational acceleration required the candidate particles to have cold temperature compared with gravitational potential
- Classical freefall measurement requires ultra-cold atom about ~10uK temperature range.
- This aim requires trapping & cooling by Penning & Paul trap.



J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561.

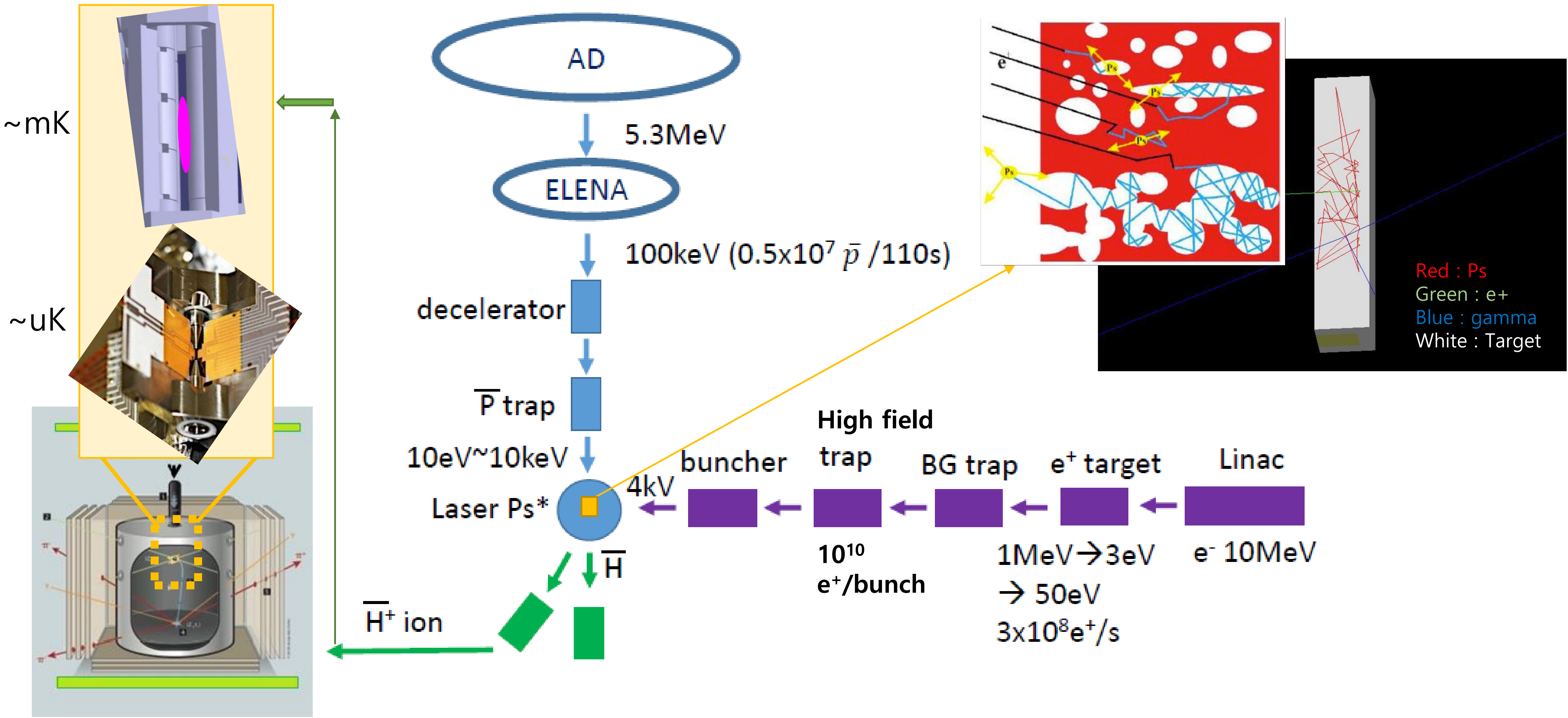
- positron trapping, cooling and accumulation

- Buffer gas trap

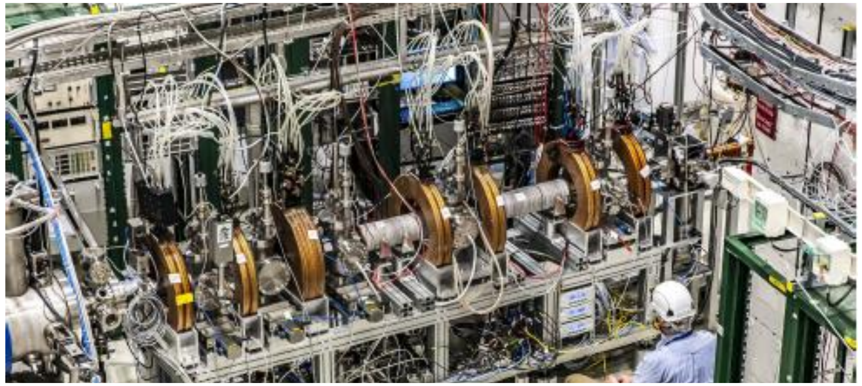
- Penning trap

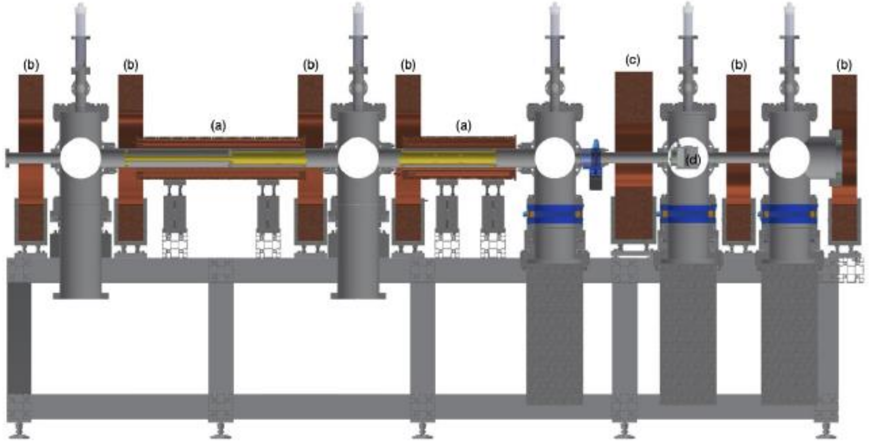
- antiproton trapping, cooling and accumulation

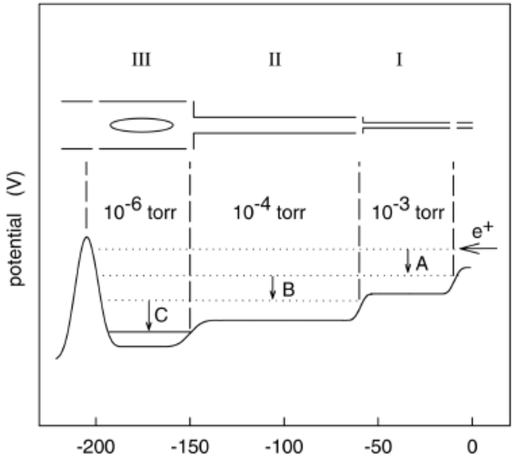
Experiment Scheme

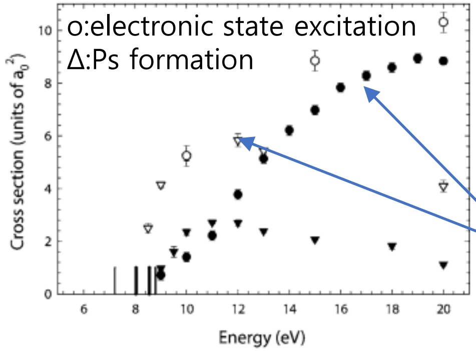


Buffer gas trap









Gas	Formula	Trapping efficiency (%)
Nitrogen	N_2	100
Carbon monoxide	CO	68
Oxygen	O_2	43
Sulfur dioxide	SO_2	33
Hydrogen	H_2	30
Nitrous Oxide	NO_2	20
Carbon dioxide	CO_2	16
Sulfur hexafluoride	SF_6	7
Carbonyl sulfide	OCS	4

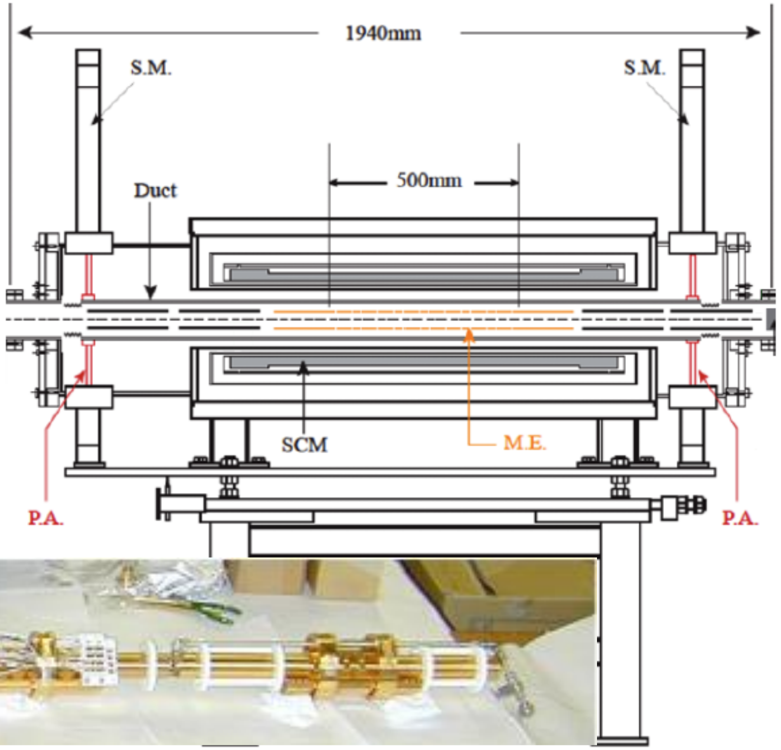
Gas	τ_a (s)	τ_c (s)
SF_6	2190	0.36
CF_4	3500	1.2
CO_2	3500	1.3
CO	2400	2.1
N_2	6300	115

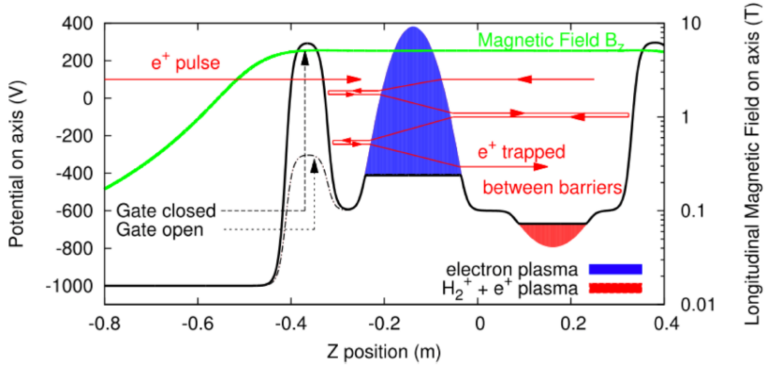
Name	Reaction	Energy thresh
Annihilation	$e^+ + N_2 \to N_2^+ + 2\gamma$	-
Electronic scattering	$e^+ + N_2 \to N_2 + e^+$	-
Rotational excitation	$e^+ + N_2 \to N_2^{rot} + e^+$	~ 1 meV
Vibrational excitation	$e^+ + N_2 \to N_2^{vib} + e^+$	~ 0.3 eV
Electronic excitation	$e^+ + N_2 \to N_2^* + e^+$	8.59 eV
Positronium formation	$e^+ + N_2 \to N_2^+ + Ps$	8.78 eV
Ionisation	$e^+ + N_2 \to N_2^+ + e^+ + e-$	15.6 eV

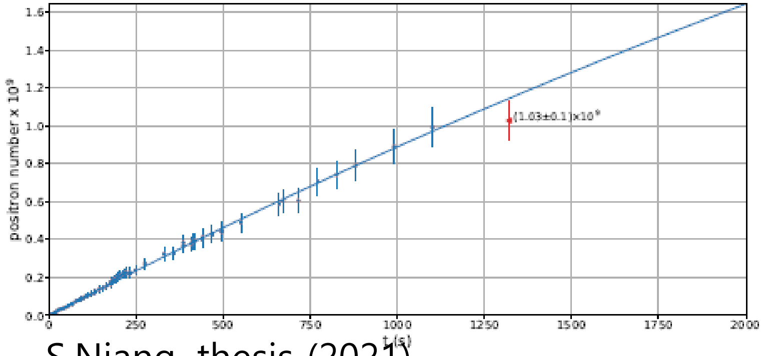
Nuclear Instruments and Methods in Physics Research B 192 (2002) 90–96,
S.Niang, thesis (2021)

- modified penning-malmberg trap (Surko-Greaves trap) for positron accumulation with small energy spread
- injected N_2 gas is used for positron trapping (E_{th_Ps} = 8.78eV)and SF_6 or CO_2 gas is used for cooling
- To reduce radial increase, rotating wall technique(giving RF wave to radially separated lenses) is used.

Penning-malmberg trap for positron



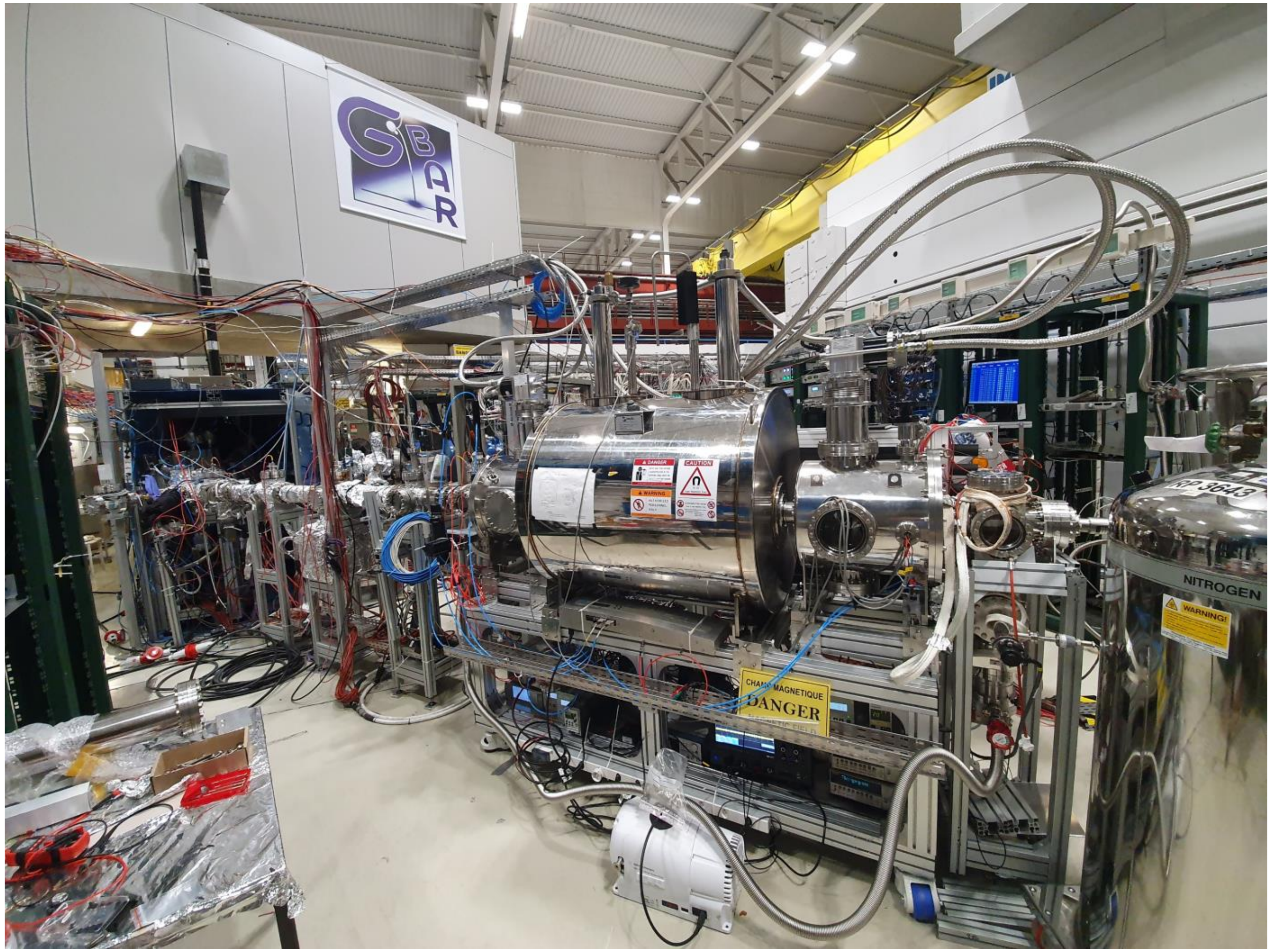




S.Niang, thesis (2021)

- Positron accumulation by high field trap : goal to $1x10^{10}$ e^+ (110s) with electron cooling
- 3T superconducting magnet,
- Four arms can move to align the multi-electrode's axis to B-field
- $T_{M.E}$ = ~10K because the plasma temperature is influenced by $T_{M.E}$.

Antiproton trap



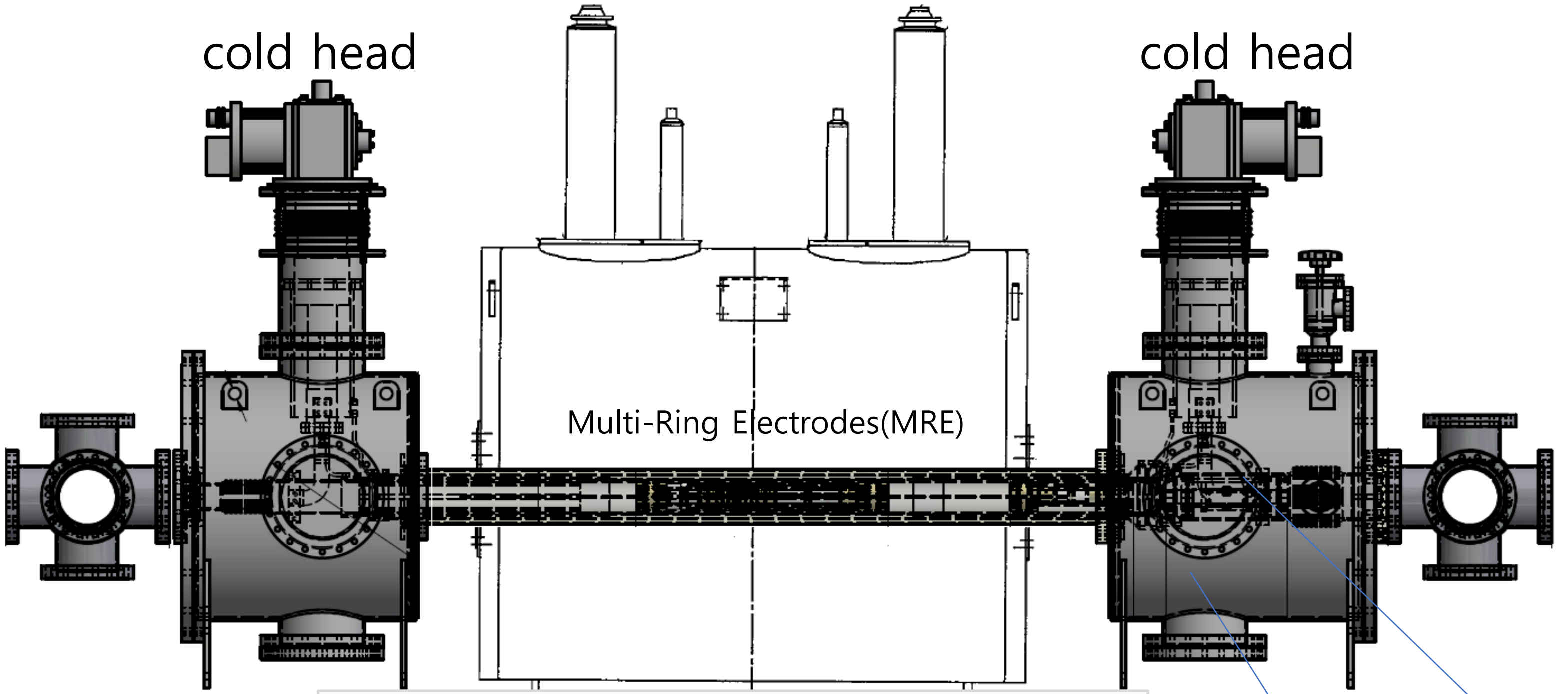
GBAR antiproton trap

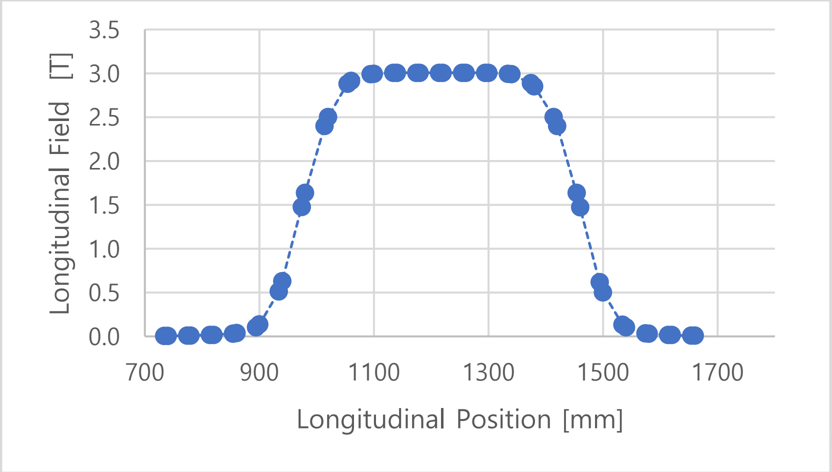
- trapping pbar beam from ELENA (+decelerator)
- reprocess to better condition by cooling and compression
- stacking if required

• Injection of pbar beam
- KE <10keV
- N=0.5E+7 pbar/pulse

• Ejection of pbar beam
- KE : 0~10keV
- σ_E <10eV
- σ_t <100ns
- high efficiency
- small size & emittance to pass through target hole ($1x1x20mm^3$) at 1.5m distance

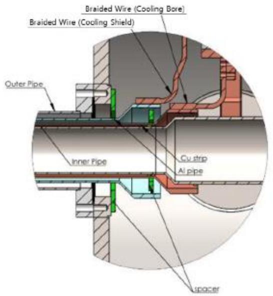
Antiproton trap



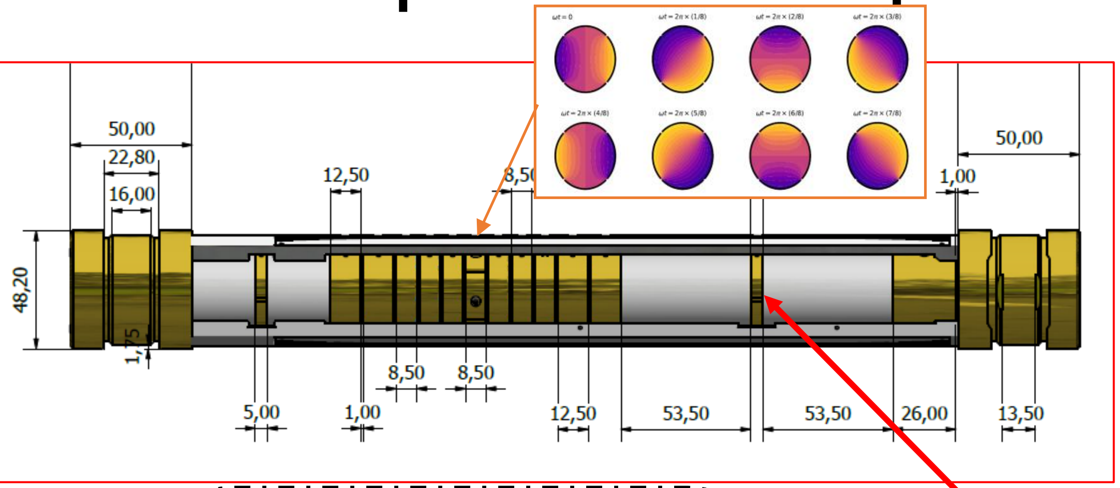


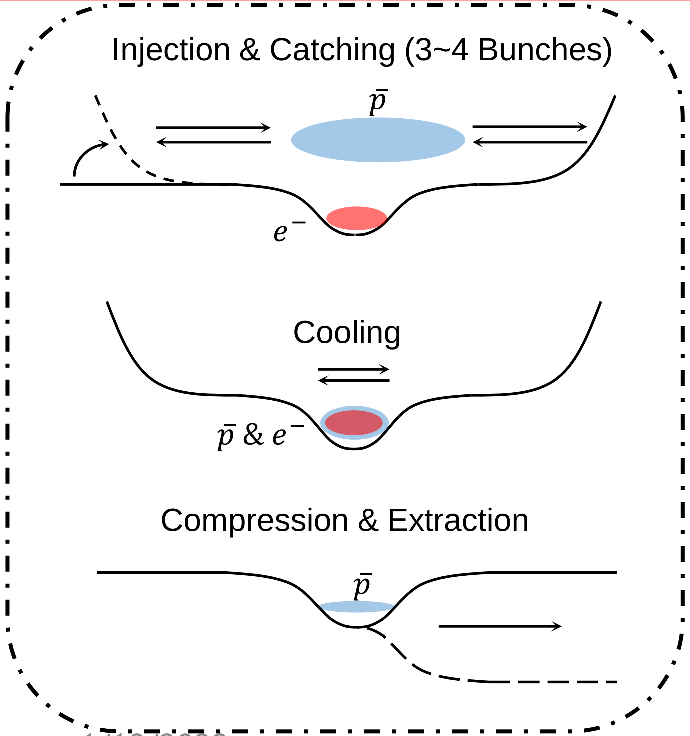
GBAR antiproton trap

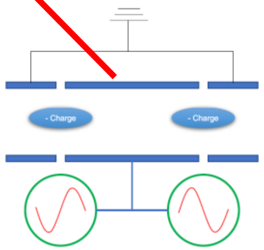
- Magnetic field : 7T
- field uncertainty : σ_B/B <1.e-3
- Zero stary field outside of the trap : 2.3mT (55cm from center)
- Pressure : P_{MRE}<1.e-10mbar (turbo pumps (#2)) : required for less interaction with residual gas
- Temperature : T_{MRE}<15K (coldheads (#2),Multi-layer insulator(MLI) layers) for better vacuum & cooling
- MRE Potential : V_{MRE} < 140V
- Buncher potential : V_{HV} < 10kV
- Total 11# MRE lenses (1# rotating wall) ← controlled by **PXI**
- HV lenses 2#(upstream, downstream) with fast switches

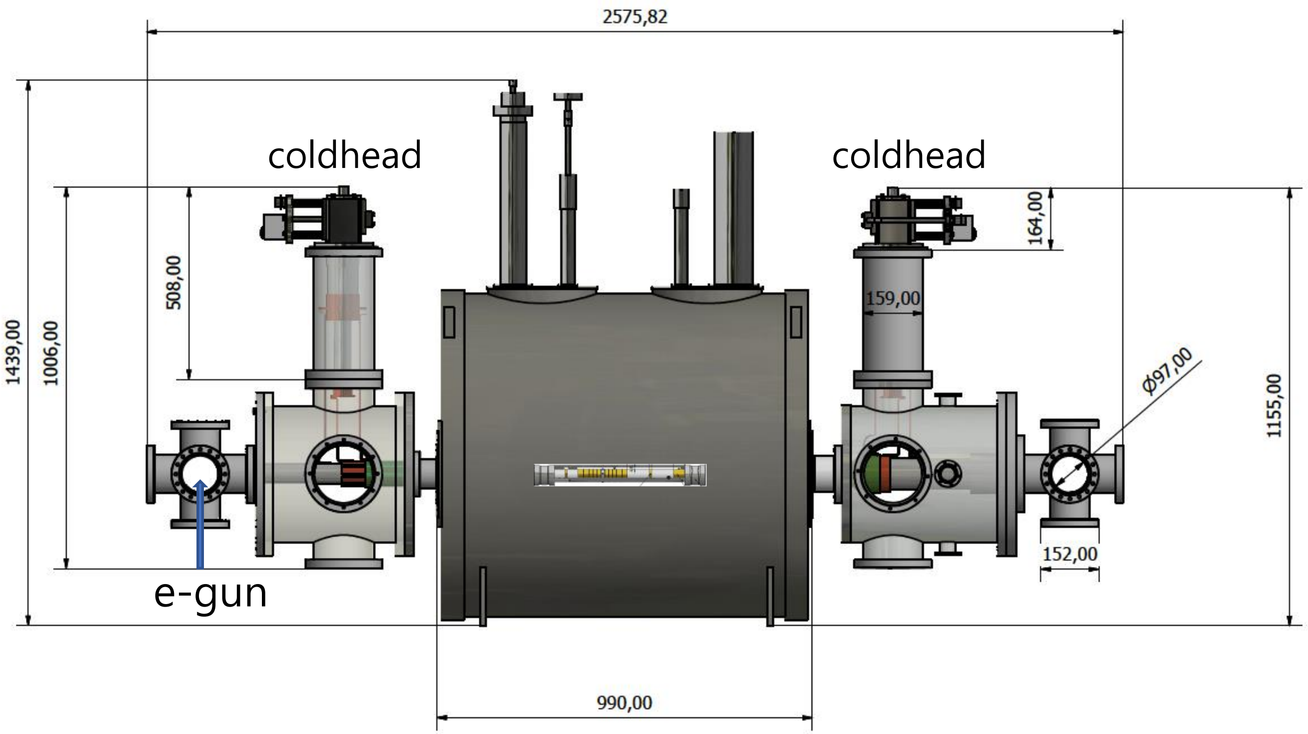


Antiproton trap





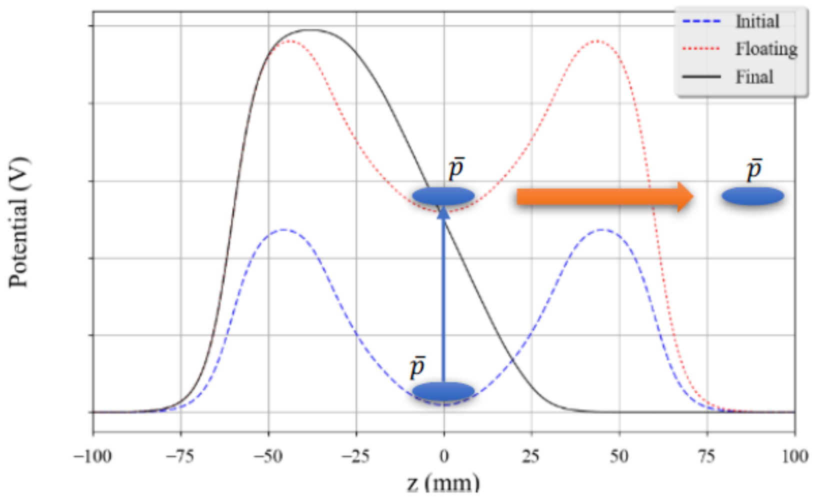




- Loading electron and cooling by cyclotron motion
- Sympathetic cooling by pre-loaded electron (cooled by radiative cooling)
- Harmonic potential wall (quadratic) by #11 MRE electrodes
- Compression by 4-split cylindrical electrodes : rotating wall
- Remove pre-loaded electrons by velocity difference
- Acceleration with bunching by double gap bunching system

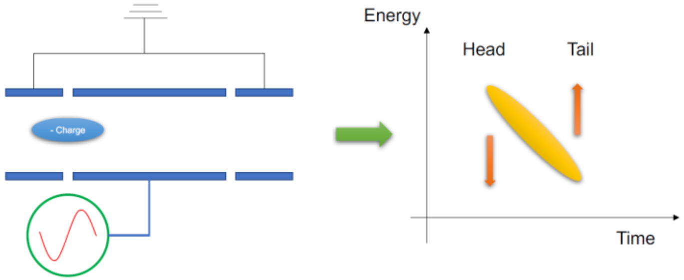
Antiproton trap

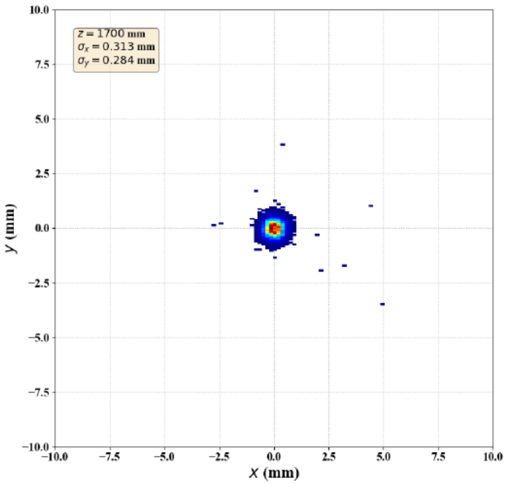
Extraction



<Extraction setting>

Beam Radius (mm)	0.22
Beam Length (mm)	25.4
Intensity	1×10^{7}
$\epsilon_x\ (mm \cdot mrad)$	0.521
$\epsilon_y\ (mm \cdot mrad)$	0.523



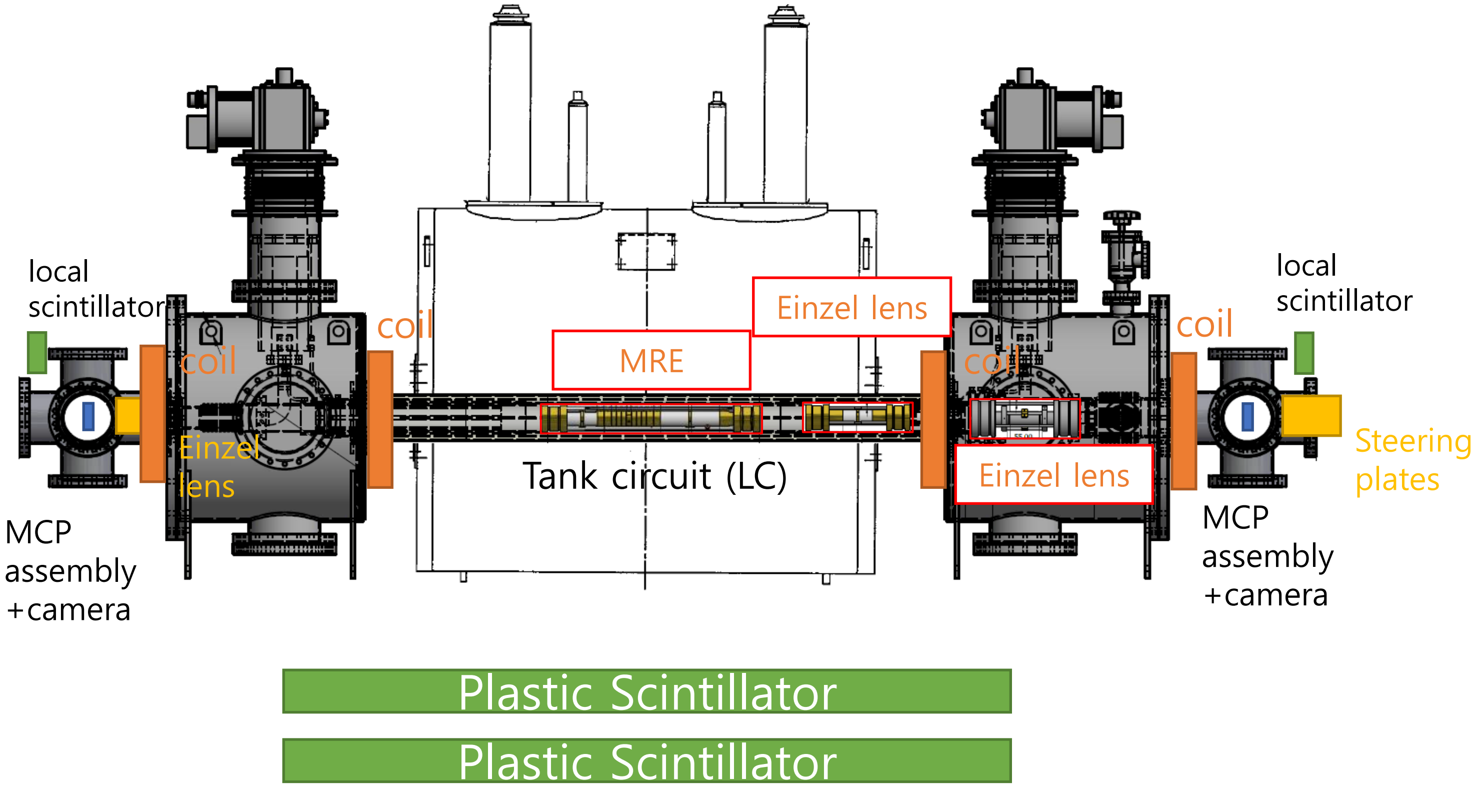


At $z = 1700\ mm$	No DGB	DGB (Sine Form)	DGB (Linear Form)
Mean Longitudinal Energy $\overline{E_z}\ (keV)$	1.00	1.01	1.00
Longitudinal Energy Spread $\sigma_{Ez}\ (eV)$	13.35	8.89	5.55
Bunch Length $\sigma_t\ (ns)$	185.16	79.07	80.01
Beam Size $\sigma_x\ (mm)$	0.392	0.329	0.313
Emittance $\epsilon_x\ (\mathrm{mm \cdot mrad})$	3.711	5.483	5.177

Extraction simulation by WARP by K.H.Yoo **(preliminary)**

- Enough beam size, energy& time spread achieved by si mulation
- Simulation will be studied deeply

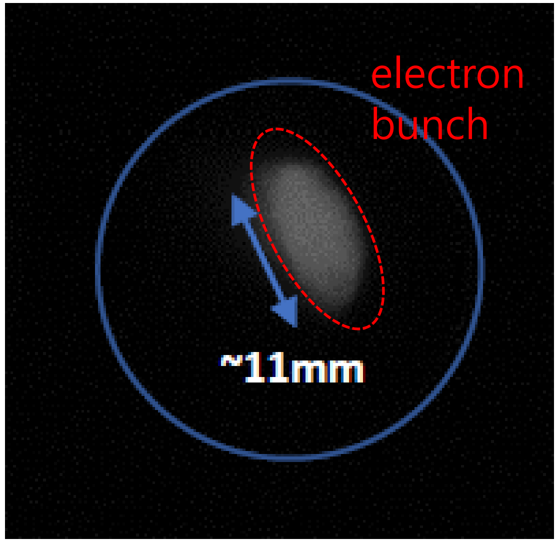
Antiproton trap



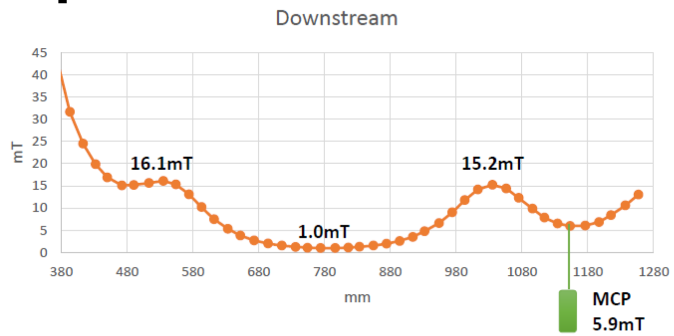
Guiding and Detection

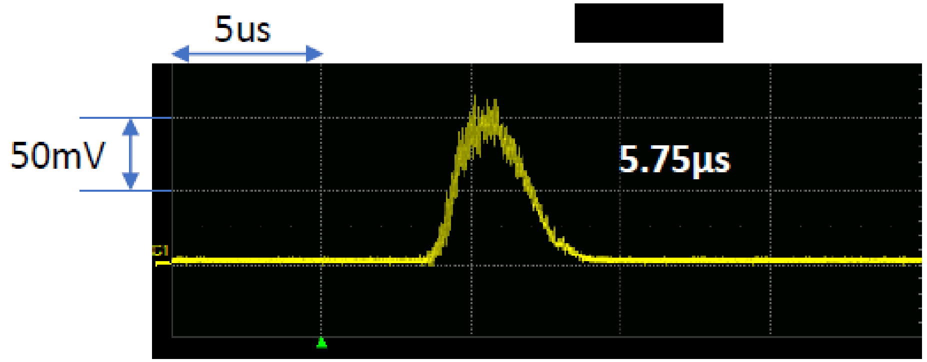
- Optics system
  - Einzel lens (upstream #1) before the B field region
  - Einzel lenses (downstream #2) and steerer (#1) after the B field region
  - Coils (#4, ~15mT) for electron guiding
- Detectors (destructive)
  - Beam image & timing : MCP (#2)
  - Beam intensity : local scintillator (#2 (2mm thickness))
  - Beam loss with tracking : long plastic scintillators (#2)
- Detectors (non-destructive)
  - Tank circuit (LC) connection to lens

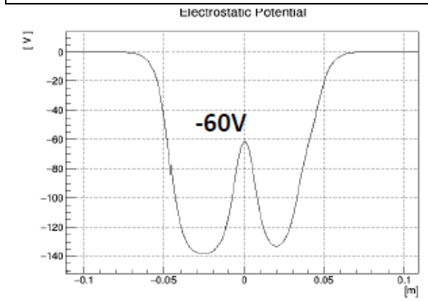
Antiproton trap



Electron pre-loading test

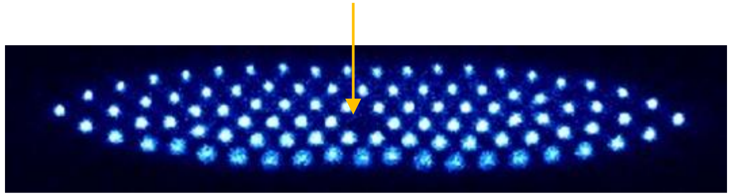


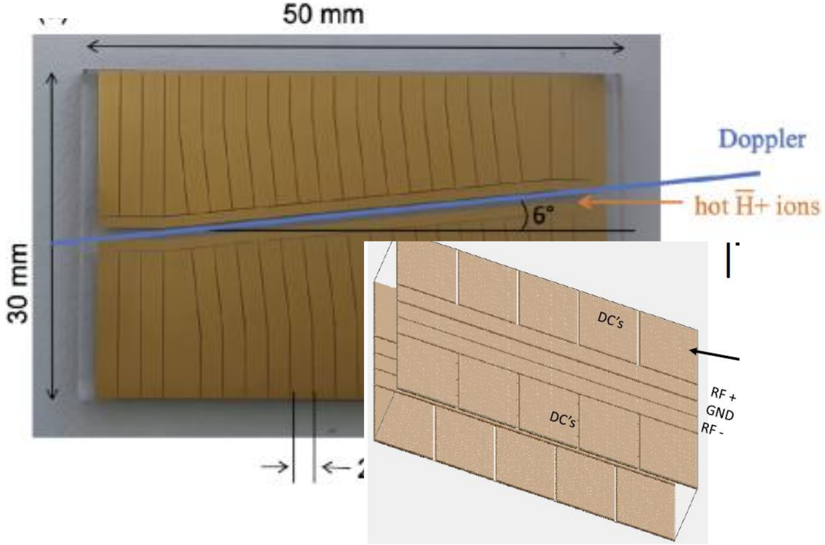


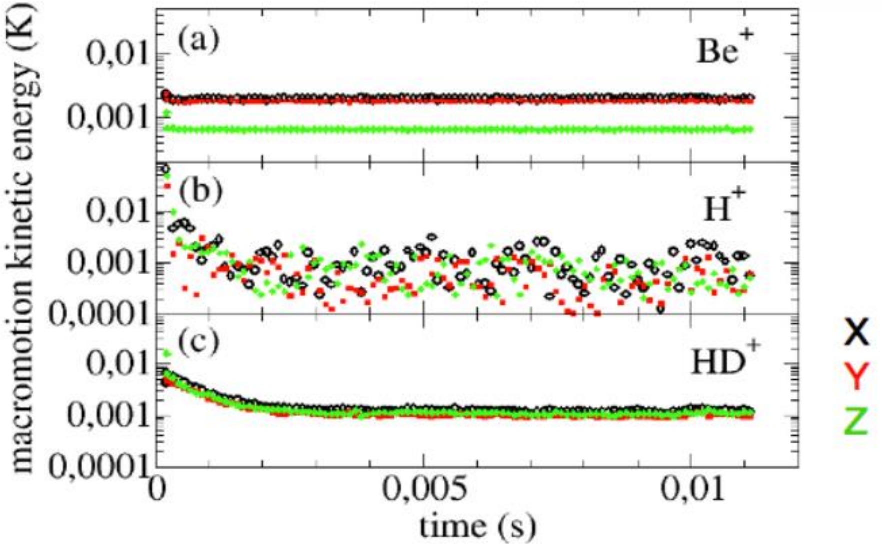


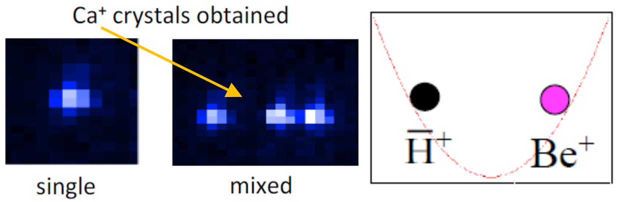
- During this year's beam time, there was no change to get antip roton beam to trap….
- Electron loading & trapping has worked and well centered elect ron bunch was measured at MCP (tectra) ← D0.3mm expected at the MRE
- Loaded electron amount is above 7.0E+7# which is enough for antiproton cooling
- Time distribution was decided by slew rate of potential at MRE

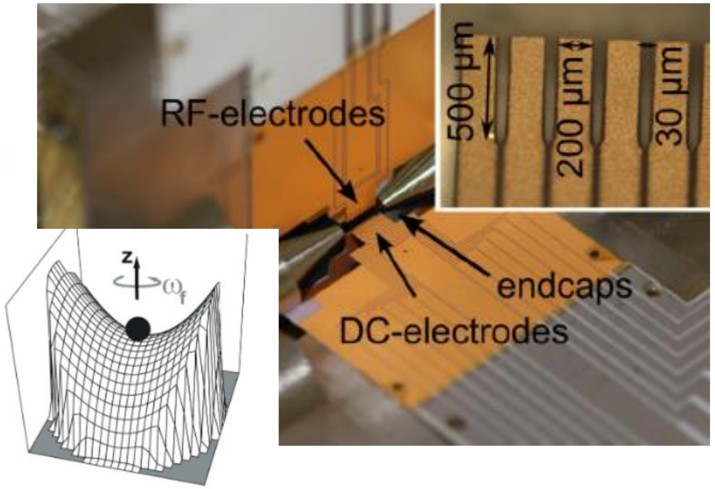
Cooling traps

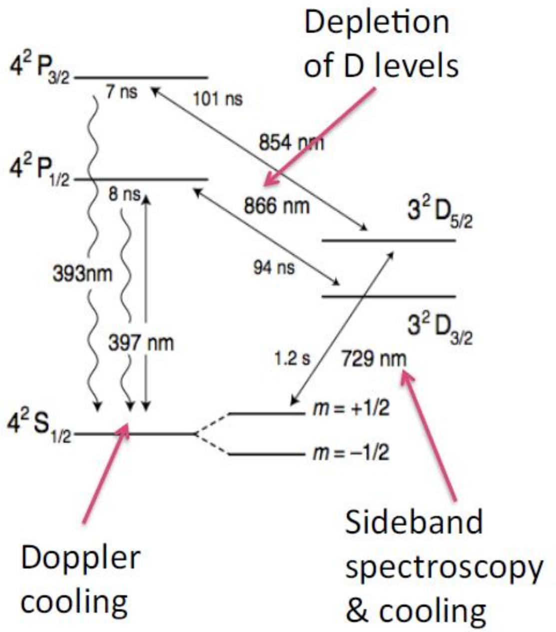












1. Capture trap (ITO trap) : capturing by DC switching+ rf voltage electrodes (#4)

Sympathetic Doppler cooling by cooled Be+ ions (>10,000 laser(313nm) cooled Be^+/HD^+ ions (Wigner crystal), 100 neV, T~mK by rf heating)

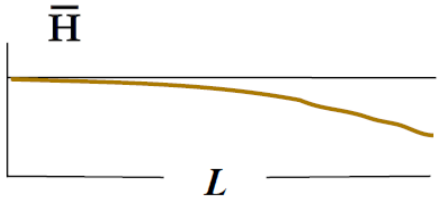
(L. Hilico et. al., Int. J. Mod. Phys. Conf. Ser. 30, 1460269 (2014))

← HD^+ to reduce mass ratio for better coupling in simulation (similar charge to mass ratio required)

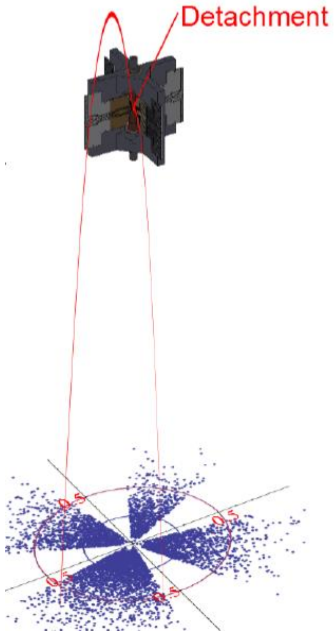
- 2. Precision trap : ion as a quantum harmonic oscillator, Raman sideband cooling for $Be^+/\overline{H}$ ion pair to T~10uK. (W. Schnitzler et. al, Physical Review Letters 102, 070501 (2009).)

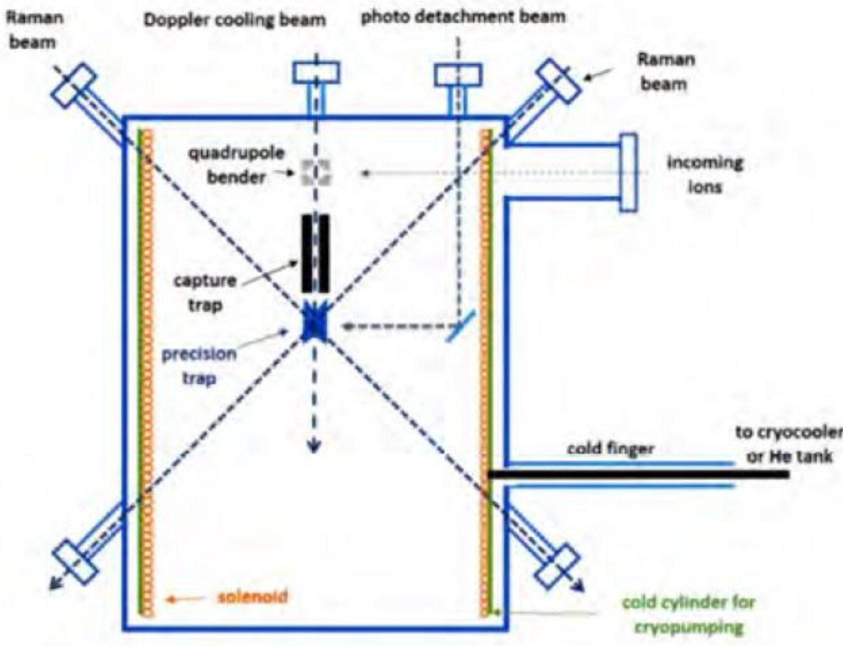
Freefall measurement

$$m_i \vec{a} = m_g \vec{g}$$



$$h = v_z^0 t + \frac{1}{2}\frac{m_g}{m_i} g t^2 = v_z^0 \left(\frac{L}{v_h}\right) + \frac{1}{2}\frac{m_g}{m_i} g \left(\frac{L}{v_h}\right)^2$$





- Initial direction : temperature (0.44m/s for 1MHz) + photon recoil(0.24m/s) + positron emission (~0.3m/s for E_c = 1ueV)
- Length :10cm, height : 30cm (cf Aegis : L = 1m, h = 20um)
- Small magnetic field gradient, UHV, etc for systematic uncertainties have been studied
- Freefall time : about 500ms for $|\bar{g}| = g$
- uncertainty : $(\Delta z_0, \Delta v_{z0} t \ll z), \frac{\Delta \bar{g}}{\bar{g}} \cong \sqrt{(\frac{\Delta z}{z})^2 + (\frac{2\Delta t}{t})^2}$~0.4 (for single $\bar{H}$), Δz(T(10uK),ΔE(1ueV):positron emission)

better description in G. Dufour et. al., Eur. Phys. J. C (2014) 74:2731

Penning trap usages at Antiproton Decelerator (AD)

Antiproton Decelerator (AD)

- ~~AD-1 ATHENA experiment~~

~~- **Antihydrogen production** and precision experiment : catching trap, Mixing trap~~

- AD-2 ATRAP experiment

- Laser spectroscopy for **trapped antihydrogen** : penning-ioffe trap

- AD-3 ASACUSA experiment

- **Antihydrogen beam spectroscopy** and collision with antiproton : penning-malmburg (**sympathetic + radiative cooling**) traps

- AD-5 ALPHA experiment

- Laser spectroscopy for **trapped antihydrogen, trapped Antihydrogen gravity** experiment : penning-ioffe trap (Evaporative cooling, laser cooling)

- AD-6 AEGIS experiment

- **Antihydrogen beam gravity interferometry** spectroscopy : penning-malmburg (**sympathetic + radiative cooling**) traps

AD-7 GBAR experiment

- **ultra-cold antihydrogen gravity** experiment : penning-malmburg traps (**sympathetic + radiative cooling**) (+ **Buffer-gas** trap)

- AD-8 BASE experiment

- Antiproton **precision** experiment (CPT test) : penning-malmburg (**sympathetic + radiative cooling + laser cooling**) (catching&analysis) trap

- AD-9 PUMA experiment

- Antiproton unstable matter annihilation (starting!)

measurement by penning trap in AD hall

- ALPHA experiment uses penning-ioffe trap as antihydrogen production& cooling (laser cooling) & detection(antihydrogen spectroscopy & gravity) by releasing

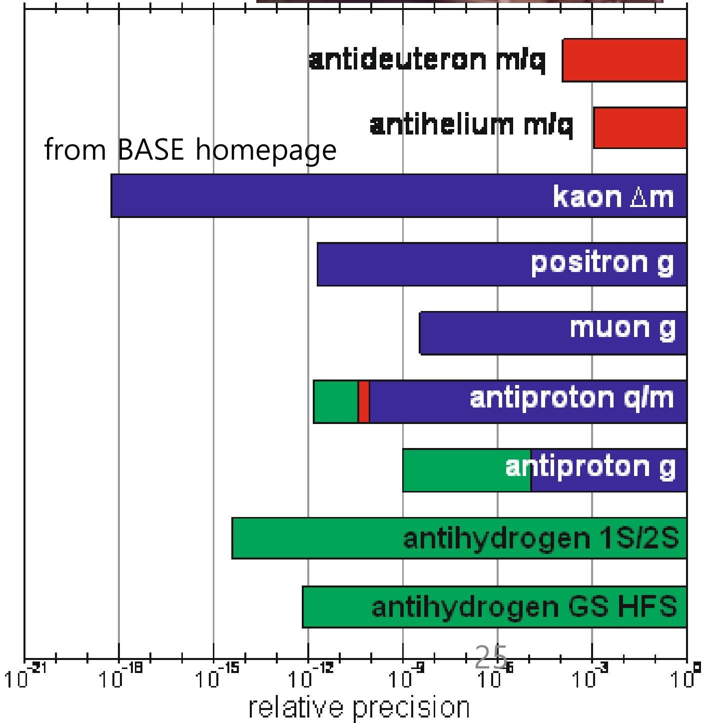
- 1S-2S transition : (hydrogen $4.2e^{-15}$) antihydrogen $2x10^{-10}$(2017) → 2x 10^{-12} (2018)

- Hyperfine splitting : observed 2% ($2P_{1/2}$-$2P_{3/2}$) (nature 548, 66-69 (2017), nature 578, 375 (2020)) by ALPHA

- Lamb shift : agreed a level of 11% ($2S_{1/2}$-$2P_{1/2}$) (nature 578, 375 (2020)) by ALPHA

- BASE experiment uses penning trap for cooling and precision measurement of antiproton property by TF-ICR – charge to mass ratio, antiproton g value

- $(q/m)_p/(q/m)_{pbar}$=1.000000000003(16) : part per trillion
- indirect gravity measurement



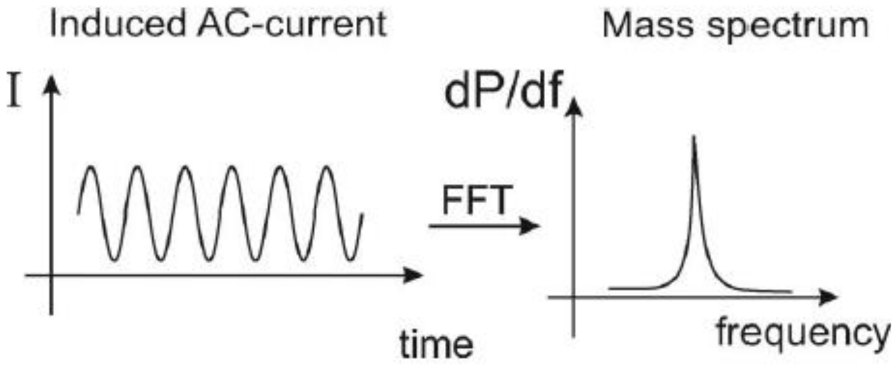
from BASE homepage

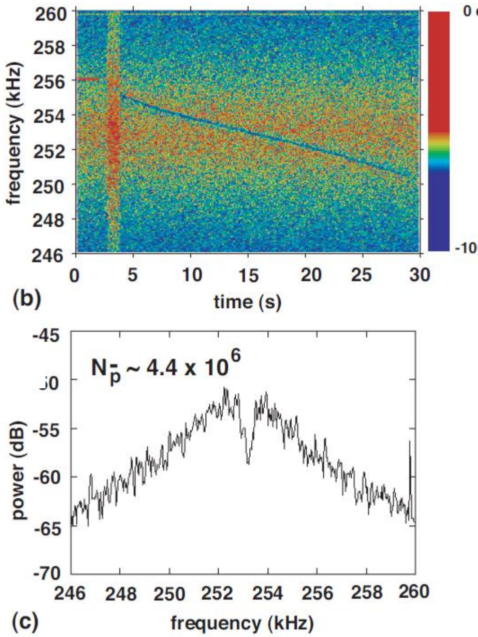
- ASACUSA experiment use TF-ICR to measure condition in the Penning trap

Measurement techniques in penning trap

- TF-ICR (non-destructive)

- Tank resonance (LC, RLC parallel) circuit to measure frequency spectrum of induced AC current (normally in cryogenic trap&electronics) Journal of Applied Physics **46**, 919 (1975)





Conf.Proc.C 100523 (2010) MOPE001

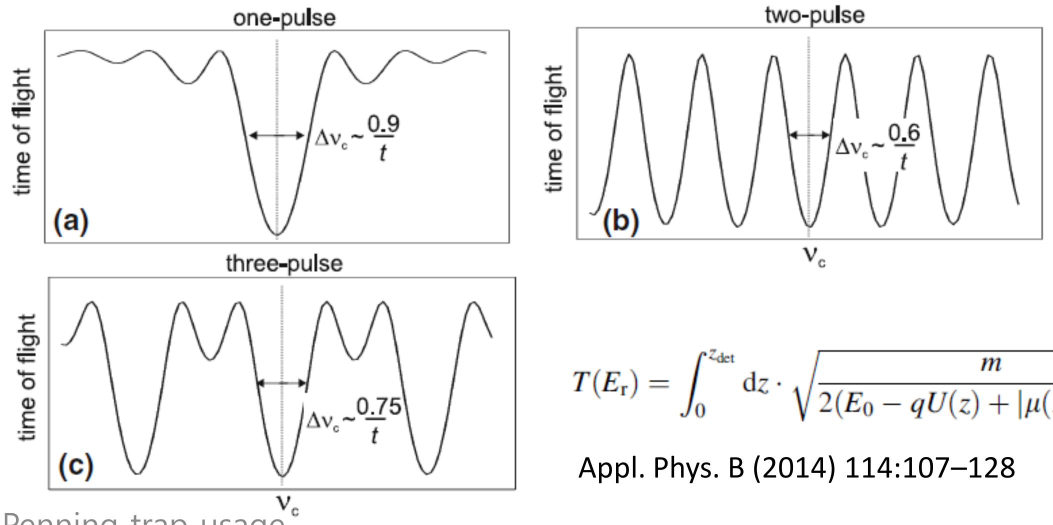
- TOF-ICR (destructive)

- Time of flight of extracted particle in low field region is changed by radial energy in high field region and field ratio (F=grad(μB) : Giving RF field to particle to change magnetic moment (please read reference for detail and Ramsey excitation..)

- PI-ICR (destructive)

- With giving dipolar rf field to change radius of magnetron motion, then measuring revolution (of moon)

Please read if you have interest : Appl. Phys. B (2014) 114:107–128



$$T(E_r) = \int_0^{z_{det}} dz \cdot \sqrt{\frac{m}{2(E_0 - qU(z) + |\mu(E_r)B(z)|)}},$$

Appl. Phys. B (2014) 114:107–128

Penning traps for precision measurement

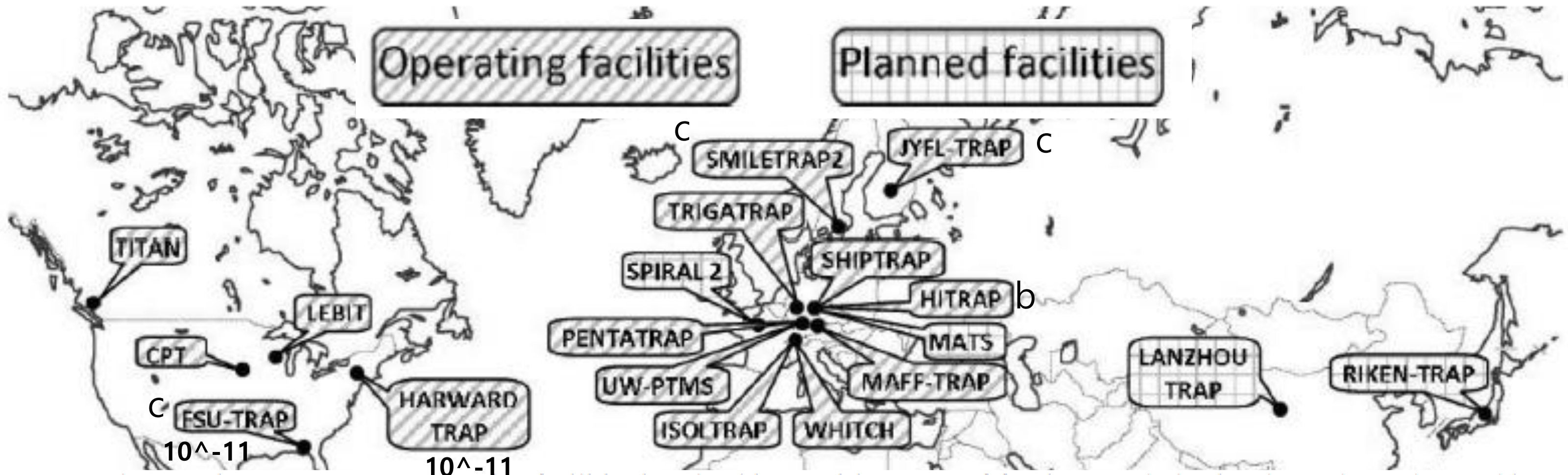


Figure 1. The Penning trap systems at major facilities involved in precision tests of fundamental physics throughout the world. The abbreviations stand for the installations situated at the following states: *America*: TITAN – Vancouver (Canada), CPT – Argonne (USA), LEBIT – Michigan (USA), MIT/FSU-TRAP – Florida (USA), Harvard-TRAP – Harvard (USA). *Europe*: ISOLTRAP – Geneva (Switzerland), WITCH – Geneva (Switzerland), SHIPTRAP – Darmstadt (Germany), HITRAP – Darmstadt (Germany), MATS –Darmstadt (Germany), TRIGA- TRAP – Mainz (Germany), PENTATRAP – Heidelberg (Germany), UW-PTMS – Heidelberg (Germany), SMILETRAP2 – Stockholm (Sweden), JYFLTRAP – Jyväskylä (Finland), Spiral2-TRAP – Caen (France), MAFF/MLL-TRAP – München (Germany). *Asia*: Lanzhou-TRAP – Lanzhou (China), RIKEN-TRAP – Tokyo (Japan).

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Table 1. Fields of application and the generally required relative uncertainty on the measured mass $\delta m/m$ to probe the corresponding physics.

Field of Science	$\delta m/m$
General physics & chemistry	$\lesssim 10^{-5}$
Nuclear structure physics – separation of isobars	$\lesssim 10^{-6}$
Astrophysics – separation of isomers	$\lesssim 10^{-7}$
Weak interaction studies	$\lesssim 10^{-8}$
Fundamental constants	$\lesssim 10^{-9}$
CPT tests	$\lesssim 10^{-10}$
QED in highly-charged ions – separation of atomic states b	$\lesssim 10^{-11}$
Neutrino physics c	$\lesssim 10^{-11}$

Annu. Rev. Nucl. Part. Sci. 2018. 68:45–74

Table 1 Penning-trap mass spectrometers at radioactive ion beam facilities[a]

Name	Year	Location	Facility	Reaction(s)
ISOLTRAP	1987–present	ISOLDE, CERN	ISOL	Spallation, fission
CPT	1998–2009	ATLAS, ANL	In-flight	Transfer, fusion–evaporation
CPT	2009–present	CARIBU, ANL	ISOL	^{252}Cf fission
SHIPTRAP	2004–present	SHIP, GSI	In-flight	Fusion–evaporation
JYFLTRAP	2004–present	JYFL, Jyväskylä	IGISOL	Various
LEBIT	2005–present	NSCL, MSU	In-flight	Fragmentation
TITAN	2007–present	ISAC, TRIUMF	ISOL	Spallation, fission
TRIGATRAP	2017–present	TRIGA, Mainz	Reactor	Fission

Penning trap usage in the nuclear physics field

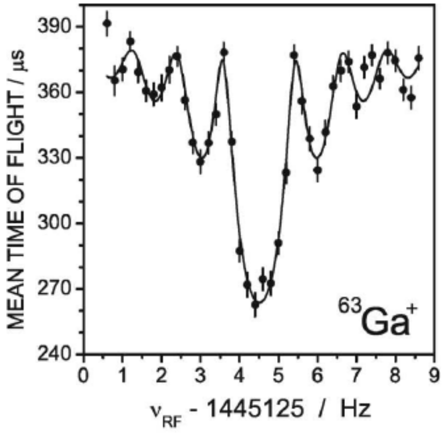
- RIB (radioactive ion beam) facility

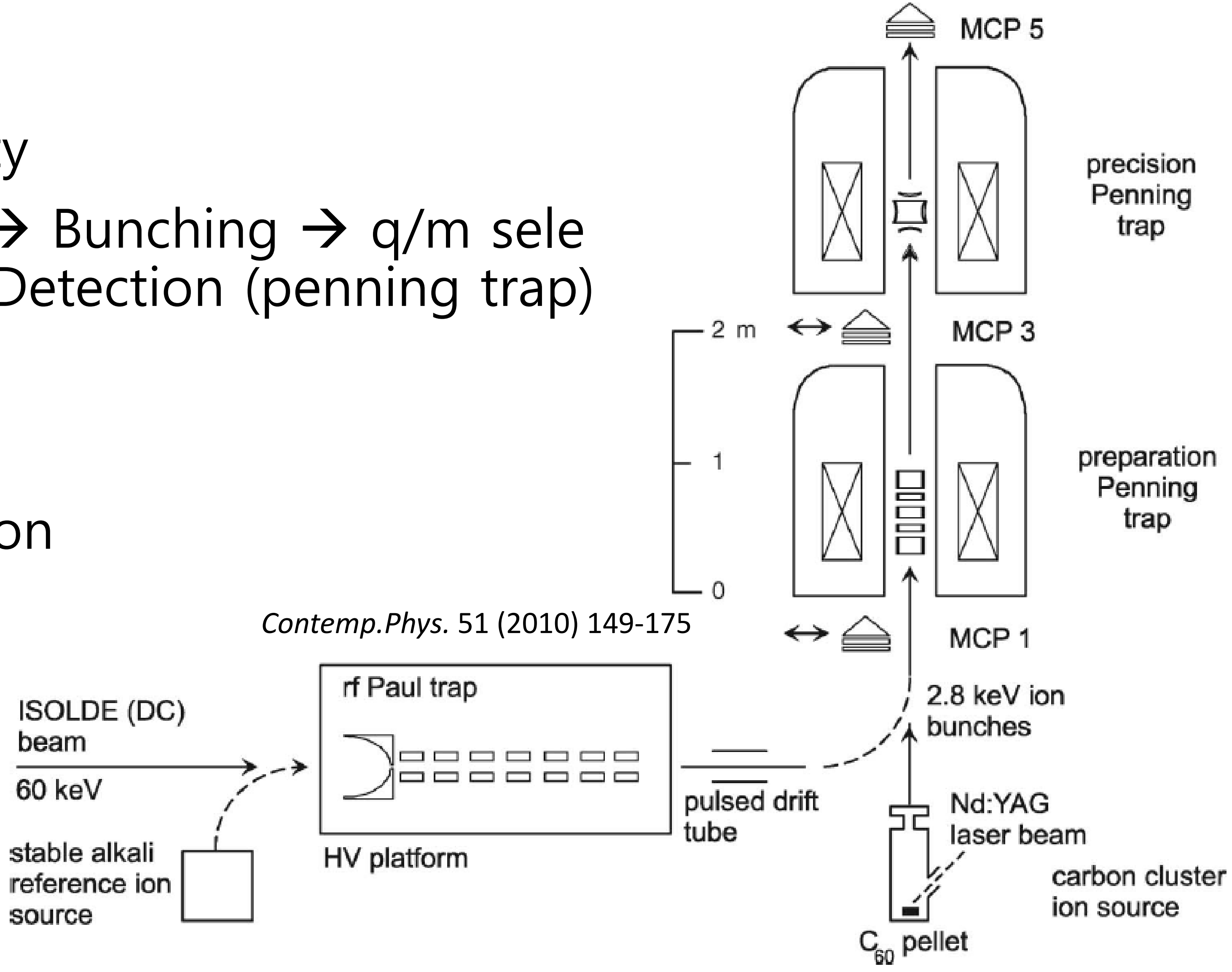
- (ISOL) ionizing → Deceleration → Bunching → q/m selection → Cooling(penning trap) →Detection (penning trap)

- Cooling : Buffer gas cooling

- Detection : Destructive methods

- δm/m ~e-8 for single charged ion





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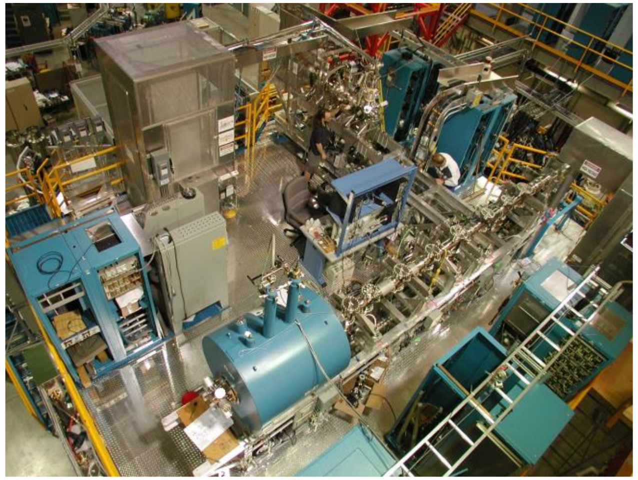
ex)TITAN facility

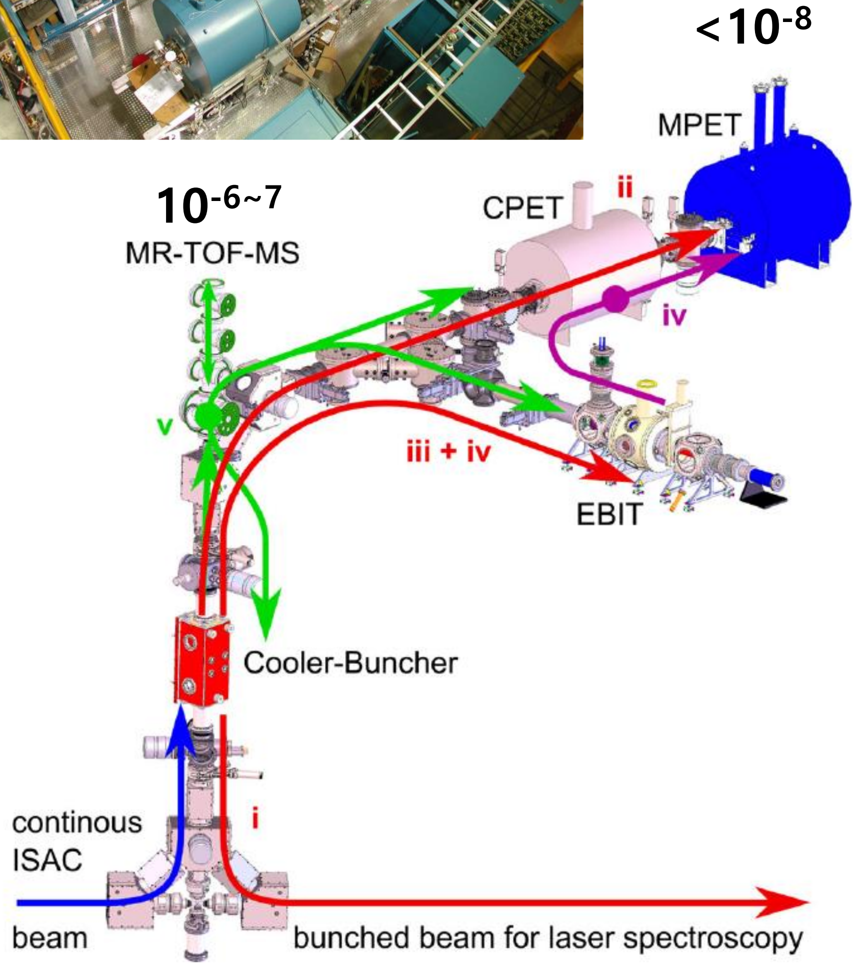


Titan : TRIUMP's Ion Trap for Atomic and Nuclear science

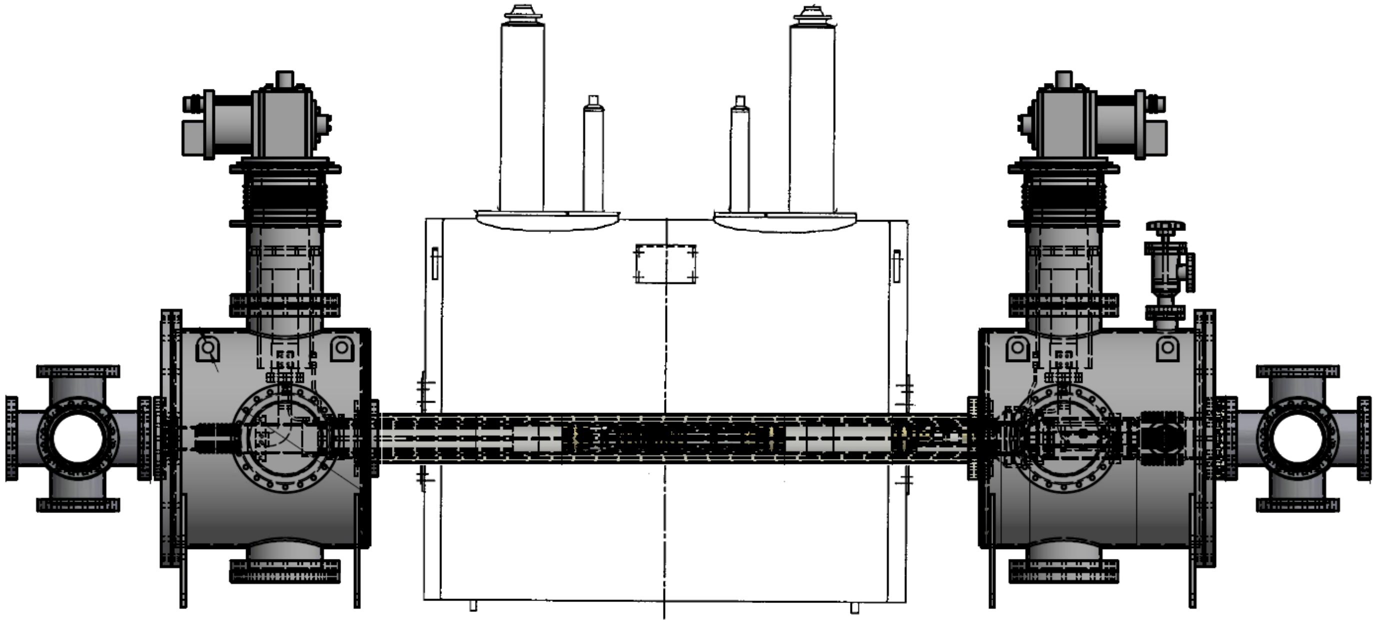
EBIT (electron beam in trap) striped by 10~300keV electron beam (SMILETRAP, WITCH)

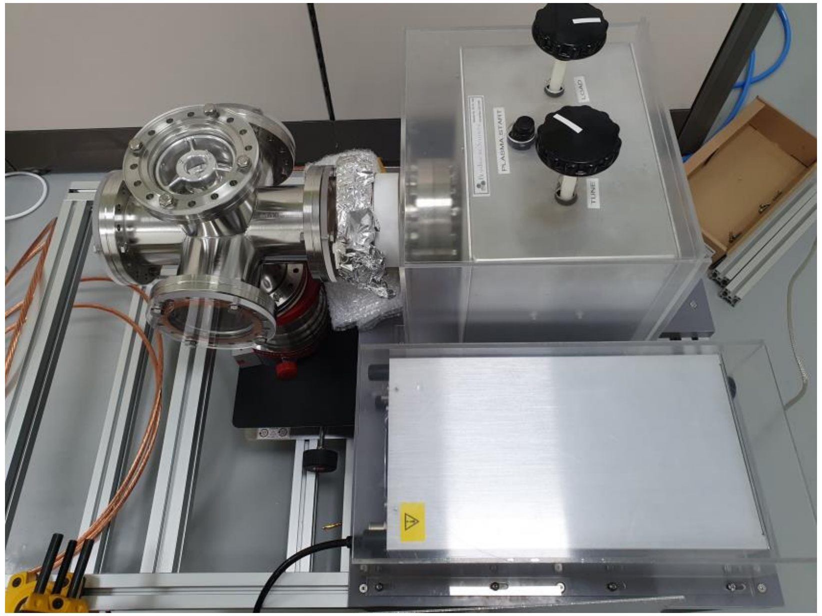
Asked to David Lunny (Orsay university)

- Titan facility has penning trap : CPET, MPET
- Because high charged particle requires good vacuum condition, MPET has been upgraded to have better pressure by being cryogenic trap (some commissioning test ongoing..)
- Recent study was done by MR-TOF-MS for a few years
- Recent publication : PHYSICAL REVIEW C **104**, 065803 (2021)
- submitted a paper on the mass of 64Cr



development at Korea





- Cryogenic vacuum system of antiproton trap is made by Korean company.
- The antiproton trap made by Korean GBAR group has successively trapping & cooling electron
- Because the antiproton trap is in CERN(Geneva), ion source(hydrogen, Argon, CO, etc ions) and te st setup (vacuum system, etc) have been prepared in IBS(Korea) for future development.

issues to concern when using penning trap

- Magnetic mirroring
- B field stability for time
- Alignment of magnetic field and electric lenses
- Ionization of residual gas
- removing contamination

Summary

- Penning trap is novel device for the mass spectroscopy and c ooling exotic particles.
- Korean GBAR group has developed penning trap for antiprot on cooling.
- There's some issues to be concern to make a penning trap bu t it can give high precision and stable trapping.