# MUONIC ANTI-HYDROGEN

## — *Possible Production and Test of CPT Theorem* —

*Workshop on Physics with Ultra Slow Antiprotons*
*March 16, 2005*
*at RIKEN (Wako)*

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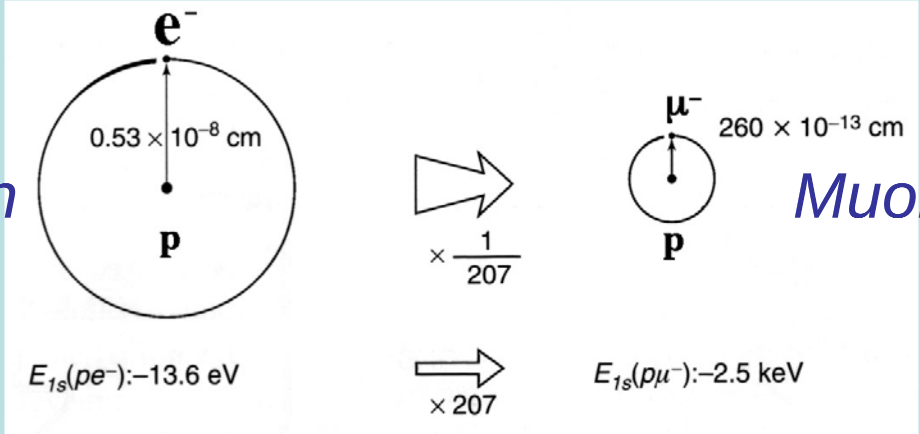
*RIKEN*

1. Introduction
2. Ultra Slow $\mu^+$; Recent Progress and Future
3. Towards Production of Muonic Anti-Hydrogen
4. Possible High Precession Spectroscopy for Test of CPT Theorem
5. Conclusion; Future Perspectives

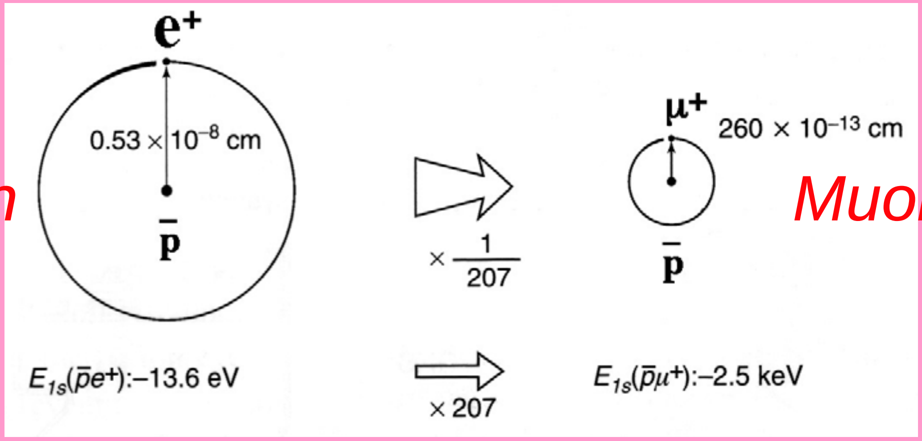
# Hydrogen, Anti-Hydrogen with ($e^-$, $e^+$, $\mu^-$, $\mu^+$)

Hydrogen




Muonic Hydrogen

Anti-Hydrogen




Muonic Anti-Hydrogen

# What is a muon ?

Muon is an elementary particle first found in the cosmic ray in 1937. Muon is now produced in large numbers by using accelerators.

| | Charge | Spin | Mass | Lifetime |
|---|---|---|---|---|
| $\mu^+$ | +1 | 1/2 | 106 MeV (1/9 of Proton) | 2.2 $\mu$s |
| $\mu^-$ | -1 | 1/2 | 106 MeV (207 x Electron) | 2.2 $\mu$s |

Structureless (point-like) particle and interacts mainly electromagnetically with atoms in matters

Pion ($\pi$) production by accelerated beam

$p(n) + N \rightarrow \pi^{\pm} + X....$

Muon ($\mu$) production by $\pi\mu$ decay

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

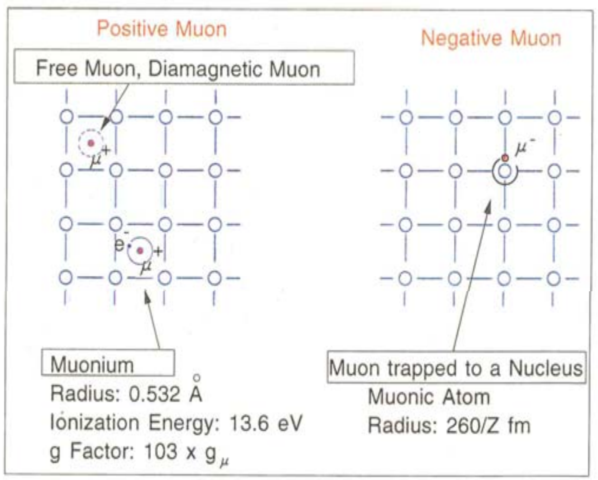
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

(26 ns)

Behavior in Matters

$\mu^+$ "Light proton"

$\mu^-$ "Heavy electron"




# Muon for human life

Heavy Electron ($200\ m_e$) → Promotion Of Cyclic Fusion Reaction → New Atomic Energy

Radioactivity **Polarization** Phenomena (2.2 μs) → Sensitive Microscopic Magnetic Probe → Characterization of New Materials & New Life Science

Heavy Electromagnetic Particle ($200\ m_{e^-}$, $200\ m_{e^+}$) → Radiography for Large-scale Substance → Natural Disasters Prevention Industrial Application

# ULTRA SLOW $\mu^+$

## *— RECENT PROGRESS AND FUTURE —*

PROPOSED & REALIZED (☆) MUON COOLING METHOD

| Energy | Method | Particles |
|---|---|---|
| | IONIZATION COOLING | $\mu^+$, $\mu^-$ |
| | PRISM | $\mu^+$, $\mu^-$ |
| MeV | PHASE SPACE COMPRESSION | $\mu^+$, $\mu^-$ |
| | $\mu^-$ RE-EMISSION FROM $\mu$CF | $\mu^-$ |
| KeV | ☆ FRICTIONAL COOLING (PSI) | $\mu^+$, $\mu^-$ |
| | ☆ COLD MODERATOR (TRIUMF/PSI) | $\mu^+$ |
| eV | | |
| | ☆ THERMAL MUONIUM IONIZATION (KEK) | $\mu^+$ |

# KEK METHOD OF ULTRA SLOW $\mu^+$

## *THERMAL MUONIUM & ITS LASER IONIZATION*

**Historical Development at KEK-MSL**

1. Thermal Muonium Production in Vacuum from Hot Tungsten (W) Surface

*A.P. Mills. Jr., K. Nagamine et al.*

*Phys. Rev. Lett. 56(1986)* ***1463***

2. Laser Resonant Ionization (1 s → 2 s → unbound )

of Thermal Muonium

*S. Chu, A.P. Mills. Jr., K. Nagamine et al.*

*Phys. Rev. Lett. 60(1988)* ***101***

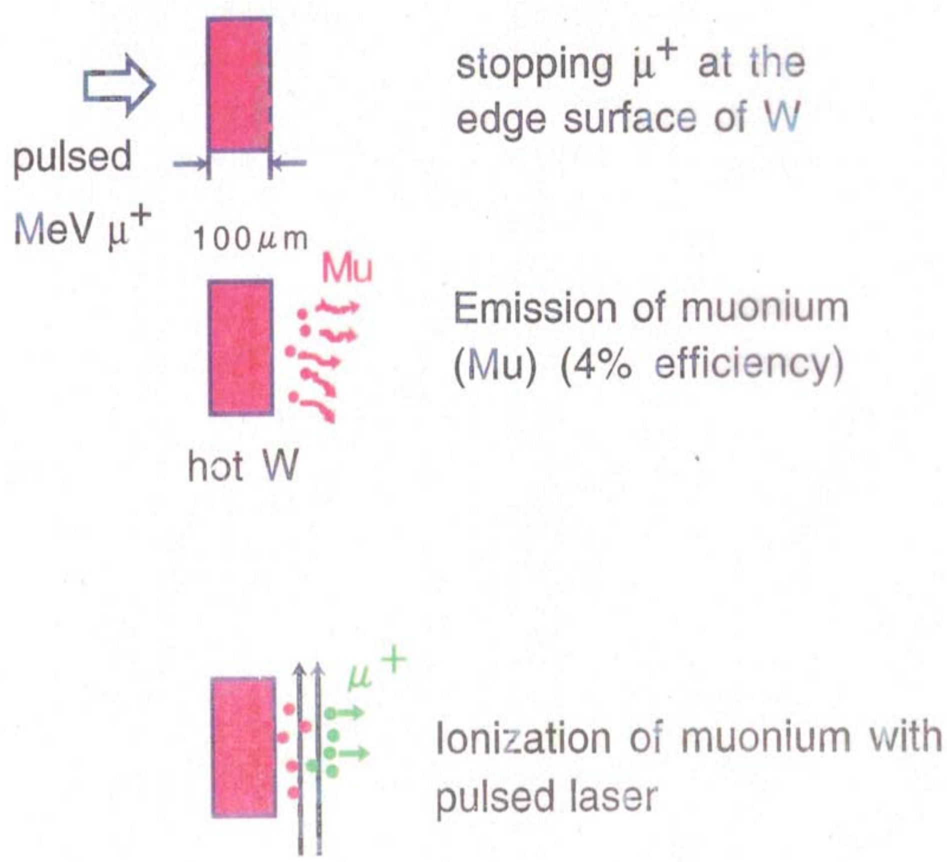
3. Laser Resonant Ionization (1 s → 2 p → unbound )

of Thermal Muonium and Ultra-Slow μ+ Production

*K. Nagamine, Y. Miyake et al.*

*Phys. Rev. Lett. 74(1995)* ***4811***

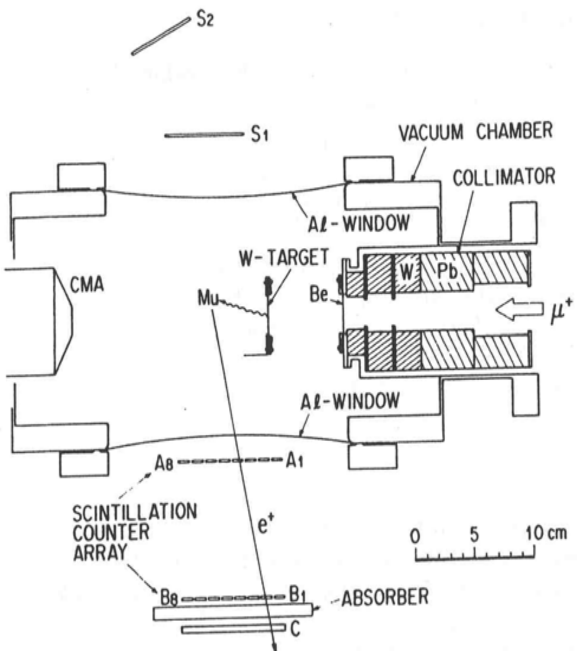
Genaratio of thermal energy muonium in vacuum



# THERMAL MUONIUM PRODUCTION IN VACUUM

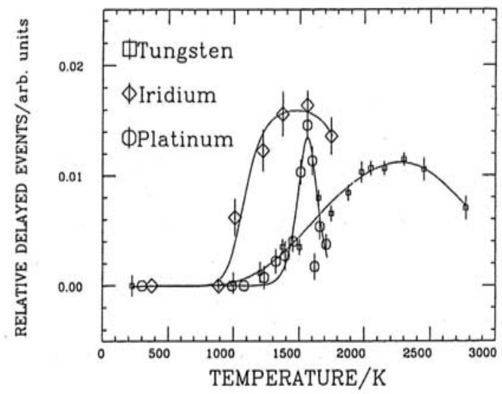
## — *Activities at KEK-MSL* —

Original
Mills et al. (1986)




$N_{Mu}/N_{\mu^+} \simeq 0.04$
$T_{Mu} \simeq T_W$

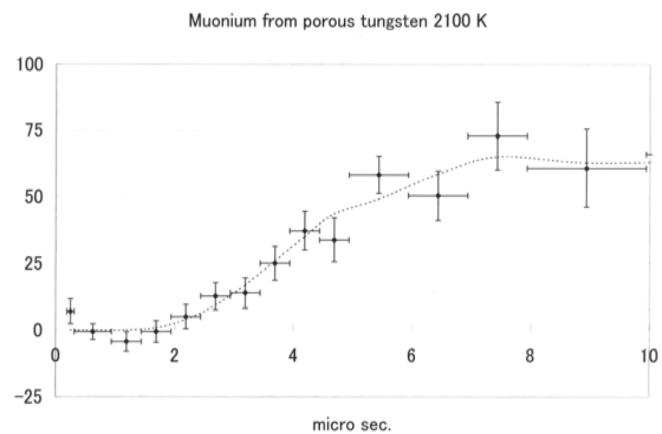
Development
Matsushita et al. (1998)




Physical parameters of thermal Mu [9,18].

| Metal | $E_{Mu}$ (eV) | $E_{ad}$ (eV) | $\phi_H$ (eV) | *Facility* |
|---|---|---|---|---|
| W | 0.66(4) | 2.9 | 1.6 | *KEKMSL* |
| W | 1.72(5) | 2.9 | 1.6 | *KEKMSL* |
| W | 1.3(1) | 2.9 | 1.6 | *RIKEN-RAL* |
| Re | 2.62(3) | 2.8 | 2.0 | *RIKEN-RAL* |
| Ir | 1.4(1) | 2.7 | 1.5 | *KEKMSL* |
| Pt | 2.9(1) | 2.5 | 2.2 | *KEKMSL* |

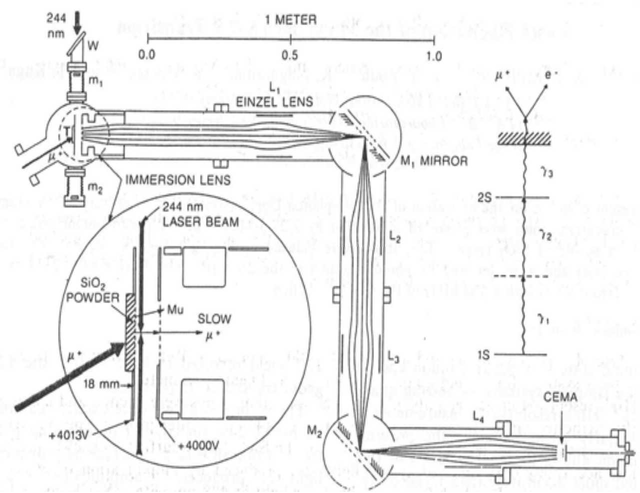
Recent Development
Miyadera et al. (2004)




$N_{Mu}$ (Porus W) $\simeq 2 \times N_{Mu}$ (W)

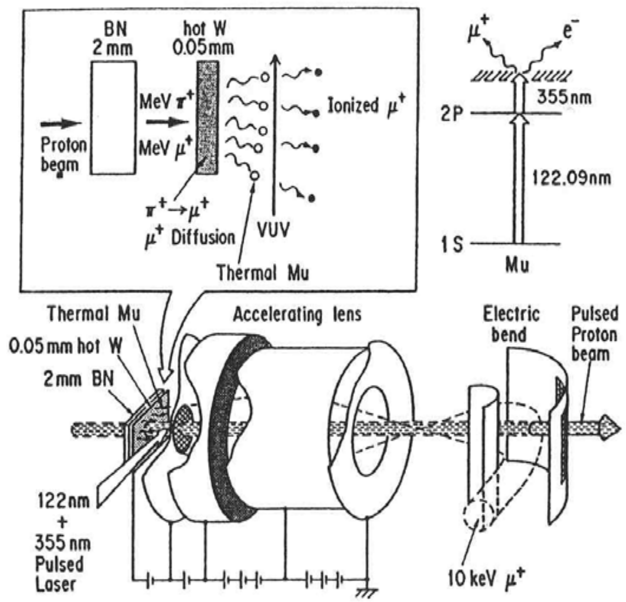
# ULTRA SLOW $\mu^+$ PRODUCTION VIA LASER IONIZATION OF THERMAL Mu

Original
Chu et al. (1989)
(KEK-MSL)



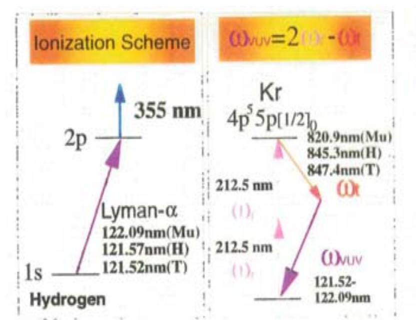

1/h/$10^3$ 4 MeV $\mu^+$

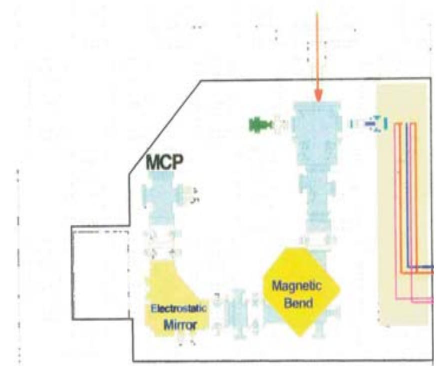
Hot W at Proton Beam
Nagamine, Miyake et al. (1995)
(KEK-MSL)




1/min/2 $\mu$A500 MeV p

Hot W at 4 MeV $\mu^+$ Beam
Bakule, Matsuda et al. (2002)
(RIKEN-RAL)




1/s/$10^5$ 4 MeV $\mu^+$

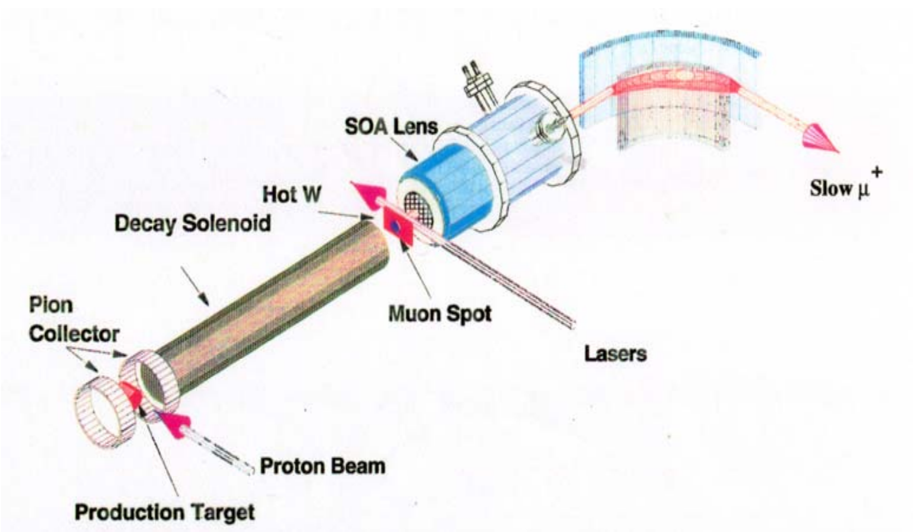
# INTENSE ULTRA SLOW $\mu^+$ IN THE NEAR FUTHRE (1)

FEFICIENT $\pi/\mu$ COLLECTOR

High Intensity Proton Driver
(1 GeV $\times$ mA $\rightarrow$ MW)

Full $\pi/\mu$ Capture

$\mu^+$ Stopping & Zero-Energy $\mu^+$ Production

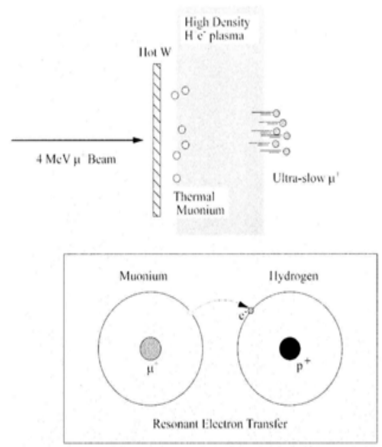



FEFICIENT Mu IONIZATION

i) Resonant $e^-$ Transfer in High Density H Plasma

$$Mu + H^+ \rightarrow H + \mu^+$$

$$\sigma_{Tr} \simeq 5 \times 10^{-15}\ cm^2$$



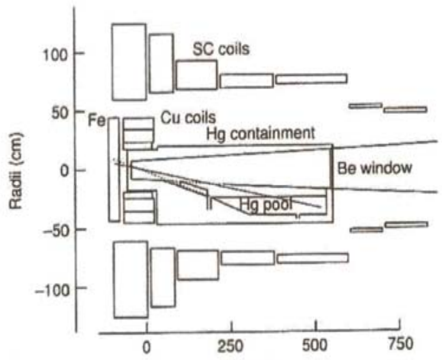

ii) Multi-Photon Mu Ionization by femto-sec Laser Pu

iii) Laser Impact Ionization of Mu at Surface

# π/μ COLLECTION AND MUON TRANSPORTATION

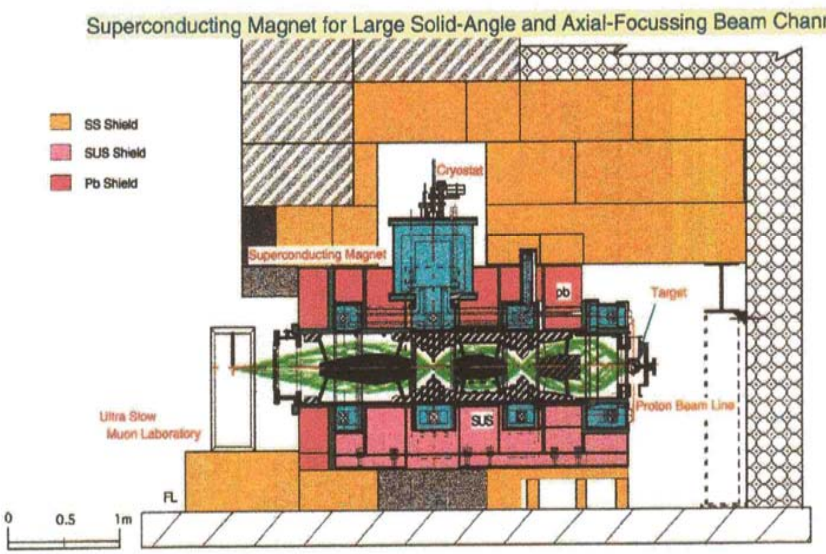
☆Based Upon Recent Progress in the Studies of Neutrino-Factory and μμ Colliders

Full Solid Angle Capture



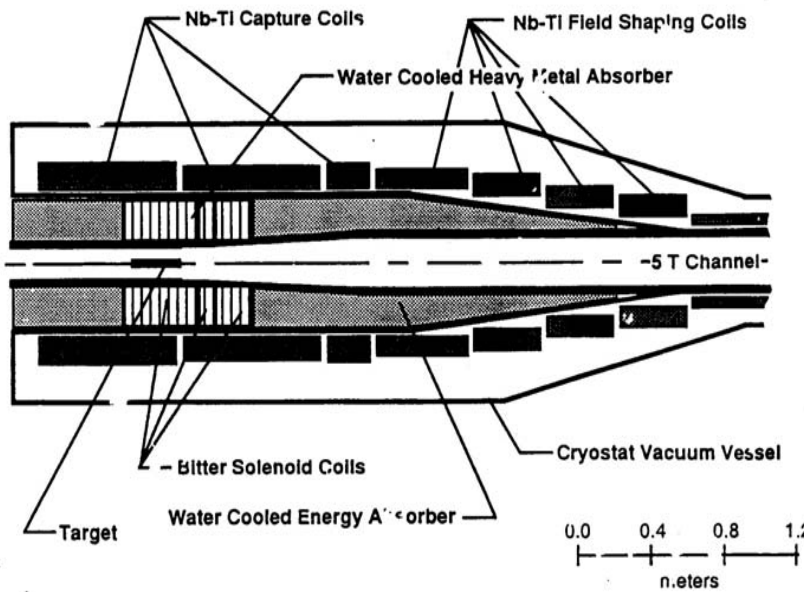
(*a*)

1 Str Acceptance for Surface $\mu^+$, DAI-OMEGA at KEK



# INTENSE ULTRA SLOW $\mu^+$ IN THE NEAR FUTHRE (2)

**Realization of more than $10^{10}$/s Ultra Slow $\mu^+$**




| | Expected Numbers ($s^{-1}$) | Conditions & Remarks |
|---|---|---|
| $N_p$ | $7.6 \times 10^{15}$ | 1 GeV × 1mA (1 Mw) |
| $N_{\pi^+}^{tot}$ | $4.8 \times 10^{13}$ | $\sigma_{\pi^+}^{tot}$ : 28mb |
| $N_{\mu+}$ | $4.8 \times 10^{12}$ | Pion Capture 2.9 T 20 cm Bore × 1.5m<br>Pion Decay 3.0 T, 25 cm Bore × 10 m<br>Full Reflection |
| $N_{Th\,Mu}$ | $\simeq 10^{12}$ | Full Stopping(100 × 10 μm Poruns W)<br>20 % Conversion |
| $N_{us\mu+}$ | $\simeq 10^{12}$ | Full Ionization |

# TOWARDS PRODUCTION OF MUONIOC ANTI-HYDROGEN

## POSSIBLE CROSSED-BEAM EXPERIMENT

$$\mathrm{Mu} + \bar{p} \rightarrow \bar{p}\mu^+ + e^-$$

$$a_0 \qquad \frac{1}{207}\, a_0$$

$$E_{1s}^{e} \qquad 207\, E_{1s}^{e}$$

$$\sigma_{Tr} \simeq 10^{-4}\, \pi\, a_0^2$$

$$\text{at } E_{\bar{p}} \simeq 207\, E_{1s}^{e}$$

$$\text{cf. } (\mu^+\mu^-) + p \leftarrow \mu^- p + \mu^+$$

$$\frac{2}{207}\, a_0 \qquad \frac{1}{207}\, a_0$$

$$\frac{207}{2}\, E_{1s}^{2} \qquad 207\, E_{1s}^{e}$$

$$\sigma_{Tr} \simeq 10^{-4}\, \pi\, a_0^2$$

$$\text{at } E_{\mu+} \sim 207\, E_{1s}^{e}$$

Q.C. Ma et al. Phys. Rev. 32A (1985) 2645

# FURTHER EFFICIENCY INCREASE

## *— Optimization of Time, Space, Character —*

☆Time Compression/Bunching

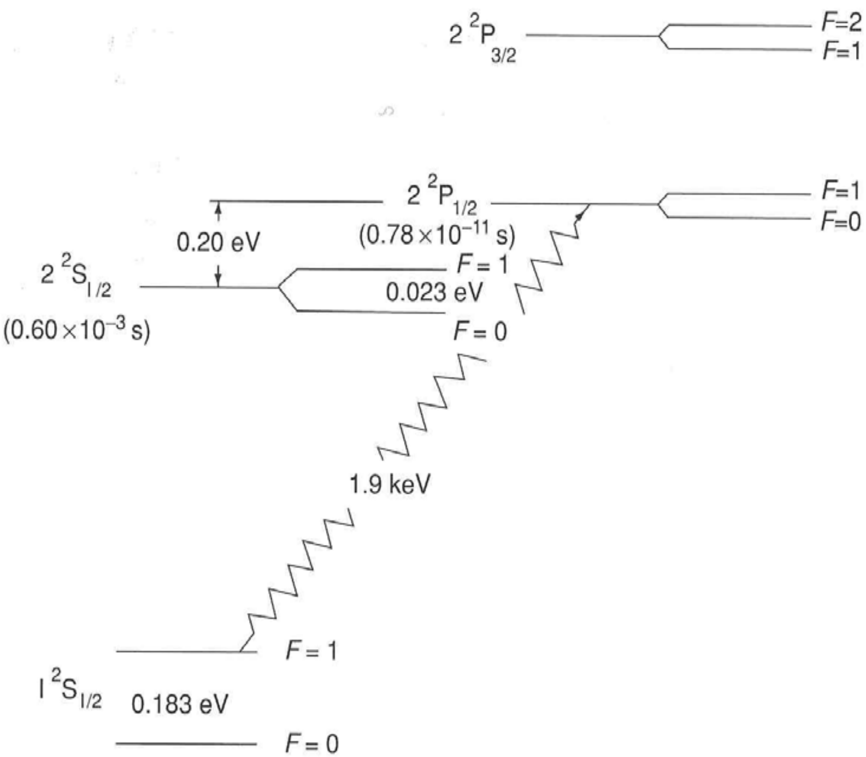
☆Acceleration & Micro-Beam

### *Yield Estimation*

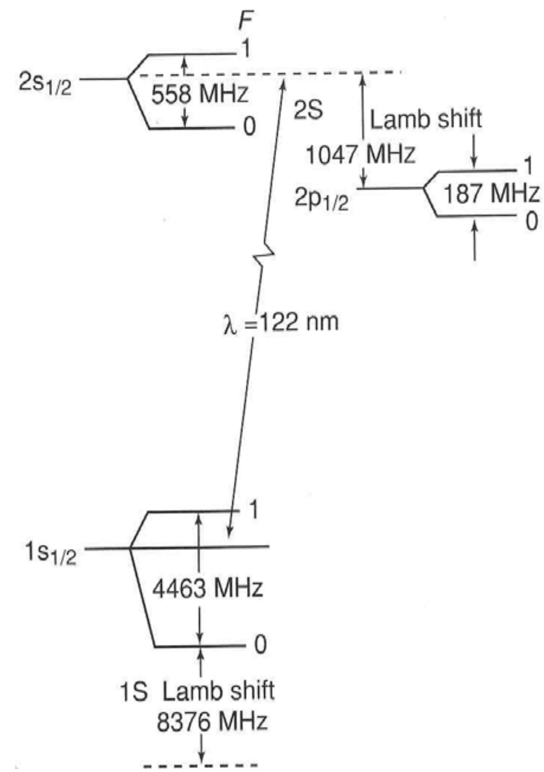
$$I_p \cdot N_{Mu} \cdot \sigma_{Tr} \simeq 1/s$$

$10^{10}$/s  $10^{10}$  $10^{-20}$ (cm$^2$)

# POSSIBLE HIGH-PRECISION SPECTROSCOPY FOR TEST OF CPT THEOREM BY USING MUONIC HYDROGEN/ANTI-HYDROGEN

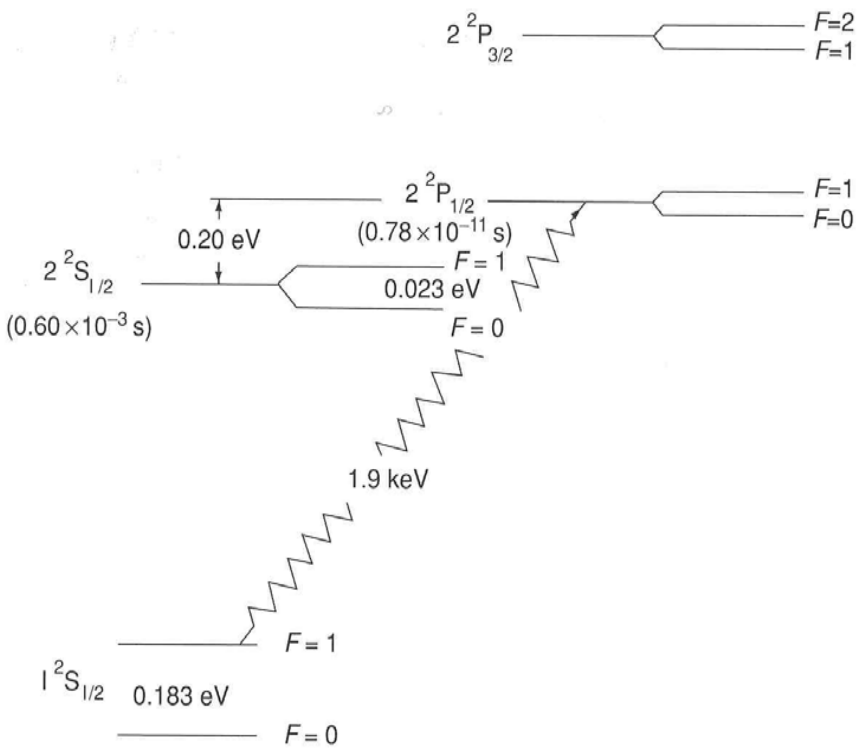



$\mu^{-}p$ and $\mu^{+}\bar{p}$ under CPT conservation




$e^{-}p$ and $e^{-}\mu^{+}$

# POSSIBLE OBSERVABLES FOR HIGH PRECISION LASER SPECTROSCOPY




1. Hyperfine Splitting at the Ground State

   $\Delta E$ (n = 1, hfs) = 0.18 eV (6.89 μm)

   Resonance Signal Detection:

   Range, Polarization, Transfer to H

2. Lamb Shift (Vacuum Polarization at n =

   $\Delta E$ ($2^2p_{1/2} - 2^2s_{1/2}$) = 0.20 eV (6.20 μm)

   Resonance Signal Detection:

   Missing $K_\alpha$ X-ray

   Laser is available!

   $CdGeAs_2$ (K. Kato et al.)

no ($\mu^-p$) experiment So far!

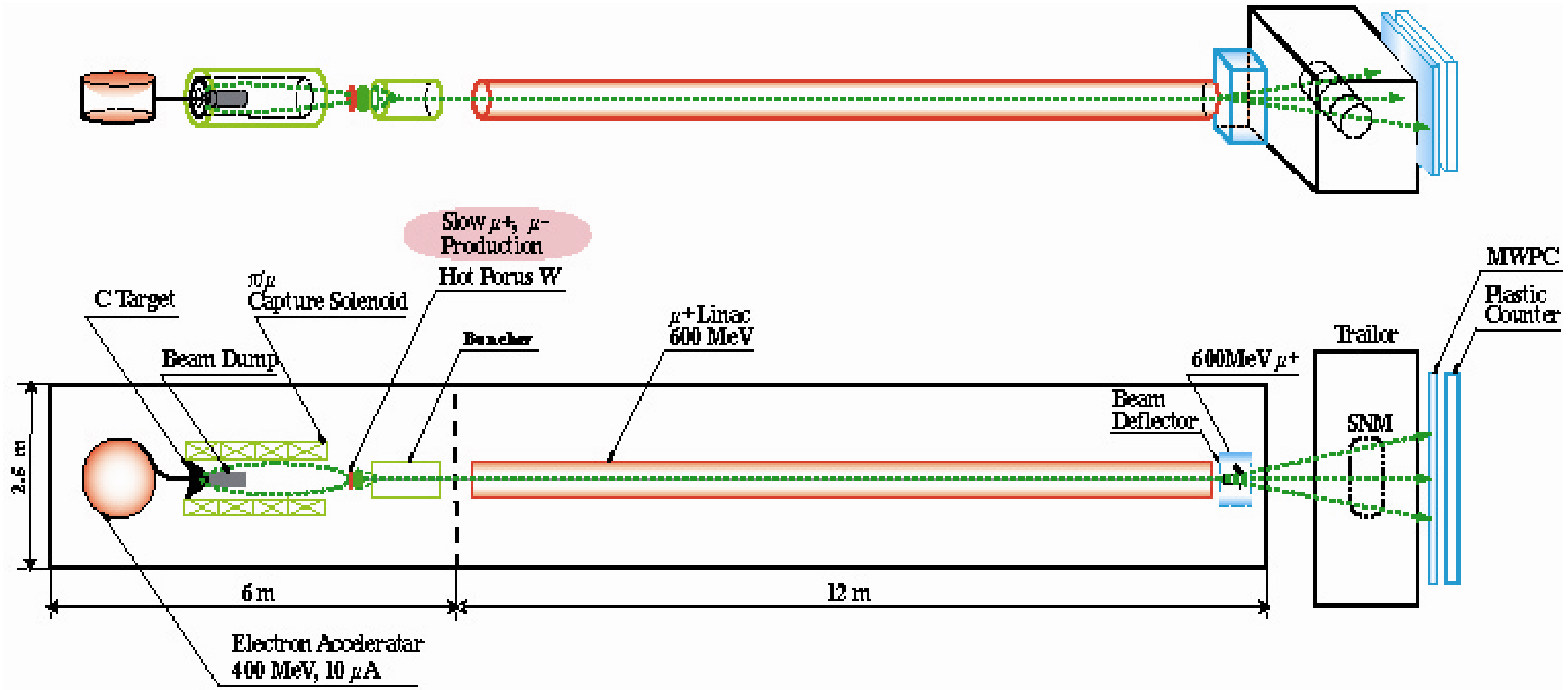
# CONCLUSION;
# FUTURE PERSPECTIVES

1. Muonic Anti-Hydrogen is not a Dream and to be realized in the 21st century

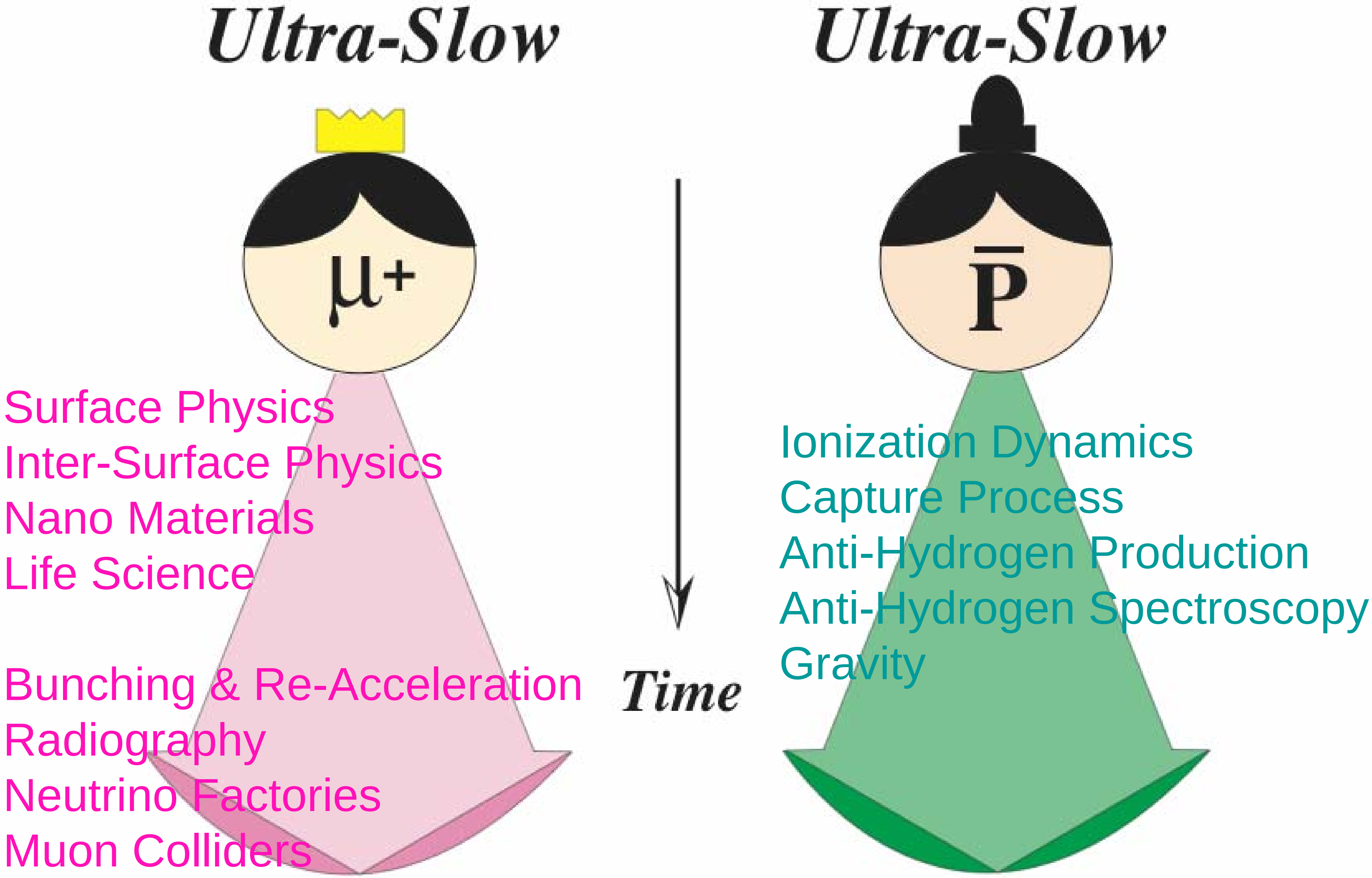
   The technology of intense and high-quality $\mu^+$ and $\bar{p}$ beam will take a rapid development *independently*, because of the needs of each community.

   Good communication between Low Energy Muon Science and $\bar{p}$ Physics Community should be encouraged.

2. Need of theoretical works on CPT violation effect in Muonic Anti-Hydrogen

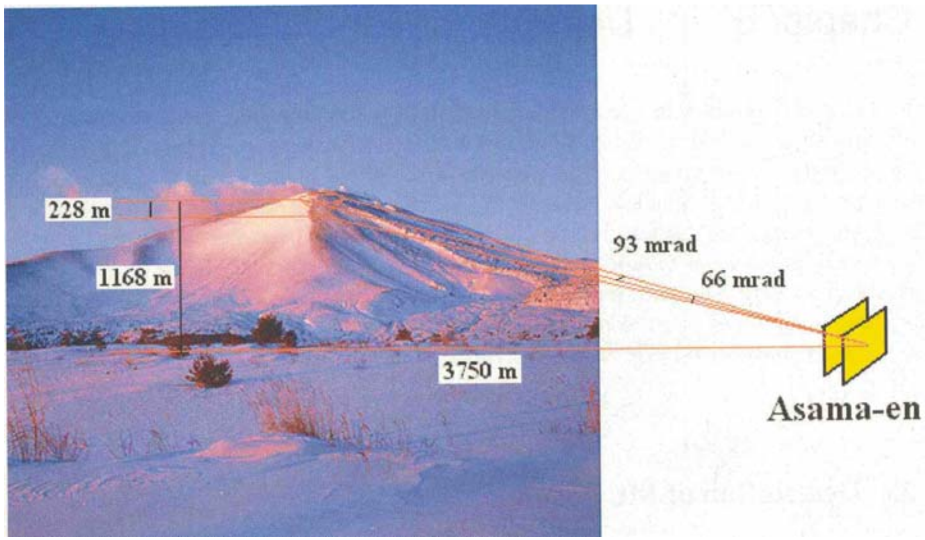



*Proposed accelerator systems for the advanced muon radiography*

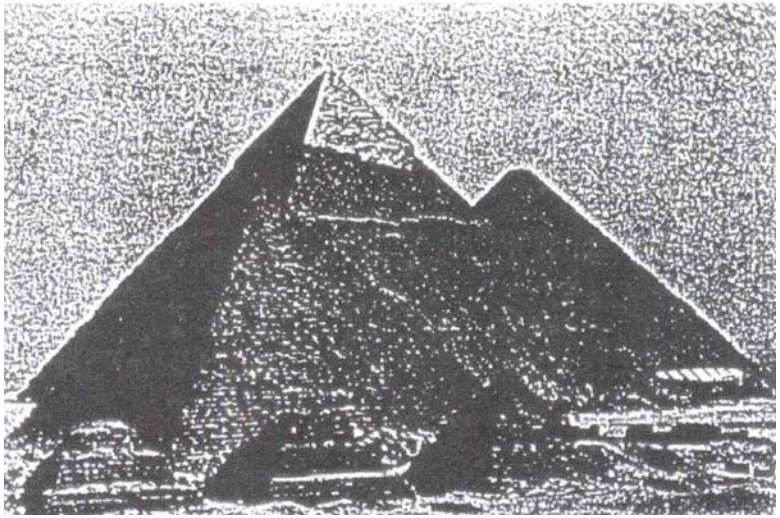

Ultra-Slow
Ultra-Slow
μ+
P̄
Time
Surface Physics
Inter-Surface Physics
Nano Materials
Life Science
Bunching & Re-Acceleration
Radiography
Neutrino Factories
Muon Colliders
Ionization Dynamics
Capture Process
Anti-Hydrogen Production
Anti-Hydrogen Spectroscopy
Gravity

# LOOKING INNER-STRUCTURE FROM OUTSIDE

## — *Keeping Objective as it is* —

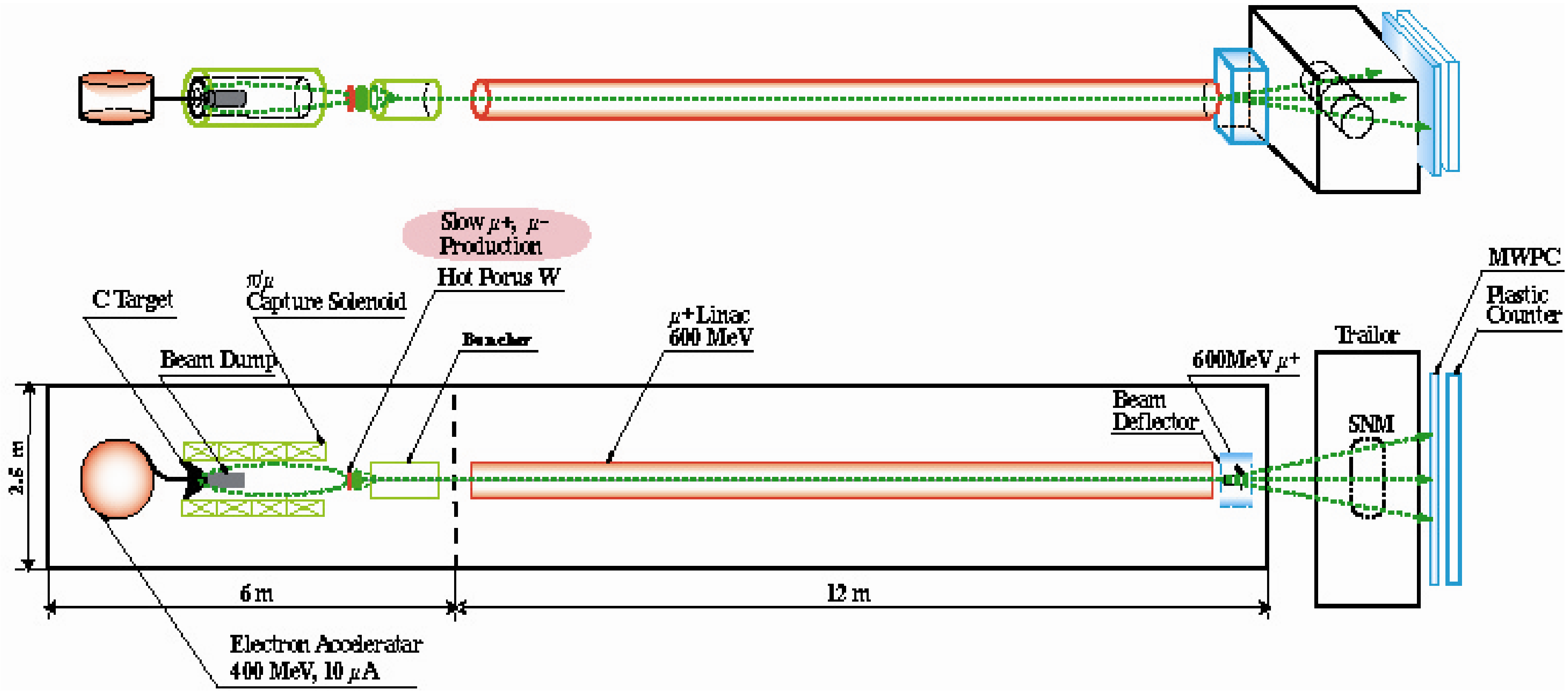



Volcano



Pyramid


Blast Furnace

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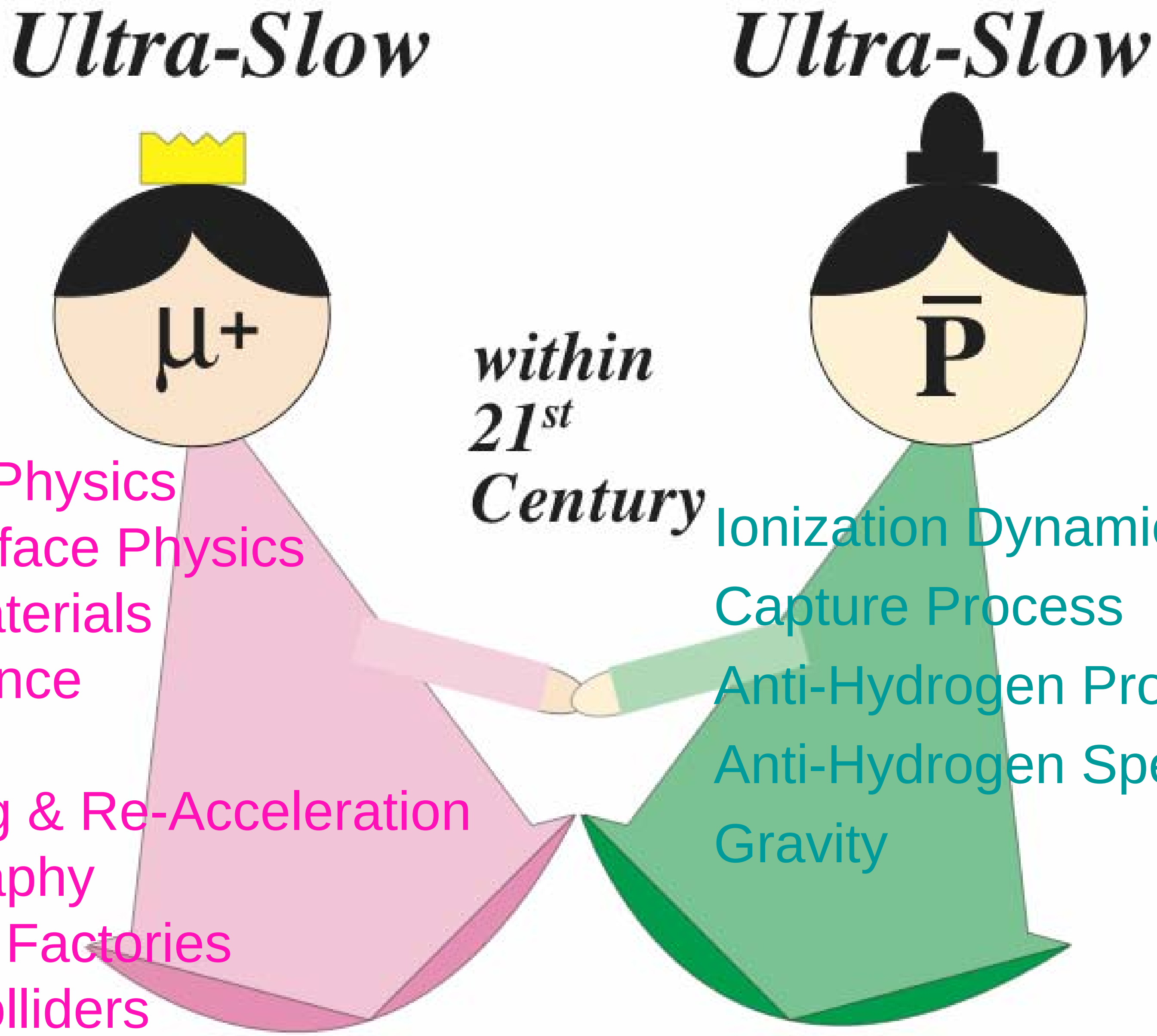


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