超低速反陽子と原子分子衝突実験装置の開発

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DEVELOPMENT OF AN EXPERIMENTAL APPARATUS FOR COLLISIONS BETWEEN ULTRA-SLOW ANTIPROTONS AND ATOMS/MOLECULES

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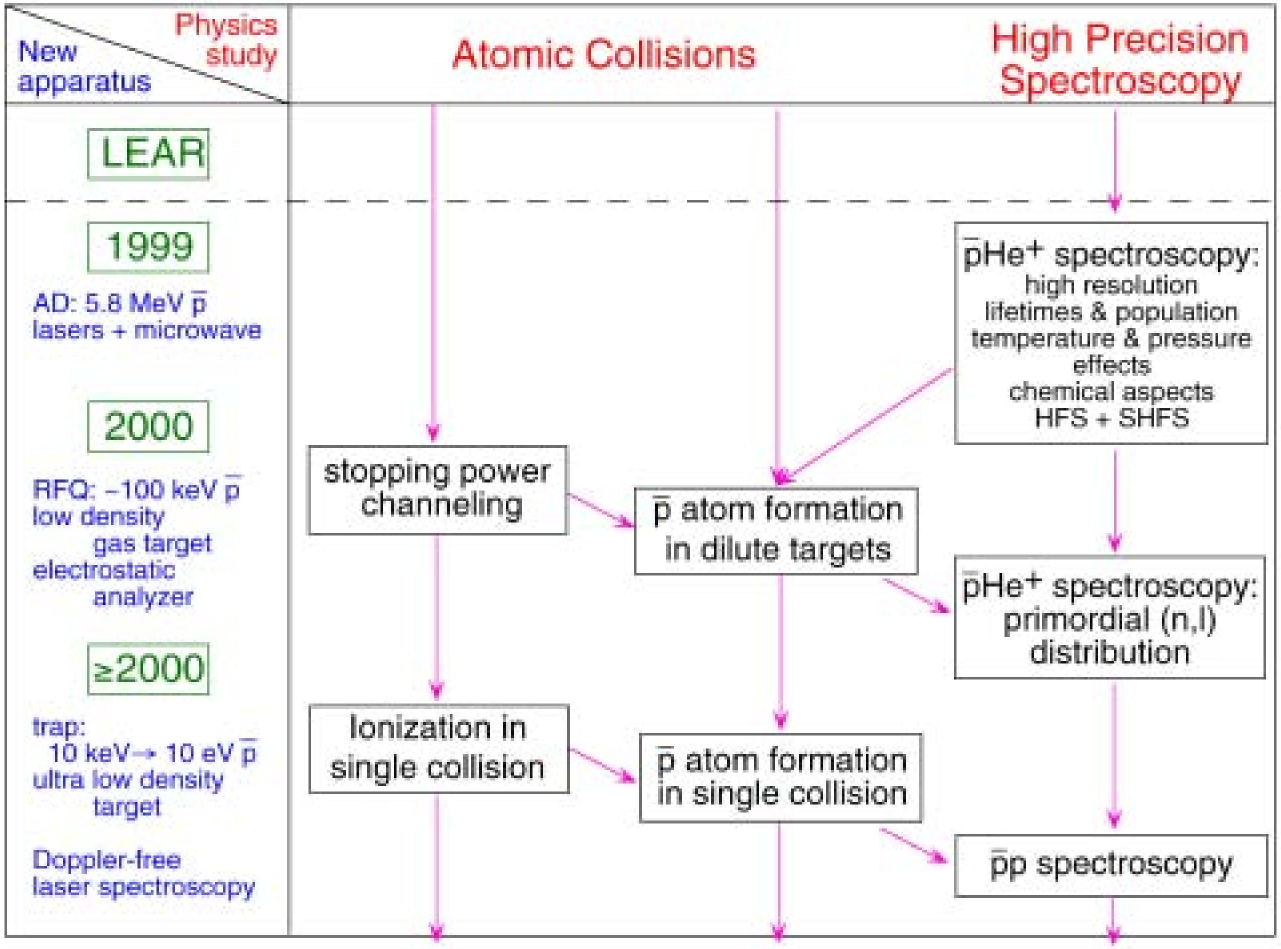
Atomic Spectroscopy And Collisions Using Slow Antiprotons (ASACUSA)



Physics study New apparatus	Atomic Collisions		High Precision Spectroscopy
LEAR			
1999 AD: 5.8 MeV $\bar{p}$ lasers + microwave			$\bar{p}He^+$ spectroscopy: high resolution lifetimes & population temperature & pressure effects chemical aspects HFS + SHFS
2000 RFQ: ~100 keV $\bar{p}$ low density gas target electrostatic analyzer	stopping power channeling	$\bar{p}$ atom formation in dilute targets	$\bar{p}He^+$ spectroscopy: primordial (n,l) distribution
≥2000 trap: 10 keV → 10 eV $\bar{p}$ ultra low density target Doppler-free laser spectroscopy	Ionization in single collision	$\bar{p}$ atom formation in single collision	$\bar{p}p$ spectroscopy

Protonium ($\bar{p}p$):

The simplest two-body system consisting of a particle and an antiparticle

$$\bar{p} + H \rightarrow \bar{p}p + e^{-}$$

$$\bar{p} + H_2 \rightarrow \bar{p}p + H + e^{-}$$

- Why ultra-slow antiproton?

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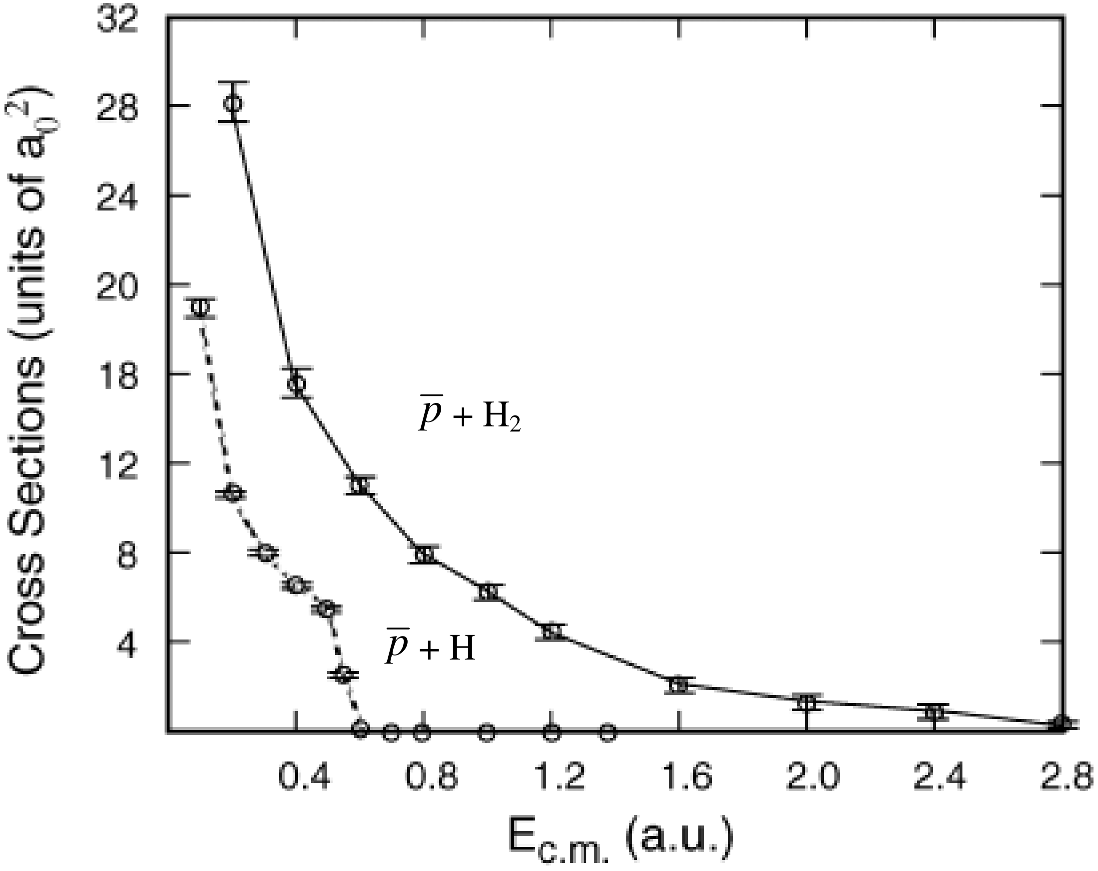


CTMC simulation of protonium formation cross sections

- How to make ultra-slow antiproton beam
- How to detect antiprotonic atoms?

$$\bar{p} + H \rightarrow \bar{p}p + e^-$$

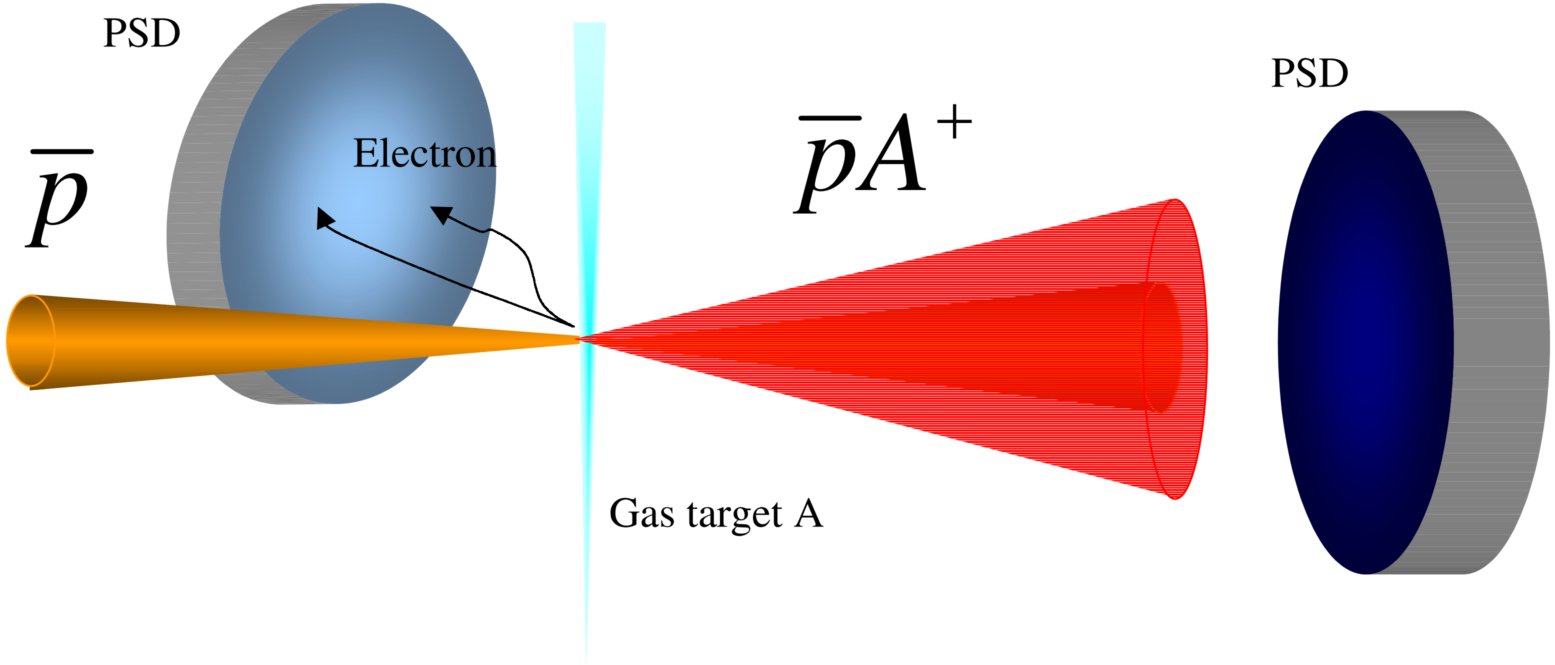
$$m_{\bar{p}} v_{\bar{p}} = (m_{\bar{p}} + m_p) v_{\bar{p}p} + m_e v_e$$

→ $$v_{\bar{p}p} = \frac{1}{2} v_{\bar{p}}$$

→ TOF measurement

→ Start signal: Electron released from target

Stop Signal: Annihilation of antiproton



Schematic drawing of antiprotonic atom detection

Antiprotonic atom formation processes

$$\bar{p} + A \rightarrow \bar{p}A^{+} + e^{-}$$

$$N_{\bar{p}A^{+}} / N_{\bar{p}} = \sigma_{\bar{p}A^{+}} n_{A} L \sim 0.1\%$$

$\sigma_{\bar{p}A^{+}}$	: Formation cross section	~ 10^{-16} cm^{2}
$N_{\bar{p}}$	: Number of antiprotons	~ 10^{6}/pulse
L	: Interaction length	~ mm
$N_{\bar{p}A^{+}}$	: Number of p-bar atoms	0.1% of $N_{\bar{p}}$
n_A	: Target density	10^{14} cm^{-3}

→ High Density $n_A L = 10^{14}$ cm^{-2}

Why H_2?

	Physics	Theoretical calculation	Target density	Cross section
H_2 target	Five-body	Only 1 (CTMC)	10^{13} cm^{-3}	High
H target	Three-body	Some	10^{10} cm^{-3}	Low

Basic Requirements for the Collision chamber:

1. 0.1% Reaction ratio

   → High Density $nL = 10^{14}$ cm^{-2} (10^{13} cm^{-3} × 1 cm)

   ↔ High gas load

2. Space for detector installation

   → 10 cm free space (in height)

   ↔ Density decrease with R^2

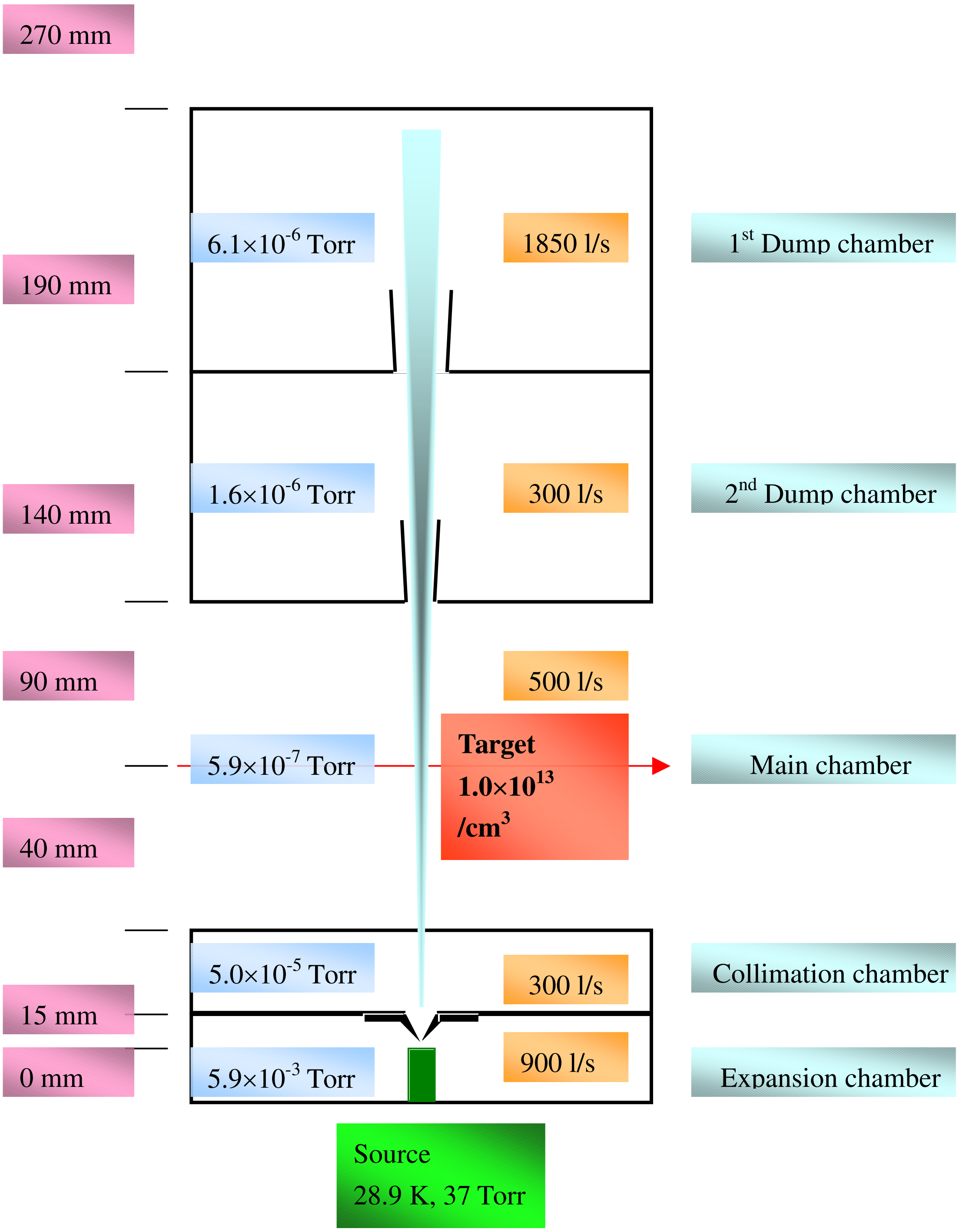
3. Differential pumping for trap and beamline

   → $< 10^{-6}$ Torr @ Collision chamber

   ↔ High Pumping requirements, especially for a large flow and H_2

Comparisons for three gas targets

	Gas Cell	Micro-capillary	Supersonic gas jet
Structure	Simple	⇒⇒	Complex
High Density Availability	Easy	Difficult	Difficult
Effective Length	Calibration	?	Geometrically
Vacuum	OK	?	OK
Pumping requirements	Low	Low	High
Feasibility	electron detection ×	Divergence ×	Pumping requirement



270 mm

6.1×10^{-6} Torr

1850 l/s

1^{st} Dump chamber

190 mm

1.6×10^{-6} Torr

300 l/s

2^{nd} Dump chamber

140 mm

90 mm

500 l/s

5.9×10^{-7} Torr

Target
1.0×10^{13}
$/cm^3$

Main chamber

40 mm

5.0×10^{-5} Torr

300 l/s

Collimation chamber

15 mm

0 mm

5.9×10^{-3} Torr

900 l/s

Expansion chamber

Source
28.9 K, 37 Torr

Schematic drawing of the supersonic gas jet

Increase the effective length to from 5 mm to 10 mm

Reduce the gas density requirement to half

Advantage of cooling

With the same geometry the total gas load can be reduced for the same density.

Total gas load $N \sim n_0 \sqrt{T_0} d_0^2$

Gas density at collision center $n \sim n_0 d_0^2$

n_0: number density in the gas container

T_0: temperature in the gas container

d_0: diameter of the nozzle

Advantage of elliptical beam

Reduce the total flow load at main chamber

Improve differential pumping

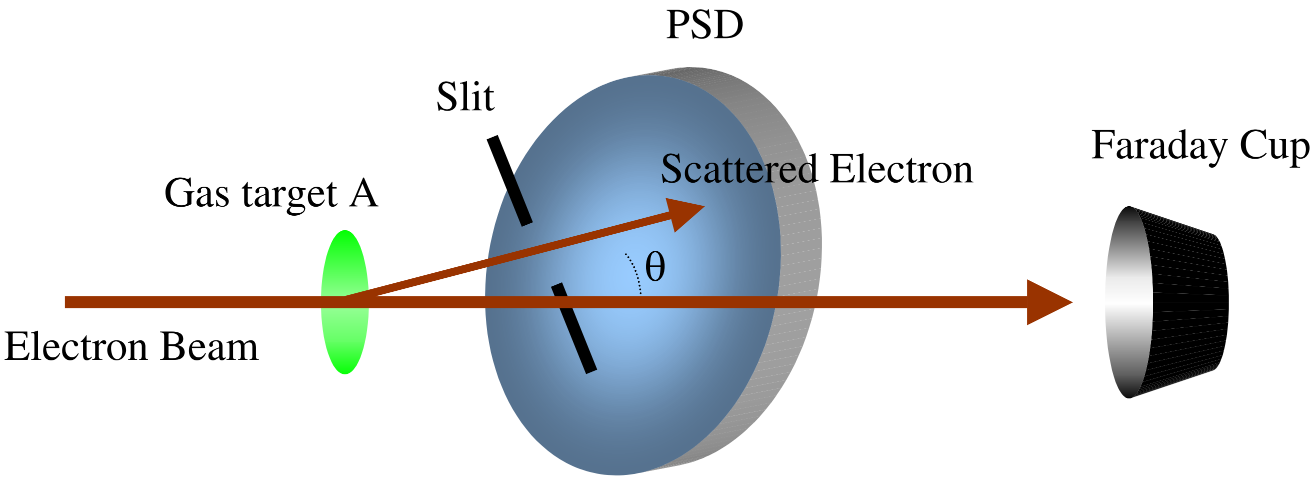
R. D. Miller, *Free Jet Sources*,
Atomic and Molecular Beam Methods, Vol. 1 (Oxford Express, 1988)

To avoid the dimer formation exceeding ~1%

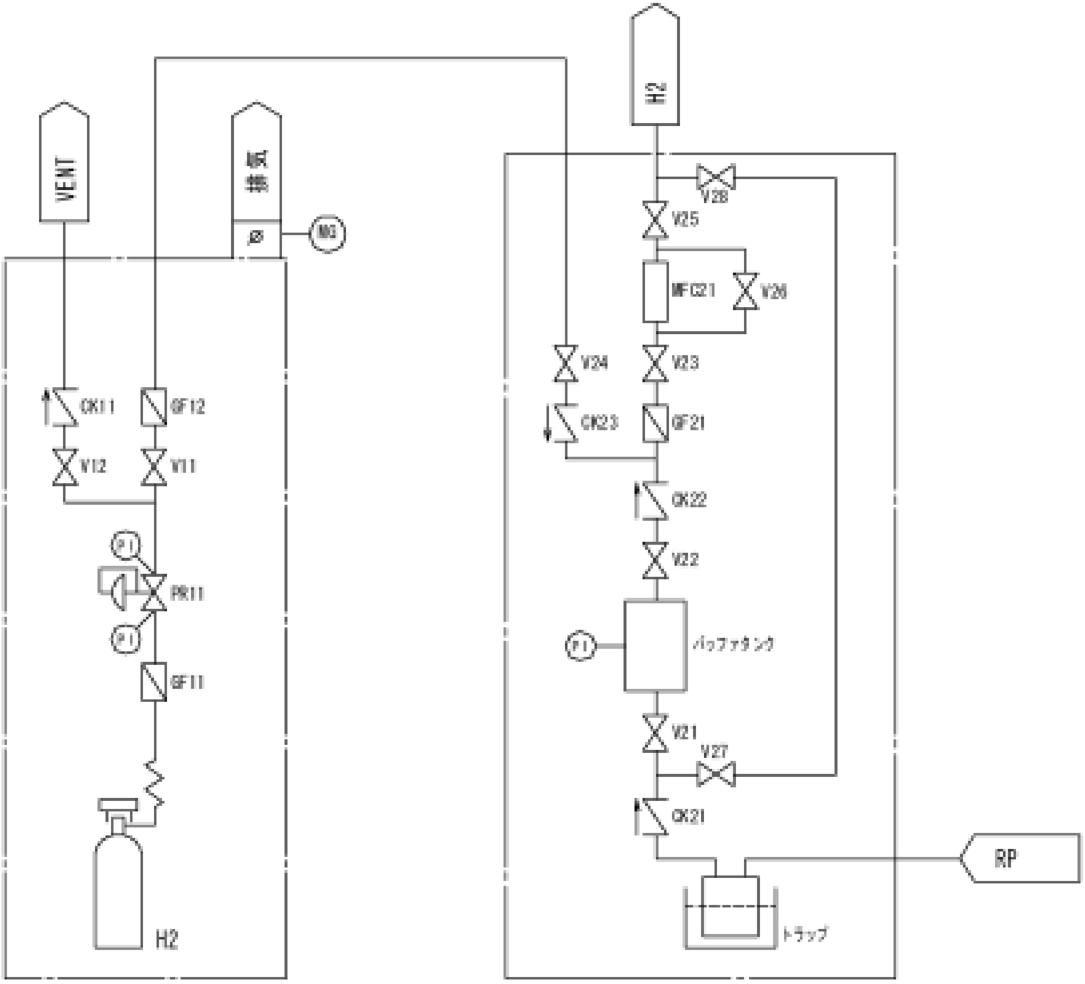
$$D^* = \frac{p_0}{\left(\frac{\varepsilon}{\sigma^3}\right)} \left(\frac{d_0}{\sigma}\right)^{0.4} \left(\frac{T_0}{\frac{\varepsilon}{k}}\right)^{-2.4} < 0.1$$

ε/k and σ are Lennard-Jones potential parameters

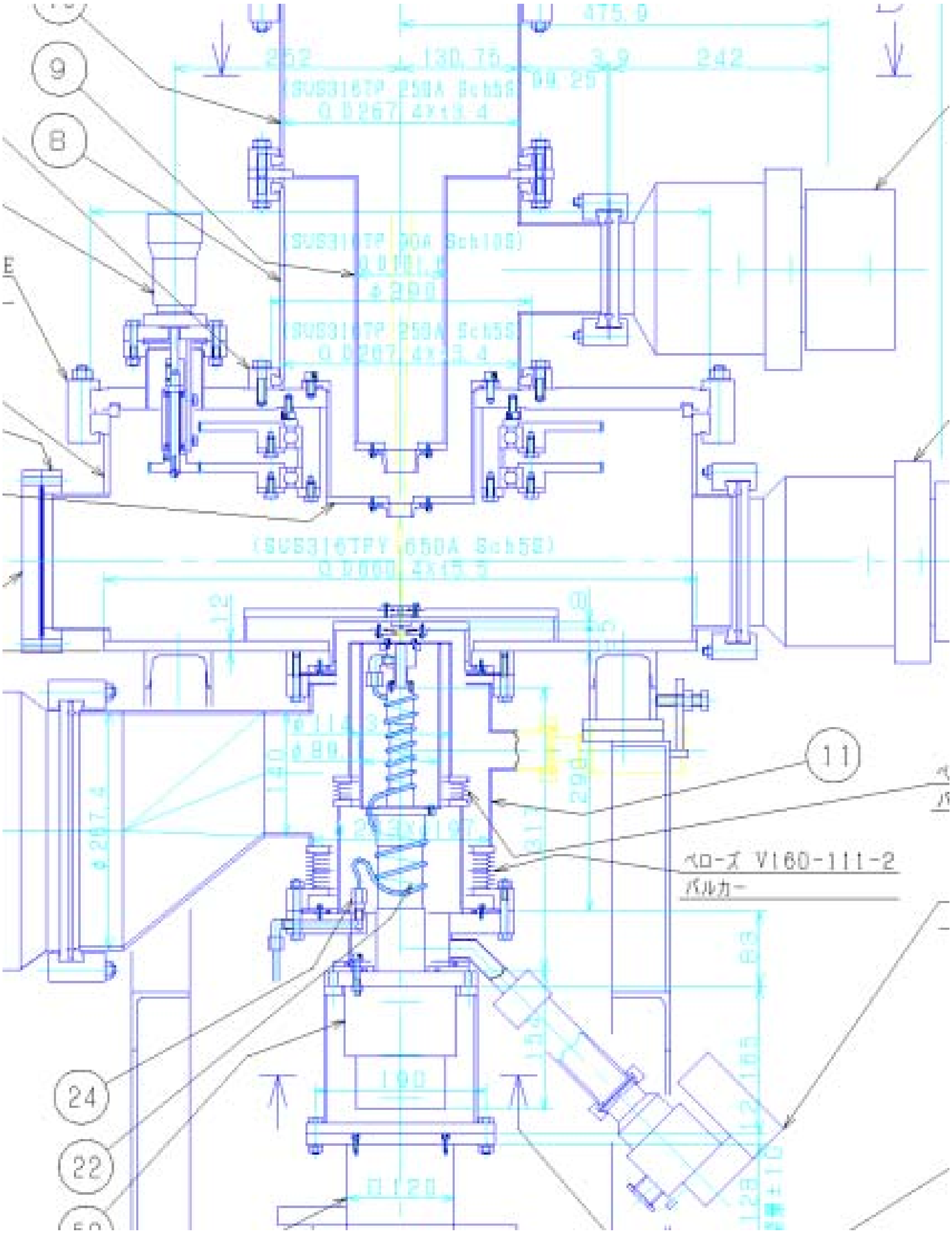
Cluster formation



Density measurement and cluster detection



Gas Recycling setup



Drawing of the chamber design (1)

Schedule

May 7 - June 1:	ESA run (dE/dx) (+ RFQD study)
June 4 - July 6:	TRAP + extraction beam line commissioning
July 9 - September 28:	antiprotonic helium
October 1 - October 26:	pbar on molecular hydrogen

Acknowledgements

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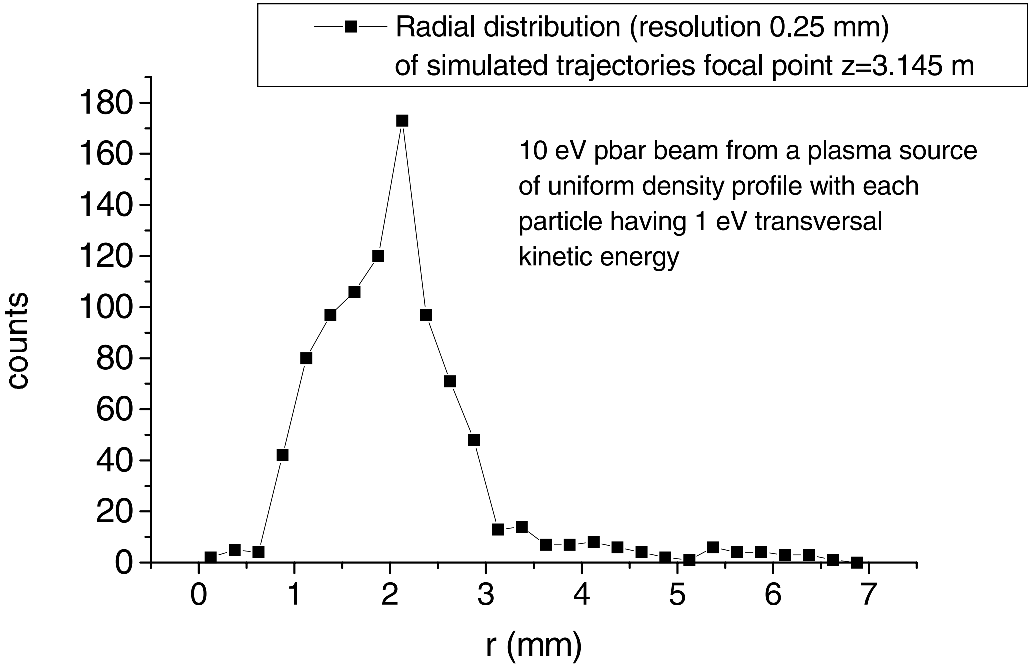
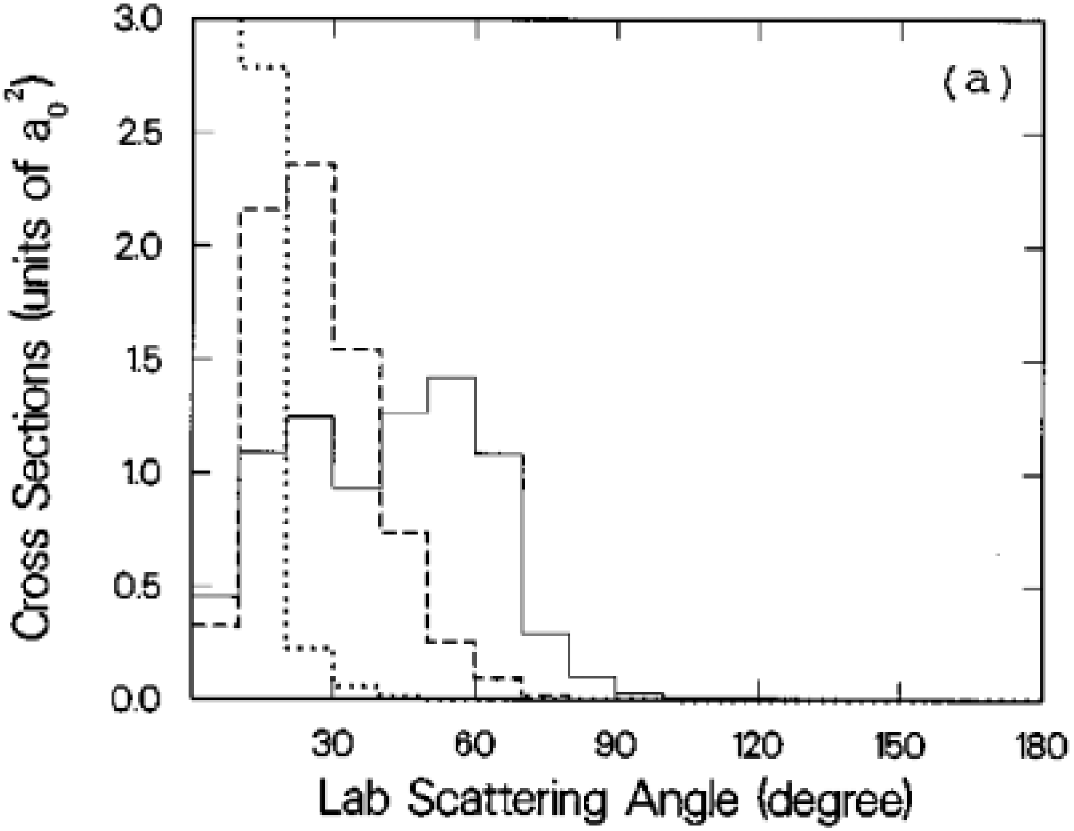
理研	神原正　様



Simulated antiproton beam profile at the collision center.



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Histogram of angular distributions of *protonium* atoms (full curve); free *pbar* accompanied by *reactive* scattering (dashed curve); and free *pbar* accompanied by non-reactive or electronic excitation scattering (dotted curve) in collisions of *pbar* with H_2 at a c.m. energy of 0.8 a.u. (laboratory energy of 32.6 eV)