Basic study on polarized D-D fusion

International Symposium on Polarized Target and its Application
Tsukioka-Hotel, Kaminoyama-Onsen, Yamagata

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Content of the Talk

- Merit of the Polarized Fusion
- Our past challenge to the confirmation of the merit
- Possible future plan to the confirmation

Realization of nuclear fusion

Nuclear Fusion: the most expected method to pull out the energy in the future

- Controllable fusion

    fundamental research on fusion by test reactor

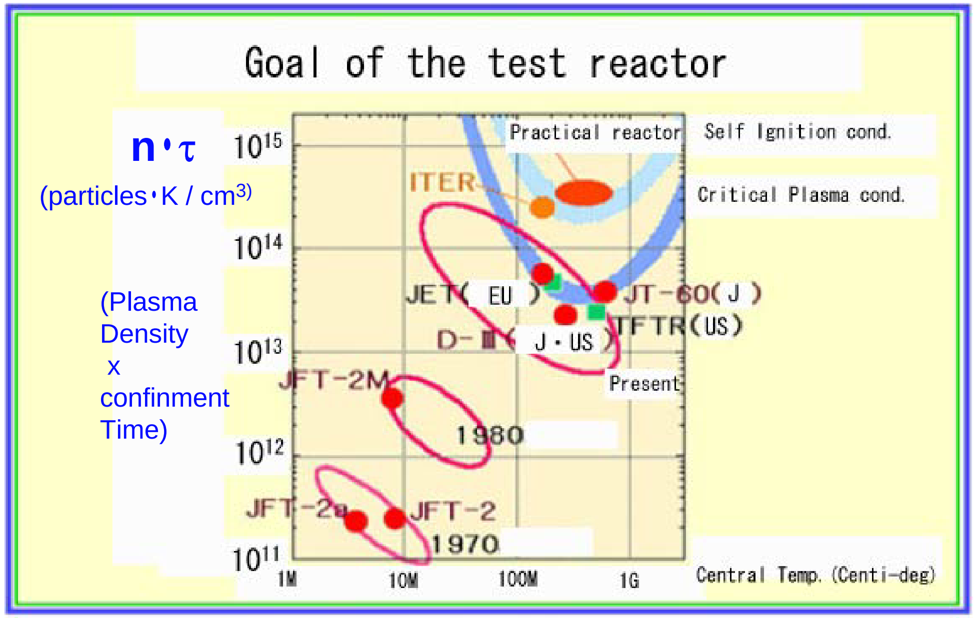
- Proof of controllable fusion by real equipment

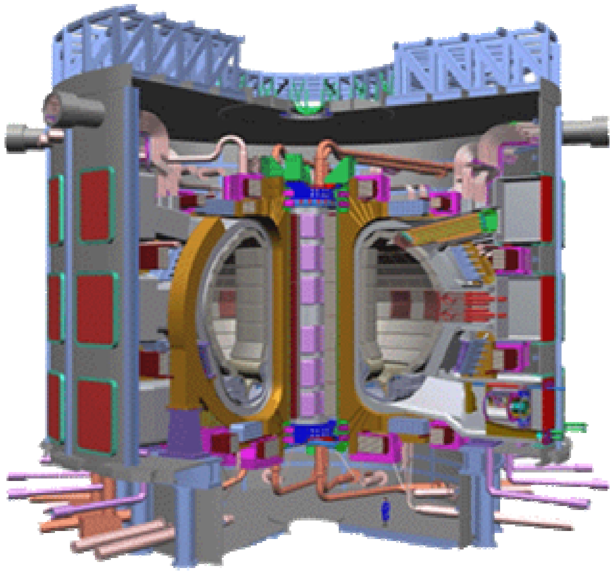
    Is it really feasible on size, long-time run etc.?

- Estimation of economical aspect

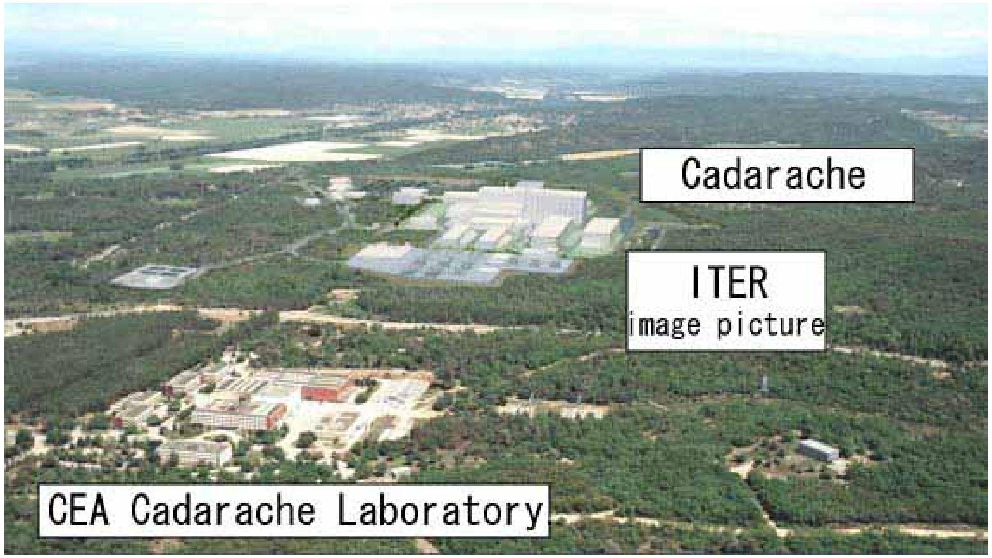
    Is the cost performance OK?

For the controllable fusion--ITER





ITER reactor



ITER:International Thermonuclear Experimental Reactor

To the Effective Fusion

—— Possible Spin Polarized Fusion ——

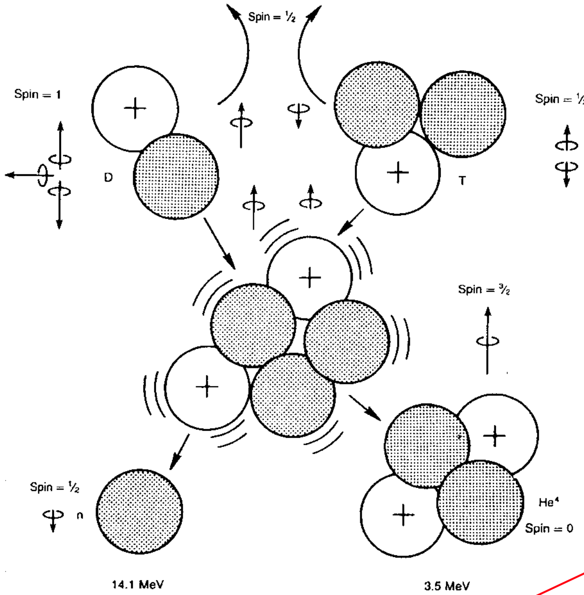
news search & discovery

Polarized plasmas may prove useful for fusion reactors

A casual cocktail-party inquiry by Maurice Goldhaber (Brookhaven) has set in motion the detailed examination of a quite novel approach to fusion in magnetic-confinement reactors. Last winter Goldhaber asked Harold Furth, director of the Princeton Plasma Physics Laboratory, whether he had ever considered polarizing the nuclear spins in a magnetically confined reactor plasma. The answer was *no*, basically because naive considerations lead one to expect that such a polarized hot plasma would much too quickly become thermally depolarized.

But the depolarization mechanisms in a reactor environment had never been examined in detail; and if one could keep a fusion plasma highly polarized long enough, several very desirable consequences could be exploited. Therefore Goldhaber and Furth, together with Russell Kulsrud and Ernest Valeo of Princeton, set out to calculate the depolarization rates that would result from various mechanisms in a toroidal or mirror fusion reactor, and to examine the benefits one could expect from various polarization schemes. In a recent Princeton Plasma Physics Laboratory Report,[1] discussed at the International Conference on Plasma Physics (Göteborg, Sweden, 9–15 June), Kulsrud and his coworkers reach the surprising conclusion that a polarized D–T, D–D or D–He^3 plasma would maintain its polarization against collisions at better than 95% for about 100 seconds in a magnetic fusion reactor—five times the life expectancy of a plasma nucleus in a tokamak.

The benefits to be expected from the polarization of a D–T, D–D or D–He^3 plasma—enhancement of desired fusion cross sections, suppression of unwanted reactions, and control of the direction of emergence of fusion products—would of course come to nothing if one were unable to supply the reactor with adequate inputs (amperes) of polarized nuclei at acceptable power cost. Happily, two recently developed techniques for producing polarized nuclei in profusion show promise in this regard. A group led by Will Happer (Princeton) has been investigating[2] the polarization of xenon nuclei by spin exchange with optically pumped rubidium. Richard Cline, Thomas Greytak and Daniel Kleppner at MIT have recently reported[3] that their high-magnetic-field, cryogenic technique for stabilizing spin-polarized atomic hydrogen (PHYSICS TODAY, June 1980, page 18) can yield protons with 99% polarization. Both groups expect that their methods can be applied straightforwardly to produce amperes of highly polarized deuterons. The optical pumping technique, Happer told us, should also be directly applicable to He^3, which, like xenon, is a noble gas.



Deuterium–tritium fusion at reactor energies proceeds primarily through an intermediate spin-3/2 resonance of He^5, 107 keV above the sum of the D and T masses. A deuteron–triton collision in a spin-½ state will contribute almost nothing to the fusion cross section. Thus if one could align all D and T spins parallel to the reactor's magnetic field, the fusion cross section would be enhanced by 50%. The emerging energetic alpha and neutron come off with an $\ell = 2$, $\sin^2\theta$ angular distribution that would be particularly useful in mirror machines. Open (shaded) circles are protons (neutrons). Each spin-S state has $2S+1$ possible orientations.

In most fusion reactions of light nuclei, some spin states contribute much more strongly to the cross section than others. For example, the most commonly considered reaction for fusion reactors, $D + T \rightarrow He^4 + n$, goes almost entirely through the spin-3/2 state. Because the deuteron and triton have spin 1 and ½, respectively, and orbital angular momentum can be neglected at reactor energies, this implies that these two heavy hydrogen nuclei will fuse most frequently when their spins are aligned

R. M. Kulsrud, H. P. Furth, E.J. Valeo and M. Goldhaber

Physics Today(August, 1982)
PRL49(1982)1248-1251

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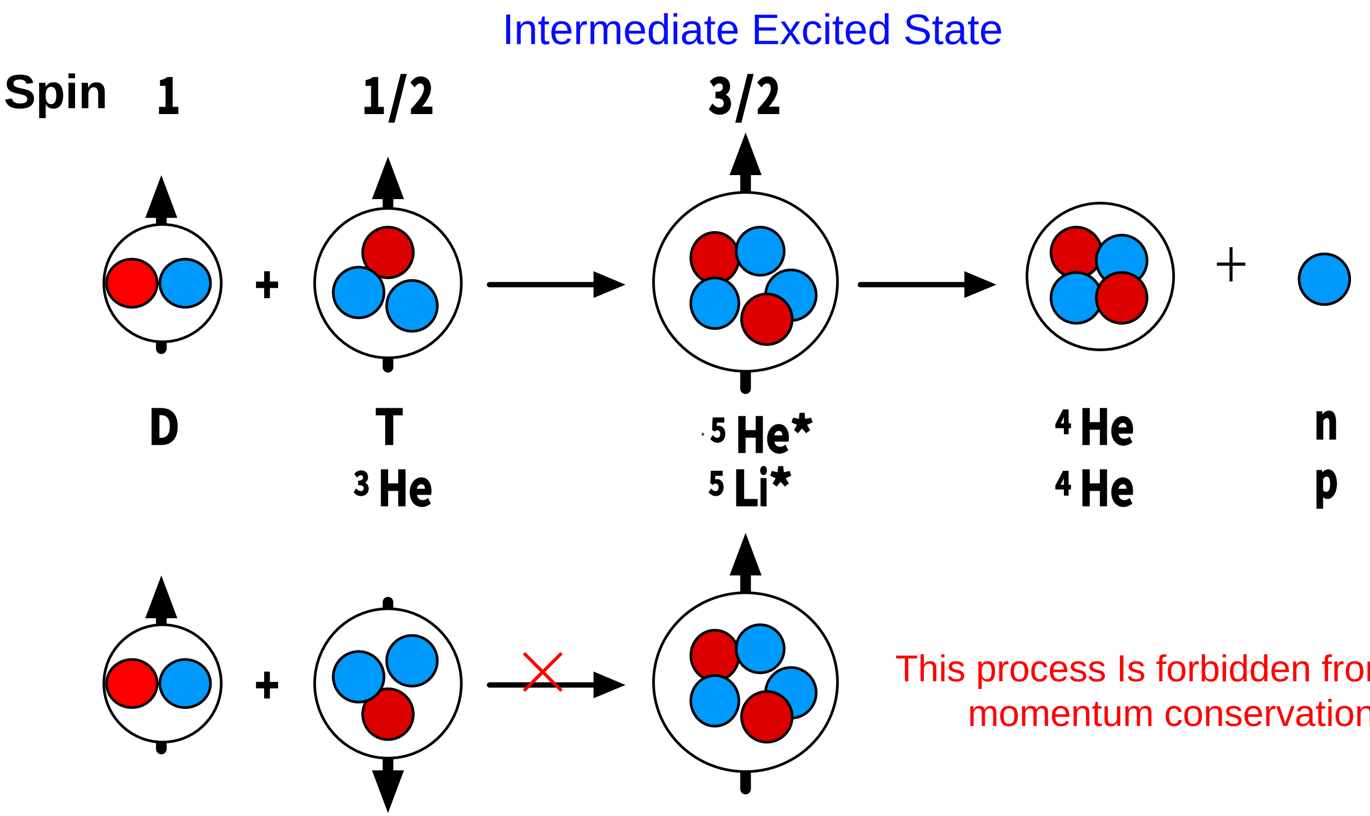
Merit in Fusion Cross Section

By angular momentum Conservation

In the case of D-T (D-^{3}He)

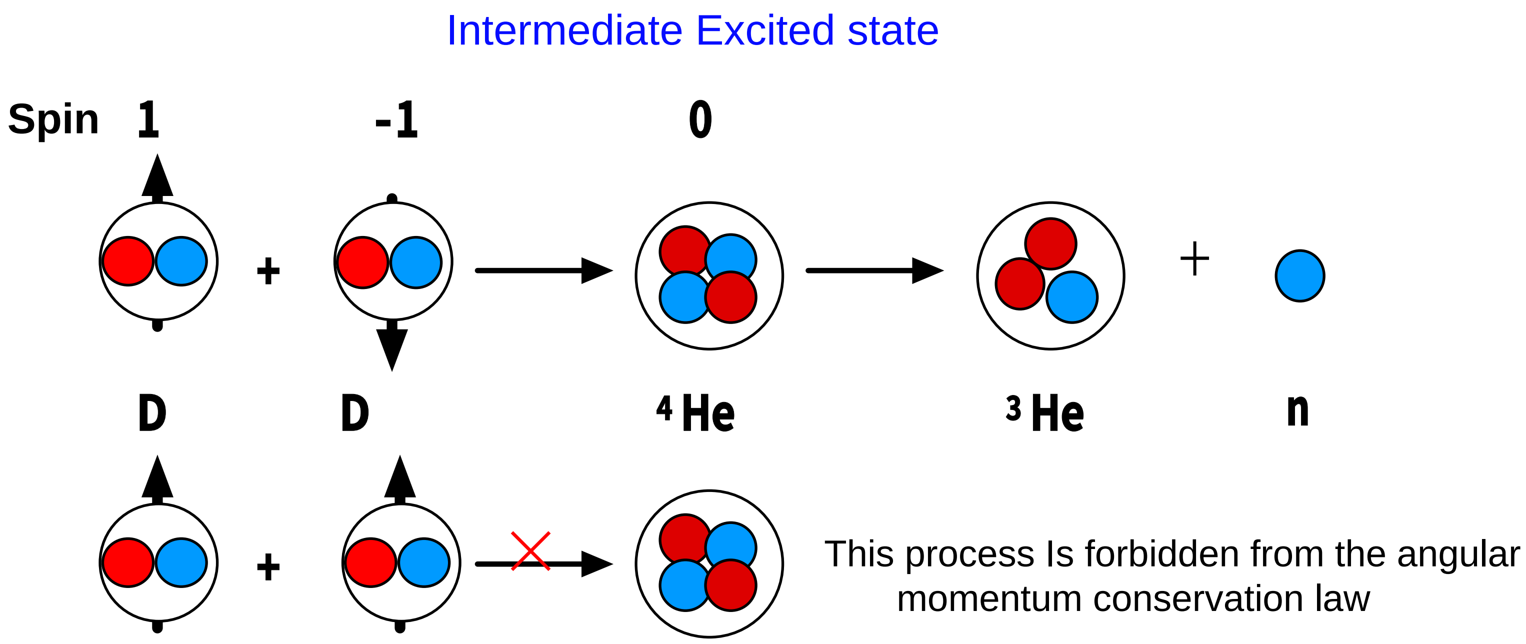
Enhancement : $\sigma^{\uparrow\uparrow} = 1.5 \cdot \sigma_0$

(σ_0 : Cross section for unpol. Beam and Target)



This process Is forbidden from the angular momentum conservation law

2. In the case of D-D : $\sigma^{\uparrow\downarrow} \sim (2-3)\ \sigma_0$



$$D + D \rightarrow {}^3He + n \qquad 3.27MeV$$

Cross section enhancement in the case of polarized D-D collision

$$\varepsilon\text{(enhancement factor)} = \frac{9f_1P_0 + 21f_3P_1}{P_0 + 7P_1}$$

by Kulsrud et al. in Preprint

P_0, P_1 : Penetration factor for Coulomb barrier at l=0, l=1 state

f_1, f_2 : weight factor for the final spin states

f –factor with spin direction

Case	D-spin state	f_1	f_3
a	↑ + ↓	1/3	1/2
b	→ + ←	1/3	0
c	↑ + ↑ ↓ + ↓	0	0

↑ , ↓ : spin direction of D before collision

Efficiency gain in the case of Pol. Collision

E(keV)	P_1/P_0	$\varepsilon(\alpha)$	ε(b)	ε(c)
0	0.008	2.92	2.83	0
100	0.021	2.81	2.62	0
200	0.033	2.72	2.43	0
300	0.054	2.59	2.18	0

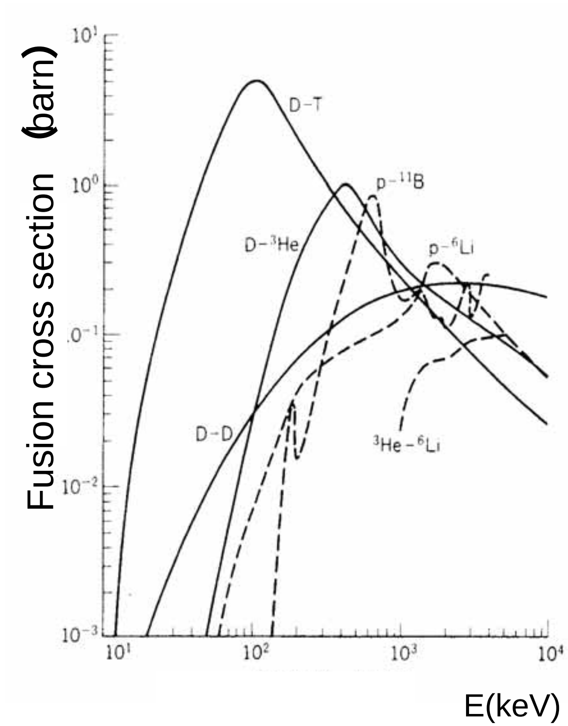
Enhancement : (2.5 -3.0)

Status of the Experiments

D-D Data in keV region

At Ed=30 - 90keV:

- **σ** : **R.E.Brown et. al.**
- iT_{11}(polarization) :**Y.Tagishi et. al(Tsukuba Univ.)**
- Ayy(Pol. transfer)
- T_{20}, T_{21}, T_{22}(Tensor analyzing power)



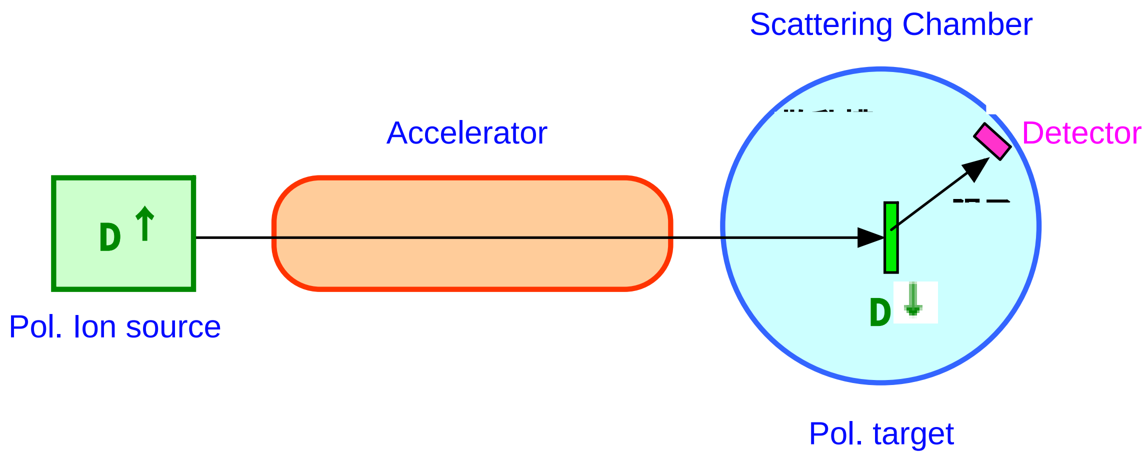
No Data on Double Spin Polarization!!

Analysis : Invariant amplitude method (by **M. Tanifuji et al.)**

No clear conclusion on double spin reaction

Possible pol. D-D Collision Experiment

1. Pol. Beam / Fixed target



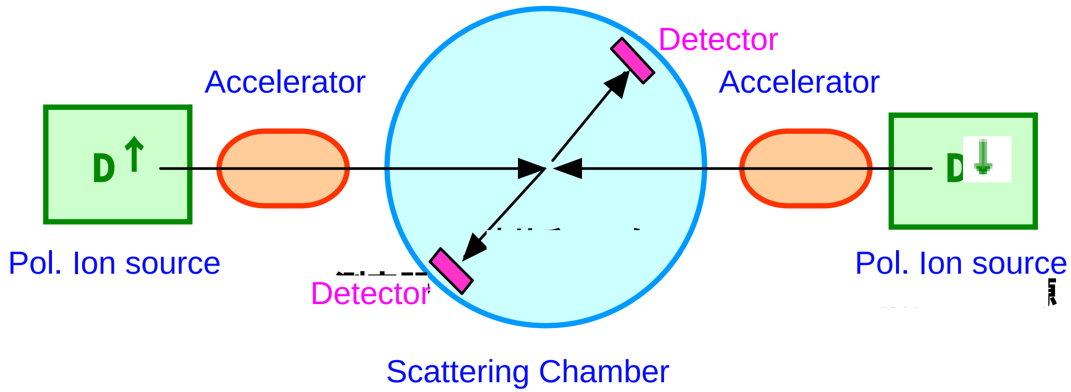
Problems

Low Temperature—>
Thermal shields、Vac. walls
Strong Mag. Field—>
Beam deflection

Production of Thin Film Target

Pol. Measurement

2. Pol. Beam / Pol. Beam collision



Enough Beam Intensity

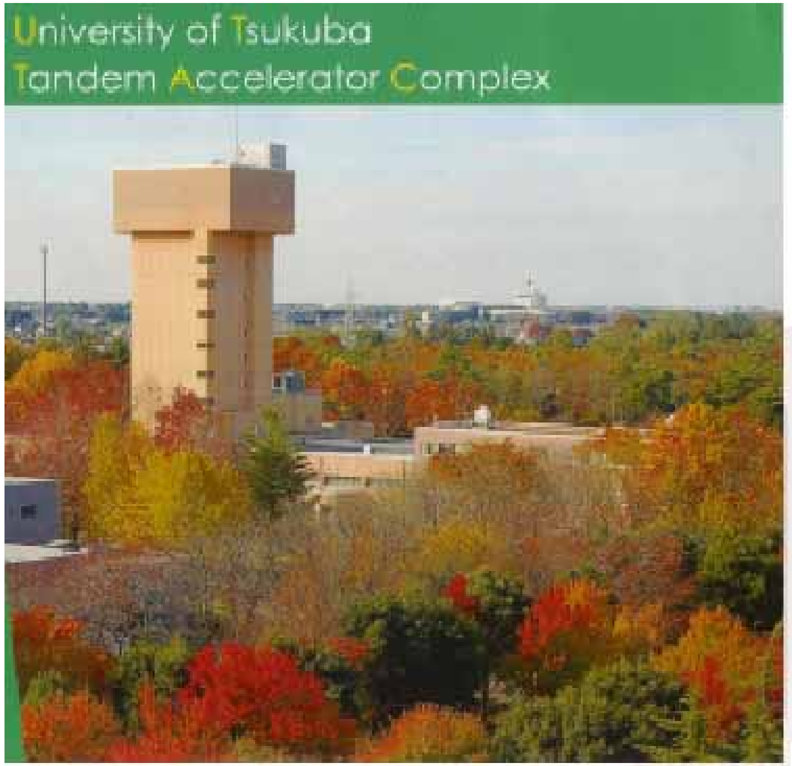
$I \sim 10^{16}$ (particles/s)

1. Challenge to D-beam and D-target

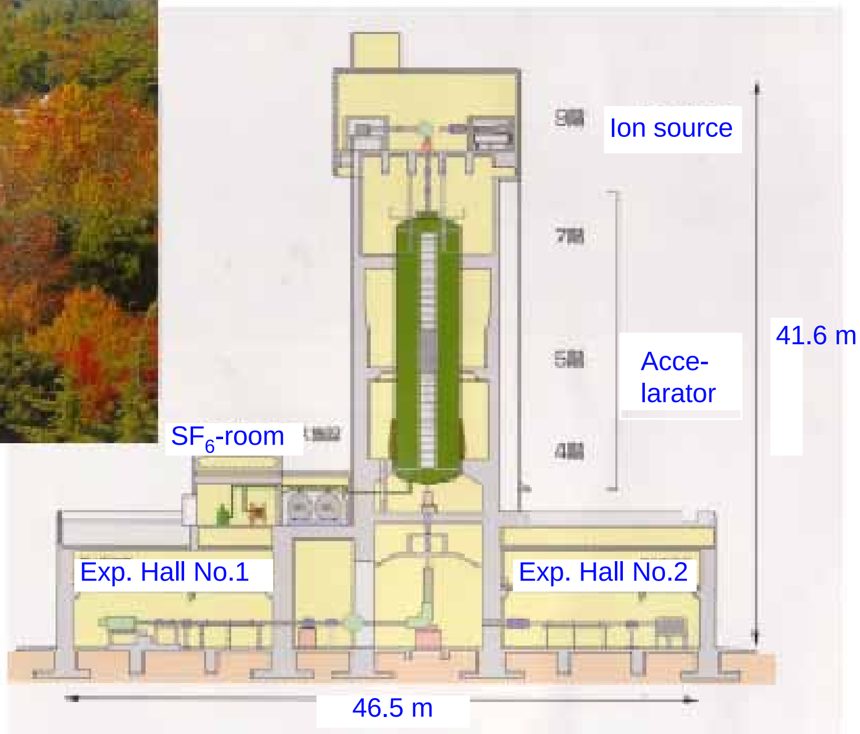
1995- 2004

Pol. D-beam : Tsukuba Univ. 20MeV(Prof. Y.Tagishi)

Pol. Target   : Nagoya Univ. + Miyazaki Univ.(Dr. I.Daito)



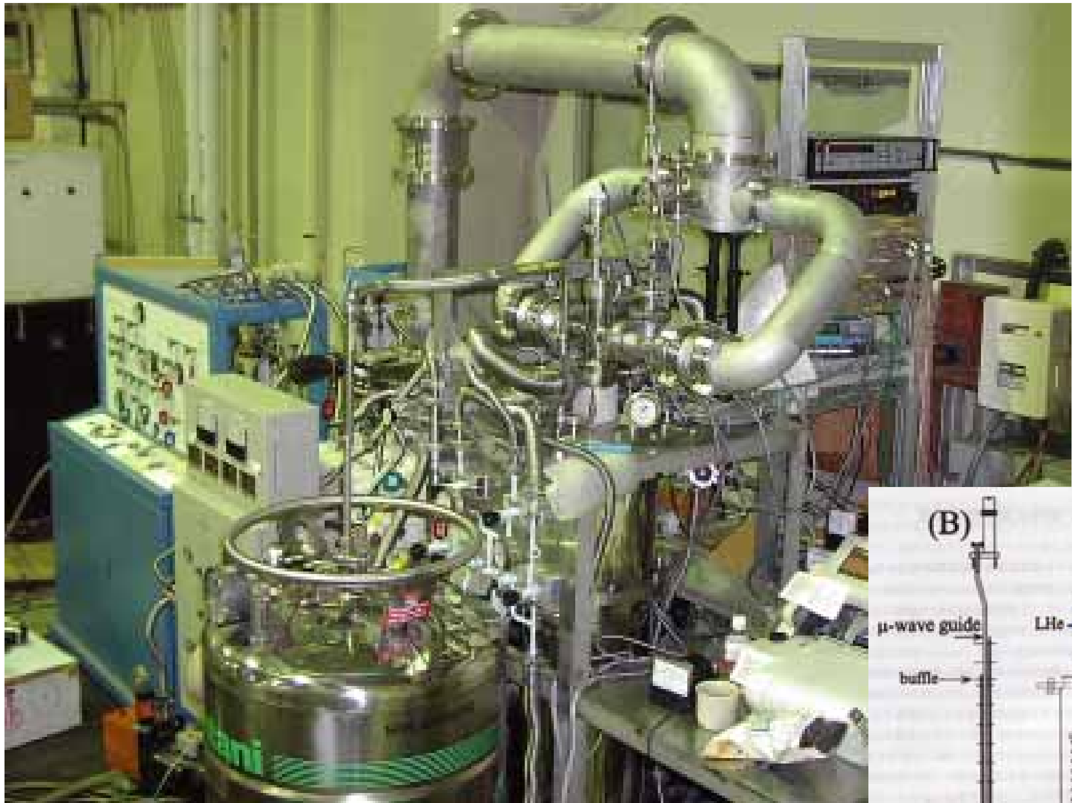
20MeV tandem accelerator



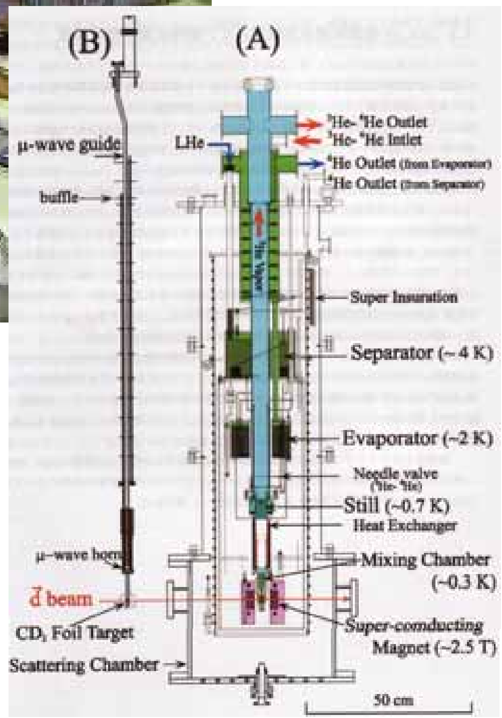
PT-System for DD-Collision

Still & Heat Exchanger

Helmholtz magnet
with a gap 5mm

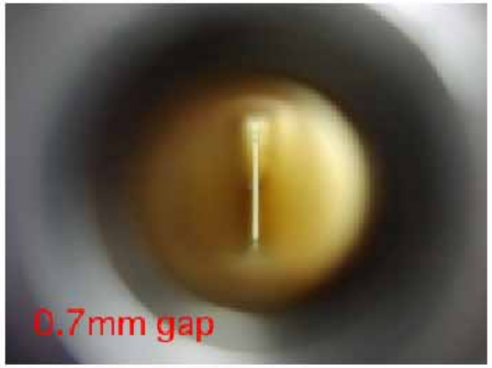


PT system



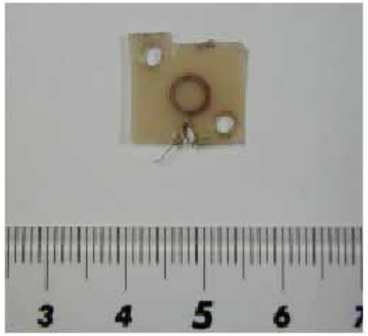
Inner structure of dilution cryostat

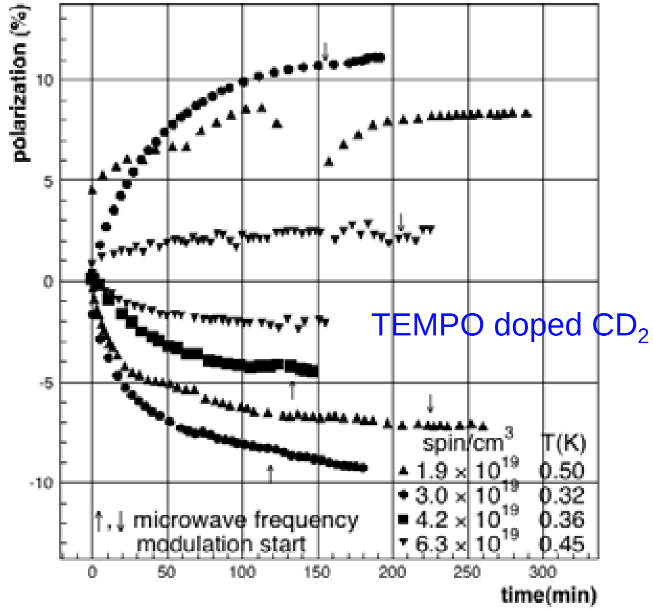
CD_2-target and D-polarization

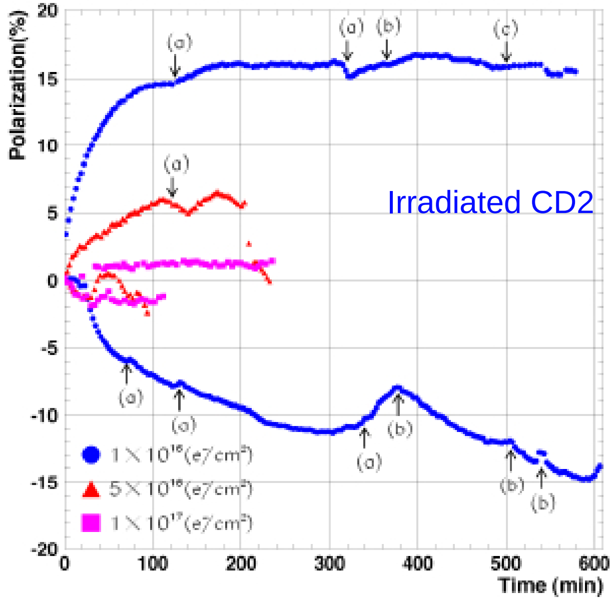


Target holder

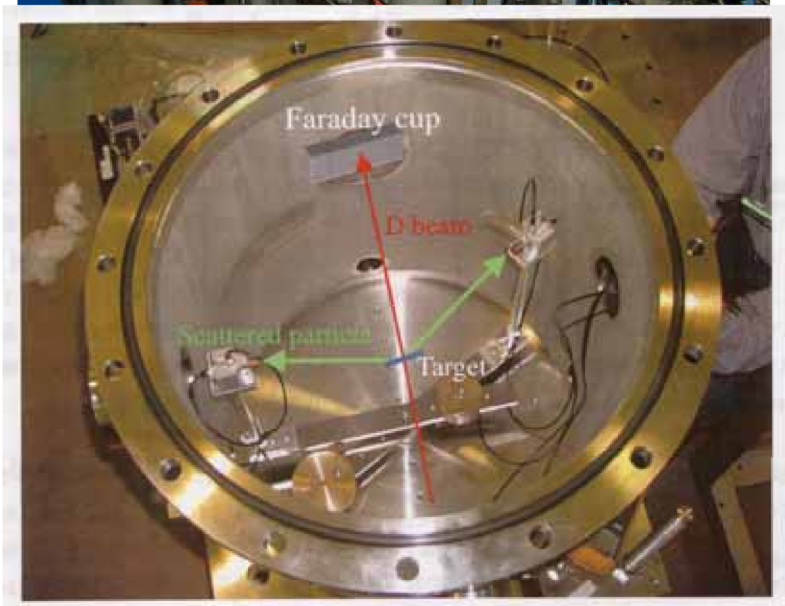
Thickness : 0.3mm





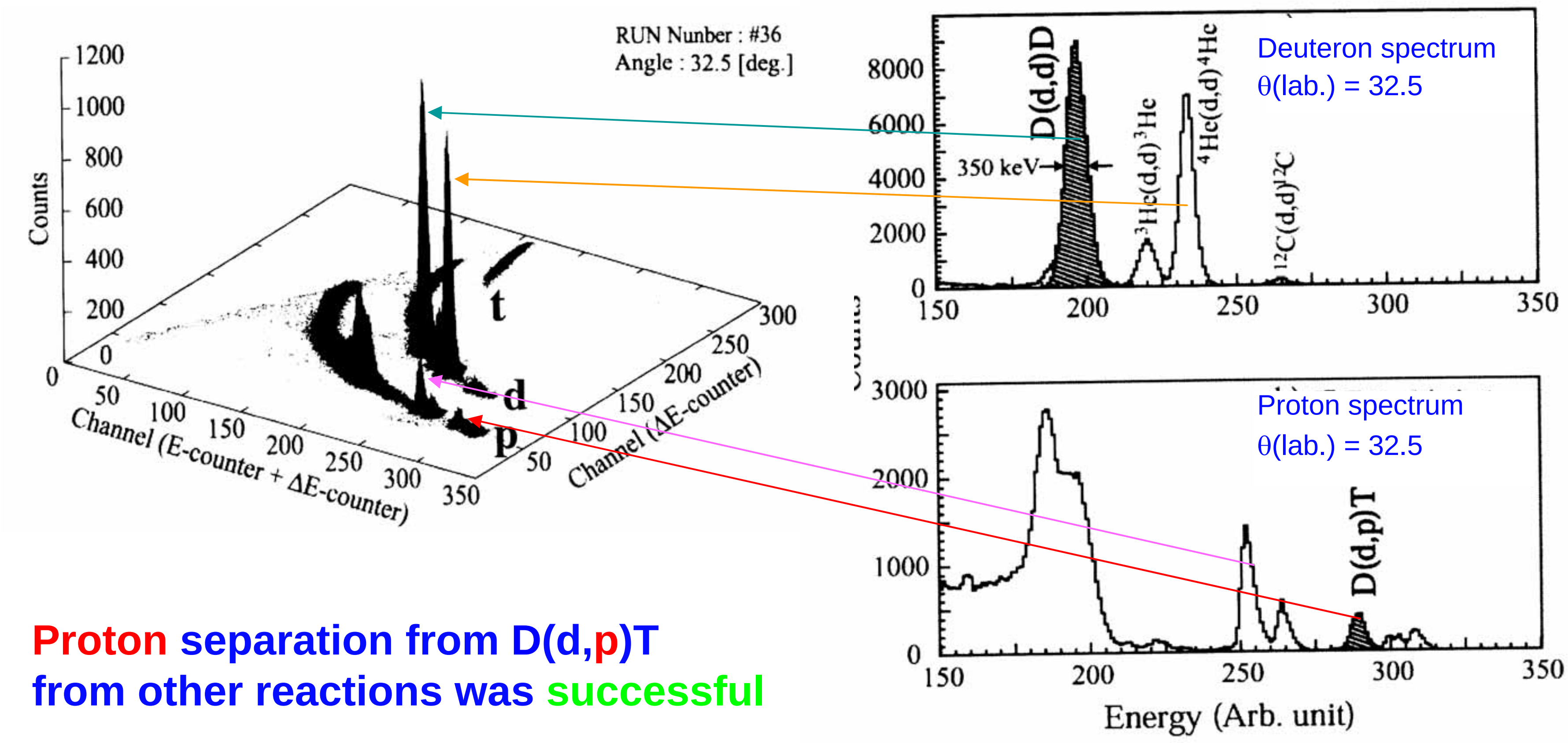


Experimental Hall of Tsukuba Univ.



Scattering chamber

DD Reaction Spectrum



Proton separation from D(d,p)T
from other reactions was successful

But, we couldn't reach the final goal !

2. Proposal for the D-Beams Collision Experiment

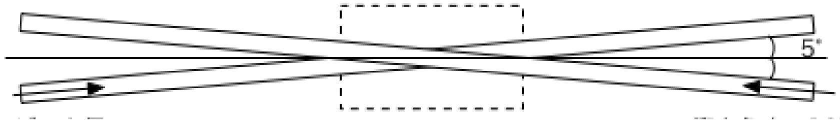
Estimation of the beam intensity

Collision Rate (particles/s) = $\sigma \cdot L$

σ :Total Cross Section

$$L \sim \frac{n_1 \cdot n_2}{2 \cdot v \cdot \pi^{1/2} \cdot \sigma_y \cdot \sin\phi}$$

Collision region



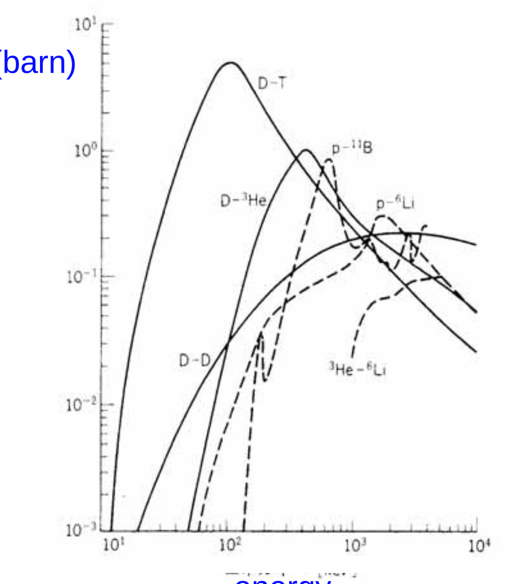
Velocity of incident particle : v

Beam daiameter:σ_y

Collision angle : 10 deg.

Total cross section for particles

(barn)



energy

For Ex. Collision Condition

$n_1 = n_2 = 10^{16}$

$\sigma_y = 0.5$ cm

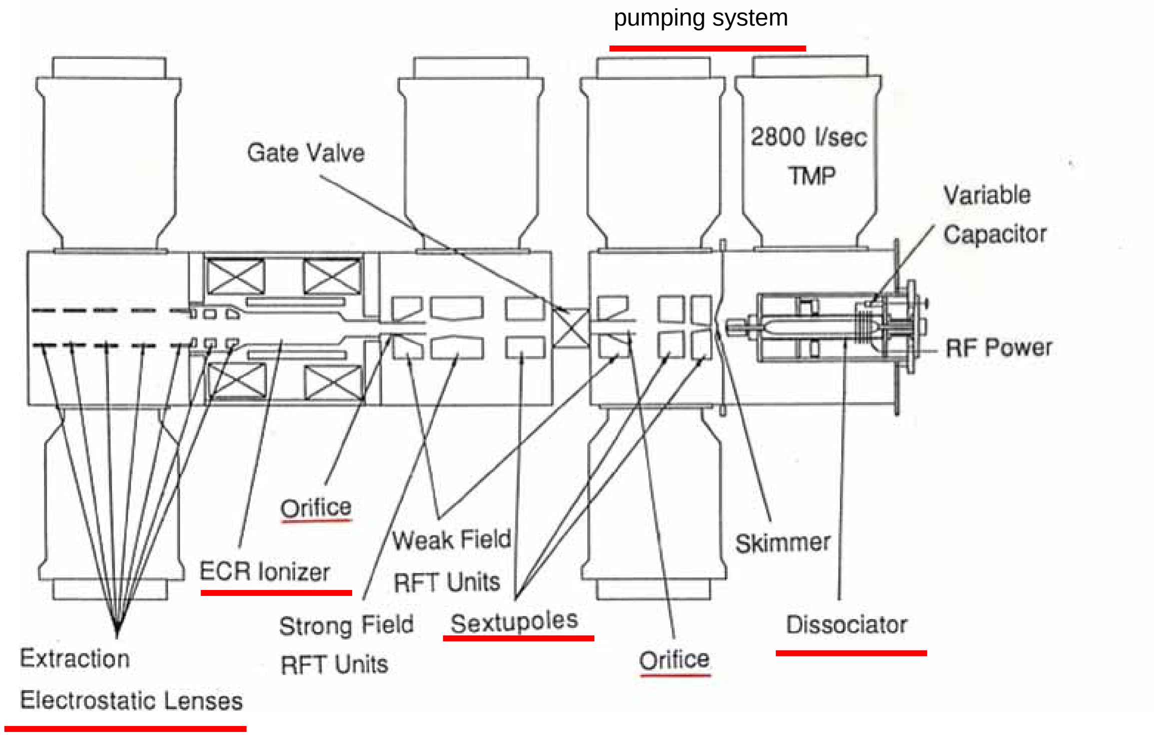
$\phi = 5°$

No. of Collision/s

E (keV)	v(x10^{8}cm/s)	L(x10^{24})	σ (x10^{-24})	$\sigma \cdot L$
10	0.98	6.62	6.0x10^{-4}	4.0x10^{-3}
25	1.55	4.18	8.5x10^{-3}	3.6x10^{-2}
50	2.19	2.96	3.2x10^{-2}	9.5x10^{-2}
100	3.1	2.09	6.4x10^{-2}	1.x10^{-1}

Polarized Ion Source(Atomic beam type)

Example of RCNP Ion Source
(by Prof. K.Hatanaka)



Example of Pol. Ion Source in some Institutes

Lab. & Institute	Beam Intensity	Beam Polarization (%)	Beam Density (/cm^2)
RHIC (USA)	1.2×10^{17} (H/s)	92.4 ± 1.8	$(1.3 \pm 0.2) \times 10^{12}$
EDDA (Germany)	5.7×10^{16}	> 85	
Indiana (USA)	1.92×10^{16} (H^+/s)	77 ± 2	
Moscow (Russia)	4.0×10^{16} (H^-/s)		

The most intense Pol. Atomic Beam(at RHIC)

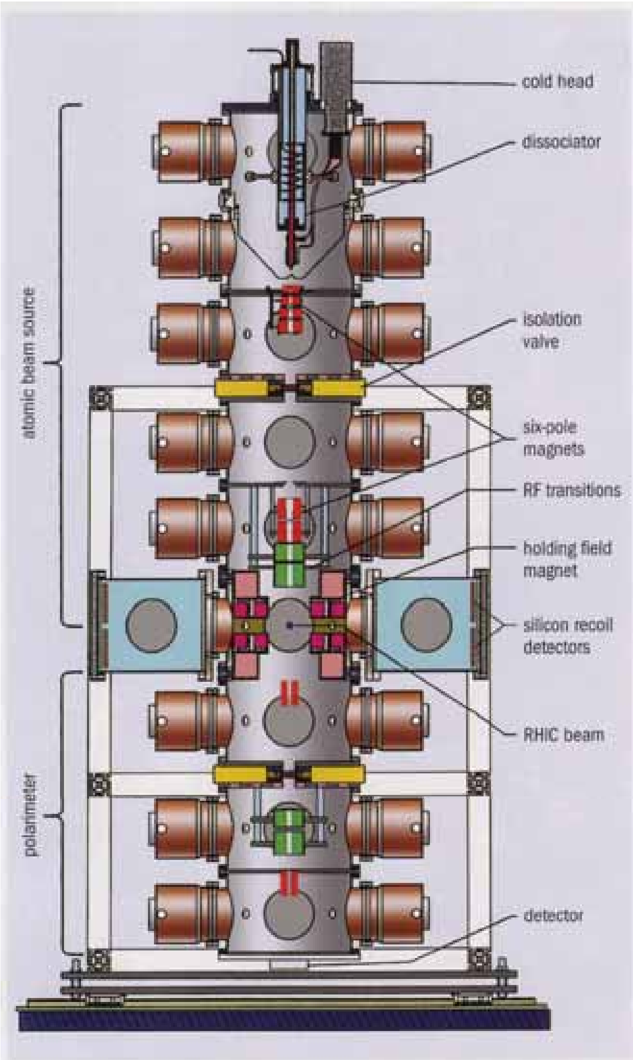
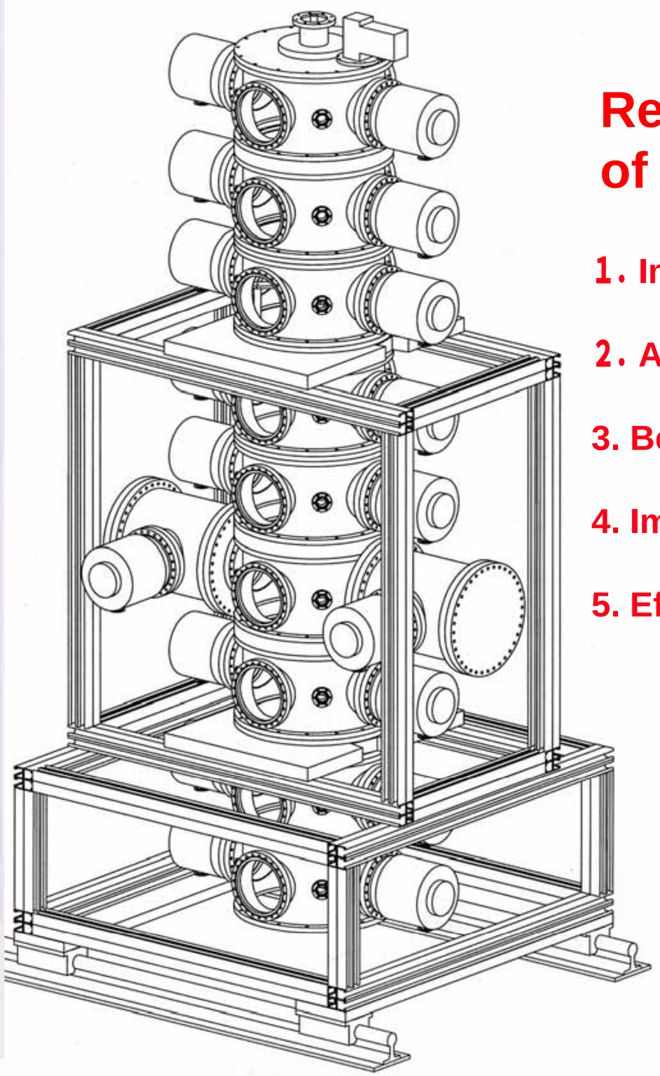


Fig. 1. The overall height of the polarized hydrogen jet target at Brookhaven National Laboratory's RHIC is 3.6 m. The nine-stage differential pumping system is evacuated by nineteen 1000 l/s turbomolecular pumps.

From CERN courier vol.45, No.8,2005



$I = 1.2 \times 10^{17}$ (H/s)

Remarks in Construction of New Ion Source

1. Improvement of Dissociator
2. Achievement of High Vacuum
3. Best positioning of 6-pole magnet
4. Improvement of ECR ionizer
5. Efficient beam extraction

Proposal for Basic Study on Spin Polarized D-D Collision

1. **Condition for the Pol. Beam**

   Beam Intensity : **I** > 10^{16} particles/s

   Beam Polarization : P > 50%

2. **Event Rate**

   E = 10 ~ 100keV Region

   About n> 10^{-2} (events/s)

3. **Data acquisition**

   Statistical Error < 5% → Confirmation of Effect of Spin Pol. Collision

Estimation of Cost and Time

1. Cost :

∗Pol. Ion Source	:	¥ 328,000,000 (for 2 stations)
∗Beam Channel	:	28,000,000
∗Scattering Ch.+ Detectors	:	40,000,000
∗Comsumable matterials	:	51,000,000
∗Employment	:	54,000,000
∗Travel Expenses	:	11,000,000
		512,000,000

2. Time schedule :

3 years : for Construction

1 year : for tuning

1 year : measurement

Summary

For the doubly polarized experiment

0. Pol. Beam + Fixed D-target is extremely difficult

1. Pol. D-D Experiment by Pol. Beam will be feasible

2. 2 Ion sources with I>10^{16}(p/s) has to be provided

3. It takes about 5 years to take data

4. About 0.5 billion yen should be prepared

Many thanks to organizing committee and audience!