九大での$^{12}C+^{4}He \rightarrow ^{16}O+\gamma$ 反応全断面積測定の現状

九大理･相良建至

天体ヘリウム燃焼の主反応は
$^{4}He+^{4}He+^{4}He \rightarrow ^{12}C+\gamma$
$^{12}C+^{4}He \rightarrow ^{16}O+\gamma$ (Ecm=0.3MeV)
である。

$^{12}C+^{4}He \rightarrow ^{16}O+\gamma$ 反応全断面積は、約50年 の世界競争を経たが、未測定である。

九大では20年前から、$^{12}C+^{4}He \rightarrow ^{16}O+\gamma$ 反応全断面積の測定に取り組んできて、今や世界で最も低エネルギーの測定を行っている。

$^{12}C+^{4}He \rightarrow ^{16}O+\gamma$ 反応全断面積測定
Ruhr U: Ecm= 5→1.9 MeV.
九大: Ecm= 2.4 →1.5 →1.2 →1.0（→0.85 →0.70 MeV ）→外挿→ 0.30 MeV
現在

九大のこれまでの歩みを報告し、残された課題への対策を提唱する。

H-burning

$4p \rightarrow {}^{4}He$
via
p-p chain &
CNO cycle

$p+p \rightarrow d+e^{+}+\nu$

He-burning

$3\,{}^{4}He \rightarrow {}^{12}C$

$\mathbf{{}^{4}He+{}^{12}C \rightarrow {}^{16}O+\gamma}$

C-burning

O-burning

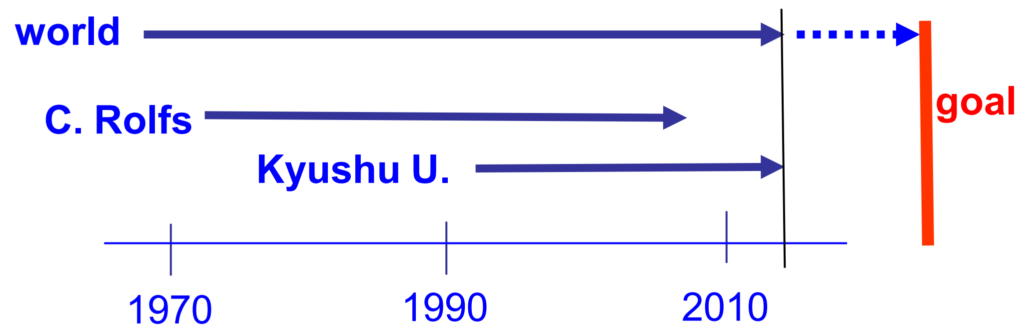
Si-burning

….

C/O ratio is determined by ${}^{4}He+{}^{12}C \rightarrow {}^{16}O+\gamma$ reaction.

Experiment gave up?

Experimental efforts have been made for **~50 years in the world**.



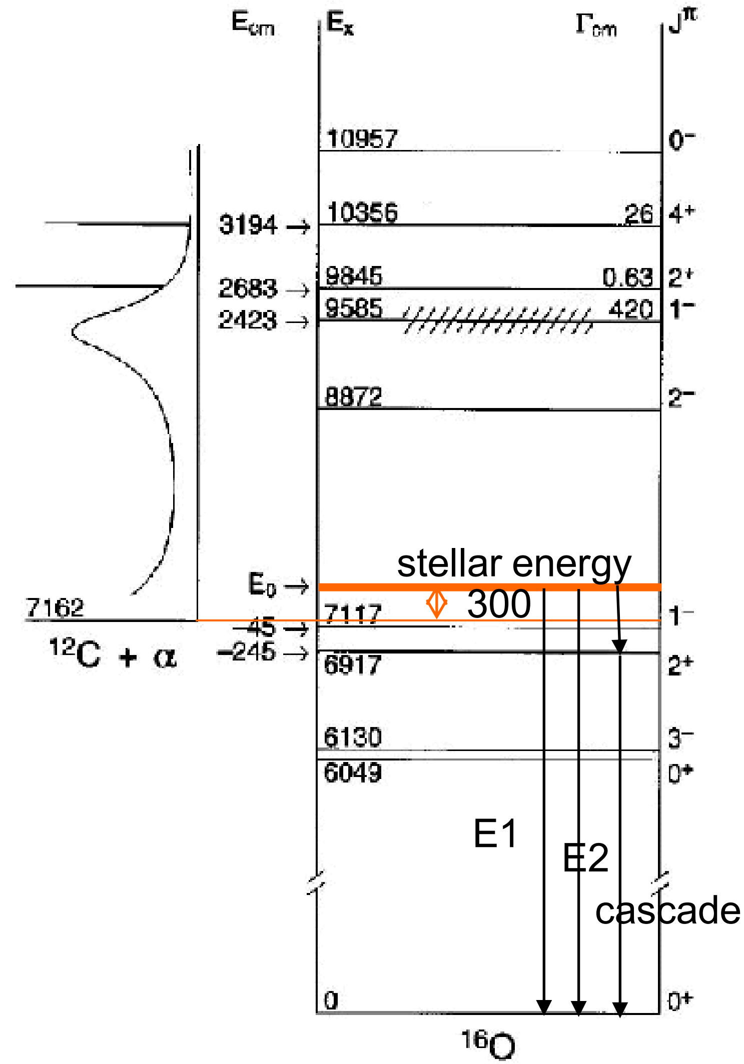
Why is 4He+12C→16O+γ experiment so difficult?

4He+12C→16O+γmeasurement (Ecm = 0.3MeV) is very difficult. Due to level structure of 16O, S-factor sharply varies around Ecm=0.3MeV.

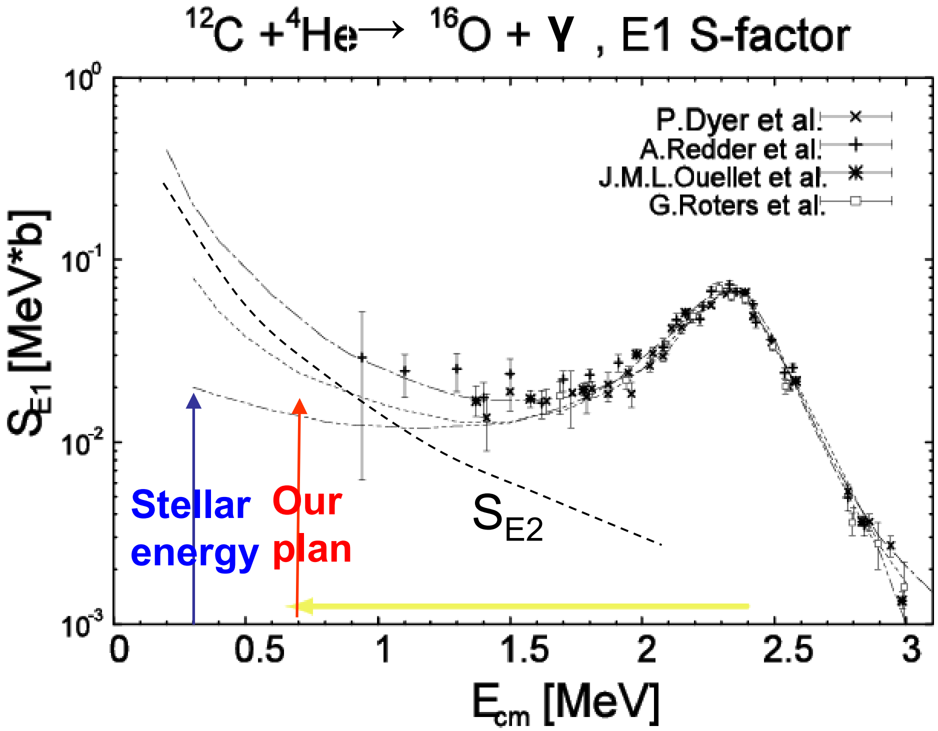
Very low-energy data（down to Ecm=0.7MeV) are necessary to make reliable interpolation.

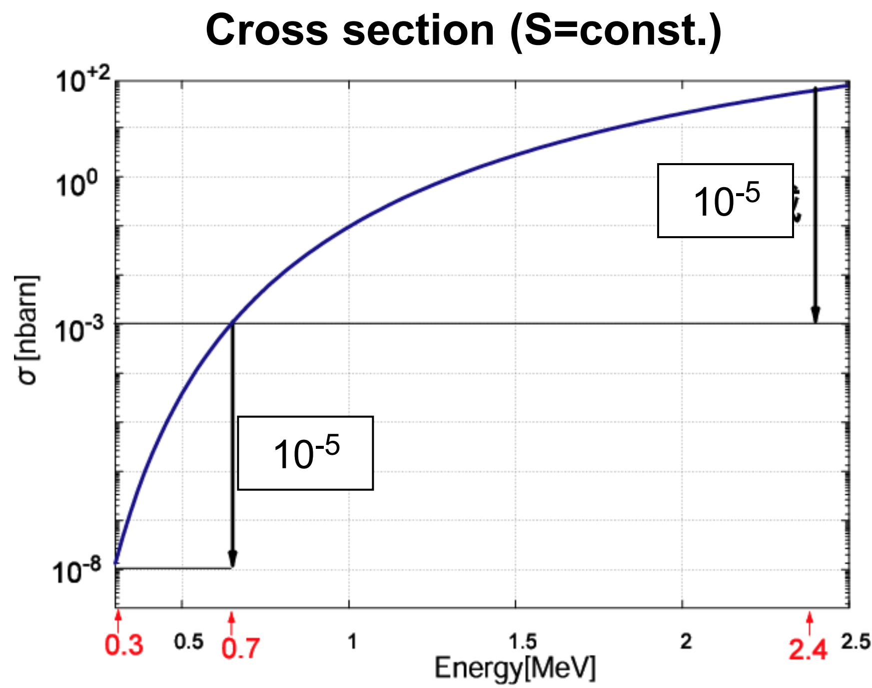
At Ecm=0.7MeV, σ ~ 1 pbarn.

At Ecm=0.3MeV, σ ~ 10^{-5} pbarn.



Total=E1+E2+Cascade





σ(Ecm=2.5MeV) ~ 100 nb

σ(Ecm=1.0MeV) ~ 0.1 nb

σ(Ecm=0.7MeV) ~ 1 pb

Our experiment (±10%)

σ(Ecm=0.6MeV) ~ 0.1 pb

σ(Ecm=0.3MeV) ~ 10^{-5} pb

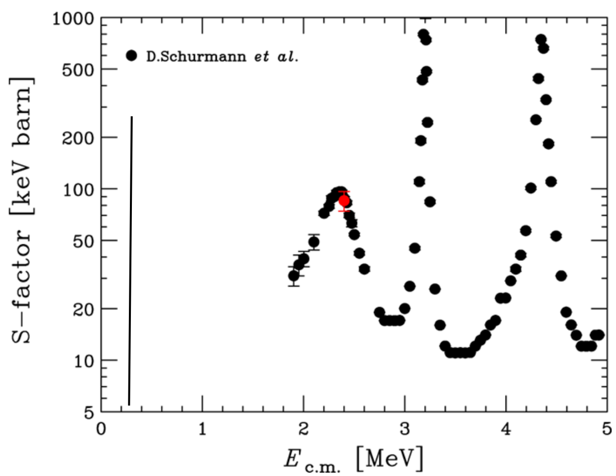
Extrapolation

Experimental methods to measure the helium burning rate in stars

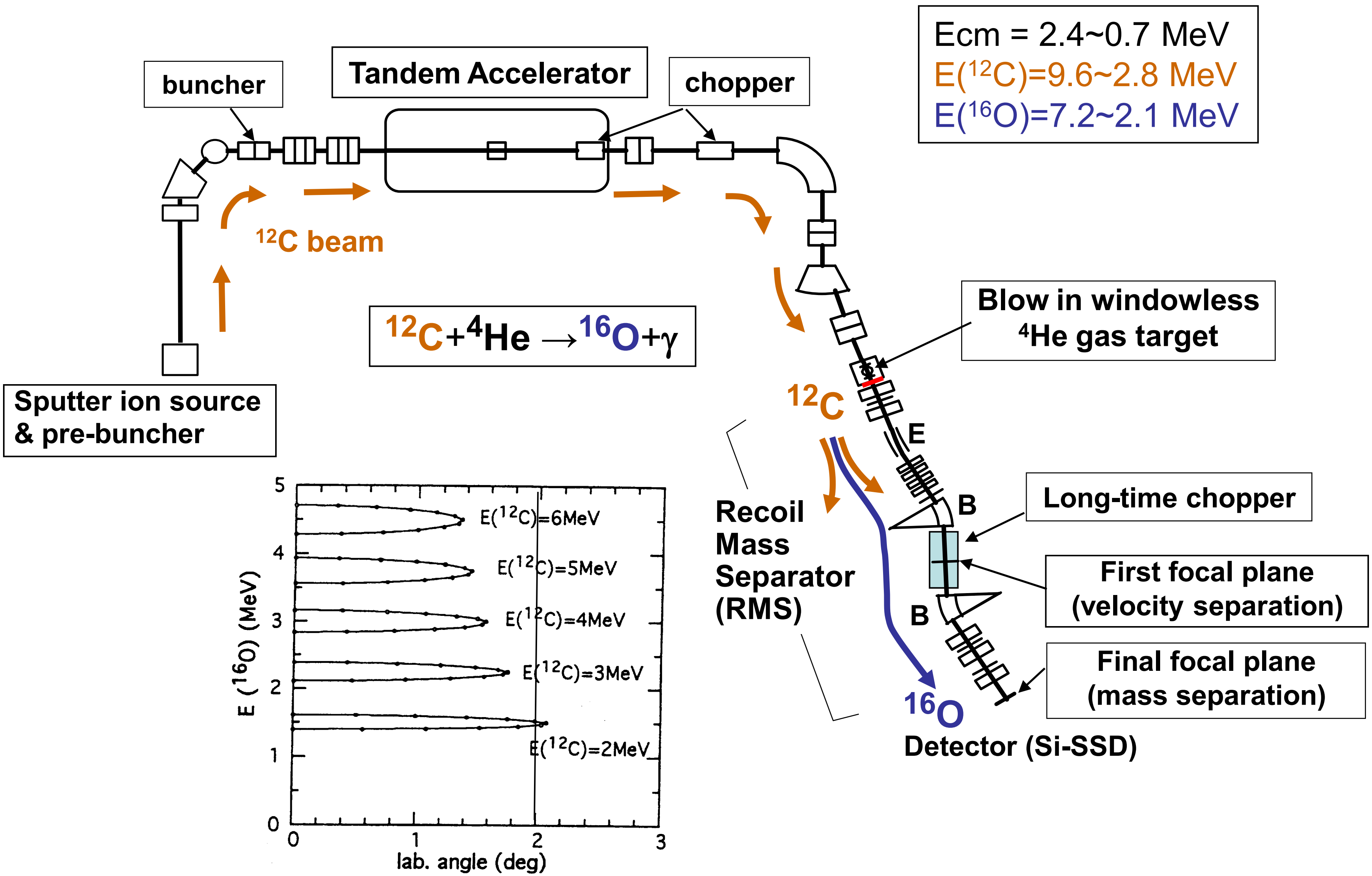
Direct reaction
1) 12C+4He → 16O+γ, γ-detection, difficulty in detection
2) 12C+4He → 16O+γ, 16O-detection, Ruhr U. & Kyushu U.

Inverse reaction
3) 16O+γ (virtual) →12C+4He, Coulomb breakup, inverse=direct ?
4) 16O+γ (real) →12C+4He, back scattered γ, inverse=direct ?

Decay (inverse)
5) 16N →β+16O
2010 16O→12C+4He, S(E1) down to 300keV was measured.



Setup for $^4He(^{12}C,^{16}O)\gamma$ experiment at Kyushu Univ. tandem lab.



$^{12}C + ^{4}He \rightarrow ^{16}O + \gamma$ yield estimation

$Y(^{16}O) = \sigma \cdot N(^{12}C) \cdot N(^{4}He) \cdot$ Det.Efficiency · Beam Time

^{12}C beam: 10pμA (Limit of our tandem accelerator)

^{4}He target: 15Torr · 5cm (Limit of ΔE in the target)

Detection efficiency: ~40% (fraction of 16O in a charge state)

At Ecm = 0.7MeV, σ ~ 1pbarn
Y(16O) ~ 5 counts/day
→ 1 month experiment

At Ecm = 0.6 MeV σ ~ 0.1 pb
→ 10 month exp.

At Ecm = 0.3 MeV σ ~ 10^{-5} pb
→ 7,000 year exp.

Increase yield.

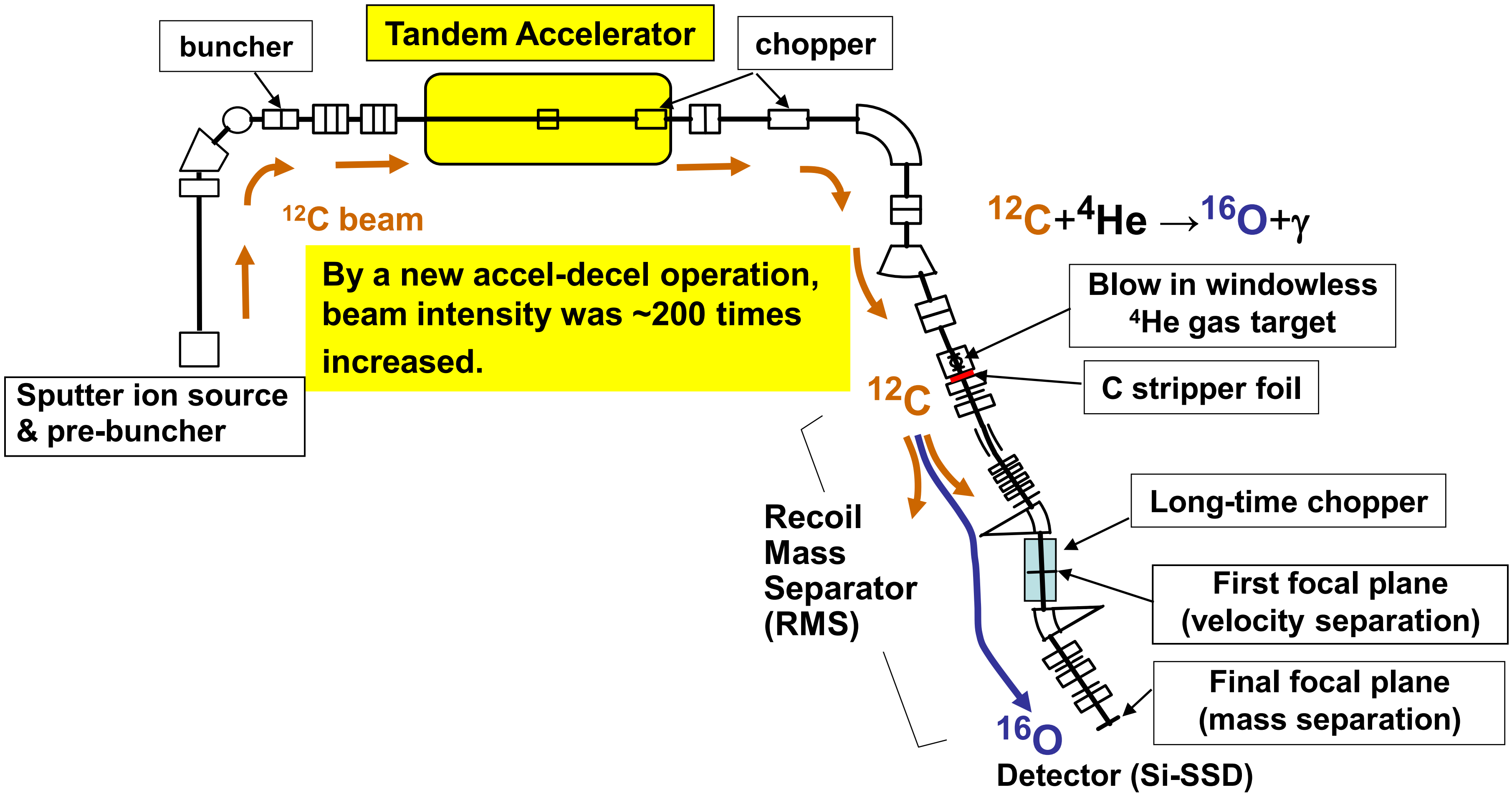
$N(16O)/N(12C) \sim 10^{-18}$

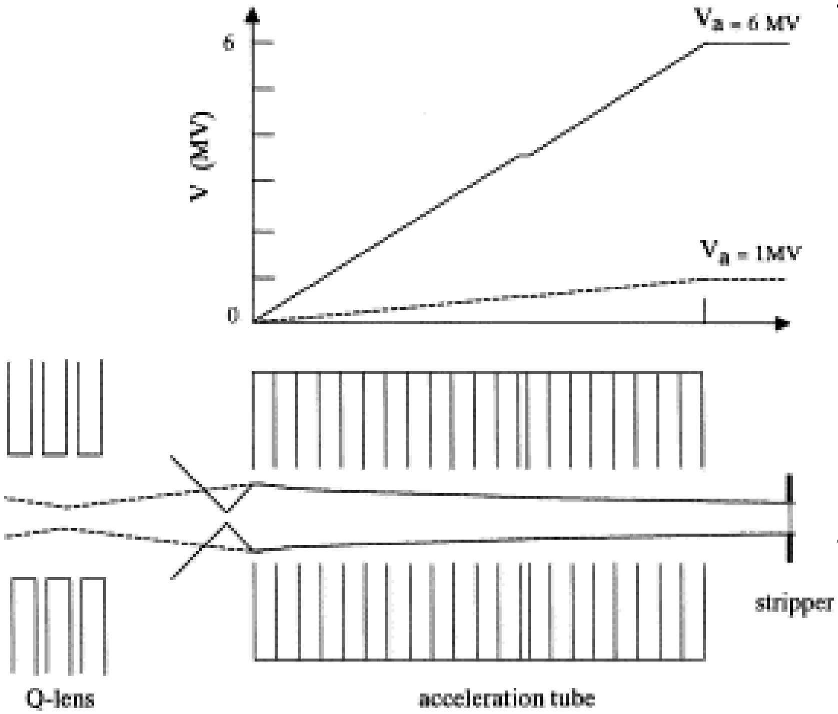
$\rightarrow N(BG)/N(12C) < 10^{-19}$

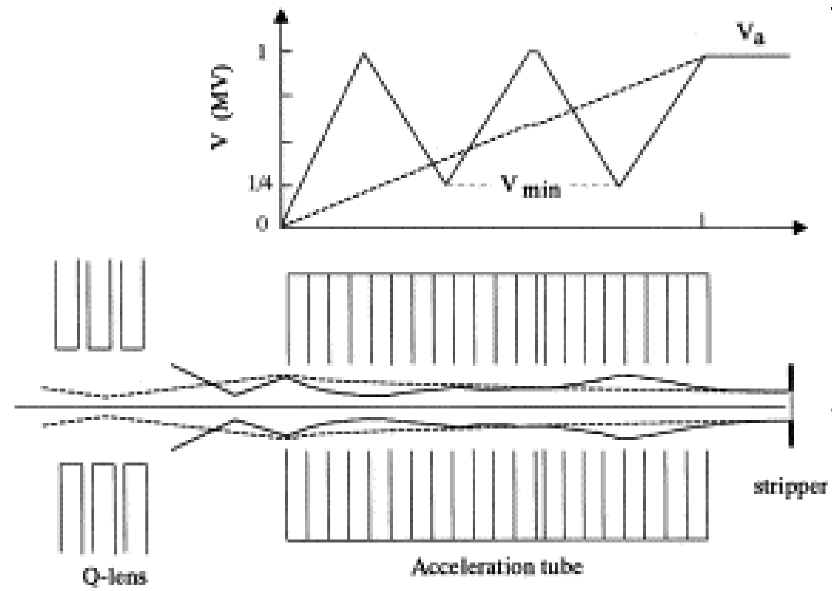
Decrease backgrounds.

$Y(16O) = \sigma \cdot N(12C) \cdot N(4He) \cdot$ Det.Efficiency · Beam Time

Beam intensity increase: New operation of tandem accelerator





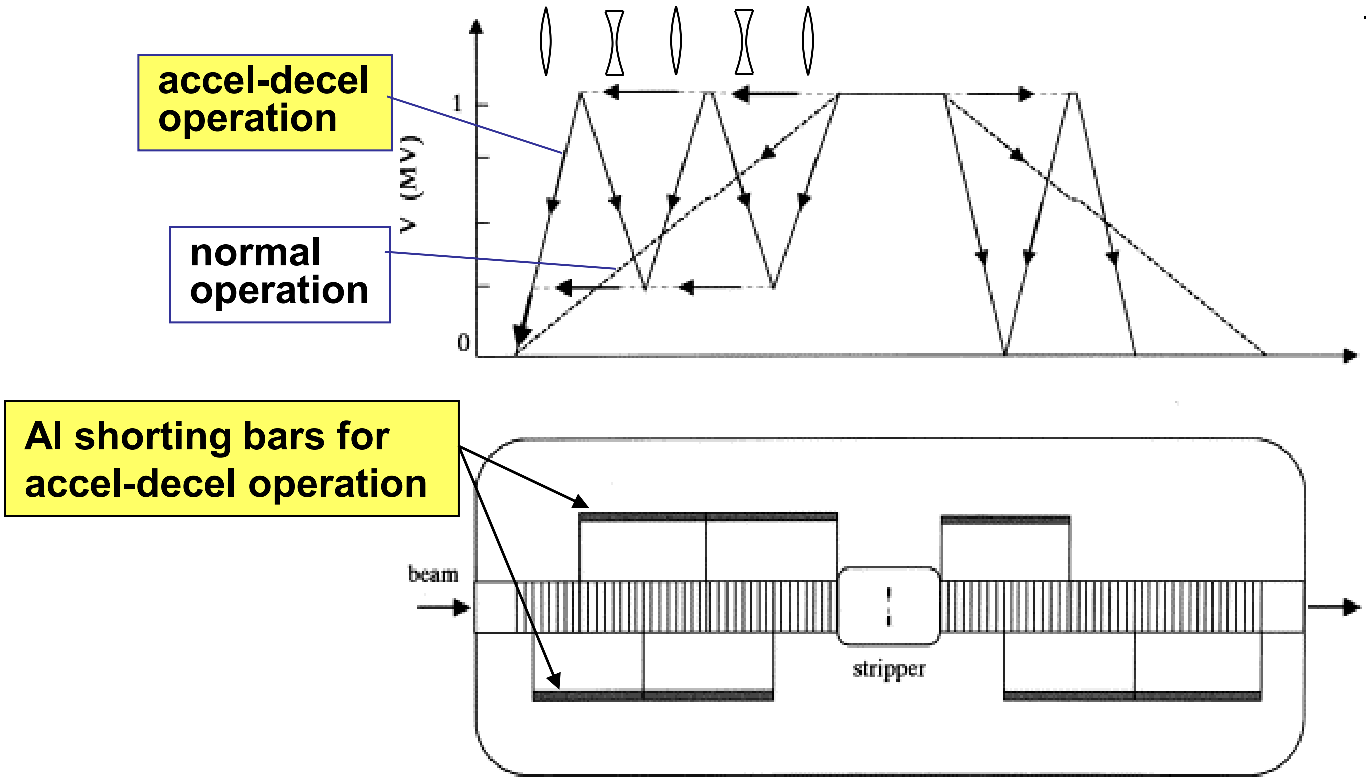


Normal operation of tandem accelerator.

At low acceleration voltage, focusing becomes weak, and beam transmission decreases.

Accel-decel operation of tandem accelerator.

By alternative focus-defocus, Focusing becomes strong, and Beam transmission increases.



By the accel-decel operation,

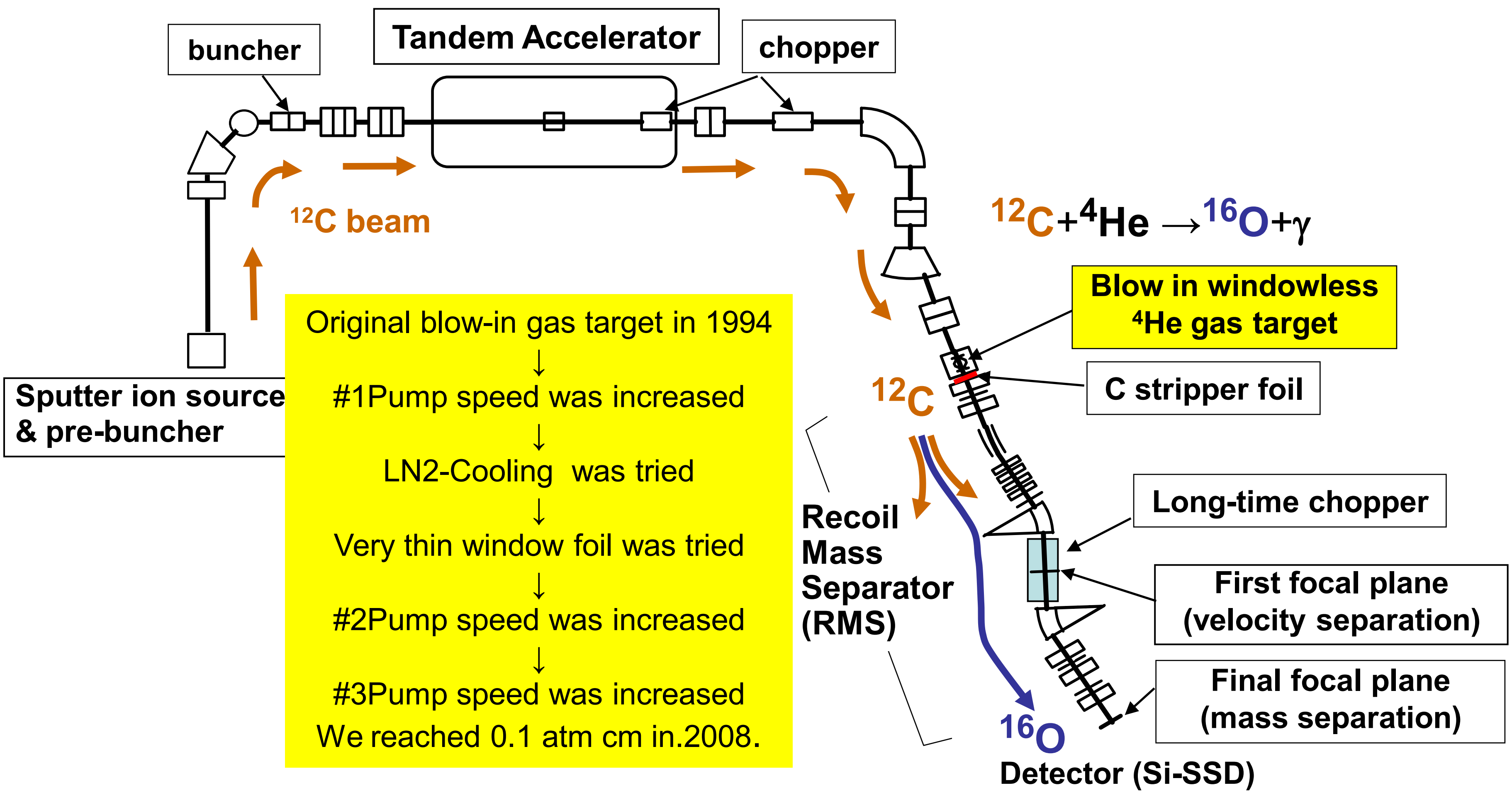
- 10 times higher beam transmission is obtained by strong focusing.
- 17.5 times more intense beam can be injected, due to higher electric power necessary for accel-decel operation.

By a large aperture (12^{ϕ}) gas stripper, spread in beam energy and angle is decreased, and beam transport to the target is ~3 times increased.

Totally, beam intensity is 300-500 times increased.

$$Y(16O) = \sigma \cdot N(12C) \cdot N(4He) \cdot \text{Det.Efficiency} \cdot \text{Beam Time}$$

Increse target thickness: 5 Torr →11Torr →25Torr



Original blow-in gas target in 1994

↓

#1Pump speed was increased

↓

LN2-Cooling was tried

↓

Very thin window foil was tried

↓

#2Pump speed was increased

↓

#3Pump speed was increased

We reached 0.1 atm cm in.2008.

↓

16O BG from the target !.

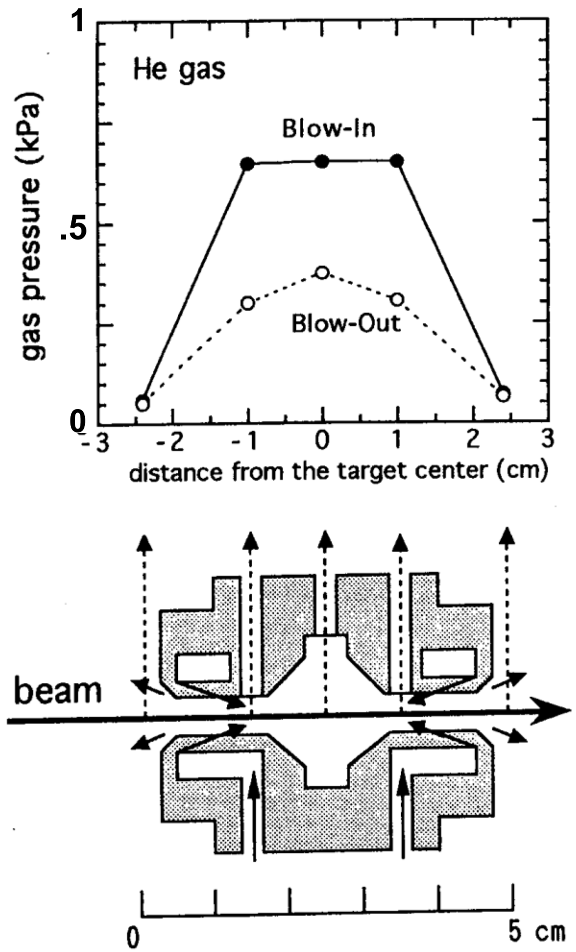


Fig. 6. The target gas pressure measured by using (p,p) scattering at $\theta_{lab} = 90°$ as illustrated in the bottom figure. The blow-in gas target is superior to the blow-out one in the gas confinement.

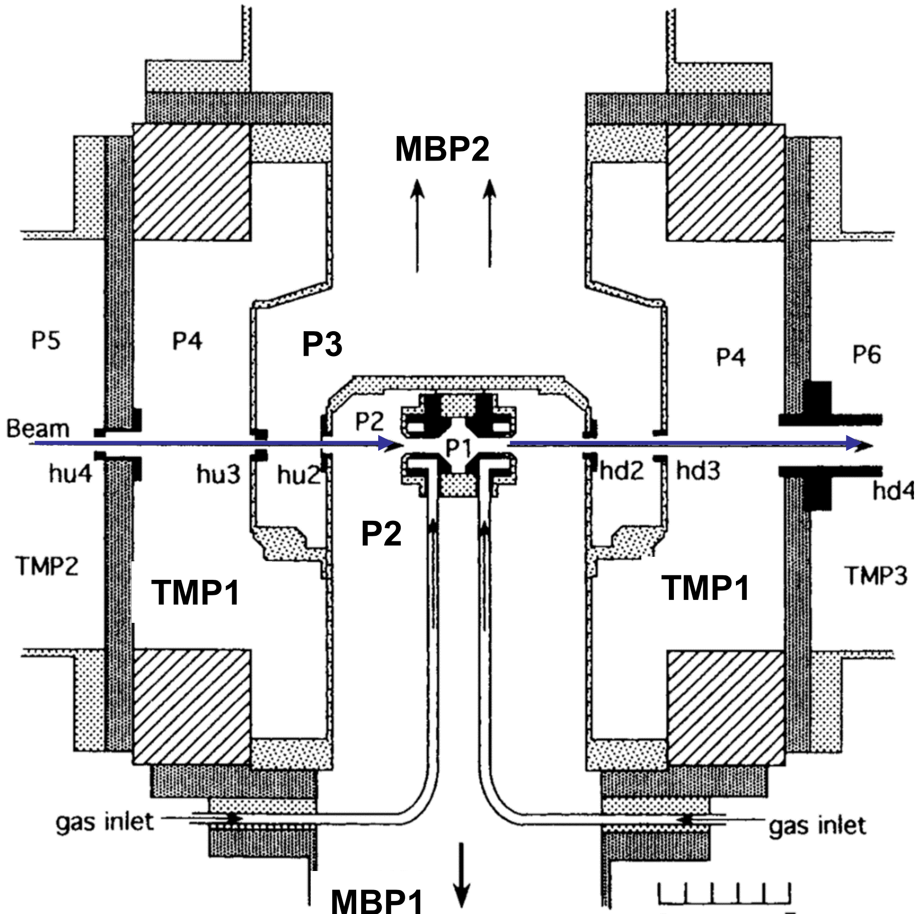
<u>Blow-in type windowless gas target</u>

Target gas pressure is flat
Gas boundary is sharp

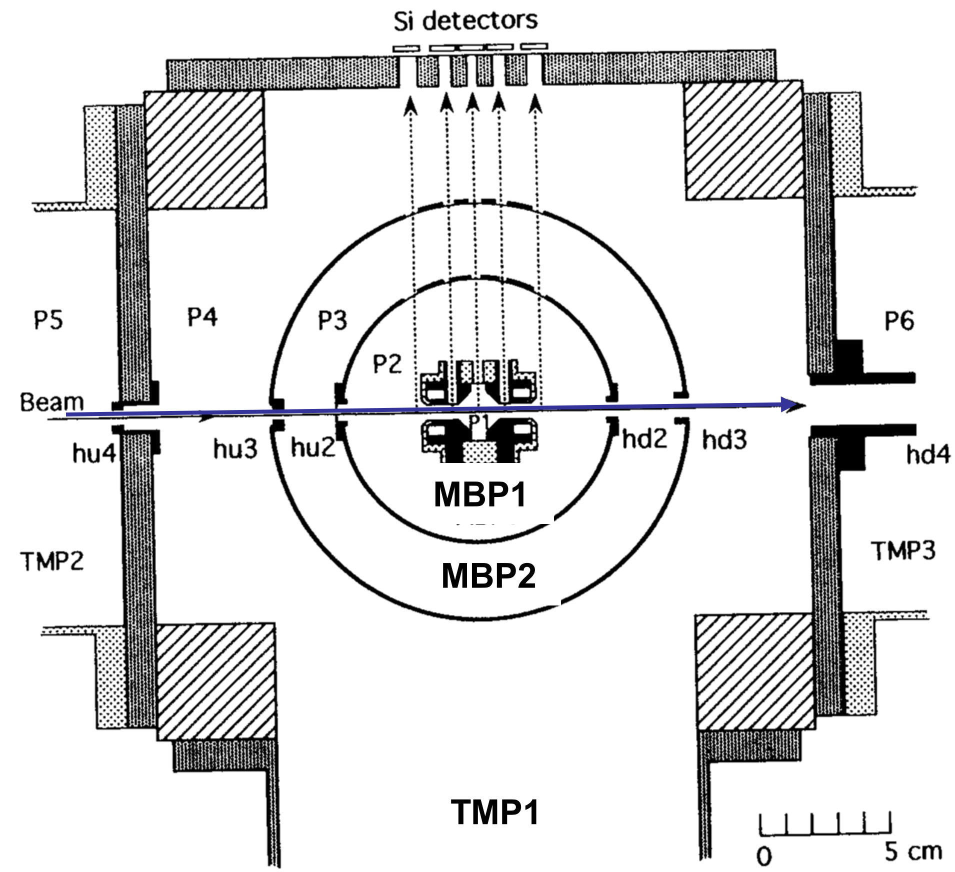
Gas target thickness
^{4}He gas : ~6Torr･3cm
N_2 gas : ~20Torr･3cm

Necessary ^{4}He gas thickness
25Torr ･3cm
↓
Cooling the target by liq.N_2

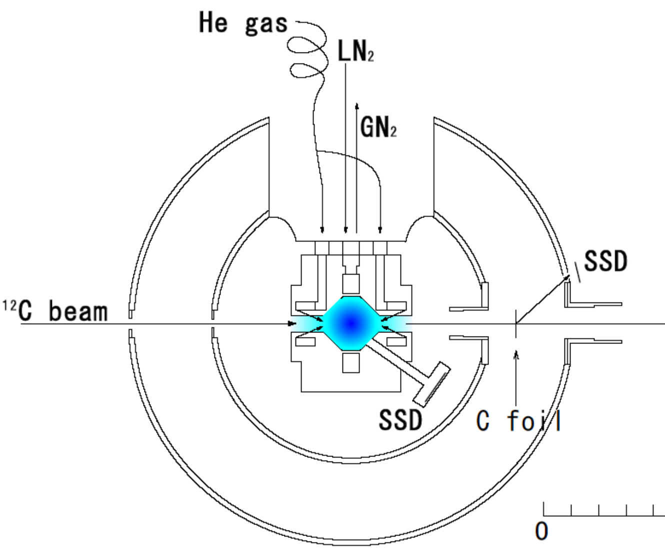
Top View

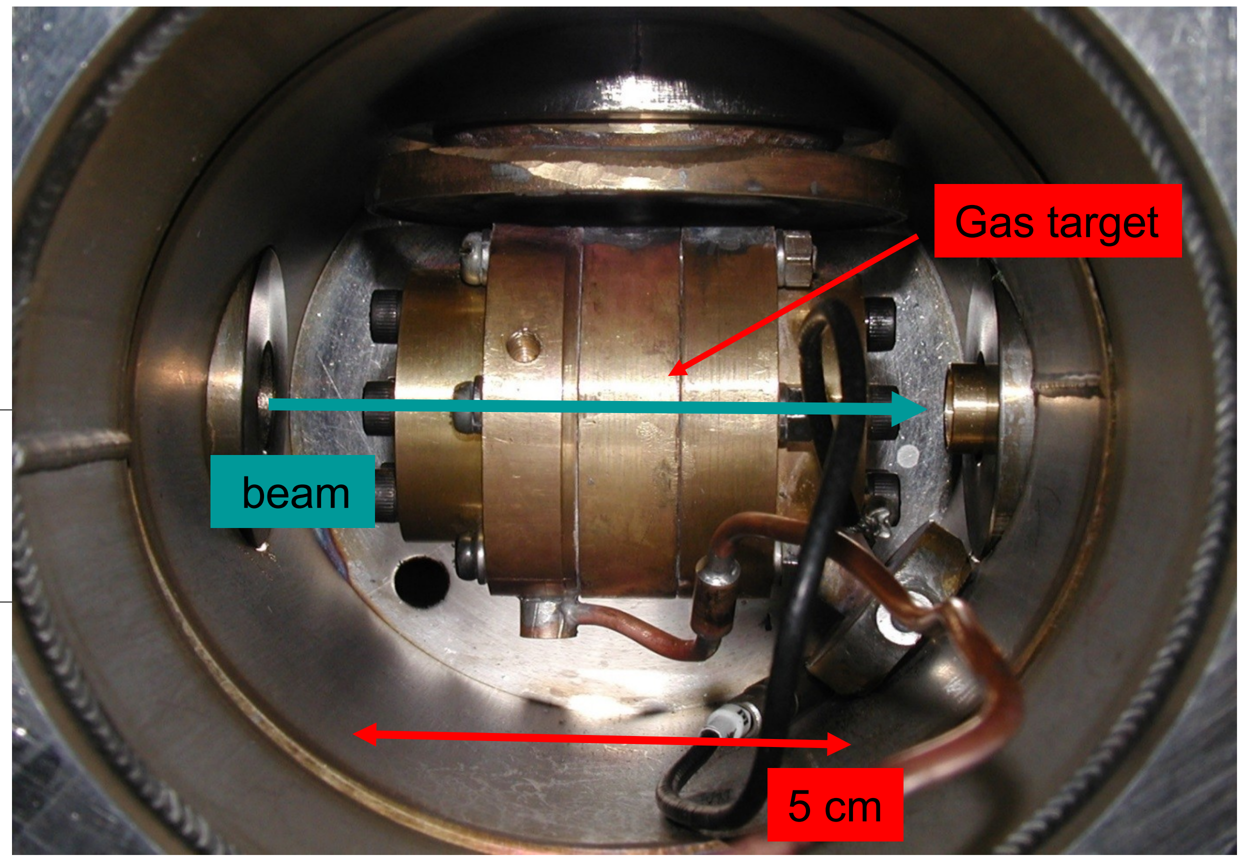


Side view

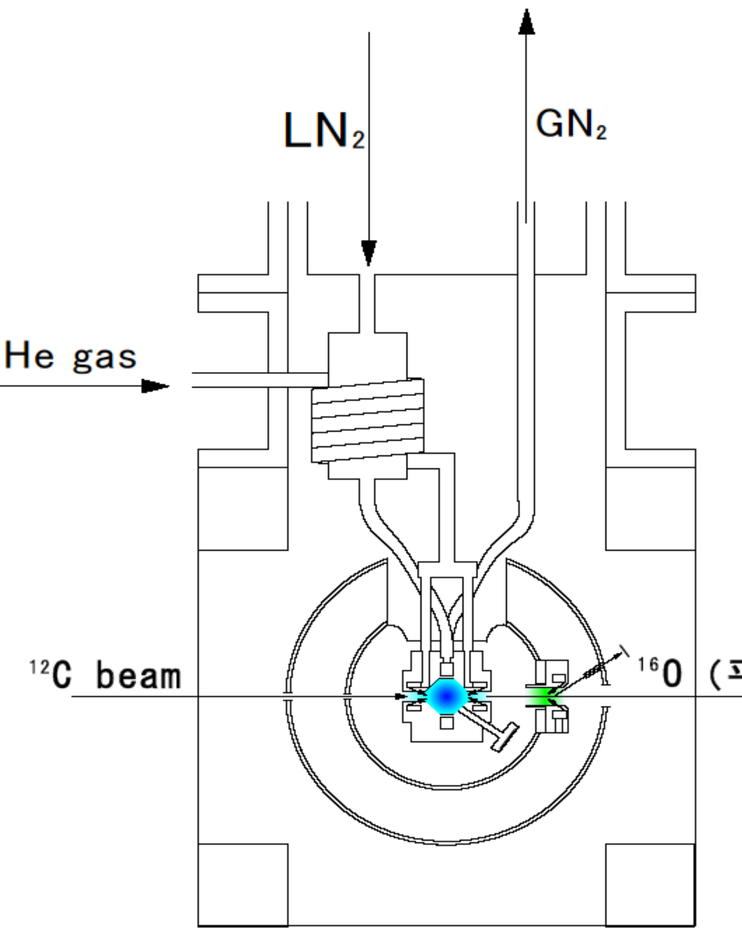


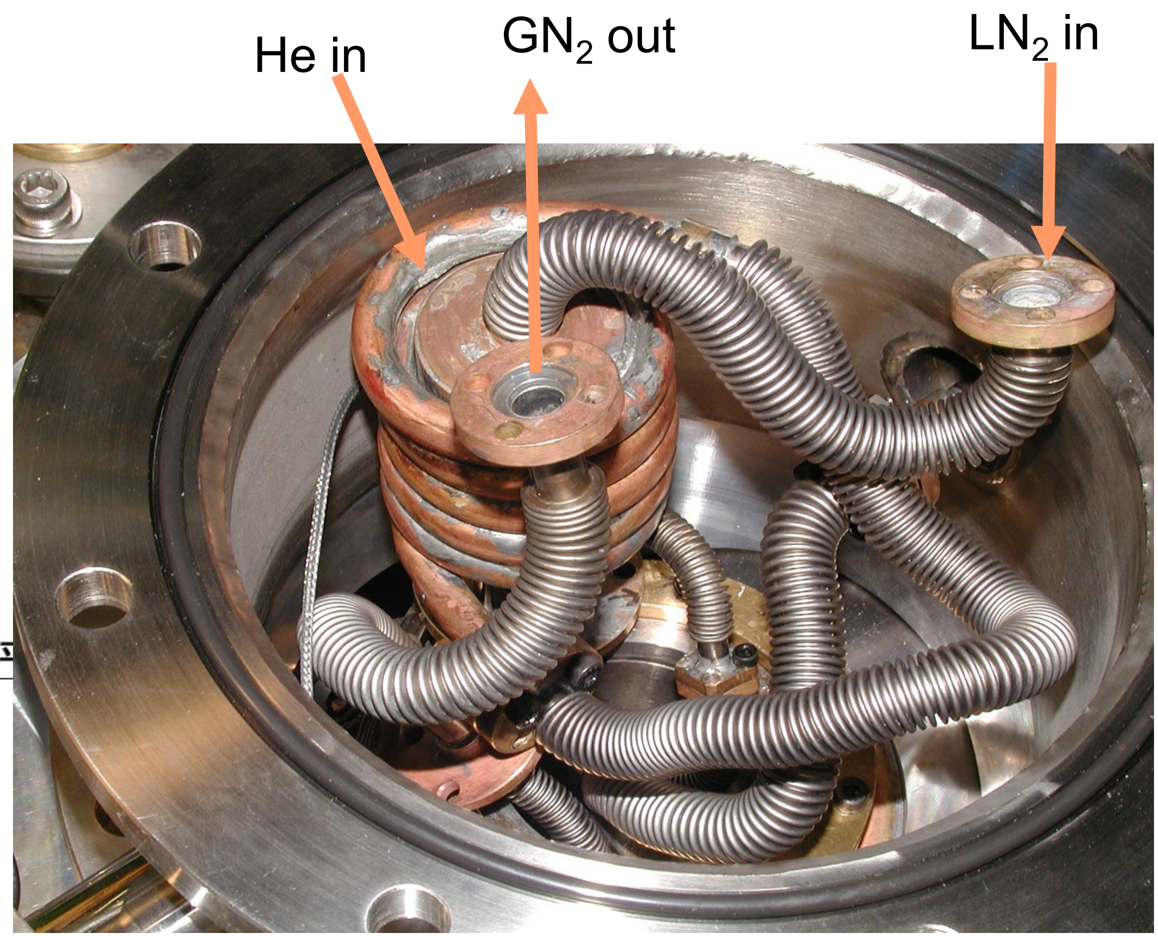
LN_2-cooled gas target





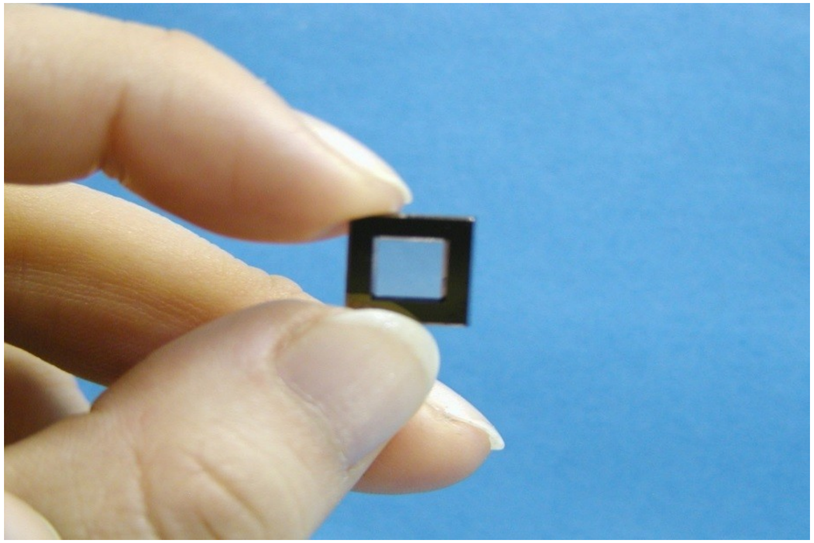
LN_2 cooled gas target

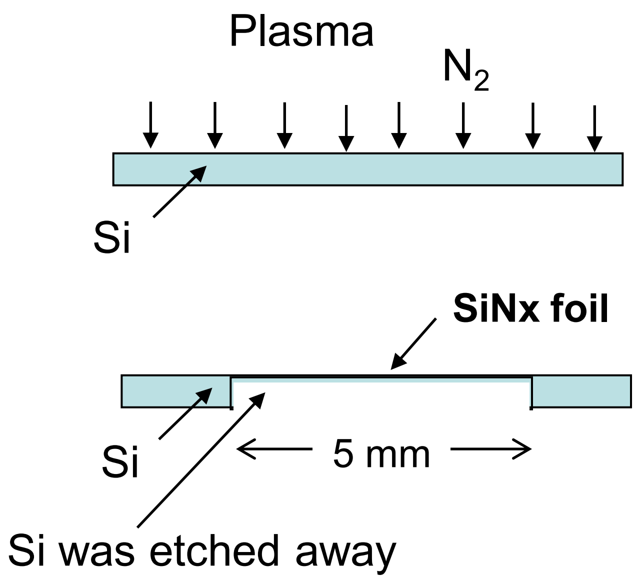




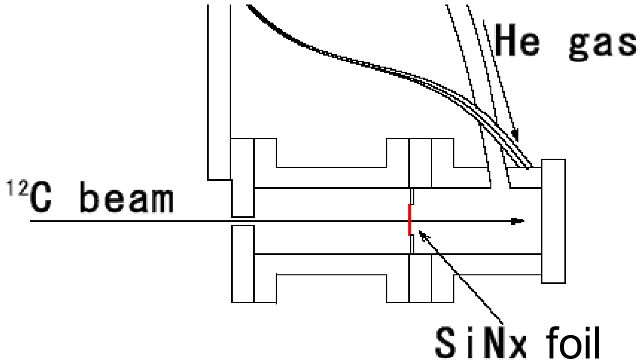
Very thin SiN_x foil

Thickness: 50nm (~12μg/cm^2)
Density: ~2.4g/cm^3
Area: 5mm x 5mm with a Si bank



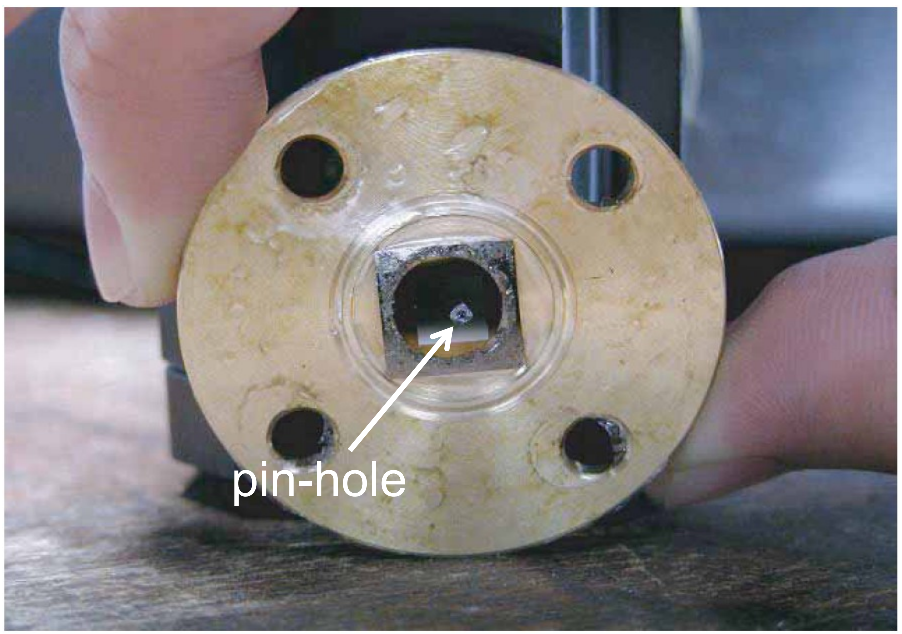


Beam damage on SiNx foil



^{12}C beam, 6MeV

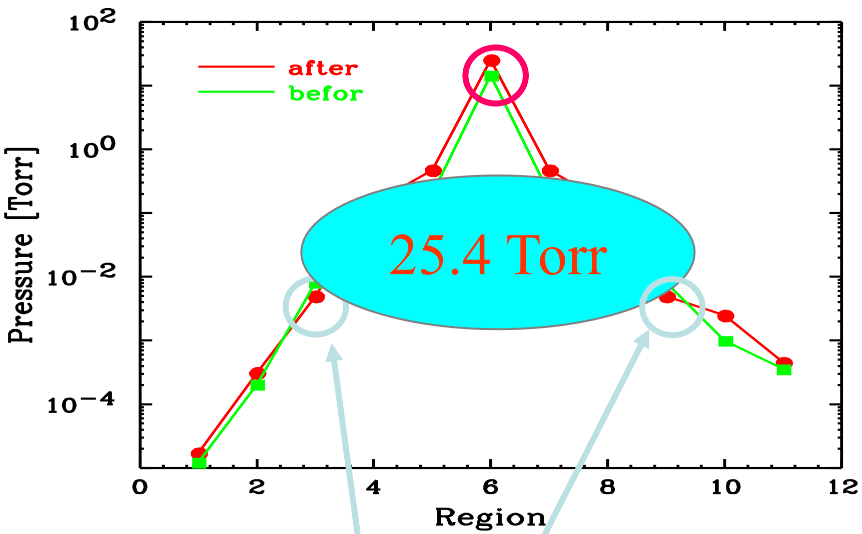
- intensity : 0.4〜1μA
- Beam size : 1.5mmϕ
- ^{4}He pressure:10Torr



SiNx foil was broken by the beam at ~103pmC/cm2 irradiation, i.e.,
at about 1 μA x 1 hour or
at about 0.5 μA x 2 hours
in1.5mm in diameter.

The breakdown may be caused not by heat damage, but by radiation damage.

#5 A big oil-diffusion pump was installed. (Brute force)



第三段領域の排気速度の増加により、中心に高いHe圧を実現.

Goal of <u>25 Torr</u> was achieved.

Background (BG) reduction

Goal: N(BG)/N(12C) < 10^{-19}

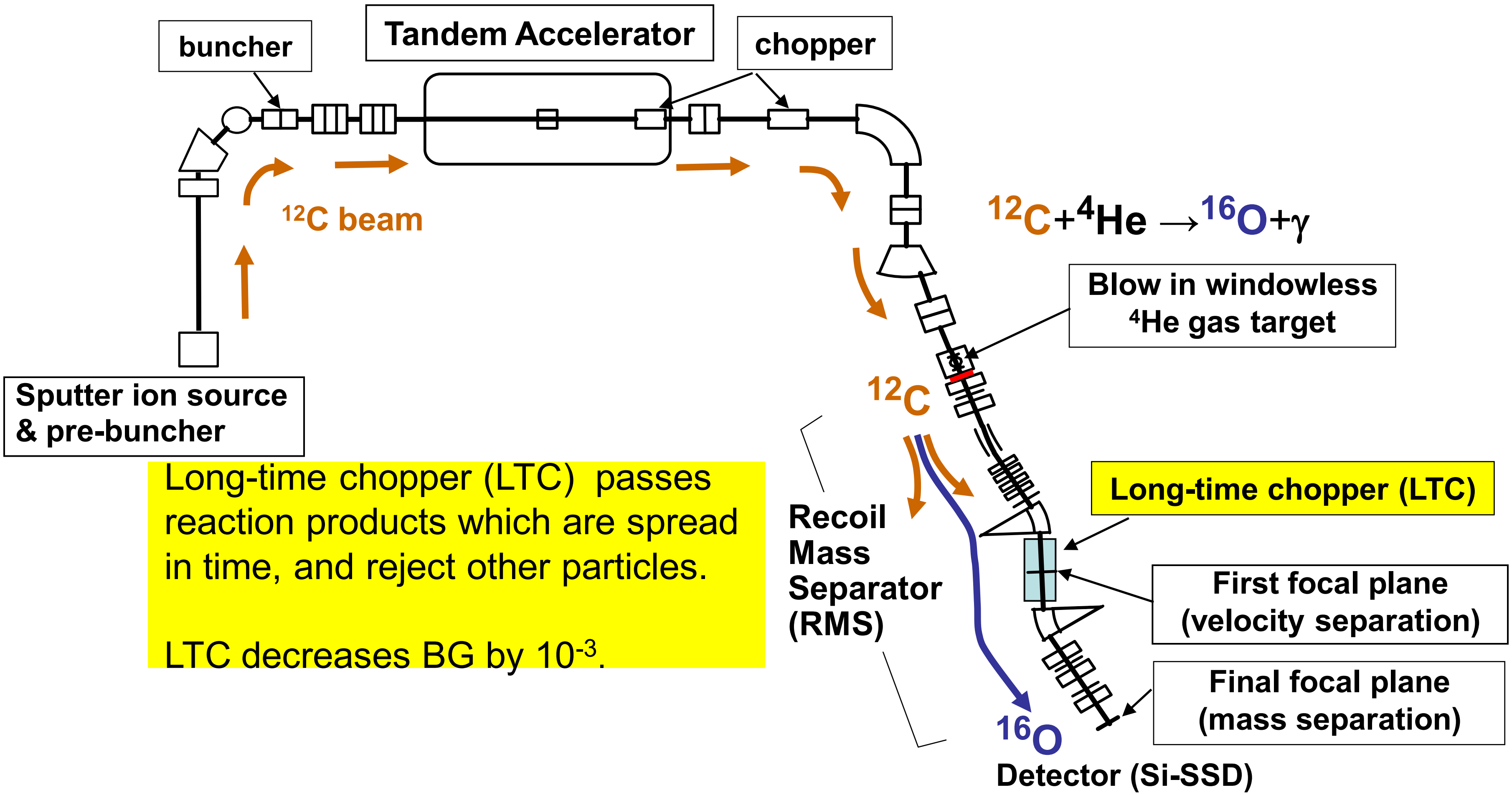
1) Recoil Mass Separator x～10^{-11} (but conditional)

2) Pulsed beam (TOF) x～10^{-2}

↓

3) Long-time chopper x～10^{-3}

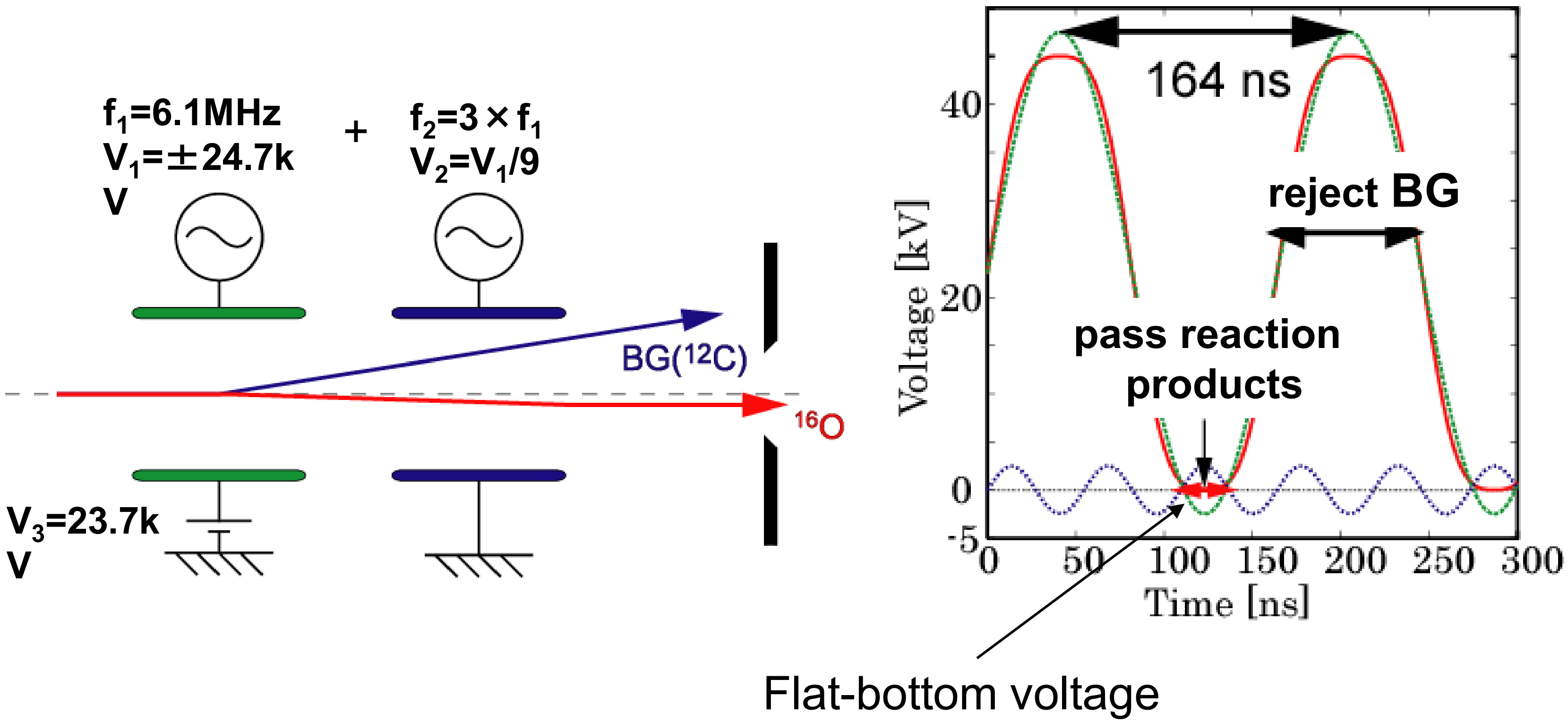
BG reduction: long-time chopper (LTC)

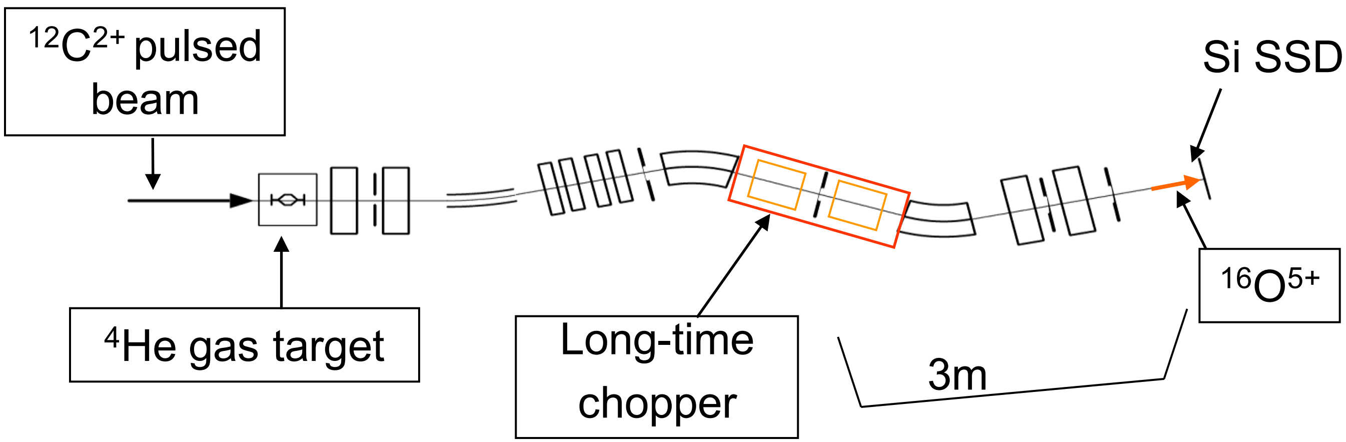


Long-time chopper (LTC) passes reaction products which are spread in time, and reject other particles.

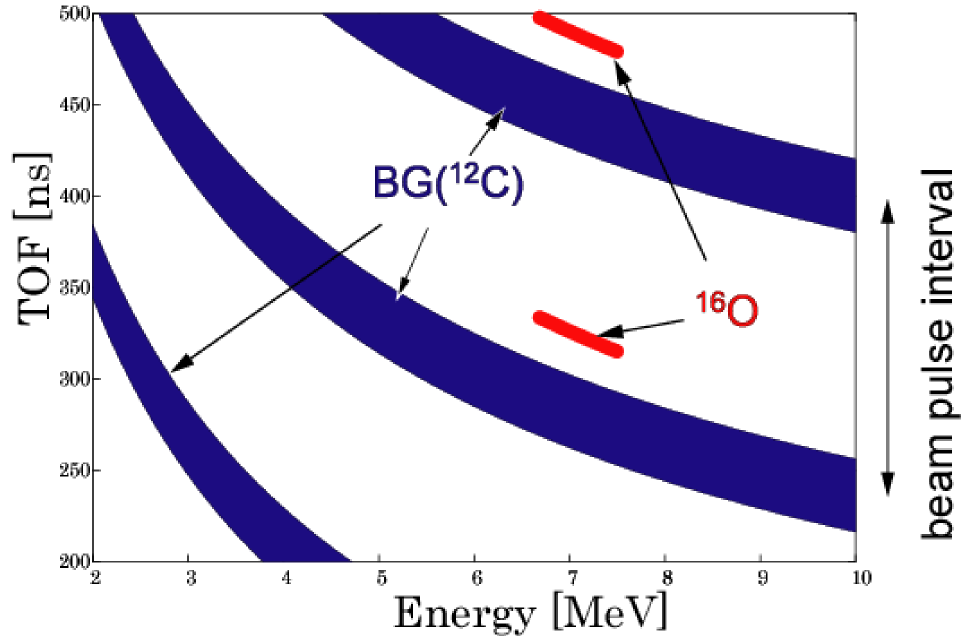
LTC decreases BG by 10^{-3}.

Long time chopper
to pass only reaction products (^{16}O) which are spread in time.





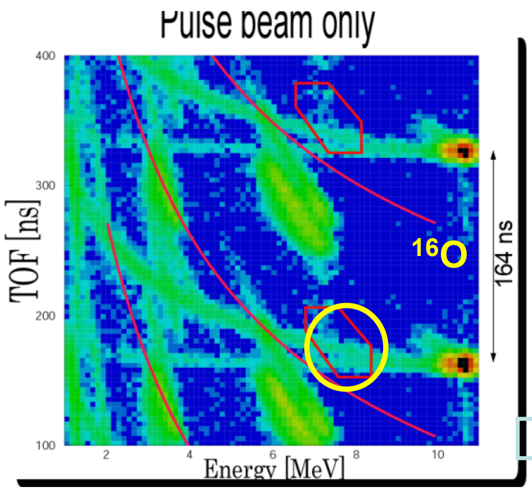
BG that passed through LTC are separated by TOF.



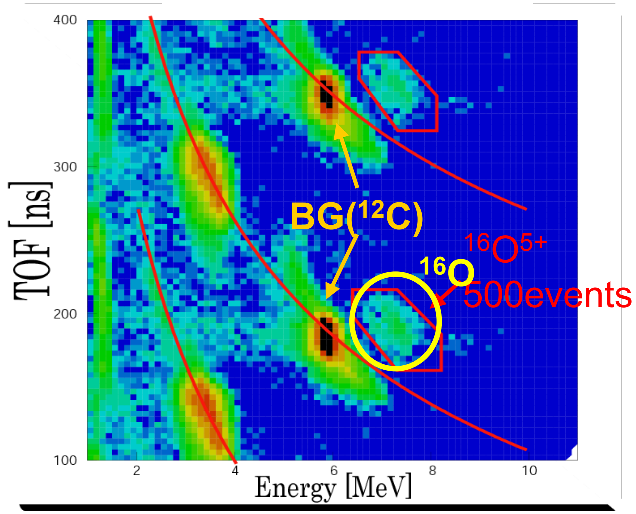
Measurement of $^4He(^{12}C,^{16}O)\gamma$ at Ecm = 2.4 MeV with long-time chopper (LTC)

Beam : 100pnA ($^{12}C^{2+}$ 9.6MeV) , Target : 4Torr × 4cm= 16Torr･cm (^4He)

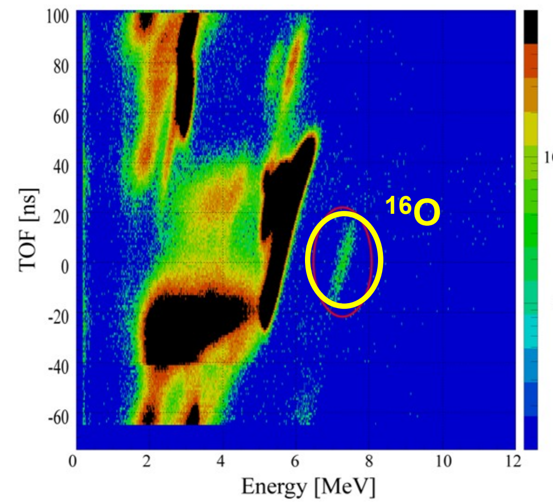
Without LTC



With LTC

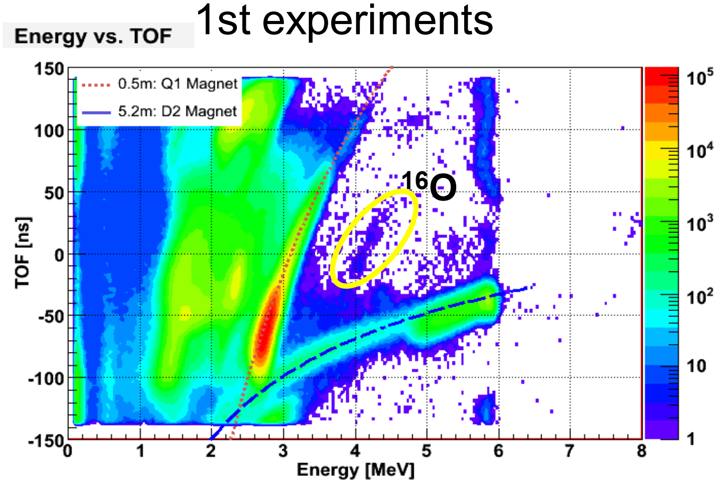


BG reduction around LTC

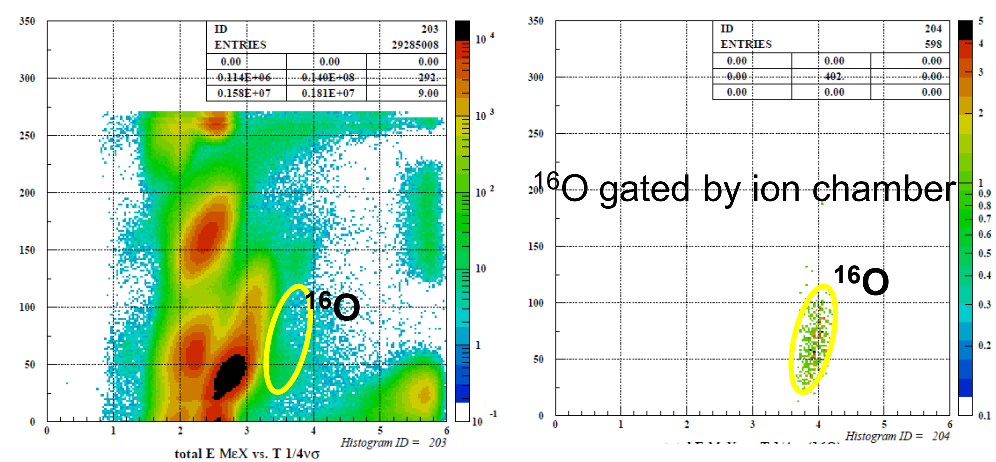


--- E_{cm}=1.5 MeV Experiments ---

1st experiments



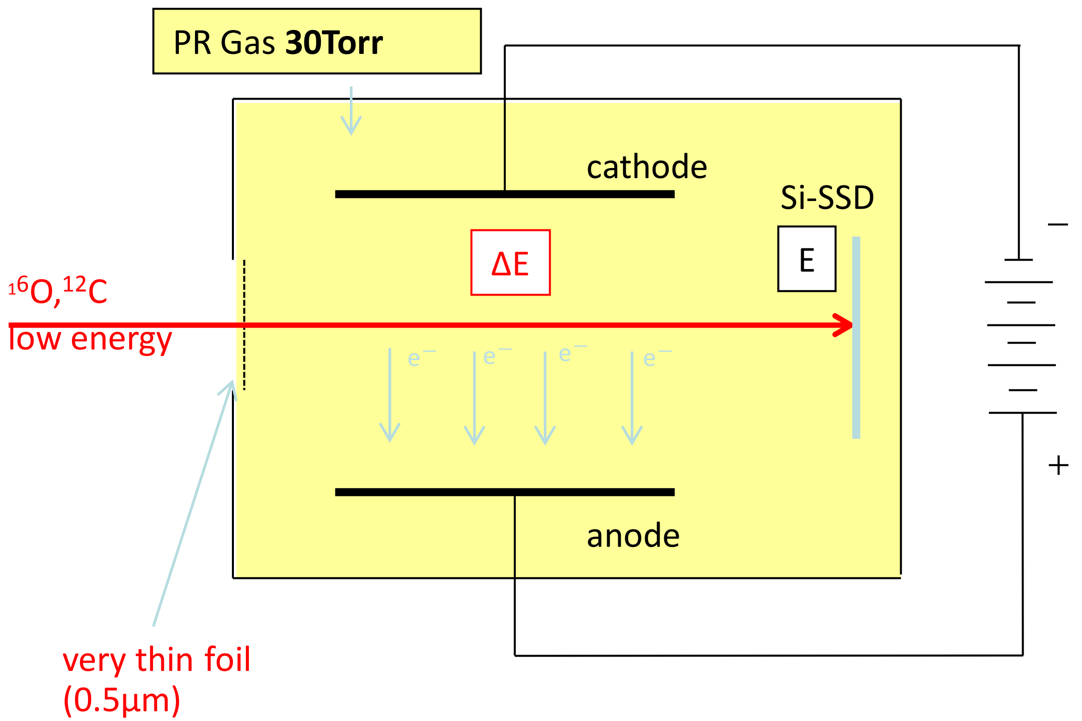
2nd experiments (with ion chamber)



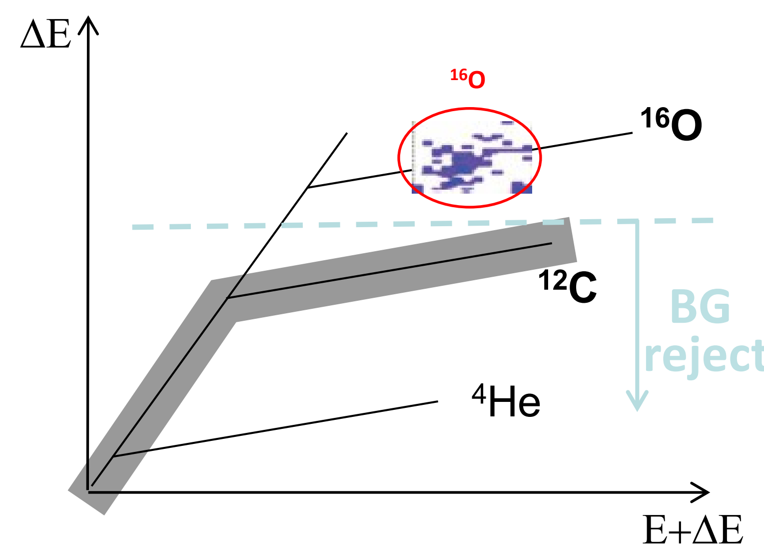
further BG reduction

^{16}O and ^{12}C separation by **Ionization chamber**

- measure the ΔE (energy loss) by an ionization chamber and E by the SSD

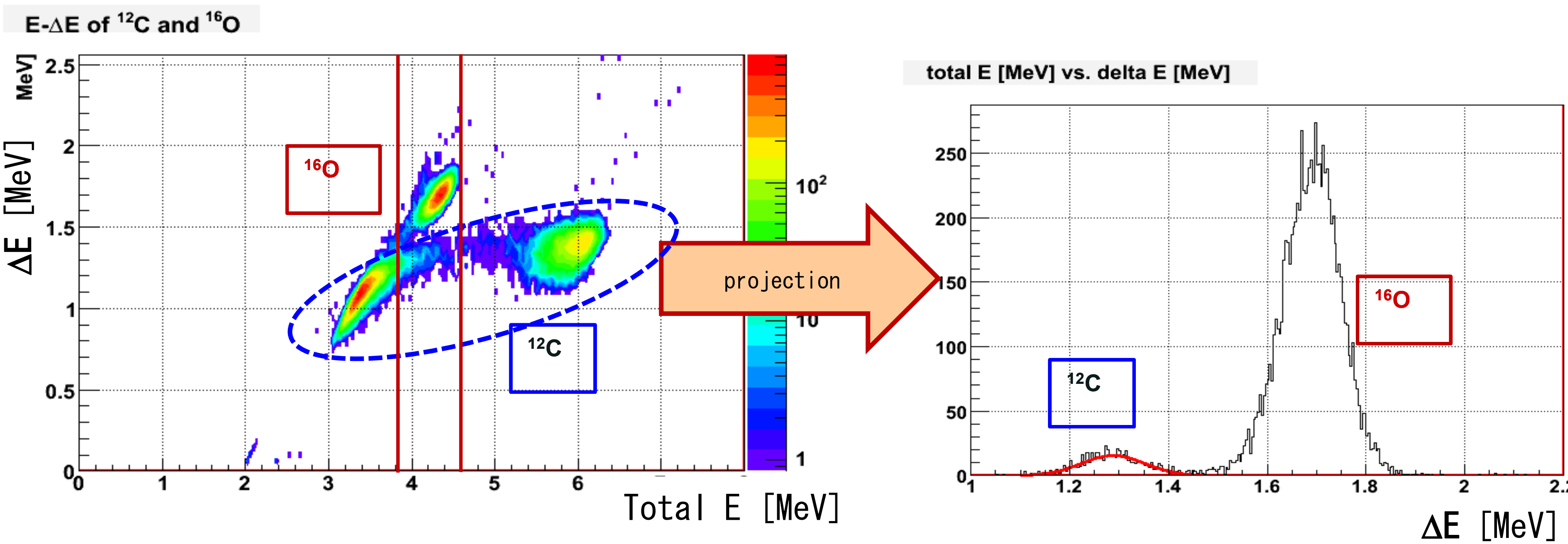


ΔE of ^{16}O is larger than ^{12}C



Performance of Ionization Chamber

- Test experiment at same setting with E_{cm}=1.5MeV measurement
  - 6.0MeV, ^{12}C beam: ~100nA
  - Pilot ^{16}O - spontaneity generating from tandem acc.

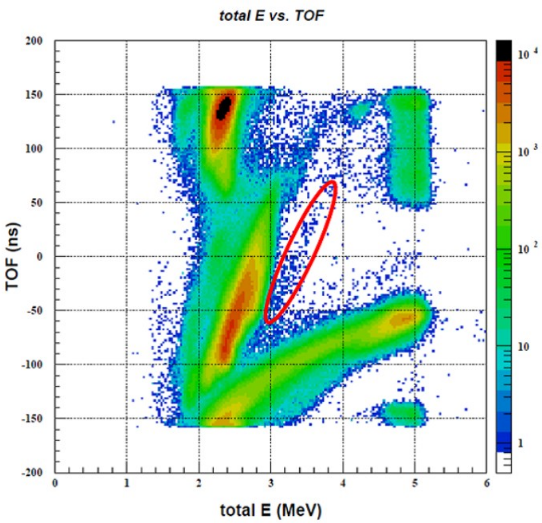


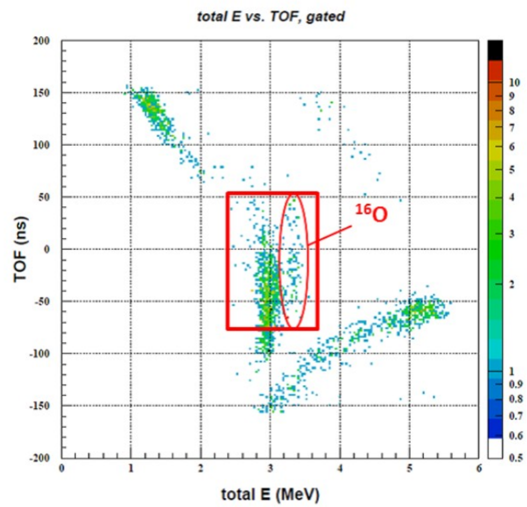
- ^{16}O(4.5MeV) and ^{12}C(3~6MeV) were separated by the ratio of 10^{-3}(99.9%)
- Energy resolution of Ionization Chamber was ΔE/E=9%(FWHM)

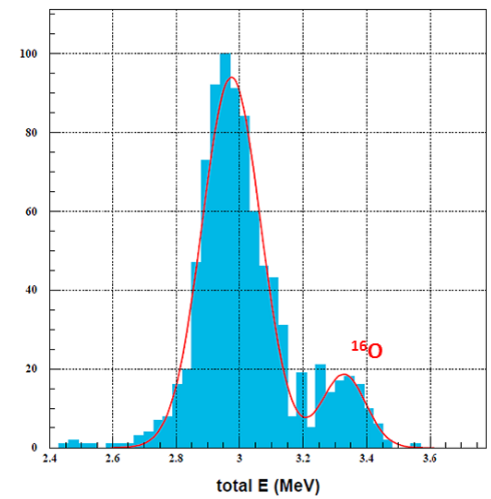
E_{cm}=1.2 MeV Experiments

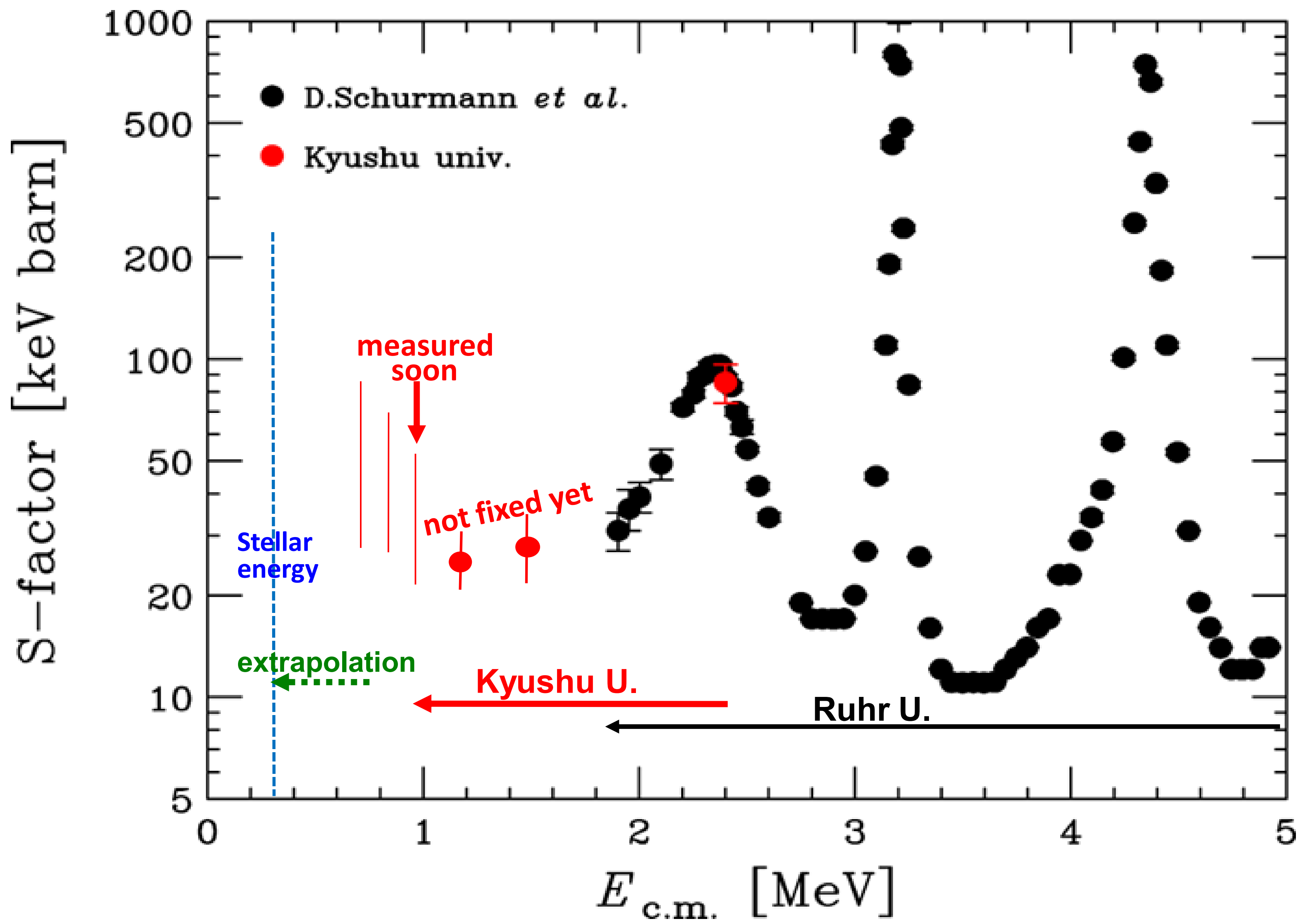
An ion chamber (ΔE counter) was developed to identify 16O and 12C (BG).

In addition to 12C-BG, 16O-BG from target cell inner surface were recognized.
→ Reduce the 16O-BG from the target cell was very very hard task.







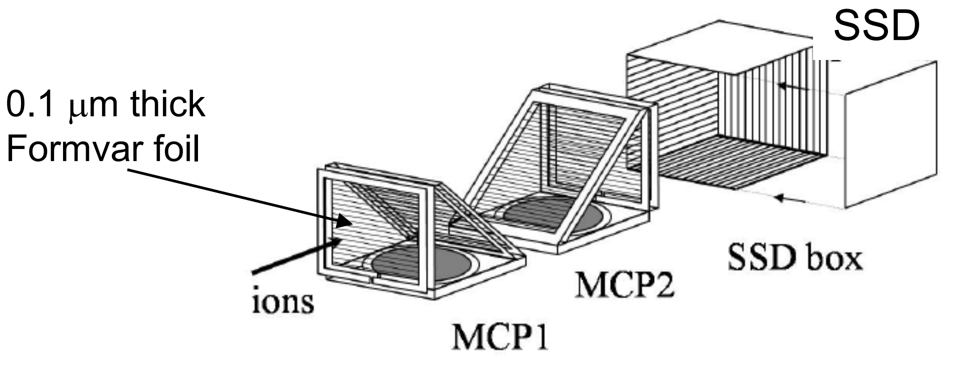


Measurement at 1.0MeV will be made till December 2014 !

Preparation for the measurement at Ecm = 1.0 MeV

A: Preparation of TOF measurement to separate 16O and 12C at 2-3 MeV.

TOF measurement system at RIKEN (Morita Group)



B: Increase the pulsed 12C beam intensity by installing a pre-buncher at I.S.

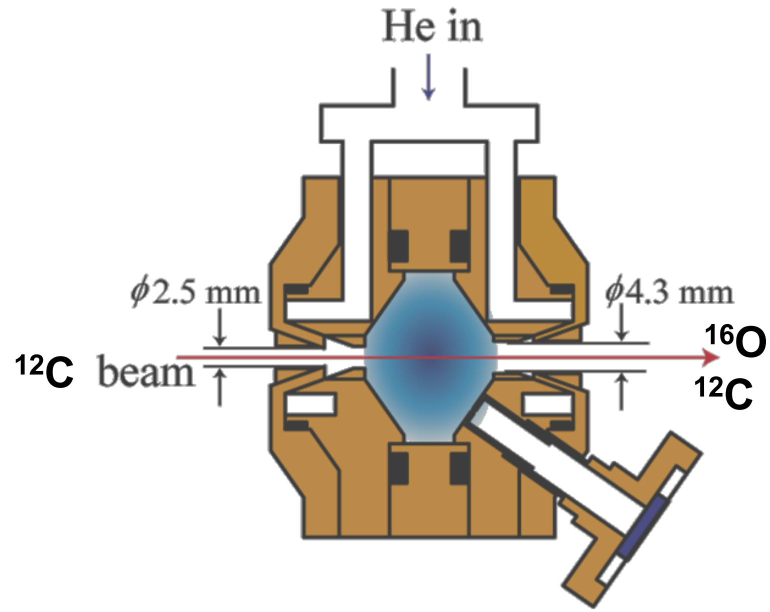
C: Enlarge RMS solid angle.

D: Decrease BG
by improving the 12C beam path and the He target system,
by enlarging RMS beam chambers, and
by new TOF system.

Measurement at 1.0MeV will be made in 2014 !

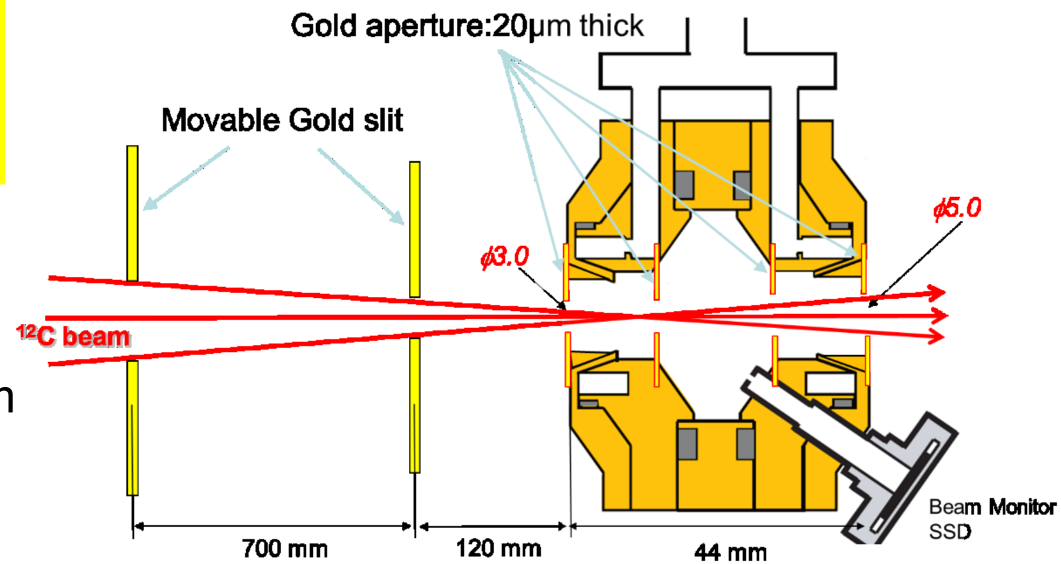
重大な問題！

^{16}O-BG from
^{4}He target



^{16}O-BG from the target inner walls (oxisided surface)!
^{12}C+ZnO→O+X, ……

→thin Au apertures
→movable Au slits for the ^{12}C beam



New Target cell (made of brass)

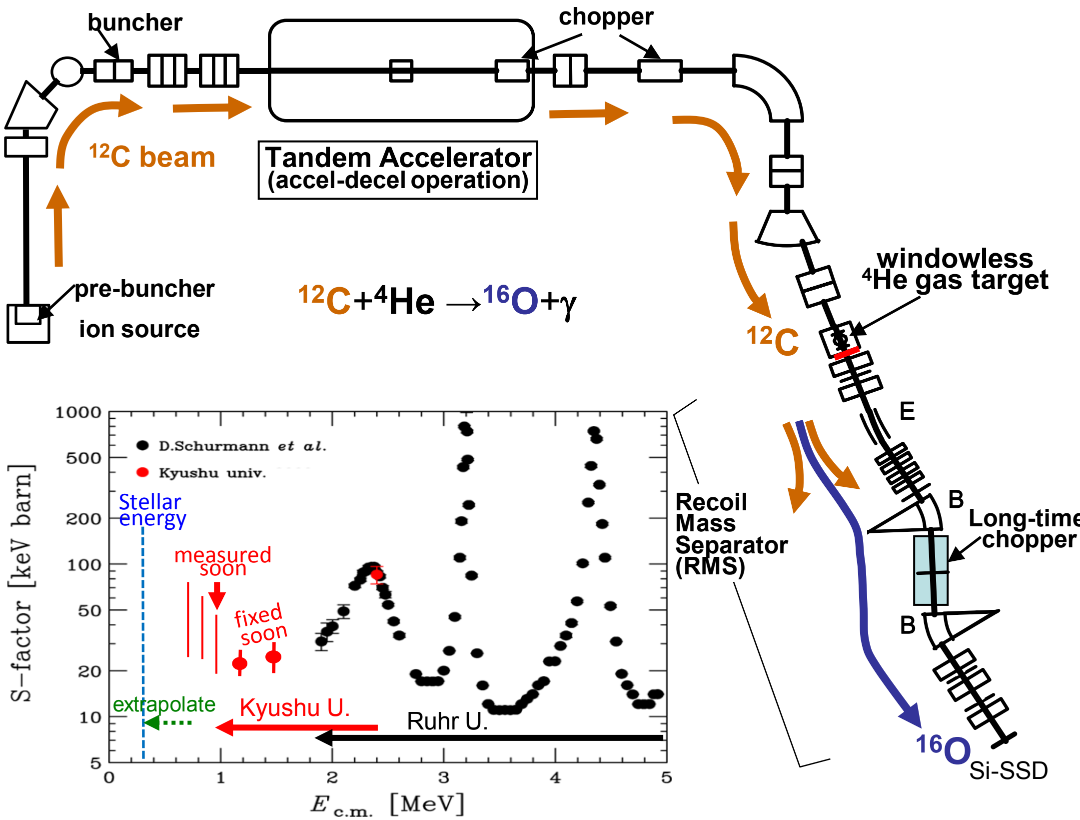
九大での$^{12}C+{}^{4}He \rightarrow {}^{16}O+\gamma$ 反応全断面積測定の現状

九大理・相良建至

「宇宙核物理実験の現状と将来」研究会
2014.8.07-08 RCNP

天体ヘリウム燃焼の主反応のひとつである$^{12}C+{}^{4}He \rightarrow {}^{16}O+\gamma$ 反応 (E_{cm}=0.3 MeV) の全断面積は、約50年の世界競争を経ても未だに測定できていない。九大では約20年前からこの全断面積測定に取組み、Ruhr大学のRolfs達の5～1.9MeVでの測定を追い越し、1.5, 1.2MeVで測定し、今は1.0MeVでの測定の準備をしている。

0.7MeVまで実測定をして結果を0.3 MeV に外挿するのが最終目的であるが、九大キャンパス移転その他で当面は目的が達成できない。 これまでの装置･手法開発を報告し、今後の測定に必要なものを提言する。



$^{12}C+{}^{4}He \rightarrow {}^{16}O+\gamma$ 反応 は16Oの共鳴準位により天体エネルギー(0.3MeV)付近で断面積(S-factor)が大きく変化する。従って0.3MeV付近まで実測定が必要だが、クーロン障壁で0.7MeVでも約1pbarnしかない。

断面積絶対値を信頼性良く測定するには、
1)直接反応測定(逆反応ではなく)
2)生成^{16}O検出（γ検出ではなく）
が不可欠である。 従って左図のようなセットアップ（九大現状）になる。ドイツ・ルール大学のセットアップも基本的に同じである。

九大では0.7MeVまで測定するため、①10pμAの^{12}C beam、②0.1atm･cmのHe膜なし標的、③^{16}O検出効率40%(1荷電状態のみ検出)、④測定時間積算1ヶ月、を目指した。①以外はすべて実現した。

上記4条件は検出量を増やす方策であるが、バックグランド(BG)を低減する方策も不可欠である。0.7MeVでは、生成^{16}Oと同じ方向の^{12}C beamの粒子数の比は、約10^{-18}である。従ってBGは10^{-19}以下に低減する必要がある。今はまだ2-3桁足りない。

九大では今年中に1.0MeVでの測定を実現する。しかし、キャンパス移転とメンバー定年等で実験は中断する。
[A] タンデトロン を入手して上記①を解決し、
[B] 執念の実験リーダー が現れれば、
0.7MeVまで実験が出来、歴史に残る仕事が出来る。