Direct measurement of the $^{4}He(^{12}C,^{16}O)\gamma$ cross section near stellar energy

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Introduction

- $^{12}C/\,^{16}O$ ratio: after helium burning process
  - affects evolution of heavy stars – supernova or white dwarf
  - abundance of element of universe

- Cross Section of $^{4}He(^{12}C,^{16}O)\gamma$
  - very small (~10^{-8} nb) – coulomb barrier
  - varies drastically around stellar energy(0.3MeV)

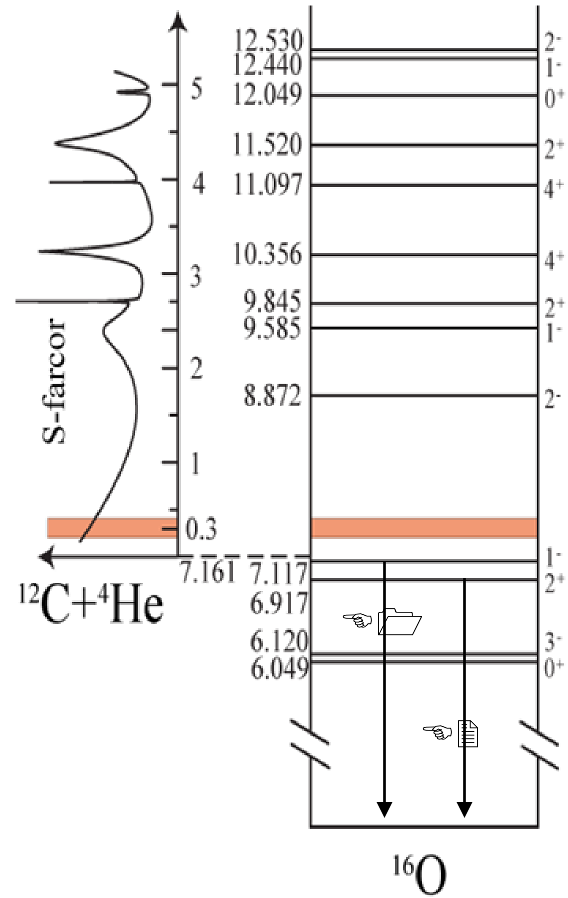
- Extrapolation with experimental data

E_{cm} (MeV)	σ (nbarn)
2.4	60
1.5	1
1.15	0.1
1.0	3×10^{-2}
0.85	10^{-2}
0.7	10^{-3}
0.3	10^{-8}

our experiment
(±10% accuracy)

extrapolation

stellar energy



^{16}O measurement

① ^{4}He beam + γ measurement

② ^{16}N decay measurement

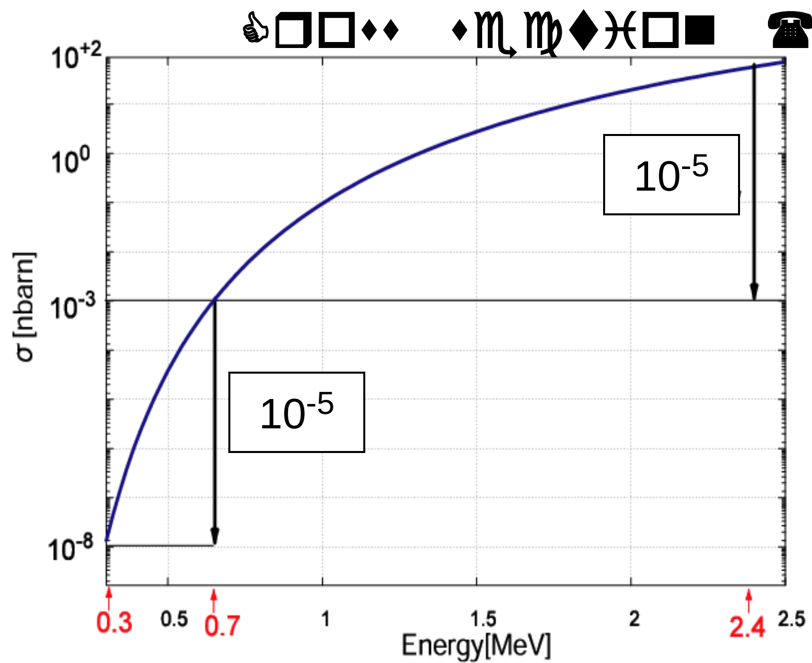
③ direct ^{16}O measurement with ^{12}C beam and ^{4}He target

- high efficiency (~ 40%: charge fraction)
- total S-factor can be obtained

- necessary components for E_{cm}=0.7MeV experiment
  - background separation system: $N_{BG}/N_{^{12}C}$ ratio of 10^{-19}
  - thick gas target : ~25 Torr x 3 cm
  - high intensity beam: ~ 10 pμA

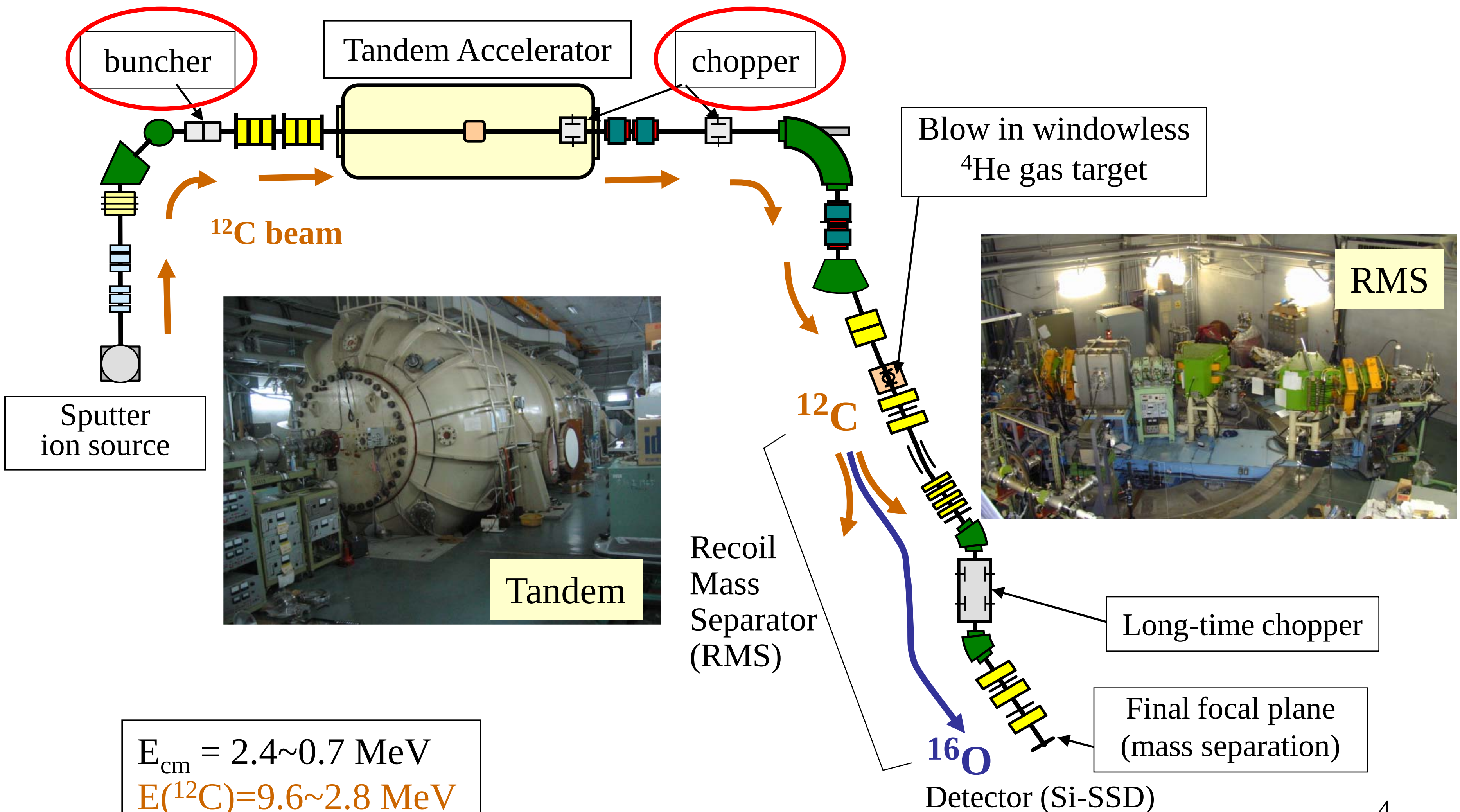
- Y(^{16}O) ~ 5 counts/day

  → 1 month experiment for 10% error



Experimental Setup

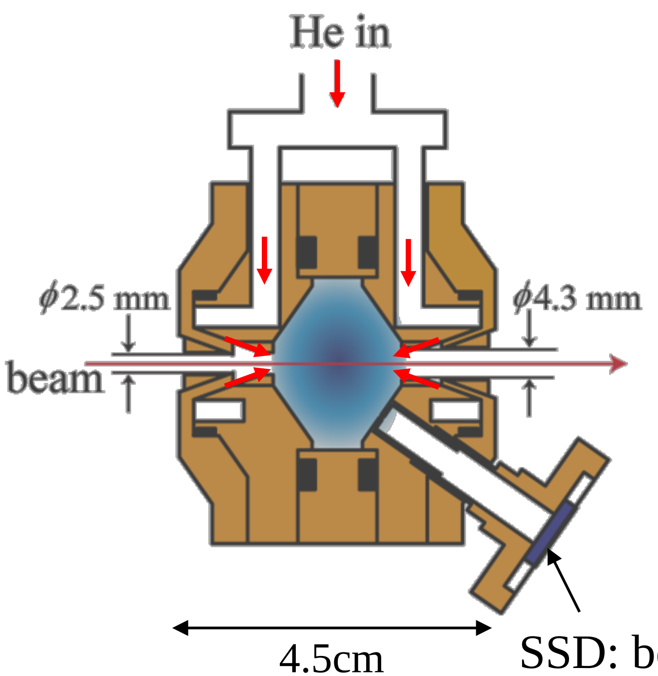
- Layout of Kyushu University Tandem Laboratory (KUTL)

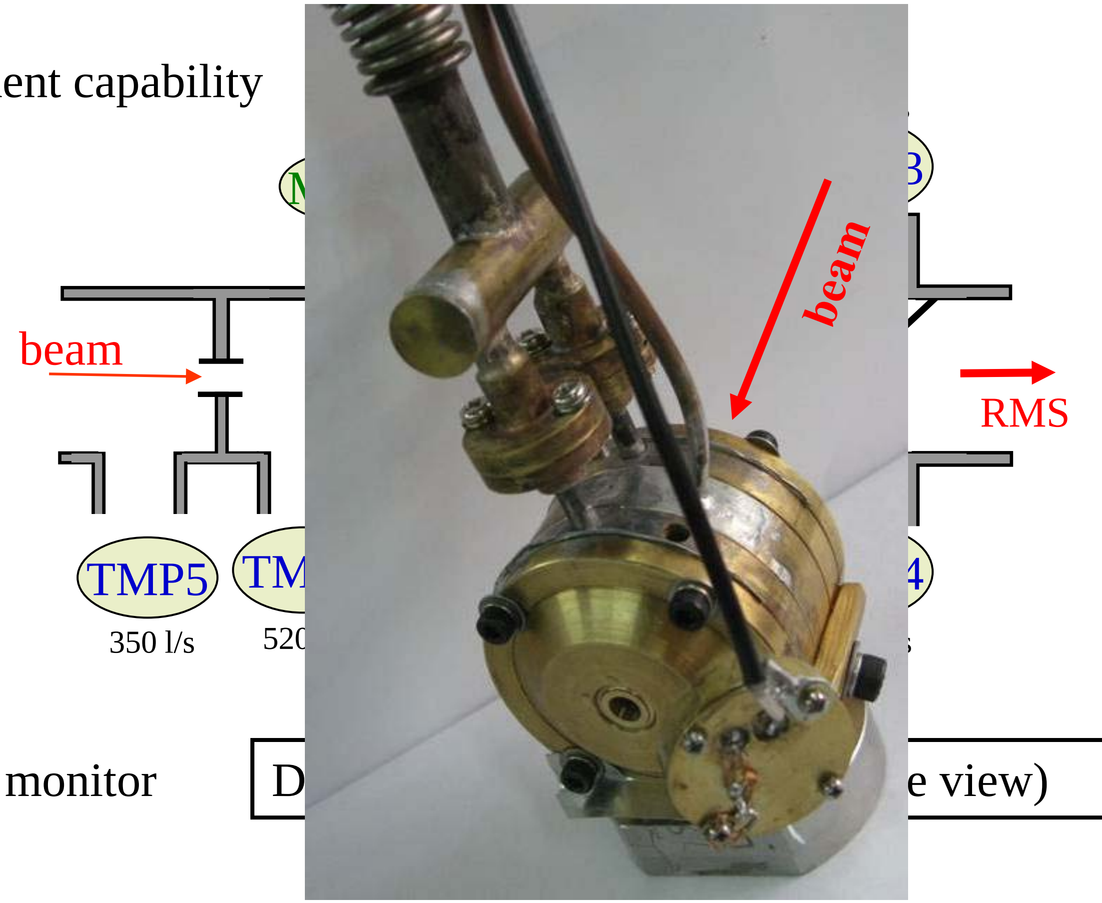


E_{cm} = 2.4~0.7 MeV
E(^{12}C)=9.6~2.8 MeV
E(^{16}O)=7.2~2.1 MeV

Windowless Gas Target

- Blow-In Gas Target (BIGT)
  - windowless & high confinement capability





- center pressure: 24 Torr - post stripper is not necessary
- effective length: 3.98 ± 0.12 cm (measured by p+α elastic scattering)

  → target thickness is sufficient for our experiment

  (limited by energy loss of ^{12}C beam)

BG Reduction and ^{16}O Detection

- Recoil Mass Separator
  - $^{12}C/^{16}O$ separation : ratio of 10^{-11}
  - angular acceptance: ±1.9deg

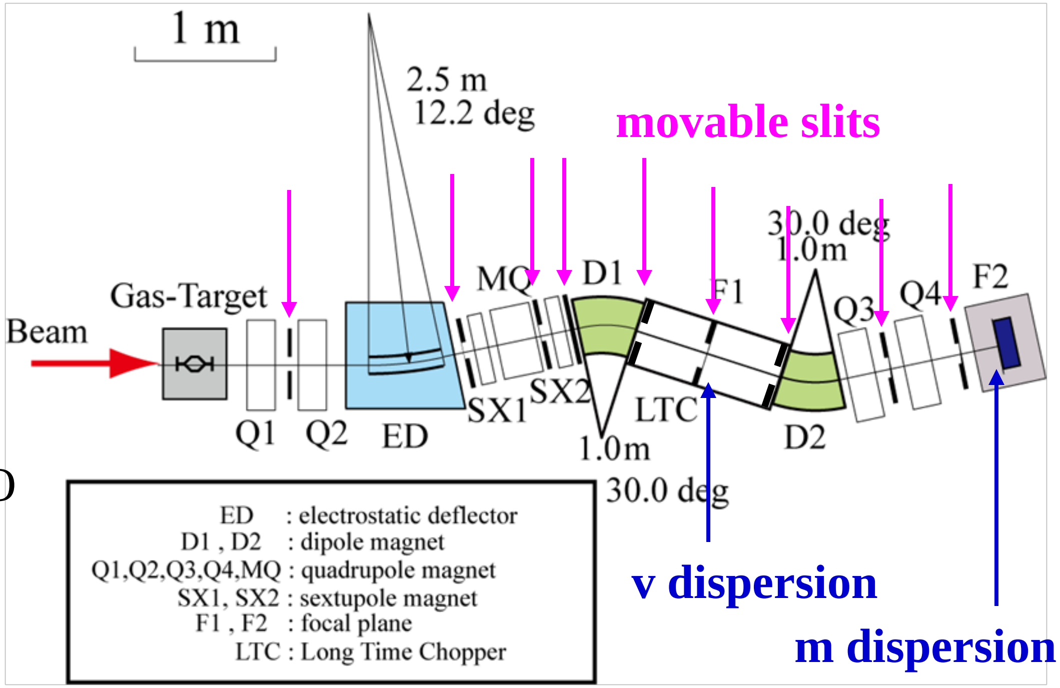
  100% ^{16}O can be observed

- Background ^{12}C
  - charge exchange
  - multiple scattering
  - p/q value is nearly equal to ^{16}O

- Background reduction

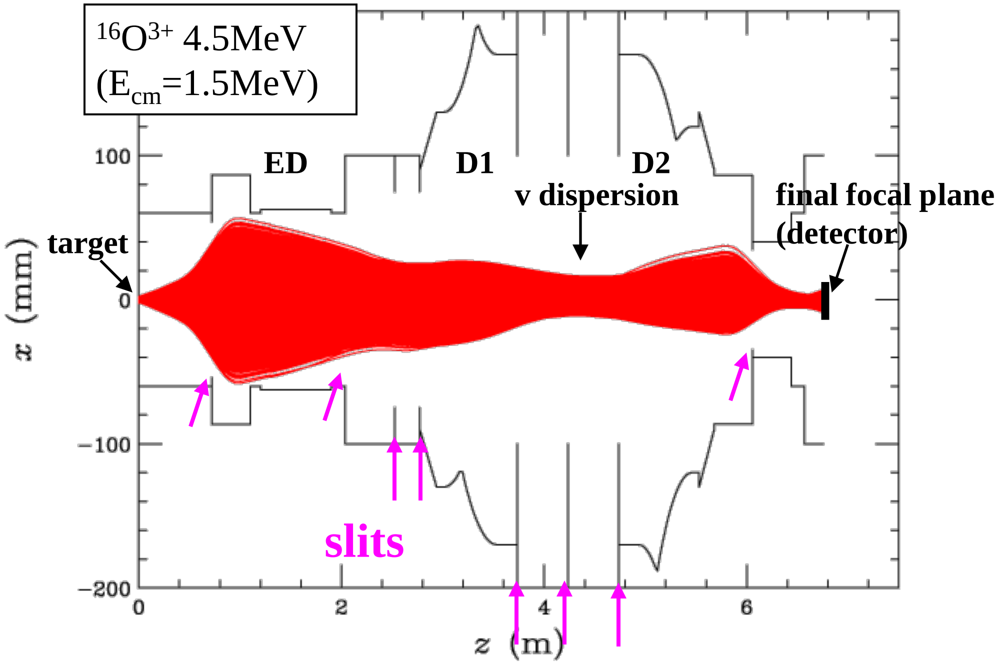
① RF deflector (Long-Time Chopper)
  - background reduction ~10^{-3}

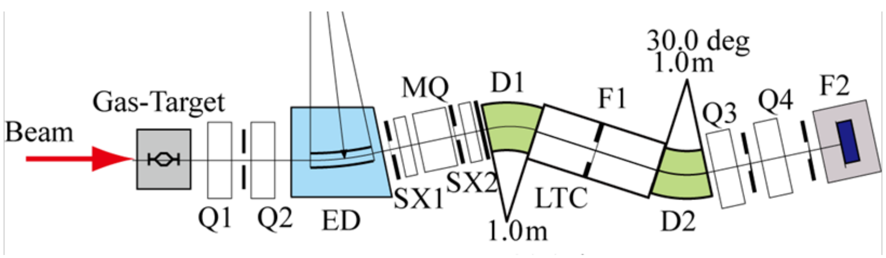
② movable slits
  - combination with trajectory analysis

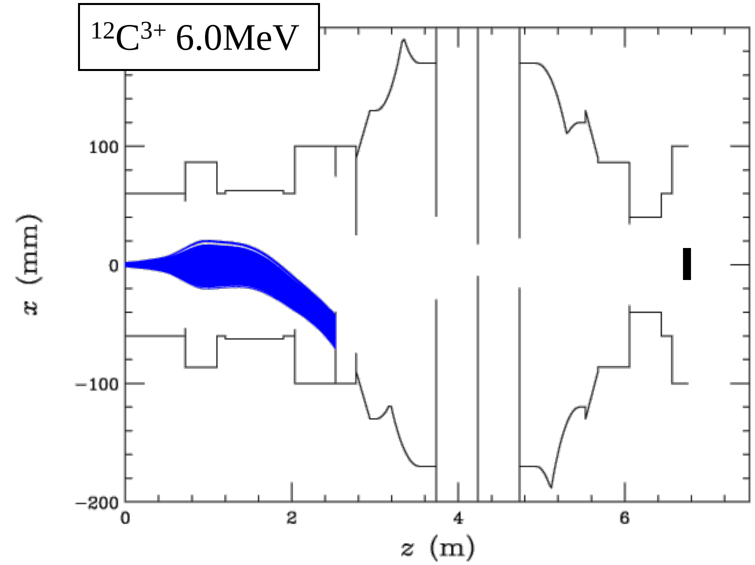


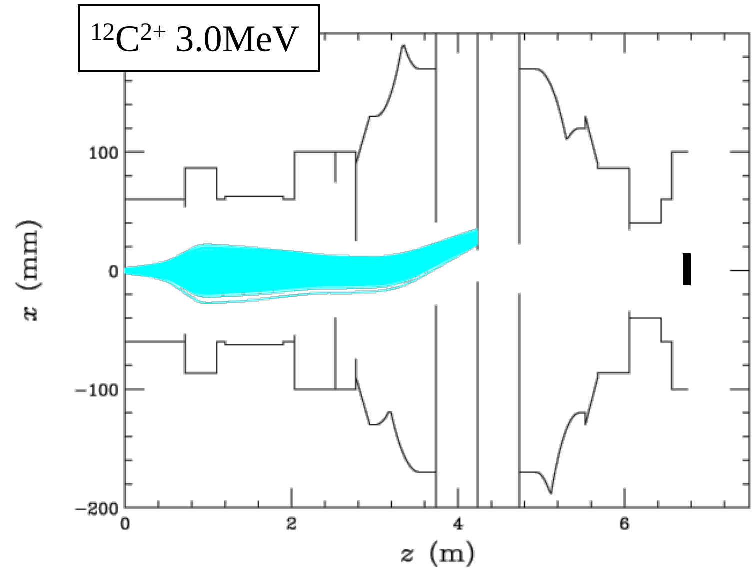
Trajectory Analysis

- ^{12}C backgrounds were rejected by slit control based on trajectory analysis





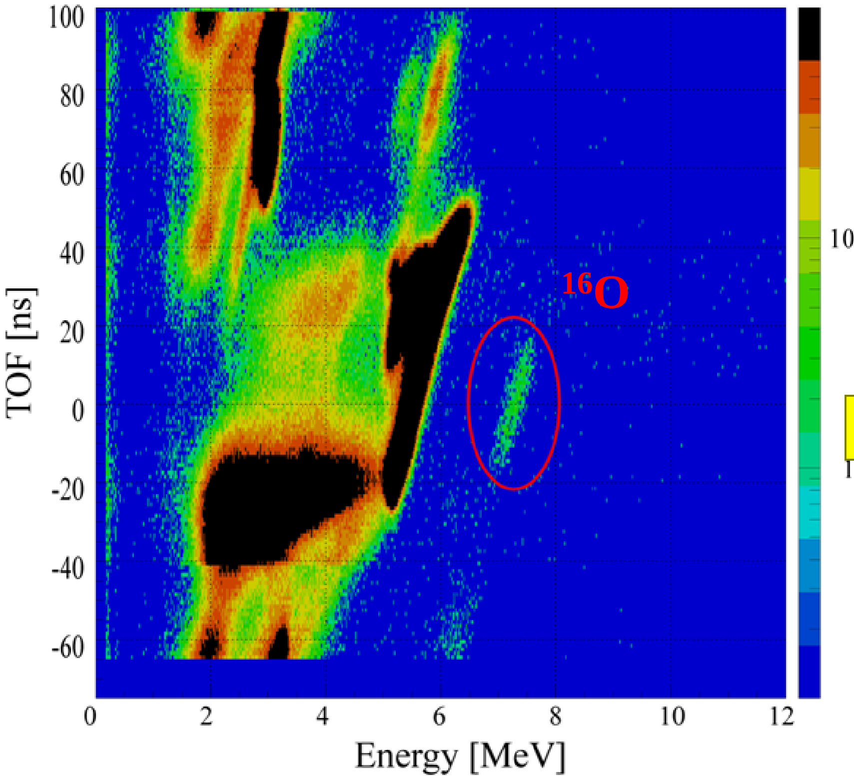


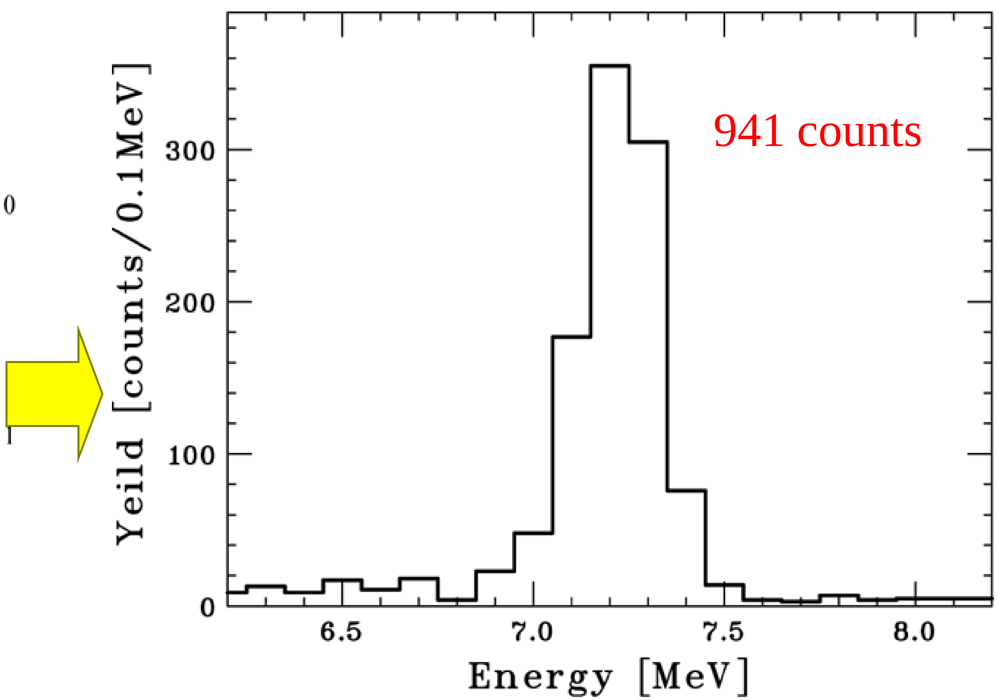


E_{cm}=2.4MeV experiment

- beam: $^{12}C^{2+}$, frequency: 6.063MHz
  - energy: 9.6MeV , intensity: ~35pnA
- target: ^{4}He gas ~ 23.9 Torr x 3.98 cm
- observable: $^{16}O^{5+}$ 7.2 ± 0.3 MeV
  - abundance = 36.9 ± 2.1 % = efficiency

29hours data



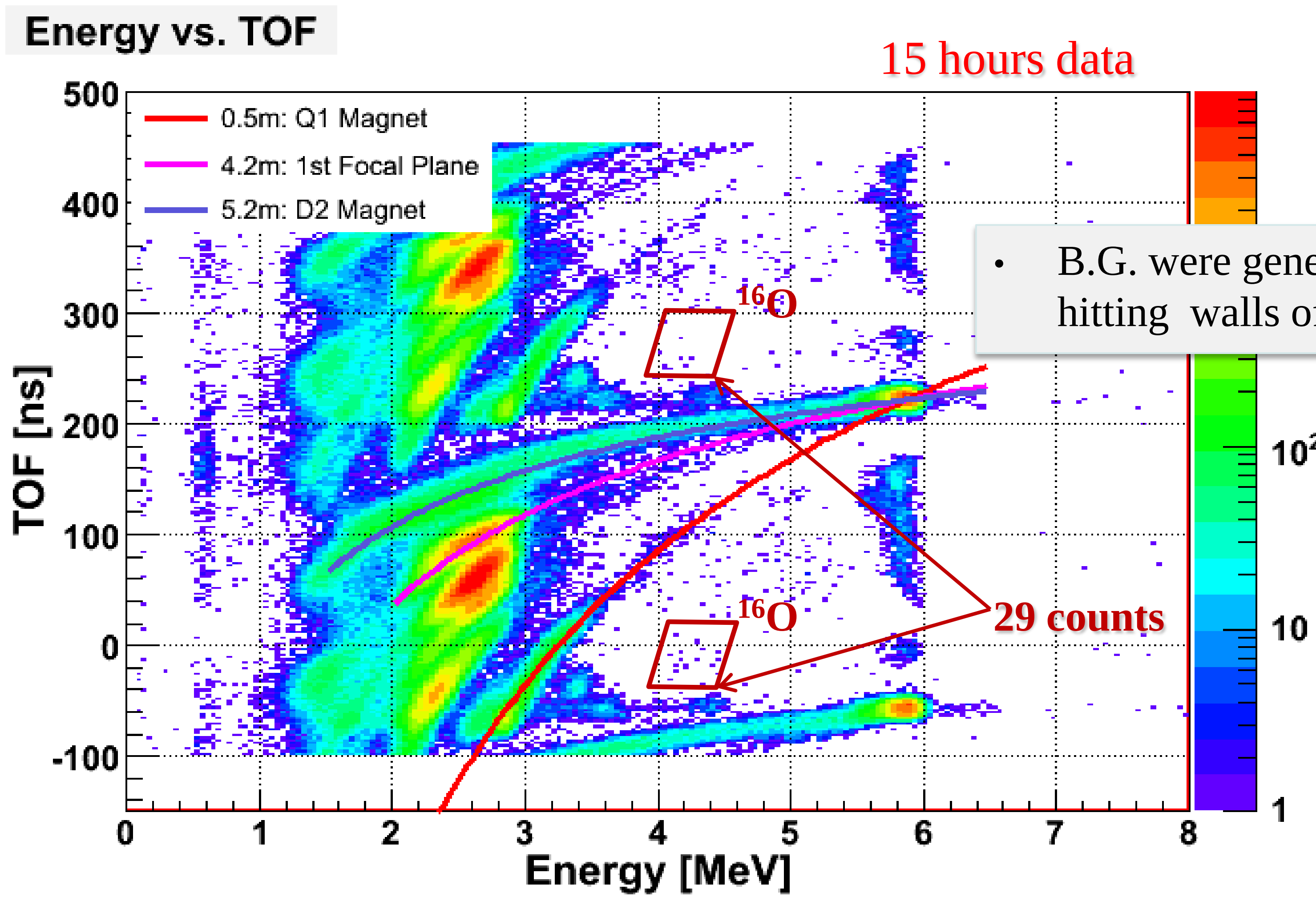


E_{cm}=1.5 MeV experiment

- beam: $^{12}C^{1+}$, frequency: 3.620MHz
  - energy: 6.0MeV, intensity: ~150pnA

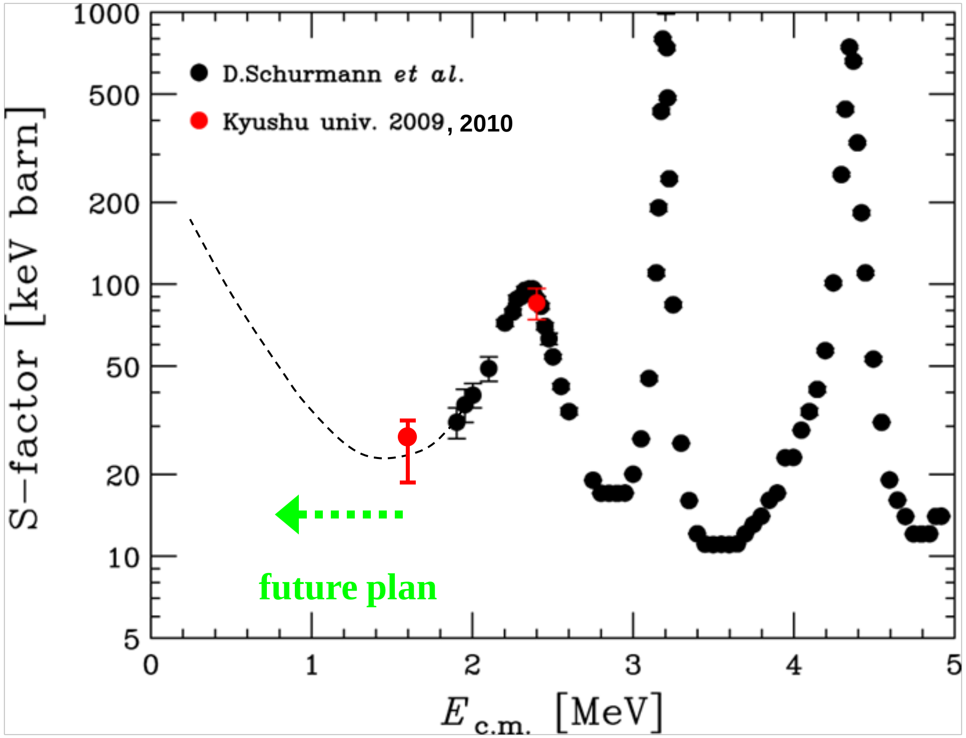
- target: ^{4}He gas ~ 15.0 Torr x 3.98 cm
- observable: $^{16}O^{3+}$, 4.5 ± 0.3 MeV
  - abundance = 40.9 ± 2.1 % = efficiency

15 hours data



- B.G. were generated from hitting walls of magnets

Cross Section and S-factor



- Our data (2009, 2010)
- D. Schurmann et al.
  Eur. Phys. J. A **26**, 301-305 (2005)

- 2.4MeV
  - $\sigma = 64.6 \pm 2.7\ \mathrm{nb}, \quad \mathrm{S}(2.4) = 89.0 \pm 3.8\ \mathrm{keV \cdot b}$
- 1.5MeV
  - $\sigma \sim 1.0\ \mathrm{nb}, \quad \mathrm{S}(1.5) \sim 30\ \mathrm{keV \cdot b}$
  - need much more statistics
  - background reduction is not sufficient

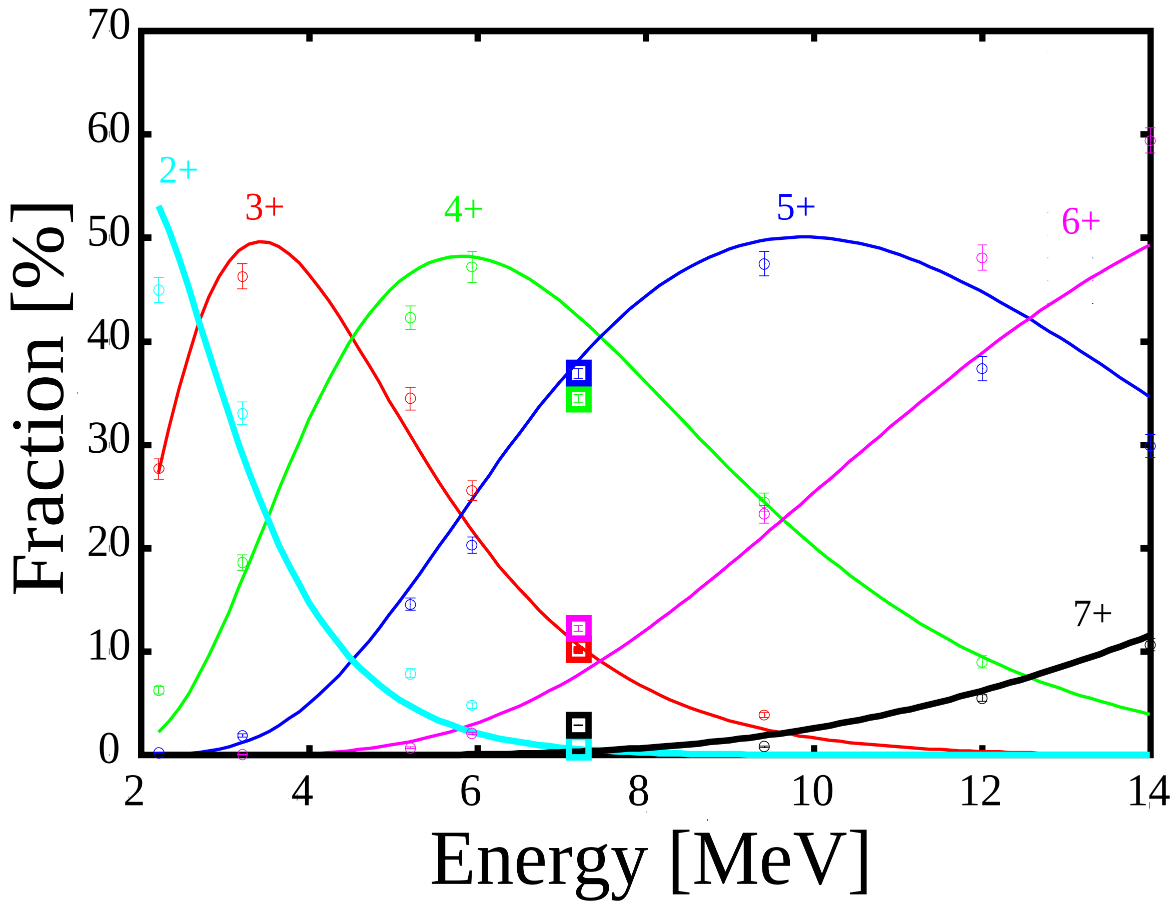
Summary

- Direct ^{16}O measurement via $^{4}He(^{12}C, ^{16}O)\gamma$ reaction was proposed to determine $^{12}C/^{16}O$ abundance ratio in stars
- Blow-in type windowless gas target was developed, and thickness of 24 Torr x 3.98 cm was achieved
- Background reduction was performed by using RMS, RF-deflector and movable slits

- E_{cm}= 2.4 MeV experiment
  - σ= 64.6 nb, S-factor = 89.0 keV b
- E_{cm}= 1.5 MeV experiment
  - $\sigma \sim$ 1.0 nb, S-factor ~ 30 keV b
  - need much more statistics, and background reduction

BACKUP

Charge State Fraction of ^{16}O



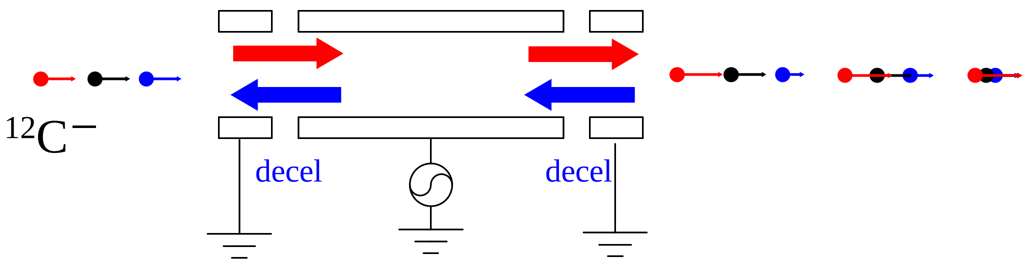
Our data

W. Liu *et al.* / Nucl. Instr. and Meth. A 496 (2003) 198–214

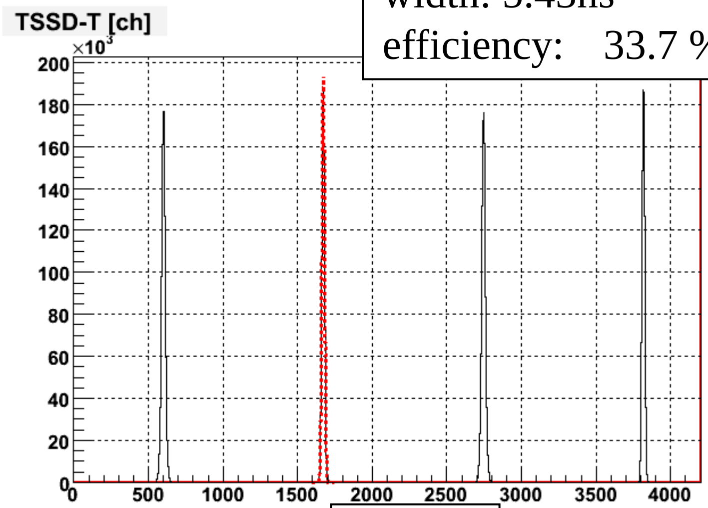
^{12}C beam

- TOF information is needed for background rejection
- pulsed beam: buncher, chopper

Buncher



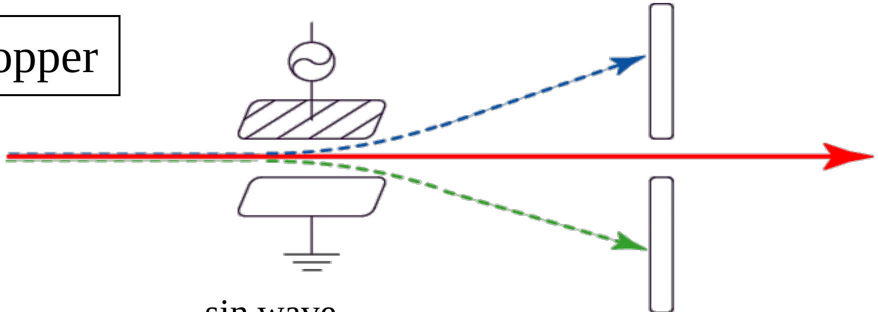
sin wave
frequency: 3.5-6.0MHz
voltage: 2.8kVpp



width: 5.43ns
efficiency: 33.7 %

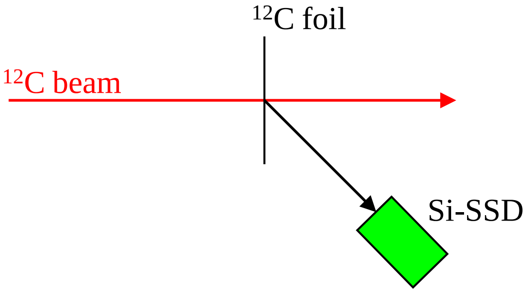
TOF [ch]

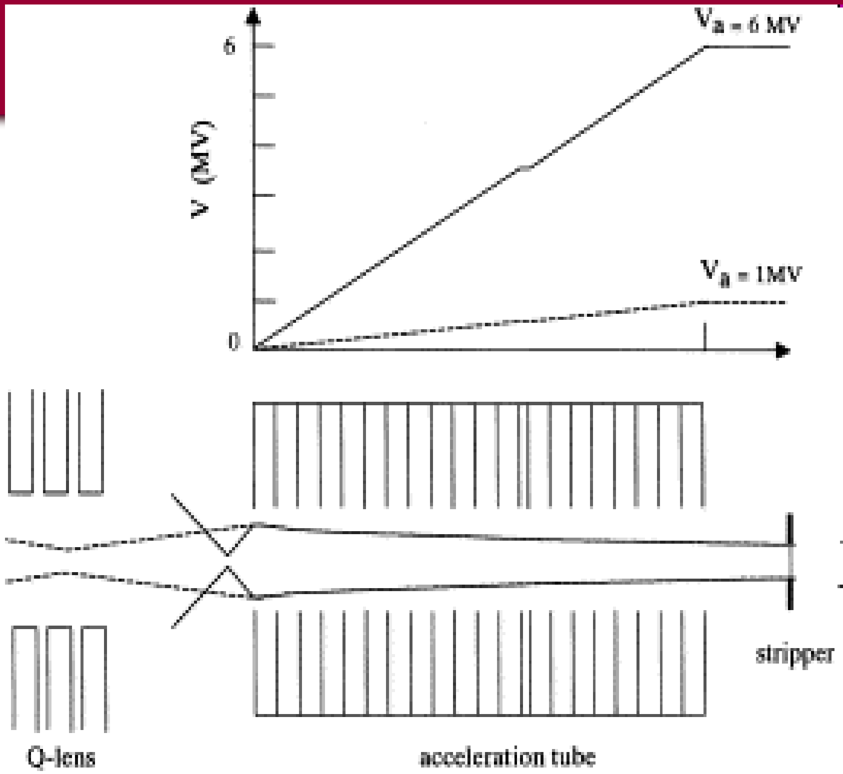
Chopper



sin wave
frequency: 3.5-6.0MHz
voltage: 3.0kVpp

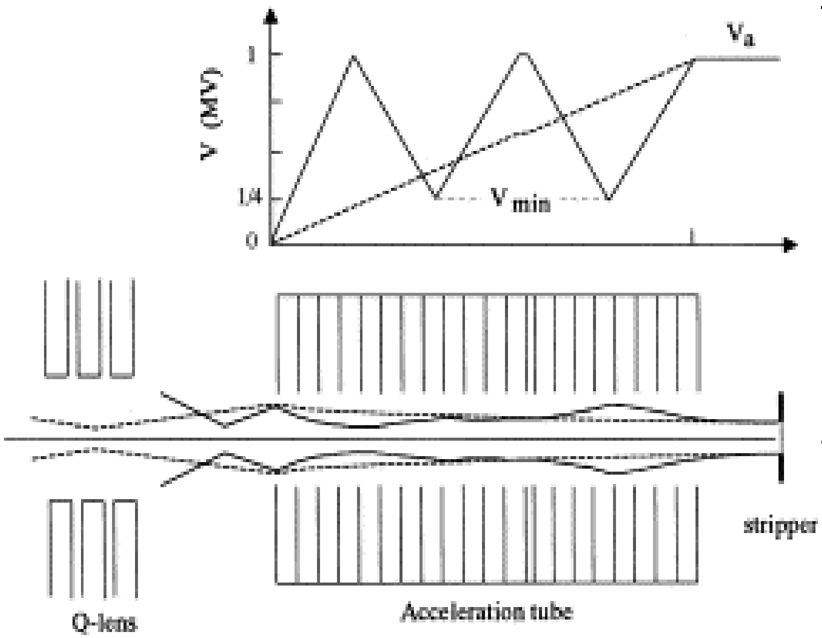
slit





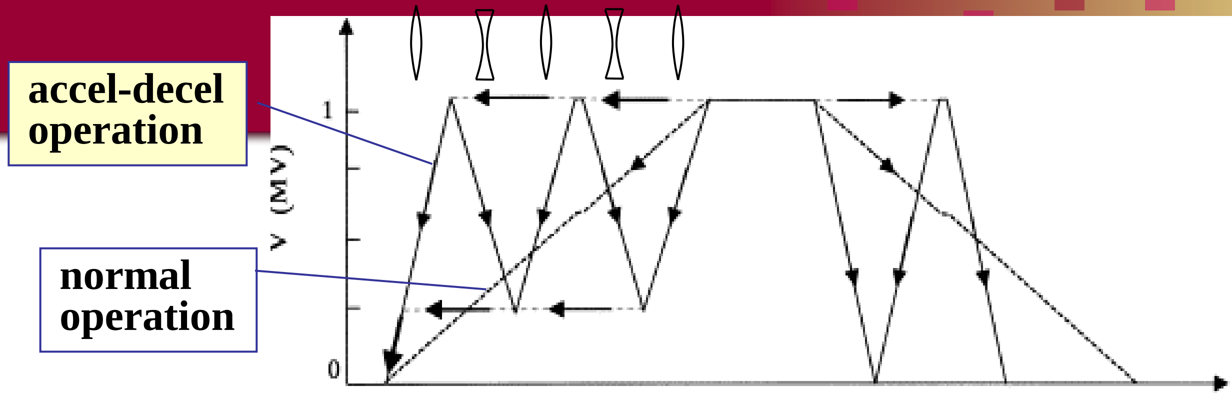
Normal operation of tandem accelerator.

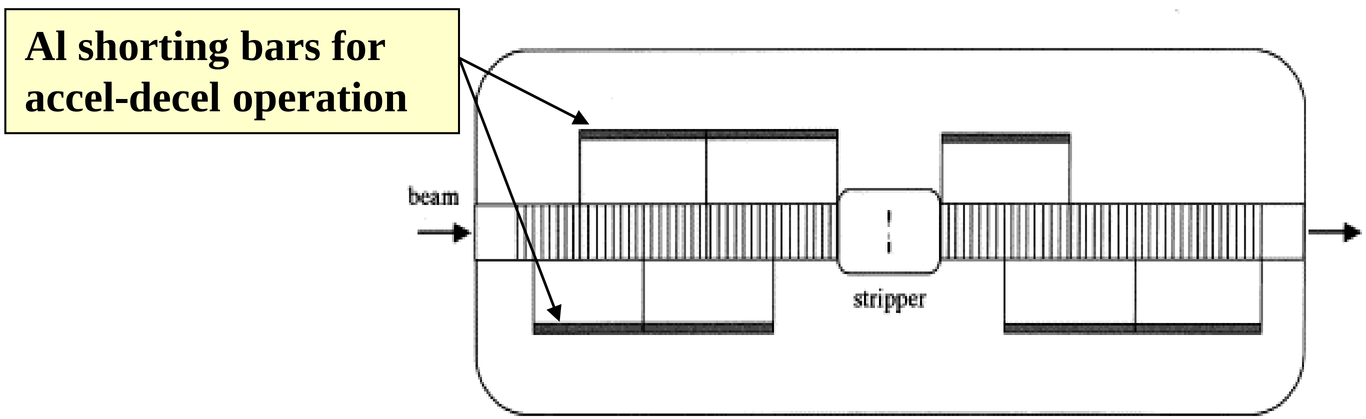
At low acceleration voltage, focusing becomes weak, and beam transmission decreases.



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^{f}) 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.

RF-Deflector (Long Time Chopper)

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