

Neutron Source for BNCT FFAG-ERIT scheme

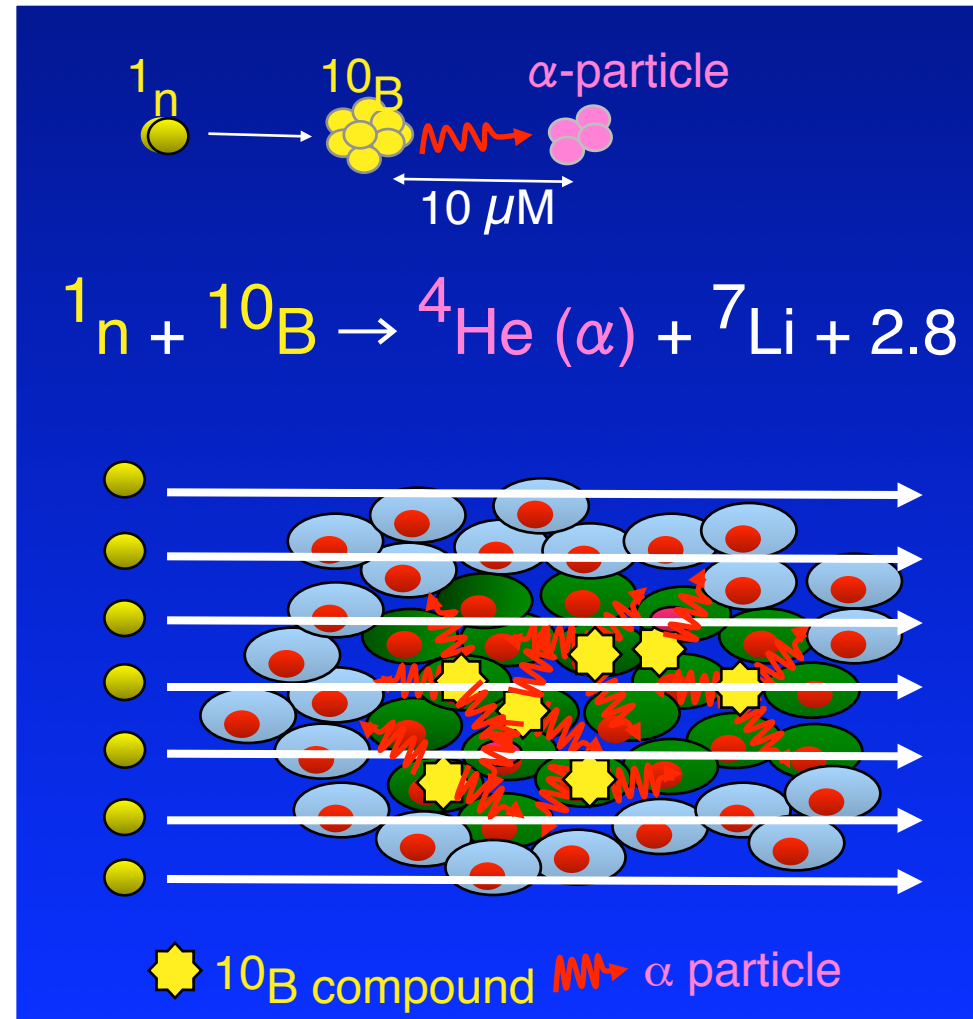
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Neutron Source for BNCT

- **Requirements**

- Large neutron flux
 $> 1 \times 10^9 \text{ n/cm}^2/\text{sec}$ at patient
- Low energy spectrum
thermal/epi-thermal neutron

Nuclear reactor only can provide these neutrons.

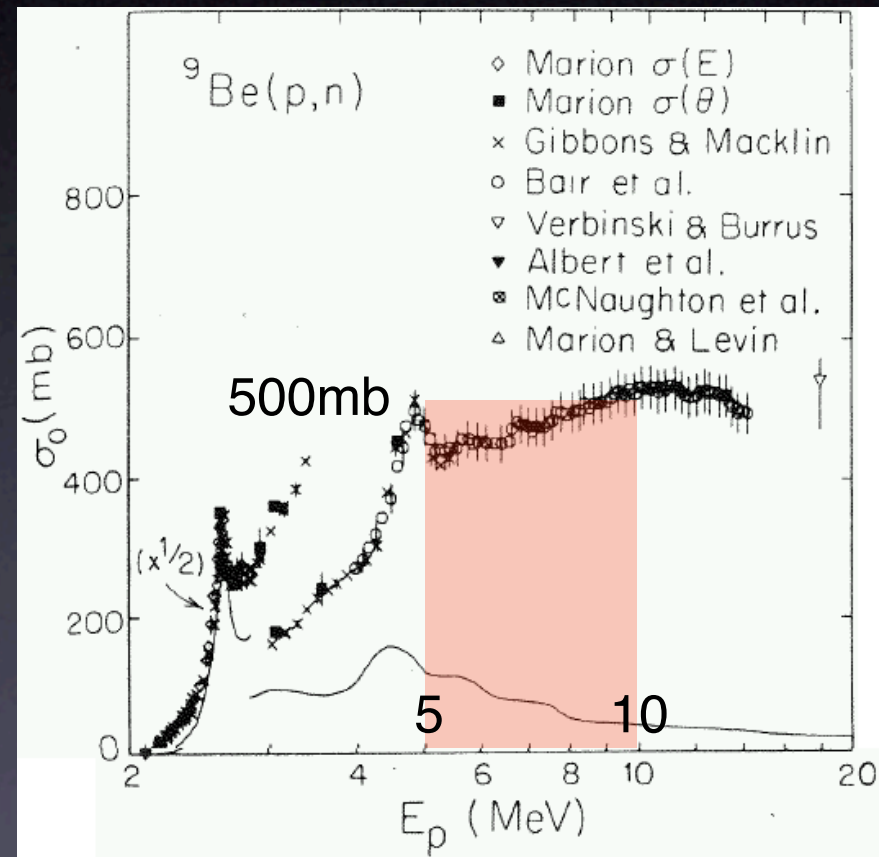


**Limited to extend the use of
BNCT widely in society.**

Accelerator based Neutron Source

**In order to obtain
 $\phi > 10E9$ n/cm²/s**

- Neutron production reactions
 - $^9\text{Be}(p,n)\text{B}$, $^7\text{Li}(p,n)\text{Be}$
- Proton beam
 - energy $\sim 10\text{MeV}$
 - current $>20\text{mA}(\text{cw})$



Difficulties

- Accelerator
 - energy is low, but beam current is very large
 - $I > 20\text{mA}$ (CW)
technically hard and expensive
- Target
 - thin target $t < 0.1\text{mm}$ $\therefore dE/dx \sim 50\text{MeV/g/cm}^2$
 - beam power is relatively large $> 100\text{kW}$
difficult cooling and shorter lifetime
- Radiation
 - full beam dumping for 100kW beam
huge shielding and large gamma-ray contamination

Proton beam power is mostly consumed by ionization in the target, not by neutron production.

- Neutron production/Ionization(energy loss)

Efficiency $\sim < 1/1000$

If the beam energy lost in the target is recovered by re-acceleration, the efficiency of neutron production can be improved.

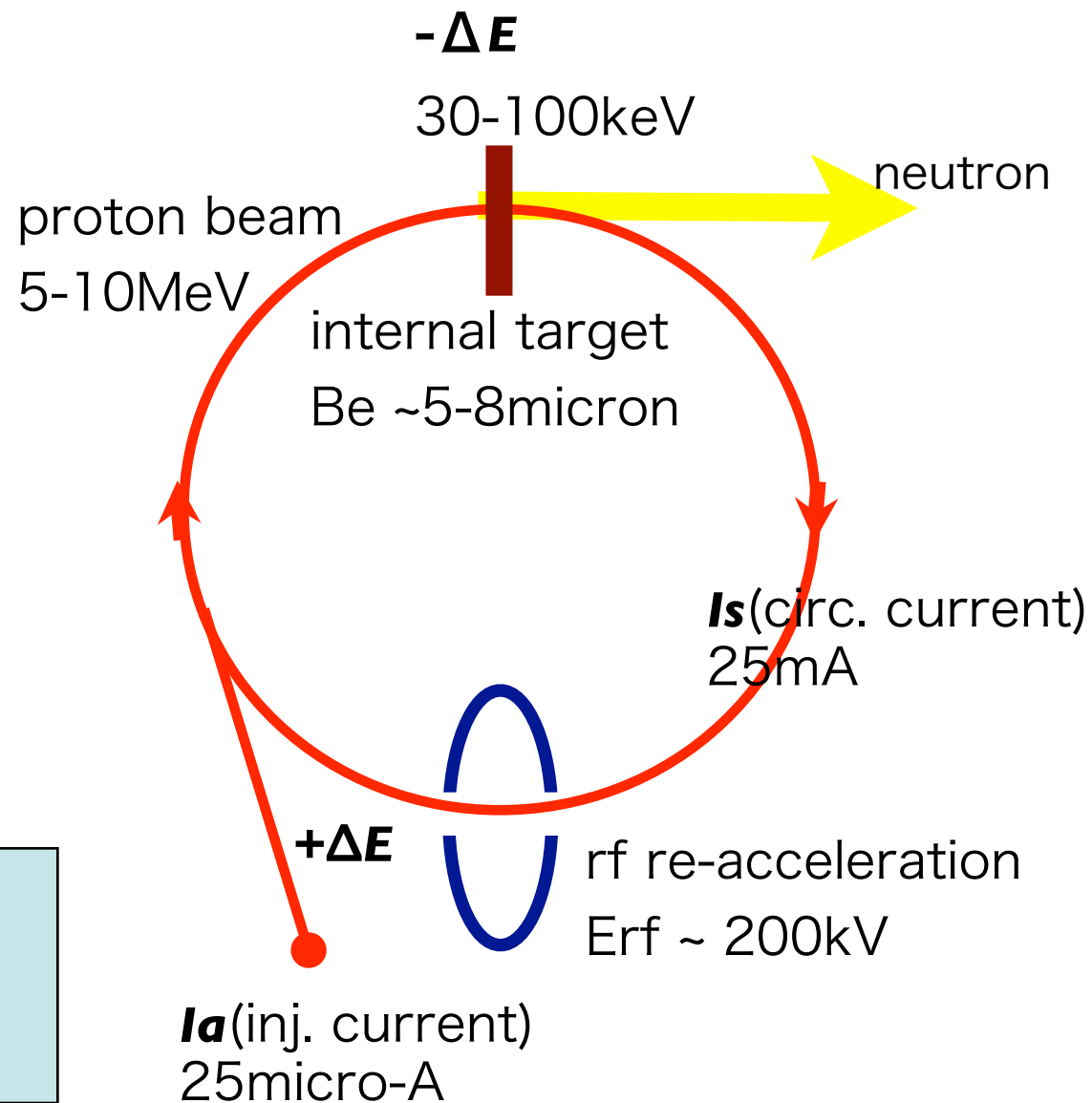
ERIT Energy Recovery Internal Target

for neutron production with FFAG accelerator

- Energy loss
 - recovered by rf re-acceleration
- Emittance growth
 - cured by Ionization Cooling
- Beam current
 - reduced by storing the beam in the ring

$$I_a = I_s / Nt, \quad Nt = 1000 \text{ turns}$$

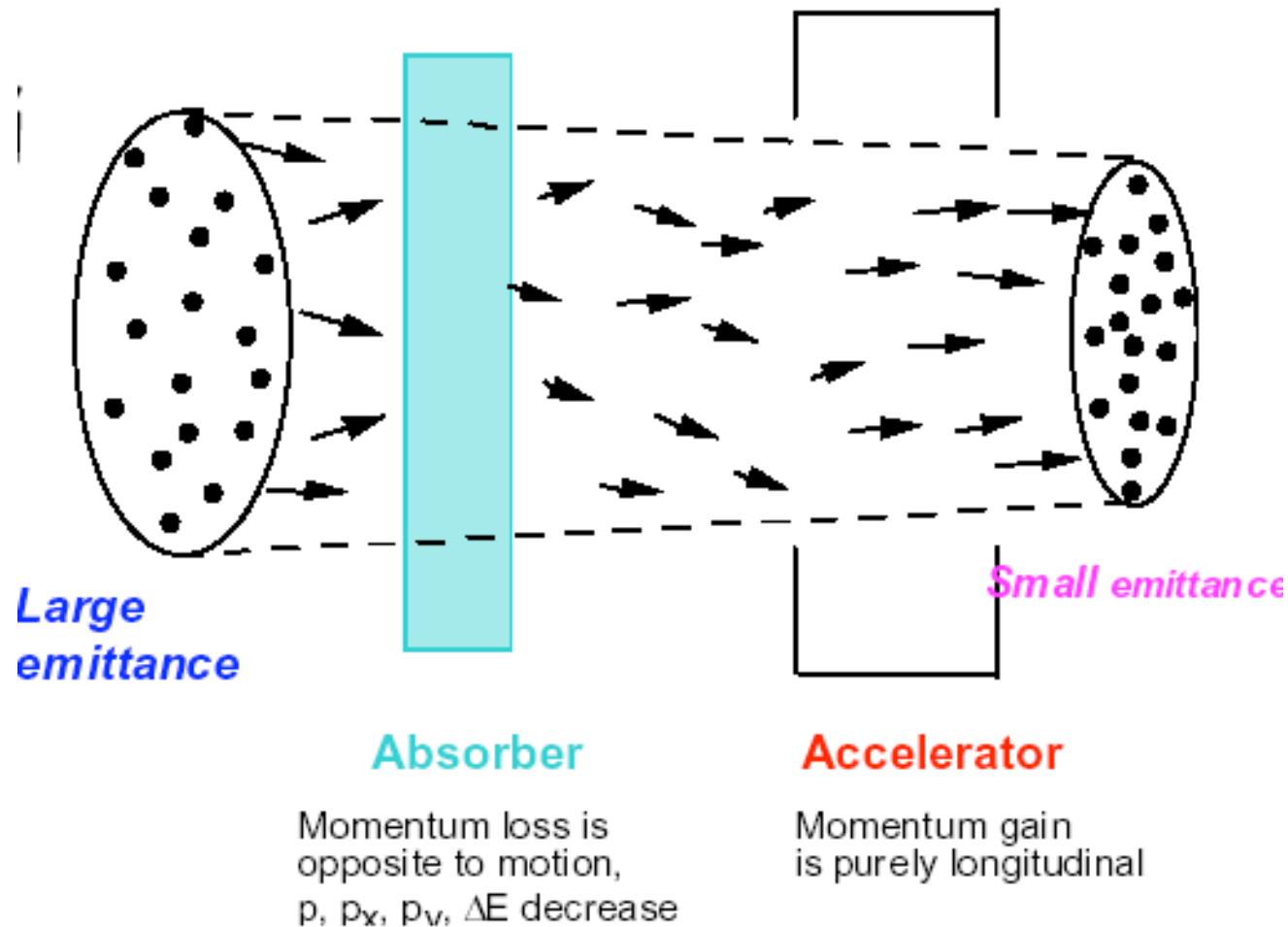
Need large momentum acceptance! -> FFAG



Emittance growth

- Using an internal target in the ring, the beam emittance can be increased in 3-D directions by Rutherford multiple scattering and stragling
- In ERIT scheme, however, the beam emittance growth can be cured by “Ionization Cooling” effect
- In other word, ERIT is “Ionization Cooling”

Ionization Cooling



Only muon!

How about proton?

$$\tau_{\mu} = 2.2\gamma \mu\text{s or } L_{\mu} = 660\beta\gamma \text{ m}$$

Ionization Cooling

$$\frac{d\varepsilon}{ds} = A\varepsilon + B$$

ε : beam emittance

transverse

$$A = -\frac{1}{\beta^2 E} \left\{ \frac{dE}{ds} \right\} \quad B = \frac{\beta\gamma}{2} \beta_T \frac{(13.6 \text{ MeV})^2}{(\beta c p)^2 L_s}$$

Rutherford multiple scattering

longitudinal

$$A = 2 \frac{\partial \left(\frac{dE}{ds} \right)}{\partial E} \quad B = 4\pi (r_e m_e c^2)^2 n_e \gamma \left[1 - \frac{\beta^2}{2} \right]$$

straggling

cf. proton beam 10MeV
Be target

3D beam cooling becomes possible
if transverse and longitudinal
motions are coupled.

Transverse → Cooling

Longitudinal → Heating

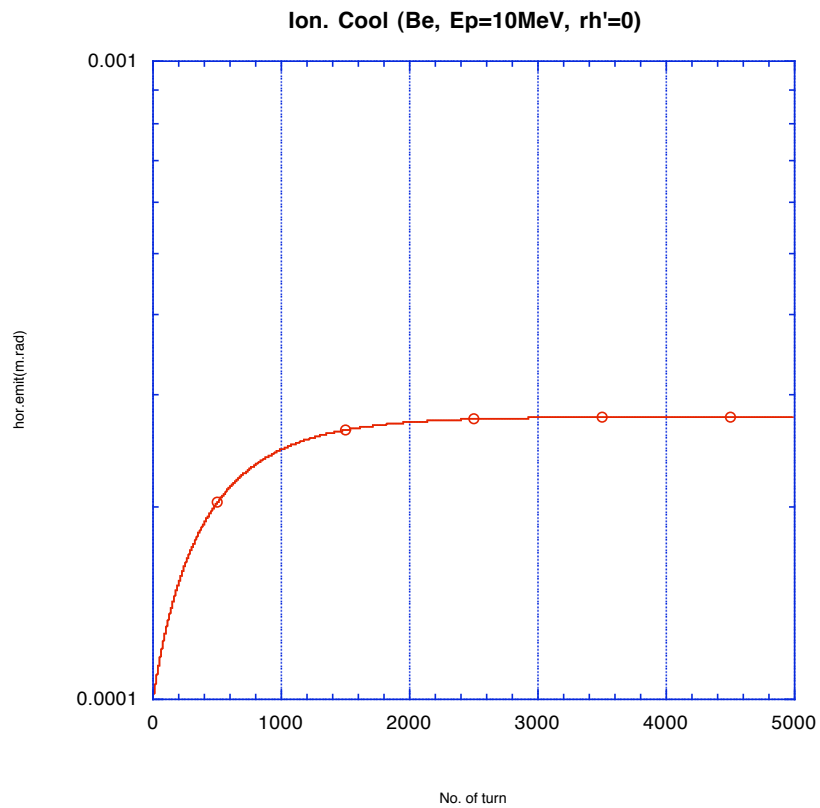
分配関数の和 > 0

$$\sum_1^3 g_i > 0$$

エミッタンス (rate equation)

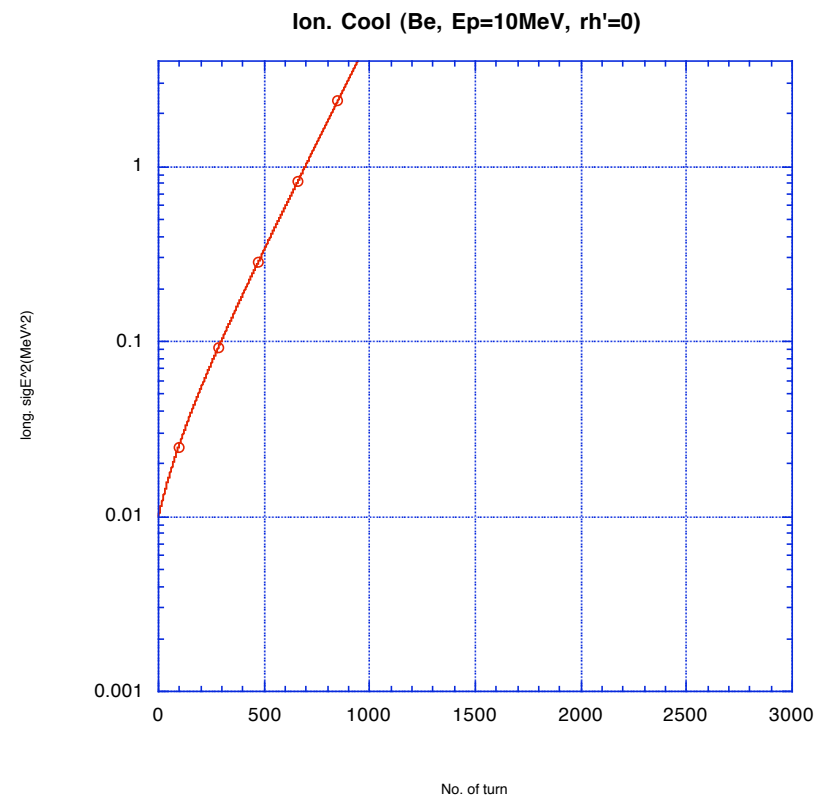
Transeverse

—○— hor.emit(m.rad)



Longitudinal

—○— long. sigE^2(MeV^2)



Coupling

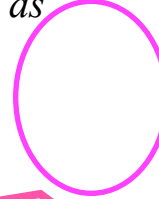
logitudinal direction $\frac{d\langle\sigma_E^2\rangle}{ds} = -2 \frac{\partial(dE/ds)}{\partial E} \langle\sigma_E^2\rangle + \frac{d\langle\Delta E_{rms}^2\rangle}{ds}$



heating by straggling

cooling condition $\frac{\partial(dE/ds)}{\partial E} > 0$

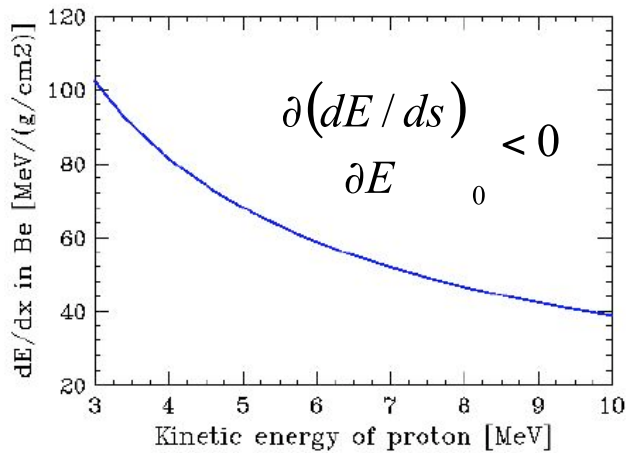
$$\frac{d\langle\Delta E_{rms}^2\rangle}{ds} \cong 4\pi (r_e m_e c^2)^2 n_e \gamma^2 \left(1 - \frac{\beta^2}{2}\right)$$



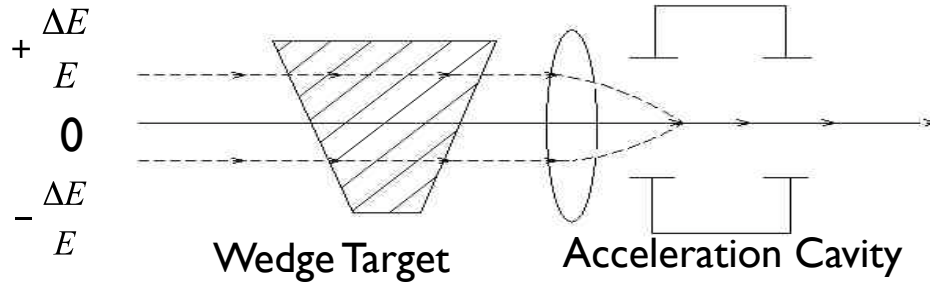
ρ' : variation of thickness

$$\frac{\partial(dE/ds)}{\partial E} \Rightarrow \frac{\partial(dE/ds)}{\partial E} \Big|_0 + \frac{dE}{ds} \frac{1}{pc\beta} D \frac{\rho'}{\rho_0}$$

dE/dx

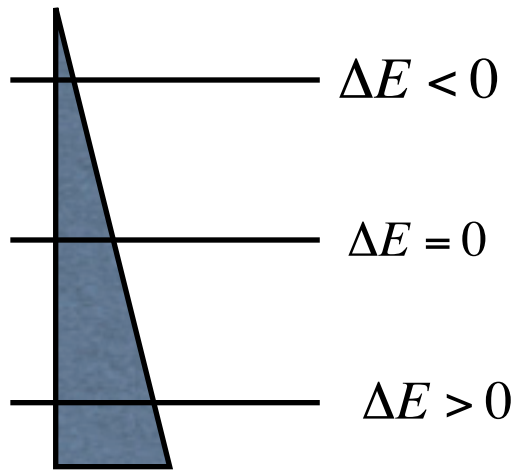


When the wedged target is placed at dispersive point $\frac{\partial(dE/ds)}{\partial E} > 0$ can be possible.

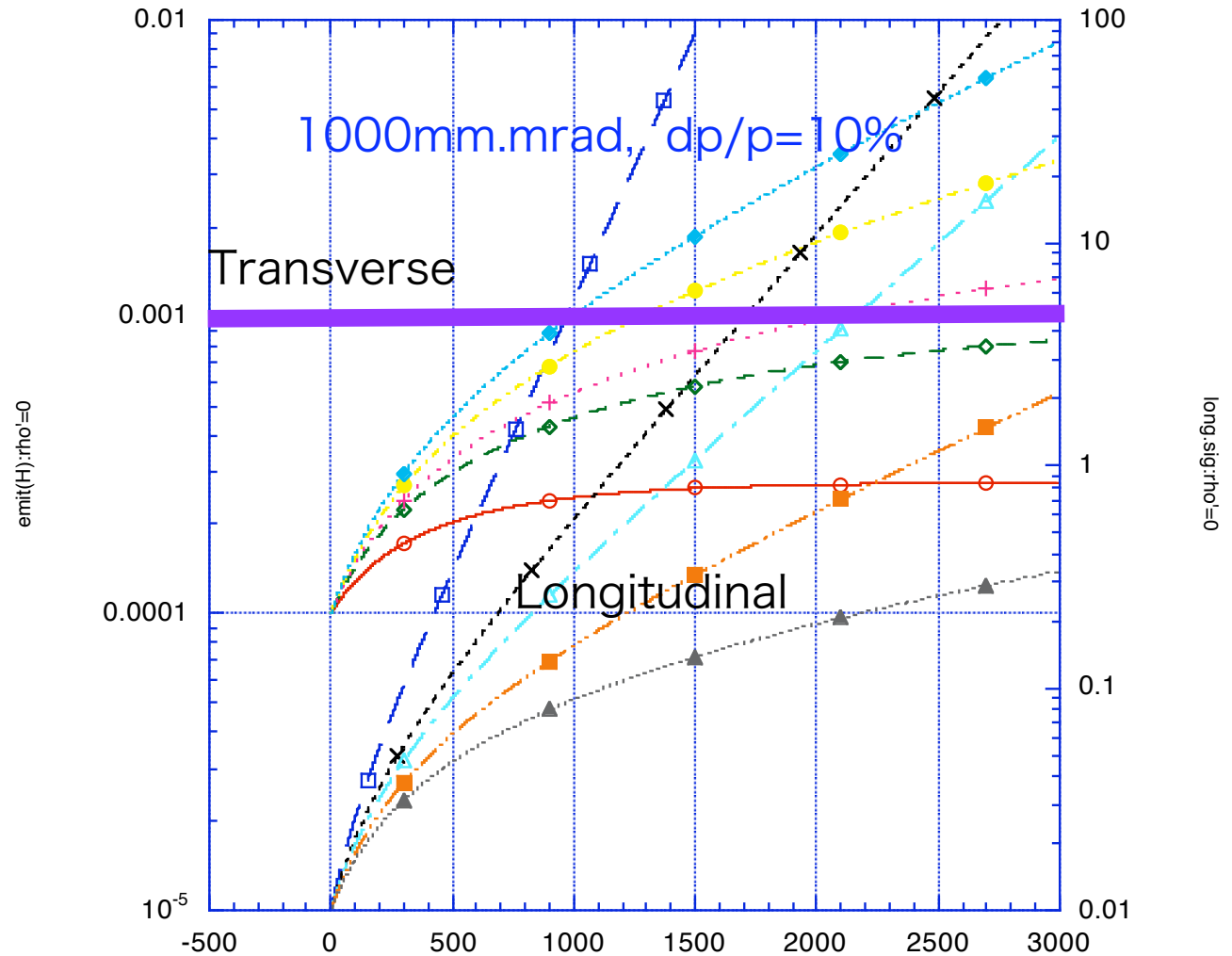
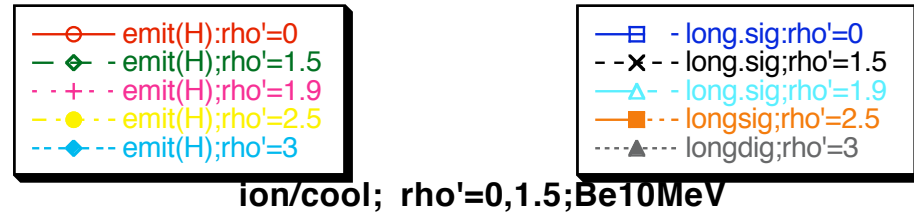


ERIT ionization cooling

coupling x-z



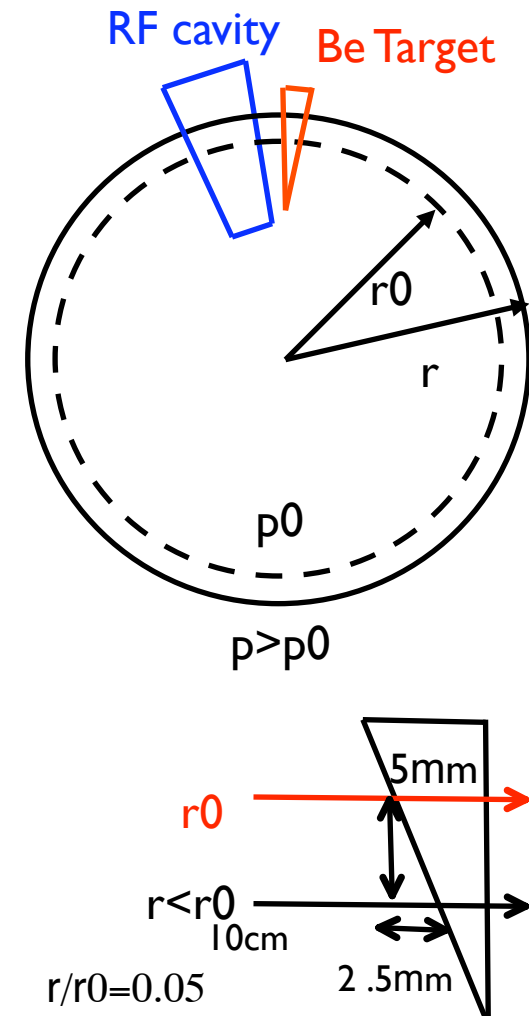
wedge target



Longitudinal tracking

simulation conditions

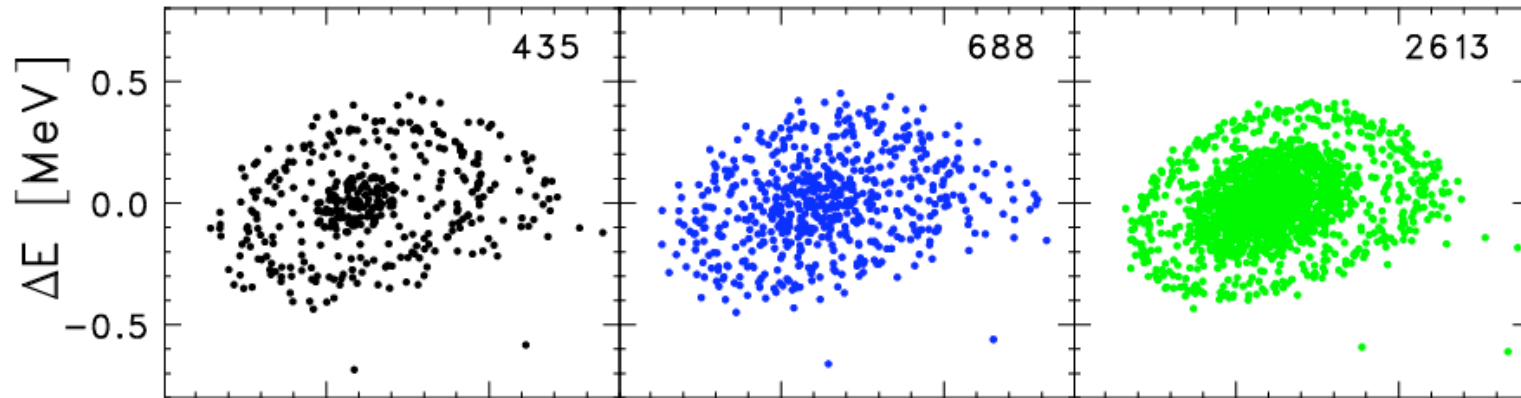
beam energy : T0 [MeV]	5	10
ring radius : r0 [m]	1.1	1.5
revolution frequency : Frev [MHz]	4.46	4.61
Dispersion : D [cm/%]	25	25
target thicknesss @ r0 : G0 [mm]	5, 8	5, 8
wedge factor : r'/r0 [1/cm]	0.03~0.07	0.03~0.07
RF accelerating voltage : Vrf [kV]	2	2
harmonic number : h	5	5
energy loss @r0 : dEt [keV]	63, 101	36, 57
straggling(s) : dEs [keV]	8.1, 10.2	8.1, 10.2
$Dr'/r0$	0.75~1.75	0.75~1.75



Simulation

$T_0 = 5 \text{ MeV}$

Be 5micron

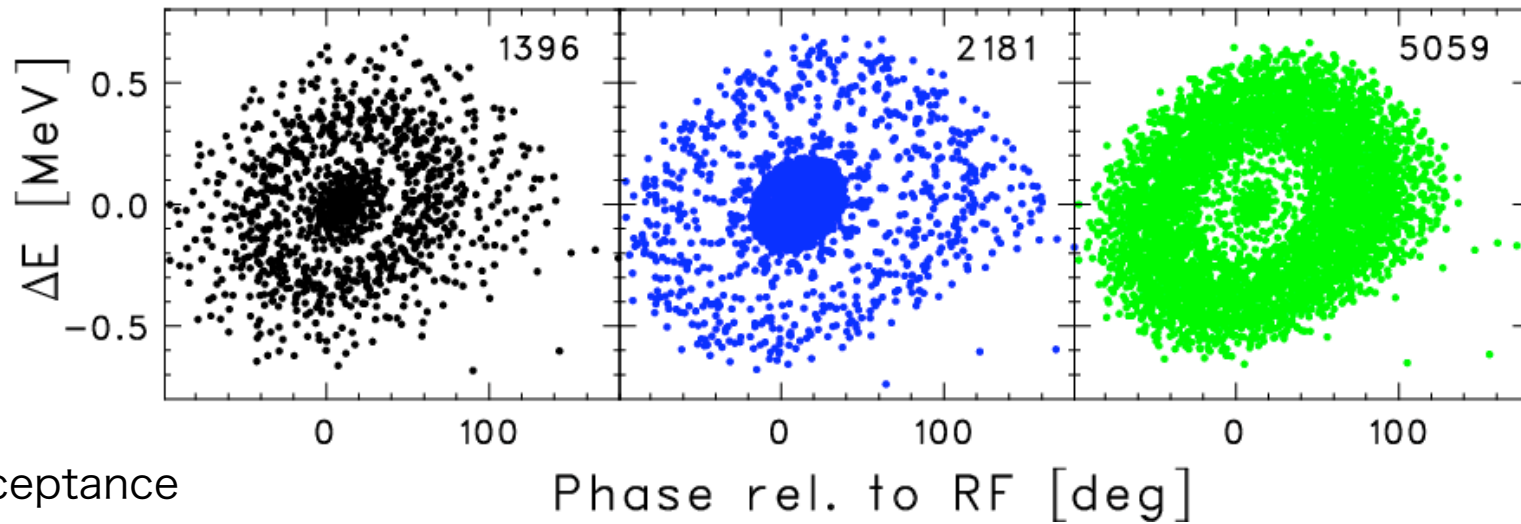


$T_0 = 10 \text{ MeV}$

No wedge

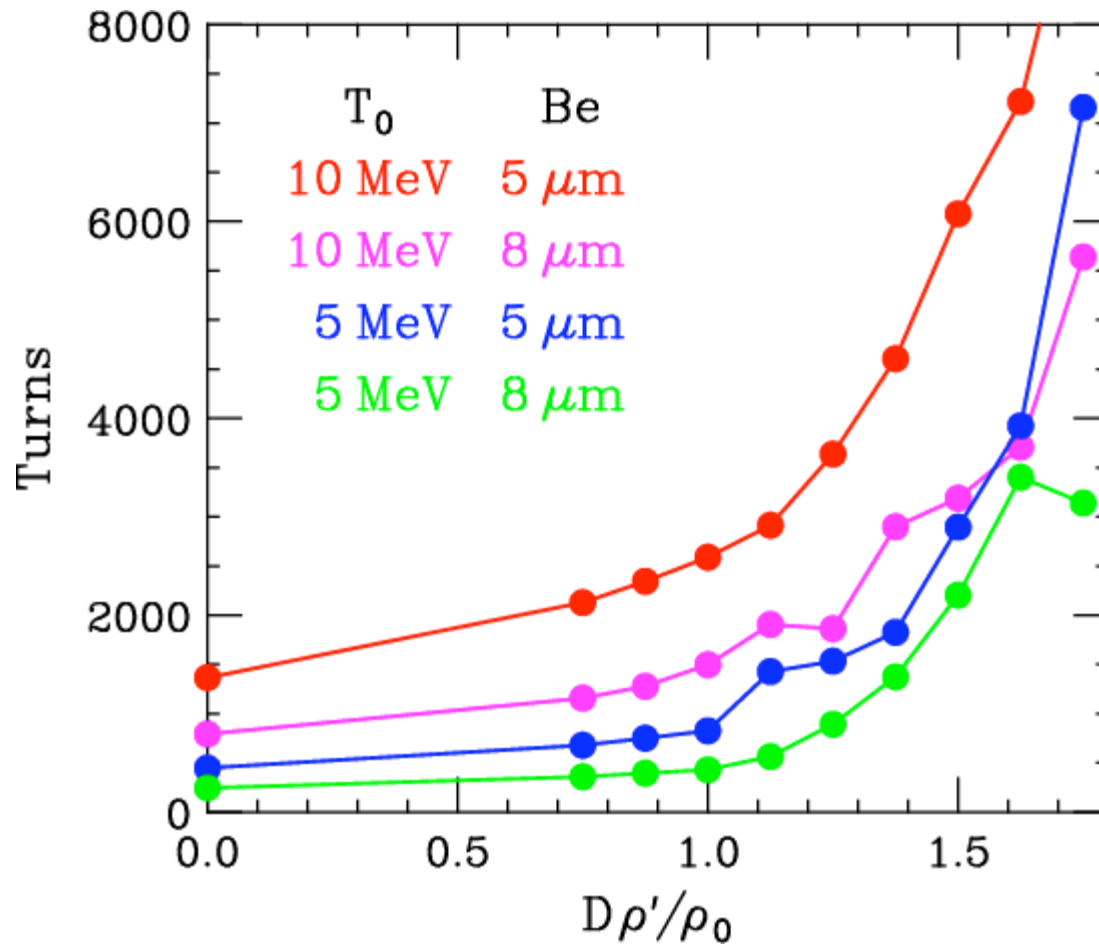
$D\rho'/\rho_0 = 0.75$

$D\rho'/\rho_0 = 1.5$



energy acceptance
 $\sim 10\%$

summary of long. cooling



Number of turns : 2~3000 turns are possible.

Target : heat load

- dE/dx ~smallest at the maximum beam energy
 - advantage of ERIT

- beam power loss at target $\Delta P = I_c \times \Delta E$

25mA x 30keV=750W only! cf. Be 5 μ m

E=10MeV

Temperature rise of Be target

heat load **500W**

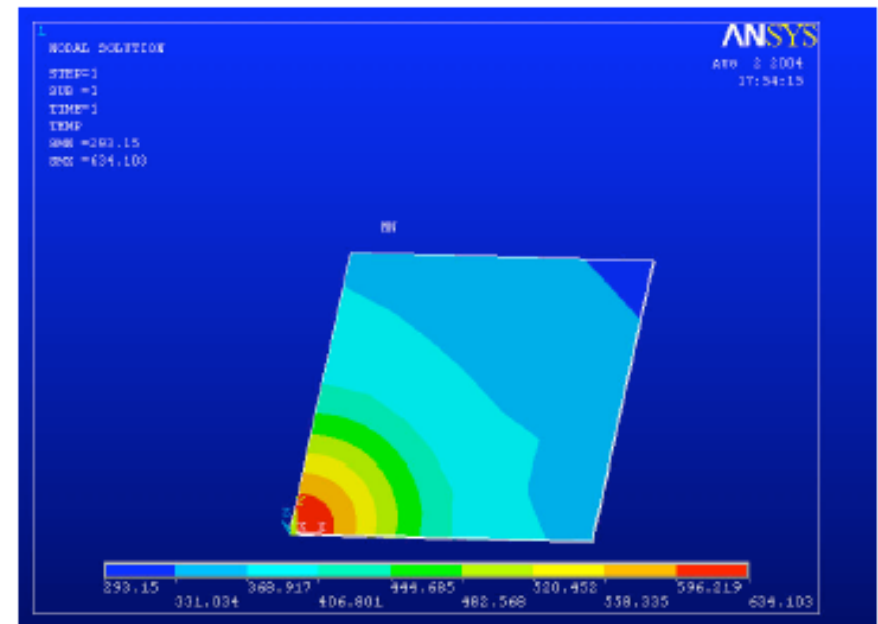
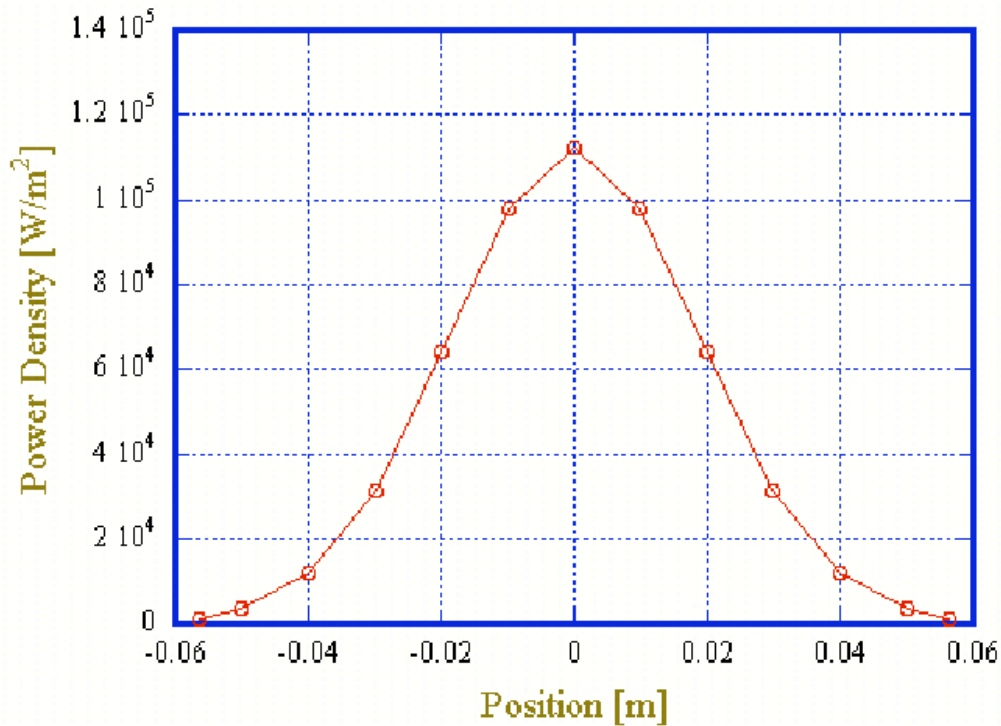
beam distr. **Gauss (3σ : 5.64cm)**

radiation $\propto T^4$

ANSYS

max. temperature $\sim 634^\circ\text{K}$

Power Density Distribution
gaussian: $3\sigma=5.64\text{cm}$

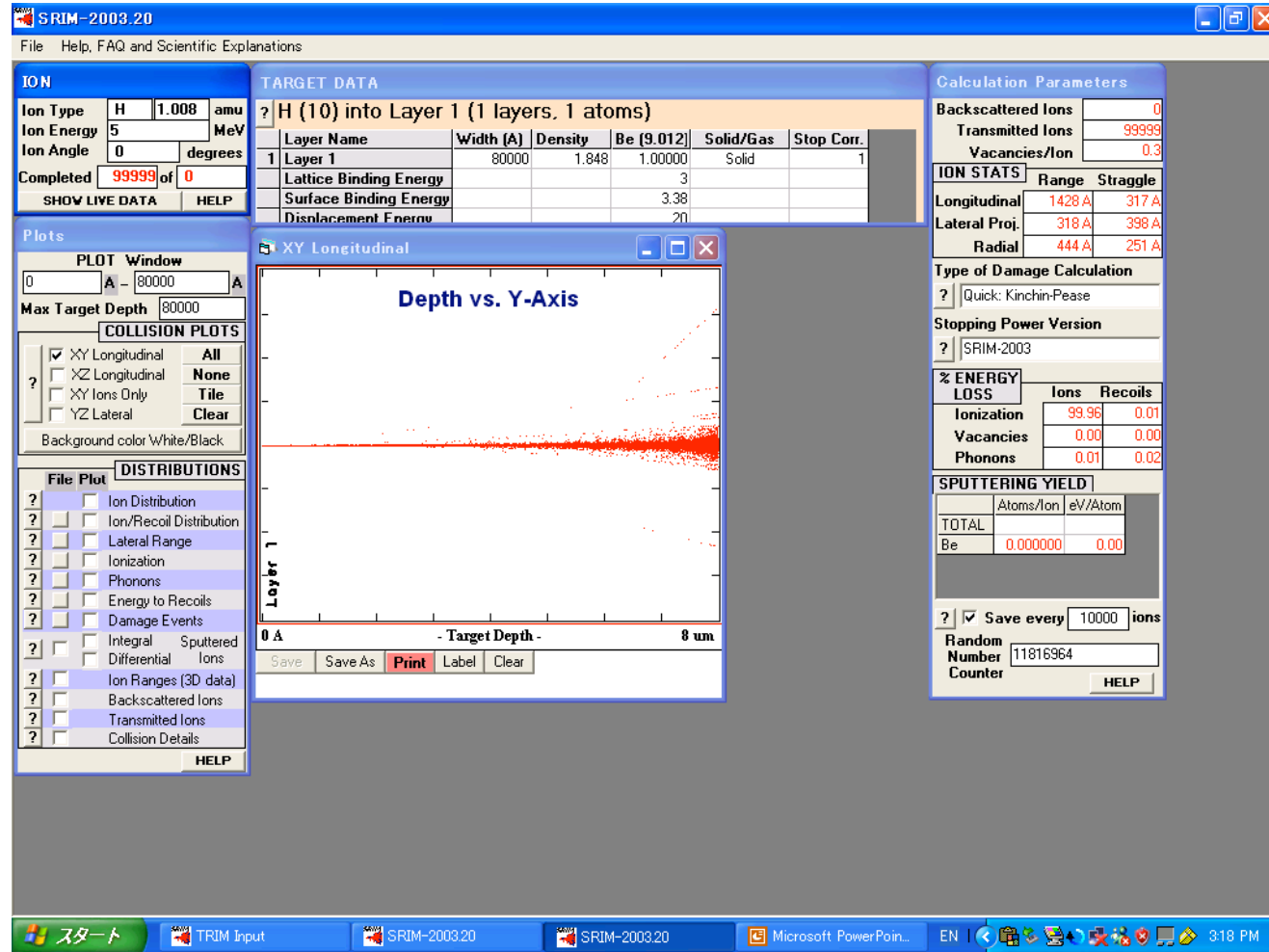


Irradiation damage of Be target

SRIM code

proton beam current 1A
energy 10MeV
Be target 8micro-m

Dislocation
< 0.1 dps
small enough

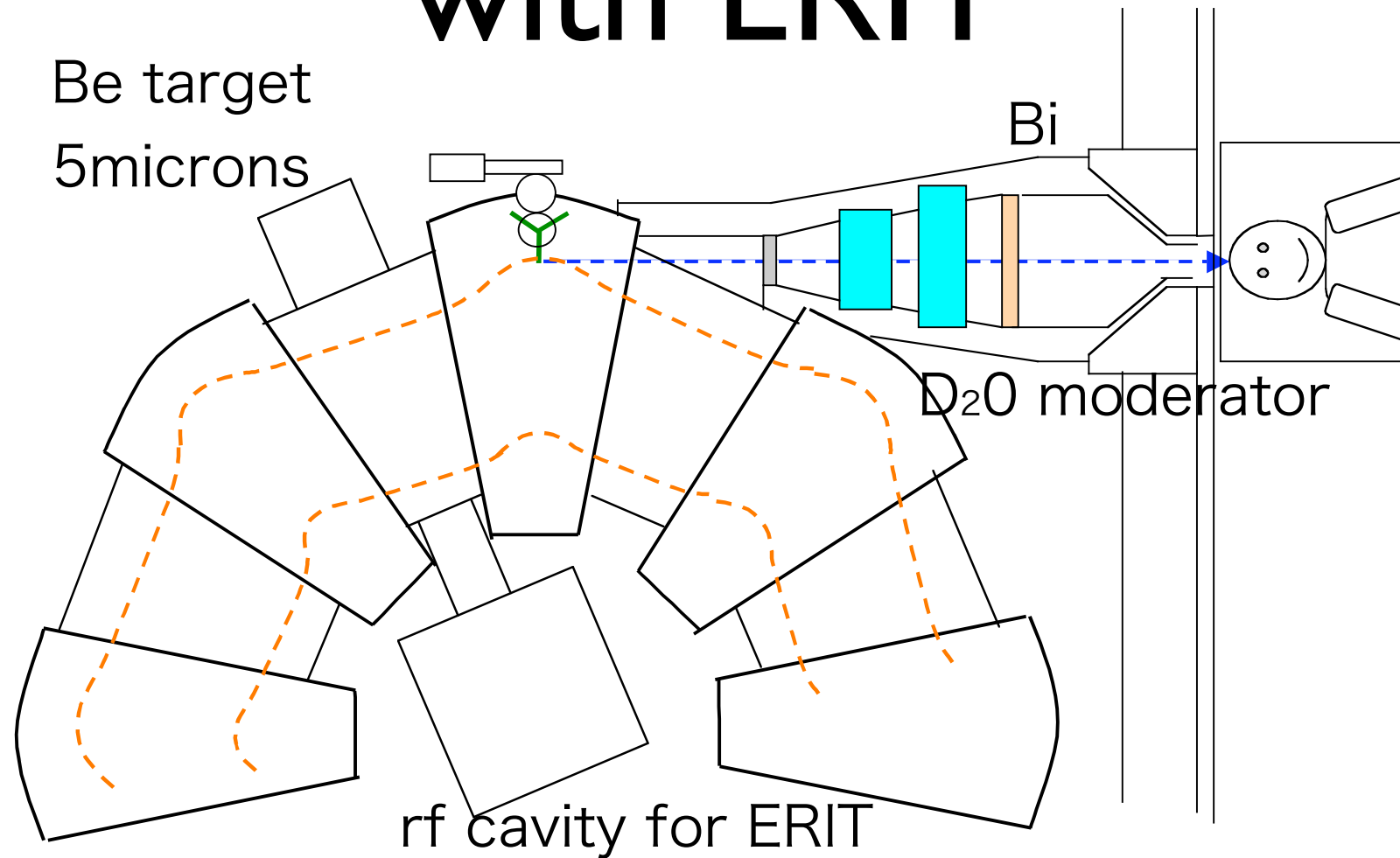


Requirements for ERIT Ring

- Beam intensity
 - 5×10^{10} ppp
- Acceptance
 - transverse : 1000mm.mrad
 - momentum : $dp/p > 10\%$
- Repetition rate
 - ~1kHz

FFAG can provide them!

FFAG neutron source with ERIT



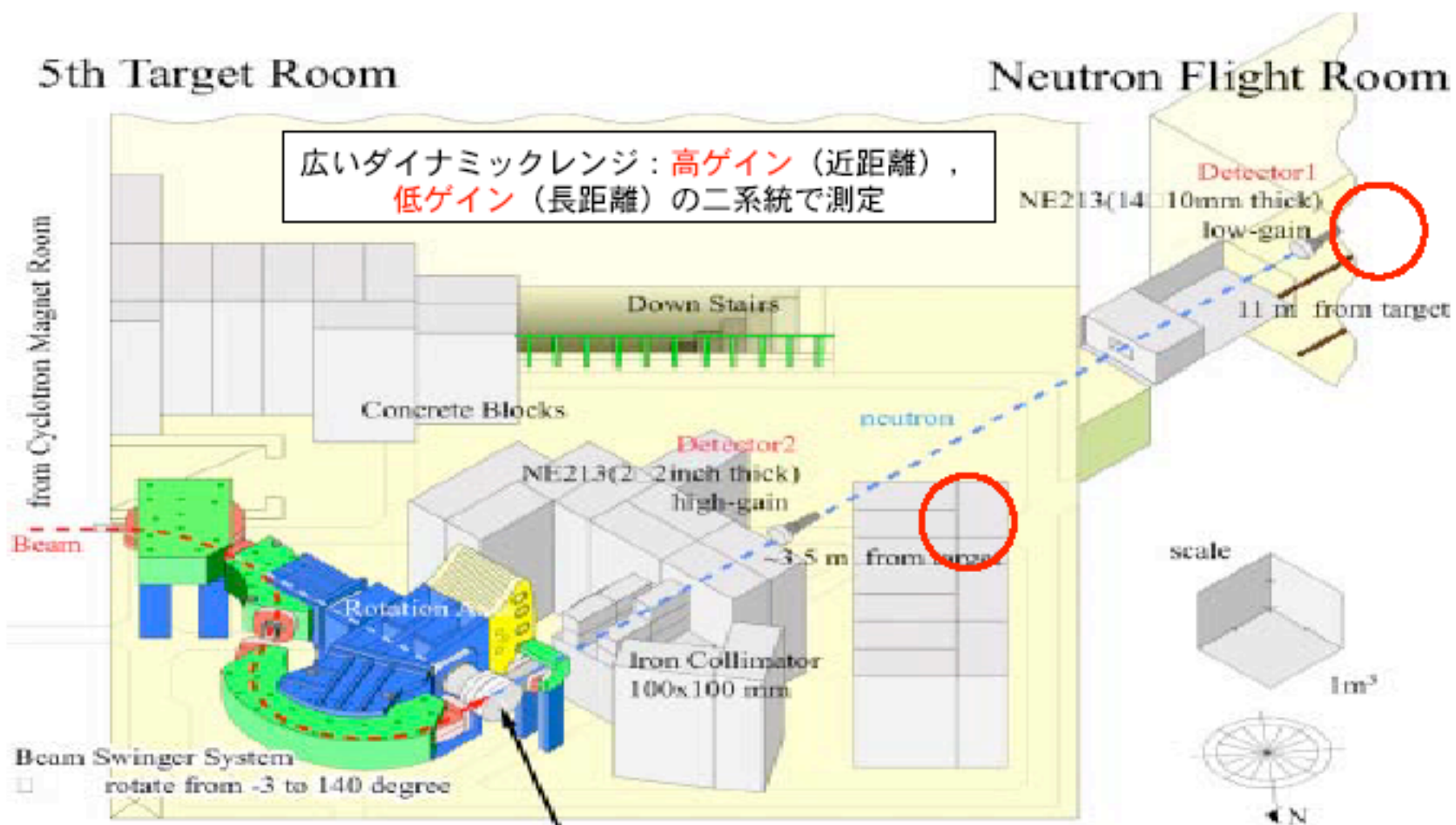
FFAG ring

Li(d,xn)Be reaction

Tohoku University

2.2 実験体系

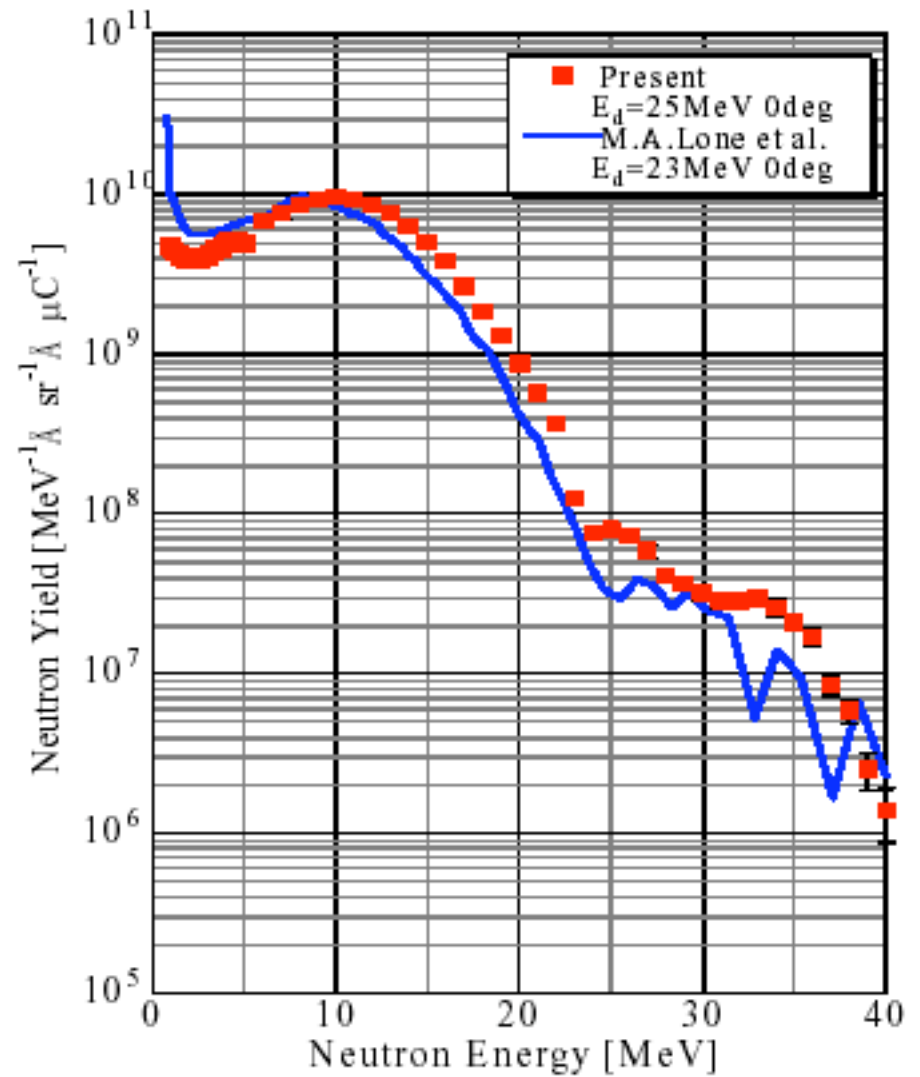
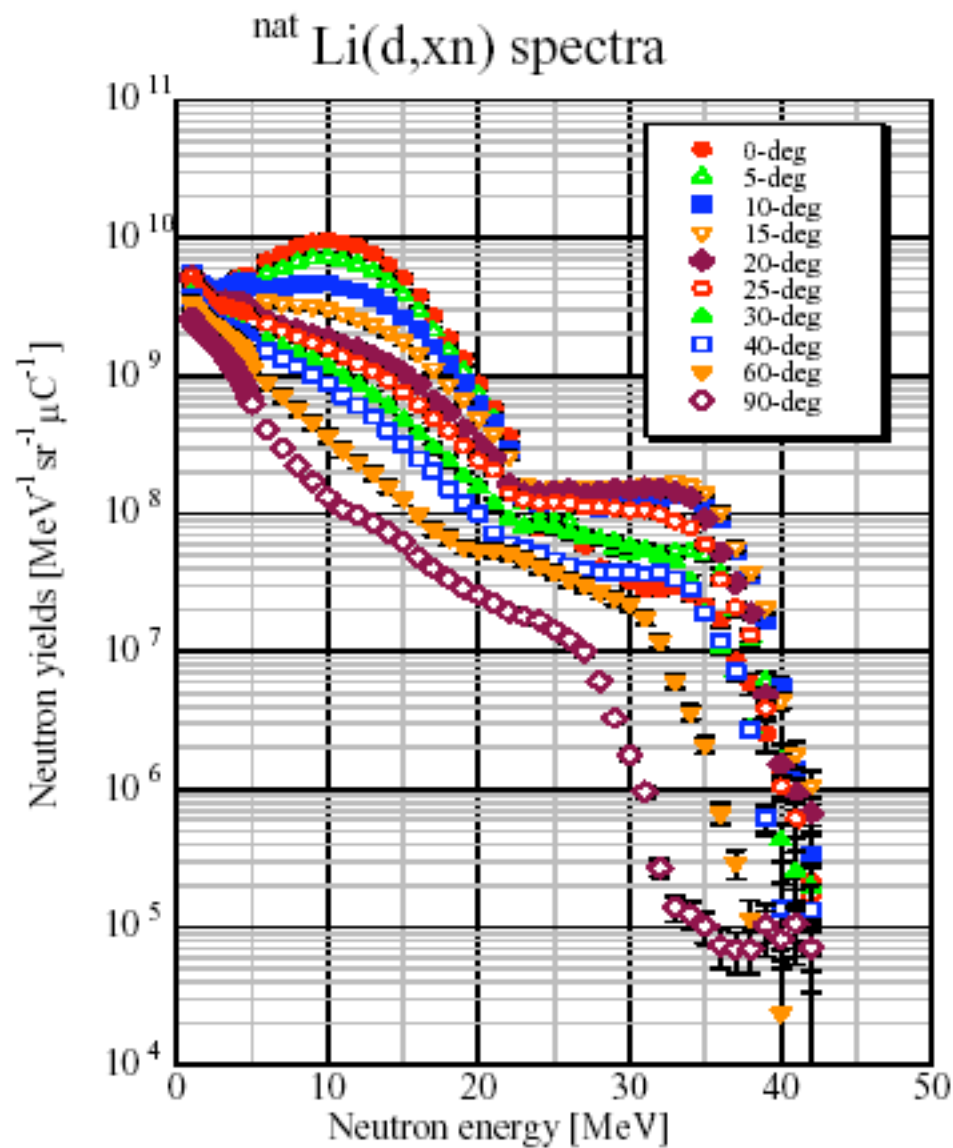
Beam-swinger system & Well collimated TOF channel



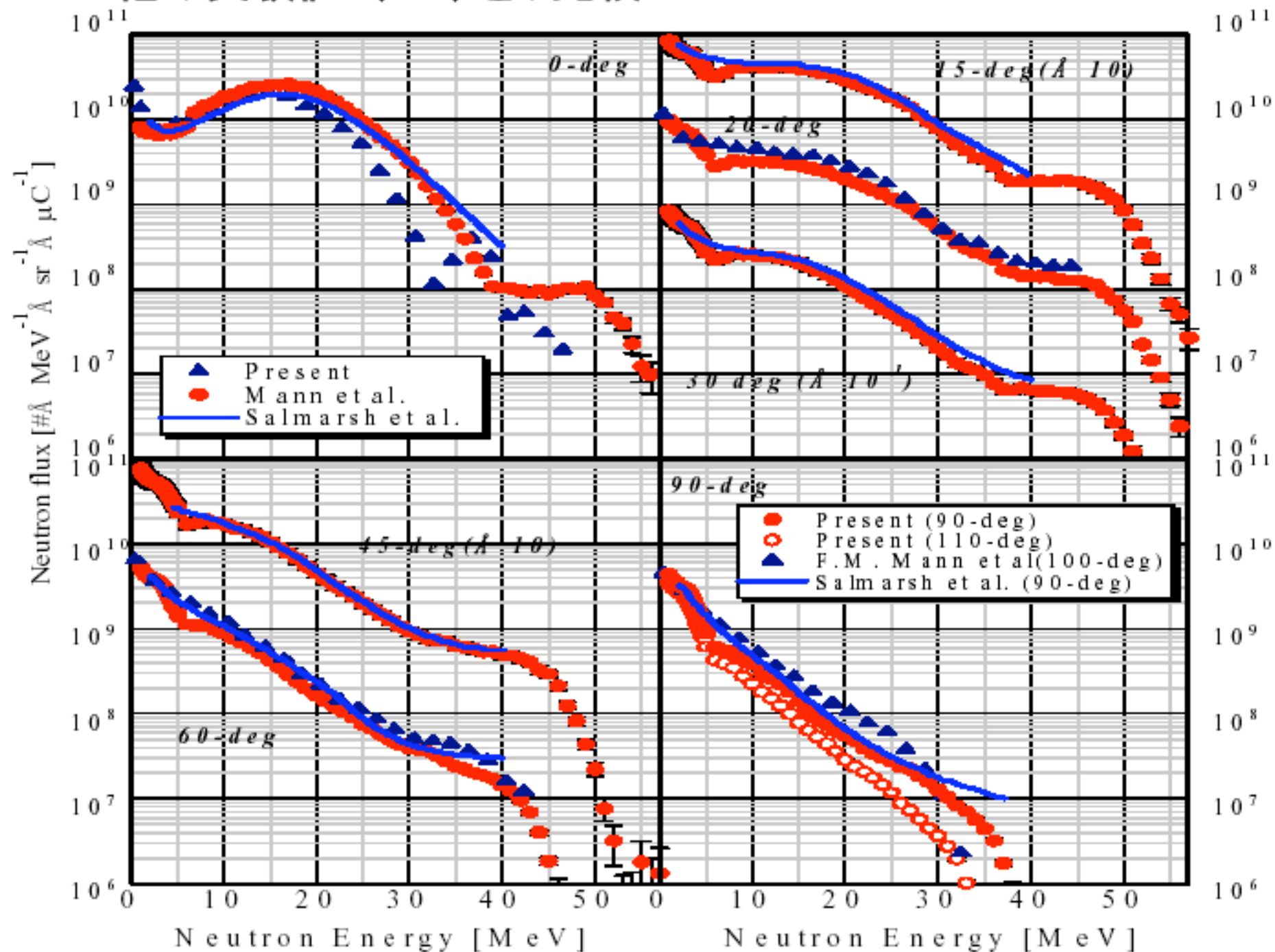
- 入射電流値・・・ターゲットから(TTY)、FCから(DDX)
- 二次電子抑制器．カレントの過大評価を防ぐ)

3. 中性子スペクトル結果

3.1 $E_d=25$ MeV



3.3. 他の実験値 (TY) との比較



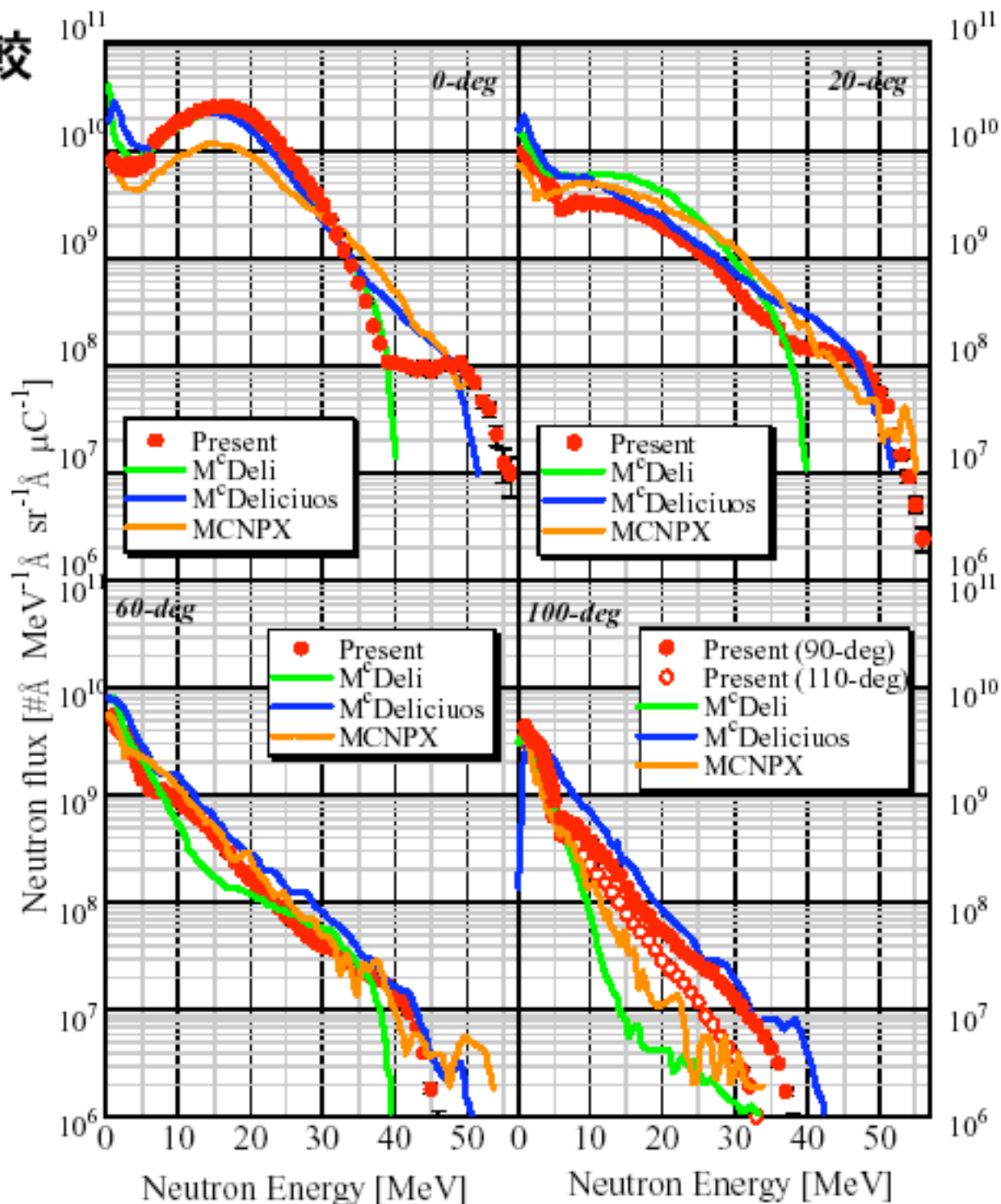
3.3. 計算値 (TY) との比較

本実験値

M^cDeLiコード
(P.H.Wilson)

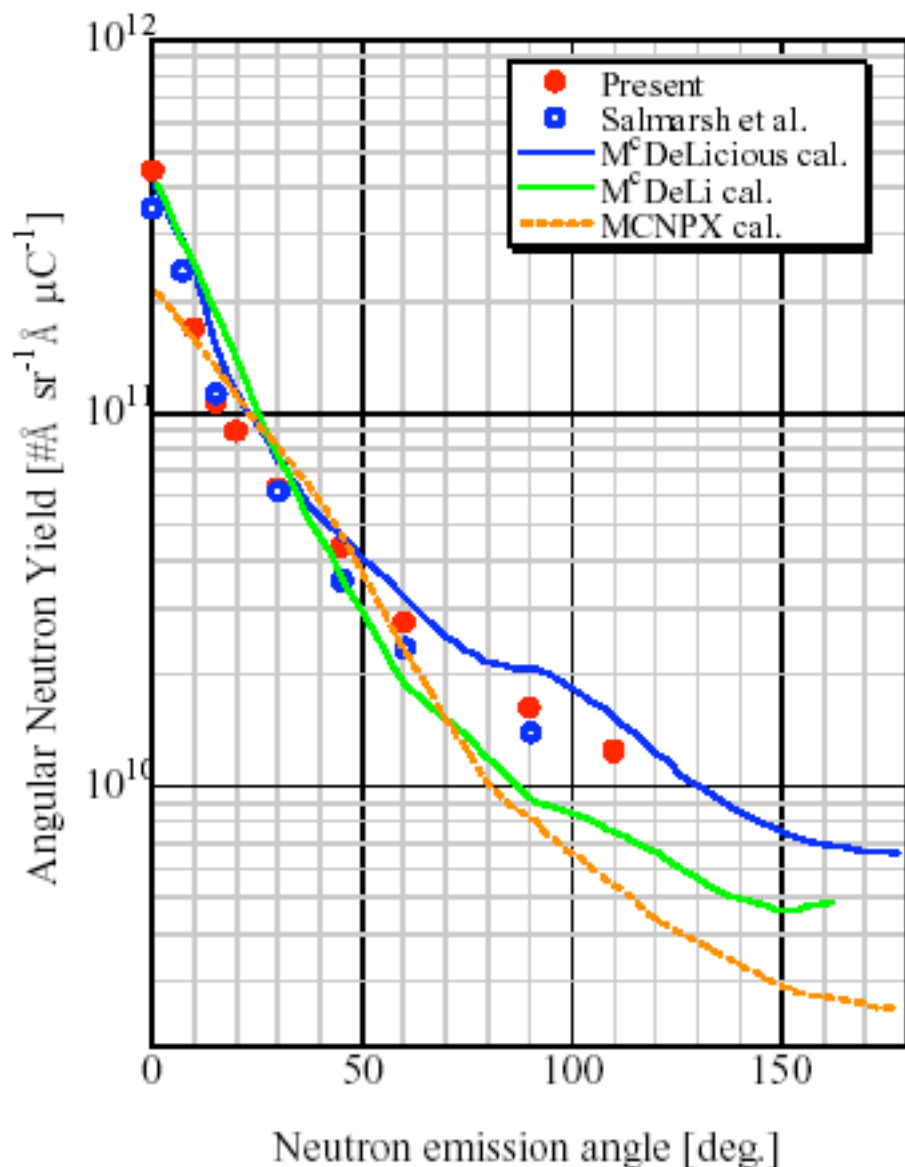
M^cDeLiciousコード
(S.P.Simakov,
U.Fischer)

MCNPX (AHET)
ISABEL model

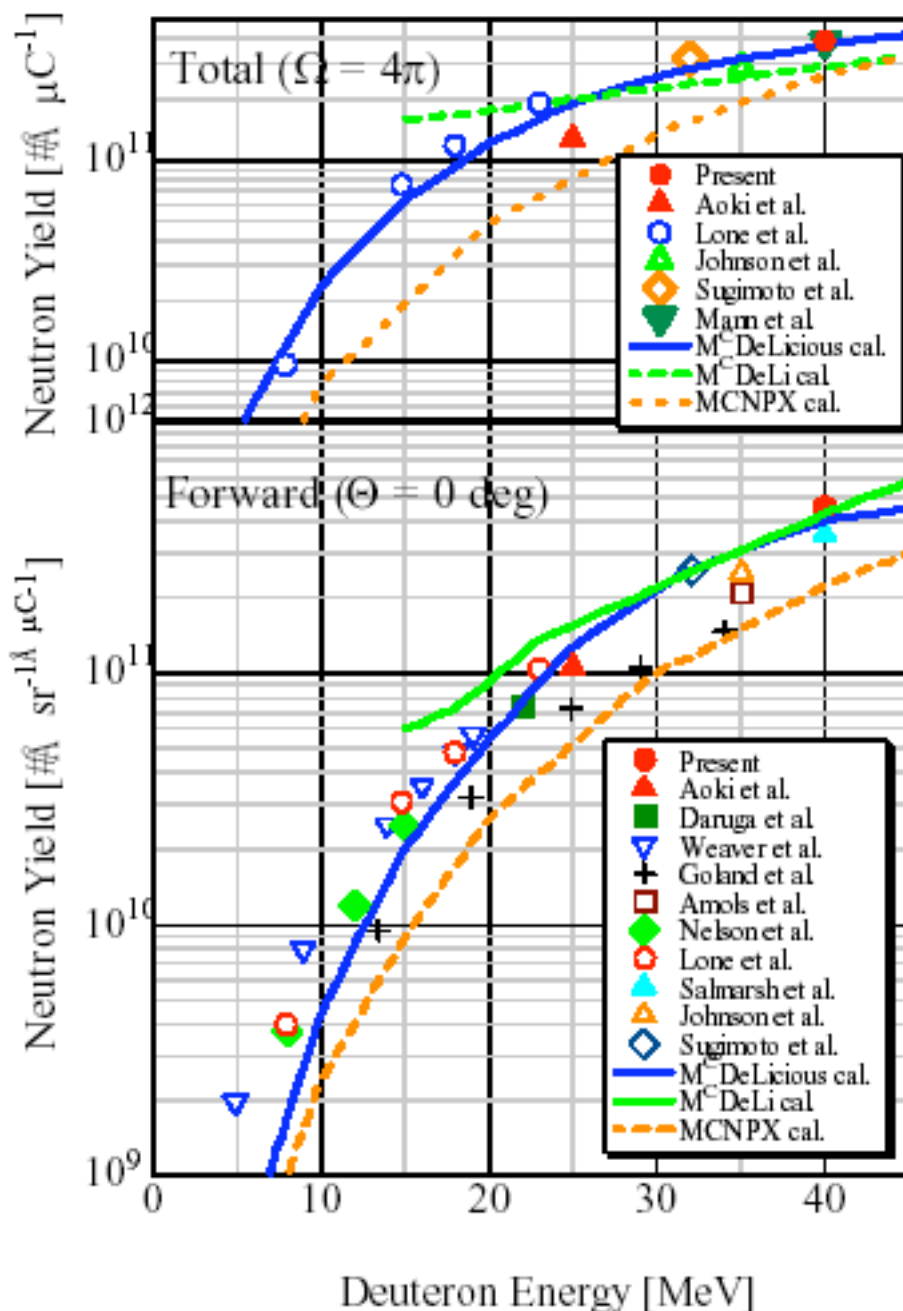


3.4. 角度分布

3.4.1 thick $^{nat}\text{Li}(d,xn)$ ADX for $E_d = 40 \text{ MeV}$



Å3.4.2 thick $^{nat}\text{Li}(d,xn)$



3.5. 計算値(DDX)との比較

本実験値

M^cDeLiciousコード

(S.P.Simakov,U.Fischer)

計算は実験値を再現できていない

二体反応のピーク

[⁷Li(d,n)⁸Be] +15.03 MeV

[⁶Li(d,n)⁷Be] +3.38 MeV

