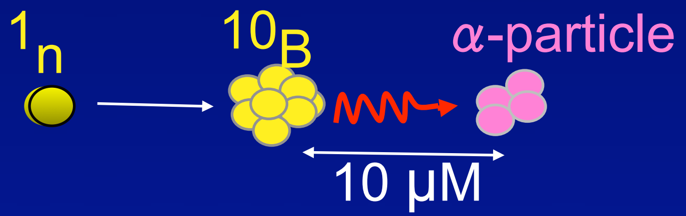
Neutron Source with Emittance Recovery Internal Target (ERIT)

Y. Mori, Y.Ishi, Y.Kuriyama, Y.Sakurai, T.Uesugi
Kyoto University, Research Reactor Institute
K.Okabe, I.Sakai
Fukui University

Boron Neutron Capture Therapy (BNCT)

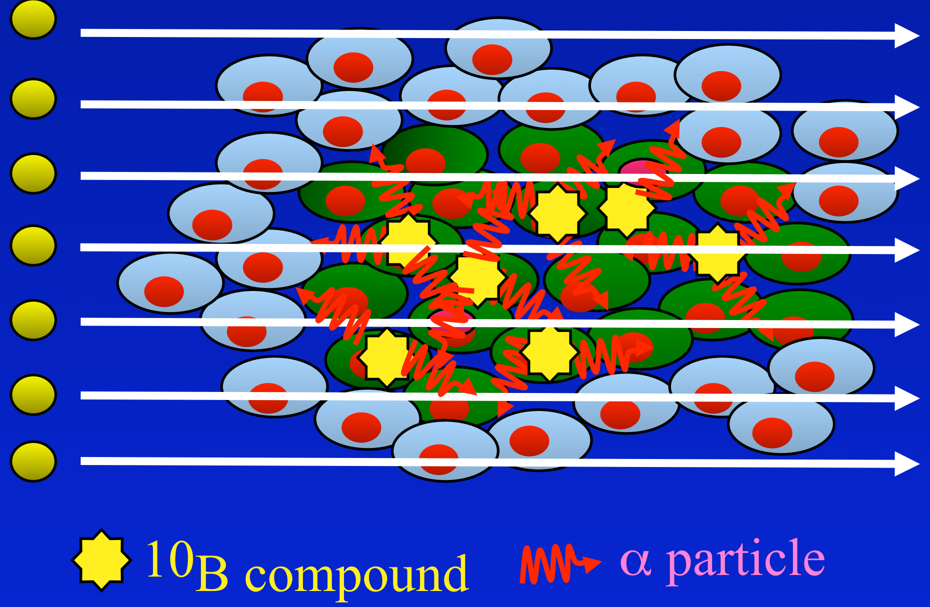


$$^{1}n + {}^{10}B \rightarrow {}^{4}He\ (\alpha) + {}^{7}Li + 2.8\ MeV$$

Li ions and a particles are high linear energy transfer particles with high biological efficiency.
Li ions and a particles destroy cells within about 10 μm path length from the site of capture reaction.

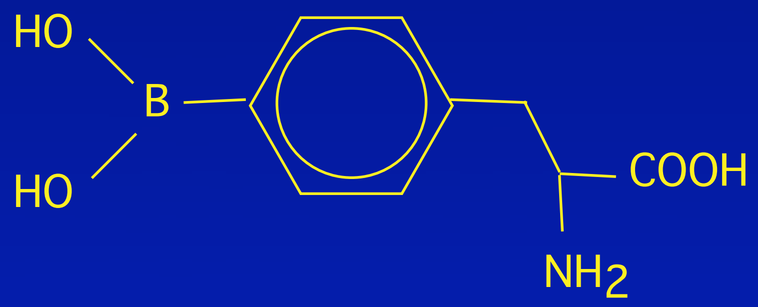
It is theoretically possible to kill tumor cells without affecting adjacent health cells, if ^{10}B atoms can be selectively accumulated in tumor cells.

How to do ?

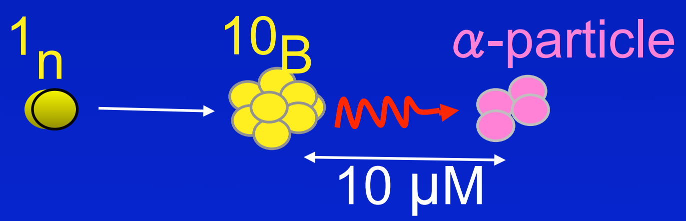


Boron Neutron Capture Therapy (BNCT)

Borocaptate sodium
(BSH)



L-p-Boronophenyl alanine
(BPA)

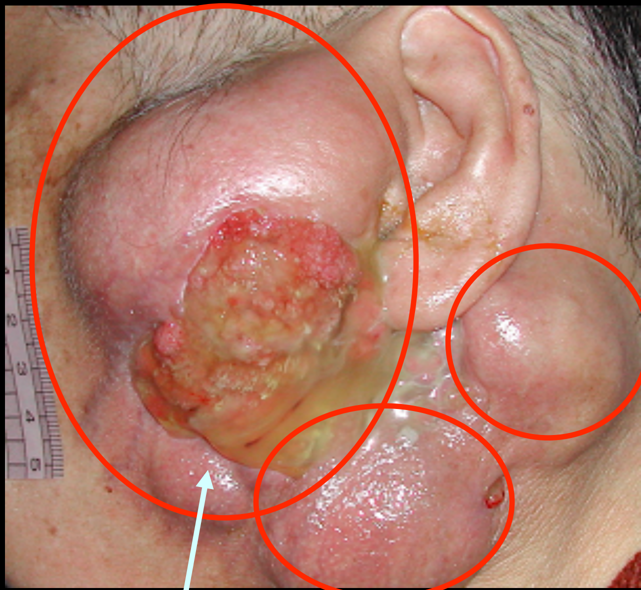


$$^{1}n + {}^{10}B \rightarrow {}^{4}He\ (\alpha) + {}^{7}Li + 2.8\ MeV$$

BNCT : parotid gland tumor

Department of Neurosurgery
Univer
Osaka Univ. Dep. of Dentistry

before treat.



after treat.

5 months after treat.

著しいがん細胞の
成長により体内に
止まらず皮膚をも
破りさらに増大

絶大なるがん細胞縮小の
効果を得ただけでなく
他の放射線治療では
成し得ない、
皮膚の再生を確認。

腫瘍はほぼ完全に縮退。

高いQOLを達成。

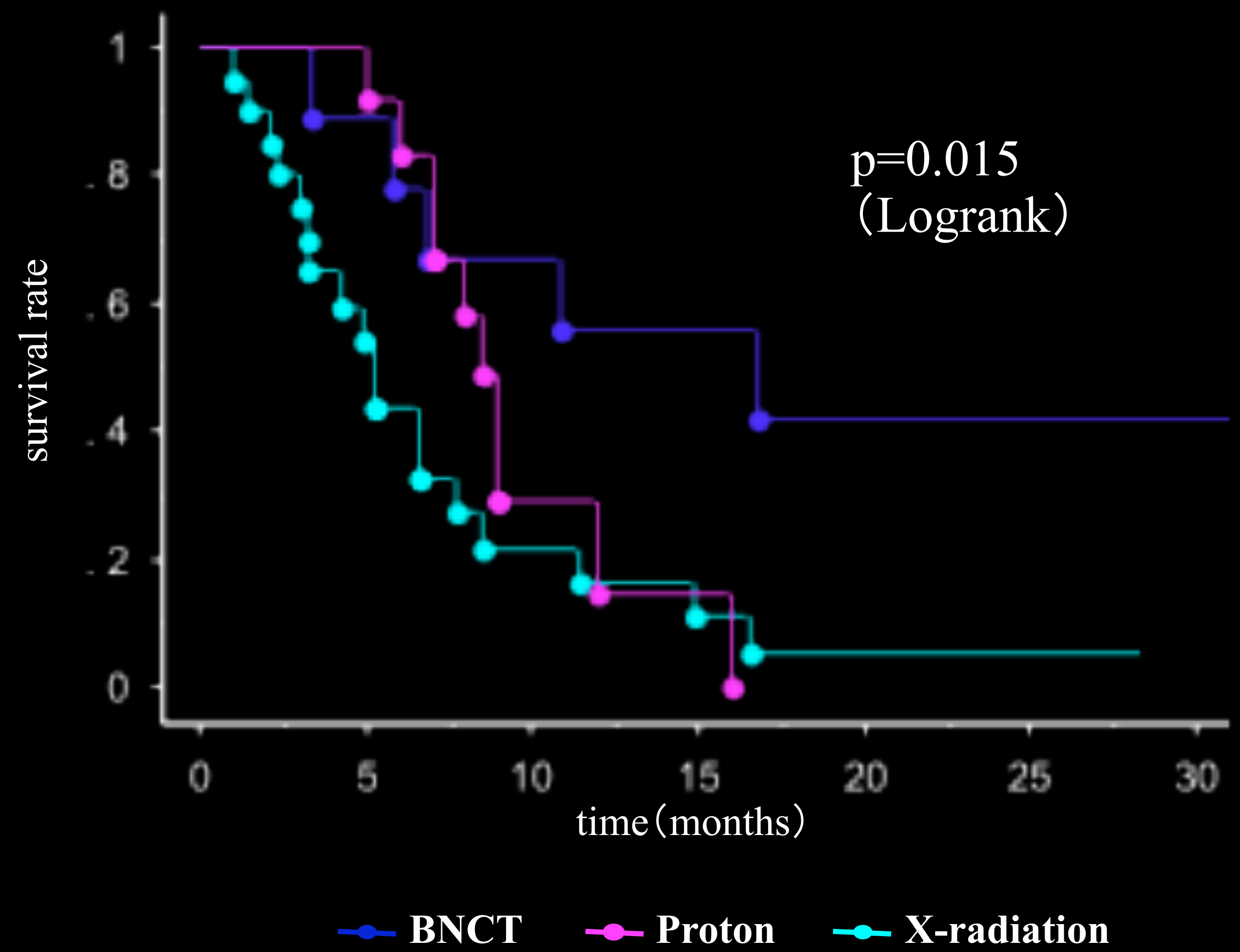
lung , liver etc.

SKY PerfecTV!
サイエンス　チャンネル
‘03，３月2日　18：00　放映
Japan Science and Technology Corporation（JST）

Department of Neurosurgery
University of Tsukuba

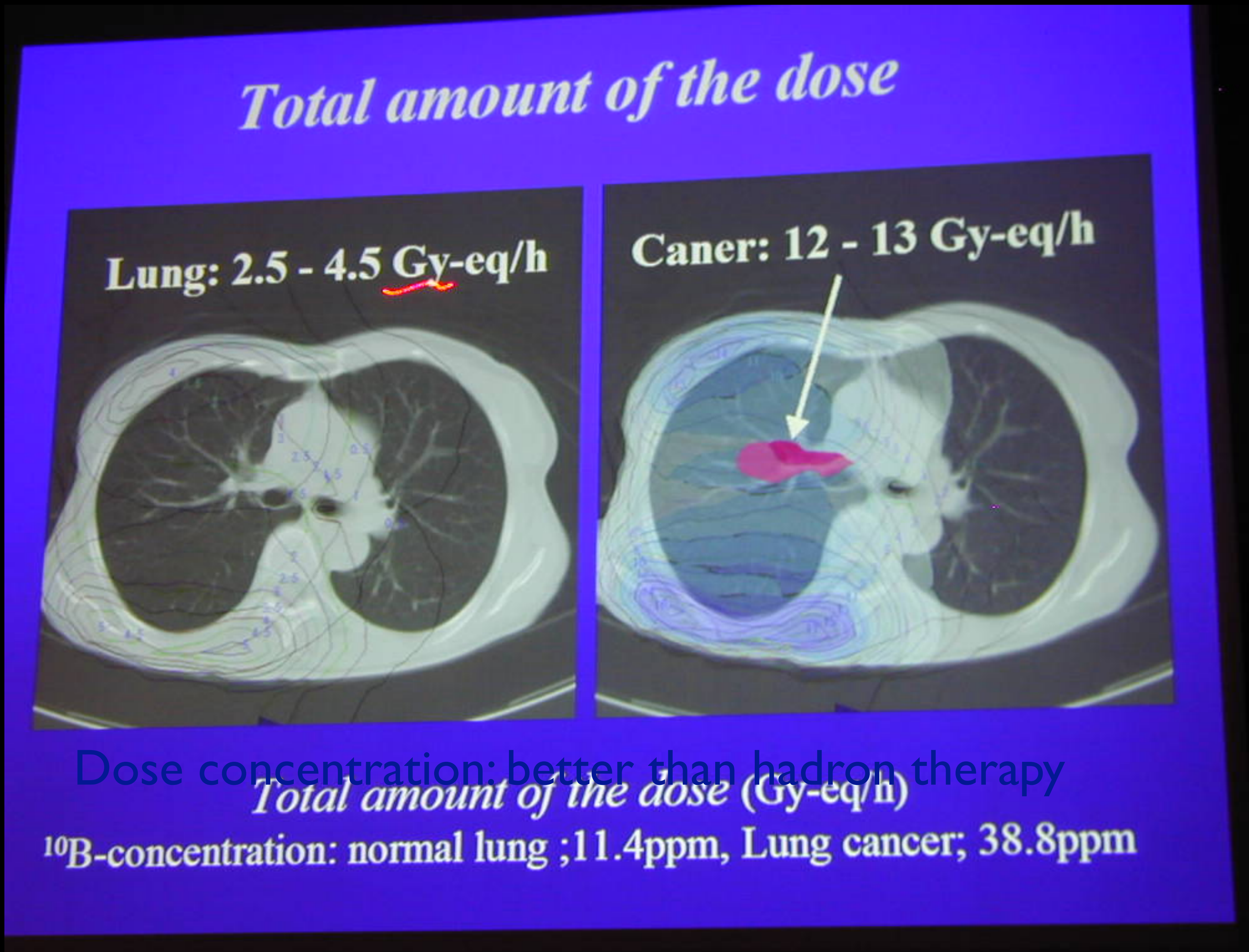
Progression-Free Survival

gliobrastomer



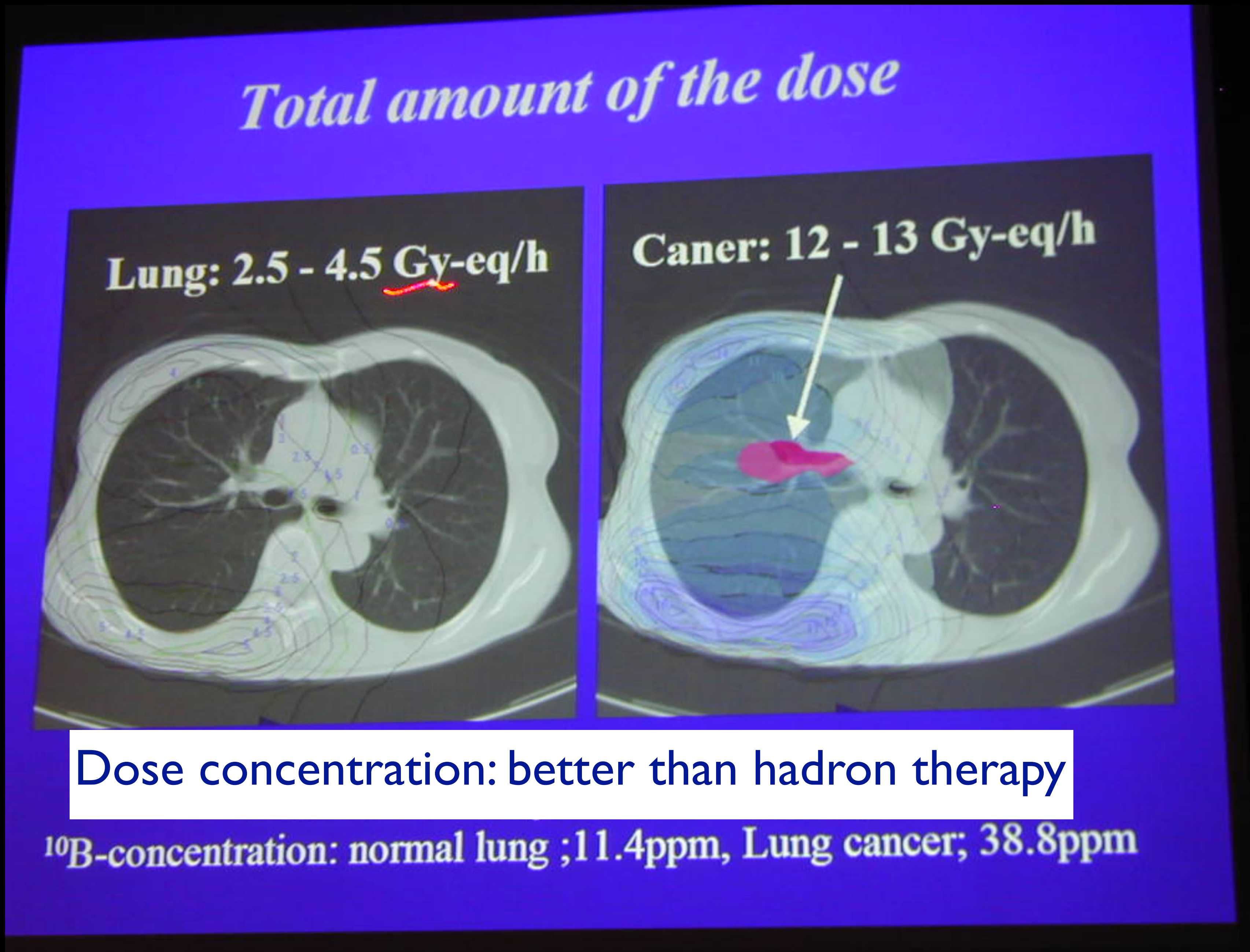
PFMST	13.4m	8.5m	5.1m

Department of Neurosurgery
University of Tsukuba



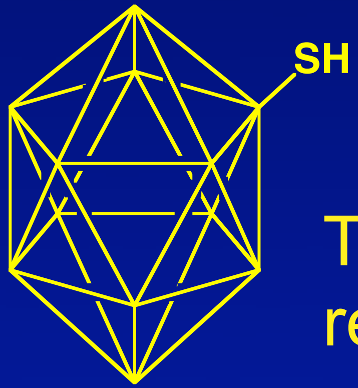
Dose concentration: better than hadron therapy

Department of Neurosurgery
University of Tsukuba



Dose concentration: better than hadron therapy

BNCT



The successful treatment of cancer by BNCT requires the selective delivery of relatively high concentration of ^{10}B to malignant tumor tissues and cells.

Advantage : α-particles with short range as 10μm

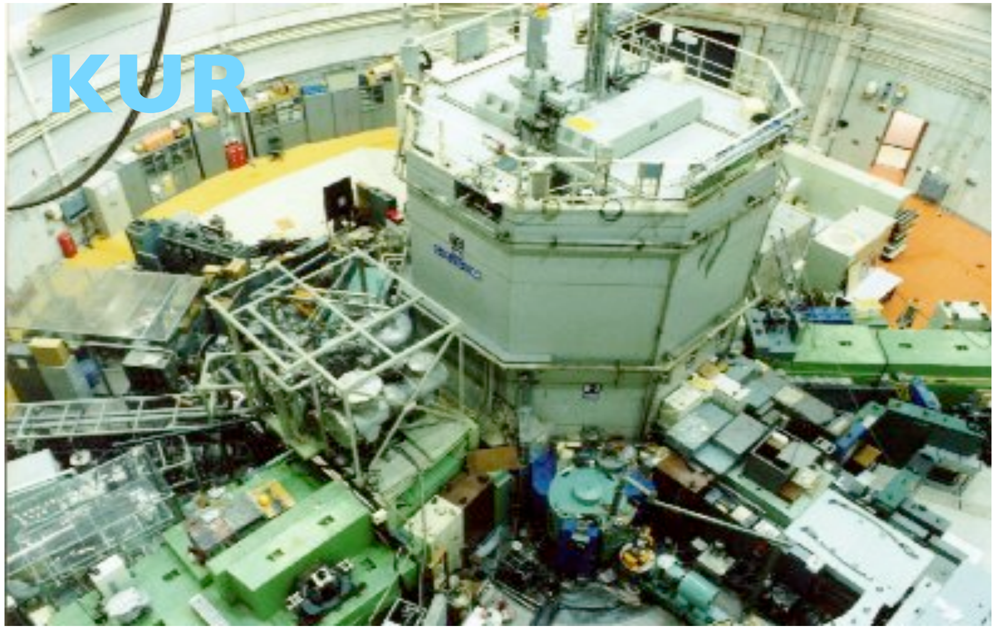
Disadvantage : (1)Low intracellular localization of ^{10}BSH against tumor cell via systemic administration
(2)Neutron source with nuclear reactor of >10MW

Strategy : (1)DDS Targeting carrier (liposome, polymer ･･･)
Ligand for internalization
(antibody, TF, EGF ･･･)
(2)ABNS Accelerator based neutron source

Neutron source for BNCT

- High flux
  - > 1 x 10^9 n/cm^2/sec at patient for 30minutes treatment
- Low energy spectrum
  - Thermal/epi-thermal (E_n<1keV) neutrons

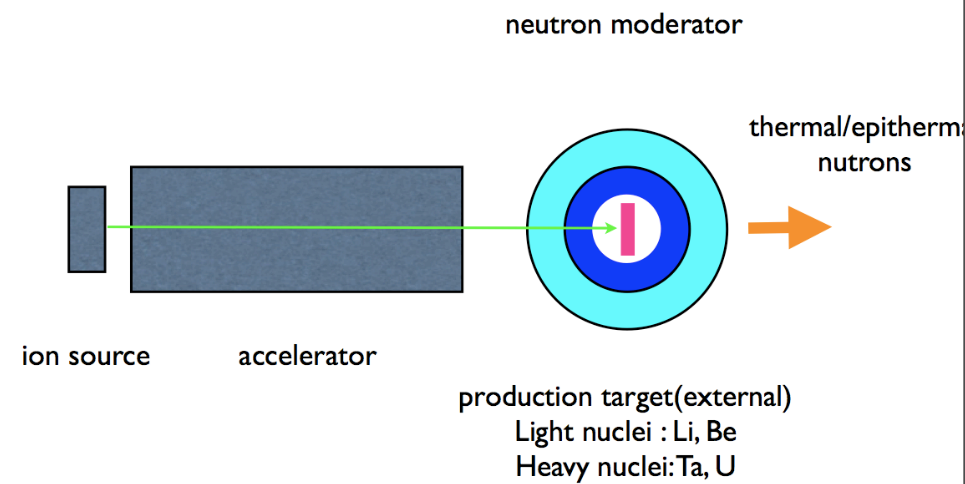
Nuclear reactor of >10MW output power is requested.



ABNS
(accelerator-based neutron source)

- Neutron production reaction
  - 9Be(p,n)B, 8Li(p,n)Be
- Low energy proton
  - 3-10MeV
    - (Coulomb barrier ~2MeV)
    - – Low gamma-ray background
- Large reaction cross section
  - ~500mb

Difficulties of ABNS with external target

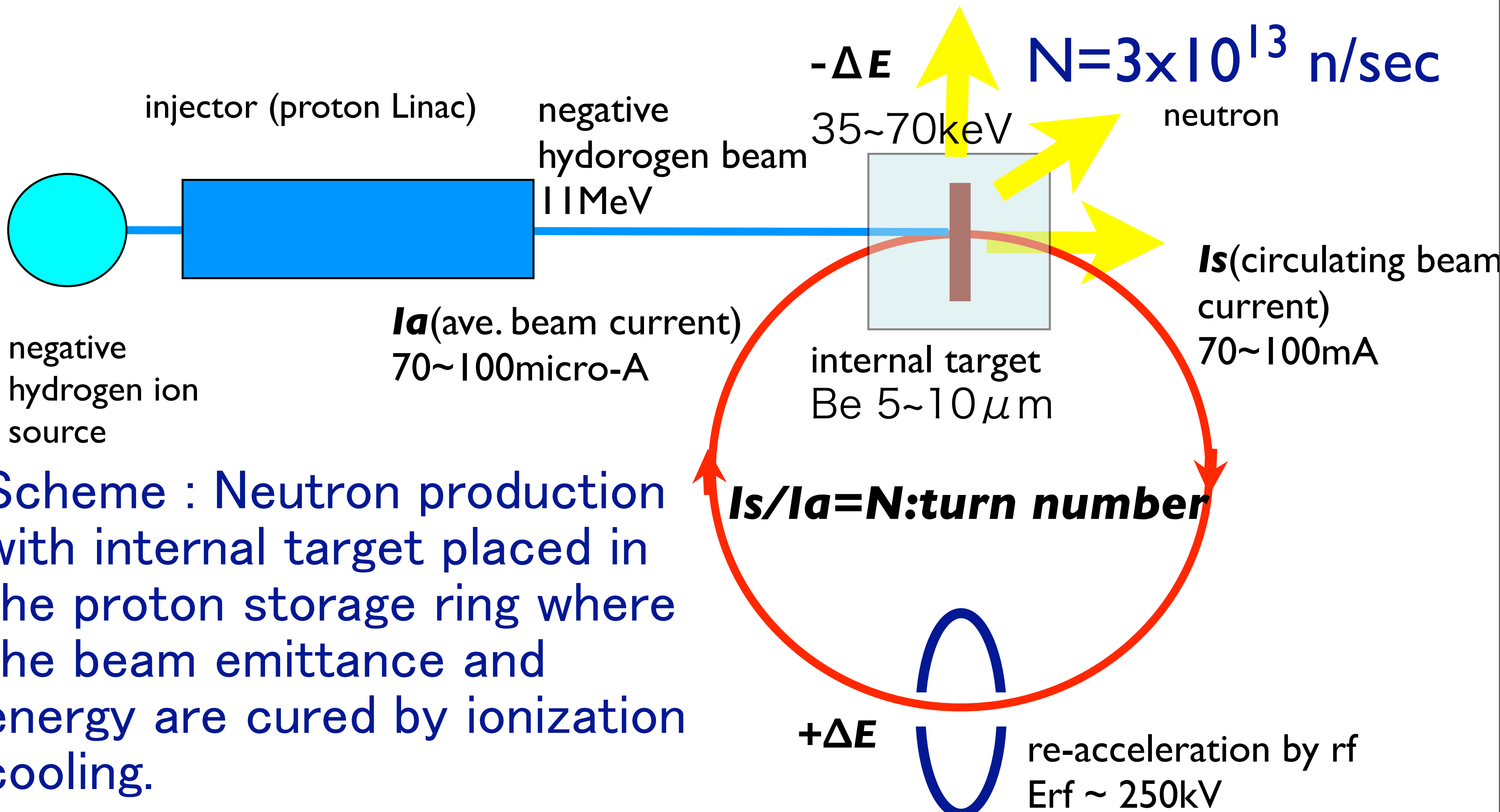


- Beam current
  - High intensity
    - ➡ Large beam current >10mA
- Neutron production target
  - Technical difficulties
    - ➡ Large heat-load beam power >10kW
    - ➡ Large radiation damage >1dps
      - dE/dx ~ 100MeV/g/cm2, Range ~1mm
- Gamma-ray radiation
  - Large gamma-ray production from target/moderator
    - ➡ difficult to shield

ABNS with internal target
FFAG-ERIT

(FFAG Accelerator with Emittance/Energy Recovery Internal Target)

Y.Mori, Nucl. Instr. Meth., PRS, A562(2006) 591-595.



Scheme : Neutron production with internal target placed in the proton storage ring where the beam emittance and energy are cured by ionization cooling.

FFAG-ERIT for ABNS

- Energy loss
  - Recovered by RF re-acceleration
- Emittance growth due to scattering
  - Cured by “Ionization Cooling”
- Beam intensity
  - Required accelerating averaged beam current is reduced by number of turns

Energy loss

- Proton energy : 10MeV(dE/dx = 30MeV/g/cm^2)
- Target thickness : 5 micron for Be
- Beam intensity : 100mA

  - Energy loss / turn ~30KeV
  - Beam power lost in the target ~ 2.4kW

- Heat load & radiation damages are modest.

Temperature rise of Be target

heat load **12W/cm²**

beam distr. **Gauss (3σ: 5.64cm)**

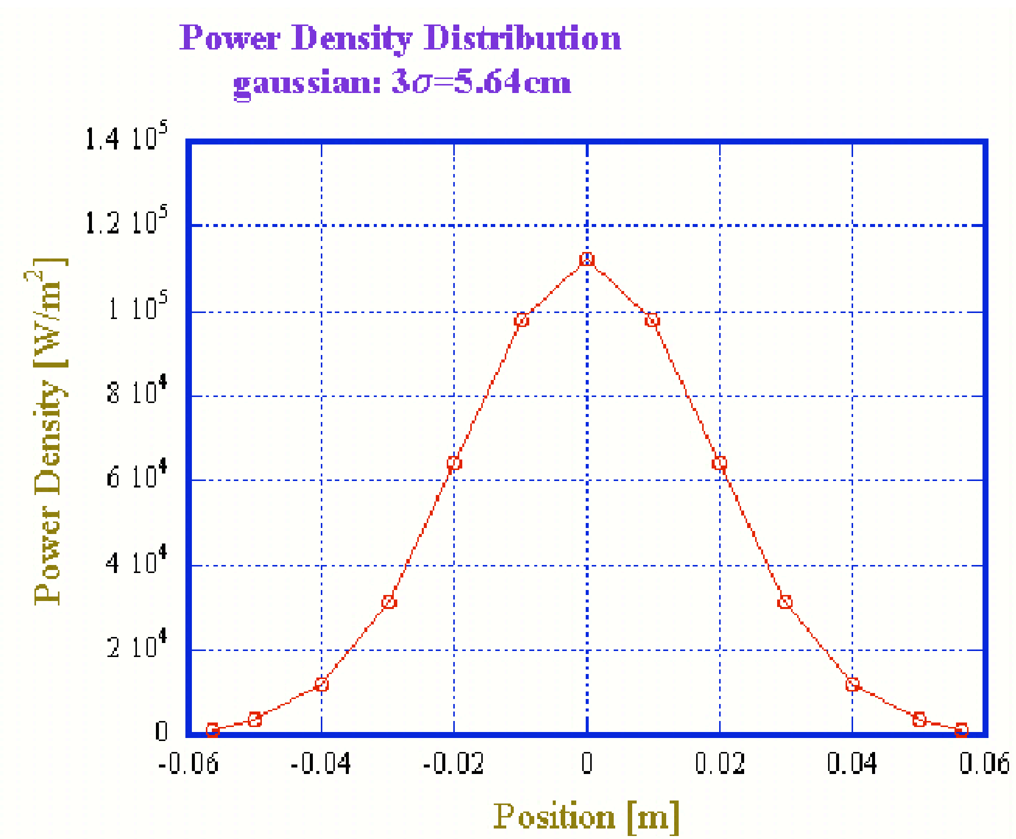
beam power 500W

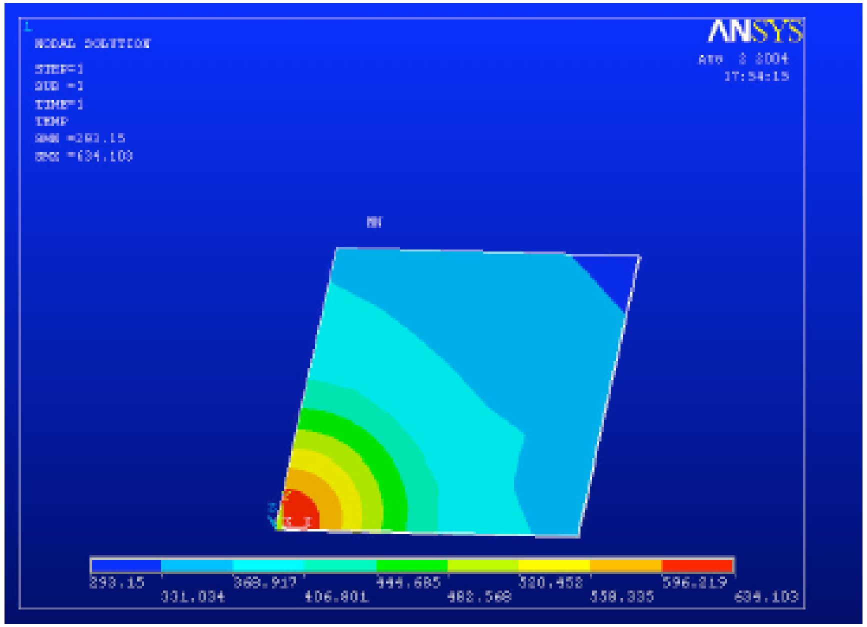
radiation $\propto T^4$

ANSYS

max. temperature rise

~634°C





Irradiation damage of Be target

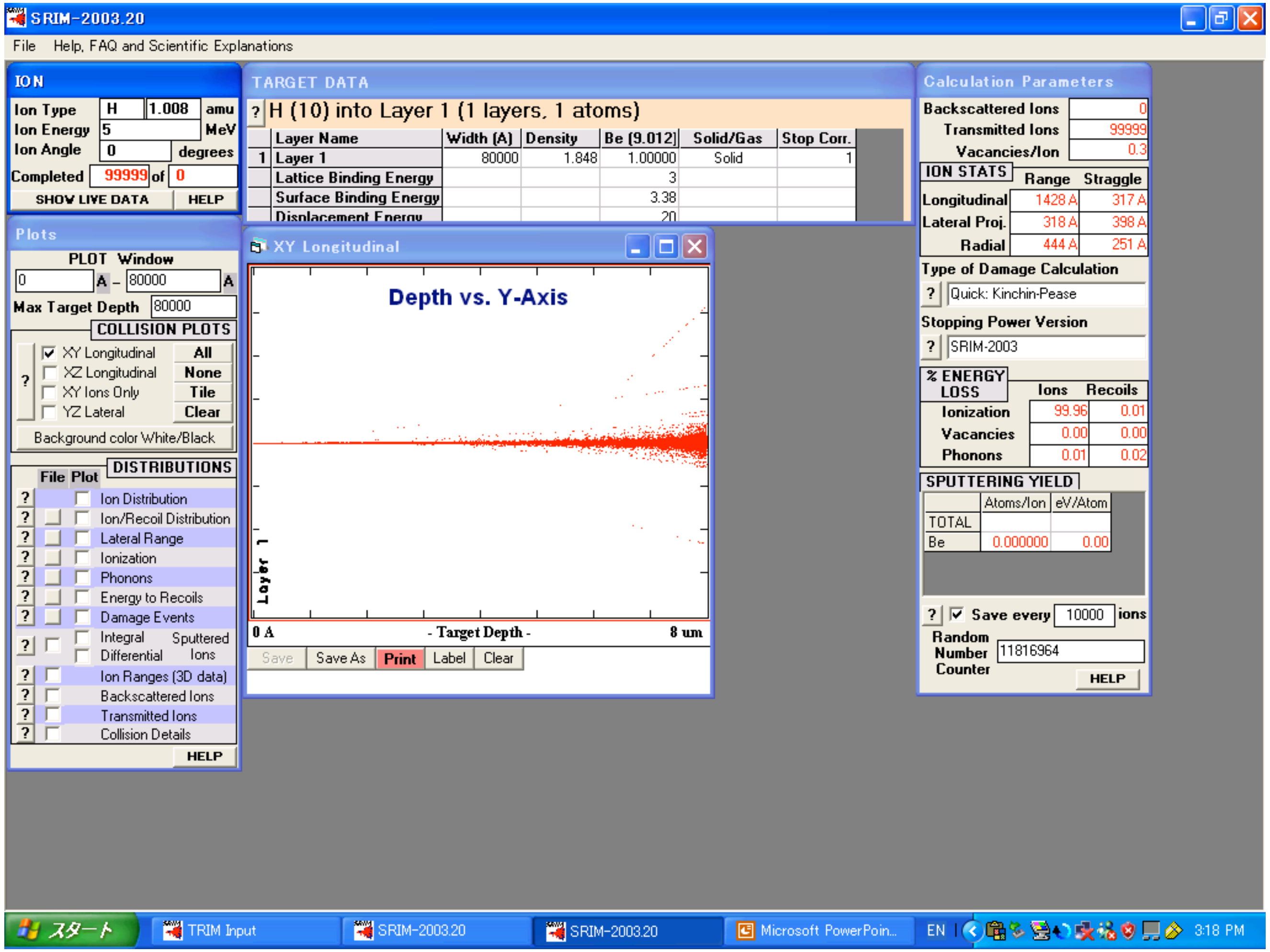
SRIM code

proton beam current   1A

energy   10MeV

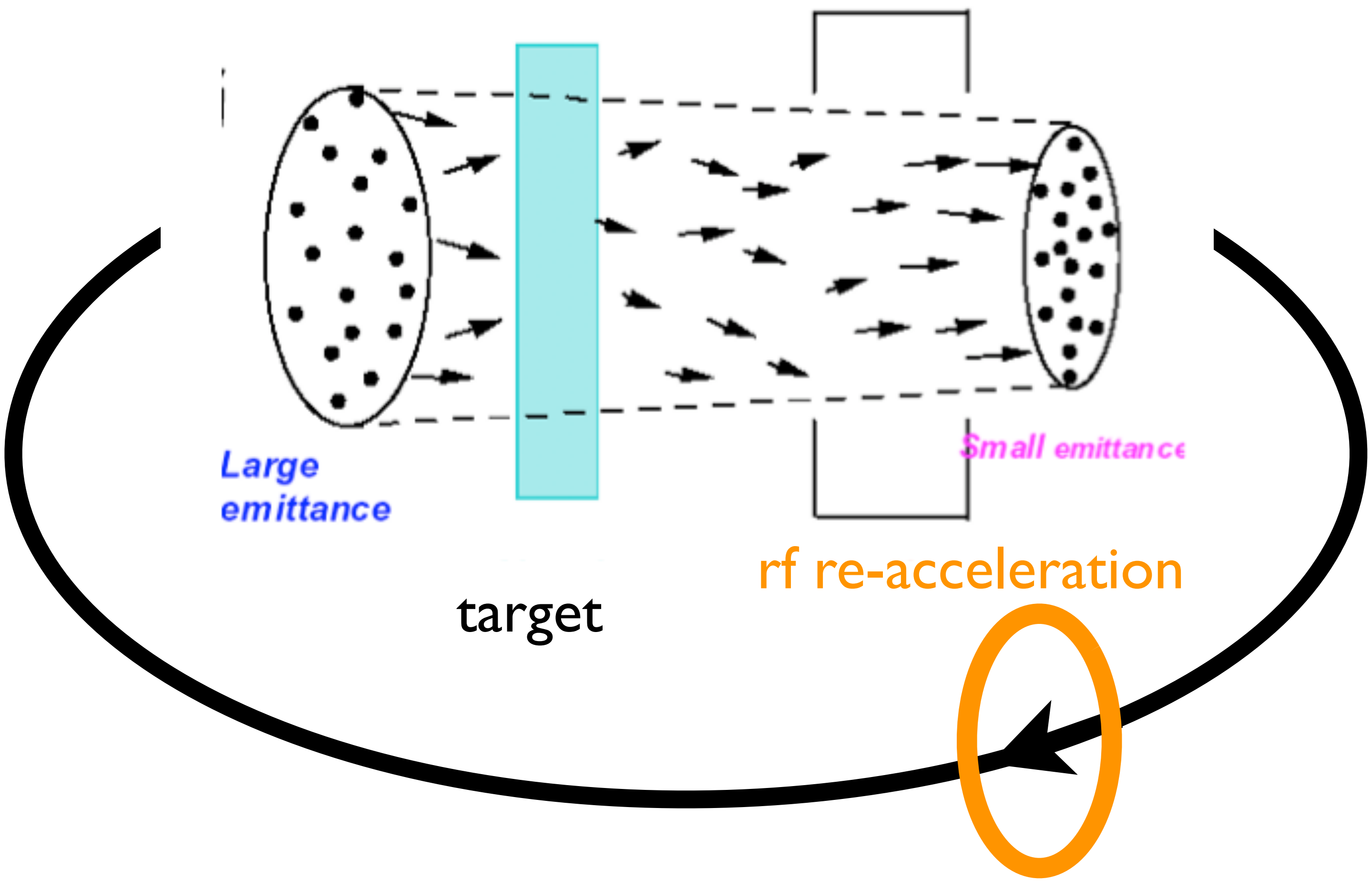
Be target   8micro-m

Dislocation
< 0.1dps
small enough



Emittance growth

- Using an internal target, the beam emittance is increased by multiple scattering and straggling. However, in ERIT, "Ionization Cooling" suppresses the emittance growth.



Ionization Cooling

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

ε : beam emittance

transverse

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

Rutherford multiple scattering

longitudinal

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

straggling

proton beam 10MeV

Be target

Transverse→Cooling

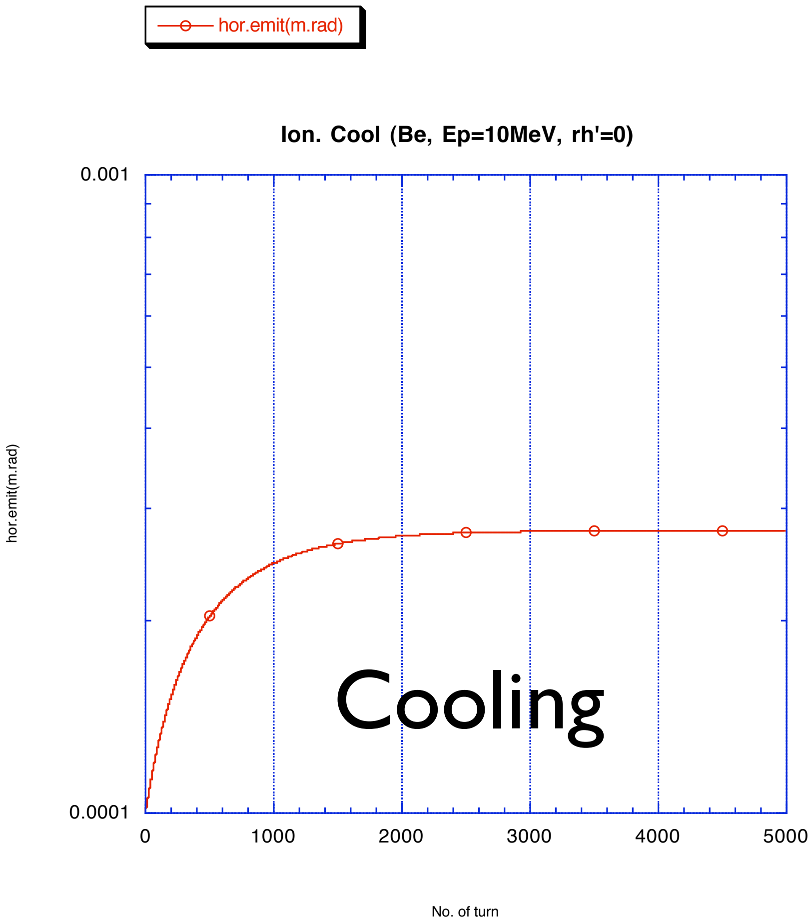
Longitudinal→Heating

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

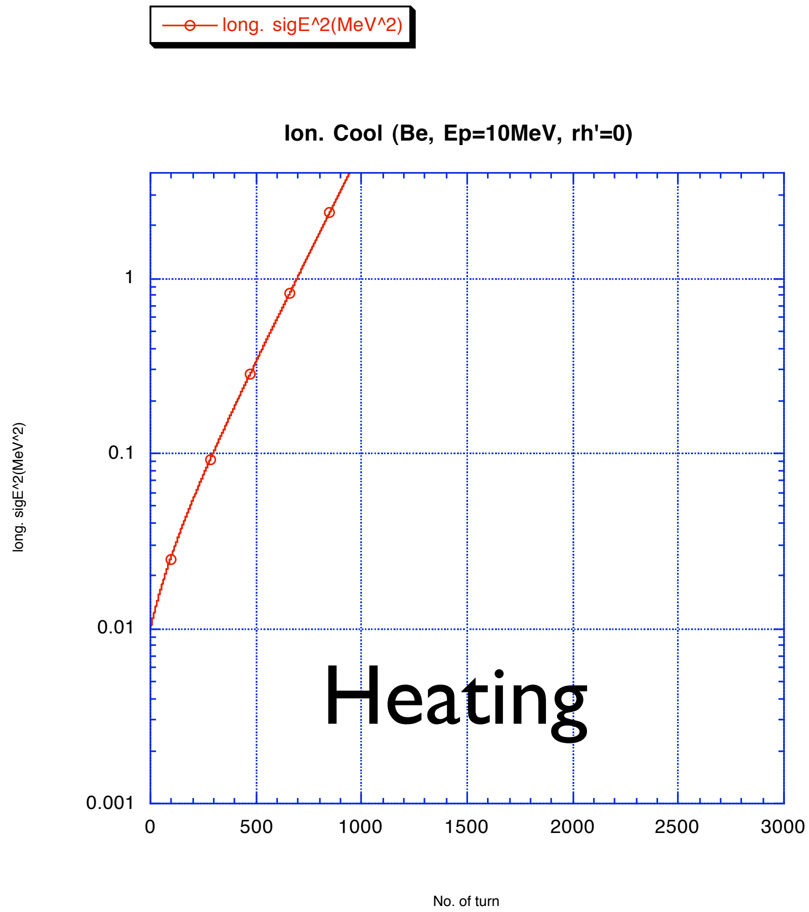
Sum of distr. function: $\sum_{1}^{3} g_i > 0$

Emittanc growth

Transeverse



Longitudinal



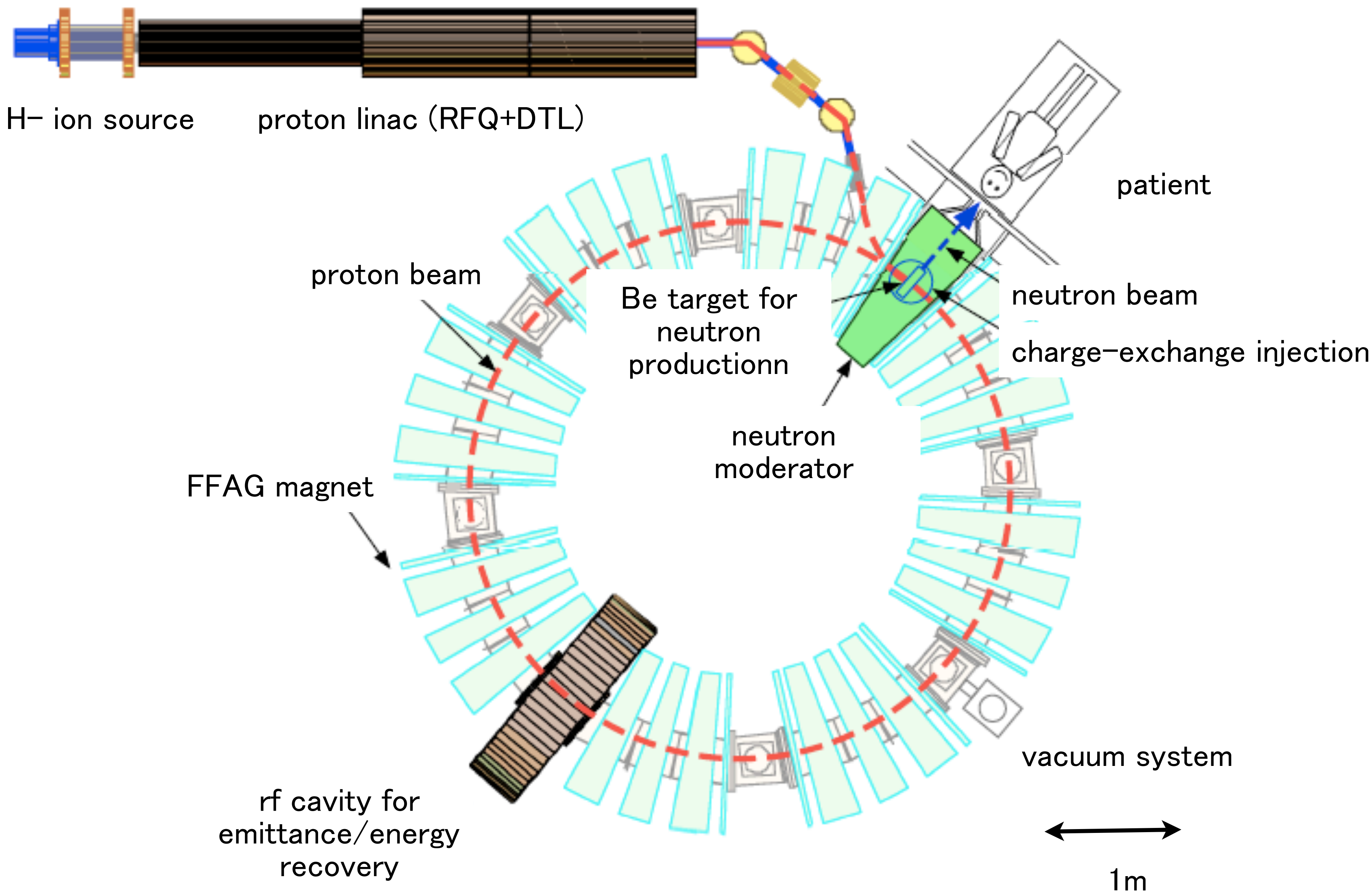
Need a large momentum acceptance ring

--> FFAG (zero-chromaticity)

R&D Project of Next-generation DDS-type Malignant Tumor Therapy System

- Purpose
  - Development of a prototype of compact accelerator-based thermal/epithermal neutron source for BNCT(boron neutron capture therapy)
- Performance
  - Neutron flux enough for 1 hour treatment
  - thermal/epithermal neutron flux：$\varphi \sim 1 \times 10^9$ n/cm^2/sec @patient
- Three-year (2005-2007) project supported by New Energy Development Organization (NEDO) in Japan
  - Construction was successfully completed.
  - Beam test has been carried out.

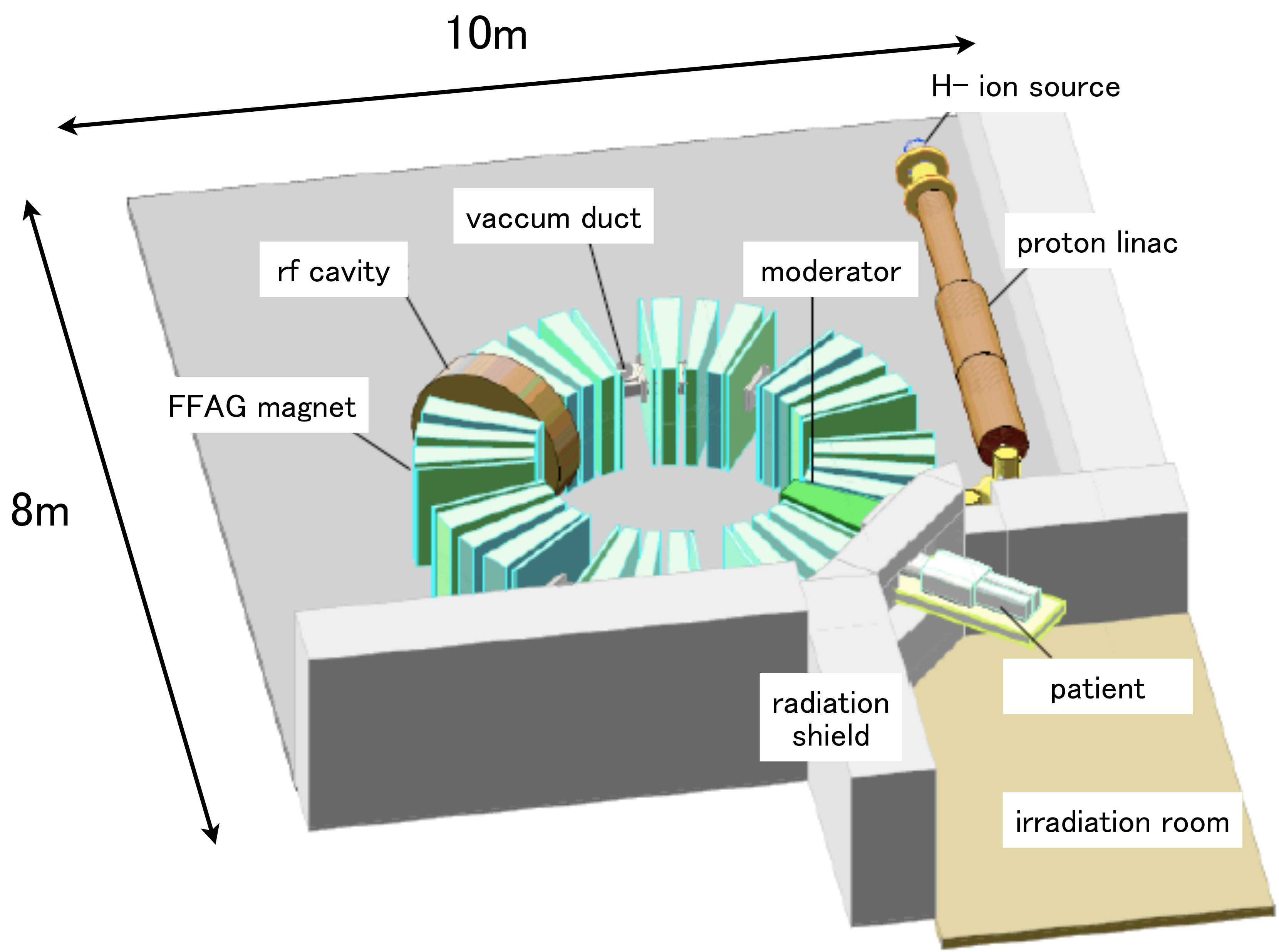
FFAG-ERIT ring for ABNS



Characteristics of ABNS with FFAG-ERIT ring

- Large beam current/beam power
  - circulating beam
    - ciruculating beam current(beam power) >50mA(500kW equi.) more than 10times compared with external target
- Modest loads for the target and accelerator
  - small heat load and low radiation damage with thin target
    - heat load ~3kW
      - ➡ radiation cooling : temeprature 650-700 C
    - radiation damage 0.1dps
    - Lifetime >month
  - small beam current for the accelerator
    - accelerator beam current : Ia = Ic／N(# of turns)
    - beam current Ia=Ic/N=50μA : if N=1000turns
- Small gamma-ray production
  - thin target, no cooling medium and no beam dump at target region
- multi-target & multi-directional irradiations
- Small radiation shielding
  - modest beam current
    - small buildings and low infrastructure cost

ABNS with FFAG-ERIT ring

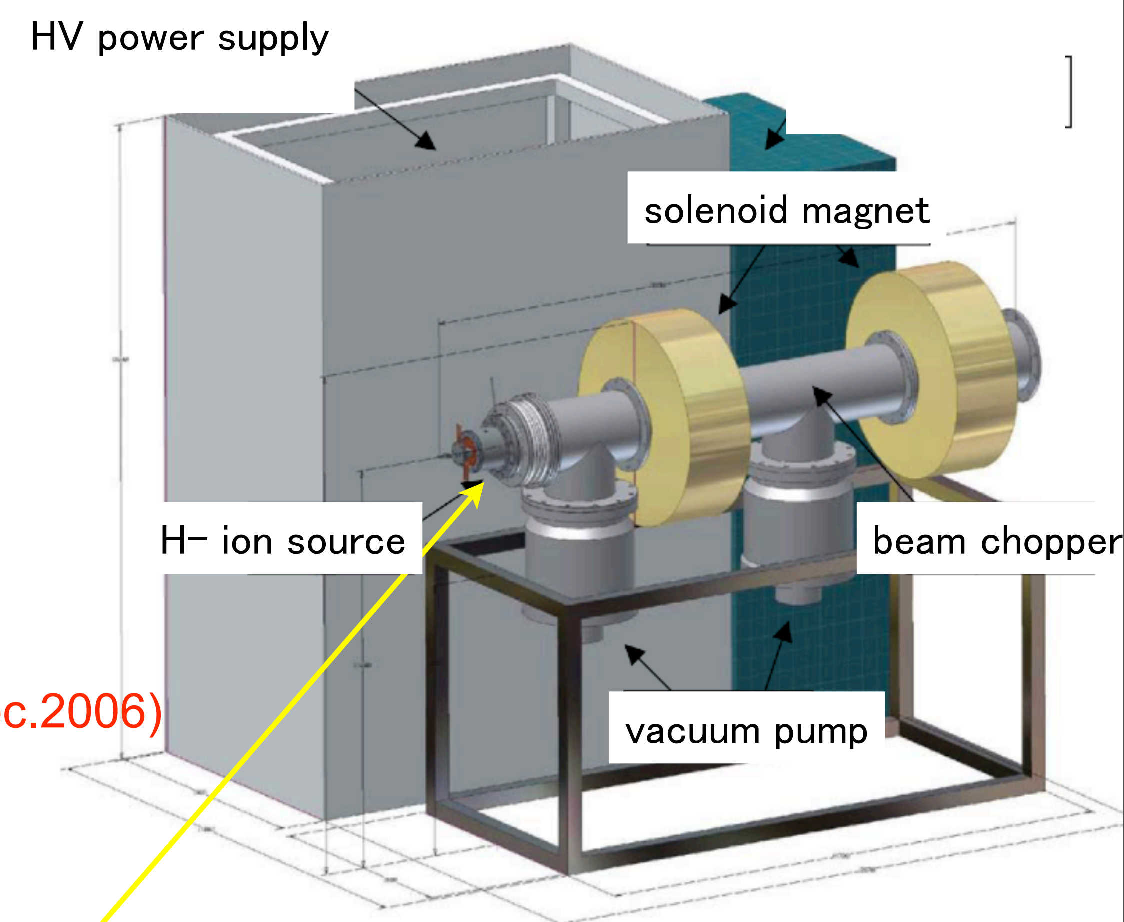


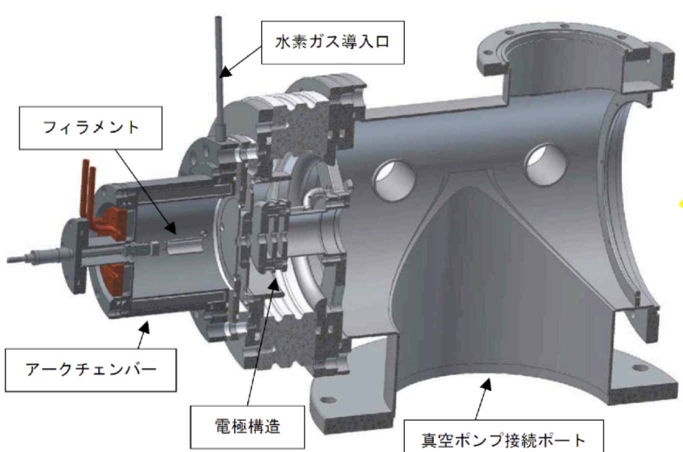
Characterisitcs & Performance

- FFAG-ERIT ring
  - circ. beam current 70mA
  - beam life(# of turns) 1000turns
  - acceptance Av>500mm.mrad(rms), dp/p>+-5%(full)
  - magnet large aperture, small fringing filed
    - gap height 15cm
  - rf cavity
    - frequency ~20MHz(harmonic number :5
    - rf voltage >200kV Injector
  - beam energy 11MeV
  - averaged beam current 70μA
- Injector
  - beam current >70μA (20-200Hz, duty ~2%)
- Neutron production target
  - Be,10μm heat load <6.6W/cm^2 ,Lifetime>1 month
- Moderator
  - thermal+epithermal >10^9 n/cm^2/sec
  - gamma-ray・fast neutron Nuclear reactor level （IAEA)

Ion Source

- particle: negative hydrogen
- extraction energy： 30 keV
- rep. rate：200Hz（goal：500Hz）
- beam duration：2%, maximu
- beam current：
    - 100μA（ave.）
    - 5mA（peak：goal10mA）
    - commissioning: 1mA(cw)achieved(Dec.2006)
- nor. emittance：<1πmm-mrad





Proton linac

AccSys Inc. PULSAR

PULSAR:developed for **PET**。

RFQ

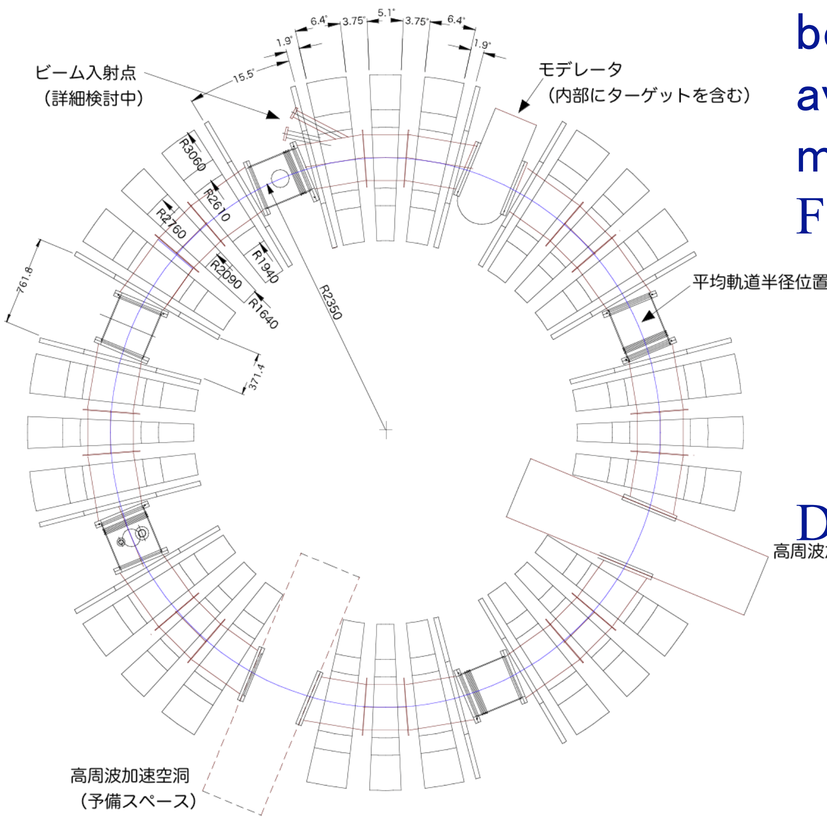
DTL

FFAG-ERIT RING

-beam energy 11MeV
-circ. beam current 70mA
-beam life(# of turns) 500-1000turns

-acceptance Av>3000mm.mrad, dp/p>+-5% (full)

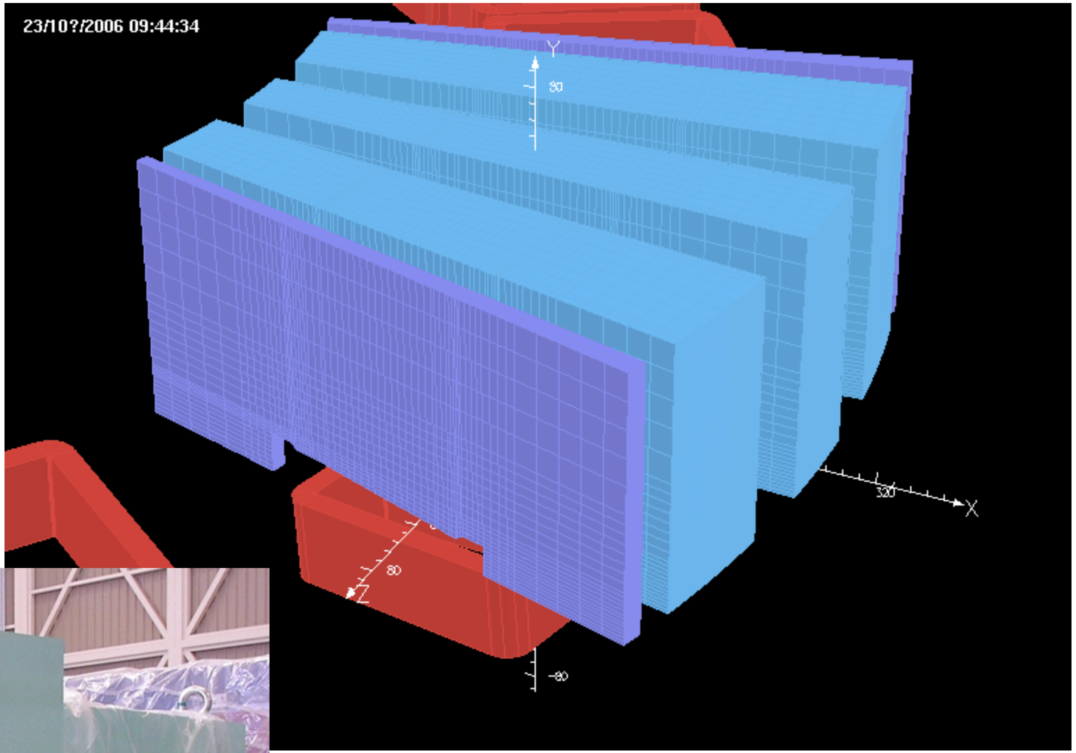
Parameters of FFAG-ERIT ring

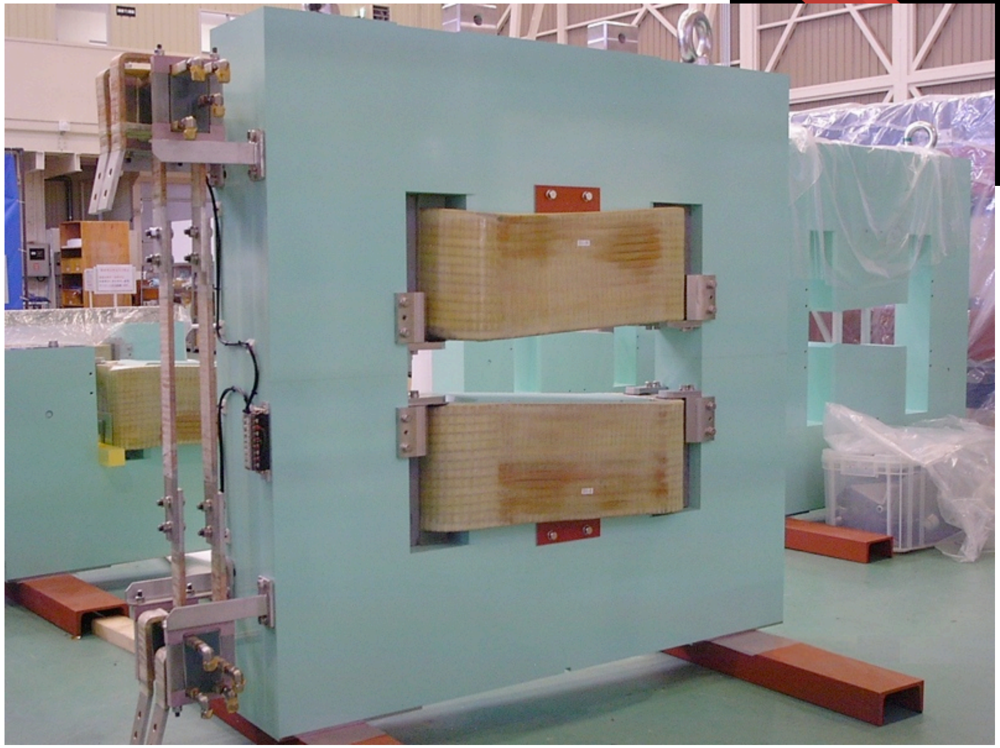


beam energy	11 MeV
ave. radius	2.35 m
most ext. radius of magnet	3.06 m
Fmagnet	
field strength	0.825 T
AT	58500 AT
orbit length（@ave. radius）	26.25 cm
mass	4.1 ton
Dmagnet	
filed strength	0.727 T
AT	54500 AT
orbit length（@ave. radius）	20.92 cm
mass	3.4 ton

Radial sector   FFAG magnet

FDF lattice
Cell num. = 8
F-Mag. = 6.4[deg],
D-Mag. = 5.1 [deg],
F-D gap 3.75[deg],
F-Clamp gap = 1.9[deg],
Clamp thick = 4[cm]
Mean radius = 2.35[m]

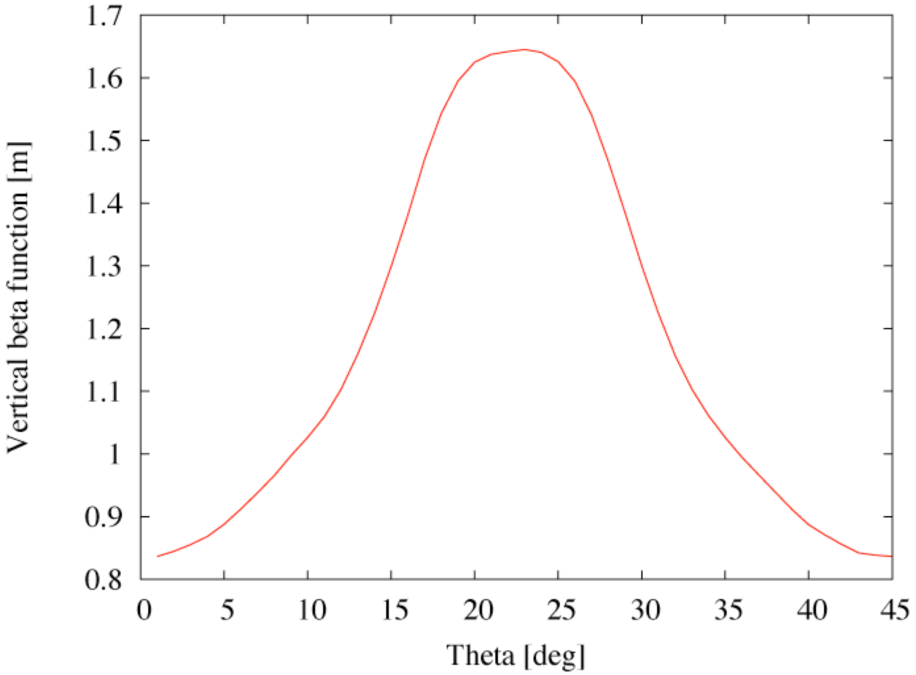


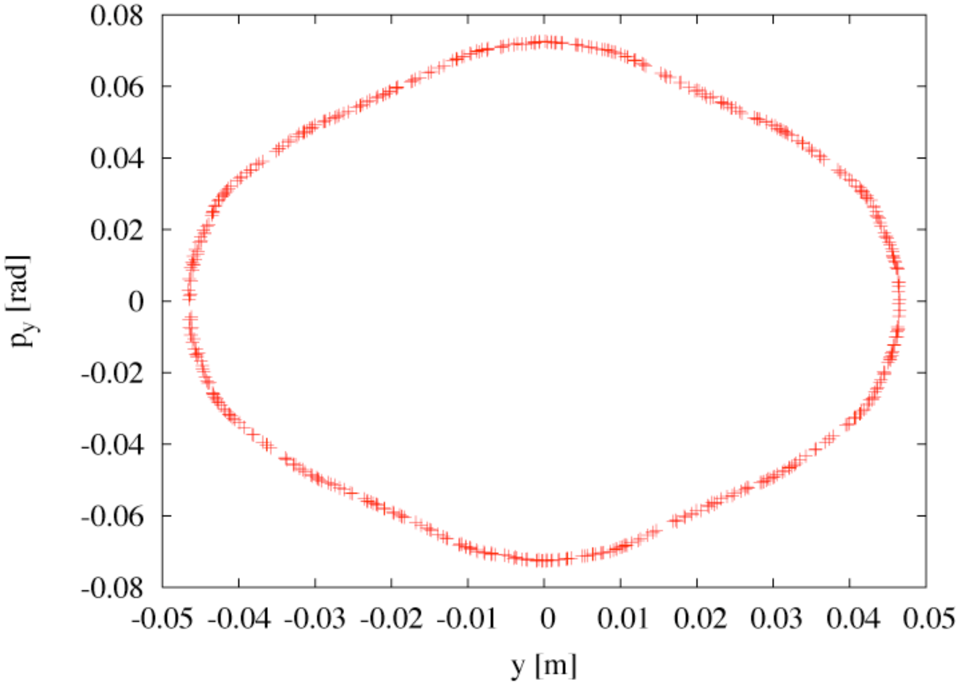


$n_x \sim 1.75$, $n_y \sim 2.23$
FD ratio ~ 3

Vertical beta function & acceptance

Beam tracking simulation with TOSCA field map



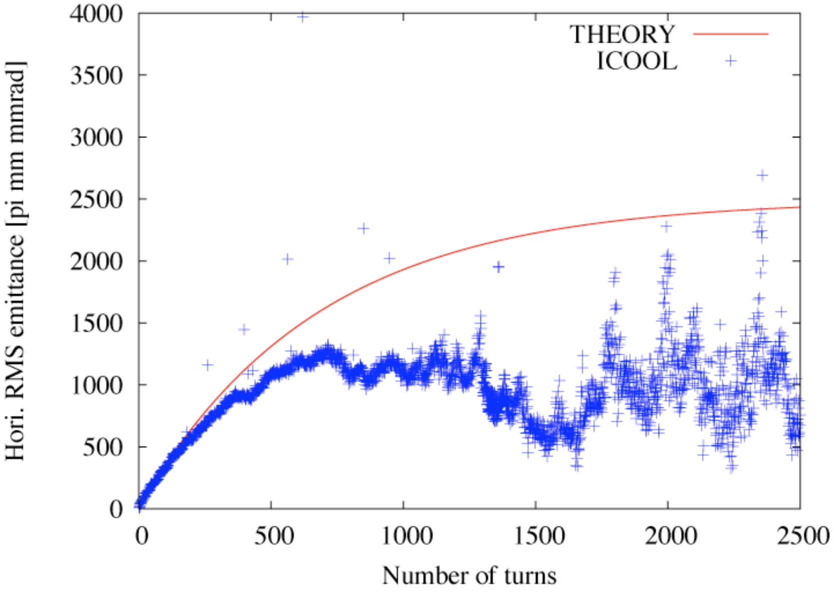


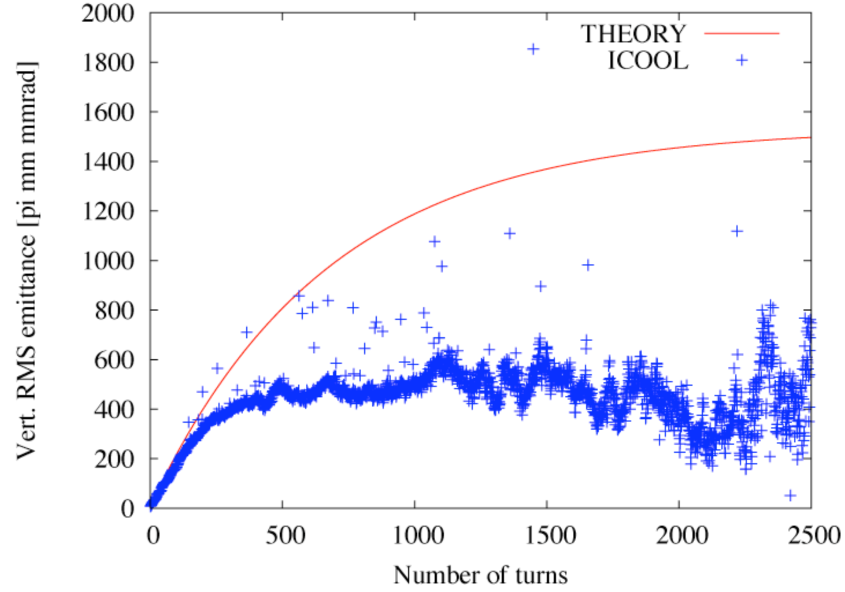
Vertical beta function@target ~ 0.83 [m]

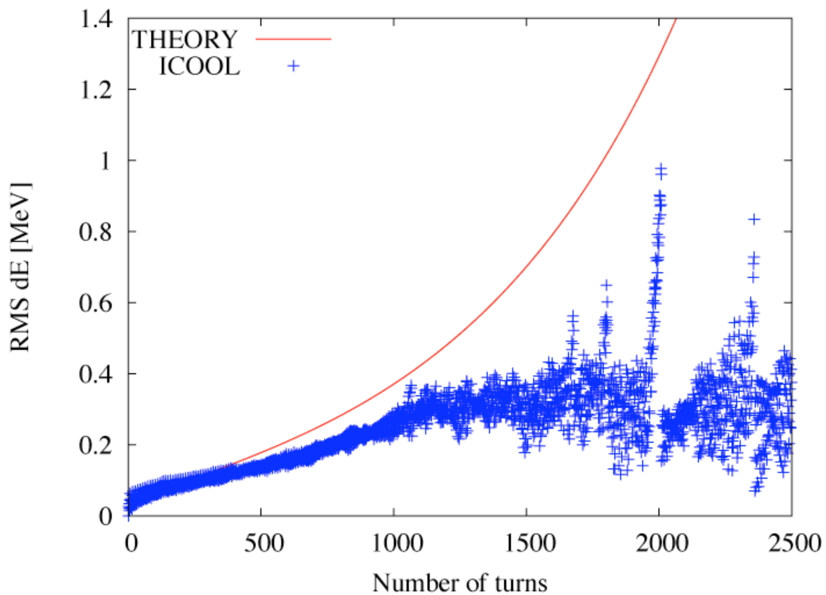
Vertical acceptance ~ 3000π [mm-mrad]

(Horizontal acceptance > 7000π [mm-mrad])

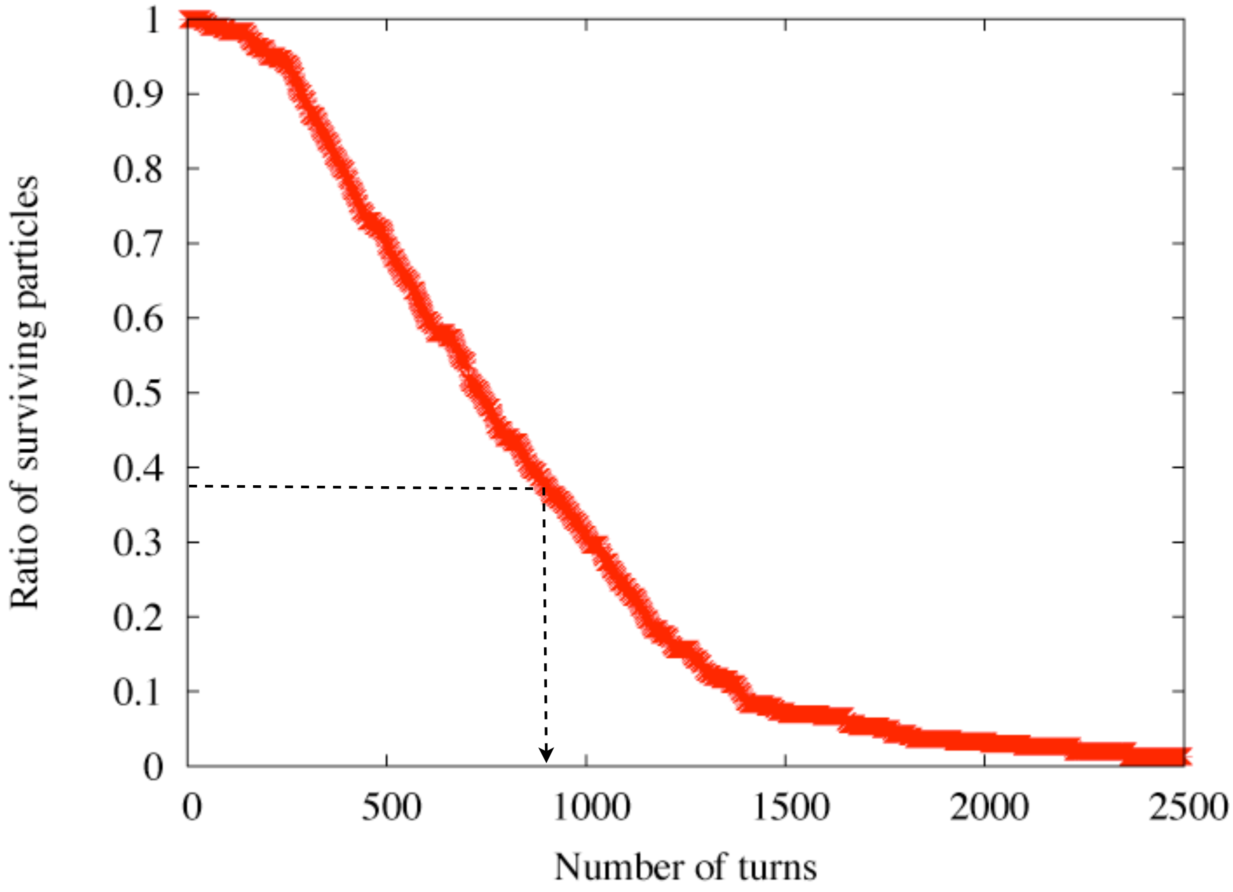
RMS emittance / energy spread





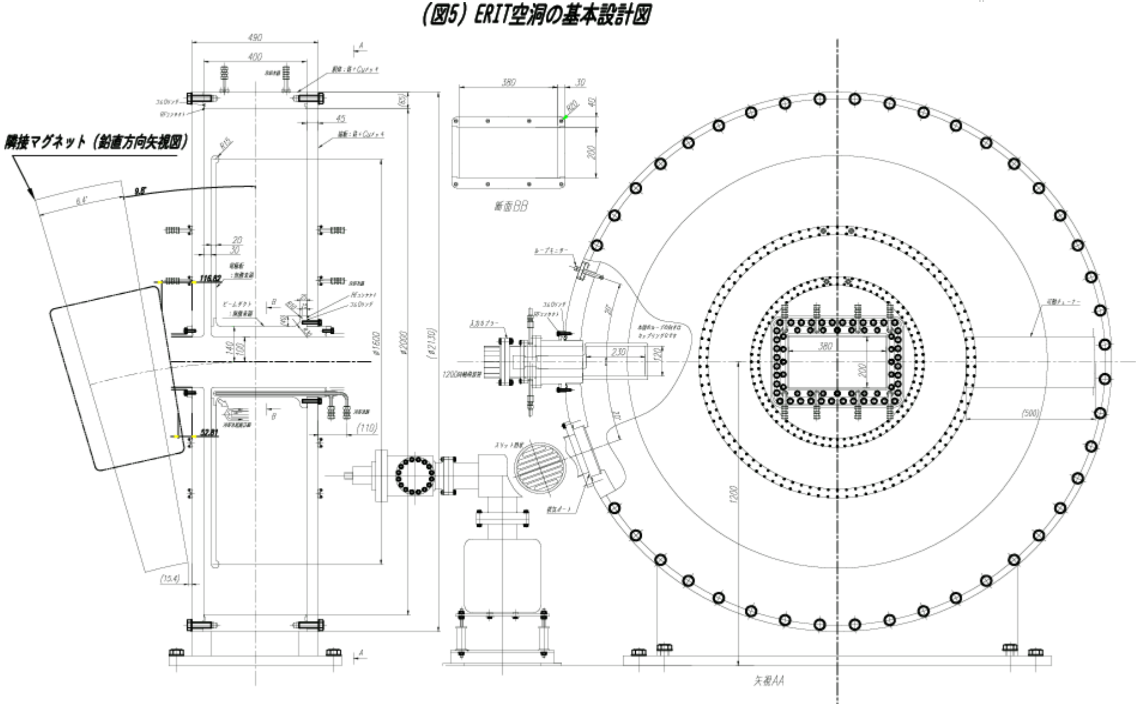


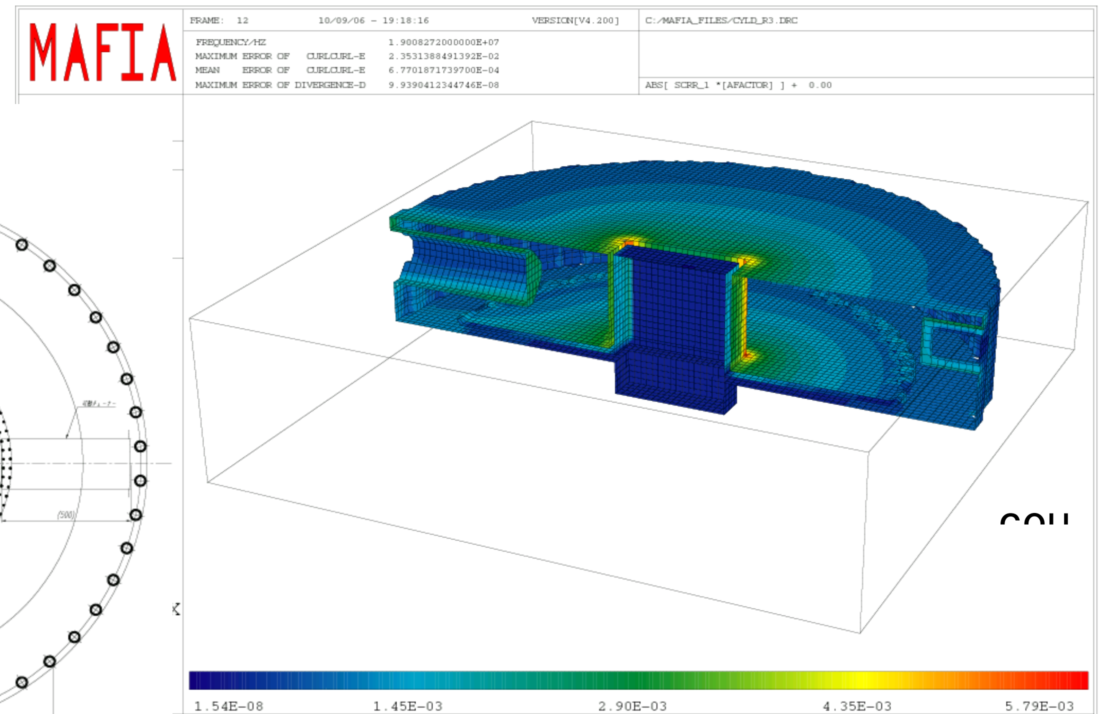
Number turns for beam survival



Average turn numbers for beam survival ~ 910 turns

rf cavity for ERIT ring





・Inner diameter φ200cm, ・axial length 40cm, cap. electrode: φ160cm × t2cm,

・ gap btw cap. electrode and cavity end plate 3cm,

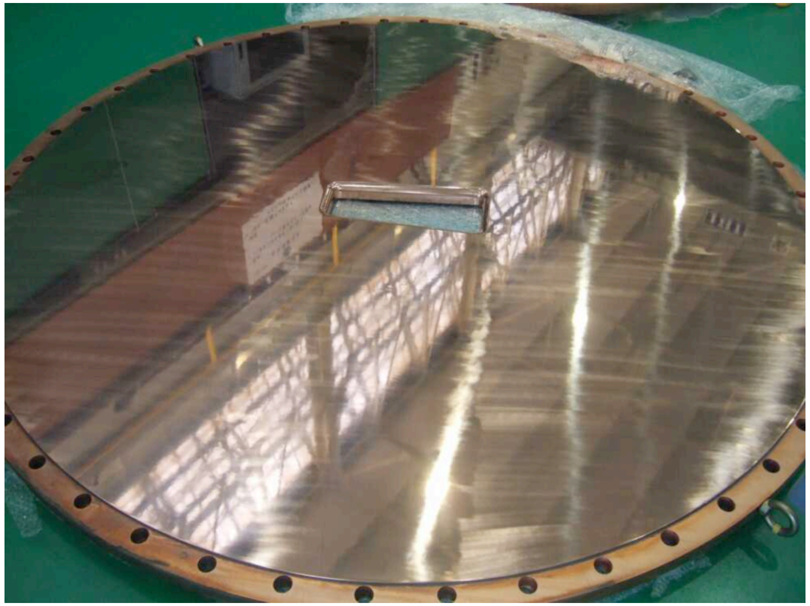
・tuner: φ20cm × L50cm,

・beam duct : w38cm × h20cm,

・coupler : diameter 12cm × L30cm, φ2cm

rf cavity for FFAG-ERIT

End plate



frequency
18.1MHz

rf voltage
>200kV

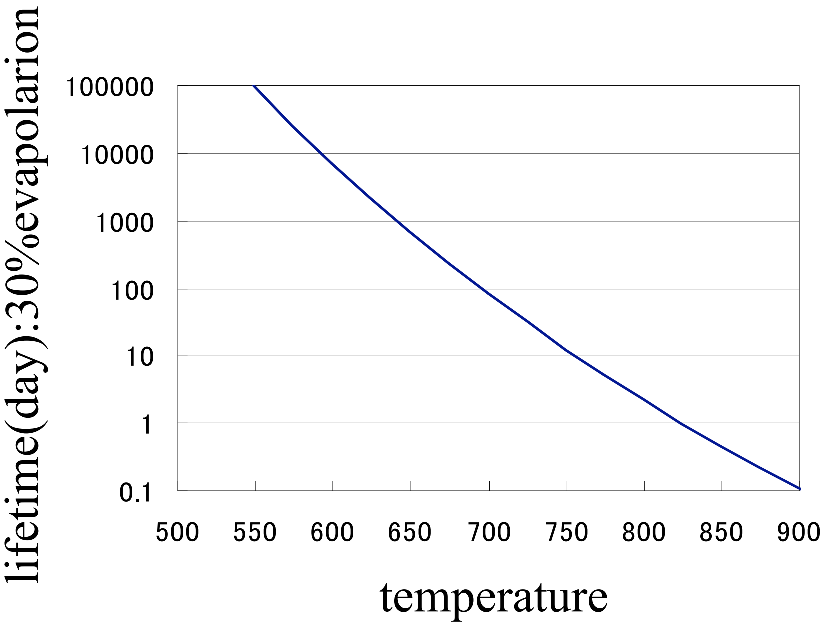
Gap capacitive plate

Neuron production target lifetime

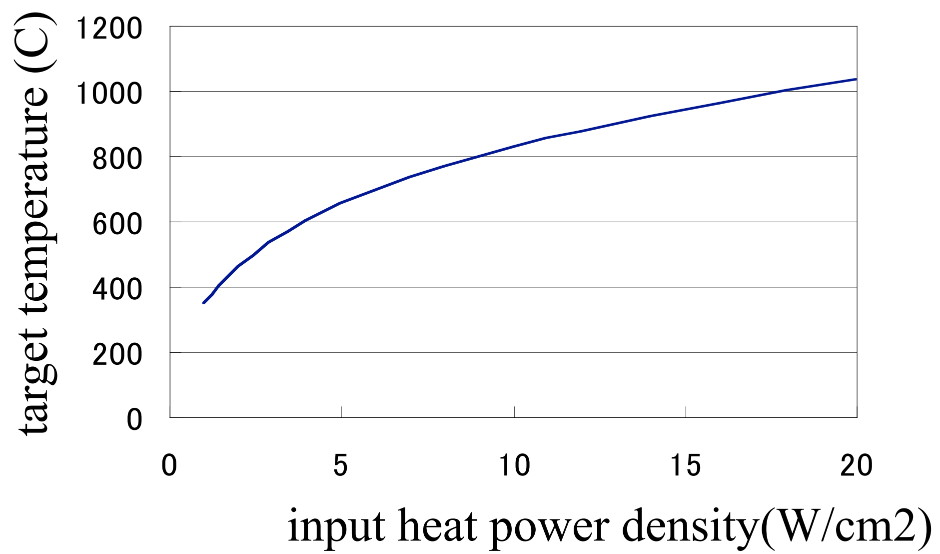
・Lifetime is mainly determined by evapolation.

→ Low temperature operation(<650C) is essential.

・Heat power density <6.6W/cm2 for 3 months operation.



Lifetime(30% evaporation) and temperature

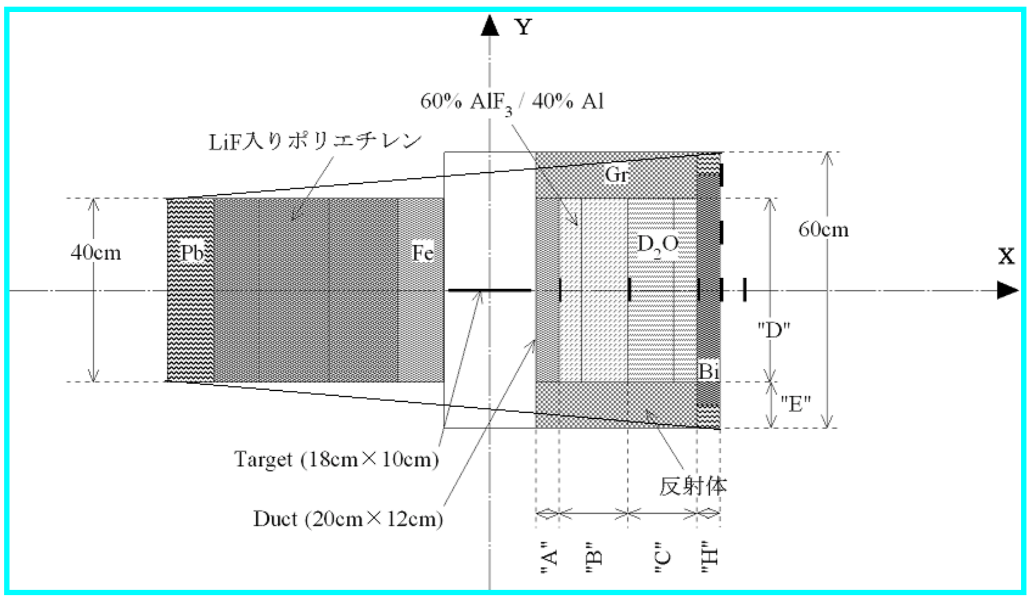


target temperature as a function of input heat power density

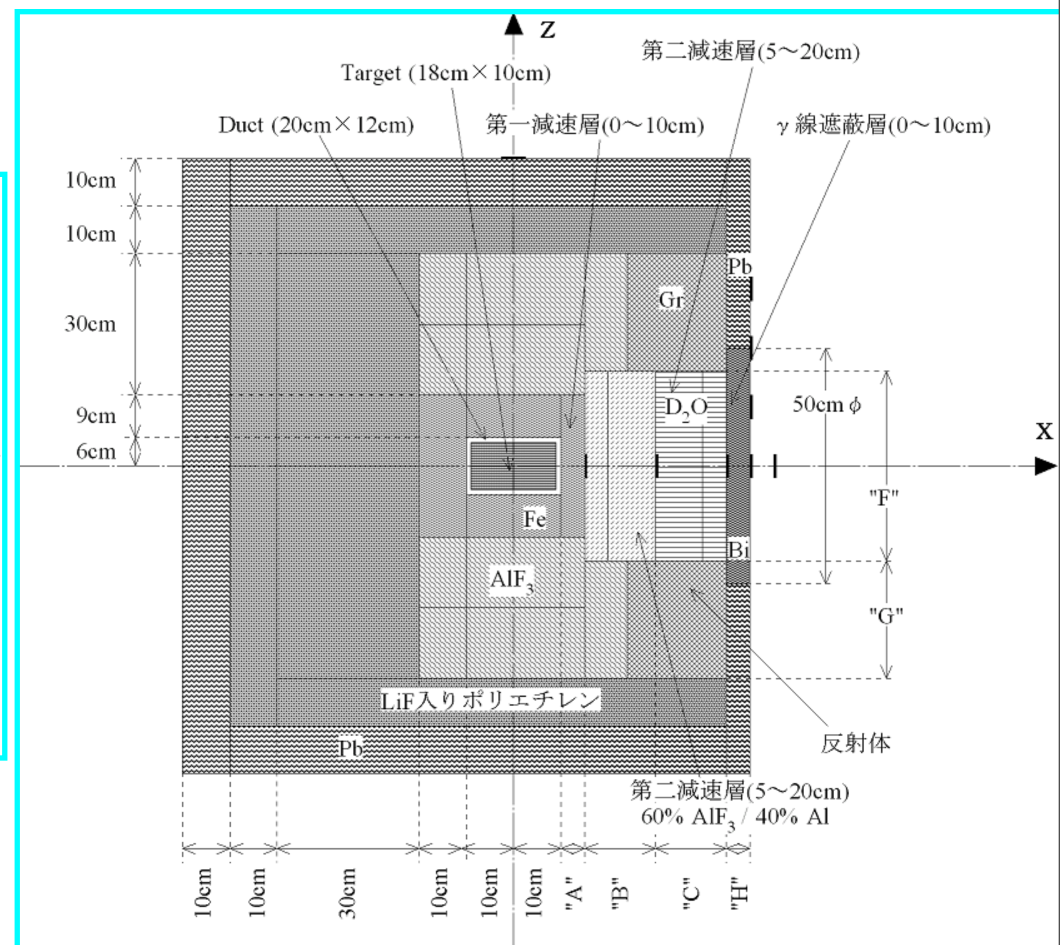
Moderator

basic layout

1st moderator (Fe/AlF3)) : 0〜10cm, 2nd moderator (60%AlF3/40%Al) : 10〜30cm,
3rd moderator (AlF3/D2O) : 10〜20cm, γ-ray shield (Bi) : 5〜10cm

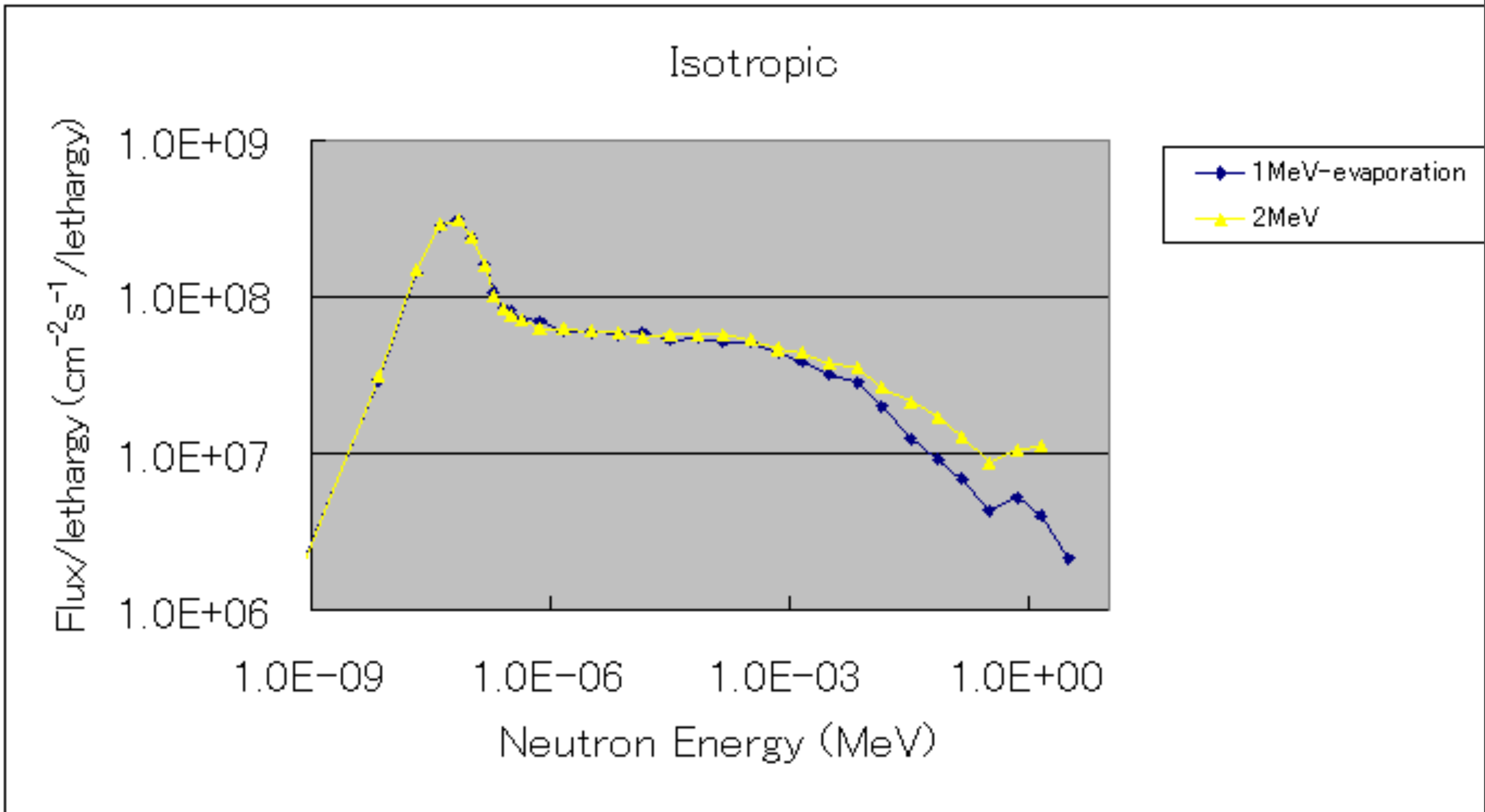


top view



side view

Neutron spectrum : example of simulation (under optimization)

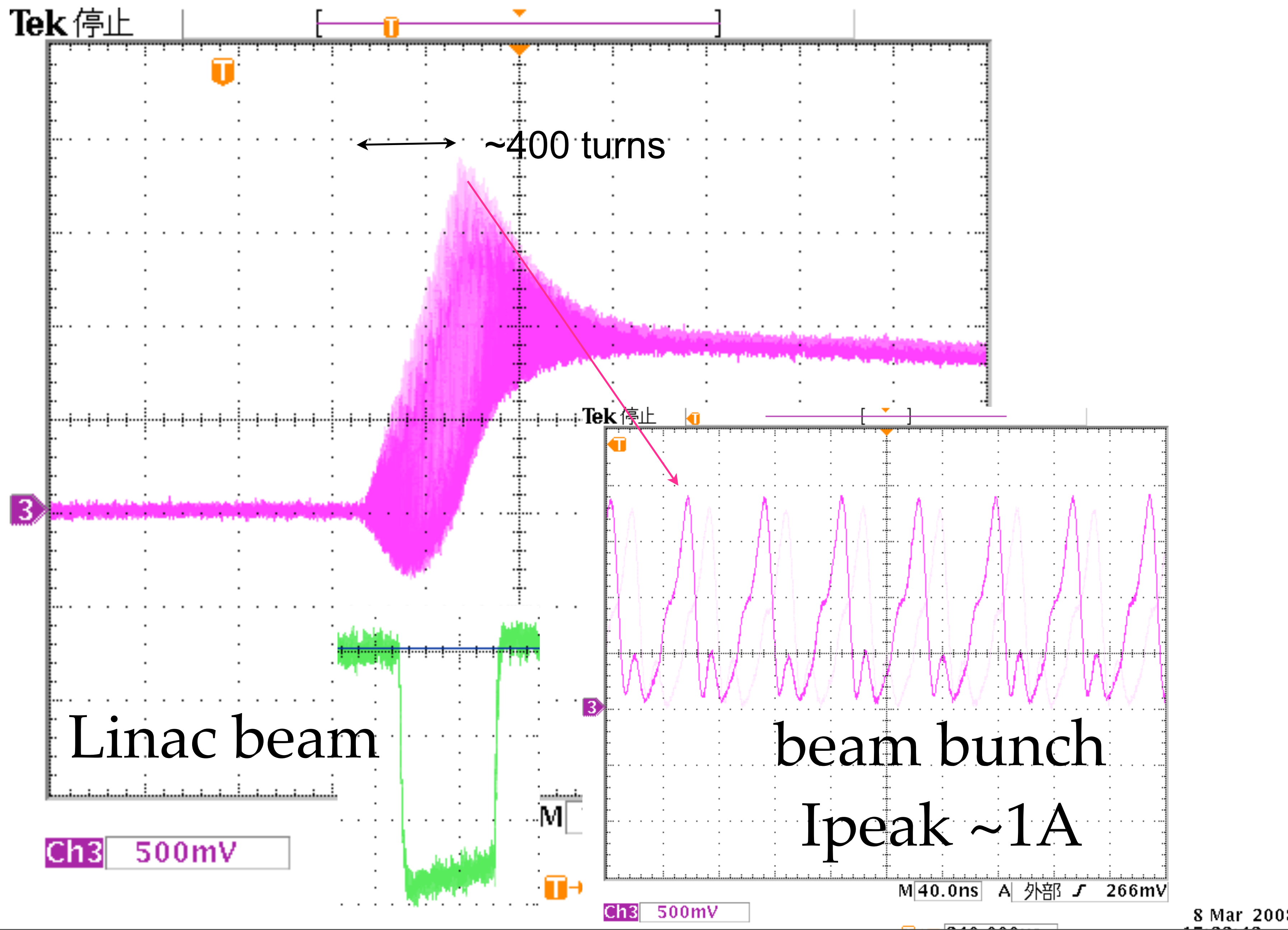


Performance of moderator

- Neutron flux
  - Thermal neutron flux : 7×10^{8} ($cm^{-2}s^{-1}$)
  - Epi–thermal neutron flux : 5×10^{8} ($cm^{-2}s^{-1}$)
  - Total (thermal + epi–thermal) : 1.2×10^{9} ($cm^{-2}s^{-1}$) @ patient
- Contamination of fast neutron
  - 2-2.5 times larger than IAEA standards, however, comparable with those from ordinary nuclear reactors(KUR,JRR4 etc.)
- Contamination of gamma- ray
  - Lower than IAEA standards, however, not includes those from target nucleus.

Beam test

first beam storaging: Mar. 12, 2008



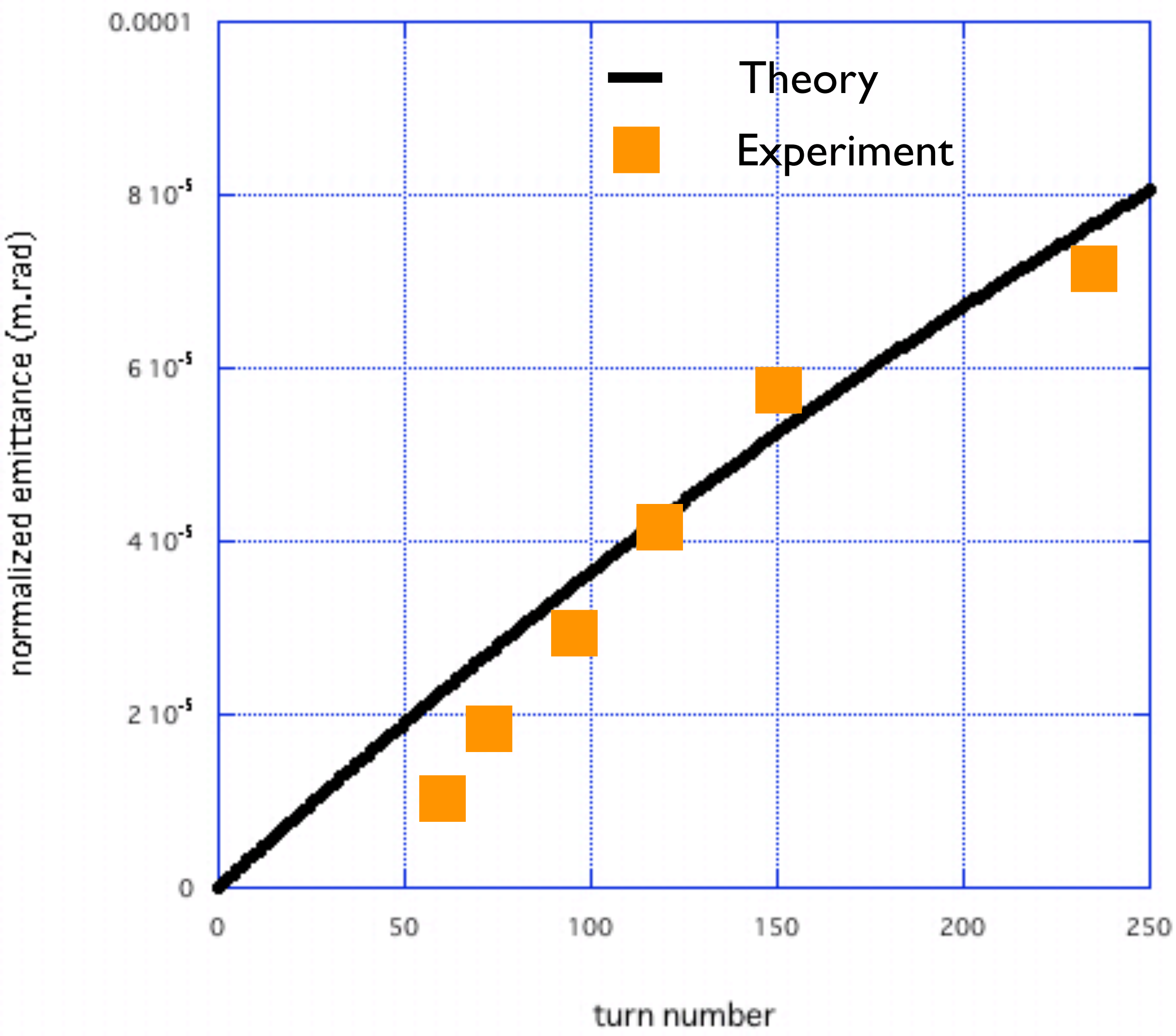
Measurement of emittance growth

- Emittance growth as a function of turn numbers is measured with beam scrapers (hor.&vert.) placed in the ring.

$$\varepsilon_T = \frac{B}{A} + \left(\varepsilon_0 - \frac{B}{A}\right)e^{-As}$$

$$A = -\frac{1}{\beta^2 E}\left\{\frac{dE}{ds}\right\}$$

$$B = \frac{\beta\gamma}{2}\beta_T \frac{(13.6MeV)^2}{(\beta cp)^2 L_s}$$



Summary

- Intense neutron source for BNCT with FFAG-ERIT(emittance/energy recovery internal target) scheme was constructed and works as expected.
  - Storage beam current was 50mA equ. for 200Hz operation.
  - Emittance growth agreed well with ionization cooling model.
  - Neutron yield measured with He^3 detector was ~$5x10^8$ n/cm^2/sec equ. for 200Hz operation at the moderator exit.
- Future
  - Target lifetime test for full beam duty operation.
  - Neutron spectrum measurement