

Development of FFAG Accelerators at KURRI

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FFAG Accelerators at KURRI

- Proton FFAG Complex for ADS study:KART Project
 - Variable energy proton FFAG
 - Rapid acceleration :120Hz
- Compact & Intense Neutron Source
 - Emittance Recovery Internal Target (ERIT) with ionization cooling
 - FFAG cooler ring with large acceptance

KART Project

(Kumatori Accelerator driven Reactor Test)

Purpose: Feasibility study of ADS

- k_{eff} for $E_p = 20 \sim 150 \text{ MeV}$
- FFAG accelerator as proton driver for ADS

Feasibility Study on ADSR Using FFAG Accelerator

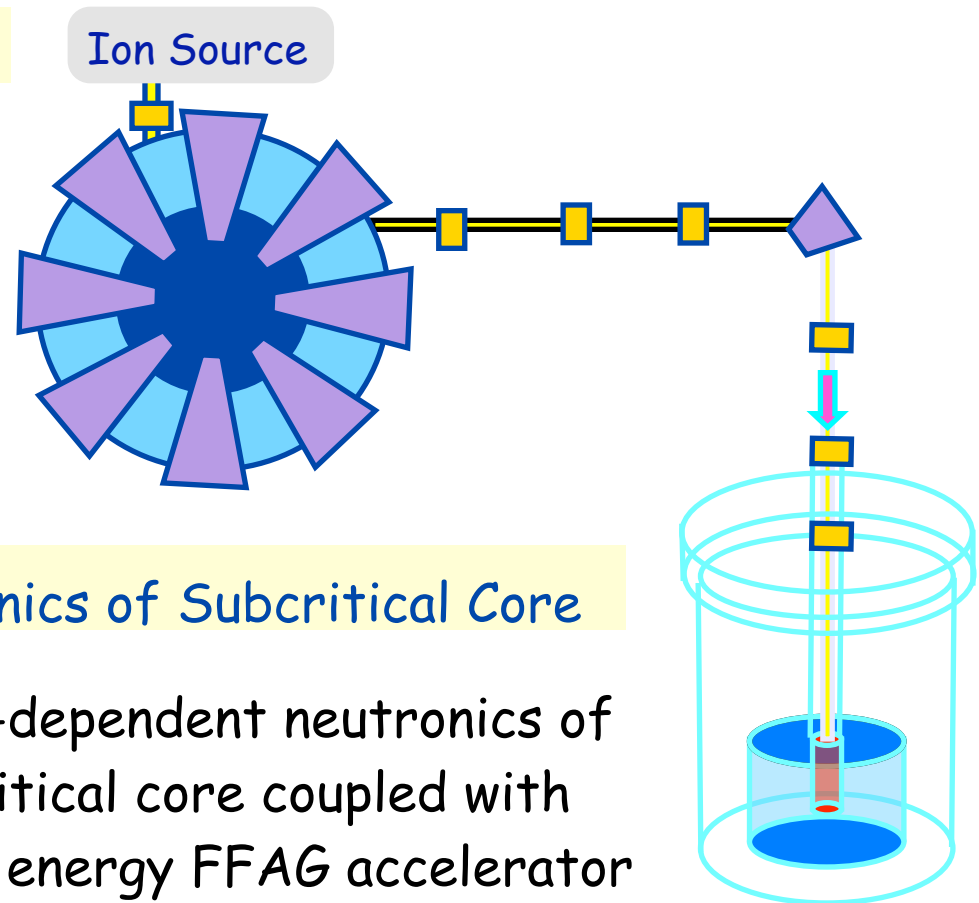
Five-year project (US\$~10M in total)

supported by

MEXT Technology Development Project for Innovative Nuclear Energy System

Accelerator Development

Development of variable energy FFAG accelerator with high acceleration efficiency



Neutronics of Subcritical Core

Energy-dependent neutronics of subcritical core coupled with variable energy FFAG accelerator

Research Reactor Institute Kyoto University

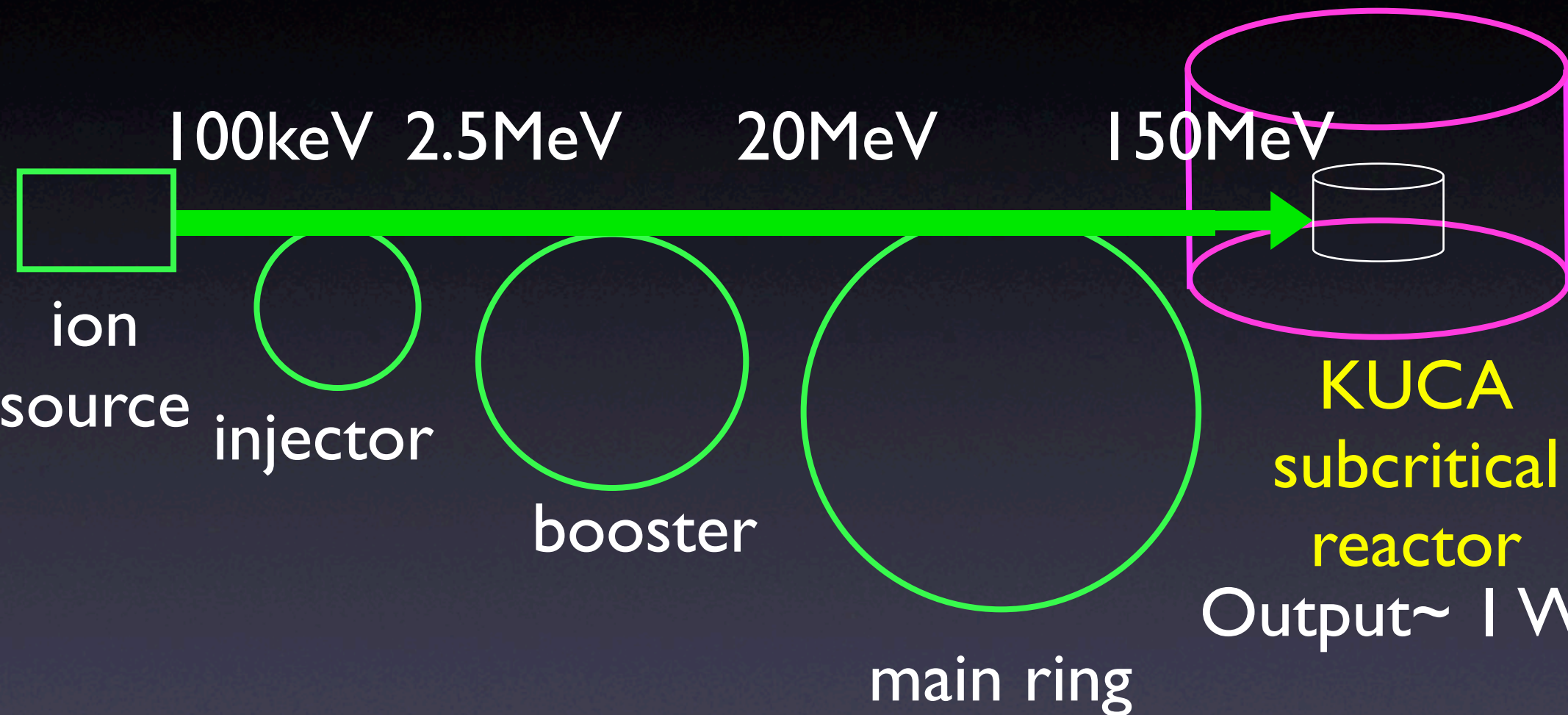
KUR - 8MW Nuclear Reactor

KUCA - Critical Assembly

KART & LAB - FFAG Accelerator



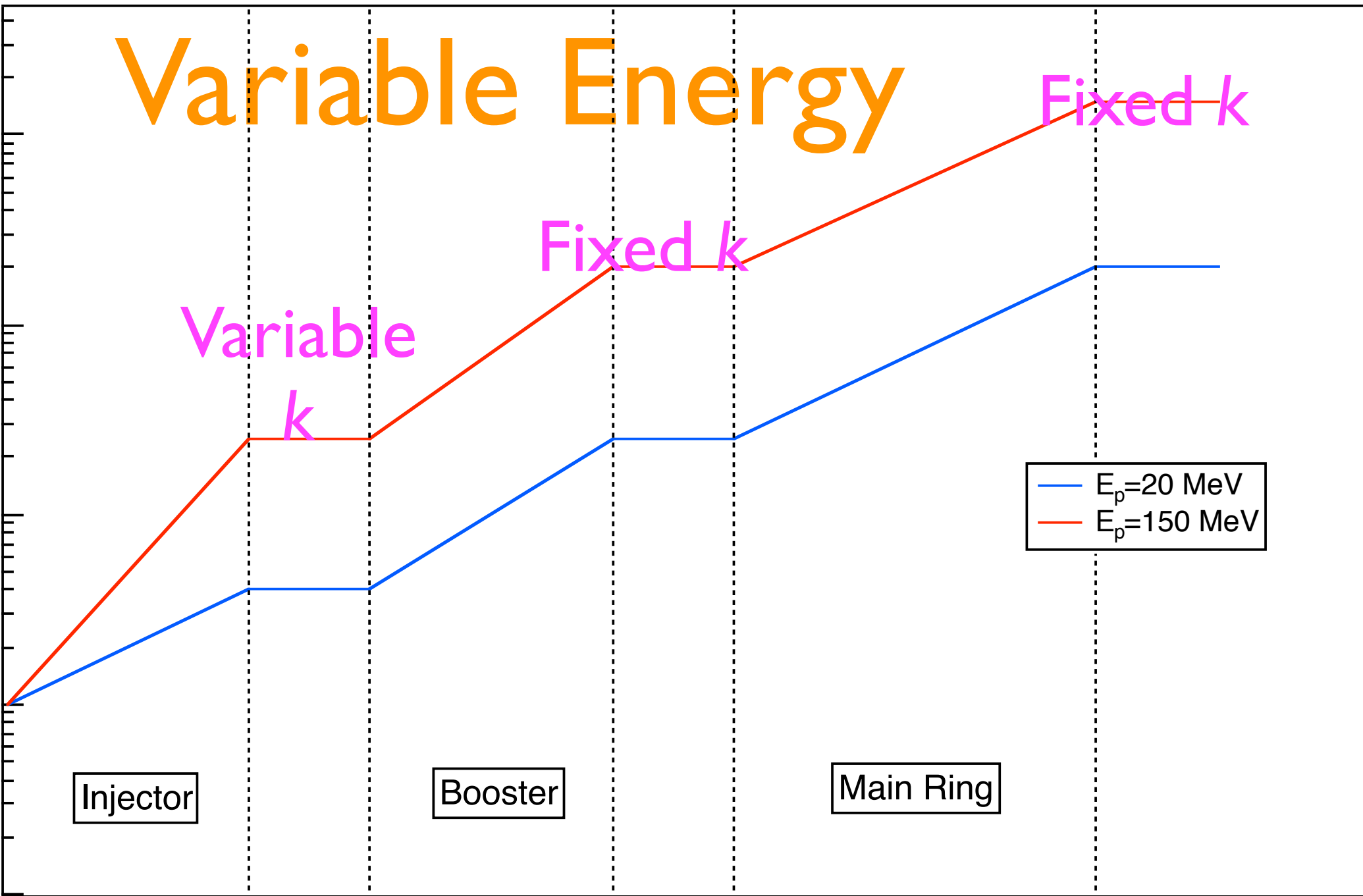
FFAG Complex for KART



Parameters for FFAG complex

| | Injector | Booster | Main |
|-------------------|-----------|------------|------------|
| E_{inj} | 100 keV | 2.5 MeV | 20 MeV |
| E_{ext} | 2.5 MeV | 20 MeV | 150 MeV |
| Lattice type | Spiral | Radial DFD | Radial DFD |
| # of cells | 8 | 8 | 12 |
| Acc. scheme | Induction | RF | RF |
| k | 2 | 2.45 | 7.5 |
| coil/pole | coil | pole | pole |
| p_{inj}/p_{ext} | 5.00 | 2.84 | 2.83 |
| r_{inj} | 0.60 m | 1.17 m | 4.54 m |
| r_{ext} | 0.99 m | 1.65 m | 5.12 m |

Variable Energy



Injector

Booster

Main Ring

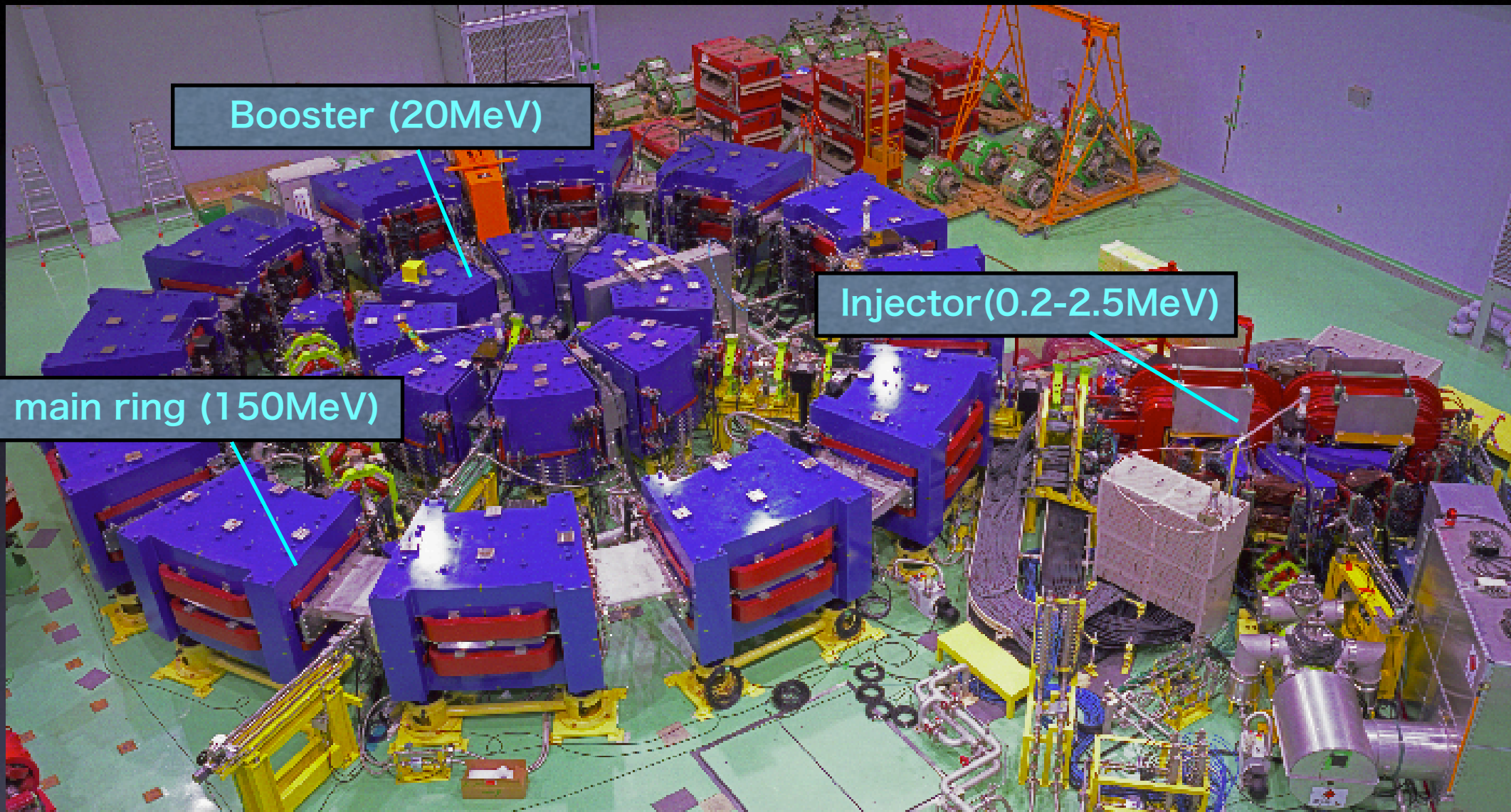
$E_p = 20$ MeV
 $E_p = 150$ MeV

Time (arbitrary unit)

Spiral Sector Magnet



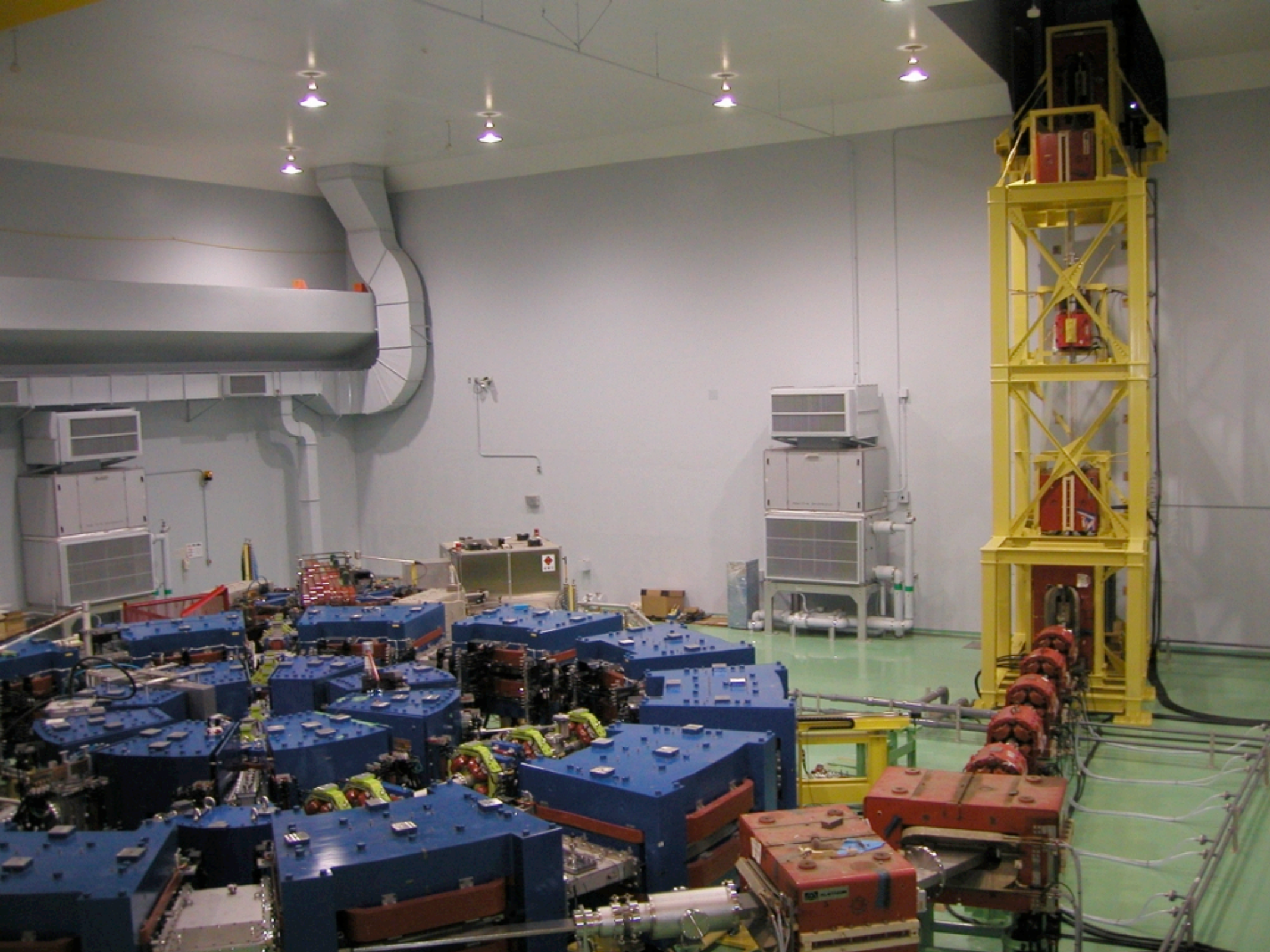
FFAG complex at KURRI



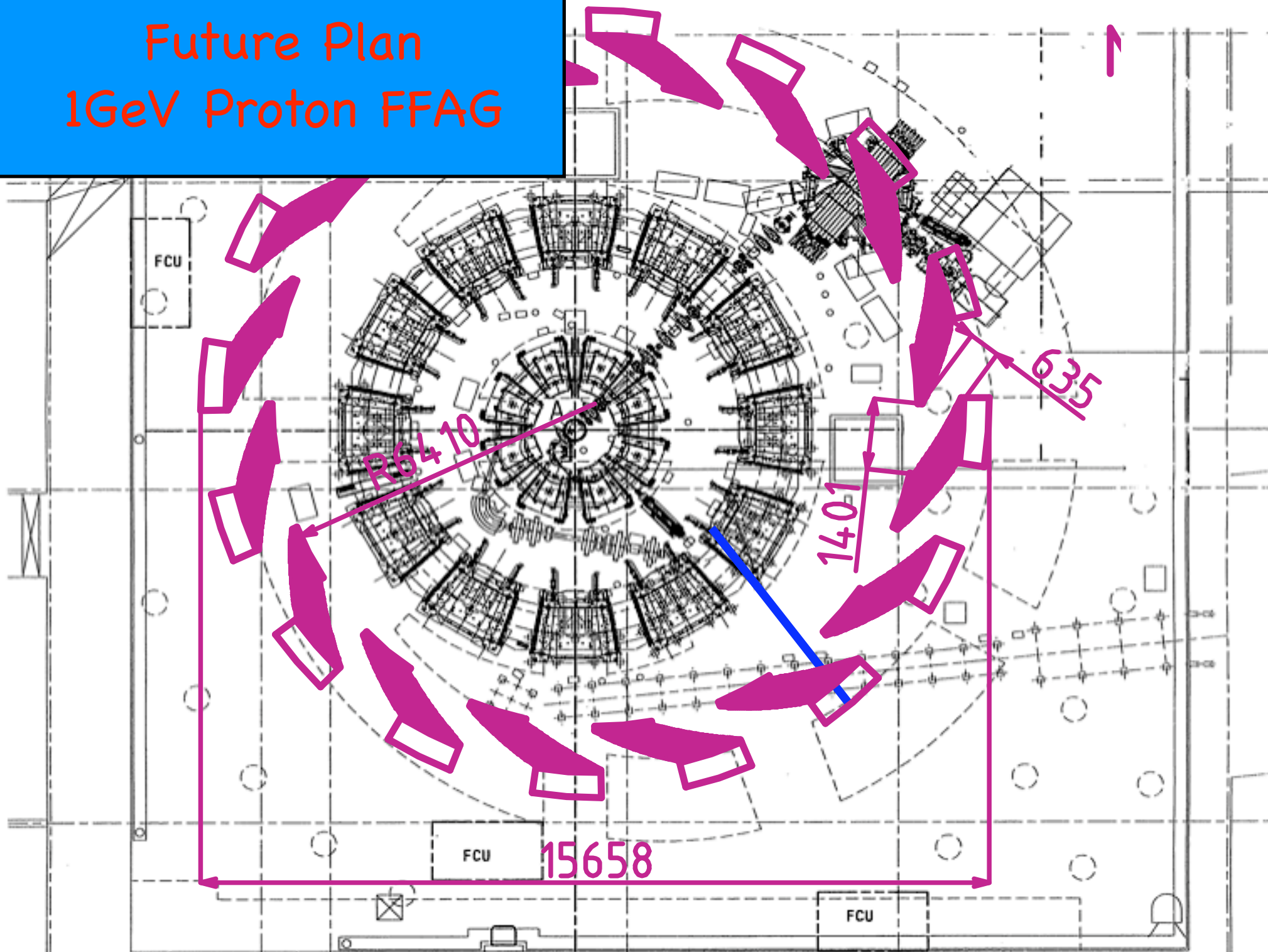
Booster (20MeV)

Injector (0.2-2.5MeV)

main ring (150MeV)



Future Plan 1GeV Proton FFAG

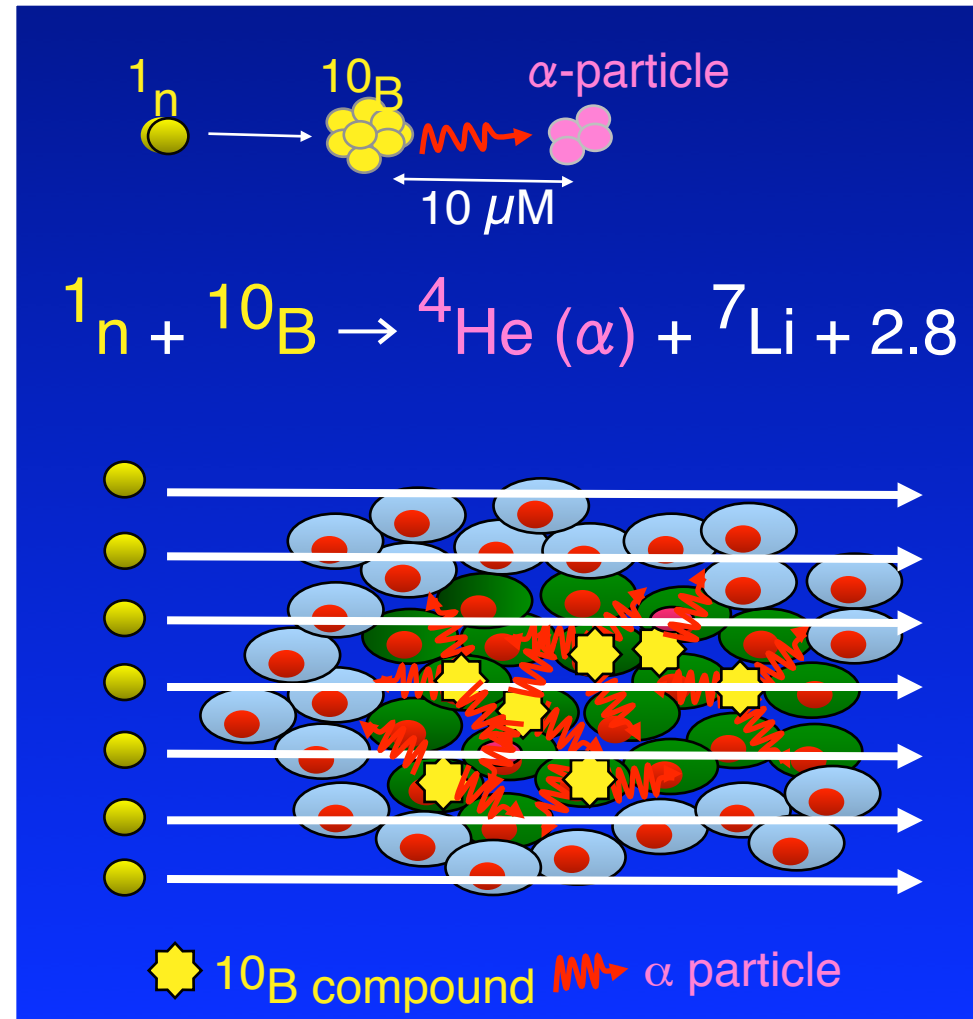


Neutron Source for BNCT

- **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

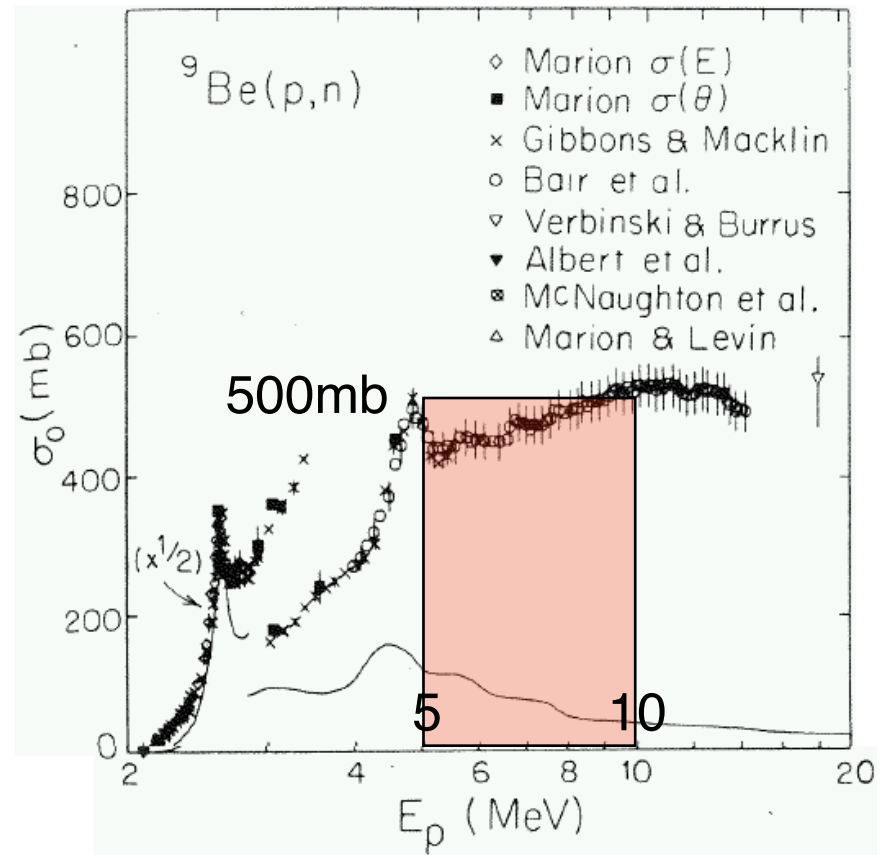
In order to obtain

$$\phi > 10^9 \text{ n/cm}^2/\text{s}$$

Neutron production

- Reaction ${}^9\text{Be}(p,n)\text{B}$, ${}^7\text{Li}(p,n)\text{He}$
- energy $\sim 10\text{MeV}$
- target thickness $\sim 10\text{micron}$
- Neutron yield $\sim 1/10000 \text{ n/p}$

Proton beam current
 $\sim 40\text{mA}$



Accelerator based neutron source : Difficulties

Accelerator

-  energy is low, but required beam current is very large
 $I > 10\text{mA}$ (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

Neutron Source with FFAG-ERIT

Emittance-energy Recovery Internal Target (ref. Nucl. Instr. Meth.)

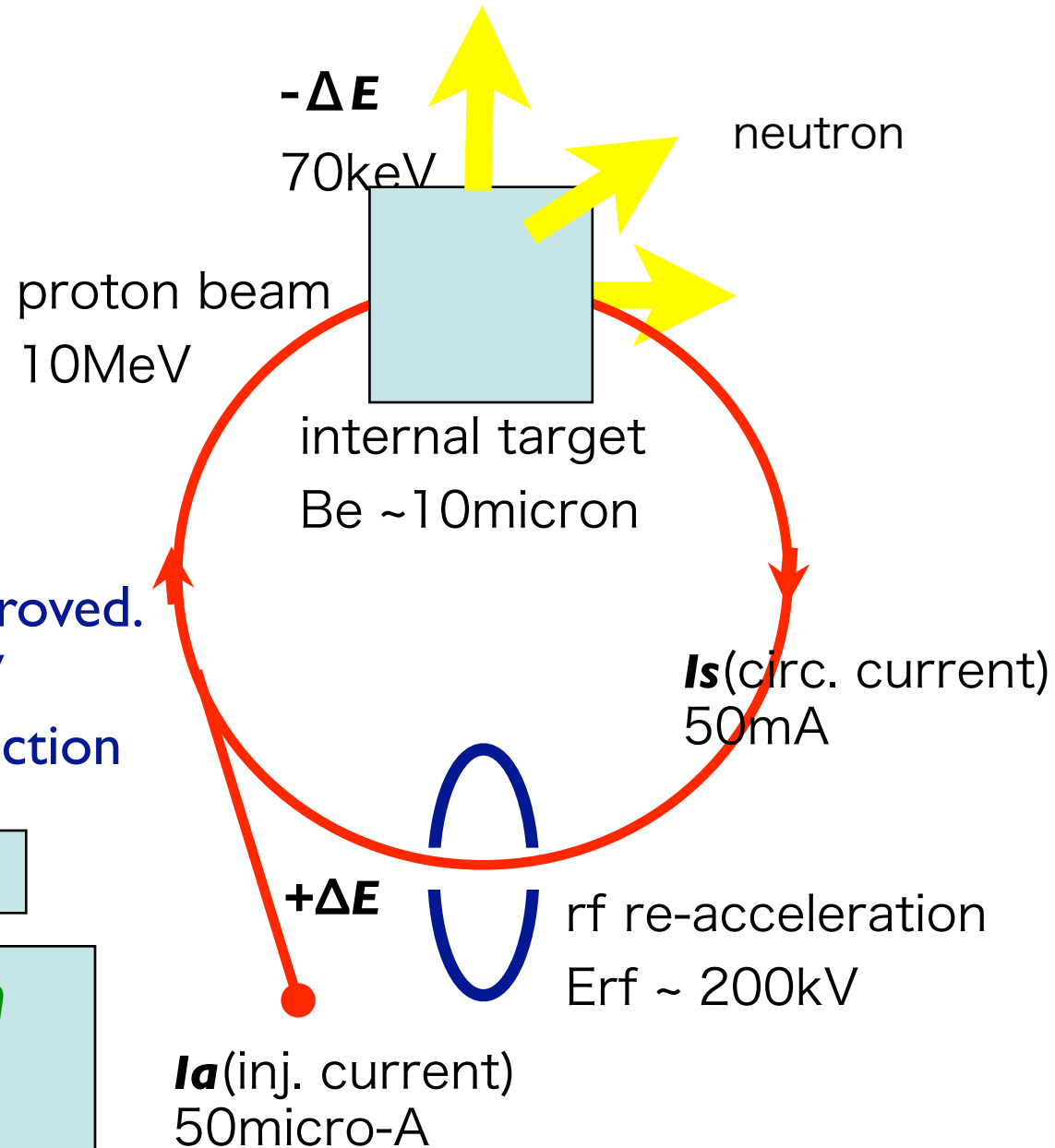
FFAG-ERIT scheme

- internal target
- energy loss
recovered by rf
- emittance growth
ionization cooling
- large acceptance
FFAG(scaling)
- target
heat loss 1-2kW

Project was approved.
2005-2007
Under Construction

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

Need large momentum acceptance! -> FFAG



BNCT with FFAG-ERIT

Injector(RFQ + IHDTL)

Full energy injection

H⁻ kinetic energy 10 [MeV]

Average beam current ~ 45 [mA]

Repetition >1 [kHz]

FFAG ring

H⁻ injection

proton kinetic energy 10 [MeV]

Average beam current ~ 45 [mA]

ERIT system

Turn number > 1000 turn

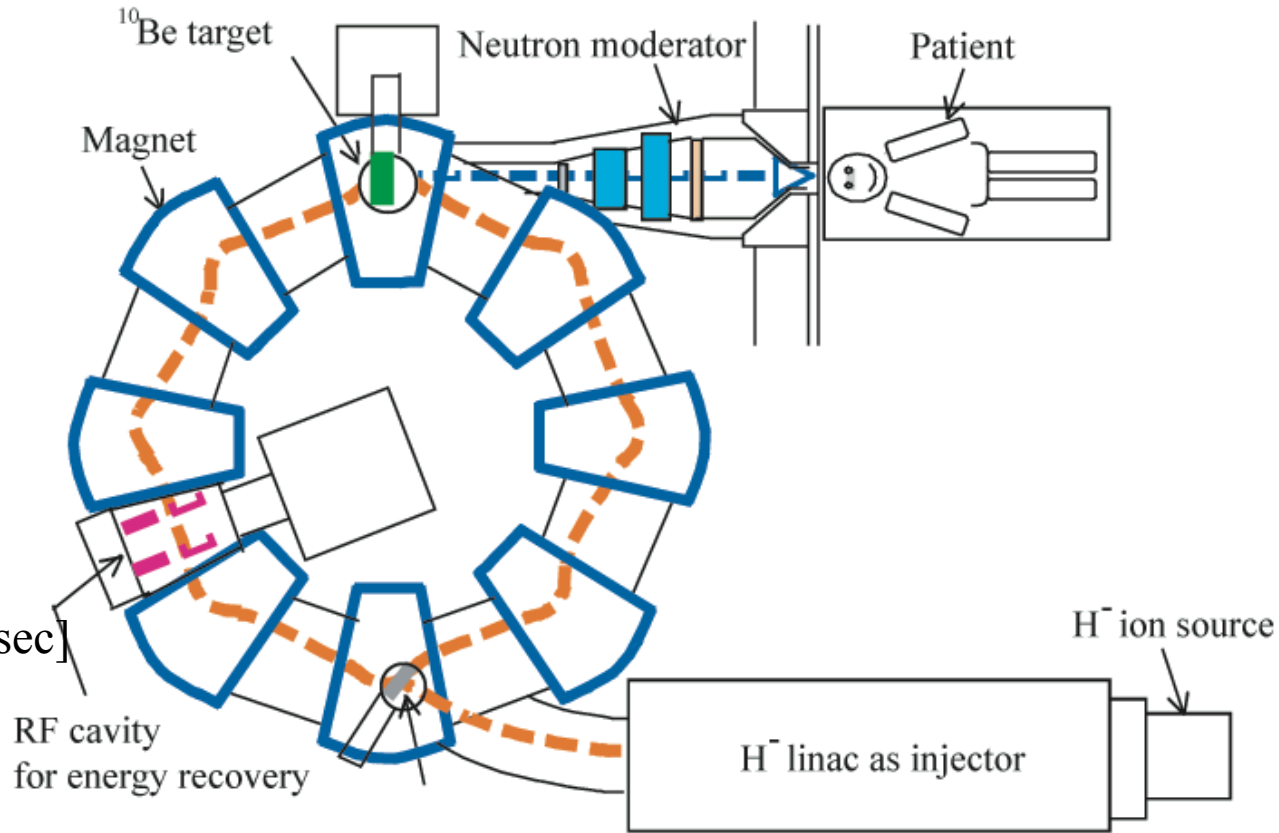
Internal target thickness ~ 5 [mm]

Neutron beam intensity > 10⁹ [n/cm²/sec]

RF cavity

RF voltage > 200 [kV]

Harmonic num. ~ 5



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

$$A = 2 \frac{\partial \left(\frac{dE}{ds} \right)}{\partial E}$$

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

straggling

cf. proton beam 10MeV
Be target

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

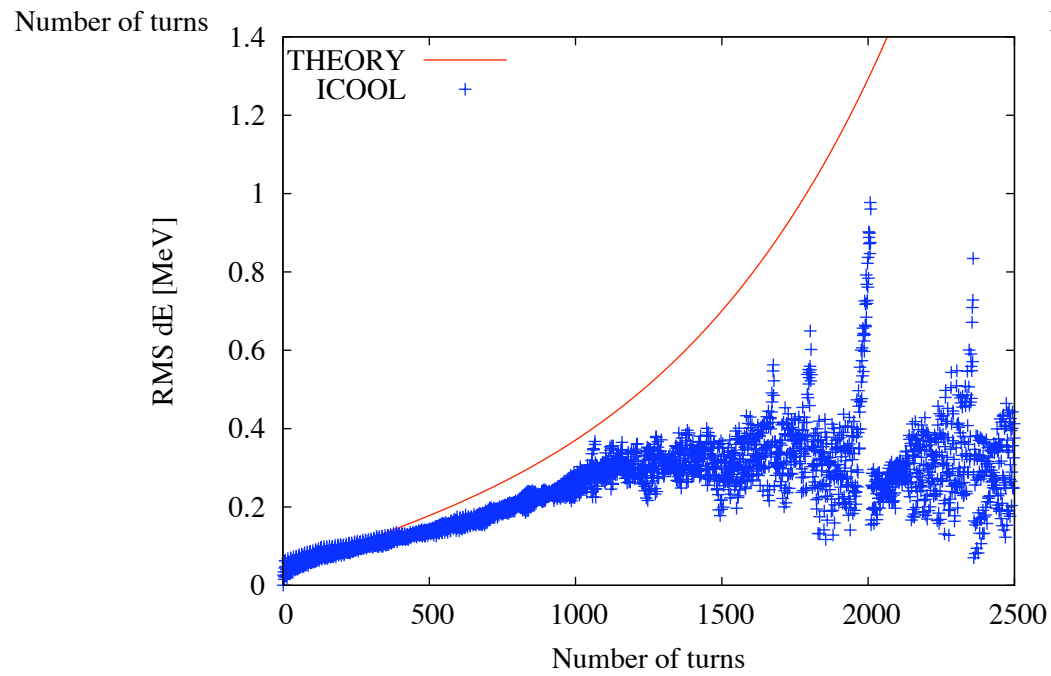
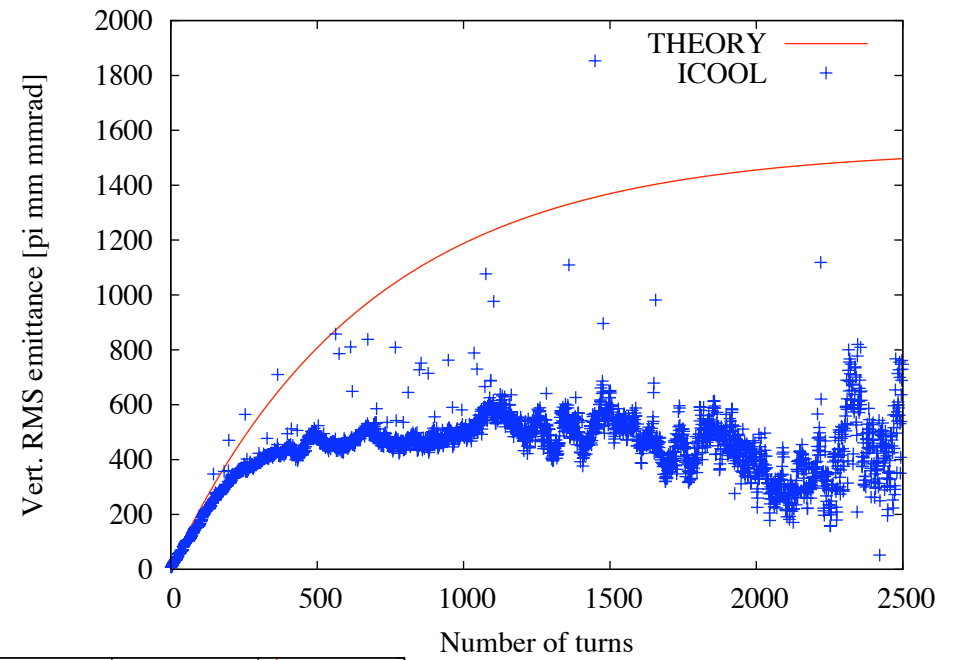
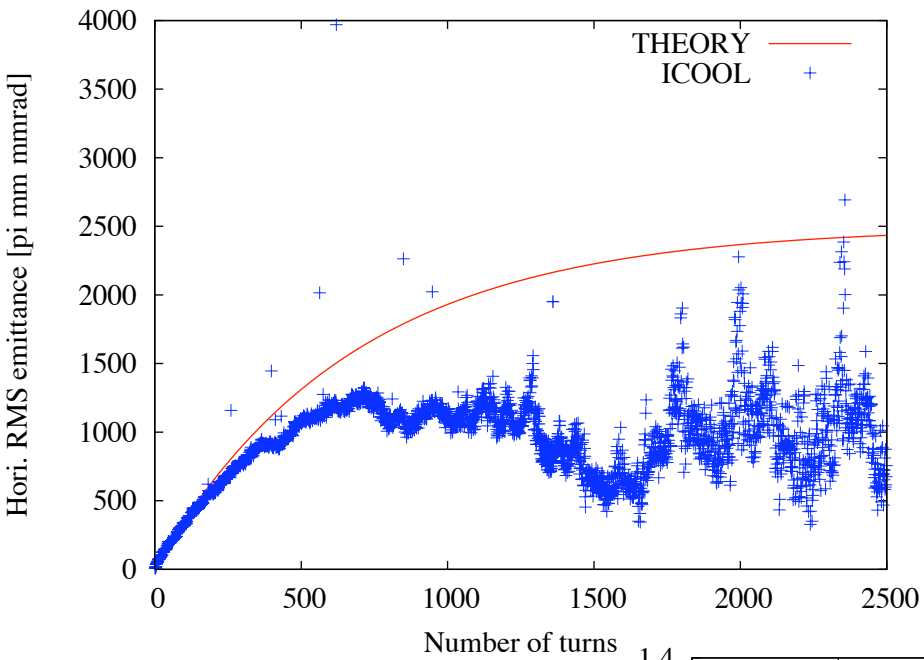
Transverse → Cooling

Longitudinal → Heating

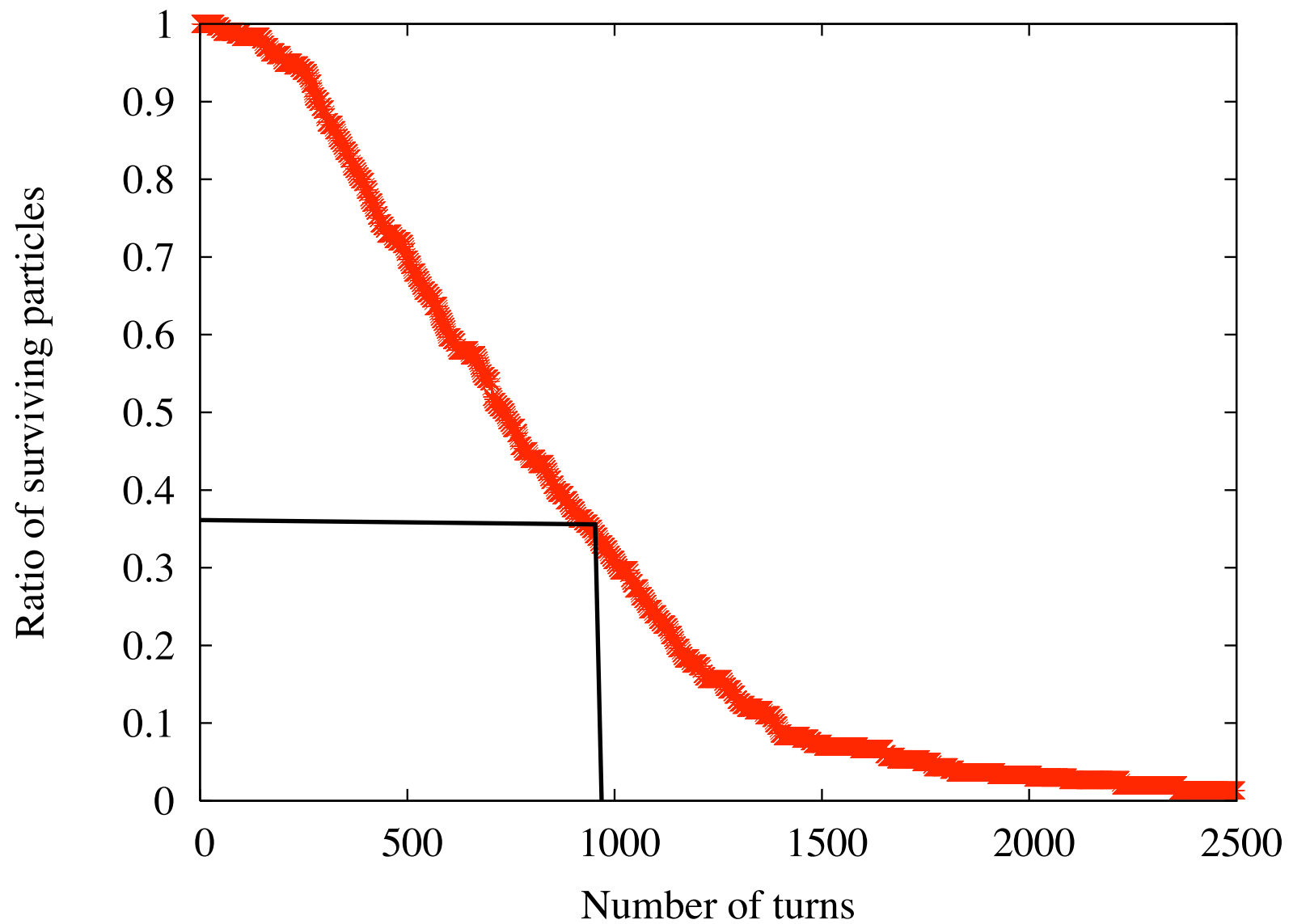
分配関数の和 > 0

$$\sum_1^3 g_i > 0$$

Emittance

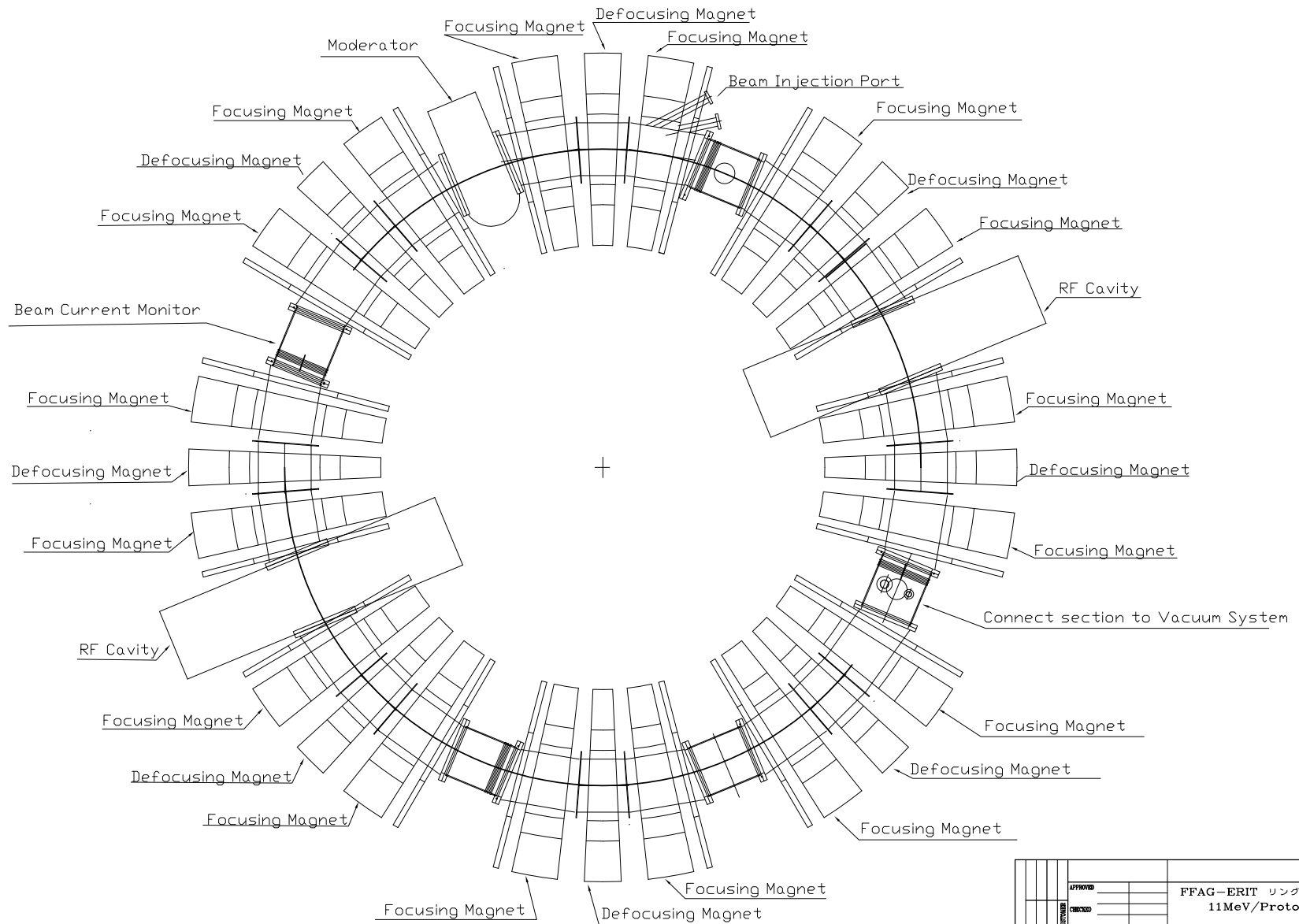


Survival



FFAG-ERIT neutron source

| | | |
|------------------------|-------------------|-------------|
| THIRD ANGLE PROJECTION | ASSEMBLY DRAWING | PLAN RECORD |
| | REFERENCE DRAWING | DRAWING No. |



DRAWING No.

| | | | |
|-------------------|------------|------------------|-------------|
| APPROVED | | FFAG-ERIT リング平面図 | |
| CHECKED | | 11MeV/Proton | |
| DRAWN | S.Mizutani | SPECIFIED No. | DRAWING No. |
| SCALE | 1/50 | | |
| DATE | | | |
| DESIGNED | | | |
| APPROVED CUSTOMER | | | |
| DATE | | | |
| DESIGNED | | | |

| | |
|---|--|
| 1 | |
| 2 | |
| 3 | |
| 4 | |
| 5 | |
| 6 | |

RF cavity for ERIT -cold model

f=25MHz

共振周波数の測定
2006/3/14

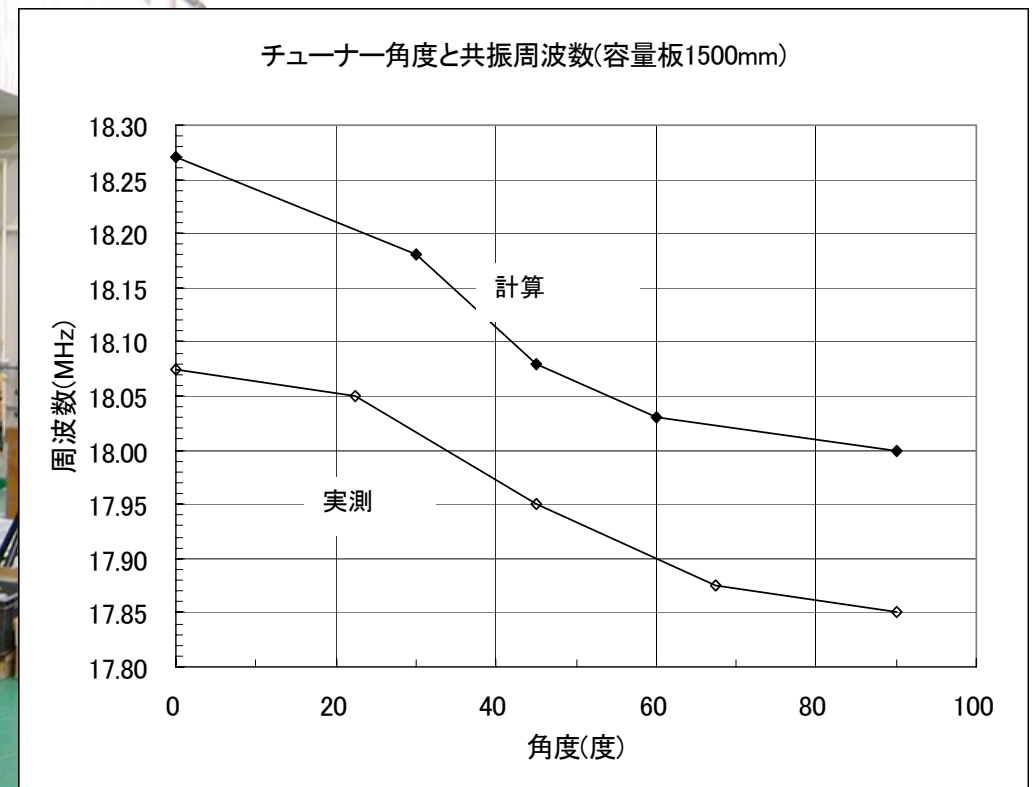
| 角度 度 | 共振周波数 MHz |
|---------|--------------|
| 0.0 | 18.075 |
| 22.5 | 18.050 |
| 45.0 | 17.950 |
| 67.5 | 17.875 |
| 90.0 | 17.850 |
| 周波数幅 | 0.225 |

容量板 $\phi 1500$ を取り付けけた状態

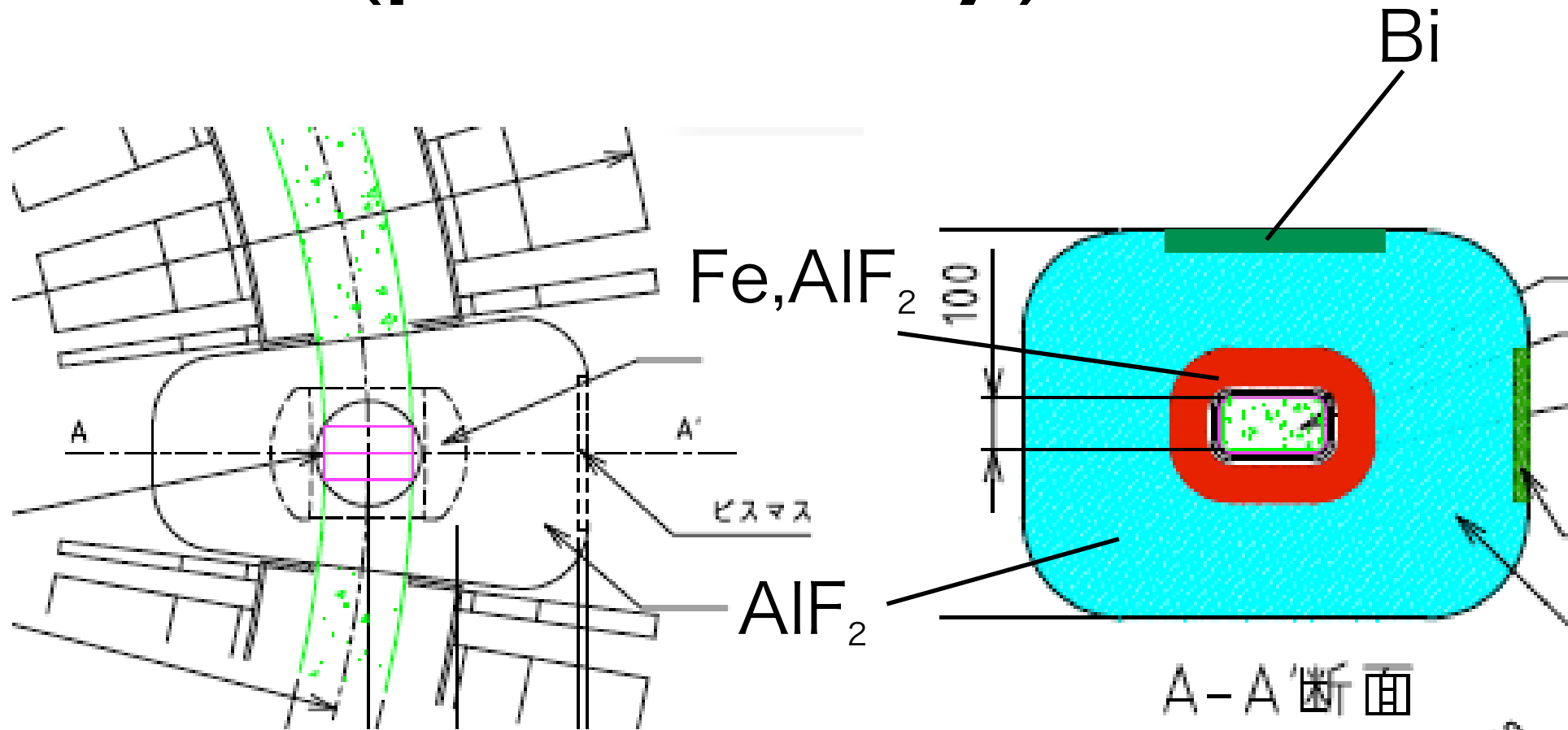
測定方法

①端板のN型コネクタに $\phi 1.7\text{mm}$ で径150mm程度のループを密結合で挿入

②ネットワークアナライザでチューナー各位置での共振周波数を測定 (アンテナのインピーダンス補正は無し)



Moderator Layout (preliminary)



Summary

- **Development of FFAG Accelerator Complex at KURRI is in a final stage**
 - Injector : completed
 - Booster : completed
 - Main Ring : under commissioning
 - Beam Line to KUCA : almost completed
- **Compact & Intense Neutron Source**
 - FFAG-ERIT : under construction -Aug. 2007