PRESENT STATUS AND FUTURE OF FFAGS AT KURRI AND THE FIRST ADSR EXPERIMENT

Y.Ishi, M.Inoue, Y.Kuriyama, Y.Mori, T.Uesugi, Kyoto University
Research Reactor Institue, Osaka, Japan
JB.Lagrange, T.Planche, M.Takashima,E.Yamakawa,Graduate School of
Engineering, Kyoto University, Kyoto, Japan
H.Imazu,K.Okabe, I.Sakai, Y.Takahoko,
Fukui University, Fukui, Japan

Contents

- Feature of ADSR
- ADSR studies in KURRI
- Design and Performance of FFAG Complex
- ADSR Experiments in KURRI
- Future plans of FFAG Complex
- Summary

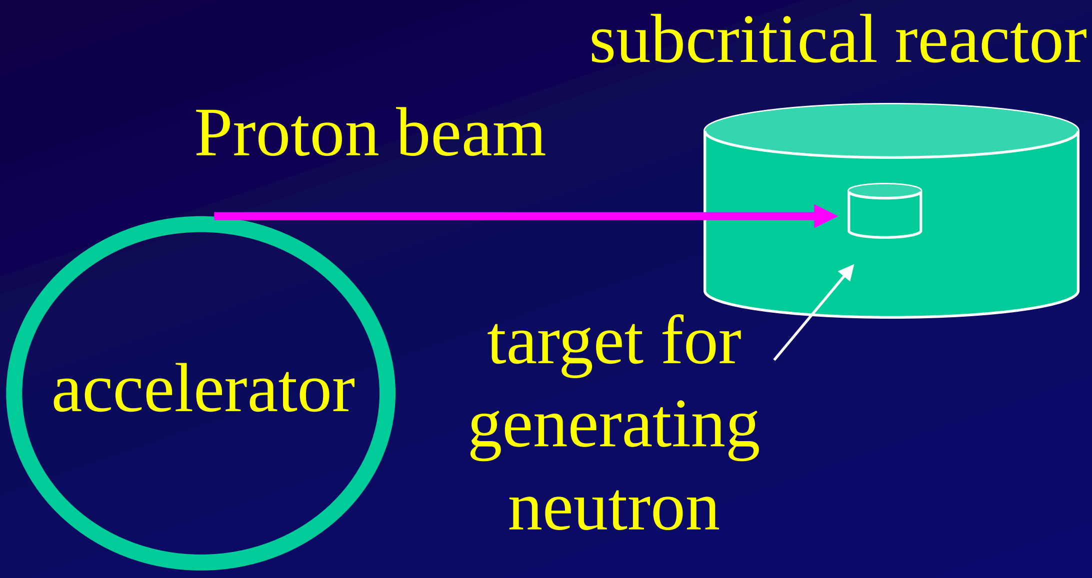
Contents

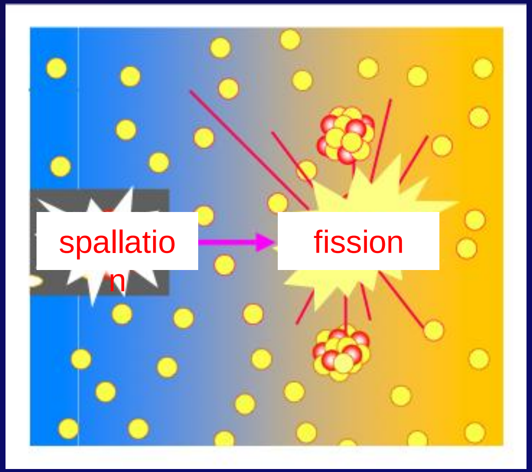
- Feature of ADSR
- ADSR studies in KURRI
- Design and Performance of FFAG Complex
- ADSR Experiments in KURRI
- Future plans of FFAG Complex
- Summary

What is ADSR?

Accelerator Driven Subcritical Reactor

ADSR is a system which keeps nuclear fission chain reaction induced by a large amount of spallation neutron obtained by irradiation of a heavy metal target using high energy proton beams generated by accelerators. In this system the nuclear reactor plays a role of neutron booster which amplifies the neutron flux from the target.





Beam off → chain reaction stops

Safer system !

Feature of ADSR

The output of the nuclear reactor can be controlled by changing the beam power from the accelerator.
Output from the sub-critical reactor is expressed as

$$P \sim \frac{S}{1 - k_{eff}}$$

S : neutron intensity controlled by energy and/or intensity of the beam from the accelerators dynamically

k_{eff} : effective multiplication factor of subcritical fuel system controlled by rods

	beam current	high energy	variable energy
Synch	× space charge	○	○
Cycl	○	△	△
FFAG	○ high rep.	○ large $k \longrightarrow$ compact	○ trim coils

Fixed Field Alternating Gradient (FFAG) synchrotron which realizes high beam current and high beam energy (variable) simultaneously has been adopted as the accelerator which drives ADSR.

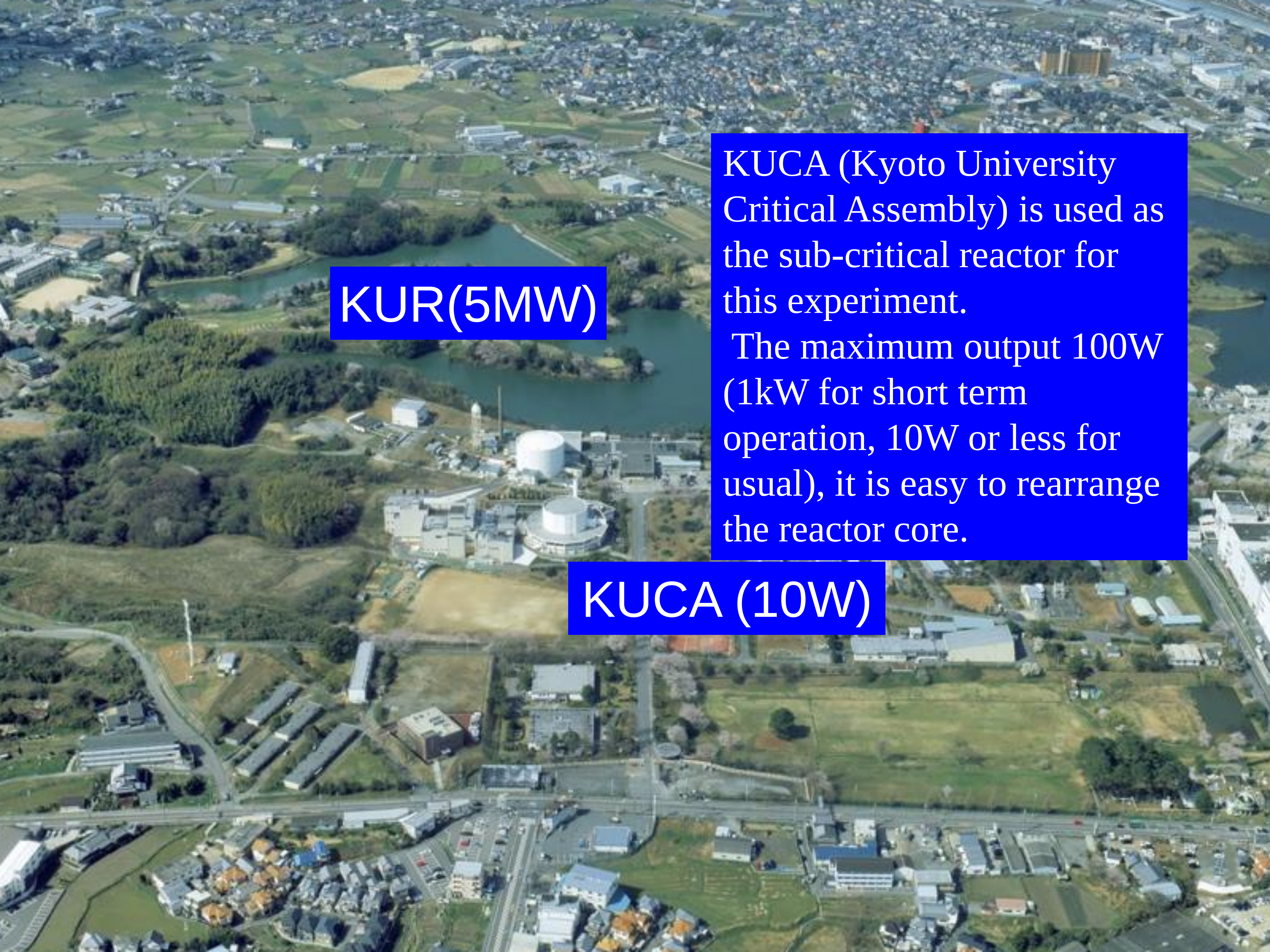
Contents

- Feature of ADSR
- ADSR studies in KURRI
- Design and Performance of FFAG Complex
- ADSR Experiments in KURRI
- Future plans of FFAG Complex
- Summary

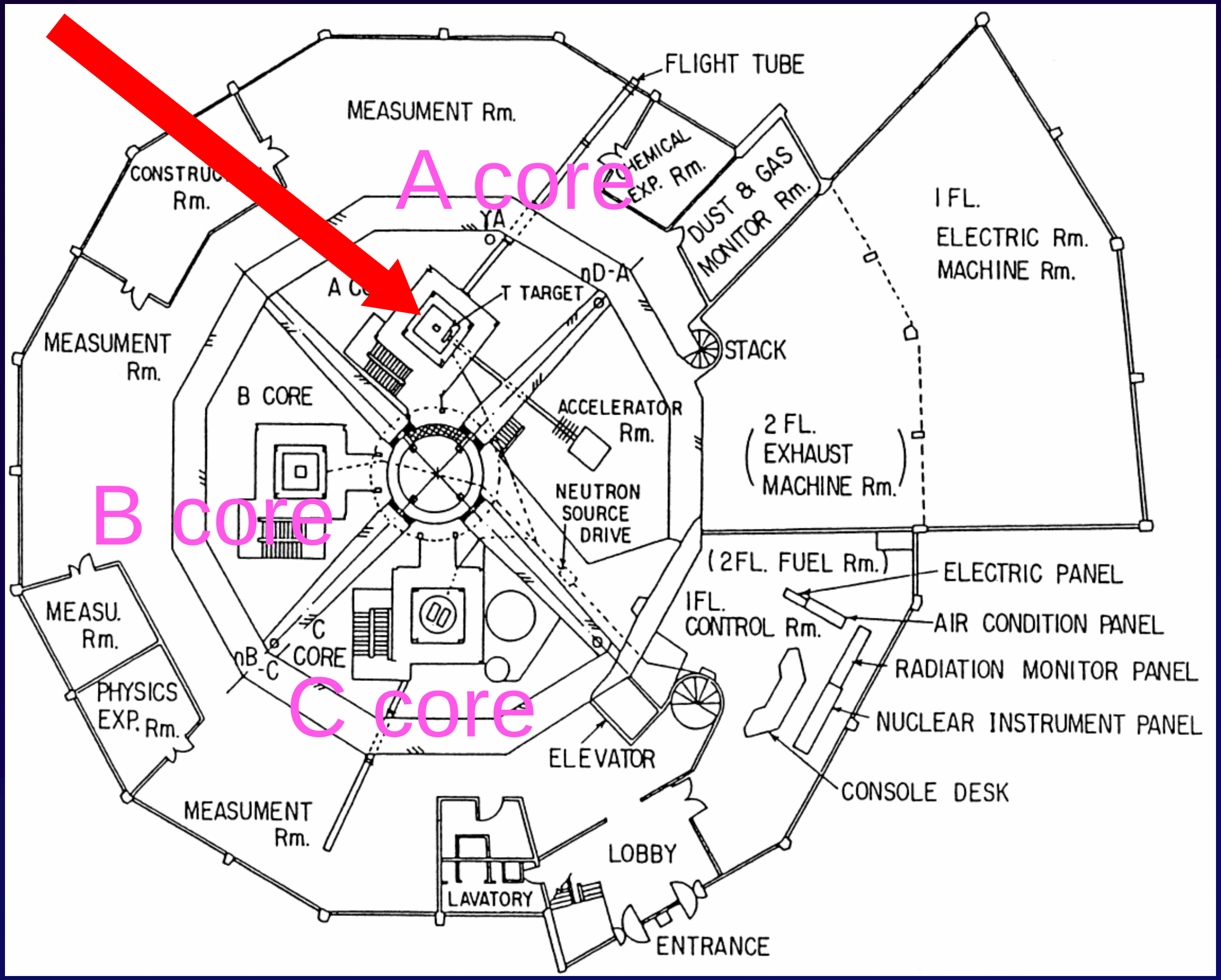
ADSR Studies in KURRI

Purpose

- The main purpose of this R&D is a basic feasibility evaluation of ADSR as an energy production device.
- It is also required to compare the nuclear design calculations with the experimental data concerning sub-critical reactor characteristics mainly on the neutron multiplication which depends on the energy of the neutrons.


KUR(5MW)
KUCA (10W)
KUCA (Kyoto University Critical Assembly) is used as the sub-critical reactor for this experiment.
The maximum output 100W (1kW for short term operation, 10W or less for usual), it is easy to rearrange the reactor core.

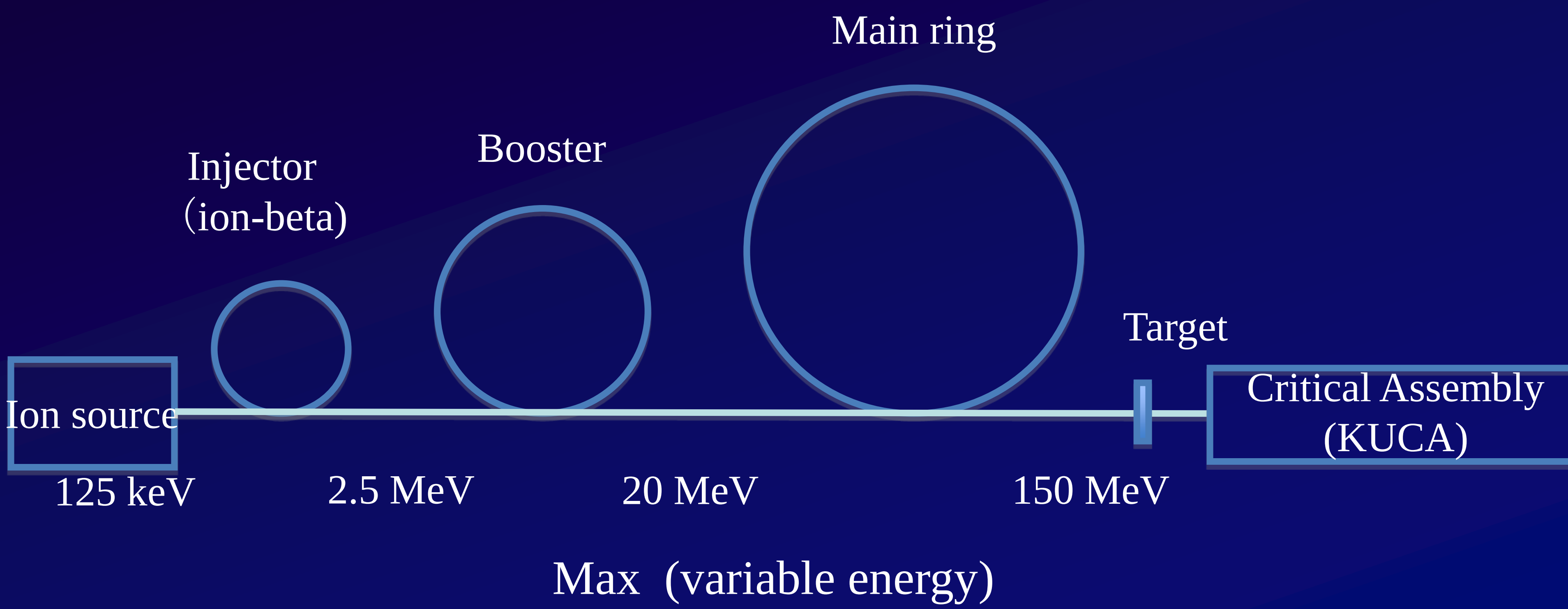
KUCA



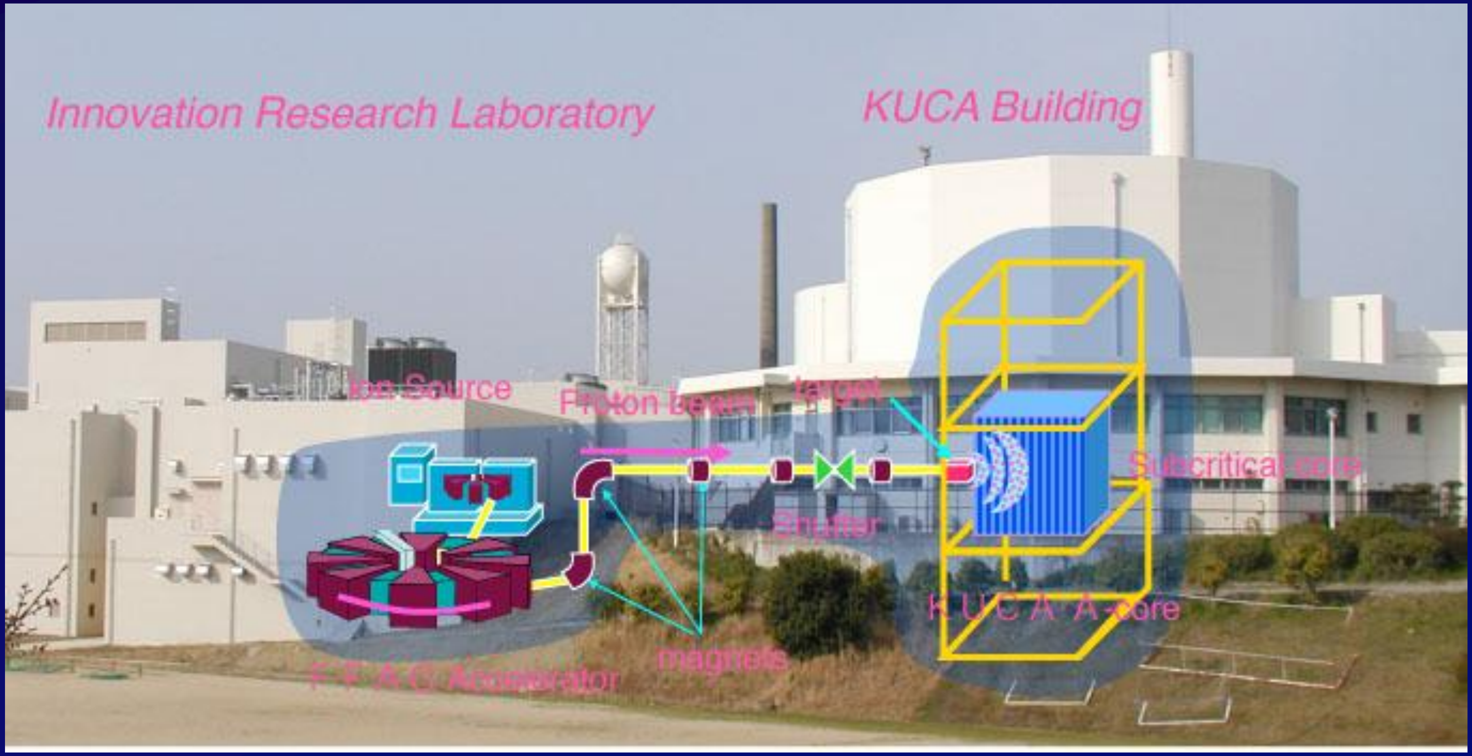
Output power ~10W
Neutron multiplication : $\alpha=1/(1\text{-keff})$.
If keff=0.99, $\alpha=100$
Beam power requirement not exceed < 0.1W!!
cf. For 100MeV proton beam, I<1nA

- **KUCA Configurations**
  - 3 critical assemblies :
    - i. A & B cores
      Polyethylene Mod./Ref.
    - ii. C core
      H_2O Mod./Ref.
  - 2 accelerator :
    - i. Cockcroft-walton type
      (D,T) reaction
      14 MeV neutrons
    - ii. FFAG type
      100 MeV protons
      from KUCA Outside

FFAG – KUCA ADSR system schematic diagram



The KURRI-FFAG accelerator complex has been constructed in the innovation research lab. ; connected to KUCA to deliver the high energy proton beam.



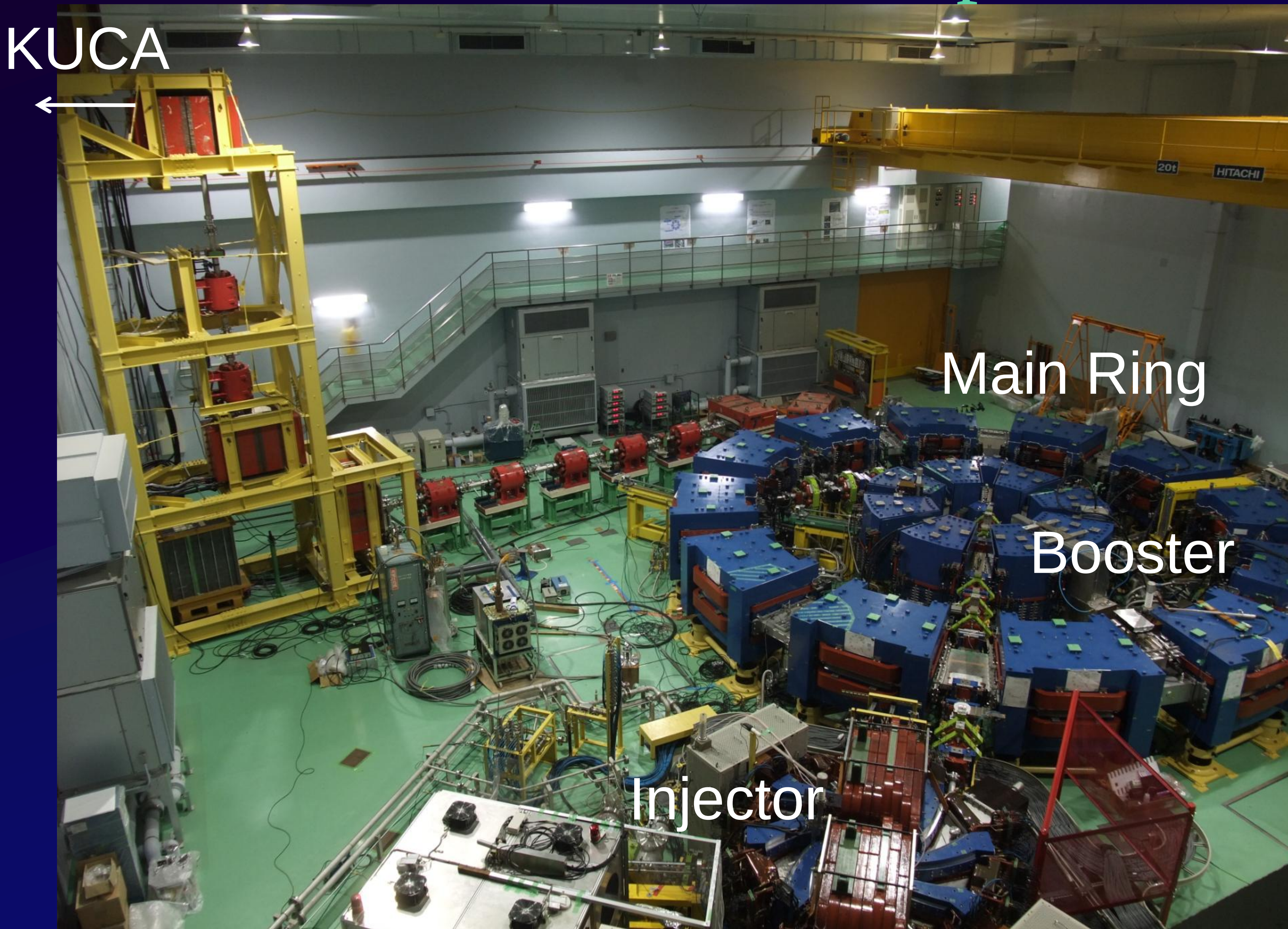
Basic parameters for ADSR experiments at KURRI

Reactor output power	~10W
Neutron multiplication	<100(max.)
Beam power of FFAG	<0.1W
Beam energy of FFAG	100-150MeV
Beam current of FFAG	<1nA

Contents

- Feature of ADSR
- ADSR studies in KURRI
- Design and Performance of FFAG Complex
- ADSR Experiments in KURRI
- Future plans of FFAG Complex
- Summary

KURRI-FFAG complex



Parameters of FFAG complex

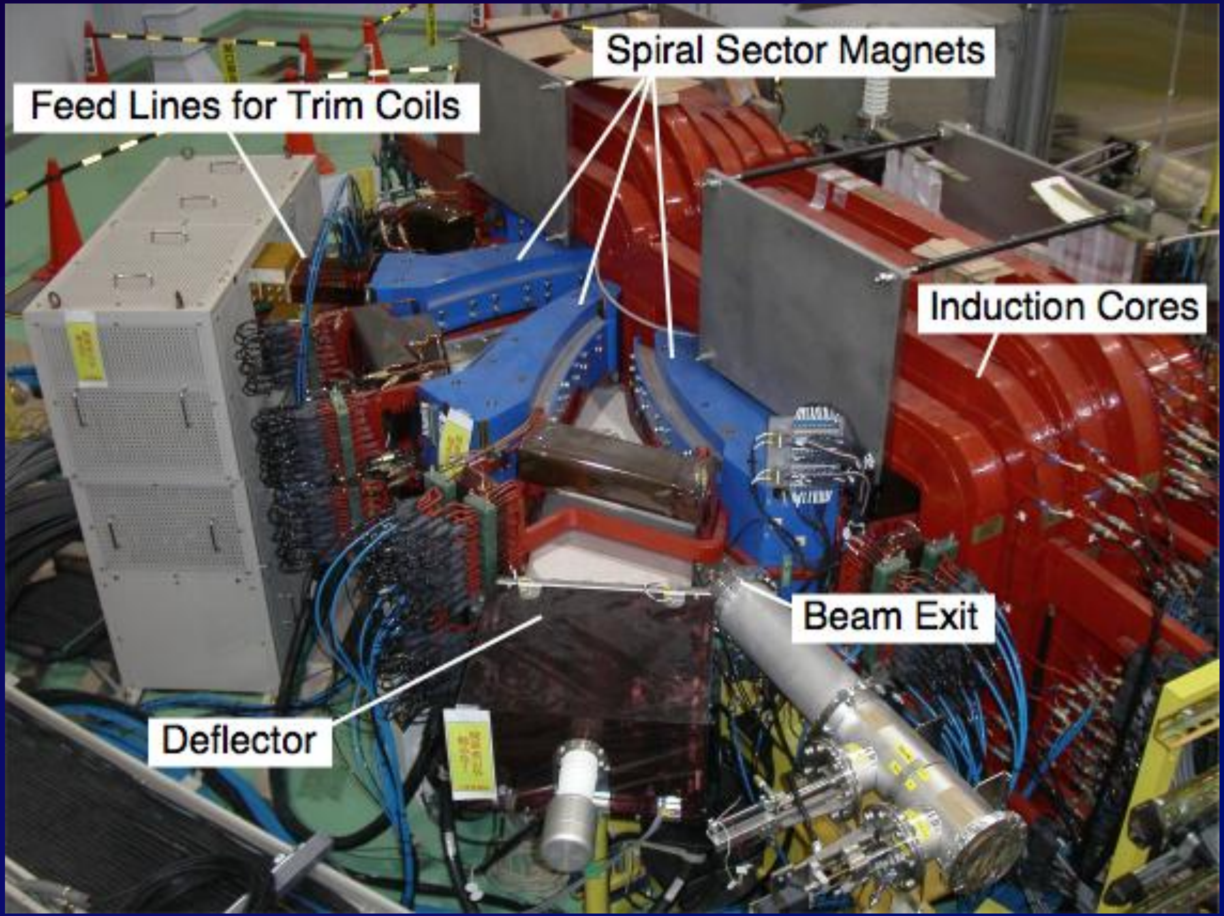
	Injector	Booster	Main Ring
Lattice	Spiral, 8 cells	Radial, 8 cells	Radial, 12 cells
Acceleration	Induction	RF	RF
Field index, *k*	2.5*	2.5	7.5
Energy (max)	1.5MeV (2.5 MeV*)	11MeV (20 MeV)	100MeV (150 MeV)
P_{ext}/P_{inj}	5.00(Max)	2.84	2.83
Average orbit radii	0.60 - 0.99 m	1.42 - 1.71 m	4.54 - 5.12 m

* Output energy of the injector is variable

The Injector (Ion beta)

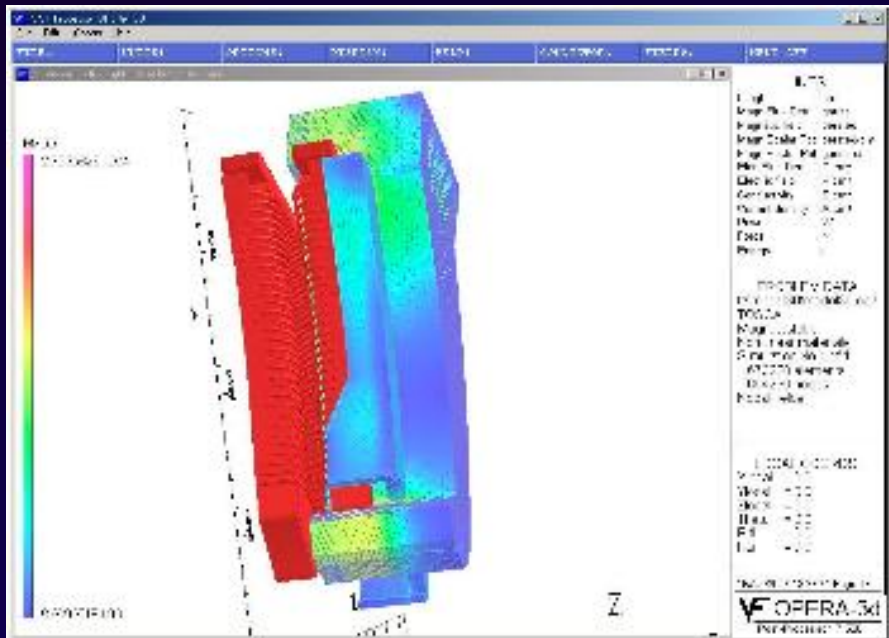
World's first trials in proton FFAG:

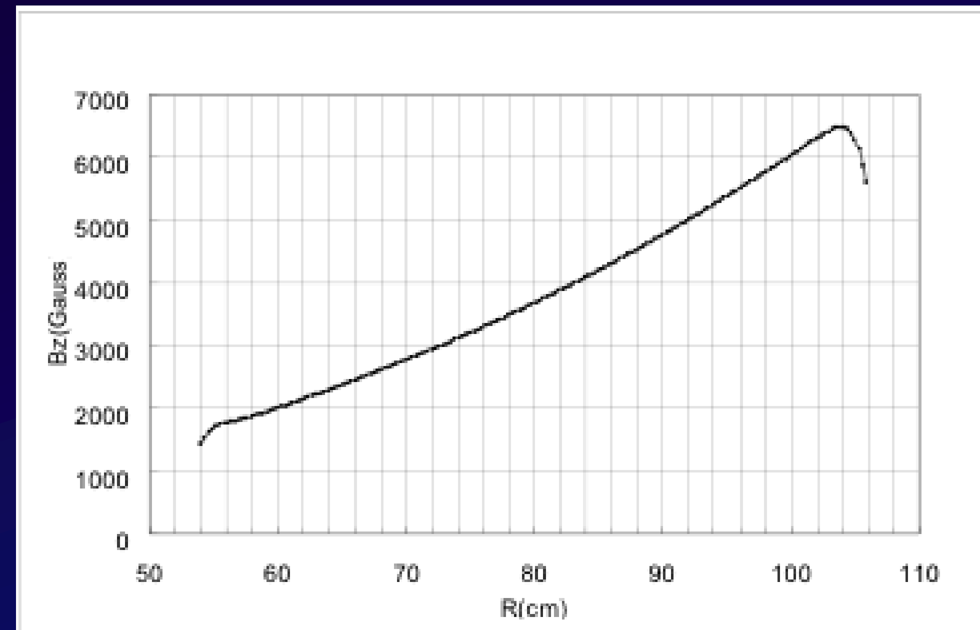
- Spiral sector magnet
- Induction acceleration
- Variable energy by using multi-pole face winding coils

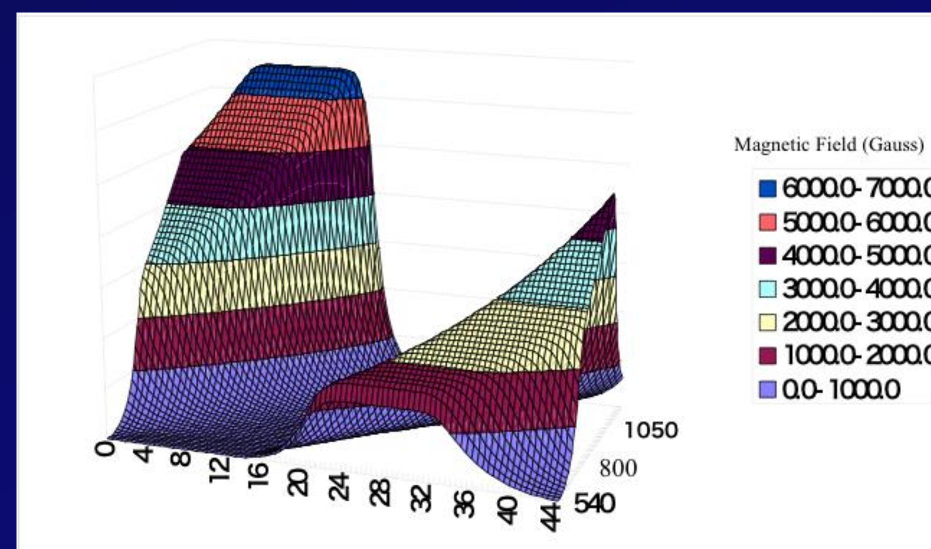


Independent 32 pole face winding coils

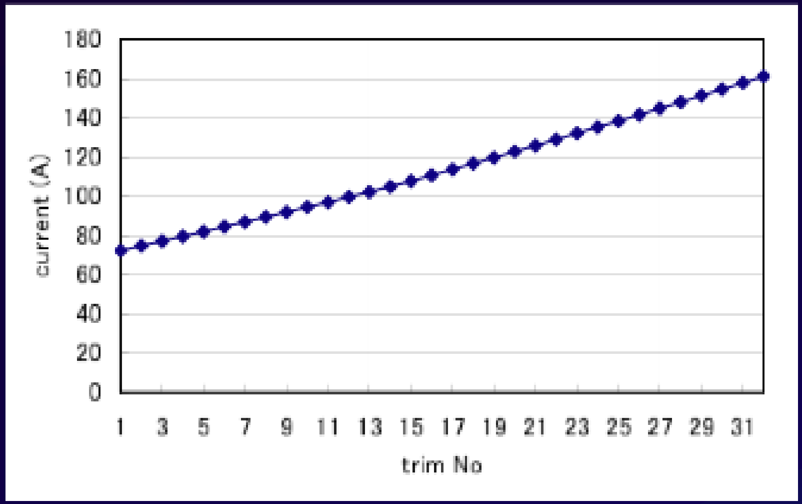
B Field by using multi coils

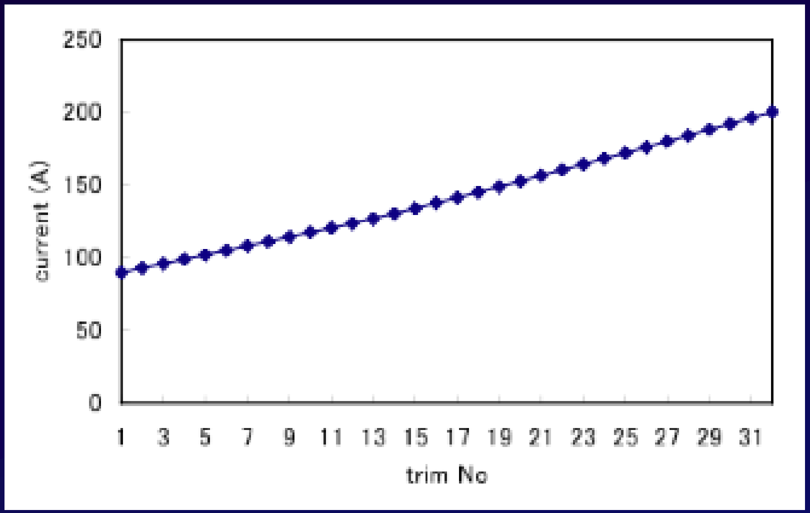






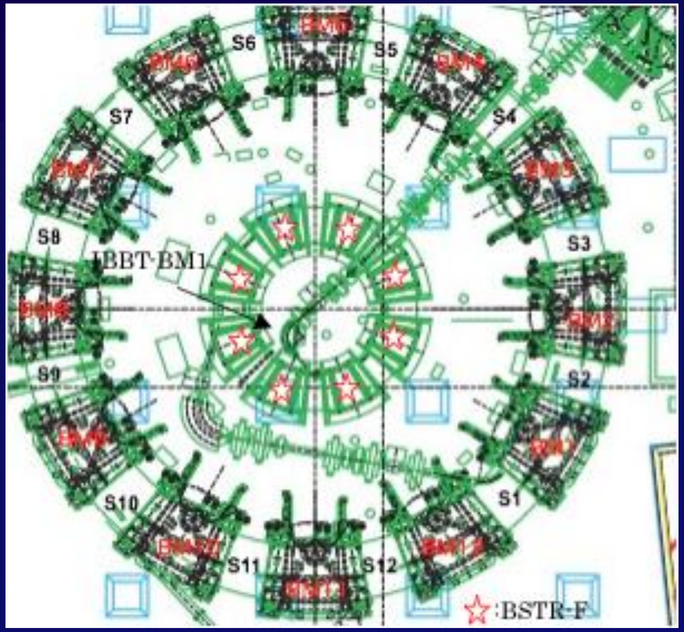
Capability of varialbe energy





Pattern I

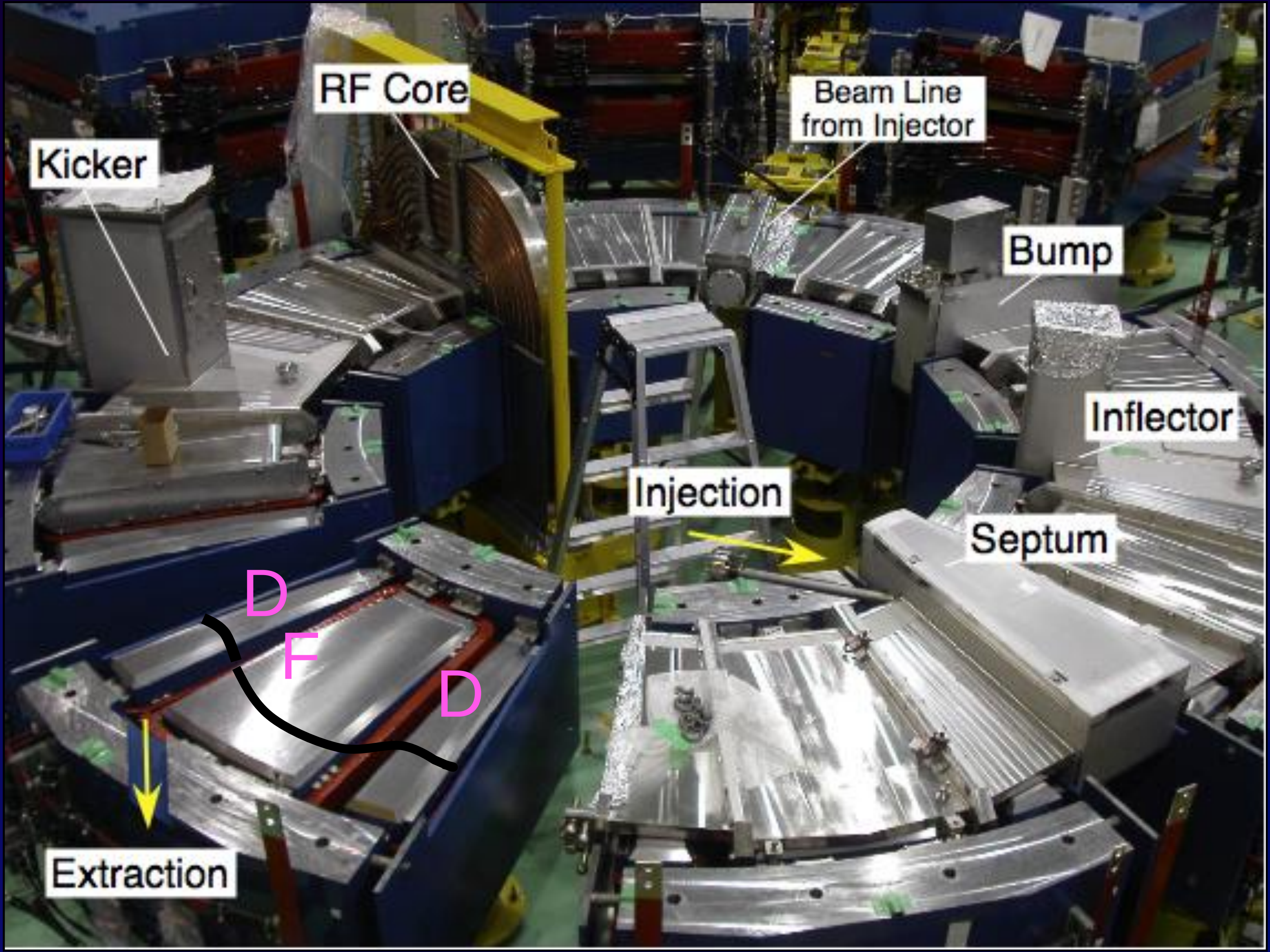
Pattern II



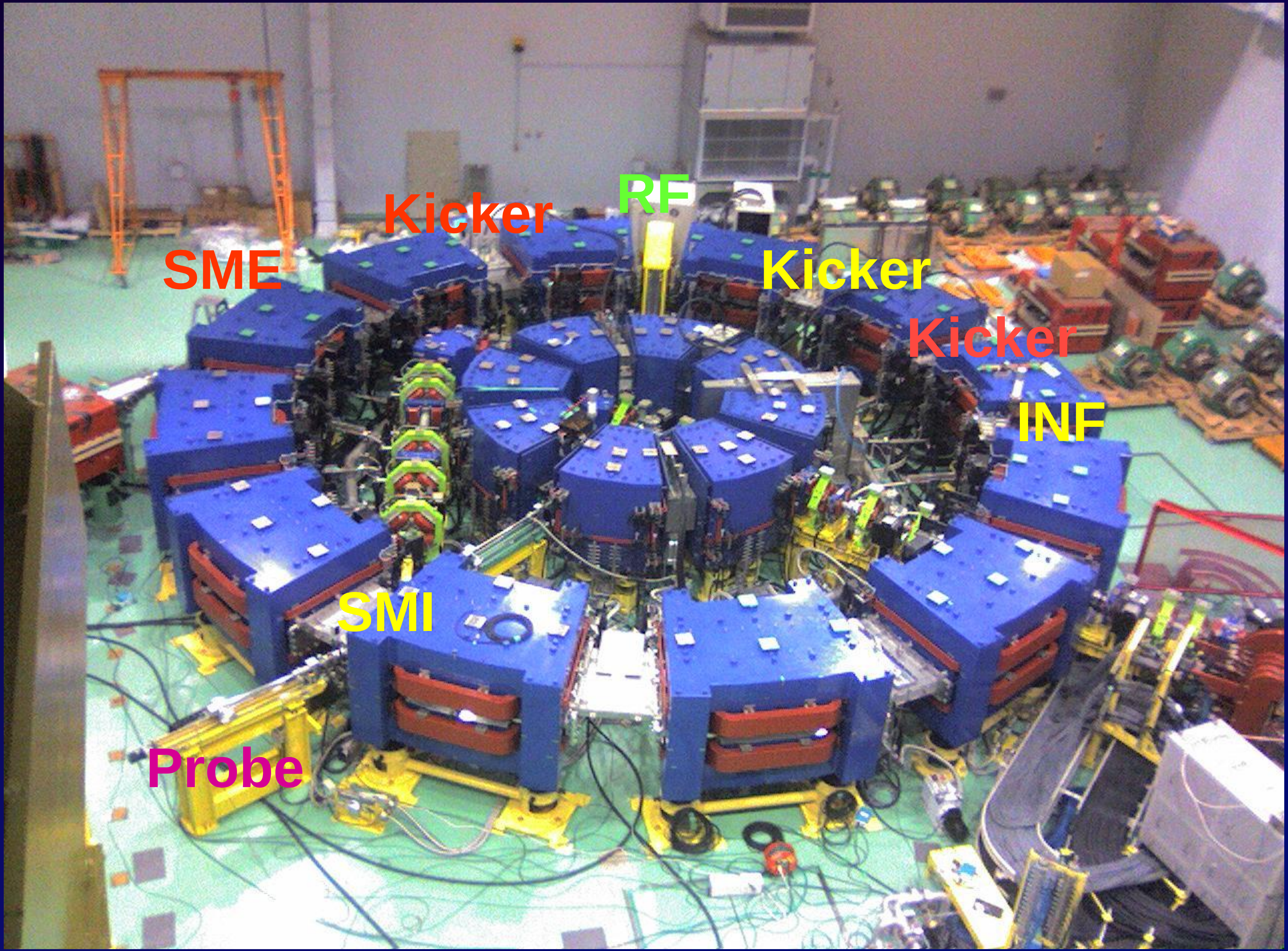
	Pattern I	Pattern II	Momentum ratio (II/I)	Energy ratio (II/I)
Capture Freq. in the Booster (kHz)	1725.1	1962.0	1.142	1.282
BSTR-F (A)	112.9	128.8	1.141	1.279
IBBT-BM1(A)	380.9	438.9	115.2	130.2

30% of energy variation has been tested with different pattern of trim coil excitation

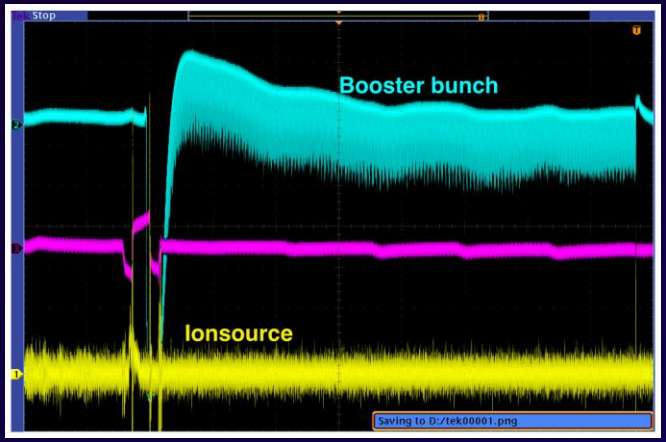
Booster

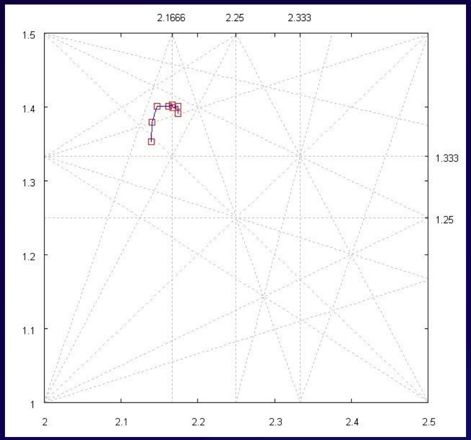

RF Core
Kicker
Beam Line from Injector
Bump
Inflector
Injection
Septum
D
F
D
Extraction

Main Ring

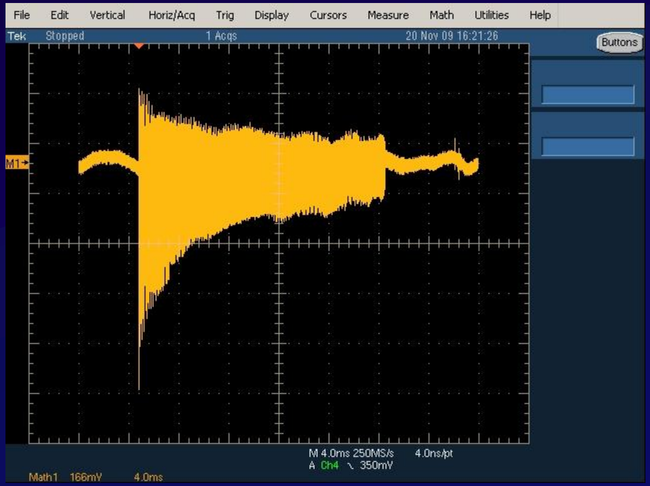


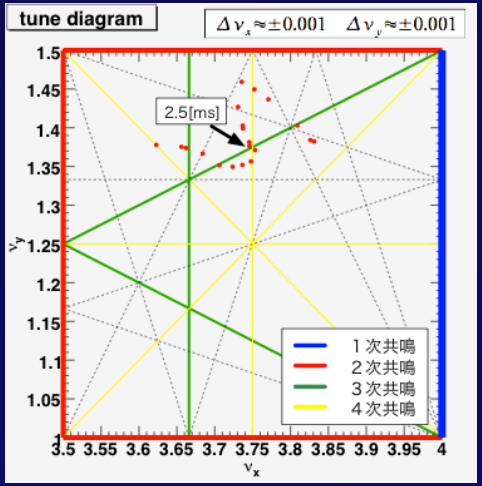
Bunch monitor signal thru acceleration





No beam loss
E=11.5MeV
I=1.5nA





E=100MeV
I=>0.1nA
(limited by
radiation safety)

Rapid beam loss caused by resonance
Qx – 2Qy = 1 at 2.5ms. → Field correction
Slow beam loss ← longitudinal

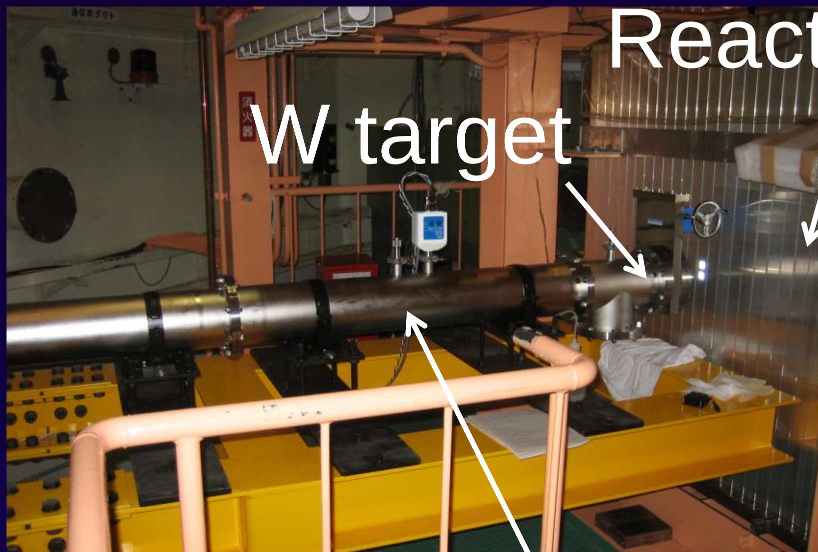
Accelerator Performance

- Injector
  - Capability of variable energy has been demonstrated
- Booster
  - Stable beam performance has been obtained
- Main Ring
  - Significant beam loss is observed at 4ms from injection
    - Mismatch of rf bucket → increase rf voltage
    - Transverse resonance → tune adjustment(F/D ratio, additional core)

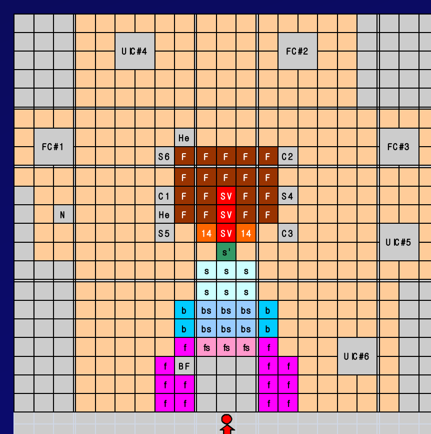
Contents

- Feature of ADSR
- ADSR studies in KURRI
- Design and Performance of FFAG Complex
- ADSR Experiments in KURRI
- Future plans of FFAG Complex
- Summary

ADSR Experiment Setup



Beam transport line



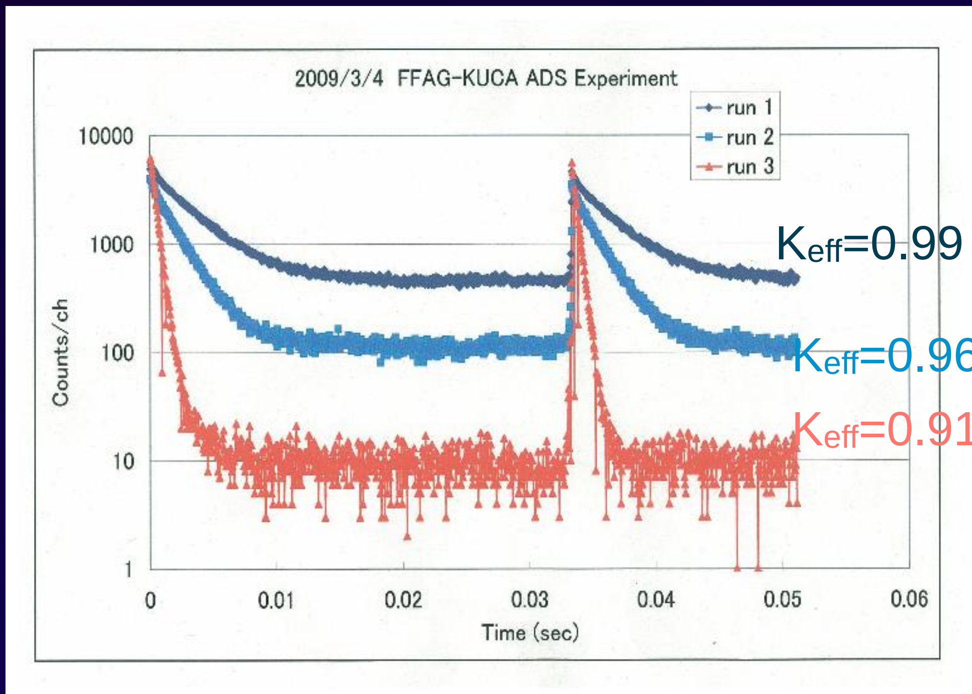
Subcritical fuel system

◆**Conditions**

- FFAG Accelerator :
  100 MeV Protons
  30 Hz repetition rate
  ~a few pA intensity
  Tungsten target
  (80mm diameter,
  10mm thickness)

- KUCA A-Core :
  93% enriched uranium
  Polyethylene moderator/reflector
  C1~C3 control rods fully inserted

World's First ADSR Experiment
(March 4, 2009)



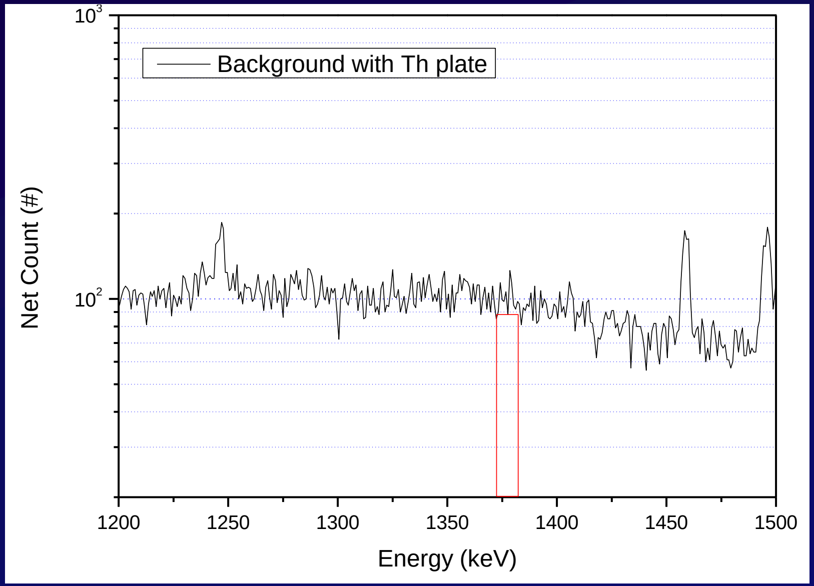
Two components in the neutron counting rate: the fast component decaying exponentially and the slow component caused by delayed neutrons almost constant in time.
The presence of the delayed neutrons indicates that neutrons generated through nuclear fission reaction inside the fuel system; it tends to have higher level with higher keff which means shallower subcriticalrity of the fuel system.

Thorium-loaded ADSR Experiment (March 3, 2010)

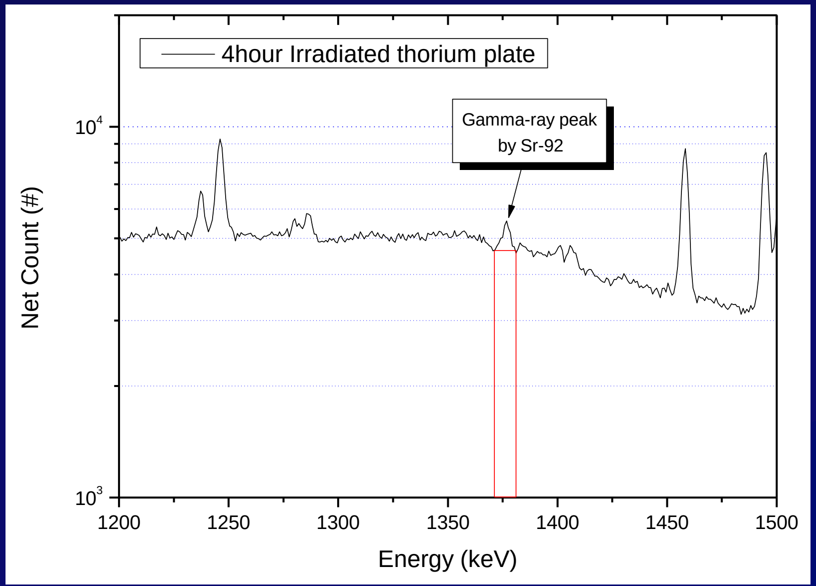
- **Proton Injection in Thorium Core**
  - FFAG Accelerator :
    100 MeV Protons
    30 Hz repetition rate
    ~30 pA intensity
    Tungsten target
    (80mm diameter, 10mm thick)
  - KUCA A-Core with Th :
    Natural thorium metal fuel
    No moderator or Graphite moderator

Verificaiton of Th Fission Reaction

- **Th Plate Measurement by HFGe Dectector** (Th plate Dim. : 2” x 2” x ¼”)
  - 22 isotopes with 5% fission yield & gamma-ray emission were selected
  - The existence of only Sr-92 was found with very small peak
    → Very difficult to find the evidence of thorium fission reaction



Count without Thorium Fuel Irradiaiton



Gamma peak by Sr-92 after Th Irradiation

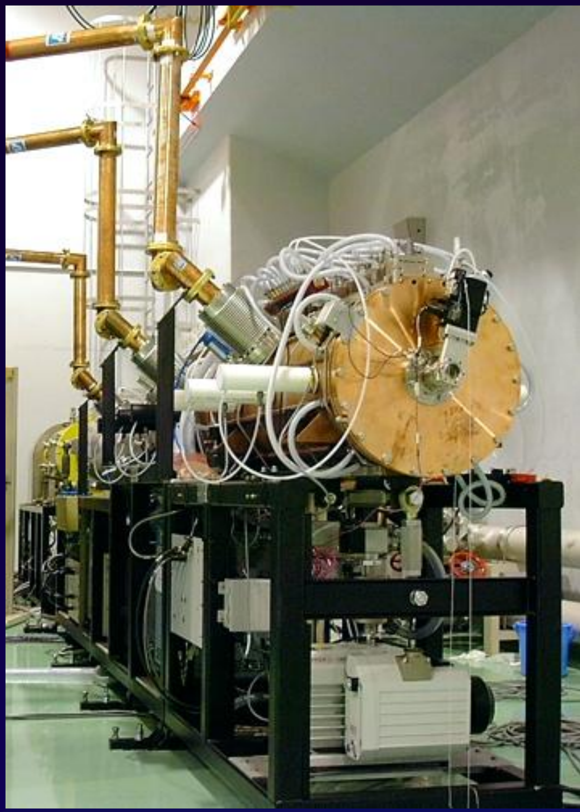
Future Plans

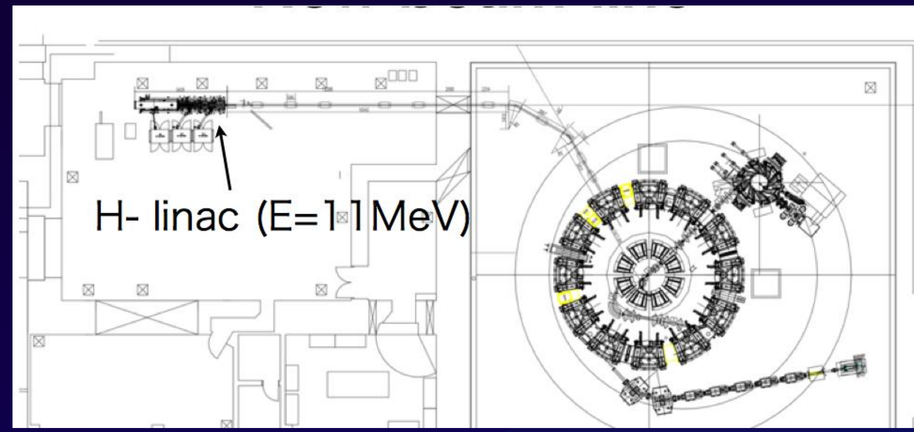
Recently in KURRI, a high intensity pulsed neutron source is desired not only for ADSR studies but for research using high intensity neutrons.

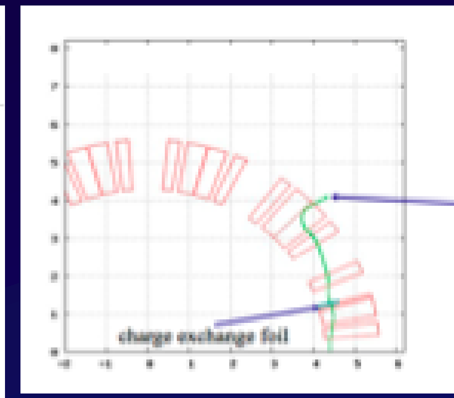
Using FFAG system as a proton driver for the neutron source, two major upgrade paths are considered:

- the intensity enhancement by changing the injector system;
- the energy upgrade up to 700MeV to enlarge the number of spallation neutrons.

H- injection



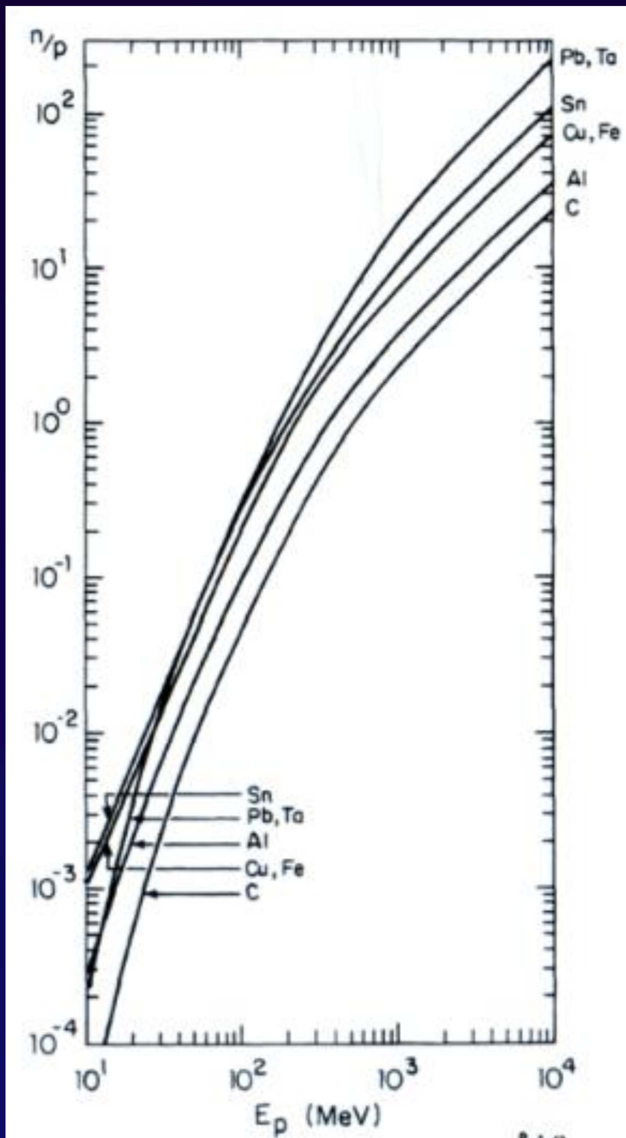




Ion：$H^{-}E_{ext}$：11MeV
Beam Pulse width(MAX)：100 μs
Peak beam current ：> 5 mA
→ 3.1×10^{12} [ppp]Rep. rate : 1Hz ~ 200HzAverage beam current : >100 μA

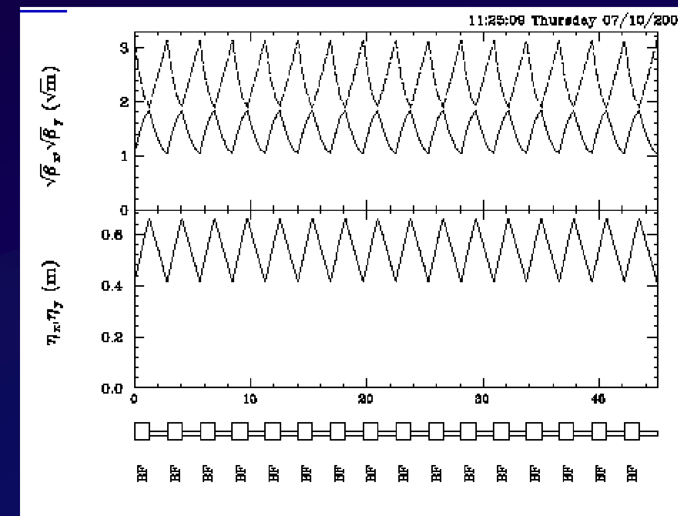
In an ordinary multi-turn injection of proton beam, accumulated beam intensity is limited by the transverse acceptance at the inflector. However charge changing H^- injection scheme can get rid of such a limitation. The space charge limit of the accumulated proton beam is estimated 12uA at a repetition rate of 100Hz.
For the injector of this scheme, ERIT injector system composed of RFQ and DTL can be used; it is installed in the same building.
The linac accelerates H^-beam up to 11MeV which is about the same as the injection energy of the main ring.
The beam line will be constructed in the summer of 2010, and the beam commissioning is planned to be done by the end of 2010.

700MeV FFAG RING



Neutron yield vs proton energy

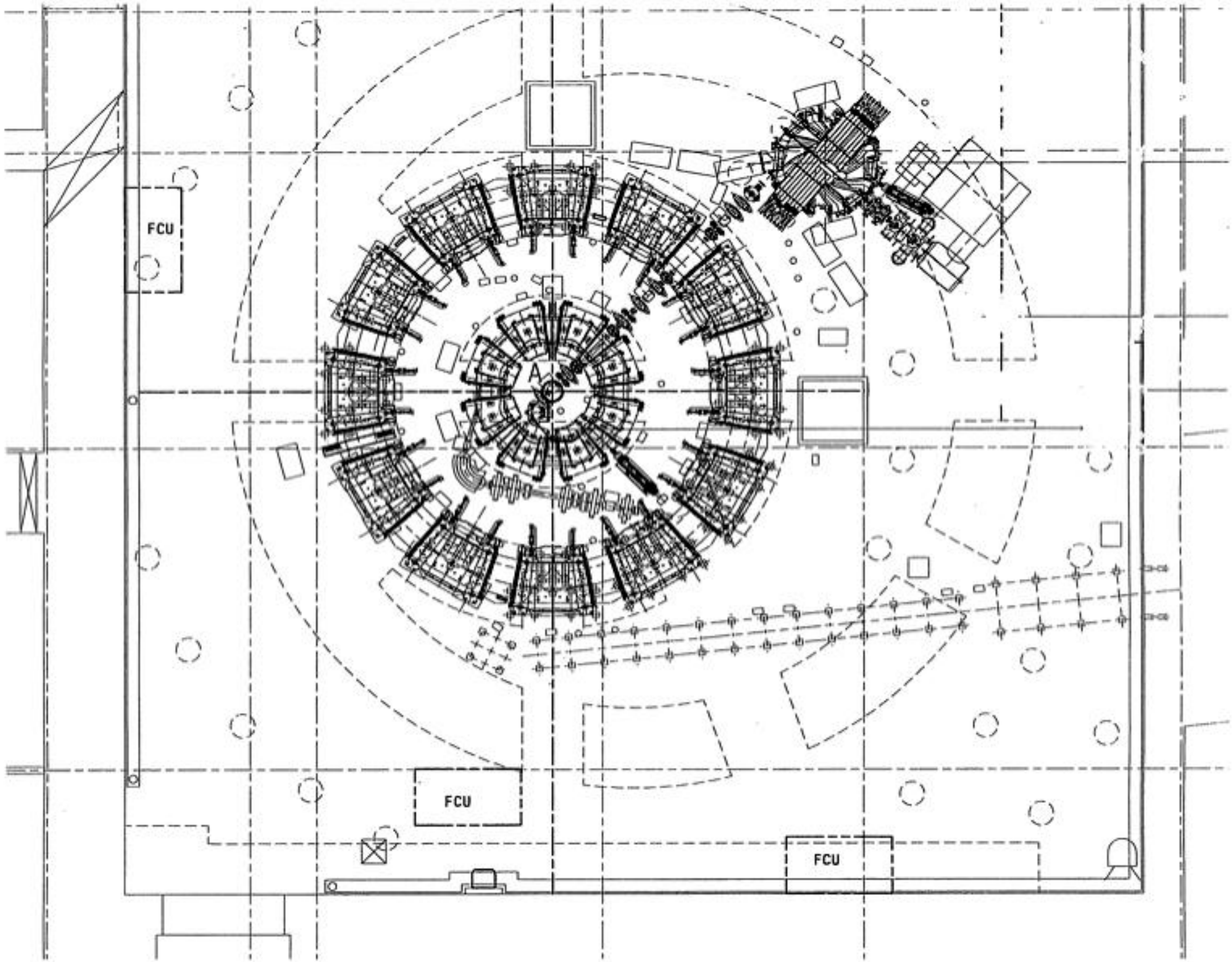
Number of neutrons produced through the nuclear spallation process is strongly dependent on the beam energy of the primary protons. If the beam energy is increased from 100MeV to 700MeV, the number of neutrons corresponding to single primary proton is increased by a factor of 30.



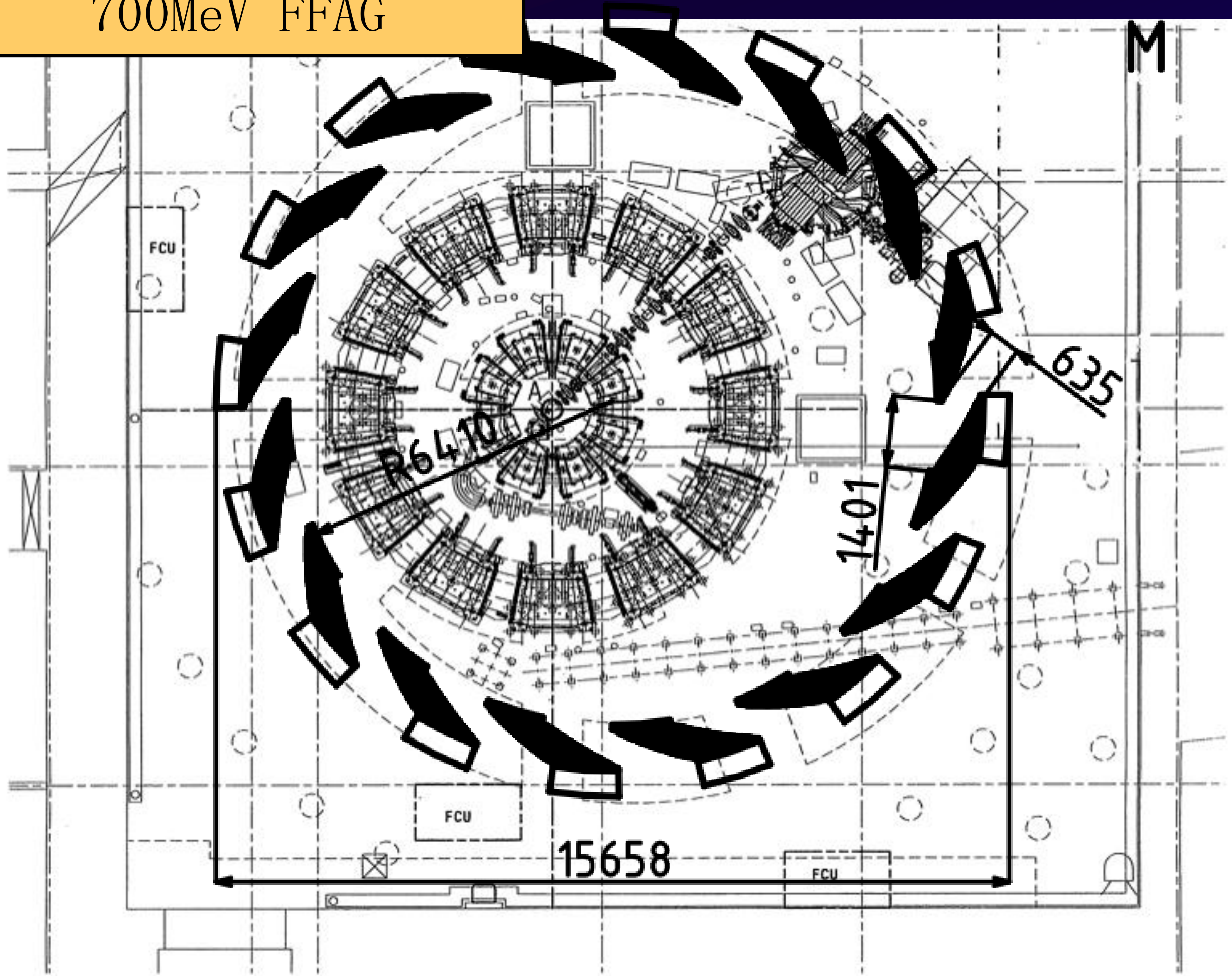
Lattice functions of 700MeV ring

Parameters of 700MeV ring

Lattice	16-cell spiral
Field index k	12
Energy	150 - 700 MeV
Average orbit radii	6.6 - 7.2 m
Magnetic field	1.5 T


FCU
A
FCU
FCU

700MeV FFAG



Summary

1. In KURRI, the FFAG accelerator complex for the ADSR study has been constructed.
2. 100 MeV proton beam from the main ring has been delivered to the sub-critical core in KUCA. World's first ADSR experiment has been successfully started on March 4, 2009.
3. In these experiments, we have obtained evidence of the chain reaction induced by the spallation neutrons produced by the high energy proton beam.
4. Not only for higher performance for the ADSR experiments but for the pulsed neutron source, intensity upgrade program using H^- injection for present main ring has been started.
5. In addition to the existing FFAG accelerator complex, a 700MeV spiral FFAG ring is now under consideration.

Thank you
for your Attention