KURRI FFAG's Future Project as ADSR Proton Driver

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Kyoto University Research Reactor Institute

OUTLINE

1. Brief explanation about ADSR
2. FFAG accelerator complex at KURRI
3. ADSR and other experiments using the proton beams from the complex.
4. Future projects
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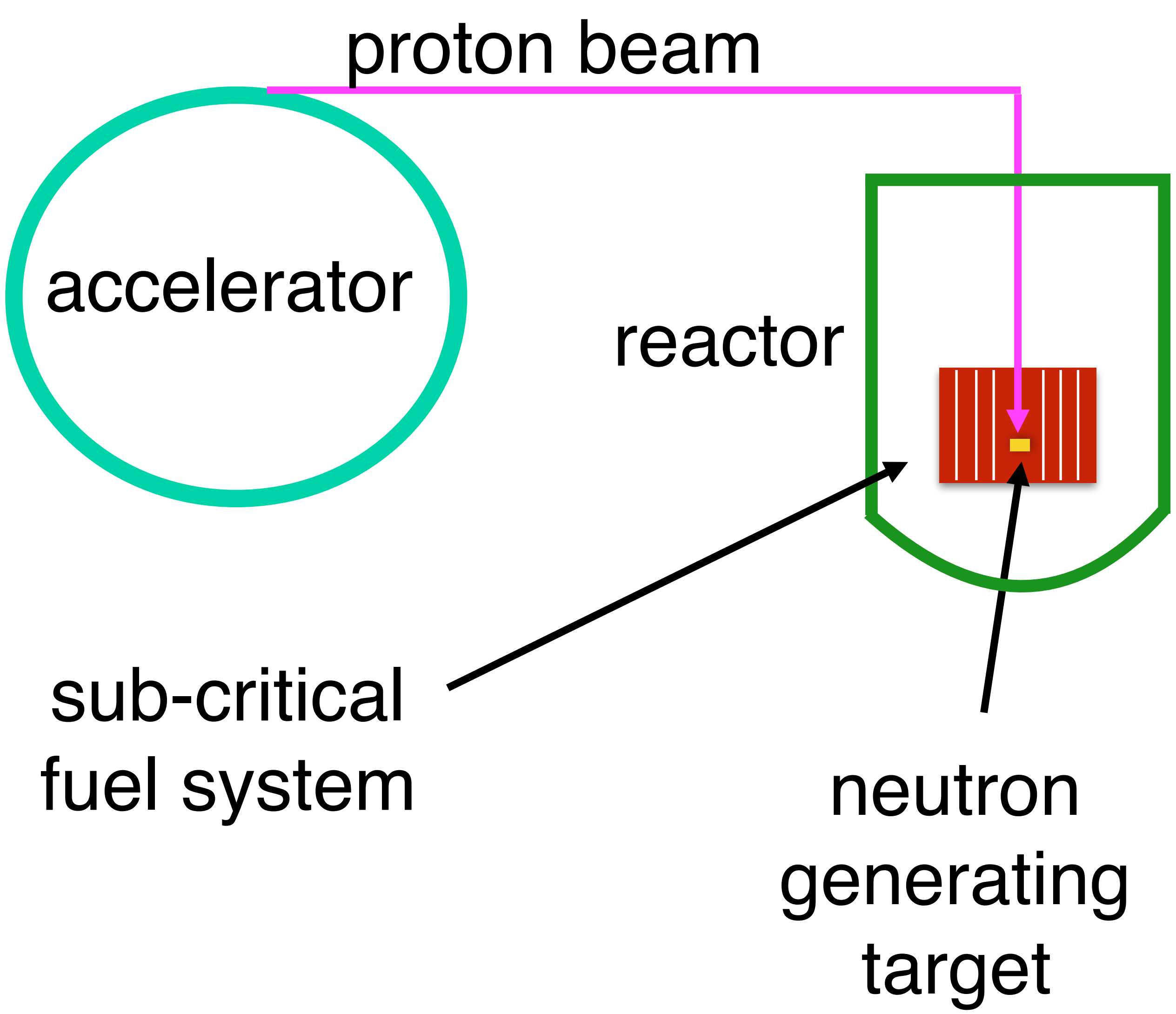
Brief explanation about ADSR

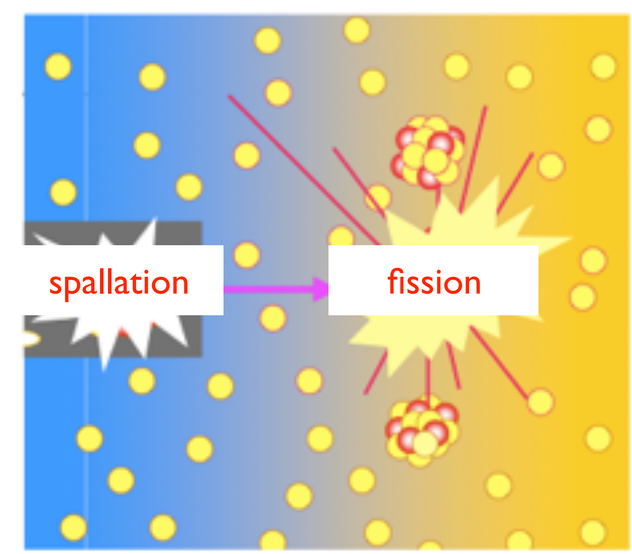
ADS : Accelerator Driven System

ADSR: Accelerator Driven Sub-critical Reactor

Accelerator Driven Subcritical Reactor

ADSR is a system which realises sustainable 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.



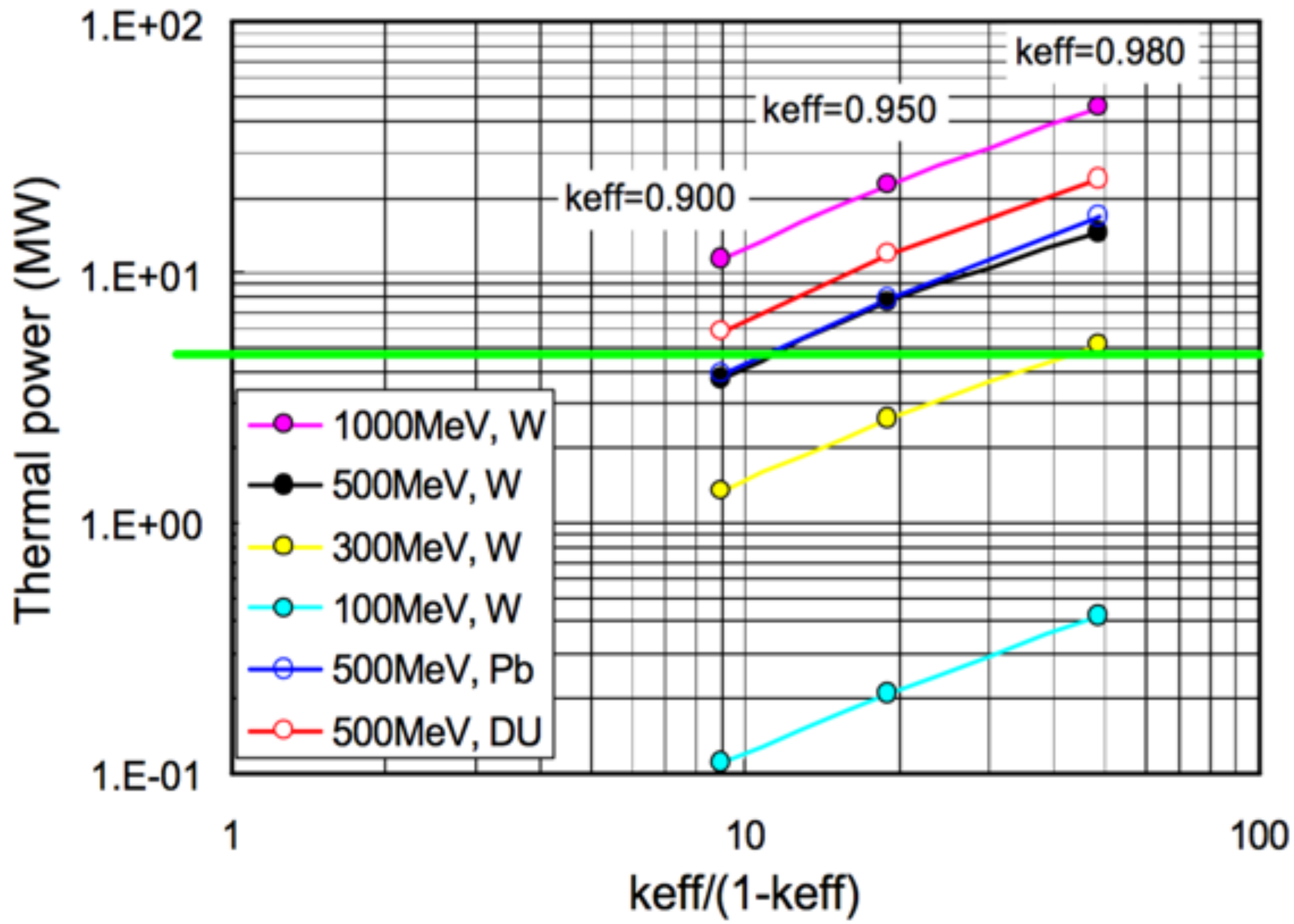


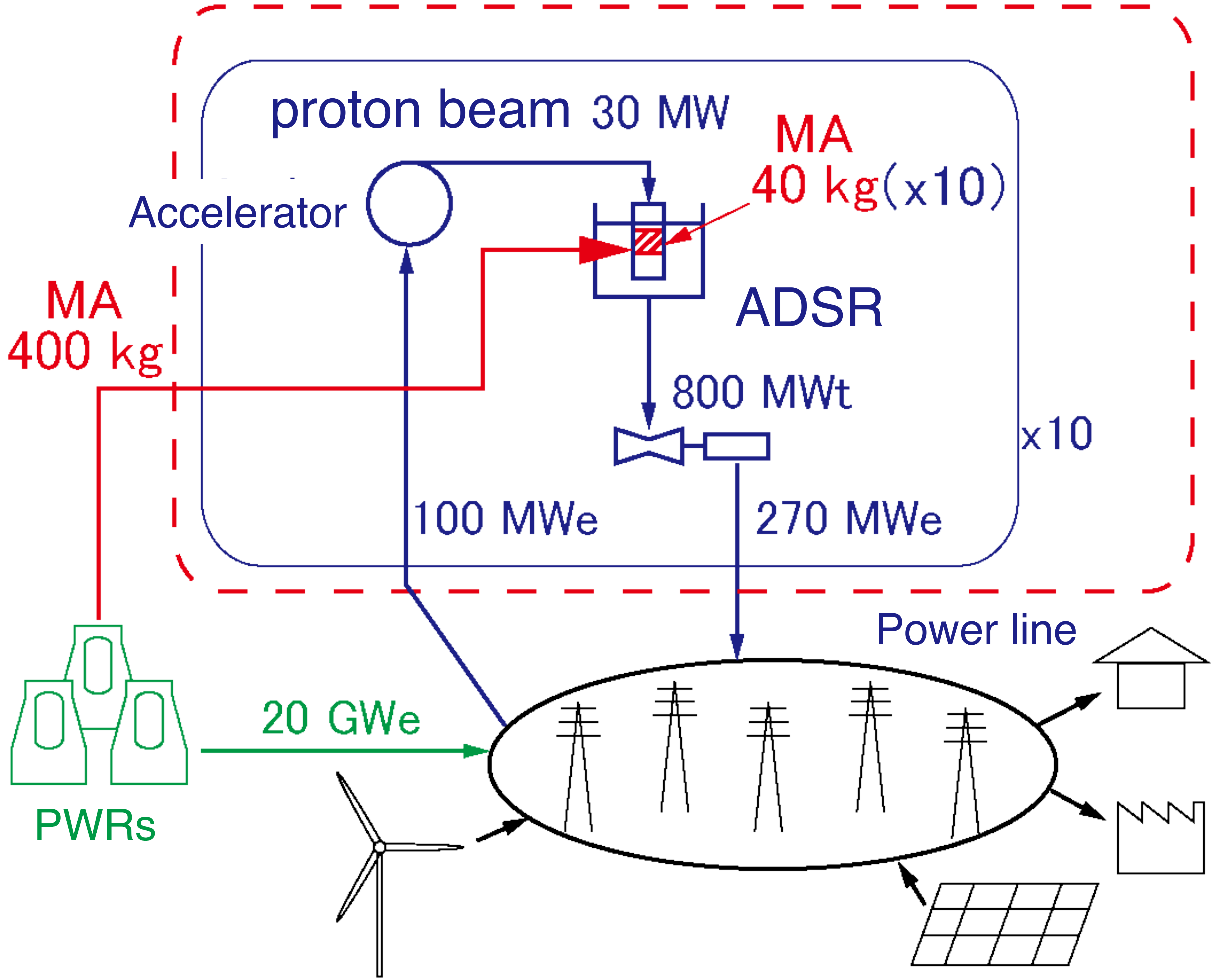
The output of the nuclear reactor can be controlled by changing the beam power from the accelerator. Output from the sub-critical reactor is expressed as

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

P: thermal power of the reactor
S: power from the neutron source
beam power of the accelerator

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





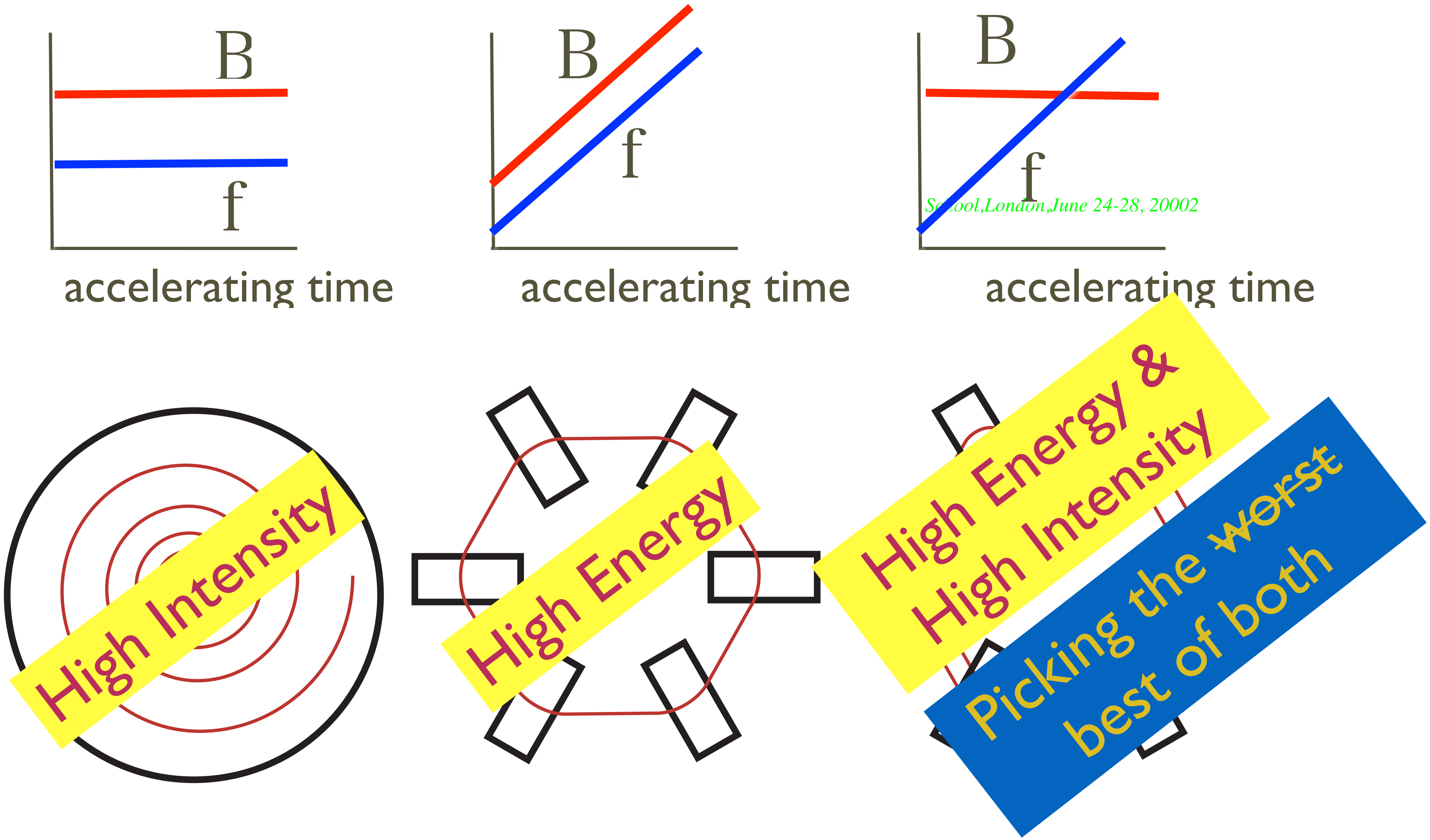
Not only energy production but the transmutation of the nuclear waste

Requirement for the Proton Driver of ADSR

1. High Energy (1.5 GeV)
2. High Intensity (20 mA)
3. Low power consumption (100 MW)
4. CW or High rep. rate (1 kHz)
5. Trip free ← heat stress of the reactor
    1. < ~~2,000~~ 20,000 tripps / Y (0 - 10sec)
    2. < ~~20,000~~ 2,000 tripps / Y (10 sec - 5 min)
    3. < 42 tripps / Y (to keep 70% duty factor of the plant)

ADSR facilities in the world

Project	accel.	spectrum	output	status
KUCA (Japan)	100 MeV FFAG	thermal	zero	ongoing
TEF (JAEA,Japan)	400MeV LINAC	fast	500 Wt	planning
MYRRHA (Belgium)	600MeV LINAC	fast	100 MWt	planning



Cyclotron

*isochronous

Synchrotron

*const. closed orbit

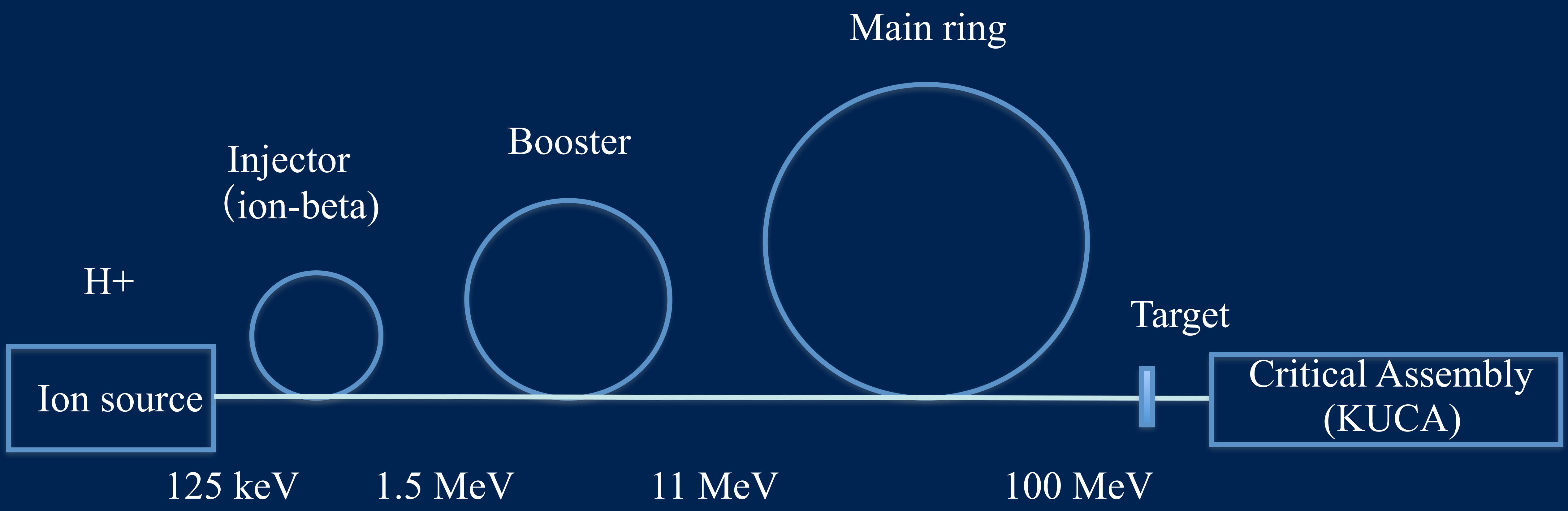
(varying mag. field)

FFAG

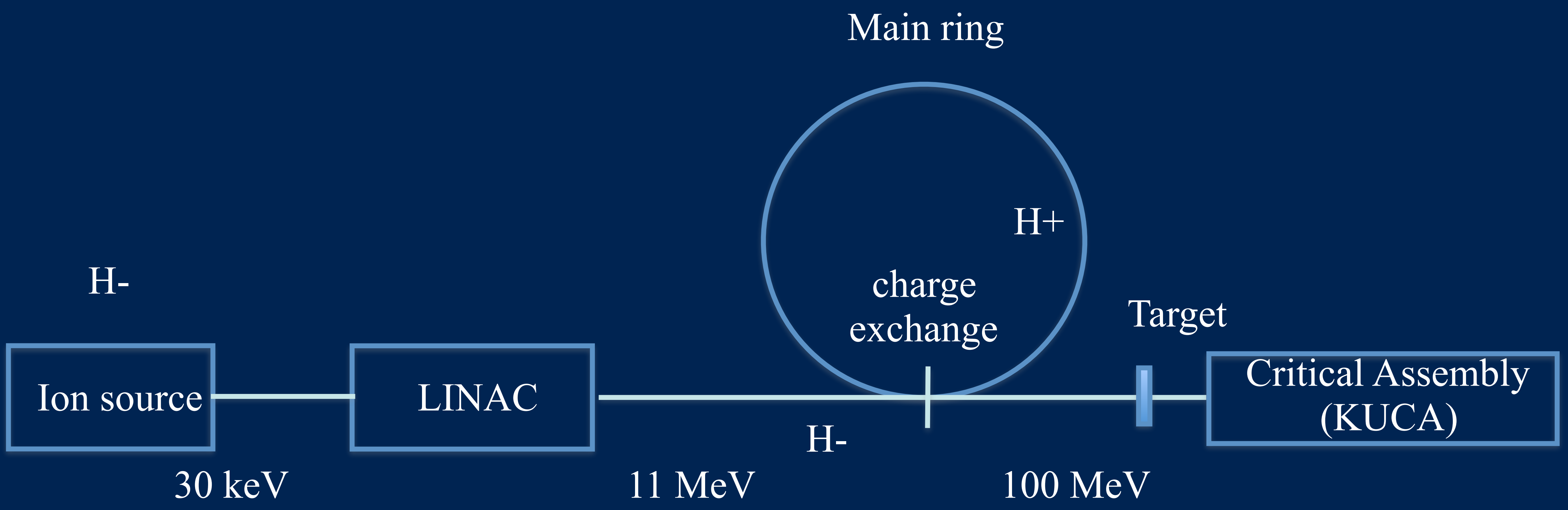
*varying closed orbit

(const. mag. field)

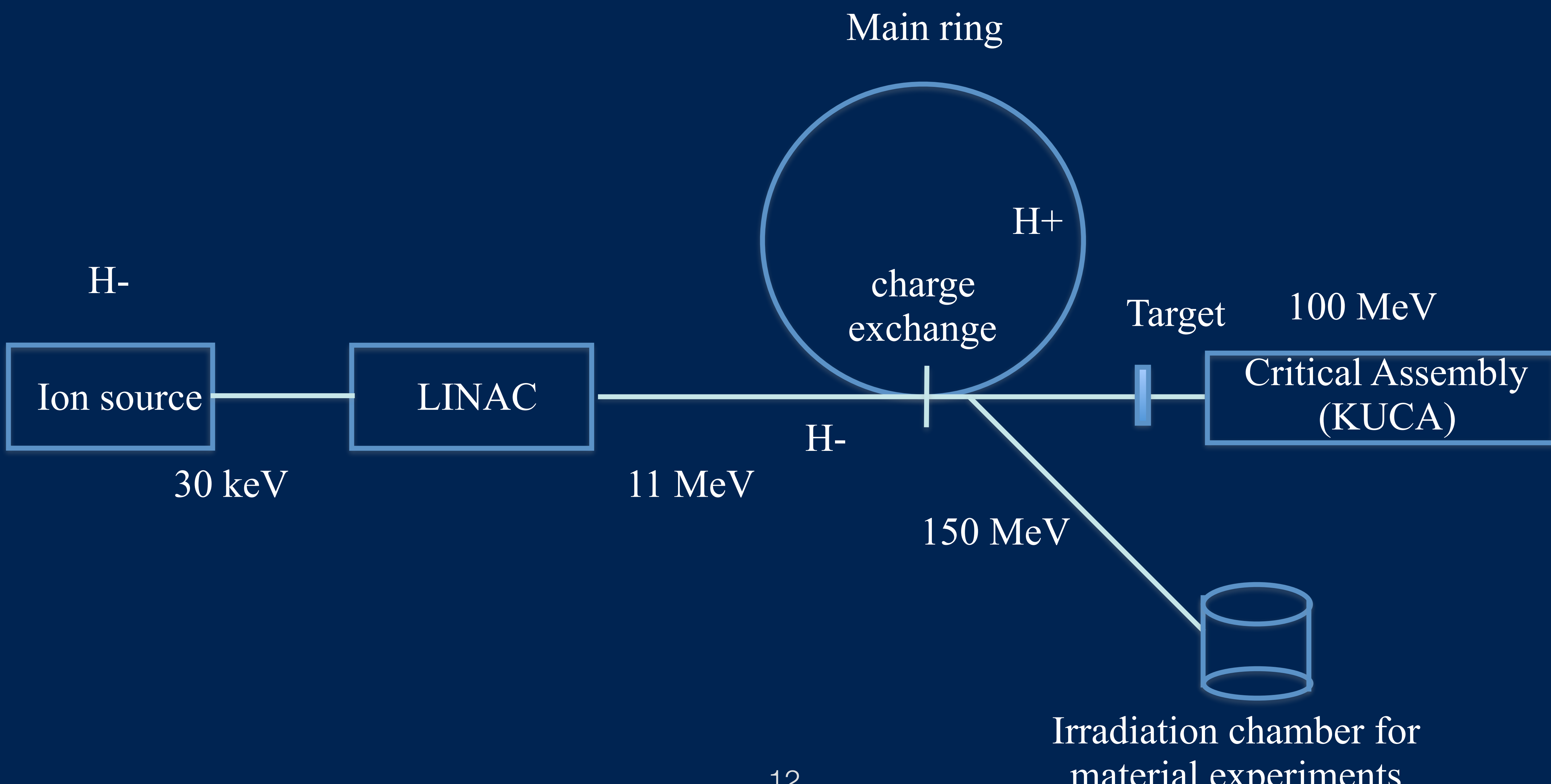
FFAG – KUCA ADS system schematic diagram (original) 2008 - 2010



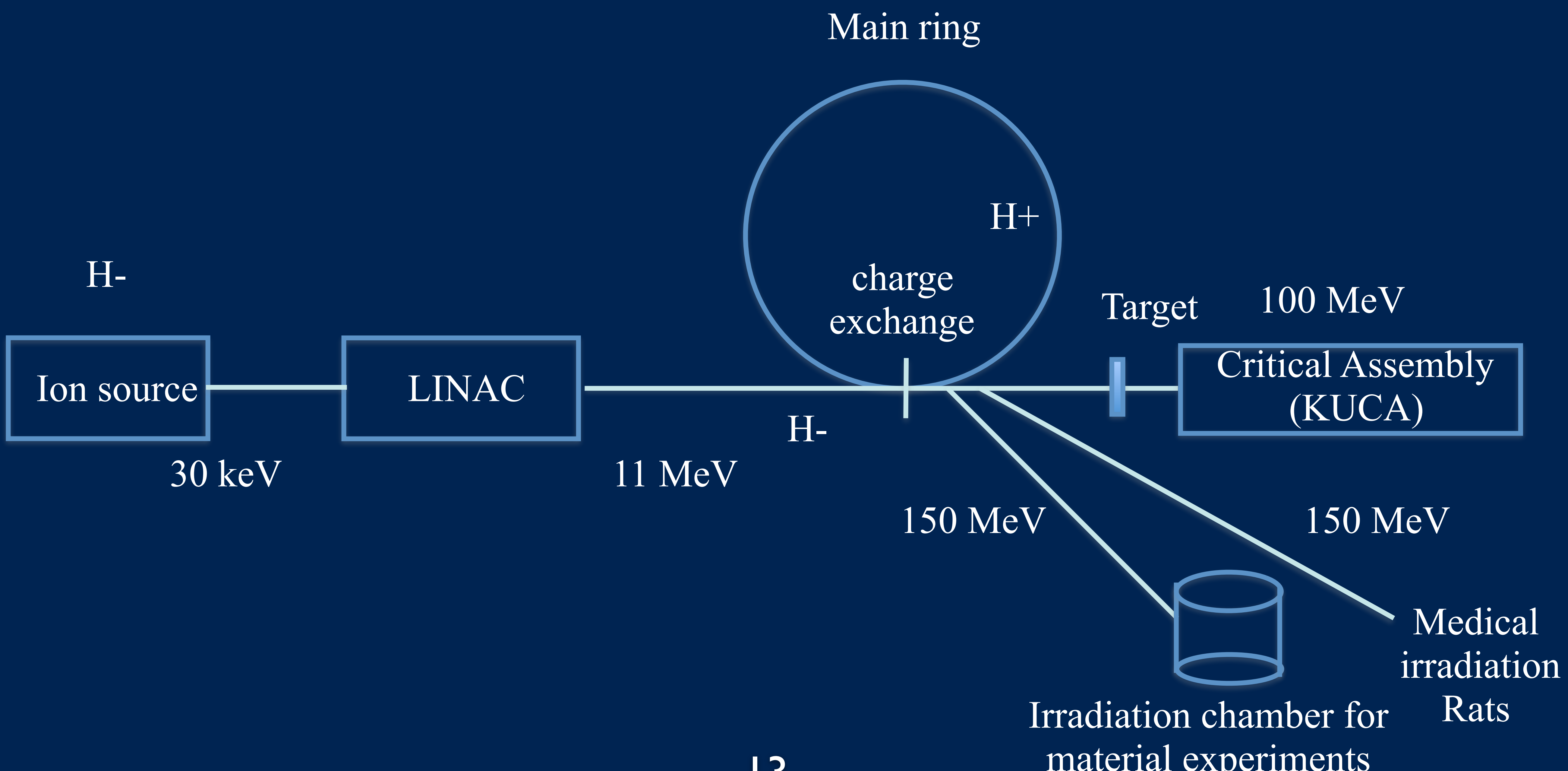
FFAG – KUCA ADS system schematic diagram (upgraded) from 2011



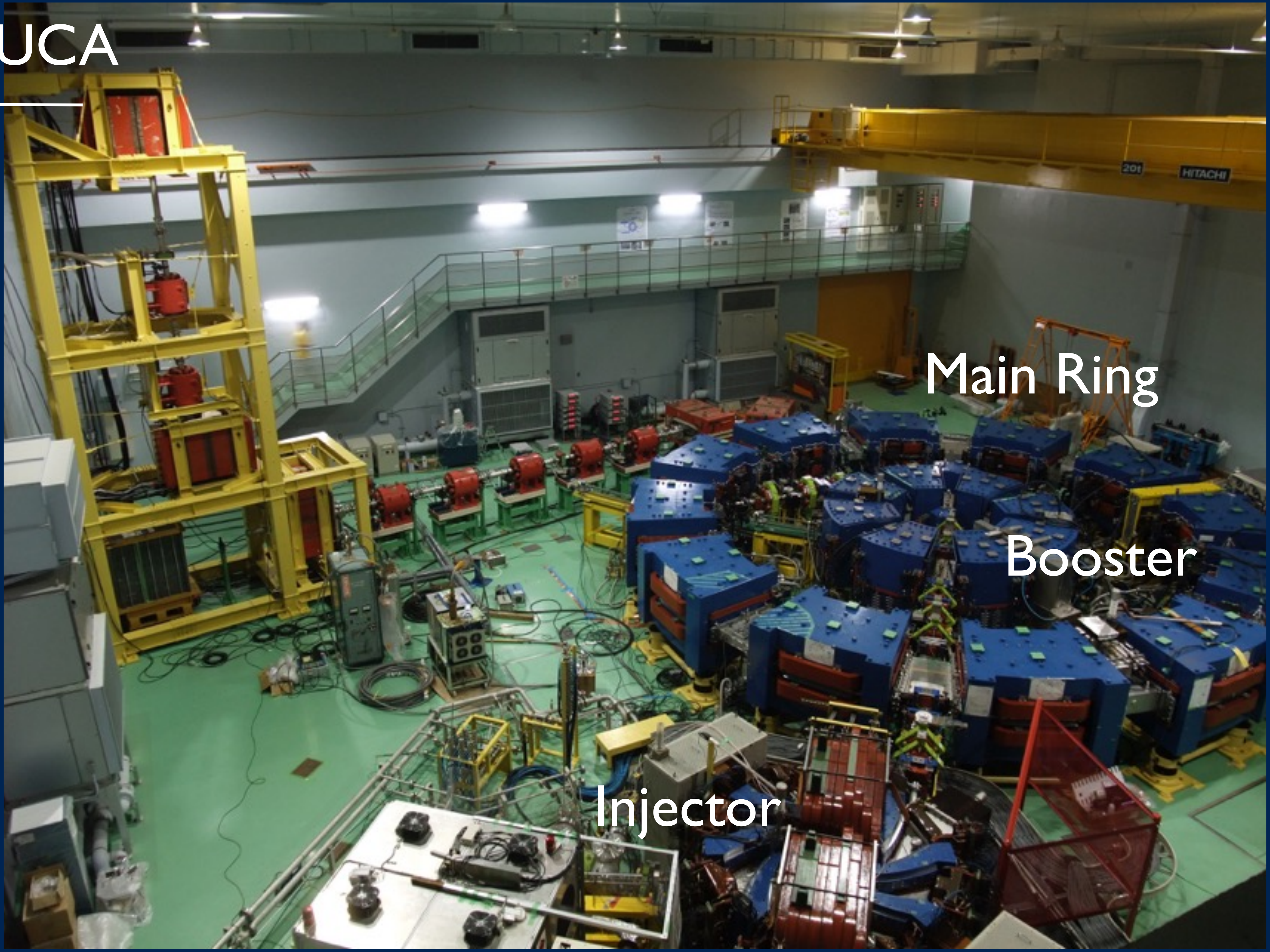
FFAG – KUCA ADS system schematic diagram (upgraded) from 2012



FFAG – KUCA ADS system schematic diagram (2011 -)



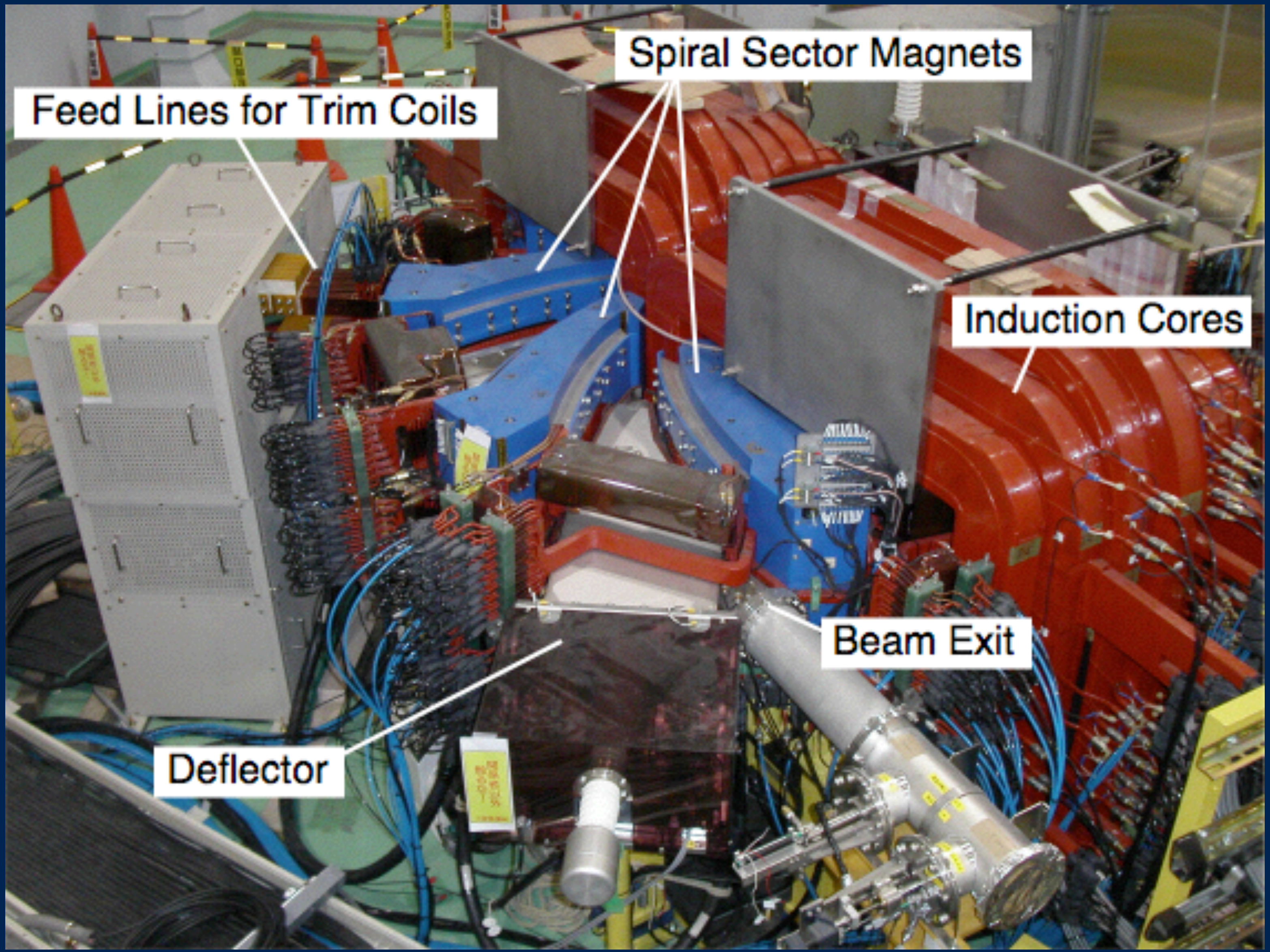
KURRI-FFAG complex (original)



The Injector (Ion beta)

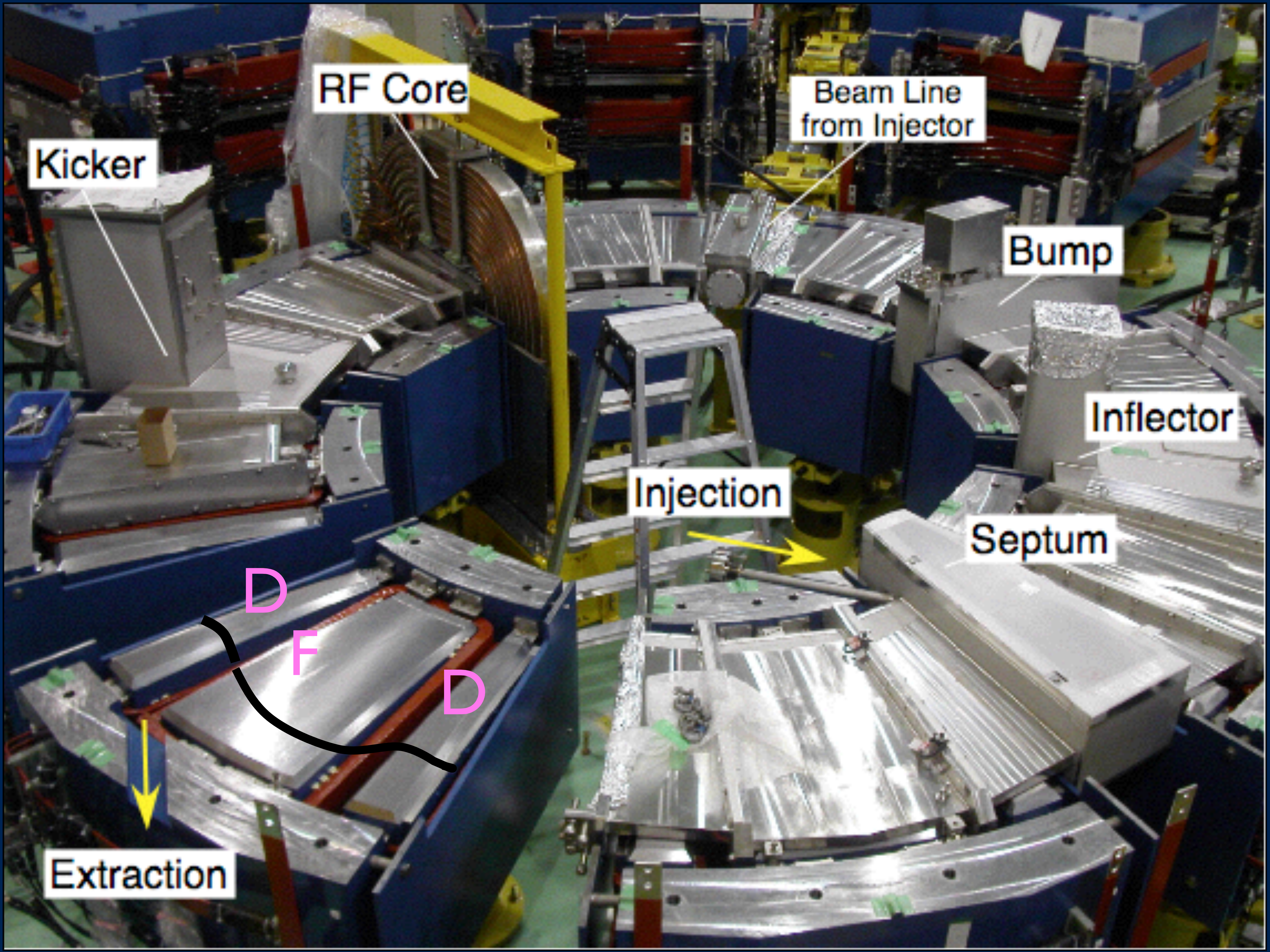
World's first trials in proton FFAG:

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

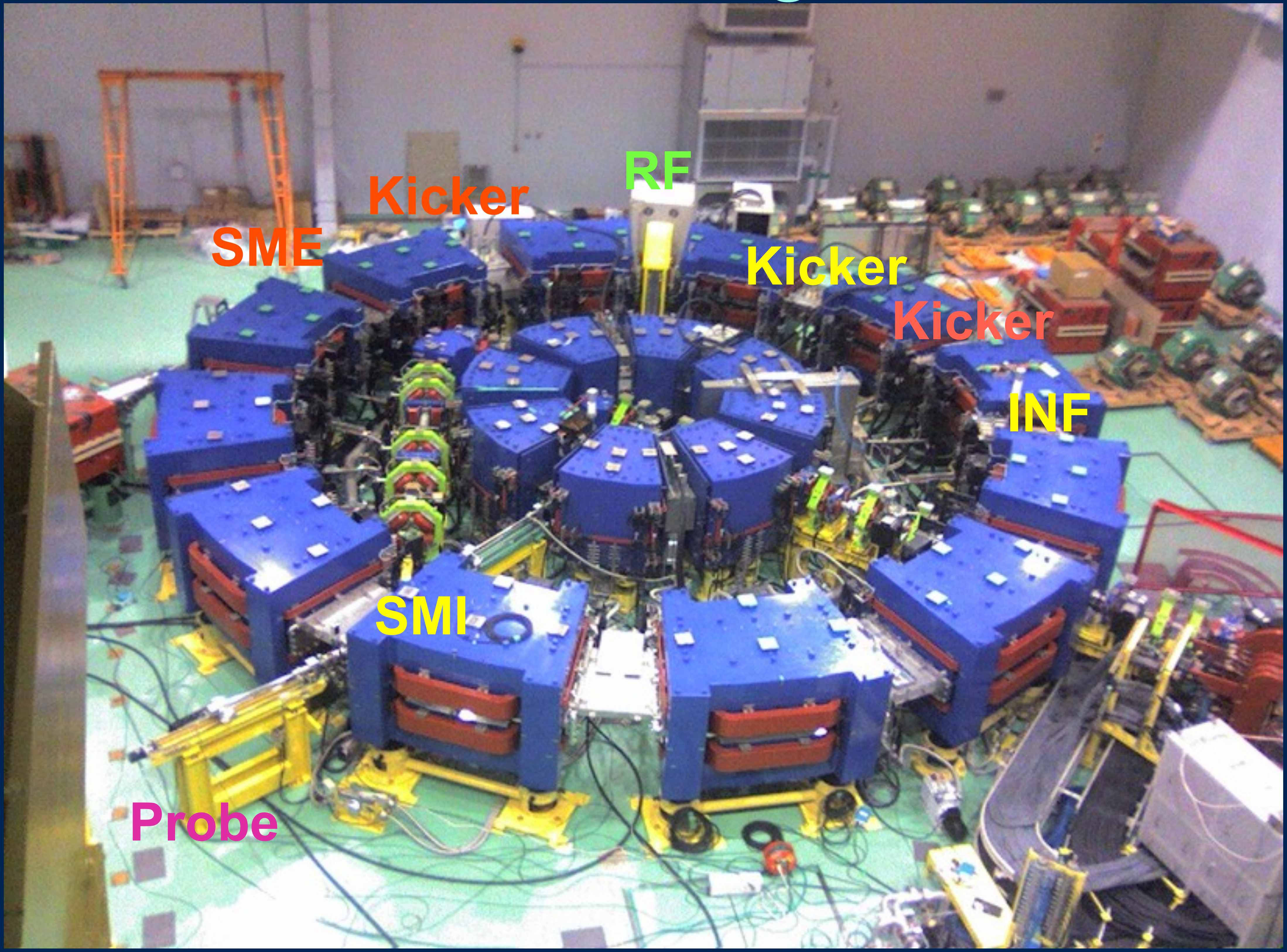


Independent 32 pole face winding coils

Booster


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

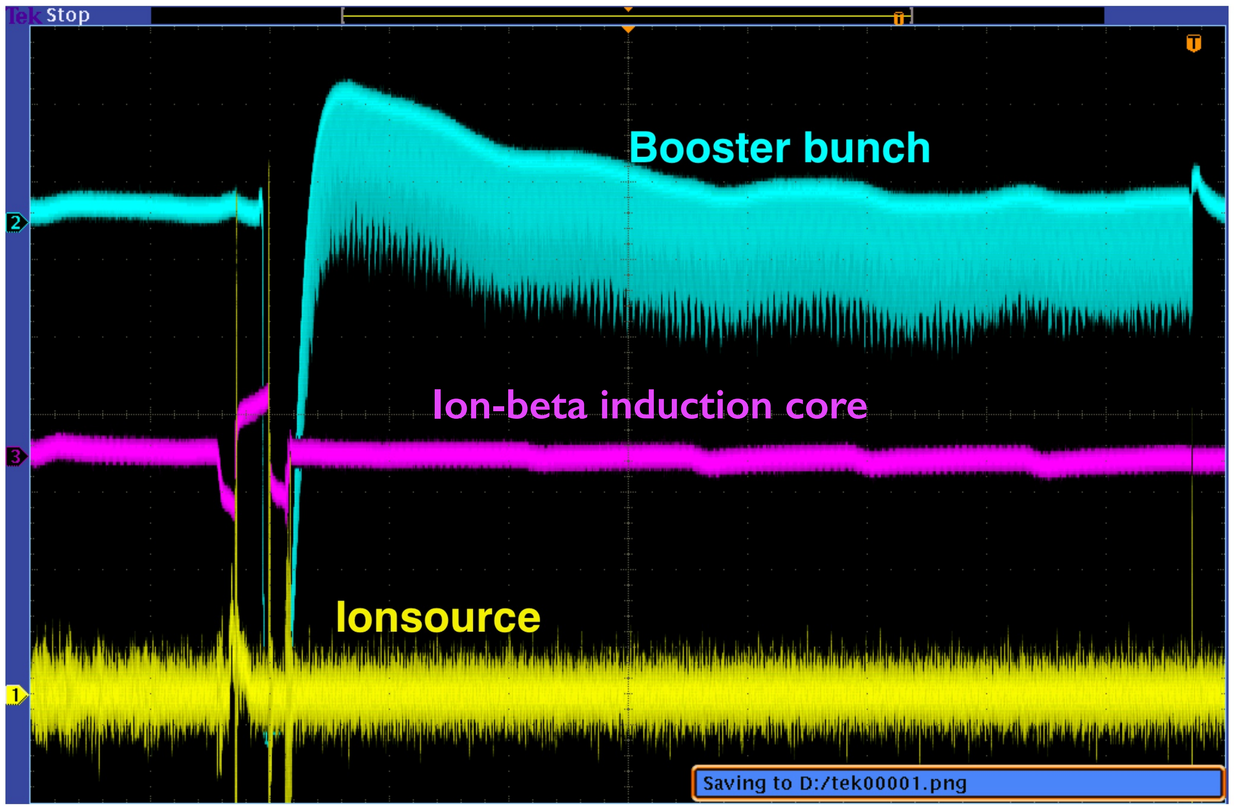
Main Ring

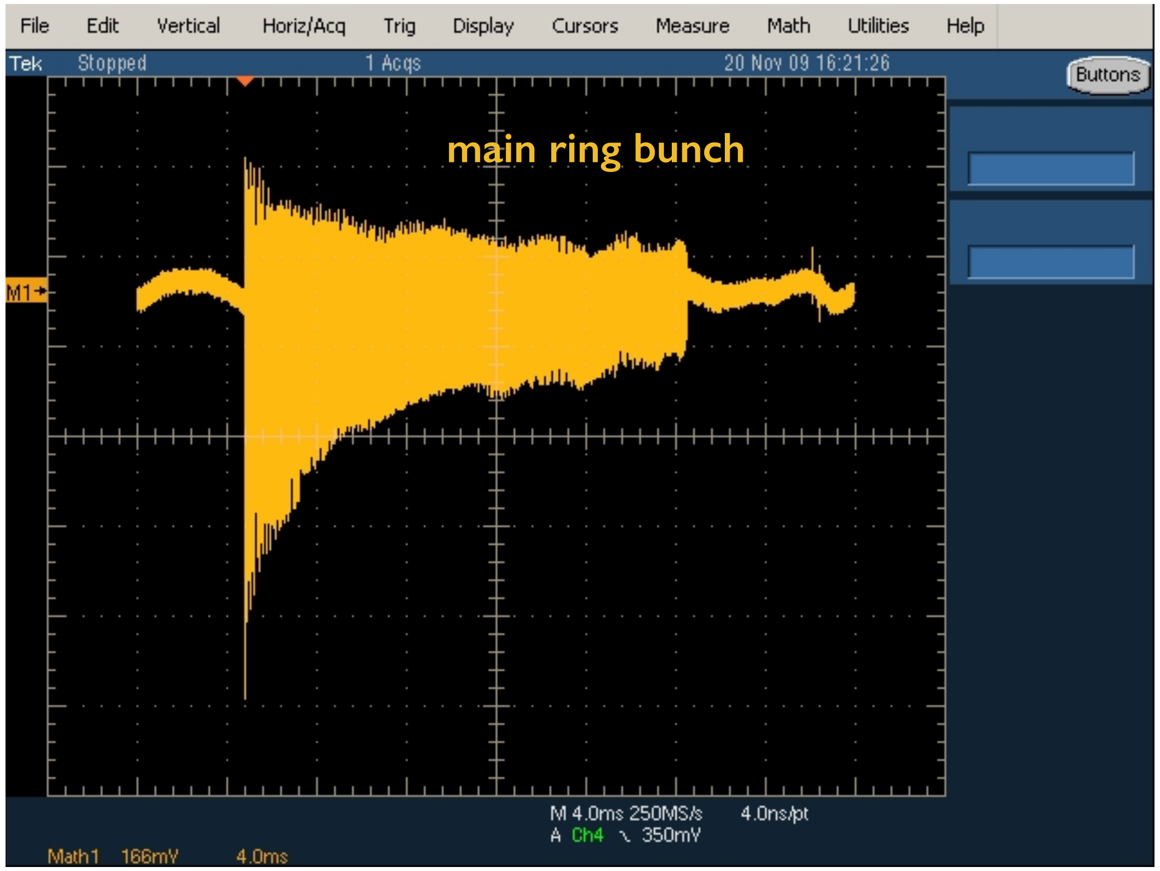


Beam characteristics of FFAGs in March 2010

Ion beta　peak current 25μA
spiral sector, induction acceleration, variable energy by using multi coil ：first trail for the proton FFAG

induction scheme：energy fluctuation is large → poor stability of the injection to the booster





Booster　average current 1.5nA（duration 7μs i.e. 14-turn injection）

Highly completed machine：It took only a few hours to reach final energy once we got rf capture.

It realized designed characteristics　→　no beam loss

But we need to optimise the injection angle by adjusting the injection septum magnet once a day.

Main ring　average current 0.1nA
Return-yoke free magnets make beam injection/extraction possible even in arc section, but they make leakage field larger.
Beam intensity can be improved by cure of beam loss.→but at most a few nA→change the injection scheme

Charge exchange injection system in FFAG main ring

target beam current extracted from the main ring ~1µA

- charge exchange by using carbon foil 10/20 µg/cm^2
- FFAG-ERIT H^-Linac(11MeV) can be used !
- space charge limit

Tune shift due to space charge effects

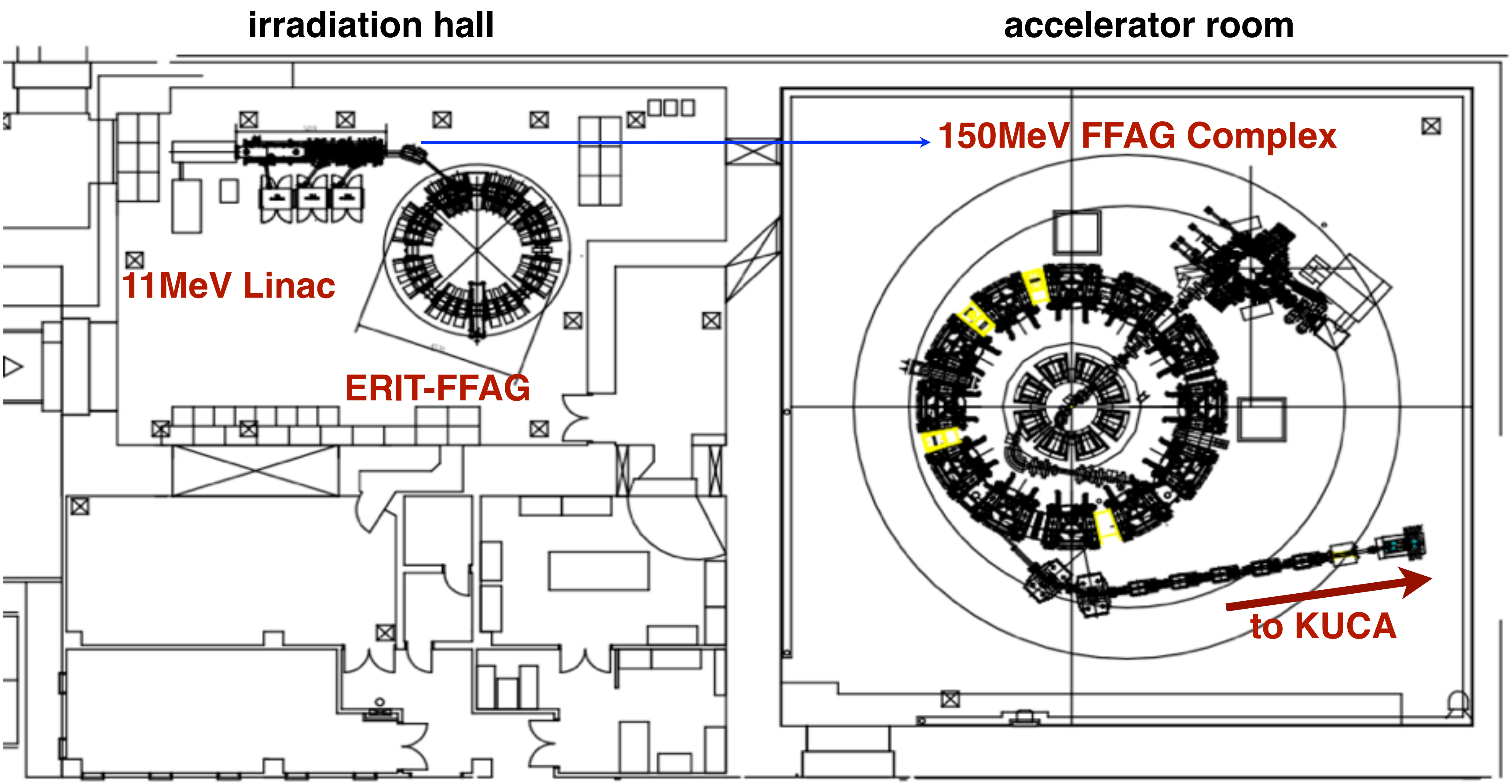
$$\begin{aligned}\Delta\nu_{y,\mathrm{inc}} &= -\frac{N r_0 R}{\pi \nu_y \beta^2 \gamma}\left(\beta^2 \frac{\epsilon_1}{h^2} + \beta^2 \frac{\epsilon_2}{g^2} + \frac{F/B}{\gamma^2 b(a+b)} \right) \\ &= -2.25 \times 10^{-5}\ \mathrm{m}^{-2} \times \left(4.\ \mathrm{m}^2 + 3.\ \mathrm{m}^2 + 14004.\ \mathrm{m}^2\right) \\ &= -0.315\end{aligned}$$

N	3.12×10^{11}	
r_0	1.53×10^{-18}	proton
R_0	4.54 m	average radius of injection orbit
β, γ	0.147, 1.011	11 MeV
ν_x, ν_y	(3.7, 1.4)	
(a, b)	(20, 15) mm	
B_f	1/5	
F	1.5	
h	32.5 mm	half gap of the vacuum chamber
g	37.9 mm	half gap of the magnet

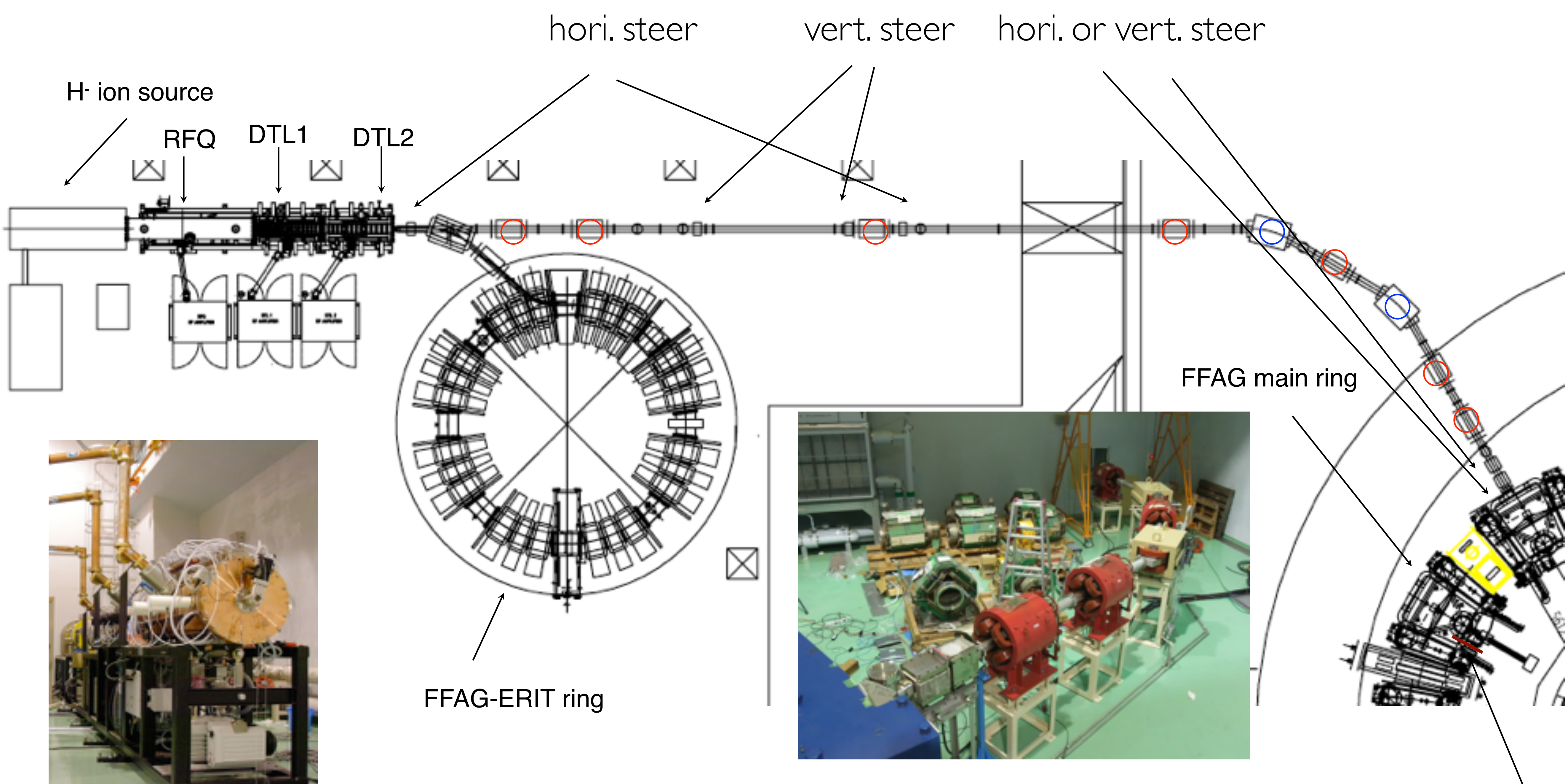
Rep. rate：100 ~ 200 Hz

Average current：5uA

Layout of accelerator complex in the Innovation Research Lab.



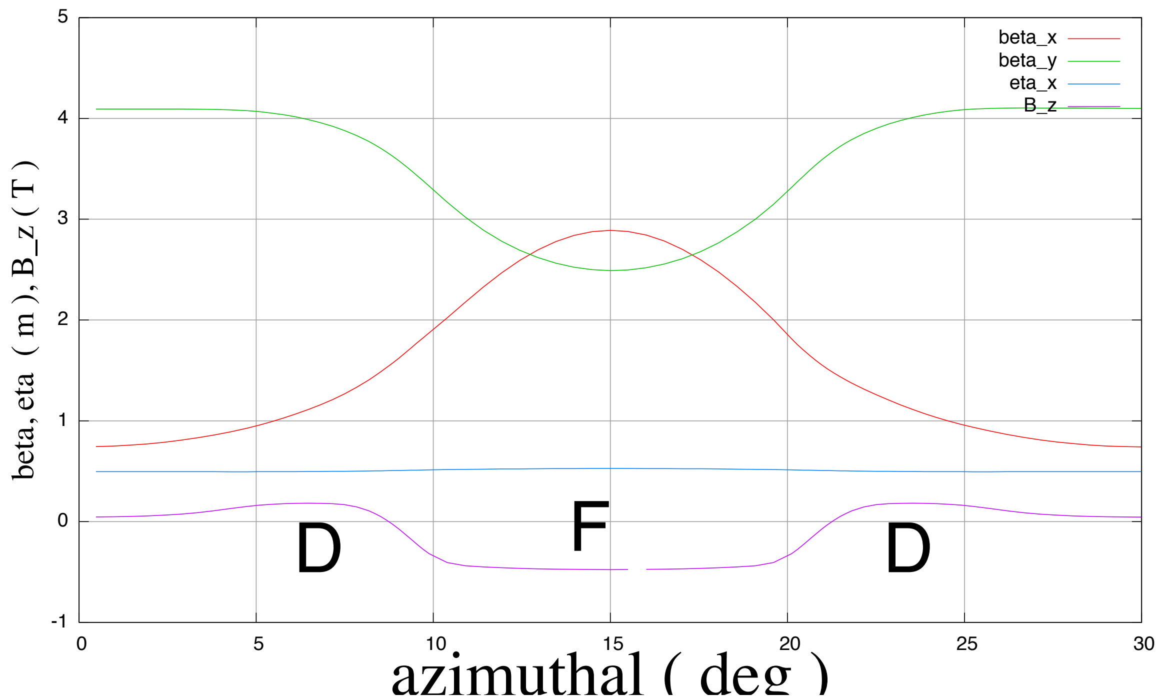
Beam Line from Linac to MR



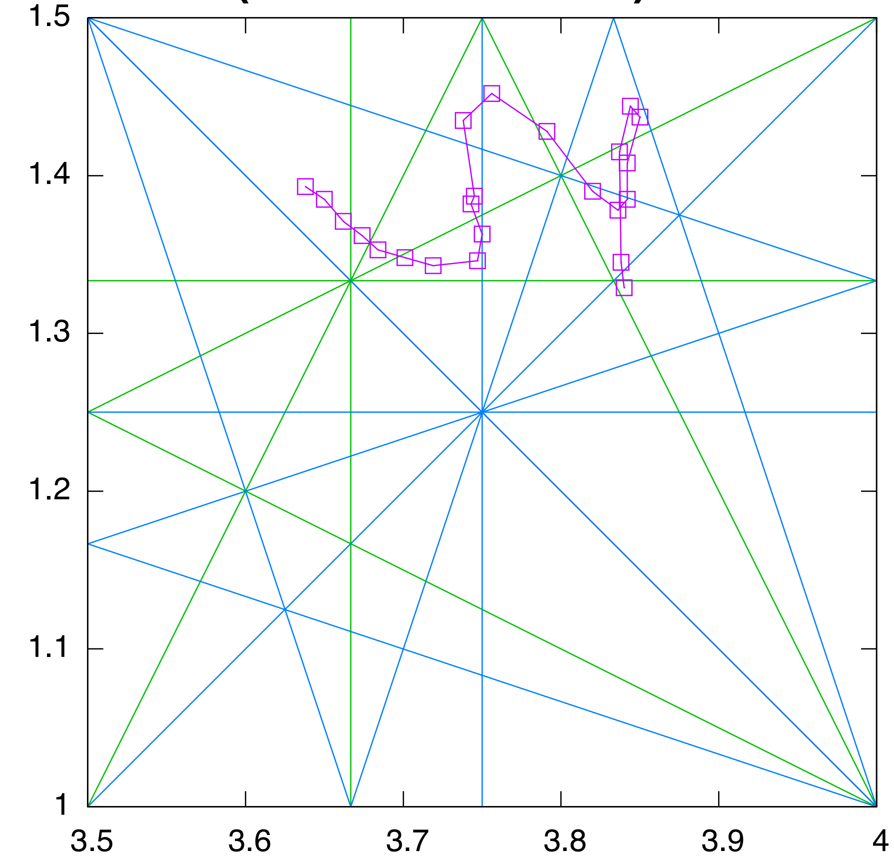
Q Magnet ×8*, B Magnet(30deg) × 2

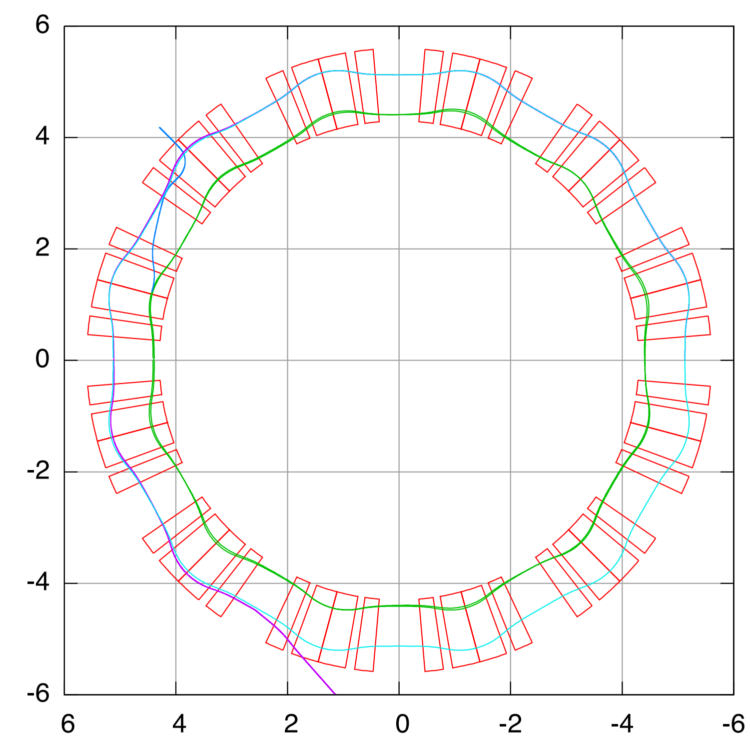
* added one QM inMay 2011

Beta functions and B field in the main ring



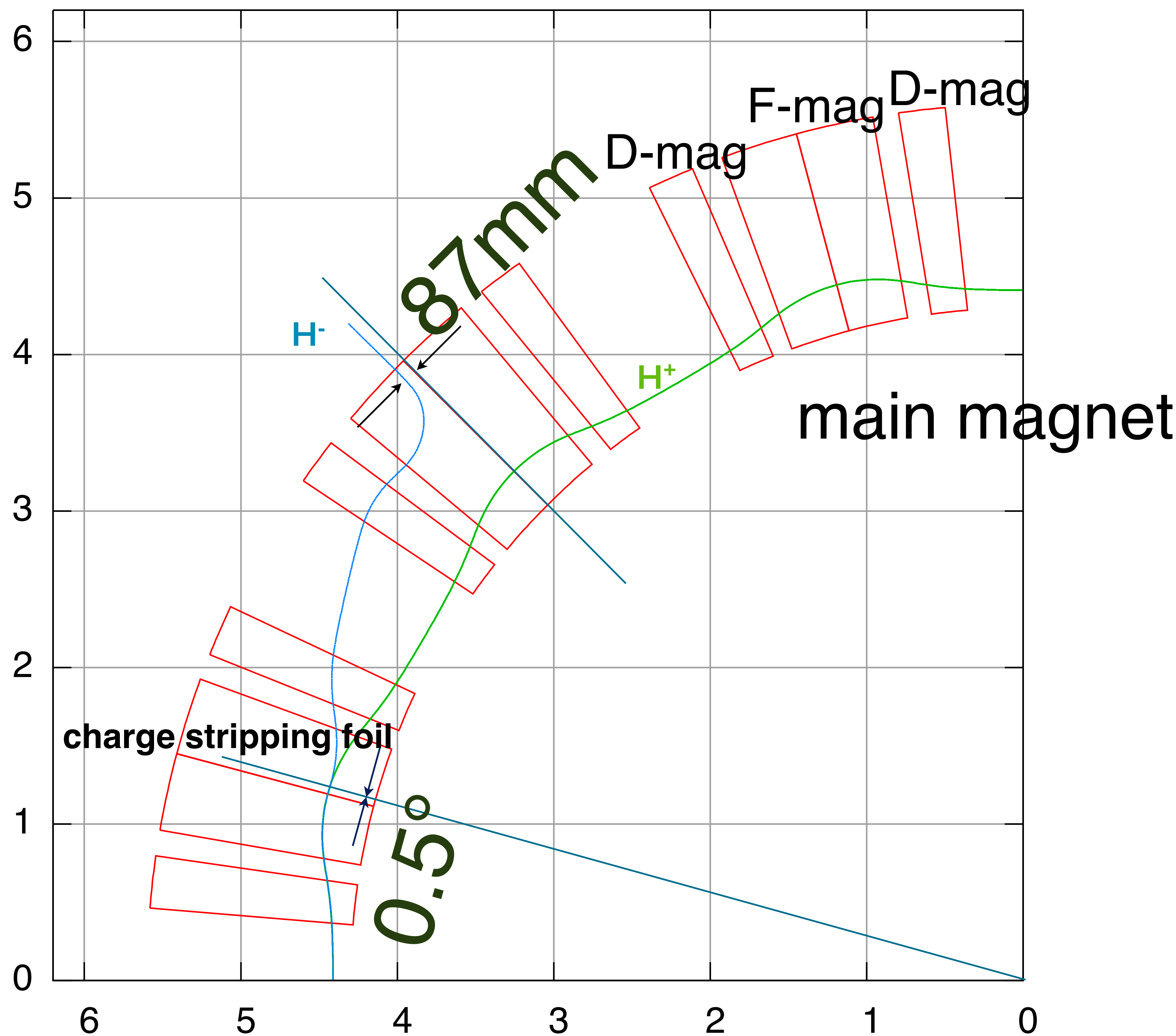
tune variation (measured)





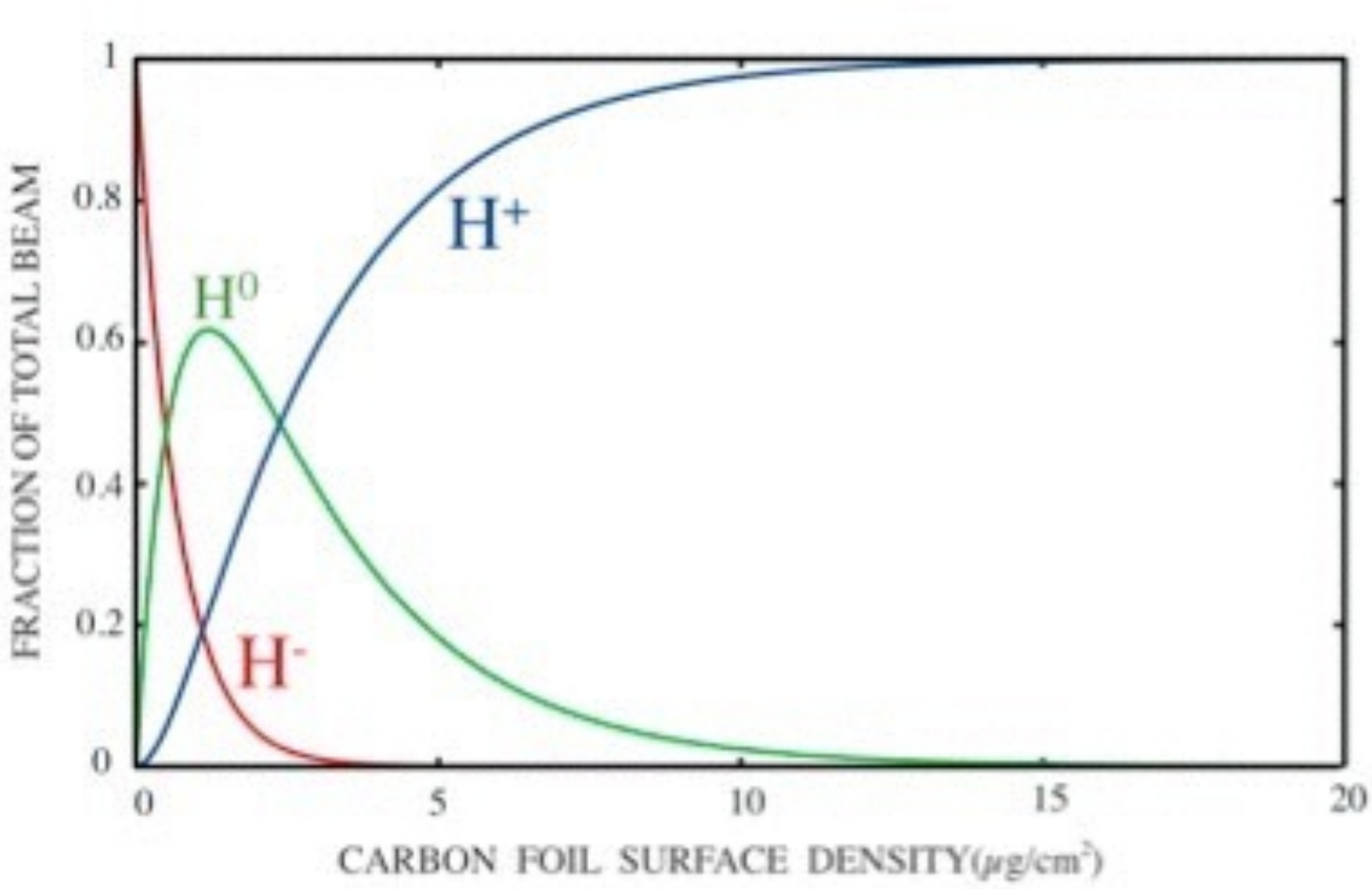
E_{inj}	11MeV
E_{ext}	100/150MeV
f_{rf}	1.6 - 5.2MHz
$< R >$	4.57 - 5.4 m
B_{max}	1.6 T

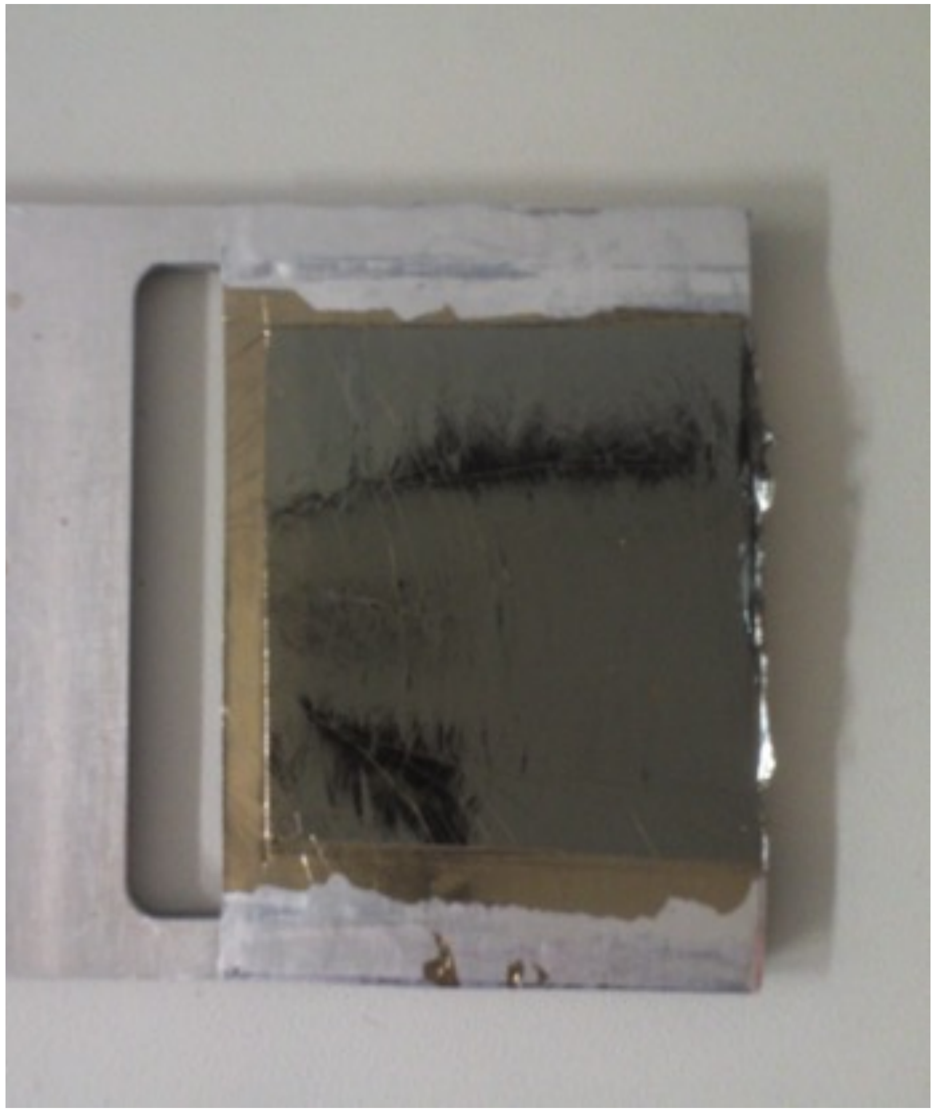
Beam injection to the main



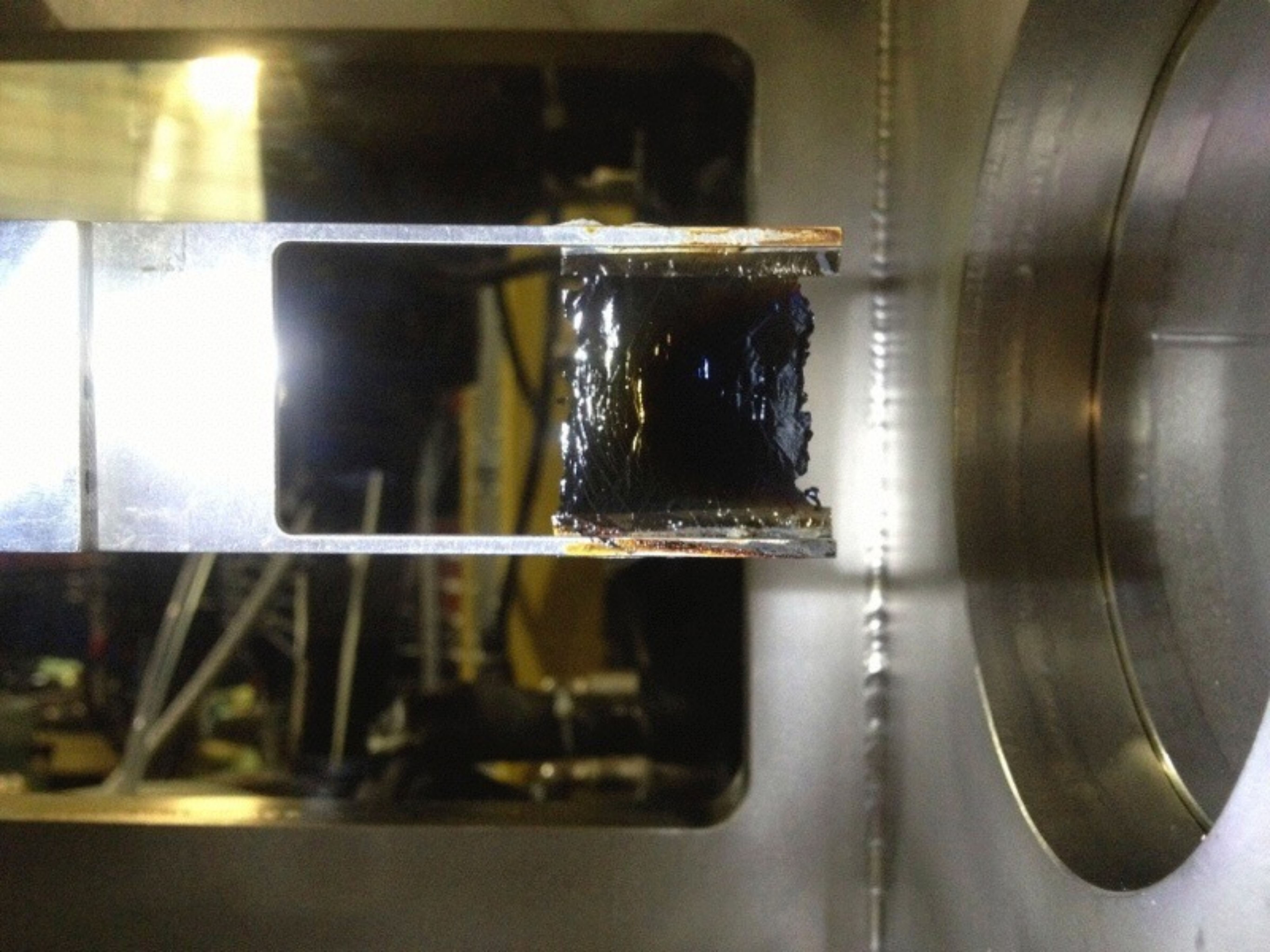
The stripping efficiency of the foil

brand-new foil
20 ug/cm2





after 1.5 years...



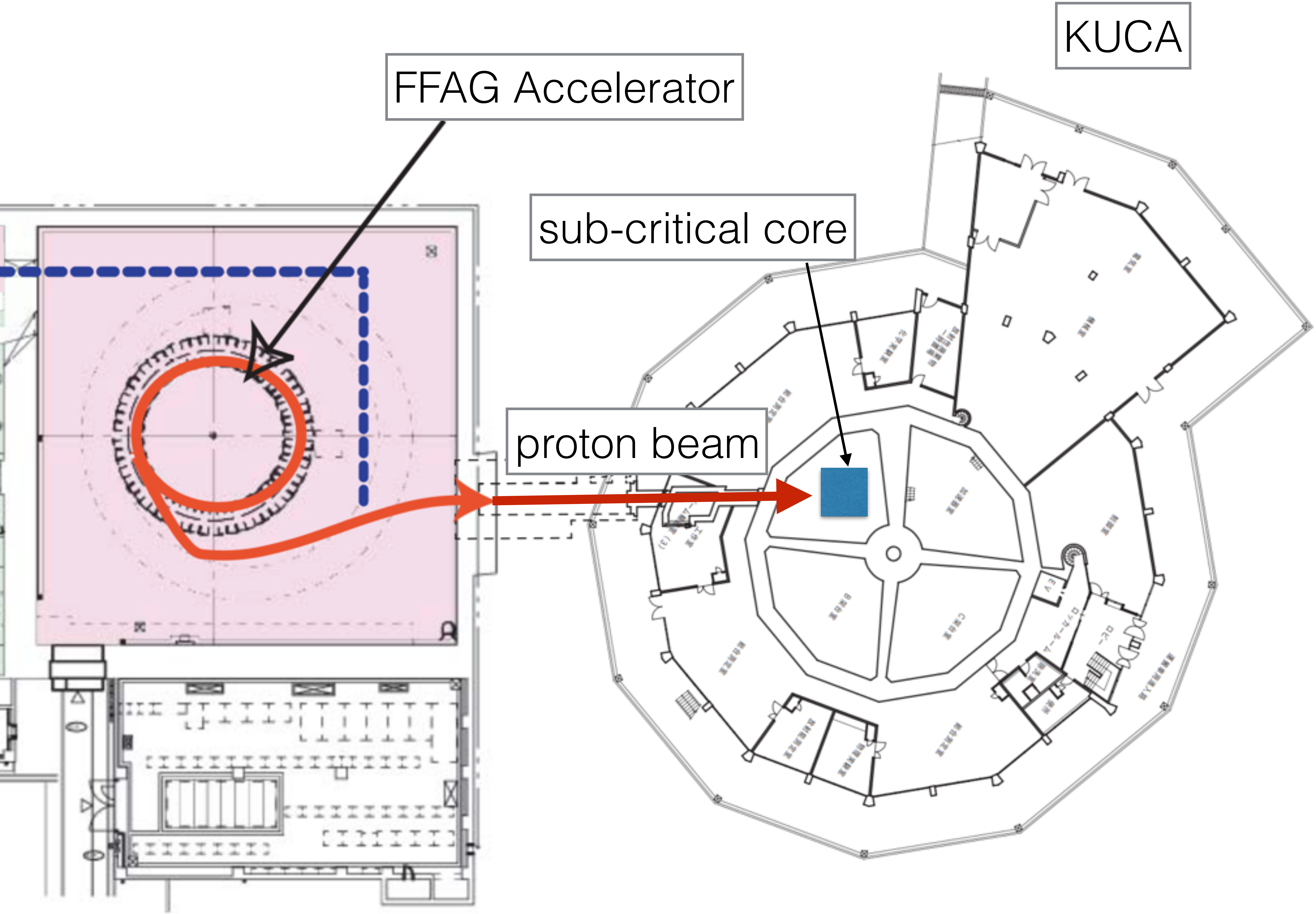
History of beam intensity and energy upgrade in recent years

year	Energy (MeV)	intensity		rep.rate (Hz)	injector	notes
		extraction	@CA target			
March 2009	100	50pA	~3 pA	30	ion beta booster	-
March 2010	100	100pA	30pA	30	ion beta booster	transport efficiency up cavity voltage 2.5 ->4kV
March 2011	100	1nA	100pA	20	H-	H- injection kicker system upgrade
March 2012	100	10nA	100pA	20	H-	bad focusing on CA target
March 2013	150	10 nA	1nA	20	H-	energy up (150 MeV for irr. exp.) still 100 MeV for ADS exp. beam tripped often due to rf trouble (in both linac and main ring)
March 2014	150	10 nA	1 nA	20	H-	reliable supply based on stable rf

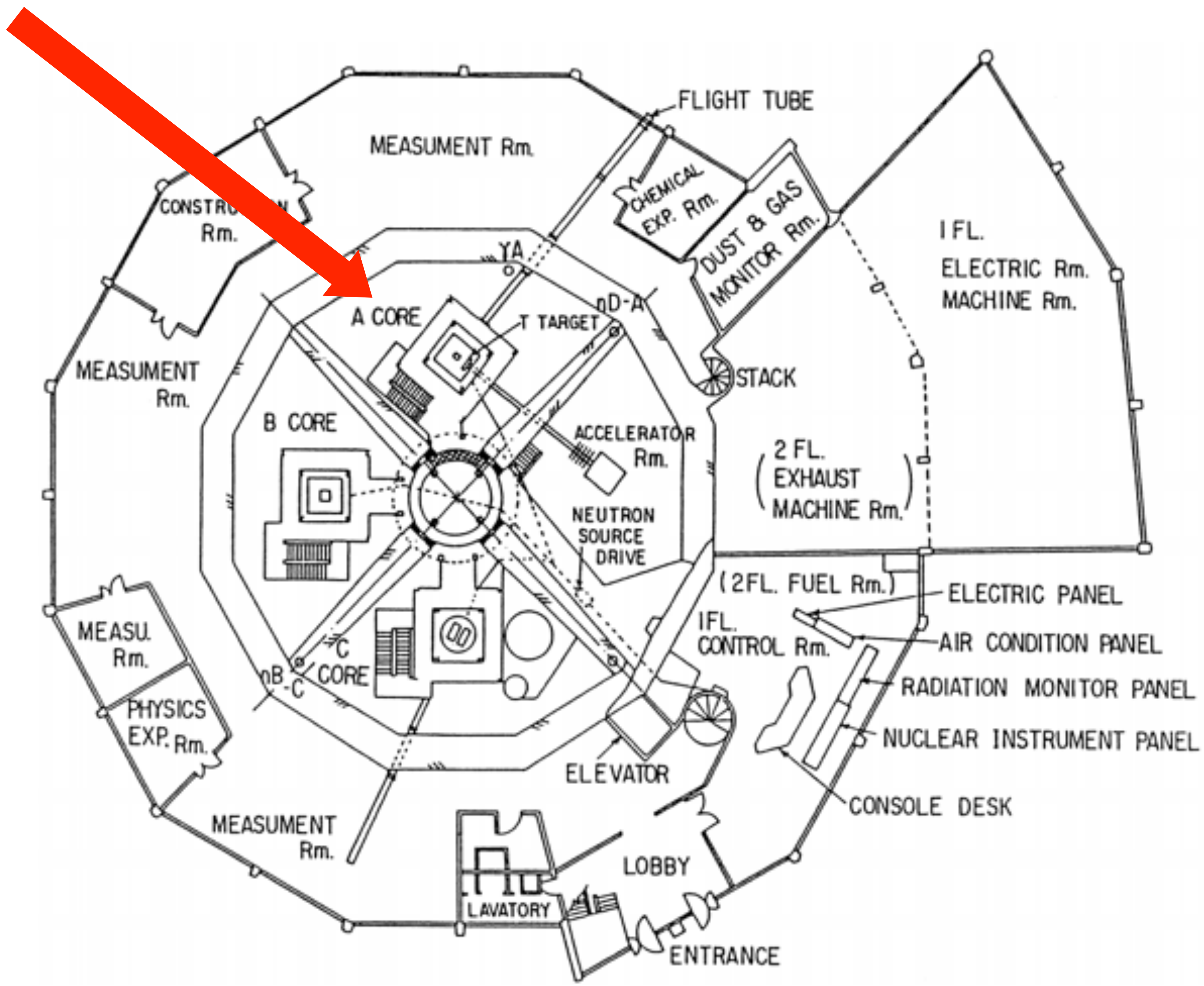
Beam Users

- ADS experiment
- Irradiation for materials
- Medical experiment (irradiation to living rats)

ADSR experiments at KURRI


KUCA
FFAG Accelerator
sub-critical core
proton beam

KUCA



Output power ~10W

KUCA Configurations

3 critical assemblies :

i. A & B cores

Polyethylene Mod./Ref.

ii. C core

H_2O Mod./Ref.

2 accelerators :

i. Cockcroft-walton type

(D,T) reaction

14 MeV neutrons

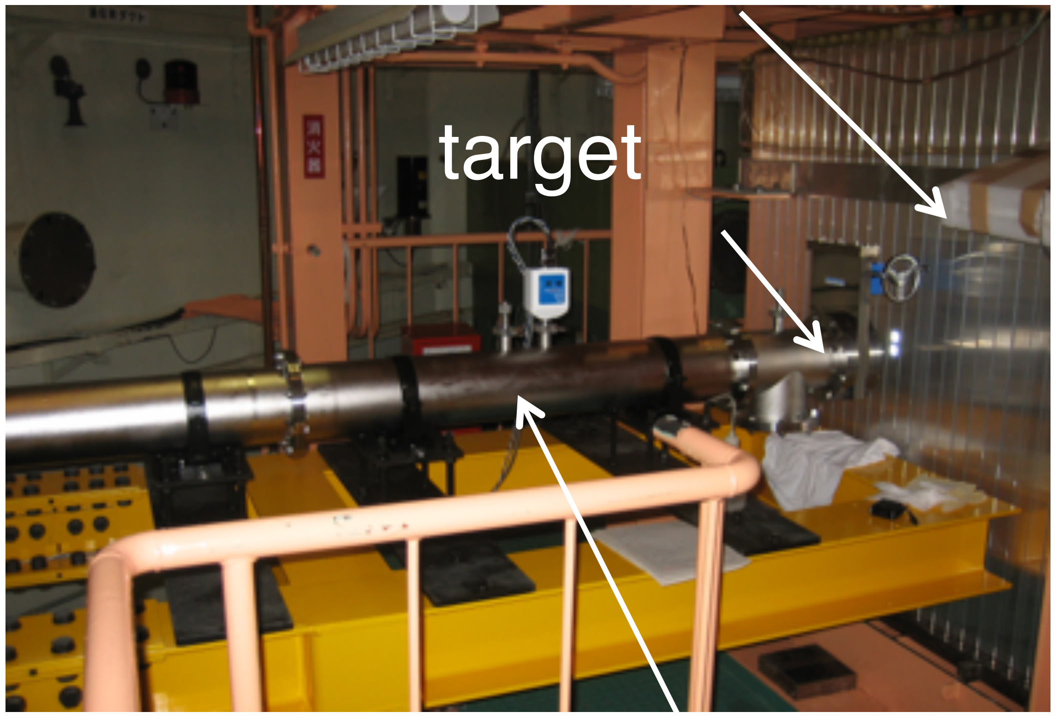
ii. FFAG type

100 MeV protons

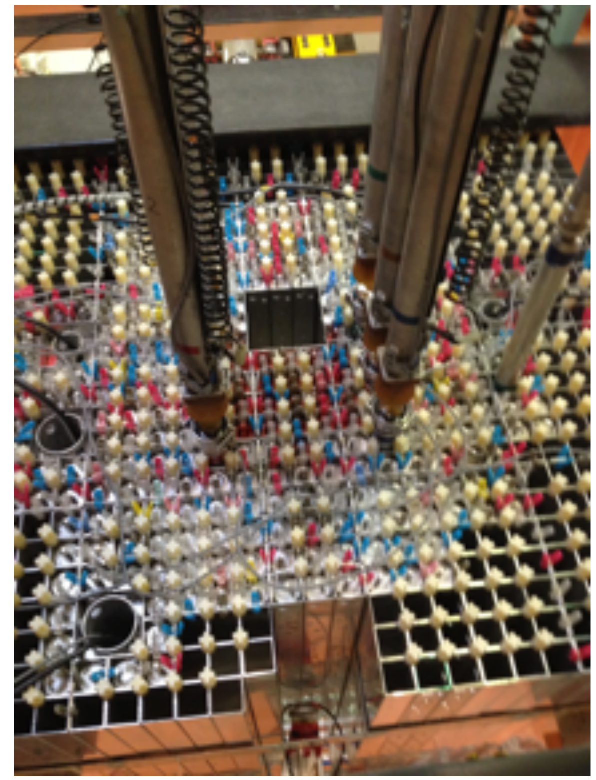
from KUCA Outside

ADSR Experiment Setup

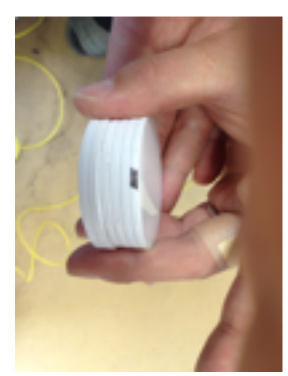
Reactor core

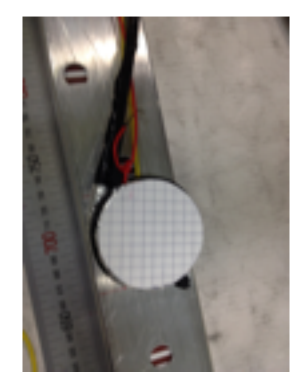


Beam transport line



Subcritical fuel system





W or Pb-Bi target w/ read out as FC

FFAG Accelerator :

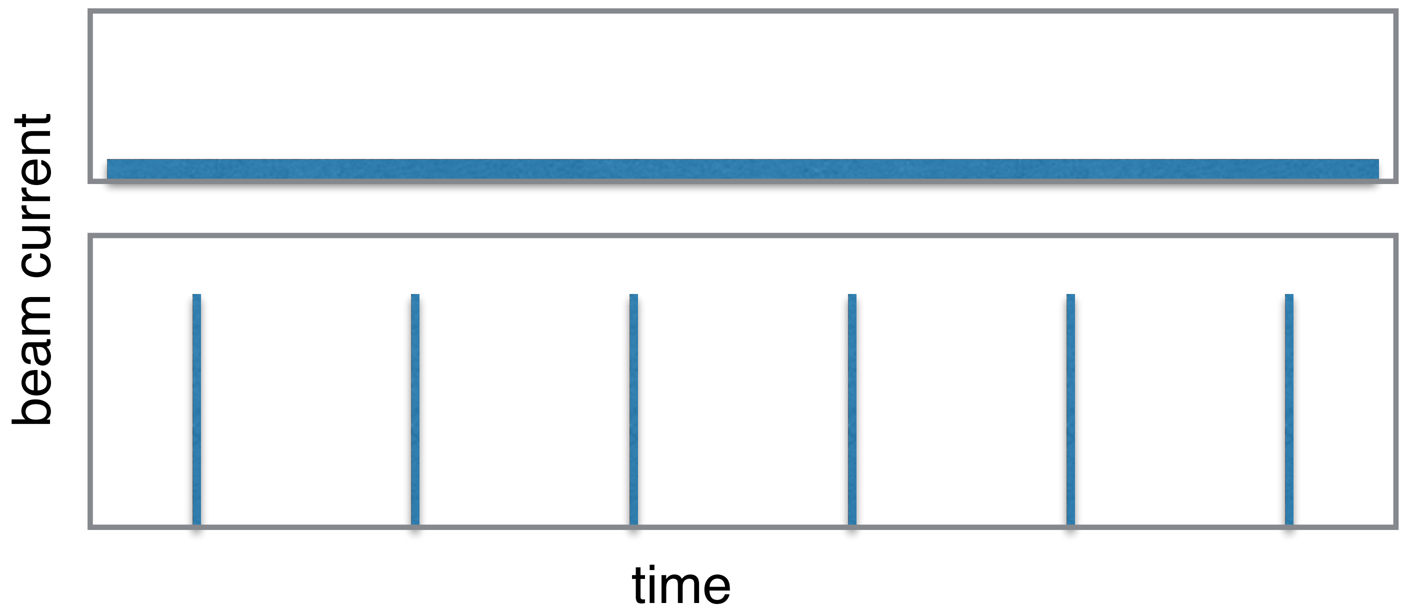
- 100 MeV Protons
- 20, 30 Hz repetition rate
- 1nA intensity
- W and Pb-Bi target

KUCA A-Core :

Basic beam parameters for ADS experiments at KURRI

KUCA	Output power	~ 10 W
	Neutron multiplication	$\alpha = 1 / (1 - k_{eff})$
		$k_{eff} = 0.99$, $\alpha = 100$
	Beam power requirement	< 0.1W
	cf. For 100MeV proton beam,	I < 1 nA

FFAG	Beam energy of FFAG	T = 100 MeV
	Beam current of FFAG	I < 1 nA
	Pulse width	~ 20 ns
	Repetition rate	20 - 100 Hz
	Energy spread	< +/- 1%



CW beam
(Super con. LINAC or Cyclotron)

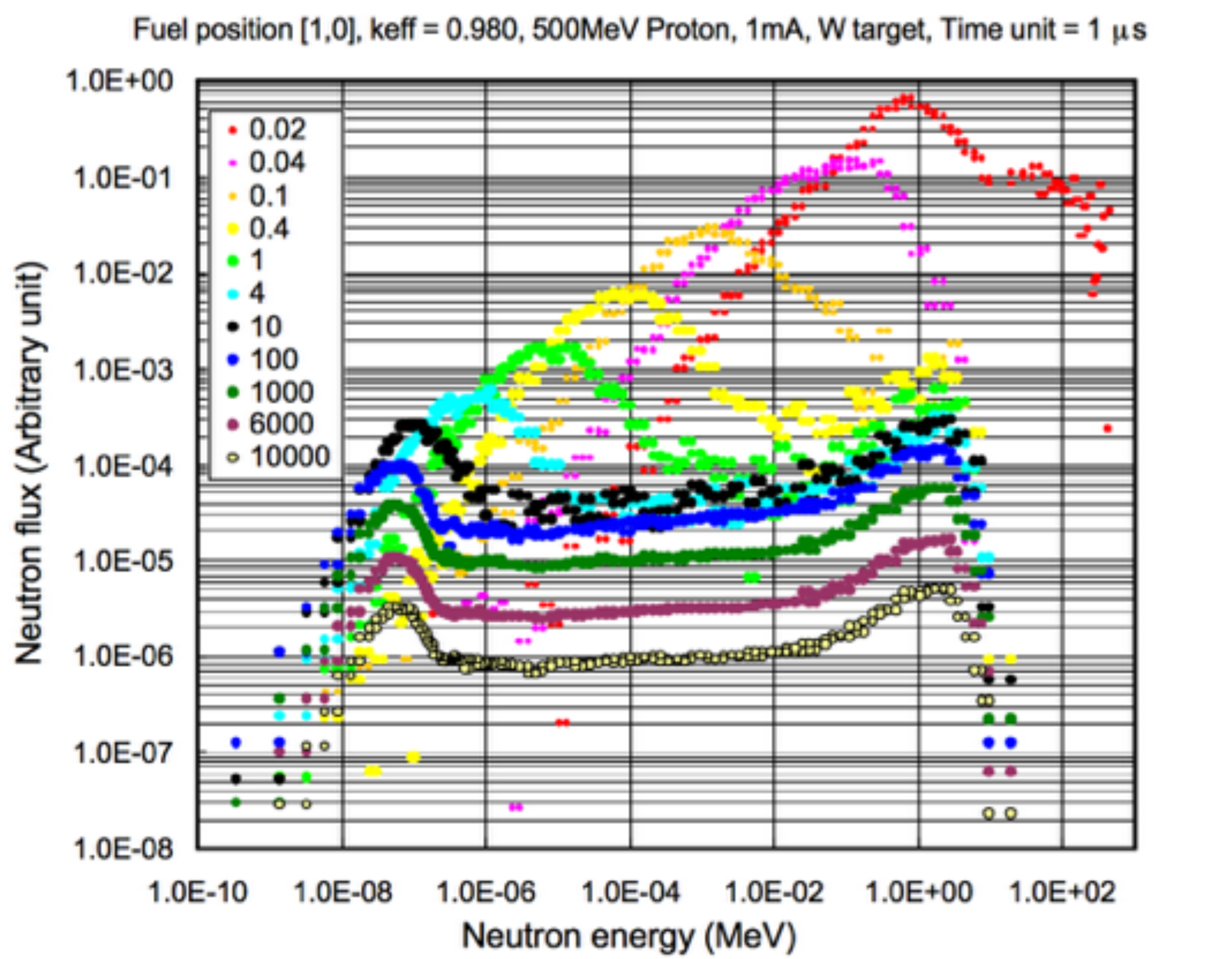
Pulse beam(RCS or FFAG)

Average current only 1nA
But peak power

$$P_{\mathrm{peak}} = \frac{100\text{ MeV x 1 nA}}{20\text{ns x 20Hz}}$$

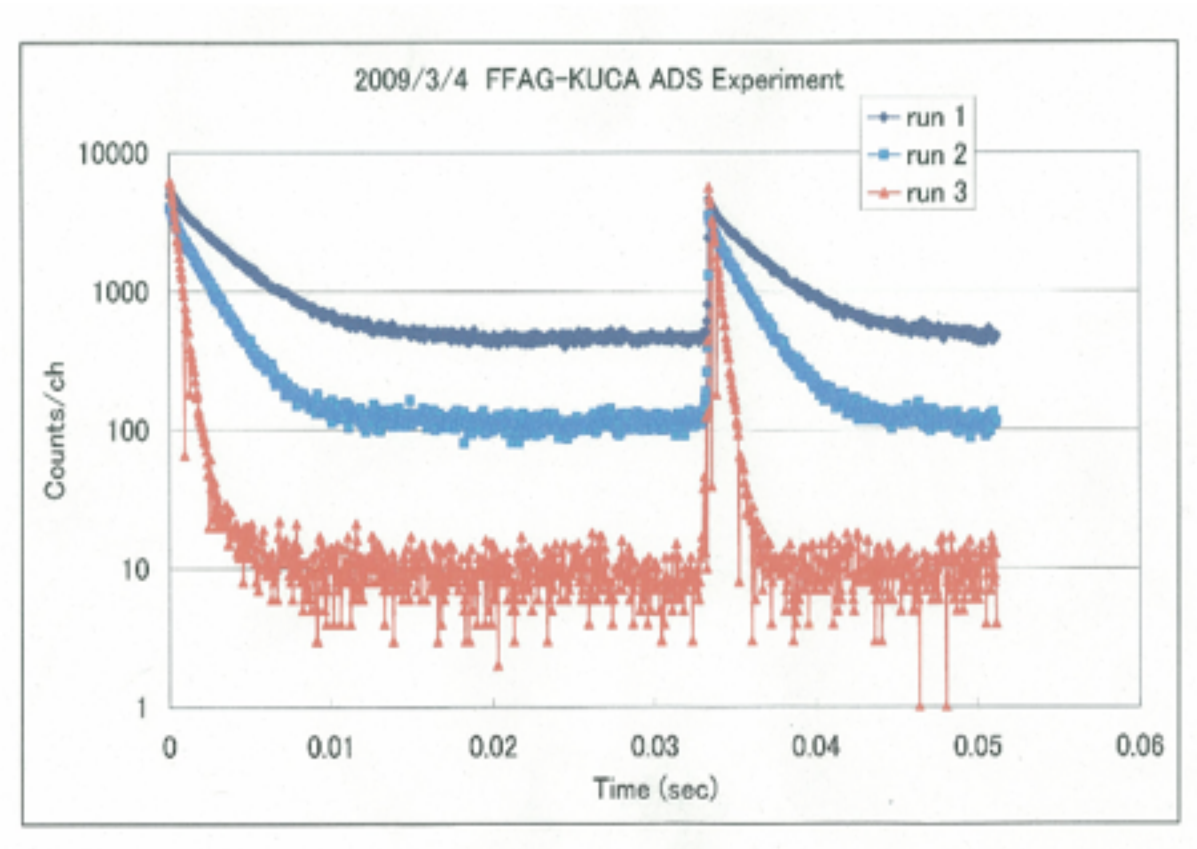
$$= .25\text{ MW}$$

Dynamic characteristics of the core within 20 ns can be measured with extremely high peak power beam



The neutron energy spectrum in the core as a function of time measured from the beam hitting the target

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



Two components in the neutron counting rate:

1. The fast component decaying exponentially

2. the slow component caused by delayed neutrons almost constant in time.

The presence of the delayed neutrons indicates that neutrons generated through nuclear fission chain reaction inside 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

Related papers

C. H. Pyeon, *et al.*, *J. Nucl. Sci. Technol.*, **44**, 1368 (2007).
C. H. Pyeon, *et al.*, *J. Nucl. Sci. Technol.*, **45**, 1171 (2008).
C. H. Pyeon, *et al.*, *J. Nucl. Sci. Technol.*, **46**, 965 (2009).
H. Shahbunder, *et al.*, *Ann. Nucl. Energy*, **37**, 592 (2010).
H. Taninaka, *et al.*, *J. Nucl. Sci. Technol.*, **47**, 376 (2010).
H. Shahbunder, *et al.*, *Ann. Nucl. Energy*, **37**, 1214 (2010).
H. Taninaka, *et al.*, *J. Nucl. Sci. Technol.*, **48**, 873 (2011).
H. Taninaka, *et al.*, *J. Nucl. Sci. Technol.*, **48**, 1272 (2011).
C. H. Pyeon, *et al.*, *Ann. Nucl. Energy*, **40**, 229 (2012).

C. H. Pyeon, *et al.*, *Ann. Nucl. Energy*, **38**, 2298 (2011).
C. H. Pyeon, *et al.*, *Nucl. Sci. Eng.*, **177**, 156 (2014).
M. Yamanaka, *et al.*, PHYSOR 2014, (2014).

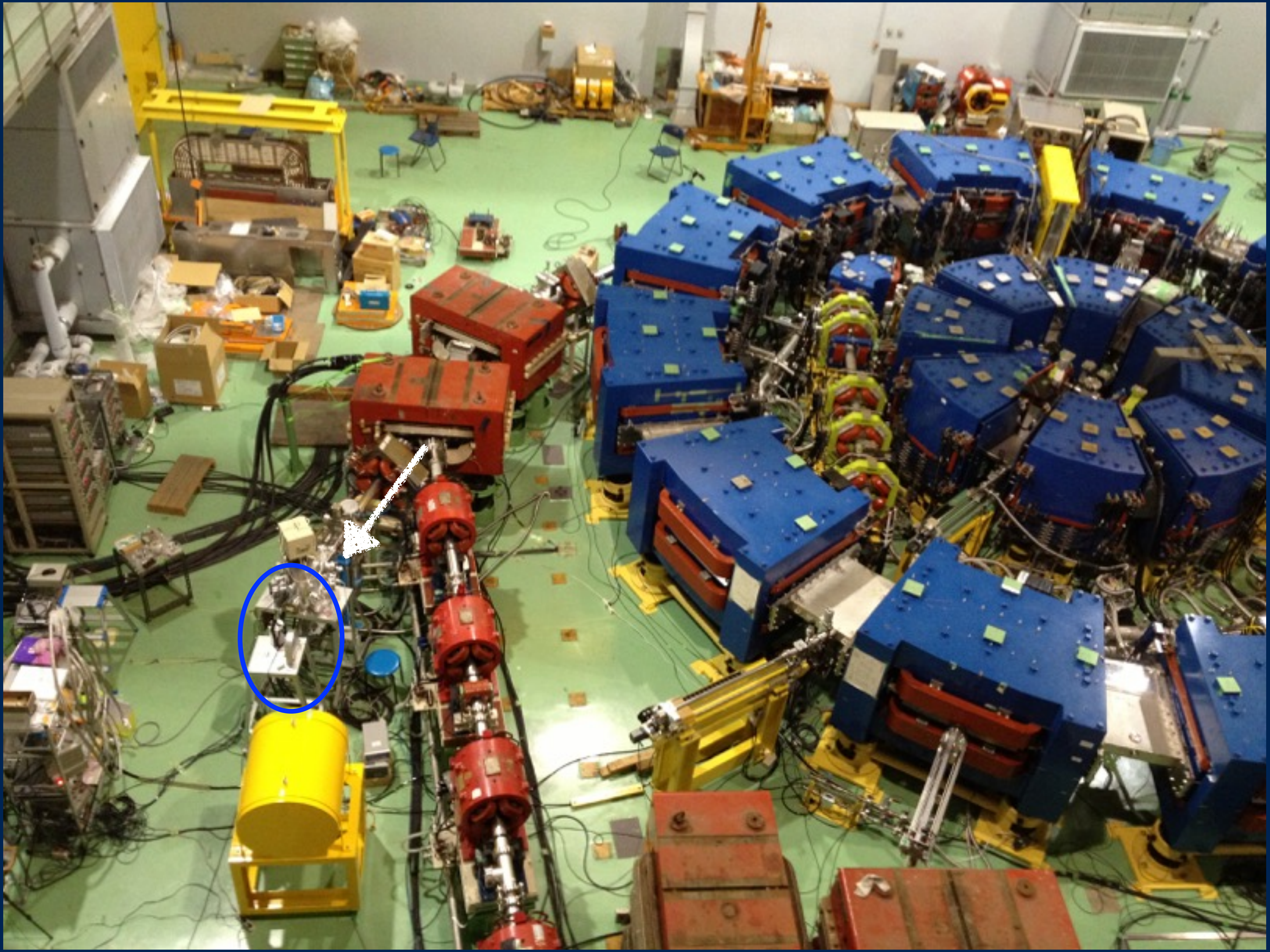
J. Y. Lim, *et al.*, *Sci. Technol. Nucl. Install.*, **2012**, ID: 395878, 9 pages, (2012).
C. H. Pyeon, *et al.*, *Nucl. Eng. Technol.*, **45**, 81 (2013).
A. Sakon, *et al.*, *J. Nucl. Sci. Technol.*, **50**, 481 (2013).
A. Sakon, *et al.*, *J. Nucl. Sci. Technol.*, **51**, 116 (2014).
C. H. Pyeon, *et al.*, PHYSOR 2014, (2014).
C. H. Pyeon, *et al.*, *Prog. Nucl. Energy*, (2014). [in print]

most cited award

"First Injection of Spallation Neutrons Generated by High-Energy Protons into the Kyoto University Critical Assembly "

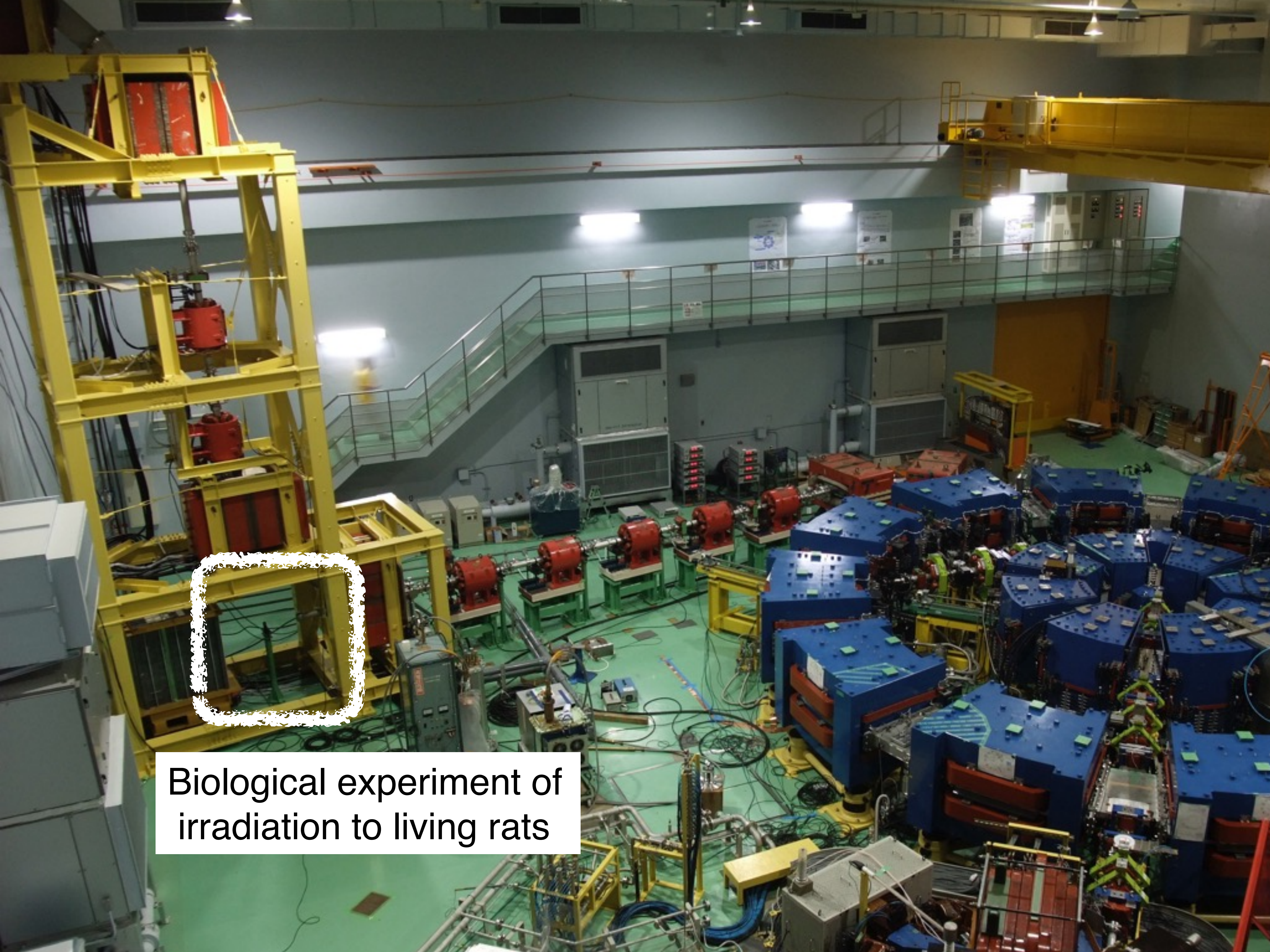
Other experiments using 150MeV proton beams from the complex

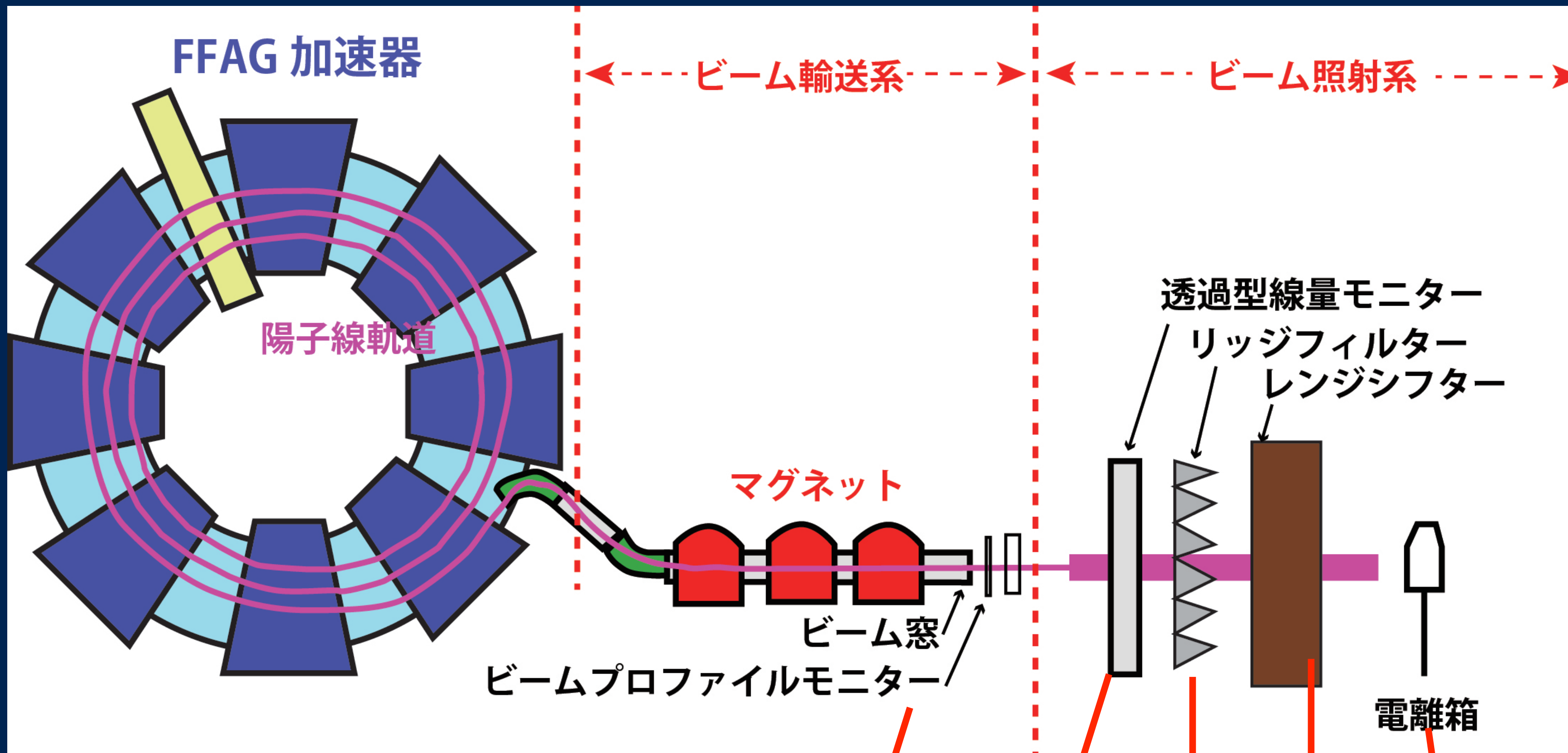
Beam Line and Chamber for Irradiation Experiments



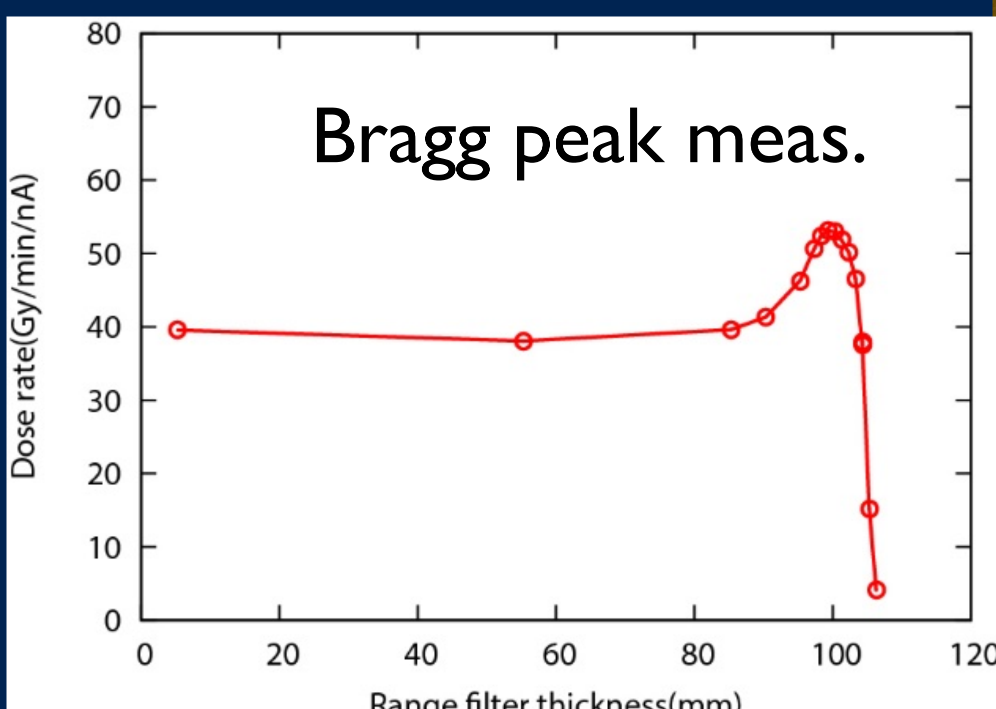
The irradiation port connected to the 150 MeV proton beam line. It has cryogenics and traction control machine inside which realize measurements under irradiation of the proton beam.

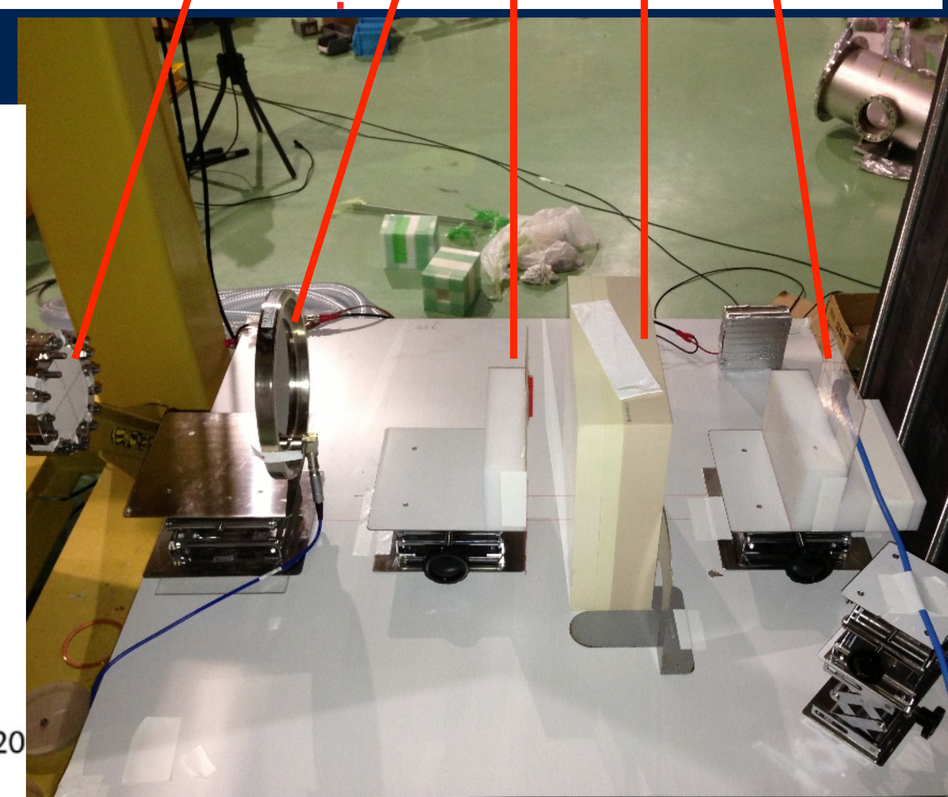
The experiments measure the effect of the irradiation of the proton beams to the material of the pressure vessel used in ADSR reactor.


Biological experiment of
irradiation to living rats

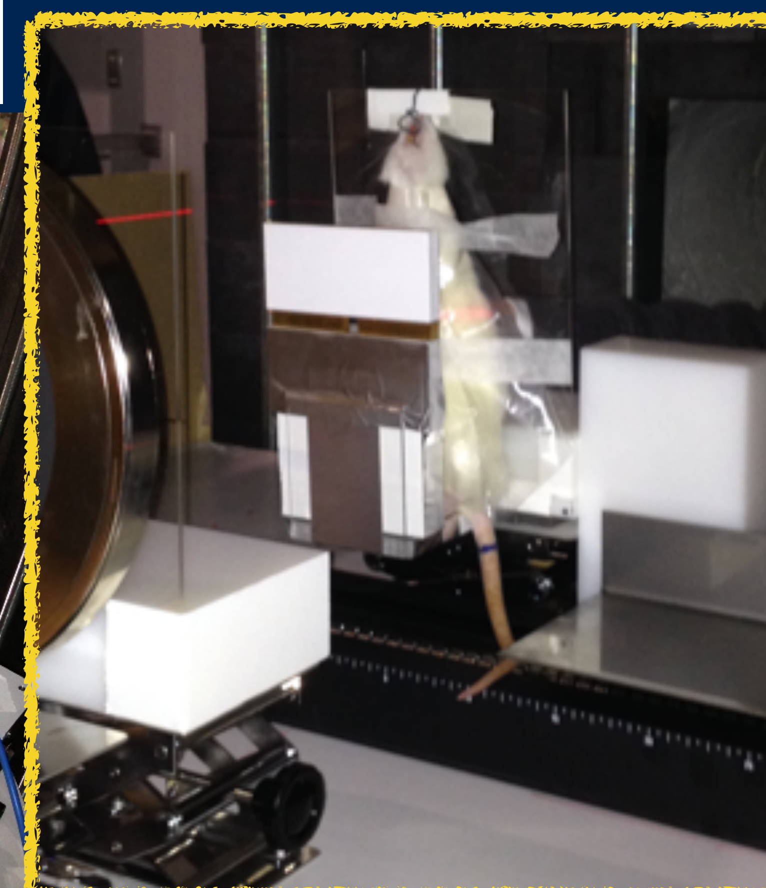


Basic study for BNCT. It investigate the effect of irradiation of the proton to the normal cells.





a narcotised rat



Future Projects

In order to make the facility multi-capable, we are investigating two upgrade possibilities:

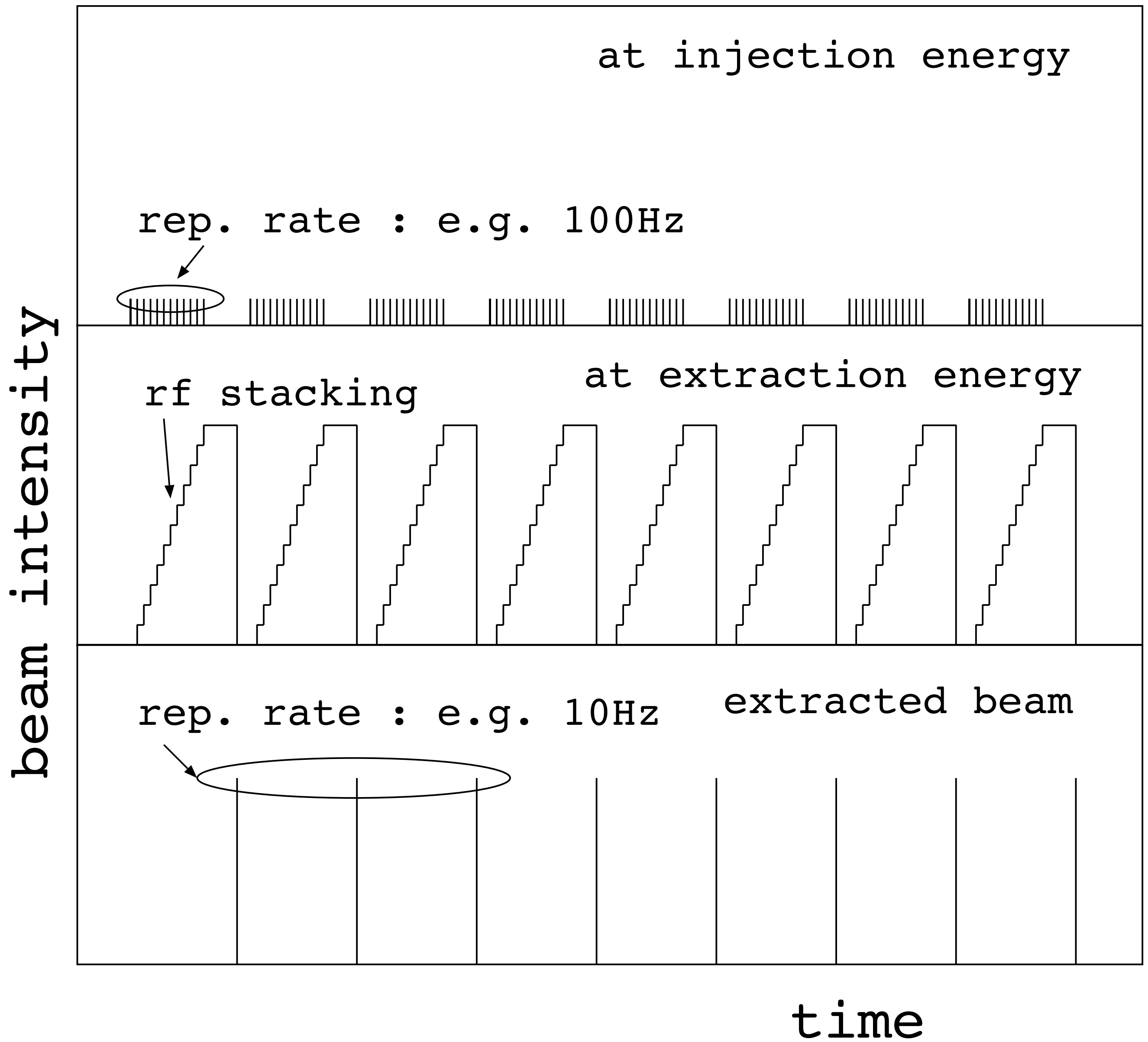
1. Increasing the beam current up to the order of µA by increasing the repetition rate at the order of 100 Hz.
    - e.g. spallation neutron source
2. Energy upgrade by adding a new ring outside the main ring.
    - further study of ADSR,
    - secondary particle production (pion , muon) using extended ERIT mechanism

Intensity upgrade

1. One of the aims of the intensity upgrade is that FFAG beams can be used for high intensity pulse neutron source.
2. Neutron radiography users desire low spill rate (~10 Hz) for the experiments e.g. neutron radiography using TOF which needs to get rid of contamination from the pulse of different timing.
3. FFAG can increase the beam intensity by raising up a repetition rate at 100 - 1000 Hz.
4. But it is not allowed for the TOF measurements.

Use RF stacking at the extraction orbit!

RF stacking at the extraction energy

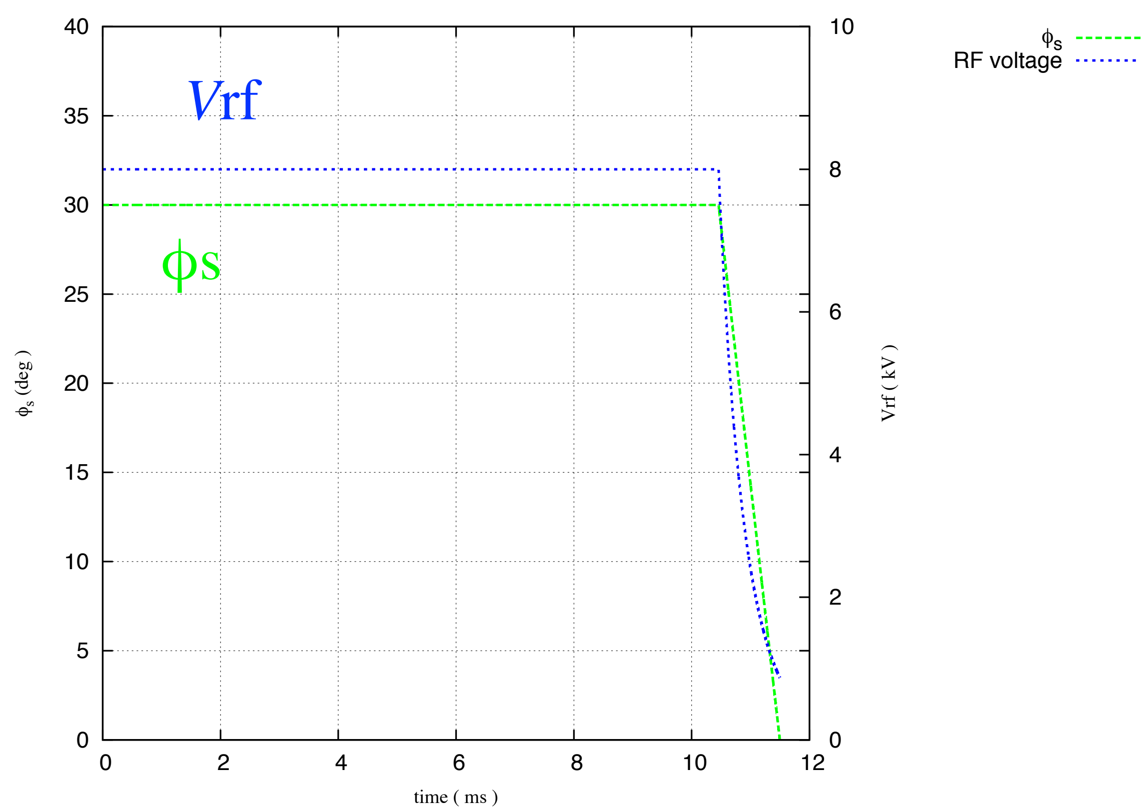


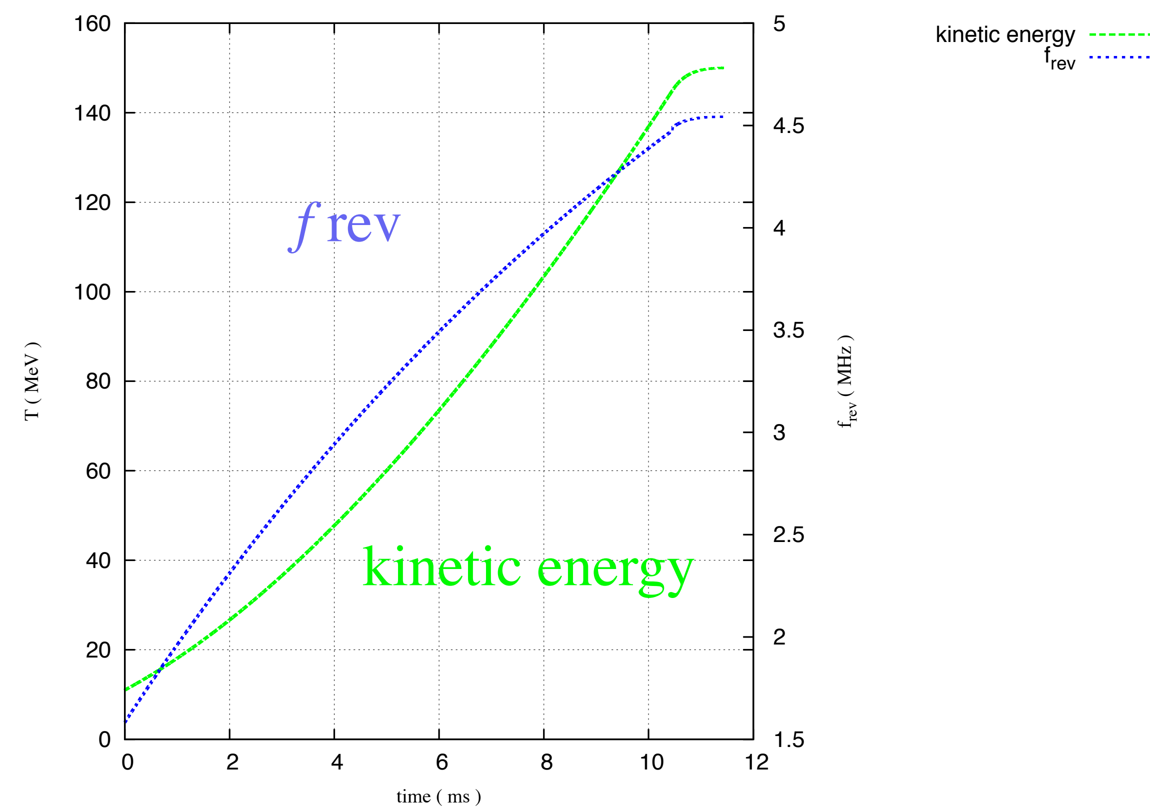
FFAG rings can provide long interval pulse for users, while the machine operation itself is kept at high repetition rate by using rf stacking after acceleration[1].

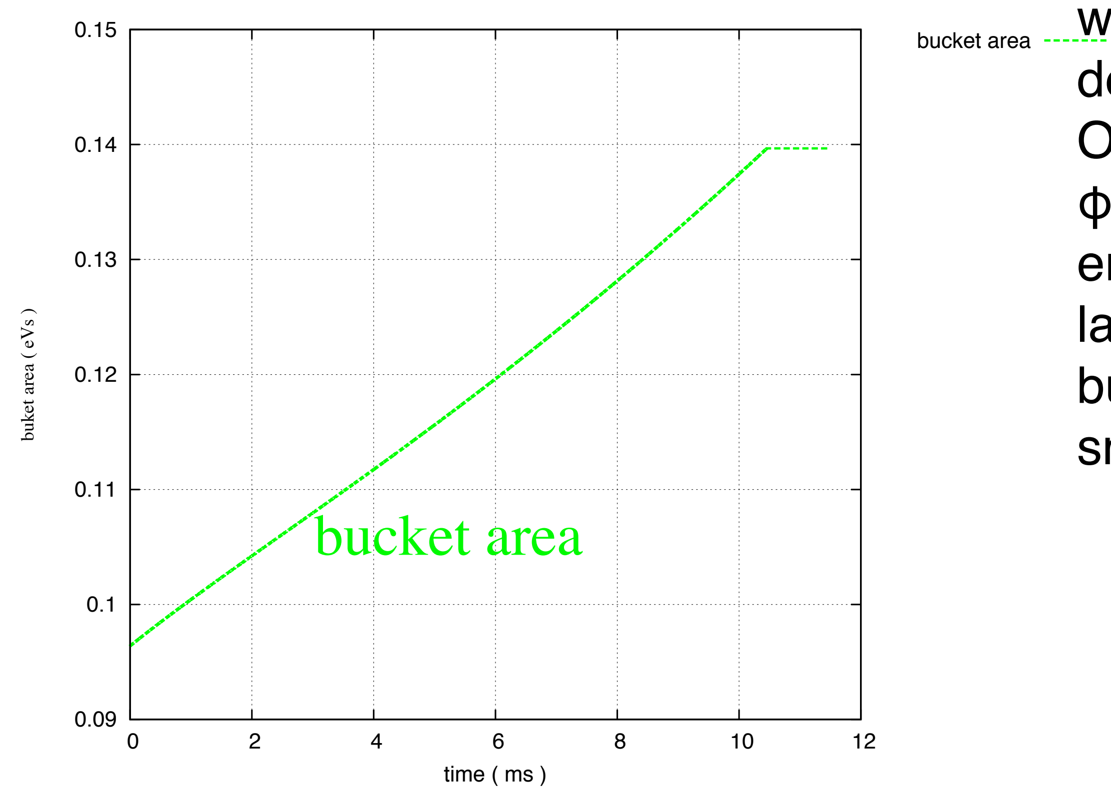
This scheme reduces space charge effects.

[1] S.Machida,“RFStackingatExtractionMomentum”,FFAG Workshop 2003,October 13-17, 2003 at BNL, http://www.cap.bnl.gov/mumu/conf/ffag- 031013/Machida2.pdf.

RF Scenario

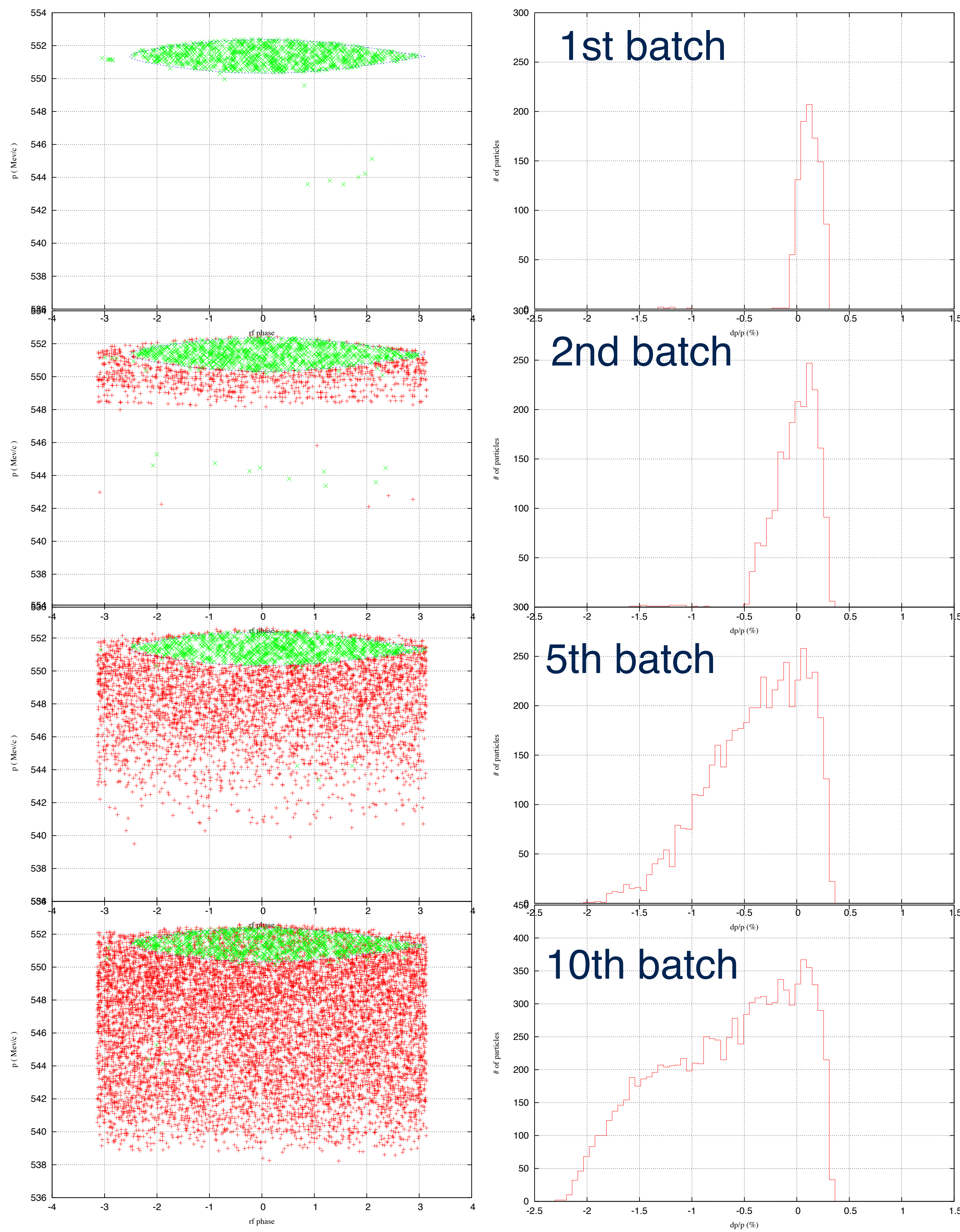






In the real machine operation, we use similar scenarios in which synchronous phase ϕs and rf voltage are fixed at 30 degree and 4 kV respectively during all the acceleration period. On the other hand, in the scenario used in this simulation study, ϕs is dropped off linearly from 30 to zero degree when the energy of the beam is between 145 and 150 MeV for soft-landing. The rf voltage is also reduced in this region so that the bucket area is constant in order to make momentum spread small at the end of acceleration.

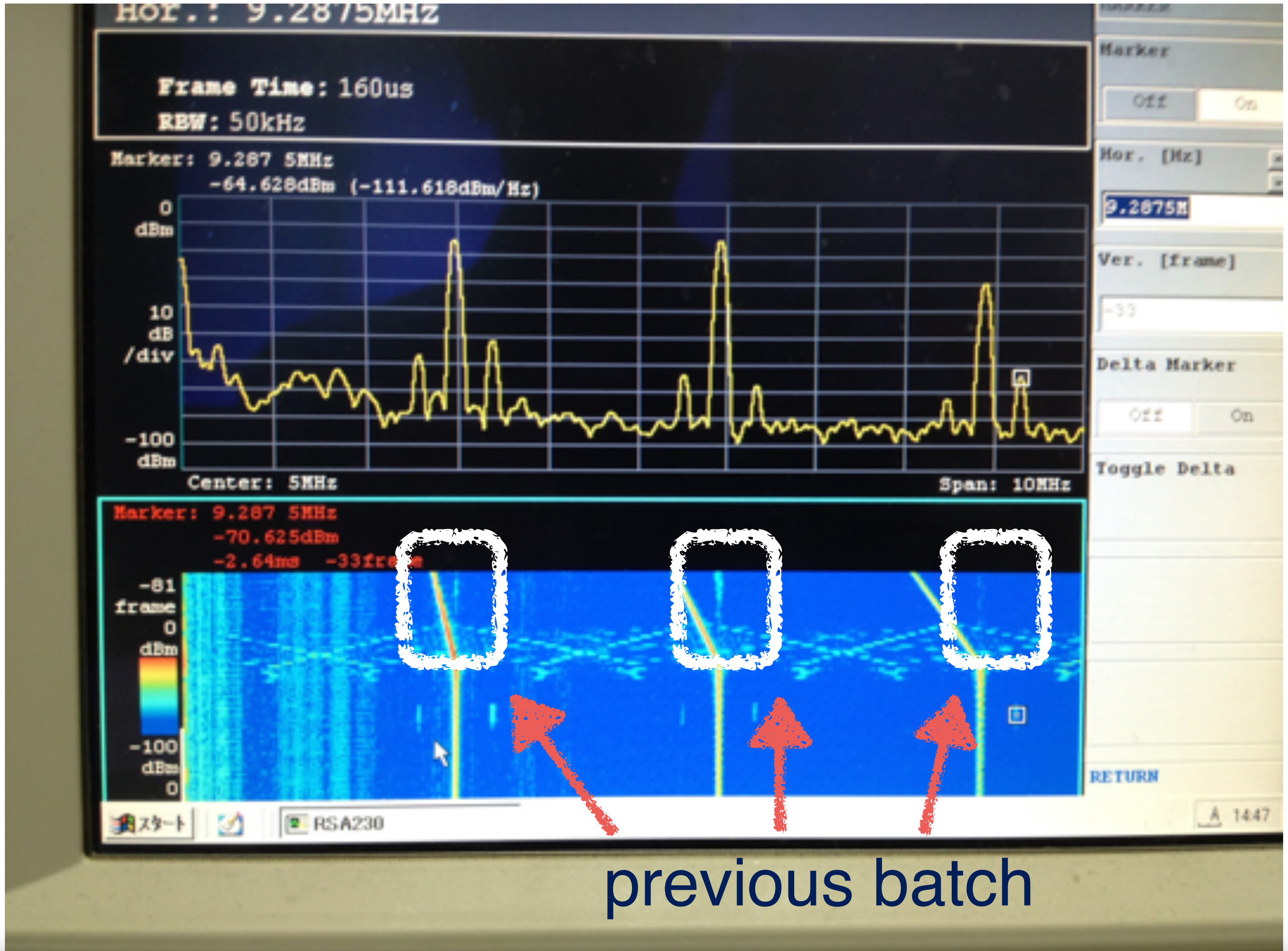
field index k	7.7
kinetic energy T	11 - 150 [MeV]
momentum p	144 - 551 [MeV/c]
circumference C	28.8 - 33.6 [m]
momentum compaction factor α	0.115
rf voltage $V_{\rm rf}$	8 [MV]
rf frequency $f_{\rm rf}$	1.6 - 4.4 [MHz]
harmonic number h	1

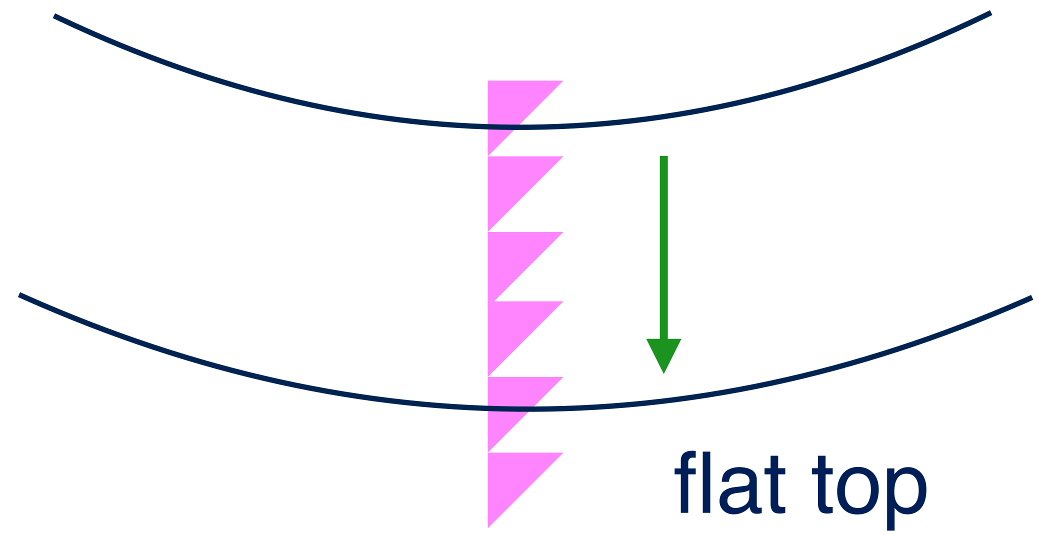


Stacking processes are simulated using 1 000 test particles for each acceleration batch.After first ac- celeration, full width of momentum spread is about 0.5%, the final momentum spread after 10 stacks is 2.5% of full width.

w/ adiabatic landing

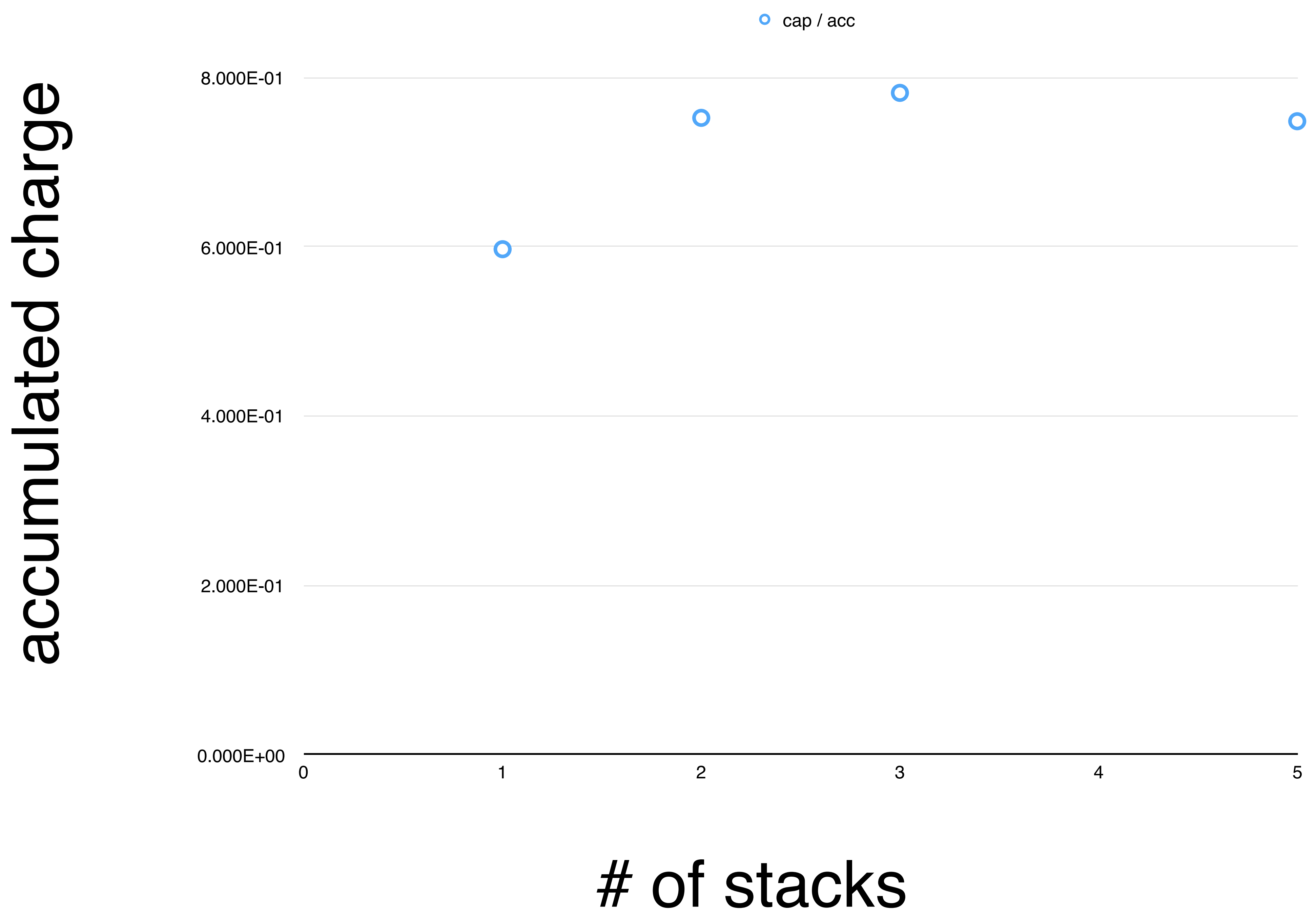
Sign of RF stacking



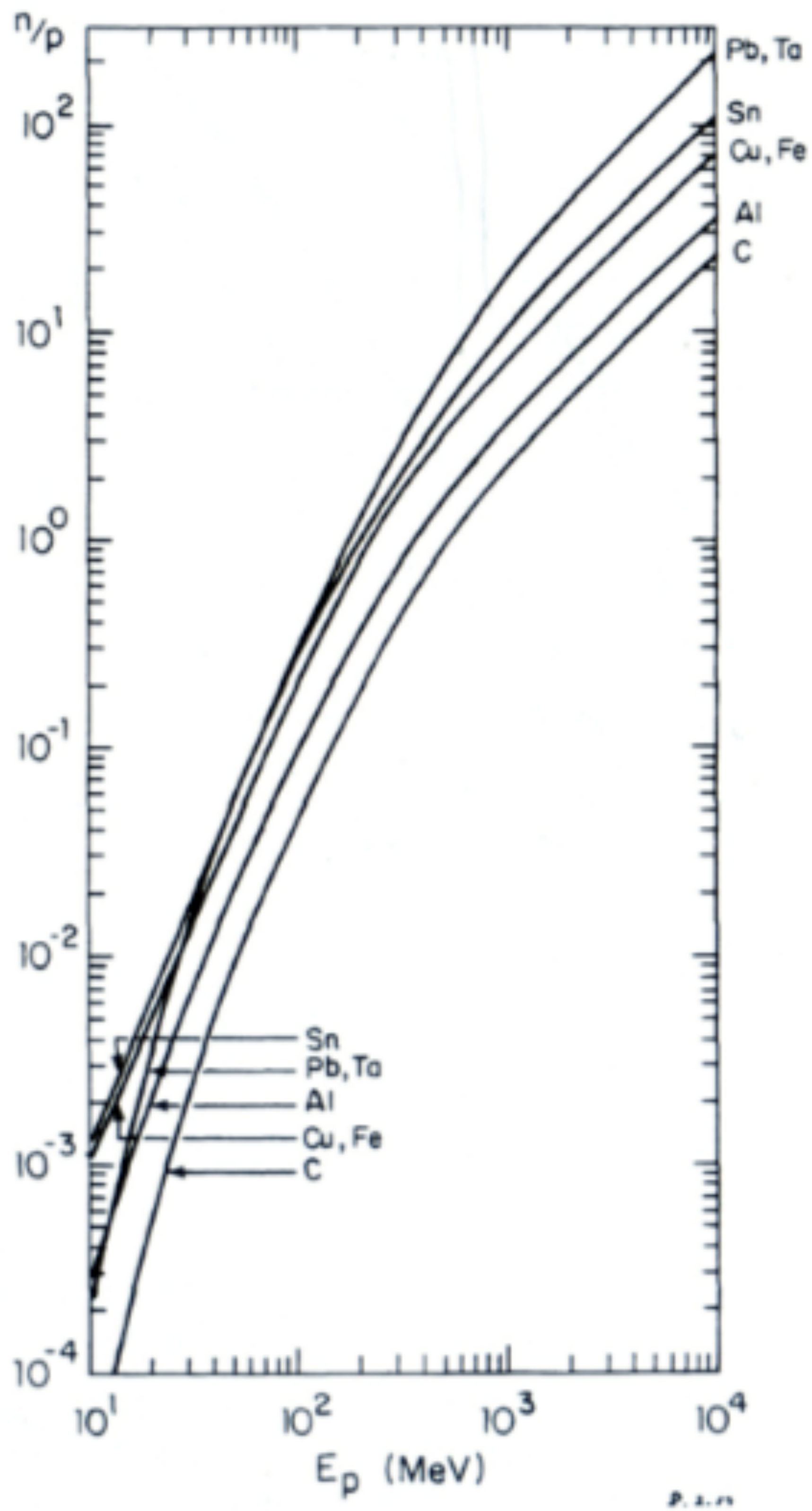


triangle bunch monitor array

Preliminary Experiment of RF stacking



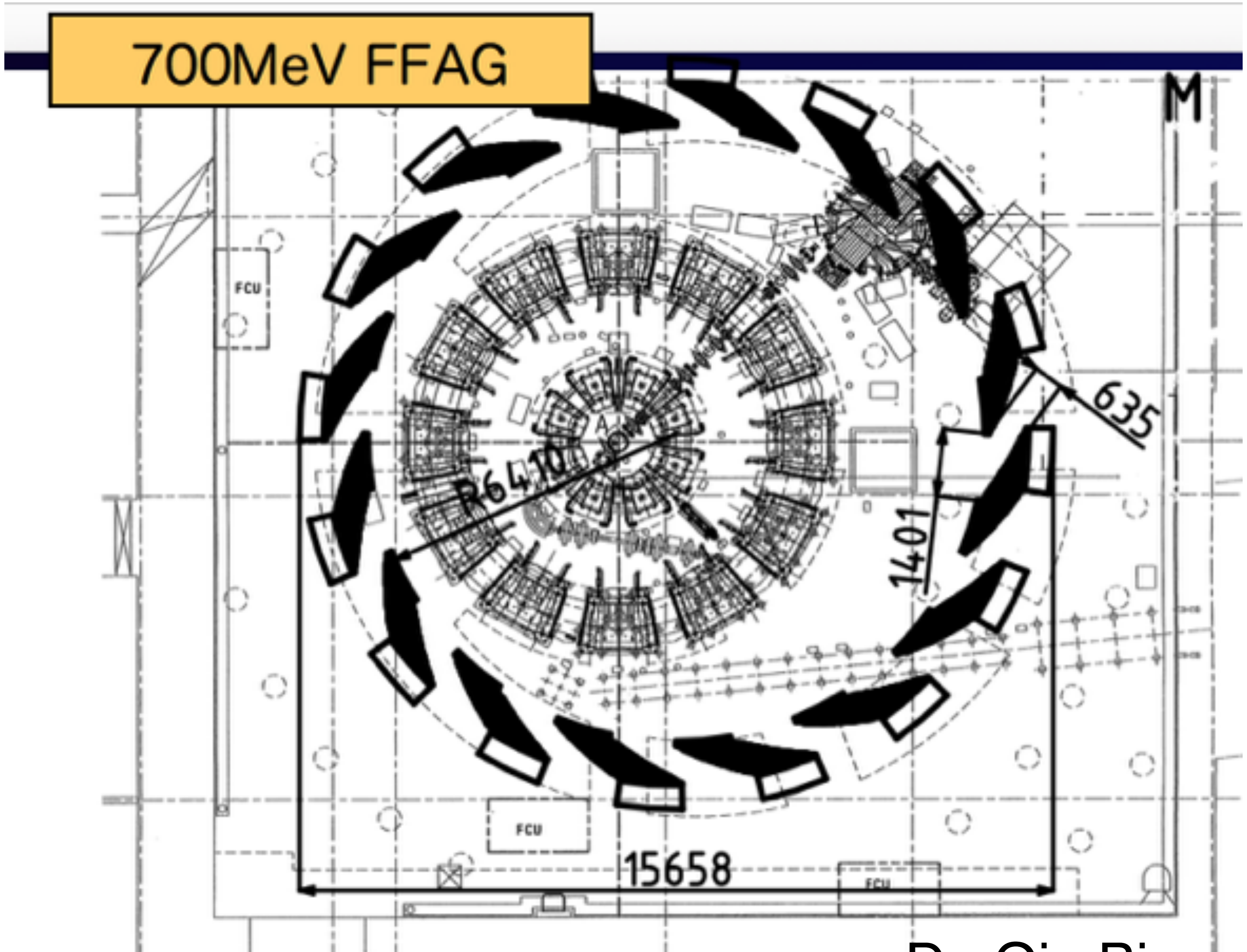
Energy upgrade

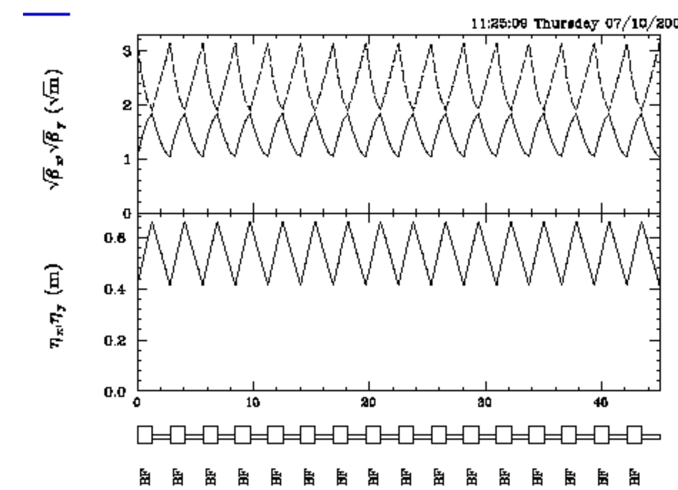


Number of neutrons produced through the nuclear spallation process strongly depends on the beam energy of the primary protons.The energy upgrade of the accelerator facility is desired by neutron users and the reactor physicists for further experiments of ADSR.

Fortunately, there is an enough space to build an additional higher energy ring outside the main ring.

700 MeV spiral FFAG ring was designed 6 years ago.





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

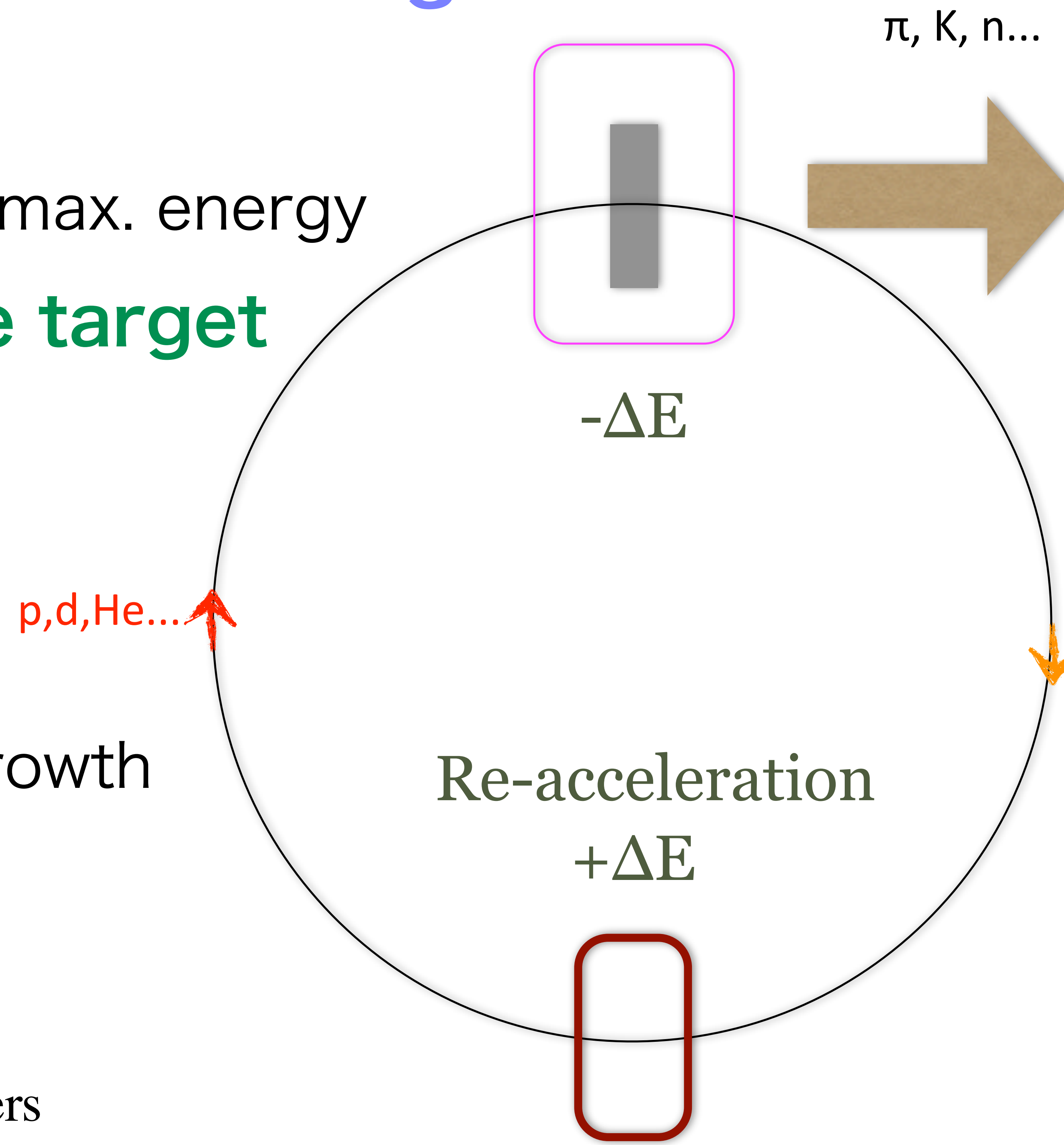
Dr. Qin Bin

Now we are interested in secondary particle production e.g. pions and their decay muons using extended ERIT mechanism.

ERIT:Energy Recovery Internal Target

Thin target & energy recovering

- No energy degradation
  - reactions occur always at max. energy
- Small destruction in the target
  - thin target
  - cf. $\pi^{-} \rightarrow \pi^{0}$
- Ionization cooling
  - suppress the emittance growth
- Effective long target



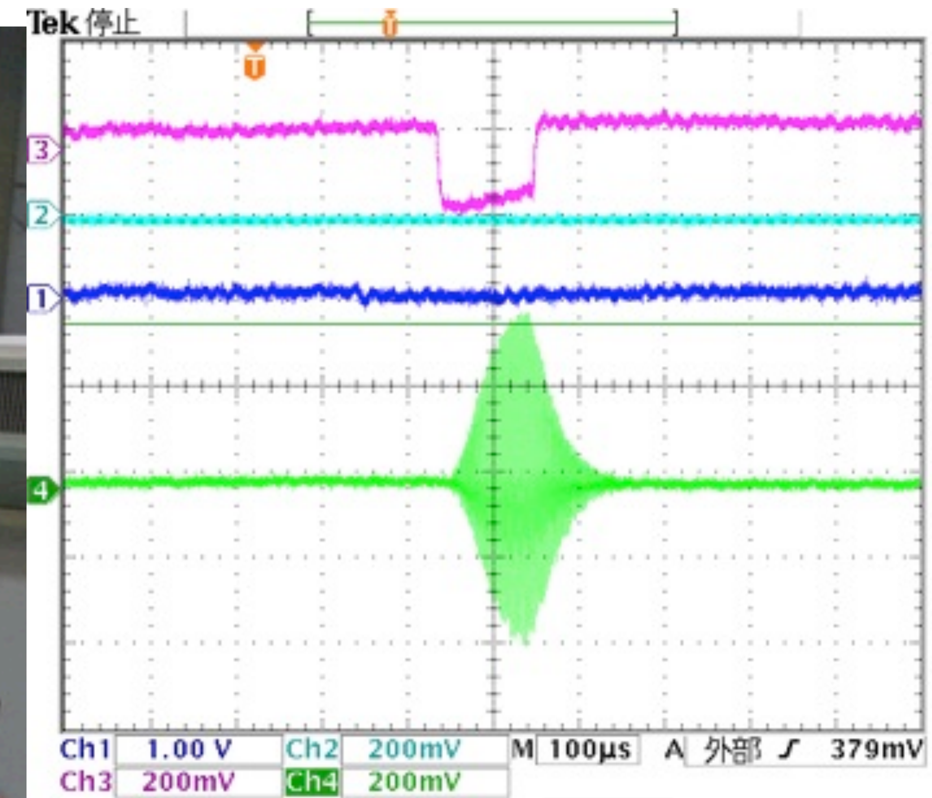
Effective target thickness

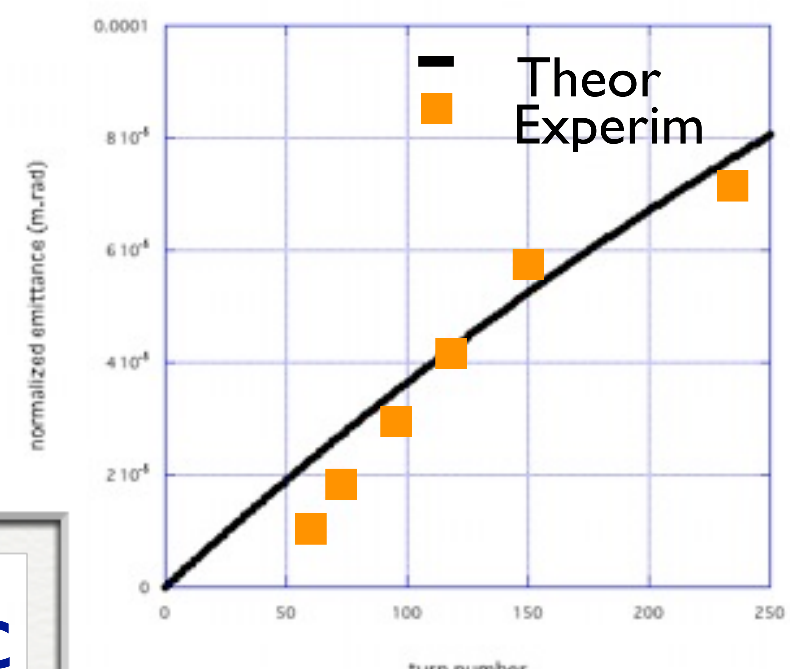
$$L_{eff} = N \times l$$

N : turn numbers

l : *thickness*

FFAG-ERIT RING_demonstration(2010@KURRI)





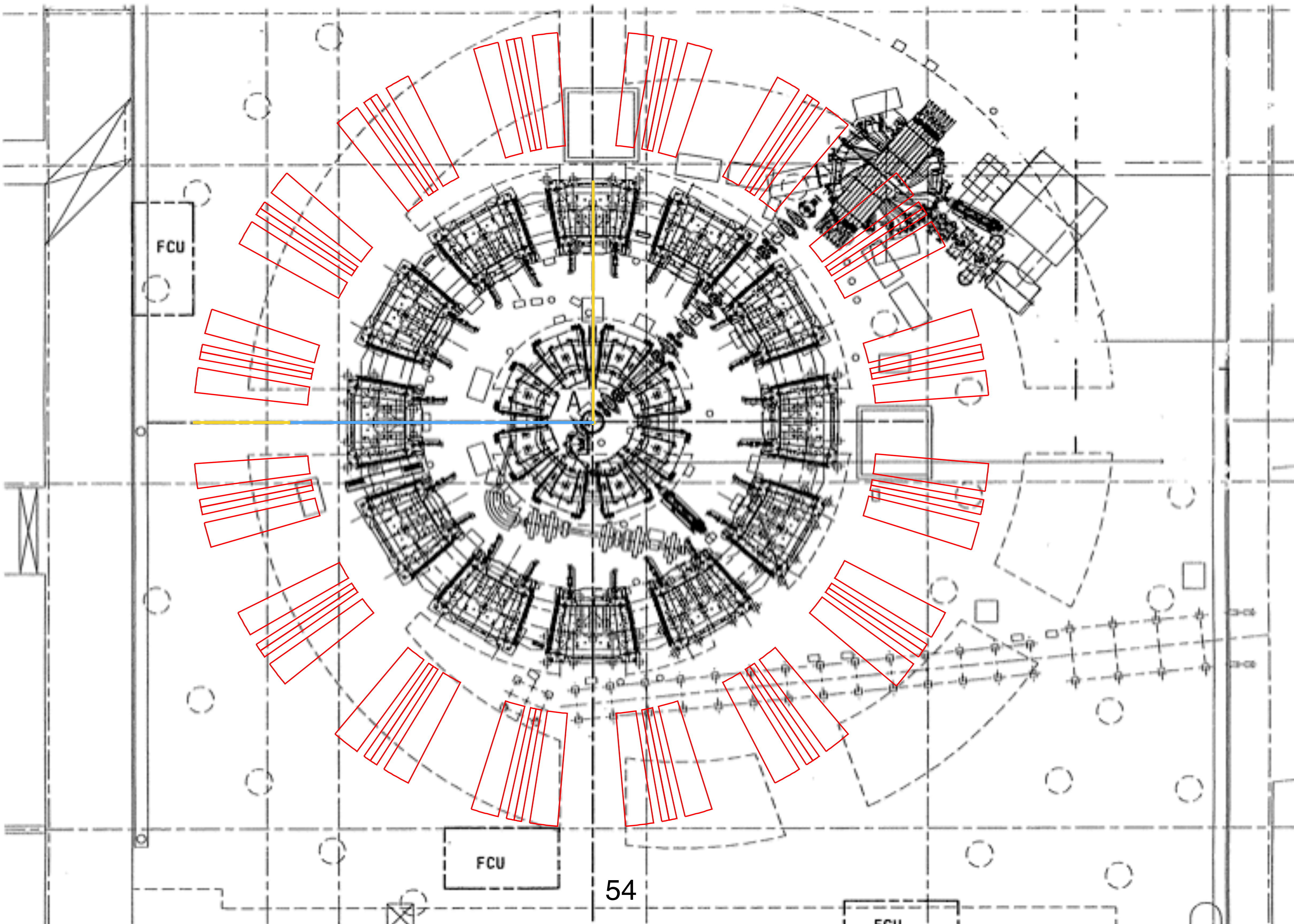
-acceptance Av>3000mm.mrad, dp/p>+-5%(full)

-ν_x, ν_y 1.77, 2.27

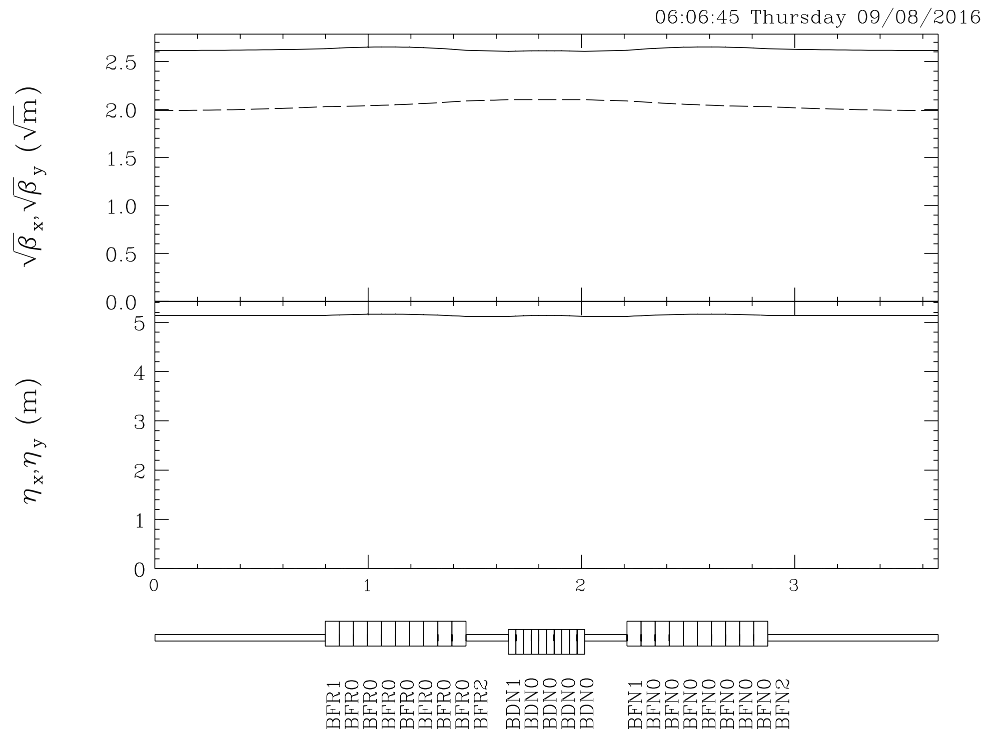
Neutron Yield

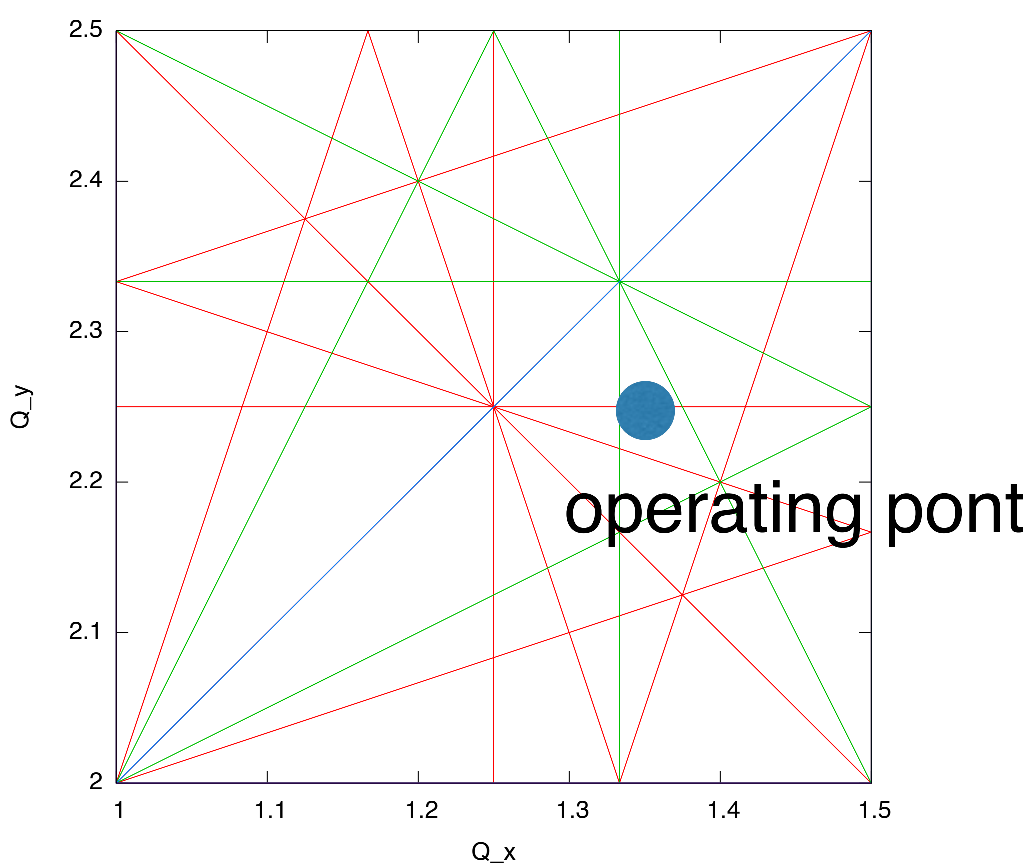
N~5x10^{12} n/sec

Newly designed 400 MeV FFAG ring.



Beta functions of the 400 MeV FFAG ring.





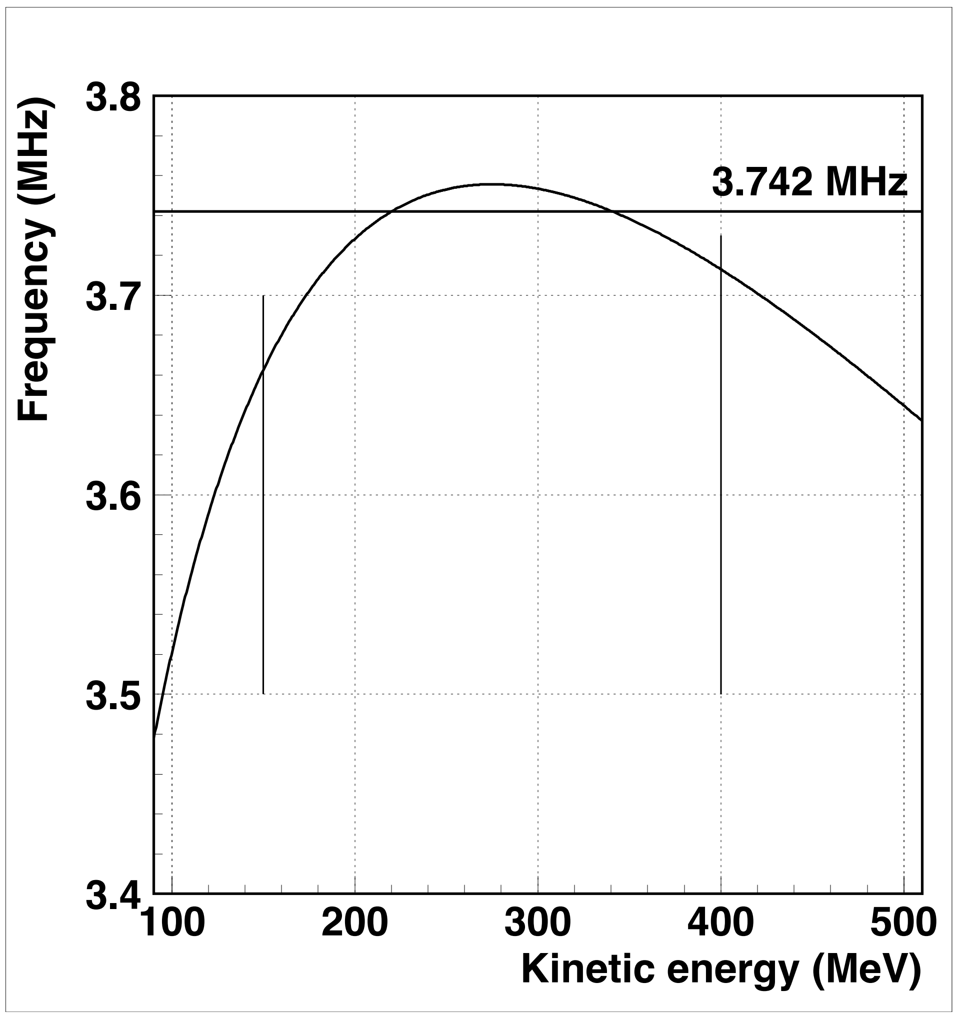
Basic parameters of the 400 MeV FFAG ring.

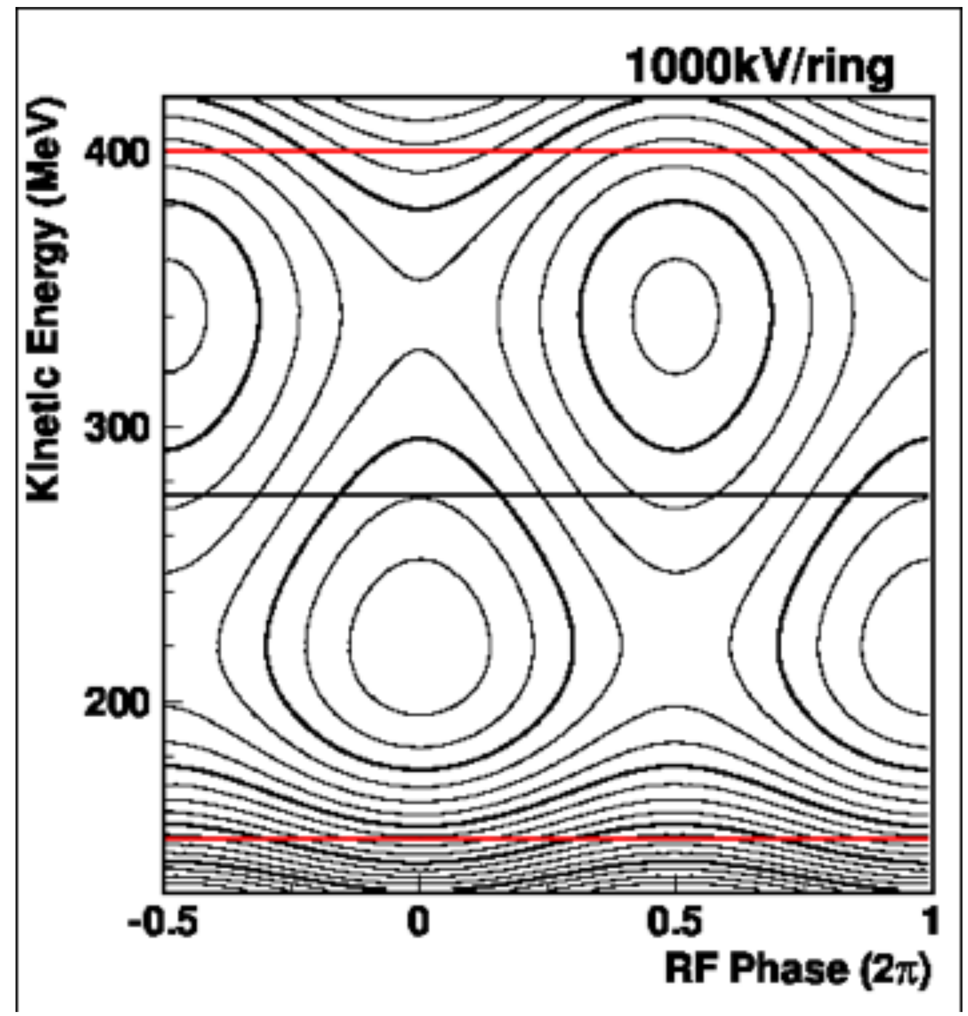
Lattice	FDF triplet
# of cells	16
k value	0.672
Energy	150 - 400 MeV
< R >	6.6 - 9.3 m
V rf / turn	5 MV
Tune	(1.356, 2.248)

The k is set to a rather small value of 0.672. This value of k makes a serpentine acceleration possible. Generally, the profits of this scheme are follows

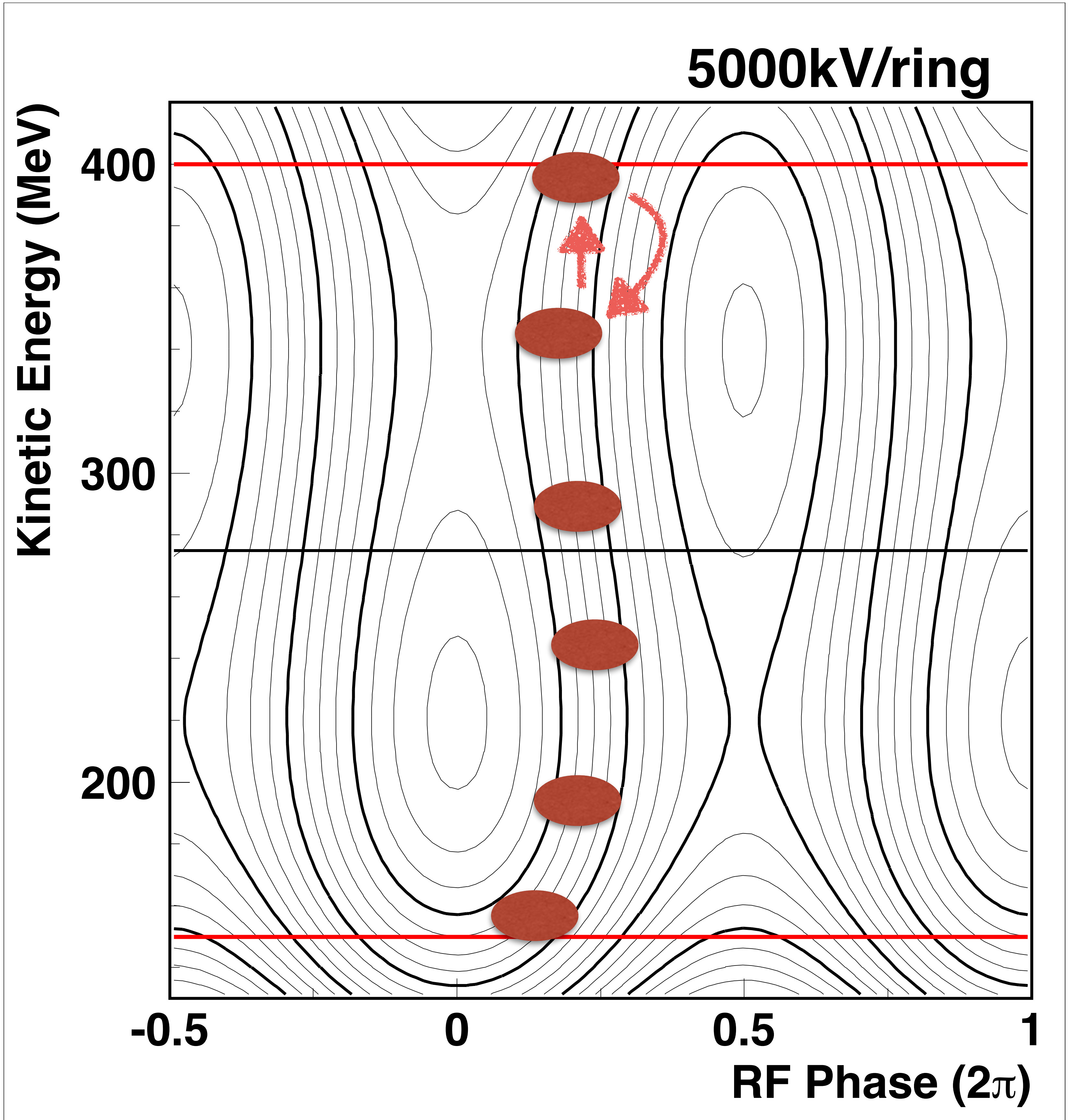
- Since a fixed frequency is used, high electric field of the acceleration cavity is easily obtained.
- This makes a fast and continuous acceleration possible.
- The ERIT mechanism can be applied to make secondary particles such as pions and their decay muons.

RF voltage condition for the serpentine channel





Extended ERIT mechanism



In the ordinary ERIT system, the ring is operated in a storage mode. However, in the extended ERIT system, the ring is in an acceleration mode. In this operation mode, since the beam hits the target at the maximum energy, the production efficiency of the secondary particles becomes high compared with the case of the storage mode.

Summary

1. An FFAG accelerator complex has been constructed for ADSR experiments.
2. These experiments has been ongoing since 2009, using 100 MeV proton beams from the complex. Fruitful results have been obtained from these experiments.
3. Irradiation experiments using 150 MeV proton beam for material science and biological science have been performed as well as for ADSR.
4. Intensity upgrade project is ongoing using RF beam stacking at the high energy orbit.
5. Energy upgrade is under consideration with an additional 400-MeV FFAG ring not only for further ADSR study but for the secondary particle production, adopting a serpentine acceleration, which realises extended ERIT mechanism.