NEUTRON SOURCES AT KURRI

Y. Mori
Kyoto University, Research Reactor Institute

OUTLINE OF KURRI (KYOTO UNIVERSITY RESEARCH REACTOR INSTITUTE)

- 1963　KURRI was established as an inter-University Research Institute and started as a Joint Research Instite.
- 1964　Reactor reached the critical stage.
- 1968　Electron linac was constructed.
- 1984　KUCA was constructed.
- 2004　Innovation research lab. was completed.
- 2008　FFAG proton accelerator complex was constructed.
- 2009　ADSR experiment with FFAGs was started.

TASK OF KURRI

- KURRI is a Joint Research Institute.
  - We have numbers of neutron sources for various science applications:nuclear engineering, chemistry, medical etc.
  - But, mostly NOT COMPACT! (Sorry for UCANS)
- KURRI is an inter-University Institute.
  - Number of users from many universities and institutions ~ >100groups /year
- Science Council of Japan has recently selected 43 major projects for promoting the Japanese scientific activities.
  - "Hybrid nuclear science and engineering program at KURRI" was assigned as one of them.

NEUTRON SOURCE AT KURRI

- KUR :Nuclear Reactor

CW

- e-LINAC
- FFAG complex
  - a) High energy (spallation neutron)
  - b) Low energy (Be(p,n) reaction)

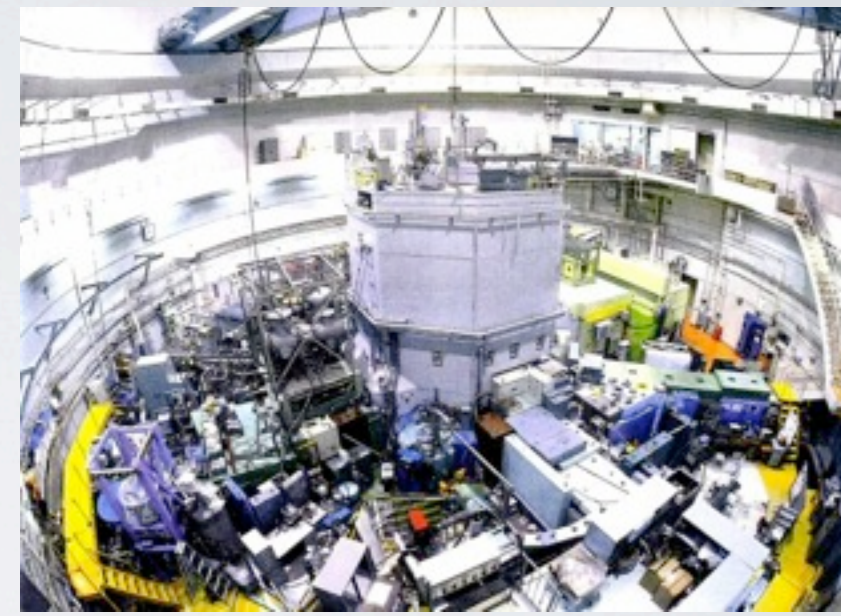
Pulse

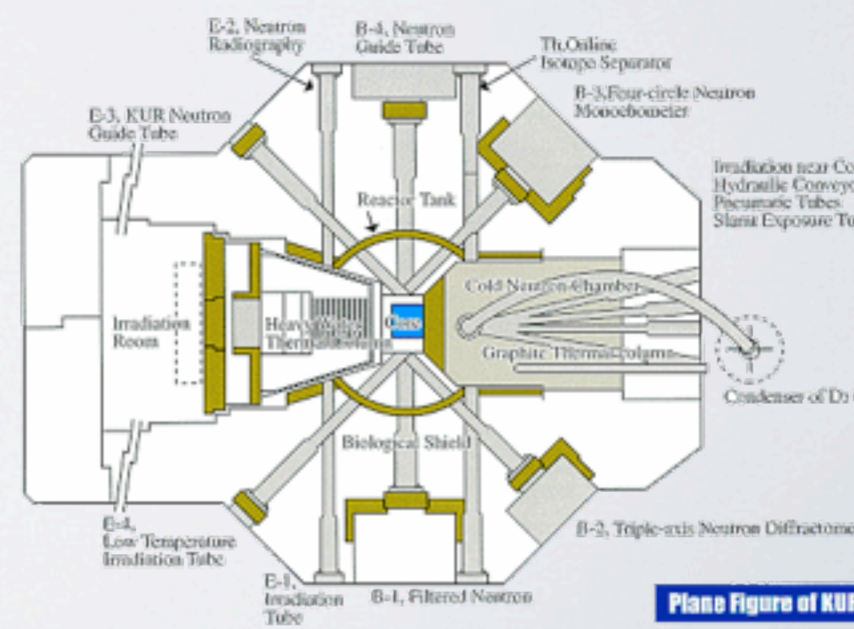
- Proton Cyclotoron

CW

KYOTO UNIVERSITY RESEARCH REACTOR

- Power
  - 5MW
- Reactor core
  - 20% enriched U fuel
  - Graphite reflector elements
  - LW moderator and coolant
- Neutron flux
  - 3×10^{13} n/cm^2/sec (thermal ave.)
- Experimental facilities
  - Hydraulic conveyer
  - Pneumatic
  - Slanat exposure tube
  - Filtered beam hole
  - Heavy water neutron irradiation facility





ACCELERATOR-BASED NEUTRON SOURCE FOR NUCLEAR ENGINEERING STUDY

- Major roles of neutron source for nuclear engineering study
- Nuclear data taking: e-LINAC
  - Reactor engineering (FBR, ADS)
  - Back-end (Transmutation: LLFP, MA)
  - Pulsed neutron : TOF
- Source for ADSR: FFAG proton accelerator
  - Spallation neutron
  - Pulsed neutron : Criticality study (time-domain)
- Pulsed neutron source is important and essential.
- Solid-state physics needs pulsed neutrons definitely.

KURRI-eLINAC

courtesy of Dr. Hori

- Introduction

The electron linear accelerator (KURRI-eLINAC) is used as various types of particle beam source, i.e. electrons, neutrons, and photons. The electron beam is generated by a thermionic gun and accelerated to 46 MeV in two accelerator tubes by L-band (1.3 GHz) microwave. The pulse width is variable from 2 ns to 4 μs. Frequency is variable up to 300 Hz. The research region covers a wide field of nuclear data acquisition with the neutron time-of-flight method and a lead slowing-down spectrometer, isotope production by the (γ,n) (γ,p) reaction, low-temperature electron irradiation, a photon activation analysis, and a spectroscopy with coherent THz radiation.

Operational since 1968

• Specs of the KURRI-Linac

▪Specification of injector

electric gun : YU-156(EIMAC)

incident voltage : 100kV DC, incident current : Max 10A

・Specification of RF driver

output : 3kW, frequency : 1300.8 MHz

・Energy of electron for neutron generation ： ～30 MeV

・Peak current : ～5A (short pulse) 2～100ns width

～0.5A(long pulse) 0.1～4 μs width

・Frequency： 1～300Hz (short pulse)

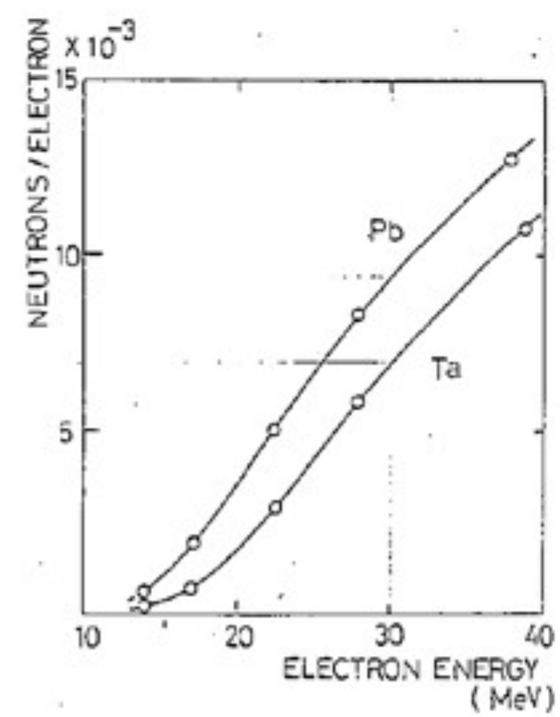
1～100Hz (long pulse)

・Neutron target : Ta with H_2O moderator

・Power on target : Maximum 6 kW (200mA, 30MeV)

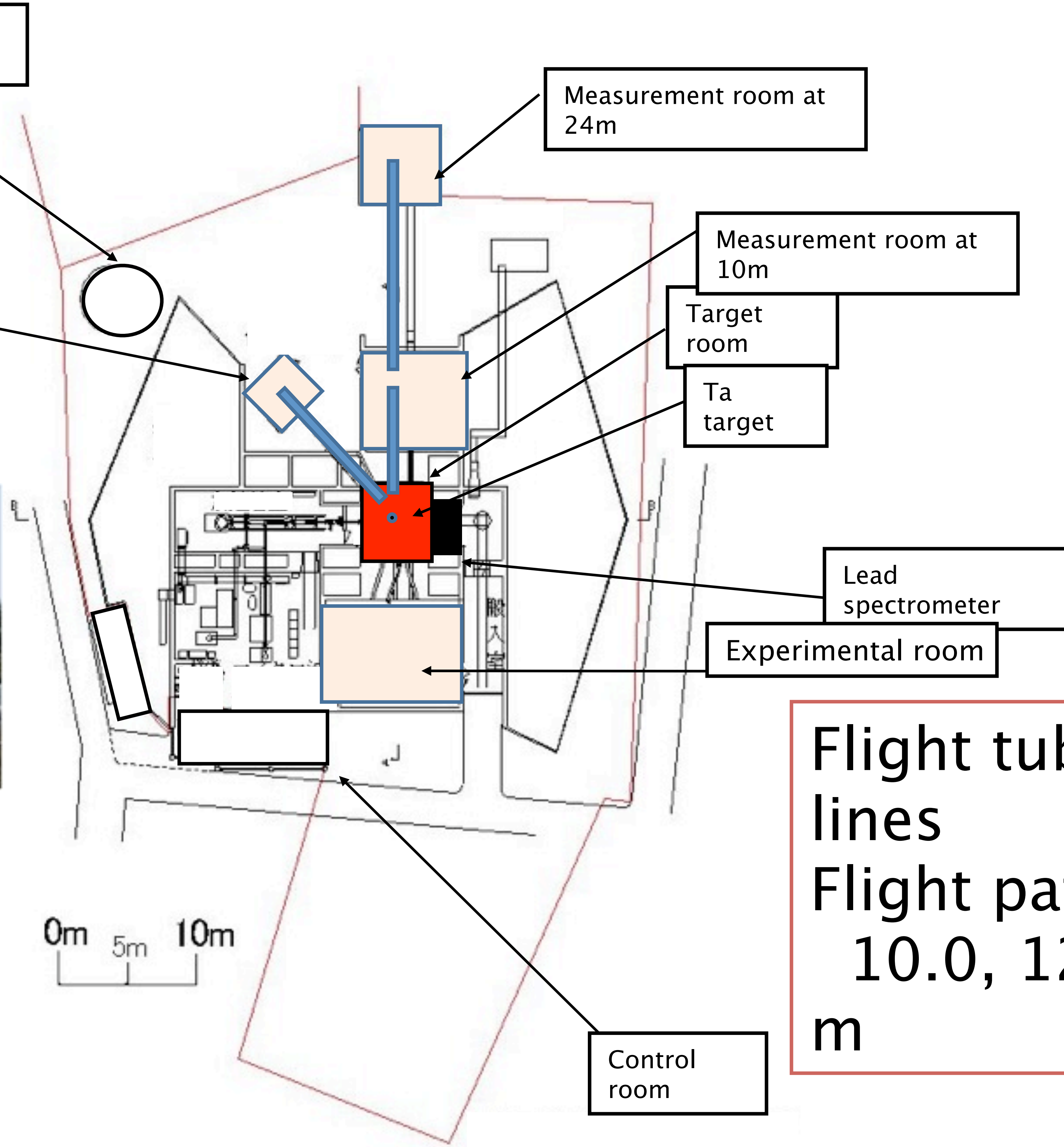
・Electron beam diameter on target : ～1 cm

・Neutron production : ～8×10^{12} n/s @6kW



7×10^{-3} n/e @30MeV

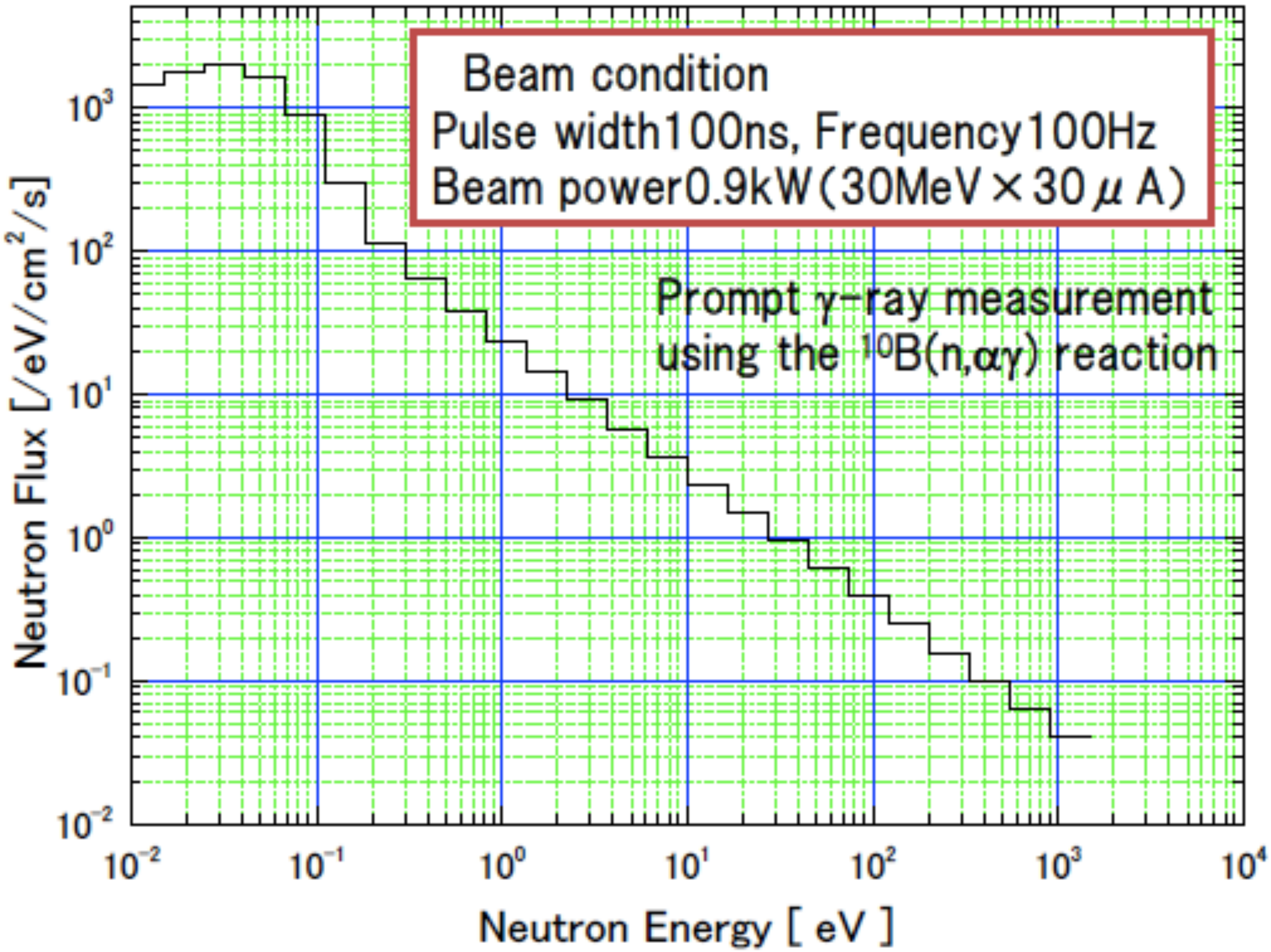
Layout of KURRI-LINAC



Flight tube : 2 lines

Flight path :
10.0, 12.7, 24.2 m

Neutron flux



Neutron flux at the sample position (L=12.7m)

Present status of nuclear data measurement at the KURRI-LINAC

Target : Minor actinide (MA), Long-lived fission product (LLFP)

- Neutron capture cross section

Prompt γ-ray measurement with a TOF method

Detector : Total absorption type BGO spectrometer, A pair of C_6D_6 detectors

Energy region : 0.005eV～40keV

- Fission cross section

Fission product measurement with a slowing down time method

Detector : Back-to-back fission chamber with a Lead spectrometer

Energy region : 0.1eV～10keV

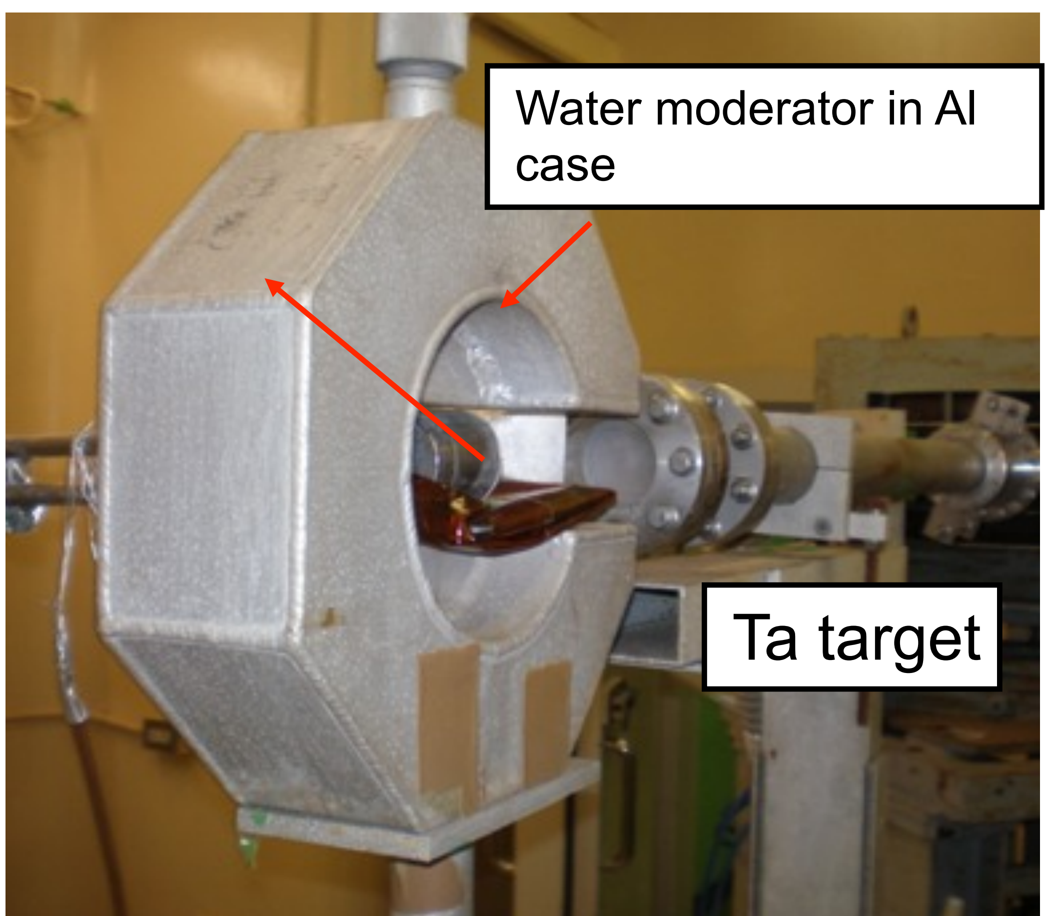
- Photo reaction cross section

Average cross section measurement with an activation method by bremsstrahlung

Energy region : 8-40 MeV

Injector and accelerator tubes

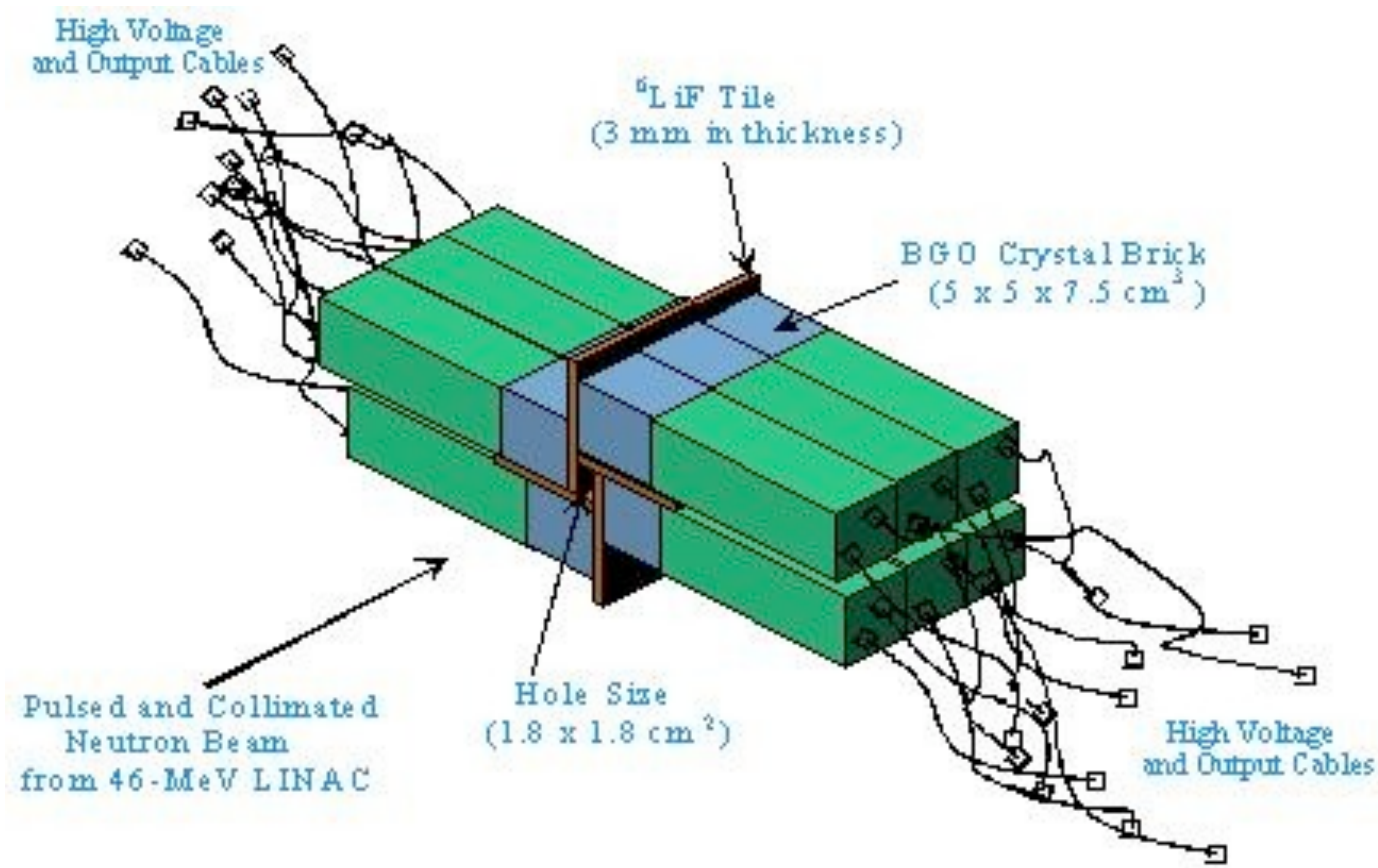
Target room



Ta target and water moderator

Lead spectrometer (1.5×1.5×1.5m^3)

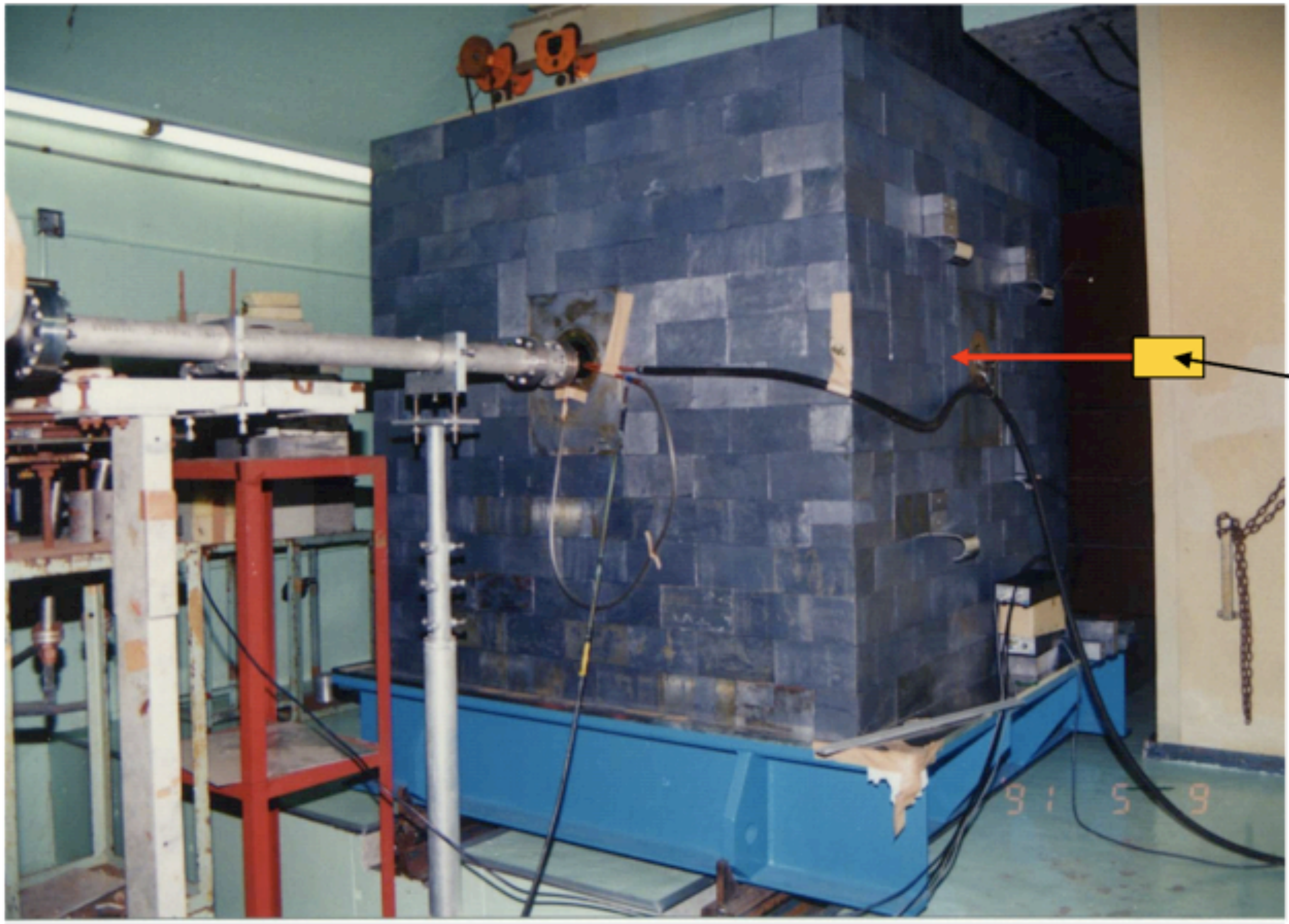
Total absorption type BGO spectrometer



The spectrometer was made up with 12 scintillators.

Kyoto University Lead Spectrometer（KULS)

Lead : 1600 blocks → 40 t (1.5× 1.5× 1.5 m^3)

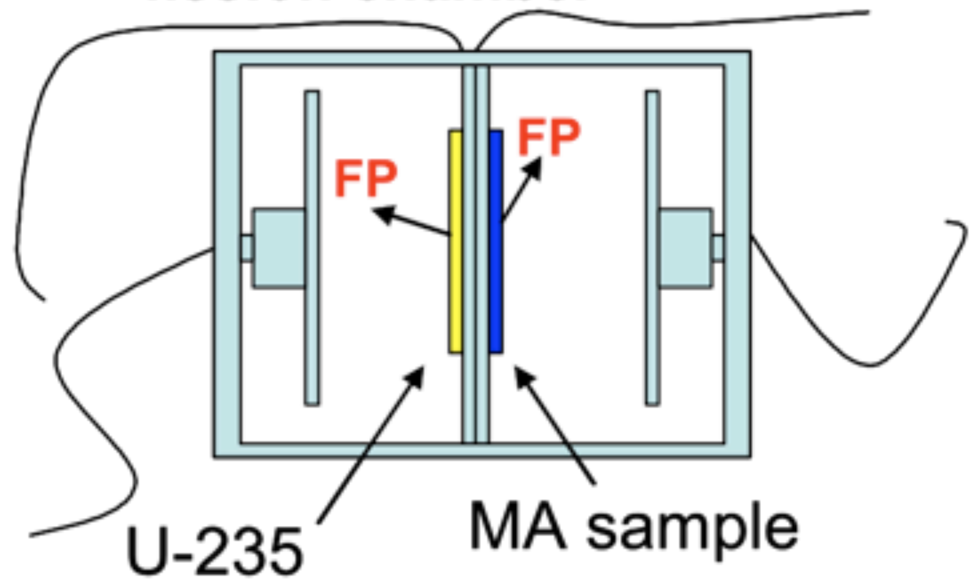


Slowing down time of neutron in the lead

↓

Pulsed neutron energy
$E=K/t^2$ K:constant

Back to back type fission chamber



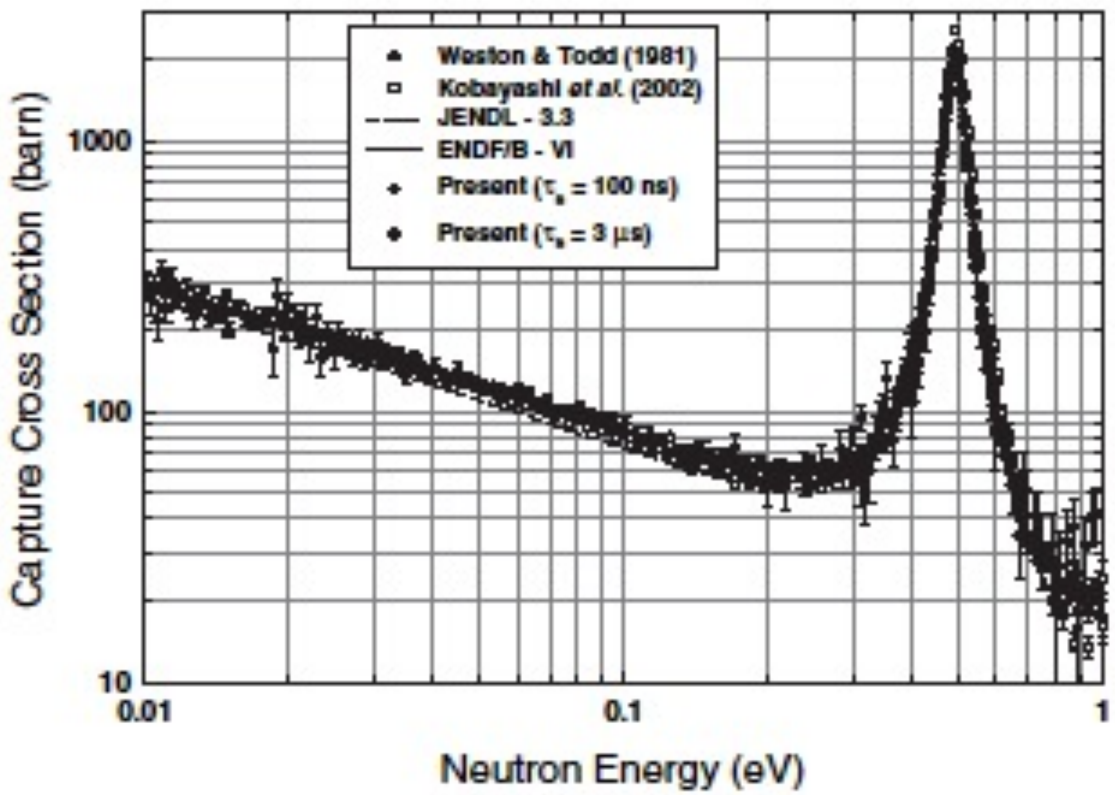
The distance between source and sample is about 10 cm → Neutron flux is high
→ High sensitivity

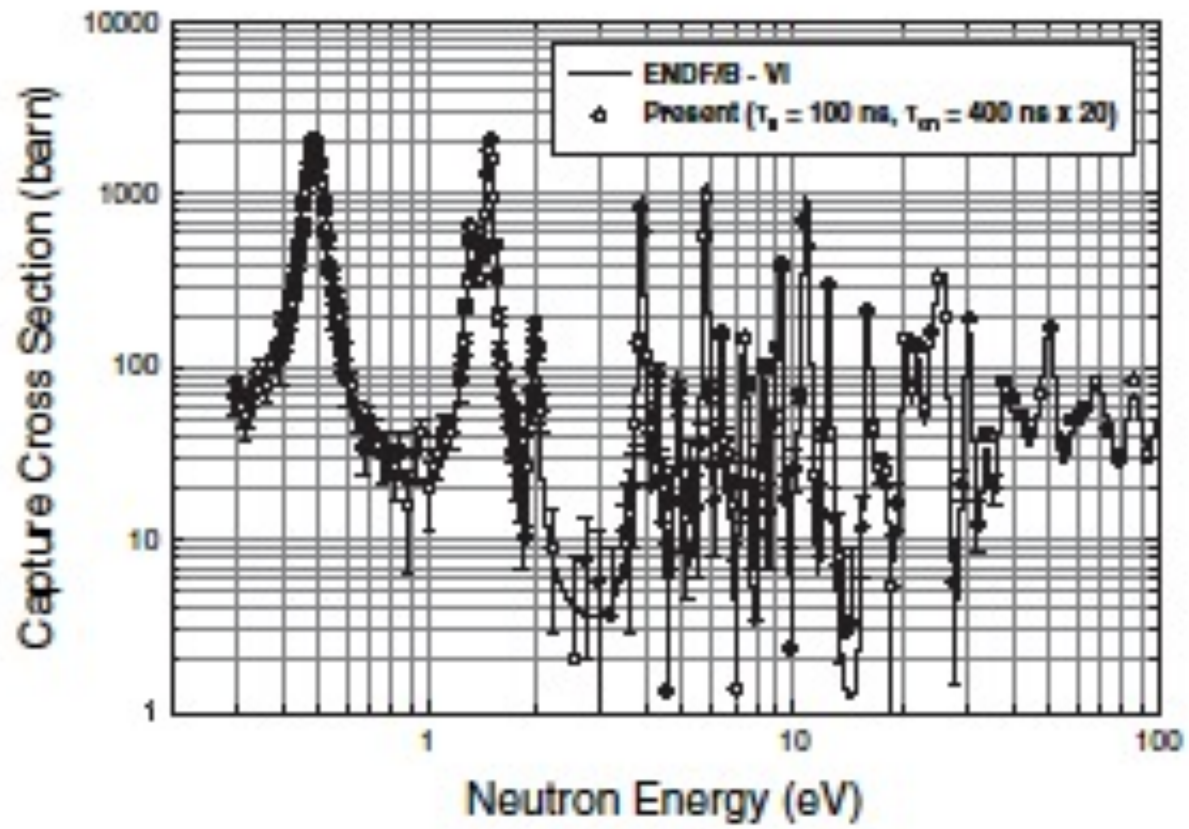
We can measure cross section of about 1 barn by using only 1 μg sample

Example

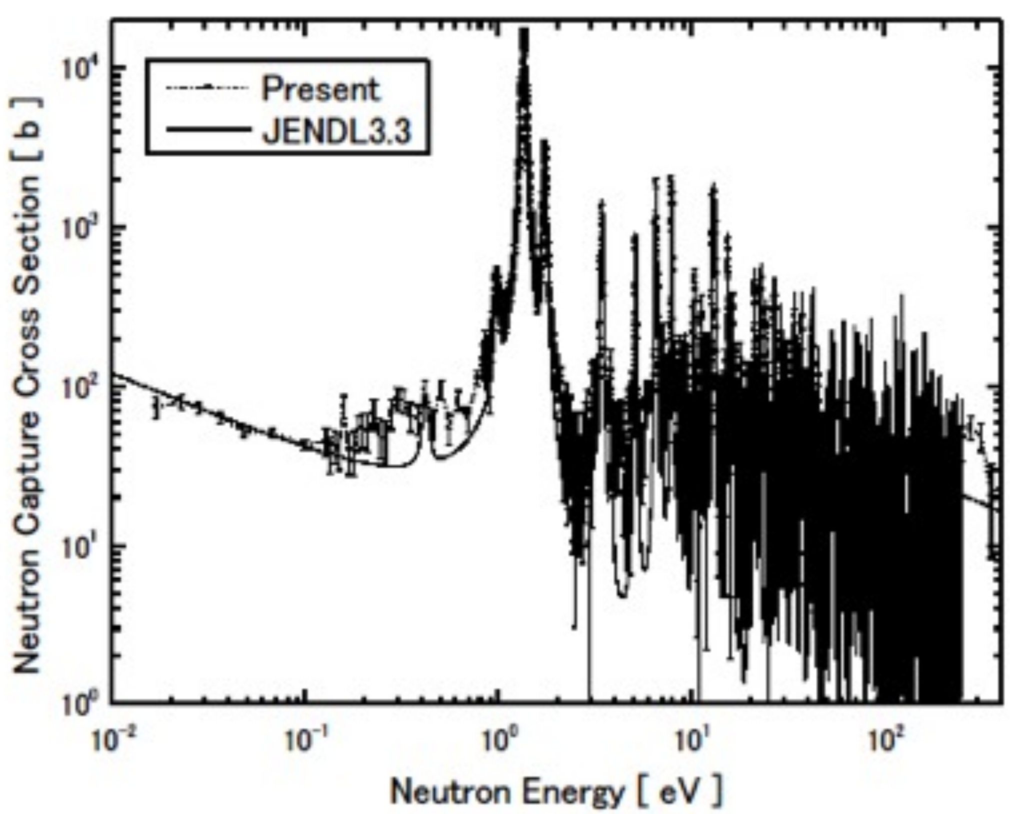
$^{237}Np(n,\gamma)$

Reference: O. Shcherbakov, *et al*., *J. Nucl. Sci. Technol.*, **42**, 2, 135-144 (2005).





$^{243}Am(n,\gamma)$



Reference: J. Hori, *et al*., Proc. the 2008 Symposium on Nuclear Data, JAEA-Conf 2009-004, 123-128 (2009).

Present study is the result of “Fundamental R&D on Neutron Cross Sections for Innovative Reactors using Advanced Radiation Measurement Technology” entrusted to “Tokyo Institute of Technology” by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

NEUTRON SOURCES WITH FFAG ACCELERATORS AT KURRI

- High energy (spallation neutron)
  - Study of ADSR(Accelerator Driven Sub-critical Reactor) experiment with KUCA(critical assembly)
  - Energy ~150MeV(variable)
  - Beam intensity ~108 ppp (H+ injection), ~1012ppp(H- injection)
  - Repetition rate 30-60Hz
  - Pulse width 30nsec
  - Neutron yield 108 npp (H+ injection), 1012 npp(H- injection)
- Low energy ((p,n) reaction)
  - Copmpact neutron source with ERIT (emittance/energy recovery internal target) for BNCT & industrial applicatios
  - Energy 11MeV
  - Beam intensity 1015ppp
  - Repetition rate 200Hz
  - Pulse width 100microsec
  - Neutron yield 109 n/cm2/sec

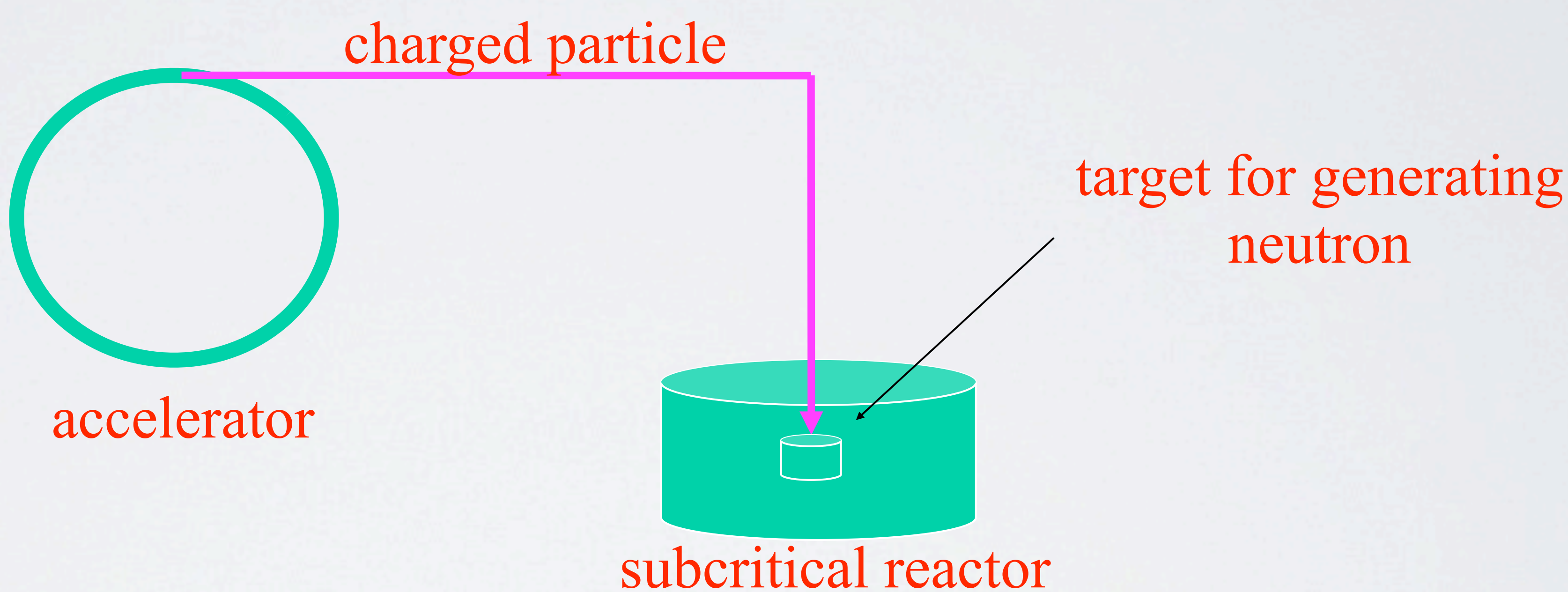
NEUTRON SOURCES WITH FFAG ACCELERATORS AT KURRI

- Study of ADSR(Accelerator Driven Sub-critical Reactor)
  - High energy (spallation neutron)
  - Proton Energy ~150MeV (variable)
  - Pulse width 30nsec
  - Proton beam intensity ~10^{9}ppp(H^{+} injection) , ~10^{12}ppp(H^{-} injection)
  - Repetition rate 30-60Hz(120Hz)
- Compact neutron source with ERIT(Emittance/energy Recovery Internal Target)
  - Low energy (11MeV : Be(p,n) reaction)
  - BNCT basic study & industrial applications
  - Proton energy 11MeV
  - Proton beam intensity 10^{15}ppp
  - Pulse width 200 μsec
  - Repetition rate 200Hz
  - Neutron yield 5×10^{13}n/sec

ACCELERATOR DRIVEN SUB-CRITICAL REACTOR (ADSR)

- What is ADSR?

Accelerator Driven Subcritical Reactor



Beam off → chain reaction stops

Safer system !

neutron amplifier $n_\infty = n_0 + k_{eff} n_0 + k_{eff}^2 n_0 + \cdots \approx \dfrac{1}{1-k_{eff}} n_0$

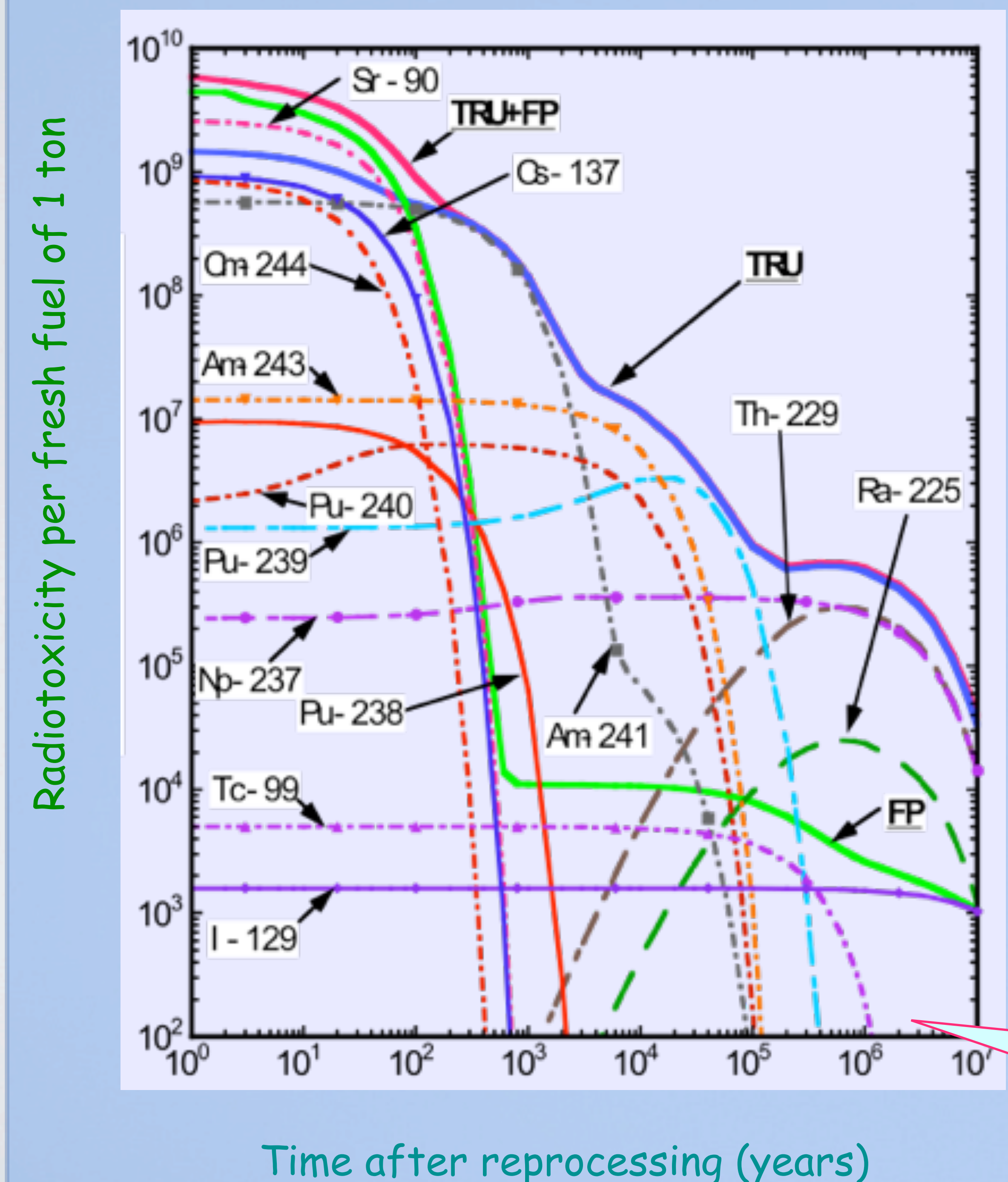
$n_\infty \approx 50$

$k_{eff} \sim 0.98$

VALIDITY OF ADSR

- Safe system : no critical accident because keff<1
- Treatment of nuclear wastes : transmutation of long-lived nuclear radio-toxicity (LLFP, MA)
- Fuel variety : Thorium instead of Uranium

TRANSMUTATION



- Radiotoxicity: ratio of the mass of nuclide to the permissible limit of annual intake
- Raiotoxicity of FP's is dominant within 100 years after reprocessing, and that of MA's thereafter

Half-lives:

Sr-90	28yrs.
Cs-137	30yrs.
Np-237	2.14 M. yrs.
Am-241	433yrs
Am-243	7370yrs.

Long term risks could be reduced by transmutation of MA's

Why Transmutation??

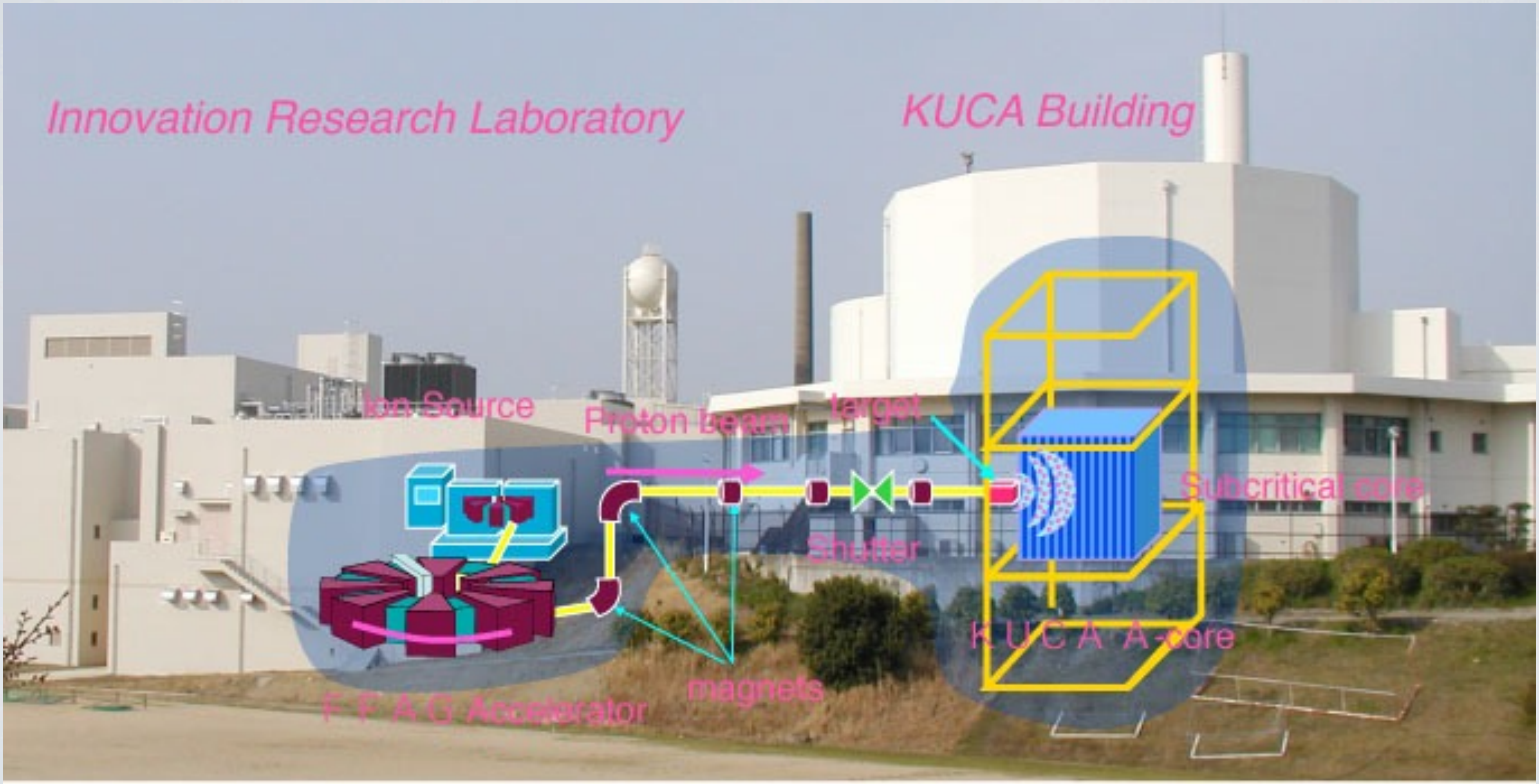
- We need **TRANSMUTATION** and/or BREEDING not because we do not like Geological Repositories but **BECAUSE IT IS THE ONLY WAY TO MAKE NUCLER ENERGY REALLY SUSTAINABLE** and consequently to make it more acceptable

by W.Gudowski

FFAG-ADSR PROJECT

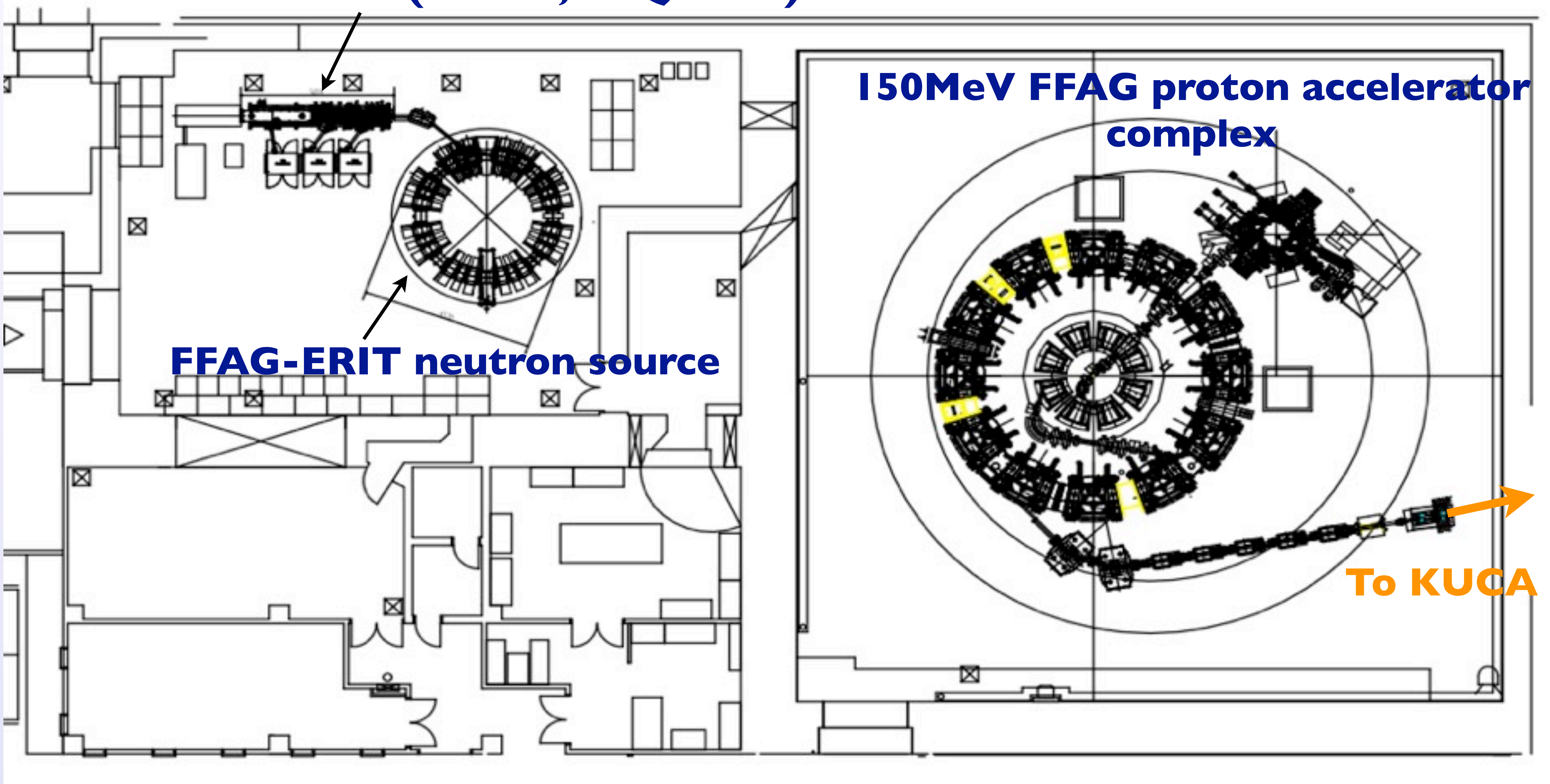
- Purpose of the project
  - Basic study for ADSR(Accelerator Driven Sub-critical Reactor) with FFAG accelerator and KUCA(Kyoto University Critical Assembly)
- KUCA
  - Output power ~10W
  - Neutron amplification : $\alpha=1/(1-k_{eff})$. If $k_{eff}=0.99$, $\alpha=100$
  - Beam power should not exceed < 0.1W!!
  - Beam power is also limited by radiation safety because the beam passes only 1m away from office.
    - cf. For 100MeV proton beam, I<1nA
- FFAG
  - Beam energy 100-150MeV (variable)
  - Beam current 1nA

FFAG-ADSR PROJECT AT KURRI



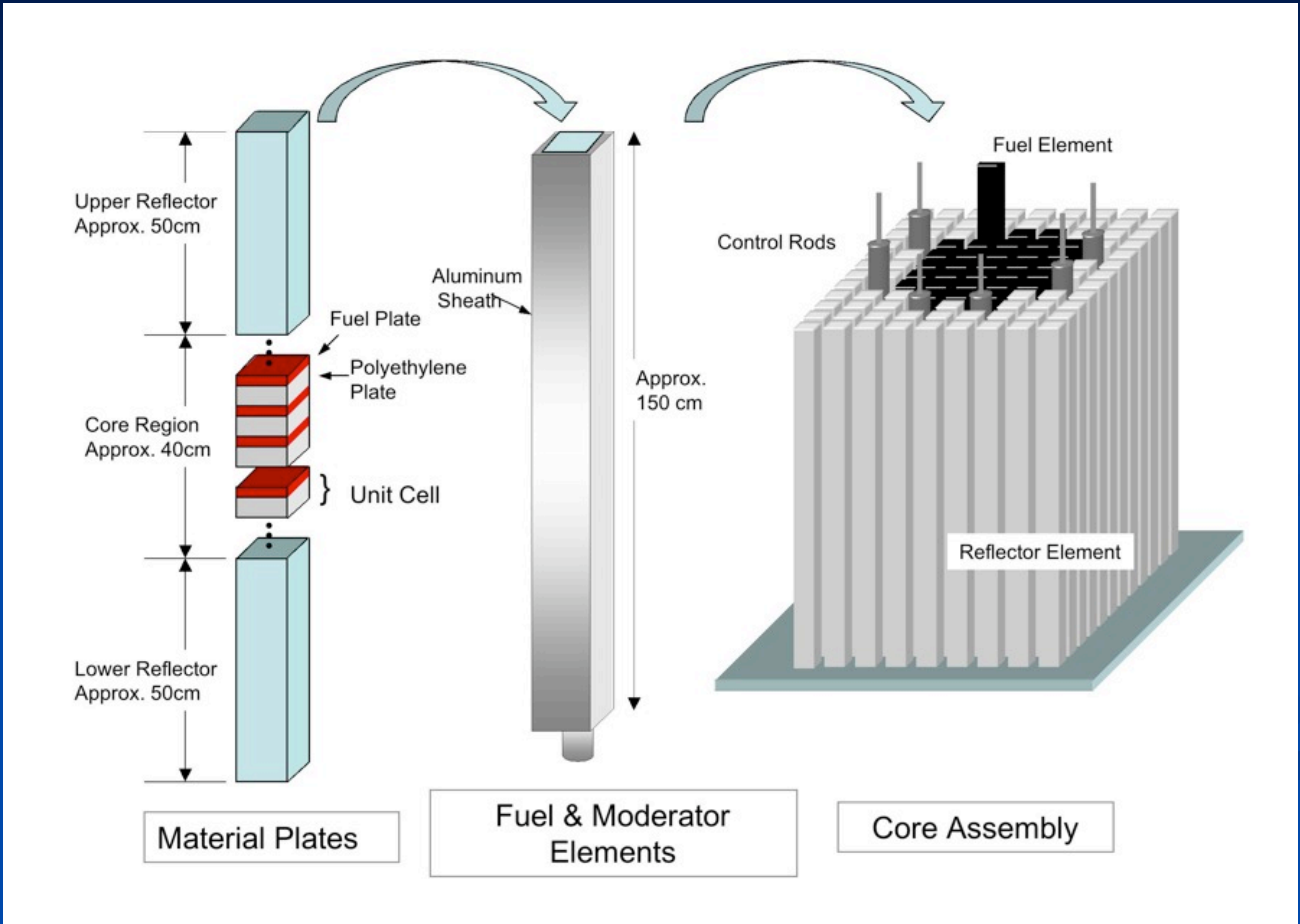
Layout of Accelerators in Innovation Laboratory

2009/09/17



FFAG COMPLEX FOR ADSR STUDY

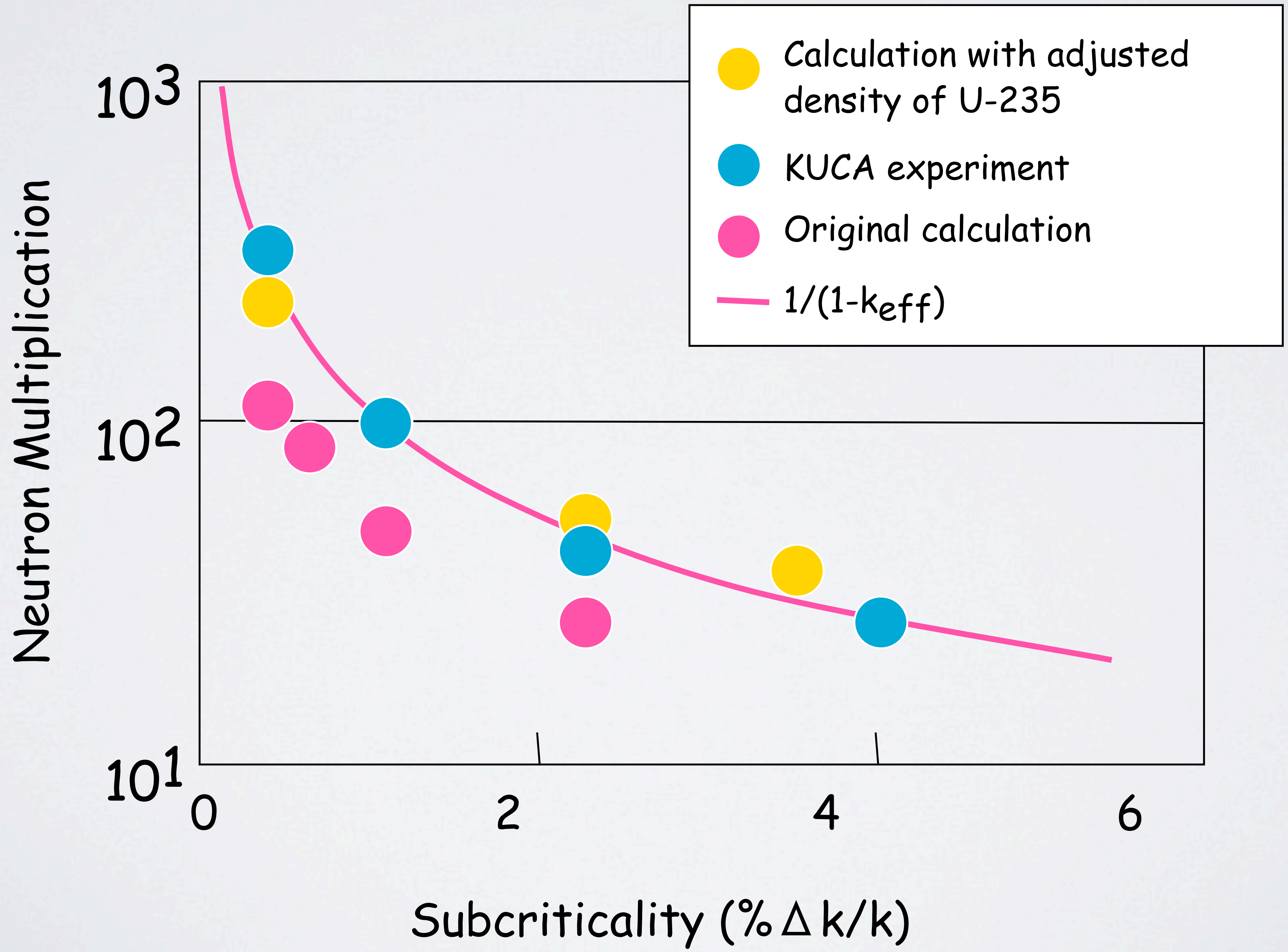
Concept of KUCA A-Core Set-up



KUCA-A Core - solid moderated and reflected -

ADSR STUDY WITH FFAG

- Neutron multiplication for sub-criticality
- Effective critical factor for spectrum index (neutron portion of less than 1eV)

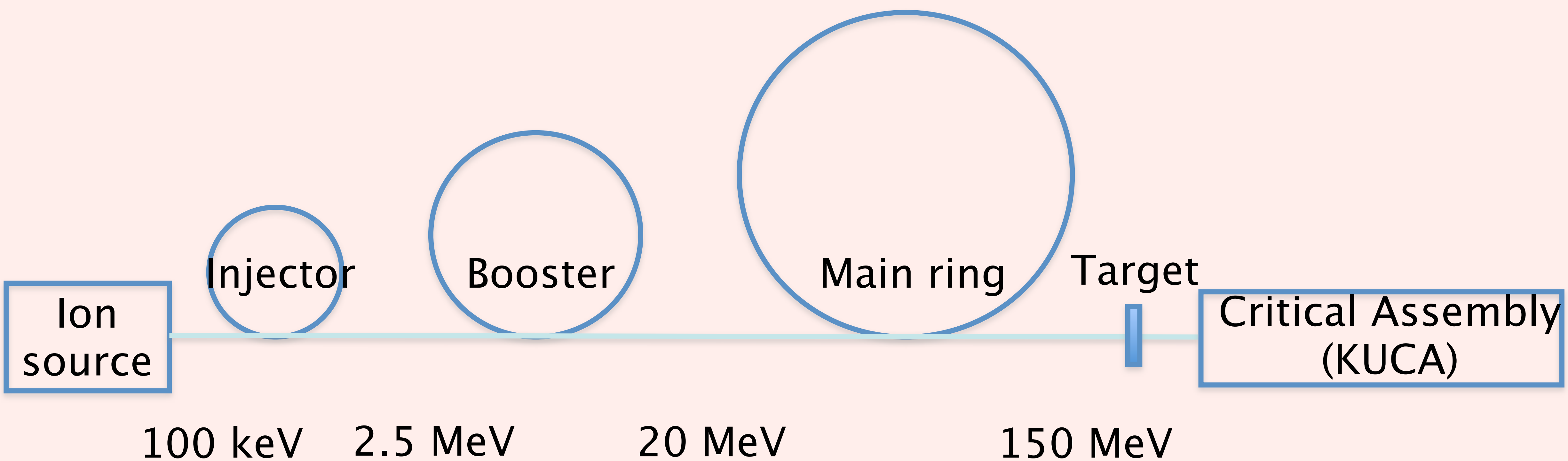


FFAG-ADS Project

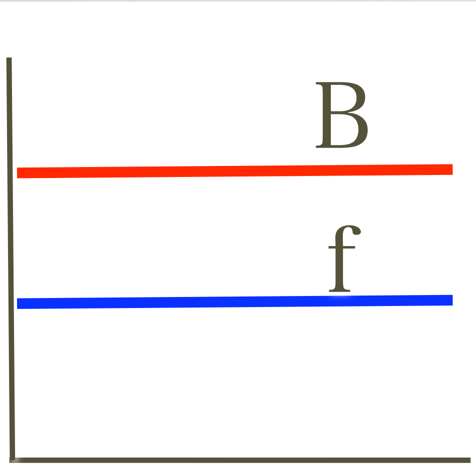
To study

Accelerator Driven Sub-critical Reactor (ADS)

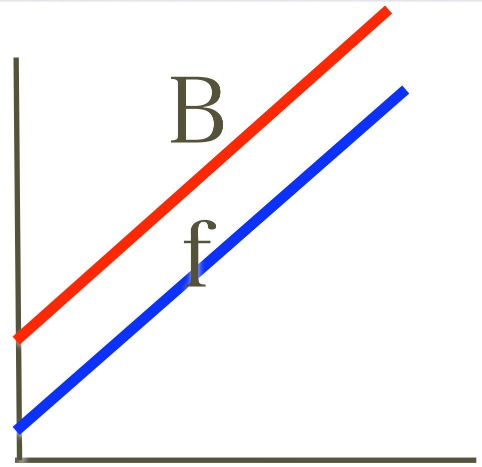
- Narrow energy spectrum of n beam
- Energy and Flux of the n beam can be easily controlled.



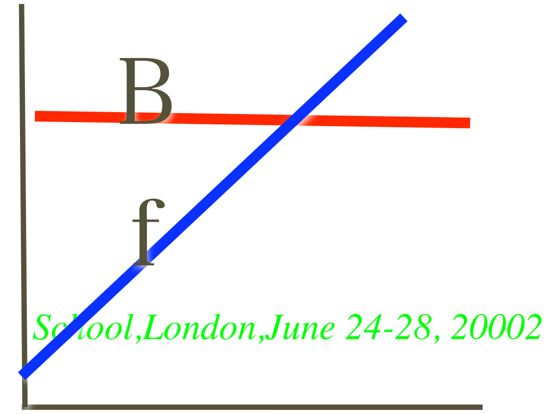
Max (variable energy)



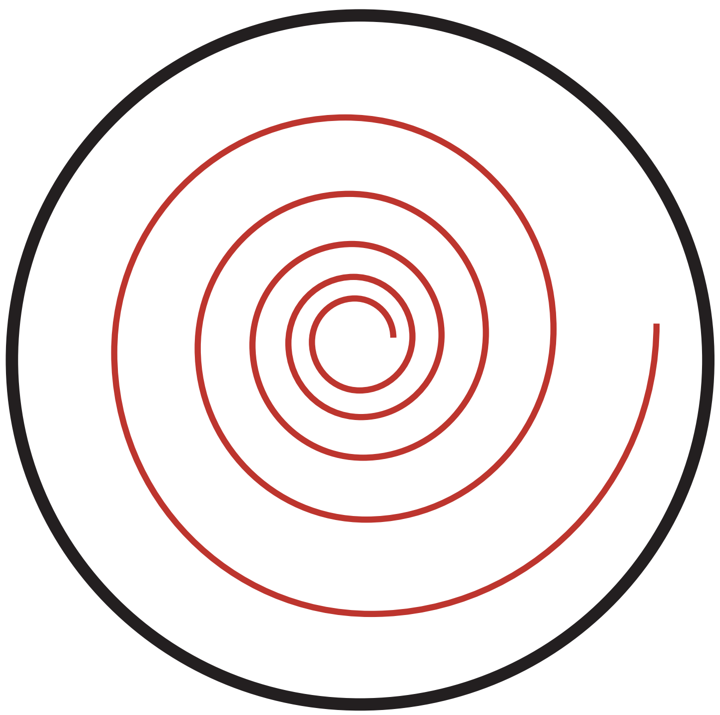
accelerating time



accelerating time

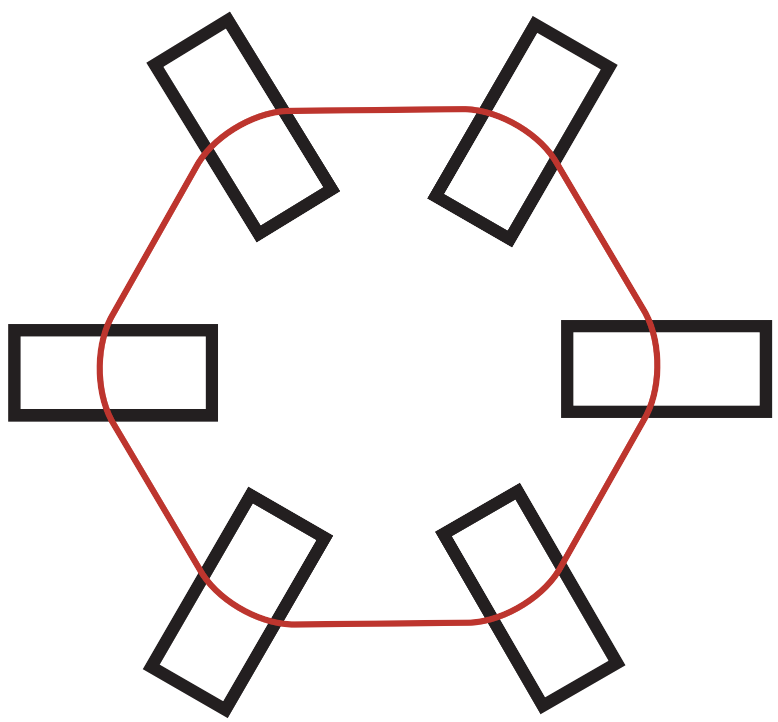


accelerating time



Cyclotron

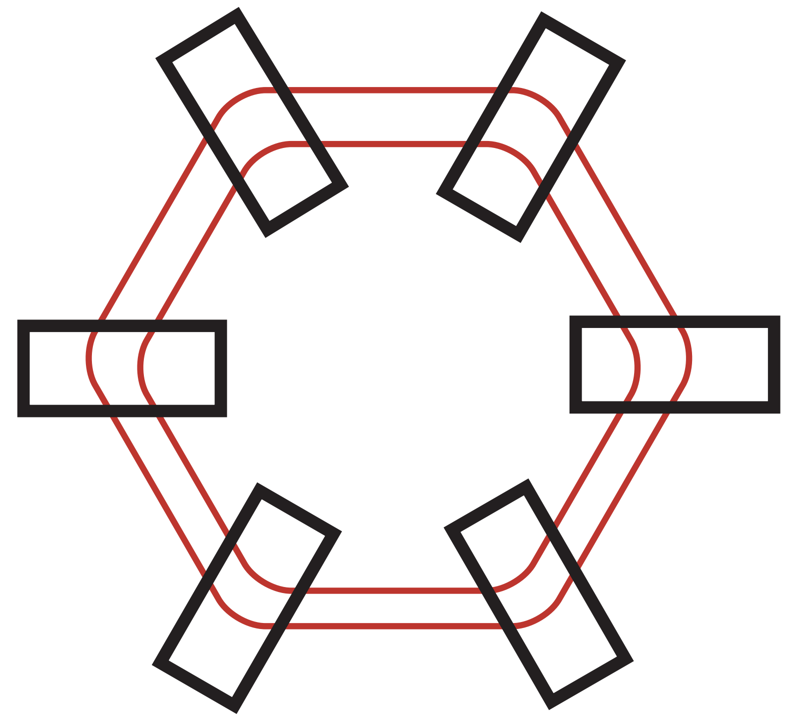
*isochronous



Synchrotron

*const. closed orbit

(varying mag. field)



FFAG

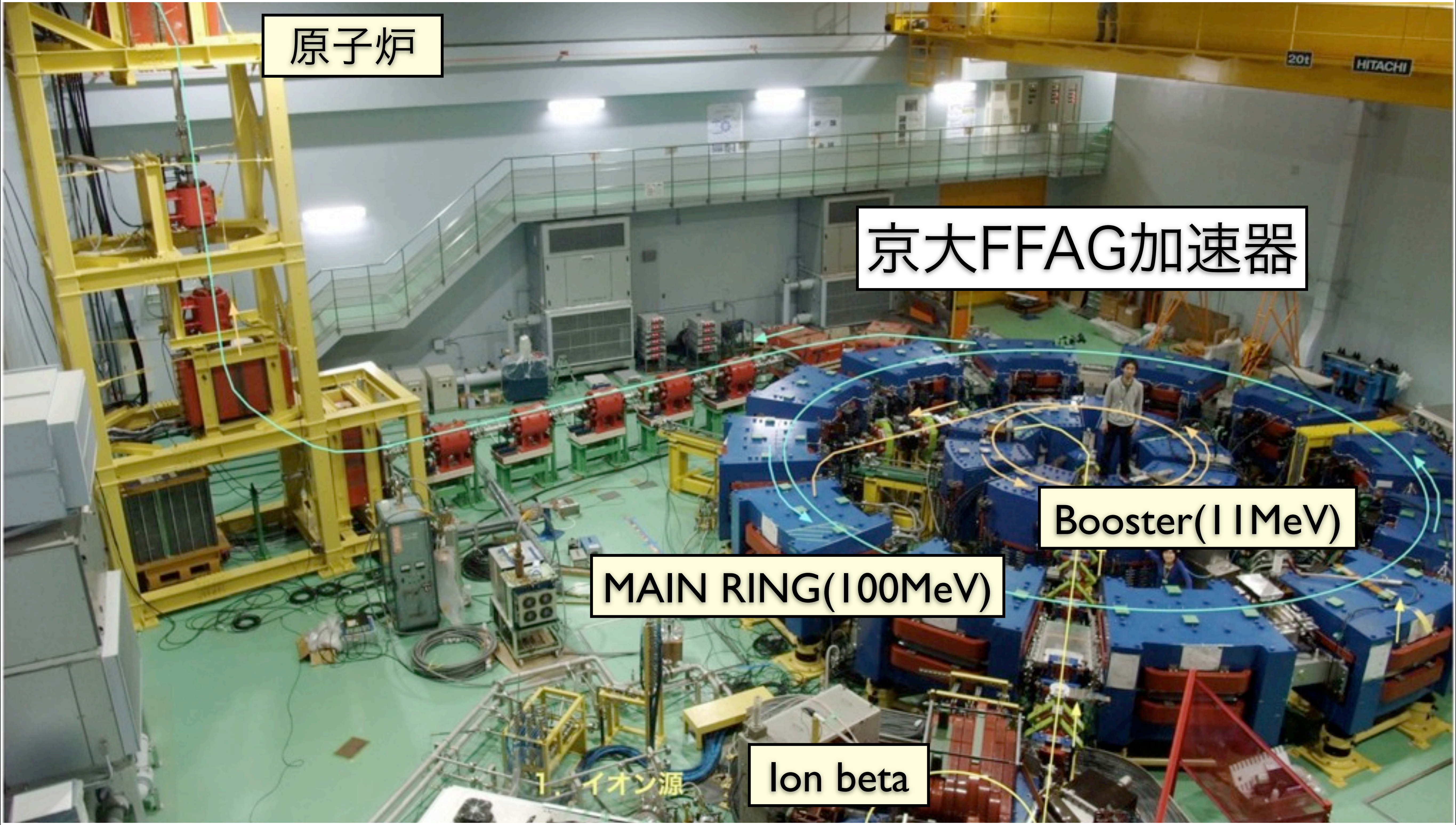
*varying closed orbit

(const. mag. field)

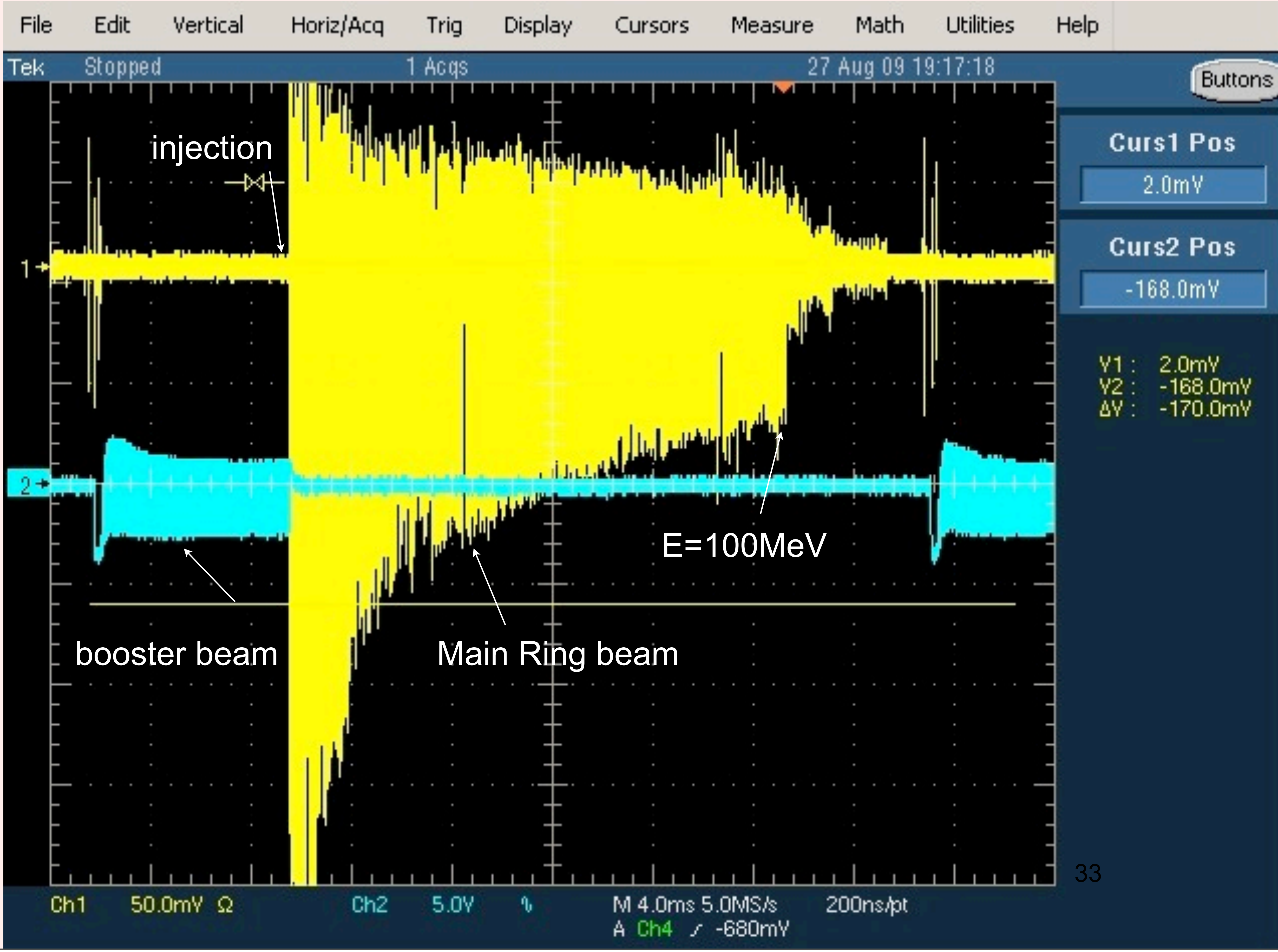
FFAG : FIXED FIELD ALTERNATING GRADIENT

- Static magnetic field: it is like cyclotron but not much orbit excursion.
  - Fast acceleration
    - Fixed magnetic field allows the beam acceleration only by RF pattern.
    - No needs of synchronization between RF and magnets.
  - Large repetition rate
    - Space charge and collective effects are below threshold.
- Strong focusing(trans. and long. directions): it is like synchrotron.
  - Large acceptance
  - Various longitudinal RF gymnastics become possible.
    - Bunching, Stacking, Coalescing, etc.
  - It is like synchrotron.

FFAG加速器システムの現状



Beam Intensity



Let’s drink! June. 3rd, 2008

FIRST ADSR EXPERIMENT

- March 4, 2009: The first beam from FFAG was successfully delivered to KUCA.

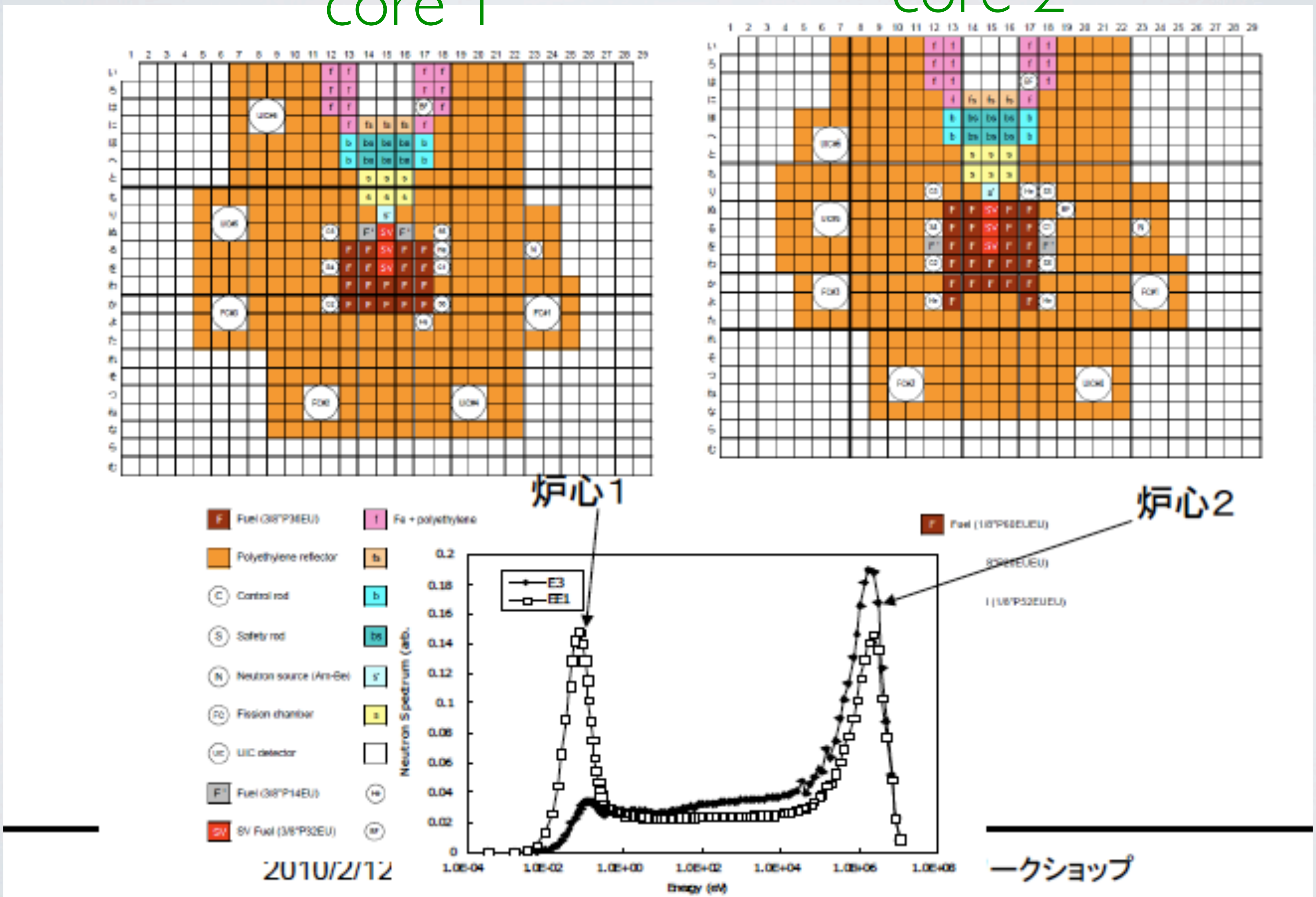
ITEMS OF ADSR EXPERIMENTAL STUDY

- High energy neutron spectrum
- Reactivity distribution, neutron distribution and proton profile at the reactor core
- Reactor response for abrupt changes in reactivity: beam trip, negative reactivity introduction, etc.
- Sub-criticality measurement with pulsed neutron method
- Dynamical behaviors with Feynman-α method

EXPERIMENTAL SYSTEM

Two types of core system were used

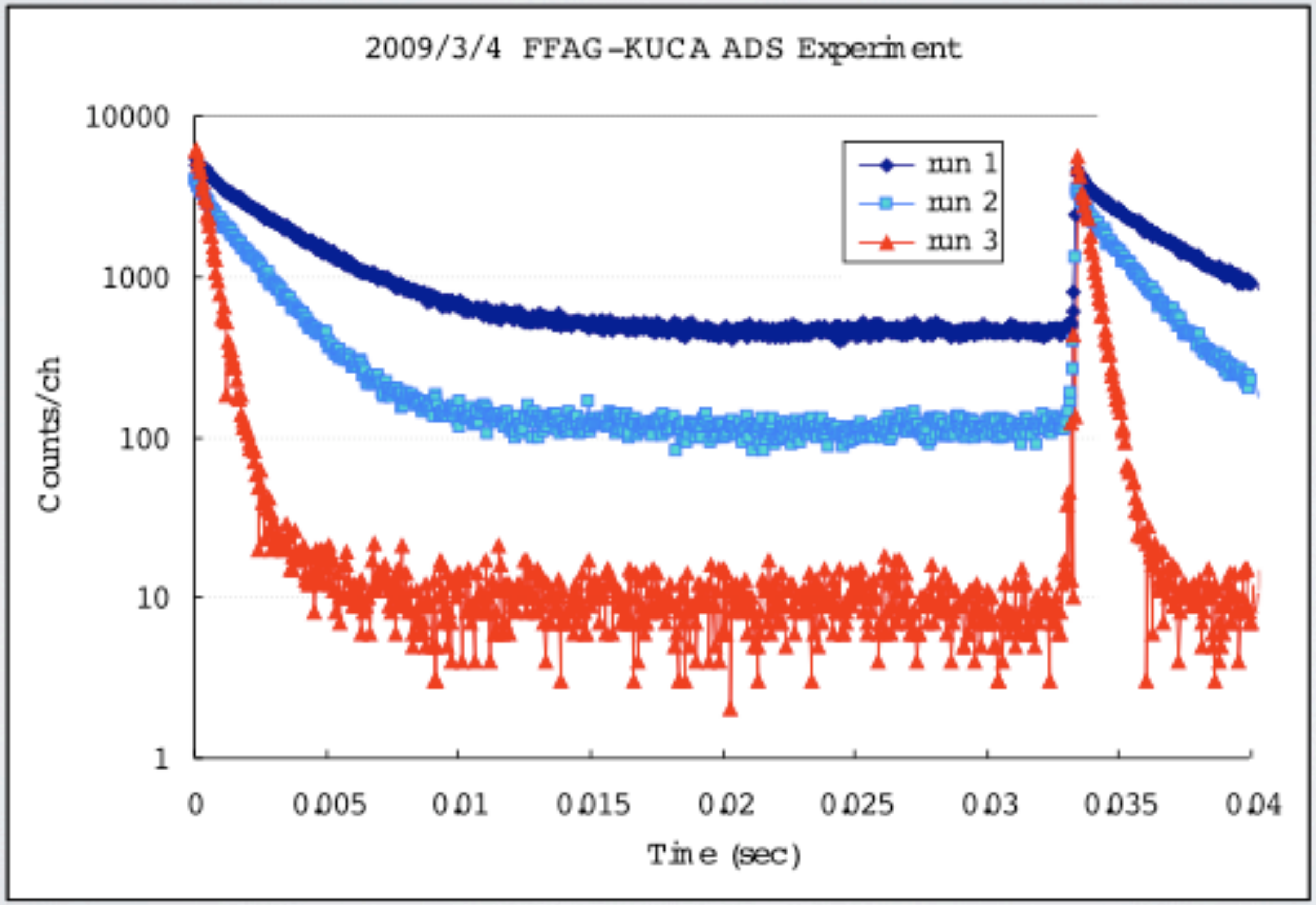
core 1 core 2



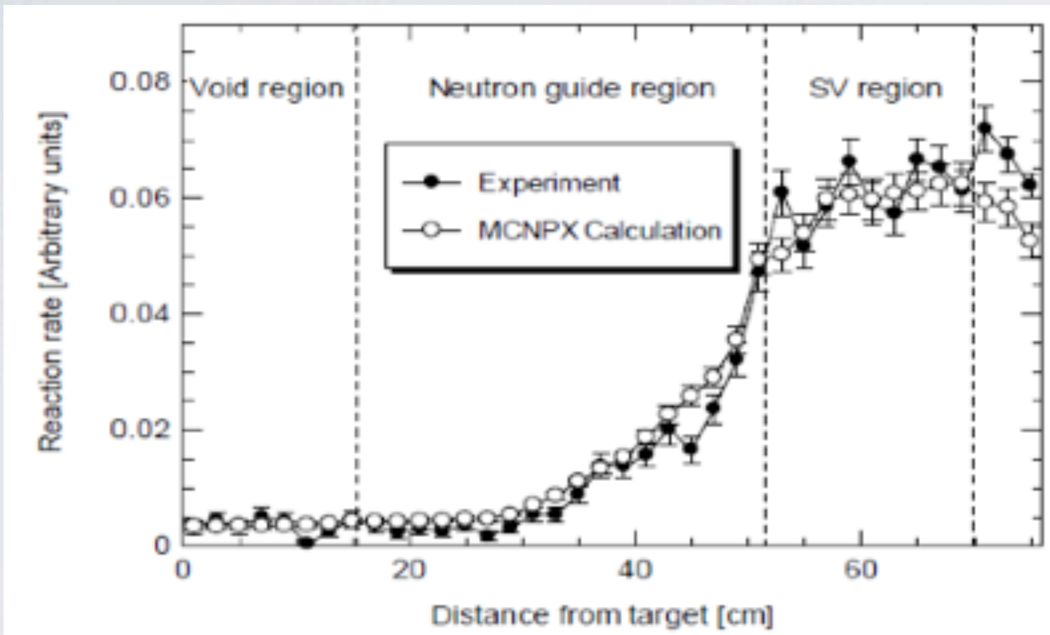
FIRST DATA

Journal of Nuclear Science and Technology, Vol.46 No.12, pp.1091-1093(2009).

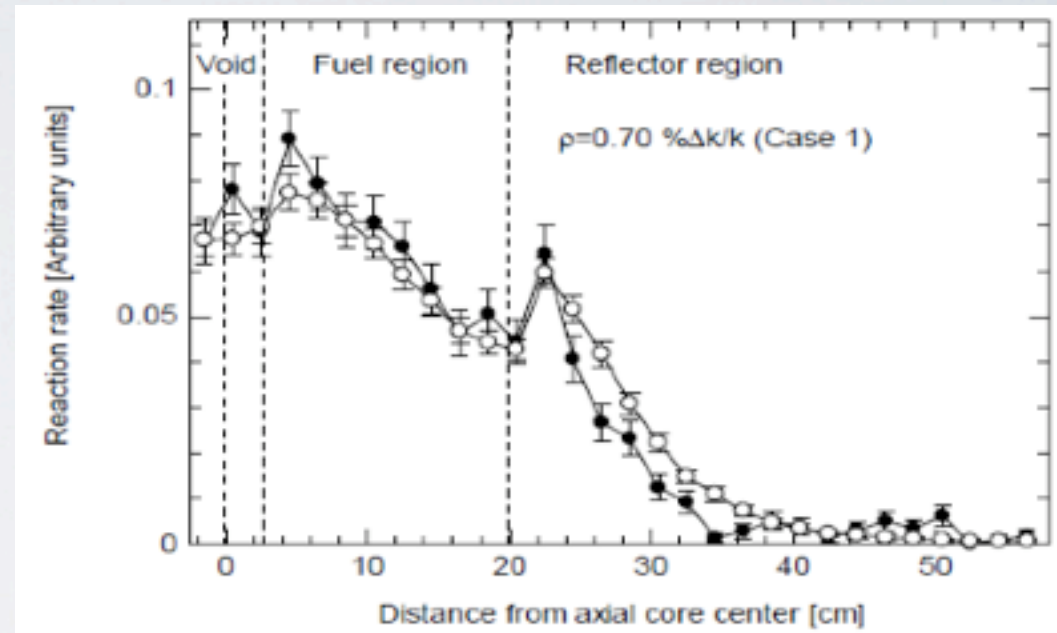
- Measurement of neutron multiplication



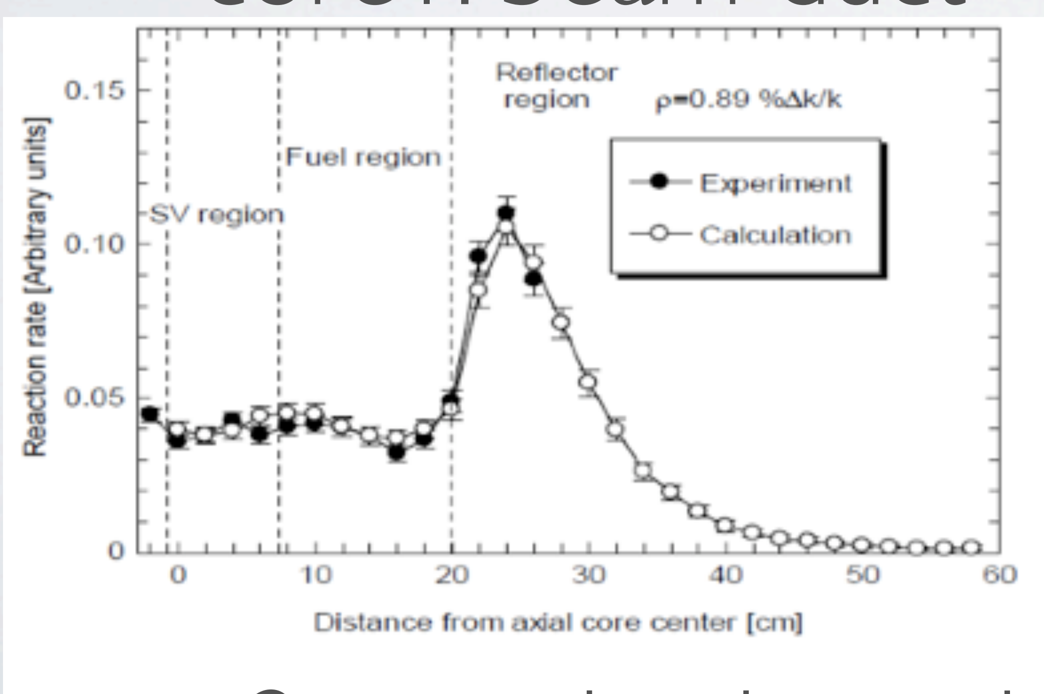
REACTIVITY DISTRIBUTION



core1: beam duct



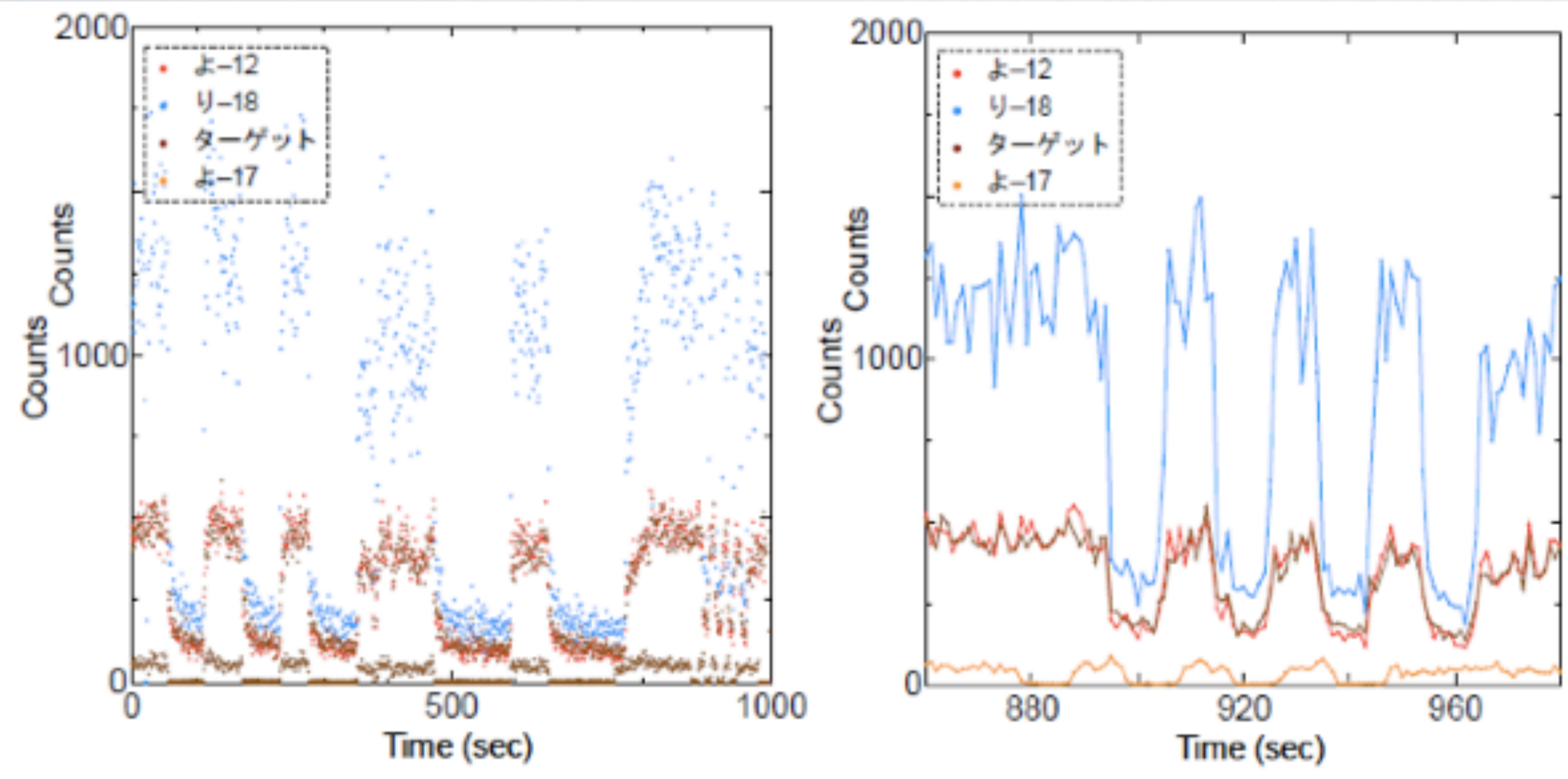
core1: core-axial

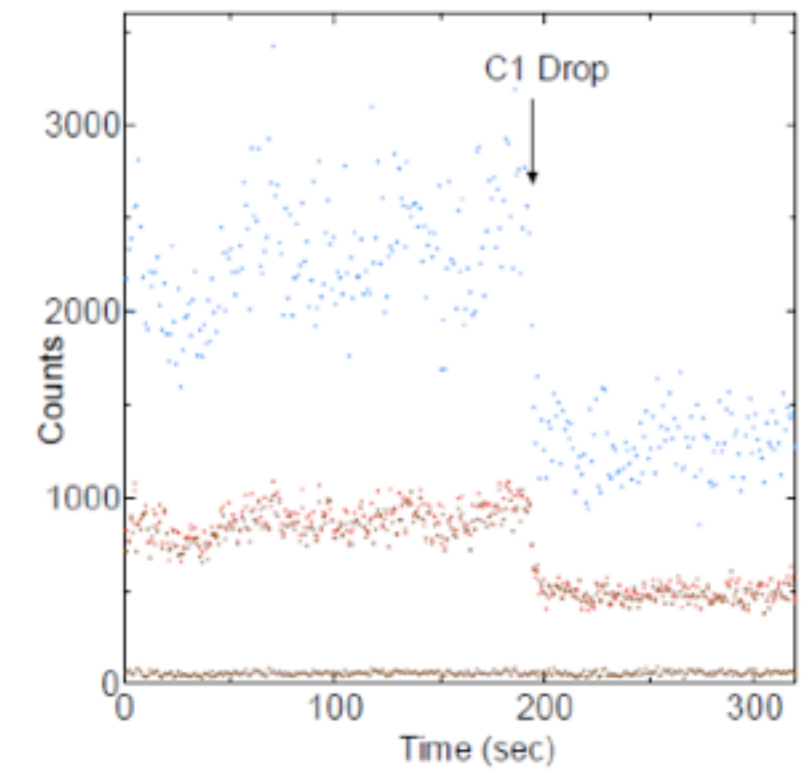


core2: core-horizontal

Good agreement with the MCNPX predictions

REACTOR RESPONSE FOR ABRUPT CHANGES IN REACTIVITY



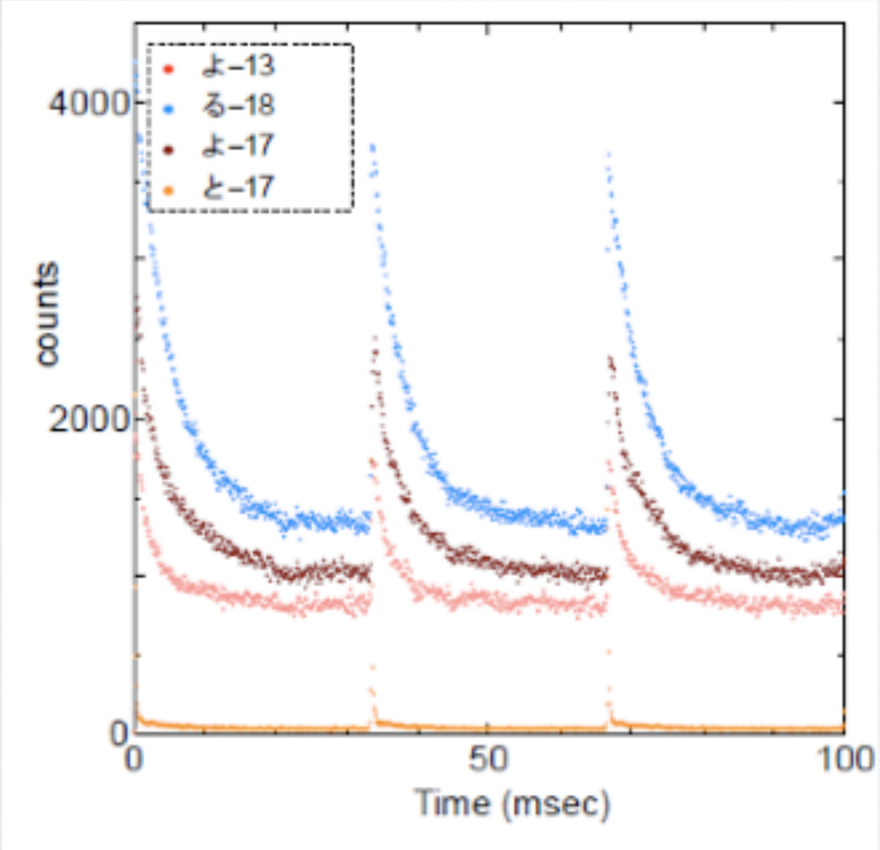


core 2: Responses for the beam switched on-off

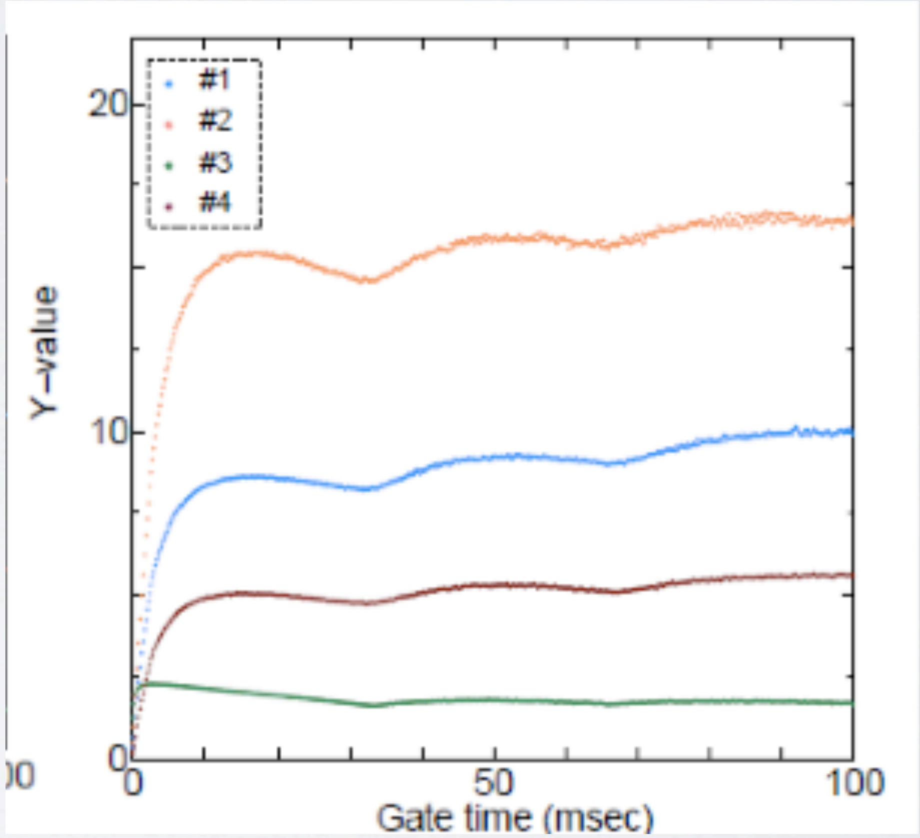
core 2: Response for abrupt injection of control rods

SUB-CRITICALITY & DYNAMICAL BEHAVIOR

PNM and Feynman-α were both useful for detecting the sub-criticality during operation.



pulsed neutron method



Feynman-α

THORIUM LOADED CORE MAR. 3RD, 2010

THORIUM LOADED CORE

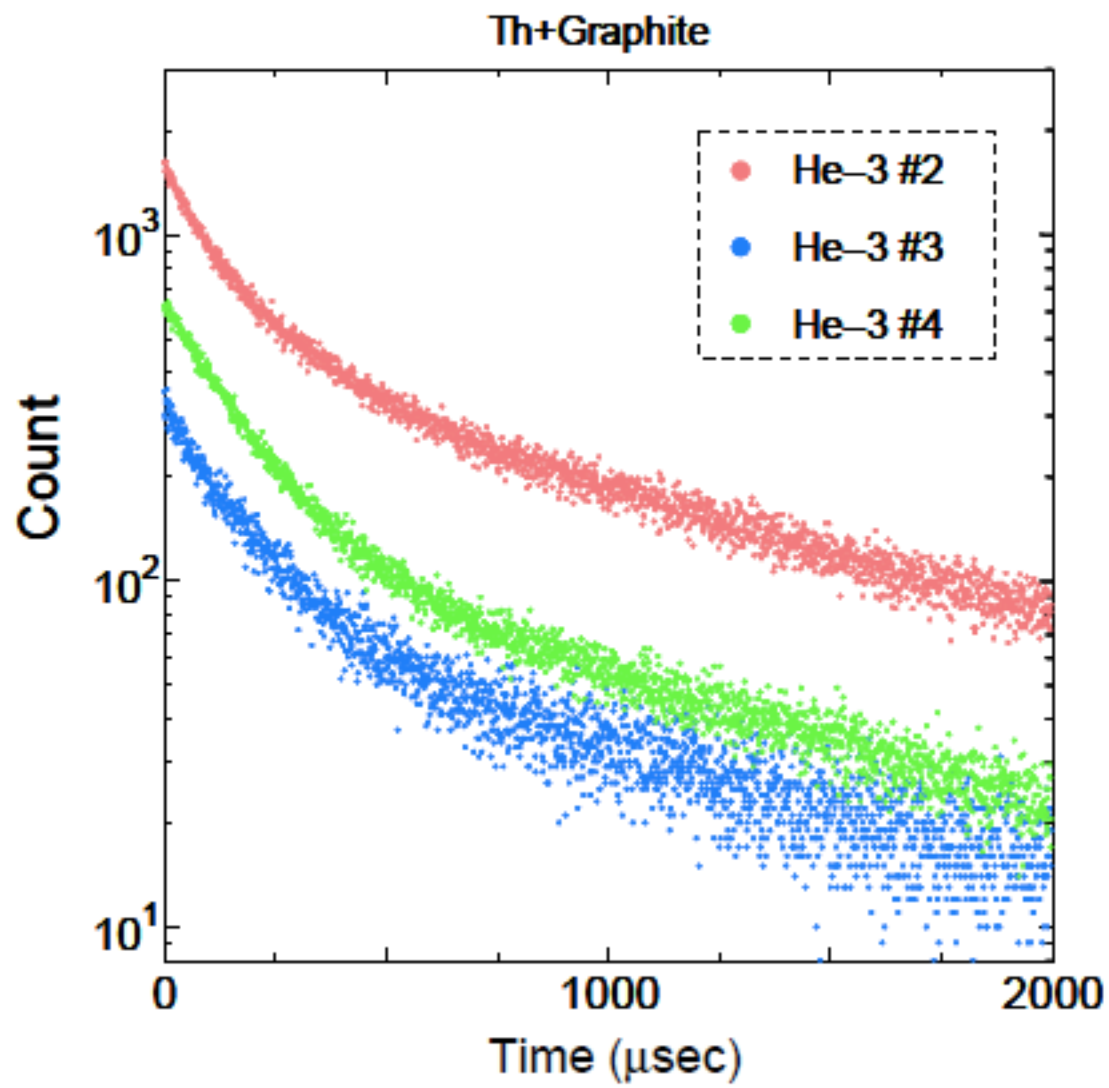
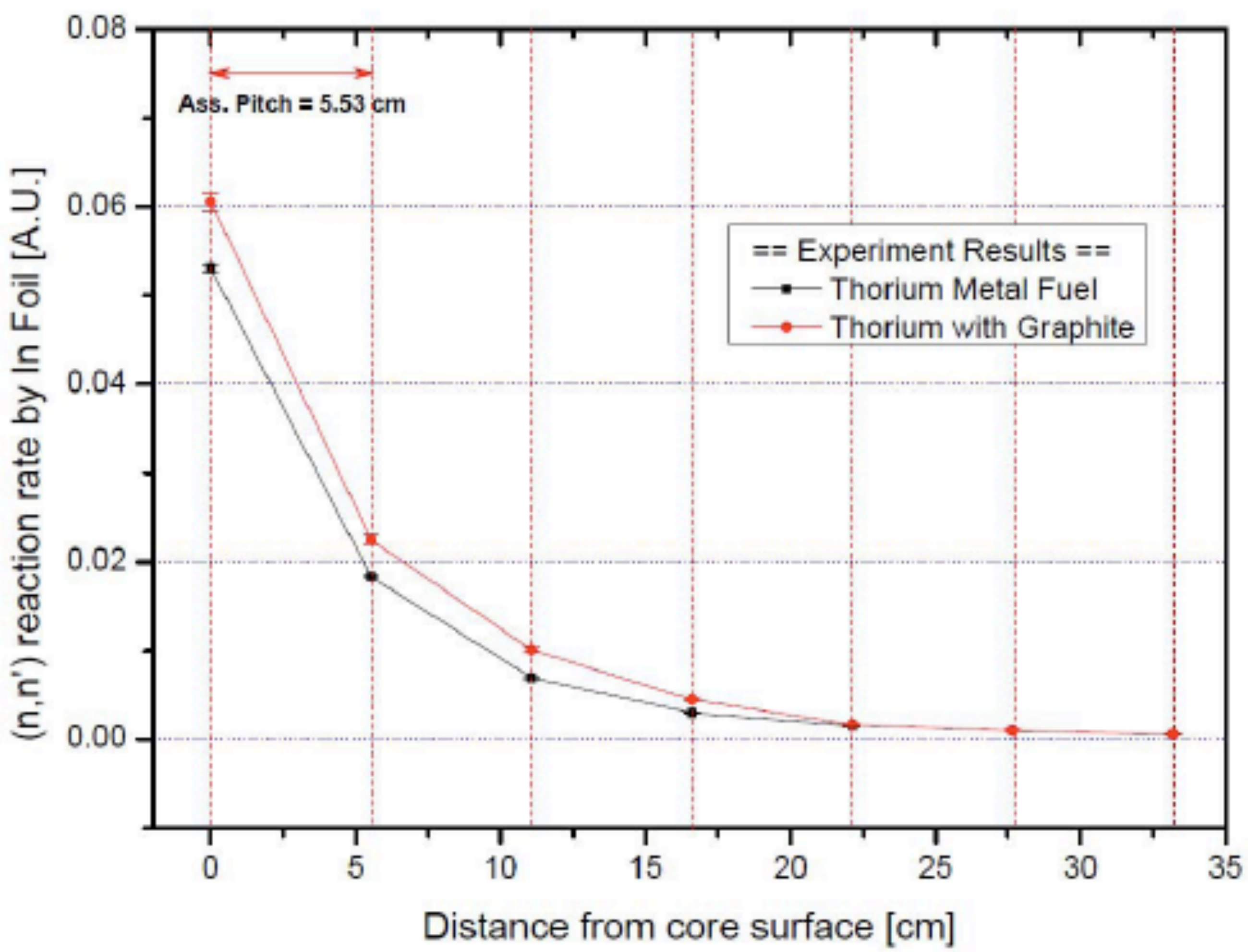


Fig. Results of pulsed neutron method at Th-Graphite core



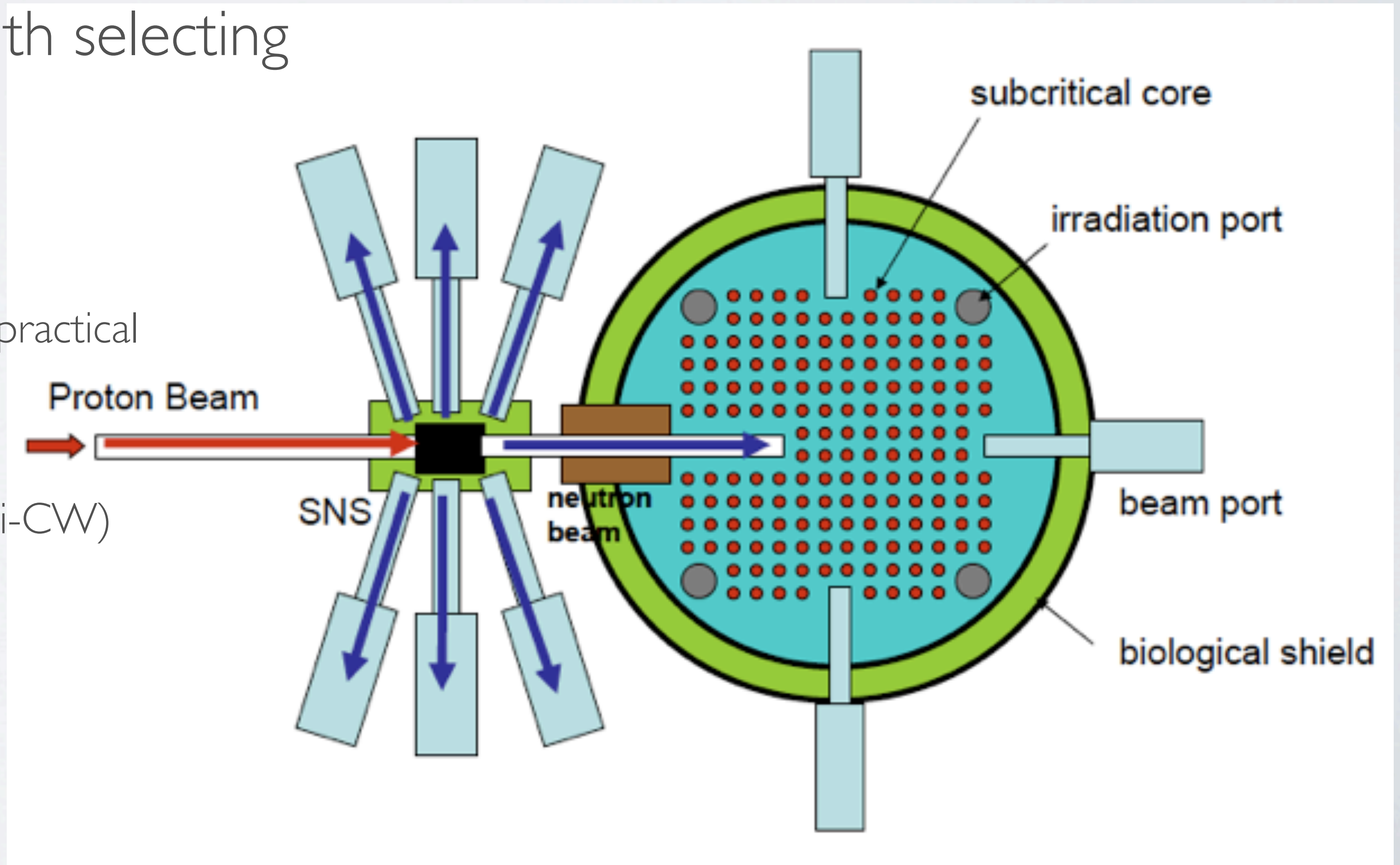
UPGRADE OF FFAG

- ADSR engineering experiment with high-power sub-critical system (not reactor)
  - Output power (SC) ~10kW: proton beam power >kW
  - Engineering study: cooling(heat transfer), materials, control of reactivity, etc.
- Nuclear data taking
  - Energy range of neutrons 0.1-10MeV : complementary for e-Linac
  - Neutron yield: 5×10^{13} n/sec @60Hz operation
- Pulsed spallation neutron source
  - Beam power >1kW
  - Innovated neutron target -> cf. 2nd target at Rutherford Lab.

SUB-CRITICAL SYSTEM +SNS

by Drs. Unesaki & Sugiyama

- Thermal power 10kW(keff=0.90)
- Neutron flux 10^{11} n/cm^2/sec
- Fuel 20% enriched TRIGA type
- Neutron spectrum variability with selecting the fuel-moderator ratio
- Aims
  - Taking nuclear engineering data for future practical ADSR(MW)
  - Providing neutron experimental field (semi-CW)

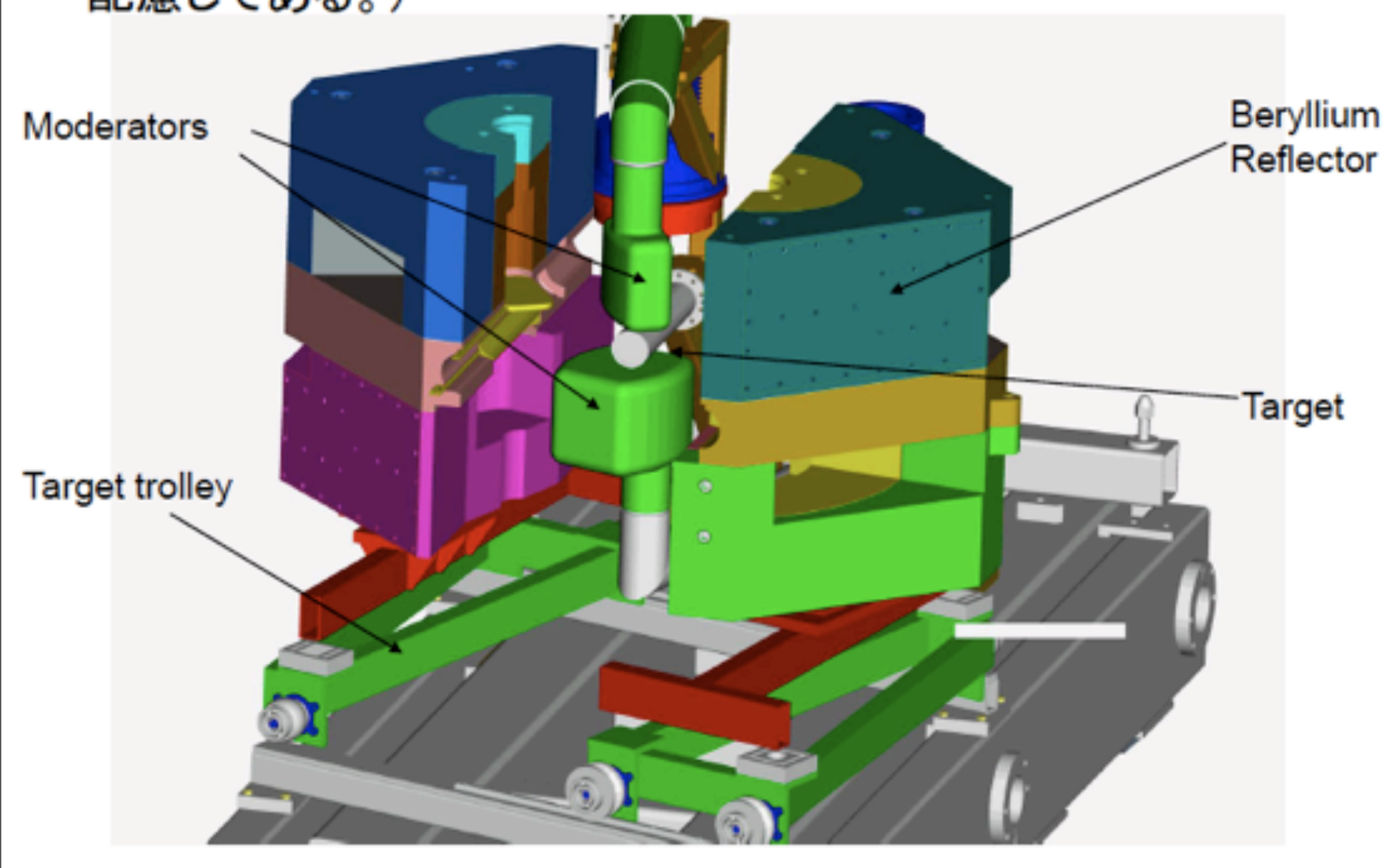


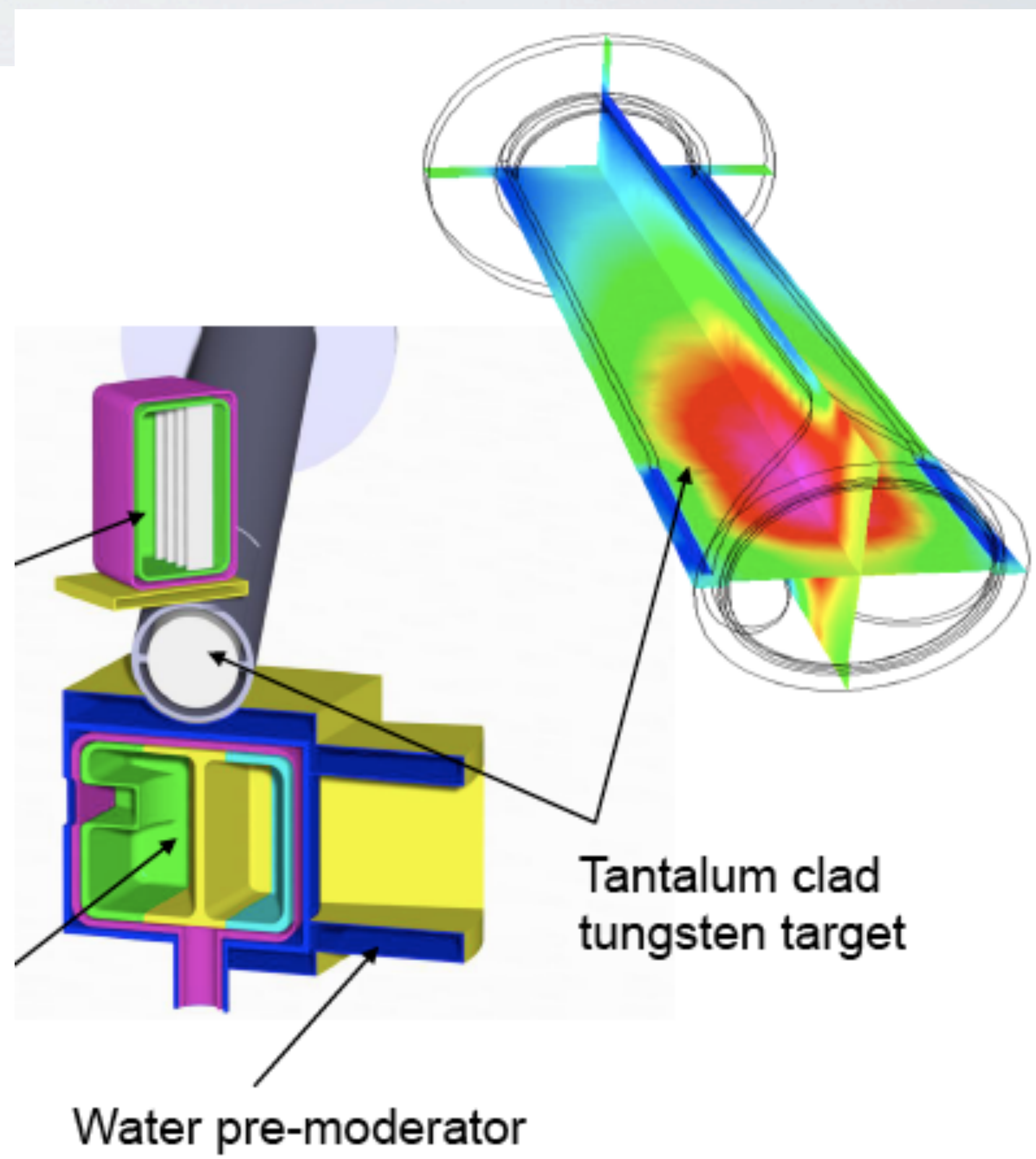
SNS TARGET

- Model : ISIS 2nd target (example)
- Beam power ~1kW
- Rep. rate 15-30Hz

courtesy of Dr. Arai(JAEA)

Target Moderator and Reflector Assembly
（非常ににコンパクトなものである。取り扱いについてもよく配慮してある。）





Future prospect of nuclear data measurement at the KURRI–FFAG

KURRI-FFAG neutron source

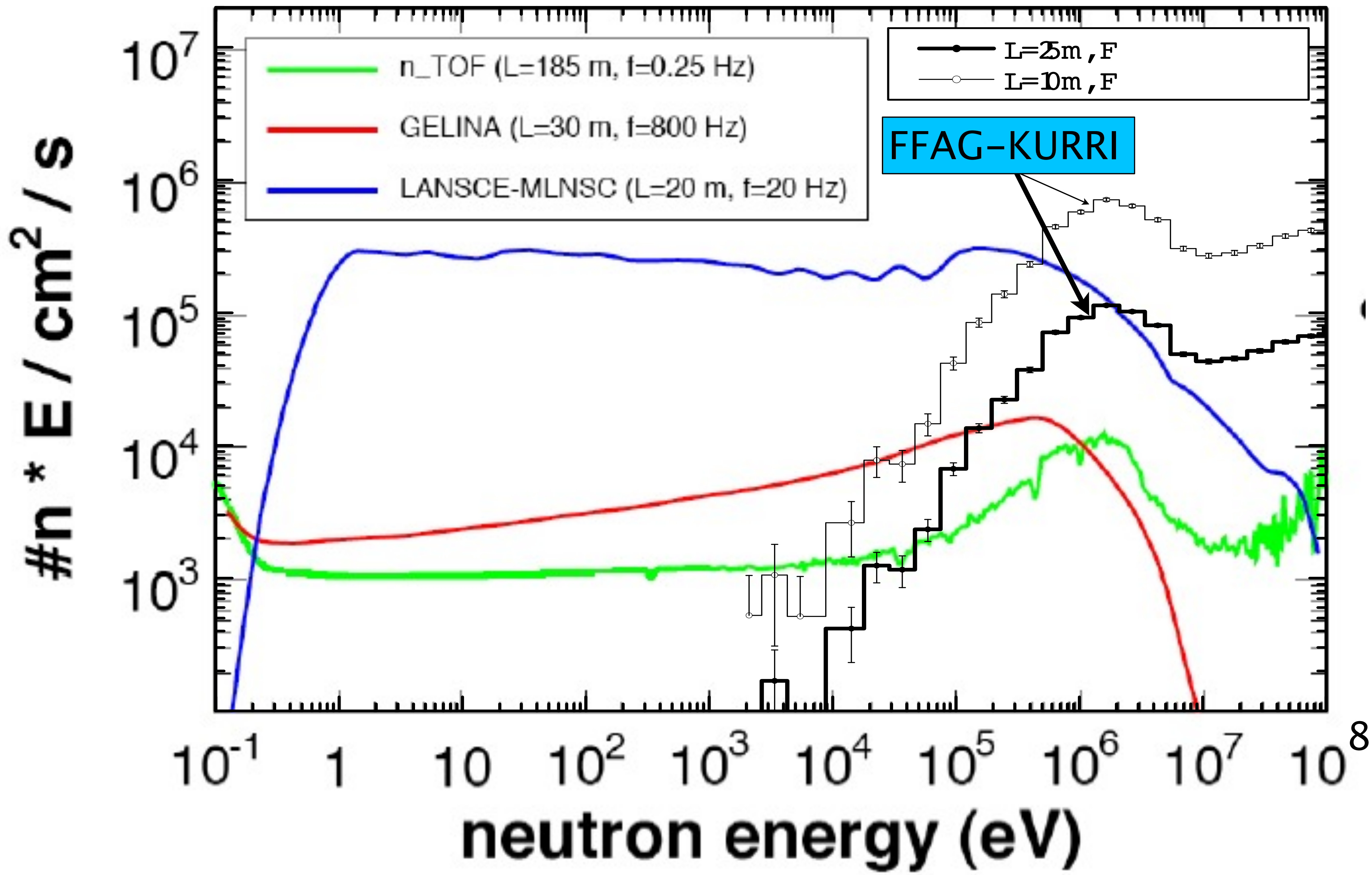
- Proton energy :   150MeV
- Proton beam intensity :   6μA(30Hz)
- Neutron energy range :   0.1-10MeV (small moderator)
- Complementary for e-LINAC neutron source(<0.1MeV)

Target : Minor actinide (MA), Long-lived fission product (LLFP)

Estimation for neutron flux of FFAG

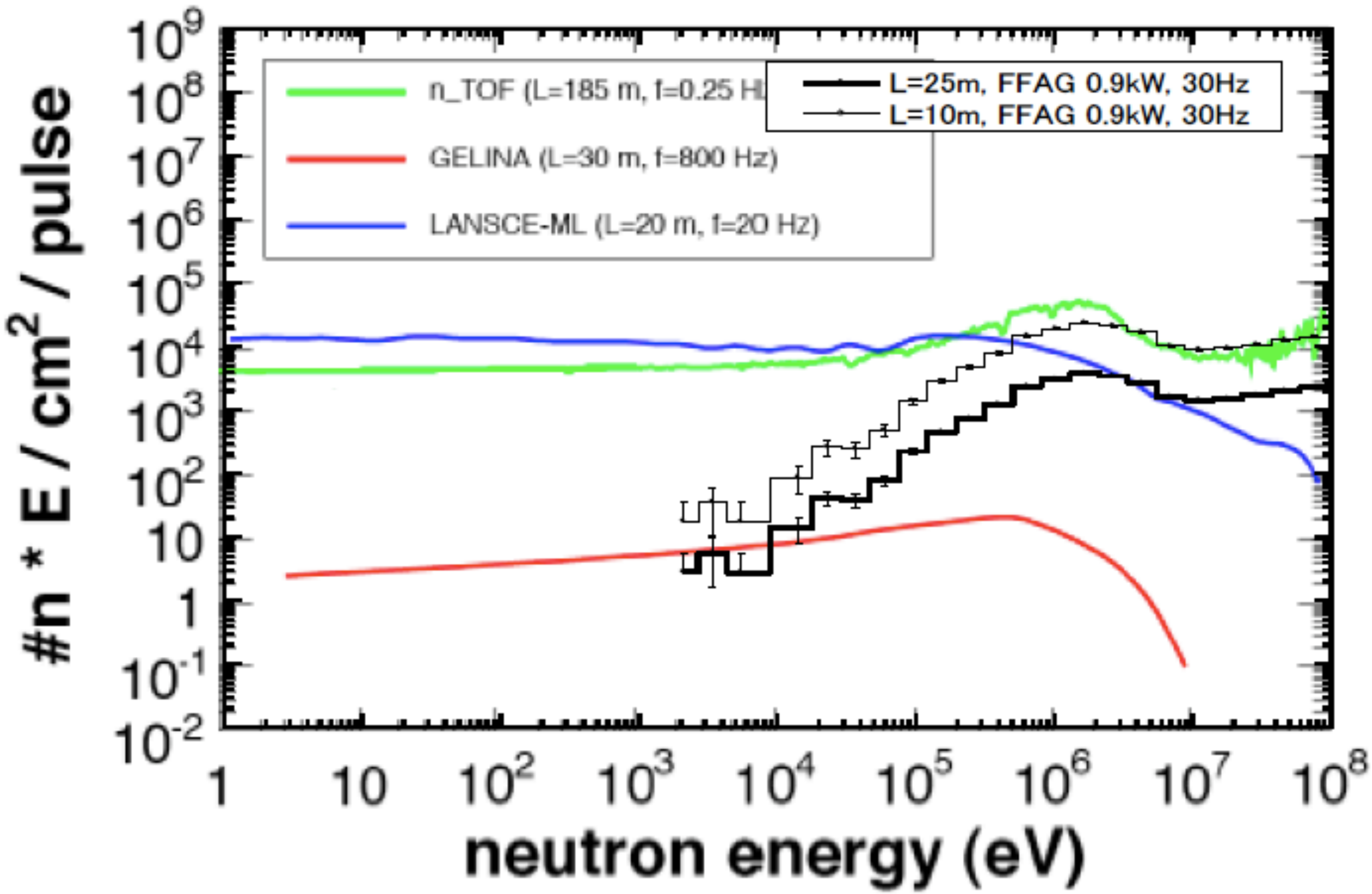
- Calculation : PHITS 2.13 with JENDL-HE data
- Target：1cmϕ ＊1.7cmt W, full stop
- Incident particle：150MeV proton, 6μA (0.9kW)
- Without moderator
- Neutron flux was calculated at the position (L=0.5m)
- Neutron flux at each sample position (L=10, 25m) was estimated with the difference of solid angle.

Average flux (per second)



Reference: F. Gunsing, et al., Nucl. Instrum. Meth.,B 261, 925-929 (2007).

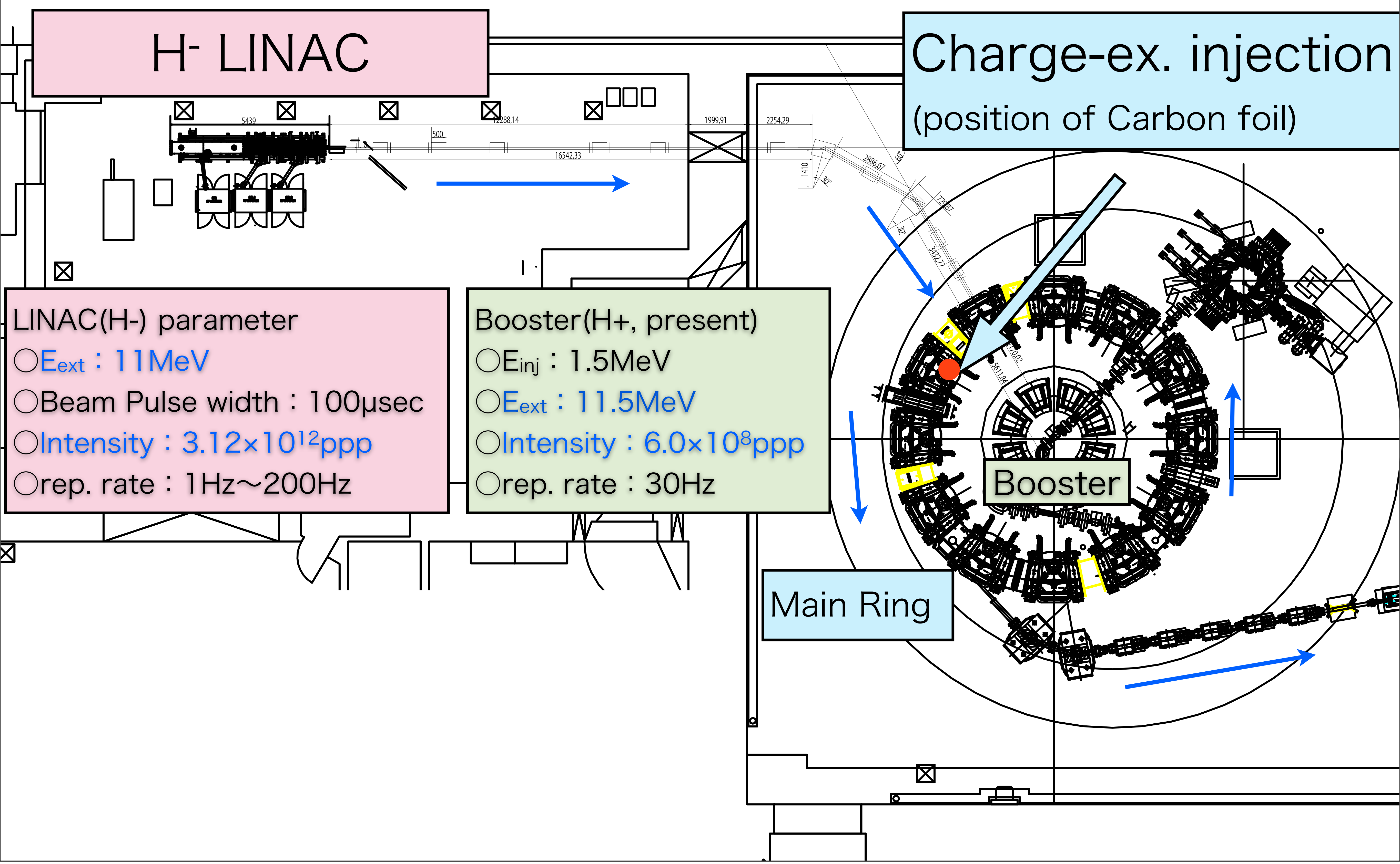
Neutron flux (per pulse)



INCREASE OF BEAM INTENSITY

- Beam intensity capability of Main Ring
  - Space charge limit ~20μA : 5×10^{12}ppp (@10MeV injection)
  - Many protons can be injected and accelerated !
- Charge-exchange injection with H^- beam
  - Multi-turn injection (>100turns)
  - Need high current H- injector (I_{peak} > 1mA)
  - We have ***11MeV H^- Linac*** for FFAG-ERIT.

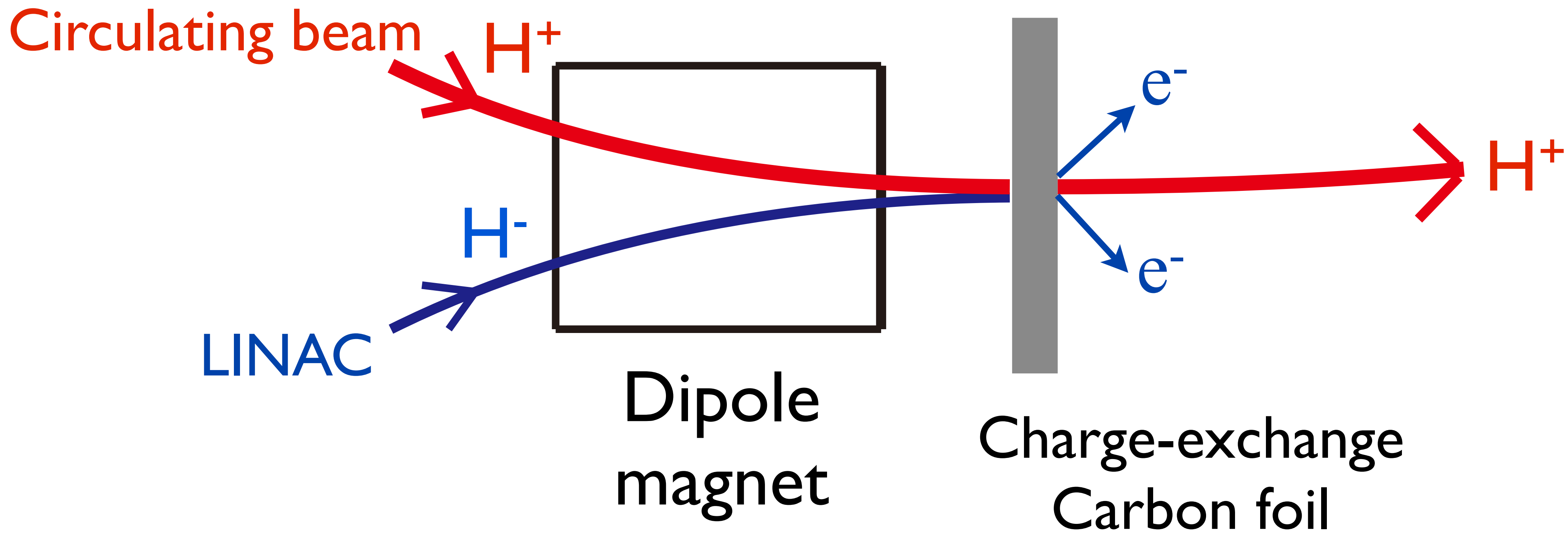
Upgrade of FFAG accelerator at KURRI



LINAC(H-) parameter
○E_{ext} : 11MeV
○Beam Pulse width : 100μsec
○Intensity : 3.12×10^{12}ppp
○rep. rate : 1Hz～200Hz

Booster(H+, present)
○E_{inj} : 1.5MeV
○E_{ext} : 11.5MeV
○Intensity : 6.0×10^{8}ppp
○rep. rate : 30Hz

H^- Charge-exchange Injection

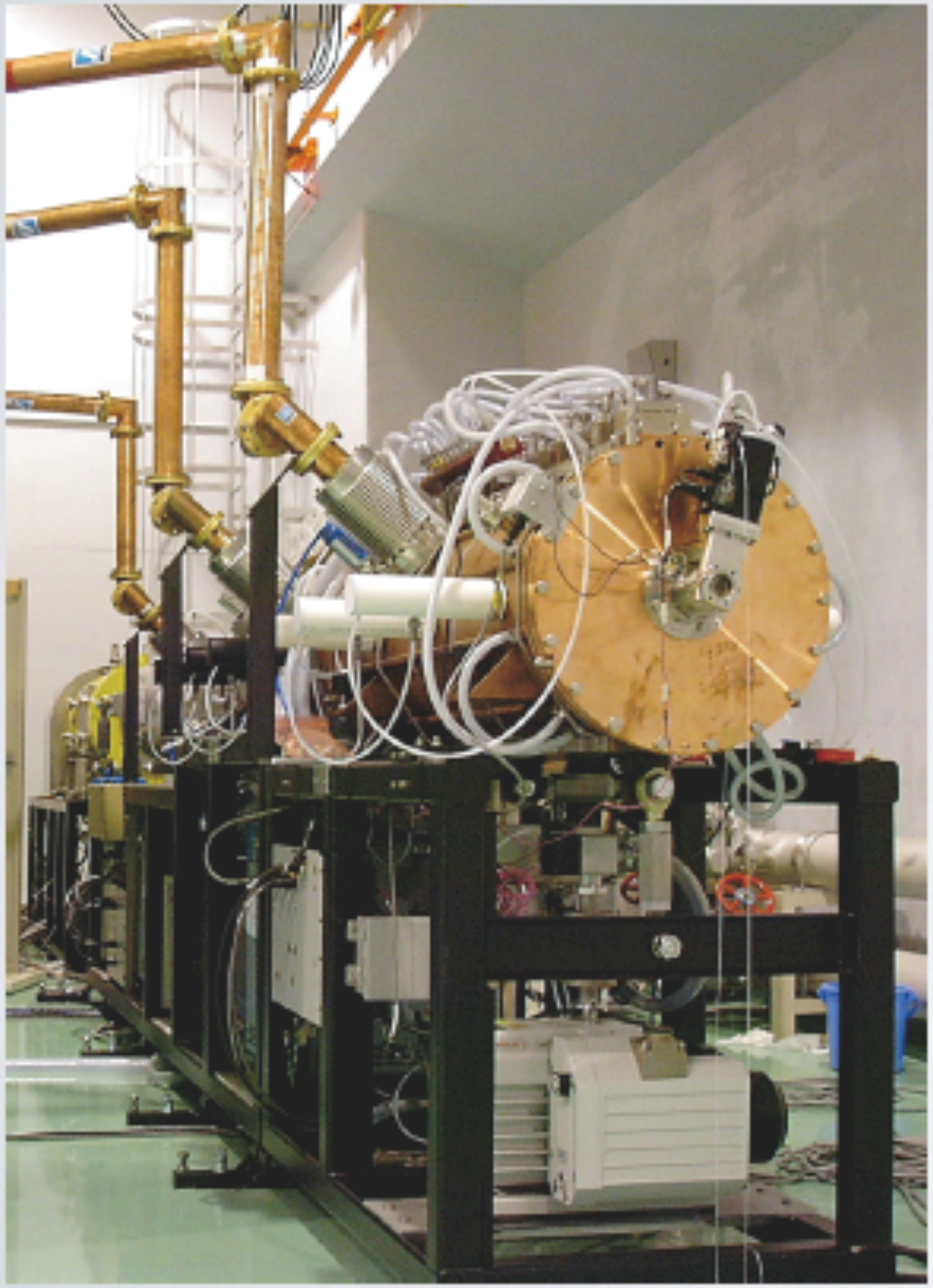


Scheme

- Inject H- ions from the linac
- Charge-exchange to H+ with C foil
- Acceleration

Advantage：Multiple injection into the phase space center

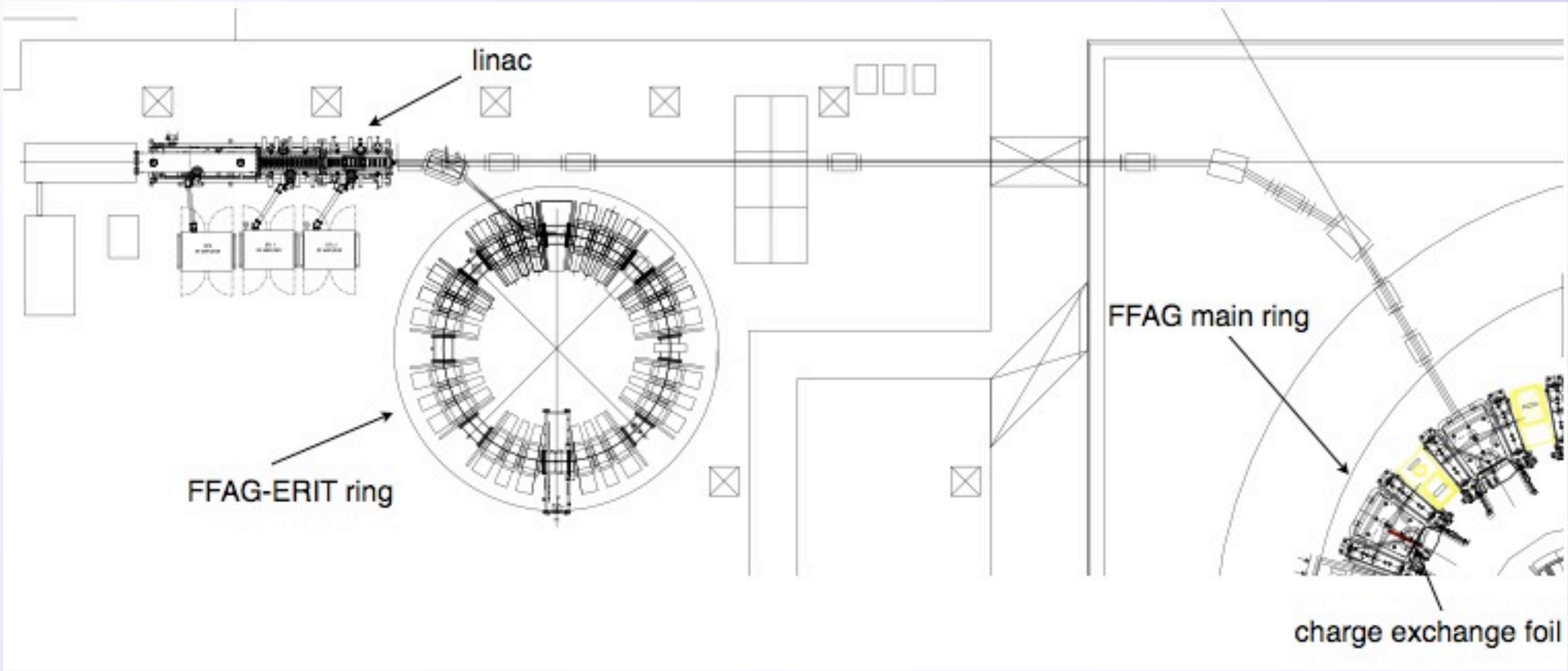
LINAC



Linac beam para.

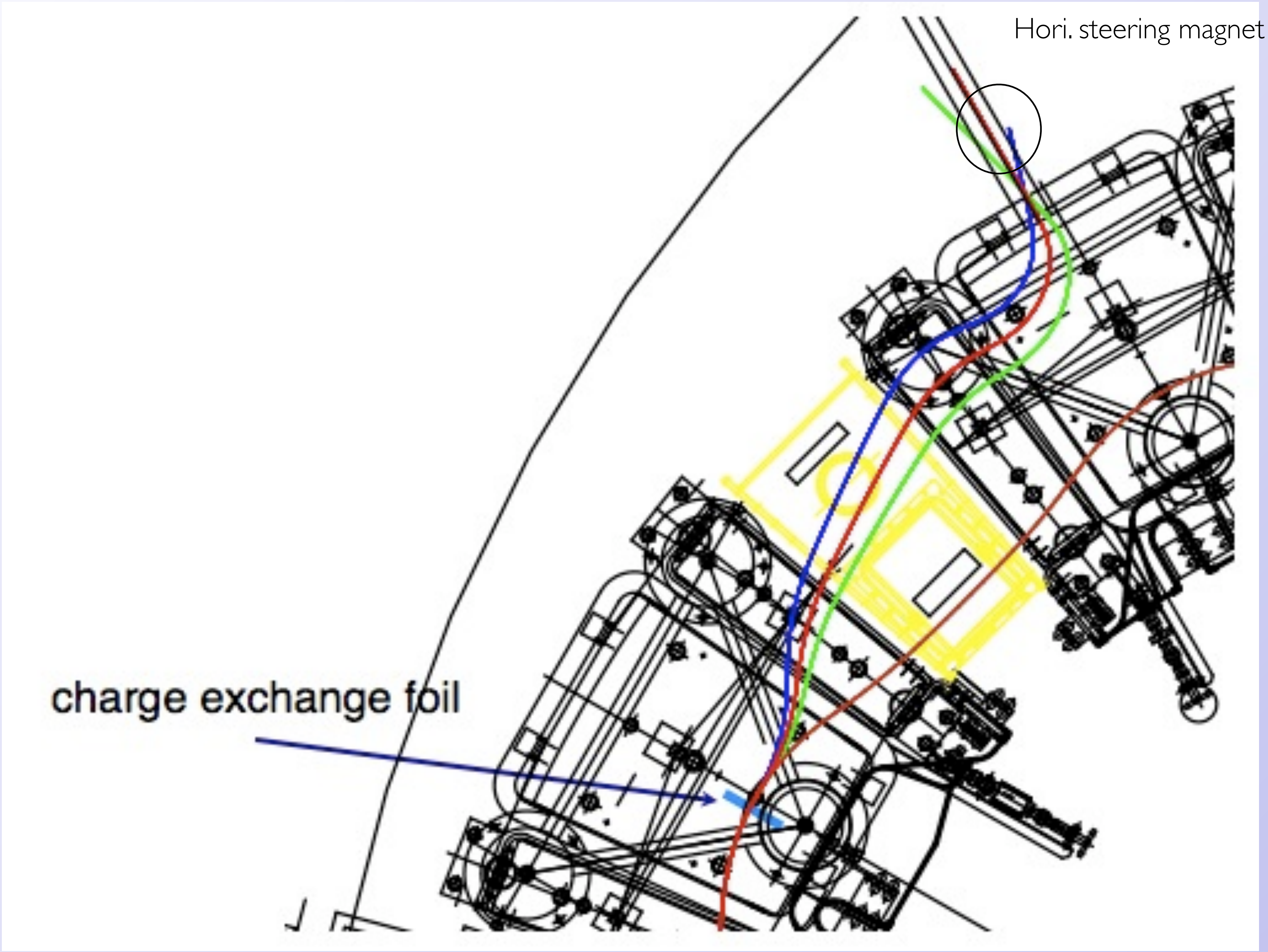
- ion : H^-
- E_{ext} : 11MeV
- Beam Pulse width(MAX) : 100 µsec
- Peak Curr.(MAX) : ~5 mA
  :$3.12*10^{12}$ [ppp]
- rep. rate : 1Hz ~ 200Hz
- unnorm. rms emittance
  Hori. : 0.896 mm mrad
  Vert. : 0.830 mm mrad

New beam-line



Q Magnet ×7, B Magnet(30deg) × 2

Injection orbit

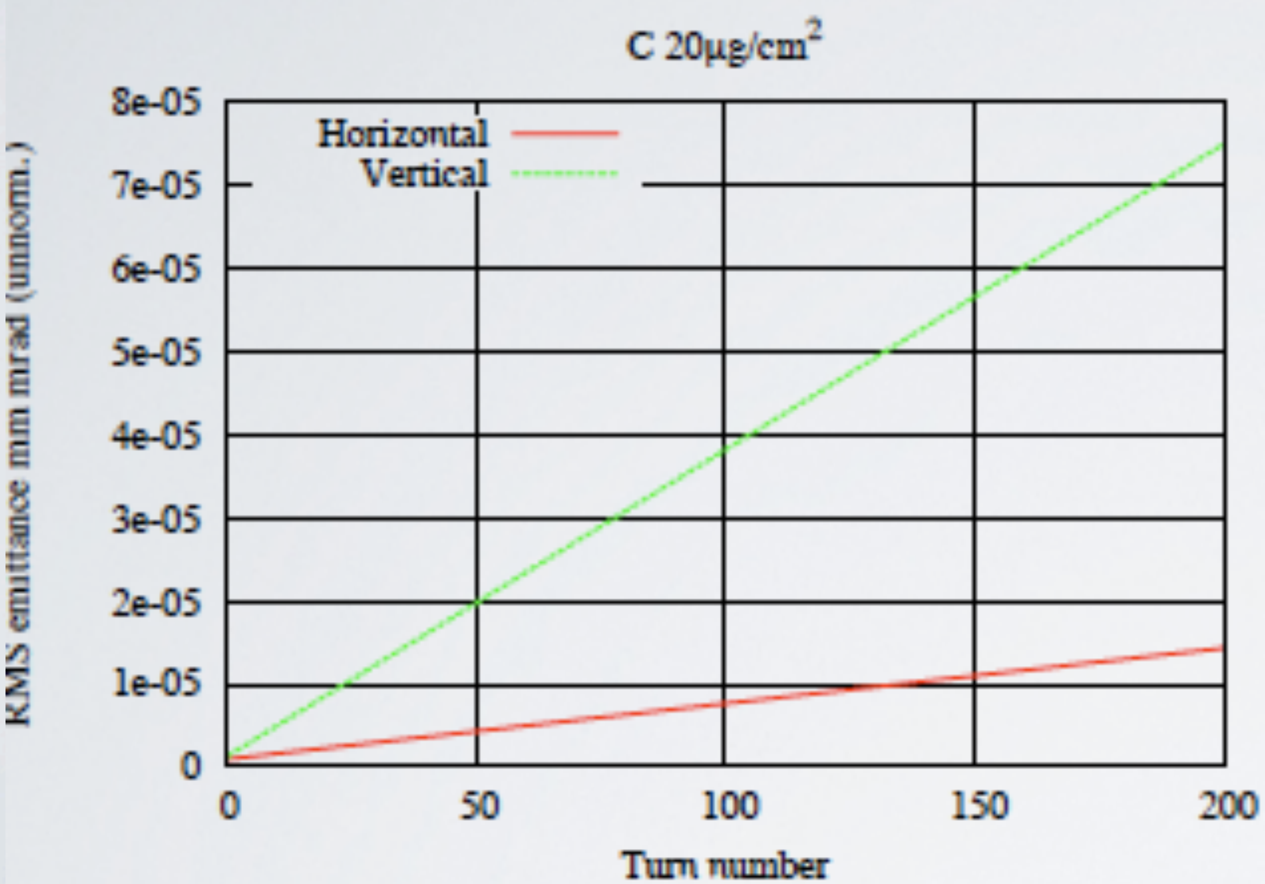


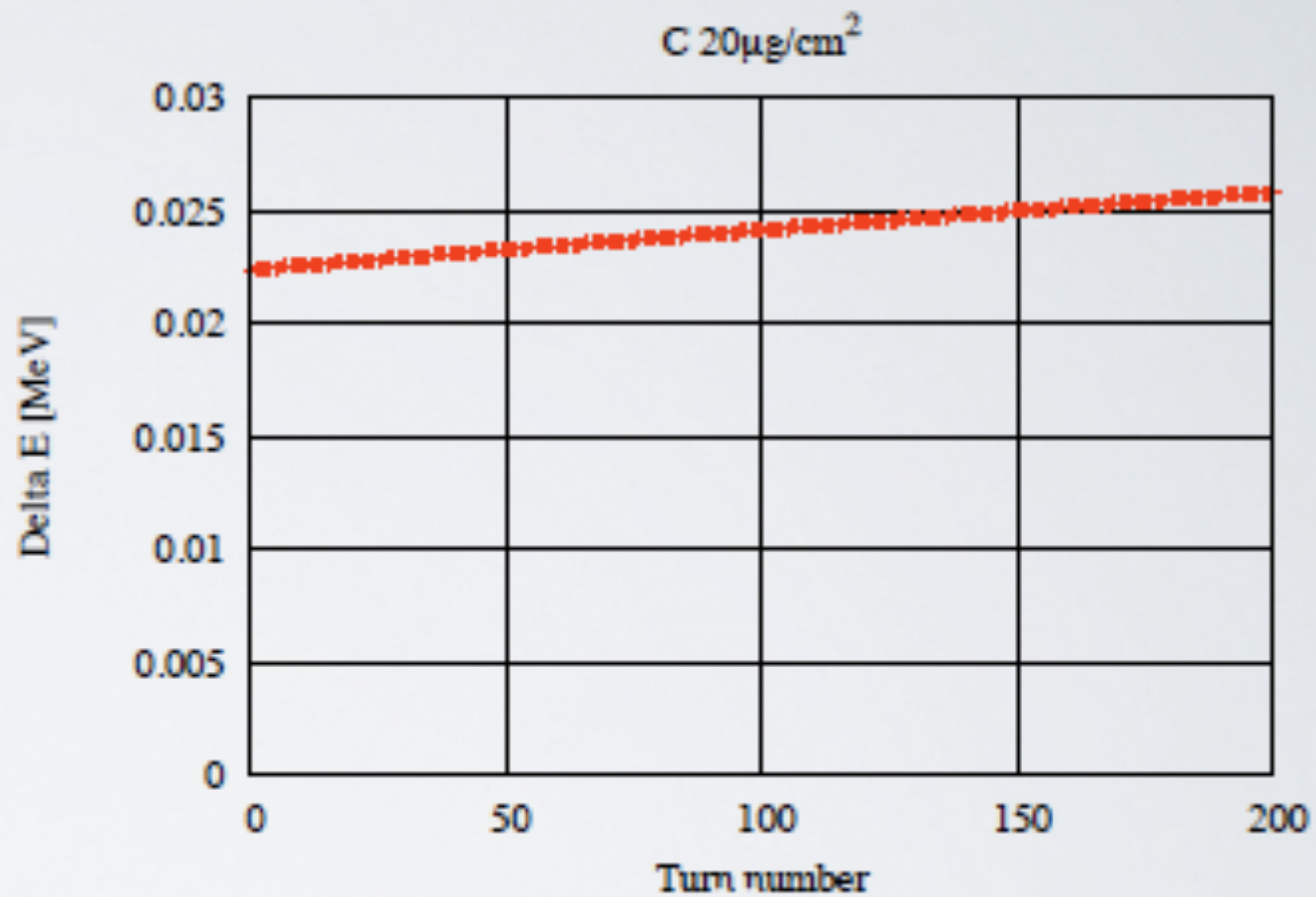
CHARGE-EXCHANGE INJECTION

- Low energy (11MeV) cf. 600eV for 20μg/cm^2 C-foil
  - large energy loss
  - large emittance growth
- Energy loss
  - rf re-acceleration as ionization cooling
- Emittance growth
  - Reduction of hitting probability
    - Off-center injection in horizontal direction
    - Moving orbit by rf acceleration (FFAG)

EMITTANCE GROWTH

- Vertical emittance growth ~5 x horizontal emittance growth
- Longitudinal emittance growth ~ negligible small

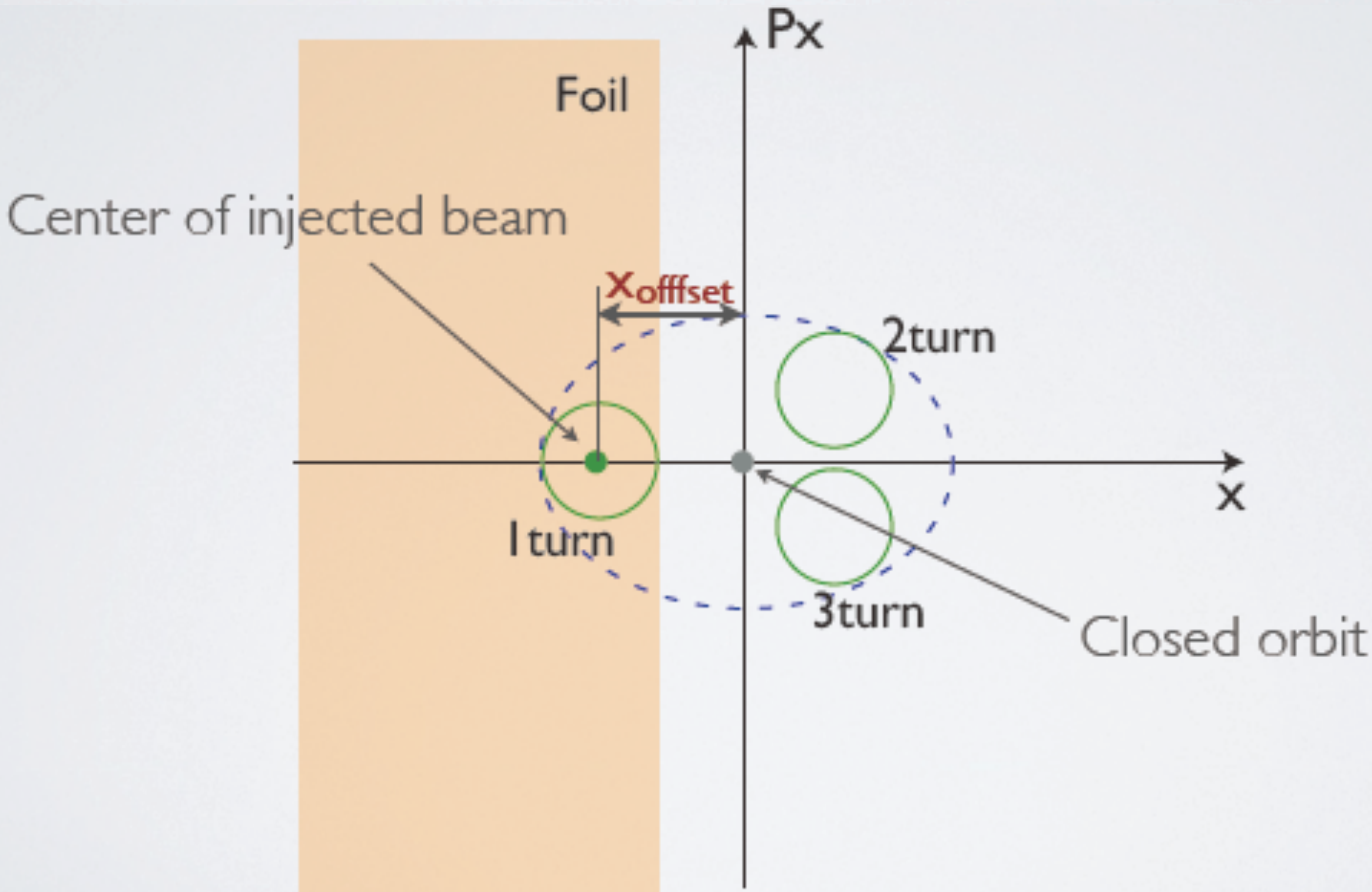




foil : 20 μg/cm²

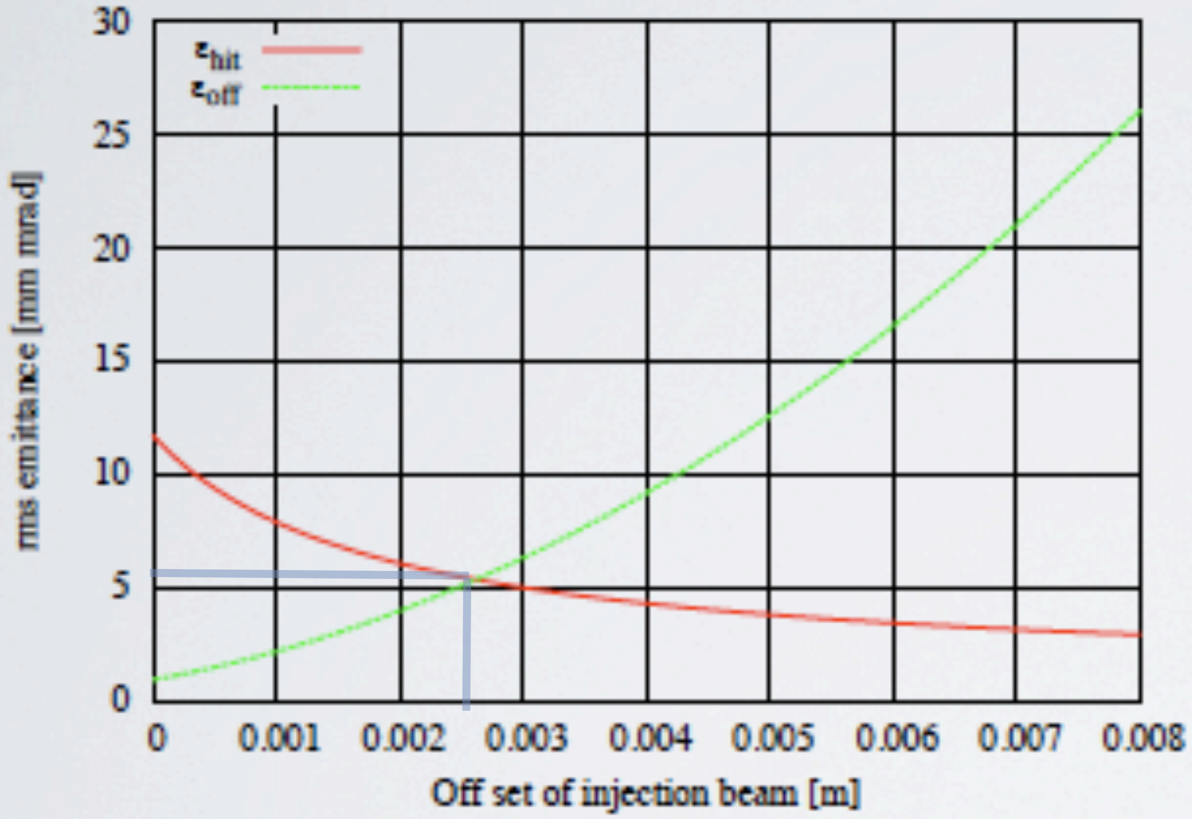
REDUCTION OF EMITTANCE GROWTH

- Hitting probability
  - Off-center (hor.) injection →betatron mismatch

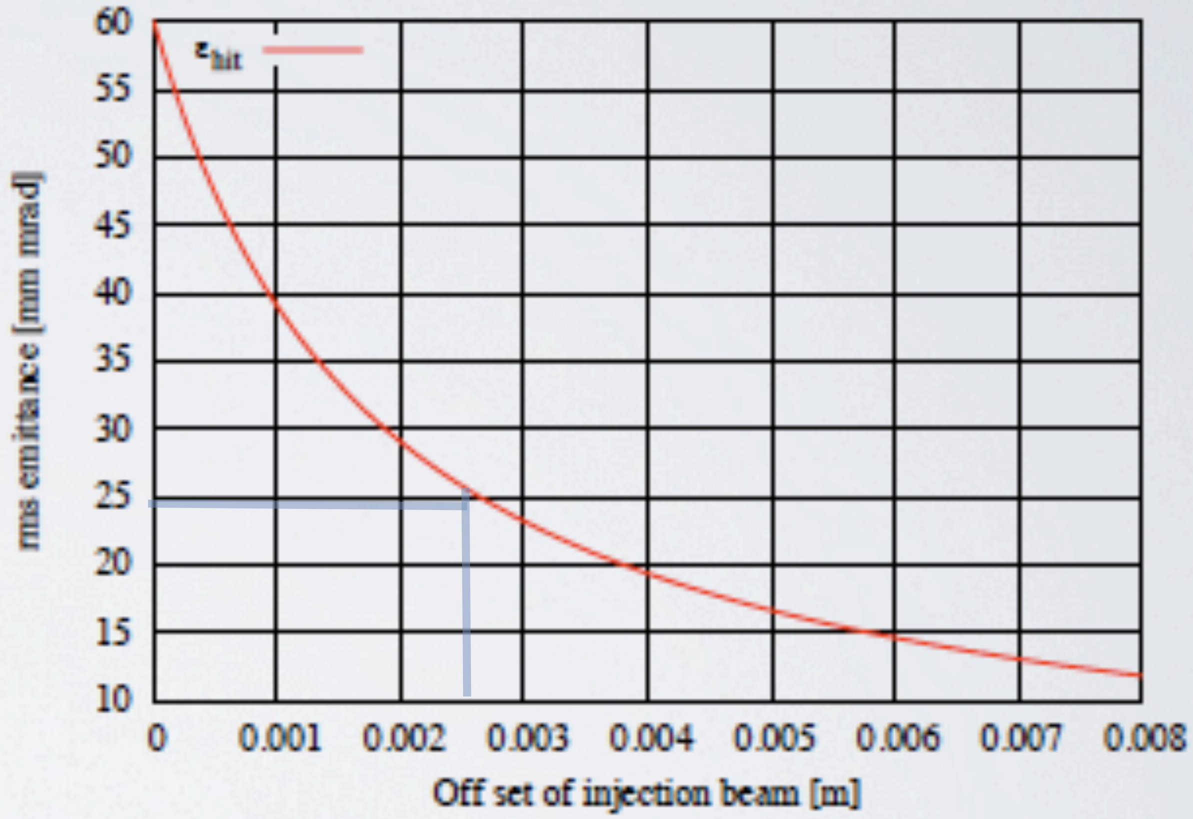


REDUCTION OF EMITTANCE GROWTH

Horizontal



Vertical



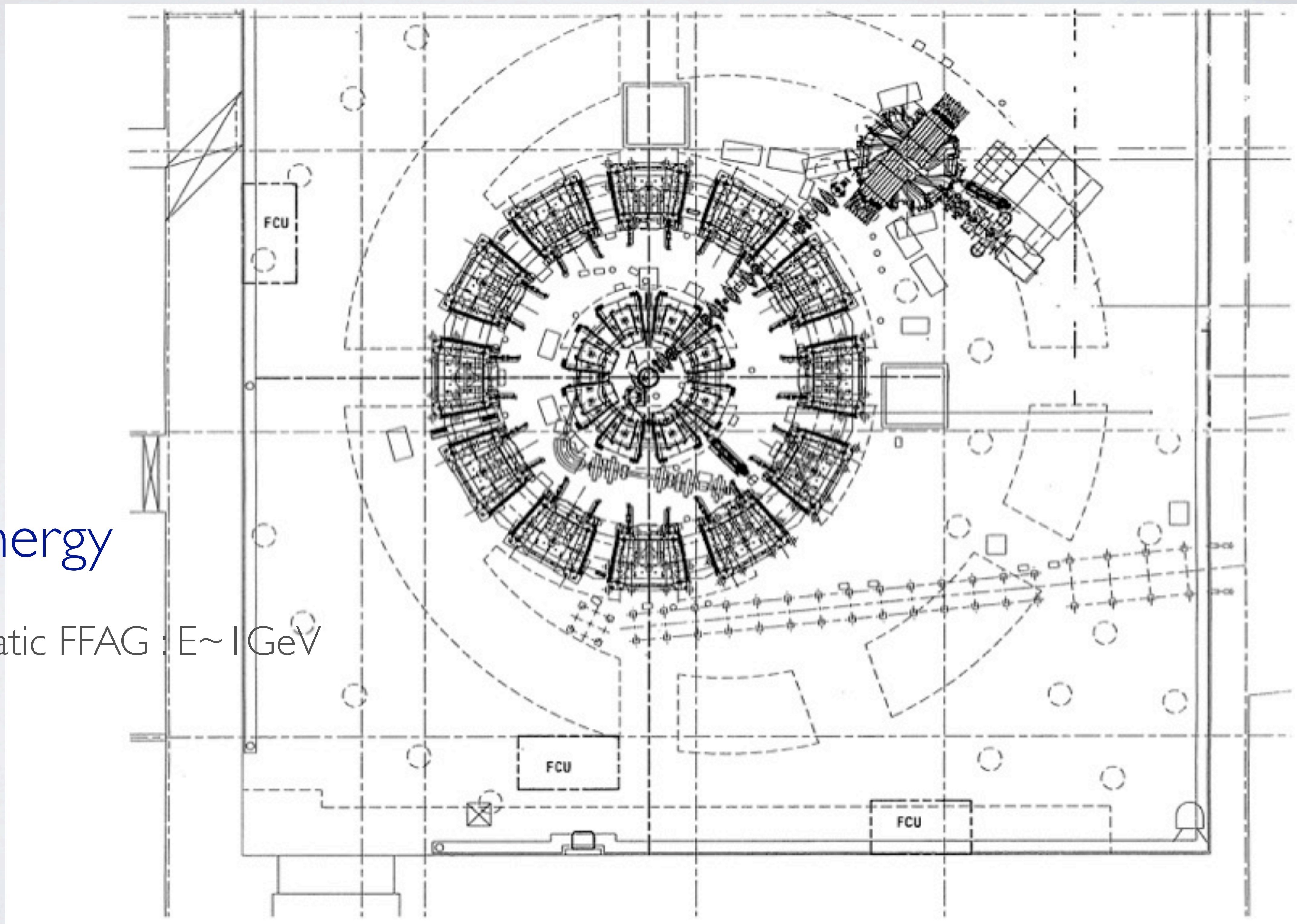
off set ~2.6mm

$\varepsilon_x \sim$ 7.7 mm mrad

$\varepsilon_y \sim$ 25 mm mrad

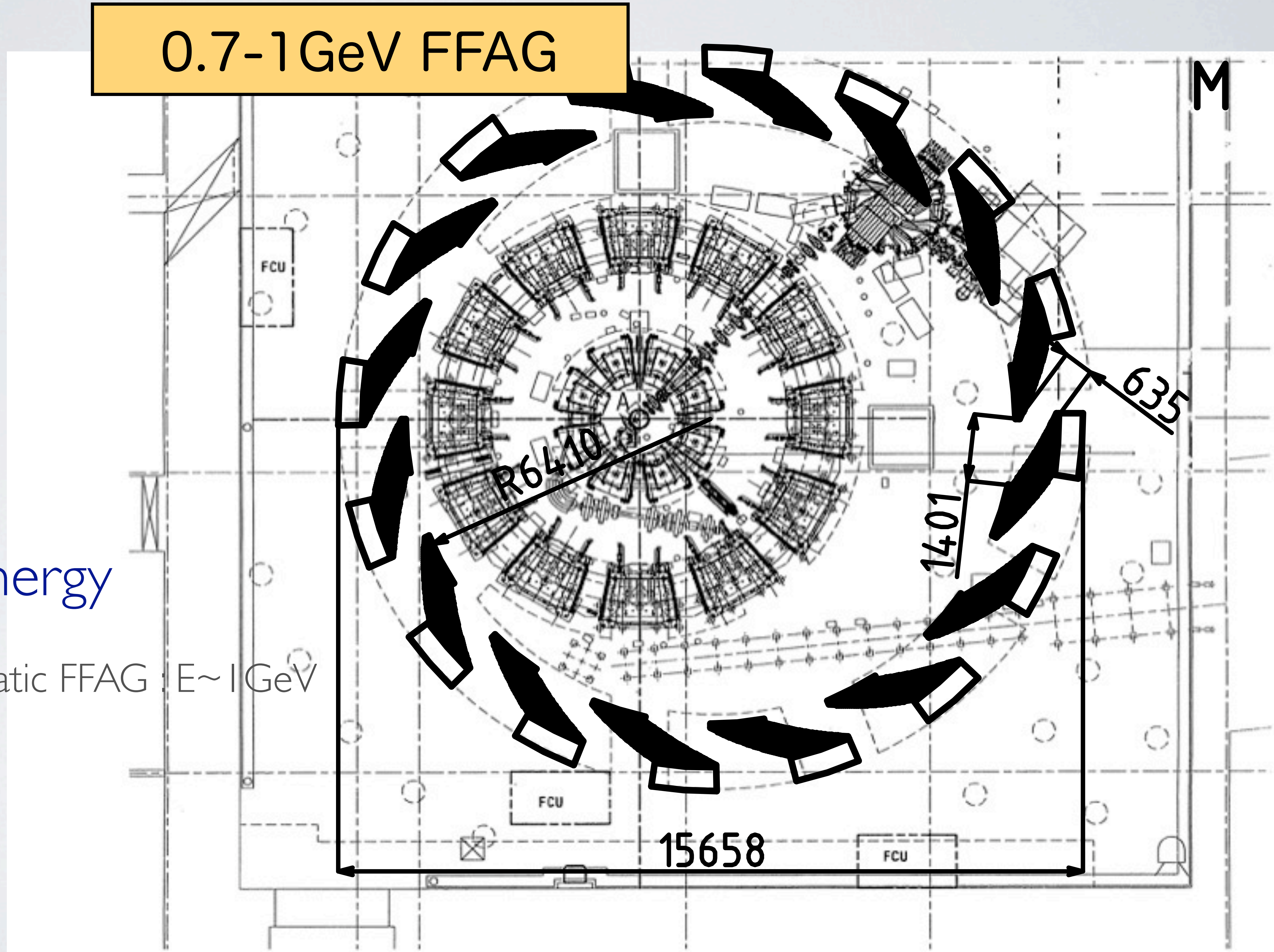
$(\varepsilon_{total}^2 \sim \varepsilon_{off}^2 + \varepsilon_{hit}^2)$

FUTURE



- Increase energy
  - zero-chromatic FFAG : E~1GeV

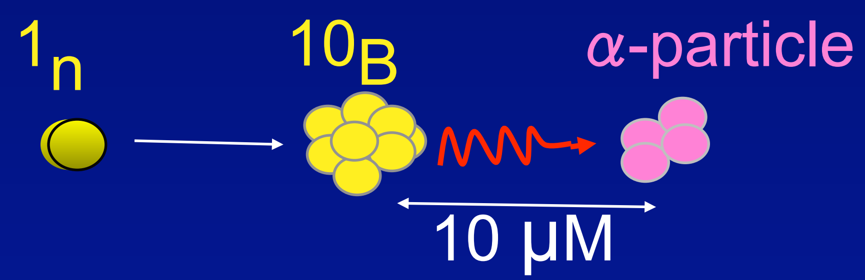
FUTURE



- Increase energy
  - zero-chromatic FFAG : E~1GeV

NEUTRON SOURCE WITH EMITTANCE RECOVERY INTERNAL TARGET FFAG-ERIT

Boron Neutron Capture Therapy (BNCT)

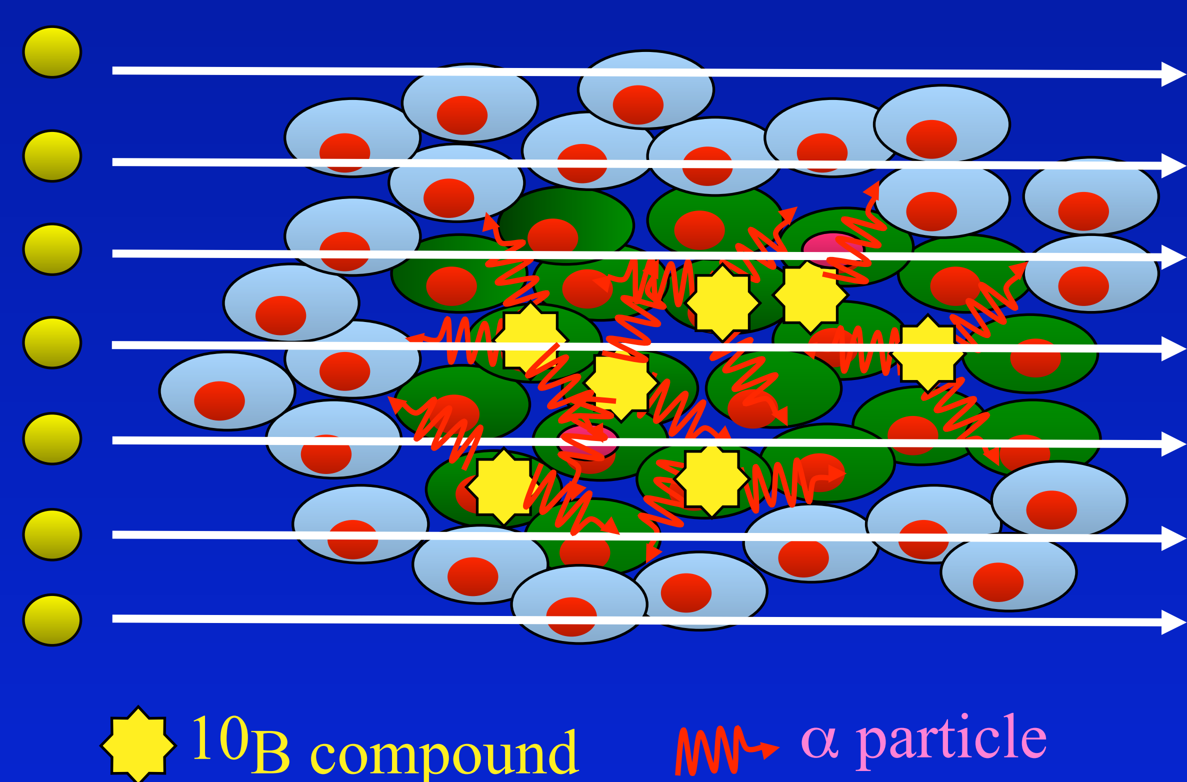


$$^{1}n + {}^{10}B \rightarrow {}^{4}He\ (\alpha) + {}^{7}Li + 2.8\ \mathrm{MeV}$$

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 *μ*m 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.

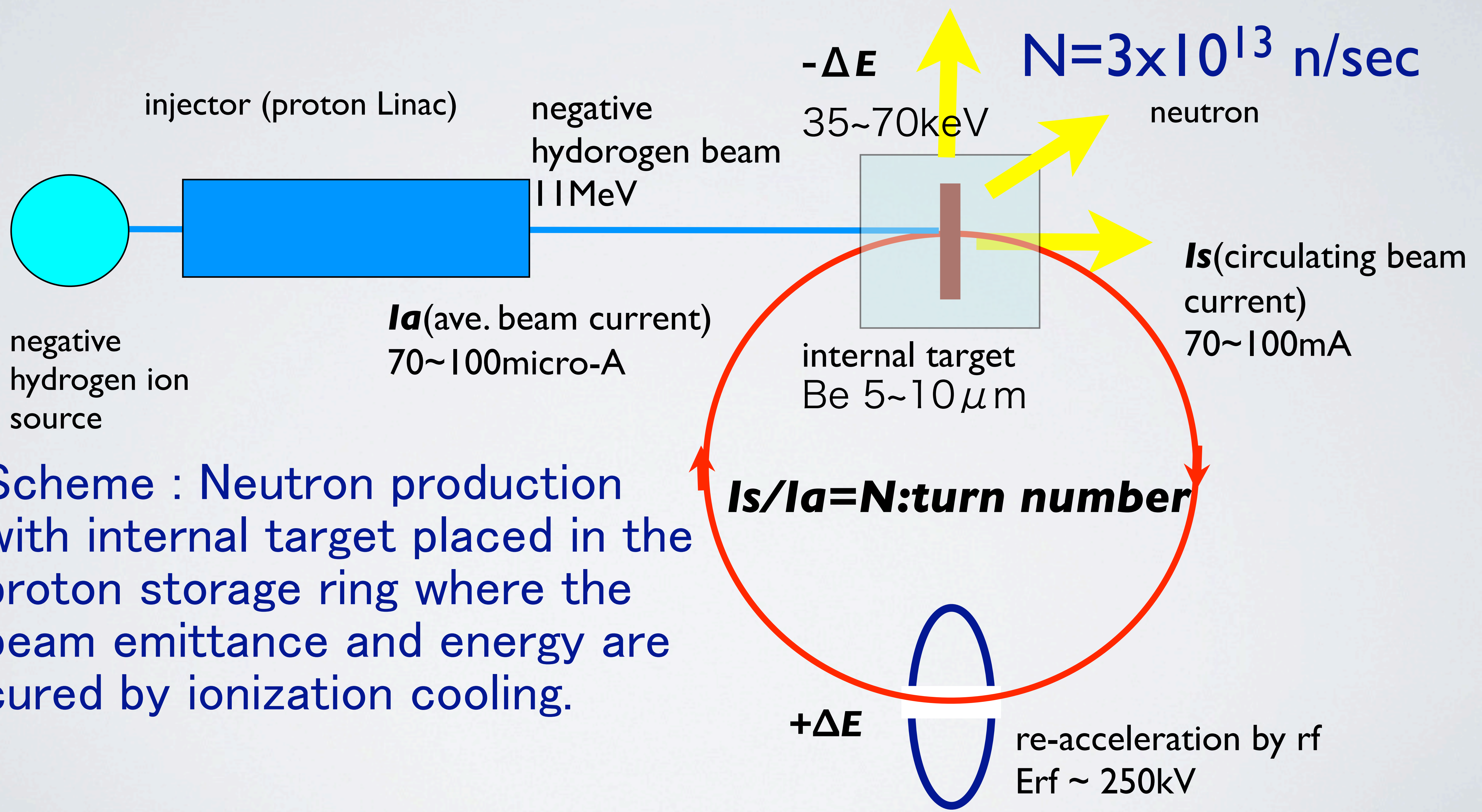
How to do ?



ABNS
(accelerator-based neutron source)

- Neutron production reaction
  - 9Be(p,n)B, 8Li(p,n)Be
  - Large reaction cross section ~500mb
  - Yield ~5×10^{13} n/sec
- Low energy proton (Ep<13MeV:should be!)
  - 3-10MeV
    - ➡ Tritium production (Ep>13MeV) ~>Ci/year
    - ➡ Radiation hazard ~ > R/hour
- High current > 5mA
  - Damages of target
    - ➡ Power deposit 50kW at small range ~<0.5mm
    - ➡ Swelling by hydrogen atoms

FFAG-ERIT



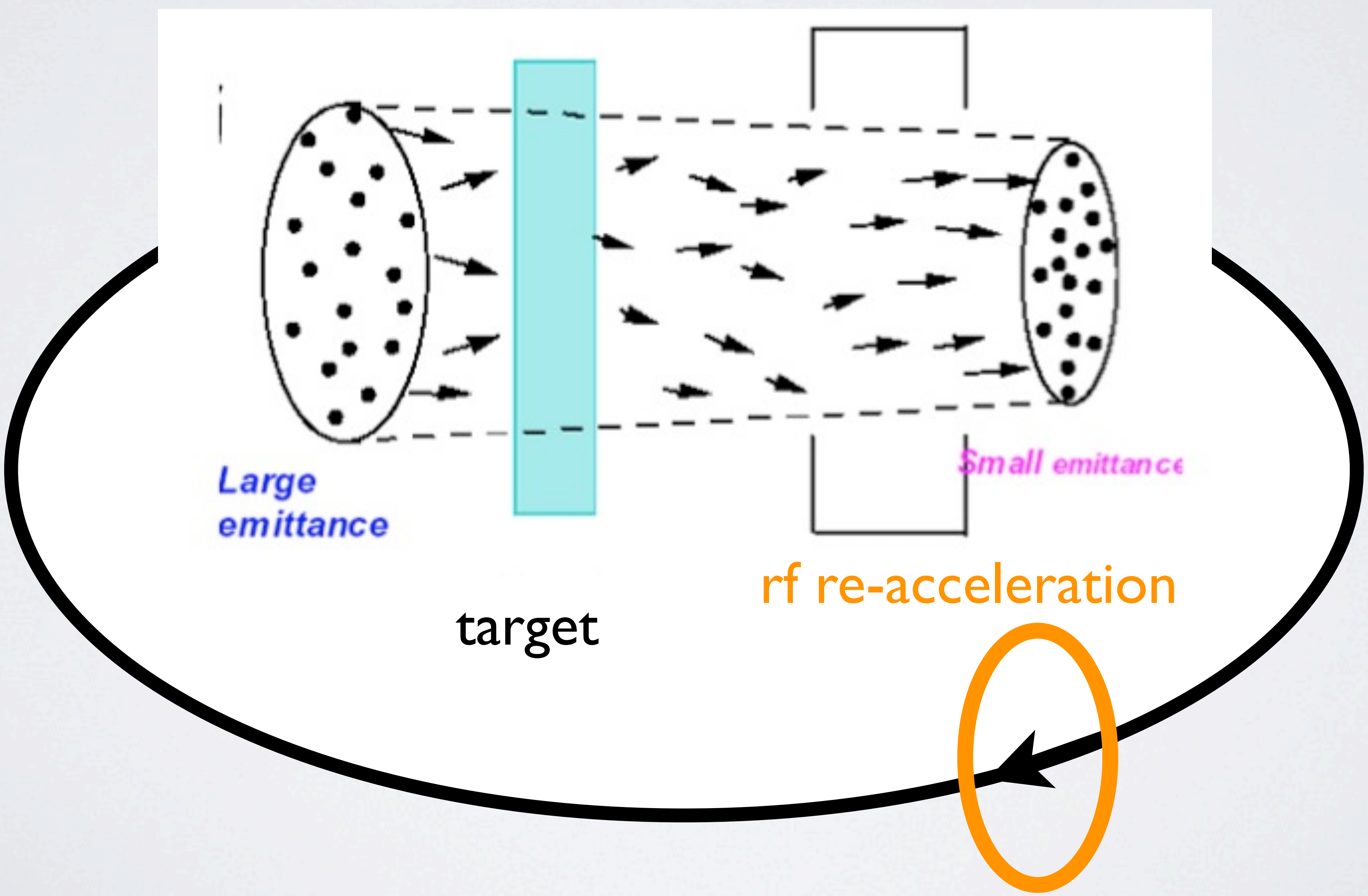
Scheme : Neutron production with internal target placed in the proton storage ring where the beam emittance and energy are cured by ionization cooling.

FFAG-ERIT

- Energy loss can be recovered by RF re-acceleration
  - ΔE~ 70keV with Vrf =250kV
- Emittane growth due to scattering is cured by "Ionization Cooling"
  - transverse cooling
- Required beam current can be increased by number of turns in beam accumulation and survival.
  - Iav = 50mA and ~1000 turns beam survival

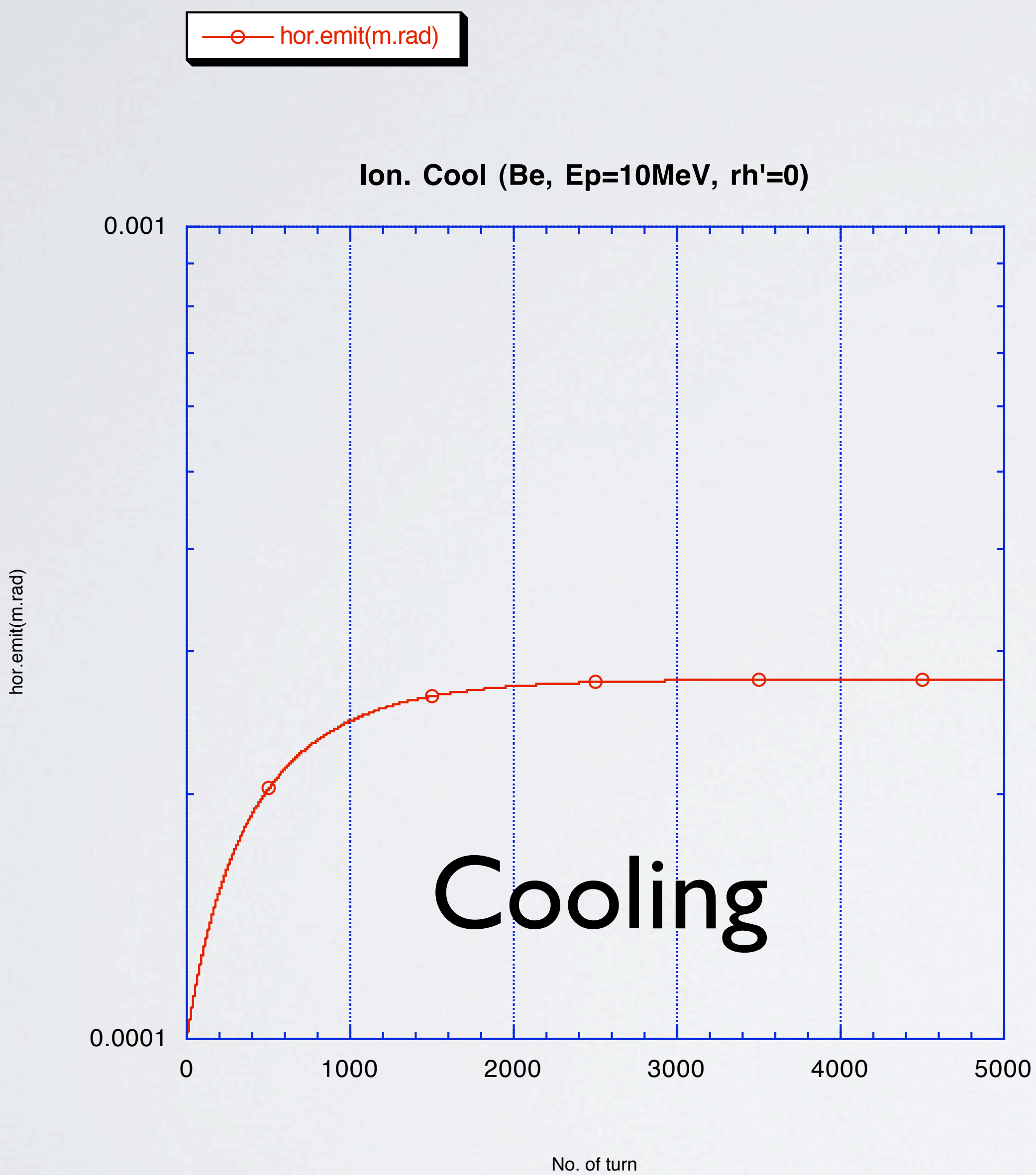
IONIZATION COOLING

- Using an ERIT, the beam emittance growth due to multiple scattering and/or straggling can be cured by ionization cooling.

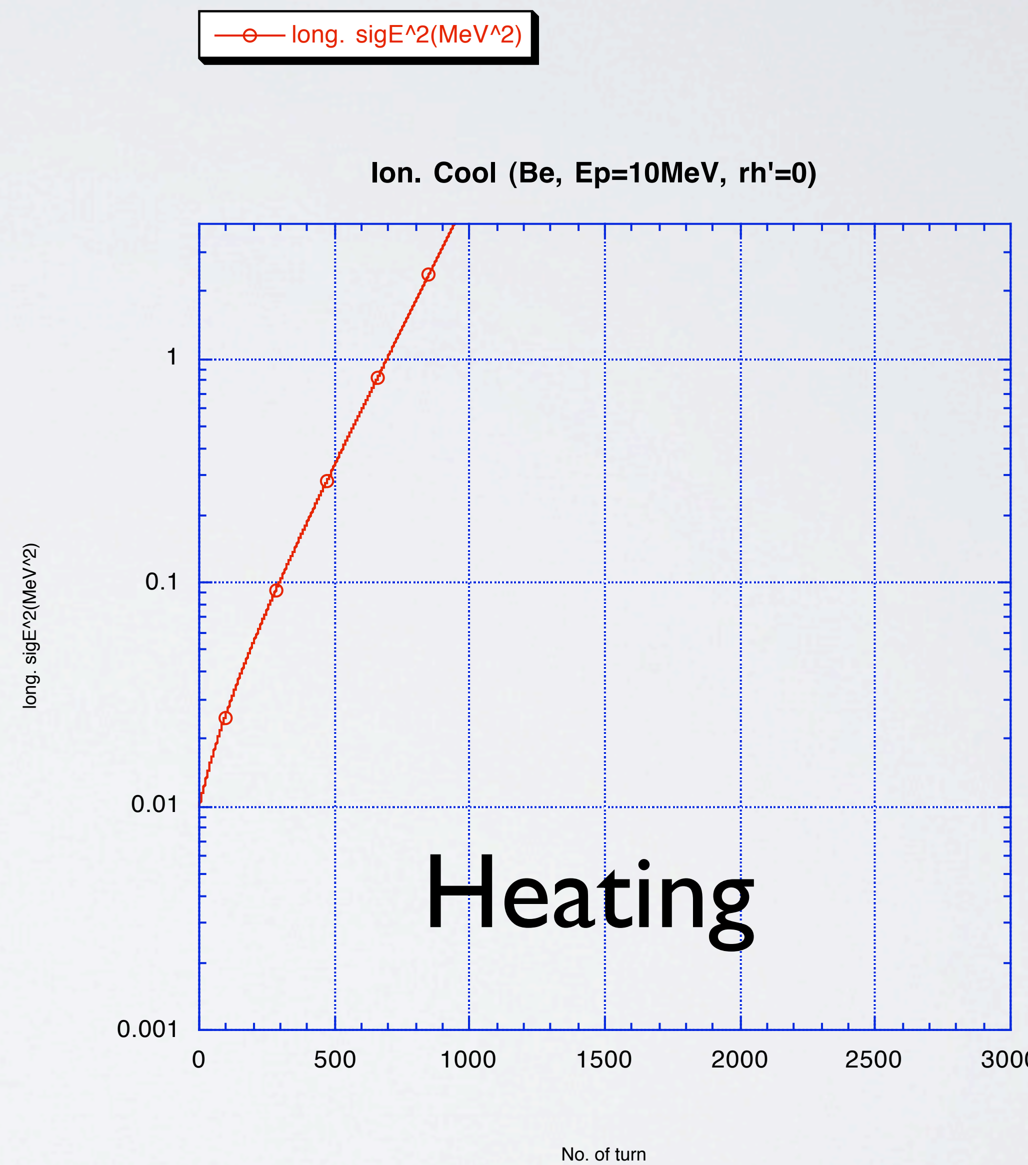


EMITTANCE GROWTH

Transeverse



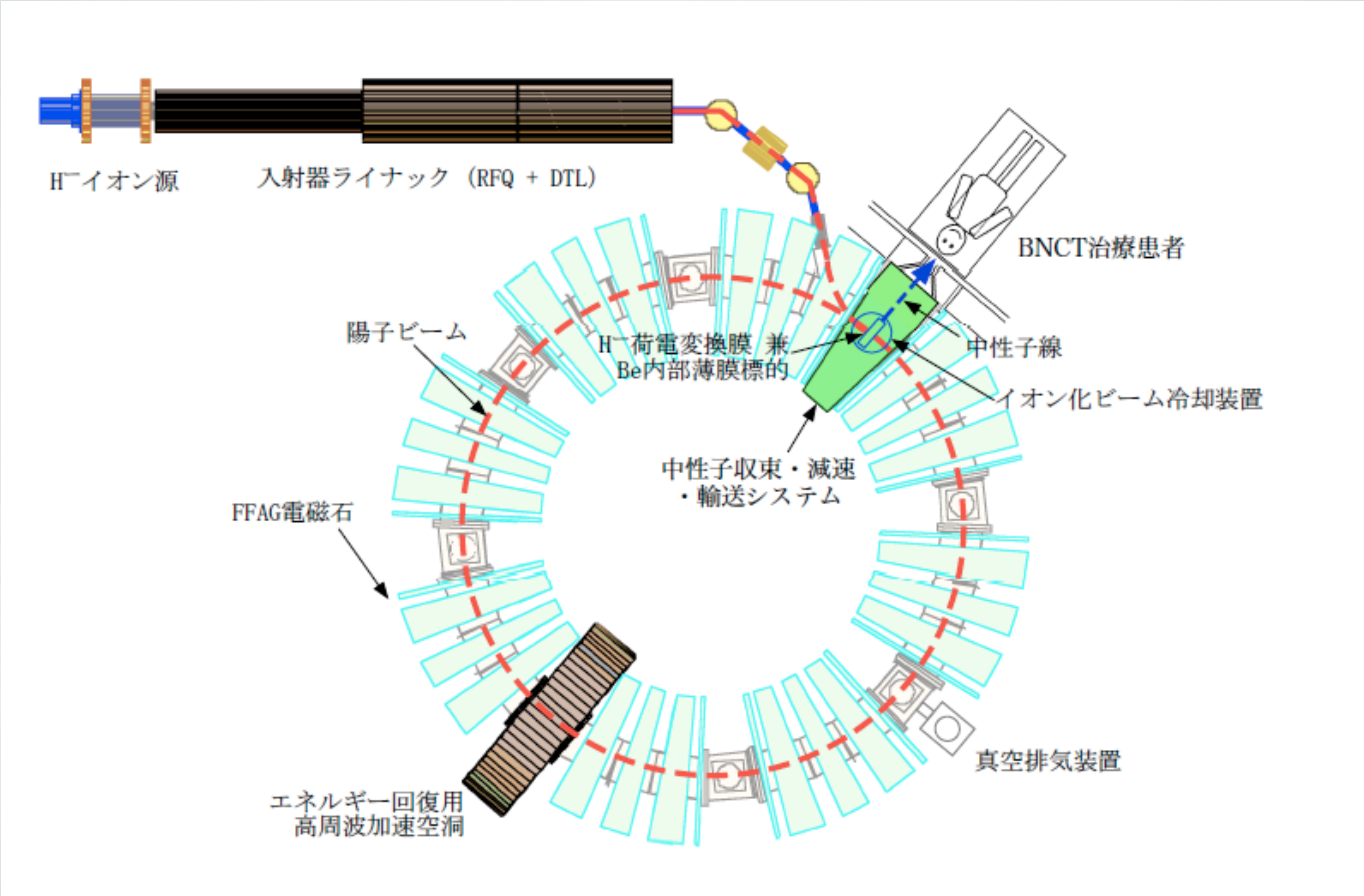
Longitudinal



Need a large momentum acceptance ring

--> FFAG (zero-chromaticity)

FFAG-ERIT ring for ABNS

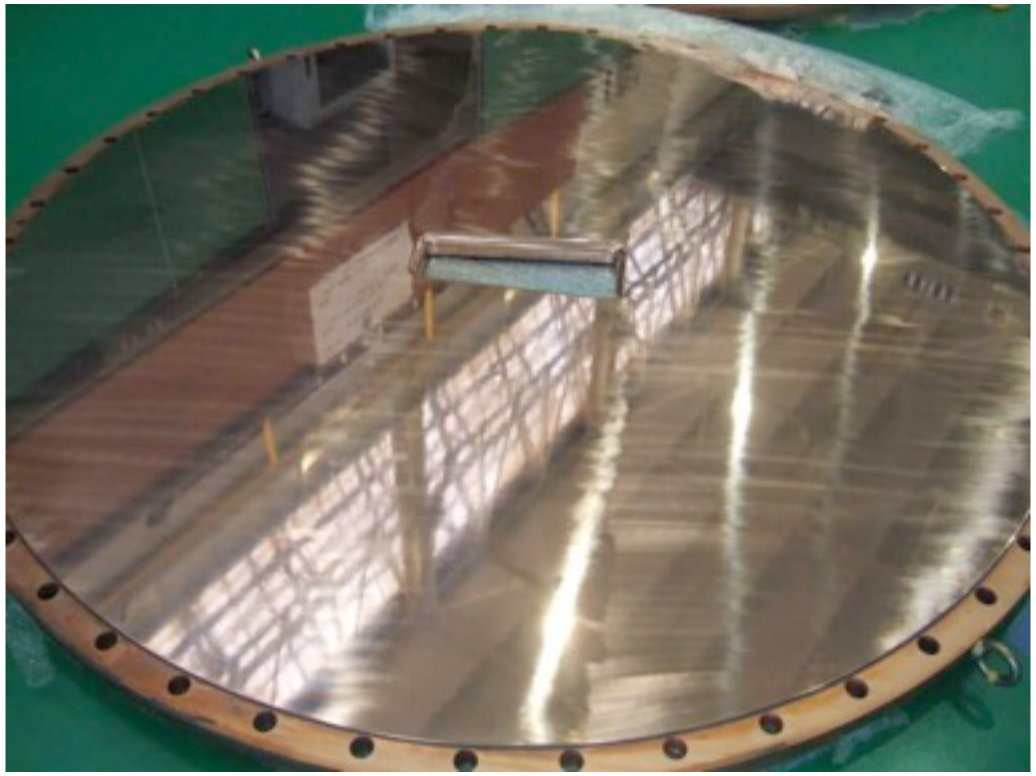


FFAG-ERIT RING

-beam energy	11MeV	-acceptance	Av>3000mm.mrad,
-circ. beam current	70mA		dp/p>+-5%(full)
-beam life(# of turns)	500-1000turns	-ν_x, ν_y	1.77, 2.27

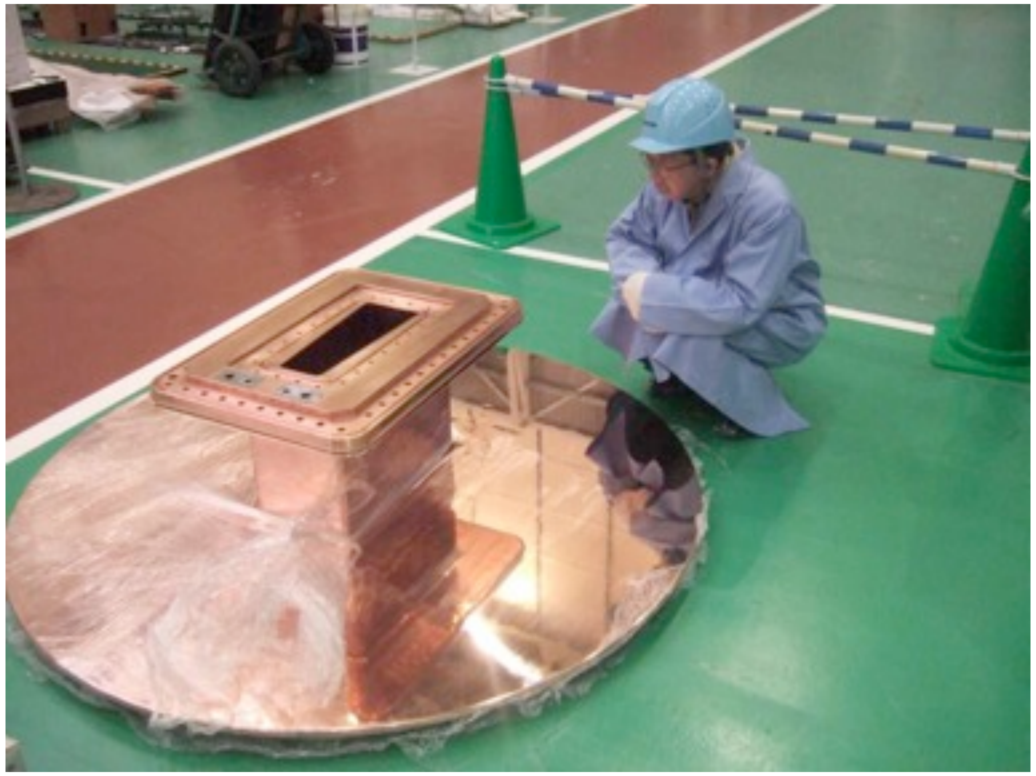
rf cavity for FFAG-ERIT

End plate



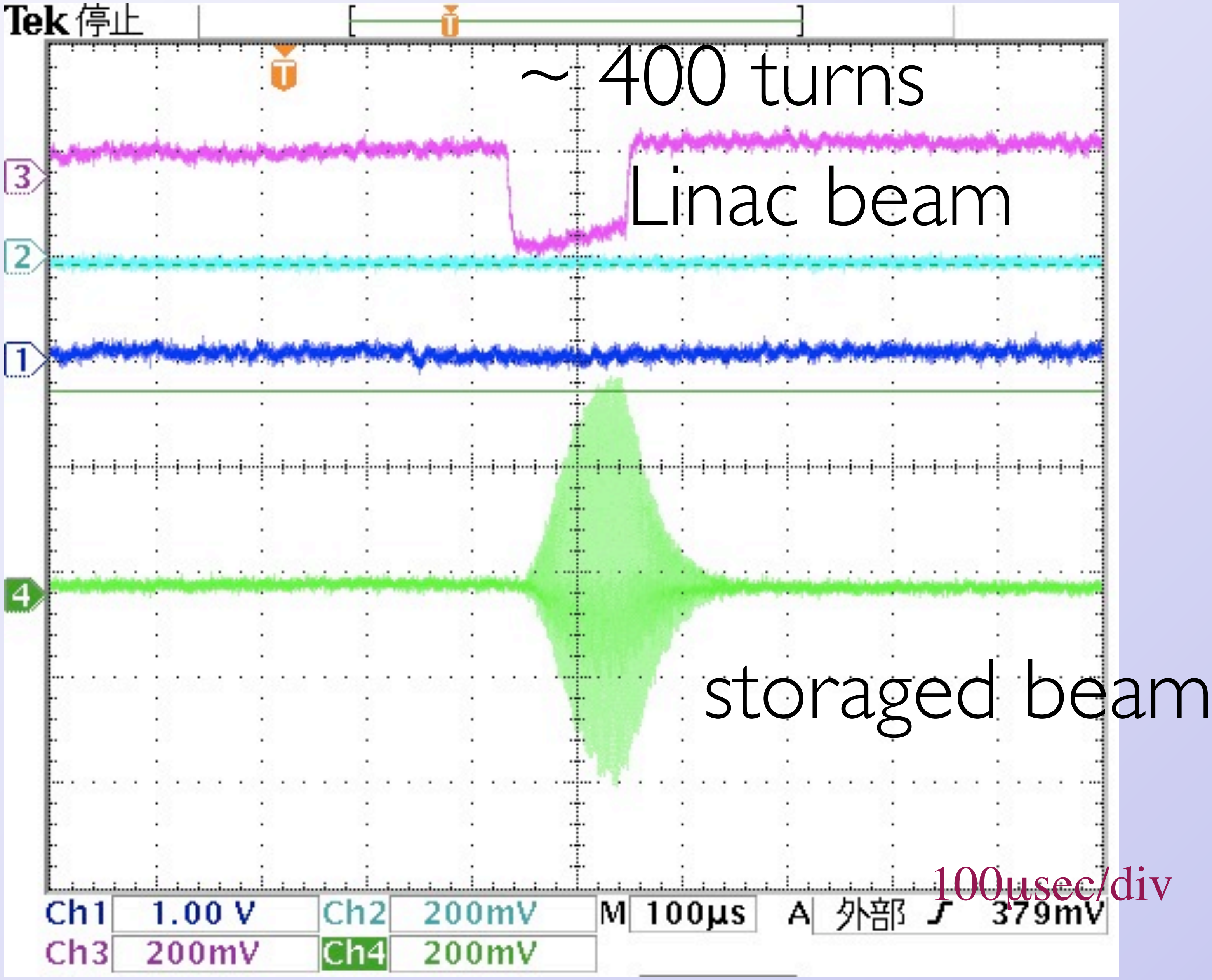
frequency
18.1MHz

rf voltage
>200kV



Gap capacitive plate

Beam storage (experimental results)



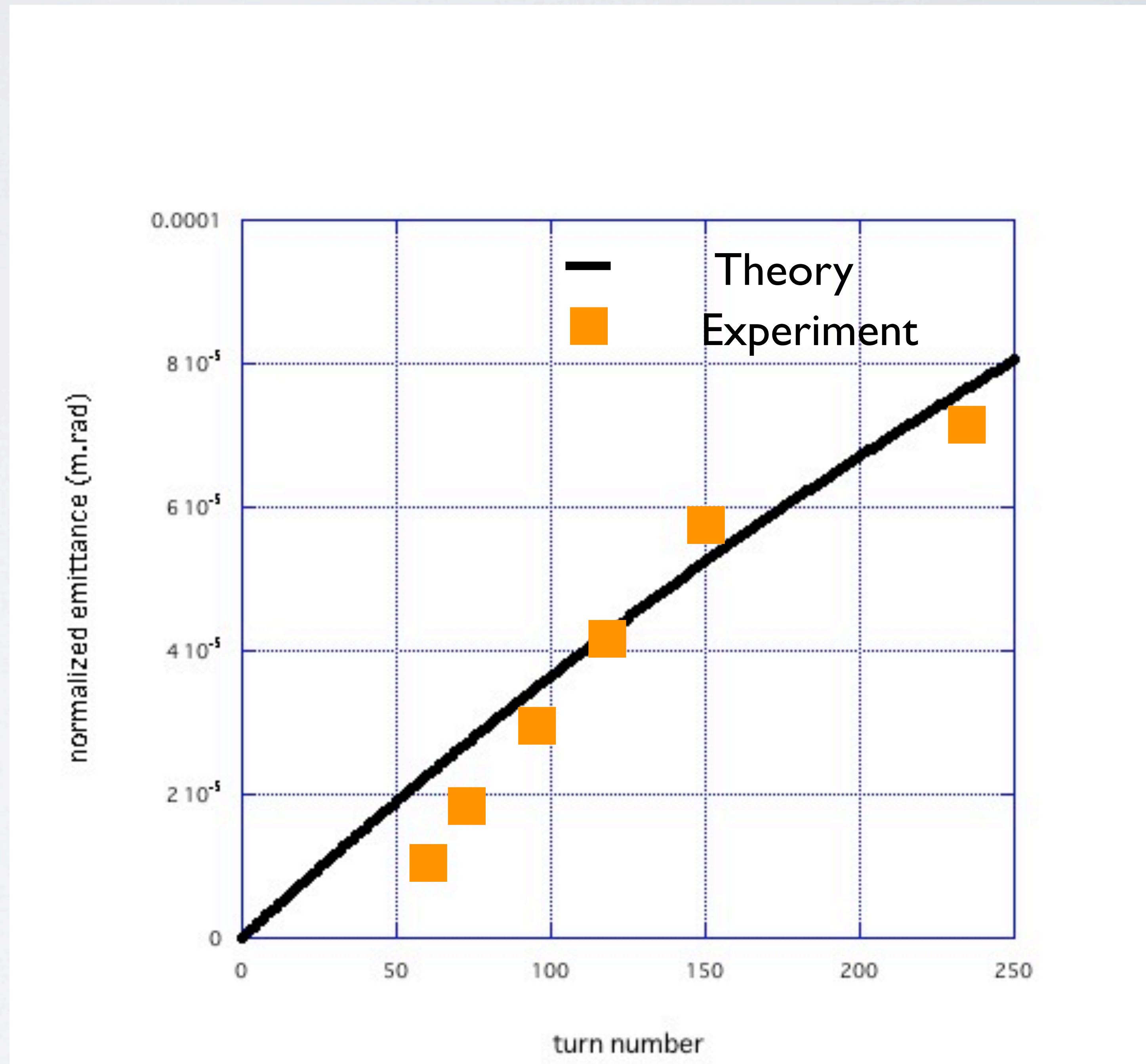
EMITTANCE GROWTH

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

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

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

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



FFAT-ERIT SUMMARY

- ERIT scheme works.
- Energy recovering
  - 20MHz,-200kV RF system works stably.
- Ionization cooling
  - Transverse: emittance growth : good agreement with theory
- beam life
  - >500 turns as expected
- Neutron yield
  - 1×10^{11} n/sec/pulse measured with irradiation method ----> 2×10^{13}n/sec@200Hz

FFAG'10

Kyoto Univ. Research Reactor Institute (KURRI)

Osaka, Japan

Oct. 26-31

- FFAG Accelerator School Oct. 26-27
- International Workshop on FFAG Accelerator (FFAG'10) Oct. 28-31

Students and young scientists are very welcome!

ERIT WITH MINIMUM VERTICAL BETAFUNCTION

Jean-B Lagrange・D2

- limitation in the number of surviving turns in existing ERIT: ionization heating in vertical.

→

- insertion of an element with a small vertical betafunction at a place where the target could be installed.

January, 23 2010

ERIT WITH MINIMUM VERTICAL BETAFUNCTION

- In order to change the least possible the existing machine, an insertion has been designed.

    - to keep the cavity, the length of the insertion is settled: 1.4m.

    - this length is too small to insert a π-section: change the k-value in the arc to make it transparent: k goes from 1.92 to 2.57.

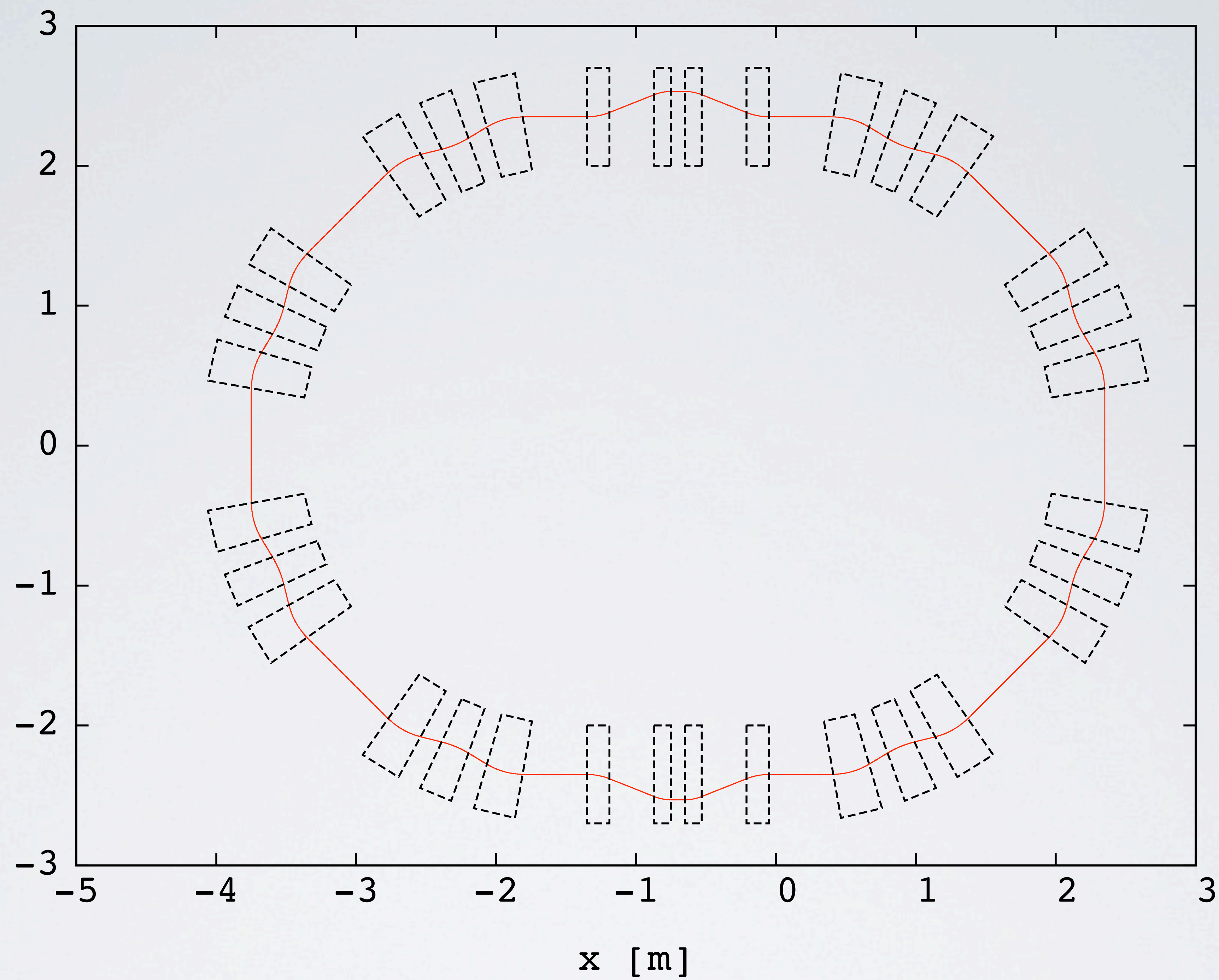
    - 10 cm are kept to install the target.

    - In existing ERIT, vertical betafunction is 0.8m at the target. A reasonable goal would be to decrease this value by a factor 3.

January, 23 2010

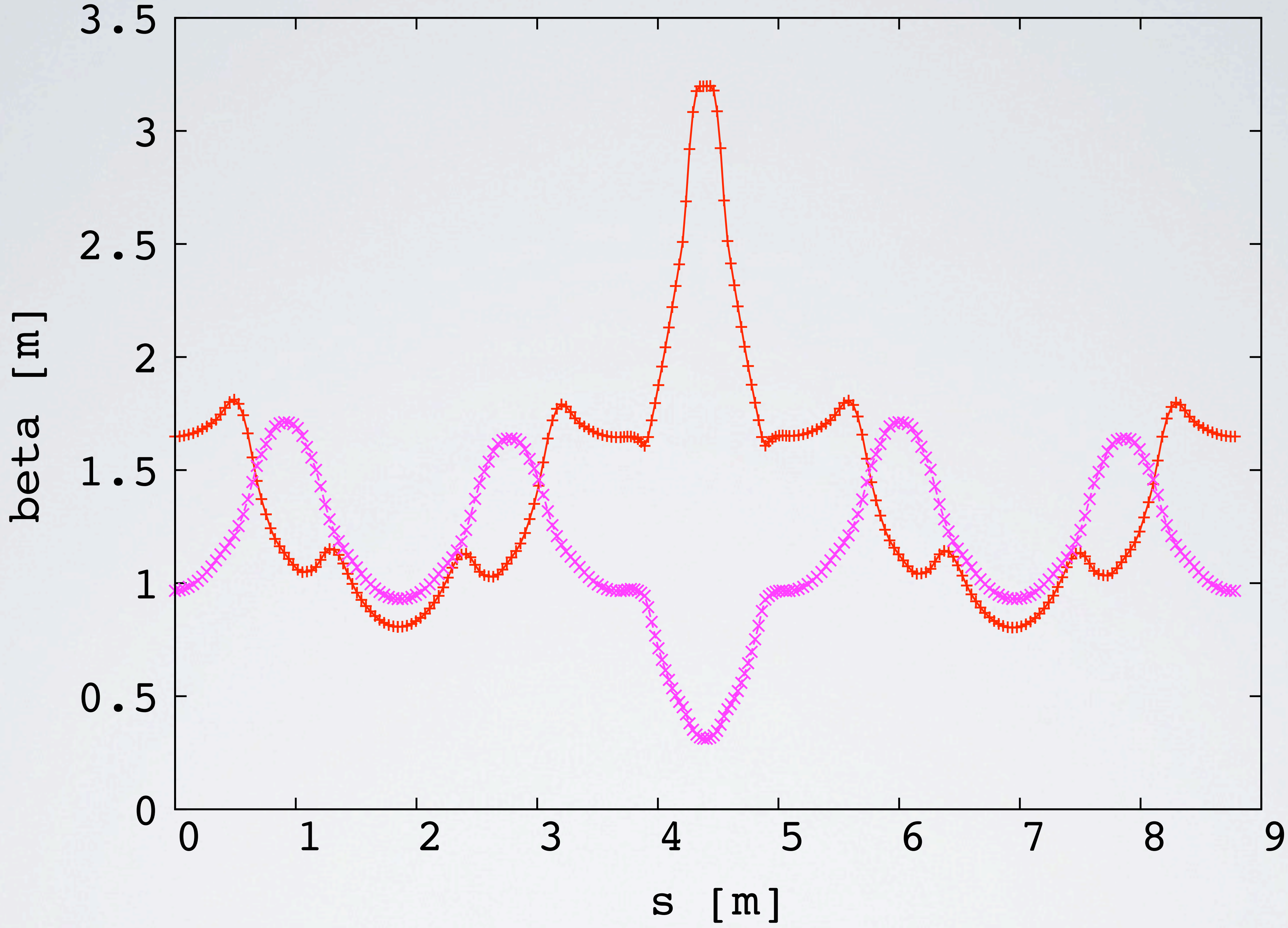
ERIT WITH MINIMUM VERTICAL BETAFUNCTION

Parameters of the insertion	
Straight scaling FFAG	
Quadruplet DFFD	
n/ρ	$1.52\, m^{-1}$
Length	$1.4\, m$
D magnets length	$16\, cm$
F magnets length	$12\, cm$
Phase advances:	
horizontal μ_x	41 deg.
vertical μ_z	148 deg.



Closed orbit for 11 MeV proton.

January, 23 2010



Horizontal (red) and vertical (purple) betafunctions of half of the ring. At the target, βx=3.2m and βz=0.29m

January, 23 2010

Advancement of FFAG Accelerator for High Intensity Proton Driver and Muon Acceleration

Yoshiharu Mori
Kyoto University, Research Reactor Institute (KURRI)

Proton Driver

- High intensity proton accelerator for secondary particle production such as neutron, pion, muon, neutrino etc.
  - ADSR: Accelerator Driven Sub-critical Reactor
    - *Neutron generator with spallation reaction*
  - Neutrino factory
    - *Muon acceleration*
- Proton energy ~GeV
- Beam power ~MW (beam current >mA)


Oct. 26-28,2009,Washington
ACCELERATORS FOR AMERICA'S FUTURE
HOME
SYMPOSIUM
RESOURCES
APPLICATIONS
WORKING GROUPS
U.S. DEPARTMENT OF ENERGY
The semiconductor industry relies on accelerator technology to implant ions in silicon chips.
More than 17,000 particle accelerators are in operation around the world. They get used by hospitals to treat cancer, industry to manufacture everyday items like radial tires and national laboratories to conduct basic research. As particle accelerator technology continues to advance, so too will the benefits to society.
Features
Advanced Electron Beams Blog
As organizations seek more clean and efficient ways to power their industrial processes, electron beams are emerging as a way to address these challenges.
Read more »
Accelerator applications: furniture finish
Who needs coasters when you
News
Brookhaven Lab, Advanced Energy Systems Open Hi-Tech Production Facility
January 15, 2010
Brookhaven National Laboratory News
Today, the U.S. Department of Energy's (DOE) Brookhaven National Laboratory and Advanced Energy Systems, Inc. of Medford, N.Y. (AES) celebrated the opening of a new hi-tech facility at the AES site that will produce crucial components used in particle accelerators around the world.
Symposium on Accelerators for America's Future
Sponsored by the Office of High Energy Physics of the US Department of Energy's Office of Science
Chairs: Walter Henning, Argonne Distinguished Fellow, ANL and Charles Shank, Director, LBNL (Retired)
On October 26, 2009, the Symposium brought together more than 400 scientists to examine the challenges for identifying, developing and deploying accelerators to meet the nation's needs in:
Discovery Science
Medicine and Biology
Industrial Applications and Production
Energy and Environment
National Security
Agenda, Slides and Videos

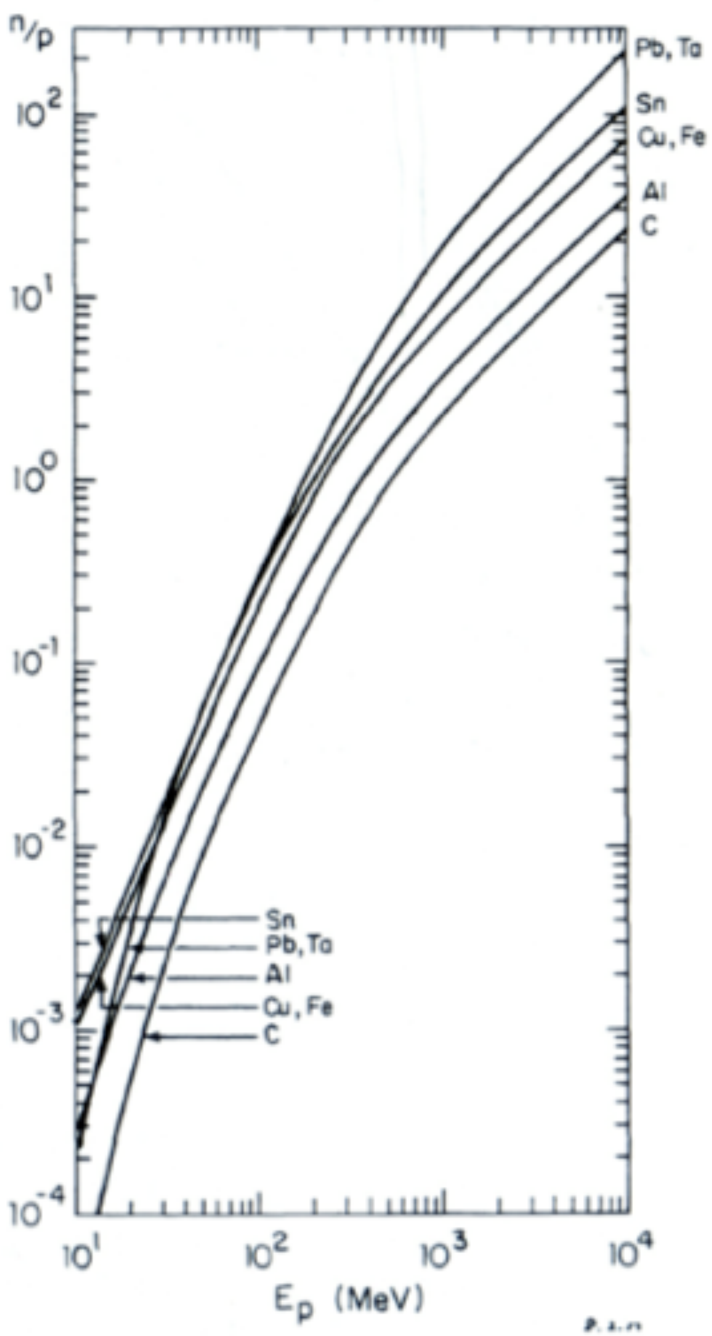
Outline

- Paving the Way for Clean Energy - Helping Reduce the Nuclear Waste Stream
  - Spent Fuel Reduction
  - Thorium Reactors
  - ICF
- Tools for Future Energy Solutions - Materials Development For Fusion and Fission Systems
  - Materials Testing Needs
    - Fission
    - Fusion
  - Materials Testing Facilities
    - Triple beam
    - IFMIF
    - Spallation
- Energy-Related Spallation Neutron Science

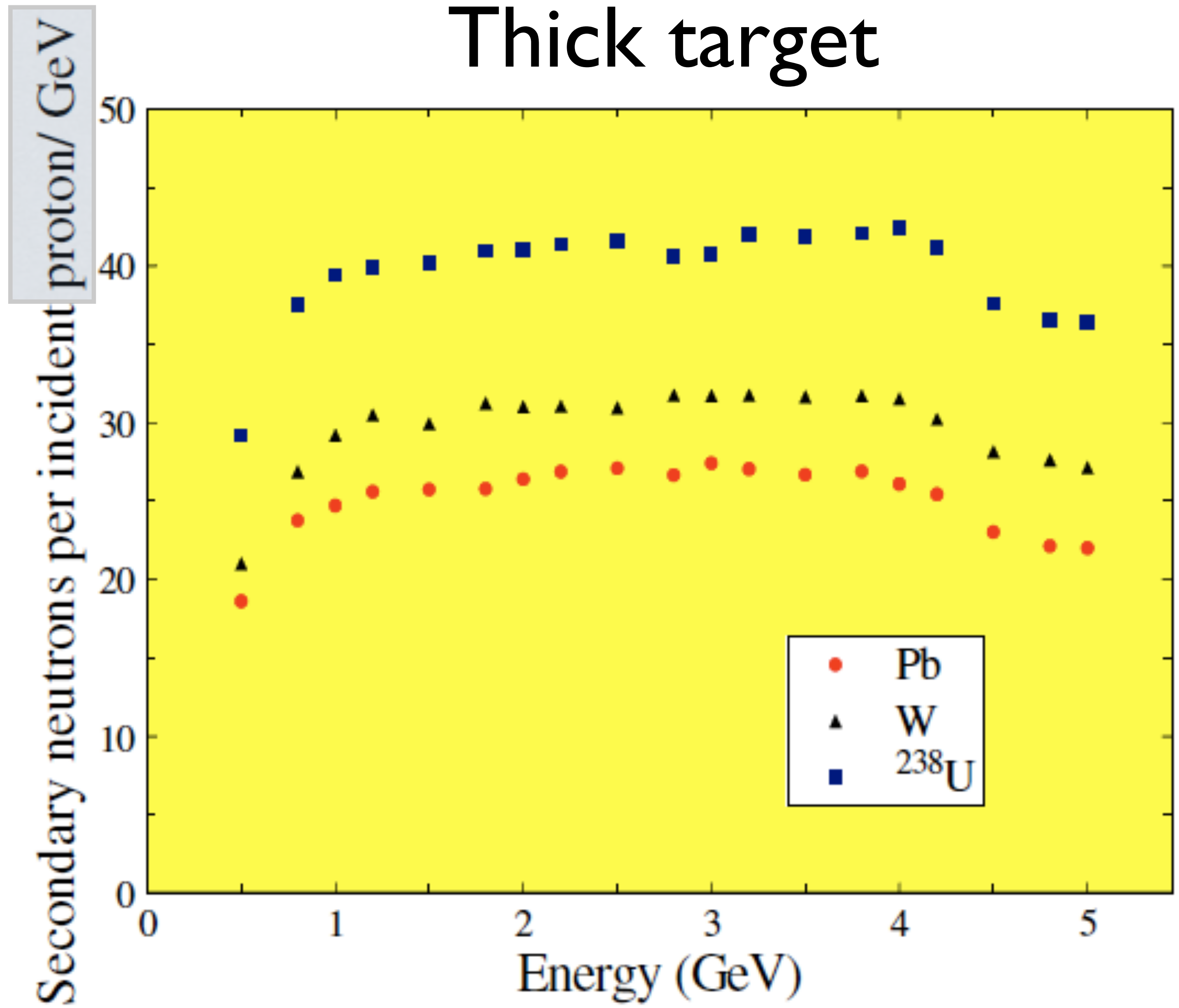
Los Alamos NATIONAL LABORATORY EST. 1943

NNSA

Neutron production



Thick target



International Symposium on Utilization of High Power Accelerators, June 2005

Fluka/MCNPX calculations

Neutron yield per proton above 1GeV is proportional to the proton beam energy.

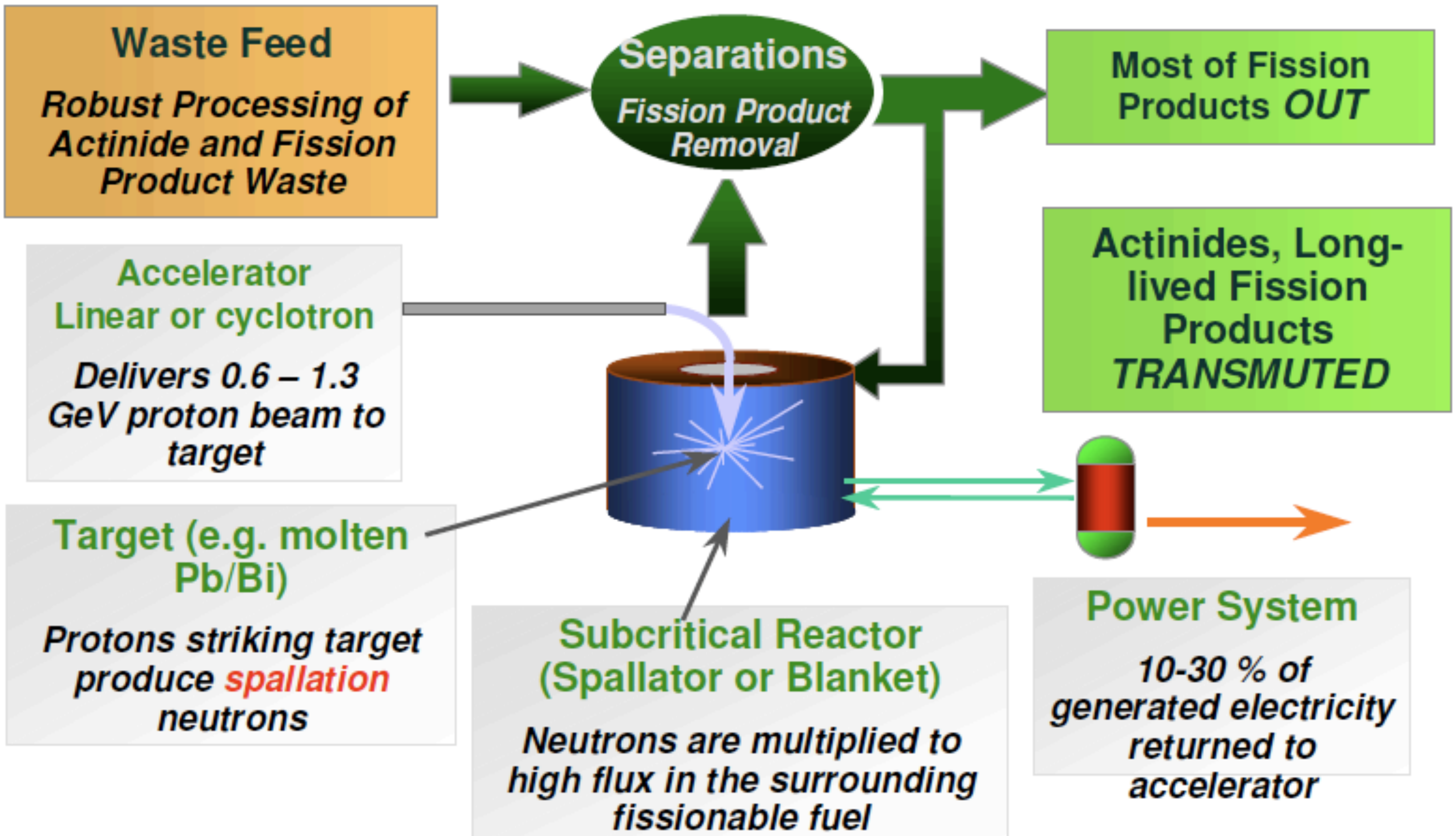
Total number of neutrons → proportional to ExI (beam power)

Proton (removal) mean free path

- Ep> 1GeV → nuclear cascade interaction
  - Hadron shower (π,K, meson production)
  - Target thickness a few 10cm (above 1GeV)

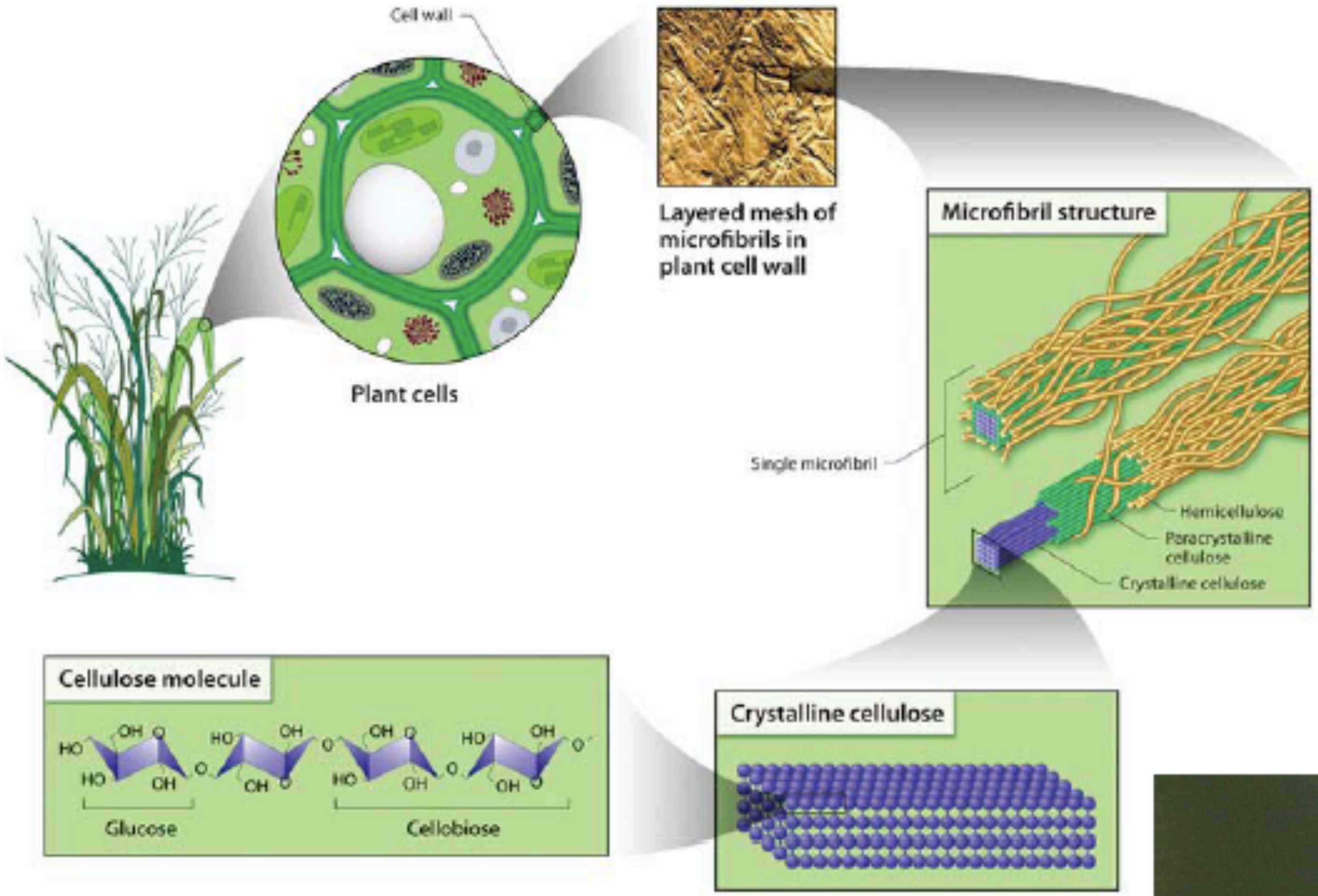
material	λ [cm]
H_2O	60.1
Be	30.03
Al	26.15
Fe	10.52
Cu	9.55
Pb	10.26
U	6.17

Accelerator driven transmutation
Principal Components



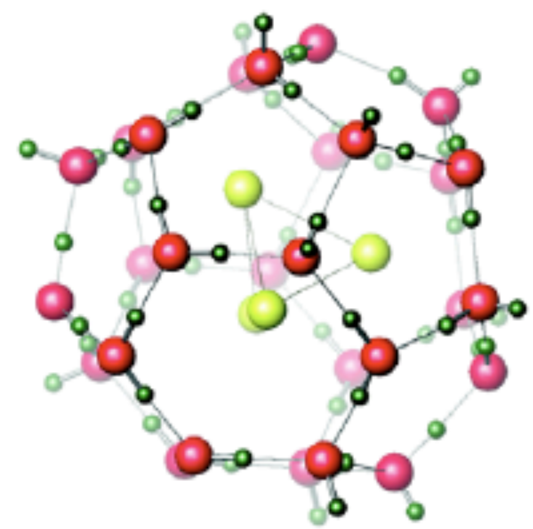
KTH

Spallation Neutron Sources Play A Key Role In Research For Energy And The Environment



Biomass structure and conversion for 3rd generation biofuels

Hydrogen storage materials



Nuclear fuel cycle

Fundamental nuclear physics measurements needed for reactor design made at WNR facility:

- Capture and high-precision fission cross sections on actinides (Np, Pu, Am, Cm…)
- Gas production: (n,p), (n,α) reactions in structural materials

Time structure of proton beam in PD

- ADSR
  - fast neutron　Transmutation, Thorium
    - *cw beam (>MHz)*
  - thermal neutron　Energy production, Neutron source
    - *cw or pulsed beam (~1kHz)*
- Pulse-spallation neutron source
  - TOF neutron energy identification
    - *pulsed beam (~10Hz, ~μsec)　pulsed beam →proton accumulation*
- Muon source
  - Short life time and fast acceleration
    - *short pulsed beam (~ 10nsec)*

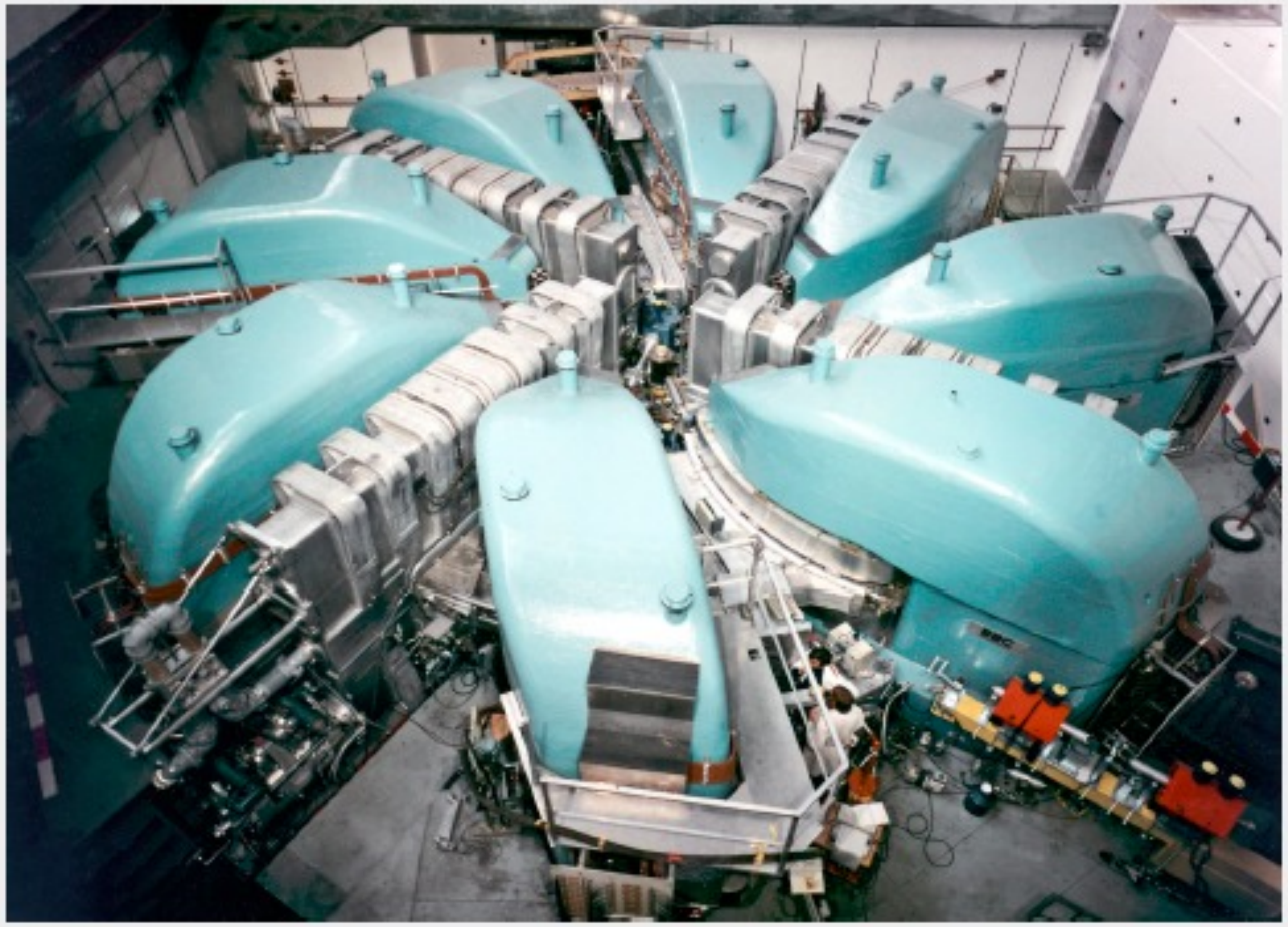
ADSR

(CW or very high repetition)

- SC Linac (Super conducting rf cavity)
- SC Cyclotron (Super conducting magnet)
- SC FFAG(Super conduction magnet)
- SC Synchrotron :not adequate
  - repetition rate <50Hz

PSI Ring Cyclotron

8 Sector Magnets:	1 T
Magnet weight:	~250 tons
4 Accelerator Cavities:	850 kV (1.2 MV)
1 Flat-Top Resonator	150 MHz
correction coil circuits:	15
Accelerator frequency:	50.63 MHz
harmonic number:	6
kinetic beam energy:	72 → 590 MeV
beam current max.:	2.2 mA
extraction orbit radius:	4.5 m
outer diameter:	15 m
relative Losses @ 2mA:	-~$1..2 \cdot 10^{-4}$
transmitted power:	0.26-0.39 MW/Res.



M.Seidel, HIPA 2009, Fermilab

Cyclotron for ADSR

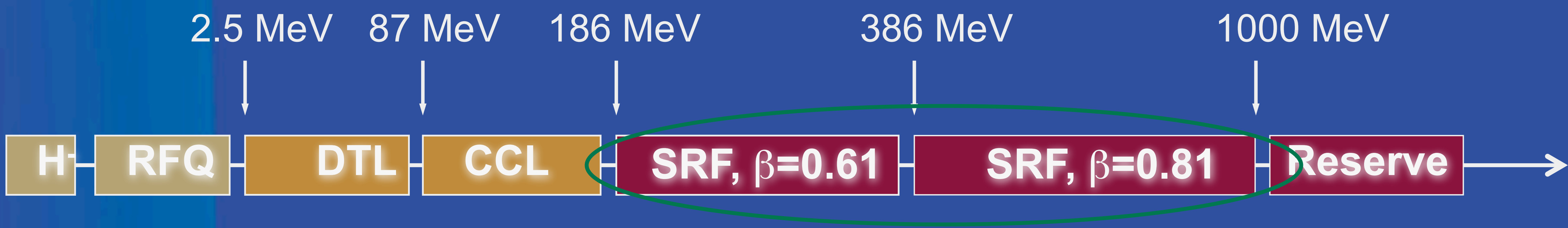
- Pro
  - simple structure
  - DC beam : large average beam current
  - high power efficiency
  - less expensive
- Con
  - injection/extraction（H^- cannot be accelerated＊）
  - energy　<1GeV
  - big magnet（thousands of tons)）

***H- ions are stripped by Stark effect (E=βcB) at high energy→Hard to accelerate more than >70MeV.**

Linear Accelerator (US-SNS project)

- **World's first high-energy superconducting linac for protons**

Linear Accelerator (US-SNS project)



- **World's first high-energy superconducting linac for protons**
- **81 independently-powered 805 MHz SC cavities, in 23 cryomodules**

Linear Accelerator　(US-SNS project)

2.5 MeV | 87 MeV | 186 MeV | 386 MeV | 1000 MeV

H⁻ – RFQ – DTL – CCL – SRF, β=0.61 – SRF, β=0.81 – Reserve →

- **World's first high-energy superconducting linac for protons**
- **81 independently-powered 805 MHz SC cavities, in 23 cryomodules**
- **Space is reserved for additional cryomodules to give 1.3 GeV**

Challenges Emerging from CW Linacs

- **CW operation**
  - dynamic heat load (rf losses) is dominant => refrigerator cost will be significant.
    - Cornell ERL design example
  - Make choices that will lower the heat load
    - Examples later
  - RF power operating is also a significant part of the overall AC power
    - Choose matched Qext (microphonics should be tolerable)
    - Choose design options that lower microphonics risk
- **High Beam current (e.g. 1 - 10 mA)**
  - Be prepared to extract and intercept HOM power
  - Need damping of Q's for HOMs to avoid beam blow up (halo?) ?
- **Preserve beam profile**
  - Low wake-fields (short bunch length 1 ps)
  - Good cavity alignment
  - Low kicks from couplers etc, esp for low energy end
  - Good amplitude and phase stability (Amplitude/phase stability ERL: 10^{-4}/0.02 d)
  - RF distribution, low level rf control system issues
- **Operation**
  - High reliability, low trip rate.
    - Favors moderate gradients (e.g. 15 -20 MV/m)

very expensive!

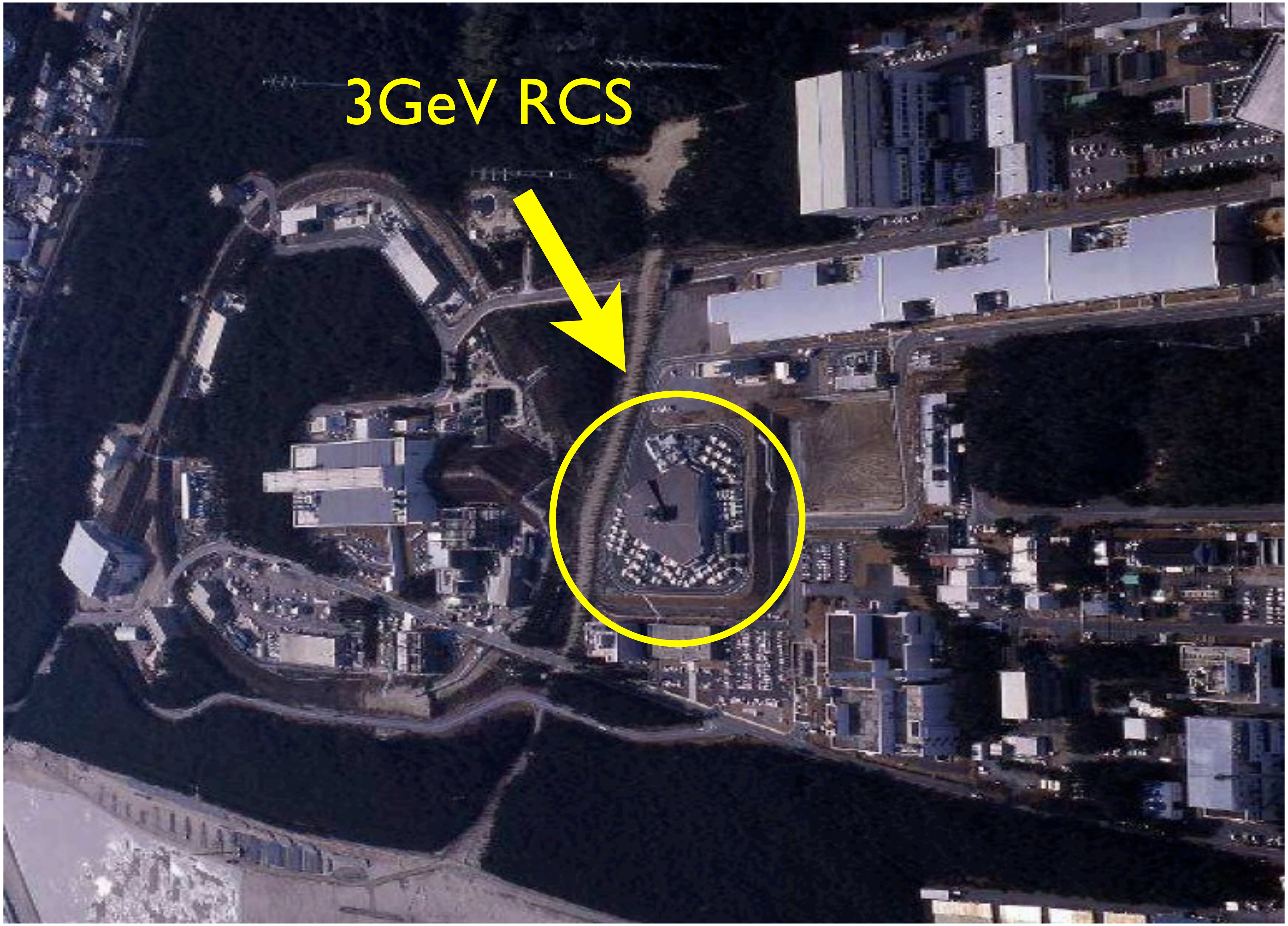
Fermilab

Pulse-SNS

(Low repetition and high peak current)

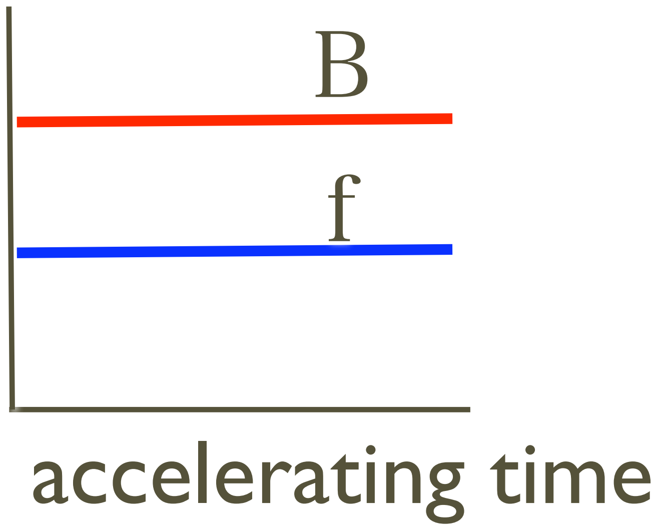
- Pulse-Linac + proton storage ring
  - H- beam : Charge-exchanged multi-turn injection at ring
- Synchrotron
  - Repetition <50Hz
  - H- beam : Charge-exchanged multi-turn injection at ring
- FFAG
  - Repetition <50Hz
  - H- beam : Charge-exchanged multi-turn injection at ring
- Cyclotron :not adequate
  - only cw (pulsed beam but low peak current)

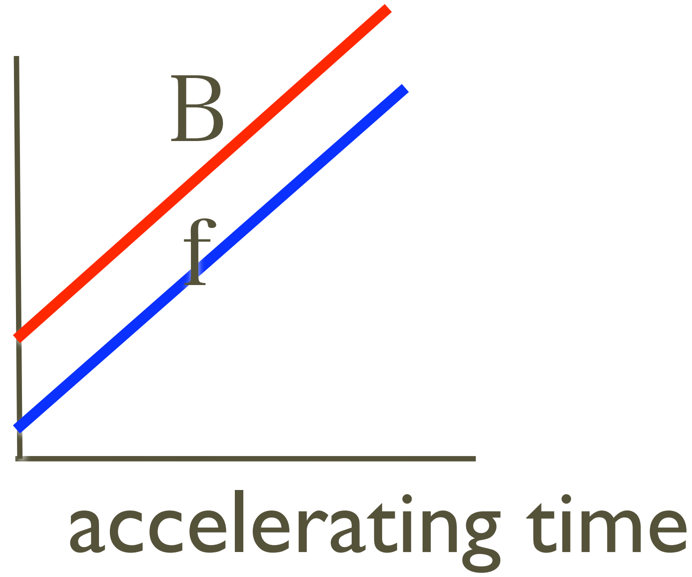
J-PARC

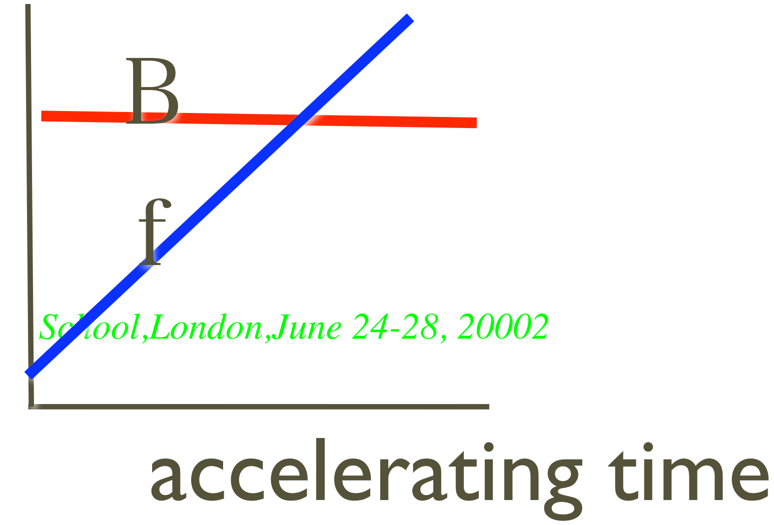


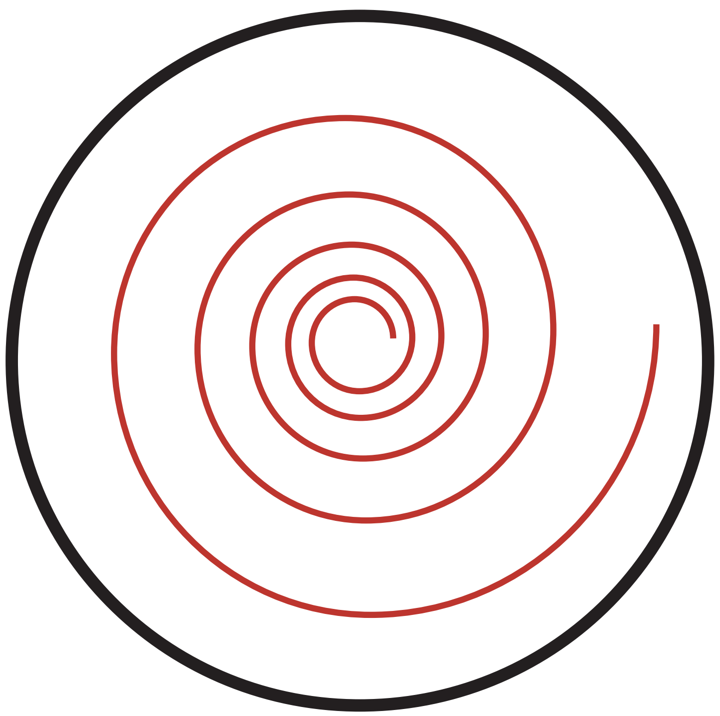
FFAGs for ADSR/Pulse-SNS

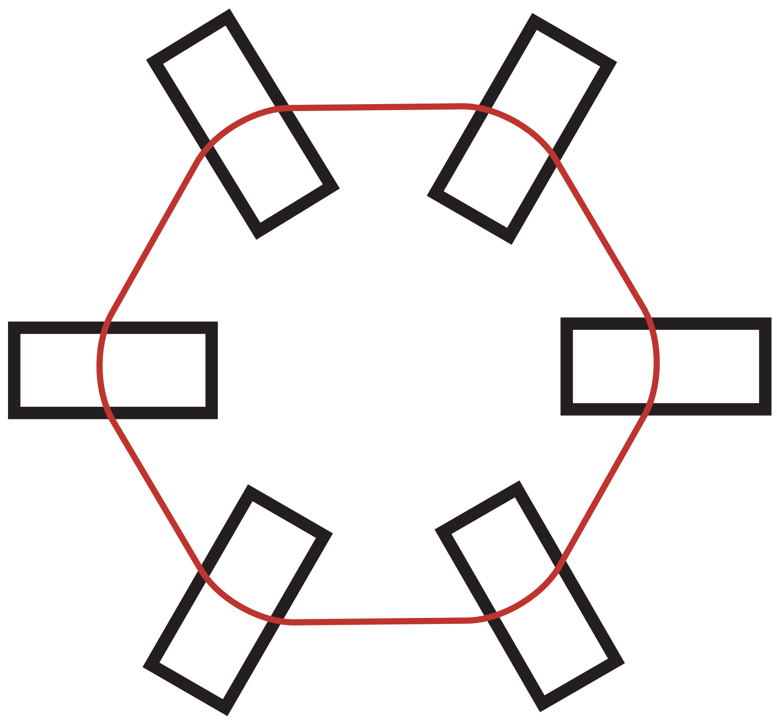
- Ultra large repetition (MHz) & CW operation are possible?
  - fast neutron ADSR
- Very rapid acceleration (acceleration period <100 turns) is possible?
  - Problems of space charge & beam instabilities caused by high beam intensity can be avoidable.
- Long straight section in the ring is possible?
  - Ease for beam injection/extraction.
  - Installation feasibility of many rf acceleration cavities

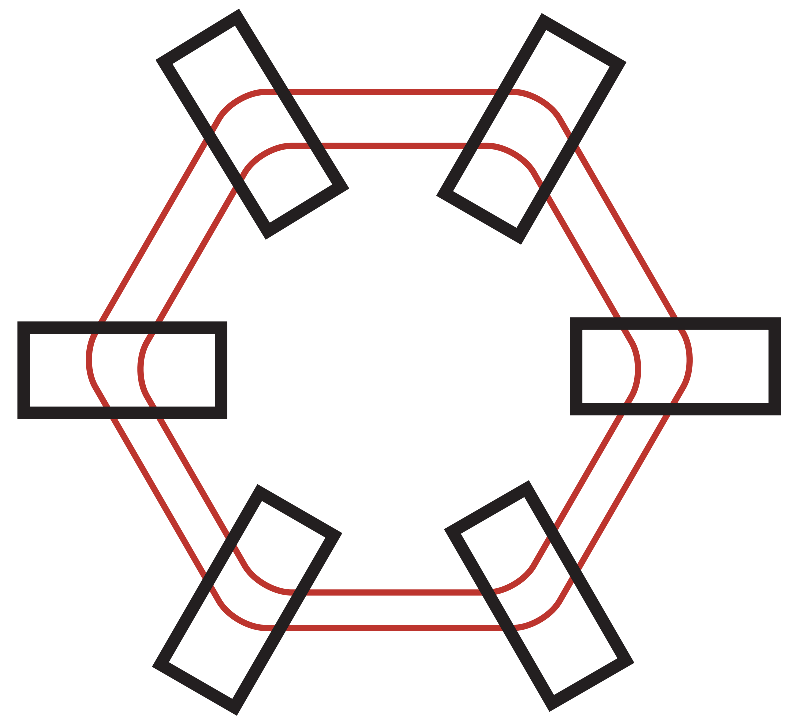












Cyclotron

*isochronous

Synchrotron

*const. closed orbit

(varying mag. field)

FFAG

*varying closed orbit

(const. mag. field)

FFAG: Fixed Field Alternating Gradient

- Fixed (Static) magnetic field

  It is like cyclotron, but not much orbit excursion

  - Fast acceleration
    - *Fixed magnetic field allows the beam acceleration only by RF pattern. No needs of synchronization between RF and magnets.*
  - Large repetition rate
    - *High intensity with large repetition rate and modest number of particles in the ring*
    - *Space charge and collective effects are below threshold.*
- 6D-strong focusing (AG focusing, phase focusing)

  It is like synchrotron.

  - Large acceptance with small gap magnet
  - Various longitudinal RF gymnastics become possible.
    - *Bunching, Stacking, Coalescing, etc.*

Type of FFAG optics

- Zero chromaticity
  - Fixed betatron tunes
    - *Fields are non-linear.*
  - Free from betatron resonance crossing
- Non-zero chromaticity
  - Varied betatron tunes
    - *Linear optics*
  - Fast resonance crossing

Zero chromaticity FFAG

- Betatron eqs. in cylindrical coordinate

$$\frac{d^2x}{d\theta^2}+\frac{r^2}{\rho^2}\left(1-K\rho^2\right)x=0$$

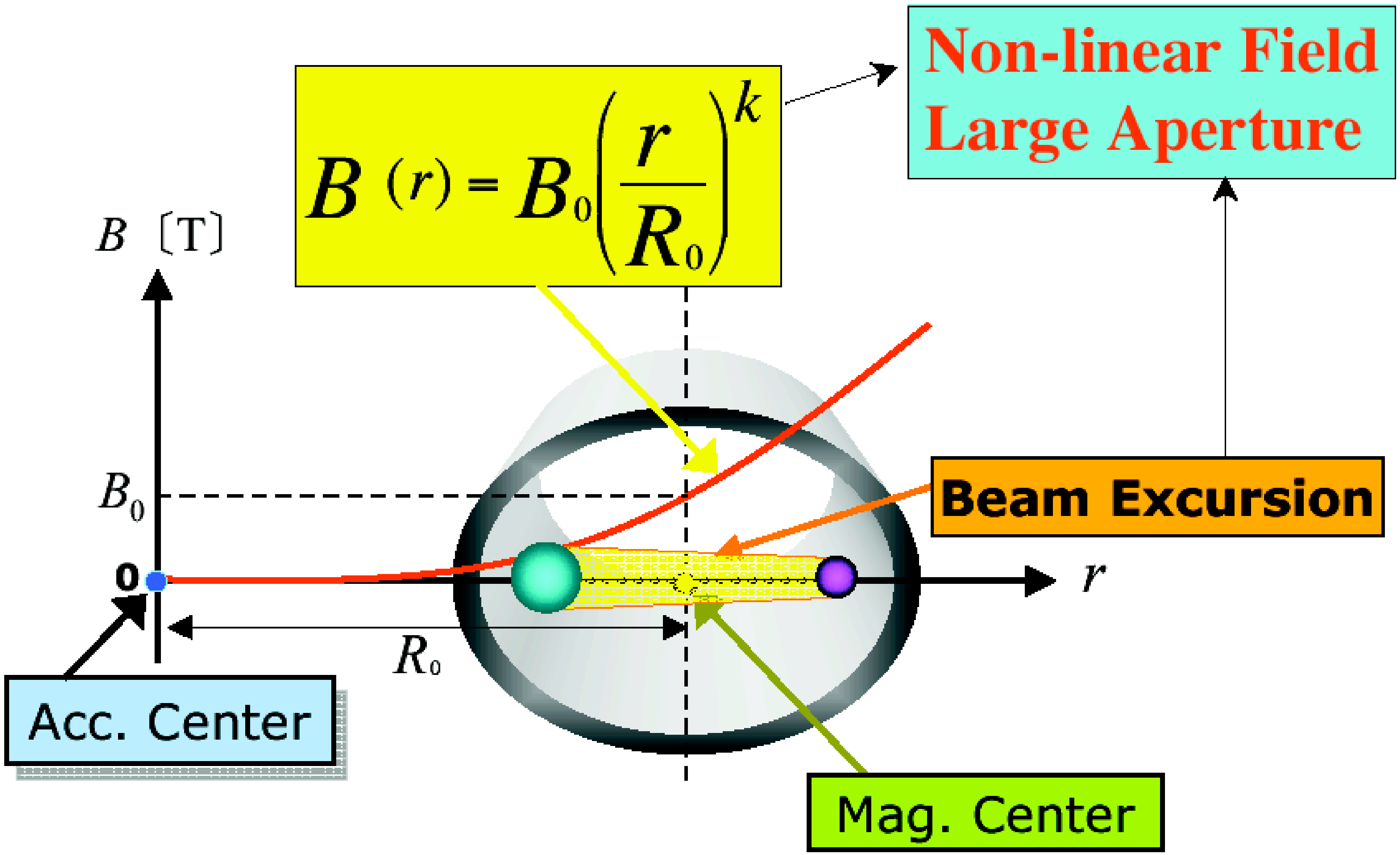
$$\frac{d^2z}{d\theta^2}+\frac{r^2}{\rho^2}\left(K\rho^2\right)z=0 \qquad K=-\frac{1}{B\rho}\frac{\partial B}{\partial r}$$

- Zero chromacitiy: Constant betatron tunes
  - Sufficient condition --> Scaling

$$\begin{cases}\dfrac{d\left(r^2/\rho^2\right)}{dp}=0\\[2ex]\dfrac{d\left(K\rho^2\right)}{dp}=0\end{cases}\longrightarrow\begin{cases}r\propto\rho\\[1ex]\dfrac{r}{B}\left[\dfrac{\partial B_z}{\partial r}\right]_{z=0}=k\end{cases} \qquad \boxed{B_z=B_0\left(\frac{r}{r_0}\right)^k f(\theta)}$$

  - Note: Above is not necessary & sufficient condition!

Magnetic field of scaling FFAG



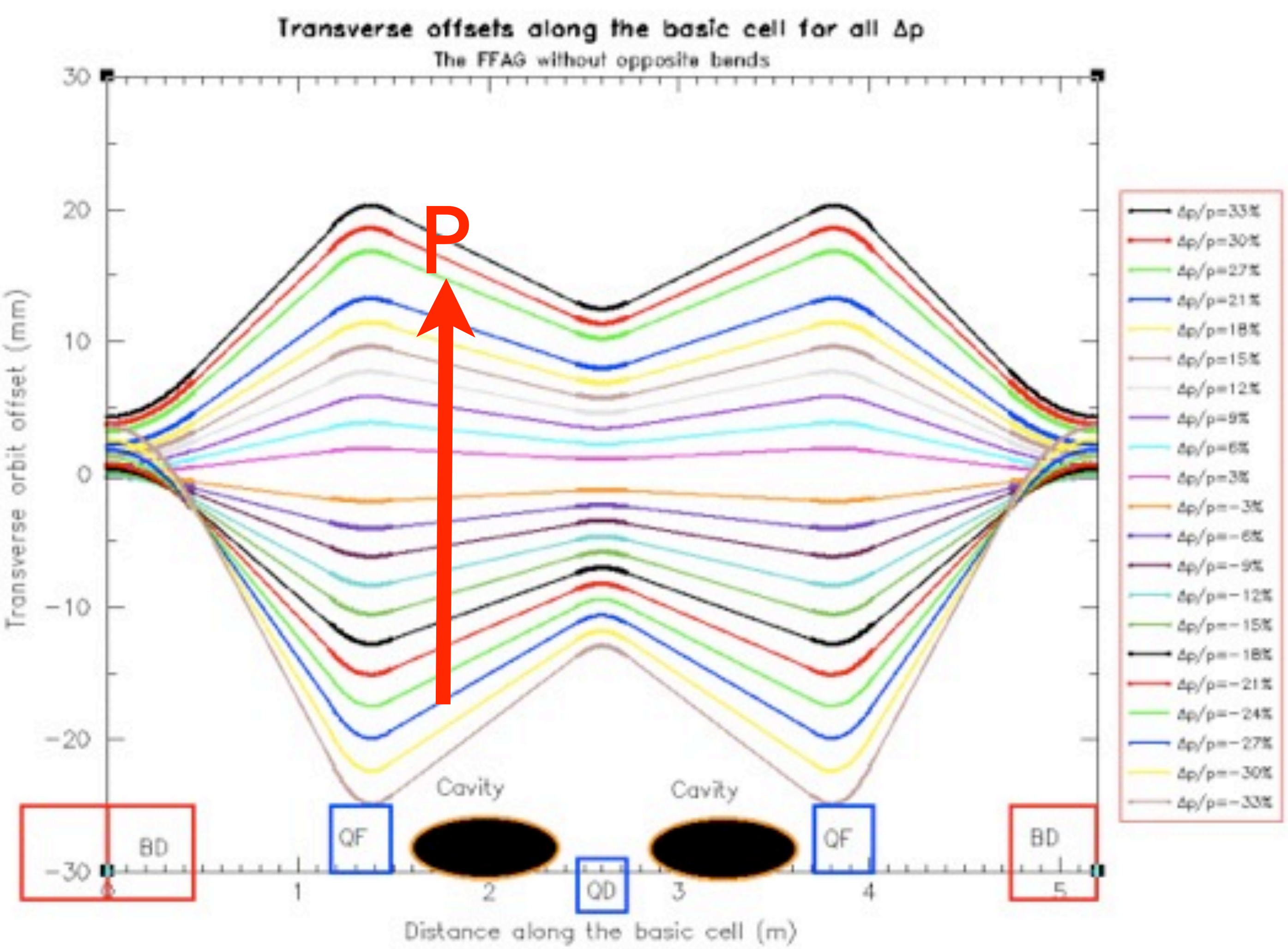
Momentum compaction: 1/k+1

Non-zero chromaticity FFAG

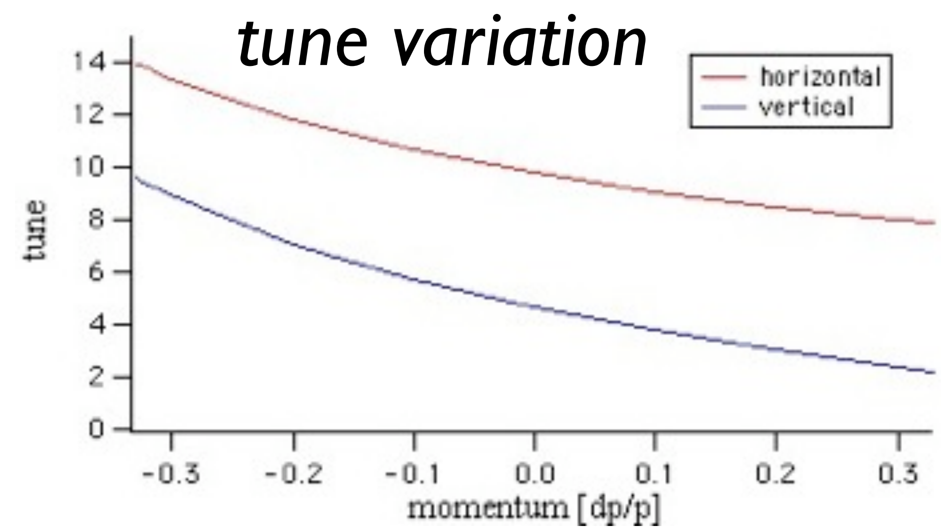
non-scaling

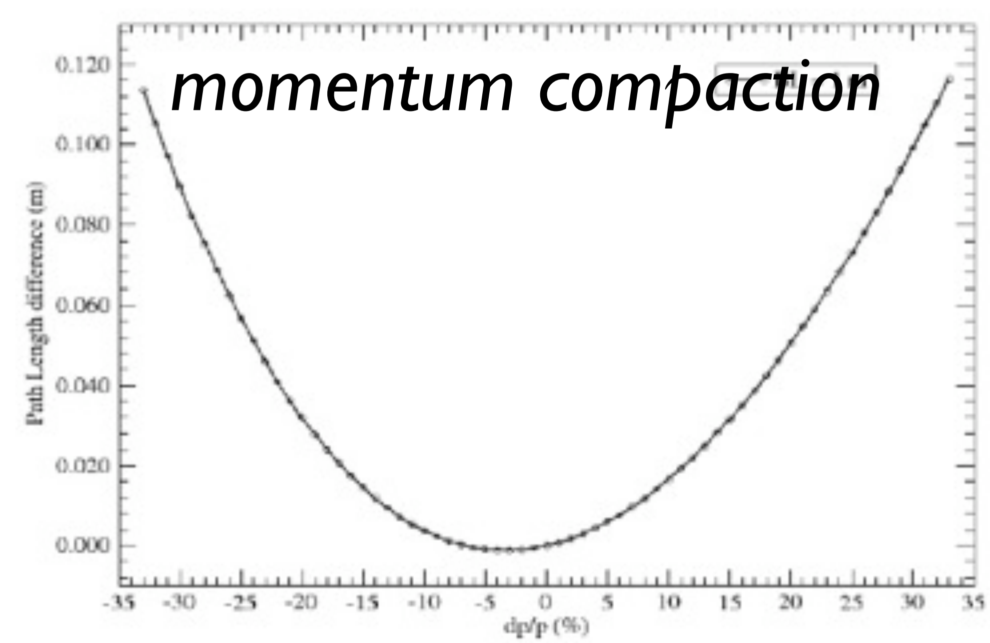
- Fields are linear: B,Q fields.
  - momentum compaction: small enough ~parabolic
- Tunes are varied: Fast resonance crossing

$$\alpha \cong C_1 \xi^2, \xi = \frac{\Delta p}{p}$$



transverse offset for all momentum

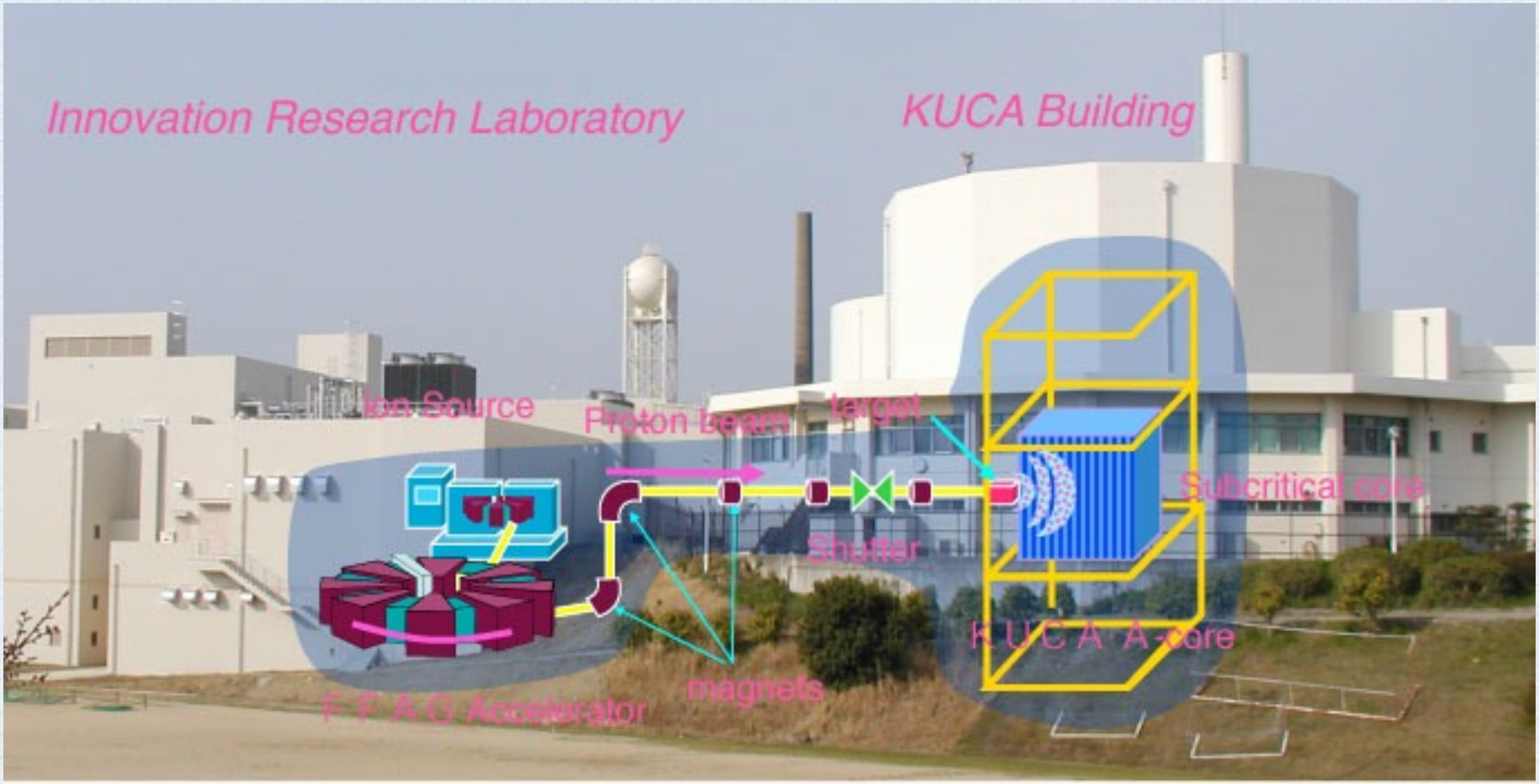




FFAG Accelerators :history

- *Ohkawa (1953), Kerst & Symon, Kolomenski*
  - *MURA project e-model, induction acceleration ~'60s*
  - *No proton FFAG for 50years!*
- *Proton FFAG (POP:World first p-FFAG, Mori et al.,2000)*
  - *Complicated field configuration : 3D design*
  - *MA(Magnetic Alloy) RF cavity :Variable Frequency & High Gradient.*
  - *150MeV p-FFAG (Mori et al.,2004)*
  - *PRISM FFAG(Kuno et al.,2008,Osaka)*
  - *p-FFAG for ADSR study, ERIT neutron source (KURRI,2008)*
  - *EMMA(e-FFAG for nuFact:World first non-scaling FFAG, England,under development)*

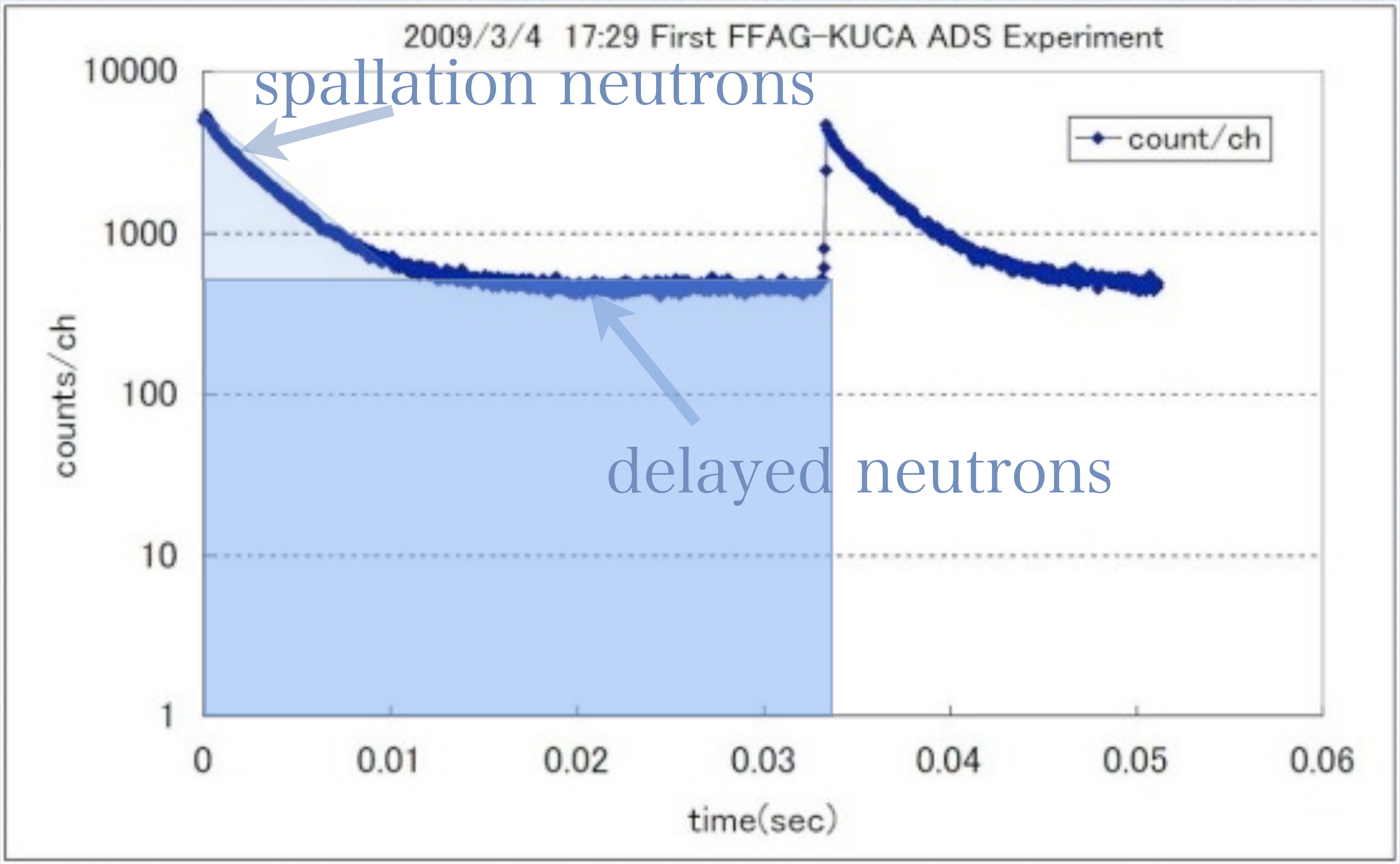
FFAG-KUCA project at KURRI



FFAG complex for ADSR study at KURRI

KUCA-A Core - solid moderated and reflected -

World first ADSR experiment with spallation neutrons - FFAG-KUCA for ADSR



C.H.Pyeon et al., Journ. of Jap.Atom.Ene.Soc.

First injection of spallation neutrons

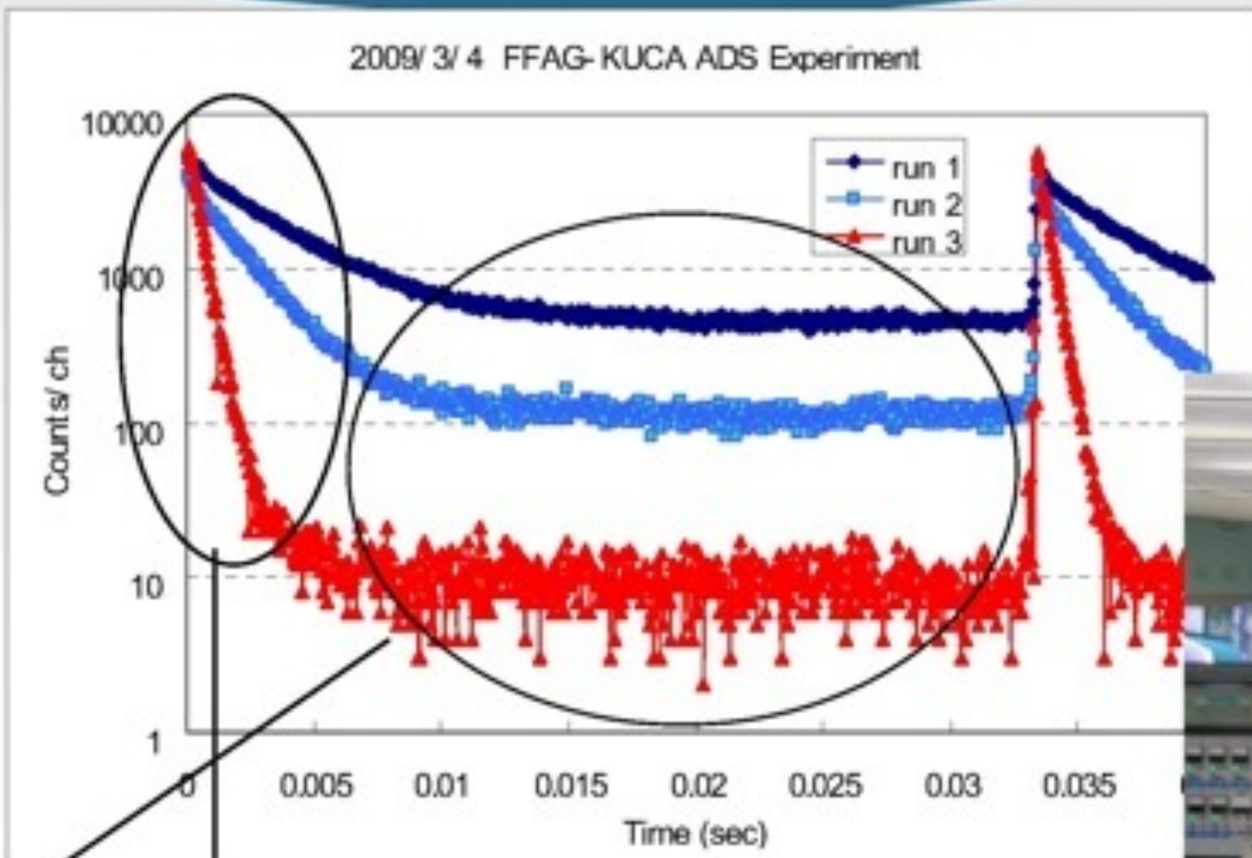
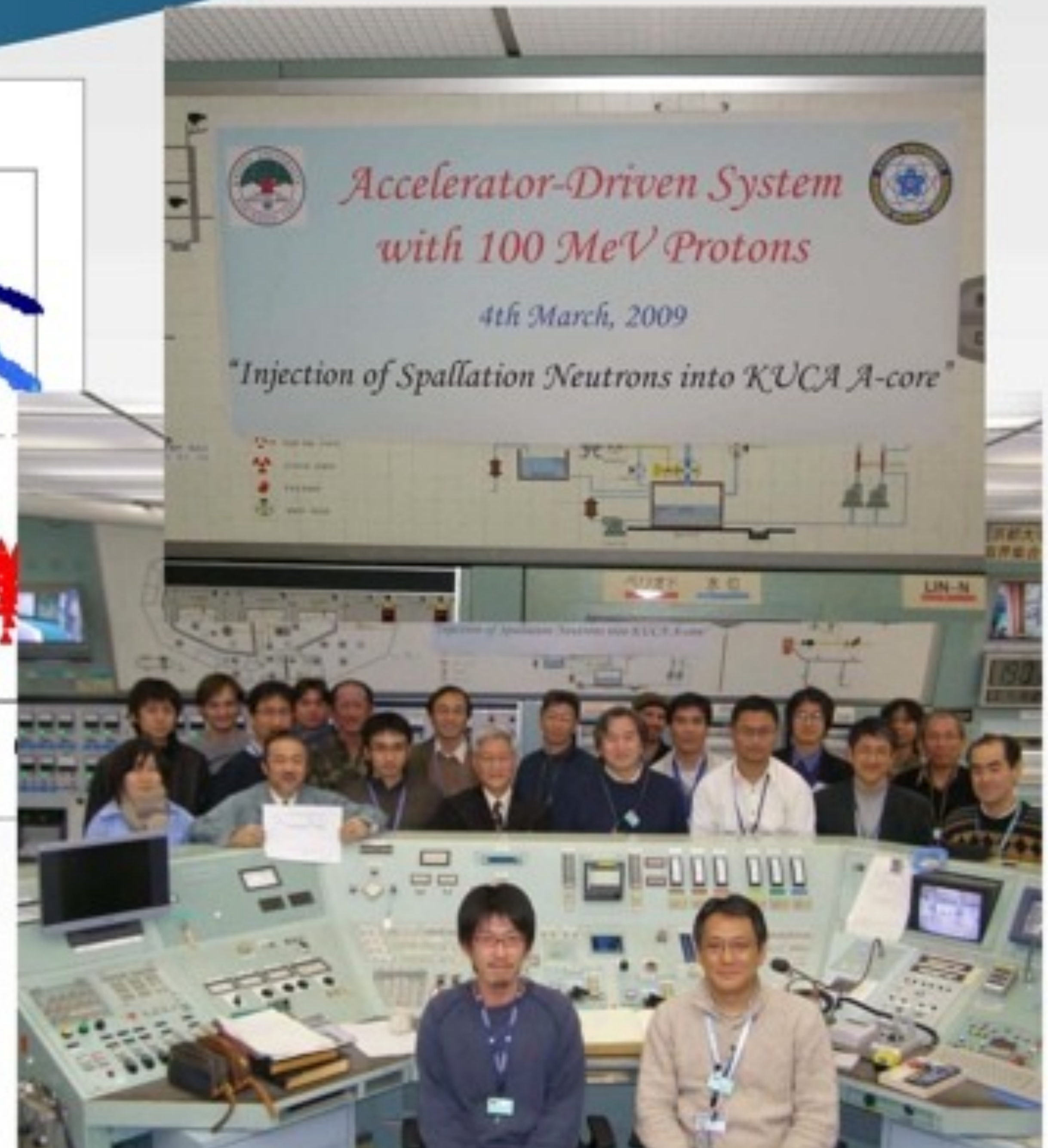


Fig. Time series of neutrons

Spallation neutrons from target

Delayed neutrons in core

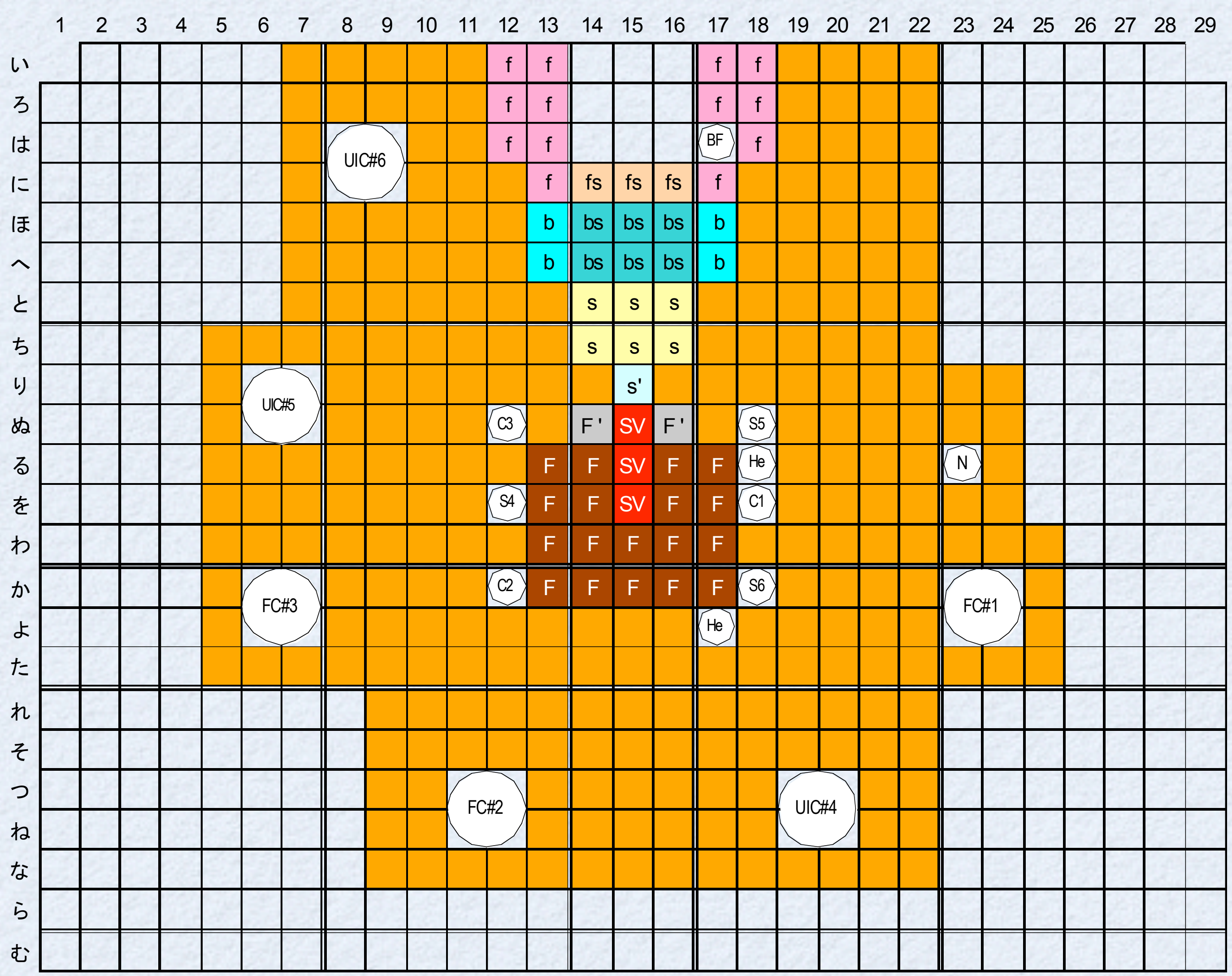


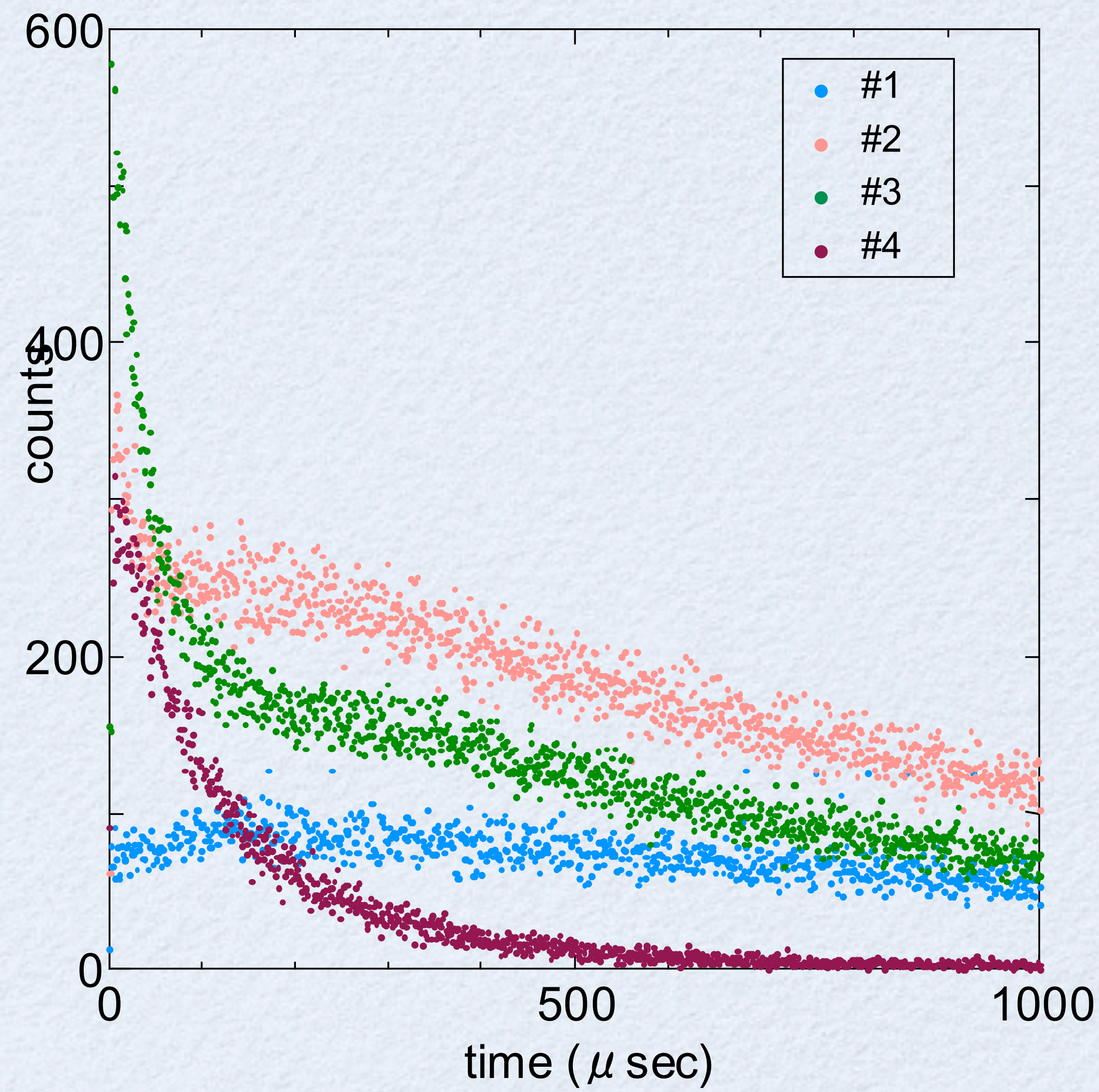
Neutron multiplication by spallation neutrons generated by protons

J-PARC JAEA

Neutron time sturucture

At various positions in the reactor





KUCA reactor core

Beam intensity upgrade

- Charge-exchanged H^- beam injection is applied.
- New injector　　H^- Linac
- Expected beam current　　>1A(peak) (cf. 10μA ave. @60Hz)

➡H^- Linac

- energy　11MeV
- Volume type of H^- ion source + RFQ + DTL

H^- LINAC

Linac beam parameters

- ion：H^-
- E_{ext}：11MeV

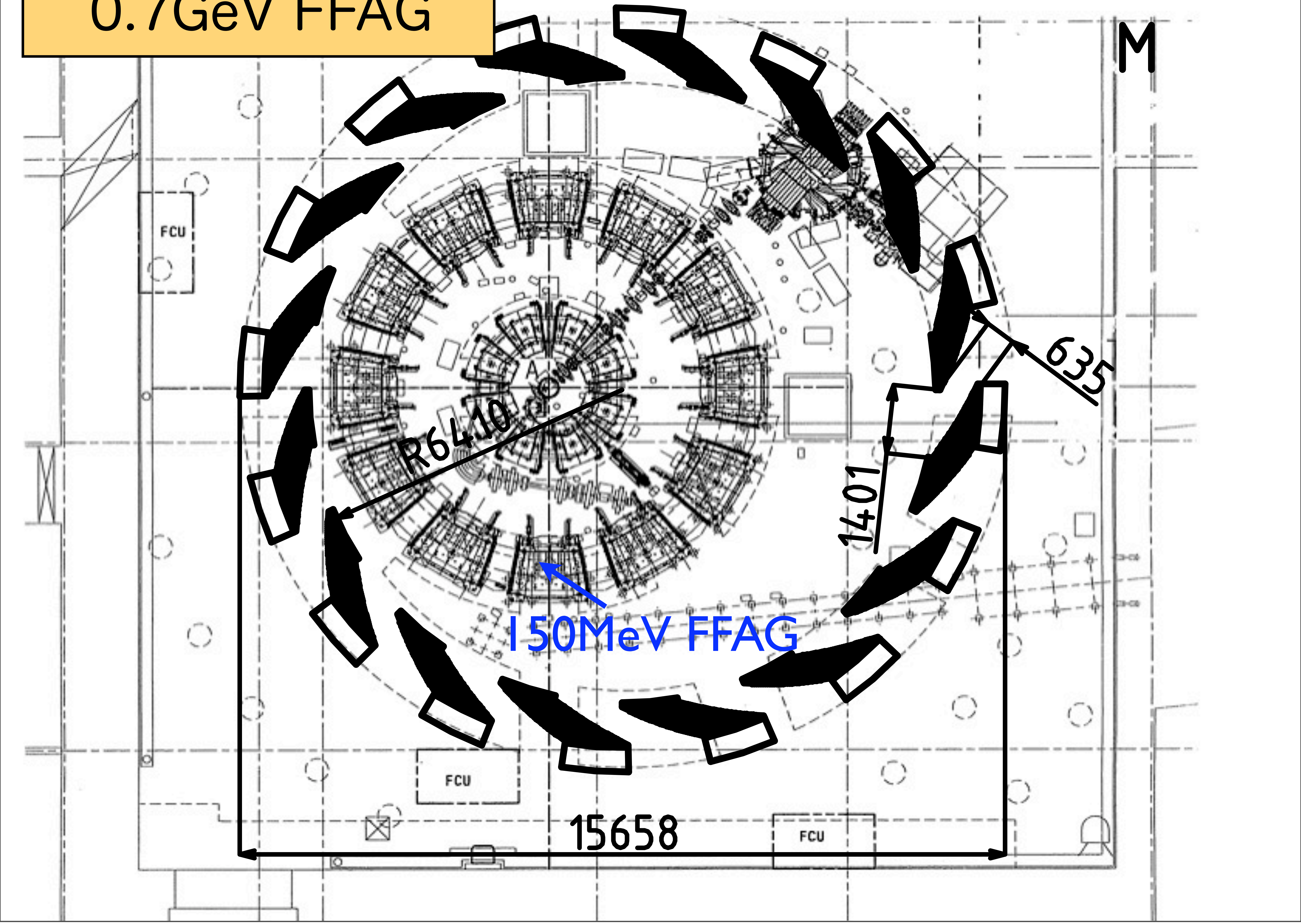
- Beam Pulse width(MAX)：100 μsec
- Beam Current :~5 mA
  :3.12*10^{12} [ppp]

- rep. rate : 1Hz ~ 200Hz

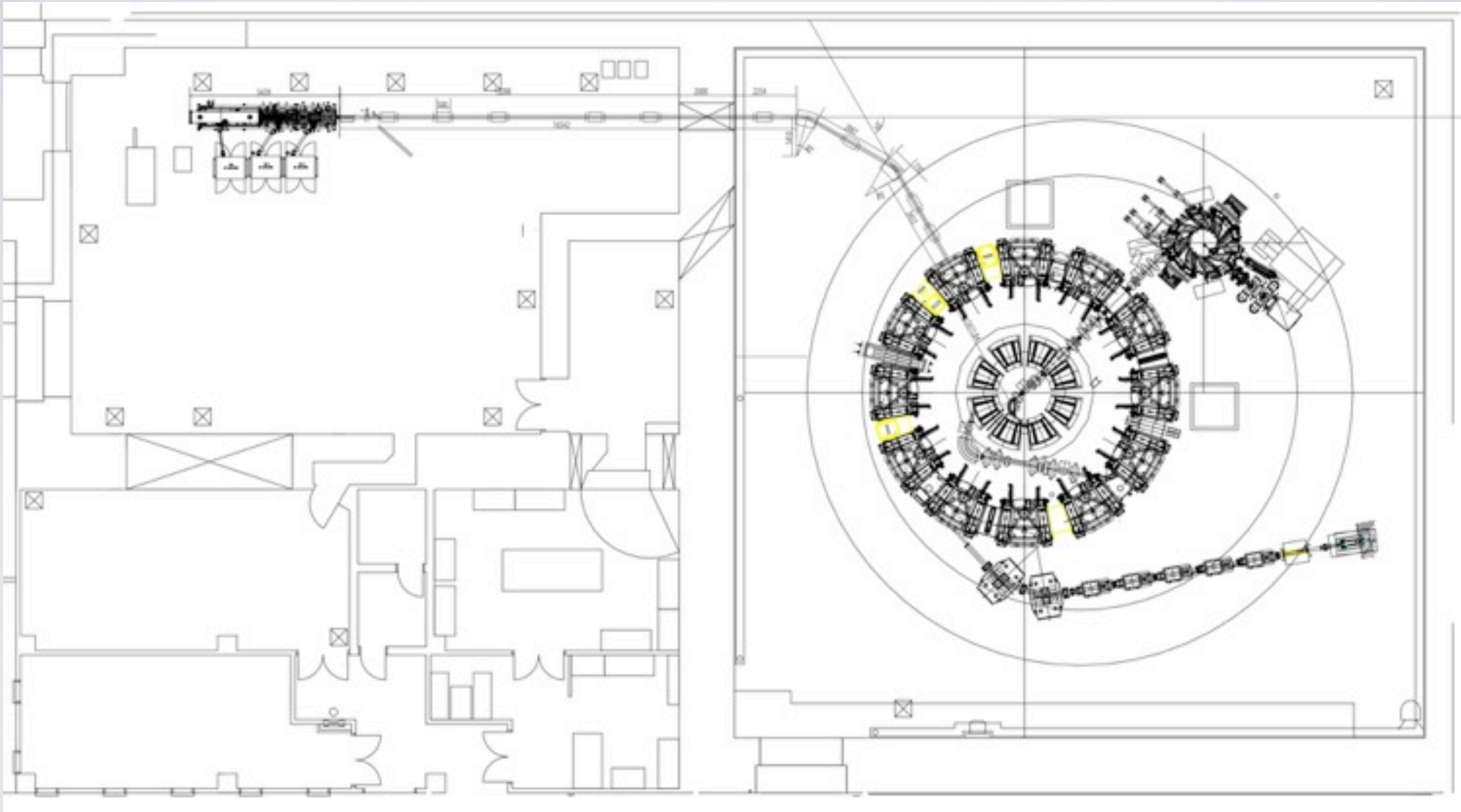
Beam energy upgrade

- Additional new FFAG ring
  - ➡Spiral type of FFAG accelerator
  - ➡Energy : 150-700MeV
  - ➡Orbit radius : 6.6-7.2m
  - ➡B field(max.) : 1.5T

0.7GeV FFAG



NEW BEAM-LINE

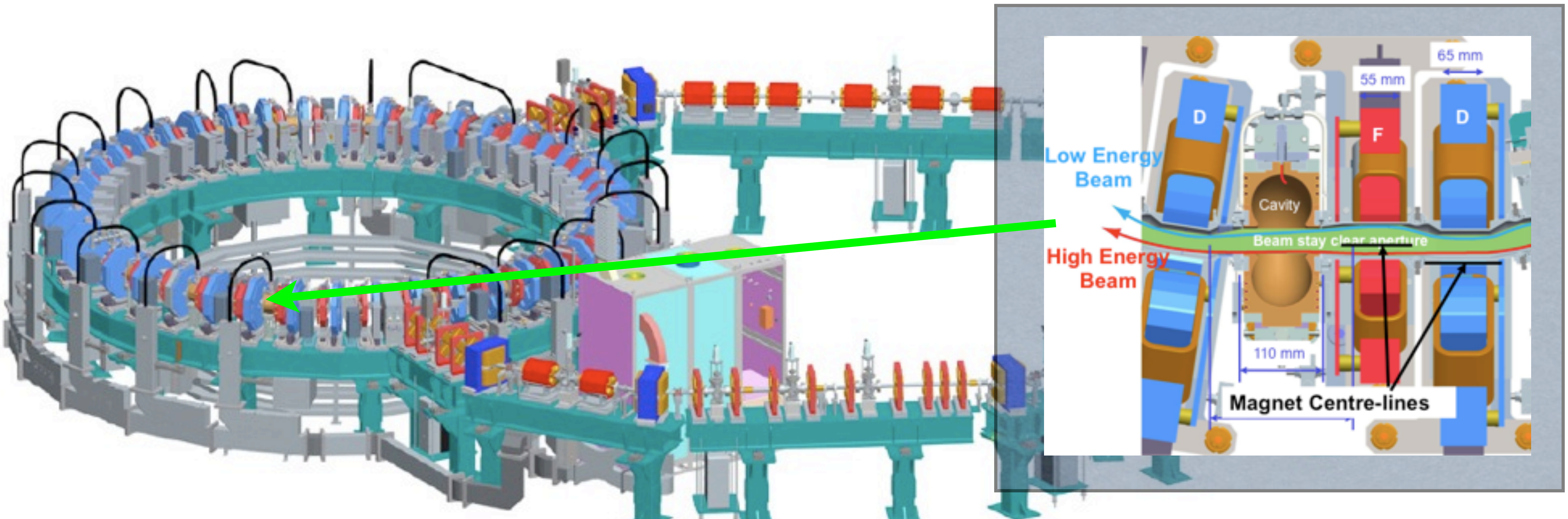


Q Mag. ×9, Bend(30deg) × 2

Non-zero chromatic FFAG

EMMA

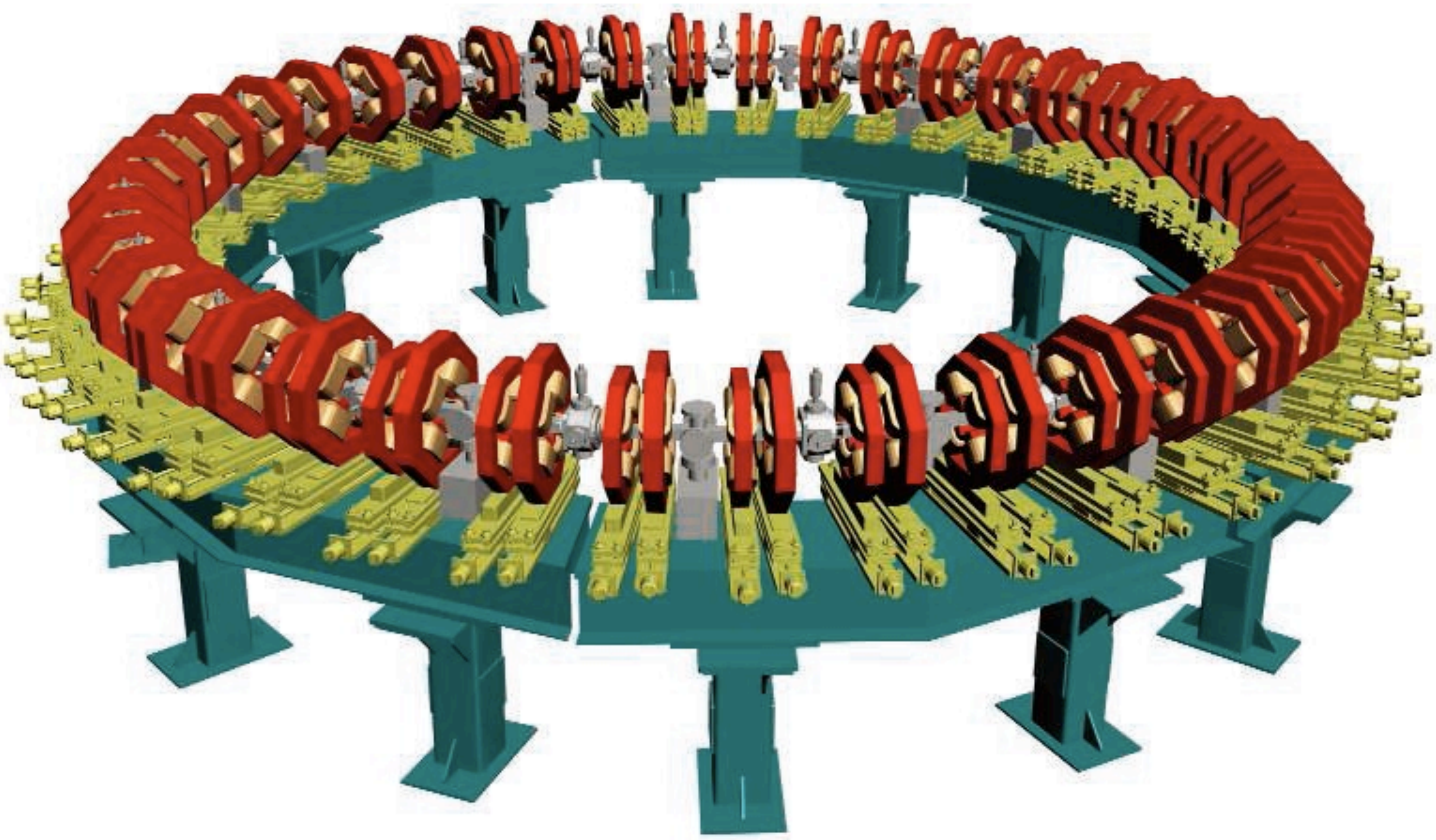
the World's First Non-Scaling FFAG Accelerator



Susan Smith STFC Daresbury Laboratory

Non-zero chromatic FFAG

EMMA:Electron Model for Muon Accelerator under constraction at UK

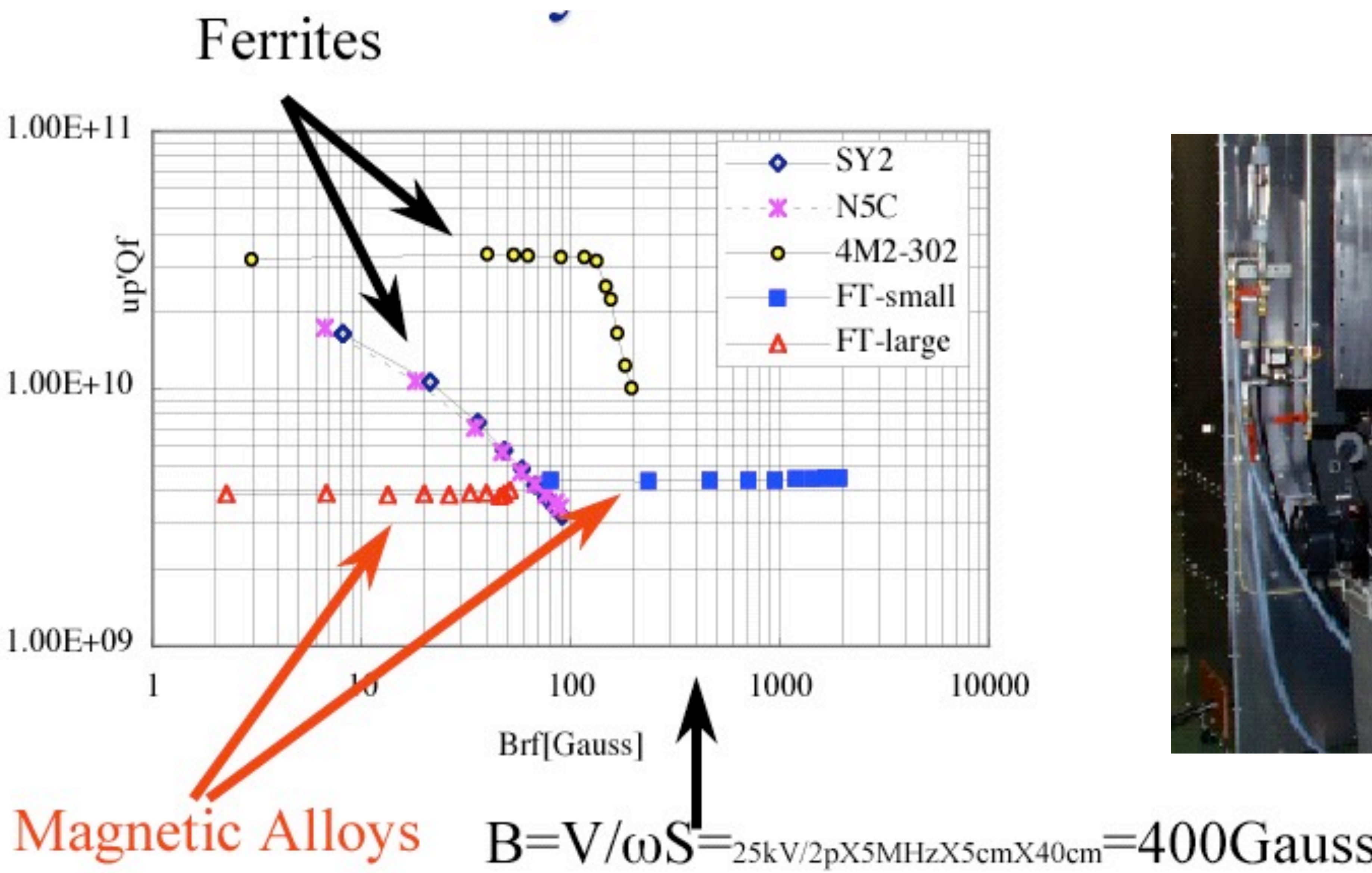


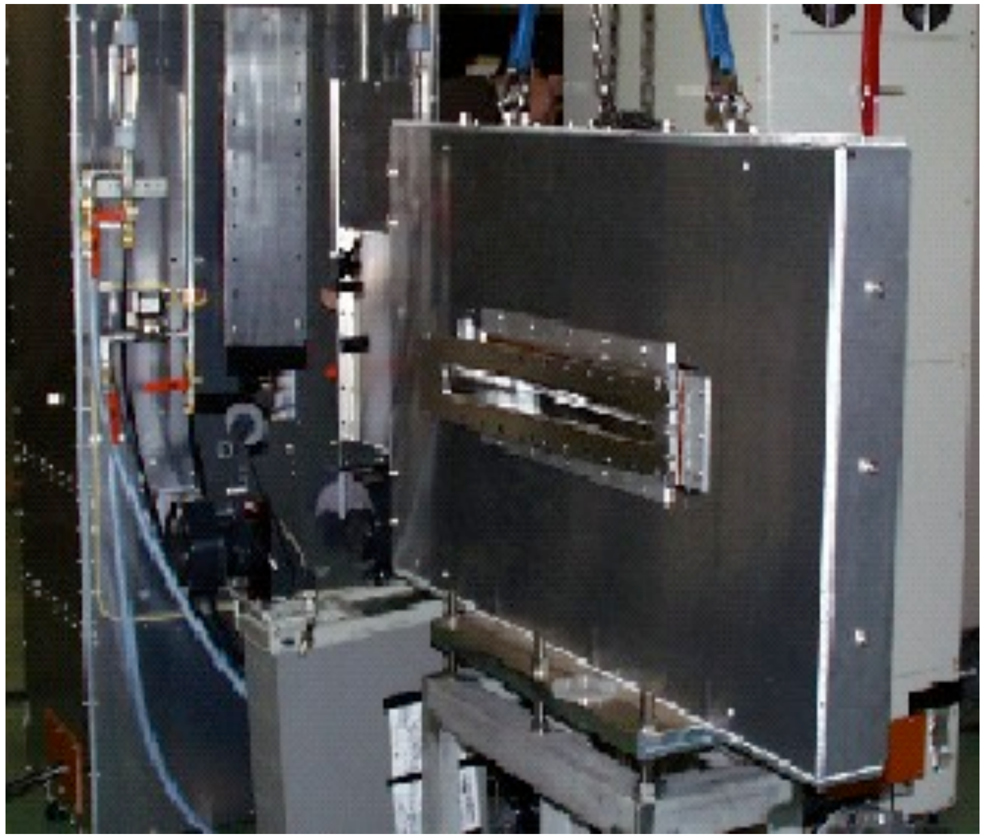
Beam acceleration(RF)

- **Beam acceleration in FFAG: large flexibility**
  - Momentum compaction can be tuned along orbit swing.
    - *Keeping phase stability like synchrotron*
    - *Realizing isochronism like cyclotron*
- Variable frequency RF
  - Broad-band RF cavity : Scaling & Non-scaling
    - *MA(magnetic alloy) cavity Q~1*
- Fixed frequency RF
  - Stationary RF bucket acceleration : Scaling
    - *constant momentum compaction(MC)*
  - Serpentine RF acceleration : Non-scaling
    - *relativistic beam & small MC(parabolic) :semi-isochronous*
  - Harmonic number jump acceleration : Scaling (non-scaling)
    - *non-zero slippage factor*

Variable RF frequency

- Broad-band RF cavity : MA(magnetic alloy) cavity
  - Fast acceleration requires fast frequency(phase) change.
    - *Low Q (Q~1) is essentianl !*
  - Adequate both for scaling and non-scaling FFAGs.

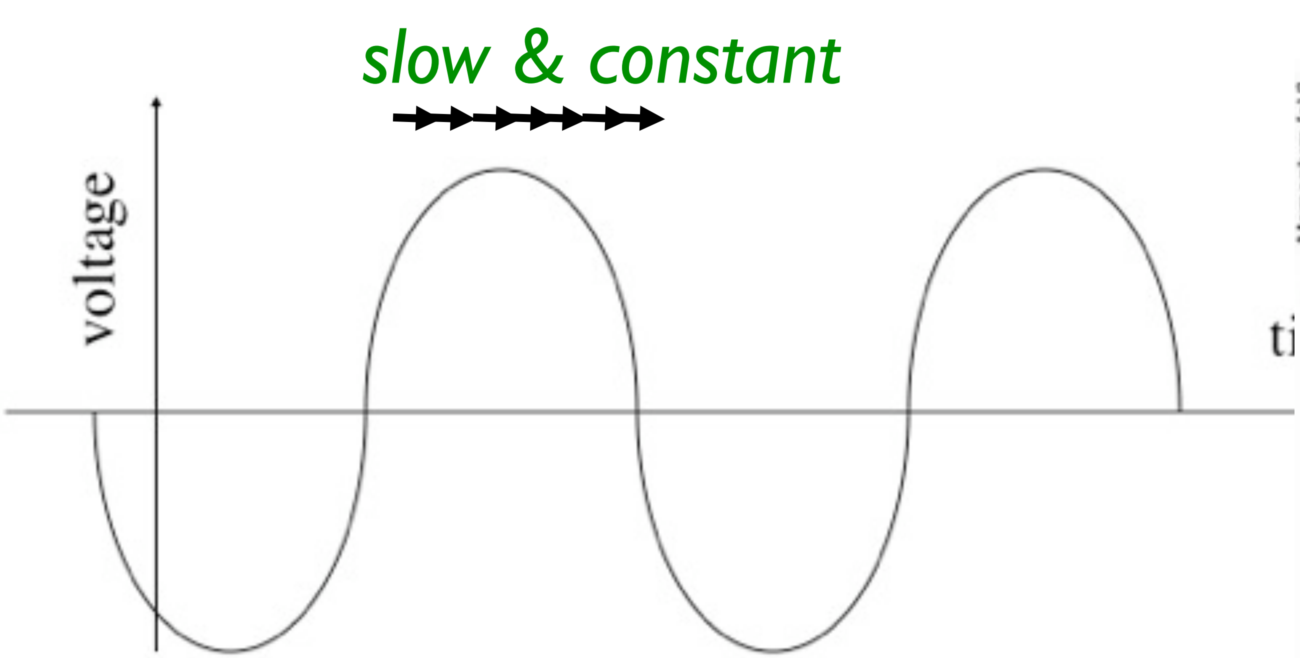


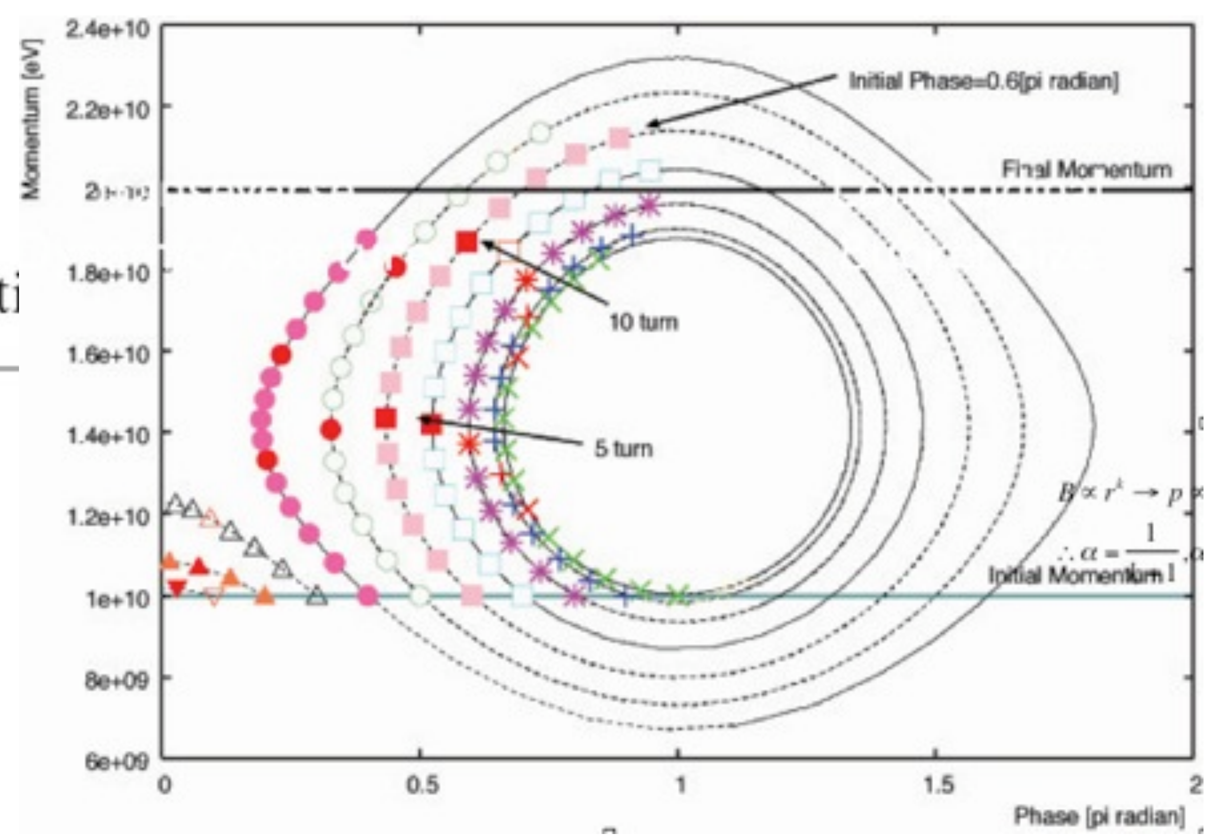


Fixed frequency(1)

- Stationary bucket acceleration
  - Constant & small enough phase slip --- Large energy gain
    - *relativistic beam*
    - *constant Momentum Compaction*
  - Adequate for scaling FFAG

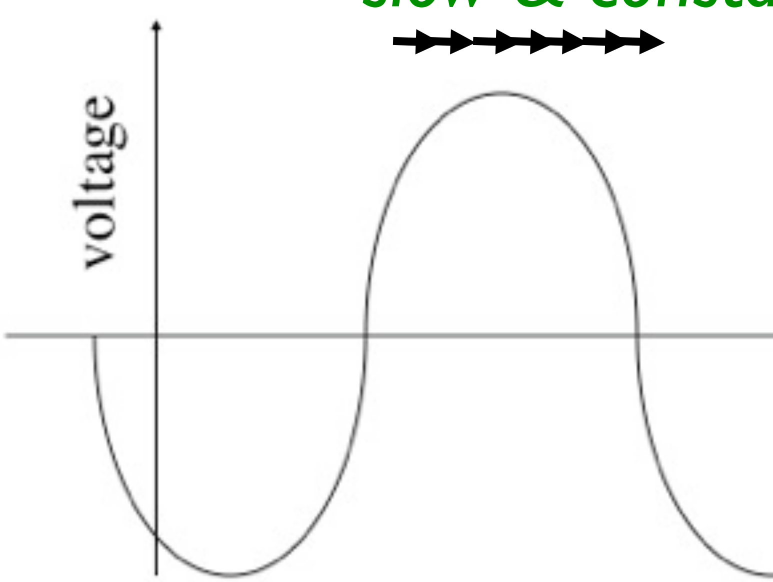
$$\eta = \frac{1}{\gamma^2} - \alpha \cong -\alpha = -\frac{1}{k+1}$$

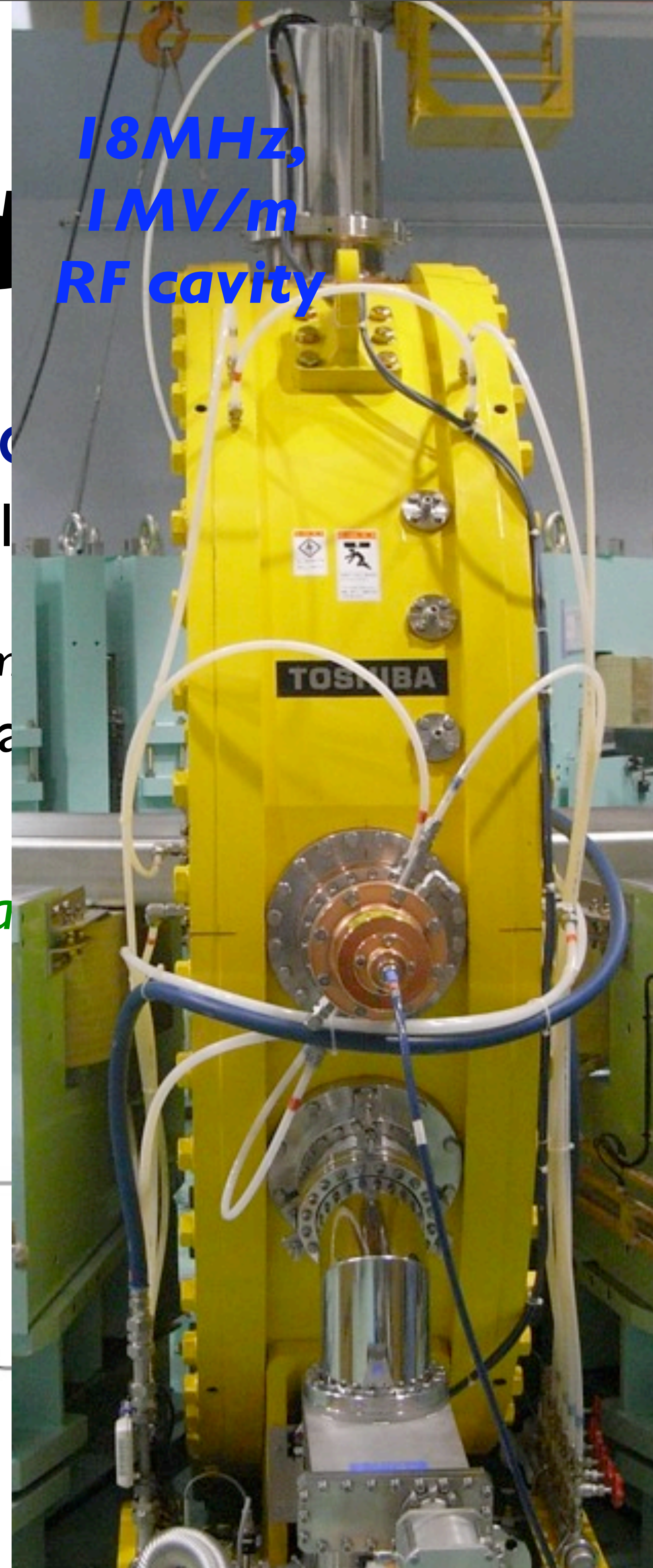


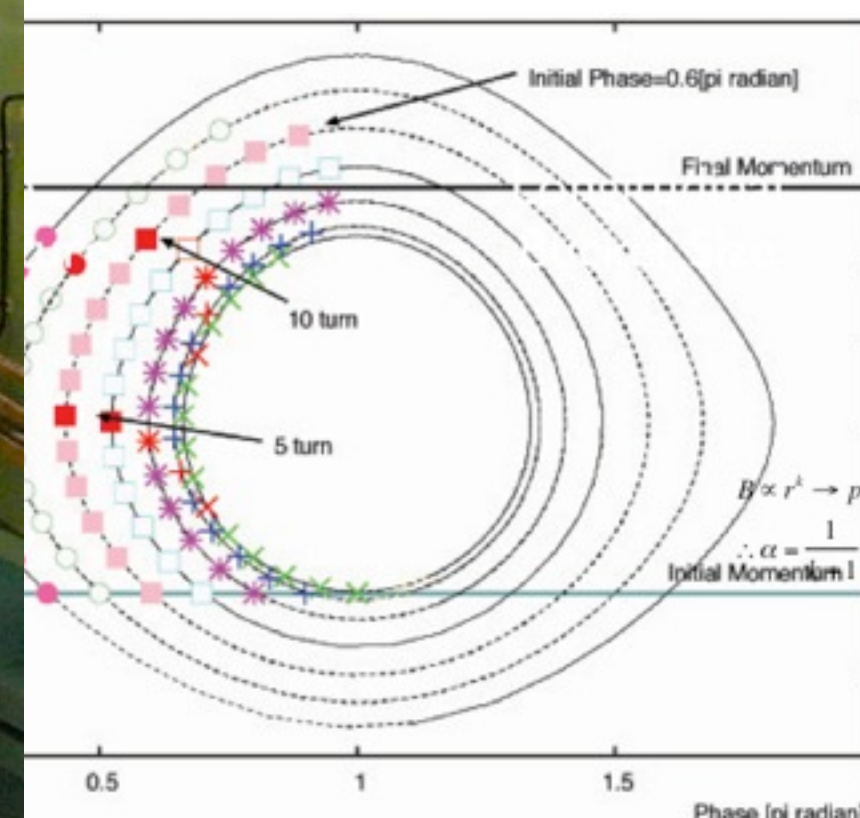


Fixed ... cy(1)

- Stationary buc...
  - Constant & smal... ...rge energy gain
    - *relativistic beam*
    - *constant Momentum...* $\ldots\alpha = -\frac{1}{k+1}$
  - Adequate for sca...



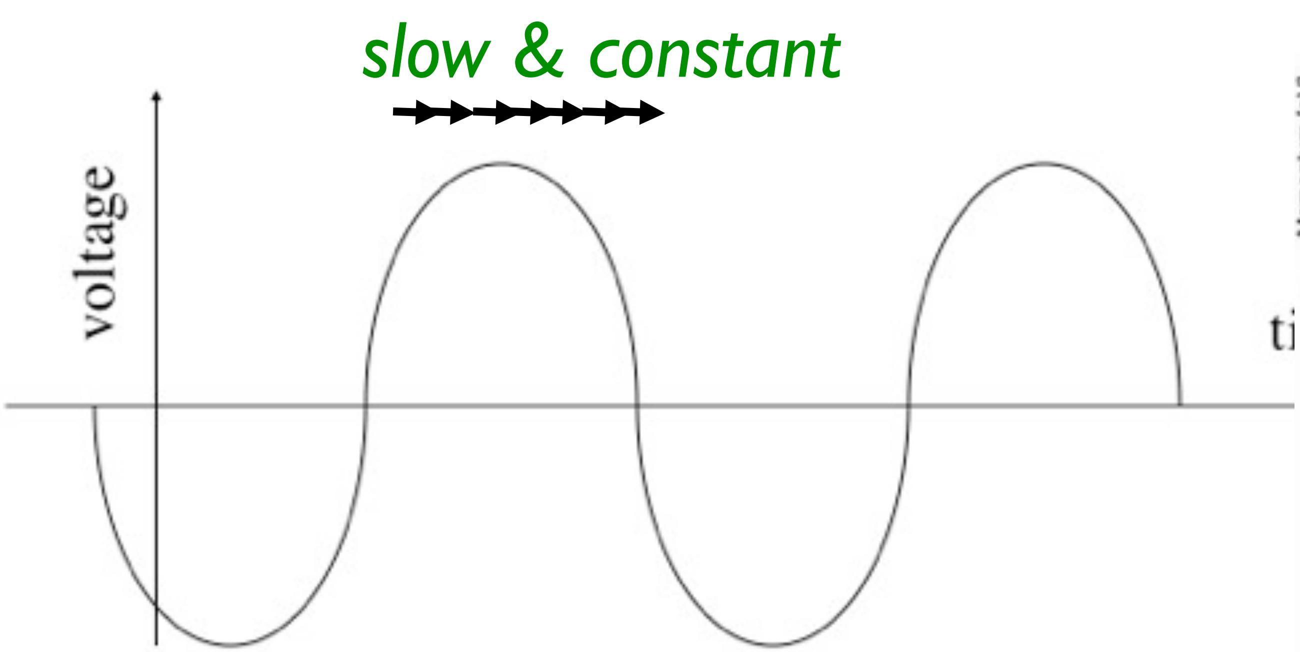


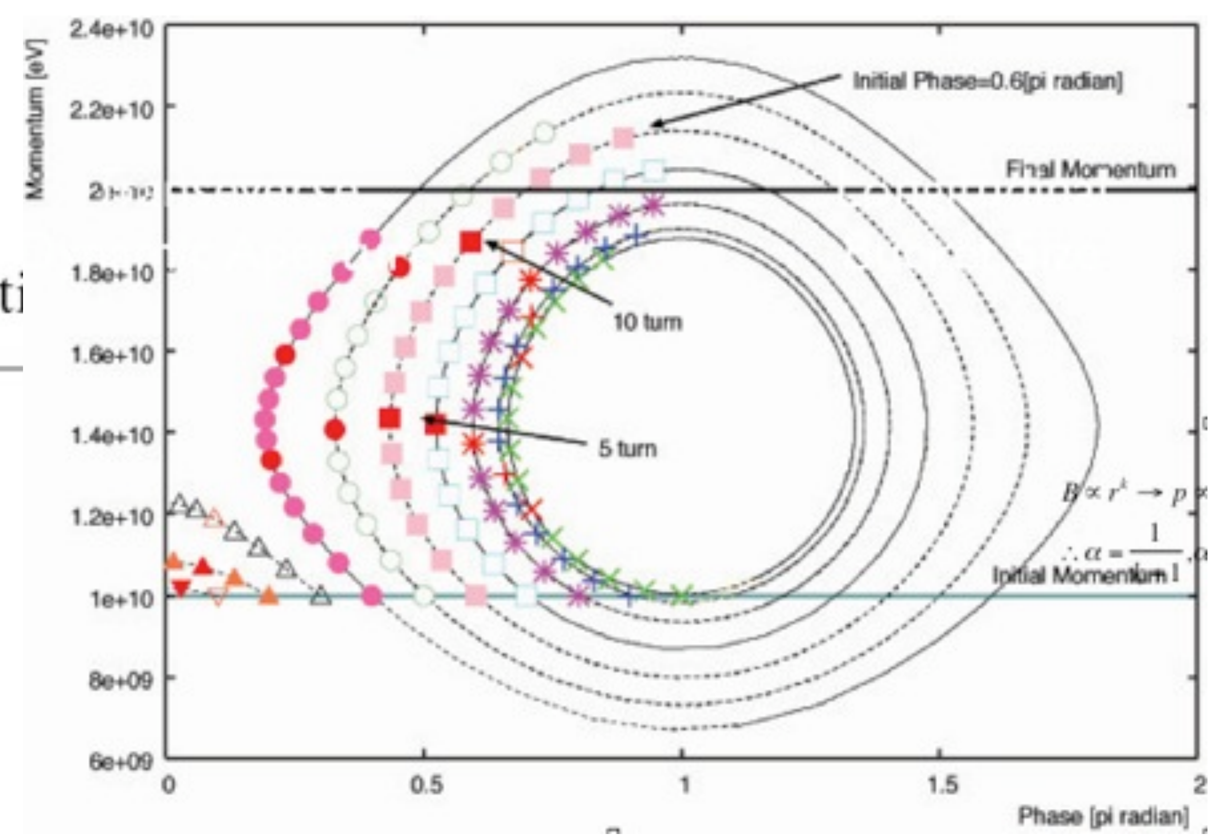


Fixed frequency(I)

- Stationary bucket acceleration
  - Constant & small enough phase slip --- Large energy gain
    - *relativistic beam*
    - *constant Momentum Compaction*
  - Adequate for scaling FFAG

$$\eta = \frac{1}{\gamma^2} - \alpha \cong -\alpha = -\frac{1}{k+1}$$





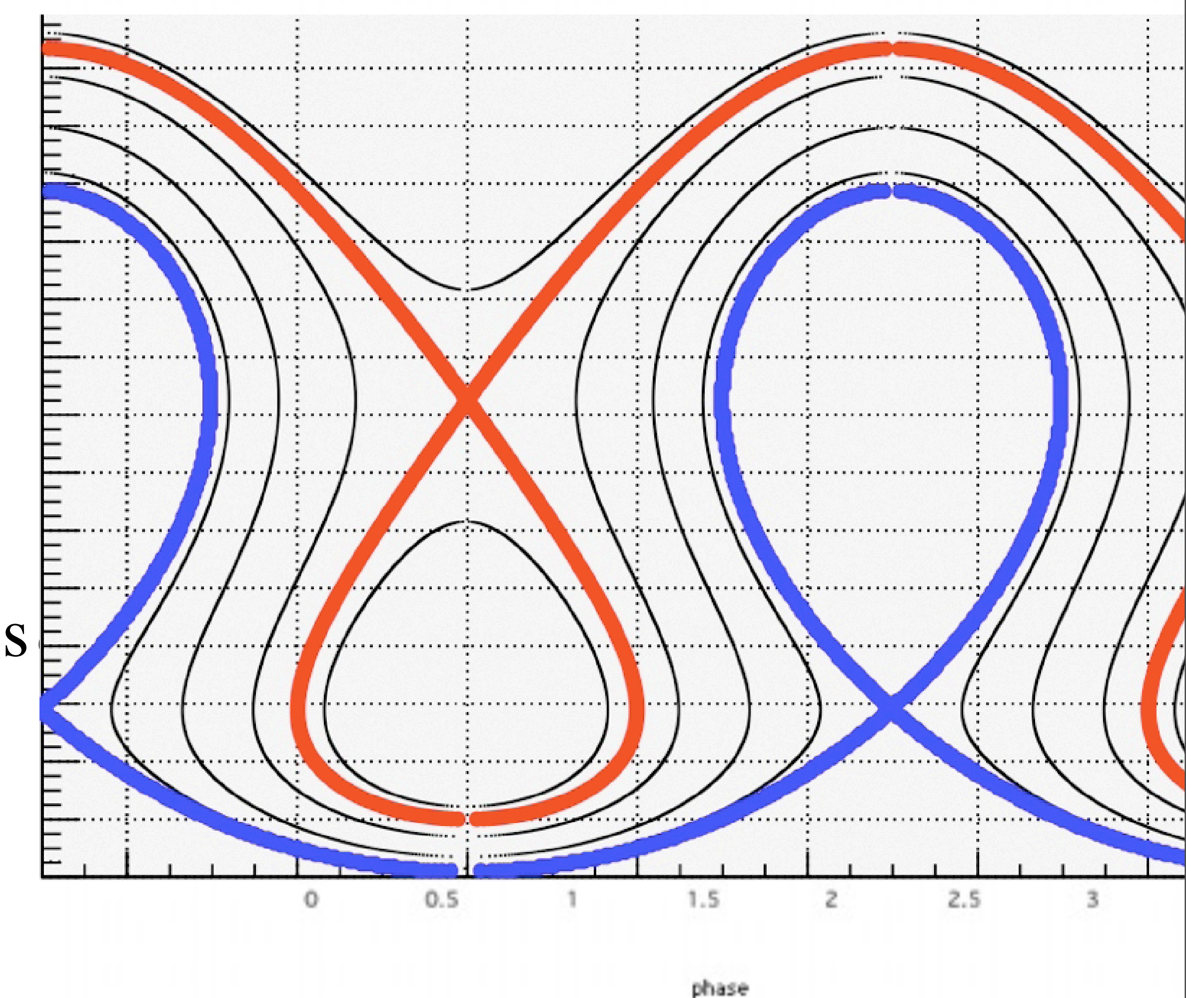
Fixed frequency (2)

- Serpentine acceleration in zero-chromatic(scaling) FFAGs
  - Non-relativistic to relativistic
  - Longitudinal Hamiltonian in scaling FFAG

$$H = 2\pi m_0 c^2 \left[\frac{\left(\gamma_s^2 - 1\right)^{\lambda}}{2\gamma_s} \frac{\left(\gamma^2 - 1\right)^{-\lambda+1}}{(1-\lambda)} + \gamma \right] + e\frac{V_{rf}}{h} f_0 \cos$$

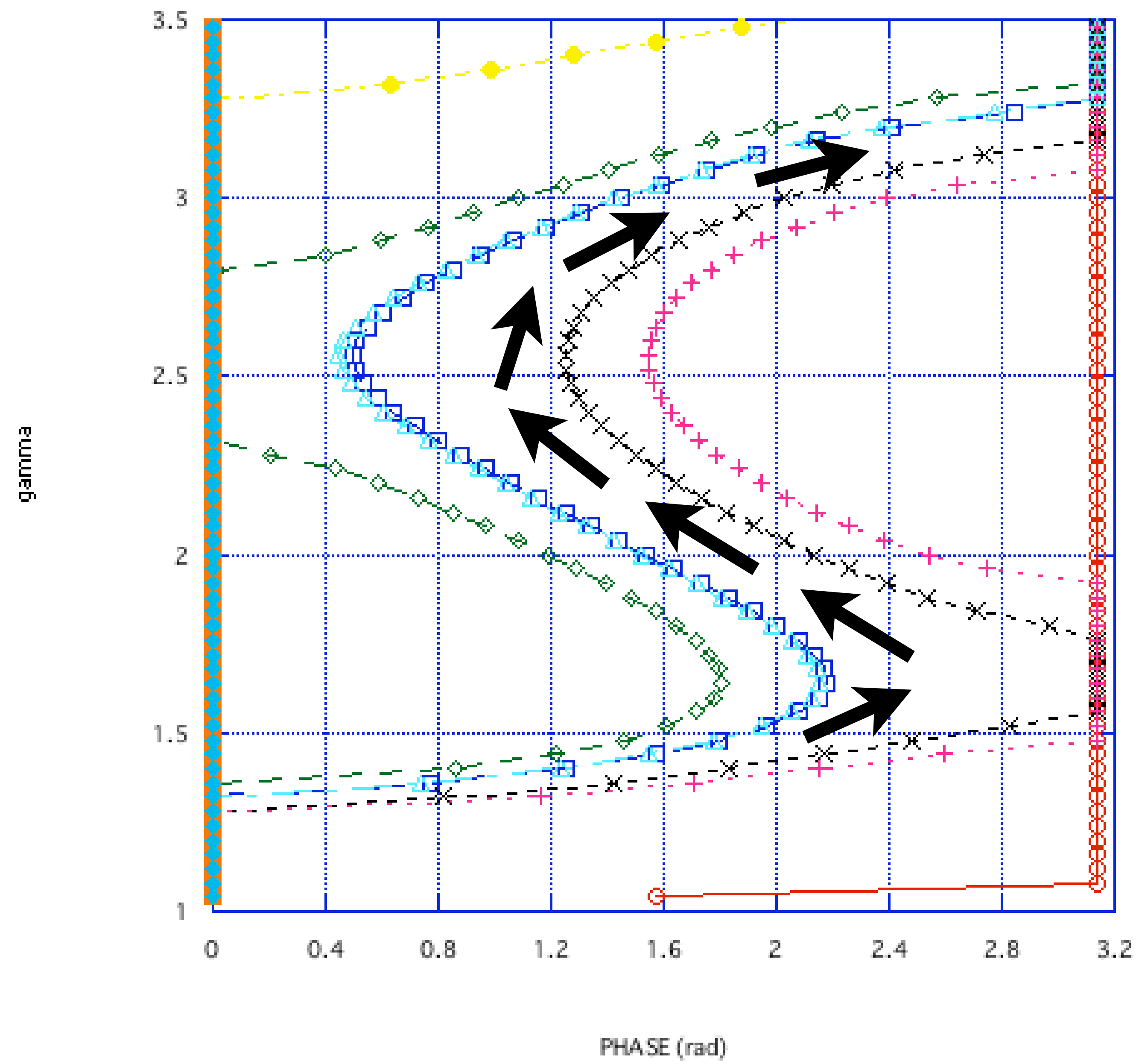
$$\lambda = \frac{k}{2(k+1)}$$

$$\frac{dp}{dT} = 0 : \quad p = \gamma_1 \text{ and } \gamma_2$$



Fixed frequency (2-1)

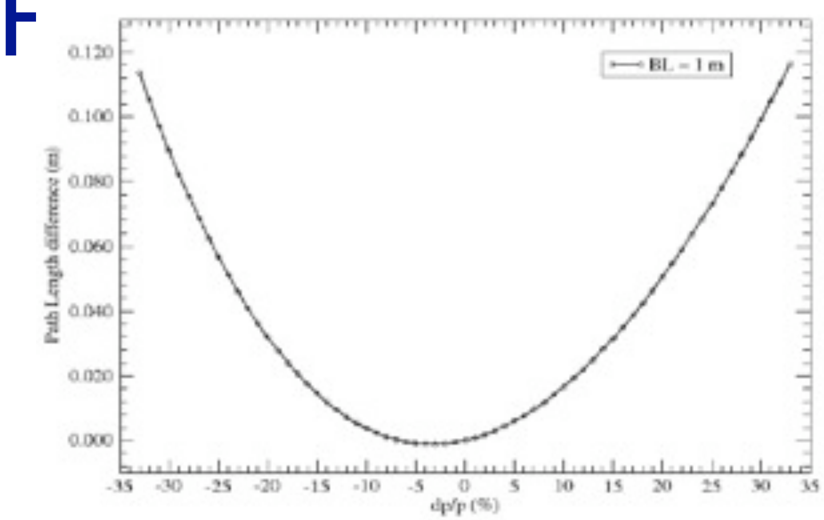
Ex. of Proton Acceleration : E=300MeV - 2.2GeV



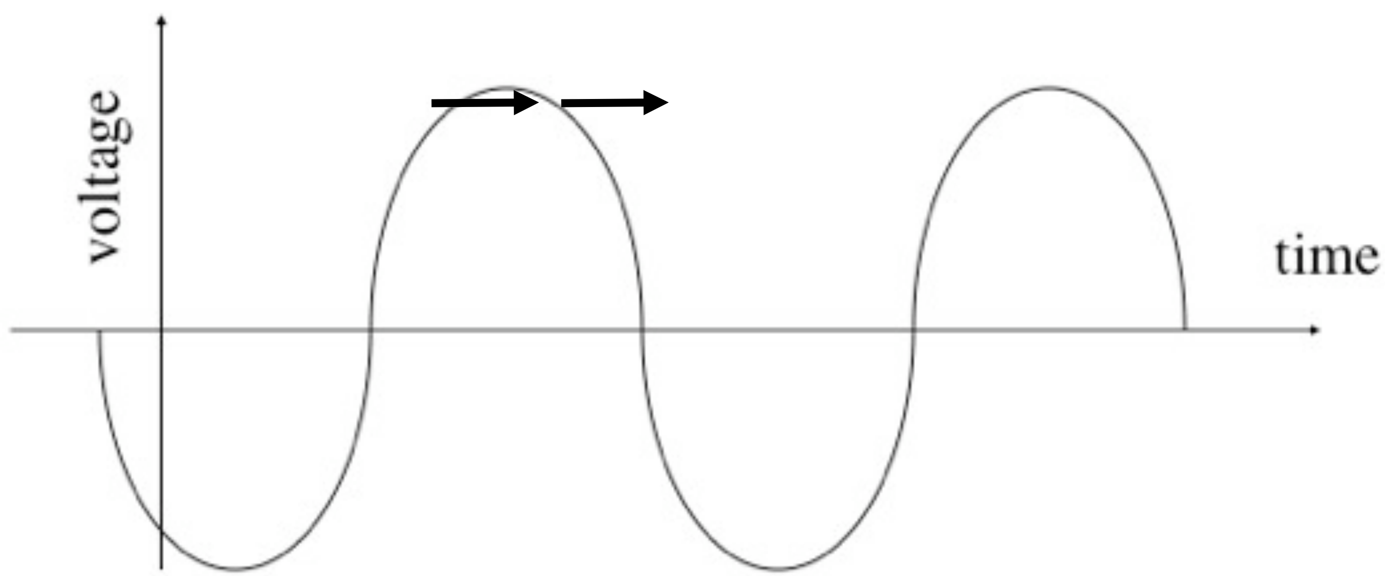
Item	value
Average radius(m)	15
Field index	3
Injection energy	300MeV
Extraction energy	2.2GeV
RF voltage per turn (h=1)	38MV

Fixed frequency(3)

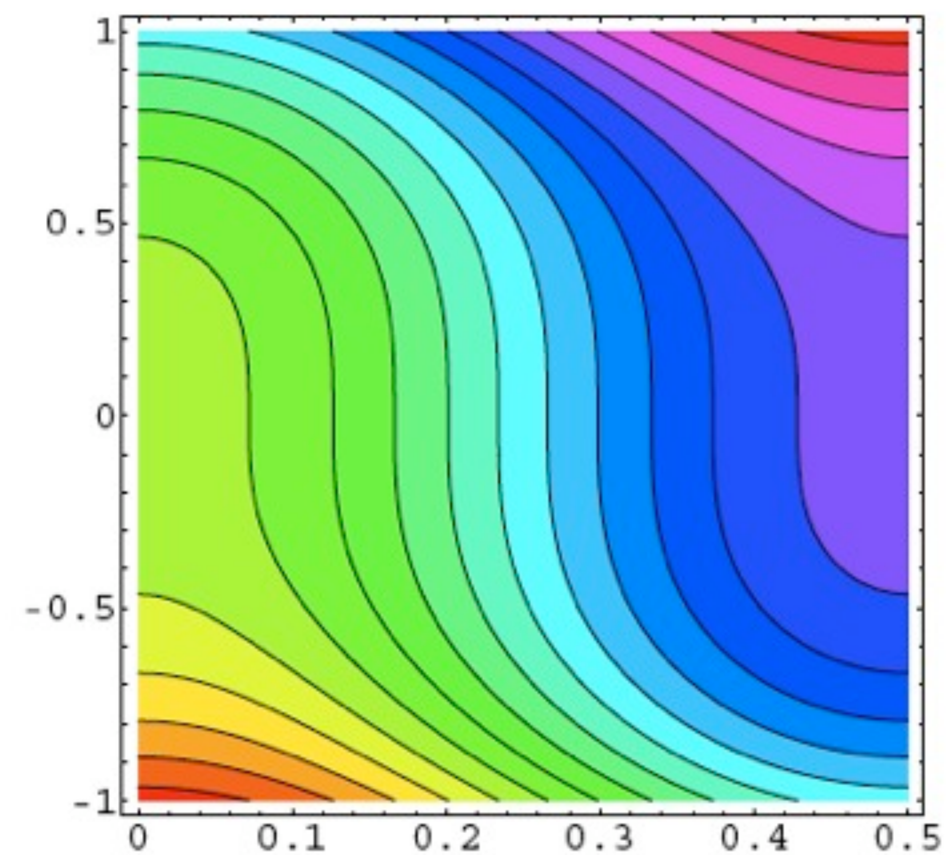
- Serpentine acceleration in non-scal.FF
  - Parabolic & small enough phase slip
    - *relativistic beam*
    - *small parabolic Momentum Compaction*
  - Adequate for non-scaling FFAG



slow & parabolic



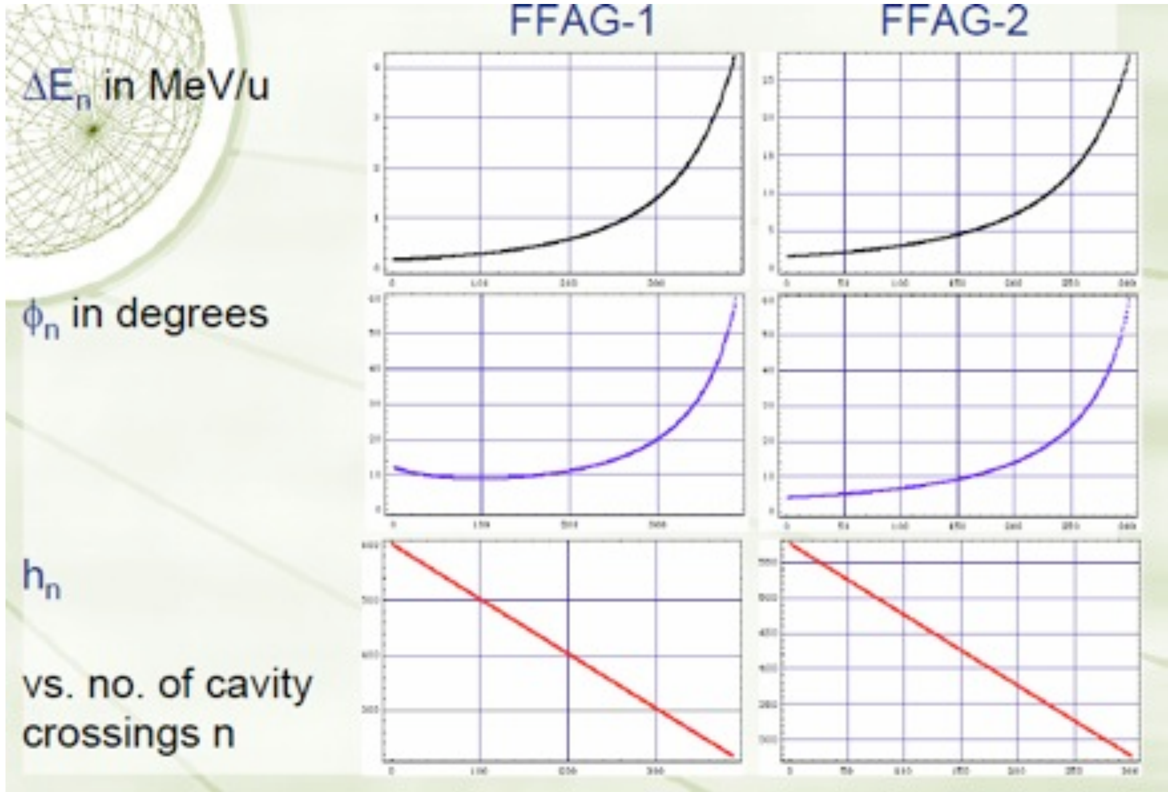
cf. S.Machida



Fixed RF frequency(4)

- Harmonic number jump acceleration
  - *m:integer, m<0: before transition, m>0: after transition*
  - Energy gain/turn can be automatically tuned if the RF voltage is high enough. ---> Phase stability
- Time slip/turn: m x Trf

$$T_{i+1} - T_i = \frac{m}{f_{RF}}$$



cf. A.Ruggiero(BNL)

Advancement of FFAG

- Zero chromaticity (scaling) FFAGs

- Pro/
  - Fixed field & Strong focusing
  - Zero chromaticity
    - *constant betatron tunes → no-resonance crossing*
  - Large acceptance (longitudinal & transverse)
- Con/
  - Relative large dispersion:Orbit excursion is large.
    - *Large horizontal aperture magnet*
    - *Large horizontal aperture rf cavity → Low frequency*
  - Short straight section
    - *Injection/Extraction difficulties → Kicker/Septum needs large apertures.*
    - *Available space for rf cavity is limited.*

- Need long straight section with small dispersion keeping "Zero Chromaticity".

Scaling FFAG linear line

- Is it possible to make a linear FFAG straight line?
  - keeping a scaling law: zero chromaticity
  - reducing dispersion: dispersion suppressor
  - making a good match with ring: insertion
- Magnetic field configuration for FFAG linear line?
  - Obviously not:

$$B = B_0 \cancel{\left(\frac{r}{r_0}\right)^k} f(\theta)$$

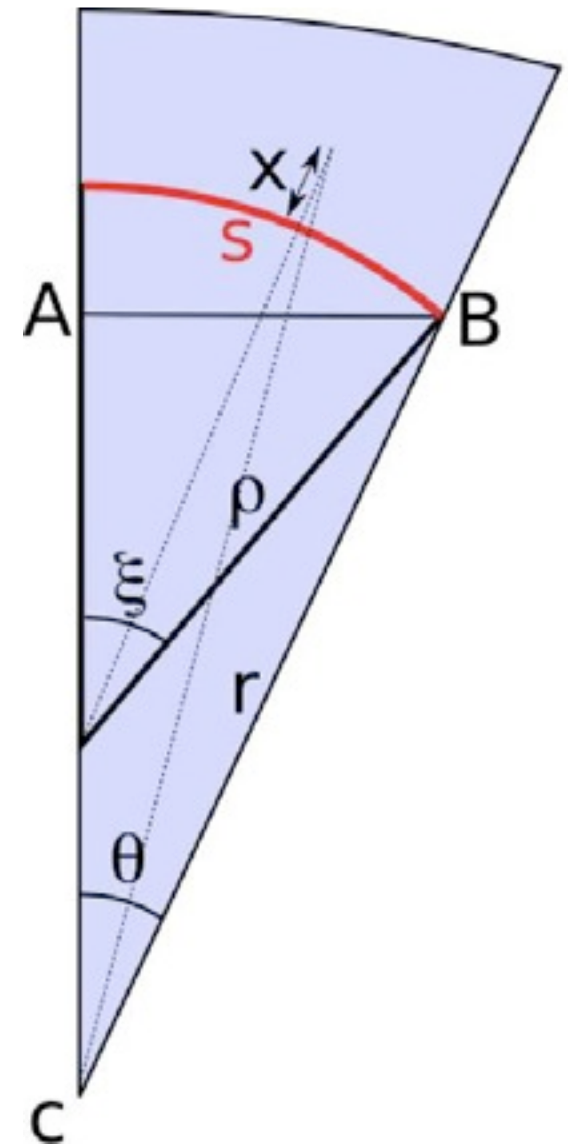
Scaling field

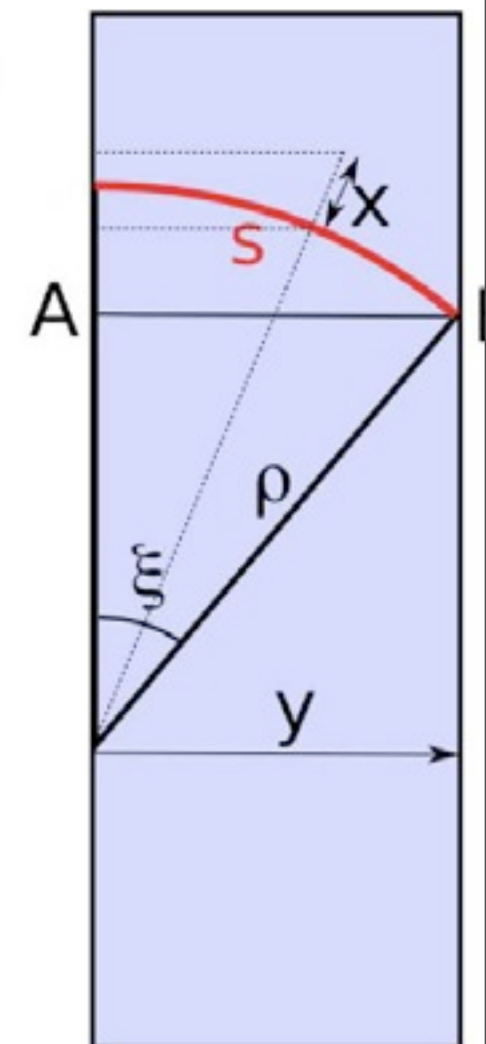
linear (straight) transport line

- Betatron eqs.

$$\frac{d^2x}{dy^2}+\frac{1}{\rho^2}\left(1-K\rho^2\right)x=0$$

$$\frac{d^2z}{dy^2}+\frac{1}{\rho^2}\left(K\rho^2\right)z=0$$





- Scaling conditions: zero-chromaticity
  - sufficient cond.

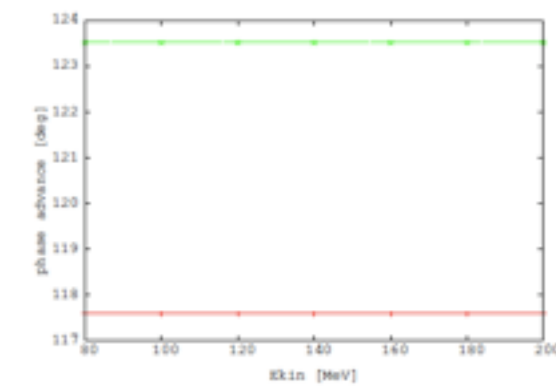
$$\begin{cases}\dfrac{d\left(1/\rho^2\right)}{dp}=0\\[2ex]\dfrac{d\left(K\rho^2\right)}{dp}=0\end{cases}\longrightarrow\begin{cases}\rho=const.\\[1ex]\dfrac{1}{B}\left[\dfrac{\partial B_z}{\partial x}\right]_{z=0}=\dfrac{n}{\rho}\end{cases}$$

  - Magnetic field

$$\boxed{B_z=B_0\exp\left[\frac{n}{\rho}x\right]}$$

$$\left[\lim_{r_0\to\infty}\left(\frac{r}{r_0}\right)^k=\lim_{r_0\to\infty}\left[\left(1+\frac{x}{r_0}\right)^{\frac{r_0}{x}}\right]^{\frac{x}{r_0}k}=\lim_{r_0\to\infty}\left[\left(1+\frac{x}{r_0}\right)^{\frac{r_0}{x}}\right]^{\frac{n}{\rho}x}=\exp\left(\frac{n}{\rho}x\right)\right]$$

Scaling linear line

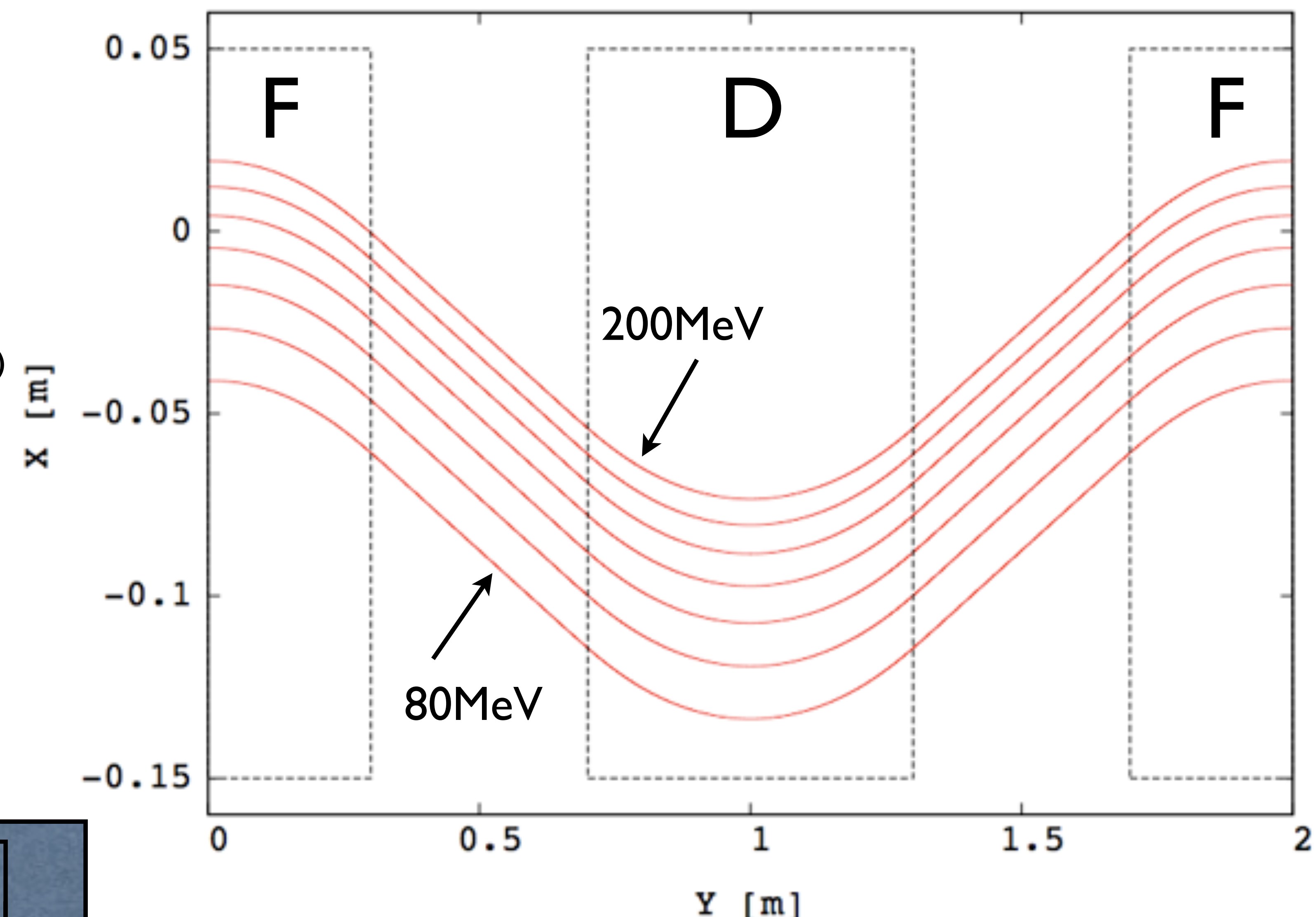


Example (JB. Lagrange)

- Perfect scaling(zero-chromatic) FFAG linear transport line
- proton 80-200MeV

Table 1: Tracking parameters

Length of the magnets	60 cm
Drift	40 cm
Kinetic energy range	80 to 200 MeV (proton)
Field index	17
Local curvature radius	2.1 m
Step size	1 mm
Phase advances:	
horizontal μ_x	104.8 deg.
vertical μ_z	112.5 deg.



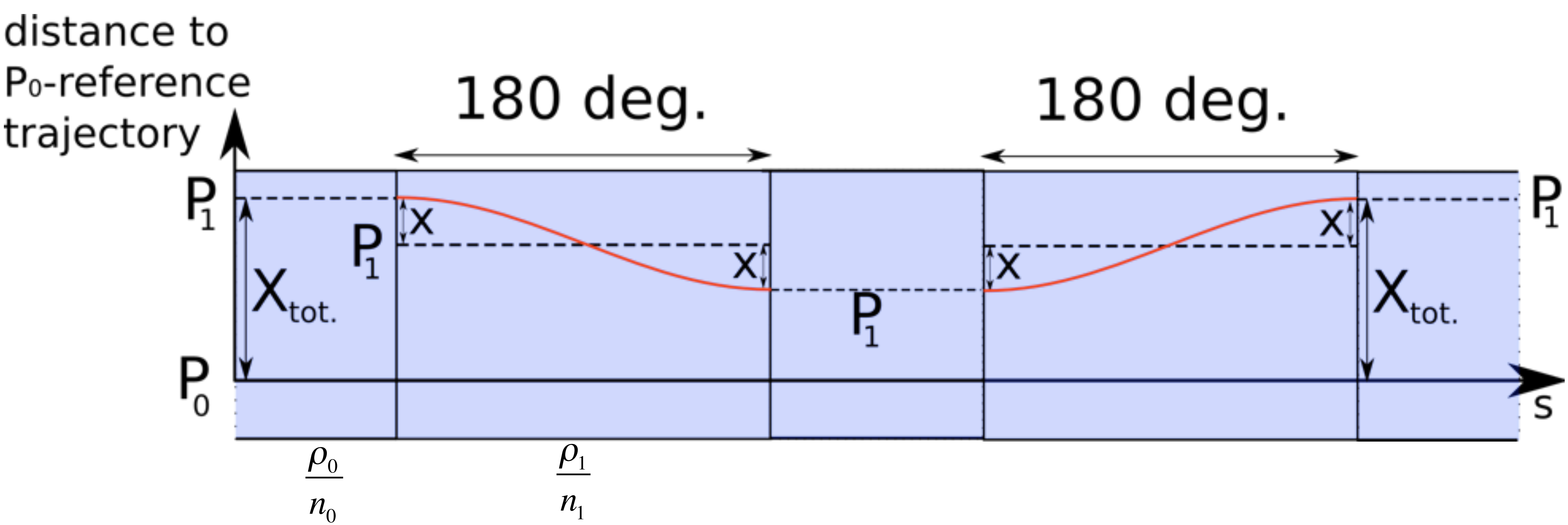
B-field

$$B_z = B_0 \exp\left[\frac{n}{\rho} x\right]$$

Dispersion suppressor

- Dispersion suppressor (Planche,Lagrange,Mori)
  - successive π-cells in the horizontal plane can suppress the dispersion.

$$X_{tot} = X_1 - X_0 = \frac{1}{n/\rho} \ln\left(\frac{P_1}{P_0}\right) \qquad x = \ln\left(\frac{P_1}{P_0}\right)\left(\frac{\rho_0}{n_0} - \frac{\rho_1}{n_1}\right)$$



Insertion Matching

btw. ring & straight line

B(closed orbit) matching condition

$$\left(1+\frac{x}{r_m}\right)^{k+1} = \exp\left(\frac{n}{\rho}x\right)$$

ring linear line

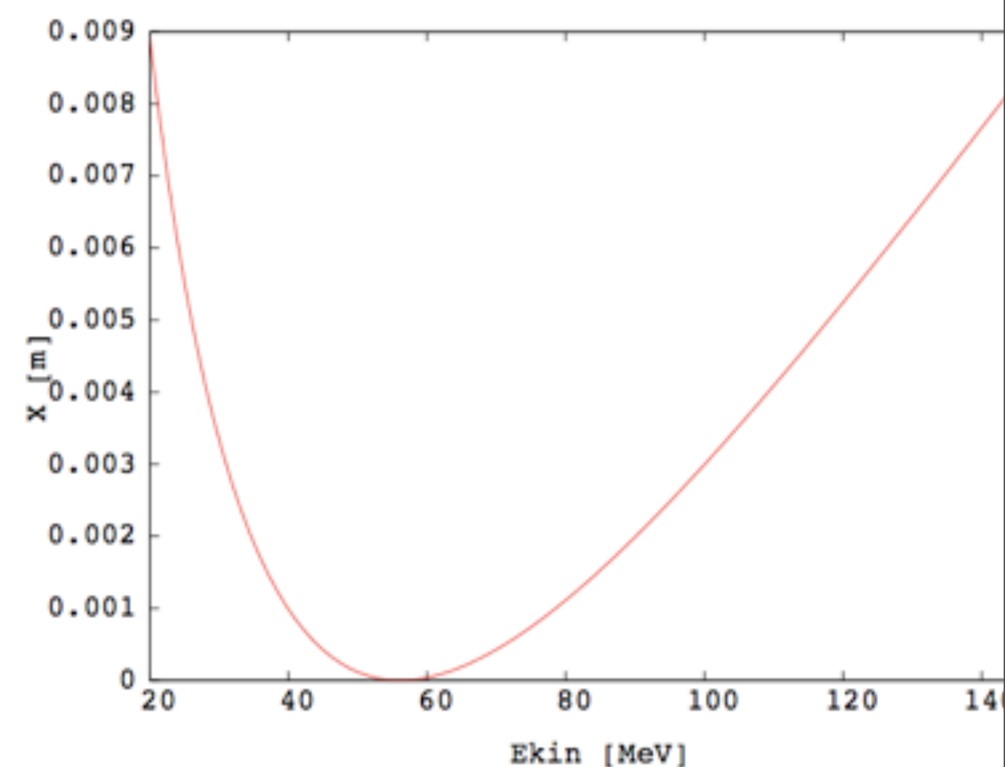
$$\boxed{\frac{k+1}{r_m} = \frac{n}{\rho}}$$

← 1st order

CO mismatch

higher order error:

→ smaller for larger ring

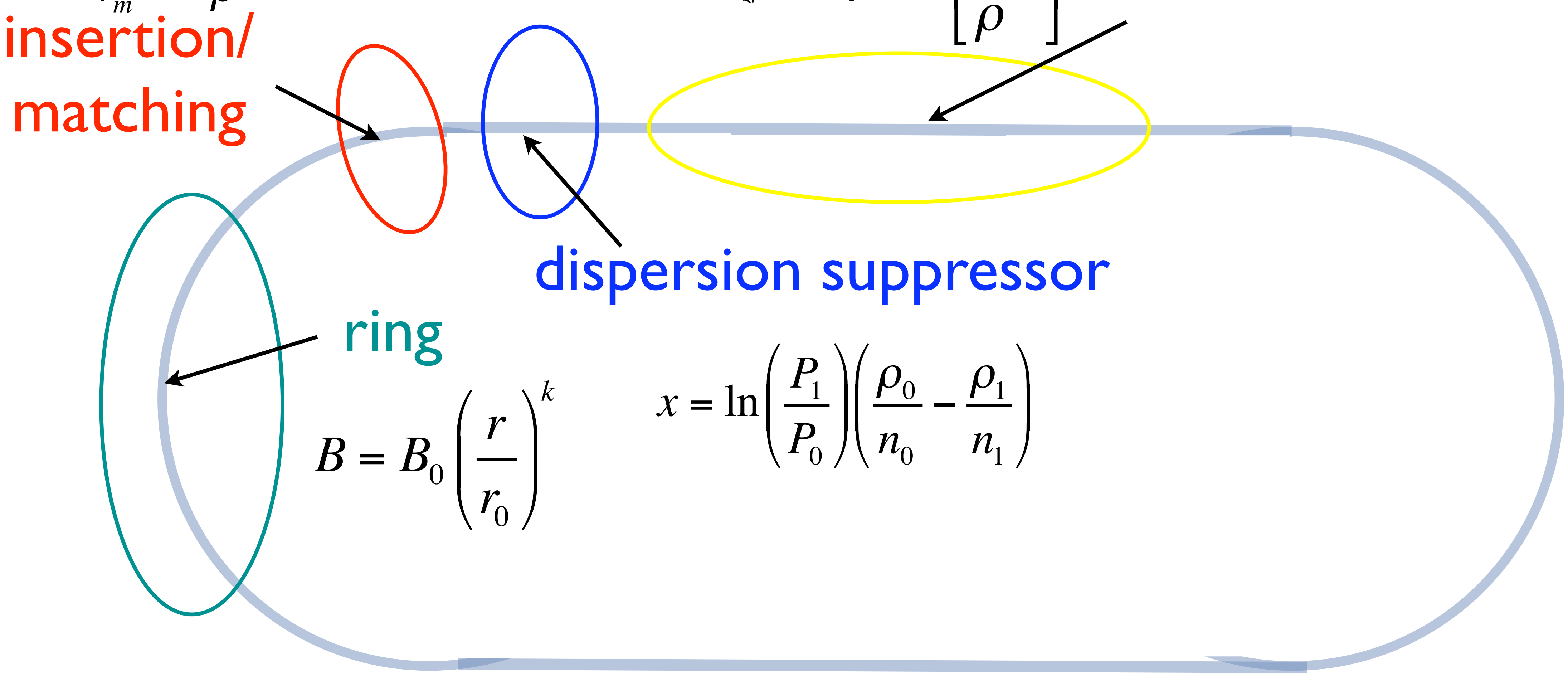


Example: 150MeV p-FFAG ring(KURRI) with insertion

Advanced scaling FFAG

$$\frac{k+1}{r_m} = \frac{n}{\rho}$$

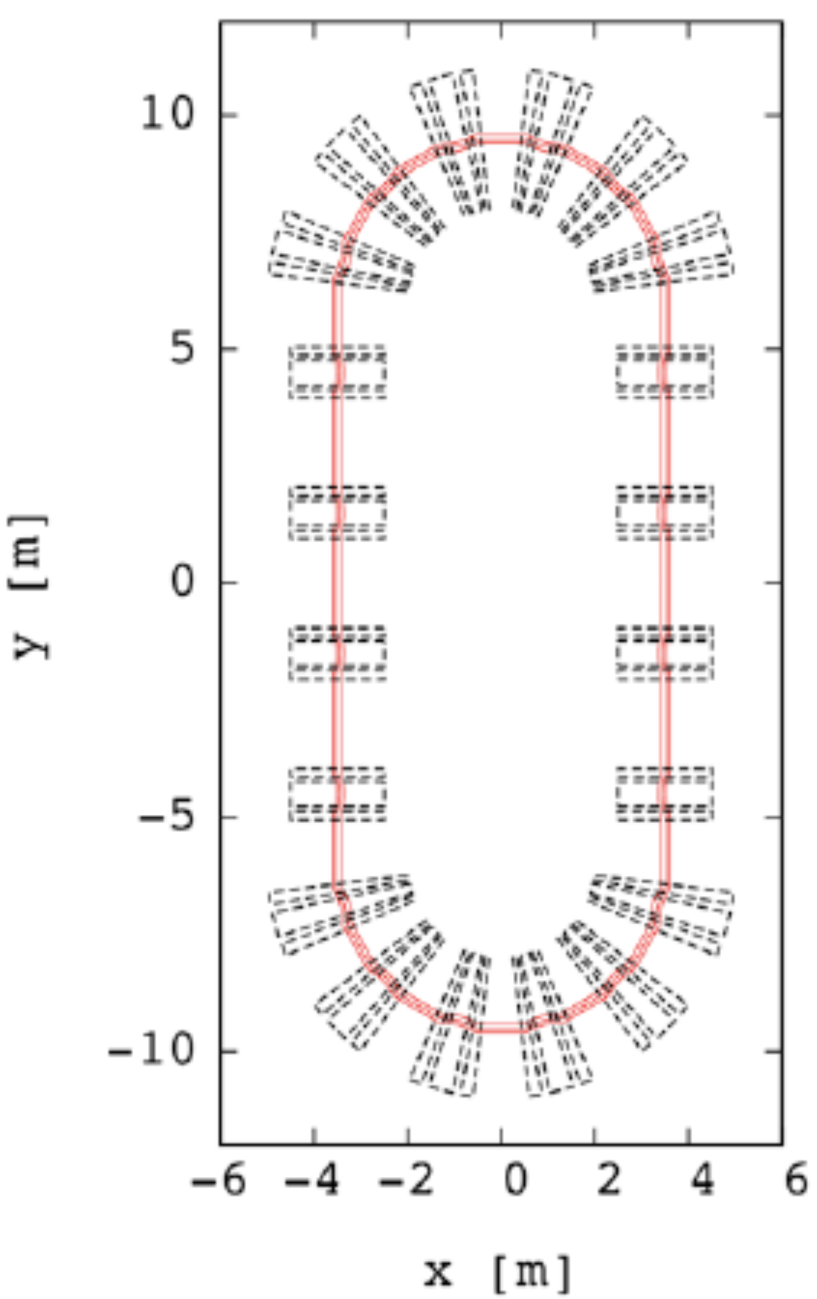
$$B_z = B_0 \exp\left[\frac{n}{\rho} x\right]$$



$$B = B_0 \left(\frac{r}{r_0}\right)^k$$

$$x = \ln\left(\frac{P_1}{P_0}\right)\left(\frac{\rho_0}{n_0} - \frac{\rho_1}{n_1}\right)$$

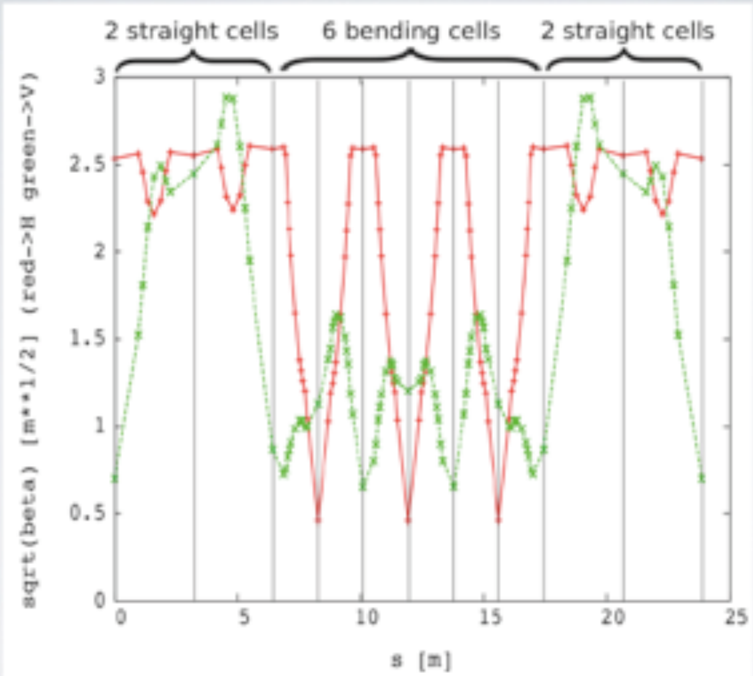
Muon phase rotation PRISM ring



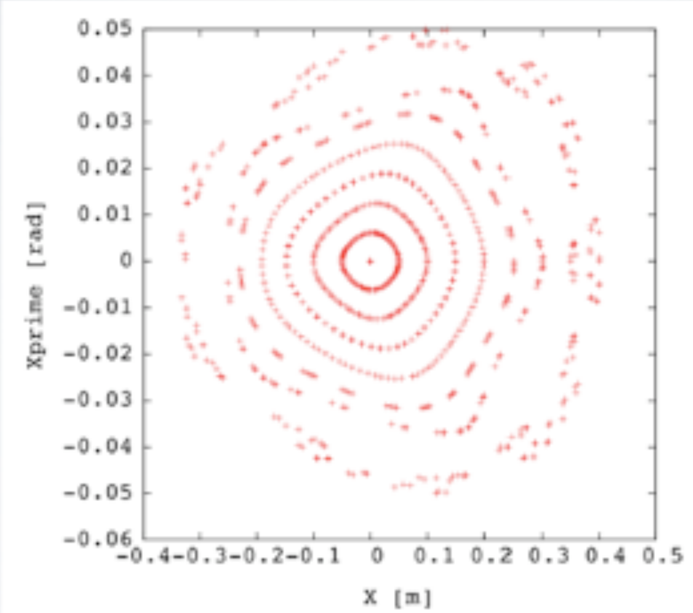
PRISM LATTICE

Bending cell	
k	6.5
Average radius	3.5 m
Phase advances:	
horizontal μ_x	90 deg.
vertical μ_z	90 deg.
Dispersion	0.47 m

Straight cell	
n/ρ	$2.14\,m^{-1}$
Length	$3\,m$
Phase advances:	
horizontal μ_x	24 deg.
vertical μ_z	87 deg.



Betafunctions of bending and straight cells (half ring)
(red: horizontal, green: vertical)



by Lagrange, Mori

Muon accelerator neutrino factory

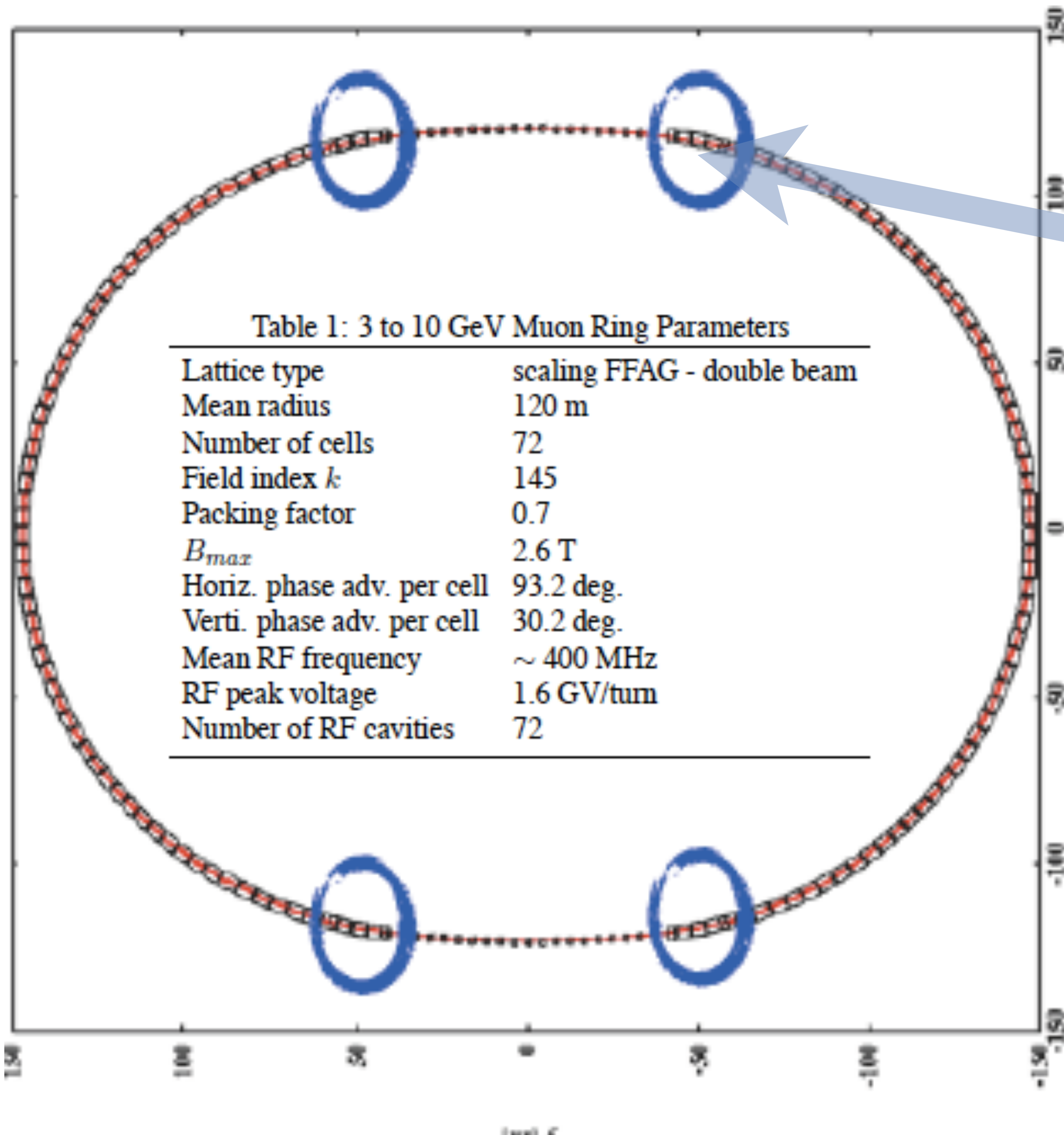
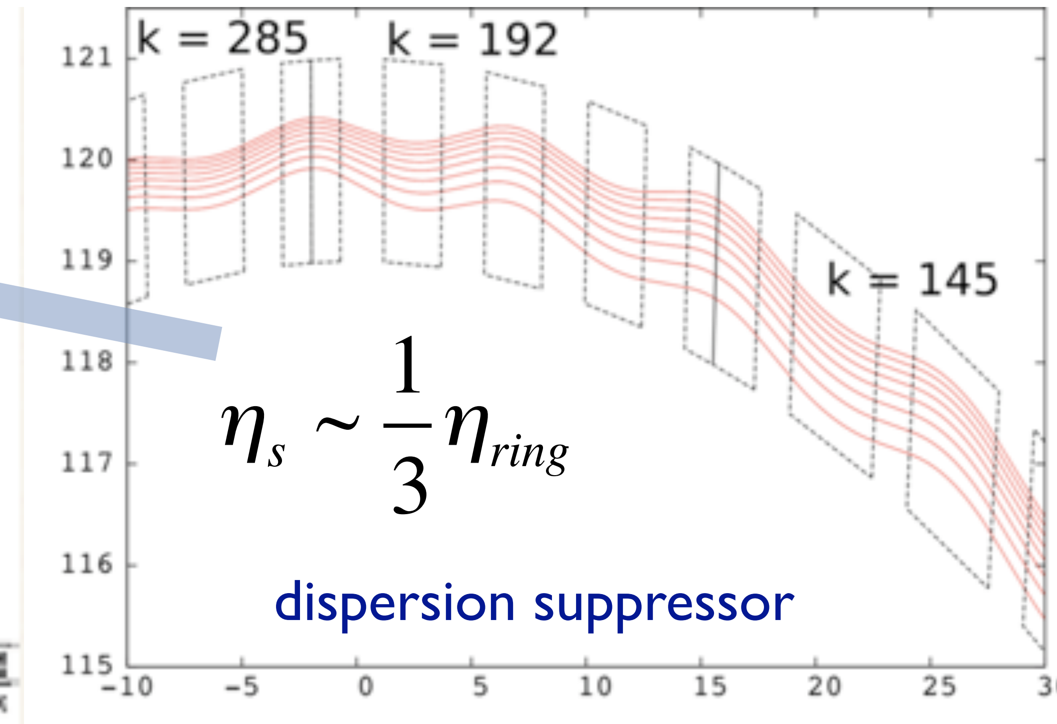


Table 1: 3 to 10 GeV Muon Ring Parameters

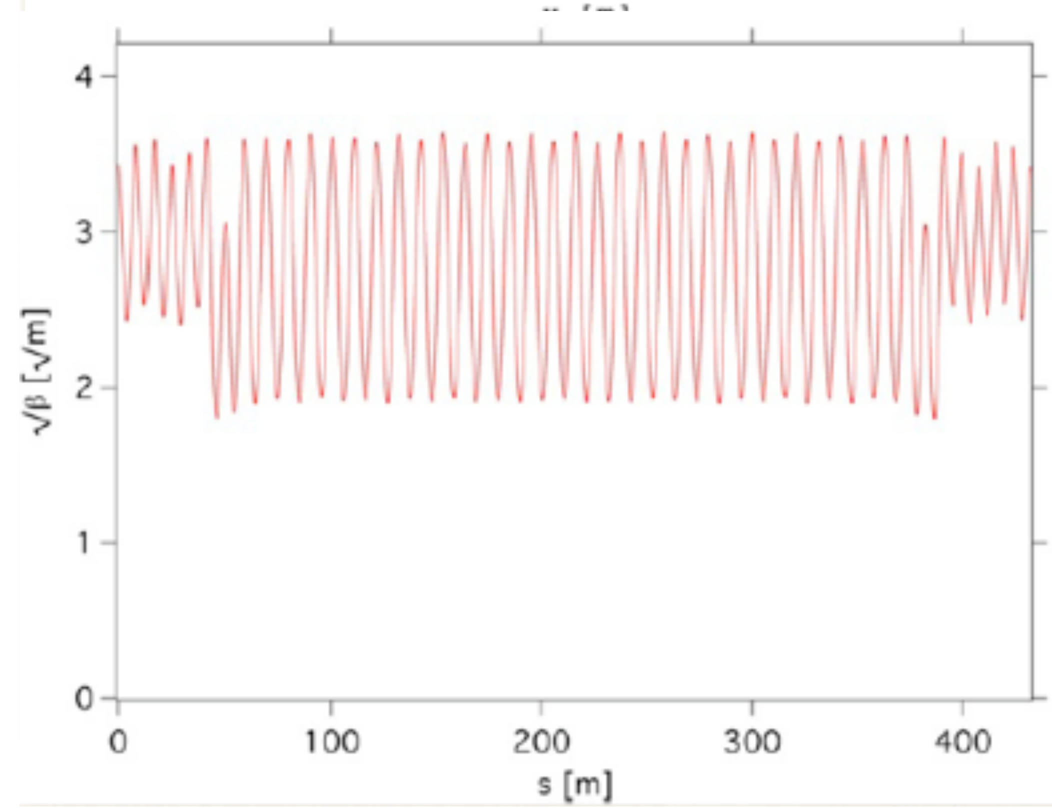
Lattice type	scaling FFAG - double beam
Mean radius	120 m
Number of cells	72
Field index k	145
Packing factor	0.7
B_{max}	2.6 T
Horiz. phase adv. per cell	93.2 deg.
Verti. phase adv. per cell	30.2 deg.
Mean RF frequency	$\sim$ 400 MHz
RF peak voltage	1.6 GV/turn
Number of RF cavities	72

Planch, Mori



$$\eta_s \sim \frac{1}{3}\eta_{ring}$$

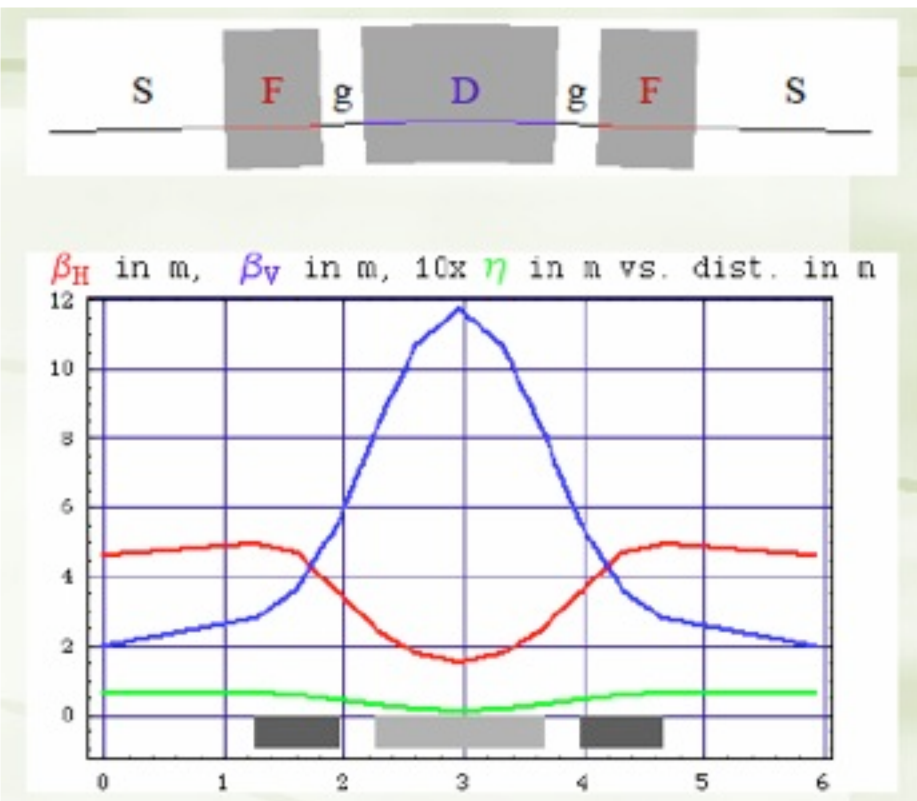
dispersion suppressor



Proton driver for ADS

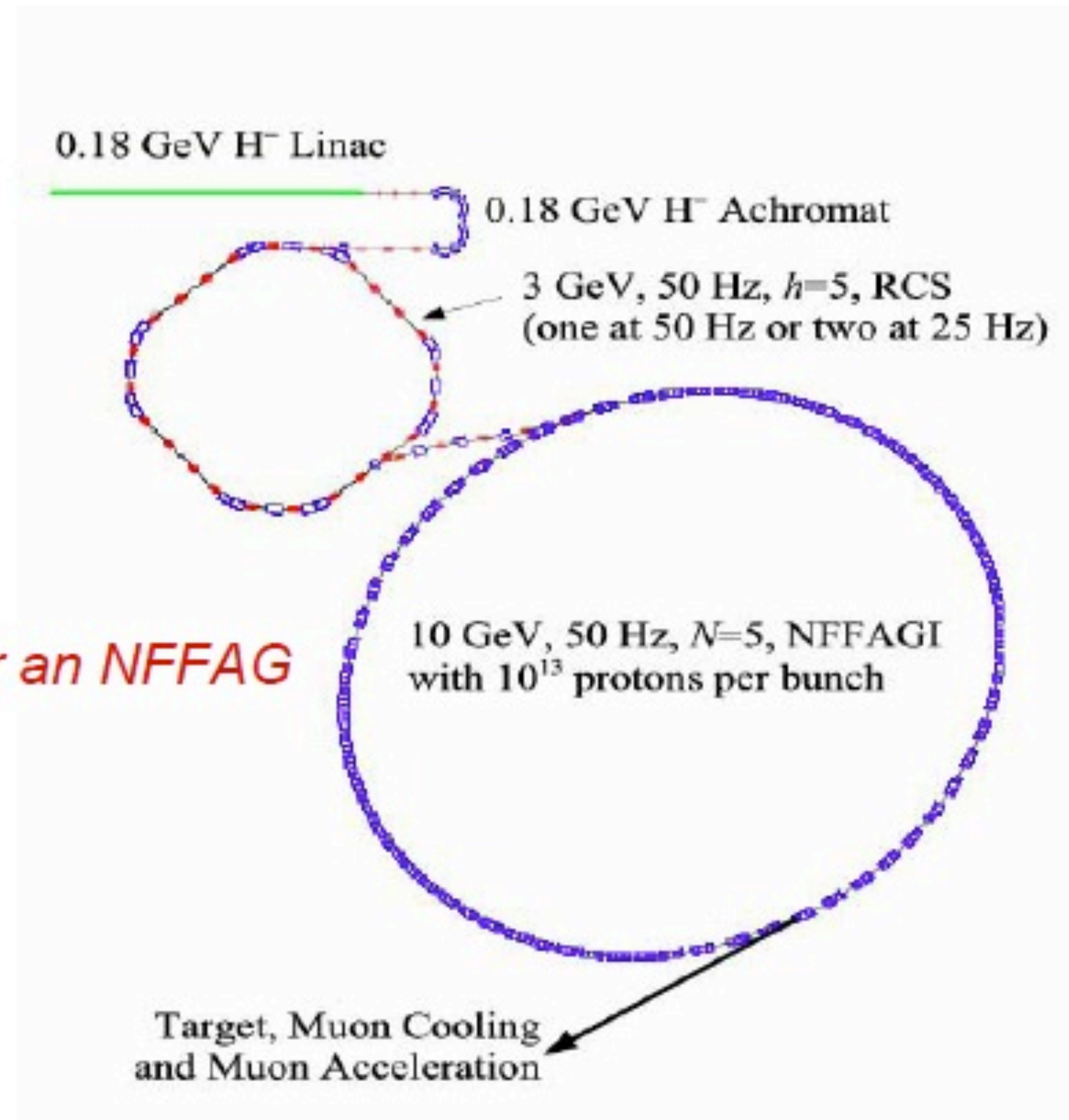
- Design works
  - Non-zero chromatic (linear) FFAG: A.G.Ruggiero (BNL)
  - Zero chromatic (isochronous) FFAG: C. Johnstone(FNAL)
  - Zero chromatic (non-linear) FFAG: Y. Mori(KURRI)
    - 1-2GeV, 10MW (single ring)
- Development for basic ADS study
  - Scaling FFAGs at Kyoto University(KURRI)
  - 150MeV
  - Combined experiment with KUCA(sub-critical reactor)

- Non-scaling FFAG by A.G.Ruggiero (BNL)
- Semi-scaling(achromatic) FFAG by G.Rees(Rutherford Lab.)

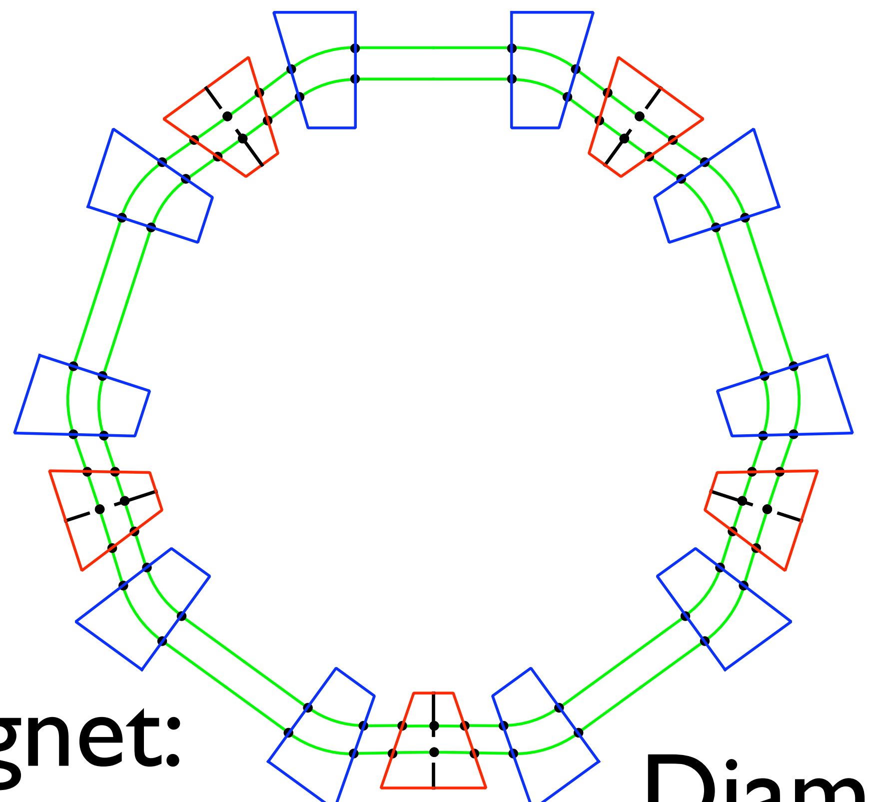


E=11.6GeV

Now favour an NFFAG

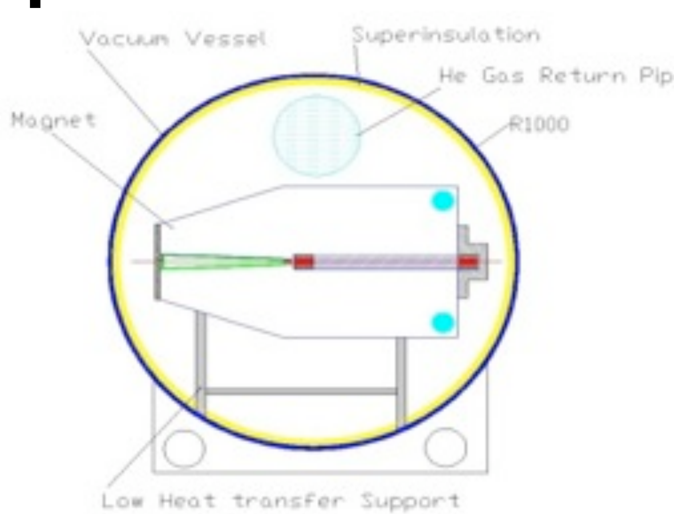


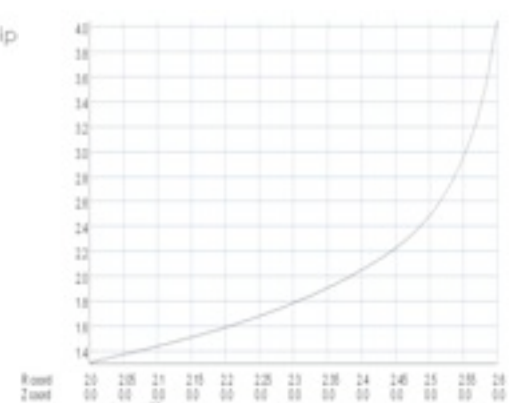
Zero-chromatic(isochronous)FFAG for ADSR C.Johnstone(FNAL)

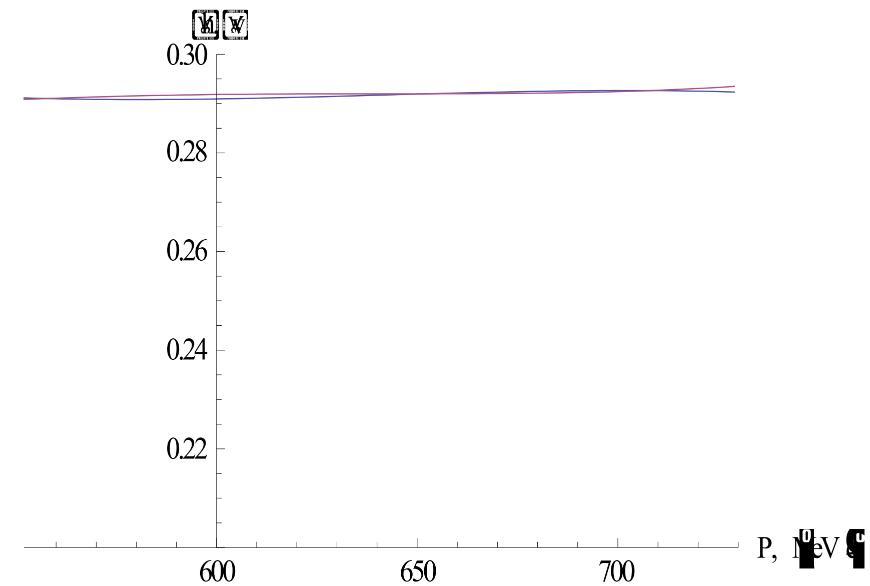


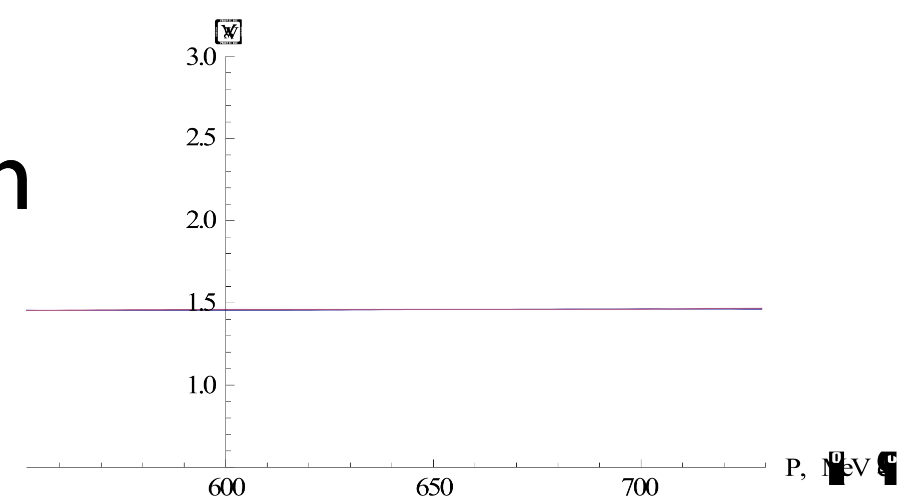
SC magnet: 4T

Diameter ~10m





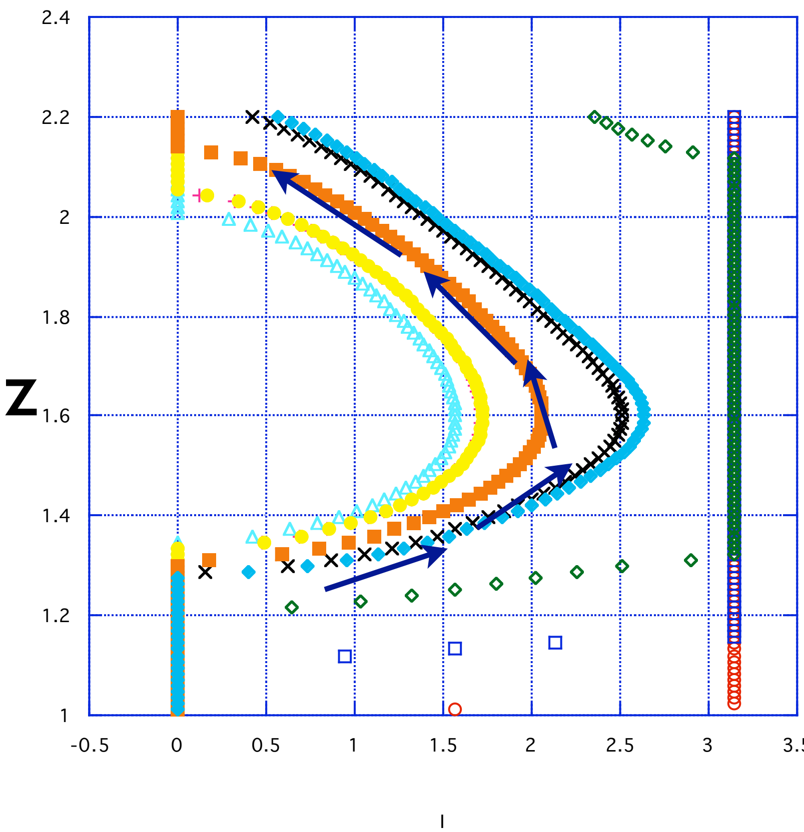


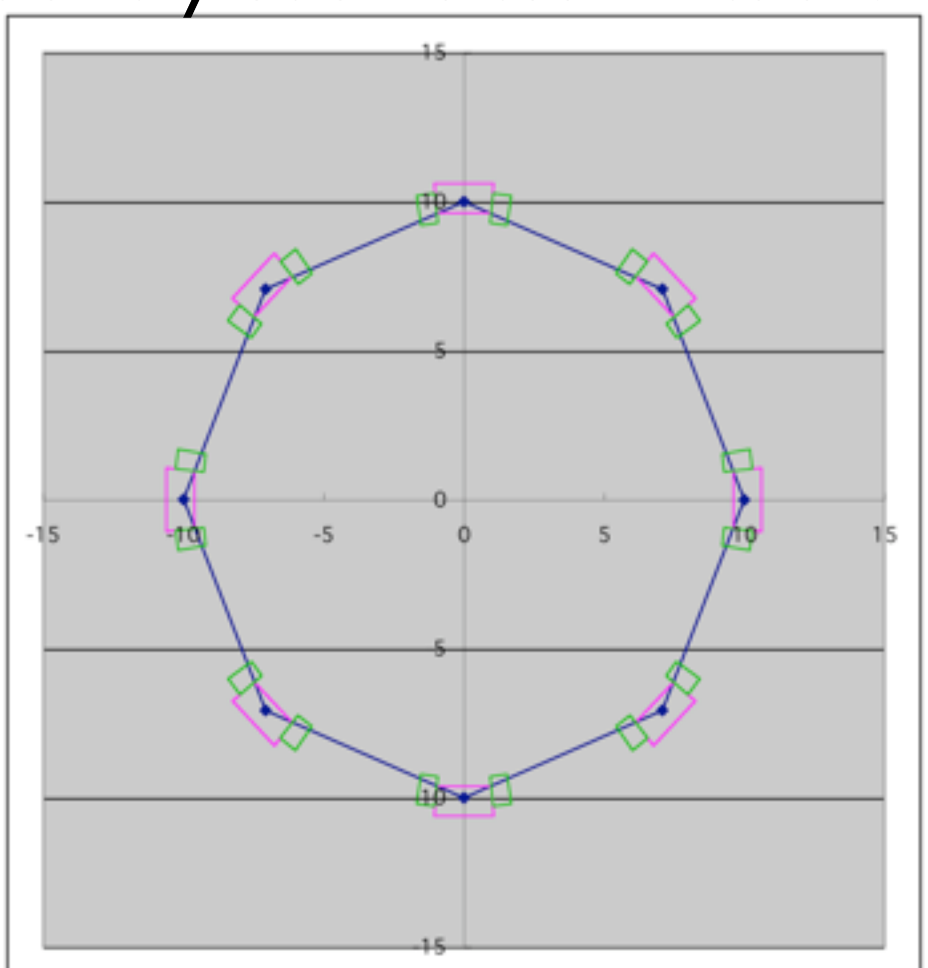


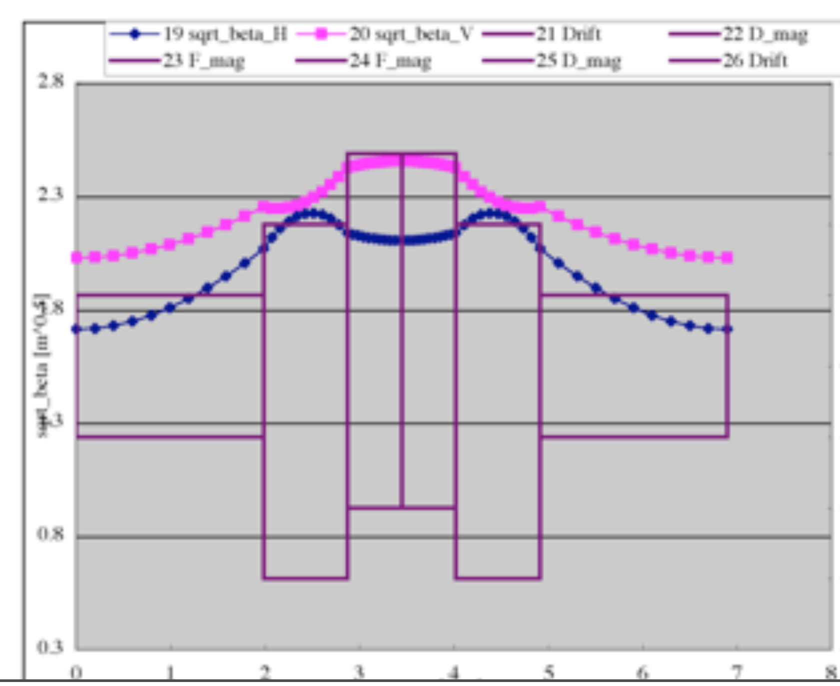
Tune per cell with up to duo-decapole (top) and ring tune (bottom)

Zero chromatic(scaling) FFAG for ADSR (1)

- Energy ~1GeV
- k=3.7 (FDF lattice)
- Radius: 10m
- B ~3T : Super ferric (High temperature
- Variable frequency acceleration: f=2.5~5MHz, 1MV, 1kHz
- Stationary bucket acceleration: f=25MHz, 100MV, cw

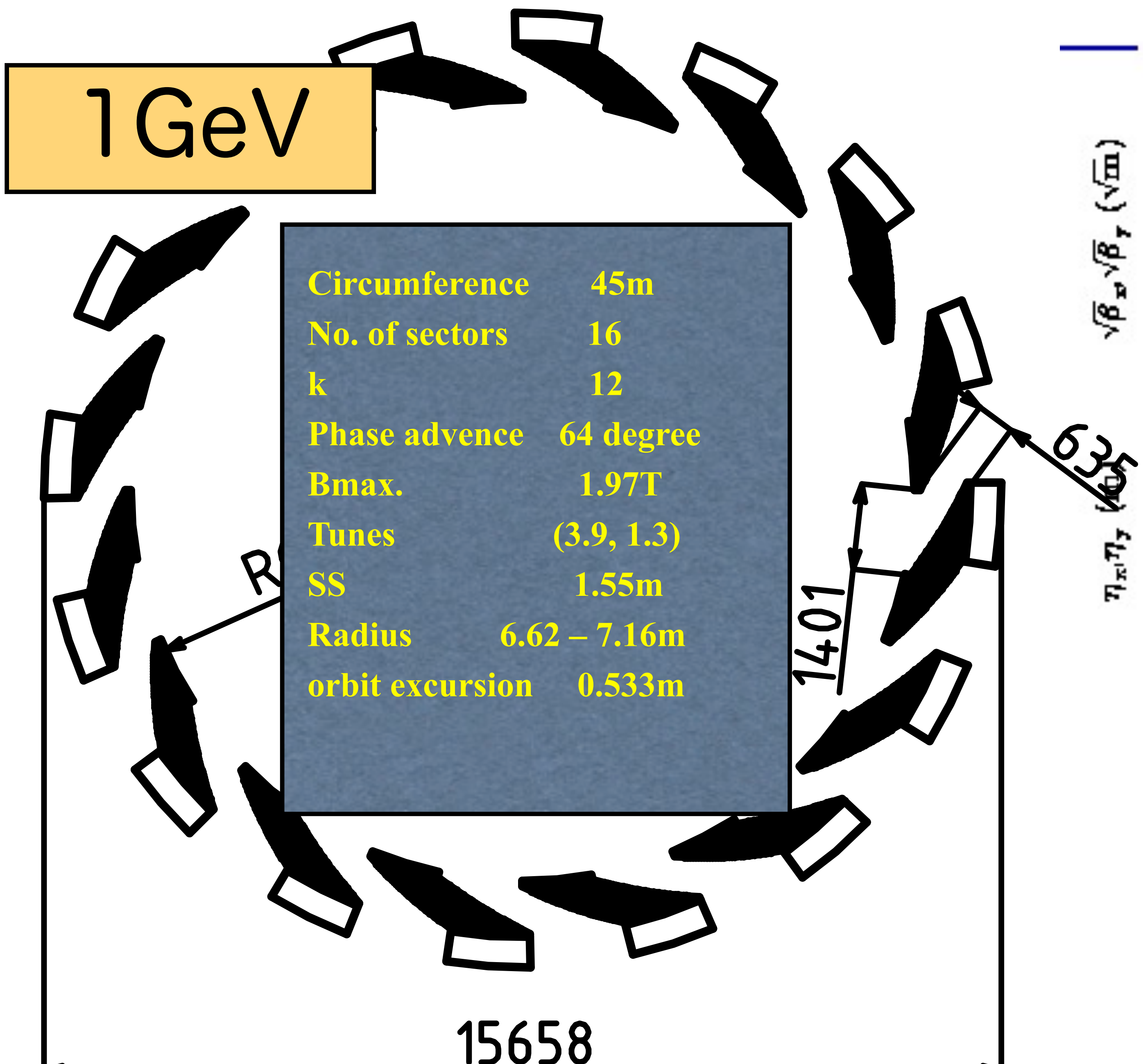




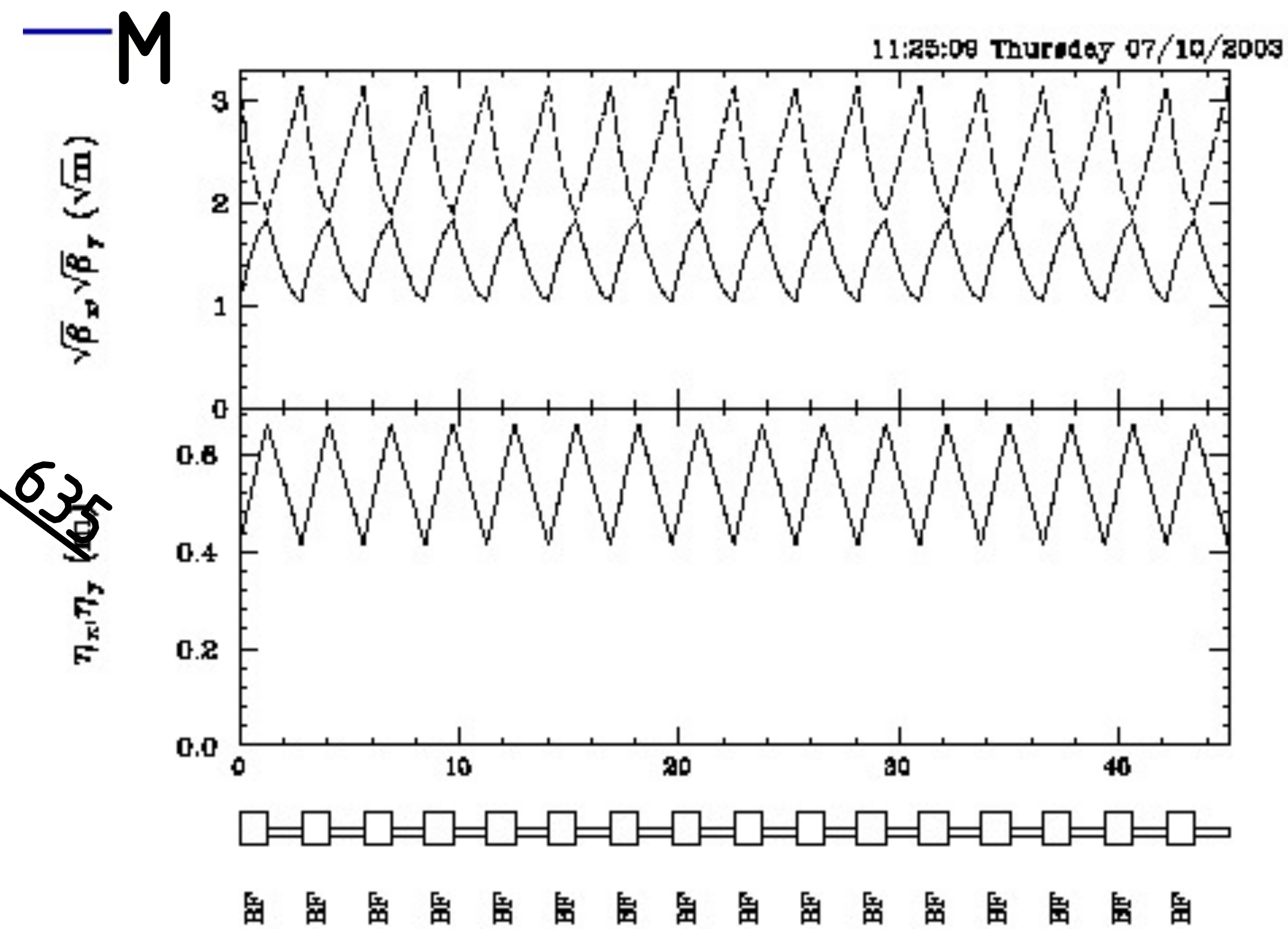


Zero chromatic(scaling) FFAG for ADSR (2)

- Spiral lattice



Circumference	45m
No. of sectors	16
k	12
Phase advence	64 degree
Bmax.	1.97T
Tunes	(3.9, 1.3)
SS	1.55m
Radius	6.62 – 7.16m
orbit excursion	0.533m

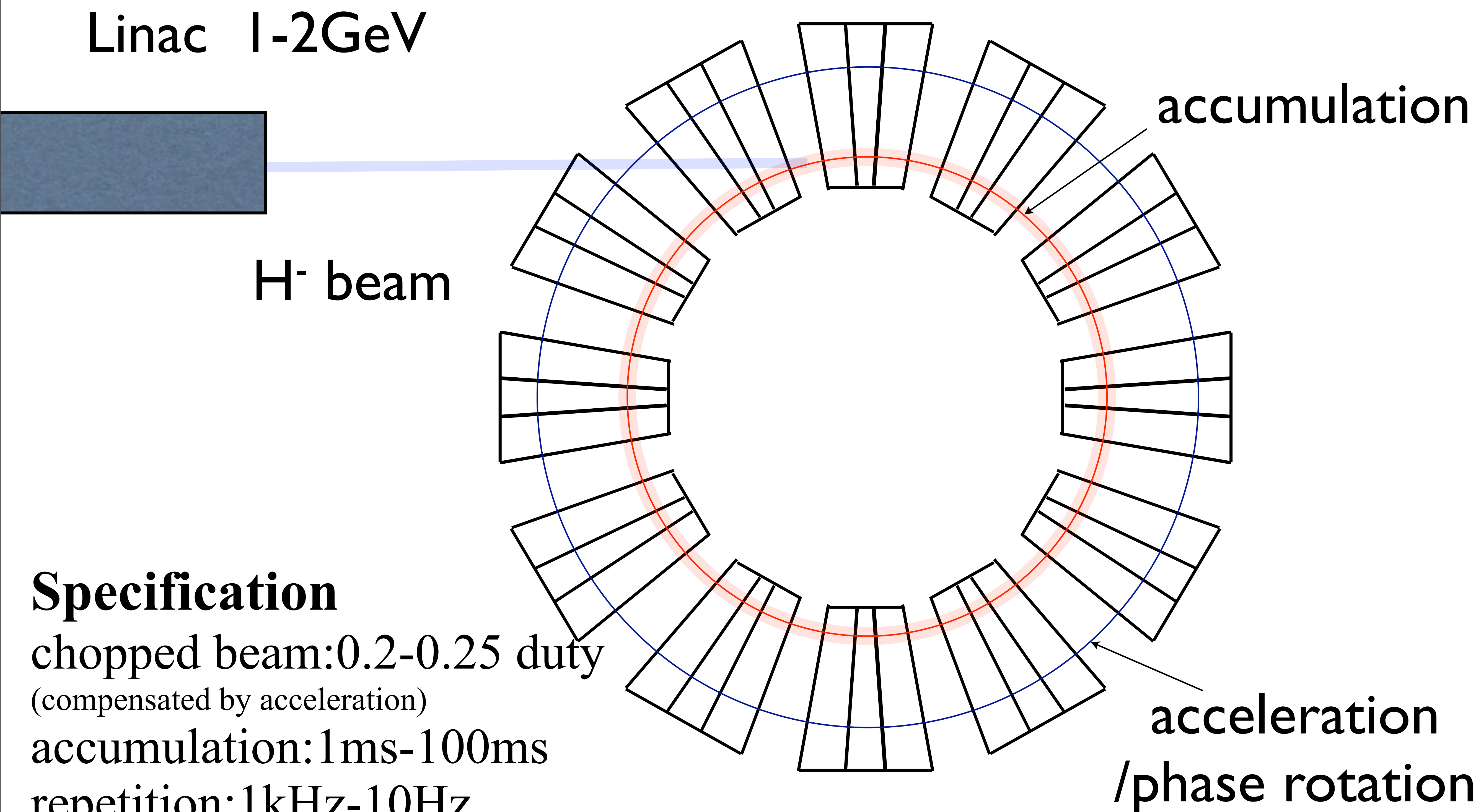


Proton Driver for Muon Production

- Require a short bunched beam.
  - bunch width ~<3nsec
  - repetition rate >100-10kHz
  - Need an accumulator and a buncher if cw linac is used as an injector.

- ***FFAG has a possibility of being worked as accumulator/buncher, and accelerator as well.***

Concept of FFAG-Accumulator/Accelerator



Specification

chopped beam:0.2-0.25 duty
(compensated by acceleration)
accumulation:1ms-100ms
repetition:1kHz-10Hz
acceleration:<100micro.s

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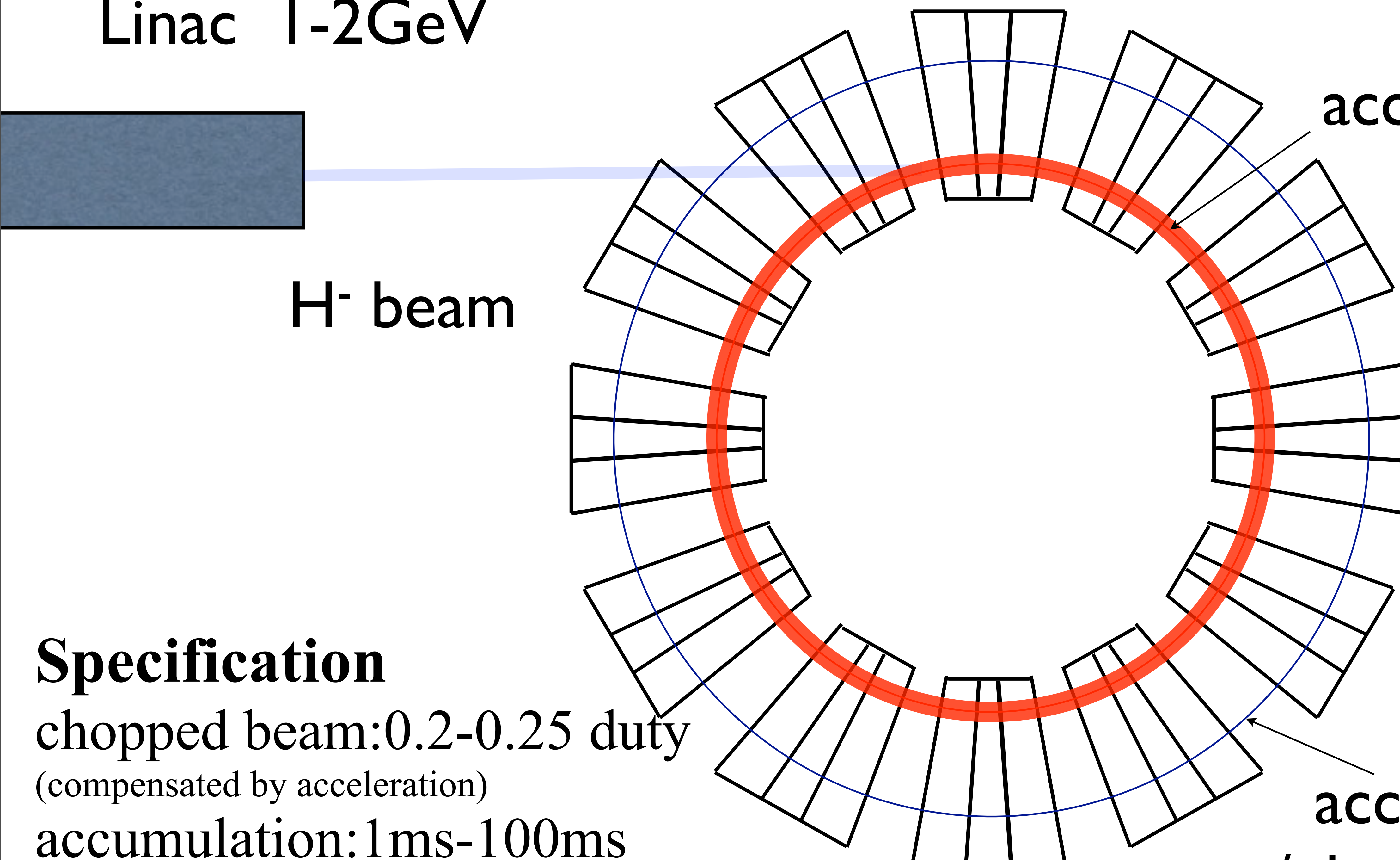

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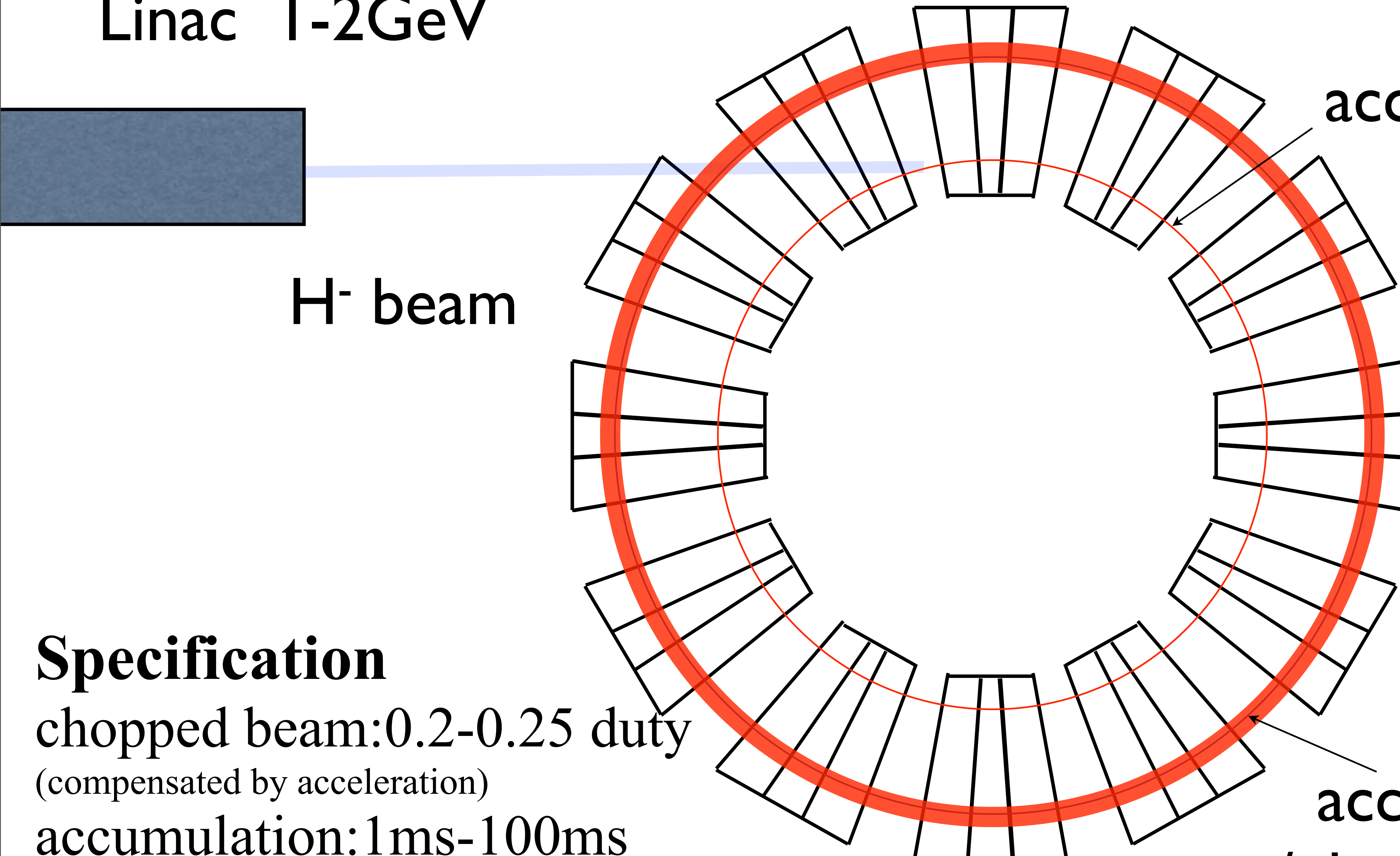

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repetition:1kHz-10Hz
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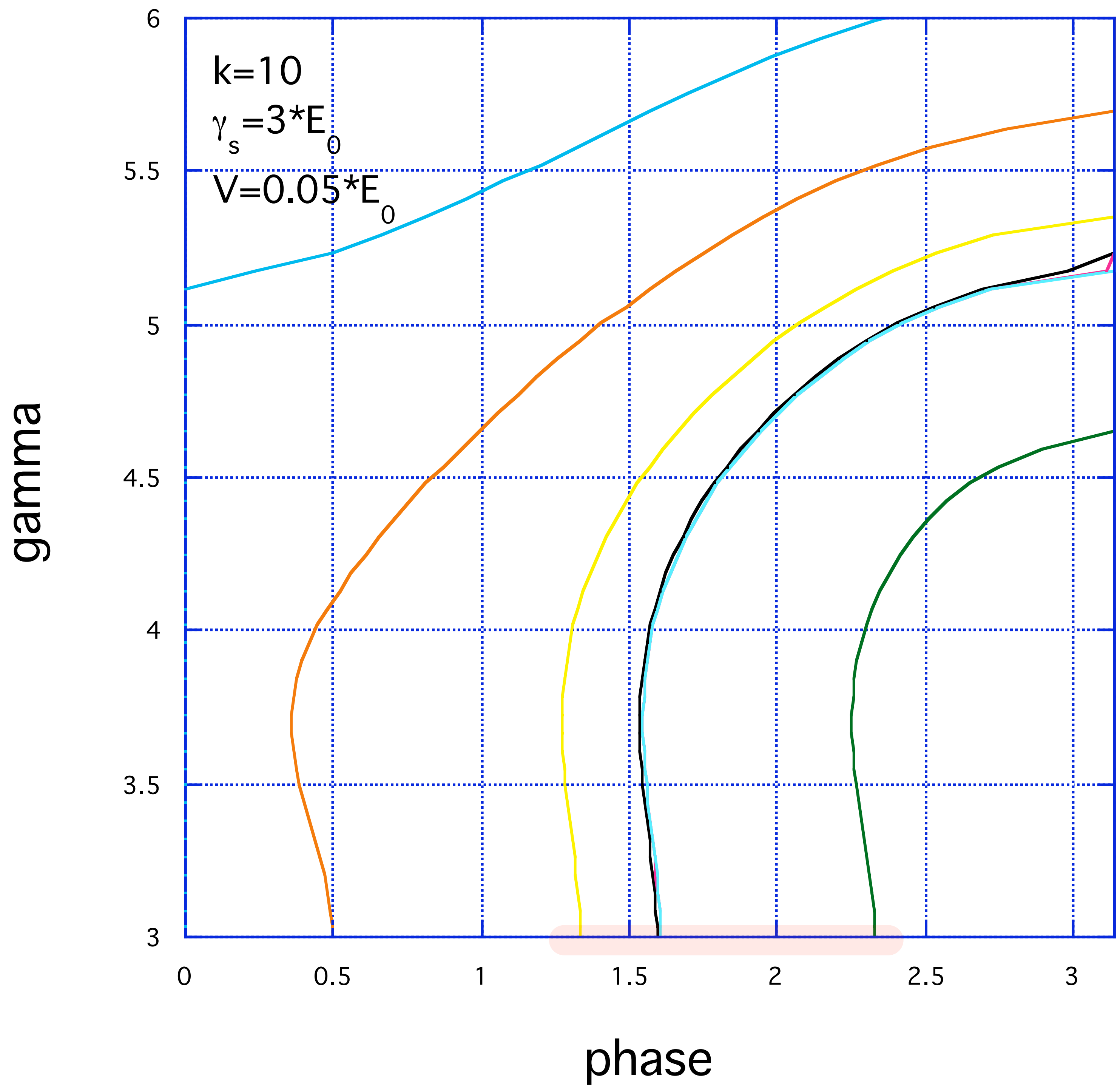
FFAG
accumulator/accelerator

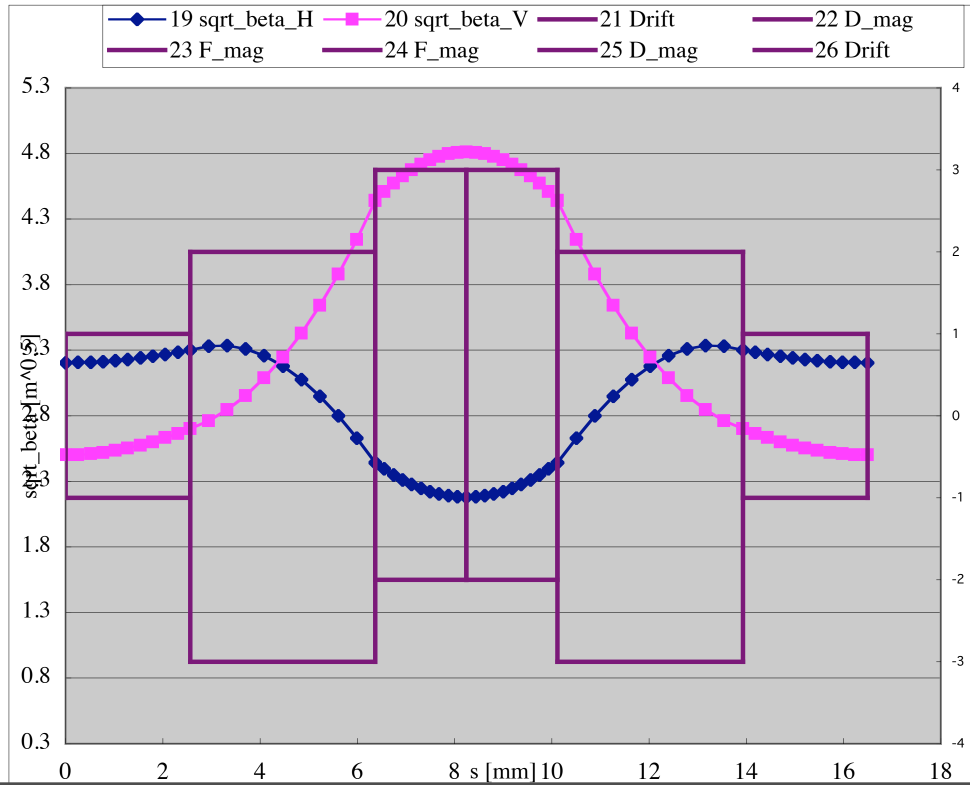
- Single ring works as accumulator and accelerator (buncher/phase-rotator)
  - Fixed field : large repetition rate >1kHz
  - Large momentum acceptance : zero chromaticity
  - Varying phase slip : from accumulation to acceleration(phase-rotation)
- Accumulator
  - Need small slippage factor. $\eta = \frac{1}{\gamma^2} - \frac{1}{k+1} < 0.01$
  - Keeping bunch length constant during charge-exchange multi-turn injection. Bunch length increase < 10% for 10,000turns
- Accelerator(phase-rotation)
  - Need large momentum acceptance. $\frac{\Delta p}{p} \geq 0.1$
  - Require large slippage factor for phase rotation. $\eta \geq 0.1$
  - Accelerate the beam rapidly keeping RF frequency constant.

FFAG longitudinal gymnastics



FFAG-ABA ring

energy range	2 - 4GeV
lattice	FDF-scaling
field index	10
number of cells	12
radius	20m
Bmax	3.4T
F/D ratio	1.98
beam excursion	1.2m
RF voltage	45MV(h=1)



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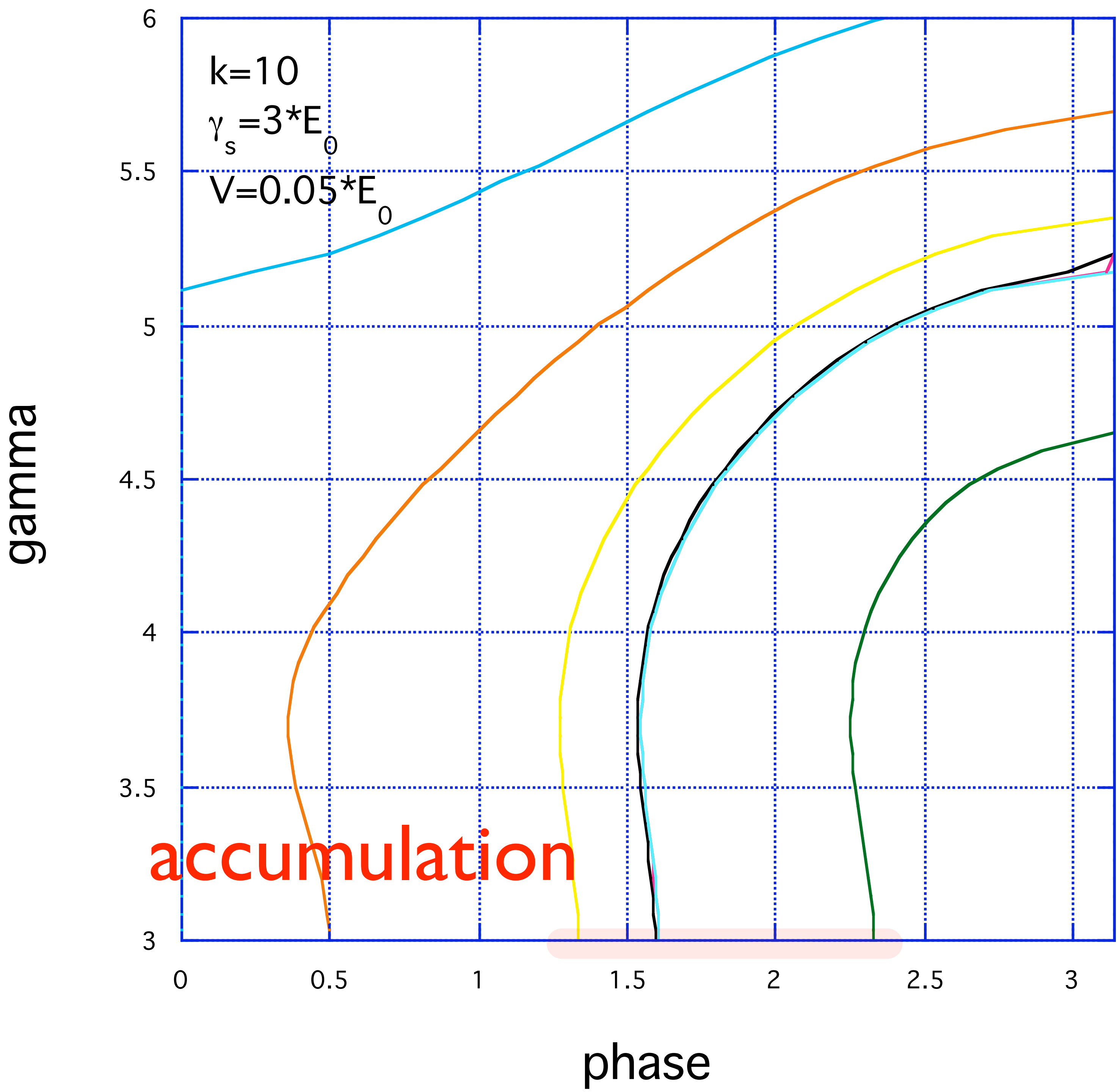

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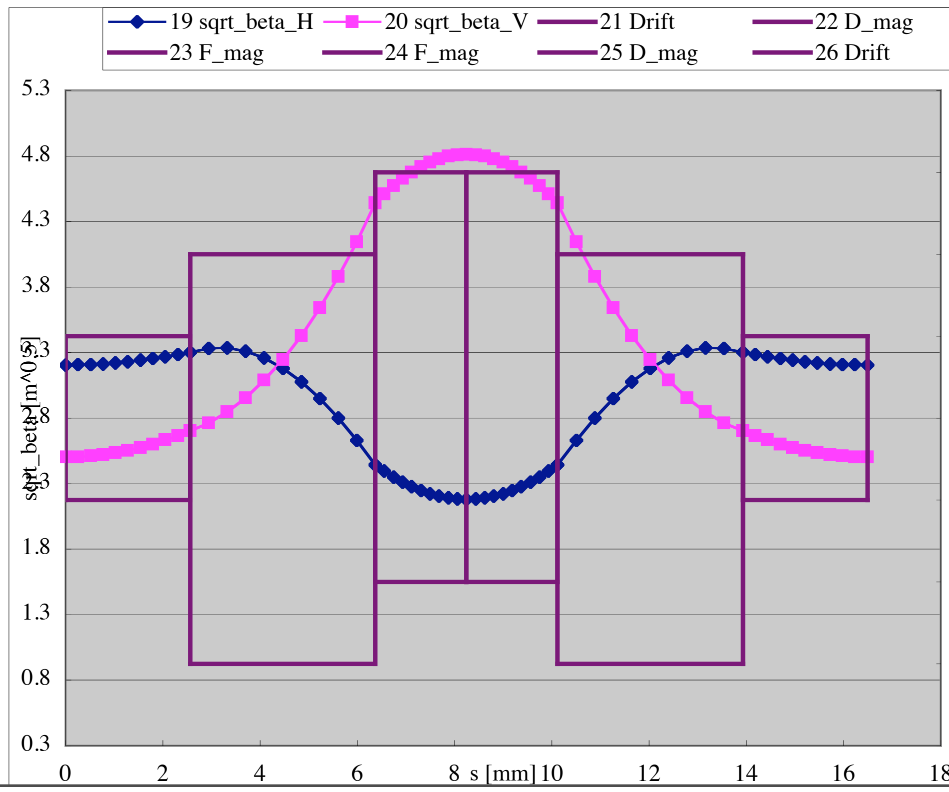

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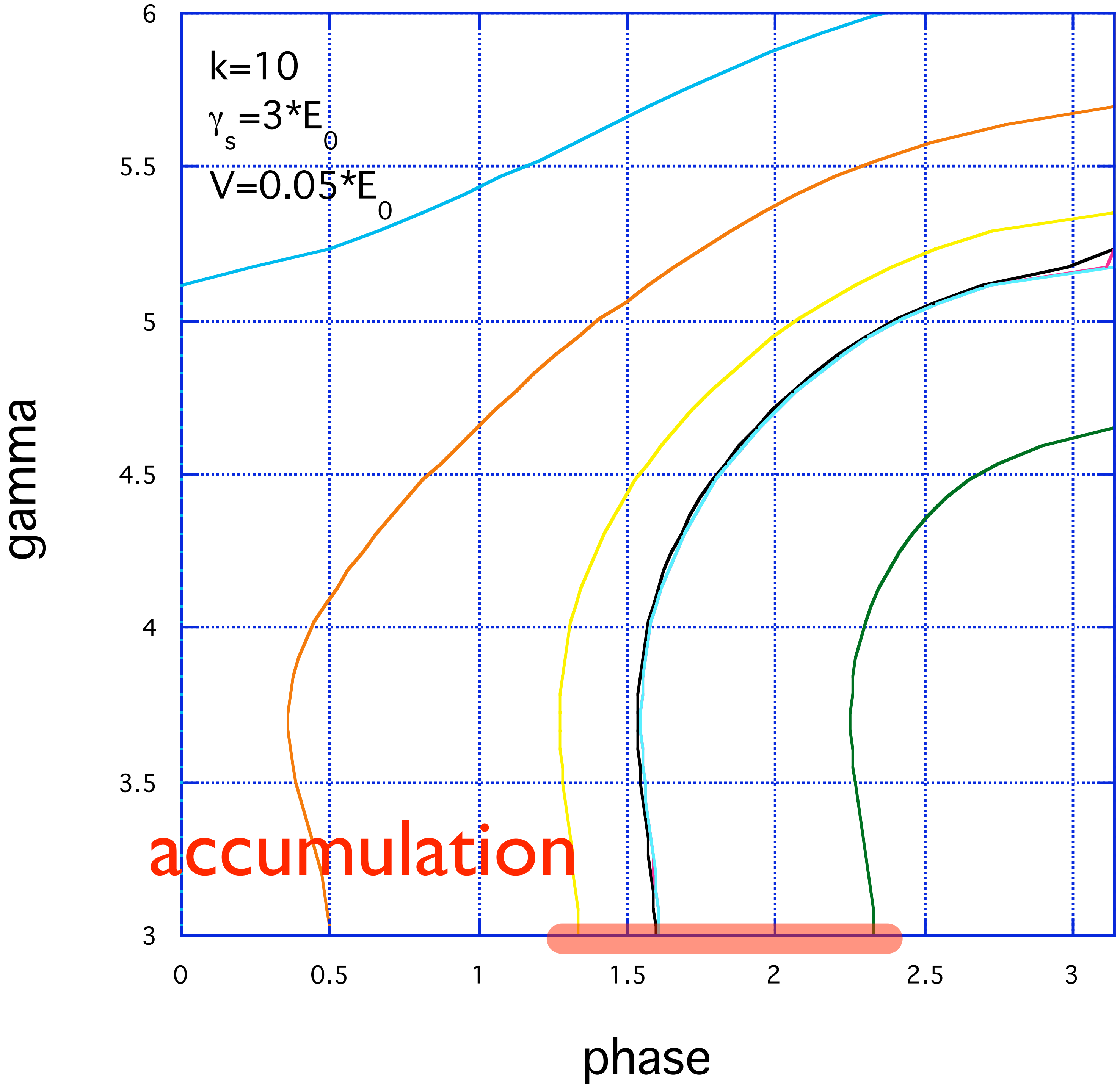

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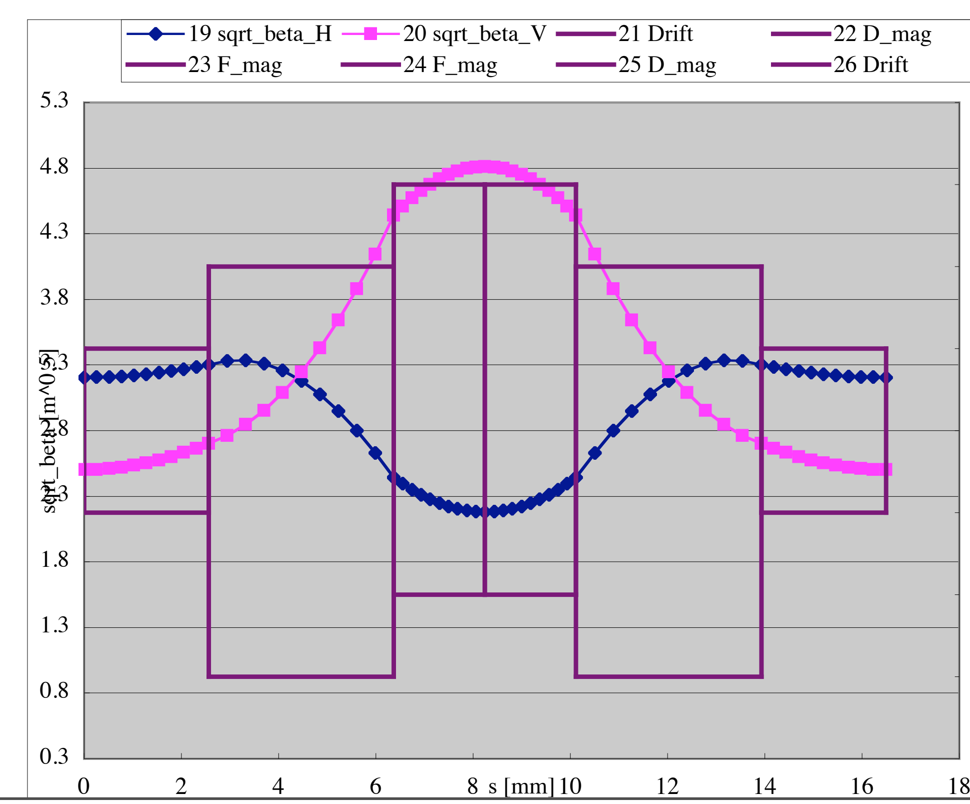

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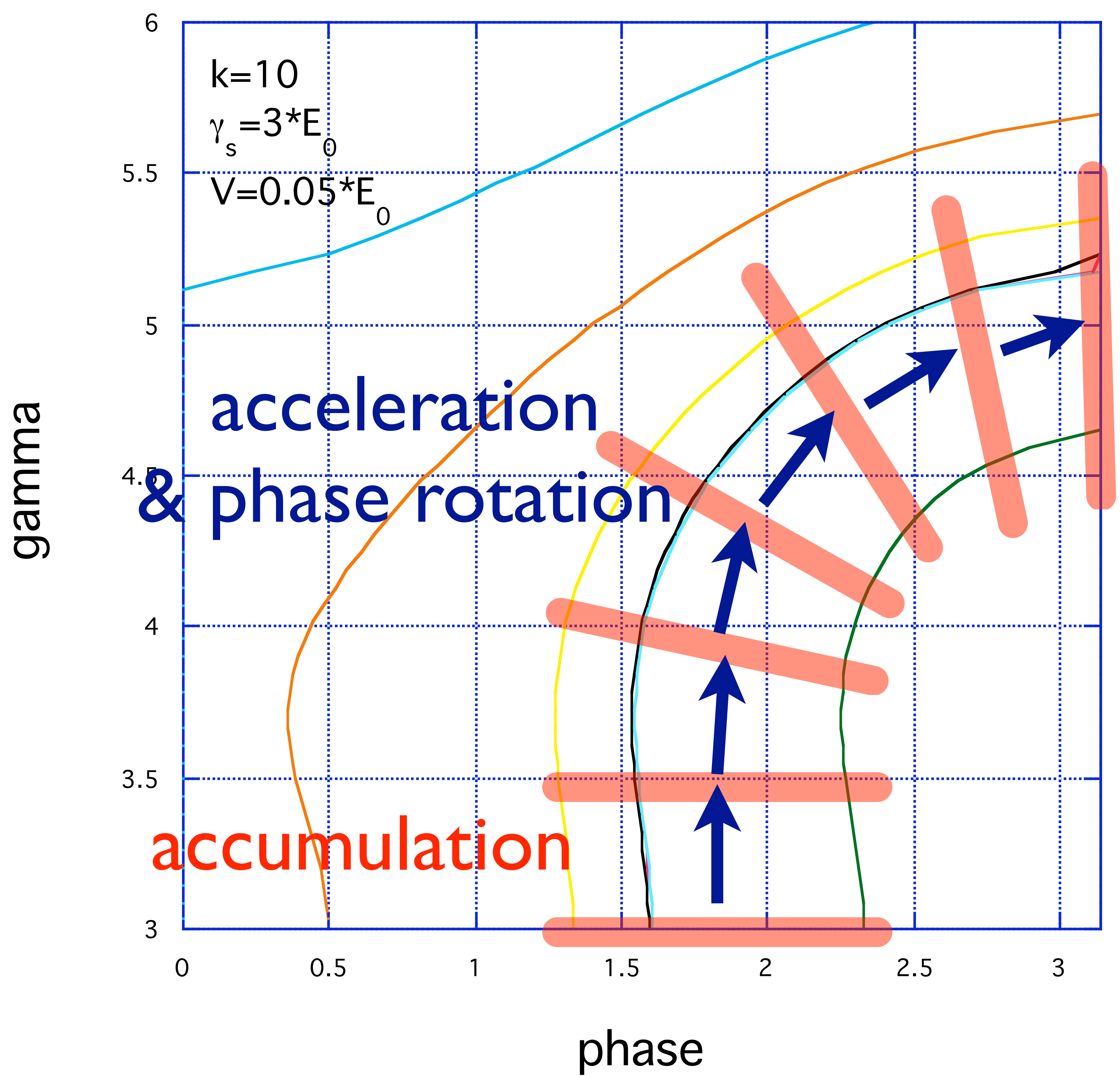

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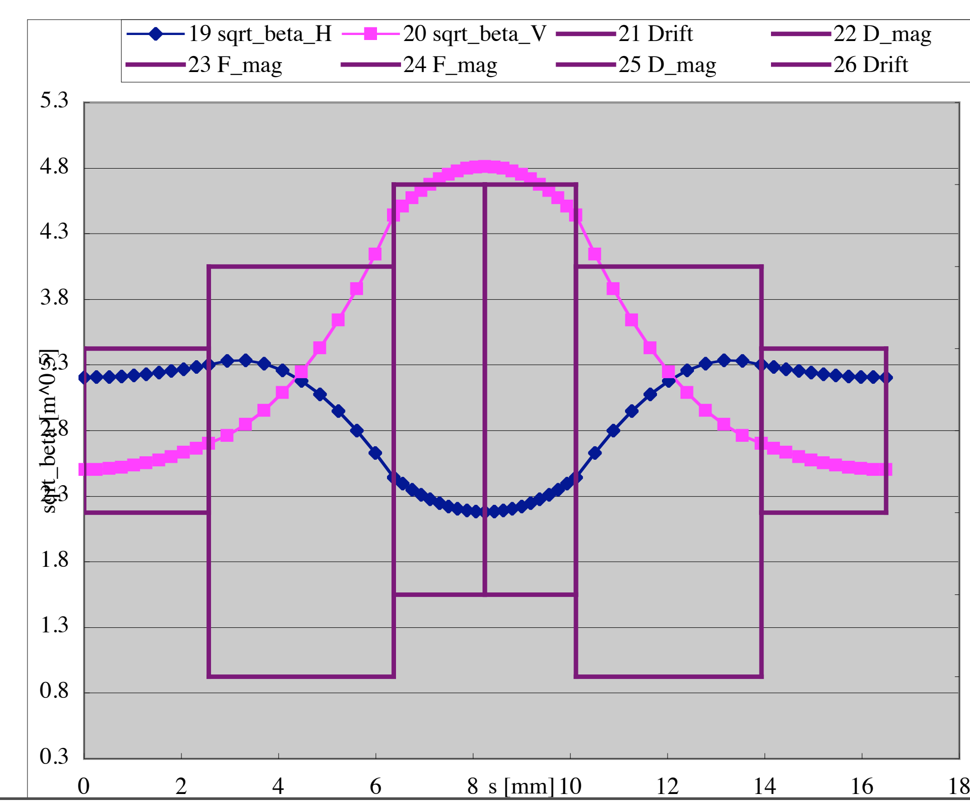

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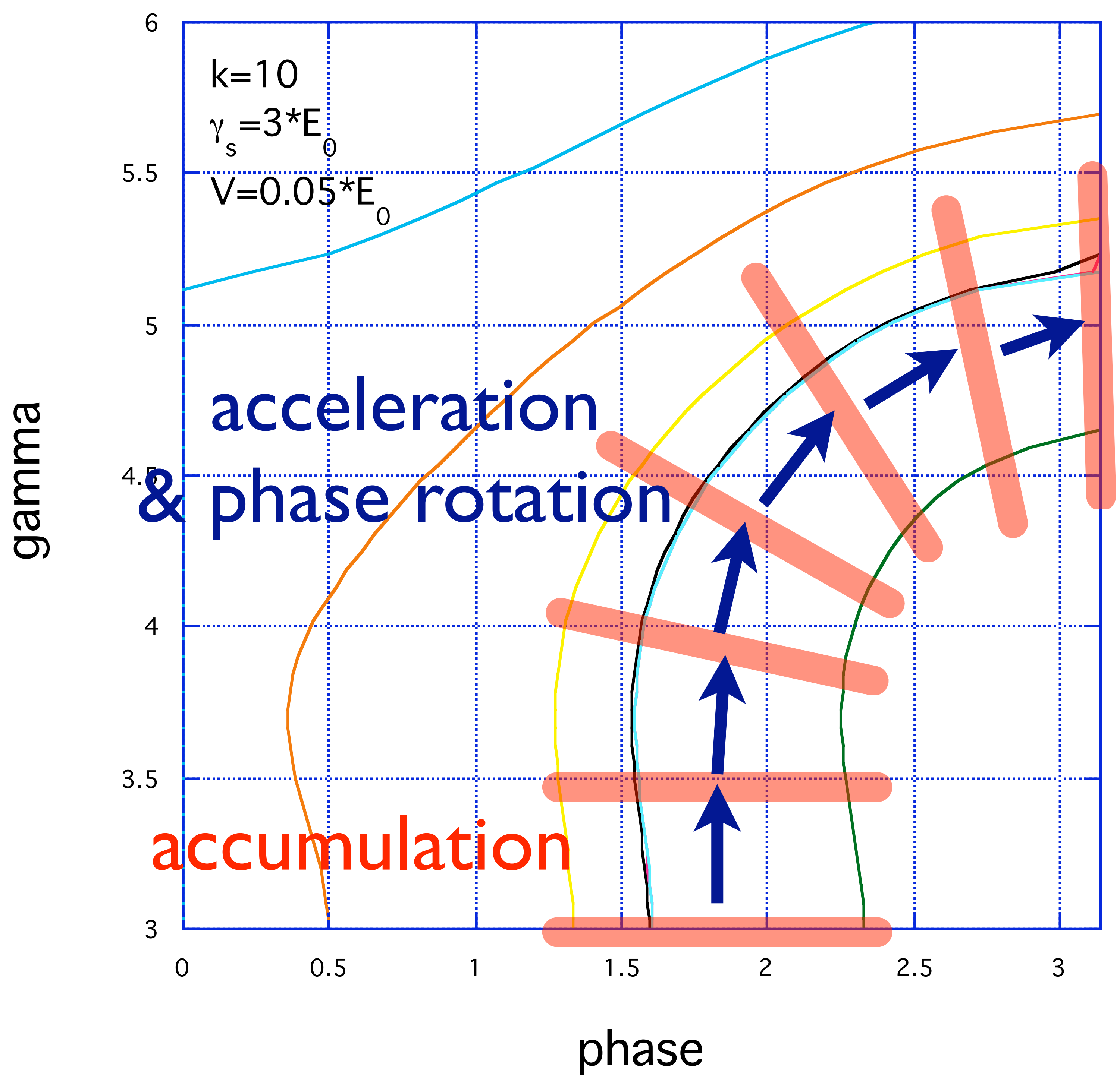

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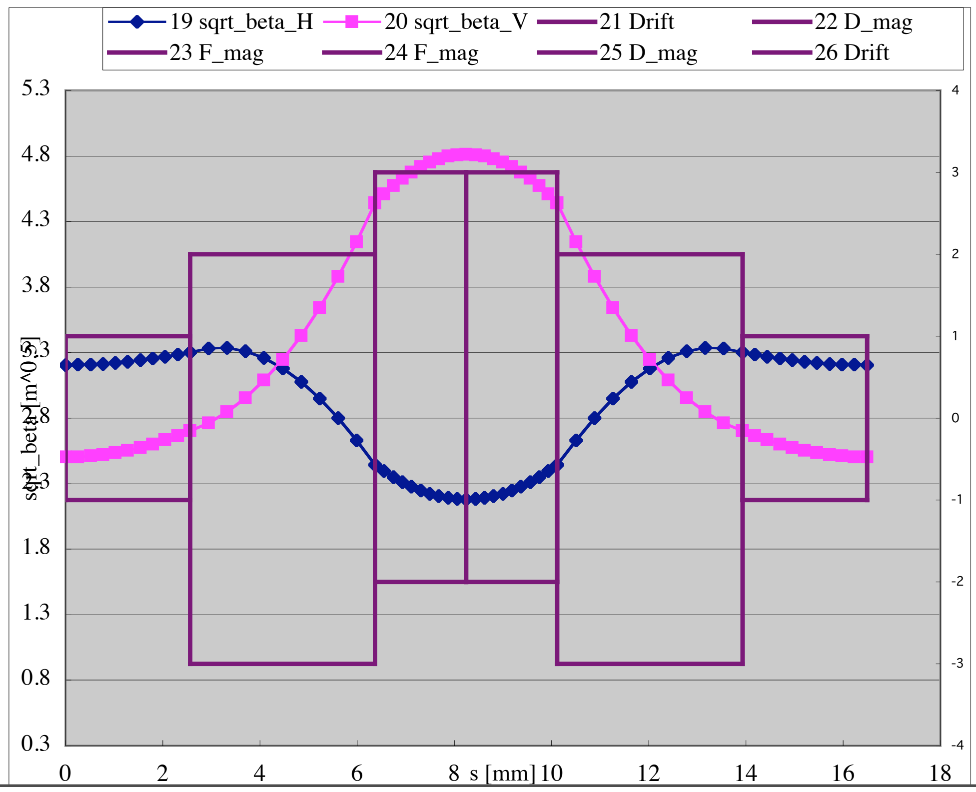


Beam power efficiency

- Beam power efficiency is an issue for high intensity accelerator.

$$BPE = \frac{\text{beam power } \left(\mathrm{E} \times \mathrm{I}_{\text{beam}}\right)}{\text{total operatonal power}}$$

- BPE should be, >25% for P_b~10MW if Keff=0.95.
- Superconducting magnet
  - High temperature SC is very attractive.

Summary

- FFAG for Proton Drivers for ADSR & Muons
  - Features : Beam Opics, Dynamics and Beam Acceleration
  - Designs : ~GeV, 10mA , P>10MW
  - Accumulator/Accelerator option for Linac injector
- ADSR works in Asia
  - India, China and Japan

SUMMARY

- Accelerator-based neutron sources for nuclear engineering are reviewed.
  - Nuclear data taking
  - ADSR study
- E-linac
- Neutron source for thermal
- FFAG proton accelerator
- Future prospect

CONTENTS

INTRODUCTION

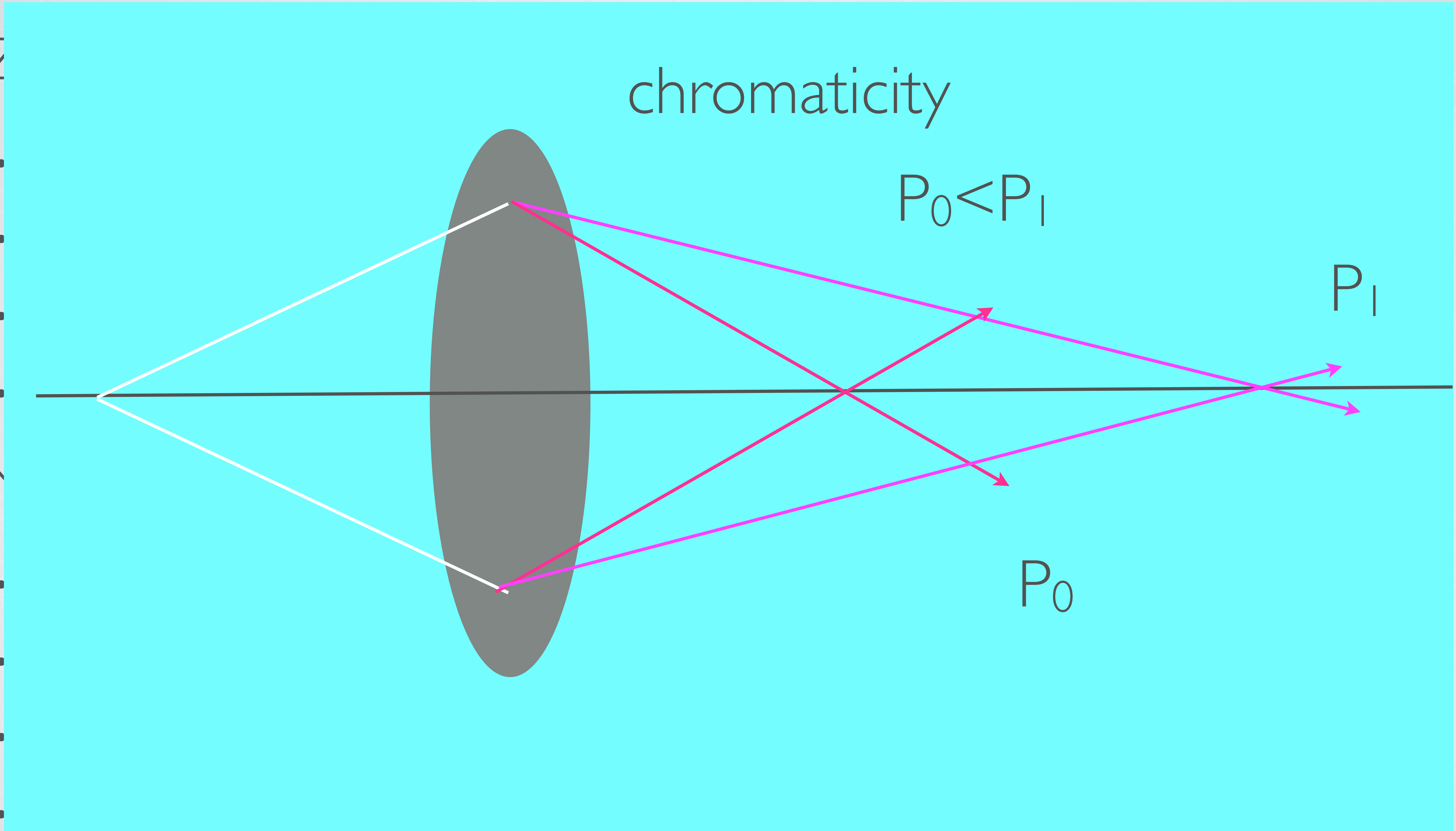
FFAG OPTICS

TYPES OF FFAG OPTICS

- Zero chromaticity : Scaling FFAG
  - Betatron tunes during acceleration are constant.
  - Free from resonance crossing.
  - Orbit configurations for different beam momentum(energy) are (nearly) similar.
  - Very Large momentum acceptance : $\Delta p/p > \pm 50\%$
- Non-zero chromaticity : Non-scaling FFAG
  - Optical elements are all linear : dipole and quadrupole magnets.
  - Betatron tunes are varied during acceleration.
  - Need fast resonance crossing : very fast acceleration.
  - Large dynamic aperture

TYPES OF FFAG OPTICS

- Z
- N



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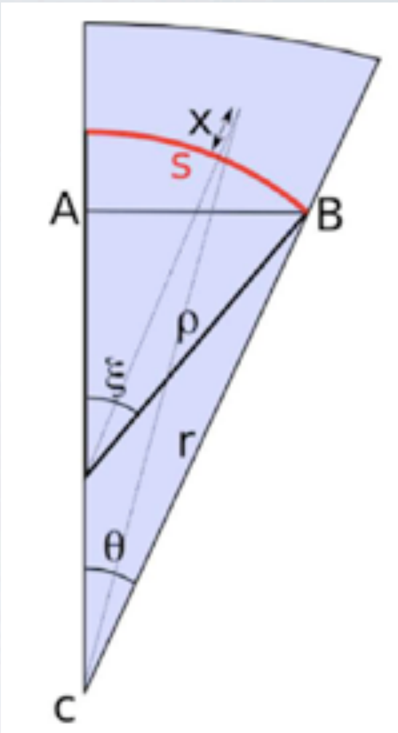
ZERO CHROMATICITY

- Betatron motion in cylindrical frame

$$\frac{d^2x}{ds^2} + \frac{1}{\rho^2}\left(1 - K\rho^2\right)x = 0,$$

$$\frac{d^2z}{ds^2} + \frac{1}{\rho^2}\left(K\rho^2\right)z = 0. \qquad K = -\frac{1}{B\rho}\frac{\partial B}{\partial r}$$

$$(ds = rd\theta)$$

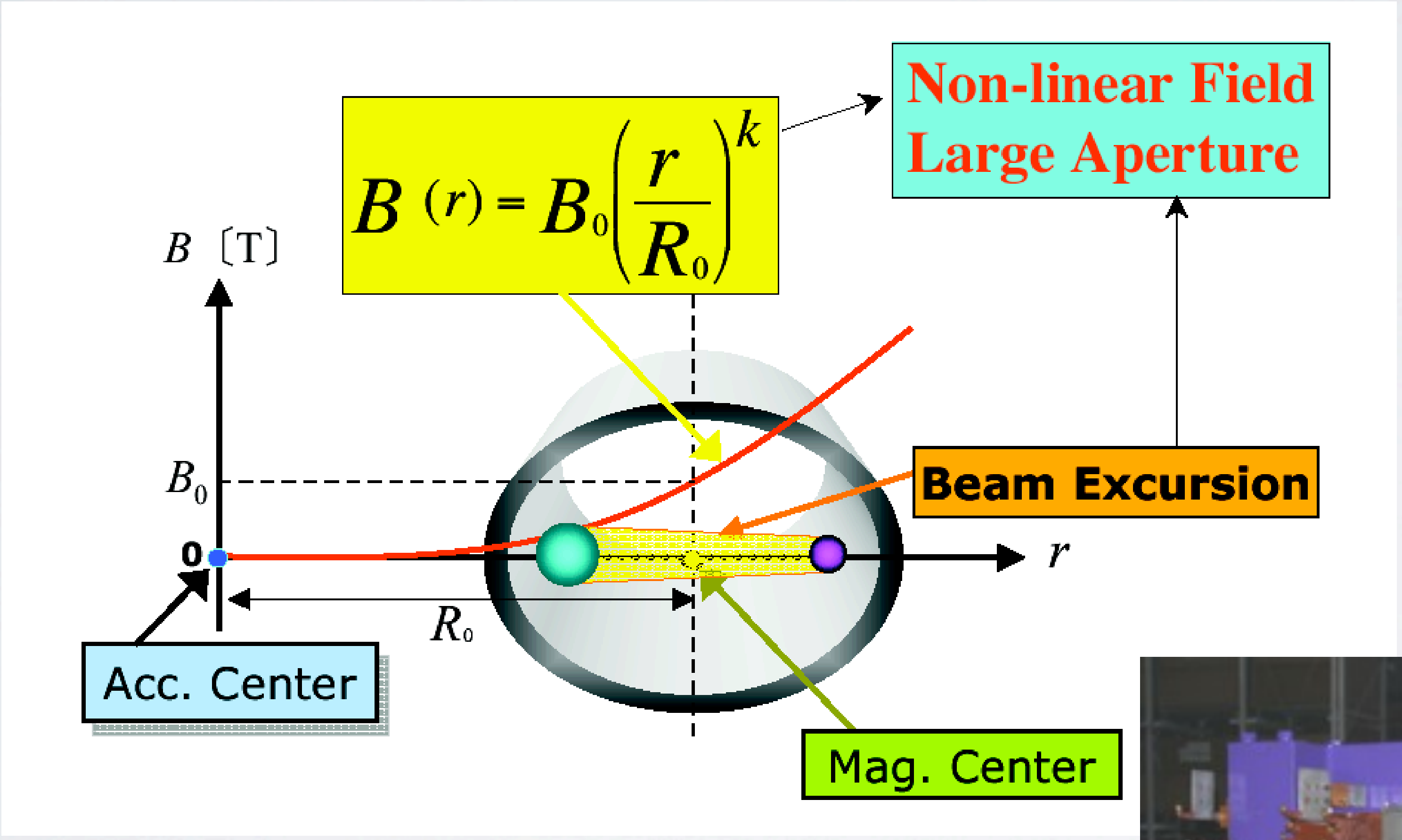


- Conditions for zero chromaticity and magnetic field

$$\begin{cases} \dfrac{d\left(r^2/\rho^2\right)}{dp} = 0 \\ \dfrac{d\left(K\rho^2\right)}{dp} = 0 \end{cases} \longrightarrow \begin{cases} r \propto \rho \\ \dfrac{r}{B}\left[\dfrac{\partial B_z}{\partial x}\right]_{z=0} = k \end{cases}$$

$$\boxed{B_z = B_0\left(\frac{r}{r_0}\right)^k f\left(\theta - \varsigma \ln\frac{r}{r_0}\right)}$$

MAGNETIC FIELD FOR ZERO CHROMATICITY



Momentum compaction: $1/k+1$

AG FOCUSING LATTICE

- FODO lattice : AG focusing
- Radial sector
  - F: positive bending
  - D:negative bending

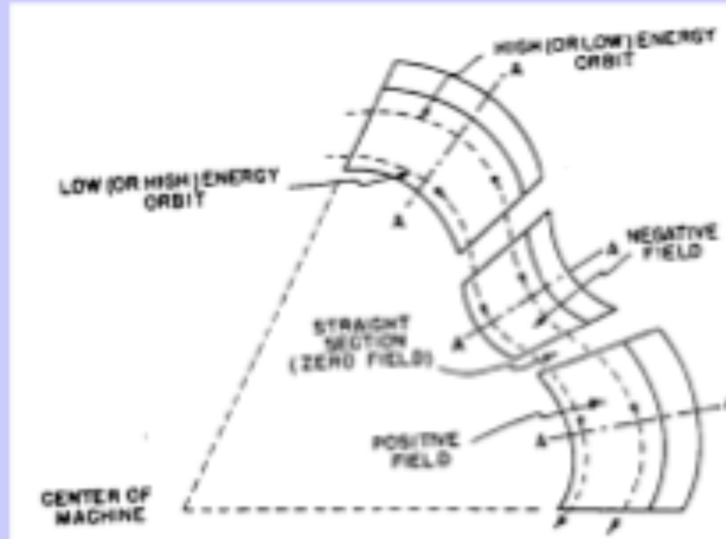


Fig. 2. Plan view of radial-sector magnets.

- Spiral sector
  - F: positive bending
  - D: edge focusing

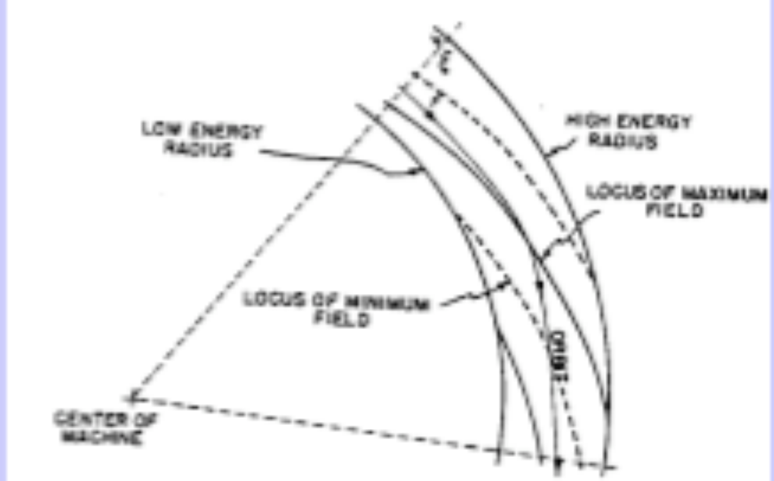
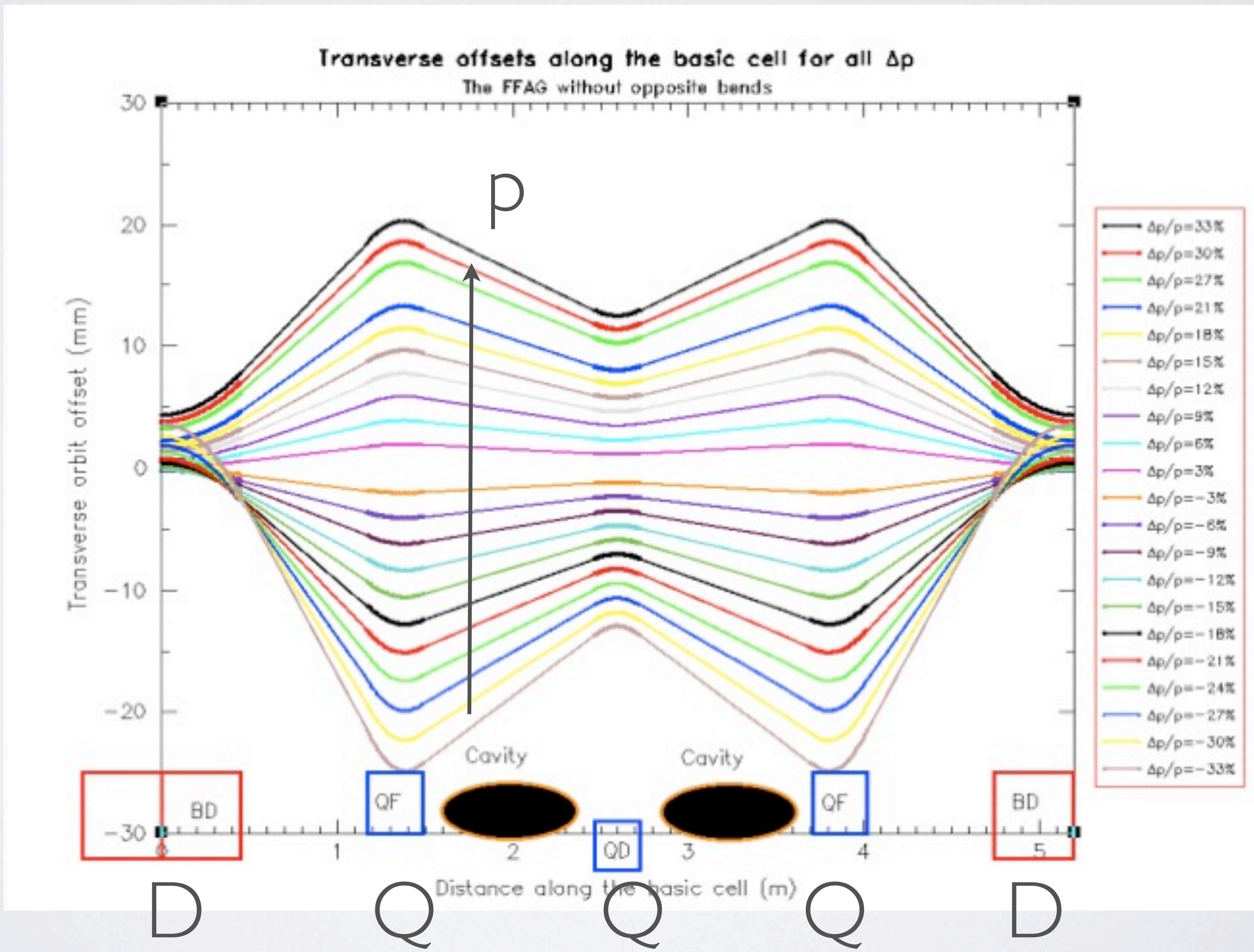


Fig. 3. Spiral-sector configuration.

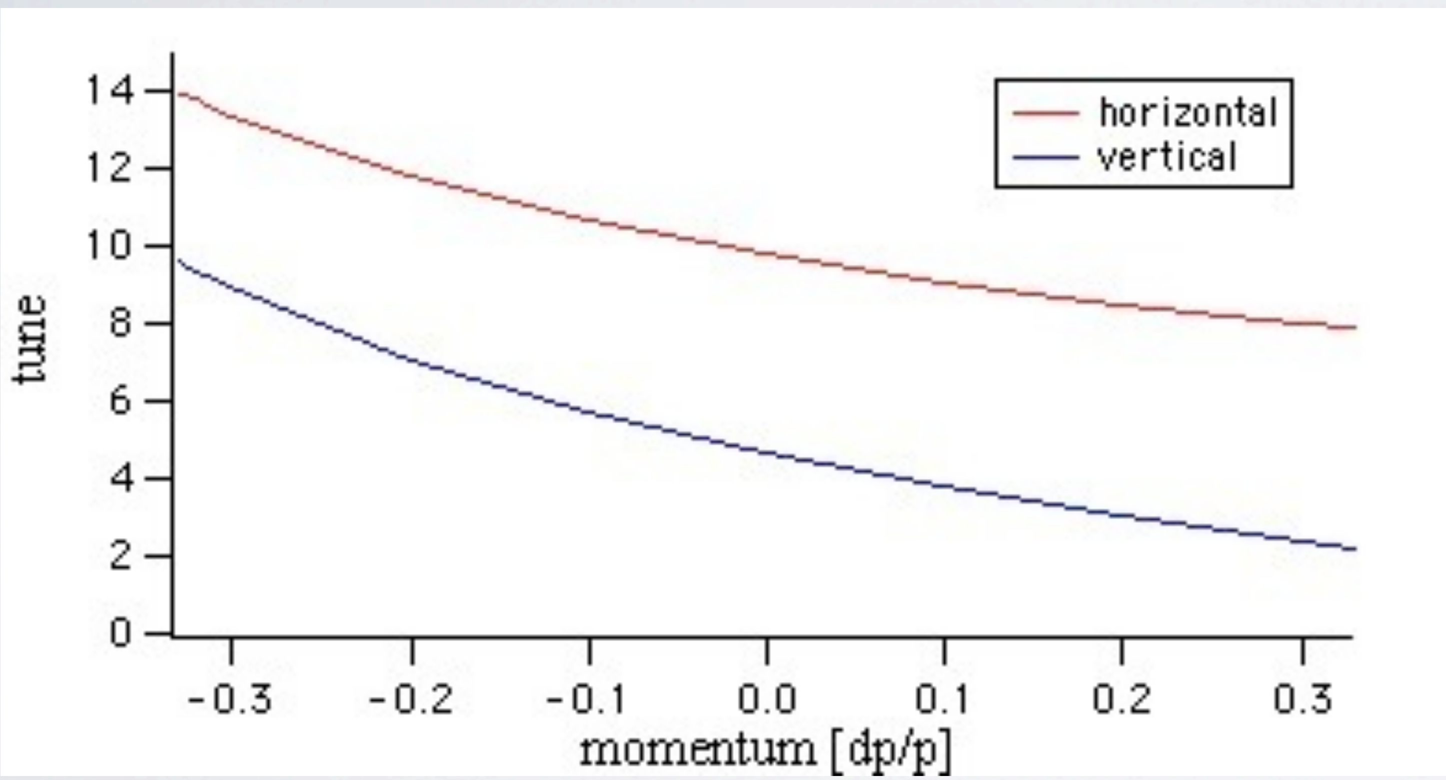
NON-ZERO CHROMATICITY

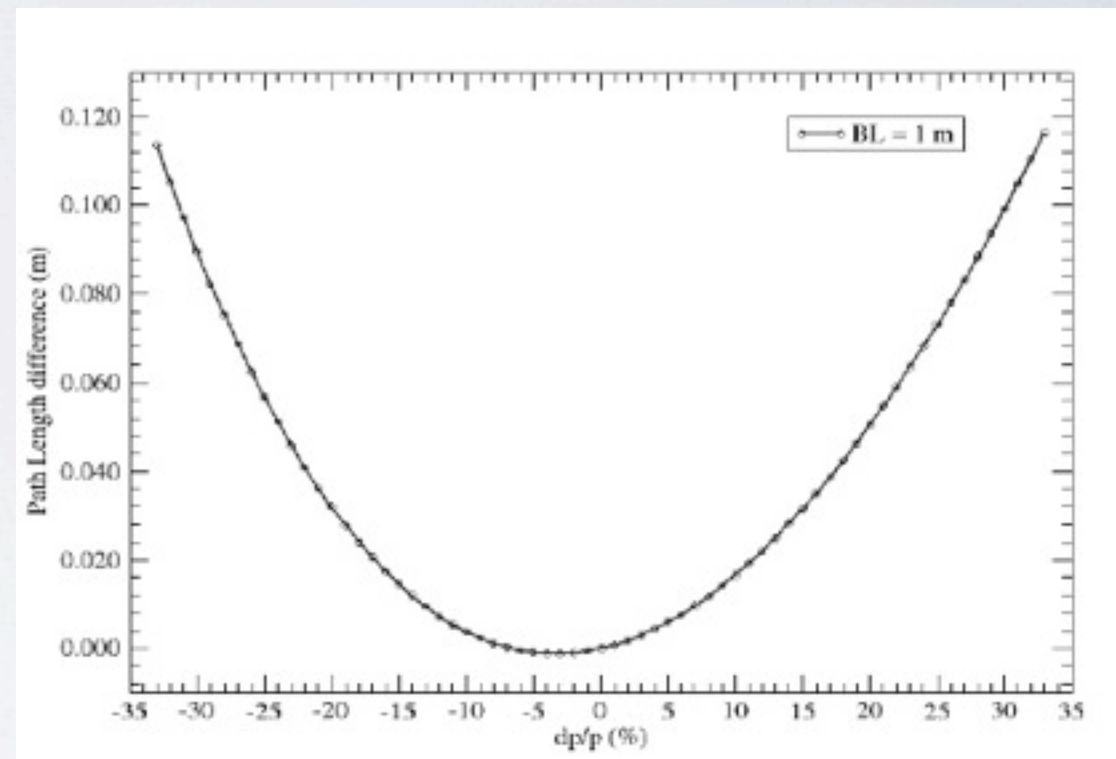
- Non-scaling lattice: linear optics (dipole and quadrupole magnets)



NON-ZERO CHROMATICITY

$$\alpha \cong C_1 \xi^2, \xi = \frac{\Delta p}{p}$$





Betatron tune variation

path length difference

HISTORY

- *Ohkawa (1953,Japan), Kerst & Symon(USA), Kolomenski(USSR)*
  - MURA project   e-model, induction acceleration   ~'60s
  - No proton FFAG for 50 years!
- *Proton FFAG (POP:World first p-FFAG, Mori et al.,2000)*
    - *Complicated field configuration : 3D design*
    - *MA(Magnetic Alloy) RF cavity : Variable Frequency & High Gradient.*
  - *150MeV p-FFAG (Mori et al.,2004)*
  - *PRISM FFAG(Kuno et al.,2008,Osaka)*
  - *p-FFAG for ADSR study, ERIT neutron source (KURRI,2008)*
  - *e-FFAG for industrial applications (NHVC, Japan, 2008)*
  - *EMMA(e-FFAG for nuFact:World first non-scaling FFAG, England,2010 first beam)*

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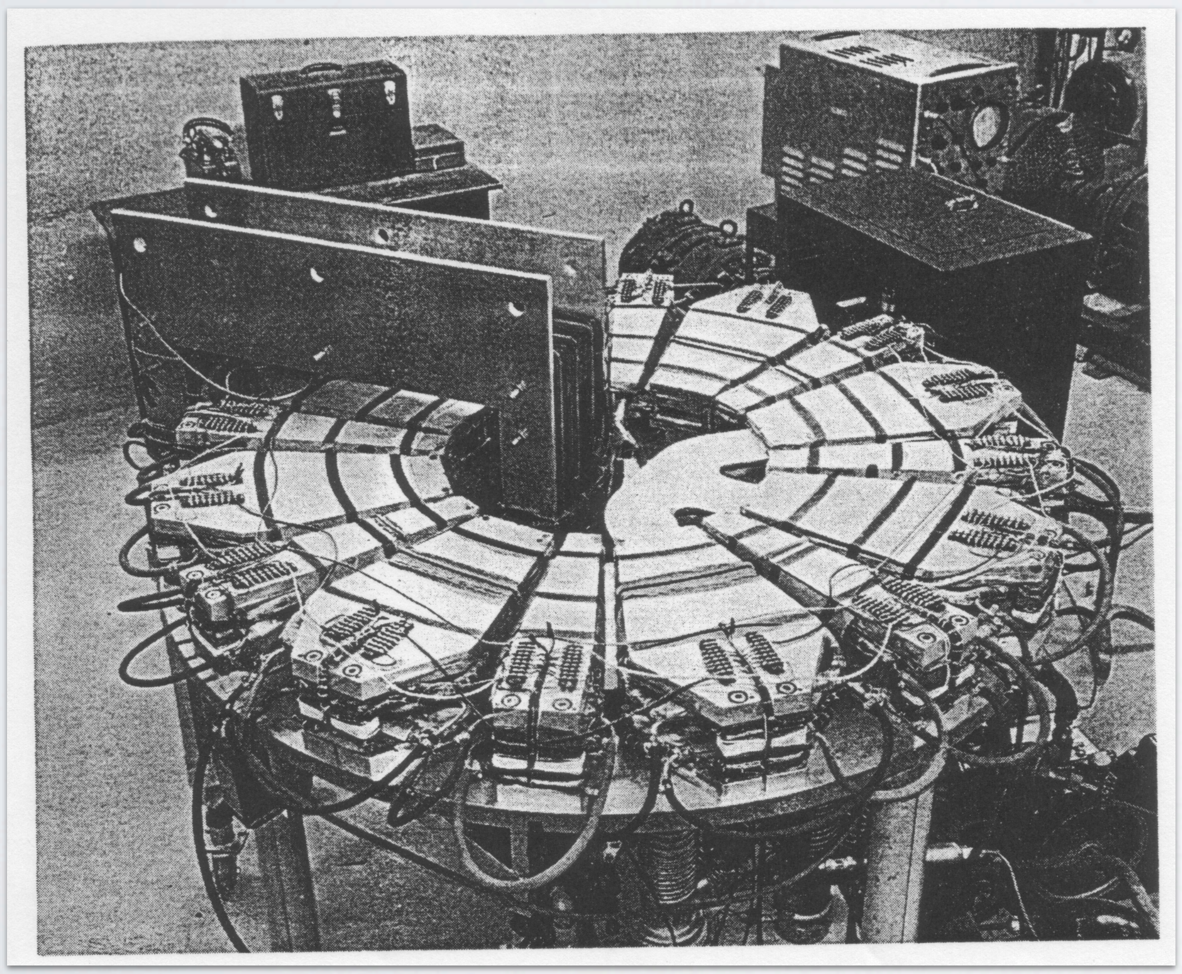
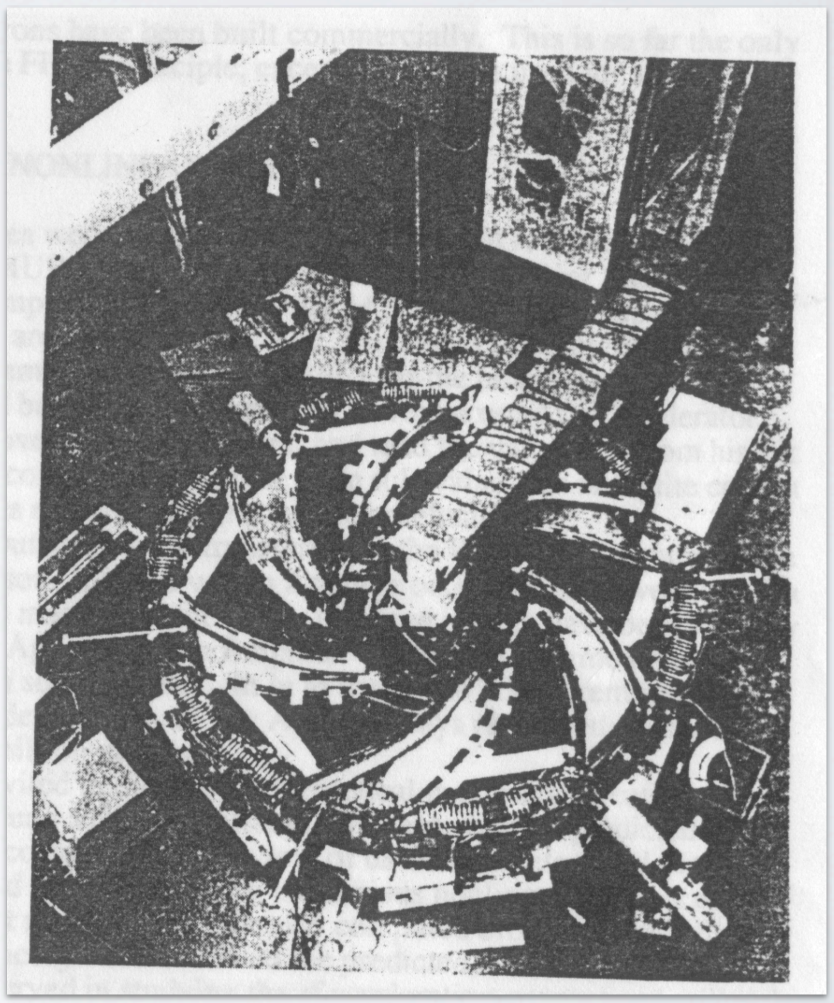
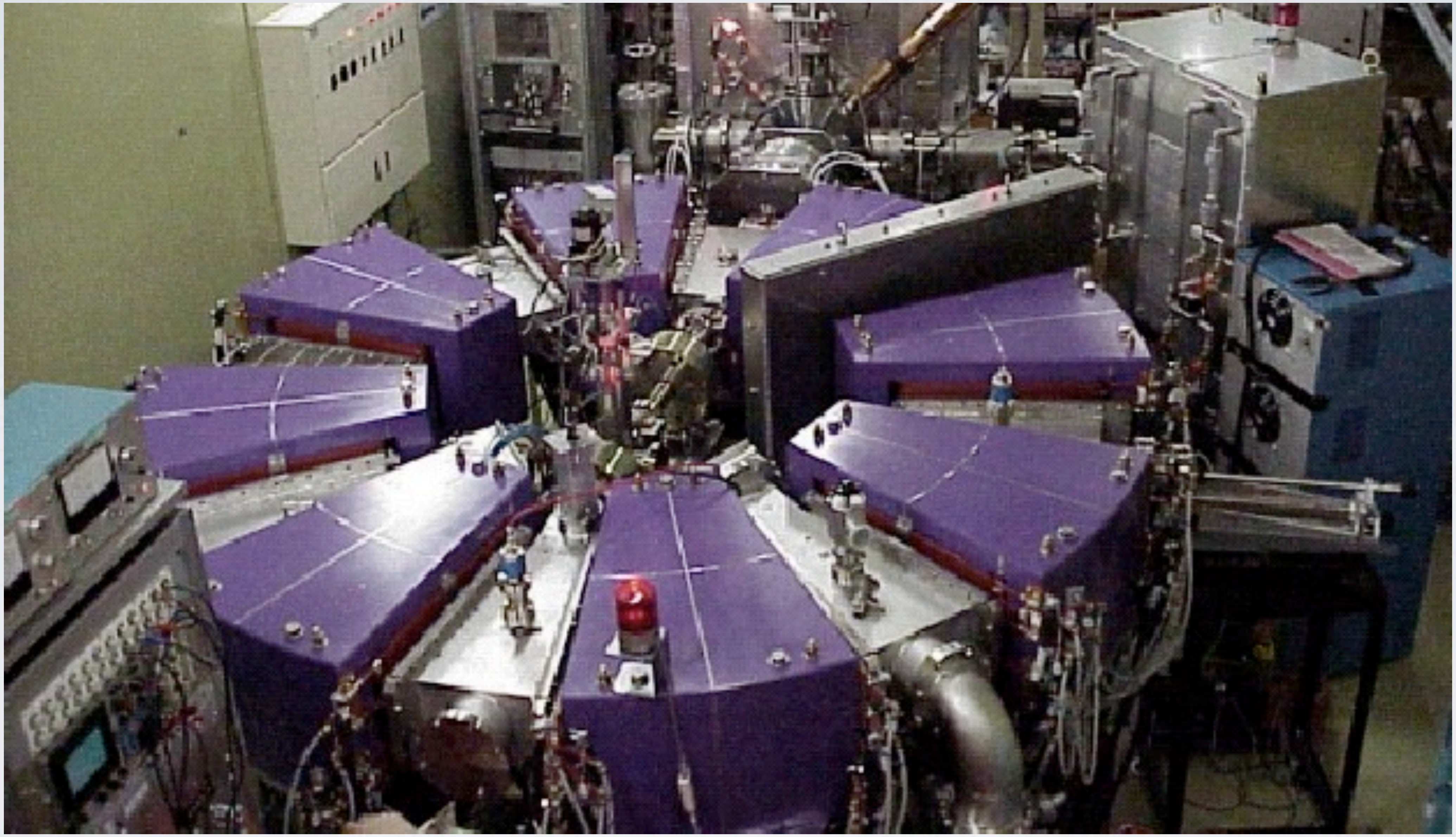
MURA PROJECT ('60)

- electron model





PROTON FFAG (2000)



Emax ~1MeV, R=2.5m

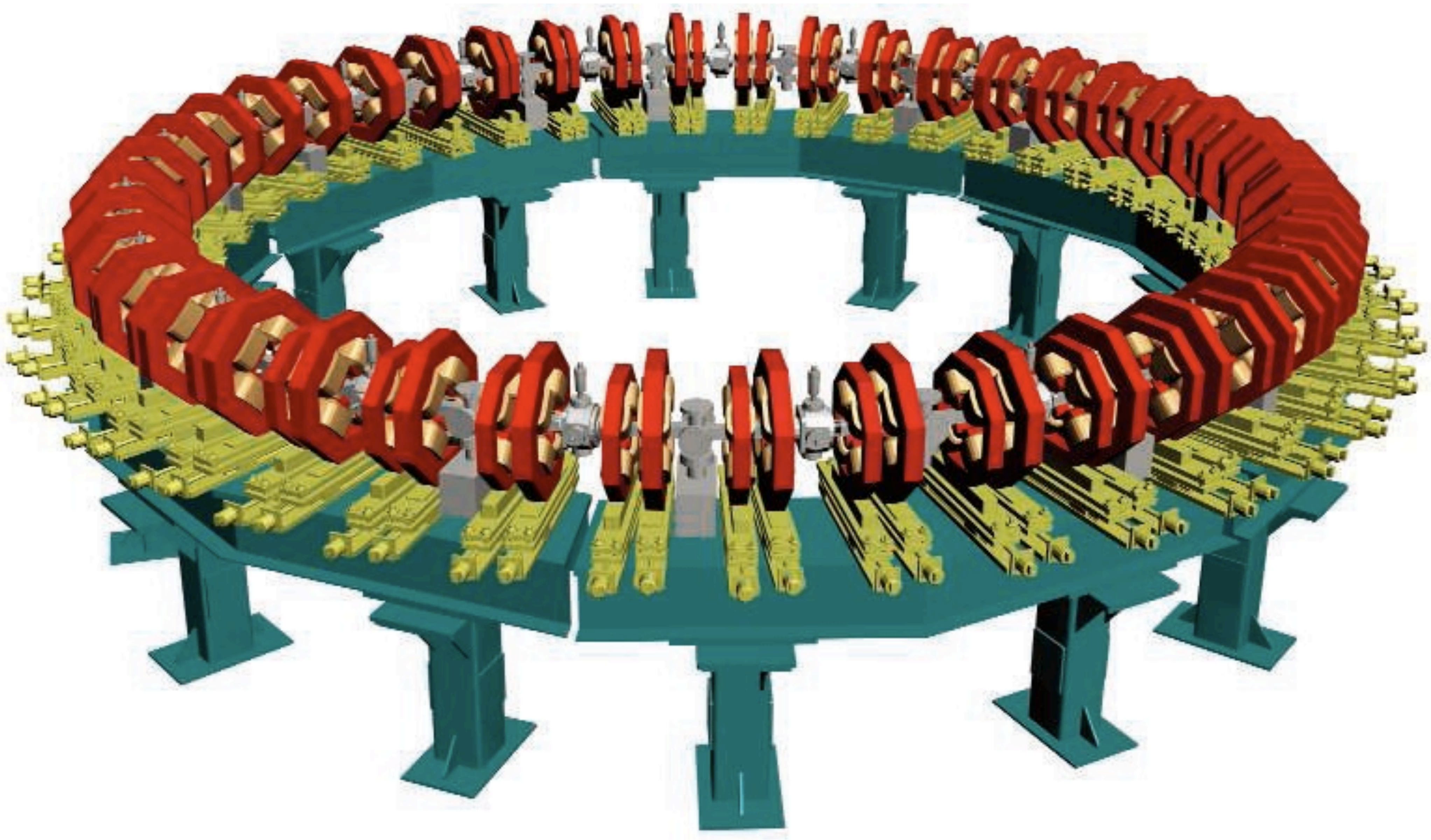
Proof-of-Principle (PoP)-Proton FFAG Accel.

FFAG complex for ADSR study at KURRI

E=150MeV

Non-zero chromatic FFAG

EMMA:Electron Model for Muon Accelerator under constraction at UK



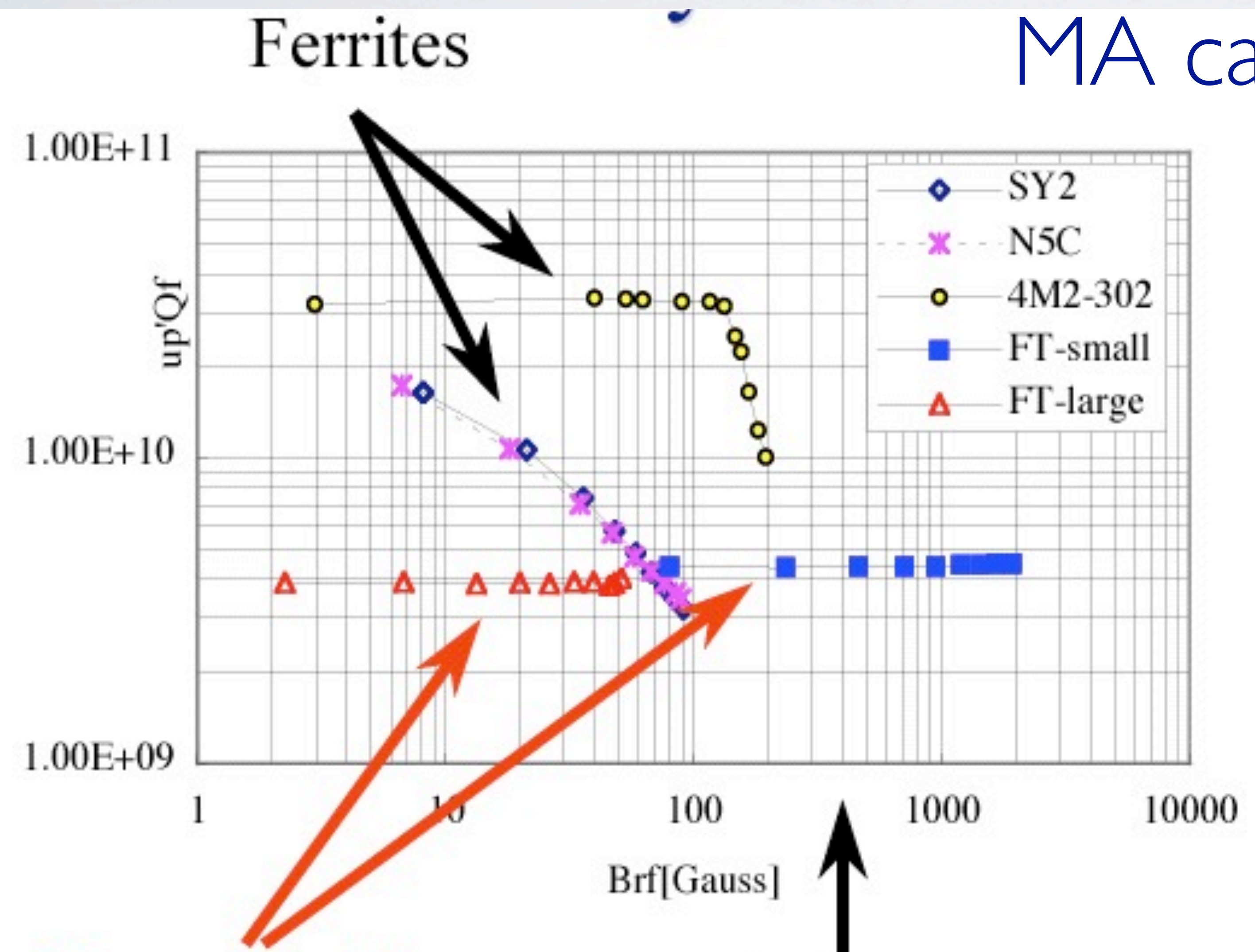
ACCELERATION

BEAM ACCELERATION IN FFAGS

- Momentum compaction can be tuned along orbit swing
  - Keeping phase stability like synchrotron
  - Realizing isochronism like cyclotron
- Variable RF frequency
  - Broad-band RF cavity : Scaling & Non-scaling
    - MA(magnetic alloy) cavity Q~1
- Constant RF frequency
  - Stationary RF bucket acceleration : Scaling
    - Constant momentum compaction(MC)
  - Serpentine RF acceleration : Non-scaling
    - Relativistic beam & small MC(parabolic) :semi-isochronous
  - Harmonic number jump acceleration : Scaling (non-scaling)
    - non-zero slippage factor

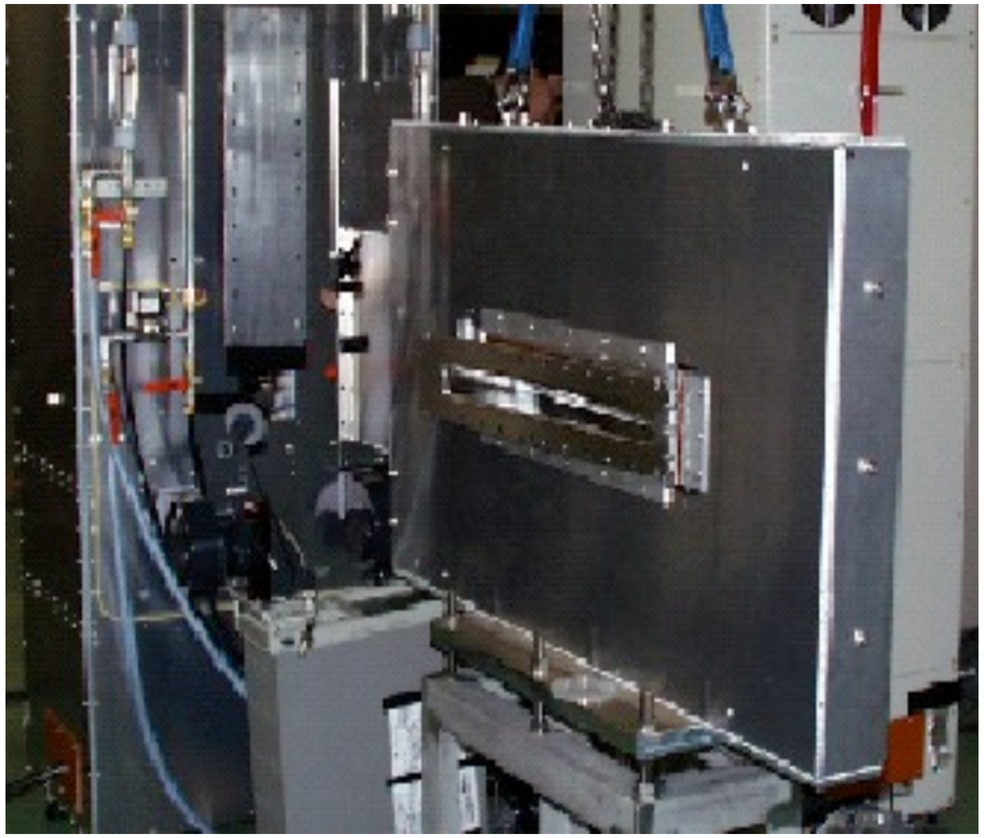
VARIABLE RF FREQUENCY

- Broad-band RF cavity : MA(magnetic alloy) cavity
  - Fast acceleration requires fast frequency(phase) change.
    - *Low Q ~1 is essentianl !*
  - Adequate both for scaling and non-scaling FFAGs.



$B = V/\omega S = {}_{25kV/2pX5MHzX5cmX40cm} = 400$Gauss

MA cavity used for POP p-FFAG

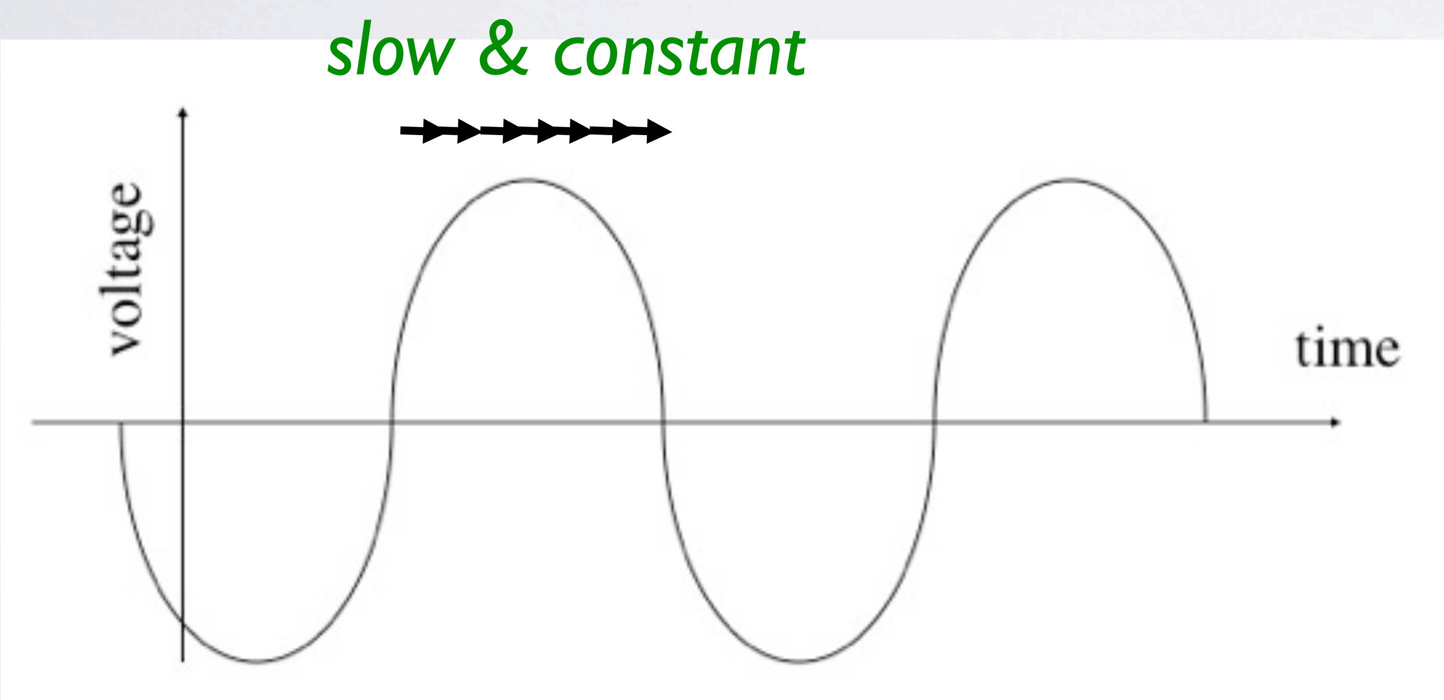


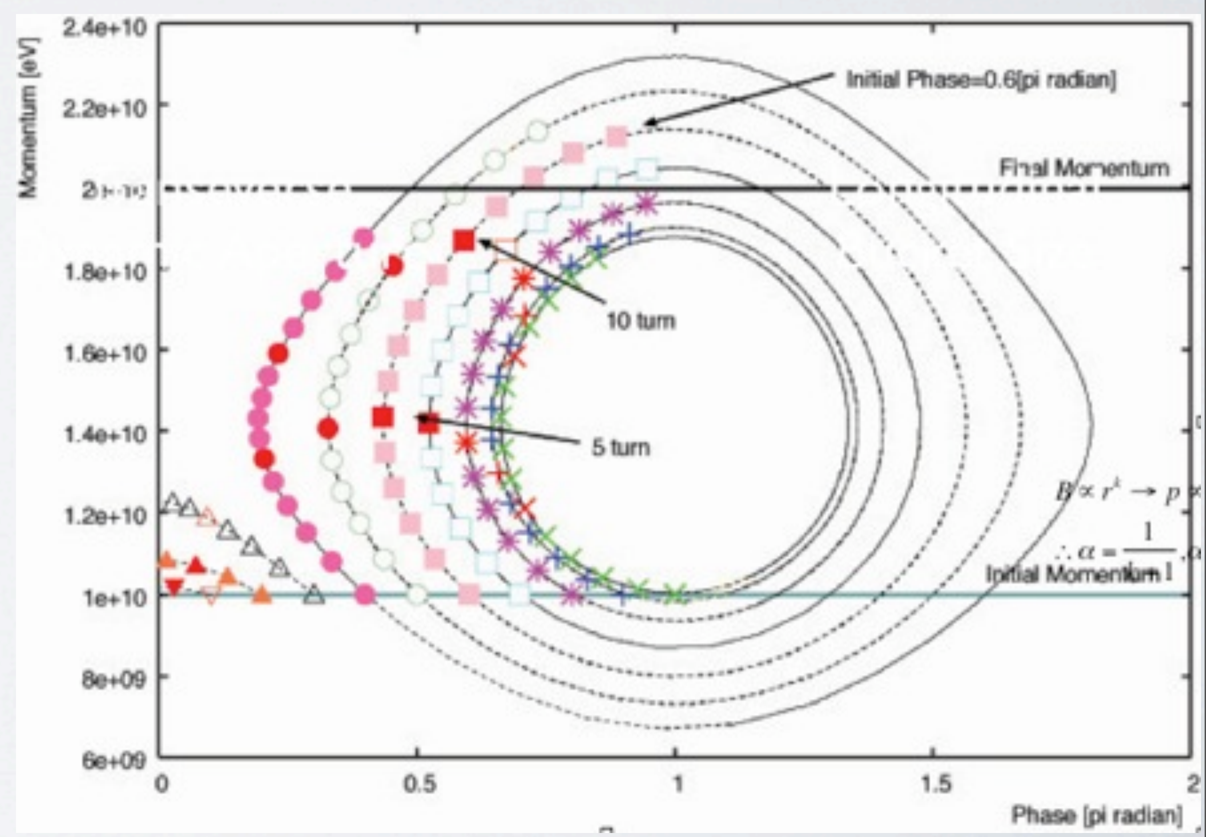
FIXED RF FREQUENCY (1)

- Stationary bucket acceleration
  - Constant & small enough phase slip --- Large energy gain
    - relativistic beam
    - constant Momentum Compaction

$$\eta = \frac{1}{\gamma^2} - \alpha \cong -\alpha = -\frac{1}{k+1}$$

  - Adequate for scaling FFAG





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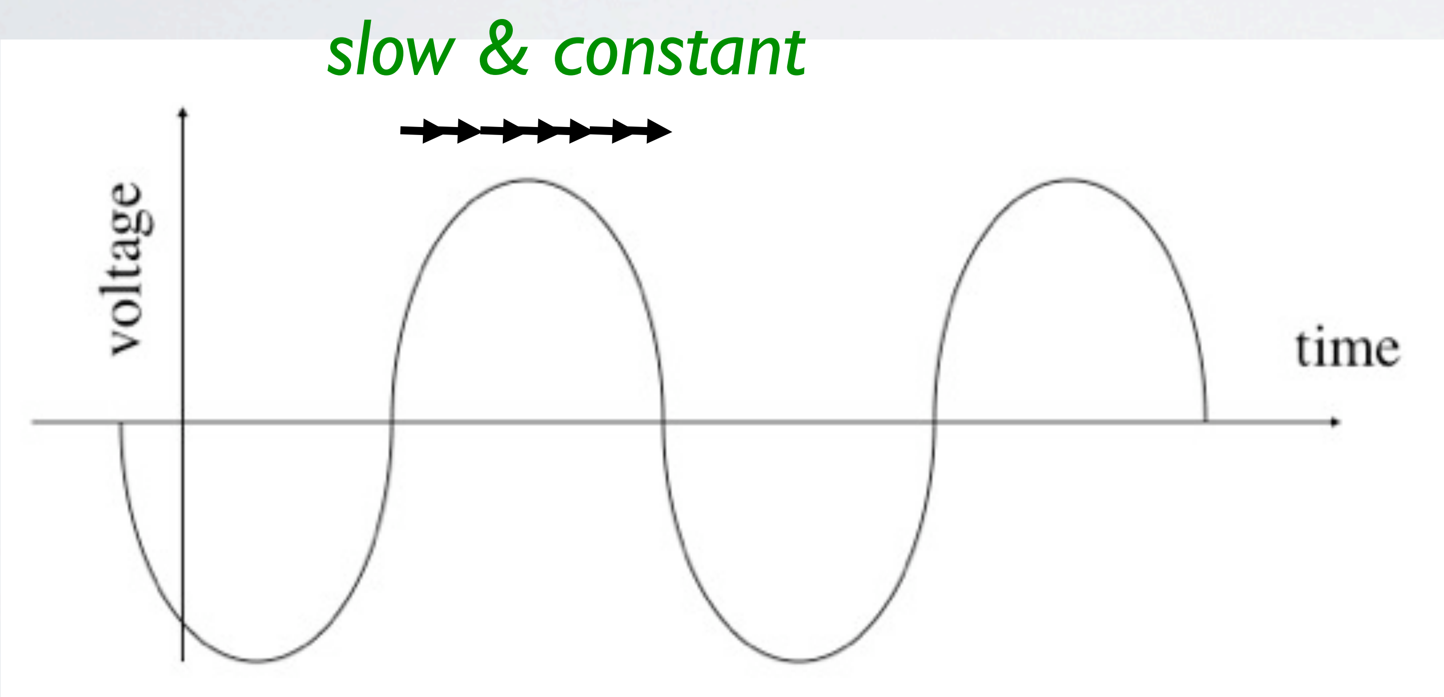
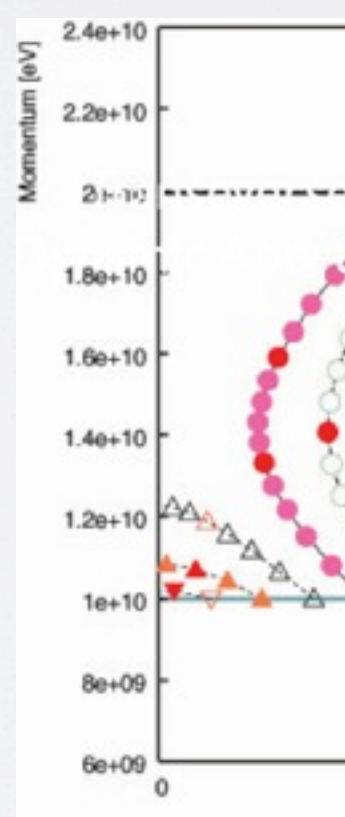
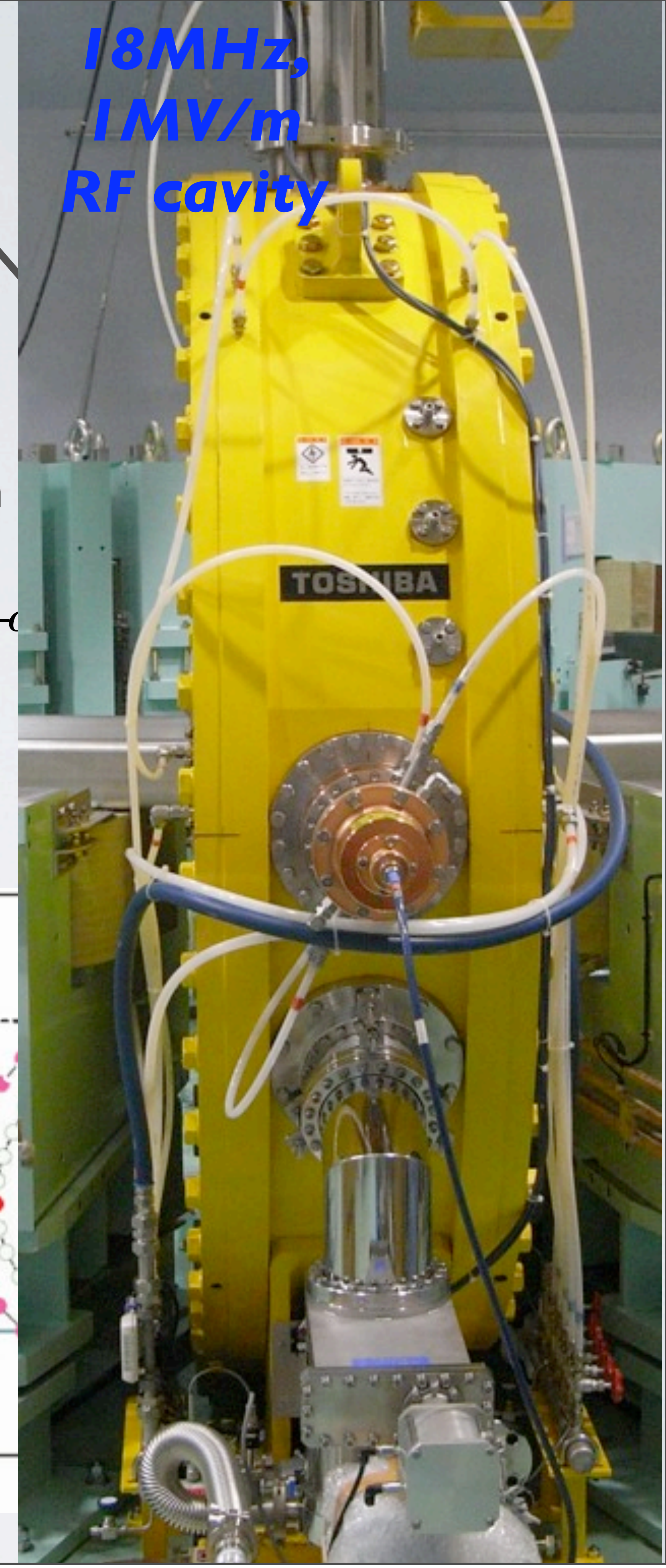




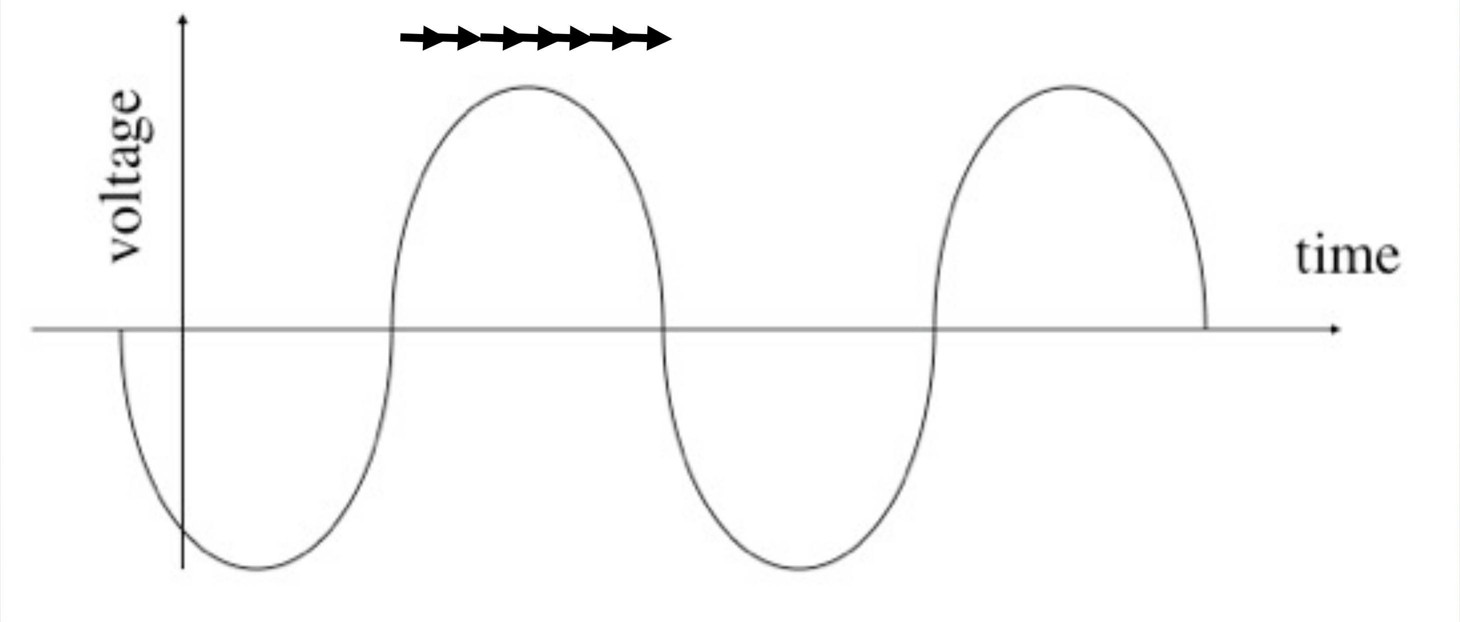


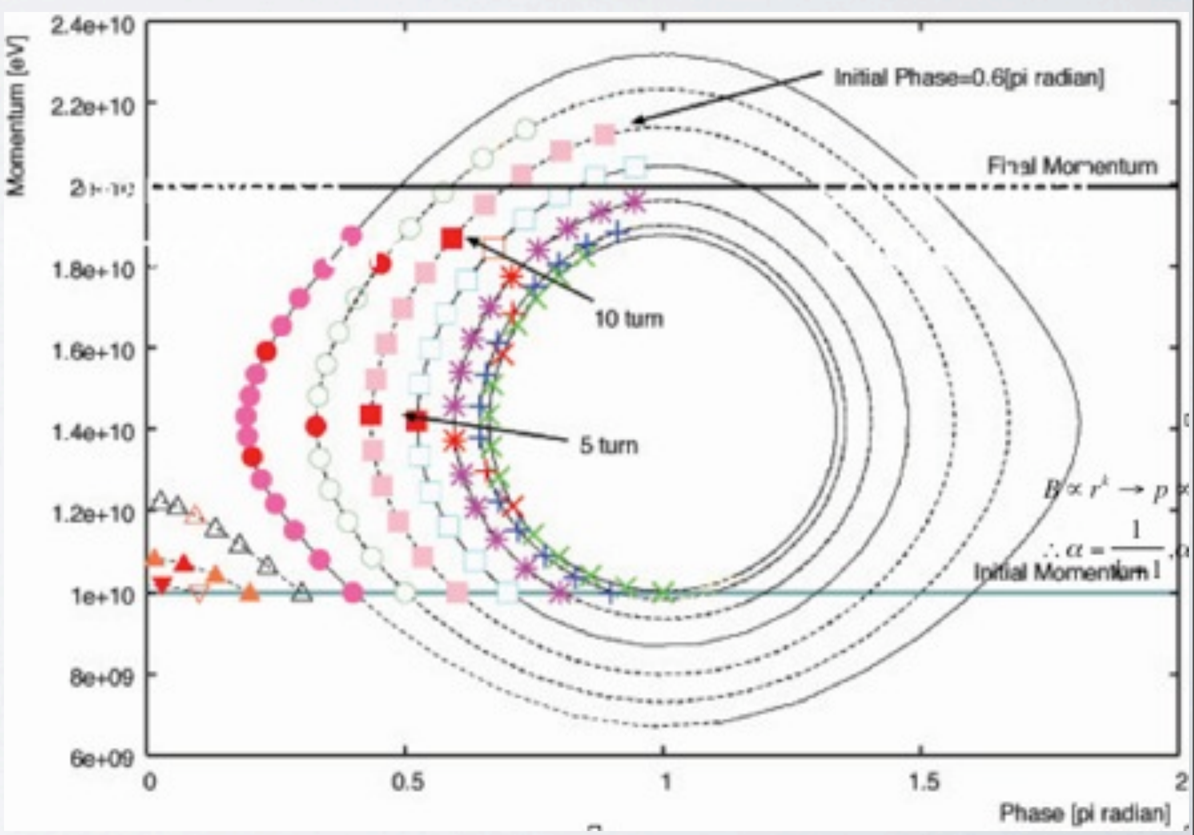
FIXED RF FREQUENCY (1)

- Stationary bucket acceleration
  - Constant & small enough phase slip --- Large energy gain
    - relativistic beam
    - constant Momentum Compaction
  - Adequate for scaling FFAG

$$\eta = \frac{1}{\gamma^2} - \alpha \cong -\alpha = -\frac{1}{k+1}$$

slow & constant





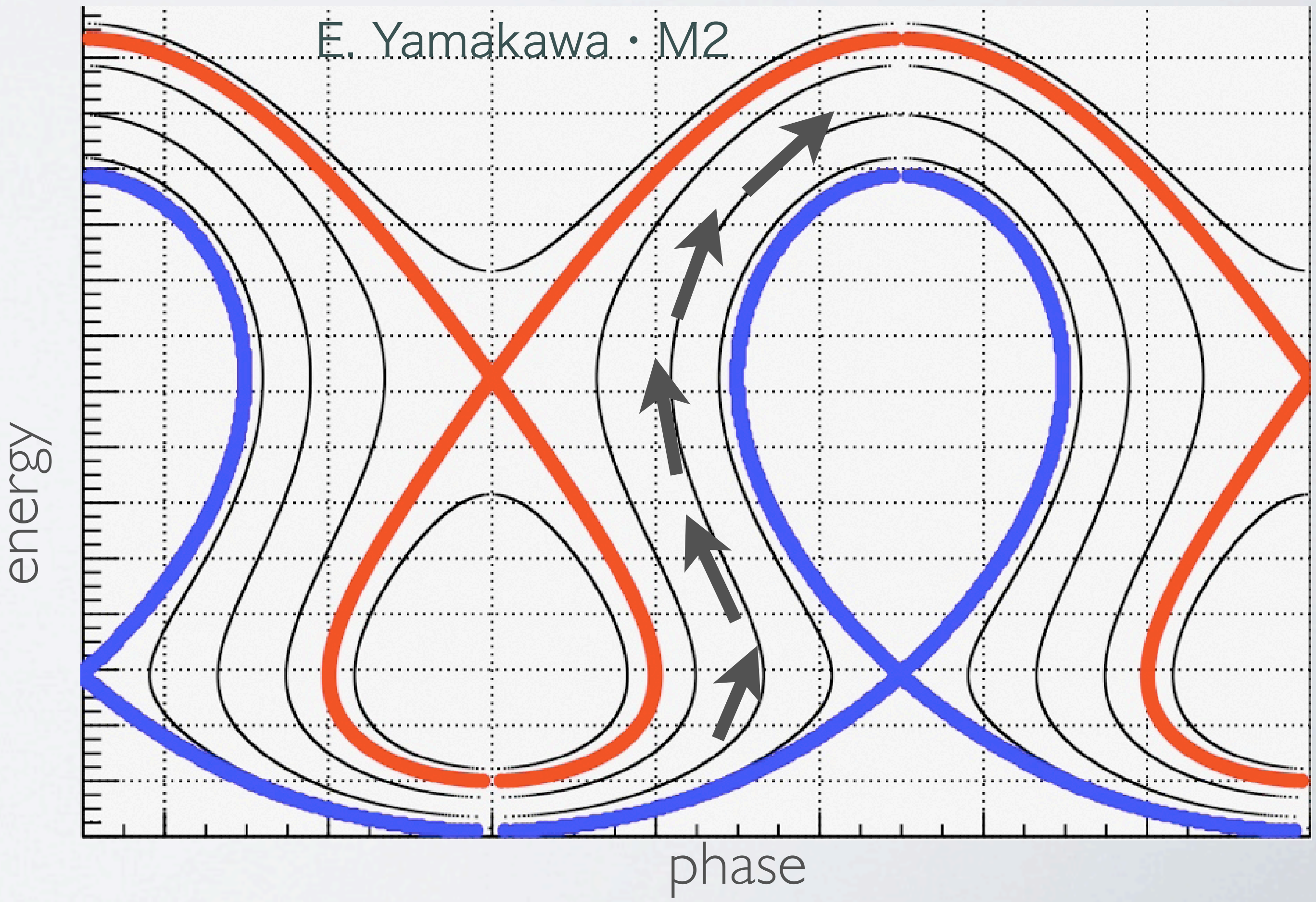
FIXED RF FREQUENCY(2)

- Serpentine acceleration in zero-chromatic(scaling) FFAGs
  - Non-relativistic to relativistic
  - Longitudinal Hamiltonian in scaling FFAG

$$H = 2\pi m_0 c^2 \left[\frac{\left(\gamma_s^2 - 1\right)^{\lambda}}{2\gamma_s} \frac{\left(\gamma^2 - 1\right)^{-\lambda+1}}{(1-\lambda)} + \gamma \right] + e\frac{V_{rf}}{h} f_0 \cos\phi$$

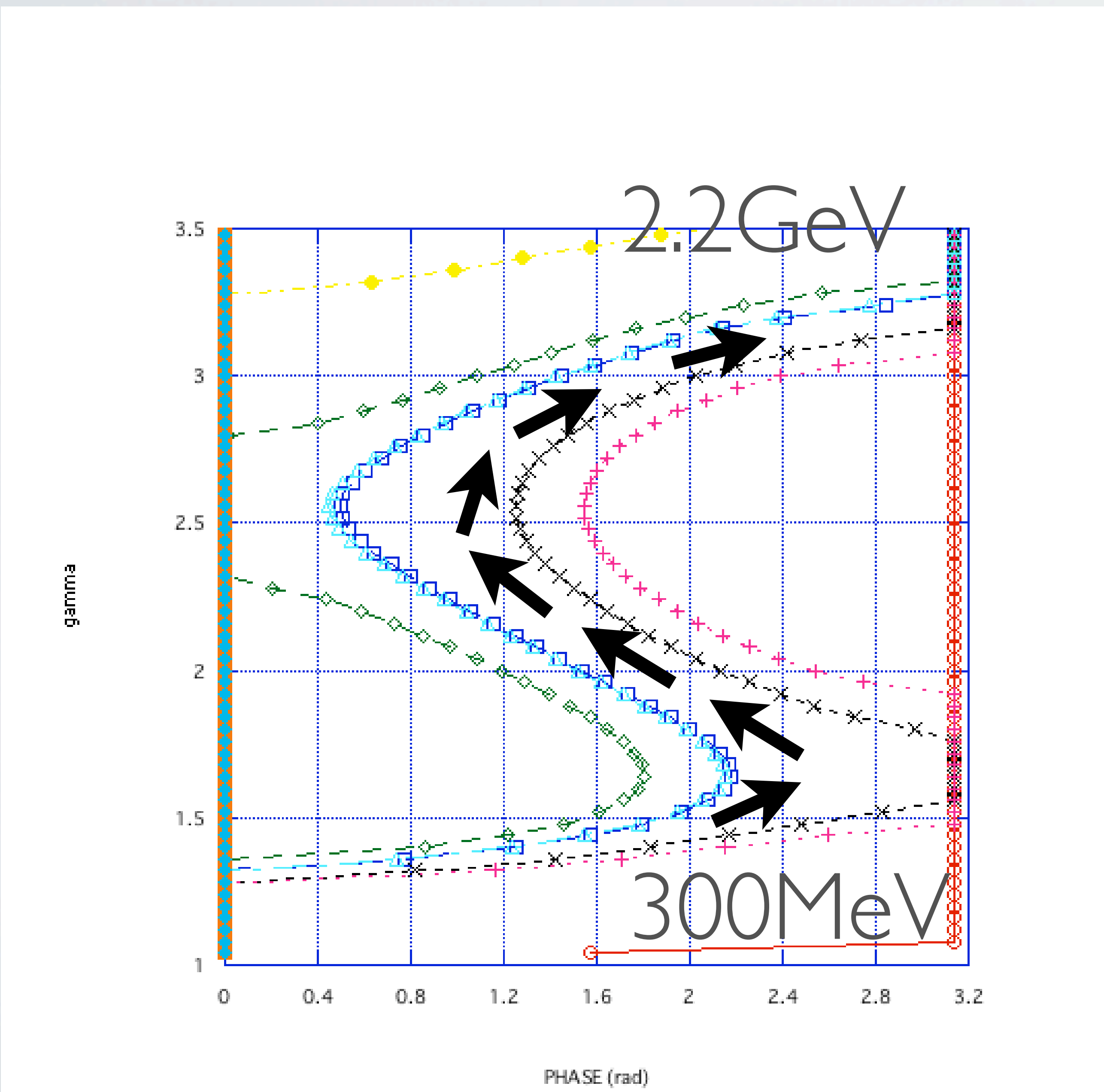
$$\lambda = \frac{k}{2(k+1)}$$

$$\frac{dp}{dT} = 0 : \quad p = \gamma_1 \text{ and } \gamma_2$$



FIXED RF FRQUENCY (2-1)

- Example of proton acceleration E=300MeV → 2.2GeV



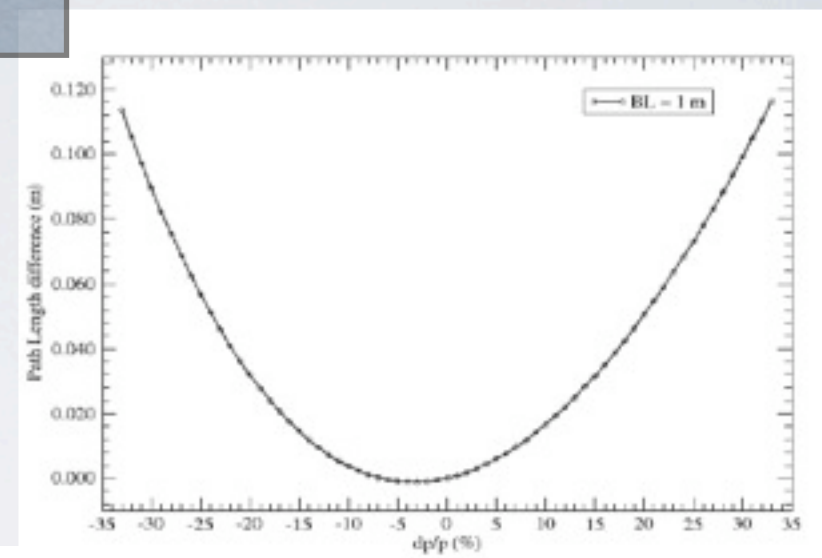
Item	value
Average radius(m)	15
Field index	3
Injection energy	300MeV
Extraction energy	2.2GeV
RF voltage per turn (h=1)	38MV

- RF frequency 20MHz (h=2)
- No. of turns : ~40 turns

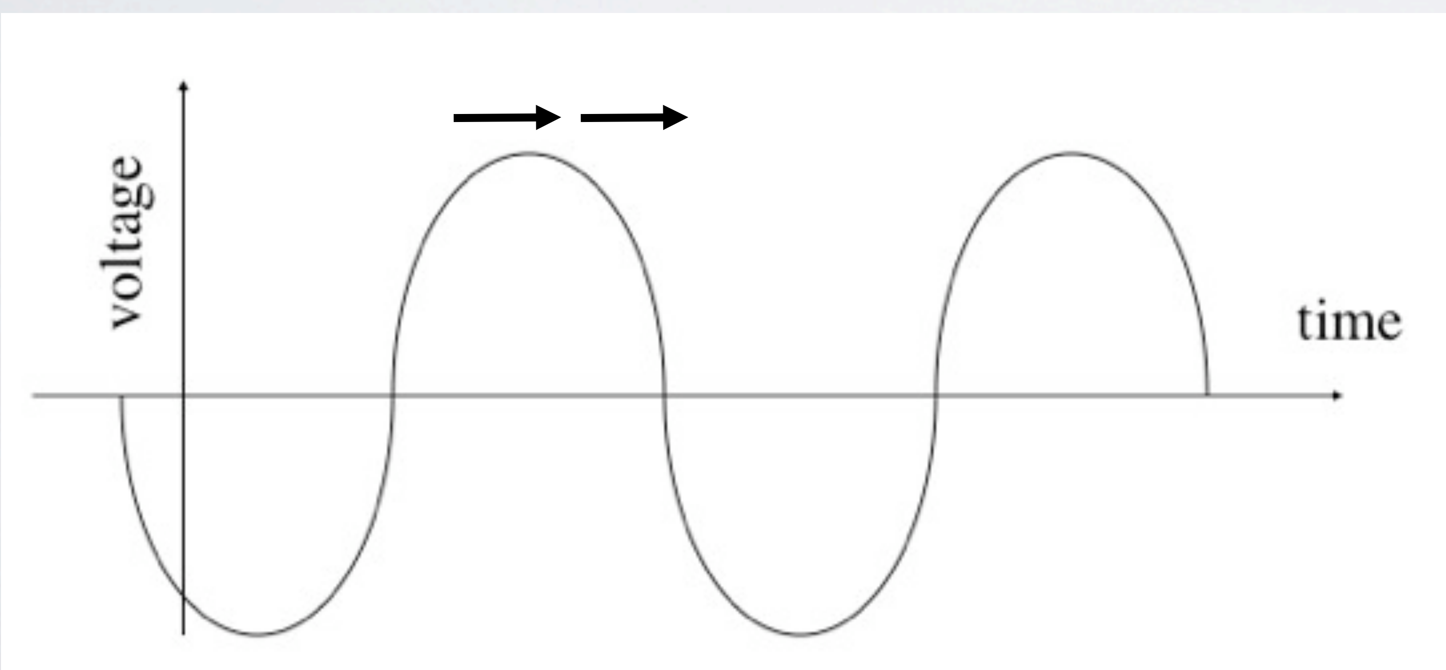
FIXED RF FREQUENCY(3)

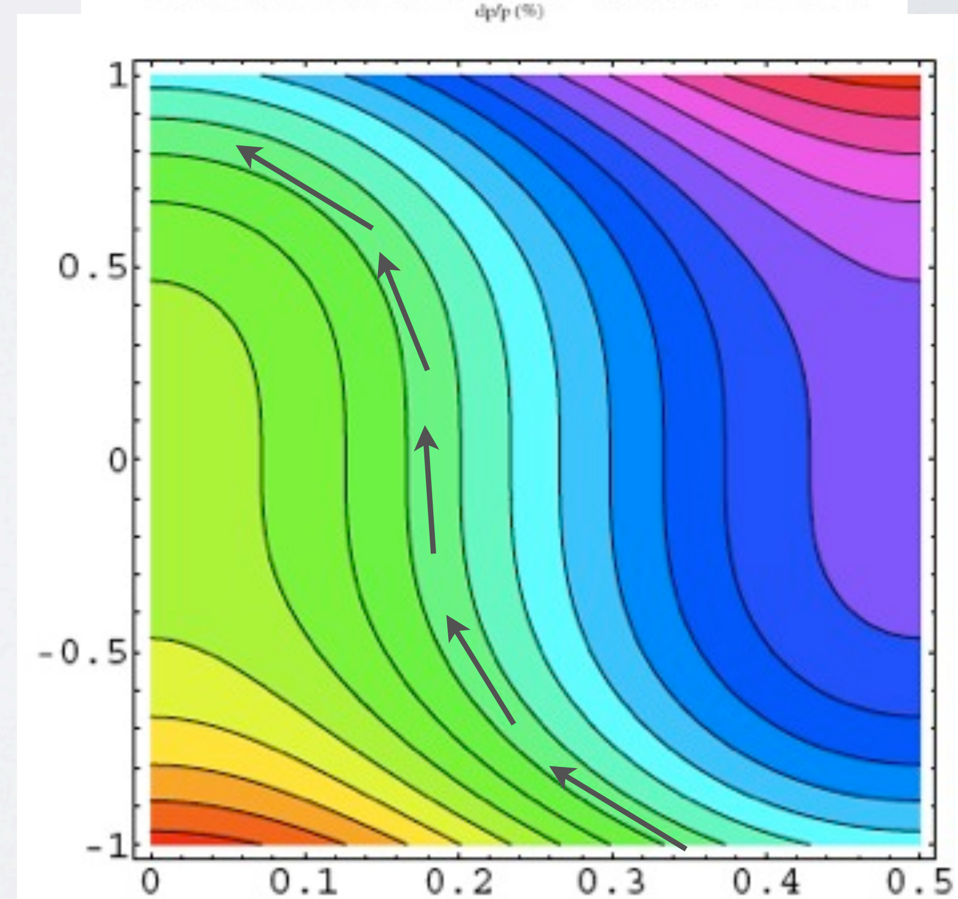
- Serpentine acceleration in non-scaling FFAG
  - Parabolic & small enough phase slip
    - relativistic beam
    - small parabolic Momentum Compaction
  - Adequate for non-scaling FFAG

$$\alpha \cong C_1\xi^2, \xi = \frac{\Delta p}{p}$$



slow & parabolic



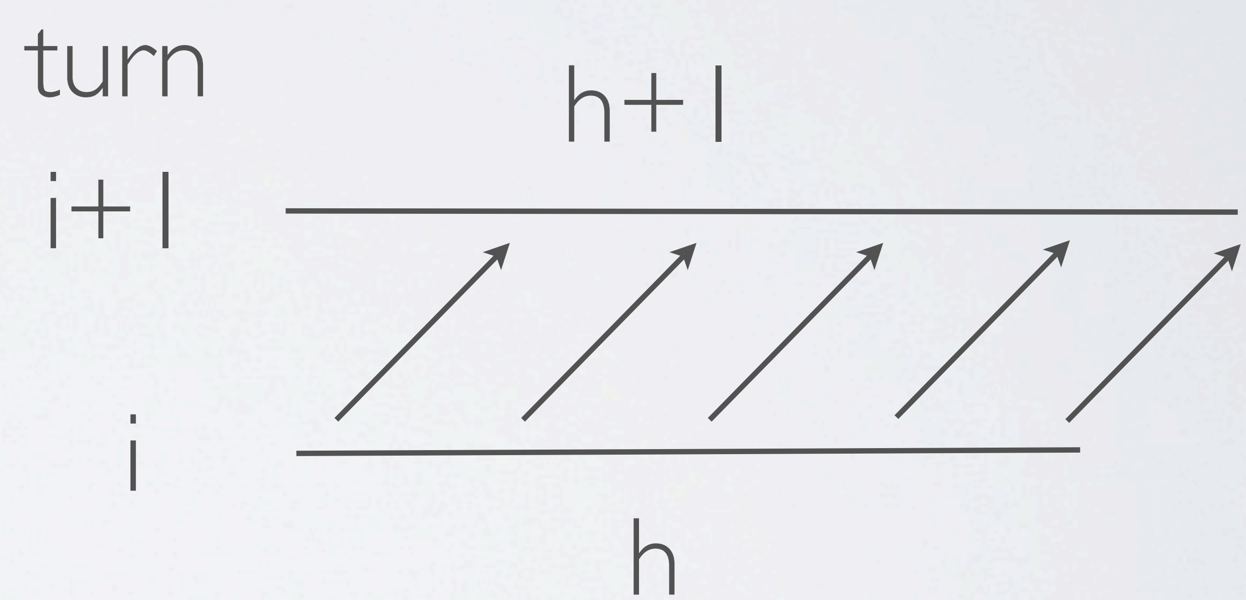


cf. S.Machida

FIXED RF FREQUENCY(4)

- Harmonic number jump acceleration
    - m:integer, $m<0$: before transition, $m>0$: after transition
    - Energy gain/turn can be automatically tuned if the RF voltage is high enough.
    - ---> Phase stability
- Time slip/turn: m × Trf

$$T_{i+1} - T_i = \frac{m}{f_{RF}}$$



ADVANCEMENT OF FFAGS

ADVANCEMENT OF FFAG

- Zero chromaticity (scaling) FFAGs
- Pro/
  - Fixed field & Strong focusing
  - Zero chromaticity
    - constant betatron tunes → no-resonance crossing
  - Large acceptance (longitudinal & transverse)
- Con/
  - Relative large dispersion:Orbit excursion is large.
    - Large horizontal aperture magnet
    - Large horizontal aperture rf cavity → Low frequency
  - Short straight section
    - Injection/Extraction difficulties → Kicker/Septum needs large apertures.
    - Available space for rf cavity is limited.
- **Need long straight section with small dispersion keeping "Zero Chromaticity".**

ADVANCEMENT OF FFAG

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    - c
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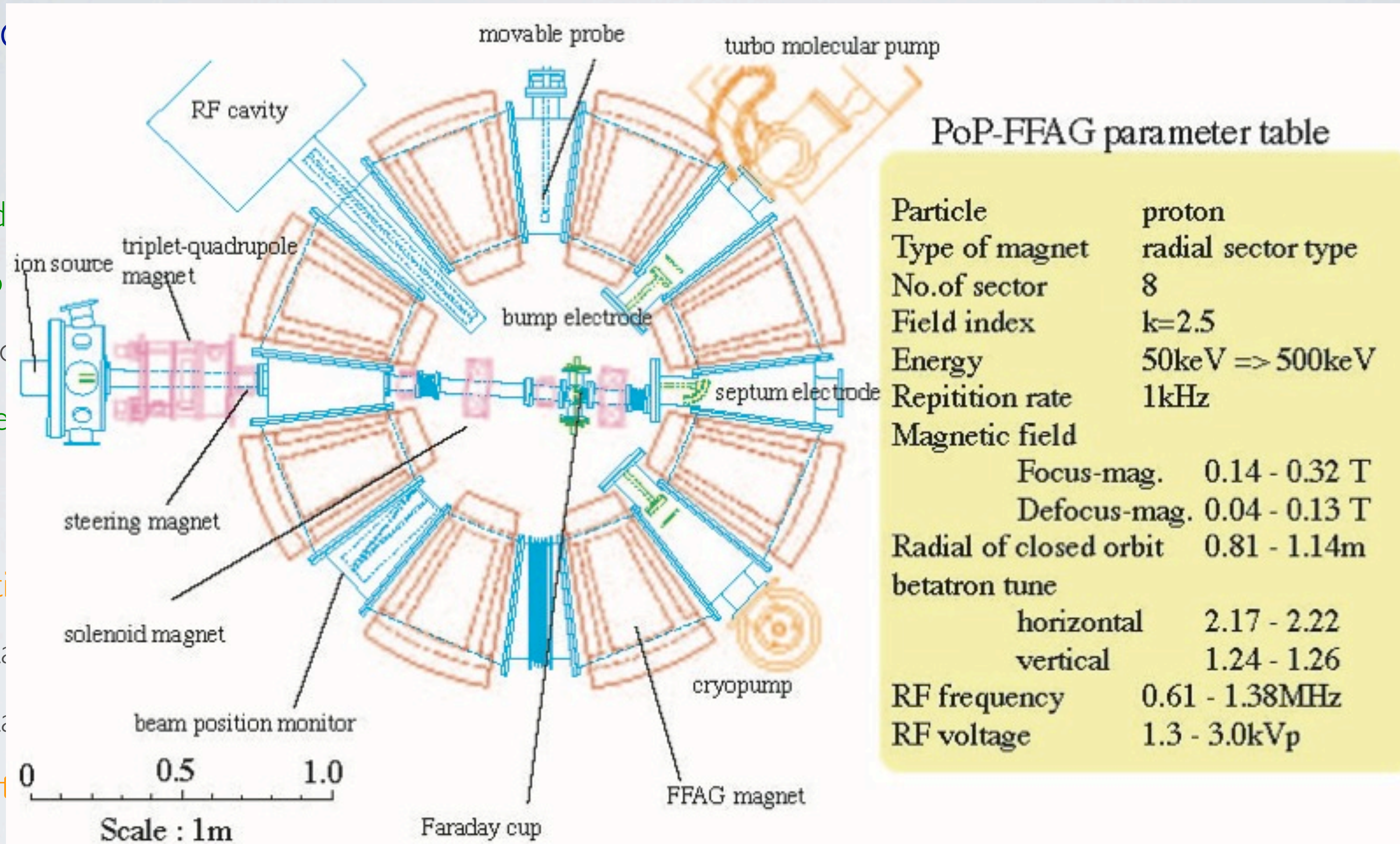

Particle		proton
Type of magnet		radial sector type
No.of sector		8
Field index		k=2.5
Energy		50keV => 500keV
Repitition rate		1kHz
Magnetic field		
	Focus-mag.	0.14 - 0.32 T
	Defocus-mag.	0.04 - 0.13 T
Radial of closed orbit		0.81 - 1.14m
betatron tune		
	horizontal	2.17 - 2.22
	vertical	1.24 - 1.26
RF frequency		0.61 - 1.38MHz
RF voltage		1.3 - 3.0kVp

- Need long straight section with small dispersion keeping “Zero Chromaticity”.

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SCALING FFAG LINEAR LINE

- Is it possible to make a linear FFAG straight line?
  - keeping a scaling law: zero chromaticity
  - reducing dispersion: dispersion suppressor
  - making a good match with ring: insertion
- Magnetic field configuration for FFAG linear line?
  - Obviously not!

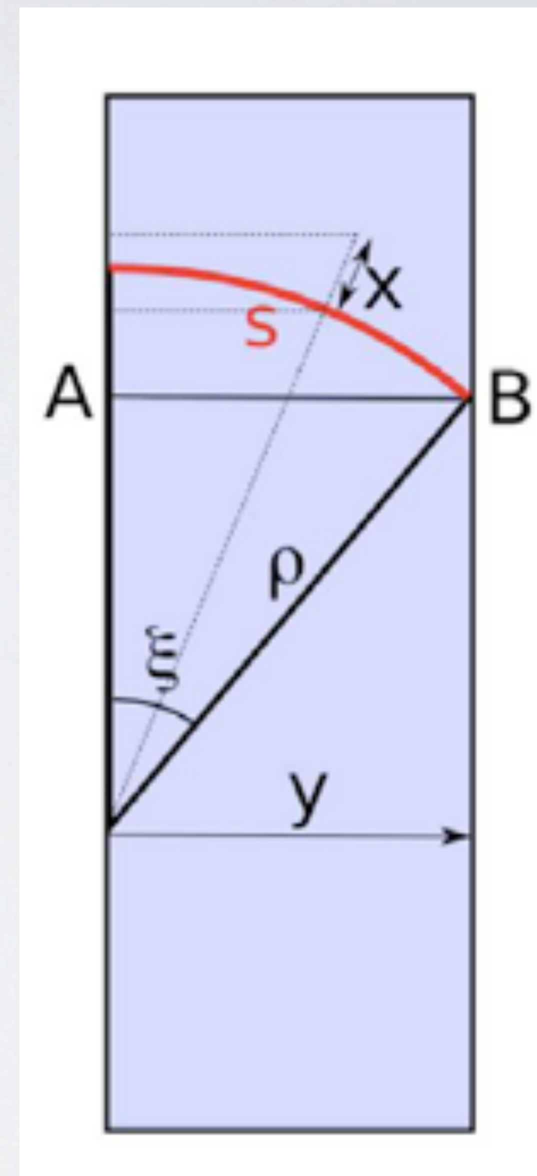
$$B = B_0 \cancel{\left(\frac{r}{r_0}\right)^k} f(\theta)$$

SCALING FIELD LINEAR(STRAIGHT) LINE

- Betatron eqs.

$$\frac{d^2x}{dy^2}+\frac{1}{\rho^2}\left(1-K\rho^2\right)x=0$$

$$\frac{d^2z}{dy^2}+\frac{1}{\rho^2}\left(K\rho^2\right)z=0$$



- Scaling conditions : zero-chromaticity
- sufficient conditions

$$\begin{cases}\dfrac{d\left(1/\rho^2\right)}{dp}=0\\[2ex] \dfrac{d\left(K\rho^2\right)}{dp}=0\end{cases} \longrightarrow \begin{cases}\rho=const.\\[1ex] \dfrac{1}{B}\left[\dfrac{\partial B_z}{\partial x}\right]_{z=0}=\dfrac{n}{\rho}\end{cases}$$

- Magnetic field

$$\boxed{B_z=B_0\exp\left[\frac{n}{\rho}x\right]}$$

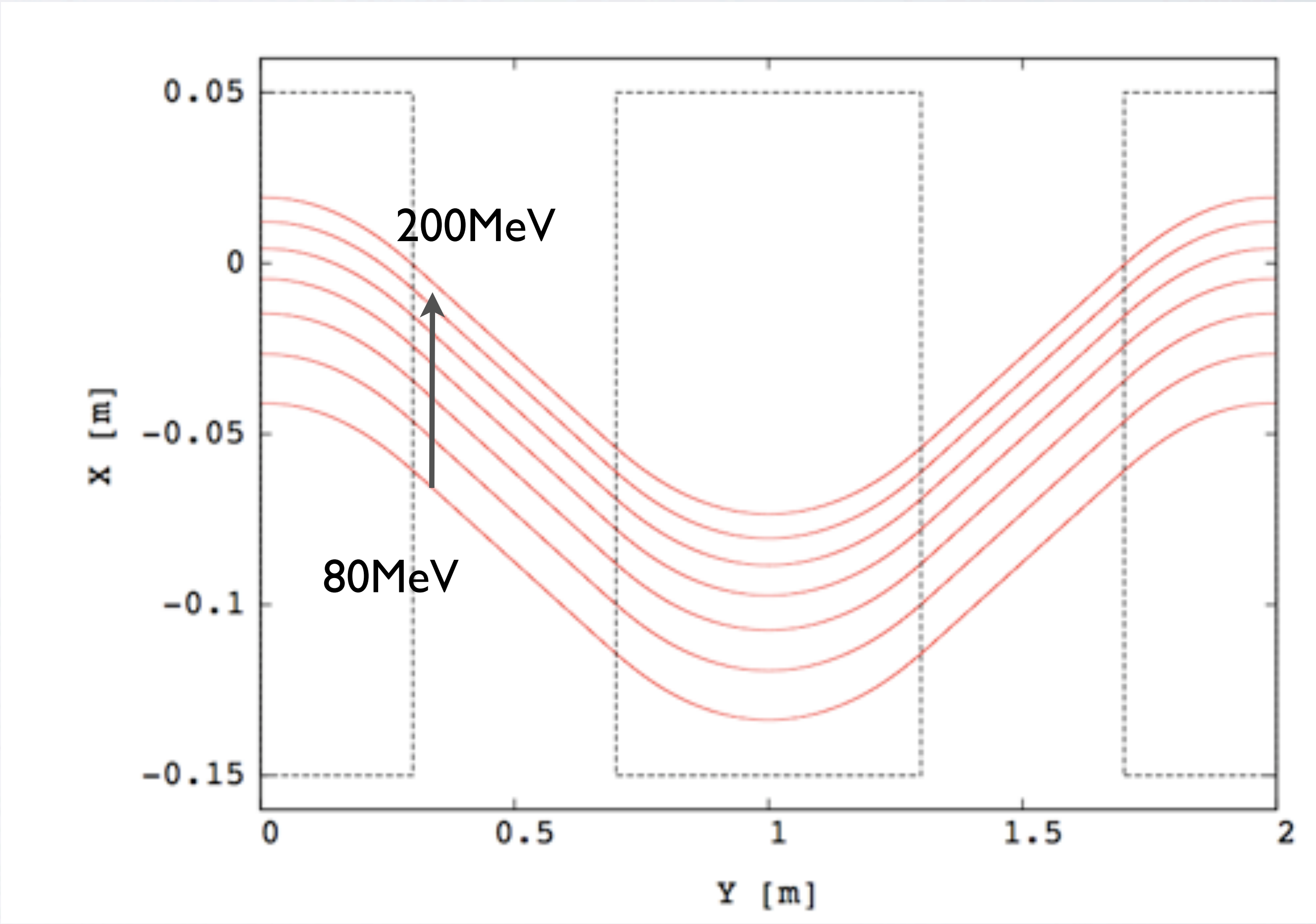
$$\left[\lim_{r_0\to\infty}\left(\frac{r}{r_0}\right)^k=\lim_{r_0\to\infty}\left[\left(1+\frac{x}{r_0}\right)^{\frac{r_0}{x}}\right]^{\frac{x}{r_0}k}=\lim_{r_0\to\infty}\left[\left(1+\frac{x}{r_0}\right)^{\frac{r_0}{x}}\right]^{\frac{n}{\rho}x}=\exp\left(\frac{n}{\rho}x\right)\right]$$

SCALING LINEAR LINE

- Example (JB. Lagrange)
  - Perfect scaling(zero-chromatic) FFAG linear transport line
  - proton 80-200MeV

Table 1: Tracking parameters

Length of the magnets	60 cm
Drift	40 cm
Kinetic energy range	80 to 200 MeV
Field index	17
Local curvature radius	2.1 m
Step size	1 mm
Phase advances:	
horizontal μ_x	104.8 deg.
vertical μ_z	112.5 deg.



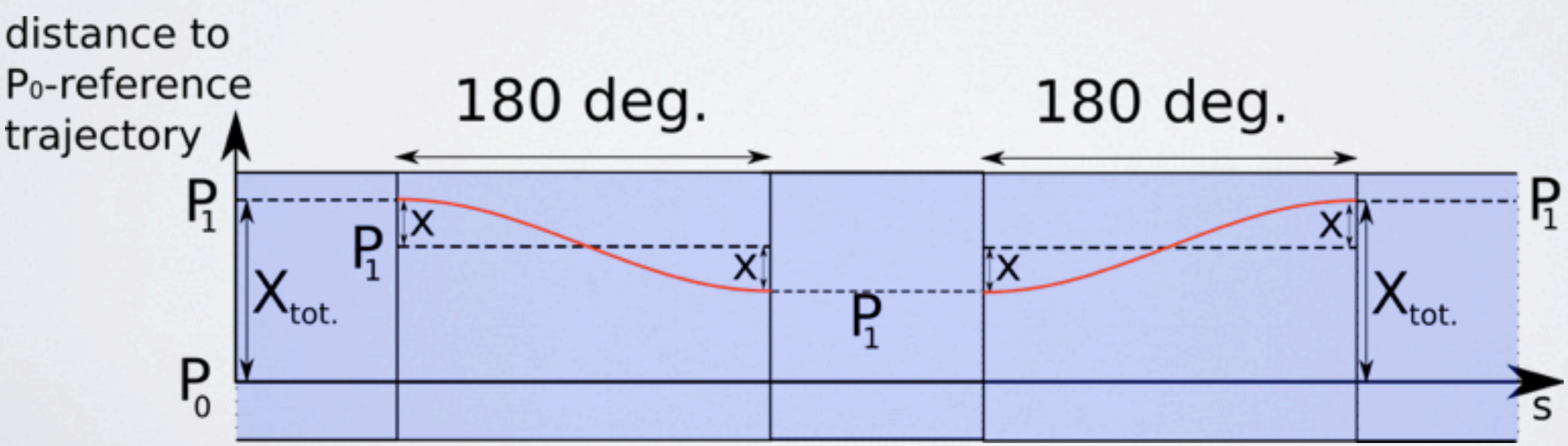
B-field

$$B_z = B_0 \exp\left[\frac{n}{\rho} x\right]$$

DISPERSION SUPRESSOR

- Dispersion suppressor (Planche,Lagrange,Mori)
    - successive π-cells in the horizontal plane can suppress the dispersion.

$$X_{tot} = X_1 - X_0 = \frac{1}{n/\rho}\ln\left(\frac{P_1}{P_0}\right) \qquad x = \ln\left(\frac{P_1}{P_0}\right)\left(\frac{\rho_0}{n_0} - \frac{\rho_1}{n_1}\right)$$



$\frac{\rho_0}{n_0}$ $\frac{\rho_1}{n_1}$

INSERTION MATCHING -RING AND STRAIGHT LINE-

- Closed orbit matching condition

$$\left(1+\frac{x}{r_m}\right)^{k+1} = \exp\left(\frac{n}{\rho}x\right)$$

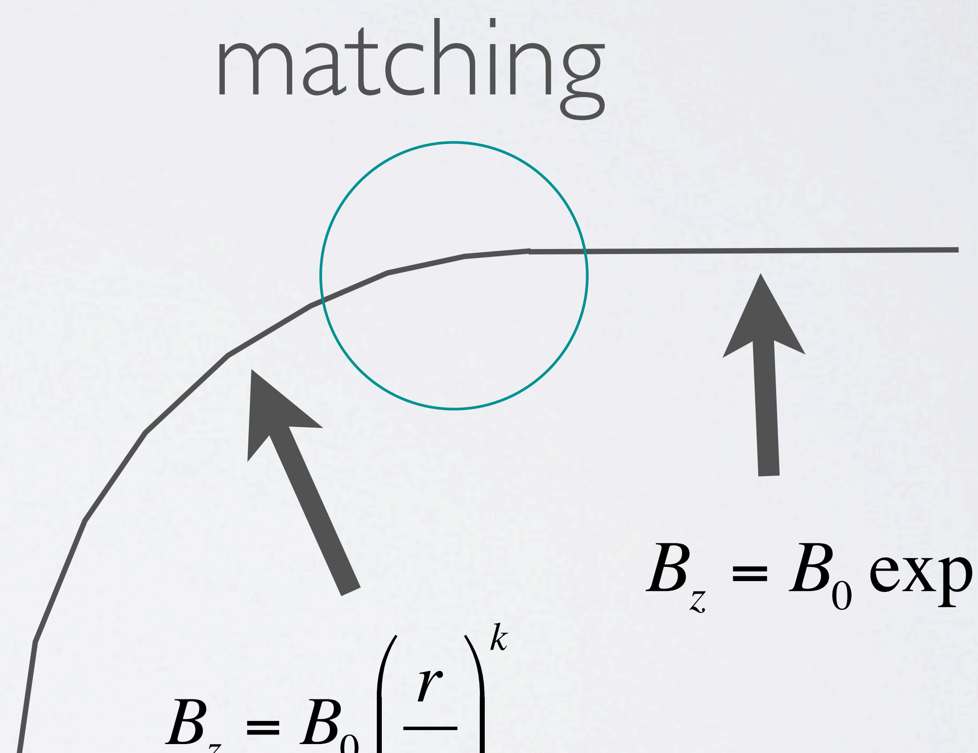
ring　　　　linear line

$$\boxed{\frac{k+1}{r_m} = \frac{n}{\rho}}$$

← 1st order

Closed Orbit mismatch
higher order error:
→ smaller for larger ring

$$\boxed{\sim \frac{1}{k}x}$$



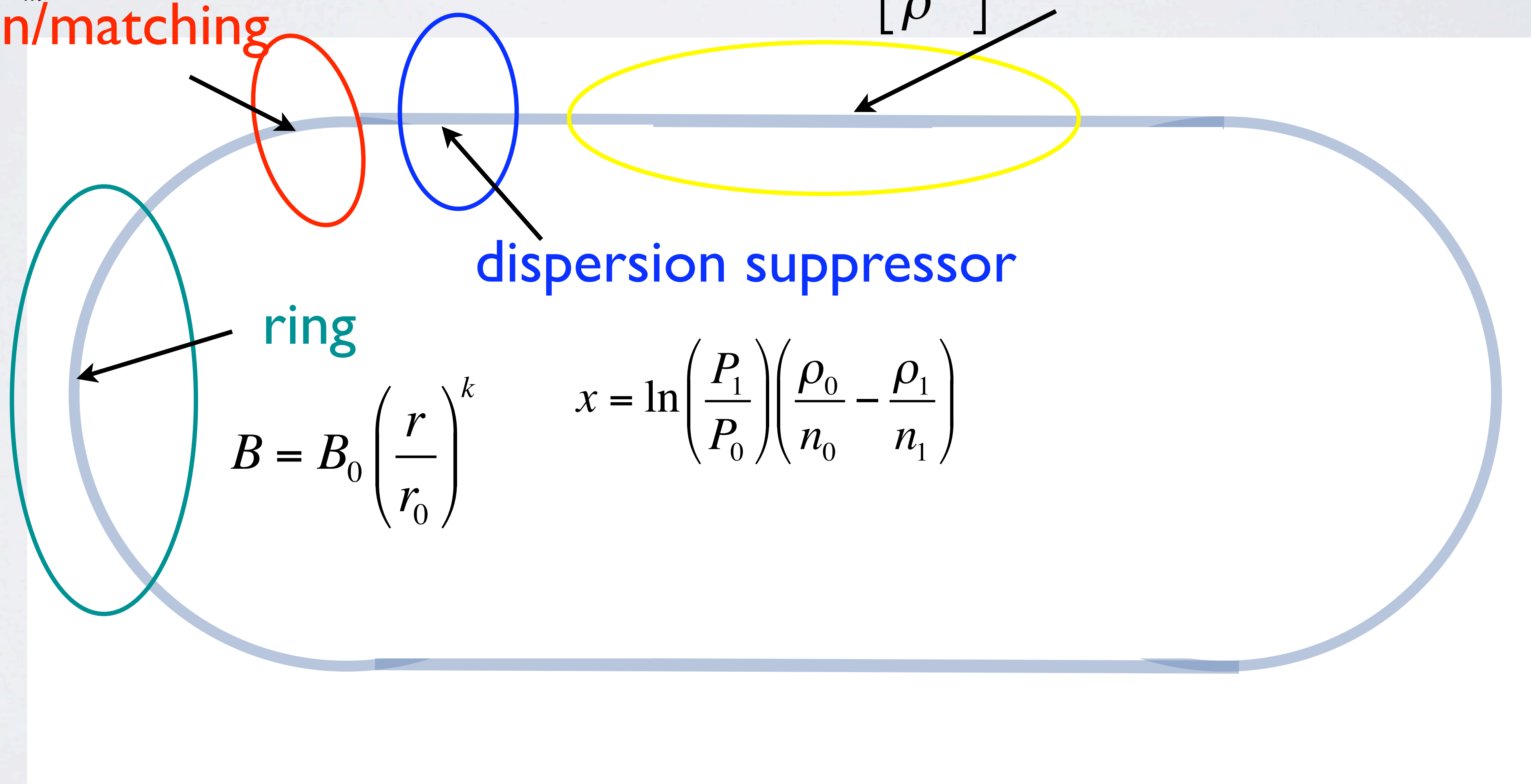
$$B_z = B_0\left(\frac{r}{r_0}\right)^k$$

$$B_z = B_0 \exp\left(\frac{n}{\rho}x\right)$$

ADVANCED SCALING FFAG

$$\frac{k+1}{r_m} = \frac{n}{\rho}$$

$$B_z = B_0 \exp\left[\frac{n}{\rho} x\right]$$



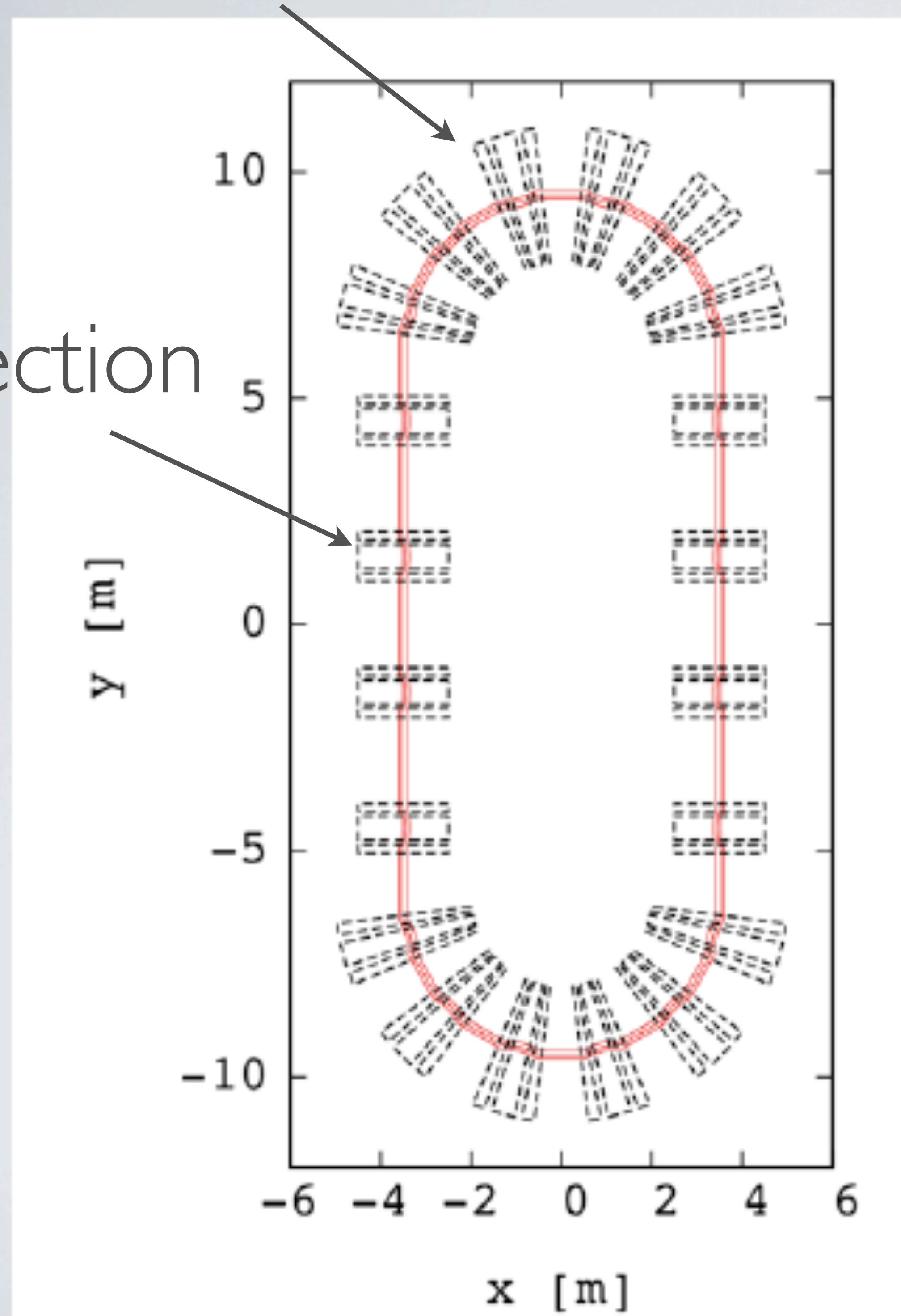
$$B = B_0 \left(\frac{r}{r_0}\right)^k$$

$$x = \ln\left(\frac{P_1}{P_0}\right)\left(\frac{\rho_0}{n_0} - \frac{\rho_1}{n_1}\right)$$

ADVANCED FFAG(1) MUON PHASE ROTATION

π-matching & ring

straight section

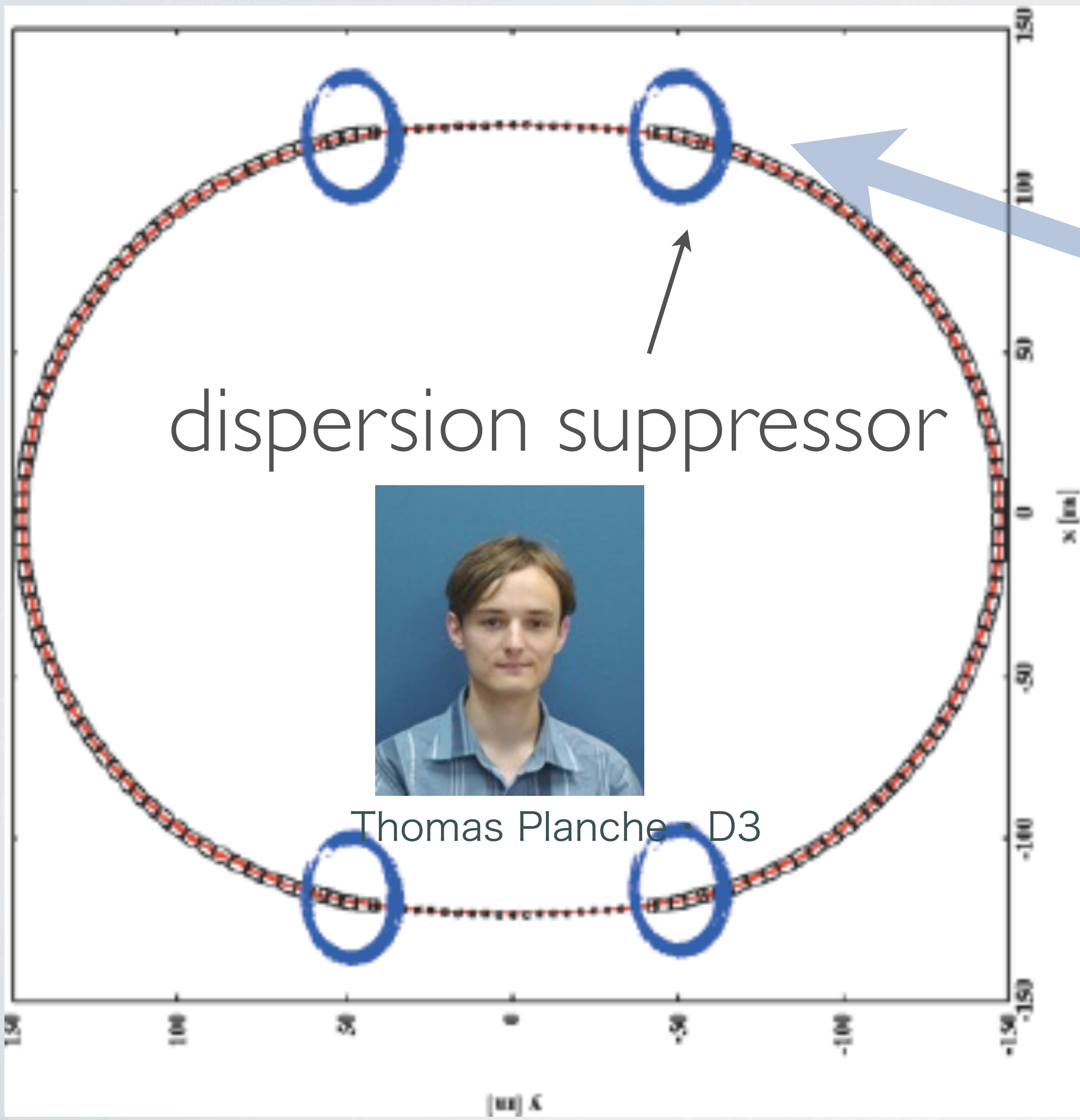


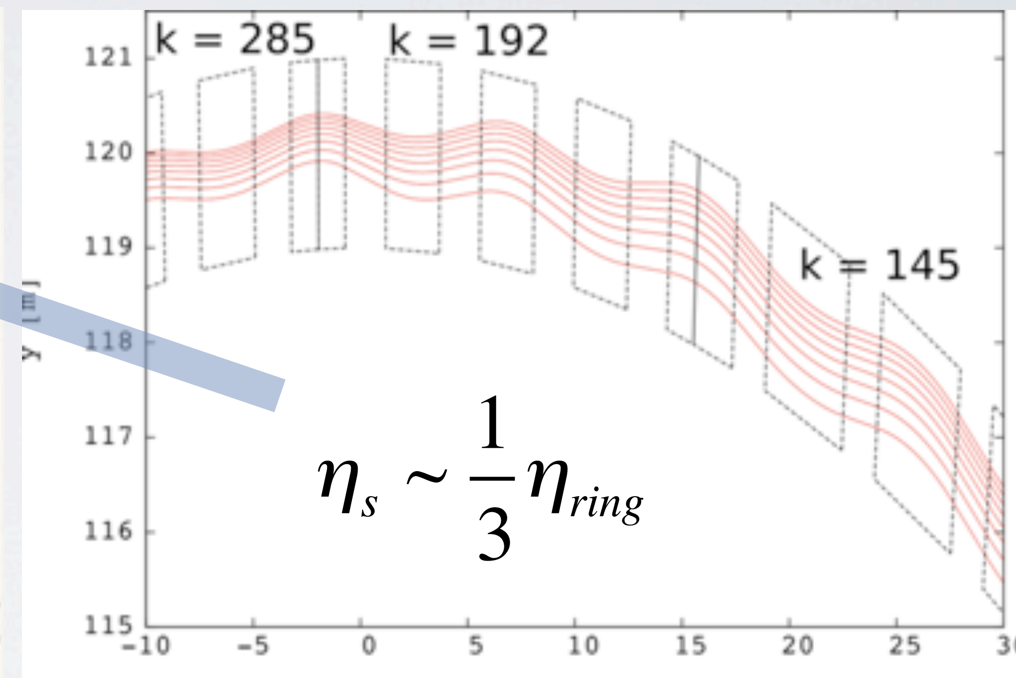
PRISM LATTICE

Bending cell	
k	6.5
Average radius	3.5 m
Phase advances:	
horizontal μ_x	90 deg.
vertical μ_z	90 deg.
Dispersion	0.47 m

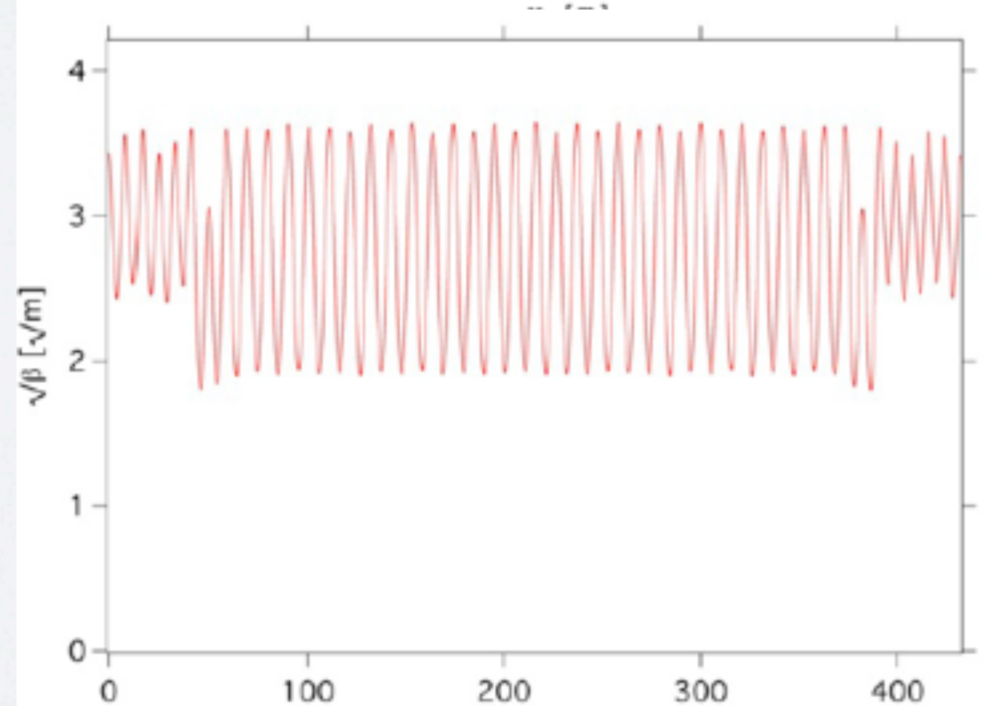
Straight cell	
n/ρ	$2.14\,m^{-1}$
Length	$3\,m$
Phase advances:	
horizontal μ_x	24 deg.
vertical μ_z	87 deg.

ADVANCED FFAG (2) MUON ACCELERATOR E=3-10GEV





$$\eta_s \sim \frac{1}{3}\eta_{ring}$$



APPLICATIONS

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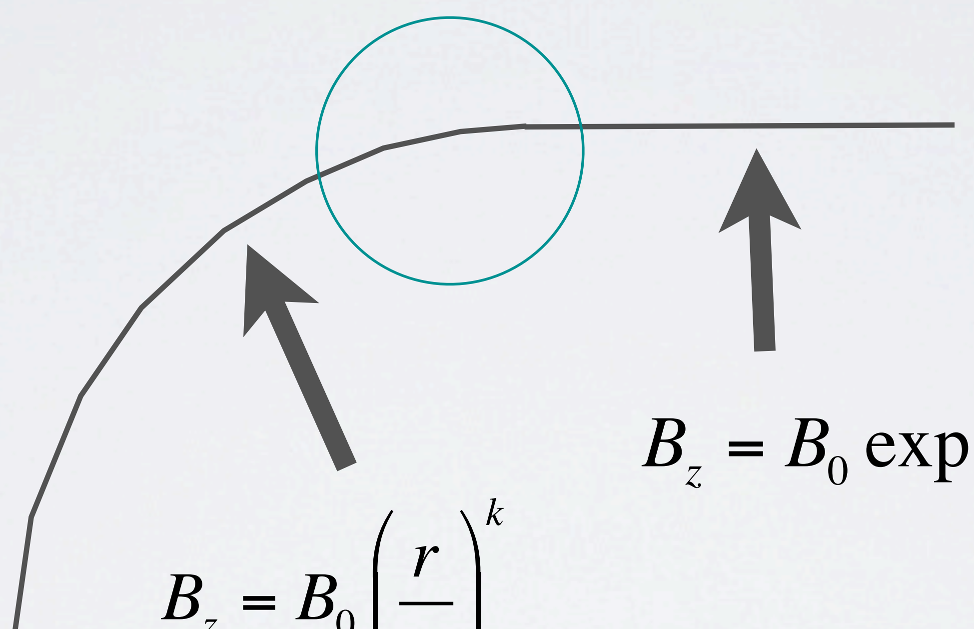
matching



$$B_z = B_0 \exp\left(\frac{n}{\rho} x\right)$$

$$B_z = B_0 \left(\frac{r}{r_0}\right)^k$$