10 YEARS OF FFAG DEVELOPMENT

Yoshiharu Mori
Kyoto University, Research Reactor Institute

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mostly in Japan

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HISTORY OF FFAG

- Backgrounds
  - Alternating Gradient(strong) focusing (by Christofolus, Courant, Snyder, Livingston)
  - Phase stability in rf acceleration (by Macmillan) :synchrotron oscillation
- Innovation of FFAG:1950's
  - Okawa(Japan), Kerst & Simon(USA), Kolomenski (USSR)
  - FODO lattice with Zero-chromaticity : betatron tunes are constant
    - Magnetic field → $B \propto r^k f(\theta)$: static magnetic field
  - No-isochronism : Acceleration → Phase stability with synchrotron oscillation

FFAG'03 at KEK

T.Okawa

FFAG'03 at KEK

T.Okawa

FFAG’03 at KEK

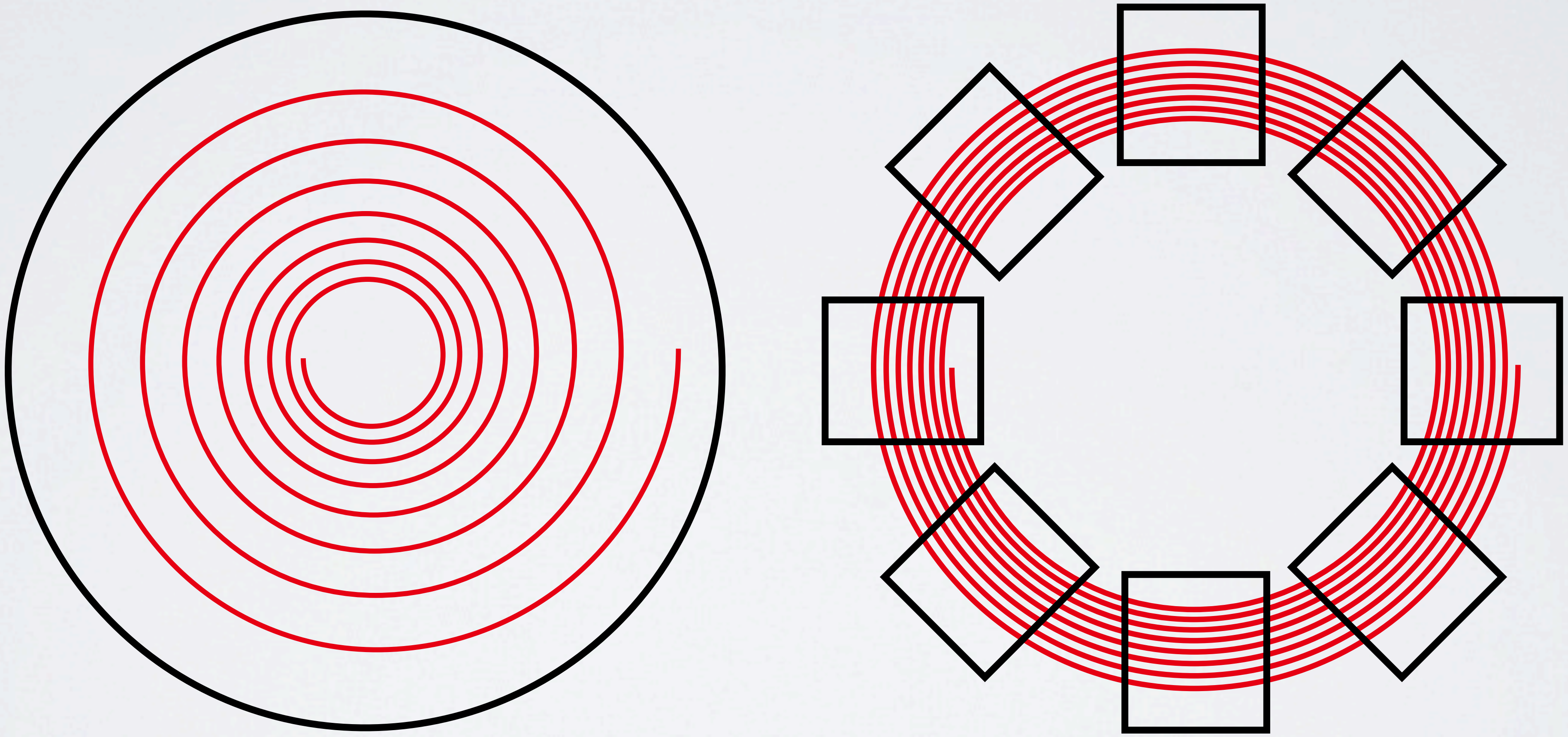
T.Okawa

HISTORY OF FFAGS

- Idea
  - 1950s Okawa(Japan), Kerst-Symon(USA), Kolomenskii (USSR)
- Developments
  - 1960s MURA project (USA) Electron models
  - 2000 POP-FFAG (KEK, Japan) First proton FFAG
  - 2004 150-MeV proton FFAGs (KEK, Kyusyu, Japan)
  - 2005 R&Ds for various applications:RACAAM(Grenoble, France), PD(FNAL, USA), etc.
  - 2008 Proton FFAGs for ADSR (Kyoto, Japan)
  - 2008 PRISM-FFAG for muon (Osaka, Japan)
  - 2009 e-FFAG(NHV, Japan)
  - 2010 EMMA(Daresbury, England) First non-scaling FFAG

FIELD INDEX
ORBIT EXCURSION

Field Index → $k = -\frac{r}{B}\frac{\partial B}{\partial r}$



$k \approx 0$

Cyclotron

$k >> 1$

FFAG

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 : $\Delta p/p > +-100\%$
- 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

AG FOCUSING LATTICE OF SCALING FFAG RING

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

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

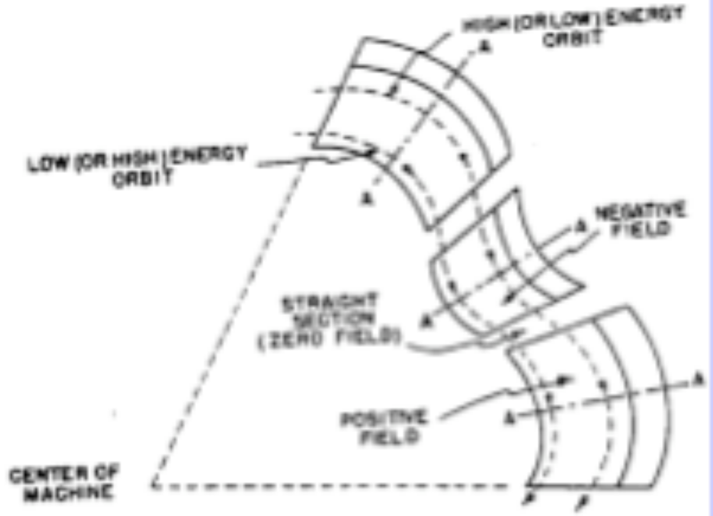


Fig. 2. Plan view of radial-sector magnets.

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

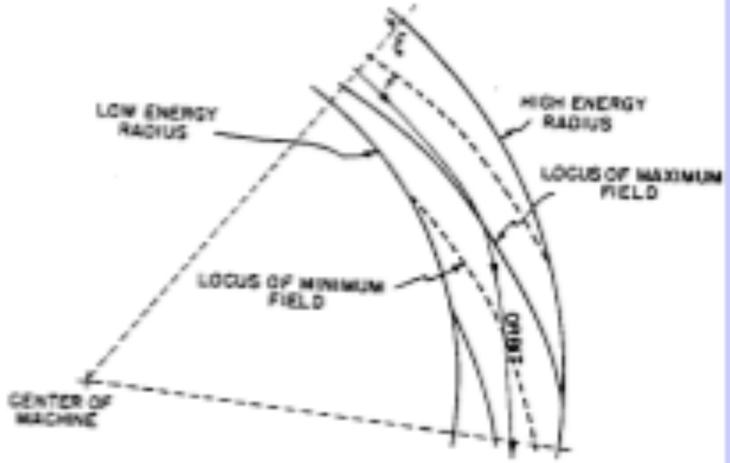
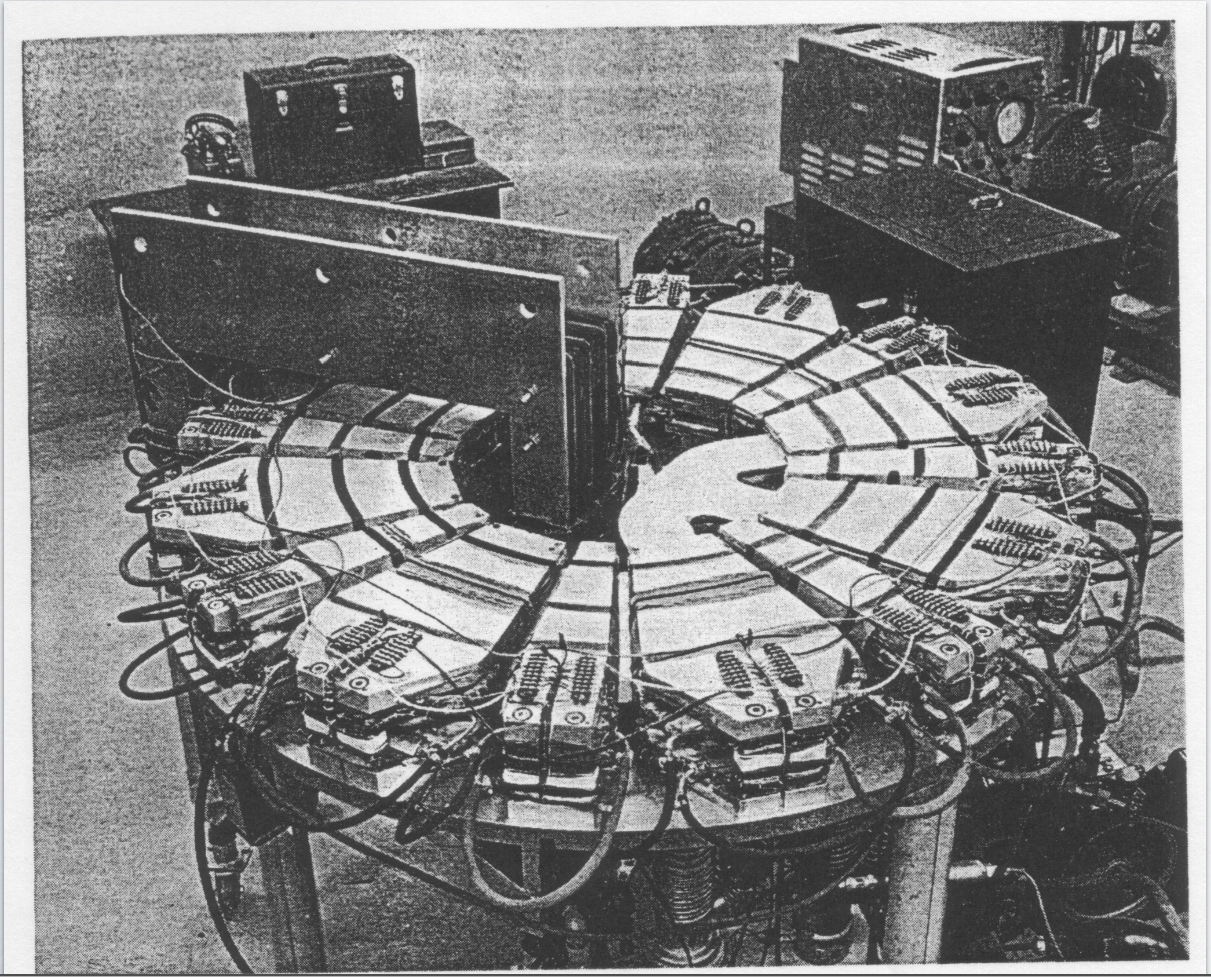
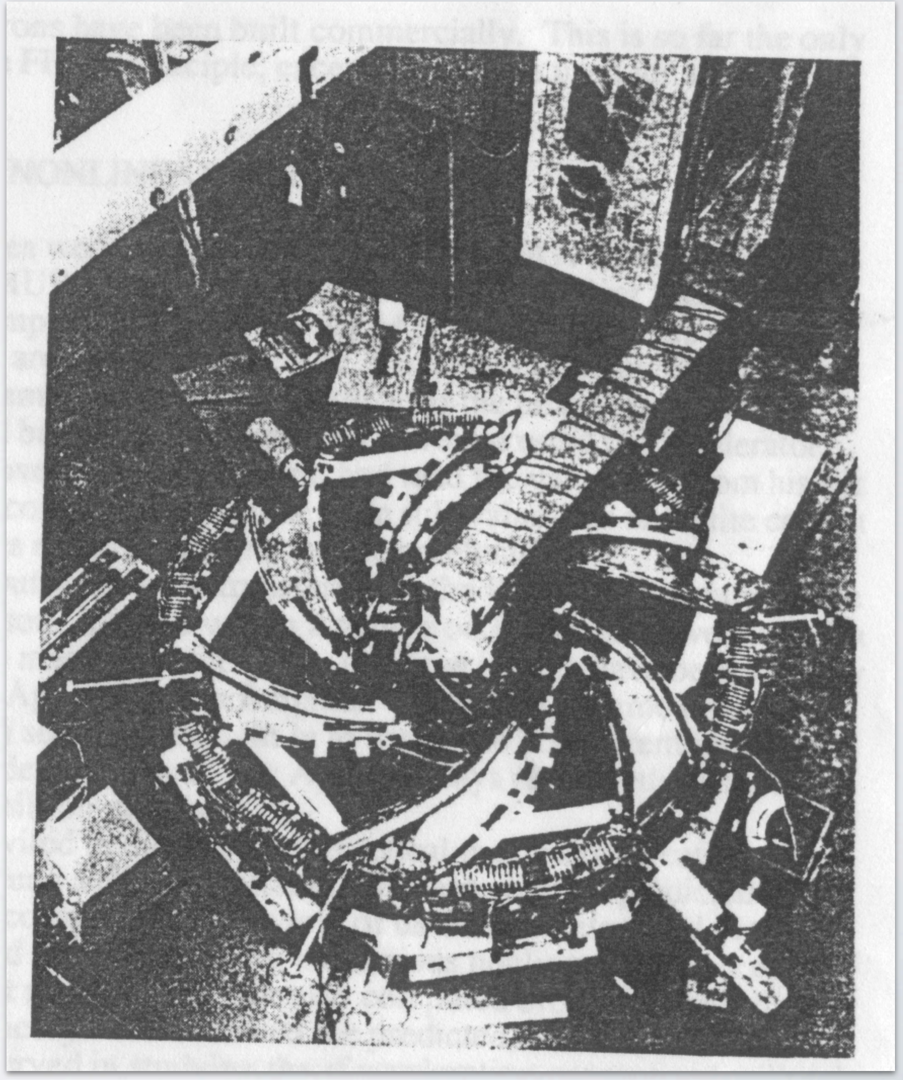


Fig. 3. Spiral-sector configuration.

MURA FFAG
ELECTRON MODEL

- 1960's MURA project (USA) : Cole et al.
- Acceleration Induction (betatron)
  No practcal RF acceleration
- No proton acceleration





DIFFICULTIES

HADRON(PROTON) ACCELERATION IN FFAGS

- Need a new rf accelerating cavity.
  - broad-band and high gradient
    - Particle velocity changes in wide range.
    - Rooms for the rf cavity are limited in the ring because of its compactness and high super-periodicity.
- Need a non-linear(high gradient) field magnet.
  - careful 3D design of magnetic field
    - Zero chromaticity is very needed because momentum gain per turn is relatively small compared with that of electron.

REQUIREMENTS OF RF CAVITY

- Broad band
  - Frequency sweep of a factor.
- High gradient
  - Make it fast acceleration possible.
- Large aperture
  - Especially in horizontal to accommodate orbit excursion.
- A few MHz to have large longitudinal acceptance

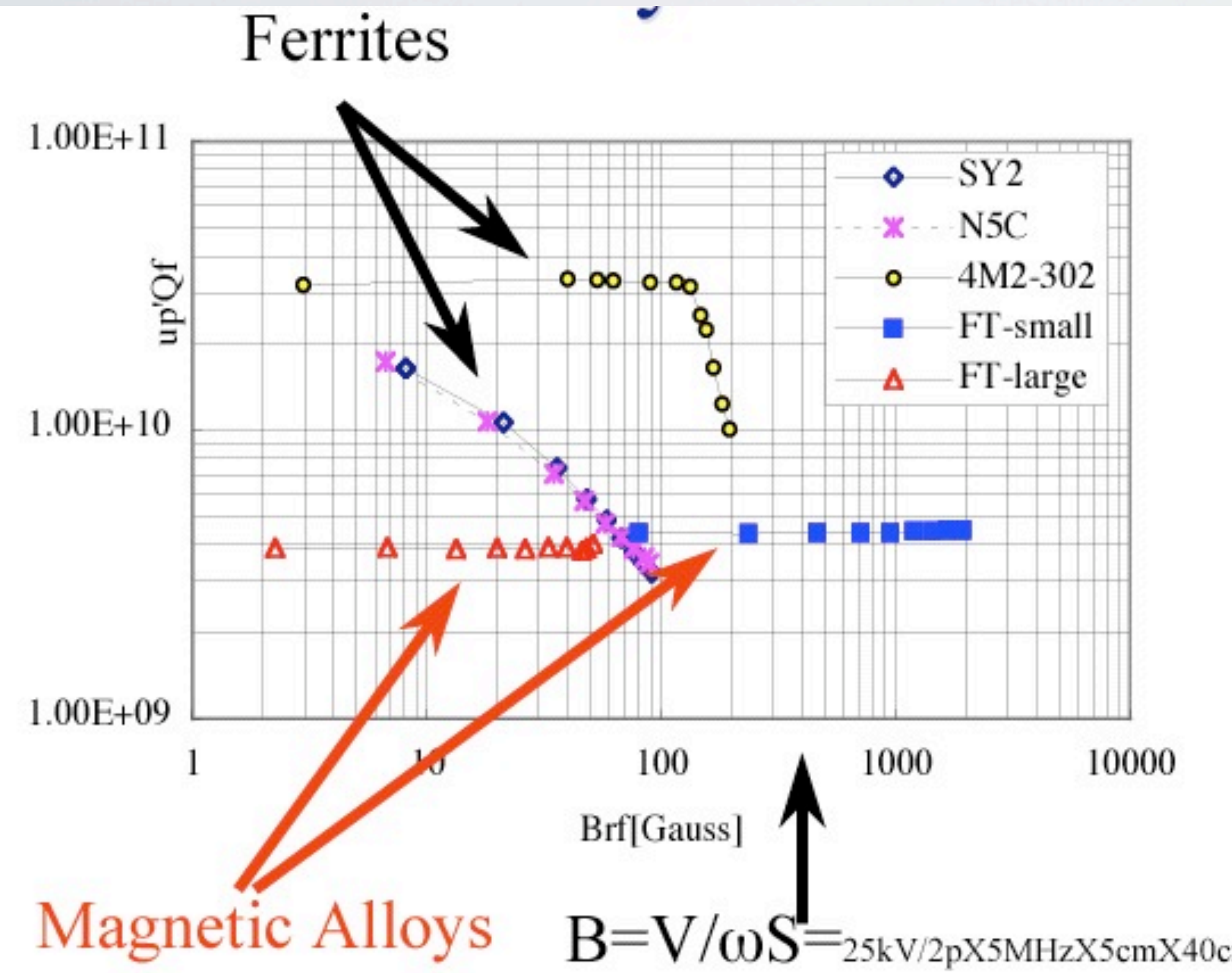
- **RF cavity with Magnetic Alloy has been developed at KEK for JPARC cavity.**

PERSONAL HISTORY

- 1995 ~2004 Design, development and construction of J-PARC synchrotrons (3GeV, 50GeV)
  - Colleagues: Machida, Ishi(ring design), Yoshii, Ohmori(rf), Tomizawa(slow extraction), Muto(magnet) ....

MQF (SHUNT IMPEDANCE)

- A μQF remains constant at high RF magnetic RF (Brf) more than 2 kG.
- Ferrite has larger value at low field, but drops rapidly.
  - RF field gradient is saturated.

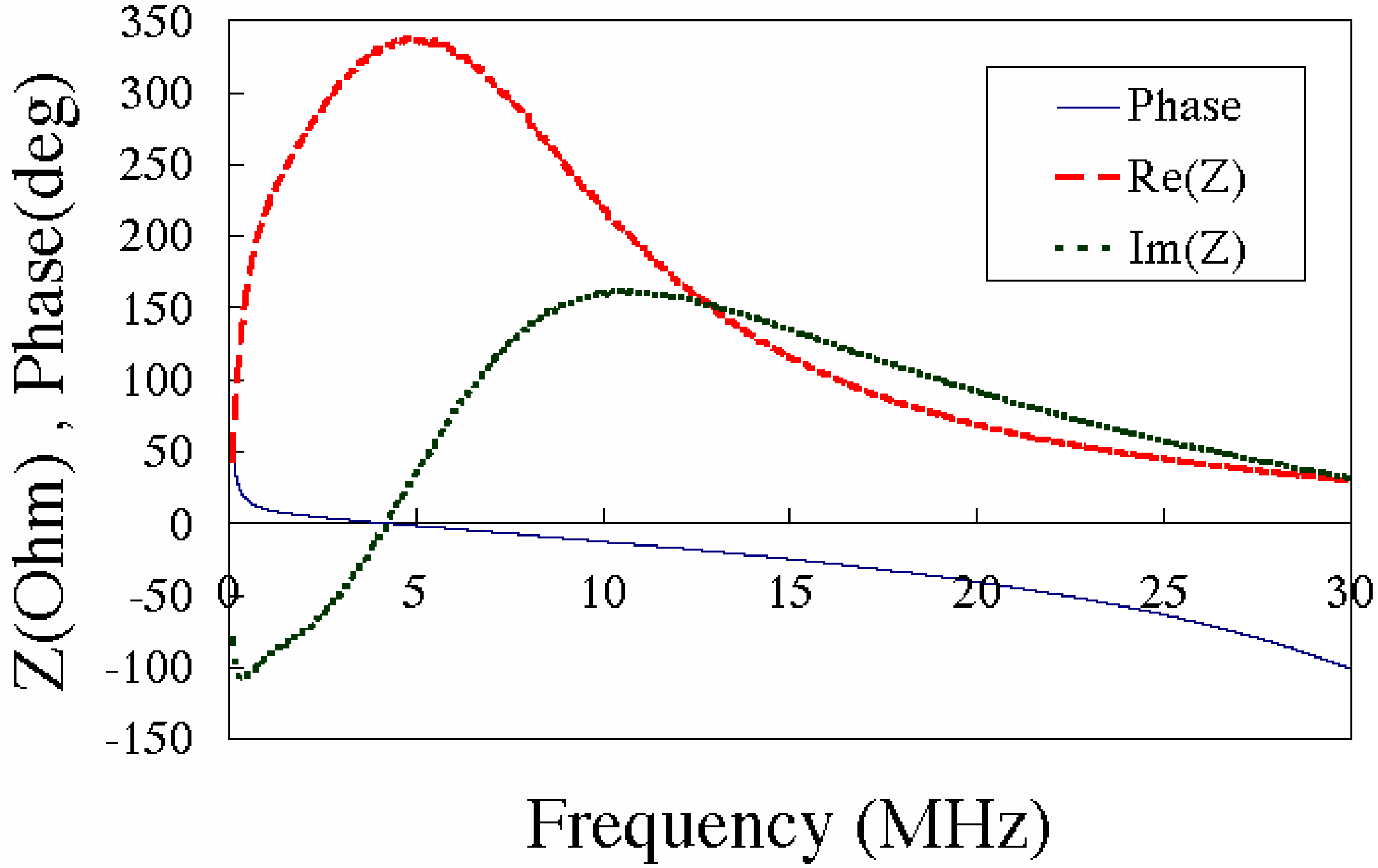


$B=V/\omega S=_{25kV/2pX5MHzX5cmX40cm}=400Gauss$

High permeability
~2000 at 5 MHz
High curie temperature
~570 deg.
Thin tape
~18 mm
Q is small
~0.6

BROAD BAND

- Q ~ 1 : no-need to tune the rf frequency
- Rapid frequency swing is possible → Rapid acceleration

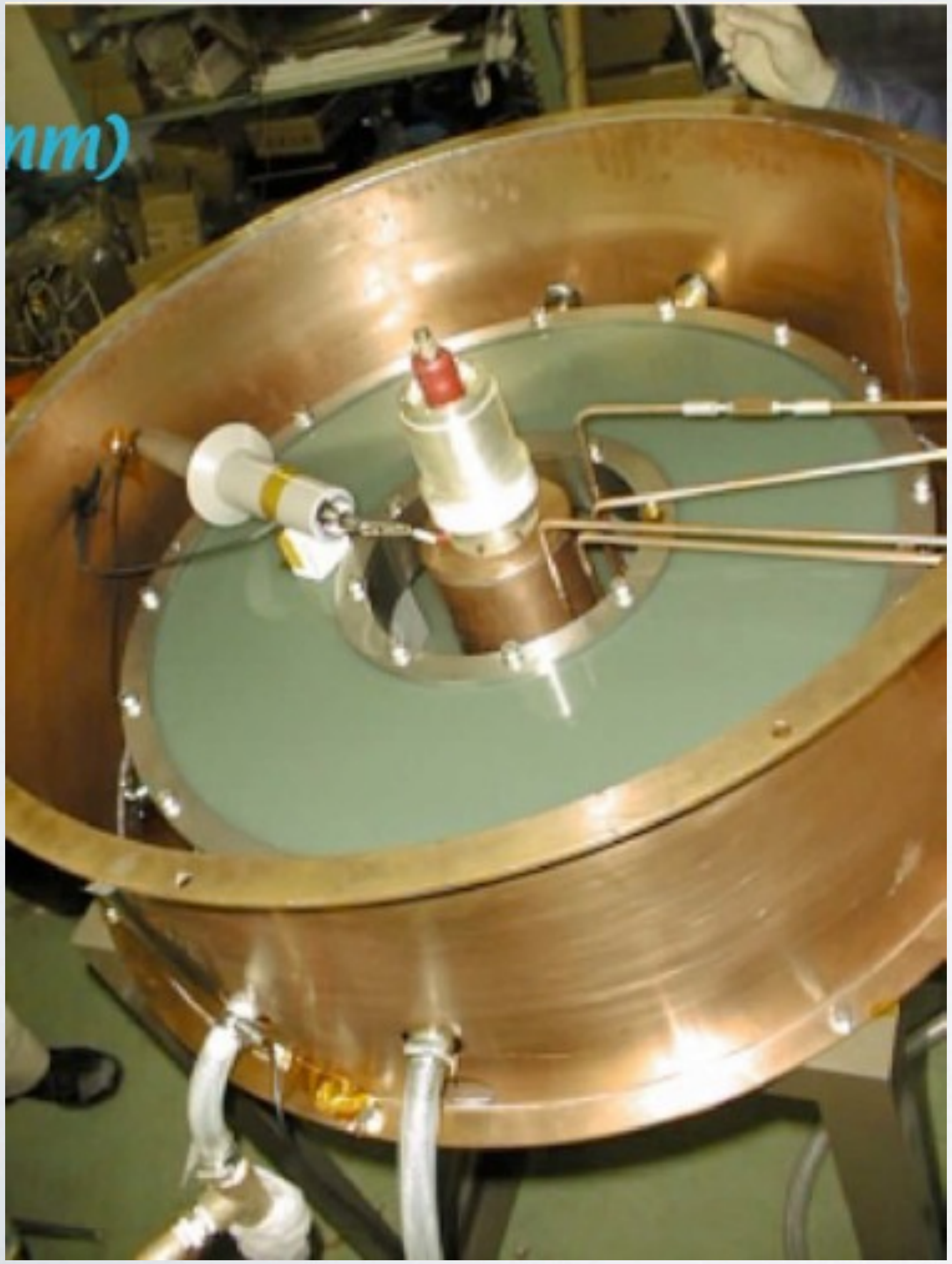


DEVELOPMENT OF MA CAVITY

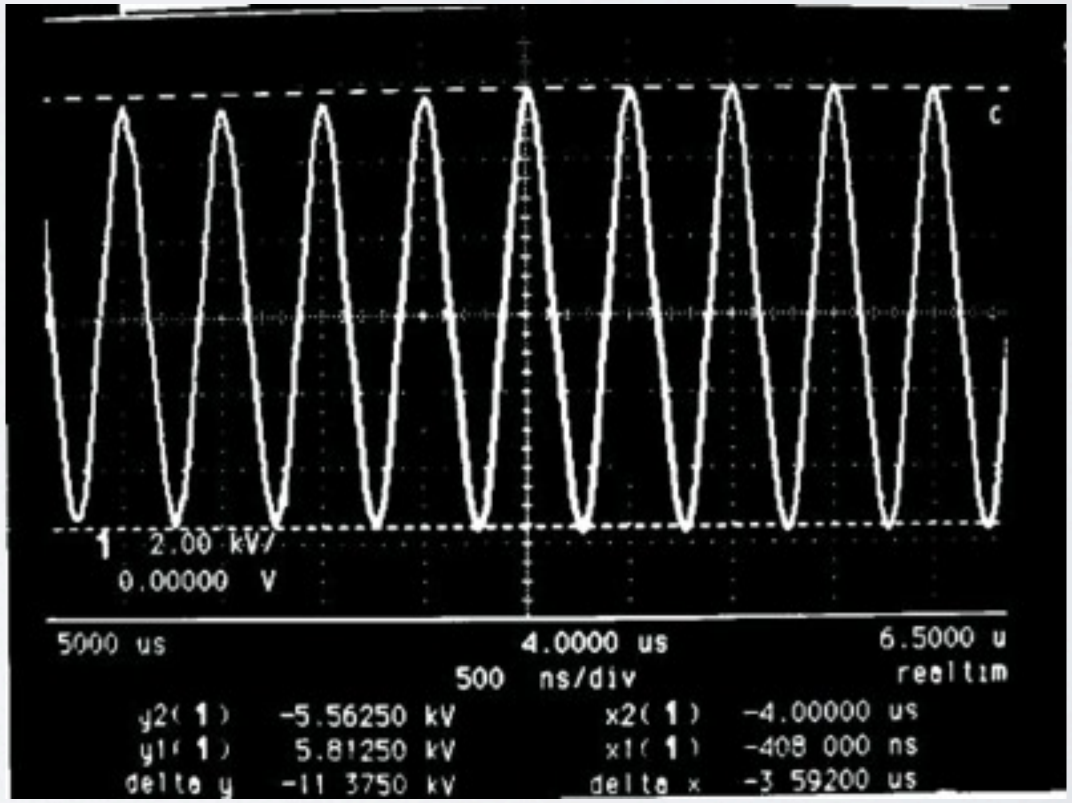
EPAC'98 (THOB03B)

TEST CAVITY

*Single core (O.D=580mm,I.D=250mm, t=25mm)
*Direct water cooling
*RF power :30kW max.(B-class)



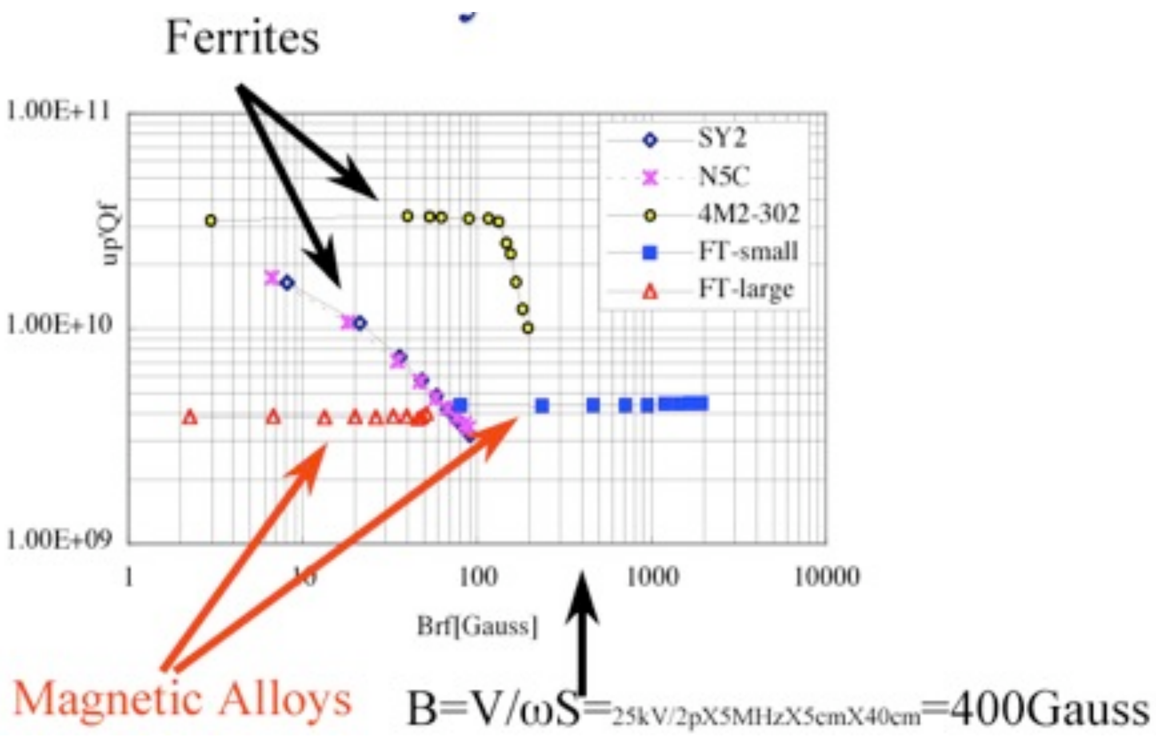
- Direct water cooled test cavity.
- Achieved
  - 100 kV/m for CW mode
  - 220 kV/m for burst mode



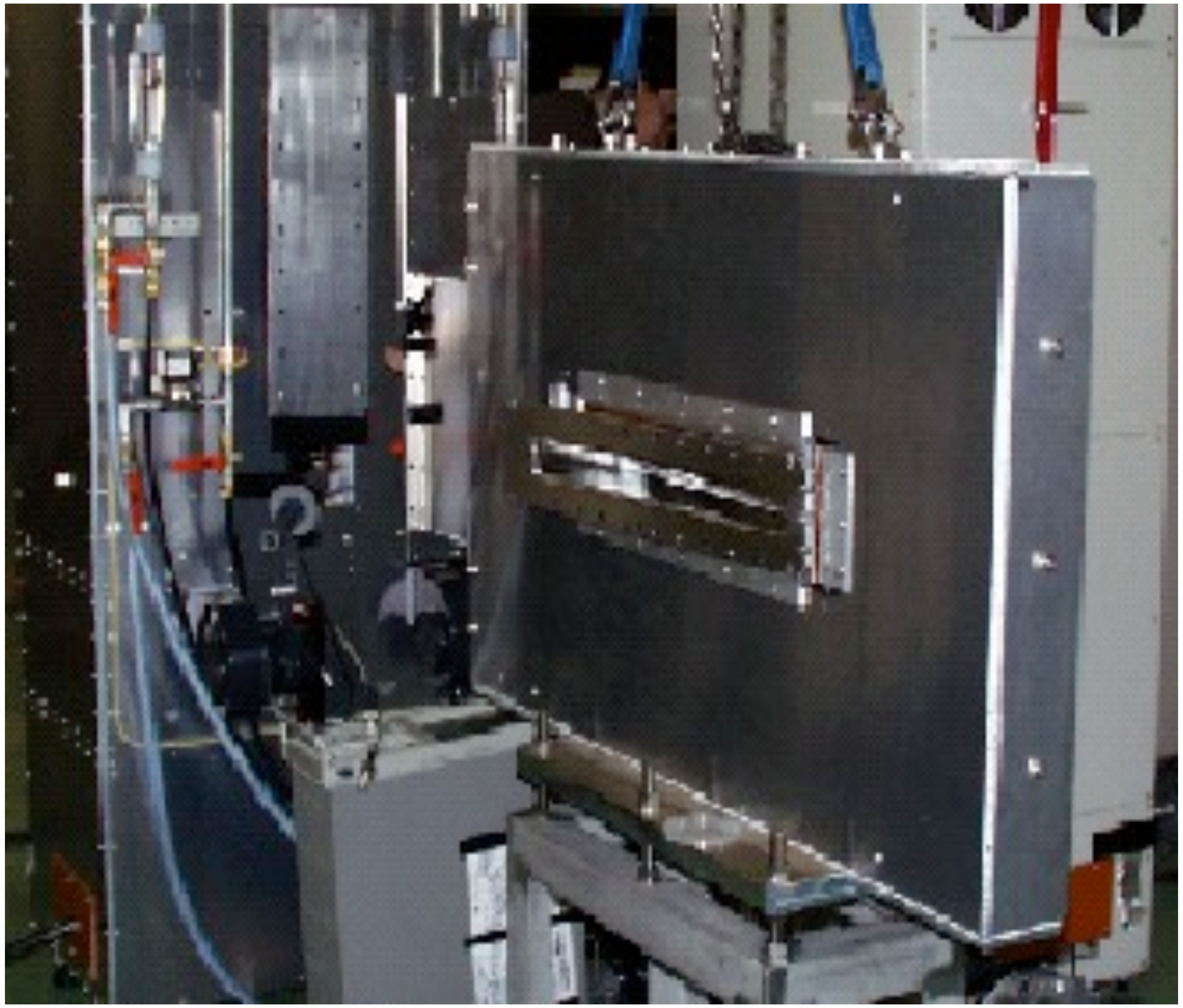
```
y2( 1 )   -5.56250 kV        x2( 1 )   -4.00000 us
y1( 1 )    5.81250 kV        x1( 1 )   -408 000 ns
delta y   -11 3750 kV        delta x   -3 59200 us
```

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.

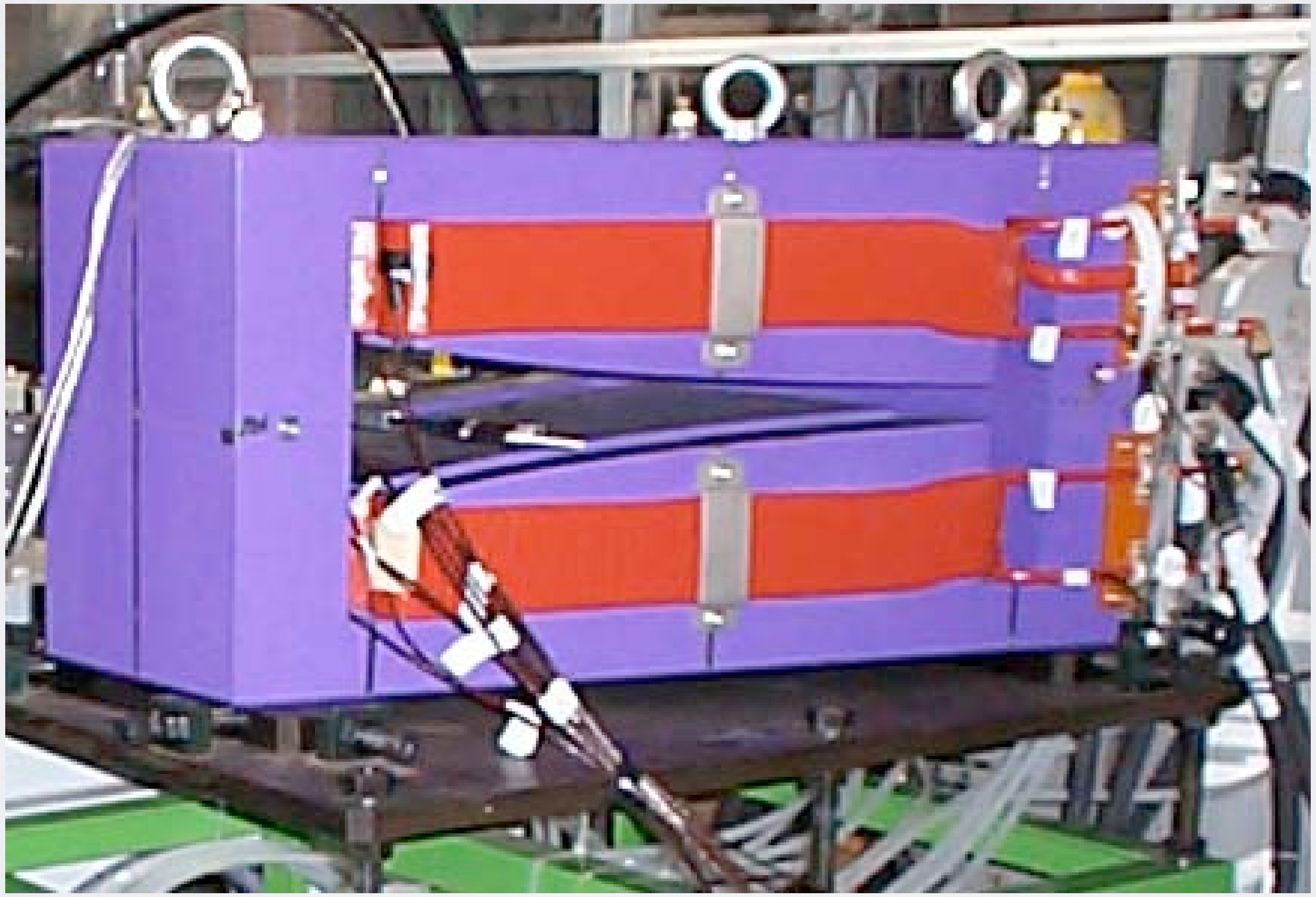


$B=V/\omega S=_{25kV/2pX5MHzX5cmX40cm}=400Gauss$

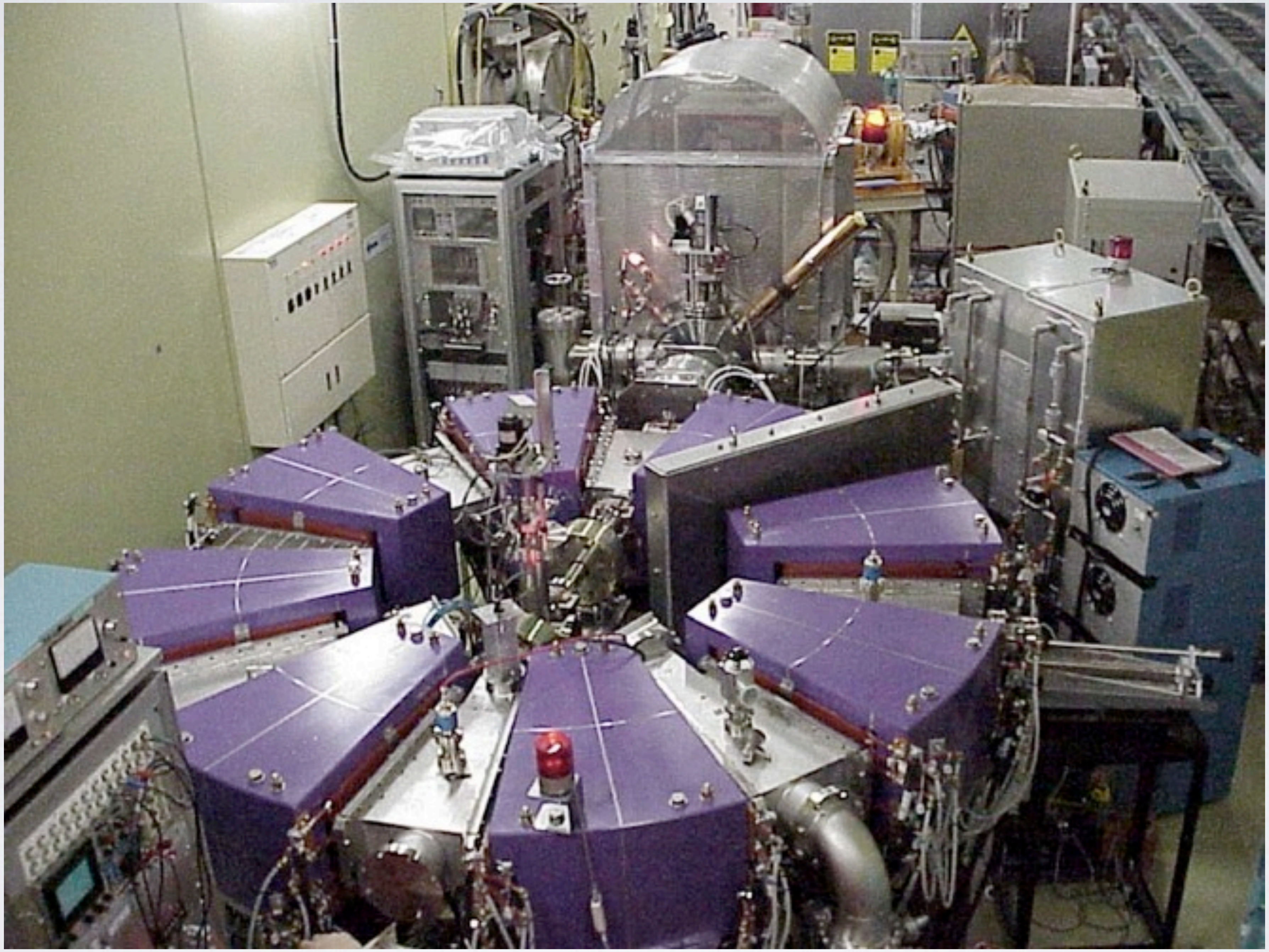


MAGNET: TAPERED GAP

- Gap(r) is proportional to 1/B(r)
  - Easiest
  - Fringe field has wrong sign.
    - g/r should be constant to have similar fringe field effects

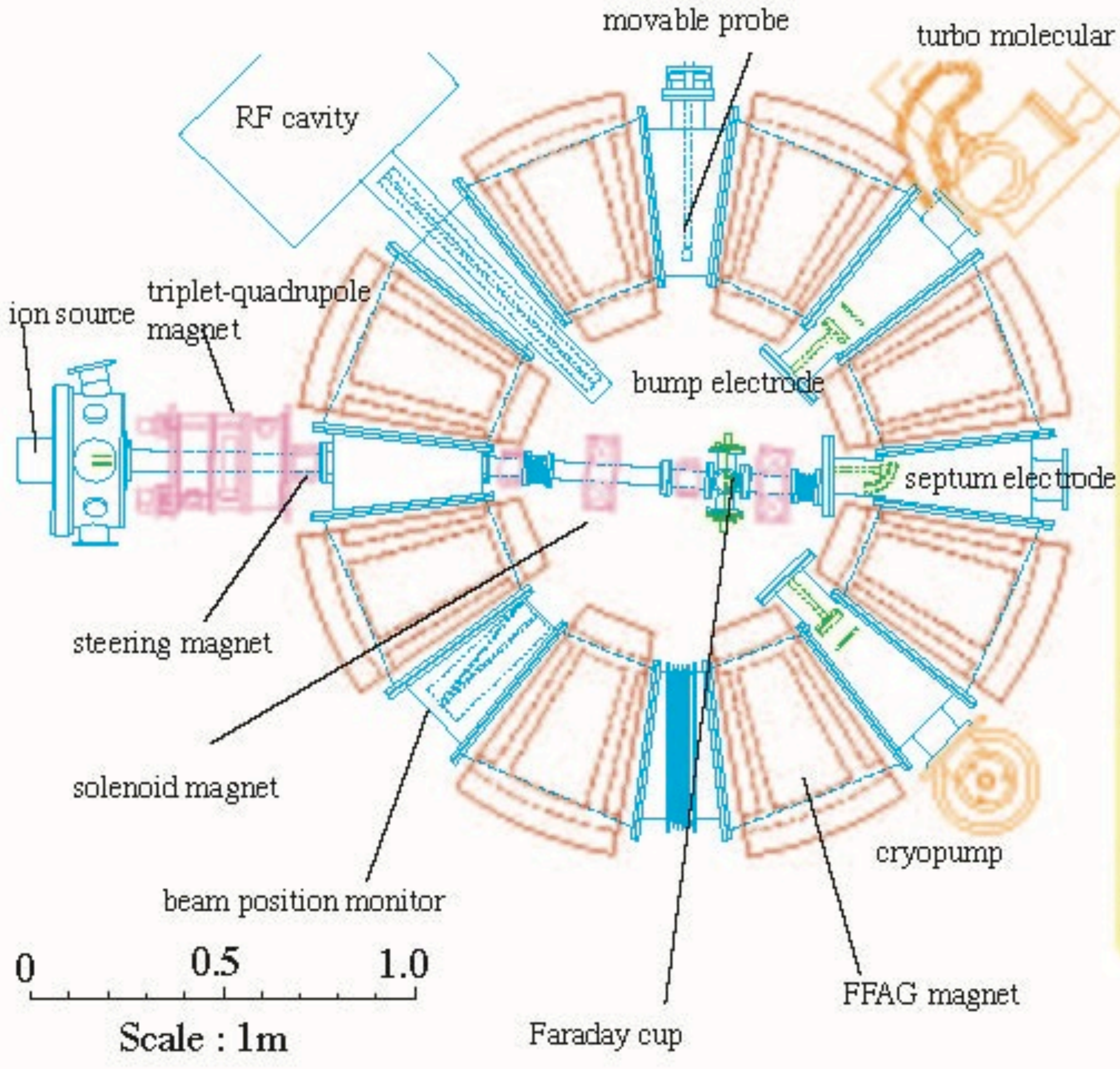


WORLD FIRST PROTON FFAG ACCELERATOR



- PoP(proof-of-principle) FFAG :KEK 2000

LAYOUT OF POP-FFAG



PoP-FFAG parameter table

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

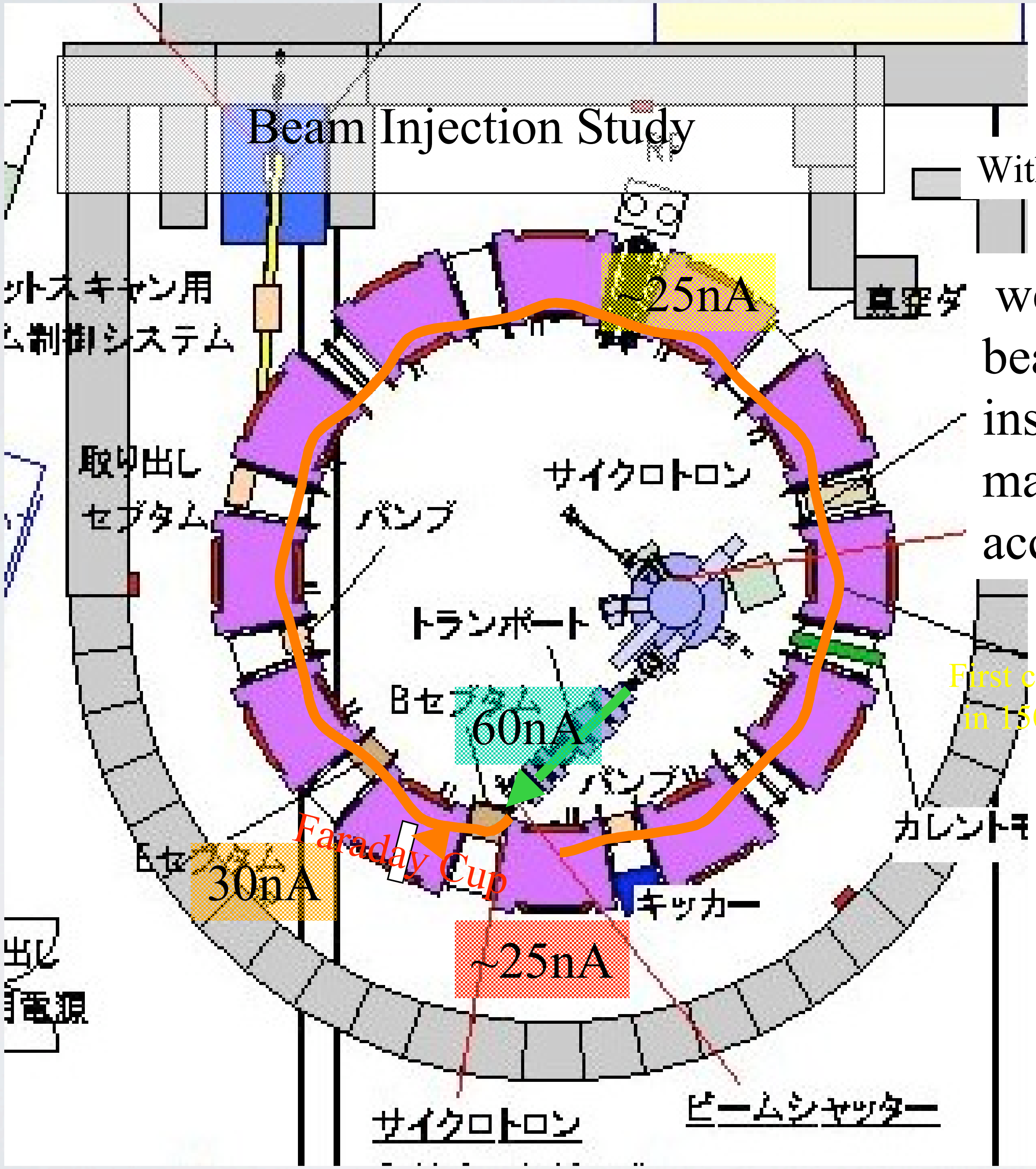
INTERNATIONAL WORKSHOP ON FFAG ACCELERATOR

- (history)
  - 1st FFAG99 (Dec. 1999) KEK PoP-FFAG first beam!
  - 2nd FFAG workshop (July 2000) CERN
  - 3rd FFAG00 (Oct. 2000) KEK
  - 4th FFAG02 (Feb. 2002) KEK
  - 5th FFAG workshop (Sept. 2002) LBL
  - 6th FFAG03 (July 2003) KEK
  - 7th FFAG workshop (Sept. 2003) BNL
  - 8th FFAG workshop (Mar. 2004) TRIUMF
  - 9th FFAG04 (Oct. 2004) KEK 150MeV proton FFAG first beam!

Almost twice per year! One the most acitive fields in accelerator physics and technology.

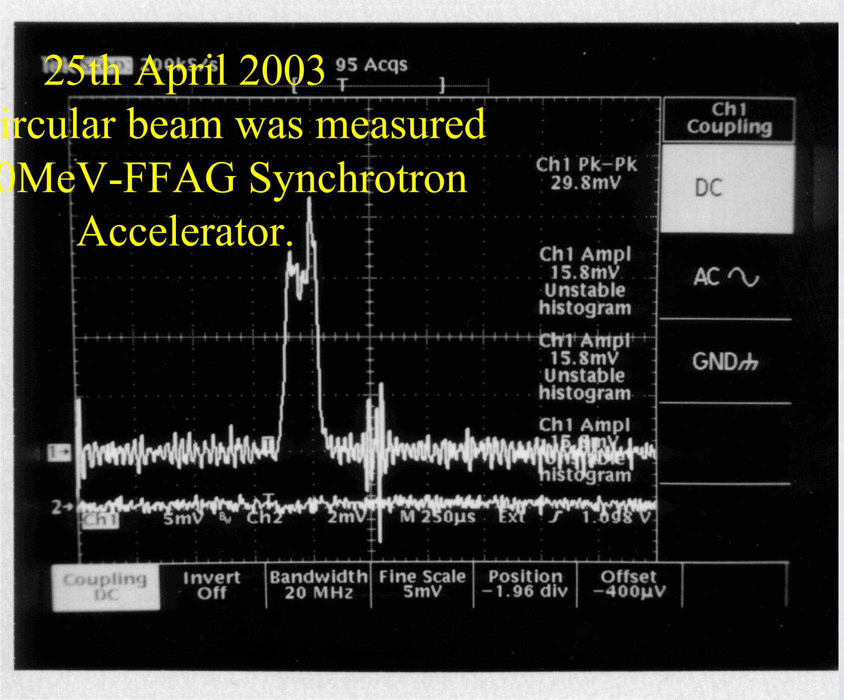
FIRST BEAM !

APR. 2003



With Magnetic and Electric Septum

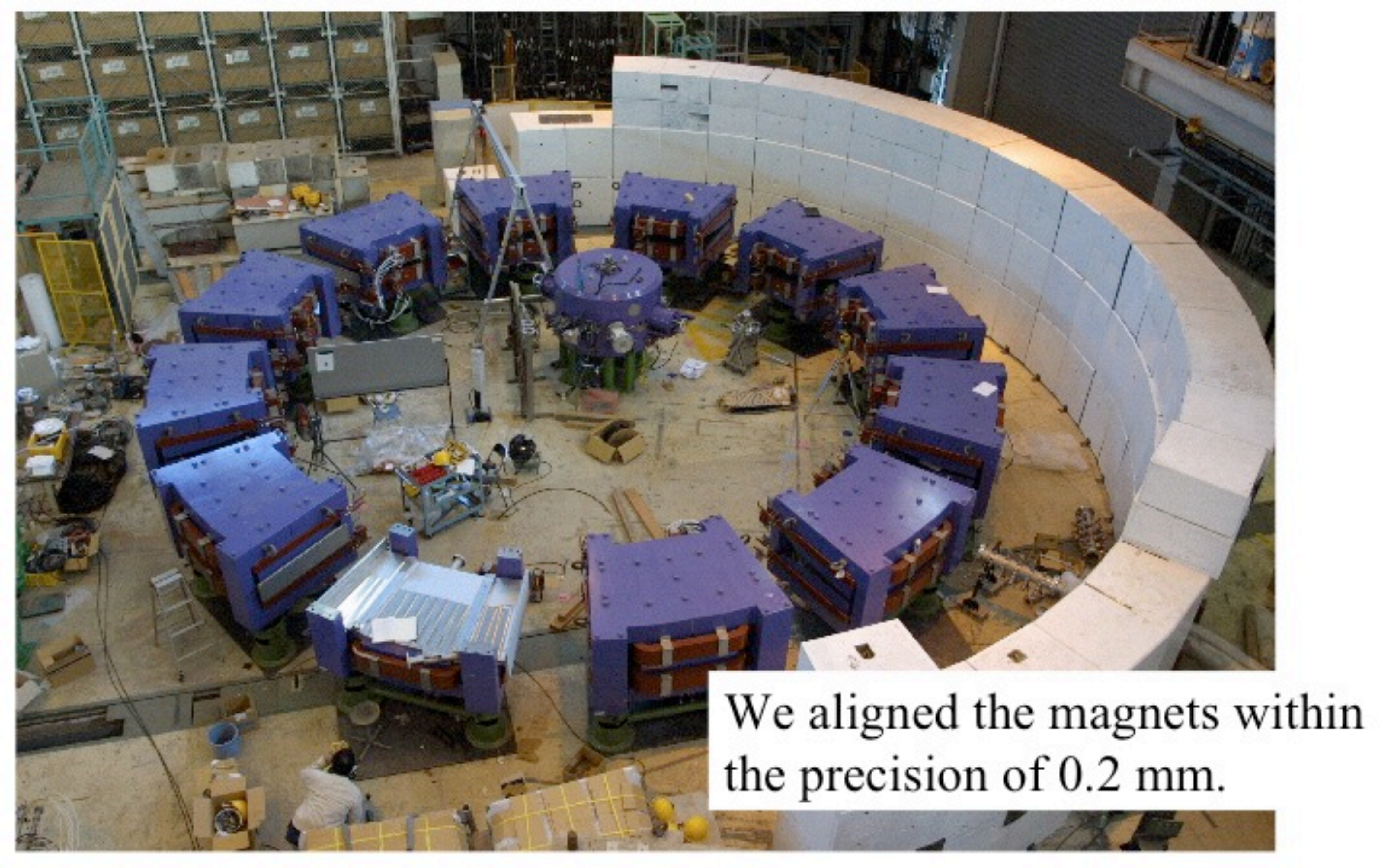
we are studying the beam orbit in detail, and installing the bump magnets for the beam acceleration



25th April 2003
First circular beam was measured in 150MeV-FFAG Synchrotron Accelerator.

ALIGNMENT

JAN. 2003



We aligned the magnets within the precision of 0.2 mm.

150MeV FFAG Proton Accelerator 2003 Apr.

Cyclotron(Injector) and Beam transport

Cyclotron

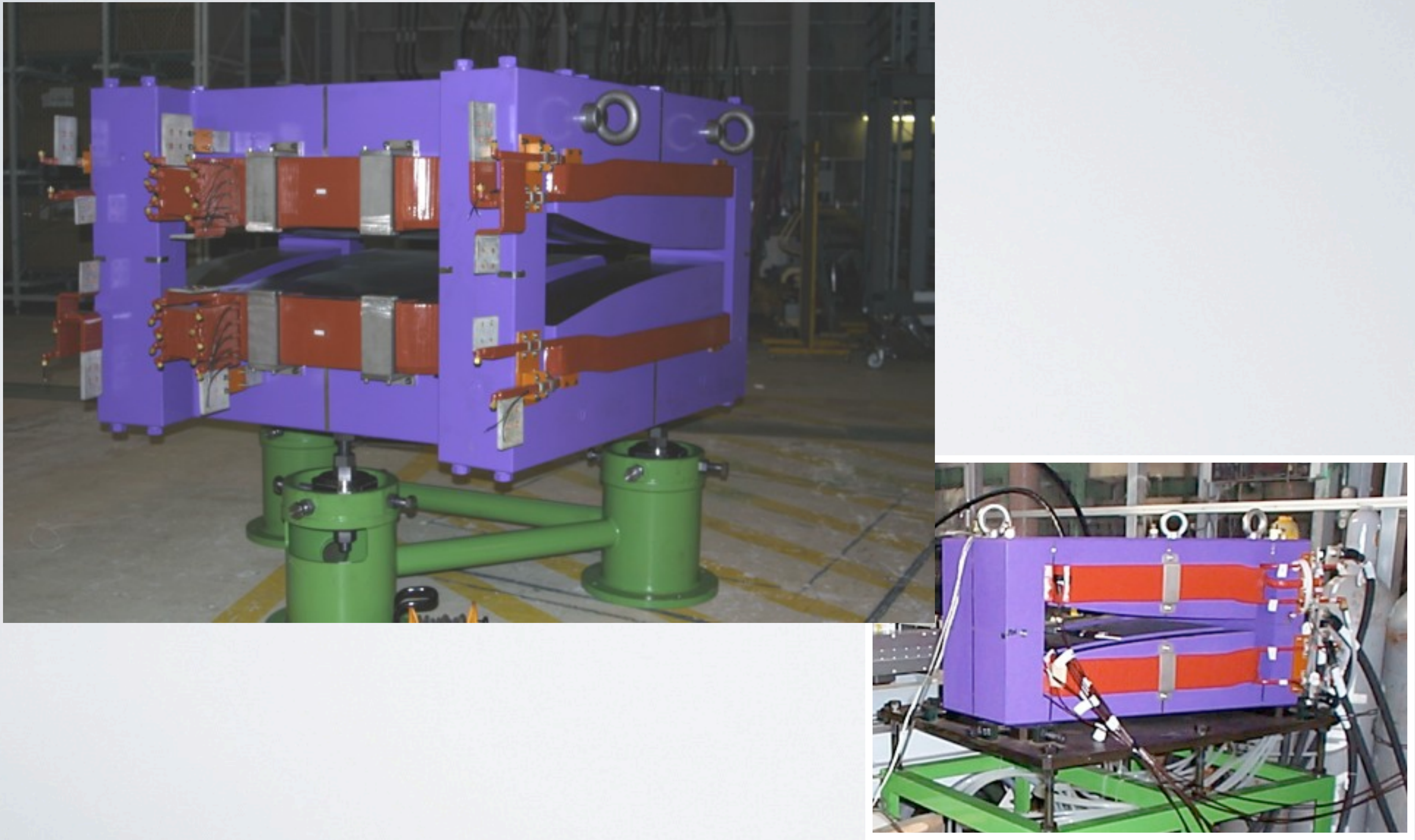
- 10 MeV proton beam
- 250Hz pulse operation
- Max. extraction current 0.5 μ A

Transport

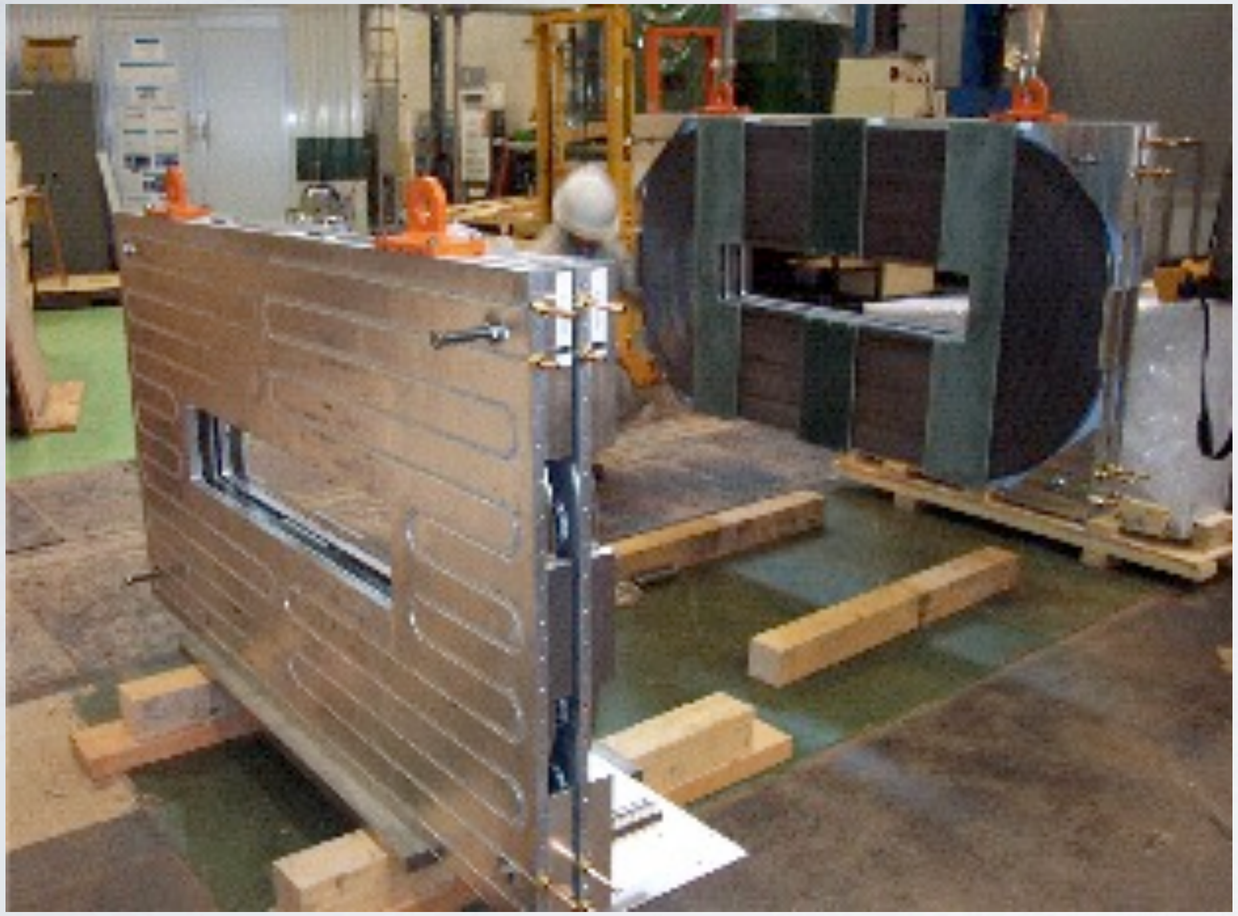
2 sets of steering+triplet Q mag.

150 MeV FFAG - Return Yoke Free Magnet

150 MeV FFAG magnet, the view from the center of the ring.



CAVITY ASSEMBLY



Number of cores	2~4
Outer size	1.7m x 1m
Inner size	1m x 0.23m
RF frequency	1.5 - 4.6 MHz
RF voltage	9 kV
RF output	55 kW
Power density	1 W/cm^3
Cooling water	70 L/min

COMMISSIONING

150MEV FFAG ACCELERATOR

Shinji Machida, Yoshiharu Mori, Joe Nakano, Yasuo Sato, Akira Takagi, Takeidhiro Yokoi, Masahiro Yoshimoto, Yoshimasa Yuasa

KEK, Ibaraki, Japan

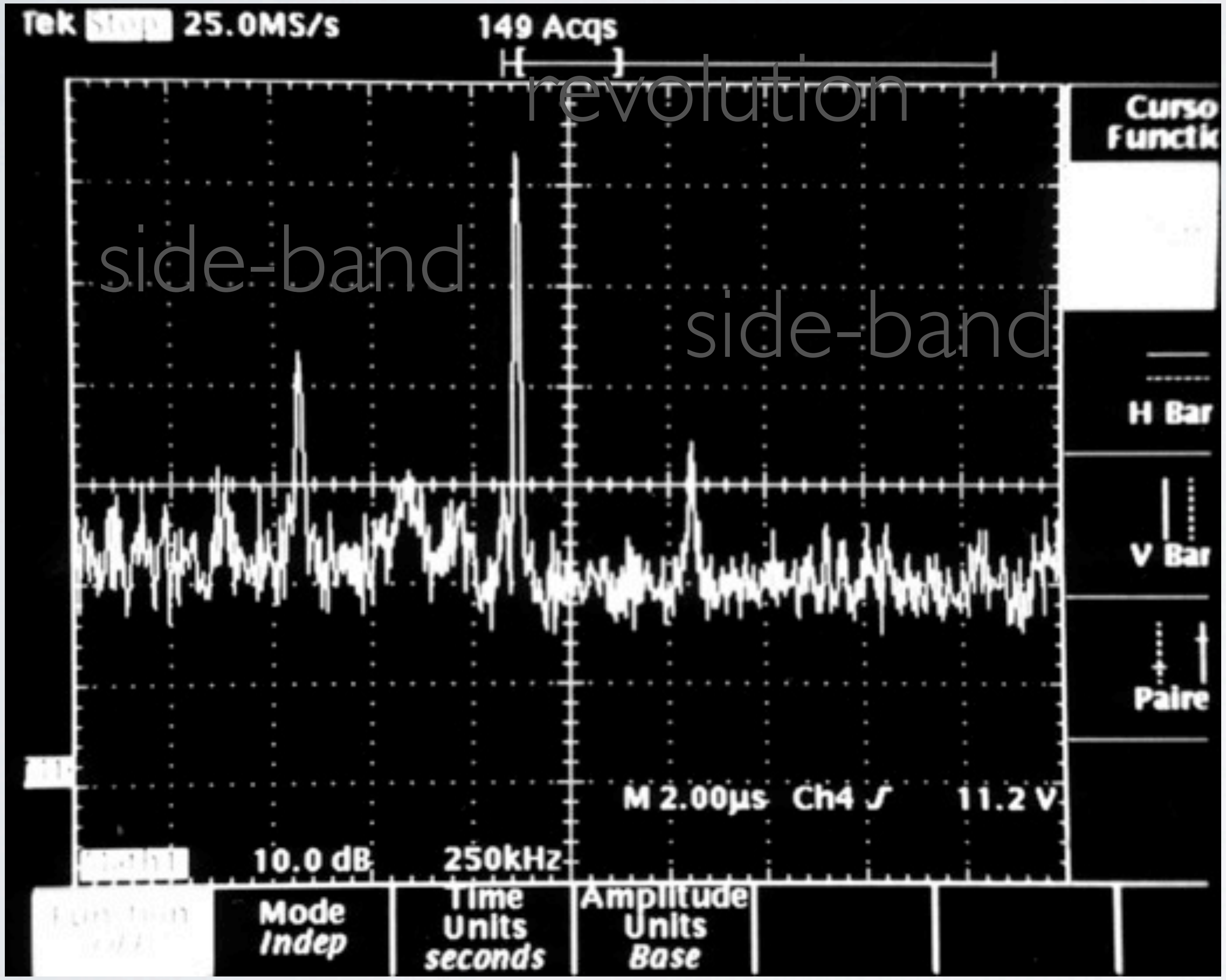
Yujiro Yonemura

Kyushu-univ., Fukuoka, Japan

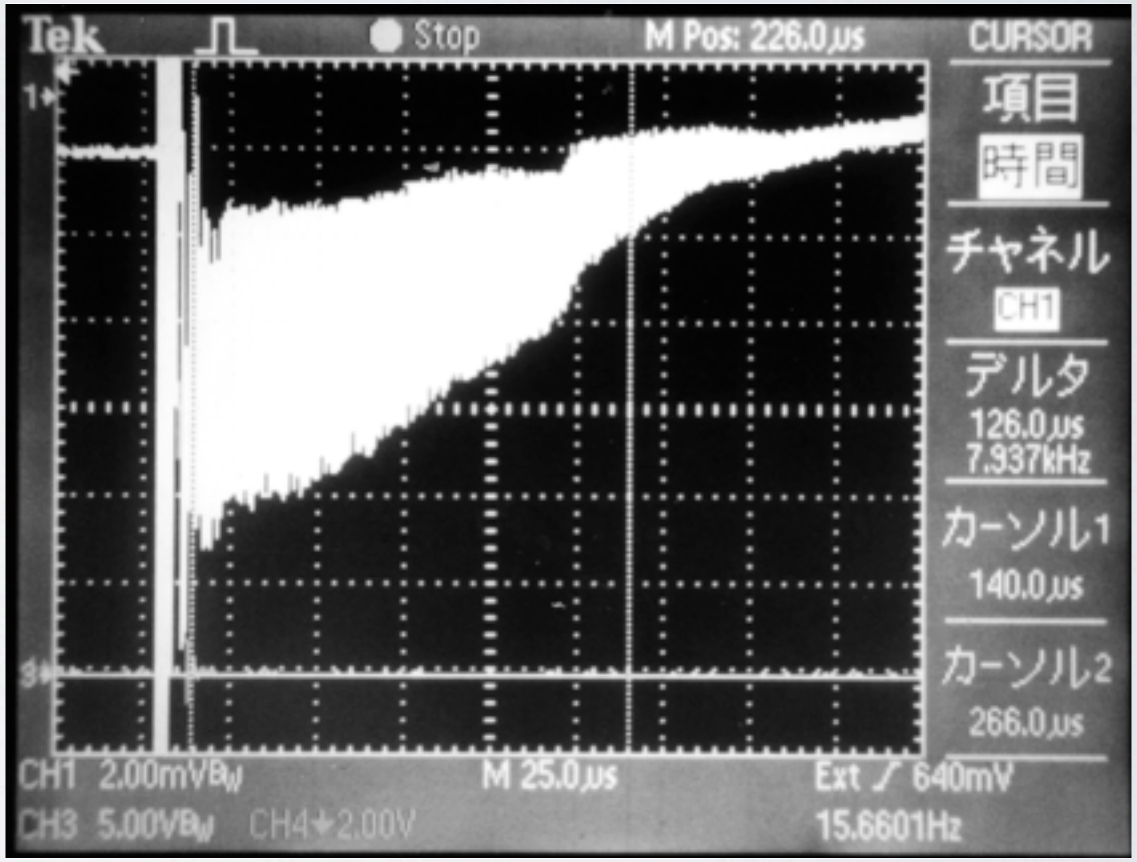
Masamitsu Aiba

Univ. of Tokyo, Tokyo, Japan

BETATRON TUNE & ΔP/P AT INJECTION

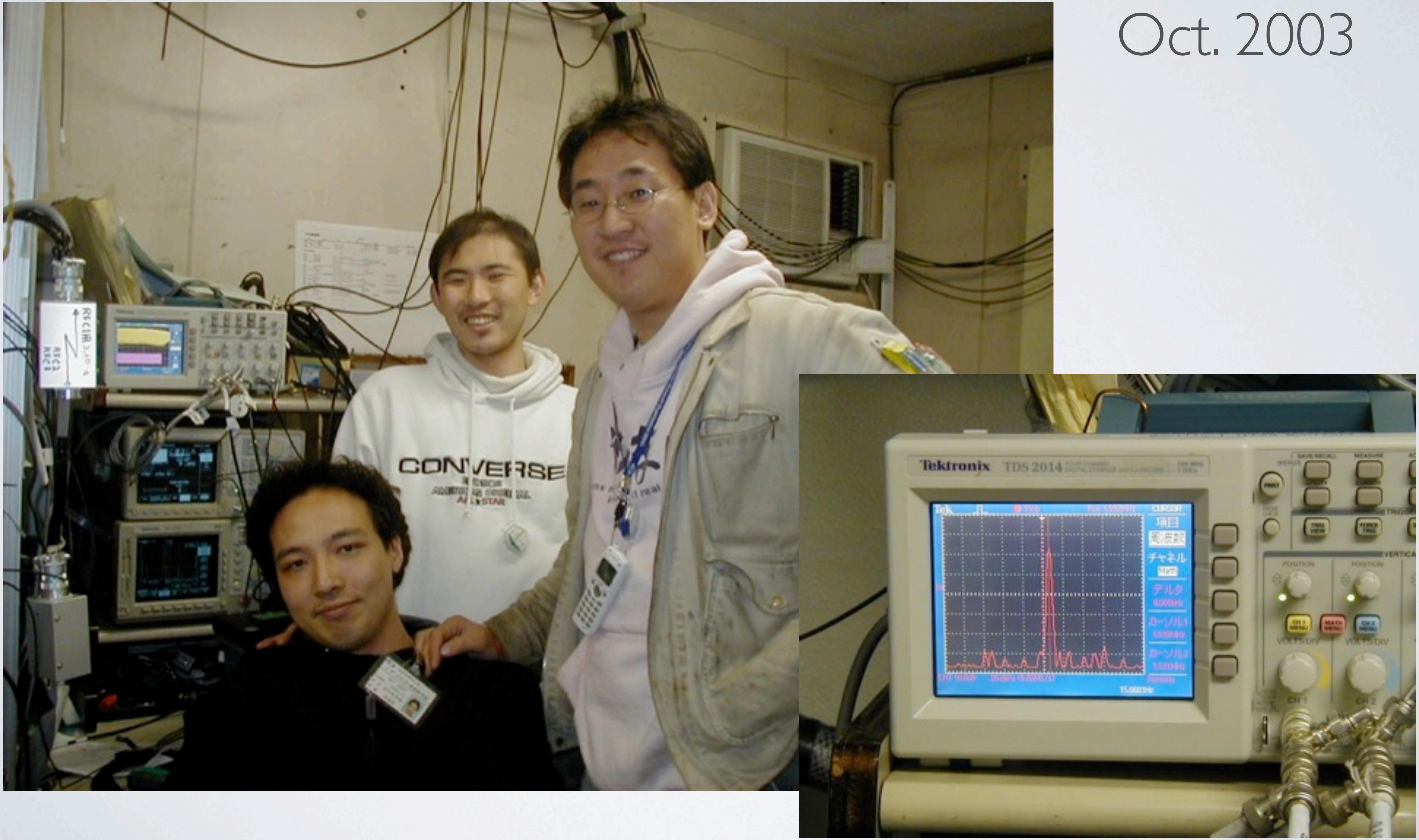


ΔQh =0.61, ΔQv =0.34



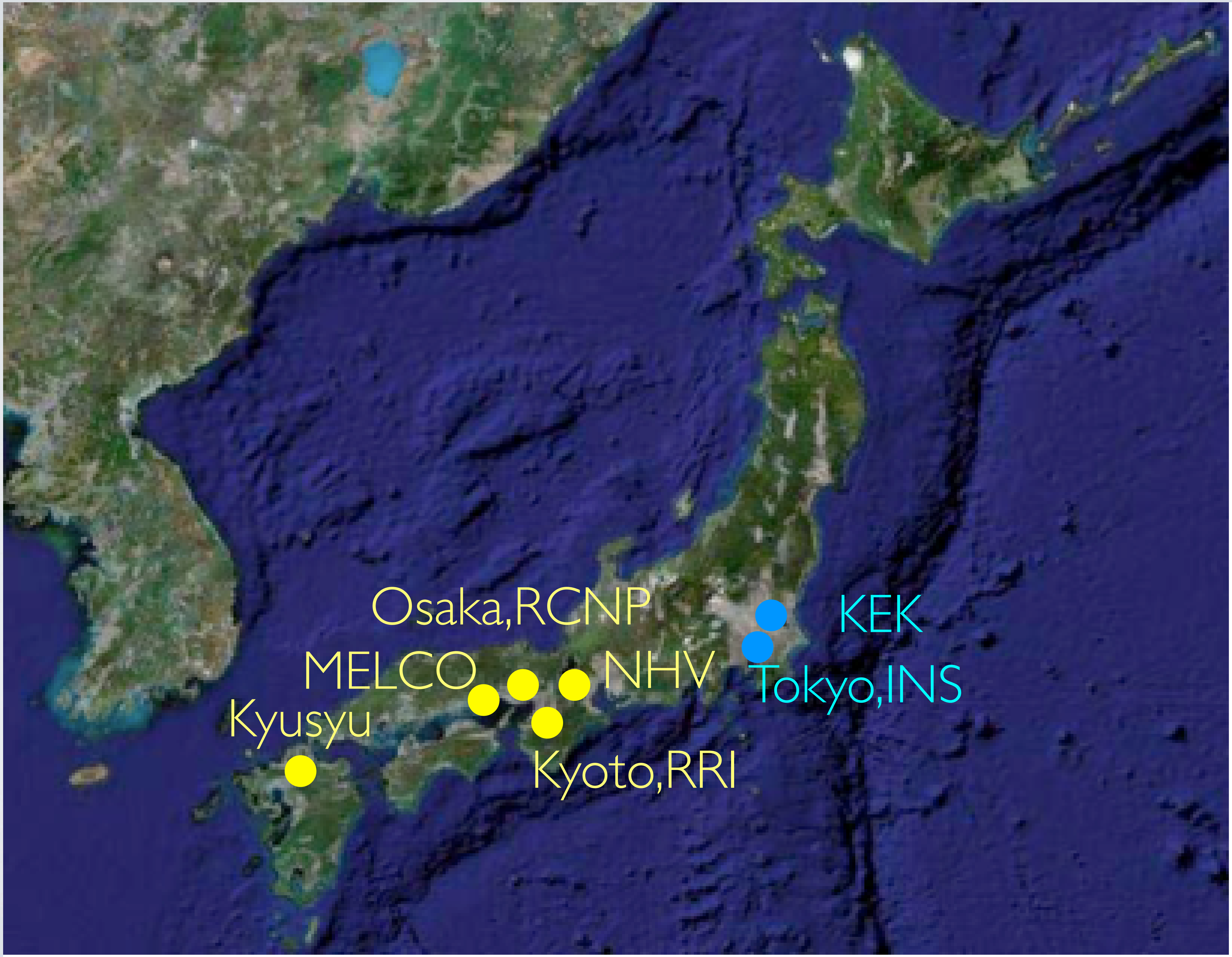
dp/p=3x10-4

CONGRATULATION!



Oct. 2003

DEVELOPMENTS OF FFAG IN JAPAN

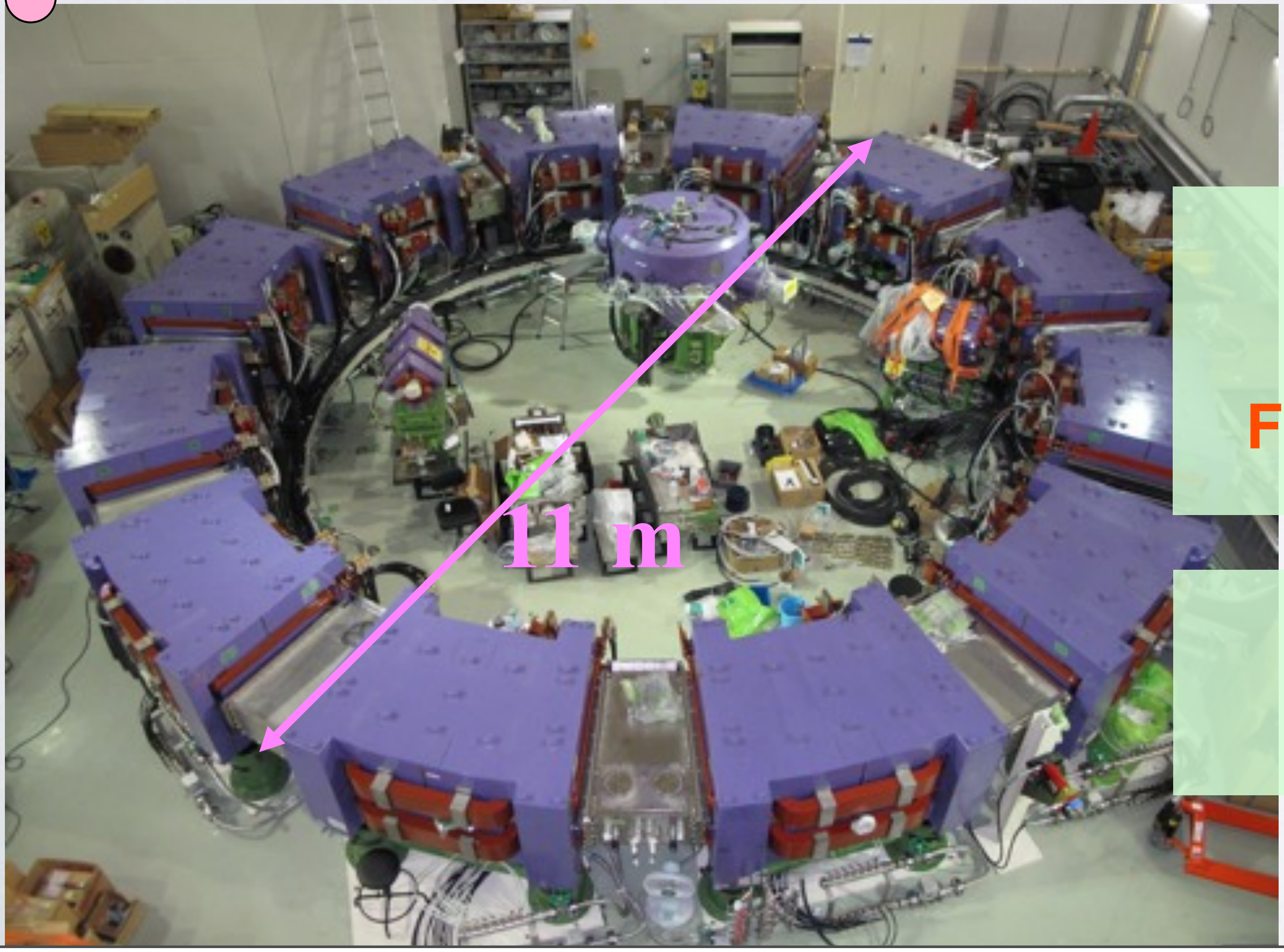


KYUSYU UNIVERSITY

Construction of new accelerator center

Main accelerator : FFAG Synchrotron

The test machine that Mori's group developed is under re-installation.



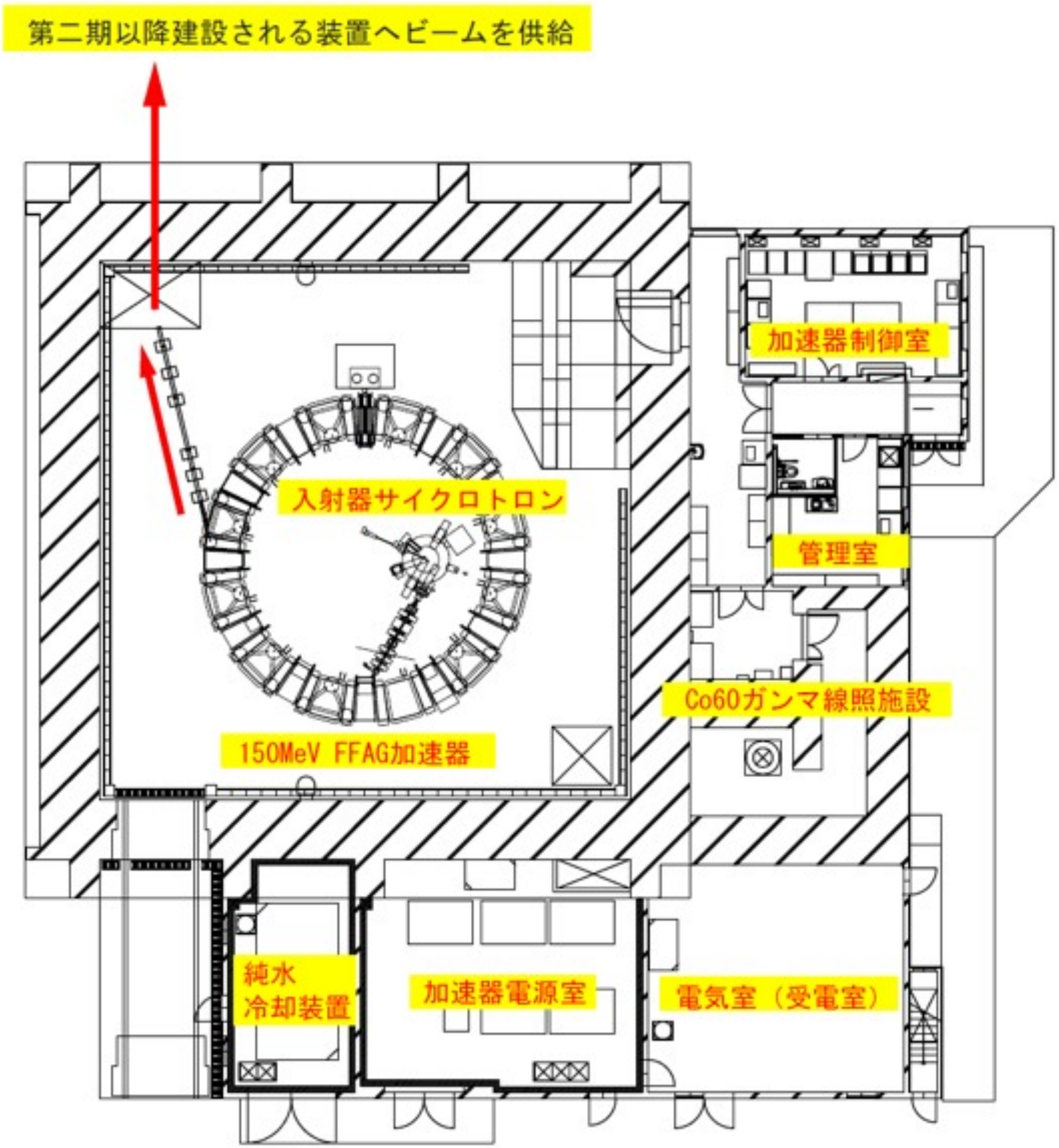
Newly constructed machine still under development

Further development at Kyushu

A machine with various possibilities

Challenges for new usage

Design values of the FFAG Synchrotron



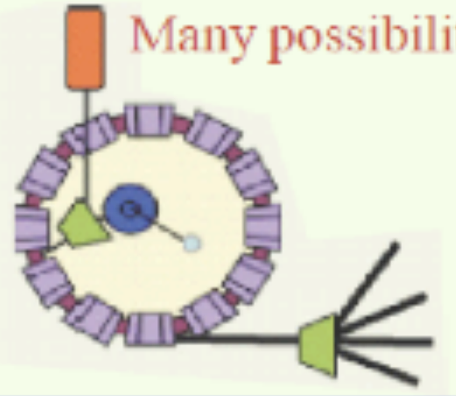
magnet	Radial sector type (DFD-triplet)
Cell	12
K-value	7.62
Beam energy	12 ⇒150 MeV (10 ⇒ 125 MeV)
Radius	4.47 ⇒ 5.20 m
Betatron tune	H: 3.69～3.80 V: 1.14～1.30
Max. field	F-field: 1.63 T
(along orbit)	D-field: 0.78 T
Circ. freq.	1.55～4.56 MHz
Repetition	100 Hz

Various field studied with FFAG

FFAG development

Accelerator science

Under-developed machine just born.



Many possibilities no other machines have.

- Flexible beam time-structure
- Large acceptance, multi-beam
- possibility as a beam delayer
- Acceleration of various beams
- High intensity by fast repetition

DNA processing, breed improvement

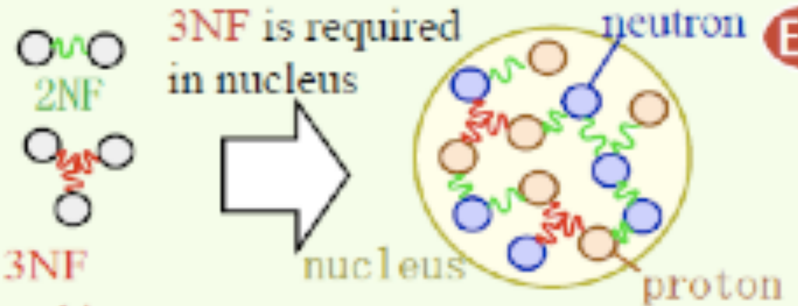
Life science

Environment science

3-body force, nuclear data

Hadron science

Energy science



3NF working to 3 nucleons simultaneously

1936:Yukawa predicted 2NF
1994:Sagara found exp. evideence of 3NF

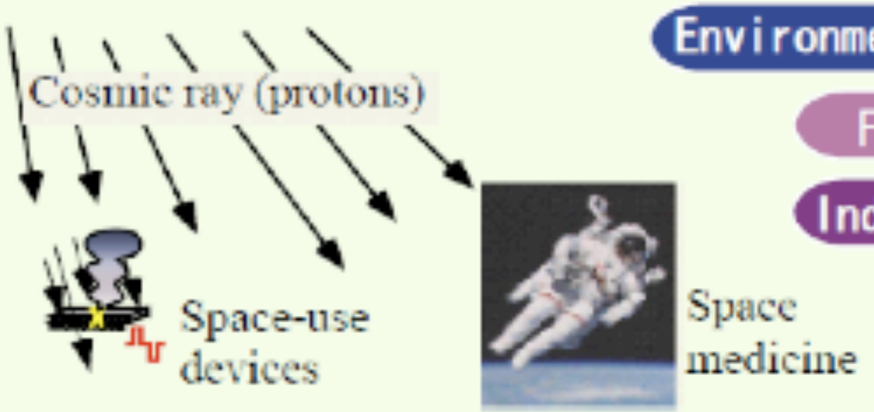
Space simulation

Life science

Environment science

Fronteer

Industry use



biological irradiation effect energy-transfer process

Energy science

Life science

Material science

Medical use (basic)

30% of incident energy are converted to other radiation

- High quality radiation treatment
- Radiation damage process of semiconductor devices

Monochro./white neutron field

Hadron science

Material science

Environment science

Industry use

Reactor material
Calibration of neutron detectors
Bacic data for acc. driven reactor
nuclear waste

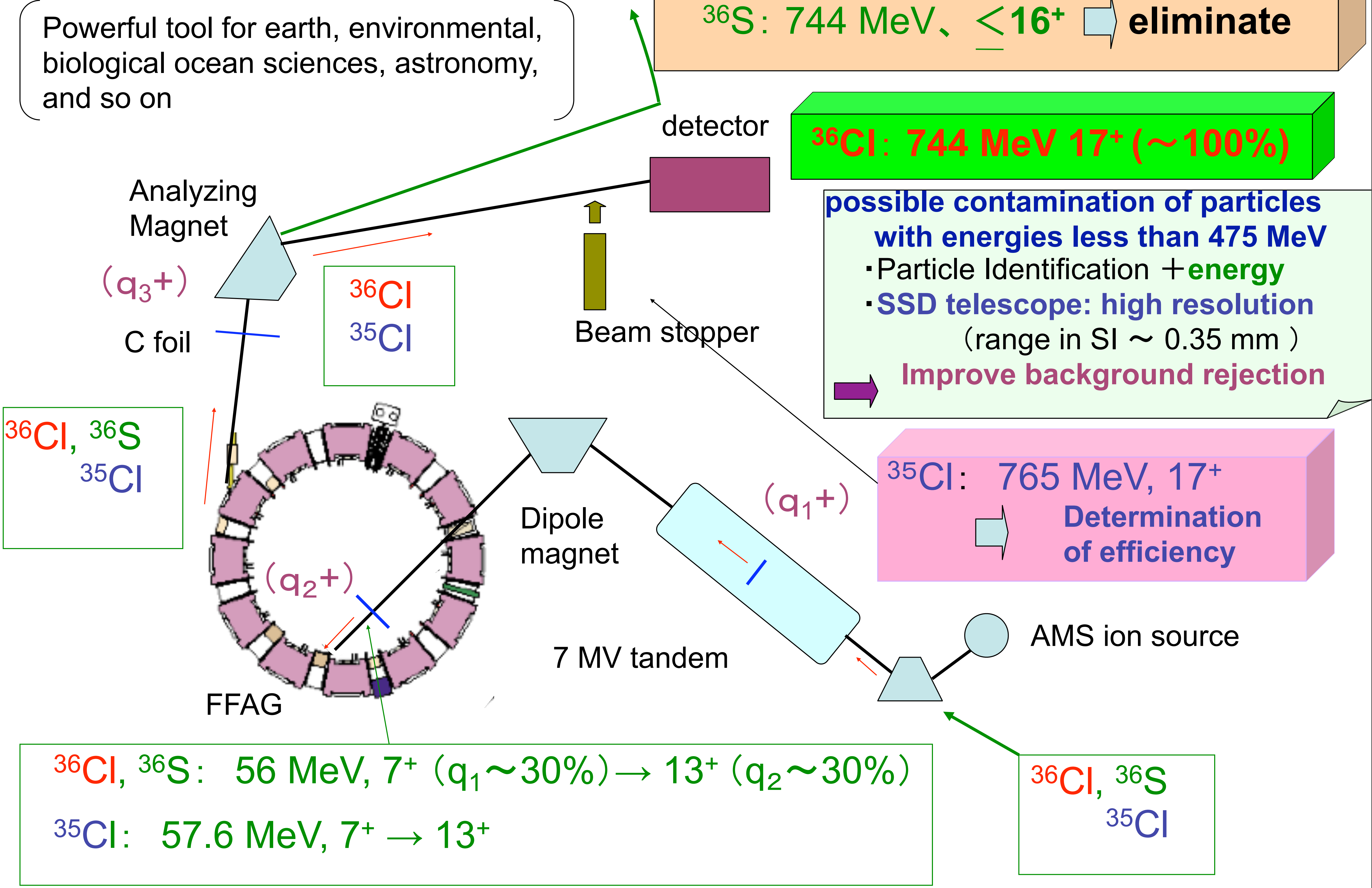
? ? ?

? ? ? science

New field

$^{36}\mathrm{Cl}$ ($T_{1/2} = 3 \times 10^{5}$ y) AMS

Powerful tool for earth, environmental, biological ocean sciences, astronomy, and so on



$^{36}\mathrm{S}$：744 MeV、$\leqq 16^{+}$ ⇨ **eliminate**

$^{36}\mathrm{Cl}$：744 MeV 17^{+} (～100%)

possible contamination of particles with energies less than 475 MeV

- Particle Identification ＋**energy**
- **SSD telescope: high resolution**

（range in SI ～ 0.35 mm ）

➡ **Improve background rejection**

$^{35}\mathrm{Cl}$： 765 MeV, 17^{+}

⇨ **Determination of efficiency**

$^{36}\mathrm{Cl}$
$^{35}\mathrm{Cl}$

$^{36}\mathrm{Cl}$, $^{36}\mathrm{S}$
$^{35}\mathrm{Cl}$

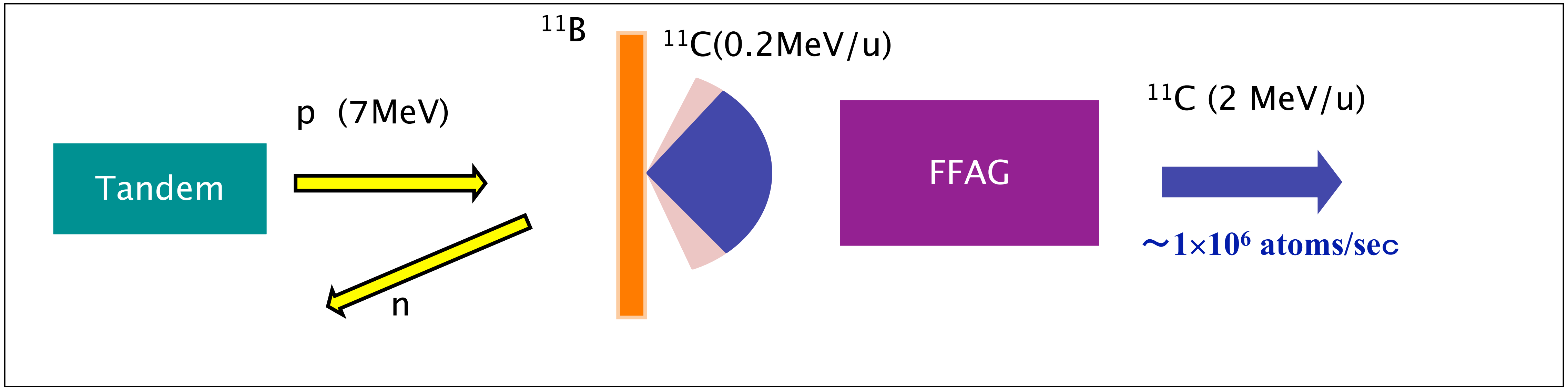
$^{36}\mathrm{Cl}$, $^{36}\mathrm{S}$： 56 MeV, 7^{+} (q_1～30%)→ 13^{+} (q_2～30%)

$^{35}\mathrm{Cl}$： 57.6 MeV, 7^{+} → 13^{+}

$^{36}\mathrm{Cl}$, $^{36}\mathrm{S}$
$^{35}\mathrm{Cl}$

Acceleration of unstable nuclei and isomers

***Acceleration of unstable nuclei**



***Acceleration of isomers**

$^{16}\mathrm{O} + {}^{39}\mathrm{K} \rightarrow {}^{52m}\mathrm{Fe} + p,n,n$
(40MeV) (10MeV)
⇒ (100MeV)

$^{18}\mathrm{O} + {}^{9}\mathrm{Be} \rightarrow {}^{24m}\mathrm{Ne} + p,n,n$
(35MeV) (20MeV)
⇒ (200MeV)

Advantage:
- High quality unstable beam for all elements

Subjects
- Structure of high-spin isomer, Astro-nuclear data
- Diffusion process in material

Requirement to accelerator
- Large acceptance (longitudinal and transverse)

OSAKA UNIVERSITY

Y.Kuno, A.Sato

- **MOTIVATION**
- Research for new physics beyond Standard Theory with **μ**-e conversion rare event experiment

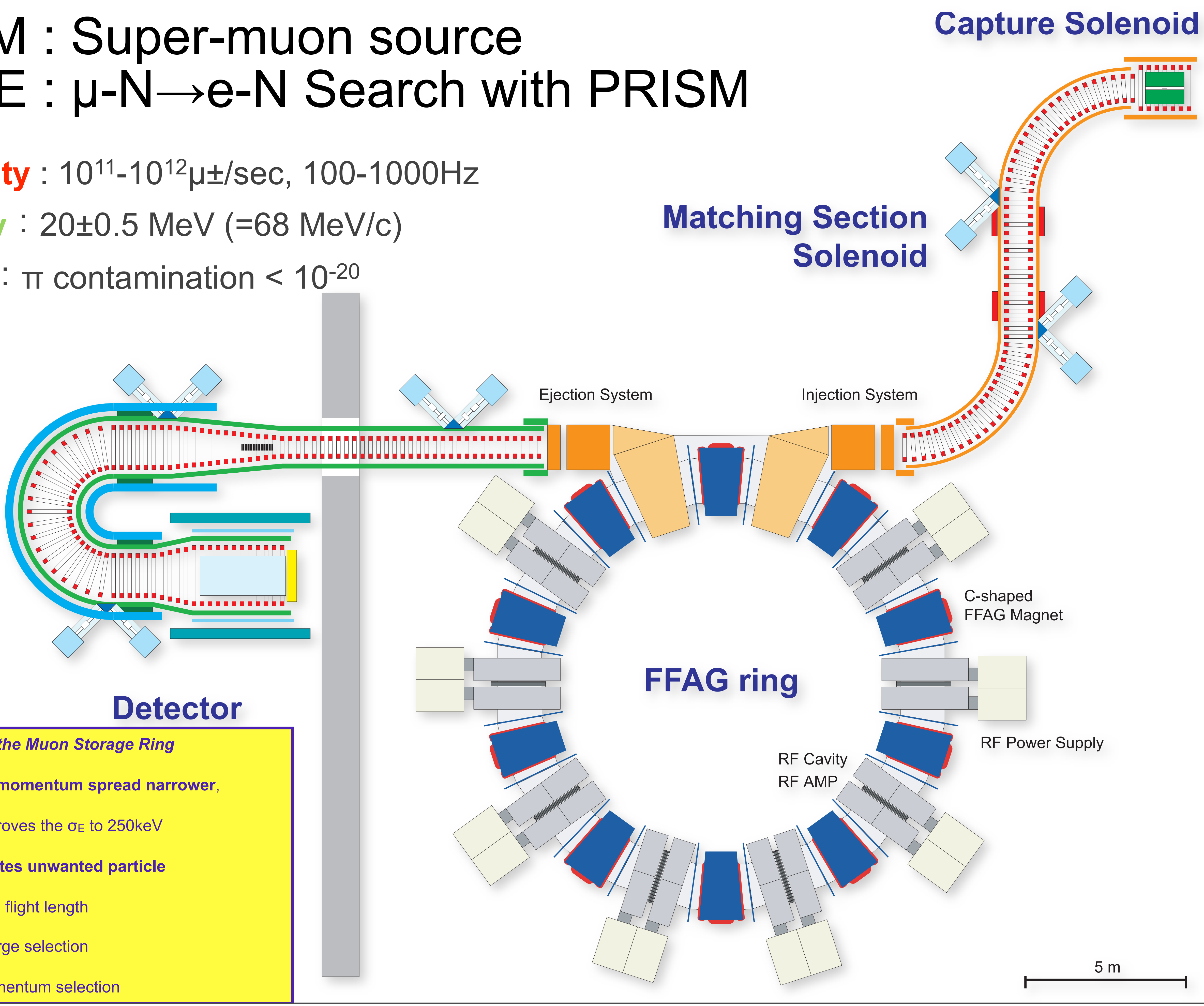
$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

- To do this,

●with a muon storage ring to reduce the energy spread and pion background.
●with a fast-extracted pulsed proton beam.
●need a new beamline and experimental hall.
●Ultimate search

PRISM : Super-muon source
PRIME : μ-N→e-N Search with PRISM

- **Intensity** : 10^{11}-10^{12}μ±/sec, 100-1000Hz
- **Energy** : 20±0.5 MeV (=68 MeV/c)
- **Purity** : π contamination < 10^{-20}



Functions of the Muon Storage Ring

- **Makes momentum spread narrower,**
  - improves the σ_E to 250keV
- **Eliminates unwanted particle**
  - long flight length
  - charge selection
  - momentum selection

PRISM : Super-muon source
PRIME : μ-N→e-N Search with PRISM

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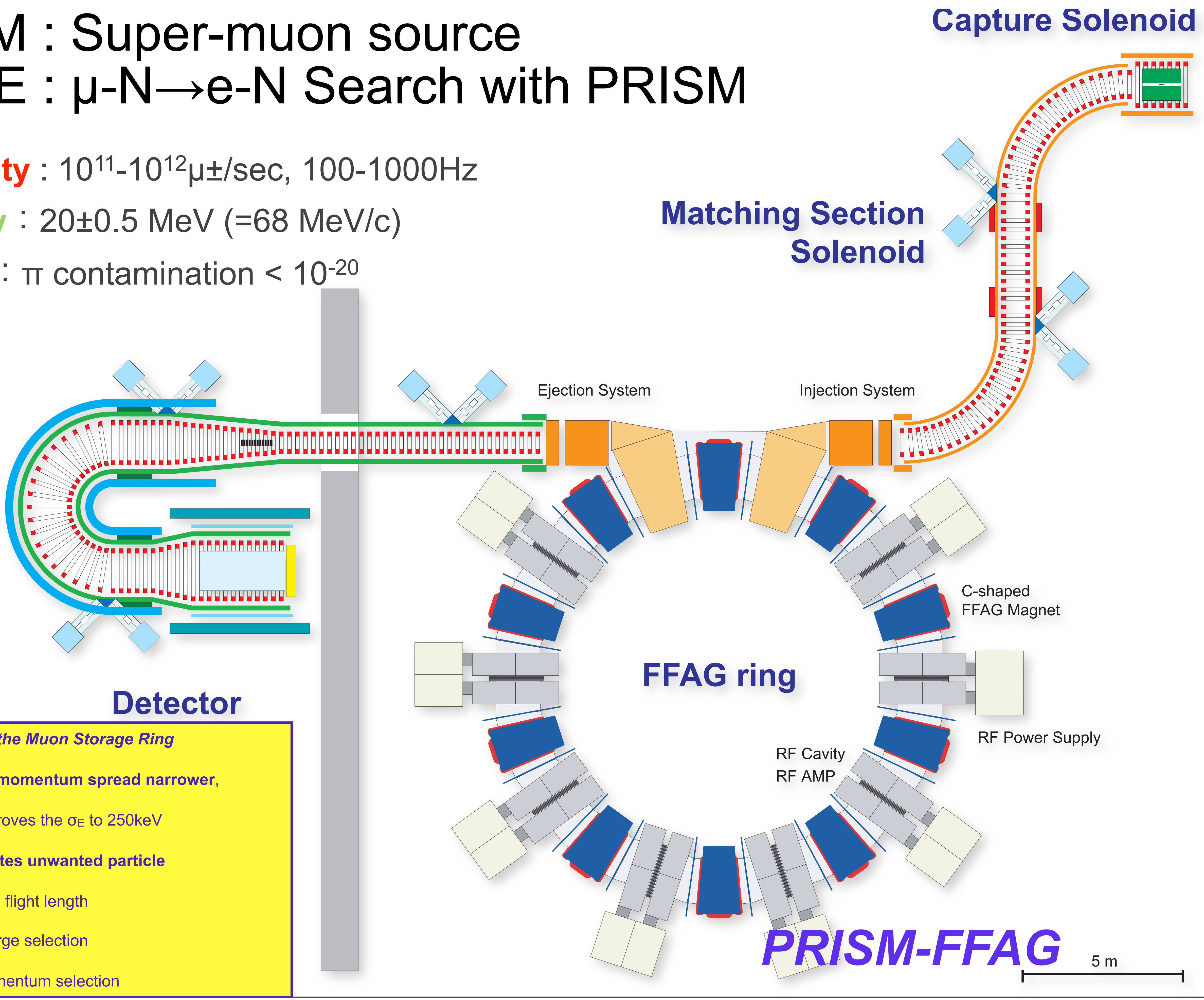

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- **Makes momentum spread narrower,**
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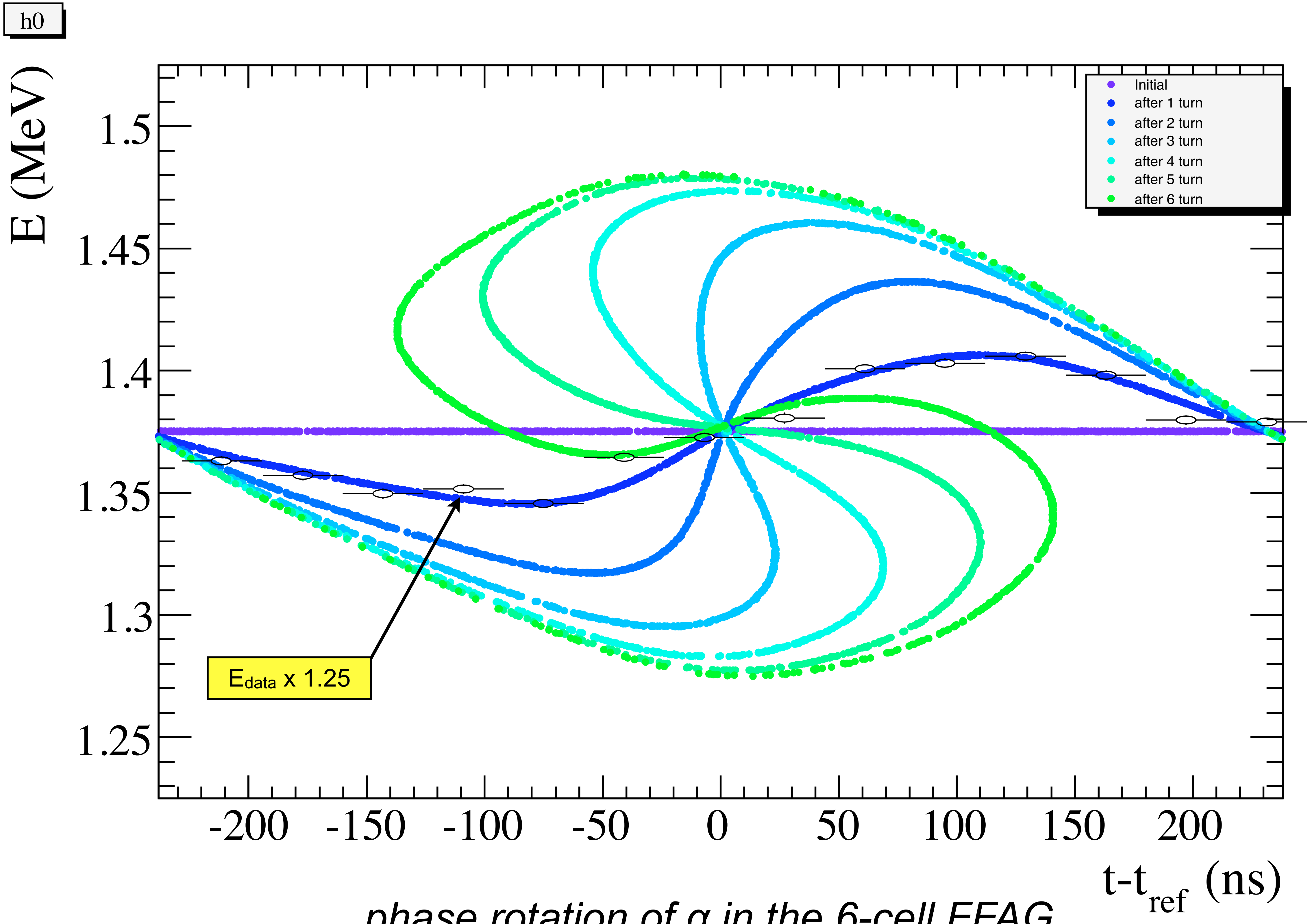
  - long flight length
  - charge selection
  - momentum selection

Demo. of Phase Rotation with α-particles

- FFAG-ring
  - PRISM-FFAG Magnet x 6、RF x 1
- Beam : α-particles from radioactive isotopes
  - ^{241}Am 5.48MeV(200MeV/c) → degrade to 100MeV/c
  - small emittance by collimators
  - pulsing by electrostatic kickers
- Detector : Solid state detector
  - energy
  - timing

6-cell PRISM-FFAG
in the M-exp. hall of RCNP, Osaka University

Comparison b/w data and simulation



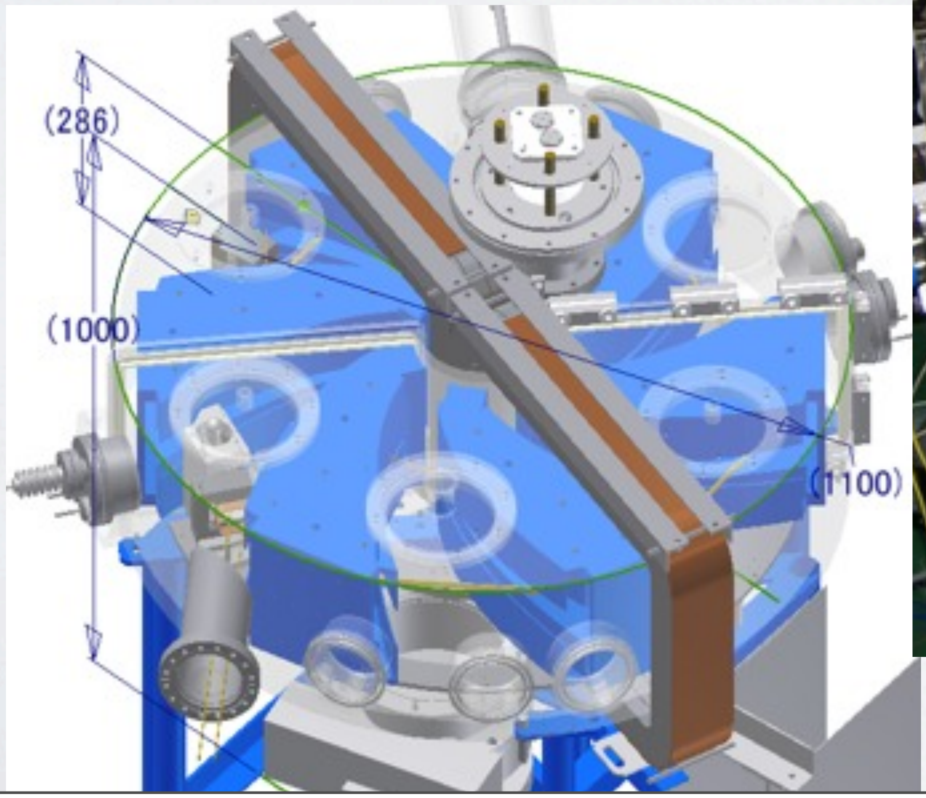
phase rotation of α in the 6-cell FFAG

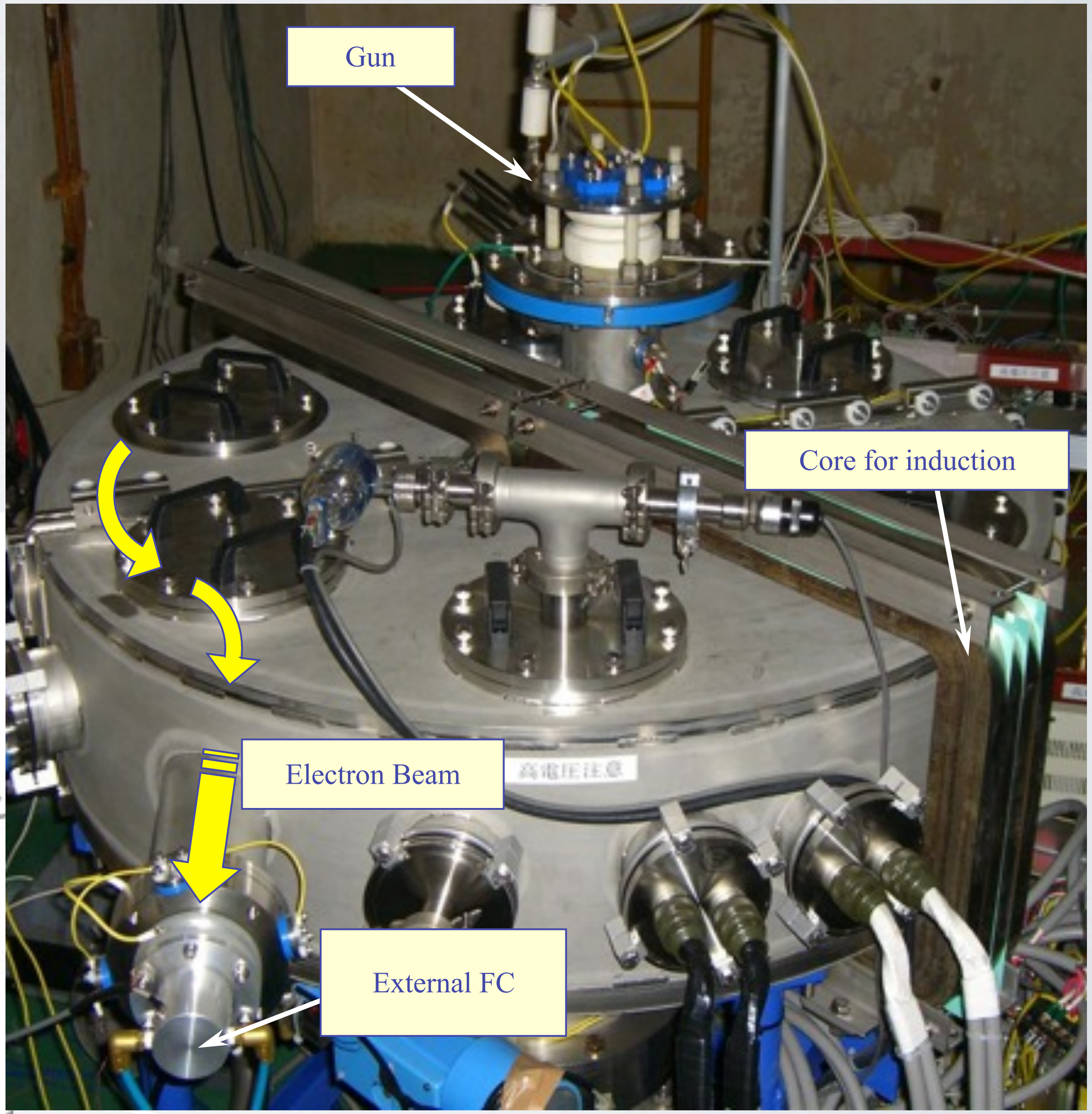
NHV CO.

T.Baba, M.Yuasa

Prototype of FFAG Electron Accelerator: sterilization etc.

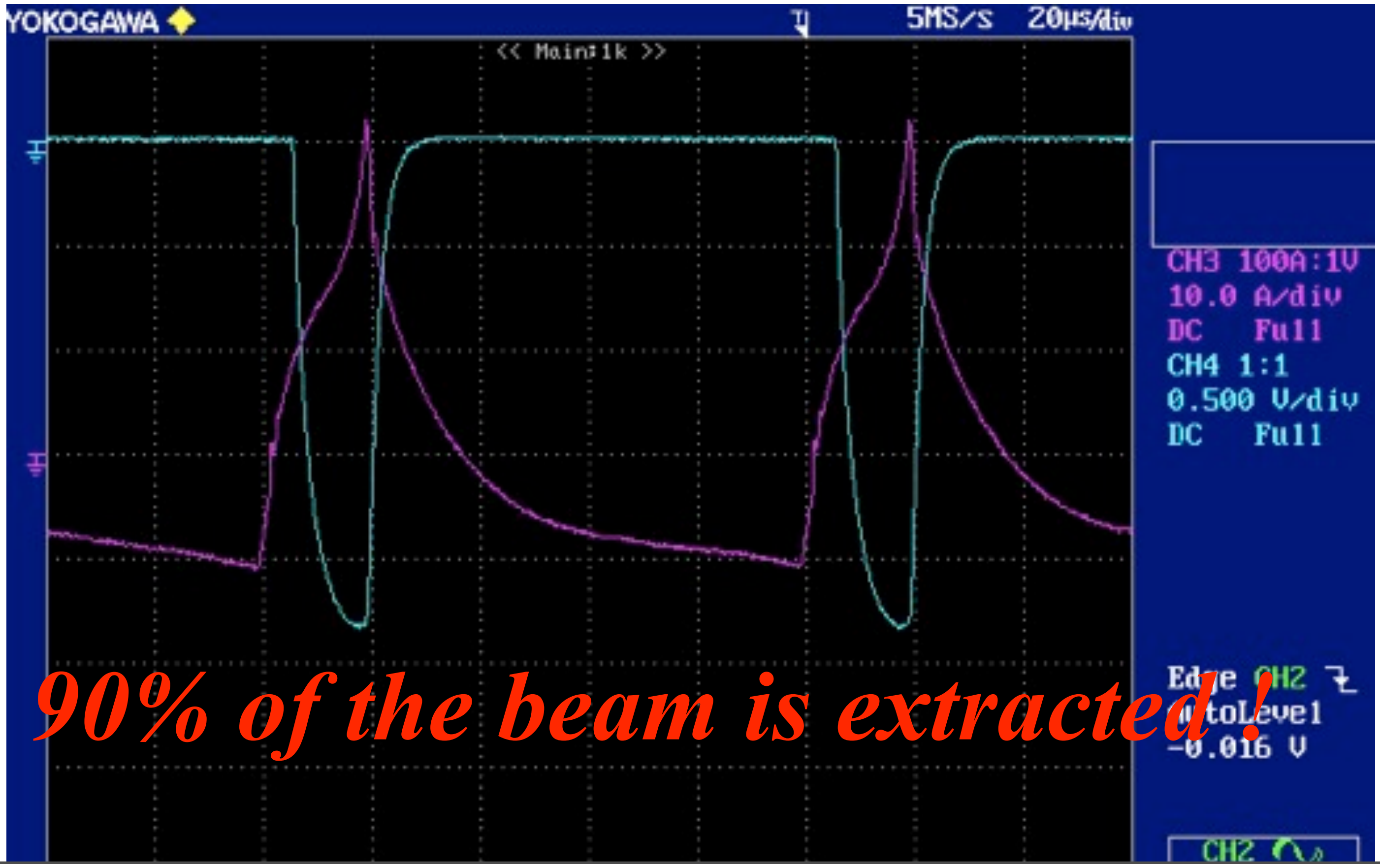
Energy Inj. / Ext.	50 / 500keV
Orbit radius Inj. / Ext.	0.19 / 0.44m
Acceleration frequency	10kHz
Beam Current	100mA peak
Duty	20%
Outer diameter	1.1m





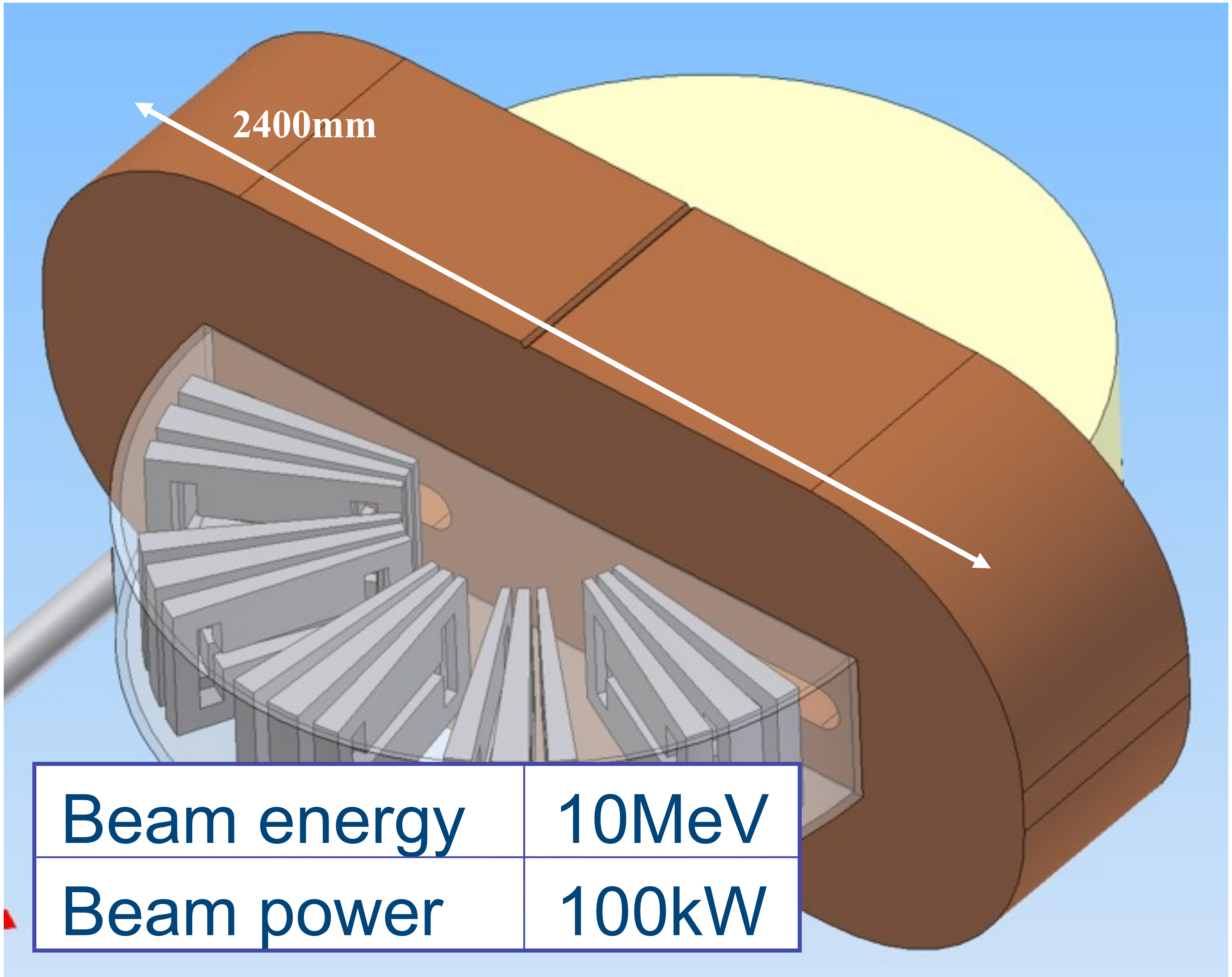
Results of the Development

- Accelerator assembling is completed.
- Beam injection and acceleration are successful.
- 90% of the beam is extracted form FFAG ring.
- Extracted beam energy is measured as same as the specified energy.



90% of the beam is extracted !

10MeV Electron Accelerator

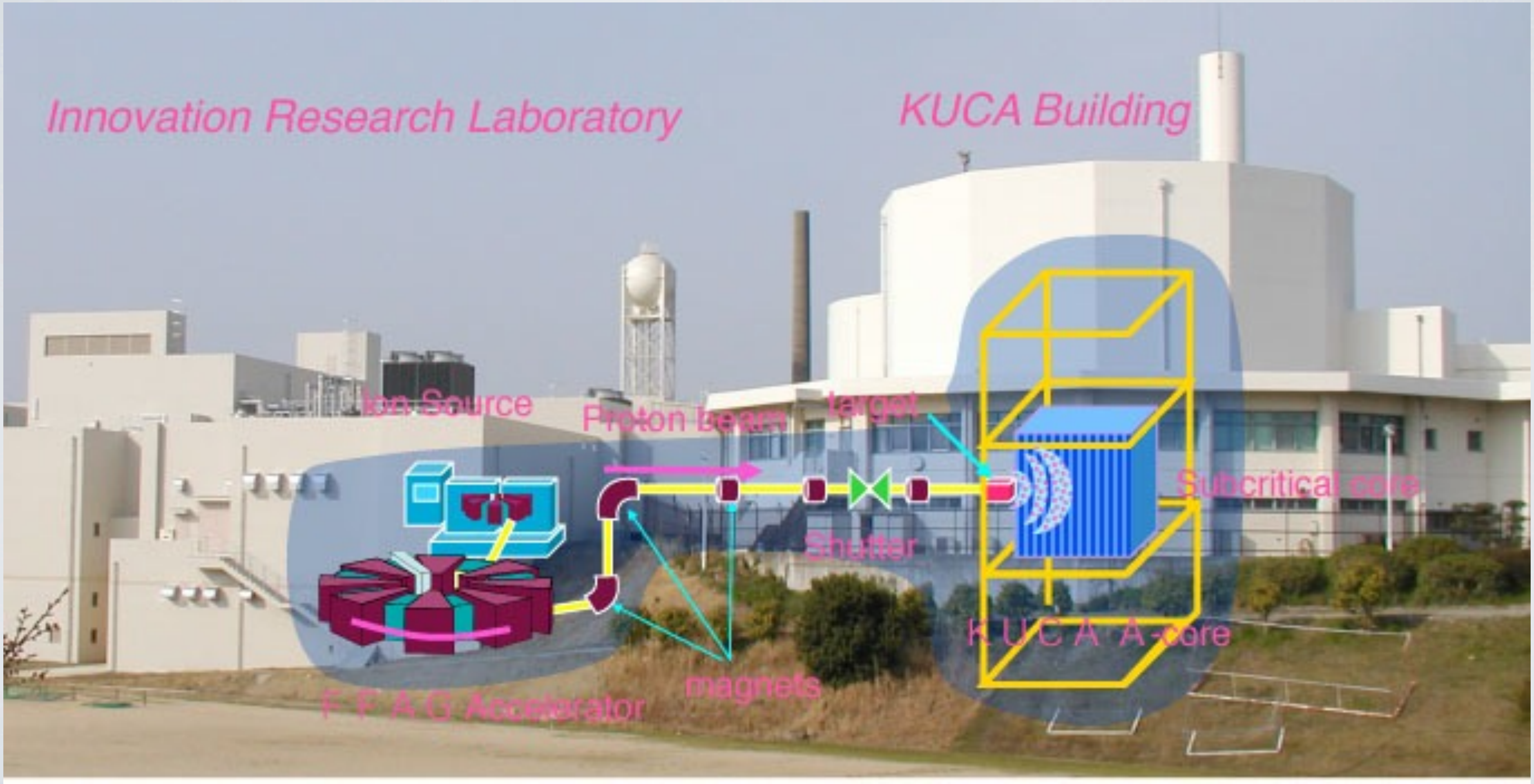


Beam energy	10MeV
Beam power	100kW

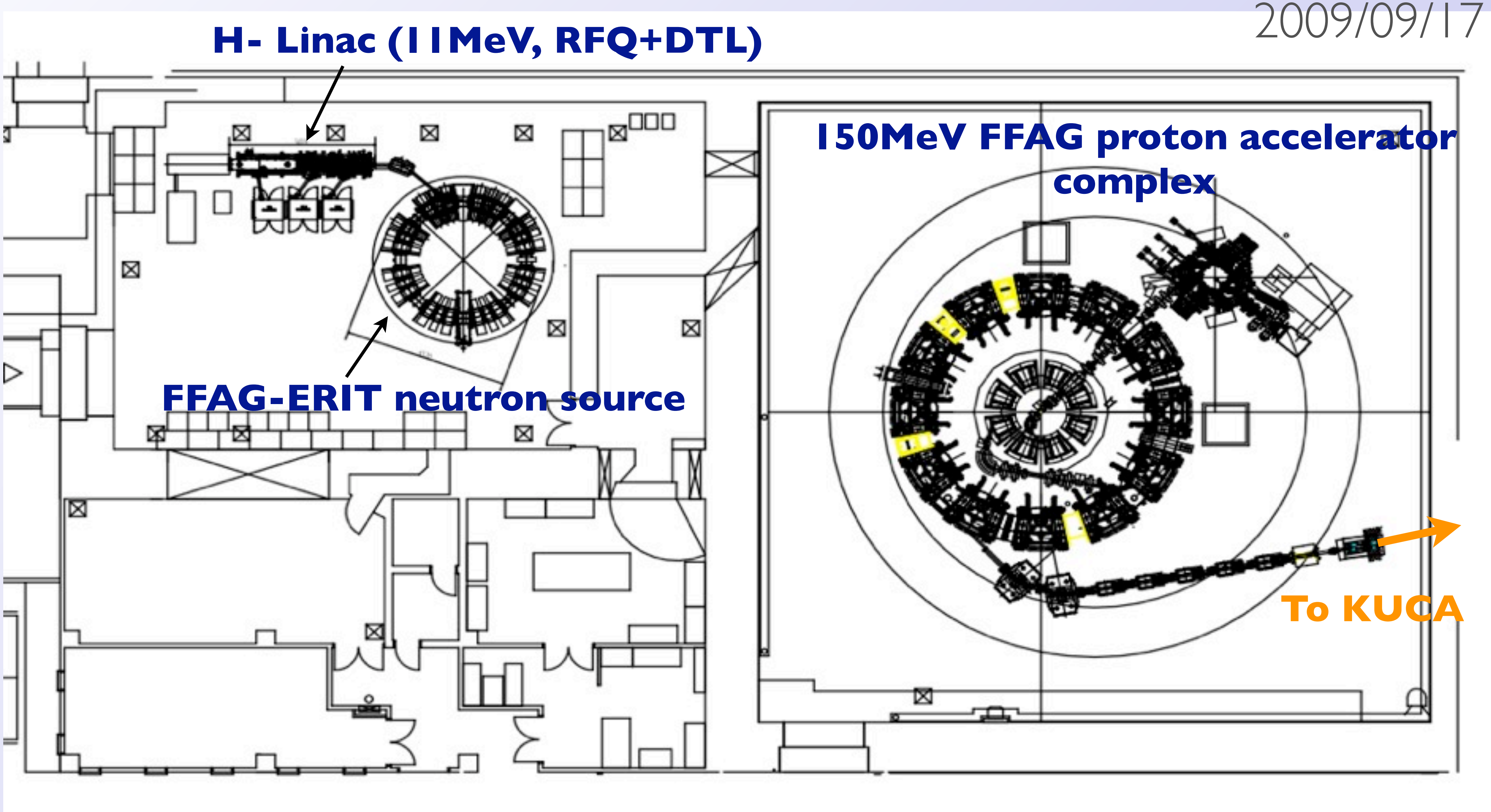
KYOTO UNIVERSITY RESEARCH REACTOR INSTITUTE (KURRI) FFAG-ADSR PROJECT

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

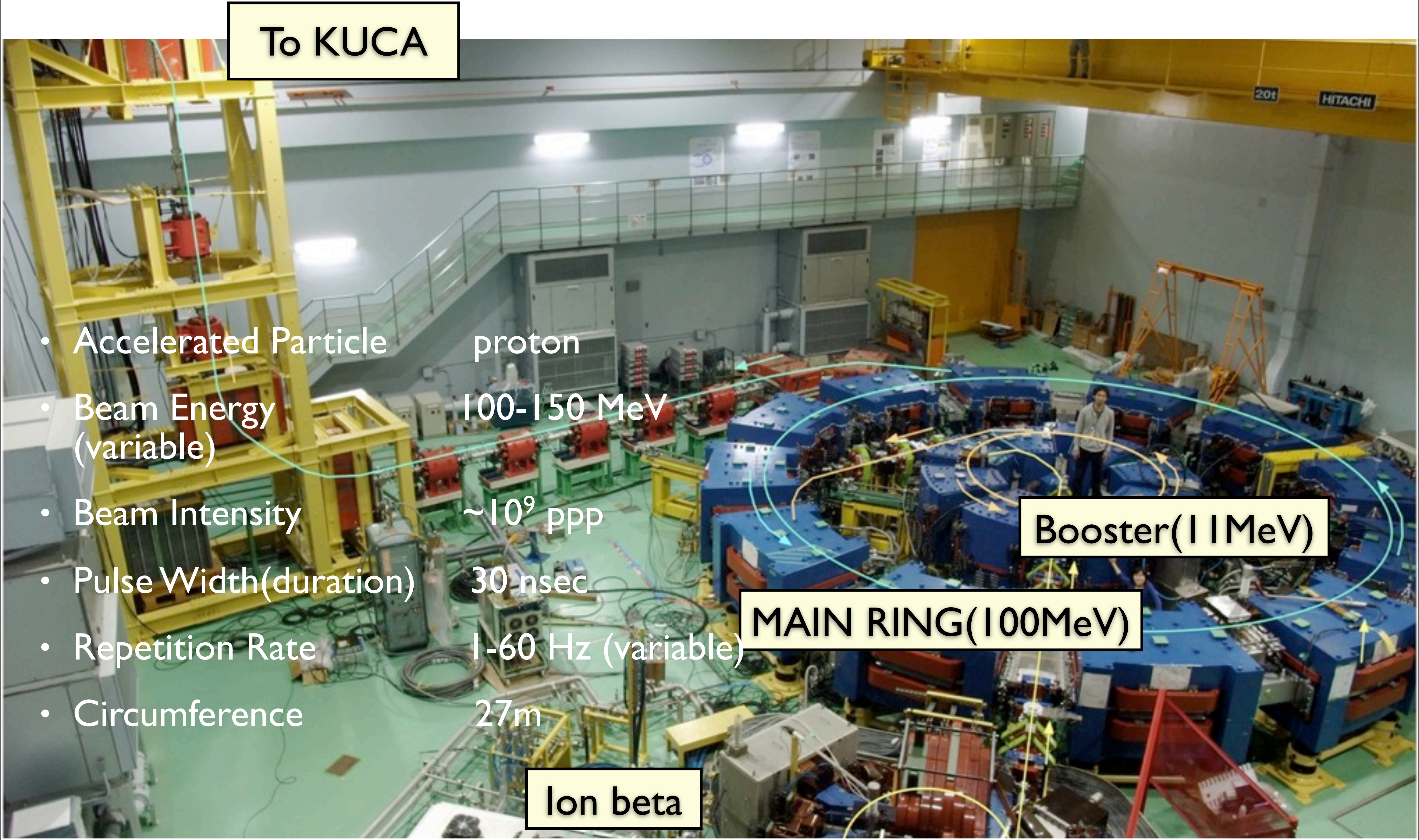
FFAG-KUCA ADSR PROJECT AT KURRI



Layout of FFAG Accelerators in Innovation Laboratory



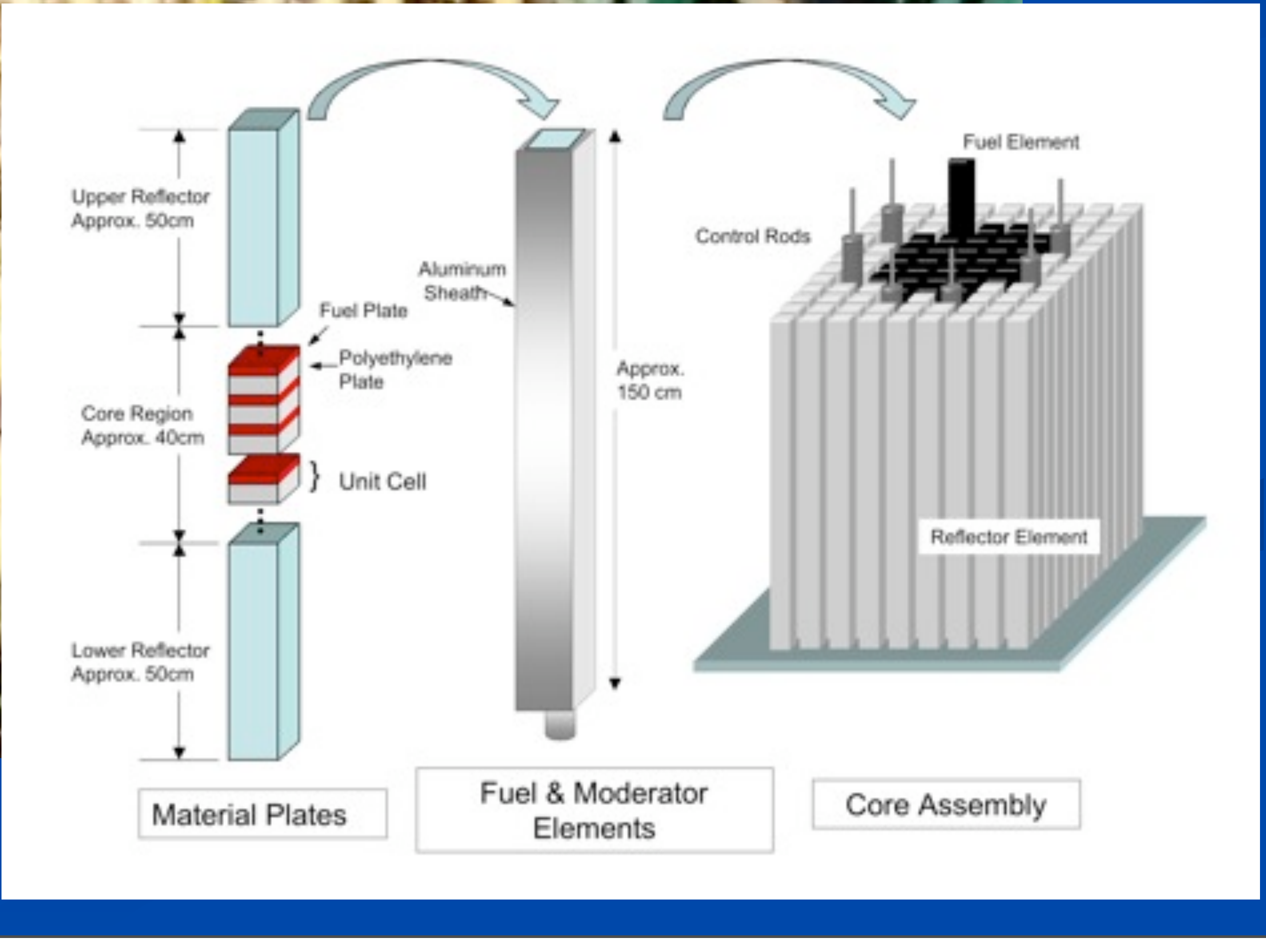
FFAG accelerator complex



Accelerated Particle	proton
Beam Energy (variable)	100-150 MeV
Beam Intensity	~10^9 ppp
Pulse Width(duration)	30 nsec
Repetition Rate	1-60 Hz (variable)
Circumference	27m

KUCA-A Core - solid moderated and reflected -

- 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



ADSR EXPERIMENT

WORLD FIRST ADSR EXPERIMENT WITH SPALLATION NEUTRONS

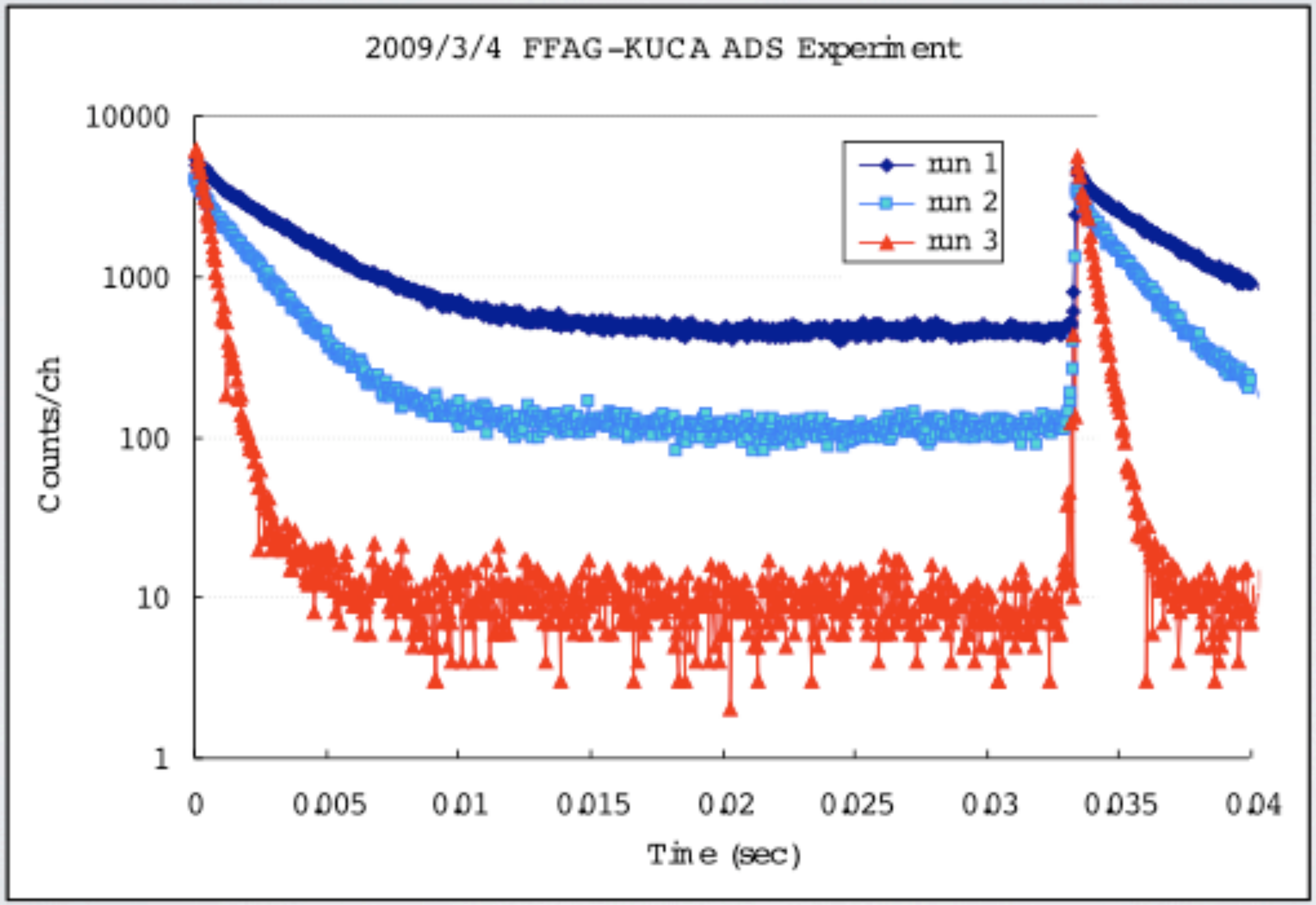
-THE FIRST FFAG USED FOR APPLICATION-

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

FIRST DATA

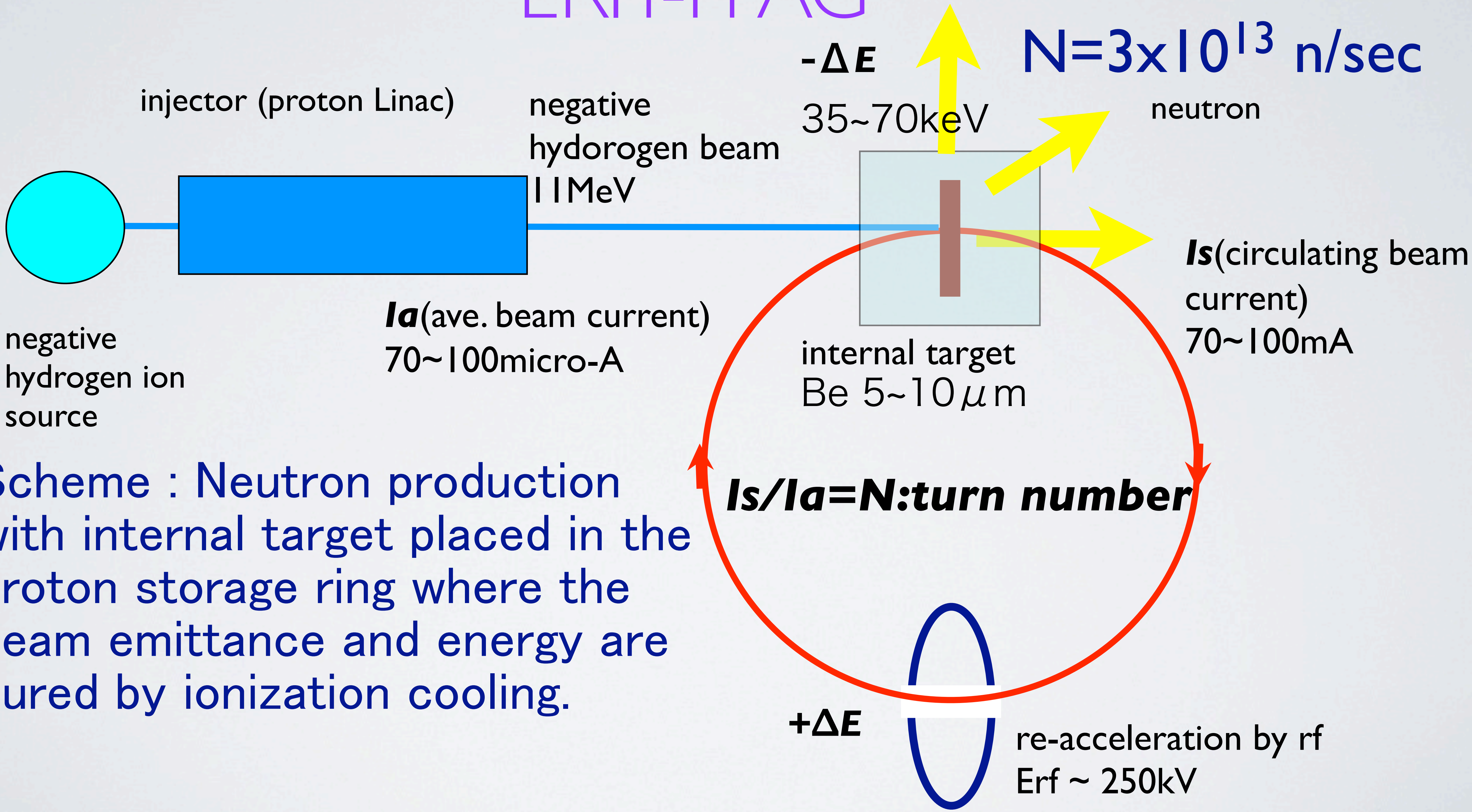
Journal of Nuclear Science and Technology, Vol.46 No.12, pp.1091-1093(2009).

- Measurement of neutron multiplication



NEUTRON SOURCE WITH EMITTANCE RECOVERY INTERNAL TARGET

ERIT-FFAG



$-\Delta E$

35~70keV

N=3x10^{13} n/sec

neutron

injector (proton Linac)

negative
hydorogen beam
11MeV

Is(circulating beam current)
70~100mA

negative
hydrogen ion
source

Ia(ave. beam current)
70~100micro-A

internal target
Be 5~10μm

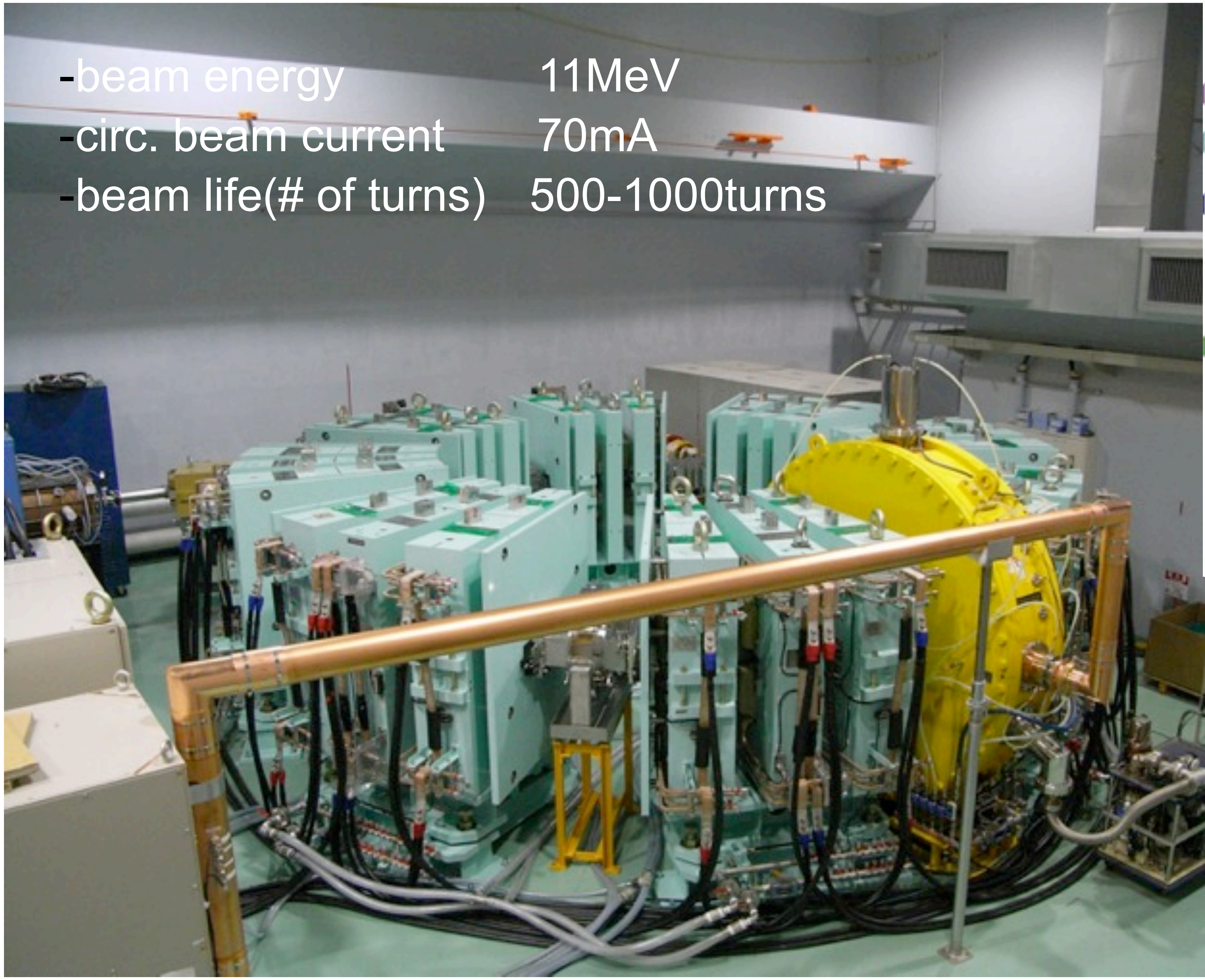
Is/Ia=N:turn number

$+\Delta E$

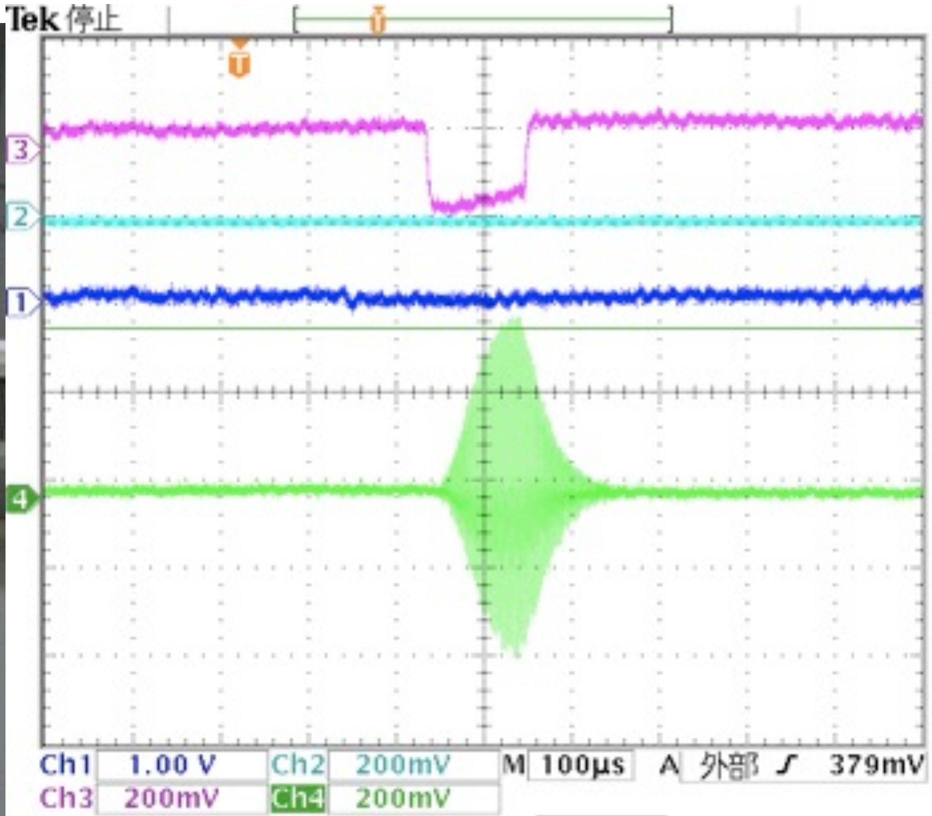
re-acceleration by rf
Erf ~ 250kV

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 RING



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

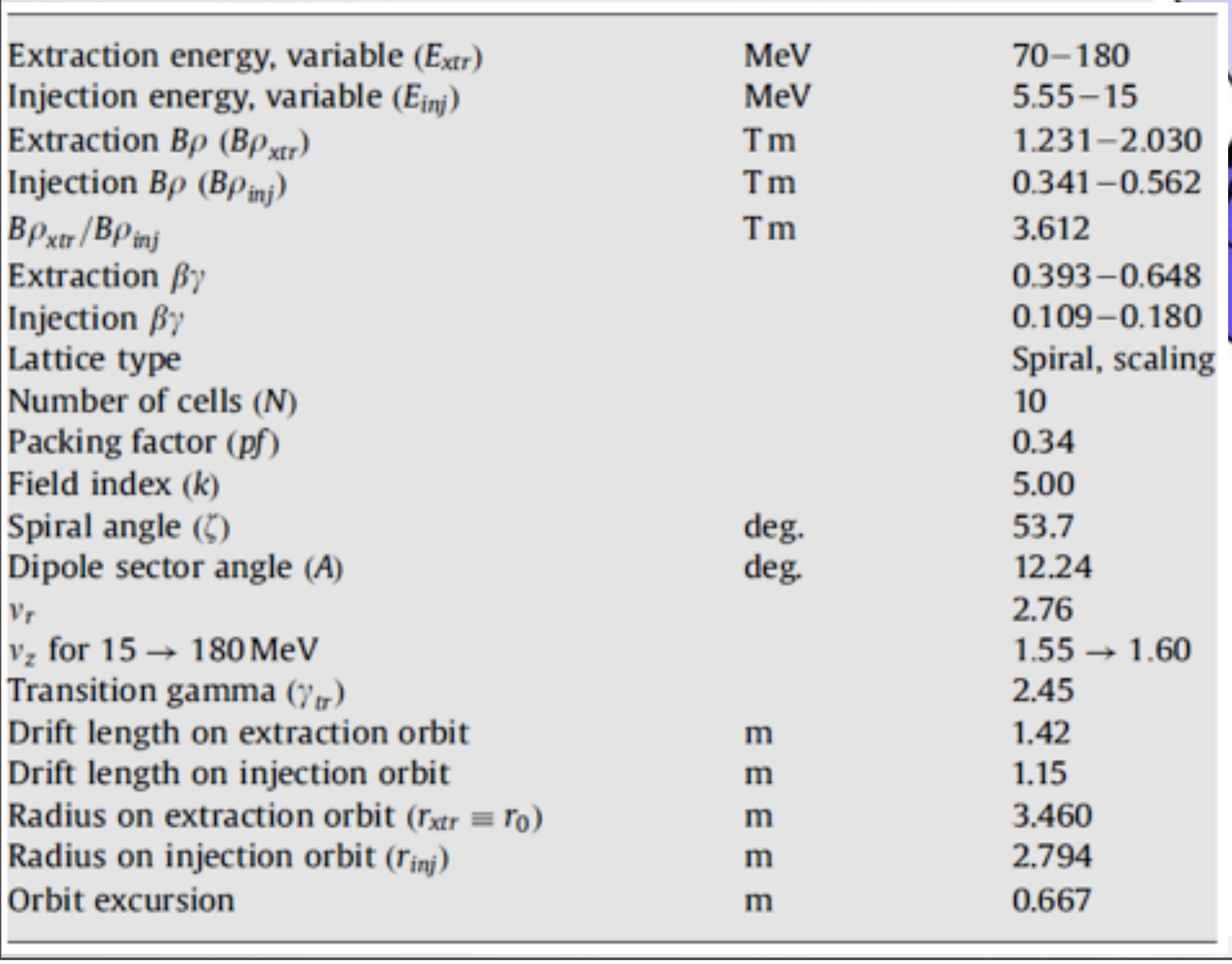


-acceptance	Av>3000mm.mrad, dp/p>+-5%(full)
-ν_x, ν_y	1.77, 2.27

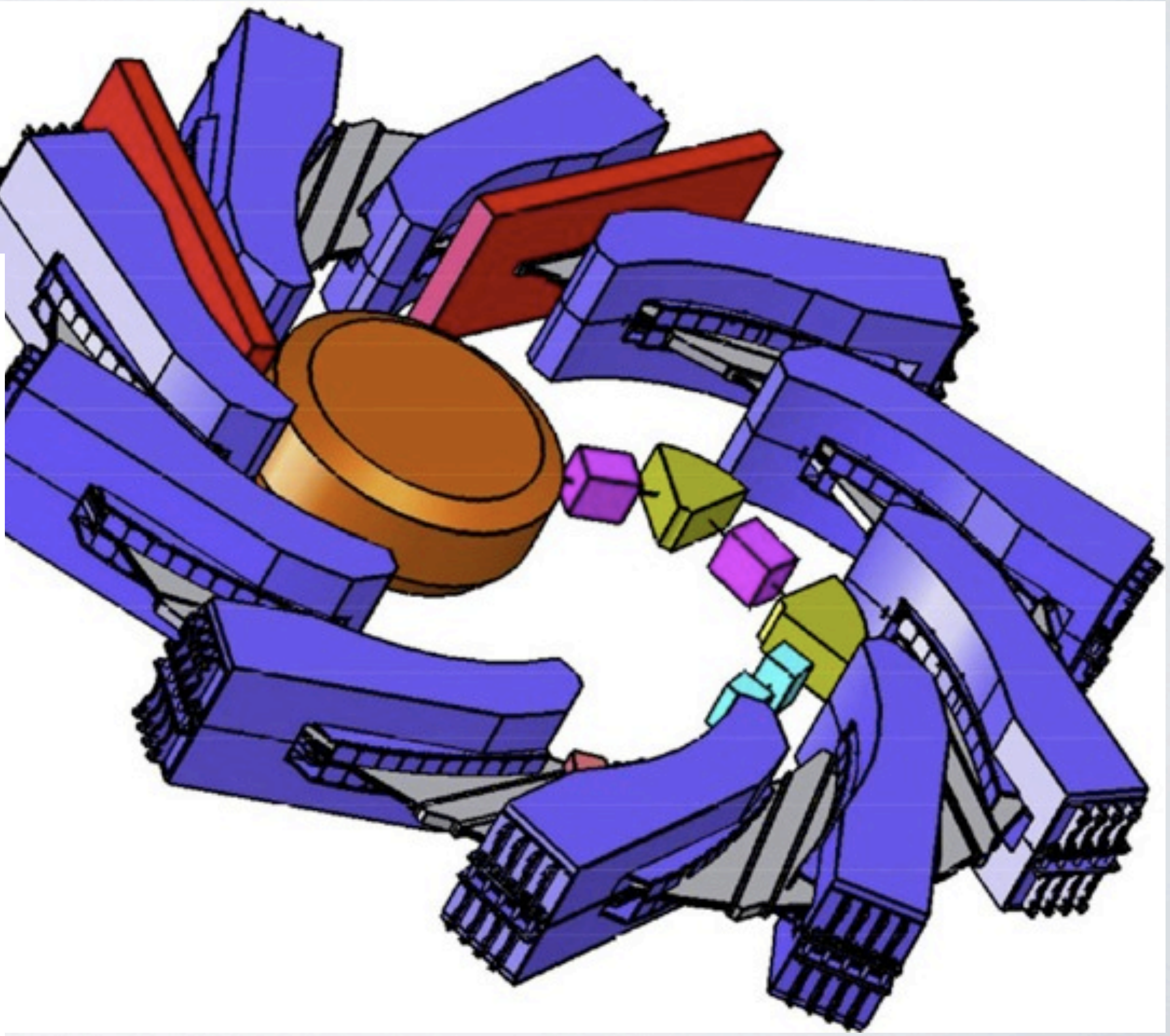
Neutron Yield > 10^{13}n/sec

RACCAM PROJECT GRENOBLE

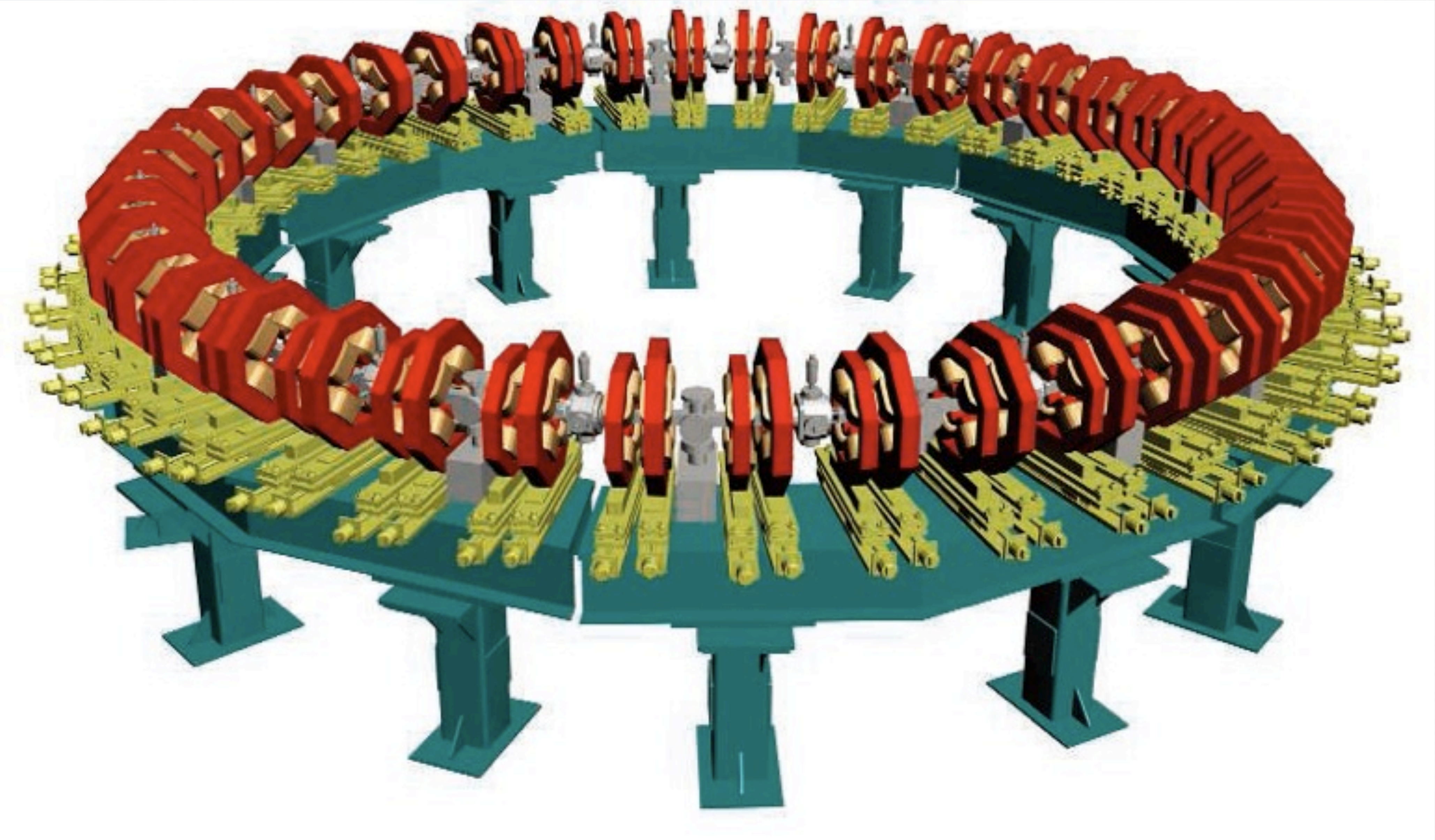
- Hadron therapy



Extraction energy, variable (E_{xtr})	MeV	70−180
Injection energy, variable (E_{inj})	MeV	5.55−15
Extraction $B\rho$ ($B\rho_{xtr}$)	T m	1.231−2.030
Injection $B\rho$ ($B\rho_{inj}$)	T m	0.341−0.562
$B\rho_{xtr}/B\rho_{inj}$	T m	3.612
Extraction $\beta\gamma$		0.393−0.648
Injection $\beta\gamma$		0.109−0.180
Lattice type		Spiral, scaling
Number of cells (N)		10
Packing factor (pf)		0.34
Field index (k)		5.00
Spiral angle (ζ)	deg.	53.7
Dipole sector angle (A)	deg.	12.24
ν_r		2.76
ν_z for 15 → 180 MeV		1.55 → 1.60
Transition gamma (γ_{tr})		2.45
Drift length on extraction orbit	m	1.42
Drift length on injection orbit	m	1.15
Radius on extraction orbit ($r_{xtr} \equiv r_0$)	m	3.460
Radius on injection orbit (r_{inj})	m	2.794
Orbit excursion	m	0.667



EMMA:Electron Model for Muon Accelerator under constraction at UK



PARAMETERS OF A 3.6 TO 12.6 GEV MUON RING

Lattice type	FDF triplet
Injection/extraction energy	3.6/12.6 GeV
RF frequency	200 MHz
Number of turns	6
RF peak voltage (per turn)	1.8 GV
Synchronous energy	8.04 GeV
Mean radius	~160.9 m
B_{max}(@ 12.6 GeV)	3.9 T
Field index k	1390
Total orbit excursion	14.3 cm
Harmonic number h	675
Number of cells	225
Long drift length	~1.5 m
Horiz. phase adv. per cell	85.86 deg.
Vert. phase adv. per cell	33.81 deg.

Table 1 - Example of 3.6 to 12.6 GeV muon scaling FFAG ring parameters.

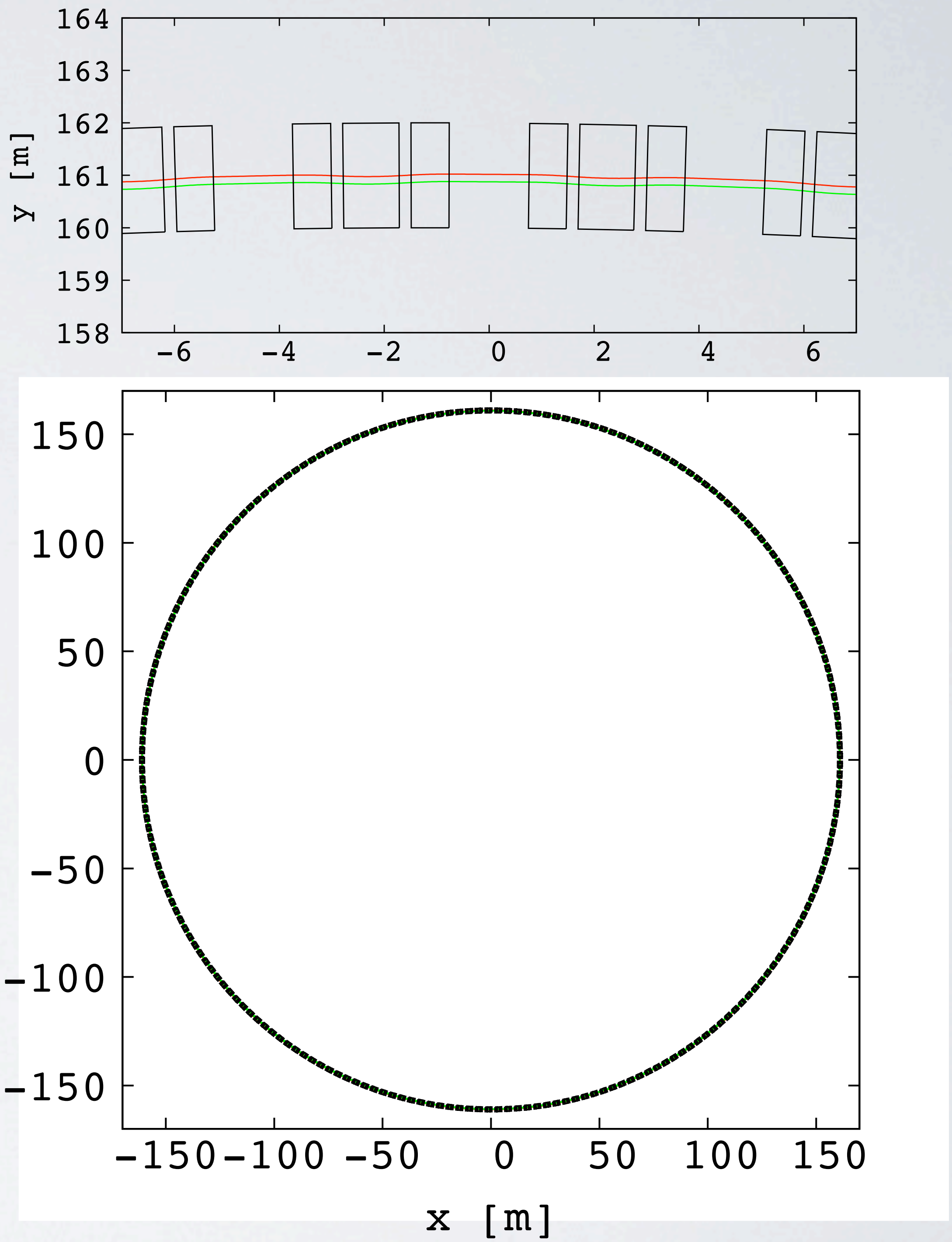


Figure 3 - Ring layout.

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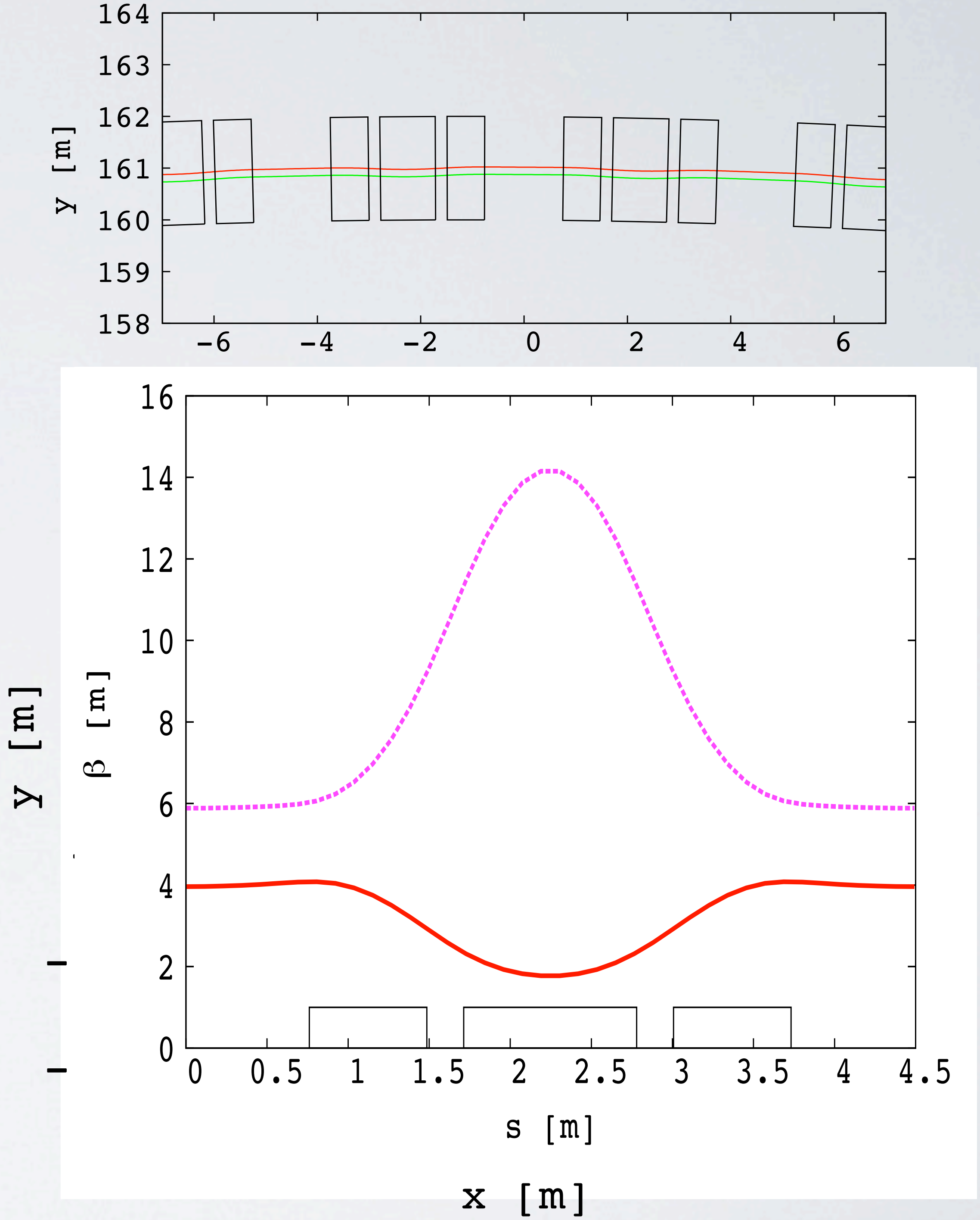

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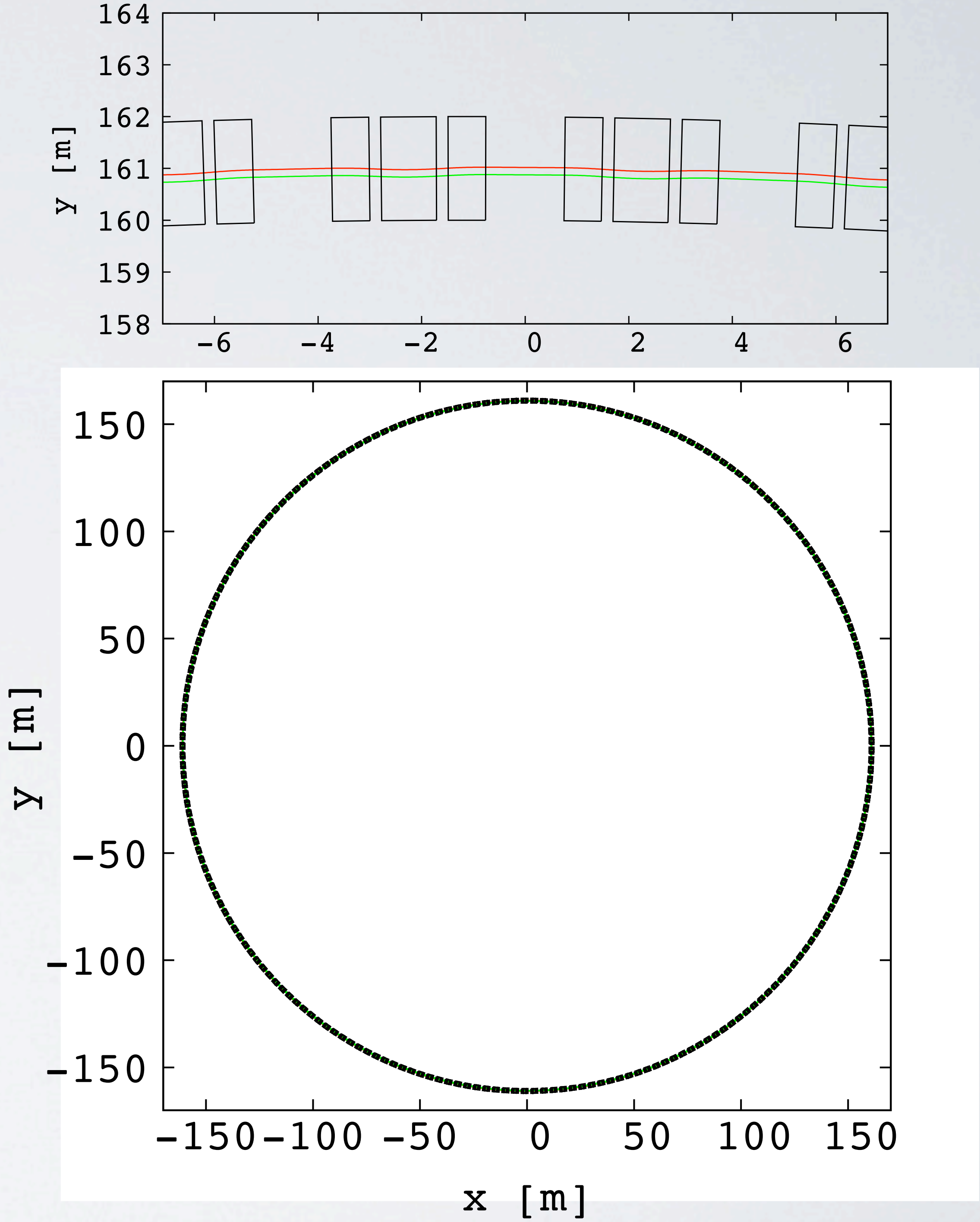


Figure 3 - Ring layout.

Muon accelerator:3.6-12.6GeV neutrino factory

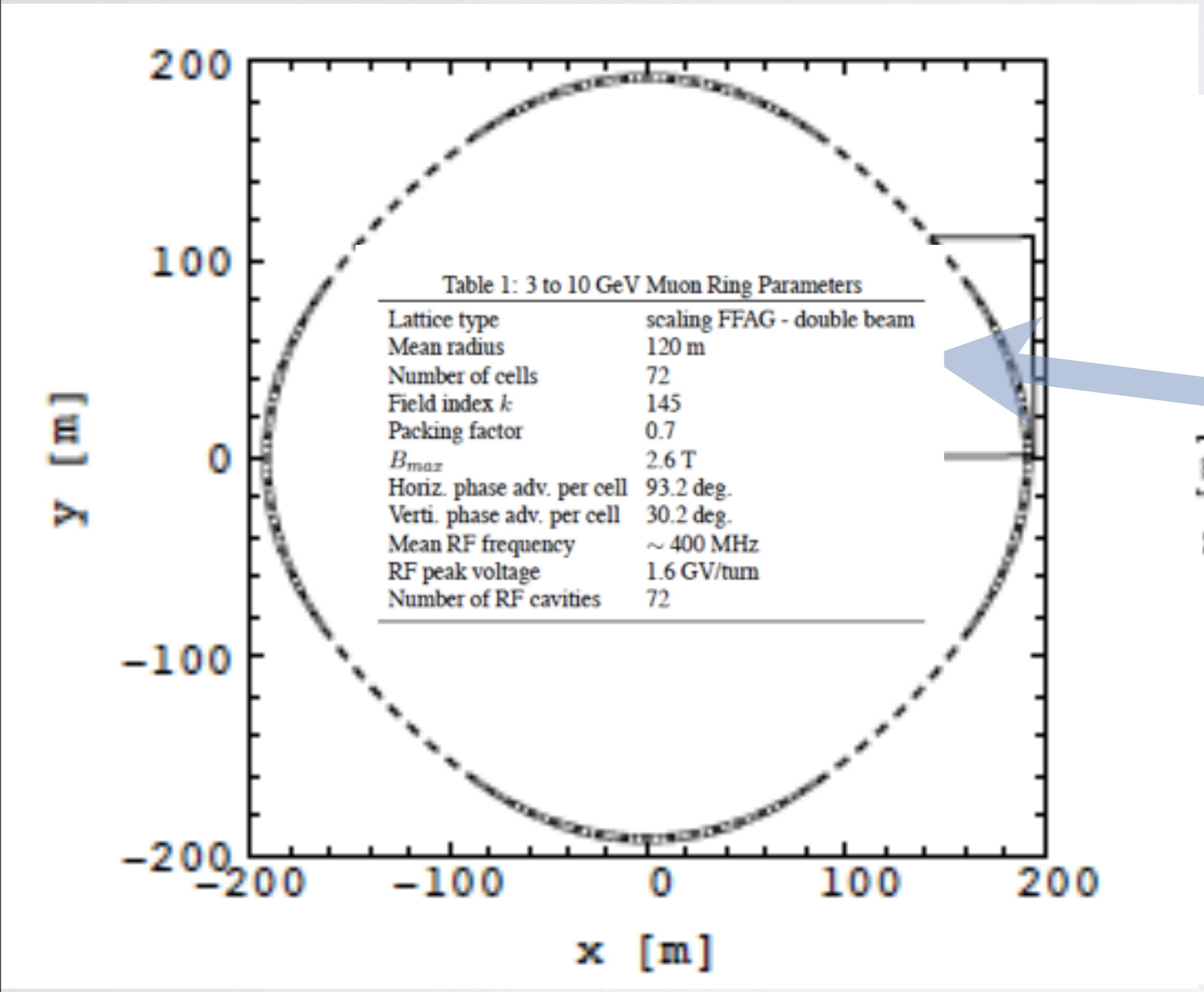
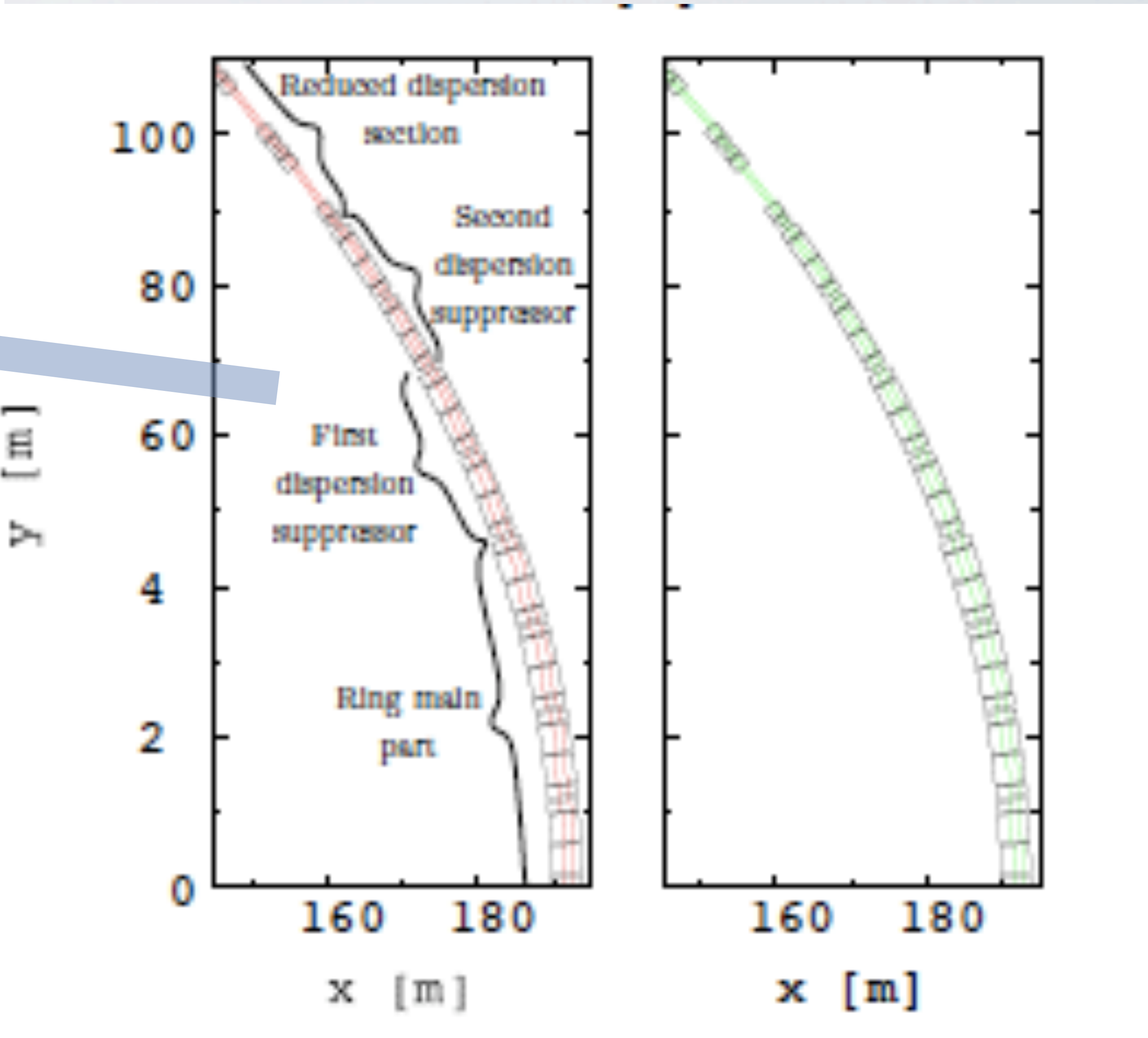
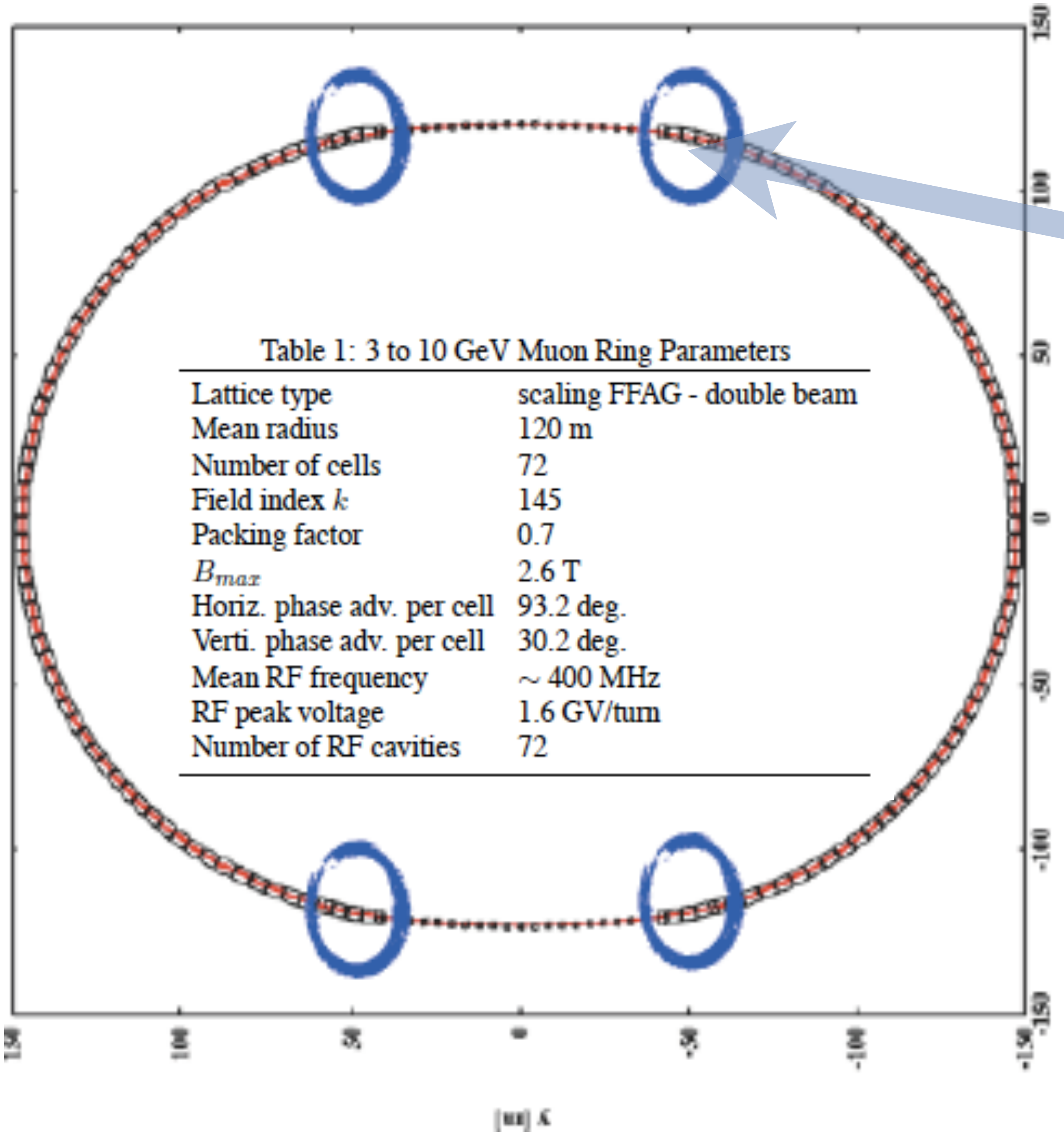


Table 1: 3 to 10 GeV Muon Ring Parameters

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	~ 400 MHz
RF peak voltage	1.6 GV/turn
Number of RF cavities	72



Muon accelerator neutrino factory



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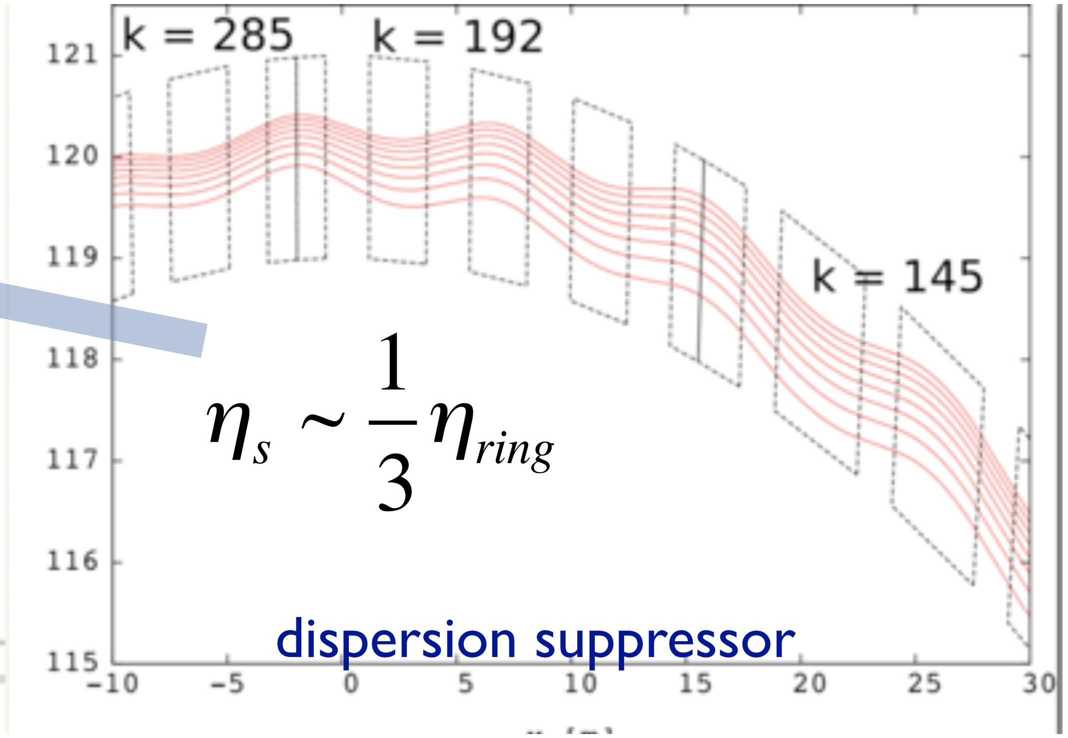
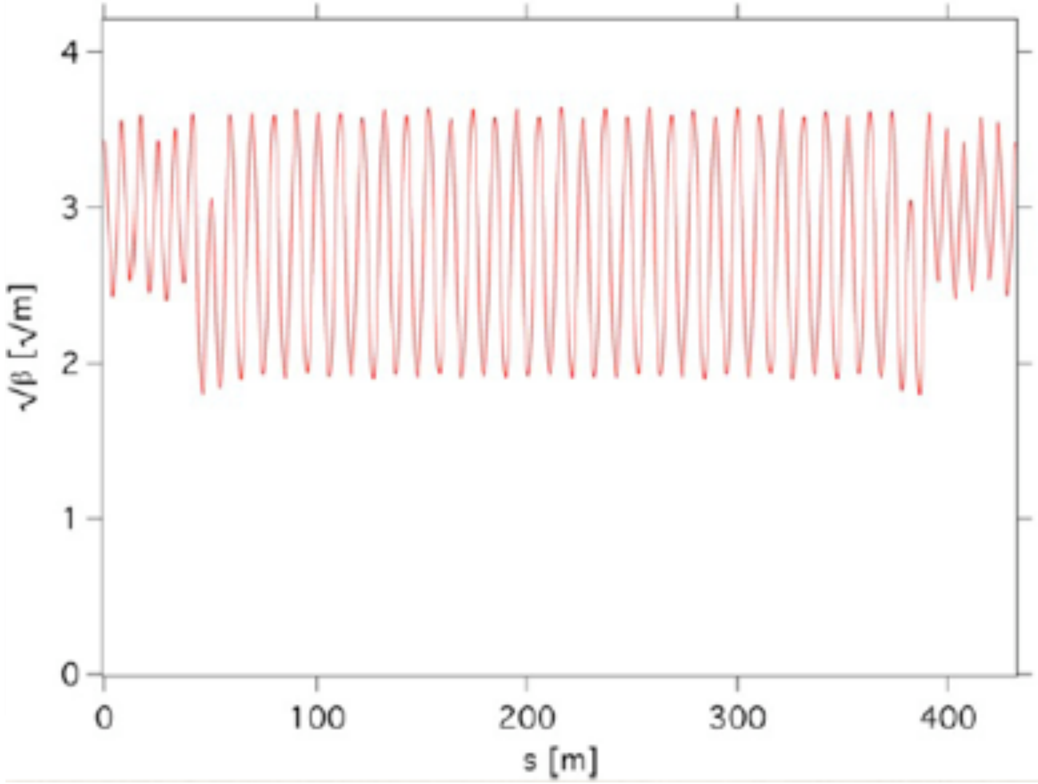


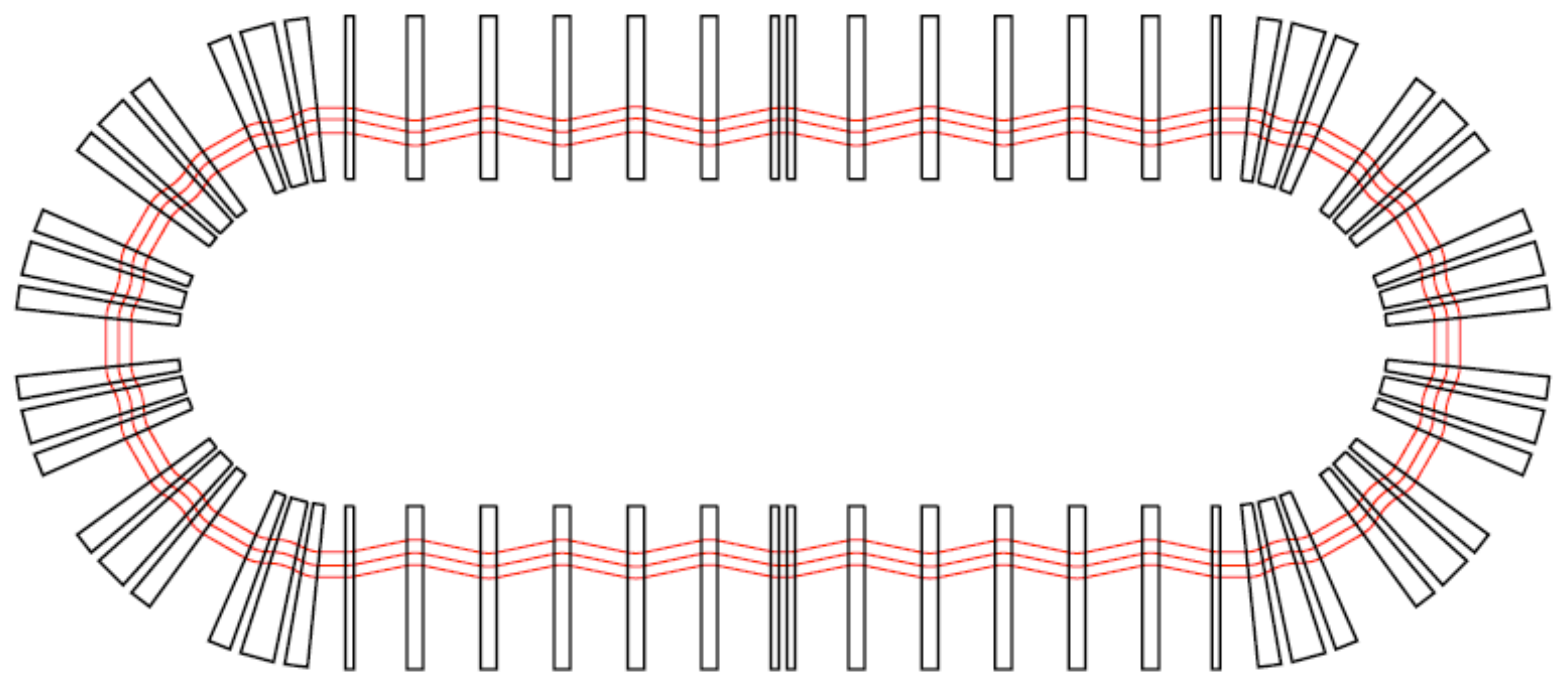
$$\eta_s \sim \frac{1}{3}\eta_{ring}$$

dispersion suppressor

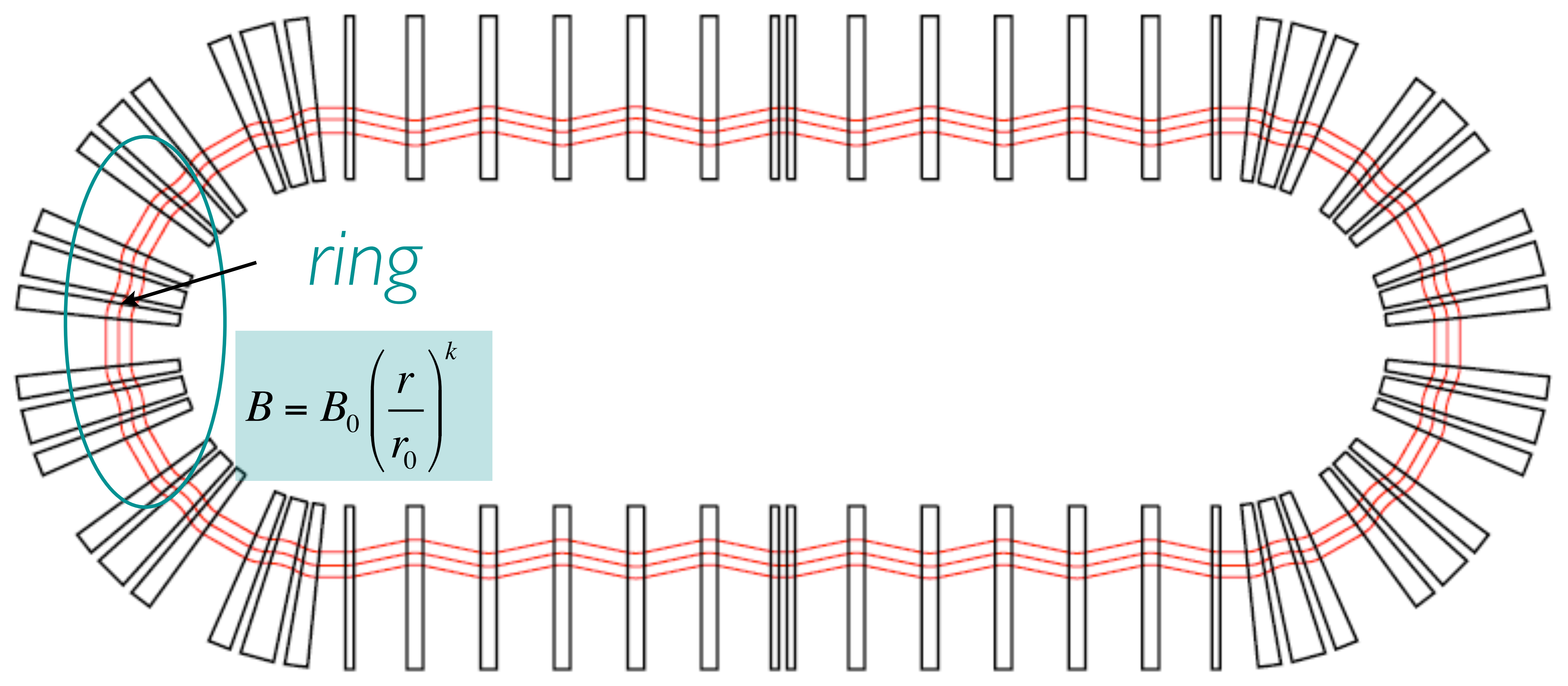


Planch, Mori

ADVANCEMENT OF SCALING FFAG



ADVANCEMENT OF SCALING FFAG

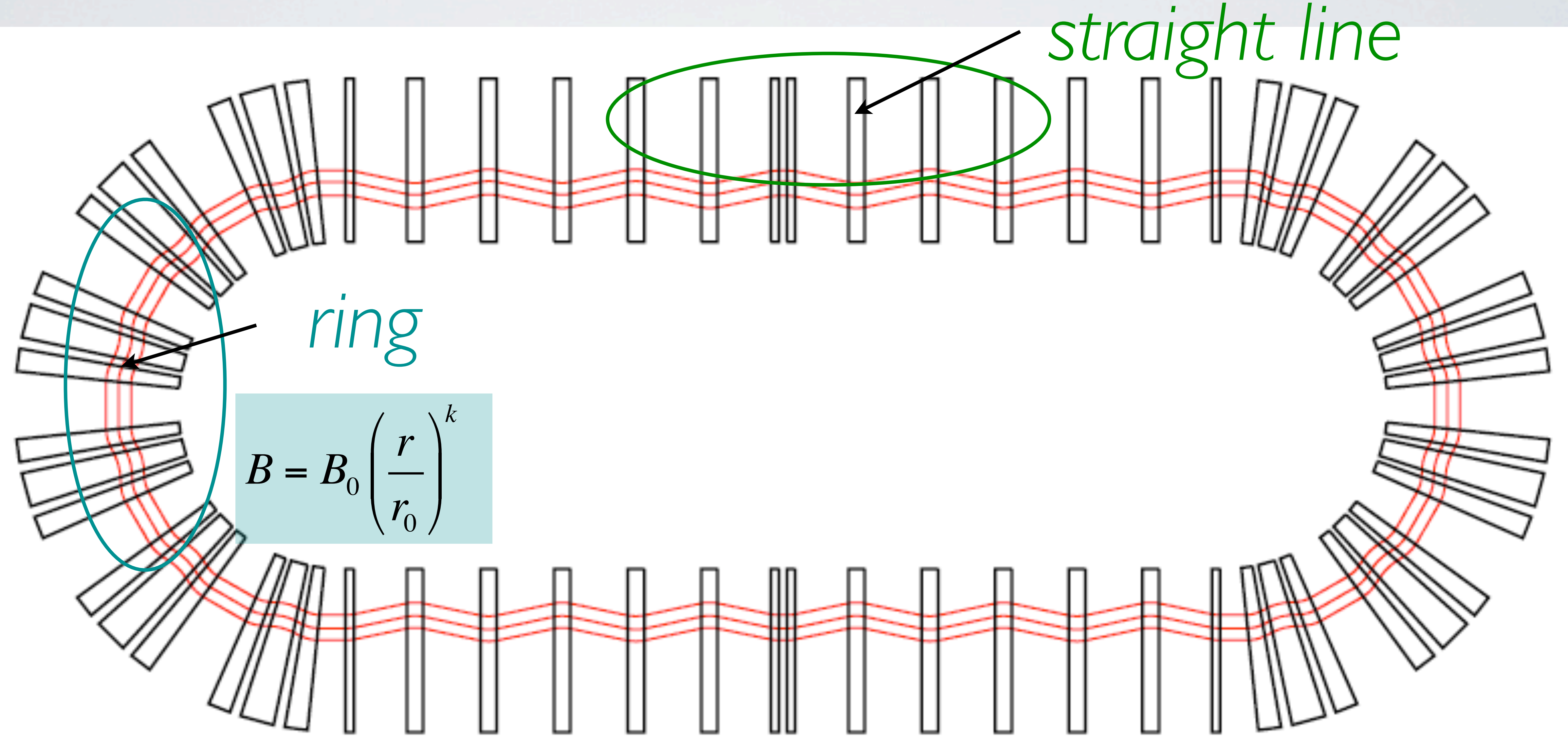


ring

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

ADVANCEMENT OF SCALING FFAG

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



straight line

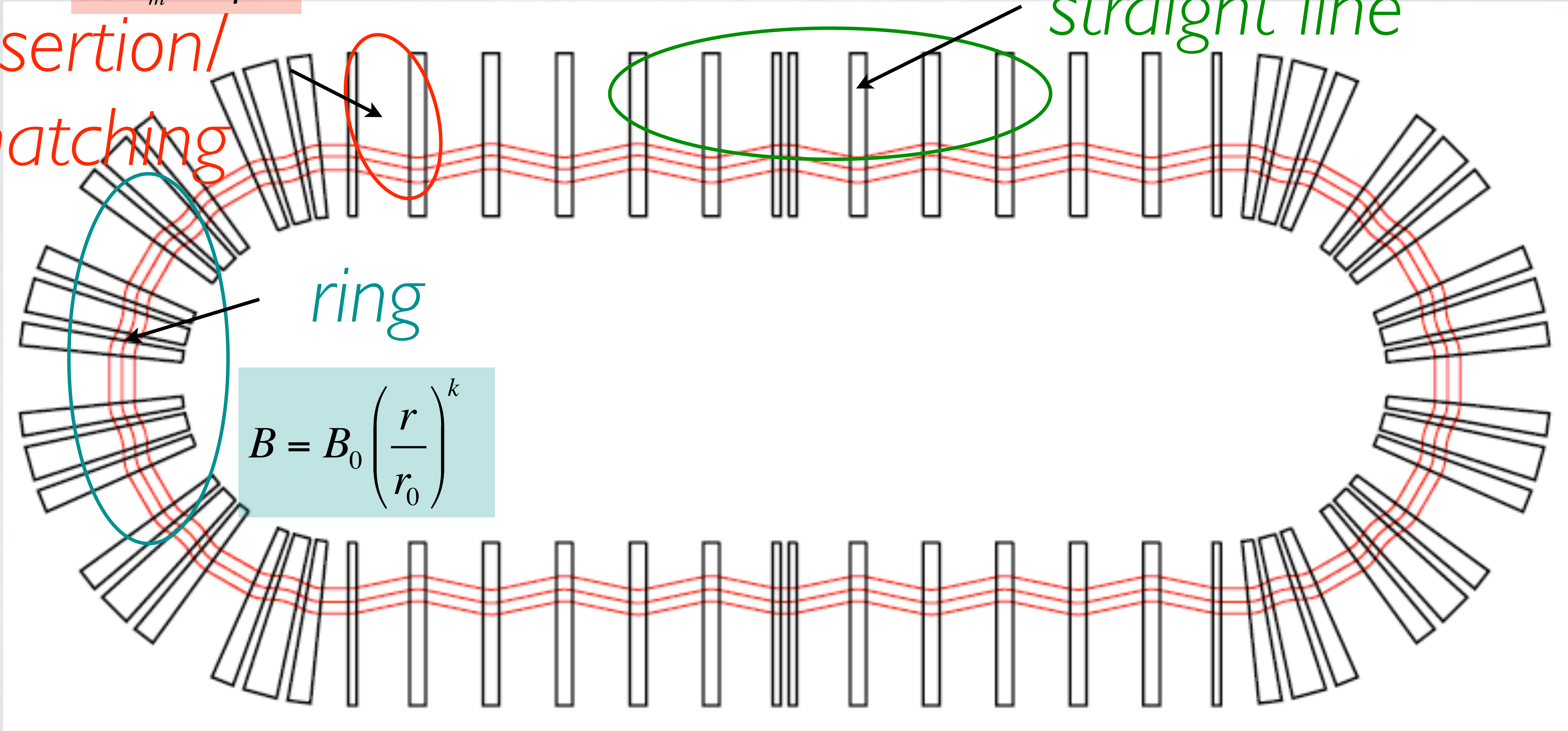
ring

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

ADVANCEMENT OF SCALING FFAG

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

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



insertion/ matching

straight line

ring

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

ADVANCEMENT OF SCALING FFAG

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

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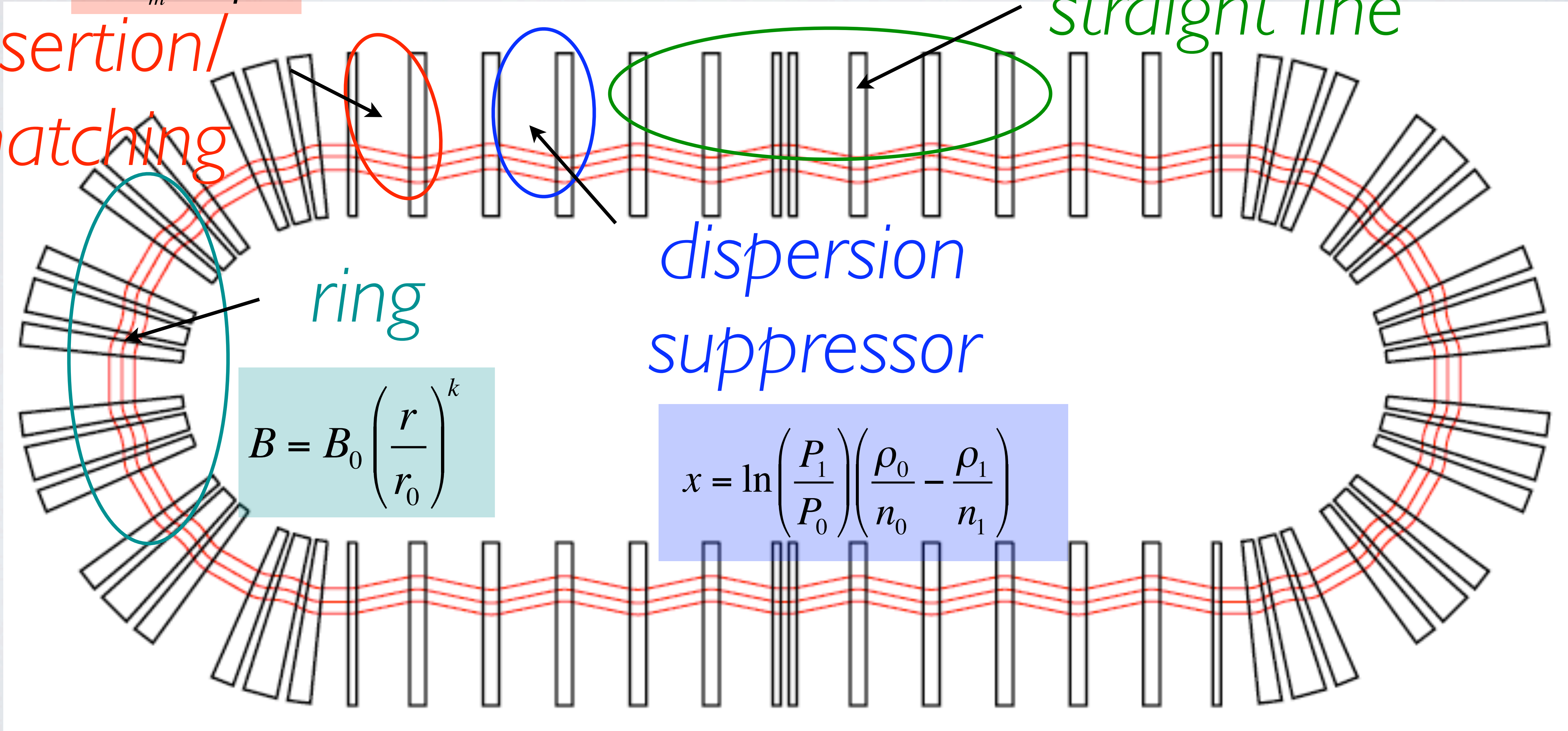

straight line

insertion/ matching

dispersion suppressor

ring

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

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

FFAG IN FUTURE

- G.W. Friedrich Hegel : Ideology must be essentially overcome.
- ヘーゲル：理想理念は必ず乗り越えられねばならない。