DEVELOPMENT OF FFAG AT KYUSYU UNIVERSITY

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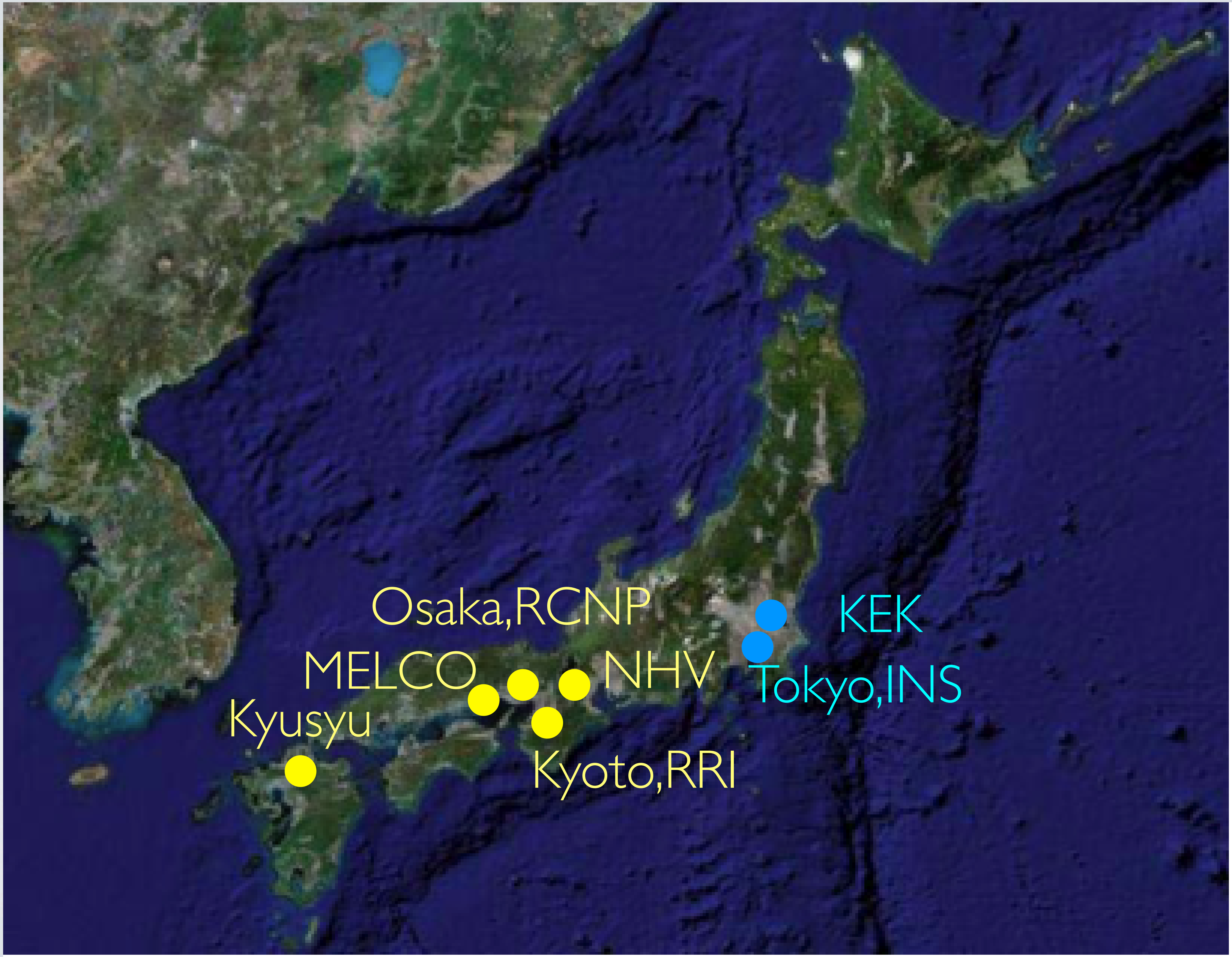
*invited

DEVELOPMENTS OF FFAG IN JAPAN

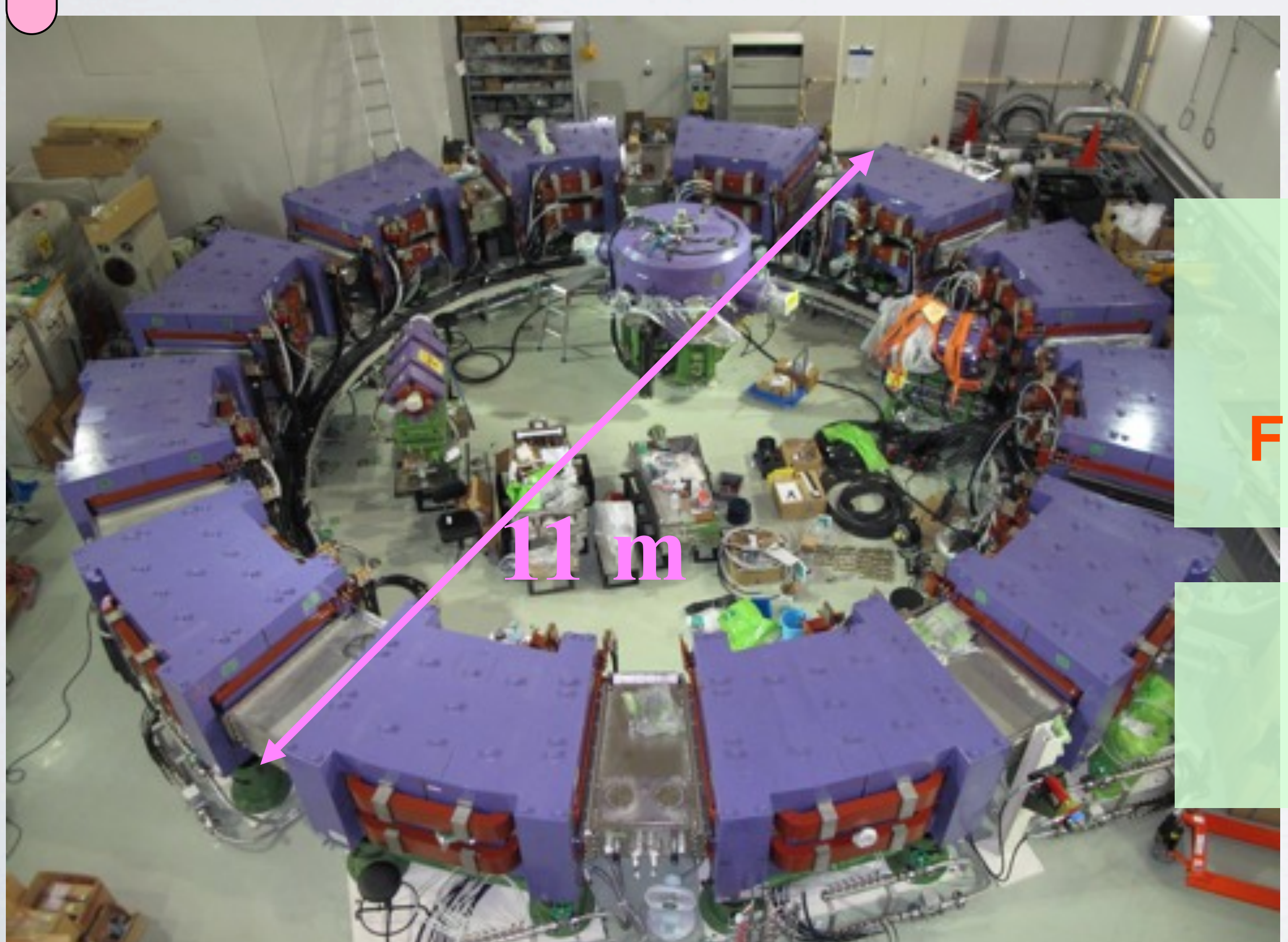


KYUSYU UNIVERSITY

Construction of new accelerator center

Main accelerator : FFAG Synchrotron

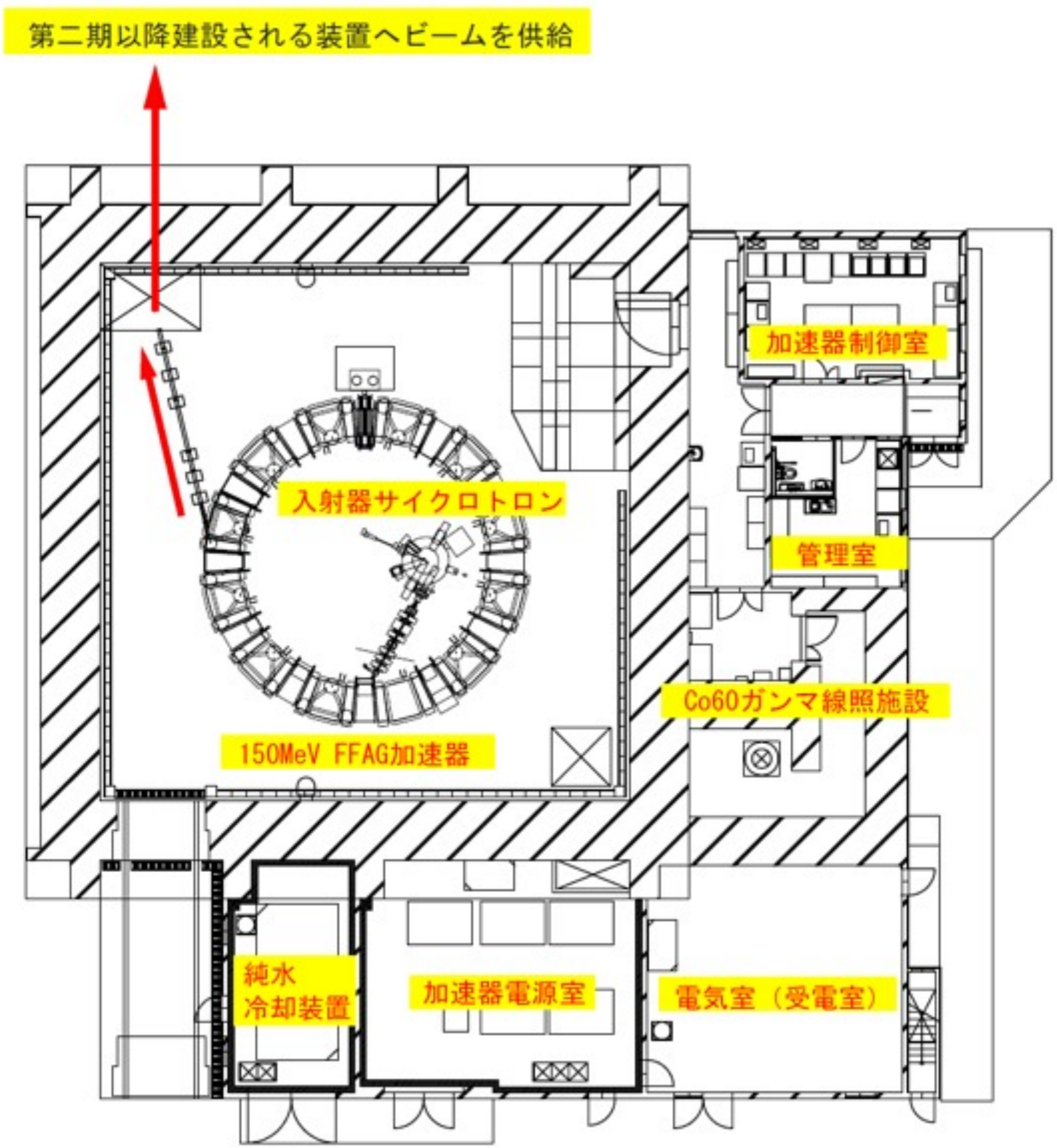
The test machine that Mori's group developed is under re-installation.



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



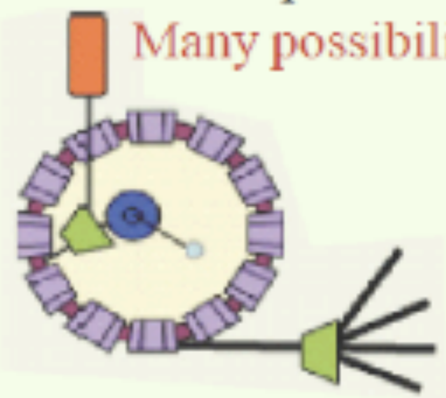
magnet	Radial sector type (DFD-triplet)
Cell	12
K-value	7.62
Beam energy	12 ⇒150 MeV (10 ⇒ 125 MeV)
Radius	4.47 ⇒ 5.20 m
Betatron tune	H: 3.69〜3.80 V: 1.14〜1.30
Max. field	F-field: 1.63 T
(along orbit)	D-field: 0.78 T
Circ. freq.	1.55〜4.56 MHz
Repetition	100 Hz

Various field studied with FFAG

FFAG development — Accelerator science

Under-developed machine just born.

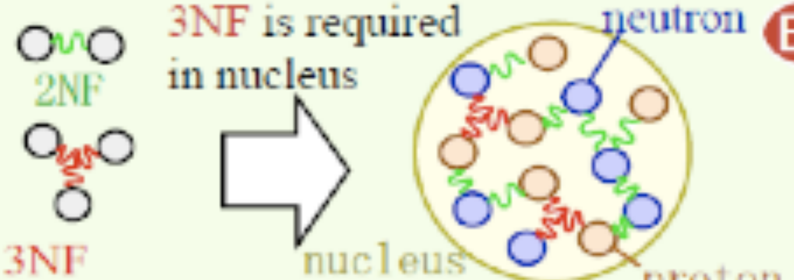
Many possibilities no other machines have.



- 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

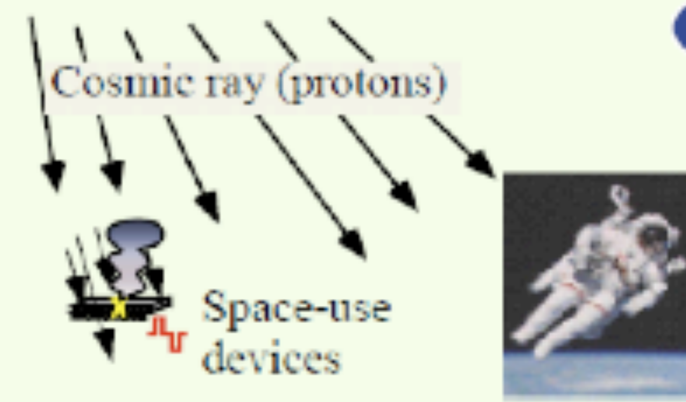
3-body force, nuclear data — Hadron science, Energy science



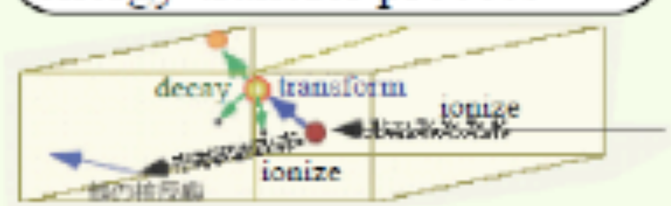
3NF working to 3 nucleons simultaneously

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

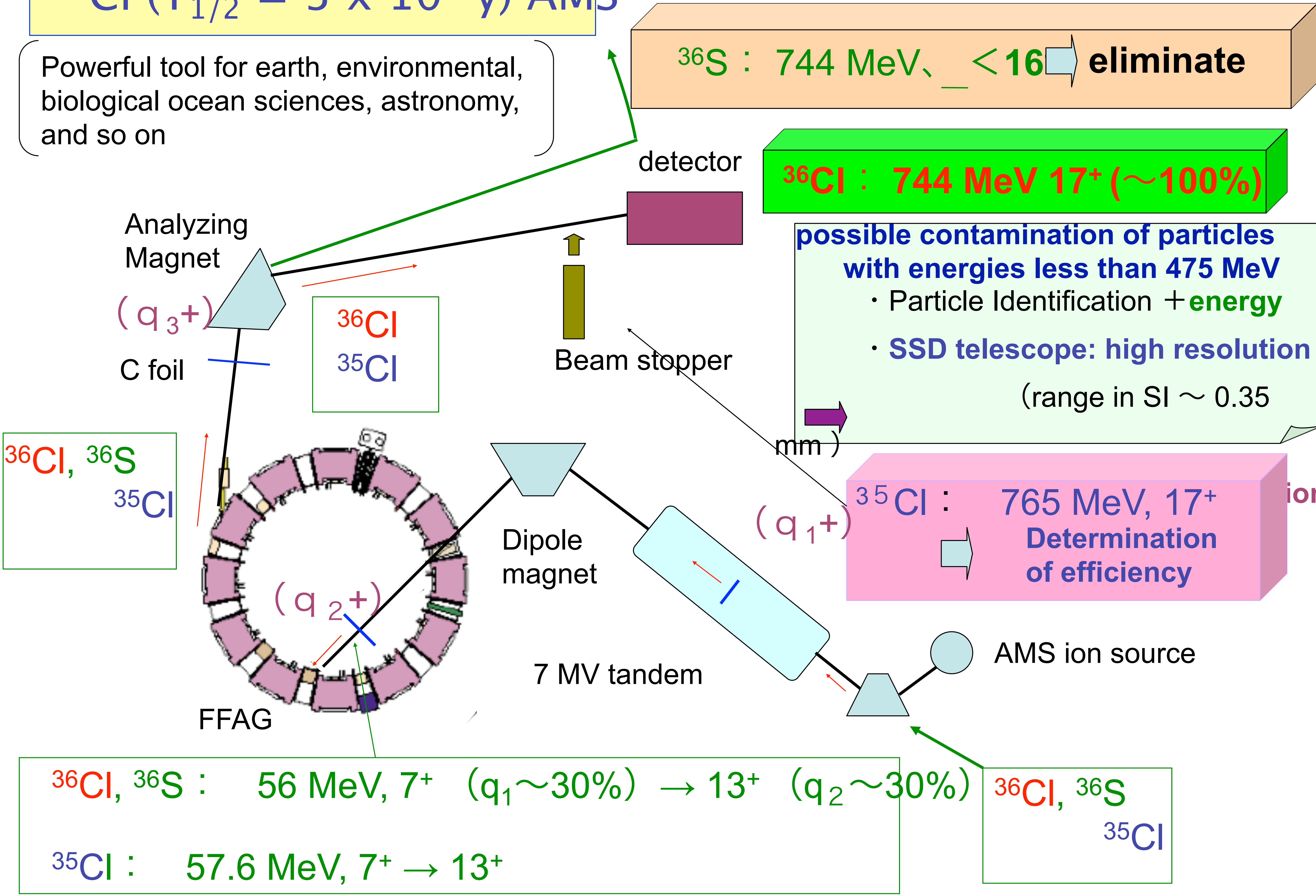
Reactor material
Calibration of neutron detectors
Bacic data for acc. driven reactor / nuclear waste

? ? ? — ? ? ? science

New field

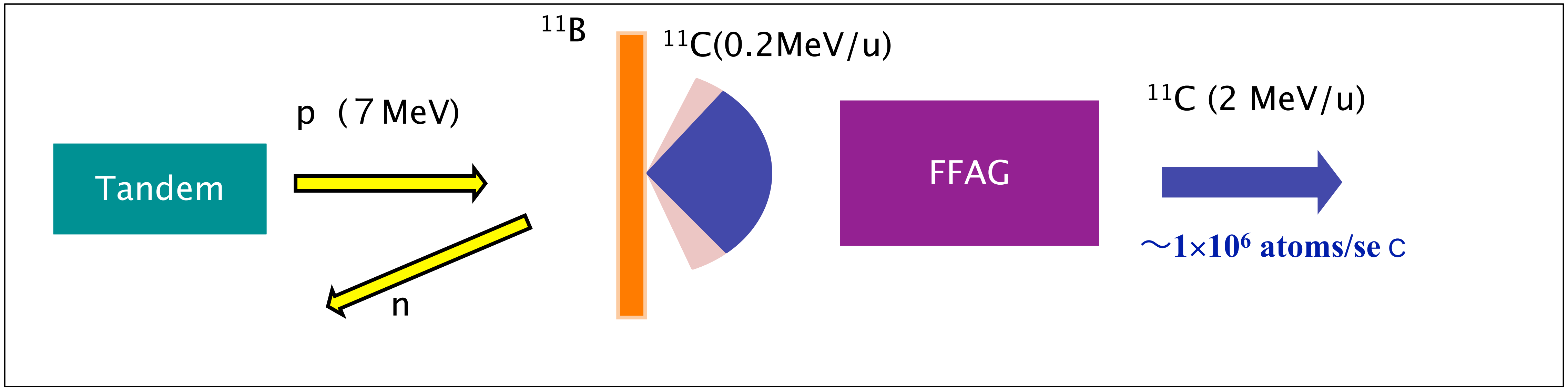
^{36}Cl ($T_{1/2}$ = 3 x 10^5 y) AMS

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



Acceleration of unstable nuclei and isomers

***Acceleration of unstable nuclei**



***Acceleration of isomers**

$^{16}O + ^{39}K \rightarrow ^{52m}Fe$ + p,n,n

(40MeV) (10MeV)

⇒ (100MeV)

$^{18}O + ^{9}Be \rightarrow ^{24m}Ne$ + p,n,n

(35MeV) (20MeV)

⇒ (200MeV)

Advantage:

- High quality unstable beam for all elements

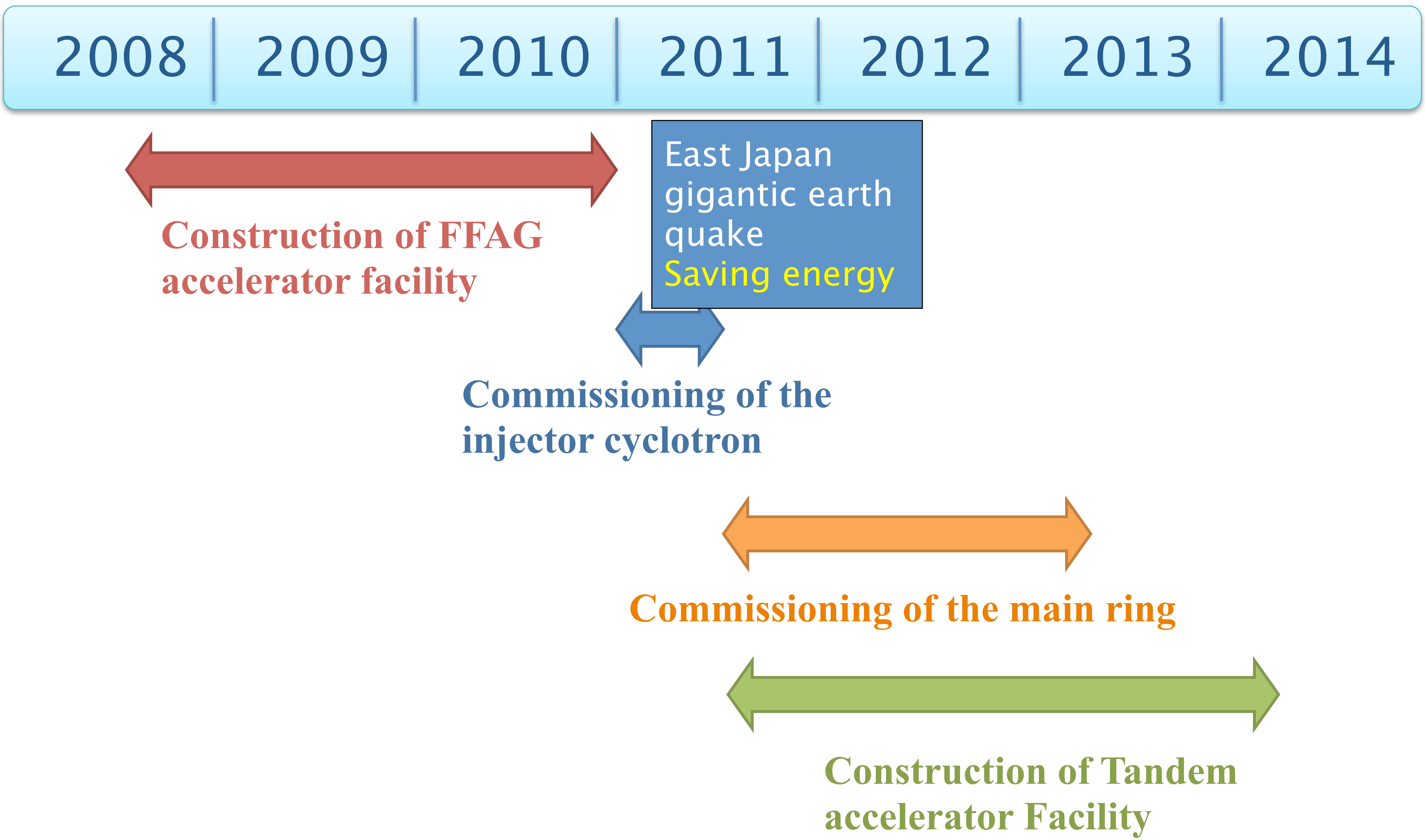
Subjects

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

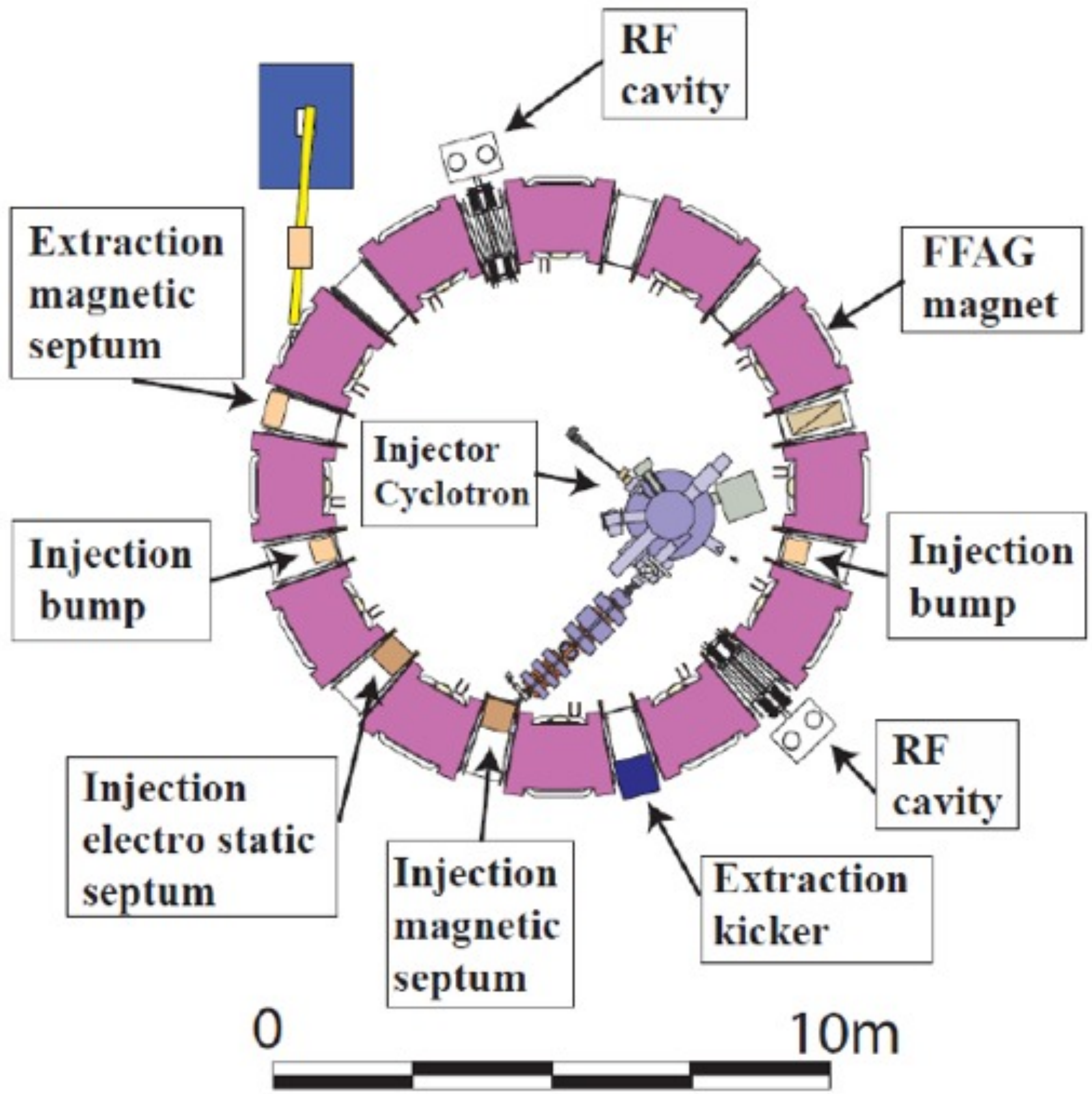
Requirement to accelerator

- Large acceptance (longitudinal and transverse)

Construction Schedule



150 MeV FFAG Accelerator



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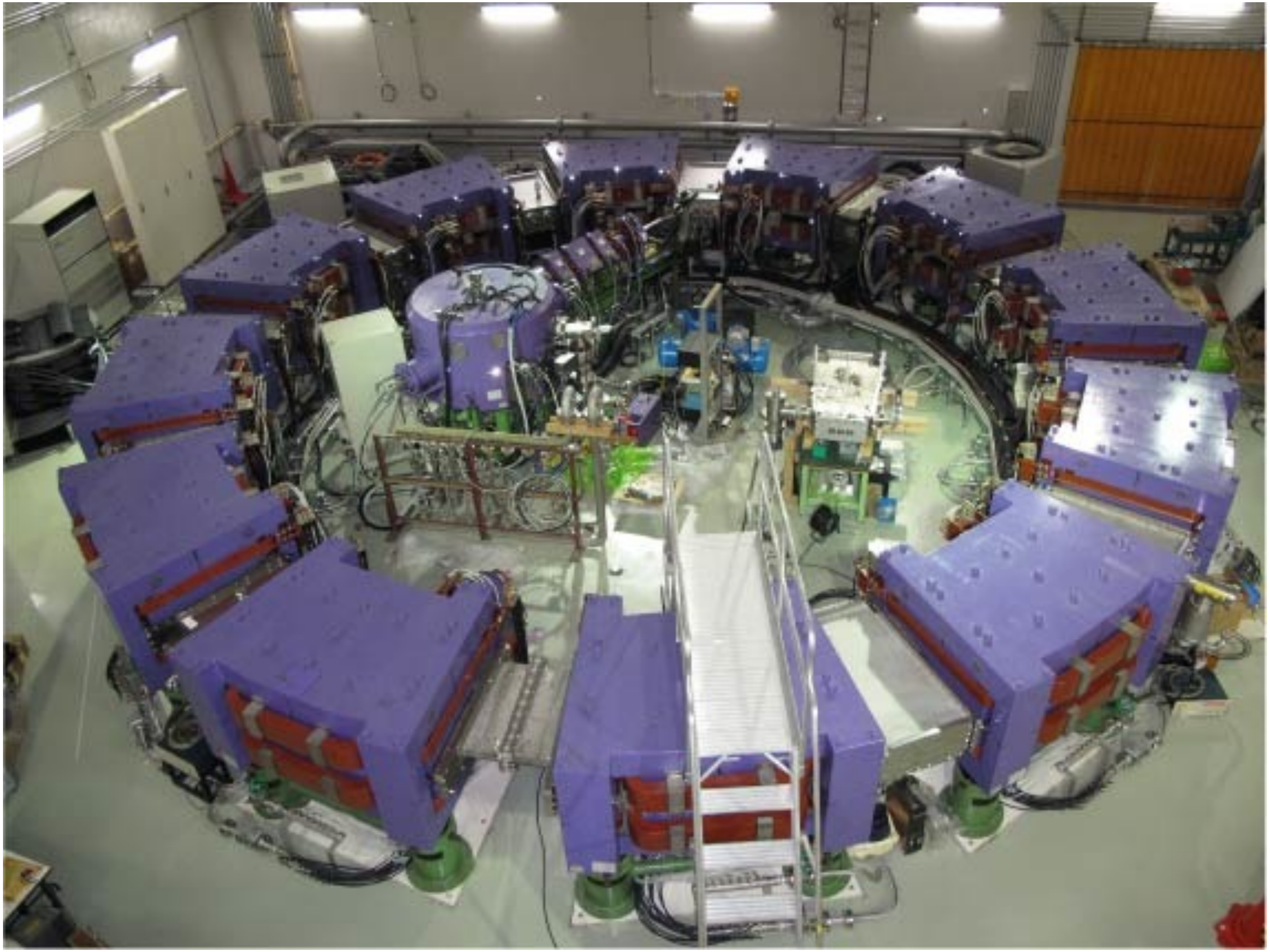
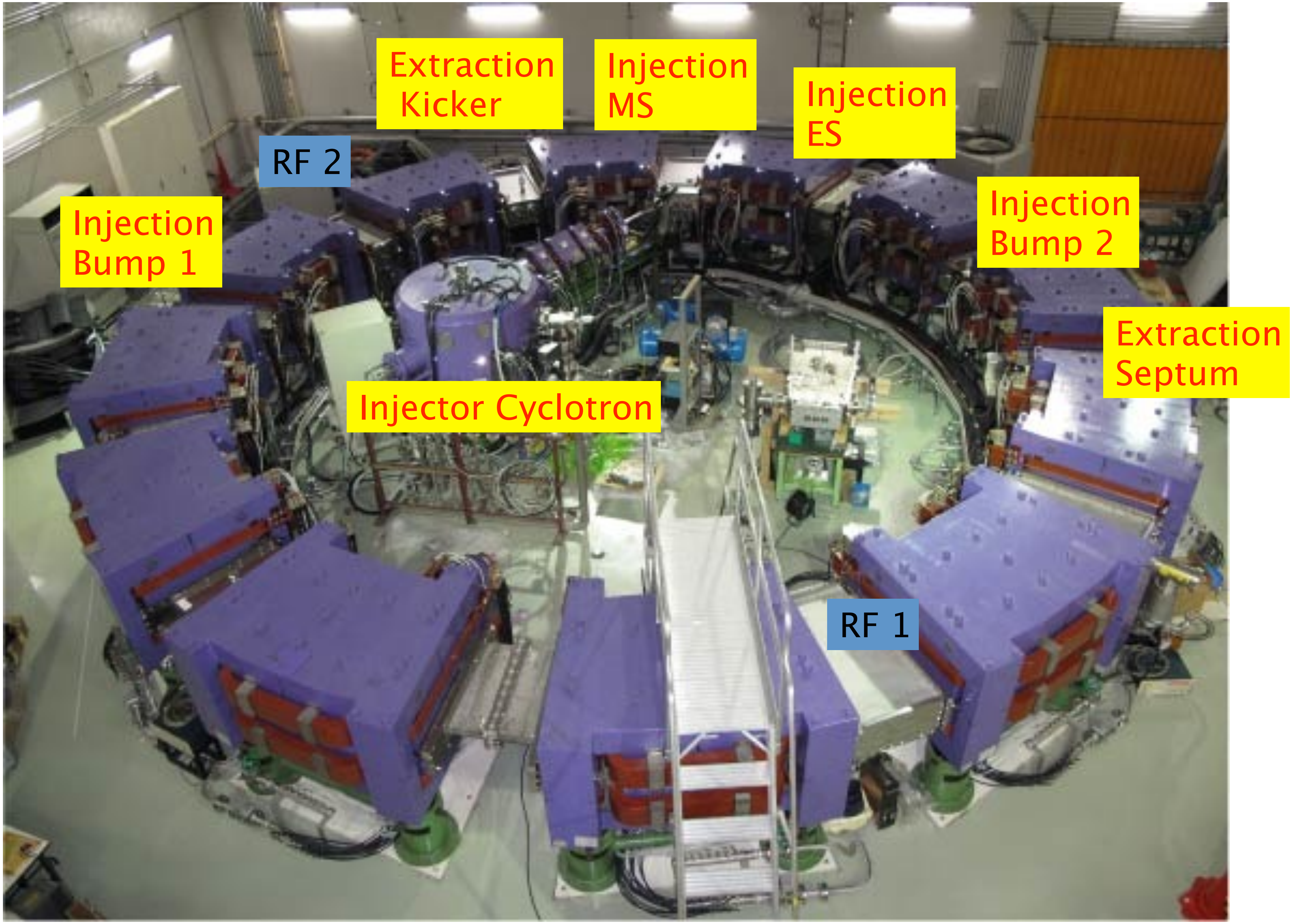
Max. field	F-field: 1.63 T
(along orbit)	D-field: 0.78 T
Circ. freq.	1.55〜4.56 MHz
Repetition	100 Hz/2 cavities
Mean current	1.5 nA

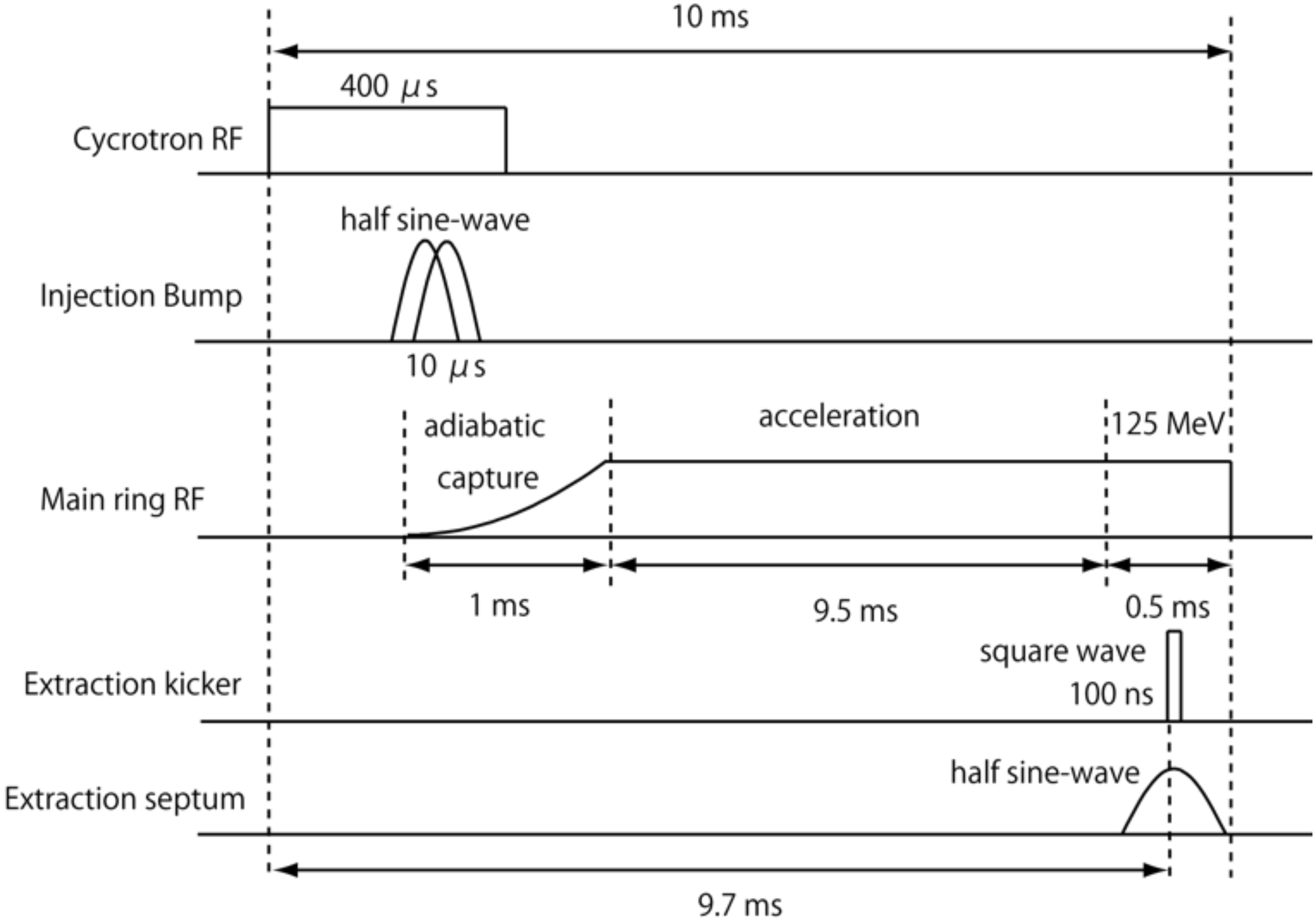



Extraction Kicker
Injection MS
Injection ES
RF 2
Injection Bump 1
Injection Bump 2
Extraction Septum
Injector Cyclotron
RF 1

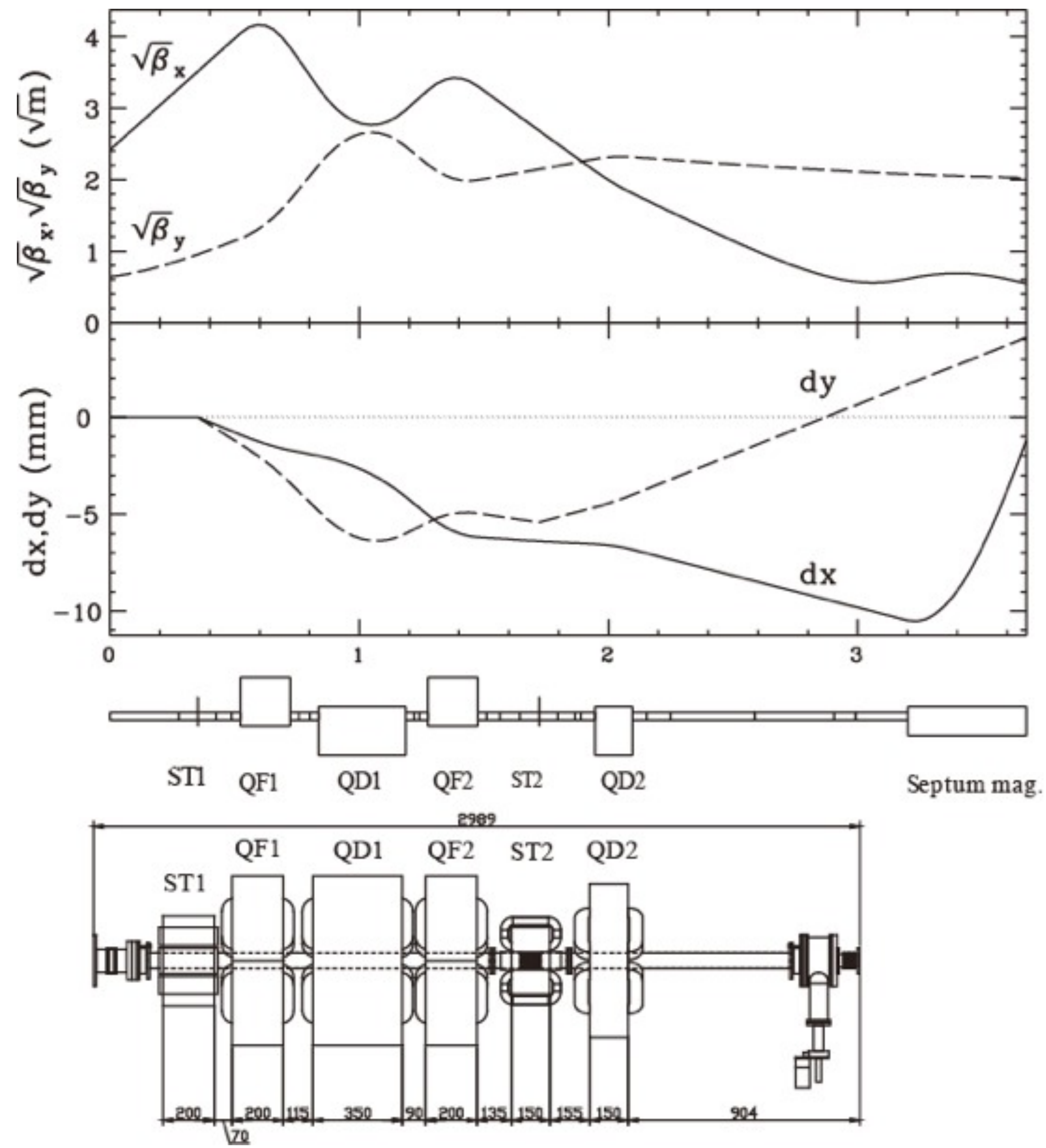
Injector Cyclotron

Type	AVF cyclotron
Beam Energy	10 MeV
Ion Source	Internal PIG (LaB_6 Cathode)
Extraction Radius	300 mm
Magnetic Field	Max. 1.54 T
RF Dee Voltage	40 kV
RF Frequency	47 MHz (2nd harmonic acceleration)
Beam Current	2 μA (Duty 4%, 100Hz)

Timing Chart of the 150 MeV FFAG



Beam Injection line



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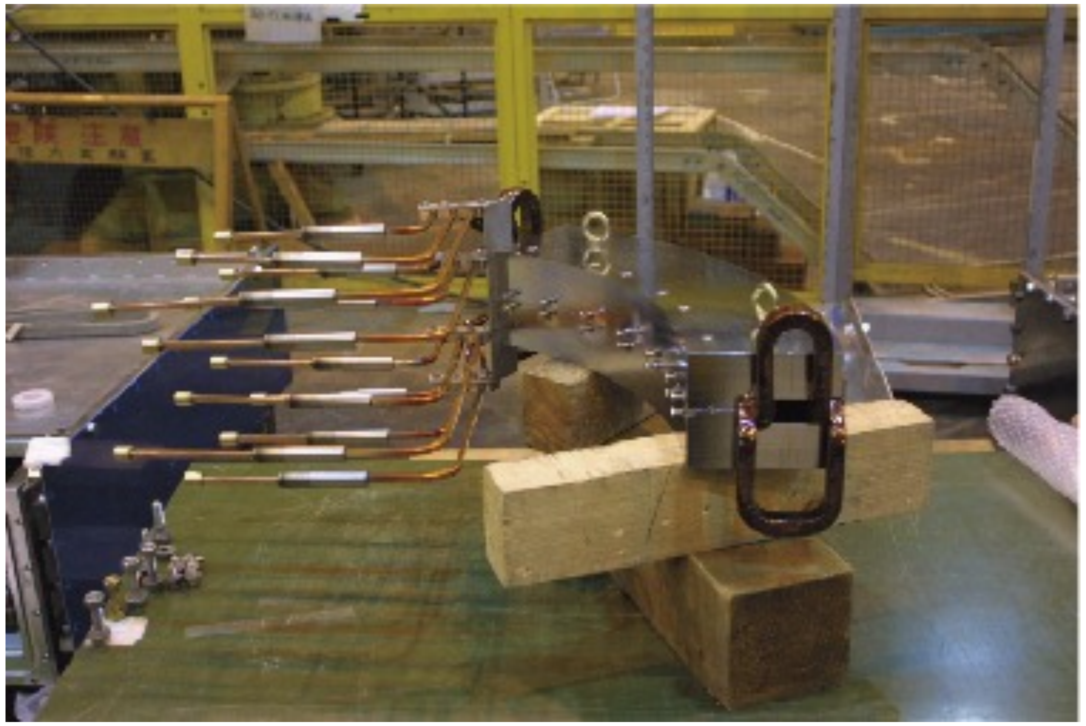
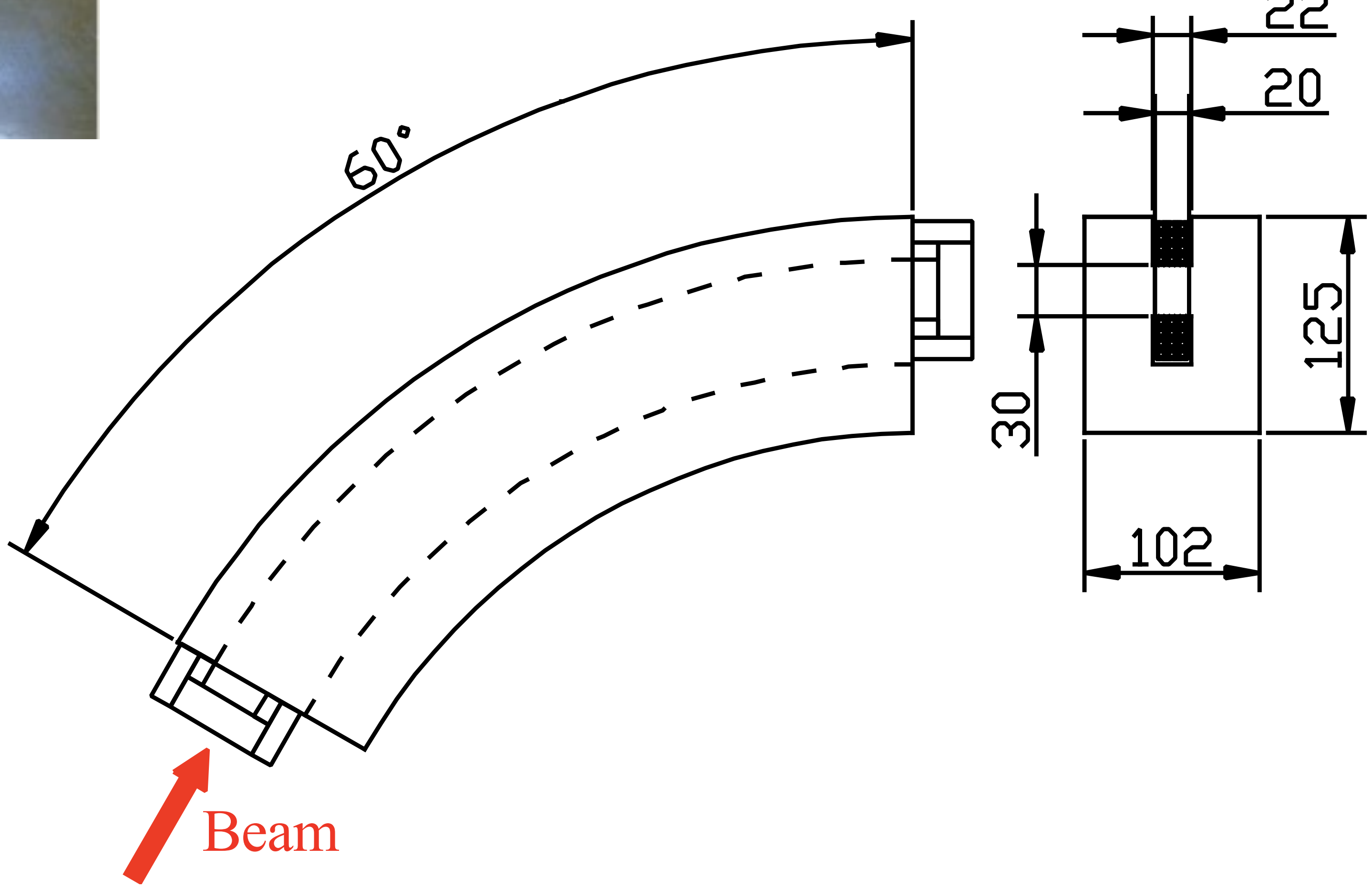
Magnetic septum for beam injection

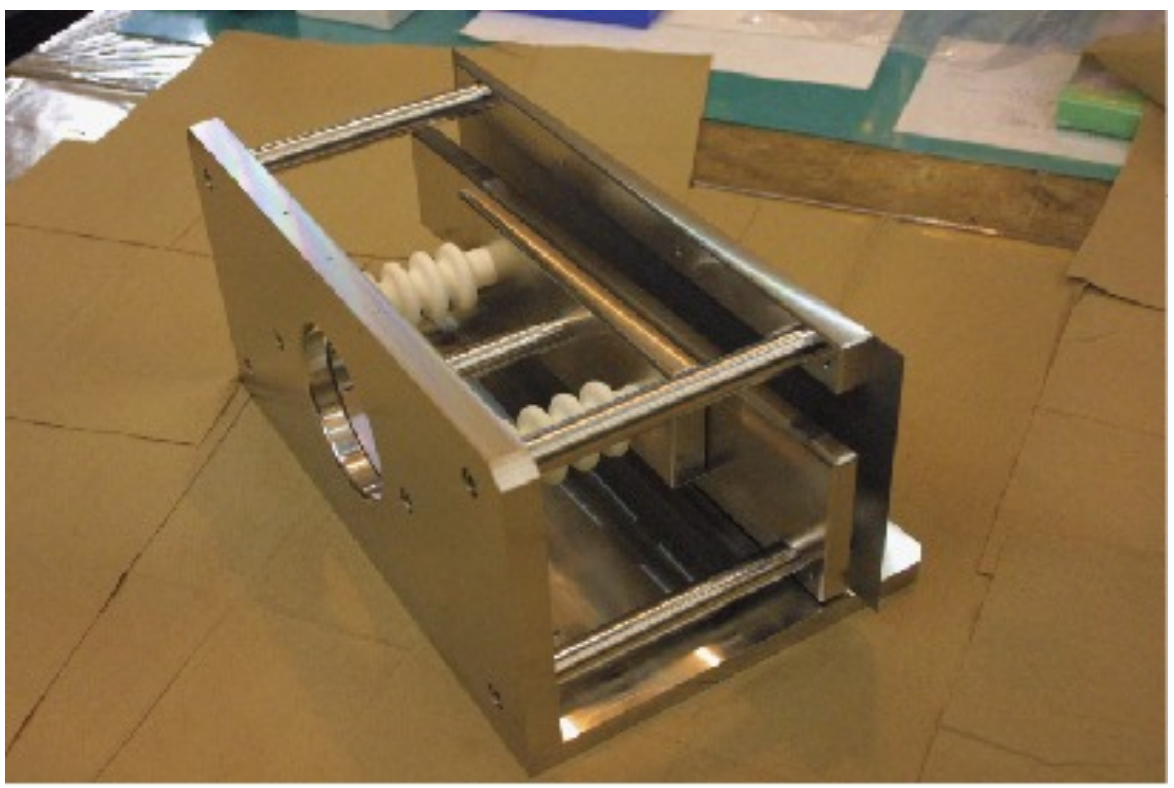


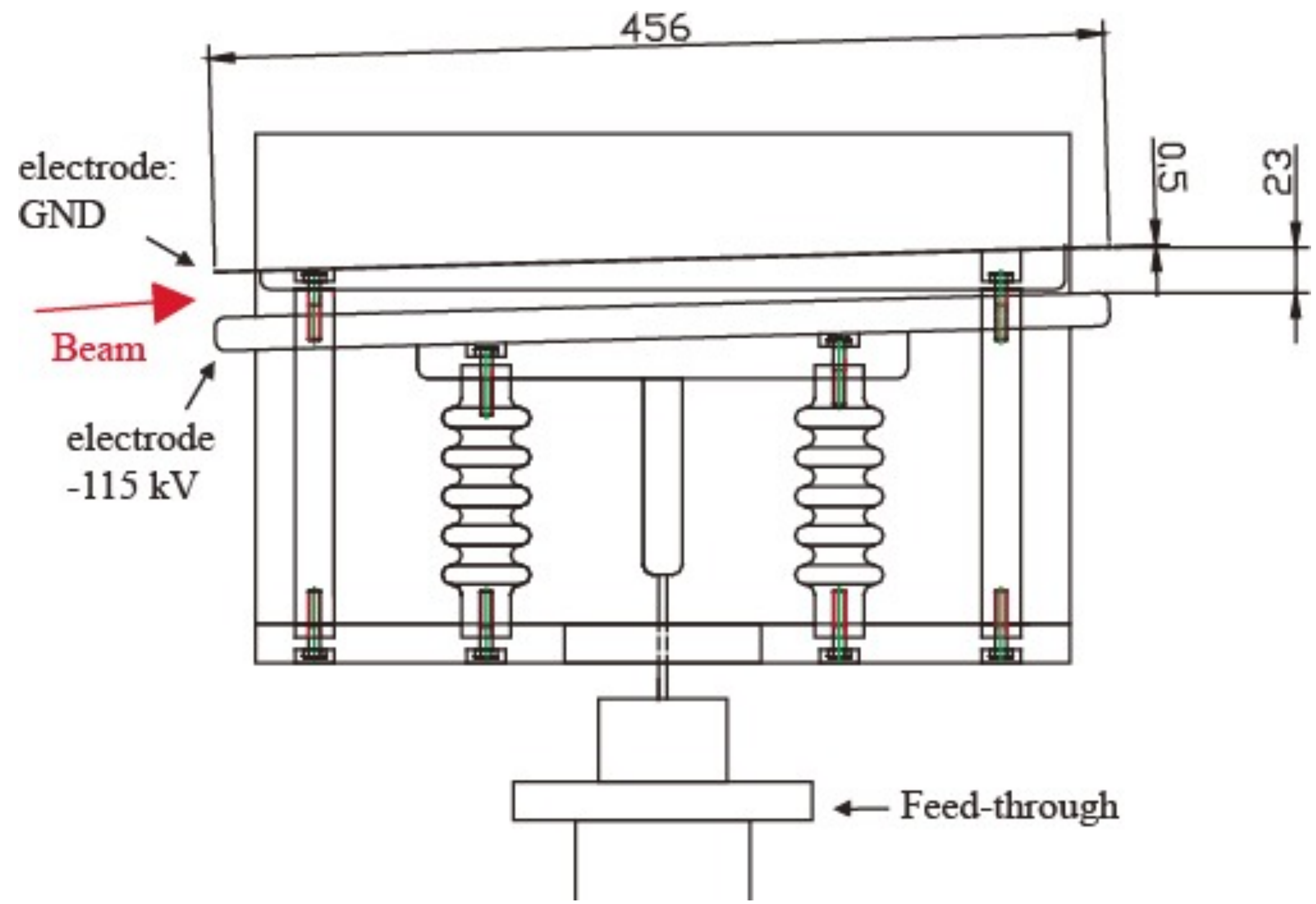
Bending angle: 60 deg.
Max. magnetic field: 1.0 T
DC Current: 1500 A



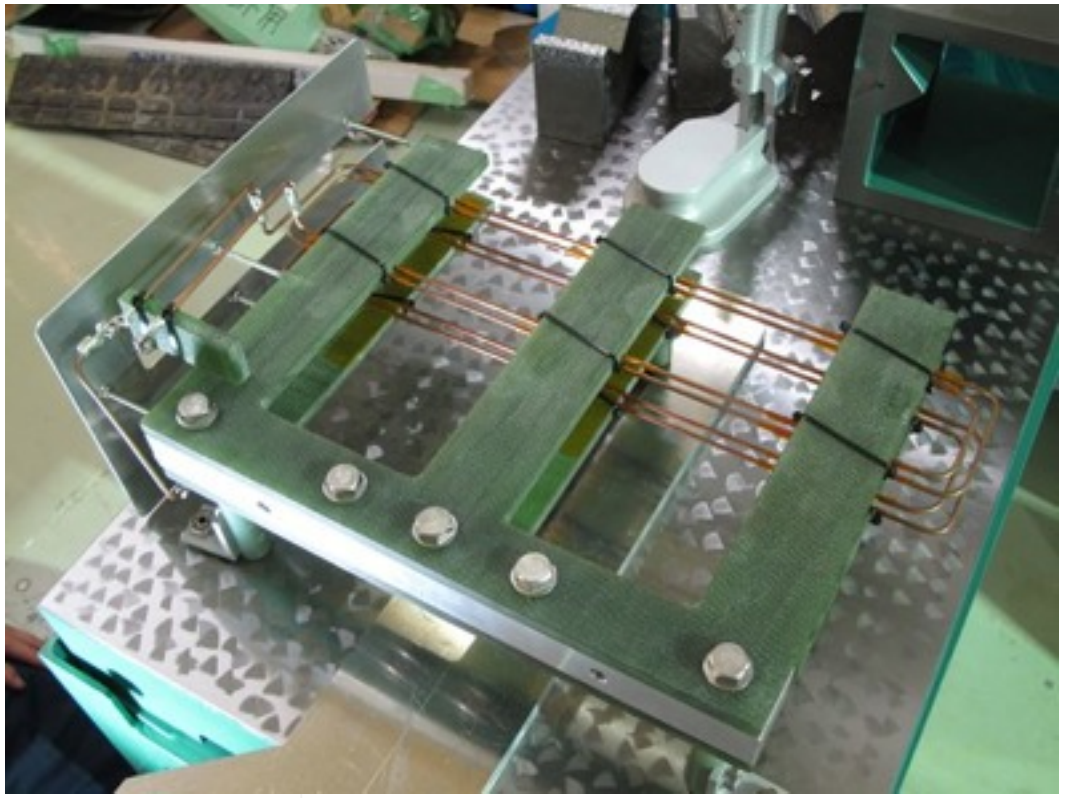
Electric septum for beam injection

Bending angle: 1.5 deg.
Thickness of GND electrode: 0.5 mm
Gap length: 23 mm
Voltage: -100 kV ~ -150 kV

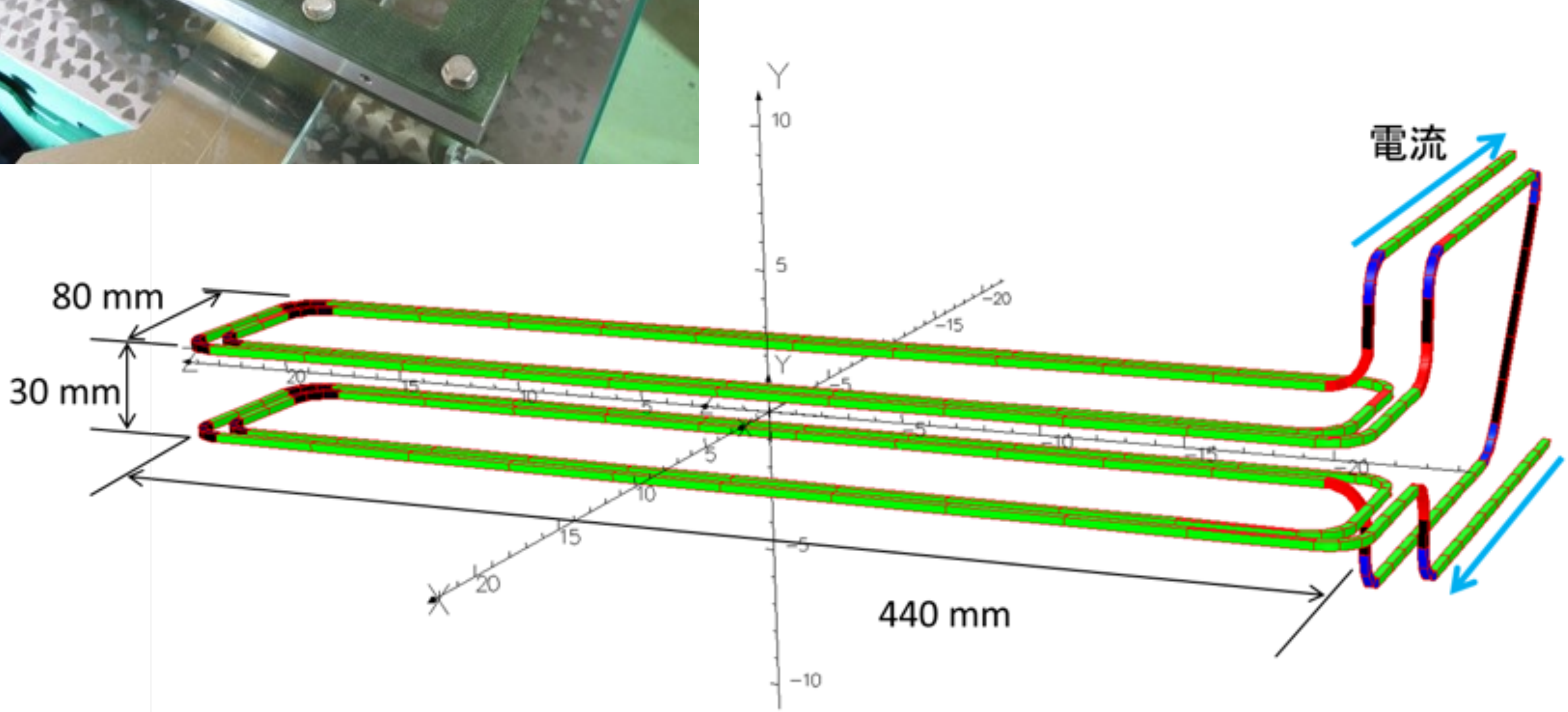




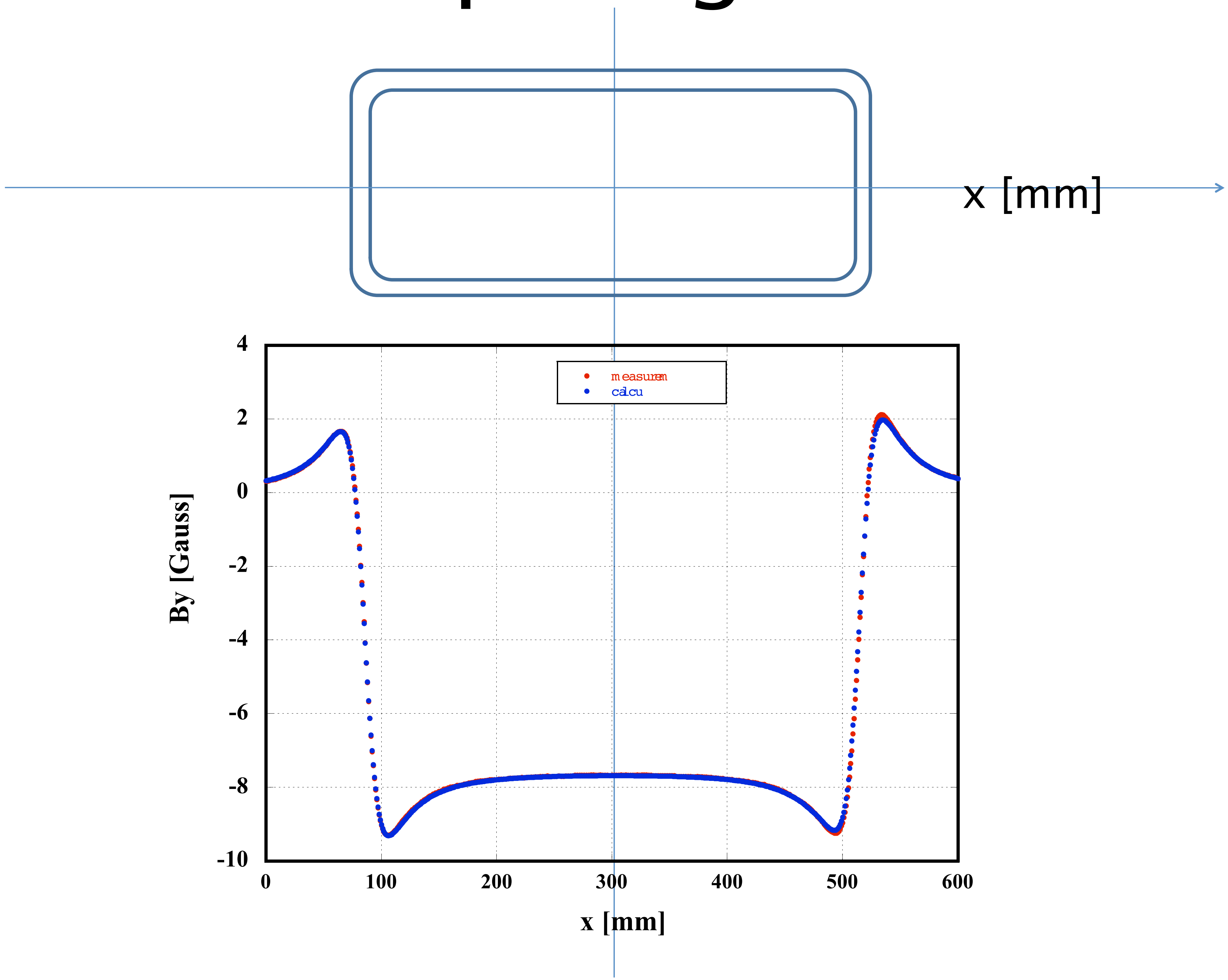
Bump magnet for mulit-turn injetion



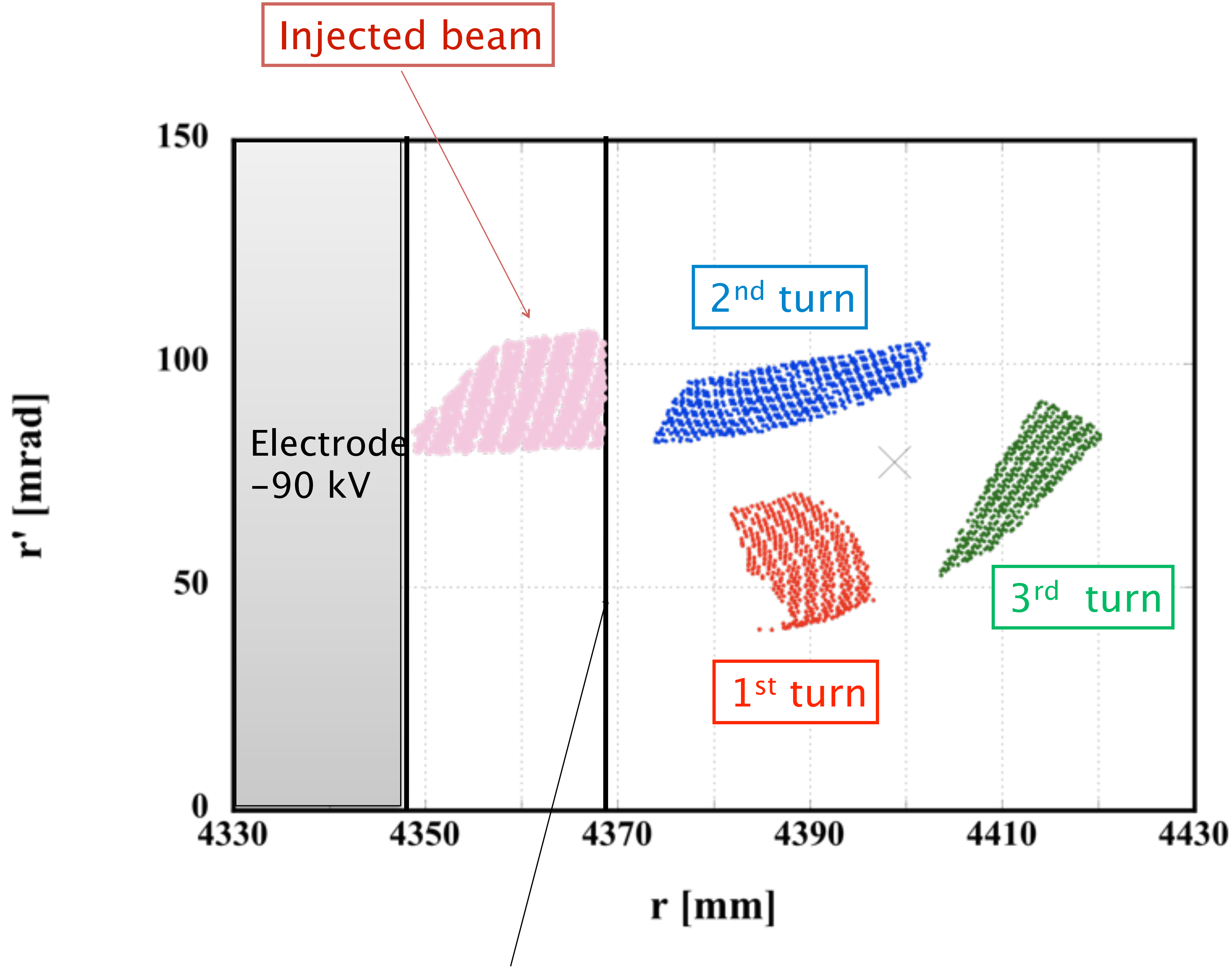
Type of magnet: air core coils (4
Current: 2000 A (half sine wave)
Magnetic field: 600 G



Measurement of magnetic field of bump magnets



Beam injection simulation



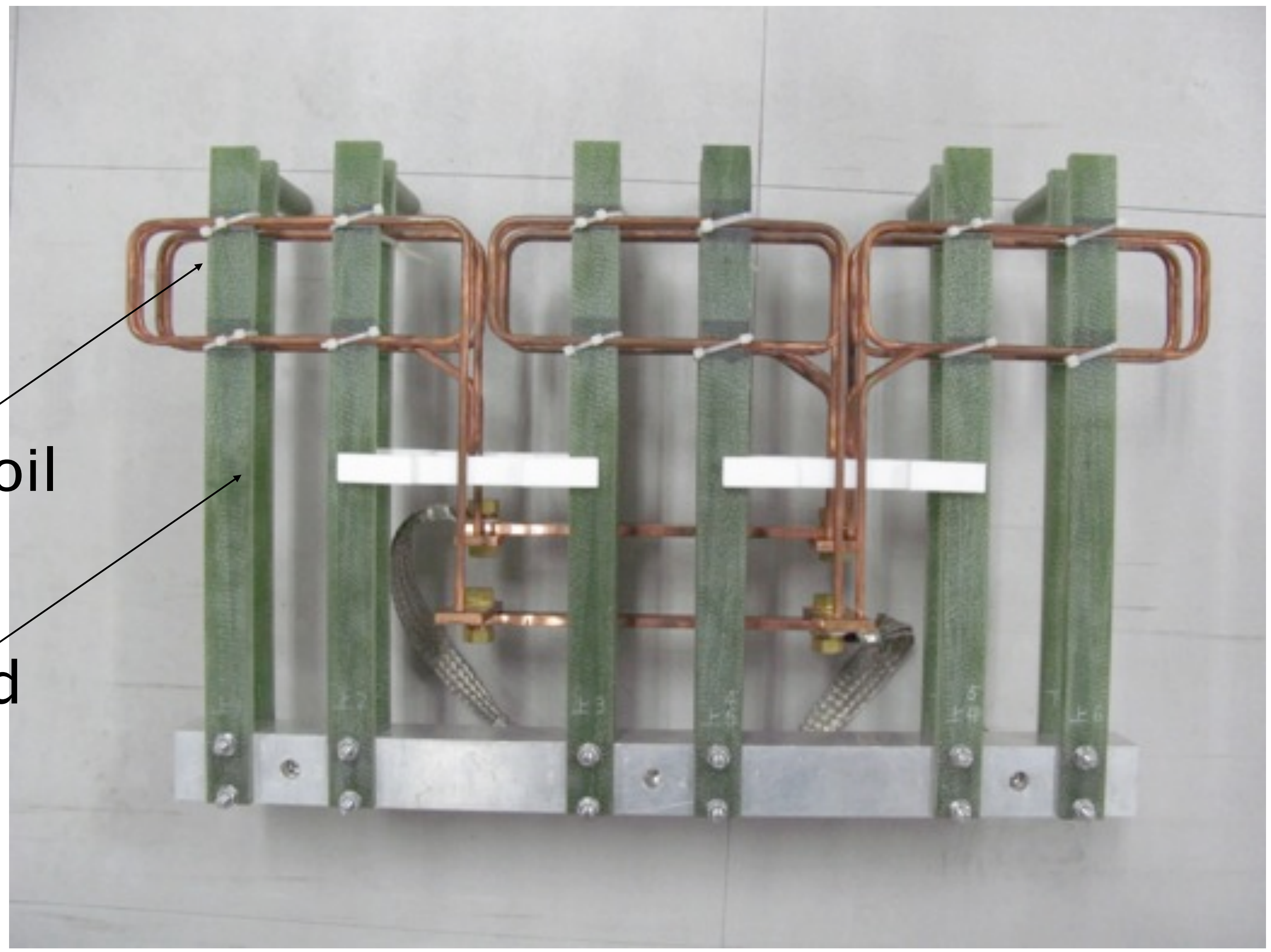
This is a septum electrode

Extraction Kicker

This is the kicker developed at Kyushu University.

Air core coil

FRP board

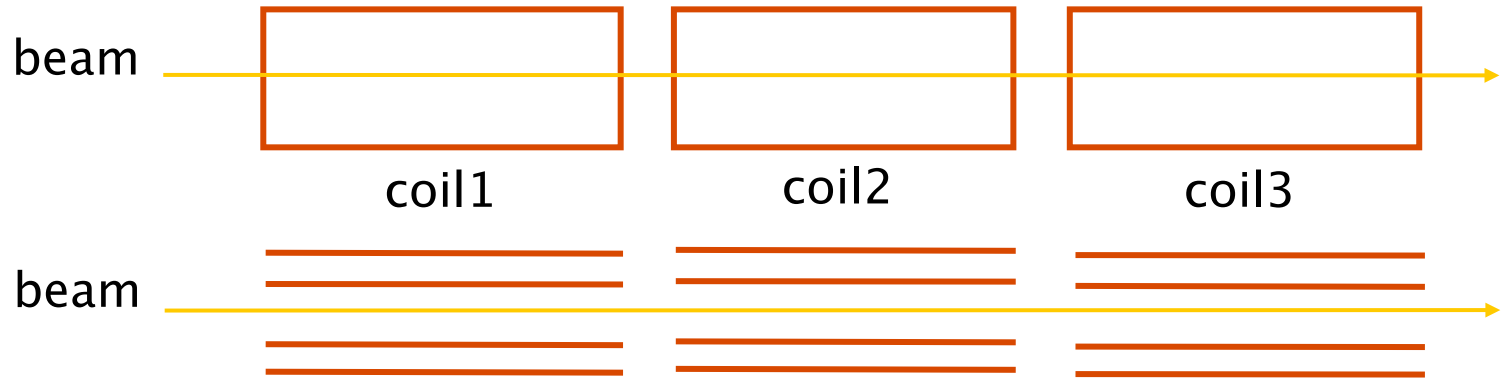


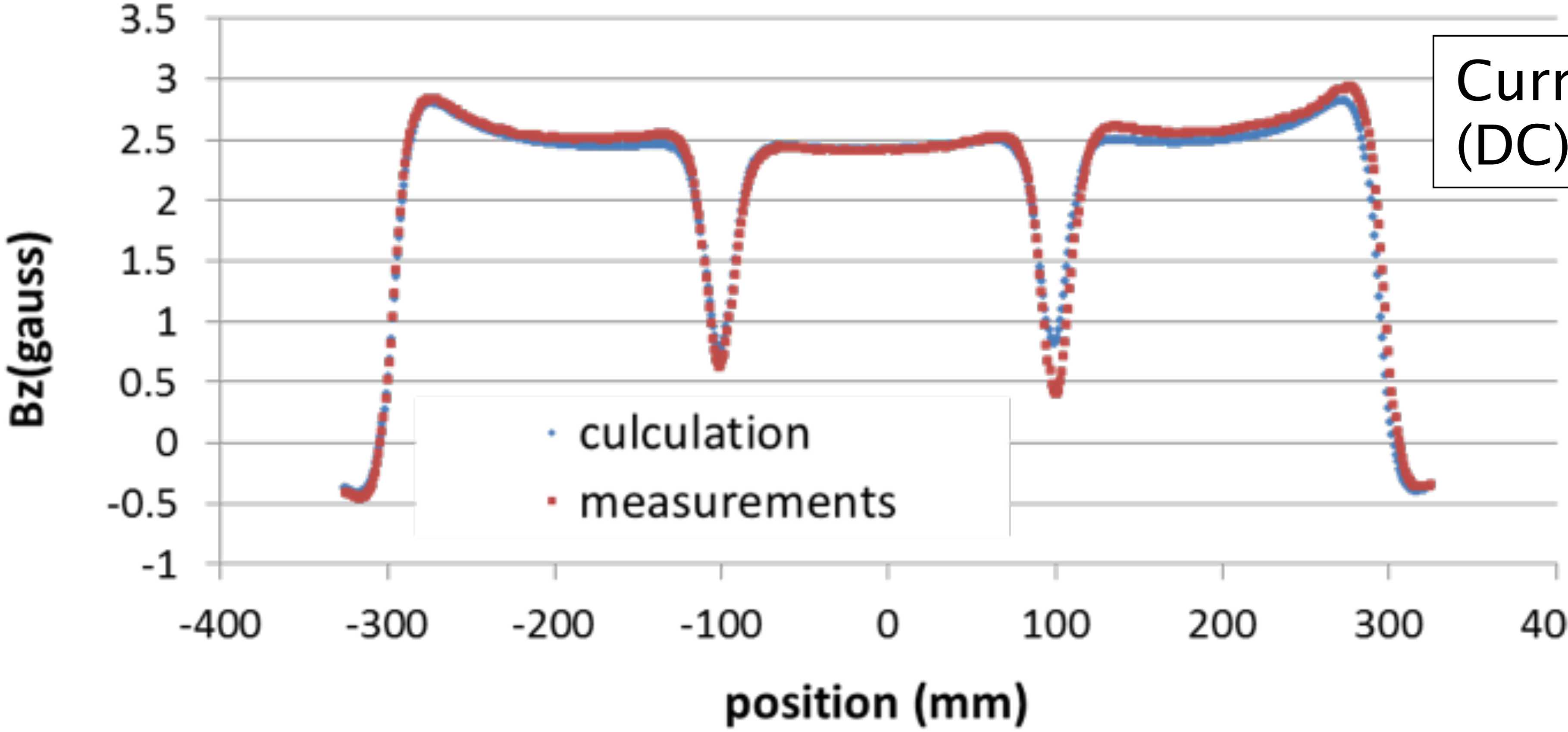
・The three divided air core coil is connected in parallel.

・Each coil is supported by FRP board.

Measured inductance is 0.95 μH.

Measurement of magnetic field of kicker magnet

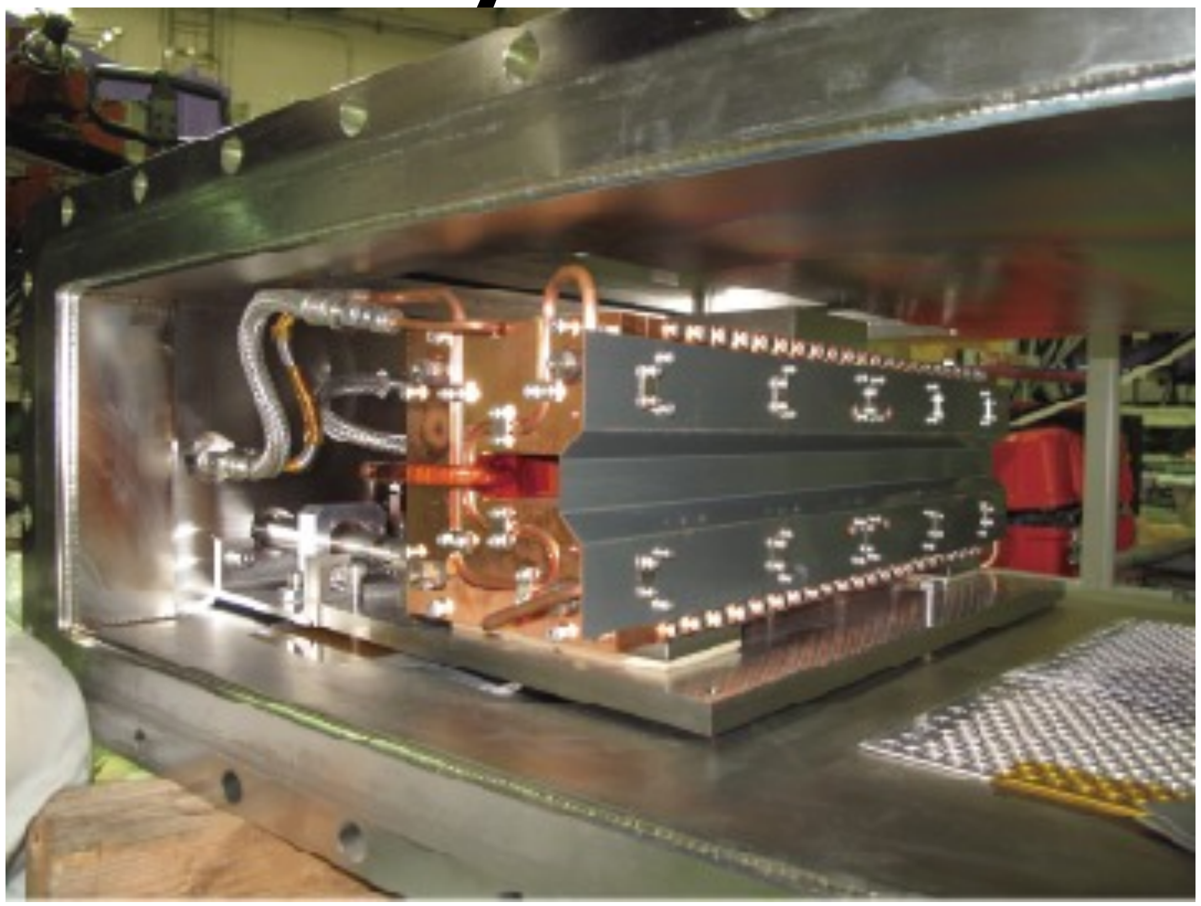




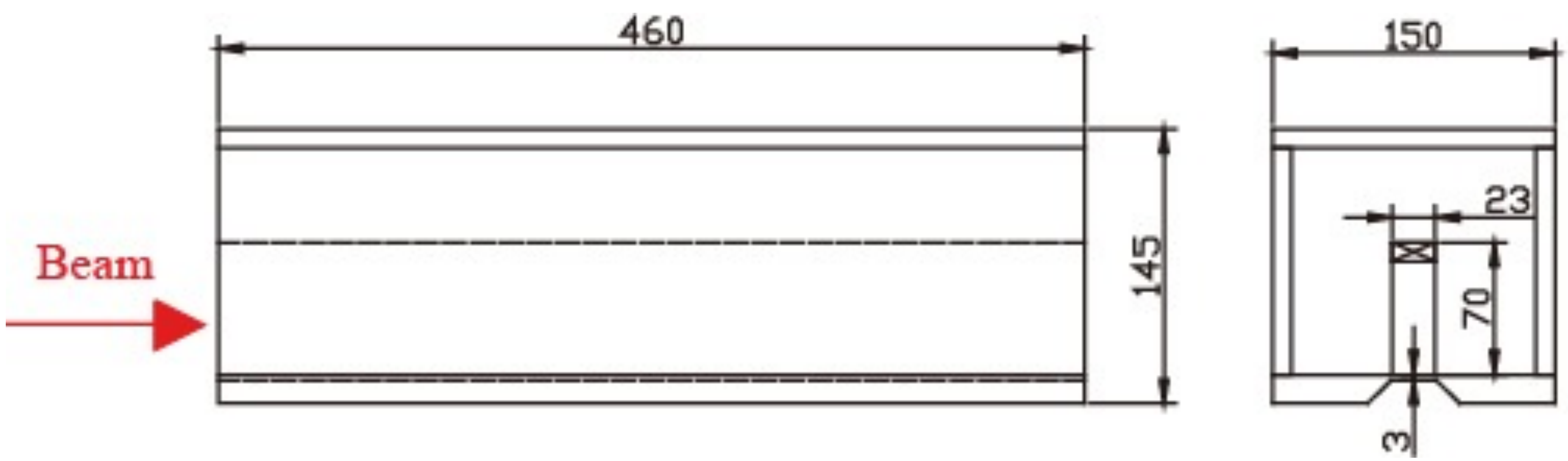
Current: 20 A (DC)

Measured magnetic field of the kicker agrees with the calculation.

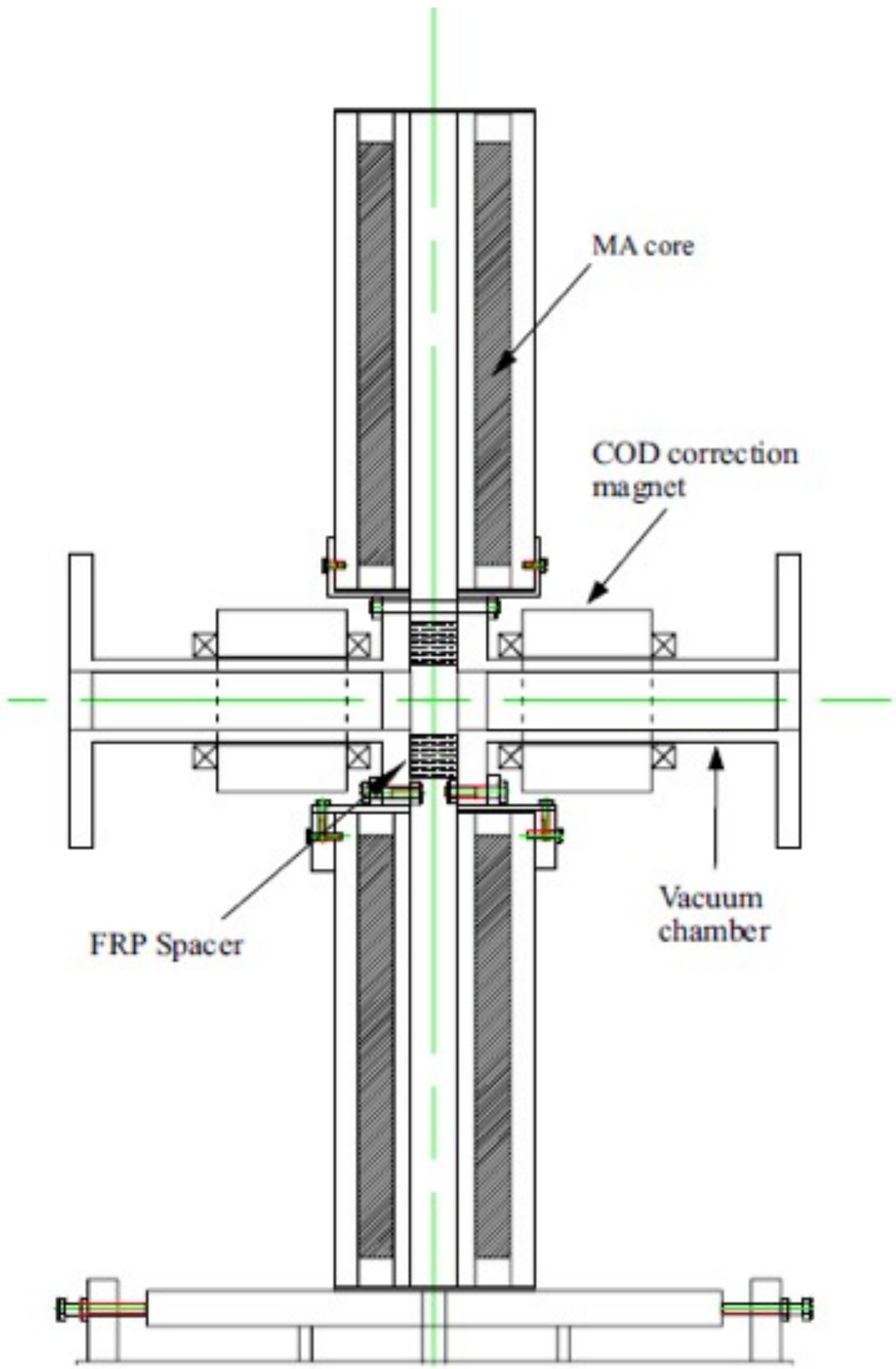
Extraction septum
Eddy current type

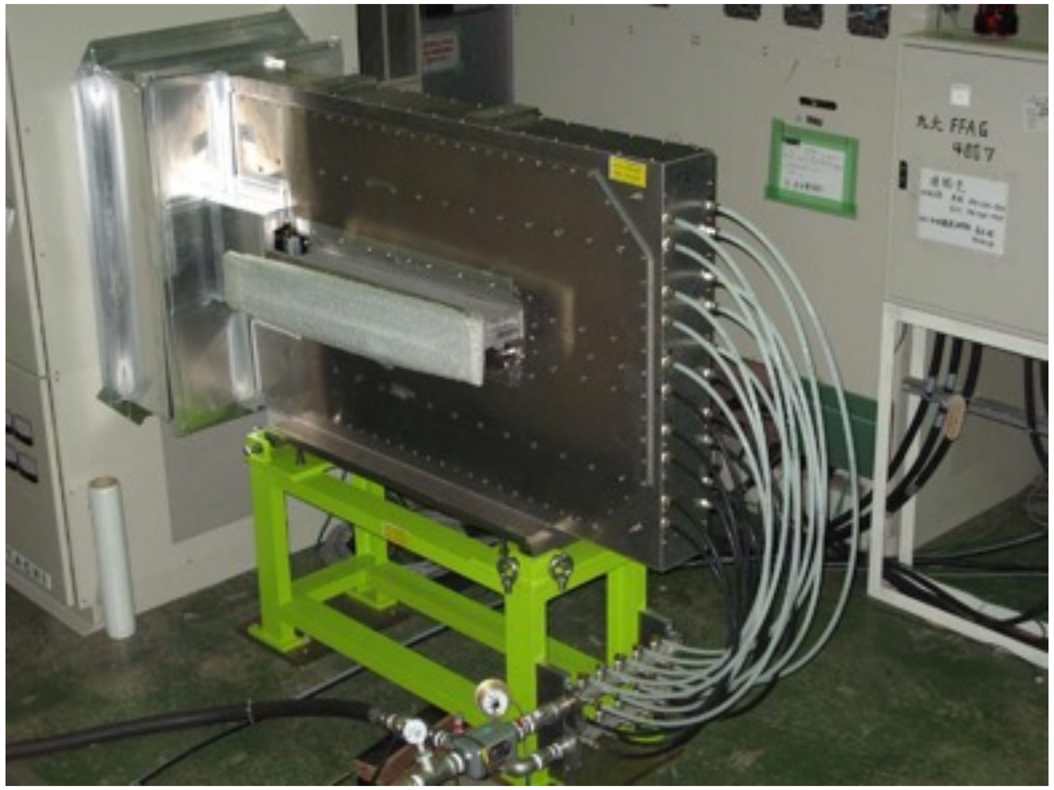


Peak Current :   2000 A (Half s
Magnetic field: 4.9 kG



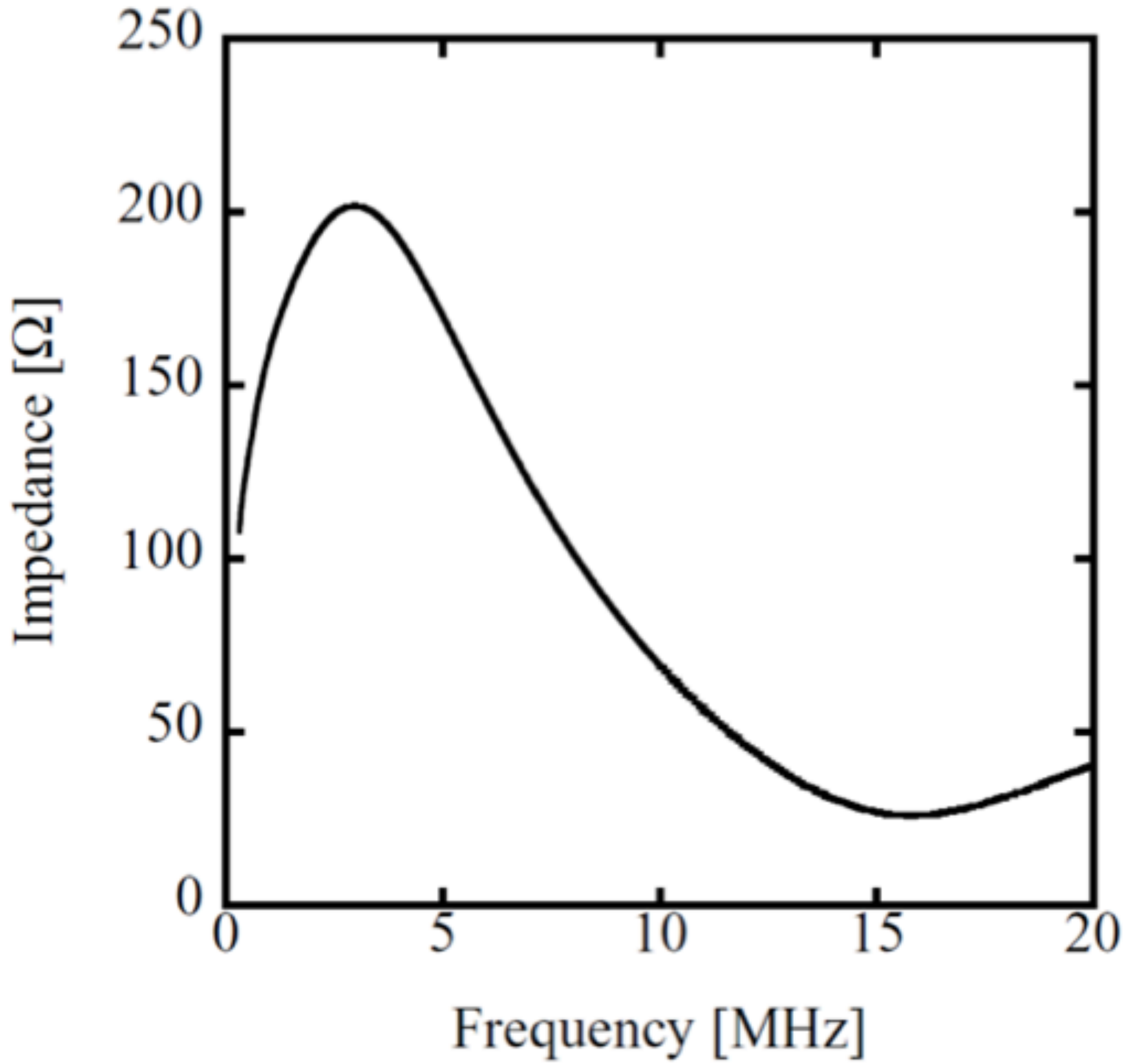
RF acceleration system





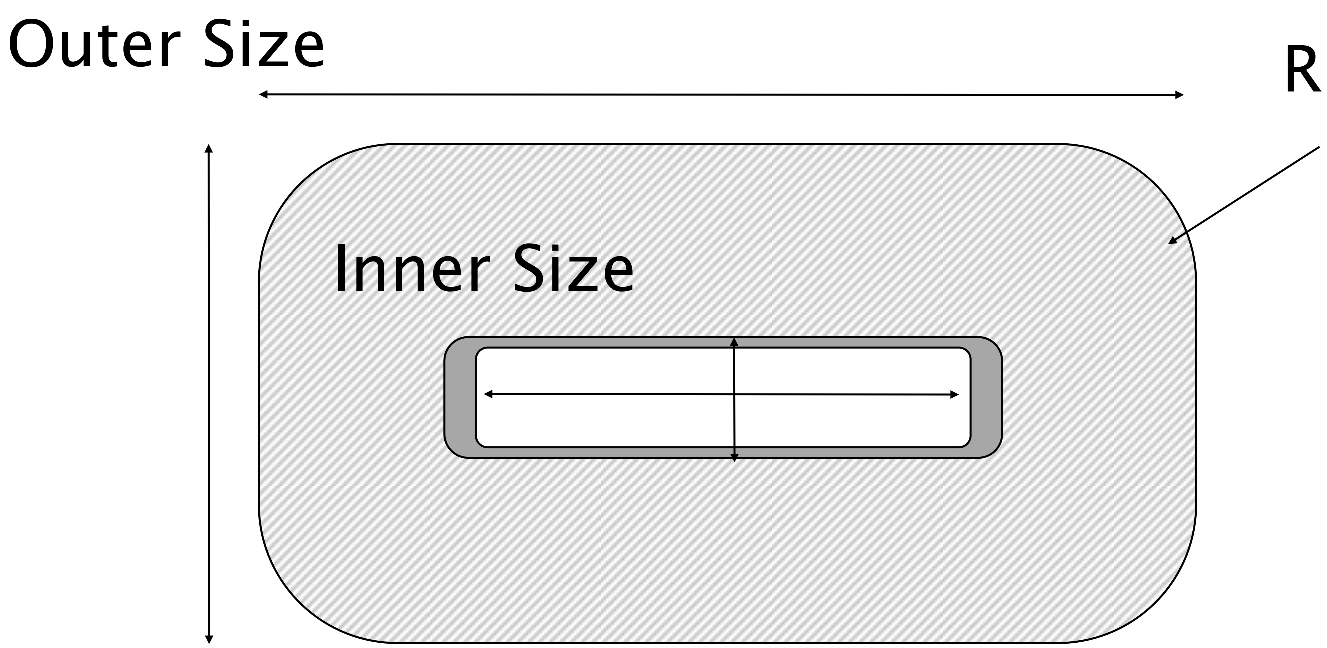
Gap Voltage	4 .0 kV/cavity
RF frequency	1.5 – 4.2 MHz
Power tube	4CW15000E × 2
Class	B class, Push-pull
Core material	FINEMET (FT-3M)
RF output power	200 kW

Measured impedance of the



The maximum shunt impedance was 200 Ω. The measured resonance frequency and the quality factor of the cavity were 2.7 MHz and 0.43, respectively.

Development of New MA core for the 2nd

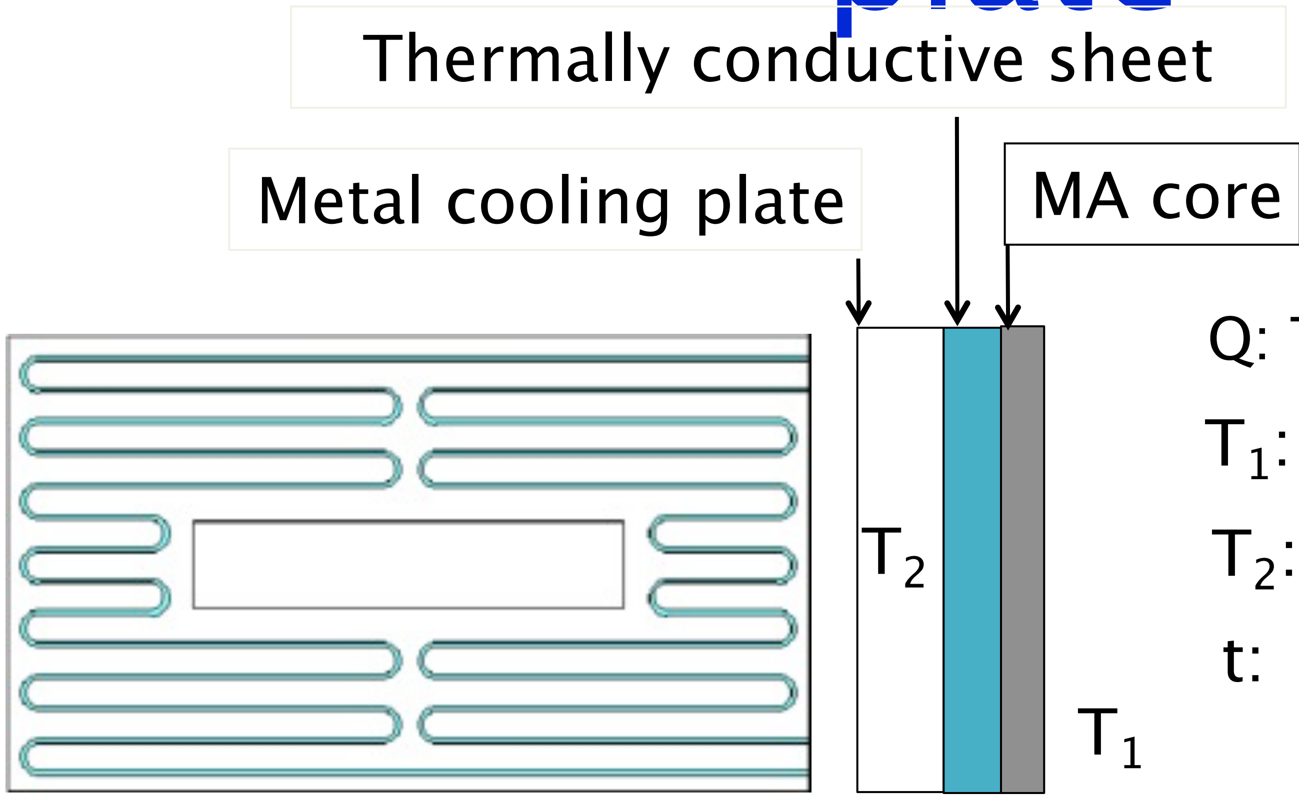


	Previous Core	New core
Outer	1700×950 mm	1780×950 mm
Inner Size	980×230 mm	1060×230 mm
Thicknes	30 mm	30 mm
R	360 mm	310 mm
Lout	4682 mm	4928 mm
Lin	2420 mm	2580 mm

Length of outer circumference

Length of inner circumference

Improvement of cooling plate



$$Q = k\frac{T_1 - T_2}{t}$$

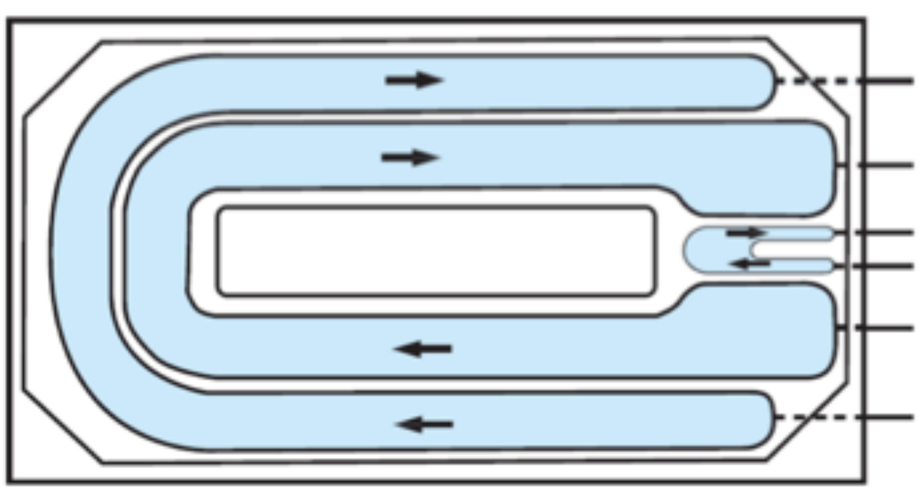
Q: Thermal Flux

T_1: Temperature of core

T_2: Temperature of cooling plate

t: thickness of thermally conductive sheet

New cooling plate

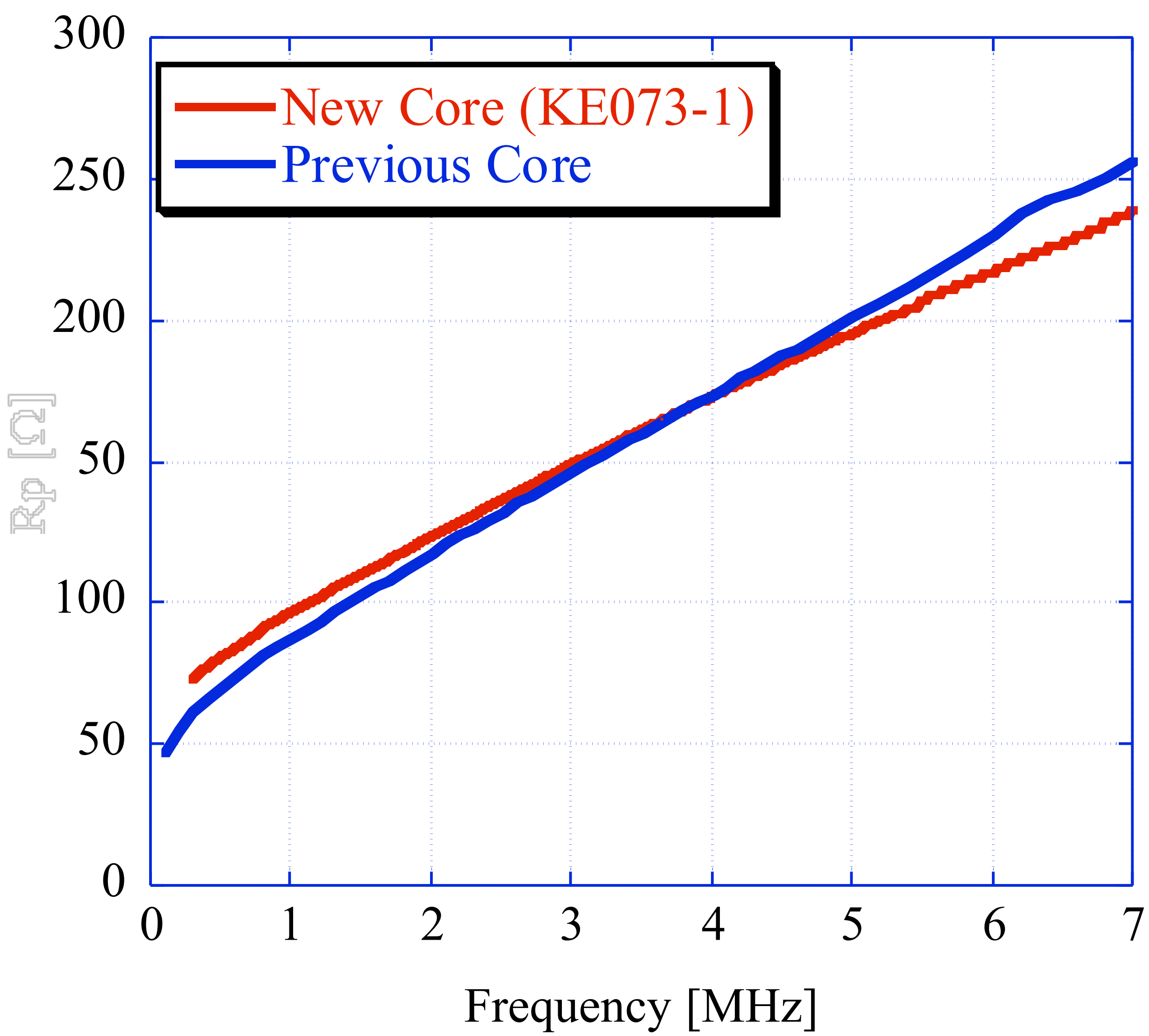


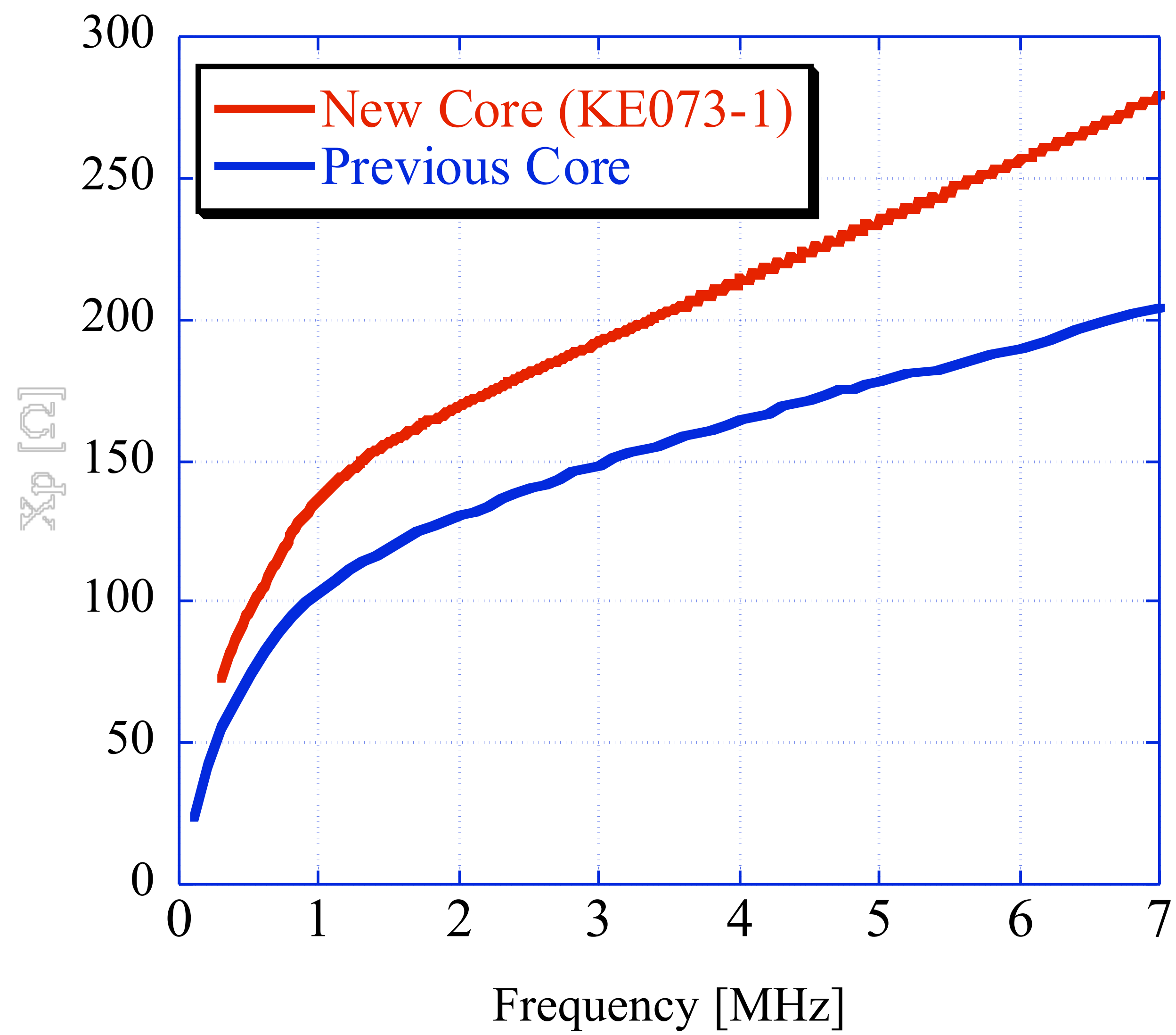
Water-jacket system & thin thrmal spacer

Thickness of thermal conductive spacer has been changed **from 3 mm to 1 mm**.

The contact area between cooling water and the core is designed to be **7 times larger** than the former cavity.

Measured impedance of new MA cores





Shunt impedance $R_p$of new core is similar to that of the previous core. Capacitive/Inductive components X_p is about 30% larger than that of the previous core.

Discussion on new injector

1. Proton linac

(1) H- ion linac

an intense proton beam of an order of 10 μA

- <u>nuclear science, nuclear engineering</u>

  three-body force、neutron reaction data

- <u>fundamentals for proton beam therapy</u>

2．Tandem accelerator

Heavy ion injector with tandem Van de Graff accelerator of 5 MV class

- ・Accelerator Mass Spectrometry (AMS)
- ・heavy-ion injection to FFAG

proposals of investigations using tandem-FFAG complex

○ **Tandem-FFAG AMS**

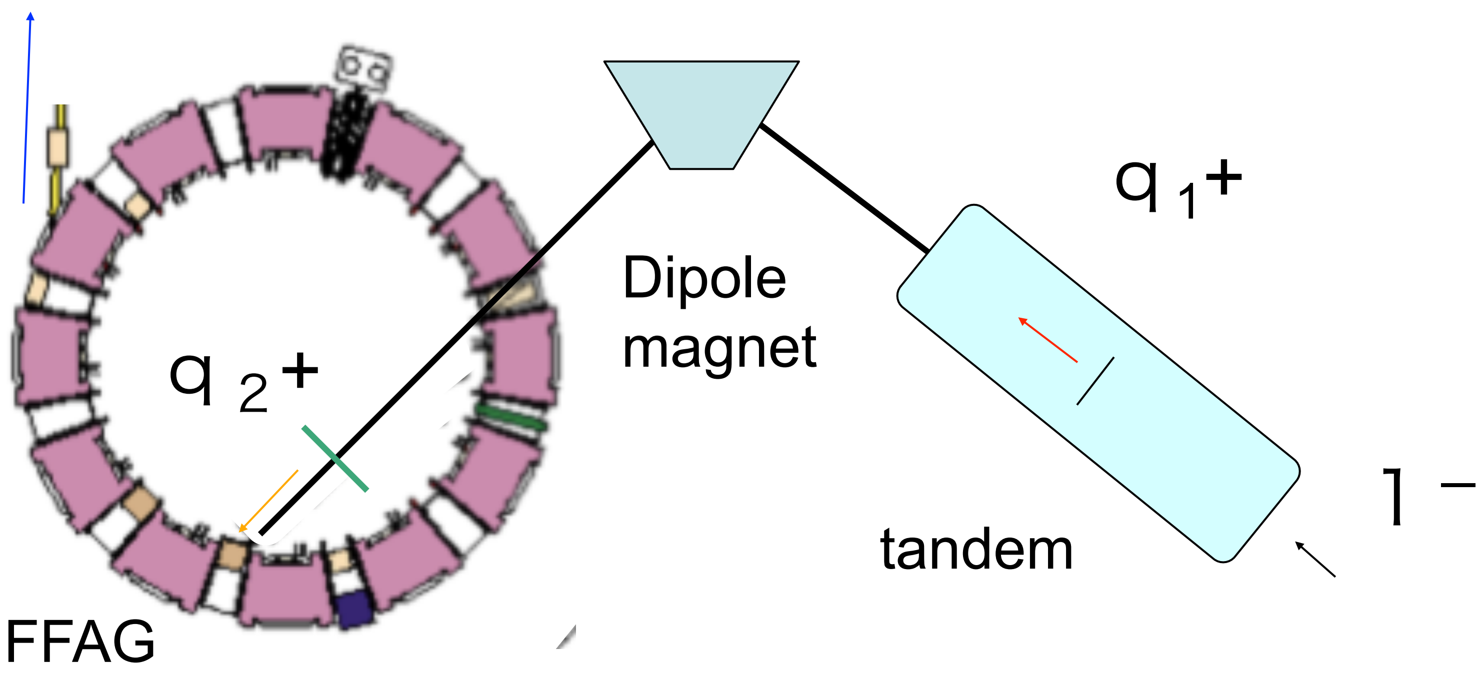
○ **cocktail beam**

○ unstable beam acceleration by tandem accelerator

Heavy-ion acceleration by using 150 MeV FFAG

	proton	Heavy-ion ($^{A}_{Z}X^{q+}$)
E/A MeV	12 → 150	$12\left(\frac{q}{A}\right)^2 \rightarrow 160\left(\frac{q}{A}\right)^2$ MeV/u (full stripped light heavy ions: 3 MeV/u → 40 MeV/u)
revolution MHz	1.6 ～ 4.6 MHz	$\frac{q}{A}$ 1.6 ～ 5.7
repetition	100 Hz	100 Hz

5 MV (3 MV) tandem accelerator



assumptions

- FFAG magnet
  9.8 – 12 MeV for protons
- charge fraction
  more than 10% in total

particle	q_1	Incident energy (MeV)	q_2	Extraction energy (MeV)	Energy per nucleon (MeV/u)
^{12}C	5^+ (4^+)	30 (15)	6^+ (4^+)	400 (200)	33.33 (16.67)
^{16}O	6^+ (5^+)	35 (18)	7^+ (5^+)	466.7 (240)	29.17 (15)
^{35}Cl	7^+ (5^+)	40 (18)	11^+	533.3 (240)	15.24 (6.86)
	8^+	45	12^+	600	17.14

Tandem – FFAG AMS

Accelerator Mass Spectrometry (AMS)

accelerator	Small tandem	Large tandem	Liniac, etc.
AMS nuclei	No stable isobar beam interface	Stable isobar beam interfaces	Negative ion cannot be produced
	^{7}Be, ^{10}Be, ^{14}C, ^{26}Al, ^{129}I, ^{236}U, Pu	^{32}Si, ^{36}Cl, ^{53}Mn, ^{59}Ni, ^{60}Fe, ^{99}Tc, ^{135}Cs	^{39}Ar, ^{41}Ca, ^{81}Kr, ^{85}Kr

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^{14}C chronological measurement for archaeological studies

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○ particle identification is not sufficient
○ necessary to eliminate isomers from sample

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^{14}C chronological measurement for archaeological studies

○ particle identification is not sufficient
○ necessary to eliminate isomers from sample

Small tandem＋FFAG

○extracted beam energy is several times higher than that from large tandem

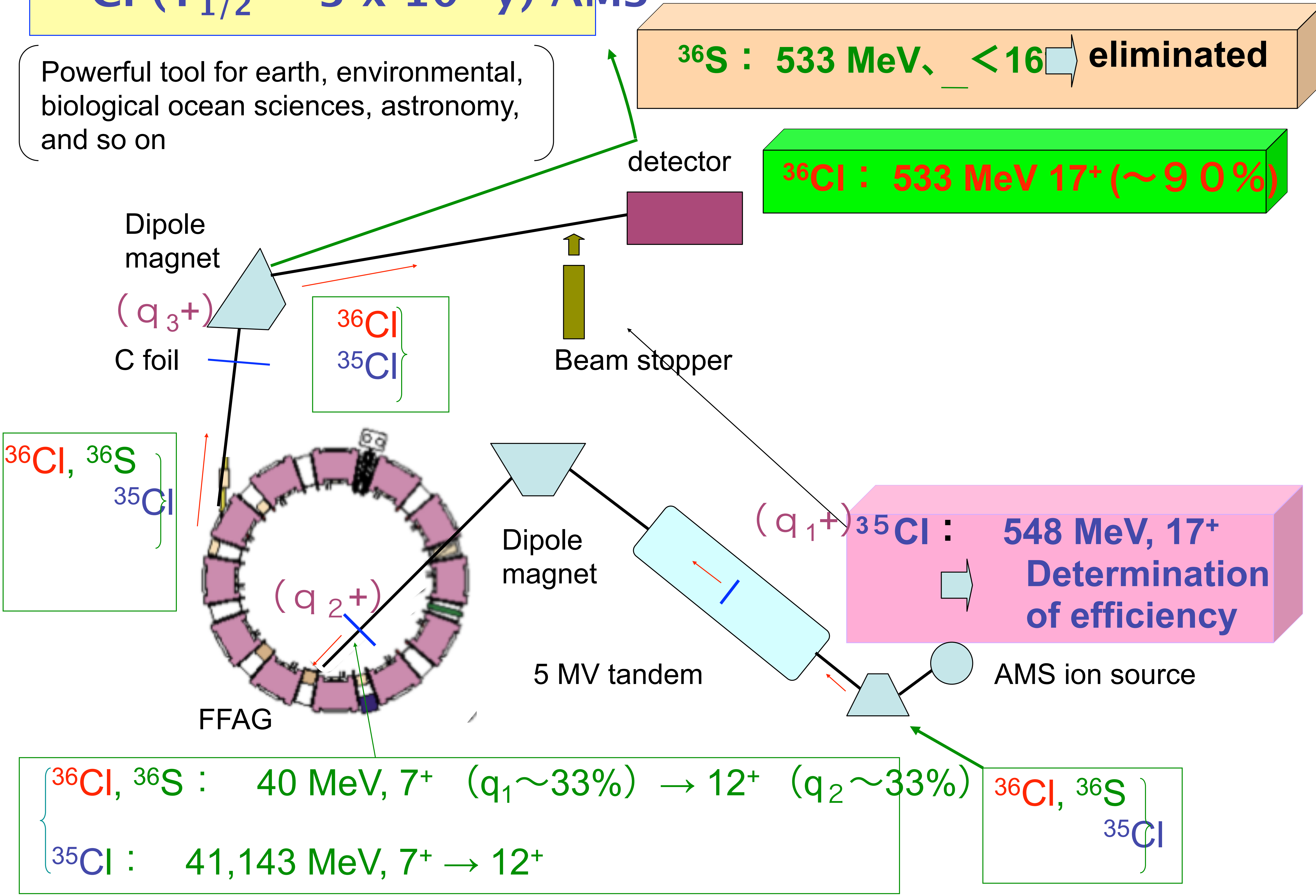
- easier to distinguish AMS particles from background
- fraction of fully-stripped ions amounts to nearly 100%

→ isomers can be eliminated by using dipole magnet when atomic number of the AMS particle is larger than that of isomer

○acceleration efficiency can be canceled by alternating acceleration of isotopes

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

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



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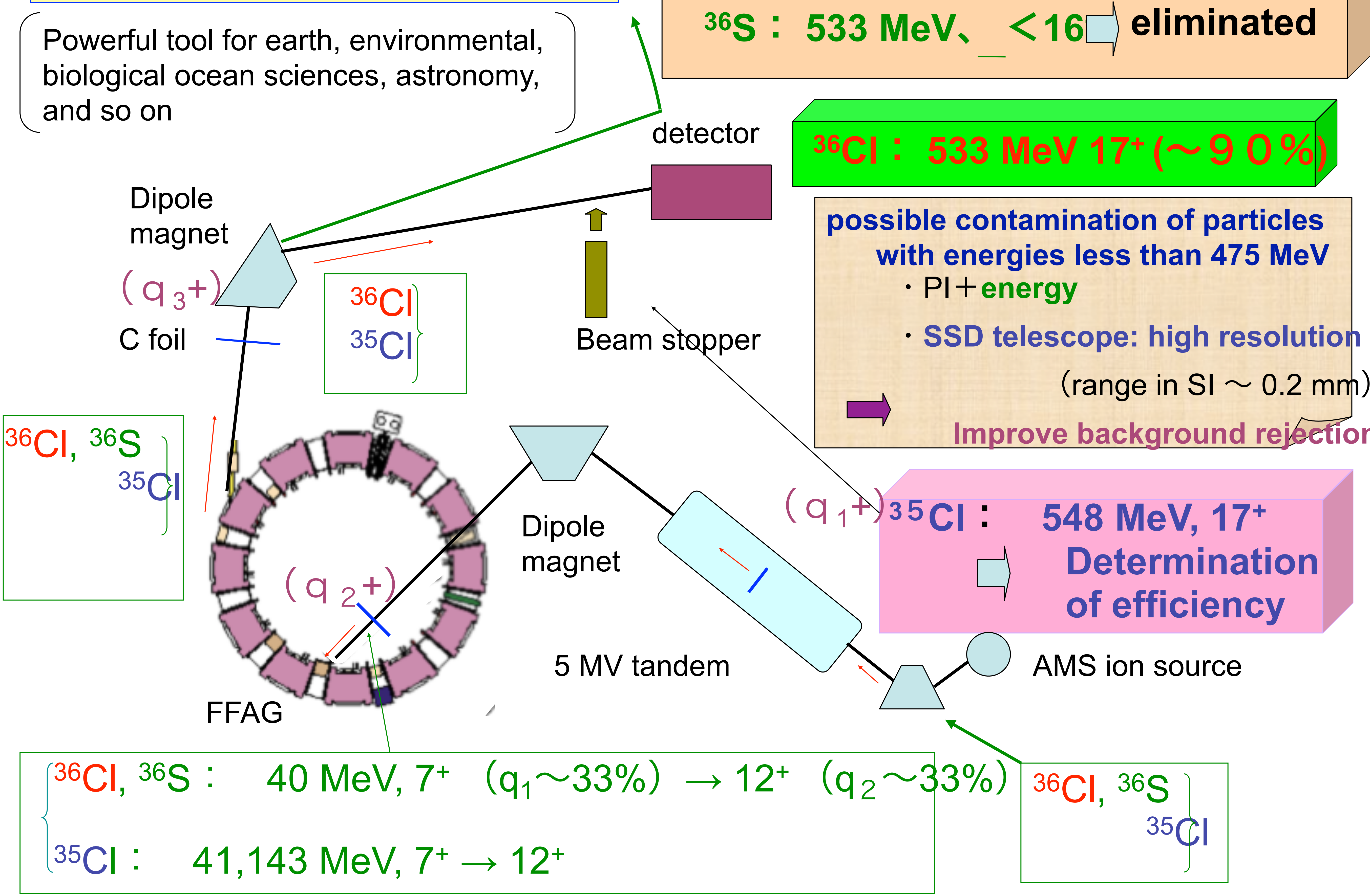

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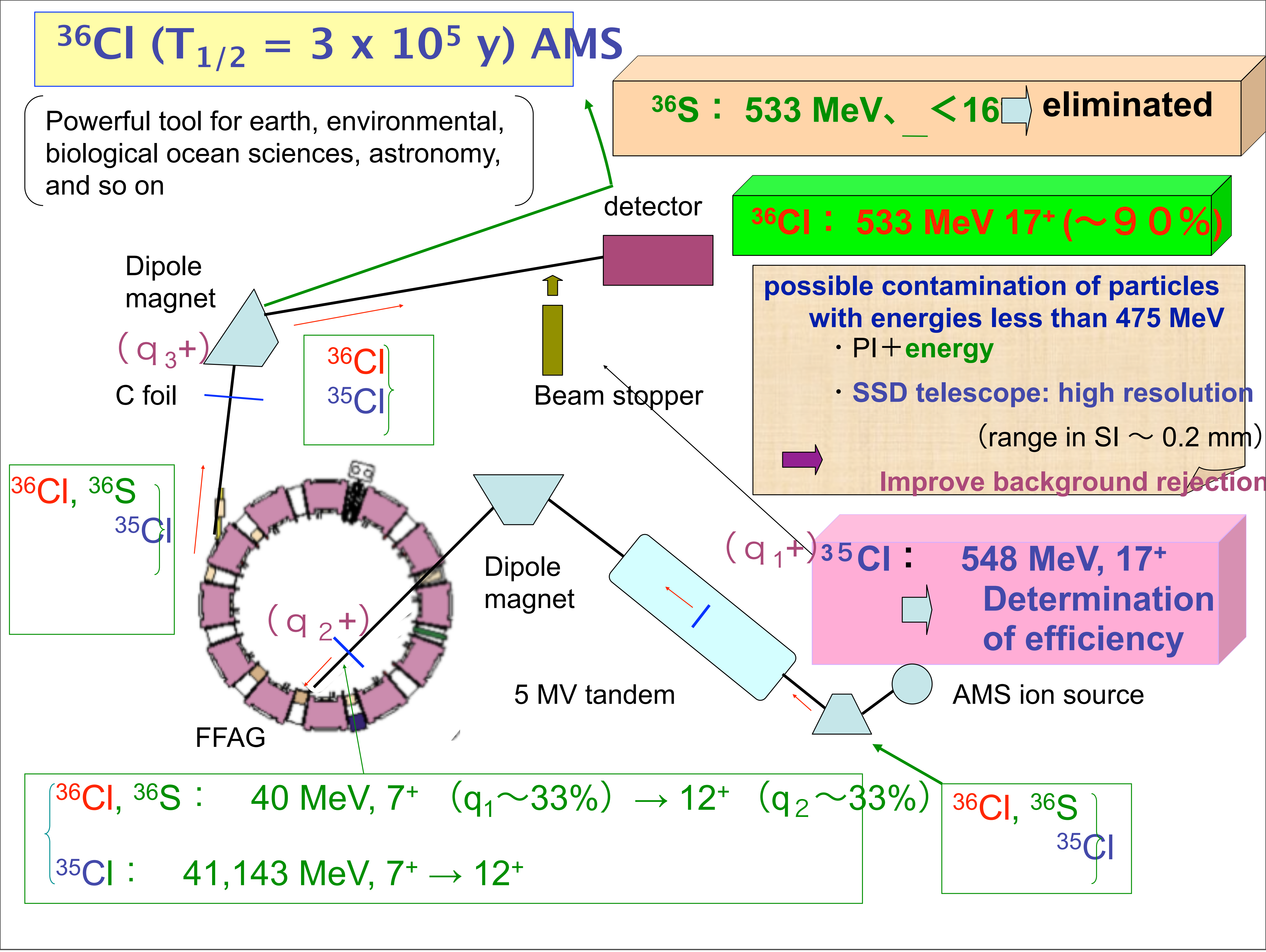
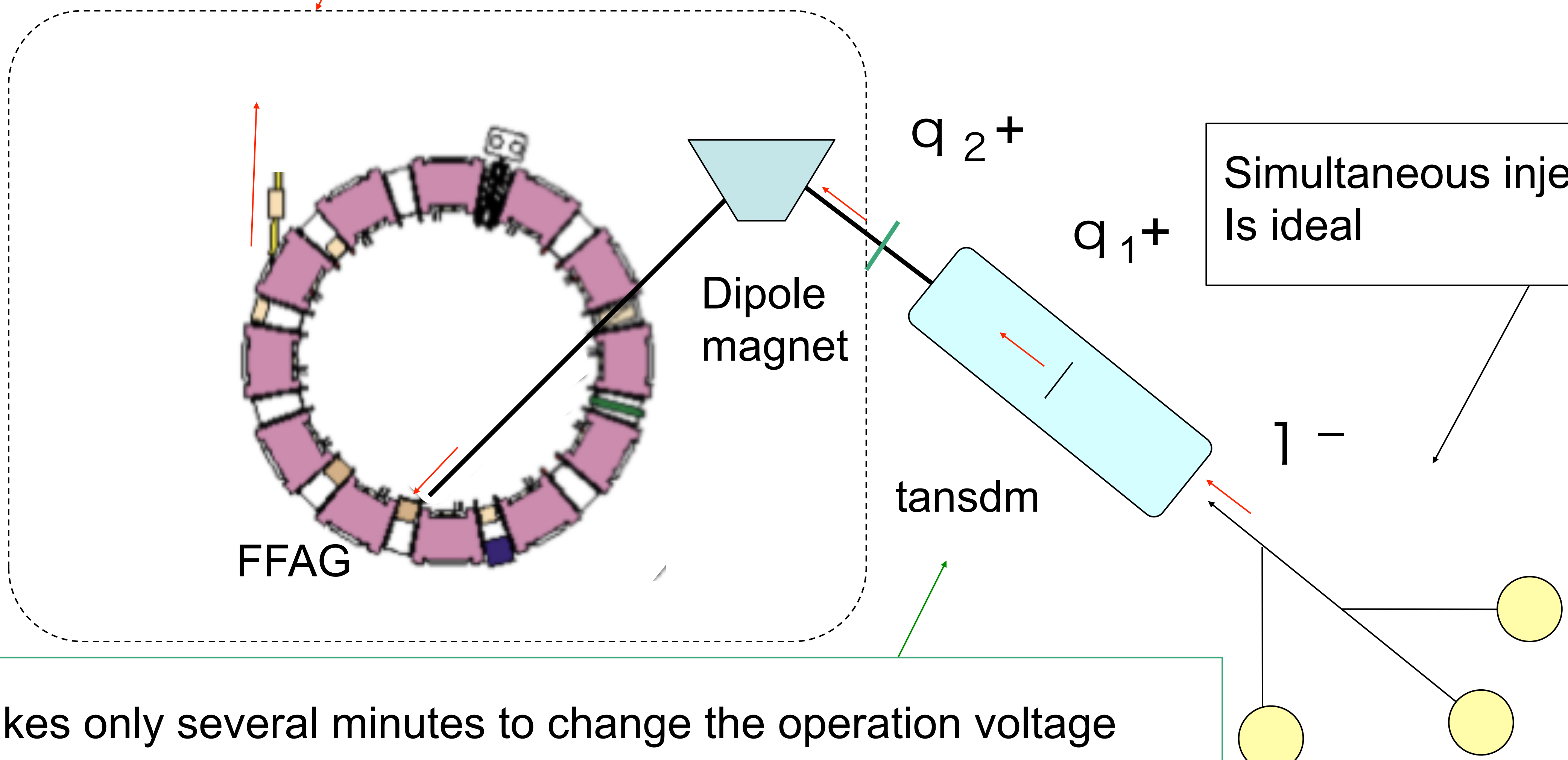

36Cl (T1/2 = 3 x 10^5 y) AMS
Powerful tool for earth, environmental, biological ocean sciences, astronomy, and so on
36S： 533 MeV、＜16 eliminated
detector
36Cl： 533 MeV 17+ (～90%)
possible contamination of particles with energies less than 475 MeV
・PI＋energy
・SSD telescope: high resolution
(range in SI ～ 0.2 mm)
Improve background rejection
Dipole magnet
(q3+)
C foil
36Cl
35Cl
Beam stopper
36Cl, 36S
35Cl
(q1+) 35Cl： 548 MeV, 17+
Determination of efficiency
Dipole magnet
(q2+)
5 MV tandem
AMS ion source
FFAG
36Cl, 36S： 40 MeV, 7+ (q1～33%) → 12+ (q2～33%)
35Cl： 41,143 MeV, 7+ → 12+
36Cl, 36S
35Cl

Cocktail beam

Provide different beams within several minutes

＊for beams with the same A/q and P/q values

Fixed operation



Simultaneous injection
Is ideal

It takes only several minutes to change the operation voltage

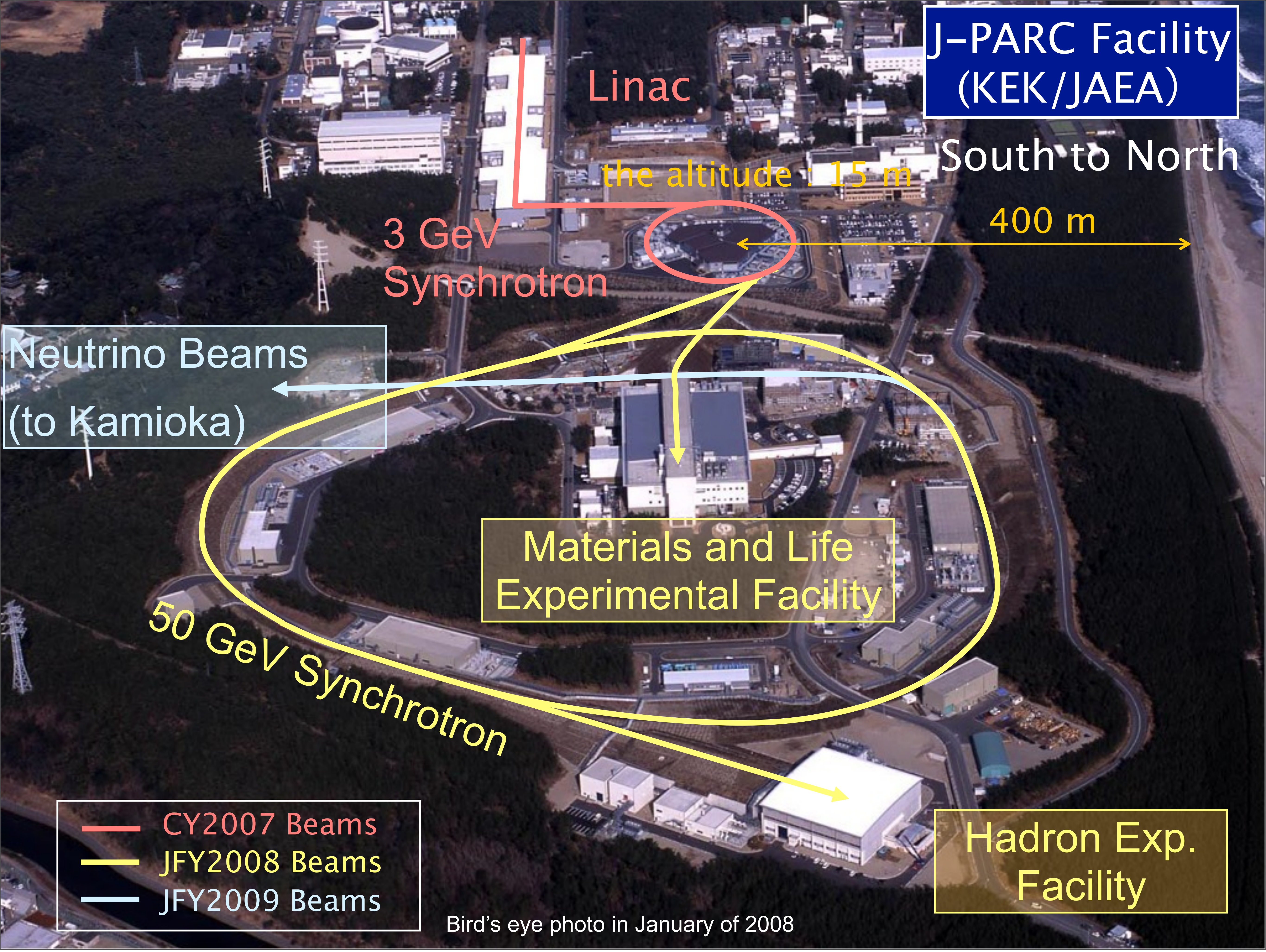
A/q = 2

particle	q_1	Terminal voltage (MV)	Injection energy (MeV)	q_2	Extraction energy (MeV)	Energy per nucleon (MeV/u)
^{2}H	1^+	2.19	4.375	1^+	58.33	29.17
^{4}He	2^+	2.92	8.75	2^+	116.7	29.17
^{12}C	5^+	4.375	26.25	6^+	350	29.17
^{16}O	6^+	5	35	8^+	466.7	29.17

A/q = 4

particle	q_1	Terminal voltage (MV)	Injection energy (MeV)	q_2	Extraction energy (MeV)	Energy per nucleon (MeV/u))
^{12}C	3^+	2.25	9	3^+	120	10
^{16}O	4^+	2.4	12	4^+	160	10
^{28}Si	5^+	3.5	21	7^+	280	10
^{60}Ni	8^+	5	45	15^+	600	10

Status of the Accelerator at J-PARC


J-PARC Facility (KEK/JAEA)
South to North
Linac
the altitude : 15 m
400 m
3 GeV Synchrotron
Neutrino Beams (to Kamioka)
Materials and Life Experimental Facility
50 GeV Synchrotron
Hadron Exp. Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

Damage – LINAC –

Entrance for Linac

About 1.5 m drop as seen above, over a wide area.
Electric wires and water pipes were all damaged.

Road in front of Linac

Serious cracks on the road. This is a typical one and can be seen all over the J-PARC area.

Electric Power Supply for Linac

Side buildings were severely damaged (due to less number of underpins), whereas central area for Linac had no damages including klystrons.

Electric Wiring Room

Cable Rack (upper) and many bundles were scattered on the floor below the cable rack (lower).

Damage – LINAC –

The flood of about 10cm was found from the floor level by the water leak of underground water in the LINAC tunnel on March 24. A diesel engine power generator, wiring work of the temporary housing enabled the pumping work to avoid further damages then.

- At present civil construction to cut-off water has been performed.

Inside Linac Tunnel

Concerning the central area of Linac, no serious damages were seen by looking from outside. As of March 17, 1 cm deep water was on the floor.

Linac Tunnel as of March 24

On March 17 the water level was only 1 cm, whereas it was 10 cm on March 24. With motor driven electric generator a pumping started on March 25.

Damage – RCS –

The subsidence of the outdoor yard and the surrounding road is extensive at the RCS.

Road around 3 GeV

Wavy road. Bump in the middle means that beam pipe is underneath it. Both sides of the bump were sinking.

3 GeV Electric Device

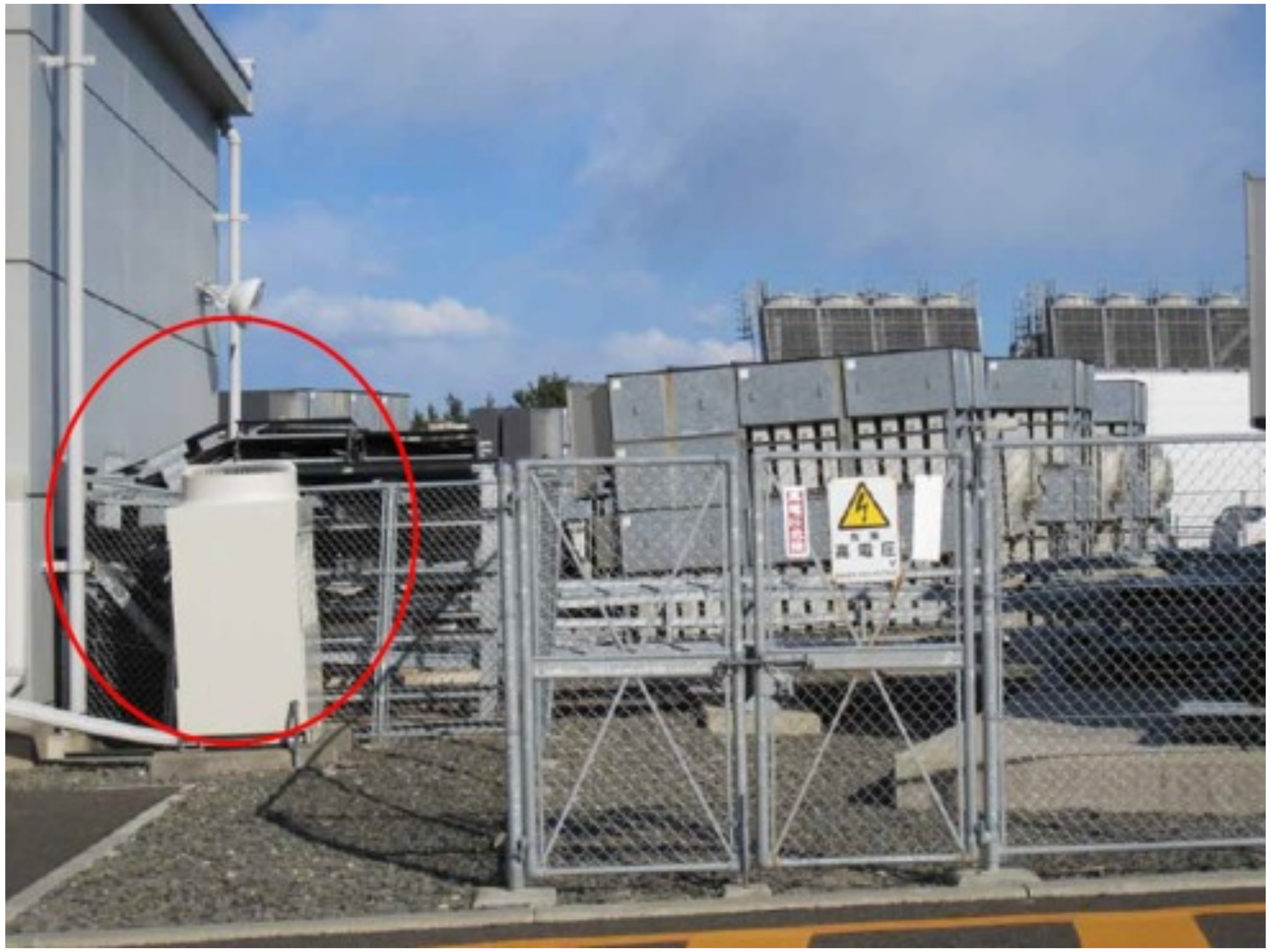
Leaning is observed as shown in the figure.

Condenser Bank for 3 GeV

Condenser bank was waved. Cables were distorted with heavy weight on them.

Damage – RCS –

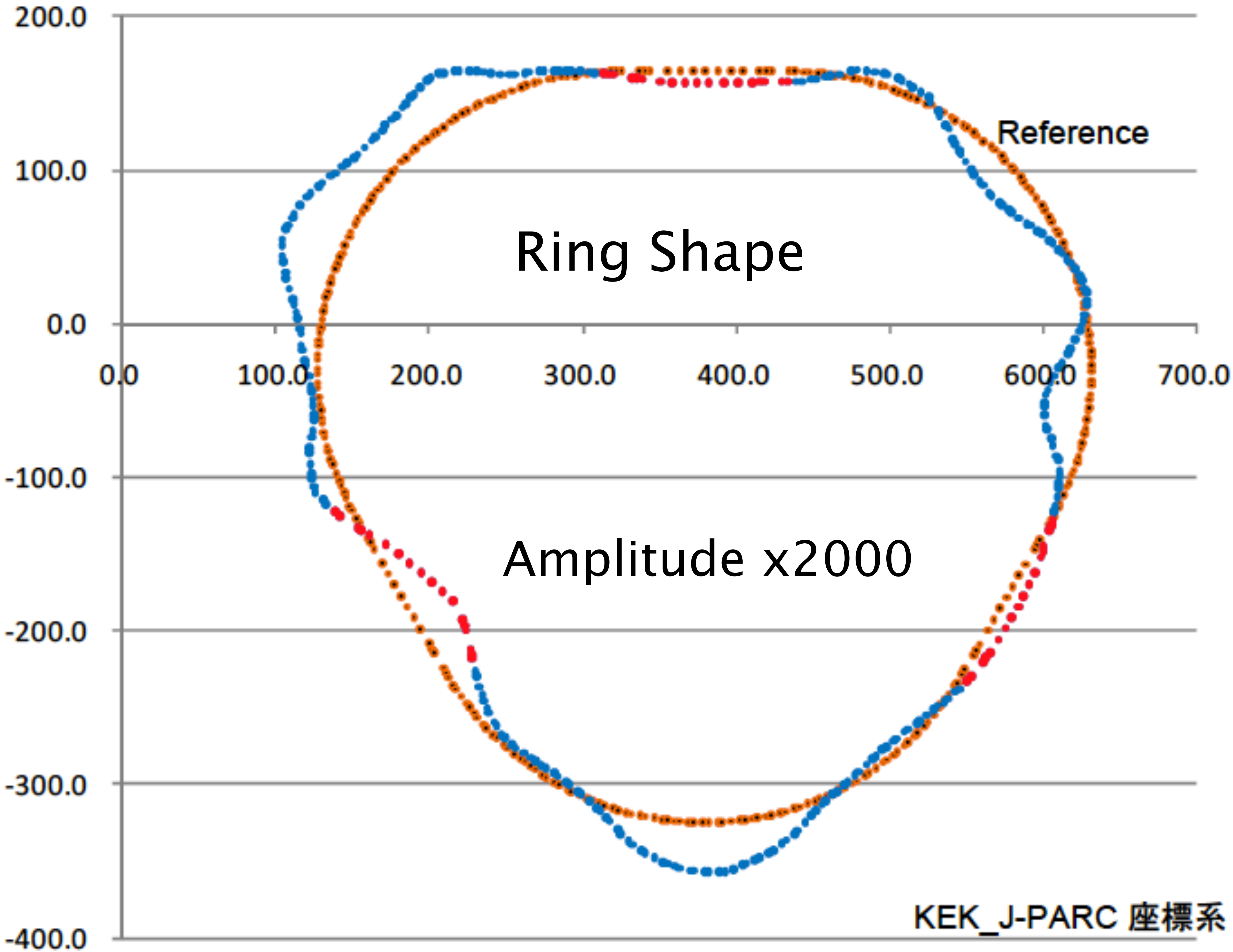
RCS Electric Power Supply



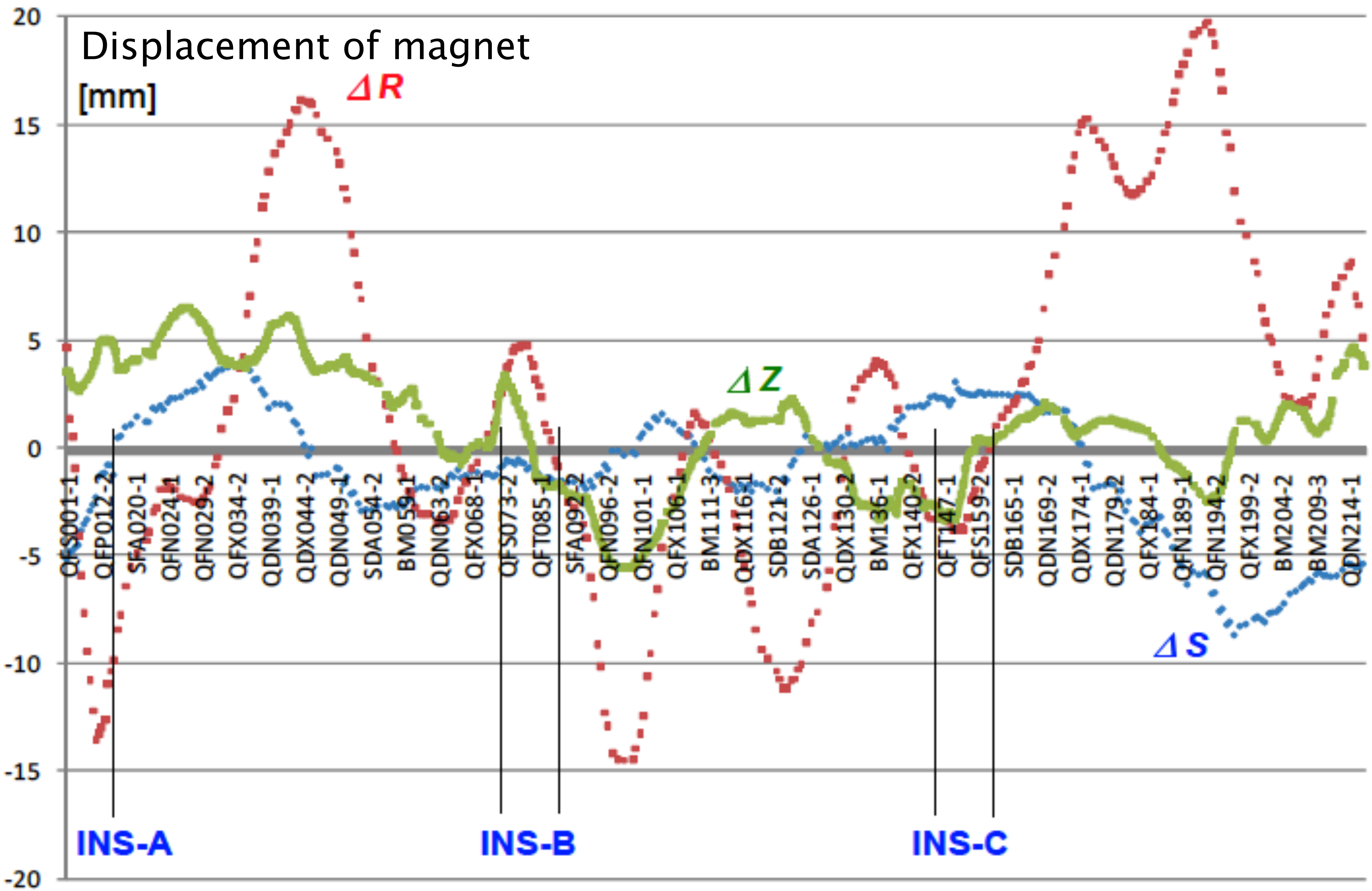
Leaning toward the left side

Cable racks were all bent.

Results of Circumference Measurement by Laser



Results of Circumference Measurement by Laser



It appeared there was a large misalignment in both horizontal and vertical directions.
All magnets have been realigned. Three teams are doing between August and

On J-PARC Recovery Schedule

from http://j-parc.jp/

J-PARC Center

Since the earthquake occurred on March 11, we, members of the J-PARC center team, have dedicated to promote an action program to recover the facility performance which suffered from damage due to a tremendous strong quake. Right after the event, we have worked on in creating a recovery master schedule. Although the present plan is by one week later than anticipated, we came to a result for the master plan which gives a goal for endeavor from now on, as follows:

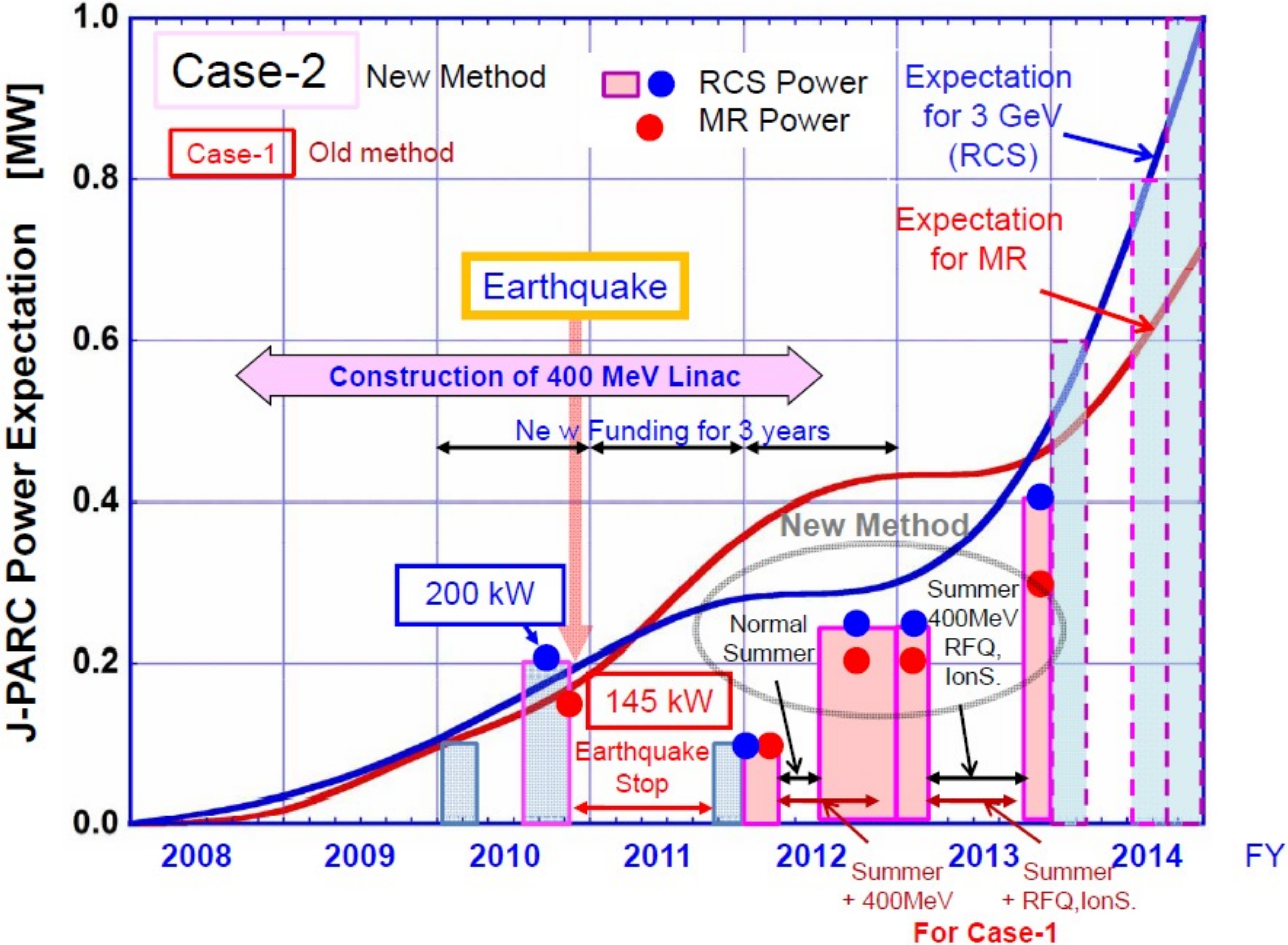
1) **We will confirm the facility recovery by a beam injection.**

2) **User program will be restarted with beam time of about 50 days that will be provided to users until the end of March 2012. (within Japanese fiscal year of 2011)**

Please see a time chart of the schedule for the recovery on the next page.

* Note that, the schedule is assumed to be valid when the budget requested in each action program is delivered on time.
* In addition, the schedule is strongly influenced by the progress of infrastructural recovery, e.g., access roads, electric power supplies, cooling water supplies, etc.

Operational Plan for JFY2012 and JFY2013



SUMMARY

- Scientific projects with proton 150MeV FFAG accelerator were reviewed.
- Present status and future prospect of FFAG accelerator system are presented.