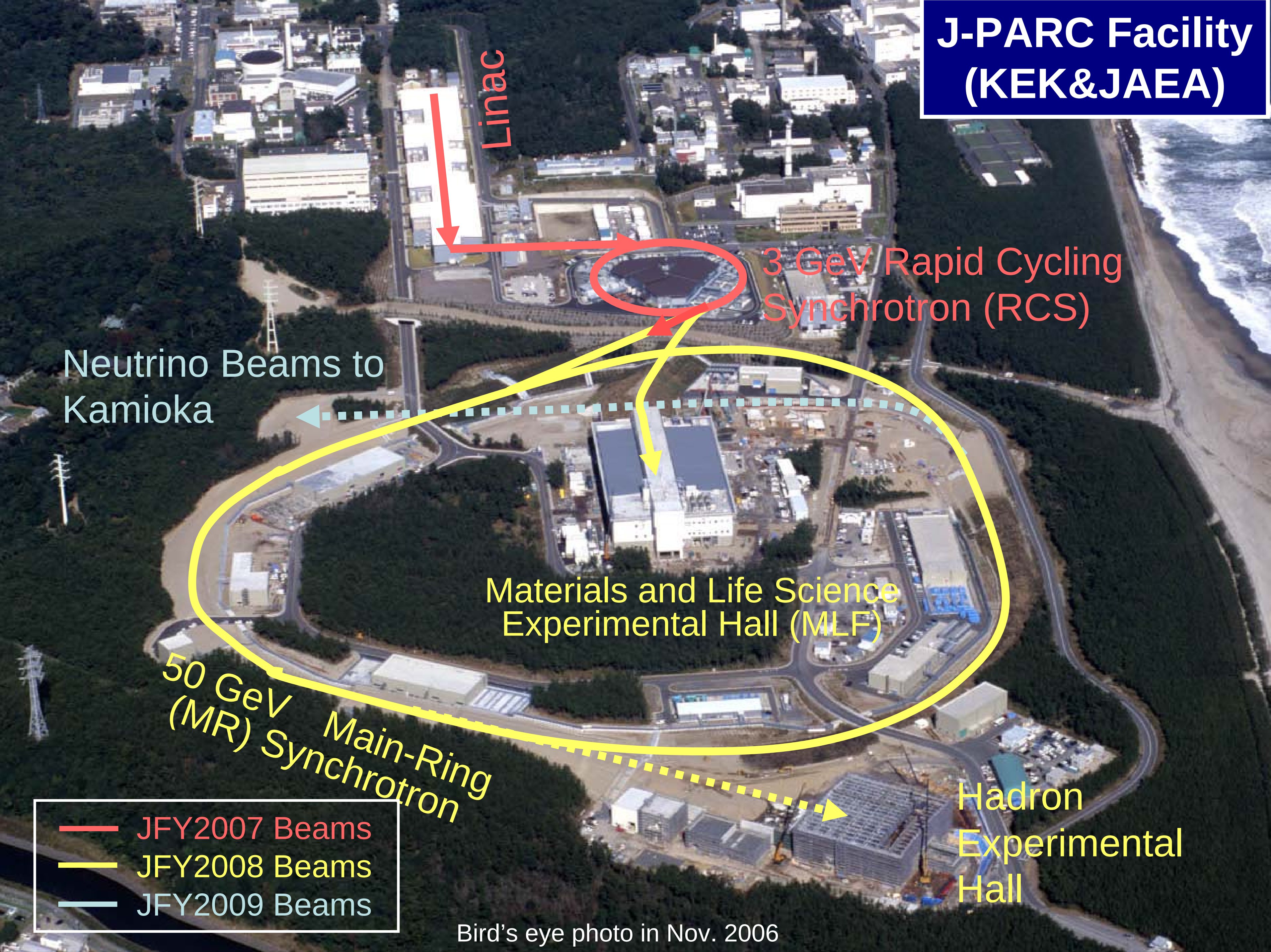
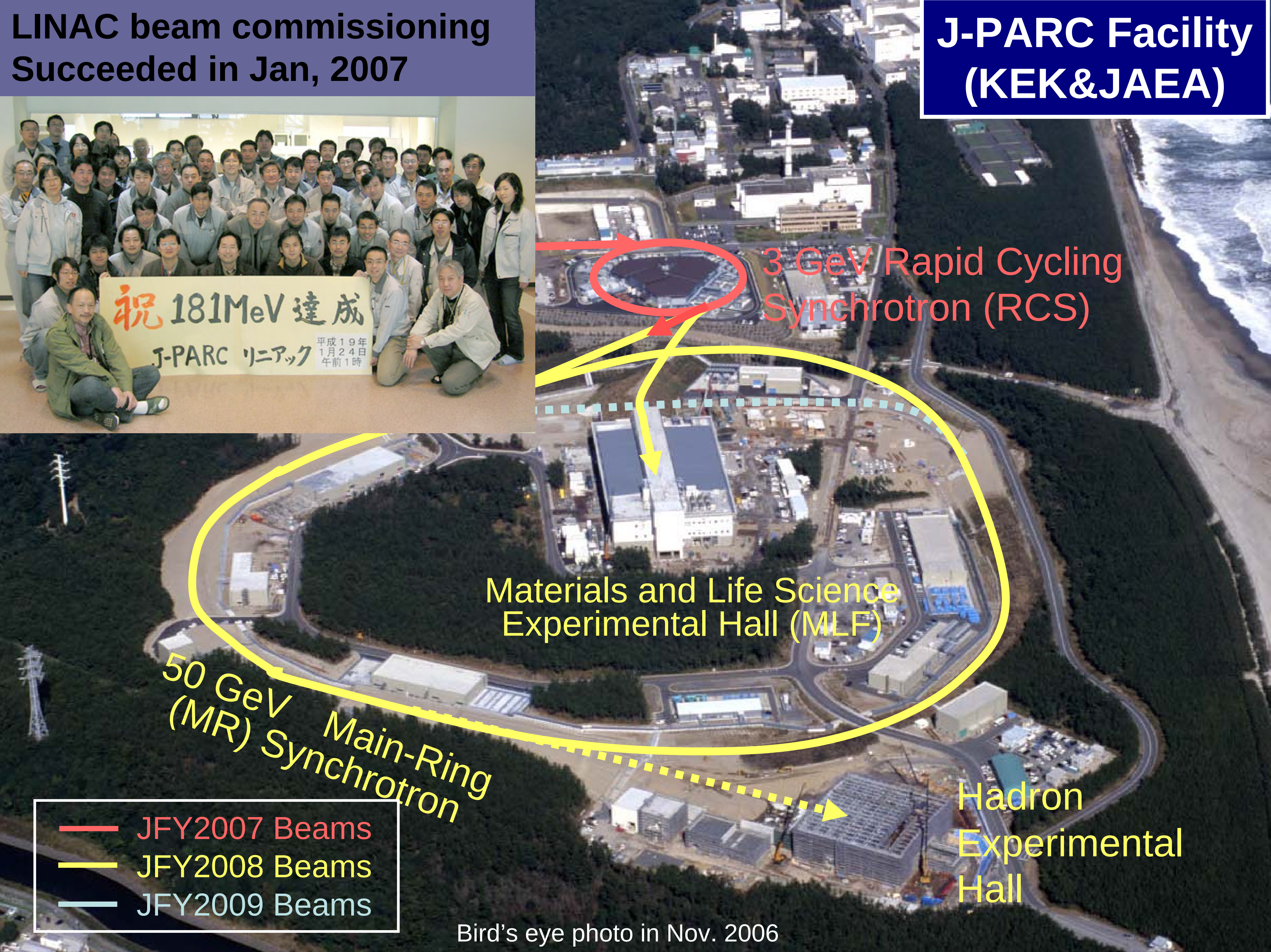
J-PARC Progress and Challenges of Proton Synchrotrons

Michikazu Kinsho
for J-PARC, KEK&JAEA

1. Introduction
2. Challenges and Issues
3. Beam Power Status
4. Conclusion


J-PARC Facility
(KEK&JAEA)
Linac
3 GeV Rapid Cycling
Synchrotron (RCS)
Neutrino Beams to
Kamioka
Materials and Life Science
Experimental Hall (MLF)
50 GeV Main-Ring
(MR) Synchrotron
Hadron
Experimental
Hall
JFY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in Nov. 2006


LINAC beam commissioning
Succeeded in Jan, 2007
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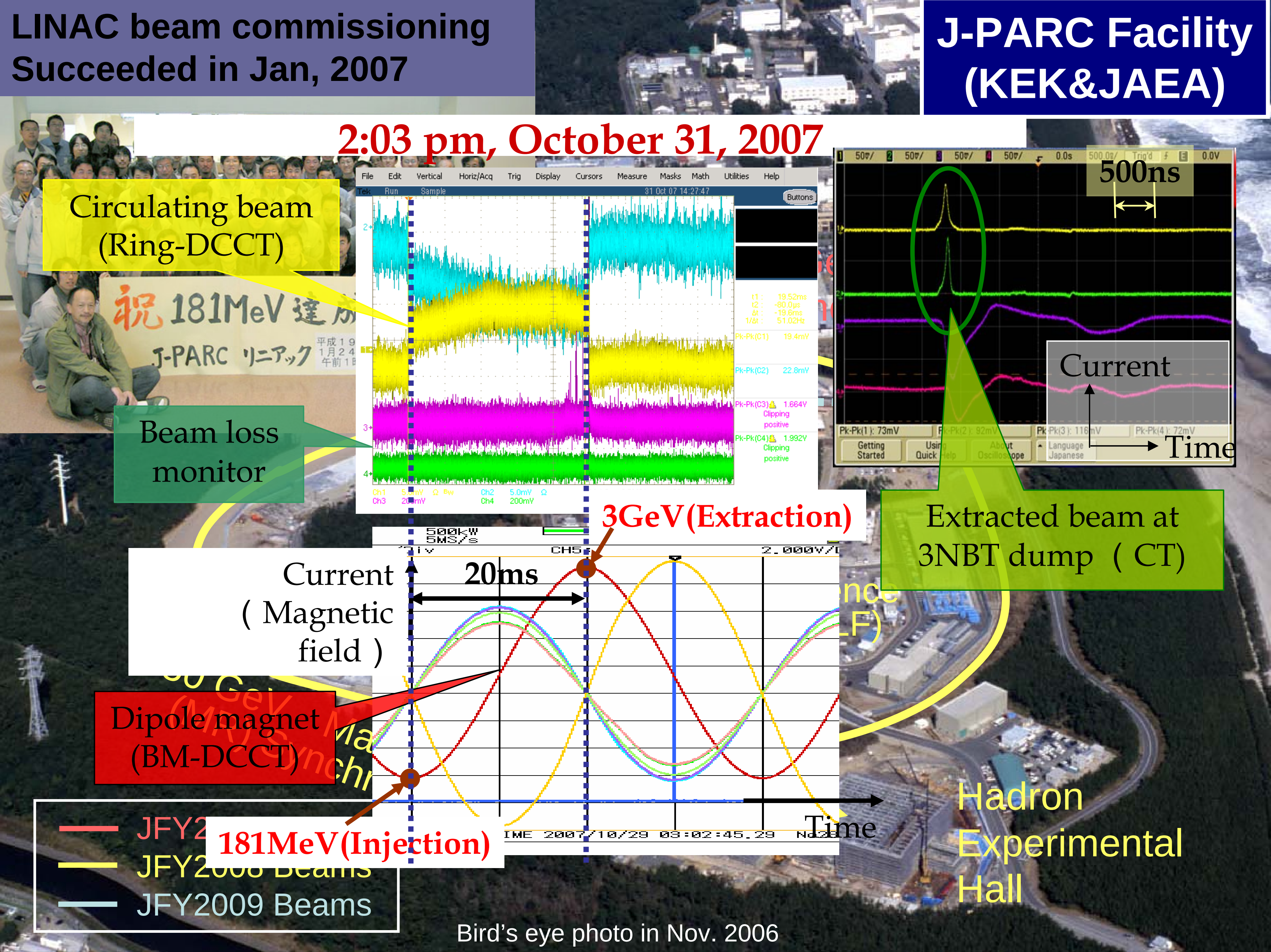
祝 181MeV 達成
J-PARC リニアック
平成19年
1月24日
午前1時


LINAC beam commissioning
Succeeded in Jan, 2007
J-PARC Facility
(KEK&JAEA)
2:03 pm, October 31, 2007
Circulating beam
(Ring-DCCT)
Beam loss
monitor
祝 181MeV 達成
J-PARC リニアック
500ns
Current
Time
Extracted beam at
3NBT dump（CT)
3GeV(Extraction)
Current
（Magnetic
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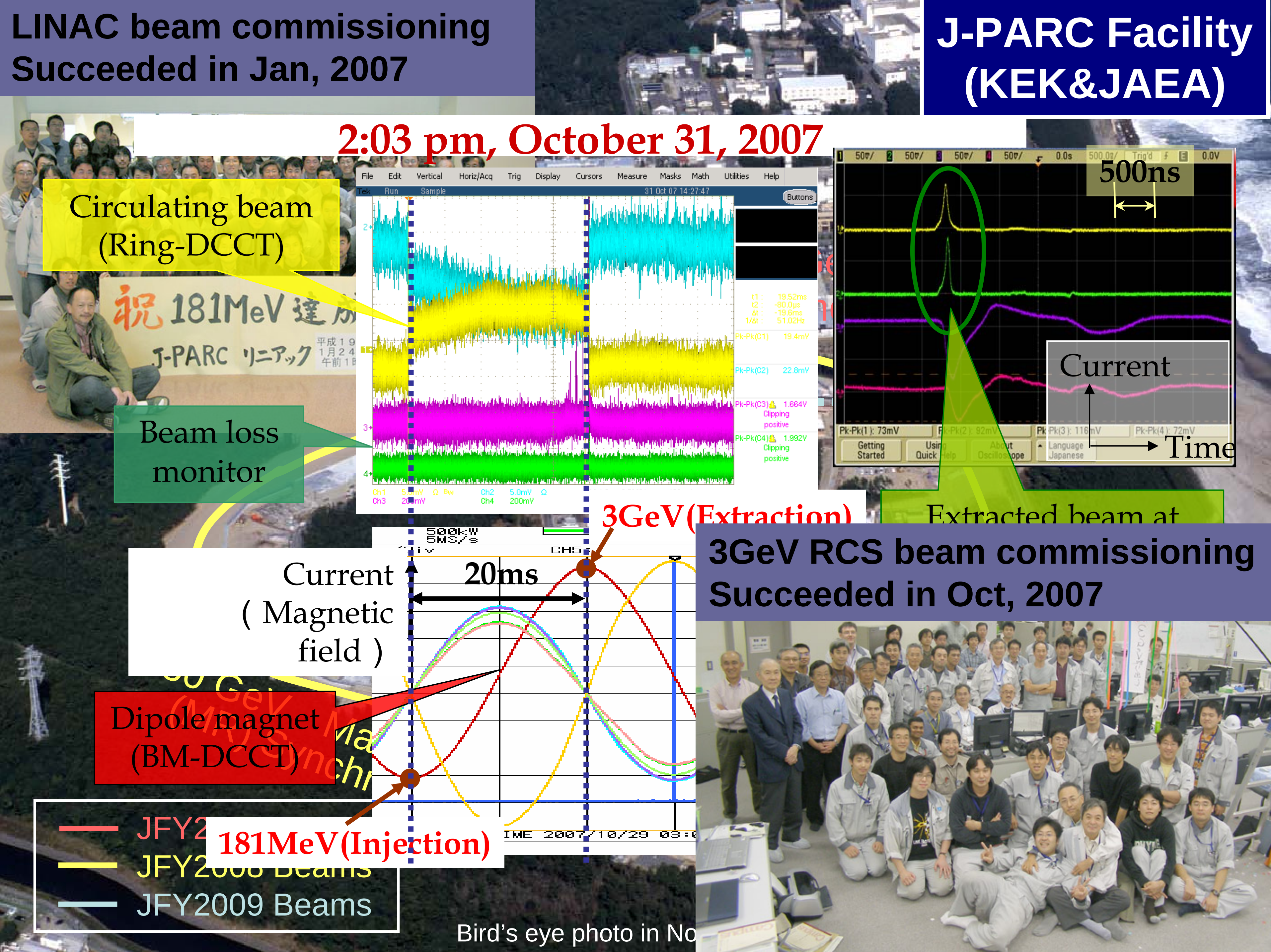

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Bird's eye photo in No

Recent progress (MR)

5/19 The beam commissioning started.

5/20 Transferred the beam to an injection dump.

5/20 The beam circulated with RF off at 21:13 (Fig. 1).

5/22 The beam was RF-captured, turned 1000 times, and was extracted from MR to the dump at 22:27. (Fig. 2)

6/19 Cleared authority's radiation inspection with 3.64-sec repetition. Continuous operation more than 3 hours with a beam power of ~60 W

Fig. 1: BPM signal

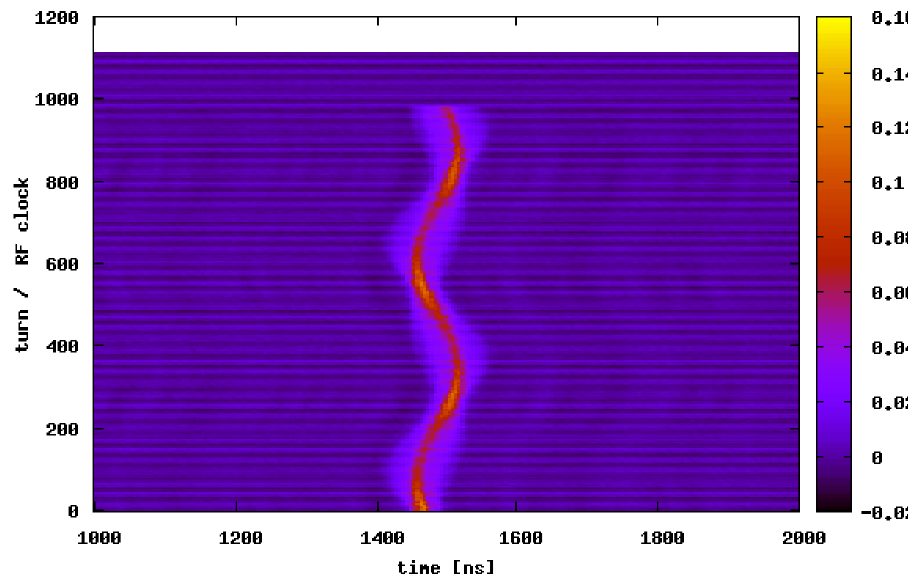
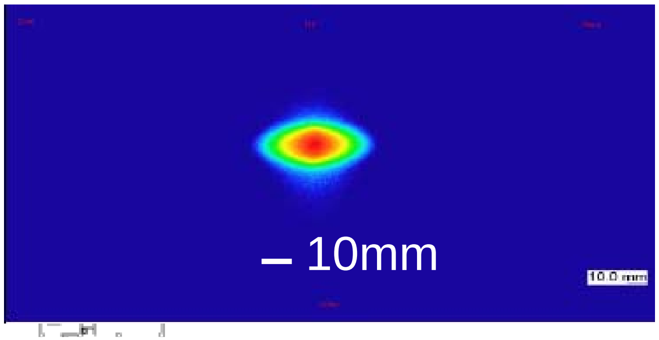
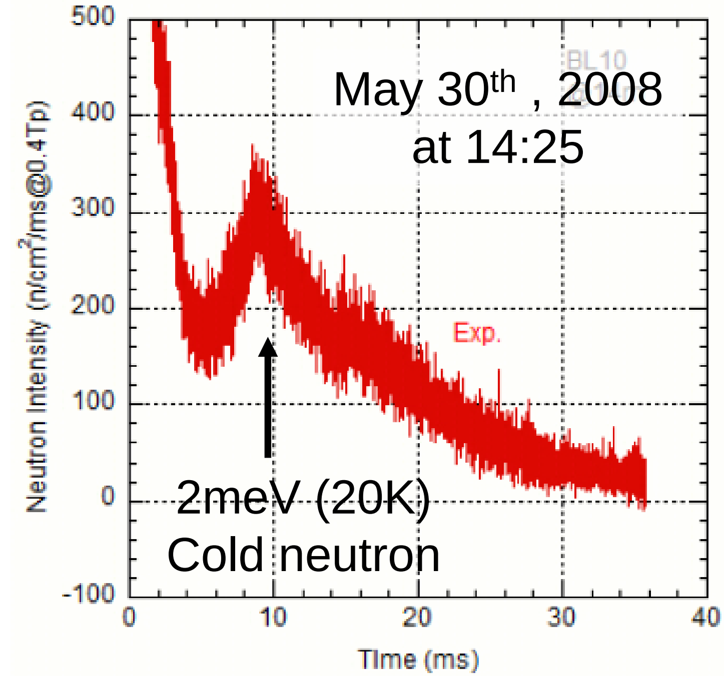


Fig. 2: WCM signal
Horizontal : time for 1 turn
Vertical : turn / fr clock

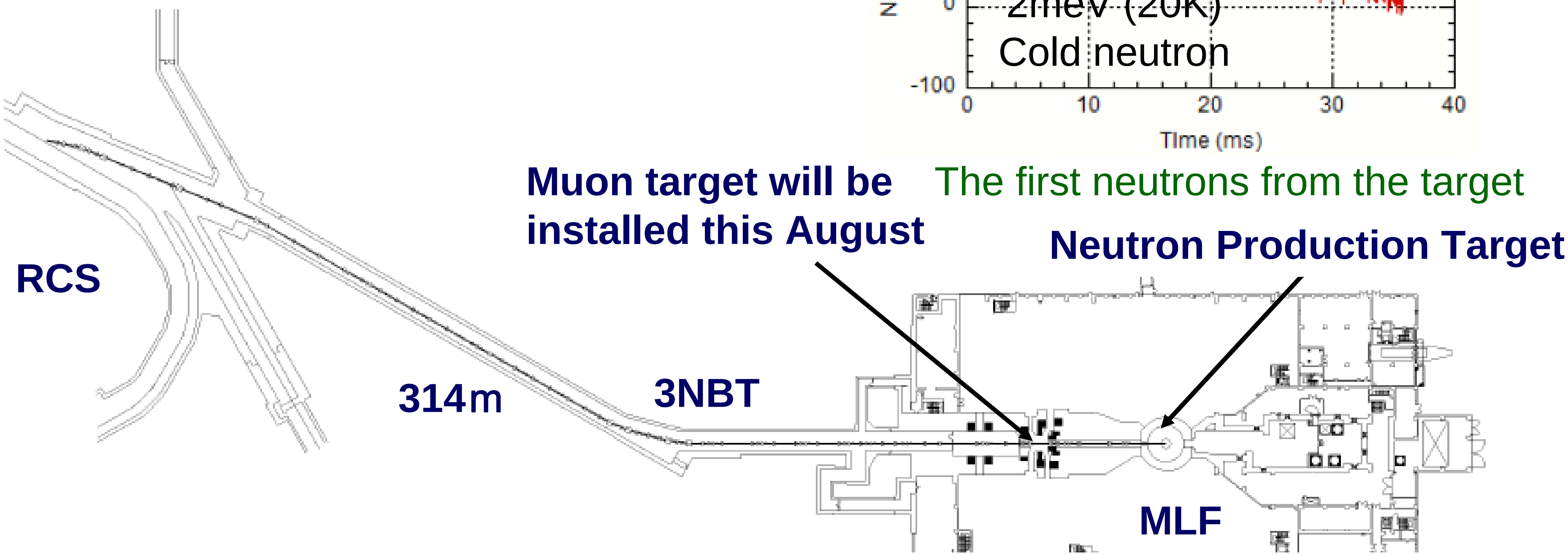
Recent progress (MLF)



Beam profile at the target



The first neutrons from the target



5/30 The beam arrived at the target immediately after the beam commissioning started.
At 14:25 the energy spectra of the neutrons from the target were measured.

Presentations for J-PARC

ID	Num	Title	Presenter
3281	MOPC105	Activities of Hitachi Regarding Construction of the J-PARC Accelerator	Y. Chida
3811	MOPC107	Beam Commissioning Results of the J-PARC RCS	H. Hotchi
3197	MOPC120	J-PARC RCS Non-linear Frequency Sweep Analysis	A. Schnase
3867	MOPC126	Beam Acceleration with Full-digital LLRF Control System in the J-PARC RCS	F. Tamura
3719	MOPC128	J-PARC Accelerator Scheme for Muon to Electron Conversion Search	M. Tomizawa
3804	MOPC132	Acceleration Voltage Pattern for J-PARC RCS	M. Yamamoto
2382	MOPC133	Radiation Level in the J-PARC Rapid Cycling Synchrotron after First Study	K. Yamamoto
3803	MOPC134	The Status of J-PARC Ring RF Systems	M. Yoshii
3229	MOPP104	Possible Upgrade Scenario for J-PARC Ring RF Cavities	C. Ohmori
3840	TUPC034	Beam Instrumentations for the J-PARC RCS Commissioning	N. Hayashi
3793	TUPC035	The Beam Position Monitor System of the J-PARC RCS	N. Hayashi
3574	TUPC036	Multi-wire Profile Monitor for J-PARC 3GeV RCS	N. Hayashi
3917	TUPC092	An Application for Beam Profile Reconstruction with Multi-wire Proportional Monitors at J-PARC RCS	H. Sako
3183	TUPC093	Beam Profile Monitor of the J-PARC 3GeV Rapid Cycling Synchrotron	K. Satou
3767	TUPD016	Pulsed Power Supply with IGBT Choppers for the Injection Bump Magnet of the 3-GeC RCS in J-PARC	T. Takayanagi
3864	TUPP013	Synchronized Data Distribution and Acquisition System Using Reflective Memory for the J-PARC 3GeV RCS	N. Hayashi
3617	WEPC138	Transient EM Analyses and Thermal Designs on J-PARC 3GeV Synchrotron Magnets	M. Abe
2860	WEPC148	Eddy Current Effects Compensation of a High-field Injection Septum Magnet for J-PARC	K. Fan
3164	THPP084	Discussion on RCS versus AR on the Basis of J-PARC Beam Commissioning for Pulsed Spallation Neutron Source	Y. Yamazaki
3201	THPP097	Commissionig Results of the kicker Magnet in J-PARC RCS	J. Kamiya
3821	THPP105	Beam Commissionig Results of the RCS Injection and Extraction at J-PARC	P. Saha
3796	THPP106	Neutrino Beamb Line at J-PARC	M. Shibata
4297	THPP107	Lifetime Comparisons of Single and Double Layered HBC-Foils using 3.2MeV Ne+ Ion Beam	I. Sugai
3740	THPP108	Temperature Measurements of Carbon Stripper Foil by Pulsed 650keV H- Ion Beam	A. Takagi
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27 Posters were/are presented

8 Posters are presented today

Challenges and Issues

- The distinctive features of the J-PARC accelerator are arising from its multi-purpose concept; the realization of the ***MW*** beam powers in ***both several GeV*** and ***several tens of GeV*** region.
- Since the 50 GeV synchrotron requires the several-GeV beam injection ***at a rapid cycle***, the accelerator scheme based upon the ***RCS*** has been chosen to provide the pulsed-neutron target with a MW beam.
- Although it is ***quite common*** to use ***the Accumulator Ring*** (AR) system with a full-energy linac for pulsed-neutron source like SNS, the RCS system may be more powerful than the AR system for the following reason.
  - A linac is easy to design, to build and to operate, since the beam automatically goes straight. A ring is also easy, since it has the stability arising from its high periodicity.
  - On the other hand, the beam is forced to inject into, and to extract from the ring. These are very difficult processes to manage.
  - Then, if one manages to inject the beam, ***why not accelerate?*** One can easily increase the beam power.

Challenges and Issues

- In other words, the RCS scheme is ***advantageous*** over the AR scheme regarding the ***lower beam current*** and the ***lower injection energy*** for the same beam power.
- The higher beam loss is allowed during the injection process, into which most of the beam loss is concentrated among all.
  - If one increases the beam energy by a factor of 7.5 like the J-PARC case, the allowed beam loss during the injection is 7.5 times as high as that for the AR with the same beam power.
- These points are discussed in more detail with Yoshi Yamazaki in this afternoon at Poster session THPP084

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I'll be waiting for you !!

Technical Issues

For these reasons, we decided to develop the ***high-power, high energy RCS*** and has ***challenged to solve many issues*** for realizing the high power proton beam as follows,

- *The rapid-accelerating system with high field gradient cavities*
- *Large aperture magnet with little eddy current effect due to rapidly changing magnetic field*
- *Precise magnetic field tracking*
- *Low-impedance ceramics vacuum chamber*
- *Injection and Extraction*
- *Transition free lattice*

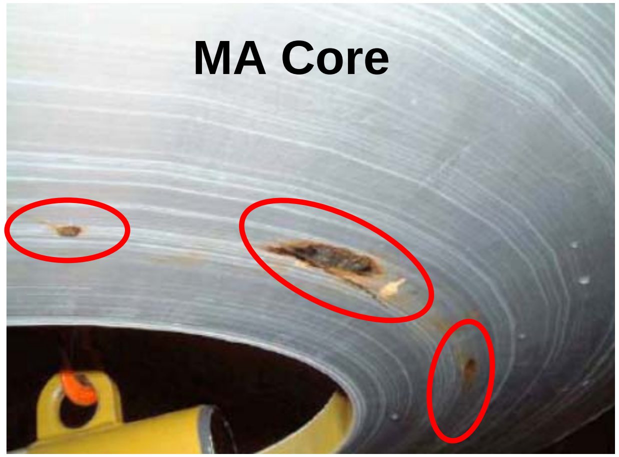
The rapid-accelerating system with high field gradient cavities

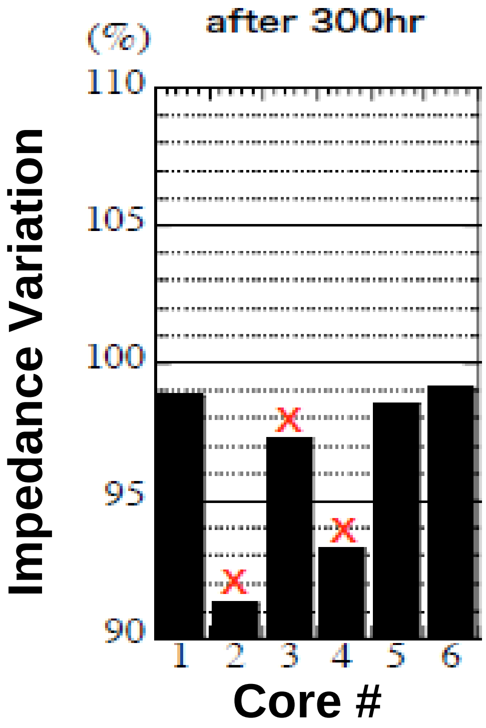
In order to realize a high-power, rapid-cycling proton synchrotron, we need the rapid acceleration.

- For the rapid acceleration we need the ***high field gradient*** in the accelerating cavity. The high field gradient at the accelerating gap can be induced only ***by high RF magnetic flux*** *in the magnetic core*.
  - **The ferrite** which has been conventionally used in proton synchrotrons has a problem that the μQf value, which is proportional to the shunt impedance, rapidly decreases, as one attempts to generate the field typically beyond ***10 or 20 kV/m***.
  - On the other hand, the μQf value of ***the magnetic alloy core*** has a flat response to the magnetic flux which produces the electric field gradient **up to an order of 100 kV/m.**
- Therefore, the high field gradient is potentially feasible by using the MA core.
- We have challenged to develop ***the RF cavity with MA cores***.
- The development had been performing smoothly ***before we started long run test.***

The long-run, high-power operation test of the MA-loaded cavity

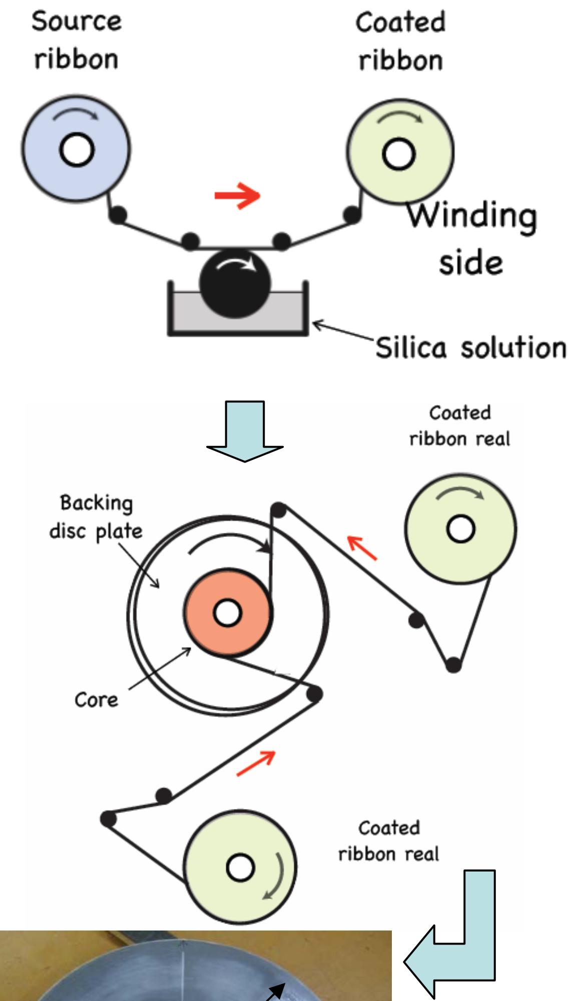
- The long-run, high-power operation test of the MA-loaded cavity has *started from 2005*.
- Then, we found one core was damaged on the surface ***around 50 hours***. This core was installed the nearest to the acceleration gap, being loaded with the highest transverse electric field.
- This was the start point to grapple with the MA core development.
- We decided to check all the cores before their installation in the cavity. Each cavity was operated up to ***300 hours***, since the problem at the initial stage usually happened ***during the first 50 hours*** operation.
- During the course of this RF cavity testing, we learned that the ***poor electric insulation*** has something to do with the damage.





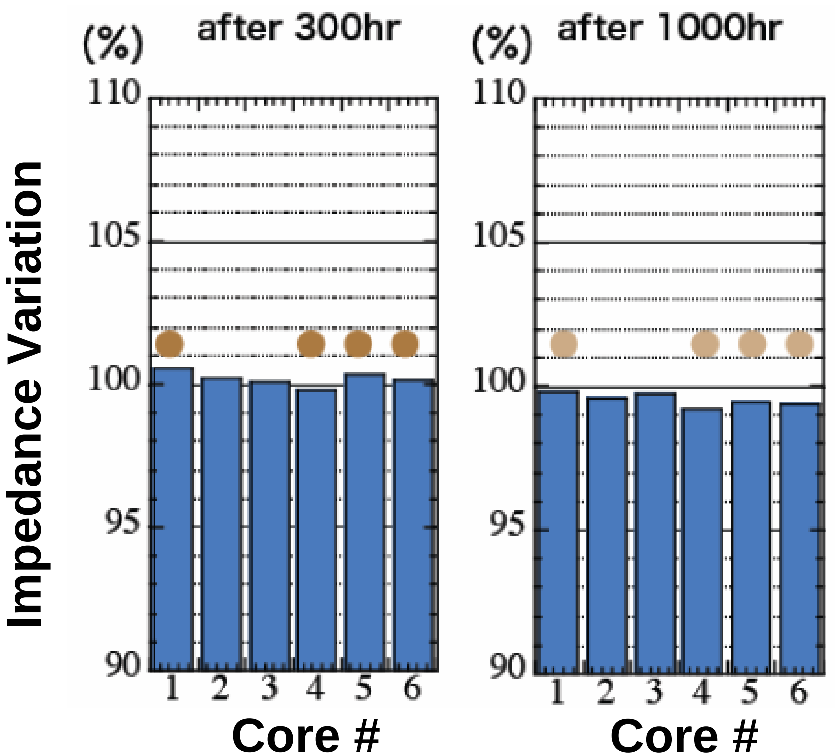
MA core development

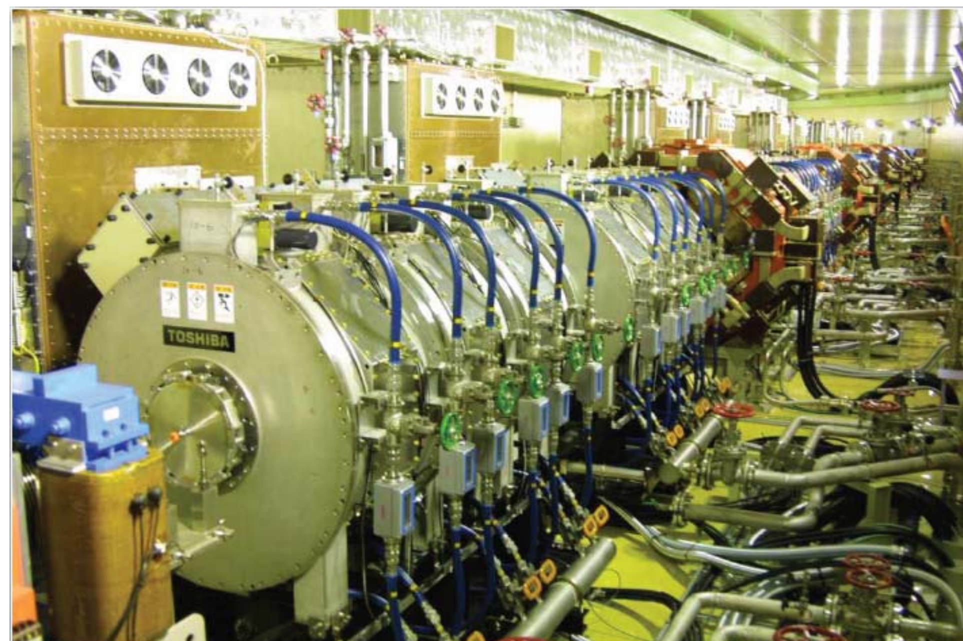
- The MA core is formed by winding the MA tapes 35 mm wide, 18 μm thick with ***2-μm silica insulator*** on one side.
- Some damaged MA cores had already revealed the low resistance ***between the MA layers*** prior to the high-power test.
- This indicates that the damage occurred at the poor insulation between the MA layers, when powered.
- We improved the manufacturing process of the MA cores in such a way that the thin silica insulators can keep the good insulation throughout the winding process and others.
- ***Afterwards the test results have been drastically improved.***



High field gradient RF cavities loaded with MA cores

- This is truly the innovative development of the accelerating cavity loaded with magnetic alloy.
- ***Ten RF cavities*** loaded with MA cores, which passed more than ***300 hours operational test***, were installed in the RCS tunnel.
- All the cavities have been in operation at the maximum acceleration gap voltage of ***40kV/cavity*** ***without any problem*** more than ***1000 hours***.

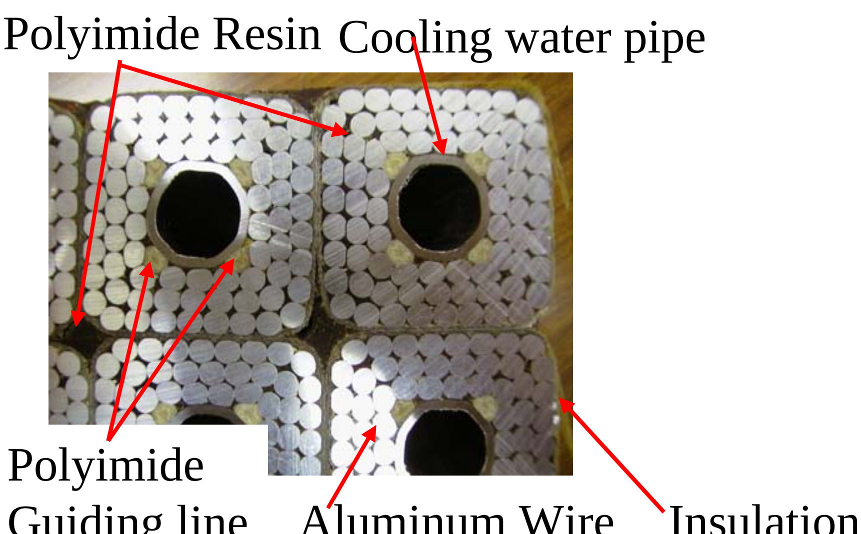


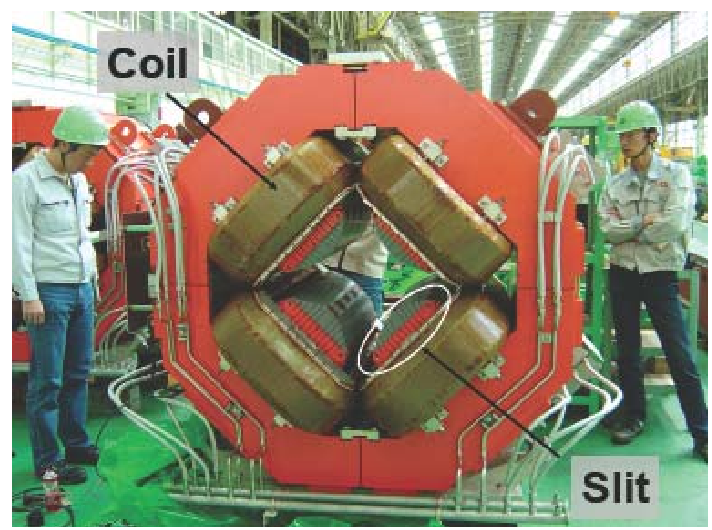


RF Cavities installed in the RCS tunnel

Large aperture magnet with little eddy current effect

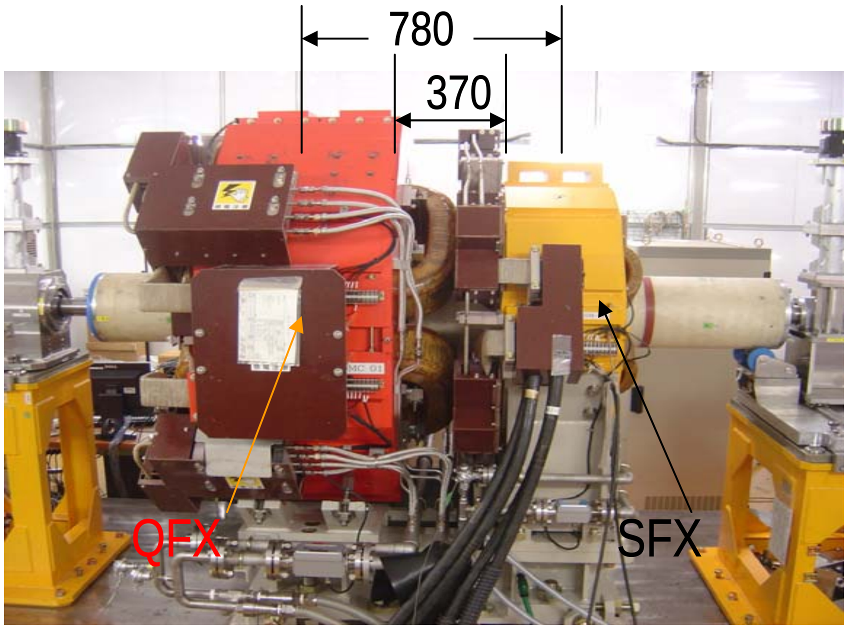
- We had to develop ***large aperture, radiation-hard magnets*** with little eddy current effect arising from the rapidly changing magnetic field.
- The coils for these main magnets are made of ***aluminum-stranded conductors*** which consists of many electrically-isolated thin wires wrapped around a stainless-steel water-cooling pipe and is isolated by ***polyimide resin*** whose resistance for radiation is ***more than 10 MGy***.
- In order to keep the sufficient acceptance for the low energy beam injection all the magnets must have the ***large physical apertures.***
- As a result, most of the quadrupole magnets are quite short with the large apertures, and are located very close to each other.

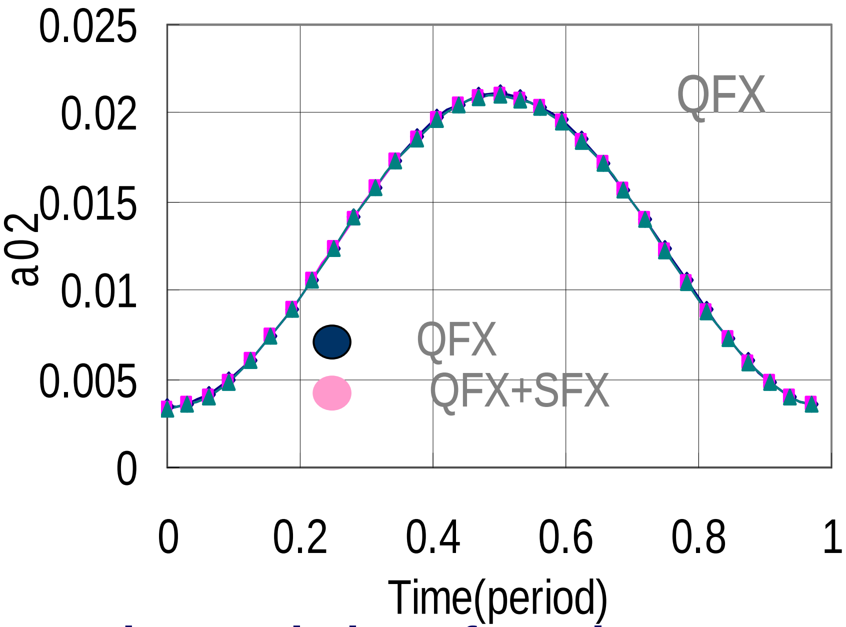




Fringing field effects

- We worried that the fringing field effects are substantial for these magnets, and the interference between the fields of the two neighbouring magnets is not negligible. In addition, the saturation effects should be taken into account at the core ends.
- These effects altogether might give rise to large ***higher multi-pole components*** in their fields, resulting in the small dynamic aperture.
- Fortunately, ***the dynamic aperture was still sufficiently large***, when the magnetic fields measured for the actual magnet layouts were taken into account in the beam simulation.

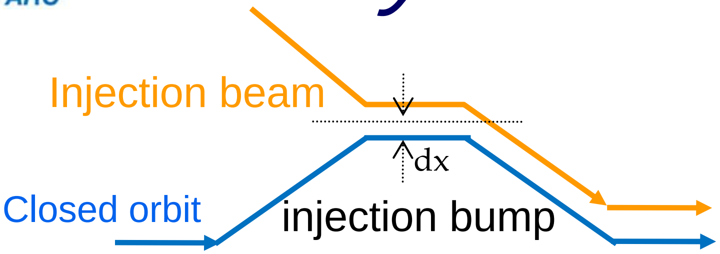


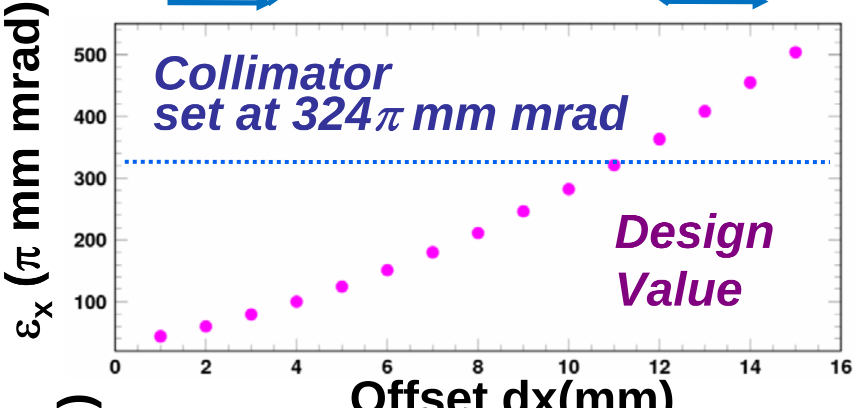


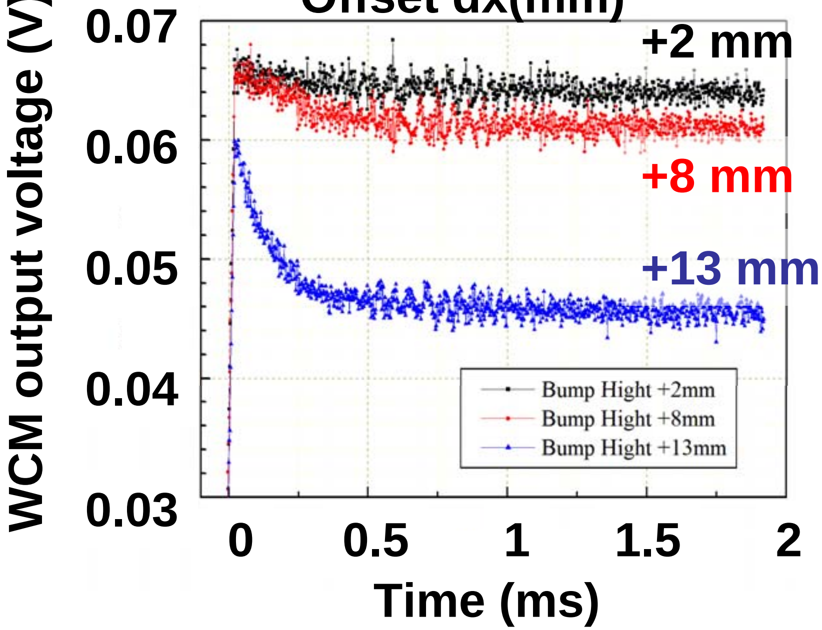
Time variation of 4-pole component

Amplitude of the allowed multi-pole components with respect to the main component : *$2x10^{-3}$ (max.)*

Physical aperture survey

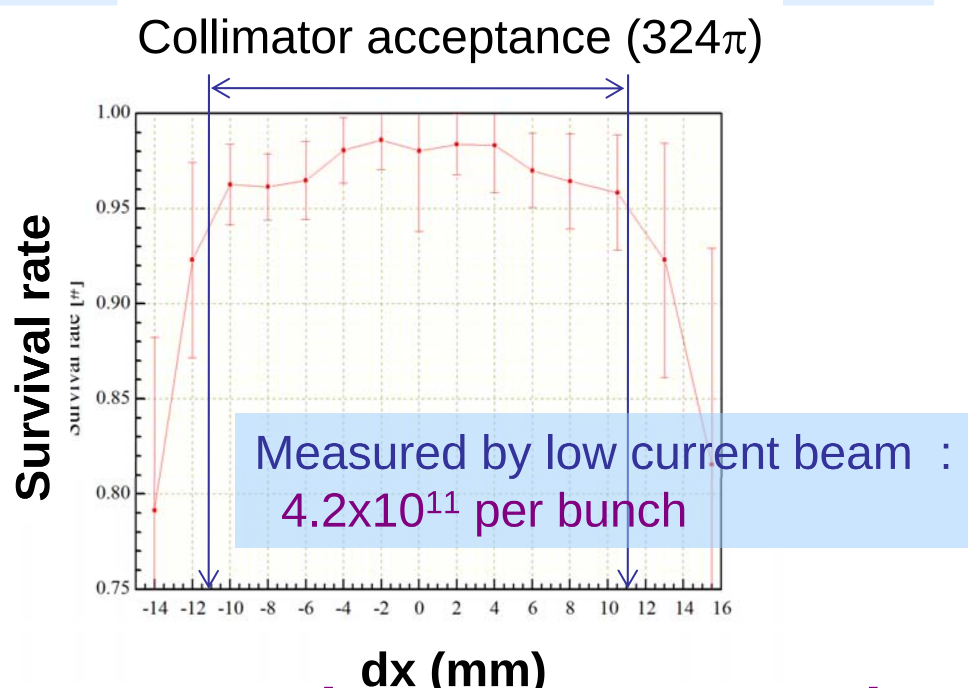






We measured a beam emittance dependence of the beam loss by the ***offset injection***

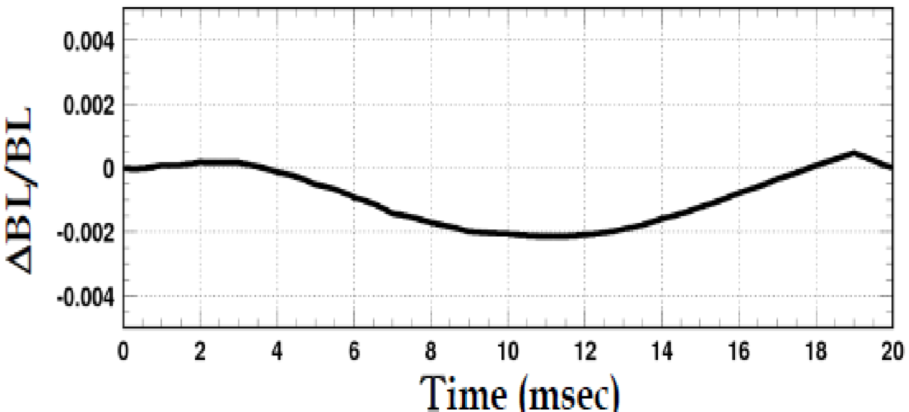
In this measurement, the horizontal beam emittance was roughly controlled by ***shifting the matching condition*** with the shift bump magnets.



Dynamic aperture exceeds collimator aperture !

Precise magnetic field tracking

- Magnet systems form resonant networks, being respectively excited by currents with *DC-biased sinusoidal waveform*.
- In general, resonant networks are configured in either parallel or series resonance. By carefully investigating *the peak current*, circuit simplicity, *current controllability*, and state of the art of power electronics, *parallel resonance* was adopted for the *dipole* magnet network and *series resonance* for the *quadruple* magnets networks.
- Since the quadruple magnets were grouped into *7 families*, *totally 8* independent resonance circuits should be excited.
- *The precise control* is necessary for tracking *all the 8 families* of the magnets, in particular, in the present case that each family of the magnets has its own saturation effect. For this purpose, the *IGBT* (Insulated Gate Bipolar Transistor) devices are ideal by its fast switching characteristics.
- The following figure shows the deviation of the dipole magnetic field from its ideal sinusoidal form (The quadrupole magnets are sinusoidally operated much more precisely). In our system, the magnetic field tracking is performing *an accuracy of 10^{-3}* during the beam operation.



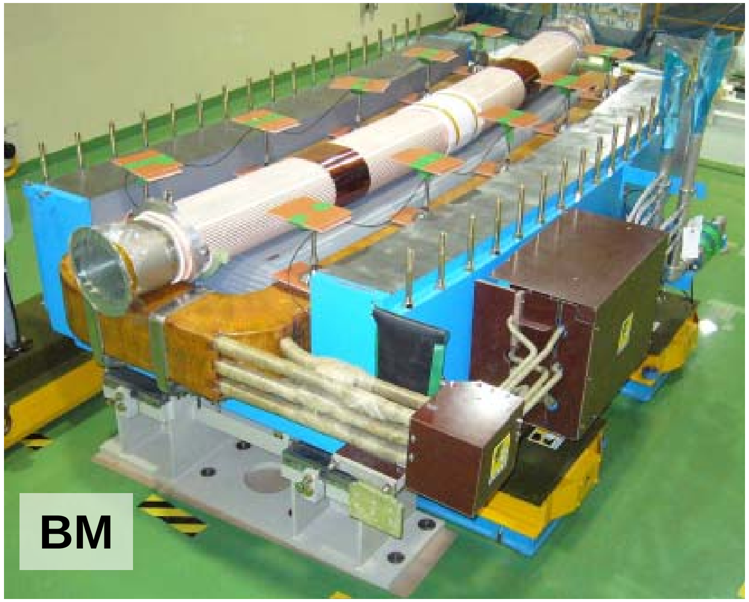
Deviation of the BM field pattern from ***the ideal sinusoidal*** curve

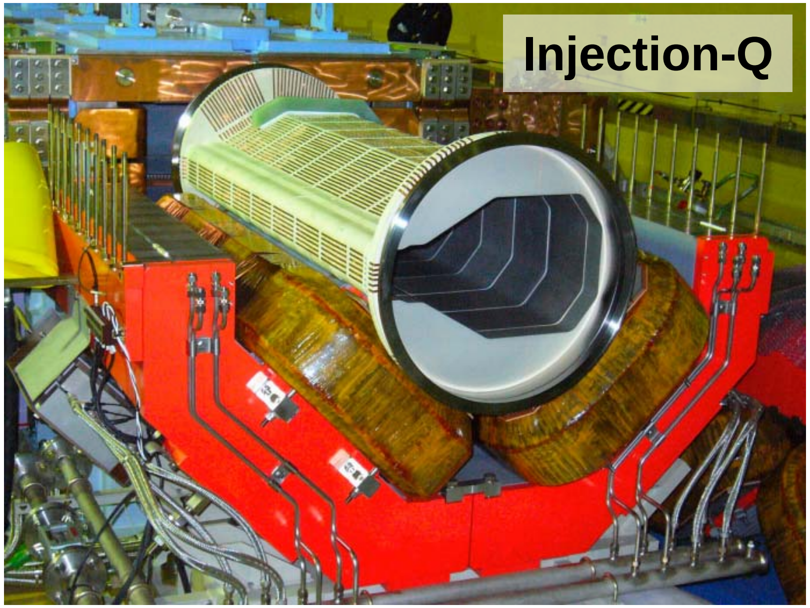
Switching noise of IGBT

- On the other hand, the fast switching implies that care should be taken of even very ***high-frequency*** components of the electromagnetic power.
- The components of the ***8 resonant circuits*** are driven by the power supplies with the very high frequency components.
- From the beginning it was foreseen that ***the electromagnetic compatibility issue*** would be hard to solve.
- For this reason, we scheduled nearly one year for powering and controlling tests in-situ.
- In fact, the circuit systems altogether form distributed three-dimensional circuit systems coupled with each other.
- Even ***some chassis*** or ***some grounds*** revealed ***several hundred volts*** at some frequency components.
- After nearly ***one year*** painstaking effort almost all the electromagnetic issues have been solved, ***except for the shift-bump system***.
- Together with these magnet-excitation tests the in-situ efforts were exerted to improve the signal-to-noise ratios of almost all the beam diagnostics systems, by means of filtering the noises.

Low-impedance ceramics vacuum chamber

- For mitigating the eddy current effect, all the vacuum chambers exposed to the fast varying magnetic fields have been manufactured of ***the alumina ceramics.***
- To use a ceramic chamber, ***some electrically conductive layer*** is necessary on the ceramics so that the ***wall impedance*** is ***reduced*** (and thus the beam is stabilized) and that the electromagnetic waves arising from the beam is prevented from radiating outside. ***The RF shield*** is thus designed as ***a high frequency pass filter***, where eddy current cannot be generated.
- In order to keep the large aperture with the reasonable cost for the bending magnet (BM), we decided to choose the cross section of the ***race-track shape*** for the ***BM*** vacuum chambers. In addition, the special shapes (***rectangular and racket-shape cross sections***) of vacuum chambers have been produced for the ***injection section***.





RF shield and Mass production

- The 99.7% alumina ceramics chambers of sub-meter in length, having racetrack or circular cross-sections, were sintered and jointed by brazing. Several chambers with rectangular and racket-shape cross sections were also produced.
- On the outside of the alumina ceramics chambers ***copper stripes*** were electroformed to reduce the impedance.
- One of the ends of each stripe is connected to a ***titanium flange*** through a ***capacitor*** so as to interrupt an eddy current circuit.
- In order to reduce the emission of the ***secondary electrons*** when protons or electrons strike the surface, ***TiN film*** is coated on the inside surface of the chambers.
- Since the development and/or the mass production of the ceramics vacuum chambers, in particular, with the special shapes, took much longer time than expected, some chambers were delivered to the J-PARC site just in time.

Ti flange

Ti sleeve

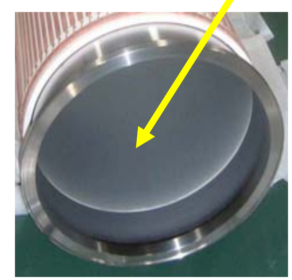
Brazing joint

Capacitors

segment

Capacitance : 330 nF

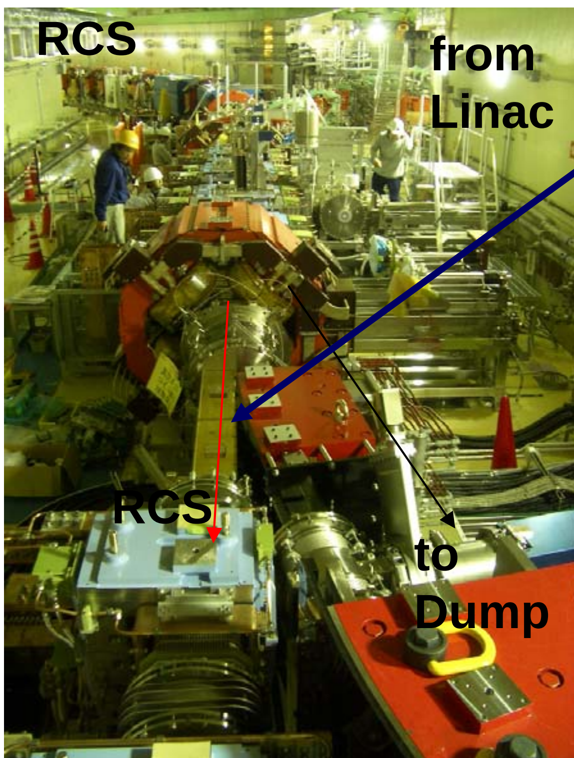
TiN coating

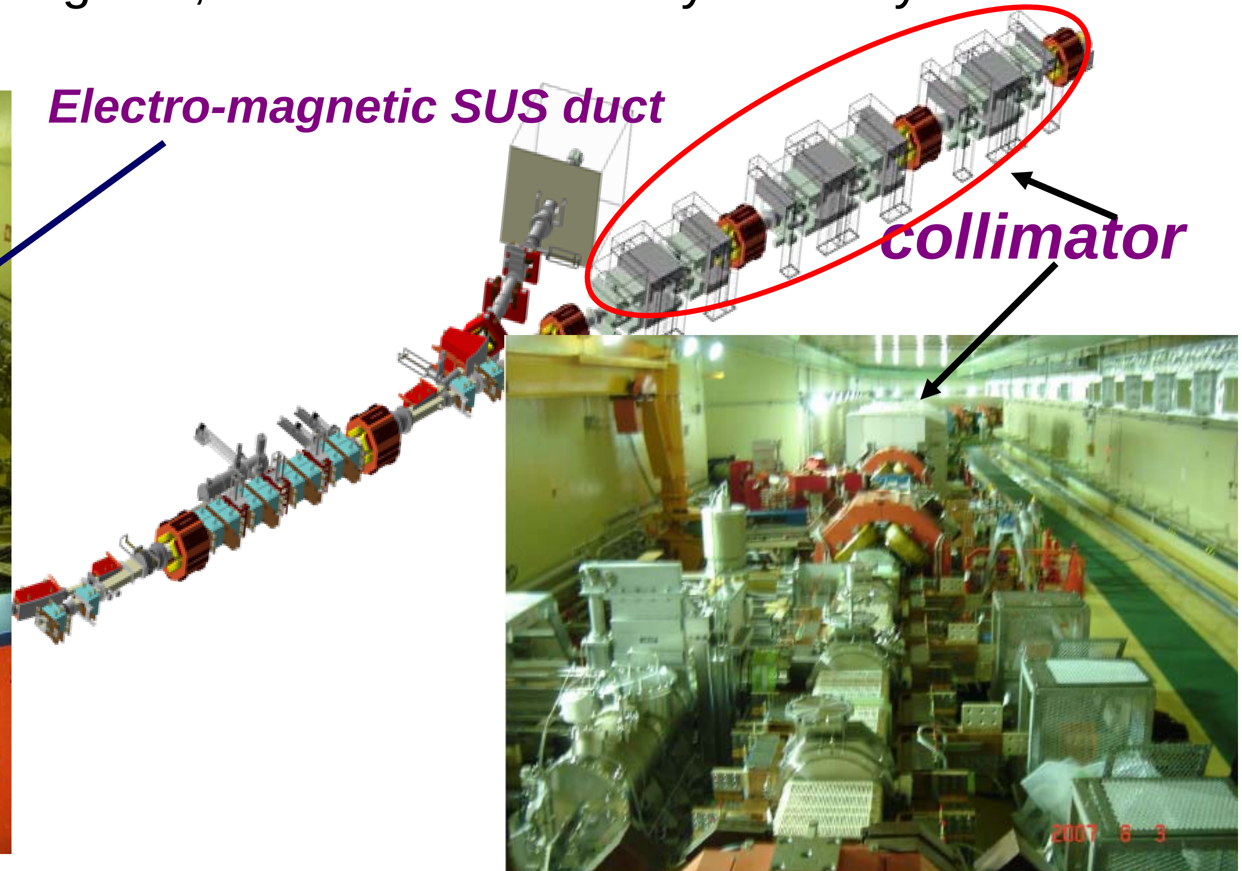


Thickness : 15 nm

Injection and Extraction

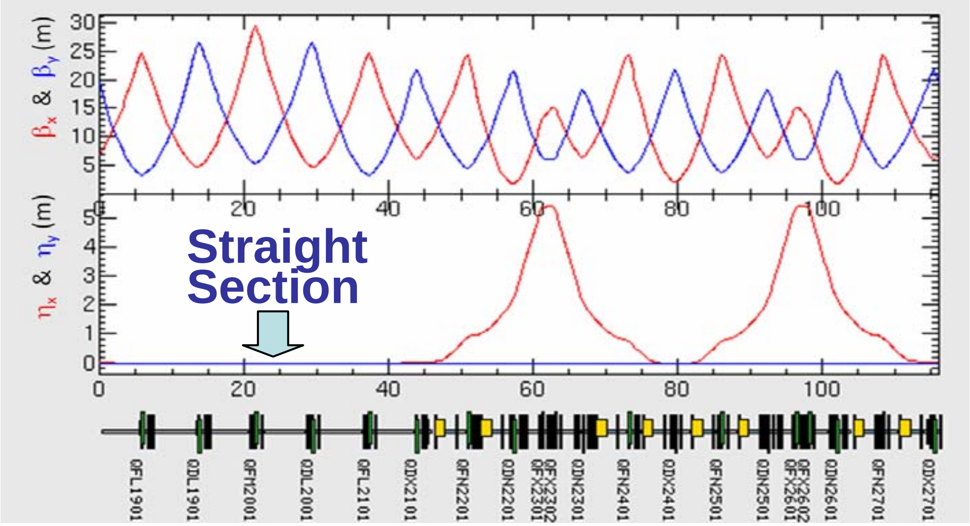
- The injection and extraction devices for the large aperture of the beams were another challenge to develop and manufacture.
- The injection scheme was hard to design for the large beam aperture. A beam collimation system is prepared to localize and to control the beam loss.
- We are designing how to shield the beam orbit from the magnetic field leaked from the septum magnets, which has been very carefully studied.





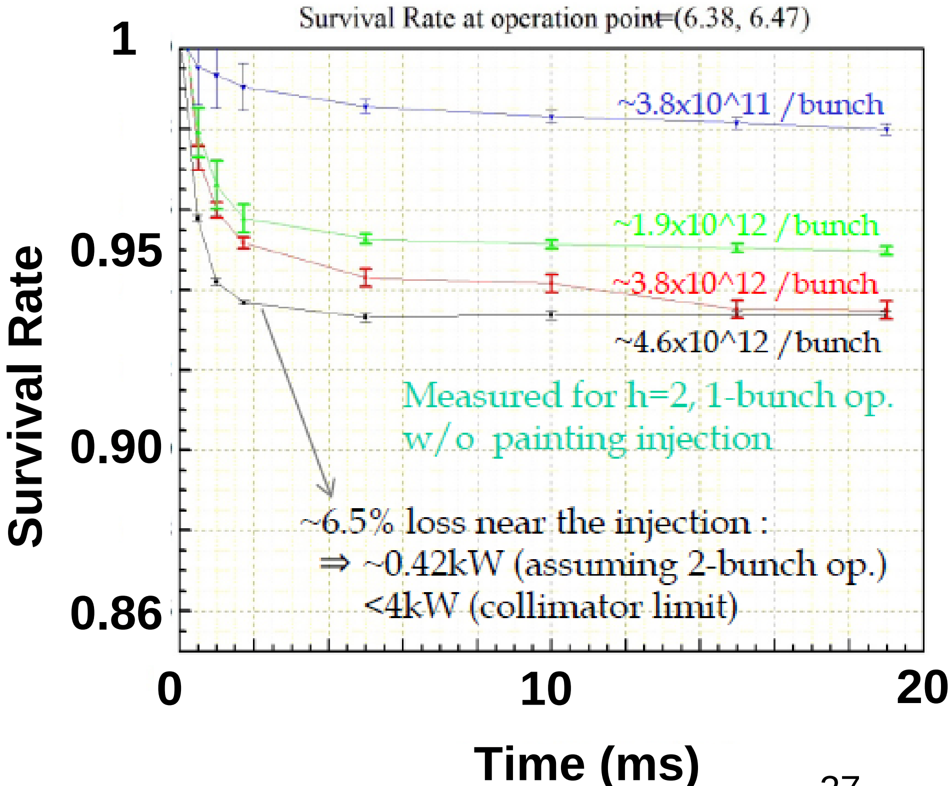
Transition free lattice

- We have chosen the lattice with three-folding symmetry. We need three ***long straight sections***. One is dedicated to the long RF acceleration section, which should be isolated from the other straight sections; one for the injection and collimation, and the other for the extraction, both of which will be radioactive.
- ***The circumference*** of the RCS ***is limited*** by two factors. One is the beam pulse length of ***less than 1μs*** for the neutron production, and the other is the circumference of the ***MR***.
- Once the circumference of the RCS is thus limited, the three-folding symmetry should be taken in order to keep one long straight section for sufficient RF acceleration. The straight sections are made ***dispersion free*** in order to avoid the synchro-betatron coupling.
- ***The transition energy is chosen far above the operation energy*.** In this case it is 9.14 GeV
  - The beam loss inherent to the transition crossing will be thus avoided.
  - As an injector the RCS has to match its beam longitudinally for the injection to the MR.



Beam loss

- In the case of ***1.07 x10^13*** protons, which corresponds to 130 kW if operated at 25 Hz (300 kW at 60 Hz), the beam loss observed at the beam collimator was about ***6.5 %.*** The figure below shows the beam survival rate during the beam operation.
- Almost all of the beam loss occurred ***during the beam injection***. In the conventional lattice design, the beam inevitably passes through the transition energy during the acceleration.
- At the transition energy, no stabilizing mechanism works for the longitudinal degree of freedom in such a way that the synchrotron frequency becomes zero, giving rise to the beam loss. In the J-PARC RCS lattice design, the transition energy was raised to ***9.14 GeV***, which is ***far above the operational energy***, by choosing the missing bend lattice.
- ***This can be the reason why no beam loss was observed during the acceleration.***

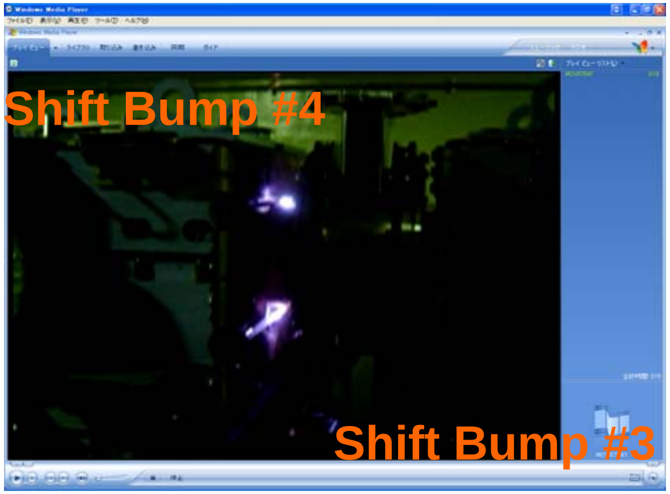


Survival Rate during Beam Operation

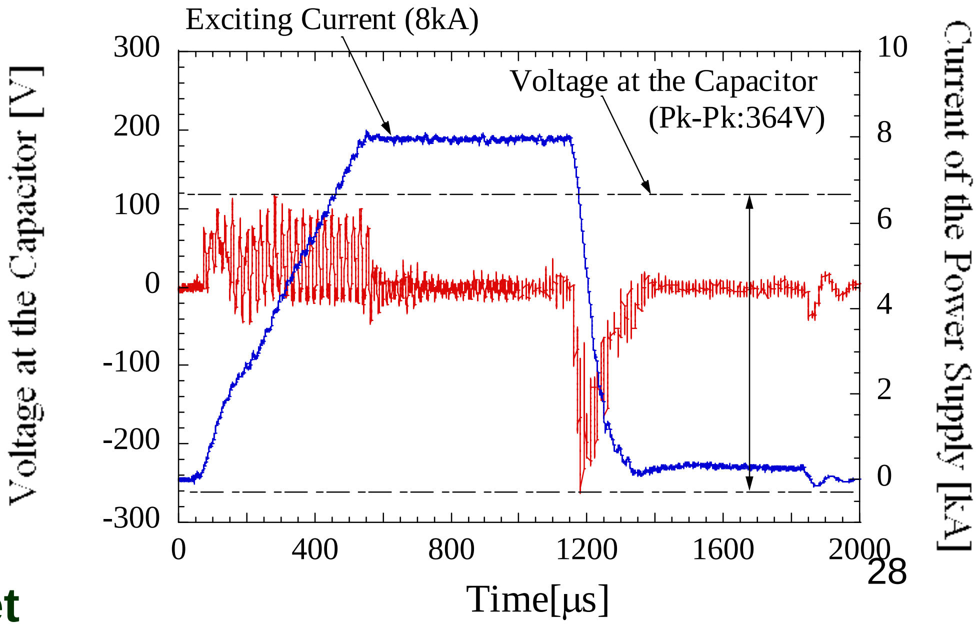
Issues

Burning of the capacitors at the ceramics chambers

- The injection shift bump magnets have still some issues arising from the fast switching of the IGBT and others, since the decay of these magnetic fields should be faster than 100 μs for reducing the number of hitting of the circulating beams on the charge-exchange foil.
- The capacitors installed to the ceramics vacuum chamber, through which ***the mirror current*** passes, were damaged by ***the fast falling field*** of shift bump magnet.
- There are the chip capacitors of the RF shield at the ceramics chamber inside the shift bump magnet. ***The capacitors were burned*** by the induced voltage due to the falling time of the current pattern and ***the current ripple of the switching*** at the IGBT choppers. Especially, the capacitors on the side, where the area of the ***eddy-current loop*** was large, were often discharged.



Discharge of capacitors under normal operation of shift bump magnet

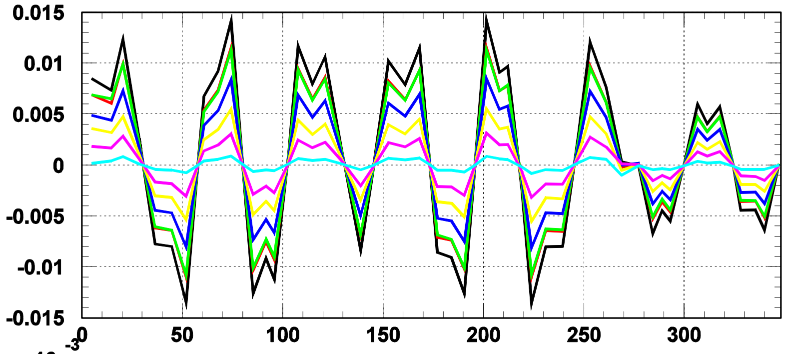


Issues

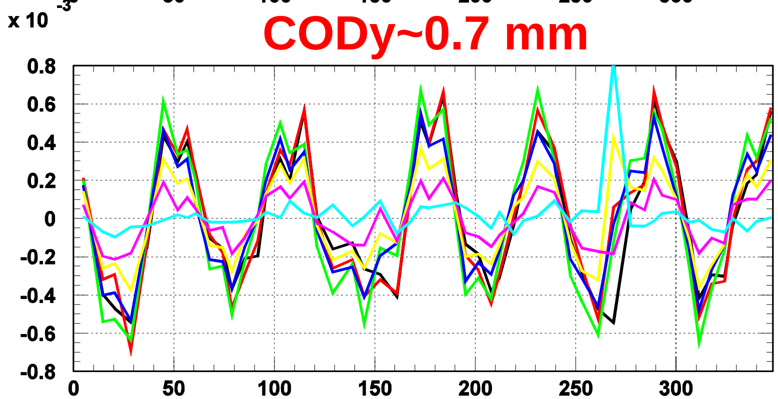
Leakage field of septum magnets make COD

by ESEPs ***(w/ ESEP excited at 3GeV)***

CODx~15 mm



CODy~0.7 mm

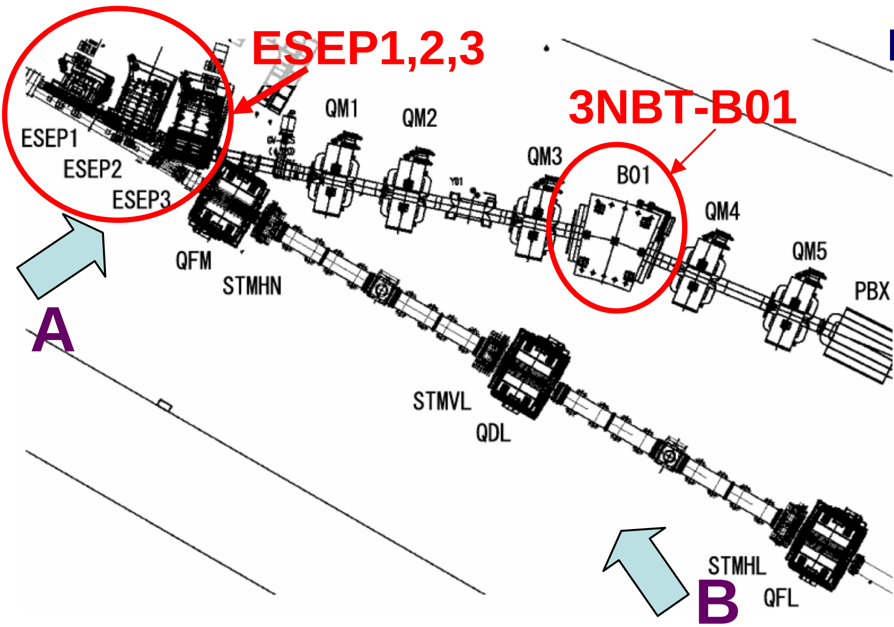


Black 12000A
Red 3GeV
Green 10000A
Blue 8000 A
Yellow 6000A
Pink 4000A
Light blue 2000A

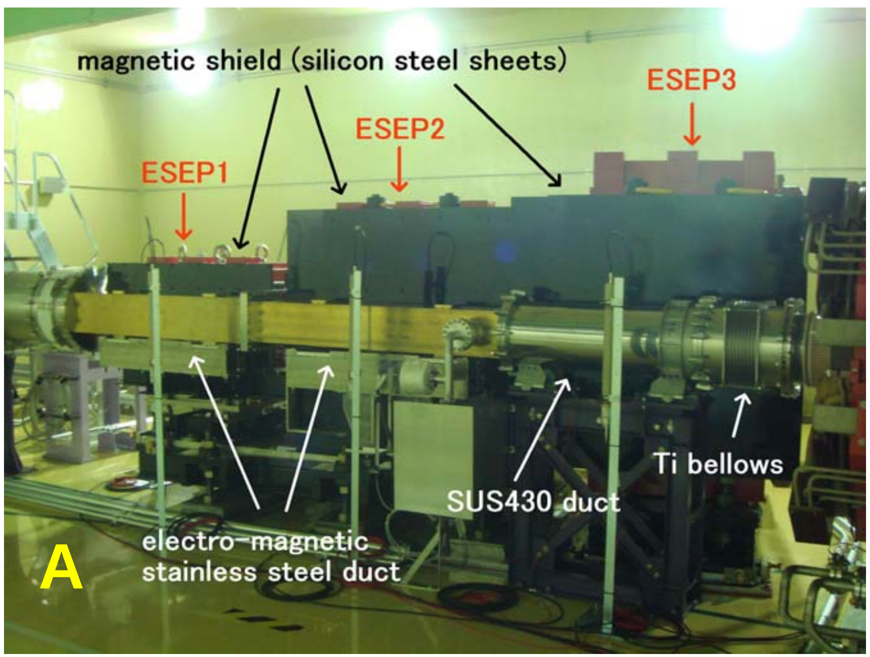
Horizontal COD observed in the "3GeV acceleration mode" gets smaller in going to 3GeV, which means ***DC fields*** in the ***injection*** and ***extraction lines leak*** to the RCS.

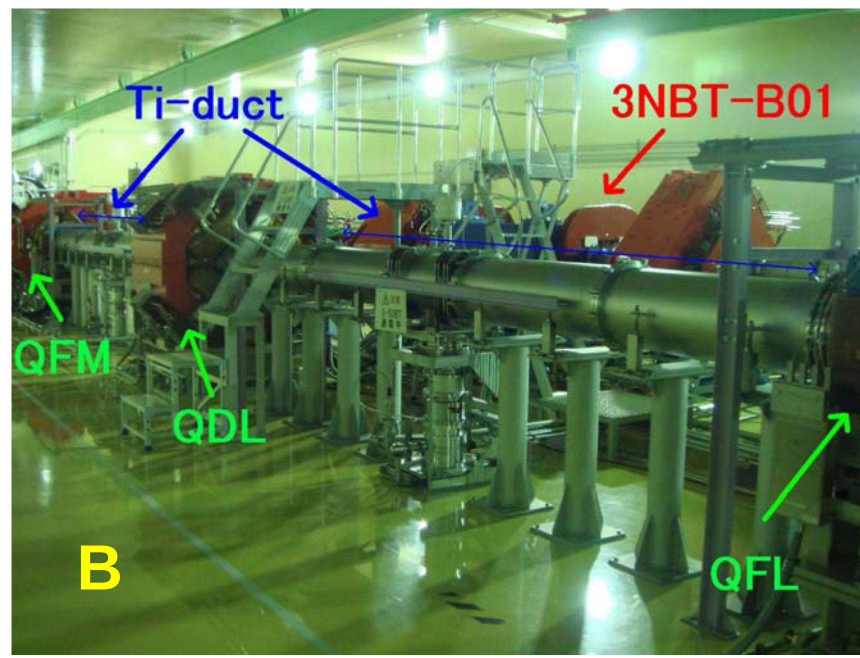
We measured ***COD*** caused by DC leakage fields from ESPSs using the "***181MeV circulating beam***".

Issues



- **Measurement of magnetic fields**
  - In order to obtain the leakage field distribution at the extraction area of the ring, the magnetic fields were measured directly in the RCS tunnel.
  - The leakage sources were 3 extraction septum magnets and bending magnet located at beam transport line.
  - The magnetic files were measured along s-axis in the vacuum chambers.





Issues

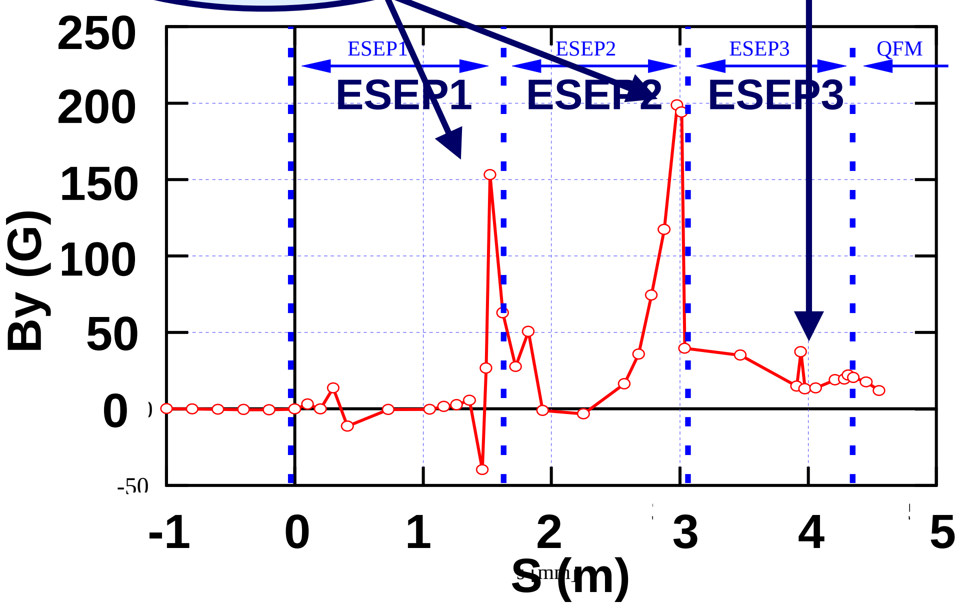
Field distribution leaked from ESEPs

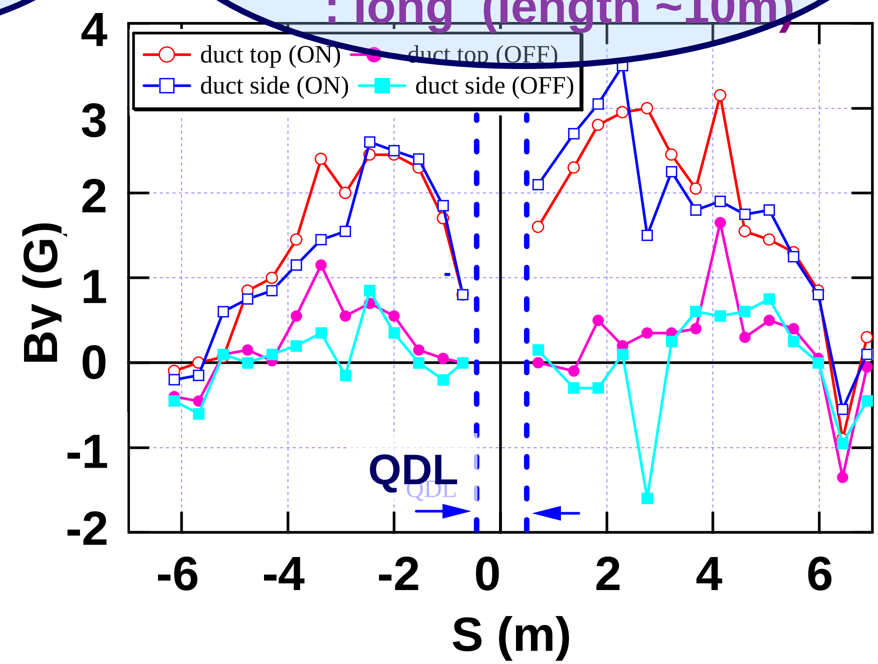
Field distribution leaked from 3NBT-B01

Directly from the coil through between 3 magnetic shield gaps.

saturation of the magnetic shield

•leakage field : small (peak ~ 3G)
•spreading the broad area : long (length ~10m)





•EM SUS & SUS430-duct; couldn't permeate.
•gaps of the flange; fields can permeate slightly
•Ti-bellows; fields can permeate thoroughly

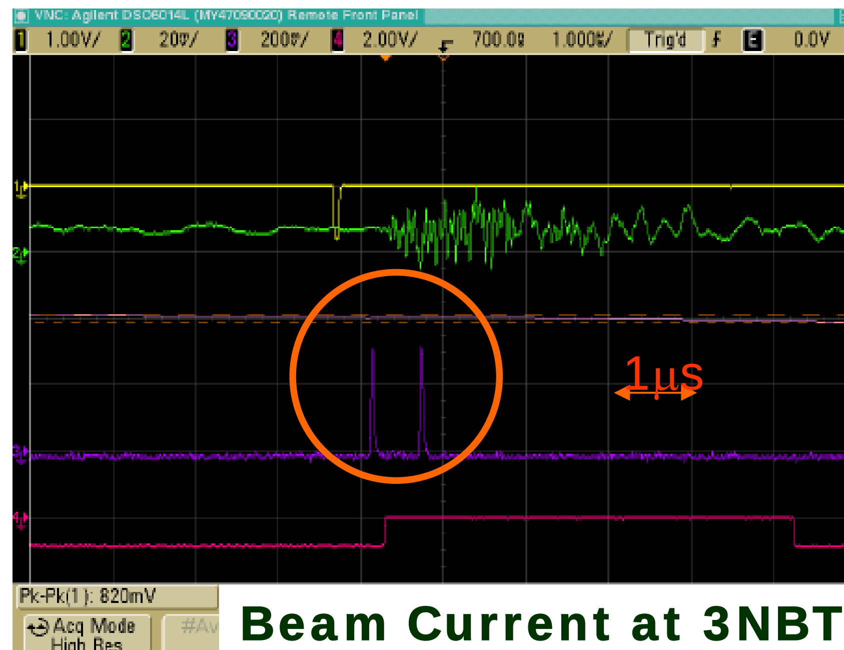
leakage field ~ 17Gm

leakage field ~ 19Gm

Additional shield !!

Beam Power

- At the end of October we had a successful acceleration in the RCS. ***Four months later***, at the end of February of 2008, the beam study result was demonstrated as follows. First, ***4.4×10^{12} protons*** were extracted from the RCS over ***4 minutes*** at the energy of 3 GeV and a repetition rate of ***25 Hz.***
- This correspond s to the beam power of approximately ***50 kW*** (note that the designed number of protons accelerated and extracted is ***8.3×10^{13}*** at the designed repetition rate of 25 Hz and at the designed energy of 3 GeV, corresponding to the beam power of 1 MW).
- The operation was terminated here, since the beam dump at the extraction could only ***accept the beam power*** of ***4 kW*** averaged for one hour. In this case, only ***one bucket*** was filled rather than two available buckets.
- Second, ***the two buckets*** were filled out to form ***two bunches*** in the RCS. In this way, ***1.07×10^{13} protons*** were accelerated and extracted just once, although all the accelerator components were in operation at a full repetition rate of 25 Hz. This correspond s to a beam power of ***130 kW***, if the beam is injected at the designed repetition rate of 25 Hz.



Beam Current at 3NBT

Beam Power

- In both cases, the linac beam with the emittance of approximately a ***few π mm mrad*** was directly injected to the RCS ***without any painting.*** (The painting is designed over the available RCS aperture of 324π mm mrad to mitigate the space charge effect.)
- Even under this condition, the beam loss observed at the beam collimator was ***only 6.5 %,*** corresponding to ***0.5 kW***, which was well below the designed capacity of ***4 kW*** for the beam collimator. Here, note that ***almost all of the beam loss*** occurred ***during the beam injection, being localized*** in the ***beam collimator*** located at injection area.
- This result demonstrates that the beam power of ***130 kW*** is promising on the neutron production target, if operated at 25 Hz, and that ***more beam power is promising, if the beam is painted over the available RCS aperture***.

Importance of LINAC stability

- A role of the injector ***linac is very important*** to inject the high intensity proton beams to a ring. The stable, low emittance beams should be prepared. In particular, ***the stability of the beam energy*** is most important. For this reason we have also been concentrating our effort into building the high quality linac.
- In order to ***minimize the radio activation*** of the accelerator components, the above beam commissioning was done with one shot of the linac beam. The usual process of the beam study was as follows.
- ***One shot*** of the linac beam was injected and data as many as possible were taken by use of this one shot of the beam. After the data was analyzed, the new ring parameters were chosen and then ***next shot*** of the beam was injected.
- Sometimes, the latter shot was injected one hour after the former shot. Even that time, the linac beam was injected to the ***exactly same position*** with ***the exactly same momentum*** as those of the former, as far as the RCS monitors could detect.
- Therefore, we could accumulate the sensible beam data ***shot by shot*** with a minimum amount of the radio activation on the accelerator components. If the integration of the data was necessary for improving the signal-to-noise ratio, the number of shots was increased until the S/N ration was improved to the required level.
- In this case, the injection repetition was 1 Hz. ***One of the reasons for the early accomplishment of the 3GeV acceleration was the extremely stable beam from the linac.***

J-PARC

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The linac performance will be detailed at LINAC Conference to be held this September in Canada.

Conclusion

- Almost all the technical issues for the RCS have been solved to some extent.
- In contrast to the expectation, the RCS reached the pretty high power level within the first four-month period, after the injection, the 3-GeV acceleration and the extraction of the RCS beams successfully started.
- This implies that the RCS is quite easy to operate, once its technical difficulties were overcome.
- The successful start of the beam commissioning of the J-PARC RCS made the RCS option very promising to achieve the high proton beam power.