# Technological Challenges for High-Intensity Proton Rings

Yoshishige Yamazaki

52nd ICFA Advanced Beam Dynamics Workshop
on High-Intensity and High-Brightness Hadron Beams

Park Plaza Beijing West, September 17th to 21st, 2012

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# *Just three years ago, at SNS*

From: Henderson, Stuart D. [mailto:shenderson@ornl.gov]
Sent: Friday, September 18, 2009 11:48 PM
To: Alex Chao; Andrew Hutton (andrew@jlab.org); Cassel, Richard; Dieter Proch; futakawa.masatoshi@jaea.go.jp; Gerald Dugan; guenter@bauer-wt.de; Robert J. Macek; Rod Keller (roderich@lanl.gov); Roland Garoby; Steve Holmes; Yoshishige Yamazaki
Cc: Anderson, Ian S.; Haines, John R.; Myles, Dean A A; Galamb on this great accomplishment os, John D.; Dodson, George W.
Subject: SNS is running at 1 MW

Dear SNS Accelerator Advisory Committee Members,

Ifm happy to announce that today, Friday Sept 18th, the Spallation Neutron Source reached a beam power of 1 MW in routine neutron production operation. The SNS staff are very excited and proud of this accomplishment. I hope you share this sense of pride and accomplishment, as your advice over the last few years has been invaluable to us as we confronted the myriad challenges on the path to 1 MW.

The beam power history since the start of the present run cycle is shown in the attachment. The upper plot shows the beam power increasing, finally being pushed over 1 MW less than an hour ago.

Best Regards,
cStuart

¡ STUART HENDERSON I
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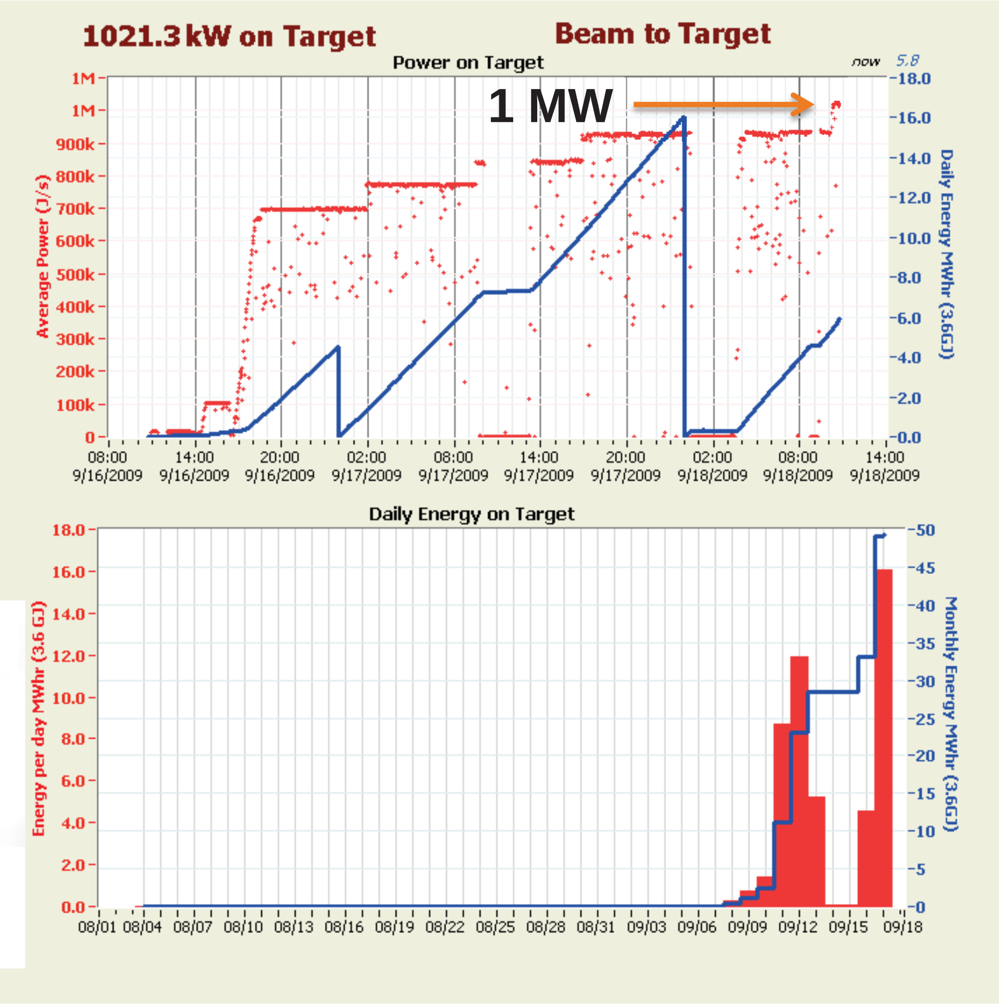
From: Yoshishige Yamazaki [mailto:yoshishige.yamazaki@j-parc.jp]
Sent: Saturday, September 19, 2009 4:21 AM
To: Henderson, Stuart D.; 'Alex Chao'; 'Andrew Hutton'; 'Cassel, Richard'; 'Dieter Proch'; futakawa.masatoshi@jaea.go.jp; 'Gerald Dugan'; guenter@bauer-wt.de; 'Robert J. Macek'; 'Rod Keller'; 'Roland Garoby'; 'Steve Holmes'
Cc: Anderson, Ian S.; Haines, John R.; Myles, Dean A A; Galambos, John D.; Dodson, George W.; 'Shoji Nagamiya'; '¬–Ñm'; hiroshi.yoshikawa@j-parc.jp; ''·'Ji'; '‹à³'
Subject: RE: SNS is running at 1 MW

Dear Stuart,

That's really a great accomplishment, which the world-wide, high-intensity proton accelerator community has been waiting for during last one decade and a half. After LAMPF, SIN, TRIUMF, MMF and ISIS started their operations, no high-intensity proton accelerator project has not started for so long time.

So, I would like to congratulate not only SNS staff, but also the community including ourselves on this great accomplishment. In particular, "one mega watt" sounds that our dream has been realized, and that the new era has started.

With best regards,
Yoshi



# Outline

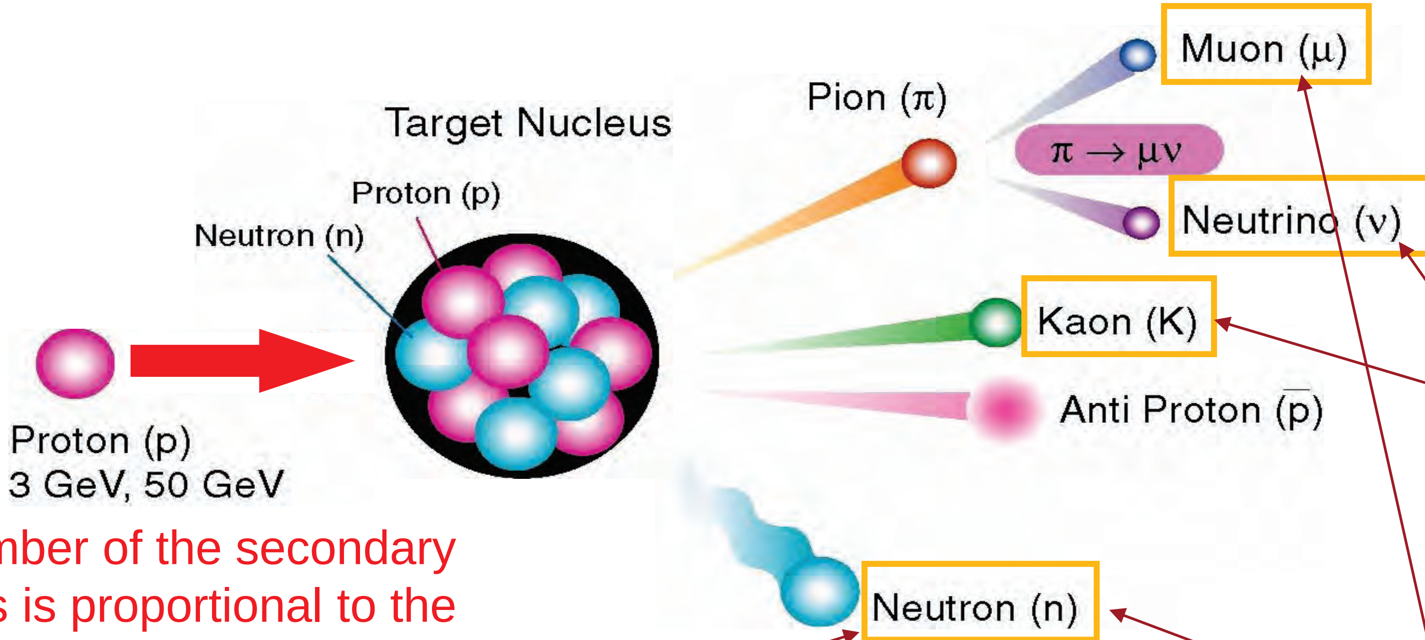
- *Introduction: Why high-intensity proton accelerators?*
- *CW Ring Accelerator*
- *Pulsed Ring Accelerator*
- *Space Charge Force and Beam Loss to Limit the Beam Power*
- *RCS versus AR*
- *Ring RF, Rapid Acceleration, High Field Gradient*
- *Summary and Future*

***Most of slides are by the courtesies of SNS, LANSCE, ISIS, J-PARC and FFAG community to be highly acknowledged***

# Introduction

## *Why high-intensity proton accelerators ?*

# The Multi-Purpose J-PARC

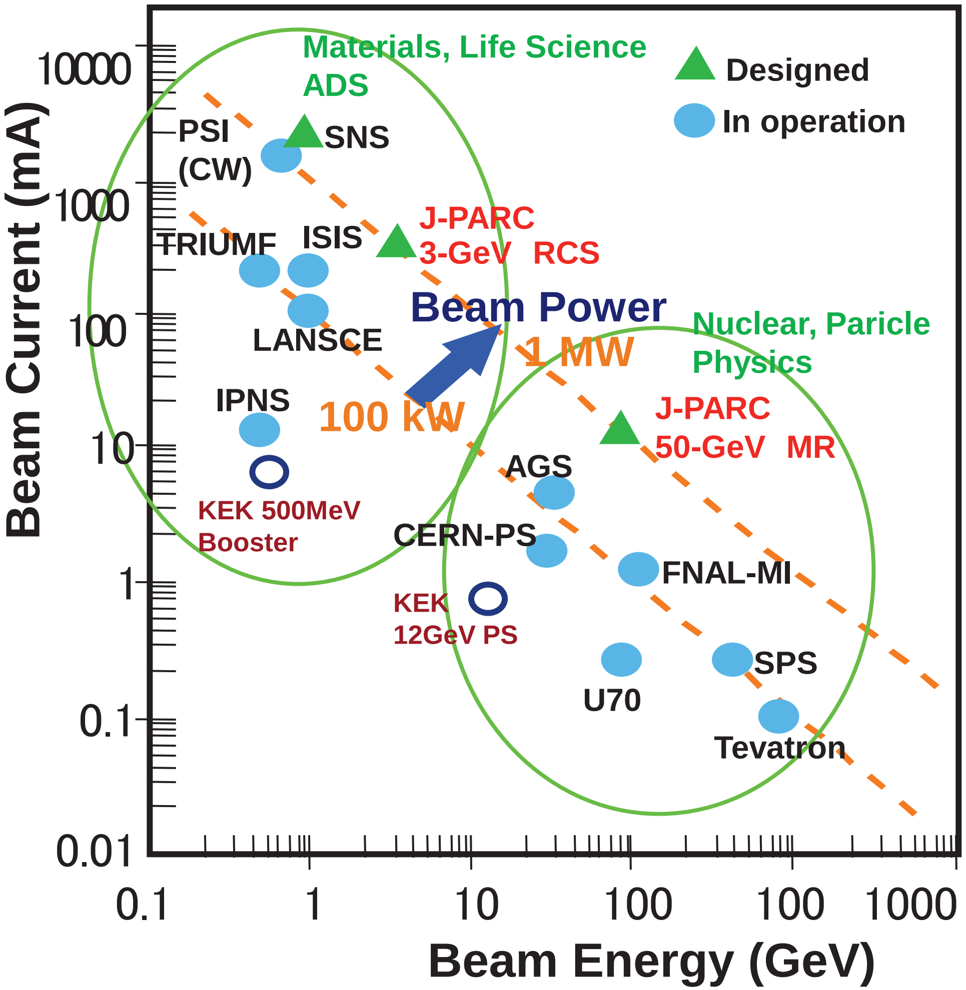



The number of the secondary particles is proportional to the proton beam power.
Need to have high-power proton beams

→ MW-class proton accelerator
(the frontier was about 0.1 MW before J-PARC and SNS)

Materials & Life Sciences at 3 GeV
Nuclear & Particle Physics at 50 GeV
R&D toward Transmutation at 0.6 GeV

# Beam Power Front



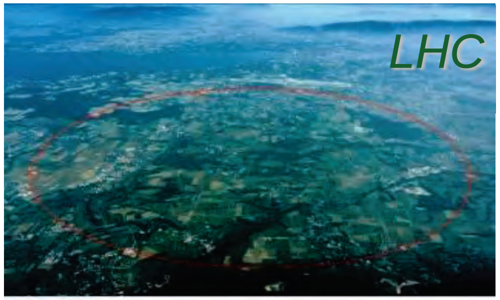

Beam Power (W)
= Beam Current (A) x Beam Energy (V)

The yield of the secondary particles per second is proportional to the beam power, if the beam energy exceeds the threshold. On the other hand, the radioactivity is also proportional to the beam loss power. Therefore, the beam loss rate should be minimized in this case.

The number of the secondary particles per pulse is crucial for some important experiments. The beams are accumulated in a ring, to be fast extracted.

Accelerate in the ring?
Yes (RCS): J-PARC, ISIS
No (AR): SNS, LANSCE

# High Energy Physics in the Next Decade
# From KEK Road Map by its Director General

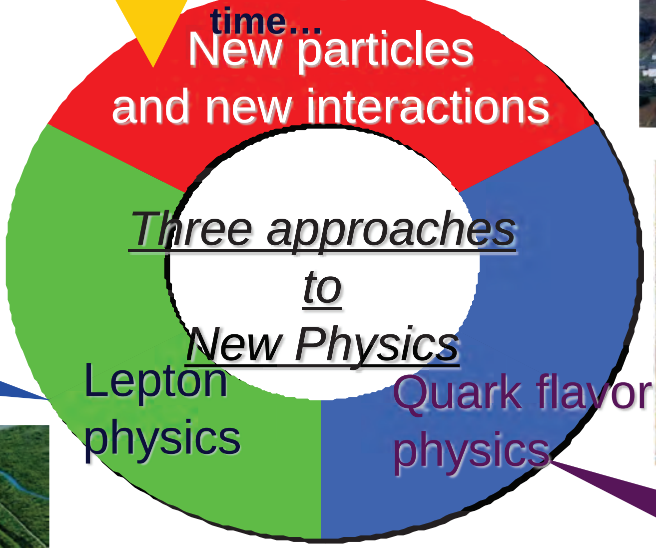




**Energy frontier experiments**
**LHC, ILC, …**

**Higgs, SUSY, Dark matter, New understanding of space-time…**





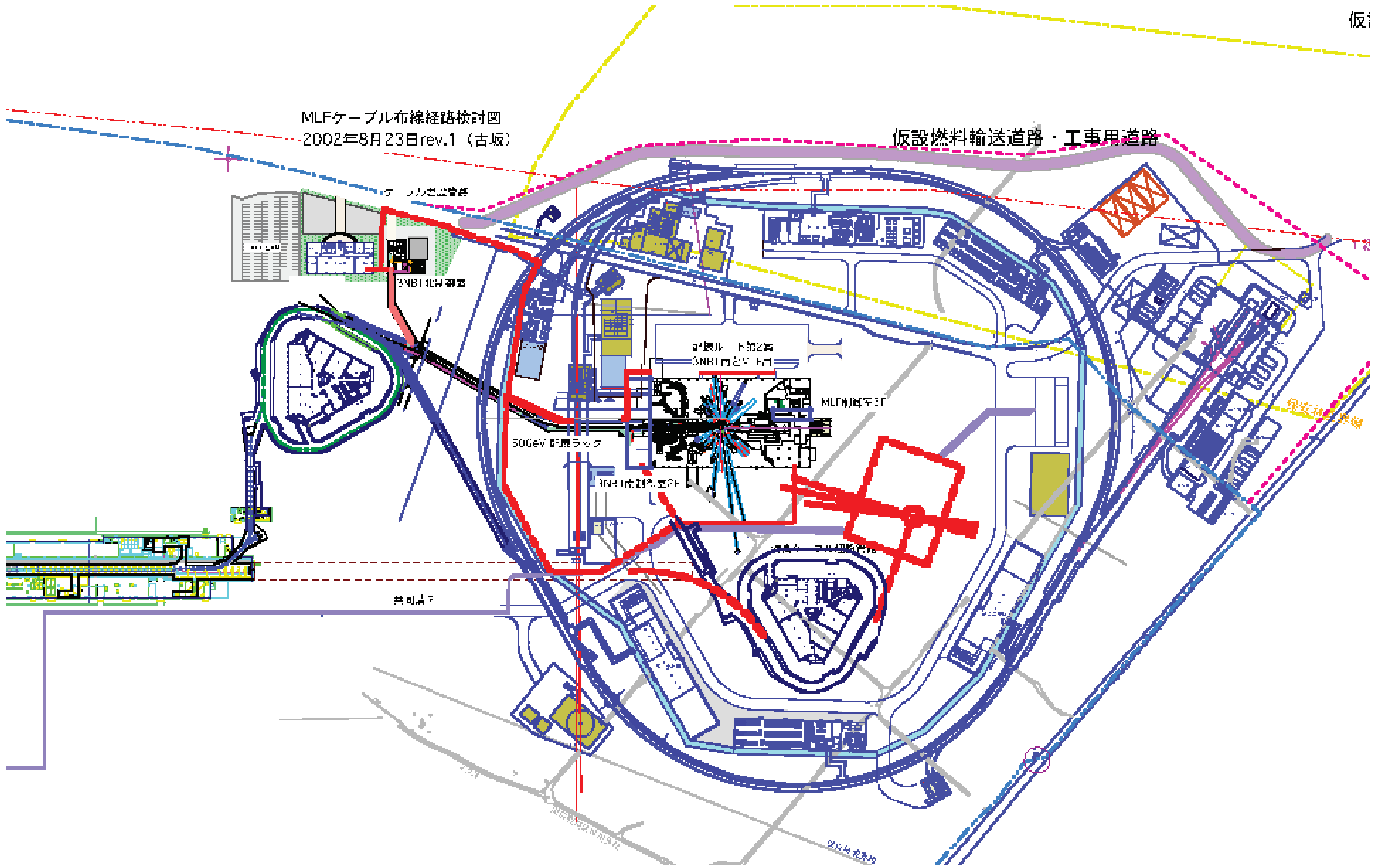

**$\nu$ exp., $\mu$ LFV, $\tau$ LFV, $g_\mu$-2, $0\nu\beta\beta$ …**

*B* Factories, LHCb, *K* exp., nEDM *etc.*


**Neutrino mixing/masses, Lepton number non-conservation…**

**CP asymmetry, Baryogenesis, Left-right symmetry, New sources of flavor mixing…**

## GeV Superconducting linac and 5~10-MW RCS with the second neutron target station



# CW
# Ring Accelerator

# “High-Intensity” Proton Rings

- ***“High intensity” implies both “high energy” and “high current”, but not “high power”, which may be very high current with a relatively low beam energy.***
- ***High intensity (or high power), that is, beam energy and beam current are not sufficient for specifying accelerator performance.***
- ***Time structure and emittances (brightness if the current divided) are other important factors.***
- ***Availability, stability, reproducibility and cost belong to another category of the machine “performance”, but of course important, in particular, the former three being vital for maximizing the scientific outputs***

# *High-Intensity Proton Rings*

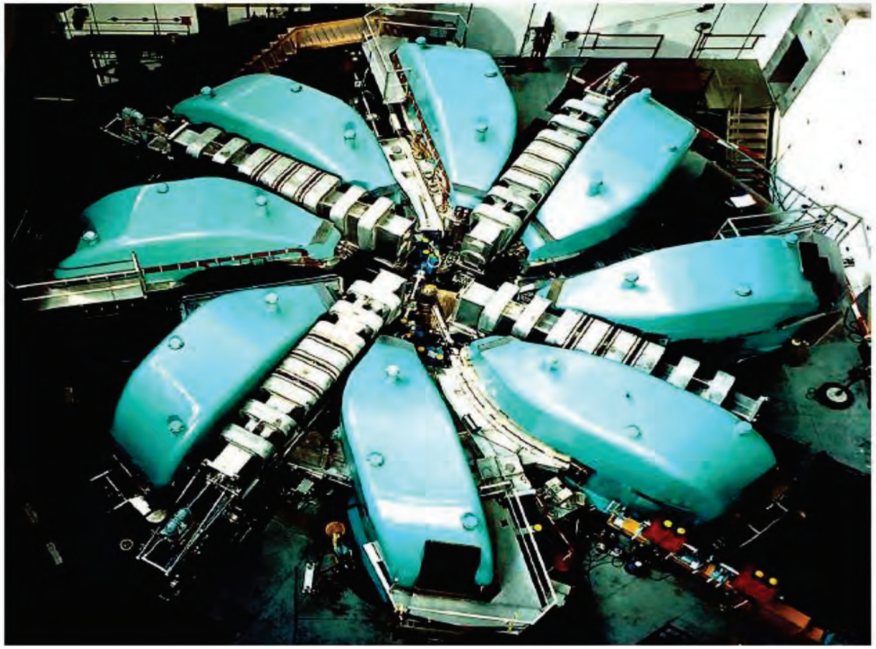
- ***For the time being, just leave aside the time structure and emittances***
- ***Then, in order to obtain the high intensity beams***

1. ***Inject and store protons as many as possible in a ring***
2. ***Accelerate them to an energy as high as possible and extract.***
3. ***Repeat these as frequent as possible (CW or DC is most preferable)***

- ***Here, the uncontrolled beam loss should be reduced to typically 1 W/m for keeping the feasibility of hand maintenance.***

# Champion Cyclotron 1 or 2 MW is a limit?

## PSI Ring Cyclotron



**Ringcyclotron**

590 MeV Protons

1.3 MW Beam Power (world record!)

8 Magnet à 250 Tons

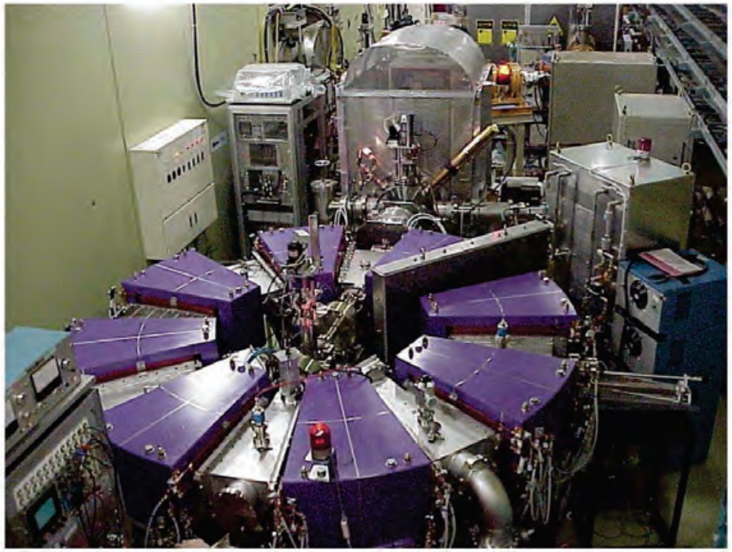
4 Cavities à 700 kV (upgraded to 1MV in 2008)

Extraction ≈ 99.97 %

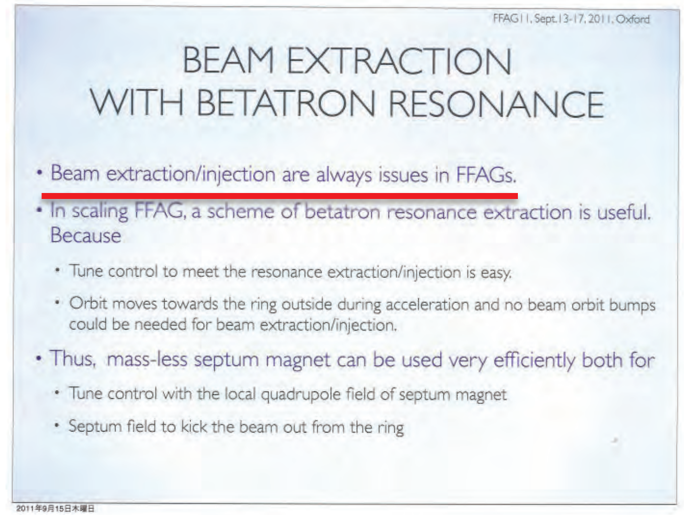
**Cyclotron: DC magnets and CW beam, ideal for achieving the high-intensity, if the pulsed beam is not requested.**

**The beam power is, however, limited by the radioactivity arising from the beam loss at the beam extraction. The separation of the beam to be extracted from the circulating is the main issue for the further power upgrade.**

# Fixed Field Alternating Gradient (FFAG) Synchrotron



KEK Proof-of-Principle 1-MeV proton FFAG




Yoshi Mori's slide in FFAG11

- **FFAG's are similar to Cyclotrons only in a sense that their magnets are DC powered, but making use of strong-focusing in contrast to the weak focusing of cyclotrons.**
- **Complicated FFAG magnets need 3-D design and the rapid acceleration needs high field gradient acceleration. Thus, FFAG was rediscovered only after these have been developed.**
- **Since the FFAG is inherently difficult to inject and to extract, the FFAG workshops should be much more devoted to these. Otherwise, FFAG application would be quite limited like a use of internal beams for RI production.**

# Pulsed Ring Accelerator

# High-Intensity Proton Rings

- *A linac is easy, since beams go straight and only deviations from this should be corrected.*
- *A ring is easy, since particles can stably circulate for the periodicity.*
- *Difficult is to inject beams into a ring and to extract particles from it.*
- *Then, for ring designs, effort should be devoted to the injection and extraction as well as acceleration*
- *For the former, high power pulsing devices with fast rising and falling and uniform flat top*
- *For the latter, high field gradient*
- *And, highly reliable, highly stable, difficult to achieve for high-power RF and pulsing devices*

# LANSCE PSR(AR)

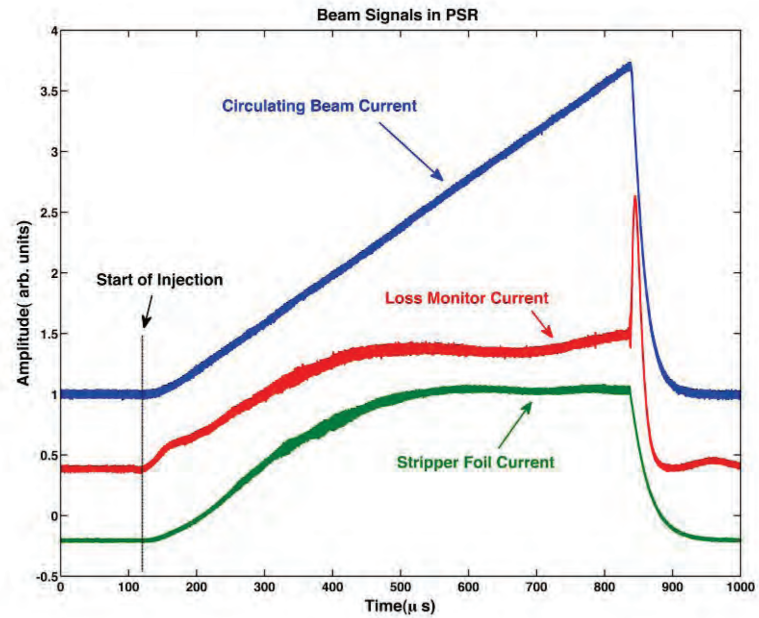
target

PSR

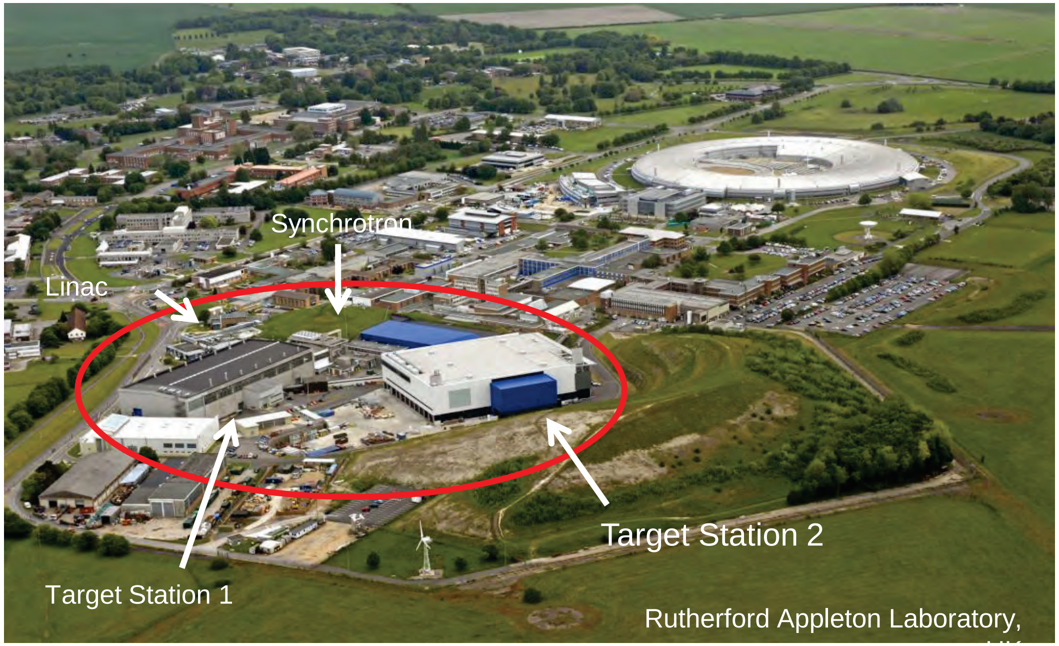
Side-coupled-cavity accelerator and equipment building (100-800 MeV)

Injector (0-0.75 MeV)

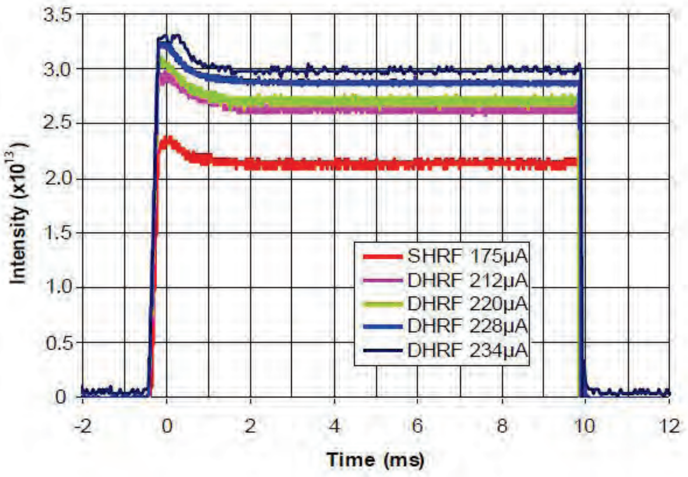
Drift tube accelerator and equipment building (0.75-100 MeV)



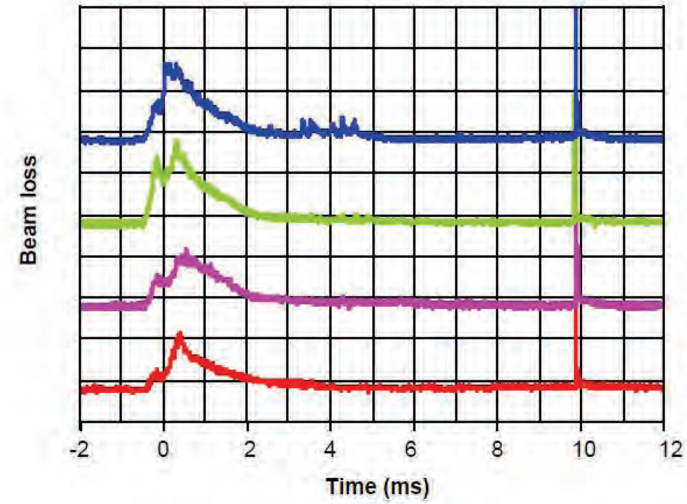
# ISIS RCS, RAL



Synchrotron
Linac
Target Station 2
Target Station 1
Rutherford Appleton Laboratory,

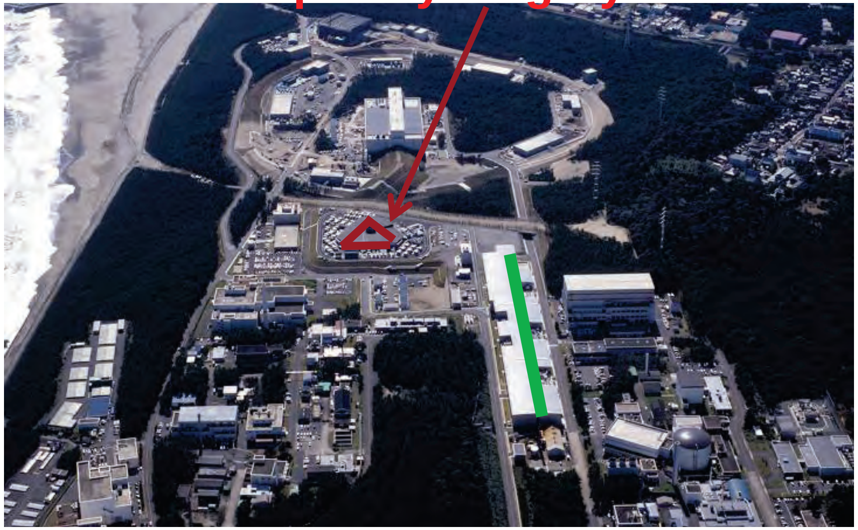
Intensity (x10^13)
Time (ms)
SHRF 175μA
DHRF 212μA
DHRF 220μA
DHRF 228μA
DHRF 234μA

Beam loss
Time (ms)

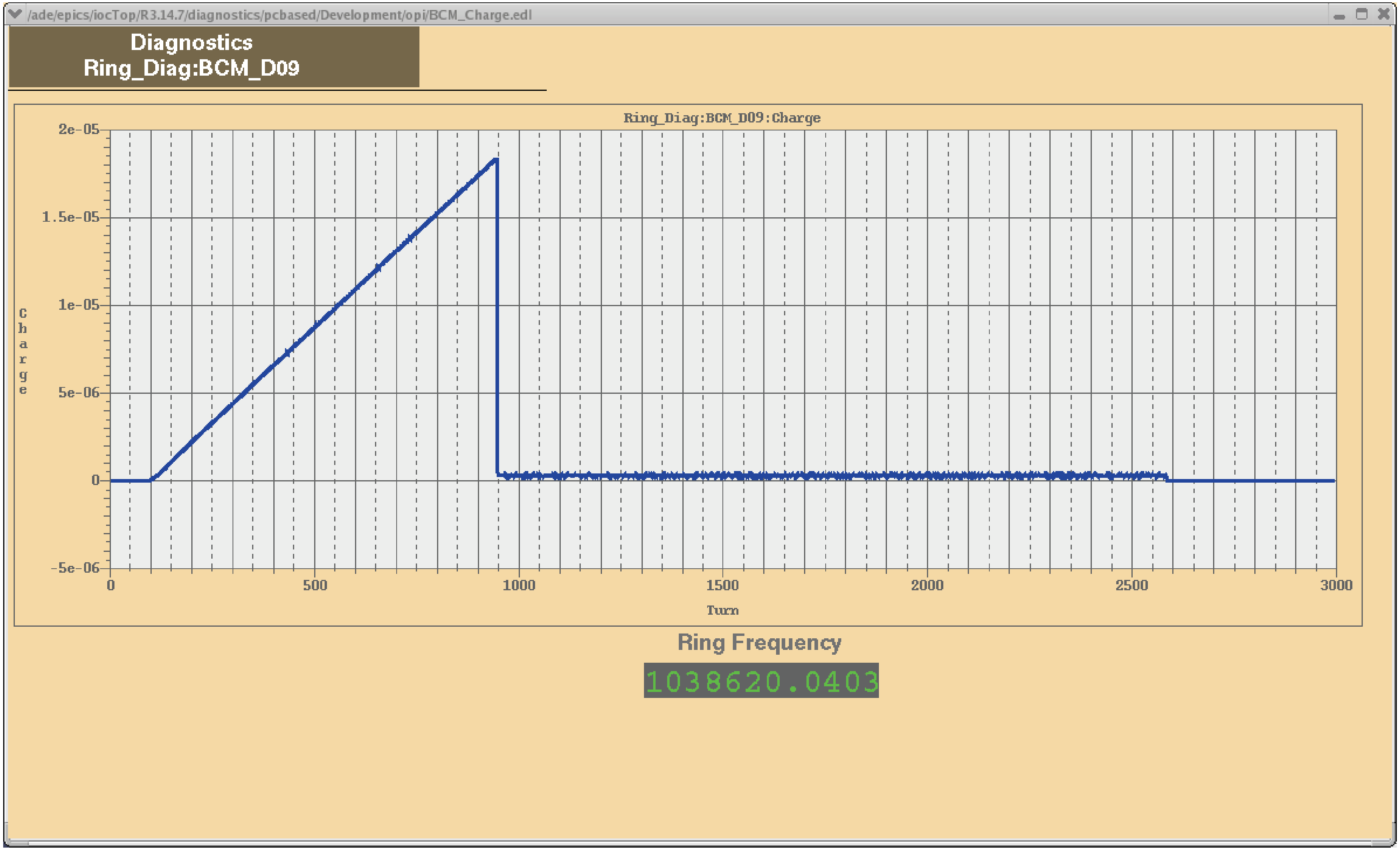
# *J-PARC RCS vs SNS AR*

**J-PARC (RCS)**
**Japan Proton Accelerator Research Complex**
**Rapid-Cycling Synchrotron**



**SNS(AR)**
**Spallation Neutron Source**
**Accumulator Ring**

# SNS AR

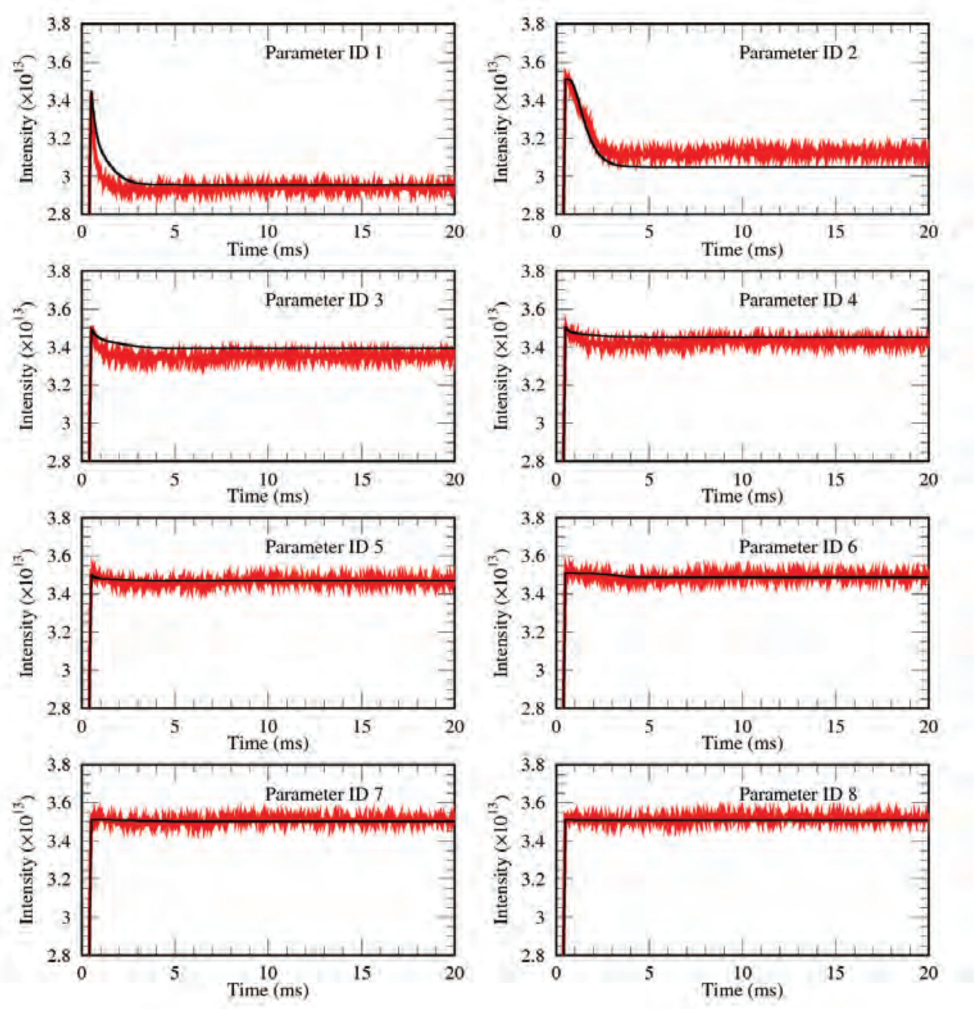

/ade/epics/iocTop/R3.14.7/diagnostics/pcbased/Development/opi/BCM_Charge.edl
Diagnostics
Ring_Diag:BCM_D09
Ring_Diag:BCM_D09:Charge
2e-05
1.5e-05
1e-05
5e-06
0
-5e-06
Charge
0
500
1000
1500
2000
2500
3000
Turn
Ring Frequency
1038620.0403

# J-PARC RCS

**$3.5 \times 10^{13}$ /pulse**

**425 kW at 25 Hz**

**Equivalent to**
**1.24 MW**
**at 400-MeV injection**



## *Space Charge Effect*
## *and*
## *Beam Loss*
## *to Limit the Beam Power*

# Lasslette Tune Shift and Space Charge Force

## *Lasslette Tune Shift:*

$$\Delta\nu_y = -\frac{N r_p}{\pi \varepsilon_y \left(1+\sqrt{\frac{\varepsilon_x}{\varepsilon_y}}\right)\beta^2\gamma^3} \frac{F}{B_f}$$

***N: the number of charges,*** $\varepsilon_y$***; vertical emittance,***
$\varepsilon_x$***: horizontal emittance,*** $r_p$***: classical radius***
***F: form factor,*** $B_f$***: bunching factor（1 for coasting beam）***

***Lasslette tune shift can be a measure of space charge effect or can be used for scaling ( - 0.15 is OK for the period of an order of 1 ms)***
***Energy dependence of*** $\beta^2\gamma^3$ ***is universal, being model-independent***

***As the particles accelerate, the magnetic force cancels the Coulomb force, while their masses increase, reducing the defocusing effect.***

# Designed Lasslette Tune Shifts

| | J-PARC RCS | SNS AR | ISIS RCS | LANSCE AR |
|---|---|---|---|---|
| Beam pulse length, μs | < 1 | < 1 | < 1 | 0.29 |
| Ring Circumference, m | 348 | 248 | 163 | 90 |
| Repetition, Hz | 25 | 60 | 50 | 20 |
| Beam stored energy per pulse, kJ | 40 | 24 | 4 | 4.5 |
| Number of protons per pulse, $10^{13}$ | 8.3 | 15 | 2.8 | 3.4 |
| Beam energy, GeV | 3 | 1 | 0.8 | 0.8 |
| Beam power, MW | 1 | 1.4 | 0.2 | 0.09 |
| Beam current, mA | 0.333 | 1.4 | 0.225 | 0.11 |
| Injection energy, GeV | 0.4 | 1 | 0.07 | 0.8 |
| $\beta^2\gamma^3$ | 1.475 | 6.750 | 0.166 | 4.497 |
| Beam emittance at painting, π mm mrad | 216 | 91 | 300 | 7 / 12 |
| Lasslette tune shift (Measure of space charge) | - 0.16 | - 0.15 | - 0.4 | - 0.22 / -0.18 |
| Linac peak current, mA | 50 | 38 | 25 | 10 |
| Linac beam pulse length, ms | 0.5 | 1 | 0.2 | 0.63 |
| Beam-on rate after chopping, % | 56 | 68 | 100 (no chopping) | 81 |

By the courtesy of J-PARC, SNS, ISIS, and LANSCE

# Accomplished vs. Designed (SNS Case)

| | SNS AR Design | SNS AR Accomplished (Operational/Best) |
|---|---|---|
| Repetition, Hz | 60 | 60 |
| Beam stored energy per pulse, kJ | 24 | 17/19 |
| Number of protons per pulse, $10^{13}$ | 21 | 11 / 15.5 |
| Beam energy, GeV | 1.0 | 0.925 / 1.0 |
| Beam power, MW | 1.4 | 1 / 1.08 |
| Beam current, mA | 1.4 | 1.1 / 1.1 |
| Injection energy, GeV | 1.0 | 0.925 / 1.0 |
| $\beta^2\gamma^3$ | 6.75 | 6.08 / 6.75 |
| Linac peak current, mA | 38 | 38 /42 |
| Linac beam pulse length, ms | 1 | 0.8 / 1.0 |
| Beam-on rate after chopping, % | 68 | 68 / 68 |

By the courtesy of SNS

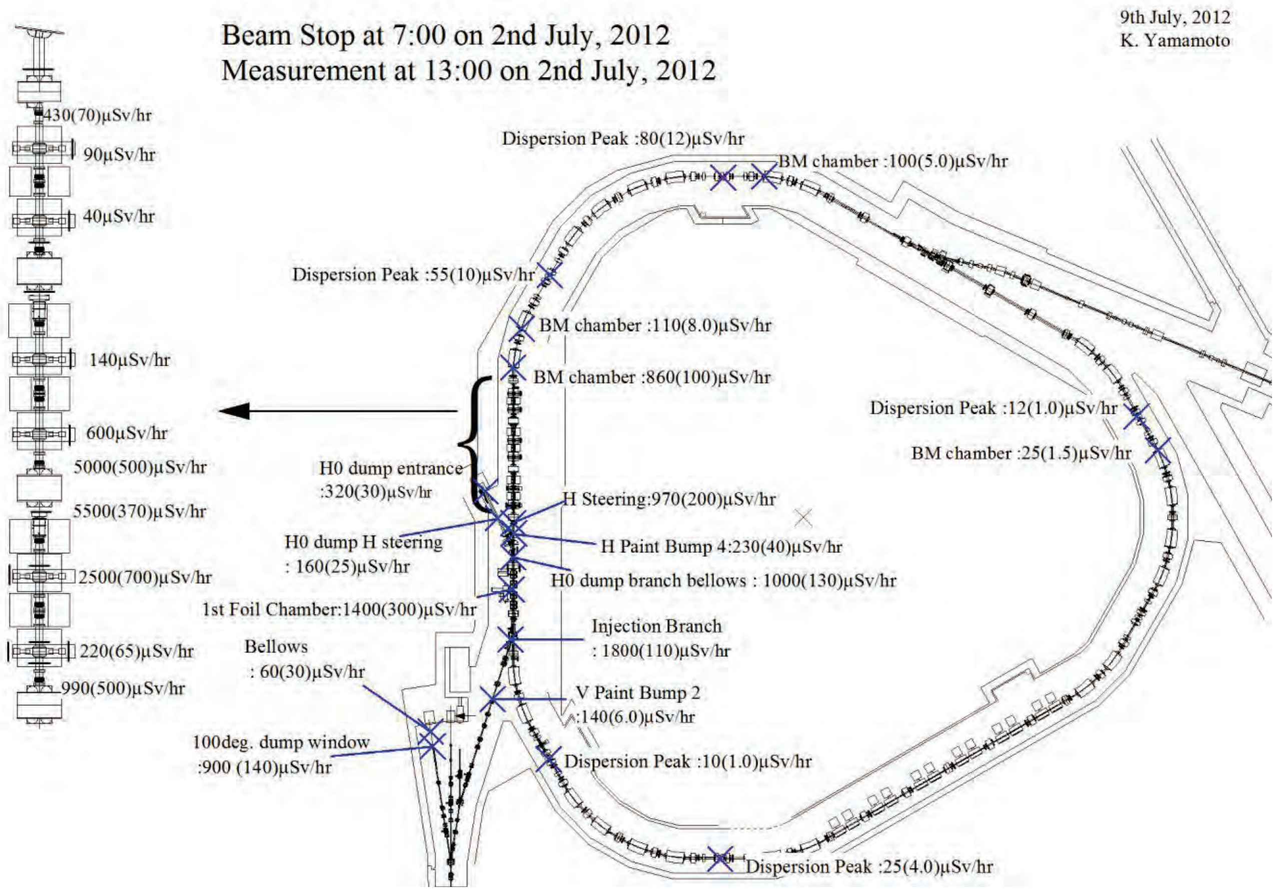
# Accomplished vs. Designed (J-PARC Case)

| | J-PARC RCS Design | J-PARC RCS Accomplished (Operational/1 hour/1 pulse) |
|---|---|---|
| Repetition, Hz | 25 | 25 |
| Beam stored energy per pulse, kJ | 40 | 11 / 12 / 17 |
| Number of protons per pulse, $10^{13}$ | 8.3 | 2.3 / 2.6 / 3.5 |
| Beam energy, GeV | 3 | 3 |
| Beam power, MW | 1 | 0.28 / 0.31 /(0.42)[a] |
| Beam current, mA | 0.333 | 0.093 / 0.103 / (0.142)[a] |
| Injection energy, GeV | 0.4 | 0.18 |
| $\beta^2\gamma^3$ | 1.475 | 0.505 |
| Linac peak current, mA | 50 | 15 / 15 / 20 |
| Linac beam pulse length, ms | 0.5 | 0.5 |
| Beam-on rate after chopping, % | 56 | 56 |

a: 25 Hz assumed

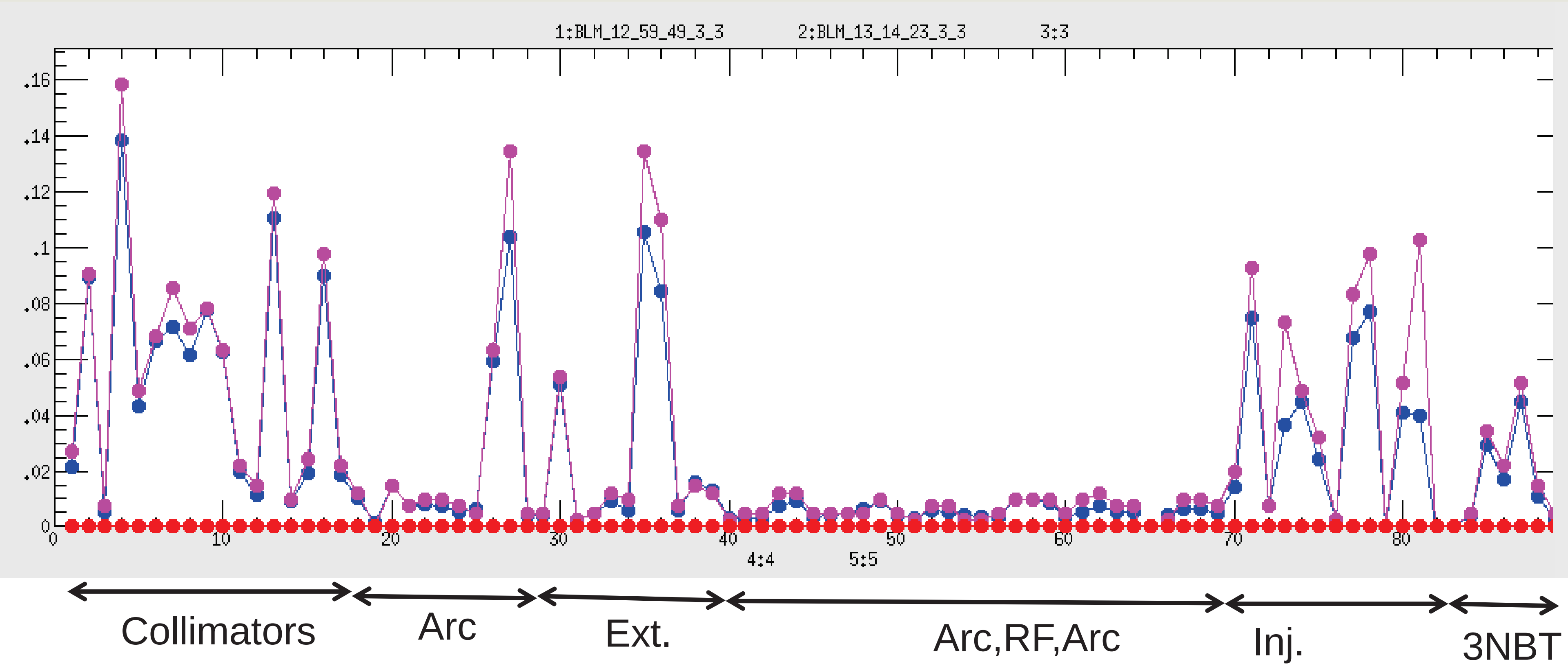
By the courtesy of Hideaki Hotchi, J-PARC

# Residual radiation dose of J-PARC RCS




**The residual radioactivity is acceptable level.**
**The RCS is ready for the beam delivery of 300 kW to the MLF from the autumn of 2012.**

# *BLM signal comparison between 215kW and 275kW*




***The beam loss signal is almost proportional to the beam current, showing no non-linear increase yet***

***The clean long straight section for RF, being isolated from those for injection , collimation and extraction***

**By the courtesy of J-PARC**

## RCS versus AR

# RCS versus AR

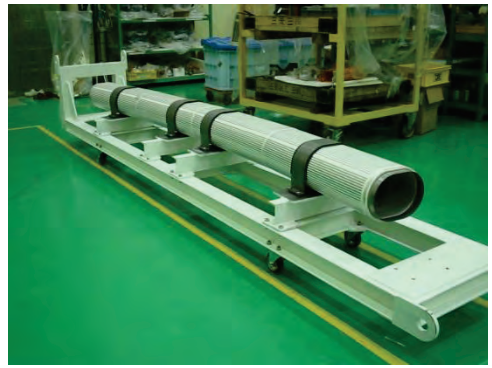
- RCS scheme has an advantage over the AR scheme, regarding the lower beam current for the same or more beam power. (the highest injection energy is practically limited to around 1.3 GeV for the reason of Lorentz stripping in the short injection section)
- The low energy injection to the RCS implies another advantage regarding the power of the beam loss.
- The point at issue is entirely regarding the engineering technique, that is, whether it is possible or how difficult it is or how costly it is to accelerate the beam current of 0.333 mA to 3 GeV for example.
- In general, it is however not a right decision to make use of technically difficult option. Non-expert does.
- J-PARC was forced to use the RCS scheme, since it should be used as an injector to higher-energy MR.

# J-PARC RCS versus SNS AR

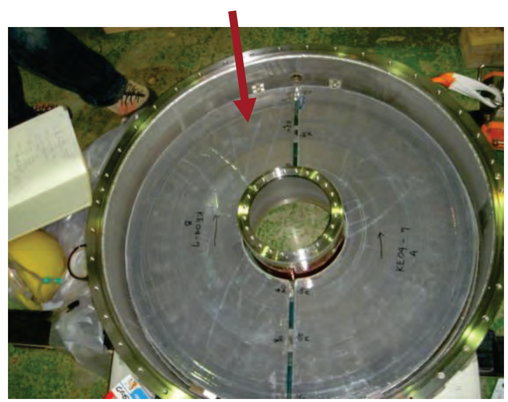
| | J-PARC RCS | SNS-like AR | SNS AR |
|---|---|---|---|
| Beam pulse length, μs | < 1 | < 1 | < 1 |
| Ring Circumference, m | 348 | 248 | 248 |
| Repetition, Hz | 25 | 25 | 60 |
| Beam stored energy per pulse, kJ | 40 | 40 | 24 |
| Number of protons per pulse, $10^{13}$ | 8.3 | 25 | 15 |
| Beam energy, GeV | 3 | 1 | 1 |
| Beam power, MW | 1 | 1 | 1.4 |
| Beam current, mA | 0.333 | 1 | 1.4 |
| Injection energy, GeV | 0.4 | 1 | 1 |
| $\beta^2\gamma^3$ | 1.475 | 6.750 | 6.750 |
| Beam emittance at painting, π mm mrad | 216 | 142 | 91 |
| Lasslette tune shift (Measure of space charge) | - 0.16 | -0.16 | - 0.15 |
| Linac peak current, mA | 50 | 150（75） | 38 |
| Linac beam pulse length, ms | 0.5 | 0.5 (1) | 1 |
| Beam-on rate after chopping, % | 56 | 56 | 68 |

# *Rapid-Cycling Synchrotron (the world-rapidest)*

- **Wide Aperture Magnets for storing a number of protons against the space charge force**
- **Stranded Coil, Ceramics Vacuum Chamber against the eddy current effect**



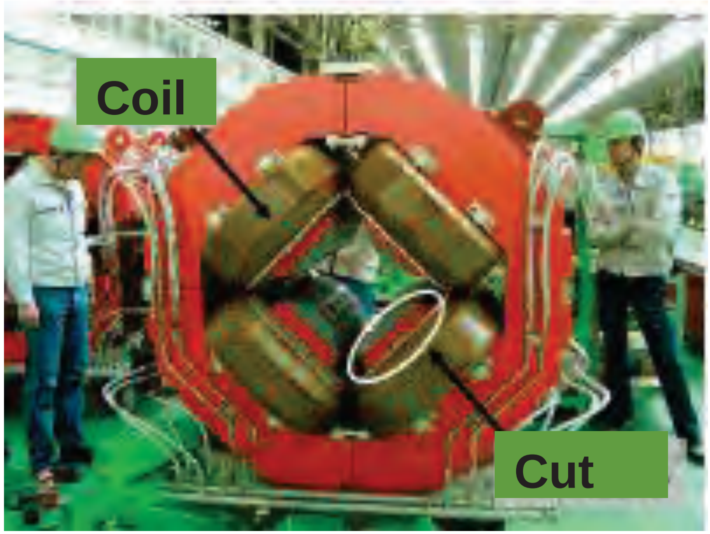
- **Magnetic Alloy（FINEMET）-Loaded Cavity**

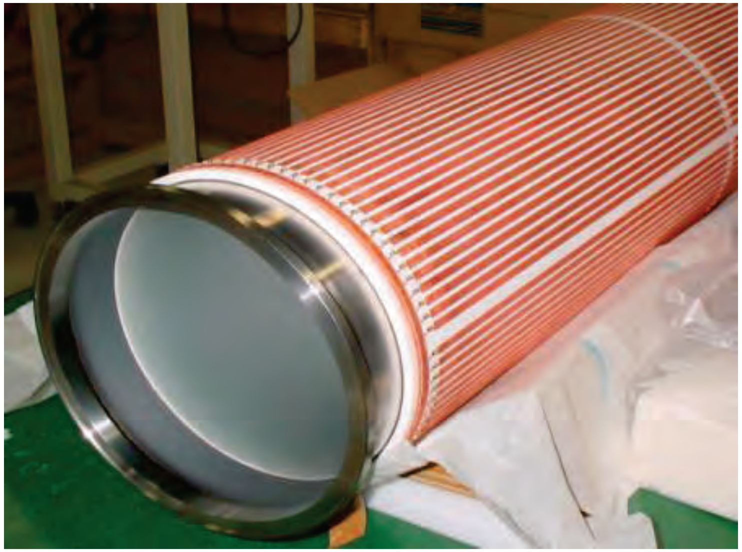


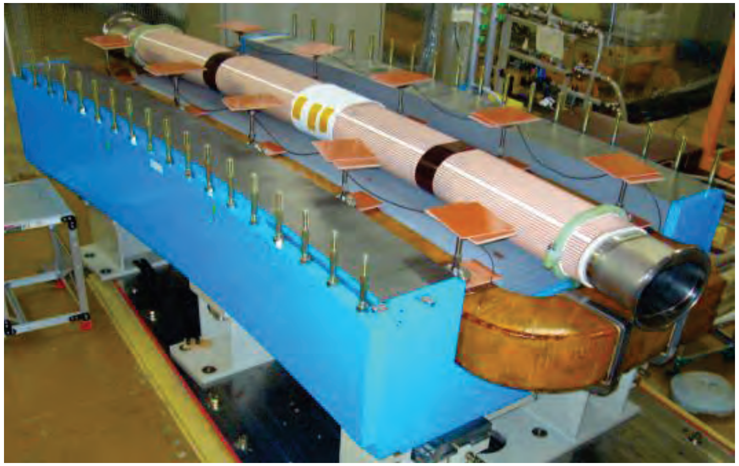
**The Highest Field Gradient Cavity For the Rapidest Acceleration (25 kV/m in contrast to around 10 kV/m of conventional ferrite-loaded cavities)**

# *Large Aperture Magnet and Ceramics Vacuum Chambers*

**Large Aperture Quadrupole Magnet and Cylindrical Ceramics Vacuum Chamber**

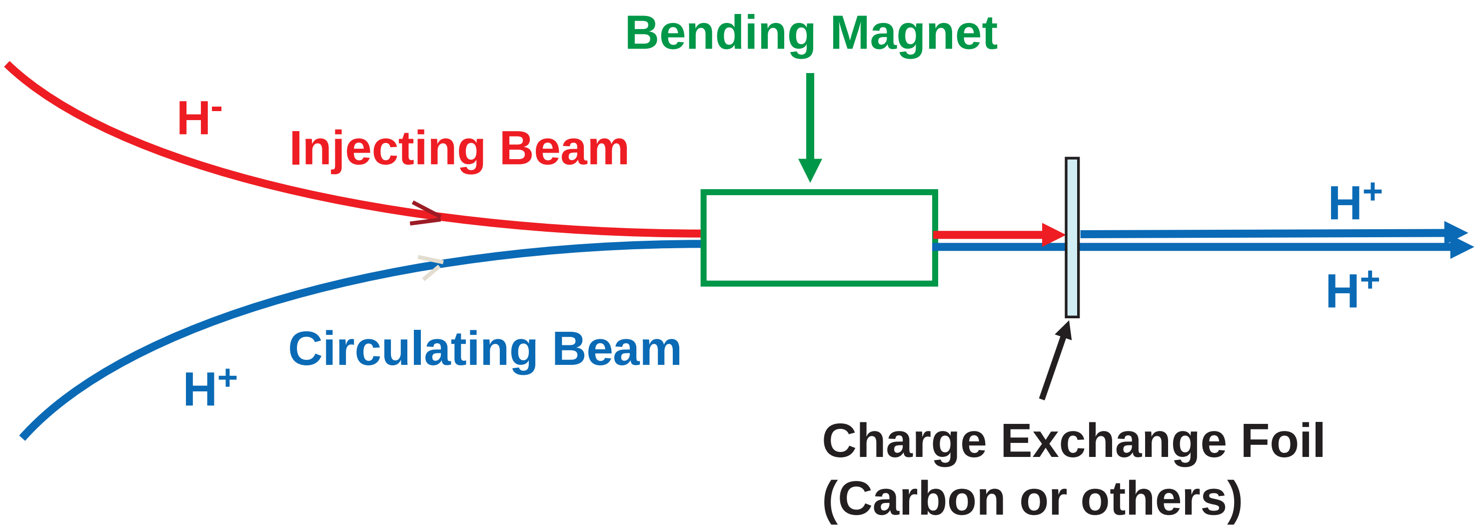




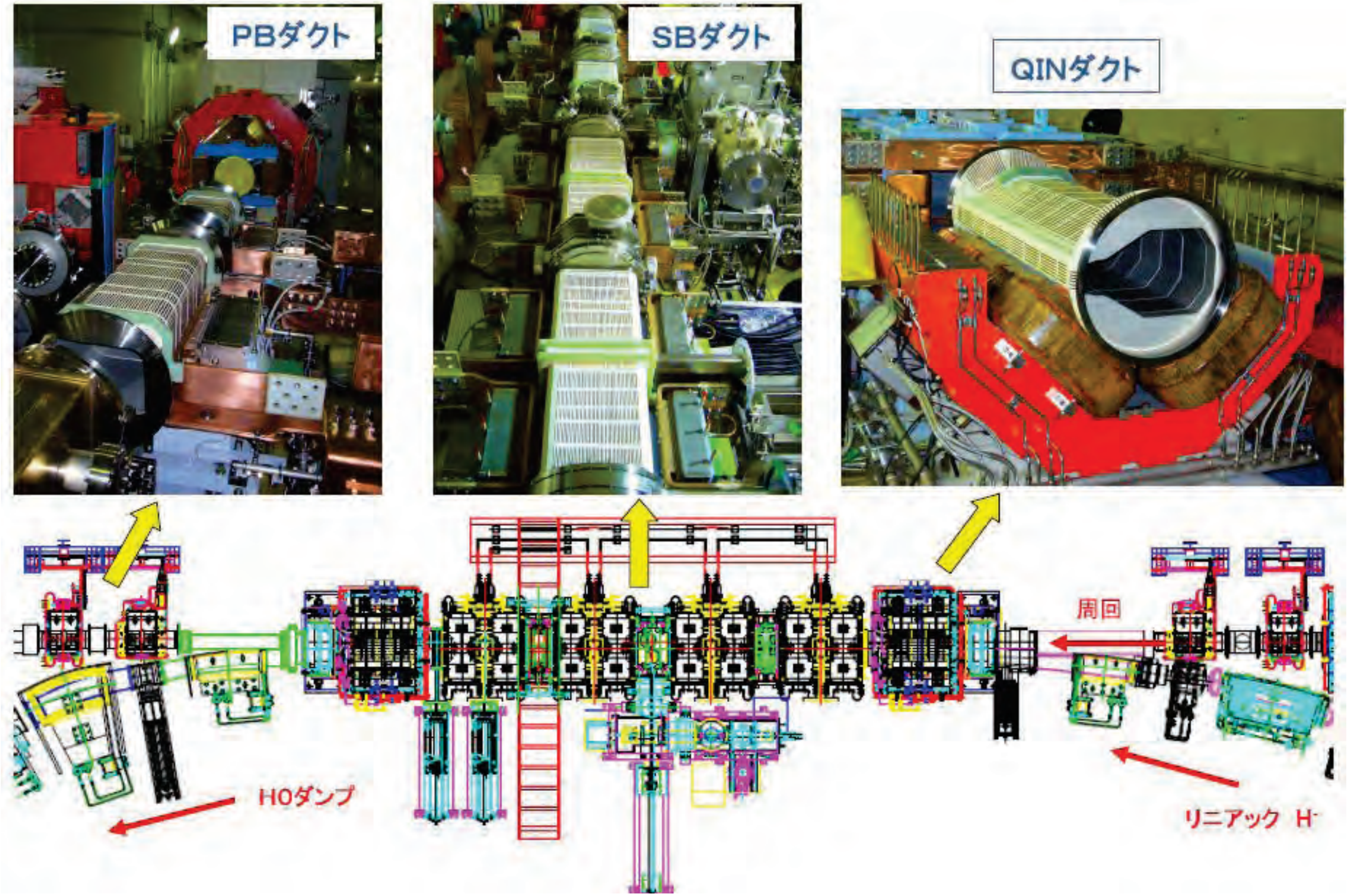
**In order to keep the large aperture with the reasonable cost for the bending magnets, we chose the cross section of the race-track shape for the BM vacuum chambers.**

# *Multi-turn $H^-$ Injection via charge exchange*




**If the foil scattering (see Hotchi's poster, J-PARC) need not to be taken into account, the beam injection can continue until the beam instability problem begins.**
**In the case of the proton injection, one can inject the proton beam only at the place where the circulating beam is absent.**

# Injection Section and Ceramics Vacuum Chambers



# Synchrotron Oscillation and Transition

**$\alpha$: momentum compaction factor, *C*: Circumference**

$$\frac{\Delta C}{C} \equiv \alpha \frac{\Delta p}{p}$$

**If the beam energy becomes higher, the beam orbit is usually pushed outside, increasing the circumference.**

***T*: revolution time, *v*: velocity**

$$C = vT$$

**Then,**

$$\frac{\Delta T}{T} = \frac{\Delta C}{C} - \frac{\Delta v}{v} = \left( \alpha - \frac{1}{\gamma^2} \right) \frac{\Delta p}{p}$$

**Define the transition gamma $\gamma_T$ by**

$$\alpha \equiv \frac{1}{\gamma_T^2}$$

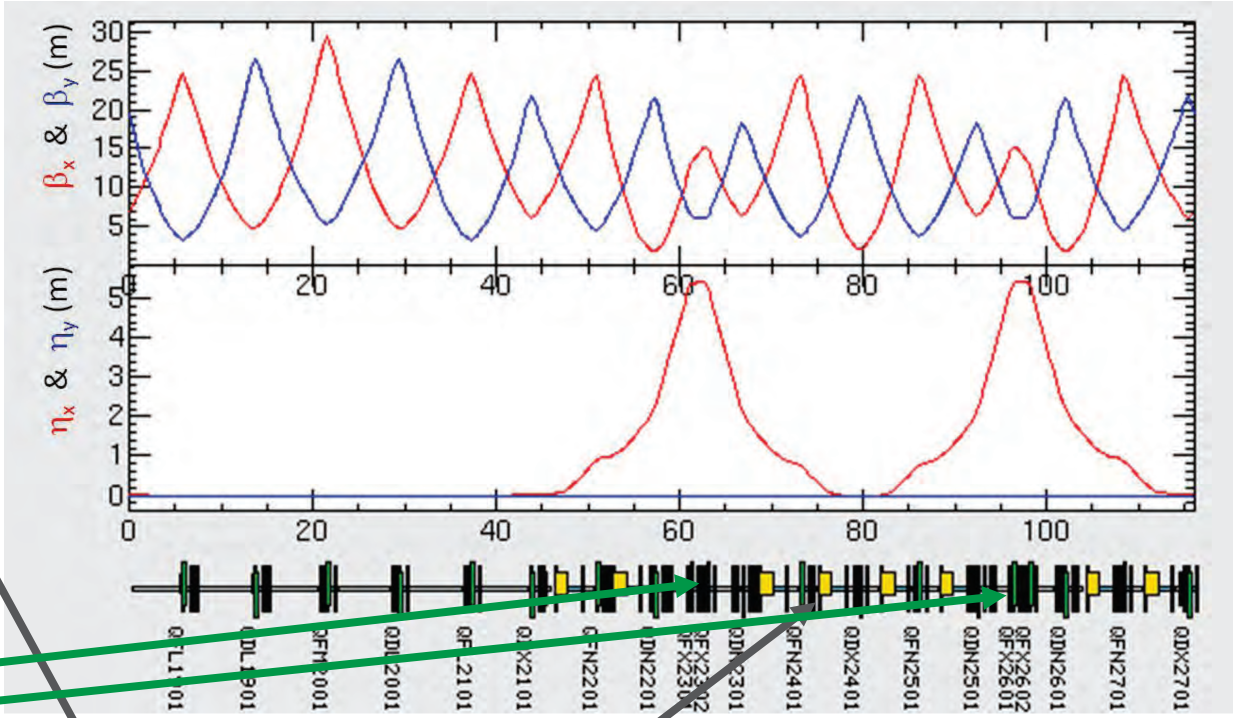
**If $\alpha$ is small, $\gamma_T$ is high.**
**If $\alpha$ is negative, $\gamma_T$ becomes imaginary.**

**At the beam energy $\gamma = \gamma_T$, the restoring force disppeared.**

$$\frac{\Delta T}{T} = \left( \frac{1}{\gamma_T^2} - \frac{1}{\gamma^2} \right) \frac{\Delta p}{p}$$

**This is the transition.**
**At the transition, the beam becomes unstable.**
**For the conventional FODO lattice, the beam passes the transition during the course of acceleration.**

# *High Gamma-T Lattice of J-PARC RCS*




Missing Bend

Straight Section

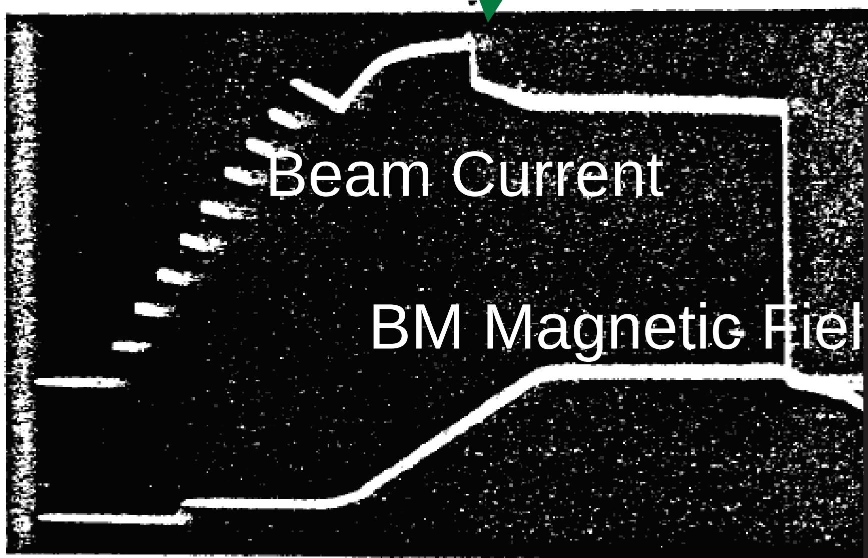
Arc Section

Bending Magnet

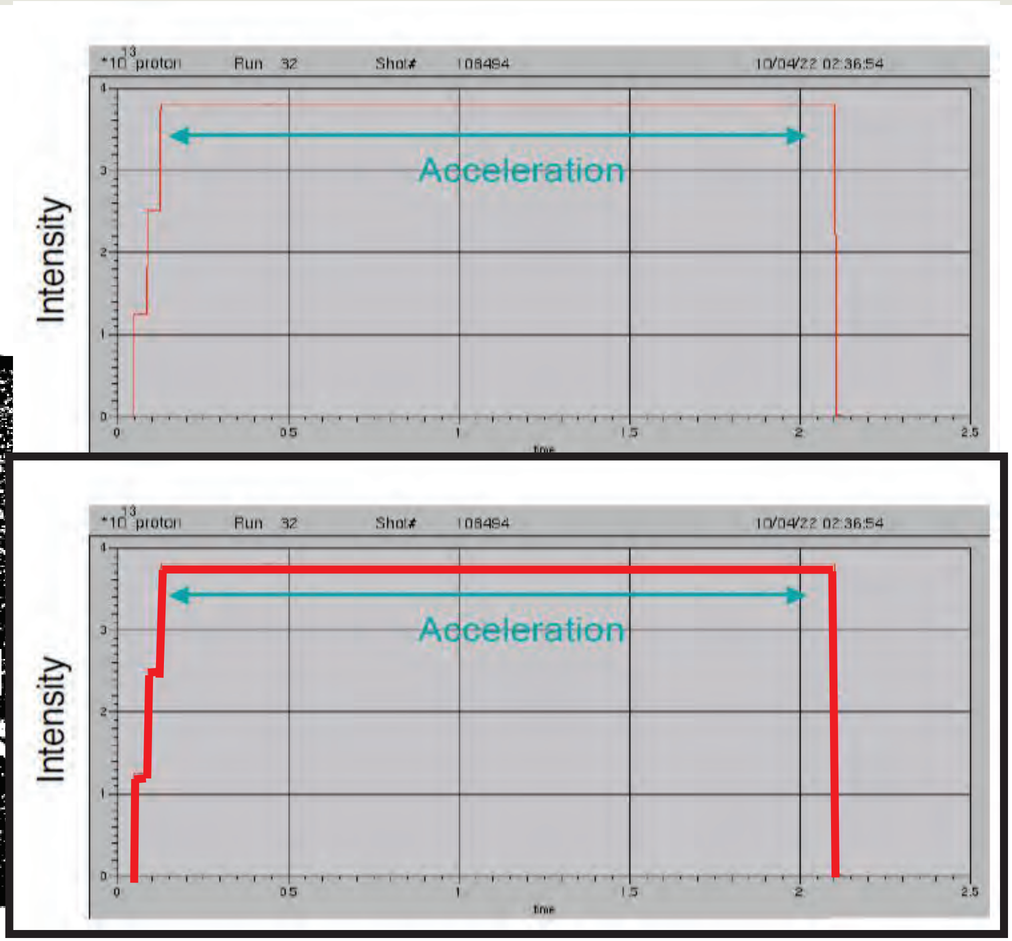
**By this missing-bend lattice, the momentum dependence of the orbit is changed so as to increase the transition energy.**
**But, longer arc section, that is, a bigger ring.**

# *No beam loss observed during the J-PARC MR acceleration*

**Transition Energy**




**KEK-PS-MR @ 1977**



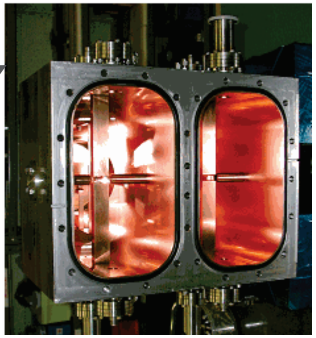

J-PARC-MR @ 2010
(50-kW operation)

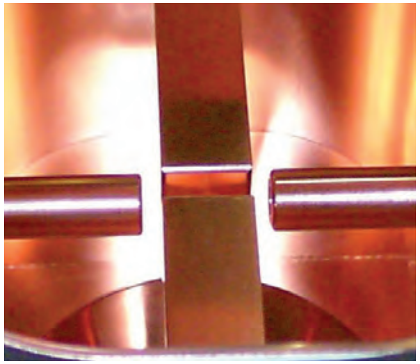
# Beam Loss Elimination

The linac beam which cannot be accepted by the ring RF is eliminated at the linac MEBT.

The RF chopper was devised by T. Kato, and was developed together with Shininan Fu, who was working for JHF at that time.
No beam observed during the chopped period (world-best performance) in contrast to the "Meandor"-type chopper being used everywhere.

**RF Beam Chopper installed at the linac MEBT**





**MR lattice**

Separated-function scheme of bending magnets and focusing magnets were invented by T. Kitagaki (published in Phs. Rev. 89 (1953) 1161) for strong focusing lattice, and were used in KEK-PS MR.

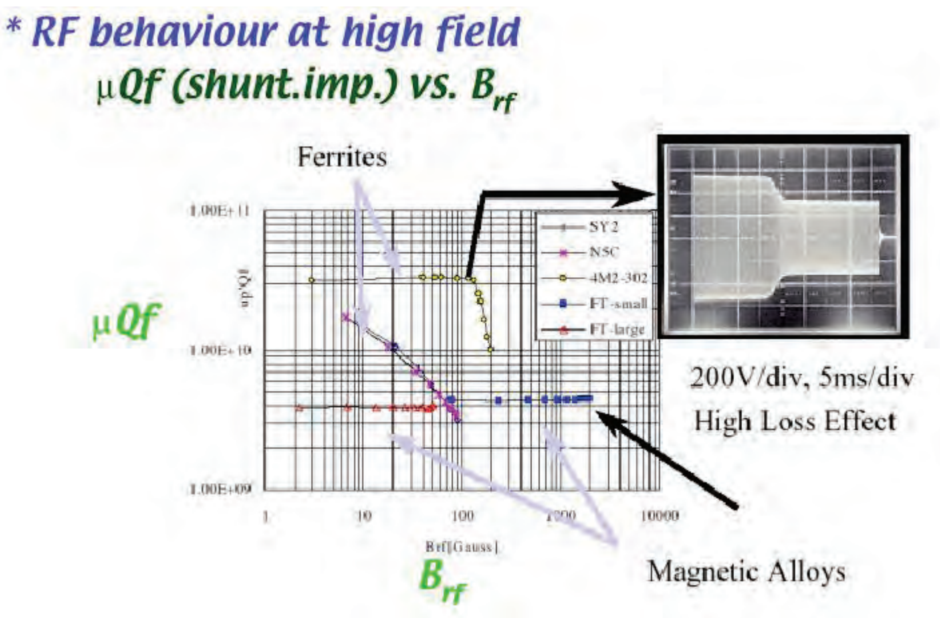
In J-PARC MR, the transition gamma is imaginary for eliminating the beam loss inherent at the transition.

# RCS versus AR

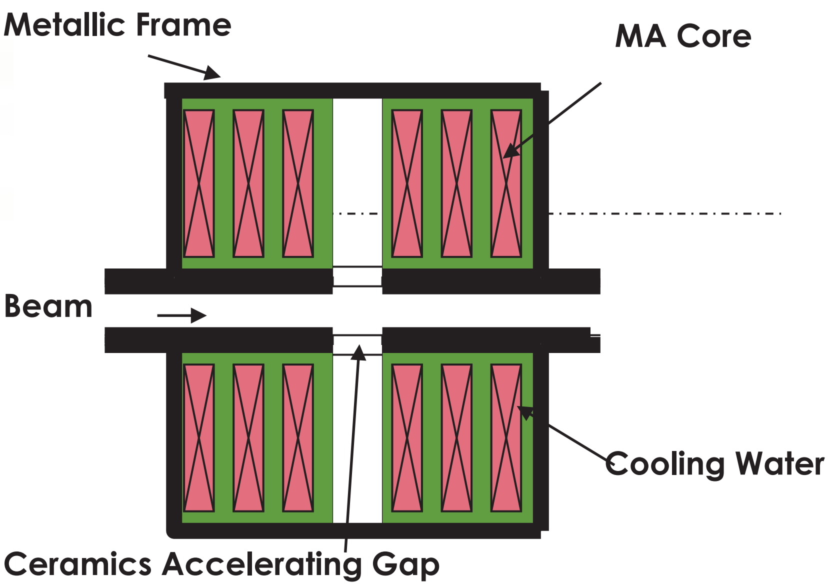
- **Almost all the technical issues for the RCS as one option for MW-class pulsed spallation neutron source have been solved to some extent.**
- **However, the controversy has not yet come to conclusion, since the beam power of 1 MW has not been achieved in any RCS.**
- **The successful start of the beam commissioning and the stable user operation of the J-PARC RCS made the RCS option very promising as well as the AR option.**
- **We believe that RCS will accomplish the beam power of 1 MW as well as AR.**
- **Then, we can combine both the technologies, SNS SC GeV linac and J-PARC RCS, together in order to realize the several and/or ten MW beam power, like Super B factory which will make use of both the KEKB ARES and PEPII comb filter together.**

**Ring RF**
**Rapid Acceleration**
**High Field Gradient**

# Magnet Alloy (MA) -Loaded Cavity is a must for high-power RCS




## Reentrant Cavity

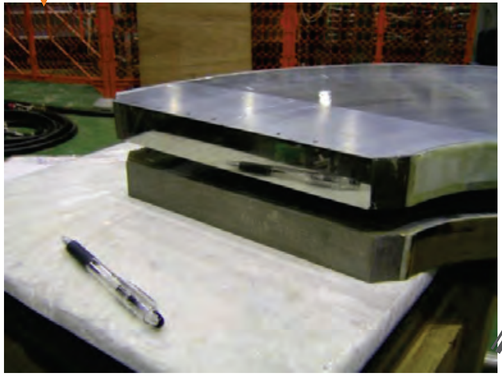



**J-PARC RF team invented a method to adjust the quality factors of MA-loaded cavities: Cut-Core method. By this method, the Q value for MR Cavities is optimized. RCS is using uncut cores.**

# Development and Operation of MA Cores

Damaged cut surface

The polishing improvement

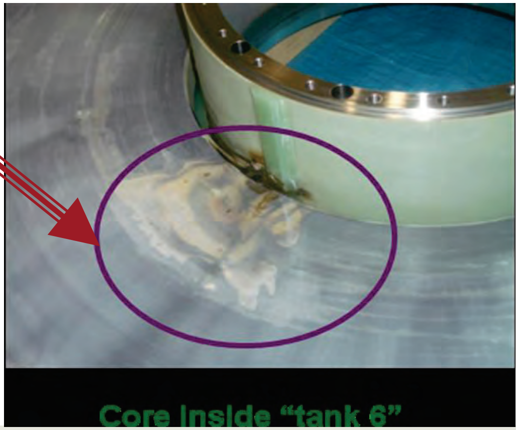


Upper: After diamond polishing
Lower: Before diamond polishing.

After 600-hour operation

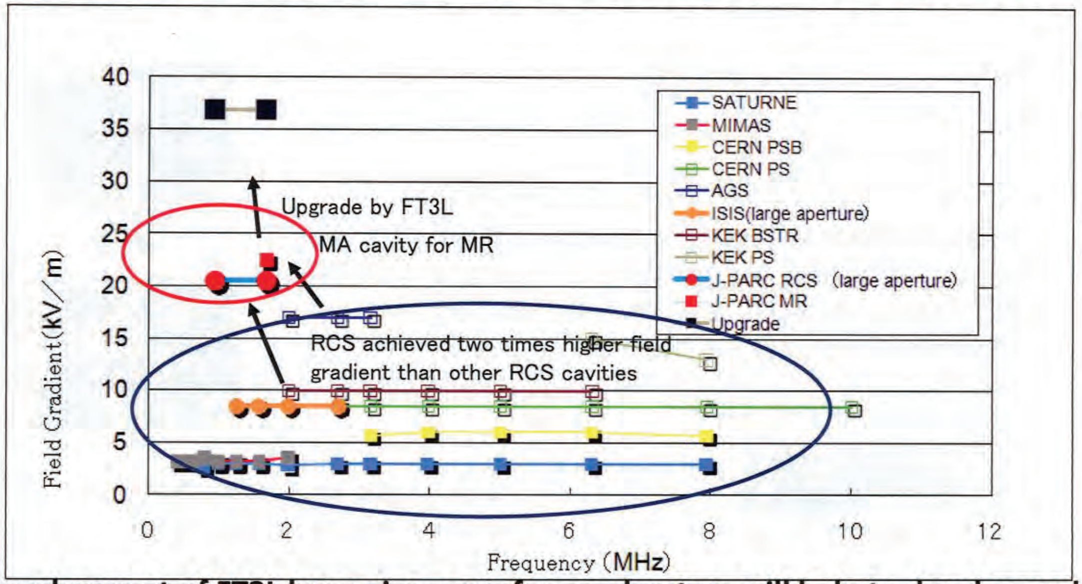
After 1000-hour operation

More than 2,000-hour operation showed a new problem in uncut cores.
This has been cured by softening the core structure.



# Path Forward and Beyond

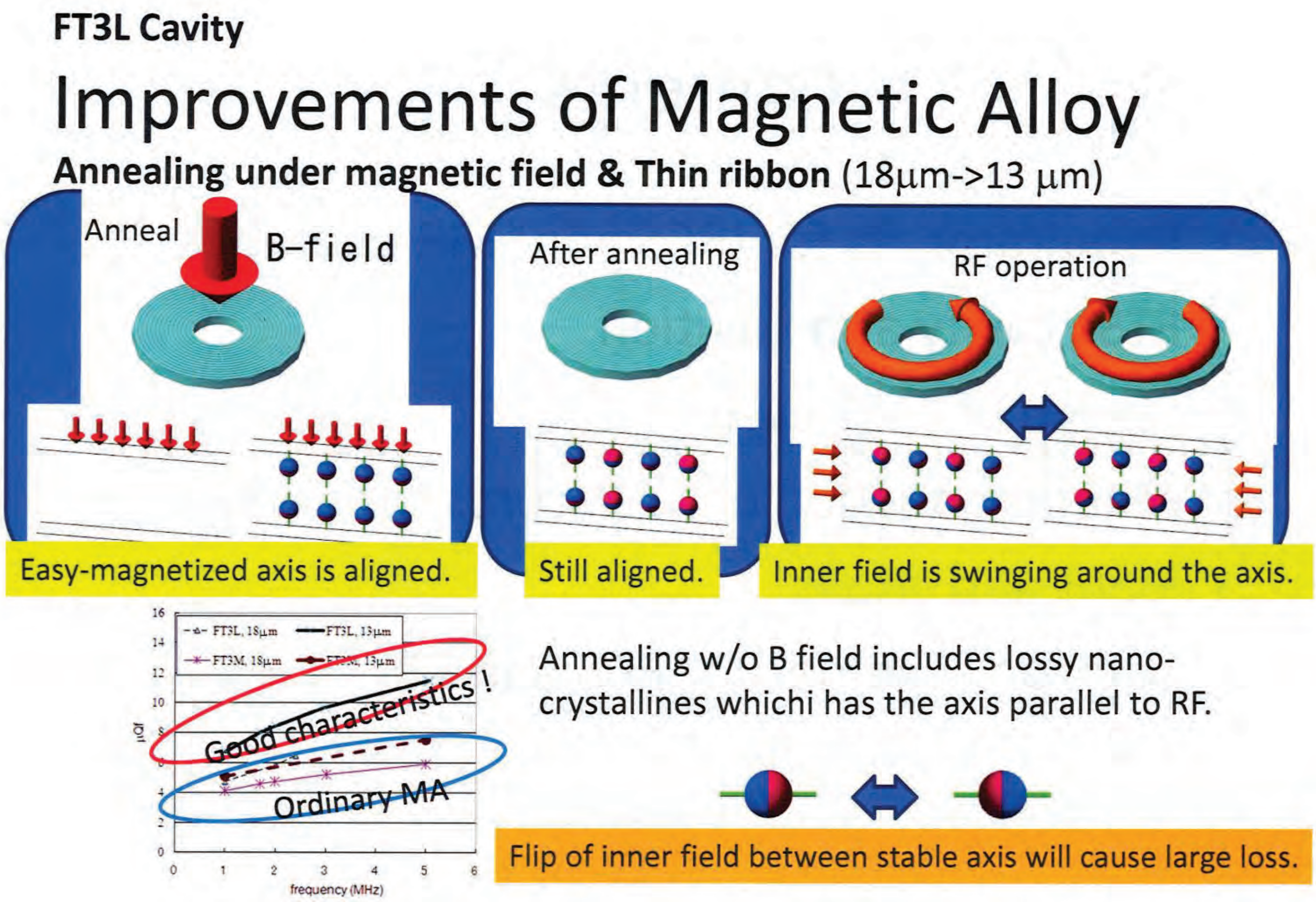
Field Gradient of RF Cavity for Proton/ion acceleration




**Development of FT3L large-size cores for accelerators will help to develop and improve other proton/ion rings.**

By the courtesy of Chihiro Ohmori, J-PARC

# *Annealing under Magnetic Field*




By the courtesy of Chihiro Ohmori, J-PARC

# Summary and Future

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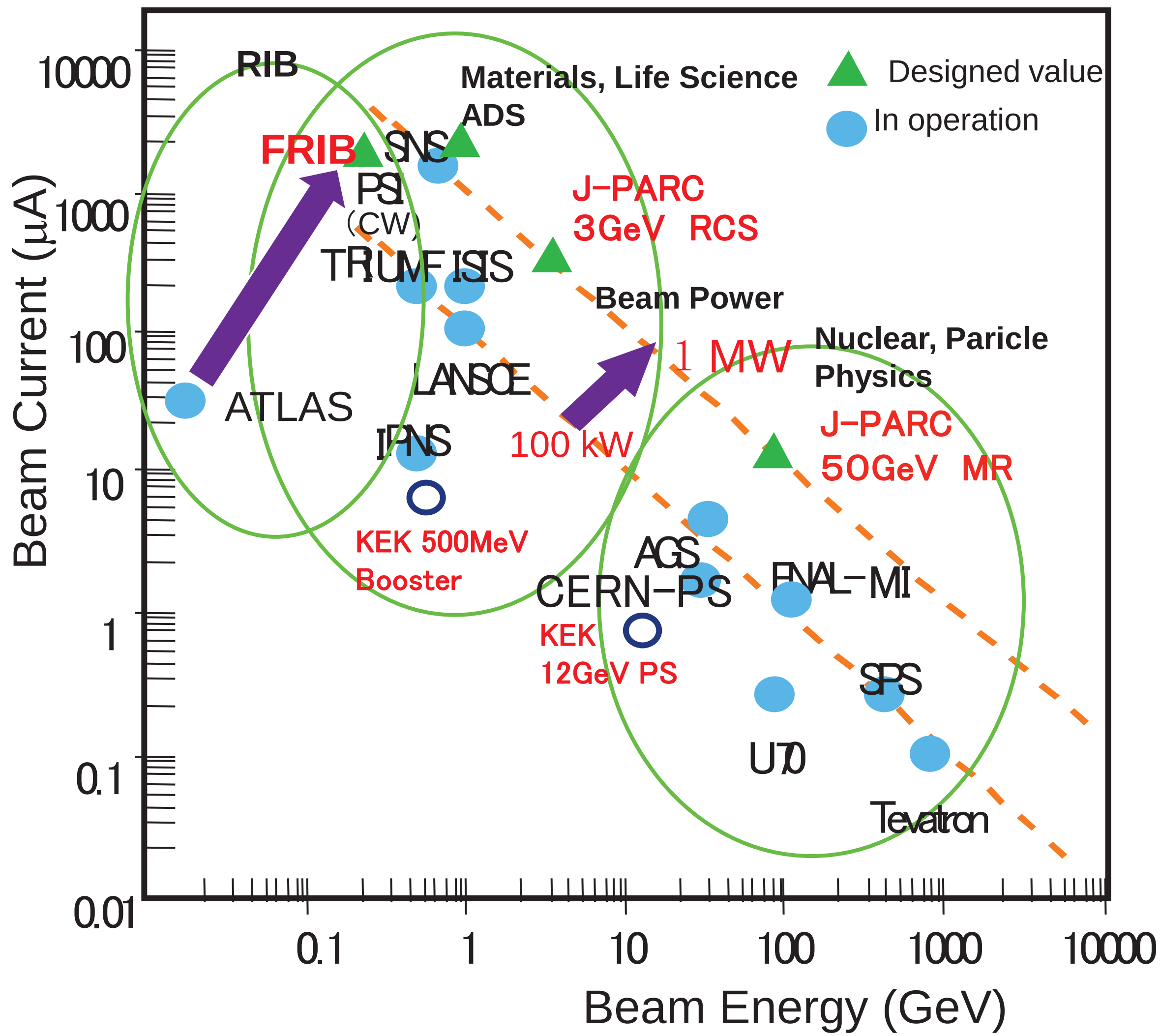
- **The 1-MW achievement of SNS and 0.4-MW of J-PARC are the results of the huge efforts of the high-intensity proton accelerator community world-wide during last one decade and a half. After LAMPF(LANSCE), SIN(PSI), TRIUMF, MMF and ISIS started their operations, no high-intensity proton accelerator project had not been funded for so long time, until the SNS and J-PARC did.**
- **The J-PARC accelerator technology is definitely based upon these efforts as well as developments starting in 1986 for Japan Hadron Project in KEK, Omega Project in JAERI (now JAEA) and others. It took 22 years.**
- **During the course of the development and construction, the technology in general has been in progress, while young scientists have grown up.**
- **This is the reason for the on-schedule, successful beam commissioning of the SNS and J-PARC accelerator.**
- **However, we still need the further effort to overcome some technological issues and for path forward and beyond.**
- **The developments and the operational experiences in SNS, J-PARC and others will contribute a lot to the world-wide technological advance in the accelerator field, for several-MW neutron sources, neutrino factories, and beyond.**
- **Therefore, we have to continue the Research and Development for the coming 20-years.**

# Heavy Ion Joining Beam Power Front by SC Linac




**Facility for Rare Isotope Beams, FRIB, has a driver linac to accelerate all the ion species up to uranium to a beam power of 400 kW with a typical beam energy of 200 MeV/u, using SC linac from 500 keV/u.**

**The facility is located in the main campus of Michigan State University, MSU.**

**Qiang Zhao will detail this machine.**