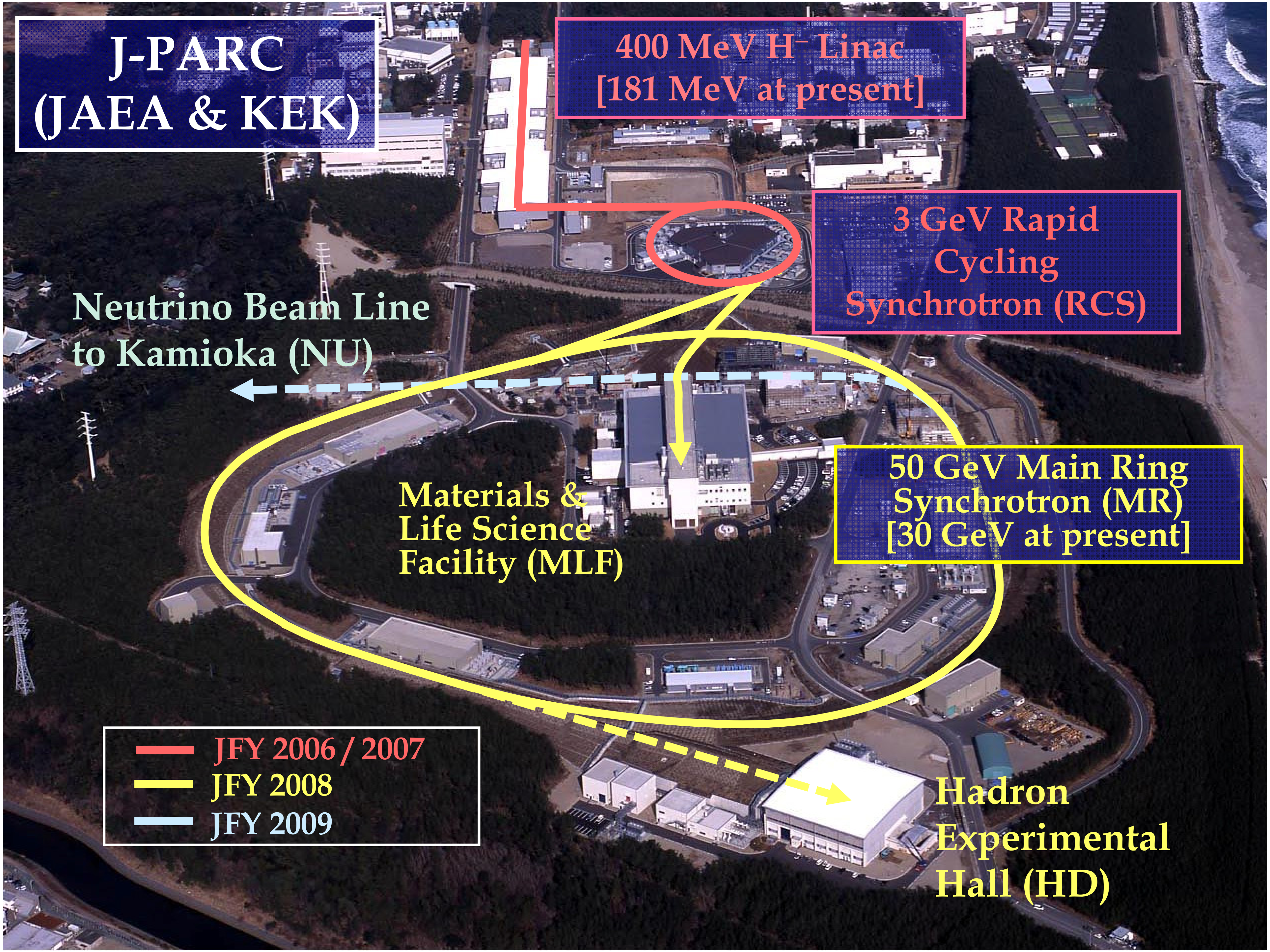
J-PARC
Beam Commissioning Progress

IPAC 2011

San Sebastian, Spain, September 4-9, 2011

Hideaki Hotchi

J-PARC, Japan Atomic Energy Agency (JAEA)


J-PARC
(JAEA & KEK)
400 MeV H⁻ Linac
[181 MeV at present]
3 GeV Rapid
Cycling
Synchrotron (RCS)
Neutrino Beam Line
to Kamioka (NU)
Materials &
Life Science
Facility (MLF)
50 GeV Main Ring
Synchrotron (MR)
[30 GeV at present]
Hadron
Experimental
Hall (HD)
JFY 2006 / 2007
JFY 2008
JFY 2009

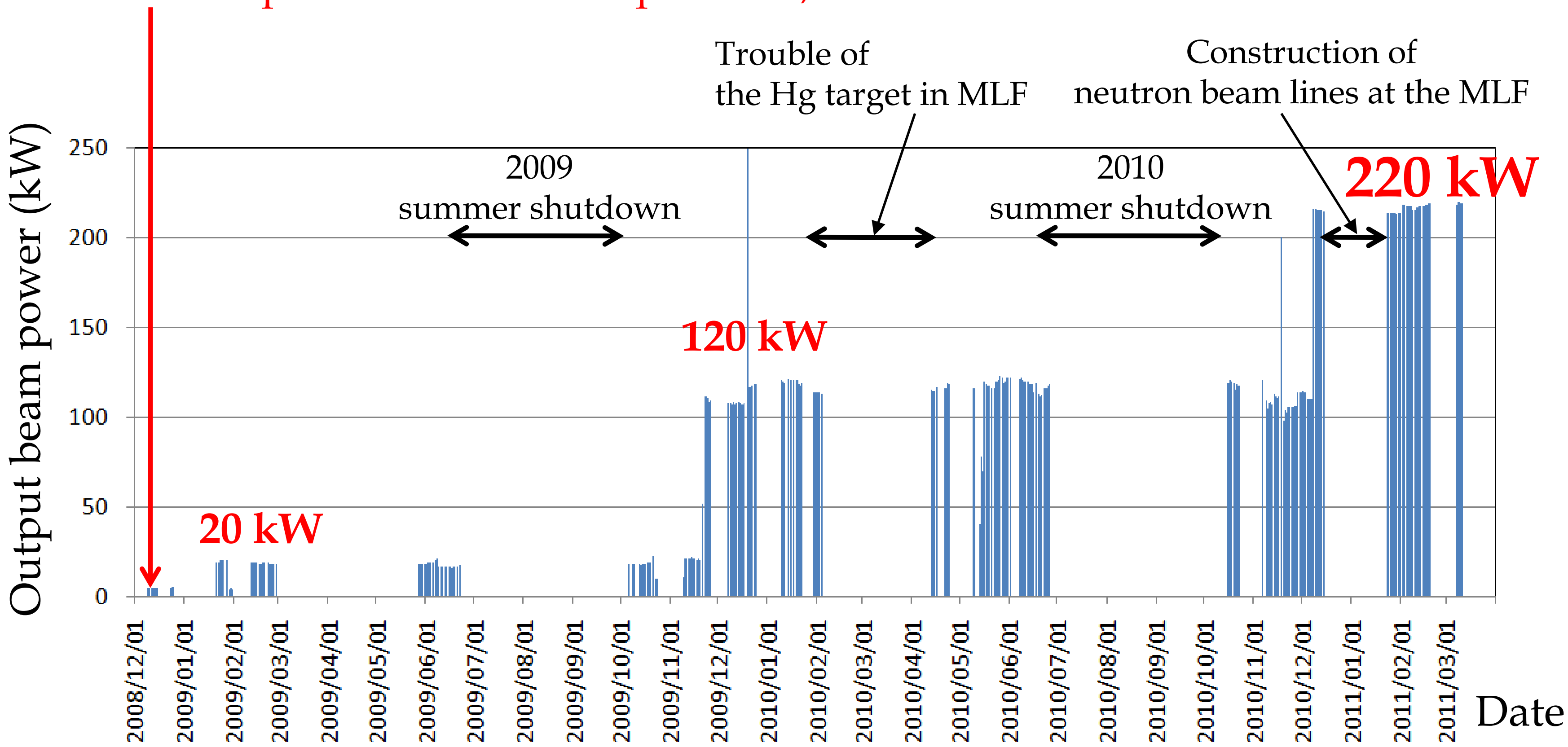
Contents

- History of the beam operation
- Current status of the linac
  - Residual radiation level
  - Beam loss in the future ACS section
- Current status of the RCS
  - Residual radiation level
  - Beam loss at the exit of 1st injection septum
  - Beam loss downstream of the charge-exchange foil
- Results of beam study recently performed in the RCS
  - Beam-based measurements of lattice imperfections
  - High intensity trial
- Future plan
- Summary

Current status of the MR;
Poster session (WEPS008) by T. Koseki,
“Operation Status and Future Plan of J-PARC Main Ring”.

History of the RCS output beam power to the MLF

- ➢Beam commissioning of the linac ; November 2006~
- ➢Beam commissioning of the RCS ; October 2007~
- ➢Startup of the MLF user operation ; December 2008~

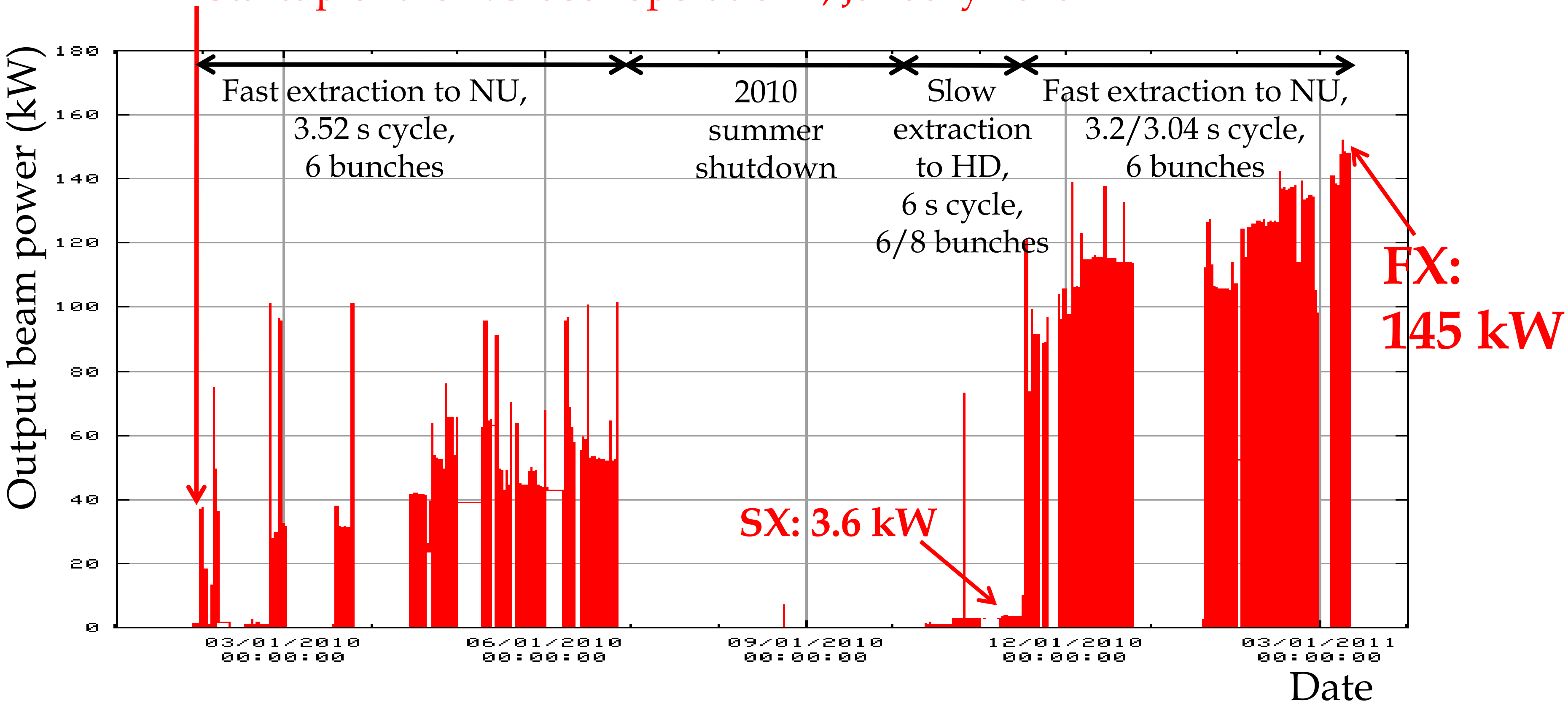


The output beam power to the MLF has been steadily increased following;

- Progression of beam tuning,
- Hardware improvements,
- Careful monitoring of the trend of residual activation levels.

History of the MR output beam power

- ➢Beam commissioning of the MR ; May 2008~
- ➢Startup of the NU user operation ; January 2010~



The output beam power of the MR has been also steadily increased following;

- Progression of beam tuning,
- Hardware improvements,
- Careful monitoring of the trend of residual activation levels.

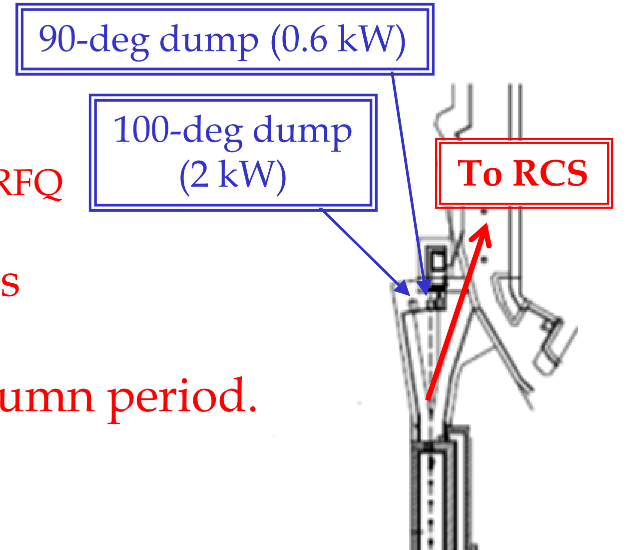
Current status of the linac & RCS in the 220-kW routine user operation to the MLF

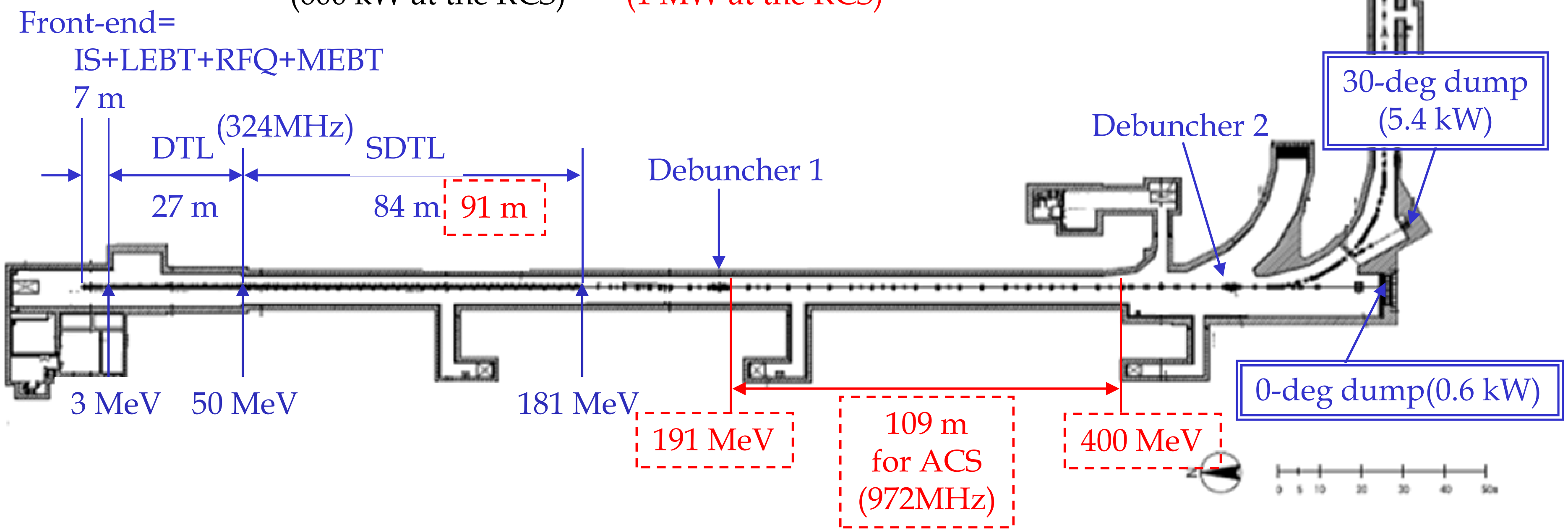
- Design parameters of the linac and RCS
- Beam loss issues of the linac and RCS
  found in the current routine user operation

Design parameters of the linac

Particles	H^-	
Output energy	181 MeV	⇒400 MeV by adding ACS
Peak current	30 mA	⇒50 mA by upgrading IS & RFQ
Pulse width	0.5 ms	
Chopper beam-on duty factor	56%	
Repetition rate	25 Hz	
Output power	36 kW (600 kW at the RCS)	⇒133 kW (1 MW at the RCS)

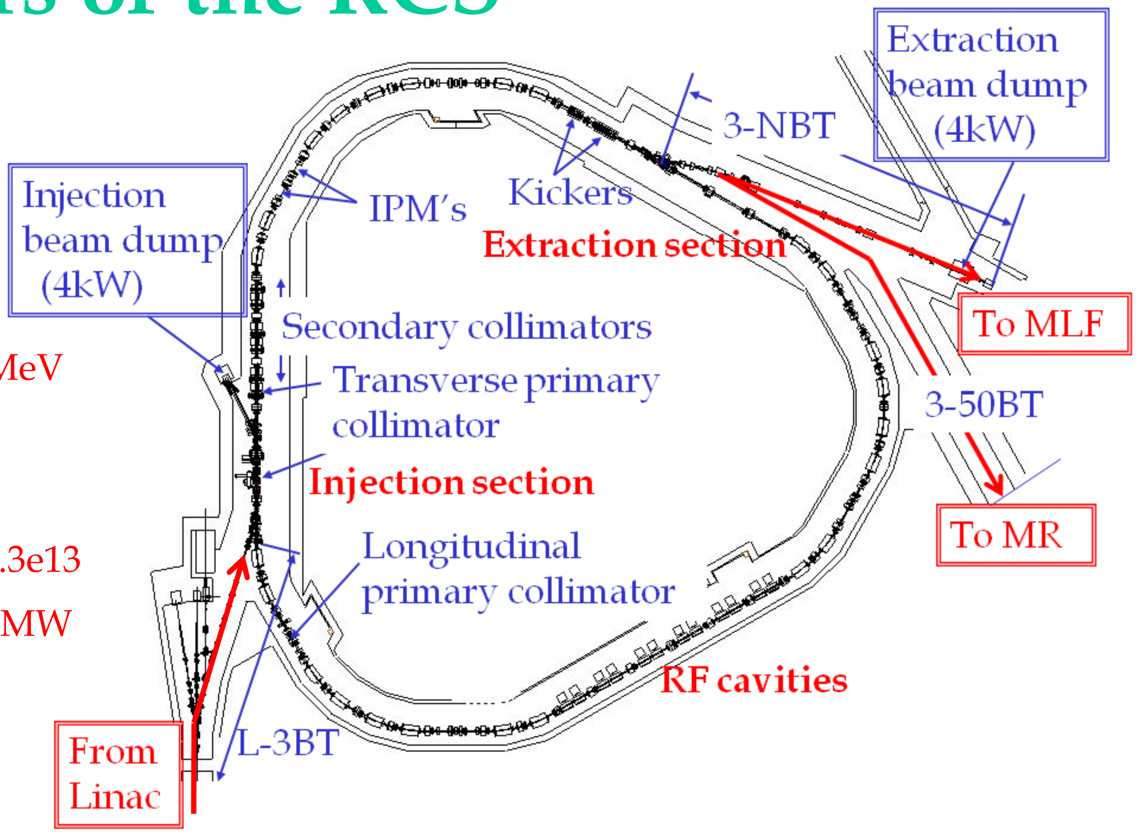
These installations are scheduled in 2013 summer-autumn period.





Design parameters of the RCS

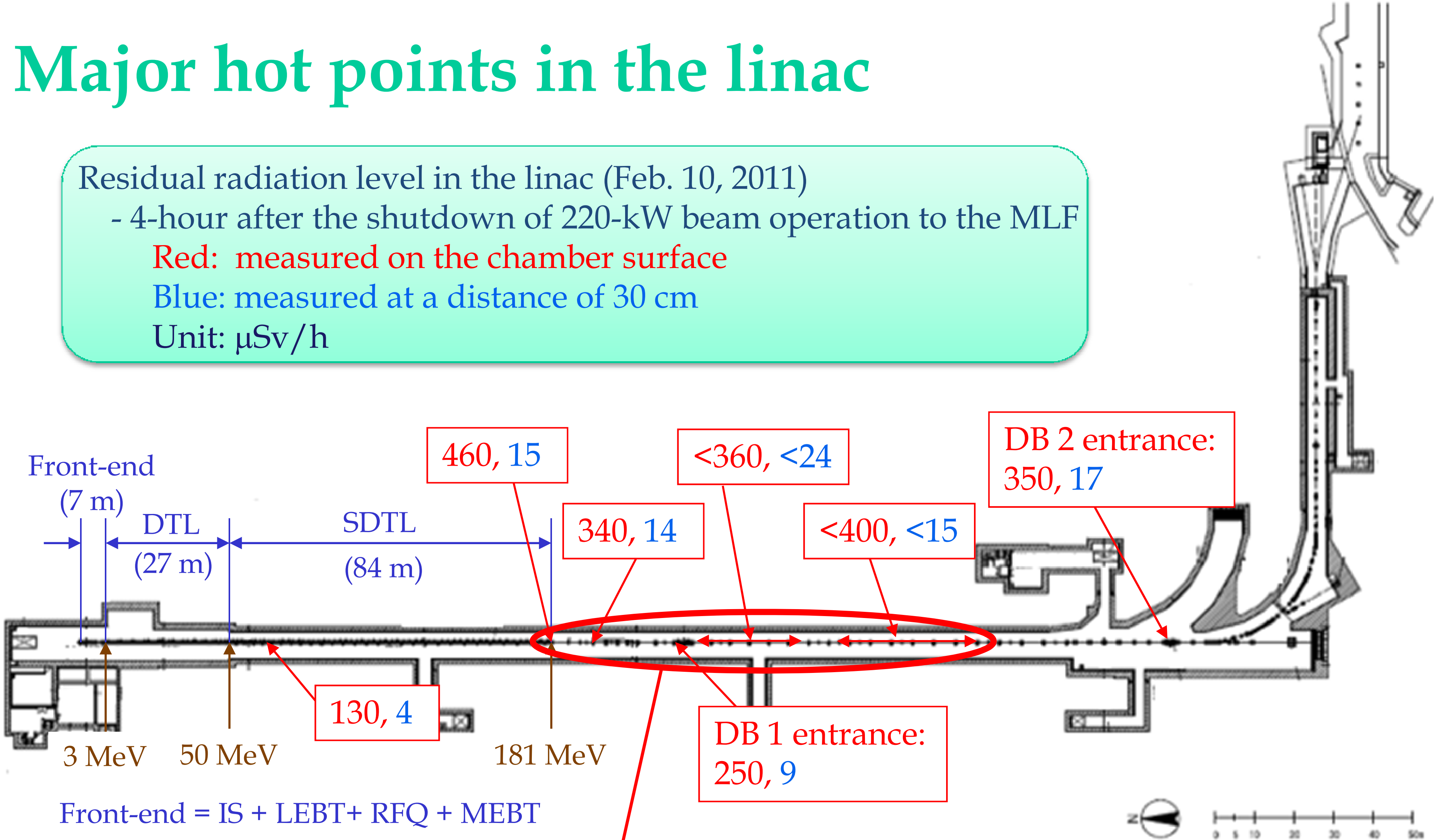
Circumference	348.333 m
Superperiodicity	3
Harmonic number	2
No of bunch	2
Injection energy	181 MeV ⇒ 400 MeV
Extraction energy	3 GeV
Repetition rate	25 Hz
Particles per pulse	2.5e13 - 5e13 ⇒ 8.3e13
Output beam power	300–600 kW ⇒ 1 MW
Transition gamma	9.14 GeV
Number of dipoles	24
quadrupoles	60 (7 families)
sextupoles	18 (3 families)
steerings	52
RF cavities	12 (11 at present)



Current output beam power in the MLF user operation by the linac and RCS;
220 kW

Major hot points in the linac

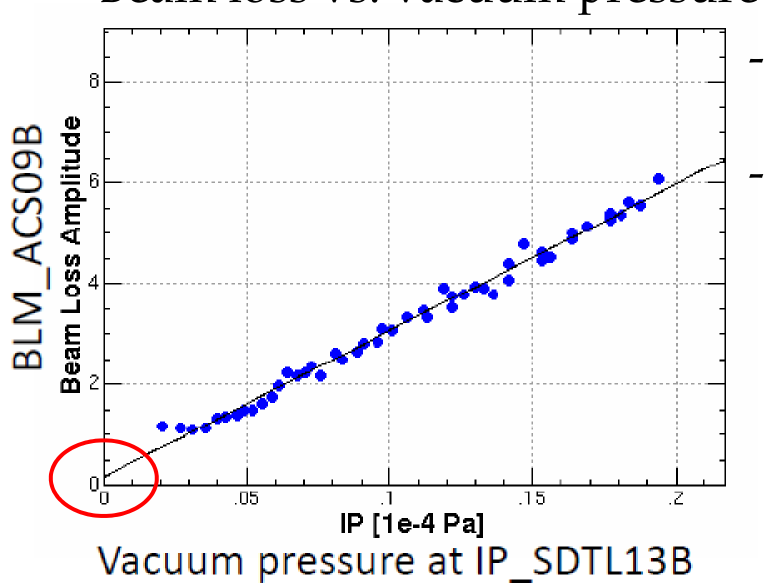
Residual radiation level in the linac (Feb. 10, 2011)
- 4-hour after the shutdown of 220-kW beam operation to the MLF
  - Red: measured on the chamber surface
  - Blue: measured at a distance of 30 cm
  - Unit: μSv/h



Residual activations widely distributed over the future ACS section

Beam loss in the future ACS section

Beam loss vs. vacuum pressure



M. Ikegami & G. Wei

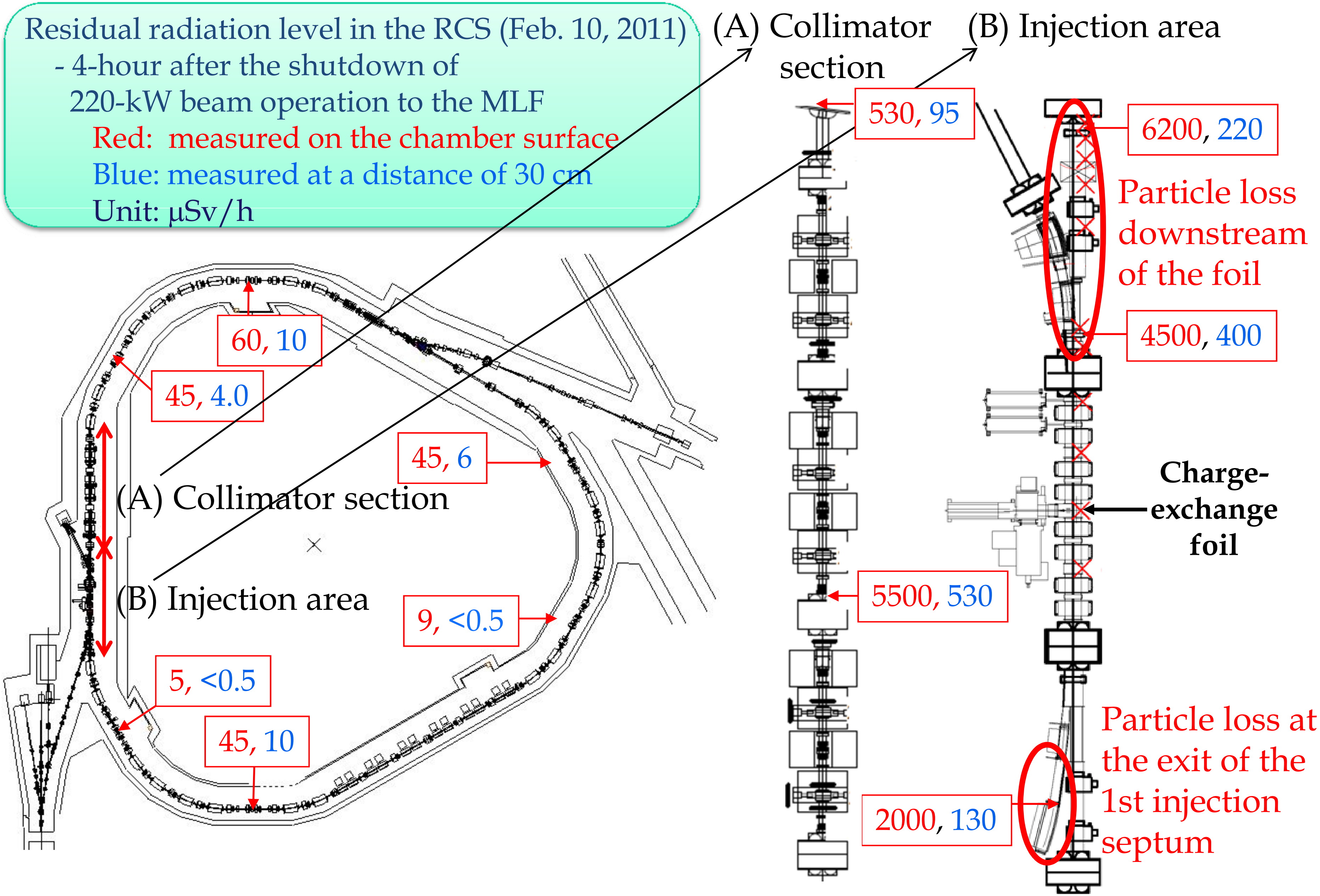
- The BLM signal at the future ACS section has a linear response for the vacuum pressure.
- The extrapolated line of the measured data practically has no intercept.

Main cause of the beam loss;
H^0 component arising from residual gas stripping.

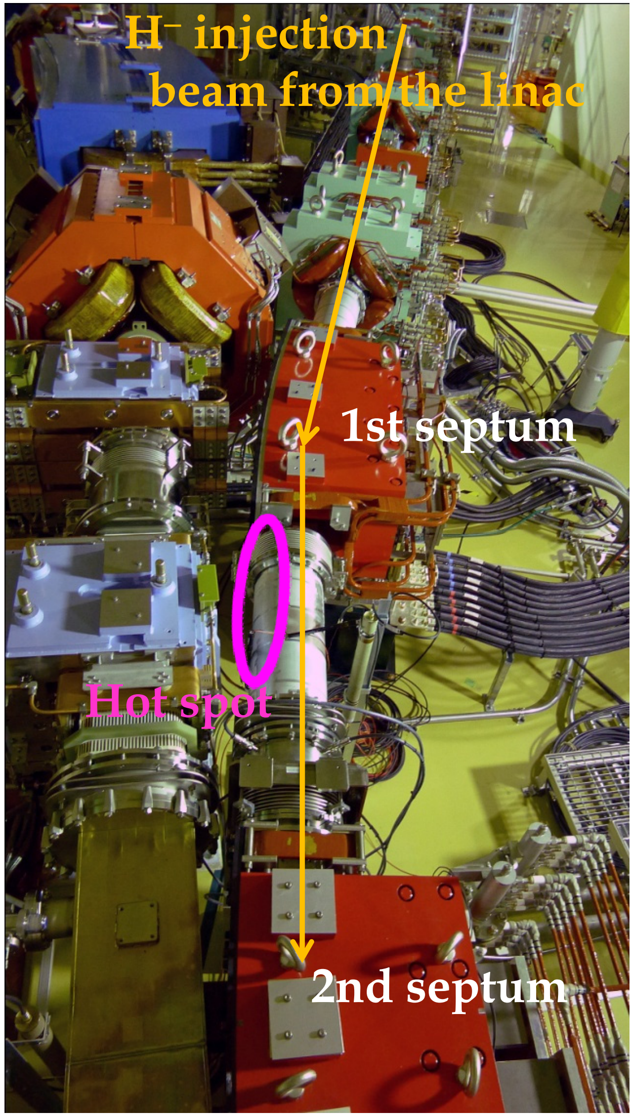
In order to get further beam loss reduction, it is necessary to make a further improvement of the vacuum system in this area.

Major hot points in the RCS

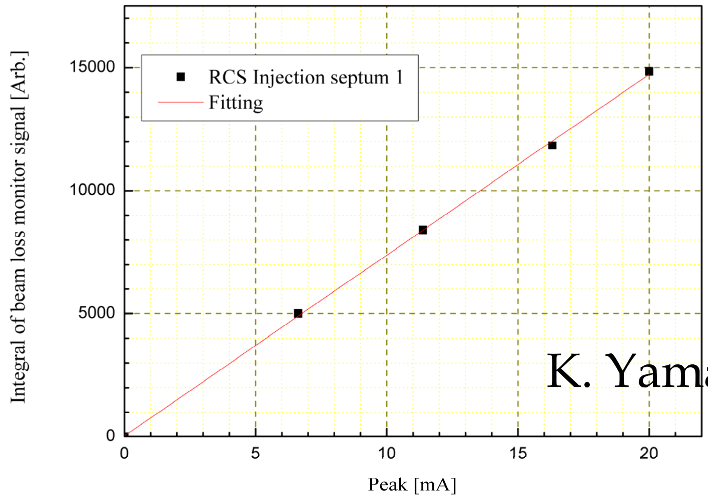
Residual radiation level in the RCS (Feb. 10, 2011)
- 4-hour after the shutdown of 220-kW beam operation to the MLF
  - Red: measured on the chamber surface
  - Blue: measured at a distance of 30 cm
  - Unit: μSv/h



Beam loss at the exit of the 1st injection septum



Peak current dependence of
the BLM signal at the injection septum



K. Yamamoto

- The residual dose is observed only at the outer side of the beam line.
- The BLM signal at this point has no significant response for a orbit change by the injection septum.
- The BLM signal at this point has a linear dependence for the peak current of the injection beam.

Possible cause of this beam loss;

H^0 component arising from residual gas stripping in the straight section upstream of 1st septum.

In order to reduce the beam loss, we will improve the vacuum system.

Beam loss downstream of the foil

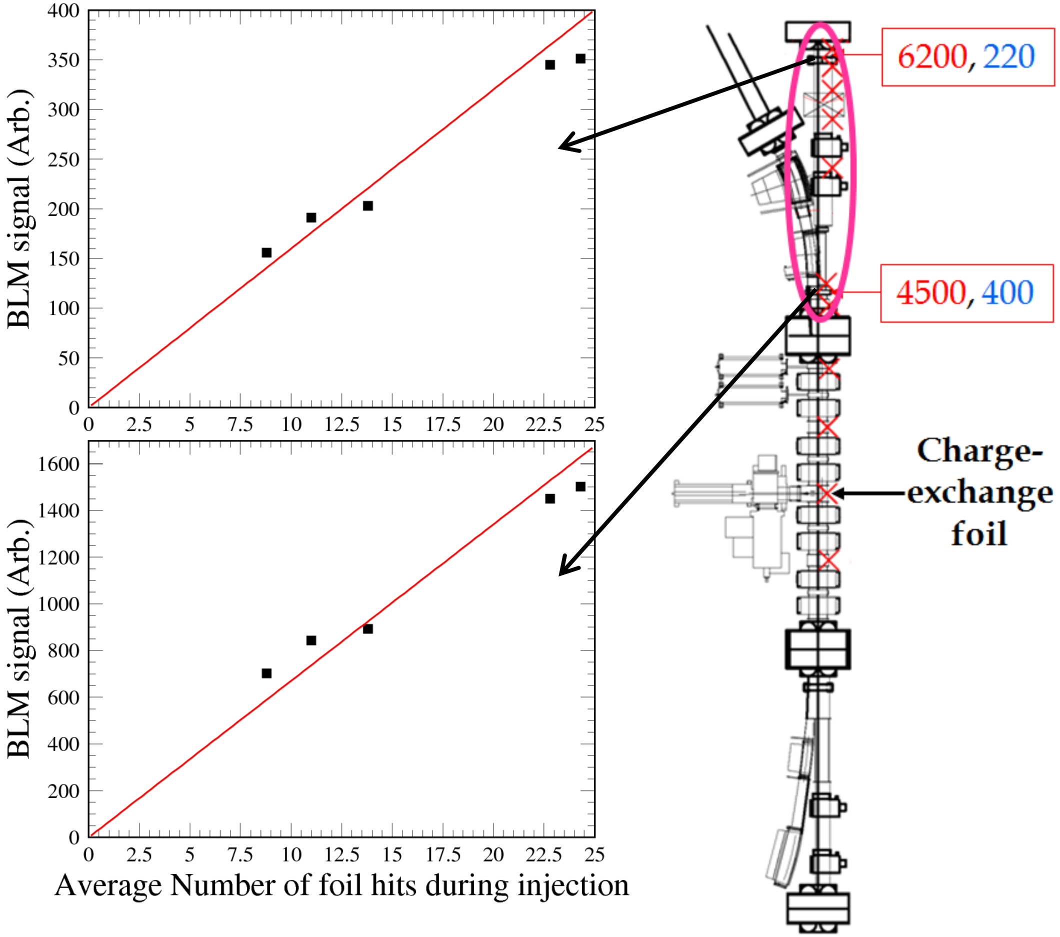
In the RCS, multi-turn charge-exchange injection with a carbon foil is adopted. In this way, the beam hits the foil many times during injection.

The BLM signals at the hot spots are proportional to the average number of foil hits during injection.

Main cause of this particle loss;

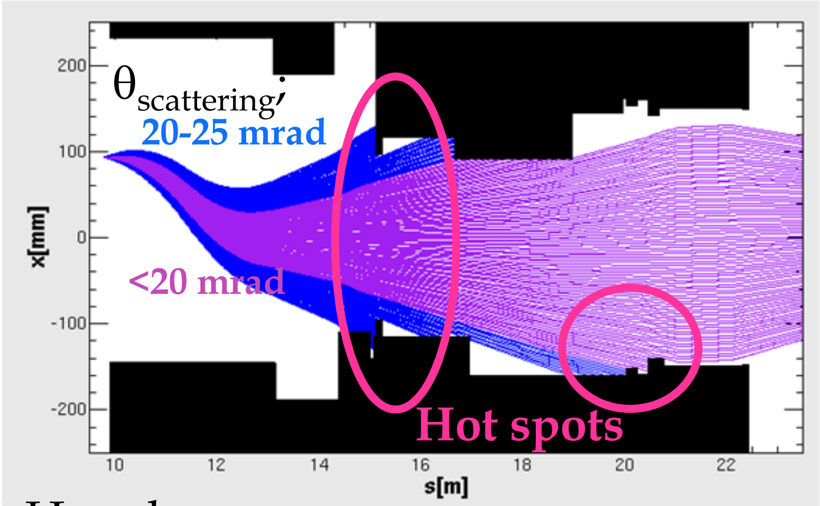
Large angle events scattered on the foil.

BLM signal vs. average number of foil hits during injection

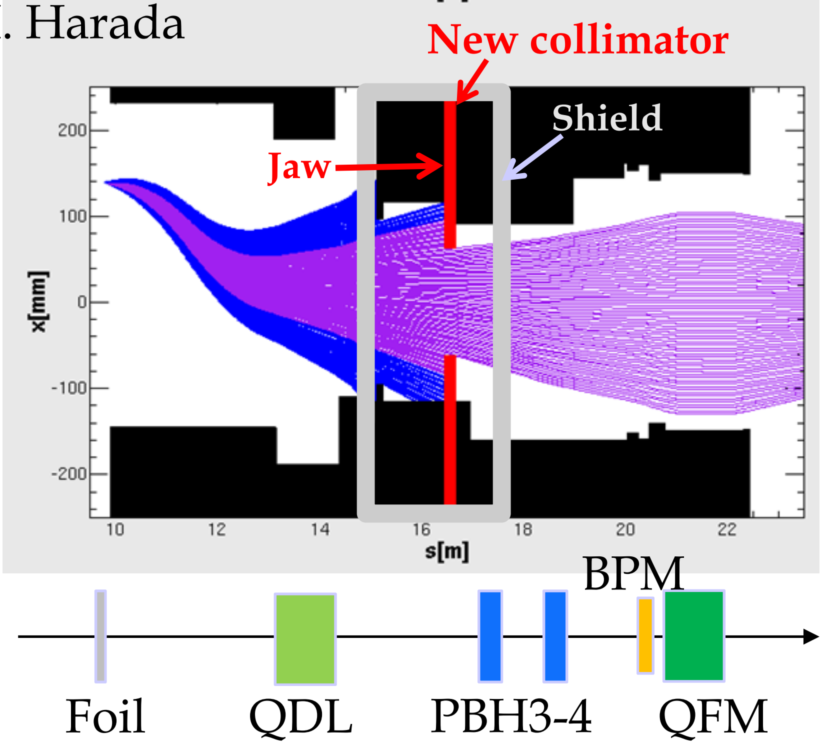


Beam loss downstream of the foil

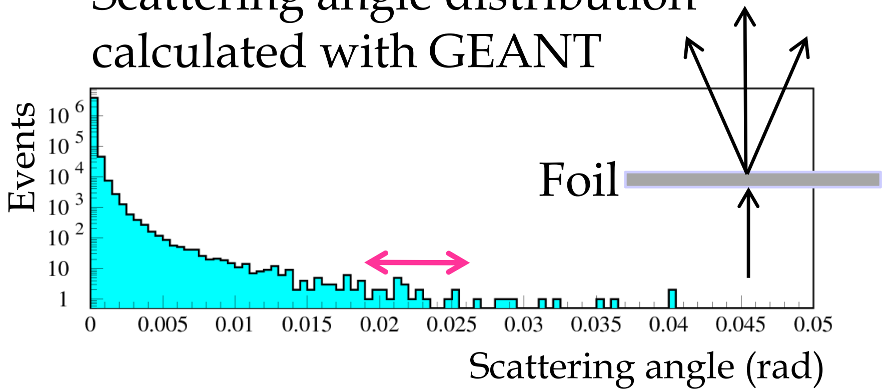
Tracking simulation for scattered particles on the foil



H. Harada



Scattering angle distribution calculated with GEANT



This tracking simulation well reproduces the observed beam loss points, and shows that large angle events with a scattering angle of 20-25 mrad make observed machine activations.

To localize the foil scattering beam loss, we will introduce a new collimation system;
- it will be installed in the present shutdown period.

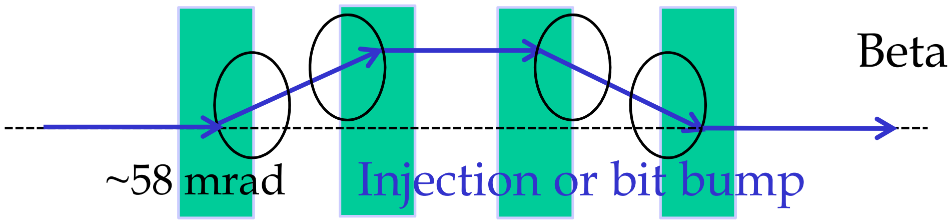
Next goal ;
300 kW to the MLF

Results of beam study recently performed in the RCS

- Beam-based measurements of lattice imperfections
- High intensity beam test

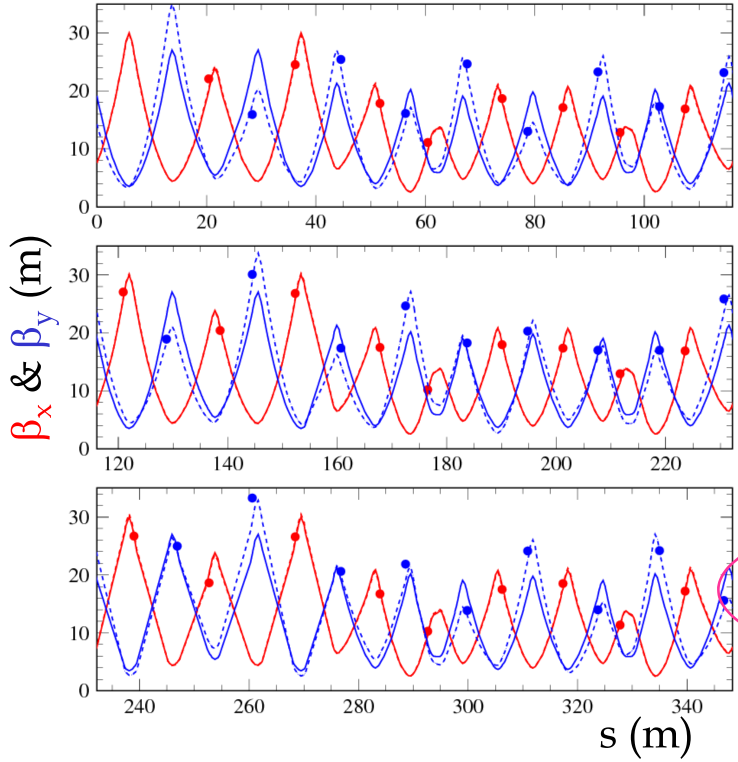
Beam-based measurements of lattice imperfections in the RCS - I -

- Edge focus of the injection-bump magnets (0.5 ms flattop + 0.5 ms fall time)



Beta modulation caused by the edge focus;
- makes a distortion of the lattice super-periodicity
- drives random lattice resonances.

Result of beta modulation measurements



Horizontal beta function

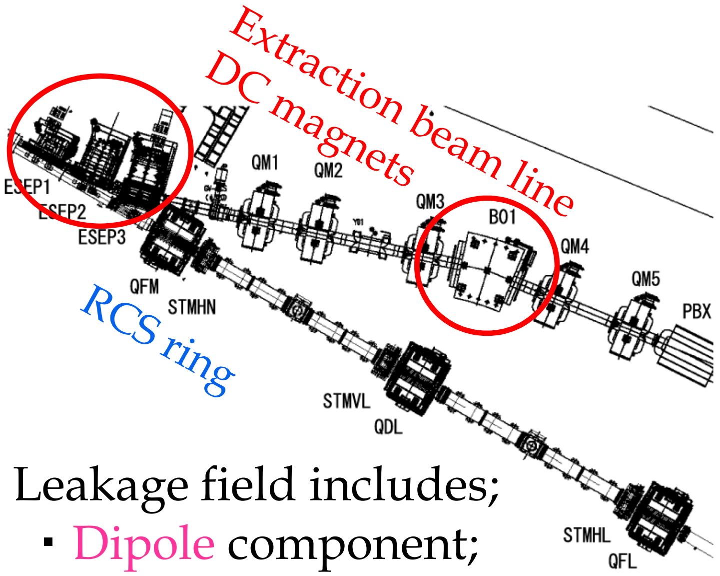
Vertical beta function

- ● measurement (injection bump ; ON)
- ⋯ calculation (injection bump ; ON)
- ― calculation (injection bump ; OFF)

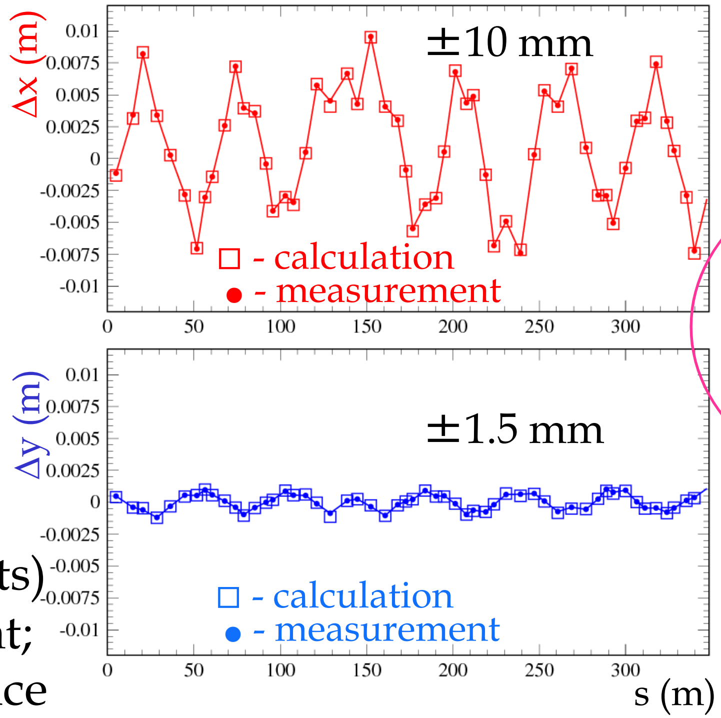
Edge focus estimated; $K_1 \sim -0.003335 m^{-1}$

Beam-based measurements of lattice imperfections in the RCS - II -

- Leakage fields from the extraction beam line DC magnets;
  - evaluation of dipole and normal quadrupole components



COD caused by the leakage fields



Dipole component estimated;
–1.14 mrad (hor.)
–0.12 mrad (ver.)

Leakage field includes;

- Dipole component;
  - makes COD (correctable by steering magnets)
- Normal quadrupole component;
  - makes a distortion of the lattice super-periodicity
  - drives random lattice resonances
- Skew quadrupole component;
  - causes linear coupling

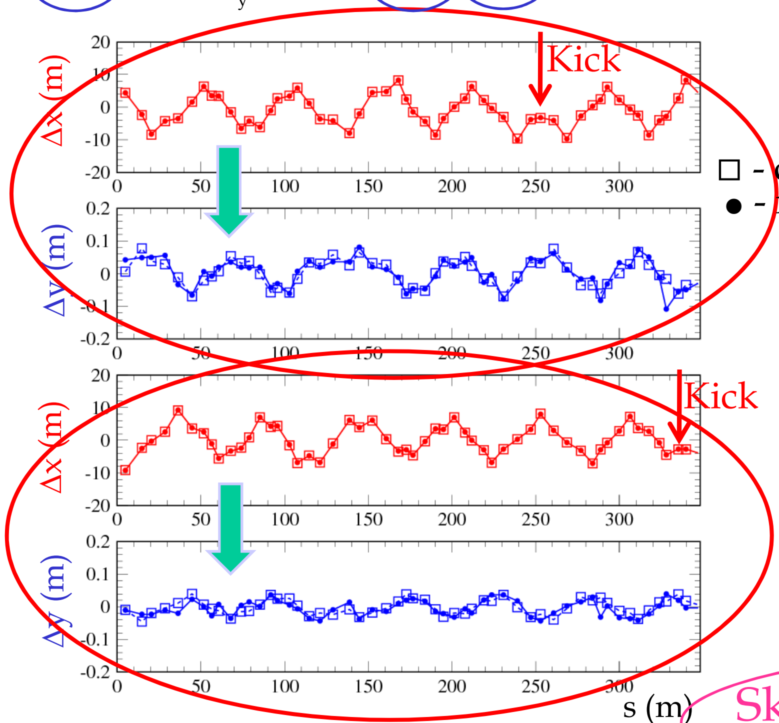
Normal quadrupole component estimated from the optics measurements; 0.0048 m^{-1}

Beam-based measurements of lattice imperfections in the RCS - II -

- Leakage fields from the extraction beam line DC magnets;
  - evaluation of skew quadrupole component

Orbit leak (Δy) to the vertical plane by a horizontal single kick

$$\Delta y(s) = \frac{\sqrt{\beta_y(s)}}{2\sin\pi\nu_y}\oint\sqrt{\beta_y(s')}SK_1(s')\Delta x(s')\cos(|\phi_y(s')-\phi_y(s)|-\pi\nu_y)ds'$$



□ - calculation
● - measurement

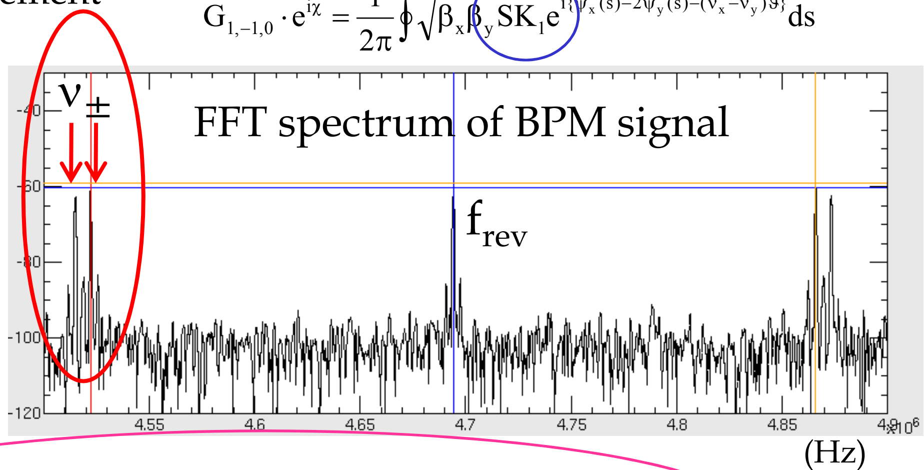
Systematic measurement of two normal mode betatron tunes ($\nu_\pm$) near a linear coupling resonance

$$x_n = A_+\cos(\nu_+\varphi+\xi_+) - \frac{G_{1,-1,0}}{\lambda+|\delta|}A_-\cos(\nu_-\varphi+\xi_-),$$

$$y_n = \frac{G_{1,-1,0}}{\lambda+|\delta|}A_+\cos(\nu_+\varphi+\xi_+) + A_-\cos(\nu_-\varphi+\xi_-),$$

where $\nu_\pm = \frac{1}{2}(\nu_x+\nu_y) \pm \frac{1}{2}\sqrt{(\nu_x-\nu_y)^2+|G_{1,-1,0}|^2},$

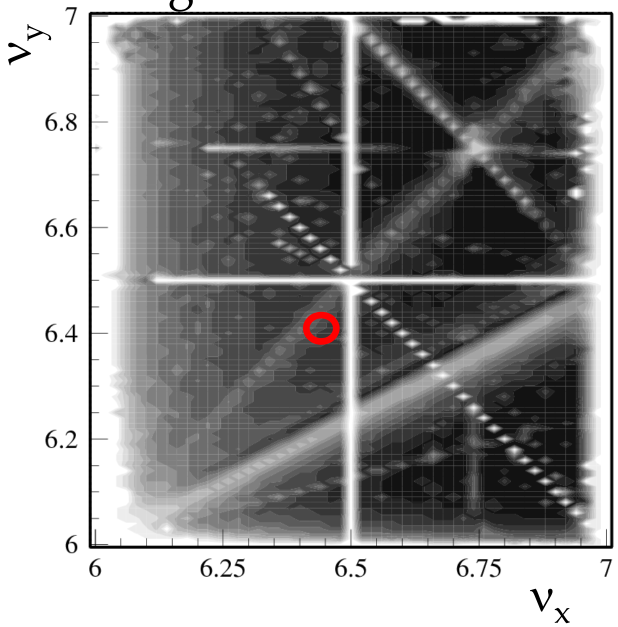
$$G_{1,-1,0}\cdot e^{i\chi} = \frac{1}{2\pi}\oint\sqrt{\beta_x\beta_y}SK_1e^{i\{\psi_x(s)-2\psi_y(s)-(\nu_x-\nu_y)\vartheta\}}ds$$



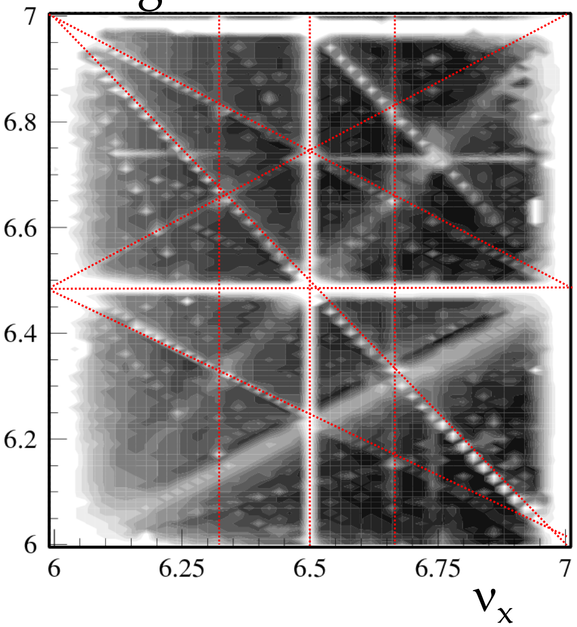
Skew quadrupole component estimated; $-0.00112\ m^{-1}$

Tune diagram

Without the measured "edge focus & leak fields"



With the measured "edge focus & leak fields"



Edge focus and leakage field;
enhance
- linear coupling resonance,
- 3-rd order random resonances,

make
- strong limit for tune-ability.

In order to get more stable and flexible tune space,
we plan to
- install additional magnetic shields
  for reducing the leakage field (in 2012 summer shutdown)
- introduce quadrupole correctors
  for compensating the edge focus effect (in 2013 summer-autumn shutdown)

Our understanding of the basic lattice properties
was deepen through such a series of beam dynamics measurements.

High intensity beam test performed in the RCS

◆We have recently performed a high intensity trial in the RCS, using the injection beam;

181 MeV/20 mA/0.5 ms/0.56 chopper beam-on duty

⇒3.5E13/pulse, corresponding to 420 kW output at 25 Hz

◆We tried to reduce the beam loss arising from the space charge effect in the low energy region employing transverse and longitudinal painting injection techniques.

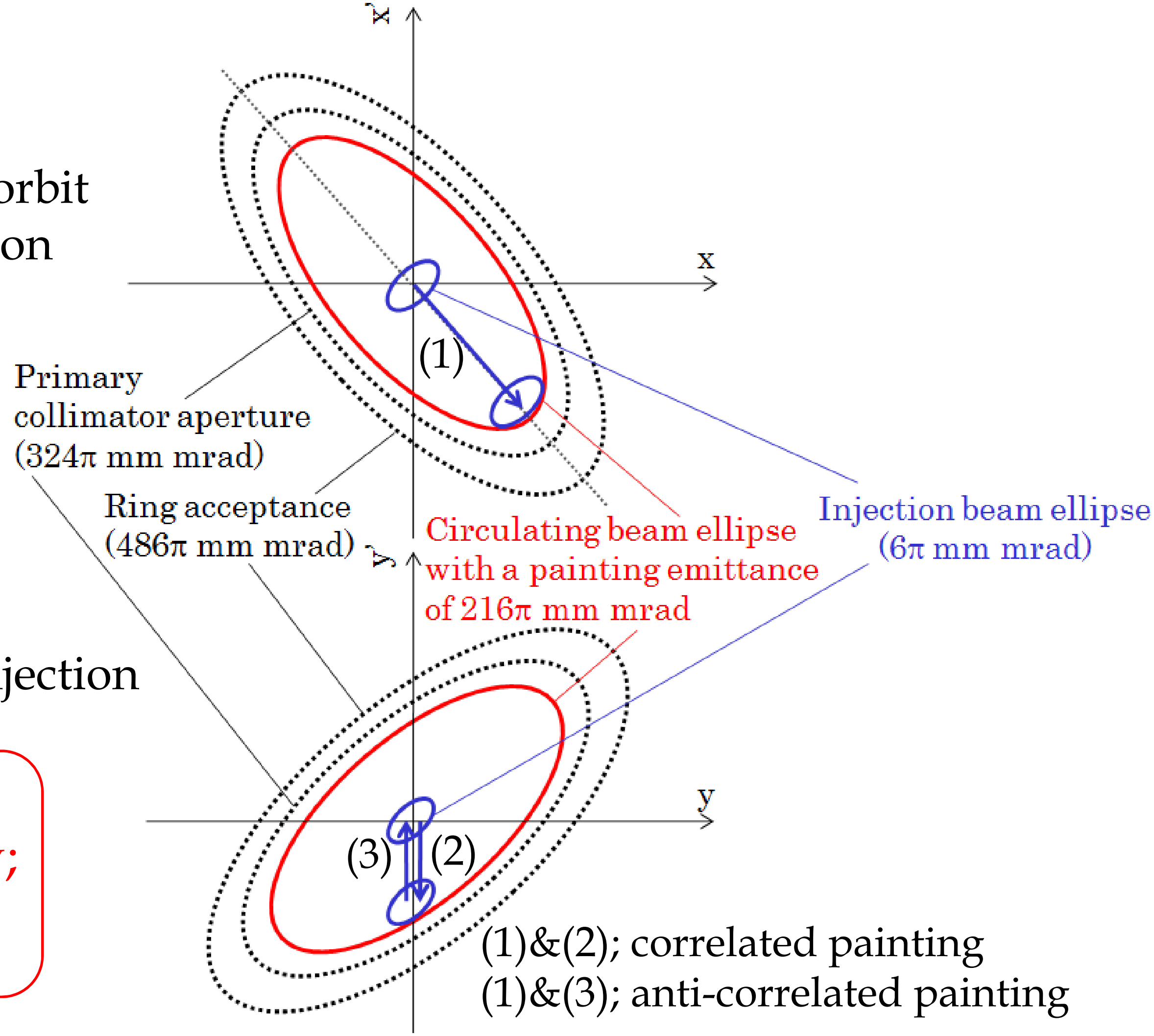
Transverse painting injection

Transverse painting makes use of a controlled phase space offset between the centroid of the injection beam and the ring closed orbit to get a uniform particle distribution of the circulating beam after the multi-turn injection.

Horizontal painting
by a horizontal closed orbit variation during injection

Vertical painting
by a vertical injection angle change during injection

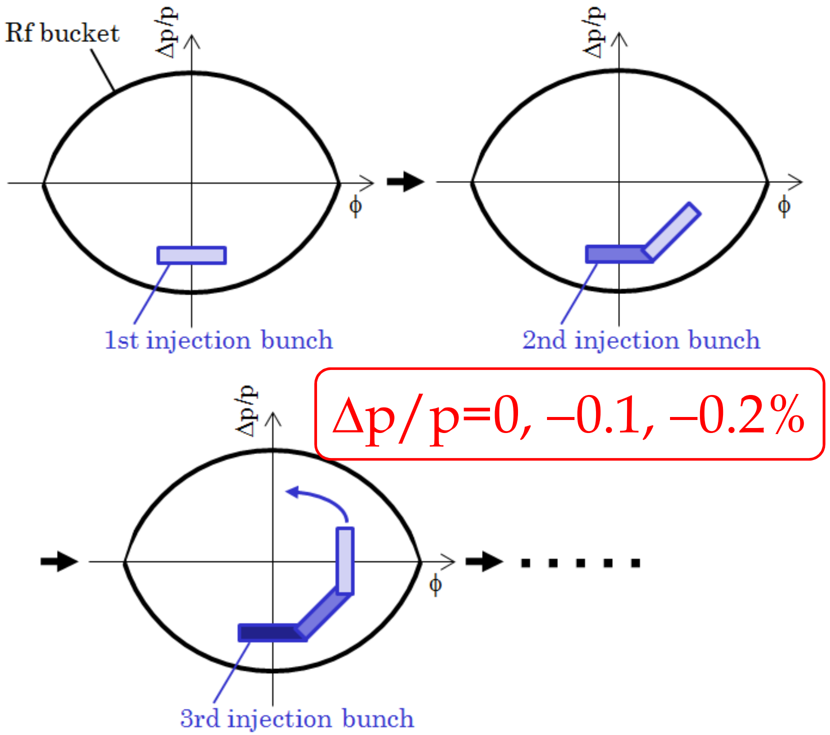
Painting emittance mainly applied in this beam study;
ε_{tp}= 50~100 π mm mrad



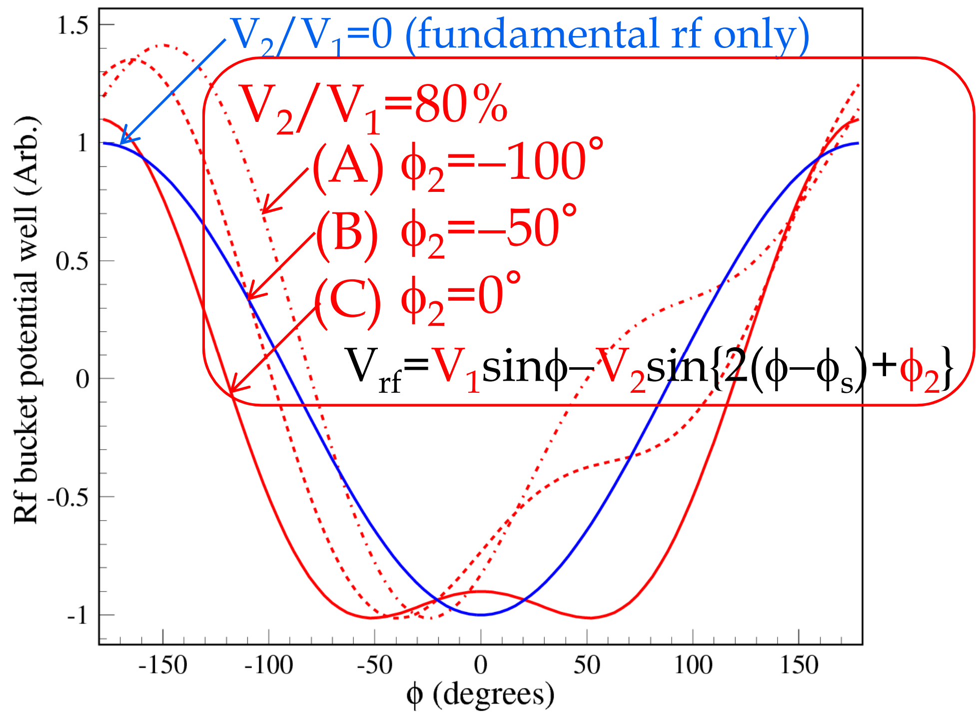
Longitudinal painting injection

Longitudinal painting makes use of a controlled momentum offset to the rf bucket in combination with superposing a second harmonic rf voltage to get a uniform bunch distribution after the multi-turn injection.

Momentum offset injection



Phase sweep of 2^{nd} harmonic rf



Uniform bunch distribution is formed through emittance dilution by the synchrotron motion in a flat and wide rf bucket potential given by superposing a second harmonic rf.

The second harmonic phase sweep method enables to control the bunch distribution through a dynamic change of the rf bucket potential.

Beam survival in the RCS (output intensity/input intensity)

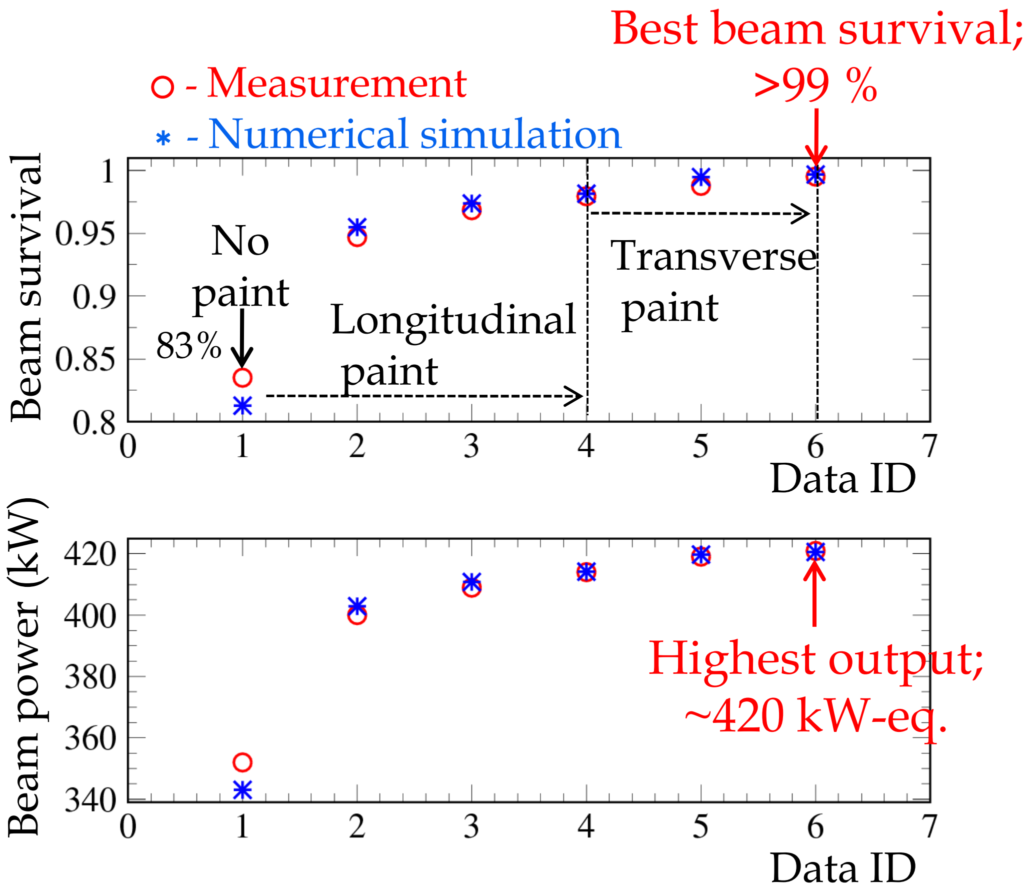
Injection beam;

181 MeV/20 mA/0.5 ms/0.56 chopper beam-on duty

⇒3.5E13/pulse, corresponding to 420 kW output at 25 Hz

Painting injection parameters

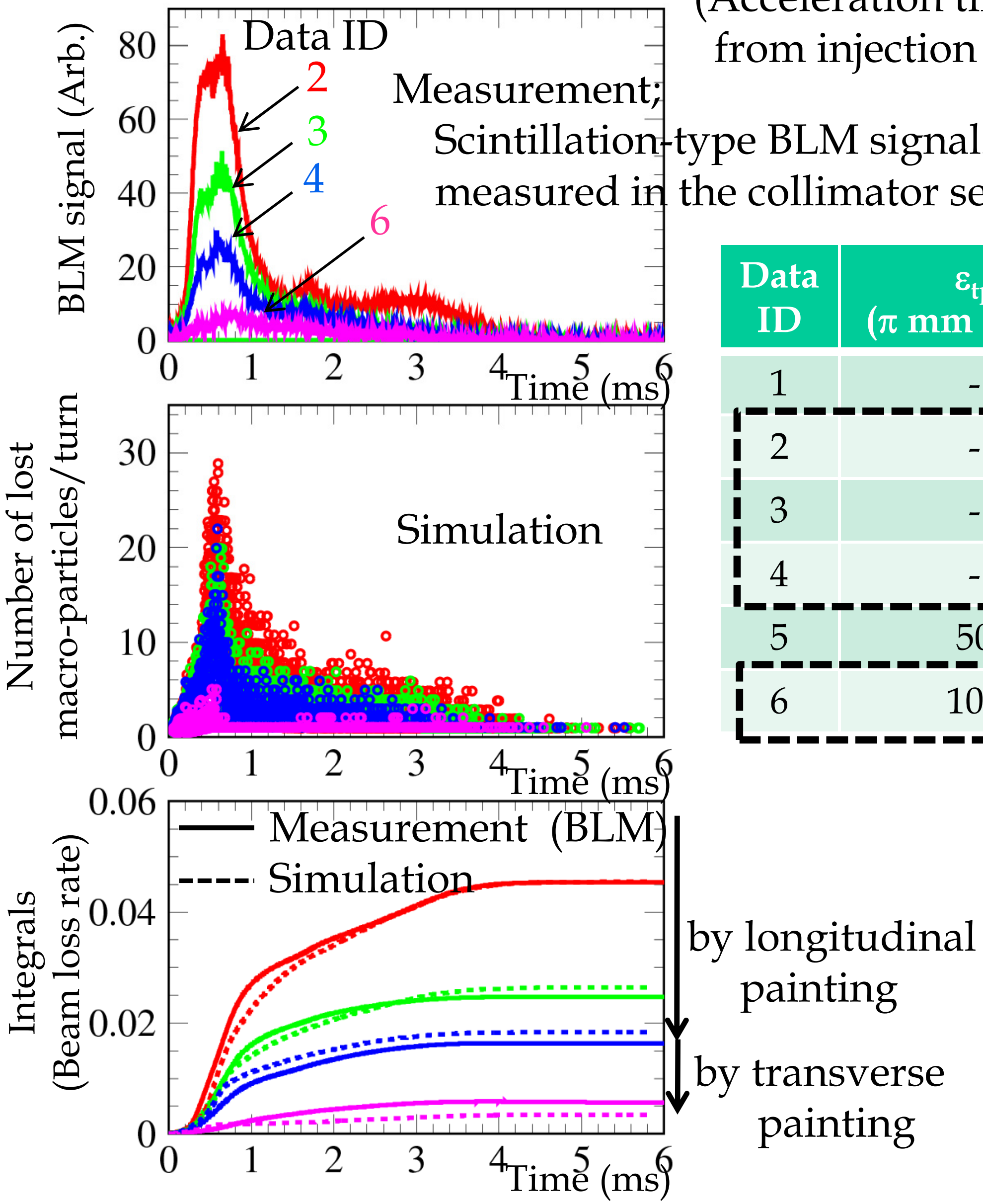
	Transverse painting	Longitudinal painting		
Data ID	ε_{tp} (π mm mrad)	V_2/V_1 (%)	ϕ_2 (deg)	$\Delta p/p$ (%)
1	-	-	-	-
2	-	80	-100	-0.0
3	-	80	-100	-0.1
4	-	80	-100	-0.2
5	50	80	-100	-0.2
6	100	80	-100	-0.2



Time structure of the beam loss

(Acceleration time
from injection to extraction; 20 ms)

Measurement;
Scintillation-type BLM signals for the first 6 ms
measured in the collimator section for data ID 2–6.



Data ID	ε_{tp} (π mm mrad)	V_2/V_1 (%)	ϕ_2 (deg)	$\Delta p/p$ (%)
1	-			
2	-	80	-100	-0.0
3	-	80	-100	-0.1
4	-	80	-100	-0.2
5	50	80	-100	-0.2
6	100	80	-100	-0.2

It was confirmed in this experiment
the present painting injection
- mitigates the space charge effect
through charge density control,
- leads to
significant beam loss reduction.

Significance of the high intensity beam test

Beam survival rate achieved for 420 kW-eq. intensity beam
in the present high intensity beam test;
>99% (residual beam loss; <1% in the injection energy region)

E_{inj}=181 MeV		E_{inj}=400 MeV
20 mA linac peak current x 0.56 chopper beam-on duty x 235 turns (0.5 ms) x 25 Hz →420 kW at 3 GeV (3.5E13/pulse)		50 mA linac peak current x 0.56 chopper beam-on duty x 307 turns (0.5 ms) x 25 Hz →1 MW at 3 GeV (8.3E13/pulse)
Laslet tune shift at injection; $\Delta\nu = -\frac{n_t r_p}{2\pi\beta^2\gamma^3\varepsilon}\frac{1}{B_f} \approx -0.19$	>	Laslet tune shift at injection; $\Delta\nu = -\frac{n_t r_p}{2\pi\beta^2\gamma^3\varepsilon}\frac{1}{B_f} \approx -0.15$

◆The present 420 kW beam operation gives more severe space-charge effect at the lower injection energy of 181 MeV than that at the higher injection energy of 400 MeV in the 1 MW beam operation as per the $\beta^2\gamma^3$ scaling law.

◆This achievement is considered to be a large step toward realizing the RCS design output beam power of 1 MW.

One of recent highlights in the J-PARC beam commissioning

Other highlights in the high intensity beam test

◆Beam loading compensation
by the multi-harmonic rf feed-forward method

“Performance of Multi-harmonic RF Feedforward System
for Beam Loading Compensation in the J-PARC RCS (WEPS097) ”
by F. Tamura et al.

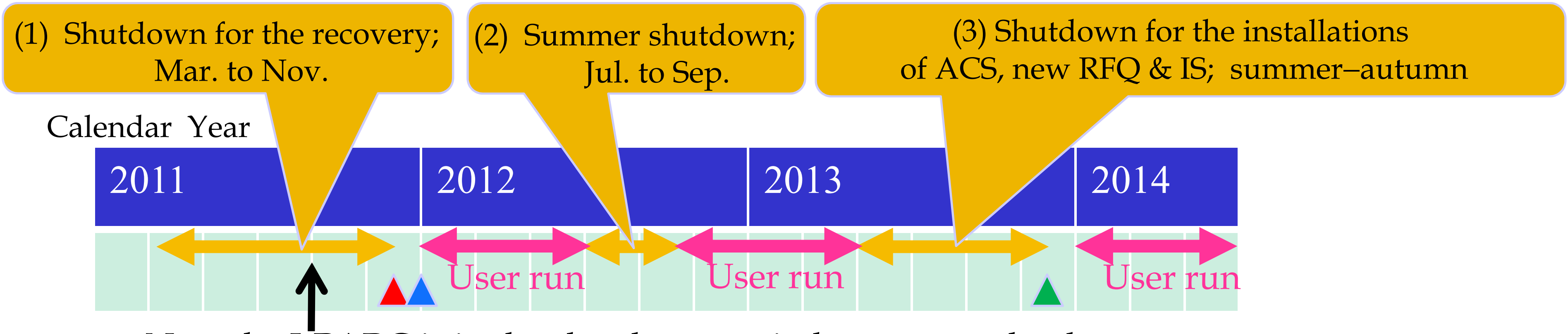
◆Observation of beam instability due to kicker impedance

“Mitigation of Beam Instability due to Space Charge Effects
at 3 GeV RCS in J-PARC (MOPS004) ”
by Y. Shobuda et al.

……… etc.

There are many presentations from the J-PARC in PAC2011.
Please refer to them and have a discussion with the J-PARC members.

Future plan



Now the J-PARC is in the shutdown period to recover the damages caused by the East Japan earthquake on March 11.

"Status of J-PARC after the East Japan Earthquake (WEPS095)" by K. Hasegawa et al.

▲ December, 2011~; Restart of the beam tests

▲ January, 2012~ ; Restart of the user operations

The next goal of the J-PARC beam commissioning is to realize the routine user operations with,

- 300 kW output beam power from the RCS
- 200–300 kW output beam power from the MR (fast extraction mode)

before upgrading the linac.

Summer–autumn, 2013; Installations of ACS, new RFQ & IS

- The mass production of the ACS modules is in progress almost on schedule, and the high power test for the first mass production module has been completed.
- The new RFQ design has been completed, and its fabrication has just started.
- The development of the new IS has just started.

▲ End of 2013~; Beam commissioning of the upgraded linac

Summary

- ◆ The J-PARC accelerators have started the user program for the MLF, NU, and HD.
- ◆ The accelerator study as well as the user operation are well in progress.
- ◆ The output beam power has been steadily increased following the progression of beam tuning and hardware improvements, and with carefully monitoring the trend of machine activation levels;
  - Output beam power to the MLF achieved ; 220 kW
  - Output beam power achieved at MR ; 145 kW (fast extraction mode)
- ◆ The RCS recently performed a high intensity beam test with 420 kW-eq. intensity beam, in which we got several significant progresses essential for realizing the 1MW design beam operation;
  - Beam loss reduction by the painting injection
  - Beam loading compensation by the multi-harmonic rf feed-forward method . . .

- ◆ The next goal of the J-PARC beam commissioning is to realize the routine user operations with,
  - 300 kW output beam power from the RCS
  - 200~300 kW output beam power from the MR, before upgrading the linac.

- ◆ The installation of the ACS, new RFQ and IS are scheduled in 2013 summer-autumn period.
- ◆ The beam commissioning of the upgraded linac will start by the end of 2013.