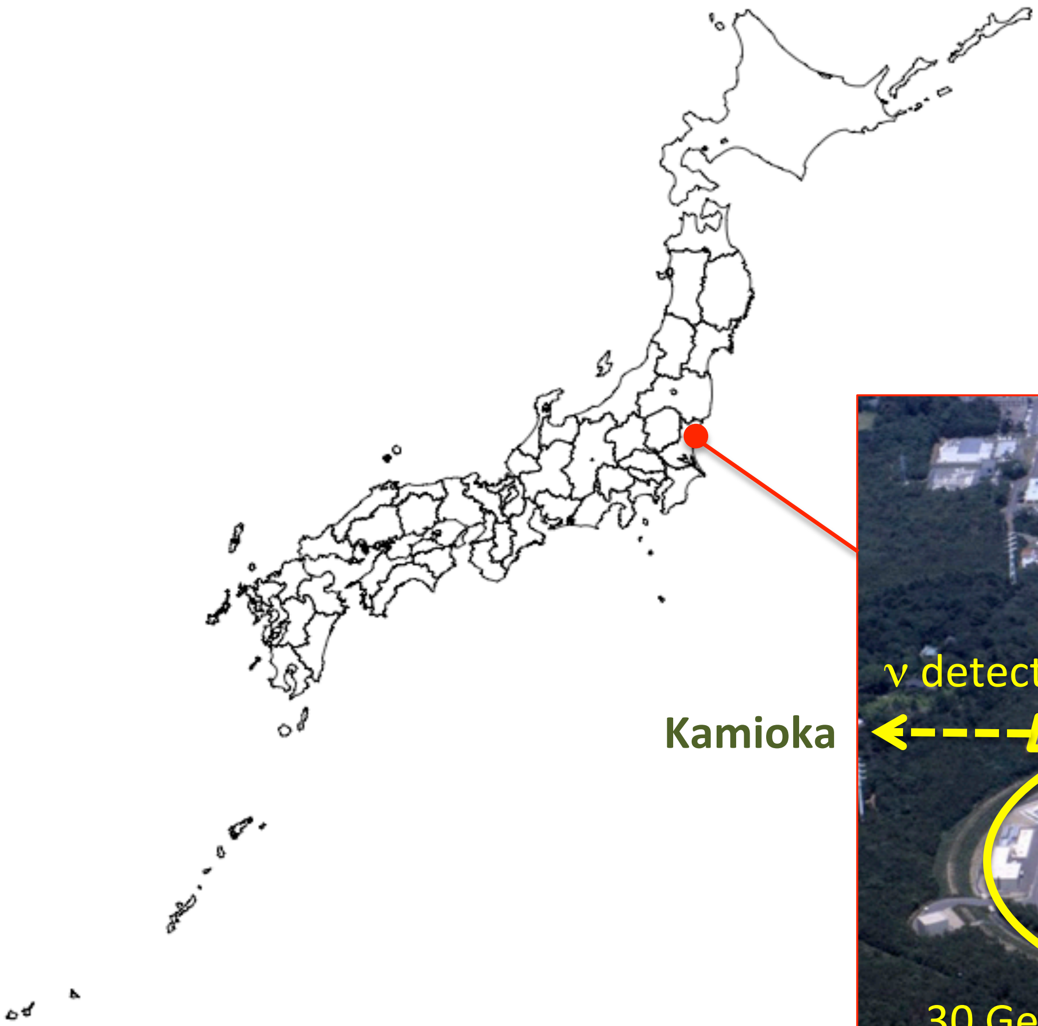
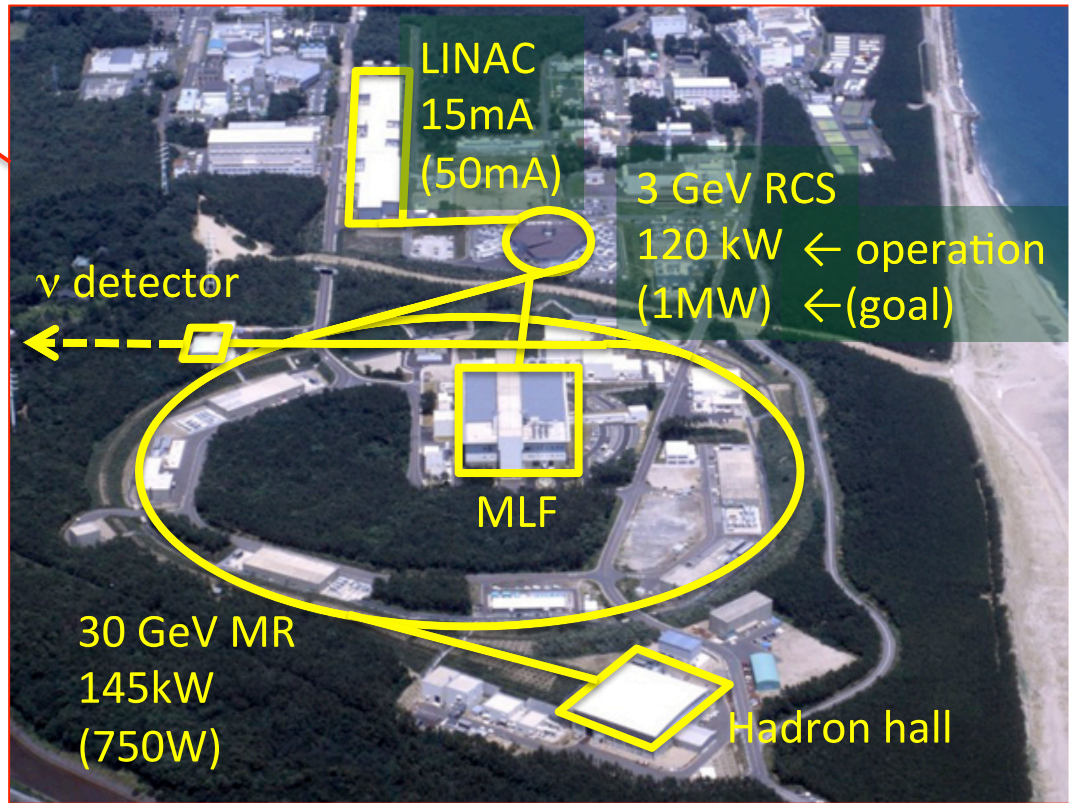
High Power Operation
and
Beam Instrumentations
in
J-PARC Synchrotrons

Takeshi Toyama
KEK / J-PARC

IPAC2013, May 12-17 2013, Shanghai China

Japan Proton Accelerator Research Complex





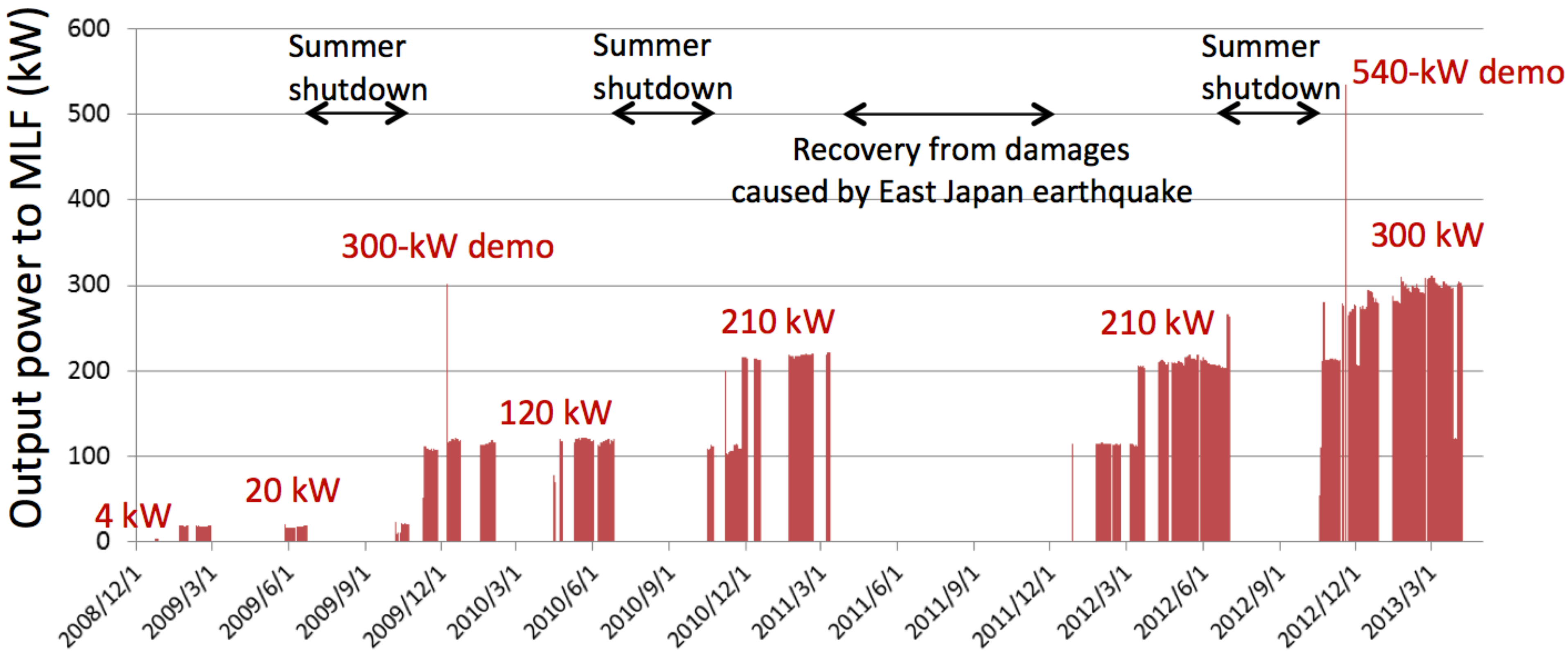
Outline

- **Introduction**
  – Beam power history of the J-PARC RCS and MR
  – Beam monitors and the beam parameters
- **Operational aspect of the instruments**
  – Identify & manipulate small beam losses:
    Current monitors, loss monitors
  – Precise machine modeling:
    BPMs with Beam based calibration
  – Profile, tail and halo measurements
  – Stripline kicker, "Exciters"
    for slow extraction
- **Summary**

Introduction

Beam power history of the J-PARC RCS and MR

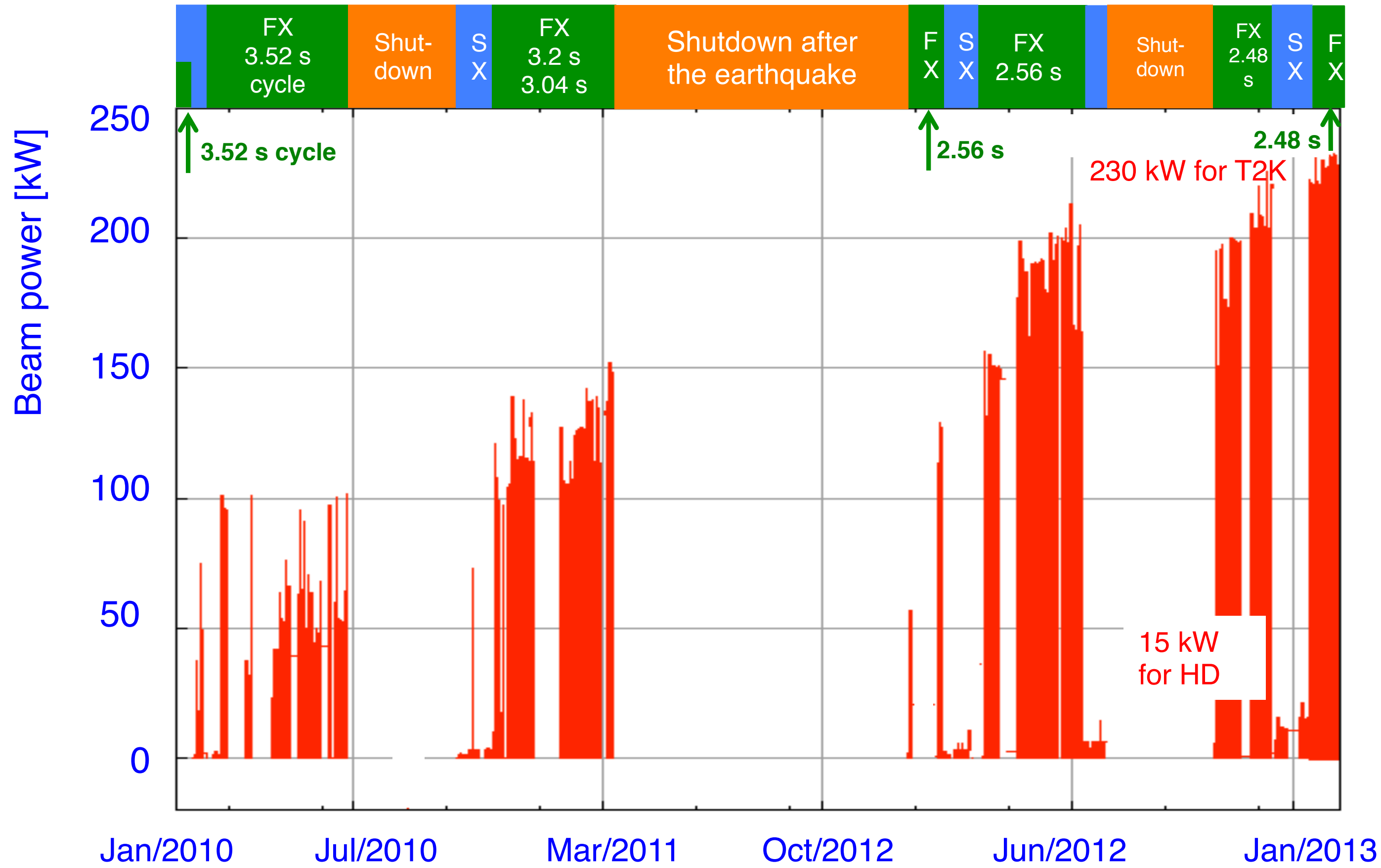
RCS output beam power history



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

H. Hotch

MR operation history from Jan 2010 to Feb 2013



- Beam commissioning of the MR — May 2008
- First beam to the Hadron target with slow extraction — Feb 2009
- T2K neutrino beamline started operation — Apr 2009

T. Koseki

Introduction

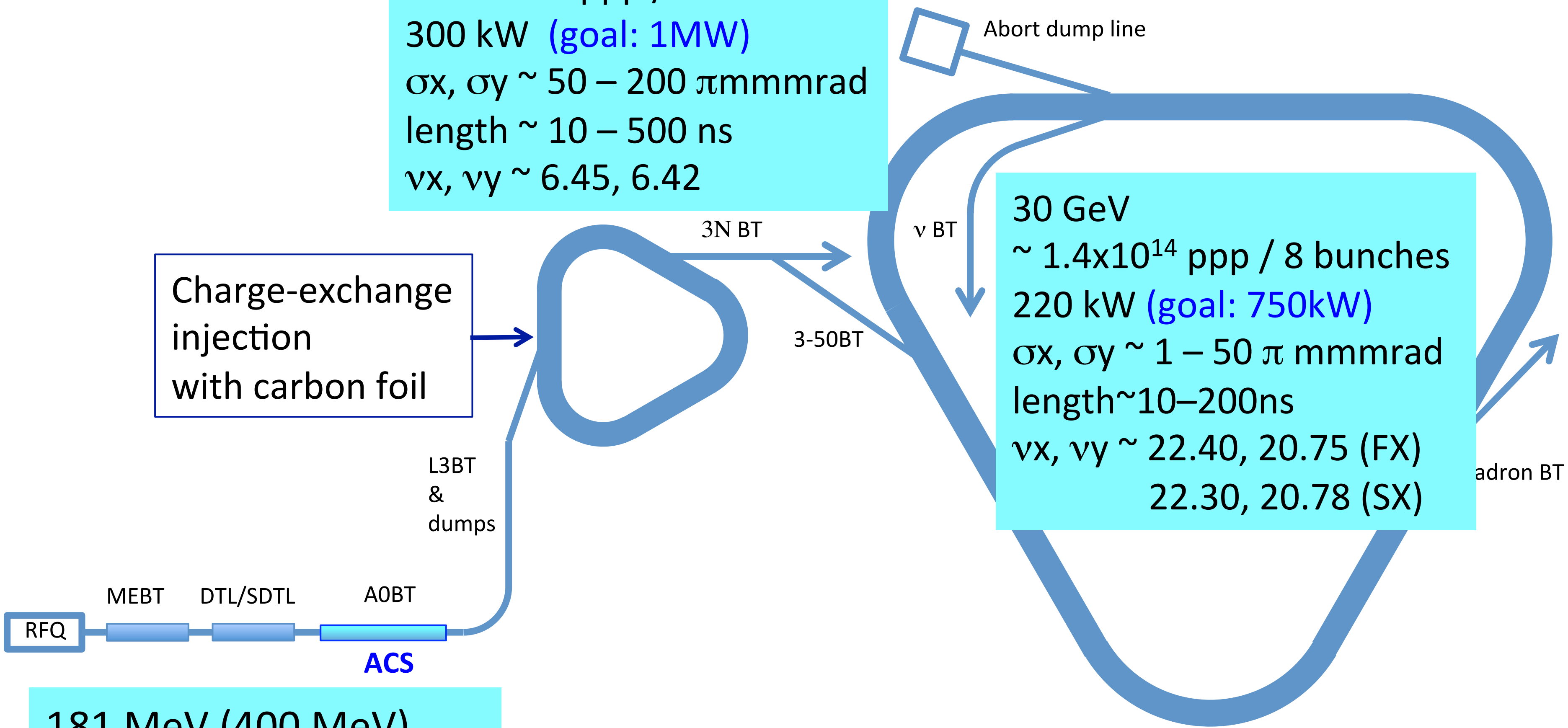
Beam monitors and the beam parameters

Beam parameters

3 GeV
~ 2.6×10^{13} ppp / 2 bunches
300 kW (goal: 1MW)
σx, σy ~ 50 – 200 πmmmrad
length ~ 10 – 500 ns
νx, νy ~ 6.45, 6.42

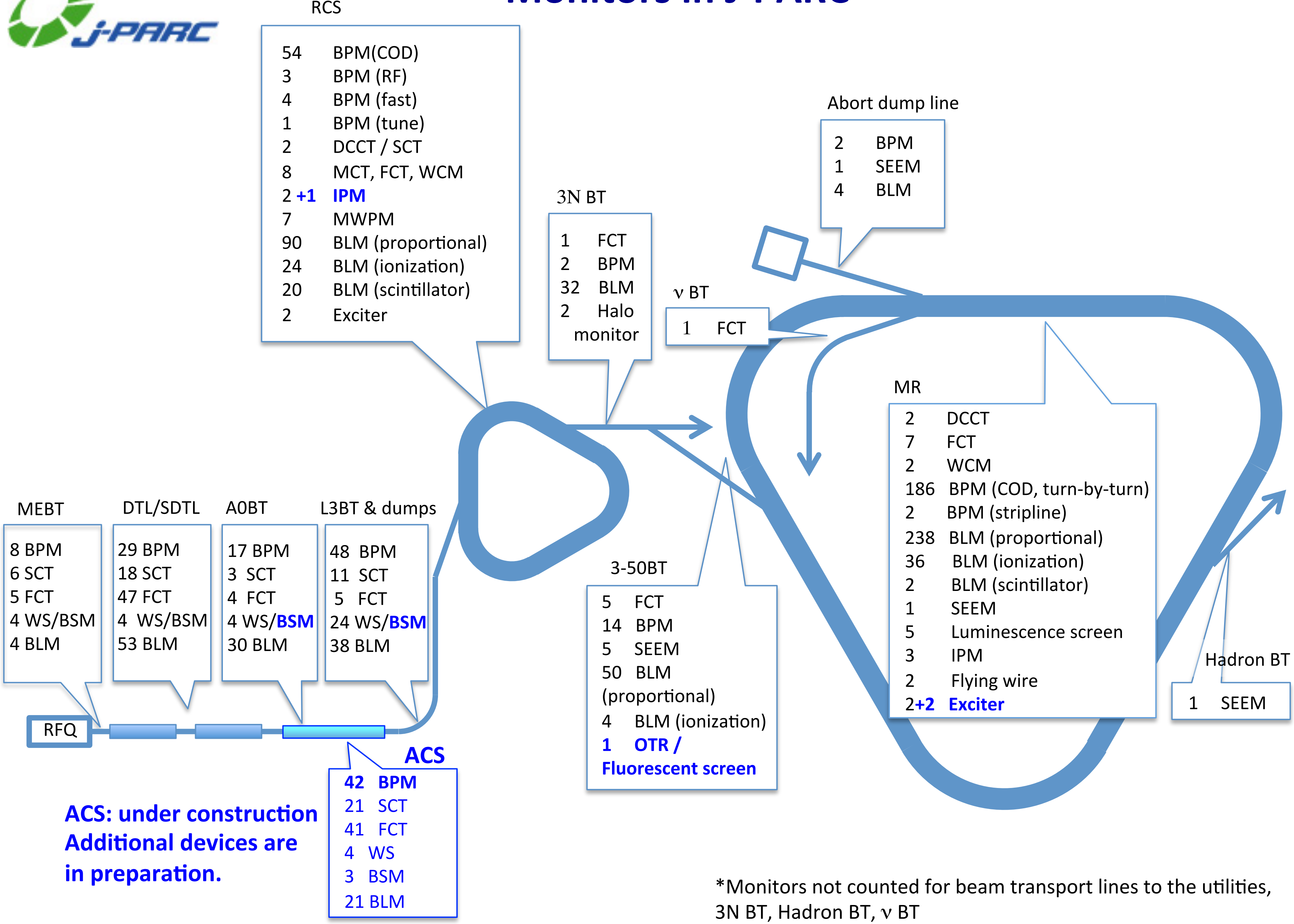
Charge-exchange injection with carbon foil

30 GeV
~ 1.4×10^{14} ppp / 8 bunches
220 kW (goal: 750kW)
σx, σy ~ 1 – 50 π mmmrad
length~10–200ns
νx, νy ~ 22.40, 20.75 (FX)
22.30, 20.78 (SX)



181 MeV (400 MeV)
H^- ~ 20 mA (goal: 50mA)
σx, σy ~ 0.1 πmmmrad
length ~ 0.1 ns

Monitors in J-PARC



ACS: under construction
Additional devices are in preparation.

*Monitors not counted for beam transport lines to the utilities, 3N BT, Hadron BT, ν BT

Operational aspect of the instruments

Identify & manipulate small beam losses:
Current monitors, loss monitors

J-PARC Required Resolution for Intensities, Losses

- Power is limited by the beam losses

- 1 W / m @RCS
- 0.5 W/m @MR

→ Resolution of beam current measurement

$$\Delta I / I < 0.1\%$$

In practice we check residual activities along the rings.

Machine study of the high intensity beam @RCS

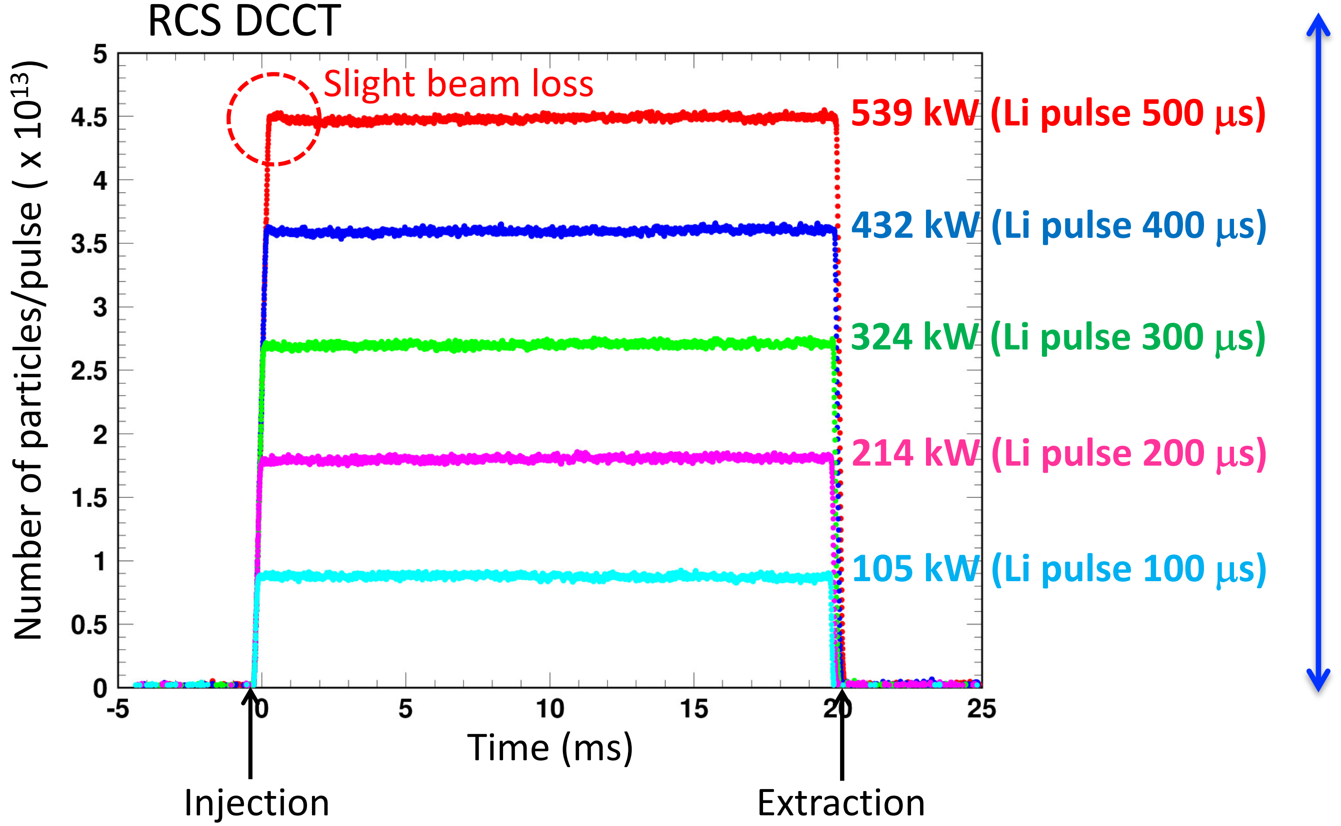
Intensity dependence of beam loss

Beam power < 540 kW

Injection beam : 24.5 mA, 100-500 μs, 640 ns, 2 bunches

Transverse painting : 100π-mm-mrad correlated painting

Longitudinal painting : V_2/V_1 80% (5ms), $\Delta\phi_{12}$ -100~0 deg, $\Delta p/p$ -0.2%



Dynamic range:

$I < 0.15, 1.5, 15A$

Resolution :

$$\left|\frac{\Delta I}{I}\right| \leq 0.1\text{-}0.8\%$$

Frequency bandwidth:

f <10k-20kHz

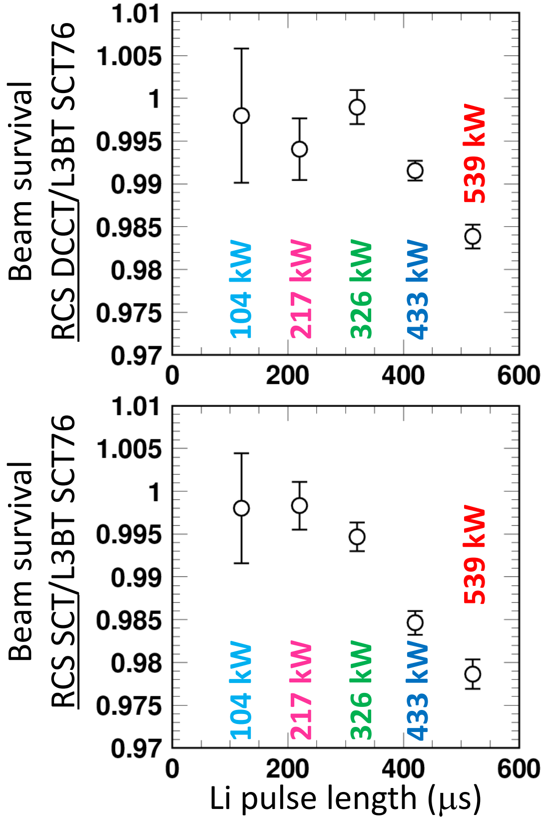
(Bergoz DCCT)

THPWO033 Hideaki Hotchi, High Intensity Beam Trial of up to 530 kW in J-PARC RCS

Current monitor vs beam loss monitor

Intensity dependence of beam loss

Beam survival : ratio of output intensity (RCS DCCT or SCT) to input intensity (L3BT SCT76)

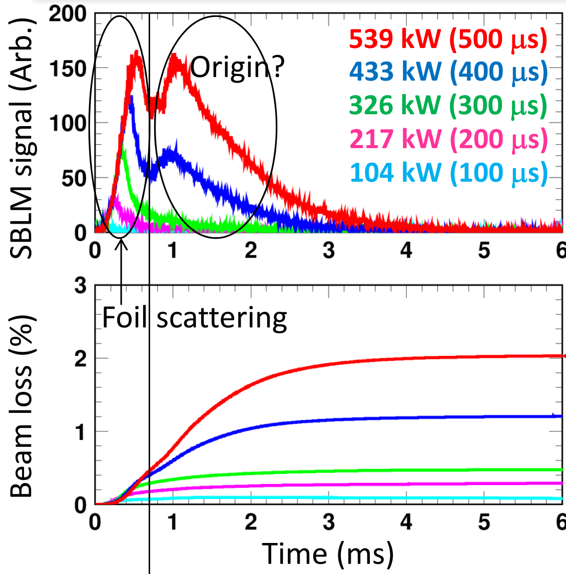


539 kW (Li pulse 500 μs) ~2% loss
433 kW (Li pulse 400 μs) 1~1.5% loss
325 kW (Li pulse 300 μs)
217 kW (Li pulse 200 μs)
104 kW (Li pulse 100 μs)
~<0.5% loss

Calibrate

Time structure of beam loss

Scintillation type BLM @ Primary collimator



The beam loss appears only for the first 4 ms in the low energy region.

Normalized to be 2%

~1.2 % loss

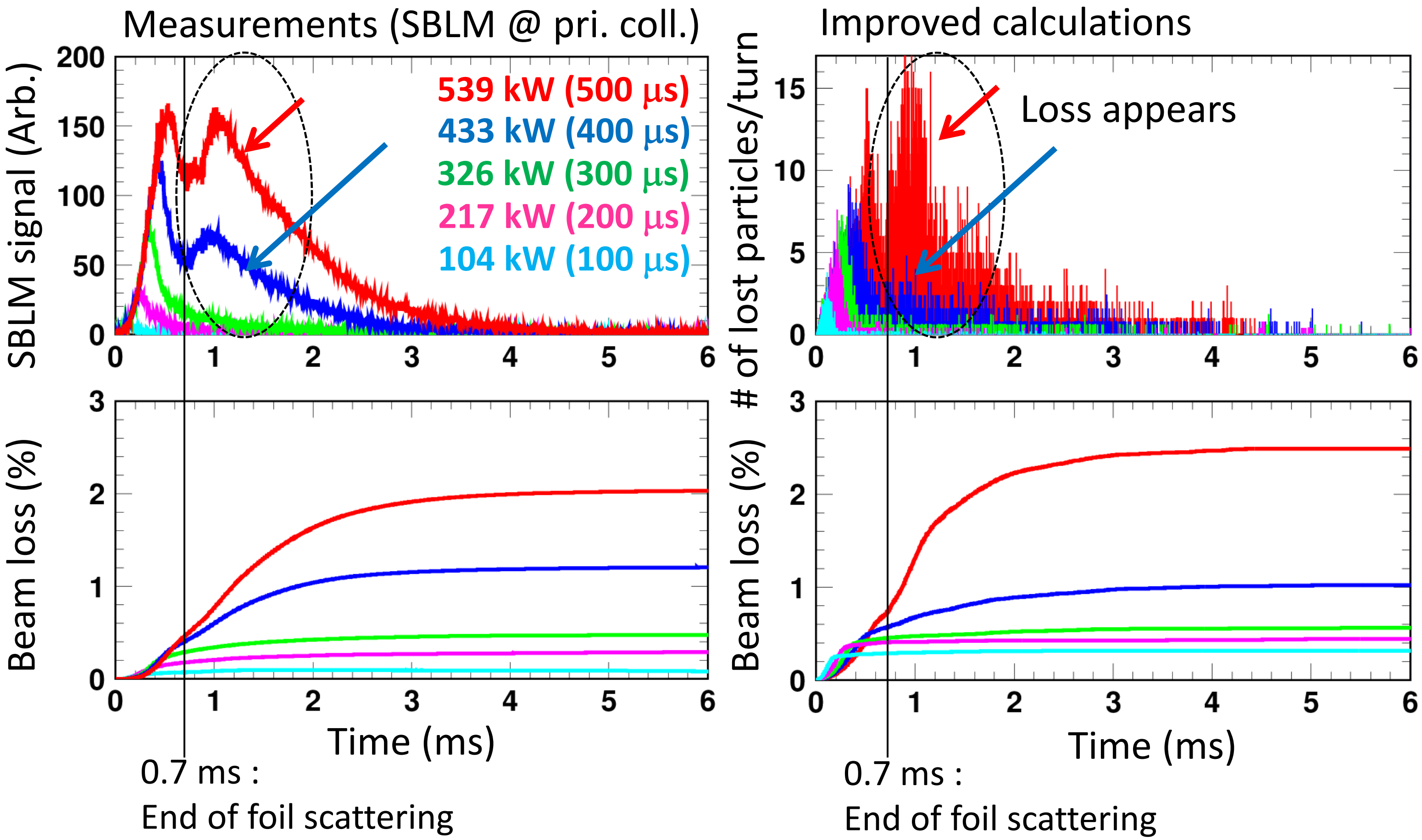
~<0.5% loss

~0.7 ms : End of foil scattering

Beam Loss monitor data

H.Hotchi et al.,2013

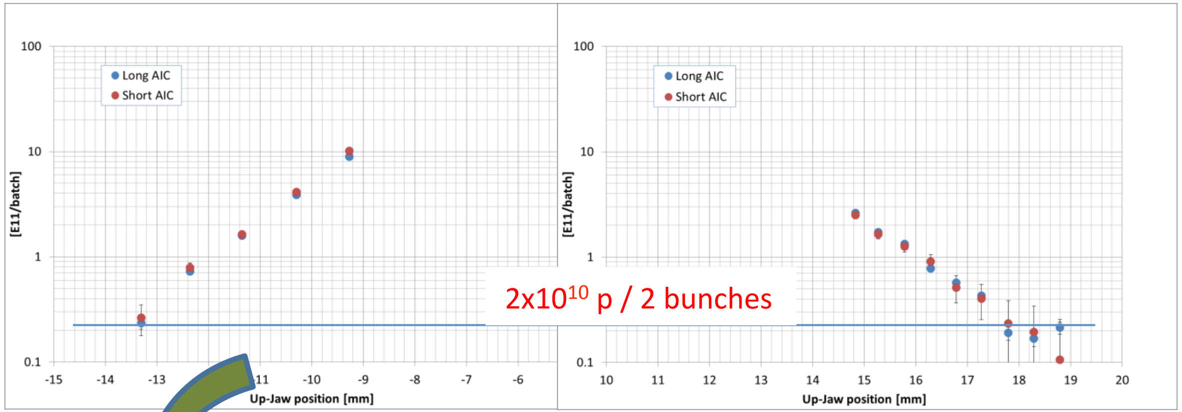
Measurements vs improved calculations
: beam loss

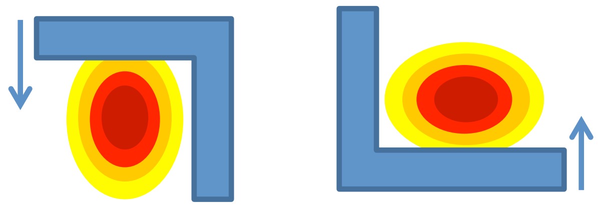


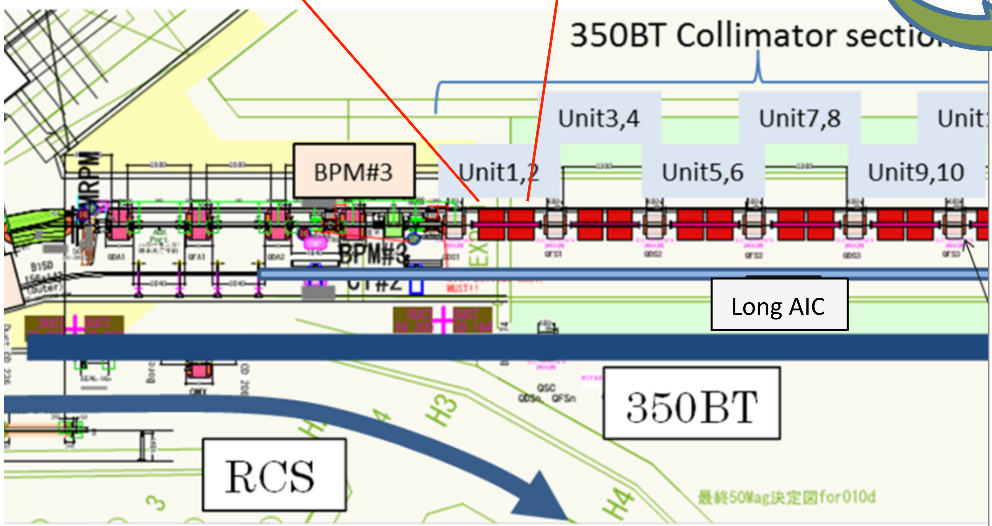
The improved calculations well reproduce the measured time dependence and intensity dependence of beam loss.

Beam tail measurement at 350BT Collimator using BLMs

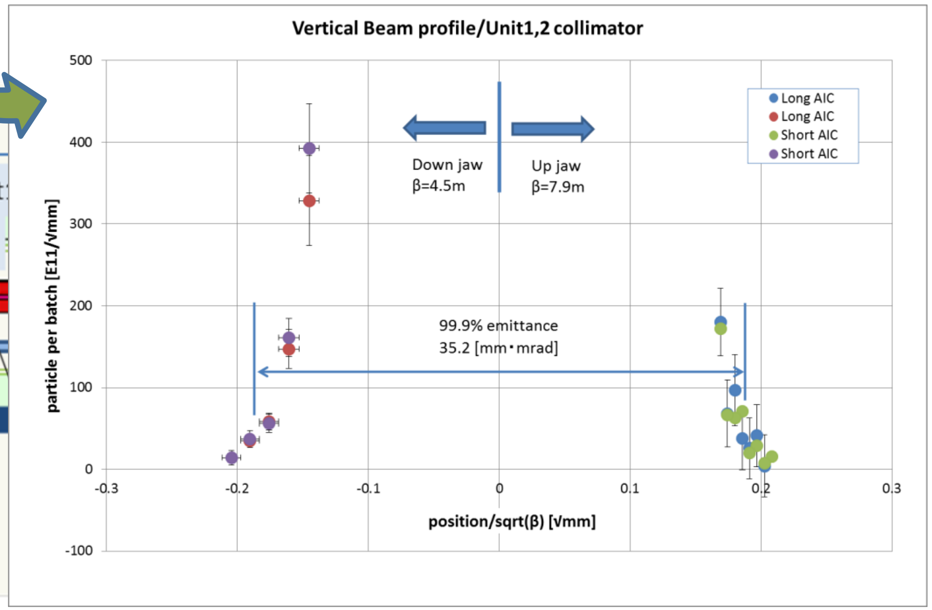
Beam tail are removed by the movable L shaped collimator jaw. The beam intensity was identified by the calibrated BLMs, short AIC and Long AIC.







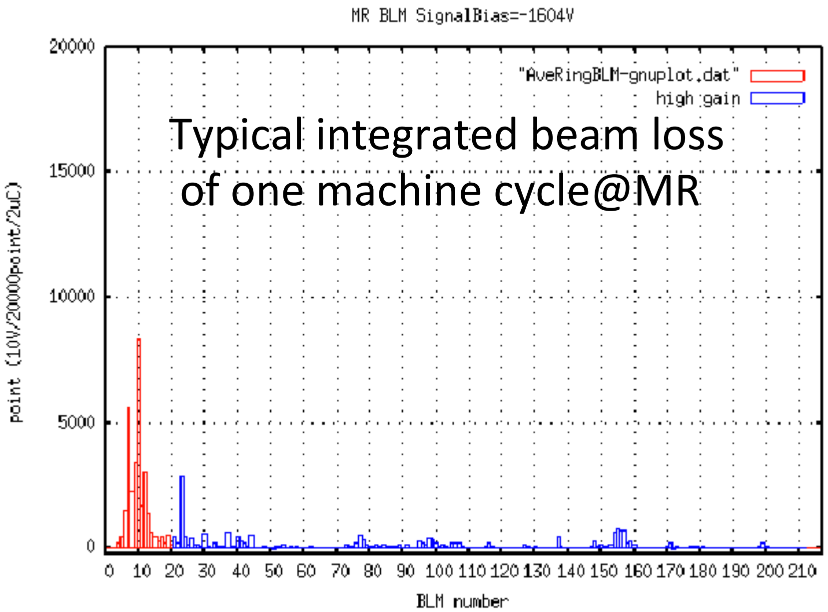
Differentiation yields beam tail profile

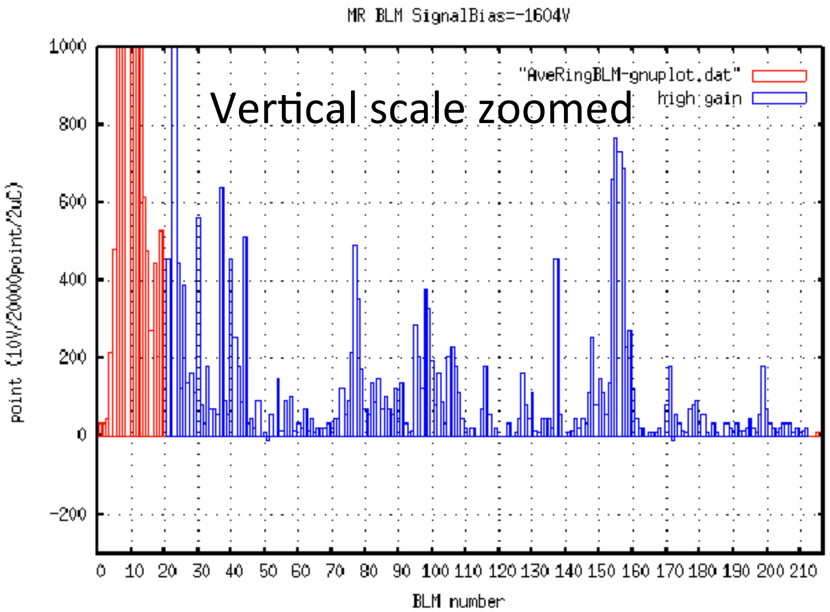


K. Satou, M. Shirakata, Y. Sato

Difficulty in some cases

In the case that the beam loss is not localized
Not all the BLMs have been calibrated
→ DCCT resolution, accuracy required!





So far we calibrated the BLMs at the straight section, "Insertion-B" for SX to estimate the extraction efficiency of the slow beam extraction.

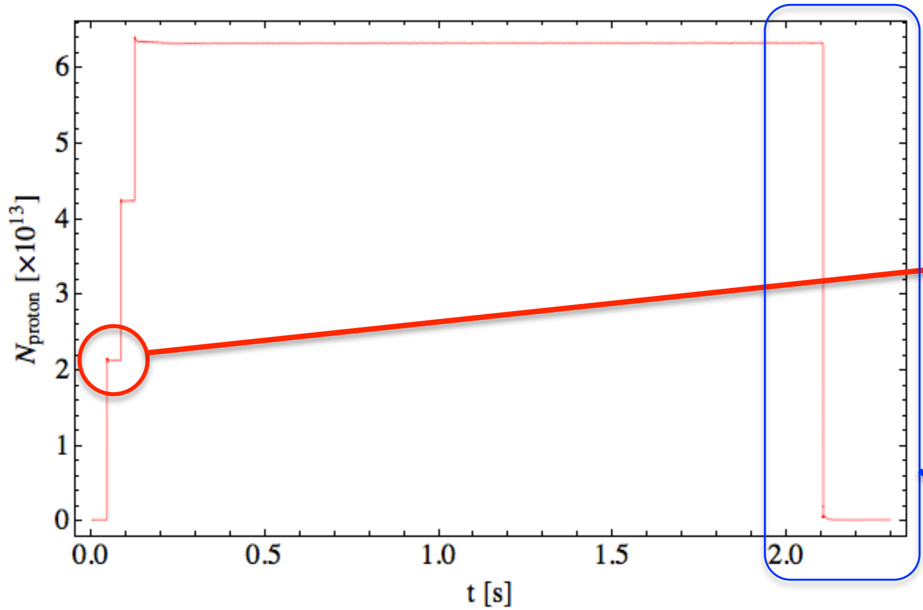
DCCT response correction with the beam

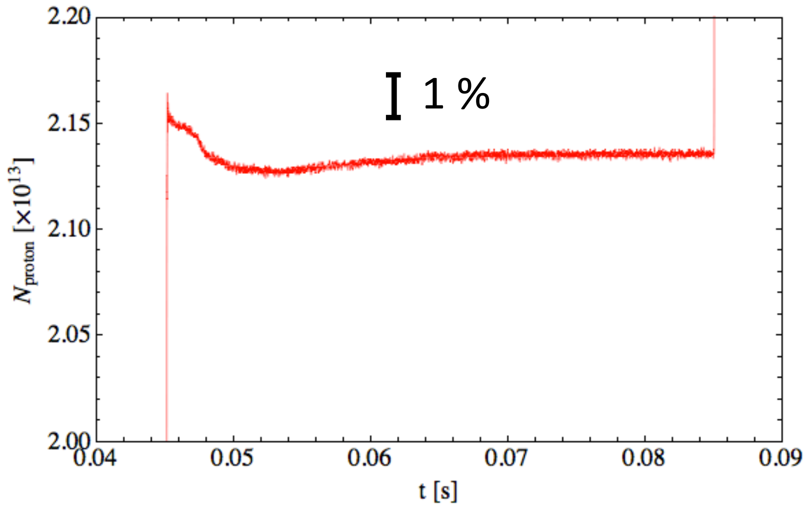
Better precision required:

to detect the beam loss of a few 10 W, ΔI ~ 100μA

especially in the injection transient

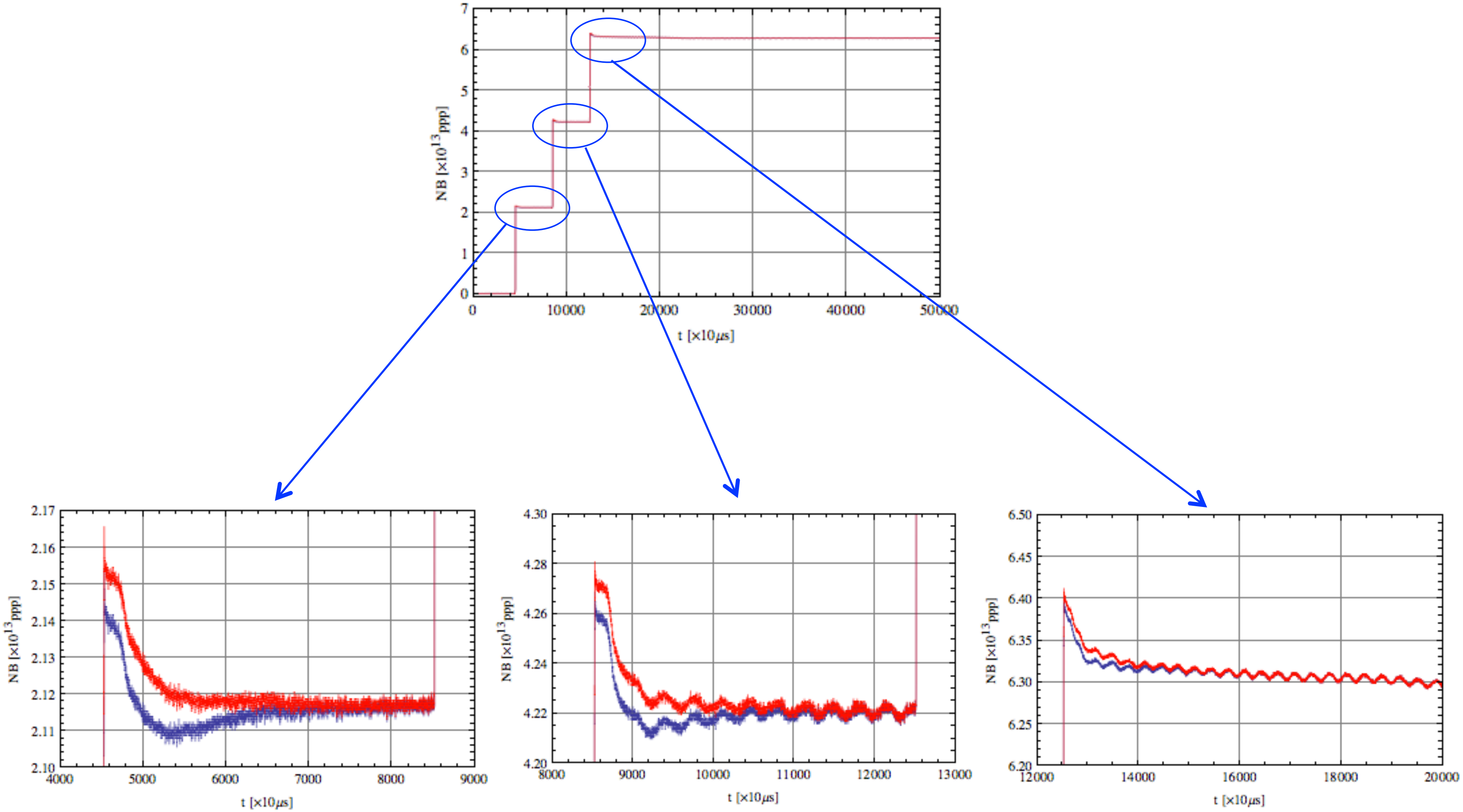
Typical beam in the MR





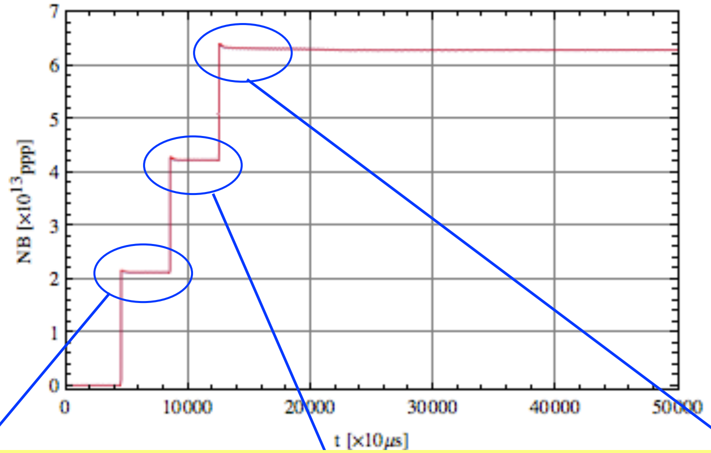
Calibrated
using step response at the end

Corrected response

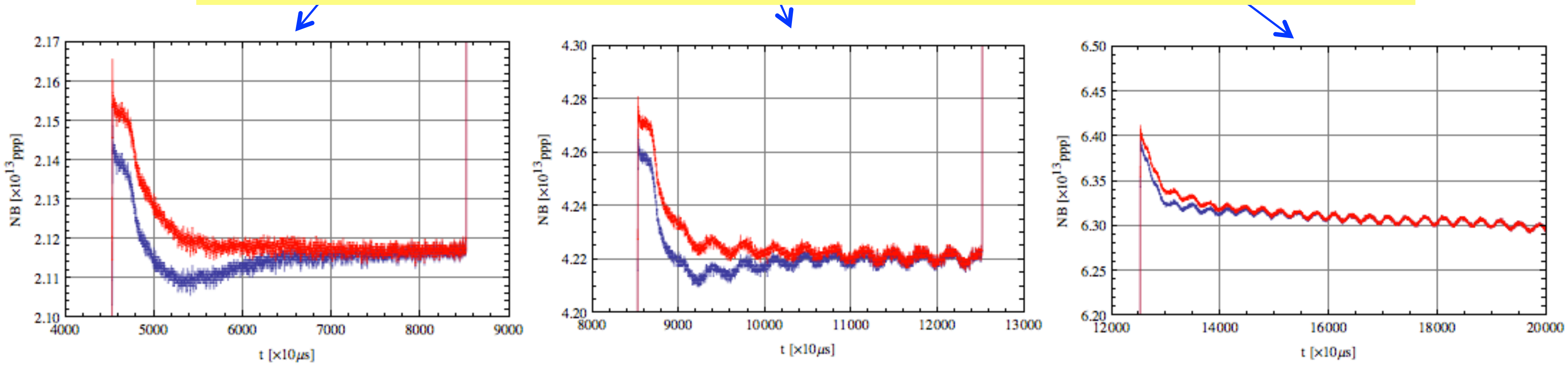


Blue : no correction red : with correction

Corrected response



The response drifts during recent high power operation under investigation



Blue : no correction   red : with correction

Operational aspect of the instruments

Precise machine modeling:
BPMs
with Beam based calibration

Beam Position Monitors (BPMs) and profile monitors (BT):

important device for ring modeling:

basis of beam simulations and control at high intensities

BPMs in J-PARC:

L3BT	RCS	350BT	MR
48	54 (COD)	14 (+3 planned)	186 (COD)
	8 (others)		2 (others)

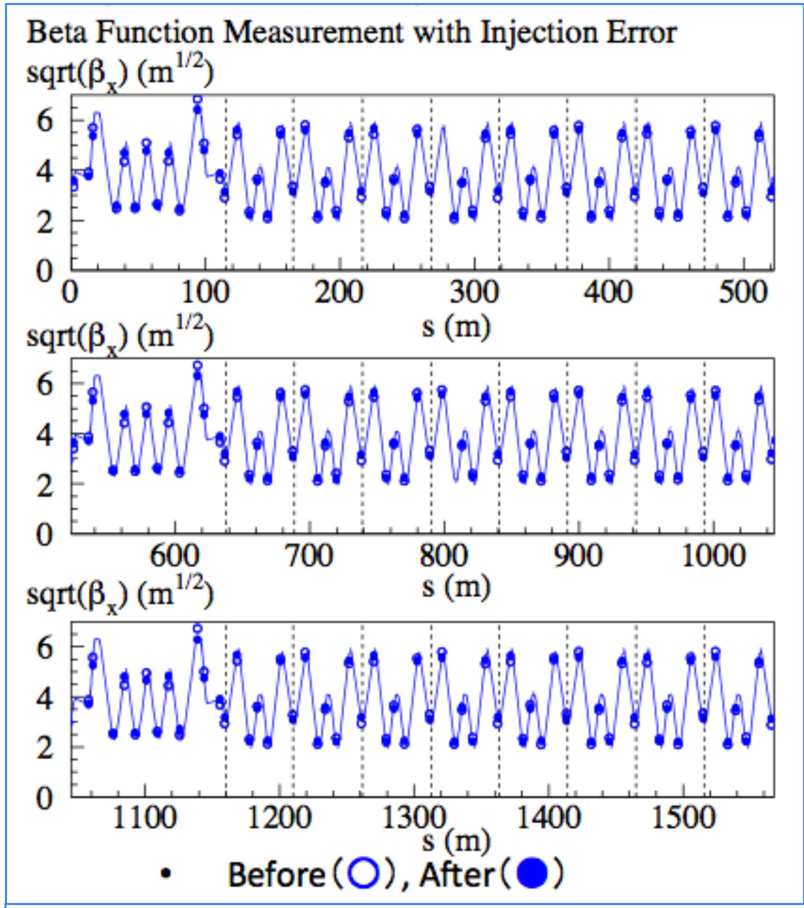
position data provides a lot of informations

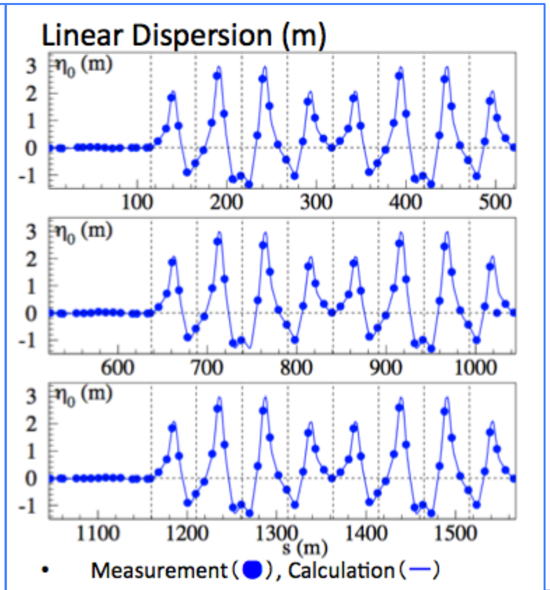
$$x,\ y = \sqrt{\varepsilon\beta}\cos\left[\left(\nu_0 + \xi\frac{\Delta p}{p}\right)\phi + \psi_0\right] + \eta\frac{\Delta p}{p}$$

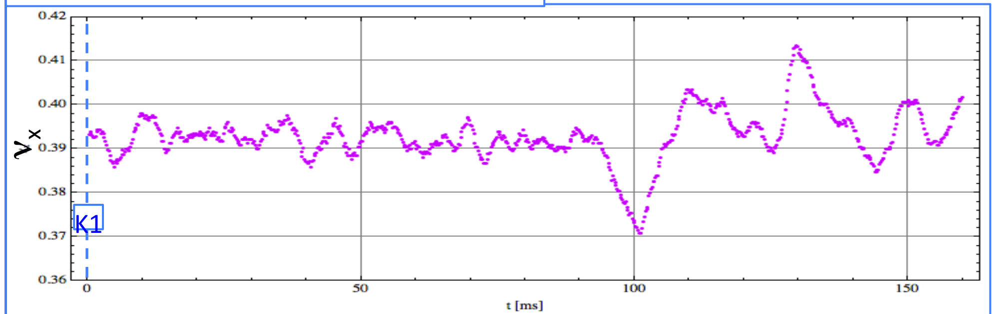
COD
bunch position
intra-bunch position

need precision, resolution

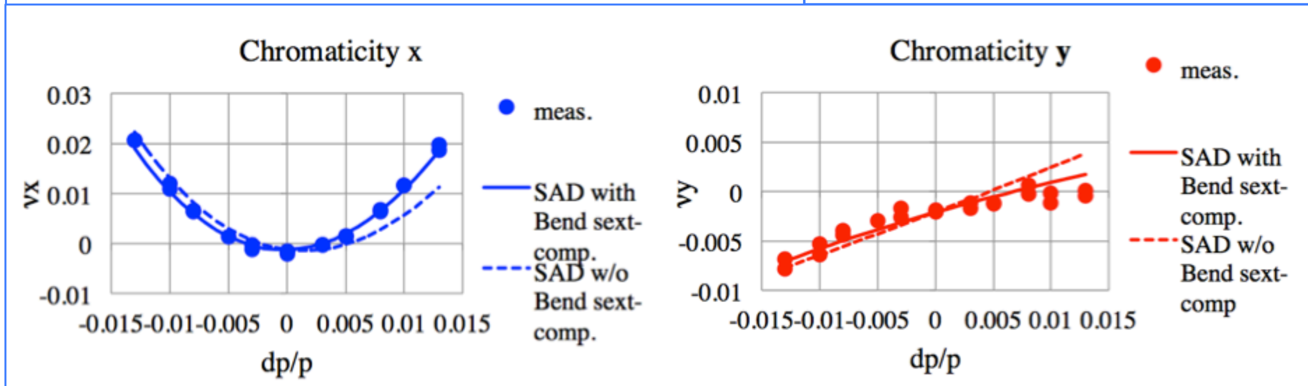
Machine parameter measurements







Examples from MR data



S. Igarashi

Beam based Alignment of BPMs

- Ordinary Beam based alignment

  Using one QM for one BPM

$$\begin{aligned} x_{2m} &= -a_{mn}\Delta K(x_{1n}+x_{2n}) \\ &= -\frac{a_{mn}\Delta K(x_{1n})}{1+a_{nn}\Delta K}. \end{aligned}$$

m : BPM location

n : QM location

- Extension to multiple BPMs with a QM family

$$x_{2m} = -\Delta K[\ a_{mn} \quad a_{ml} \quad a_{ms}\ ](I+\Delta K A)^{-1}\vec{x_1}$$

m : BPM location

n, l, s : QM location

N. Hayashi *et al.*, IPAC10, and HB2010

BBA at RCS

RCS 54 BPM

7 QM families (60 QMs)

BBA with QM families

σ ~ 500μm

BPM itself:

σ ~ 20 μm (averaged)
σ ~ 300 μm (turn-by-turn)

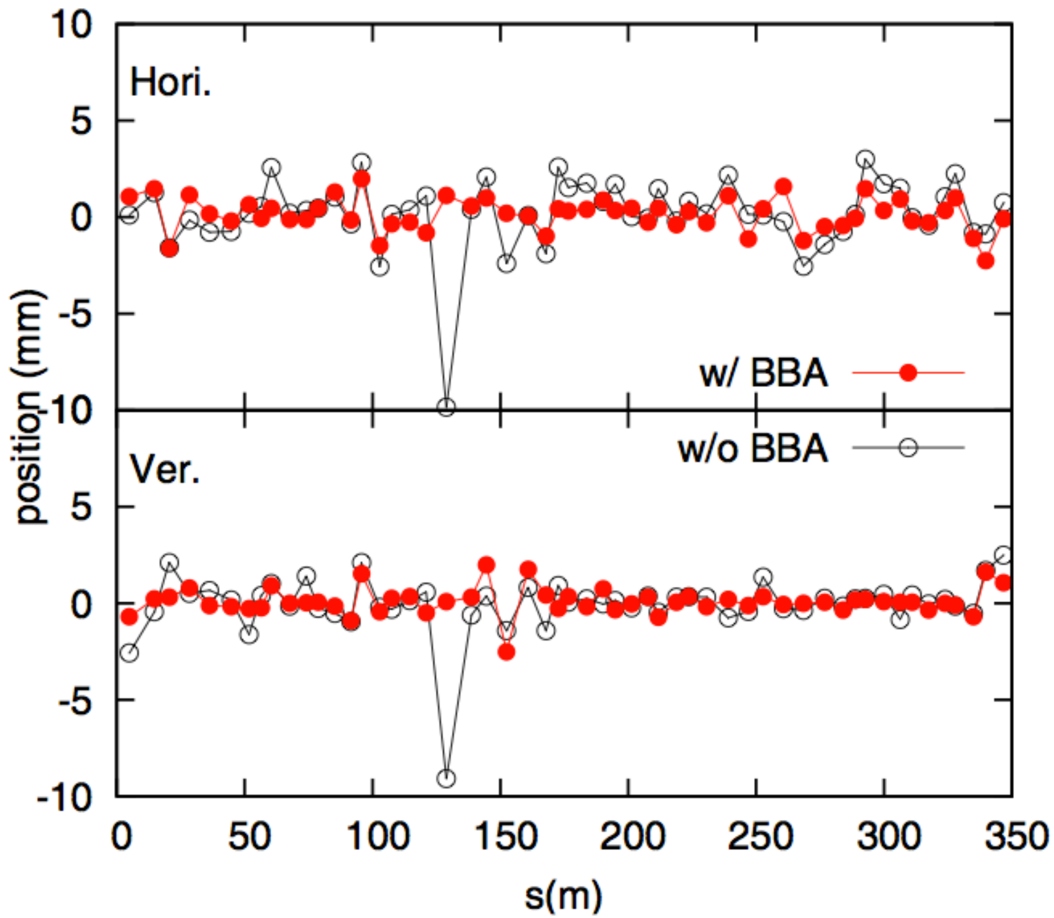


Figure 3: COD correction without (open circle) and with (closed circle) using BBA results. Upper is for horizontal and lower is vertical one.

N. Hayashi *et al.*, NIM A677 (2012) 94-106

BBA at MR

MR

186 BPMs

11 QM families (216 QMs)

Comparison of BBA
with one QM
and
with QM families

σ ~ 100μm

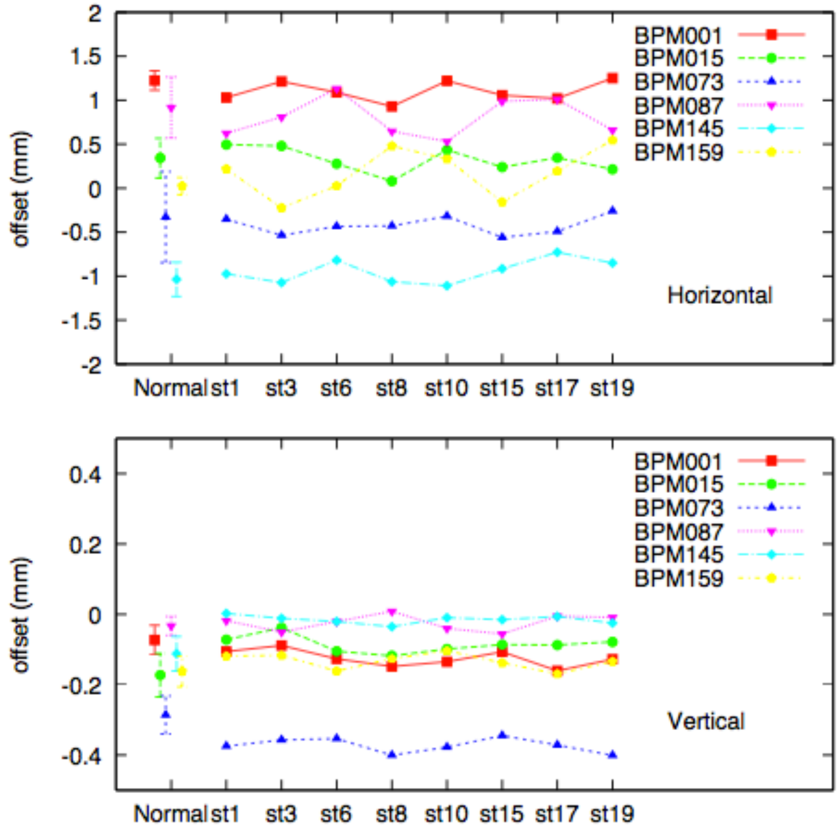
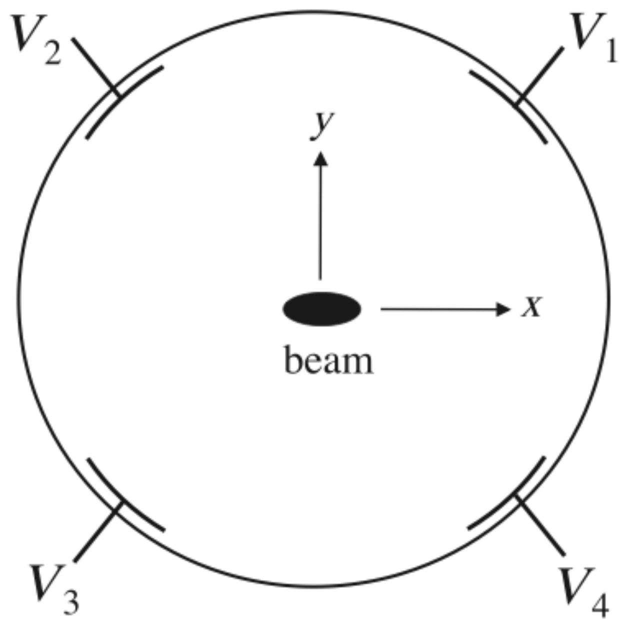


Figure 3: MR BBA offset estimation of BPM attached to QFS family magnets. Upper and lower are horizontal and vertical, respectively. Most left data is determined by single QM sweeping and reference. Eight data sets are independent measurements for different initial orbits defined by various steering magnets.

N. Hayashi *et al.*, IPAC10, and HB2010

Beam-based gain calibration

Gain of 4 pickups are
calibrated with the beam.



$V_{i,j} = g_i \cdot q_j \cdot F_i(x_j, y_j)$

g_i : gain

q_j : charge of j-th measurement

x_j, y_j : beam position of j-th measurement

Number of pickups: $i = 1,2,3,4$

Number of measurements: $j = 1, \ldots, m$

If the number of unknown parameters < total number of data

3 + 3 m < 4 m

we can solve the equation

Successfully applied to the KEKB BPMs

Improvement of "consistency"

@ KEKB

The four beam positions can also be obtained from the output voltage of any three electrodes chosen out of four electrodes as

$$\begin{cases} x_1 = F_{1,x}(h_1, v_1), & x_2 = F_{2,x}(h_2, v_1), & x_3 = F_{3,x}(h_2, v_2), & x_4 = F_{4,x}(h_1, v_2) \\ y_1 = F_{1,y}(h_1, v_1), & y_2 = F_{2,y}(h_2, v_1), & y_3 = F_{3,y}(h_2, v_2), & y_4 = F_{4,y}(h_1, v_2) \end{cases}, \quad (6)$$

$$h_1 = \frac{V_1 - V_2}{V_1 + V_2}, \quad h_2 = \frac{-V_3 + V_4}{V_3 + V_4}, v_1 = \frac{V_2 - V_3}{V_2 + V_3}, \quad v_2 = \frac{V_1 - V_4}{V_1 + V_4}. \quad (7)$$

"consistency" = root-mean-squares of the four beam positions

Before
the gain calibration

After
the gain calibration

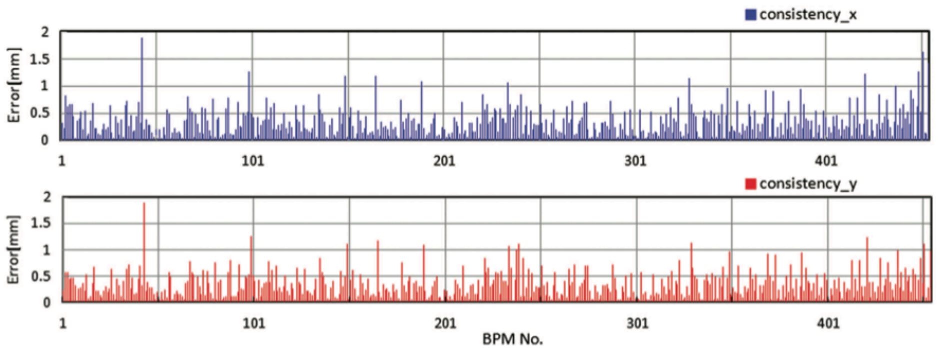
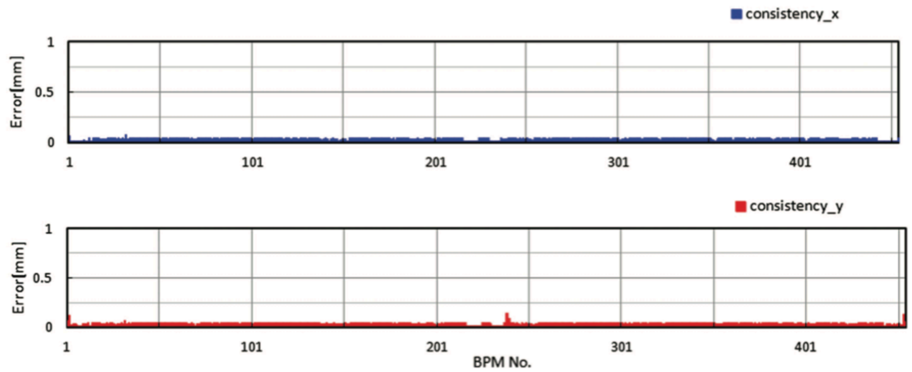


Fig. 28. Consistency before gain calibration in the LER.



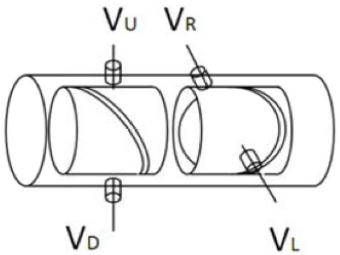
g. 29. Consistency after gain calibration in the LER.

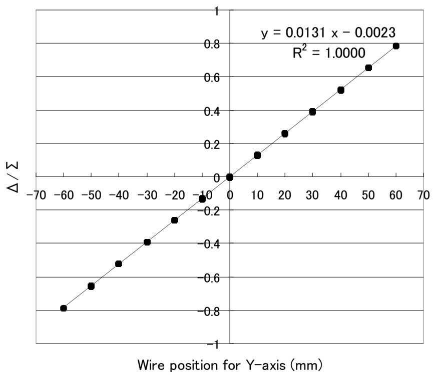
K. Sato, M.Tejima, Proc. of PAC1995, p.2482
M. Arinaga et al., Prog. Theor. Exp. Phys. 2013, 03A007

Gain calibration of the diagonal-cut BPM

J-PARC Ring BPM:

- **Good linear response**





Signal from the electrodes:

$L_k = \lambda_k (1+x_k/a)$

$R_k=\lambda_k g_R (1-x_k/a)$

$U_k=\lambda_k g_U (1+y_k/a)$

$D_k=\lambda_k g_D (1-y_k/a)$

$\lambda_k,\ x_k,\ y_k\ (k=1,2,\cdots,n)$

$g_R,\ g_U,\ g_D$

Simplified as follows:

$L_k+R_k/g_R-U_k/g_U-D_k/g_D = 0$

Problem is to solve 3 g_ks:

$$\begin{pmatrix} -R_1 & U_1 & D_1 \\ & \vdots & \\ -R_k & U_k & D_k \\ & \vdots & \\ -R_n & U_n & D_n \end{pmatrix} \begin{pmatrix} \frac{1}{g_R} \\ \frac{1}{g_R} \\ \frac{1}{g_R} \end{pmatrix} = \begin{pmatrix} L_1 \\ \vdots \\ L_k \\ \vdots \\ L_n \end{pmatrix}$$

Test was done with this algorism

Table 2: Test of Beam Based Gain Calibrations

BPM001	g_2	g_3	g_4
TLS	1.0062	1.0024	0.9873
LS	1.0103	1.0045	0.9892
BPM002	g_2	g_3	g_4
TLS	0.9568	0.9811	0.9463
LS	0.9617	0.9838	0.9487

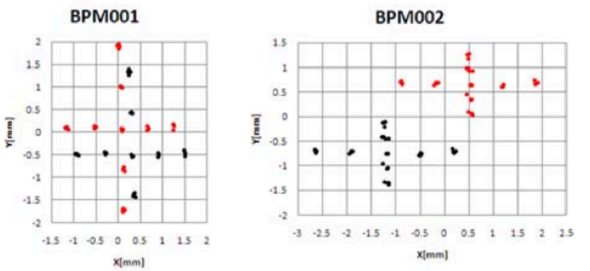


Figure 5: Reconstructed mapping data. Red: (x, y) without correction, Black: (x, y) with TLS.

M.Tejima et al., IBIC2011

Operational aspect of the instruments

Profile, tail and halo measurements

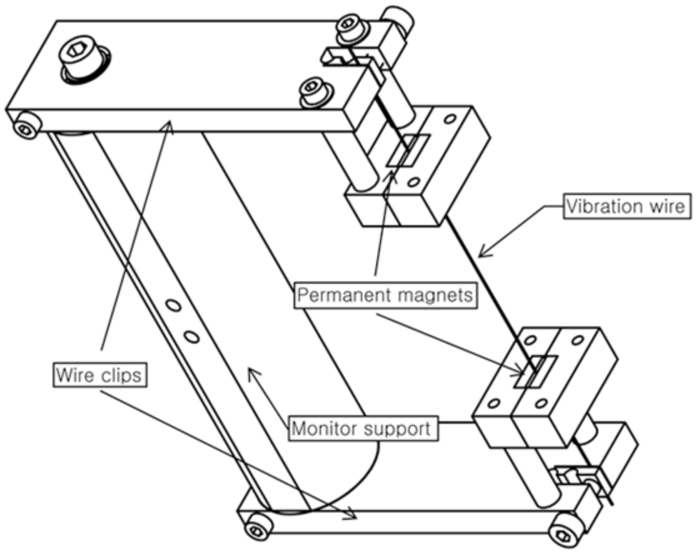
Vibration wire monitor

The principle of the VWM is to pick up its temperature rising-induced frequency shift by irradiating vibration wire with a beam.

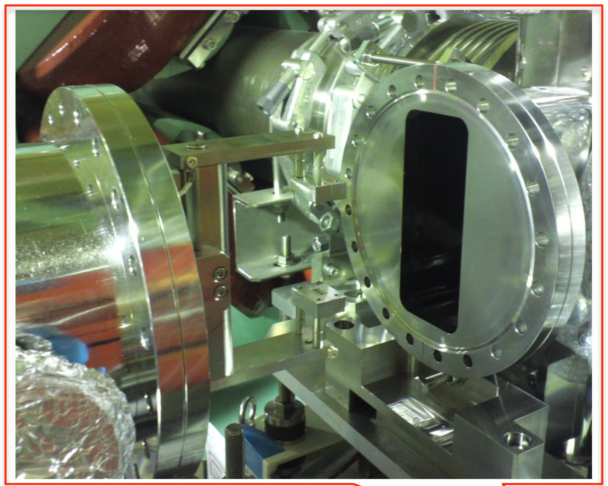
Futures of VWM

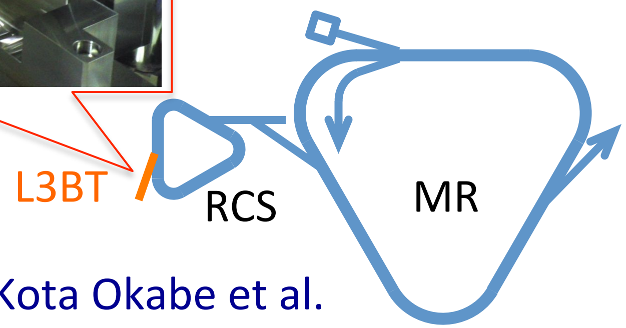
- We assume that the VWM potential dynamic range of 10^{-5} will be achieved.
- The VWM is insusceptible secondary electrons

In last year, the VWM was installed in L3BT to demonstrate the feasibility of the beam halo measurement.



S. G. Arutunian, et. al., PRST-AB, 2, 122801 (1999)
Begoz instrumentation



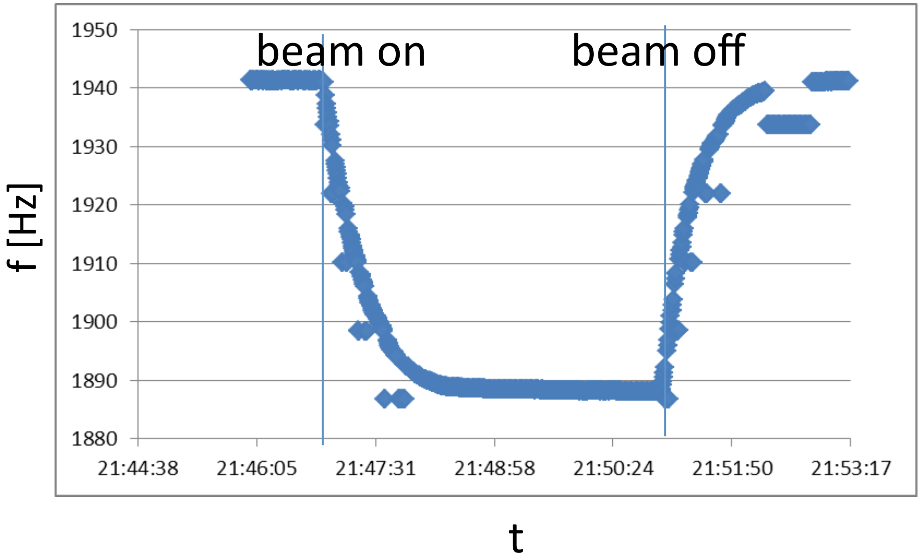


MOPME028 Kota Okabe et al.

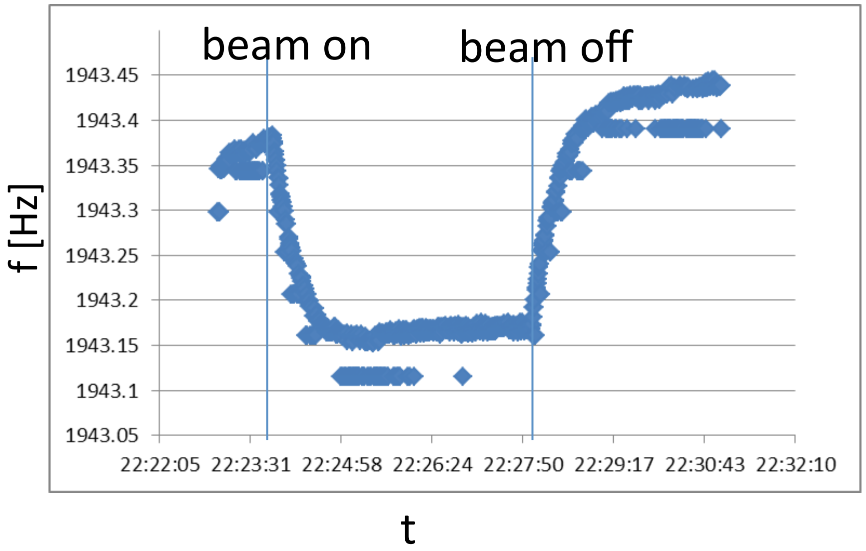
Frequency shift with beam irradiation

- The natural frequency of the VWM without beam irradiation was about 1943 Hz.
- The proton beam hit the wire only in a period between 0 sec and 247 sec.
- A frequency decrement of about 53.13 Hz (0.25 Hz) was measured at 1.3mm (-6.7mm) of distance from beam center.
- A length of time before temperature equilibrium is about 120 sec.

position : +1.3mm(from beam center)



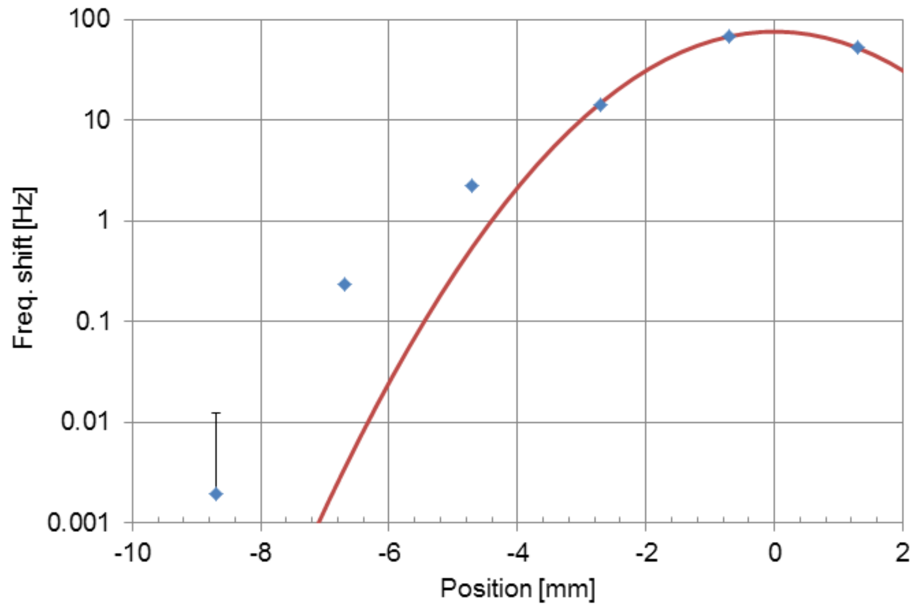
position : -6.7mm(from beam center)



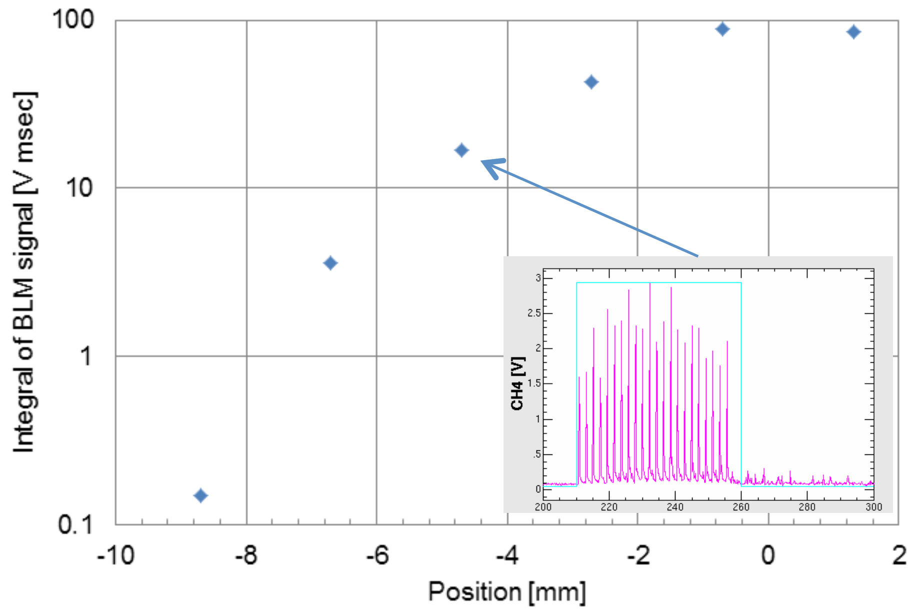
Beam profile measurements by the VWM

- The solid line represents the profile of the beam approximated by the mean square method of a gaussian function with a standard deviation of σ_x = 1.498 mm.
- The beam profile measured by the VWM is almost consistent with the MWPM measurements (σ_x = 1.442 mm) and integrated BLM signals.

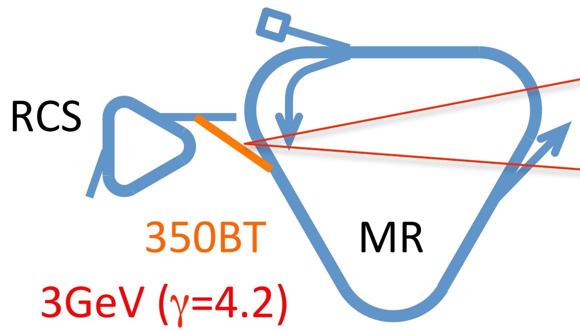
Beam profile measurement of the VWM

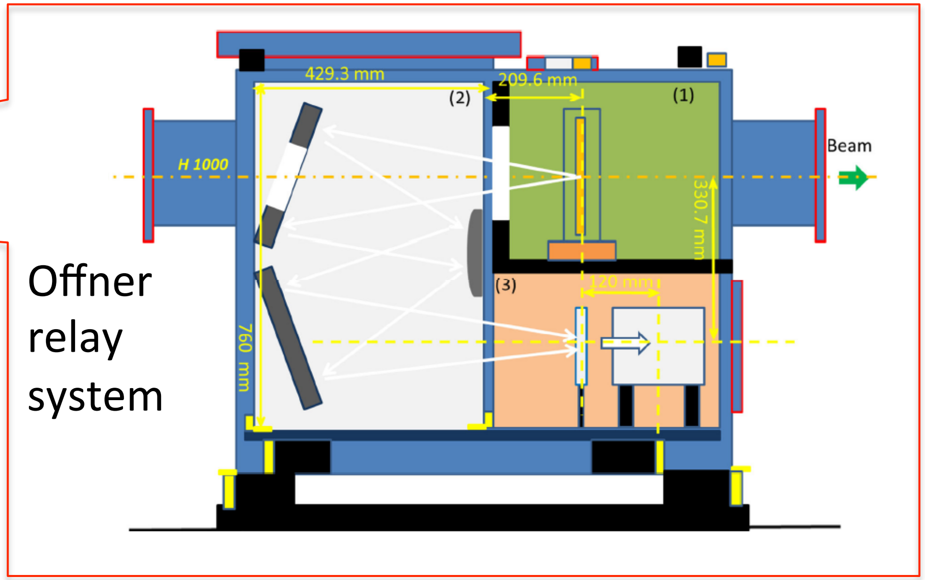


Integrated signals of the BLM



OTR and fluorescence monitor

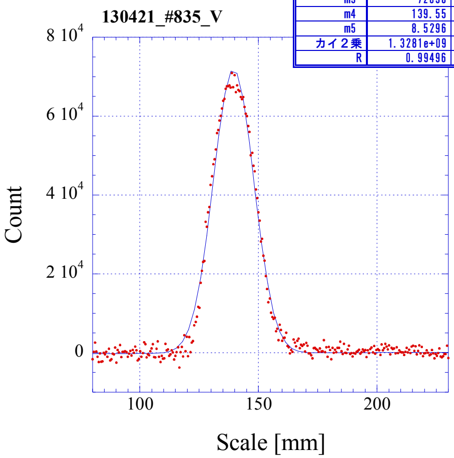


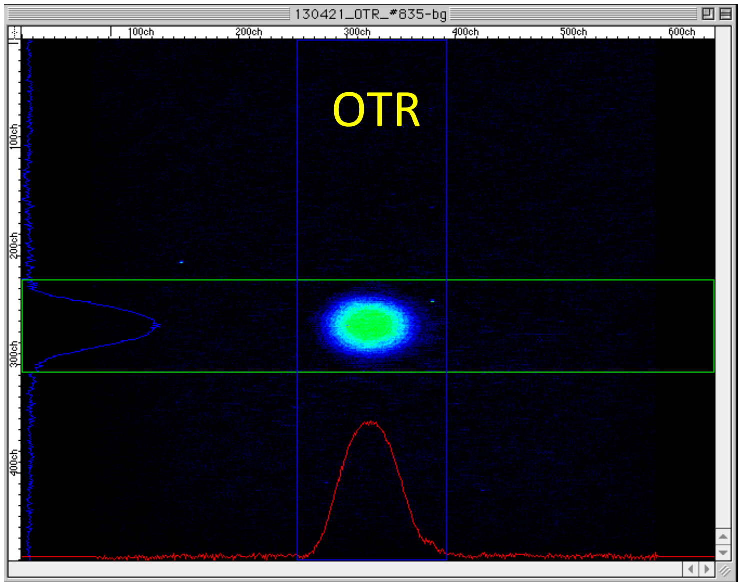


High Power Beam trial:
Intensity 4.2x10^{13} p / 2bunches

σ_V = 8.53 mm

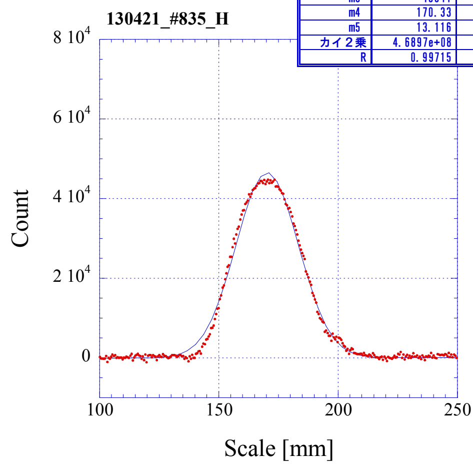
y = m1 +m2*M0 + m3*EXP(-(M0-...		
	値	エラー
m1	-428. 59	154. 63
m2	2. 2724	1. 0443
m3	72056	388. 16
m4	139. 55	0. 052497
m5	8. 5296	0. 054341
カイ２乗	1. 3281e+09	NA
R	0. 99496	NA





σ_H = 13.12 mm

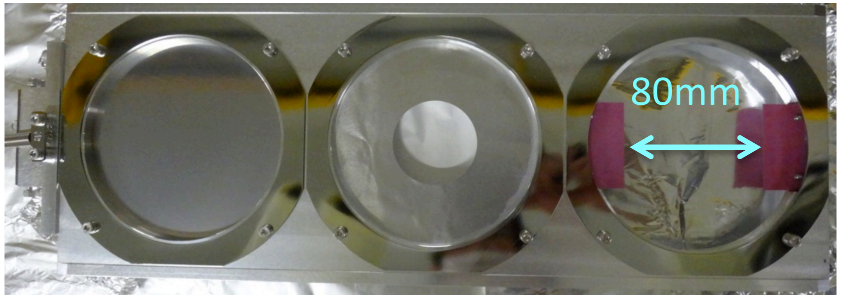
y = m1 +m2*M0 + m3*EXP(-(M0-...		
	値	エラー
m1	-178. 85	70. 075
m2	1. 0317	0. 34778
m3	46541	161. 17
m4	170. 33	0. 051844
m5	13. 116	0. 053903
カイ２乗	4. 6897e+08	NA
R	0. 99715	NA



M. Tejima, Y. Hashimoto, T. Mitsuhashi, et al. IBIC2012

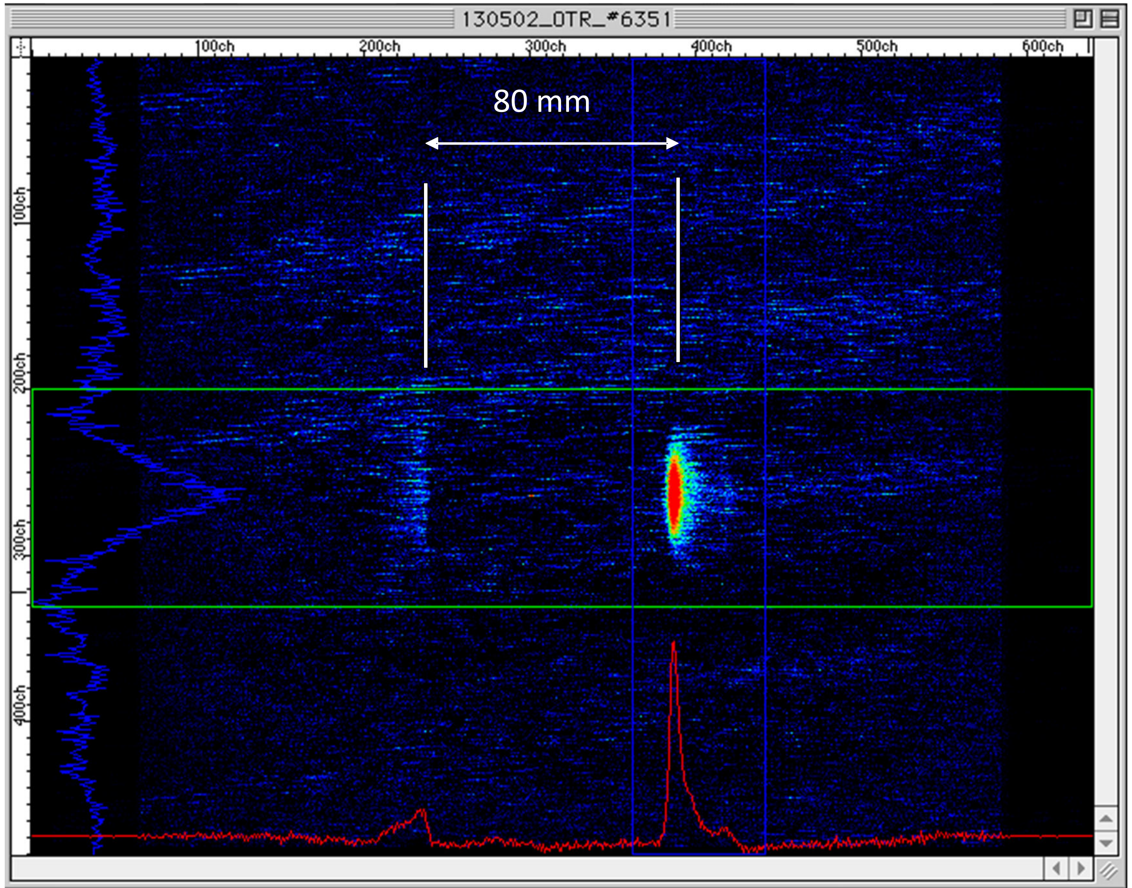
Fluorescence screen

Targets:
- (1) Ti foil 10μm thick
- (2) Al foil 100μm thick with a hole 50mm diameter,
- (3) fluorescence screen Al_2O_3+Cr 500μm thick



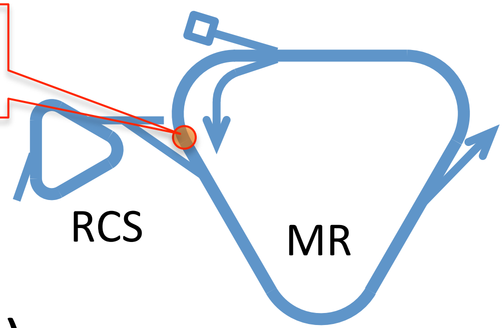
(1) (2) (3)

Tail, Halo Measurement with fluorescence screen just started



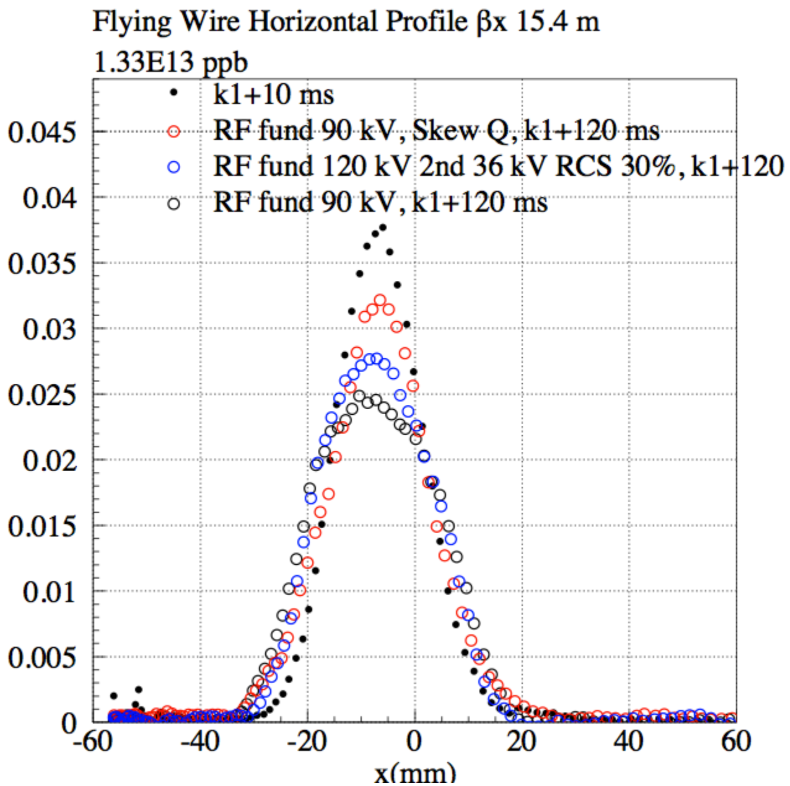
Flying wire profile monitor

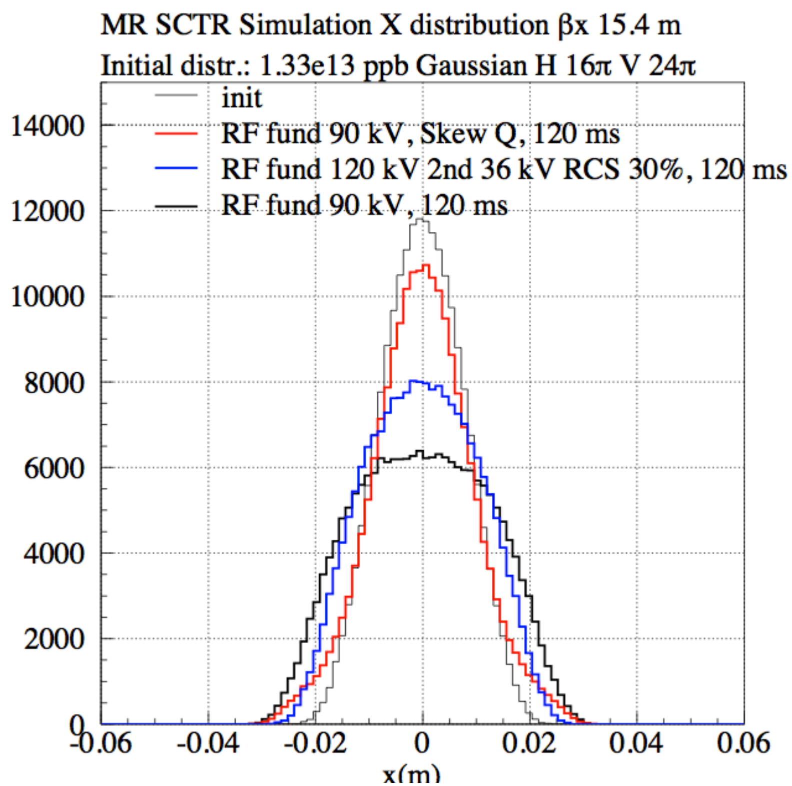
Carbon wire, 7 μm diameter



Horizontal Beam Profiles (Measurement and Simulation)

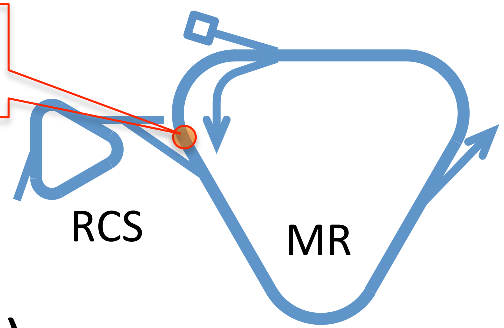
- 2.7e13 ppp (2 bunch injection)
- Flying Wire measurements at K1+10 ms and K1+120 ms.
- SCTR simulation with initial distribution of 16π mmmrad of Horizontal 2σ emittance and 24π for Vertical 2σ emittance.





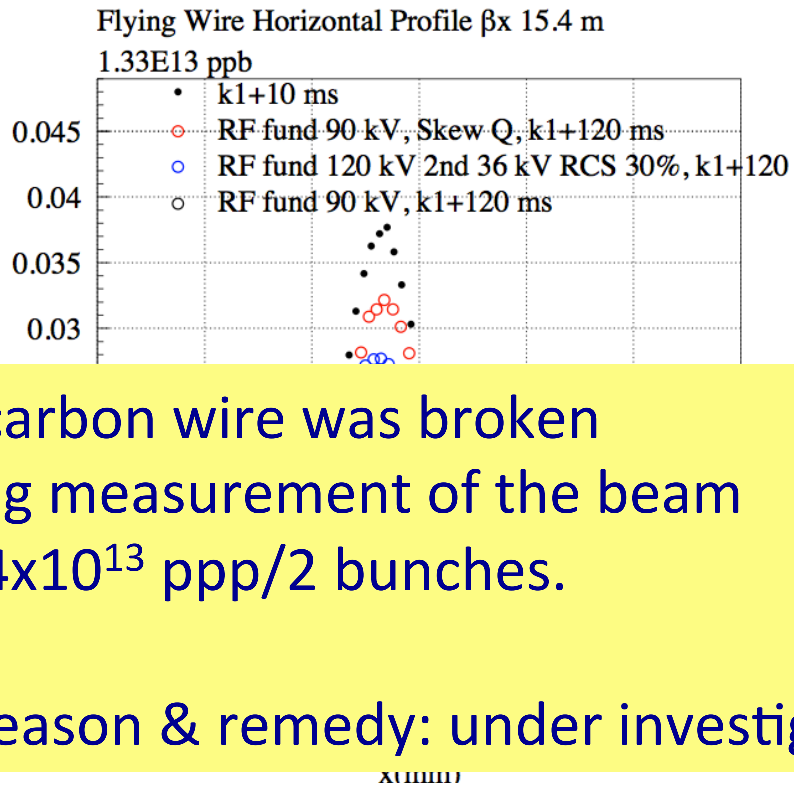
Flying wire profile monitor

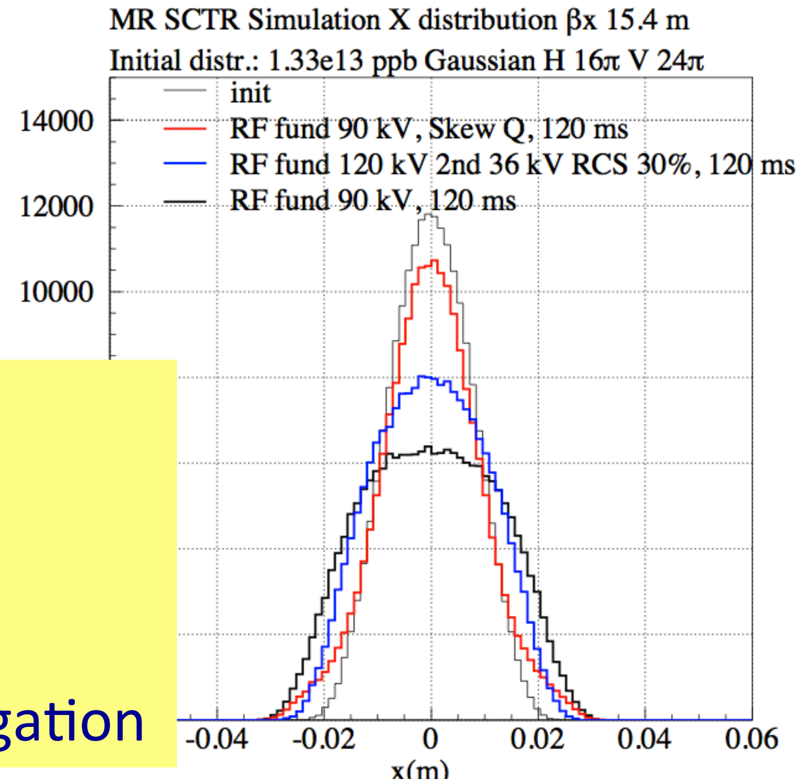
Carbon wire, 7 μm diameter



Horizontal Beam Profiles (Measurement and Simulation)

- 2.7e13 ppp (2 bunch injection)
- Flying Wire measurements at K1+10 ms and K1+120 ms.
- SCTR simulation with initial distribution of 16π mmmrad of Horizontal 2σ emittance and 24π for Vertical 2σ emittance.

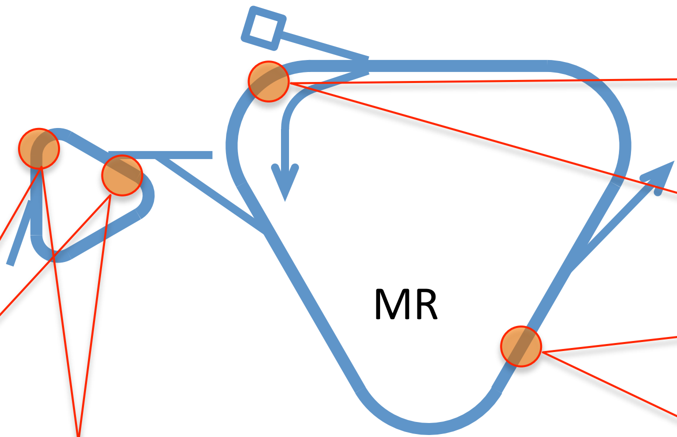


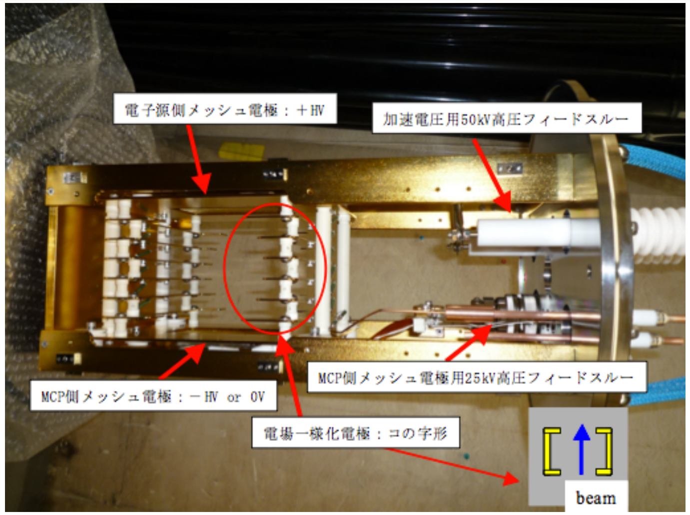


The carbon wire was broken during measurement of the beam @4.4x10^{13} ppp/2 bunches.

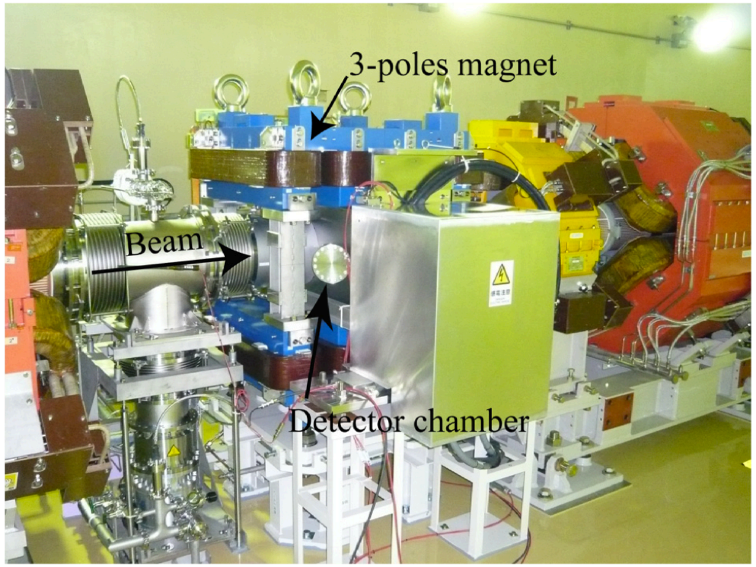
the reason & remedy: under investigation

IPMs (Ionization Profile Monitors)





K. Satoh et al.

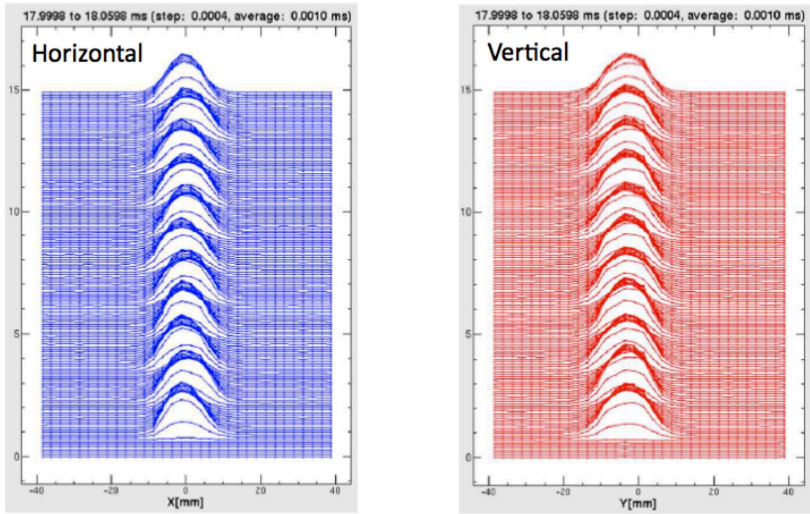


Electron collection for high intensity beams

E-field uniformity improved

MOPME021 H. Harada et al.,
Ionization Profile Monitor (IPM) of J-PARC 3-GeV RCS

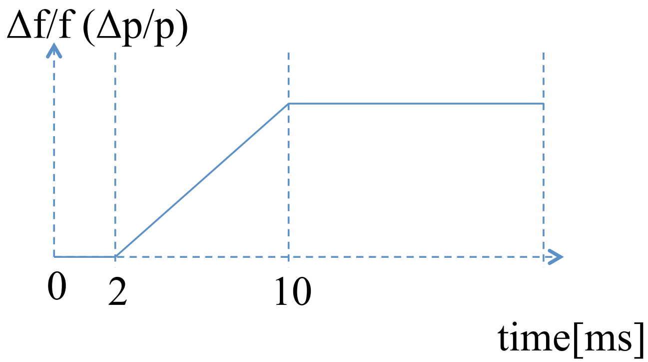
Injection matching (ion collection mode)



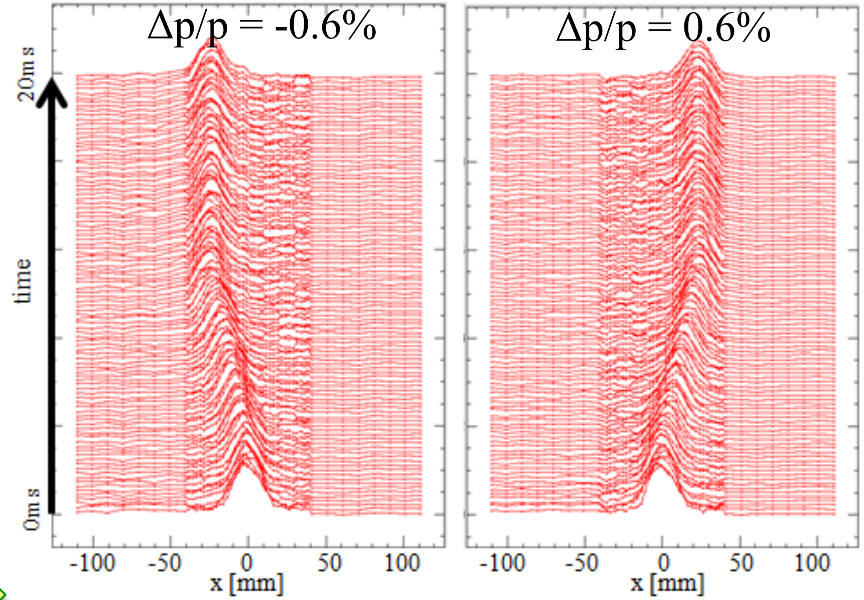
Electron collection with magnet is foreseen.

Improved IPM @RCS

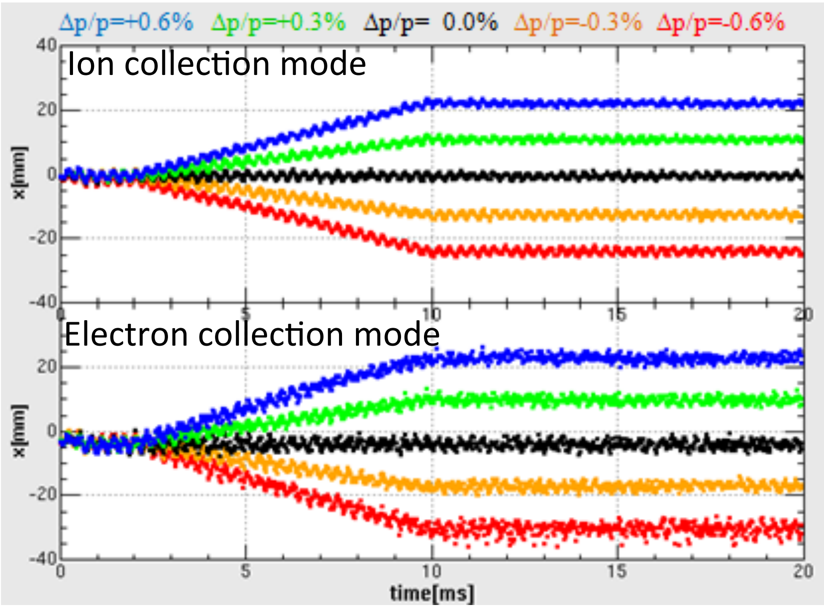
Calibration with the beam shifted in Δp/p
Dispersion @IPM $\eta_x = 4.054$m



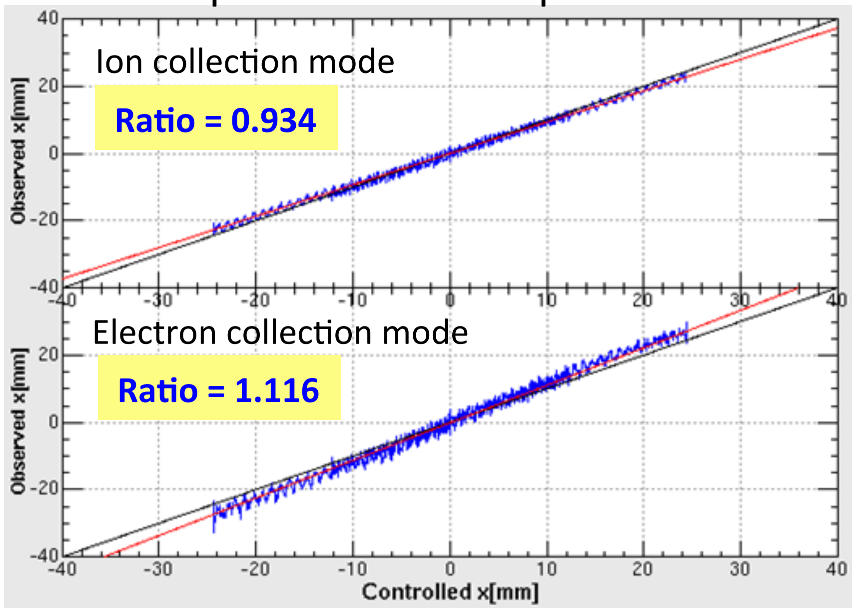
An example of the data (ion collection mode)



Beam center (Gaussian fit)



Comparison to the expected value



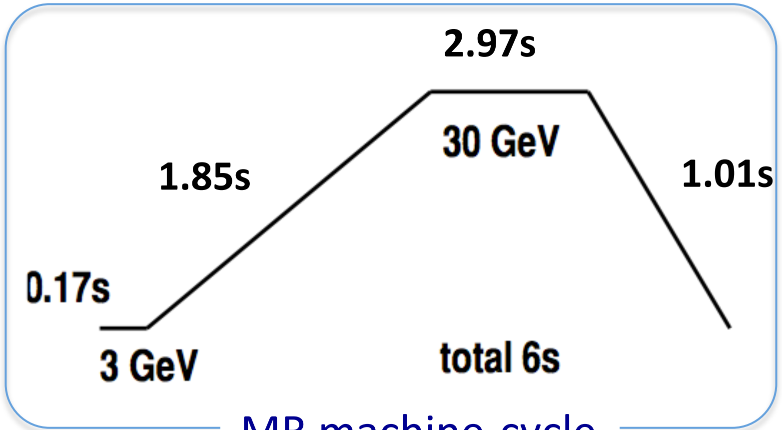
MOPME021 H. Harada et al., Ionization Profile Monitor (IPM) of J-PARC 3-GeV RCS

Operational aspect of the instruments

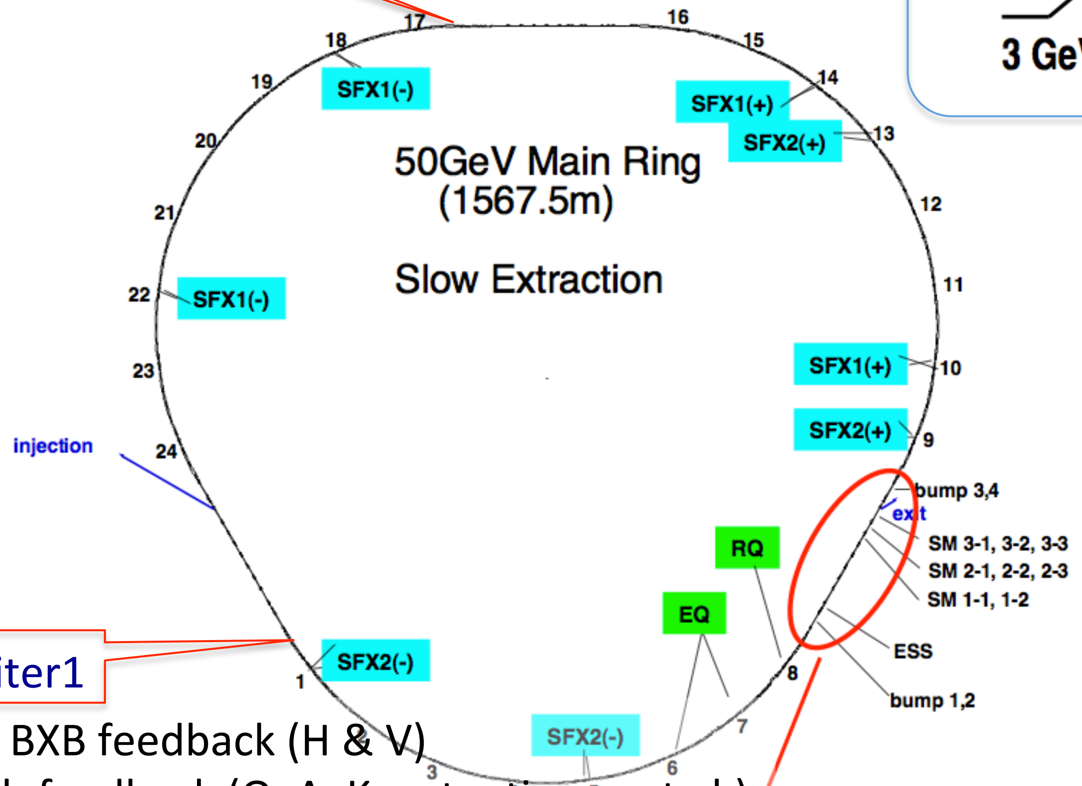
Stripline kicker, "Exciters"
for slow extraction

MR slow extraction @MR

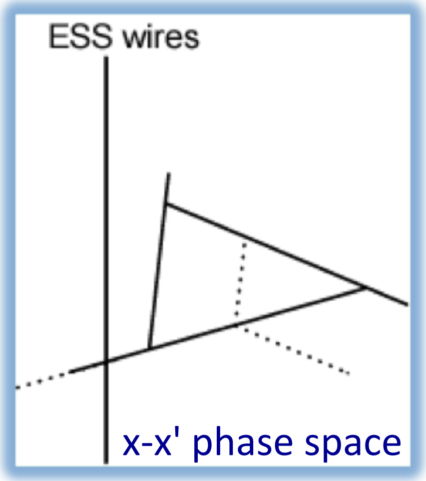
Exciter2
Transverse BXB feedback (Hor.)
"Stochastic slow extraction"



MR machine-cycle

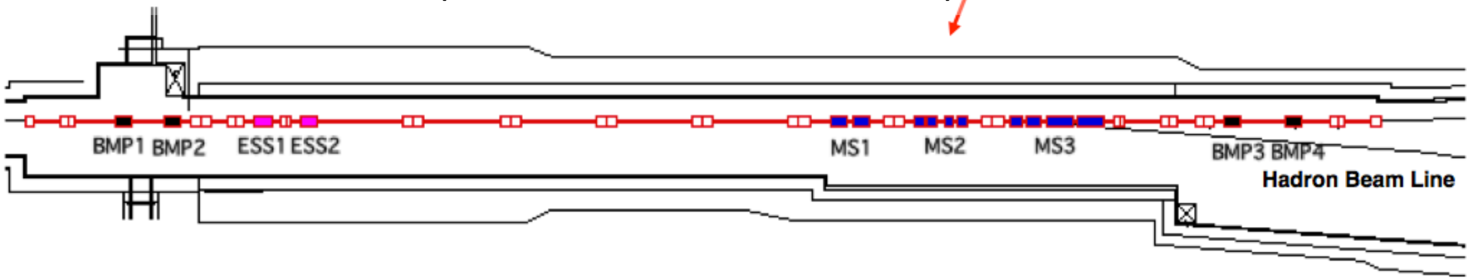


Exciter1
Transverse BXB feedback (H & V)
Intra-bunch feedback (O. A. Konstantinova et al.)



x-x' phase space

Third-integer resonance
$3\ \nu_x = 67$



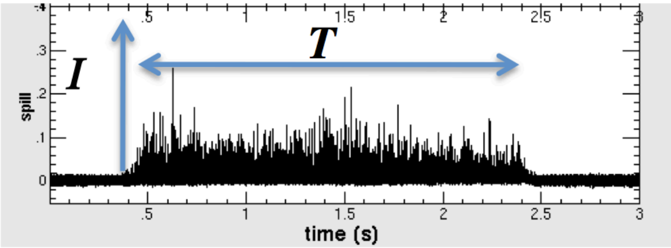
M.Tomizawa et al.

Improvement of the spill duty factor

- Beam spill is deteriorated by the quadrupoles and bends field ripple, which cause tune ripple.

- Evaluation: duty factor

$$D = \frac{\left[\int_{T_1}^{T_2} I(t)\,dt\right]^2}{(T_2 - T_1)\int_{T_1}^{T_2} I(t)^2\,dt}$$



I(t): PM signal sampled at 100KHz through 10KHz LPF

D = 1 for I(t) = constant

- Remedies
  - **Transverse RF (**"Stochastic slow extraction"**)**
  - Feedback control with "EQ" and "RQ"
  - AUX-coil short-circuited during the flat top
    = the ripple current is bypassed to the AUX coil
  - Power supply improvement

ν sweep + stochastic slow extraction

Larger dN_B/dt at local area in phase space
→ better duty factor and GOOD spill length
Original idea by Van der Meer, longitudinal direction
CERN-PS-AA-78-6 1978, . . . , @ CERN, Jülich, . . .
→ Transverse direction: @ NIRS, **J-PARC MR**, . . .

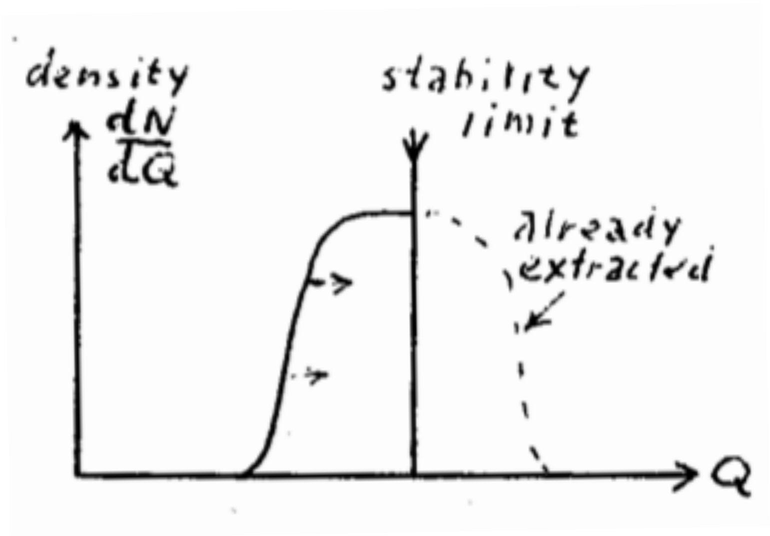


FIG. 1

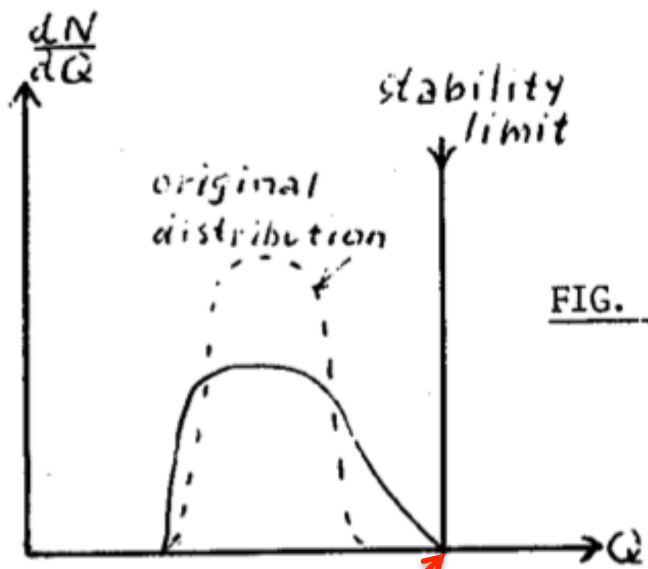
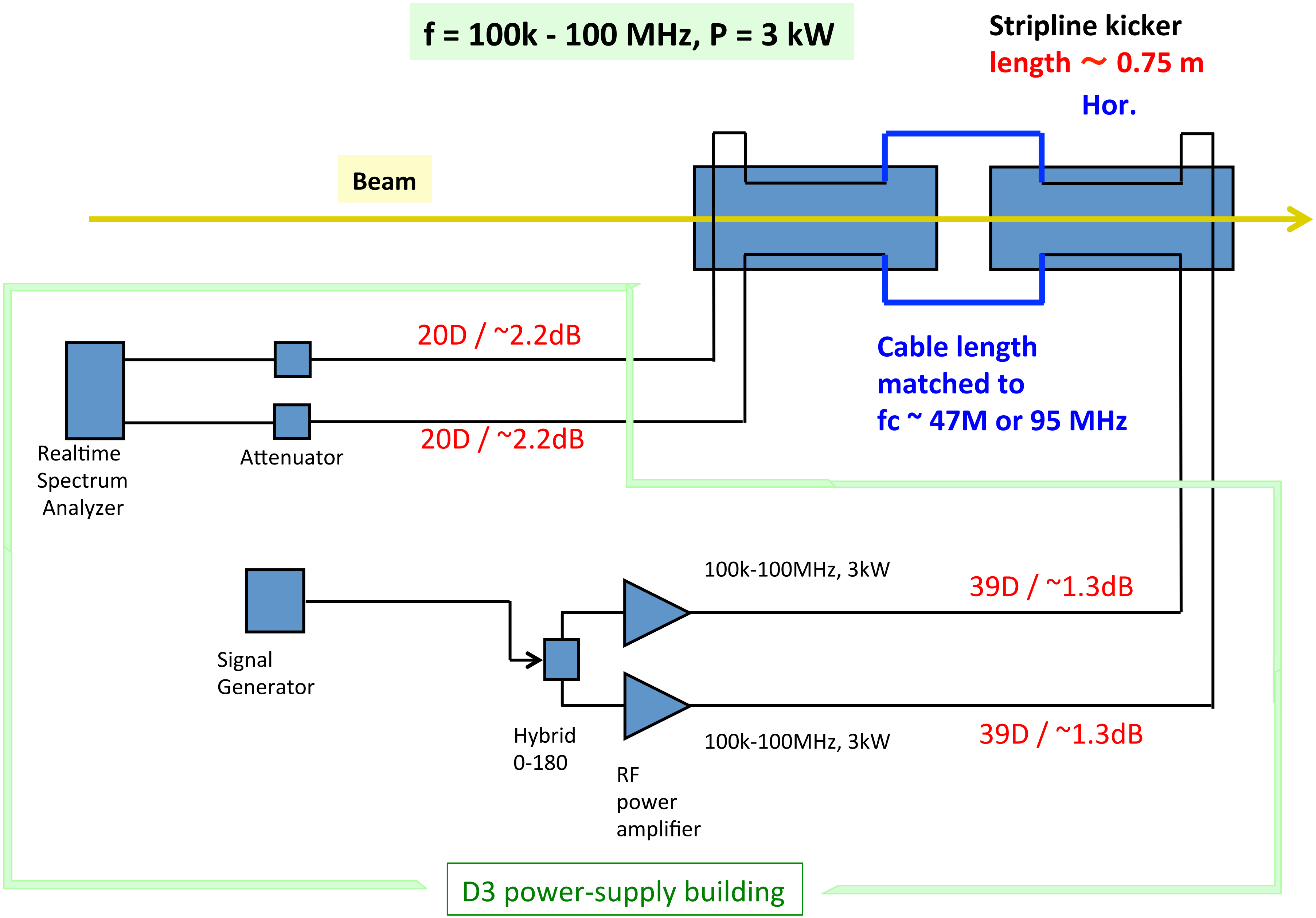


FIG. 2

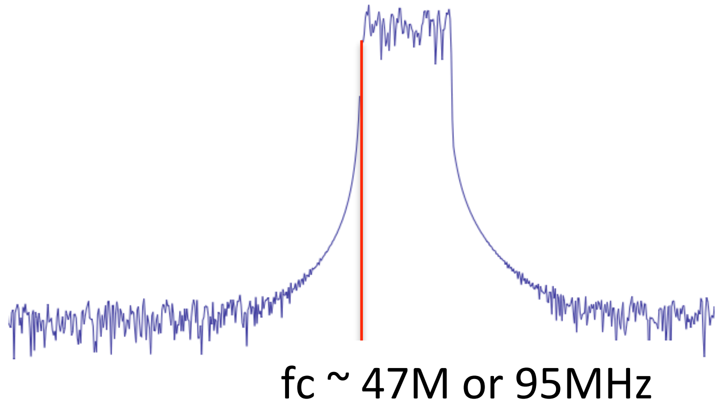
Diffusion: small local density,
high mean particle flux

Transverse kick by the EXCITER2

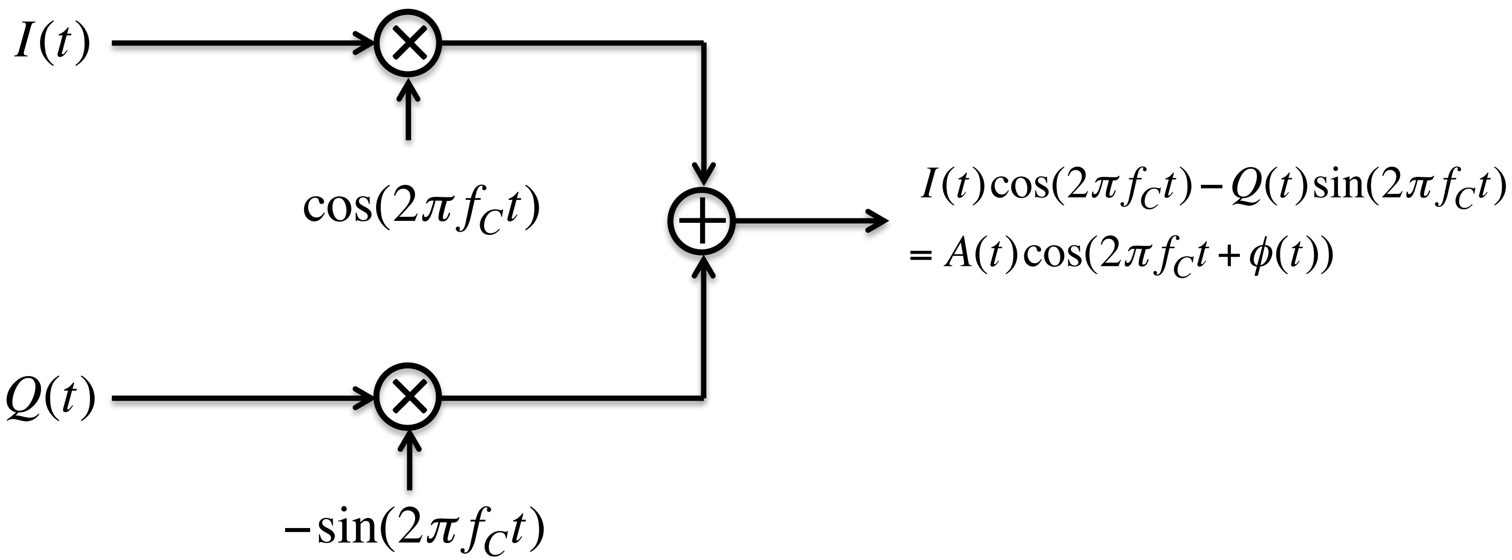


Generation of "transverse RF"

Narrowband Noise signals
with minimized amplitude variation
in time domain



IQ modulation

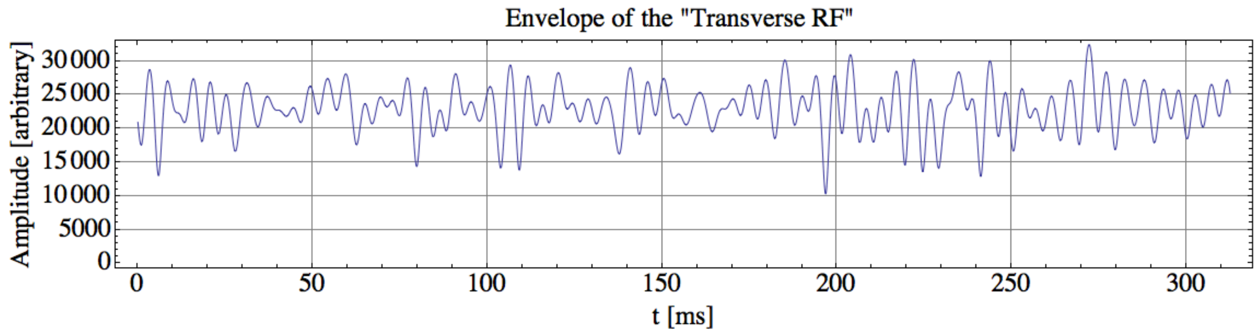


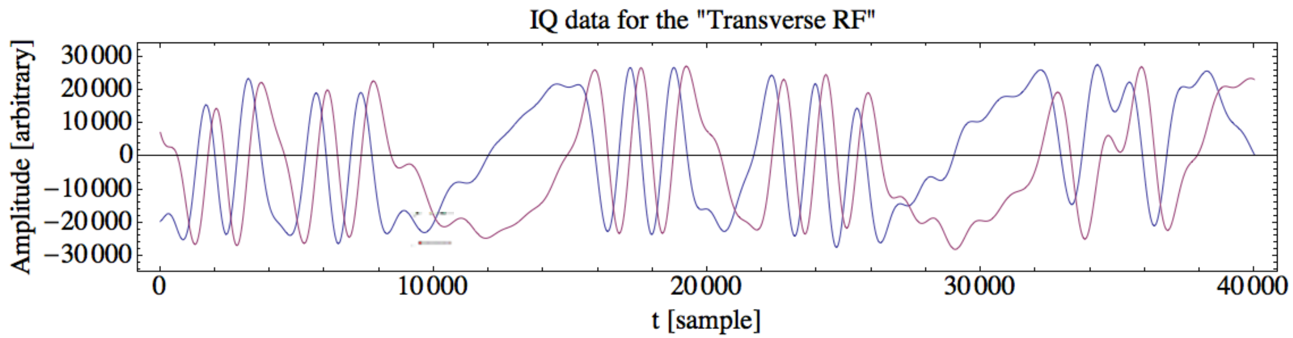
$$I(t) = A(t)\cos\phi(t)$$
$$Q(t) = A(t)\sin\phi(t)$$

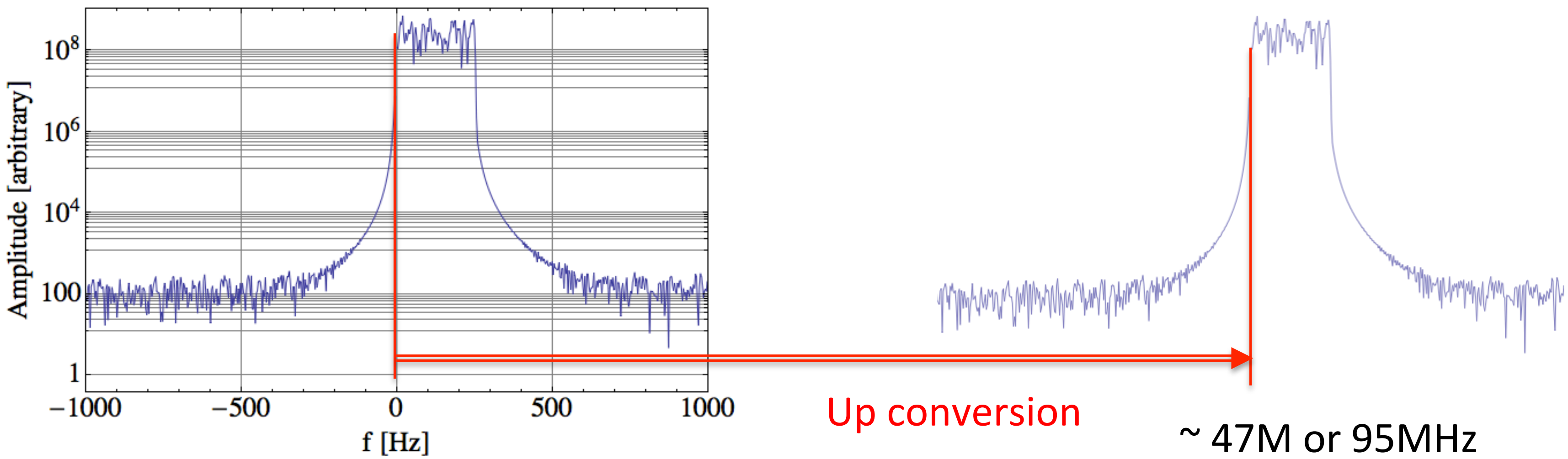
Modulation
in amplitude, A, and phase, ϕ.

IQ modulation

Narrowband
Noise signals
with minimized
amplitude variation







Up conversion

~ 47M or 95MHz

"Baseband"

$A e^{j\phi}$ $\times e^{j\omega_c t}$ $A e^{j\phi} e^{j\omega_c t}$

A. Schnase et al. LLRF 2011

Suppression of the multipacting

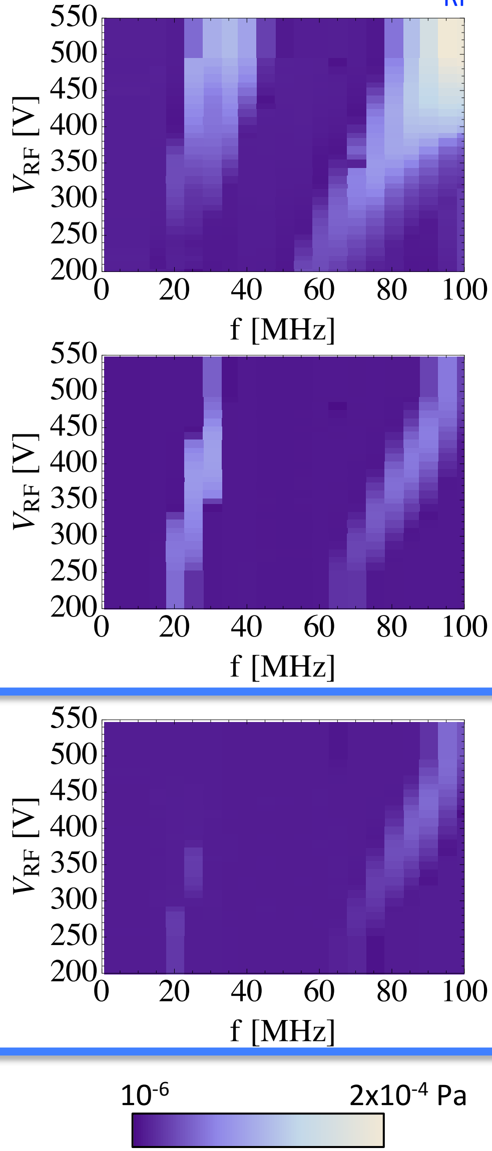
Coating of the electrodes → Solenoid windings

Pressure rise vs f & V_{RF}

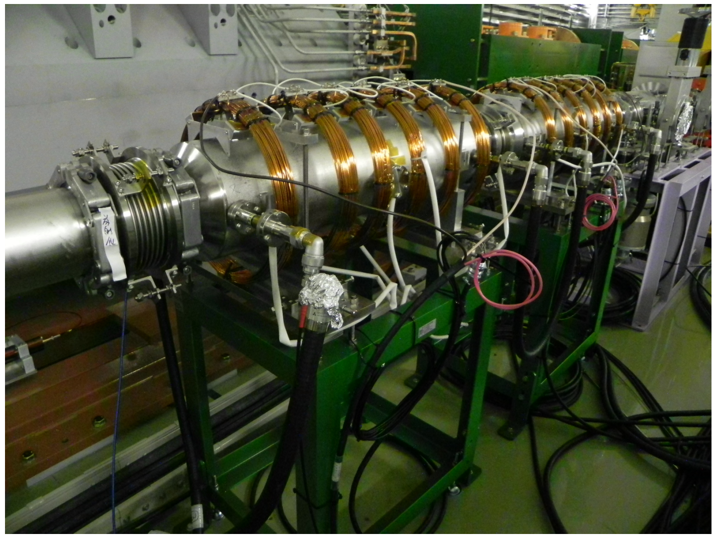
SUS

TiN coated ~t1μm

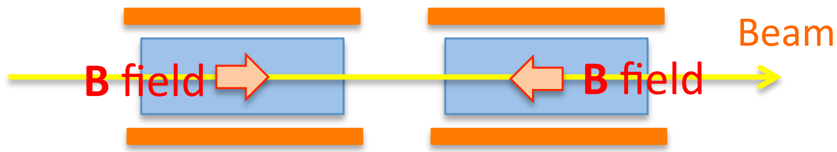
DLC coated ~t1μm



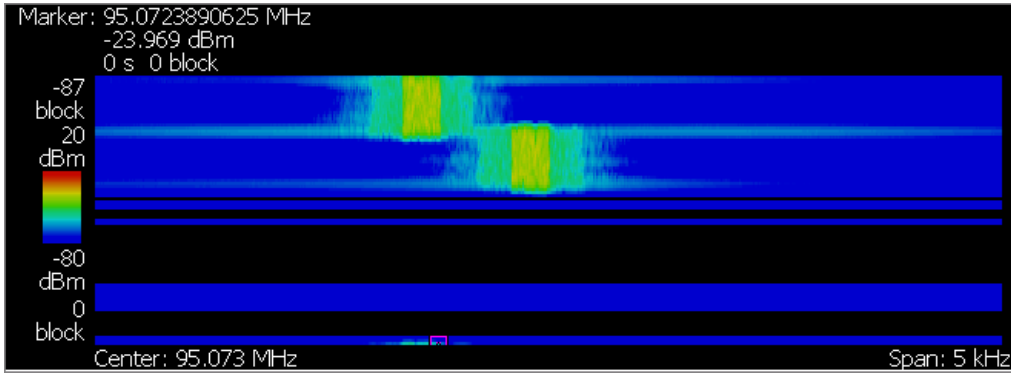
Coating is not sufficient.
Field of ~ 30 G is introduced to suppress the multipacting (vacuum pressure rise).



Two exciters
solenoids: reverse polarity



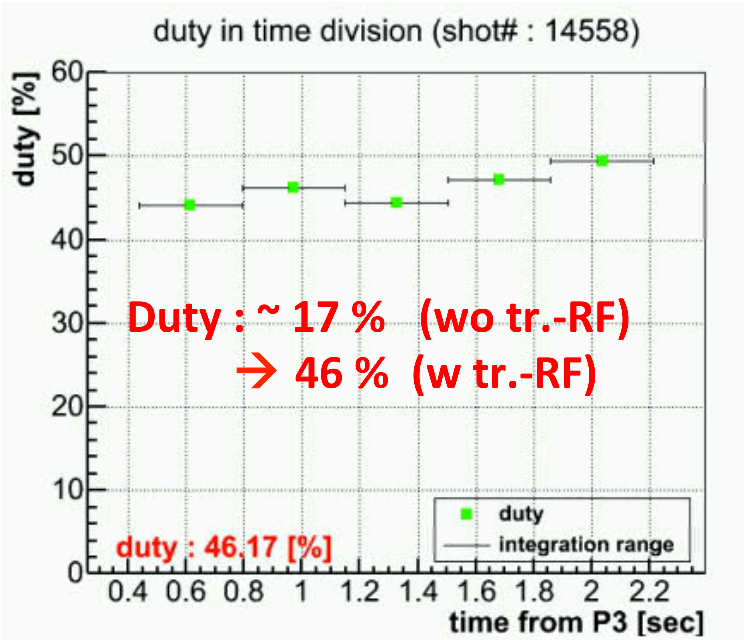
Spill duty improvement @ 15 kW beam

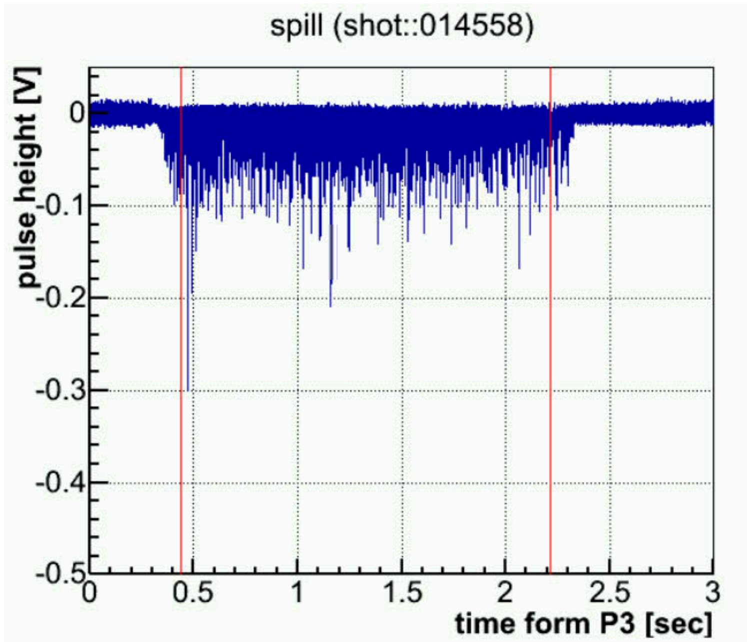


fc = 95.0730MHz

0.0-1.2s edge -0.8KHz width 0.2KHz P=3dBm

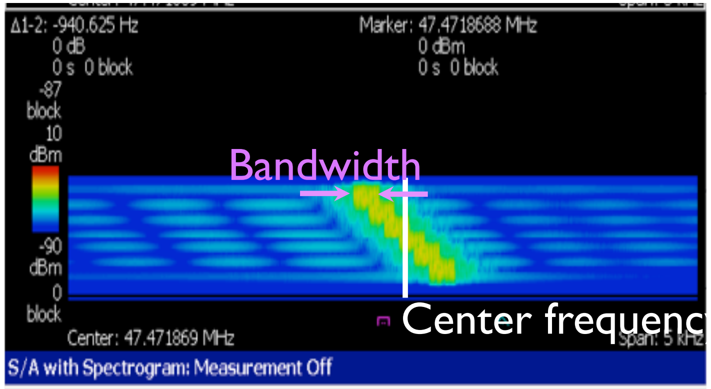
1.2-2.4s edge -0.2KHz width 0.2KHz P=3dBm

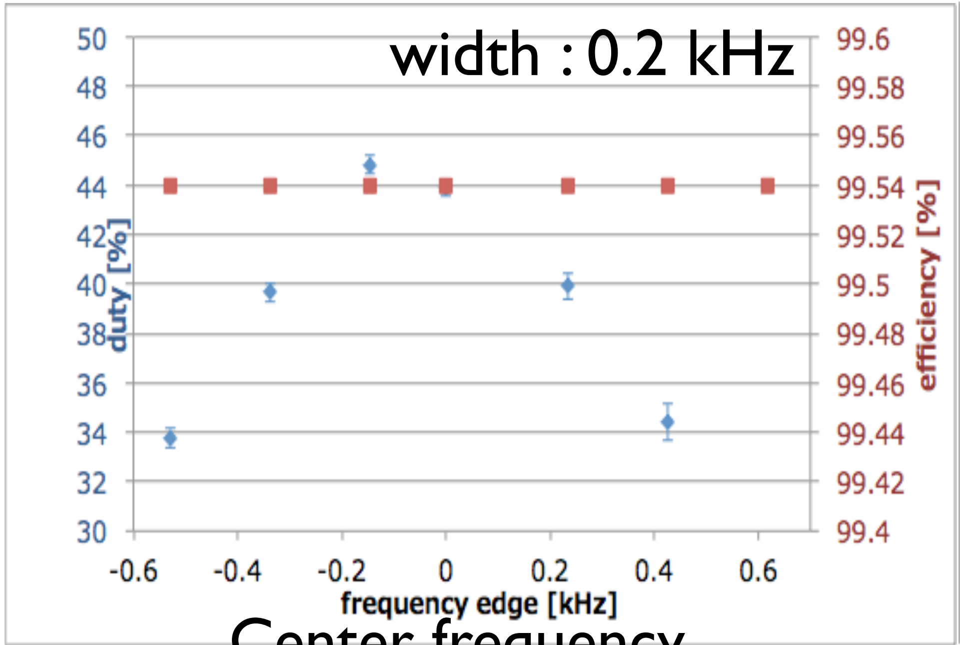




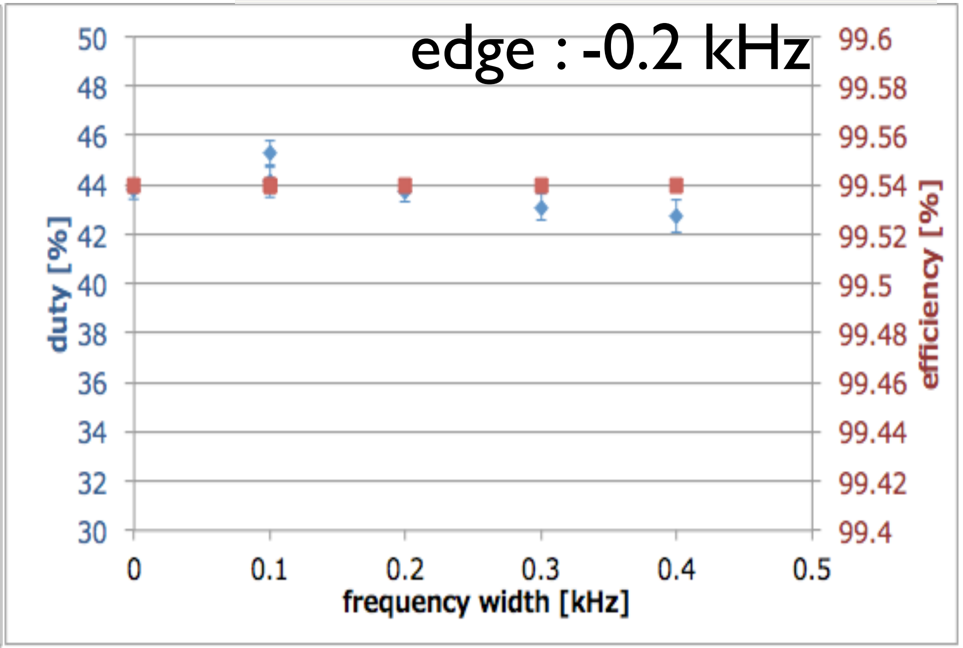
T. Simogawa, M. Tomizawa et al.

Optimization





Center frequency
[0 = 47.471937 MHz]



Bandwidth

※error : 5-shot's σ

- duty : ~45 %
- Ext. efficiency : 99.54 %

Summary

- Beam intensities and losses are investigated in the order of
  0.1 % or less
  in the machine commissioning, studies and operation.

- BPMs have been calibrated with the beam
  RCS all 54 BPMs,
  MR 15 for H, 3 for V / 186 BPMs.
  with the uncertainties of 100μm – 500μm.

- Measurements of
  high intensity beam profiles; Flying wire, IPM, OTR
  high intensity beam tail and halo; collimator & BLM, VWM, OTR/Fluorescence
  are ongoing.

- "Exciters" have been successfully applied to
  Bunch by bunch feedback (transverse)
  Transverse RF to mitigate the spill ripple in slow extraction

Acknowledgment

Beam monitor of MR:

Dai Arakawa , Mitsuhiro Arinaga, Kotoku Hanamura, Yoshinori Hashimoto, Masashi Okada, Shigenori Hiramatsu, Susumu Igarashi, Seishu Lee, Hiroshi Matsumoto, Junichi Odagiri, Kenichiro Sato, Masaki Tejima, Makoto Tobiyama

Beam monitor of RCS:

Hiroyuki Harada, Naoki Hayashi, Kazami Yamamoto, Shuichiro Hatakeyama

Beam commissioning:

Tadashi Koseki, Yoichi Sato, Susumu Igarashi, Masashi Shirakata,
Hideaki Hotchi, Hiroyuki Harada

SX:

Ryoji Aragaki, Katsuya Okamura, Takuro Kimura, Ryotarou Muto, Hikaru Sato, Tetsushi Shimogawa, Hisayoshi Shirakabe, Fumihiko Tamura, Masahito Tomizawa, Hideaki Nakagawa, Daisuke Horikawa, Shigeru Murasuhgi, Kouichi Mochiki, Eiichi Yanaoka, Masahito Yoshii, Alexande Schnase

Control group:

Norihiko Kamikubota, Noboru Yamamoto

Vacuum Group:

Yoichiro Hori, Masahiko Uota, Masayuki Shimamoto, Yoshihiro Sato

System commissioning group:

Takao Oogoe, Chikashi Kubota