Beam Instrumentation in J-PARC

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For the J-PARC beam monitor team

KEK / J-PARC

DIPAC2011, *Hamburg, 16 May-19 May, 2011*

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  - – BPM BBA – ordinary, family QM
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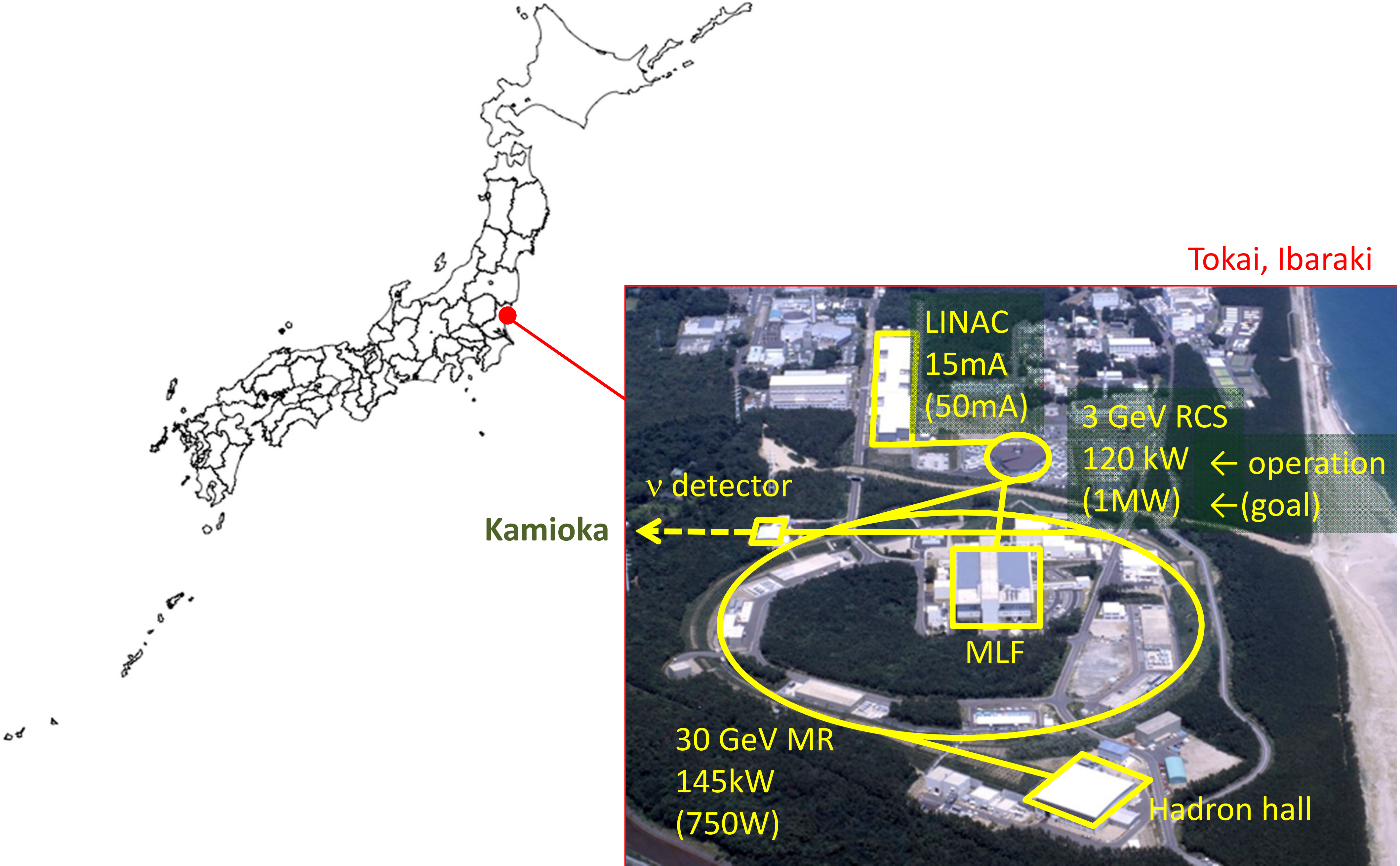
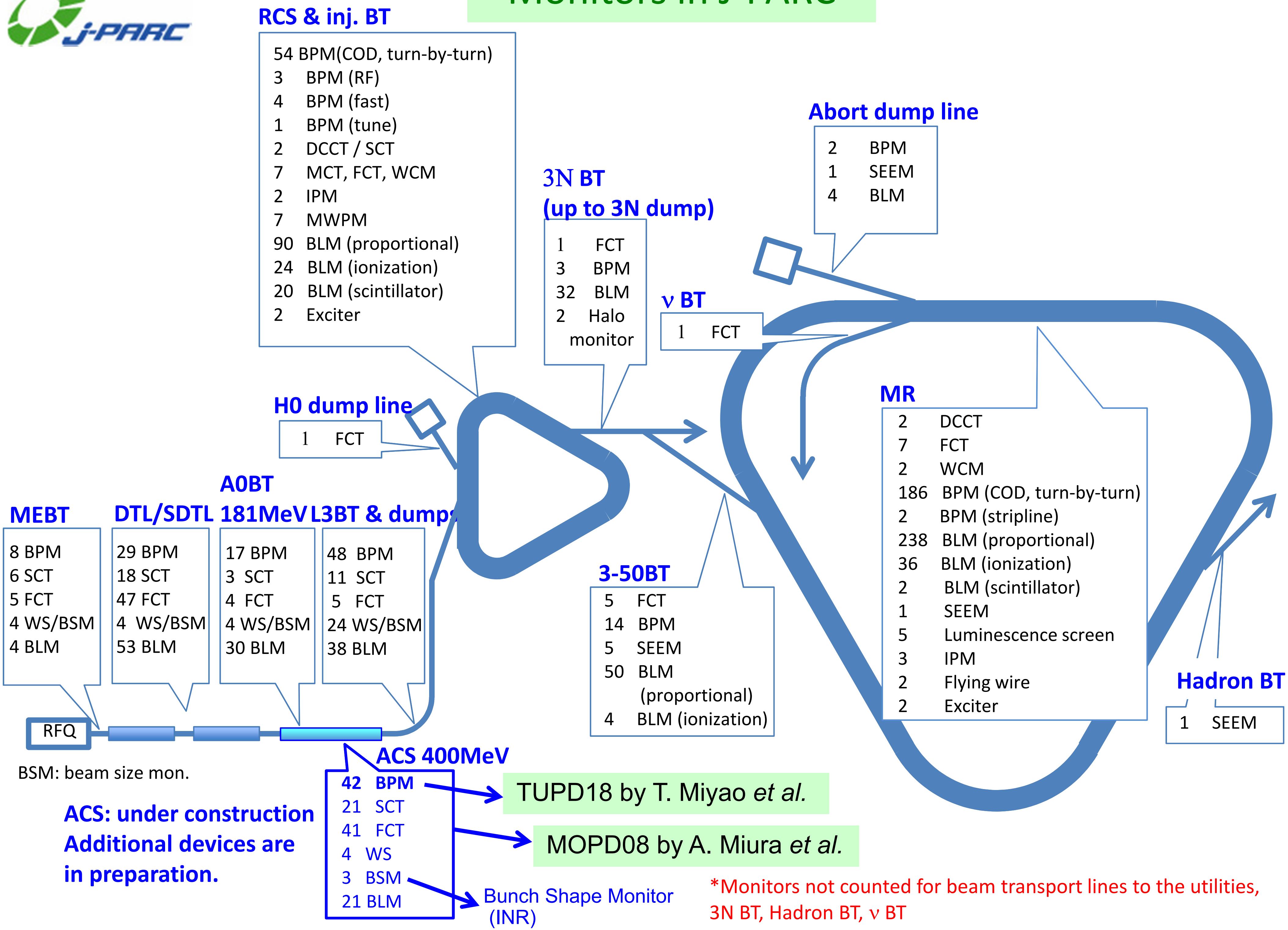
  - – DCCT response calibration
  - – Beam loss monitor sensitivity
- Influence of the earthquake 3.11

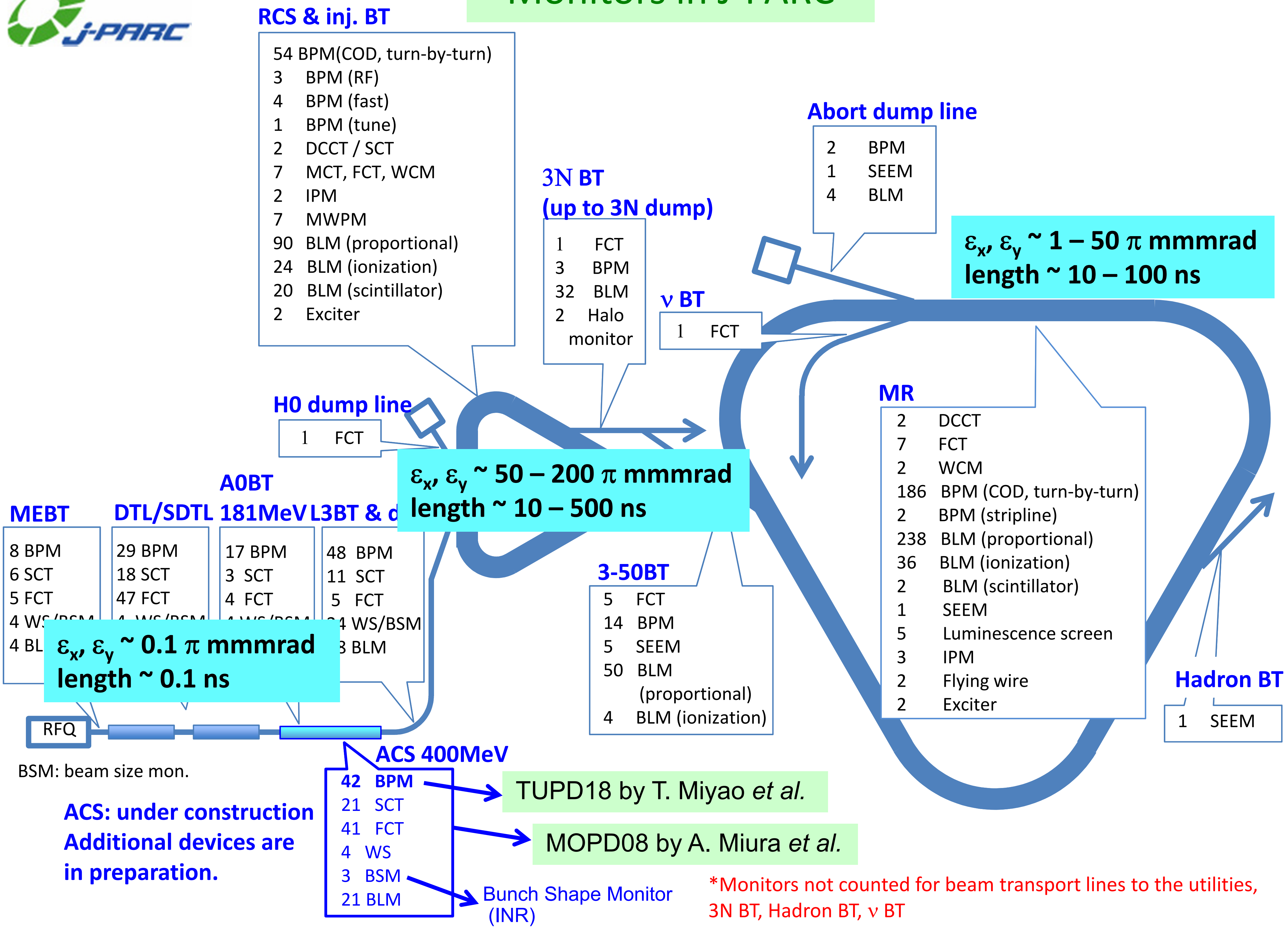
Overview of J-PARC



Monitors in J-PARC



Monitors in J-PARC



BSM: beam size mon.

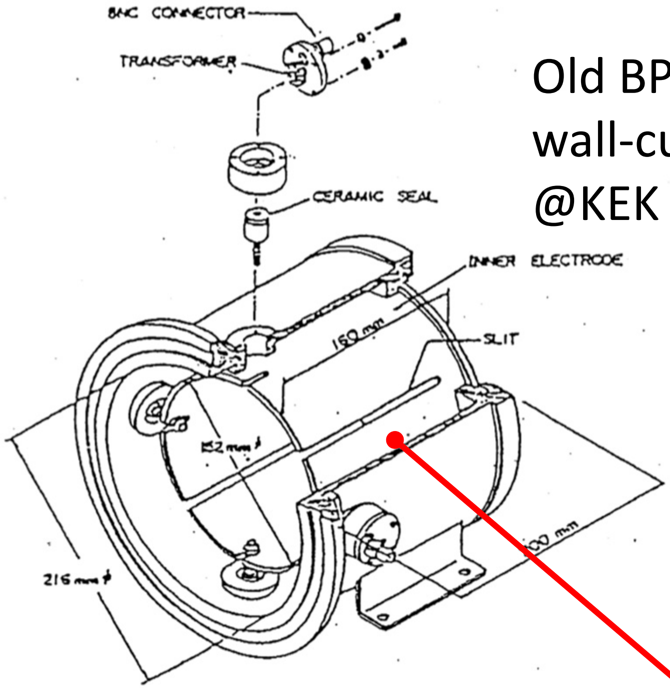
ACS: under construction Additional devices are in preparation.

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

Beam instability issues

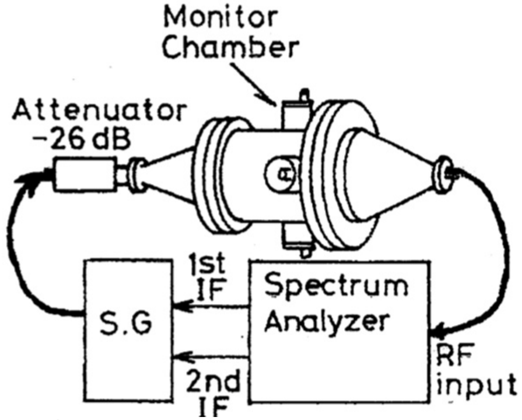
BPM impedance reduction

BPM impedance affected the instability @ the shutdowned KEK PS (1997-1998)

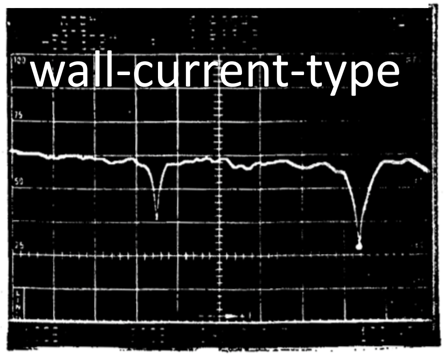


Old BPM
wall-current-type
@KEK 12GeV-PS

Cavity structure



Measured transmission: S_{21}
f = 0 – 1.8 GHz, 10dB/div



replaced

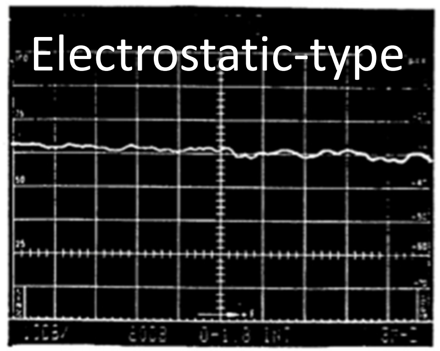


TABLE I. Resonant impedance (measurement/calculation).

	$\omega_\lambda/2\pi$ (GHz)	Q	R_{shunt} (Ω)	R/Q (Ω)
BPM	0.636/0.667 /1.13	77/2650 /3769	$1.5 \times 10^3/2.6 \times 10^4$ $/6.2 \times 10^4$	19.4/9.8 /16.3
	1.498/1.377	230/8222	$5.3 \times 10^3/3.3 \times 10^5$	23/40

K. Takayama *et al*. Phys. Rev. Lett. 78 (1997) p.871

D. Arakawa, in KEK Proceedings 98-1 (*Japanese*)

BPMs for the RCS and MR in J-PARC

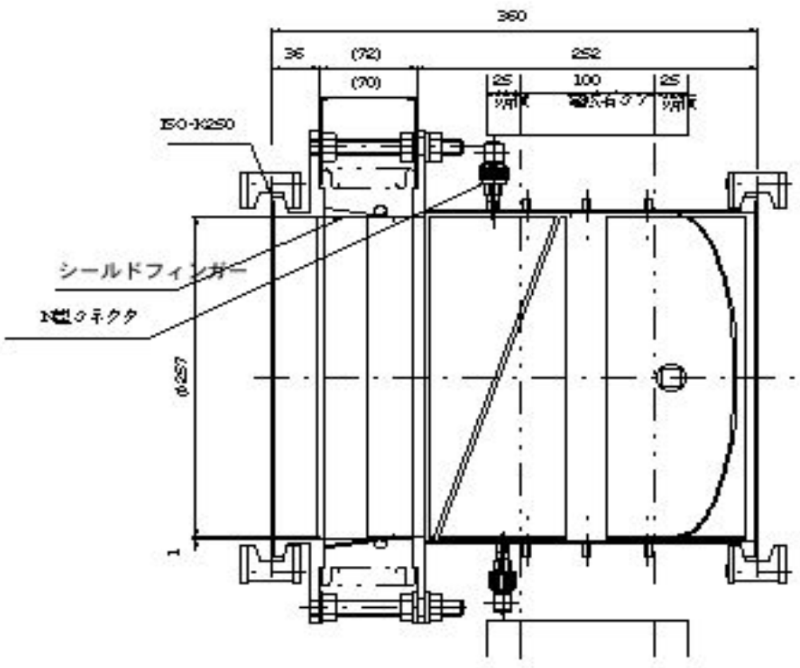
- Diagonal-cut BPMs are employed for linear position response
- Electrostatic monitor
- To reduce the impedance

the gap between the electrodes and the vacuum pipe wall is reduces → larger capacitance:

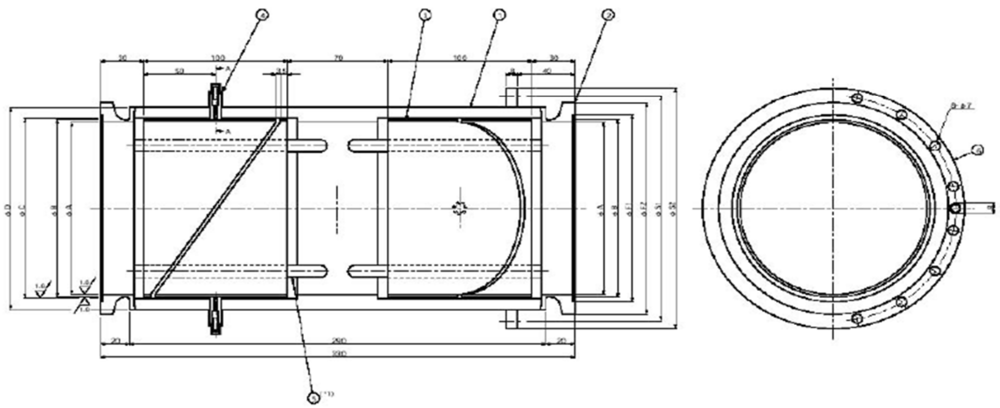
2 mm for the RCS, 1 mm for the MR

$$Z_{\parallel} = \frac{1}{2}\left(\frac{\omega l_0}{\beta c}\right)^2 \frac{R_L}{1 + j\omega C R_L}$$

Zotter, Kheifets,
"Impedances and Wakes in High-Energy Particle Accelerators"

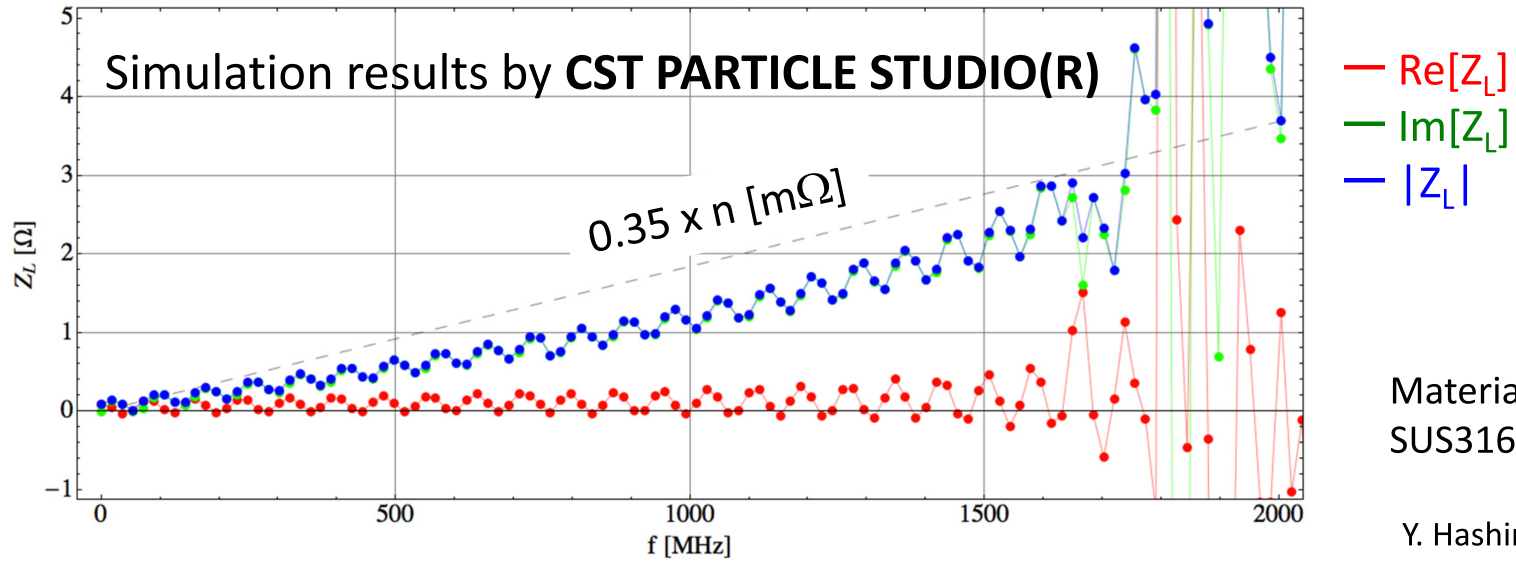


RCS BPM



MR BPM

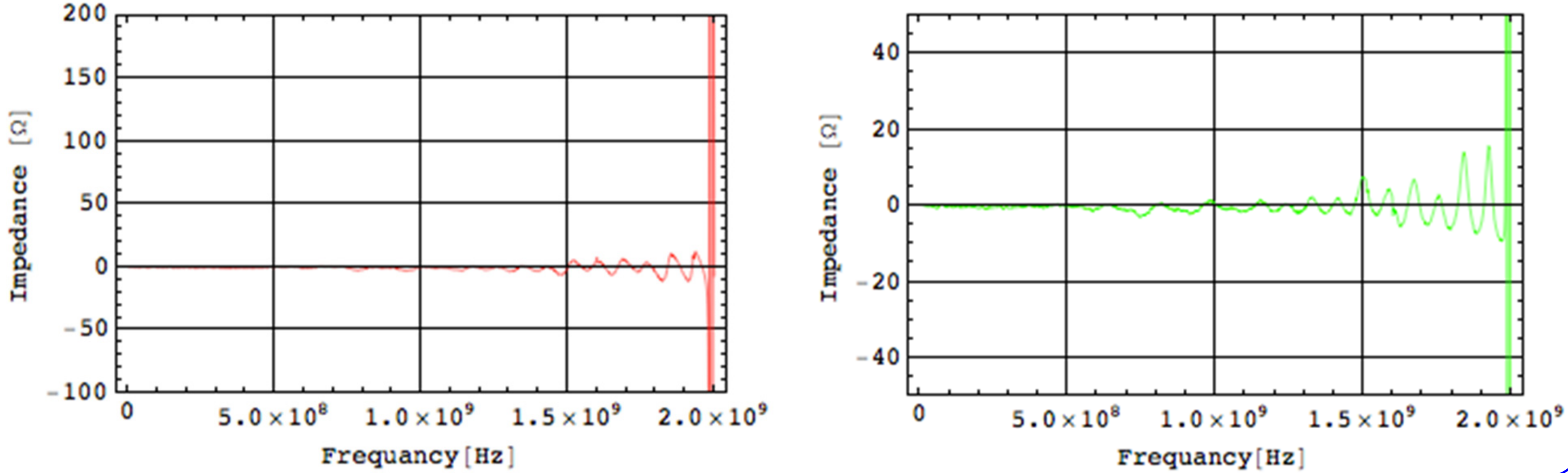
BPM @J-PARC, MR



Material:
SUS316L(JIS)

Y. Hashimoto

Measured by the stretched wire method



\# of BPM

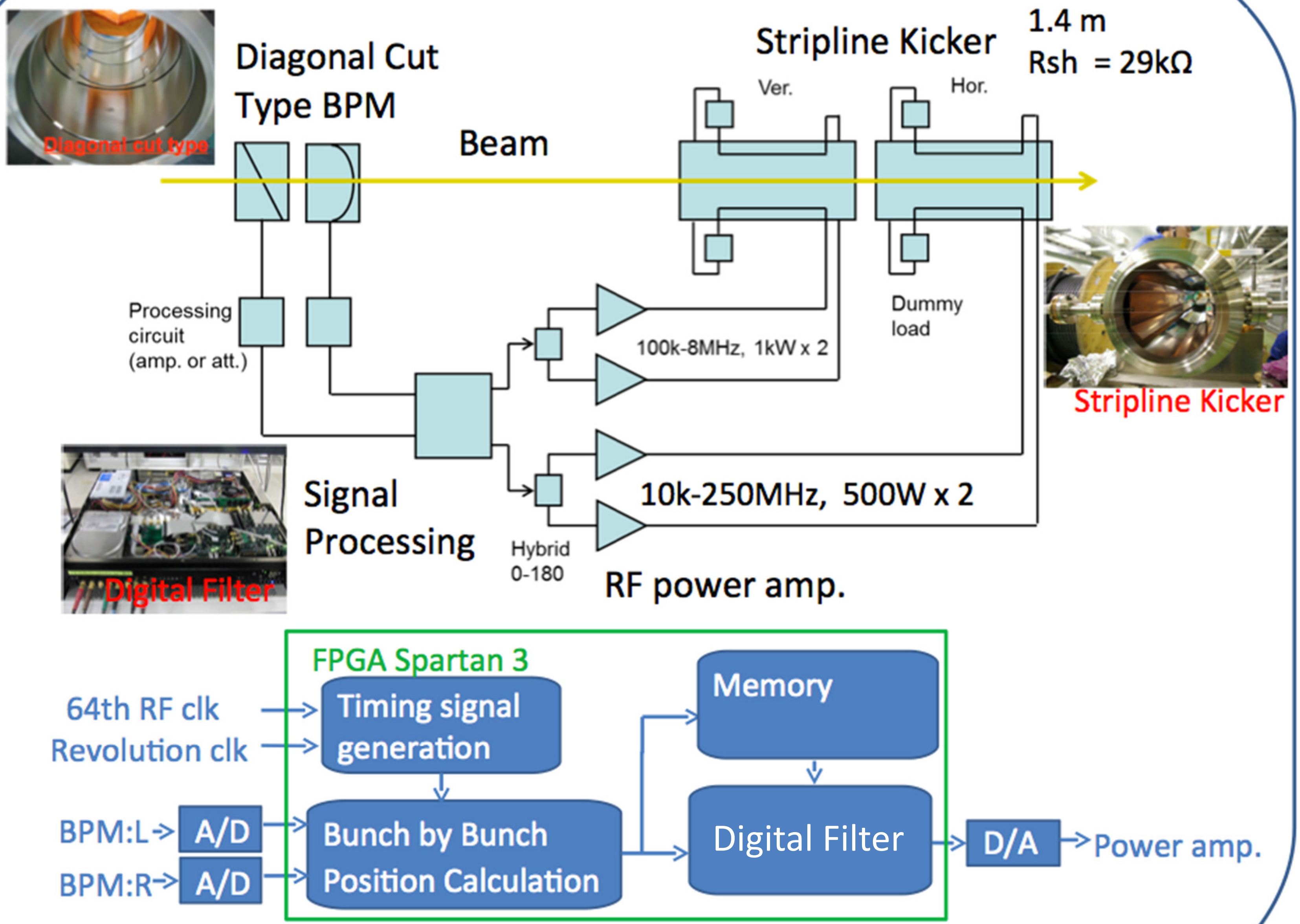
No significant resonance, $|Z_L/n| < 0.35 \times 186\ m\Omega = 65\ m\Omega \ll 9\ \Omega_{max}$ (Keil-Schnell criterion)

Y.Shobuda

fcut-off TM01 = 1.95GHz for Coax. wave guide (ϕ0.16μm/ϕ130mm)

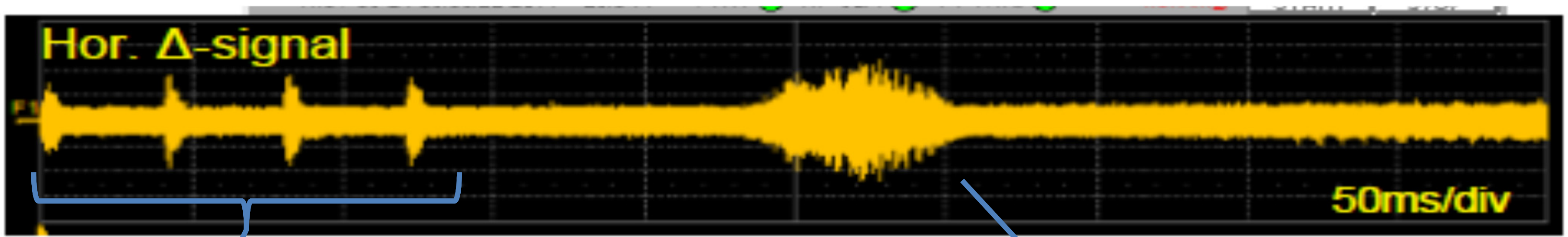
TM01 = 1.77GHz for Cylindrical wave guide

Transverse bunch-by-bunch feedback



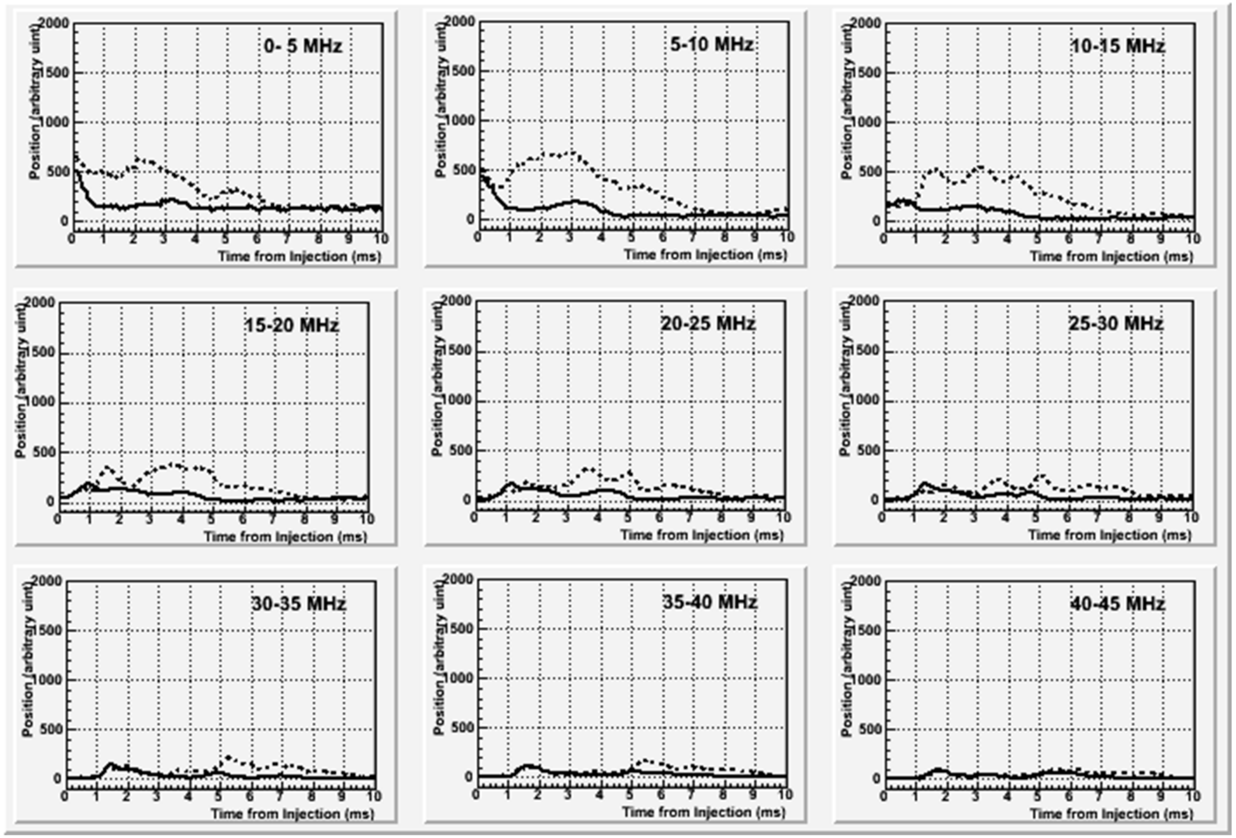
→ TUPD74 by Y. Kurimoto et al.

Bunch-by-bunch feedback works well @ $N_B > 10^{13}$ p/bunch

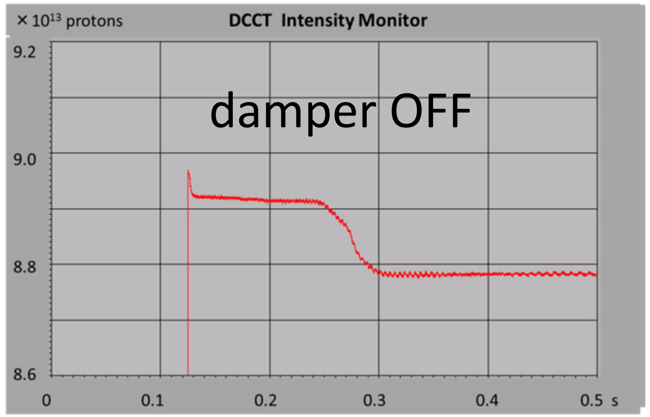


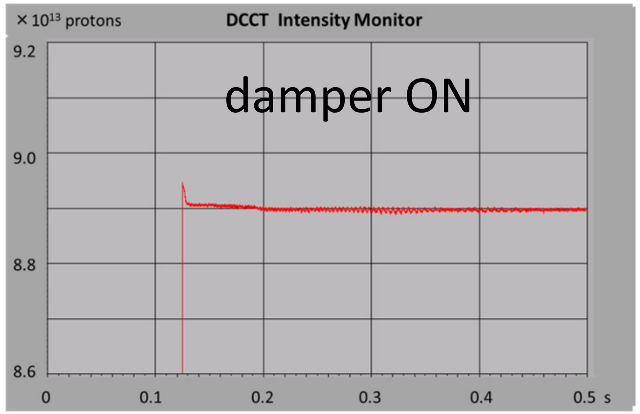
Oscillation at the injection

damper OFF - - -   damper ON —



Collective instability @ accel.

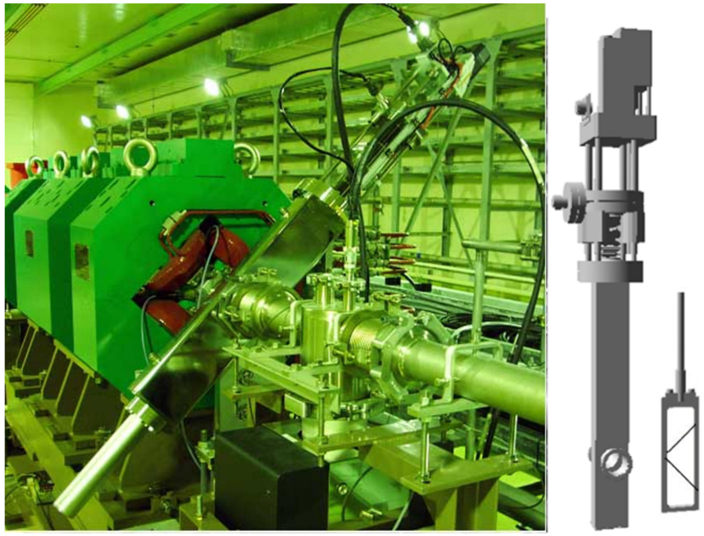




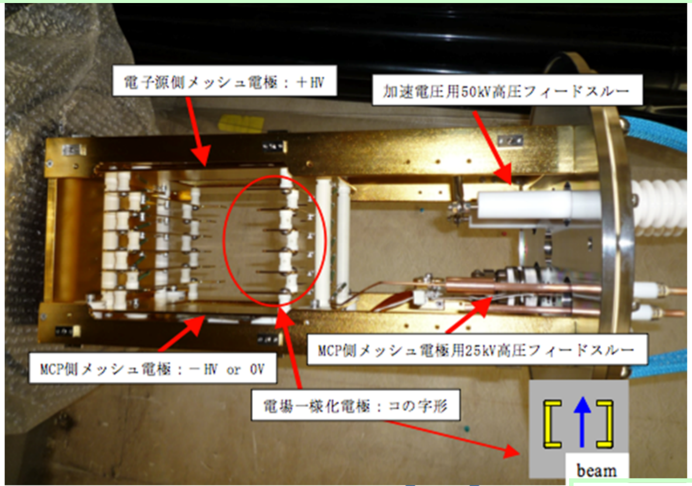
Beam power > 140 kW @MR achieved

Rad-hard monitor

Beam profile monitor



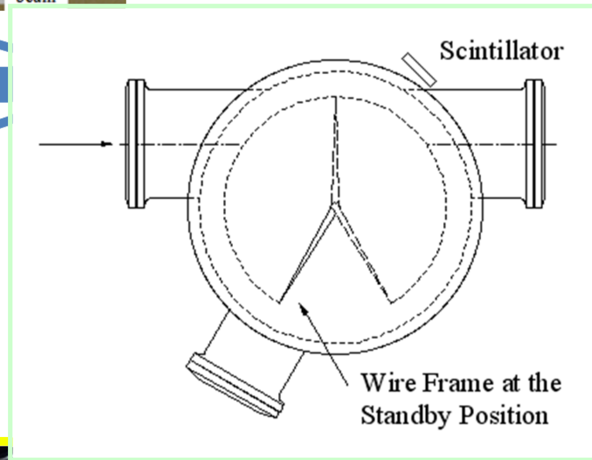
Wire scanner (LINAC)
A. Miura et al.
H. Akikawa et al.



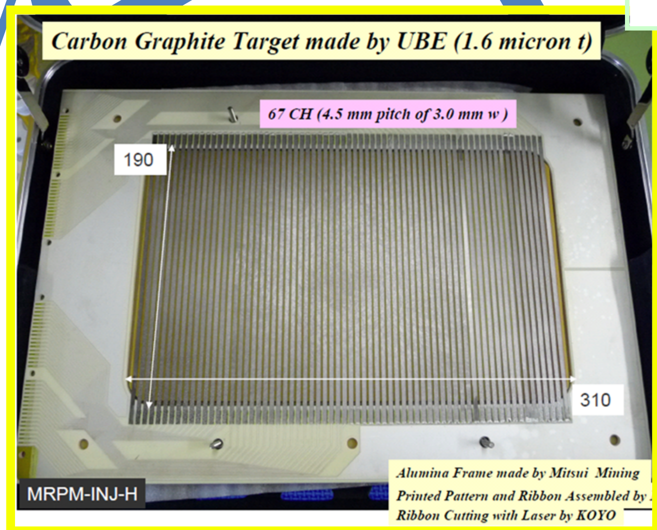
IPM (RCS, MR)
K. Satoh et al.

3N BT
ν BT
3-50BT
Hadron BT
RFQ
MEBT
DTL/SDTL
A0BT(ACS)
L3BT

Multi-wire (RCS)
S. Hiroki et al.



Flying Wire (MR)
S. Igarashi et al.



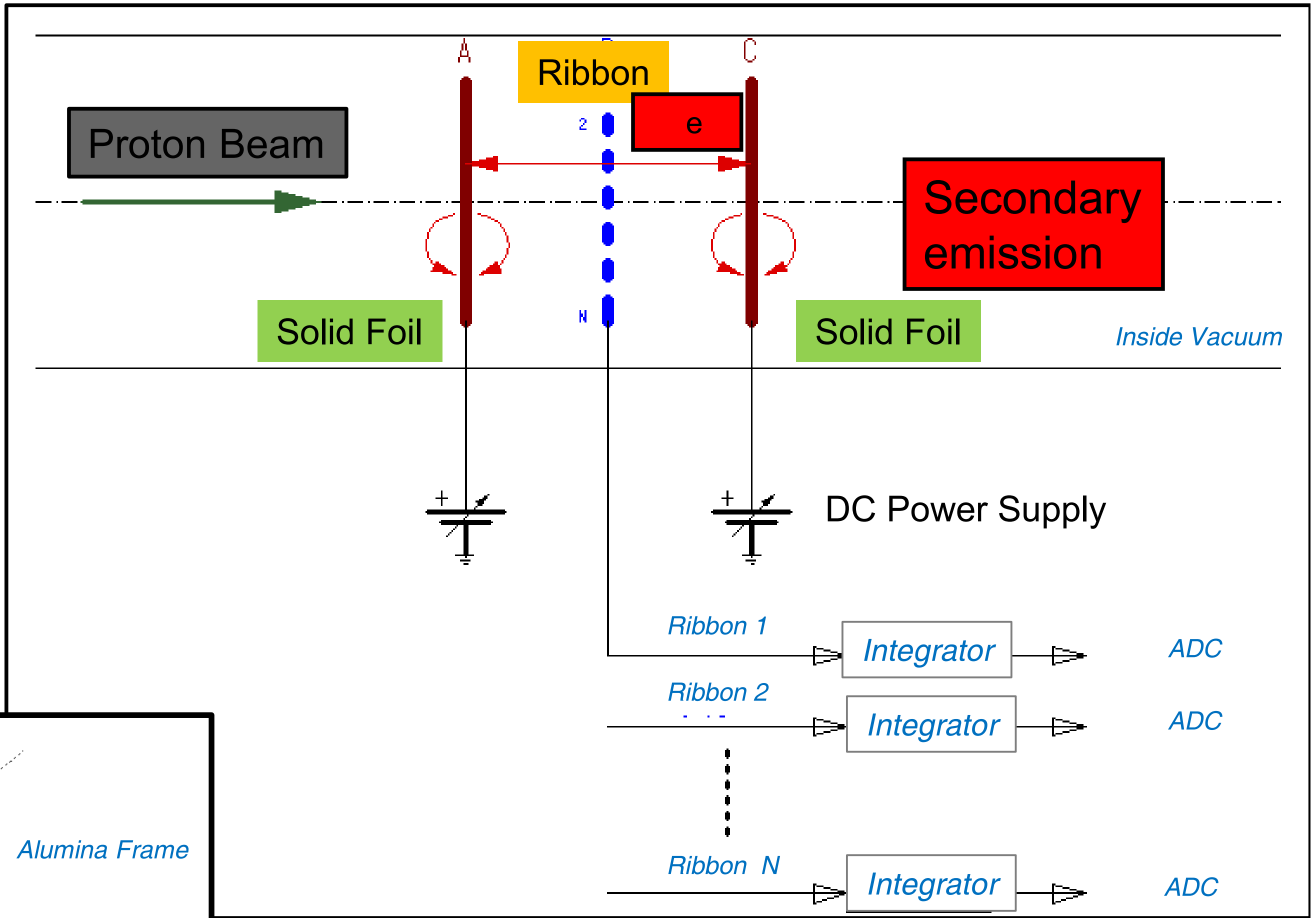
Multi-ribbon(3-50BT, MR,Hadron BT)
Y. Hashimoto et al.

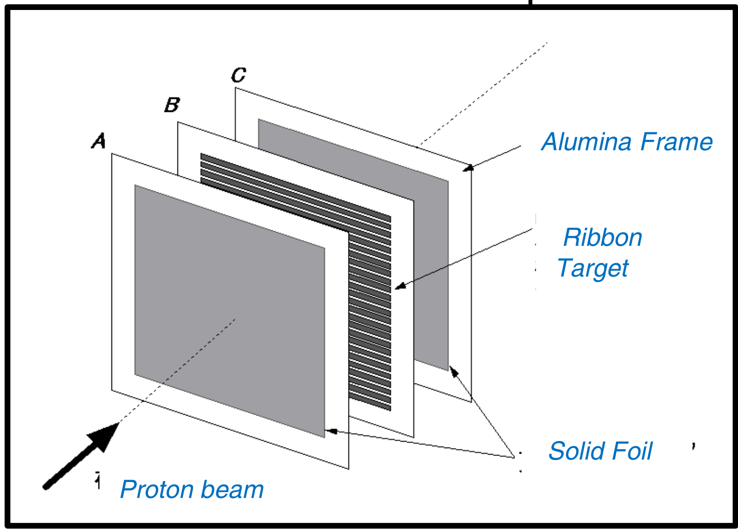
Multi-ribbon Beam Profile Monitor

Ribbon Type Detector

Distance 10 mm

Emissivity (secondary electron/proton)
2.1 % (P_E= 3 GeV)



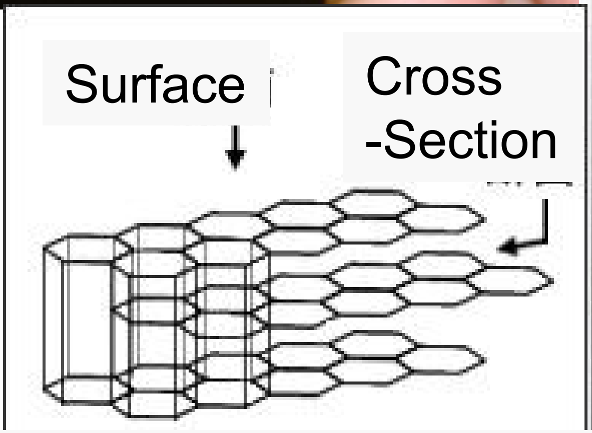


Y. Hashimoto *et al.*, HB2010

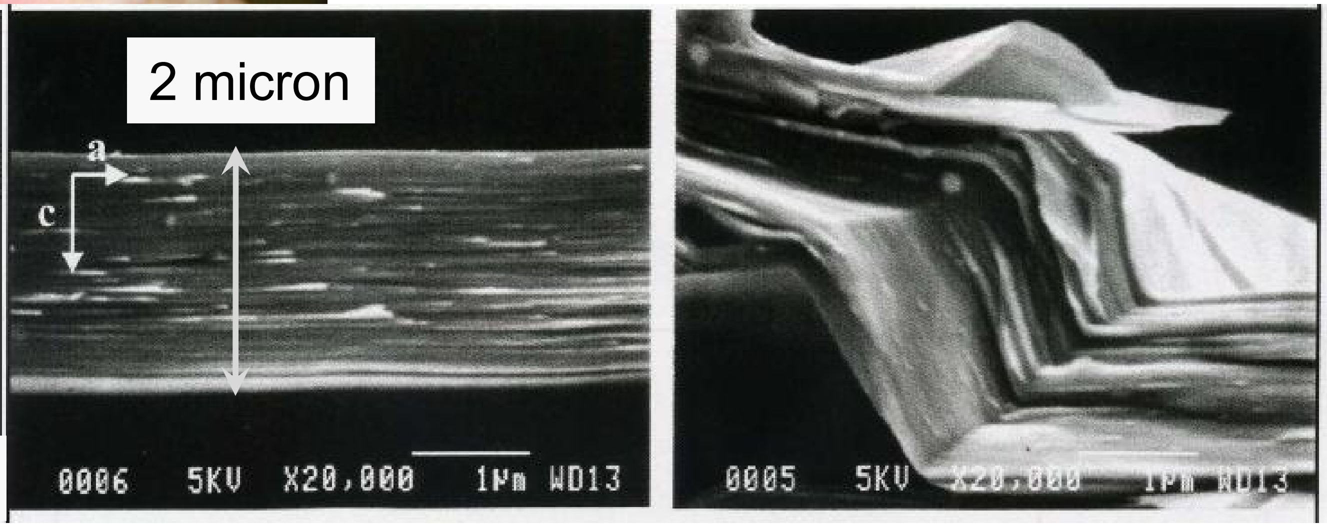
Developed Target Material : Graphite (made by UBE)

Thickness: 1.6～2 μm
Flexibility
Self-supporting
Large size :160 x 320 mm^2 max.
Firing temperature : 2600 degree C

UBE's Graphite has larger Crystallite
Adding toughness.



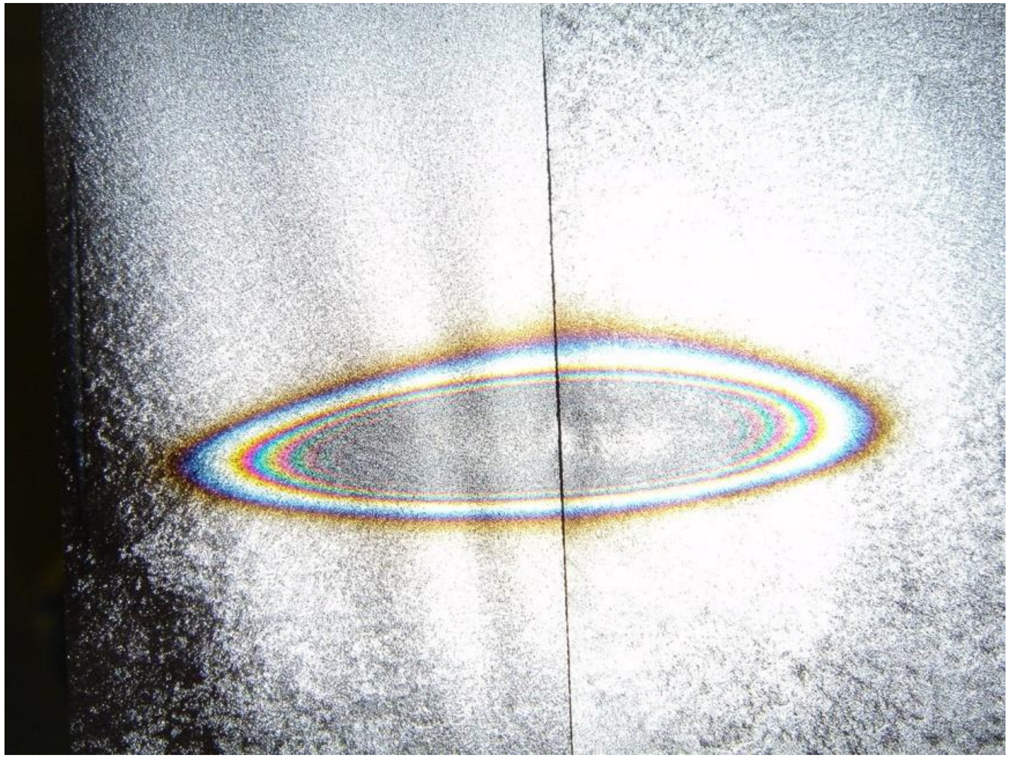
Layered oriented Benzene ring



Endurance Test

Long-Run Test (Net. 11 months)

Beam: Proton
Energy: 500 MeV
Intensity: 2e12 ppb, 20Hz
Beam Size : $45^{H} \times 15^{V}$ mm^2

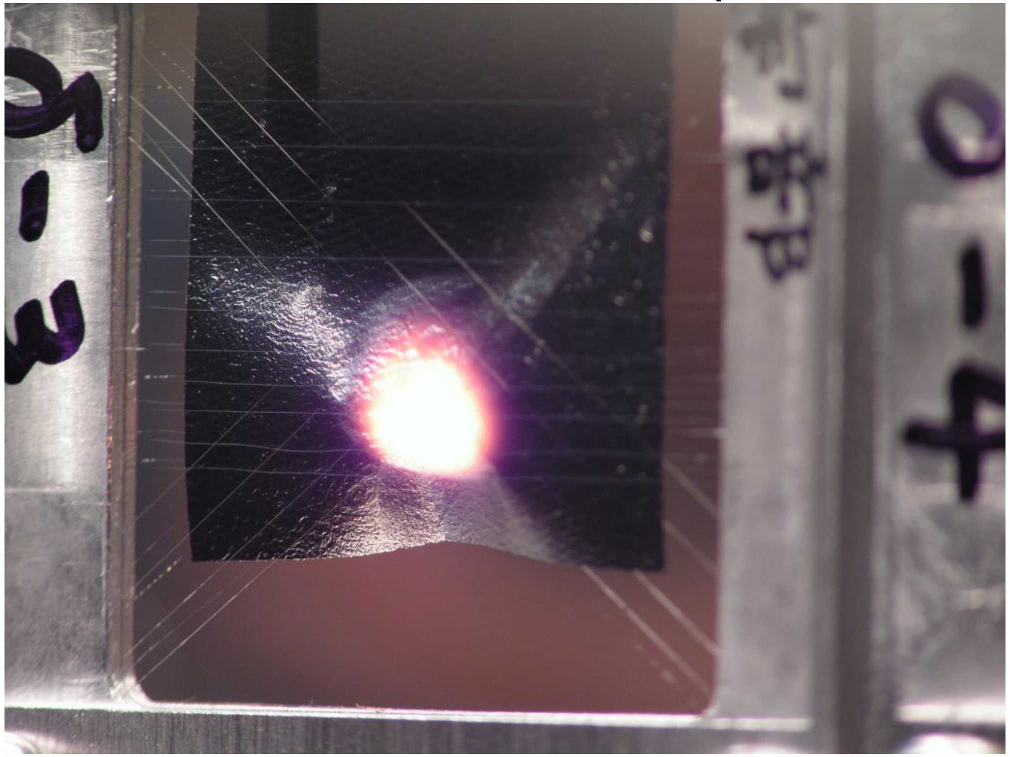


Total Particle Number: $\geq 5 \times 10^{20}$ ALIVE

∗ Electro-Conductive Binder remains :sticked tightly.

High Temperature Test

Beam: Ne+
Energy: 3,2MeV
Current: 3.0 μA
Beam Size 8 mmφ



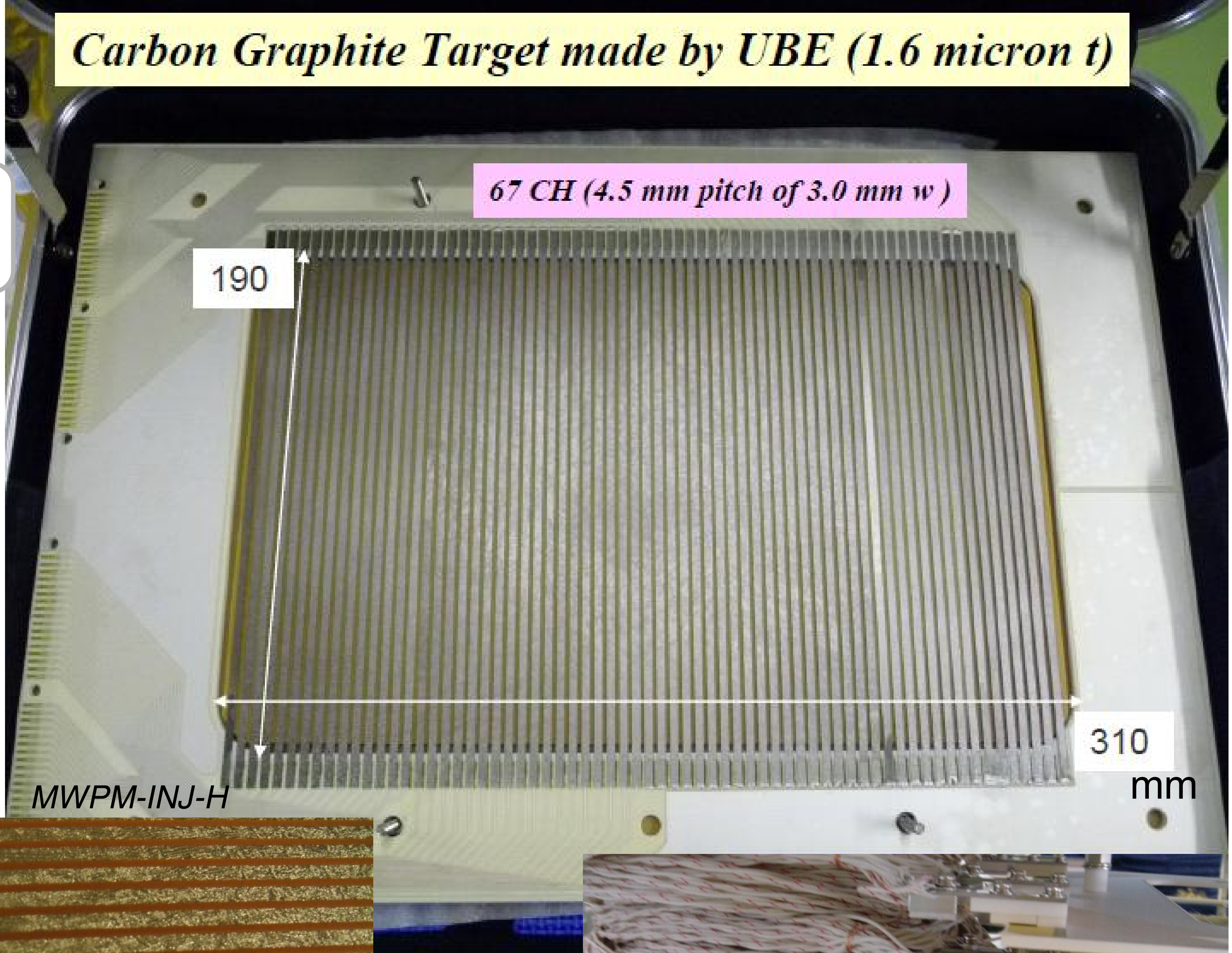
Foil Temperature1400 ℃ after 67 min : BROKEN

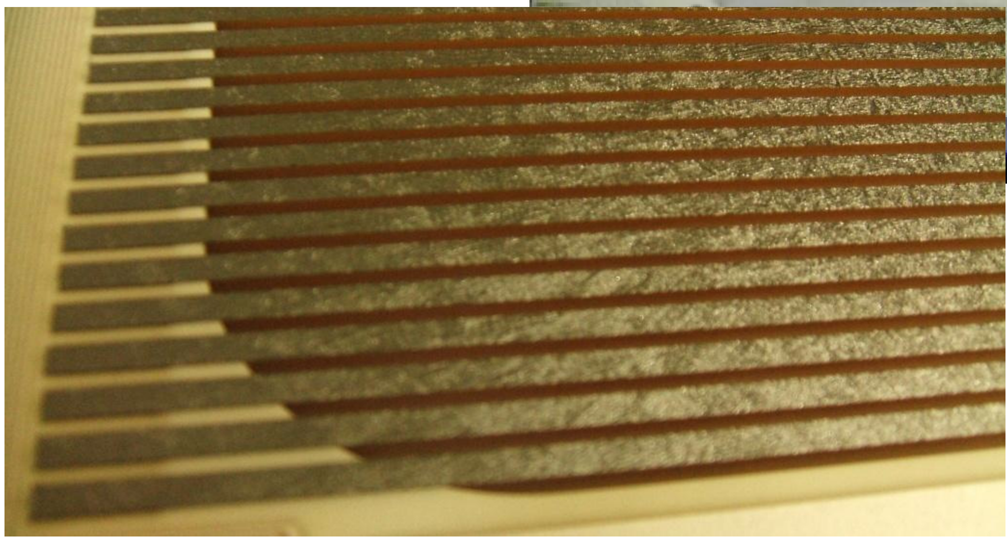
T @3-50BT < ~200℃

Ribbon Target

Alumina Frame:
410H×290V mm^2

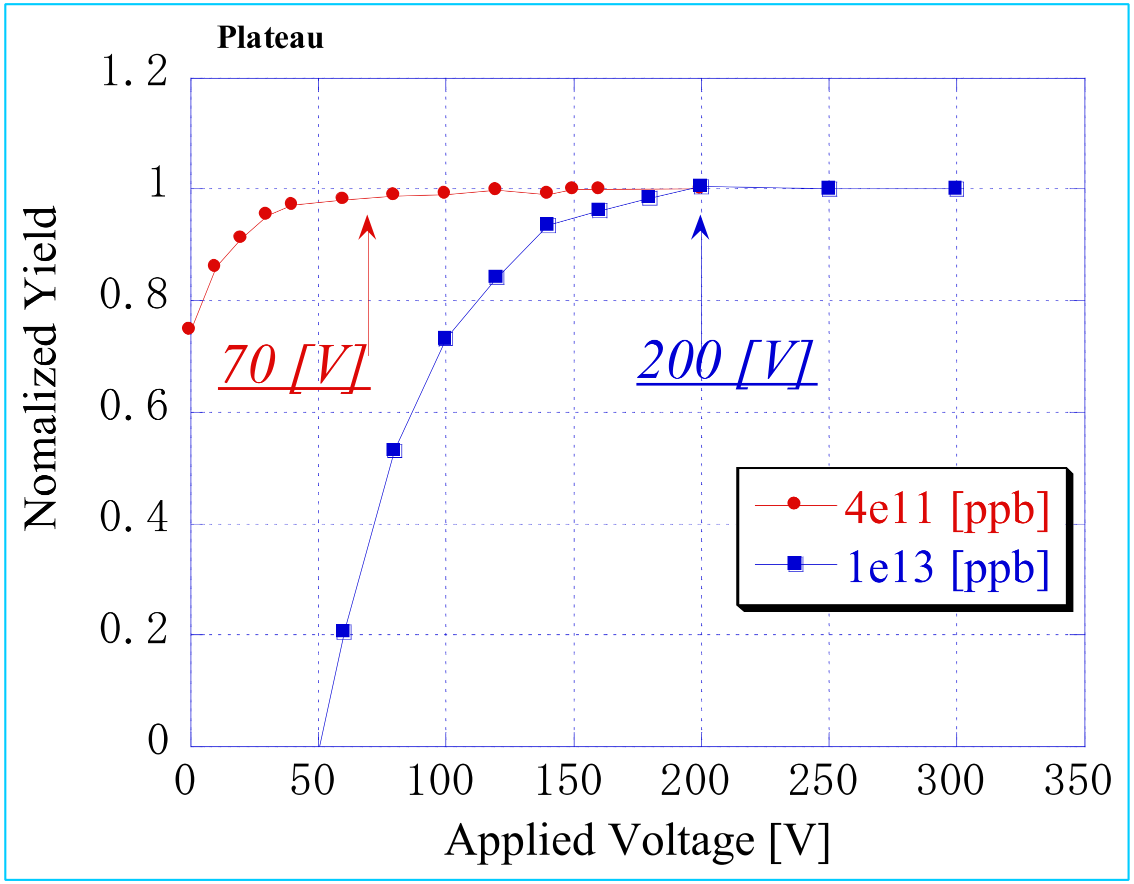
Printed Pattern
Electrode :AgPt
Connector: Au



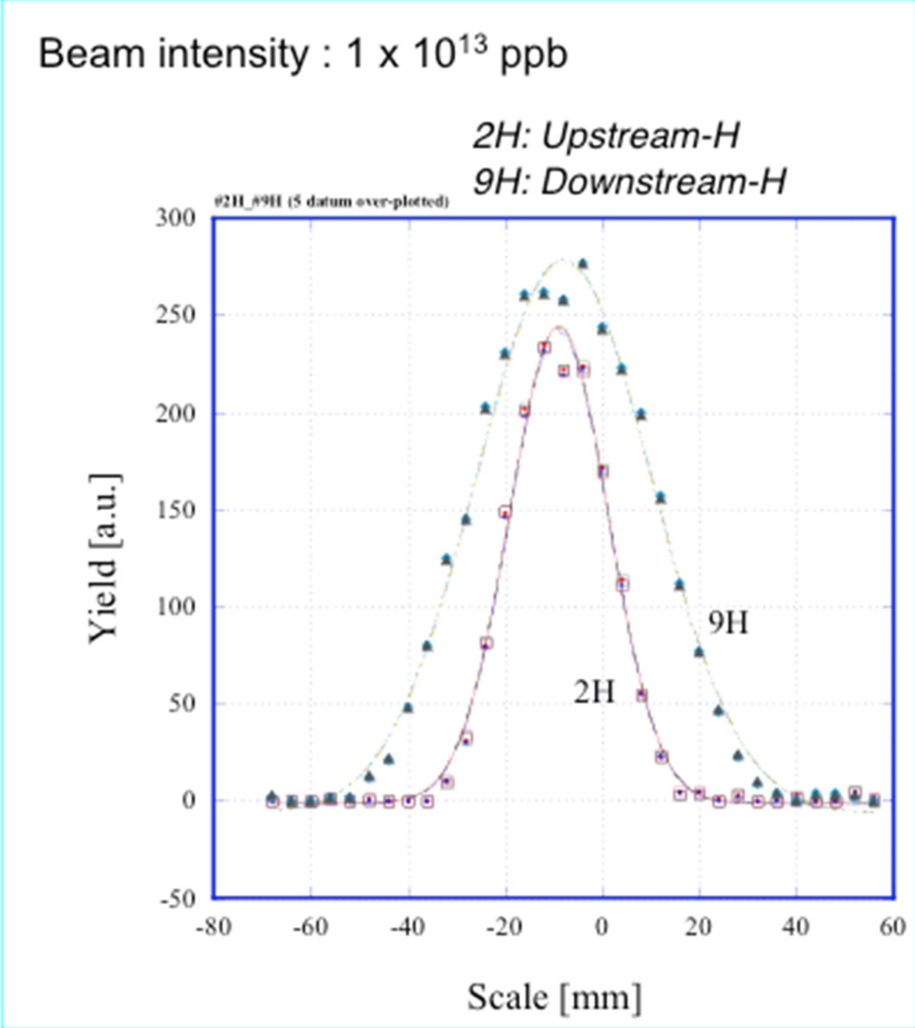


Alumina Connector

Plateau Curve: Compared with two intensity's
4e11 [ppb] (bunch length:100ns, beam size: 35H x 16V mm2)
1e13 [ppb] (bunch length:100ns, beam size: 80H x 30V mm2)



Plateau Curve



Measurement of the beam

Beam based characterization of monitors

Beam based Alignment of BPMs

- Ordinary Beam based alignment

  Using one QM for one BPM

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

m : BPM location

n : QM location

ΔK: increment of the n-th QM

x_1 : beam position without QM variation

x_2 : beam position variation with the increment ΔK

$$\mathrm{a}_{mn} = \frac{\sqrt{\beta_m \beta_n}}{2\sin(\pi\nu)}\cos\left(\pi\nu - |\phi_m - \phi_n|\right)$$

- Extension to multiple BPMs with a QM family

  BBA using one QM for one BPM is impossible in the RCS

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

$$A = [\mathrm{a}_{mn}]$$

$$\vec{x}_1 = \begin{bmatrix} x_{1n} \\ x_{1l} \\ x_{1s} \end{bmatrix}$$

m : BPM location

n, l, s : QM location

(this case: the family comprises 3 QMs)

Present version = model (Twiss parameter) dependent analysis

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

BBA

LINAC 102 BPMs

BBA with one QM

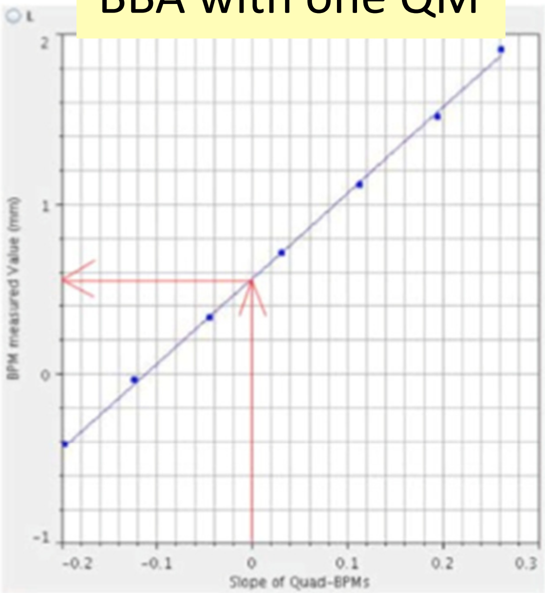


Figure 5: Example of the beam based calibration. This measurement gives -563 micro-meter (pointed by red arrow sign) for the offset parameter for BPM-5th-y in MEBT1. Horizontal-axis [a.u.] or [mm/Ampere]: slope defined by formula-(5) (see explanation in the text). Vertical-axis [mm]: "BPM (N) position"

Not all the BPMs were calibrated,
because of the lack of the steering magnets

Δx, Δy ~ 10μm

S. Sato *et al.*, PAC'07

RCS 54 BPMs

7 QM families (60 QMs)

BBA with QM families

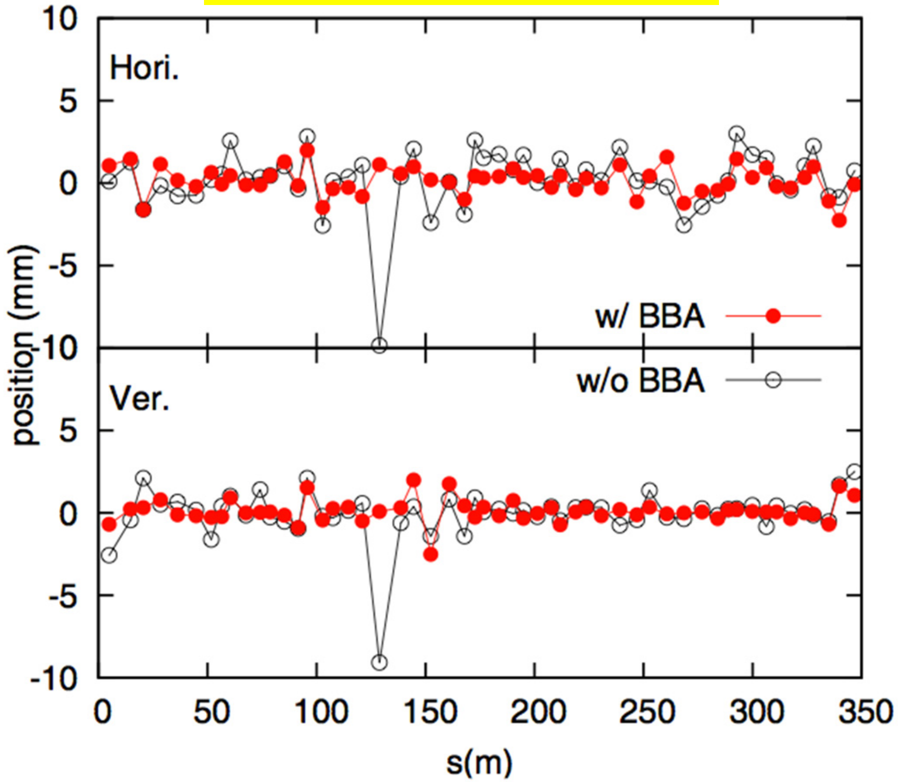


Figure 3: COD correction without (open circle) and with (closed circle) using BBA results. Upper is for horizontal and lower is vertical one.

Δx, Δy ~ 500μm

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

MR

186 BPMs

11 QM families (216 QMs)

Comparison of BBA
with one QM and with QM families

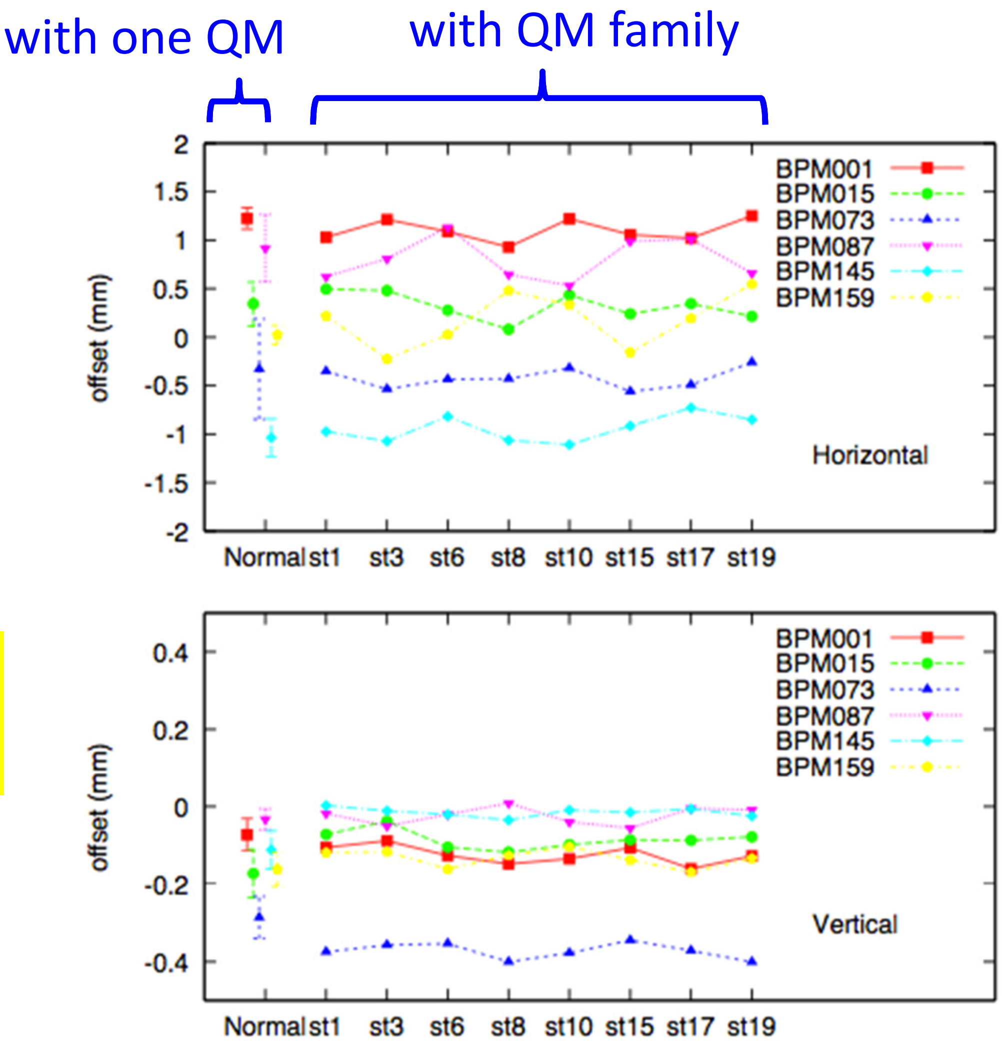


Figure 3: MR BBA offset estimation of BPM attached to QFS family magnets. Upper and lower are horizontal and vertical, respectively. Most left data is determined by single QM sweeping and reference. Eight data sets are independent measurements for different initial orbits defined by various steering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

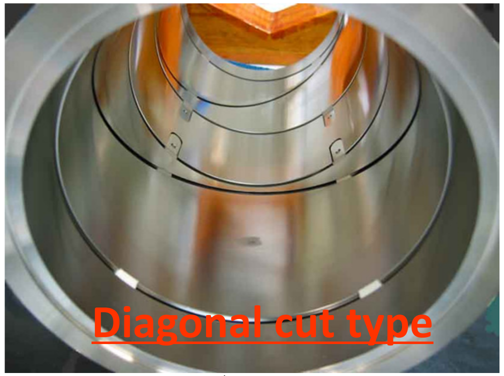
$\Delta x, \Delta y \sim 50$ - $500\mu m$

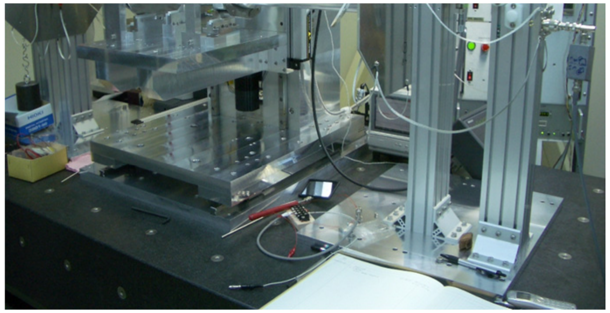
N. Hayashi *et al.*, HB2010

BPM gain calibration

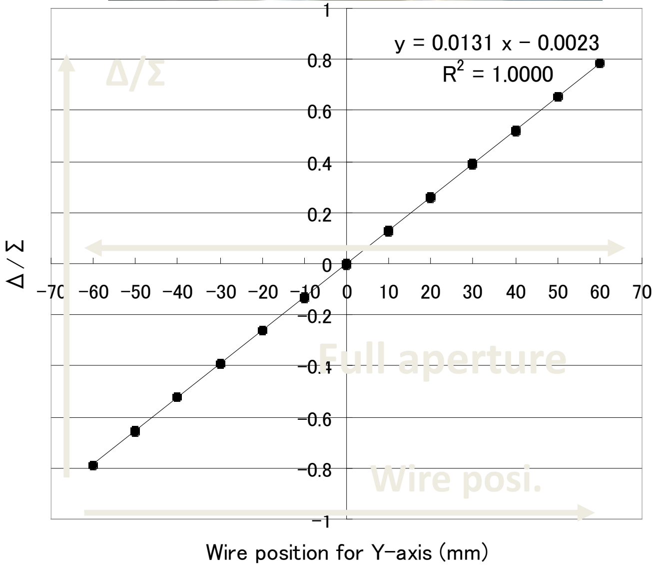
Ring BPM:

- **Mainly used in the ring**
- **Good linear response covering full aperture**
- **Bore: Φ130mm(standard),**
  Φ134, 165, 200, 257, 140x302mm(special)





Calibration : wire method



Errors (in rms unit)

- **Sensitivity: ±0.3%**
- **Offset: ±0.12 mm**
- **Rotation: ±3.6mrad**

corrected on the computer

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_k's:

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

→ MOPD22 by M. Tejima *et al.*

Algorithm

Errors included in all signals: L_k, R_k, U_k, D_k

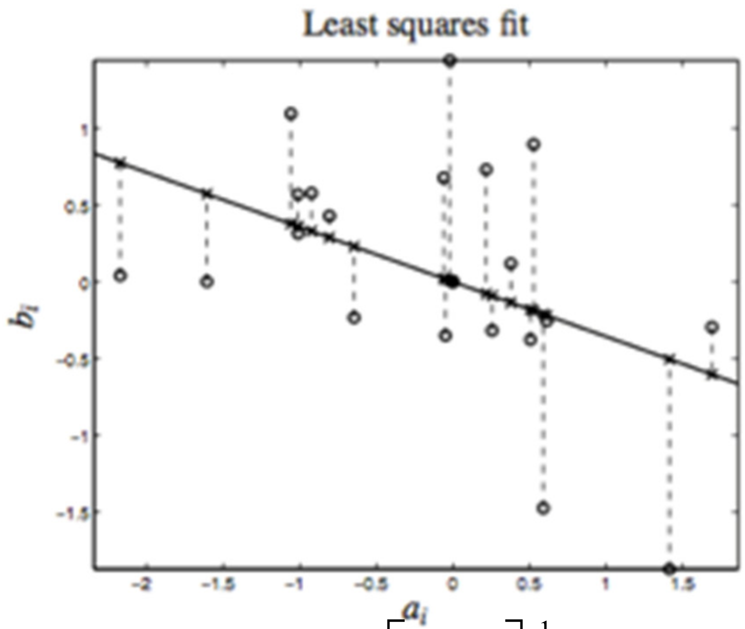
"Total least squares" algorithm is employed

The function: $-R/g_R + U/g_U + D/g_D = L$
Noises are included in L, R, U, D.

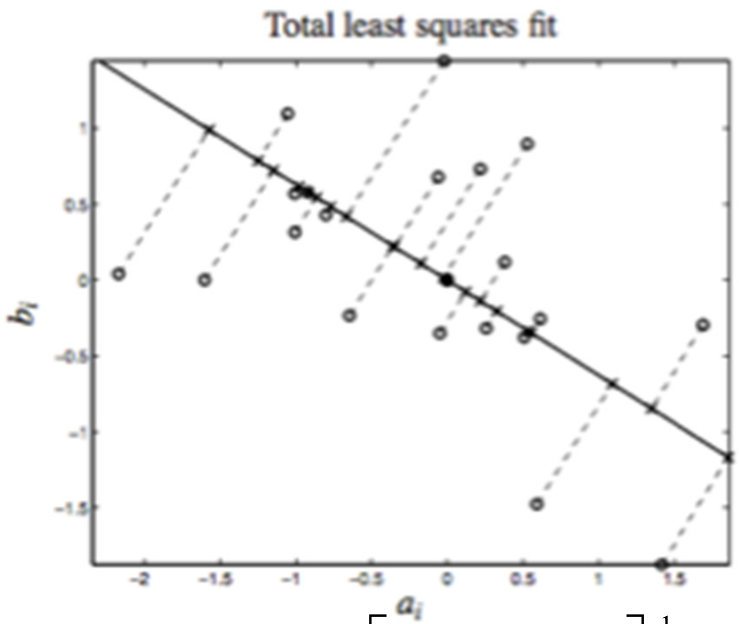
Using Matrix form : **A X = b**

- A – – – {−R, U, D}
- b – – – {L}
- Ab – – – {−R, U, D, L}

X_{TLS} – – – $\{1/g_R, 1/g_U, 1/g_D\}$: fit by TLS
X_{LS} – – – $\{1/g_R, 1/g_U, 1/g_D\}$: fit by LS



$$\mathbf{X}_{LS} = \left[\mathbf{A}^{\mathrm{T}}\mathbf{A}\right]^{-1}\mathbf{A}^{\mathrm{T}}\ \mathbf{b}$$



$$\mathbf{X}_{TLS} = \left[\mathbf{A}^{\mathrm{T}}\mathbf{A} - \sigma_{n+1}^{2}\mathbf{I}\right]^{-1}\mathbf{A}^{\mathrm{T}}\ \mathbf{b}$$

Evaluation with simulations and beams

BPM#1 beam based gain cal.

- 2010. 11. 30 data

9 shots

10ms COD mode

100 points average (1 sec)

(*** Total Least Squares ***)

{1.00013, 1.00478, 0.979091}

(*** Least Squares ***)

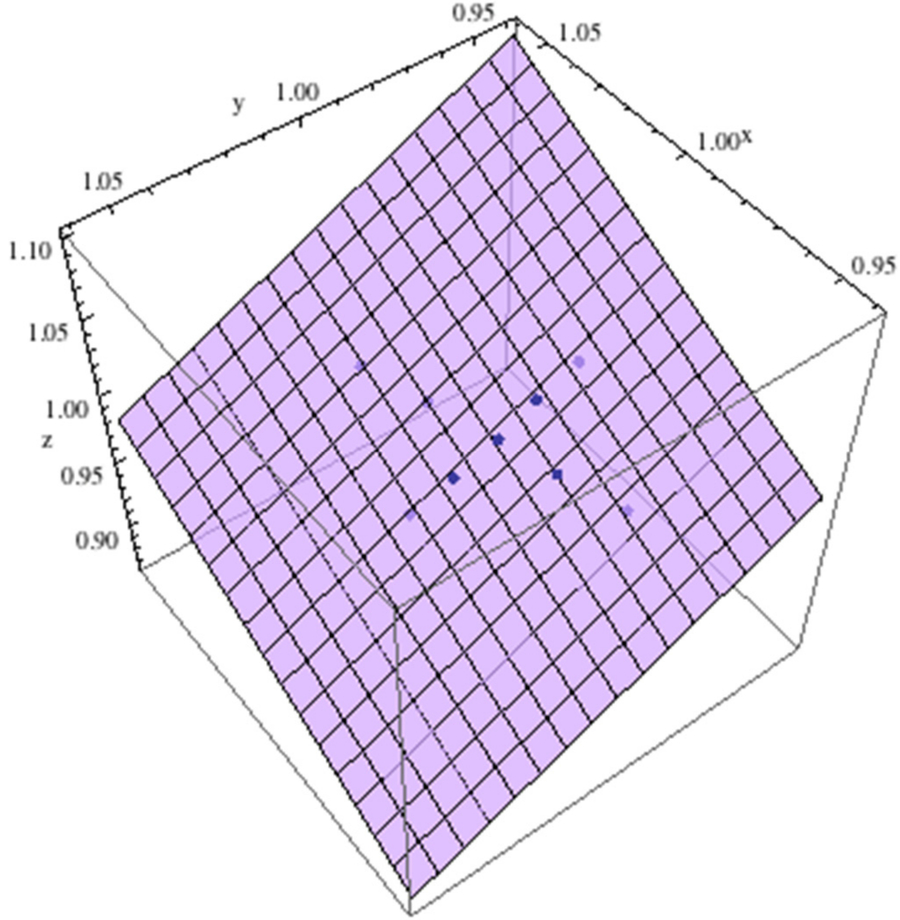
{1.00187, 1.00567, 0.979927}

→ MOPD22 by M. Tejima et al.

$$L + R/g_R = U/g_U + D/g_D$$

$$\rightarrow (D/L) = g_D \{ 1 + (R/L)/g_R - (U/L)/g_U \}$$

$$\rightarrow \quad z = 1 + x\, g_D/g_R - y\, g_D/g_U$$



DCCT response calibration with the beam

Required precision:

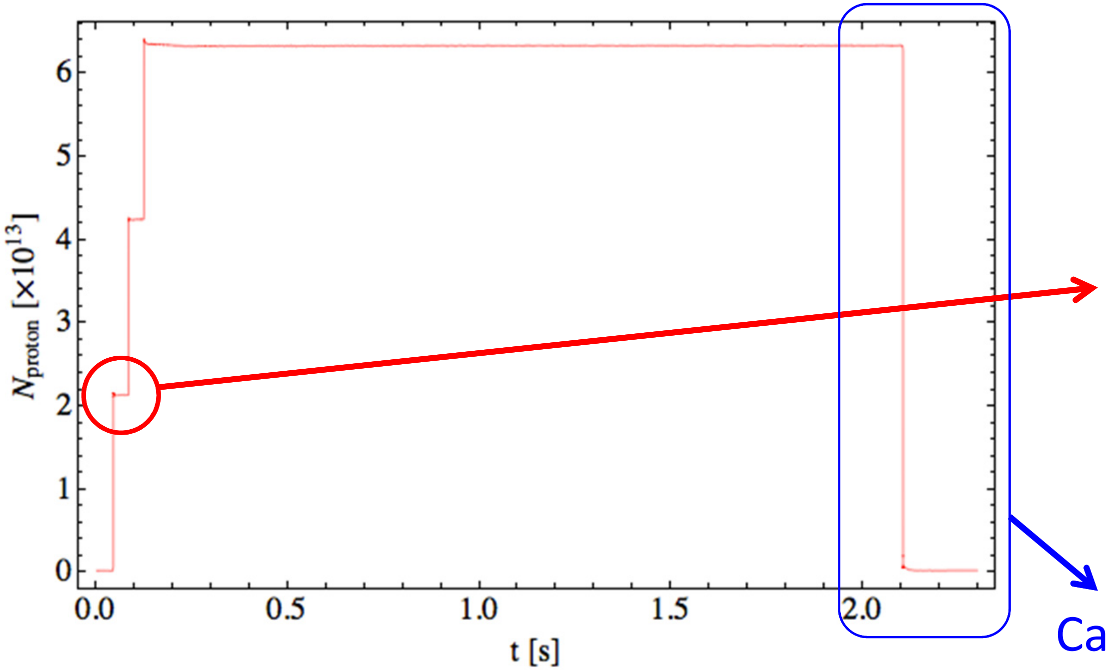
to detect the beam loss of a few 10 W, ΔI ~ 100μA

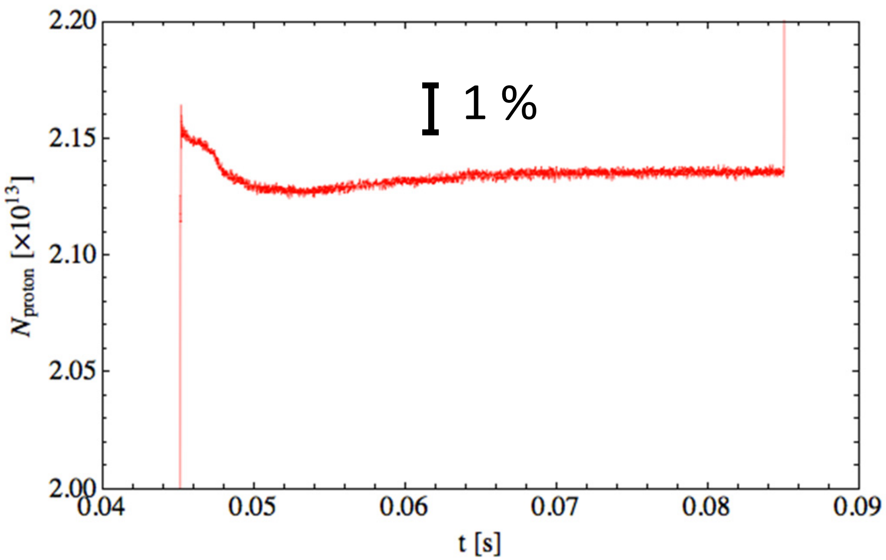
especially in the injection transient

MR DCCT
I < 20A
f = DC- 26 kHz

S. Hiramatsu et al.

Typical beam in the MR





Cal. using step response at the end

Apparent error, physically impossible!

Easy to be claimed from users

Moreover, very important for high intensity beam tuning

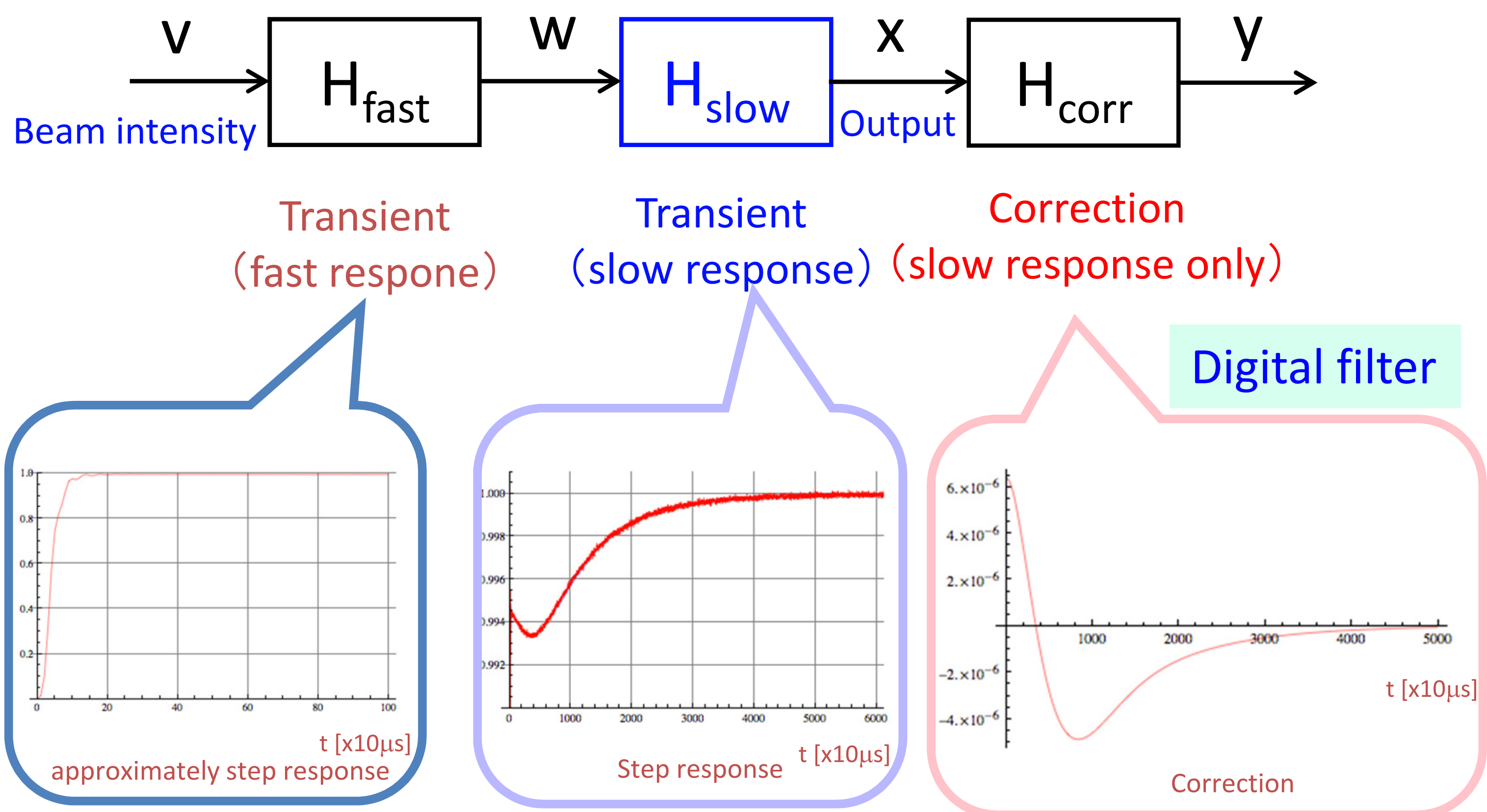
DCCT response calibration with the beam

Basic idea:

Fast beam extraction (FX) = one turn extraction in ~5 μs
can be considered as the step response in ms order

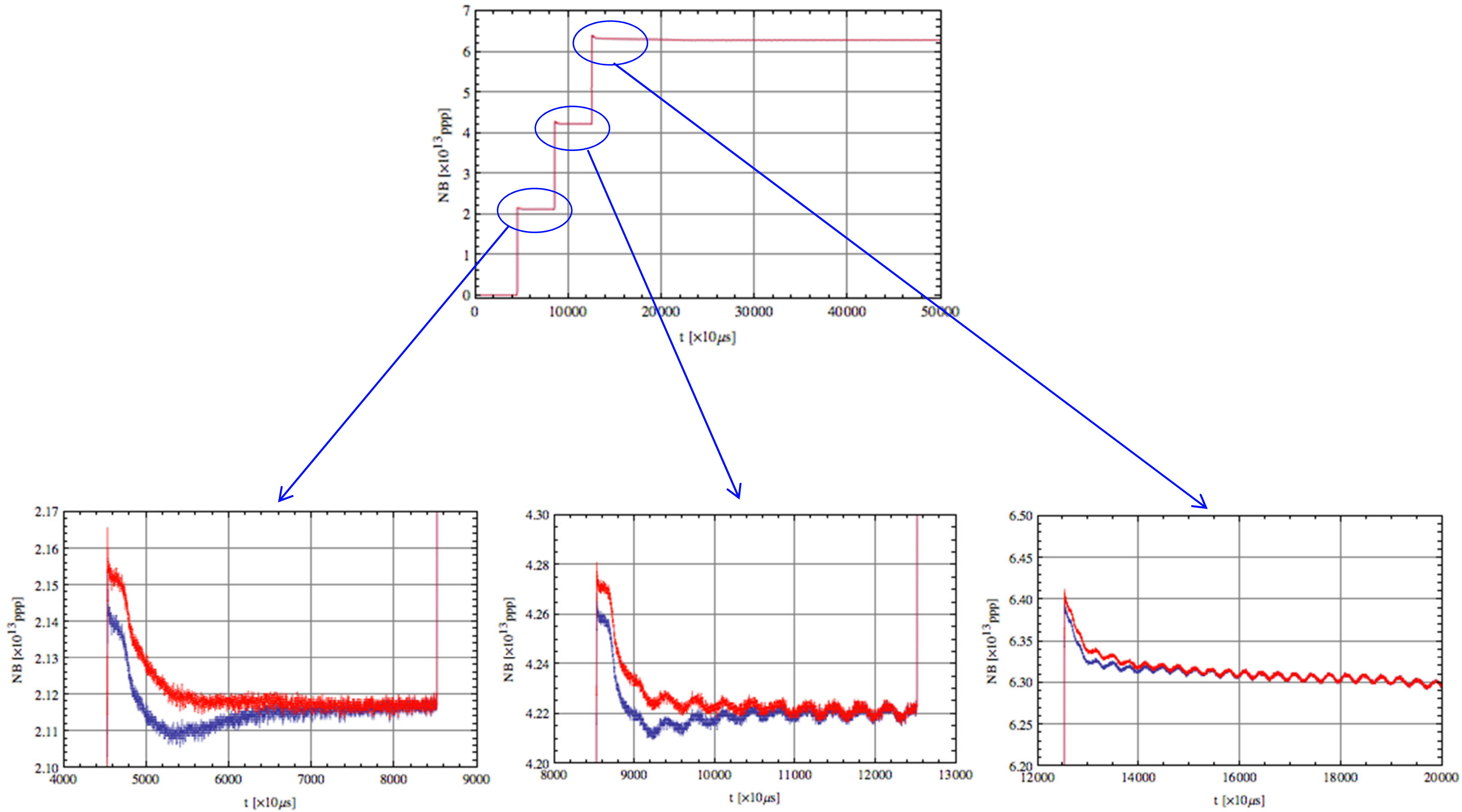
→ obtain the the step response using the beam @ FX

→ correct the DCCT response



At present processed off-line. In future implemented in FPGA or DSP.

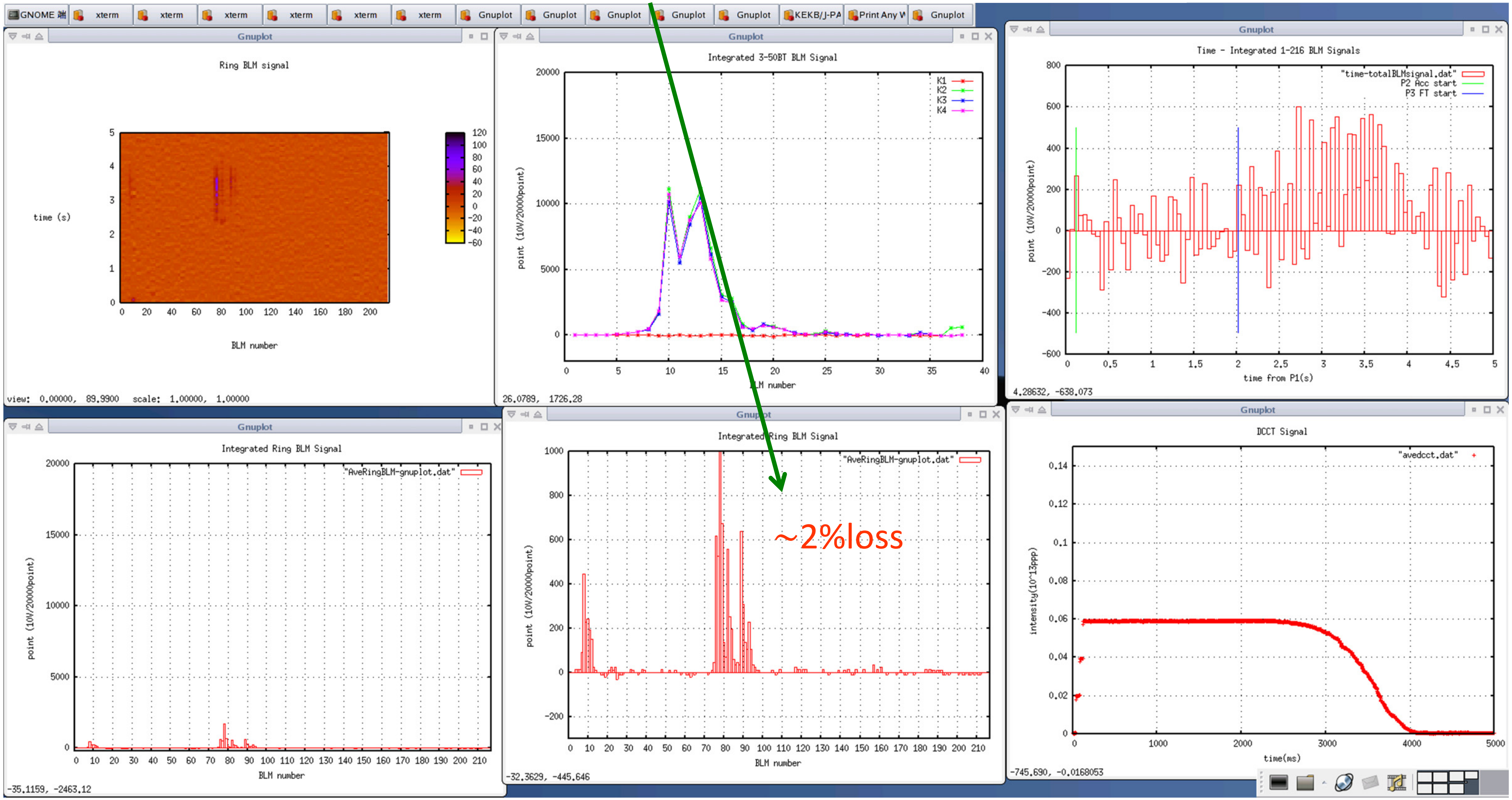
Correction applied on
MRDCCT Run34 Shot0000119 @2010.06.07_18.16.43.698



Blue : no correction red : with correction

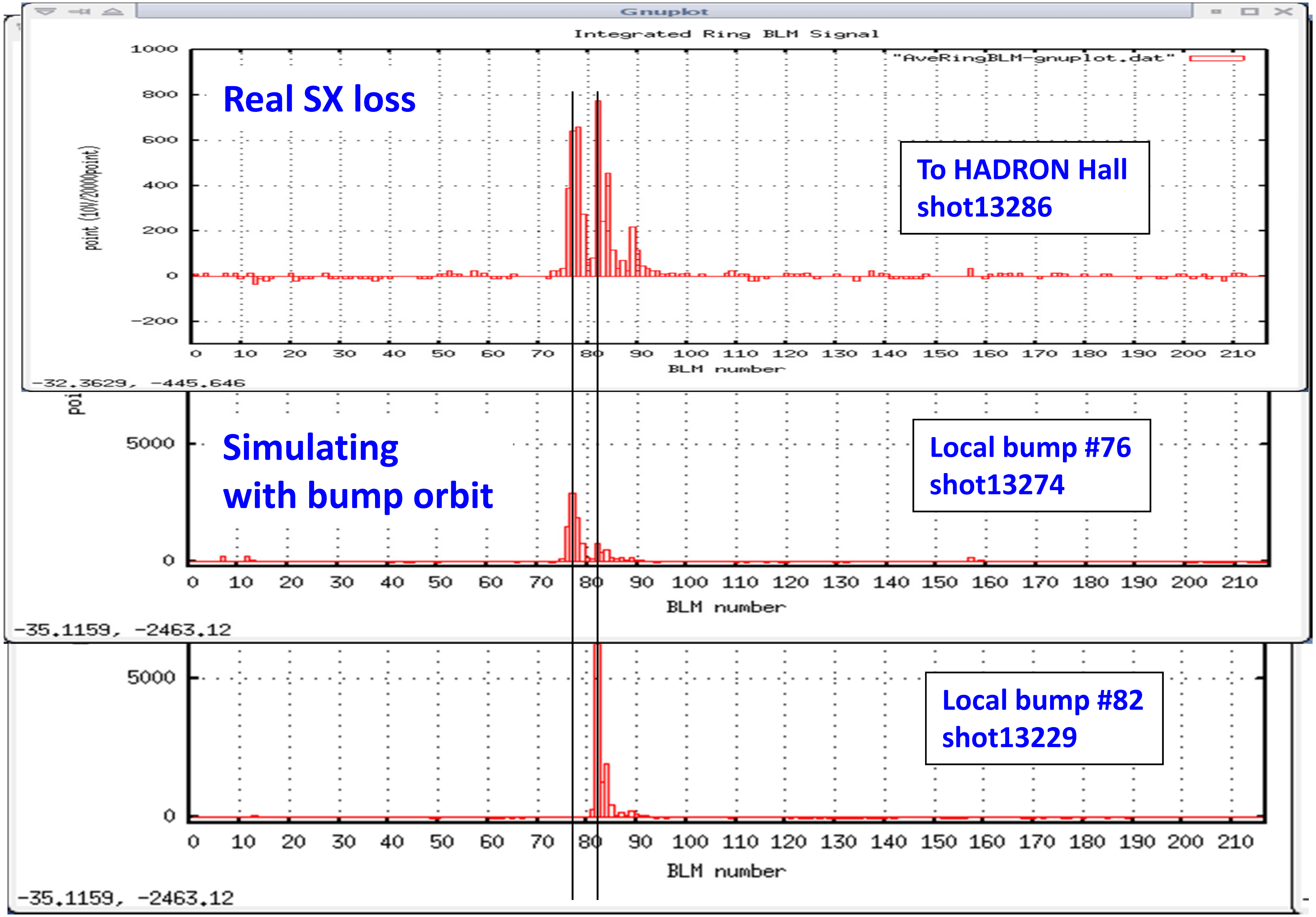
BLM sensitivity calibration

Beam losses along the slow extraction section

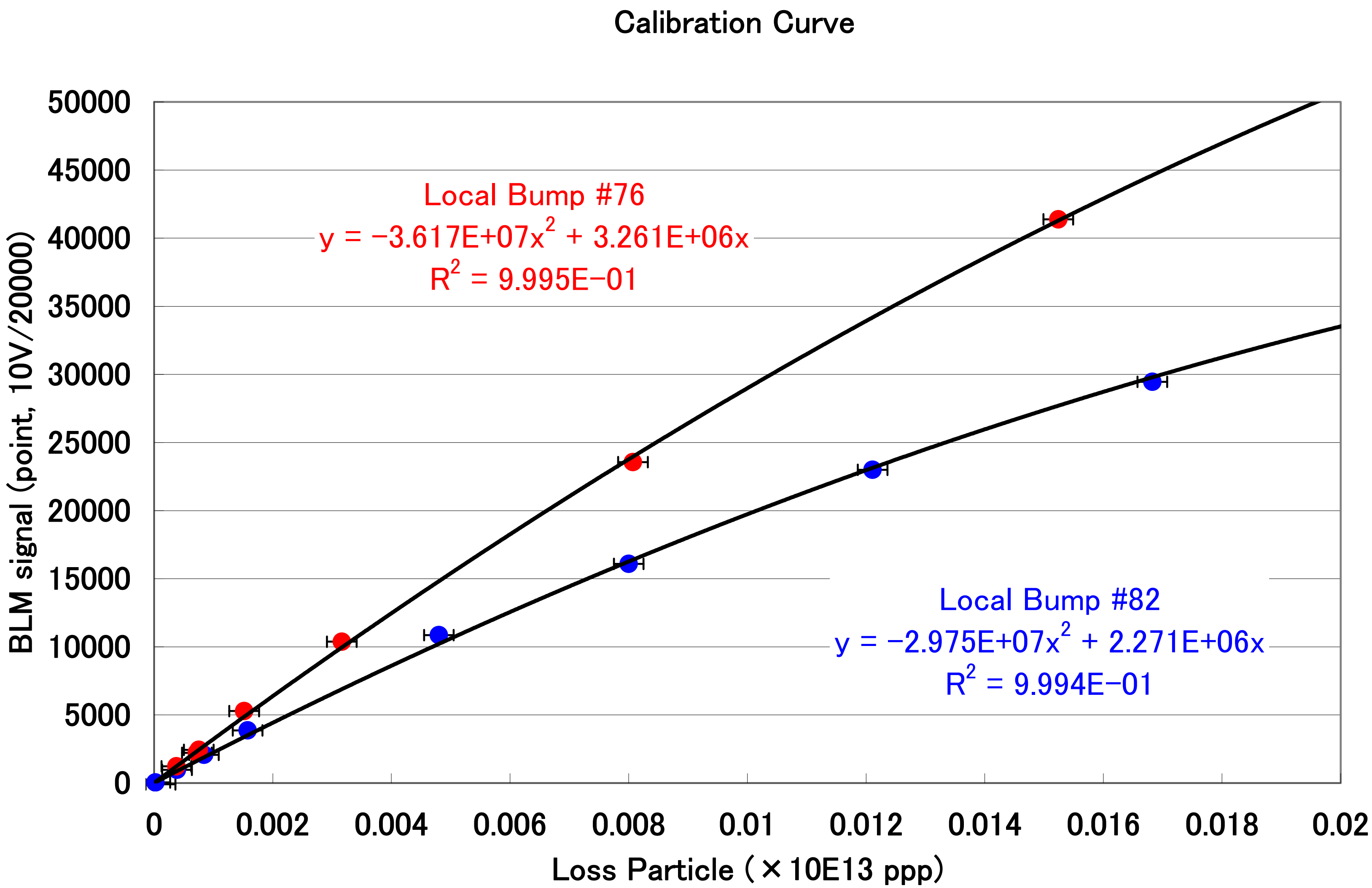


K. Satoh

Beam loss during SX process is approximated by the loss by local bump orbits



BLMs are calibrated with the DCCT



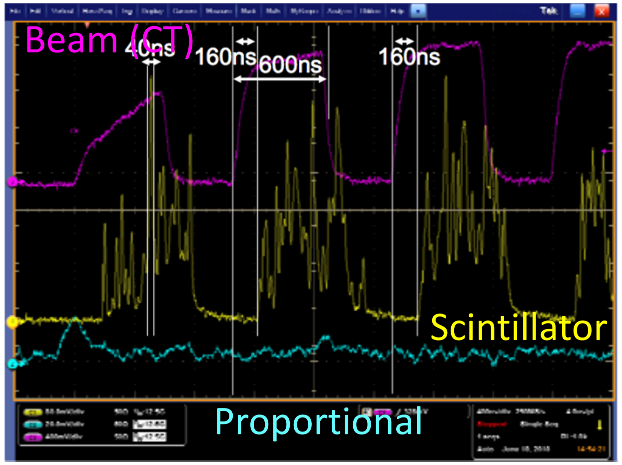
Beam Loss Monitor present status and future plan

LINAC : Proportional

sensitive to X-ray from the cavity → add Scintillator + PTM

→ MOPD43by A. Miura et al.

RCS : Proportional,
Scintillator + PTM,
(Air Ionization chamber(AIC))



MR : Proportional (1m)
(long-AIC)

Saturation at large loss → add AIC (1m)
→ processing circuit

Not resolving bunches → specified detector
like Scintillator + PTM, SSD, Diamond(?)

Summary

- **Measures to high intensity proton beams**

  Low impedance BPMs by diagonal-cut ESM

  Transverse BxB feedback

  Rad-hard SEM with multi-ribbon of graphite

- **Precision enhancement**

  Beam based characterization:

  BPM BBA (one-BPM by one-QM, **multiple-BPMs by family-QM**)

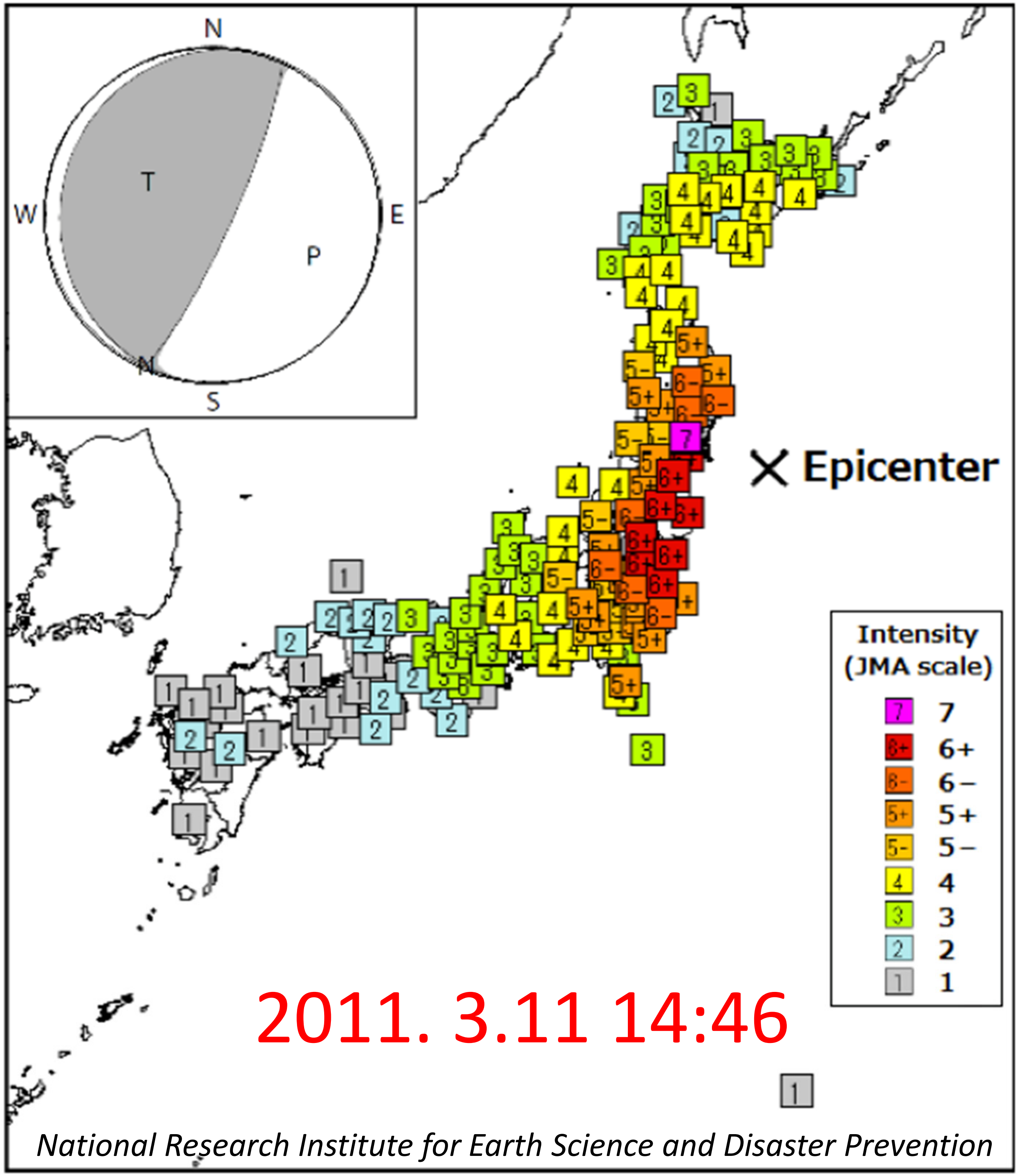
  BPM gain calibration

  DCCT step-response

  BLM sensitivity

These are successfully implemented, or in progress.

"Off the Pacific coast of Tohoku Earthquake"

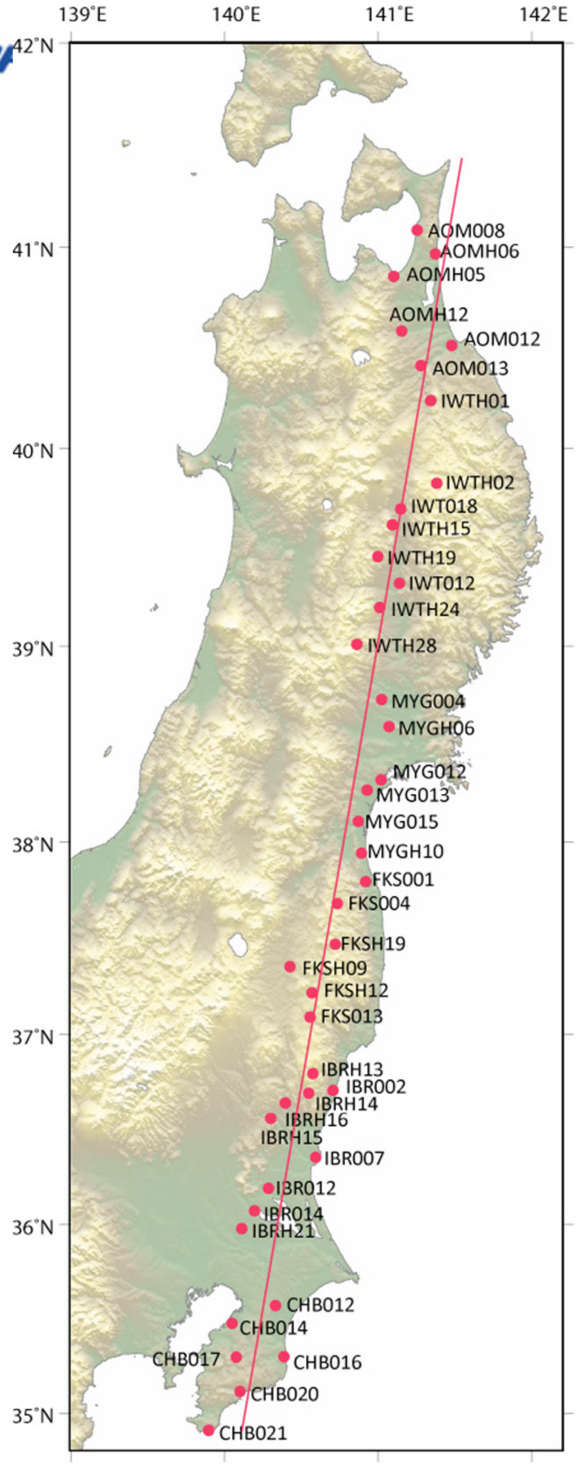


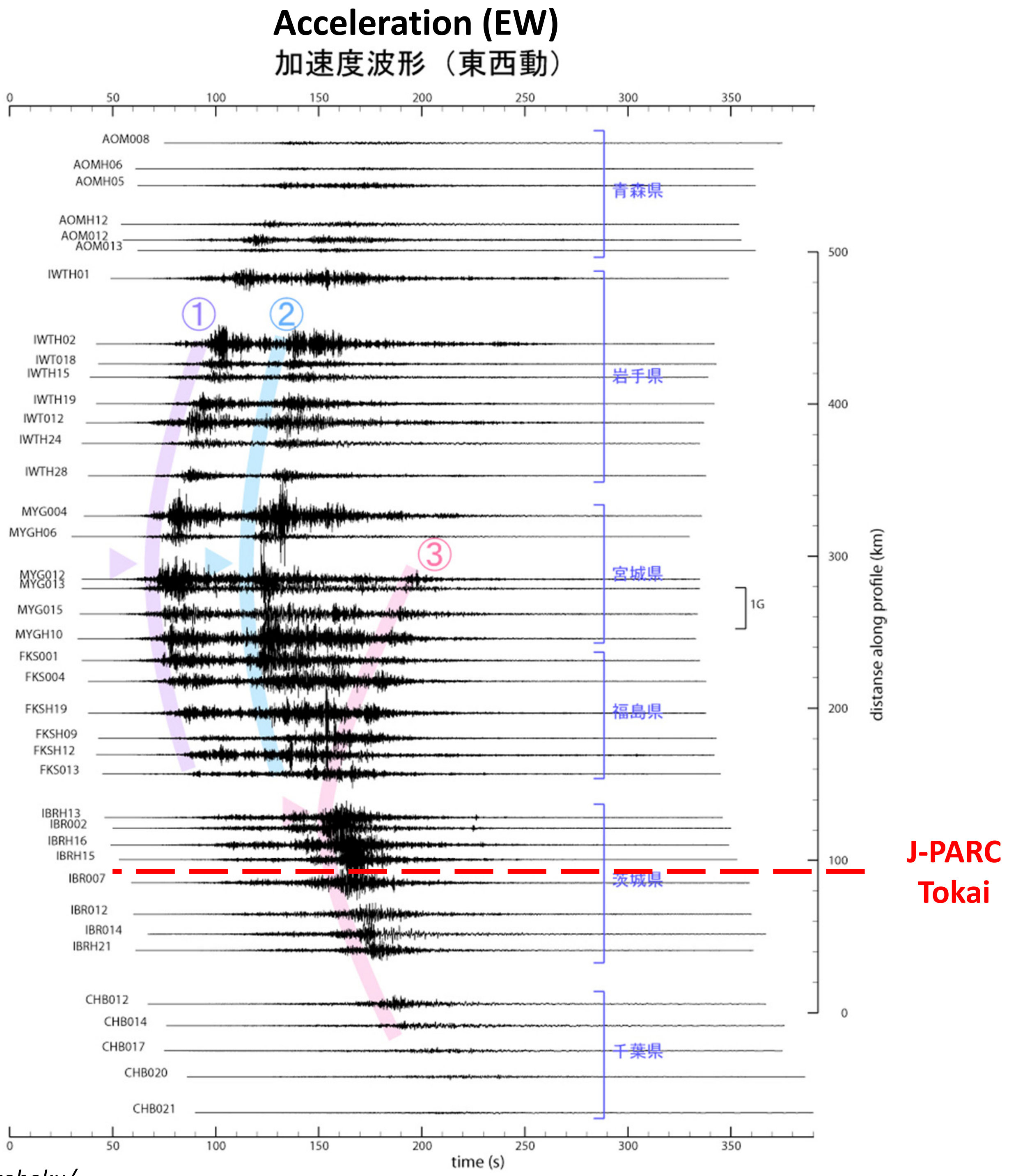
6- @J-PARC, Tokai

NS < 214 gal
EW < 225 gal
UD < 189 gal
@ B2F , Tokai daini
nuclear power station

http://www.japc.co.jp/tohoku/index.html

Three ruptures occurred



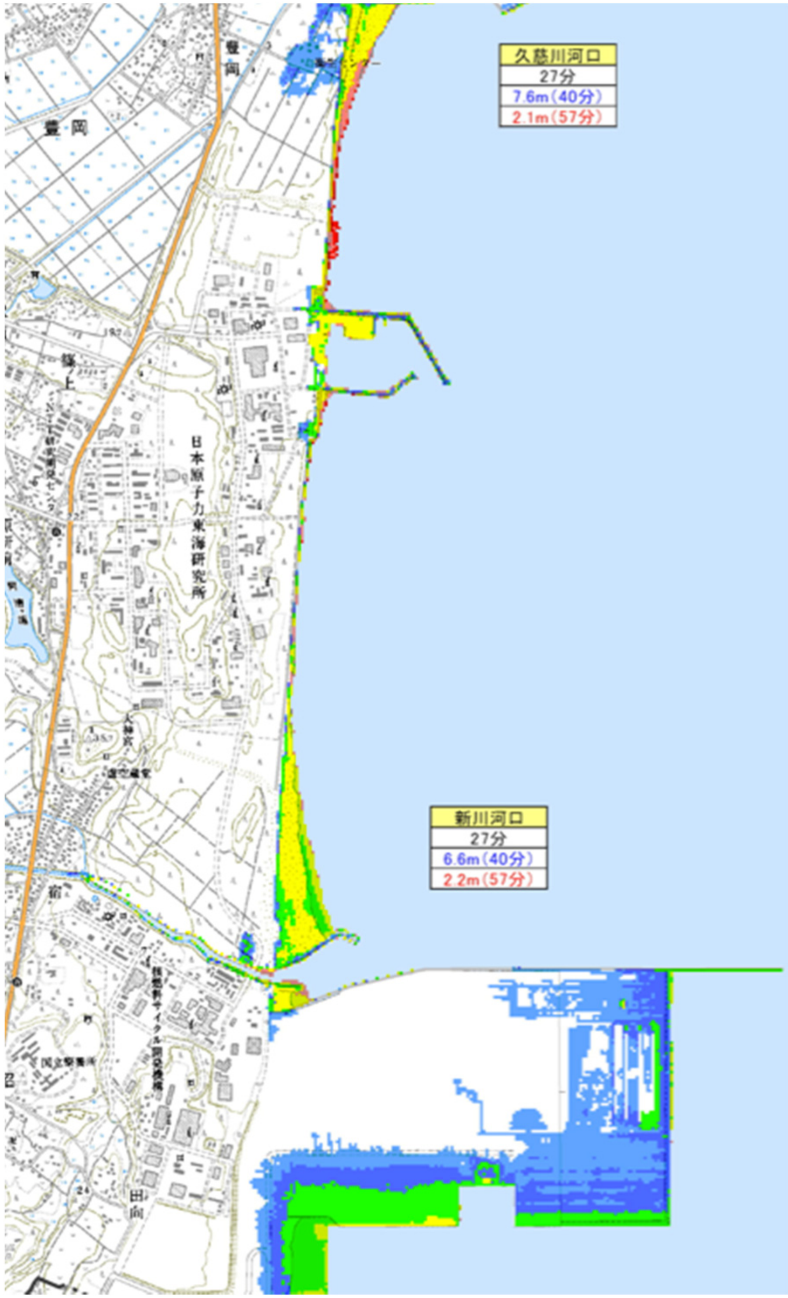


http://outreach.eri.u-tokyo.ac.jp/eqvolc/201103_tohoku/

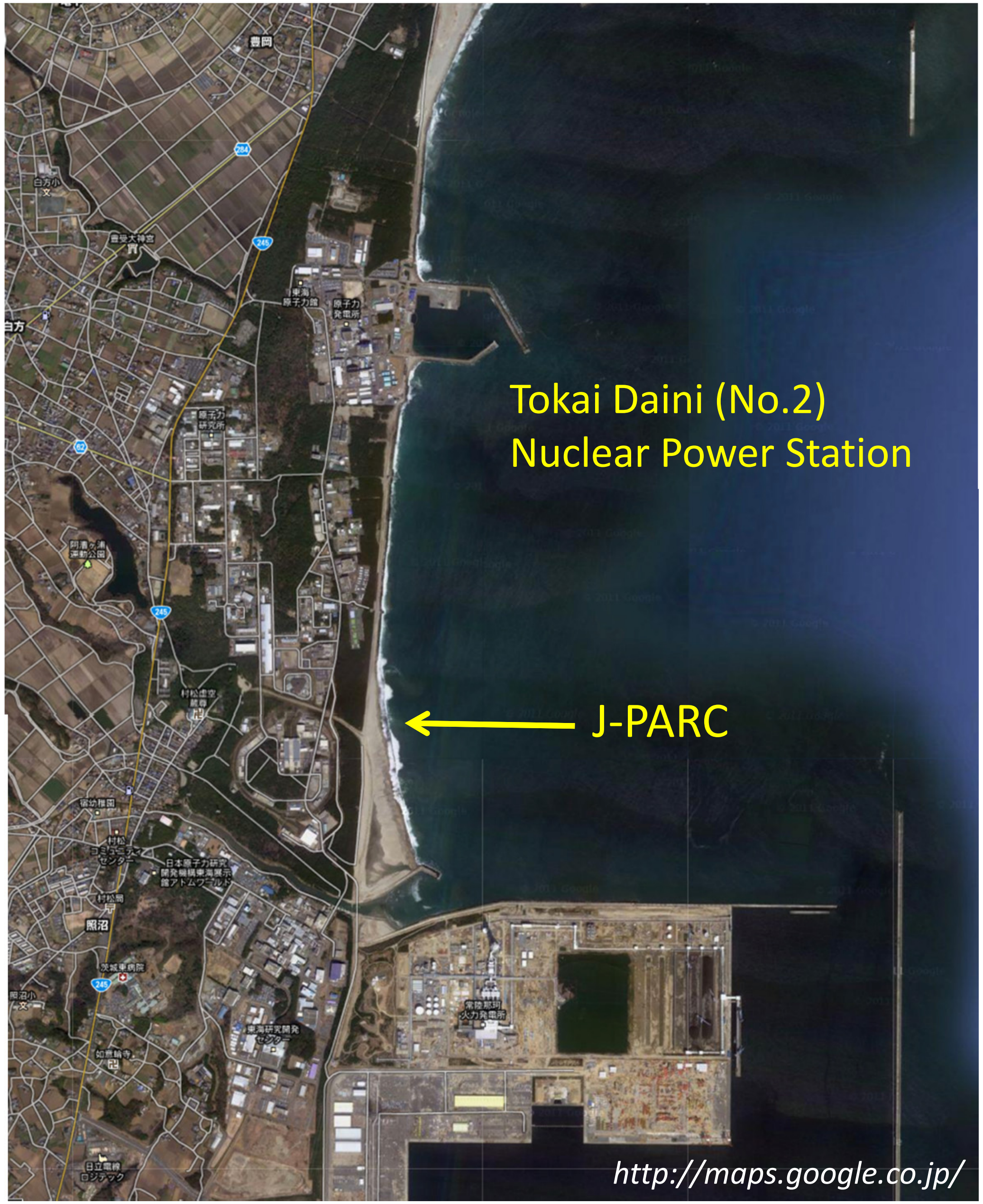
Hazard map

Tsunami Height, *expected by the Ibaraki prefectural government, 2007 Mar.*

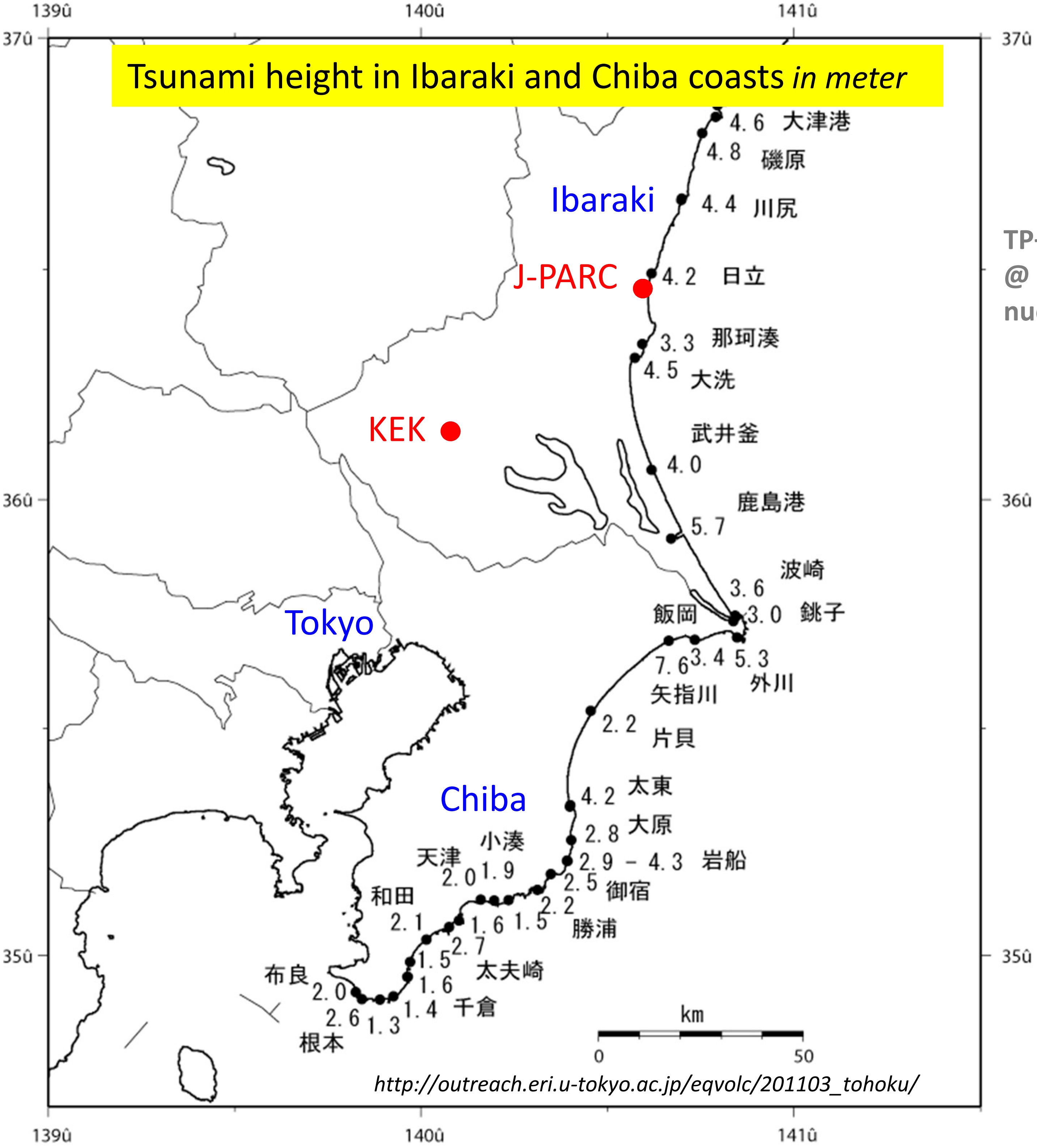
Assumption: the Enpō-Bōsō (1677, M8.0), and Meiji-Sanriku (1896, M8.2-8.5)



- < 0.5m
- 0.5m – 1.0m
- 1.0m – 2.0m
- 2.0m – 4.0m
- 4.0m – 6.0m
- 6.0m <



Tsunami height in Ibaraki and Chiba coasts *in meter*

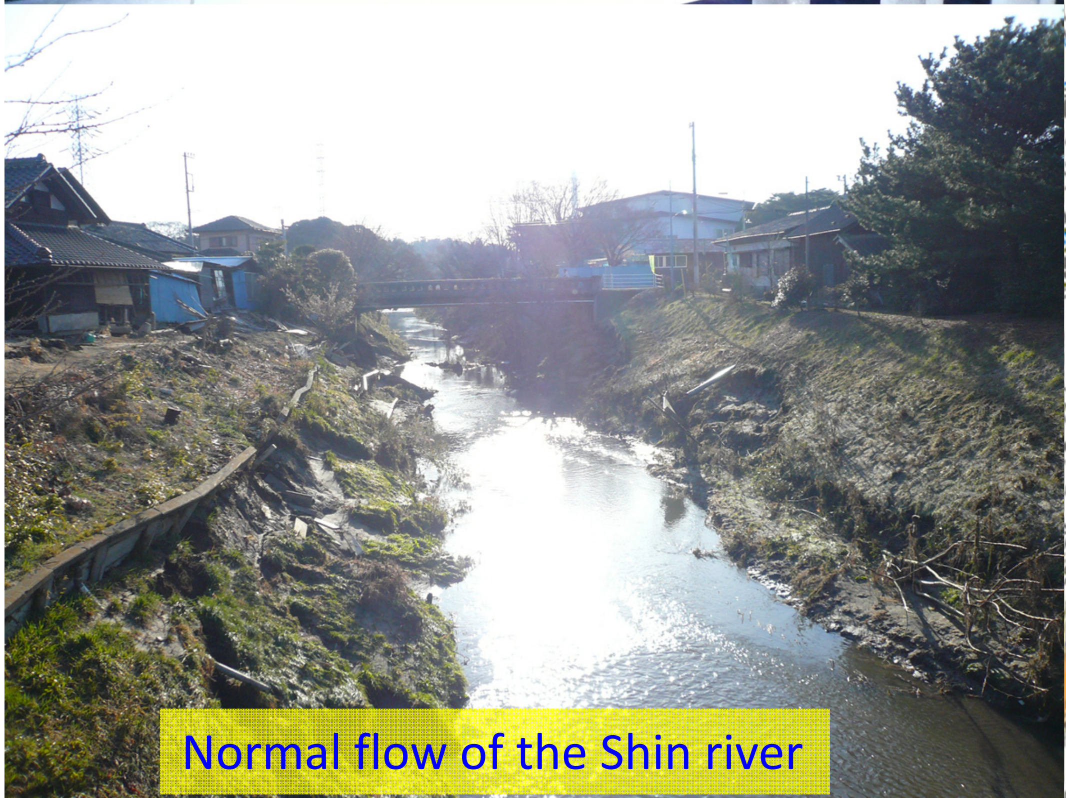


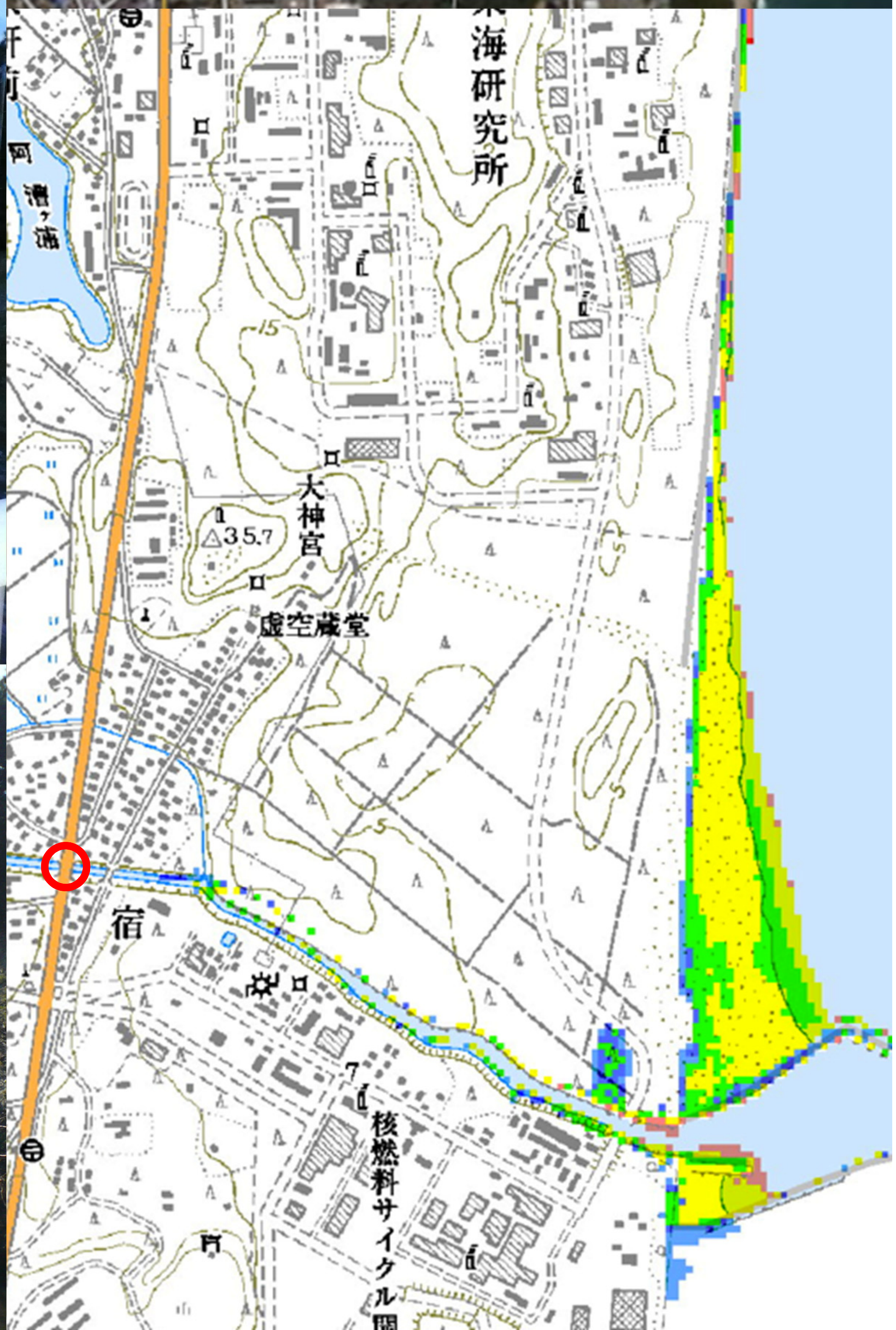
http://outreach.eri.u-tokyo.ac.jp/eqvolc/201103_tohoku/

TP+5.4 (max)
@ Tokai daini
nuclear power station

http://www.japc.co.jp/tohoku/index.html

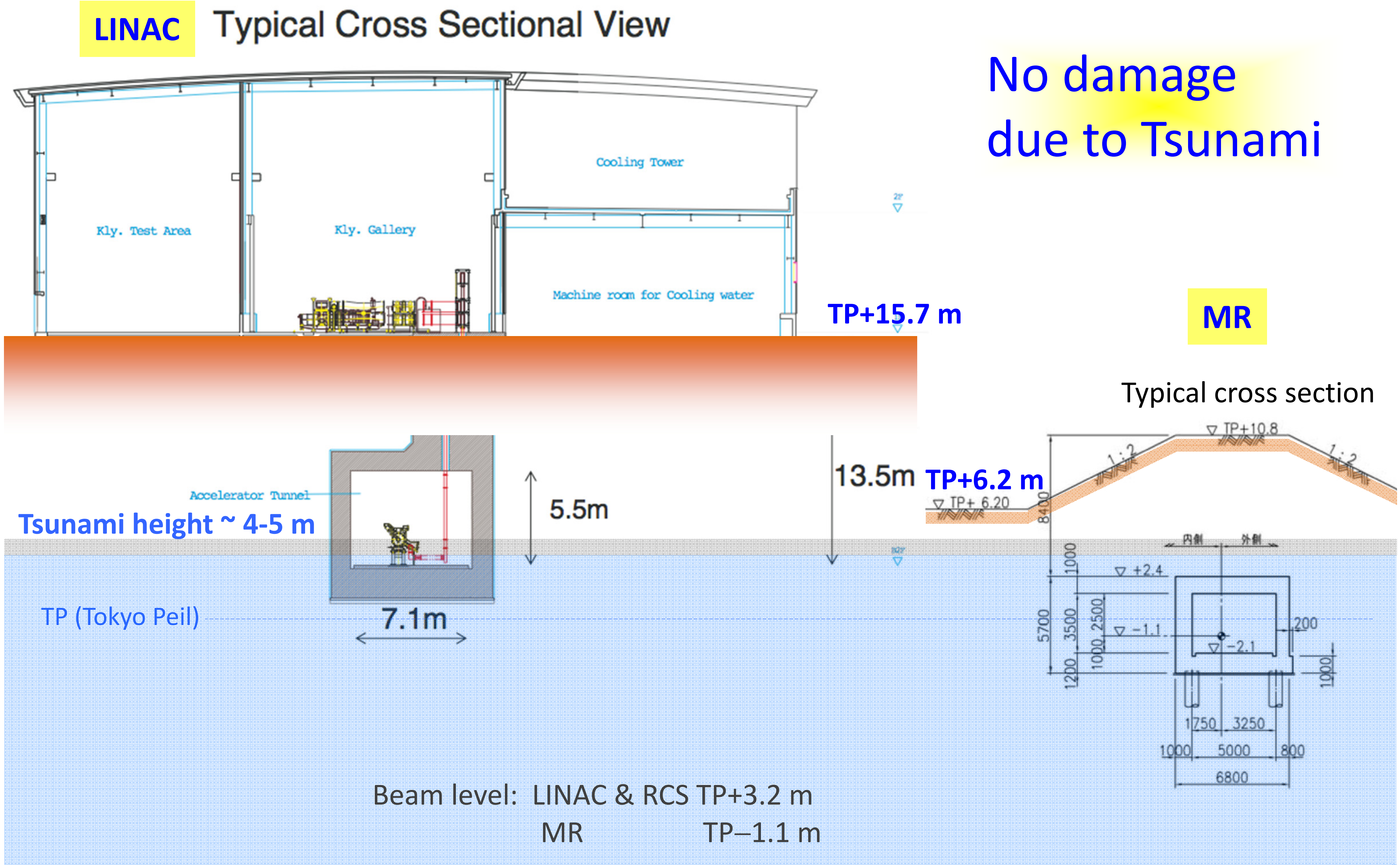

Tsunami came to the Shin river


Normal flow of the Shin river


海研究所
大神宮
△35.7
虚空蔵堂
宿
核燃料サイクル

Tsunami height and J-PARC tunnel cross section

No damage due to Tsunami



Beam level: LINAC & RCS TP+3.2 m

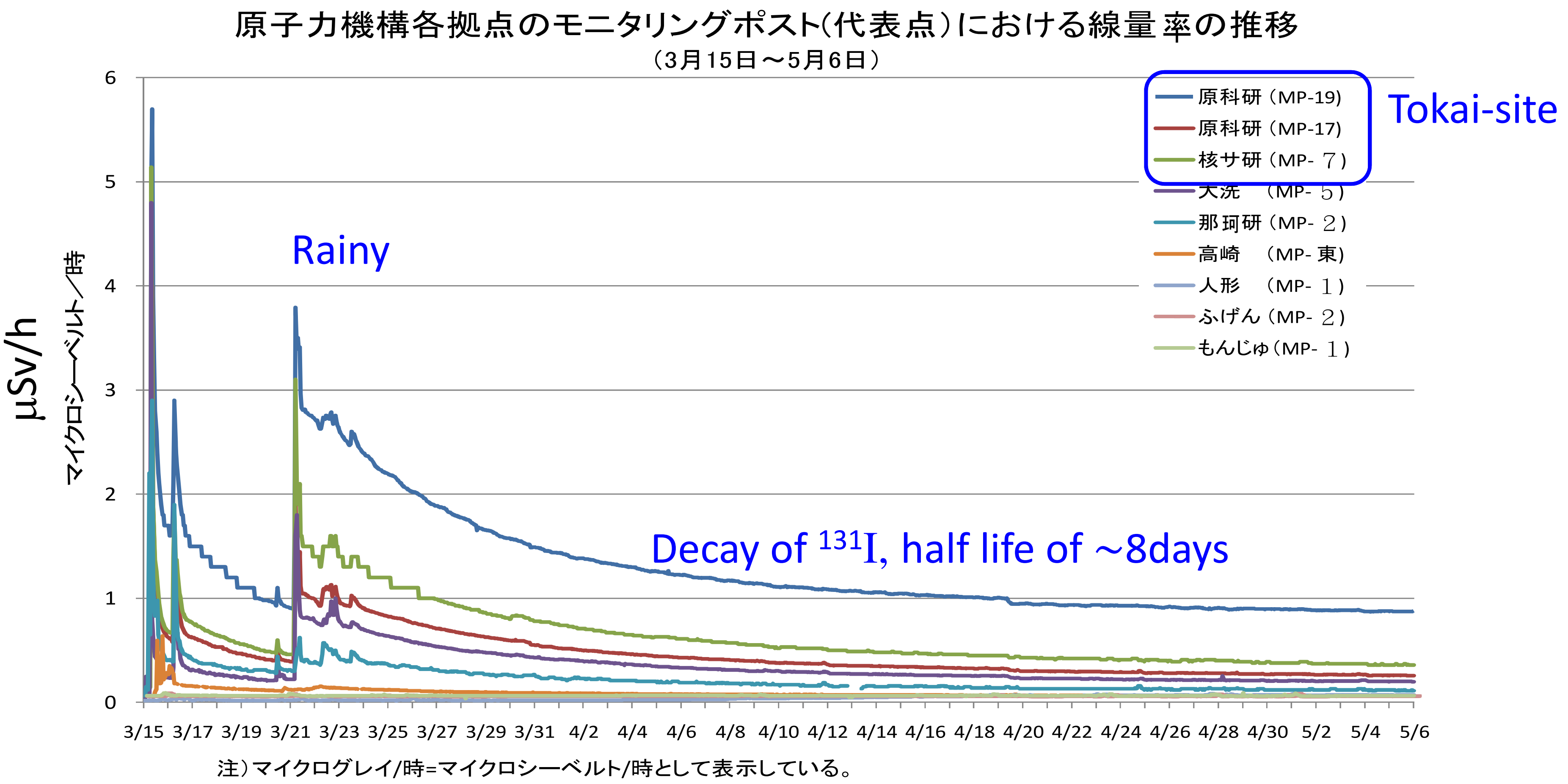
MR TP–1.1 m

After the earthquake

- Huge quake: LINAC: beam start-up operation → beam stop
  RCS: waiting the beam
  MR: maintenance in the tunnel → evacuation
- Electricity cut off → backup power supply (~ 3 hours)
- Evacuation from the facility :
  All the personnel moved behind the LINAC (TP+16m)
  No injuries are observed for J-PARC related persons
- No electricity, water, . . .
  more than a week in Tokai area
- Radiation from the Fukushima daiichi Nuclear Power Plant
- Damage inspection of the facility . . .

Radiation from the Fukushima daiichi Nuclear Power Plant

The equivalent dose of radiation measured at the monitoring posts of JAEA facilities



No serious situation, even though
the restriction value for radiation controlled area (20μSv/week)
was temporarily exceeded.

http://www.jaea.go.jp/

Damage inspection of the facility

- In the tunnel:
  Vacuum leaks
  damages of bellows, monitors
- Infrastructures
  Tunnel: Water leaks from the walls
  Displacements, tilts, . . .
  Buildings: Damages of pillars
  Displacements and bends
  of cable- and pipe-racks, cables and water- and helium-pipes itself
  Ground and streets around the buildings subsidence
  Power supply yard: base tilt, subsidence, . . .
- Alignment Work in progress, will be completed by the summer
  Measurement of GPS
  Standard point
  Detailed measurement with Laser trackers
  After that, further detailed measurement will be planned.
- Electric Power: Except 3 GeV powers are recovered (some Linac is not yet available.).
- Cooling Water: Not yet available for the entire facilities.

Entrance for Linac

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

http://j-parc.jp/en/topics/2011/en.html

Road in front of Linac

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

http://j-parc.jp/en/topics/2011/en.html

Capacitor Bank for 3 GeV

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

http://j-parc.jp/en/topics/2011/en.html

50 GeV The Second Entrance Area

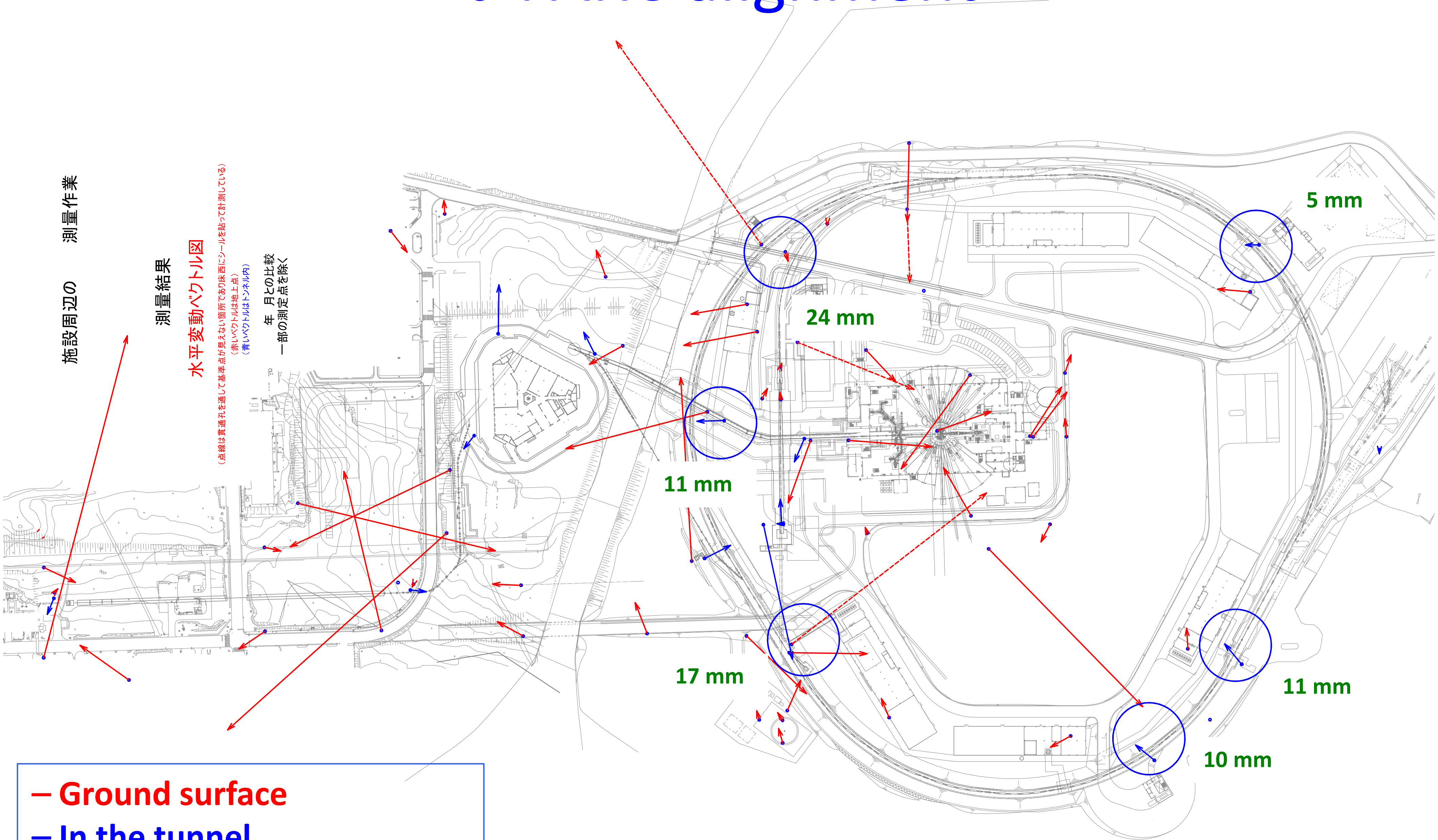
Over the region of 1 m by 10 m
about 50 cm dropped.

http://j-parc.jp/en/topics/2011/en.html

Main Control Room

Main Control Room was in a reasonable shape.

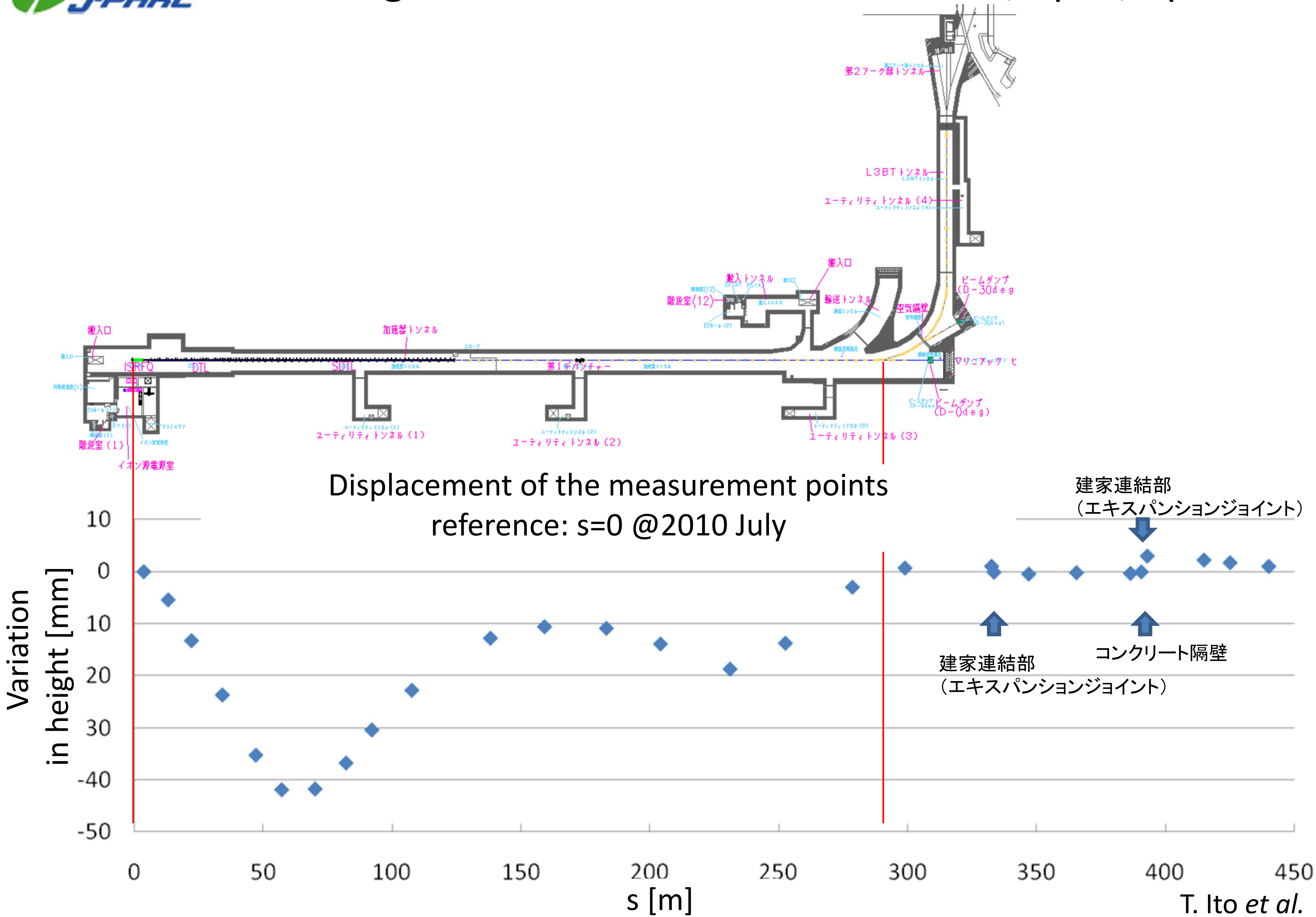
J-PARC alignment



– **Ground surface**
– **In the tunnel**
displacement from 2010 Aug.

M. Shirakata *et al.*, more detail will be presented at IPAC2011

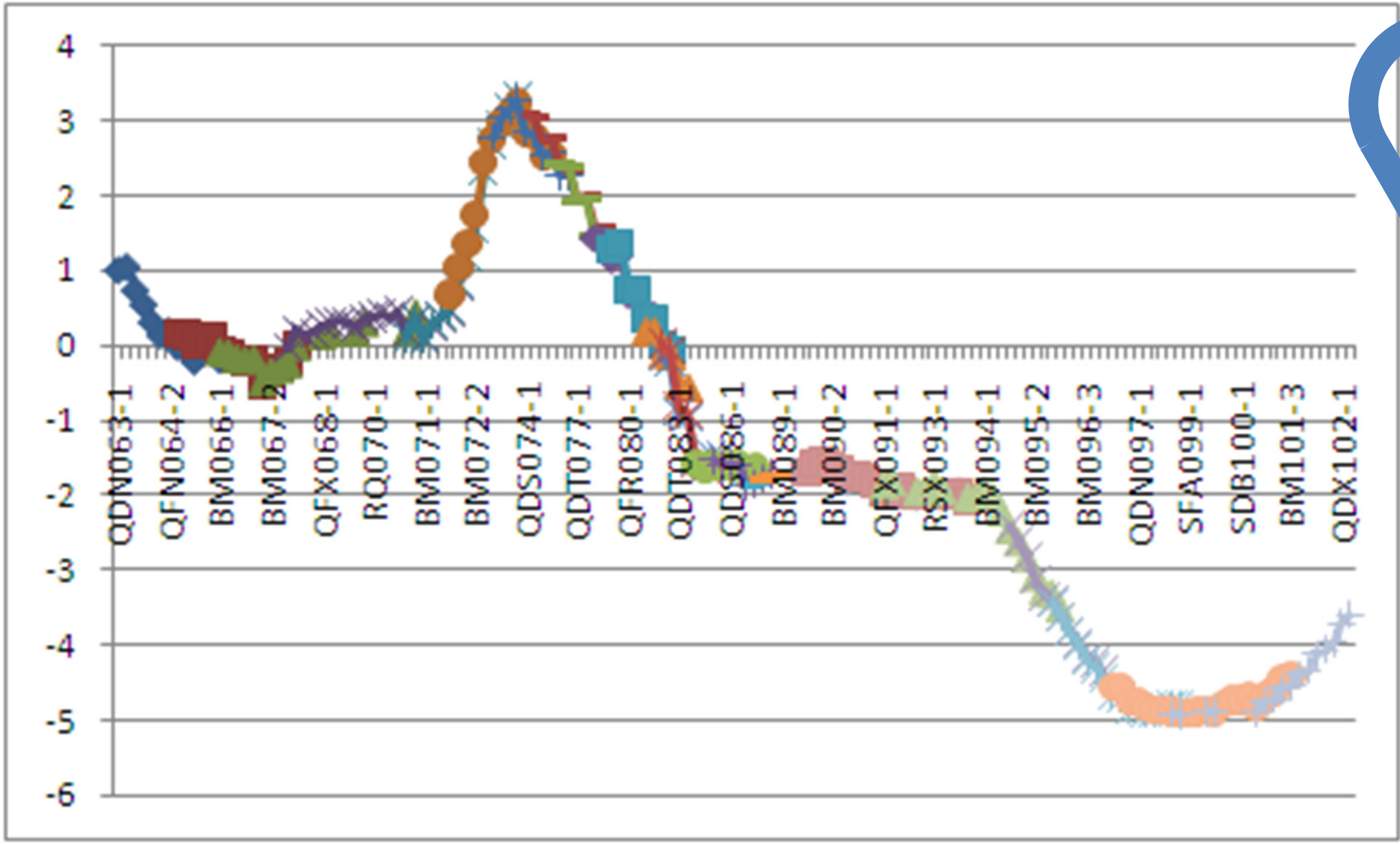
LINAC alignment（measured in 2011 Mar.31, Api.1, Apr.11）

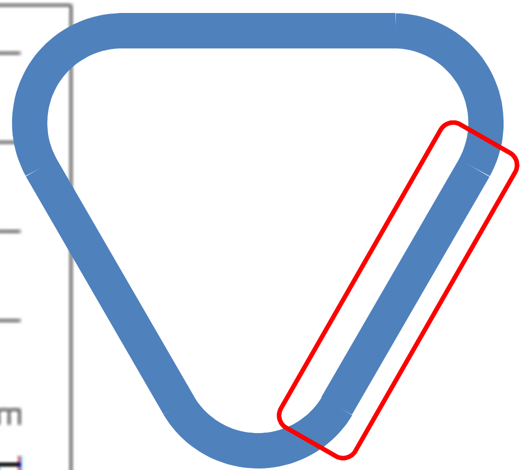


T. Ito *et al.*

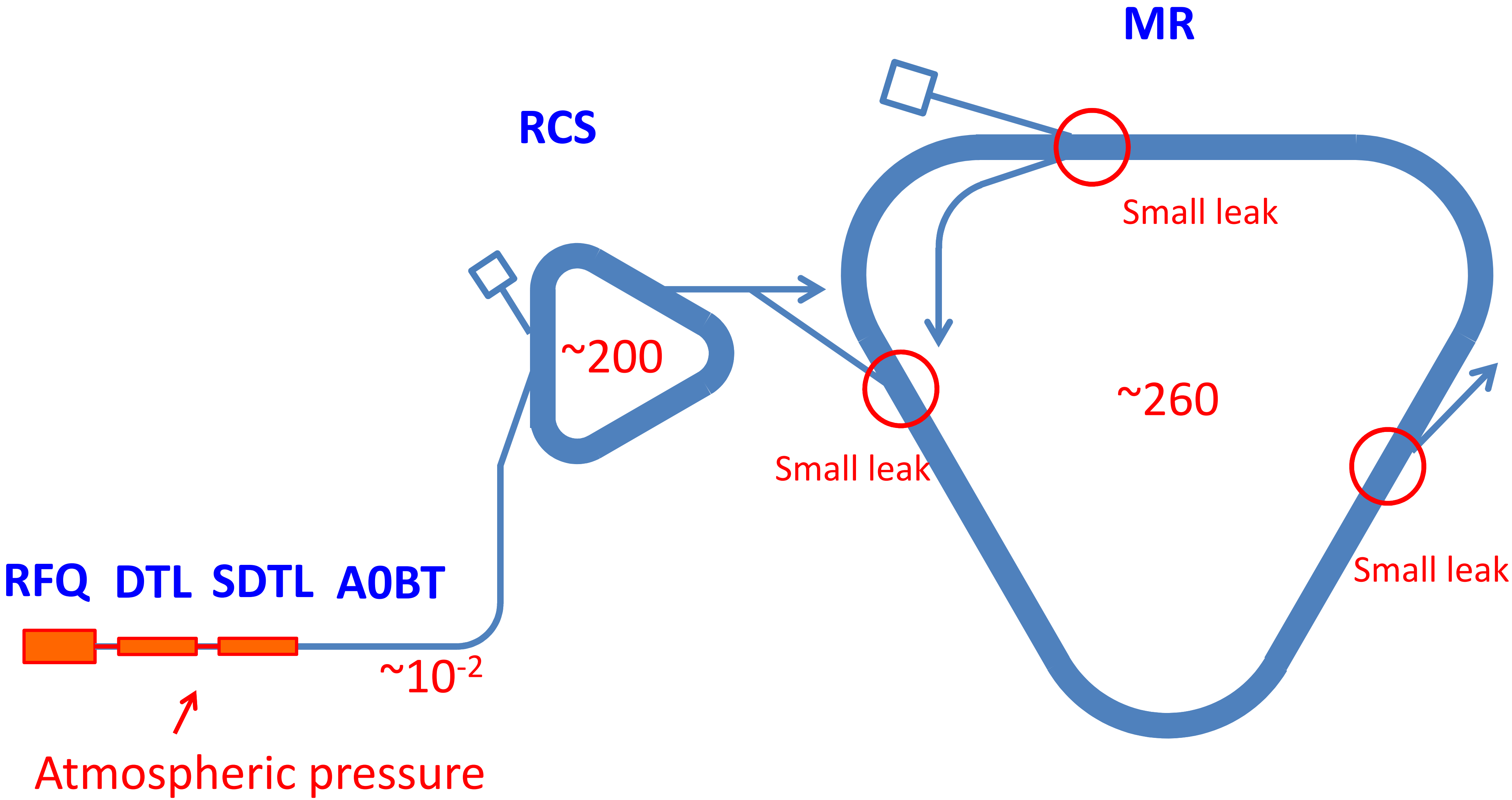
MR alignment（measured in 2011 May）

(mm) **Level along the MR beam line ~ 1/5 of the ring**





Vacuum status
Pressure after the earthquake
(Unit: Pa)

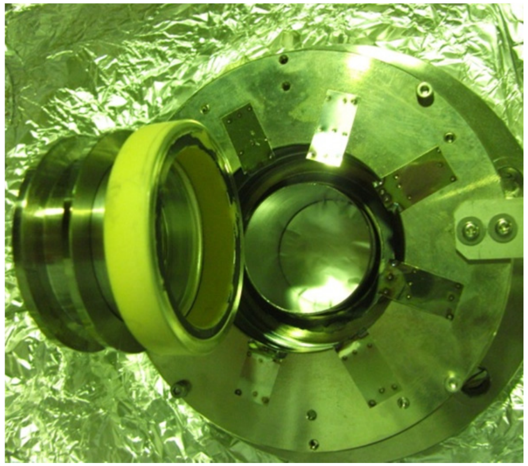


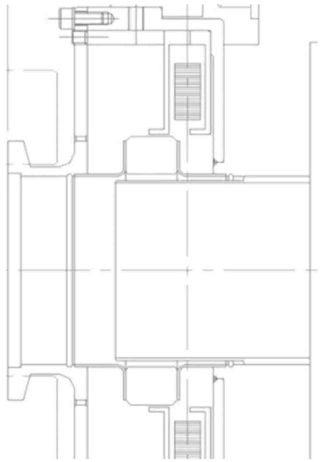
J-PARC vacuum group

Damages on the beam instruments

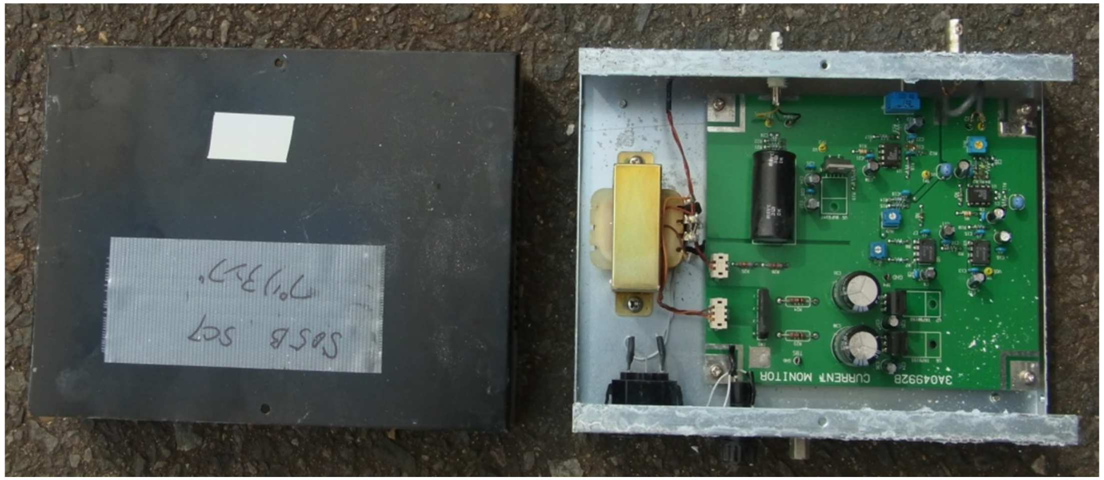
LINAC

FCT
Detachment of the brazing section between the ceramic tube and SS duct





SCT
Preamplifier for the SCT on the tunnel floor
Corrosion due to the water leakage



BPM-bellows pair
Bellows was broken

A .Miura et al.

RCS

Inspection progressing

No serious damages have been observed

MR

No vacuum leak

Some BLM heads and cables shipped water

TDR measurement suggests some cables having a fault, although not severe

Recovery Schedule of J-PARC

・We will try to resume J-PARC activity including accelerator complex, MLF, Hadron and Neutrino by December, 2011.

・Within JFY2011 (until March 2012) we set a goal to have at least 2 cycle operation for users.

・Based on this, both KEK and JAEA submitted the supplemental budget on April 22.

・Scheduling, in particular, for construction and repairs for buildings and roads are currently being negotiated both within JAEA and KEK.

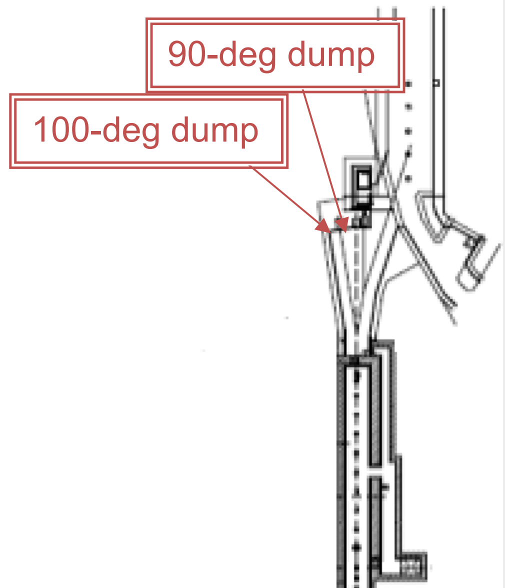
http://j-parc.jp/en/topics/2011/en.html#Operation

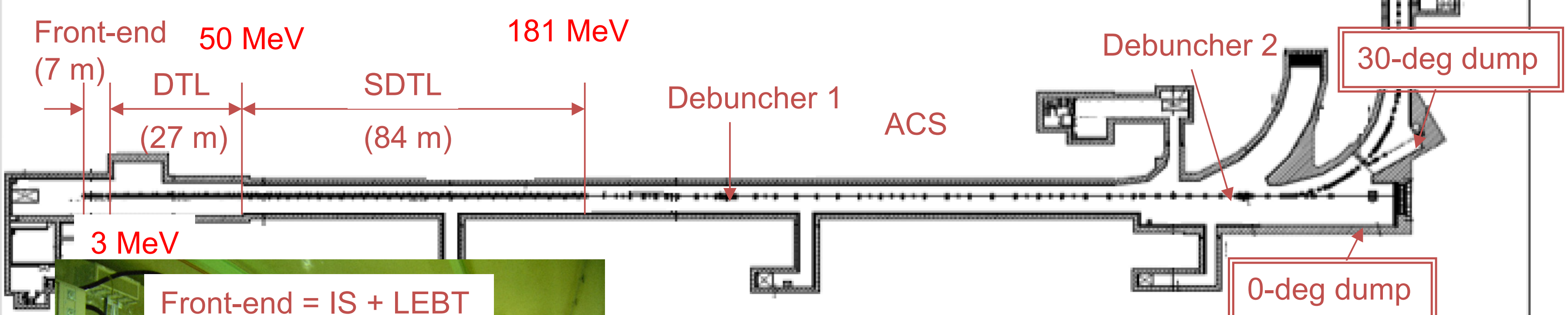
Thank you
for all the helps and care
from all over the world
to Japan,
Tohoku people,
and
J-PARC.

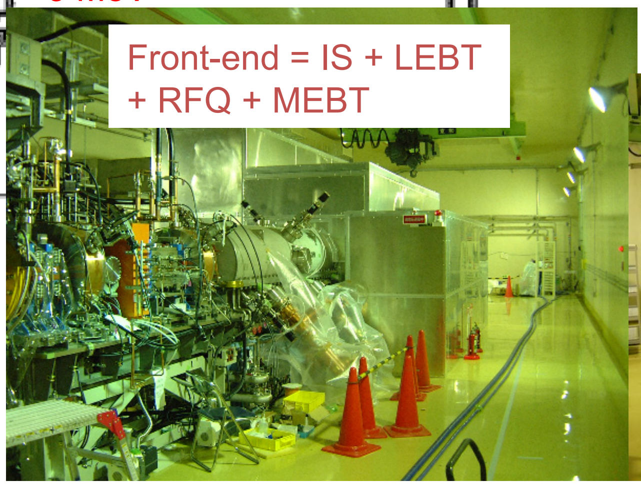
Beam Parameters

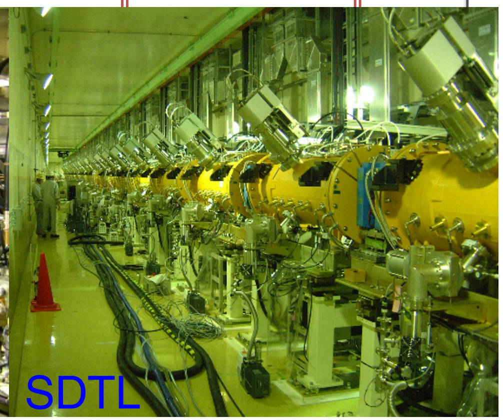
Linac!

- **Particle:** !H^{-} !
- **Energy: !** !181 MeV at present !
  - ! ! !400 MeV by installing ACS in 2012!
  - ! ! !(Construction of ACS has been started.) !
- **Peak current:** !30 mA at 181 MeV !
  - ! ! !50 mA at 400 MeV in the future !
- **Repetition:** !25 Hz !
- **Pulse width:** !0.5 msec!







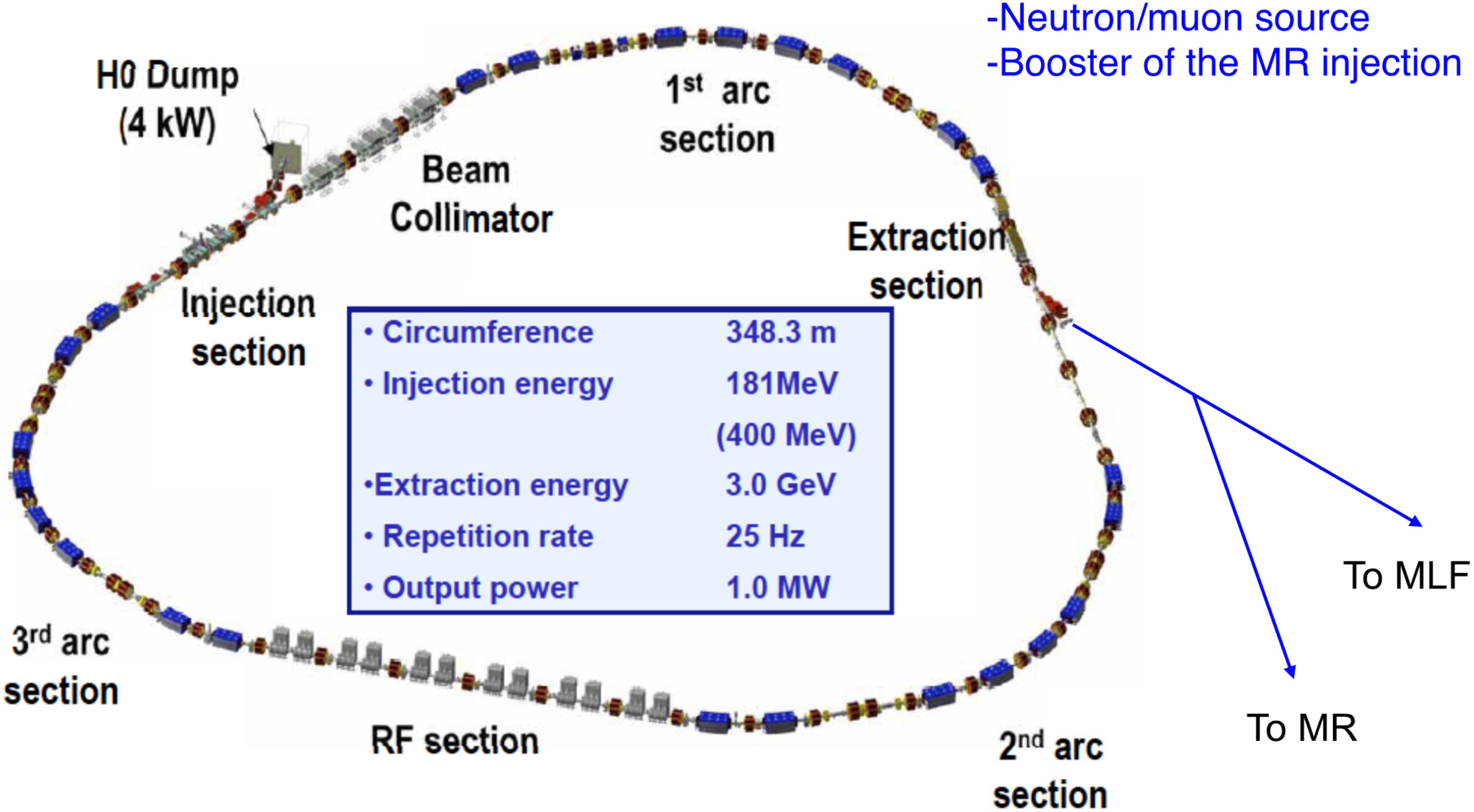


T. Koseki, HB2010

Beam Parameters

RCS (Rapid Cycling Synchrotron)

Multi-purpose machine:
-Neutron/muon source
-Booster of the MR injection



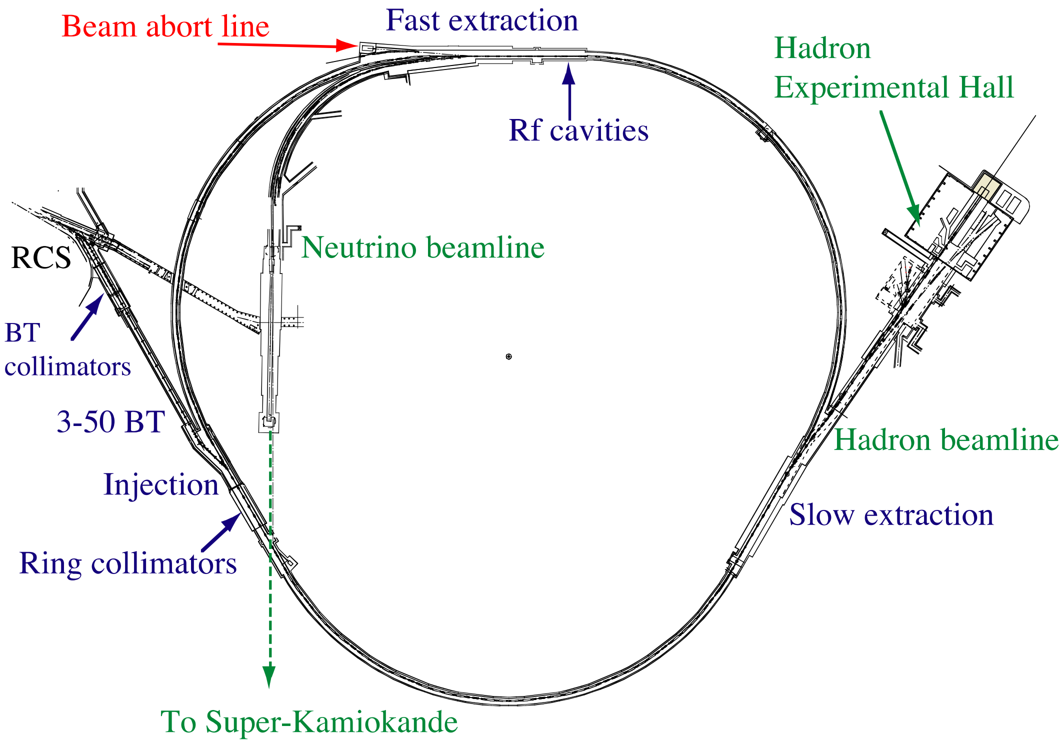
• Circumference	348.3 m
• Injection energy	181MeV
	(400 MeV)
•Extraction energy	3.0 GeV
• Repetition rate	25 Hz
• Output power	1.0 MW

T. Koseki, HB2010

Beam Parameters

Main parameters of MR

Circumference	1567.5 m
Repetition rate	~ 0.3 Hz
Injection energy	3 GeV
Extraction energy	30 GeV(1st phase)
	50 GeV (2nd phase)
Superperiodicity	3
h	9
Number of bunches	8
Rf frequency	1.67 - 1.72 MHz
Transition γ	j 31.7 (typical)
Number of dipoles	96
quadrupoles	216 (11 families)
sextupoles	72 (3 families)
steerings	186
Number of cavities	5
Beam power	750 kW



Three dispersion free straight sections of 116-m long:

- Injection and collimator systems
- Slow extraction (SX)
  to **Hadron experimental Hall**
- MA loaded rf cavities and Fast extraction(FX) (beam is extracted inside/outside of the ring)
  outside: Beam abort line
  inside: **Neutrino beamline** (intense ν beam is send to SK)

T. Koseki, HB2010

Beam Energy Loss: at Graphite Target by 3GeV Beam

Parameter	*Value*
Atomic Number Z	**6**
Material Energy Loss @ 3GeV proton	**2.0 [MeV.cm2/g/proton]**
Target Thickness	**2 [micron]**
Total Energy Loss	**0.8 [keV/proton]**

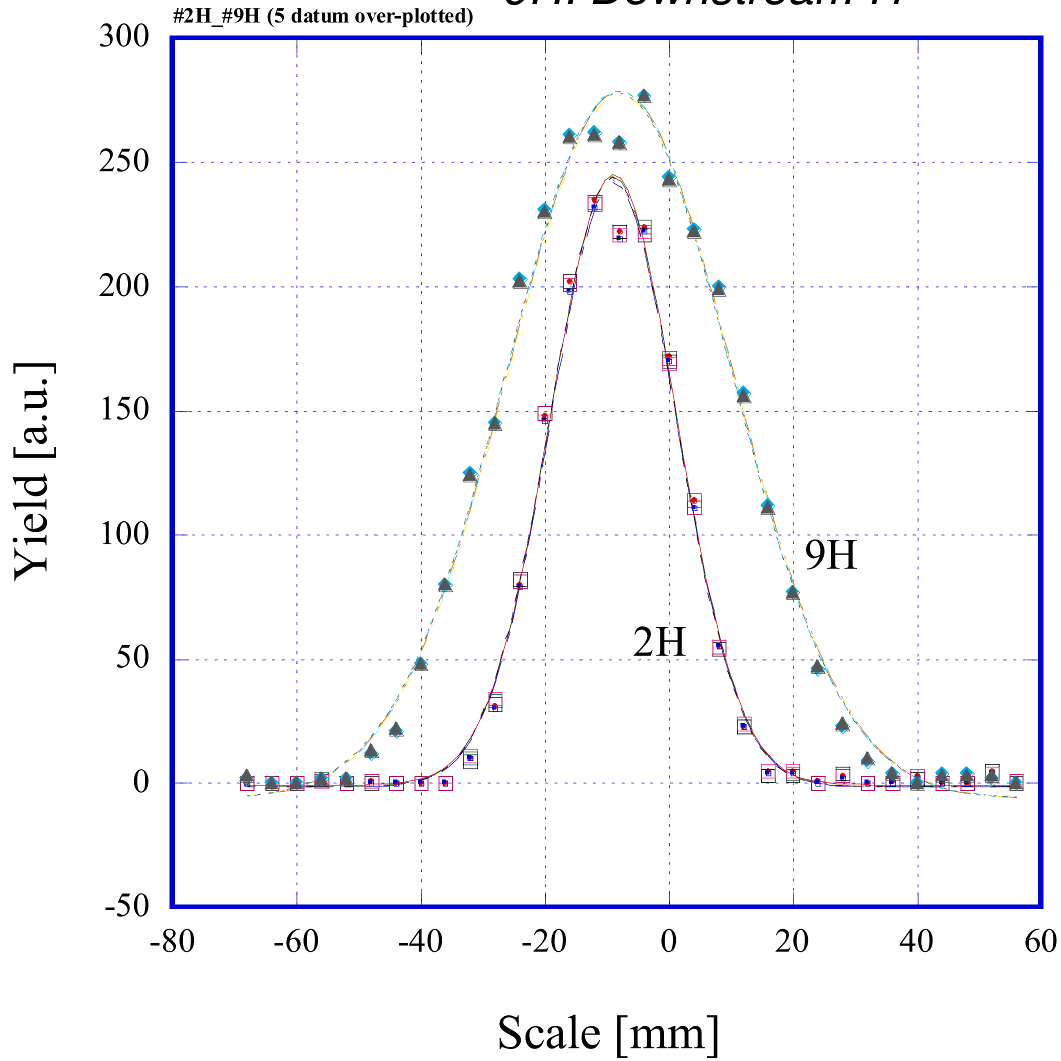
Energy Deposition by 3-50 BT Beam at Graphite Target

Parameter	*Value*
Design Beam Intensity	**4e13 [ppb]**
Energy Deposition by bunch	**5.1e-3 [J/bunch]**
Energy Deposition by 8 bunch	**4e-2 [J]**
Estimated Temperature Raise	**Several 10 ~ 200 [℃]**

Beam Measurements @ 3-50 BT

Beam intensity : 1 x 10^{13} ppb

2H: Upstream-H
9H: Downstream-H



Both are over plotted and fitted by arbitral five another time's measurement

Deviation was small
Good reproducibility.

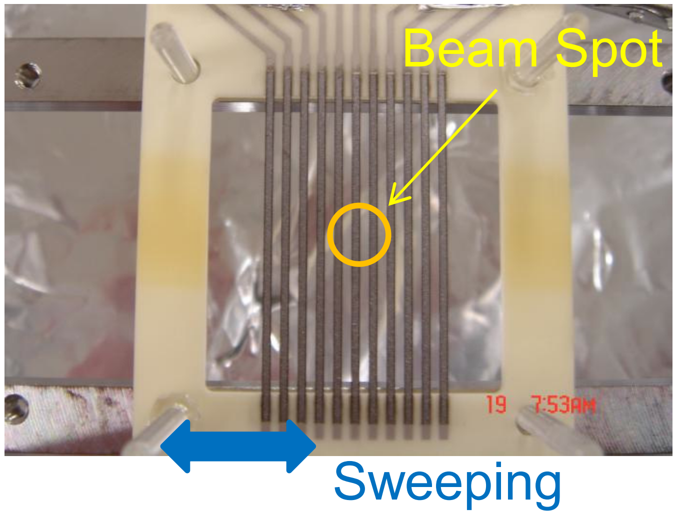
Uniformity of Electron Emission from Carbon Graphite

Measurement Accuracy ⇔Uniform Emissivity

Beam Test: HIMAC C^{6+} 6MeV/u Beam

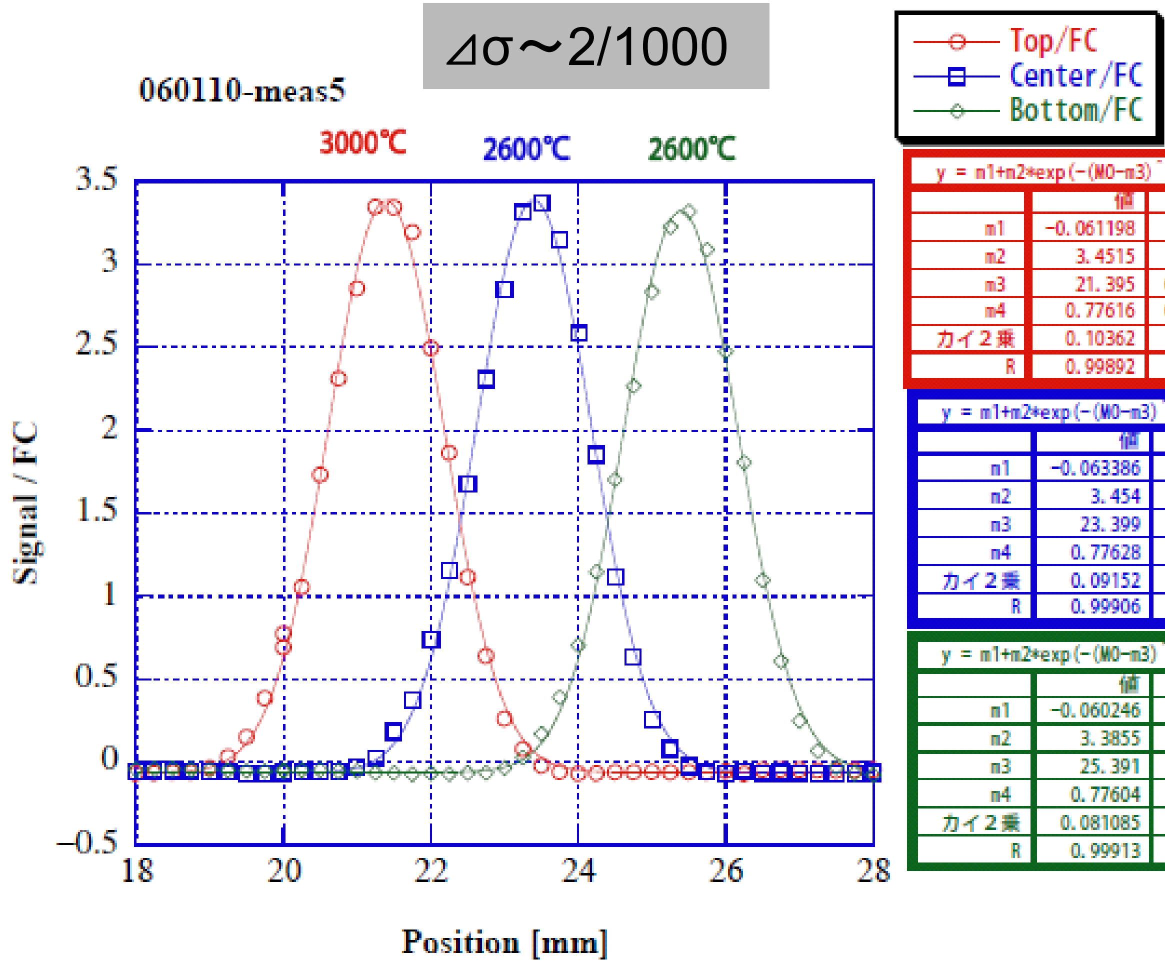
Un-uniformity≦1 %

Test Samples :Ribbon Array
Different Foil, Different Part



∗ Various Sample was tested.

⊿σ～2/1000



y = m1+m2*exp(-(M0-m3)^2/(2...

	値	エラー
m1	−0.061198	0.010552
m2	3.4515	0.028104
m3	21.395	0.0069366
m4	0.77616	0.0075221
カイ２乗	0.10362	NA
R	0.99892	NA

y = m1+m2*exp(-(M0-m3)^2/(2...

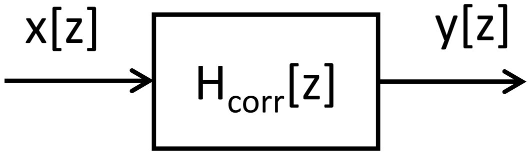
	値	エラー
m1	−0.063386	0.0097221
m2	3.454	0.026524
m3	23.399	0.0066493
m4	0.77628	0.007333
カイ２乗	0.09152	NA
R	0.99906	NA

y = m1+m2*exp(-(M0-m3)^2/(2...

	値	エラー
m1	−0.060246	0.0091376
m2	3.3855	0.024977
m3	25.391	0.0063845
m4	0.77604	0.0070318
カイ２乗	0.081085	NA
R	0.99913	NA

Correction

$H_{corr}[z] \rightarrow H_{corr}[t]$



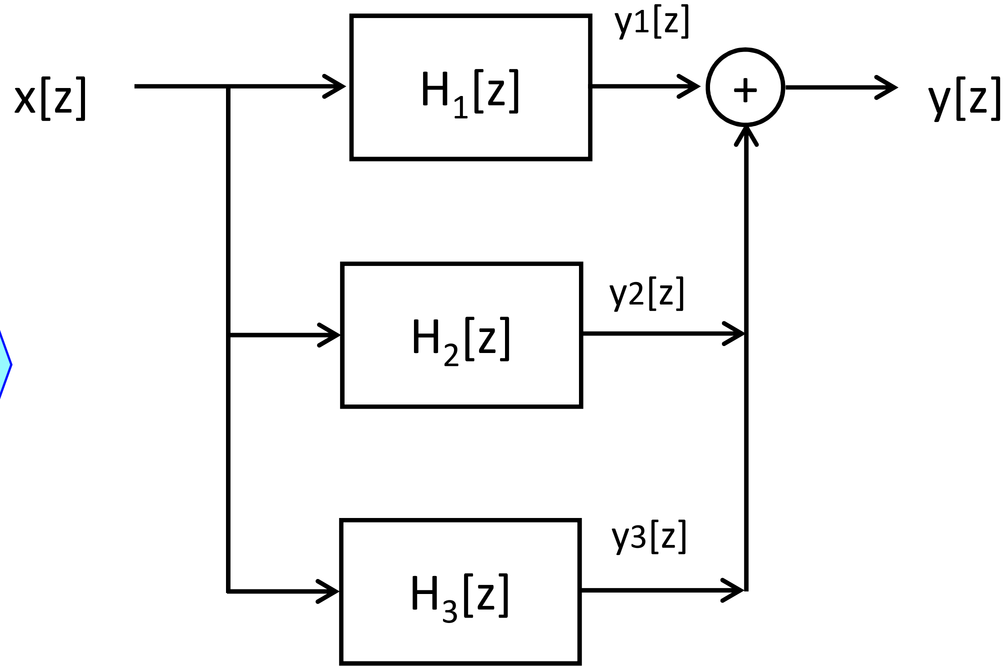
$$H_{corr}[z] = H_1[z] + H_2[z] + H_3[z]$$

$$H_1[z] = \frac{y_1[z]}{x[z]} = b_{10}$$

$$H_2[z] = \frac{y_2[z]}{x[z]} = \frac{b_{21} z^{-1}}{1 + a_{21} z^{-1}}$$

$$H_3[z] = \frac{y_3[z]}{x[z]} = \frac{b_{31} z^{-1} + b_{32} z^{-2}}{1 + a_{31} z^{-1} + a_{32} z^{-2}}$$

Using a parallel circuit



Difference equation

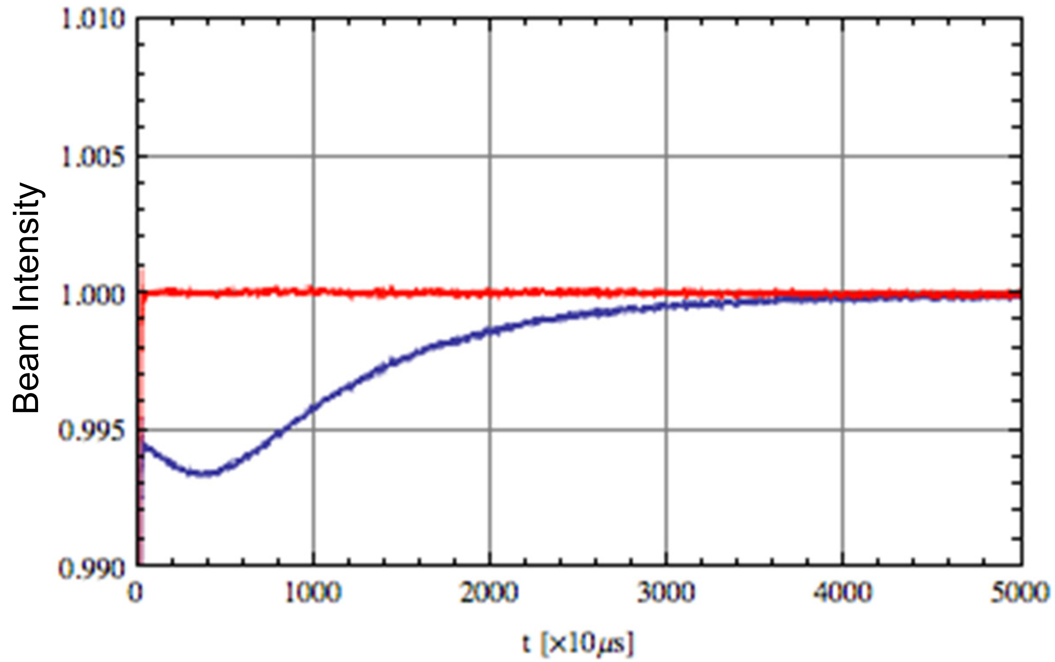
$$y[n] = y_1[n] + y_2[n] + y_3[n]$$

$$\begin{cases} y_1[n] = b_{10} x[n] \\ y_2[n] = b_{21} x[n-1] - a_{21} y_2[n-1] \\ y_3[n] = b_{31} x[n-1] + b_{32} x[n-2] - a_{31} y_3[n-1] - a_{32} y_3[n-2] \end{cases}$$

$$\begin{cases} b_{10} = 1.0053523211092454 \\ b_{21} = -0.0001229963483934014 \\ a_{21} = -0.9989375397628791 \\ b_{31} = 0.0001859462714492987 \\ b_{32} = -0.0001848868230882864 \\ a_{31} = -1.9936616986069362 \\ a_{32} = 0.9936789012049905 \end{cases}$$

System offset : corrected separately

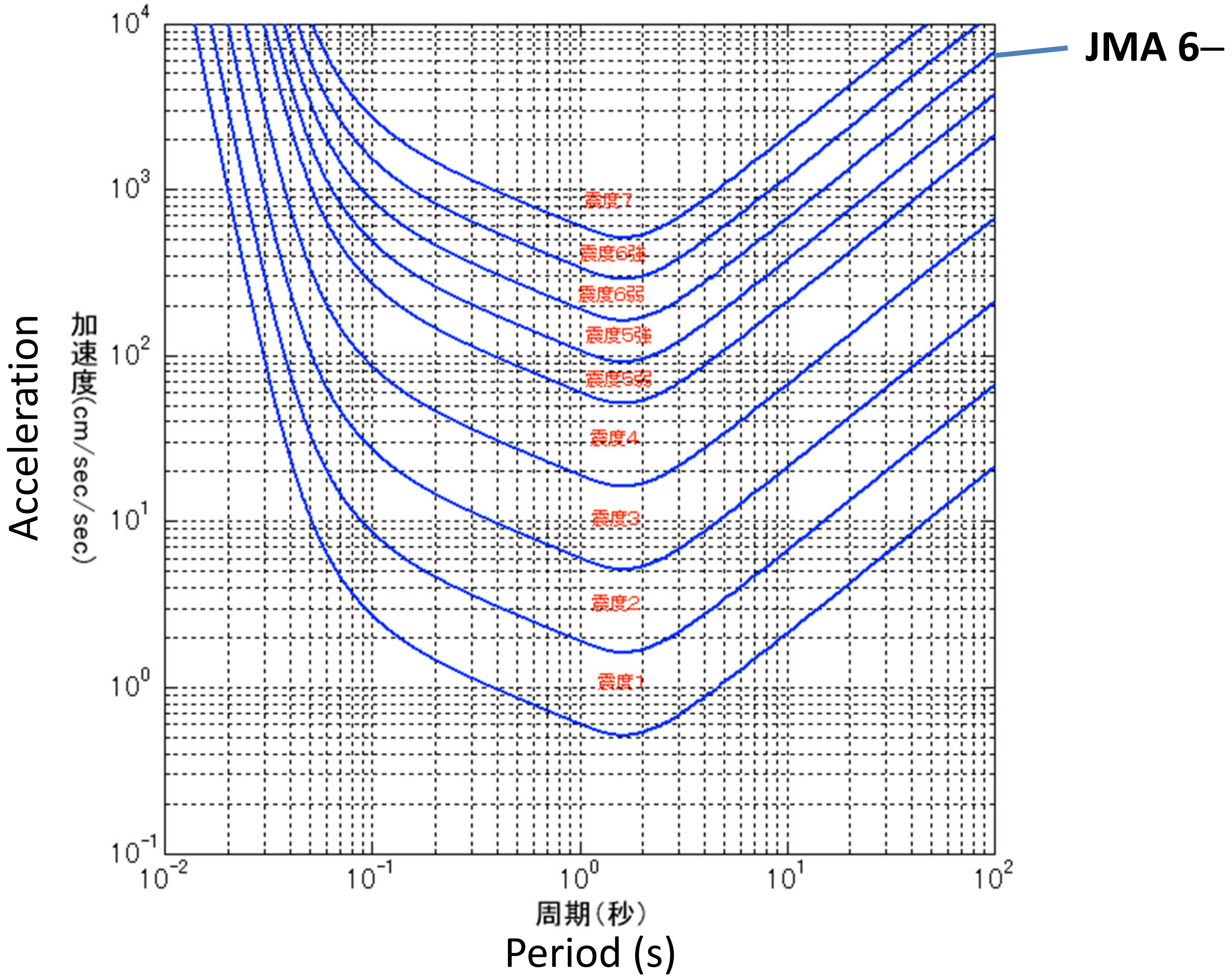
Application of correction to the DCCT output @ FX timing (inverted and normalized to 1)



Blue : no correction   red : with correction

[＊] The difference from 1 < 2.8×10^{-4}
except the fast transient

Relation between the seismic intensity, JMA scale and the acceleration, "gal"



http://www.seisvol.kishou.go.jp/eq/kyoshin/kaisetsu/comp.htm

Tsunami hazard map by Ibaraki prefecture

Maximum of two tsunami's

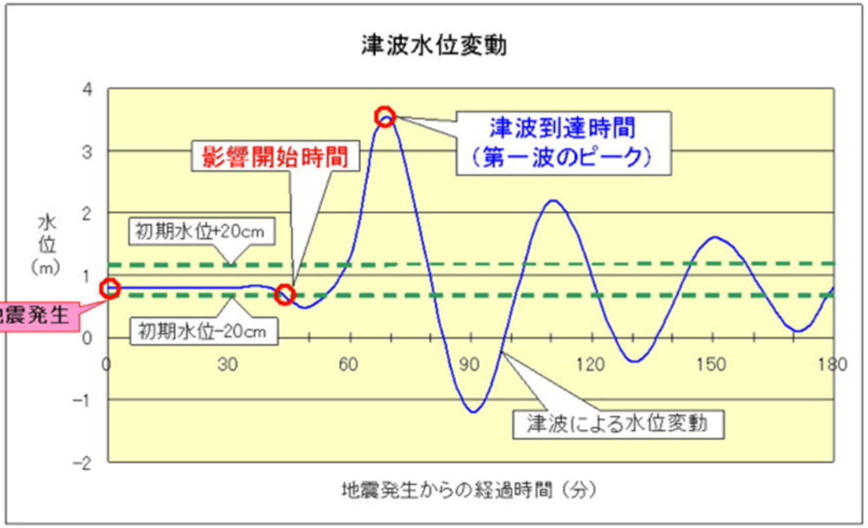


図1

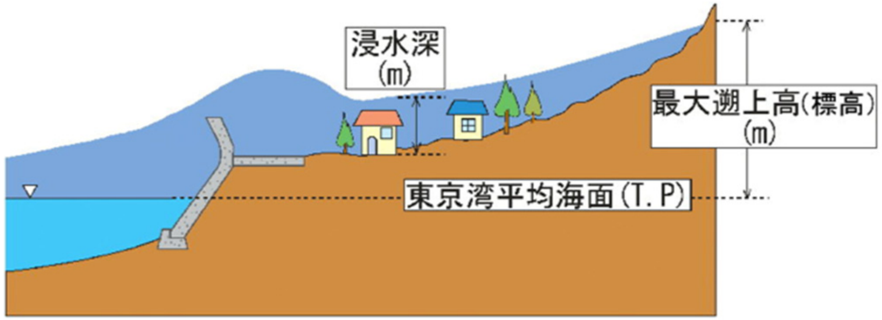


図2

凡　例

津波浸水予測範囲
（2つの想定津波の最大浸水深）

- 0.5m未満
- 0.5m以上　1.0m未満
- 1.0m以上　2.0m未満
- 2.0m以上　4.0m未満
- 4.0m以上　6.0m未満
- 6.0m以上

各地で予測される影響開始時間・
最大遡上高・津波到達時間

地区名
2つの想定津波で予測される影響開始時間のうち最短の値
延宝房総沖地震津波の最大遡上高（津波到達時間）
明治三陸タイプ地震津波の最大遡上高（津波到達時間）

震源域図