Experience with RCS Injection and Extraction Systems

Inj. And Ext. of the Main ring(MR)
→Dr. T. Koseki (this morning)

Pranab SAHA

for the RCS of J-PARC

August 27, 2008

42nd ICFA

Advanced Beam Dynamics Workshop
on High-Intensity, High-Brightness Hadron Beams
(HB2008)
(Nashville, Tennessee, USA. August 25-30, 2008)

Introduction and Outline

Injection is one of the key issues of RCS and has impact on the whole system, where an well extracted beam reflects the overall performance.

In order to mitigate the space-charge effect, the beam density in the transverse plane is controlled by utilizing the painting injection in RCS

- General

    Injection system, Extraction System

- Beam commissioning of Injection and Extraction

    Comparison with design stage parameters,   System performance

- Painting injection study

    Reconstruction of the phase space footprint using

    (1) BPM pairs with a turn-by-turn mode, (2) Using a tune BPM spectrum

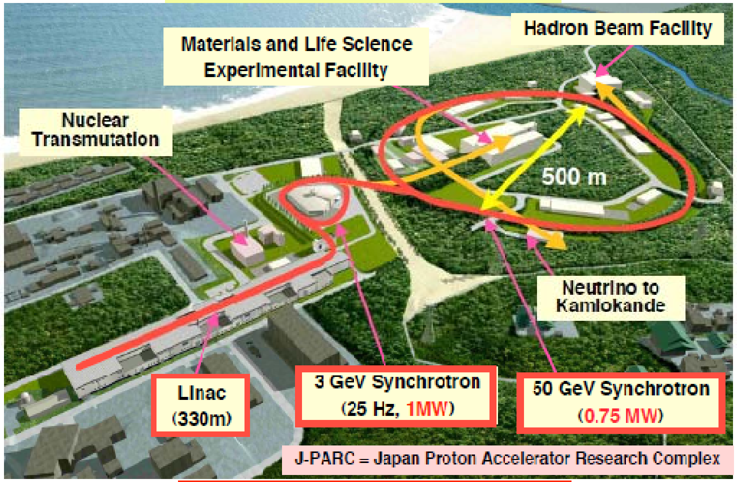
- Beam loss at the injection and Extraction

    Comparison with design stage estimation

    Near future study concerning beam loss related to injection

- Summary

J-PARC Facility



Joint Project between KEK and JAEA

RCS of J-PARC

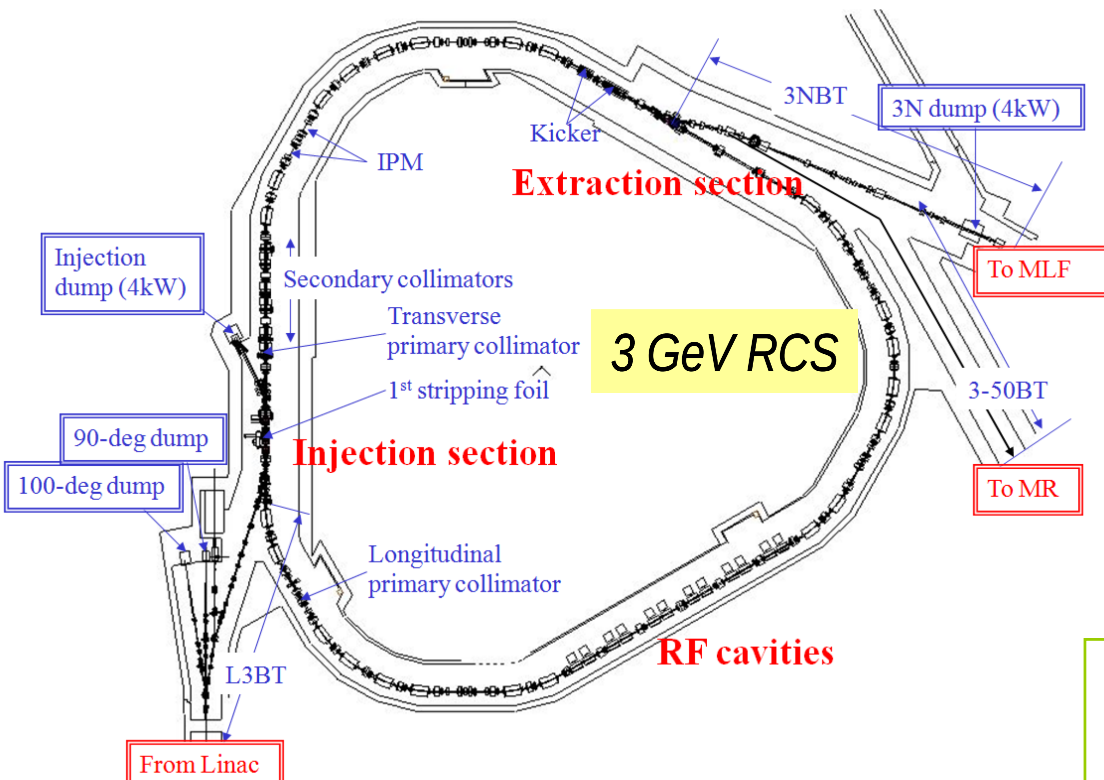
Layout and key parameters

Accelerators at J-PARC facility:

☆ *400 MeV (181 MeV at present) LINAC*

☆ *3 GeV 25 Hz Rapid Cycling Synchrotron (RCS)*

☆ *50 GeV Main Ring Synchrotron (MR)*



Design parameters of RCS

Circumference: 348.333 m

Cell Structure: (6 DOFO arc + 3 DOFO insertion) x 3

Nominal tune: (6.68, 6.27)

Natural chromaticity: (−8.5, −8.8)

Injection energy: 0.4 GeV(*)

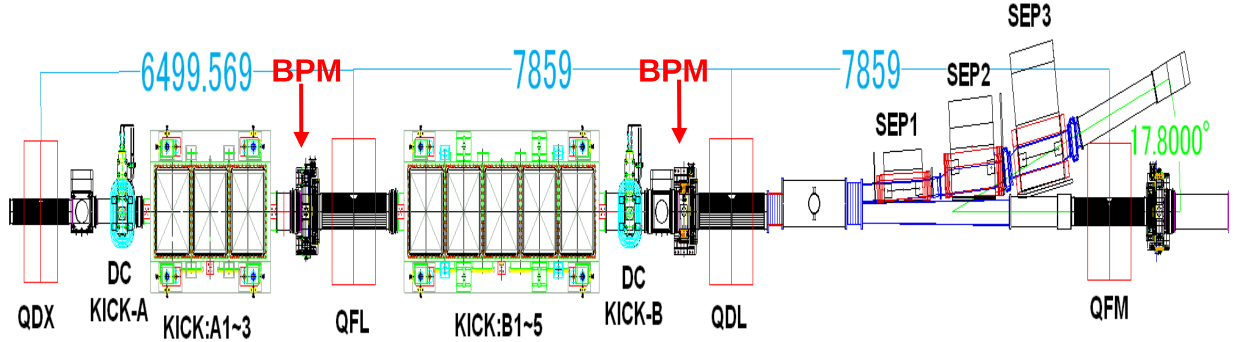
Extraction energy: 3.0 GeV

* Day1 inj energy: 0.181 GeV

Output Goal: 0.3 ~ 0.6 MW

(other related numbers are also thus different)

RCS Injection and Extraction Systems



Inj. - H0 dump line components

Magnets:

Shift bump: 4 (SB1~4)
Hori. Paint bump: 4(PB1~4)
Vert. Paint Bump: 2 (VPB1~2)
Septum:4(ISEP1~2, DSEP1~2)
DC Str. magnets: 6
Inj. 4(2H, 2V), Dump 2(1H, 1V)
Pulse Str. magnets: 2 (PSTR1~2)
Quad: 3 (QFL, QDL , Dump-Q)

Monitors:

MWPM (Multi-wire Profile Monitor):7(6)
BPM (Beam position monitor): 4 (2)
K-BPM, I-BPM (Big-BPM1,2)

1st Foil , 2nd Foil, 3rd Foil, etc..

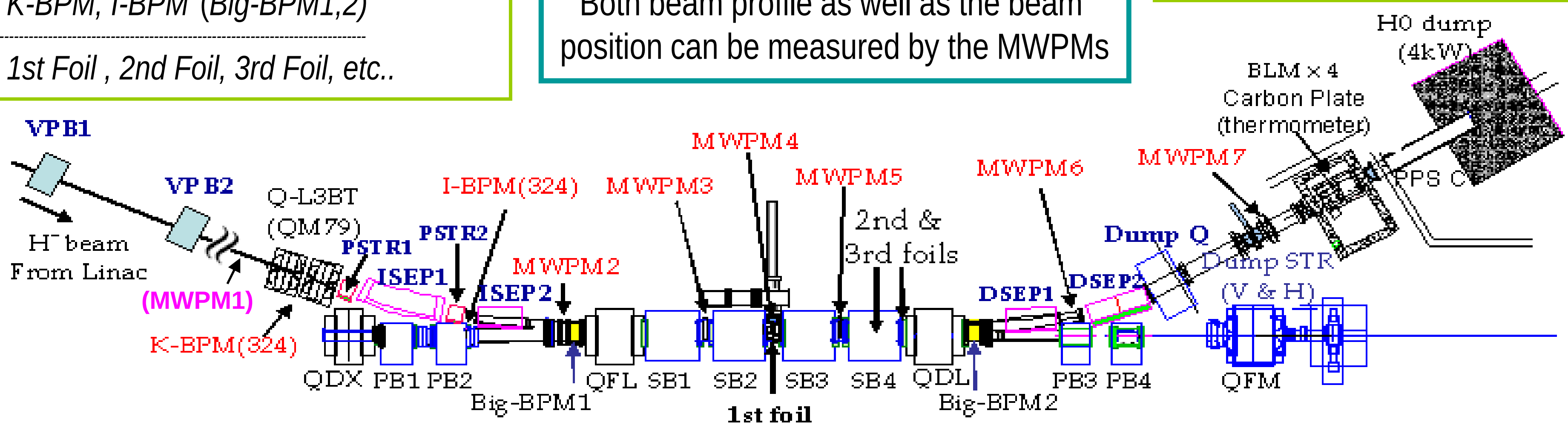
Injection beam control @ foil

X → w/ Isep or SB
X' → w/ Isep
Y, Y' → Inj. STR
Monitors: MWPM 3,4(5)

Both beam profile as well as the beam position can be measured by the MWPMs

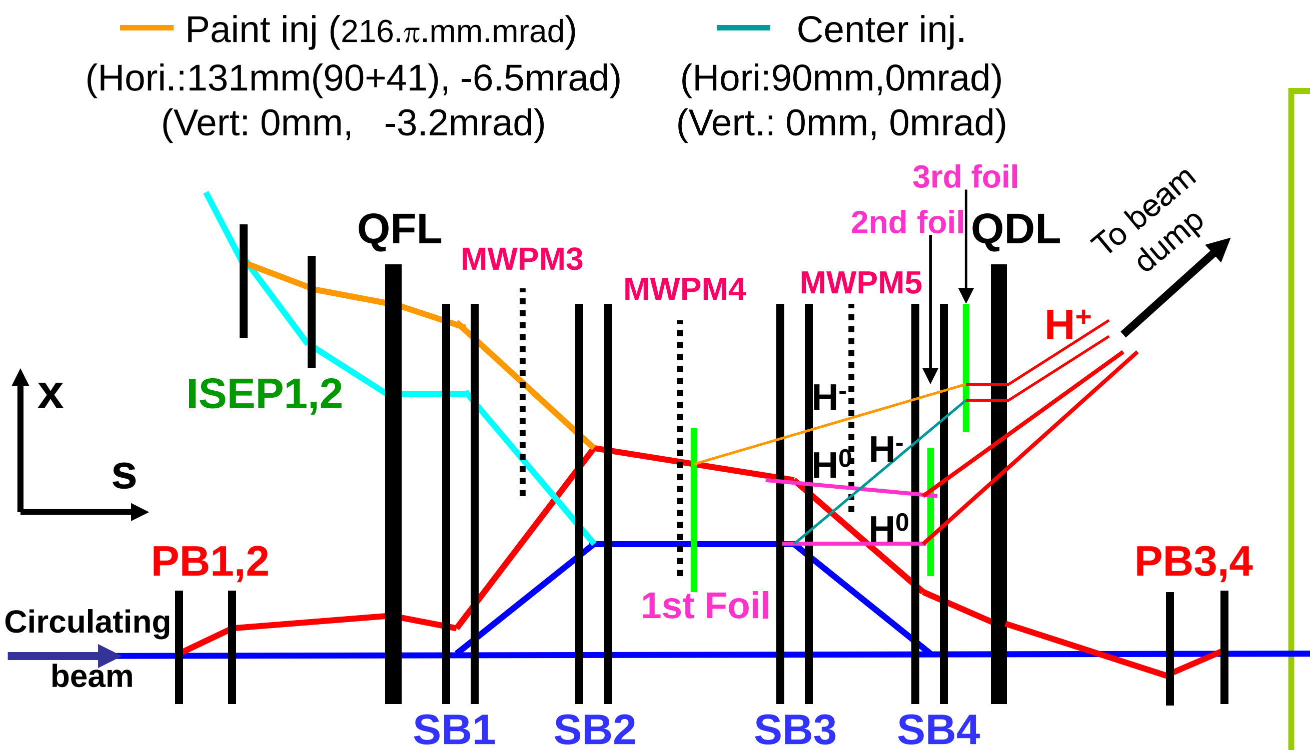
Ext. area components:

DC kickers: 2 (KICK-A,B)
Pulse Kickers: 8
(KICK-A1~3, KICK-B1~5)
QUAD: 2 (QFL, QDL)
Septum: 3 (SEP1~3)
Monitors: BPM: 2 (in the ring)



Injection – H0 dump line

Injection scheme in RCS



Design twiss parameters at the foil w/ nominal tune

	Inj. beam	Circulating beam
α_x	-1.452	1.550
β_x(m)	11.138	11.275
α_y	-0.400	-1.589
β_y(m)	10.998	11.062
η_x(m)	0.00	0.00
η'_x	0.00	0.00

Paint area for MLF target: 216π.mm.mrad
Paint area for MR inj: 144π.mm.mrad
(@ 400 MeV Linac)

To change painting area in the horizontal plane, X' of the inj beam will be change by two pulse steering magnets(PSTR1,2)

Measured response matrix with **ISEP1,2 and MWPM3,4,5**
→ Used for controlling X and X' of the inj beam at the foil paint inj parameters in the hori. Plane

Measured response matrix with **IVSTR1,2 and MWPM3,4,5**
→ Used for controlling Y and Y' of the inj beam at the foil.

For painting in the vertical plane, measured response with **VPB1,2 and MWPM3,4** was used

Beam commissioning of Injection and Extraction

Linac Energy: 181MeV
Peak current: 5mA

* Run#9 data

Inj.–H0 dump line orbit looking from RCS central orbit

	IBPM	MWPM2	BigBpm1	MWPM3	MWPM4	MWPM5	BigBpm2	MWPM6	MWPM7
Cal:	*418.6*	*226.0*	*214.7*	*133.7*	*87.70*	*132.2*	*213.5*	*481.0*	*3416*
Meas:	*412.0*	*228.8*	*214.0**	*133.4*	*87.70*	*132.3*	*219.0**	*491.1*	*3435*

Comparison of Magnet Parameters (K0)

	Cal(mrad)	**Used**(mrad)	**Diff(%)**
ISEP1	107.0	110.0	**+2.8**
ISEP2	160.4	173.8	**+8.35**
DSEP1	146.4	144.0	**-1.66**
DSEP2	311.4	317.4	**+1.93**

Measured response matrix near the present orbit was exactly similar with the model cal
→ Efficiently used for the beam commissioning in both the center and paint injection.

Present center inj orbit is very much different than the design painting orbit, while 2 Pulse STR magnets in addition to septum using in the design stage are not available.
The beam orbit passes very off-center through ISEP2, where no field measurement through this orbit couldn't reach
→May be the main reason!!

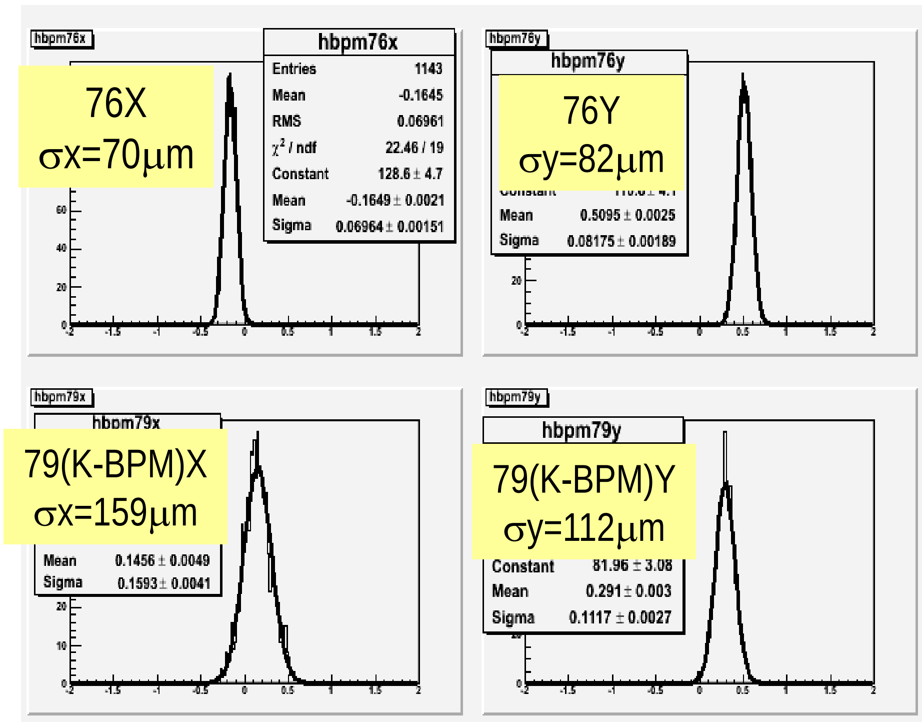
w/ paint orbit (100p), the difference becomes: +5.3%
→ Gets better but not sufficient → under study

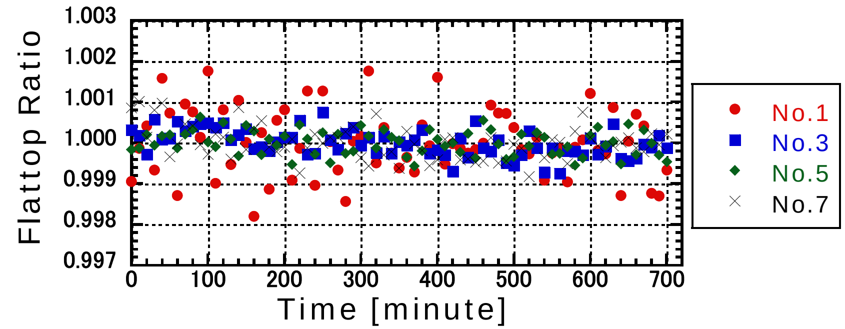
Concerning extraction, no sufficient data but the overall agreement is satisfactory

Unlike, injection area, there are lack of monitors in the extraction section

Stability of the injection and extraction beam (*system performance*)

Inj. Beam jitter @ last few BPMs in the L3BT line

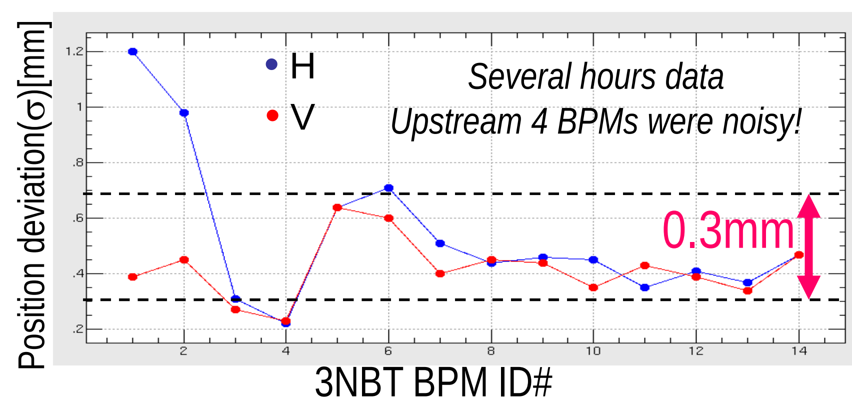




Stability of the ext. kicker magnets: ~ 0.2%

→ Dx ~0.1mm at the exit of ext. septum → negligible

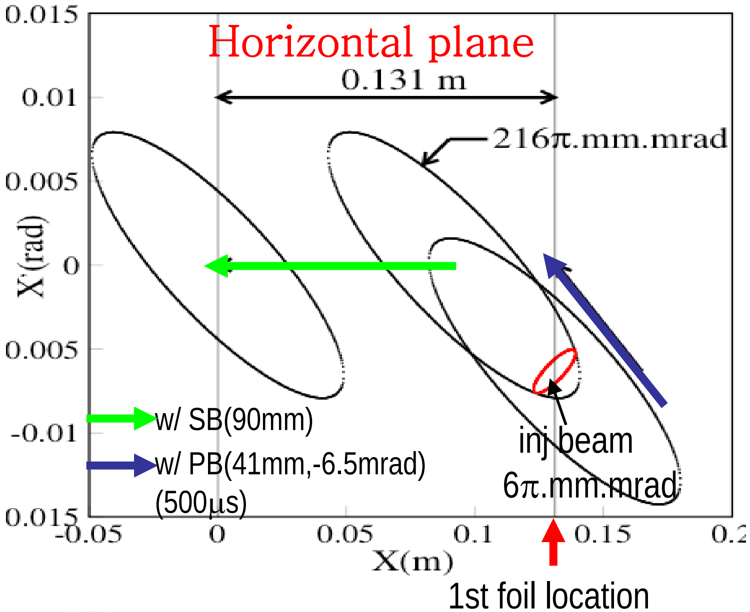
Finally, the ext. orbit stability was measured as follows:

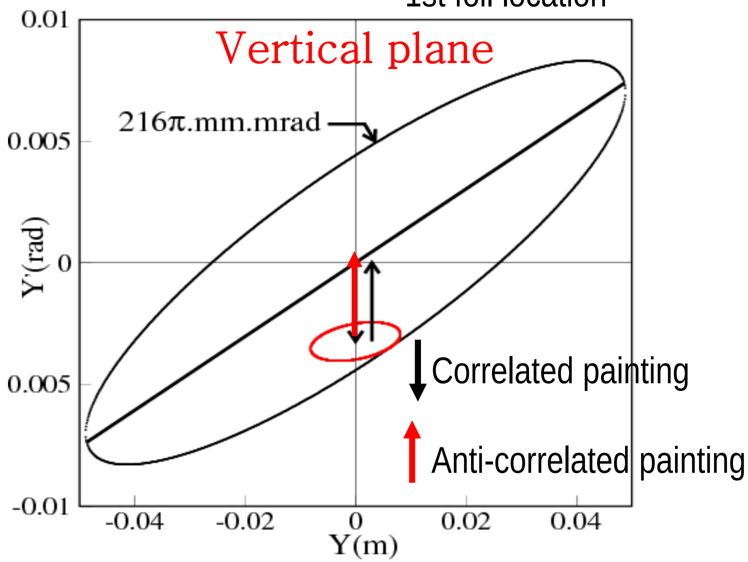


In RCS, the fluctuation of the Shift bump flat top was within ± 1%, while all other DC magnets both in the injection and the extraction line were just stable!

Painting injection study: *Run# 16, 17*

Painting process in RCS: schematic view





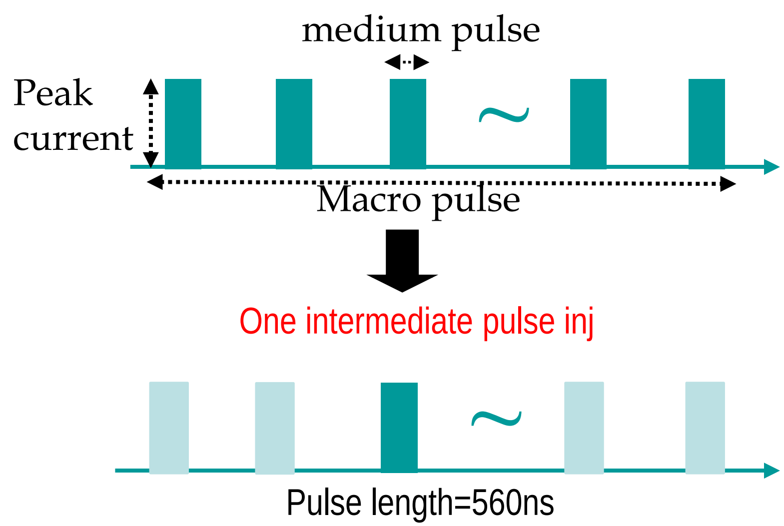
Painting injection major study items:

1. Horizontal Painting for 100π, 150π and 200π painting area.

2. Vertical Painting for 100π painting area
[both with i) constant flat top and ii) with decay pattern]

3. Horizontal and vertical together for 100π with decay pattern

Beam conditions
Linac peak current: 30mA
One intermediate pulse inj
RCS DC circulating mode
RF chopping: 560ns



Painting injection study: *Run#16, 17*

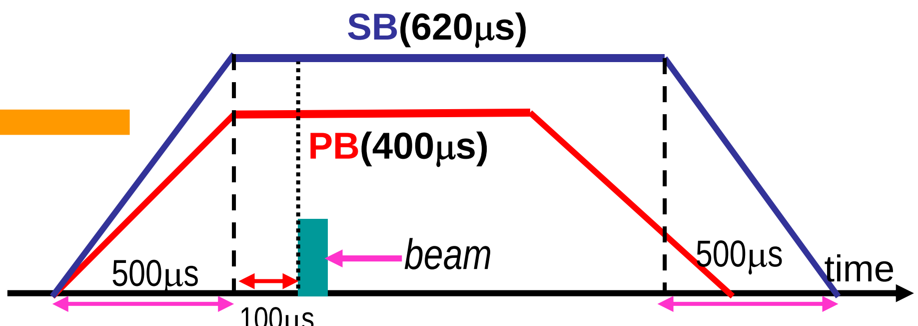
The top of the paint bump first fixed with a constant pattern by measuring directly the phase space coordinates at the foil using MWPM 3&4

The decay pattern was then made using following functions:

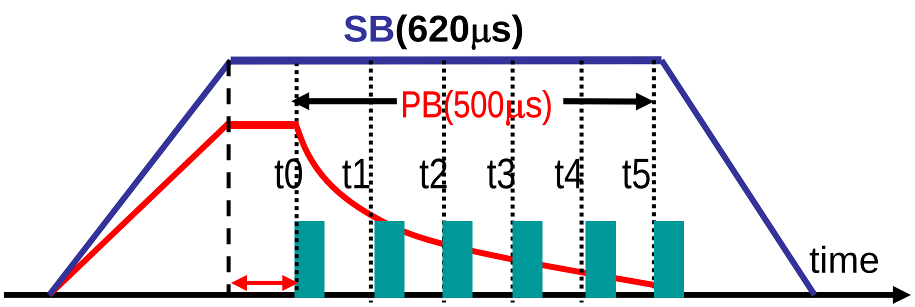
Hori: I_{max}[1-Sqrt(t/T)]

Vert: I_{max}[Sqrt(t/T)]

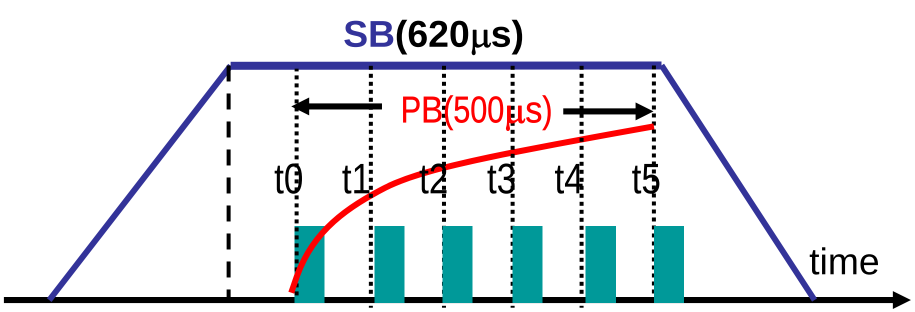
Pattern for 150π and 200π were scaled from 100π and was perfect !!



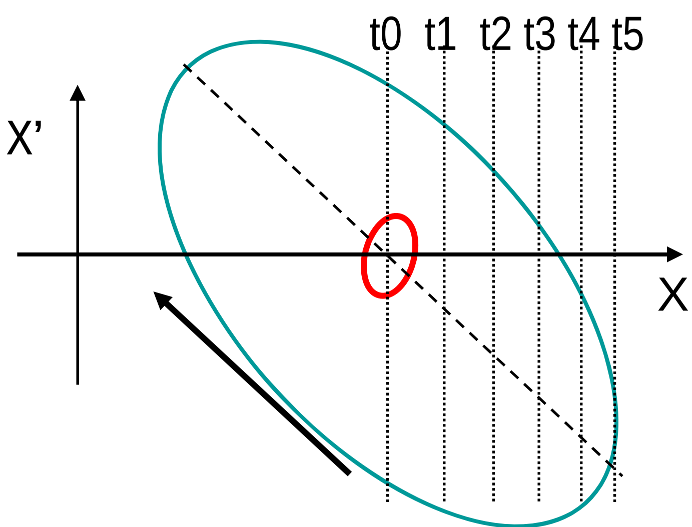
Hori. paint bump pattern@constant flat top inj(i)



Hori. paint bump @ decay pattern(ii)
Pattern moved t0~t5 w/ 100 μs step



Vert. paint bump @ decay pattern(ii)
Pattern moved t0~t5 w/ 100 μs step



Schematic view for study with decay pattern

Painting injection study cont'd

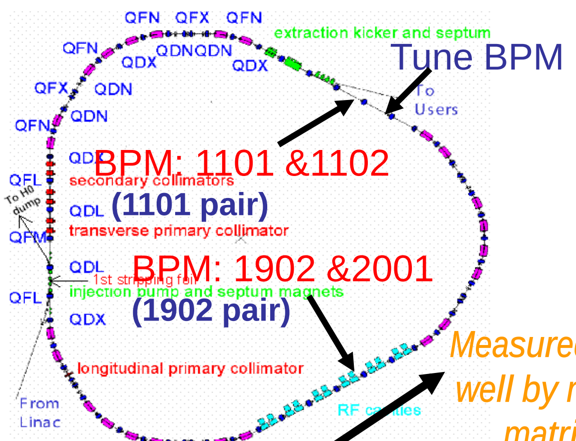
(Reconstruction of the phase space footprint)

Method: 1

BPM with single pass mode

Using turn-by-turn data of BPM pair

Two BPM pairs in drift space
1st pair: BPM id # 1101 and 1102
2nd pair: BPM id # 1902 &2001



Measured optics is reproduced well by model and the transfer matrices used here was calculated by the model !

$$\begin{pmatrix} X\_BPM \\ X'\_BPM \end{pmatrix} = \begin{pmatrix} \mathbf{M}^n \end{pmatrix} \begin{pmatrix} \mathbf{M} \end{pmatrix} \begin{pmatrix} X\_foil \\ X'\_foil \end{pmatrix}$$

X_BPM and X': phase space coordinate of the beam center measured with BPM pair after subtracting COD
M^n is the one turn transfer matrix
M is the transfer matrix from foil to the BPM
X_foil and X'_foil : reconstructed phase space coordinate at the foil

Method: 2

Using spectrum of a Tune BPM

measuring a betatron response matrix and by detecting the real and imaginary part of the betatron sideband peak gives the phase space coordinates at the injection point

(Detail : H. Harada, to be published in Ph.D. thesis)

$$\begin{pmatrix} \mathbf{Re}\,[X_e(\omega_x)] \\ \mathbf{Im}\,[X_e(\omega_x)] \end{pmatrix} = R(\omega_x) \begin{pmatrix} x_e \\ x'_e \end{pmatrix}$$

$R(\omega_x)$ = Measured Response matrix

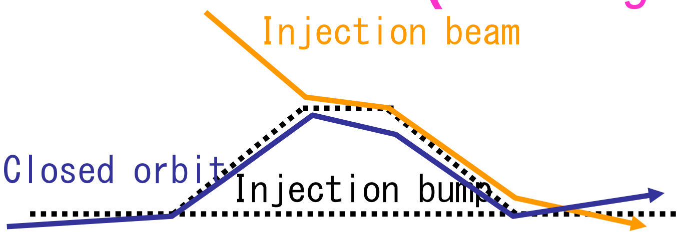
$$= \begin{pmatrix} A(real) & B(real) \\ A(imag) & B(imag) \end{pmatrix}$$

Re $[X_e(w_x)]$ and **Im** $[X_e(w_x)]$: Real and imaginary part of the betatron sideband peak

X_e and x'_e : reconstructed phase space coordinate at the foil

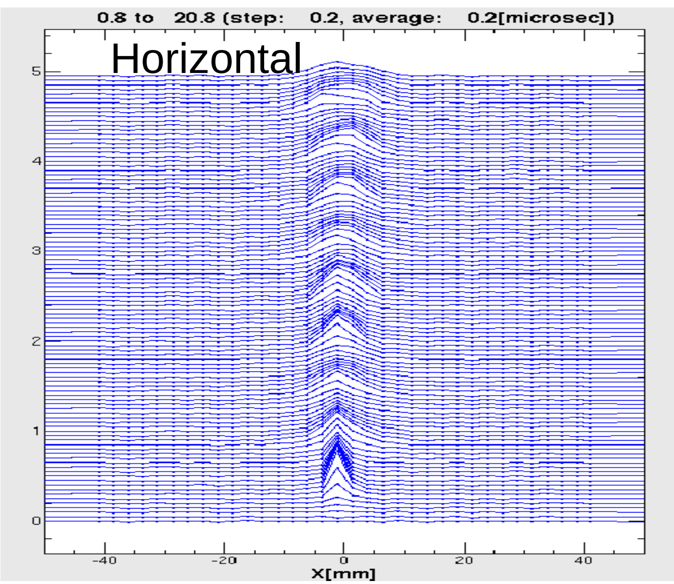
Checking of both methods first

(*matching of the injection and the closed orbit*)



Single pass BPM:	X[mm]	X'[mrad]	Y[mm]	Y'[mrad]
1101 pair	-2.28	0.69	-2.73	-1.05
1902 pair	-2.20	0.71	-3.32	-1.12
Tune BPM	-1.81	0.65	-1.10	-0.70

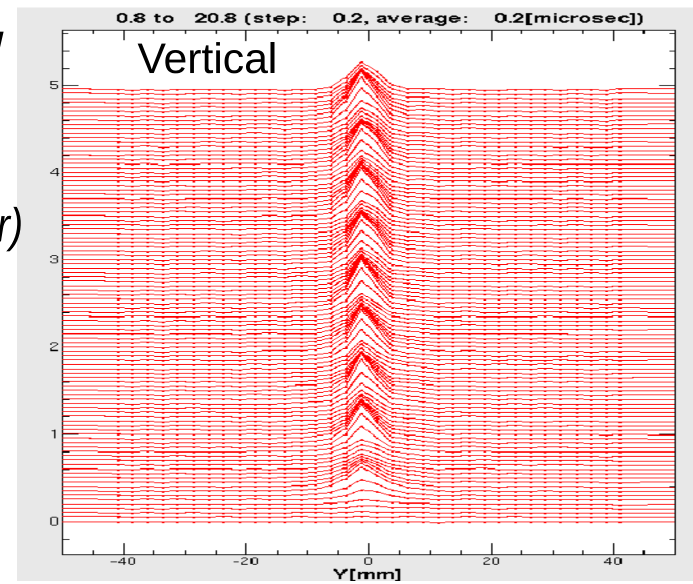
Both methods gave quite close and accurate results !!



Just a single trial !!
Quite accurate !!

Checked by IPM
(Ionization profile monitor)
Mountain plot of
the beam profile

Well minimized
Betatron oscillation !!



Then, starting with 100π painting, at first balance of 4 horizontal paint bump magnets were adjusted by measuring and correcting the COD during the paint bump on(0~1msec). Parameters for 150π and 200π were then just scaled.

Vertical direction: → By measuring directly Y and Y' of the inj beam at the foil with MWPM3,4

Painting study results

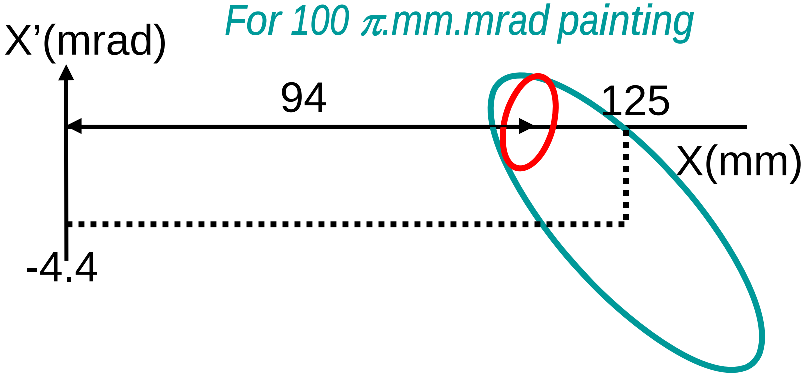
with constant paint bump pattern

Measured Twiss parameters @ foil

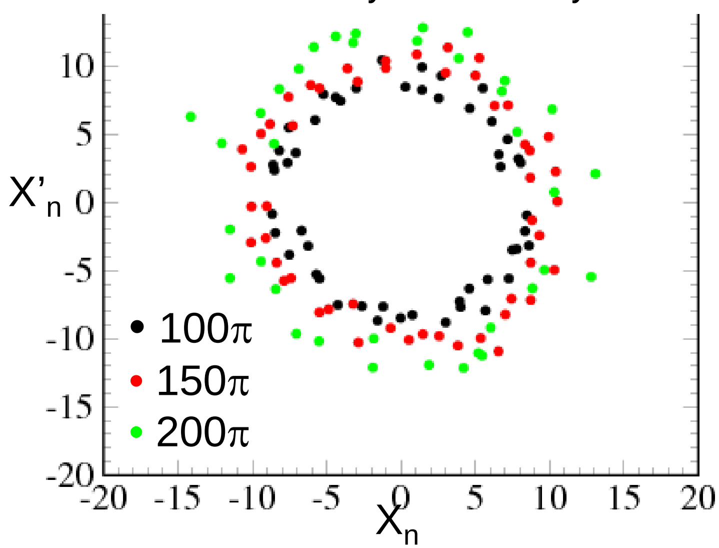
Inj. Beam:	**Circulating beam**
αx=-0.3302	αx=1.7144
αy=-0.23088	αy=-1.8712
βx=3.2207m	βx=12.9575m
βy=4.8071m	βy=12.3682m

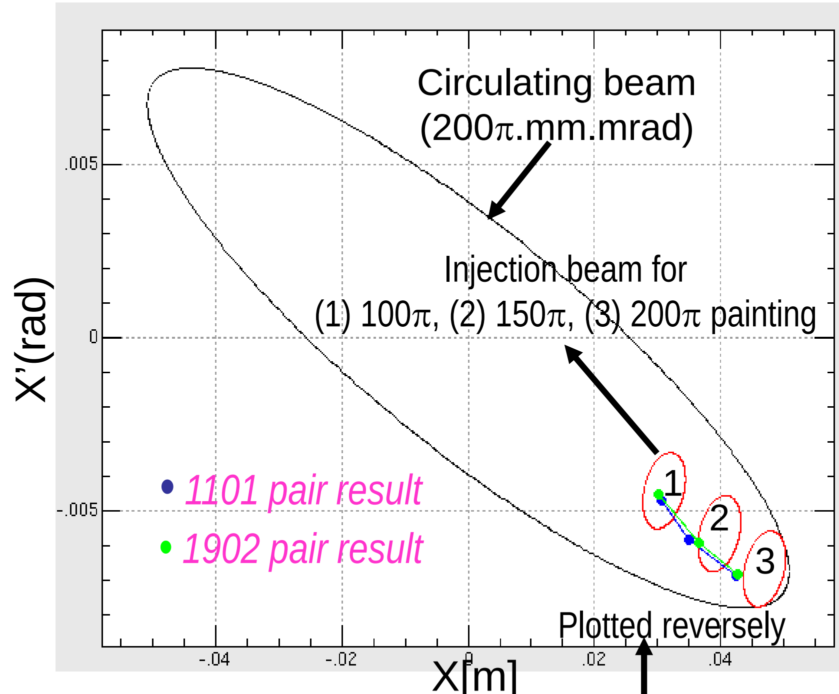
$\varepsilon x, \varepsilon y \approx 3.5\pi$.mm.mrad ($3\sigma$)

For 100 π.mm.mrad painting



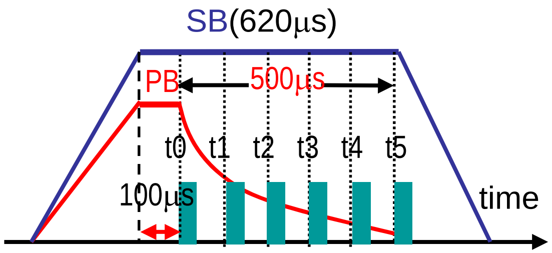
Normalized phase space plot of the beam center measured by BPM turn-by-turn data





	Δx[mm]	Δx'[mrad]
For 100p target :	-31.1	4.4
Results:		
Single pass 1101 pair:	-30.6	4.69
Single pass 1902 pair:	-30.1	4.52
Tune BPM(h=1&upper):	-29.9	4.90
Tune BPM(h=1&downer):	-29.1	4.66
Measurement w/MWPM :	-31.2	4.61

Footprint with Horizontal paint bump decay pattern



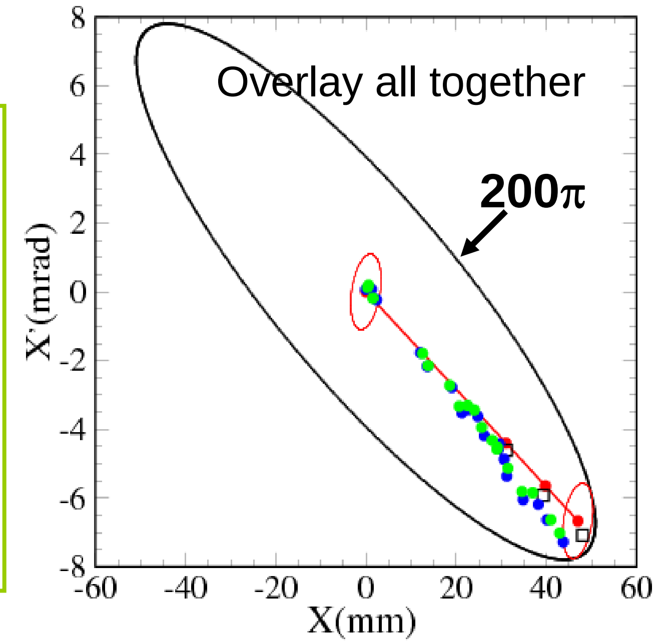
Hori. paint bump @ decay pattern
Pattern moved t0~t5 w/ 100 μs step

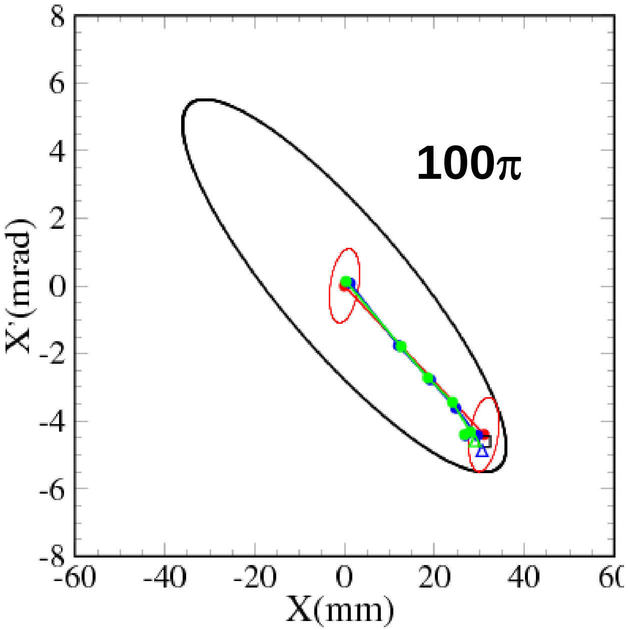
- ● Target
- ● Single pass BPM 1101 pair
- ● Single pass BPM 1902 pair
- △ PB magnet off at t5 (1101 pair)
- △ PB magnet off at t5 (1902 pair)
- □ Measured by MWPM3-4

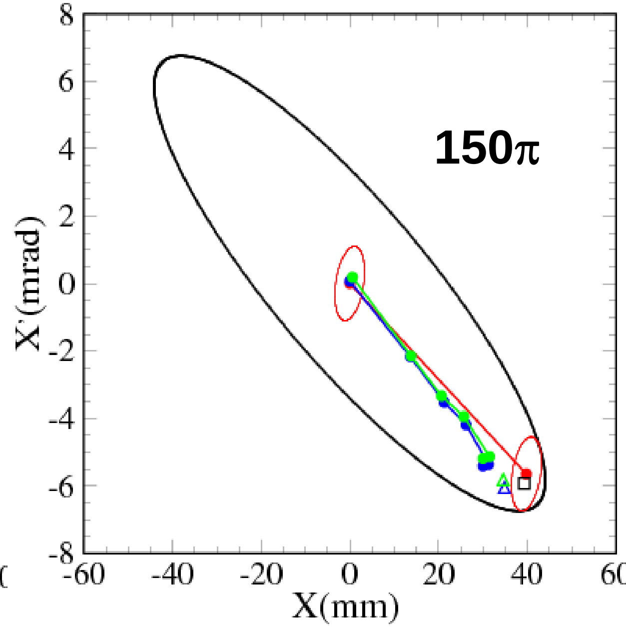
Well reconstructed the phase space Footprint by the BPM single data.

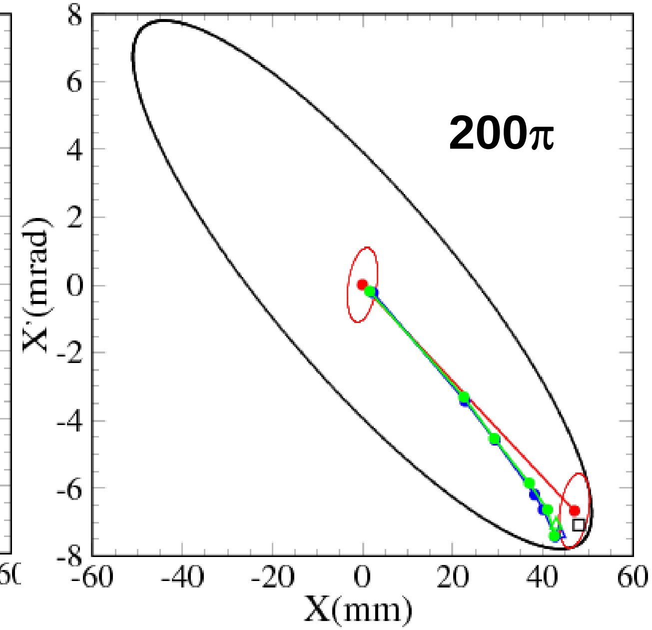
At t =t5, the pattern was a bit strange and was confirmed by the measurement with PB off at t=t5.

Gets little disagreement with larger amplitudes → Under Inspection !!



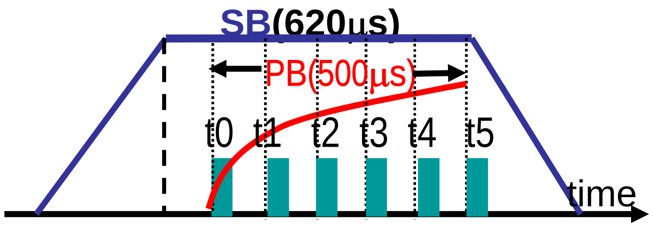




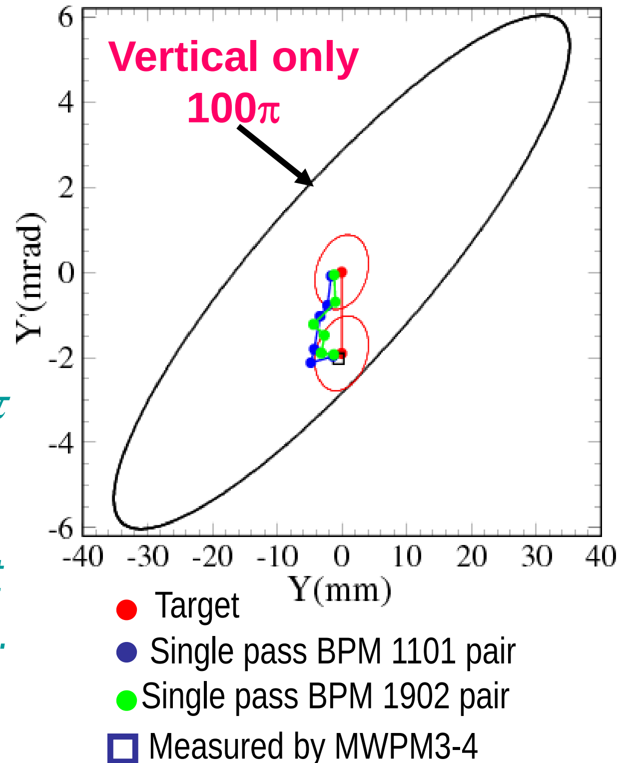


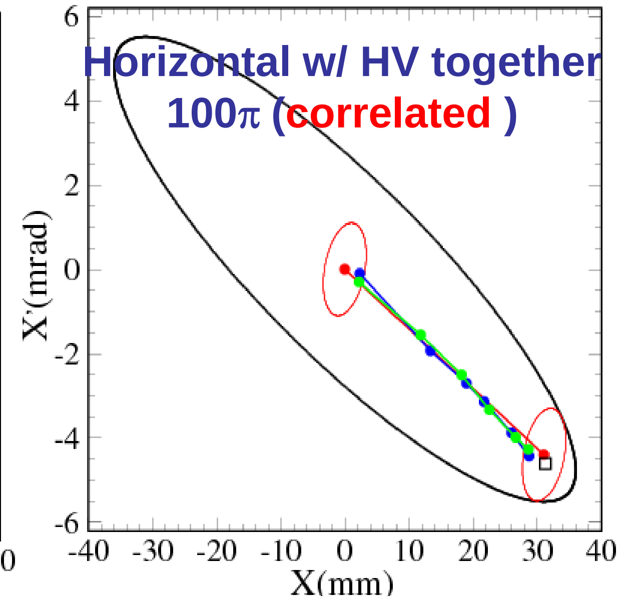
Footprint with vertical decay pattern(100π)

Horizontal and vertical together(100π)



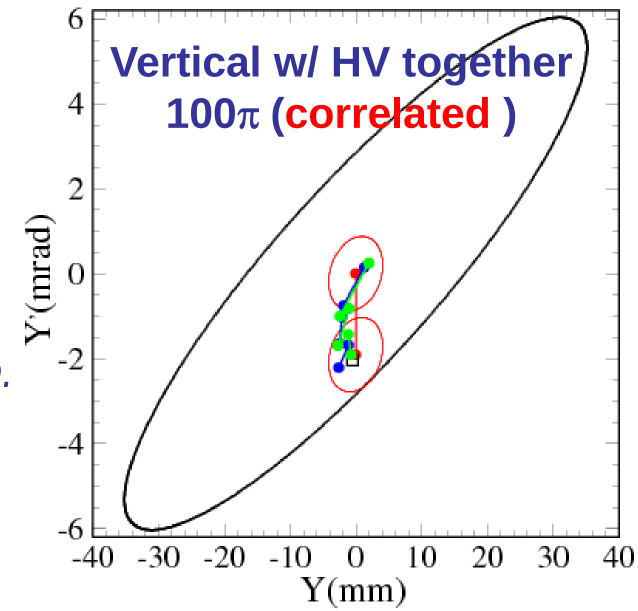
Vert. paint bump @ decay pattern
Pattern moved t0~t5 w/ 100 μs step





In the vertical plane, only with 100π painting study was performed. Reconstructed footprint in the vertical plane found a bit zigzag but finally gets to the expected position.

A correlated painting study with 100π was also performed and the reconstructed results were expected



Basic painting study in Run#16 was done very successfully.
BPM with single pass mode was found to very effective and accurate.
(Detail with method 2 under analysis)

Paint bump patterns made in this study was used for the painting with high power run

Beam loss @ Injection and Extraction areas

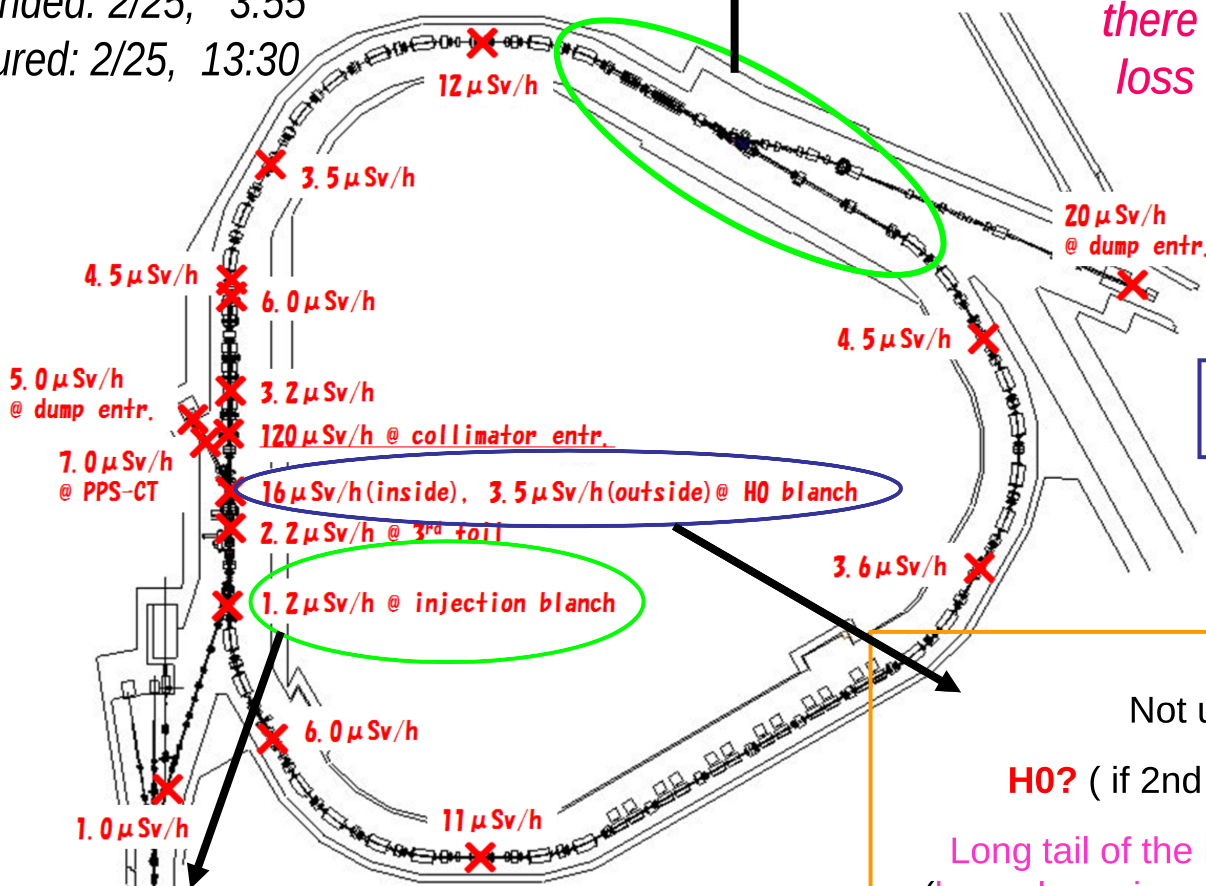
Residual level measured after Run#14

(w/ high current operation)

Run ended: 2/25, 3:55

Measured: 2/25, 13:30

Except H0 branch, there is no significant beam loss in the inj and ext areas



Losses in the arc sections
→ During RF study

Injection branch
Mainly because of the present center inj orbit
Very close to the aperture limit!!

H0 dump branch
Not understood yet clearly !!

H0? (if 2nd foil not working well !)

Long tail of the inj. Beam + scattered?
(beam loss signal even in the 1/3 mode !)

…………………………

Foil system broken →no study done so far
→To be done in the next run
(foil system recovered)

Beam loss in the RCS injection area

(Estimation vs. reality)

Major sources and quantity of the beam loss in the injection area:

(Considering inj beam power of 18kW [0.3MW@RCS extraction])

1. Lorentz striping loss of the injection(H-) beam: << 1W

→Inj beam line clean!!

2. H0 excited states losses: < 2W

→1st foil to the bump region clean!!

3. Nuclear scattering together with multiple coulomb scattering at the charge-exchange foil:

→ Major source among all

Total loss: 38W(~0.2%)

P.K. Saha, PAC07 (GEANT + SIMPSONS)

Simulation with Real painting process (Space charge: off)

Foil size: 32mm x 36mm (design)

and with ideal bump systems

Average foil hits: **24**

Mostly may be due to the 3rd source:

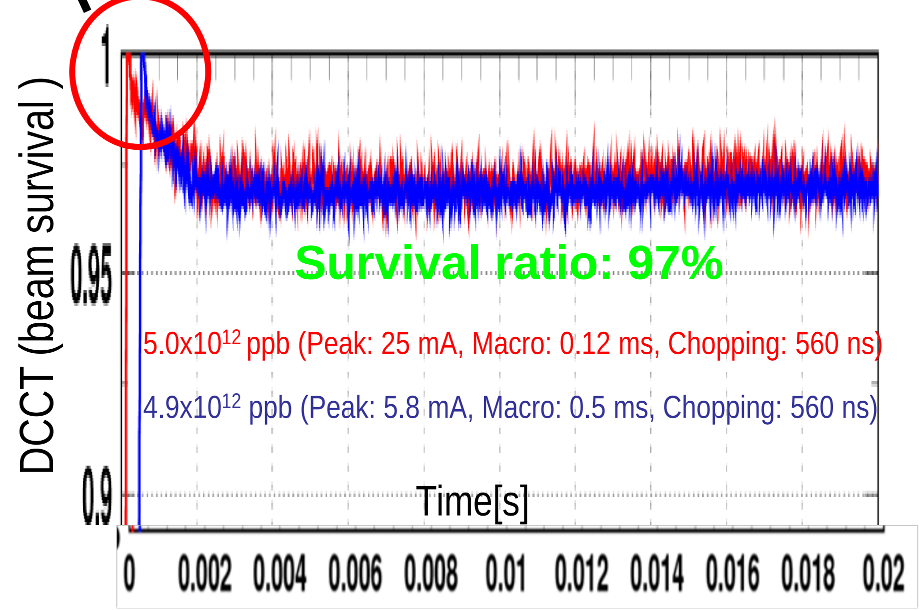
Average foil hit with present foil and bump systems: ~**200**

→ 8 times higher than the design

→ Checked with simulation

θ_{rms}(hand cal)=~1mrad ! → large !!

Detail study to separate foil scattering loss with recovered foil and systems to be done in the next run



Summary and future plan

The injection and extraction systems of RCS are found to be performed well during the beam commissioning so far.

Except one case, design stage parameters are found to be consistent with the beam commissioning parameters, where the relative values were exactly similar each other
→ Beam commissioning proceeded quite smoothly for any operation

Painting study utilizing one intermediate pulse injection was successfully performed by measuring accurately the phase space footprint..
→ *Phase space control can be done in the painting inj.*

Estimation of the beam loss in the design stage was found to be consistent.
Detail study with nuclear scattering loss is planned to perform in the next run.

Discussion on several questions by the committee

Does the system perform as expected?

Ans: System performance satisfactory so far! No remarkable trouble concerning inj and ext.
Bump system working fine. Problem remains with Bump falling time and hope soon gets better.
Foil system gets recovered

Did the simulations/calculations performed during the design stage accurately predict the actual performance?

Ans: Yes. Inj and ext. beam orbit even with very different parameters goes through expectation.
The beam profiles are also quite similar.
The relative parameters of all magnets are exactly similar to the simulation/calculation.
Needs more experimental data

What are the major limitations in performance? Were they known in the design stage?

Ans: Foil system was one big limitation of the injection commissioning. But it's going to be fine from the next run.
So far not face any other big limitation and would be clear with long time (and high power) operation.
No BPM in the extraction section is one small limitation concerning extraction.

If someone were to begin now designing the same type of system for a similar machine, what is the one piece of advice that you would give them?

Ans: Please try to have enough monitors, especially in the complicated areas like injection and extraction.

Keep (check for) enough space for not to push nearby magnets/elements nor make thinner the shield at the last moment to install later elements/magnets

Backup Slide 1

Results with constant flat top cont'd

(for 150π, 200π painting)

150π Target:
Δx = -39.86 mm
Δx'= 5.65 mrad

Result from single pass BPM
1101 pair: -35.1 mm, 5.83 mrad
1902 pair: -36.6 mm, 5.92 mrad

Measuring with MWPM3,4
Δx = -39.30 mm
Δx' = 5.92 mrad

w/ inj beam 150π paint orbit but PB off:
1101 pair: 37.2 mm, -6.13 mrad
1902 pair: 36.3 mm, -5.90 mrad

200π Target:
Δx = -47.02 mm
Δx'= 6.67 mrad

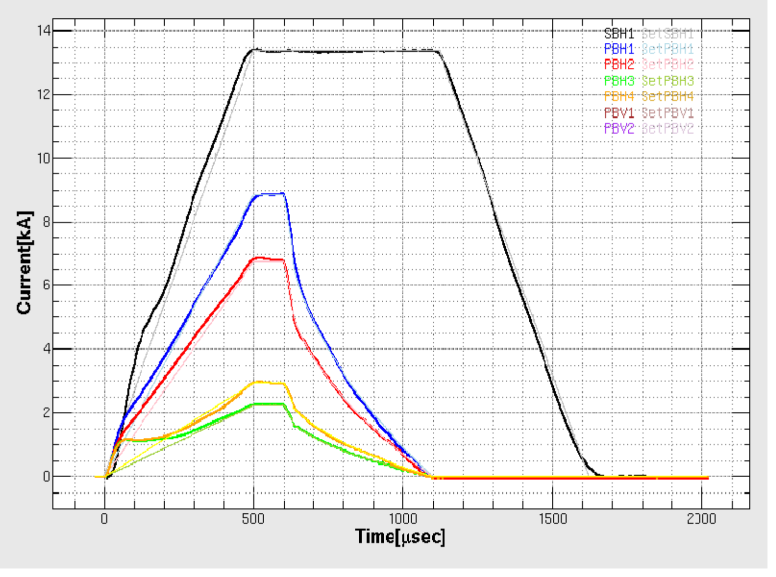
Result from single pass BPM
1101 pair: -42.5 mm, 6.85 mrad
1902 pair: -42.8 mm, 6.81 mrad

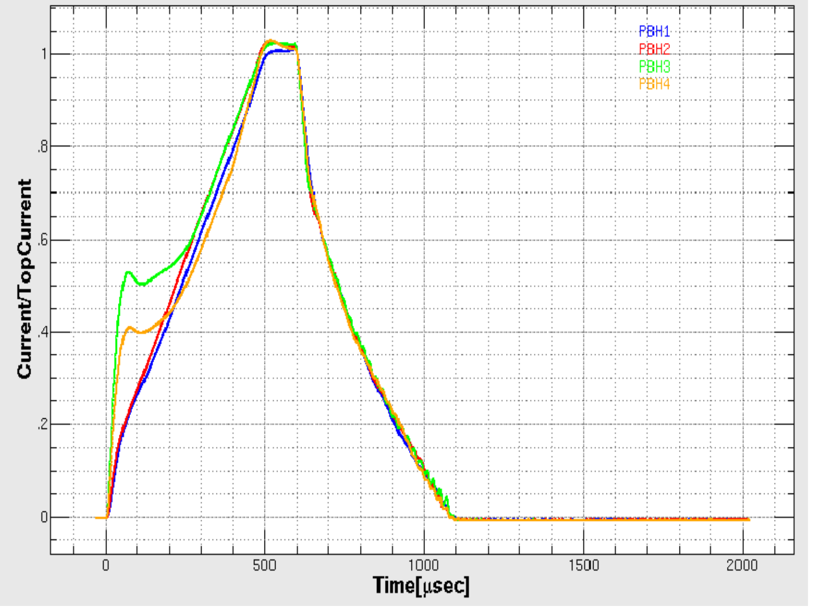
Measuring with MWPM3,4
Δx = -48.05 mm
Δx' = 7.076 mrad

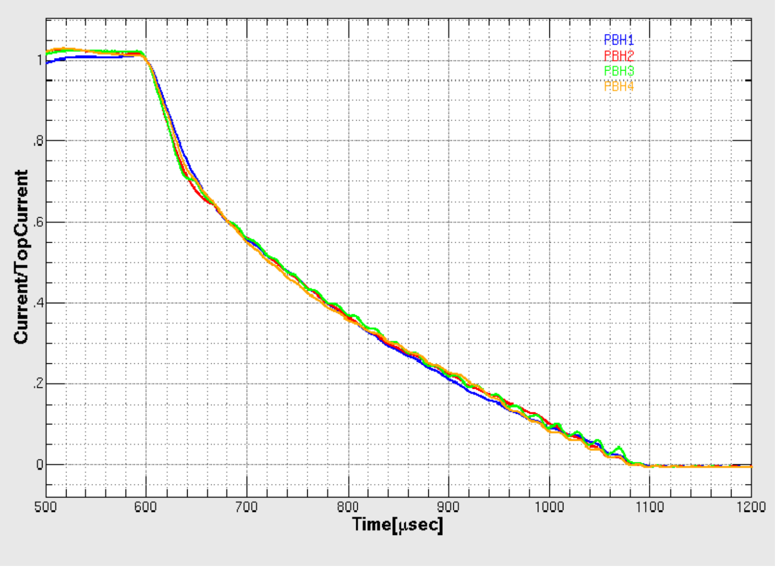
Not measured w/
inj beam 200π paint orbit but PB off

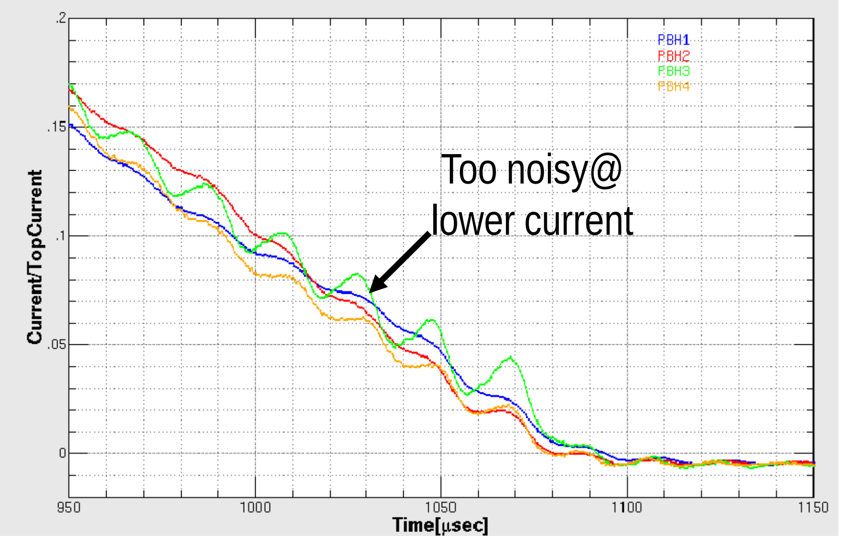
Backup Slide 2

Bump pattern@paint inj study



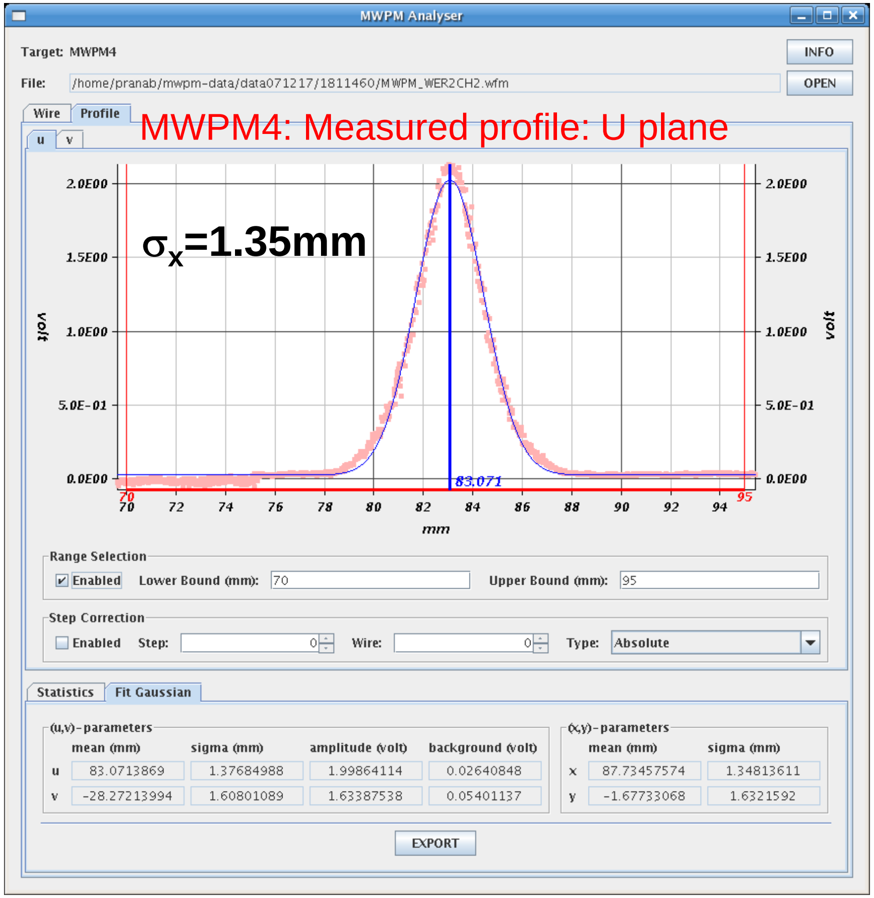


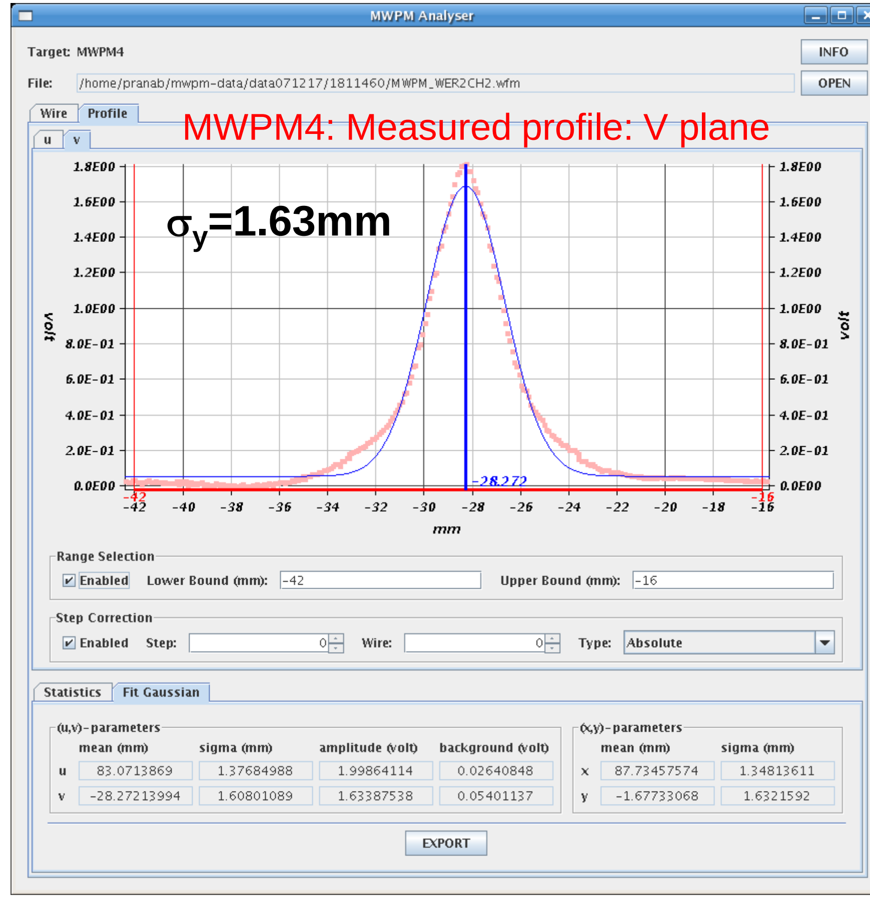




Backup Slide 3

Measured beam profile by MWPM





The mean and the width of the measured profiles in the U and V planes were transformed to the X and Y plane as follows:

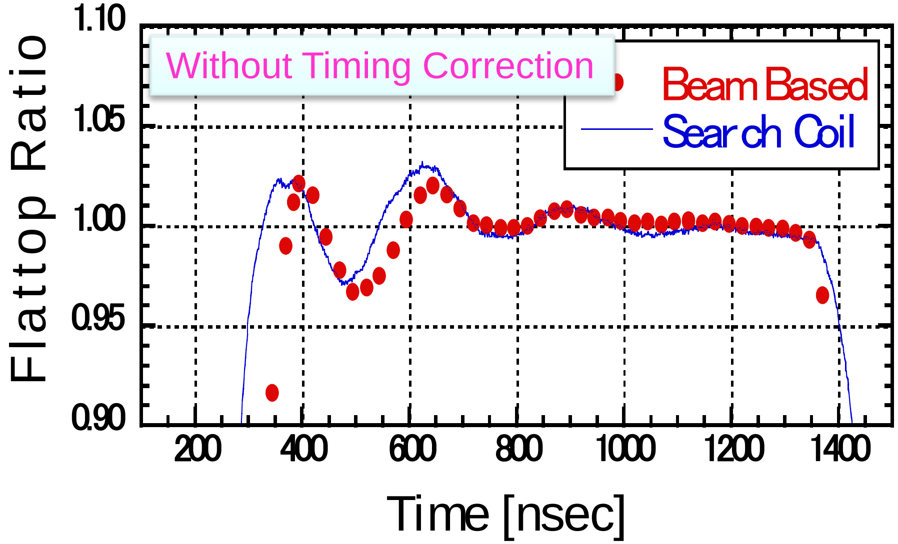
$$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

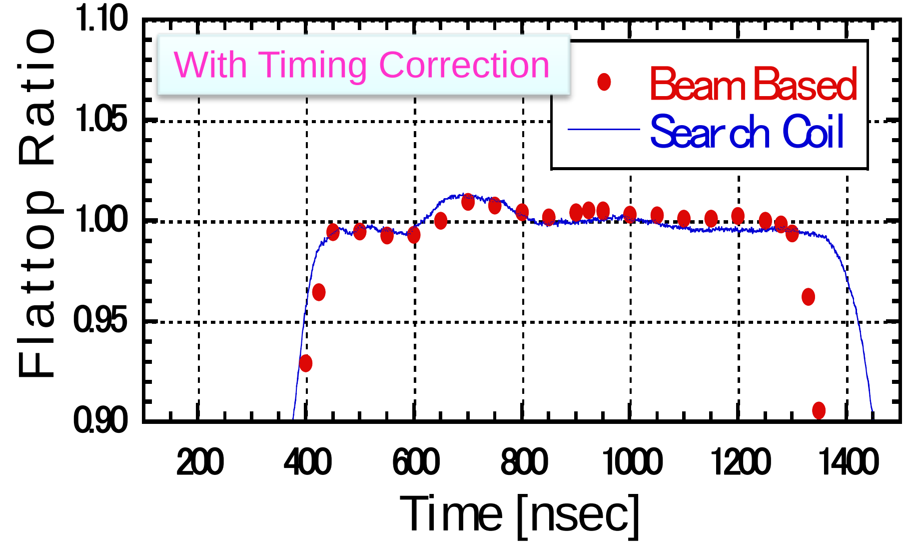
θ is the wire inclination: 17.7 deg.

$$\begin{bmatrix} \sigma^2 u \\ \sigma^2 v \end{bmatrix} = \begin{bmatrix} \cos^2\theta & \sin^2\theta \\ \sin^2\theta & \cos^2\theta \end{bmatrix} \begin{bmatrix} \sigma^2 x \\ \sigma^2 y \end{bmatrix}$$

Backup Slide 4

Ext. Kickers flat top measurement





- *Required flatness = 2 % in the time length of 840 nsec*

- The trigger timing of the each kicker was adjusted in order to cancel out the peaks and troughs of the flattop.

- *The flatness of 2 % was achieved in the time length of 850 nsec!*