Development of a beam flattening system at J-PARC/JSNS

(J-PARC/JAEA) Shin-ichiro MEIGO

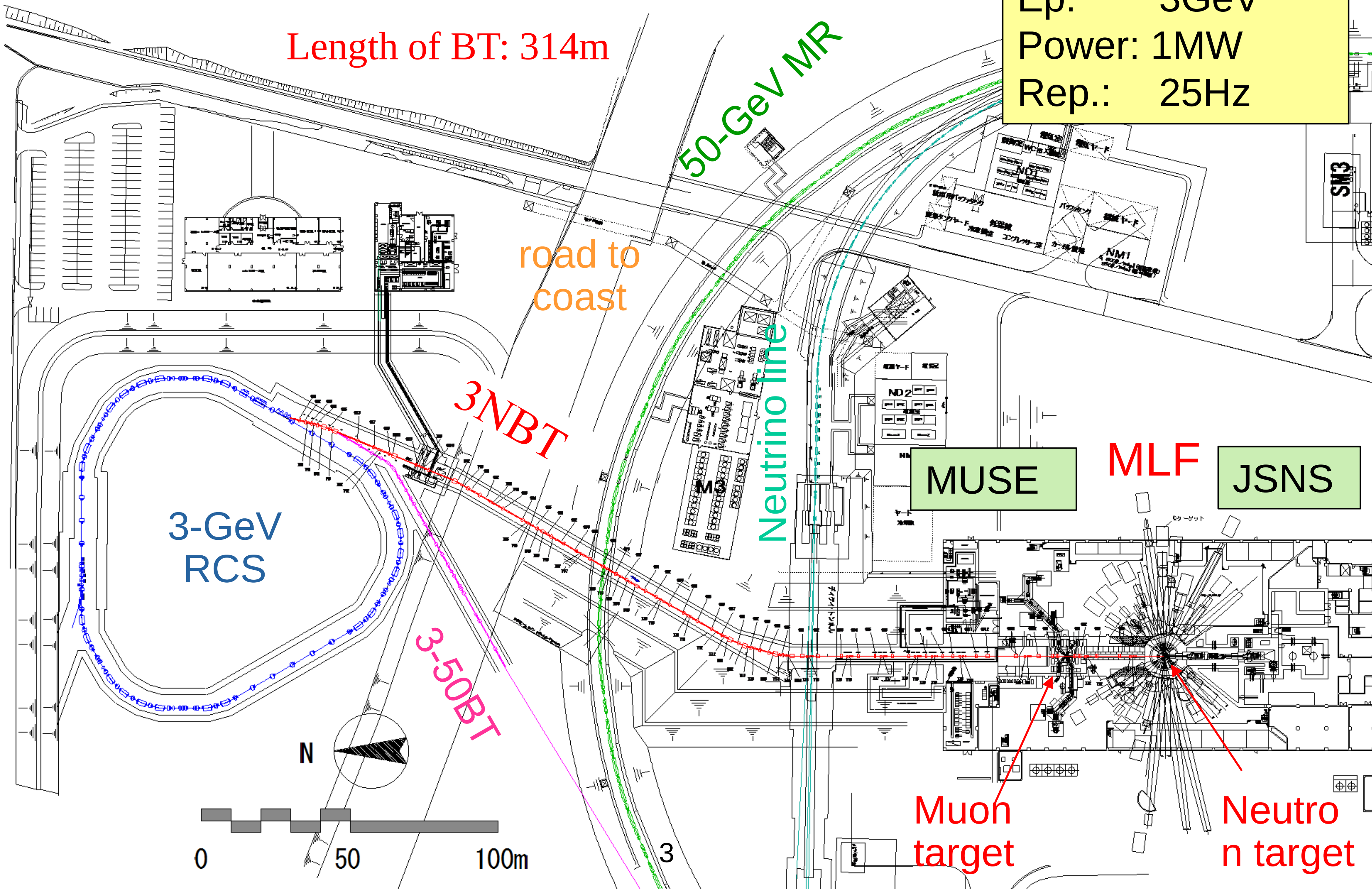
Workshop on Non-linear beam expander systems in high-power accelerator facilities
ISA, Department of Physics and Astronomy, Aarhus University, Aarhus, Denmark 26th and 27th March 2012

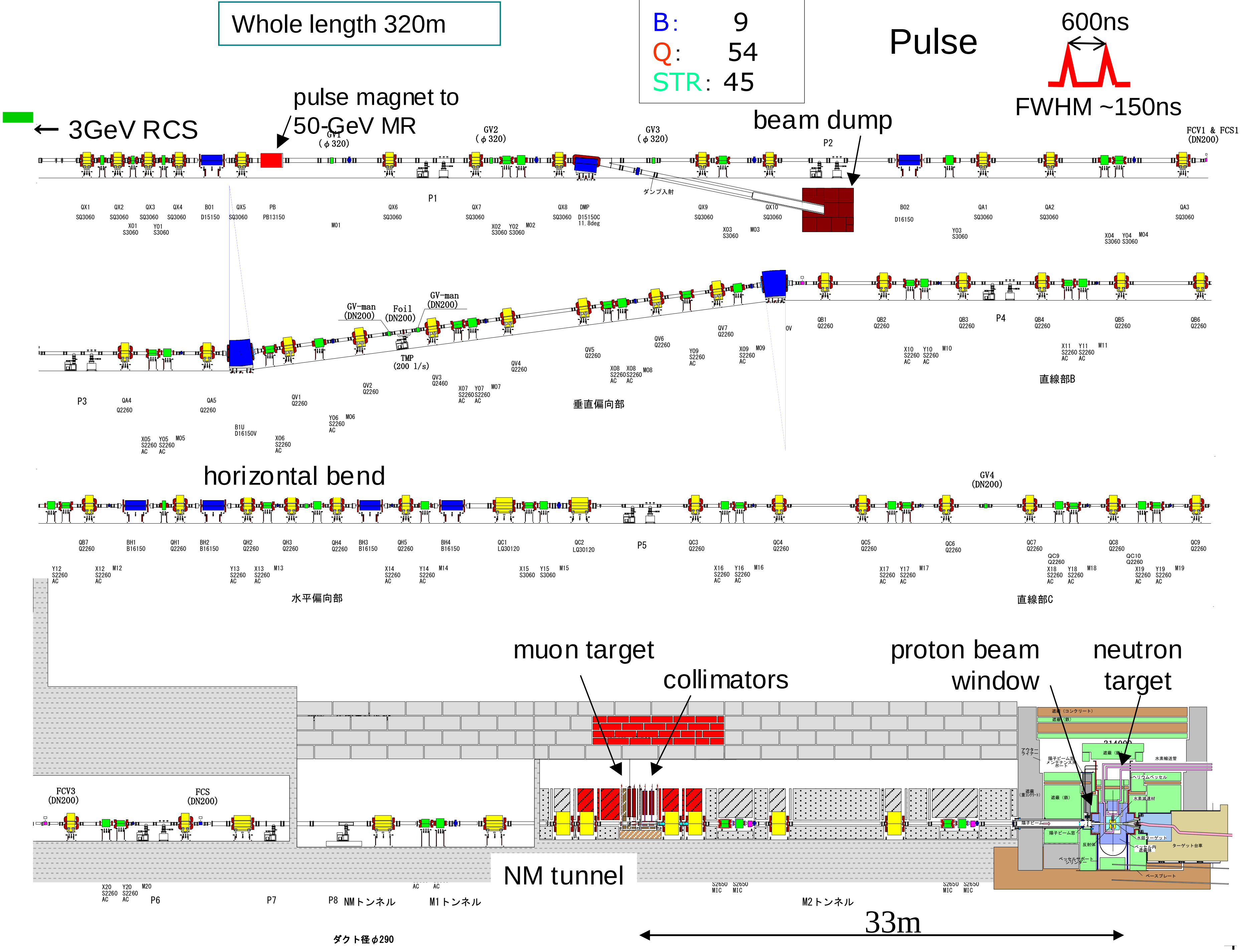
Outline

- Introduction
  - Present status of JSNS
- Beam flattering system
- Effect of miss alignment
  - Edge peak effect
  - Requirement of magnet located downstream
- Beam peak reduction

Proton beam transport line

Ep: 3GeV
Power: 1MW
Rep.: 25Hz

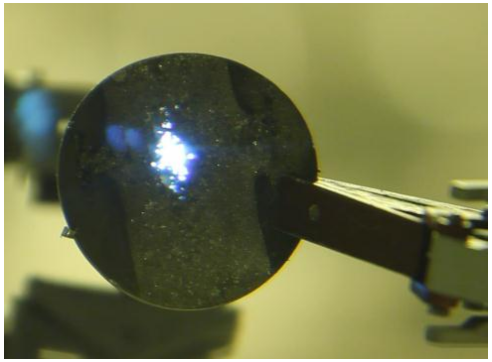




Whole length 320m
B: 9
Q: 54
STR: 45
Pulse
600ns
FWHM ~150ns
← 3GeV RCS
pulse magnet to 50-GeV MR
beam dump
horizontal bend
muon target
collimators
proton beam window
neutron target
NM tunnel
33m
垂直偏向部
直線部B
水平偏向部
直線部C
NMトンネル
M1トンネル
M2トンネル
ダクト径φ290

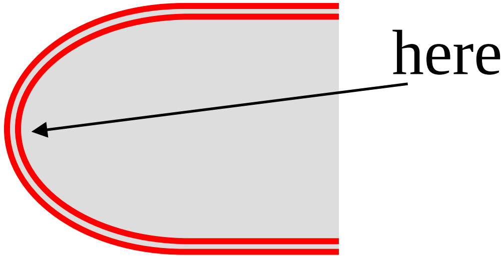
Proton beam at the target

- 3NBT･MLF beam operational status
  - Beam study with 0.4 MWeq beam (Mar 2012)
  - 1h demo of 0.3 MW beam (Dec 2009)
  - User operation 0.2MW beam
- Handling of high intensity proton beam
  - Beam profile is important.
    - Pitting damage (P4 Law)
    - Profile measurement with high reliability
- Condition of JSNS is harder than SNS
  - SNS:60Hz, storage ring without muon target
  - JSNS:25Hz, RCS with muon target
    - Target must be changed when pin holes was detected by the radiation monitor
  - Control of beam profile at JSNS becomes important
  - SNS has a record of exchanging new vessel within only 2 weeks after found fail.
  - In JSNS, failure of the vessel will take much longer time due to difficulties of handle of RI especially for release of tritium.
- Peak reduction becomes very important!



Pin holes at target of SNS

Pin holes are permitted at the inside wall of SNS but not allowed at JSNS



Target vessel

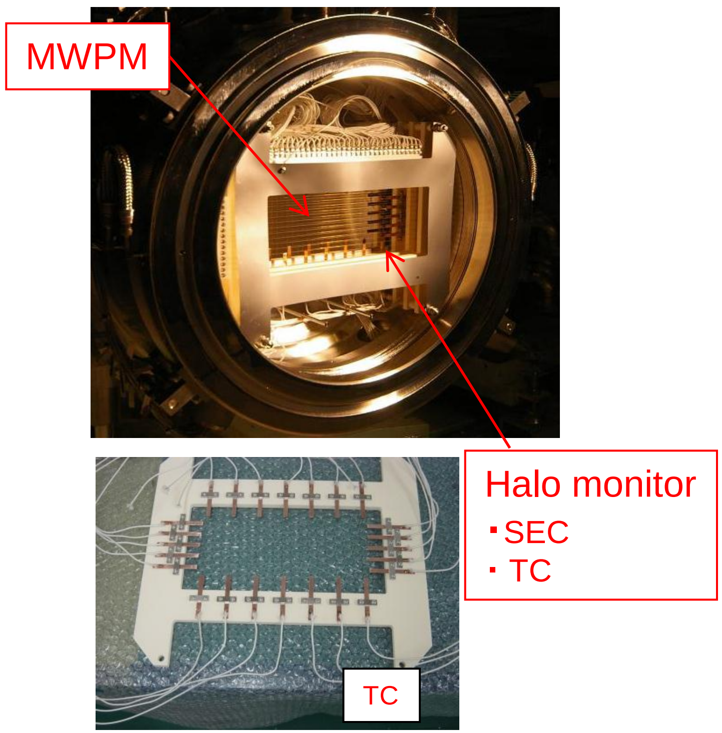
SNS: 4 walls
JSNS: 3 walls

Diagnostics of beam profile and halo

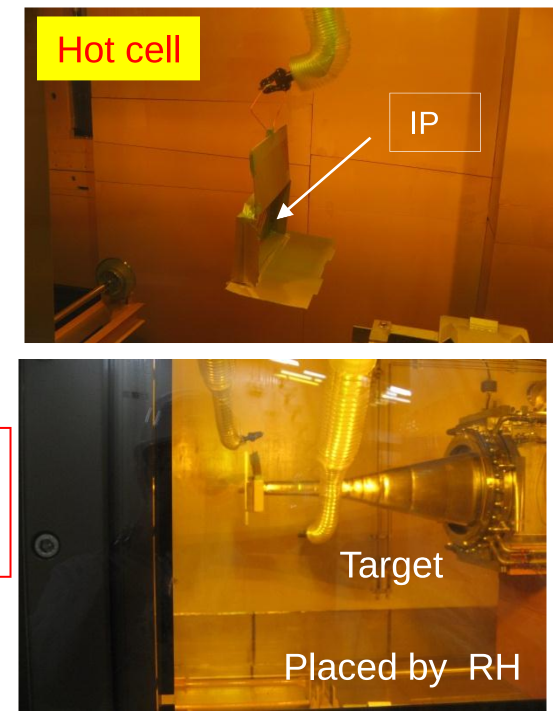
- Beam profile monitor and beam halo monitor (online type)
  - Multi Wire Profile Monitors (MWPMs) (15 sets located) : SiC wires
  - At the proton beam window (PBW), MWPM located (1.8m from the target)
- 2D profile： Activation by the Imaging Plate (IP) (Offline type)

  After beam operation: IP was attached at the target by the remote handling

MWPM



Monitors at PBW



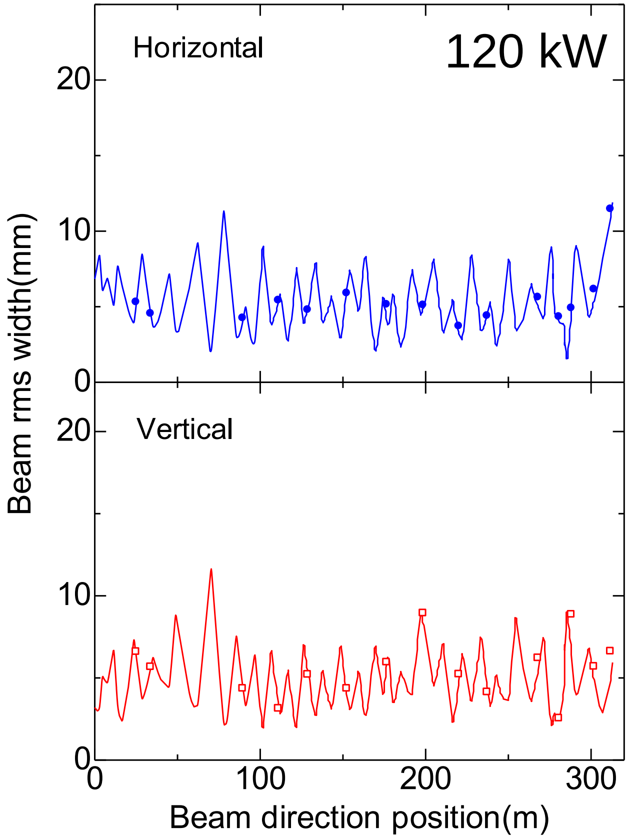
Imaging Plate

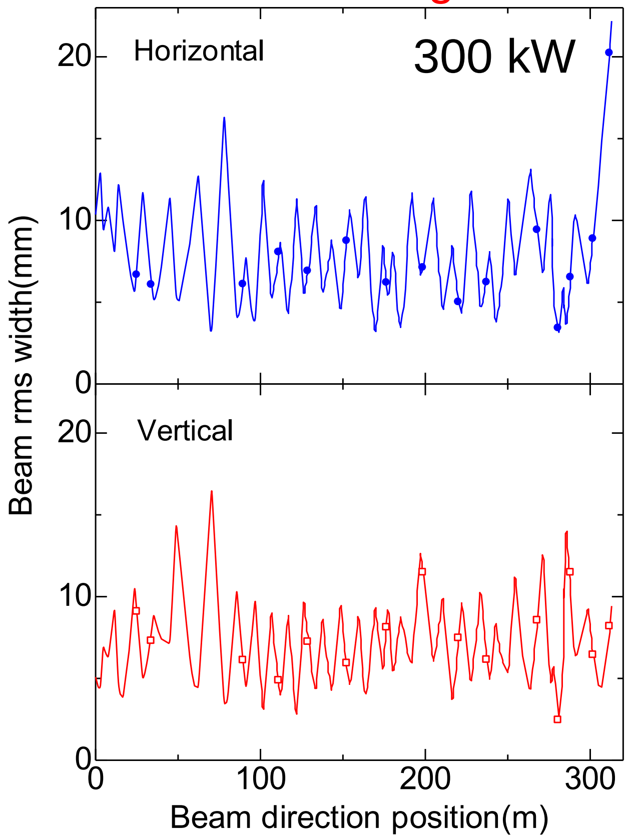
Beam behavior

Beam emittance and twiss parameters fitted by the observed beam width

⇒ Good agreement in whole beam line

Consistence from the accelerator to the target.





Residual dose at beam line:
Back ground except several points

Result of RMS emittance
unit: mm mrad

300kW:
$\varepsilon_{h,v}$ 5.7, 4.9 π
120kW:
$\varepsilon_{h,v}$ 2.7, 2.7 π

Twiss parameter at exit of RCS

300kW twiss parameter
αx -1.84, βx 20.4m
αy 0.57, βy 5.26m

Calculation of 300 kW case (by RCS team)

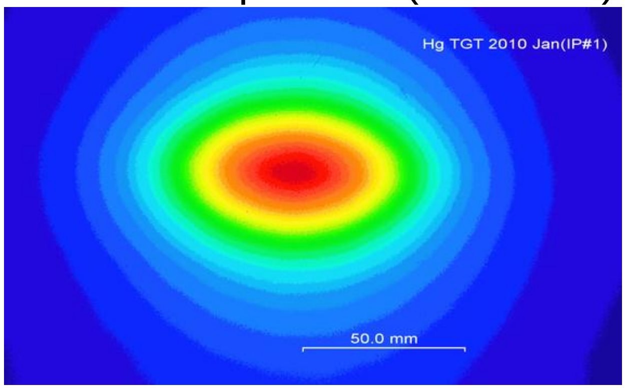
ε 5.4 π
αx -2.35, βx 24.8m
αy 0.89, βy 5.88m

Good agreement with the design calculation

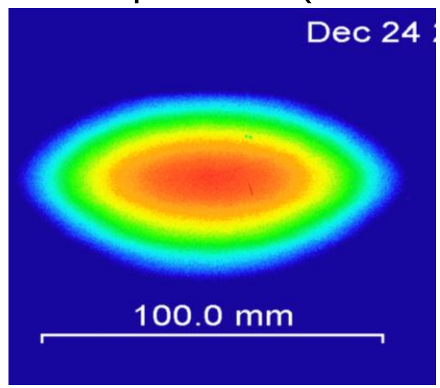
Beam profile at the mercury target

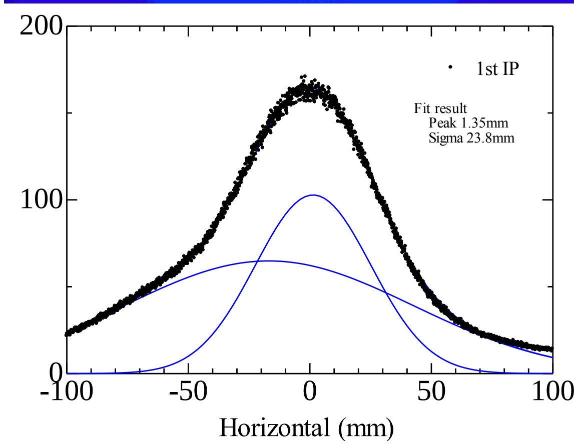
2-D measurement by IP

0.1 MW operation (2009 Dec)



0.2 MW operation (2010 Dec)

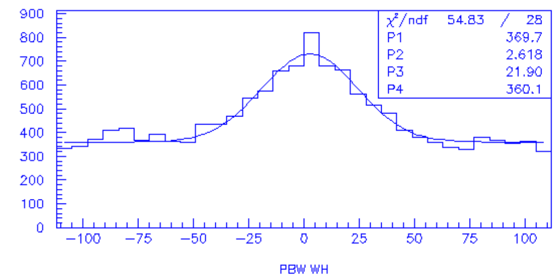


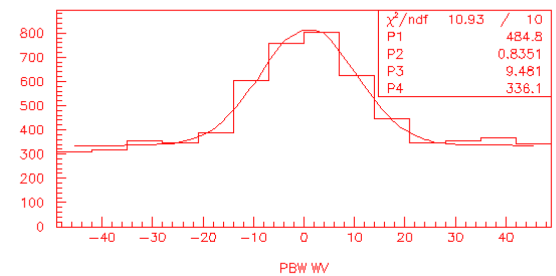


Obtained only 6 days of cooling duration after irradiation of 0.2 MW beam
⇒ Possible for 1MW with certain cooling time

Profile result by the IP
- Fitted by two Gaussian curves
  Contribution of primary protons and secondary particles (mainly neutrons)

MWPM at the PBW





Result by MWPM
Fitting by Gaussian
- Width of each pulse obtained
- Beam width transformed to the width at the target

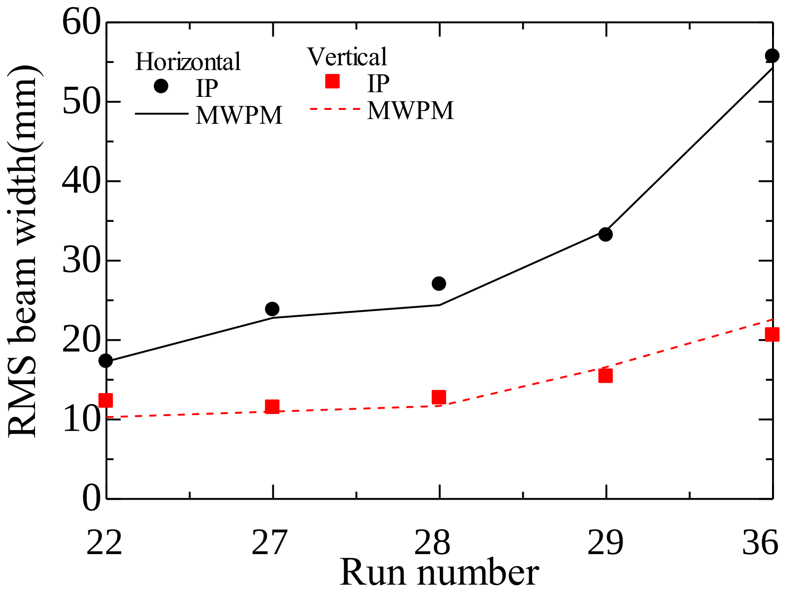
Trend of beam width at the mercury target

- Comparison of experimental results

To obtain low peak density, beam width gradually expanded

Unit: mm

	2009 Apr (Run#22)		2009 Nov (Run#27)		2009 Dec (Run#28)		2010 Jan (Run#29)		2010 Dec (Run#36 200kW)	
	σh	σv	σh	σv	σh	σv	σh	σv	σh	σv
MWPM	17.3	10.3	22.8	11.0	24.4	11.7	33.8	16.6	54.3	22.6
IP	17.3	12.3	23.8	11.5	27.0	12.7	33.2	15.4	55.7	20.6

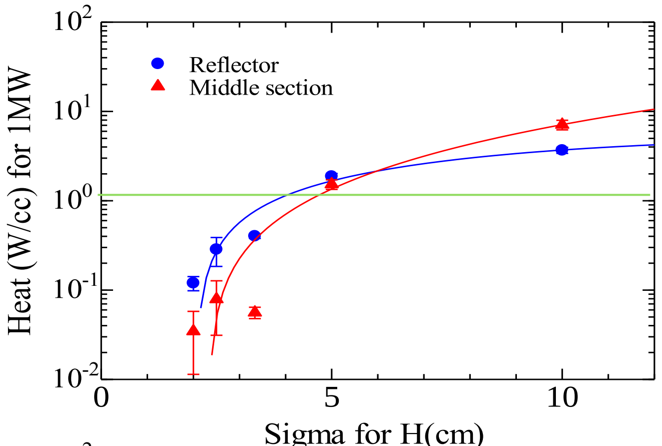


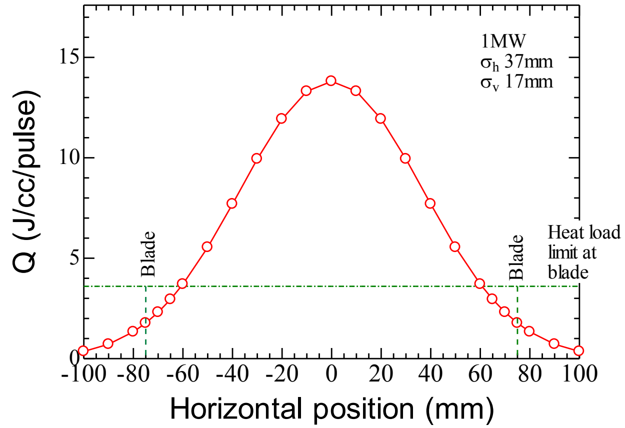
- Both results by MWPM and IP show good agreement
  - Demonstration of reliable method
  - Reliable peak density can be obtained by MWPM in real time.

- Found the higher activation at M23 than the estimation calculation, too much wide beam?

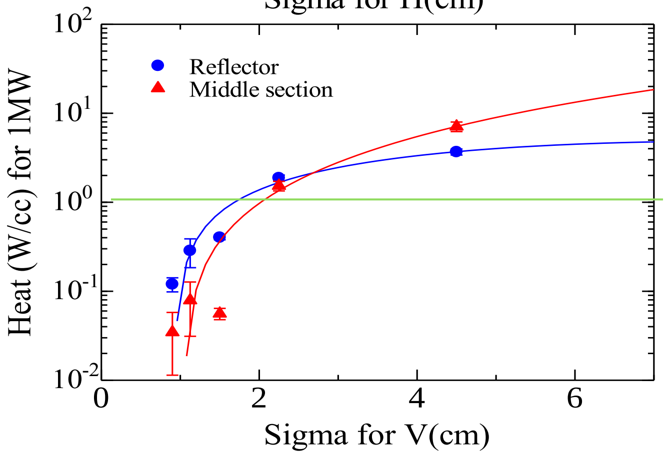
Beam expand by linear optics

- MWPM shows that the distribution is monotonous Gaussian.
- Expanding Gaussian beam to decrease the peak density
  - Vicinity of the target < 1W/cc(0.04J/cc/pulse)
  - Target blade < 90W/cc(3.5J/cc/pulse)
- Beam halo was approximated to follow as monotonous Gaussian.





Conserve beam aspect ratio
H:V=2.2:1

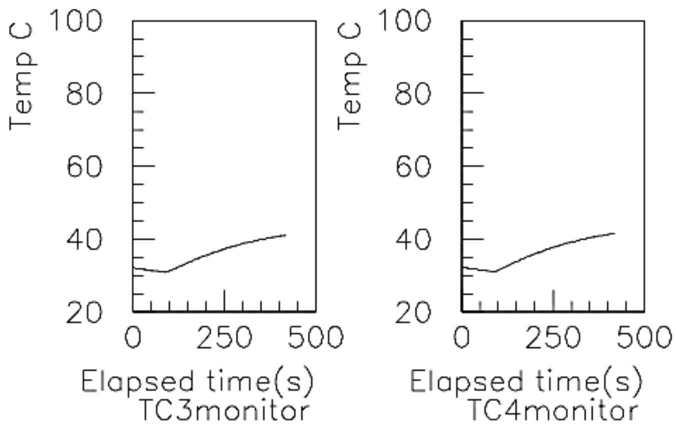


Heat deposition at vicinity＜1W/cc
σ_h <37mm, σ_v <17mm
Target blade: no issues

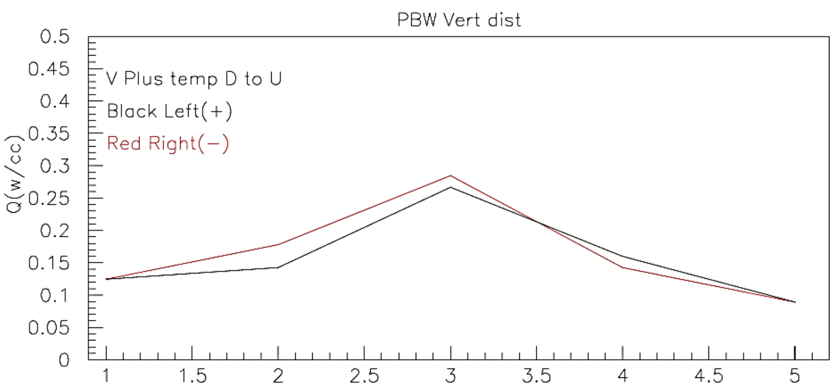
- Limit for 1MW operation without beam flattening system.
  Peak at the target: 14J/cc/pulse

Beam halo measurements

- Heat deposition was measured by the thermo couples (TCs) located at the vicinity of the target and the beam window.
  - Given by the temp rising due to beam irradiation
    $Q(w/cc)=\rho C dT/dt$
    ρ : Density(g/cc), C: Thermal capacity (J/g/K), T:Temp (K),t: Time(s)



Trend of temp at halo monitor at the PBW



Result of heat deposition at halo monitor

For beam of 200 and 300kW: Heat at vicinity ∼0.3W/cc

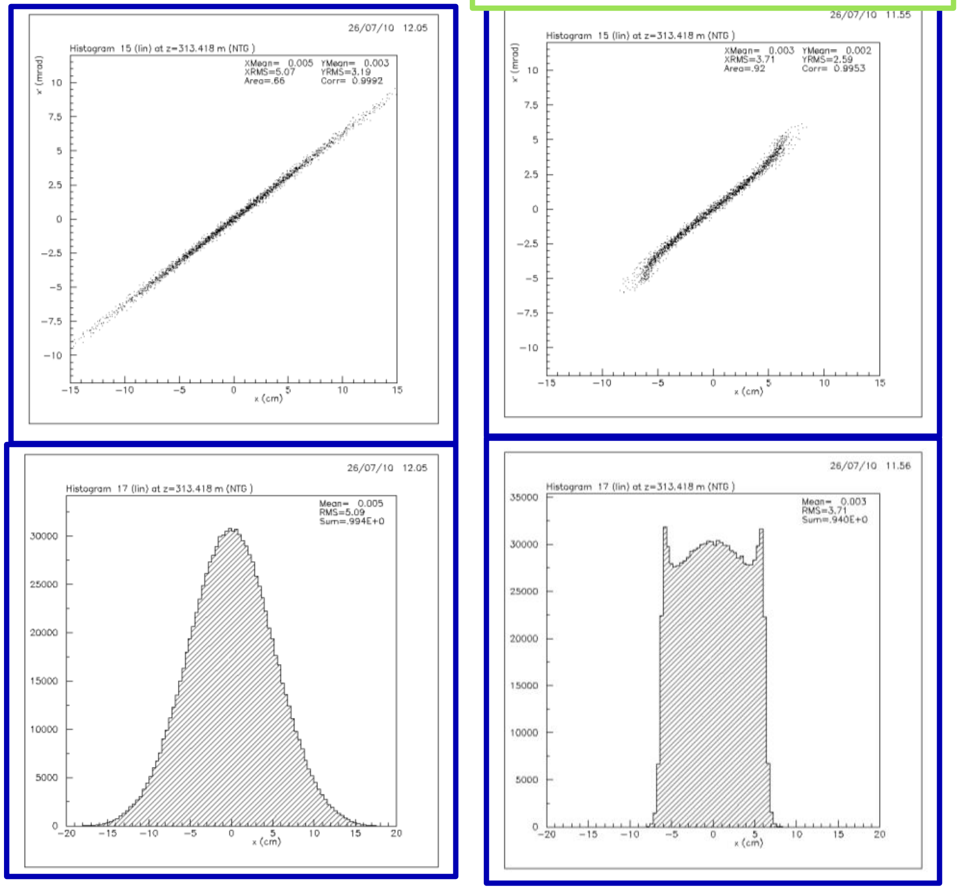
- Peak density and beam halo ⇒ Giving optimum parameter
- Developed expert system for beam control (Beam orbit and profile)
  - Even a rookie can control the beam with confident as an expert.

Conceptual design of flattening

- Beam edge folding by non-linear optics

Linear optics

Non-linear optics
w/ octupole



Phase space distribution (horizontal)

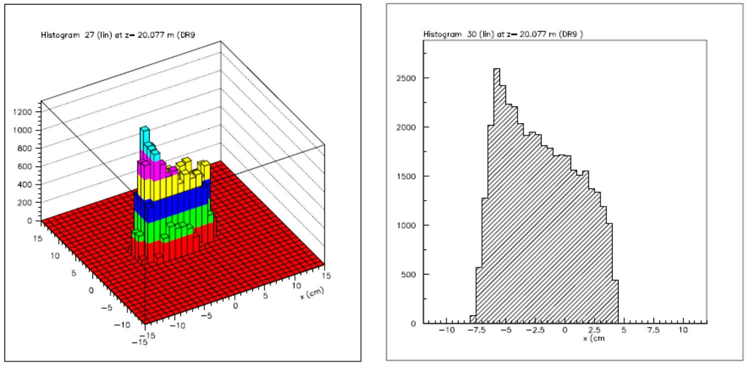
Beam flattening using octupoles

- Present case is provably the first trial to the high intensity facility such as 1MW class.

- Points:
  - For the ideal system, octupole magnets (OCTs) can be placed at an arbitrary position.
  - 2 set of OCTs for flattening in horizontal and vertical directions
  - Increase the β function at OCTs within appropriate aperture → Expand the beam width at each OCTs
  - Maximize beam aspect ration
    - At horizontal OCT making large aspect ratio of H/V
  - Appropriate phase advance to the target

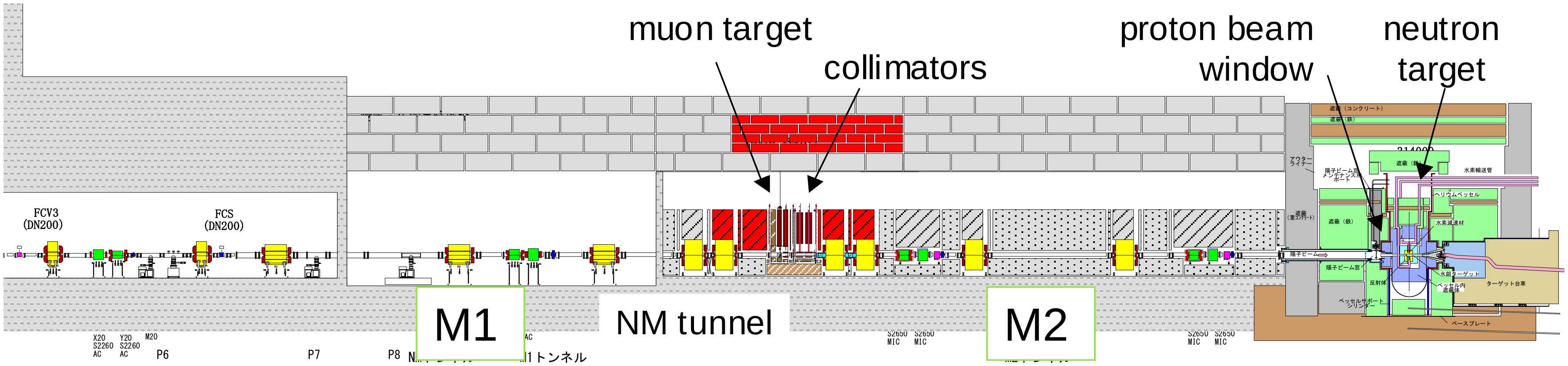
S. Meigo, JAERI-Tech 2000-088

- Peak edge appears contrary
  - Beam offset cause the peak edge



Where we should place OCTs?

- Location of OCTs:
  - Preferable at near the mercury target (M2 tunnel)
    -> Pragmatically very difficult
    - High radiation and difficulty of precision alignment at M2 tunnel
    - Recent beam study shows that beam should be kept smaller in M2 due to the beam loss.



- Before beam commissioning, we hesitated to install octupole magnets. However, due to the following superiority of the J-PARC RCS･3NBT, we understand that the beam flattening by the octupole is possible.
  - Very good stability of beam position
  - Deeply understanding of the beam optics

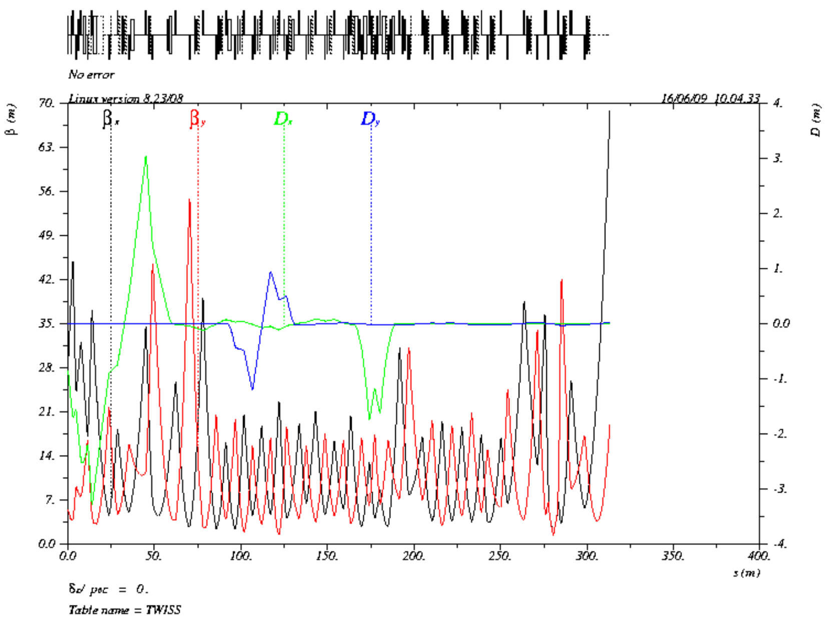
Beam optics using OCT

- Flattening by the realistic magnet field of OCT(K_{oct}), large beta function (β) at OCTs is necessary for the phase advance of ϕ and RMS emittance ε

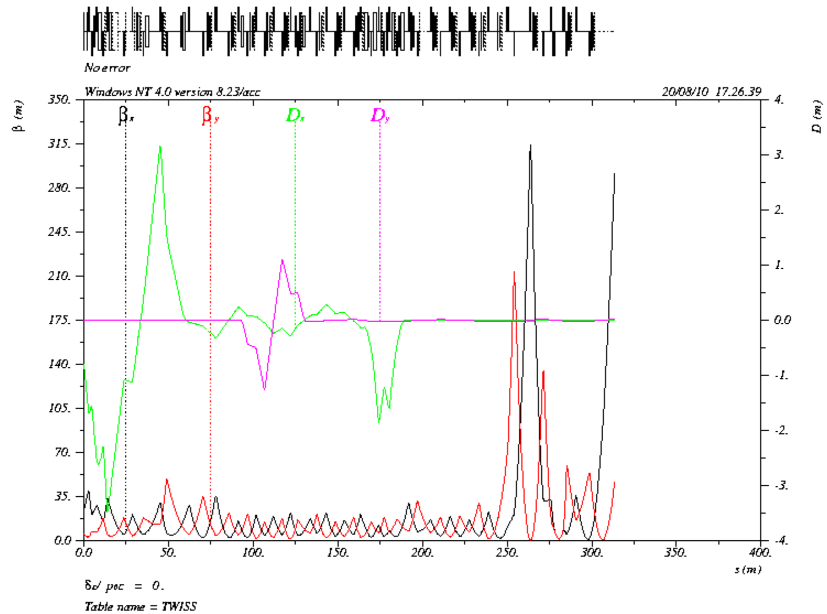
  $$K_{oct}=1/\varepsilon\beta^2\tan\phi$$

  - Large β makes difficult to have large beam acceptance
    - RCS collimator: 324πmm mrad (For β =100m -> 0.36m in diam)
- From the preliminary result of the beam halo measurements, smaller acceptance than 324πmmmrad may be applicable.
- Having large β at OCT1,2 -> Beam acceptance to be100 πmmmrad

Present beam optics



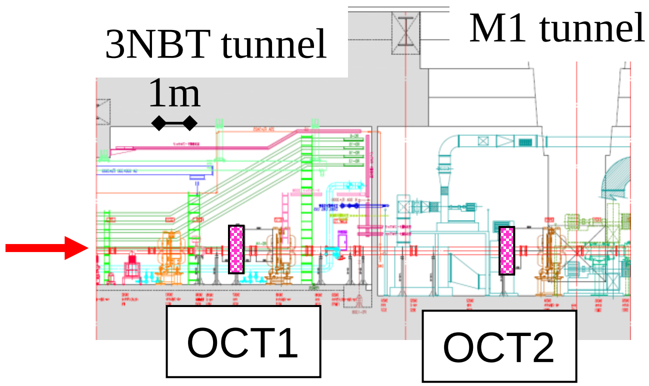
Beam optics for flattening by OCTs



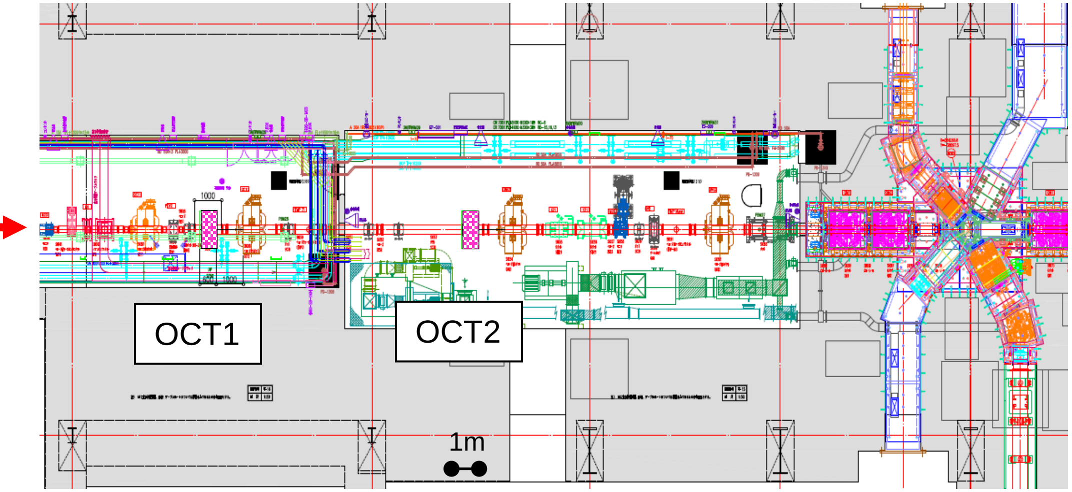
Large beta at OCT1,2

Octupole magnet

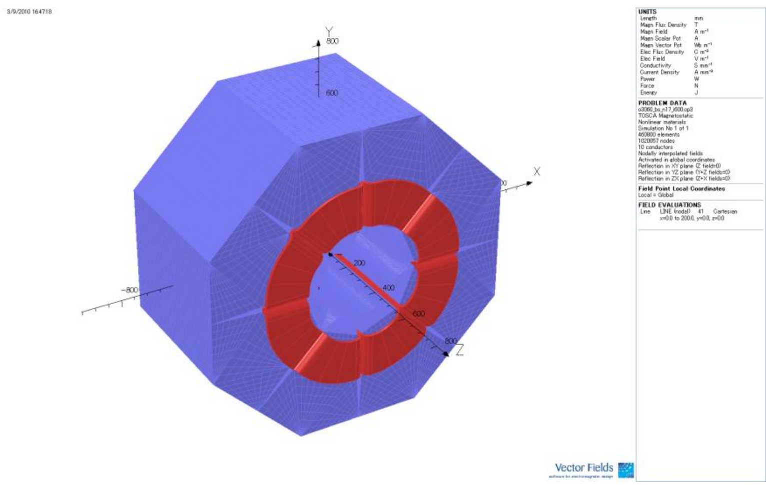
- OCT1 and 2 will be installed at upstream of QC12, QNQ1.
  - at 3NBT tunnel and M1 tunnel
  - Q-O magnets distance is 1m
  - length of magnetic pole: 0.6m
  - Bore diameter 0.3m
- Install new steering magnet:
  - At downstream of QC12



Vertical view

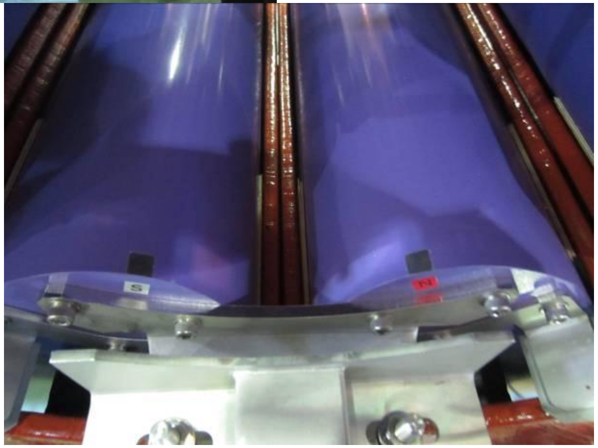


Horizontal view



Octupole magnet (800T/m^3)
O3060(Width 1.2m, Length 0.6m, 6t)

Octupole magnets



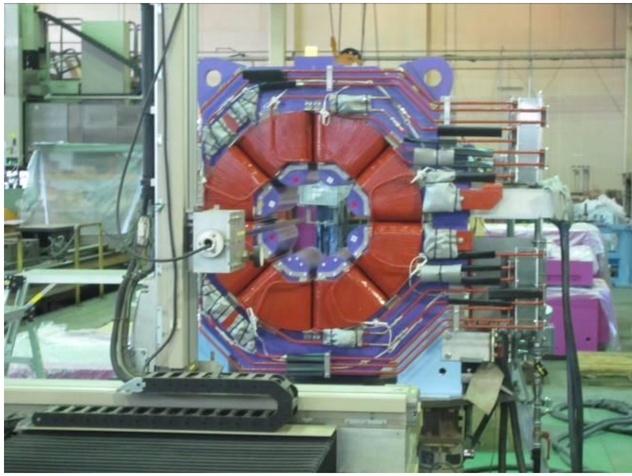
Excellent of shape of the coil

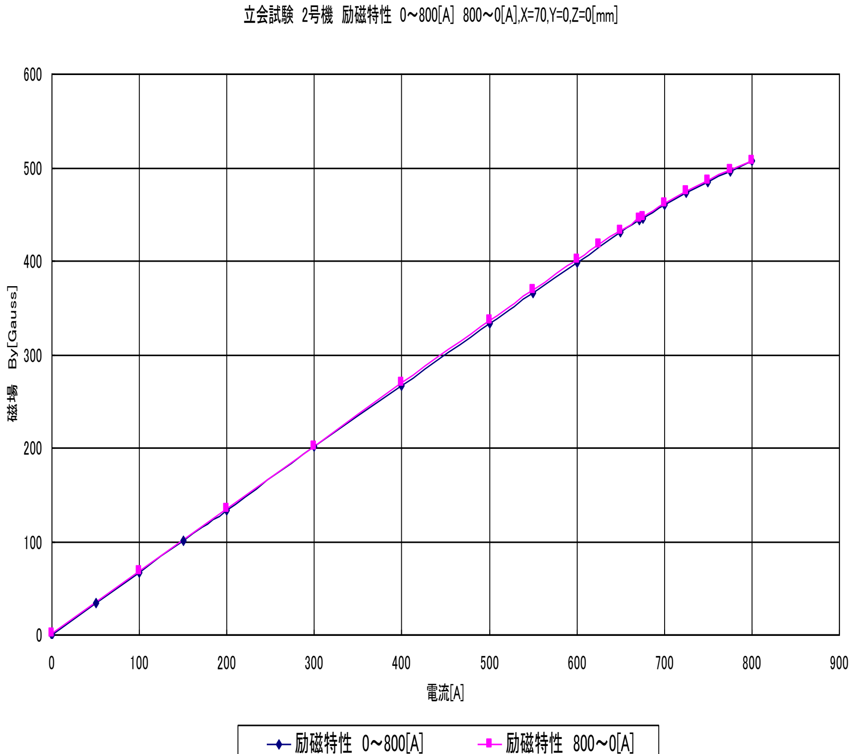
- Installation: Summer in 2013 during long shutdown

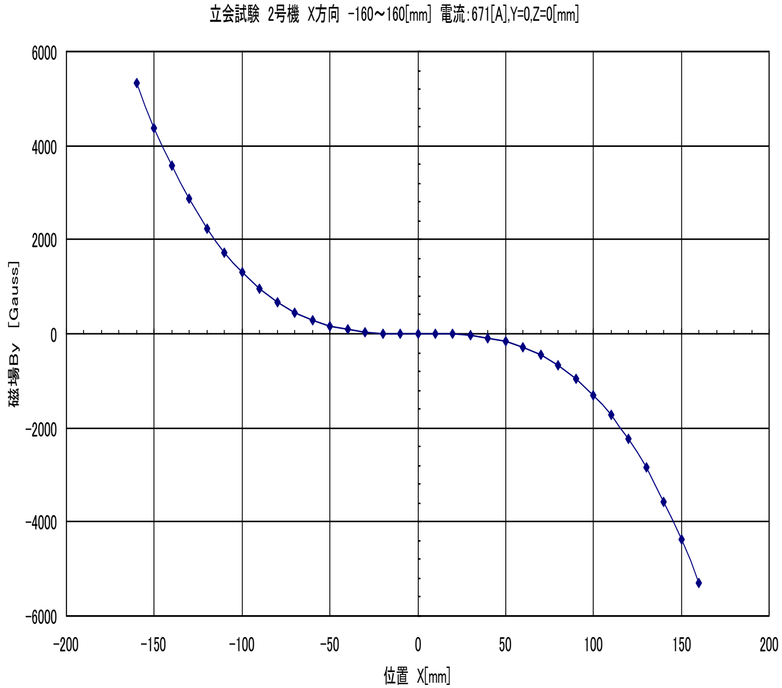
Field measurements

- Mapping by hole probe
  - Field gradient 780 T/m^3 @671A
  - Agreement with calculation

- Confirmation agreement with design calculation



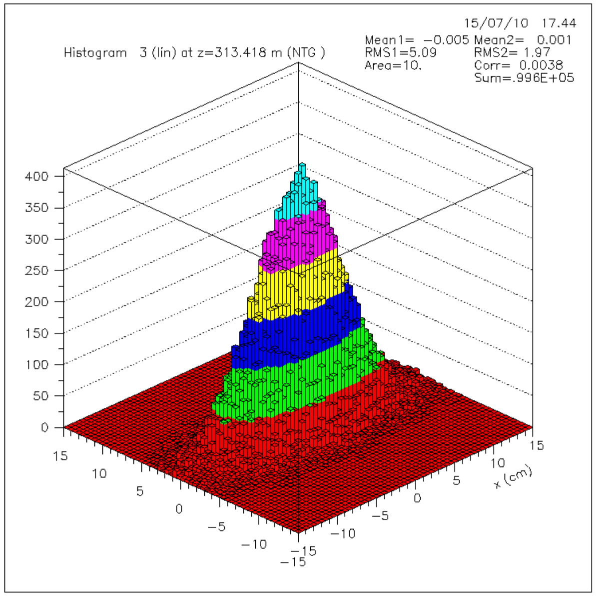




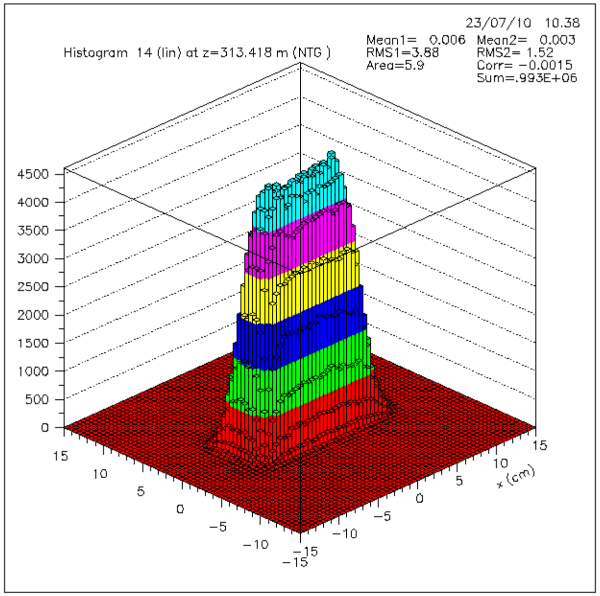
Simulation of the profile

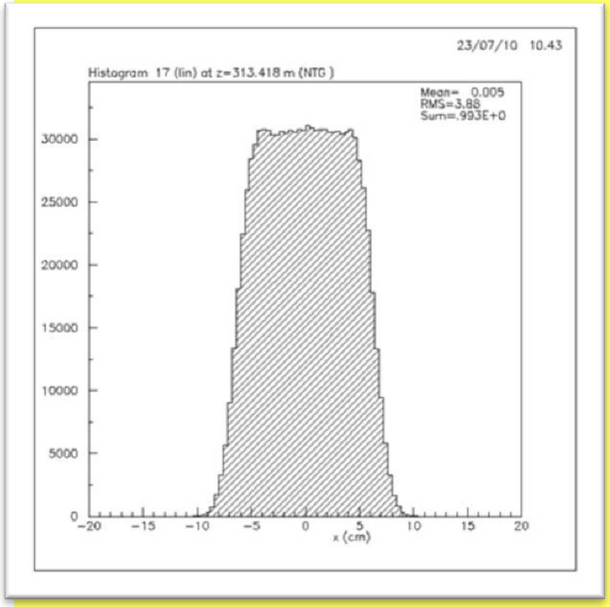
- DECAY-TURTLE (PSI version)
- One of result ignoring the reality
  - Ignore muon production target
  - Small acceptance of beam: 81π mm mrad
- Using this optics let's discuss the alignment error effect

W/O OCT



W/ OCT

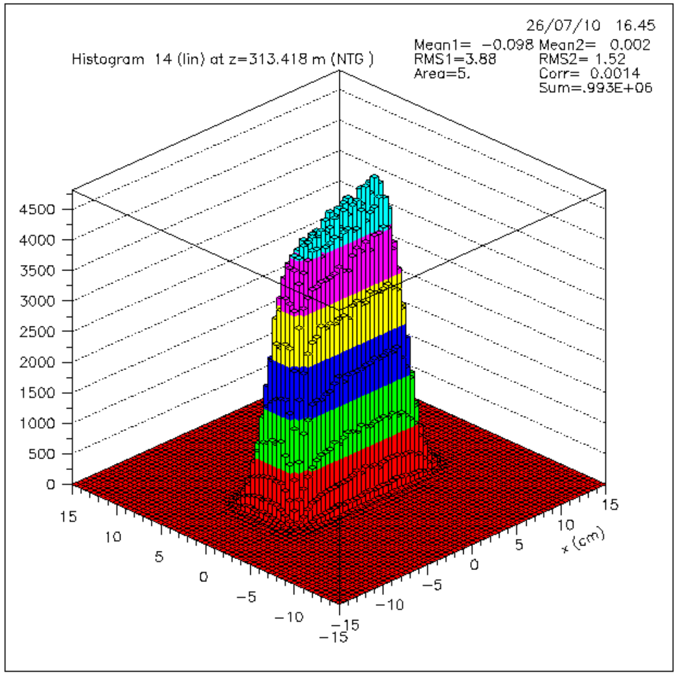


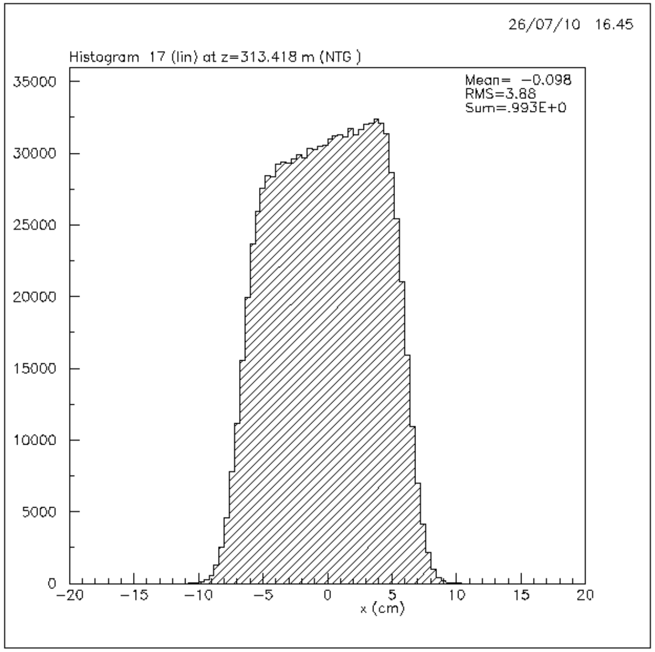


Achieved flat shape!

Alignment accuracy of octupole magnet

- Beam offset at OCT 2mm in horizontal ->Edge peak appears
  - Beam shift at OCT2(for horizontal): 2mm in horizontal





2D Profile at the target

- Increase about 8 % at the edge
- Beam tuning for flattening system

  Beam position monitor (BPM) is placed at each octupole magnets

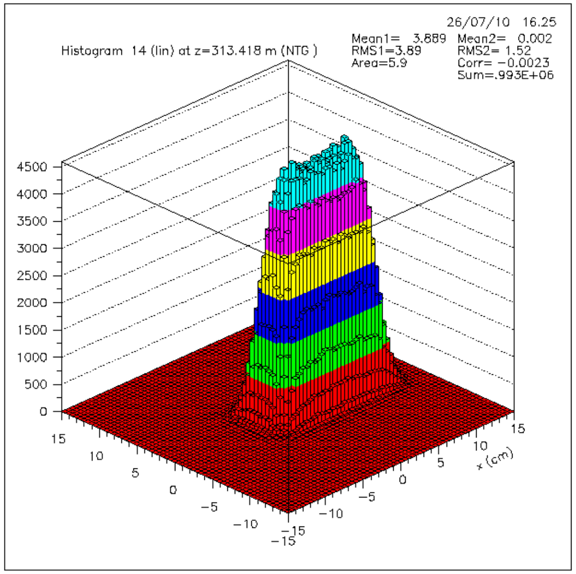
  Additional new steering magnets for horizontal and vertical

  Beam center within 1 mm -> 4%

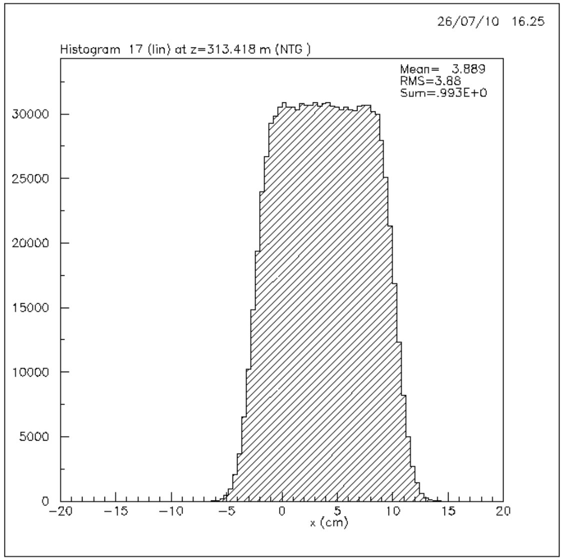
Alignment of downstream magnets

- Realignment of downstream magnets is quite difficult
- Calculation:
  - All magnets at M2 has 2 mm offset in horizontal.
- Result:
  - Betatron oscillation is found in the beam orbit, no influence on the beam shape

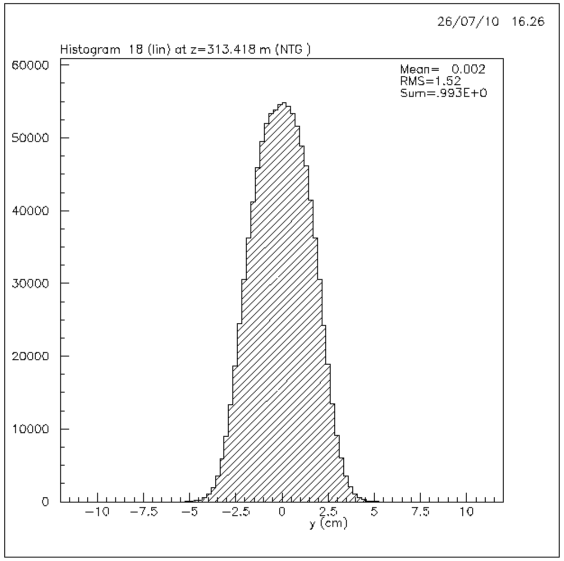
⇒ No need realignment at M2



2D Profile at the target



Horizontal



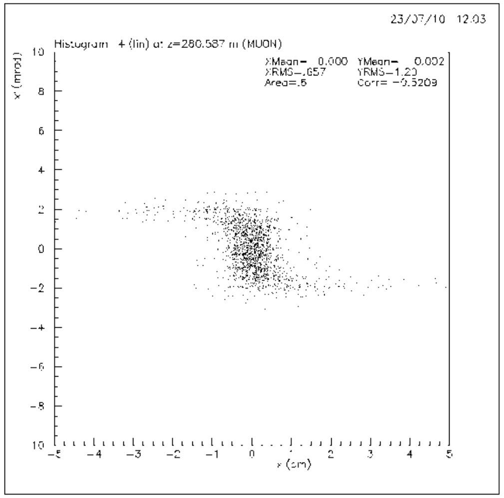
Vertical

Effect due to muon target

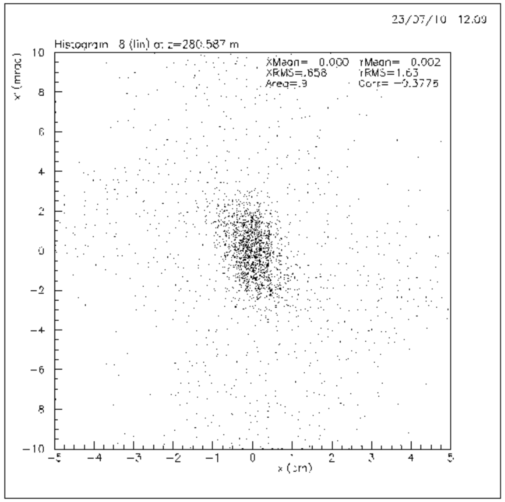
- Phase space distribution distorted as Gaussian

Phase space distribution at muon production target

Without scattering effect



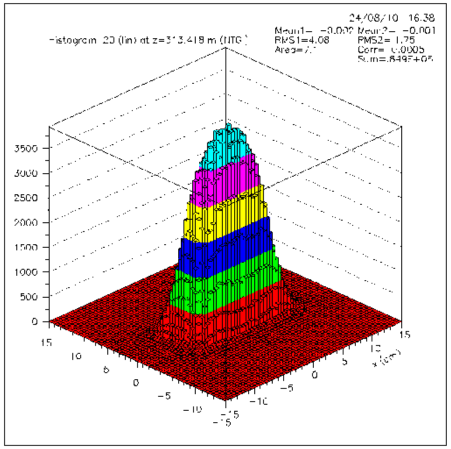
With scattering effect



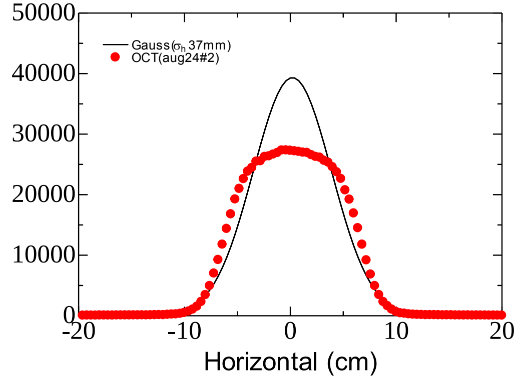
- To minimize this effect
  - Focusing on the muon target as small as possible
  - Increase divergence ⇒ Smaller effect

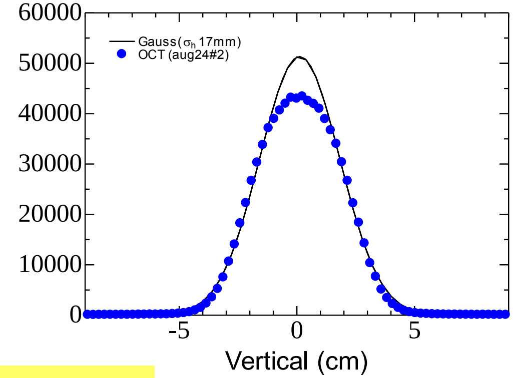
Beam profile with flattening system

Profile at the mercury target

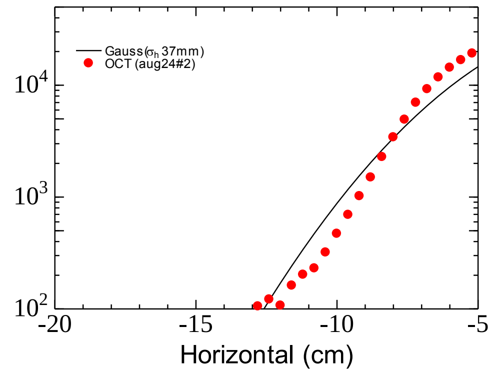


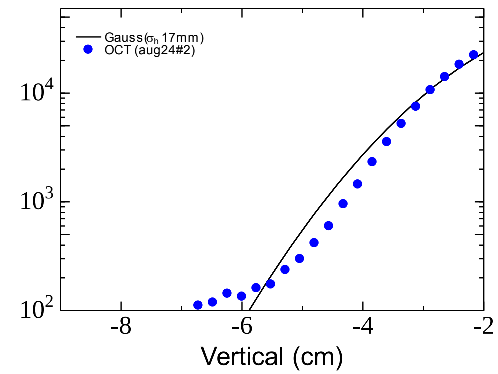
Projection profiles on horizontal and vertical axis compared with Gaussian





Closing up at vicinity





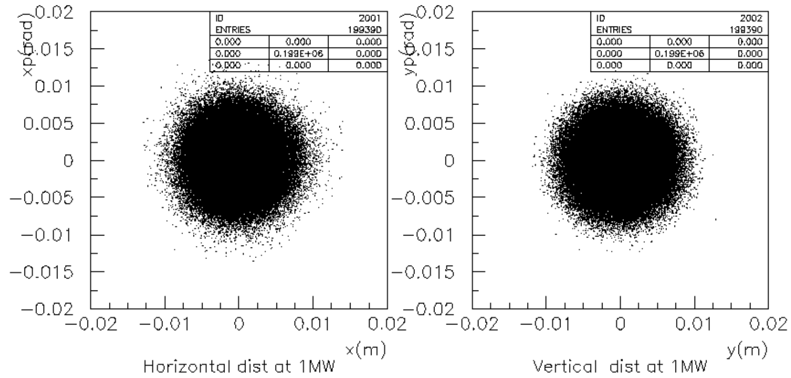
Muon target: With muon target
RMS Beam emittance: 5π
Peak: 1.3Tp/cm²
9.4J/cc/pulse
Beam Loss: 80.8 kW
(mainly due to interaction at the muon target)
Acceptance: Horizontal 114π
Vertical 111π

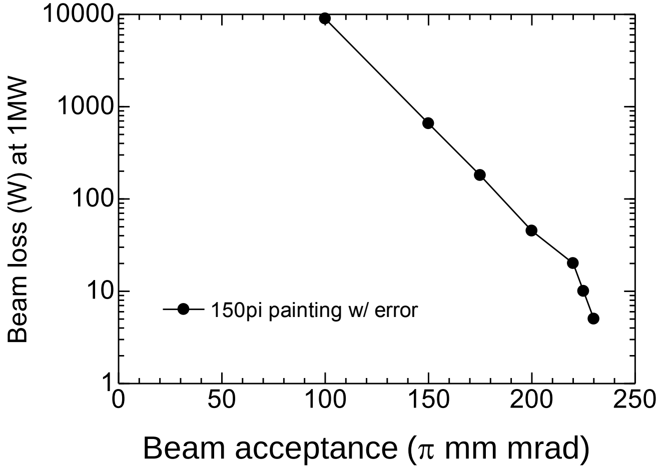
Reduction of peak 42 % of Gaussian
By P4 law: 0.68^4=0.2 (very small)

It is better to have larger beam acceptance at OCTs.

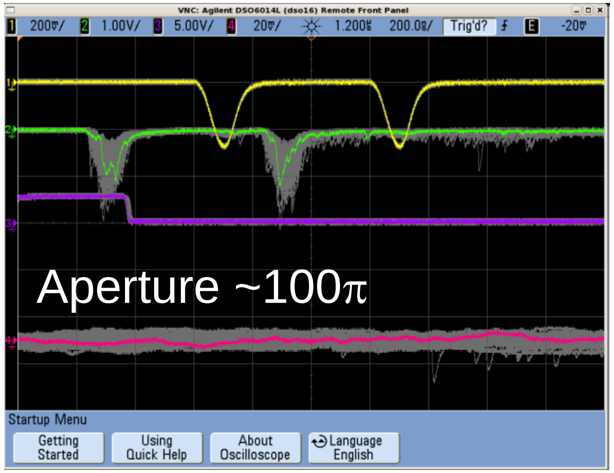
Beam study for octupoles optics

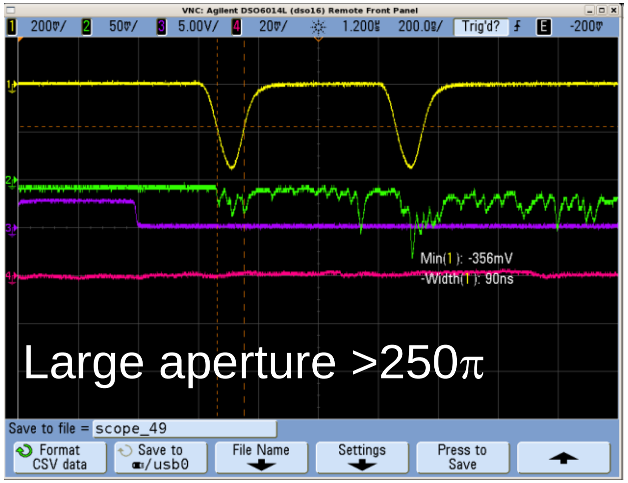
Phase space distribution RCS extraction beam (0.4GeV injection)





Required aperture ~250 π





Previous OCT opt w/o MTG

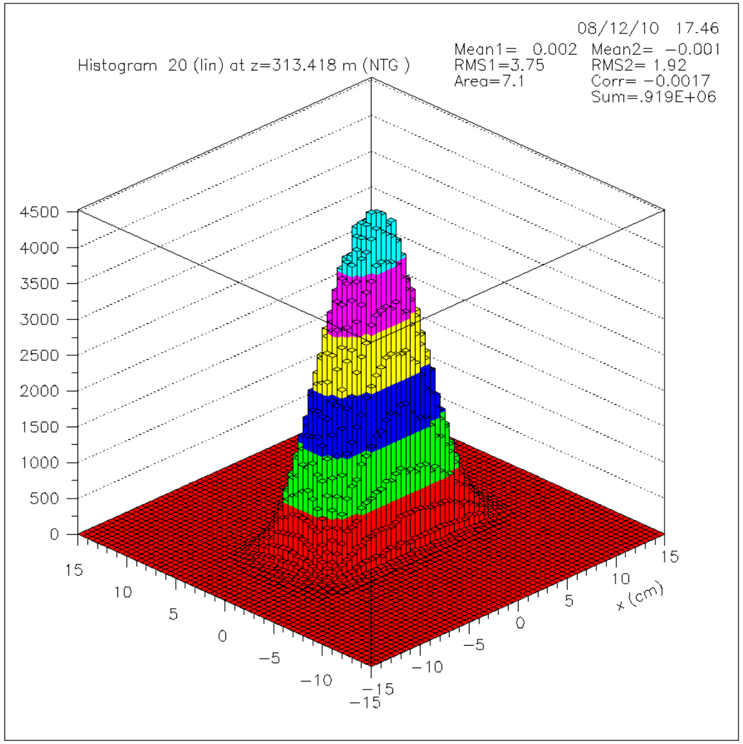
Revised OCT opt w/o MTG

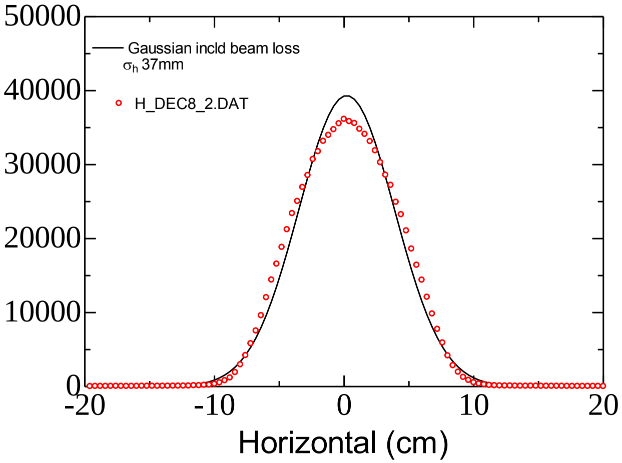
Found slightly beam loss

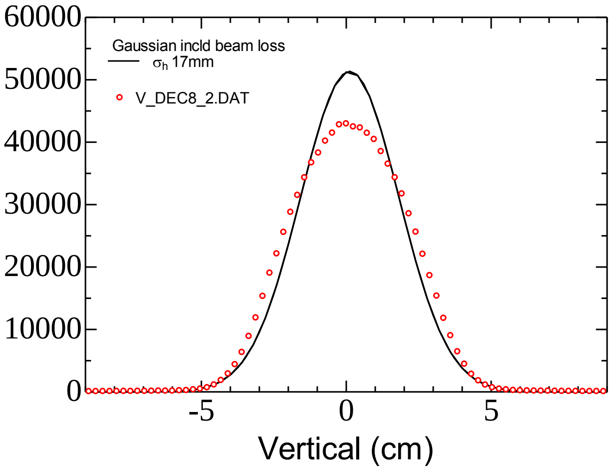
No significant beam loss for 0.18GeV inj

Beam profiles using flattening system

Having larger aperture than 250 π mm mrad

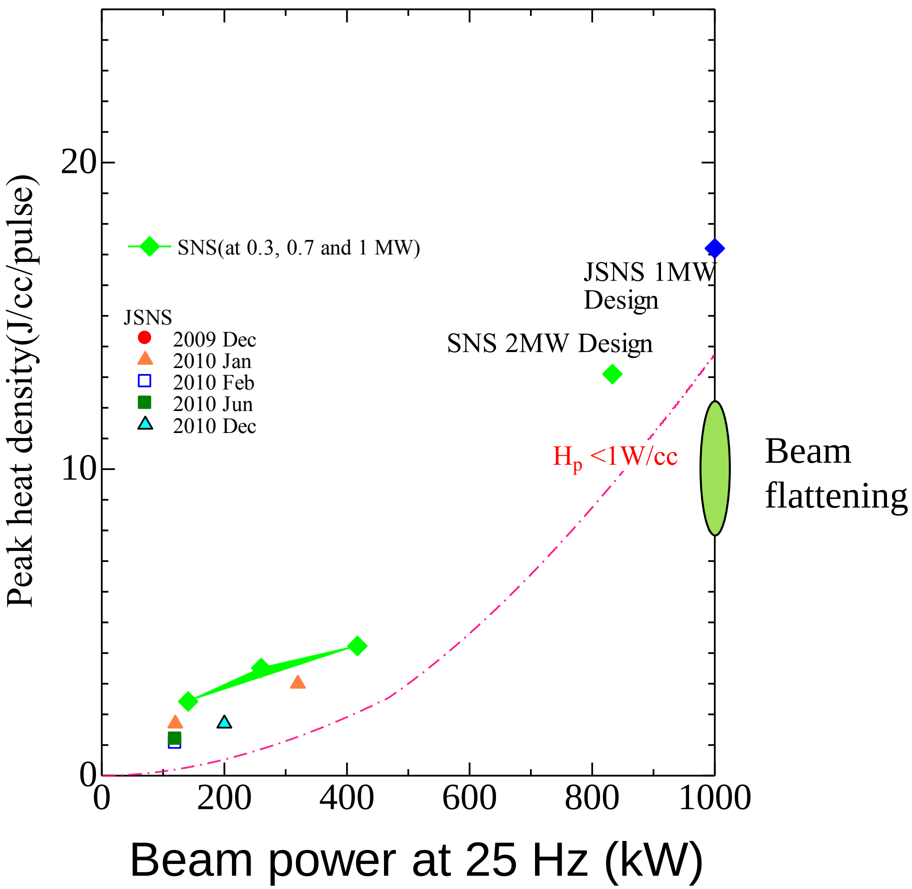






Peak density ~11J/cc/pulse

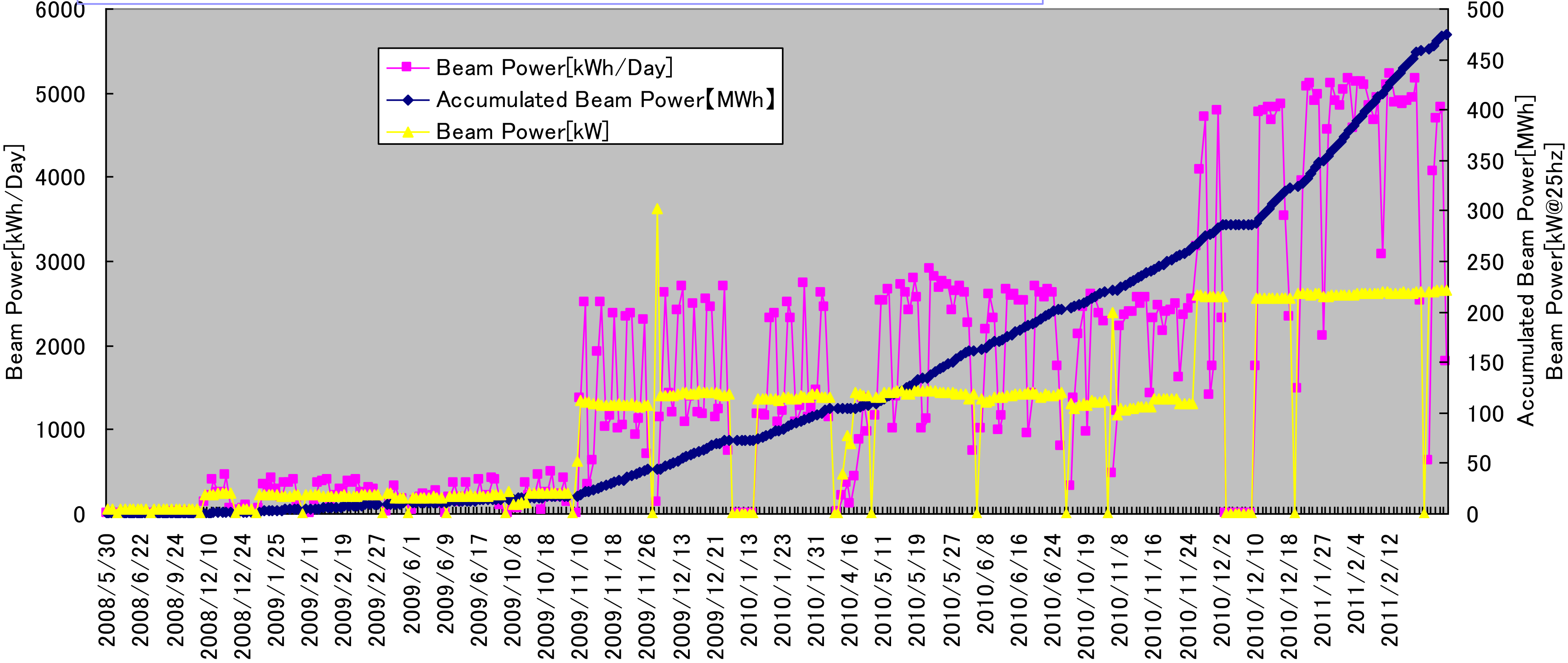
Peak heat density by flattening



- Even in the beam optics having large beam acceptance such as 250 π, reduction of the peak enables by the ~30% of Gaussian case.
- By the beam study, we can carry out the beam flattening with the appropriate the beam acceptance which has beam loss < 1 W/m at the OCT.

Beam power trend

High power with very high availability (~90%)



- 0.1-0.2 MW operation begun after earthquake.
- After installation He bubbler in the target, 0.3 MW operation will begin

Pulse neutron yield

	(/sr/pulse)
SNS(1MW)	$4.2x10^{12}$
J-PARC/JSNS(0.3MW)	$5.4x10^{12}$

Summary

- Flattering system
  - 30~40% of peak reduction
  - Due to scattering at the muon production target, makes difficult for flattening.
  - Focusing at the muon target is key at J-PARC/MLF
  - Beam acceptance is key issue of the system.
  - For 0.18GeV LINAC case, the case of 250 π mm mrad showed acceptable.
- Octupole magnet
  - Fabrication has been done
  - Good agreement with the magnetic field of design
  - Installation in summer 2013

Thank you for attention

- *Note: Bulldogs have flat face*

Y. Yuri et al., Phys rev special topics Accelerators and Beams 10, 104001 (2007)

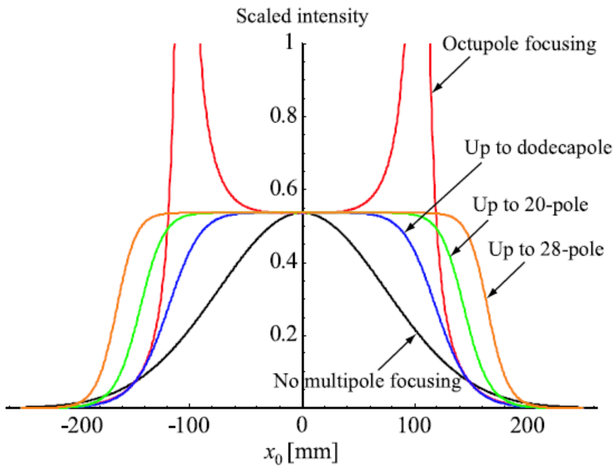


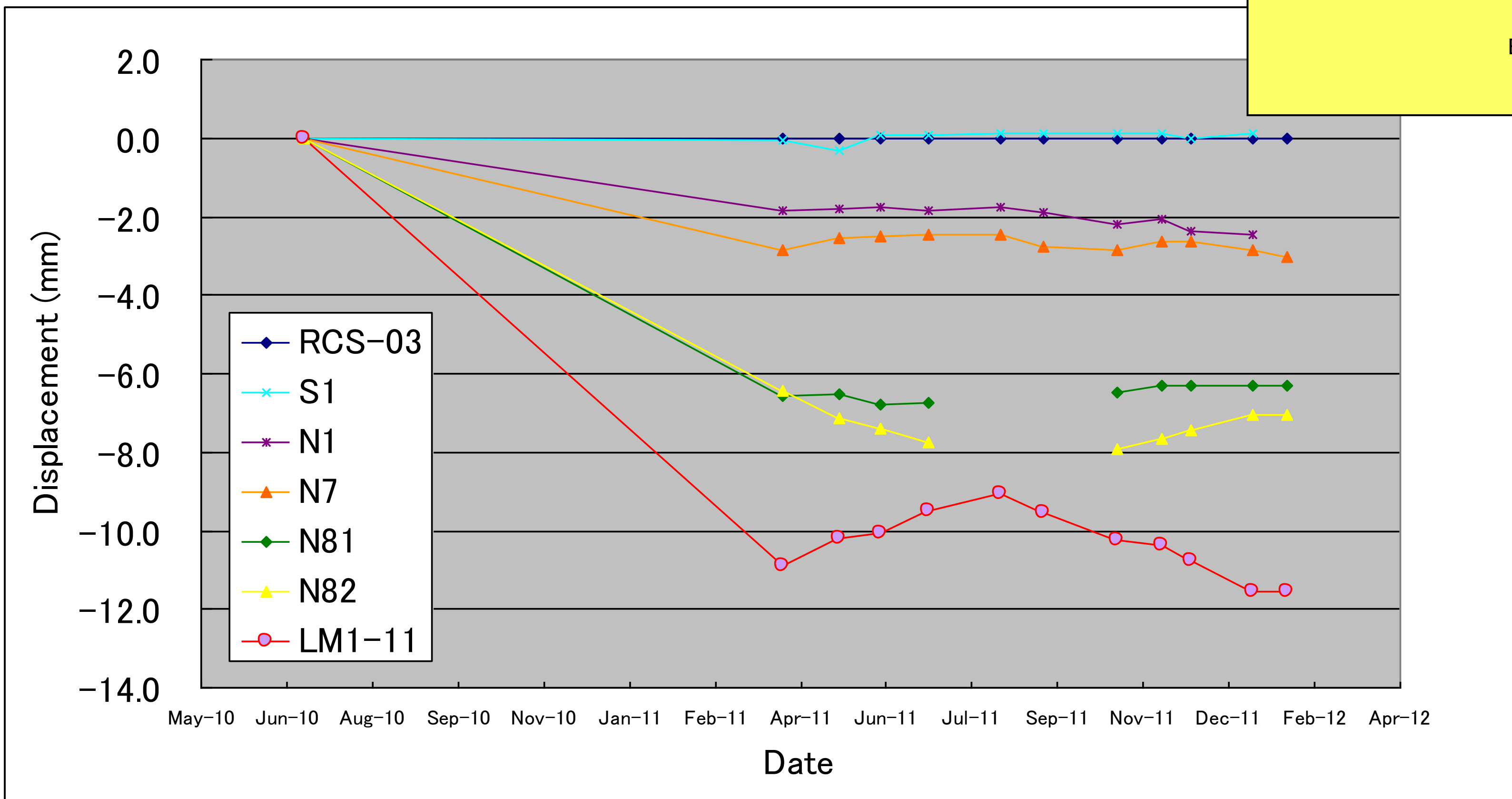
FIG. 7. (Color) Final distribution at the target calculated from Eq. (6) for five different combinations of multipole focusing. Adding higher odd-order multipole components predicted using Eq. (10), we can obtain a uniform distribution with a steeper edge. Note that the full width of the uniform region does not coincide with the theoretical prediction since the abscissa is not the coordinate of the target but that of the multipole magnet position to avoid causing analytic complication in Eq. (6).

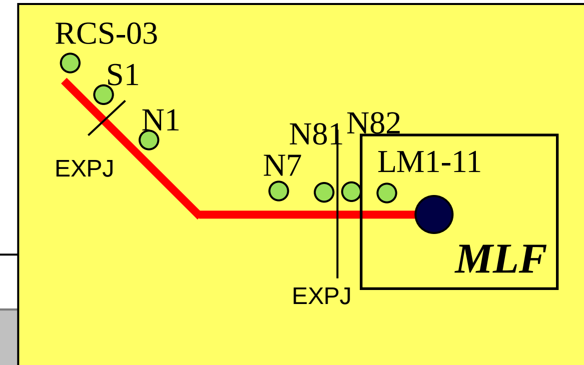
$K_{2n}=(n-2)!(-1)^{n/2}/(n/2-1)!(2\varepsilon\beta)^{n/2-1}\beta\tan\phi$ $(n=4,6,8,10\ldots)$

$\Rightarrow$ $K_{oct}=1/\varepsilon\beta^2\tan\phi$,
$K_{dodeca}=-3/\varepsilon^2\beta^3\tan\phi$

Settlement

- Periodical survey for floor level

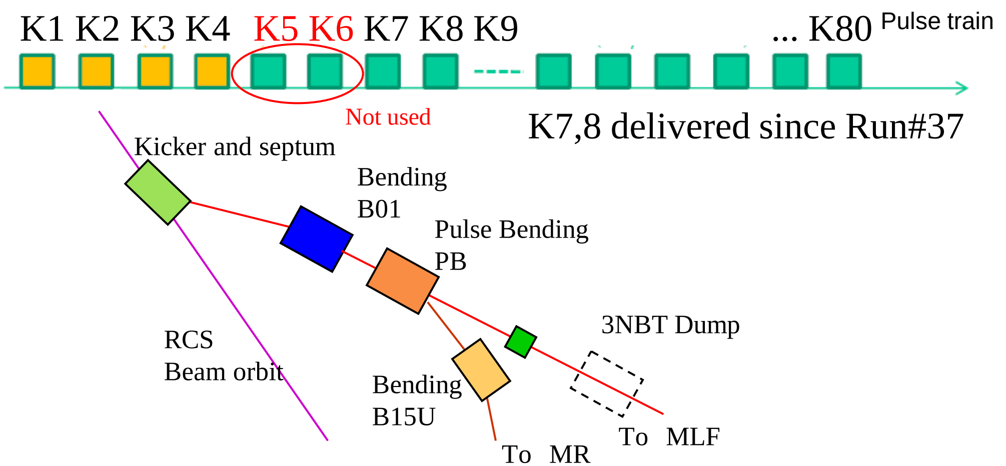




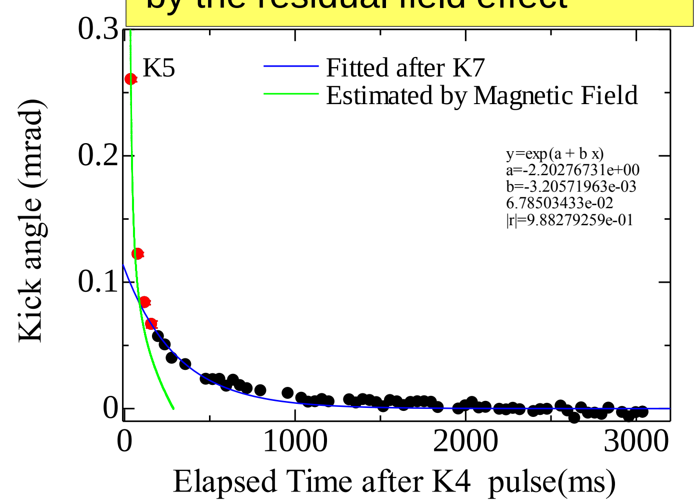
- Swing of 2mm observed at downstream
- Stable ??? → Scheduled periodical beam adjustment is necessary.

Effect of residual field of pulse bending magnet

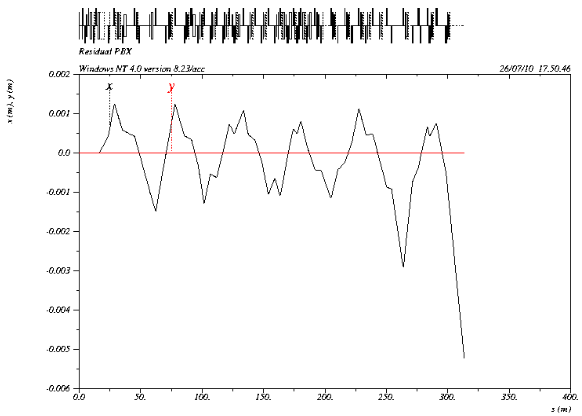
- In every 80 pulses(3.2s)
  - 4 pulses(K1-4): injected MR 74 pulses(K7-80): transport to MLF
- Residual magnetic field distorts the beam orbit to MLF
- Measurement effect of residual field



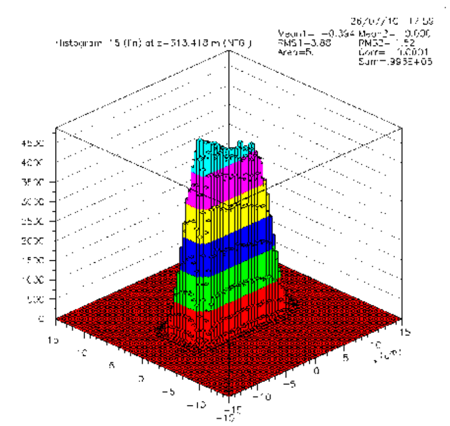
Time dependence of kick angle by the residual field effect



Spatial distribution for K9 having kick angle of 0.06 mrad by residual field (calculation)



Beam profile for K9 pulse (0.06mrad)



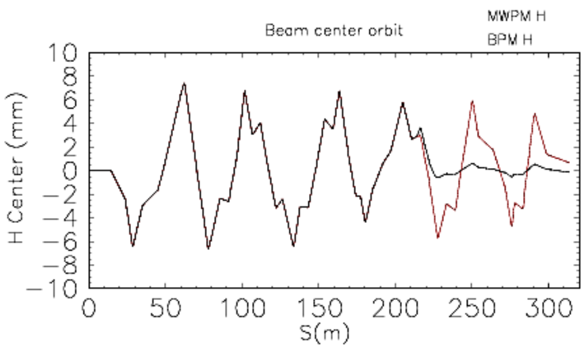
2~3 pulses in every pulses increases ~8 % at the edge

By the pulse steering magnets with slow response, possible to compensate residual field
> 76 pulses can be utilized.

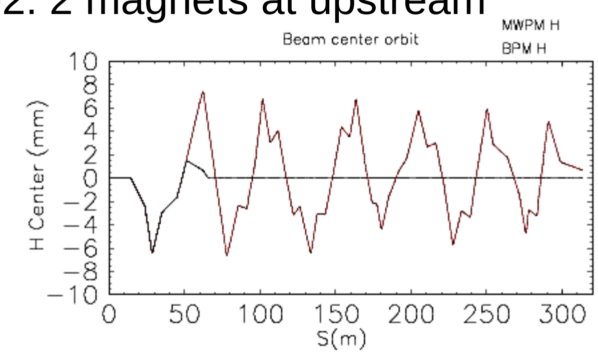
Residual field compensator

Orbit by compensation

Case1: 2 magnets at downstream



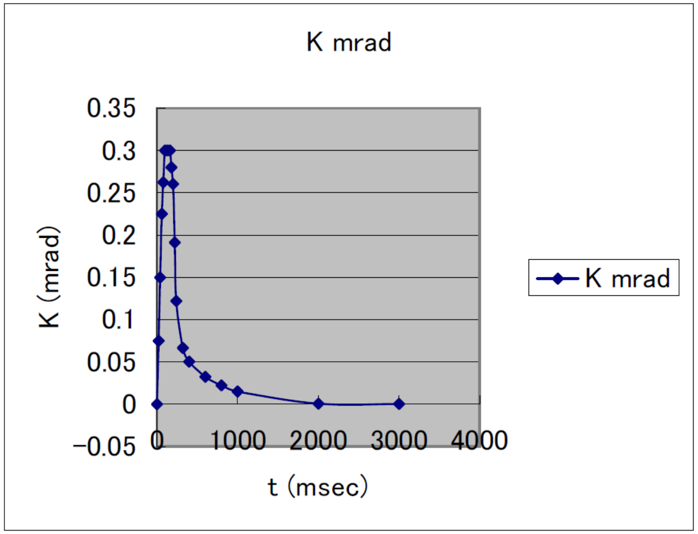
Case2: 2 magnets at upstream



Required kick angel

Case1: 0.3 mrad, Case2: 0.6 mrad

Response of field for compensation for case1



Pulse steering magnet