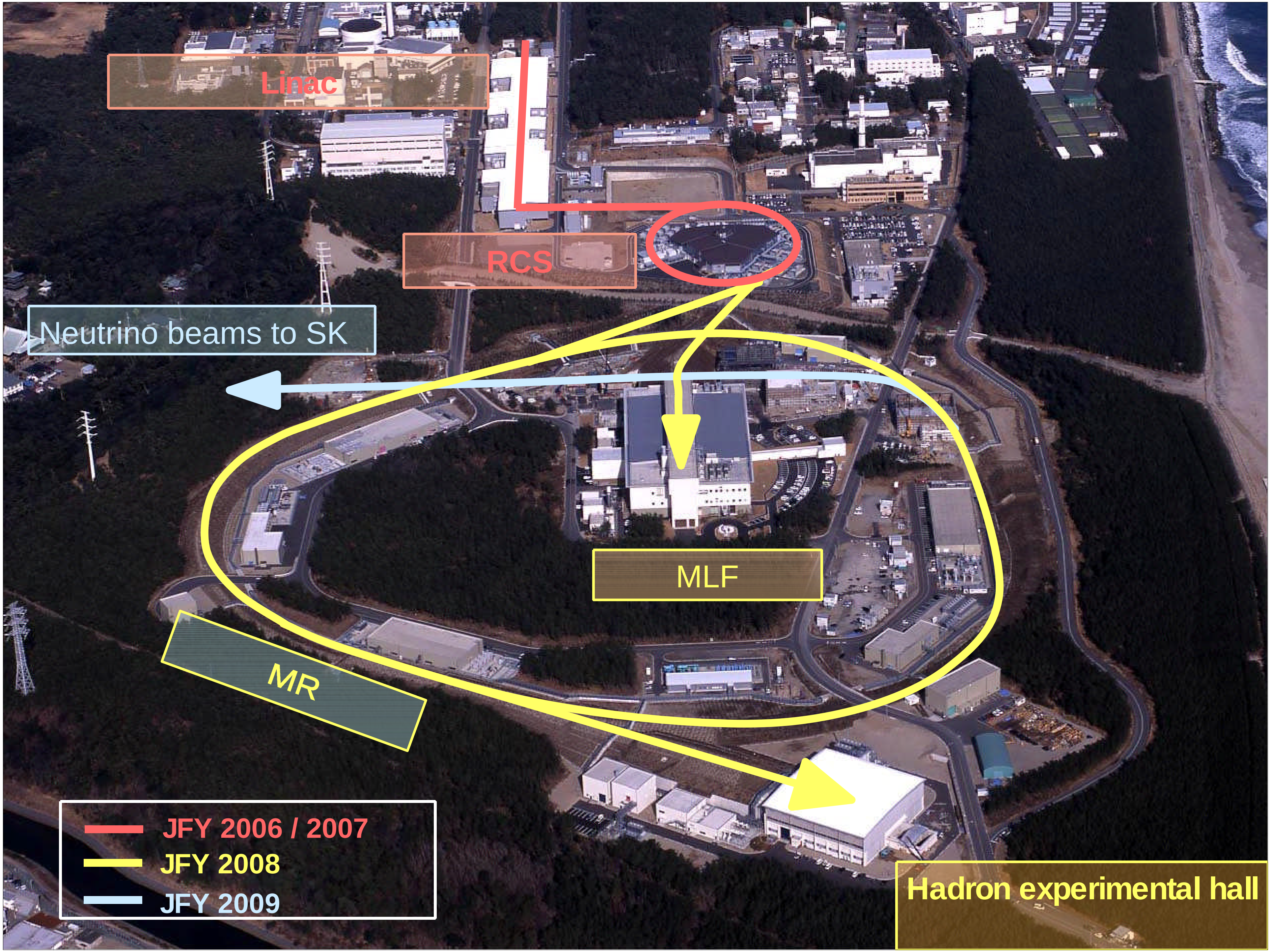
KAON09, 11 June, 2009

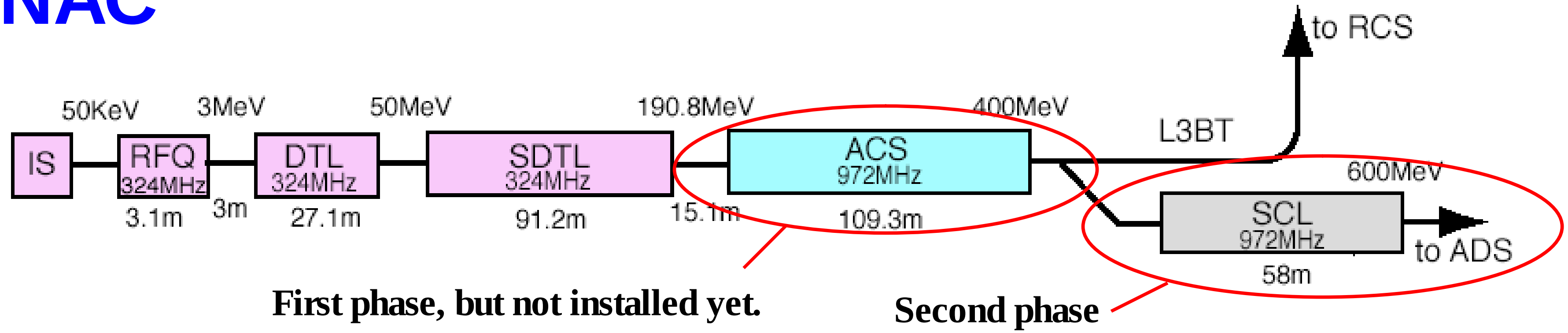
J-PARC accelerator complex and facilities

Introduction of the J-PARC Accelerator Complex

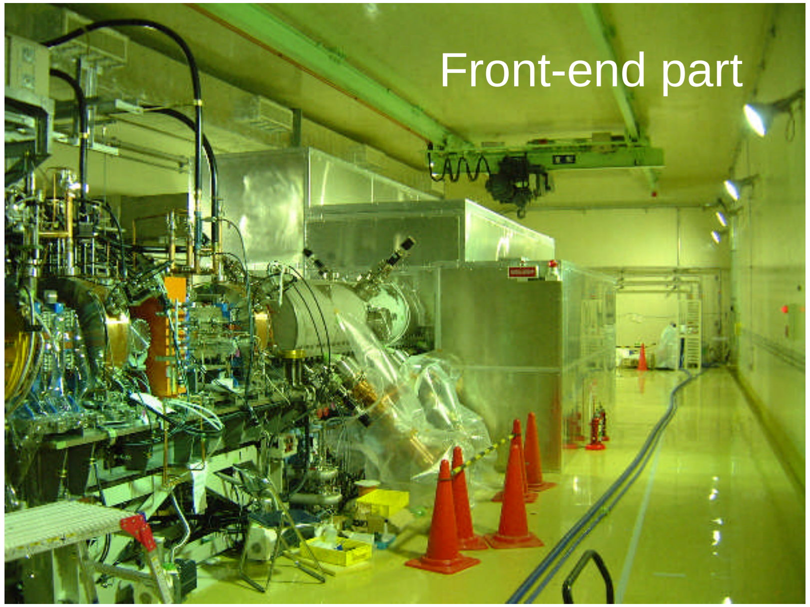
Masashi Shirakata (Accelerator Laboratory, KEK)
J-PARC accelerator group

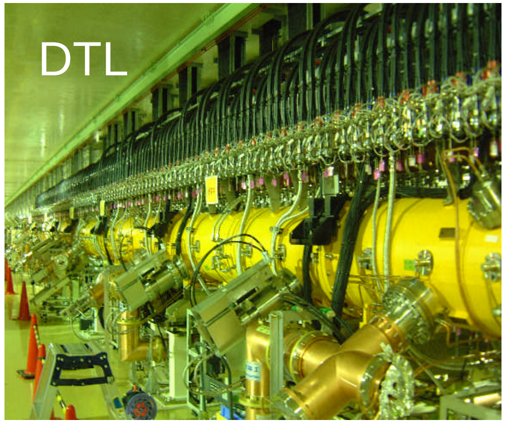

Linac
RCS
Neutrino beams to SK
MLF
MR
Hadron experimental hall
JFY 2006 / 2007
JFY 2008
JFY 2009

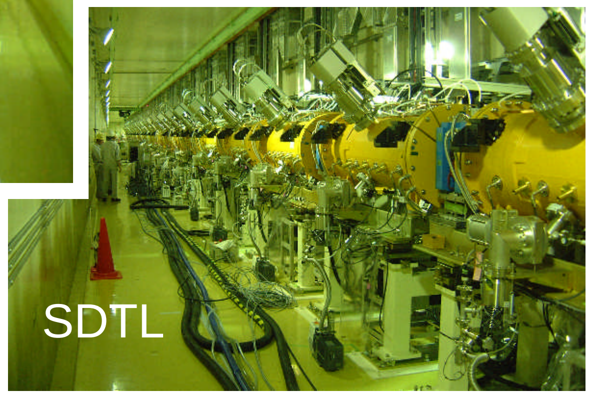
LINAC



LINAC beam energy: 181 MeV at the present



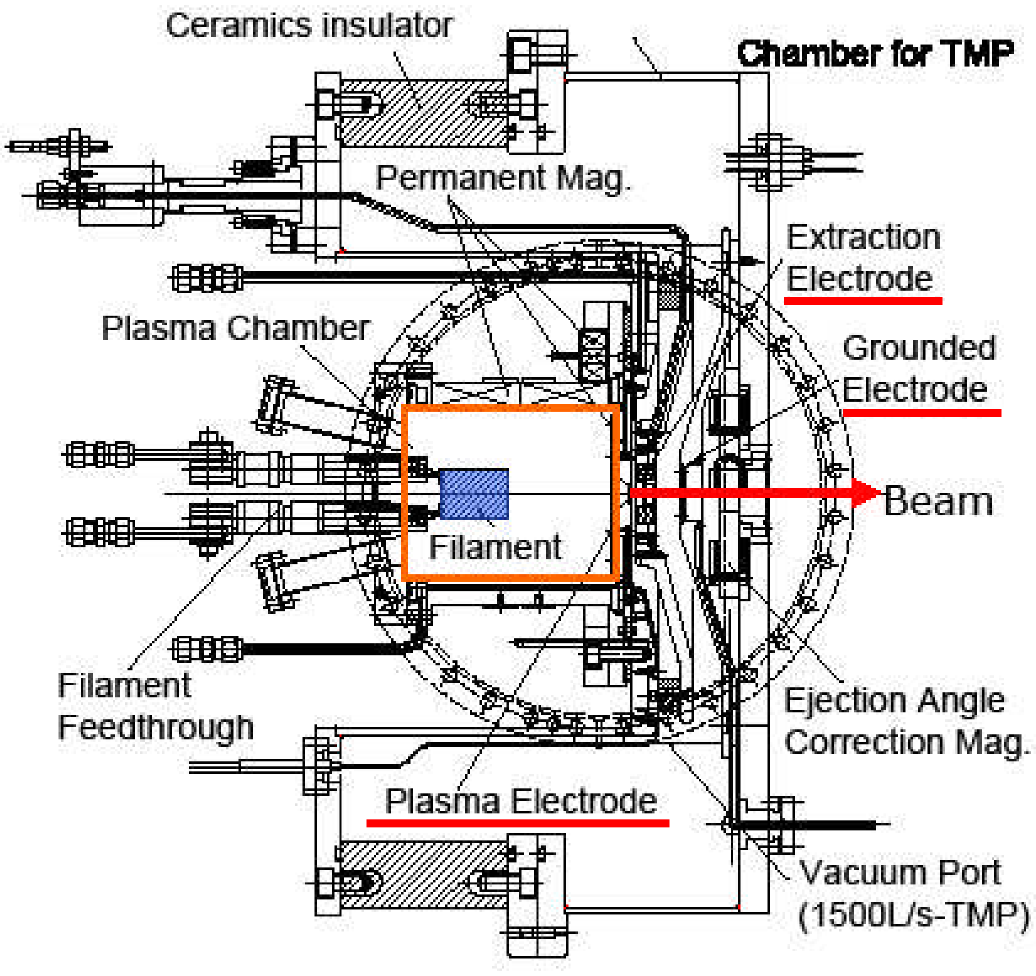




Ion source, LEBT, RFQ,
MEBT(2 choppers, 2 bunchers)

- **Particle**
  H^- (Negative hydrogen)
- **Energy**
  - **on day-one** 181 MeV
  - **with ACS** 400 MeV
- **Peak current**
  - **at 181 MeV** 30 mA
  - **at 400 MeV** 50 mA
- **Repetition** 25 Hz
- **Pulse width** 0.5 msec

Ion Source



Cross sectional view of J-PARC Ion source

J-PARC Ion Source

*Plasma production :

Arc discharge (LaB_6 filament)

*Number of filament : 1

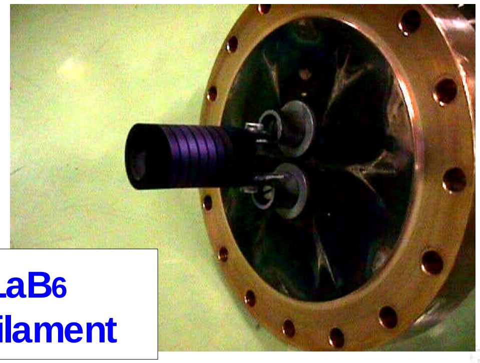
*Cesium : free

*Beam aperture : 9mm diam.

Ion : H- (Negative hydrogen)

Voltage among electrodes

Ground
| - 42 kV
Extraction
| - 8 kV
Plasma



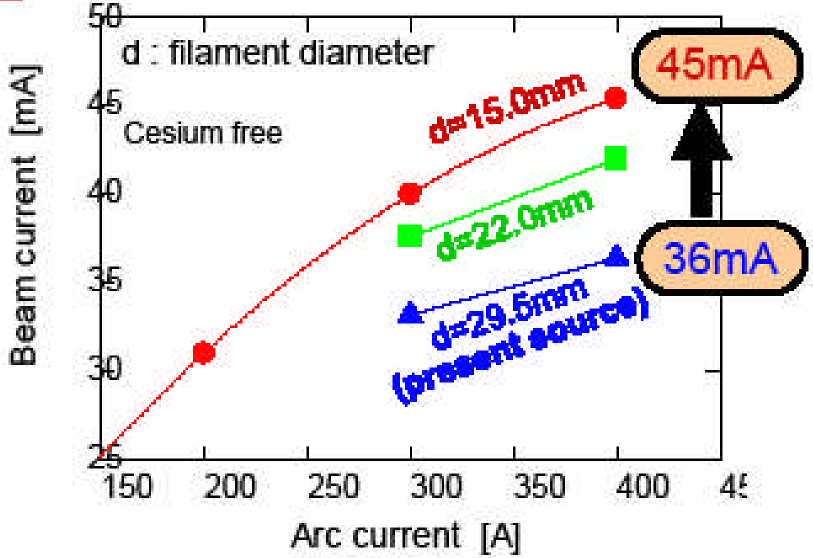
LaB6 filament

Original slide from K. Hasegawa, ATAC2009

Specification of ion source

Parameters	Present source	Requirement	
		#1 stage source	1MW source
H- current [mA]	∼35	∼36	∼60
Duty factor [%]	0.875	1.25	1.25
Pulse length [μs]	350 (arc)	500	500
Repetition rate [Hz]	25 (arc)	25	25
Continuous operation time [h]	157*	500	500

*After 157 h operation, beam current decreased from 35mA to 5mA by request of beam commissioning task.



Beam current vs. arc current for various filament diameter

Example of R&D result for beam current improvement

Issues of ion source

for #1 stage source:

-> Demonstration of 500 h continuous operation at 36 mA has not been yet.

for 1MW source

-> Enhancement of the peak H- current is needed.

***Strategy**

(a) Improvement of the present source (filament shape, electrode material, and so on)

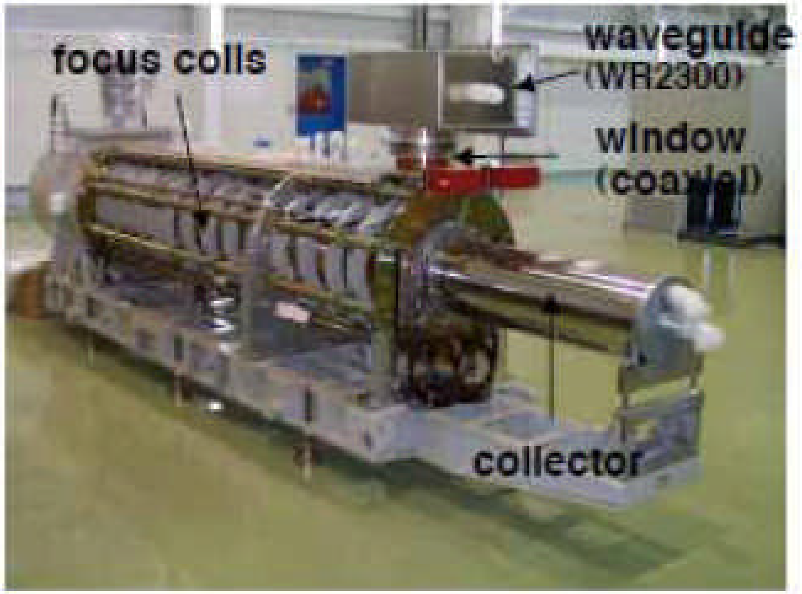
(b) Development of new type source (cesium seeded type, RF discharge, and so on)

Marginal man power for the R&D.

Original slide from K. Hasegawa, ATAC2009

RF System: Klystron

- 20-unit of klystrons have been operated for 8,470 hours. (from 2006 Oct. to 2009 Jan.)
- There are no serious troubles, such as a discharge in e-gun, vacuum degradation, arcing in output window.

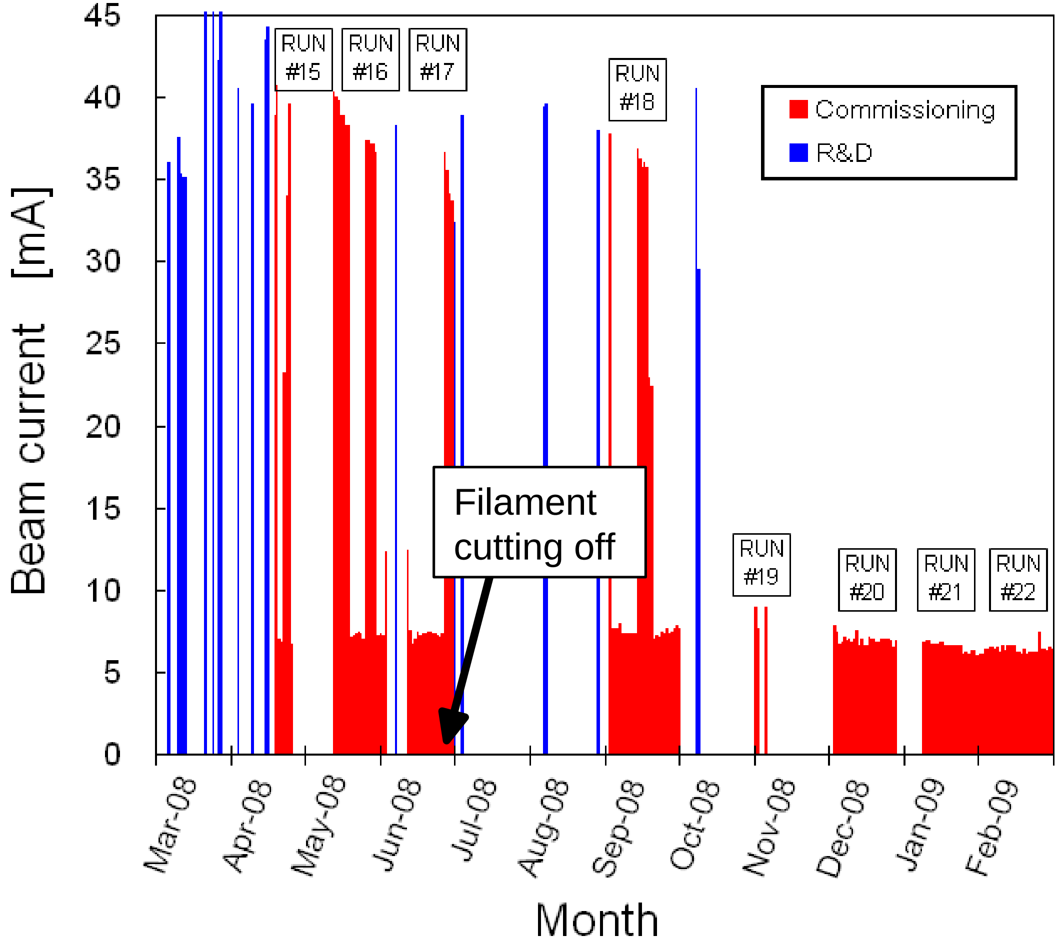


324MHz Klystron (E3740A)

Peak Power	2.5 (max. 3.0) MW
Pulse Width	650 μs
Repetition	50 Hz (25 Hz)
μ-Perveance	1.37 A/V $^{3/2}$
Gain	50 dB
Efficiency	55 %
Beam Voltage	105 (max. 110) kV
Beam Current	45 (max. 50) A
Mounting Position	Horizontal
No of Klystron	23 = 20 + 3 (spare)

Original slide from K. Hasegawa, ATAC2009

Ion source status in the last one year



Operation history of ion source
(May-2008 ~ Feb-2009)

Remarks

(during beam commissioning)

24 hours continuous beam operation has started from RUN#15.

Beam operation without ion source operator has started from RUN#15 (only in night time).

On 28th June, 2008 (during RUN#17), filament had a trouble of cutting off. The filament was used in 9 commissioning runs (2030 h).

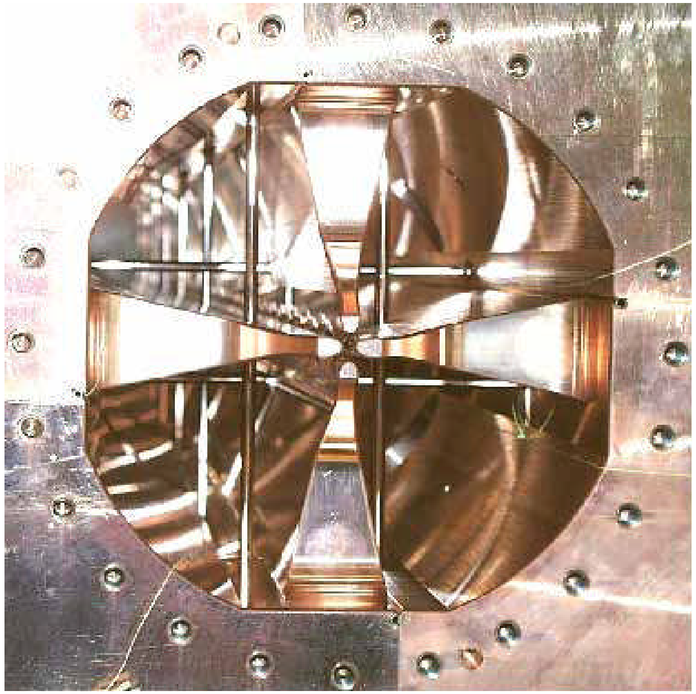
The typical beam current is set to 5 mA for the MLF expriments and MR commissioning.

Discharge problem in the RFQ

- The first severe discharge problem in the RFQ occured in September 2008.
- Before this problem, the availability of linac was more than 90 %.
- After the problem, we are suffering from sporadic unscheduled shutdown due to discharge problem in RFQ.
- A run cycle scheduled in Oct. 2008 was cancelled for RFQ conditioning.
- The RFQ downtime (both scheduled and unscheduled) dominated the machine time in runs in Dec. 2008 and Jan. 2009.

↓

"RFQ backup group" has been organized, who prepares the "backup RFQ" though it takes about one year.



Inside view of RFQ

RFQ (Radio Frequency Quadrupole) uses electric quadrupole field for beam focusing. Discharge may occur at the surface with high voltage potential.

Present Status of LINAC

General

- The linac and RCS have been commissioned successfully.
- The stability of linac beam is sufficiently good for beam commissioning of RCS, MLF, and MR. (except for the following problem...)
- Availability and beam power is limited by mainly RFQ at the present.
- We decided to temporarily limit the beam power to 1.2 kW (corresponds to 20 kW RCS beam) in order to ease the RFQ discharge problem.

For the high intensity

- Ion source and RFQ must be upgraded for 1 MW beam power of RCS.
- The construction of 200 to 400MeV part (Annular Coupled Structure) of the linac was funded through the supplementary budget of JFY2008.
- Design and construction of ACS is still going on.
- Installation of ACS modules is scheduled on January to March, 2011.

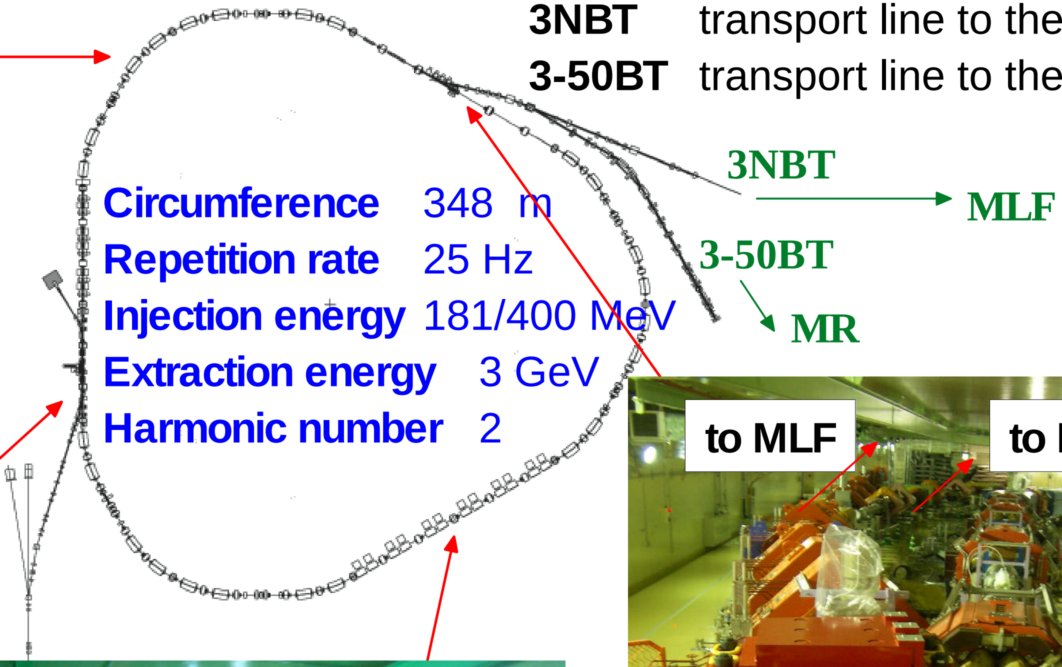
RCS (Rapid Cycling Synchrotron)

Neutron/Muon source and **booster of the MR.**

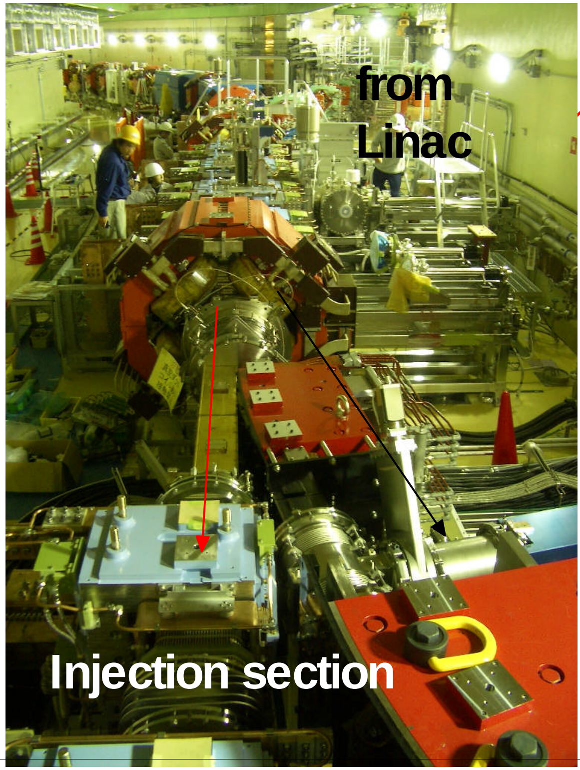
Two beam transport lines:

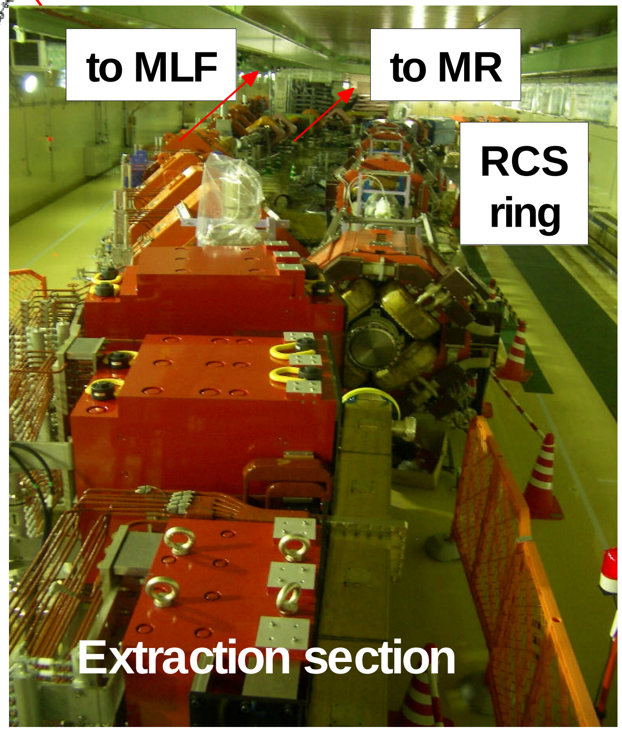
3NBT transport line to the MLF

3-50BT transport line to the MR



Circumference	348 m
Repetition rate	25 Hz
Injection energy	181/400 MeV
Extraction energy	3 GeV
Harmonic number	2





Recent runs and operations

(1) Run#16 (May 13~June 2, 2008)
- Tuning and study for the transverse beam painting
- Startup of the beam delivery to MLF and MR for their beam commissioning
  (5 mA peak/0.1 ms long/280 ns intermediate pulse width/1 bunch; 5 kW eq.)

(2) Run#17 (June 12~30)
- Tuning and study for the transverse and longitudinal beam painting
- Beam delivery to MLF and MR (5 mA/0.1 ms/280 ns/1 bunch; 5 kW eq.)

(3) Run#18 (September 11~29)
- Tuning and study for the transverse and longitudinal beam painting
- High-intensity demonstrations (10-15 mA/0.5 ms/560 ns/2 bunches; 200-300 kW eq.)
- High-power demonstration (15 mA/0.5 ms/420 ns/2 bunches/25 Hz; 225 kW)
- Beam delivery to MLF (5 mA/0.1 ms/280 ns/1 bunch; 5 kW eq.)

(4) Run#19 (November 3) Suspended due to RFQ trouble

(5) Run#20 (December 2~26)
- High-power demonstration (5 mA/0.5 ms/560 ns/2 bunches/25 Hz; 100 kW)
- 25 Hz stable beam operation (Startup of user runs at MLF)
* MLF 5 mA/0.4-0.1 ms/280 ns/1 bunch/25 Hz; 20-5 kW
* MR 5 mA/0.1 ms/140-280 ns/1 bunch/single shot or 0.16 Hz

(6) Run#21 - #24 (January 13~June 1, 2009)
- 25 Hz stable beam operation
* MLF 5 mA/0.1 ms/560 ns/2 bunches/25 Hz; 20 kW
* MR 5 mA/0.1 ms/140-280 ns/1 bunch/single shot or 0.16 Hz

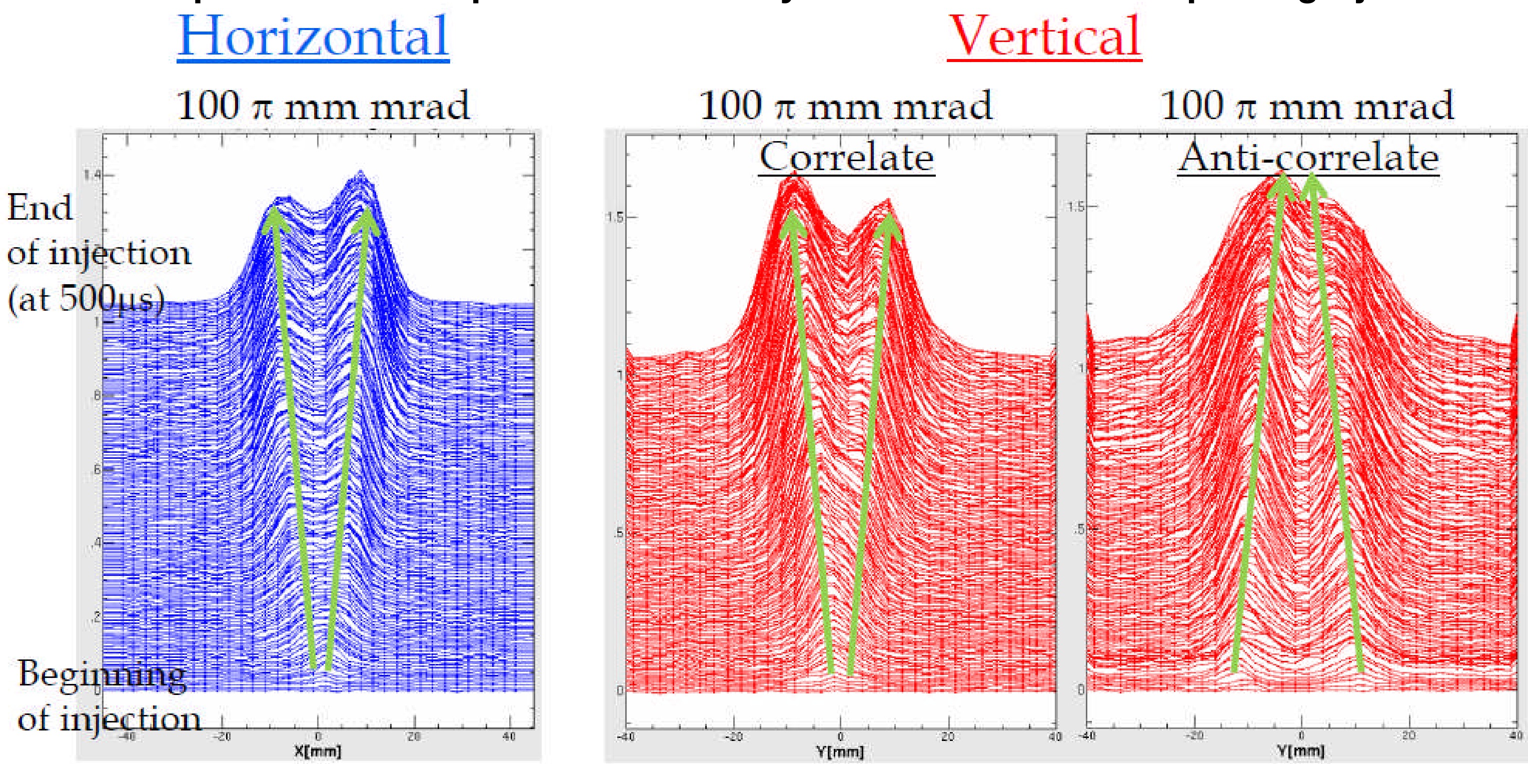
Transverse painting

In order to reduce the space charge force, artificial off-center injection scheme (painting) was tested with paint-bump system for both horizontal and vertical plane.

When the beam profile had a broad shape, space charge force is eased. As a result, beam loss gets smaller.

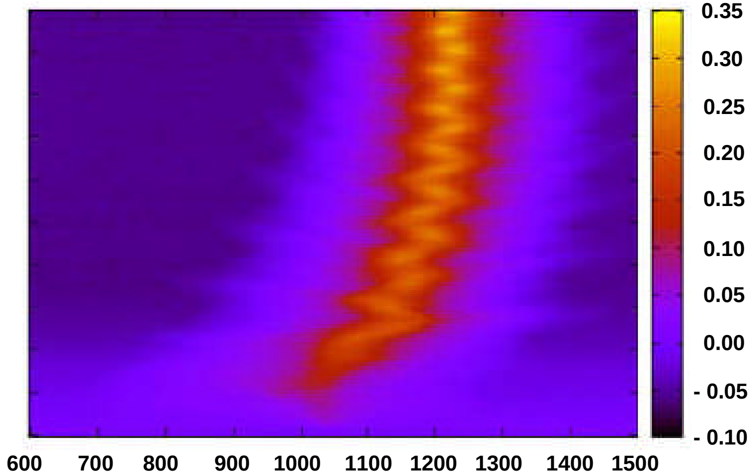
Beam parameter
5 mA peak, 0.5 ms long,
560 ns intermediate-pulse width

Mountain plot of the beam profile measured by IPM for the transverse painting injection

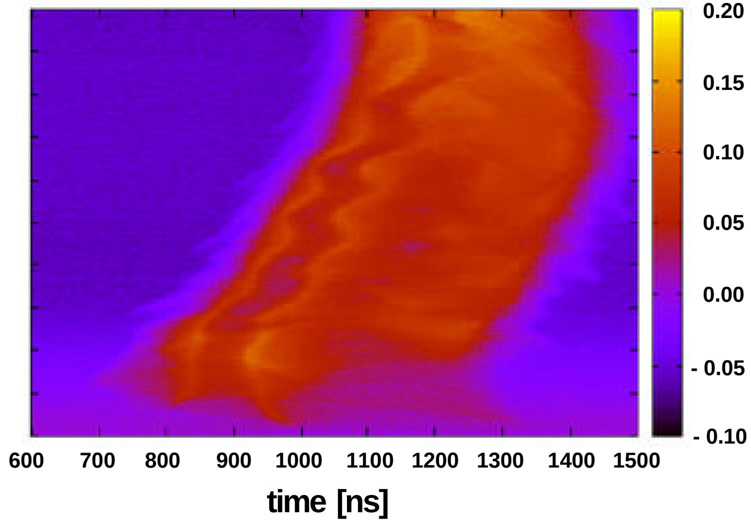


Longitudinal painting

- Only Fundamental -



- 2nd harmonics: 80% -



Beam parameter
10 mA peak, 0.5 ms long,
560 ns intermediate-pulse width,
2 bunches
* Vmax: 402 kV/turn (with 10 cavities)
* Phase FB on

In the longitudinal painting, the RF frequency and the phase of second harmonic RF voltage are varied during injection.
Figure shows mountain plots and the bunching factors w/w.o longitudinal painting.

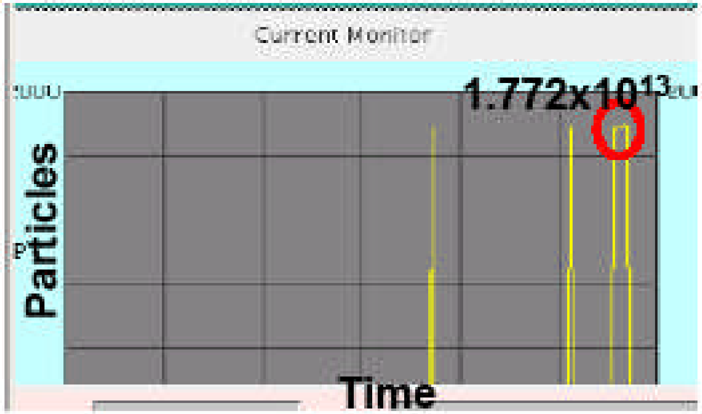
Momentum offset: -0.2%
Phase sweep of 2nd harmonics:
-80 to 0 degree

↓

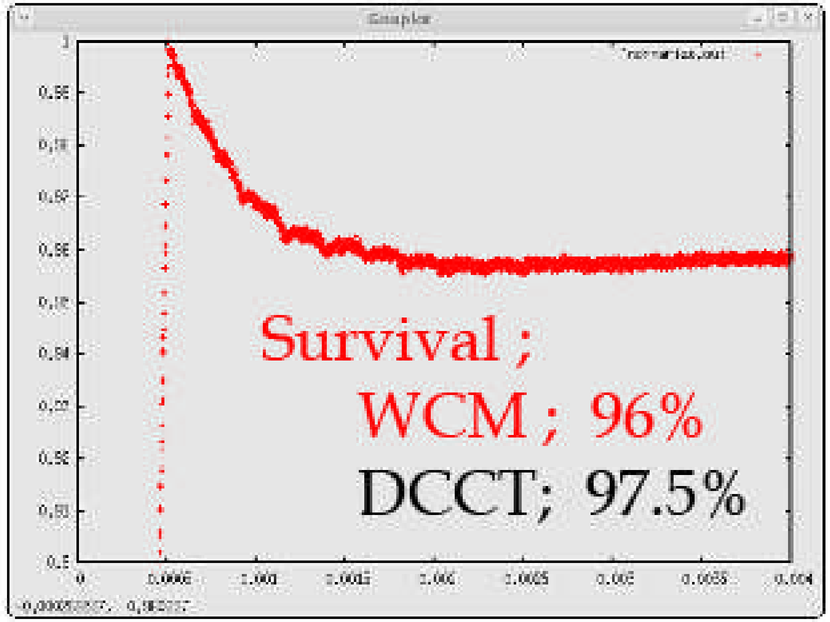
200 kW output was achieved !

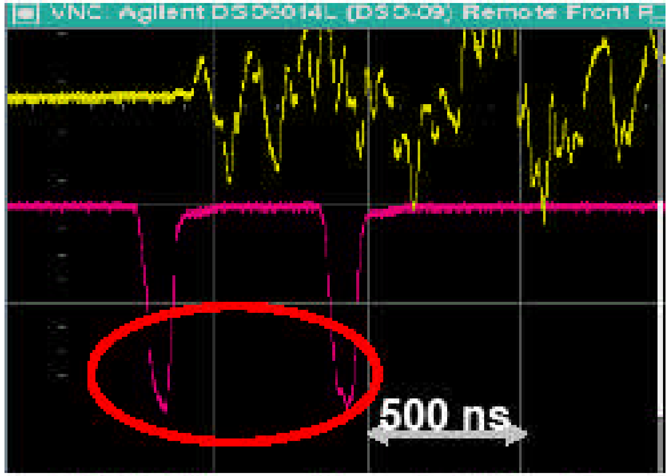
High intensity demonstrations

- On18th September of 2008, the highest beam power of ***0.21 MW (1.77 x10^{13} ppp)*** was demonstrated for **70 seconds**.
- Note that duration of 70 seconds was limited by the authorized beam dump capacity at that time.
- The beam loss was about 3 %.



3NBT Current Monitor Signal





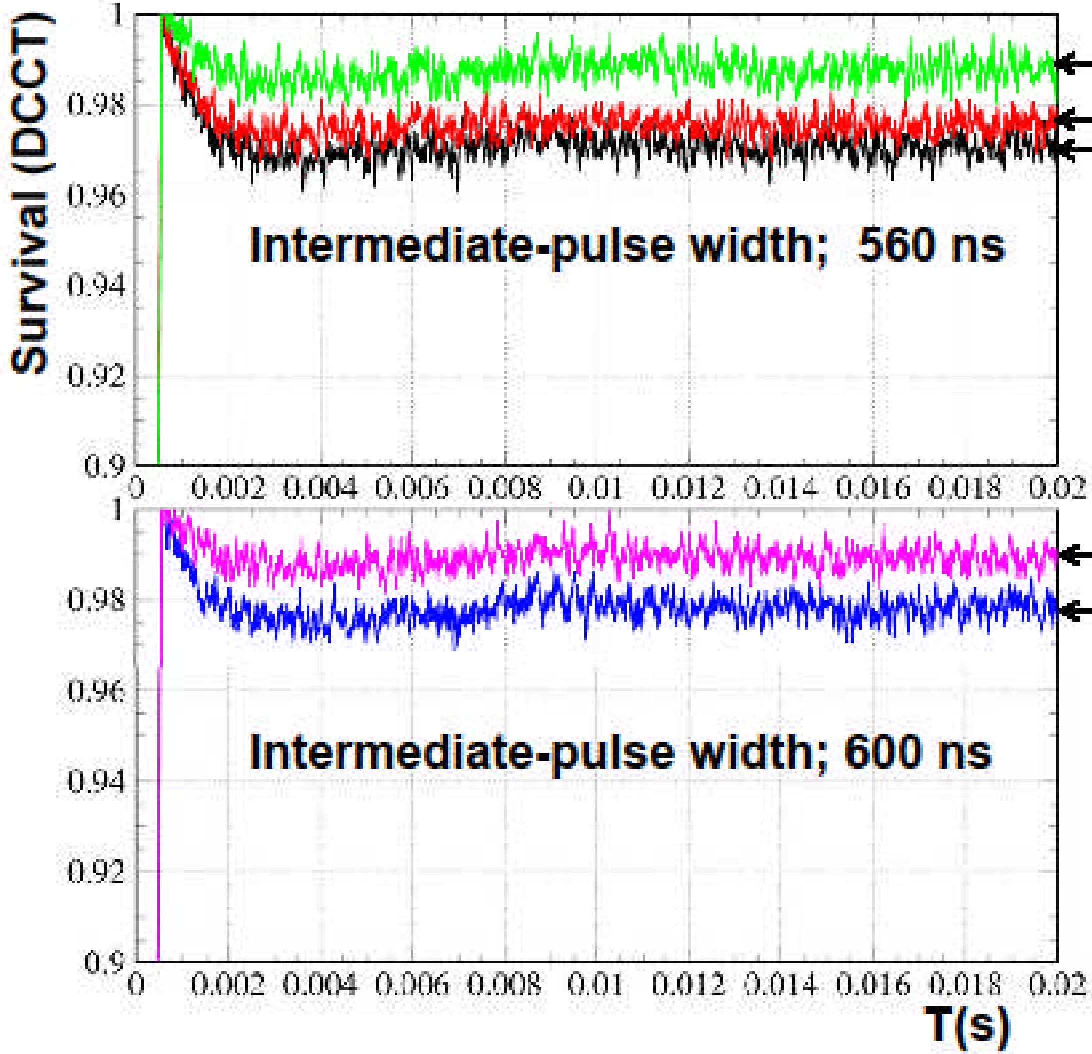
3NBT Beam Bunch Signal

Original slide from M. Kinsho, ATAC2009

High intensity demonstrations cont.

15 mA peak, 0.5 ms long, 560-600 ns intermediate-pulse width, 2 bunches

Transverse painting ; 150 π correlate both for H & V



2nd harmonics (80%)
-0.1% momentum offset

2nd harmonic (80%)

No longitudinal paint

2nd harmonic (80%)
-0.1% momentum offset
Phase sweep -80 to 0 deg

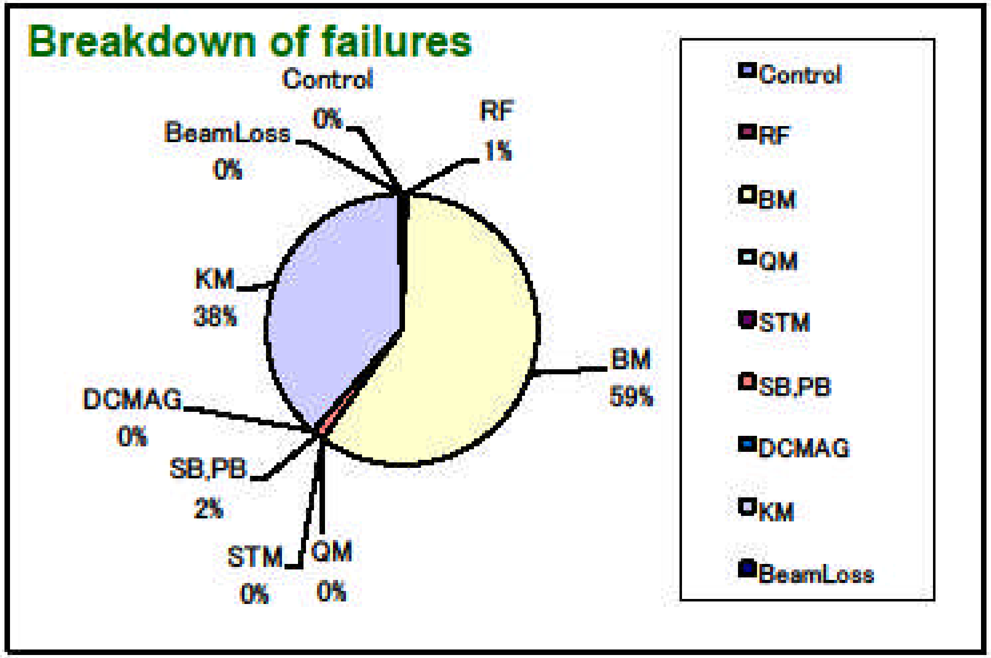
2nd harmonic (80%)
-0.1% momentum offset

2.58×10^{13} ppp
(310 kW eq.)
at extraction

Original slide from M. Kinsho, ATAC2009

Availability

	RUN20 (94:00)		RUN21(310:00)		RUN22(454:00)		Total (858:00)	
	Counts	Stop Time	Counts	Stop Time	Counts	Stop Time	Counts	Stop Time
Control	0	0:00:00	1	0:00:00	13	0:00:00	25	0:00:00
RF	1	0:09:38	1	0:06:00	2	0:14:44	4	0:30:22
BM	0	0:00:00	1	20:16:46	2	30:38:48	3	50:55:34
QM	0	0:00:00	0	0:00:00	0	0:00:00	0	0:00:00
STM	0	0:00:00	0	0:00:00	0	0:00:00	0	0:00:00
SB,PB	0	0:00:00	0	0:00:00	5	1:15:32	5	1:15:32
DCMAG	0	0:00:00	0	0:00:00	0	0:00:00	0	0:00:00
KM	7	2:29:34	69	16:23:48	66	13:51:24	141	32:44:46
BeamLoss	2	0:00:00	11	0:06:04	19	0:11:04	32	0:17:08
Total	10	2:39:12	83	36:52:38	107	46:11:32	210	85:43:22



Availability for user operation : 90.0 %

Failures were mainly caused as follows

RF : "OC/UV" interlock of the screen grid , anode and/or control grid dc-power supply.

KM : pre-fire of thyratron for extraction kicker magnet.

SB, PB : power supply was down by the noise. This noise happened when BM power supply was down.

BM : troubles

Original slide from M. Kinsho, ATAC2009

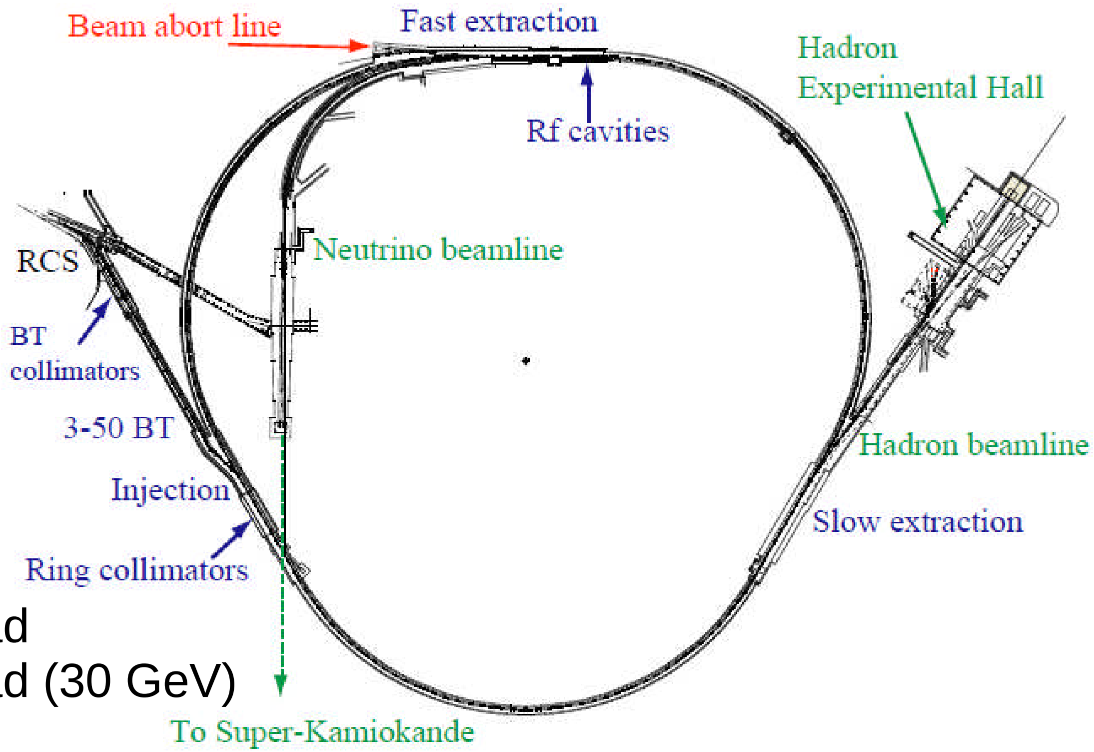
Present Status of RCS

The RCS have been commissioned successfully.

- **The optics measurement and its correction were successfully performed.**
- **Transverse and longitudinal painting injections were well-demonstrated.**
- **It was confirmed that the beam loss at the early stage of acceleration was well-improved by the painting injection scheme especially in the longitudinal plane for 200-300 kW-equivalent intensity beam.**
- **Consecutive 100 kW (for 1 hour to MLF) and 213 kW (for 70 s to 3NBT dump) output operations at 25 Hz were well demonstrated.**
- **Stable beam operations for MLF (user run) and also MR commissioning have been performed with 20 kW output beam power since December 2008.**
- **For higher beam intensity, comissioning and study will continue...**

MR (slow cycling Main Ring synchrotron)

Circumference	1567.5 m
Repetition rate	~ 0.3 Hz
Injection energy	3 GeV
Extraction energy	30 GeV
Superperiodicity	3
harmonic #	9
No of bunches	8
Transition γ_t	j 31.7
Typical tune	(22.4, 20.8)
Transverse emittance	
At injection	~54 π mm mrad
At extraction	~10 π mm mrad (30 GeV)

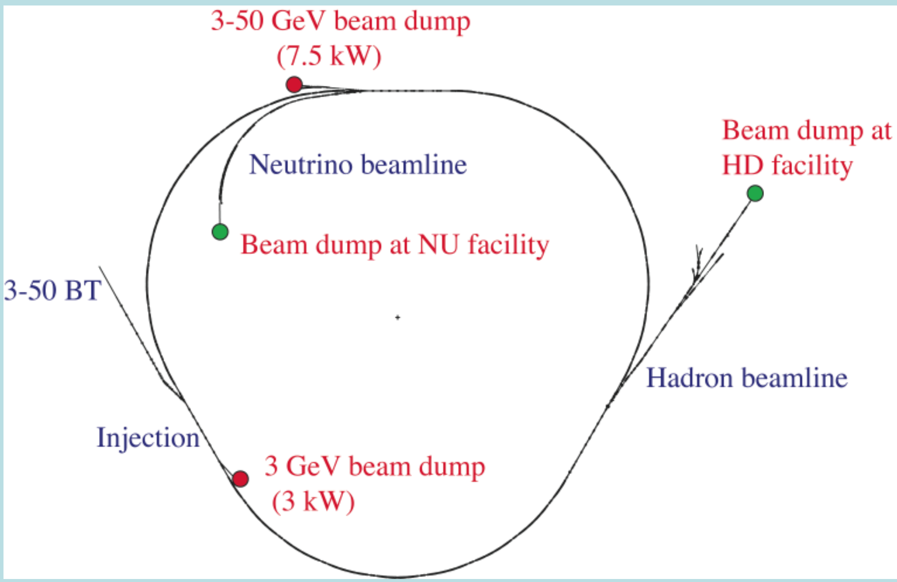


Three dispersion free straight sections of 116-m long:
- **Injection and collimator systems**
- **Slow extraction (SX)**
  to Hadron experimental Hall (Rare decay, hyper nucleus..)
- **Rf cavities and Fast extraction(FX) (beam is extracted inside/outside of the ring)**
  outside: Beam abort line
  inside: Neutrino beamline (intense ν beam is send to SK located 300 km west)

MR beam commissioning schedule

1st stage (May - June 2008)
Available beam dump: at the injection.
Beam transport in 3-50 BT, injection, closed orbit, rf capture, extraction to beam dump at 3 GeV.

Installation of FX and SX components
(July 2008-Nov. 2008)
FX septa (SM1,2, SM33), FX kickers, SX devices, neutrino beamline components, tuning of main magnet power supplies.



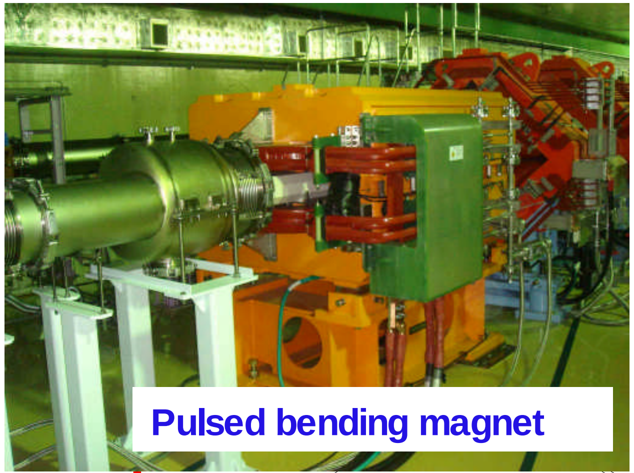
Layout of beam dumps

2nd stage (Dec. 2008 - Feb. 2009)
Available beam dump: at the abort beamline and HD beamline.
Acceleration from 3 to 30 GeV, extraction to abort line, extraction to hadron beamline.

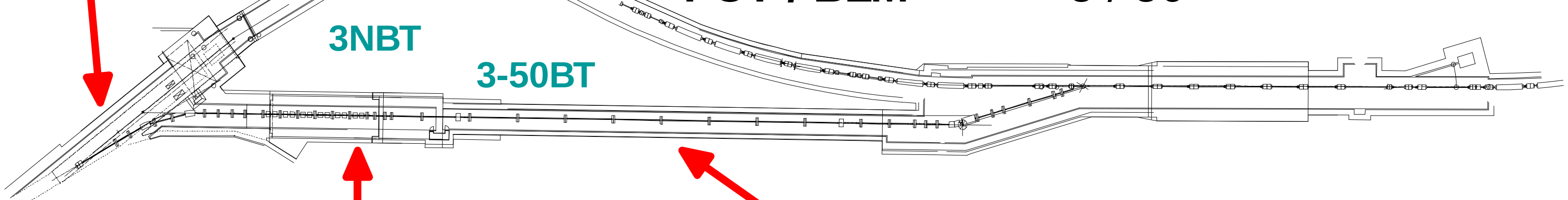
3rd stage (April - June 2009)
Available beam dump: at the NU beamline.
Extraction to neutrino beamline.

We‘ve just completed !!

3-50 Beam Transport Line


Pulsed bending magnet

Length	230 m
Dipole	1 (pb), 3 (h), 2 (v)
Quadrupole	38
Steering	14
Collimator	12 units (120 - 54 π mm mrad)
Monitor	
BPM / MWPM	14 / 5 (9)
FCT / BLM	5 / 50




BT collimators


Slope section

Magnet system

Main magnets

Dipole	96
Quadrupole (11 families)	216
Sextupole (3 families)	72

Steering magnets

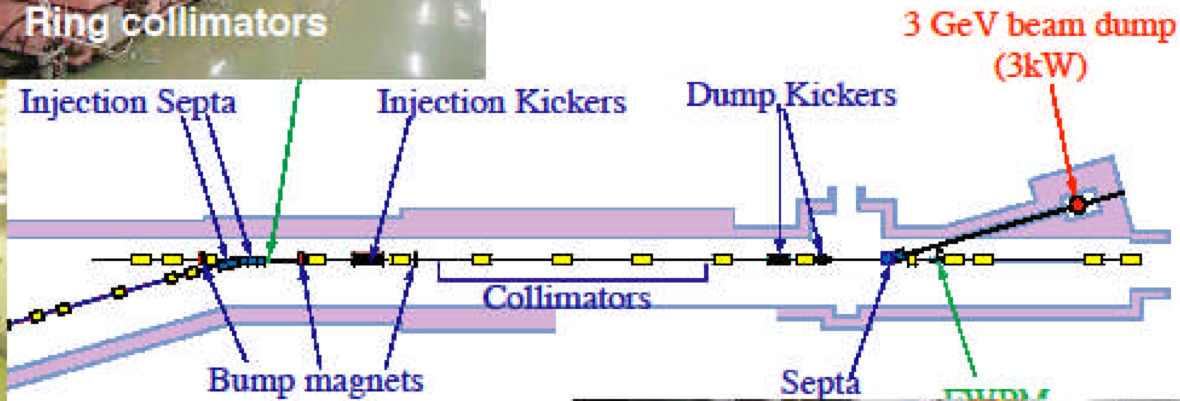
Hori. Steerings	92
Vert. Steerings	93
Abort Steering	1

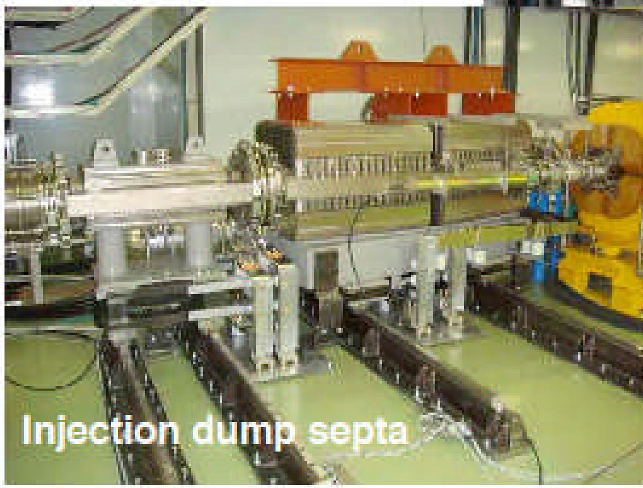
Precise alignment of all the main magnets was completed in 2007.

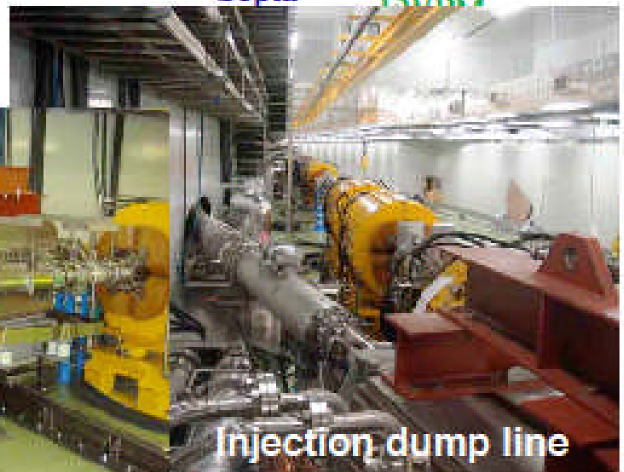
Hardware commissioning of the main and steering magnet systems started in December 2007 as scheduled.

The total harmonics distortion (THD) of AC voltage ~1% with a harmonic filter of 6.5 Mvar unit when all the power supplies operated in 30 GeV.

Injection devices







MA loaded rf cavity

The MA (magnetic alloy) cut core is adopted to the MR cavity.

At initial operation in the second stage of commissioning, required rf voltage is ~ 160 kV for 30 GeV (Nominal voltage is 40 kV/cavity).

Long-term high power operation test of MA cores

All 90 cores (for 5 cavities) have been tested

> 300 hrs with nominal rf gap voltage of 15 kVp with 60% duty.

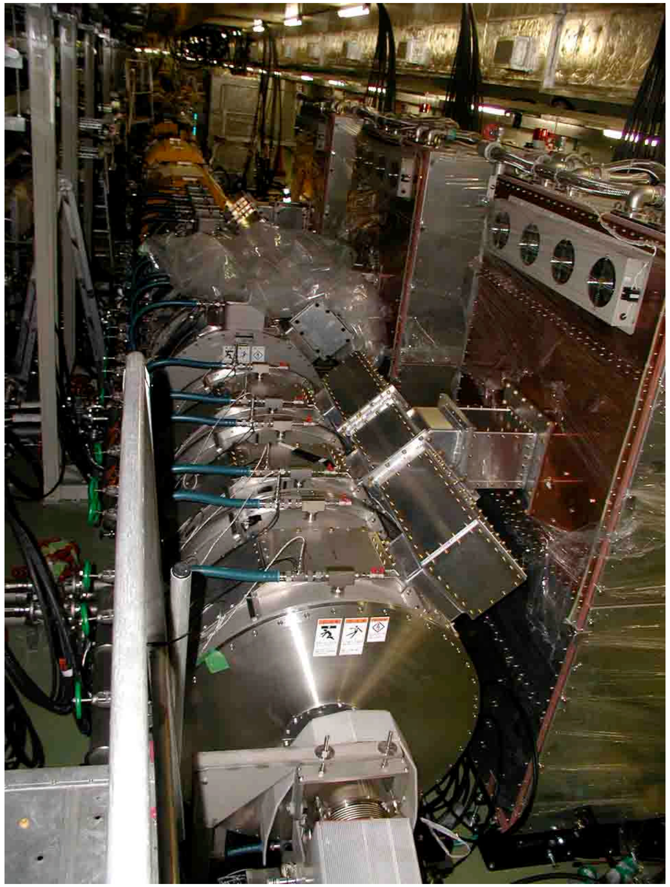
↓

Serious core damages have not been observed.

For the first stage of beam commissioning, four cavities have been installed.

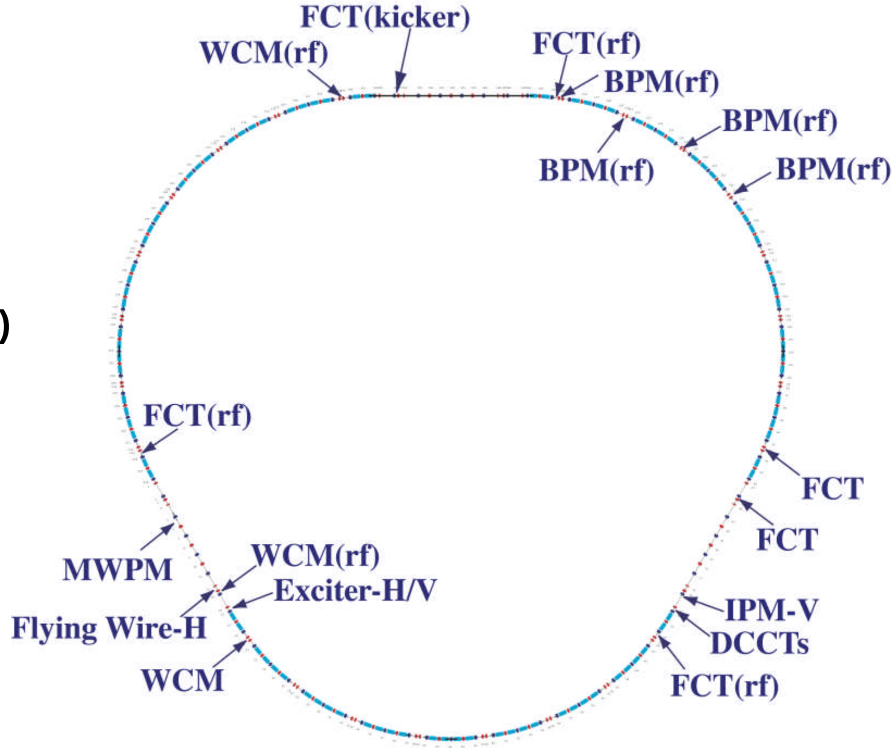
Hardware commissioning started in March 2007.

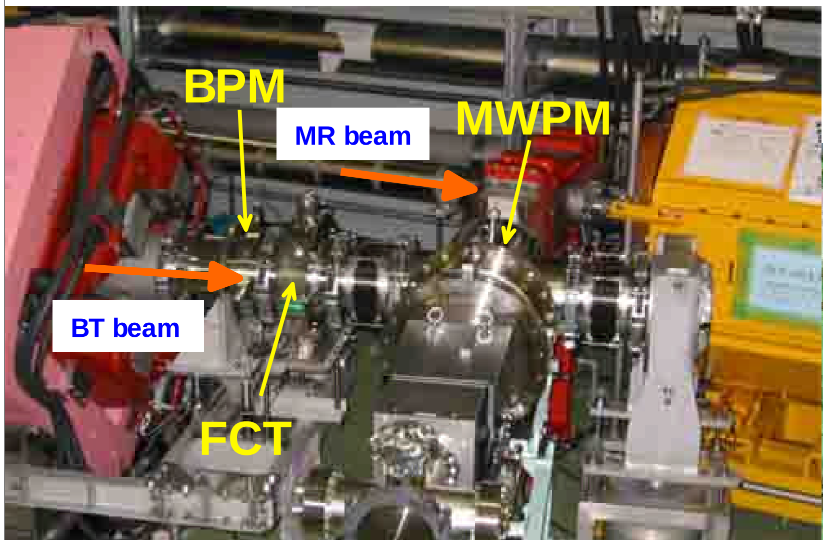
The fifth cavity will be installed in summer 2009.



Beam monitors

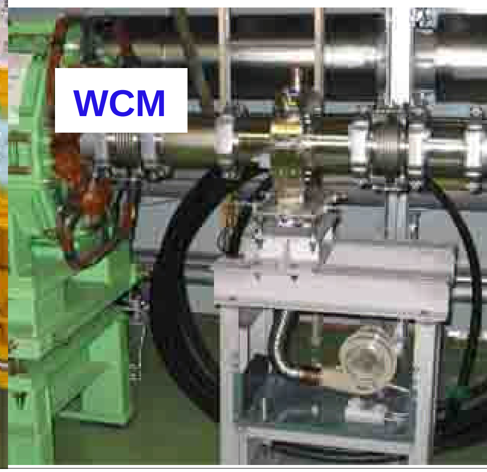
BPM	186
Abort/dump BPM	2+2
WCM (>100 MHz)	3
FCT (~ 20 MHz)	6
DCCT(DC - 30 kHz)	2
MWPM	1(inj.) + 1(SX) + 1(abort)
FWPM(H/V)	1 / 0
IPM(H/V)	1 / 1
Tune meter (H/V)	1 / 1
Quad. mode BPM	2
BPM (BT)	14
FCT (BT)	5
MWPM (BT)	6
BLM(BT&MR)	338





3-50 BT@just upstream of injection

Installation, cabling and calibration still continue.



Beam Commissioning

Procedure

1st stage: Injection and 3 GeV DC

- 3-50BT orbit correction
- Injection tuning
- COD correction

} Itelate while necessary

- Closed orbit establishment
- RF capture
- η -function measurement
- β -function measurement

Ring parameter measurement

- Tune measurement & survey
- Optimization of operating point
- RF parameter tuning
- Chromaticity correction

2nd stage: Acceleration

- Acceleraion
- Optimization process same as above
- FX devices tuning
- Confirmation of adiabatic damping

Linac/RCS beam for MR commissioning

Linac: 5 mA, 100 µsec, chopped beam
RCS: without painting,
~10 π mm mrad
one bunch operation (h=2)
< 4e11 ppb (1 % intensity),
single shot

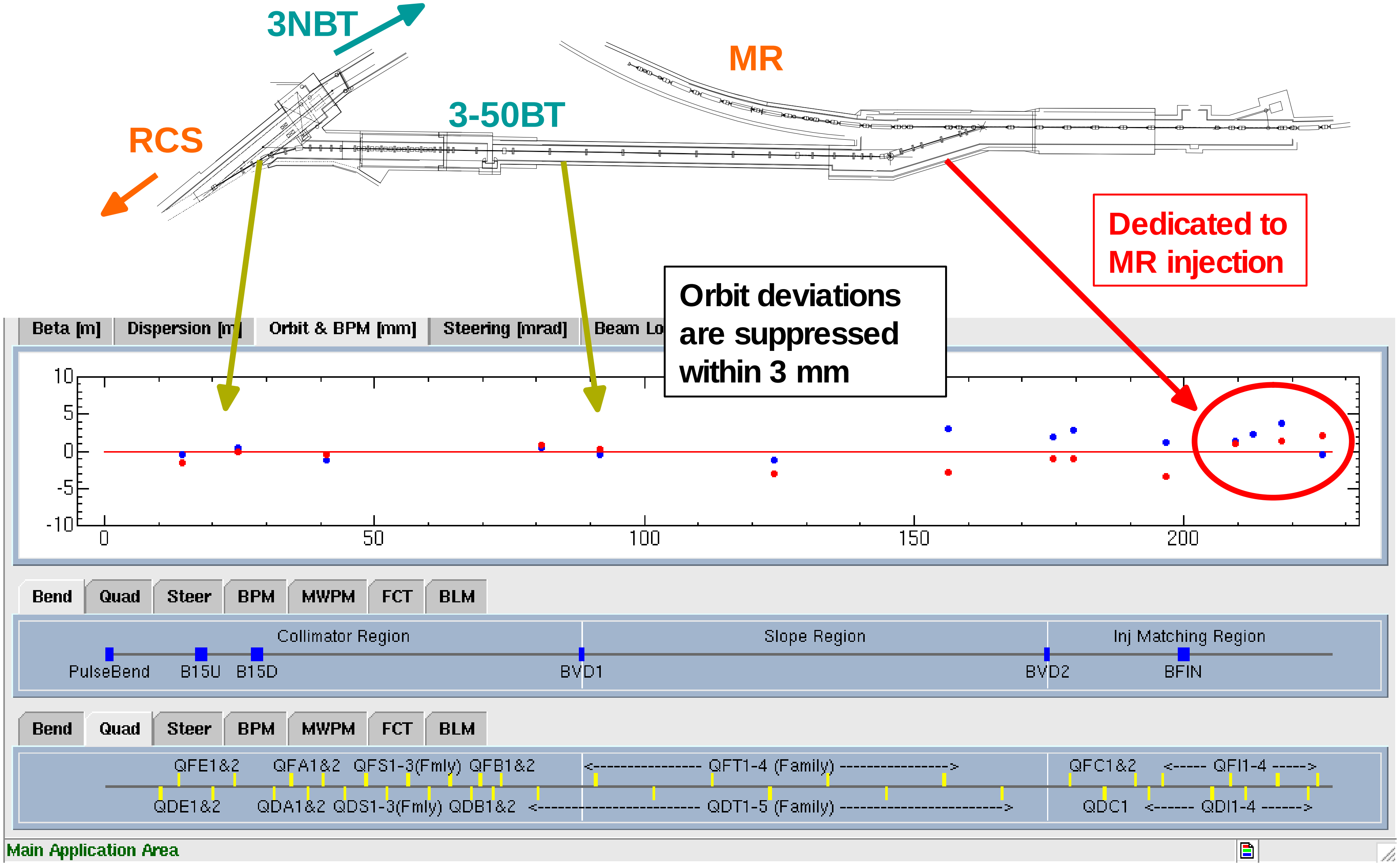
Beam extraction to HD beamline

- Establish optimum operating point
- Tune Survey
- Physical aperture survey
- Dynamic aperture survey
- Beam extraction tuning
- HD beamline tuning
- SX devices tuning
- Spill control (Sep. 2009 ~)

Beam extraction to NU beamline

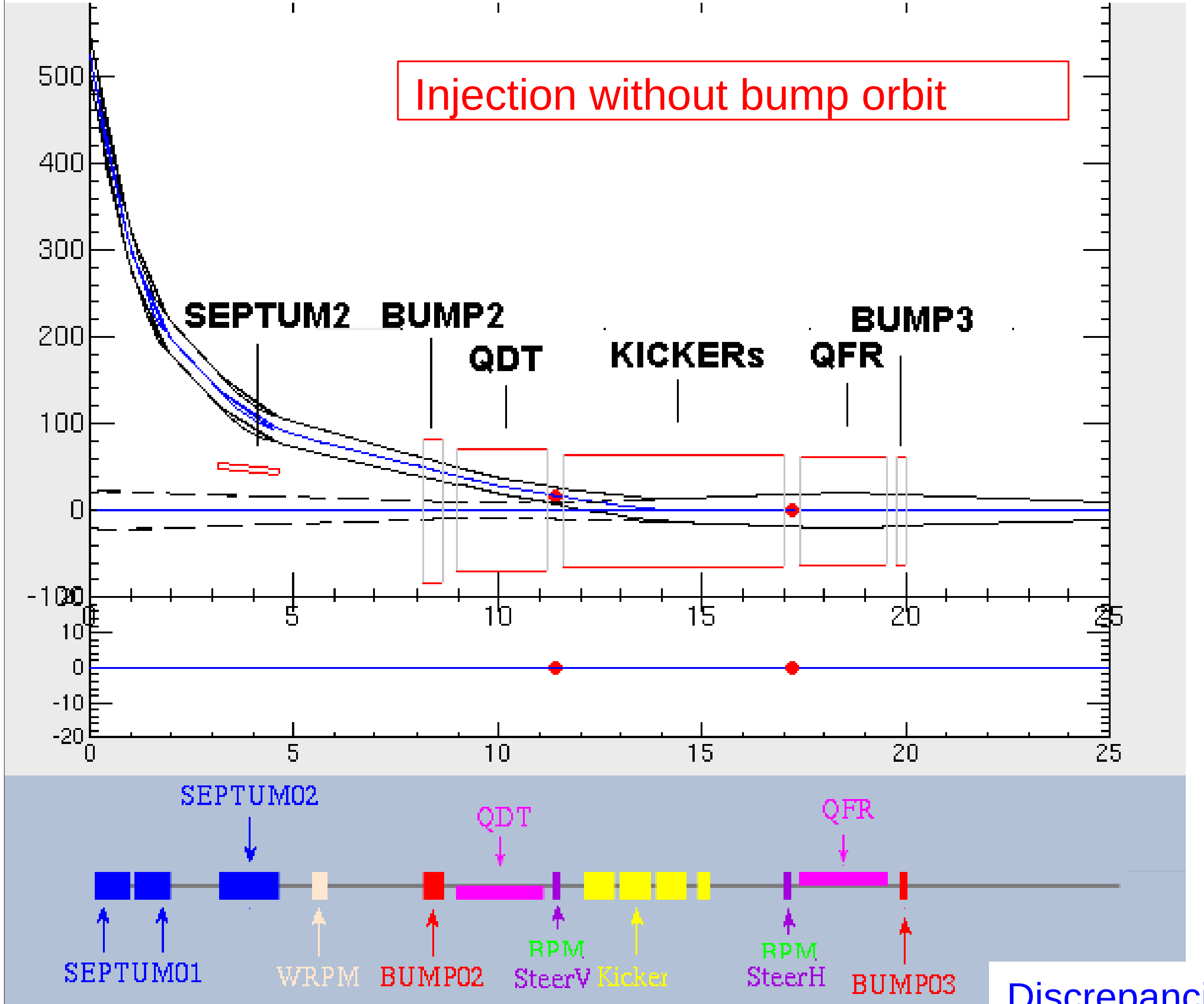
- Establish optimum operating point
- Beam extraction tuning
- NU beamline tuning

Orbit correction in the 3-50BT



Injection Tuning 1

Injection beam envelope and layout of the components



Tunable knobs

Ring
Septum1, 2
kicker1, 2, 3

3-50BT
zsh09, 10
zsv11, 12

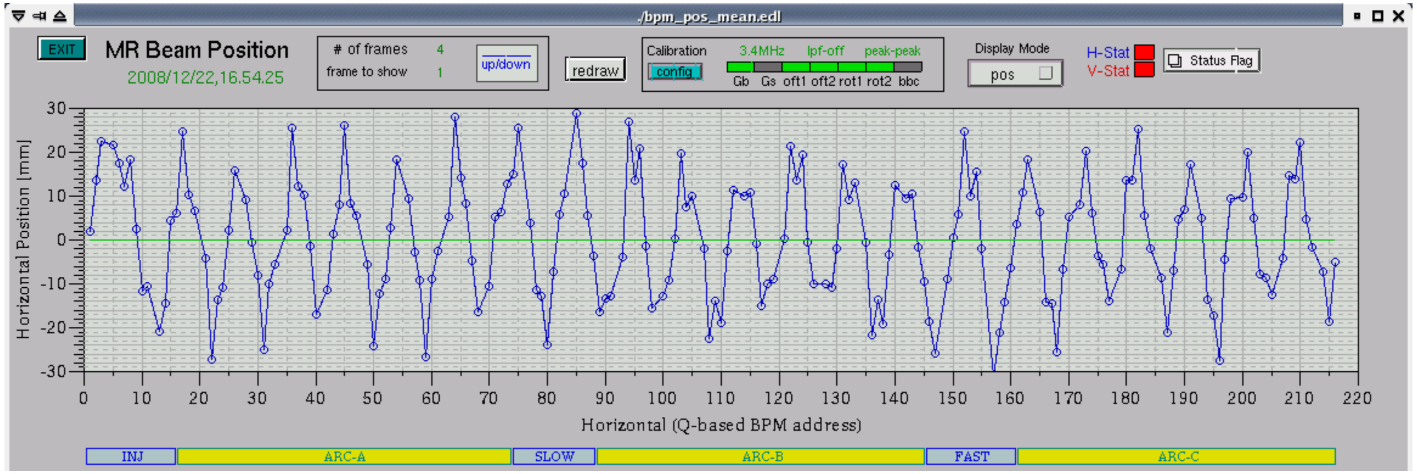
Bump magnets are installed to make a local bump to secure the large physical aperture for the circulating beam. But we did not use the local bump in the 1st stage because of the small beam size.

Discrepancies from the design are small.

Injection Tuning 2

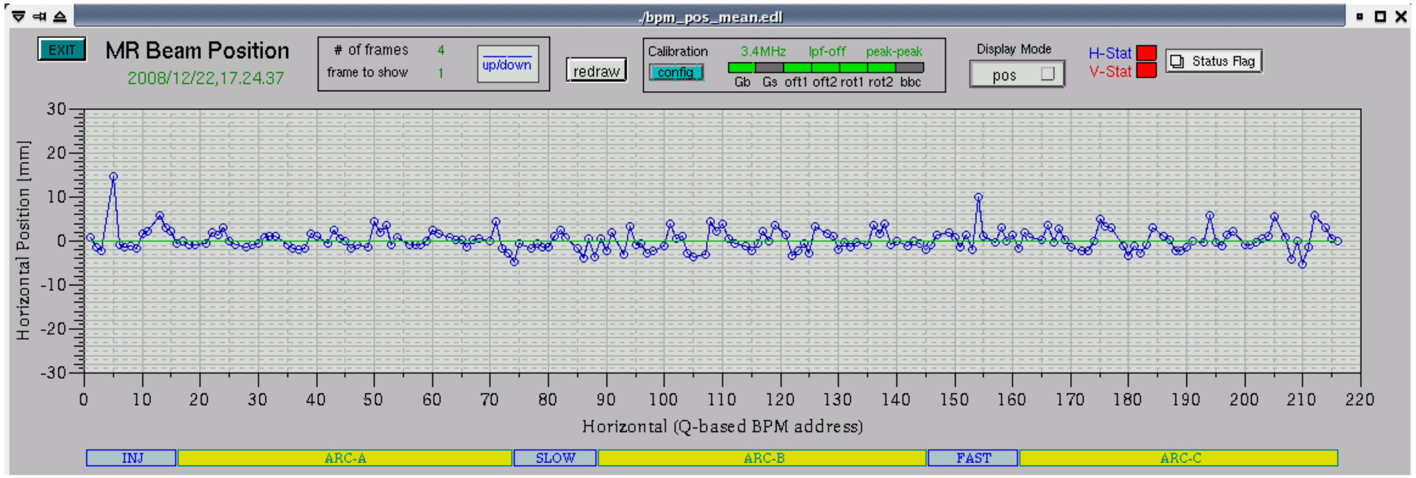
BPM: Turn-by-turn mode

Before



Injection error was well suppressed.

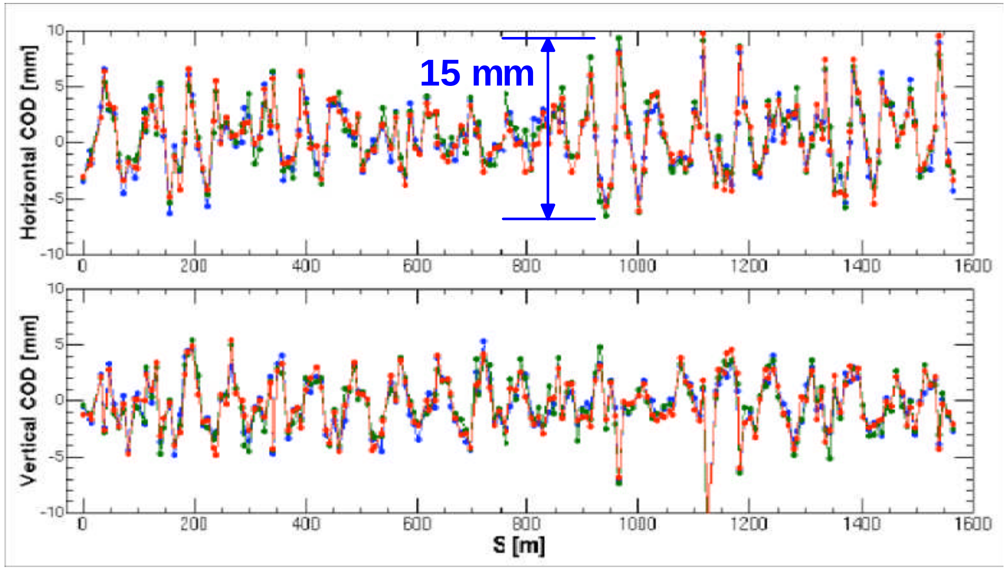
After



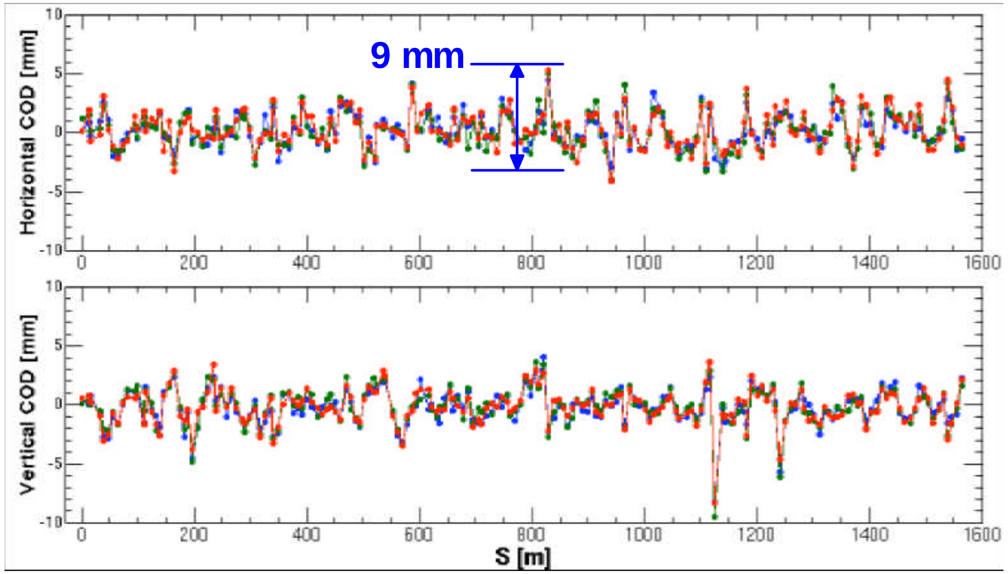
COD Correction

BPM: COD mode

In COD mode, BPM measures the averaged position of the beam.



Amplitude of orbit distortions was suppressed!

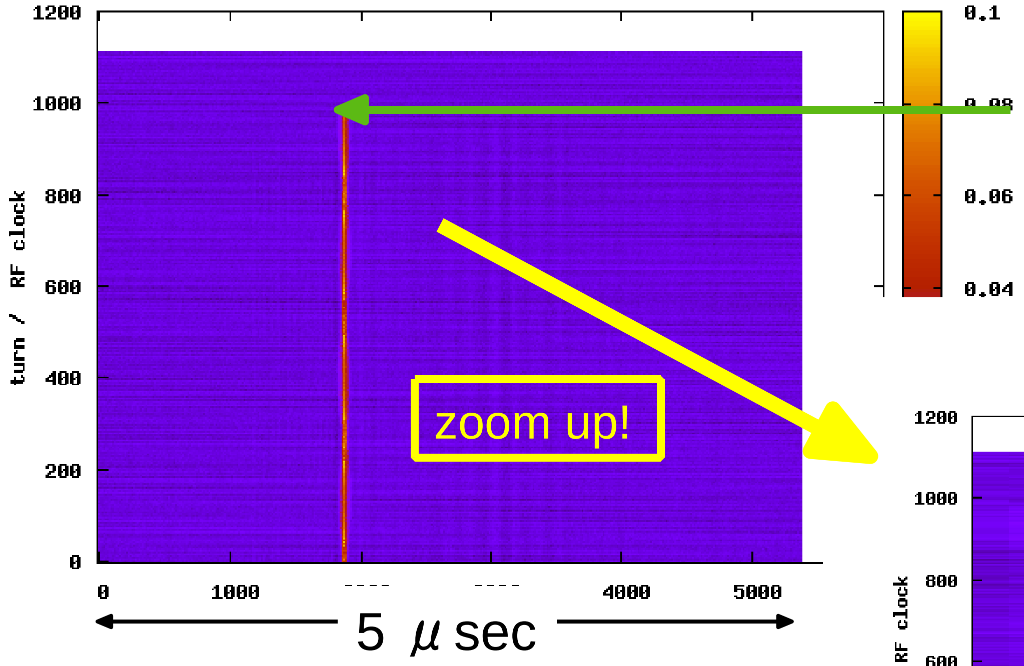


Orbit analysis
&
Correction by steering magnets

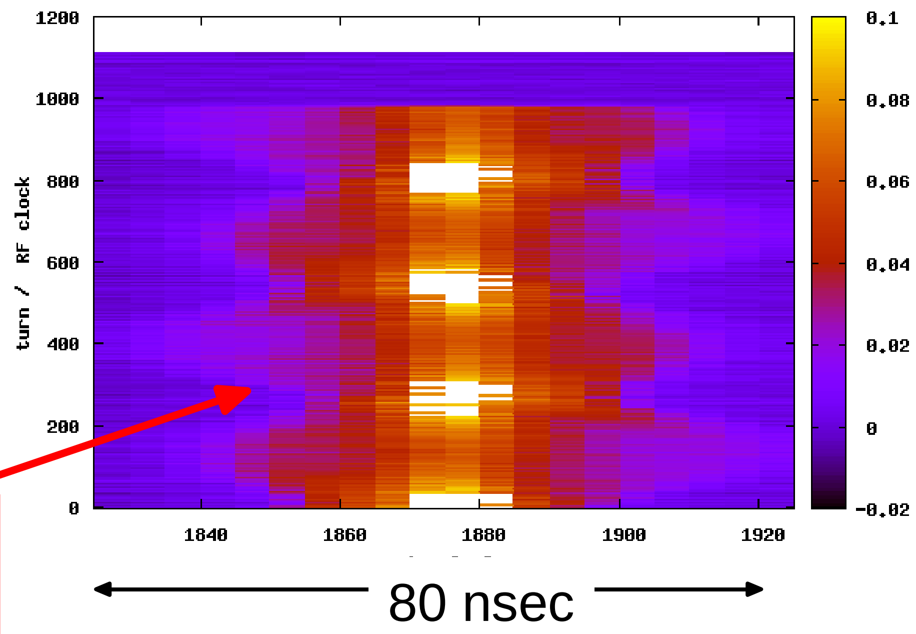
RF Capture

Matching between field of dipole magnet and RF frequency

Mountain plot of longitudinal beam profile measured by WCM



1000 turn mode:
Beam is extracted after 1000 turns from the injection.

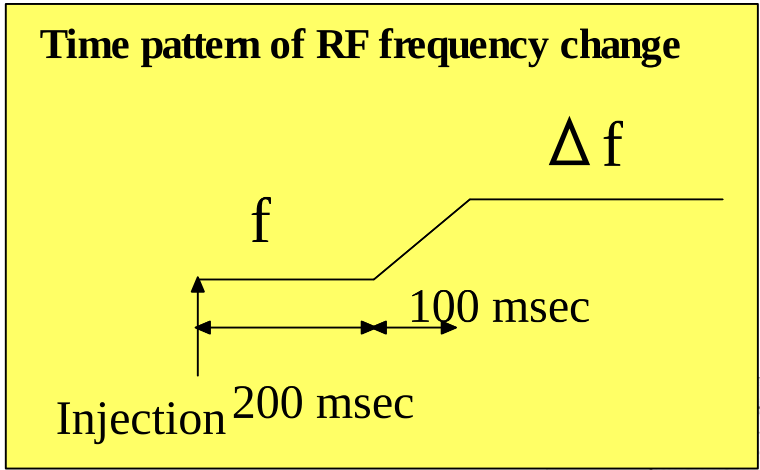


f_{rf} = 1.6715 MHz
V_{rf} = 160 kV

The frequency is well matched and no dipole oscillation is observed.

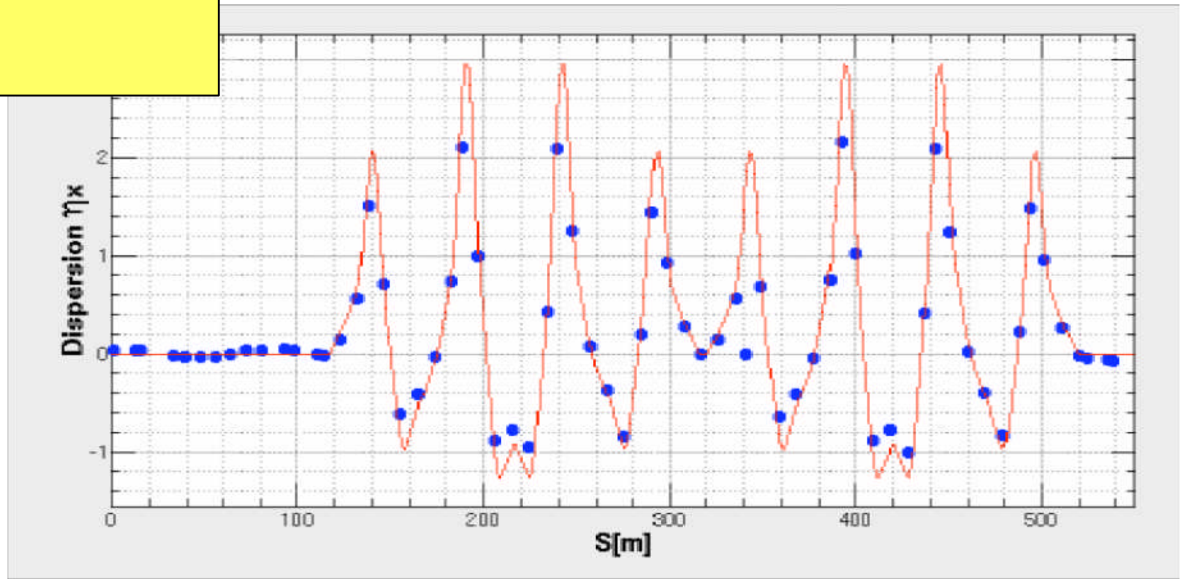
η -function Measurement

The $\Delta p/p$ dependence of the closed orbit is measured by changing RF frequency.



$$\Delta x = \eta_x \Delta p/p$$

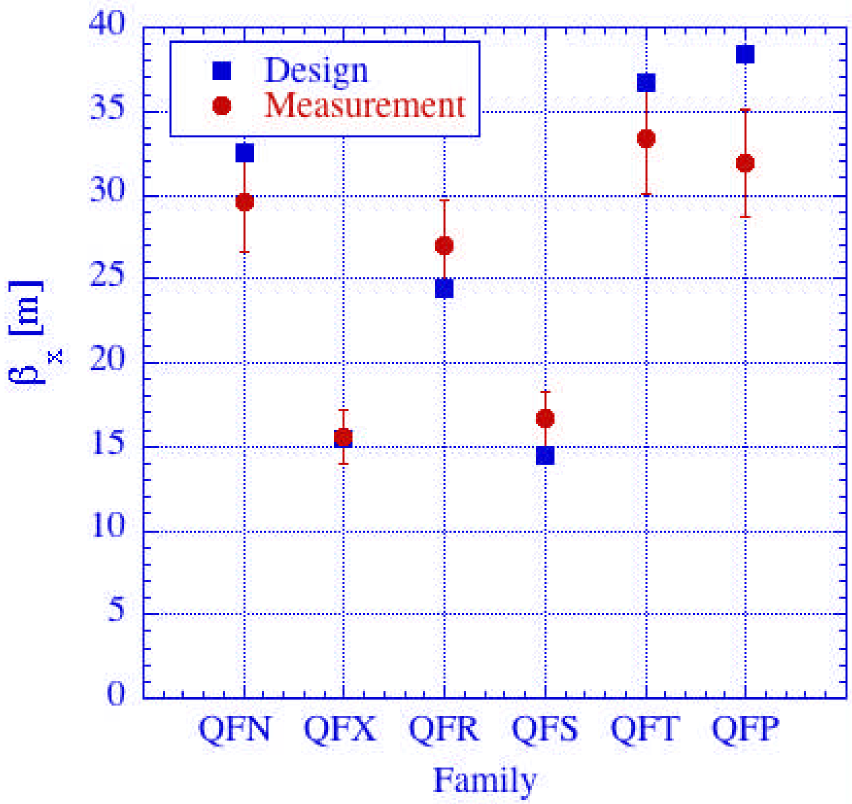
RF shifts the beam momentum.
Beam orbit represents the η -function.

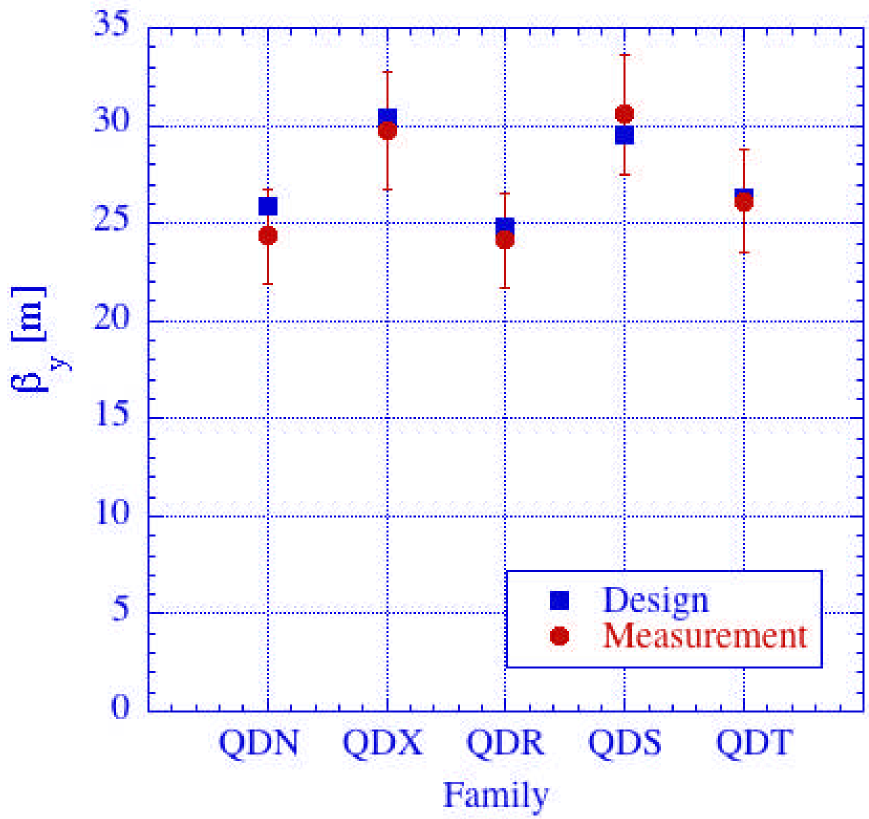


Measured results agree well with design.

β -function Measurement

- We measured β -function using the relation: $\beta \Delta k \dashrightarrow \Delta \nu$
  Averaged β at the position of each Q families
- Measurement error : $\Delta \beta / \beta$ ~10 %.





Measured results agree with the designs within the measurement error.

Tune and Resonance

- **Particles in beam oscillates with a characteristic frequencies both in horizontal and vertical planes. These are called tune: ν_x and ν_y, respectively.**
- **When the error field existed, particles are affected periodically. When the particle motion is synchronized to the affection, the amplitude of particle motion gets larger. (This is called as the "resonance")**
- **Resonance conditions can be expressed in the tune diagram which is a 2D plot of ν_x and ν_y.**

- **Strength of resonances**

Resonant condition: $m\nu_x + n\nu_y = k$

ν_x **: horizontal tune,** ν_y **: vertical tune**

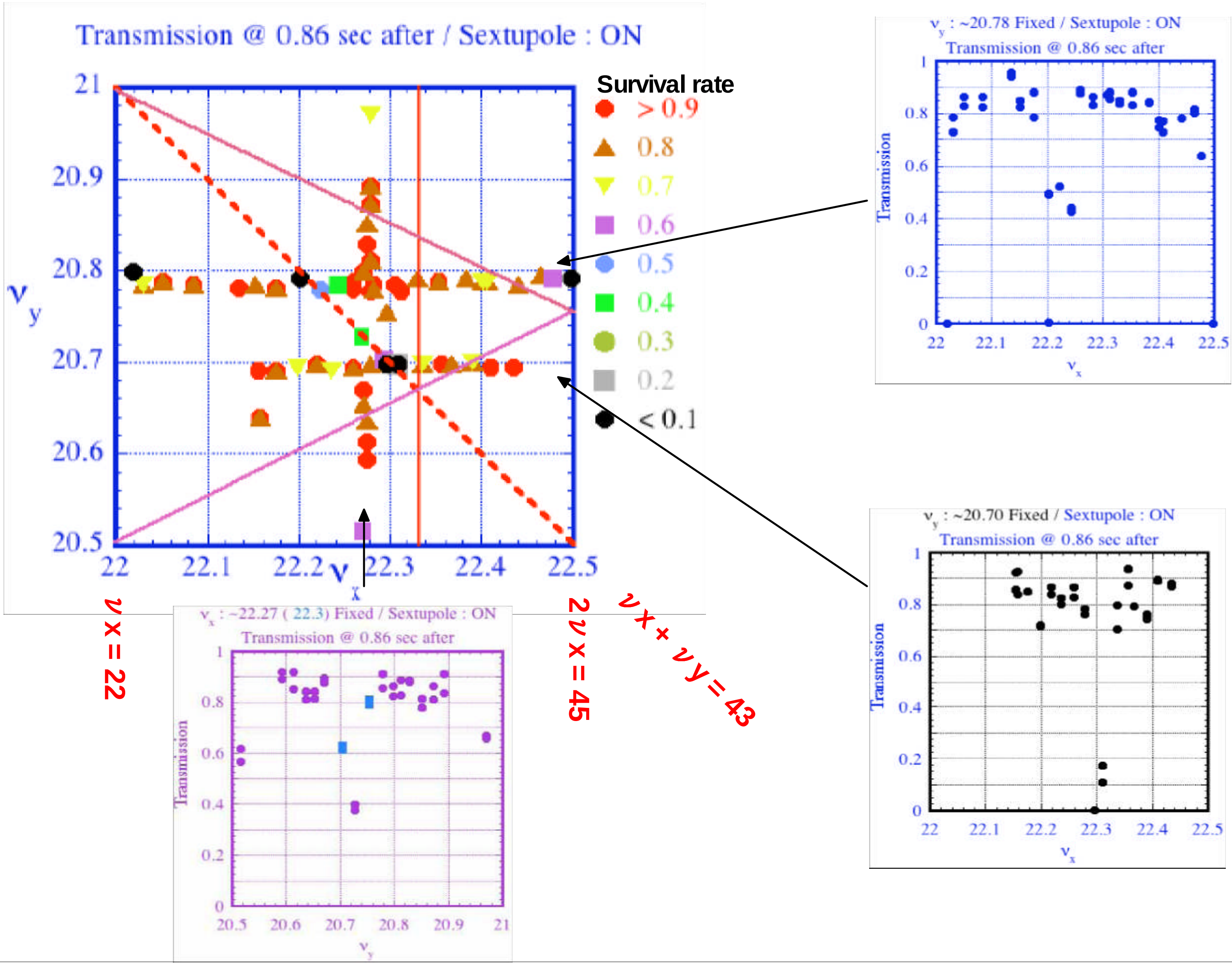
***m*, *n*, *k* are integers.**

(|*m*|+ |*n*|): order of resonance; Low order resonances are strong and halmful.

- **Expected resonances** (example)

$\nu x = 22$	**(integral resonance: very strong)**
$2\nu x = 45$	**(half-integral resonance: very strong)**
$\nu x + \nu y = 43$	**(sum resonance: strong)**
$\nu x = 22.333$	**(3νx = 67, third order resonance used in slow extraction)**
$\nu x + 2\nu y = 64$	

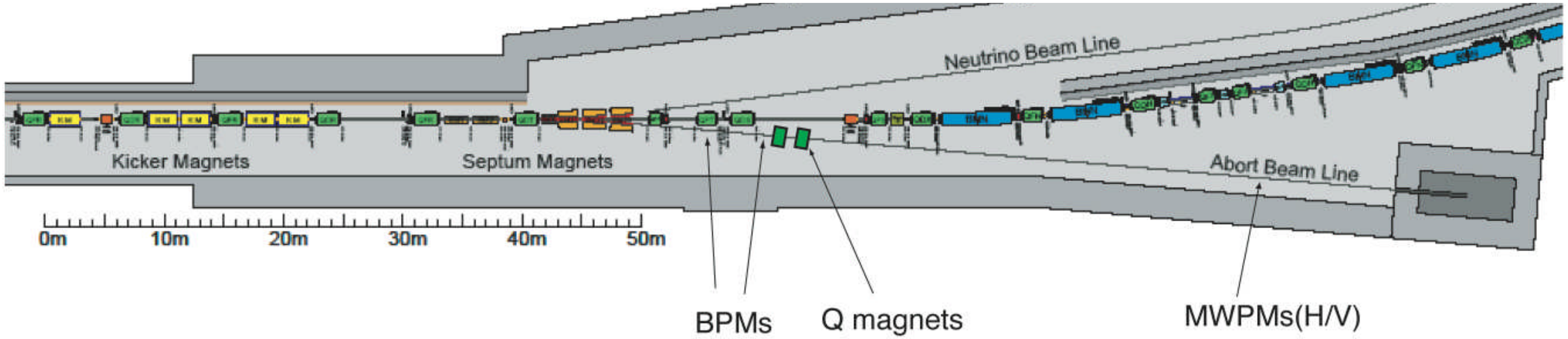
Tune Survey

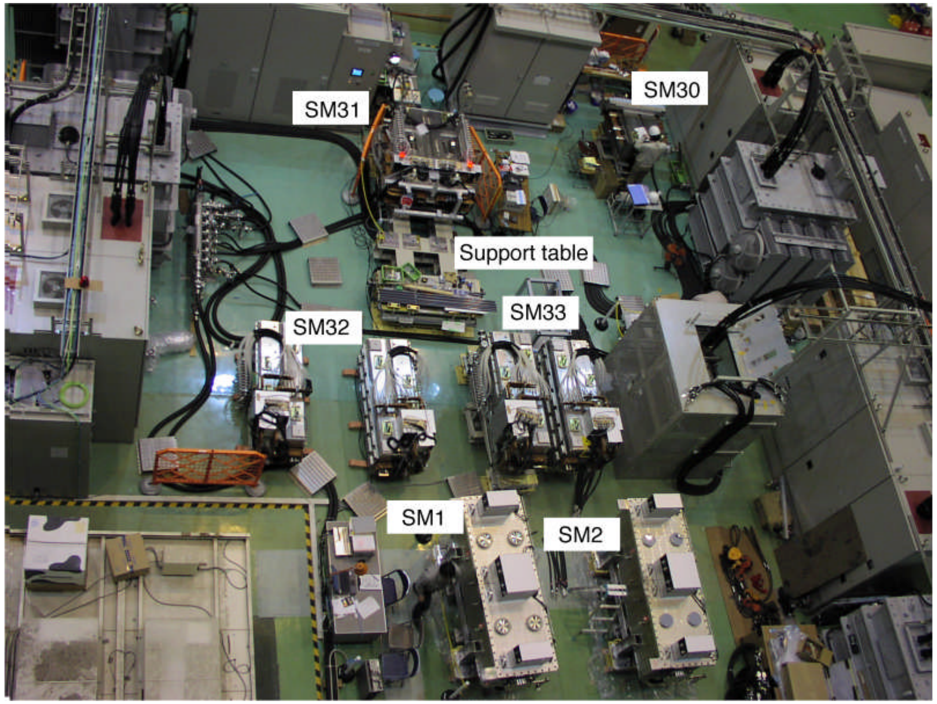


Transmission @ 0.86 sec after / Sextupole : ON
Survival rate
> 0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
< 0.1
ν x = 22
2 ν x = 45
ν x + ν y = 43
ν y : ~20.78 Fixed / Sextupole : ON
Transmission @ 0.86 sec after
ν y : ~20.70 Fixed / Sextupole : ON
Transmission @ 0.86 sec after
ν x : ~22.27 (22.3) Fixed / Sextupole : ON
Transmission @ 0.86 sec after
Transmission

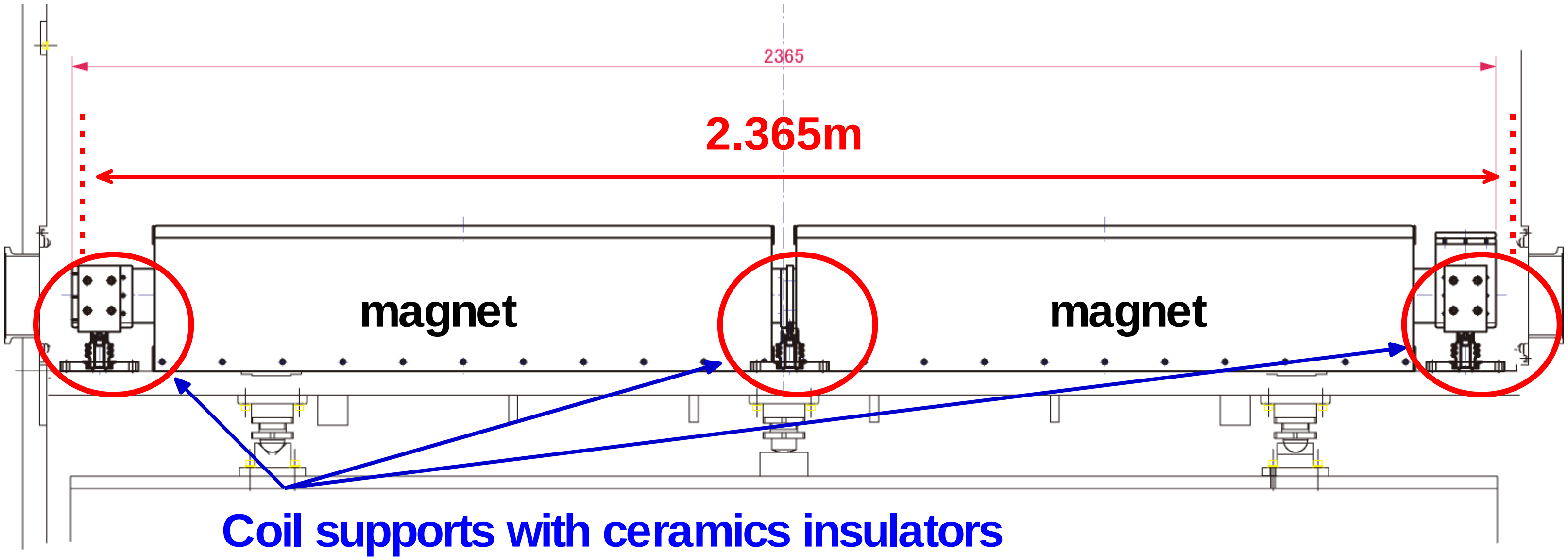
Fast extraction devices

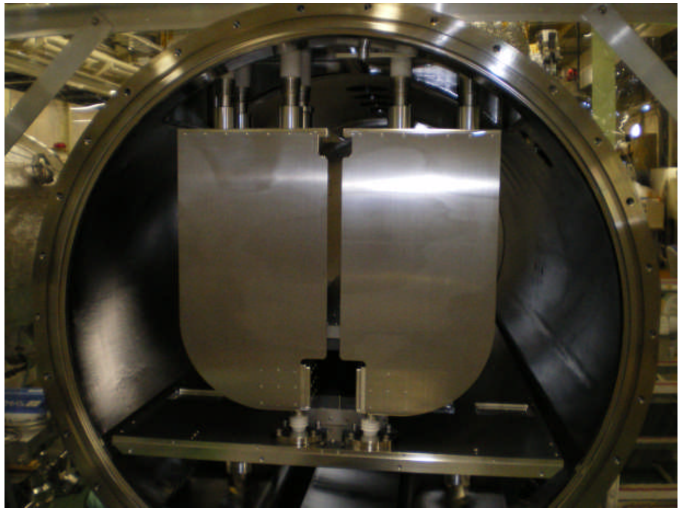
Fast extraction system comprises 5 bipoler kicker magnets and 8 bipolar septum magnet systems.





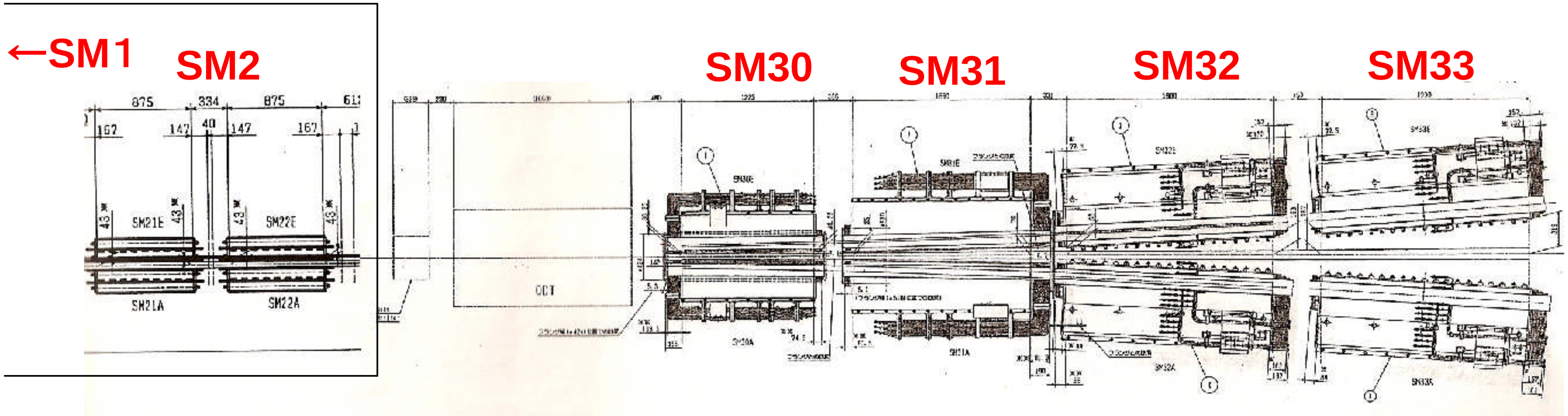
Lumped constant kicker magnet

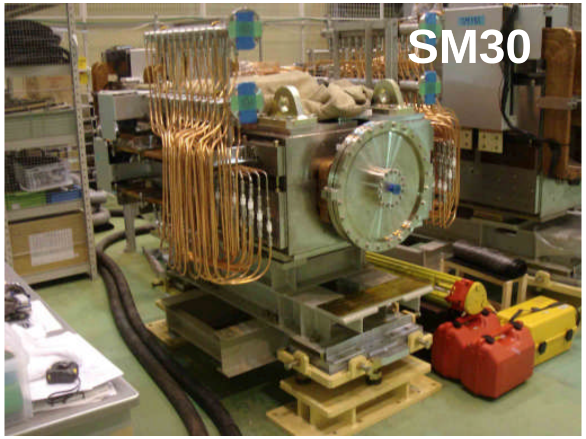


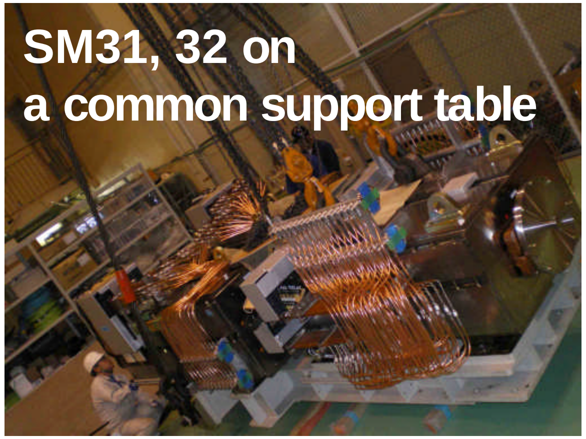


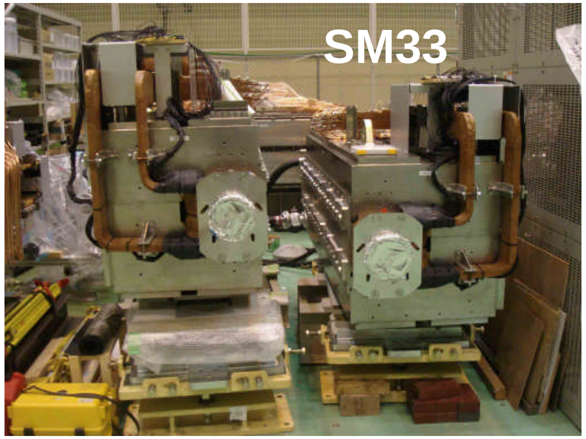
Vacuum chambers and ferrite cores of the traveling type kickers are used.
The maximum voltage between coil and ferrite cores is <1.5 kV/mm.

Fast extraction septum magnets









SM30-32 were Installed in the ring tunnel before the first MR beam.
SM33, SM1,2 were installed in summer of 2008.

Abort beam line

Abort beam is bent outward in the fast extraction section and transported to 7.5 kW dump.

- Beamline length ~ 73 m
- DC Q-doublet is installed at 10 m from the extraction point.

Quadrupole (recycled)

DC PS (recycled)

ϕ 746 Beam duct

The abort beamline components was installed in summer of 2008.

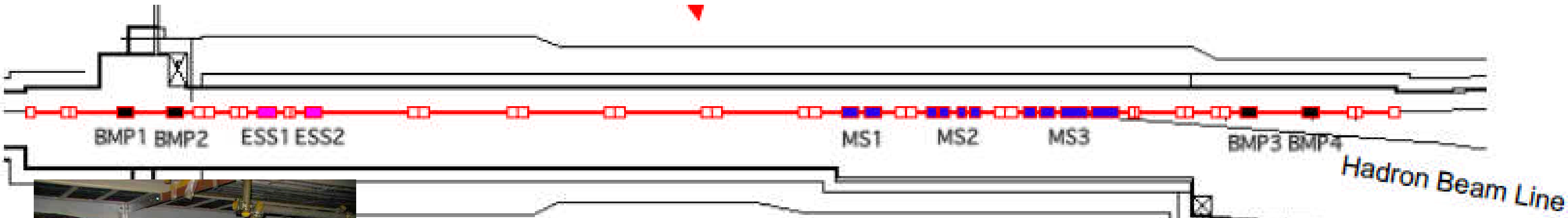
Slow extraction system

Installed before the first MR beam
Resonant Sextupole (8)

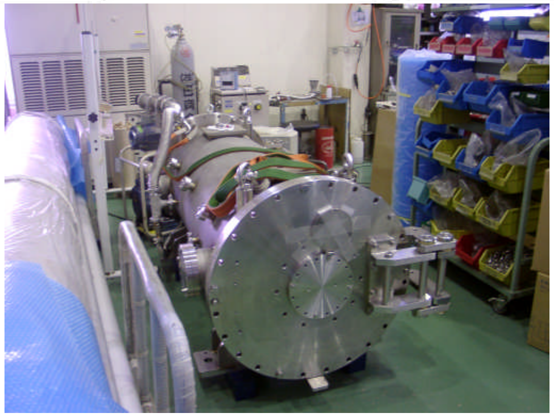
Manufactured in 2007,
installed in summer of 2008
Electro-static septum (2)
Thin septum magnets:
1.5 mm (1), 3.5 mm (1), 7.5 mm (4)

Strong field septum magnets (4)
Shift bump magnet (4)
Power supplies (recycled/manufactured)

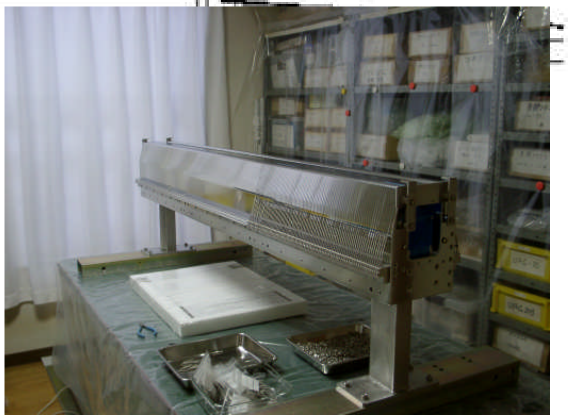
Manufactured in 2007-2008,
to be installed in summer of 2009
Extraction Q's for spill control



Resonant sextupoles



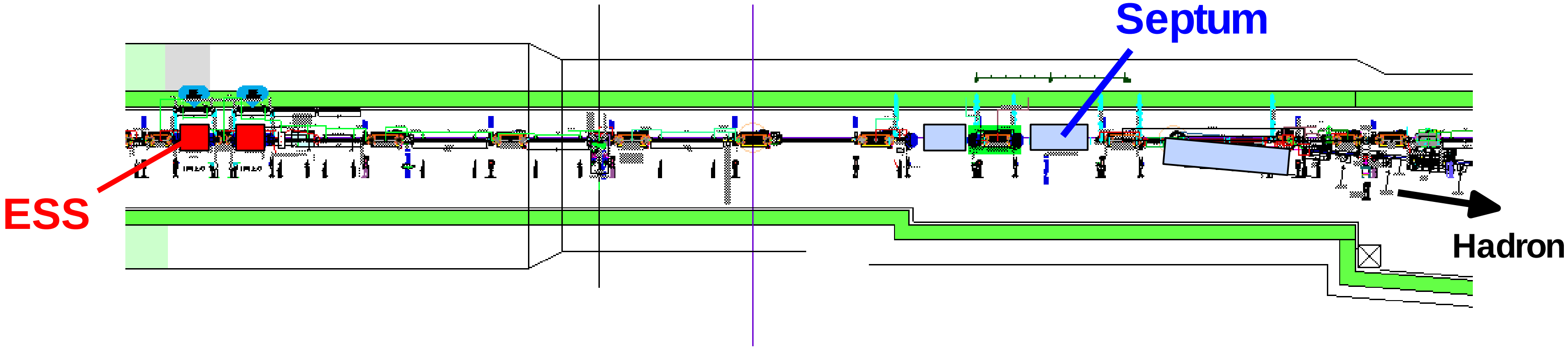
Vacuum vessel of ESS



Yoke and 30μm ribbon type septum of ESS

Details are given by M. Tomizawa

Slow Extraction procedure



bunched beam

↓ Turn off the RF

coasting beam without RF binding force (DC beam)

↓ move to ν_x = 22.333 and enhance the resonannce

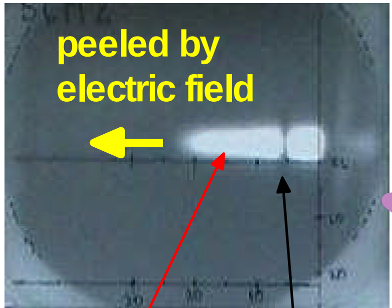
Particle motion becomes unstable due to the resonance.

expanding horizontally

peel off the spilled particles

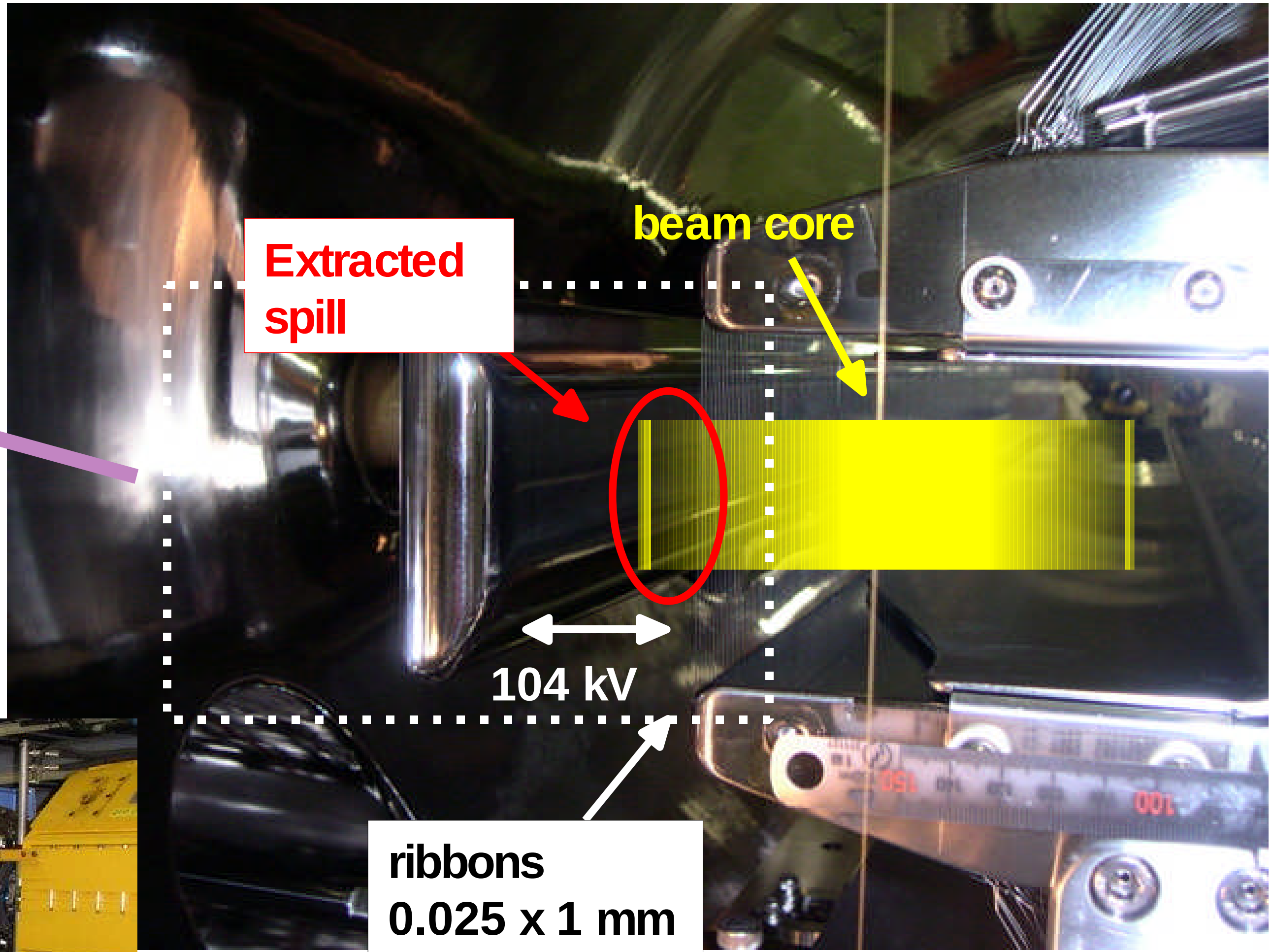
Beam peeling in Electro Static Septum

Observed beam
by the luminescence
screen monitor



Extracted
spill

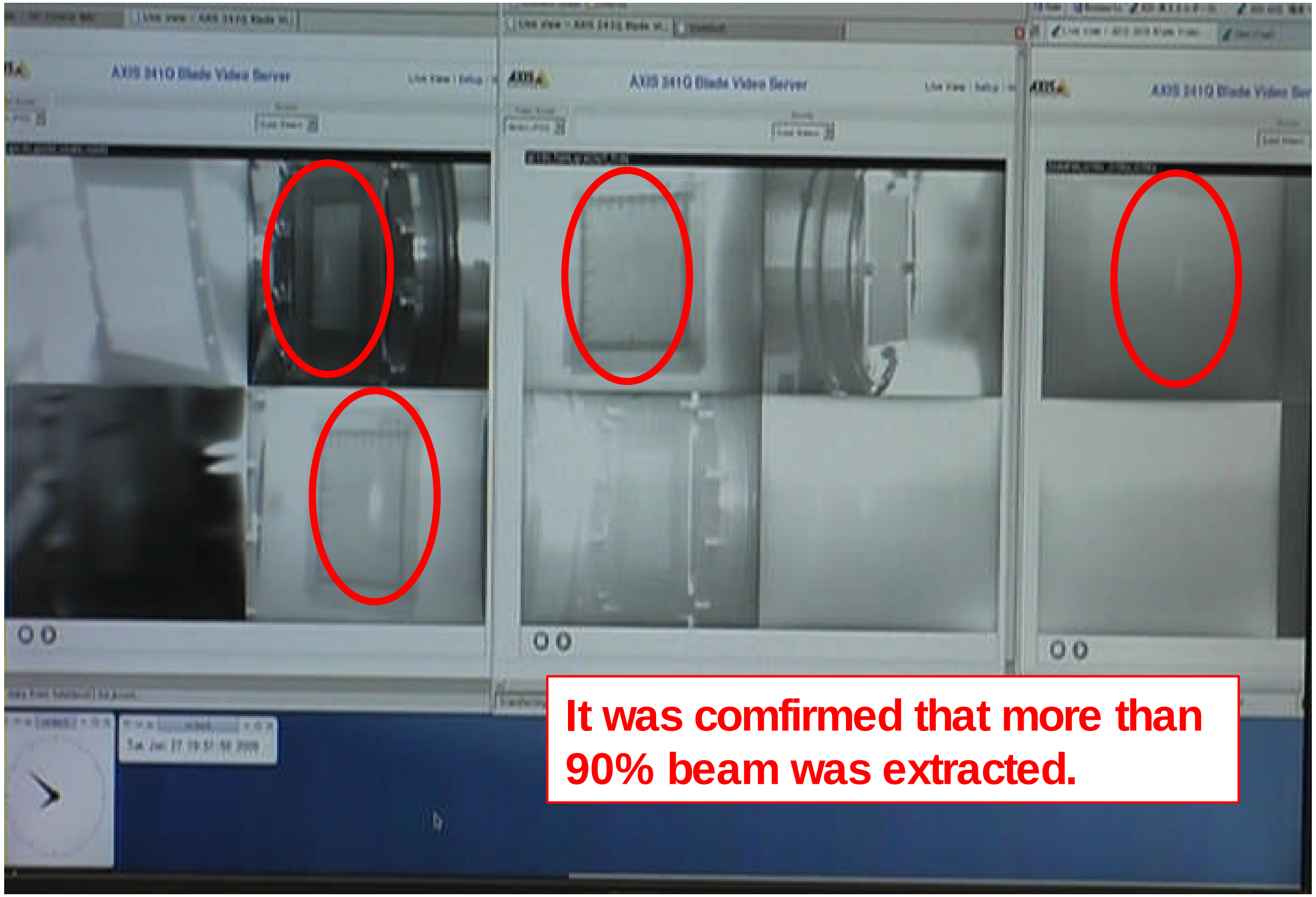
shadow
of ribbons



Inside view of ESS

Observed Beam Spill

Beam spot can be observed in some luminescence screen monitors in hadron beam line.



Present status of MR

Installation of accelerator components is now in progress as schedule.

Off beam commissioning has started in December 2007.
Beam commissioning has started in May 2008.

1st stage (May - June 2008)

3 GeV DC opetration

2nd stage (Dec. 2007- Feb. 2008)

Acceleration to 30 GeV

Beam extraction to the abort dump and hadron beamline

3rd stage (April - June 2009)

Beam extraction to neutrino beamline

The first mission has been COMPLETED !!

Milestones

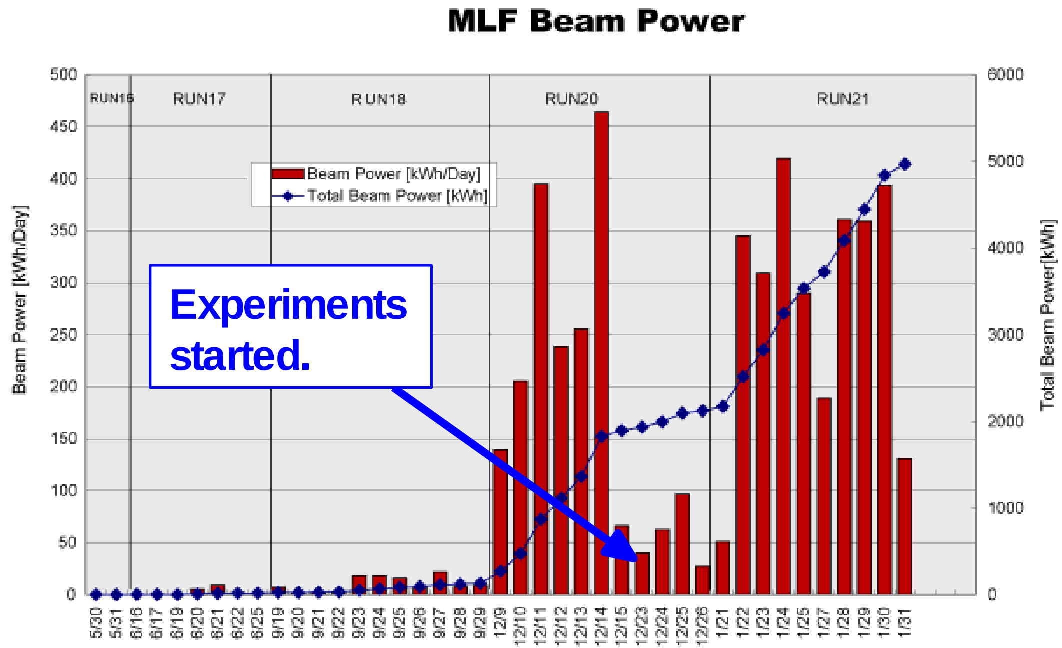
- Linac Beam Commissioning started in Nov, 2006.
- The linac accelerated the beam to a design value, 181 MeV on 24th Jan, 2007.
- RCS Beam Commissioning started in Oct., 2007.
- The RCS accelerated the beam to a design value, 3 GeV on 31st Oct, 2007.

- Beam Commissioning of MR started in May, 2008.
- Installation of FX and SX components were installed in summer, 2008.
- Hadron and Neutrino beamline components were installed in summer, 2008.
- MLF experiments started on 23rd Dec, 2008.

- The MR accelerated the beam to a design value, 30 GeV on 23rd Dec, 2009.
- Extraction to hadron beamline on 27th Jan, 2009.
- Secondary beam was comfirmed 11th Feb, 2009.
- Extraction to neutrino beamline on 23rd April, 2009.
- Neutrino beam was comfirmed 23rd April, 2009.

Present status of MLF

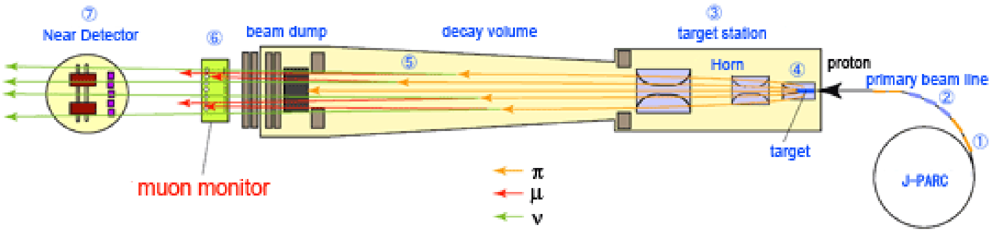
Since 30th May, 2008

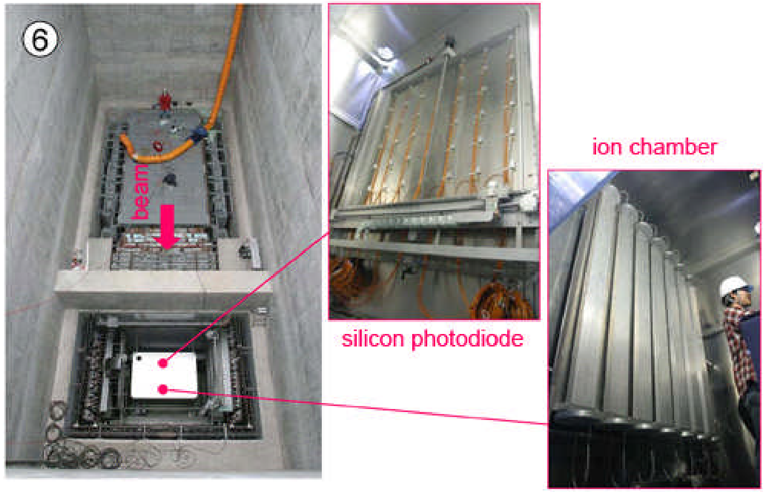


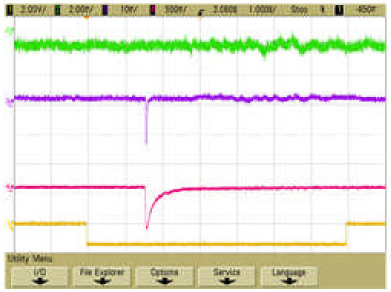
Available beam lines:

BL01 4D space access neutron spectrometer (4 SEASONS)
BL03 IBARAKI Biological Crystal Diffractometer (iBIX)
BL04 Neutron-Nucleus Reaction Instrument (NNRI)
BL08 Super high resolution powder diffractometer (SuperHRPD)
BL10 NeutronBeam-line for Observation and Research Use (NOBORU)
BL14 Cold-neutron disk-chopper spectrometer (AMATERAS)
BL16 High-Performance Neutron Reflectometer with a Horizontal Sample Geometry (ARISA-II)
BL19 Engineering Diffractometer (TAKUMI)
BL20 IBARAKI Materials Design Diffractometer (iMATERIA)
D1 D1 instrument (Muon beam line)

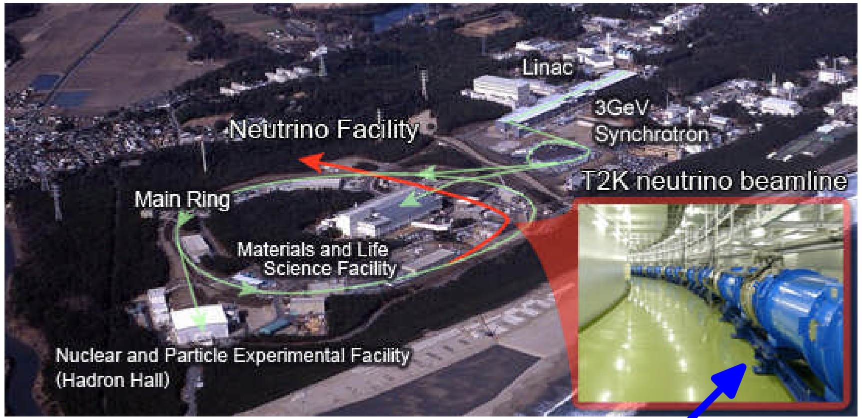
Observation of the neutrino beam production







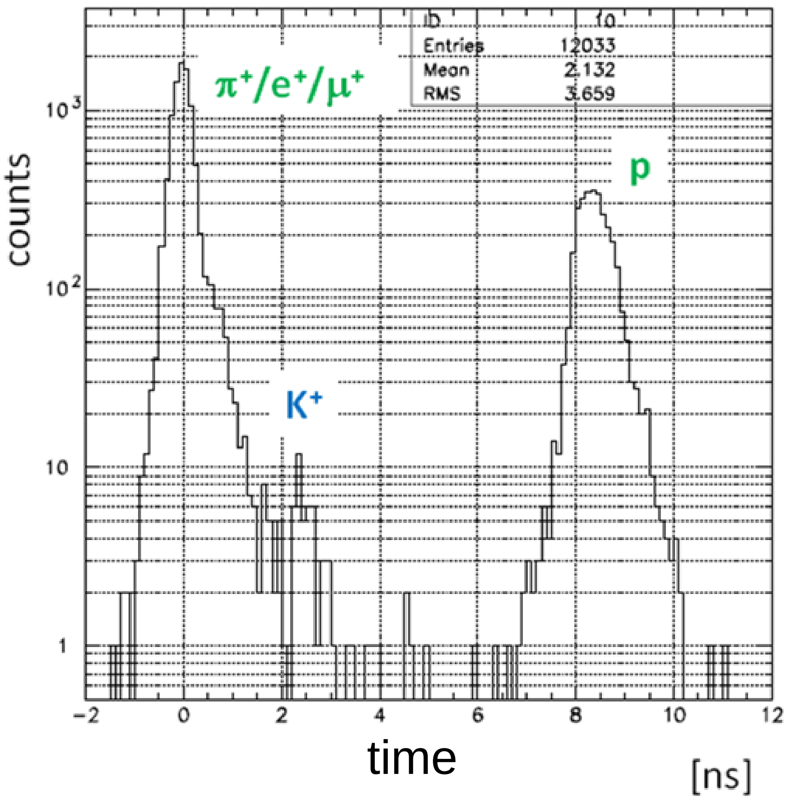
Muon Monitor and its first muon signal.



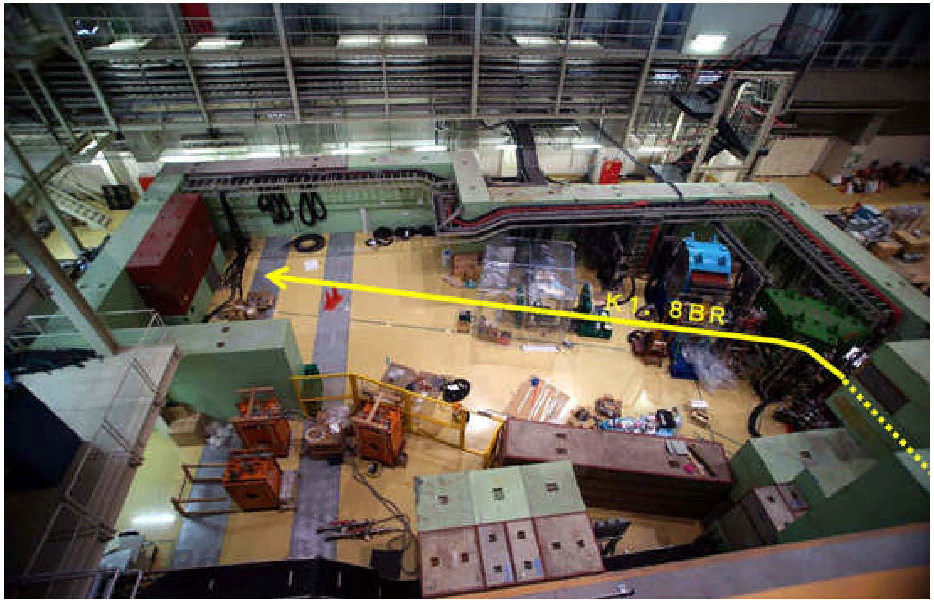
Superconducting bending magnets

Identification of kaons

Joint experimental team, E17 lead by Prof. R. Hayano, University of Tokyo and E15, lead by Dr. M. Iwasaki, Riken, has successfully confirmed kaon generation in the secondary beams at the K1.8BR. (J-PARC News)



TOF spectrum



For more details,

Please ask to the machine staff at J-PARC

Thank you for your attension !!