NBI 2014@FNAL
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J-PARC Accelerator
- Status and upgrade plan -

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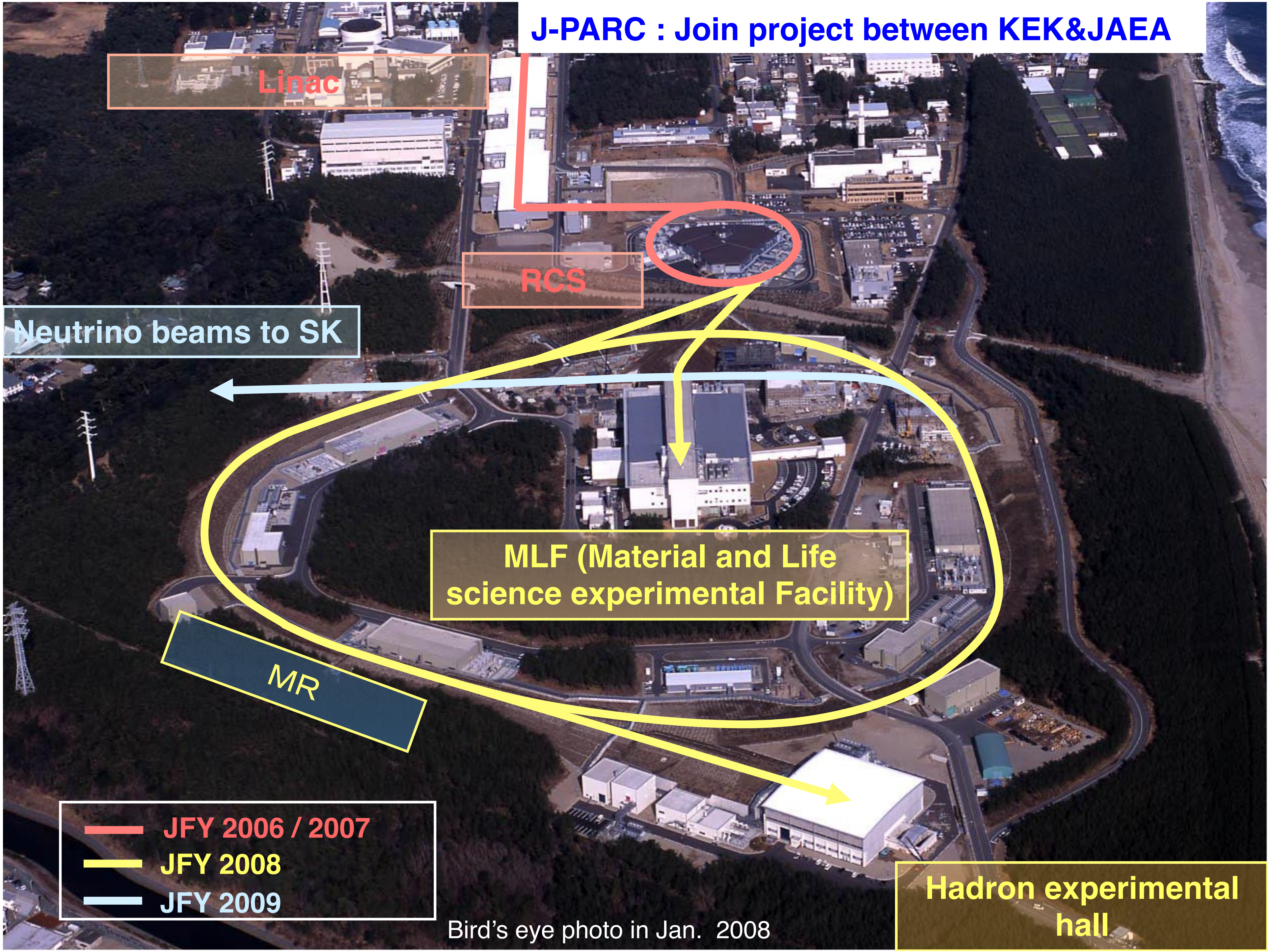
Contents

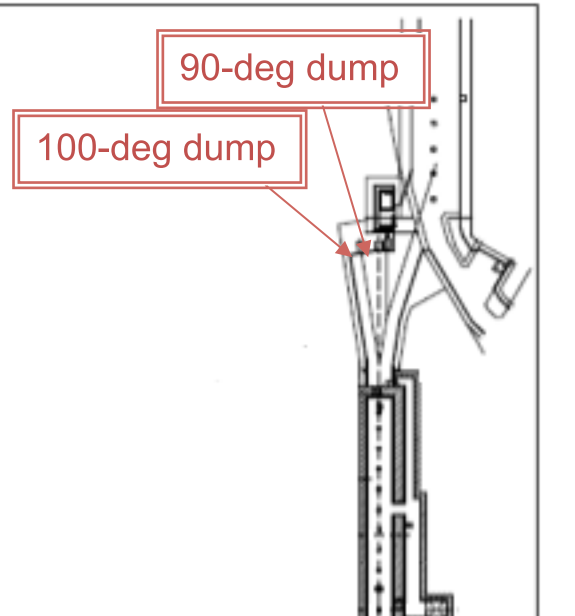
Overview of J-PARC facilities



Bird’s eye photo in Jan. 2008

Linac

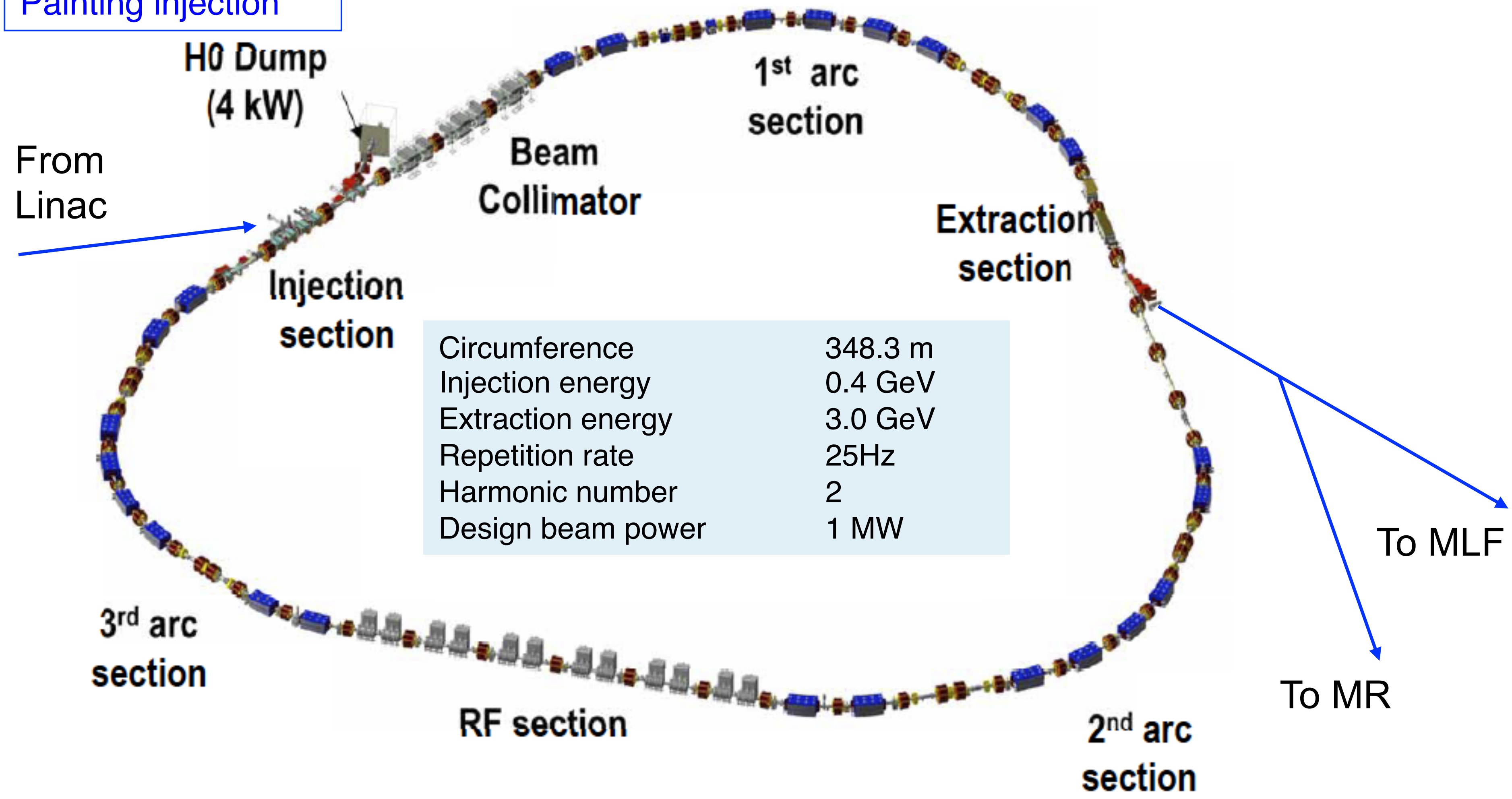
- **Particle:** H$^-$
- **Energy:** 181 MeV (~ May 2013)
  400 MeV (Jan. 2014~) by installing ACS
- **Peak current:** 30 mA (~ June 2014)
  50 mA by replacing front-end in 2014
- **Repetition:** 25 Hz
- **Pulse width:** 0.5 msec



RCS (Rapid Cycling Synchrotron)

Two purposes of the RCS:
- Proton driver for neutron/muon production in MLF
- Booster of the MR injection

Charge-exchange & Painting injection

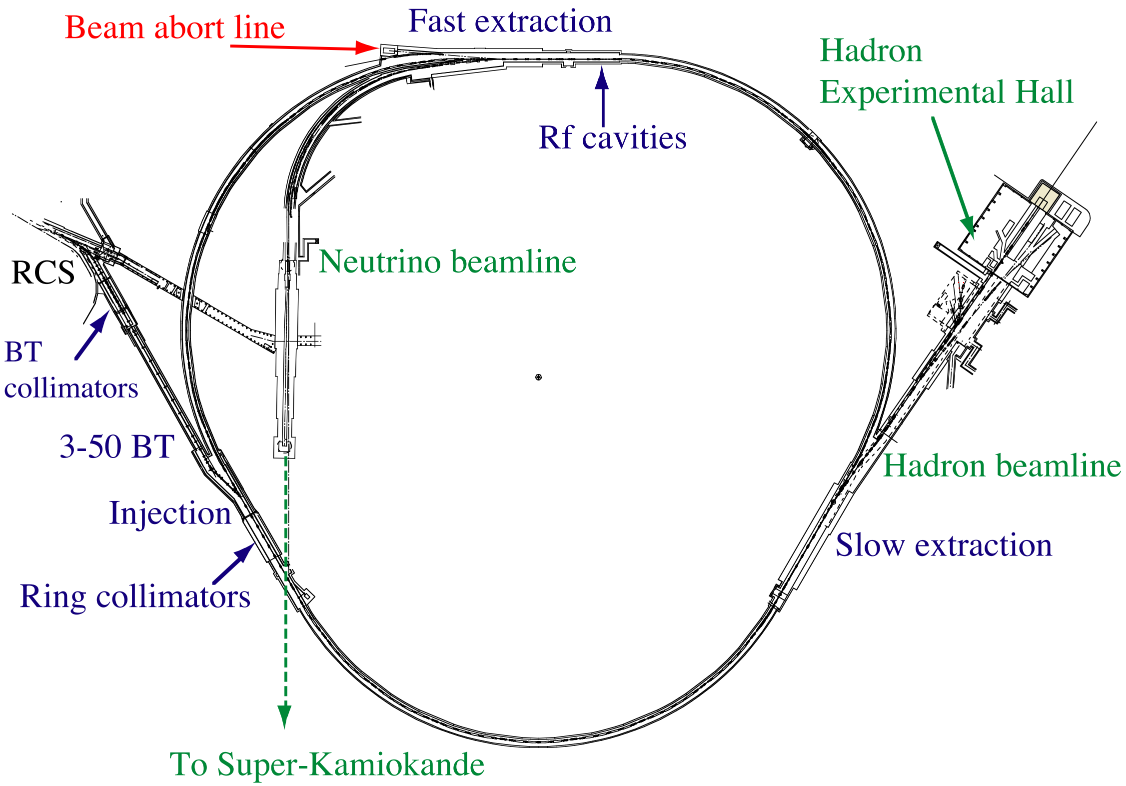


Circumference	348.3 m
Injection energy	0.4 GeV
Extraction energy	3.0 GeV
Repetition rate	25Hz
Harmonic number	2
Design beam power	1 MW

Main parameters of MR

Circumference	**1567.5 m**
Cycle time	**6 s for SX**
	2.48 s for FX
Injection energy	**3 GeV**
Extraction energy	**30 GeV**
Superperiodicity	**3**
h	**9**
Number of bunches	**8**
Rf frequency	**1.67 - 1.72 MHz**
Transition γ	**j 31.7 (typical)**

Physical Aperture	
3-50 BT Collimator	**54-65 π.mm.mrad**
3-50 BT physical ap.	**> 120 π.mm.mrad**
Ring Collimator	**54-65 π.mm.mrad**
Ring physical ap.	**> 81 π.mm.mrad**



Three dispersion free straight sections of 116-m long:

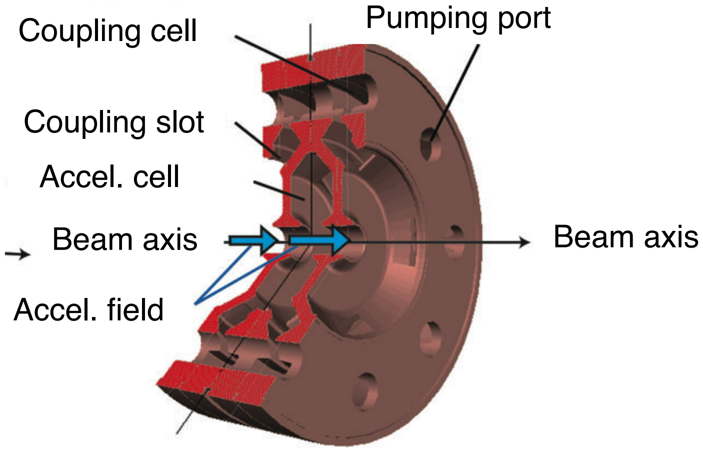
- **Injection and collimator systems**
- **Slow extraction (SX)**
  to Hadron experimental Hall
- **MA loaded rf cavities and Fast extraction(FX) (beam is extracted inside/outside of the ring)**
  outside: Beam abort line
  inside: Neutrino beamline (intense ν beam is send to SK)

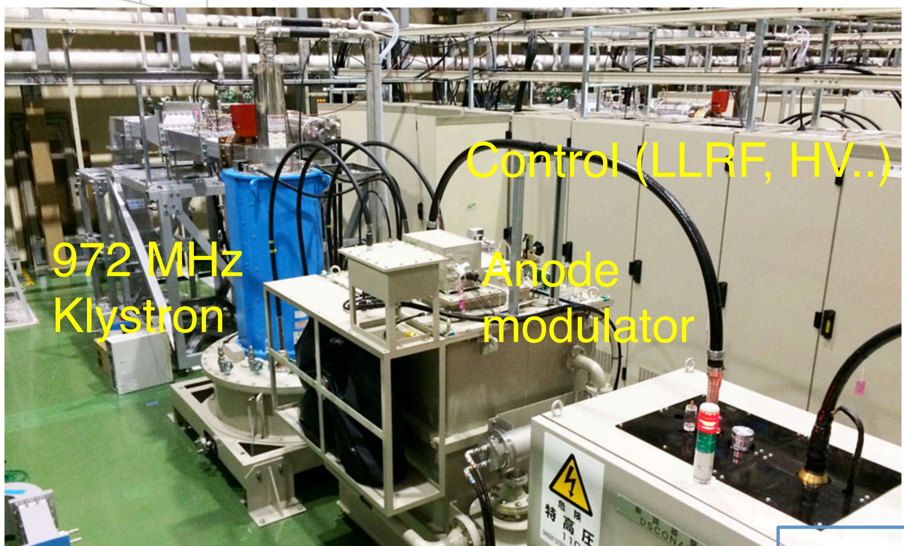
Status of accelerator operation and achievements

The ACS system

The ACS (Annular-ring Coupled Structure linac) system

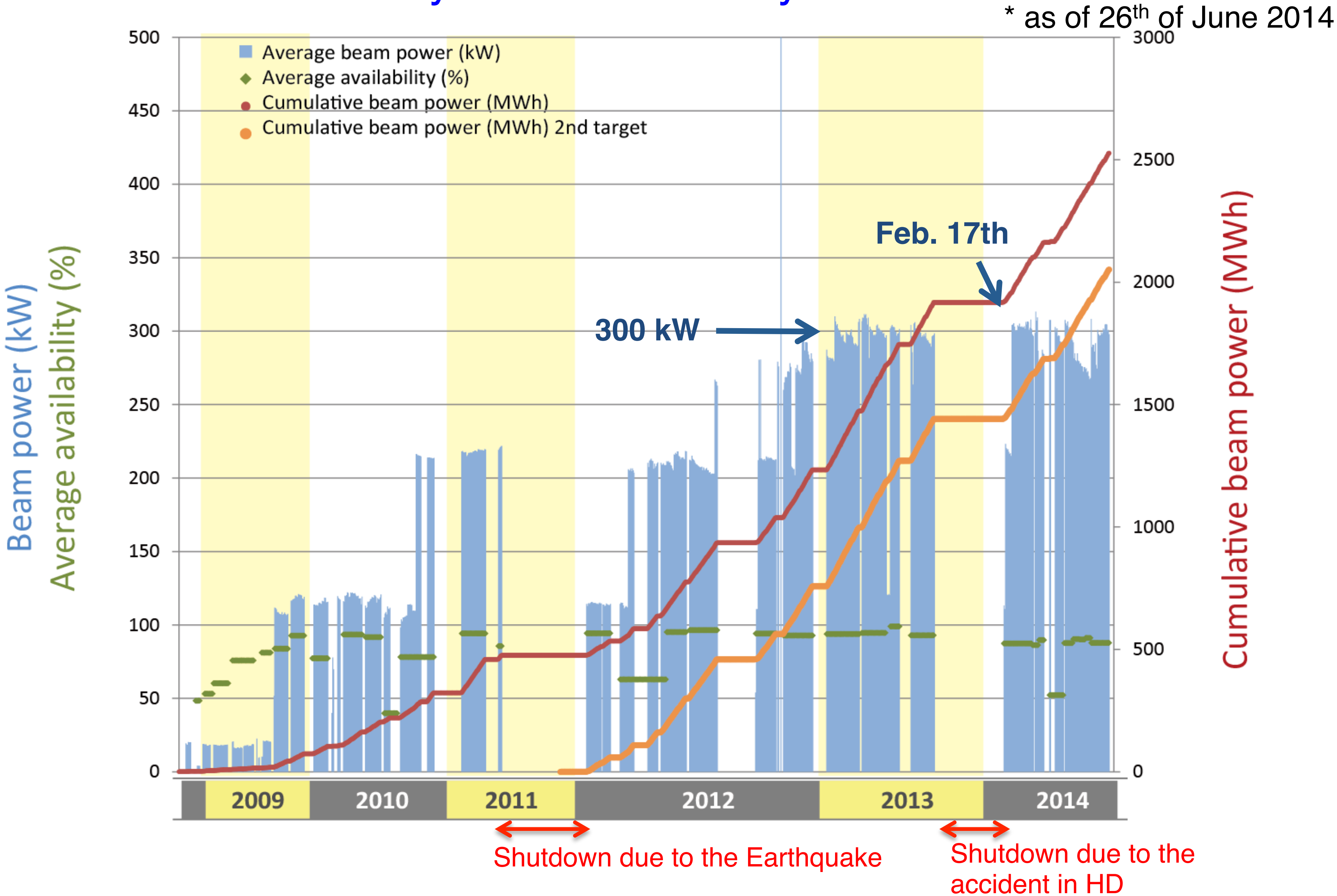
- Frequency : 972 MHz
- 21 accelerating modules
- 4 debuncher modeules





400-MeV acceleration was achieved on Jan. 17, 2014.

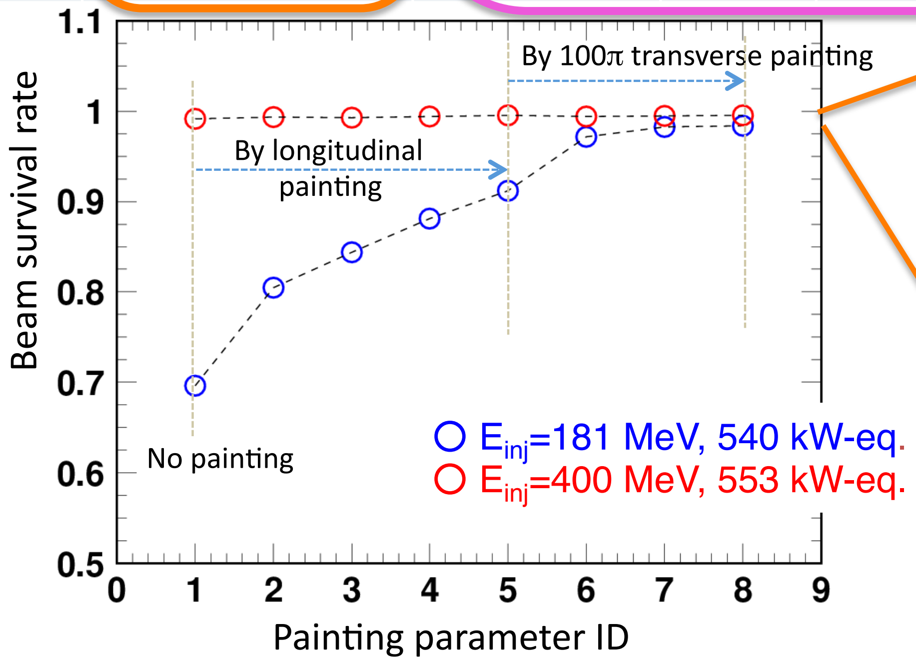
History of beam delivery to the MLF

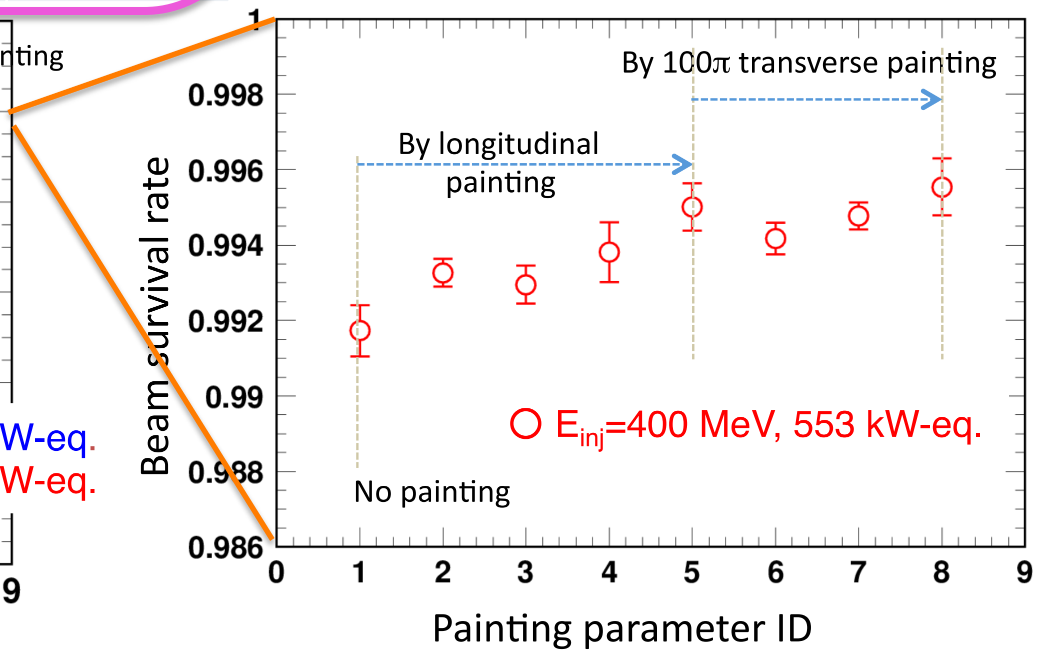


After the 9-month shutdown due to the accident in the HD hall, beam operation resumed in Feb. 2014.

Painting parameter dependence of beam loss

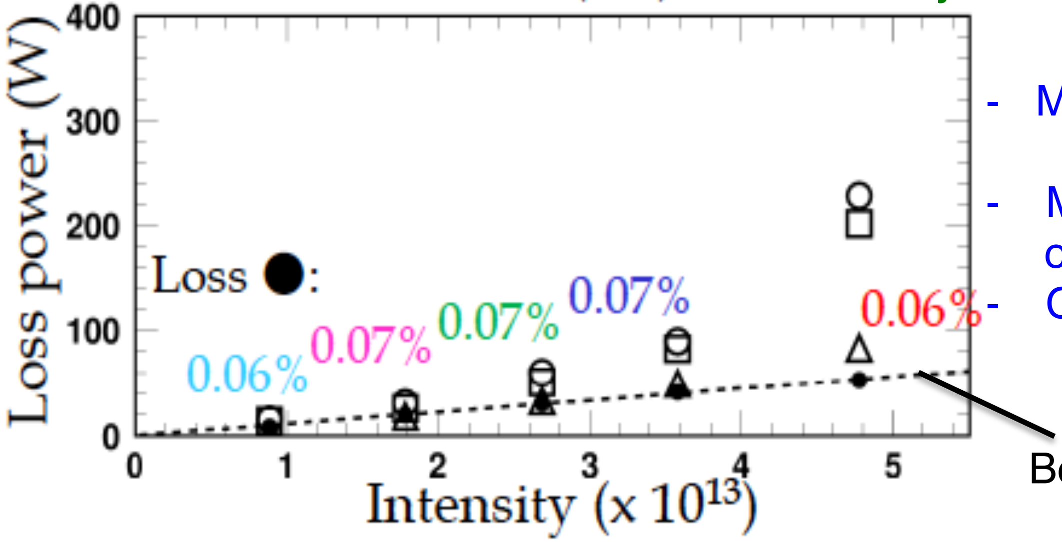
ID	Trans.-paint (π mm mrad)	RF V_2/V_1 (%)	ϕ_2 (deg)	dp/p (%)
1	-	-	-	-
2	100	-	-	-
3	-	80	-100	-0.0
4	-	80	-100	-0.1
5	-	80	-100	-0.2
6	100	80	-100	-0.0
7	100	80	-100	-0.1
8	100	80	-100	-0.2





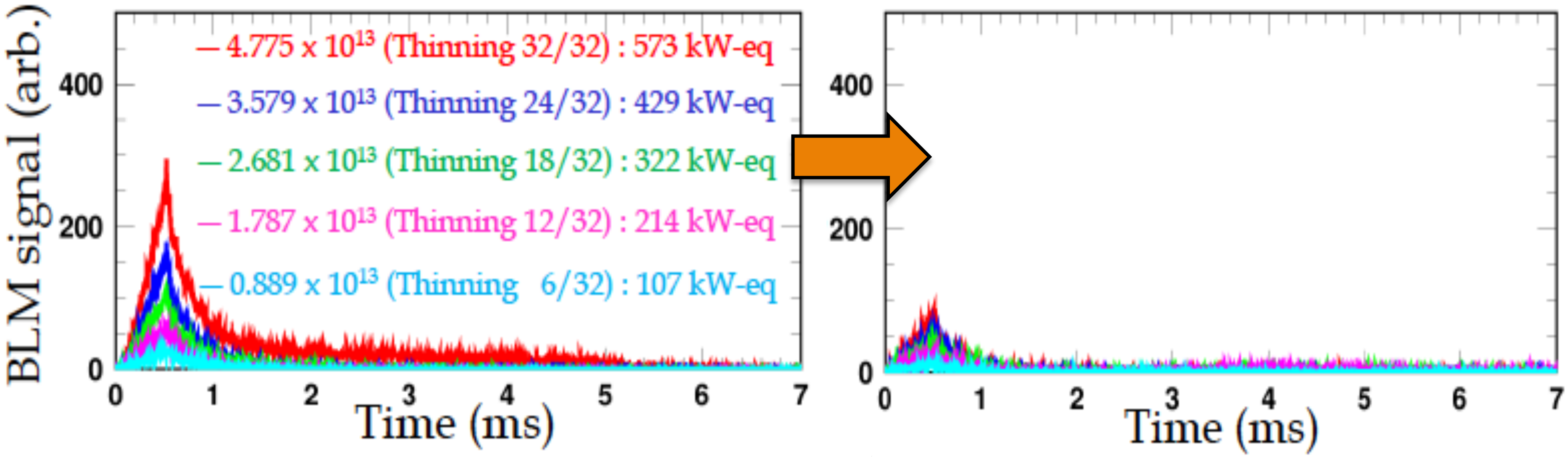
Minimization of beam loss

Results of beam study in the end of June, 2014.



- Momemtum spread of the injection beam
  dp/p : 0.106 % → 0.066 % : ○→□
- Mismatch correction of the Twiss parameters of the injection beam :□→△
- Operating point
  (νx, νy)=(6.45,6.42) →(6.38, 6.42):△→●

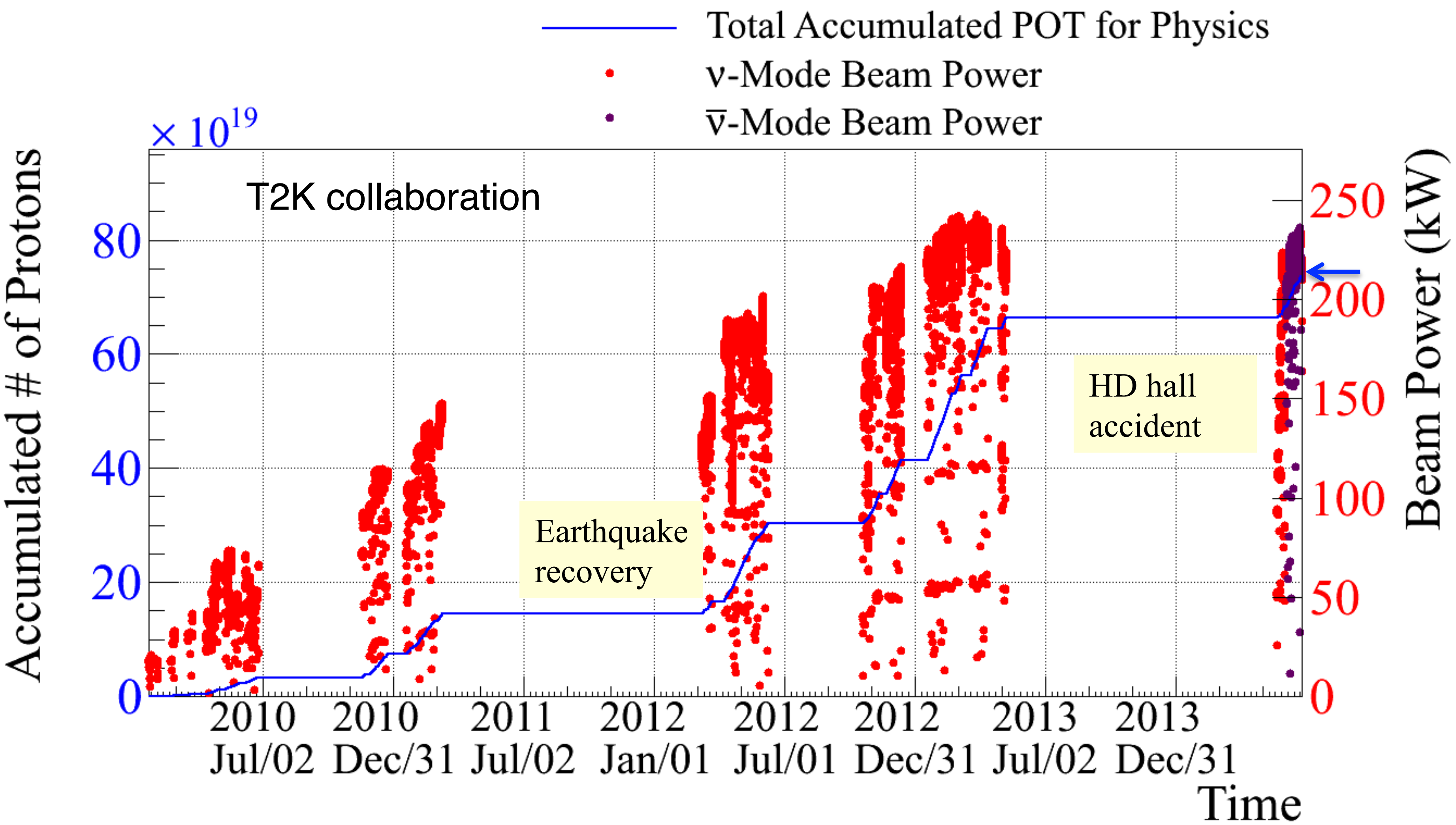
Beam loss due to the foil scattering



Beam loss of the RCS is well understood and minimized.

Beam delivery to the T2K experiment

* as of 26th of June 2014



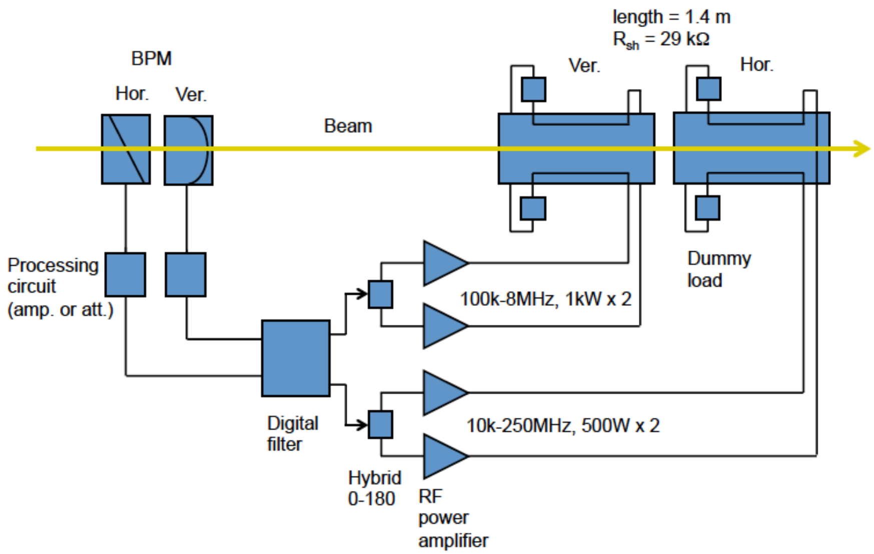
The max. delivered beam power ~ 240 kW (1.24×10^{14} ppp)

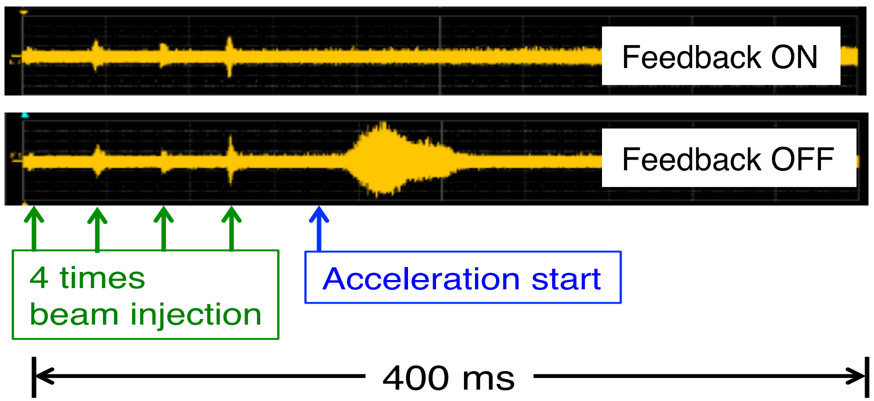
Accumulated number of proton ~7.5×10^{20} POT.

Feedback system for suppression of beam instability

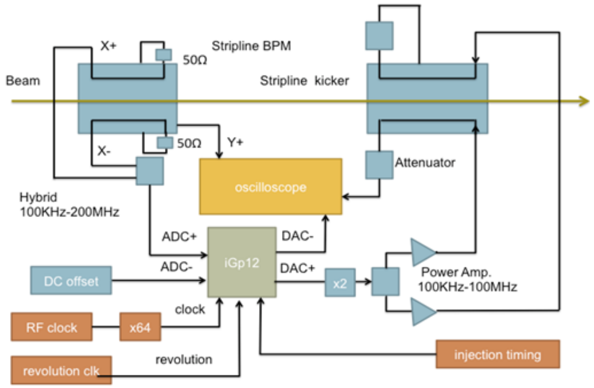
Transverse instabilities are observed at the injection and the beginning of acceleration at the MR.
The instabilities are suppressed by the bunch feedback systems.

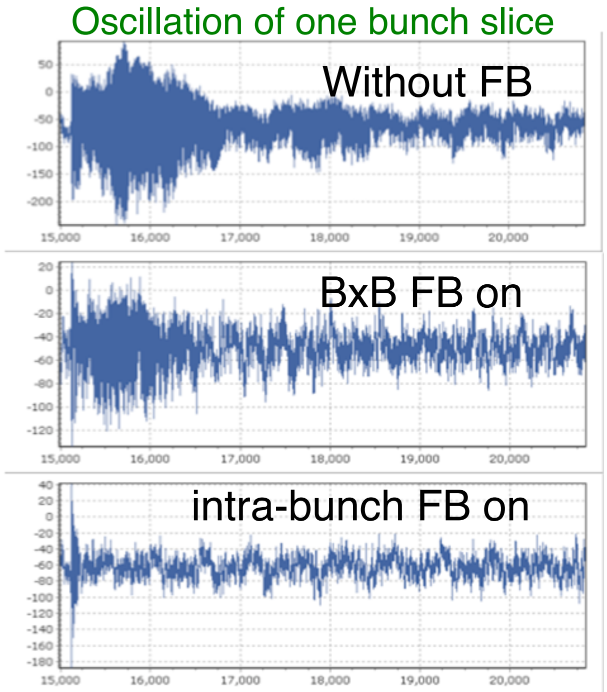
BxB FB (narrow-band FB) since 2012

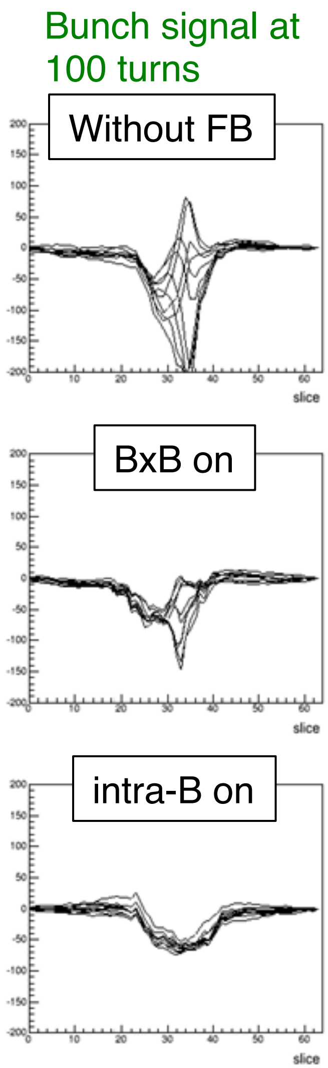




Intra-bunch FB (wide-band FB) since 2014





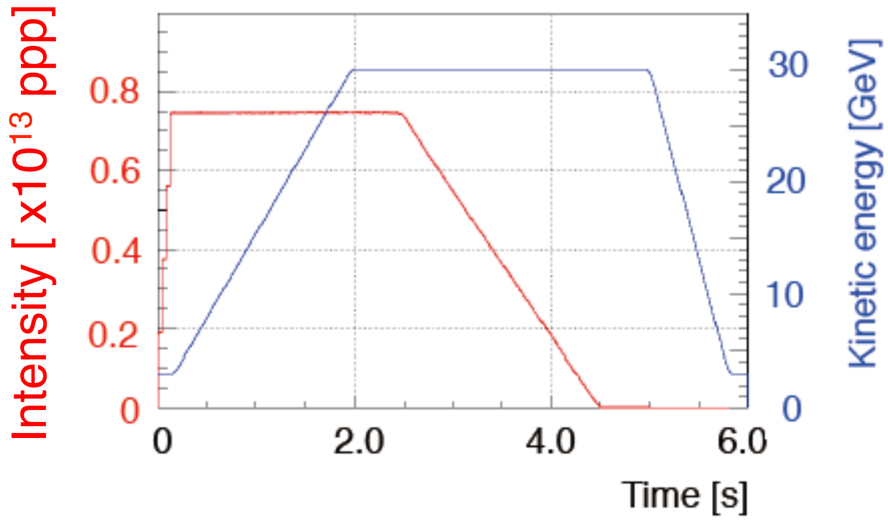


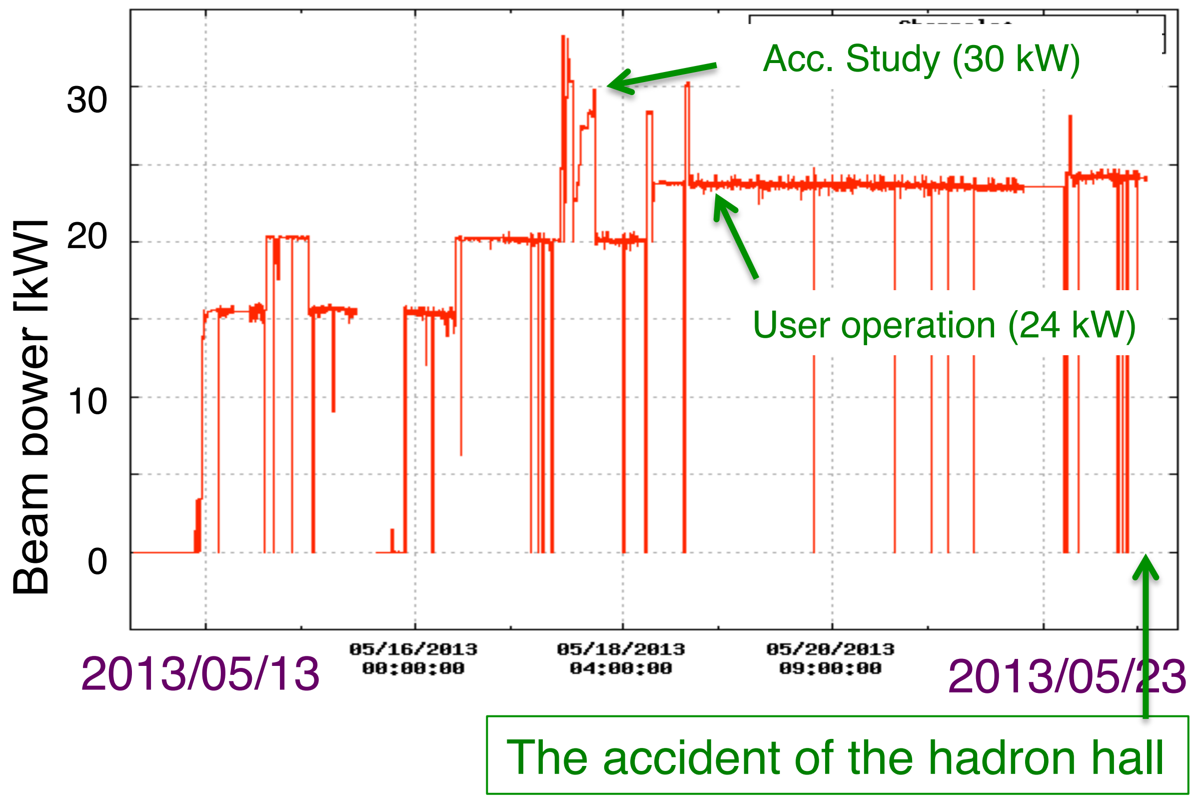
Slow Extraction

- Third-integer resonance extraction
  (νx=67/3)

- Extraction efficiency ~ 99.5 %
  with the "dynamic bump" system

- Beam power
  ~ 15 kW (until April 2013)
  ~ 24 kW (from May 18, 2013)

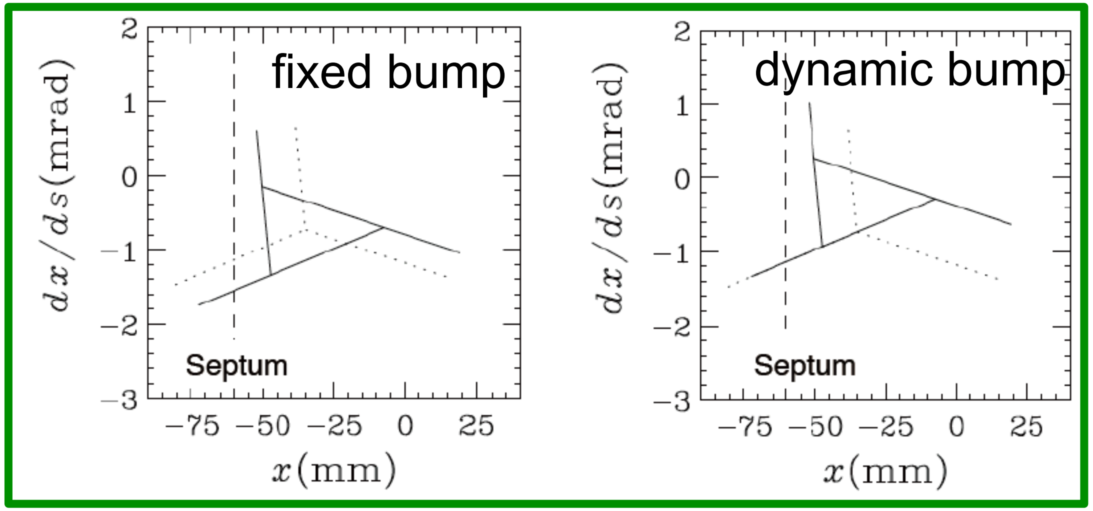


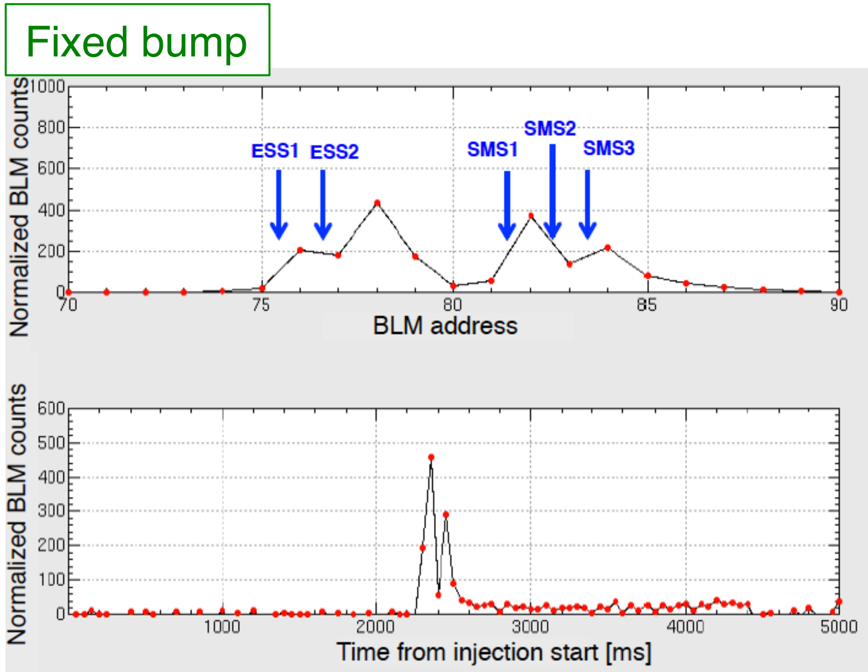


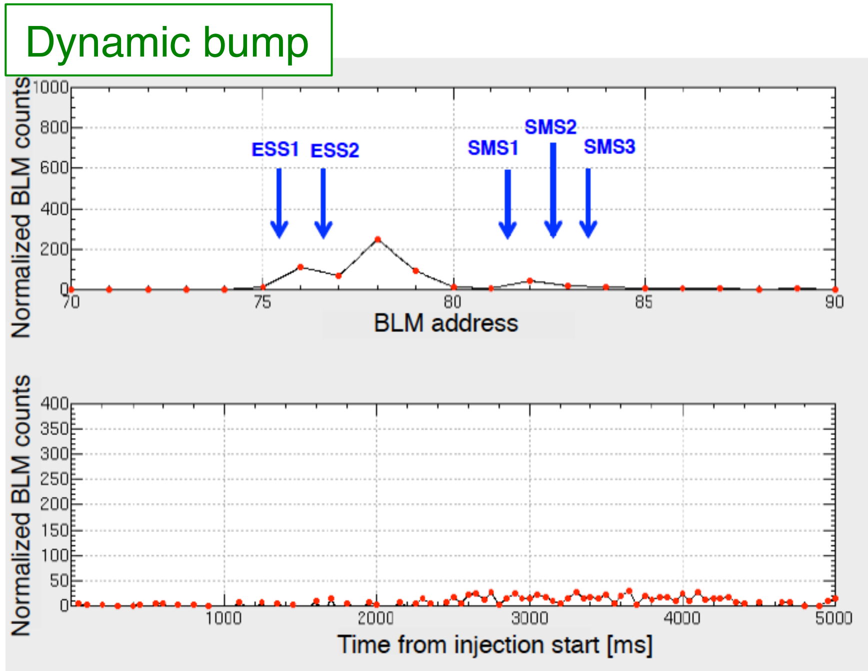
Slow extraction with dynamic bump system

Dynamic-bump system : The center of the separatrix is adjusted to fix the beam angle at the ESS septum during the extraction. It can reduce the impact rate of the beam on the septum.

Separatrices at the ESS for the fixed and dynamic bump schemes.

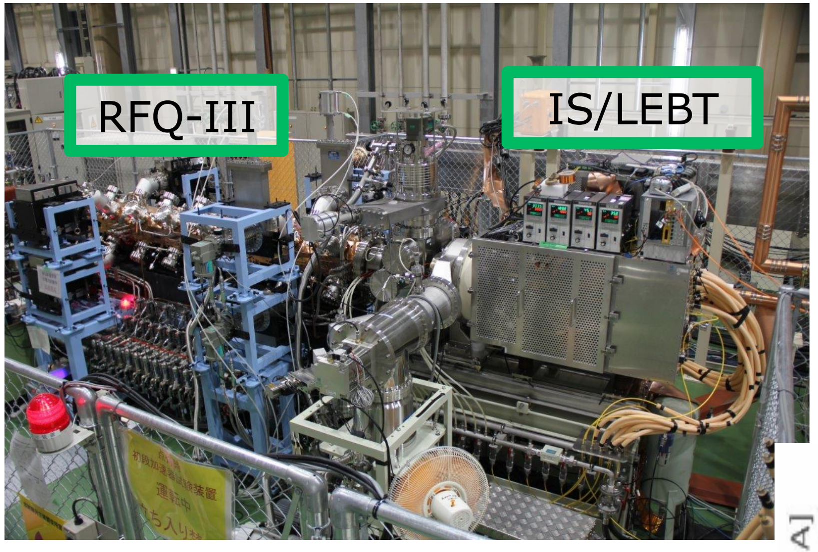




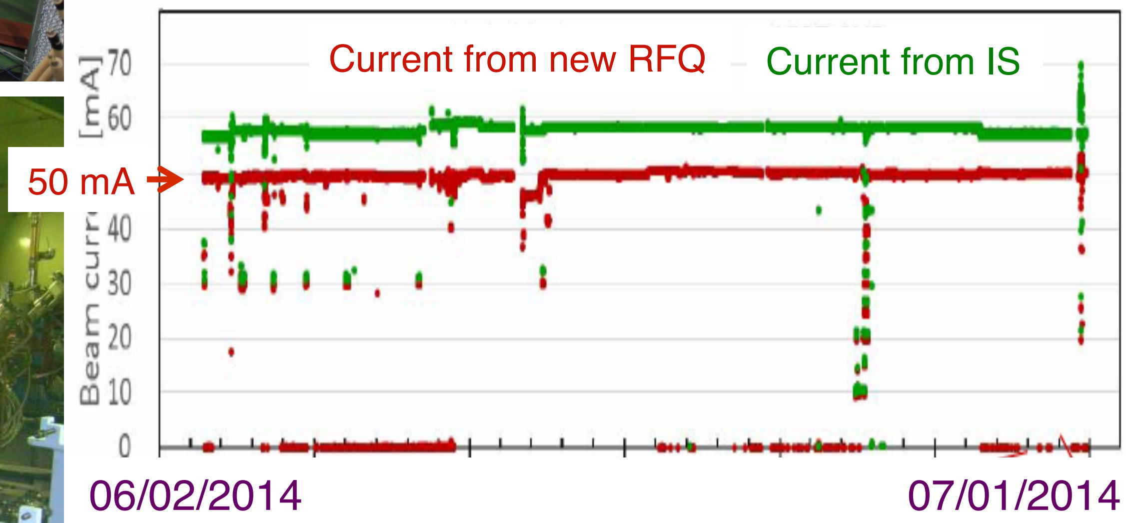


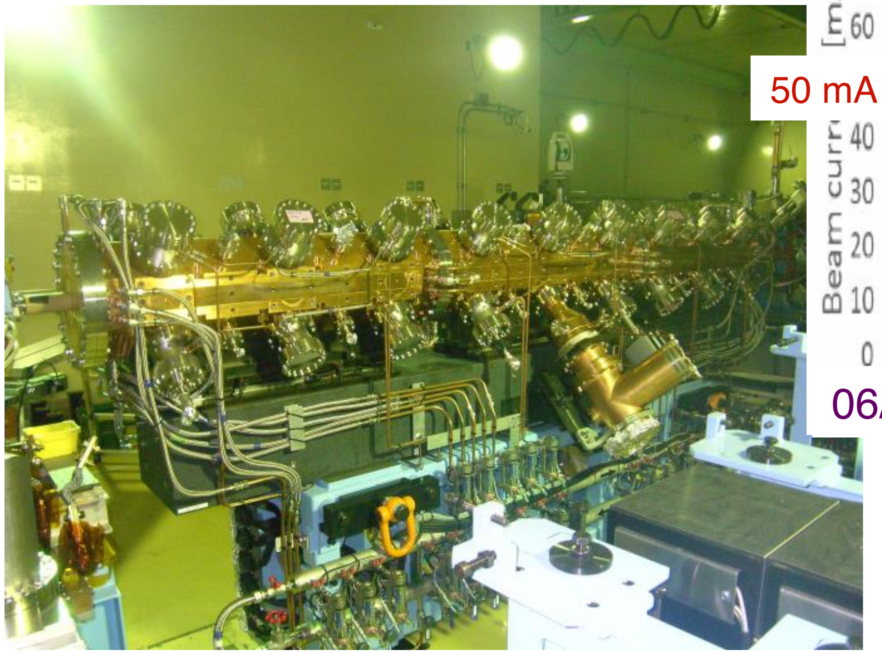
Status of new front-end system for peak current upgrade

An newly developed rf-driven H^- ion source and new RFQ for the peak current of 50 mA were tested in a test bench. Long-term continuous operation of 50 mA for one month was successfully demonstrated .



Long-term continuous operation in the test bench





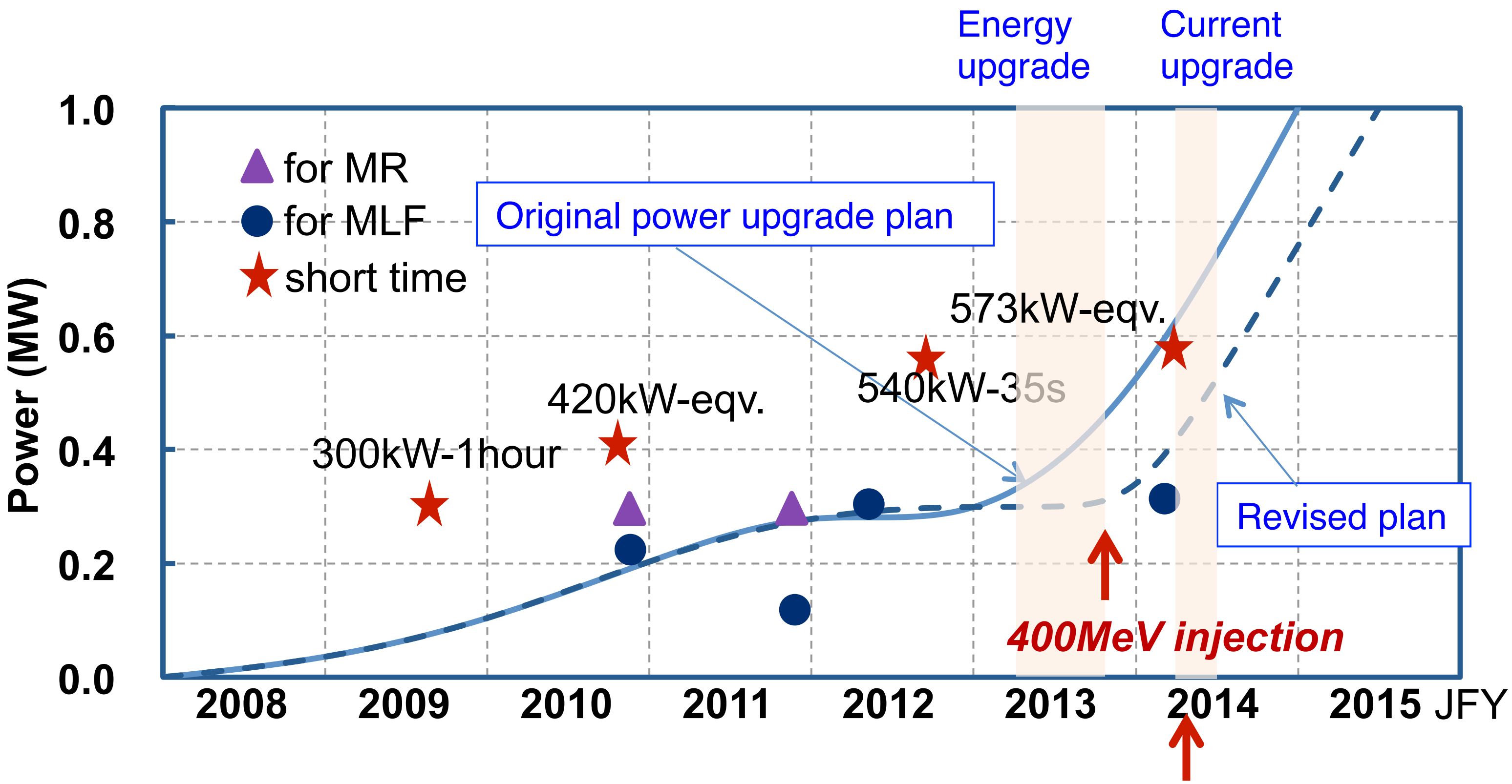
The front-end system installed in the linac tunnel in August, 2014.

Medium-term plan in JFY2013-2017

- Linac upgrade in 2013 (and 2014)
- RCS 1 MW by 2015
- MR-FX 750 kW by 2017 with high repetition rate operation
- MR-SX 100 kW by 2017

The mid-term plans for the five years from 2013 to 2017 were endorsed by the review committee meeting held in March – May of 2012 in MEXT.

RCS power upgrade plan



User operation of the 1-MW beam power will start in JFY2015.

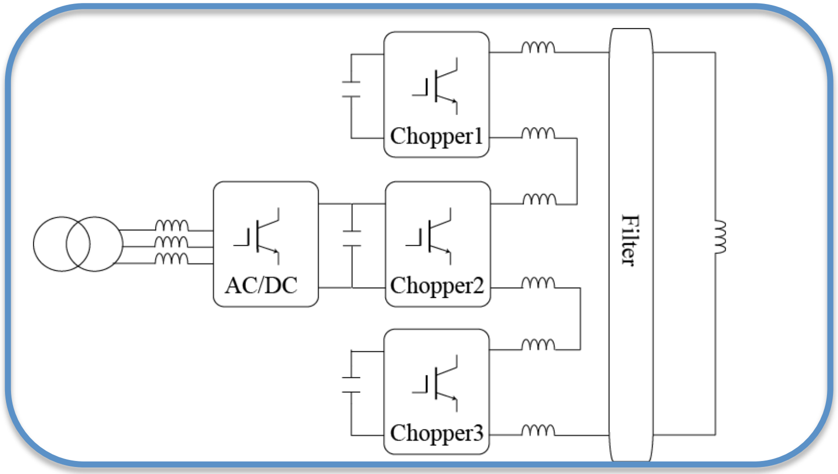
Mid-term plan of MR

FX: The high repetition rate scheme is adopted to achieve the design beam intensity, 750 kW. Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's and RF cavities.
SX: Parts of stainless steel ducts are replaced with titanium ducts to reduce residual radiation dose. The beam power will be gradually increased toward 100 kW watching the residual activity.

JFY	2011	2012	2013	2014	2015	2016	2017
			Li. energy upgrade	Li. current upgrade			
FX power [kW] (study/trial)	**150**	**200**	**200 - 240**	**200 –300 (400)**	→	→	**750**
SX power [kW] (study/trial)	**3 (10)**	**10 (20)**	**25 (30)**	**20-50**	→	→	**100**
Cycle time of main magnet PS	3.04 s	2.56 s	2.48 s				1.3 s
New magnet PS for high rep.	R&D →	R&D →	R&D →	R&D →	Manufacture installation/test →	Manufacture installation/test →	→
Present RF system	Install. #7,8	Install. #9					
New high gradient rf system	R&D →	R&D →	R&D →	Manufacture installation/test →	Manufacture installation/test →	Manufacture installation/test →	Manufacture installation/test →
Ring collimators	Additional shields	Add.collimators and shields (2kW)	Add.collimators (3.5kW)				
Injection system	Inj. kicker	Kicker PS improvement, Septa manufacture /test →	→	→	→	→	→
FX system		Kicker PS improvement, LF septum, HF septa manufacture /test →	→	→	→	→	→
SX collimator / Local shields	SX collimator				Local shields →	Local shields →	Local shields →
Ti ducts and SX devices with Ti chamber		SX septum endplate	Beam ducts	Beam ducts ESS			

New power supplies for 1 Hz operation

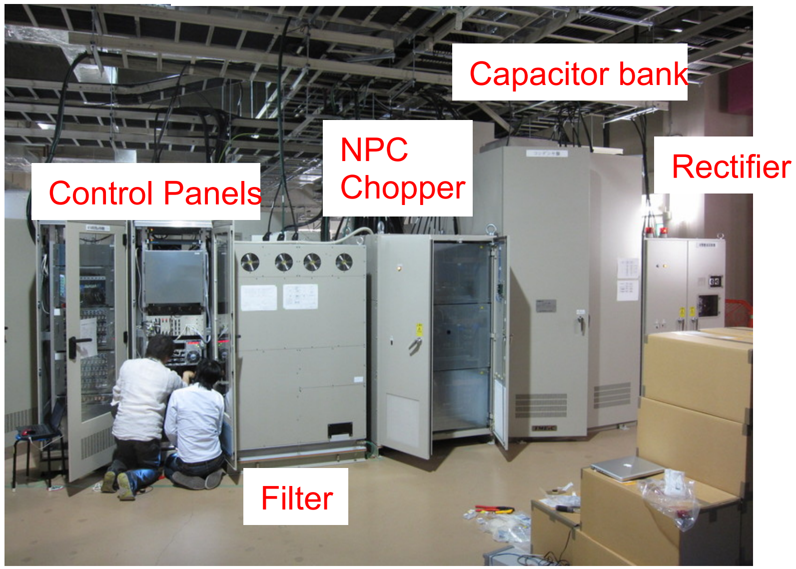
Large scale PS for bending magnets and quad. magnets in arc setions

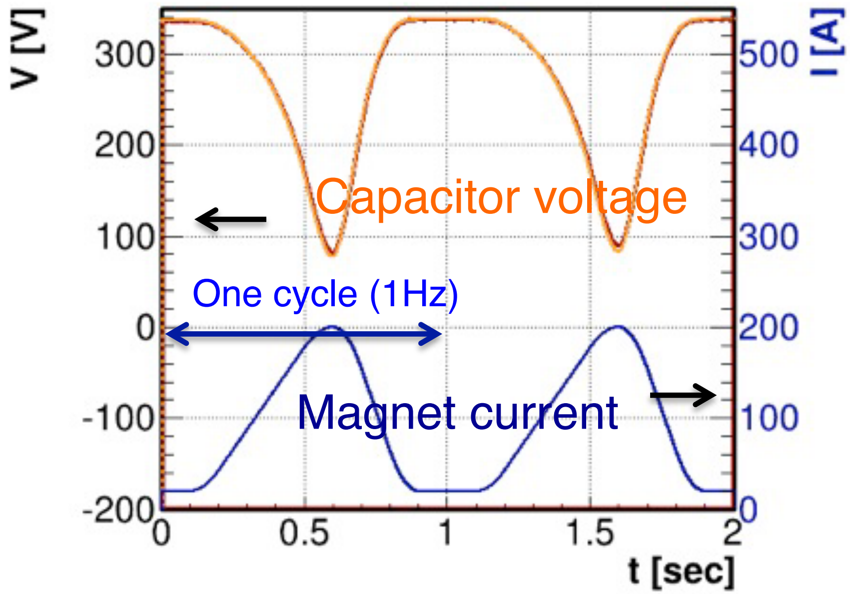


Two large converters and large capacitance for energy recovery, symmetric power module circuit

R&D is now in progress.
The total PS system will be tested in JFY2014

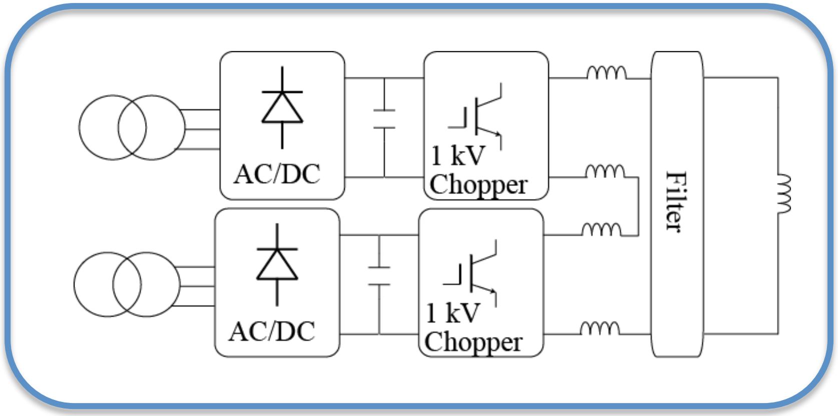
A mini-prototype model test using the real bending magnet and capacitors.





R&D of new power supplies for 1 Hz operation (cont'd)

Small scale PS for Quad. Magnets in straight section and sextupole magnets

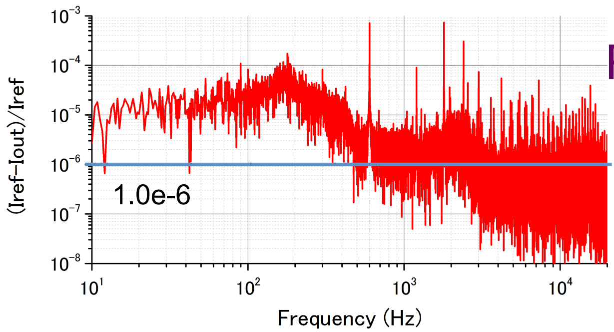


Diode rectifiers, two 1kV choppers are connected in series, symmetric power module circuit

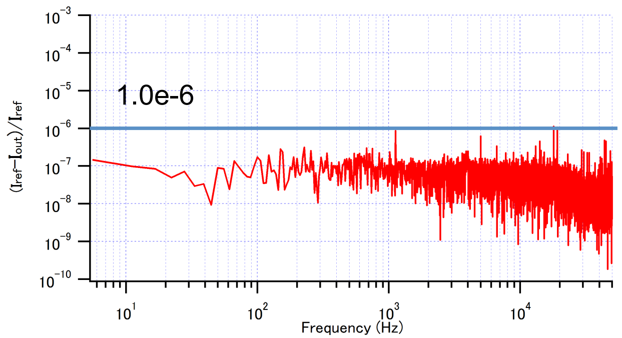
It is possible to build with the combination of existing products.

The model PS system was tested using the real sextupole magnet network.

Current ripple at 30 GeV



Present IGBT-PS

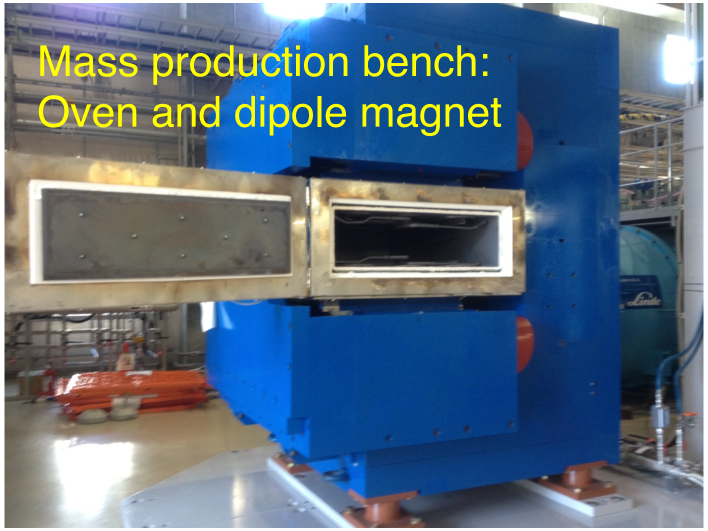


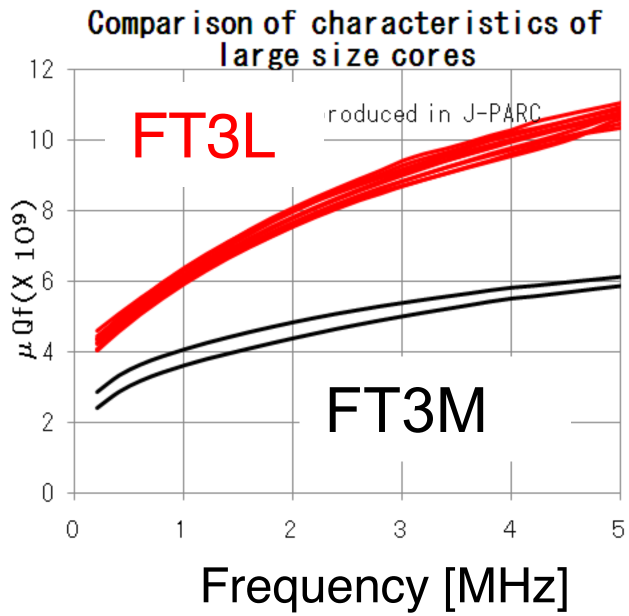
The new PS

Mass production will start in JFY2015 if the budget request is approved by the government.

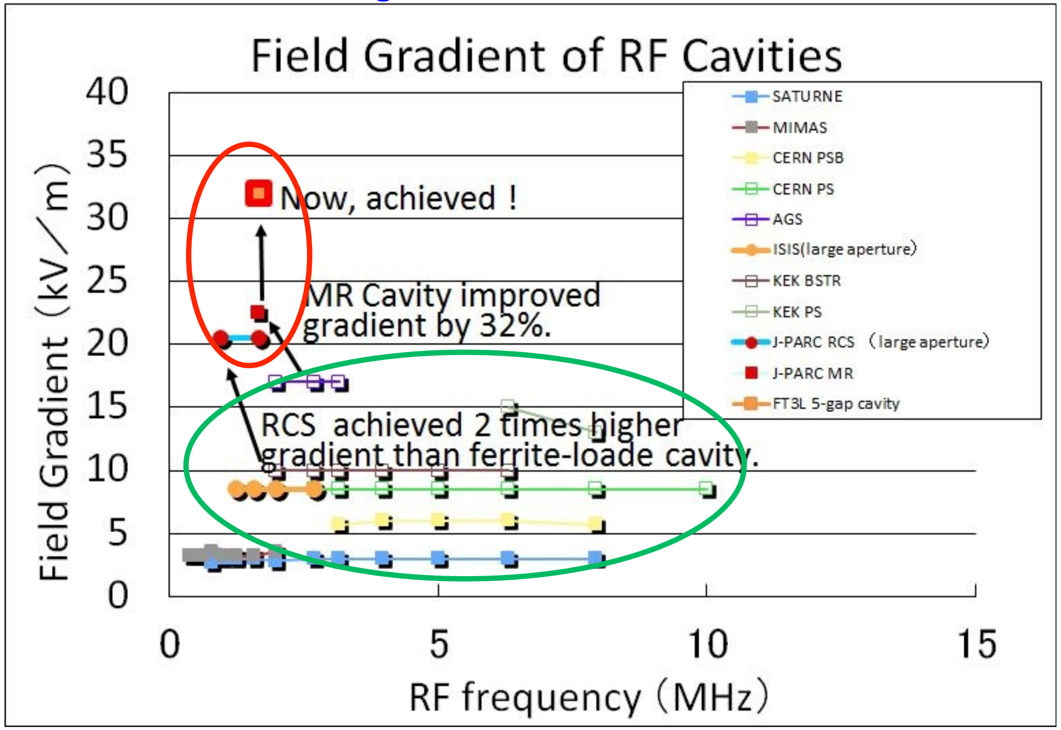
High impedance rf system

A new type of the magnetic alloy (MA) core, FT3L(made by Hitachi Metal), is adopted to increase shunt impedance of the rf cavity. The core is processed by annealing with magnetic field.





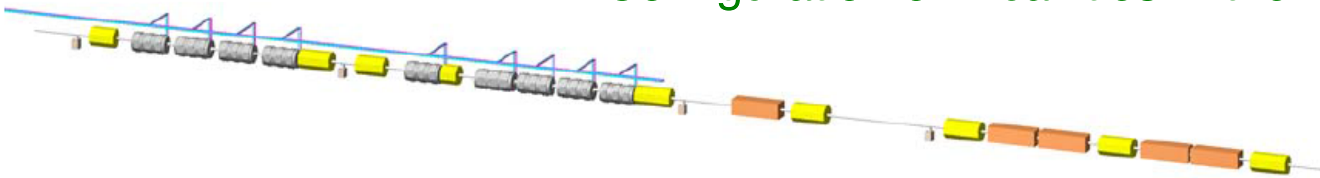
Comparison of field gradient of rf cavities for hadron rings.



Performance of cavities depends on core materials: ferrite and MA.
J-PARC already achieved very high field gradient.

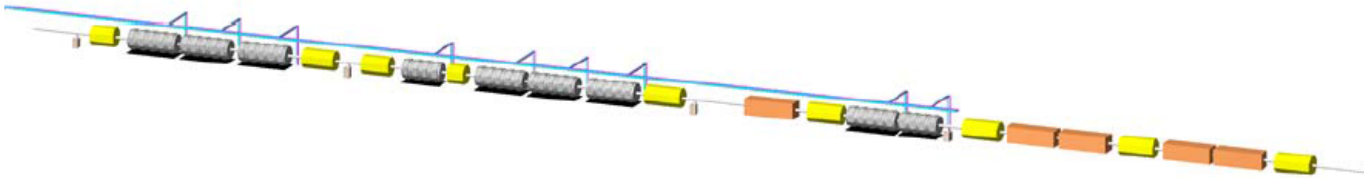
High impedance rf system (cont'd)

Configuration of rf cavities in the MR



Current situation : 3gap X 9 = 27 gaps

Total rf voltage ~ 270 kV



After replacement : 4gap X 2 + 5gap X 7 = 43 gaps

Total rf voltage ~ 645 kV

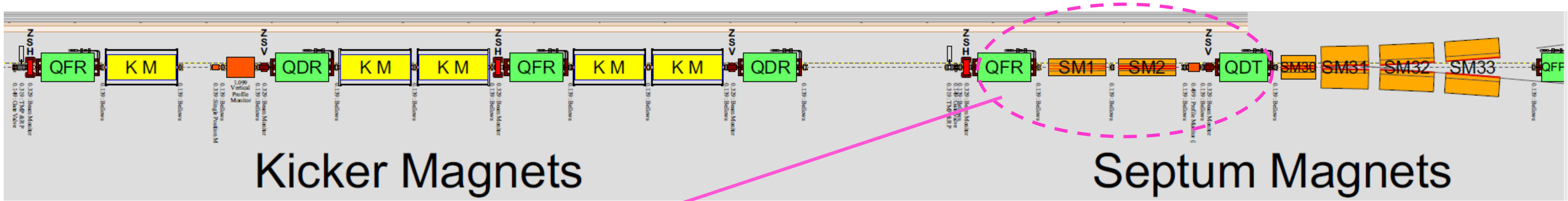
A second harmonic cavity is also installed in the injection straight section.

1st 5-cell FT3L cavity under 80 kV high power test

Budget for the new rf cavities is mostly secured by supplementary budgets in JFY2011 and 2012.
All the cavities will be ready to install in JFY2015.

The developed FT3L cores are adopted to the PSB for LHC injector upgrade .

New low field FX septum: Eddy current type

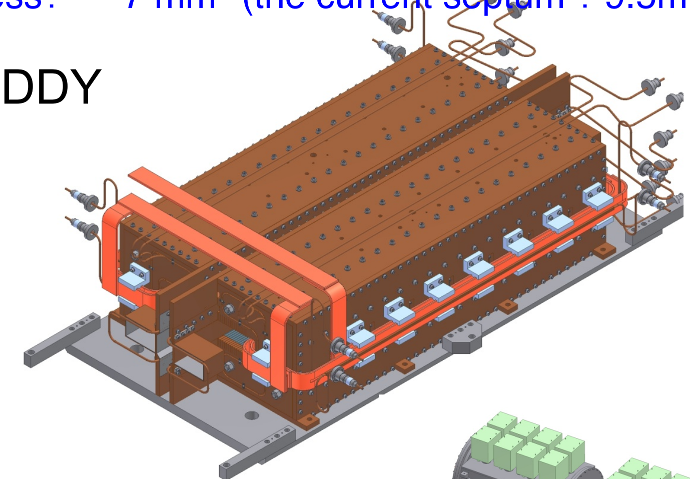


Current FX low field septum

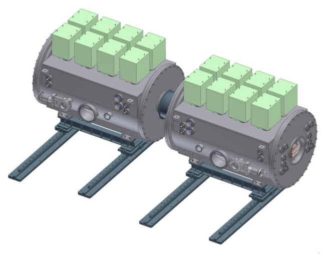
Eddy current type septum is adopted to the new system

- Small Power Consumption (possible at low cooling capacity)
- Small Leakage Field: ～10^{-4} (the current type septum : 10^{-3})
- Stable (low vibration)
- Thin Septum Thickness: ～7 mm (the current septum : 9.5mm)

New FX EDDY



	New FX Eddy model	Current FX low Field
# of magnets	Nu 2 + Abort 2	Nu 4 + Abort 4
# of coil turns	2	4
Pole Length	1.5 m	0.875 m
Septum Thickness	7 mm	9.5 mm
Current / Voltage	11 kA / 3 kV	3250 A / 144 V
BL (Tm)	0.3 × 1.5 × 2 = 0.90	0.224 × 4 = 0.90
Aperture (H×V)	150 ×80 mm	80 ×70 mm
Inductance	36μH (2magnets series)	27 × 8 = 216 μH
Pulse or Pattern	0.7 ms half sine (3rd order)	Pattern
Leakage Field	～ 10^{-4}	～ 10^{-3}



The magnet has been manufactured. It will be installed in the 2015 summer shutdown.

Space Charge Simulation Results

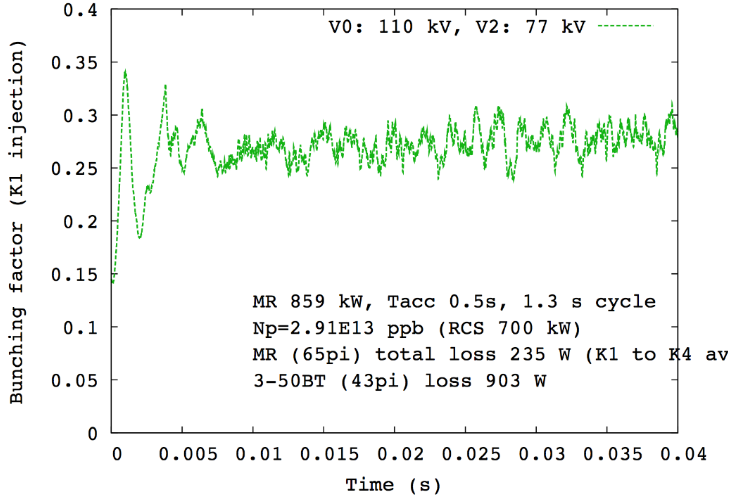
RCS:
- 700 kW equivalent 2.91e13 ppb

3-50BT:
- Collimators 43π
- Beam Loss 1.0%, 0.9 kW

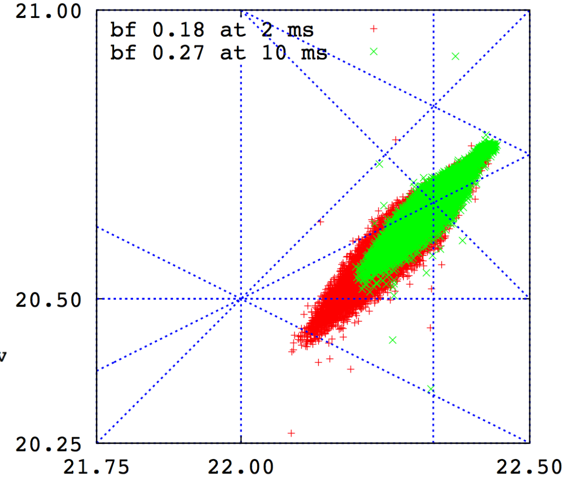
MR:
- RF fundamental 110 kV,
  2nd 77 kV at Injection
- RF fundamental 550 kV,
  2nd 0 kV at Acceleration
- Collimator 65π
- Skew Q correction on
- MR Beam Loss 540 W
- Repetition 1.3 s

→ MR Beam Power 856 kW

Bunching factor

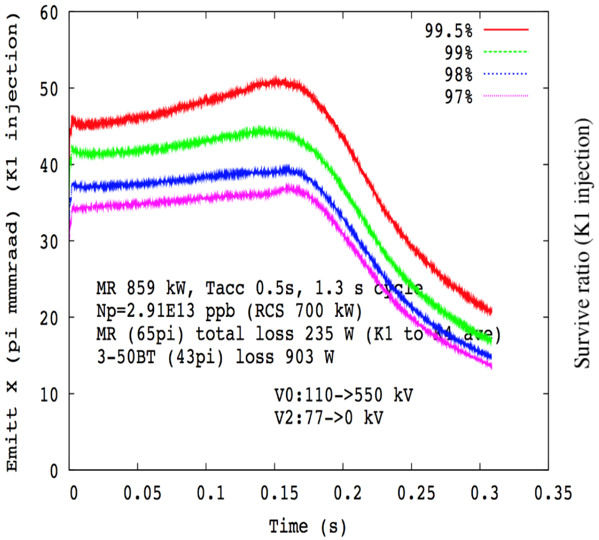


Incoherent tune shift



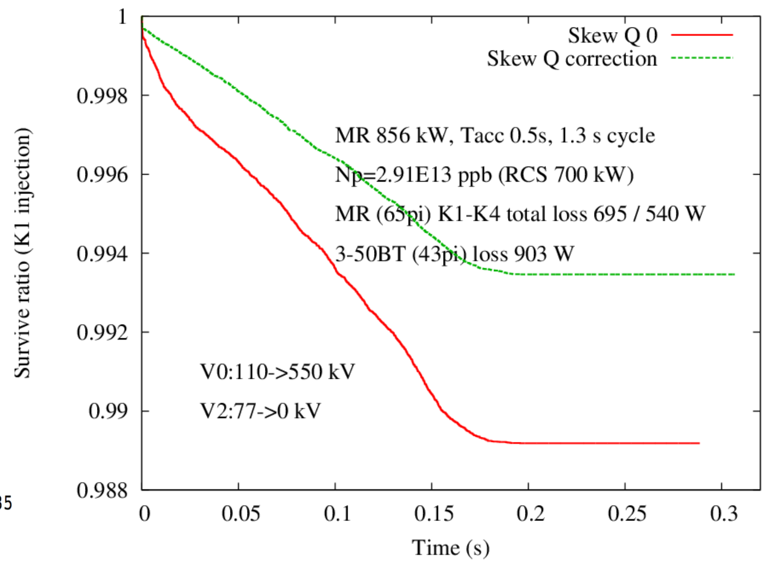
Horizontal emittance growth

Injection Acceleration



Beam survival

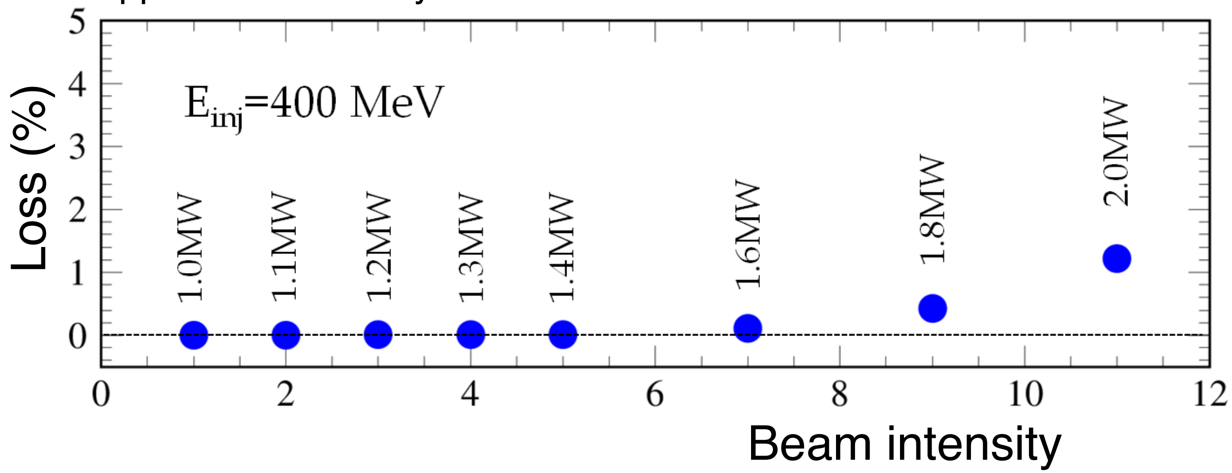
Injection Acceleration



Long-term plan

Feasibility of the RCS

Injection beam parameters:
Energy : 400 MeV
Peak current : 50 mA~100 mA
Pulse length: 0.5 ms
Chopper-beam on duty : 0.53



RCS intensity	Loss	Loss power at 25 Hz
1.0 MW	~0.3%	400 W
1.1 MW	~0.3%	440W
1.2 MW	~0.3%	480 W
1.3 MW	~0.3%	520 W
1.4 MW	~0.3%	560 W
1.6 MW	~0.5%	1067 W
1.8 MW	~0.7%	1680 W
2.0 MW	~1.5%	4000 W

RCS collimator limit ~4 kW
→ RCS has a feasibility to operate 2 MW

- Linac 100 mA/0.5 ms (50 mA/1.0 ms) operation is required.
  R&D of ion source / long pulse operation of linac
- The rf system should be replaced to compensate a heavy beam loading.
- The collimator capability should be upgraded to get a margin for the beam loss.
- Activation downstream of the charge exchange foils should be reduced.

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Future proton driver for long-baseline neutrino experiment

The maximum beam intensity is limited by the physical aperture of the MR.

The scenarios for achieving much larger beam power than the design specification for neutrino experiment are now discussed.

1. Booster ring for the MR (emittance damping ring)

   The BR with an extraction energy ~ 8 GeV, is constructed between the RCS and the MR

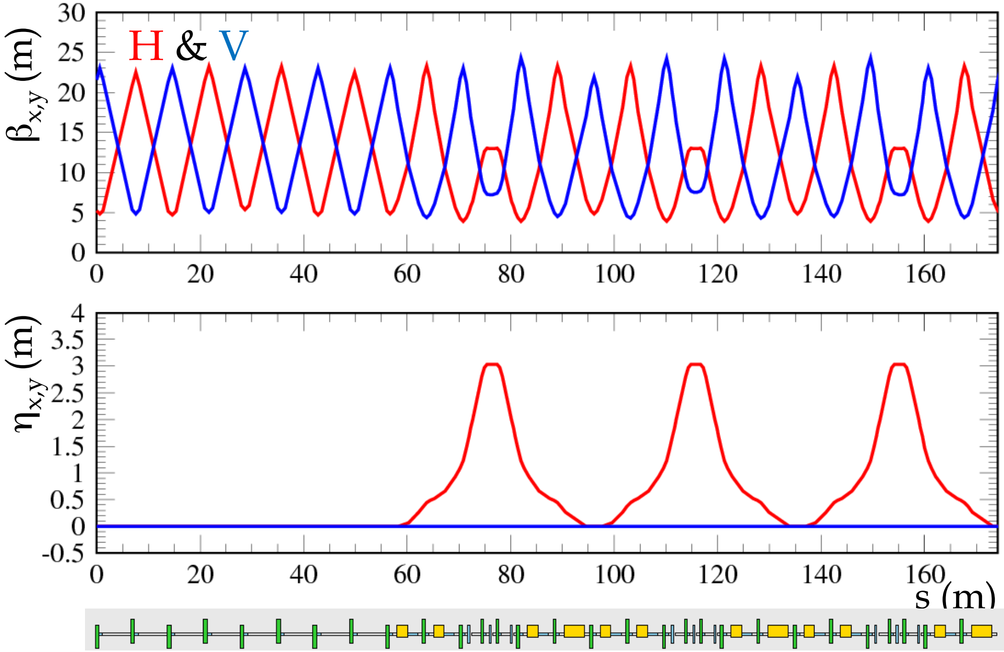
2. New proton linac for neutrino beam production

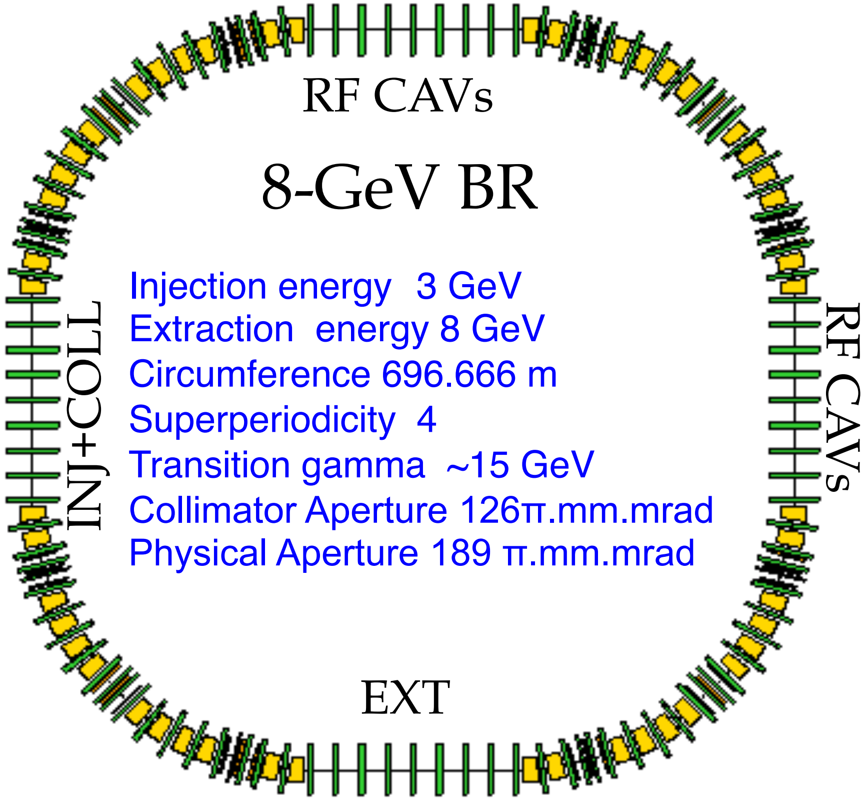
   (Construction site may not be the Tokai campus)

   - Linac with an beam energy > 9 GeV
   - The MR is operated only for the SX users

The 8-GeV booster ring

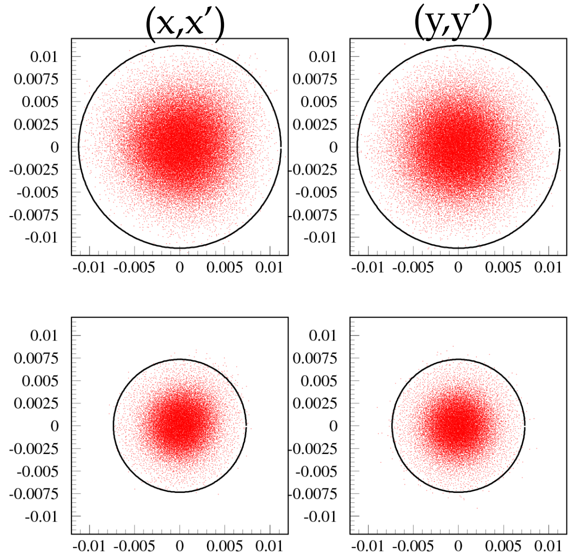
Beta & Dispersion for 1-superperiod





- Injection energy 3 GeV
- Extraction energy 8 GeV
- Circumference 696.666 m
- Superperiodicity 4
- Transition gamma ~15 GeV
- Collimator Aperture 126π.mm.mrad
- Physical Aperture 189 π.mm.mrad

Phase plot @ inj.(3GeV) & extr.(8GeV)

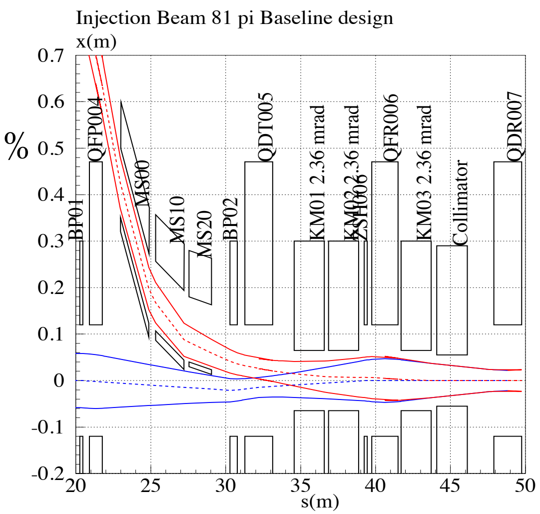


@ 3GeV

ε>125.5π ~0.04%

@ 8GeV

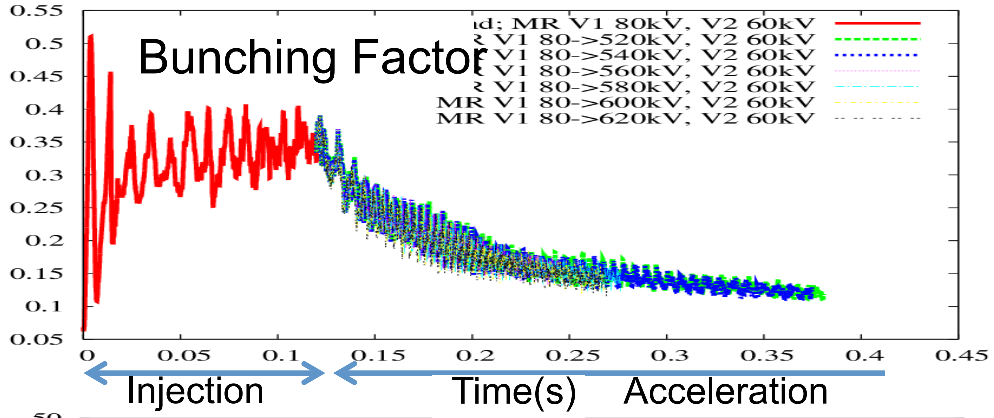
ε>54π ~0.06%

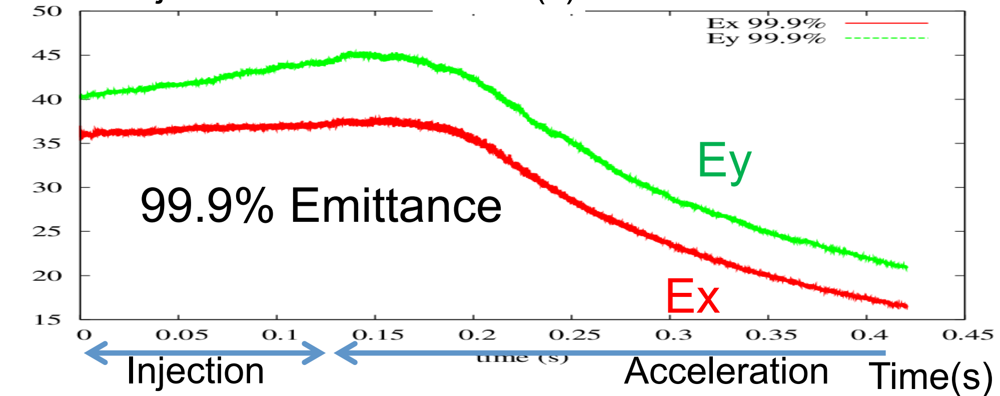


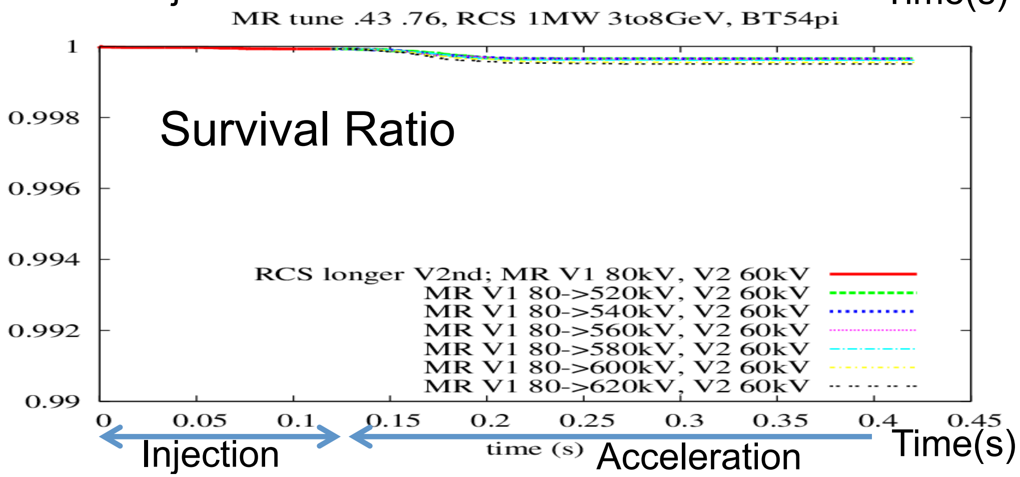
8 GeV injection in the MR using new septa&kickers

Space Charge Simulation Results

RCS 1MW → 8GeV BR → MR Simulation







RCS:

- 1 MW equivalent 2.91e13 ppb

MR:

- MR Trep=1.0s
- 8-50BT loss (54π) 8 W
- RF pattern:
  - fundamental inj 80 kV → acc 520 kV
  - 2^{nd} RF inj 60 kV → acc 0 kV
- νx=22.43, νy=20.76
- Ex(99.9%) < 38π mmmrad
- Ey(99.9%) < 46π mmmrad

→ MR power 1.6 MW

with MR total collimator loss (65π) 124 W

RCS : 1.6 MW equivalent

→ MR power > 2.6 MW

RCS : 2 MW

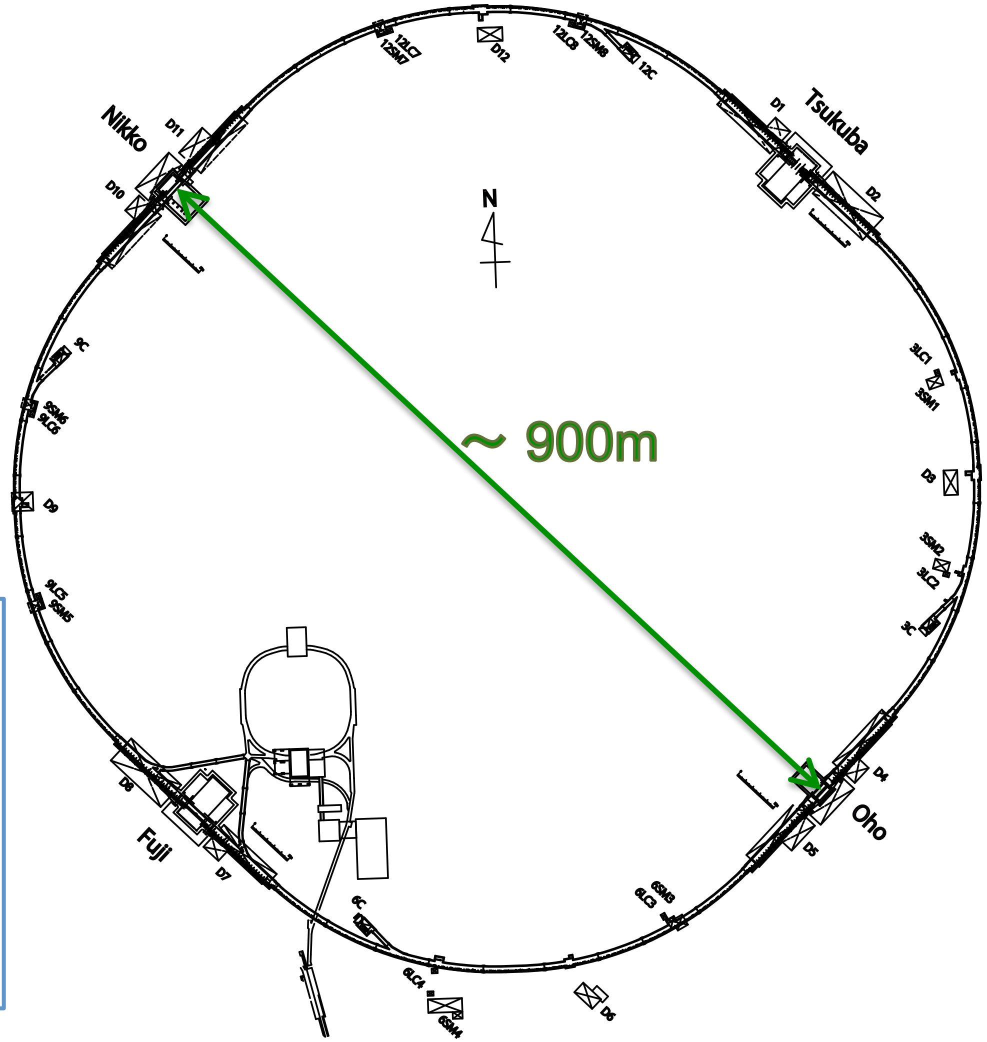
→ MR power > 3.2 MW

Proton Driver in the KEKB Tunnel

We start discussion as one of the post-Super KEKB project.

KEKB tunnel:

- fourfold symmetric configuration.
- Circumference: ~ 3 km
  - Straight section： beam acceleration
    200 m x 4 = 800 m
  - Arc section： beam transportation to
    the next straight section.
    550 m x 4 = 2200 m



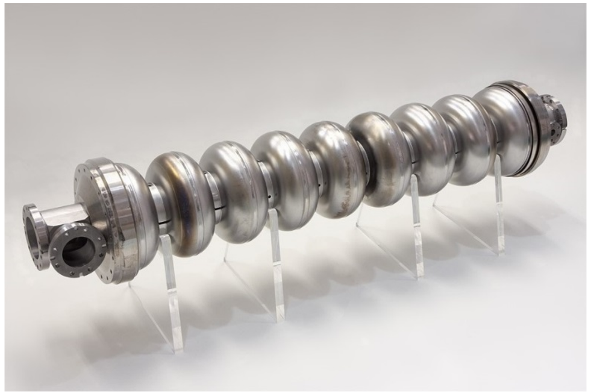
Subjects：

- Feasibility of 9 GeV proton linac in straight sections of 800 m.
  ⇒ High acceleration field is required.
  ⇒ SC accelerator is essential.
- Beam transport at Arc sections.

SC Cavity for 2nd to 4th Straight Sections

For the acceleration in the 2nd to 4th straight section, the ILC cavity is adopted.

<u>ILC cavity</u>



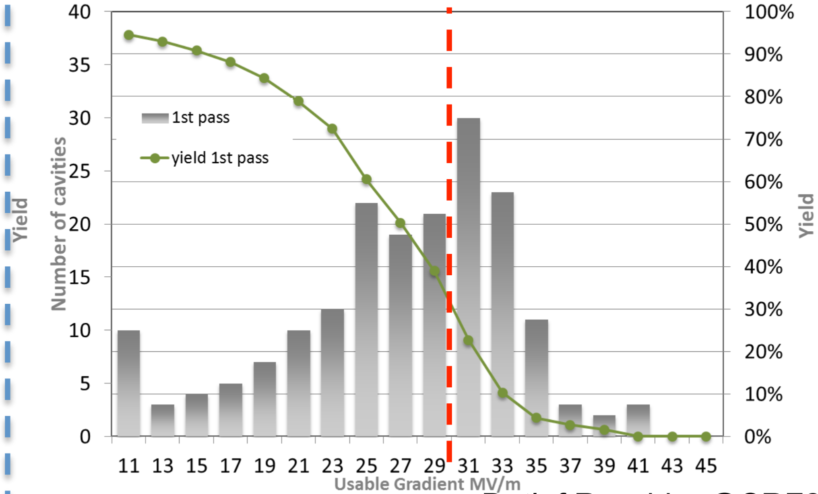
Shape	ellipse
RF frequency	1.3 GHz
# of cells per cavity	9
Quality factor	> 1 x 10^{10} @ 2K

<u>ILC cryomodule</u>

KEK has rich experience and know-how of ILC cavity and cryomodule fabrication.

Average gradiend (E_0) ?

Yield of usable gradient of 185 ILC cavities as received (European XFEL)



Detlef Reschke @SRF2013

Average **usable** gradient:

(26.2 ± 7.5) MV/m

With the expectation of further R&D, we set the E_0 to **30 MV/m**.

Outline of the Proton Driver using ILC Cavity

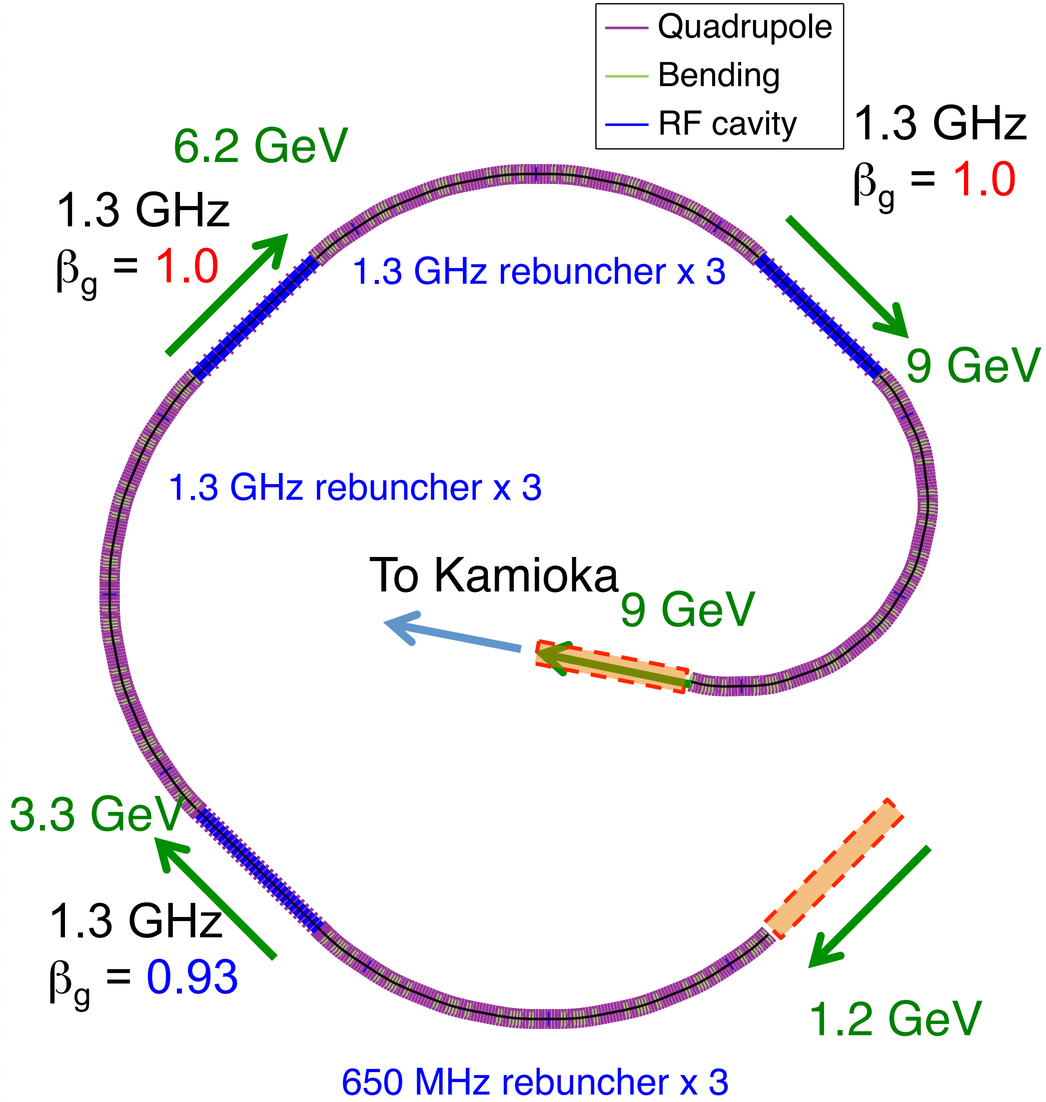
- Outline of acceleration :
  - 1.2 GeV in 1st straight.
  - 3.3 GeV in 2nd straight.
  - +2.9 GeV in 3rd and 4th straight.
    3.3 + 2.9 x 2 = 9.0 GeV

- Peak current : 100 mA (pulse)
- Beam duty : 1 %

- Beam power :
9000 MeV x 0.1 A x 1 % = **9 MW**

- β_g of SC cavities :
  - 2nd straight : β_g = **0.93**
  - 3rd and 4th straight: β_g = **1.0**

- Normalized RMS emittance
  - Transverse : 0.30 π･mm･mrad
  - Longitudinal : 0.37 π･MeV･deg

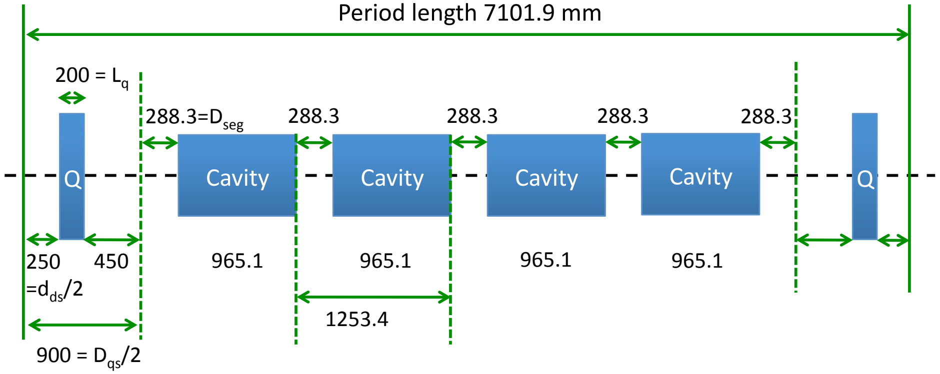


Configuration of the cryomodules

The 2nd straight section:

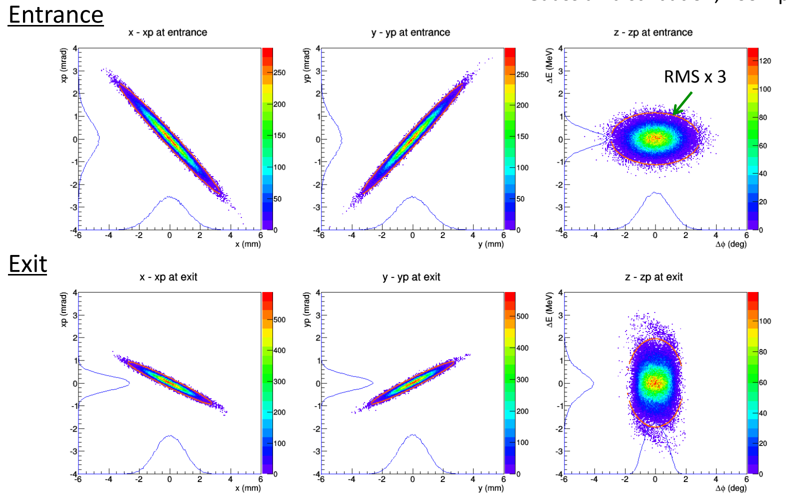
- Doublet lattice with SC quadrupole magnets.
- 4 SC cavities (β_g = 0.93) are in each cryomodule.
- 27 cryomodules are placed in the section.
  7.1 x 27 = 192 m

Filling factor = 0.544



Beam profile at the 2nd straight section

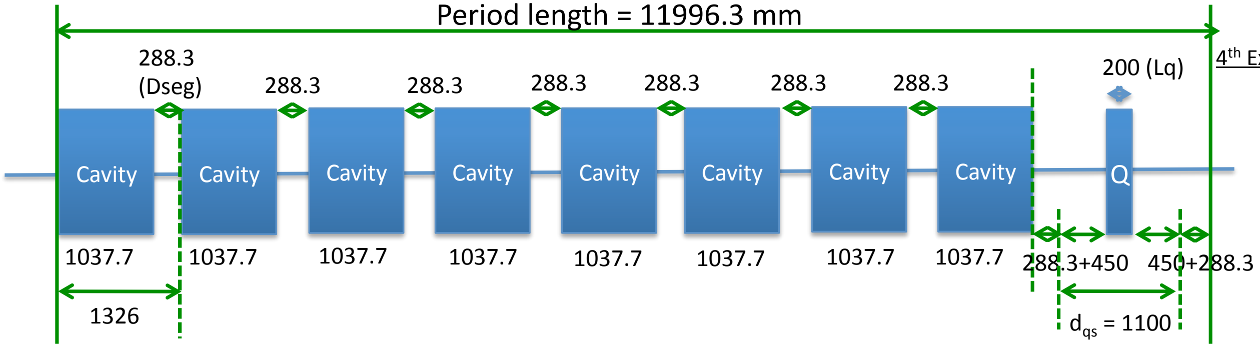
Gaussian distribution, 100 k particles



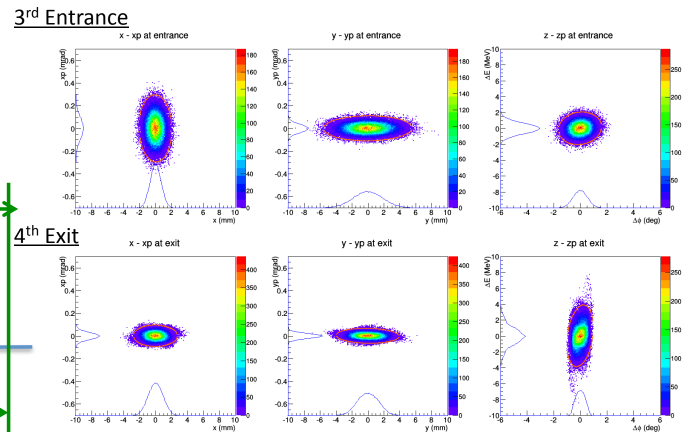
The 3rd and 4th straight section:

- Singlet lattice with a SC quadrupole magnet.
- 8 SC cavities (βg = 1.0) are in each cryomodule.
- 16 cryomodules are placed in each straight section.
  12.0 m x 16 = 192 m

Filling factor = 0.692



Beam profile at the3rd and 4th straight section



R&Ds are necessary : Higher gradient SC cavities, High power target, Horn…

Summary

Status and operation summary:

- The J-PARC linac was successfully upgraded to 400 MeV with the ACS system.
- Achieved beam power in user operation is :
  - 300 kW for MLF users
  - 240 kW and 24 kW for the T2K experiment and HD users, respectively.

The mid-term plan :

Linac intensity upgrade :

- The front-end system has been replaced for increasing peak current from 30 mA to 50 mA in the 2014 shutdown period.

For the MLF:

- The RCS will deliver the design beam power of 1 MW by middle of 2015.

For the MR:

- Goal of the 5 year mid-term plan is the design power of 750 kW for the FX, and 100 kW for the SX in 2017. The 750-kW beam is achieved by high rep. rate of 1 Hz with 30 GeV.

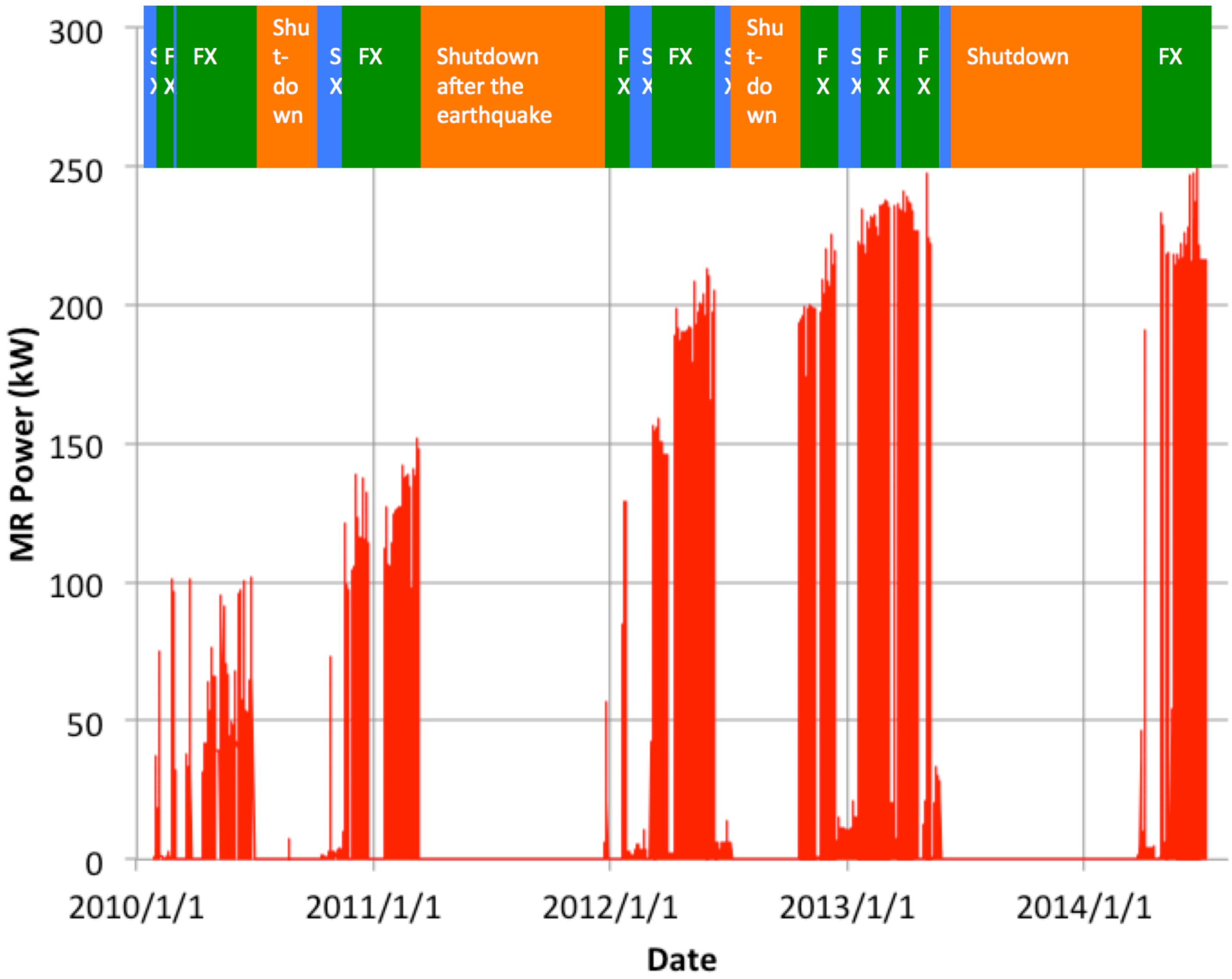
Long-term plan

- Simulation shows the RCS has capability to increase beam power ~ 2 MW.
- Some scenarios to achieve beam power beyond current design for neutrino experiment are now under discussion; the 8 GeV booster, 9 GeV linac, etc.

Backup

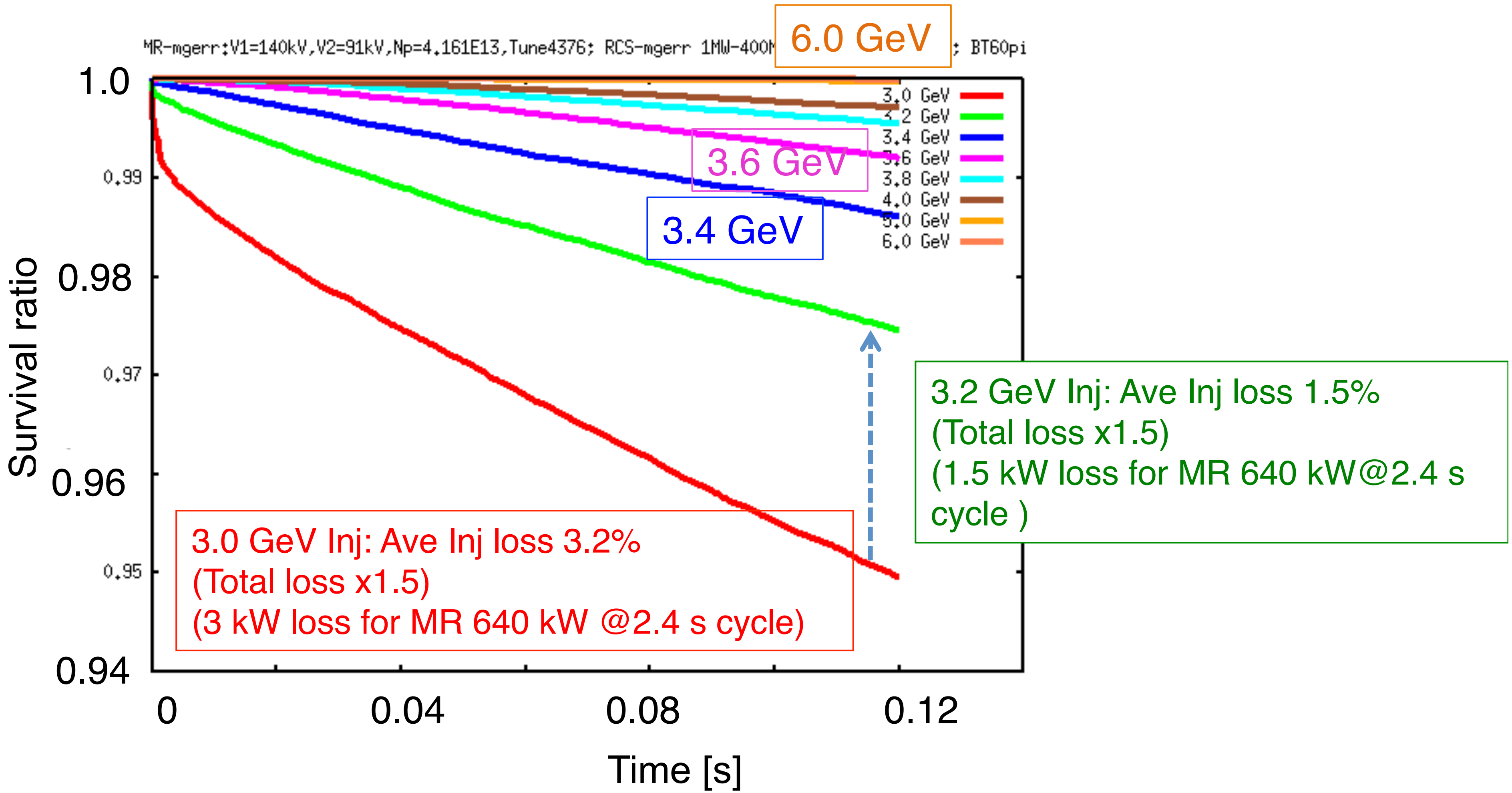
MR Operation History from January 2010 to June 2014

FX: Fast Extraction. The beam power of 240 kW in maximum has been delivered to the T2K experiments.
SX: Slow Extraction. The 24 kW beam has been delivered to the experiments in the hadron hall .

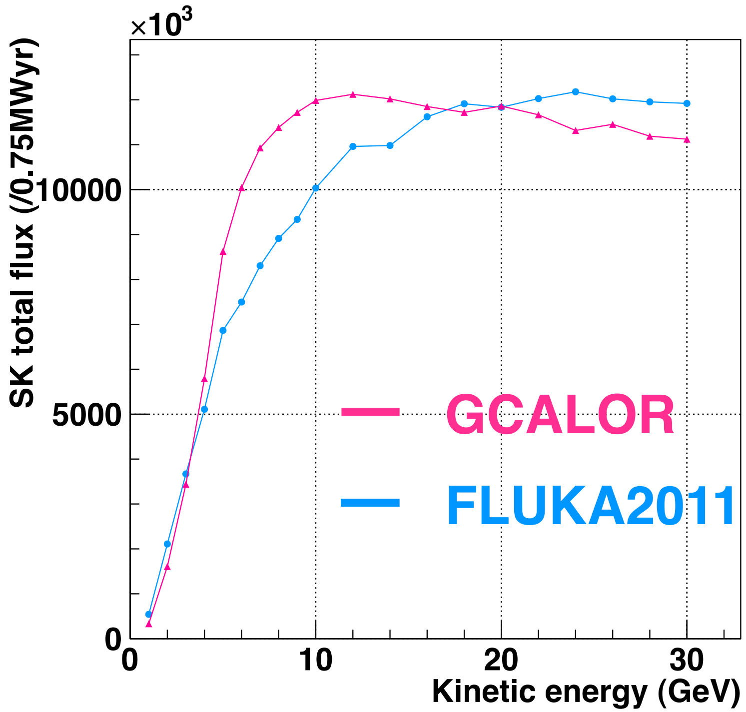


Injection energy and beam loss in the MR

Simulation of beam survival in the injection period of the MR
for the RCS 1MW eq. beam (4e13 ppb)



Integrated ν Flux/energy vs. Beam Energy



K. Sakashita

- Neutrino flux at Super Kamiokande as a function of proton energy.
- Hadron generation model.
  - GCALOR
  - FLUKA2011
- Off axis beam 2.5 deg.
- 3 Horn magnet scheme same as T2K.

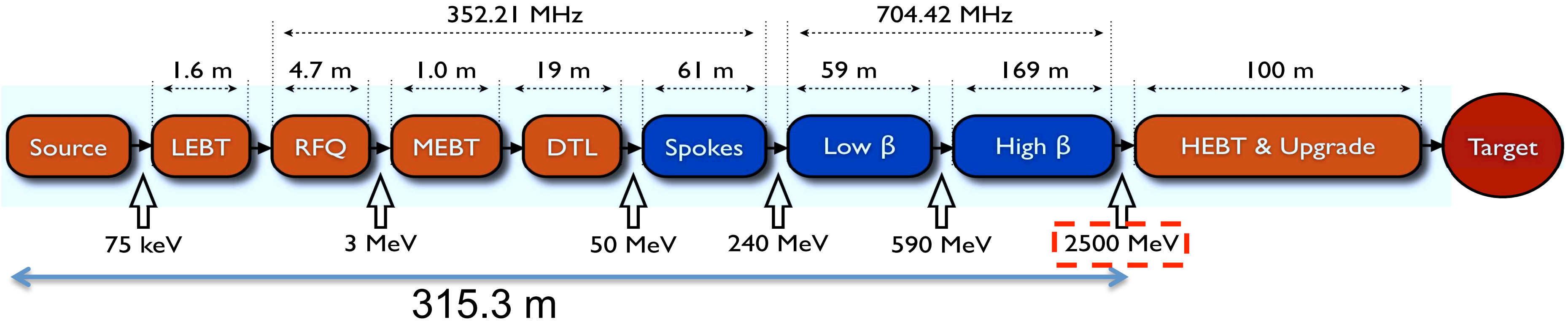
- Neutrino flux per energy increases as beam energy to be high.
- The flux almost saturates around 9 GeV.

Beam power = [Beam energy] x [Peak current] x [Duty]

- 9 GeV proton accelerator
- Linac configuration for high duty
- Construction at the KEKB tunnel for cost issue.

- European Spallation Source (ESS)

M. Eshraqi et. al., TUO1B0 HB2010 (2010)

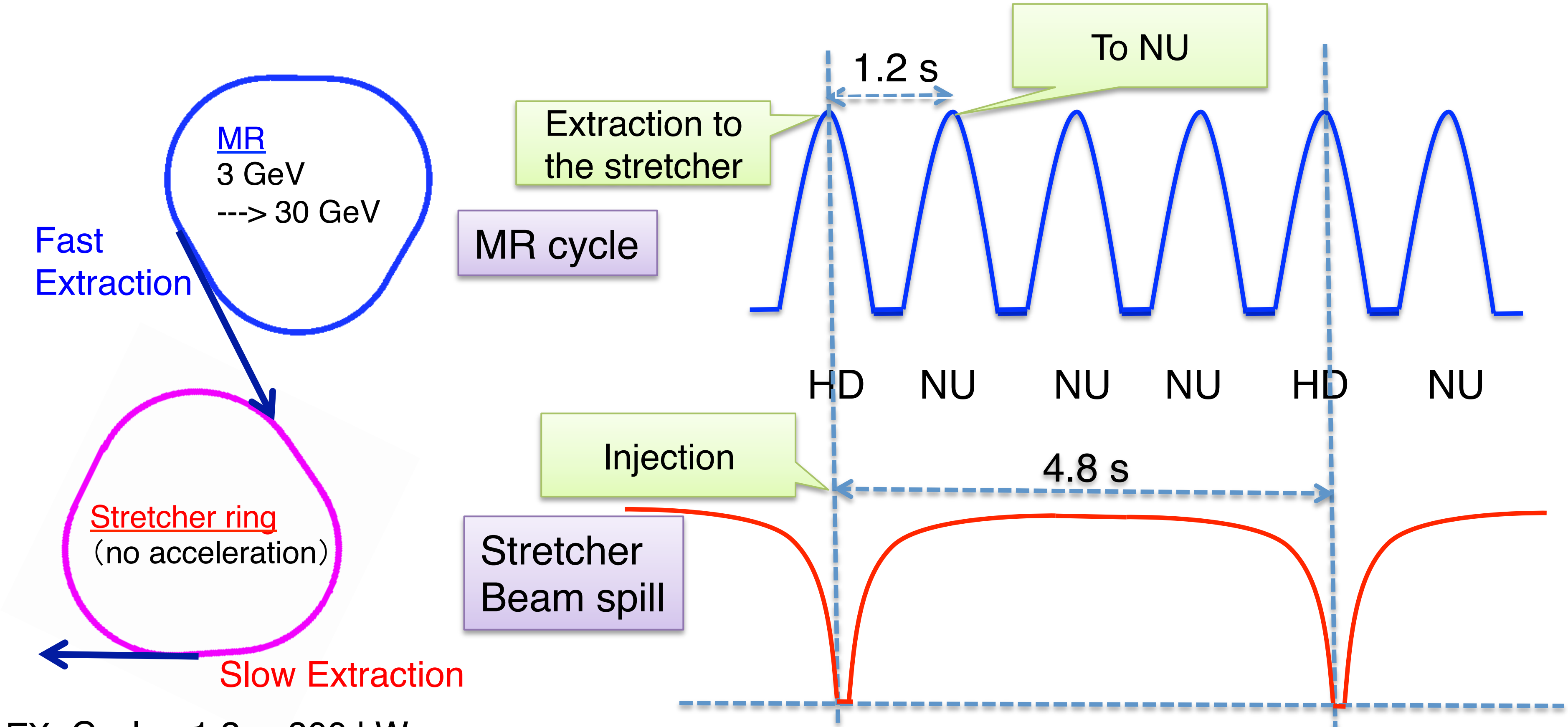


Parameter	Value	Parameter	Value
Ion species	p	Repetition (Hz)	20
Output energy (MeV)	2500	Macro-pulse duty factor (%)	4
Peak current (mA)	50	Average beam current on target (mA)	2
Chopper beam-on duty factor (%)	100	Beam power on target (MW)	5
Pulse width (ms)	2	Length (m)	315.3*

*Energy reaches 1200 MeV at 230

Proton beam can be accelerated to 1～1.2 GeV in the 1st straight section

Stretcher ring for increasing operation time of HD users



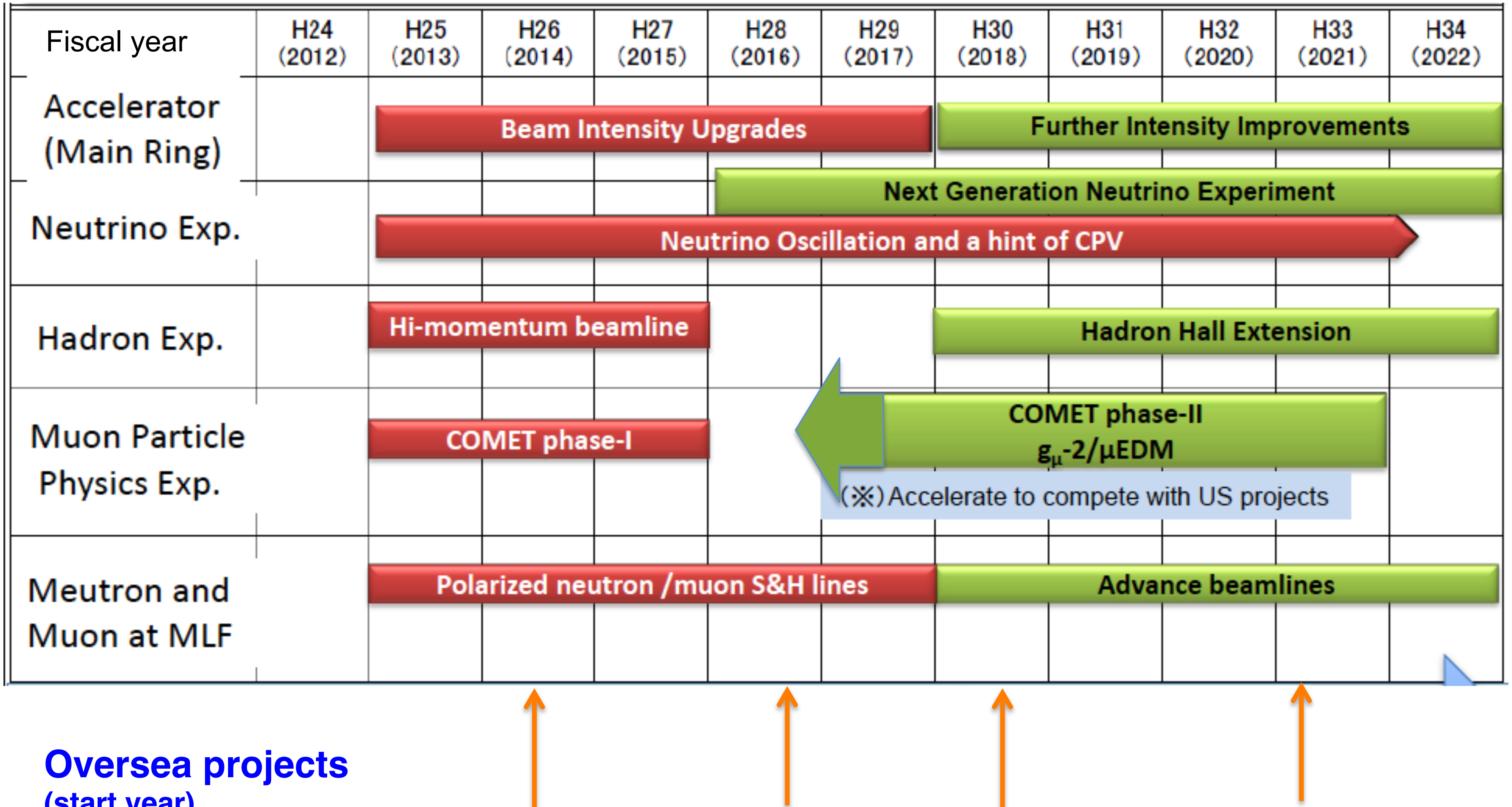
FX: Cycle= 1.2 s, 800 kW
SX: Cycle= 4.8 s (flat-top 3.6 s)
Circumference of the stretcher is same as the MR

Integrated beam power for 200 days/year;

- NU : 800kW x 3/4 x 200 days =600kW x 200 days
- HD : 800kW x 1/4 x 200 days =200kW x 200 days

Long-term plan of particle/nuclear physics at J-PARC

"Elucidation of the origin of matter with an upgrade of J-PARC experimental facility" submitted to science council of Japan.



Oversea projects
(start year)

NOvA at Fermilab (2014-)

g-2 at Fermilab (2016 -)

FAIR at GSI (2018 -)

Mu2e at Fermilab (2021 -)