Power Upgrade Plan of J-PARC Linac and Loss Estimation

Workshop on Upgrading Existing High Power Proton Linacs
November 8th – 9th 2016

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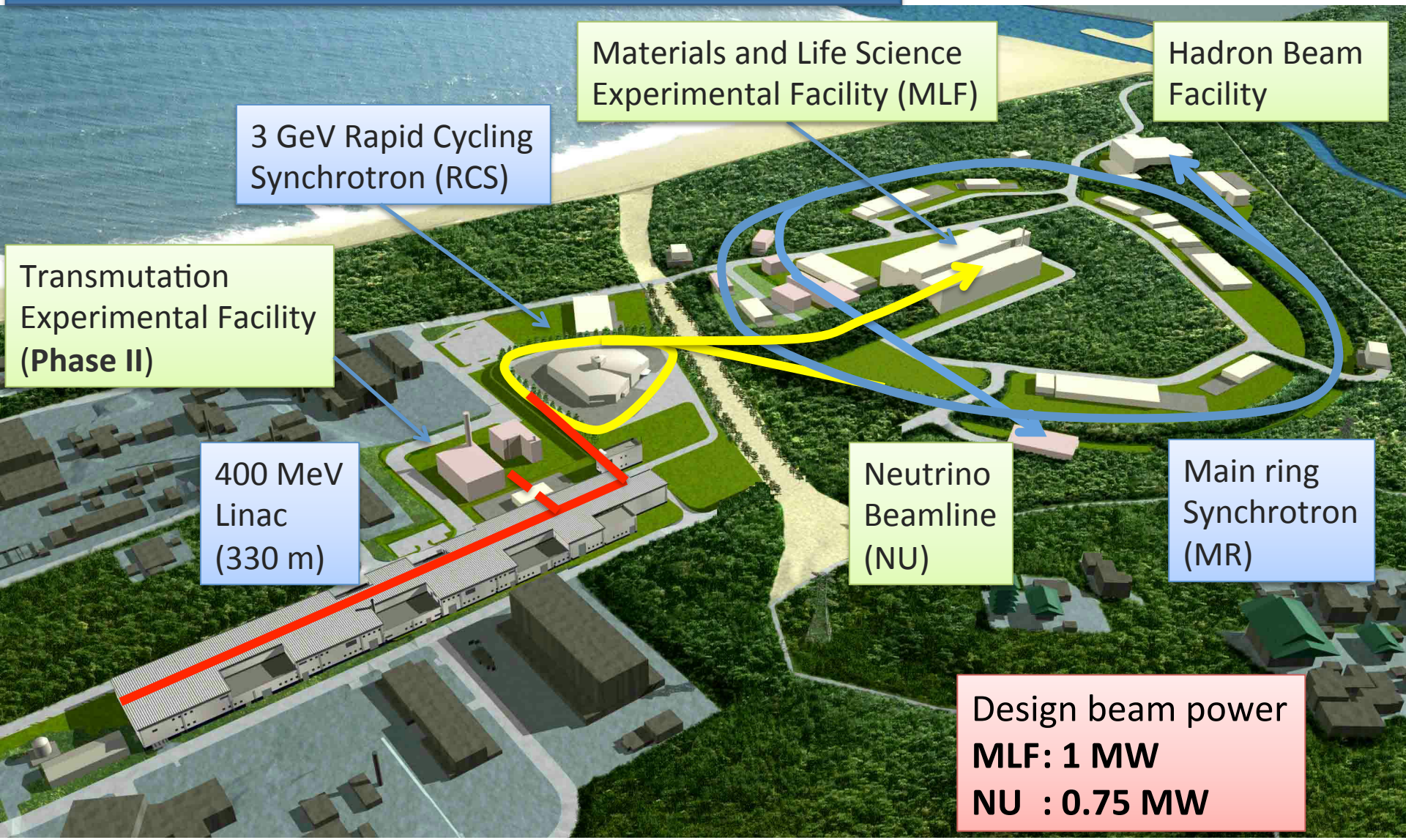
J-PARC Facility

Japan Proton Accelerator Research Complex



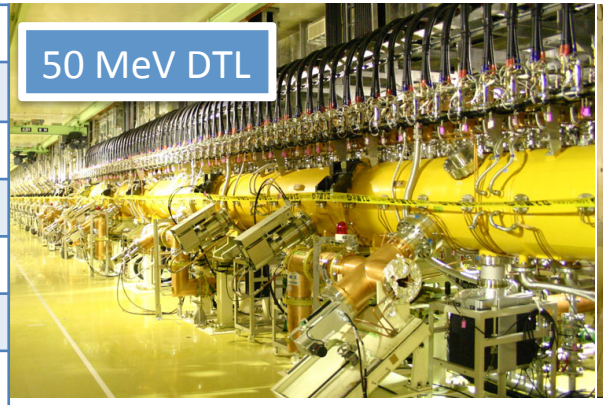
Design beam power
MLF: 1 MW
NU : 0.75 MW

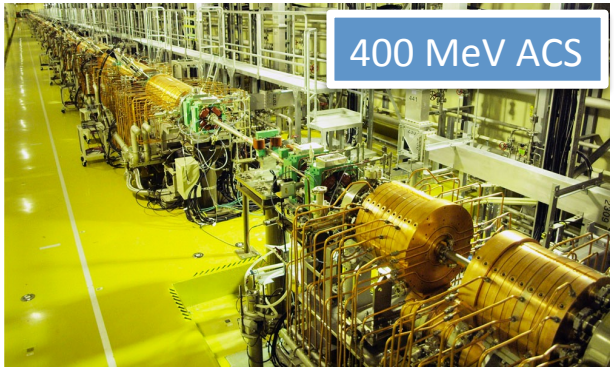
Outline of the J-PARC Linac

Main parameters

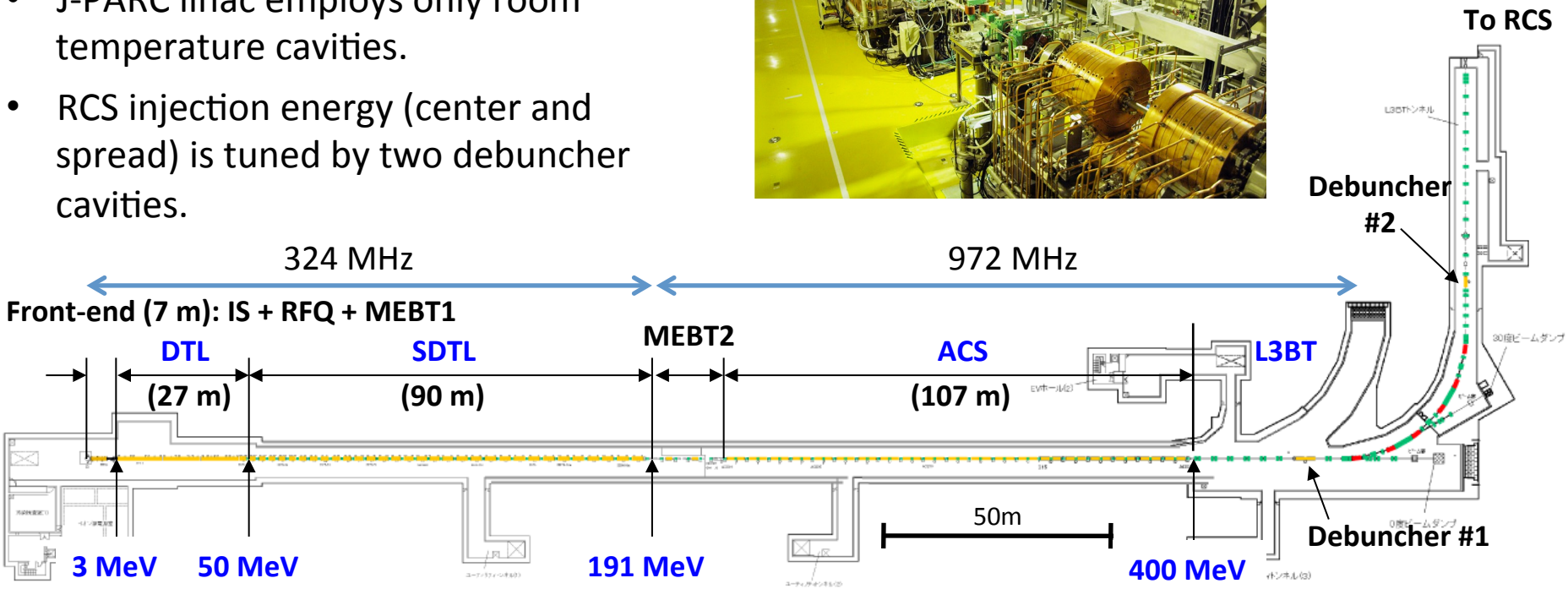
Particles	H^-
Output energy	400 MeV (Jan. 2014)
Peak current	50 mA (Oct. 2014)
Pulse width	0.5 ms
Chopper beam-on duty	53%
Repetition rate	25 Hz (50 Hz*1)
Max. beam power	133 kW (383 kW*1)
RF frequency	324, 972 MHz

*1: Phase II



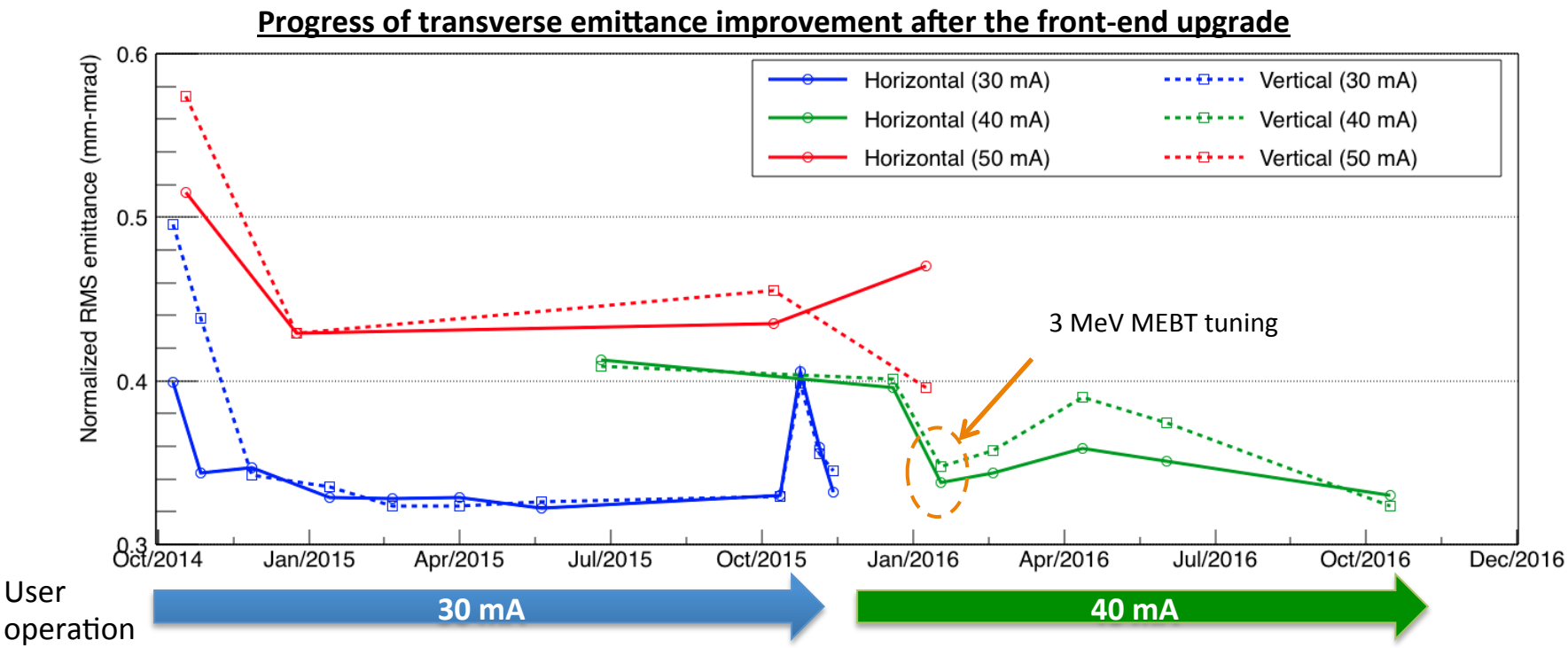


- J-PARC linac employs only room temperature cavities.
- RCS injection energy (center and spread) is tuned by two debuncher cavities.



Progress of the Linac Commissioning

The transverse emittance has been gradually improved by occasional beam studies.



- Ion source to MEBT tuning significantly improves beam emittance.
  Fine tuning at upstream section is important for beam quality improvement
- The operational current has increased to meet a downstream facility requirement.
  We stably supply 40 mA beam to the downstream facility stably.

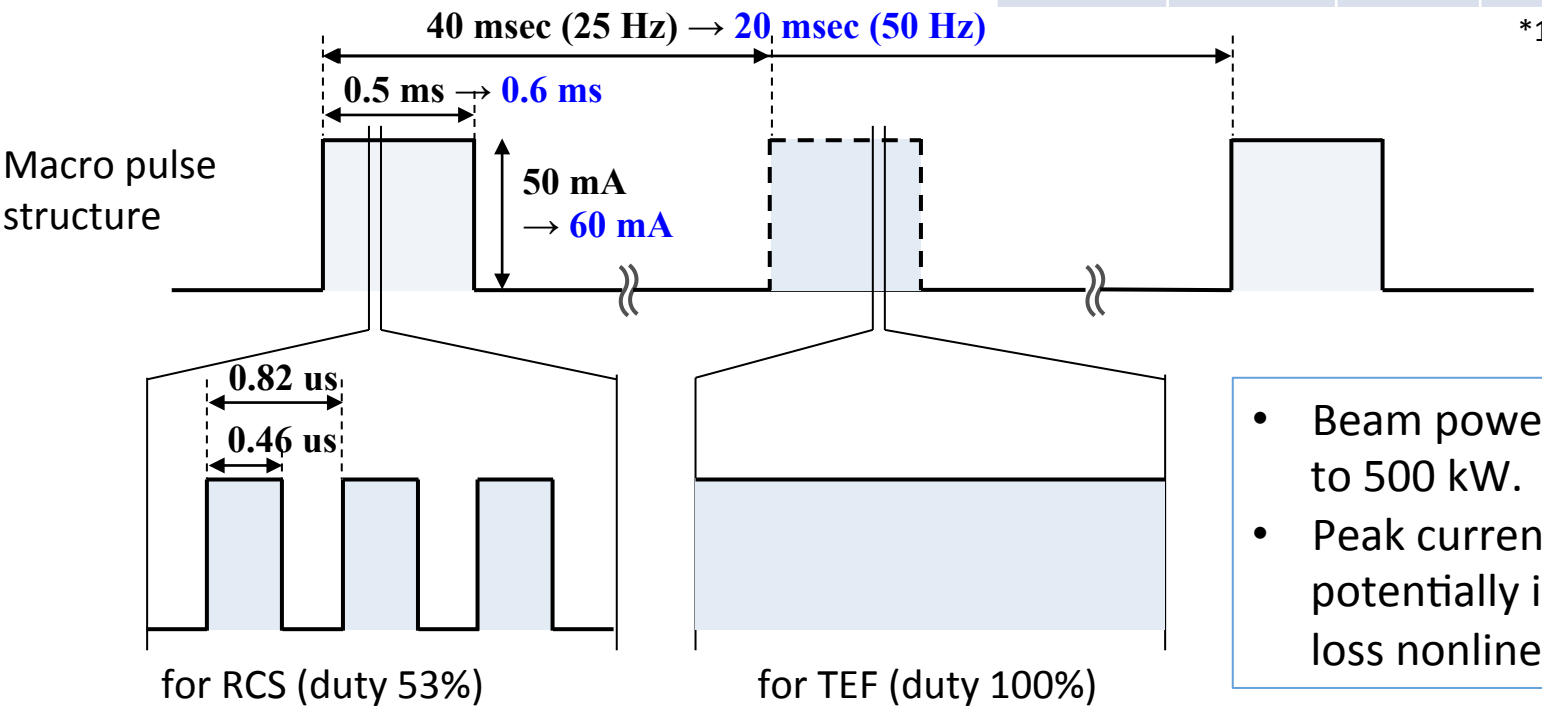
Beam Power Upgrade Plan of J-PARC Linac

J-PARC linac is under considering two-step beam power upgrade.

1) Supply to TEF (Transmutation Experimental Facility) in parallel with 3 GeV RCS.
   - Repetition rate: 25 Hz to 50 Hz
2) Extension of RCS beam power to **1.5 MW**
   - Peak current: 50 mA to 60 mA
   - Macro pulse: 0.5 ms to 0.6 ms

	Peak current [mA]	Pulse width [ms]	Rep. [Hz]	Beam duty [%]	Beam power [kW]
Present	50	0.5	25	0.7	133
1)	50	0.5	**50**	**2.0**[*1]	283
2)	**60**	**0.6**	50	2.0[*1]	**492**

*1 Chopper beam-on duty:
- RCS: 53%
- ADS: 100%



- Beam power finally closes to 500 kW.
- Peak current enhancement potentially increases beam loss nonlinearly.

Conclusion of Linac Task Force

Task force was organized to seriously check the availability of each element for the upgrade

Peak current [mA]	Pulse length [ms]	Repetition rate [Hz]	Beam power to RCS [kW]	Beam power to TEF [kW]	IS	RFQ	DTL	SDTL	MEBT2	ACS	L3BT	HPRF	LLRF	Beam dynamics	Monitor	Alignment	Utility (Cooling water)
50	0.5	25	133	--	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎
50	0.5	**50**	133	**133**	◎	△	◎	◎	◎	◎	◎	◎	○	○	◎	◎	○
50	0.5	**50**	133	**250**	◎	◎	◎	◎	◎	◎	◎	△	○	○	◎	◎	○
60	**0.6**	50	192	160	△	△	◎	◎	◎	◎	◎	○	○	○	○	○	○
60	**0.6**	50	192	300	△	△	◎	◎	◎	◎	◎	△	○	○	○	○	○

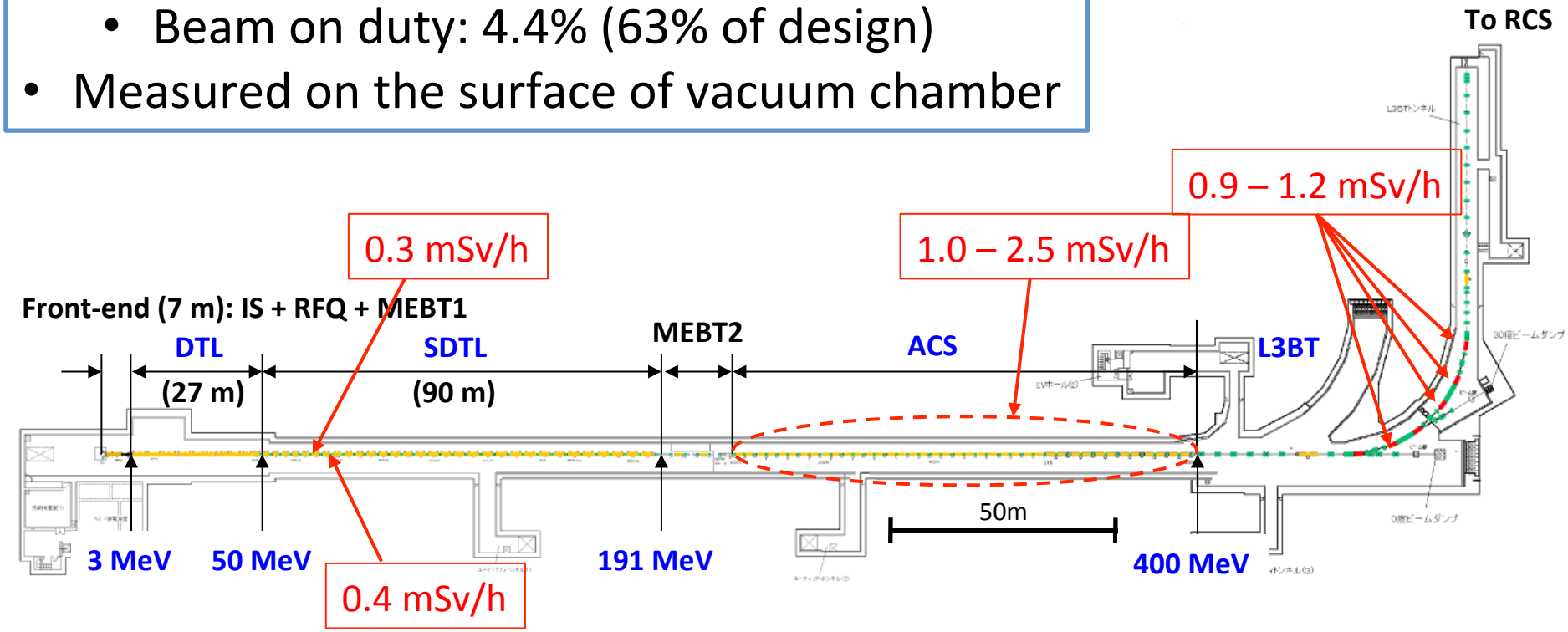
◎: Achieved, ○: Existence technics applicable, △: development necessity , ×: Innovation necessity

Shibata-san's talk in tomorrow

The upgrade is difficult, but not impossible!

Residual Dose after 0.5 MW Operation

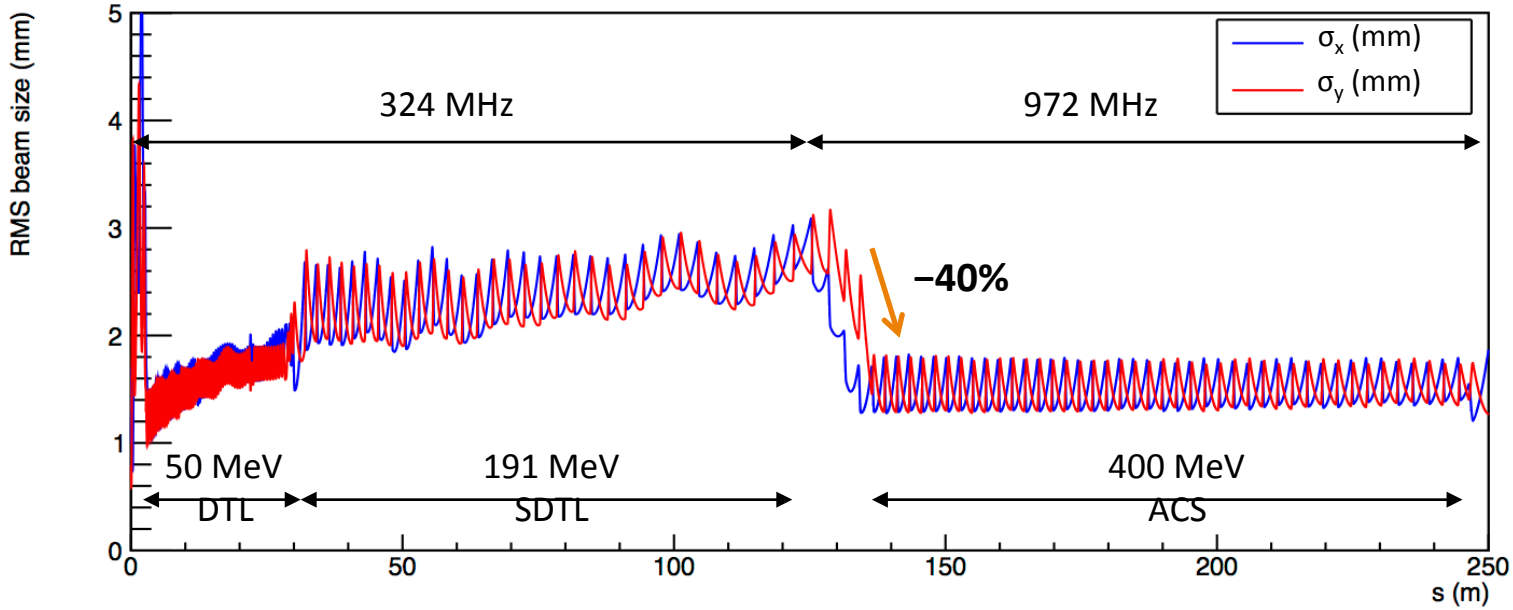
- On April 2015
- 4 hours after 500 kW MLF operation
  - Linac beam power: 67 kW
  - Linac peak current: 40 mA
  - Beam on duty: 4.4% (63% of design)
- Measured on the surface of vacuum chamber



Significant residual dose have been observed in entire ACS and the Arc section.

Beam Size and Loss in Current Operation

Design beam envelope (T = 1.0)



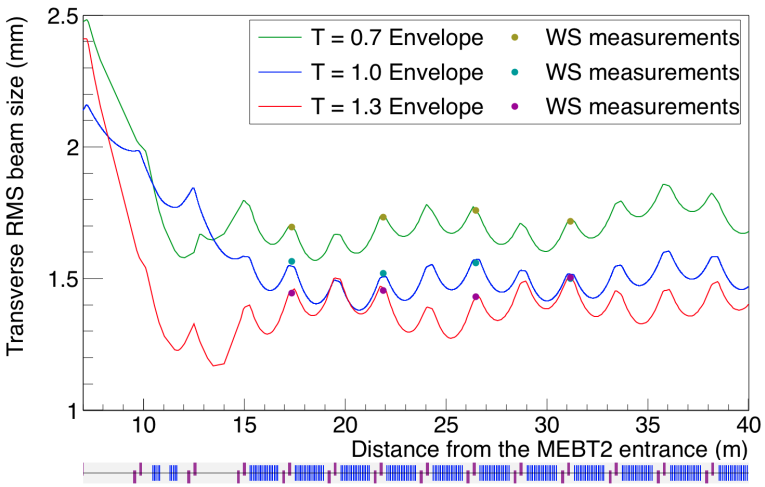
$$T \equiv \frac{\varepsilon_x k_x}{\varepsilon_z k_z} = 1$$

- **Equi-partitioning condition** is adopted for all linacs (RFQ, DTL, SDTL, ACS) to suppress transverse and longitudinal coupling resonance.
- 3 times RF frequency jump at ACS makes small beam size and it enhances IBSt loss.

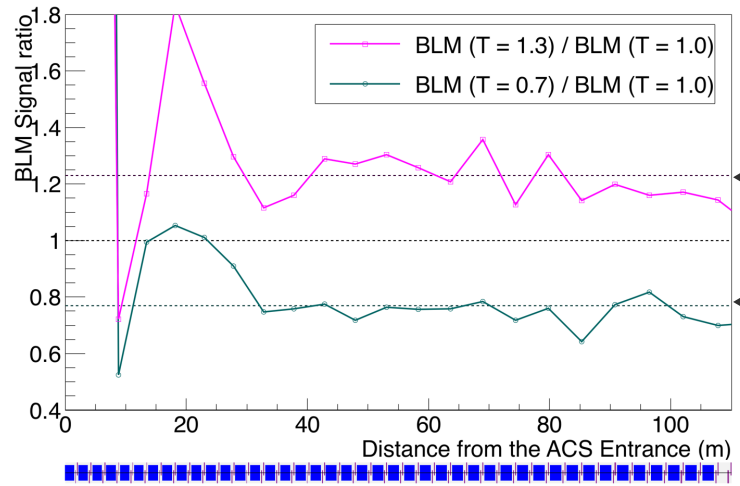
Evaluation of IBSt loss in ACS

In 30 mA beam, we confirmed that IBSt is dominant source in ACS

Beam envelopes around ACS injection



Measurement (Ratio of BLM signal)



Calculation

$$\frac{\text{BLM } (T = 1.3)}{\text{BLM } (T = 1.0)} = +23\%$$

$$\frac{\text{BLM } (T = 0.7)}{\text{BLM } (T = 1.0)} = -23\%$$

The beam loss is measured for three different T-ratio (**0.7**, **1.0** and **1.3**) optics, and compared them with an IBSt calculation.

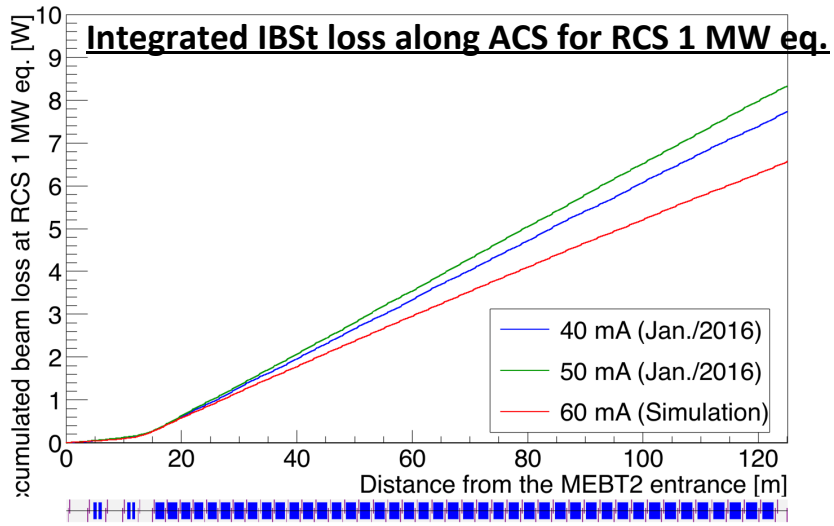
- T-ratio variation leads different beam size
- The calculation shows the variation of -23% (T = 1.0 to 0.7) and +23 (T = 1.0 to 1.3) and the measured loss shows same trend.

IBSt is confirmed to be main source.

Estimation of IBSt in ACS after the Upgrade

Input Norm. RMS emit	40 mA (Jan./2016)	50 mA (Jan./2016)	60 mA (Assumption)
ε_{xy} (mm-mrad)	0.37	0.42	0.46
ε_z (deg-MeV)	0.20	0.24	0.24

60 mA : 0.057 W/m
50 mA : 0.074 W/m
40 mA : 0.069 W/m
} for 1MW RCS operation



- The 60 mA IBSt per RCS 1 MW slightly reduce due to bigger emittance.
- IBSt at various beam operation is calculated from the above estimation.

Peak current		40 mA		50 mA		60 mA	
RCS power	(MW)	0.5	0.8	1.0	1.0	1.5	1.5
TEF operation		OFF	OFF	OFF	**ON**	OFF	**ON**
IBSt loss	(W/m)	0.034	0.054	0.072	0.20	0.10	0.22
ACS Residual Radiation • Chamber surface	(mSv/h)	< 0.6	< 0.9	< 1.3	< 3.5	< 1.8	< 4.1

- RCS 1.5MW is just beyond the tunnel design of 0.1 W/m.
- TEF operation is severely enhance the loss.

→ After TEF operation, we may not maintain the equipartitioning condition

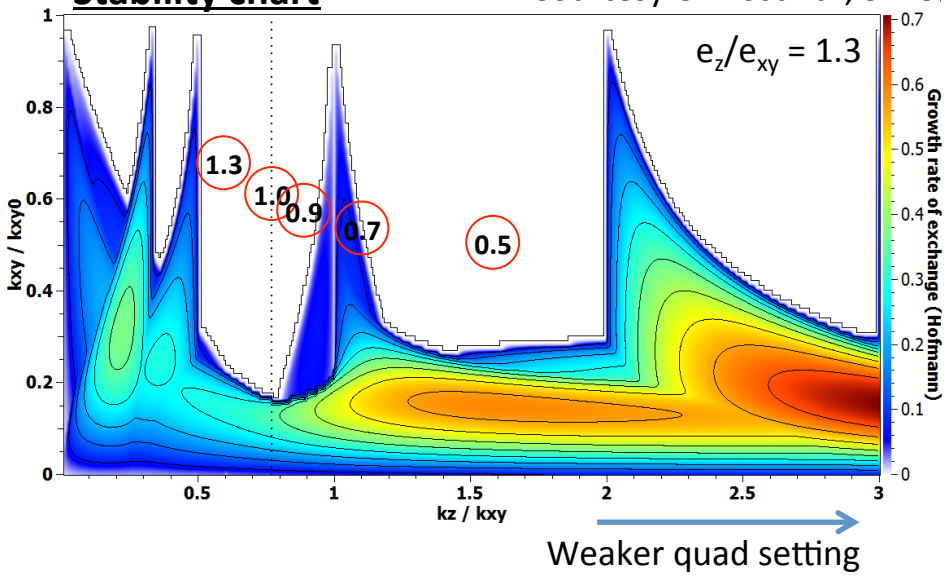
Loss Mitigation Study

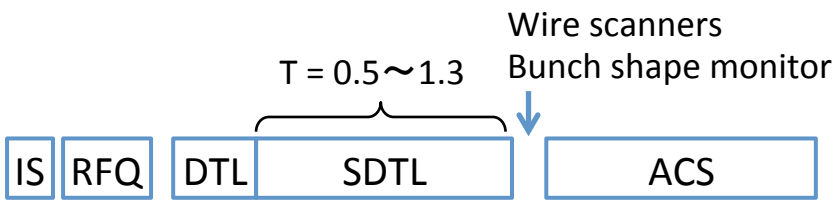
Y. Liu et. al., HB2016

- The IBSt is a dominant source in ACS. Further beam current increment boosts this loss.
- Wide beam size suppresses this loss.
  - ex: ～23% reduction at T = 0.7
- But it could excite the transverse-longitudinal coupling resonance.
- The understanding of resonance is essential to determine the new operation point.

Stability chart

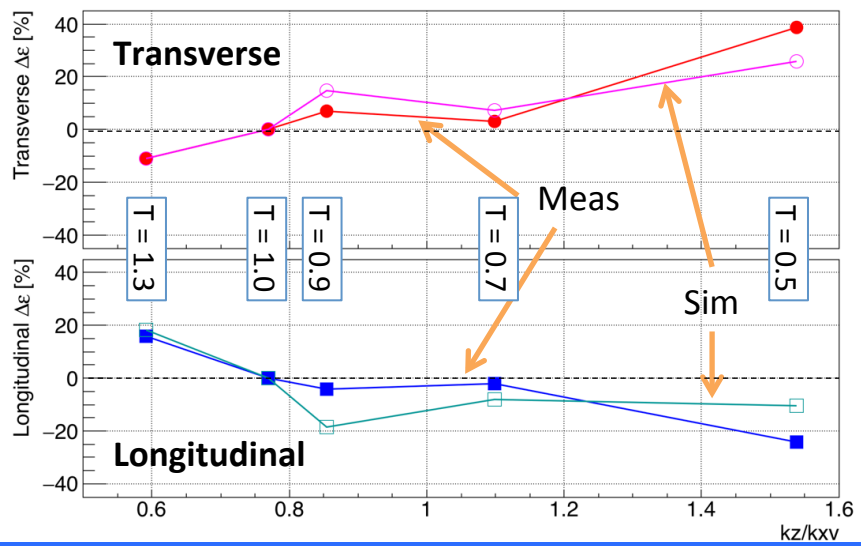
Courtesy C. Plostinar, STFC





- Set SDTL optics to T = 0.5 ～ 1.3
- longitudinal / transverse emittances measured at SDTL exit

Emittance at SDTL exit

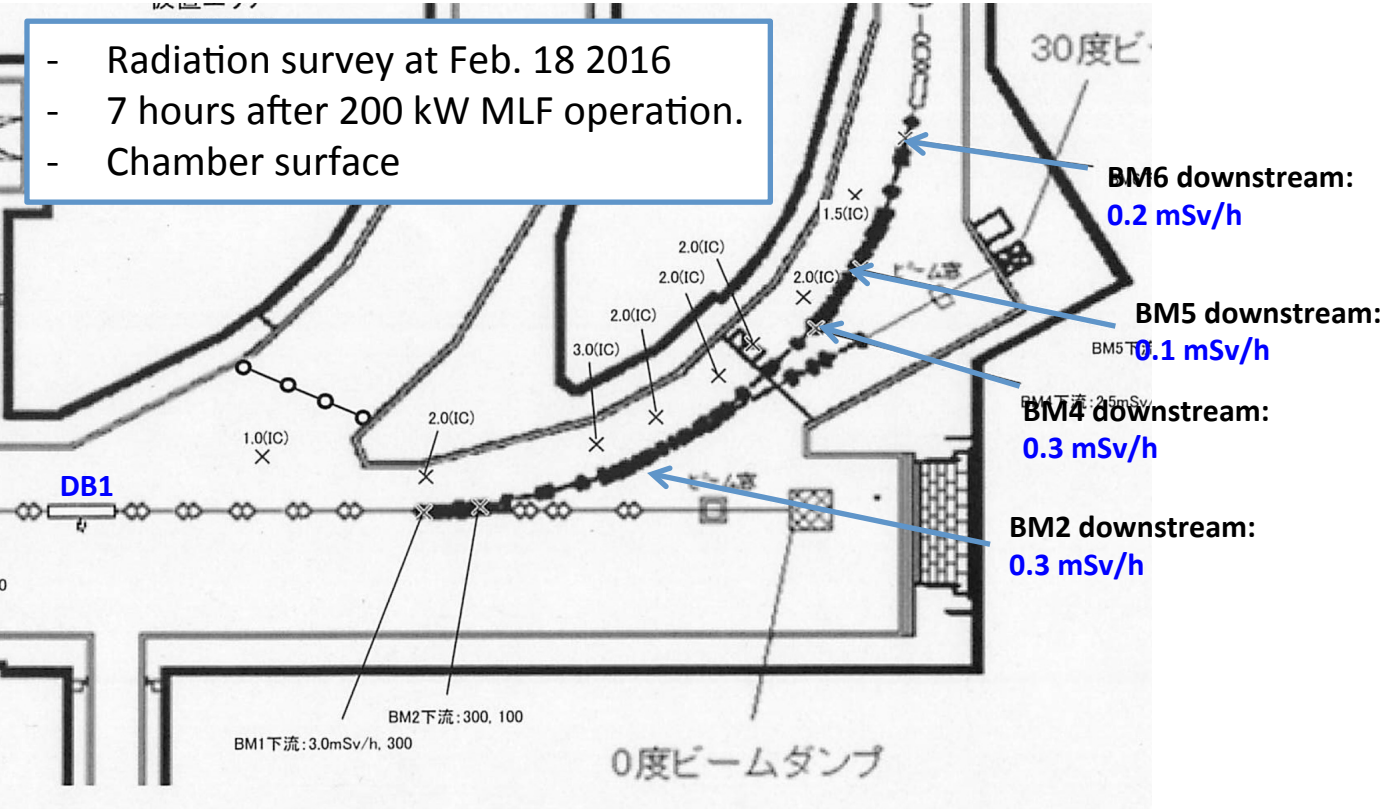


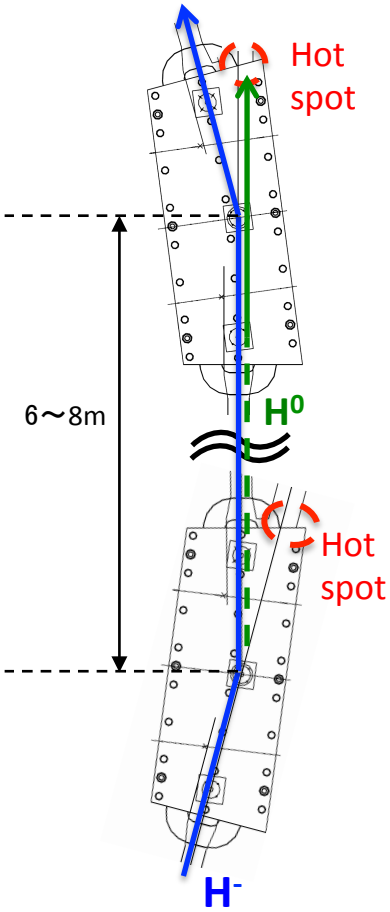
- The trend looks consistent.
- T = 0.7 is minimum exchange. Candidate of new operation point

Further study is on going

Residual Radiation in the 1st Arc Section

We found that there are hot spots in the 1st Arc section.



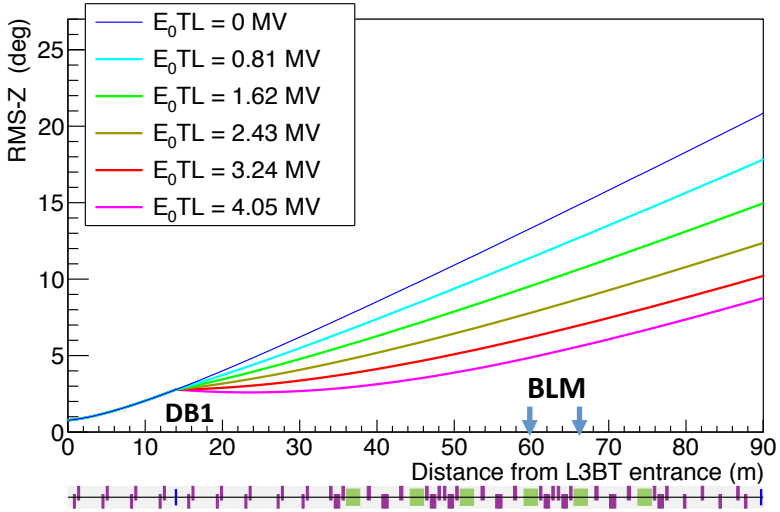


- All hot spots present on the extension of H- injection line
  → H^0 generated from the last BM may irradiated the hot spots.
- BLMs were installed at these hot spots for monitoring the loss.

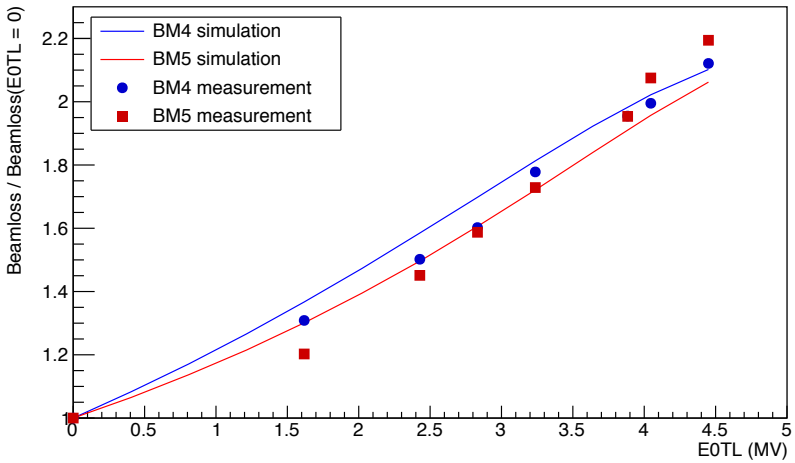
Evaluation of IBSt Loss in Arc

If IBSt is the source of these hot spots, the loss depends on H- density.
→ Measure the loss with various longitudinal beam size.

Longitudinal beam size



BLM signal vs. DB1 E_0TL



- Debuncher1 RF amplitude varies different σ_z afterwards
  - E_0TL = 0.8 MV step from 0 MV to 4 MV
  - σ_z = 5 ~ 13 degree
- The E_0TL dependence of measured loss is well consistent to the IBSt calculation.
  → IBSt is again main source of this loss

Estimated loss after the upgrade

Peak current	RCS power	Loss (W/m)	Residual radiation
40 mA	0.2 MW	0.009	0.3 mSv/h
40 mA	0.8 MW	0.037 (+300%)	1.2 mSv/h
50 mA	1.0 MW	0.045 (+380%)	1.5 mSv/h
60 mA	1.5 MW	0.044 (+376%)	1.4 mSv/h

The radiation is still tolerable after the upgrade

Summary

- J-PARC linac currently considering beam power upgrade in two-step upgrade, which contains peak current increase to 60 mA.

- We experimentally confirm that both of them are came from intra beam stripping.

- From the beam density squared rule of IBSt, the beam losses after the upgrade are estimated.
  - ACS loss is considered to be untolerable. We have intensively conducing beam study to find another operation point w/ wide beam size
  - Arc section loss could be tolerable even after the upgrade.