Beam Commissioning of J-PARC 400 MeV Linac

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J-PARC / KEK
on behalf of linac commissioning Gr.

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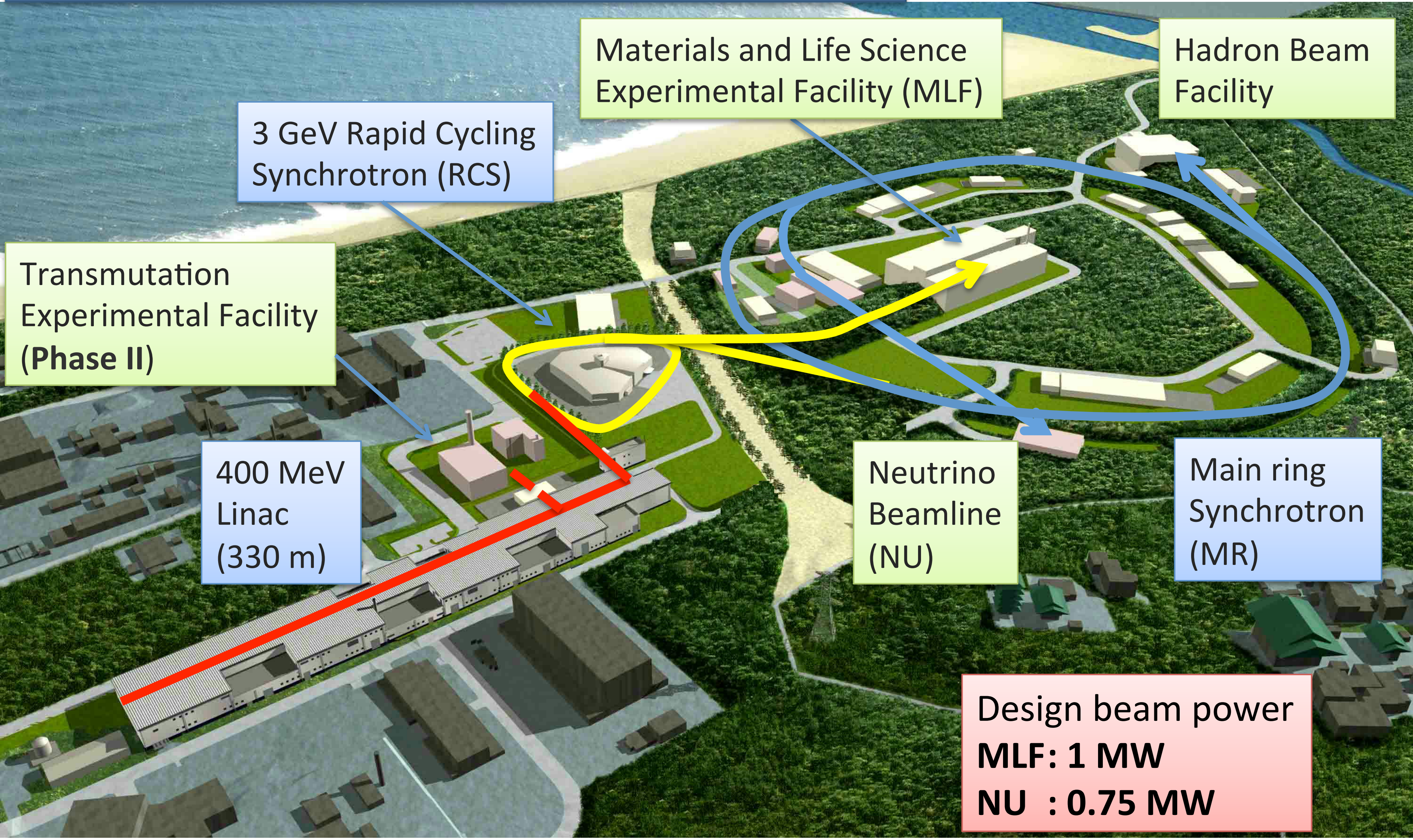
J-PARC Facility

Japan **P**roton **A**ccelerator **R**esearch **C**omplex



Materials and Life Science Experimental Facility (MLF)

Hadron Beam Facility

3 GeV Rapid Cycling Synchrotron (RCS)

Transmutation Experimental Facility **(Phase II)**

400 MeV Linac (330 m)

Neutrino Beamline (NU)

Main ring Synchrotron (MR)

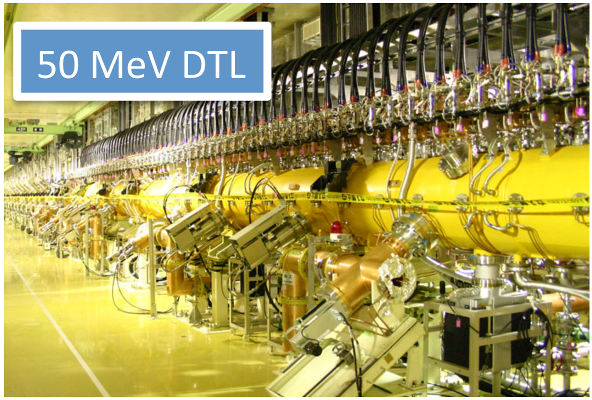
Design beam power
MLF: 1 MW
NU : 0.75 MW

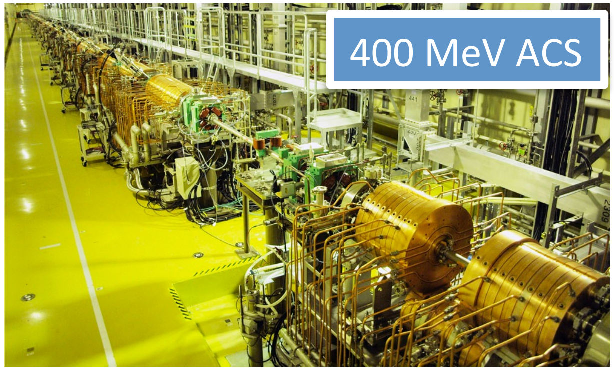
Outline of the J-PARC Linac

Main parameters

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

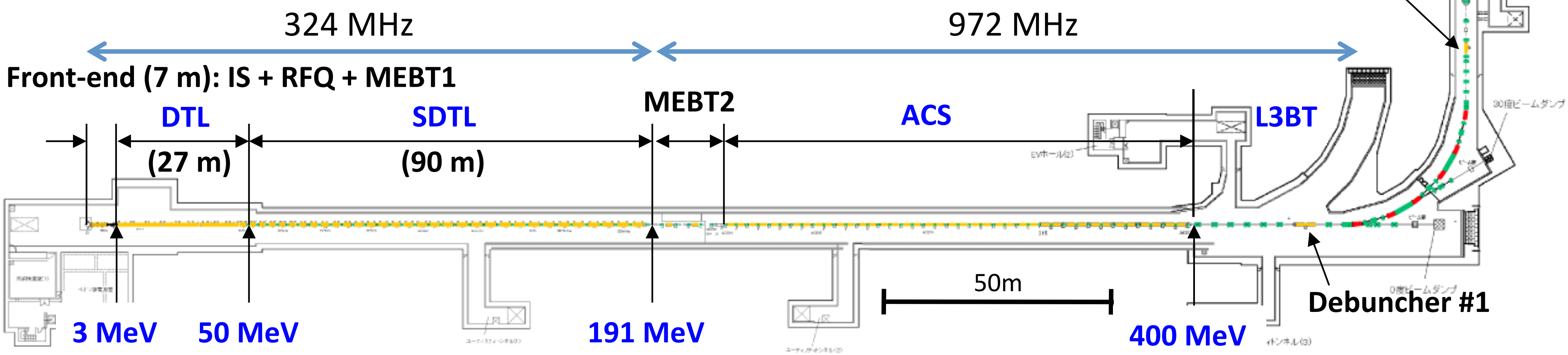
*1: Phase II





Equi-partitioning is adopted for all linacs (RFQ, DTL, SDTL, ACS) to suppress transverse longitudinal coupling resonance.

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



Toward Design Beam Power

Two-step upgrade:

1) 181 to 400 MeV by adding ACS in January 2014.
   - Tune shift at RCS injection within reasonable range in 50 mA
   - Achievement of 400 MeV at January 17th

2) 30 to 50 mA by the front-end replacement in Oct. 2014
   - IS of LaB6 filament, Cs free → IS of RF driven, Cs seed
   - RFQ designed for 30 mA → RFQ designed for 50 mA

0) 2007 January

181 MeV
30 mA

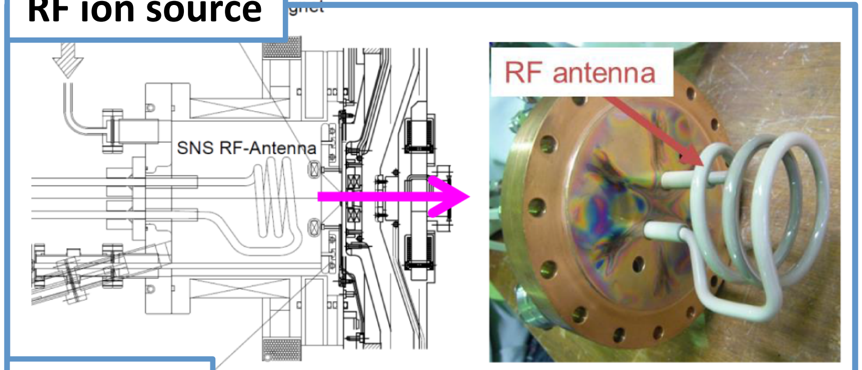
1) 2014 January

400 MeV
30 mA

2) 2014 October

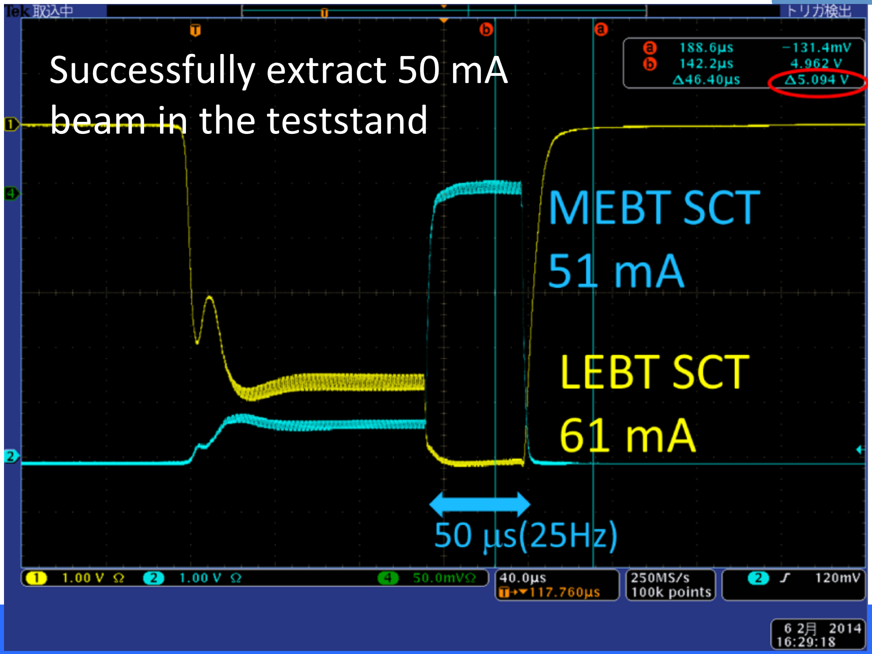
400 MeV
50 mA

RF ion source



New RFQ

→ T. Shibata, IS and LEBT tuning MOPLR052



Successfully extract 50 mA beam in the teststand

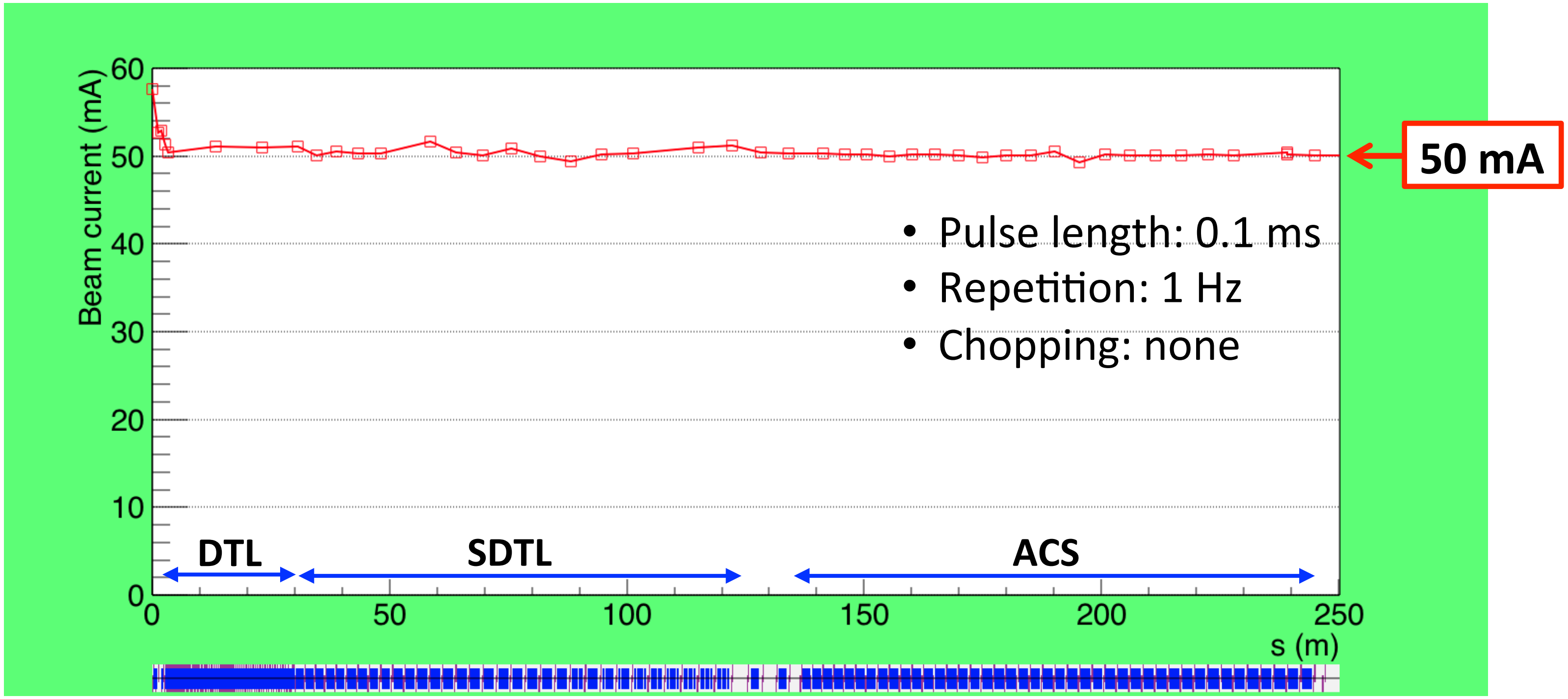
MEBT SCT
51 mA

LEBT SCT
61 mA

50 µs(25Hz)

50 mA Trial with New Front-end

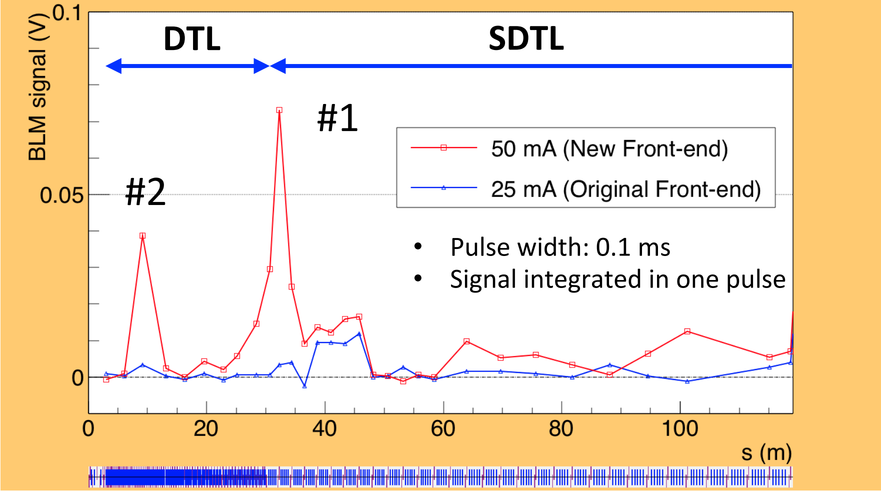
- The 1st beam commissioning started at September 29th 2014.
- 50 mA beam tuning started October 11th after RF phase scan in 5 mA and 30 mA tuning.
- On October 15th, after 5 days study, 50 mA beam is accelerated to 400 MeV without any decline of beam current after DTL.



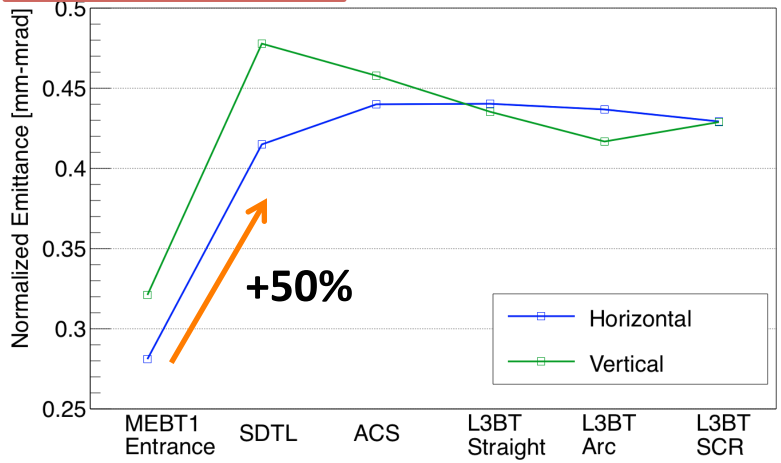
- Pulse length: 0.1 ms
- Repetition: 1 Hz
- Chopping: none

BLM and Emittance in 50 mA

Beam Loss Monitor



Trans. Emittance



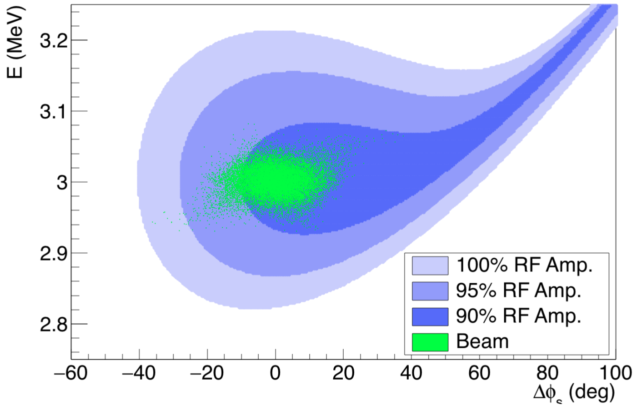
- Two losses were observed in DTL and SDTL.
  - #1 locates DTL end to SDTL entrance. We identified this was longitudinal beam loss by measuring the DTL longitudinal acceptance.
  - #2 locates 1st DTL tank. This loss can be interpreted as transverse beam loss. Envelope may oscillate in DTL. 50% emittance growth supports this interpretation. New MEBT1 optics was developed based on Q-scan measurements.
- The ACS loss entirely increased more than peak current scaling. We identified that this loss source is intra beam stripping (IBSt).
- No emittance growth after SDTL is observed. DTL injection matching is essential.

DTL Longitudinal Measurement

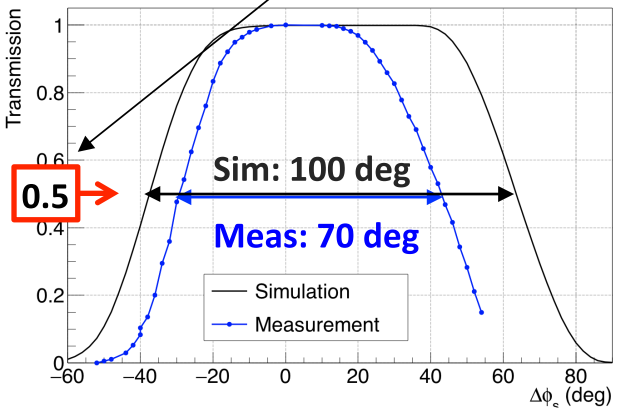
- In design, DTL longitudinal acceptance sufficiently covers a beam bunch.

Acceptance
- -40 to 60 degree
- -0.2 to 0.2 MeV

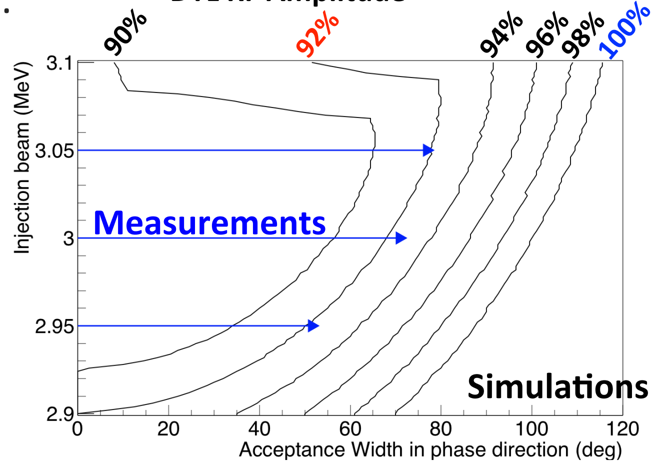
Beam (RMS)
- 8 degree
- 0.02 MeV


DTL Longitudinal acceptance

- This acceptance shrinks as RF amplitude being low. Thus Low RF amplitude potentially causes a beam loss.
- The DTL phase acceptance was experimentally measured to confirm that this acceptance is as design.
  1. Measure transmission with varying DTL driven phase.
  2. Calculate phase width of transmission higher than 0.5.
  3. Same measurement shifting the injection energy by +/-0.05 MeV.
- All measurements shows 30% narrow acceptance.
- It is equivalent to 8% lower RF Amplitude.



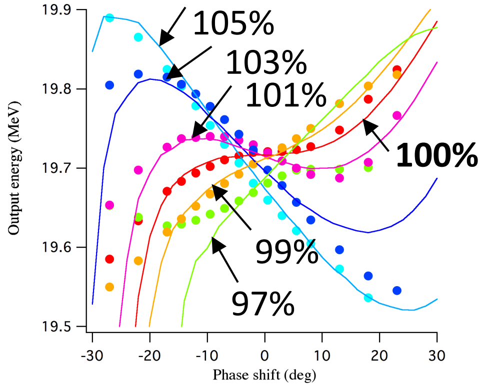
DTL RF Amplitude

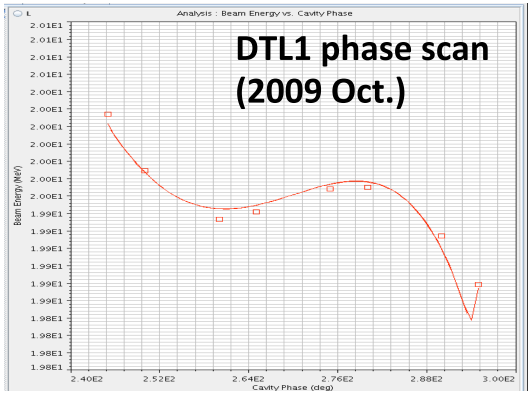


Why 8% lower RF Amplitude?

The 1st DTL cavity was 8% lower RF amplitude because of **wrong phase scan reference**.

DTL1 phase scan
(2007 Dec.)





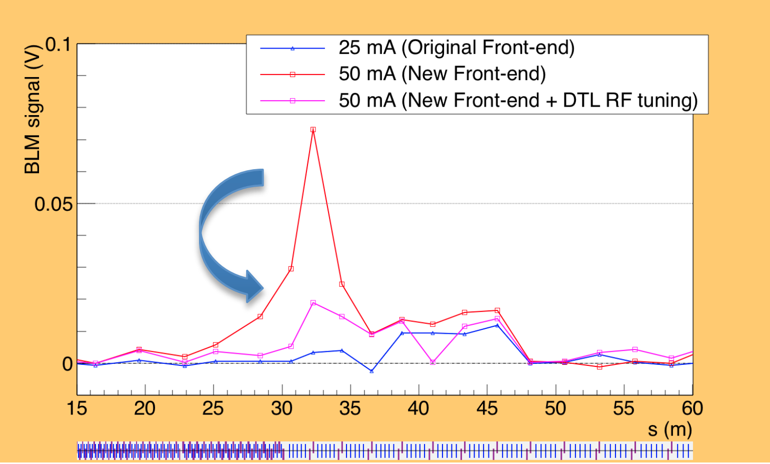
DTL1 phase scan
(2009 Oct.)

- DTL is comprised from 3 cavities and RF is individually supplied from a klystron.
- New phase scan reference was introduced but wrong DTL1 reference curves before 2009.
  - Only the DTL1 is made by shift the injection phase.
  - Nobody noticed this mistake until recently because no significant loss had been observed.

Lessons learnt:

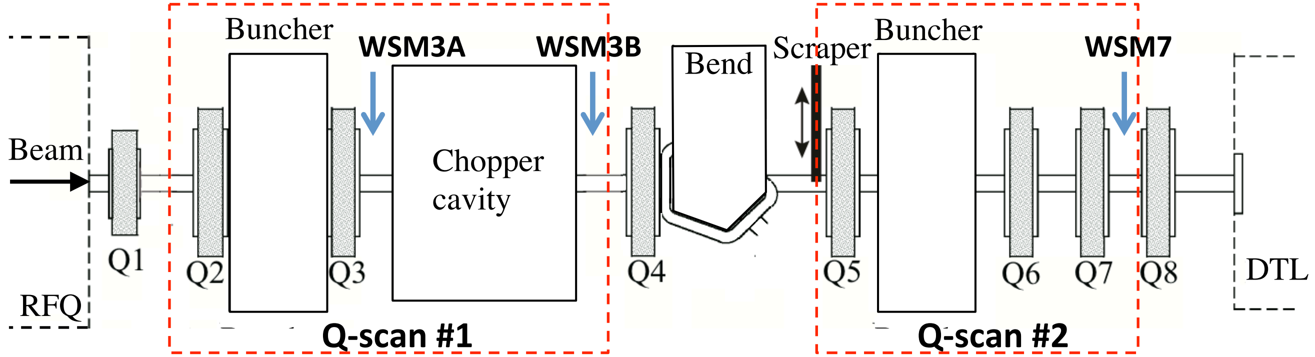
- Something new, careful check is necessary.
- Phase acceptance measurement is powerful tool.

After correcting DTL1 RF amplitude and phase, and optimize buncher amplitudes, the loss between DTL to SDTL was significantly reduced.



3 MeV MEBT1 Q-Scan in 40 mA

MEBT1 tuning was performed in 40 mA



MEBT1 configuration

- Quadrupole x 8
- Buncher x 2
- Wire scanner x 4
- Chopper system x 1
- Bending magnet x 1

Quadupole + Drift:

$$\sigma^2_{WSM} = \varepsilon\left[(1+Lk)^2\beta - 2(1+Lk)L\alpha + L^2\gamma\right]$$

σ_{WSM} : Measured RMS beam size by wire scanner

$\alpha, \beta, \gamma, \varepsilon$: Twiss parameter, emittance

→ **free parameter for fitting**

L : Distance from quad to WSM

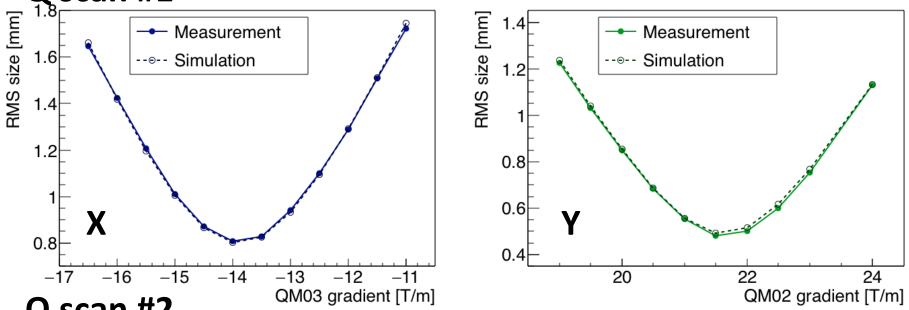
k : Focusing gradient

- Q-scan is conducted in two locations.
- Each scan plays different role.

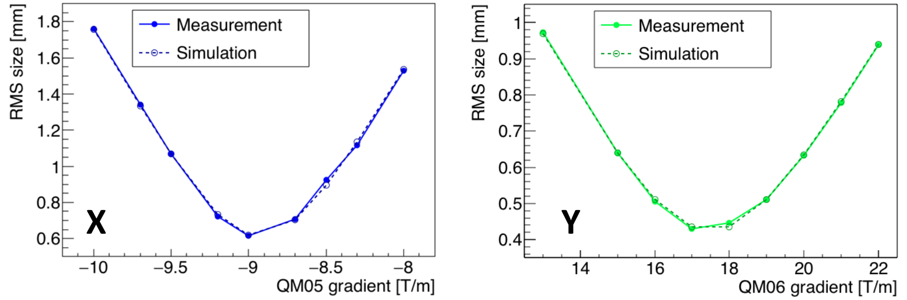
#1: Optics tuning of upstream of MEBT1

#2: DTL injection matching

Q scan #1



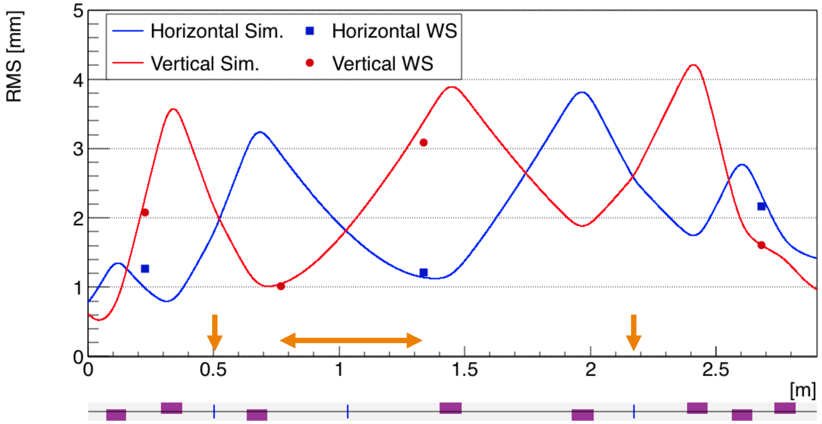
Q scan #2



The scan curves are fit with 3D PIC (IMPACT).
The fitting well reproduces scan curves.

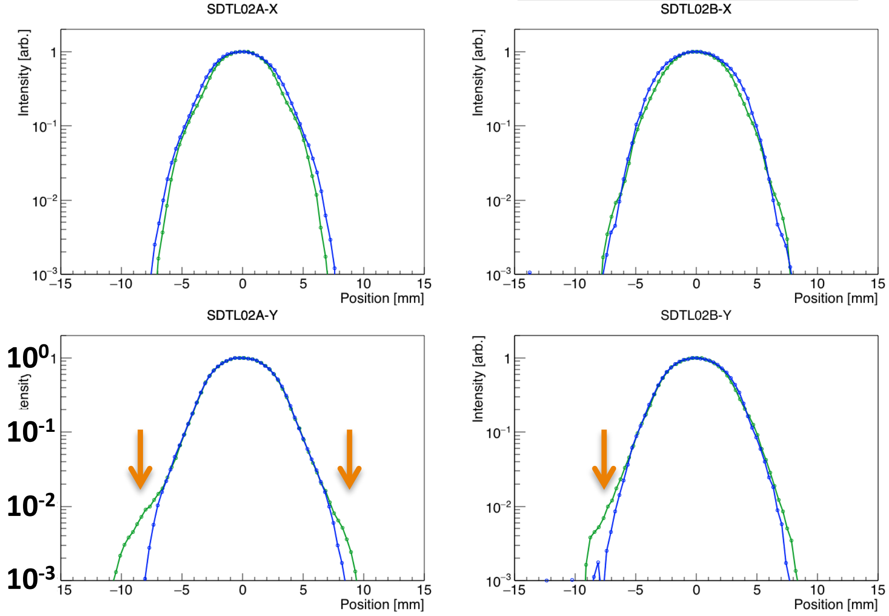
Improvement of Beam in 40 mA

- The new MEBT1 optics is designed from the obtained profiles.
  - Circular and reasonably narrow beam at buncher and chopper cavities.
  - Matched to DTL injection
- Measured beam size are good agreement with envelopes.

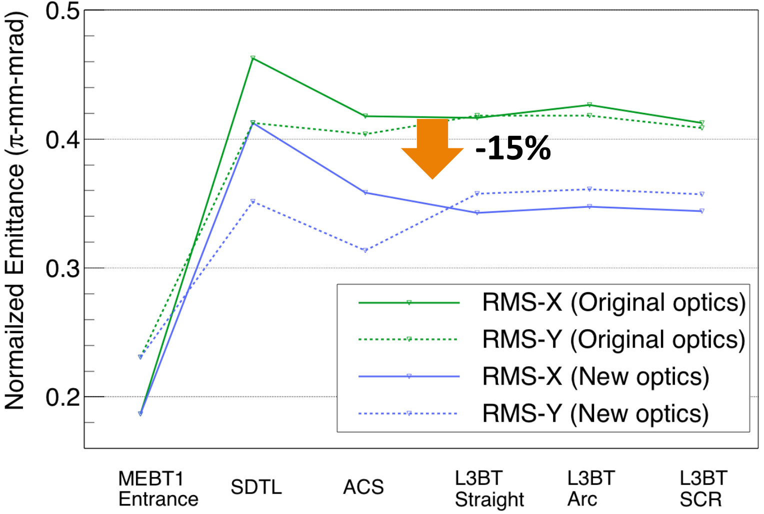


WS profiles at DTL exit

Green : **Original** optics
Blue : **New** optics



Transverse emittance



- Halos in 10^{-3} level are distinguished.
- The emittance is decreased by 15%.

Tuning scheme established

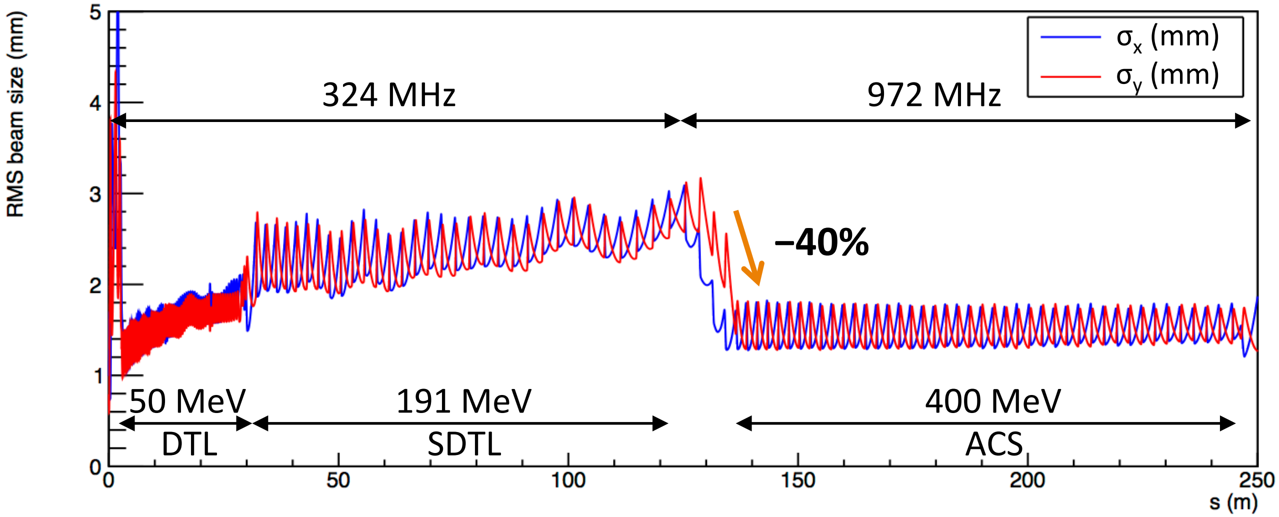
What is the Beam Loss Source in ACS?

- Continuous beam loss is observed in the whole ACS section.
  - 0.3 – 0.6 mSv/h on chamber surface 5 hours after 200 kW MLF operation.
- Intra Beam Stripping (IBSt) is potentially dominant source.
  - IBSt ∝ particle density^2
  - Beam current is > 30 mA from 15 mA in user operation after FE upgrade.
  - Beam size shrinkage in ACS due to Equi-partitioning condition
    - 3 times higher RF frequency in ACS

Equi-partitioning condition

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

Design beam envelope (T = 1.0)



The IBSt was experimentally measured with 30 mA beam

Outline of IBSt Measurement in 30 mA

Compare the beam loss of different beam size with a calculation

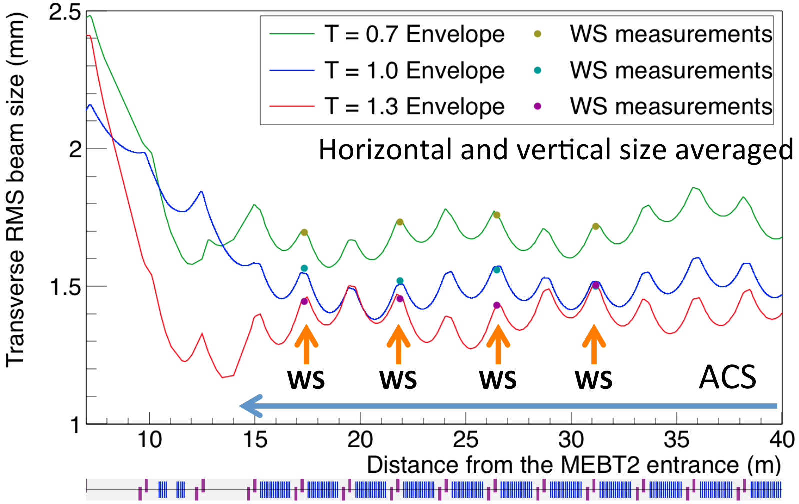
1) Prepare three ACS optics with different T-ratio (**0.7**, **1.0** and **1.3**).
   - T-ratio variation leads different beam size
   - DTL and SDTL optics are Identical
   - Injection beam is matched to minimize halo formation

2a) Measure BLM signals

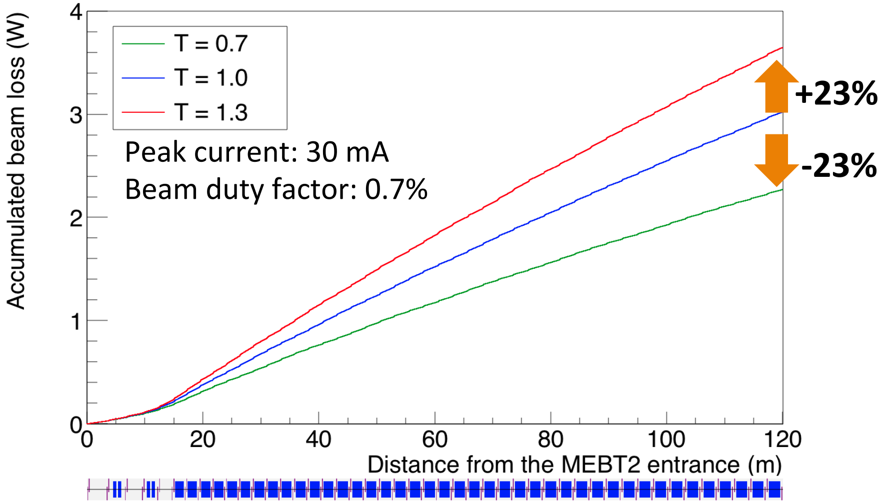
2b) Reconstruct the envelope from WS measurements and calculate IBSt loss

If IBSt is dominant, these loss variation must be consistent

Beam envelopes around ACS injection



Integrated IBSt loss (Calculation)

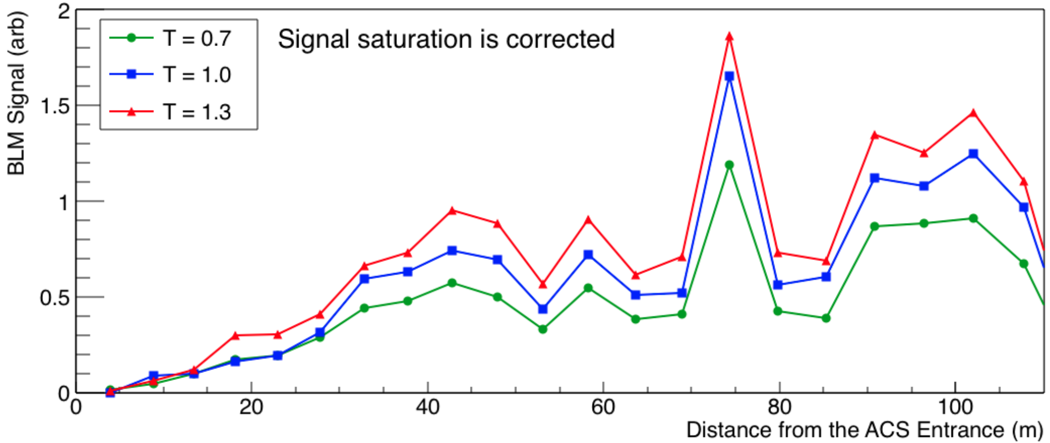


Comparison of ACS Loss with Calculation

- Beam condition:
  - Beam current: 30 mA
  - Pulse width: 0.1 ms
- 21 BLMs are placed in the ACS section
  - Proportional counters are used
- Signal is integrated pulse-by-pulse
- More than 10 pulses are averaged for statistical error mitigation.

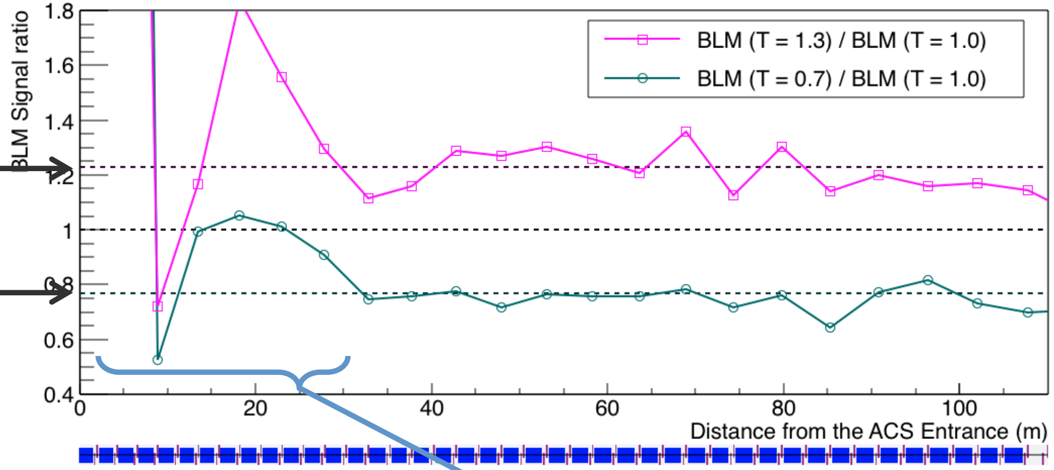
- BLM signals of T = 1.3 and 0.7 are scaled by signals of T = 1.0.

BLM signals in ACS w/ different T-ratio



Calculate signal ratio

Ratio of BLM signals in ACS



Calculation

$$\frac{\text{BLM}\ (\mathbf{T = 1.3})}{\text{BLM}\ (\mathbf{T = 1.0})} = \mathbf{1.23}$$

$$\frac{\text{BLM}\ (\mathbf{T = 0.7})}{\text{BLM}\ (\mathbf{T = 1.0})} = \mathbf{0.77}$$

The ratios of BLM signal well consistent w/ the calculation.
We clearly identified that **IBSt is a main source of ACS beam loss.**

Gas-stripping suspected.
J. Tamura, MOPLR063

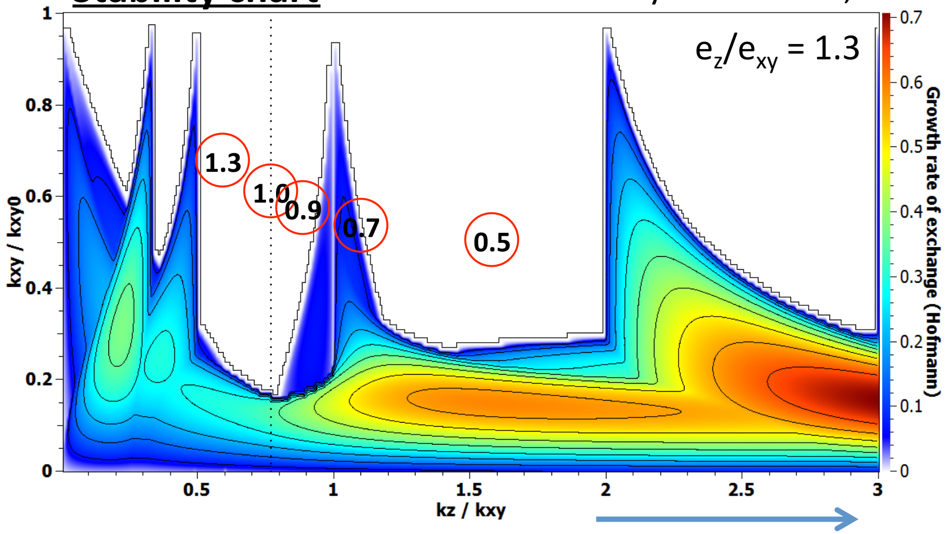
Loss Mitigation Study

Y. Liu et. al., HB2016

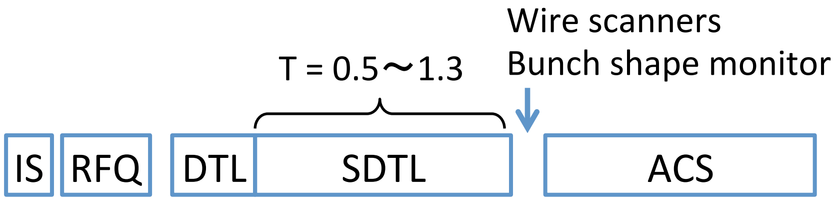
- The IBSt is a dominant source in ACS. Further beam current increment boosts this loss.
- Wide beam size suppresses this loss.
  - ex: ∼25% reduction at T = 0.7
- But it could excite the transverse-longitudinal coupling resonance.
- The understanding of resonance is essential to determine the new operation point.

Stability chart

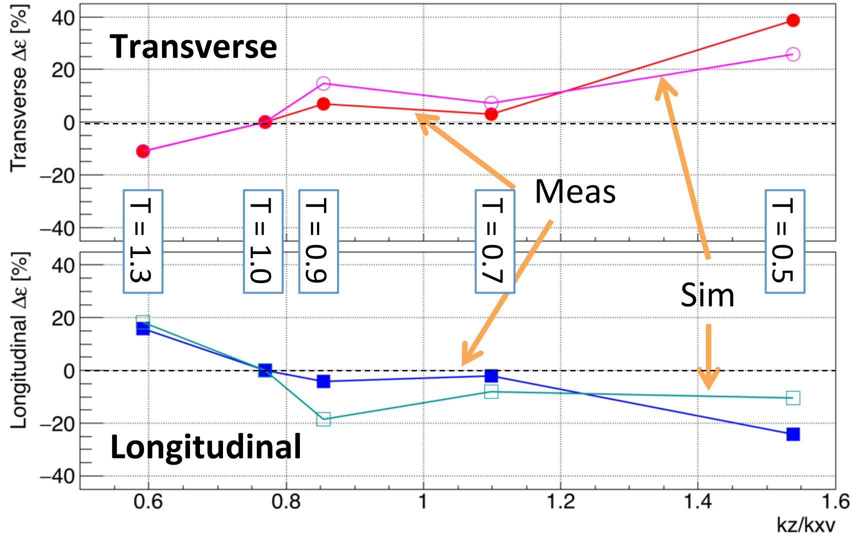
Courtesy C. Plostinar, STFC



Weaker quad setting

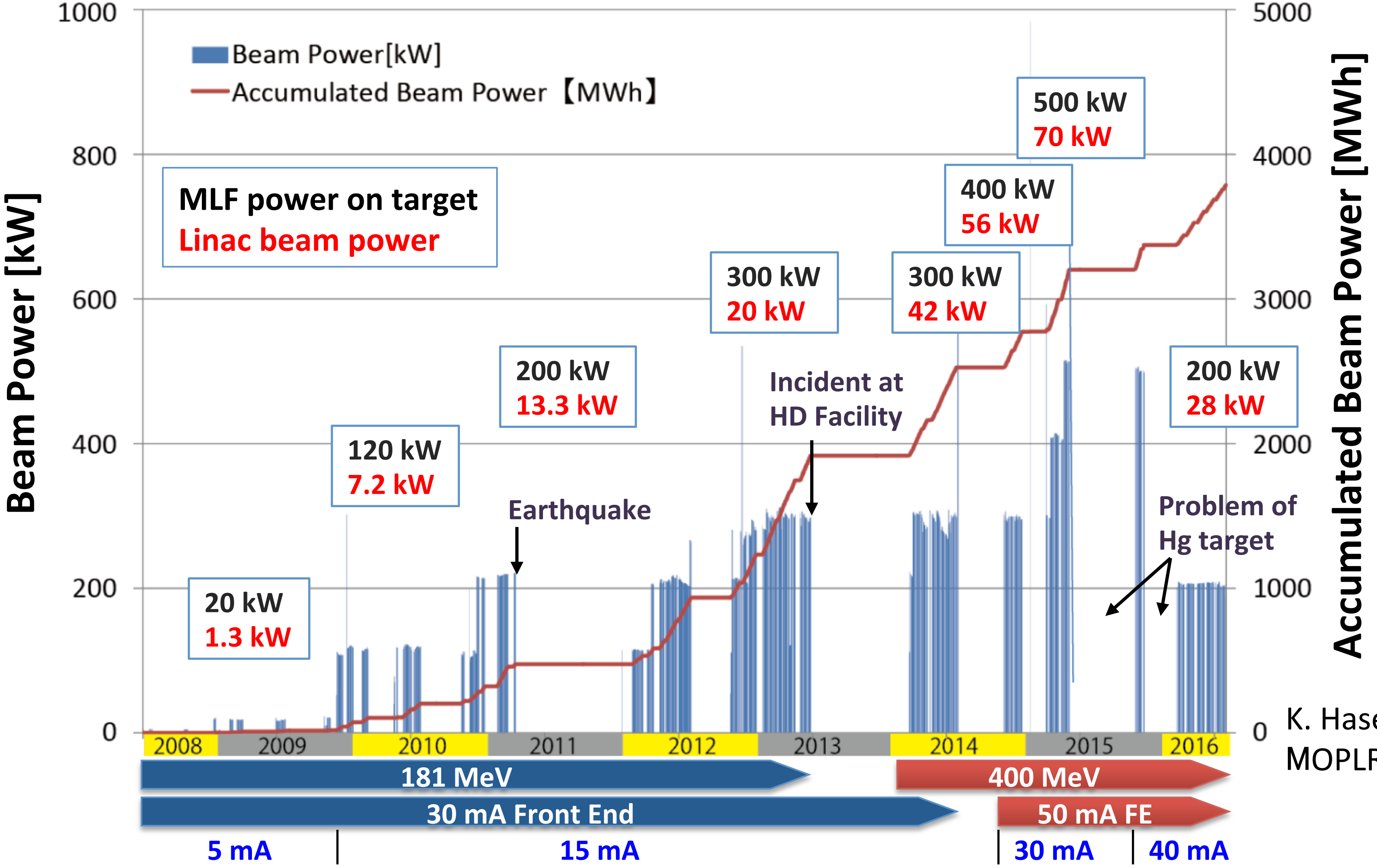


- Set SDTL optics to T = 0.5 ∼ 1.3
- longitudinal / transverse emittances measured at SDTL exit



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

MLF Neutron Source Operation History



K. Hasegawa
MOPLR054

The linac beam current has gradually increased 5 mA to 40 mA as matching operation power of downstream facilities.

Summary

- The 50 mA beam has been successfully accelerated to 400 MeV in October 2014, in the 1st commissioning after beam intensity upgrade.

- Several issues are solved for beam loss in new front-end
  - Recovery of DTL1 RF amplitude mitigates the loss after DTL.
  - MEBT1 optics was re-designed. The new optics shrinks transverse emittance by 15% and distinguishes 10^{-3} level beam halo in 40 mA.
  - Intra beam stripping is identified as a dominant source of the ACS beam loss. The resonance study was conducted for less beam loss operation search.

- 40 mA beam has been stably supplied to RCS in user operation from Jan. 2016.