High intensity aspects of J-PARC linac including re-commissioning after earthquake

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Masanori Ikegami
KEK/J-PARC

Outline

We don't reiterate the history of beam commissioning after the earthquake, which was covered by the following references:

- M. Ikegami et.al., IPAC12.
- M. Ikegami et.al., LINAC12.
- M. Ikegami et.al., 9th PASJ* meeting.

* Particle Accelerator Society of Japan

Instead, we focus on **the beam loss we experienced for the first time after the earthquake**, and **our attempt to reproduce the beam loss in a particle simulation**.

- Layout of J-PARC linac
- Irregular RF setting
- Experimentally observed beam loss
- Particle simulation
- Discussion and summary

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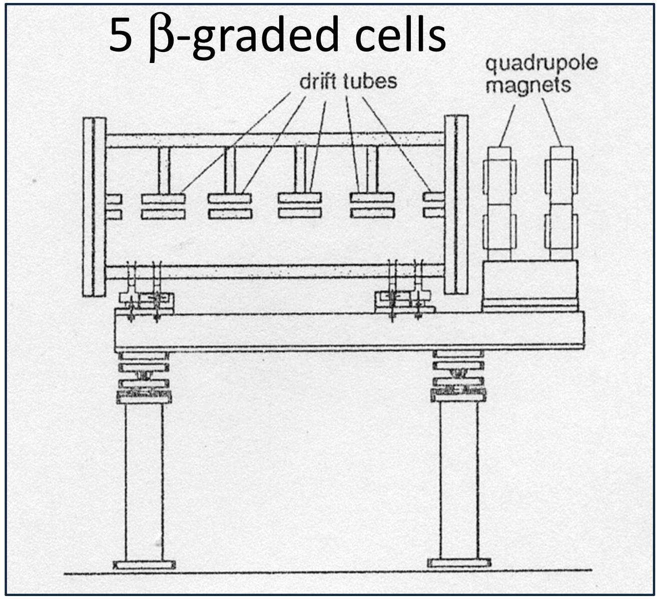
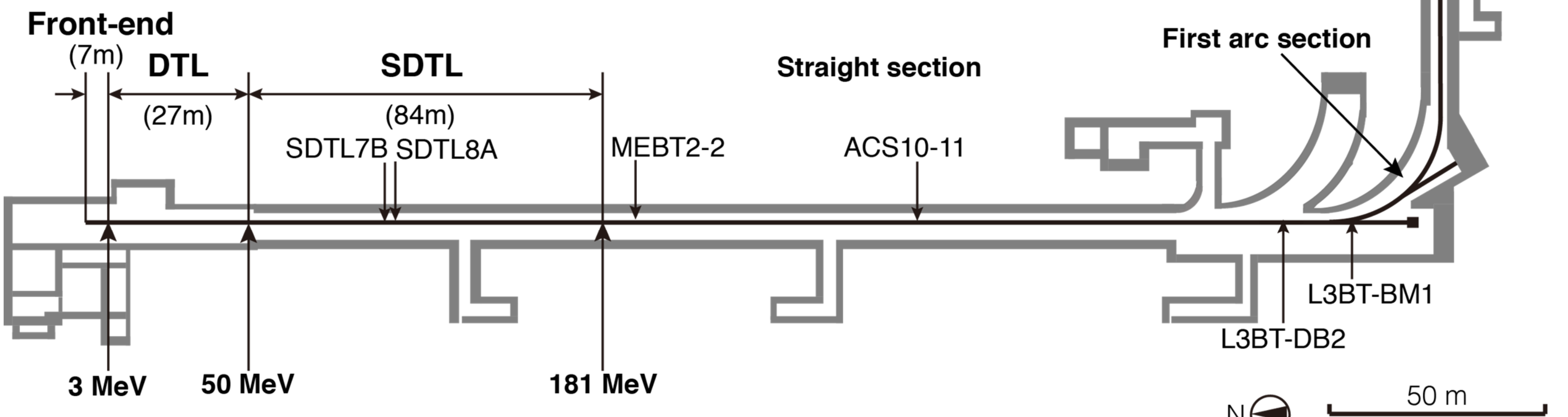
J-PARC Linac Layout

- Particle: Negative Hydrogen Ion
- Frequency: 324 MHz
- Output energy: 181 MeV
- Peak current: 30 mA (15 mA)
- Pulse width: 0.5 ms
- Repetition: 25 Hz
- Chopper duty: 53 % (39 %)
- Beam power 36 kW (13.3 kW)

Parameters for nominal operation in ().



SDTL = Separate-type DTL



Front-end = Ion source + LEBT + RFQ + MEBT

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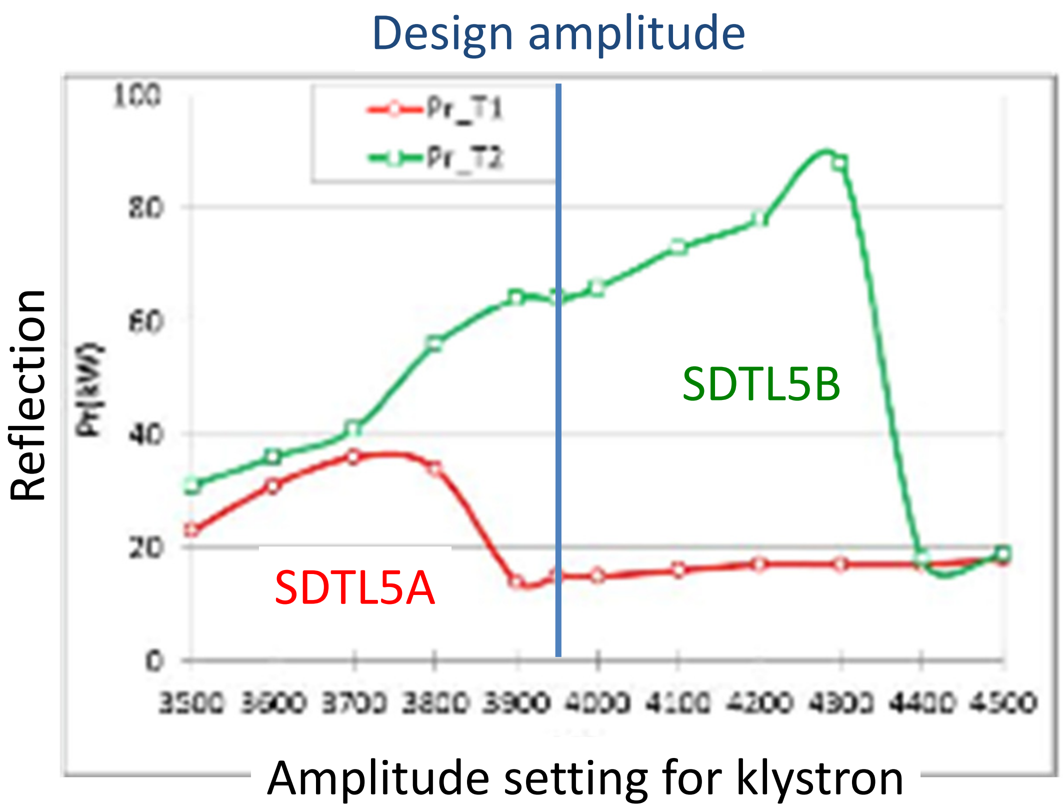
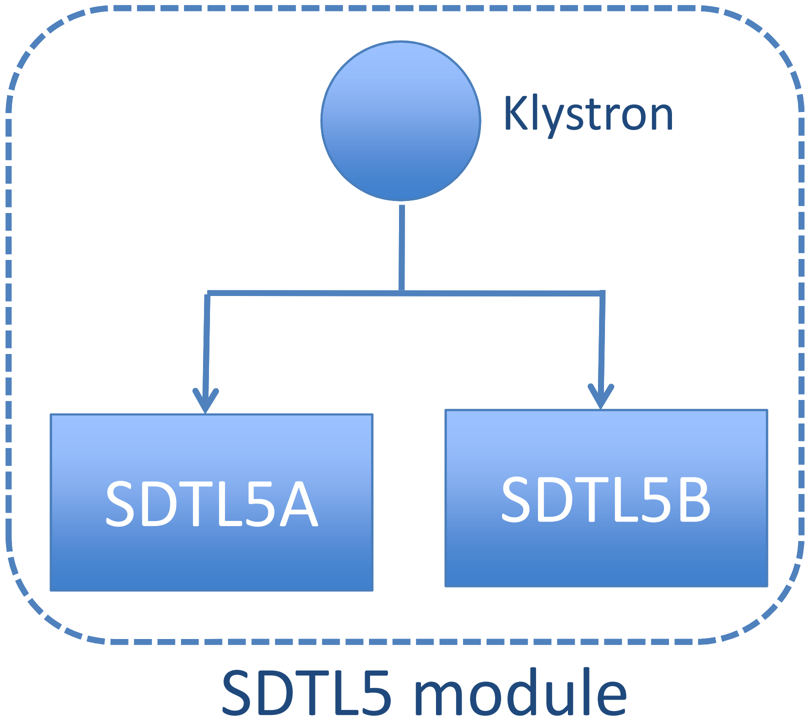
Multipactor at an SDTL Cavity





- After the earthquake, it become difficult to operate SDTL5 with the design RF amplitude due to multipactor.
- It forced us operate SDTL5 with higher amplitude (currently 116 % of the design) to avoid the multipactor.

Three RF Settings

We tried three RF settings to accommodate 116 % amplitude for SDTL5.

- **Case-I: Phase-amplitude scan tuning result**
  For SDTL5, the amplitude is fixed to 116 % and the phase is adjusted to give the design energy gain. The phase and amplitude for other SDTL modules are tuned to the design values with phase-amplitude scan.

- **Case-II: Phase shift tuning result**
  The phase shifts for SDTL5 and SDTL6-15 are taken as two tuning knobs. Adopting Case-I as the starting point, the phase shifts are tuned by trial-and-error method to minimize the beam loss downstream.

- **Case-III: Design longitudinal focusing**
  The phase for SDTL5 is adjusted to give the design longitudinal focusing with 116 % amplitude. The phase and amplitude of SDTL4 are adjusted to give the design longitudinal focusing and to compensate the excess energy gain in SDTL5.

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- **Experimentally observed beam loss**
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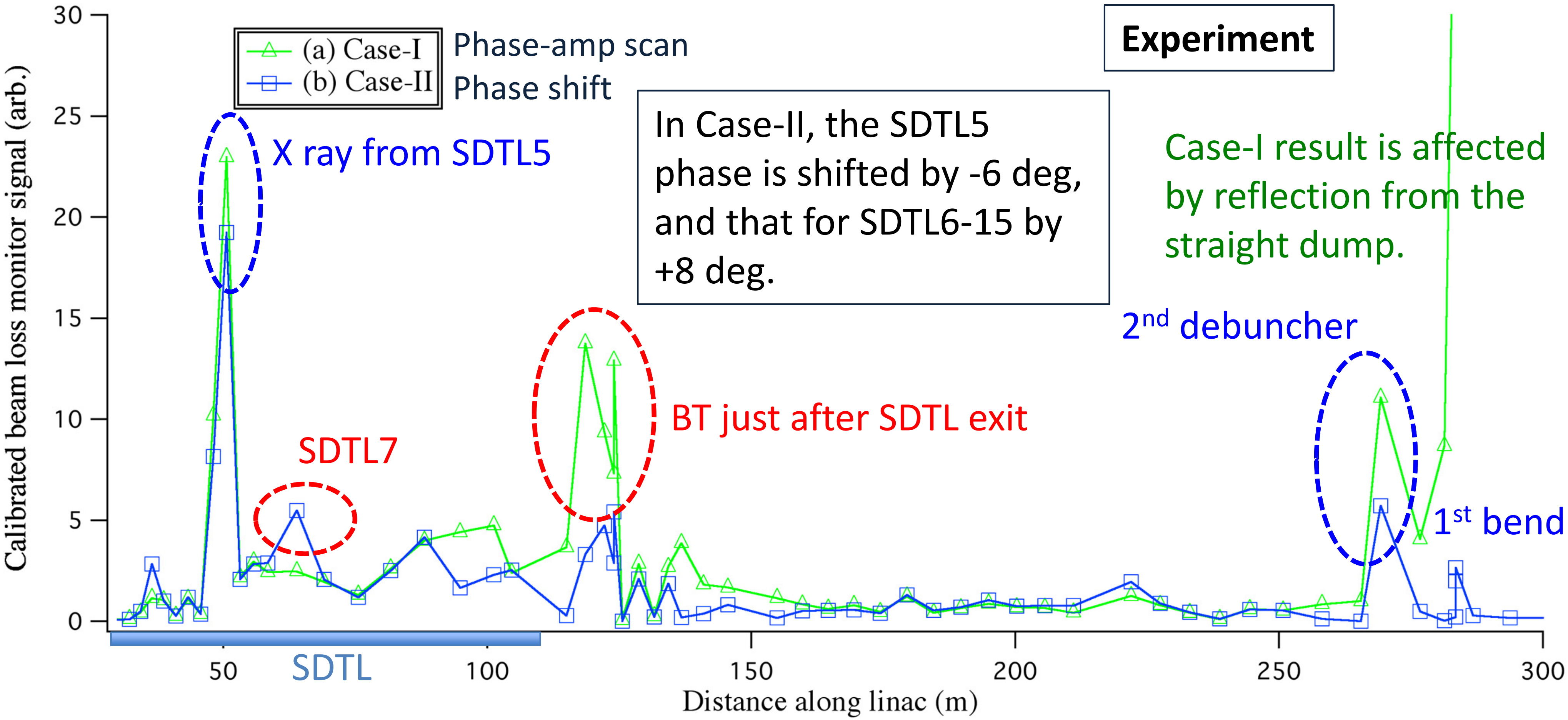
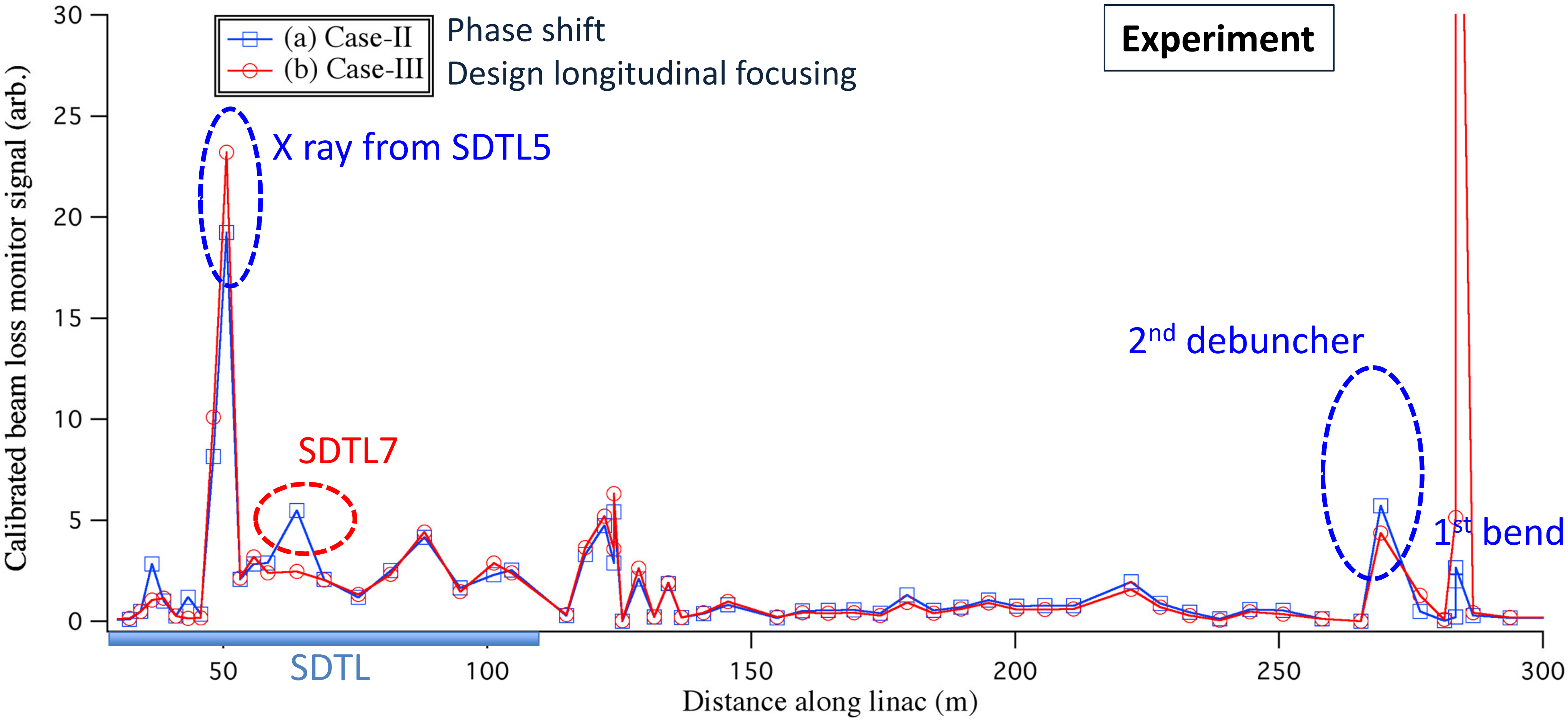
Observed Beam Loss (I)



- We have severe beam loss with Case-I around the SDTL exit.
- We can reduce the beam loss by adopting Case-II, but the beam loss arise at around SDTL7.

Observed Beam Loss (II)



- We have succeeded in mitigating the beam loss around SDTL7 in Case III.
- The beam loss at the 1st bend is increased in Case-III, which is found to be caused by protons.

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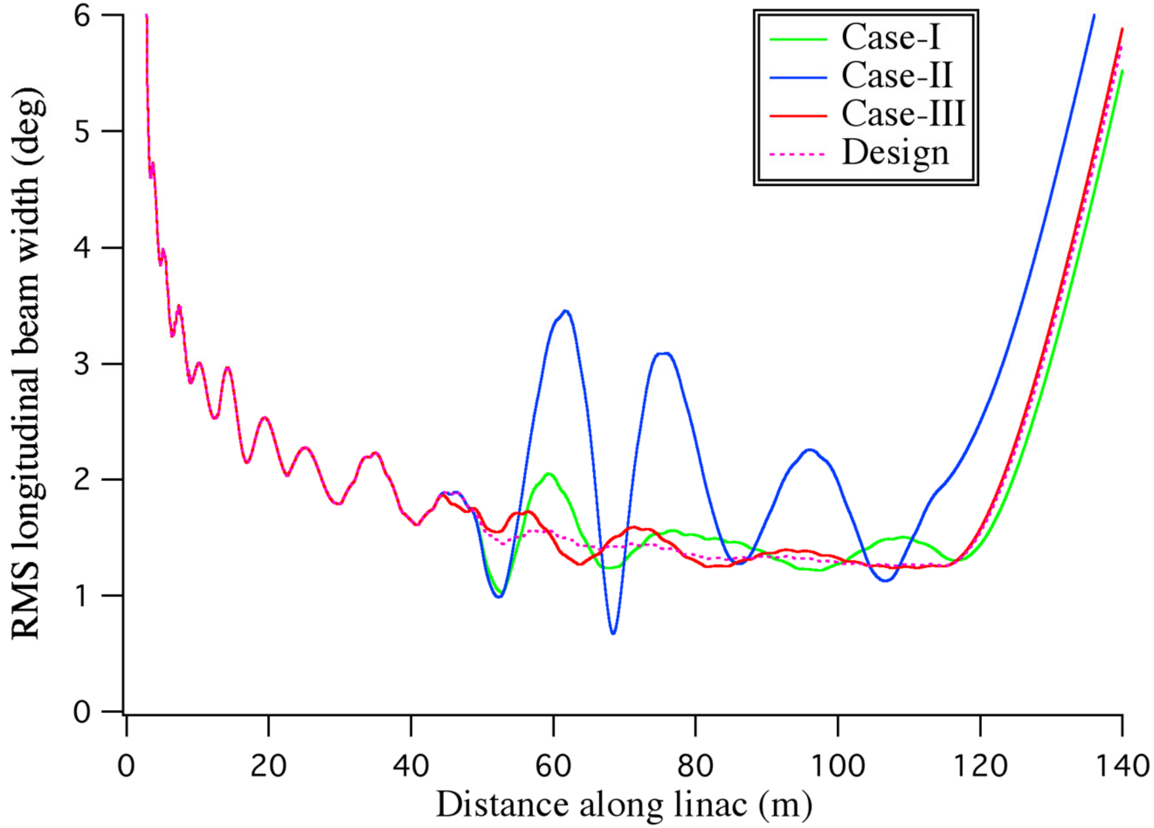
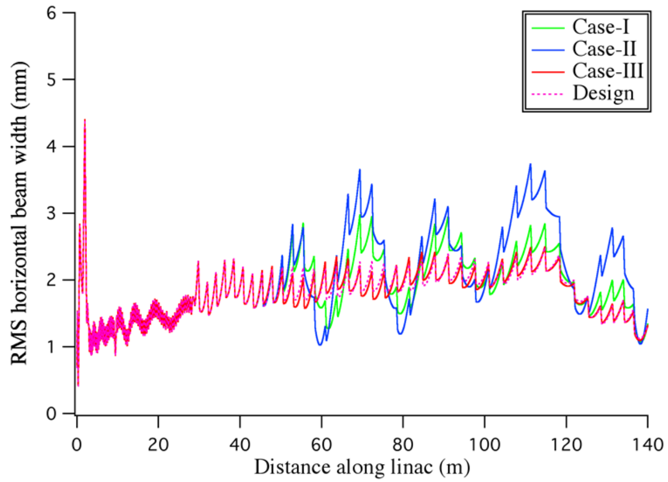
Simulation Condition

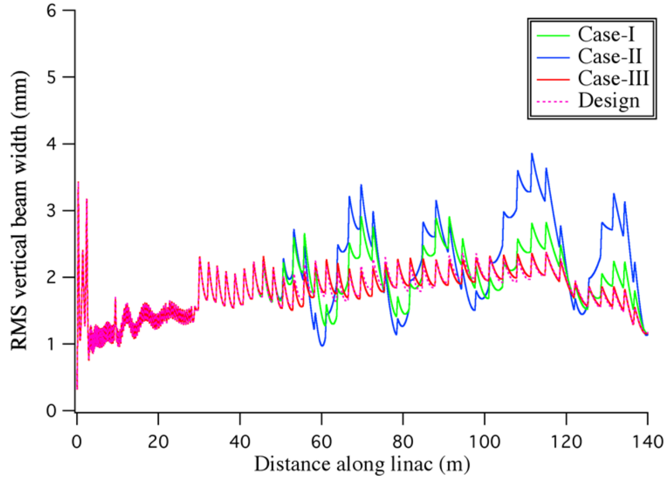
- Simulation code: **IMPACT**
- Initial distribution: PARMTEQ output
- Num. of particles: 953,220
- Num. of meshes: 32x32x64
- Integration step width: $\sim\beta\lambda/100$
- Integrator: Lorentz
- Assumed errors:
  - Distribution: Uniform random
  - RF phase error: ± 1 deg
  - RF amplitude error: ± 1 %
  - Quad misalignment: ± 0.1 mm
  - Quad gradient error: ± 1 %

An error analysis is conducted with 20 seeds for each case.

Simulated Envelope





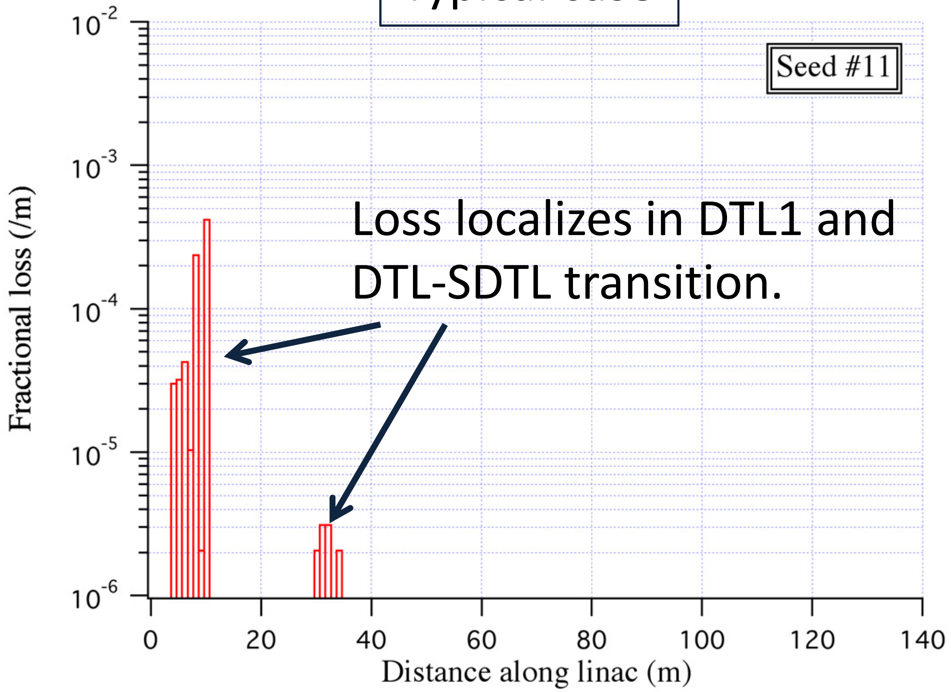


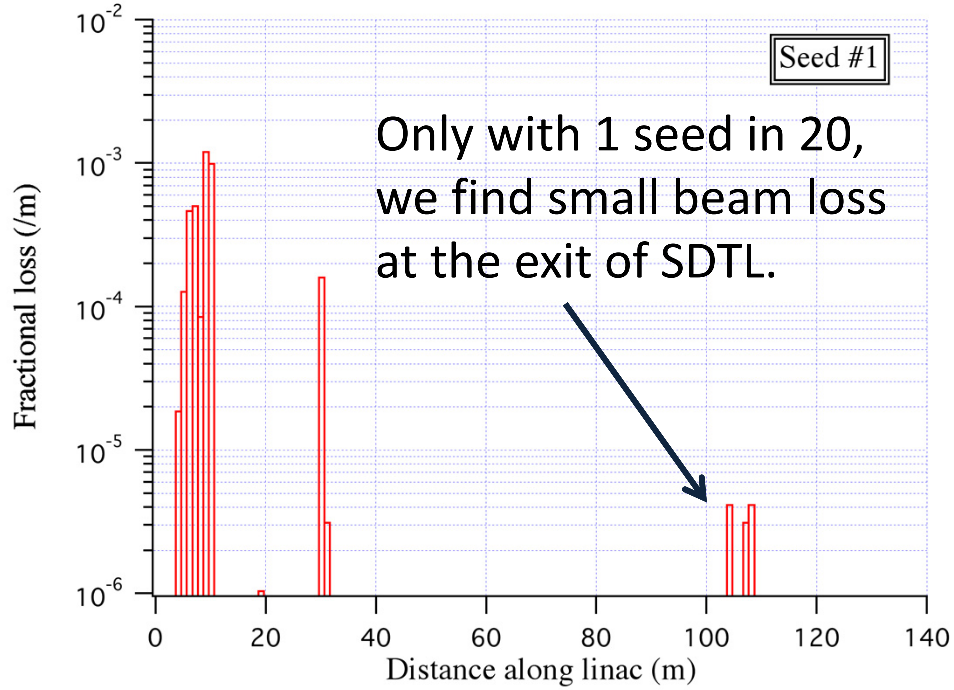
- The largest mismatch oscillation is invoked in Case-II.
- It is counter-intuitive to have less significant beam loss in Case-II than in Case-I.

Simulated Loss: Case-I

Phase-amplitude scan result

Typical case

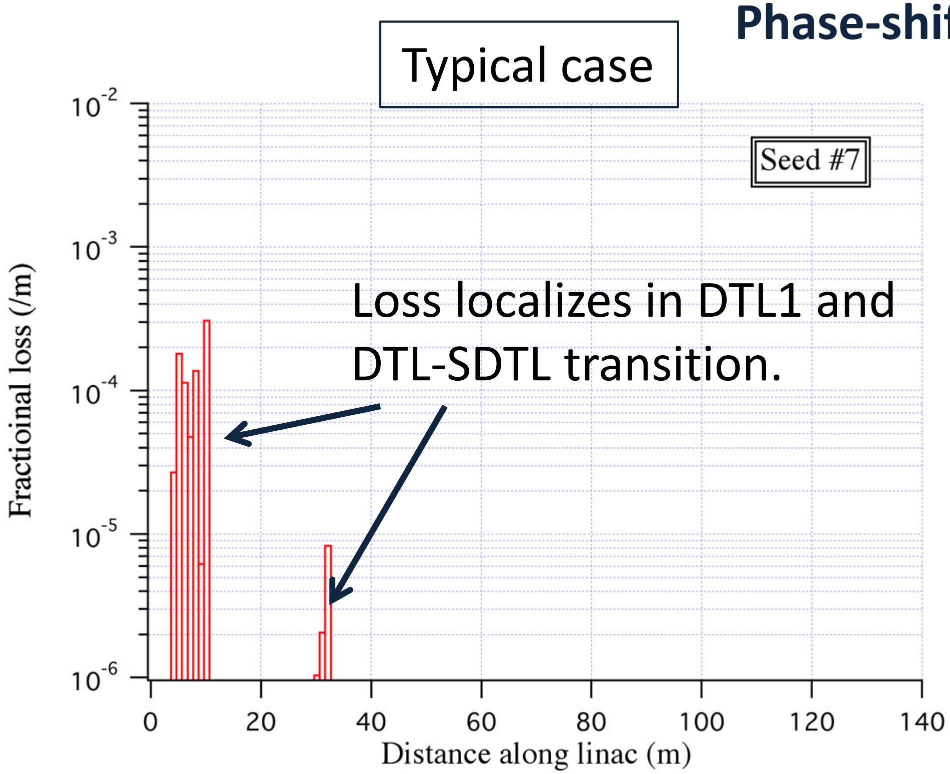


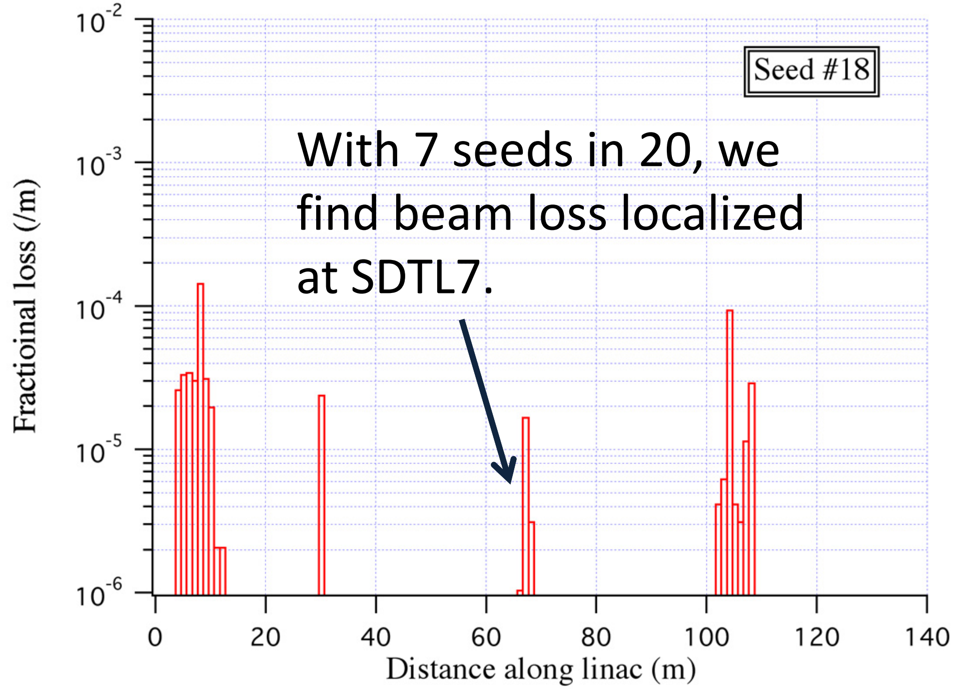


- Only with 1 seed in 20, we find small beam loss at the exit of SDTL.
- However, it might be too small to account for the beam loss we experimentally observed around the exit of SDTL.

Simulated Loss: Case-II

Phase-shift tuning result

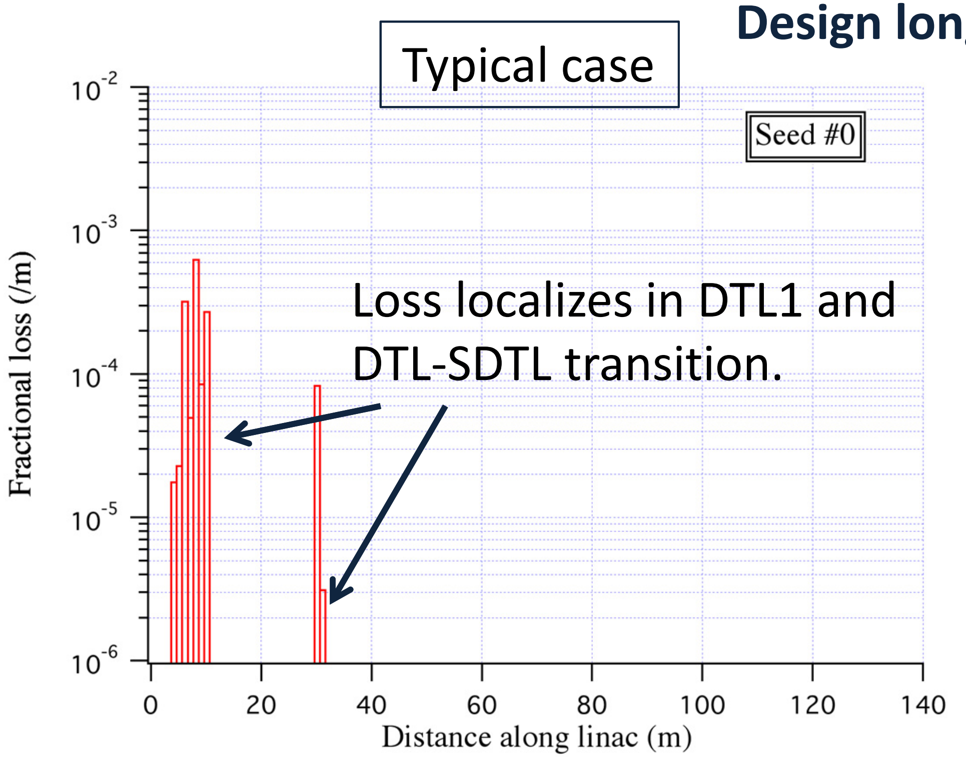




- With 7 seeds in 20, we find beam loss localized at SDTL7.
- However, all runs with those seeds accompany more significant beam loss around the exit of SDTL than around SDTL7.

Simulated Loss: Case-III

Design longitudinal focusing



- With all seeds, we find no beam loss around SDTL7 and SDTL exit.
- It is consistent with the experimental observation.

Conclusion

- **Case-I:** In the experiment, beam loss around the SDTL exit is the highest in three cases.

  → **Not reproduced**.

- **Case-II:** In the experiment, beam loss is specifically localized at SDTL7.

  → **Reproduced**, but with excess beam loss around the SDTL exit.

- **Case-III:** In the experiment, the beam loss is the lowest in three cases without any specifically localized loss.

  → **Reproduced**.

The experimentally observed beam loss behavior has not been fully reproduced by the particle simulation.
However, the localized loss at SDTL7 found in simulation for Case-II does not seem to be a mere coincide.

- Layout of J-PARC linac
- Irregular RF setting
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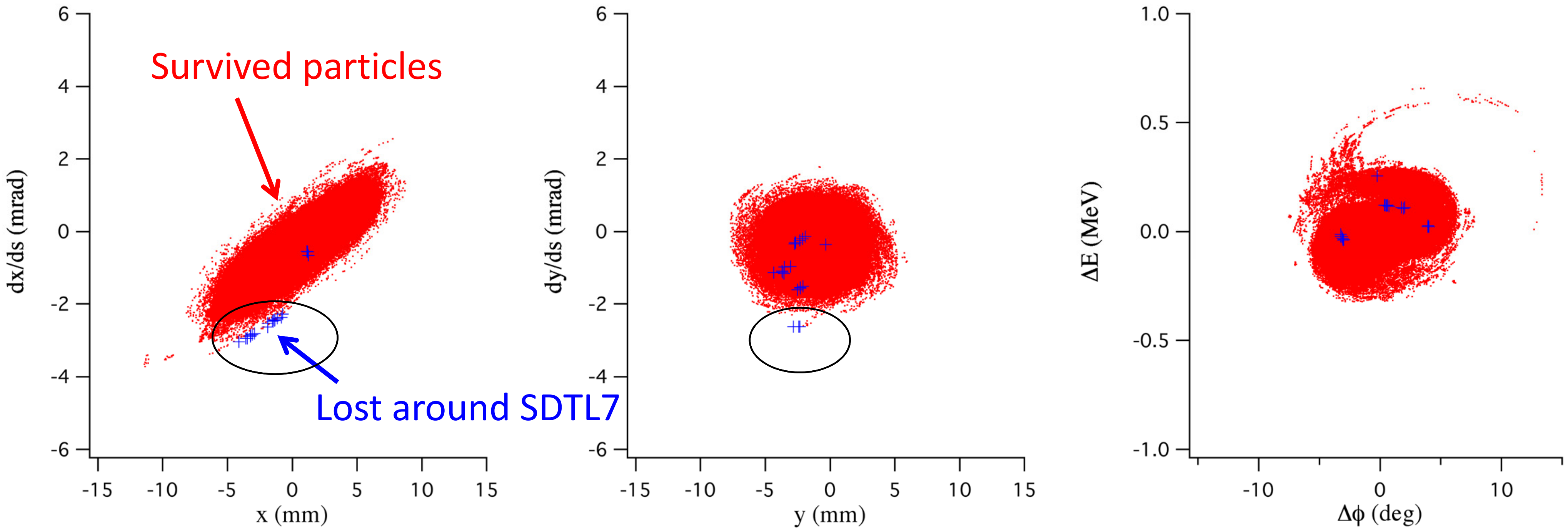
- Particle simulation
- **Discussion and summary**

Source of Beam Loss (I)

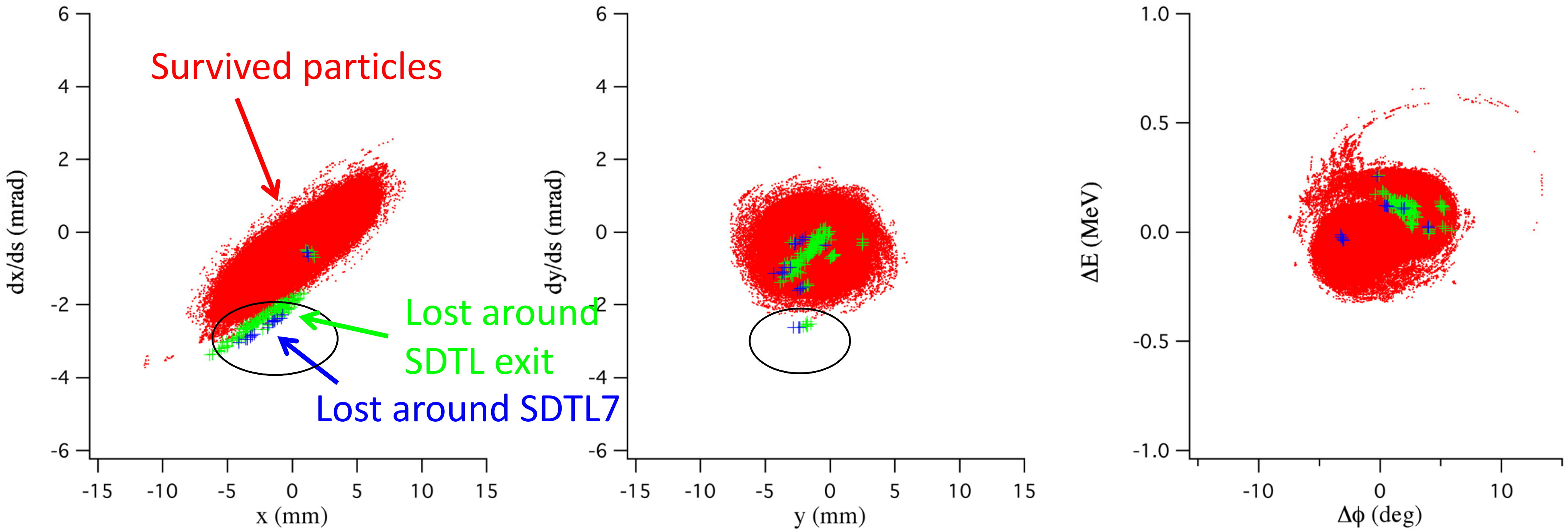
Simulated distribution at SDTL5 entrance (Seed #18 in Case-II)



- Particles lost at around SDTL7 are located at the transverse edge at the SDTL5 entrance.
- It indicates that a part of transverse tail is lost at SDTL7 in Case-II due to too significant transverse mismatch oscillation.

Source of Beam Loss (II)

Simulated distribution at SDTL5 entrance (Seed #18 in Case-II)



- Simulation result indicates that the beam loss around SDTL exit is caused by the same mechanism as around SDTL7.
- The particles narrowly survive at SDTL7 are finally lost around the SDTL exit.

Discussion (I)

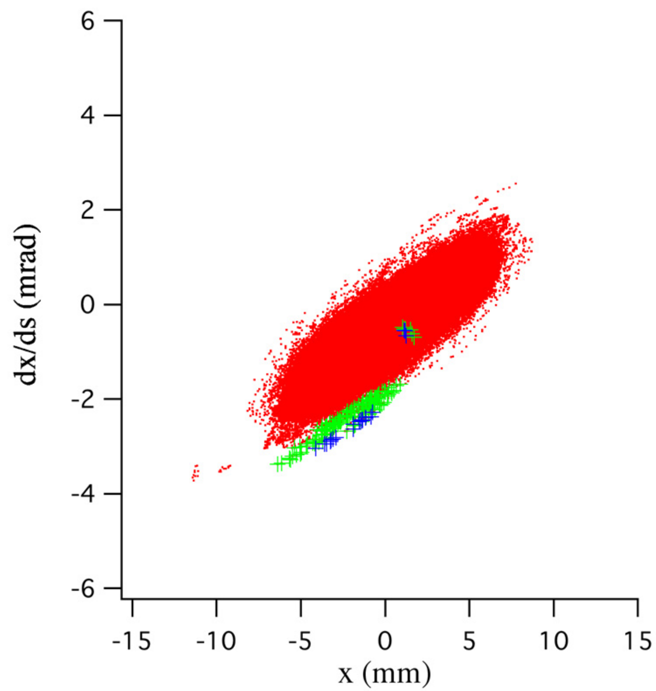
- Experiment shows a counter-intuitive beam loss behavior: less significant beam loss for more significant mismatch.

  We have concerned that we might have an unexpected beam behavior in the longitudinal phase space due to the irregular RF setting.
- Simulation’s answer is NO.

  We may have excess beam loss due to irregular RF setting, but it is simple scraping of transverse tail due to mismatch oscillation.

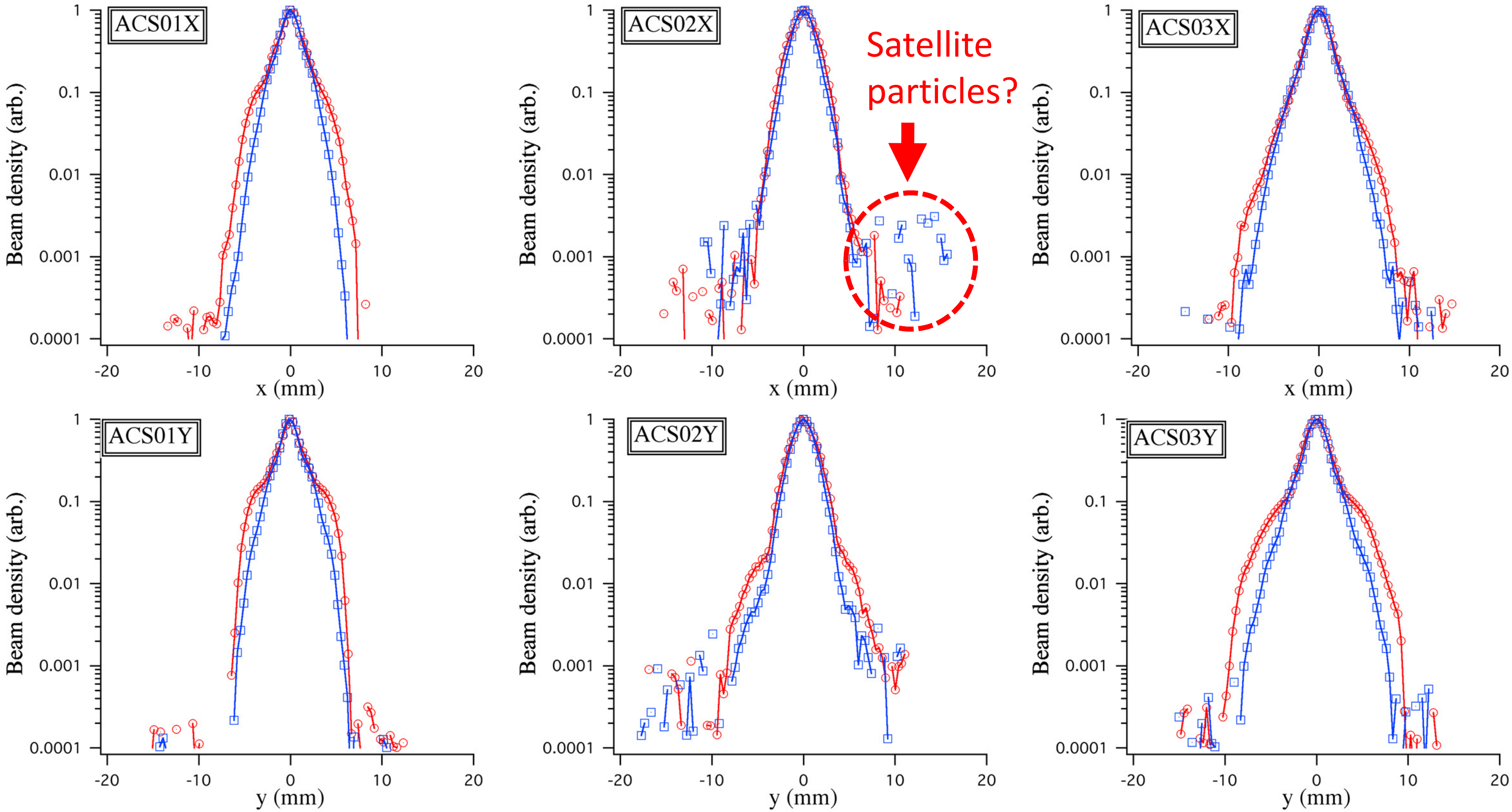
If this picture is correct…

The beam loss is cause by satellite particles.



Measured Beam Profile

Experimentally measured beam profile at SDTL exit with wire scanners



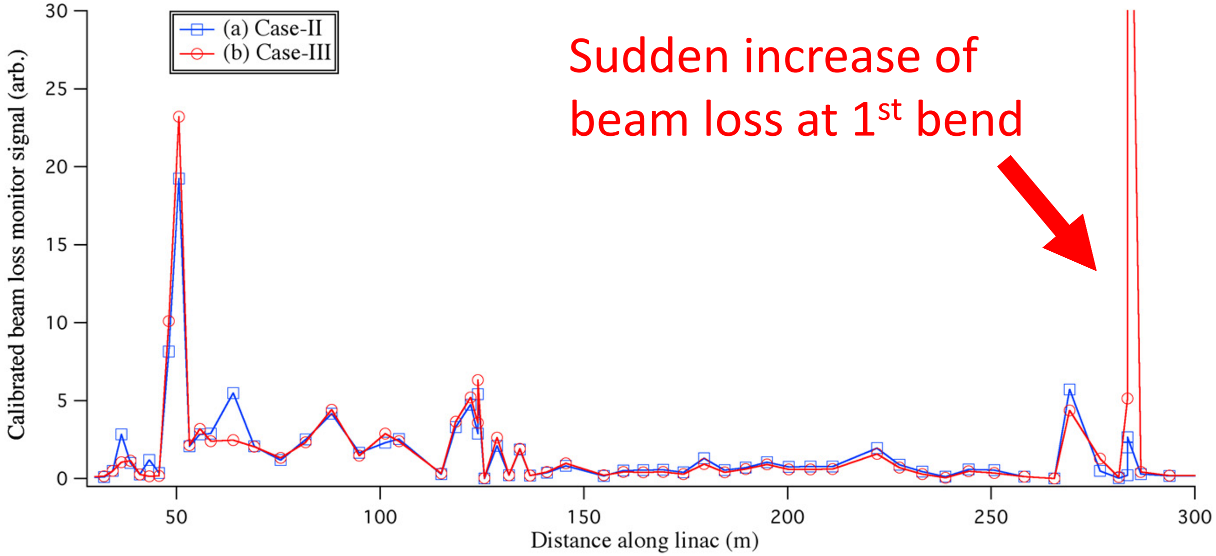
Red: Case-II, Blue: Case-III

Discussion (II)

- A new question arises: What is the source of the satellite particles?
- We have an important observation:
  - The beam loss at the 1st bend is increased in Case-III, which has been identified to be caused by protons.

If you permit a speculation…

The satellite particles could be protons(?).



It is still a speculation, but we suppose it is likely to be the case.

Summary

- In the beam commissioning of J-PARC linac after the earthquake, multipactor at an RF cavity forced us to operate with irregular RF settings some of which caused excess beam losses.
- We have performed particle simulation to reproduce the experimentally observed beam loss.
- Simulation has not fully reproduced the beam loss behavior, but it leads us to conclude that the beam loss is cause by satellite (proton?) particles.
- While it needs further study to confirm it, the particle simulation provides us with an important insight into the beam loss mechanism in the J-PARC linac beam commissioning.

Backup slides

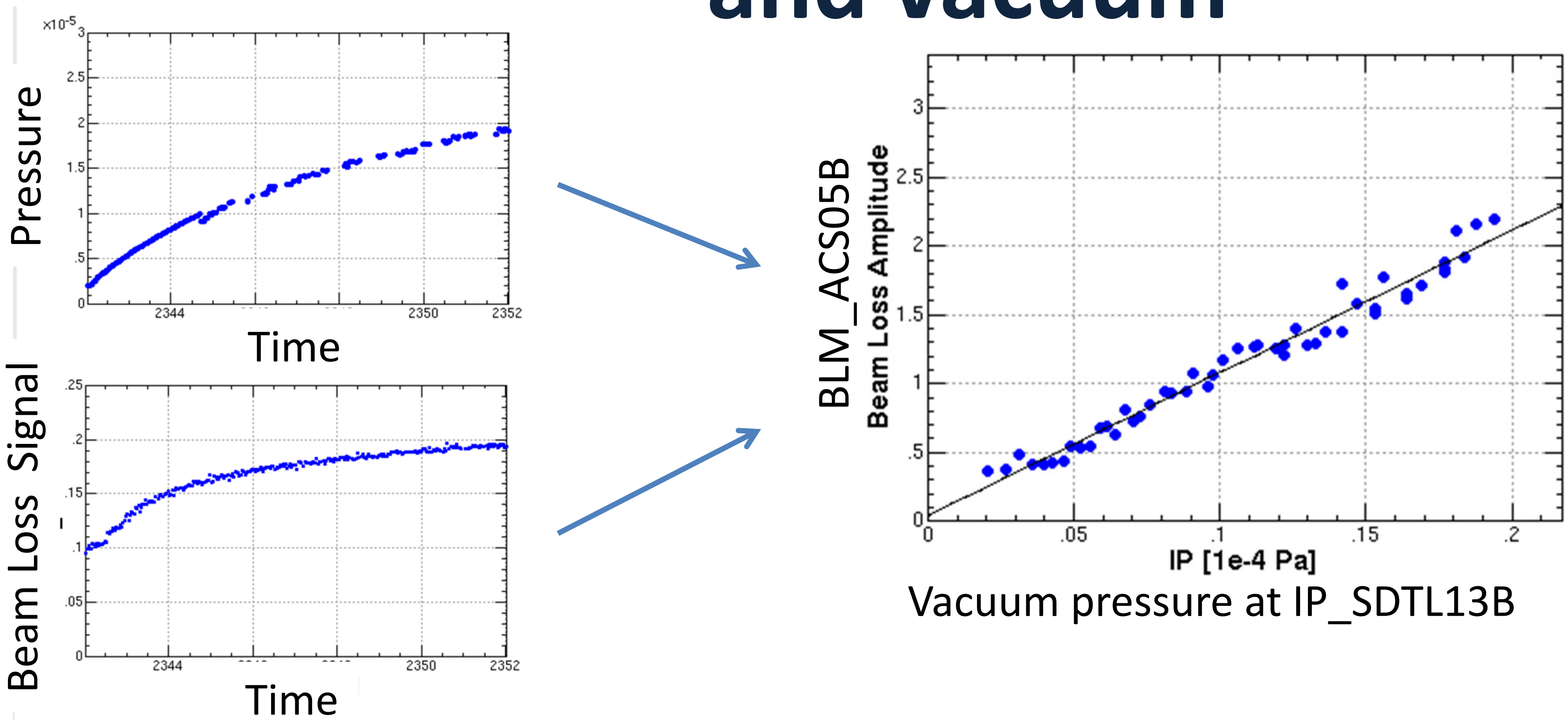
Residual Radiation

- We operated with Case-II for 10 days with the beam power of 7.2 kW and 8 days with 13.3 kW.
- The resultant residual radiation at around SDTL7 reached 4 mSv/h on contact several-hours after beam shutdown.
- The high dosage was observed two neighboring inter-tank spacings, and then the loss is not too sharply localized.

This result could provide a rare opportunity of code benchmarking on its ability of reproducing the beam loss.

- We didn’t operate with Case-I for a long term. Then, there is no data for the residual radiation in Case-I.

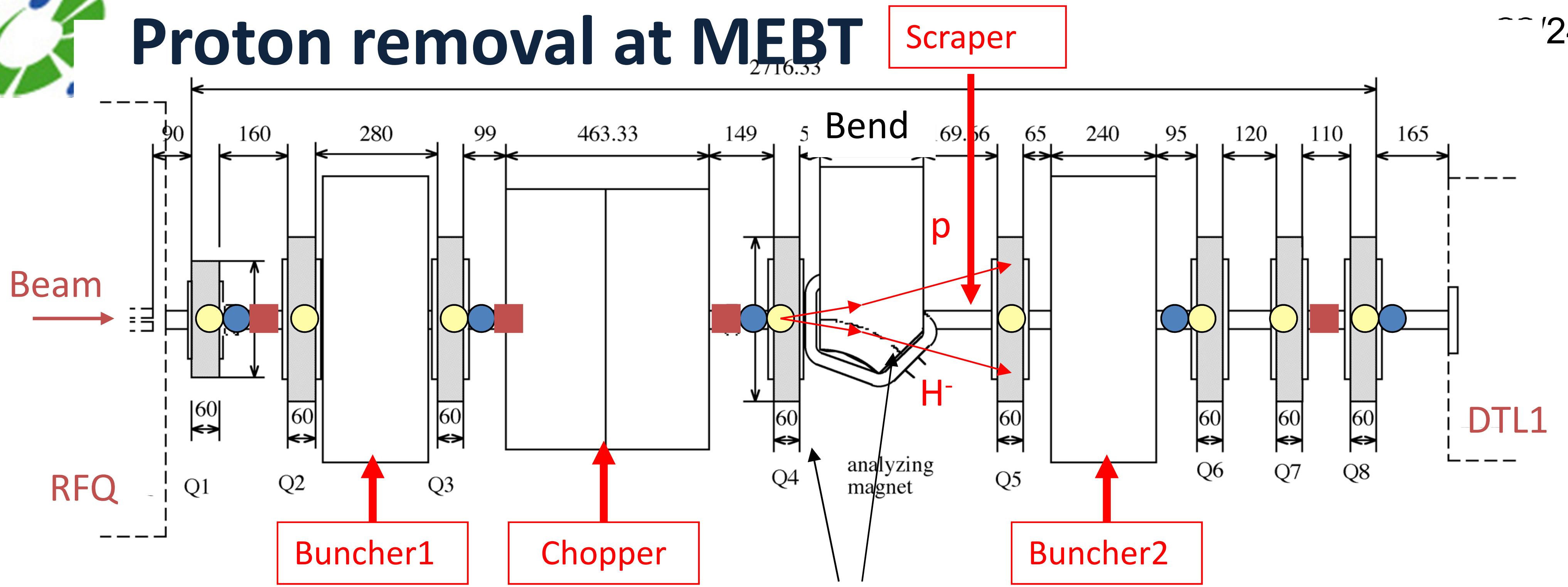
Correlation between beam loss and vacuum



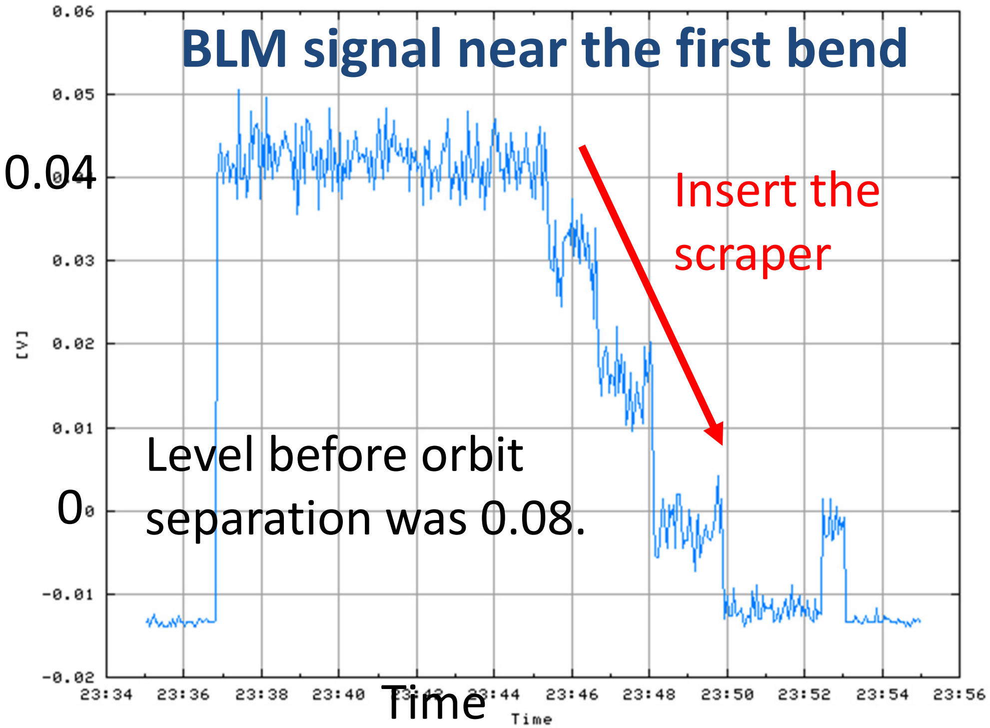
- We turn off the vacuum pumps at the downstream half of SDTL section, and monitor the beam loss and vacuum pressure level.
- The correlation between vacuum pressure level and beam loss indicates that the main cause of the beam loss is the H0 generated in a residual gas stripping of H-.

Ref. G. Wei et. al., IPAC11.

Proton removal at MEBT



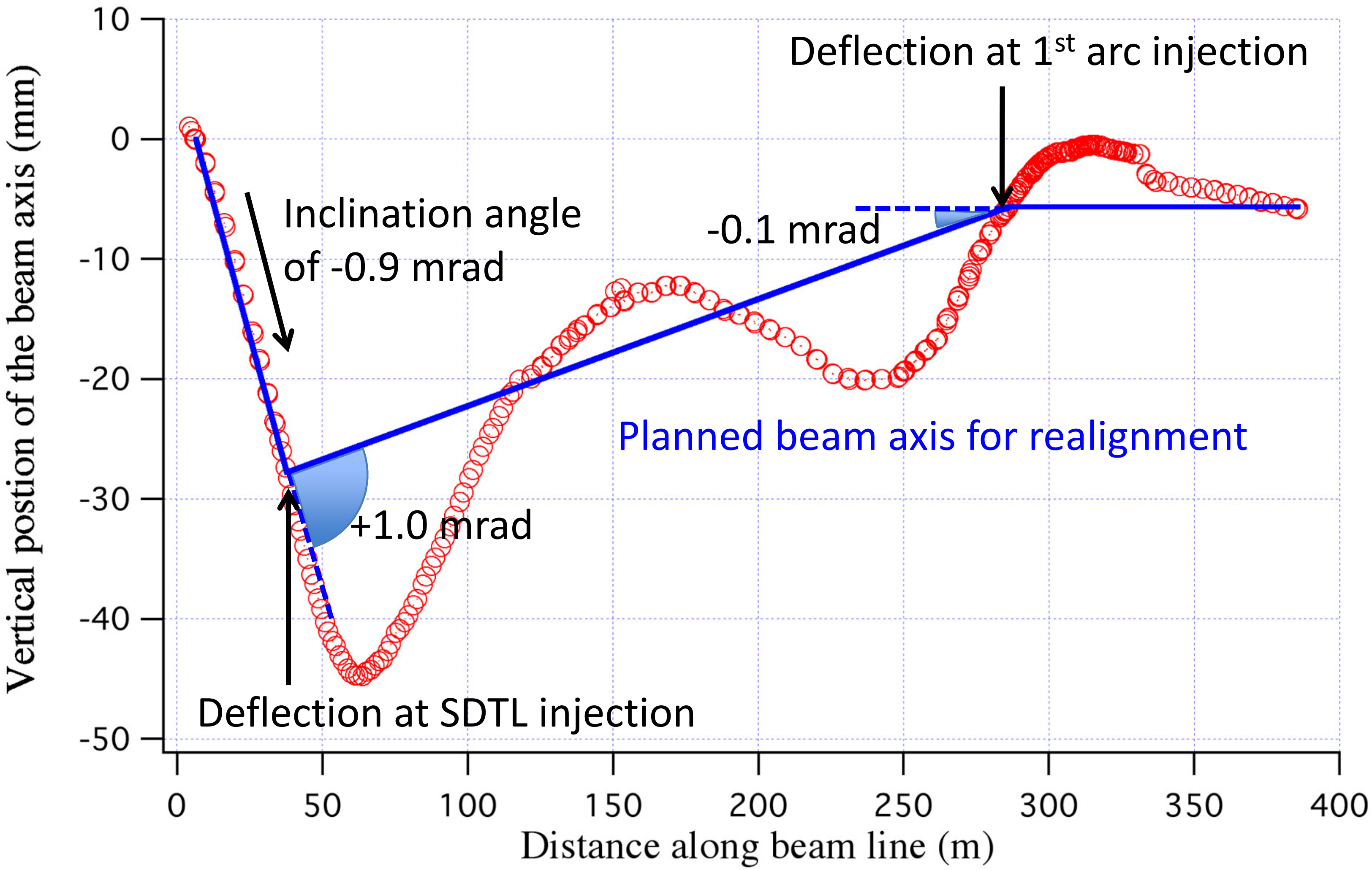
Separate with Q4 steering and bend



- We experienced a significant residual radiation at the first high duty factor operation.
- We assume that the protons generated in LEBT are accelerated and finally causes the beam loss. Then, we tried to remove the protons with a chicane in MEBT.
- In this experiment, we confirmed that the beam loss at the first bend was caused by protons.
- We are using this proton removal in a nominal operation。

Ref. H. Sako et. al., Trans. Nucl. Sci. 57 (2010), p.57.

Re-alignment after earthquake



- To enable swift restoration, we decided to tolerate deflection in the alignment axis.

Ref. M. Ikegami et.al., IPAC11; T. Morishita et. al., IPAC11.