Systematic Mitigation of Intra-Beam Stripping and Distributed Beam Loss in High-Intensity H^- Linacs: Experimental and Operational Experience at J-PARC

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Outline

J-PARC & Linac Specifications

Motivation and Challenges of High-Intensity H^- linacs（Why H^- and Why IBSt?）

A Platform for Systematic Beam-Loss Studies （Why&How J-PARC?）

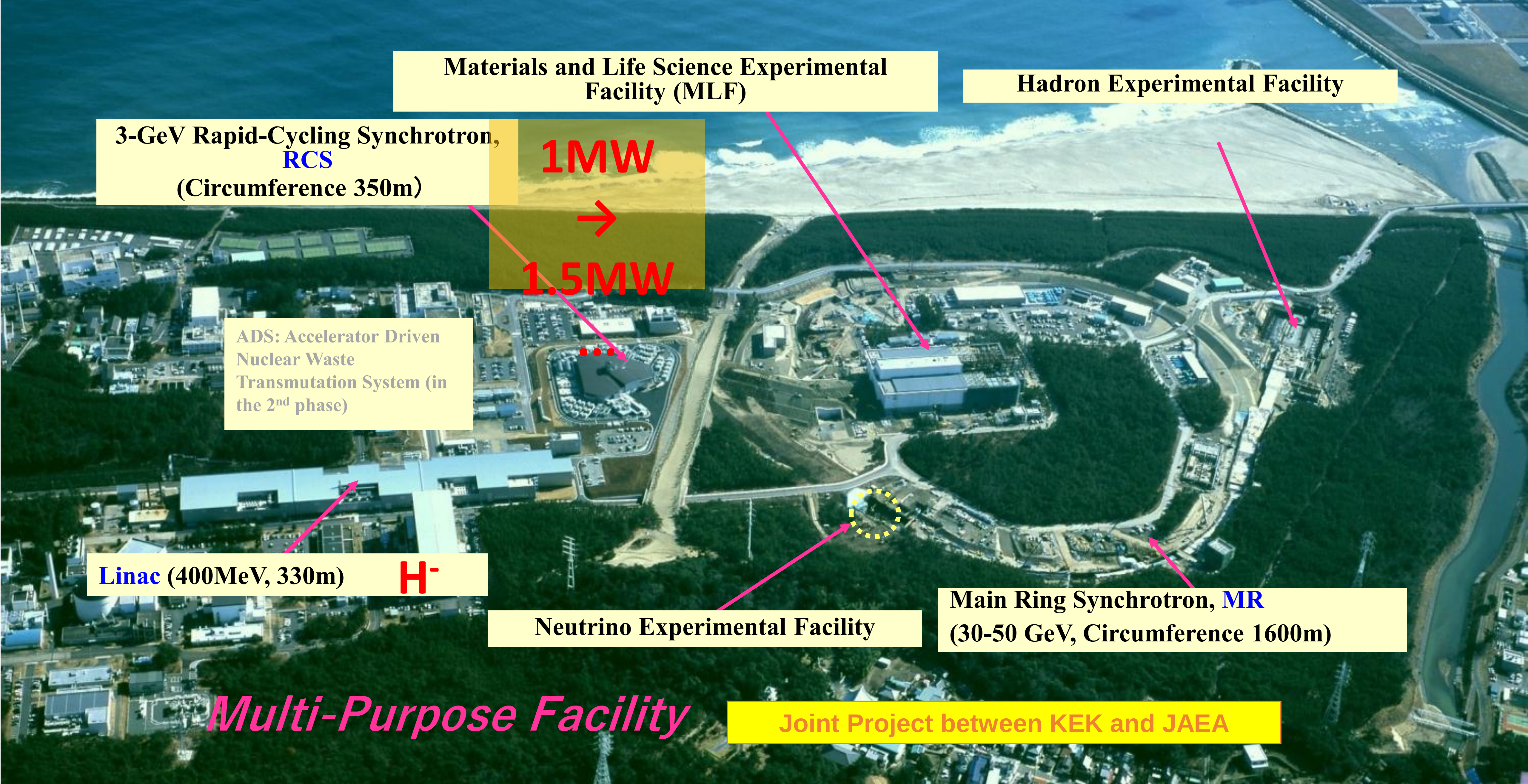
From Understanding to Mitigation（Beam Characterization → Phase-Space Physics → Prediction → Optimization）

Design Lessons for Future High-Intensity H^- Linacs

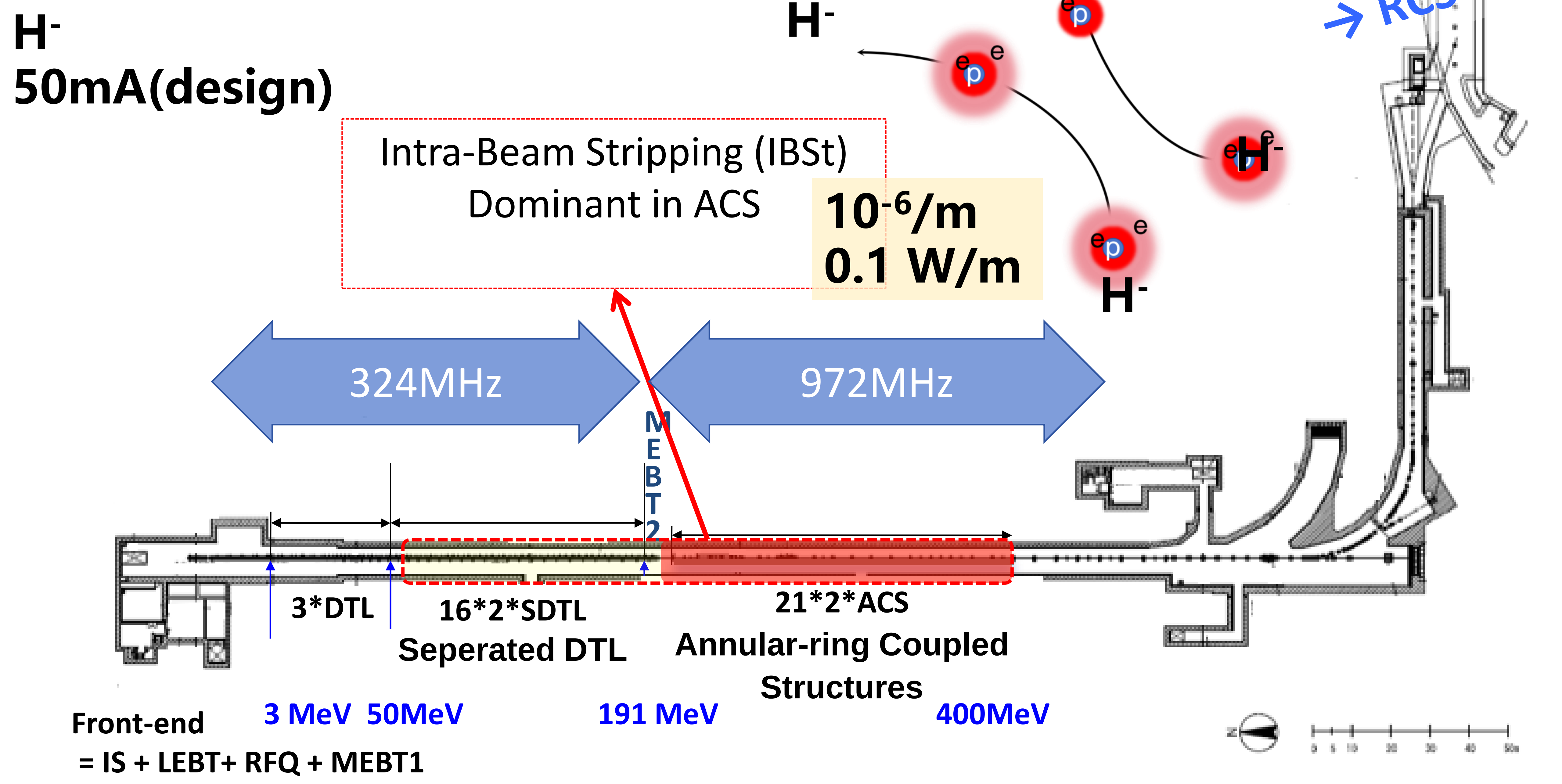
Summary & Outlook

33rd Linear Accelerator Conference (LINAC 2026),
Aug.16~21 2026, Daejeon, Korea

J-PARC Facility Layout at Tokai, JAEA Site



J-PARC Linac Layout



Electron-Stripping Mechanisms in High-Intensity H^- Linacs

H^- charge-exchange injection: >10× Higher Accumulation vs. Proton Multi-turn Injection

Mechanism	Origin	Typical Location	Importance	In J-PARC	Mitigation
Residual Gas Stripping	H^- + gas molecules	Entire linac	★★★	SDTL	Better vacuum
Lorentz Stripping	Magnetic field	Bending sections	Design constraint ★★	Avoided	Field limitation
Blackbody Radiation Stripping	Thermal photons	High energy section	Usually negligible ★	Negligible	Cooling
Intra-Beam Stripping (IBSt)	H^-–H^- interaction	Entire beam	★★★★★	**ACS Dominent**	Lattice optimization

~mSv/h@surfac
e

IBSt emerges as the dominant beam-loss mechanism and a beam-dynamics challenge.

Origin of IBSt Enhancement in the High-Energy Linac

IBSt rate

$$\frac{dN}{ds}\Big|_{\mathrm{IBSt}} \propto \frac{N^2\sqrt{\gamma^2\theta_x^2+\gamma^2\theta_y^2+\theta_z^2}}{\gamma^2\sigma_x\sigma_x\sigma_z}F(\gamma\theta_x,\gamma\theta_y,\theta_z)$$

smooth approx.

$$\frac{\sqrt{\gamma^2\epsilon_x/\overline{\beta_x}+\gamma^2\epsilon_y/\overline{\beta_y}+\epsilon_z/\overline{\beta_z}}}{\gamma^2\sqrt{\epsilon_x\overline{\beta_x}\cdot\epsilon_y\overline{\beta_y}\cdot\epsilon_z\overline{\beta_z}}}$$

Fixed lattice

$$\beta = \mathrm{const.}$$

$$\boxed{\frac{dN}{ds}\Big|_{\mathrm{IBSt}} \propto \epsilon^{-1}}$$

Not the relevant operational constraint.

Fixed beam size

$$\sigma^2 = \epsilon\beta = \mathrm{const.}$$

$$\boxed{\frac{dN}{ds}\Big|_{\mathrm{IBSt}} \propto \epsilon}$$

Maintaining a well-controlled beam envelope matters.

Lower emittance helps!

(With lattice manipulation)

Origin of IBSt Enhancement in the High-Energy Linac

IBSt rate

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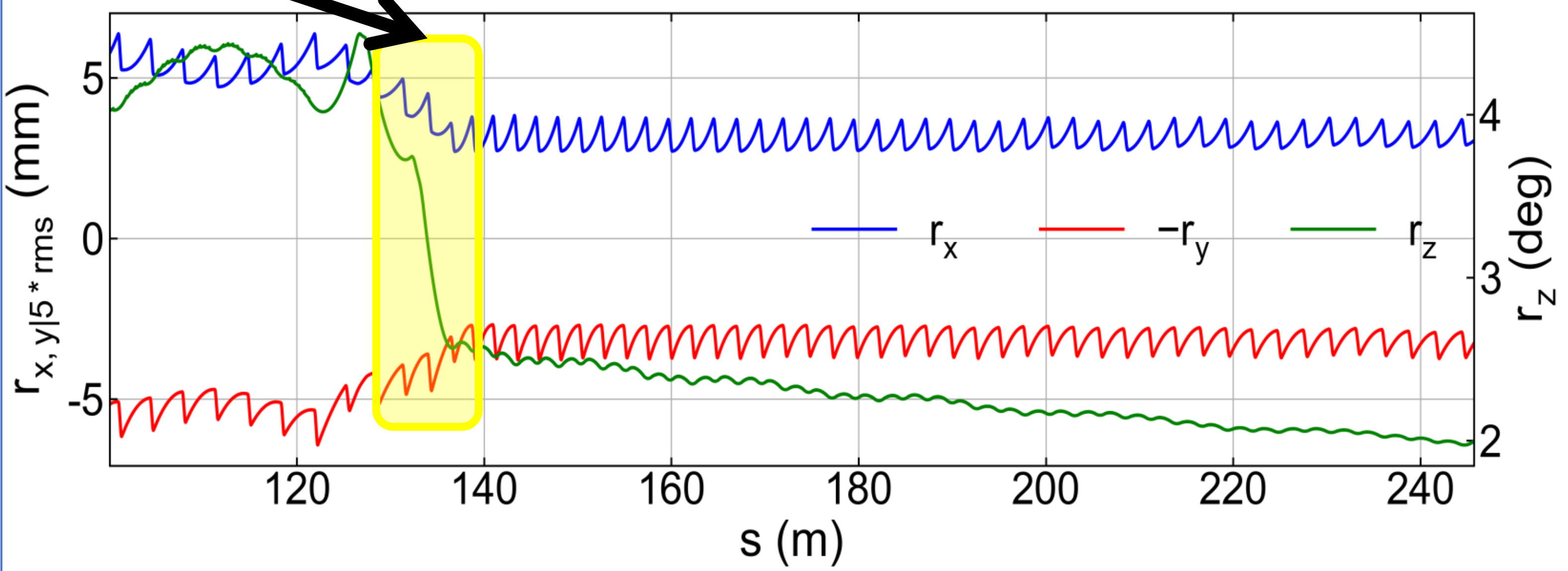
324 MHz
↓
972 MHz Frequency Jump
↓
Increased Longitudinal Focusing
↓
Increased Transverse Focusing
(EP condition)
↓
Increased Beam Interaction
↓
Increased IBSt Rate

Original J-PARC design T=Tx,y/Tz=1.0
(equi-partition, EP)

$$\frac{T_{x,y}}{T_z} \equiv \frac{r_{x,y}^2 k_{x,y}^2}{r_z^2 k_z^2} = \frac{\epsilon_{x,y} k_{x,y}}{\epsilon_z k_z}$$

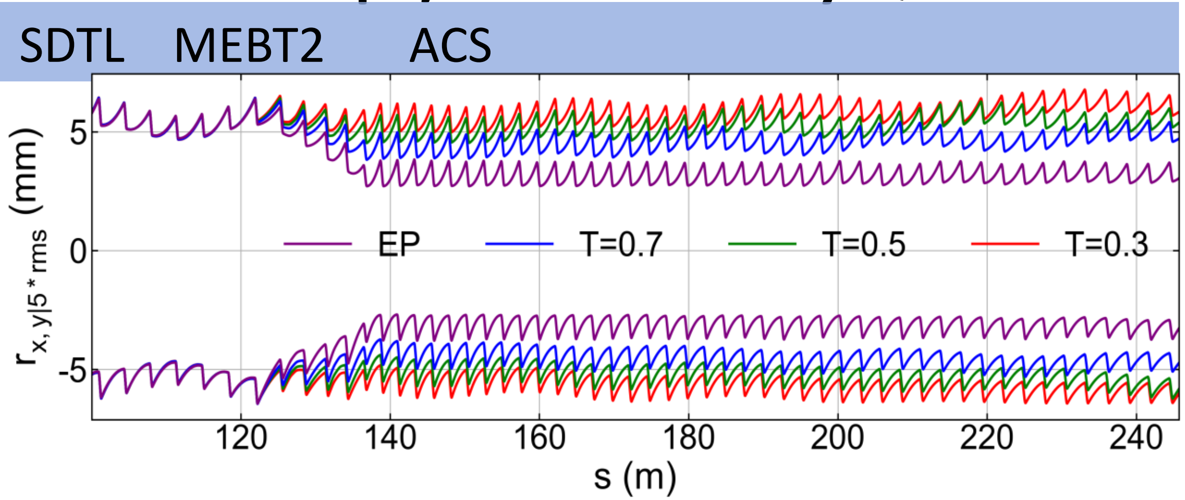
SDTL MEBT2 ACS



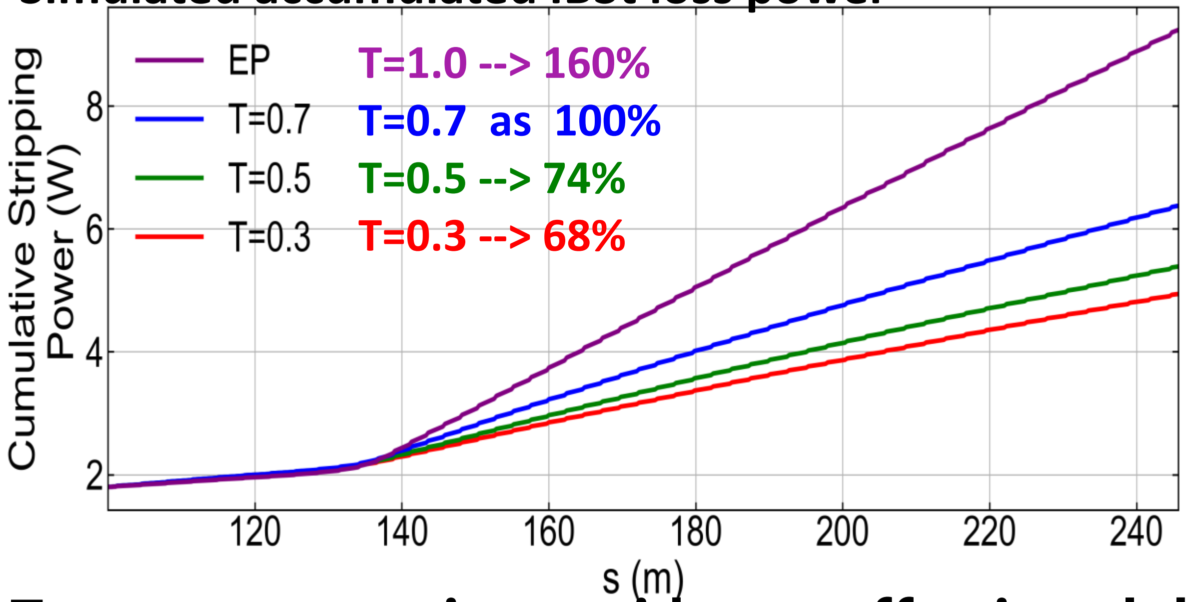
The dream EP lattice optimized for beam stability and emittance preservation is not necessarily optimal once IBSt dominates.

Lattice Controlled with Temperature Ratio

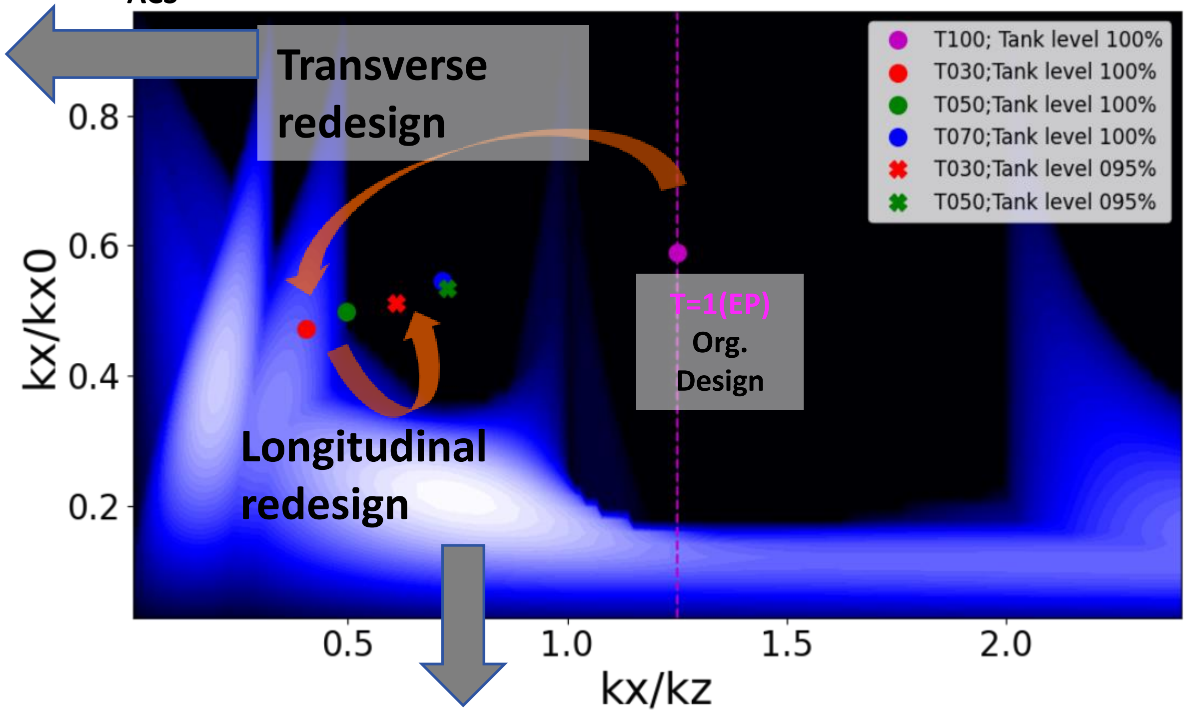
Envelope/T controlled by Quad

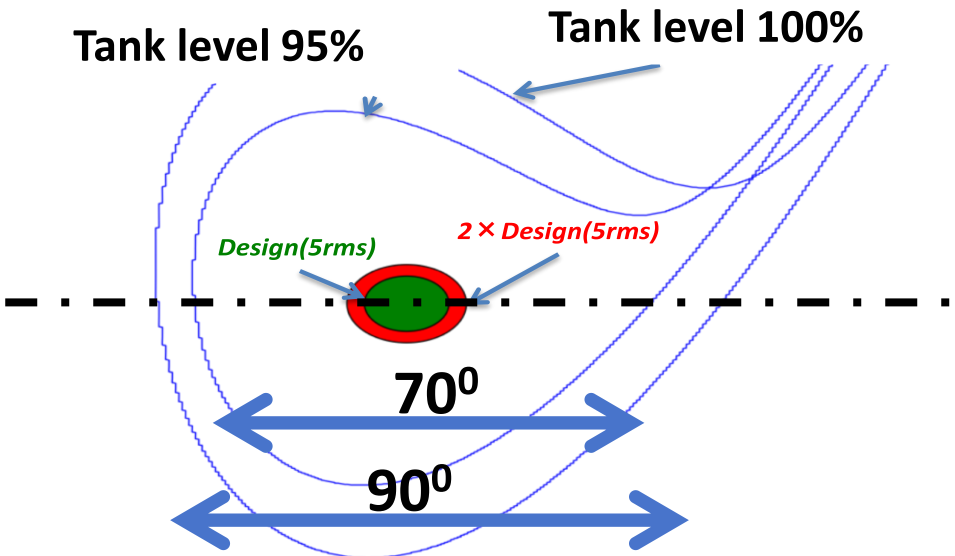


Simulated accumulated IBSt loss power



T_{ACS}=(design1.0-->operaion0.7)-->0.5,0.3



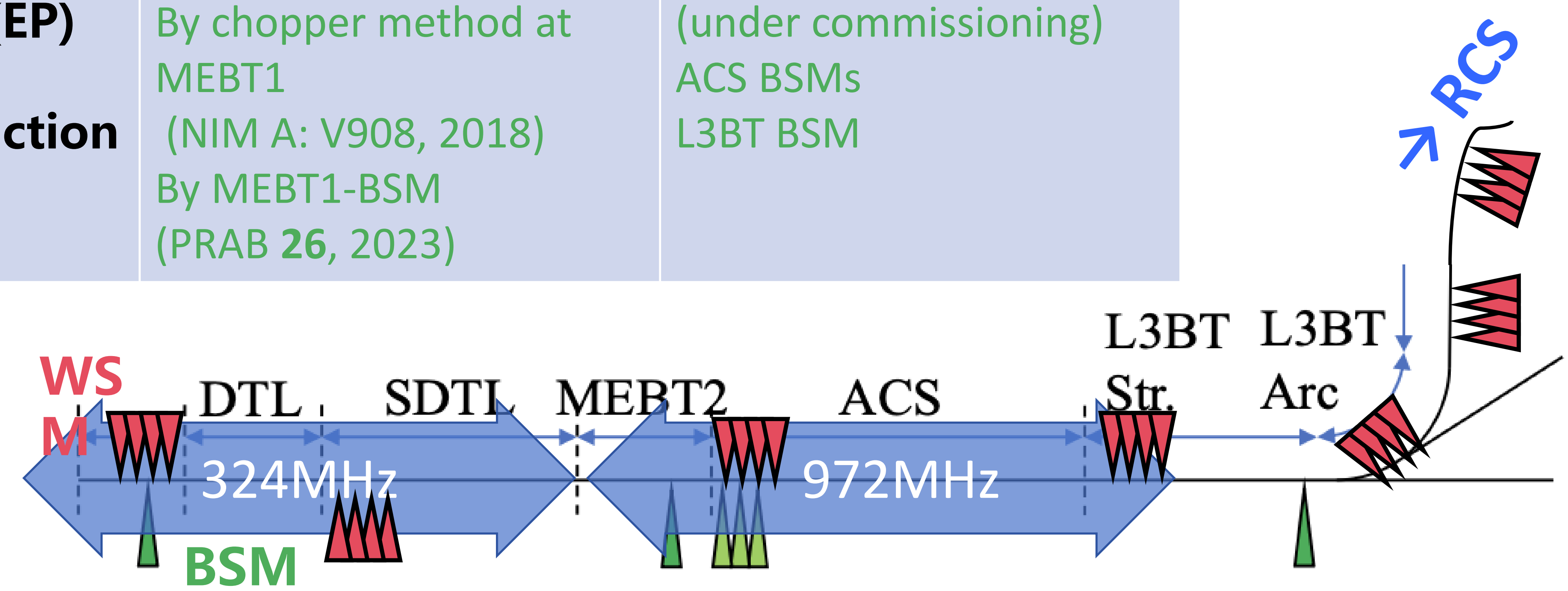


Temperature ratio provides an effective global control parameter for IBSt mitigation.

Transverse and Longitudinal Beam Characterization

Design	Initial Validation	Global Validation
RFQ Simulation ↓ **Init. Twiss** ↓ **Linac Lattice (EP)** ↓ **J-PARC Construction**	Transverse Twiss: Q scan in MEBT1 Longitudinal Twiss: By chopper method at MEBT1 (NIM A: V908, 2018) By MEBT1-BSM (PRAB **26**, 2023)	Transverse Twiss: 5 matching sec. + 2 Longitudinal Twiss: (under commissioning) ACS BSMs L3BT BSM

K. Moriya, R. Kitamura, M. Otani, A. Miyao



Reliable beam characterization provides the foundation for predictive beam-dynamics and beam-loss studies.

J-PARC as a Platform for Systematic Beam-Loss Studies

EP lattice as the baseline (T=1)

↓

Flexible lattice control (T_{ACS}=...,0.3,0.5,0.7,1.0,...,2.0)

+

Well-characterized beam (phase-space, beam loss measuremet)

↓

Systematic studies

↓

Predictive beam-loss analysis

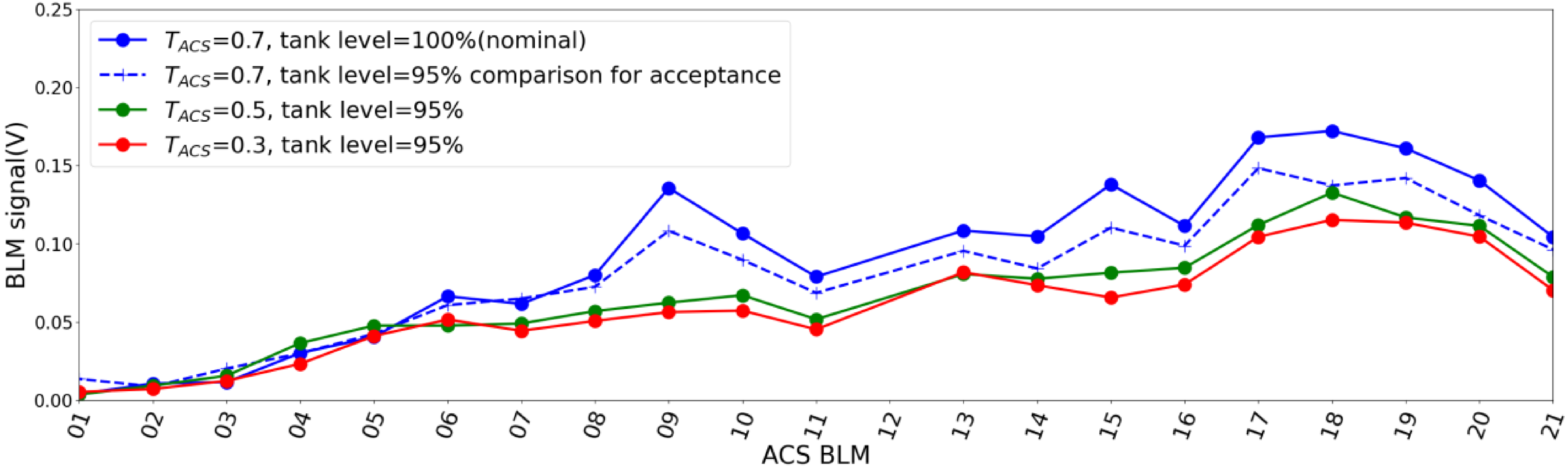
↓

Operational verification

Reliable beam characterization + flexible lattice manipulation
→ predictive and systematic beam-loss mitigation

Experimental Observation of Beam-Loss Reduction

Typical experimental results for T=0.5 and 0.3 with ACS tank level 95%



Loss mitigation is consistent with (theoretical prediction in bracket)
T=0.5: -26 %(-26%), **T=0.3**: -34 %(-32%) compared with T=0.7

T=0.5 → Candidate operating point for 1–1.5 MW

T=0.3 → Promising candidate for >1.5 MW, pending further beam-dynamics validation.

Stripping Location ≠ Loss Location

Relative loss reduction

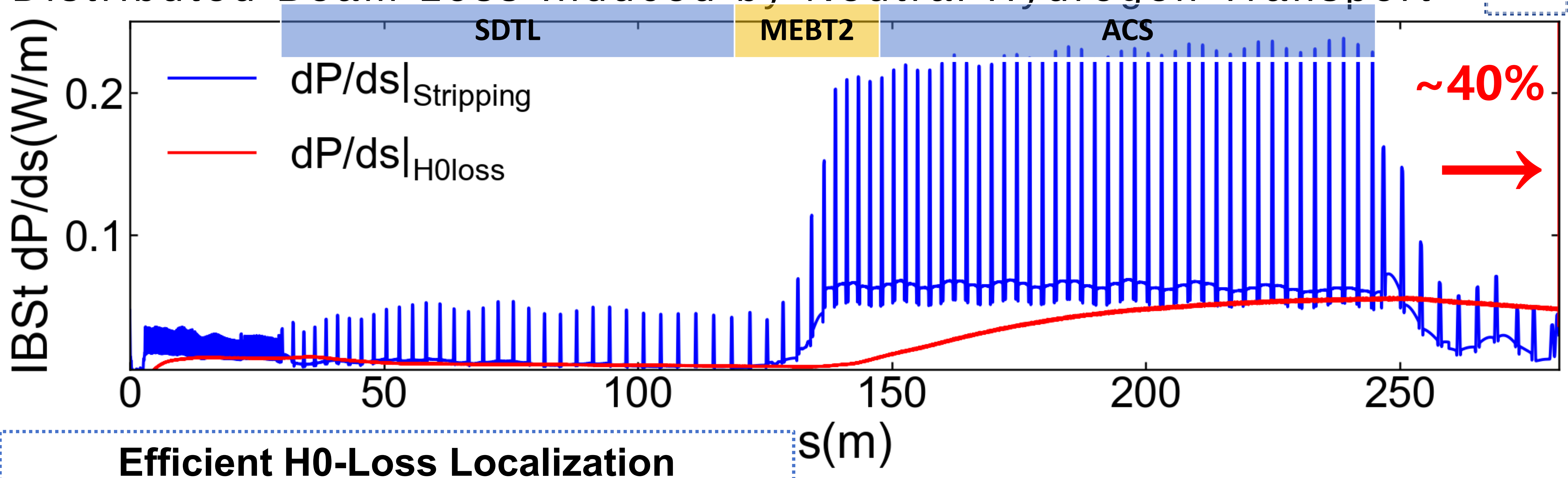
Measurement ≈ IBSt prediction ✓

Spatial loss pattern

Measured loss ≠ stripping distribution ?

Missing link: H^0 transport → aperture interception

Distributed Beam Loss Induced by Neutral Hydrogen Transport



Efficient H0-Loss Localization

Ballistic transport+Geometry interception

Challege: resolution

10^{-6}loss/m ~1.5×10^{9} H0 macro-particles

~~**Step-by step trajetory**~~

→ One-step ray tracing

Paradigm Shifts

Lattice spikes → Smoothed

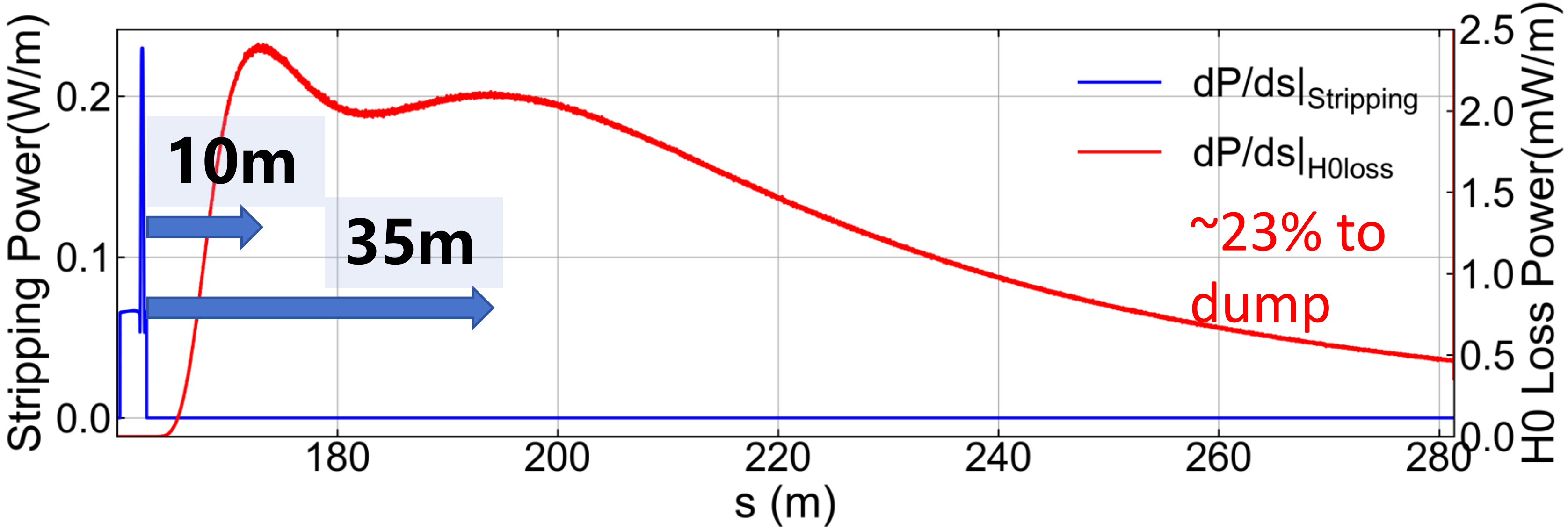
Instantaneous?→ **Loss is delayed**

All uncontrolled? → **>40% go to dump**

From Stripping to Beam Loss: A Completely Different Picture

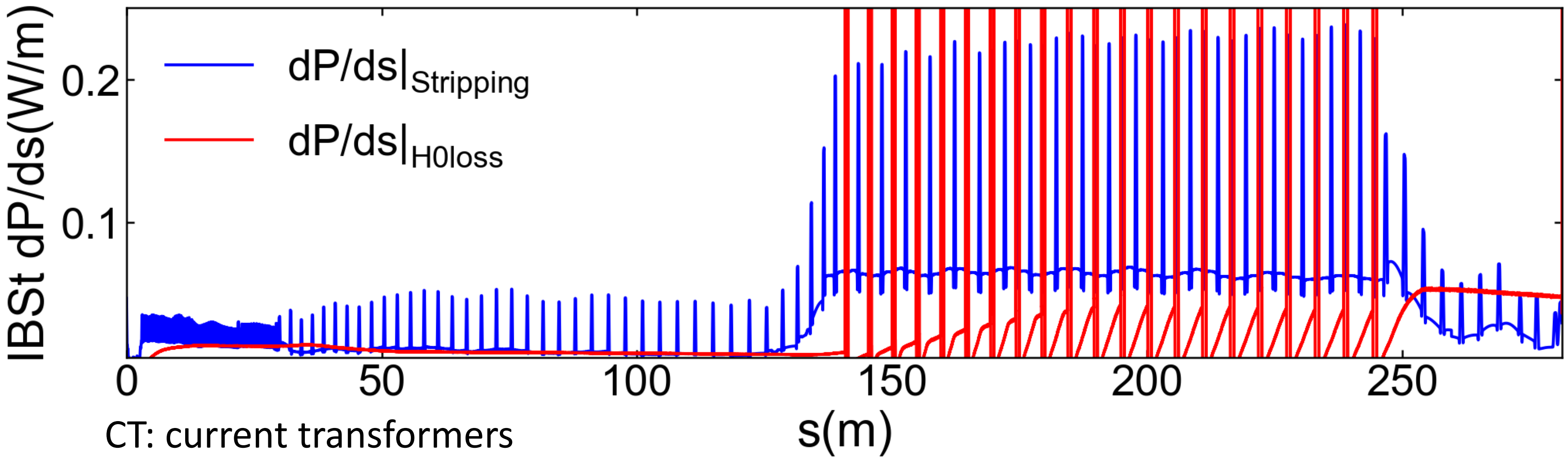
Neutral Hydrogen Transport and Aperture Effects

Long-Range H⁰ Transport from **a Single Doublet Period** (ACS06A, 11th/42)



H⁰ survives far beyond

Hotspots Caused by 37-mm CT Apertures in a 40-mm Beam Line



CT: current transformers

A J-PARC Lesson

Most H⁰ was intercepted at bottlenecks.
3mm reduction created 3.5 mSv/h (surface) hotspots (500 kW).

Identified through H⁰ transport analysis and eliminated in 2018.

Loss localization is governed by H⁰ transport and local geometry

Evolution of Beam-Loss Mitigation at J-PARC

Hotspots found

↓

Identified through H⁰ transport analysis

↓

Aperture modification (~~37mm Bottleneck~~ 2018)

Hotspots elimination

↓

Lattice optimization (T=1.0→0.7, 2019)

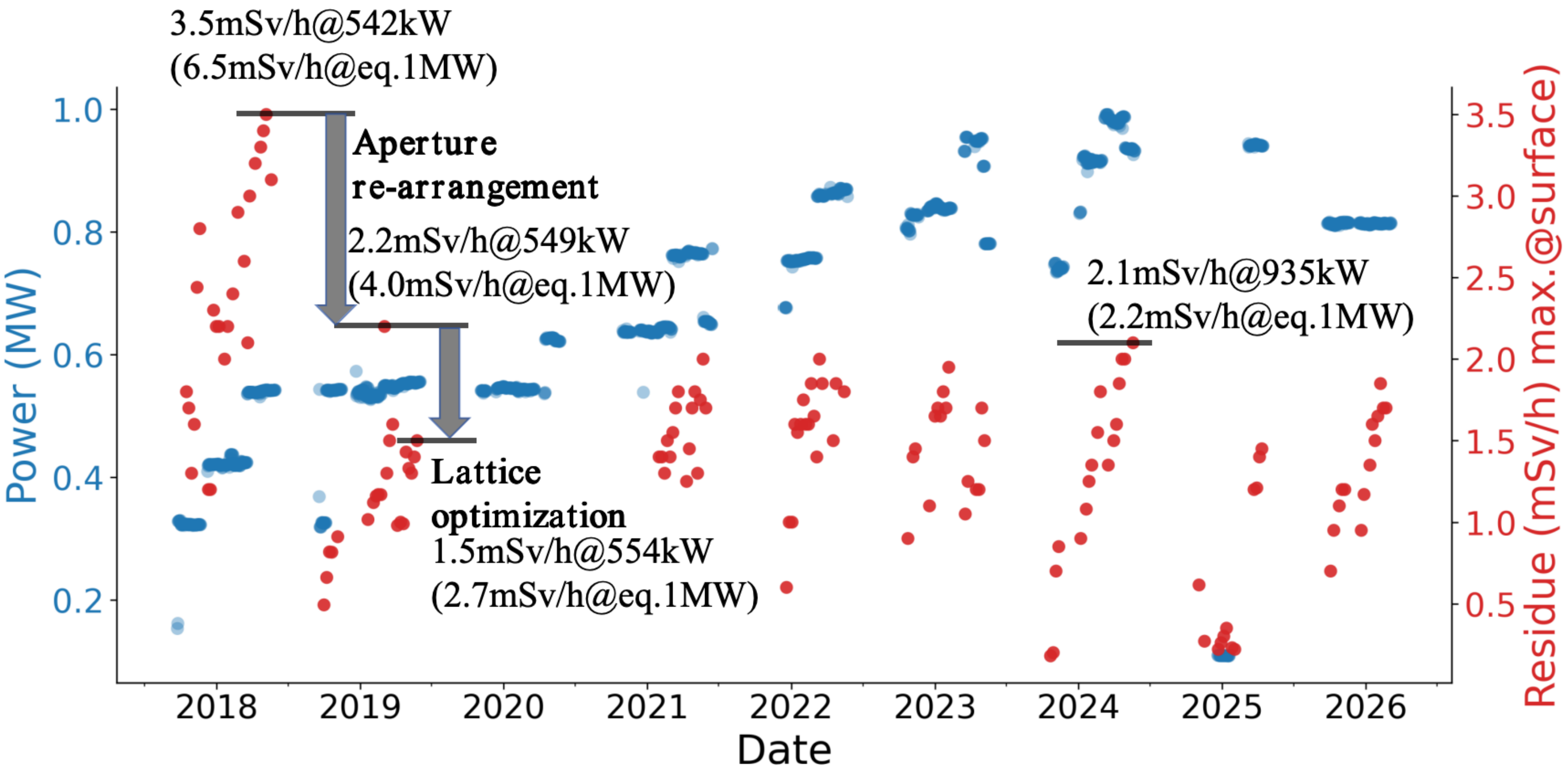
↓

Stable MW operation

(loss to 1/3)

↓

Aim at 1.5 MW preparation



Note: All dose rates shown are surface residual doses. The corresponding dose at 30 cm is typically ~10× lower (current maximum: 220 μSv/h at 30 cm, normalized to 1 MW).

Physics understanding enabled systematic and sustainable beam-loss control.

Design Lessons for Future High-Intensity H^- Linacs

Design Aspect	Lesson from J-PARC Experience	Implication
RF frequency & transition	Higher final frequency strengthens longitudinal focusing; larger frequency jumps increase beam density, both unfavorable for IBSt mitigation.	Use the highest practical base frequency, minimize frequency transitions. Treat RF frequency selection and lattice design as a coupled optimization problem.
Aperture and loss localization	(Assuming a well-matched, stable lattice) Apertures intercept H^0 rather than H^-. Loss localization is governed by H^0 transport and local aperture geometry. (sensitive to aperture, delayed, travelling over long distances).	Avoid local bottlenecks. Larger apertures are preferred; superconducting helps. Aim for full control of H^0 losses via dedicated dumps/experimental areas.
Longitudinal emittance (εz) and focusing	Small εz expands the longitudinal focusing margin.	Minimize εz throughout the linac; Consider as an RFQ design objective. Use the available focusing margin: weaker in IBSt-dominated sections and stronger where nonlinear control is prioritized.
Transverse emittance ($\varepsilon x,y$) and focusing	The apparent IBSt benefit of larger $\varepsilon x,y$ at fixed optics is only a density effect; low emittance remains preferred for IBSt mitigation and longer H^0 transport.	Maintain low emittance and optimize focusing to control particle density.

Conclusion and Outlook

- Foundation for predictive beam-loss studies

  Reliable beam characterization

- Understand the full chain

  Phase space → H^0 production → transport → loss localization

- Two complementary knobs

  Global optics → reduce H^0 production

  Local geometry → control H^0 interception

- Design and optimize the system as a whole

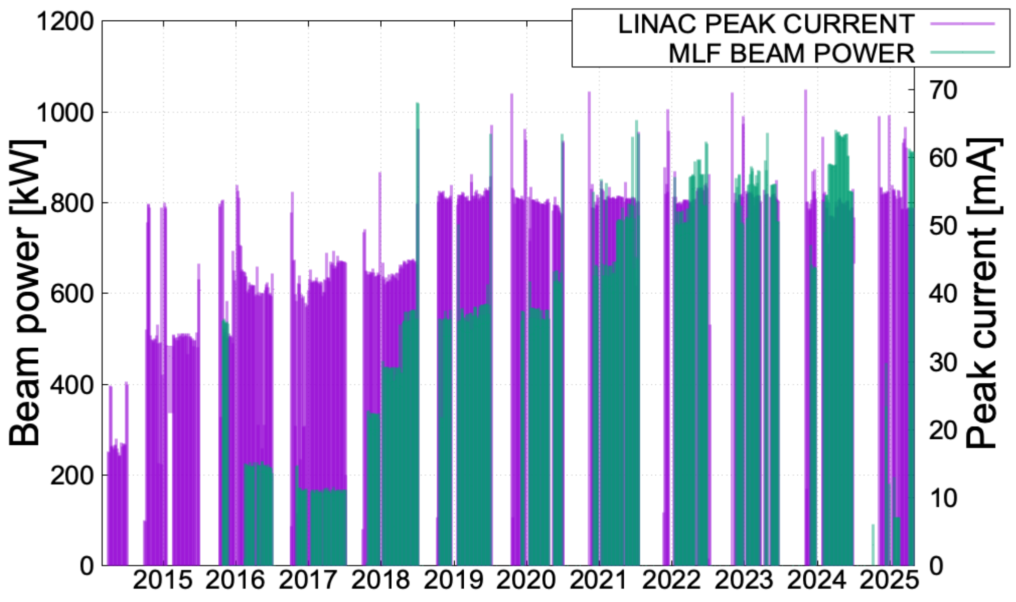
  Beam characterization → lattice manipulation & geometry optimization → controlled loss localization

Toward an integrated design framework for high-intensity H^- linacs

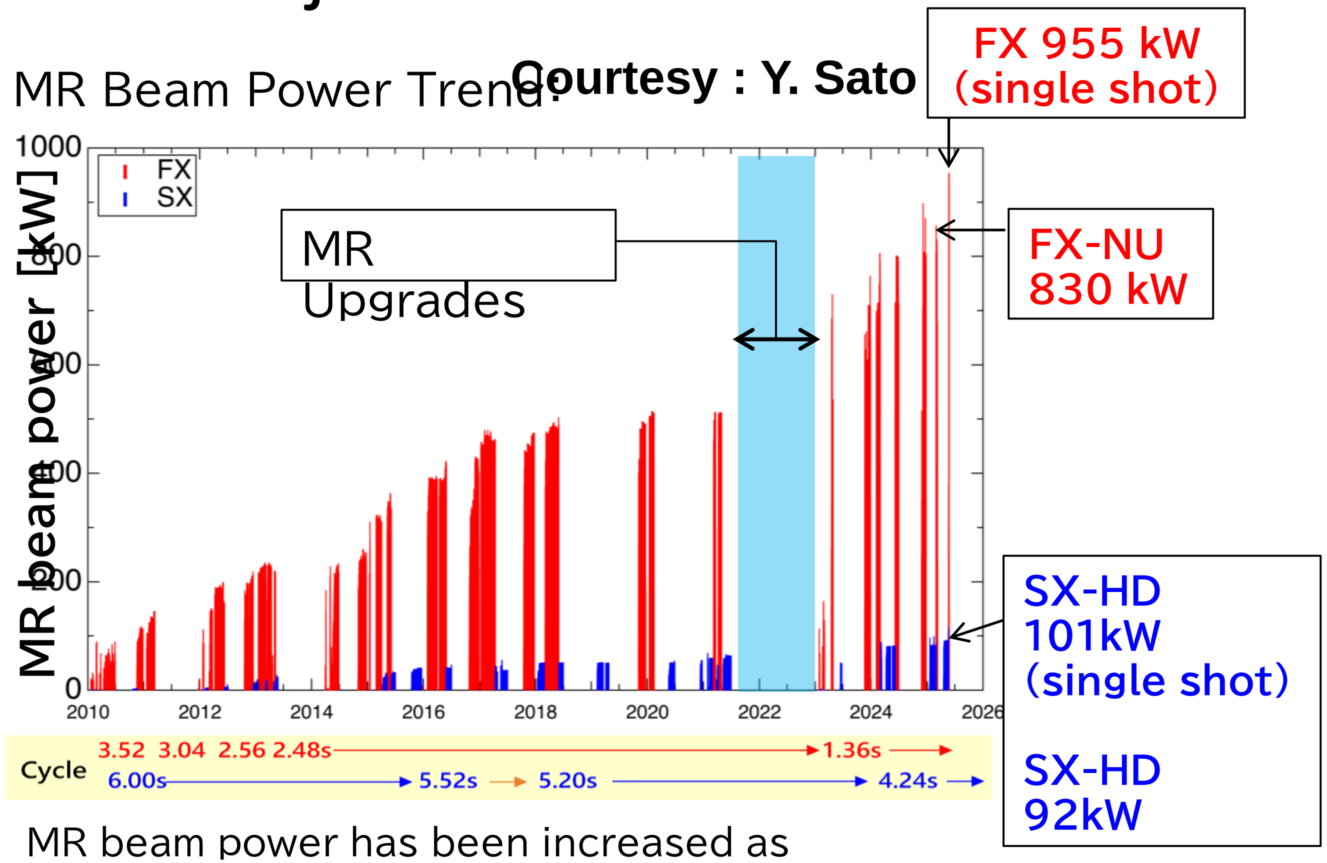
Backup

J-PARC Power Upgrade and Linac Objectives

MLF Beam Power Trend: **Courtesy : R. Kitamura**



MR Beam Power Trend: **Courtesy : Y. Sato**



MR beam power has been increased as schedule

Objectives of Linac Beam Study

- Ensure stable 1 MW operation (@RCS, 50 mA × 500 μs in Li)
- Optimize for future 1.5 MW (@RCS, 60 mA × 600 μs)
- Maintain beam quality for high-power MR operation

Injection scheme comparison based on J-PARC parameters

H.Harada, P.Saha

	Proton Multi-turn Injection	H^- Charge Exchange Injection
Accumulated beam	200π	50 - 250π (controllable)
Injected beam	4π	4π
Theoretical turns	~50	inf
Practical turns	20–40	300–500+
Major Limitation	Acceptance (Liouville)	Space charge / foil scattering

Still ~10× higher!

H^- injection remains unmatched for MW-class beam power;
electron stripping is the price we pay.

Electron-Stripping Mechanisms in High-Intensity H⁻ Linacs

H⁻ charge-exchange injection: >10× Higher Accumulation vs. Proton Multi-turn Injection

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Blackbody Radiation Stripping	Thermal photons	High energy section	Usually negligible ★	Negligible	Cooling
Intra-Beam Stripping (IBSt)	H⁻–H⁻ interaction	Entire beam	★★★★★	**ACS Domient**	Lattice optimization

~mSv/h@surface

IBSt emerges as the dominant beam-loss mechanism and a beam-dynamics challenge.

Measurements after RFQ

M.Otani

Transverse: Q-scan

Longitudinal: RF deflector

[NIMA 908(2018) 313-317]

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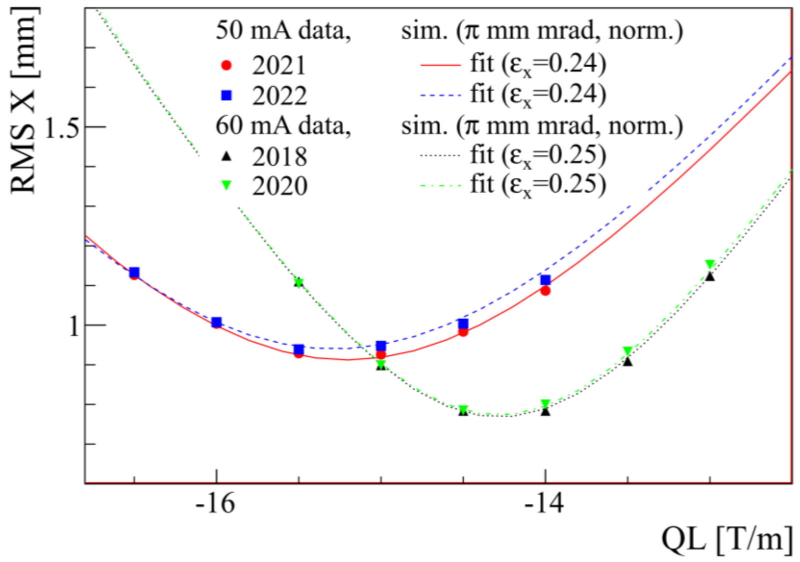

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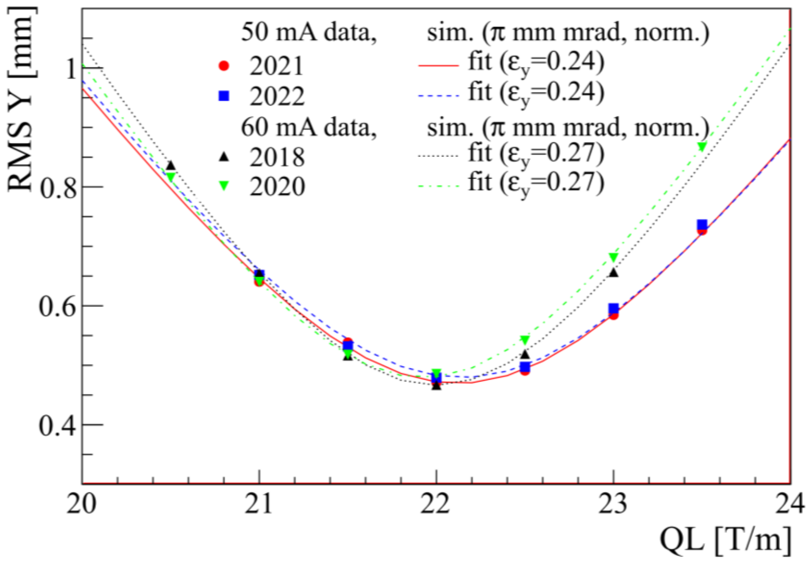

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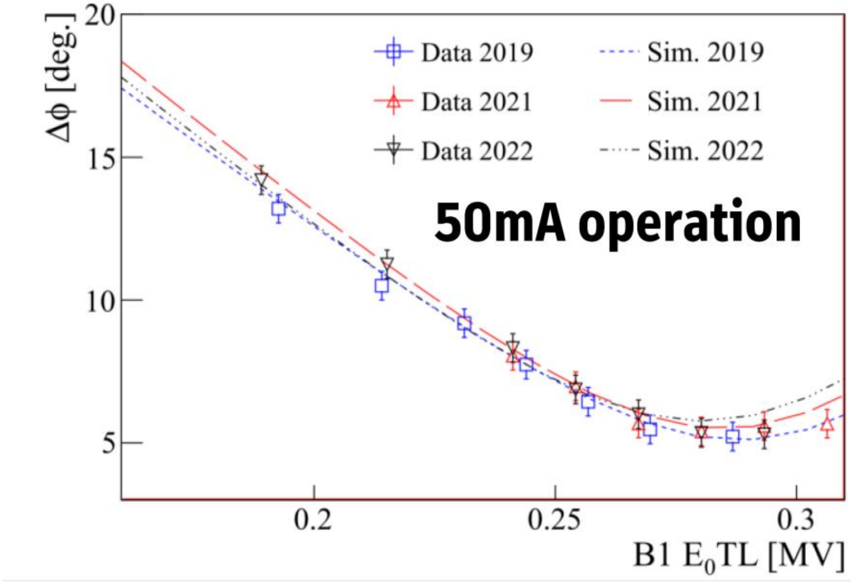
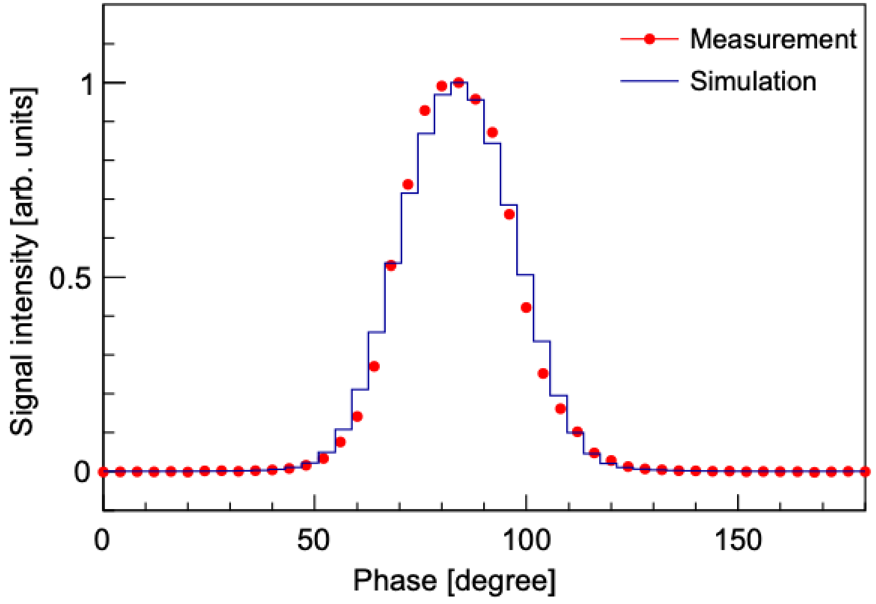


Simulation reproduces measurement well and stable every period.

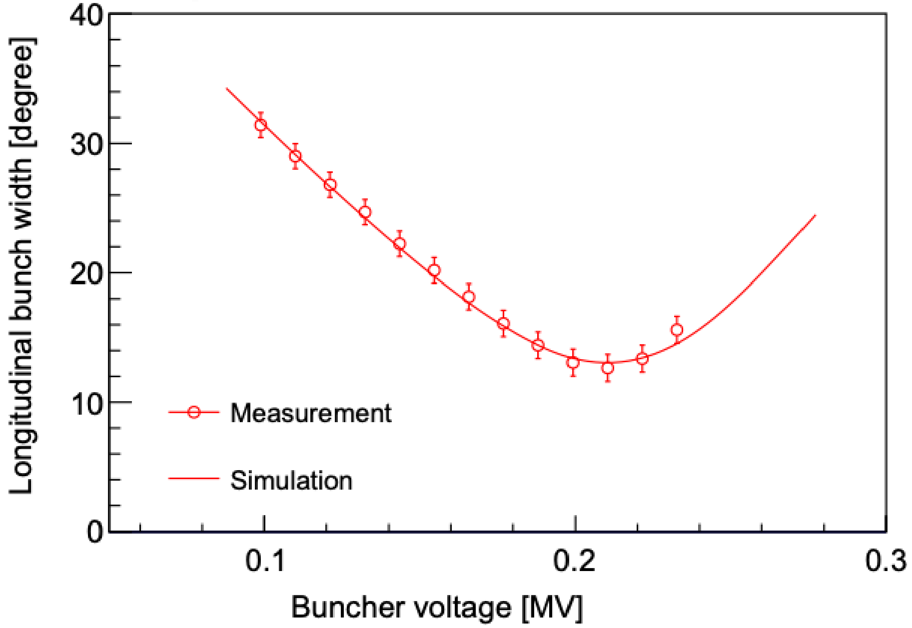
Longitudinal Measurement at MEBT1-BSM

R.Kitamura

Long. profile measured with BSM



Amplitude scan with buncher



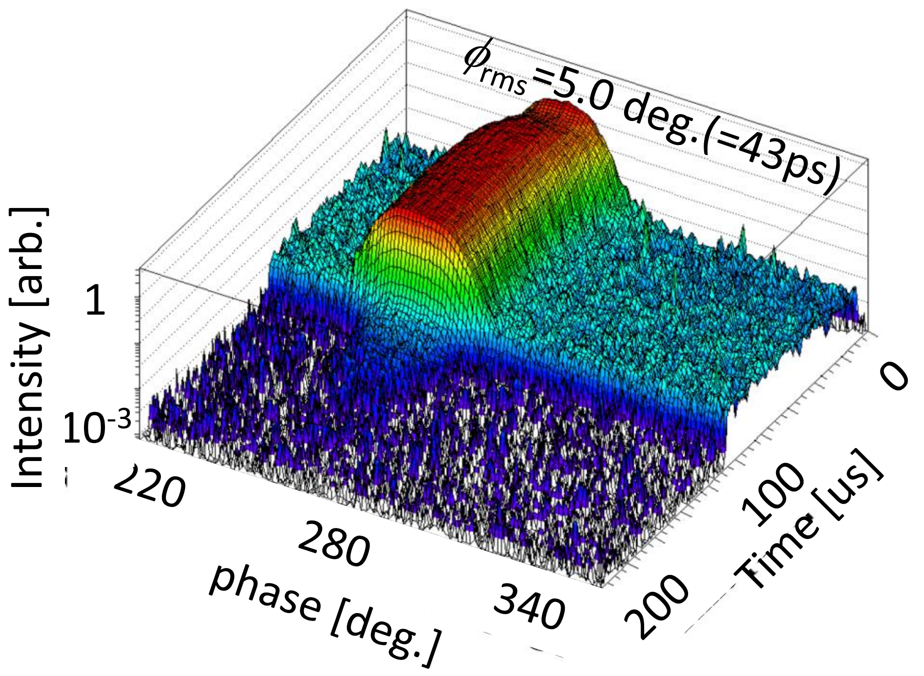
R. Kitamura *et al.*, "Measurement of the longitudinal bunch-shape distribution for a high-intensity negative hydrogen ion beam in the low-energy region", Phys. Rev. Accel. Beams **26**, 032802 (2023).

- Longitudinal profiles are measured with the BSM in MEBT1.
- Longitudinal Twiss parameters and emittance, which are initial parameters of the LINAC, can be evaluated with the amplitude scan using the buncher cavity.

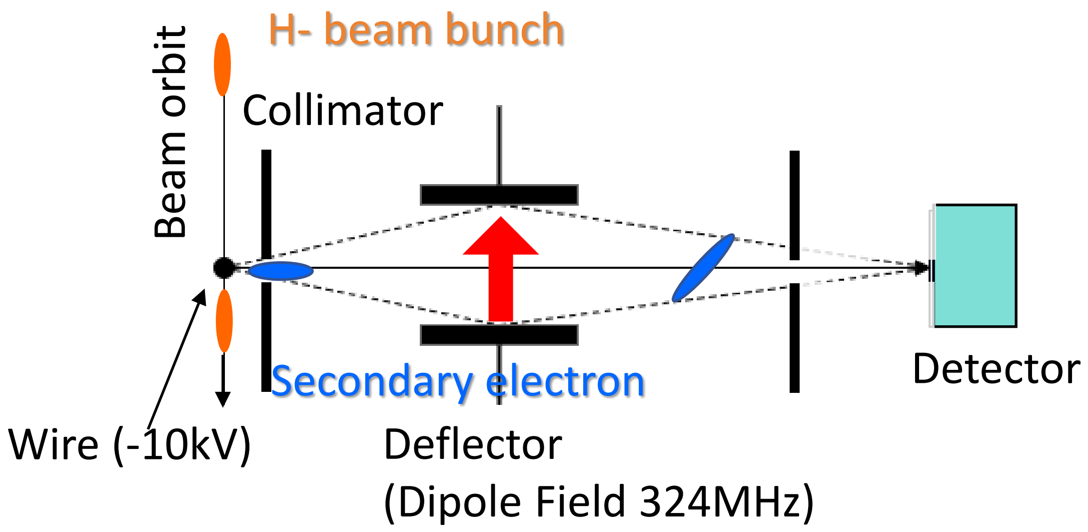
Bunch Shape Monitor (BSM)

K.Moriya

Longitudinal beam profile measurements with bunch shape monitors (BSMs) started in 2012 and have since evolved through several generations of instrumentation.



longitudinal profile at ACS section



1. Insert the wire into the beam line.
2. Secondary electrons are emitted when the H^- beam strikes the wire.
3. The RF deflector converts the time structure into a transverse profile.
4. Scan the RF phase to reconstruct the longitudinal bunch profile.

Resolution: ~ 0.5 degrees at 324 MHz

Dynamic Range: 10^2

One-Step Virtual Aperture Ray Tracing (VA-RT)

VA-RT Methodology

Step 1. Aperture Classification

Step 2. Virtual Aperture Tube Construction

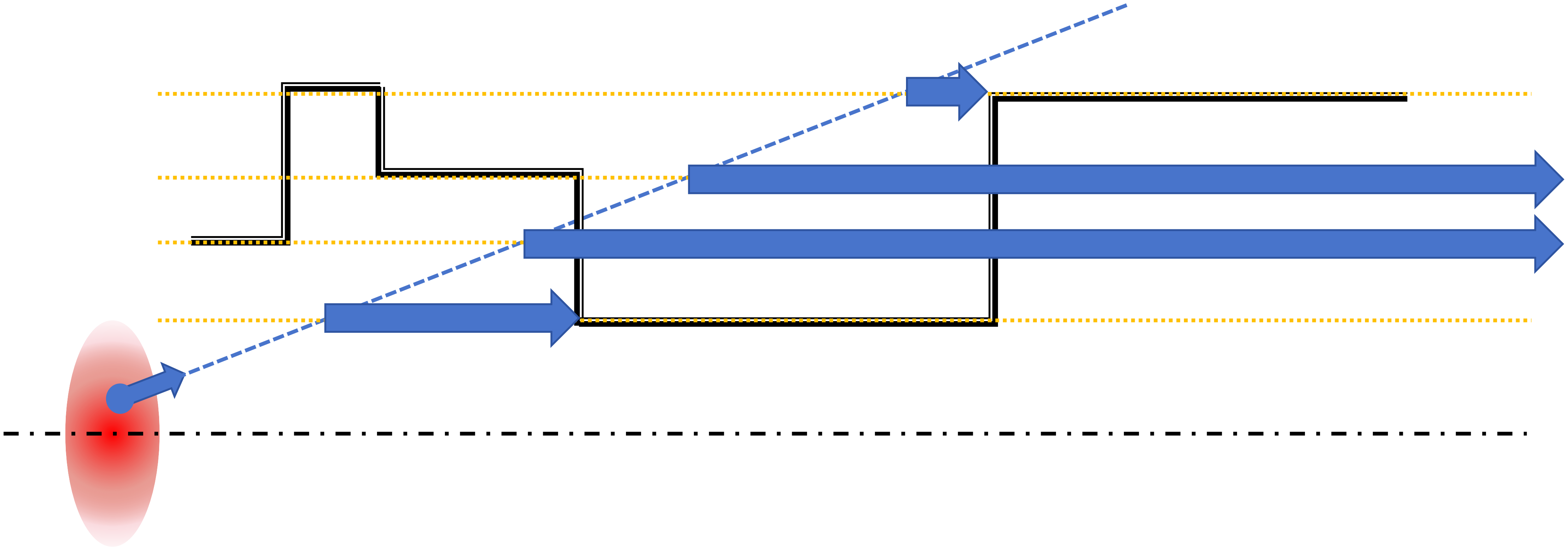
Step 3. First Virtual Intersection

Step 4. Virtual-to-Physical Aperture Mapping

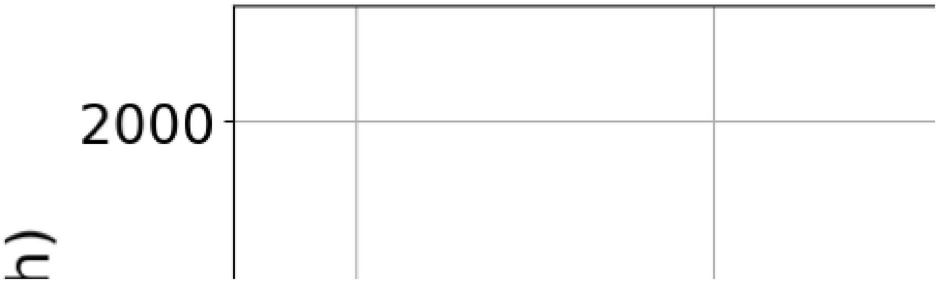
Step 5. First Physical Interception Selection

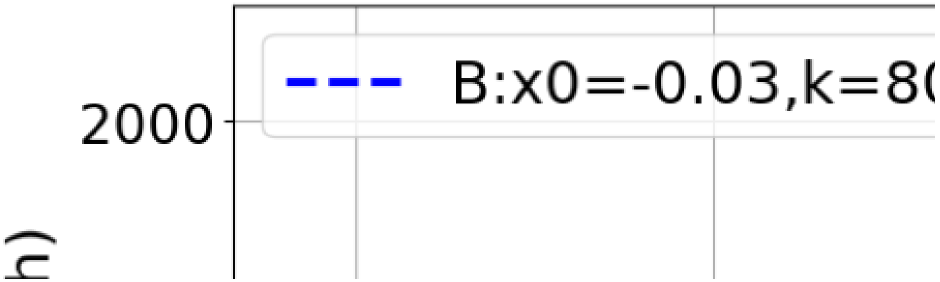
Computational Characteristics

- Ballistic-particle formulation
- One-step localization
- Geometry-based formulation
- No trajectory-history accumulation
- General applicability



ACSビームロス測定と残留線量分析・予測





ACS残留線量測定(50mA 950kW運転時)と60mA 950kW運転時線量予測