Experimental investigation of emittance exchange in J-PARC linac with non-equipartitioning setting

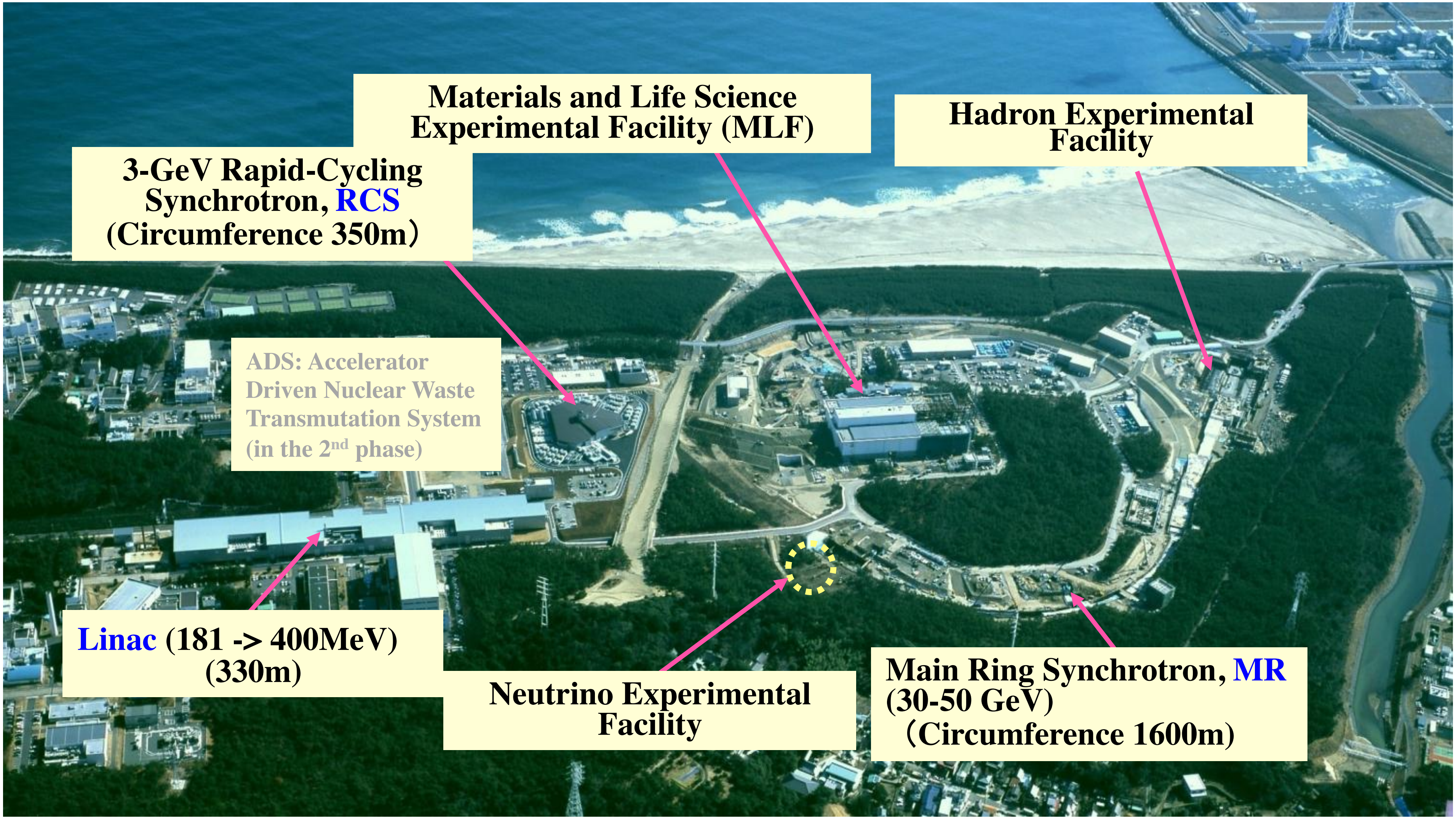
Y. Liu, T. Maruta, T. Miyao, KEK/J-PARC, Ibaraki-ken, Japan
A. Miura, JAEA/J-PARC, Ibaraki-ken, Japan
C. Plostinar, STFC/ASTeC, Harwell, UK
M. Ikegami, FRIB, East Lansing, USA

HB2016, Malmö, Sweden, 3-8 July 2016

Outlines

- Progress of J-PARC linac commissioning
- J-PARC linac lattice settings
- Efforts for IBSt mitigation and positive results
- Experimental investigation for emittance exchange in linac
- Conclusion and outlook

J-PARC Facility Layout at Tokai, JAEA Site



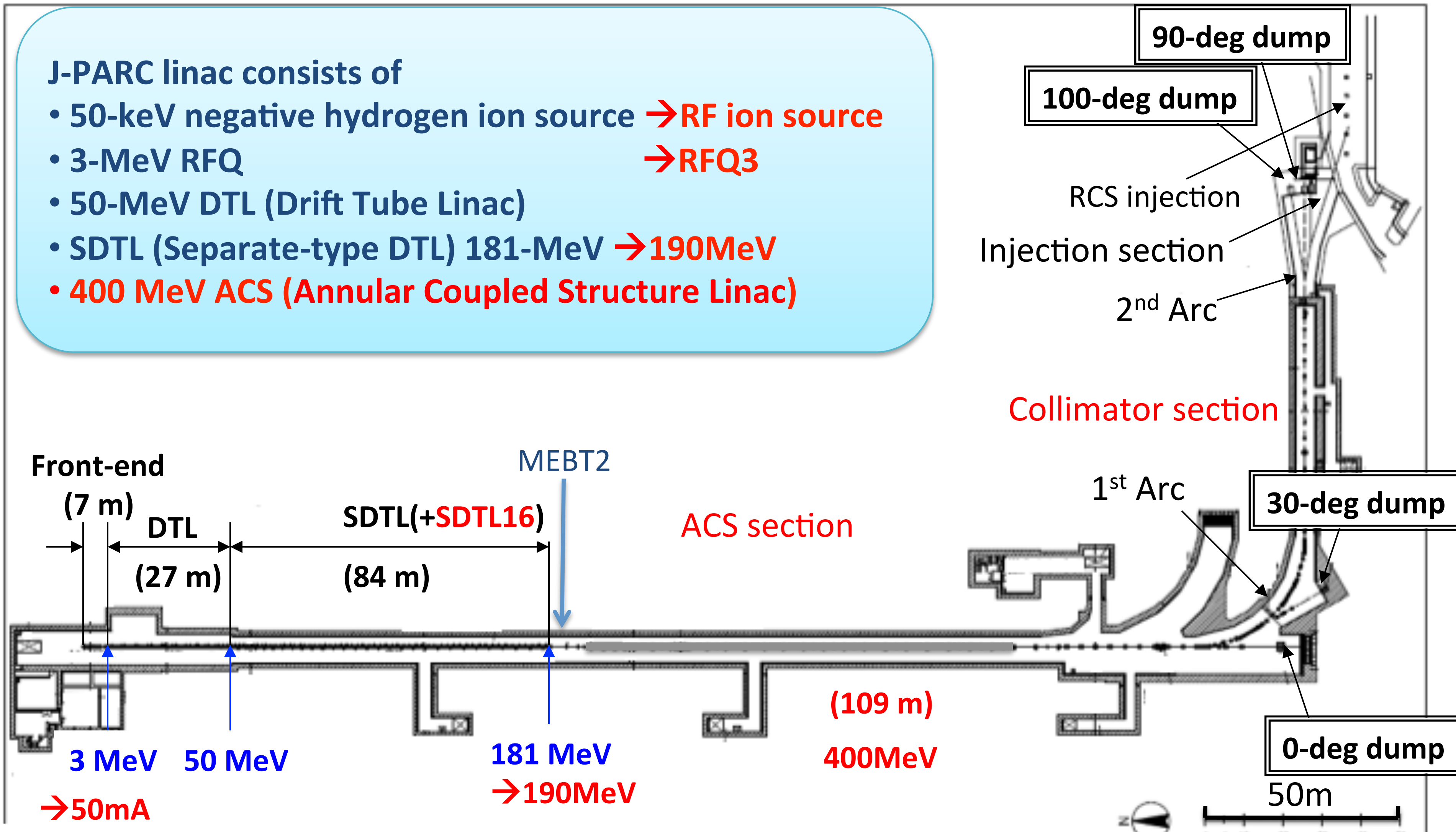
Multi-Purpose Facility

Joint Project between KEK and JAEA

J-PARC Linac Layout and Upgrade Scheme

181/190MeV → 400MeV: installation in 2013 Summer, accomplished in Jan., 2014
15/30mA → 30/50mA: on-line in 2014 Summer, accomplished in Oct. 2014

J-PARC linac consists of
- **50-keV negative hydrogen ion source →RF ion source**
- **3-MeV RFQ →RFQ3**
- **50-MeV DTL (Drift Tube Linac)**
- **SDTL (Separate-type DTL) 181-MeV →190MeV**
- **400 MeV ACS (Annular Coupled Structure Linac)**



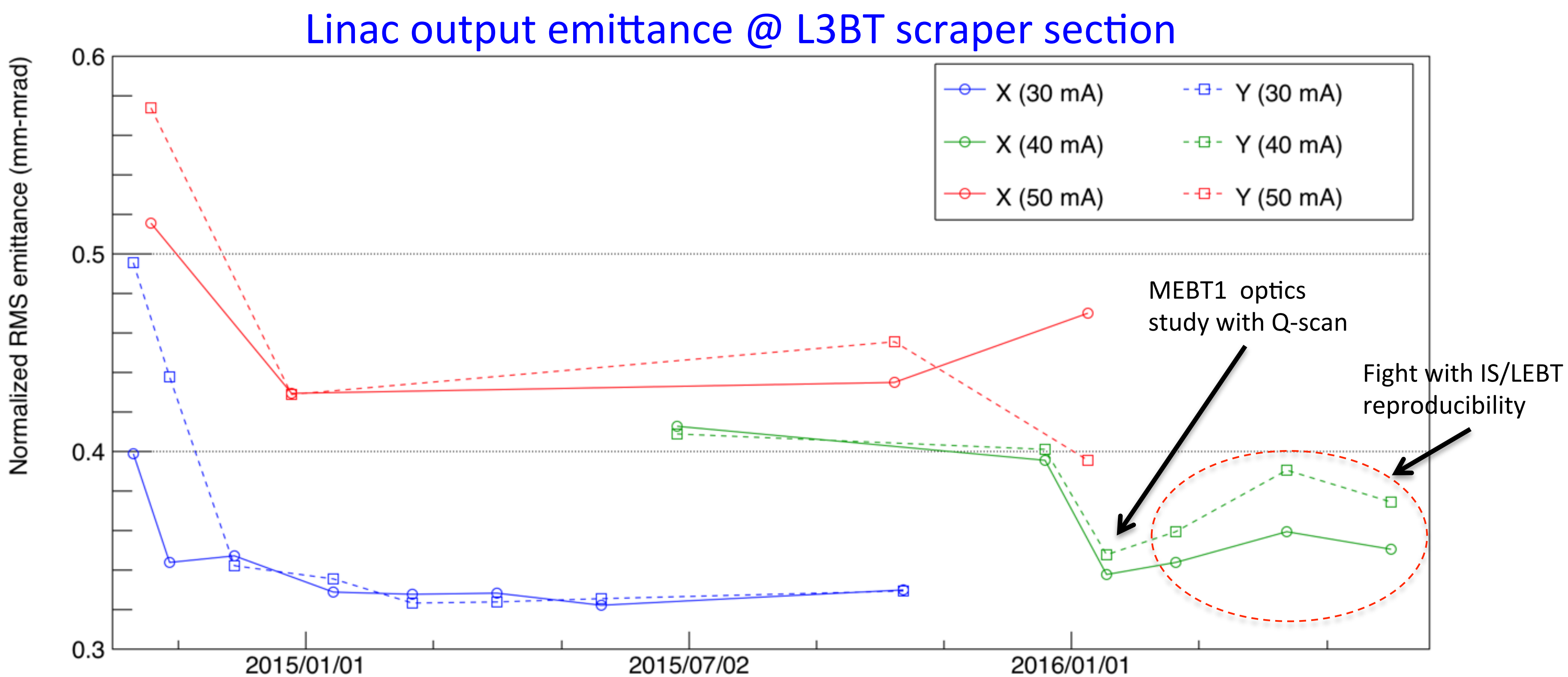
Front-end = IS + LEBT+ RFQ + MEBT

Progress of J-PARC linac commissioning

Jan. 2014: → 400MeV

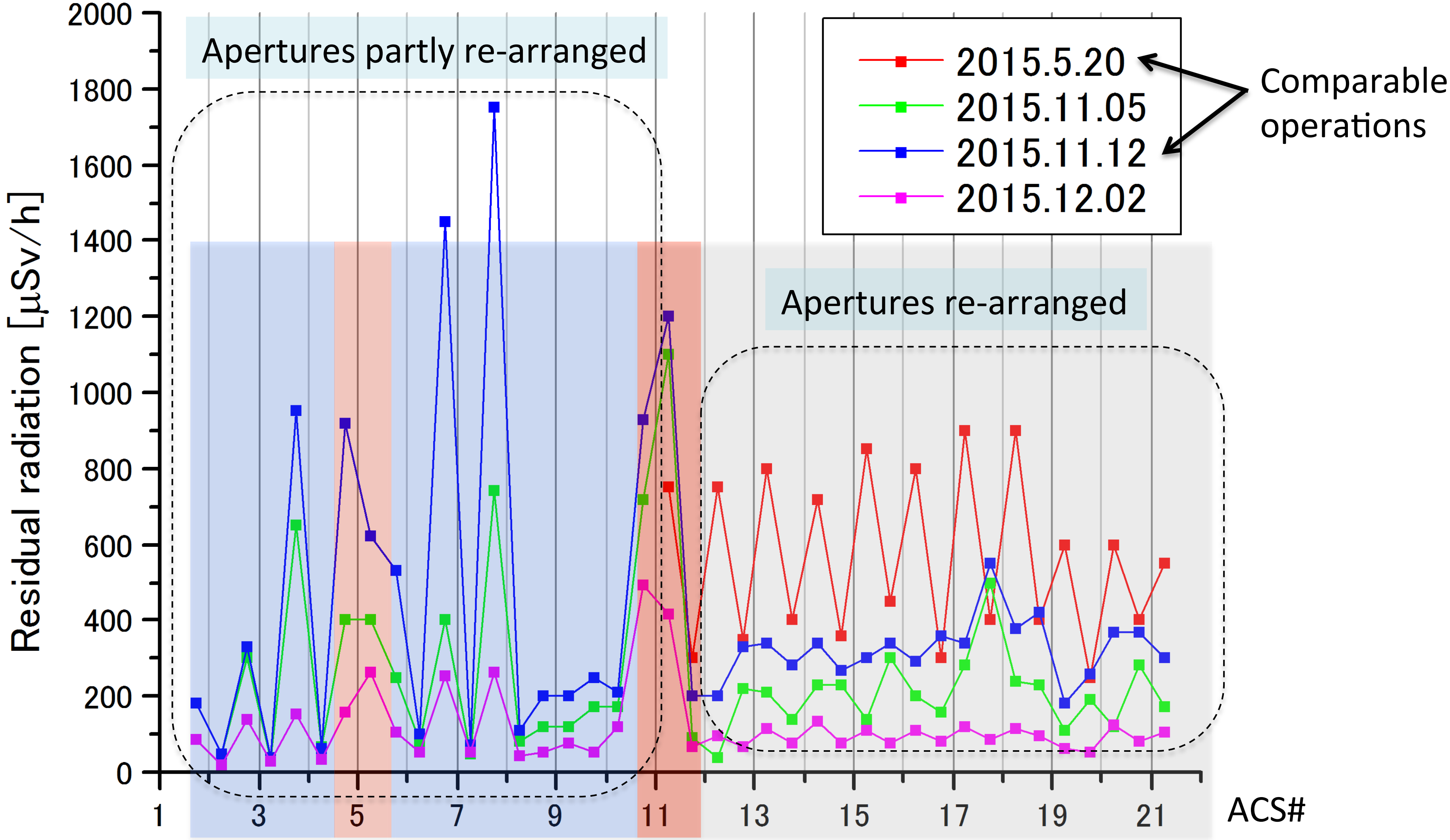
Oct. 2014: → 50mA for 1MW RCS

For user operation: 30mA(~2015) → 40mA(2016)



For each current beam quality has been improved with fine matching

Examples of Residue Dose (Surface) at ACS section



With linac 30mA, RCS 300kW user operation(red & blue), residue dose (surface) reach 1mSv/h level ~ 1/10 of 1W/m

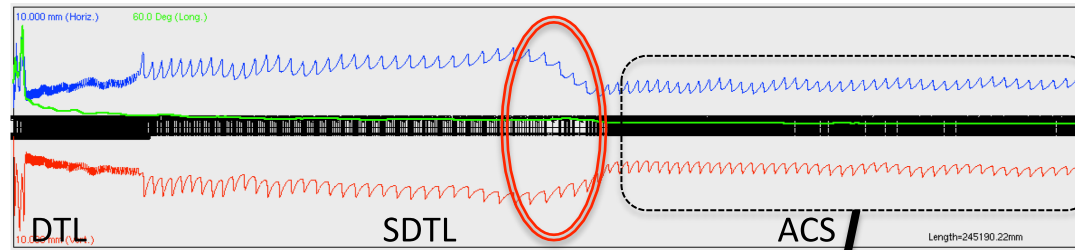
New aperture re-arrangement (partly done in 2015, to be finish 2016 shutdown) is in progress

IBSt supposed to be dominant in ACS (200~400MeV) $\sigma_{IBSt} \propto I^2$

J-PARC Linac Parameter Space

J-PARC Linac applies Equipartitioning (EP) condition as the **baseline** setting

rx ry rz



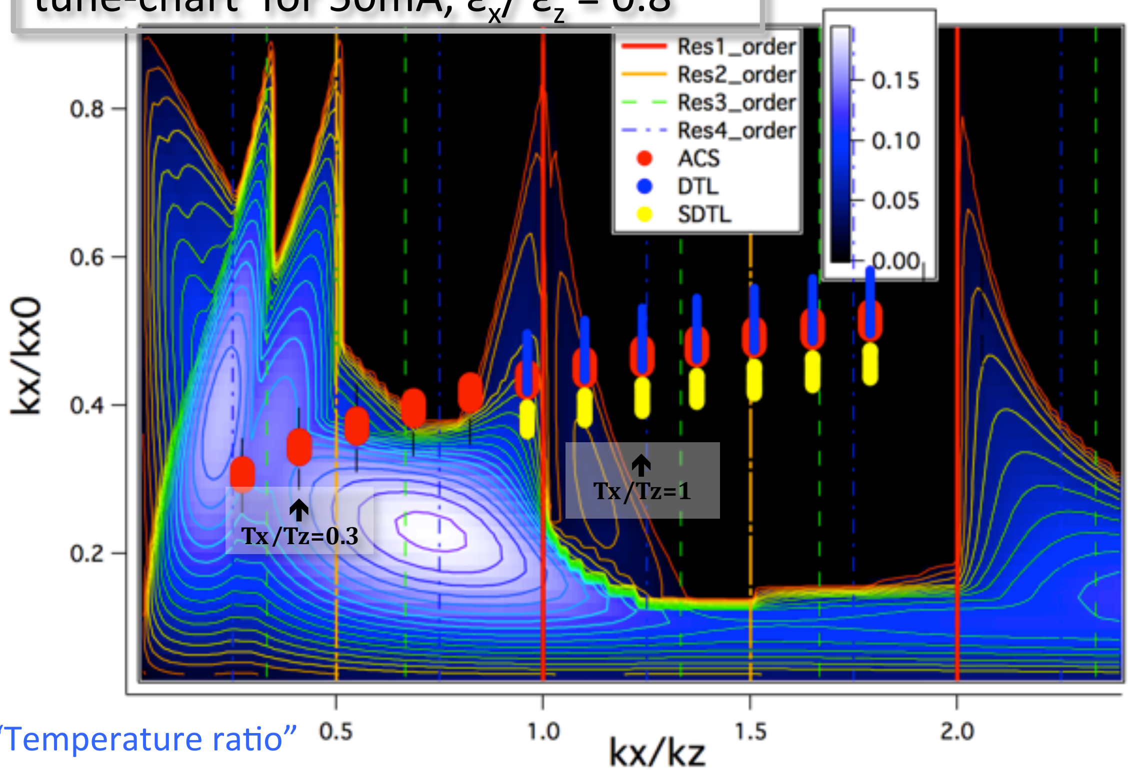
324MHz → 972MHz

rx,ry 50%

beam loss by IBSt found to be dominant

J-PARC Linac has flexibility for
Investigating the physics principles
Possibilities for further optimizations

tune-chart for 50mA, $\varepsilon_x / \varepsilon_z = 0.8$



"Temperature ratio"

$$\frac{T_x}{T_z} \equiv \frac{r_x^2 k_x^2}{r_z^2 k_z^2} = \frac{\epsilon_x k_x}{\epsilon_z k_z}$$

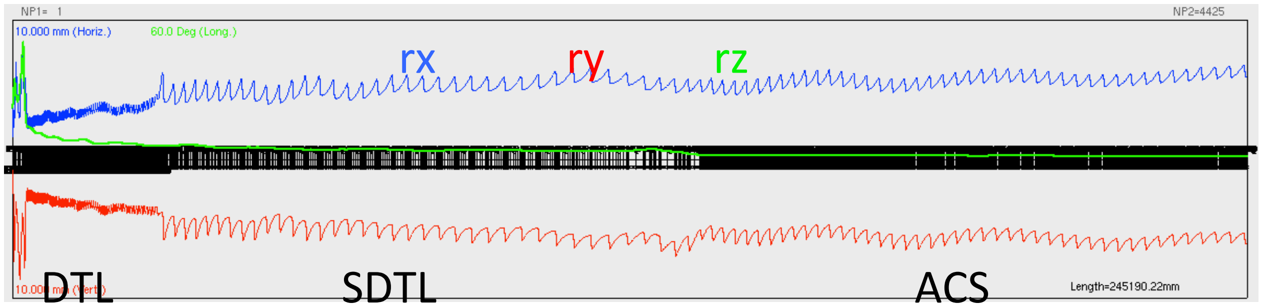
Stronger quad setting →

IBSt is almost ONLY affected by lattice. A weaker transverse focusing may help.
Lattice constant trans. envelope
T=Tx/Tz → 0.3
Quad. setting @T=Tx/Tz

$GL|_{ACS@T=0.3} \sim 70\% GL|_{ACS@T=1.0}$

Off-EP Lattice with Relaxed Transverse Focus

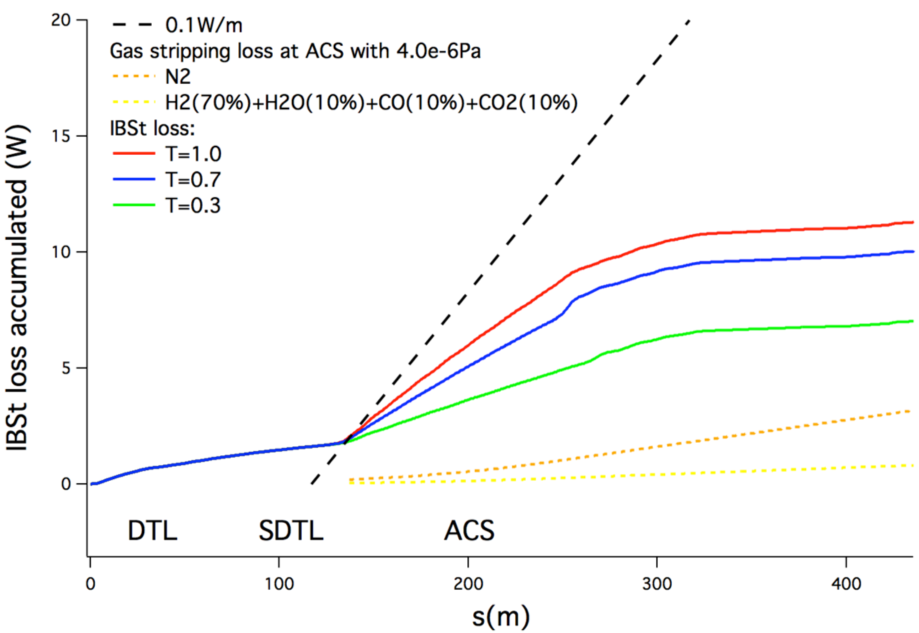
J-PARC lattice with constant continuous envelope at Freq. jump, with ACS@T≡ Tx/Tz=0.3

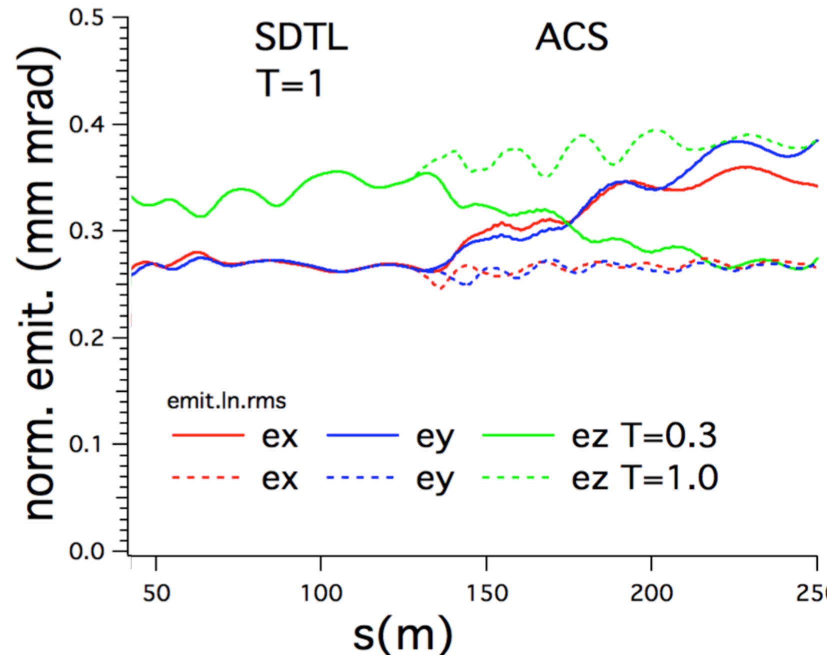


T=1 vs. ACS@T=0.3

IBSt: 4×10^{-5} → 1.3×10^{-5} ,

0.06W/m to 0.02W/m (0.7% beam duty)





Simulation with IMPACT

Emittance exchange found; but very limited total emittance growth

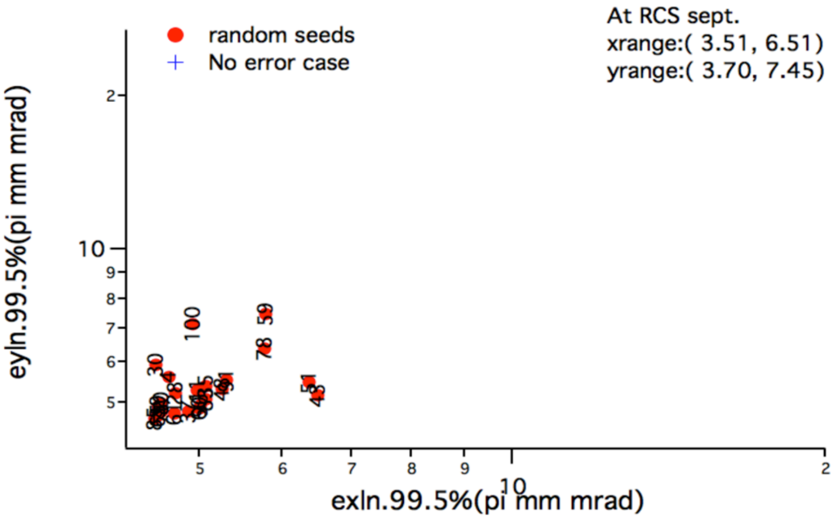
→ Seemed possible to apply

Property of off-EP Setting T=0.3: Lattice Stability 9

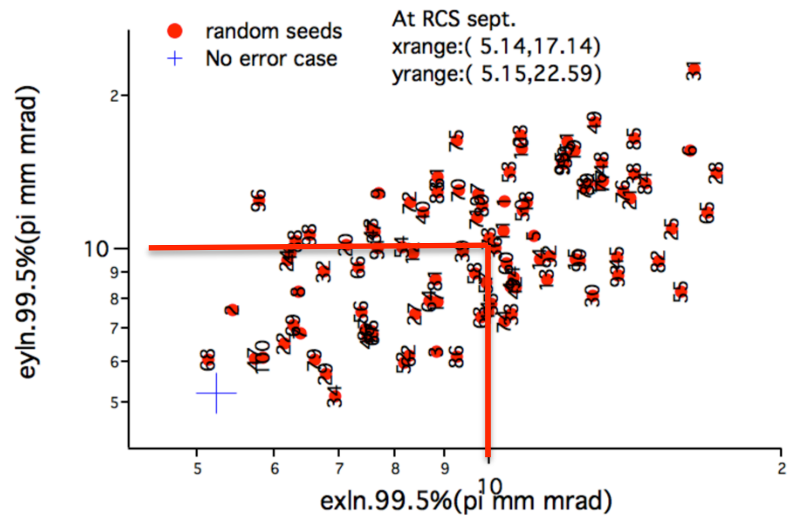
Lattice Stability problem found in error study

- Simulation with IMPACT
- Q alignment error ± 0.1mm
- RF amplitude error ± 1%, phase error ± 1^0
- 100 seeds

T=1



T=0.3



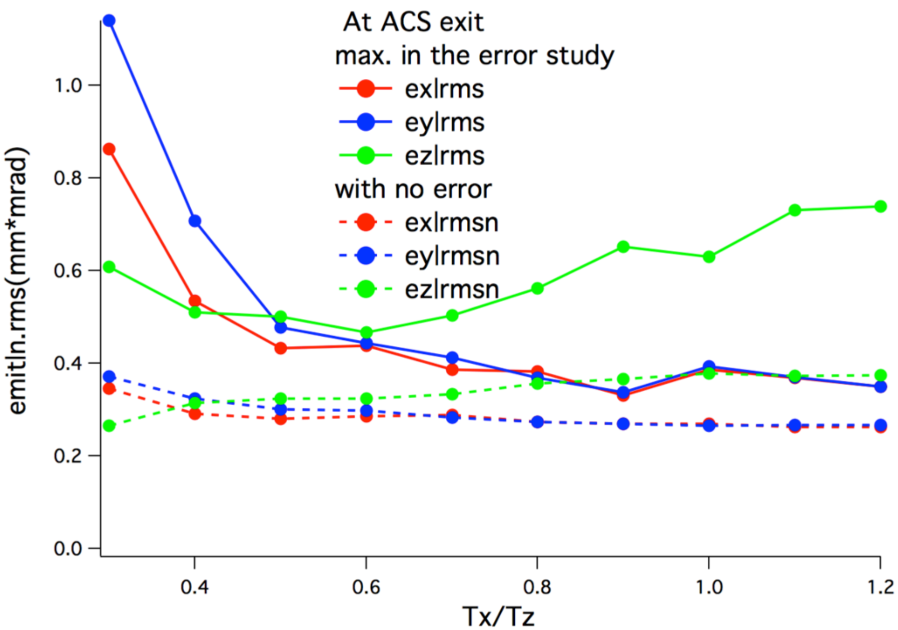
Very different sensitivity to errors!

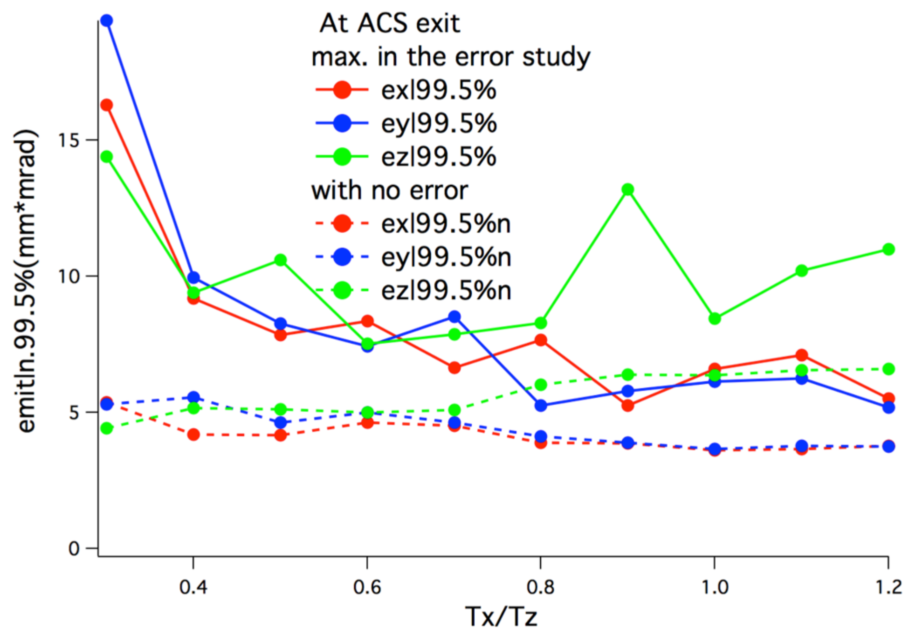
Transverse emit-99.5% 10 π mm mrad: more than half of the seeds exceed for T=0.3

Error Sensitivity vs. T

Same simulation for T=0.3~1.2

Comparison of no-error case and worst error seed





Considering emittance sensitivity (in all planes) to errors

EP setting is the most stable

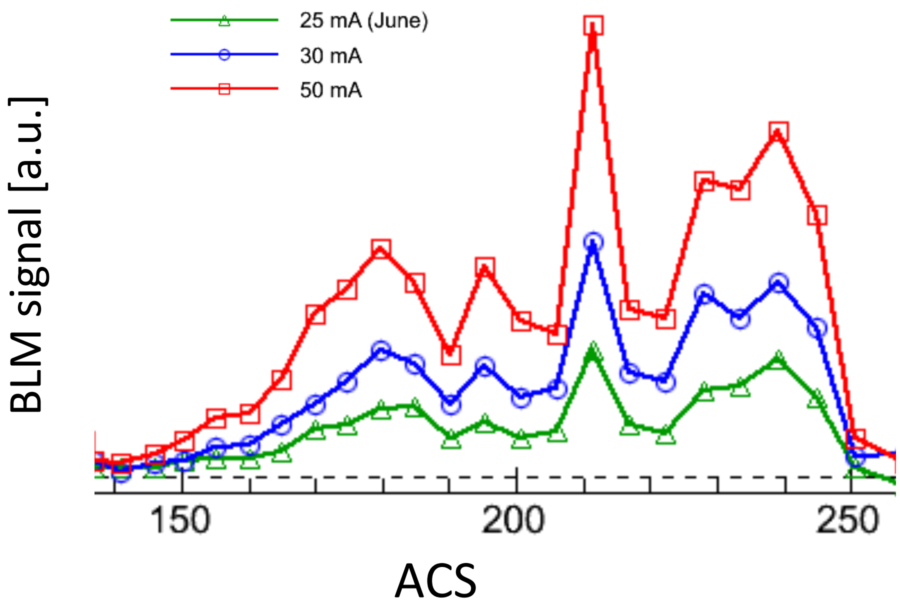
Some abnormal behavior, T=0.5, T=0.9

T=0.4 stands on the border according to simulation

Identification of IBSt in ACS

- Look for IBSt signature $\sigma_{IBSt} \propto I^2$: verified

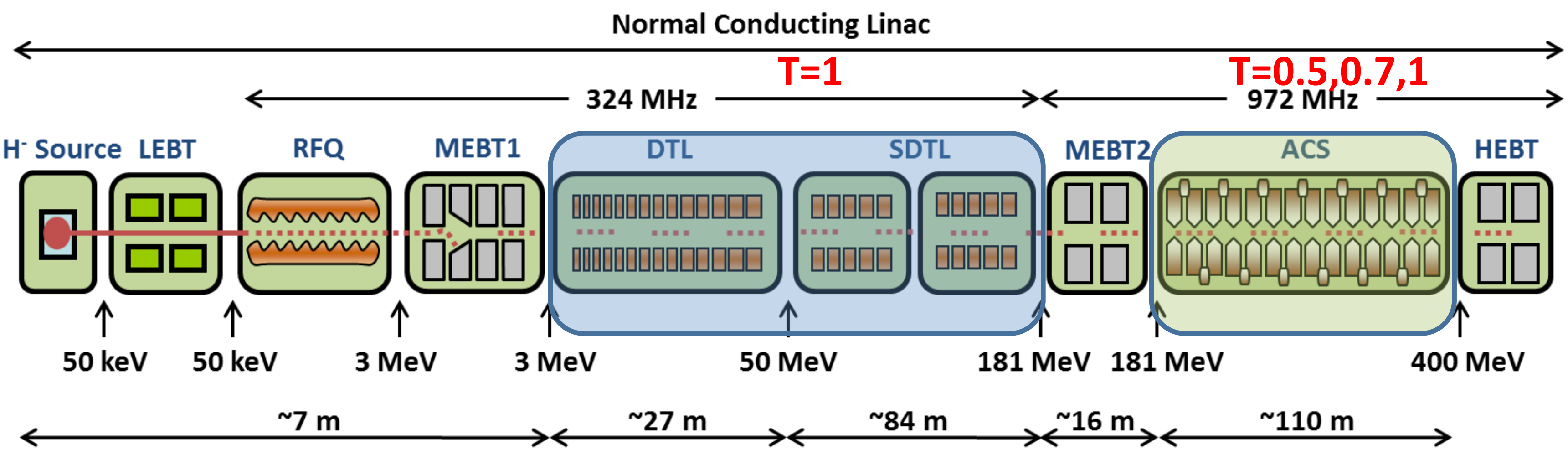
Beam loss @ACS, comparison before/after current upgrade in Oct. 2014



At first glance, beam loss ∝ I
By taking into account emittance
IBSt signature was identified in ACS
IBSt dominates in ACS (200~400MeV)

- Another identification is the beam loss dependency on the lattice (to be shown later)

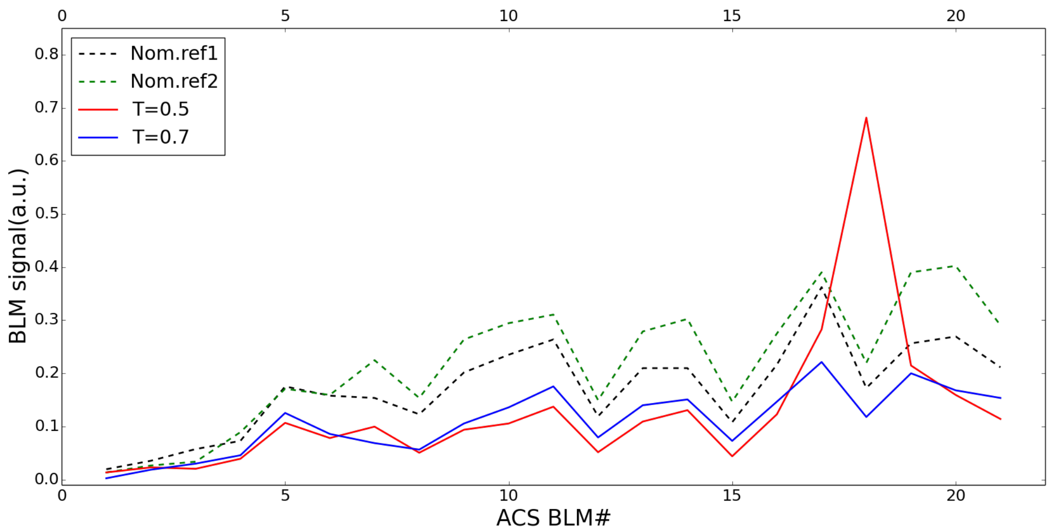
Efforts to Mitigation of IBSt in Commissioning

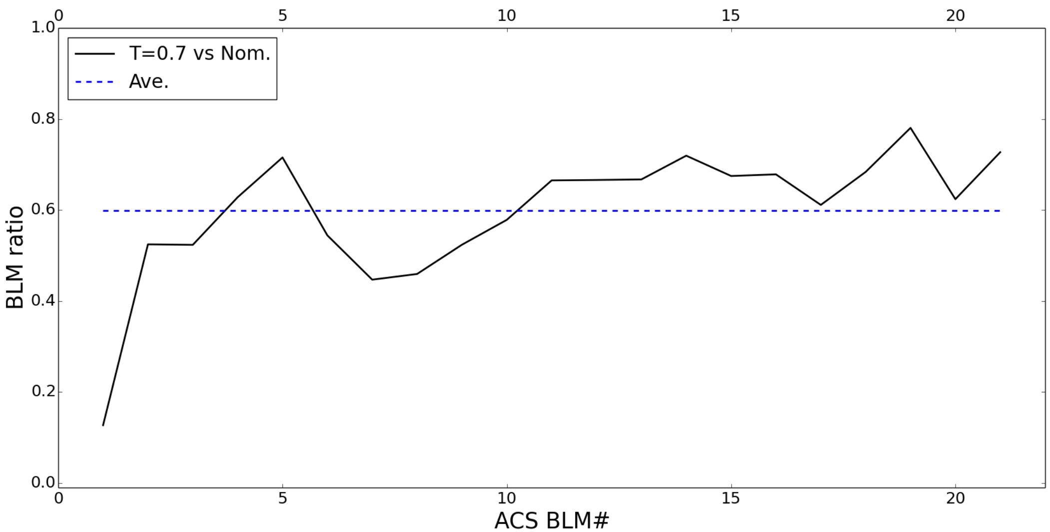


Lattice study with ACS(only) @T=Tx/Tz=0.5, 0.7 and 1 (EP, the nominal setting)
Jan. 2016, I=50mA

Beam Loss Measurements Comparison

for ACS (only) setting with Tx/Tz=0.7, 0.5 and 1 (nominal)





3D Matching were done for each setting

Beam loss correlated with T

→consistent with simulation

→IBSt was identified as the dominant source of beam loss at ACS section

Beam loss: T=0.7, -40% reduction of beam loss vs. nominal.

Consistent with simulation!

- **T=0.7 seems promising** as a backup setting
- **T=0.5**: more reduction at most part, but extra loss found at the end of ACS

Summary of Lattice with ACS (only) at T=0.7, 0.5 and 1 And Further Questions

Measured emittance after ACS

	T=1.0	T=0.5	0.5 vs.1.0	T=0.7	0.7 vs.1.0
$5\varepsilon_{rms}$(t3d)			$\Delta\varepsilon/\varepsilon$(%)		$\Delta\varepsilon/\varepsilon$(%)
H	2.31	2.72	18.03	2.56	10.95
V	2.03	2.51	24.15	2.40	18.60

Bigger emittance found for T=0.5 and 0.7 vs. T=1
But T=0.7 lies in resonance free region according to Hofmann?
-Longitudinal matching might be not precise enough, the real tune is crossing nearby resonances

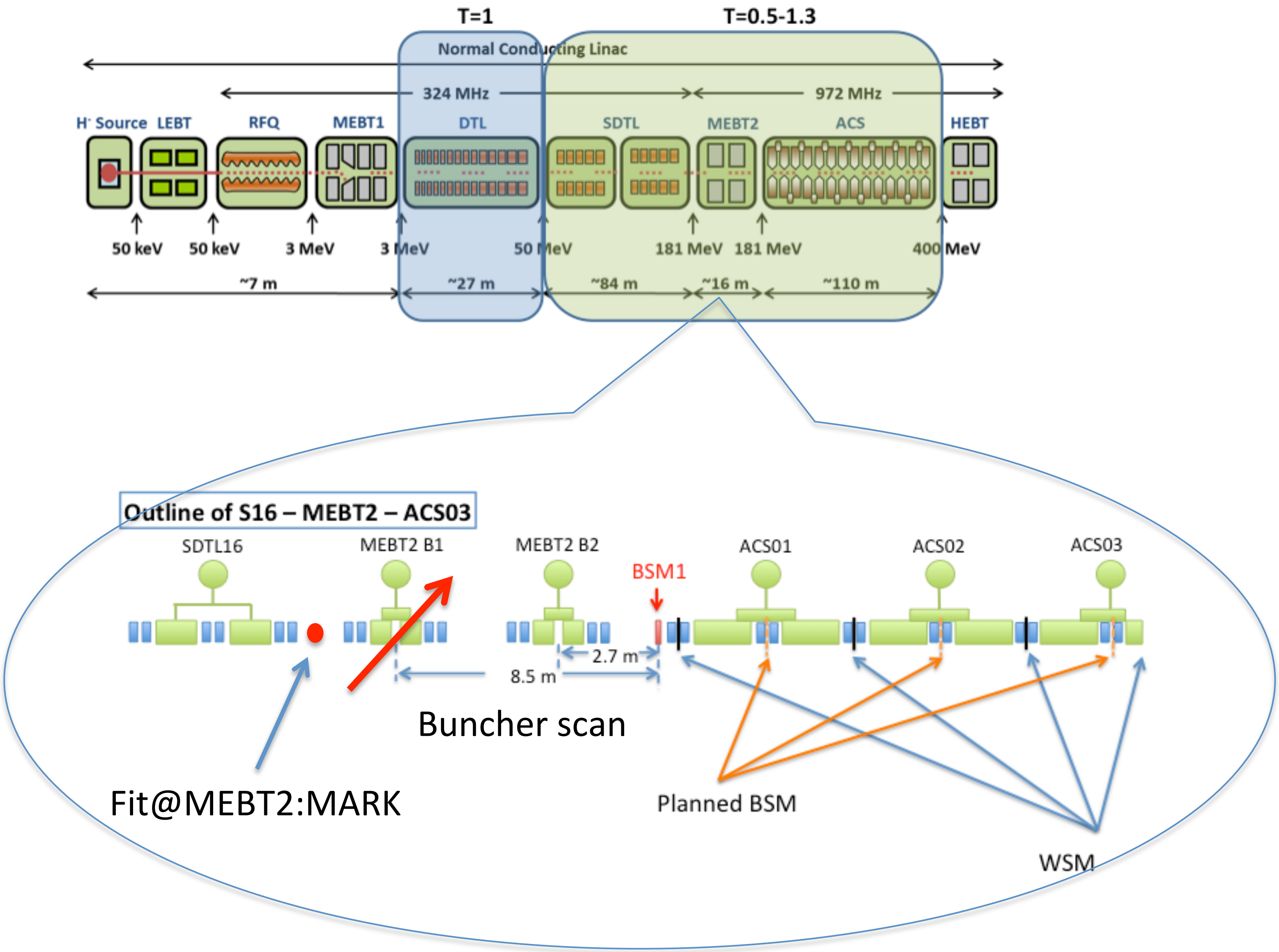
No longitudinal measurement after ACS, no way to know whether the emittance exchange happens or not

Better understanding and consistency between theory and experiment is necessary to refine and secure the new lattice around T_{ACS}=0.7

→ **Motivation for resonance study with SDTL+ ACS set at off-EP**
Longitudinal (and transverse) measurements are available

Experiment Setup and Scheme of Measurement

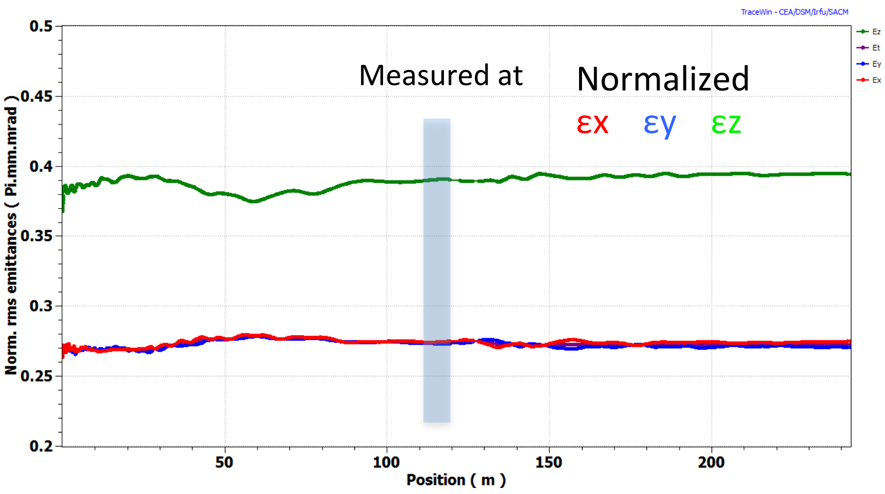
Jan. 2016, I=40mA



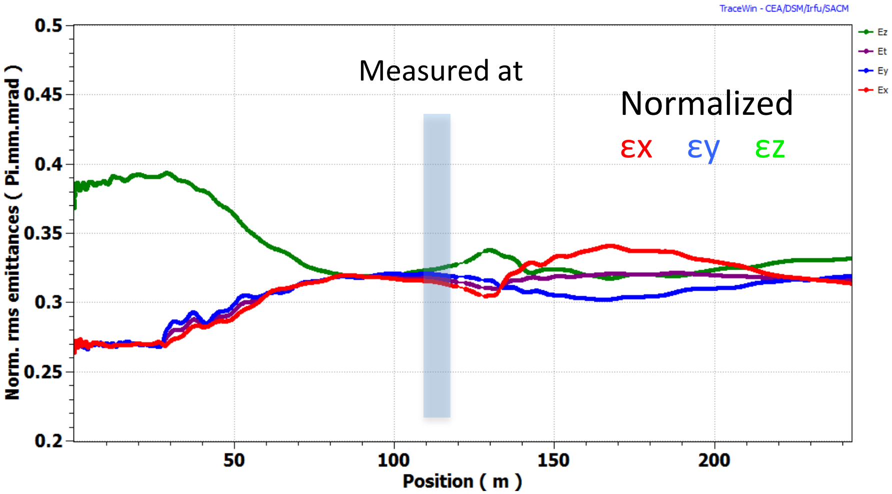
Simulation Results

By Dr. C. Plostinar

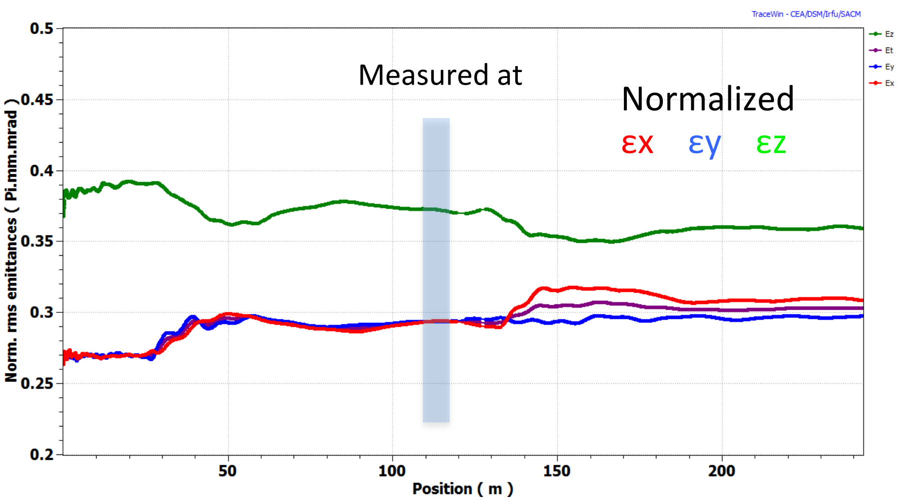
Nominal (Tx/Tz=1)



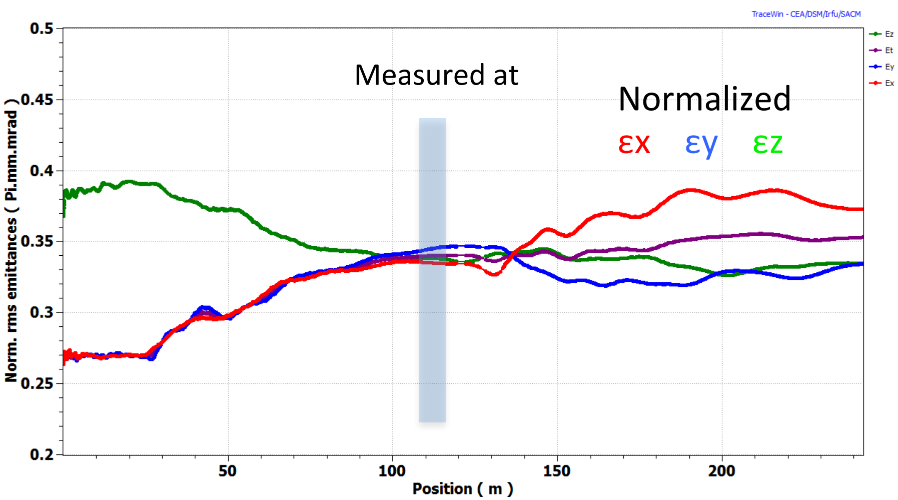
Tx/Tz=0.9, emit. exchange: Yes



Tx/Tz=0.7, emit. exchange: almost No



Tx/Tz=0.5, emit. exchange: Yes



Experiment Setup and Scheme of Measurement

Fit/simu.@MEBT2:MARK

exp.

	Nom.	T_{S+A}=0.5		T_{S+A}=0.7		T_{S+A}=0.9		T_{S+A}=1.3	
	$\varepsilon_{rms.n.}$(mm)	ε_{rms}(t3d)	$\Delta\varepsilon/\varepsilon$(%)	$\varepsilon_{rms.n.}$(mm)	$\Delta\varepsilon/\varepsilon$(%)	$\varepsilon_{rms.n.}$(mm)	$\Delta\varepsilon/\varepsilon$(%)	$\varepsilon_{rms.n.}$(mm)	$\Delta\varepsilon/\varepsilon$(%)
H	0.38	0.45	18.8	0.37	−1.1	0.39	4.3	0.33	−13.4
V	0.35	0.55	58.7	0.37	7.0	0.38	9.9	0.32	−8.5
L	0.34	0.26	−24.2	0.33	−1.9	0.32	−4.1	0.39	15.9
$\varepsilon^3_{rms.n.}$(mm^3)	0.0440	0.0628	42.8	0.0457	3.9	0.0483	10.0	0.0404	−8.2

Relative only!

simu.

	Nom.	T_{S+A}=0.5		T_{S+A}=0.7		T_{S+A}=0.9		T_{S+A}=1.3	
	$\varepsilon_{rms.n.}$(mm)	ε_{rms}(t3d)	$\Delta\varepsilon/\varepsilon$(%)	$\varepsilon_{rms.n.}$(mm)	$\Delta\varepsilon/\varepsilon$(%)	$\varepsilon_{rms.n.}$(mm)	$\Delta\varepsilon/\varepsilon$(%)	$\varepsilon_{rms.n.}$(mm)	$\Delta\varepsilon/\varepsilon$(%)
H	0.27	0.33	22.2	0.29	7.4	0.31	14.8	0.24	−11.1
V	0.27	0.35	29.6	0.29	7.4	0.31	14.8	0.24	−11.1
L	0.38	0.34	−10.5	0.35	−7.9	0.31	−18.4	0.45	18.4
$\varepsilon^3_{rms.n.}$(mm^3)	0.0277	0.0393	41.8	0.0294	6.3	0.0298	7.5	0.0259	−6.4

--Emittance growth happened for exp. cases (could be well reproduced by introducing errors, but emittance ratio does not change in simulation)

--Neglecting absolute measured longitudinal emittance, look at the relation between each other.

Trend of emittance relation looks consistent!

Conclusion and Outlook

- J-PARC Linac is improving beam quality after energy and current upgrades

- IBSt has been identified as the dominant loss after 190 MeV

  So that beam loss will get more serious than linear with the peak current

- Transverse-relaxed (and off-EP) lattices were tried in ACS section (190~400MeV)

  Lattice-dependency of beam loss were verified and found to be consistent with the simulation

  Beam loss could be mitigated by 40% for Tx/Tz=0.7 case → next candidate?

  Abnormal beam loss found for Tx/Tz=0.5 at the end

- Further experimental studies were carried out in SDTL section (50~190MeV) with transverse and longitudinal measurements. Consitent with simulation

- For structures with cell num~20, Tx/Tz=0.7 was found resonance-free both from simulation and experiment. Could be a candidate for working tune. IBSt cut by 40%