J-PARC's Accelerator Construction, Commissioning and Operation (400MeV Linac and 3GeV-ring) -II

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Outlines

- First Beam Commissioning

  Basic settings and Integrated schedule

  Li commissioning: schedule, results, problems

  RCS commissioning : schedule, results, problems

- Re-commissioning after earthquake
- 181→400MeV Energy-upgrade
- 30→50mA Current-upgrade
- DTL1 issue after 50mA operation
- 60mA beam study
- Beam loss mitigation

J-PARC Milestones

Year	Event
2002	Linac bldg. construction start MR bldg. construction start RCS bldg. construction start
2005	RCS bldg. is completed Linac bldg. is completed
2006	Beam commissioning start (Linac)
2007	181 MeV acceleration is achieved at linac MR bldg. is completed 3 GeV acceleration is achieved at RCS
2008	30 GeV acceleration is achieved at MR
2011	Earthquake and recovery
2014	Linac upgrade (energy & intensity) plan is completed.
2015	Equivalent 1 MW operation is achieved
2018	Continuous operation with a beam power equivalent to 1 MW is succeeded

Commissioning goal

First beam (5, 30 mA)
Preparation for operation

Power rampingup
Fine tuning (15, 30 mA)

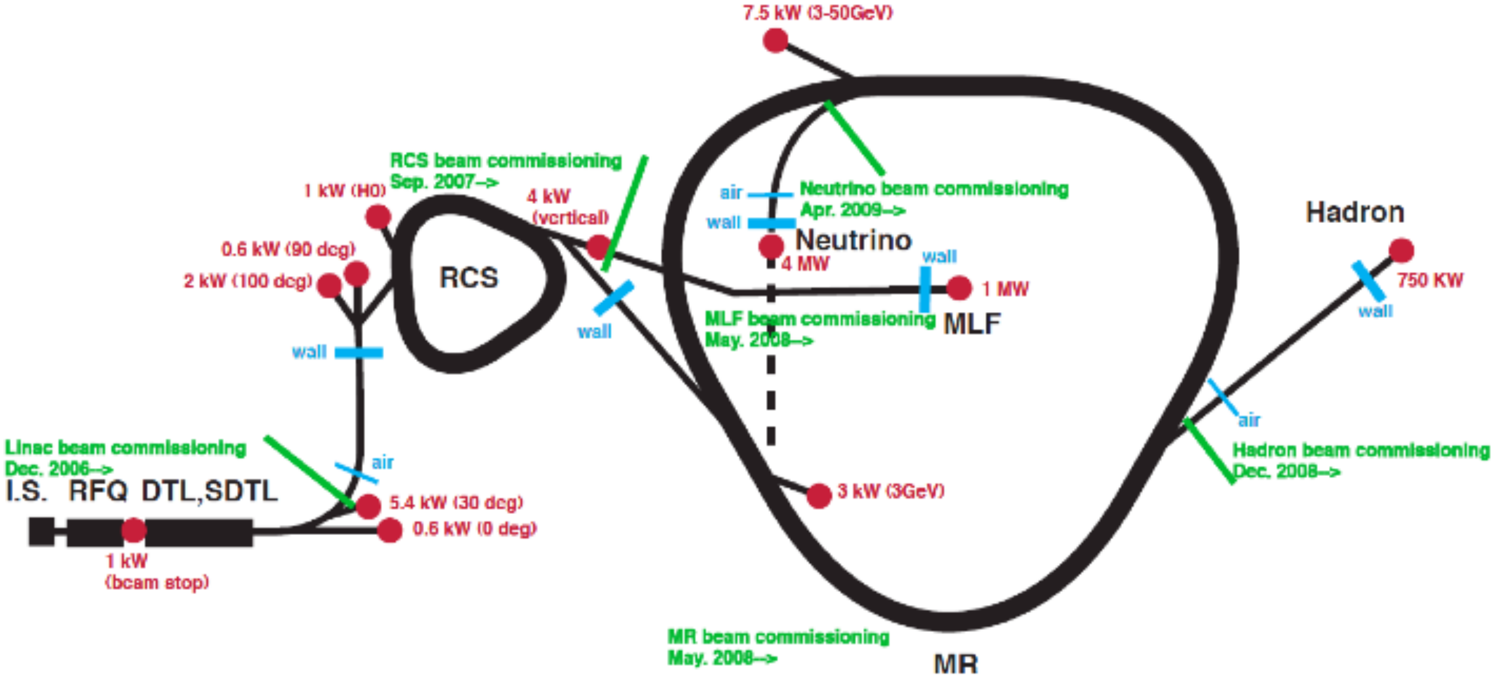
Re-commissioning

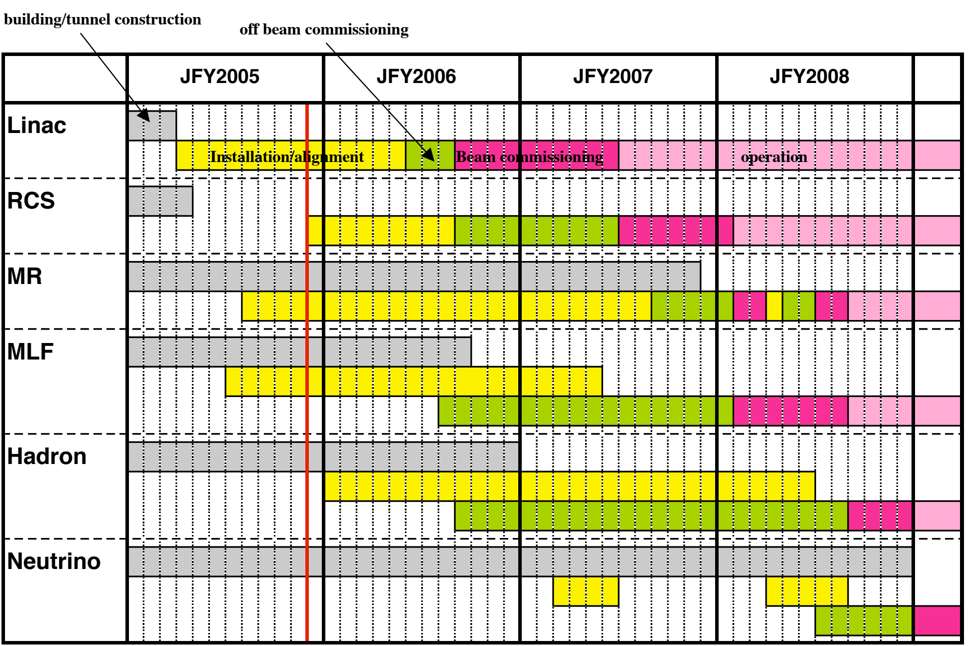
Commissioning for upgrades

Fine tuning (30, 50 mA)

Fine tuning (50, 60 mA)

Basic Settings and Integrated Schedule





Beam commissioning of upstream during installation/alignment of downstream

- **Radiation shielding walls and/or air-tight separators**
- **Day/night time sharing**

An "integrator" is important

Commissioning Including…

- **Off beam commissioning**

(with machines being on line)

-air conditioner, cooling water
-vacuum evacuation
-scheduled timing, synchronization
-control system, interlock system (PPS, MPS)
-comprehensive machine operation
-EMC
-… (eg. For rings BM and QM tracking study, etc)

J-PARC Control/Monitor System Condition before Linac "Day 1"

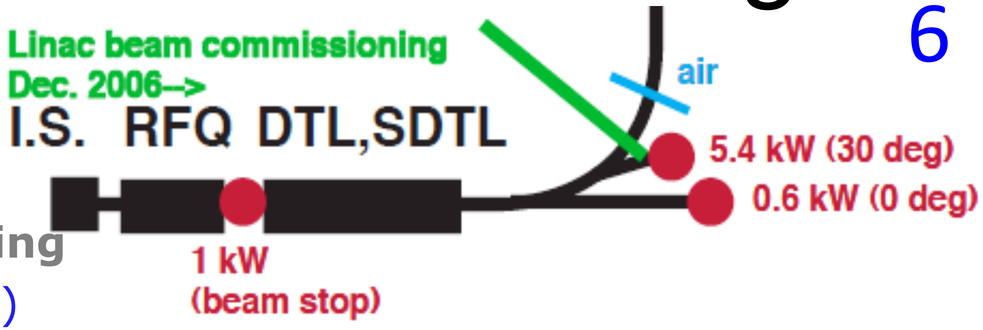
All device status were monitored through the control system.

Most of devices could be controlled through the control system.

Ill-behaved devices causing multi-cast storm and eating-up network bandwidth were identified and removed.

- **Beam commissioning**

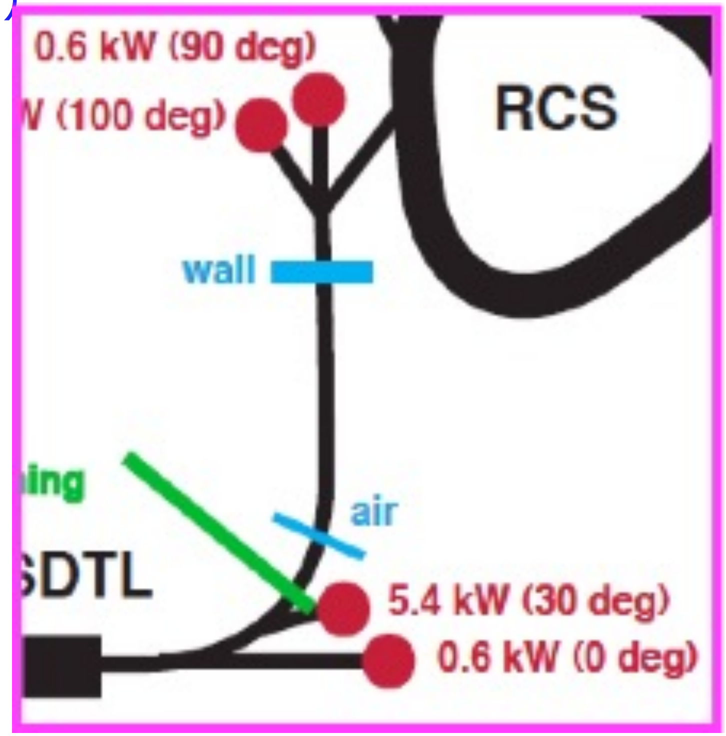
“Day-1” Linac Beam Commissioning



- **Procedures:**

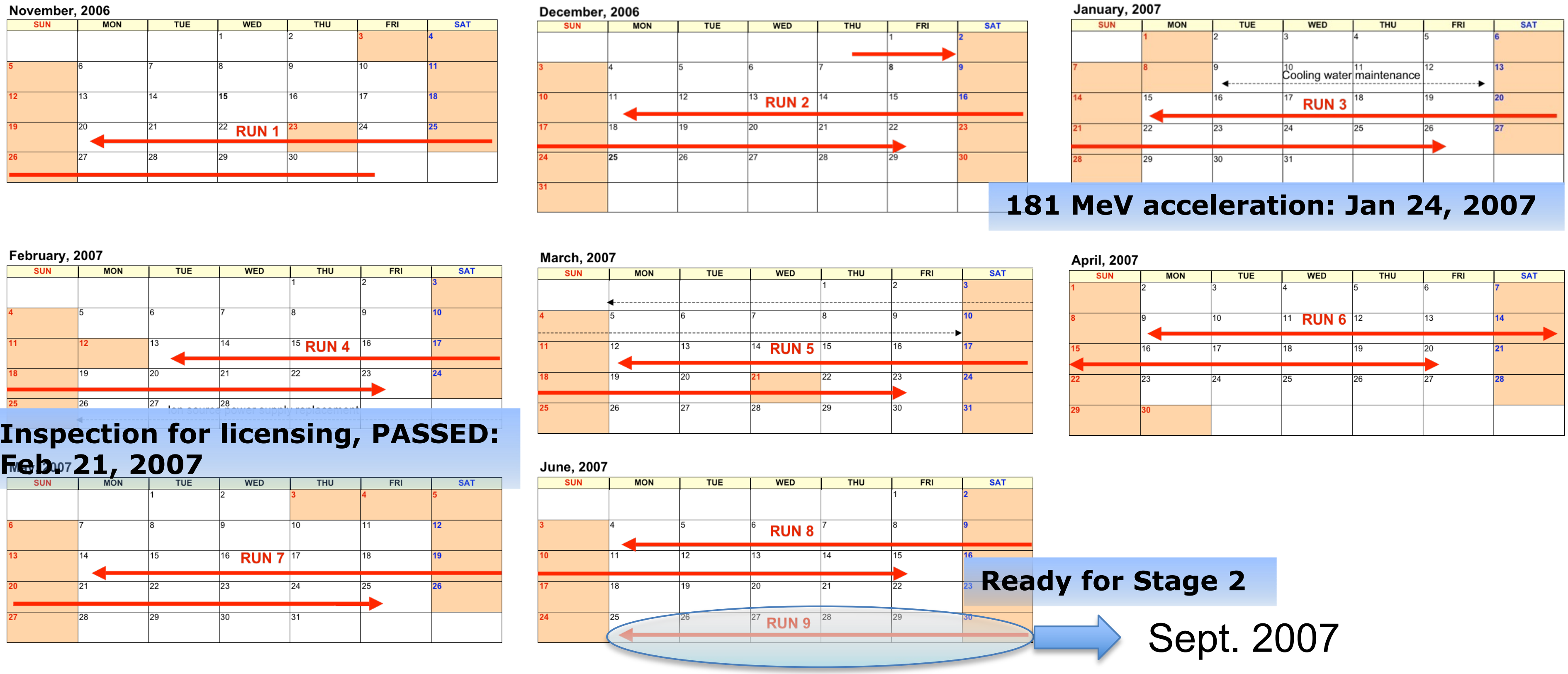
Ion Source test
RFQ, DTL, SDTL high-power conditioning
RFQ, MEBT tuning (5mA, 3MeV beam stop)
RFQ, MEBT tuning (30mA, 3MeV beam stop)
DTL tuning (5mA, w/o chopping, 0 deg dump)
SDTL tuning (5mA, w/o chopping, 0 deg dump)
Overall tuning for straight section (5mA, 0 deg dump)
High intensity operation (30mA, 0 deg dump)
Arc tuning (5mA, w/o chopping, 30 deg dump)

- **Dec. 2006 ~ Sep. 2007 Linac 0, 30 deg dump**
- **Sep. 2007~ Linac 30, 90 deg dump**



low current mode	**high current mode**
180 MeV	180 MeV
5mA peak current	30mA peak current
50μs width	50μs width
5 Hz (also single shot)	1 Hz
w/o chop	w/o chop
0.23 kW	0.27 kW

Linac Beam Commissioning Runs



Beam commissioning cycle: 9 * (12-day run + 9-day interval)

(Intervals are adjusted to accommodate maintenance periods.)

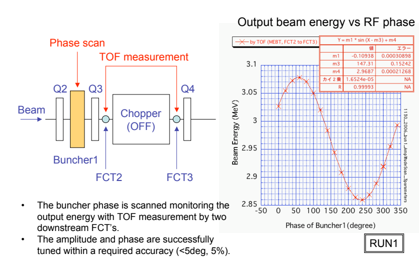
24-hour operation for RF/12-hour beam test
“Commissioning”/“Conditioning” pattern

Li Beam Commissioning Items

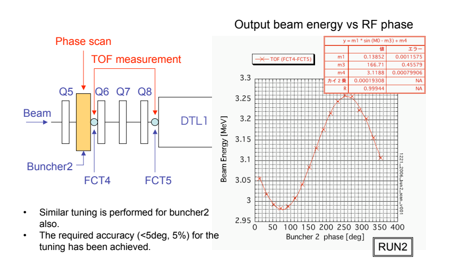
- Ion Source test [Apr.-Nov., 2006]
- RFQ, DTL, SDTL high-power conditioning [Sep.-Nov., 2006]
- **RFQ, MEBT tuning (5mA, 3MeV beam stop) [Dec., 2006]**
  - RFQ, LEBT tuning
  - Minimum beam orbit correction (transmission optimization)
  - Beam diagnostics test (CT , FCT , BPM, WS)
  - Emittance measurement (bend line)
  - Buncher phase/amplitude scan
  - Chopper tuning
  - Single shot operation
  - Beam diagnostics test with chopper or single shot operation
  - BPM beam-based alignment
- **RFQ, MEBT tuning (30mA, 3MeV beam stop) [Jan., 2007]**
  - The same items with the above 5mA tuning
- **DTL tuning (5mA, w/o chopping, 0 deg dump) [Feb., 2007]**
  - Minimum beam orbit correction (transmission optimization)
  - Phase/amplitude scan
- **SDTL tuning (5mA, w/o chopping, 0 deg dump) [Mar., 2007]**
  - Minimum beam orbit correction (transmission optimization)
  - Phase/amplitude scan
  - Transverse matching at DTL-SDTL transition and SDTL exit
  - BPM beam-based alignment
- **Overall tuning for straight section (5mA, 0 deg dump) [Apr., 2007]**
  - Debuncher phase/amplitude scan
  - Orbit correction
  - Chopper tuning
  - Single shot operation
- **High intensity operation (30mA, 0 deg dump) [May, 2007]**
  - Transverse matching
  - Orbit correction
  - Chopper tuning
- **1/3 arc tuning (5mA, w/o chopping, 30 deg dump) [Jun., 2007]**
  - Bend tuning
  - Achromaticity check
- **Ready for injection tuning [Sep., 2007]**
  - High duty(5.4kW) operation (using 30deg dump)
  - Bend tuning (remaining 4bends)
  - Achromaticity check for entire 1st arc
  - Transverse matching to 1st arc and collimator section
  - Orbit correction
  - 100 deg dump current monitor calibration
  - Collimator tuning
  - Injection line tuning(using RCS H0dump)

Reproduction of beam commissioning at Tsukuba

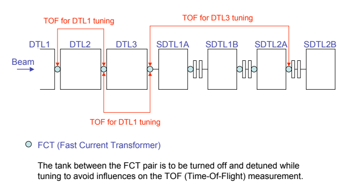
MEBT buncher1 phase scan



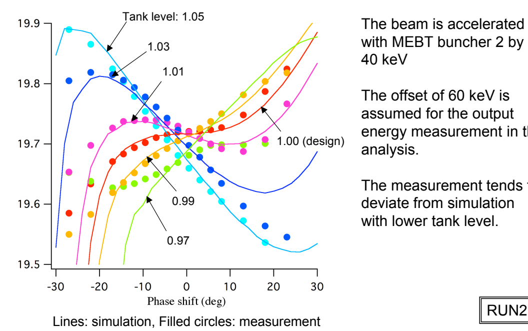
MEBT buncher2 phase scan



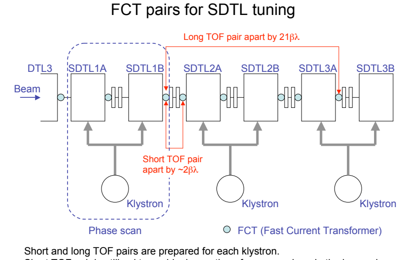
FCT pairs for DTL tuning



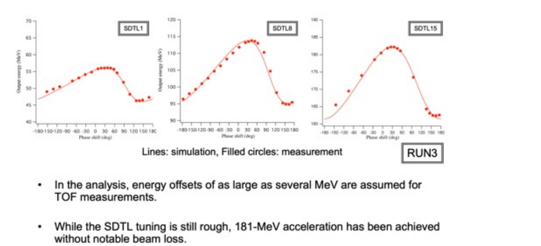
DTL1 phase scan



FCT pairs for SDTL tuning



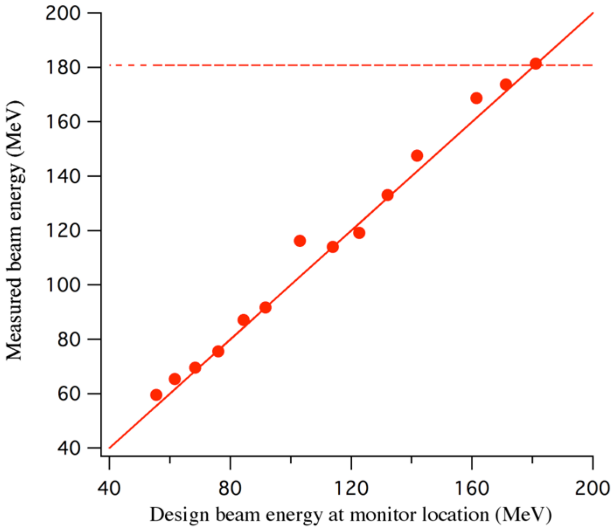
1st trial of SDTL phase scan (cont.)

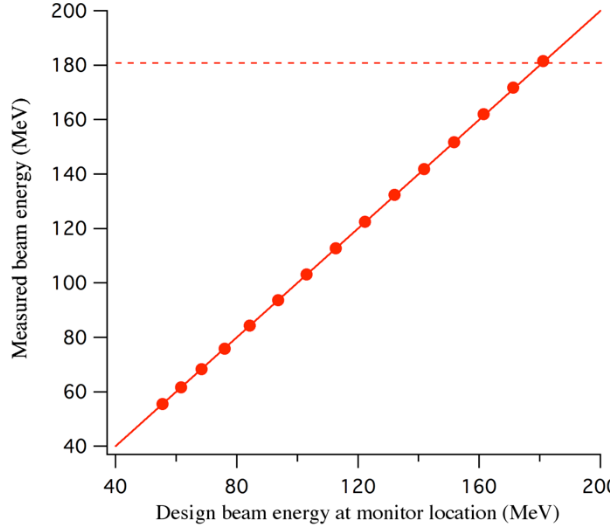


Li First Beam and Fine Tuning Results

Beam energy measurement vs. design in SDTL(1~15)

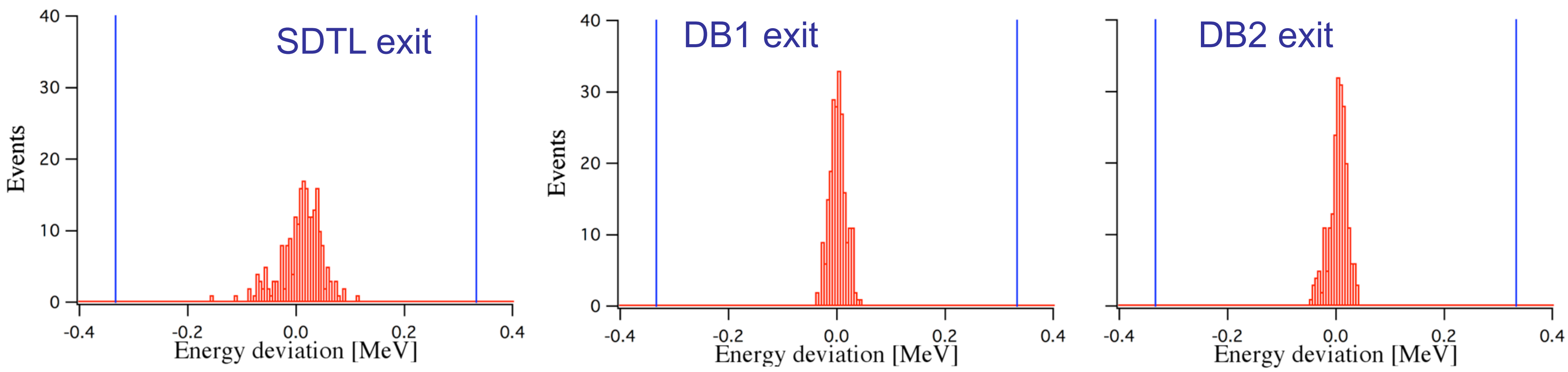
Jan. 2007 Run 3 → Sep. 2007 Run 9





Downstream residual radiation reduced to <1/3!

Energy jitter suppression measured in Run 9

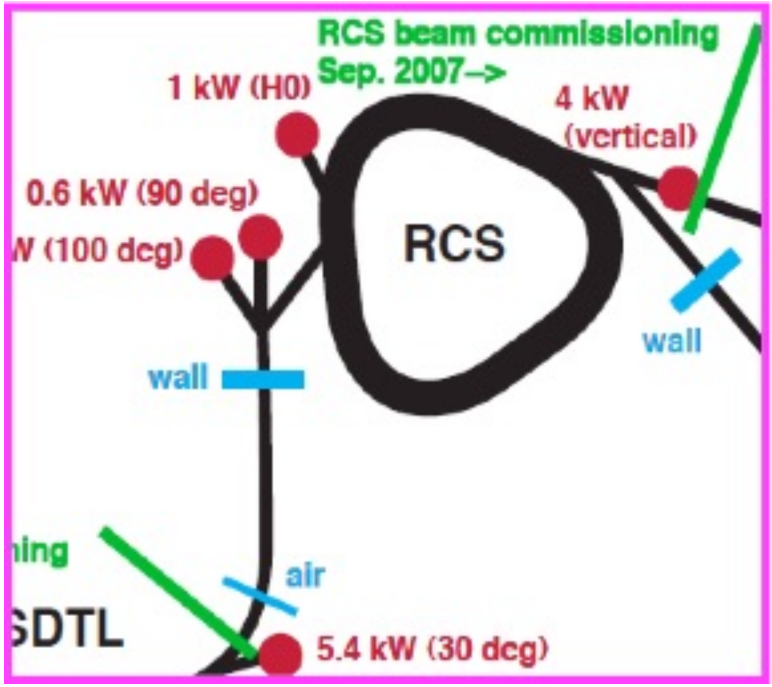


"Day-1" RCS Beam Commissioning

- Sep. 2007 ~ Apr. 2008

Linac beam condition

5 mA peak
50 μs (RCS 24 turns injection)
chopped beam
single shot or very low beam rep.,



RCS

Start with "center injection" (no transverse painting)
Machine @ 25 Hz

(1) 90 deg dump <---> RCS injection commissioning [H0 dump] ("H0-dump mode")
(3rd foil is used for charge exchange H--->H+)
(2) injection orbit study using DC kickers [3GeV dump] ("1/3 RCS mode")
(3) storage and RF capture study (30π mmmrad) ("DC mode")
tune, COD.... [3GeV dump]
(4) acceleration [3GeV dump] ("Acc. mode")
(5) extracted beam study (10π mmmrad) [3GeV dump]
---> $0.8 \cdot 10^{12}$ ppp (10kW, if 25Hz rep.)

Sep., 2007 (RUN#9)

Sun	Mon	Tue	Wed	Thu	Fri	Sat
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30						

Oct., 2007 (RUN#10)

Sun	Mon	Tue	Wed	Thu	Fri	Sat
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31			

Mov., 2007 (RUN#11)

Sun	Mon	Tue	Wed	Thu	Fri	Sat
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	

Dec., 2007 (RUN#12)

Sun	Mon	Tue	Wed	Thu	Fri	Sat
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30	31					

Jan., 2008 (RUN#13)

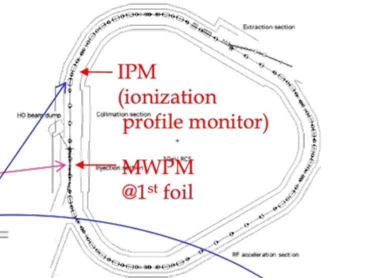
Sun	Mon	Tue	Wed	Thu	Fri	Sat
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31		

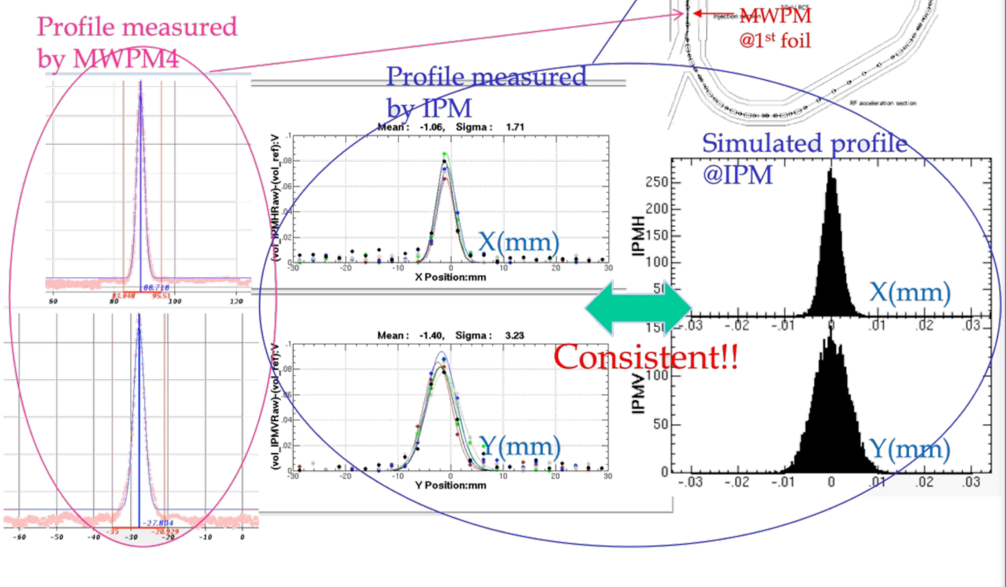
Feb., 2008 (RUN#14)

Sun	Mon	Tue	Wed	Thu	Fri	Sat
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	

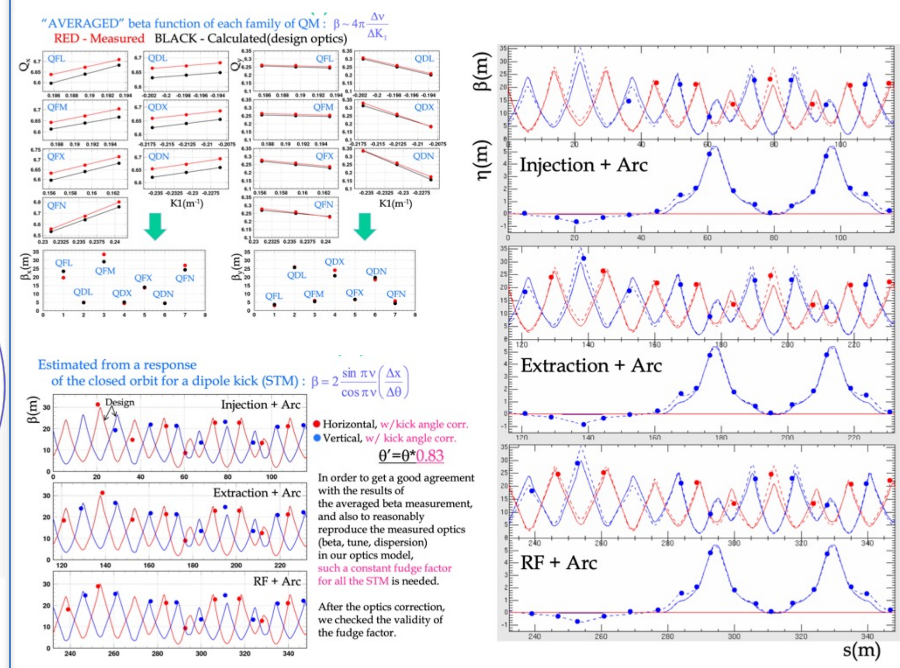
RCS First Beam Commssioning Results

Consistency of the measured profiles of the injection beam

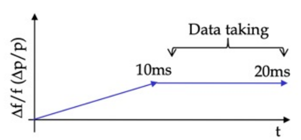




Measured β-functions → correction

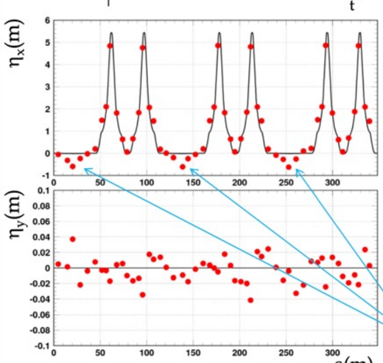


Measured dispersion → correction



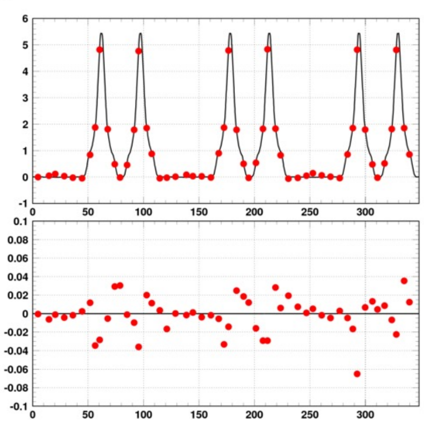
We measured dispersions by looking at a rf-frequency dependence of closed orbit.

In order to minimize the dipole oscillatio rf-frequency was slowly changed to 10 m and after 10ms it was fixed.

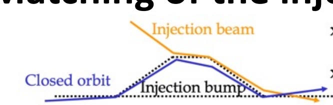


In the dispersion-free straight sectior a dispersion of ~-0.8 m was observed because of an imbalance of the focusing strengths among the quadrupole families.

to be corrected to ~0



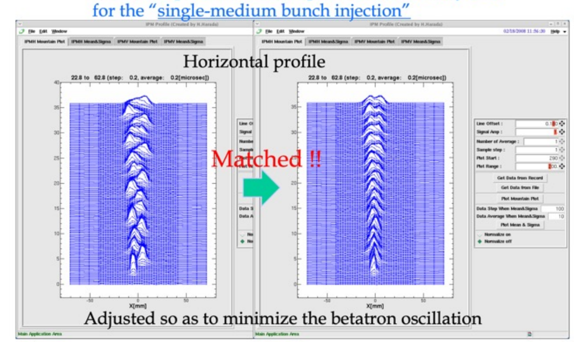
Matching of the injection & closed orbits



x at the 1st foil of the injection & closed orbits : adjusted by the shift bump magnet

x' at the 1st foil of the injection orbit : adjusted by the injection septum magnets.

Mountain plot of the beam profile measured by IPM for the "single-medium bunch injection"



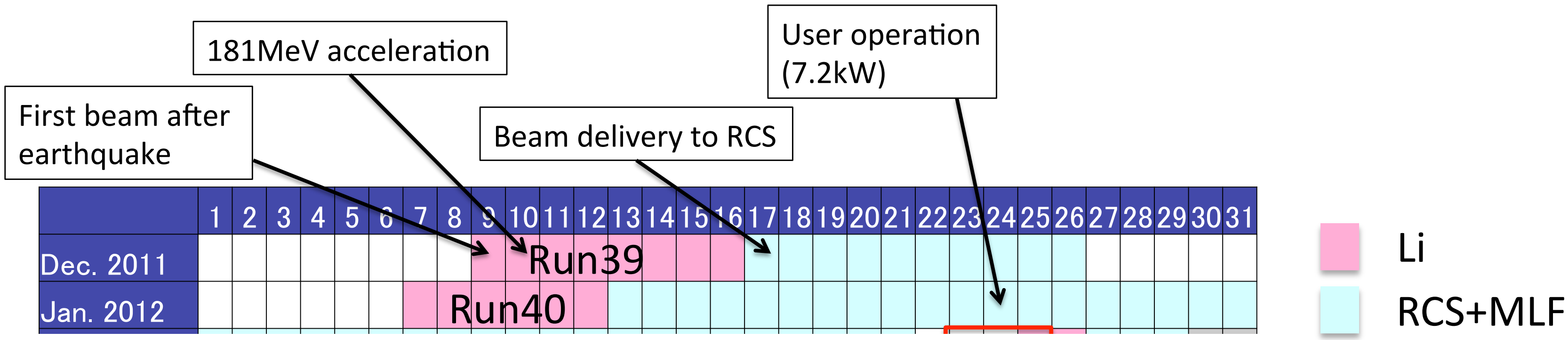
Linac Issues found in “Day 1”

- **Linac risks for RCS Day One: Spares. We have prepared spare klystrons. However, other spares have not been sufficiently stored or ordered for other components, although it is difficult to estimate the “sufficient” spares.**
- **Linac control should be made more intelligent before the RCS beam commissioning.**
- **Beyond RCS/MR Day One, we have a lot to do: the ion source development for a full power operation, stable and reliable operation, the sufficient beam quality both longitudinal and transverse for high-intensity RCS injection, and so forth.**

Sufficient monitoring and just-in-time anaysis

Long-term stability and reproducibility

Re-commissioning after the Earthquake 2011



Problems and solutions

Beam loss & increased residue radiation (~mSv/h on contact)

Misalignment → re-alignment and abnormal orbit setting before DTL1

FCT (Fast Current Transformer) and cable replaced → recalibration

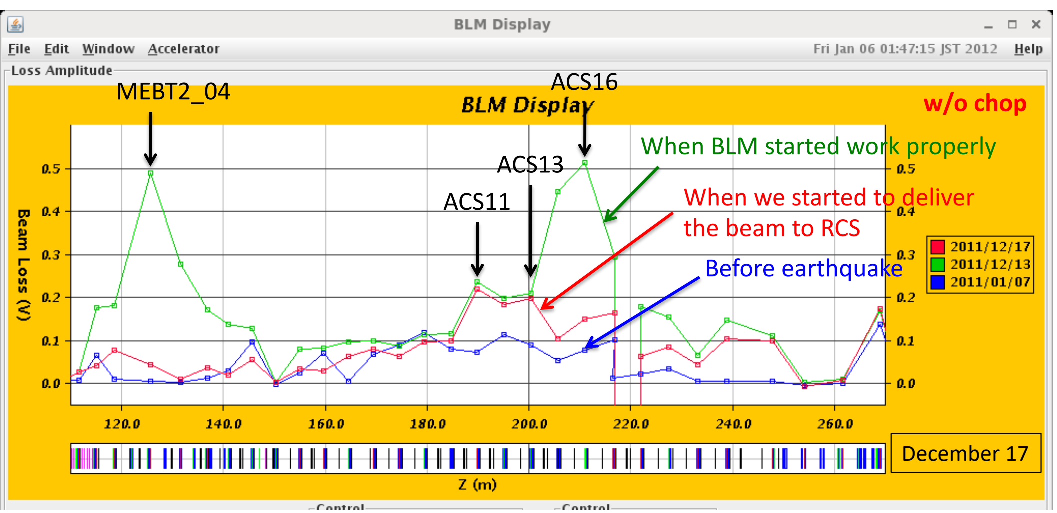
SDTL5 became unstable→ set to higher amplitude (109% ~ 116%) to avoid multipactor

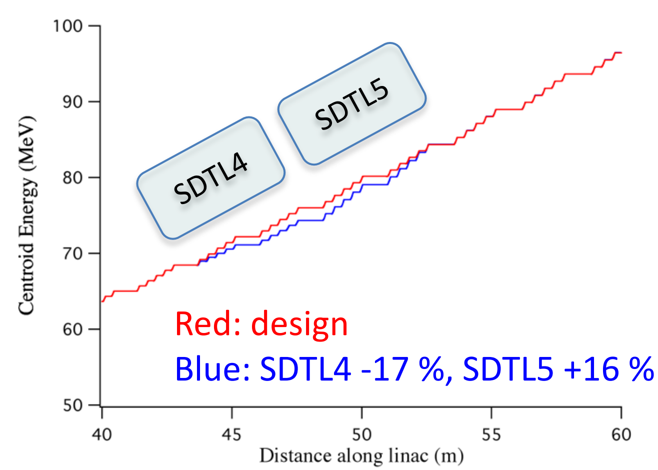
Beam Power was recovered and later ramped up

SDTL5 problem:

Method 1: Trial-and-error phase tuning

Method 2: Re-design longitudinal focusing





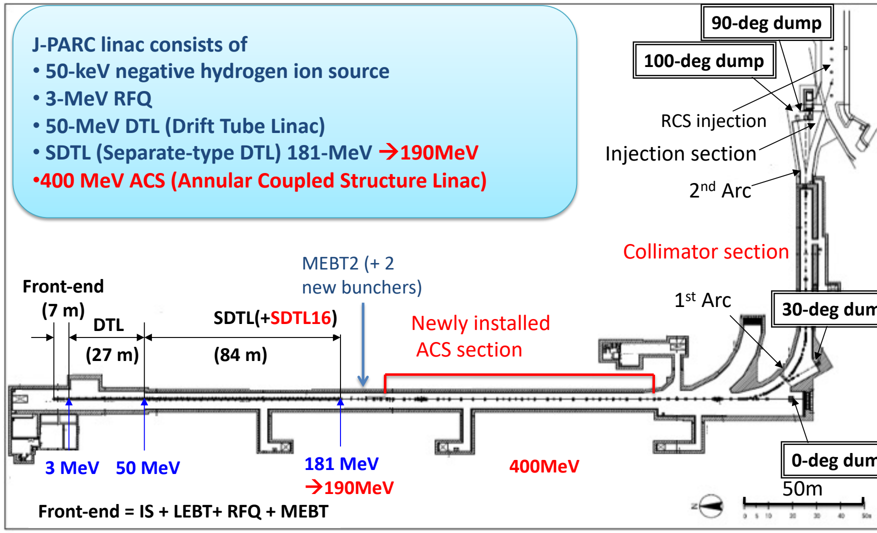
Energy Upgrade

Linac commissioning and beam studies for 400MeV upgrade: Scheme

181MeV → 400MeV

ACS Installation in summer shutdown of 2013

Commissioning in Dec. 16, 2013 ~ Jan. 30, 2014



Sources and pattern of beam loss were changed!

- Before energy upgrade

  Proton in the RFQ output: suppressed by MEBT1 chicane

  H^0 from gas stripping at SDTL and lost at downstream
- After energy upgrade

  Good vacuum at ACS: no worry about gas stripping at ACS

  →**intra-beam stripping (IBSt)** @ACS
- Other effects (very important)

  Shielding effects and saturation of BLM

  Dependency of residue dose on surround materials

  Energy effects for 181→400MeV, factor of 2~10?

  Improvement of alignment

Major Tasks/Steps

- Establishment of 181MeV and monitor check
- Establishment of 400MeV

  Phase scan of S16, ACS, bunchers and debunchers
- Fine tunings, matching

  Preparation for user operation at 15mA

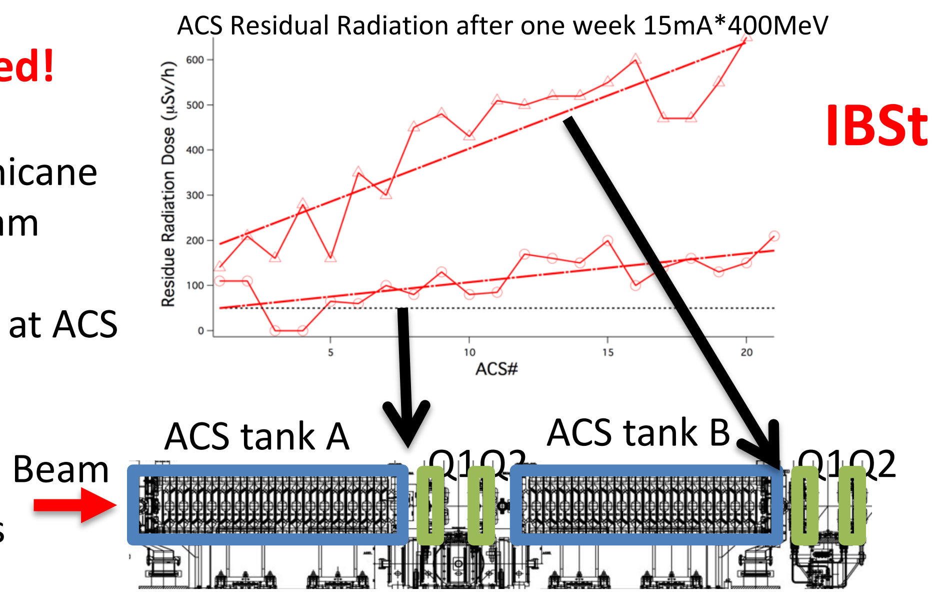
  High power study at 25mA
- Preparation for operation

  Check beam loss along linac and beam line

  Check orbit, center energy, energy jitter

  Check emittance for RCS injection

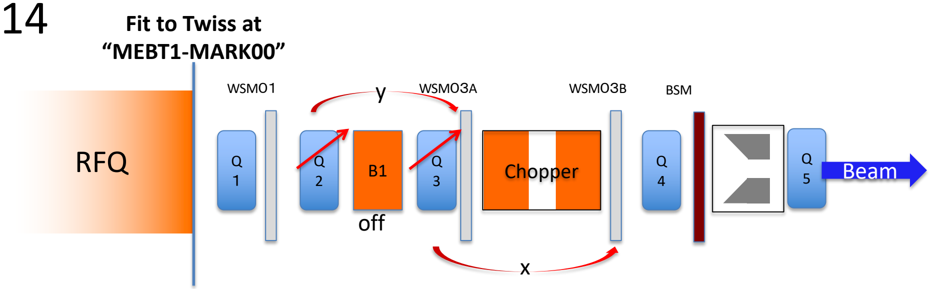
An abnormal loss pattern in all ACS cells



Current Upgrade

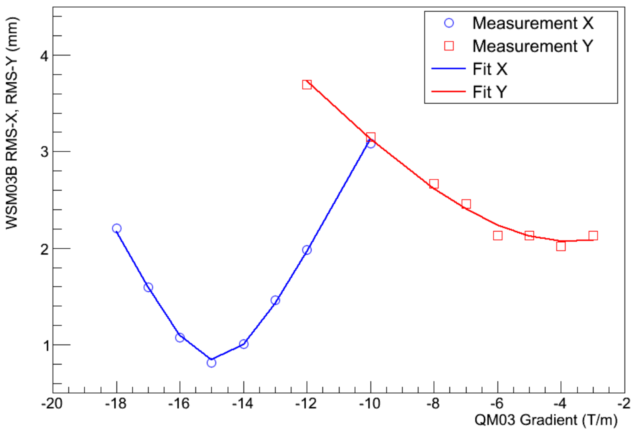
Li peak current
Operation/Study 15/30mA → 30/50mA: Oct. 2014

New type ion source: LaB6 → RF IS
New RFQ: RFQ1→RFQ3
New MEBT1 (including new RF chopper)

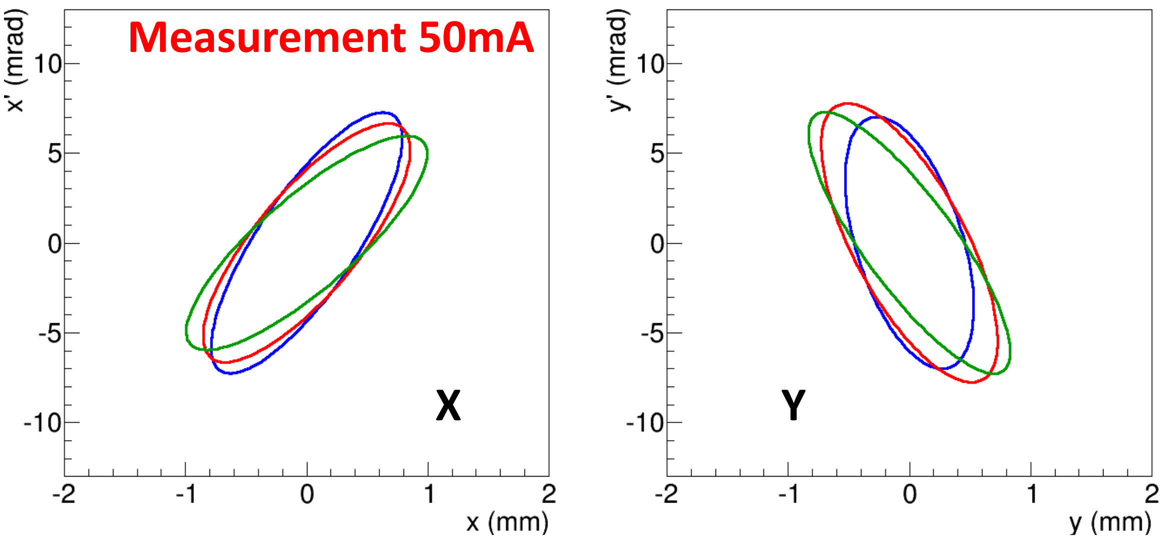


Q-scans were applied to verify the initial Twiss

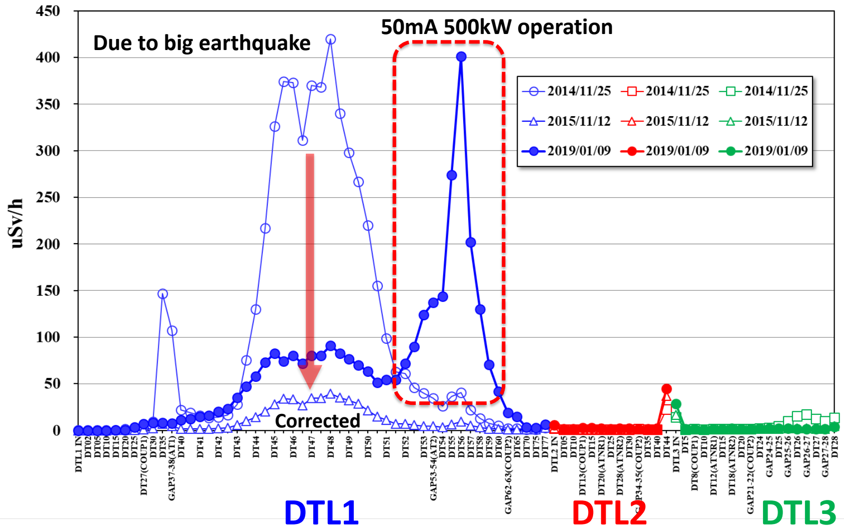
Q-scan 50mA,Q3 vs. WSM03B



RFQ3 Simulation (30~50 mA identical)
Measurement 30mA
Measurement 50mA



DTL1 Beam Loss Issue in 50 mA Operation



DTL1 Residue Radiation Increase after 50mA Operation

Residue **radiation increase** at DTL1 aperture

Around DT56,7 the aperture transition **Φ13→Φ18**

Hard to see from transmission (≲1%) or BLMP

Reason：

Increased envelope of 50mA compared with 40mA

EP lattice → increasing envelope along DTL

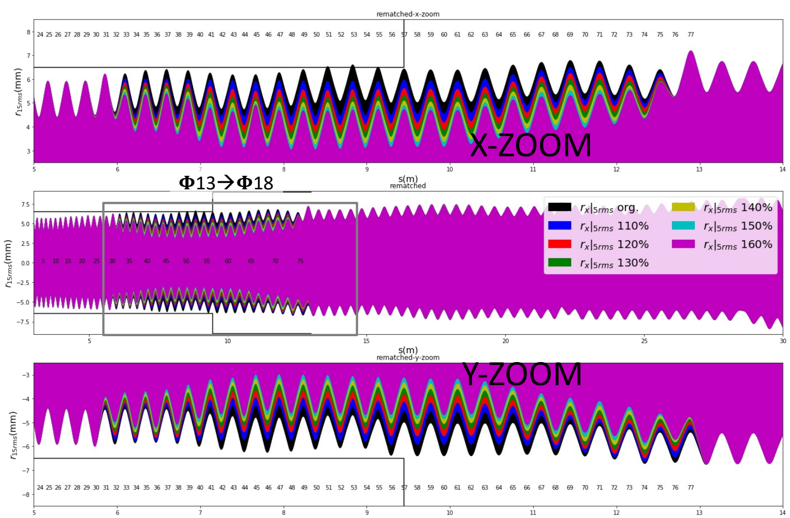
DTL1 deformation caused by the earthquake 2011.3

It was solved with abnormal orbit setting in MEBT1

But NOT fully cured

Lattice Redesign for DTL1 Beam Loss

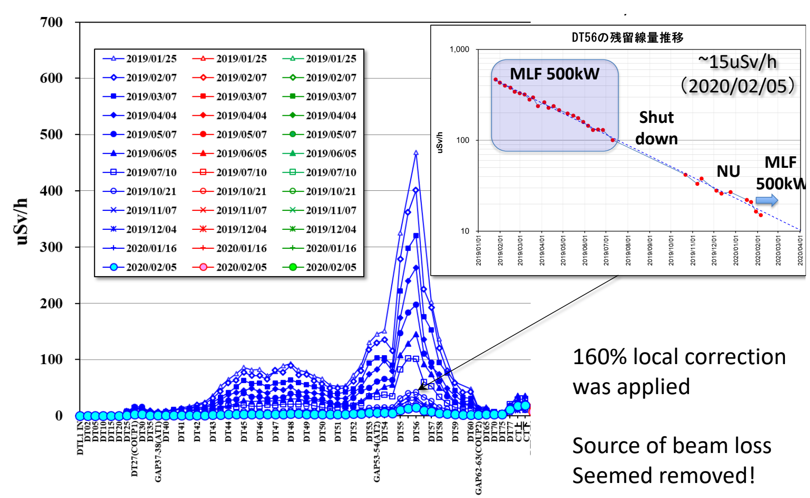
Ramping up nearby DTQ gradient → Local envelope correction



Solution:

Local envelope correction

Verified by scintillation monitor measurement



60mA Study

Motivation:
For future 1.5MW operation
Ensuring stable 50mA operation

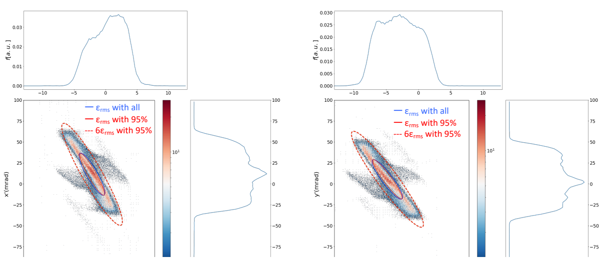
Difficulties:
Increased halo from IS

Countermeasures:
RFQ 106%
MEBT1 Scraper adjustment

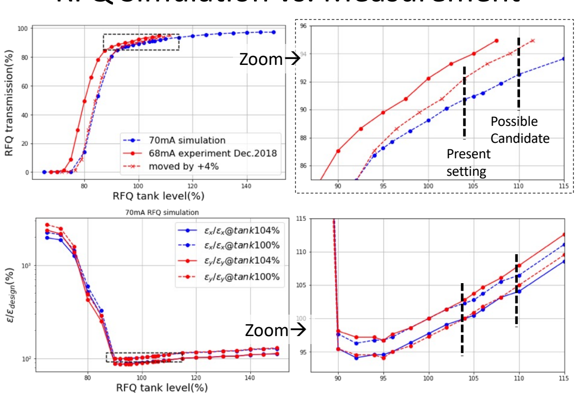
Milestones of J-PARC LINAC Intensity Upgrade

181/190MeV → 400MeV: Jan., 2014
Operation/Study 15/30mA → 30/50mA: Oct. 2014
→400MeV, 50mA: ready for 1MW from RCS (Demo:Dec.2014)
-------------------- Design accomplished --------------------
40mA in Operation: Jan. 2016
Next step: 50→60mA or/and 500→600us: aim at 1.2/1.5MW@MLF
1st Trial of 60mA: Jul.5 2017: 68mA(IS) 62mA(MEBT1)
2nd Trial of 60mA: Dec.25,26 2017 60mA(DTL no accel.), 57mA(Li)
3rd Trial of 60mA: Jul.3, 2018 62mA(Li)
50mA in Operation: Oct. 2018
50mA, 600us injection to RCS : Oct. 19, 2018 (~1.2MW@RCS)
60mA (4th Trial), 500us injection to RCS : Dec. 26, 2018 (~1.2MW@RCS)
60mA (5th Trial), 600us injection to RCS : Jul. , 2019 (~1.5MW@RCS)
60mA (6th Trial), 600us injection to RCS with Li fine tuning : Dec. , 2019 (~1.5MW@RCS) …

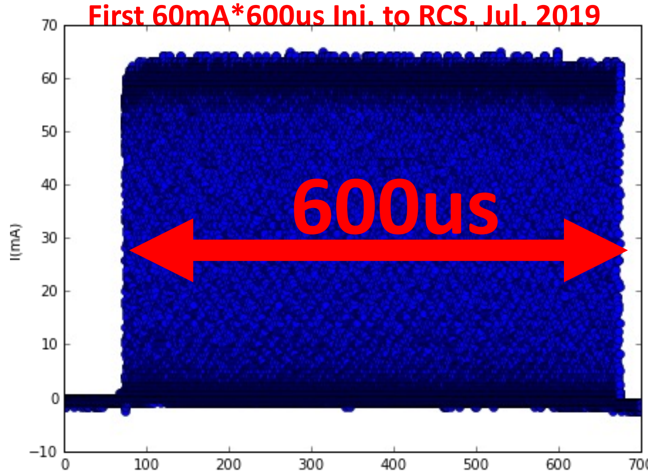
Measured Distribution from IS (66mA)



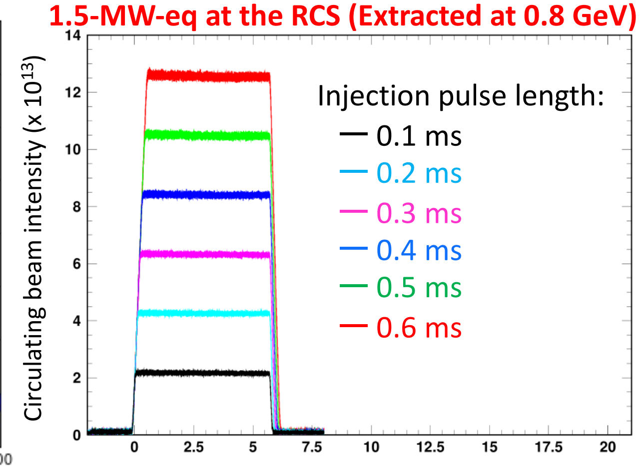
RFQ Simulation vs. Measurement



First 60mA*600us Inj. to RCS, Jul. 2019



1.5-MW-eq at the RCS (Extracted at 0.8 GeV)



Li Beam Loss Mitigation

- After upgrades, **intra-beam stripping (IBSt)** became the dominant source of beam loss
- IBSt rate can be only affected by lattice
- IBSt loss localization is sensitive to aperture
- Highest：200MeV~400MeV esp. ACS

Several hot spots (surface)**3.5mSv/h**@500kW(40mA) before 2018.7 @ACS-A entry

Source：IBSt

- Beam loss localization (ACS aperture rearrangement、2018.7)

Highest hot spots@ACS-A entry **3.5 →1.4 mSv/h**@500kW(~2019.3)

Highest hot spots@ACS QM ~**2.4mSv/h**@500kW(~2019.3)

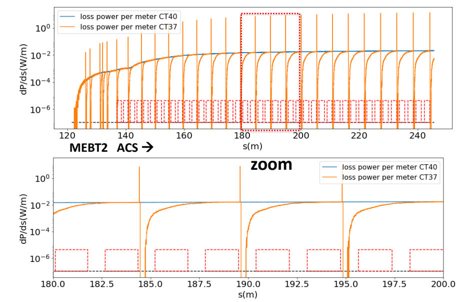
- Beam loss mitigation

IBSt mitigation lattice T_{ACS}=0.7(2019.4~)

→ Highest hot spots@ACS QM **~1.5mSv/h**@500kW

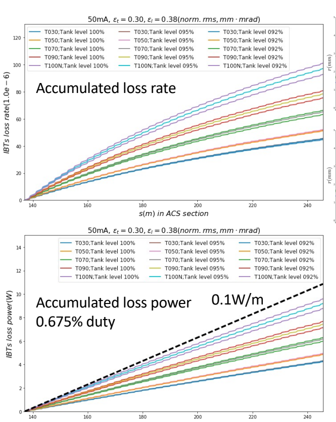
→ Highest hot spots@ACS QM **~2.0mSv/h**@800kW(present)

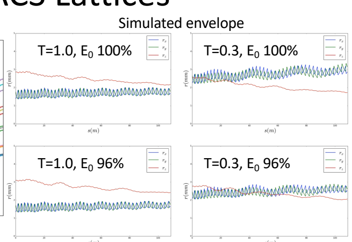
Simulated H0 Loss-localization



The abnormal pattern in all ACS were removed after aperture re-arrangement

IBSt vs. ACS Lattices

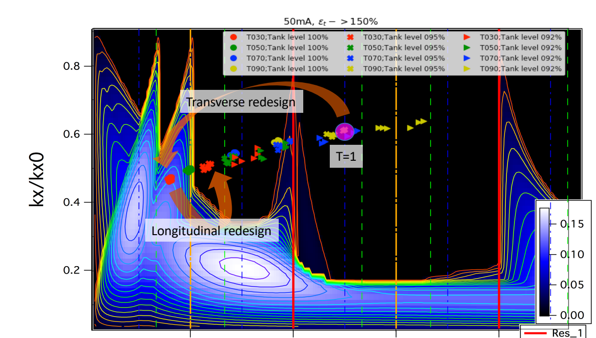




For 50mA operation with optimized emittance IBSt loss power is close to 0.1W/m at ACS

T=0.3 helps to reduced more than 50%

Stability?



"Temperature ratio"

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

Stronger quad setting *or weaker longitudinal focusing*

Conclusion and Outlook

- J-PARC started its first beam with 5mA from Nov. 2006,

now operates at 50mA, 800kW BoT with satisfying stability and reproducibility, and on the way toward 1MW and 1.5MW operation

- Continuous study activities for 50mA operation and 60mA study in J-PARC

Investigation of 3D initial beam property (frontend)

Beam loss mitigation (IBSt is the dominant)

Improvements for long-term stability (with AI etc., too)

All other operation-related issues

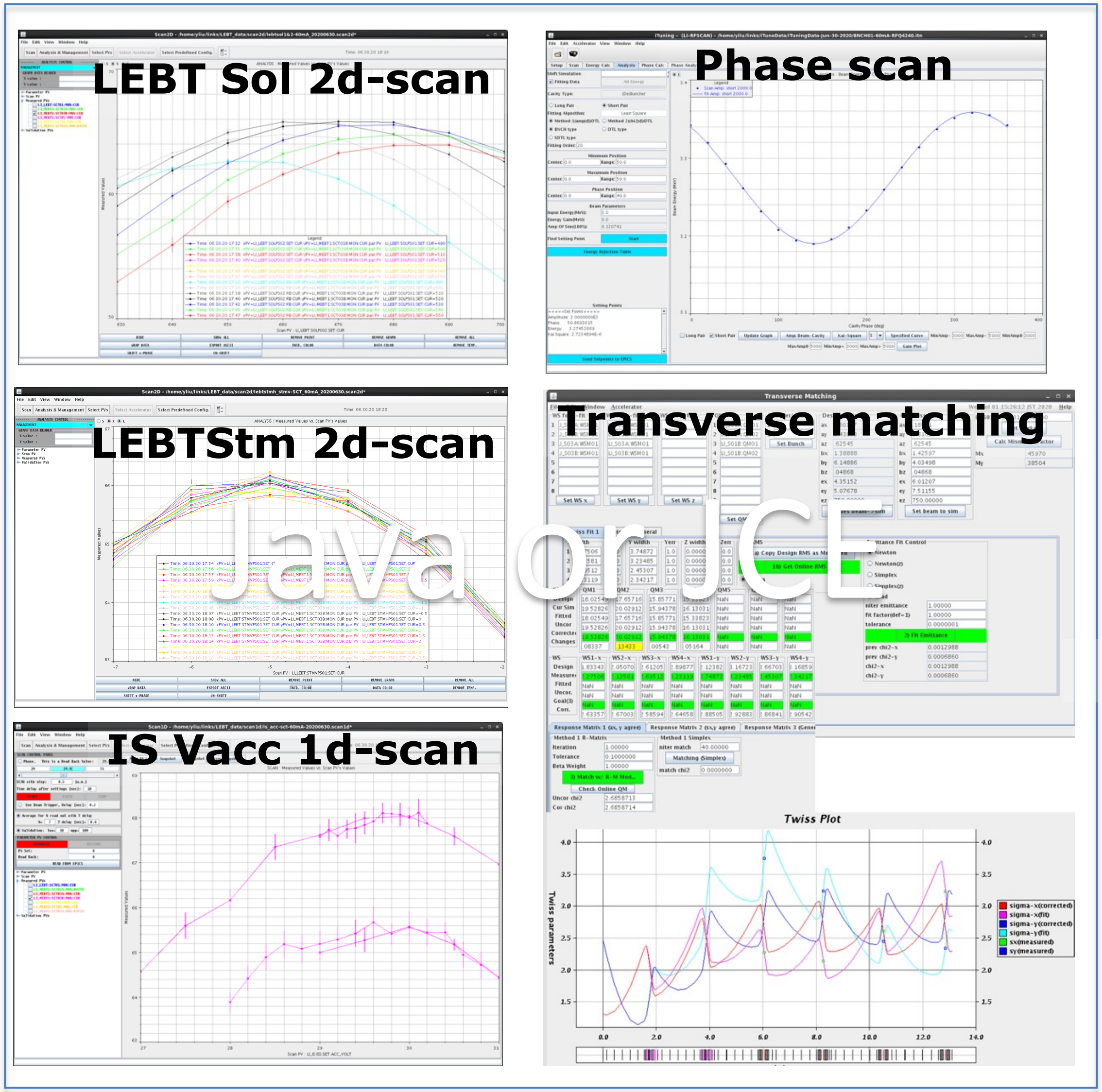
Beam halo control for 60 mA

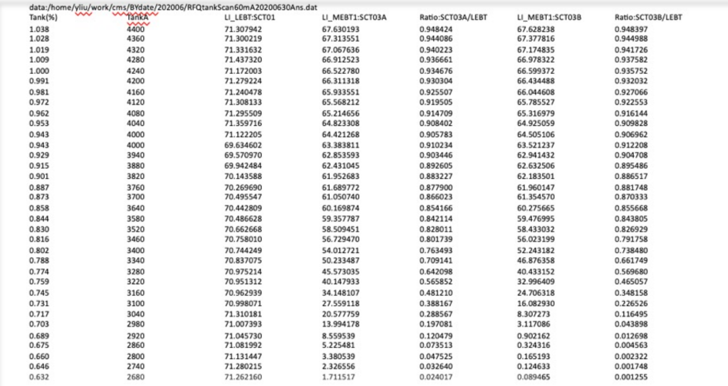
- We try to run J-PARC exactly as design (or re-design) avoiding arbitrary manual optimizations

Best wishes to ESS and ESS-J-PARC collaboration

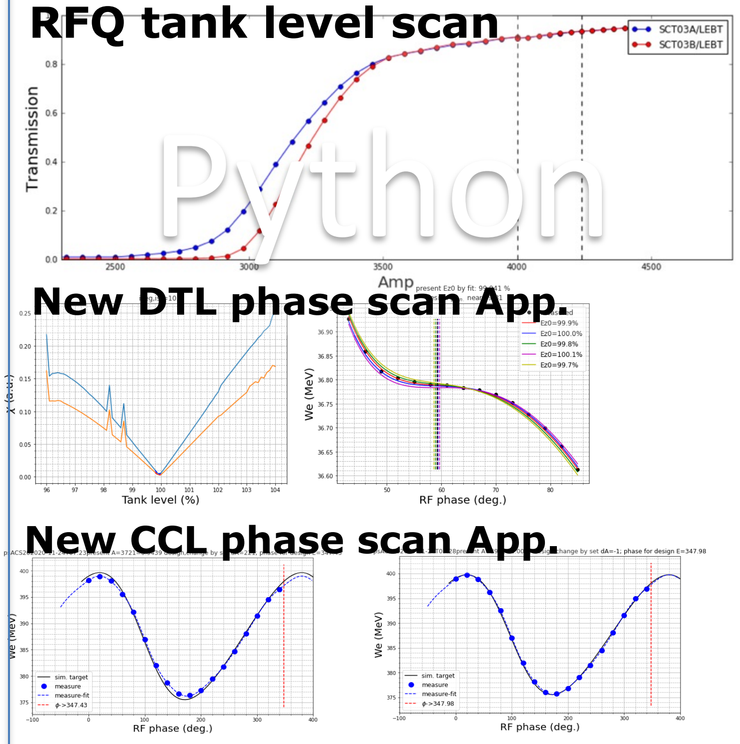
Backup

J-PARC Li Commissioning App




data:/home/yliu/work/cms/BYdate/202006/RFQtankScan60mA20200630Ans.dat

Tank(%)	TankA	LI_LEBT:SCT01	LI_MEBT1:SCT03A	Ratio:SCT03A/LEBT	LI_MEBT1:SCT03B	Ratio:SCT03B/LEBT
1.038	4400	71.307942	67.630193	0.948424	67.628238	0.948397
1.028	4360	71.300219	67.313551	0.944086	67.377816	0.944988
1.019	4320	71.331632	67.067636	0.940223	67.174835	0.941726
1.009	4280	71.437320	66.912523	0.936661	66.978322	0.937582
1.000	4240	71.172003	66.522780	0.934676	66.599372	0.935752
0.991	4200	71.279224	66.311318	0.930304	66.434488	0.932032
0.981	4160	71.240478	65.933551	0.925507	66.044608	0.927066
0.972	4120	71.308133	65.568212	0.919505	65.785527	0.922553
0.962	4080	71.295509	65.214656	0.914709	65.316979	0.916144
0.953	4040	71.359716	64.823308	0.908402	64.925059	0.909828
0.943	4000	71.122205	64.421268	0.905783	64.505106	0.906962
0.943	4000	69.634602	63.383811	0.910234	63.521237	0.912208
0.929	3940	69.570970	62.853593	0.903446	62.941432	0.904708
0.915	3880	69.942484	62.431045	0.892605	62.632506	0.895486
0.901	3820	70.143588	61.952683	0.883227	62.183501	0.886517
0.887	3760	70.269690	61.689772	0.877900	61.960147	0.881748
0.873	3700	70.495547	61.050740	0.866023	61.354570	0.870333
0.858	3640	70.442809	60.169874	0.854166	60.275665	0.855668
0.844	3580	70.486628	59.357787	0.842114	59.476995	0.843805
0.830	3520	70.662668	58.509451	0.828011	58.433032	0.826929
0.816	3460	70.758010	56.729470	0.801739	56.023199	0.791758
0.802	3400	70.744249	54.012721	0.763493	52.243182	0.738480
0.788	3340	70.837075	50.233487	0.709141	46.876358	0.661749
0.774	3280	70.975214	45.573035	0.642098	40.433152	0.569680
0.759	3220	70.951312	40.147933	0.565852	32.996409	0.465057
0.745	3160	70.962939	34.148107	0.481210	24.706318	0.348158
0.731	3100	70.998071	27.559118	0.388167	16.082930	0.226526
0.717	3040	71.310181	20.577759	0.288567	8.307273	0.116495
0.703	2980	71.007393	13.994178	0.197081	3.117086	0.043898
0.689	2920	71.045730	8.559539	0.120479	0.902162	0.012698
0.675	2860	71.081992	5.225481	0.073513	0.324316	0.004563
0.660	2800	71.131447	3.380539	0.047525	0.165193	0.002322
0.646	2740	71.280215	2.326556	0.032640	0.124633	0.001748
0.632	2680	71.262160	1.711517	0.024017	0.089465	0.001255



Most of original App. are of Java or Java based environment
Still work today
New features → Python