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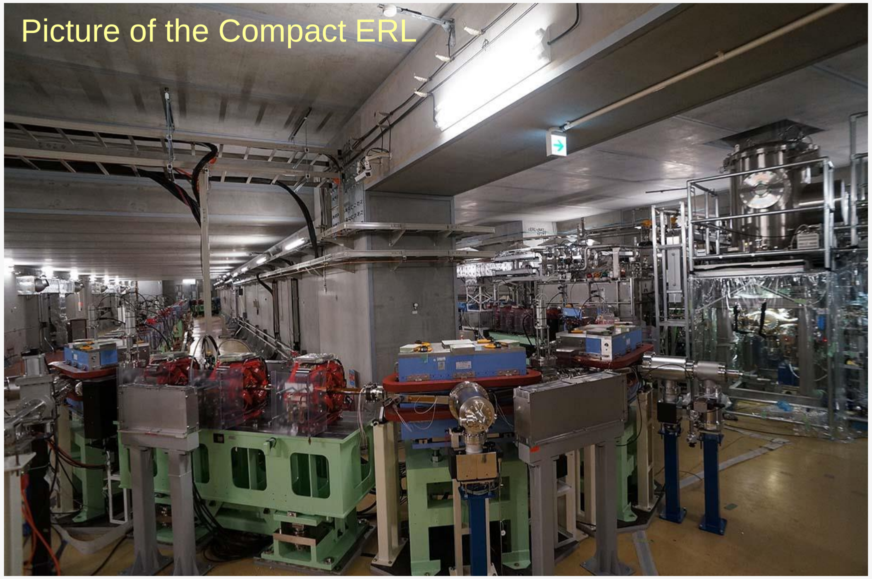
Successful Result of the Commissioning on cERL in KEK

Shogo Sakanaka (KEK), on behalf of the cERL team



v2

ERL2015, Stony Brook, NY, USA, June 7-12, 2015.

cERL Team

High Energy Accelerator Research Organization (KEK)
M. Adachi, S. Adachi, T. Akagi, M. Akemoto, D. Arakawa, S. Araki, S. Asaoka, K. Enami,K. Endo, S. Fukuda, T. Furuya, K. Haga, K. Hara, K. Harada, T. Honda, Y. Honda, H. Honma, T. Honma, K. Hosoyama, K. Hozumi, A. Ishii, X. Jin, E. Kako, Y. Kamiya, H. Katagiri, R. Kato, H. Kawata, Y. Kobayashi, Y. Kojima, Y. Kondou, T. Konomi, A. Kosuge, T. Kubo, T. Kume, T. Matsumoto, H. Matsumura, H. Matsushita, S. Michizono, T. Miura,T. Miyajima, H. Miyauchi, S. Nagahashi, H. Nakai, H. Nakajima, N. Nakamura, K. Nakanishi,K. Nakao, K. Nigorikawa, T. Nogami, S. Noguchi [on leave], S. Nozawa, T. Obina, T. Ozaki, F. Qiu,H. Sagehashi, H. Sakai, S. Sakanaka,S. Sasaki, K. Satoh, M. Satoh, Y. Seimiya, T. Shidara, M. Shimada, K. Shinoe, T. Shioya,T. Shishido,M. Tadano, T. Tahara, T. Takahashi, R. Takai, H. Takaki, O. Tanaka, T. Takenaka,Y. Tanimoto, N. Terunuma, M. Tobiyama, K. Tsuchiya,T. Uchiyama, A. Ueda, K. Umemori, J. Urakawa,K. Watanabe, M. Yamamoto, N. Yamamoto, Y. Yamamoto, Y. Yano, M. Yoshida

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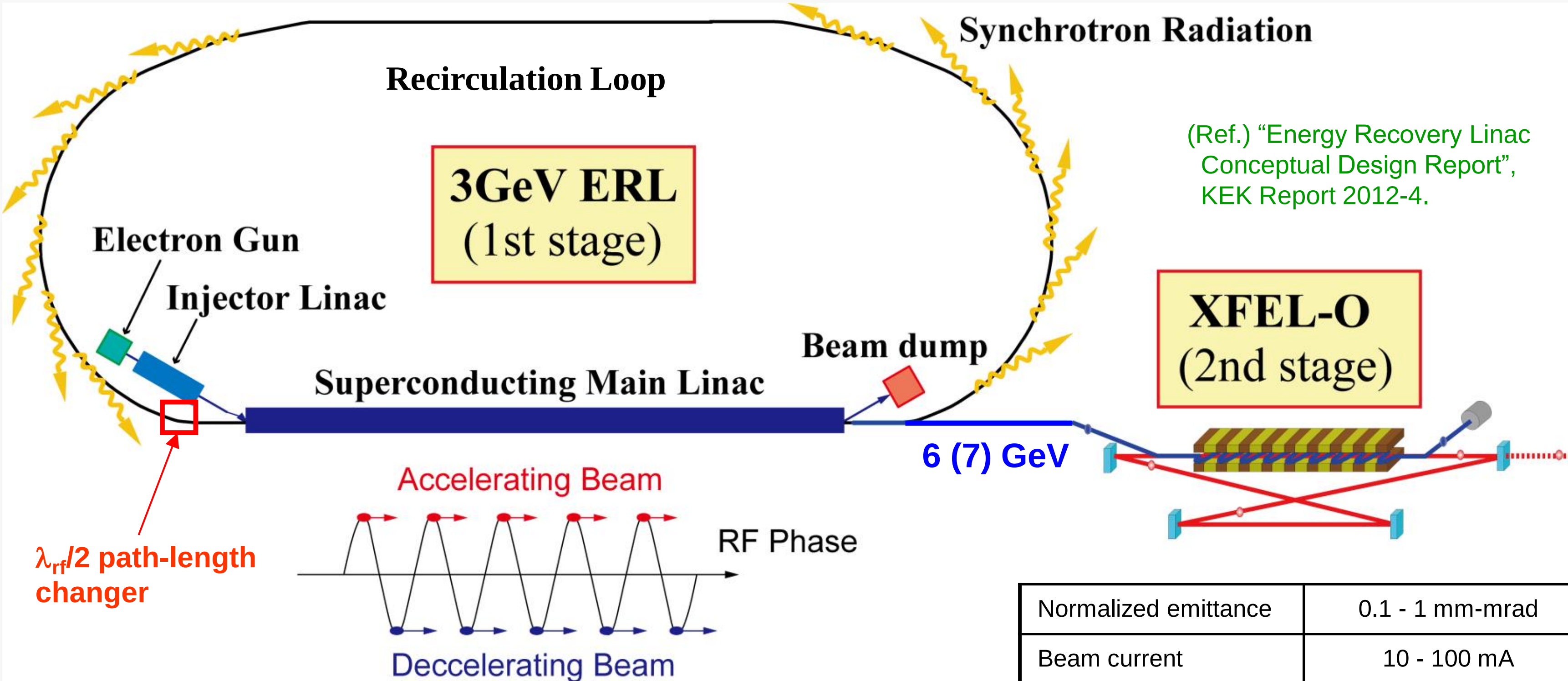
Hiroshima University
M. Kuriki

The Graduate University for Advanced Studies (Sokendai)
E. Cenni [on leave]

1. Introduction

Future Plan: ERL Light Source Project at KEK



(Ref.) "Energy Recovery Linac Conceptual Design Report", KEK Report 2012-4.

Normalized emittance	0.1 - 1 mm-mrad
Beam current	10 - 100 mA
Bunch charge	7.7 - 77 pC
RF frequency	1.3 GHz

3 GeV ERL

- Diffraction-limited X-ray source
- Ultra-short-pulse light source
- Driver for XFEL-O (2nd stage)

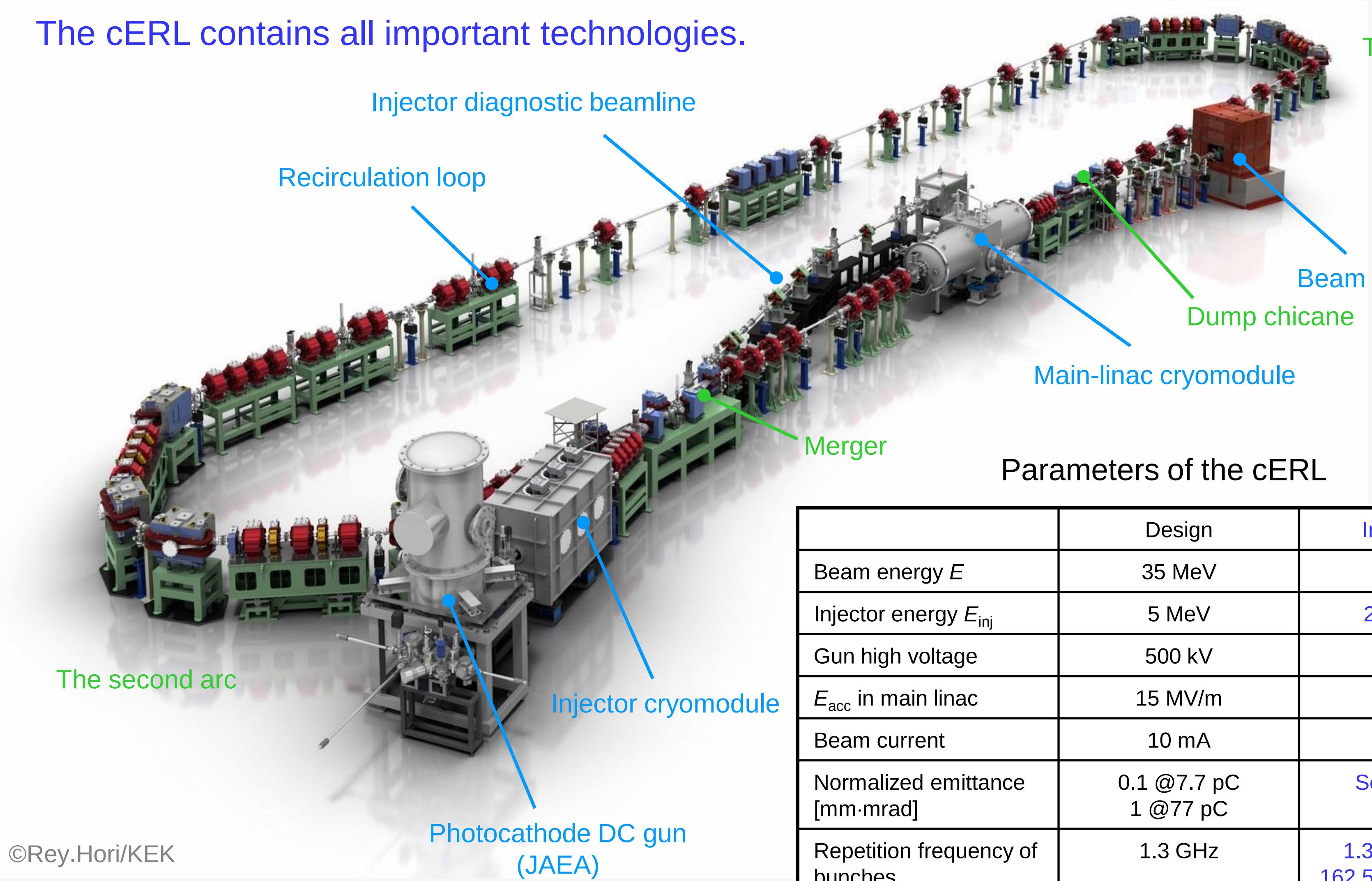
demonstrate ←

The Compact ERL

- Injector (low ε, high I_0)
- Main linac (CW, ~15 MV/m)
- Beam dynamics
- Beam losses

The Compact ERL (cERL)

The cERL contains all important technologies.



Circumference: ~ 90 m

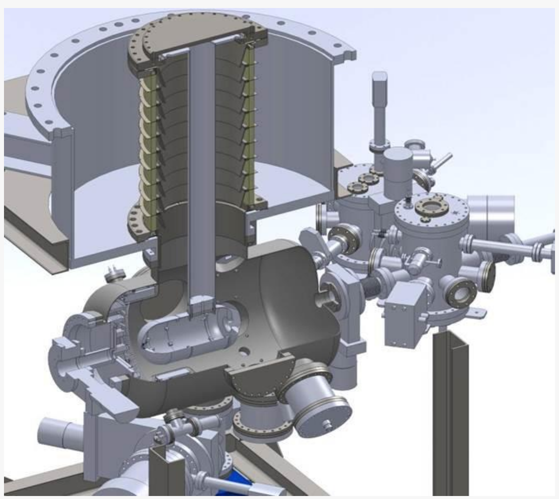
Parameters of the cERL

	Design	In operation
Beam energy E	35 MeV	20 MeV
Injector energy E_{inj}	5 MeV	2.9 - 6 MeV
Gun high voltage	500 kV	390 kV
E_{acc} in main linac	15 MV/m	8.2 MV/m
Beam current	10 mA	80 μA
Normalized emittance [mm·mrad]	0.1 @7.7 pC 1 @77 pC	See, page 21
Repetition frequency of bunches	1.3 GHz	1.3 GHz (usual) 162.5 MHz (for LCS)
RMS bunch length	1-3 ps (usual) ~ 100 fs (compress.)	1-3 ps (usual)
Max. heat load at 2K	80 W	80 - 100 W

Critical Components

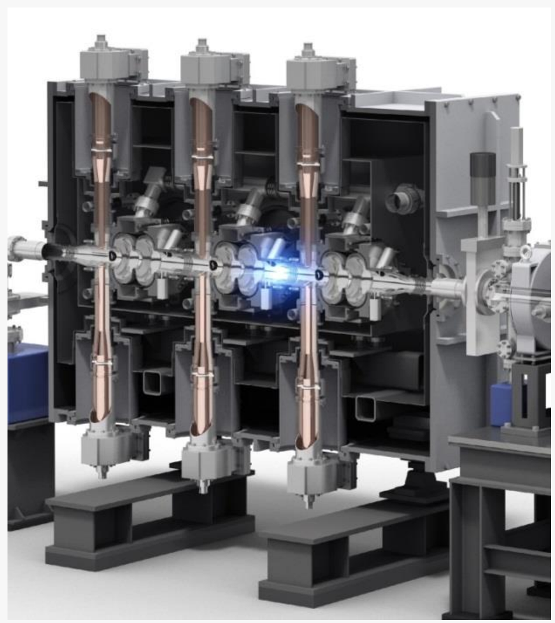
Photocathode DC gun

- GaAs photocathode,
- Drive laser: 532 nm
- Conditioned up to 550 kV (at JAEA)
- In stable operation at 390 kV (at cERL)



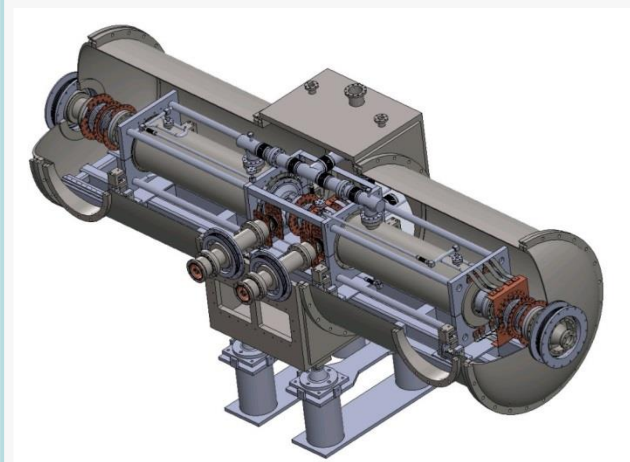
Injector Cryomodule

- Three 2-cell cavities
- Conditioned up to E_{acc}=8 MV/m (CW); limited by heating-up of HOM couplers
- In stable operation at E_{acc}=3.2 - 7 MV/m at cERL



Main-Linac Cryomodule

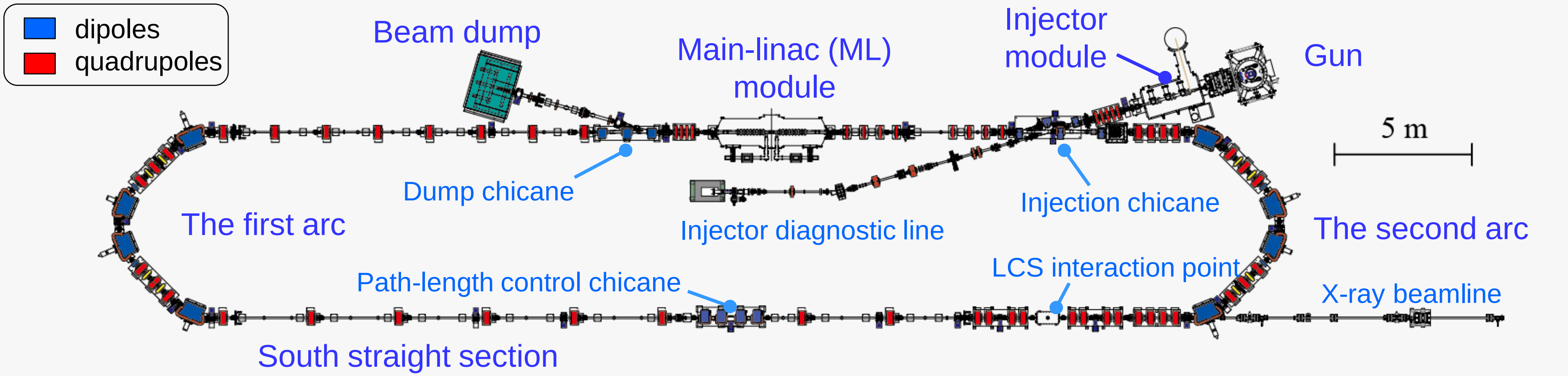
- Two 9-cell cavities
- Demonstrated E_{acc}=13.5 MV/m (CW)
- In stable operation at E_{acc}=8.2 MV/m at cERL; limited by field-emission

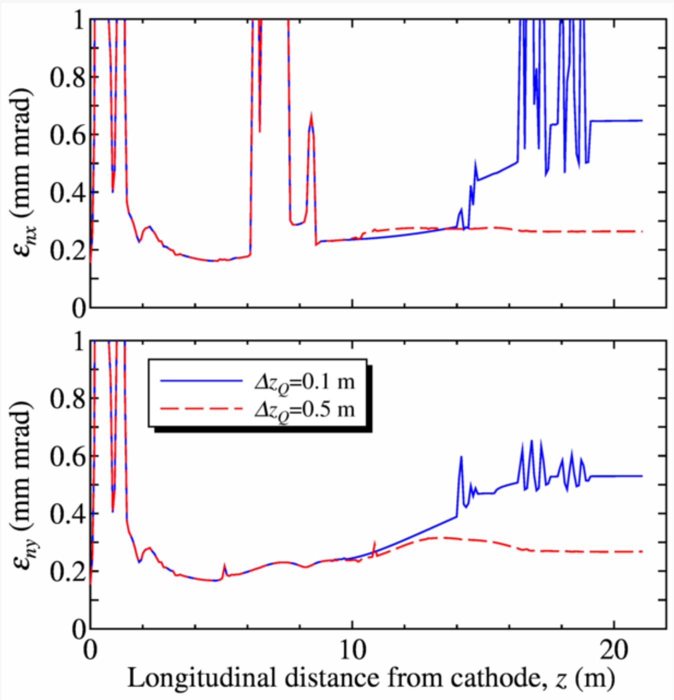


Nishimori's talk (Tuesday)

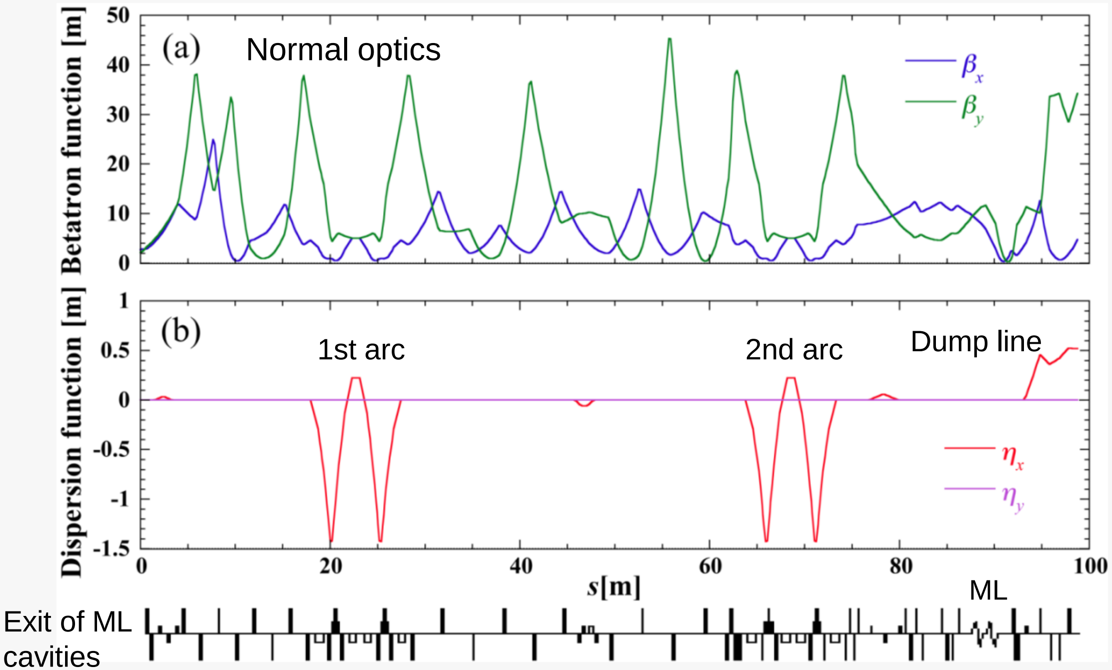
Sakai's talk (Wednesday)

Beam Optics of cERL





Injector (gun → exit of main linac).



Recirculation loop (exit of main linac → beam dump).

Construction and Commissioning of cERL

2008	2009	2010	2011	2012	2013	2014	2015

Refurbishment of building

Clearing radioactive materials

Construction of radiation shielding

Construction of injector

ERL2013

Commissioning of injector

Construction of recirculation loop

Commissioning of cERL (with loop)

Construction of LCS system

Commissioning of LCS system

Construction

Commissioning/Operation

ERL2015

2. Construction of Recirculation Loop

Construction of Recirculation Loop (Jul. - Nov. 2013)

Determine beam energy (E = 20 MeV, p_{loop}/p_{inj} = 6-7) → determine the coordinates of all magnets

↓

Survey and marking beamline

↓

Installation of girders and magnets

↓

Alignment of magnets

↓

Installation of vacuum chambers. Wiring

↓

Survey of magnets

↓

Cool-down and conditioning of SC cavities

↓

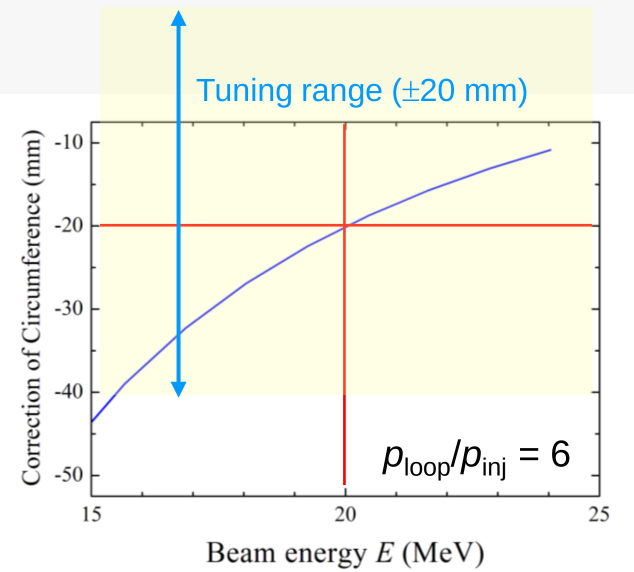
Commissioning

Precise Prediction of Path Length of the Loop

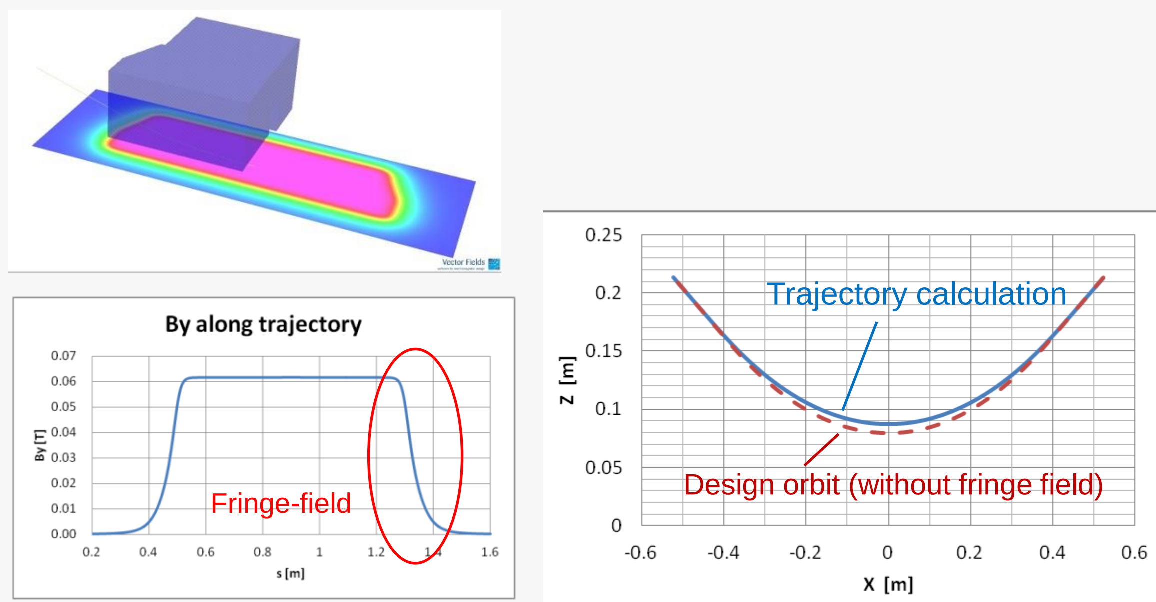
- Precise prediction and installation of path length is essential for energy recovery:

$$\omega C/(\beta c) = (2n+1)\pi \quad (C\text{: circumference})$$

- Optimum path length depends on:
  1) speed (βc) of particles
  2) heights in injection and dump chicanes (depends on p_{loop}/p_{inj})
- Before the construction, we chose the nominal energy of E=20 MeV and p_{loop}/p_{inj} = 6-7
- Trajectory length in each bending magnet was precisely predicted based on 3D field analysis

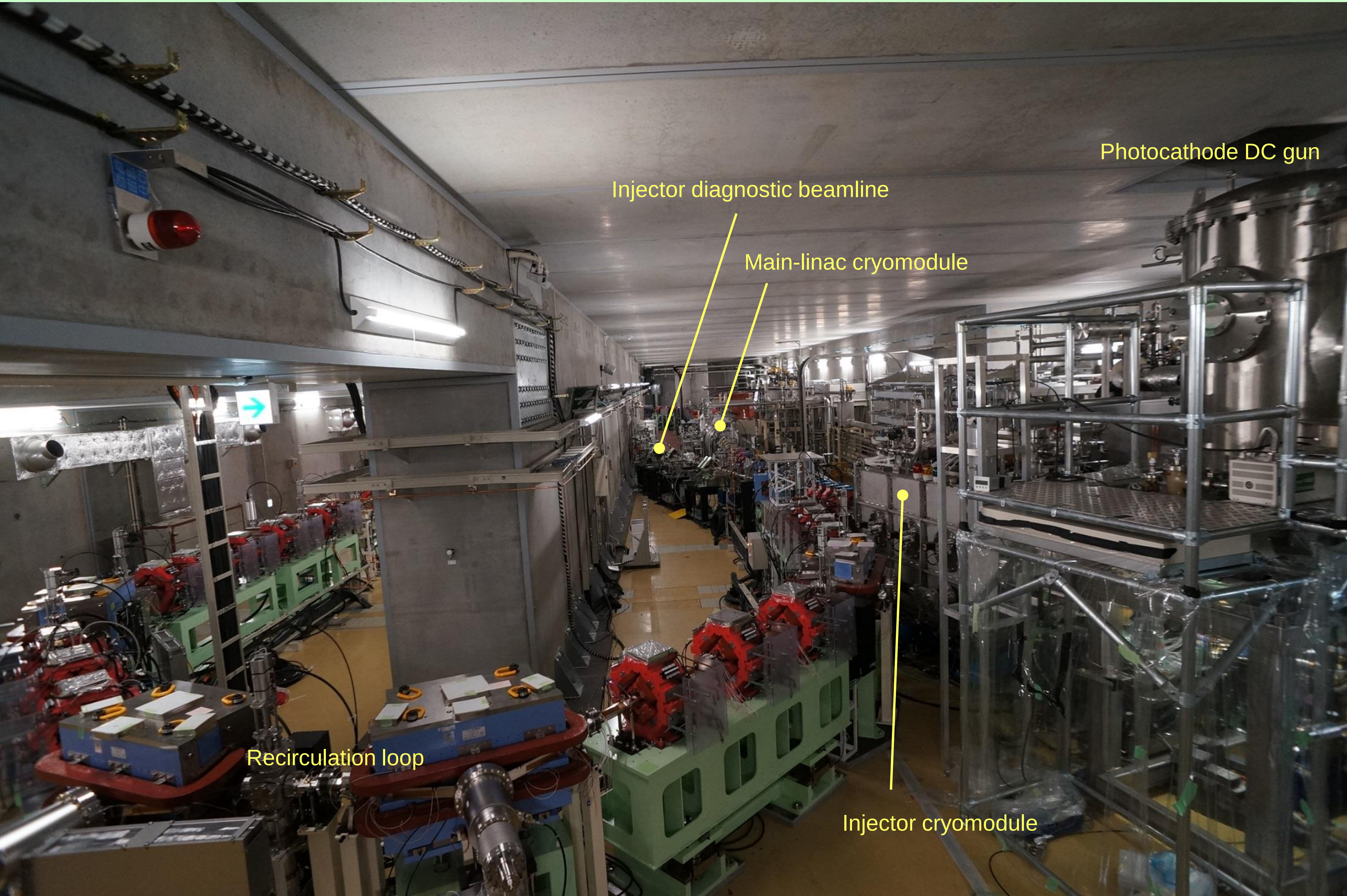


Dependence of the optimum circumference on the beam energy



Precise prediction of trajectory-length in the bending magnet, which is based on OPERA-3D calculation.

Picture of the cERL

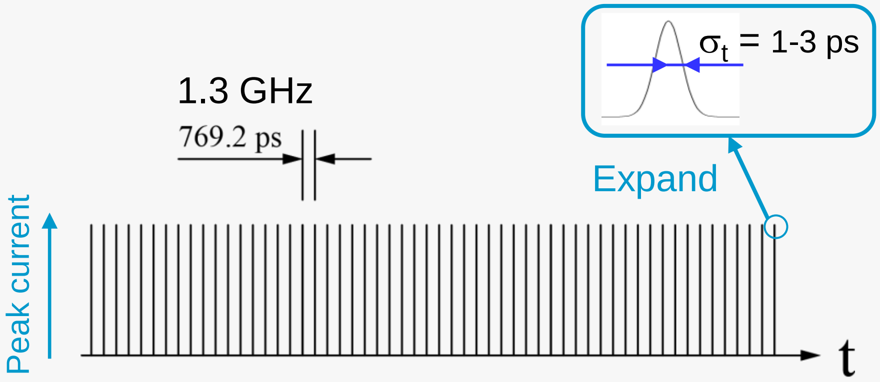


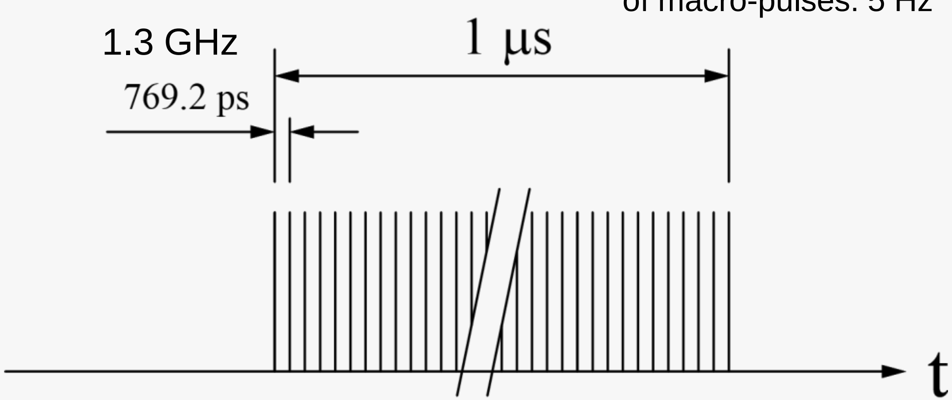
3. Commissioning of cERL

Time Structure of Beams

CW beam
(for high currents)

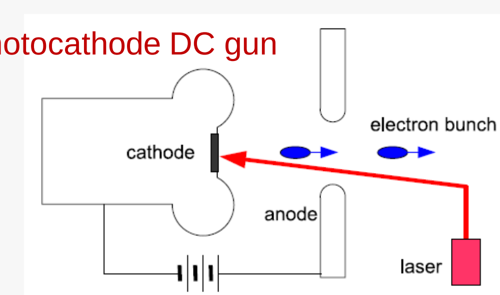
Burst beam
(for beam tuning)





Bunch charge: 7.7 pC → average current: 10 mA

Initial conditions are determined by the gun-drive laser.



The First Transportation of Beams to the Dump (Feb. 6, 2014)

Beam energy (*E*)
- Injector: 2.9 MeV
- Recirculation loop: 19.9 MeV

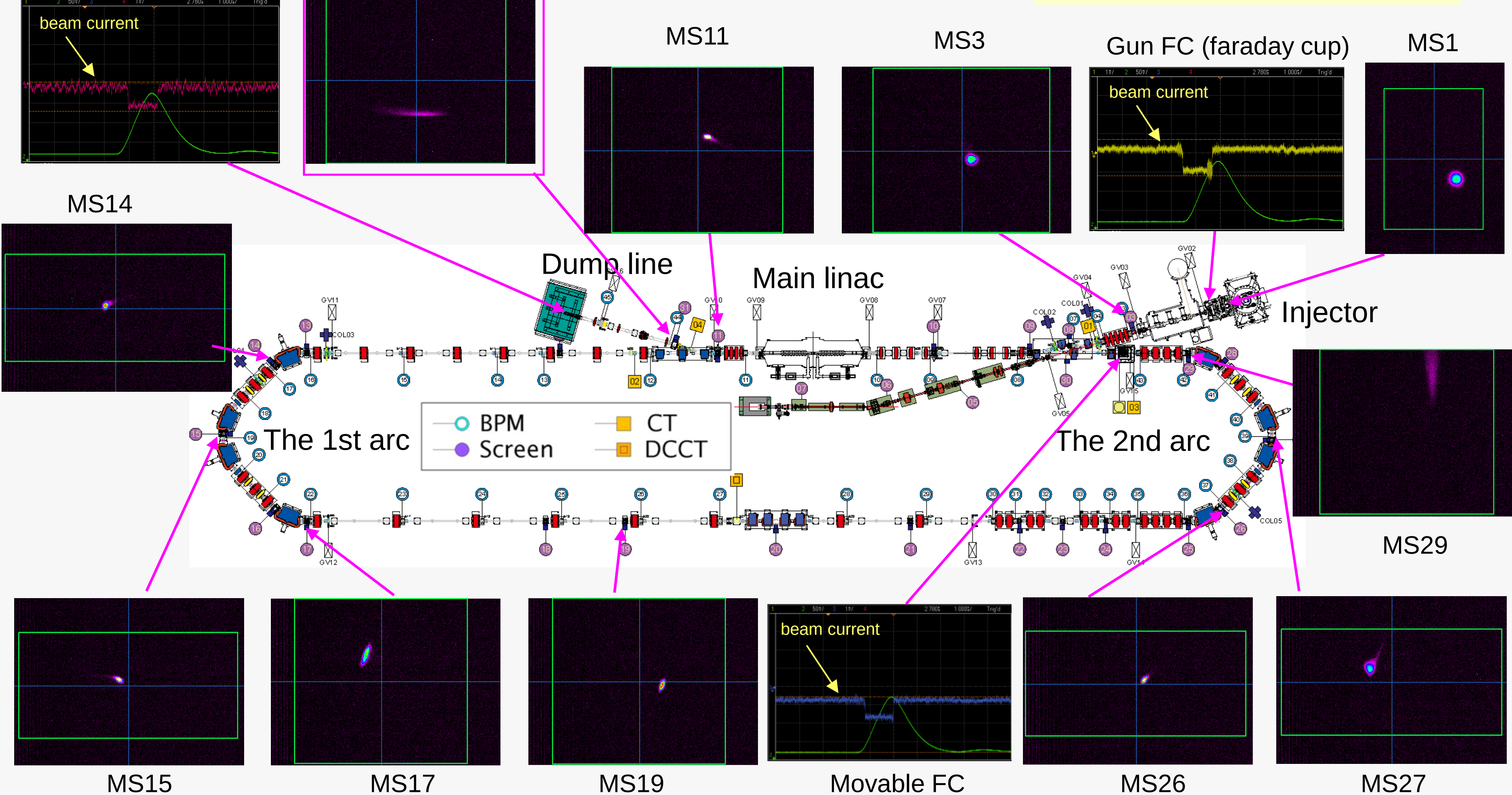
Parameters
- Gun voltage: 390 kV   Buncher: OFF
- Injector cavities: E_{acc} = (3.3, 3.3, 3.1) MV/m
- Main-Linac cavities: V_c = (8.57, 8.57) MV

Beam pulses (macropulse)
- peak current: ~24 μA
- macropulse width: 1.2 μs
- repetition of bunches: 1.3 GHz
- repetition frequency: 5 Hz
- average beam current: ~ 140 pA

Dump FC

MS31 (dump line)

Beam profiles on screen monitors.



Procedure of Start-Up Tuning

(3) Main linac

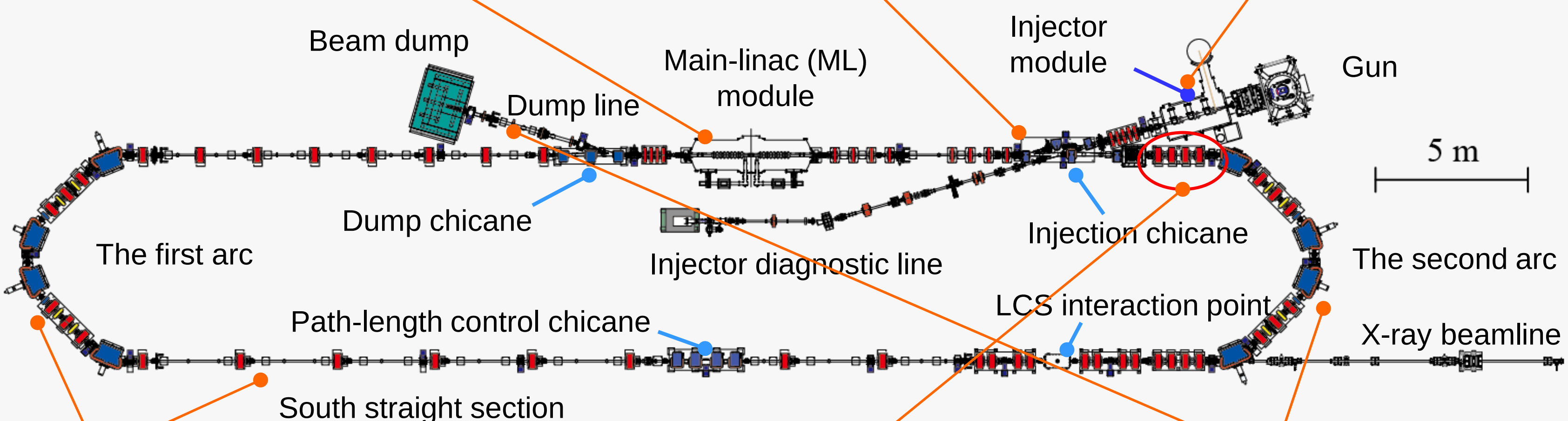
- Adjust rf phases (on-crest)
- Steering beam to the centers of ML cavities (option)
- Adjust beam energy

(2) Merger and beam transport

- Steering to the centers of QMs
- Adjust beam energy at injector

(1) Injector

- Steering beam to the centers of solenoids and QMs (optionally, to the centers of cavities)
- Adjust rf phases (on crest)



(4) Arcs and south-straight sections

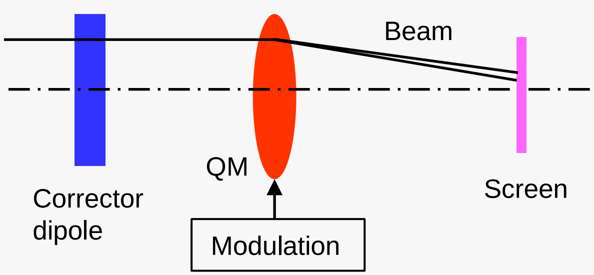
- Steering beam to the centers of QMs
- Optics matching (option) - describe later

(5) Beam tuning for ML section (second passage) and dump line

- Adjust steering coils of these QMs so that the beam passes the ML cavities and appears at the dump line
- Adjust K-values of these QMs finely to adjust the beam profiles at the dump line

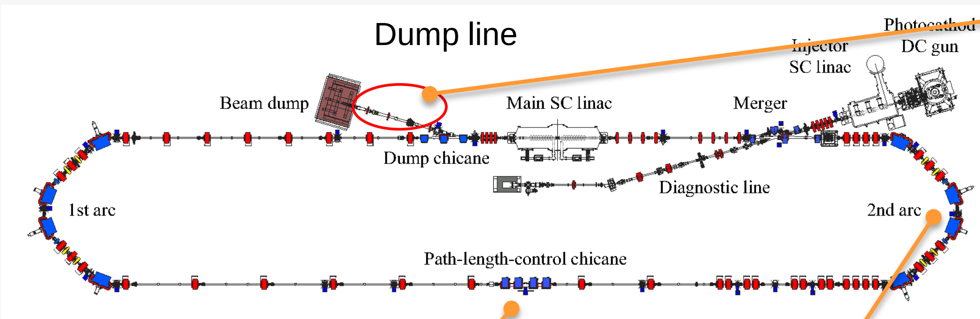
(6) Path-length correction

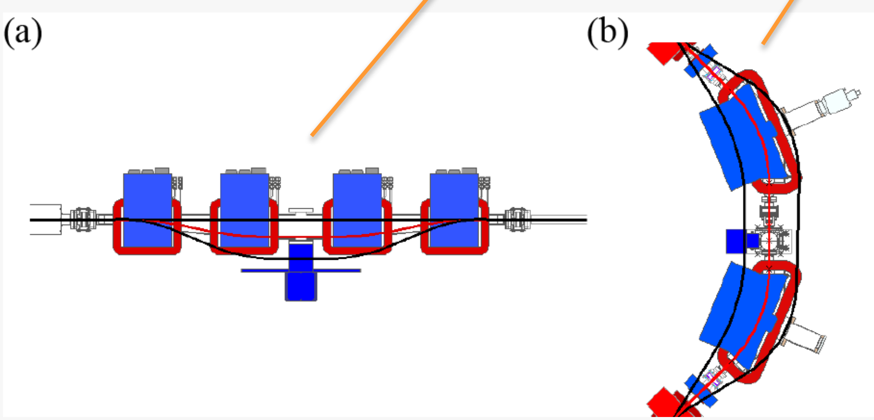
- Correct the path length so that the beam momentum take a minimum at the dump line



Correction of Path Length for Optimum Energy Recovery

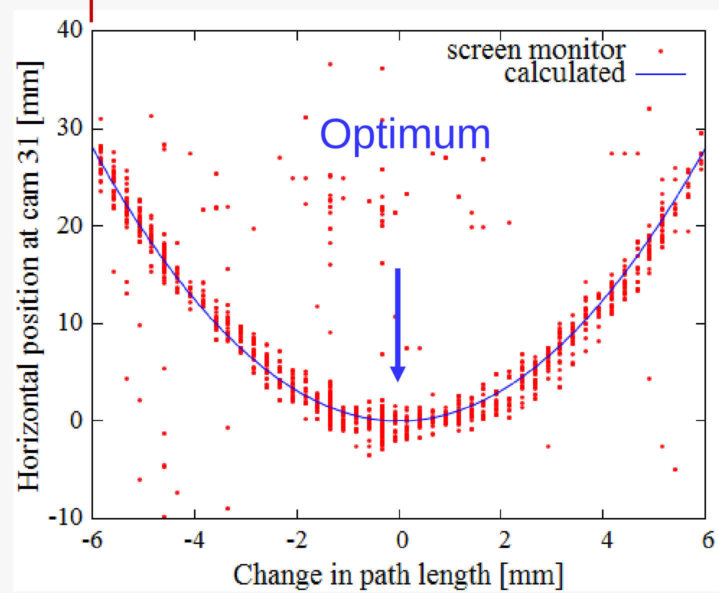
- Two measures for path-length correction were prepared
- Path length was corrected so that the beam momentum took a minimum at the dump line





Position at a screen monitor in the dump line

$\propto$ (momentum at the dump line)



Path-length control chicane

- Tuning range: ±5 mm
- Large hysteresis
- Currently fixed

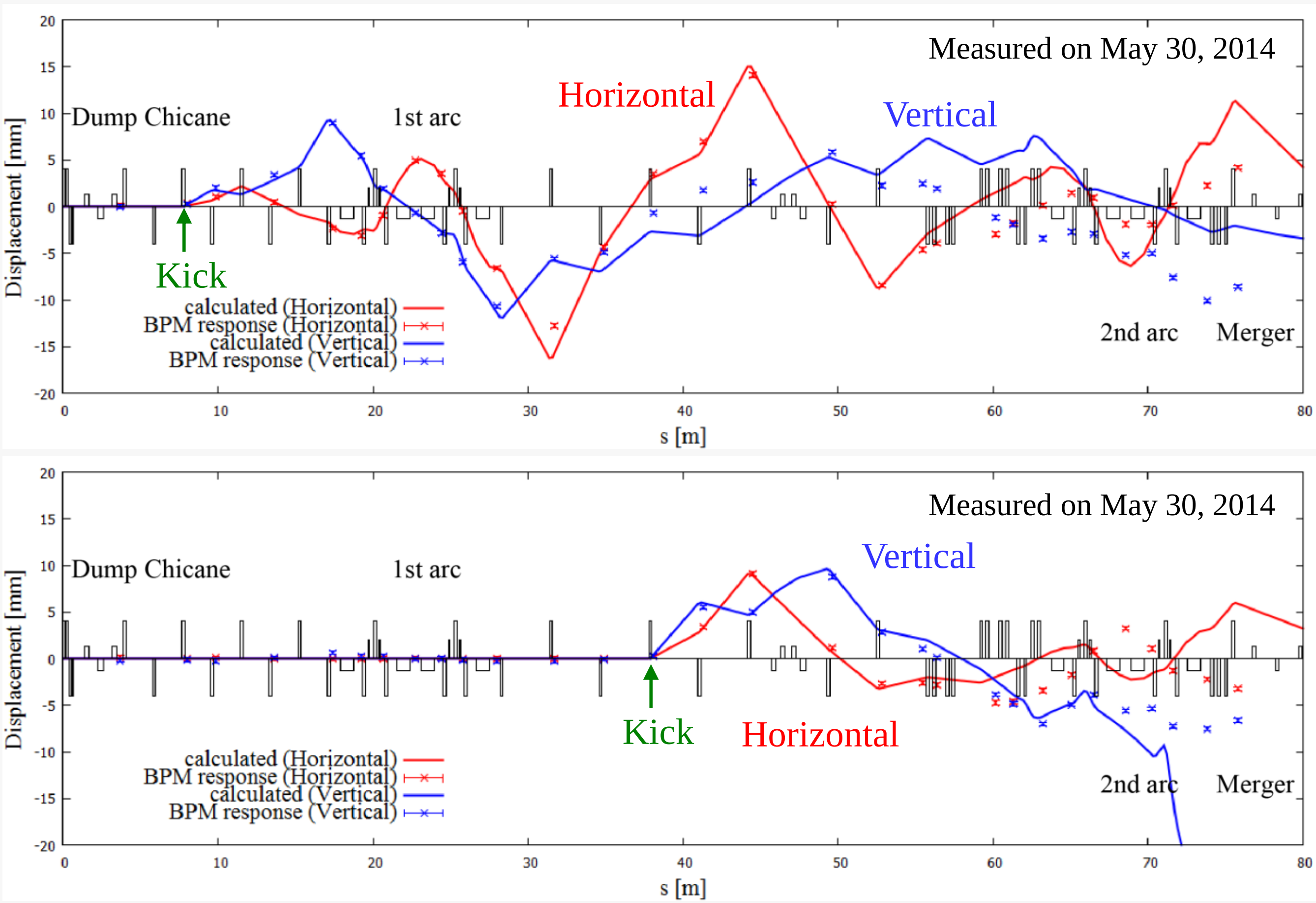
Orbit bump in the arc

- Tuning range: ±10 mm/arc
- Routinely used

Determination of an optimum path length

Single-Kick Response Measurement

- Measured responses agreed with those calculated within a range of 20-30 m after the kick.
- Large differences in downstream locations suggested accumulation of gradient errors.



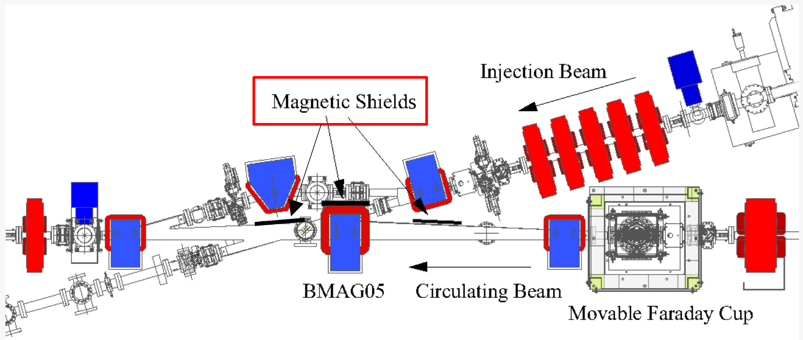
Measured (cross) and calculated (line) responses to single-kicks.

Sources of Magnetic-Field Errors

Ambient fields

Cold cathode gauges (shielded)

Leakage fields from neighboring magnets



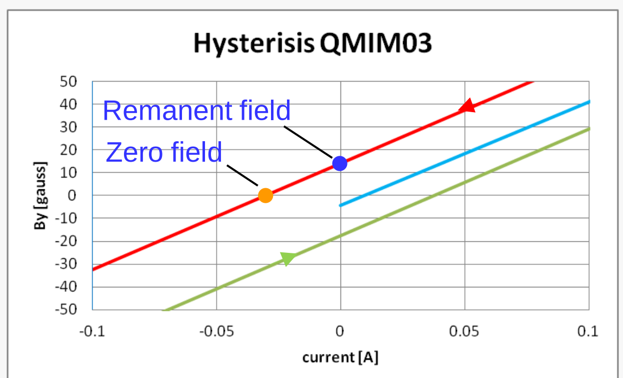
Merger section

Magnetic fields from Super-KEKB (due to cable of main dipoles)

B ~ 20-30 mG (at cERL)

Remanent fields and hysteresis of quadrupoles

- Remanent fields in quadrupoles cause large gradient errors: $\Delta K/K \geq$ 10-20%
- Gradient errors also accumulate through daily operations



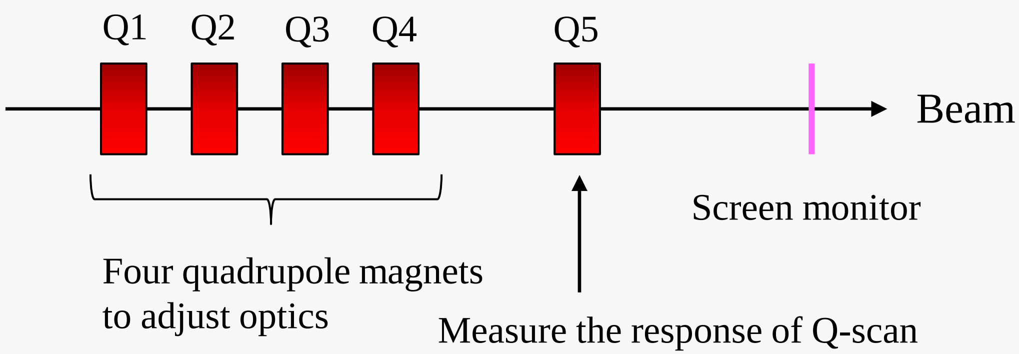
Measured hysteresis curve of a quadrupole (QMIM03).

Countermeasures (under study)

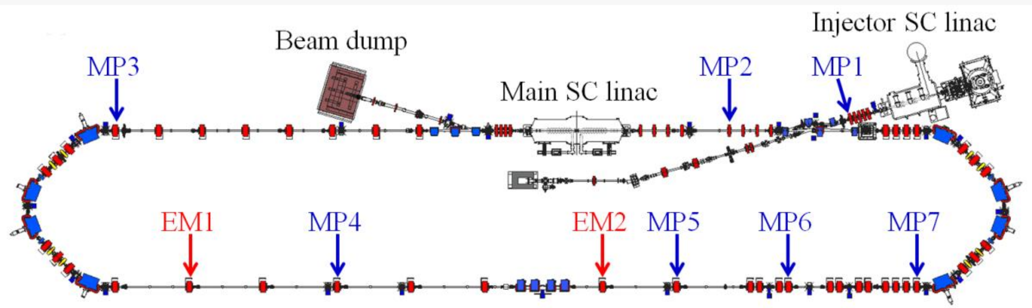
- Standardized excitation
- Subtract/add offsets due to remanent fields (when we set K-values for operation)

Method of Optics Matching

T. Miyajima
IPAC'15

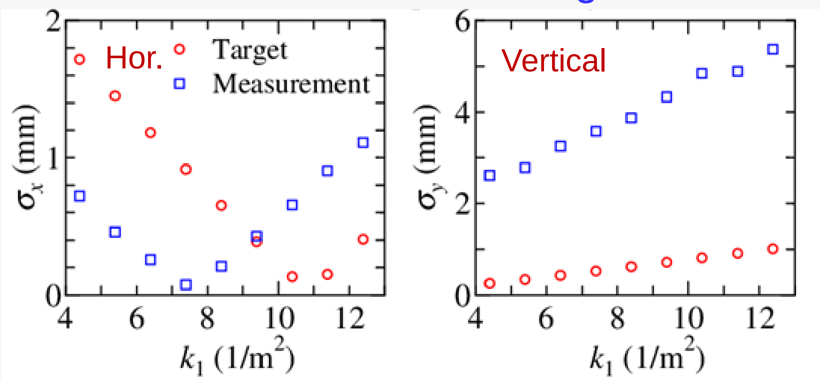


- Single quadrupole (Q5) is used to measure the quadrupole-scan response (information of ε, α, β)
- Adjust the upstream 4 QMs so that the response curve agrees with the design one.

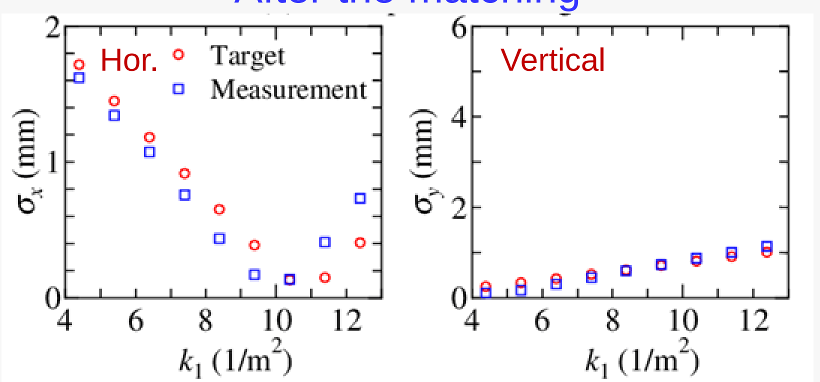


Locations of matching points (MP1 - MP7).

Before the matching



After the matching



(Right) Results of quadrupole-scan measurements before and after the optics matching at a location "MP2".

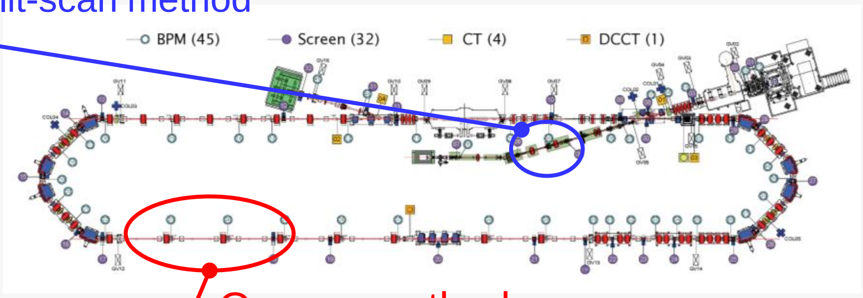
Emittance Measurements

(normalized emittance: ε_n [mm·mrad] = $\beta\gamma\varepsilon$)

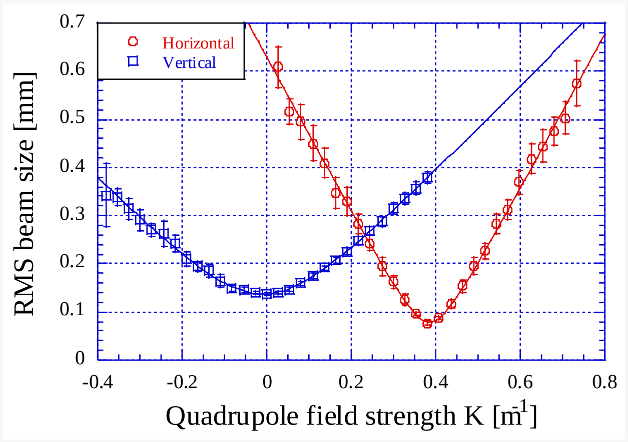
Injector (E = 6.1 MeV)

Bunch charge	At injector
0.02 pC	0.17 mm·mrad
0.77 pC	≈ 0.3 mm·mrad
7.7 pC	0.5 - 0.8 mm·mrad

Slit-scan method



Q-scan method



Recirculation loop

(at injector energy of E = 2.9 MeV)

$p_{loop}/p_{inj} = 7$

Bunch charge	At injector (E=2.9 MeV)	At recirculation loop (E=19.9 MeV)
0.02 pC	-	0.14 / 0.14
0.5 pC	-	0.32 / 0.28
7.7 pC	(2.5 / 2.9)	(5.8 / 4.6)

($\varepsilon_{n,x}$ / $\varepsilon_{n,y}$)

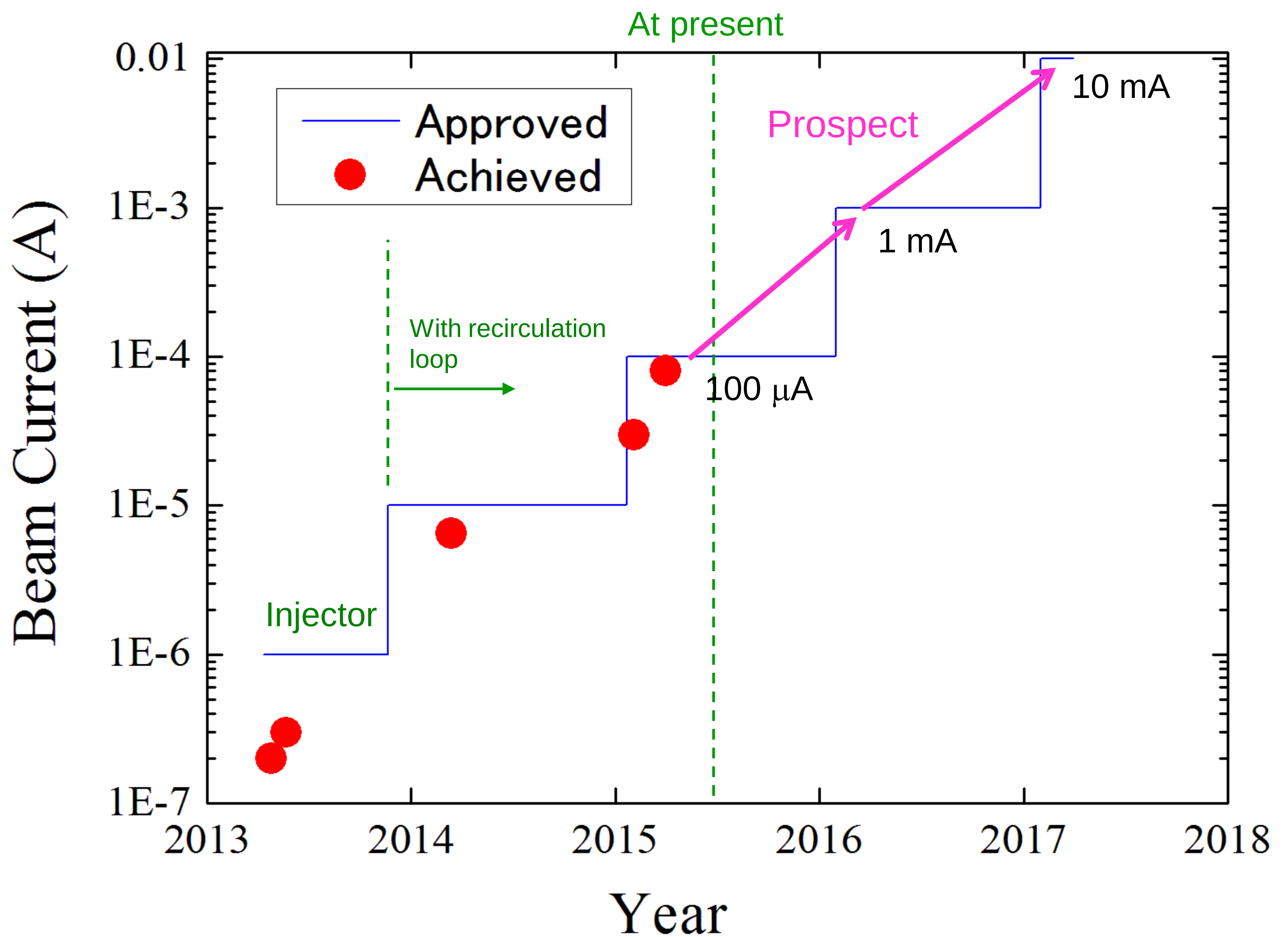
← For LCS experiment

← Very preliminary (under study)

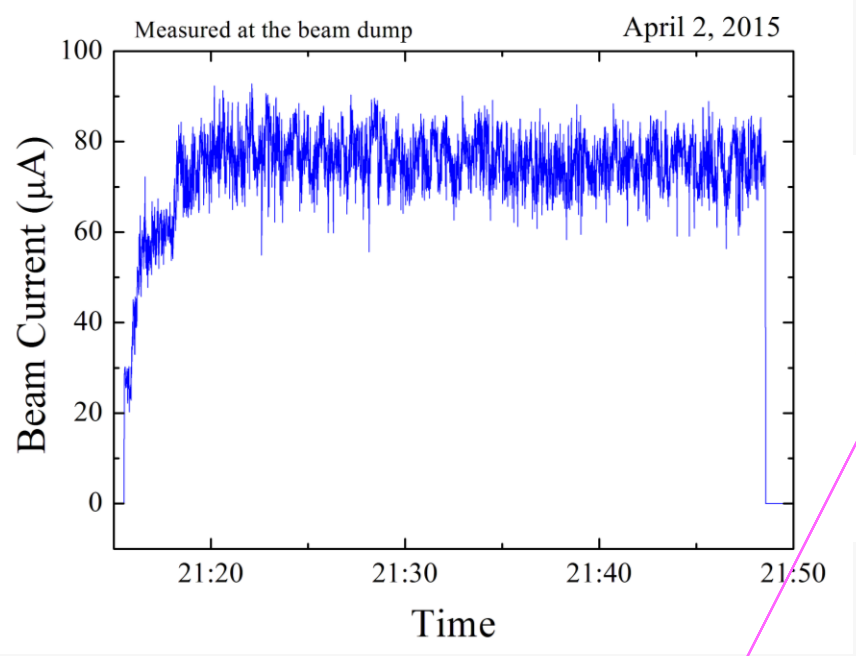
Tuning for low-emittance at high charges is under study

4. High-Current Operation and Other Important Topics

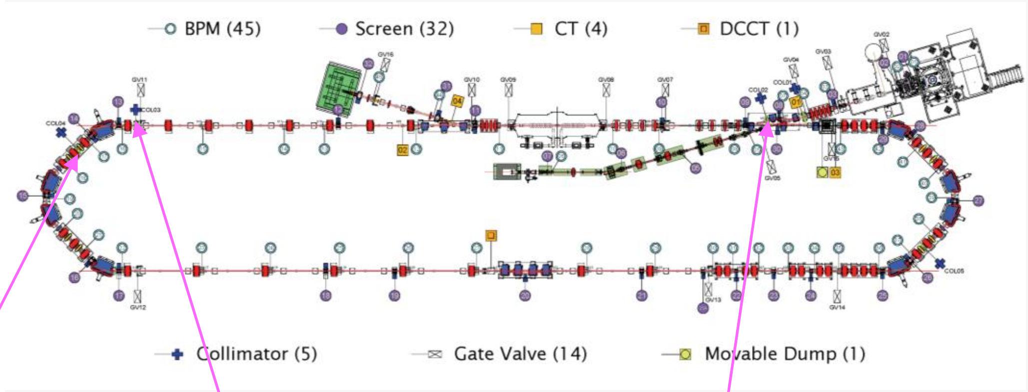
Beam Currents: Achievement and Prospect

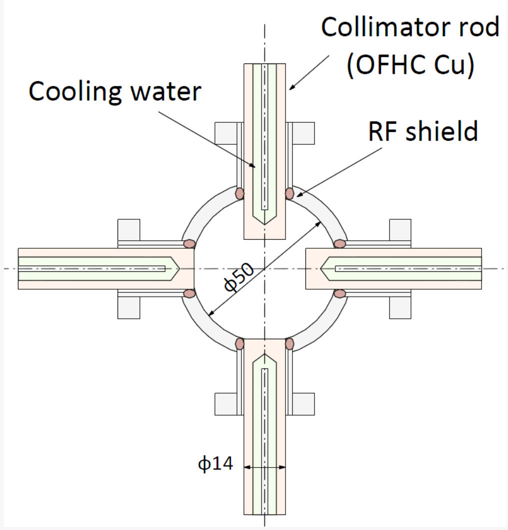


Beam Current of 80 μA (CW) was Recirculated



Collimators were used to cut beam halo/tails





Beam collimator

COL4:

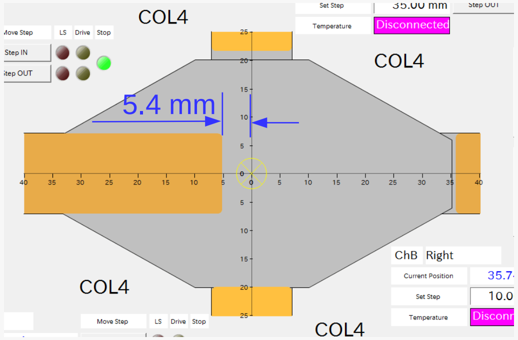
- at arc section
- η= -1.28 m
- cut low-energy tails (not very effective)

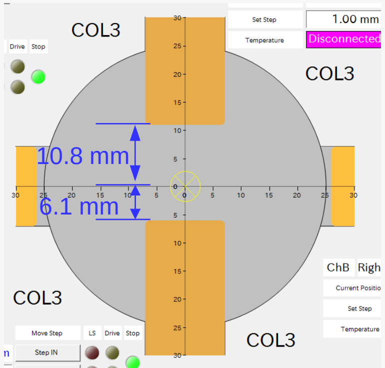
COL3:

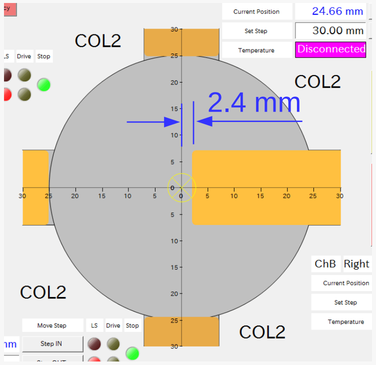
- at straight section
- η= 0
- cut halos (large β_y)

COL2:

- at merger
- η=0.23 m
- cut low-energy tails







Radiation and Beam Losses (at beam current of ~80 μA)

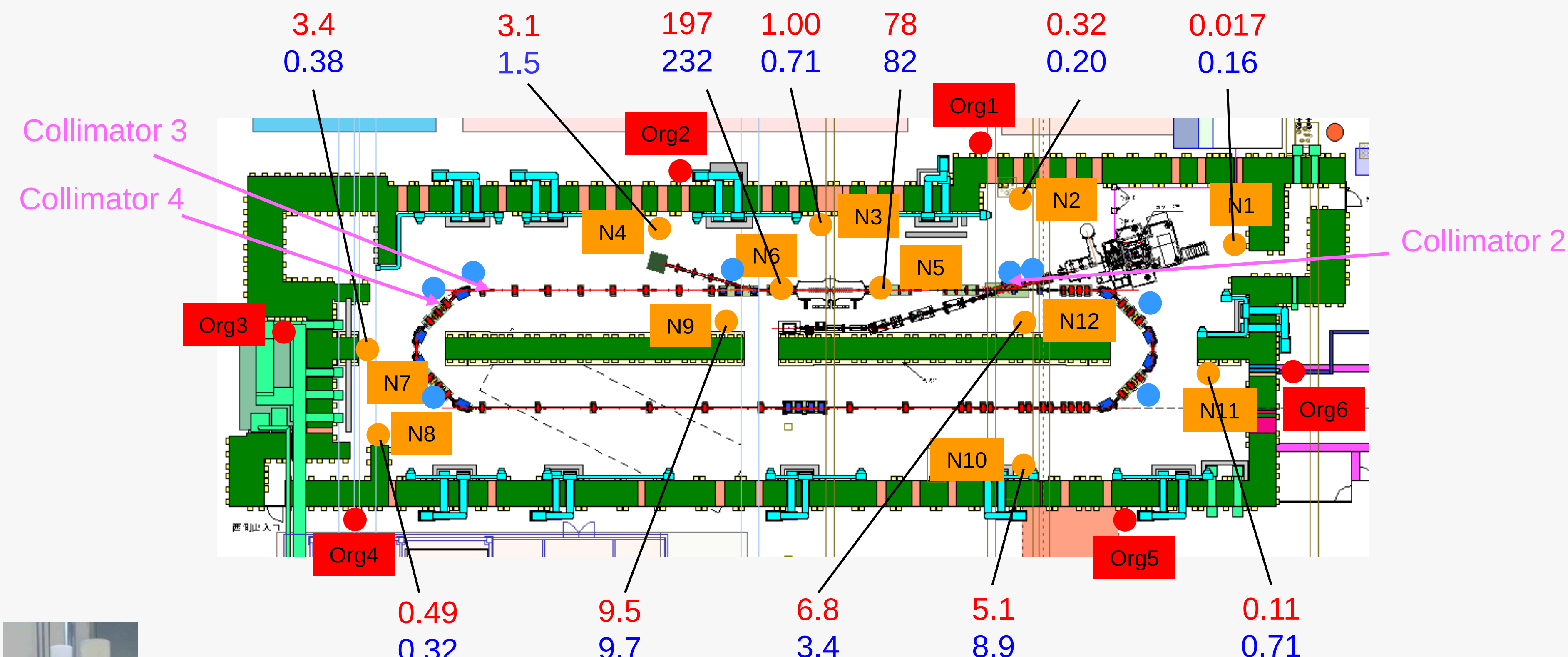
Unit: mSv/h

Radiation levels inside the accelerator room under two conditions:

Red: using collimators No. 2, 3, 4 (shown in the previous page), on April 2, 2015

Blue: using collimator No. 2 (right 2.0 mm, top 3.4 mm), on April 3, 2015

Beam optics: LCS



Radiation monitors (Organge1-6), for interlock (PPS)

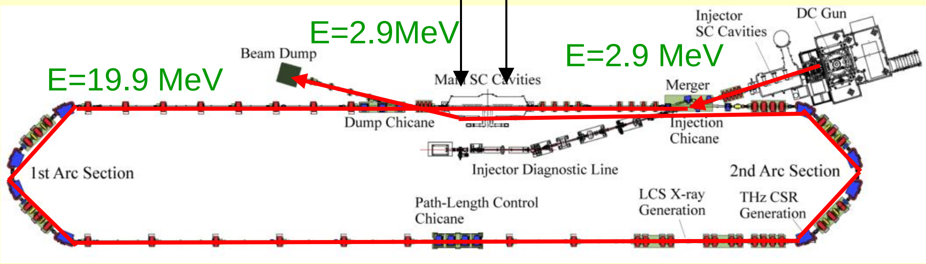
Loss (radiation) monitors, ALOKA MAR-782, for interlock (MPS)

Fast loss monitors, for fast interlock (MPS)

Demonstration of Energy Recovery (I_0 = 30 μA)

ERL operation

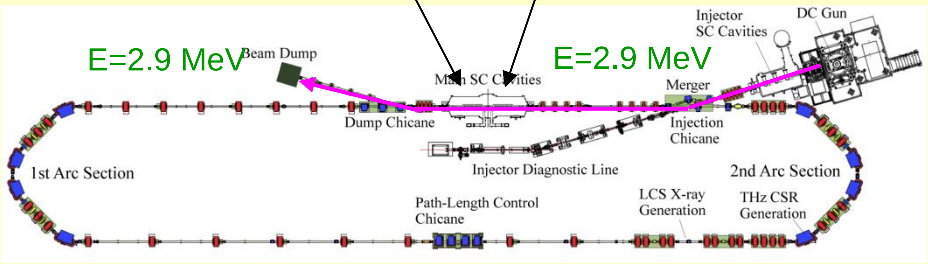
Cavities 1 and 2: acceleration (1st pass) and deceleration (2st pass)



Non-ERL operation

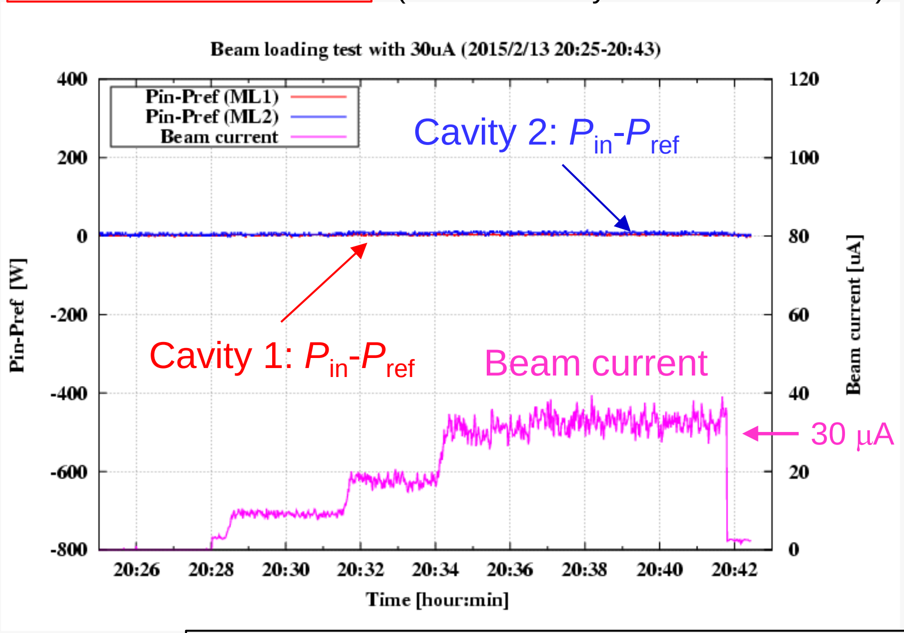
Cavity 2: deceleration (Vc=8.57 MV/cavity)

Cavity 1: acceleration (Vc=8.57 MV/cavity)

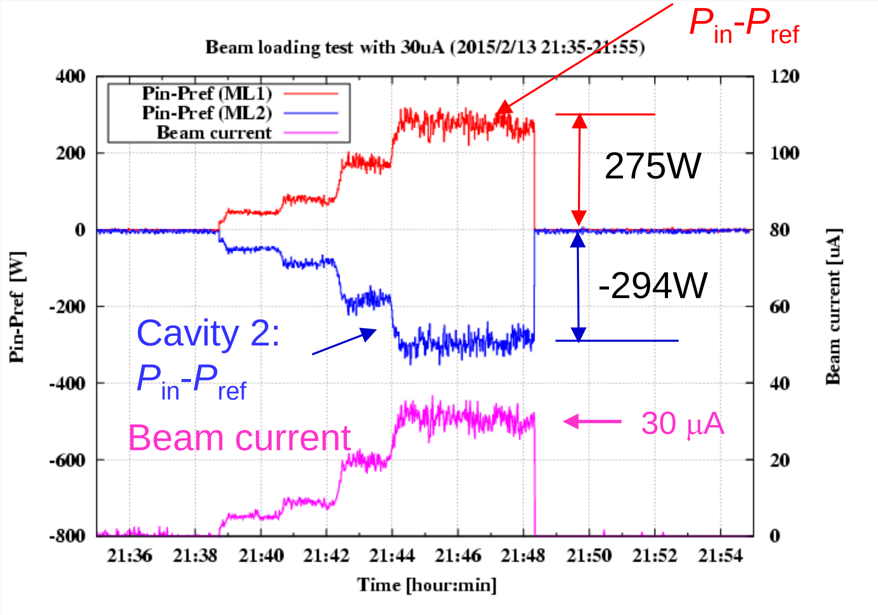


No beam loading

Energy recovery: 100-98.6% (within accuracy of the measurement)



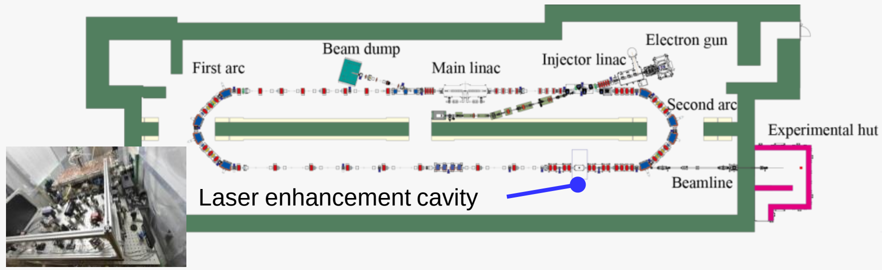
Beam loading (+ and -)

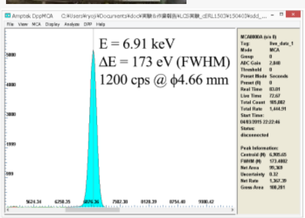


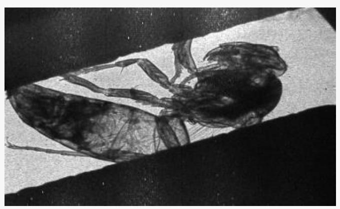
(Power lost in cavity) = (P_{in} : input power to cavity) - (P_{ref} : reflected power from cavity)

Other Important Topics

Successful Production of X-ray From Laser Compton Scattering (LCS)

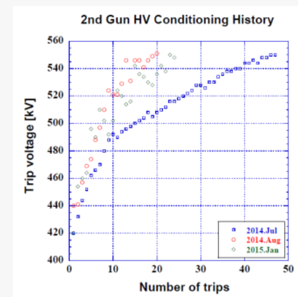


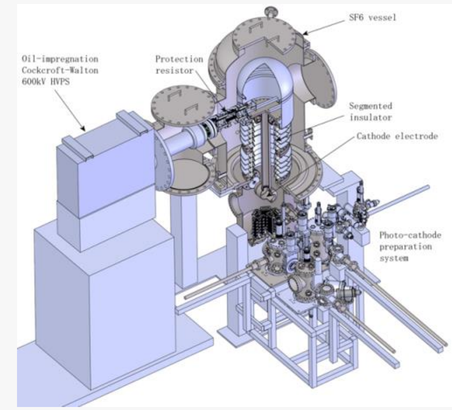




Hajima's talk (Wednesday)

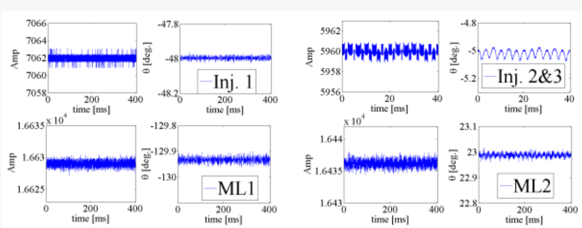
Development of the Second Photocathode DC Gun

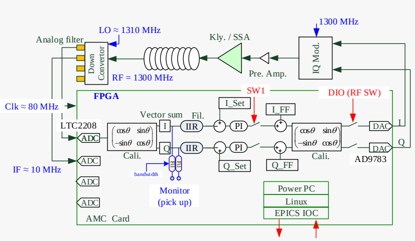




Yamamoto's talk (Tuesday)

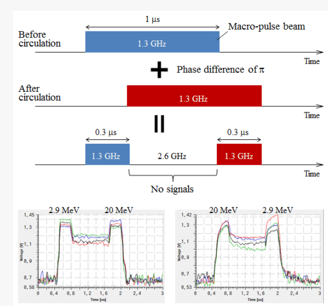
Achievement of High RF Stability Using Sophisticated Digital LLRF System

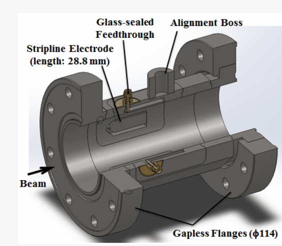


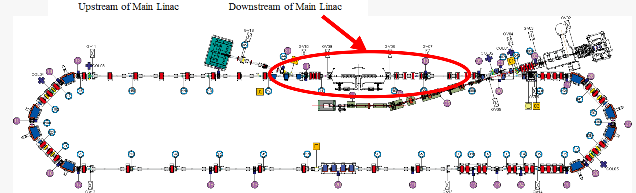


Qiu's talk (Wednesday)

Non-destructive Beam Position Monitoring in Two-Beam Section

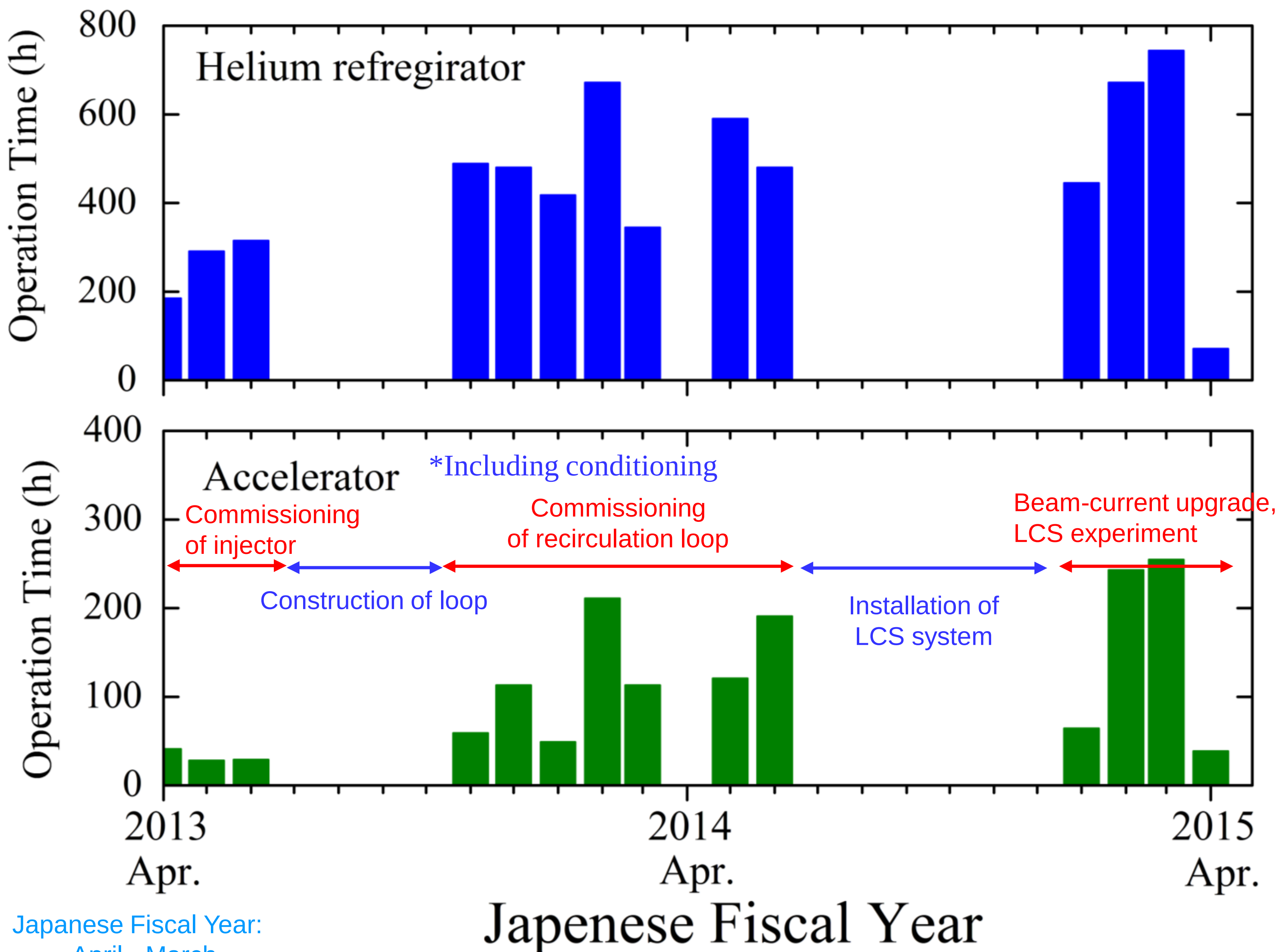






Obina's talk (Wednesday)

Statistics of Operation Time (per month)



Japanese Fiscal Year:
April - March

Summary and Outlook

- The Compact ERL was commissioned and is in stable operation.
- Learned many lessons from the commissioning.
- The photocathode DC gun and both (injector and ML) SC cavities are operating very stably.
- Achieved beam current of 80 μA.
- Achieved low beam emittance (< 1 mm·mrad) at low bunch charges (< 0.5 pC/bunch).
- X-ray production from Laser Compton Scattering was successfully demonstrated.

Subjects in the near future

- Lower emittance at high buhch-charges ($q_b \geq 7.7$ pC)
- Beam current: 1 mA ($\rightarrow$ 10 mA)
- Bunch compression (σ_t ~ 100 fs) and THz production

We have established many important technologies for the ERL light source.
We continue to conduct R&D effort on remaining issues such as:

- Improved cavity-assembly technique for higher accelerating gradient
- Mass-production technique for main-linac cavities

Acknowledgment

We have learned much from designs and experiences of JLab IR-FEL and Cornell Injector.
We appreciate useful information and advices from
JLab: George Neil, Steve Benson, Geoffrey Krafft, David Douglas, Kevin Jordan,
Carlos Hernandez-Garcia, Pavel Evtushenko, Vashek Vylet, Andrew Hutton,
Cornell: Georg Hoffstaetter, Bruce Dunham, Ivan Bazarov, Christopher Mayes,
and many other people.
We would also thank the people of ERL community for useful discussions and encouragement.