First Beam Recirculation and Energy Recovery in the Compact ERL at KEK

Shogo Sakanaka (KEK),
on behalf of the ERL Development Team in Japan

TTC Meeting, 24-27 March, 2014, at DESY

v2b

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Outline

I. Introduction to the ERL Project “PEARL”

II. Design and Construction of the Compact ERL

III. Commissioning of Injector (Apr.-June 2013)

IV. Commissioning of cERL (Dec. 2013 - Mar. 2014)

V. Conclusion

VI. Acknowledgment

I. Introduction to the ERL Project “PEARL”

ERL Light Source Project (PEARL) at KEK

Photon Factory ERL Advanced Research Laboratory

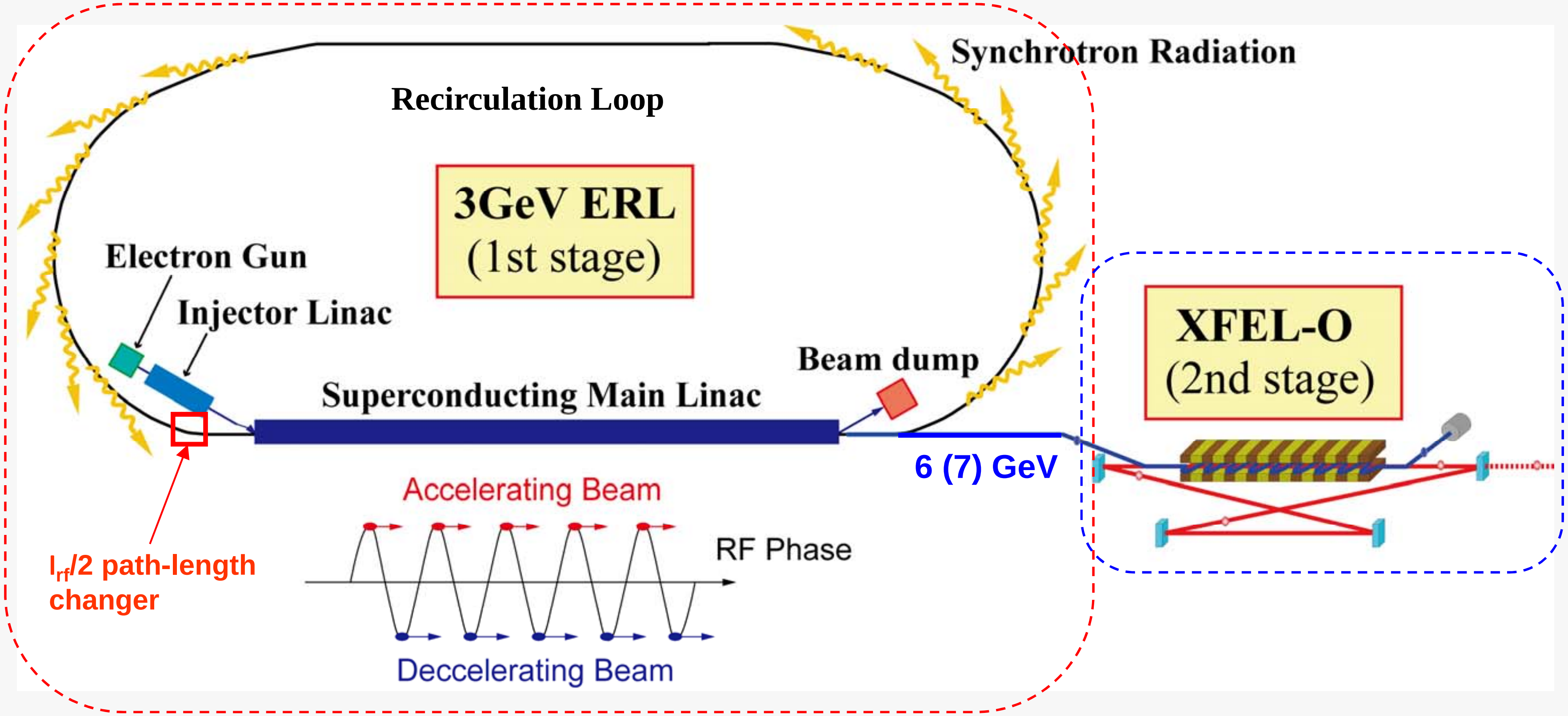
PEARL Photon Factory

ERL-based Light Source Project at KEK (2 Stages)

① 3-GeV ERL as X-ray and VUV SR source

② 6-7 GeV XFEL Oscillator

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



[1] "Energy Recovery Linac Conceptual Design Report", KEK Report 2012-4 (Oct. 2012); http://ccdb5fs.kek.jp/tiff/2012/1224/1224004.pdf

Challenges in 3-GeV ERL

ERL-based light source
(KEK-PERAL, Cornell, FSF at HZB, ...)

CW Operation
Low beam emittance
High beam current

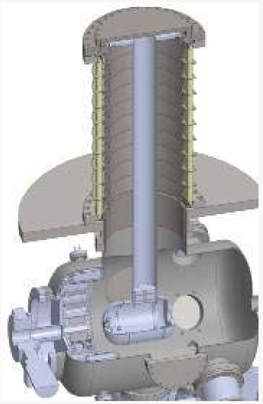
Common challenges with
high-repetition-rate FELs
(like LCLS-II)

Electron gun
- CW beams (1.3 GHz)
- Low-emittance
- High average current
- Long cathode lifetime

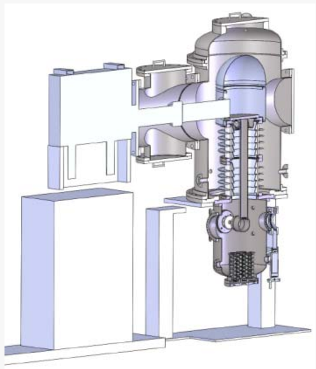
Superconducting cavities (Injector/Main-linac)
- CW operation
- HOM couplers or absorbers
- High-power couplers (injector)
- High unloaded-Q (Q_0) (main-linac)
- Strong HOM damping (main-linac)

Beam dynamics
- Injector design
- Emittance preservation
  - space charge effect
  - CSR
  - rf focusing
  - alignment errors
  - stray fields, ...
- BBU
- Beam losses
- ...

Photocathode DC guns (500 kV)



#1
(JAEA)



#2
(KEK)

2-cell cavity
for ERL injector

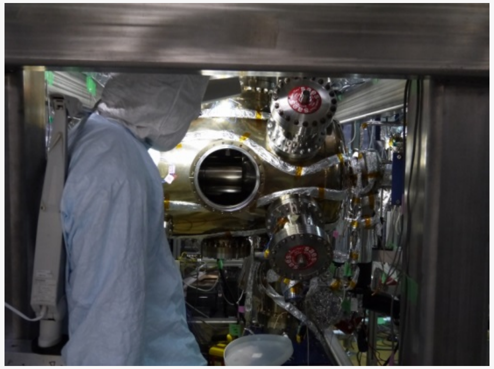
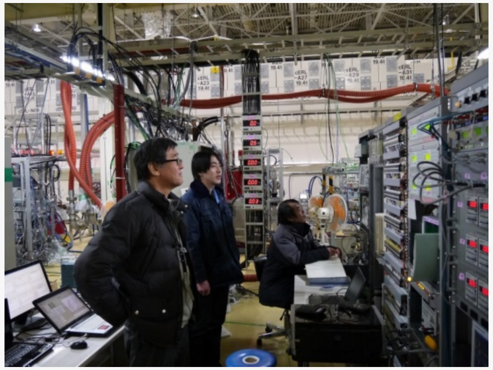
9-cell cavity for
ERL main linac

Proof of technology
at the Compact ERL

II. Design and Construction of the Compact ERL



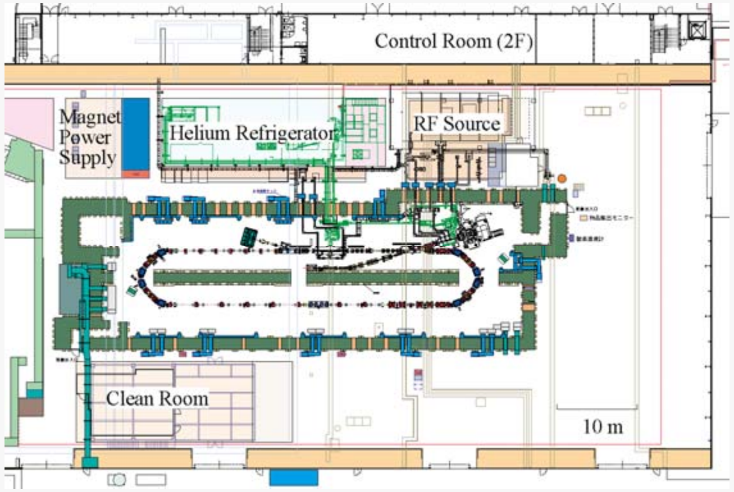


The Compact ERL (cERL) at KEK

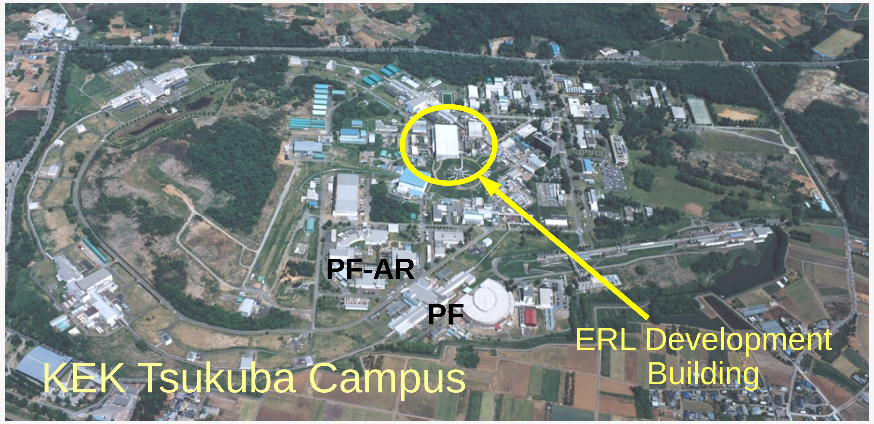
Purpose of the Compact ERL

- To demonstrate the generation and recirculation of ultra-low emittance beams
- To demonstrate reliable operations of our R&D products (guns, SC-cavities, ...)
- Initial goal: 1 mm·mrad @7.7pC/bunch (10mA), 35 MeV



Design parameters of cERL

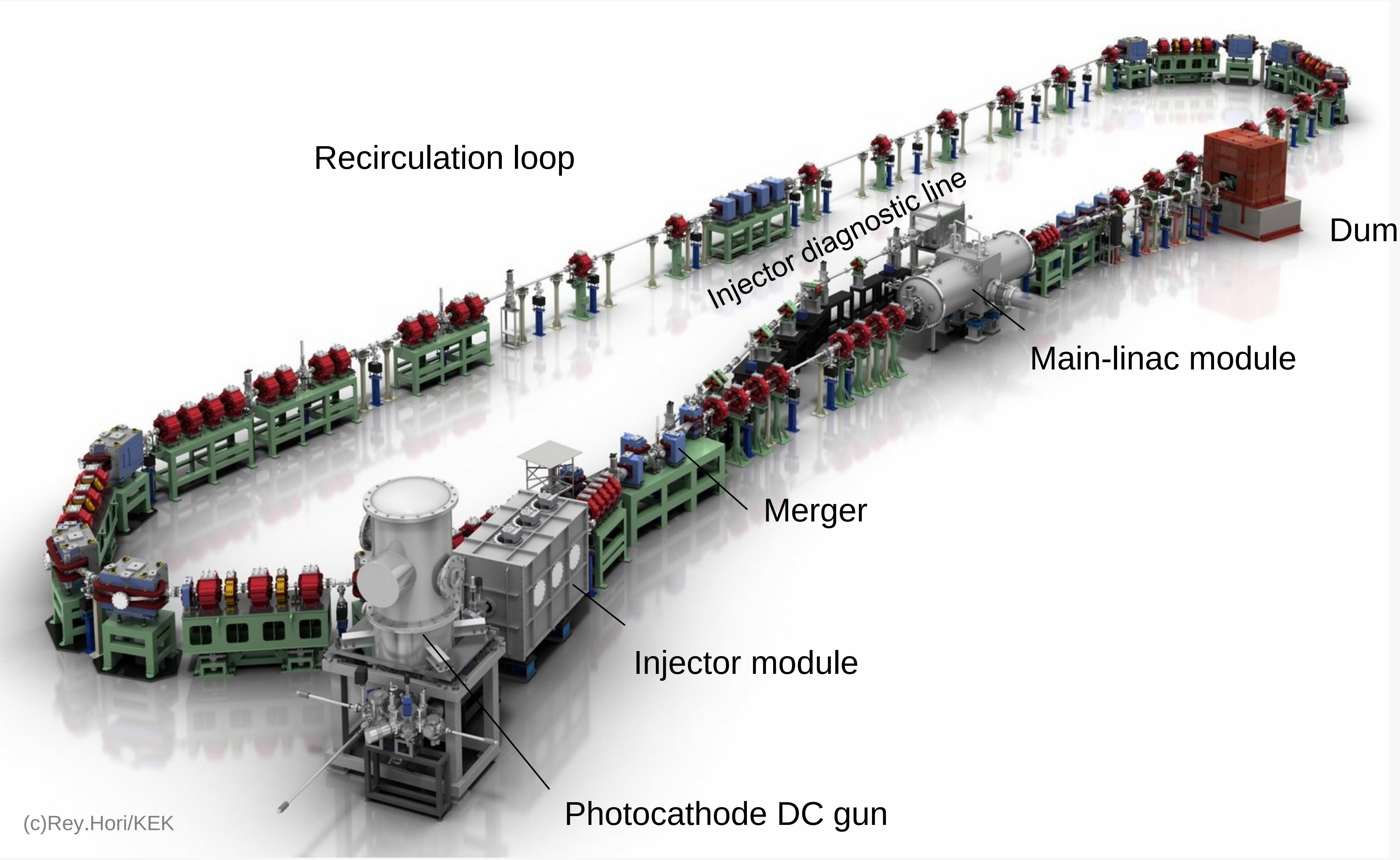
Parameter	Goal (future goal in ())
Beam kinetic energy	35 MeV (upgradable to 125 MeV)
Injector kinetic energy	5 MeV (10 MeV)
Average current	10 mA (100 mA)
Normalized emittance @bunch charge	0.3 mm·mrad @7.7 pC 1 mm·mrad @77 pC
Bunch length (rms)	1 - 3 ps < 150 fs (with B.C.)
Accelerating gradient (main linac)	15 MV/m
RF frequency (= bunch repetition frequency)	1.3 GHz



Construction Site

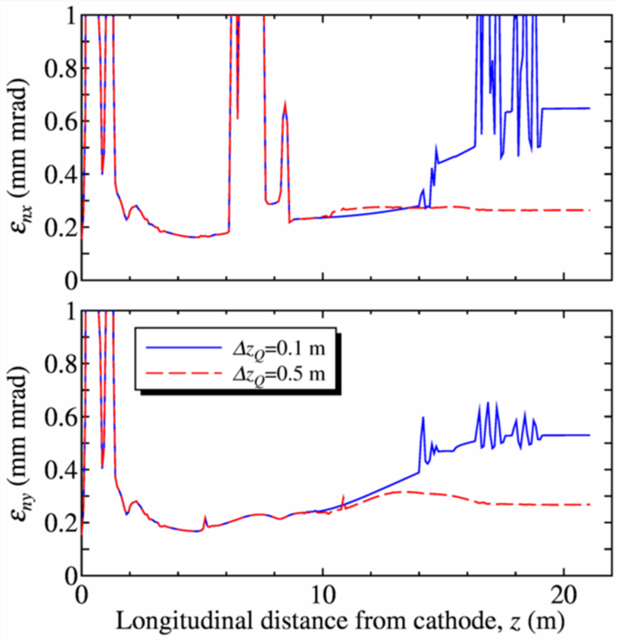
Commissioned in Dec. 2013.

The Compact ERL



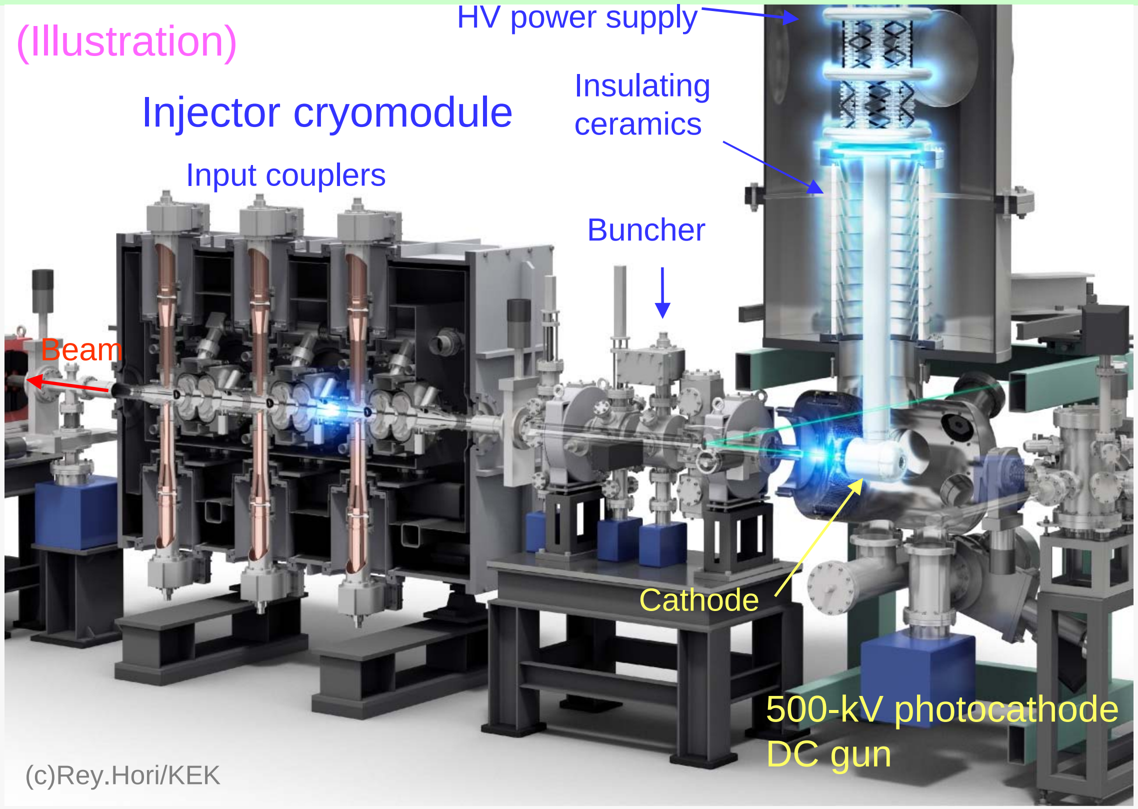
High-Brightness CW Injector of the cERL

Bunch charge: 7.7 pC



Example of GPT simulation

(Illustration)

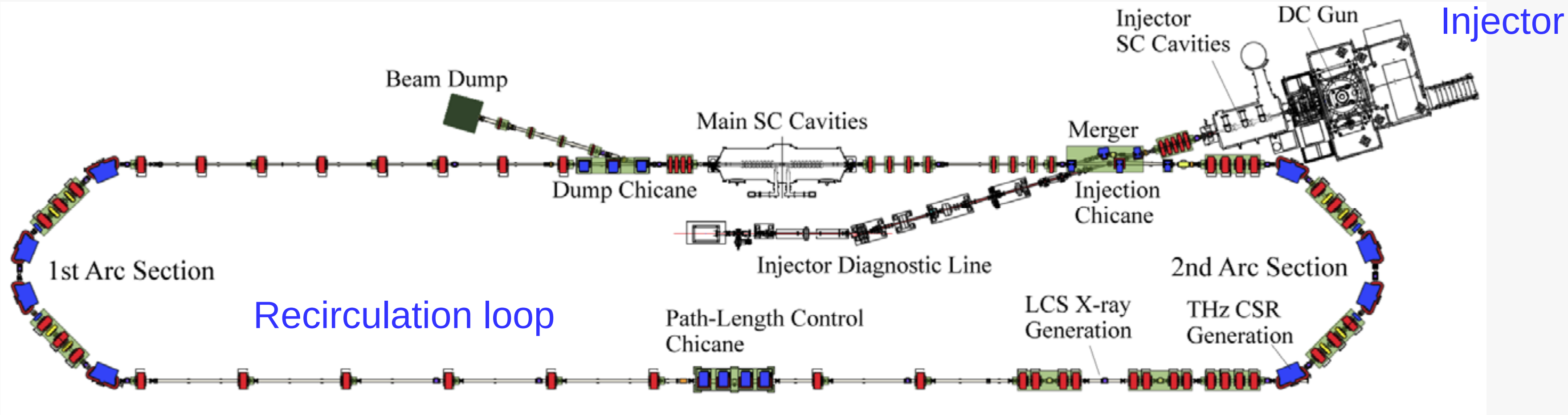


Goals of the cERL injector

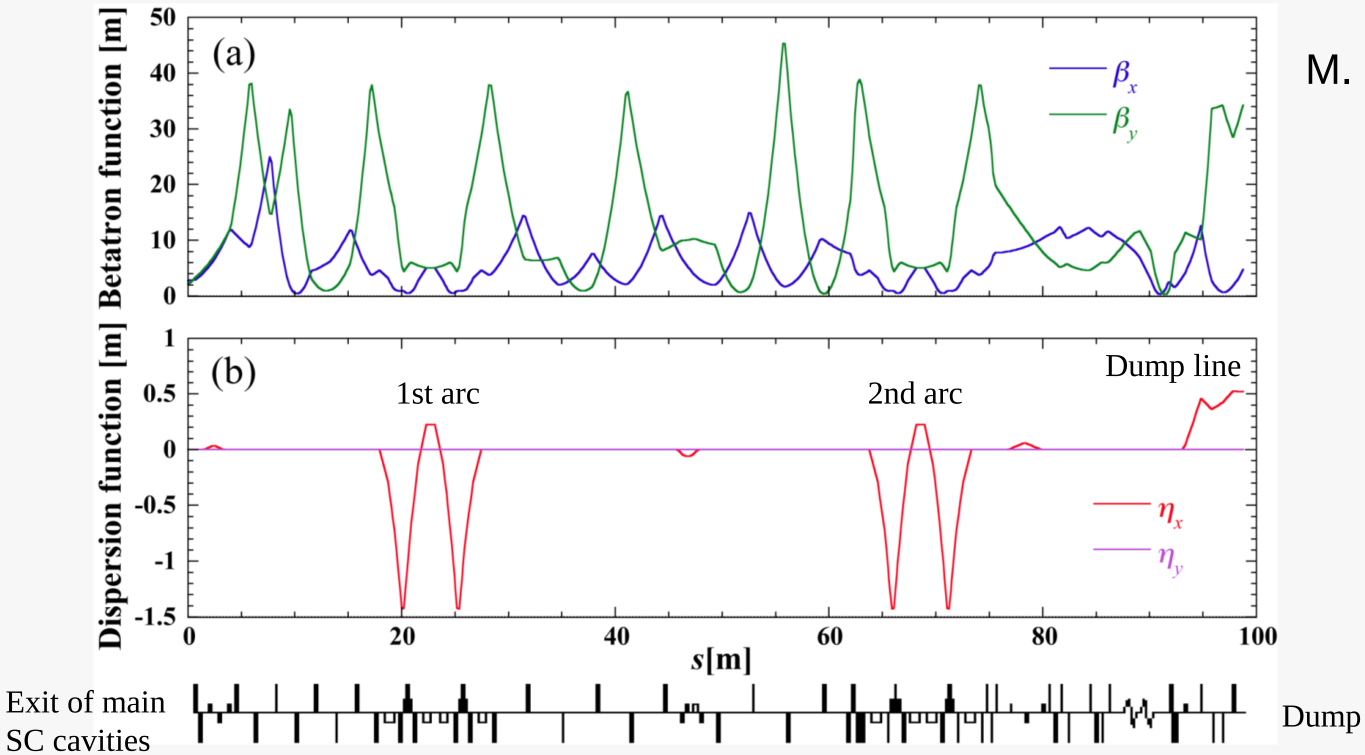
	cERL goal
Gun voltage	500 kV
Injector energy (MeV)	5 MeV
Beam current	10 mA
Normalized emittance (mm·mrad)	1 (77 pC/bunch) 0.3 (7.7 pC/bunch)
Bunch length (ps; rms)	1-3

(Real picture)

Recirculation Loop



M. Shimada



Construction of cERL (2012)

Construction of shielding room (Mar. - Sep. 2012)

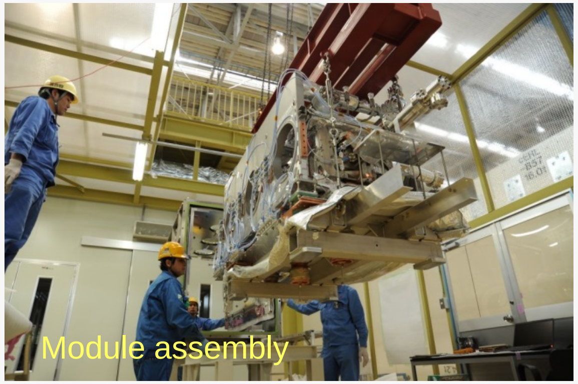
Mar. 2012

May 2012

Finished in Sep. 2012
(picture: Mar. 2013)

Construction and Installation of Injector cryomodule (Apr.-June, 2012)

Apr. 2012



June 2012

June 2012

Construction of cERL (2012-2013)

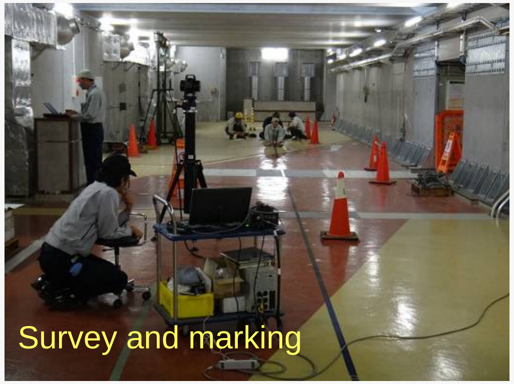
Construction and installation of main-linac cryomodule (Aug. - Oct., 2012)

Aug. 2012

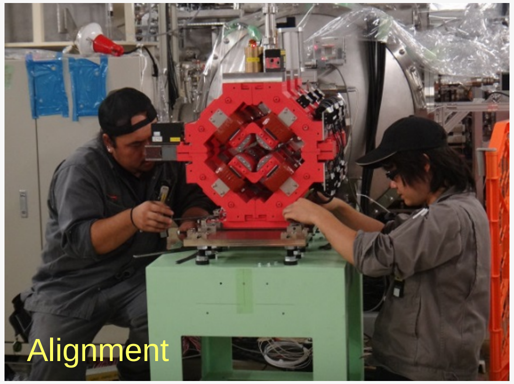
Sep. 2012

Oct. 2012

Construction of recirculation loop (Jul.-Nov., 2013)



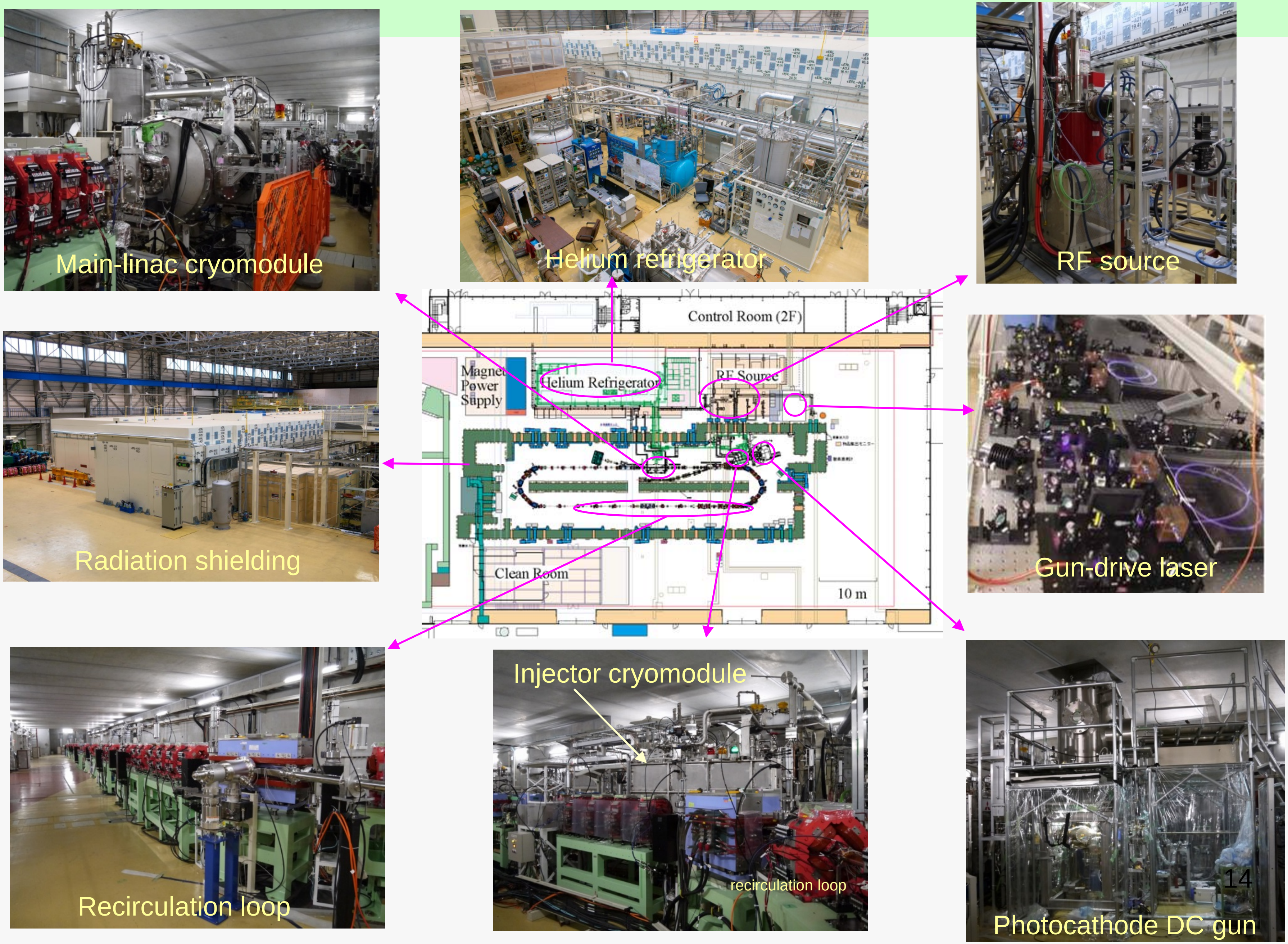
Jul. 2013



Sep. 2013

Nov. 2013

The cERL was completed (Dec. 2013)



The First 500-kV Photocathode DC gun: developed at JAEA and installed in cERL

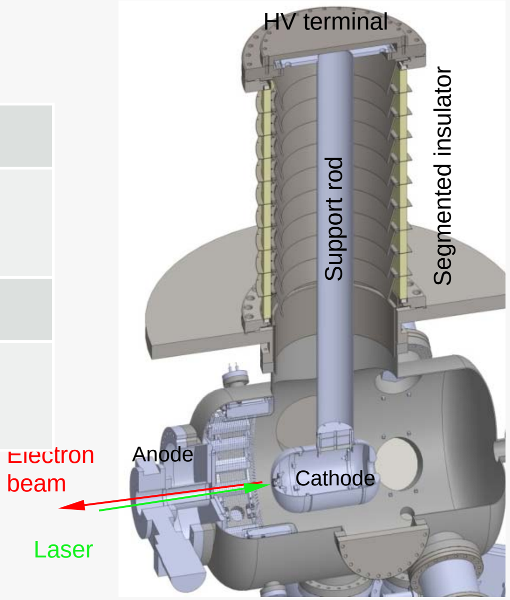
N. Nishimori et al.

Design

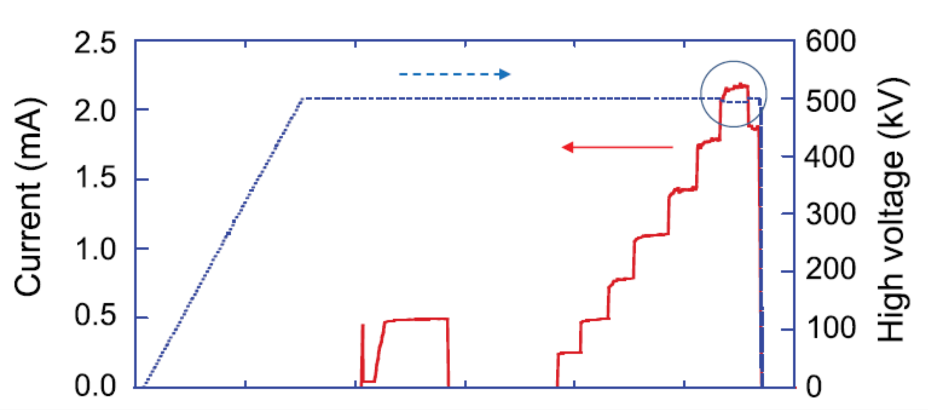
- Segmented insulator for protecting ceramics
- Measures for avoiding big sparks
  - Improved pumping speed
  - Increasing anode-cathode gap: 100 → 160 mm (E: 6.7 → 5.8 MV/m)

Goals

High voltage	500 kV
Electric field on cathode	> 5 MV/m
Beam current	100 mA
Normalized emittance	0.1-1 mm·mrad



Test at JAEA: successful production of 500-keV, 1.8 mA beam



N. Nishimori et al., Appl. Phys. Lett. 102, 234103 (2013).

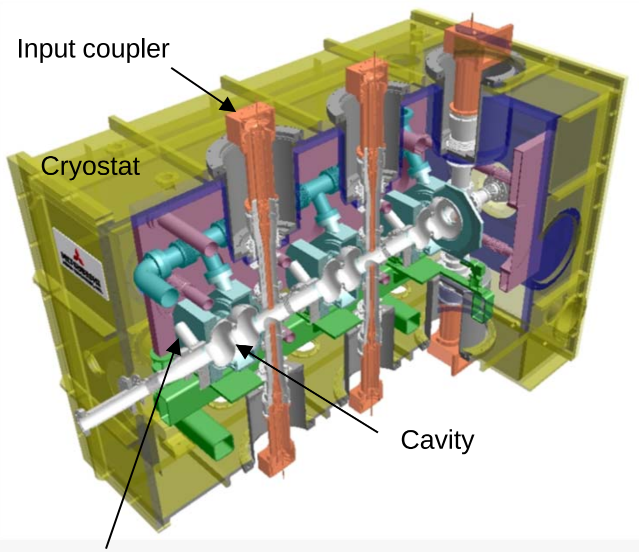
Transported to KEK

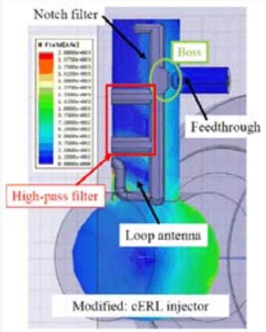
Summary of performance

- Successful production of 500-keV, 1.8-mA beams at JAEA
- Long dark life of GaAs photocathode: > 10,000 hours
- Normalized emittance: 0.07 mm·mrad @10fC (at cERL, V=390 kV)
- Long term operation (~ 260 hours) at V=390 kV at cERL

Injector Cryomodule: design and performance

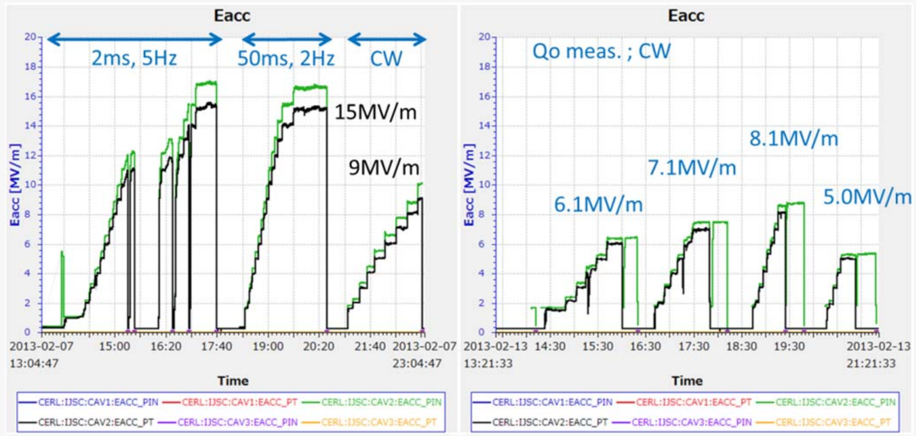
E. Kako
TTC meeting 2013



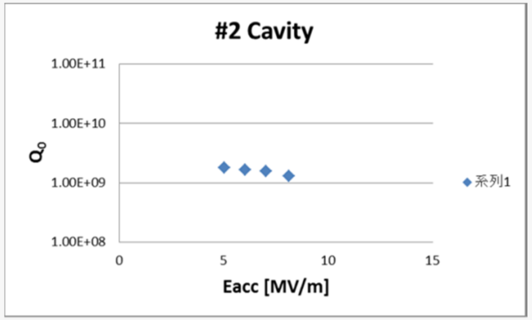


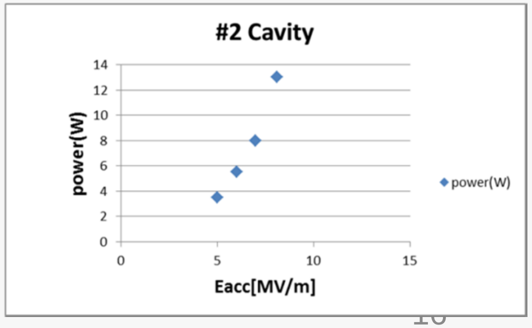
HOM coupler suitable for CW operation

Processing of Cavity -2 : (2013, Feb. 7-8, 13)



Q_0 measurement of Cavity -2





Features and specifications

- Improved HOM couplers for CW operation
- High-power input couplers
- Beam current: 10 mA (100 mA in future)
- ΔT=5 MeV with three two-cell cavities

Summary of performance

- Demonstrated E_{acc} = 15 MV/m in pulsed operation (duty 10%)
- Demonstrated E_{acc} = 8 MV/m in CW operation
- Stable long-term operation (~260 hours) at E_{acc}=7.1 MV/m. Almost no trips during cERL operations.
- Relatively-large dynamic losses (low-Q_0) due to heating-up of HOM feedthroughs. We plan to improve the feedthroughs and cooling.

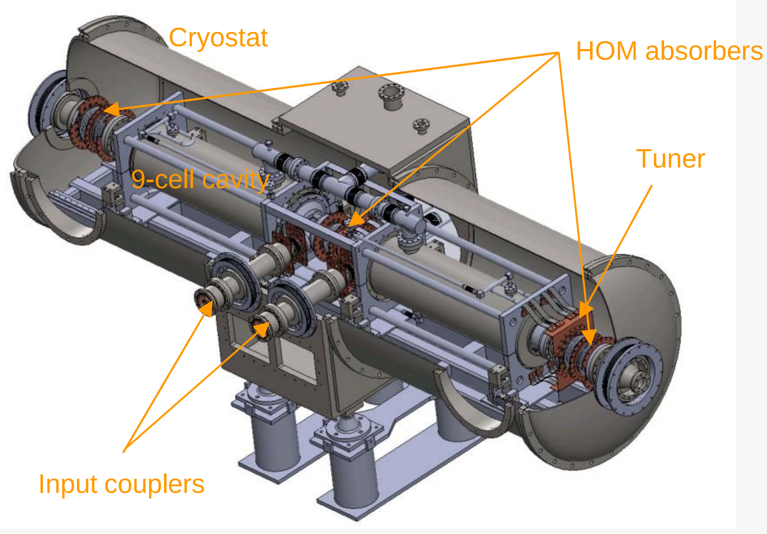
Main-Linac Cryomodule

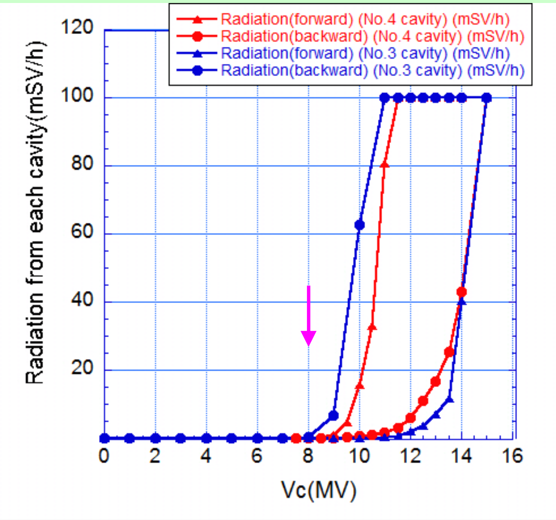
H. Sakai in WG8

T. Furuya
K. Umemori
H. Sakai et al.

Specifications

- **RF frequency: 1.3 GHz**
- **Input power : 20 kW CW (CW)**
- **E_{acc}: 15 - 20MV/m**
- **Unloaded-Q: $Q_0 > 1\times10^{10}$**
- **Beam current : 100 mA max. (HOM-damped cavity)**

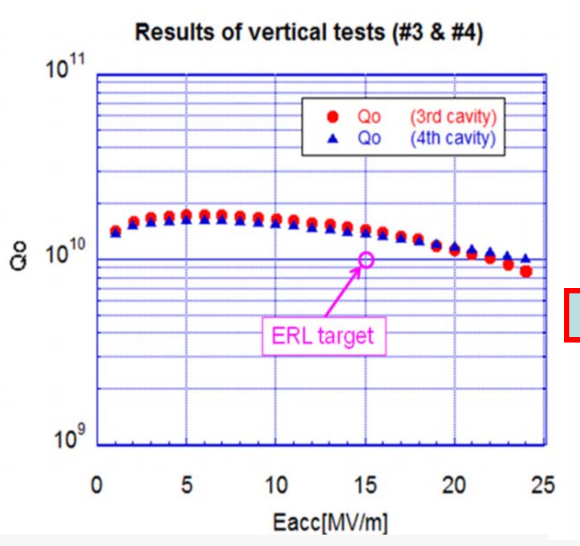




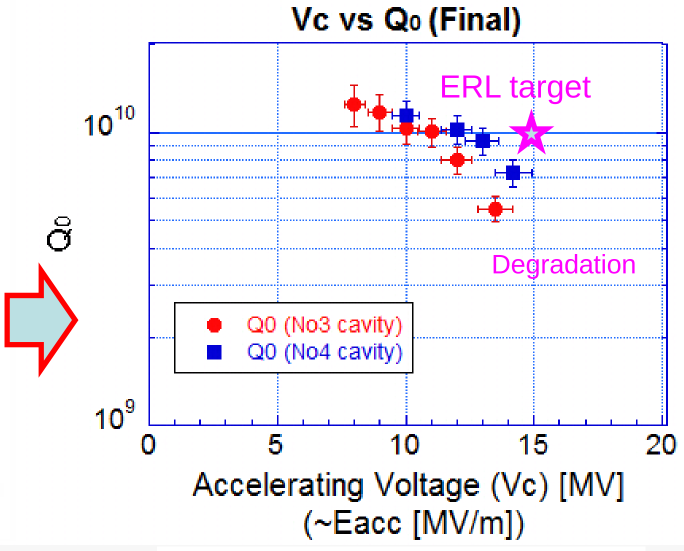
Onset of radiation

Summary of performance

- V_c=16 MV was achieved for both cavities.
- V_c=13.5-14 MV could be kept for more than 1 hour
- Onset of radiation due to field emission: 8-10 MV/cavity
- To increase the onset of field emission, we plan to refine module-assembly technique.



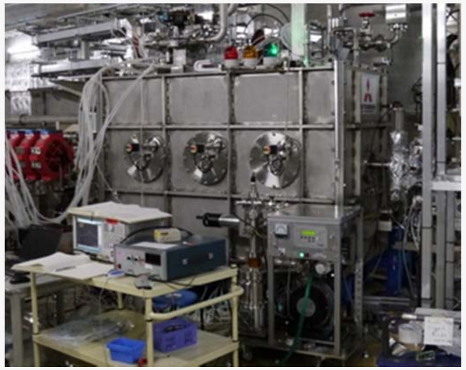
Vertical Test



After installation to module
($V_c = 1.038\times E_{acc}$)

III. Commissioning of cERL Injector

(April - June, 2013)

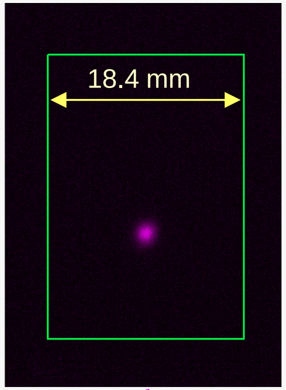


First Acceleration of Beams to 5.6 MeV (22-26 April, 2013)

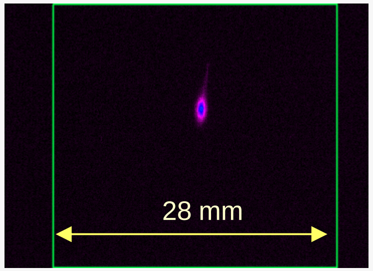
Gun voltage: 390 kV
Injector cavities: E_{acc}=7.1 MV/m
Macro-pulse beams for diagnostics
Maximum beam current achieved: 200 nA

Bunch repetition rate	1.3 GHz
Macropulse widths	1 μs or 1.6 ms (for high current)
Repetition of macropulses	5 Hz
Charge/bunch	Typically 20 fC

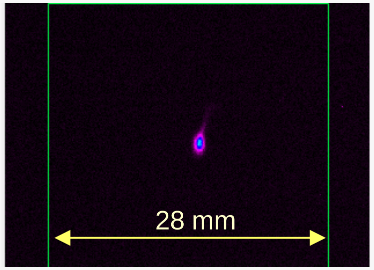
MS2
T=390 keV



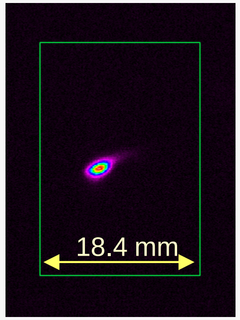
MS3
T~5 MeV



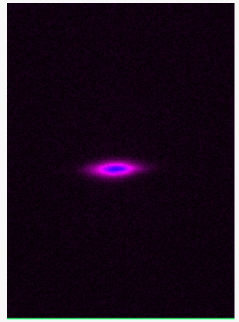
MS4
Accelerated beam



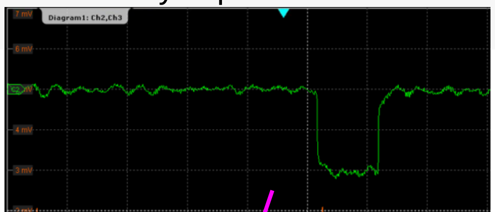
MS6
(before BM)



MS7 (after BM)
h=0.825 m



Beam-current signal at a faraday cup



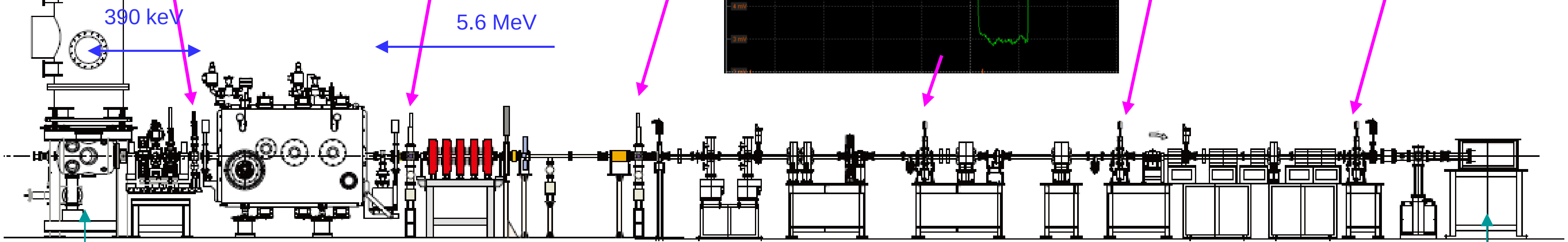


Photo-cathode DC gun

Injector cryomodule

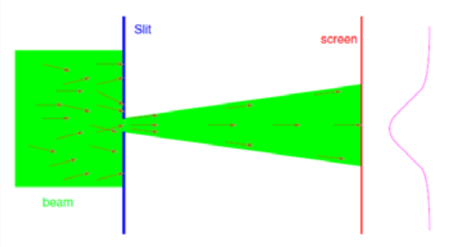
Beam

Injector beam dump

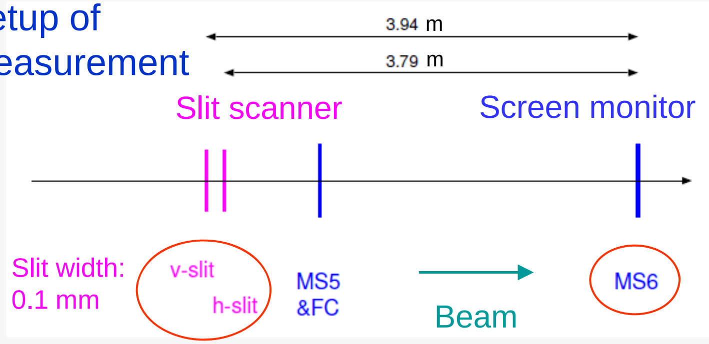
Beam Emittances of Accelerated Beams (T=5.6 MeV, low bunch charges)

Y. Honda

Slit-scan method



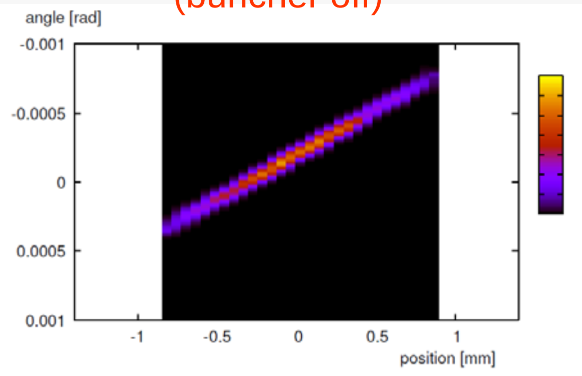
Setup of measurement



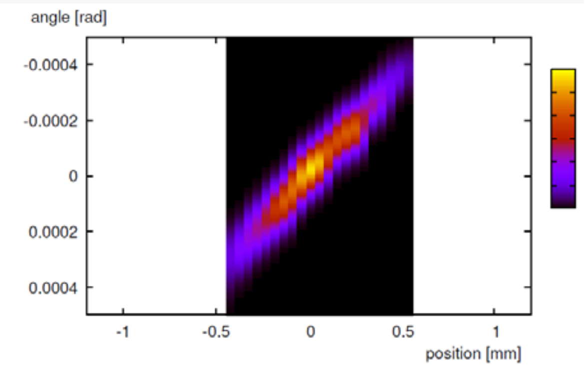
Measurement conditions:

Measured on 21-June-2013
After fine RF-phase tuning
Buncher: OFF or ON (Vc=40 kV)
Laser: short-pulse (~3 ps rms)
Bunch charges: 0.02, 0.77 pC

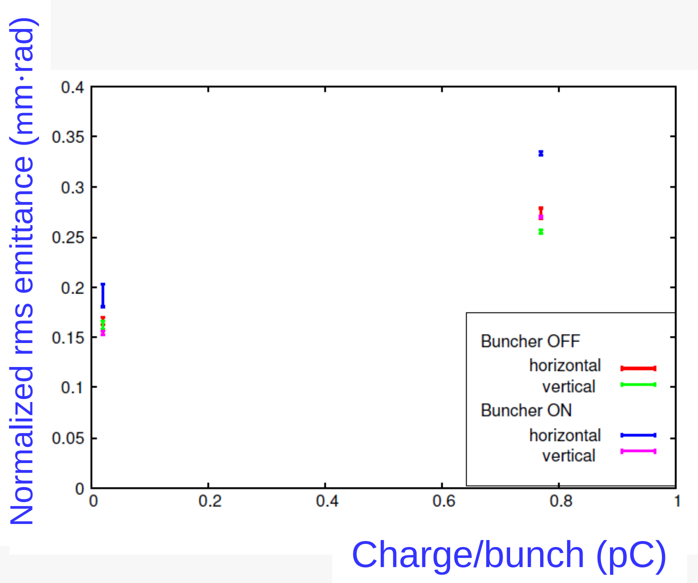
Charge: 0.02 pC/bunch (buncher off)



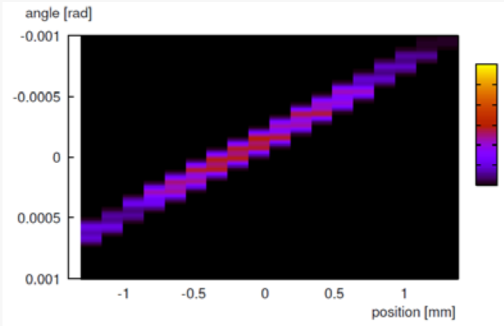
Horizontal phase-space distribution



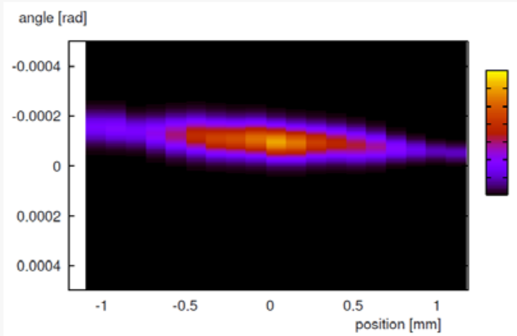
Vertical phase-space



Charge: 0.77 pC/bunch (buncher off)



Horizontal phase-space



Vertical phase-space

Results :

$\varepsilon_n \approx 0.17$ mm·rad at 0.02 pC

$\varepsilon_n \approx 0.3$ mm·rad at 0.77 pC

Emittances might be smaller due to the limitation of the measurement

Result from the Injector Commissioning (Apr. - June, 2013)

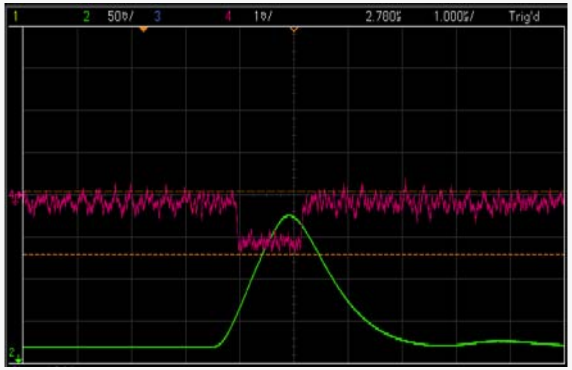
Reported in ERL13 workshop

Parameter	Achieved	Comment and Outlook
Kinetic beam energy T	5.6 MeV (typ.), 5.9 MeV (max.)	T $\leq$ 6 MeV is allowed at present.
Average Beam current I_0	300 nA (max.)	$I_0 \leq 1$ mA is allowed at present. Beam current will be increased step by step.
Gun High Voltage V_{gun}	390 kV (typ.)	Very stable for more than 200 hours. Higher voltage is expected by polishing insulating ceramics.
Accelerating gradient of injector cavities E_{acc}	7 MV/m (typ.)	CW operation. Very stable for more than 200 hours.
Normalized beam emittance (T=390 keV, low charge)	$\approx$ 0.07 μm·rad (@~10 fC/bunch)	
Normalized beam emittance (T$\approx$5.6 MeV, low charge)	$\approx$ 0.17 μm·rad (@0.02 pC/bunch)	Close to the limitation of present instrumentation. Emittance might be smaller.
Normalized beam emittance (T$\approx$5.6 MeV, high charge)	$\approx$ 0.8 μm·rad (@7.7 pC/bunch)	Further improvement is expected by optimizing machine parameters and by higher gun voltage.
Momentum jitter $(\Delta p/p)_{rms}$	6×10^{-5}	On-crest acceleration. With high rf-feedback gain.
Bunch length and energy spread	See graphs in these slides. (depend on bunch charges)	Parameters have not been optimized yet under space-charge effect.

IV. Commissioning of the Compact ERL

(Dec. 2013 - Mar. 2014)

Commissioning of the cERL started on 16 Dec., 2013



Beam was successfully accelerated up to 20 MeV in the main linac, decelerated, and transported to the entrance of dump line (Dec. 16-20, 2013)

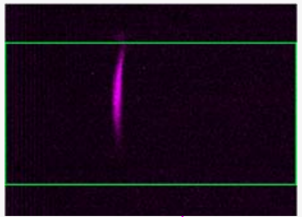
Beam energy (*E*)
- Injector: 3.4 MeV
- Recirculation loop: 19.9 MeV

Parameters
- Gun voltage: 390 kV Buncher: OFF
- Injector cavities: E_{acc} = (3.6, 3.6, 3.4) MV/m
- Main-Linac cavities: V_c = (8.3, 8.3) MV

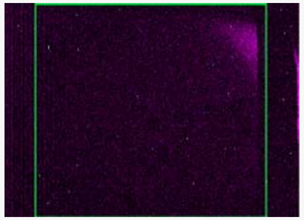
Beam pulses (macropulse beams)
- peak current: ~20 μA
- macropulse width: 1.2 μs
- repetition of bunches: 1.3 GHz
- repetition frequency: 3 Hz
- average beam current: ~ 70 pA

Beam profiles observed with screen monitors

MS14

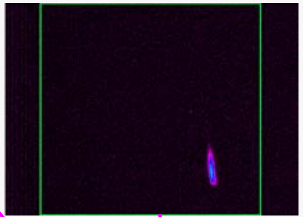


MS31 (dump line)

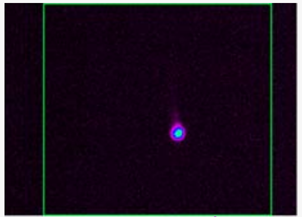


At this time, we could not transport beams to the dump.

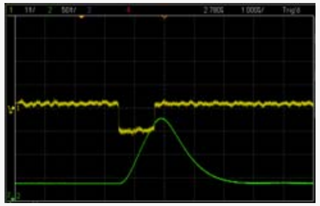
MS11



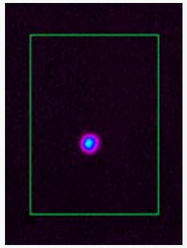
MS3

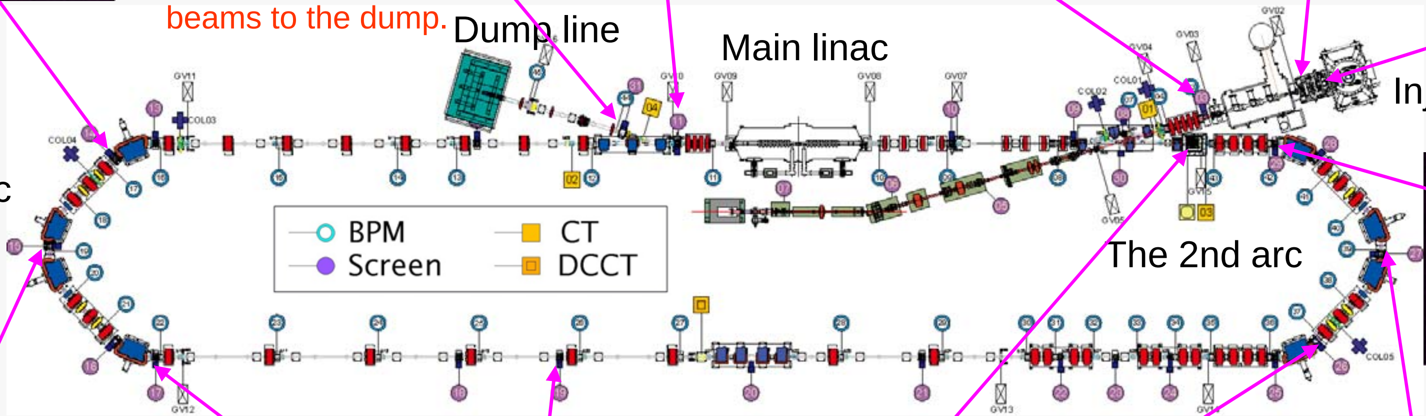


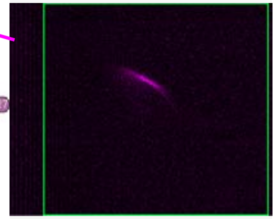
Gun FC (faraday cup)



MS1

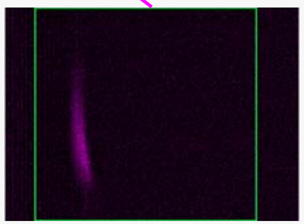




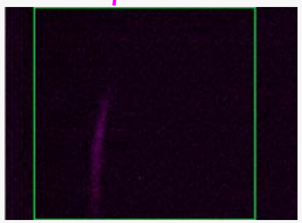


MS29

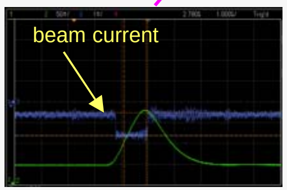
MS15



MS17

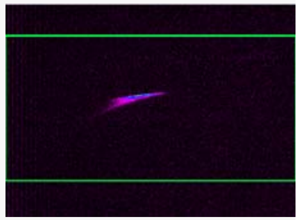


MS19



Movable FC

MS26



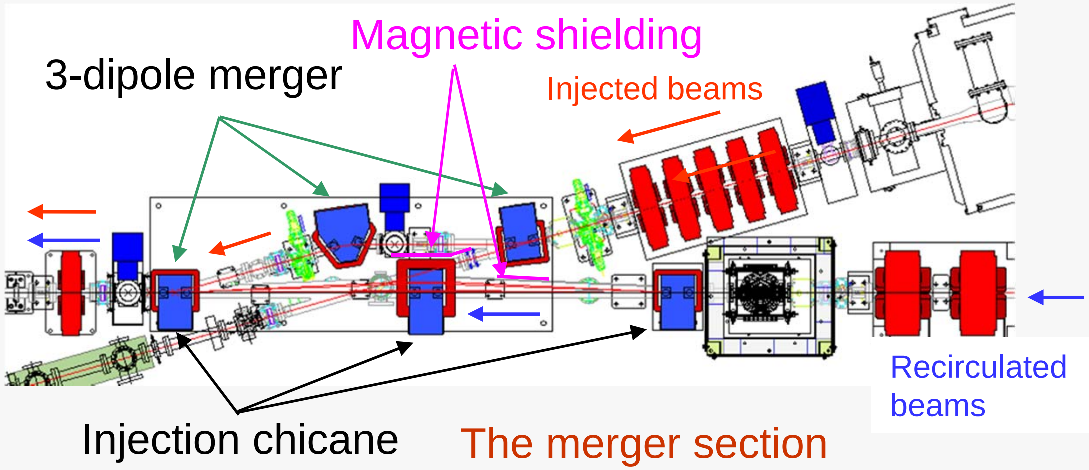
MS27

Problems and Cures during/after the Initial Commissioning (5 days)

1. Magnetic isolation between “merger” and “injection chicane”

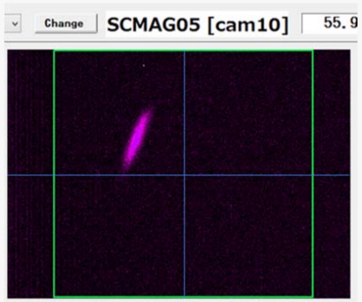
   $p_{inj} \sim 3$ MeV/c

   Also in the dump line



2. Removal of stray magnetic fields due to (four) CCG’s in the merger section.

   Maybe some other sources.



Unwanted x-y coupling (at an entrance of the main-linac cavity).

CCG (after removed its magnet)

3. Increased momentum ratio:

   $p_{recirculation}/p_{injection} = 6 \rightarrow 7$

   Easy to monitor in the injection chicane

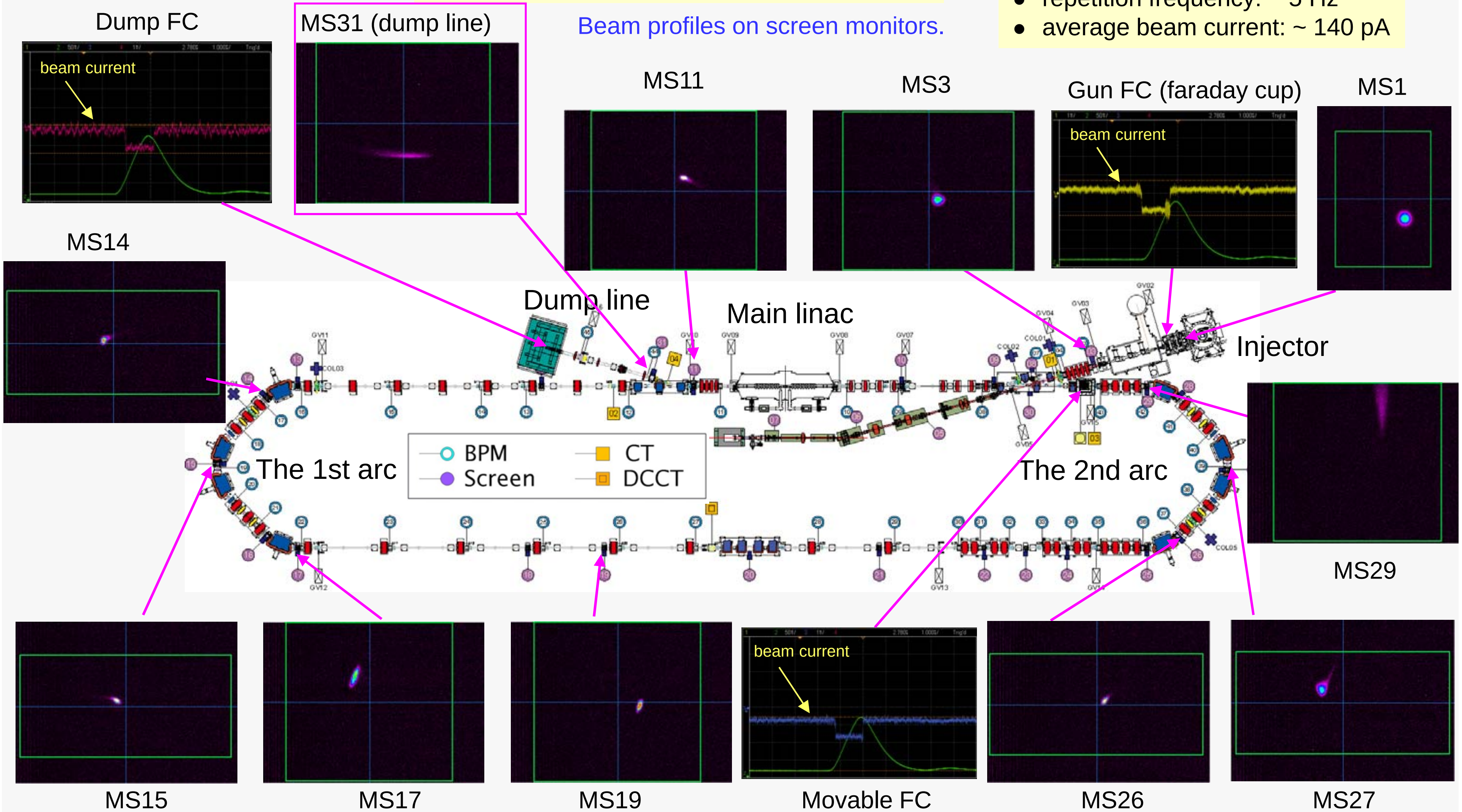
Beam was first transported to the dump.
(Feb. 6, 2014; the 11th day)

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: Vc = (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

Beam profiles on screen monitors.



CW beams of up to 6.5 μA was recirculated

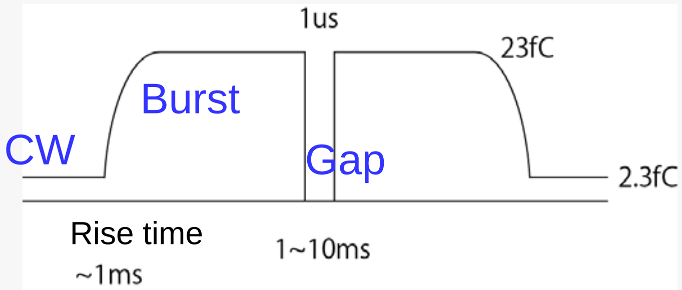
Typical parameters (Mar. 14, 2014)

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

Parameters
- Gun voltage: 390 kV Buncher: V_c = 30.7 kV
- Injector cavities: E_{acc} = (3.2, 3.3, 3.1) MV/m
- Main-Linac cavities: Vc = (8.58, 8.59) MV

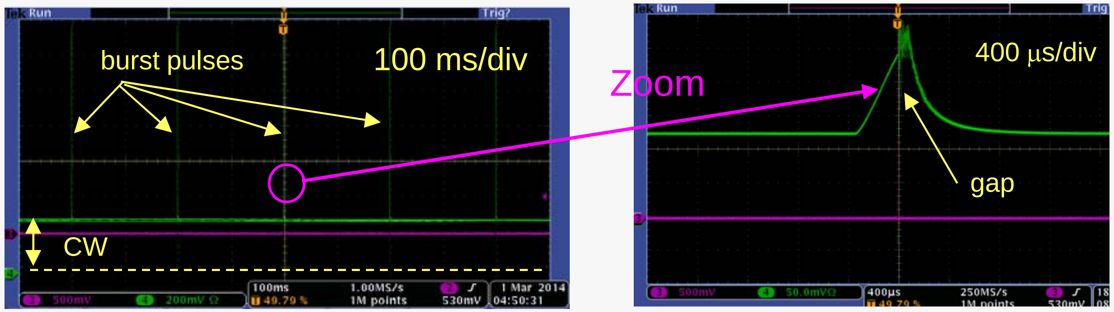
Beam conditions:
- CW (with burst & gap for beam position measurement)
- Repetition of bunches: 1.3 GHz

Beam current: CW + burst + gap



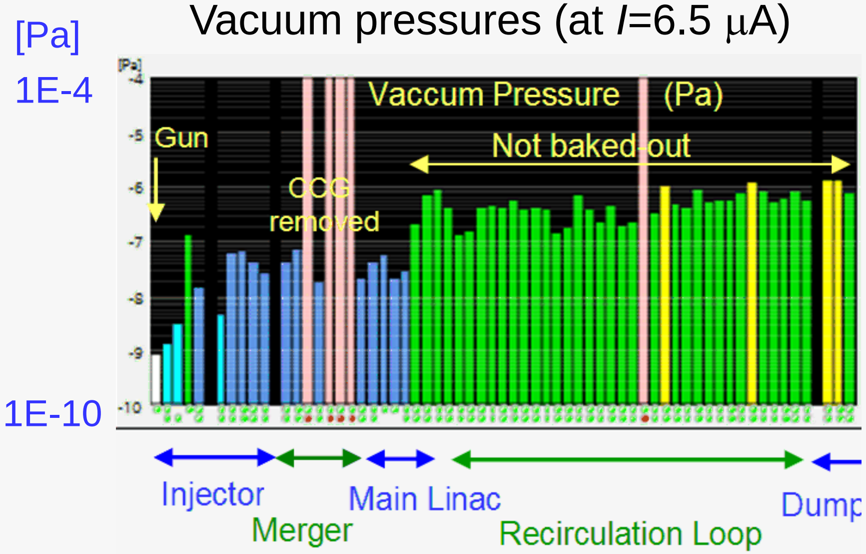
To measure the beam positions easily (by Y. Honda and T. Obina)

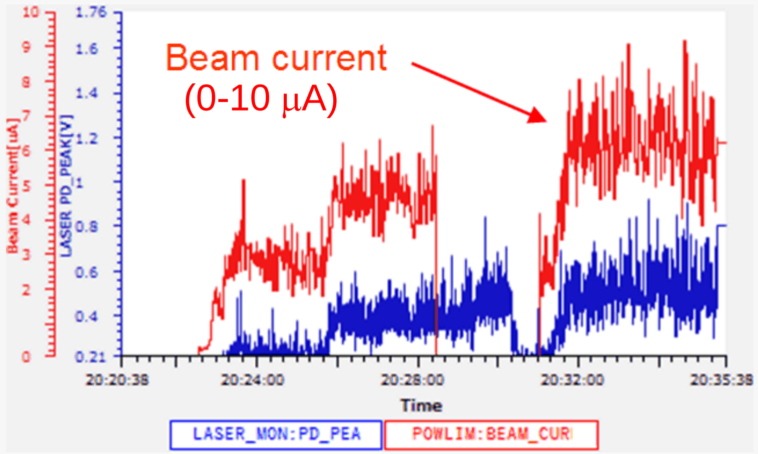
Green traces: laser waveform detected by a photodiode



(notice: above two pictures were taken in different day)

Vacuum pressures (at I=6.5 μA)



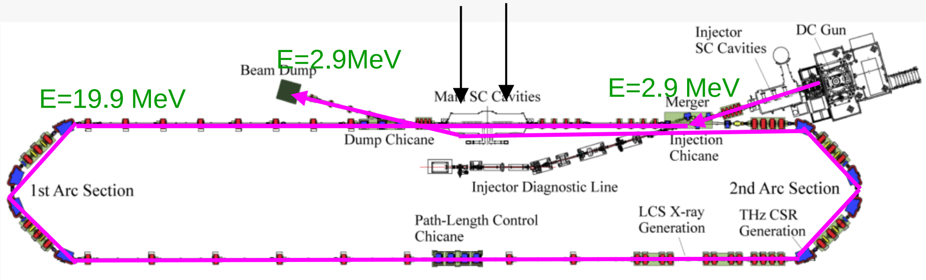


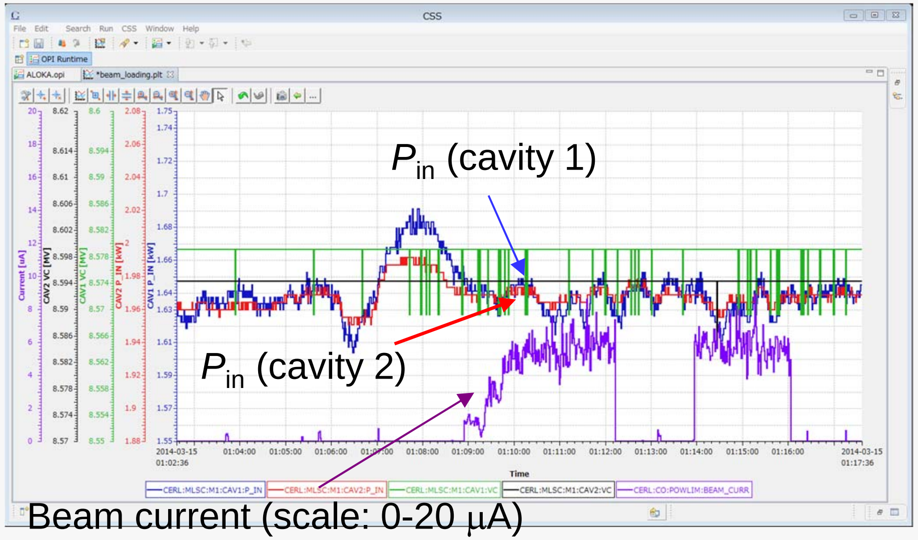
Confirmation of Energy Recovery in the Main-Linac Cavities（Mar. 14, 2014）

K. Umemori et al.

ERL operation

Cavity 1 and 2: acceleration (1st passage) and deceleration (2nd passage)



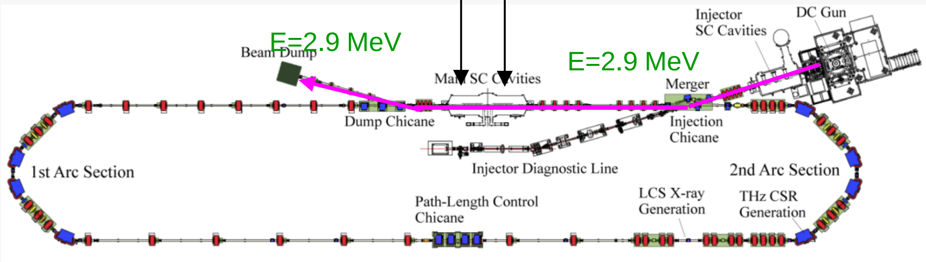


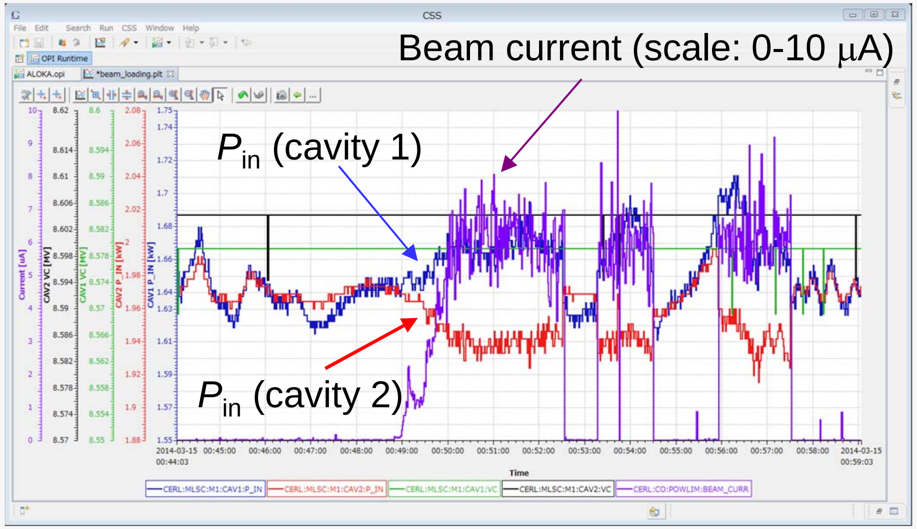
Change in input RF powers of the main-linac cavities when the beam current increased. Cavity voltages were kept constant. Scale: P_{in} (cavity 1): 1.55-1.75 kW, P_{in} (cavity2): 1.88-2.08 kW, Beam current: 0-20 μA.

Non-ERL operation (reference)

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

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

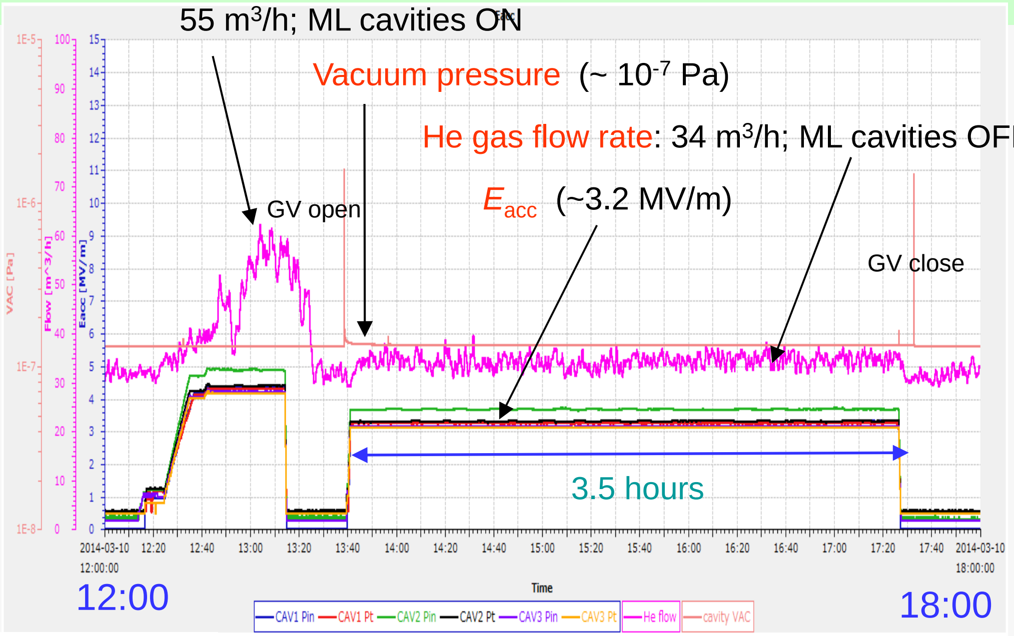


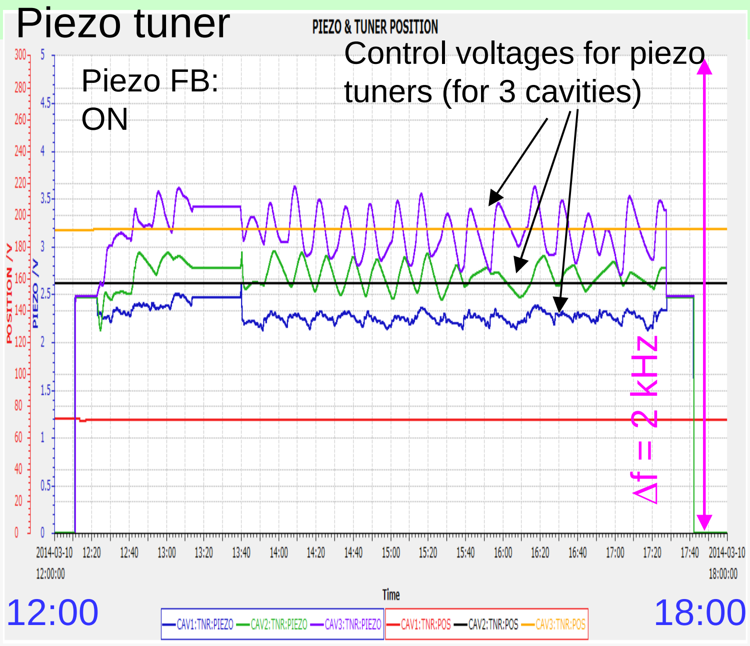


Change in the input RF powers of the main-linac cavities when the beam current increased. Cavity voltages were kept constant. Scale: P_{in} (cavity 1): 1.55-1.75 kW, P_{in} (cavity2): 1.88-2.08 kW, Beam current: 0-10 μA.

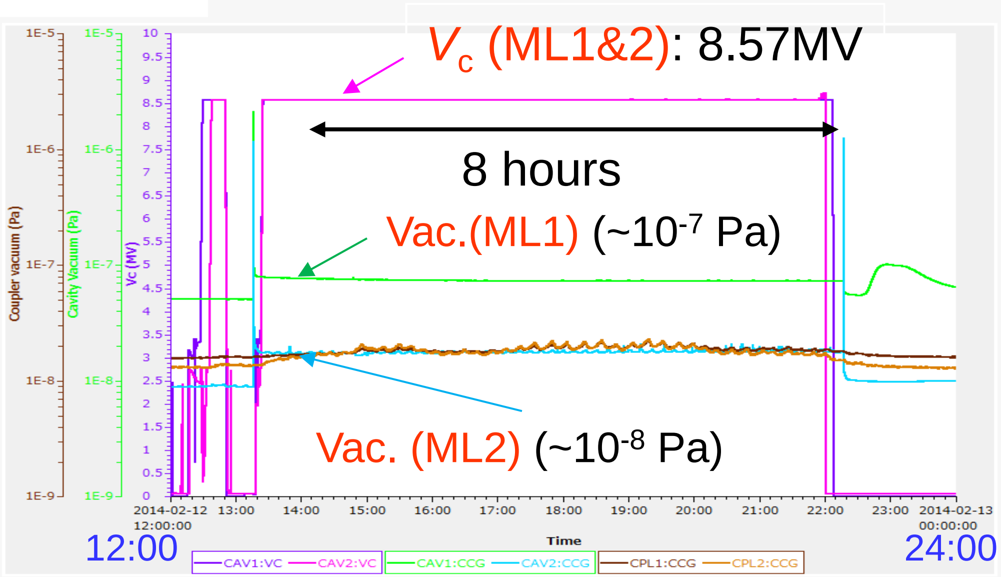
Both injector and main-linac cavities worked very stably

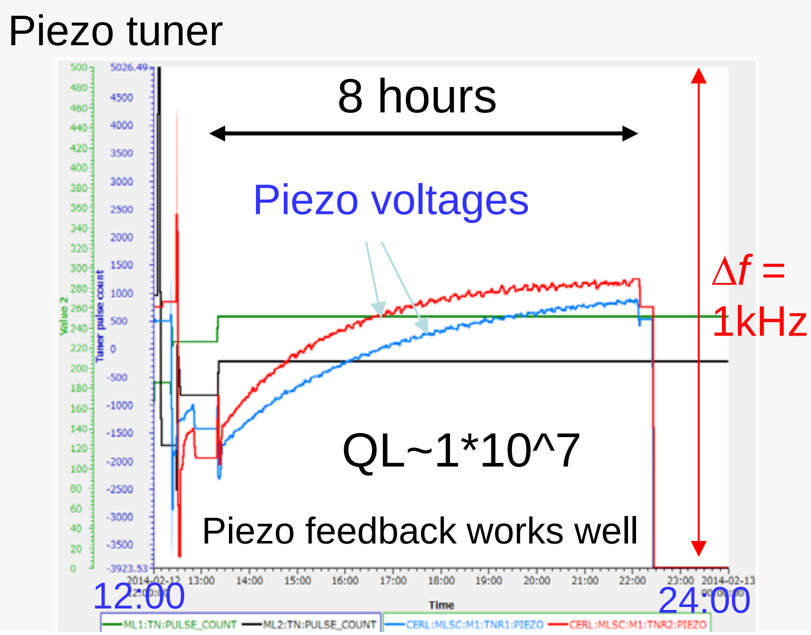
Injector





Main linac

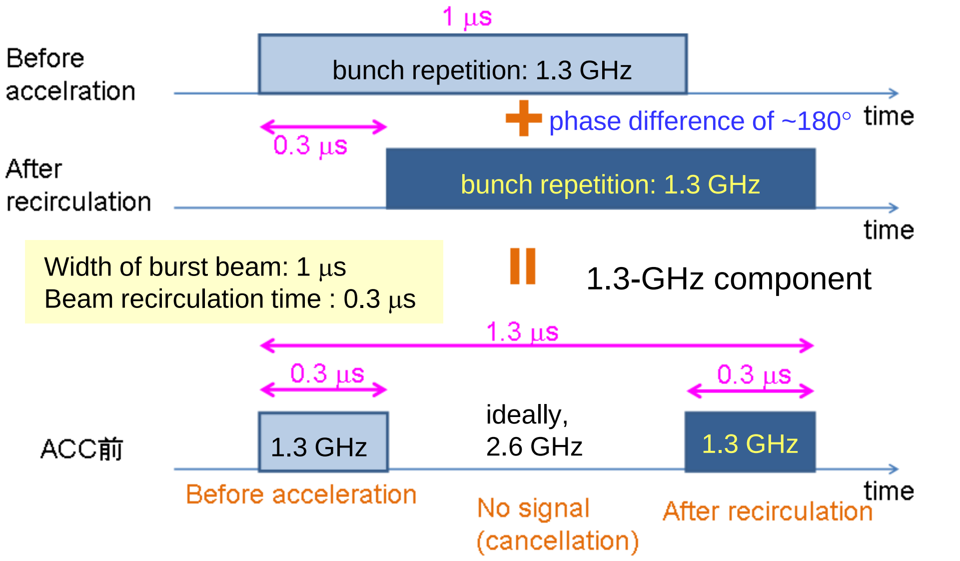




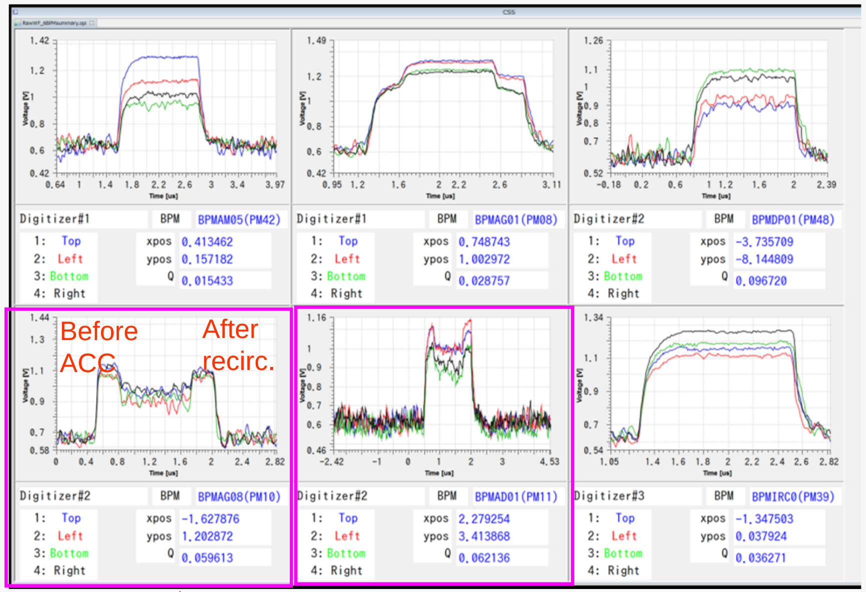
Beam position monitors in the main-linac (ML) section where two overlapped beams pass

T. Obina

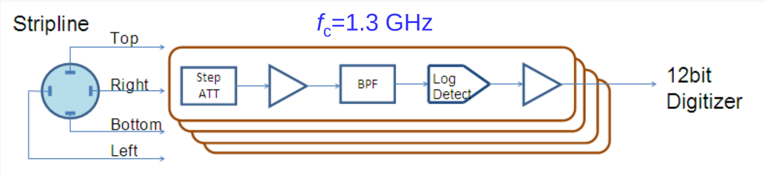
Method of BPM for two beams (burst mode)

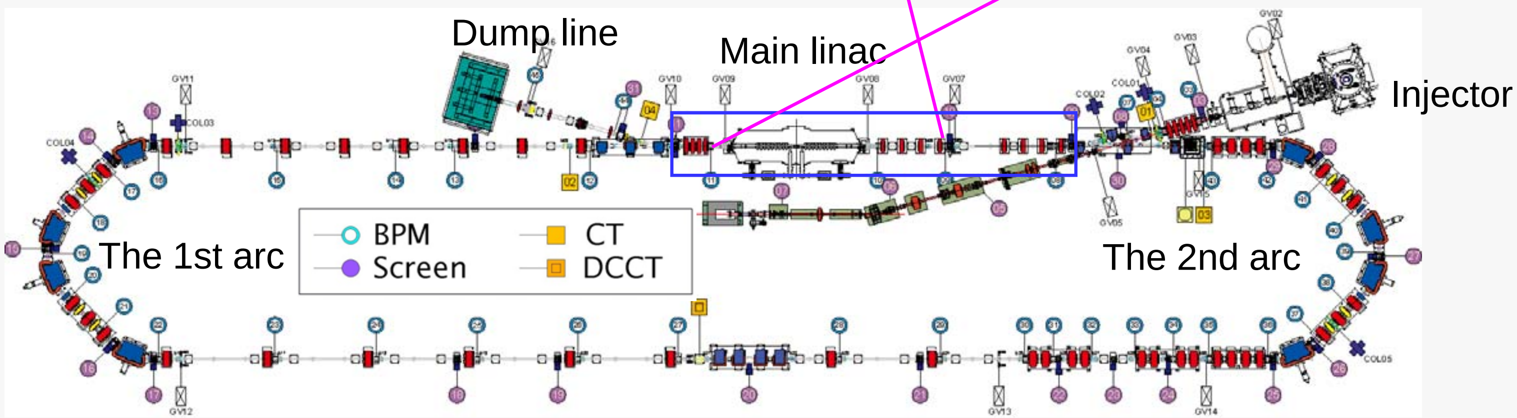


Signals from 4-stripline electrodes; after log amp (Feb. 6, 2014)



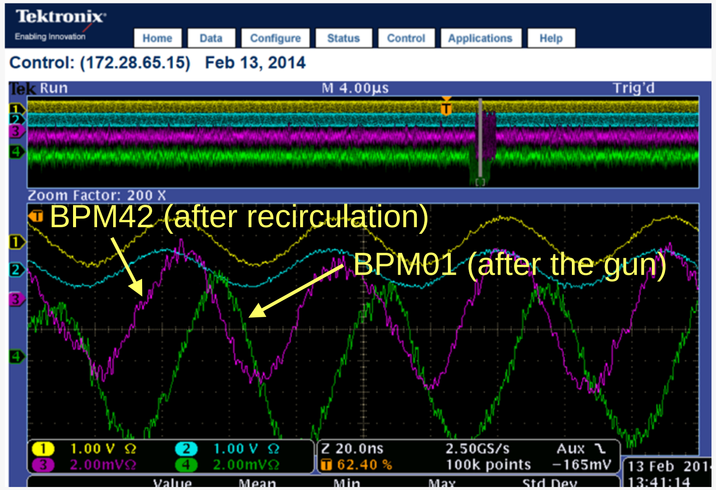
Block diagram





Monitor and Control of Recirculation Time

1. Detection of phase difference between two BPM signals Y. Honda



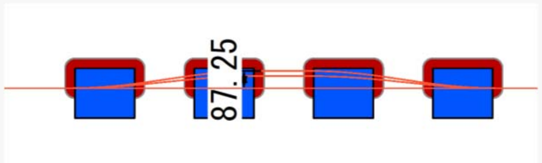
(20 MHz)

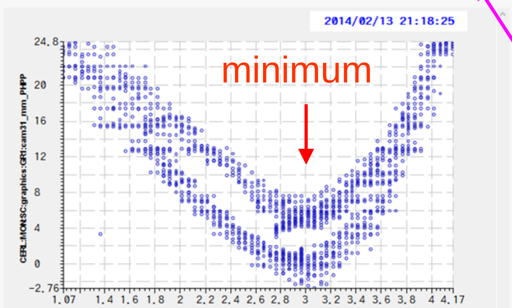
L.O.

DOWN CONVERTER
1.3 GHz → 20 MHz

2. Path-length control

(1) Chicane

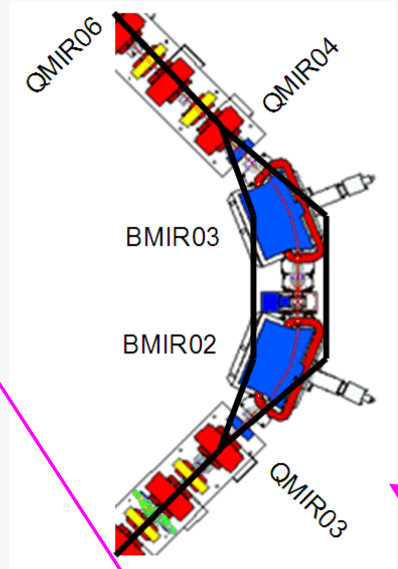


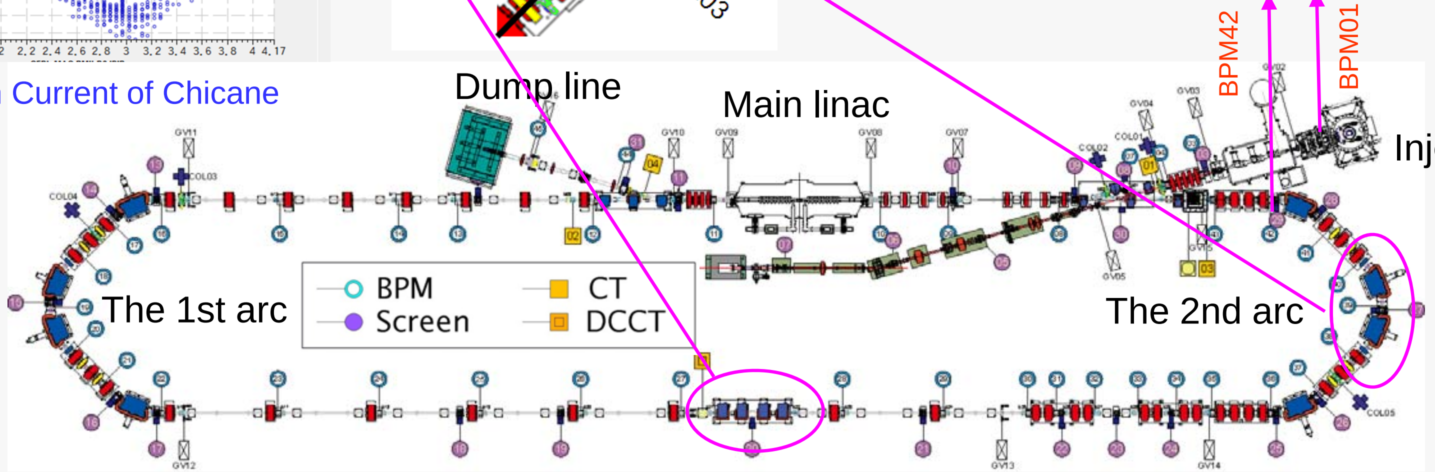


Momentum of dump beam

Excitation Current of Chicane

(2) 2nd arc



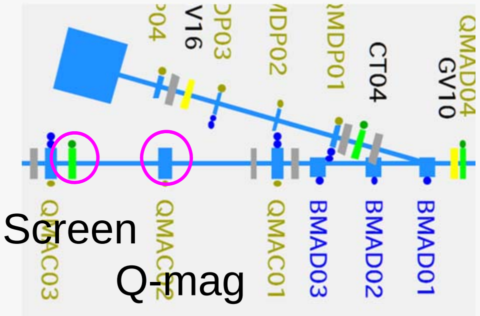


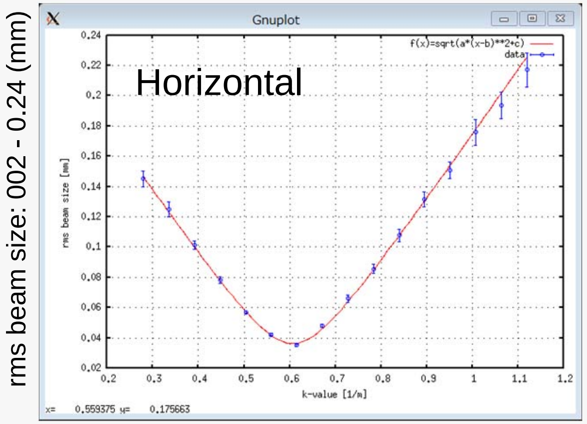
Measurement and Tuning of Beams

Beam emittance measurement: Q-scan method

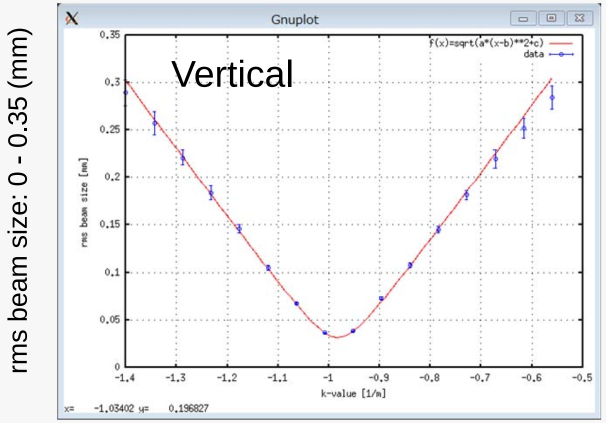
R. Takai

Results are in analysis





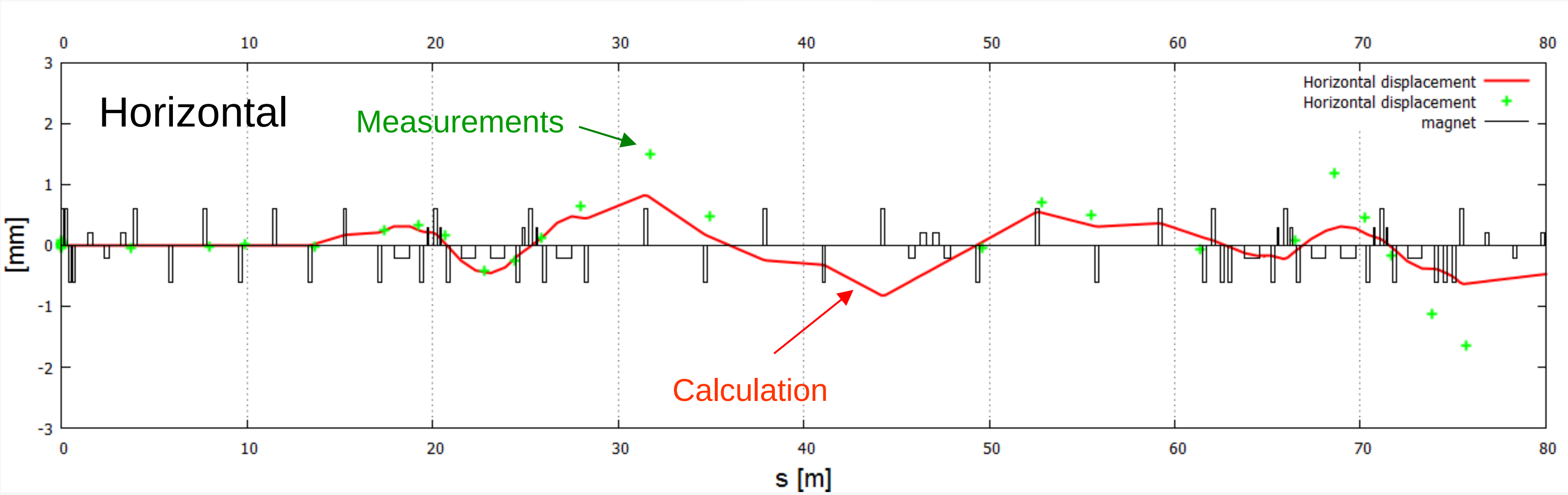
k-value: 0.2 to 1.2 (m^{-1})



k-value: -1.4 to -0.5 (m^{-1})

Single-kick response measurement

M. Shimada et al.



Statistics of cERL Operations (Apr. 2013 - Mar. 2014)

* Including conditioning

Month	Machine Operation Time* (hours)	Beam ON Time (hours)	Operation Time of Helium Refrigerator (hours)
Injector commissioning (Apr. - June, 2013)			
Apr. 2013	92	24	185
May 2013	111	70	291
June 2013	157	106	315
Subtotal	361	202	792
cERL commissioning (Dec. 2013 - , Mar. 2014) * conditioning was done in Nov. 2013			
Nov. 2013	59	0	489
Dec. 2013	113	36	480
Jan. 2014	49	11	418
Feb. 2014	211	121	672
Mar. 2014	113	71	345
Subtotal	487	240	2404
Total	848	442	3196

V. Conclusion

- The Compact ERL was completed and commissioned in Dec., 2013.
  - It was within two years after starting the assembly of injector module.
- The commissioning progressed very smoothly. Both injector and main-linac cavities worked very stably.
- We have so far achieved:
  - acceleration of beams up to 20 MeV using a main-linac cryomodule (8.6 MV/cavity $\approx$ 8.3 MV/m)
  - recirculation, deceleration, and transportation of beams to the dump (i.e. ERL operation)
  - recirculation of CW beams up to 6.5 μA
  - confirmation of energy recovery (with rough accuracy)
- Measurement and tuning of beams are under way

Prospect

- We will continue accelerator study to achieve the goals for the 3-GeV ERL.
  - beam current will be increased in stages: $\rightarrow$ 100 μA $\rightarrow$ 1 mA $\rightarrow$ 10 mA
- X-ray production by Laser Compton Scattering (LCS):
  - Laser system and beamline will be installed in 2014 (by JAEA and by the Photon and Quantum Basic Research Coordinated Development Program)
- Terahertz beamline for users is under consideration.

VI. Acknowledgment

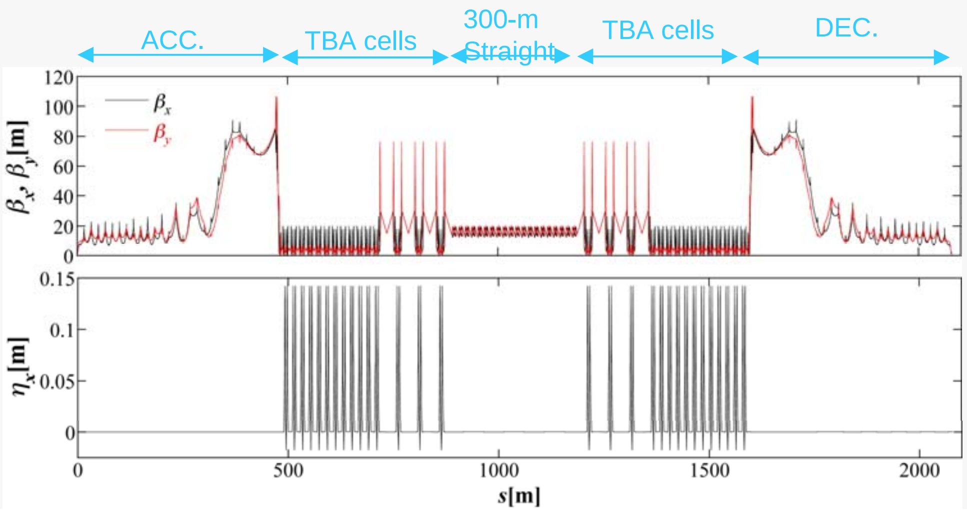
We are grateful to the Cornell University, Argonne National Laboratory, Jefferson Lab., TRIUMF, HZDR, HZB, ASTeC, and the other institutes, for useful discussions, advices, or collaboration.

Backup Slides

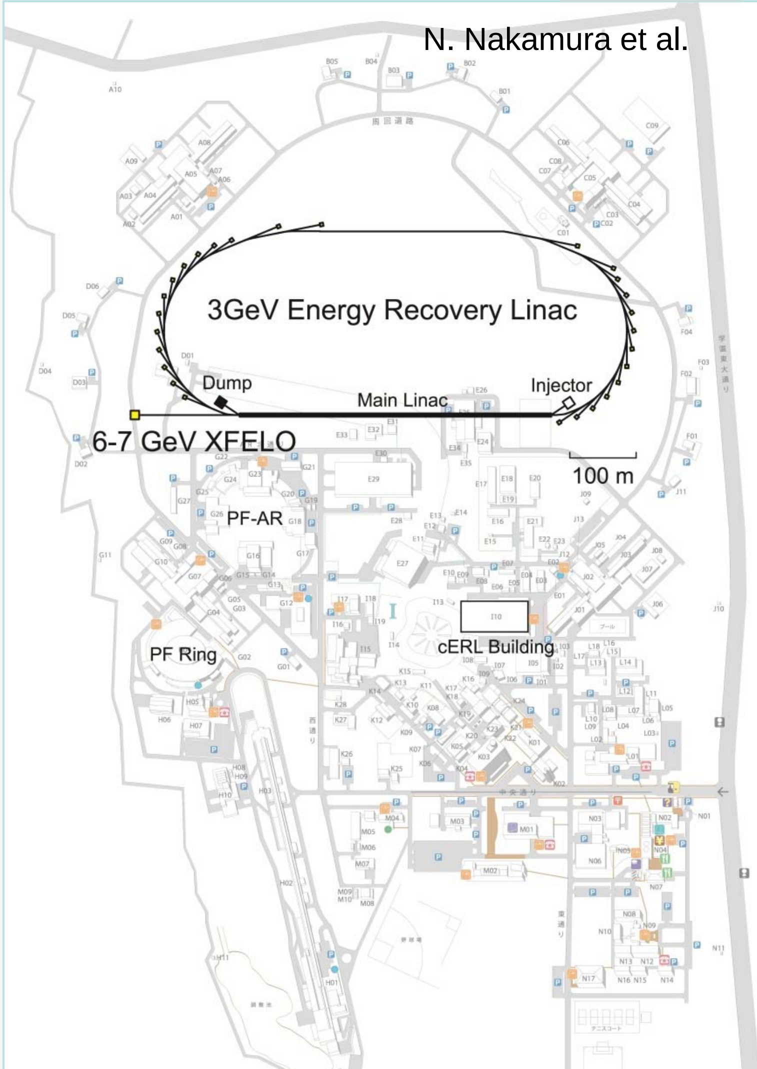
Tentative Design of 3-GeV ERL

Typical parameters

Parameter	3-GeV ERL	XFEL-O
Beam energy E	3 GeV	6-7 GeV
Injection energy E_{inj}	10 MeV	10 MeV
Average beam current I_0	10 - 100 mA	20 μA
Charge/bunch q_b	7.7 - 77 pC	20 pC
Bunch repetition rate f_{rep}	1.3 GHz	1 MHz
Normalized beam emittance ε_n	0.1 - 1 mm·mrad	0.2 mm·mrad
Bunch length (rms) : normal : ultra-short	2 ps < 100 fs	1 ps
RF frequency f_{rf}	1.3 GHz	1.3 GHz
E_{acc} in main linac (tentative); in CW	13.4 MV/m	13.4 MV/m

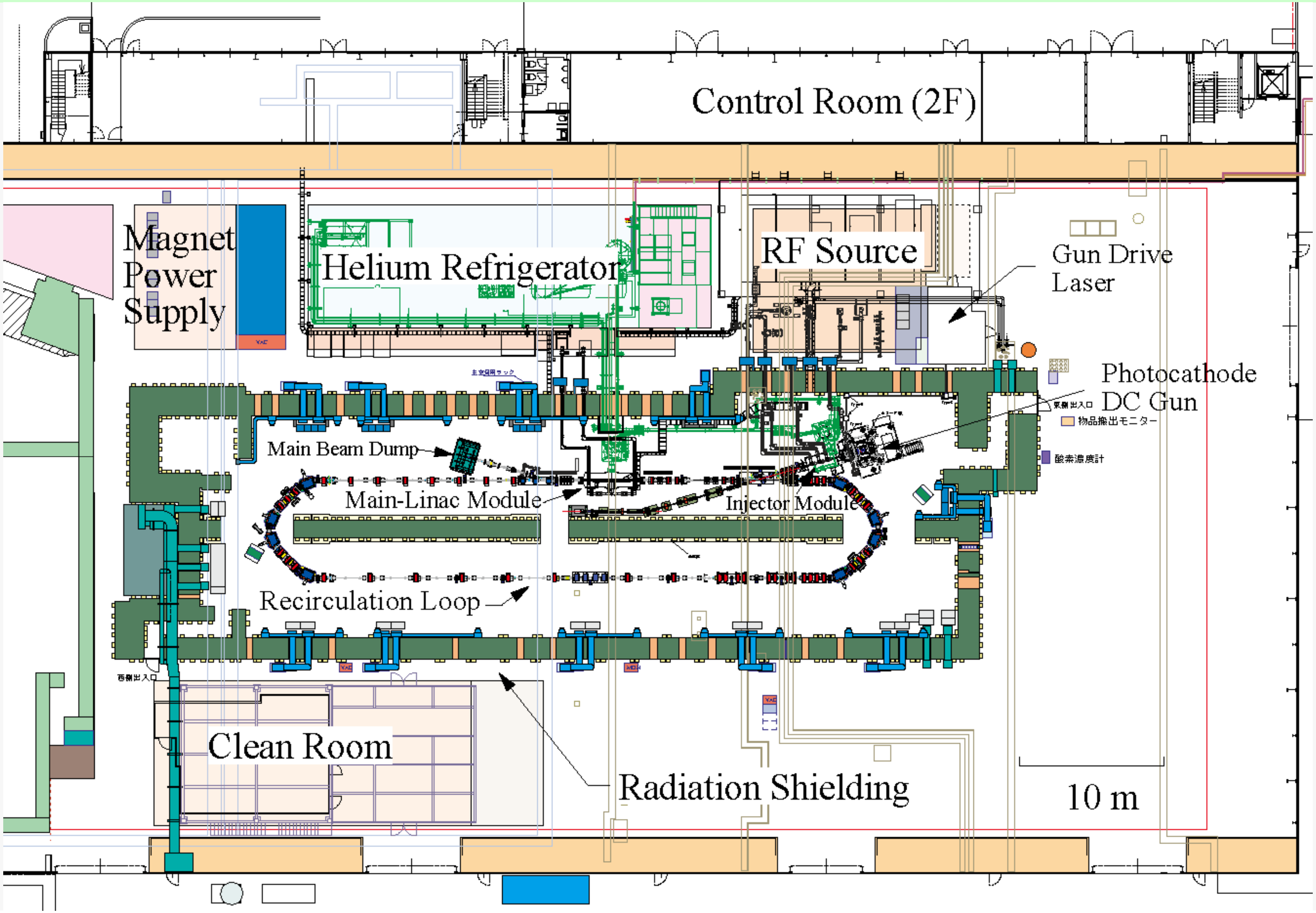


N. Nakamura et al.



Layout at KEK Tsukuba Campus

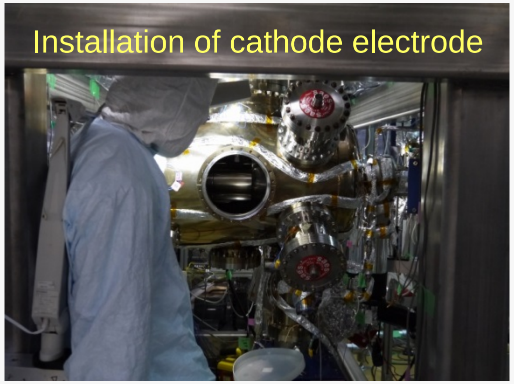
Layout of cERL (March, 2014)



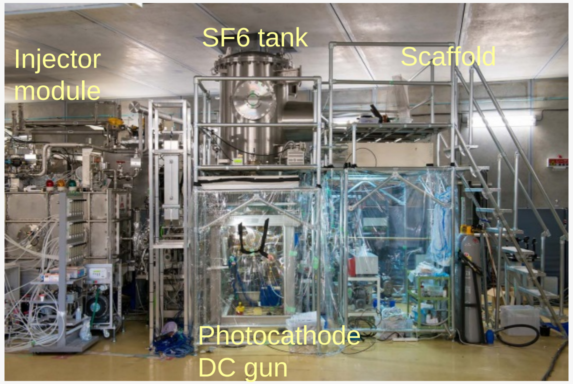
Construction of cERL (2012-2013)

Installation of 500-kV photocathode DC gun #1 (Oct. 2012 - Mar. 2013)

Oct. 2012



Mar. 2013



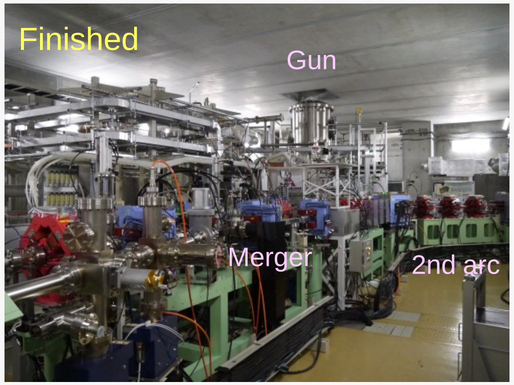
Finished in Mar. 2013

38

Installation of vacuum chambers (Sep.-Oct., 2013)

Sep. 2013

Oct. 2013



Finished

Typical Operation Parameters of cERL during the Commissioning

Parameter	Value
Beam energy of injector E_{inj}	2.9 MeV
Beam energy in recirculation loop E_{recirc}	19.9 MeV
Momentum ratio p_{recirc}/p_{inj}	7 (or 6)
Maximum beam current I_{max}	6.5 μA (CW)
Gun voltage V_{gun}	390 kV
Accelerating gradient of injector cavities $E_{acc,inj}$ (for recirculation) (for individual operation of injector)	3.3 MV/m typ. 7.0 MV/m typ.
RF voltage of main-linac cavities $V_{c,ML}$ ($V_c = 1.038 \times E_{acc}$)	8.6 MV/cavity typ.
Typical macropulse-beam for beam tuning	pulse width: 1.2 μs, 15 fC/bunch, 5 Hz
Repetition frequency of bunches	1.3 GHz

* Beam properties (emittance, ...) are in analysis.