# Construction and Commissioning of Compact-ERL Injector at KEK

Shogo Sakanaka (KEK)
for ERL Development Team in Japan

ERL-2013, 9 -13 September, 2013, at BINP, Novosibirsk, Russia

Slide v2

# ERL Development Team in Japan

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# Outline

I. KEK “PEARL” project and status of Compact ERL

II. Commissioning of cERL injector

III. Construction status of return loop

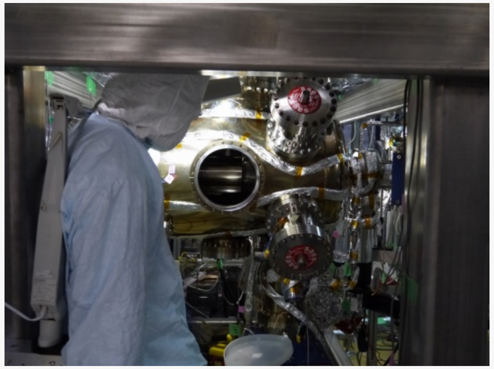
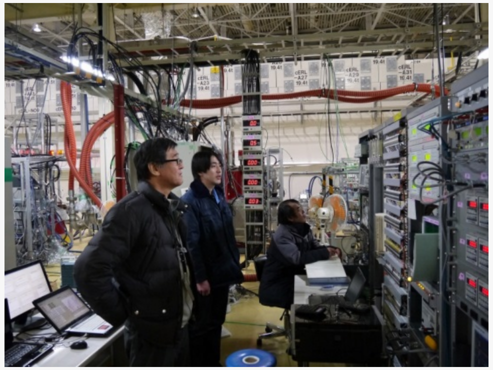
IV. Conclusion

V. Acknowledgment

# I. KEK “PEARL” Project and Status of Compact ERL





# ERL Light Source Project (PEARL) at KEK

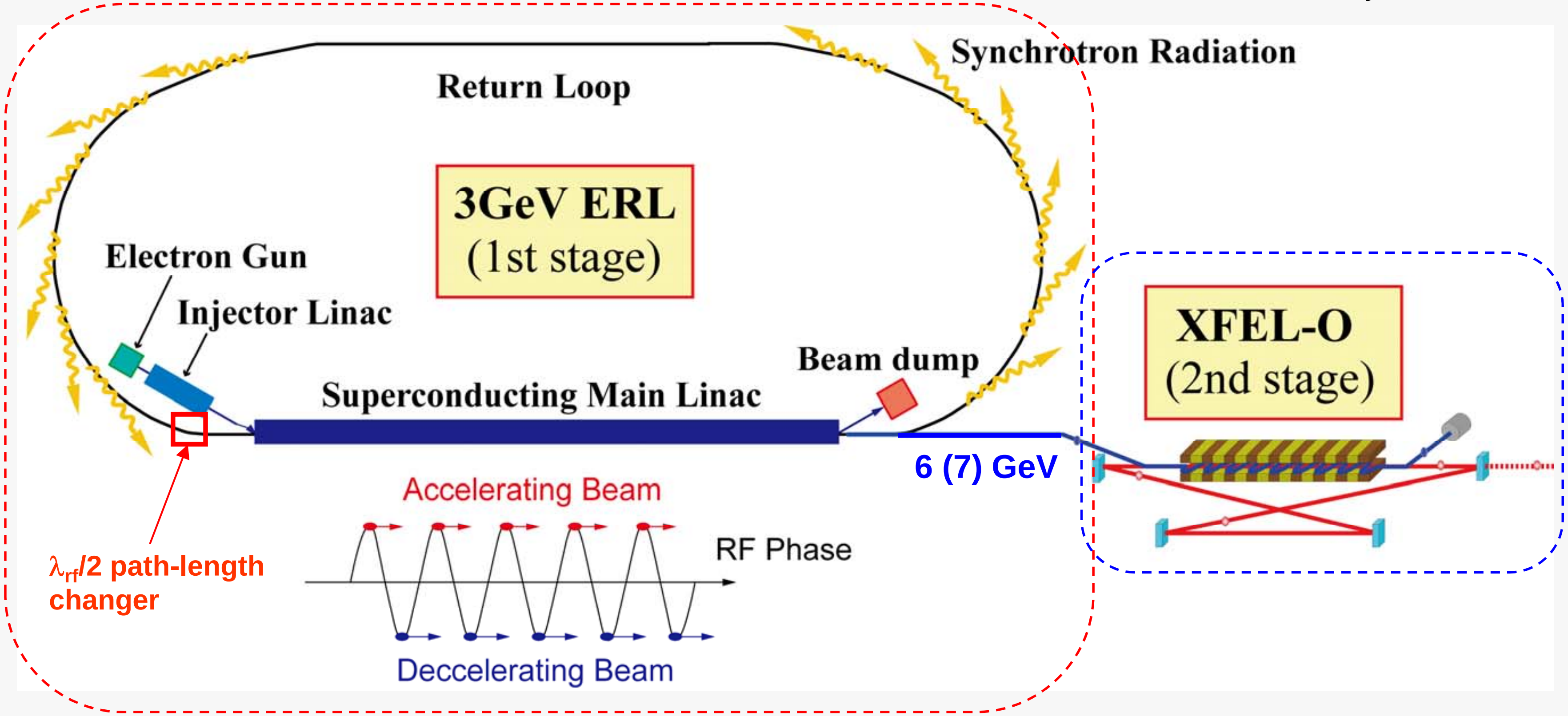
ERL-based Light Source Project at KEK (2 Stages)

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

② 6-7 GeV XFEL Oscillator

PEARL
Photon Factory

Photon Factory ERL
Advanced Research
Laboratory



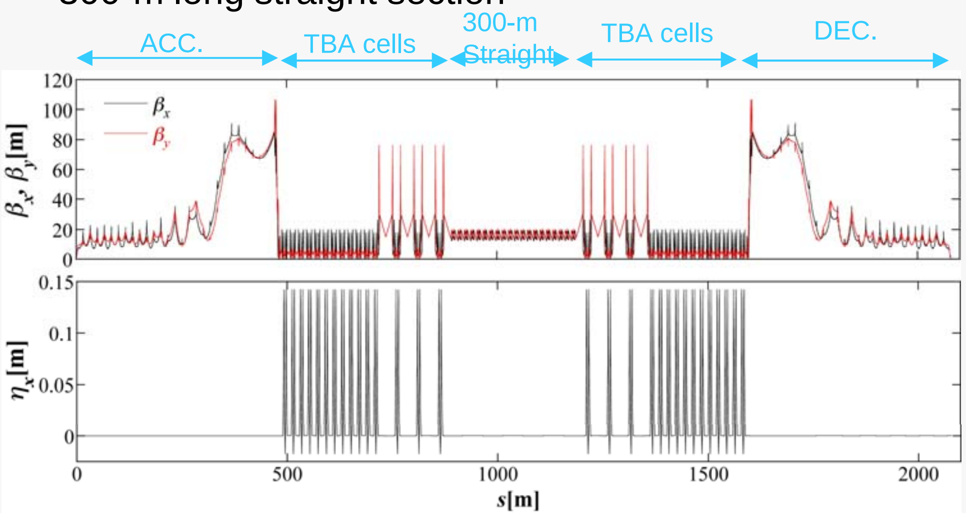


[1] “Energy Recovery Linac Conceptual Design Report”, KEK Report 2012-4 (Oct. 2012); http://ccdb5fs.kek.jp/tiff/2012/1224/1224004.pdf

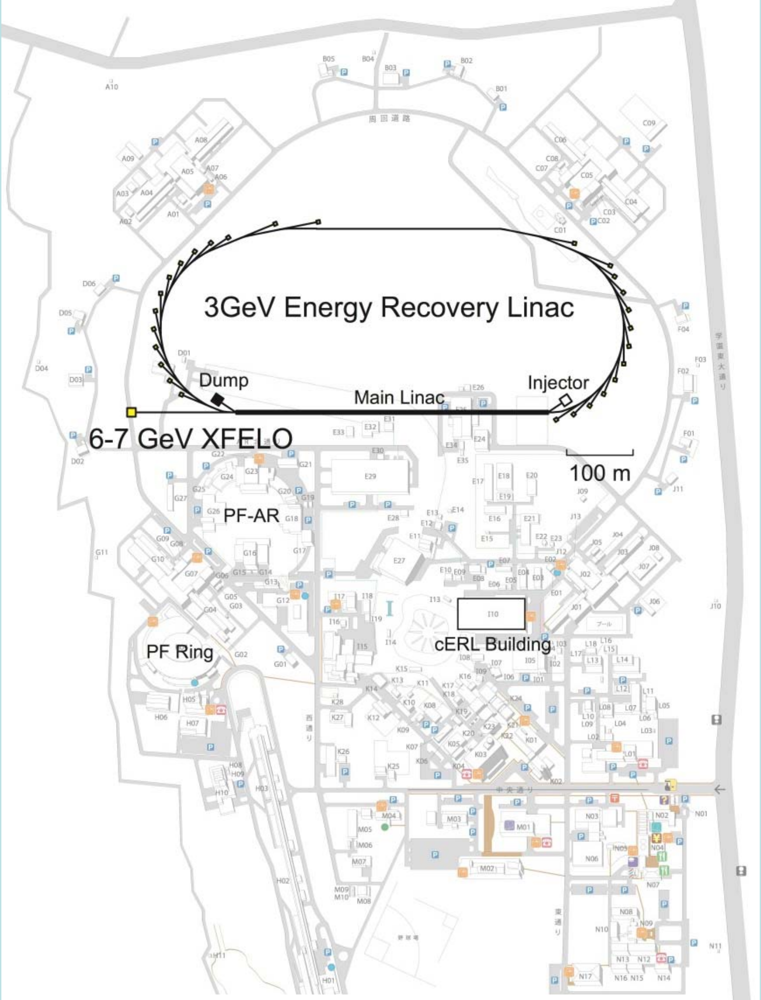
# Tentative Design of 3-GeV ERL

Assumptions:

- Beam energy
  - Full energy: 3 GeV
  - Injection and dump :10 MeV
  - XFEL-O: 6-7 GeV
- Circumference : ~ 1600 m
- Main linac
  - Eight 9-cell cavities in a cryomodule
  - 28 cryomodules (224 cavities)
  - Cavity acc. gradient : 13.4 MV/m
  - Triplet QMs between cryomodules
  - Total length : ~ 470 m
    (average acc. gradient : 6.4 MV/m)
- TBA cells for ID's
  - 22 x 6 m short straight sections
  - 6 x 30 m long straight sections
- 300-m long straight section




By N. Nakamura, M. Shimada, and Y. Kobayashi



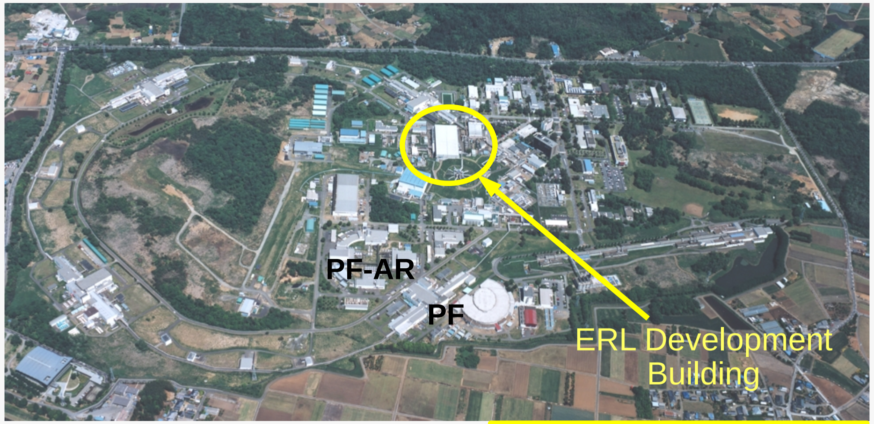

Layout at KEK Tsukuba Campus

# Purpose of the Compact ERL (cERL) at KEK

- To demonstrate generation, acceleration, and recirculation of low-emittance, high-current beams, which are needed to construct the 3-GeV ERL.
- To demonstrate stable operation of critical components such as the photocathode DC gun and superconducting cavities
- Initial goal: normalized emittance of 1 mm·mrad @7.7pC/bunch (10mA), 35 MeV
- After commissioning, use cERL as laser-Compton X-ray source and high-intensity terahertz source

## Design parameters of cERL

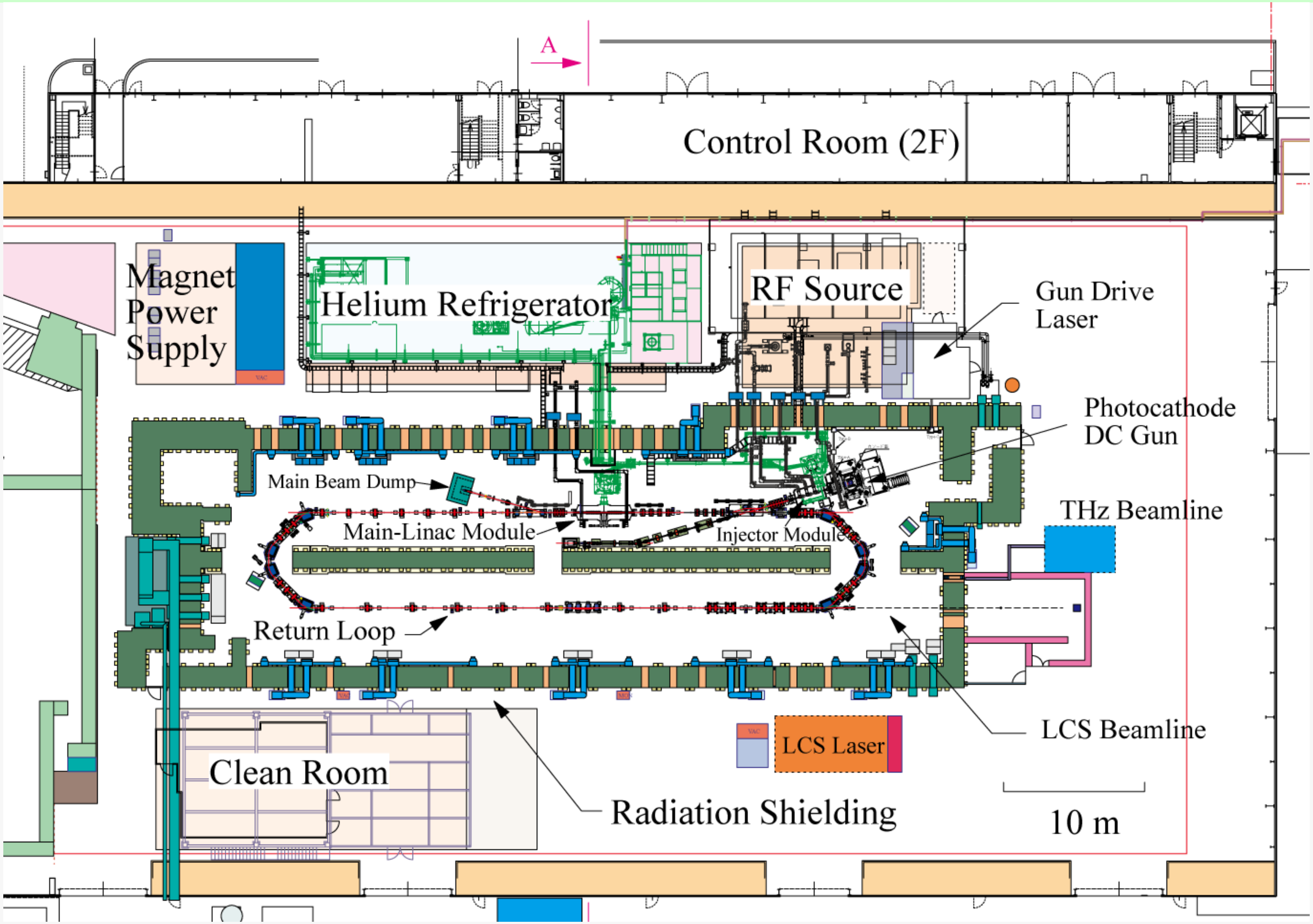
| Parameter | Goal (future goal in () ) |
|---|---|
| Beam kinetic energy | 35 MeV (upgradable to 125 MeV) |
| Injector kinetic energy | 5 MeV (10 MeV) |
| Average current | 10 mA (100 mA ) |
| Normalized emittance @bunch charge | 0.3 mm·mrad @7.7 pC<br>1 mm·mrad @77 pC |
| Bunch length (rms) | 1 - 3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



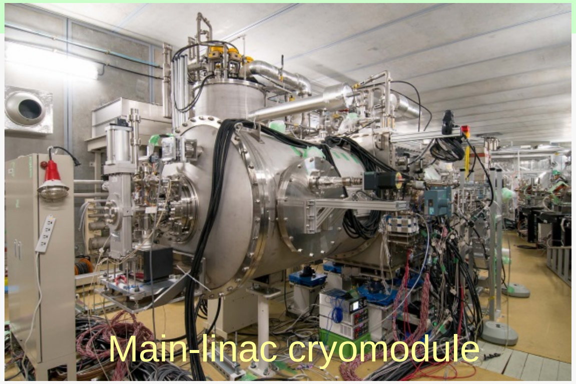

**Construction Site@KEK**

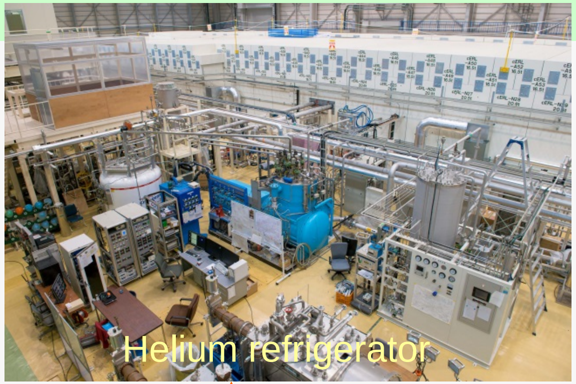
Commissioning of injector started in April, 2013.

# Layout of cERL (plan)

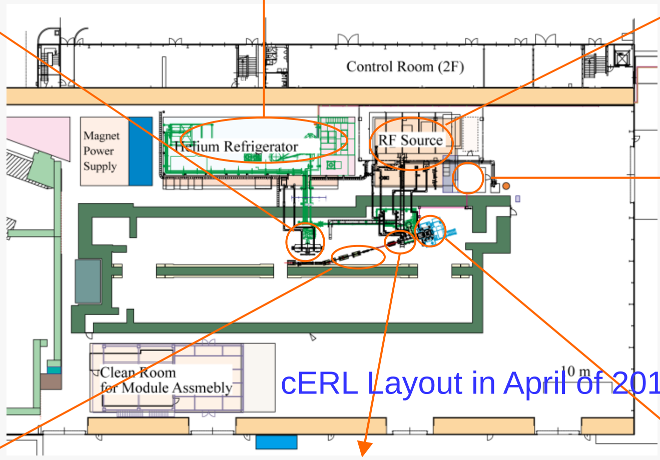


# cERL Injector was completed (April, 2013)



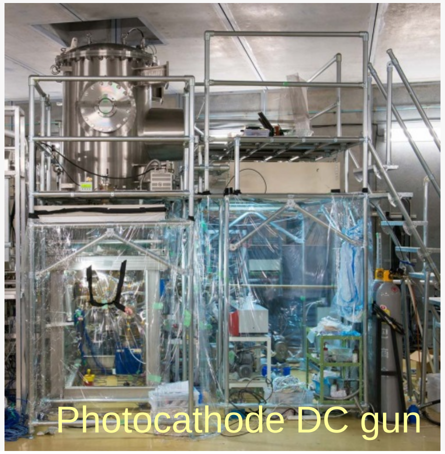











# 500-kV Photocathode DC gun (#1) at JAEA

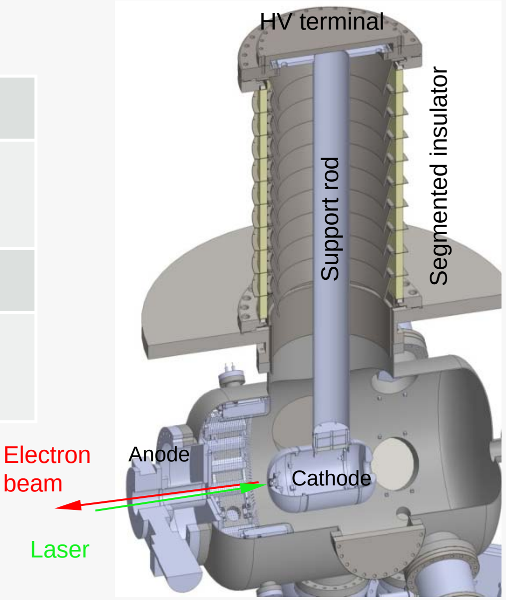
Nishimori's Talk

## Ideas

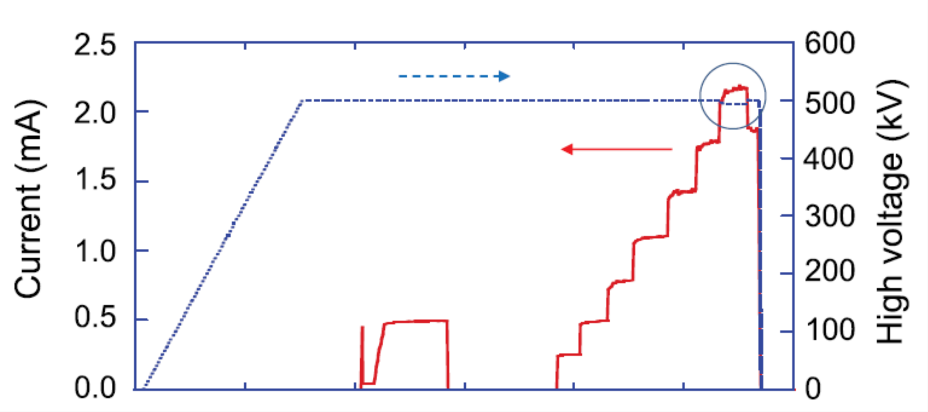
- Segmented insulator for protecting ceramics
- Measures for avoiding big sparks
  - Improved pumping speed
  - Increasing anode-cathode gap: 100 → 160 mm ($E$: 6.7 → 5.8 MV/m)

## Goals

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




**Successful production of 500-keV, 1.8 mA beam**




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

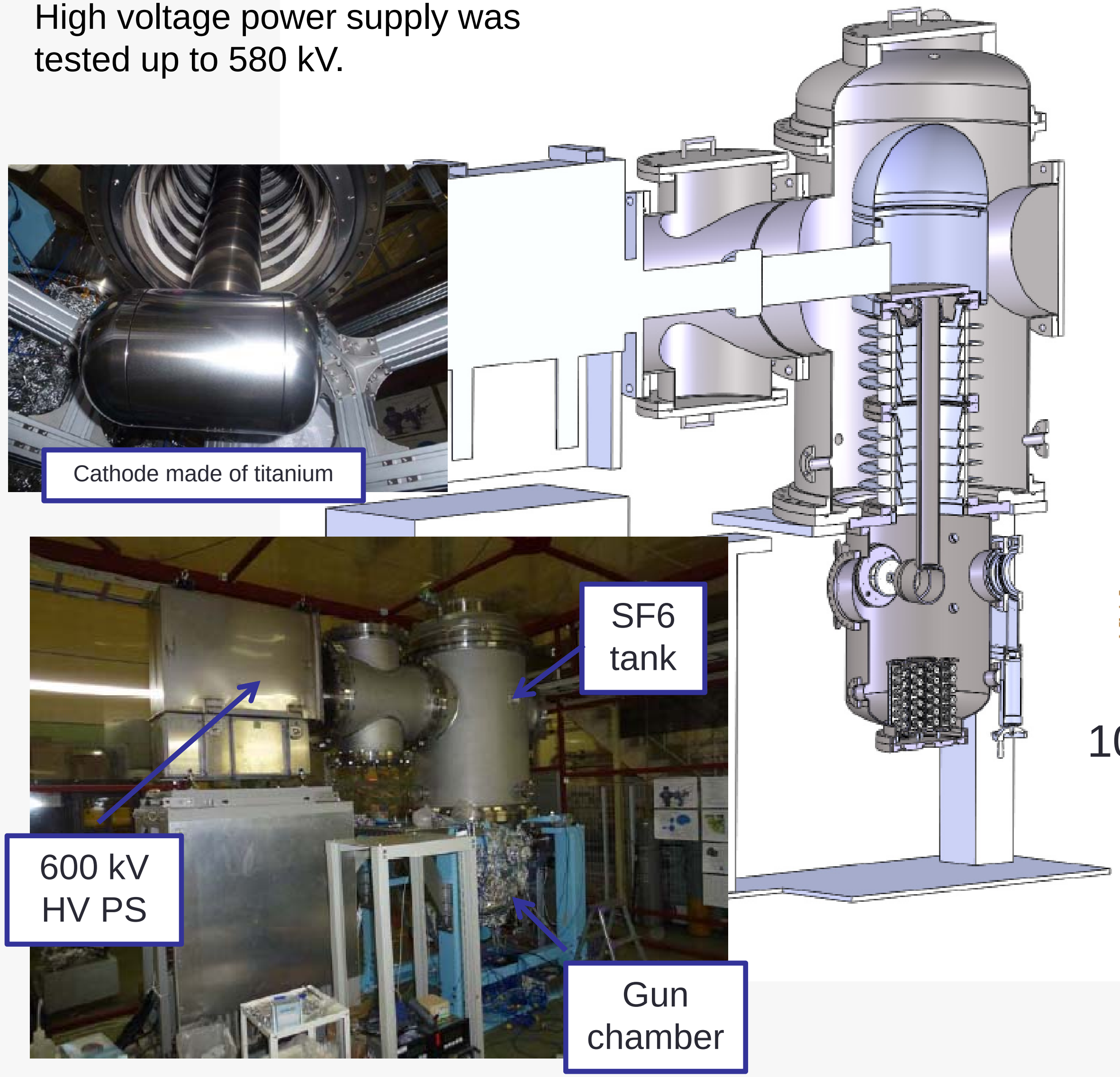
## Summary of performance

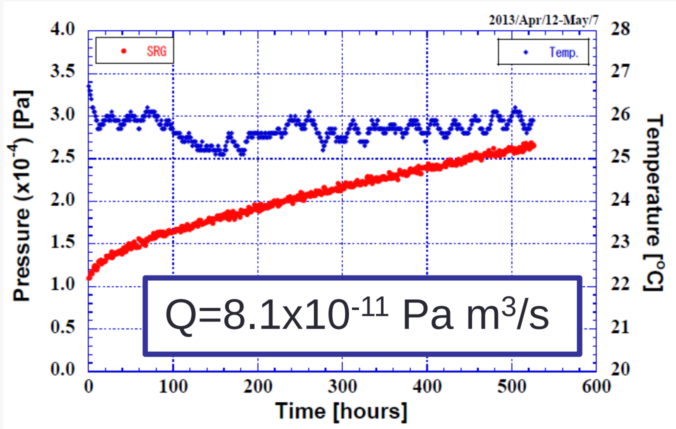
- Successful production of 500-keV, 1.8-mA beams at JAEA
- Maximum electric field on cathode: 5.8 MV/m (@500 kV)
- Normalized emittance: 0.07 mm·mrad @10fC (at cERL, V=390 kV)
- Long term operation (~ 260 hours) at V=390 kV at cERL

# Status of 500-kV Photocathode DC Gun (#2)

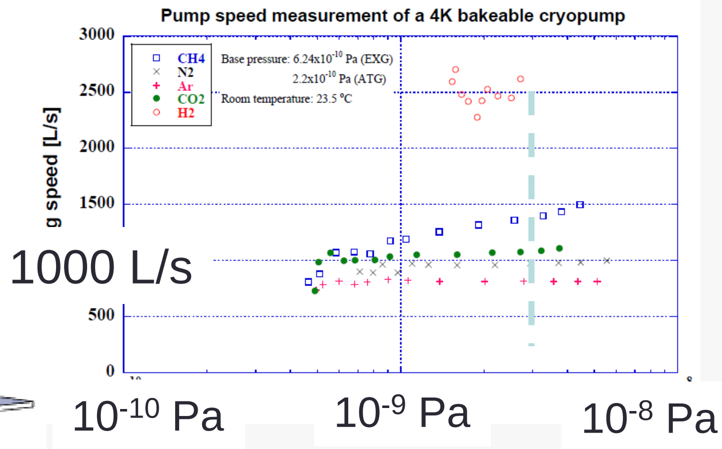
Yamamoto's Talk

High voltage power supply was tested up to 580 kV.




Very-low outgassing rate in overall gun-system




High pumping speed of bakable cryopump under extremely-high vacuum

# Gun-Drive Laser System

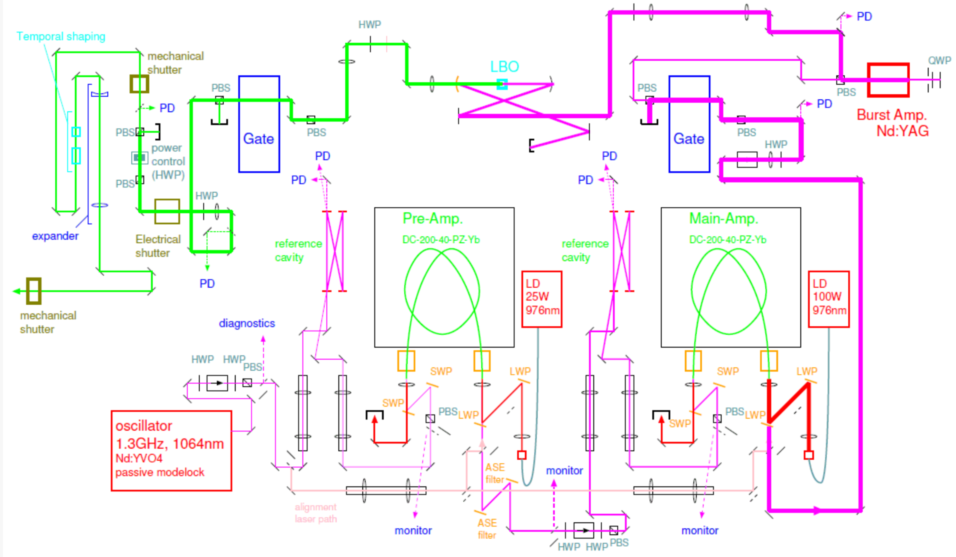
By Yosuke Honda

## System

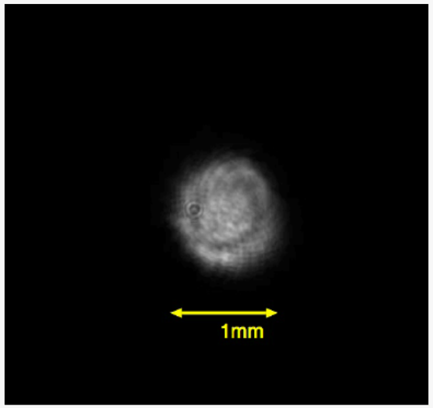
- 1.3GHz Nd:$YVO_4$ oscillator (λ=1064 nm)
- Yb photonic-fiber amplifiers (two stages)
- Second-harmonic generation (λ=532 nm)
- Temporal shaping with birefringent crystal
- Gate system for CW/macropulse operations

## Specifications

- Maximum beam current: 10 mA (CW)
- Laser power: 2.3 W@532 nm (if Q.E.=1%)
  (P=70 W@1064 nm has been demonstrated)

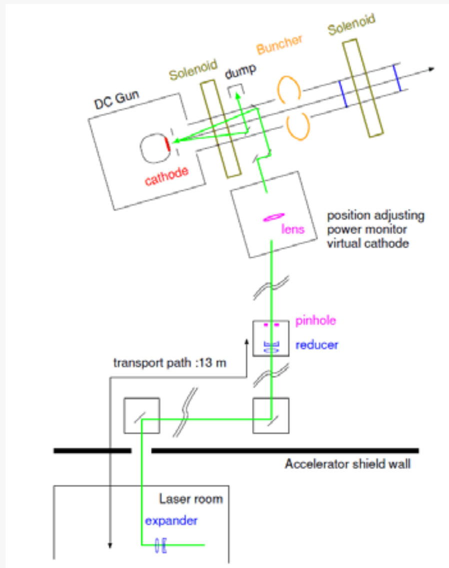



Gun-Drive Laser System




Laser profile at virtual cathode CCD camera.

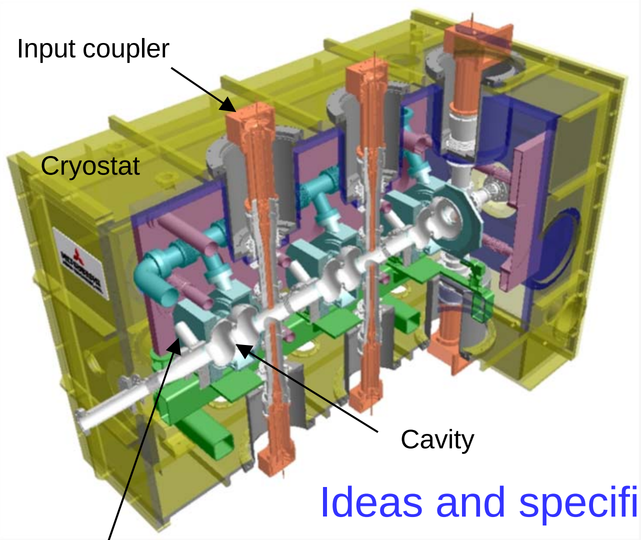
Drive-Laser System

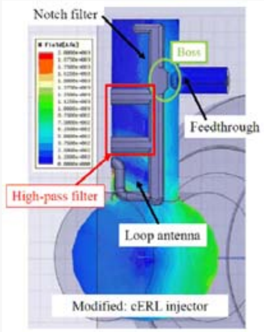



Laser transport line

# High-Power Test of Injector Cryomodule

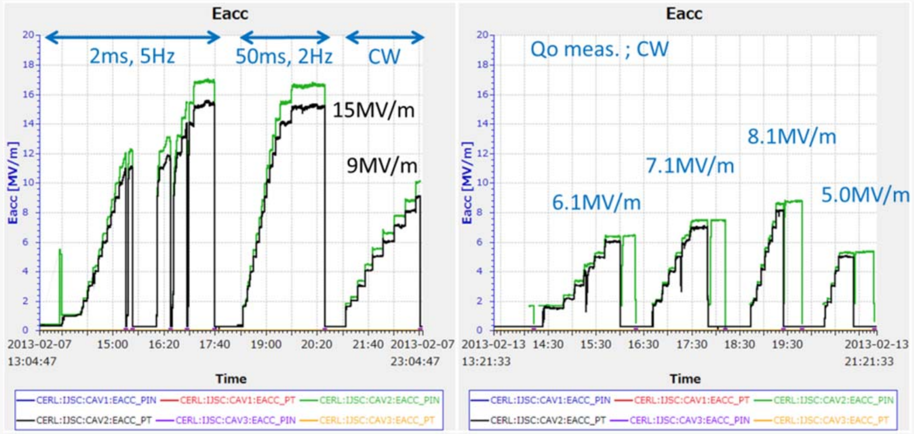
By E. Kako et al.




HOM coupler suitable for CW operation

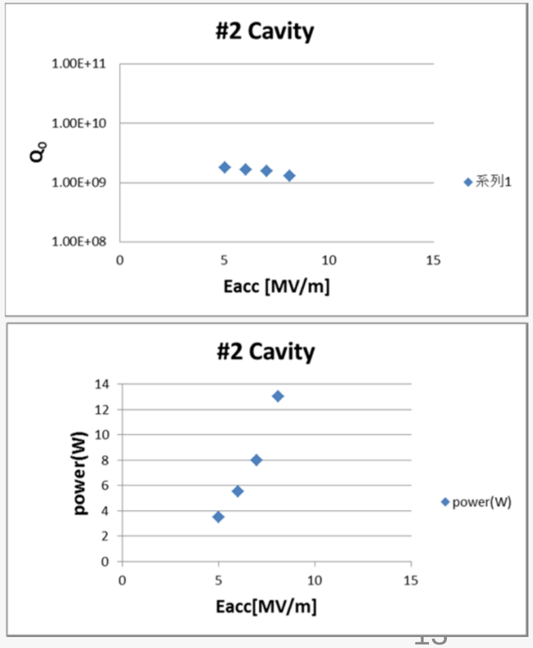
## Processing of Cavity -2 : (2013, Feb. 7-8, 13)




## Ideas and specifications

- Improved HOM couplers/feedthroughs for CW operation
- Beam current: 10 mA (100 mA in future)
- ΔT=5 MeV with three two-cell cavities
- Two input couplers/cavity
- Five HOM couplers/cavity

## Qo measurement of Cavity -2




## 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.

# High-power Test of Main-Linac Cryomodule

By T. Furuya et al.

Hara's poster (PS15)

## Specifications

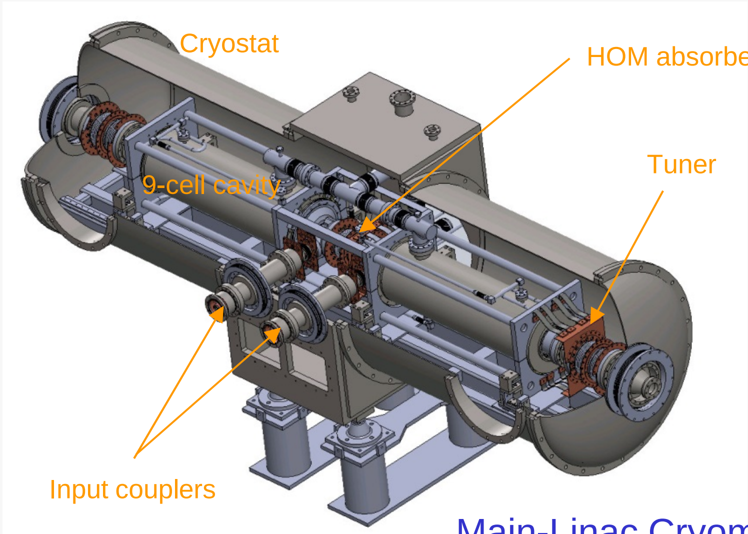
**RF frequency: 1.3 GHz**

**Input power : 20 kW CW (SW)**

**$E_{acc}$: 15 - 20MV/m**

**Unloaded-Q: $Q_0 > 1\times10^{10}$**

**Beam current : max 100mA (HOM-damped cavity)**

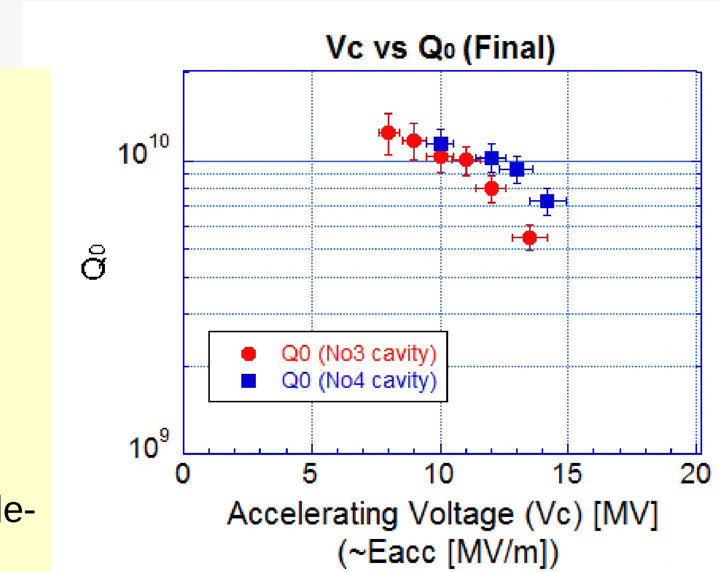



Main-Linac Cryomodule

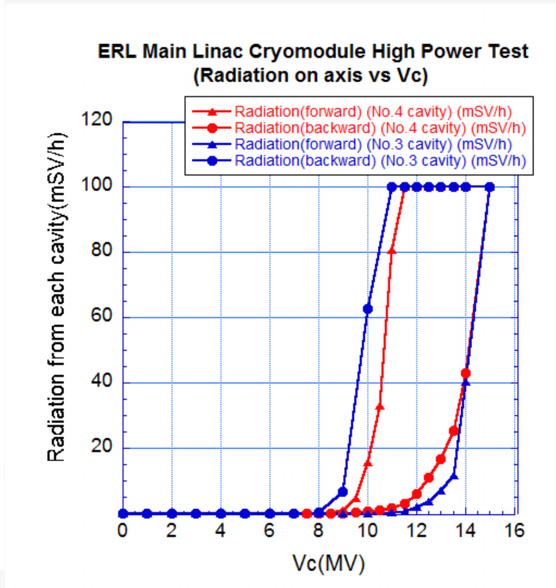


## Summary of performance

- Vc=16 MV was achieved for both cavities.
- Vc=13.5-14 MV could be kept for more than 1 hour
- Onset of radiation due to field emission: 8-10 MV/cavity (not very good)
- To increase the onset of field emission, we plan to refine module-assembly technique.

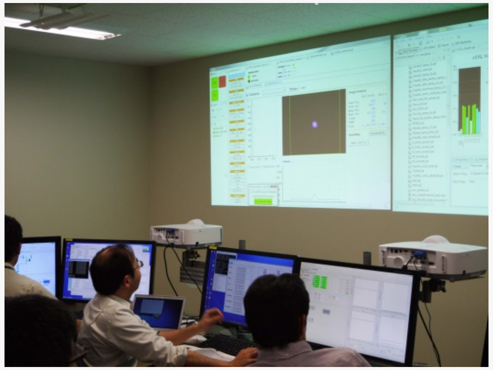


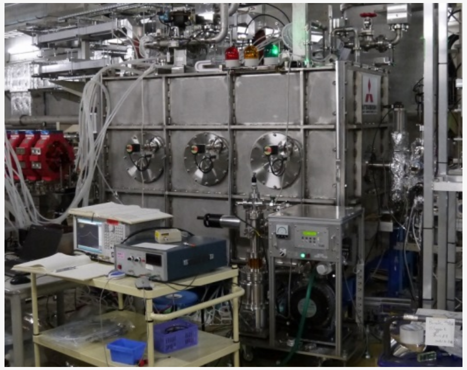

Measured $Q_0$ vs $V_c$ ($V_c = 1.038\times E_{acc}$)



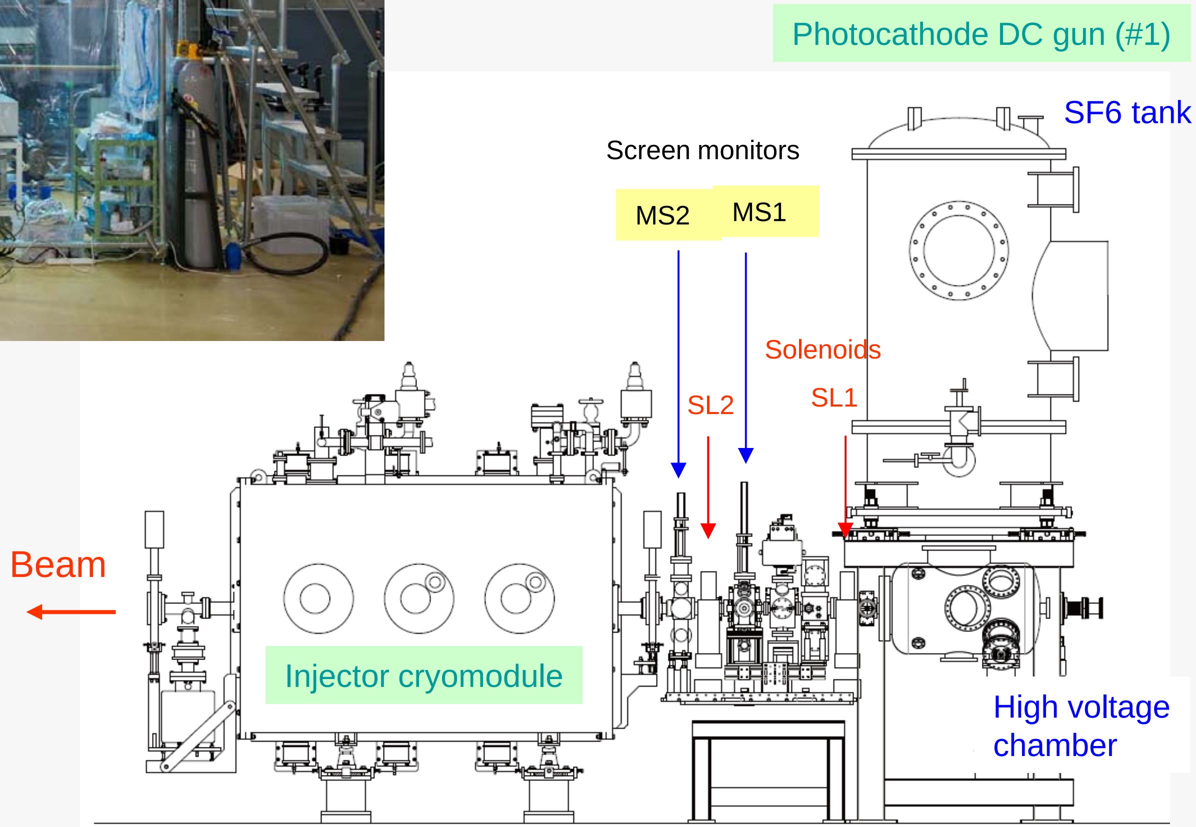

Onset of radiation (field-emission)

## II. Commissioning of cERL Injector



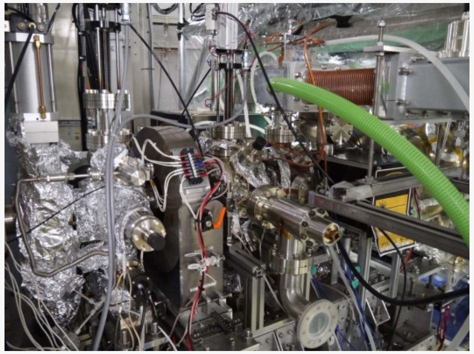


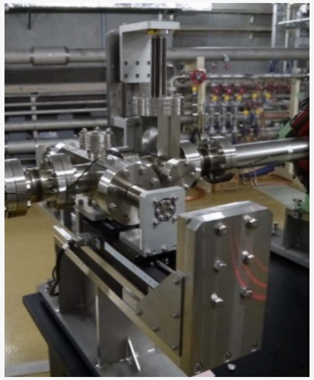
# cERL Injector (upstream part)

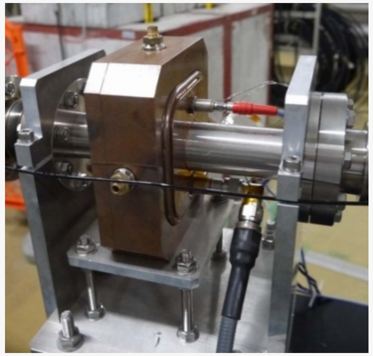


# Injector Beamline and Diagnostics

By T. Miyajima
and Y. Honda





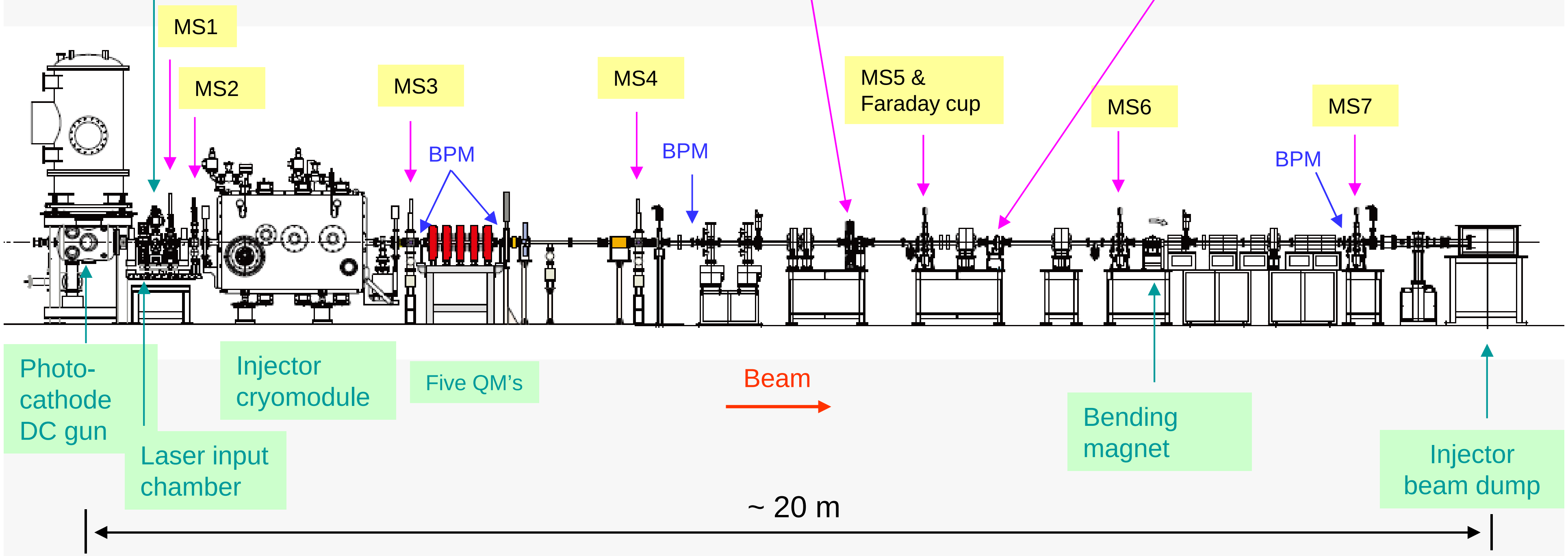


Buncher cavity

Screen monitors
(MS1 - MS7)

Slit scanner for
emittance measurement

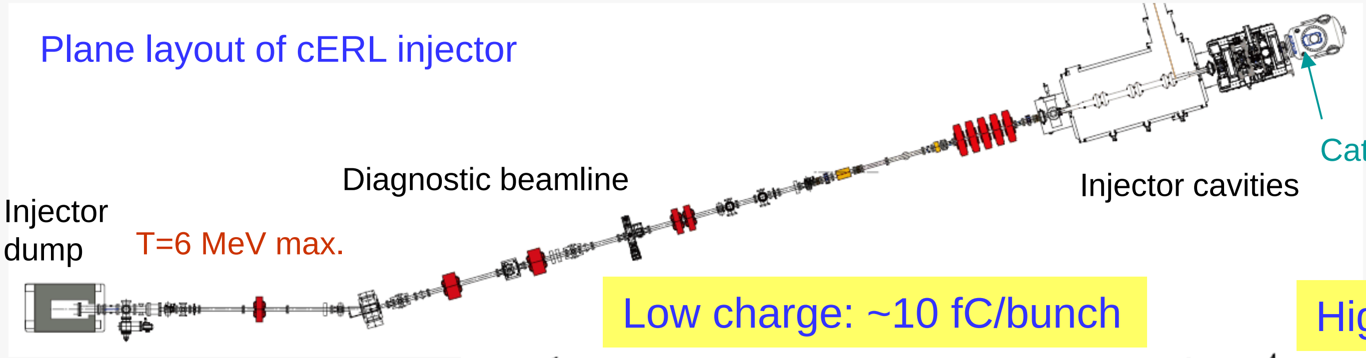
2.6-GHz deflecting cavity for
bunch-length measurement



# Optics Design of cERL Injector

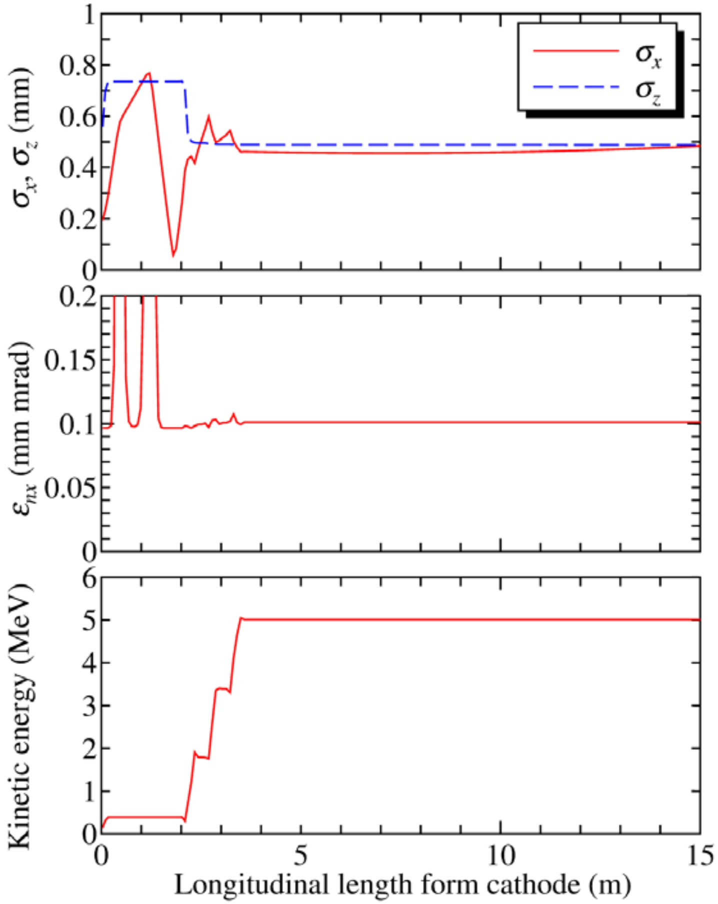
By T. Miyajima

Plane layout of cERL injector

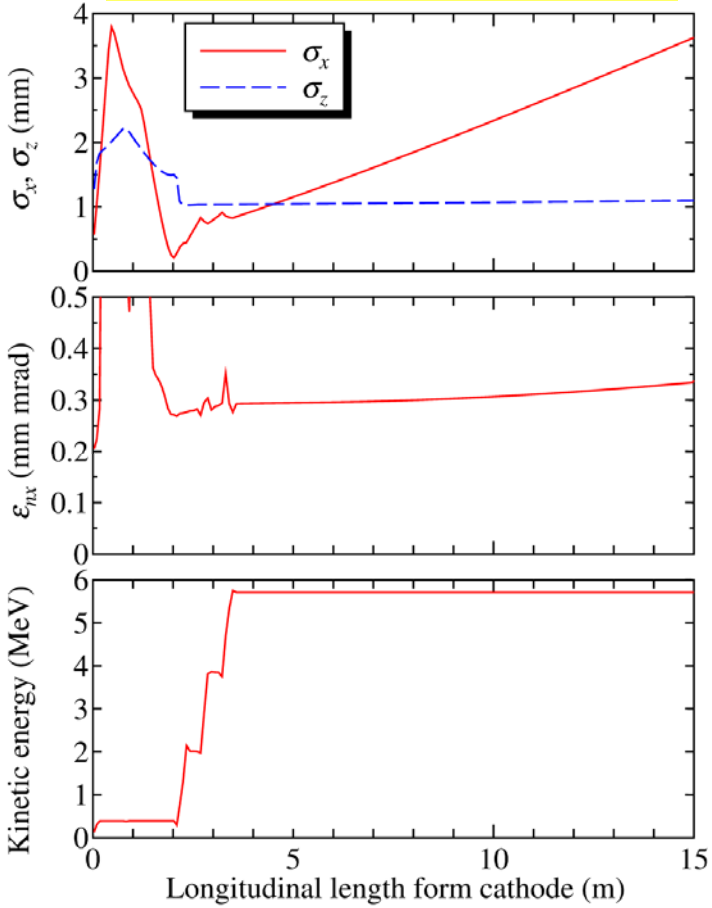



Simulations using GPT code

Low charge: ~10 fC/bunch




High charge: 7.7 pC/bunch




- Parameters for simulations are given in the next slide.
- Note that similar parameters to those under beam operations were chosen.
- These parameters might not be optimum for emittance minimization.

# Typical Parameters of cERL Injector

By T. Miyajima
and Y. Honda

| | Simulation (low charge) | Simulation ($q_b$=7.7 pC) | Operation (low charge) | Operation ($q_b$=7.7 pC) |
|---|---|---|---|---|
| Charge/bunch | ~ 10 fC | 7.7 pC | ~10 fC | 7.7 pC |
| Gun DC voltage | 390 kV | 390 kV | 390 kV | 390 kV |
| Spot diameter of laser | 1.1 mm | 1.1 mm | 1.2 mm | 1.2 mm |
| Laser pulse width | 3 ps rms (Gaussian) | 16 ps FWHM (flat) | 3.3 ps rms (Gaussian) | 15.7 ps FWHM (semi-flat) |
| Magnetic fields of solenoids #1, #2 | (0.020, 0.024) T | (0.029, 0.018) T | (0.0248, 0.0103) T | (0.0286, 0.0172) T |
| Voltage and phase of buncher cavity (0 degree: on-crest) | 0 kV | 50 kV, -90 deg. | 0 kV or 40 kV, -90 deg. | 50 kV, -90 deg. |
| $E_{acc}$ of three injector cavities | (6.1, 6.1, 6.1) MV/m | (7, 7, 7) MV/m | (6.2, 6.7, 6.2) MV/m | (6.2, 6.7, 6.2) MV/m |
| Phase of three injector cavities (0 degree: on-crest) | (0, 0, 0) degree | (0, 0, 0) degree | (0, 0, 0) degree | (0, 0, 0) degree |
| Beam kinetic energy after acceleration | 5 MeV | 5.7 MeV | Typ. 5.5 MeV | Typ. 5.5 MeV |

Parameters similar to those under beam operations were chosen (not optimum for emittance minimization).

## Typical parameters of macropulse-beam operation:

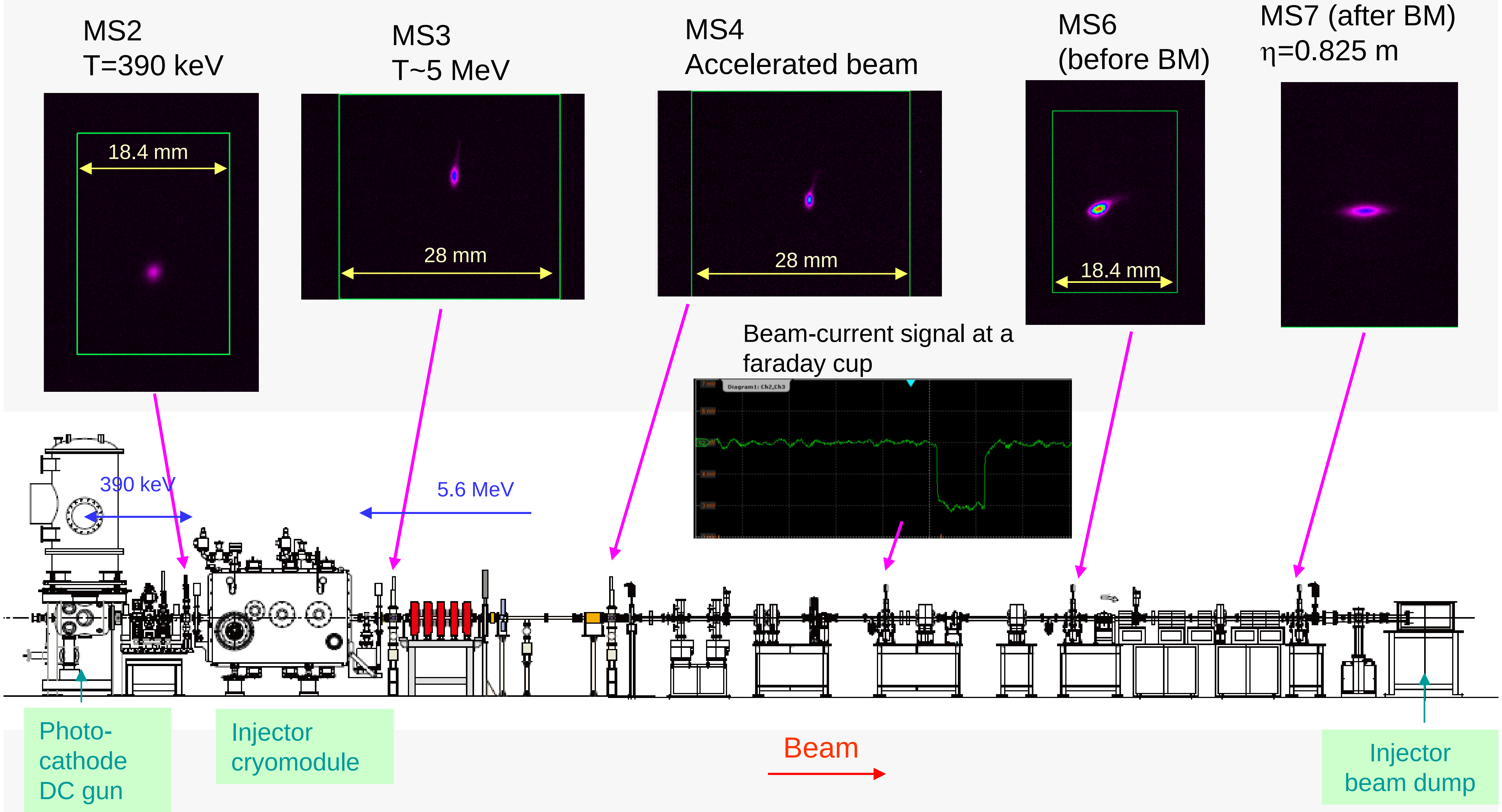
Macropulse beams were used for destructive beam measurements.

| | |
|---|---|
| Repetition frequency of bunches | 1.3 GHz |
| Charge/bunch | 10 fC - 7.7 pC |
| Repetition rate of macropulses | 5 Hz (typ.) |
| Width of macropulse | 1 μs (typ.) or 1.6 ms (for high average current) |
| Rise/fall times of macropulse | ~10 ns |

# Successful Accelerataion 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 |
| Mcropulse widths | 1 μs or 1.6 ms (for high current) |
| Repetition of macropulses | 5 Hz |
| Charge/bunch | Typically 20 fC |



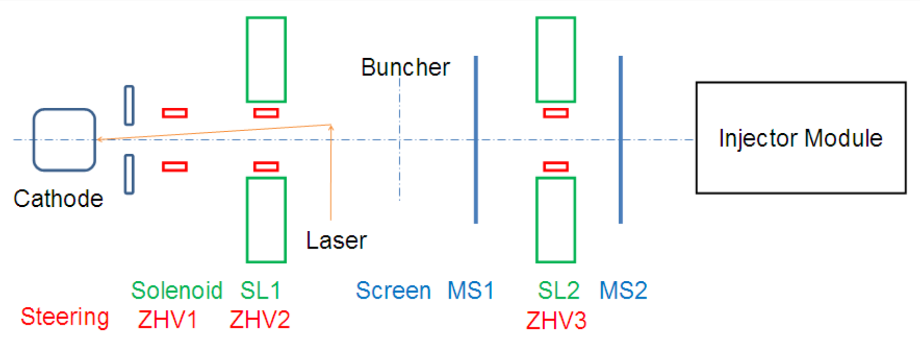
# Emittances of Beams from the Gun
## (T=390 keV, very-low charge)

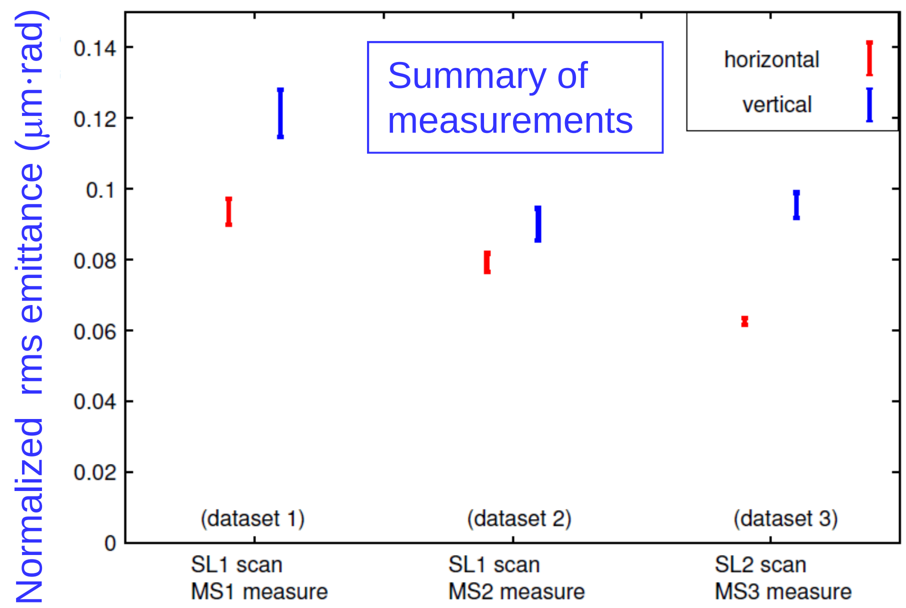
Honda's Poster (PS03)

Gun voltage: 390 kV, Charge/bunch ~10 fC

**Solenoid-scan method**

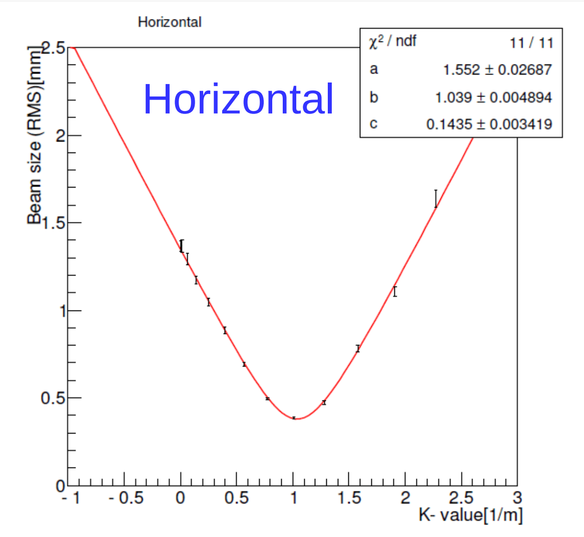
$$k = \left( \frac{eB_0}{2mc\beta\gamma} \right)^2 \ell_{sol}$$

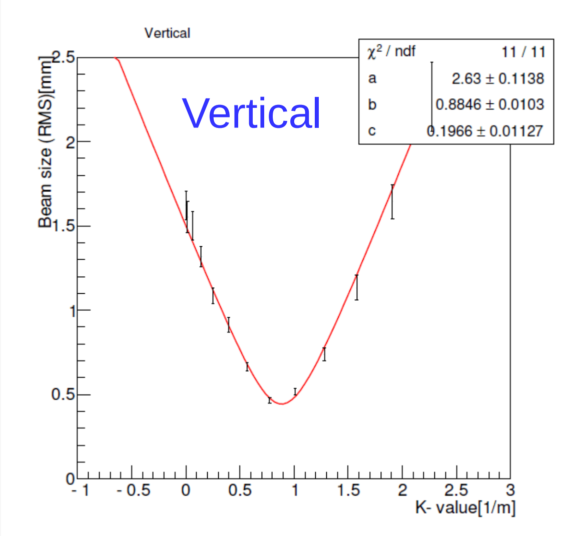



Set of measurements

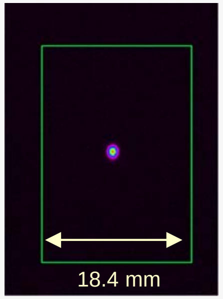
Example of solenoid scan (scan SL2, monitor MS3)




Normalized emittance:
$\varepsilon_n \approx 0.07$ μm·rad
(at T =390 keV)

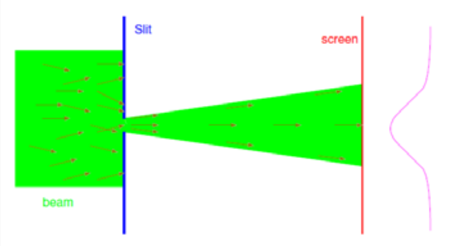
Typical beamprofile at screen monitor MS1



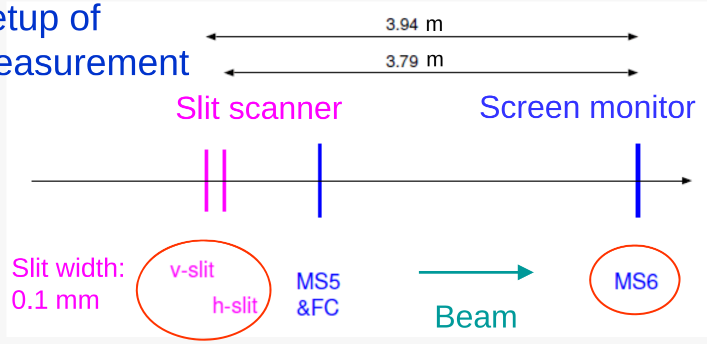
# Beam Emittances of Accelerated Beams (T=5.6 MeV, low bunch charges)

Honda’s Poster (PS03)

## Slit-scan method



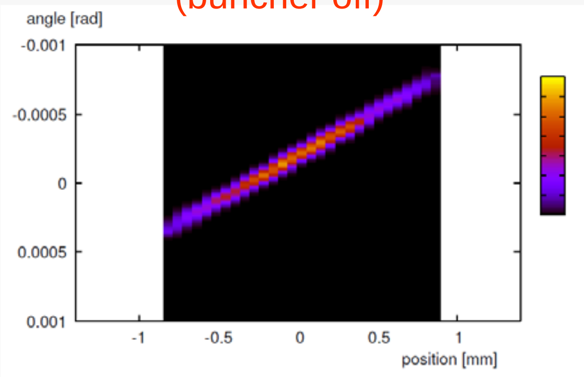

## Setup of measurement



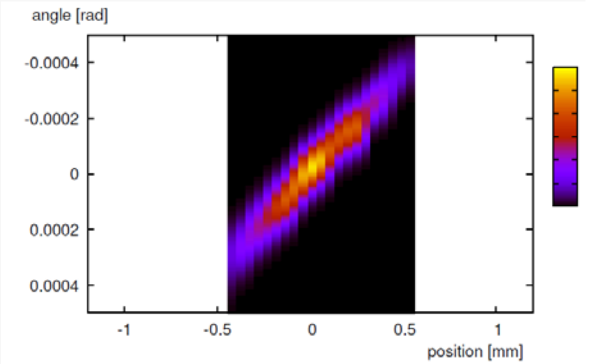

**Measurement conditions:**

- 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

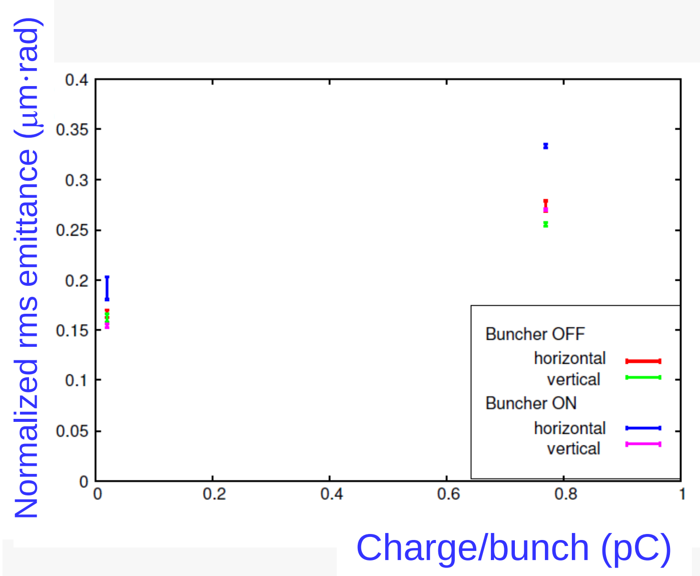
### Charge: 0.02 pC/bunch (buncher off)




Horizontal phase-space distribution




Vertical phase-space



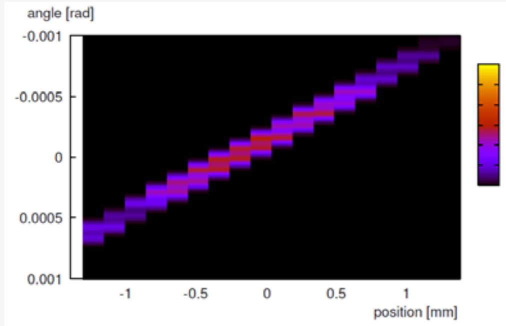

**Results:**

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

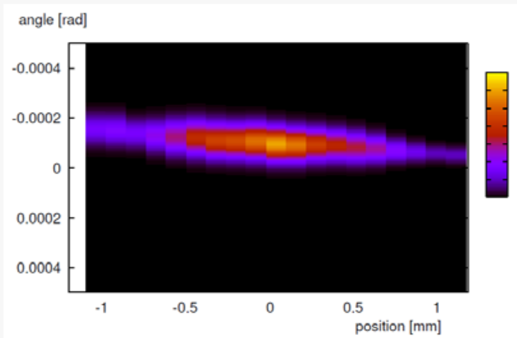
$\varepsilon_n \approx 0.3$ μm·rad at 0.77 pC

Emittances might be smaller due to the limitation of the measurement

### Charge: 0.77 pC/bunch (buncher off)




Horizontal phase-space




Vertical phase-space

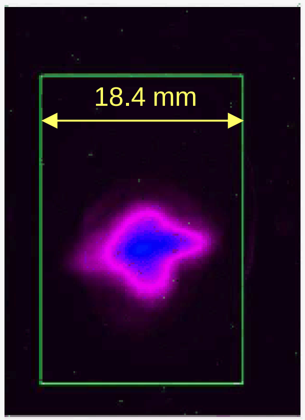
# Beam Emittances at High Charges (tentative results)
# (T=5.6 MeV, up to 7.7 pC/bunch)

Honda's Poster (PS03)

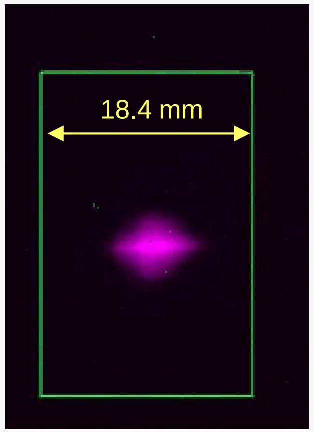
## Conditions of measurements

| Meas. Date | Bunch charge (pC) | Width of laser pulse | Buncher Vc (kV) | Solenoids (SL1, SL2) |
|---|---|---|---|---|
| 21-June-2013 | 0.02, 0.77 | 3 ps (rms, Gaussian) | 40 | 7.8/8.7, 3.0 |
| 26-June-2013 | 3.1, 7.7 | 3 ps (rms, Gaussian) | 50 | 8.3, 4.99 |
| 28-June-2013 | 1.5, 7.7 | 16 ps (FWHM, semi-flat) | 50 | 8.3, 4.99 |

Beam profiles at screen monitor MS6



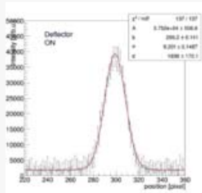

7.7 pC/bunch



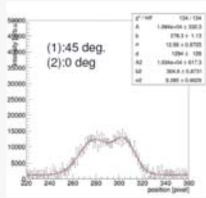

1.5 pC/bunch

## Bunch lengths

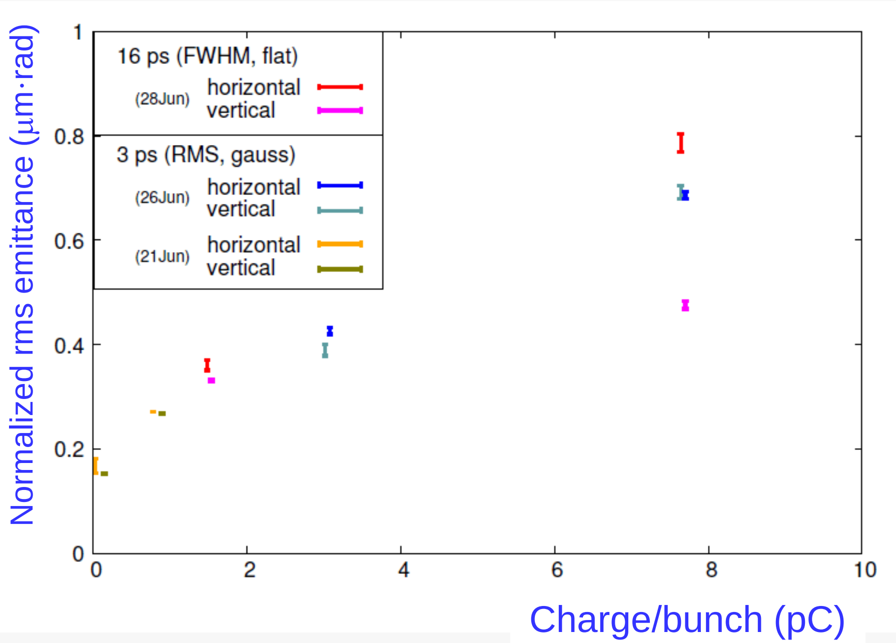
3-ps laser




16 ps semi-flat




## Summary of measurements




**Tentative result:**
$\varepsilon_n \approx 0.8$ μm·rad at 7.7 pC
(not fully optimized yet)

## Comments

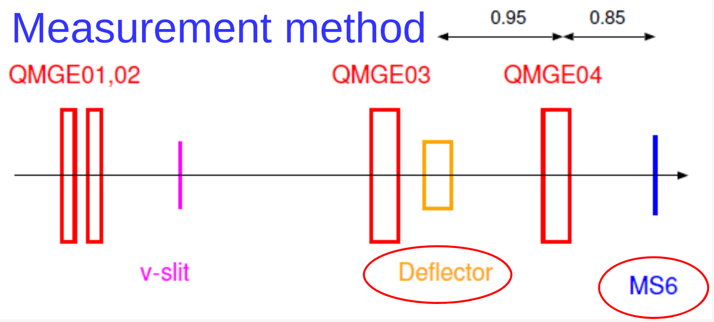
- Axially asymmetric beam profile. Not yet understood. (Due to beam offset in SC/buncher cavities?)
- Tentatively, beam emittances depended only weakly on laser-pulse widths.
- Gun voltage is lower than the design value ($V_{gun}$ = 390 kV)

Machine parameters have not been optimized yet !

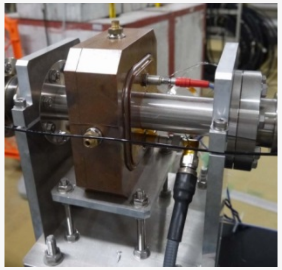
# Bunch-Length Measurements

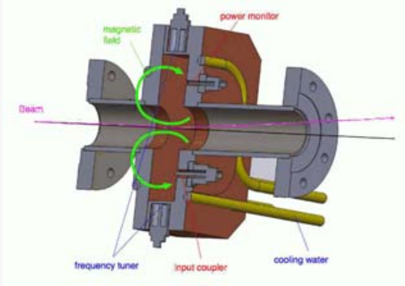
Honda's Poster (PS03)

## Measurement method

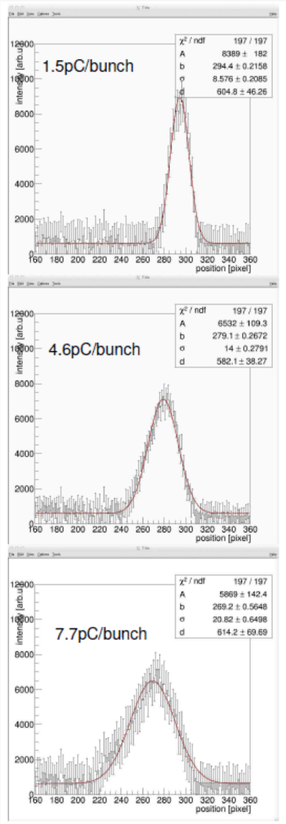



Deflecting cavity（$f$ = 2.6 GHz)

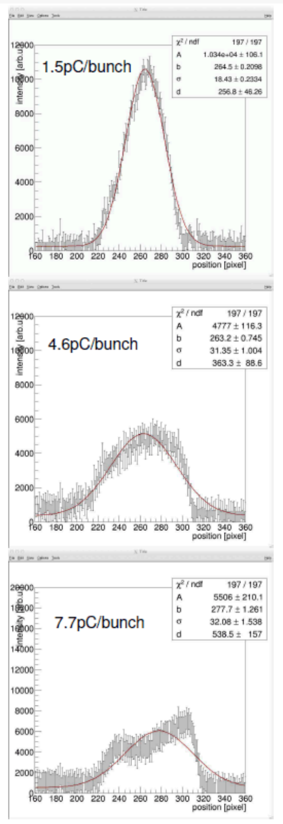




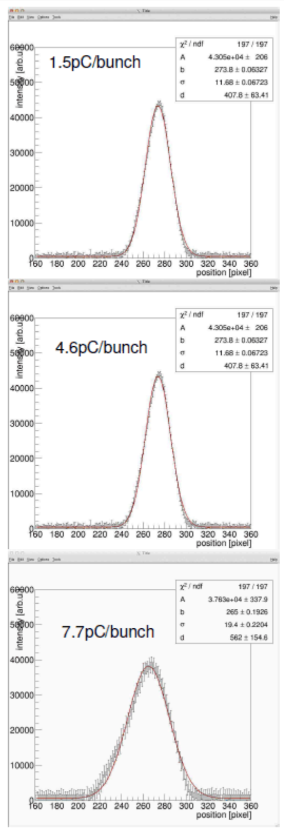

Resolution of the measurement: ~0.7 ps




Laser: 3 ps rms
Buncher 50 kV

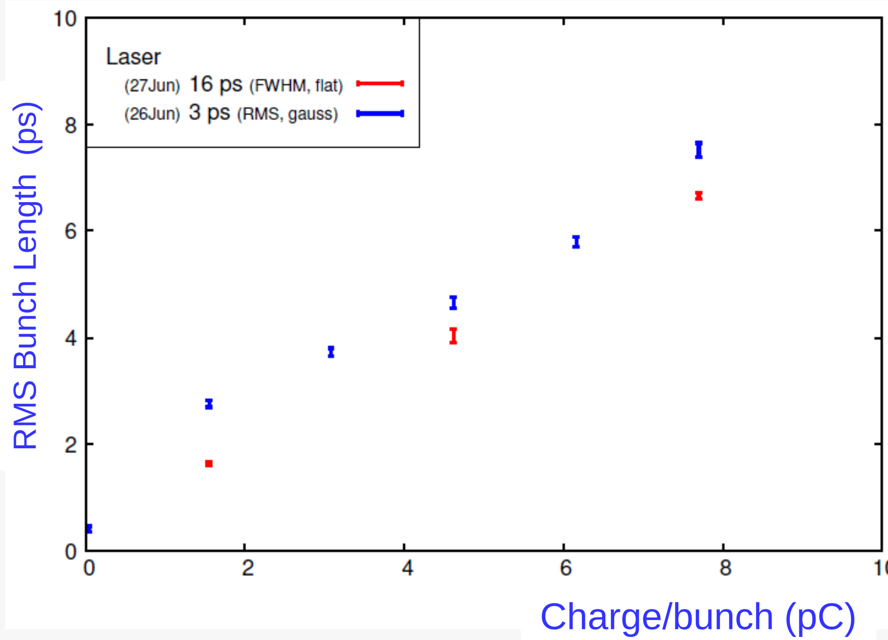


Laser: 16 ps semi-flat
Buncher OFF



Laser: 16 ps semi-flat
Buncher 50 kV

## Bunch length vs. bunch charge (buncher Vc=50 kV)

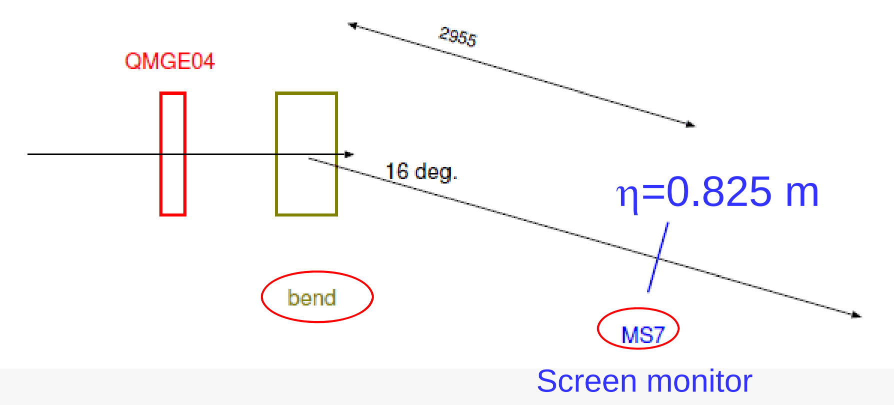



* Machine parameters were probably not optimum under space-charge effects

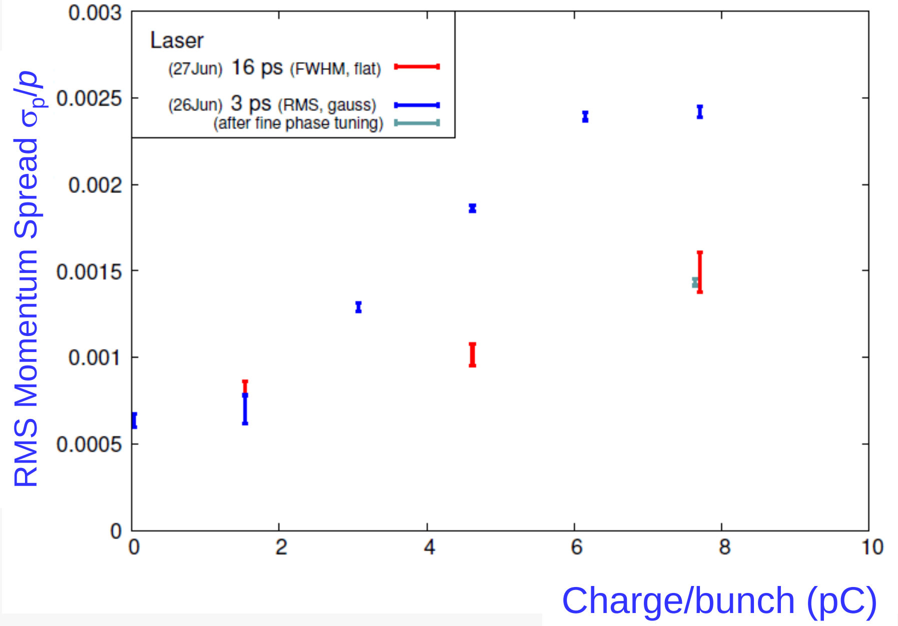
# Spread and Stability of Beam Momentum

By Y. Honda
and T. Miura

## Setup of measurement



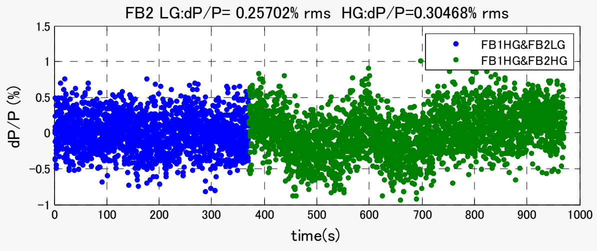

## Energy Spread vs. bunch charge (buncher Vc=50 kV)




## Stability of beam momentum

Miura's talk

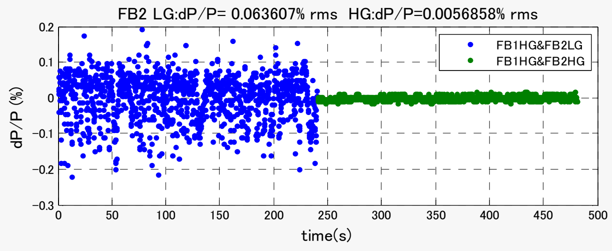
### Before optimization




FB1: high gain
FB2: low gain

FB1: high gain
FB2: high gain

### After optimization




FB1: high gain
FB2: low gain

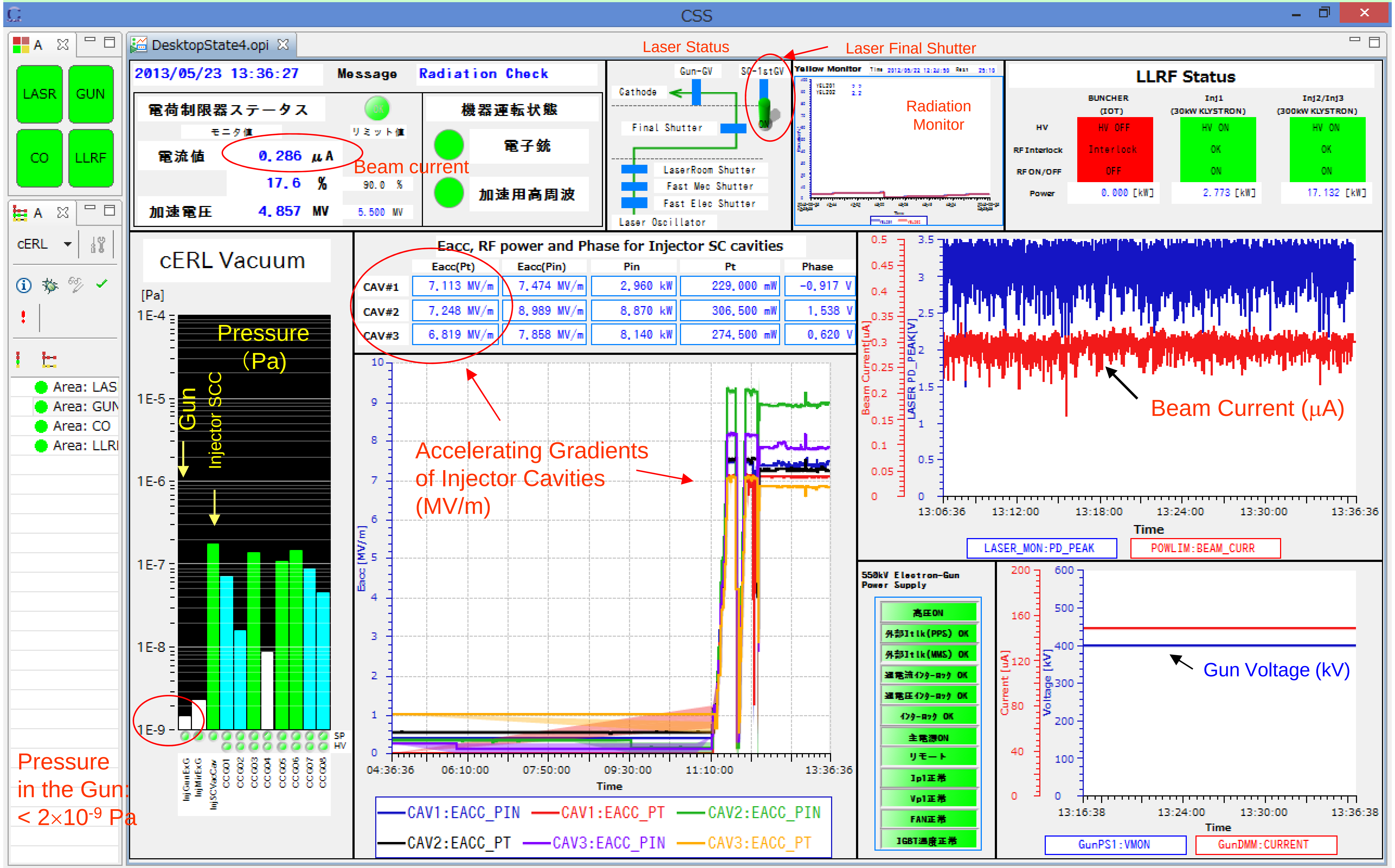
FB1: high gain
FB2: high gain

Momentum jitter :
$(\Delta p/p)_{rms} \approx 6\times10^{-5}$

### What was optimized?

- Parameters of digital RF-feedback system
- On-crest phases of three injector cavities were precisely adjusted

# Typical Operation Status (23-May-2013)



# Operation Statistics of cERL-Injector (April - June, 2013)

| Month | Machine Operation Time* (hours) | Beam ON Time (hours) | Operation Time of Helium Refrigerator (hours) |
|---|---|---|---|
| April | 92 | 24 | 185 |
| May | 111 | 70 | 291 |
| June | 157 | 106 | 315 |
| Total | 361 | 202 | 792 |

* Including conditioning

# Present Performance of cERL Injector (at the end of June, 2013)

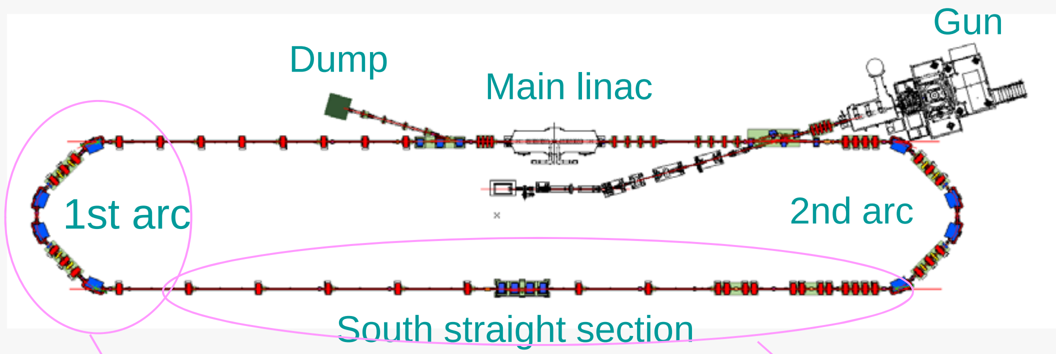
| Parameter | Achieved | Comment and Outlook |
|---|---|---|
| Kinetic beam energy $T$ | 5.6 MeV (typ.), 5.9 MeV (max.) | T ≤ 6 MeV is allowed at present. |
| Average Beam current $I_0$ | 300 nA (max.) | $I_0 \leq 1$ μA is allowed at present. Beam current will be increased step by step. |
| Gun High 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) | ≈ 0.07 μm·rad (@~10 fC/bunch) | |
| Normalized beam emittance (T≈5.6 MeV, low charge) | ≈ 0.17 μm·rad (@0.02 pC/bunch) | Close to the limitation of present instrumentation. Emittance might be smaller. |
| Normalized beam emittance (T≈5.6 MeV, high charge) | ≈ 0.8 μm·rad (@7.7 pC/bunch) | Further improvement is expected by optimizing machine parameters and by higher gun voltage. |
| Momentum jitter $(\Delta p/p)_{rms}$ | $6\times10^{-5}$ | 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. |

# III. Construction Status of Return Loop

# Return loop is under construction (July - November, 2013)

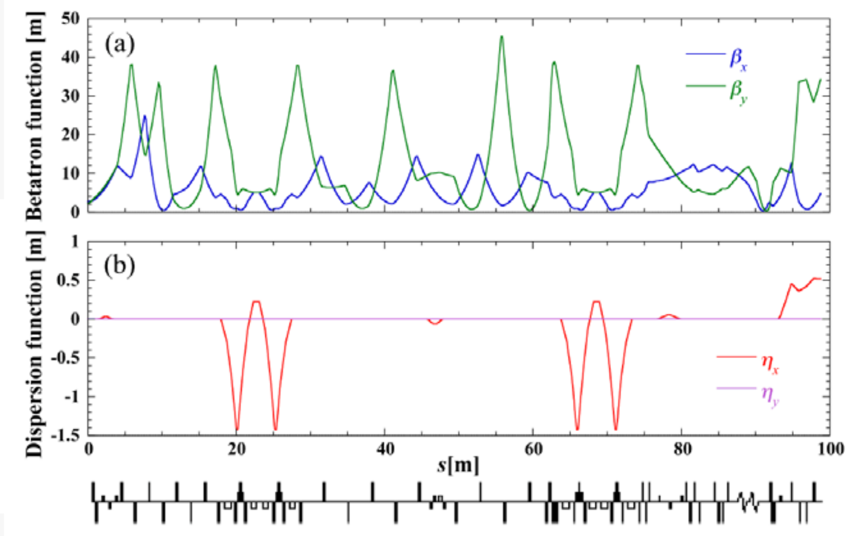
## Schedule

- Jul. - Nov., 2013 : Construction of return loop
- Nov. (2nd half) : Conditioning of SC cavities
- Dec. 2013 : Commissioning of cERL




Linear optics of cERL

Shimada's Talk




1st arc

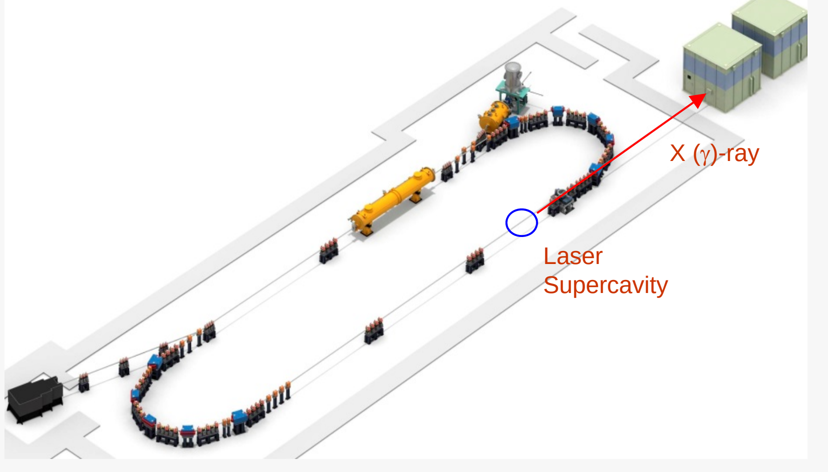
South straight section

Alignment of magnets

# Future Schedule

| | |
|---|---|
| Dec. 2013 - Mar. 2014 | Initial commissioning of cERL<br>(beam current: 10 μA max.) |
| Apr. - Dec. 2014 | Operation and study of cERL<br>Construction of Laser-Compton Scattering (LCS) beamline |
| Jan.(?) - Mar., 2015 | Commissioning of LCS beamline (by JAEA)<br>Increasing beam current |
| Apr. 2015 - | Machine study<br>Operation for LCS and THz beamlines → Nozawa's Poster (PS01) |

Laser-Compton Scattering
X(γ)-ray Beamline
(by JAEA)



# IV. Conclusion

## Construction

- 6-MeV cERL injector was completed and commissioned in April 2013.
- Return loop of cERL is under construction (Jul. - Nov. 2013).
- Commissioning of entire cERL is scheduled in Dec. 2013.

## Commissioning of injector

- We operated cERL injector for about three months (22 Apr. - 28 Jun., 2013)
- Both photocathode DC gun (V=390 kV) and injector SC cavities ($E_{acc}$=7 MV/m) could be operated very stably. We observed almost no trips due to these components.
- We observed very-low normalized emittances (≈0.1-0.2 μm·rad) at low charges (~10 fC/bunch) at T=390 keV and T=5.6 MeV.
- At high charges (~7.7 pC/bunch), we are on the way to optimize the parameters. At the moment, we observed normalized emittances of about 0.8 μm·rad.
- We also observed axially asymmetric profiles of beams at high charges, which should be understood. (Maybe, hybrid effect of space charge and beam offset in cavities?)

# V. Acknowledgment

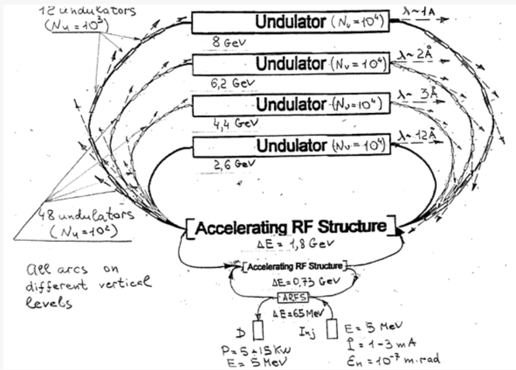

## Collaboration and Discussions

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.

## Special Thank

We sincerely express our thank to Dr. Gennady N. Kulipanov, the chairman of this workshop, for his series of seminars and fruitful discussions during his stay in KEK (Sep. - Oct., 2001). His deep insight stimulated us interests in future light sources based on recirculating linacs and ERLs.


Dr. Kulipanov




One of the OHP sheets of his seminar in 2001.

# Let’s collaborate together !


Picture taken on March 27, 2013