Commissioning of Compact-ERL injector

2013.11.28

Beam physics workshop/OIST

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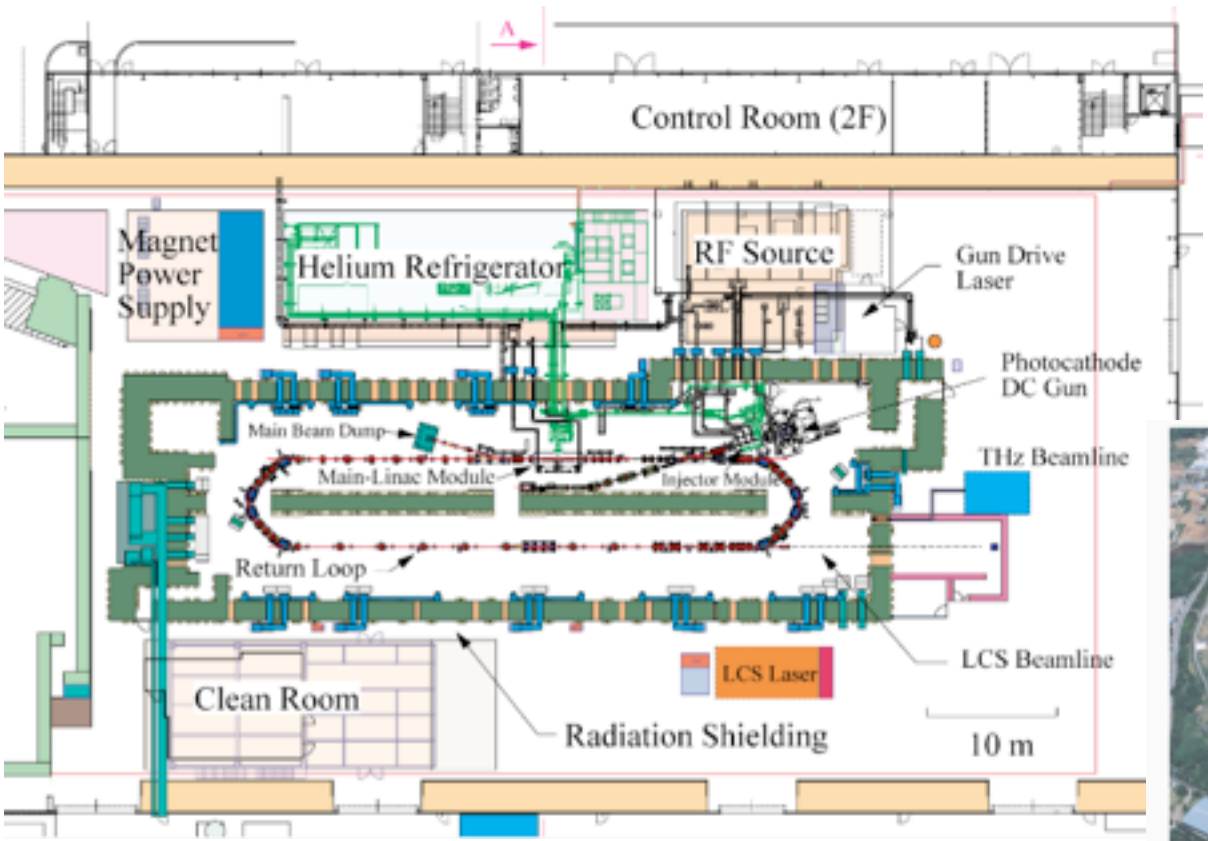
- An ERL test accelerator (cERL) has been constructed in KEK.
  - The injector part started operation since Apr. 2013.
- Activity of cERL has not been reported well in past domestic conferences, here might be a chance.
  - Sorry in advance, if this presentation is not appropriate.
- A future proposal at cERL

Compact ERL

- Energy Recovery Linac, a new scheme of accelerator.
  - Can be a high current CW linac
  - One of the application is a light source
- Purpose of compact ERL
  - Development of critical components
  - Restructure/training of a new group of ERL
- Construction started 2008, shield completed 2012.
- Injector commissioning has started since Apr.2013.

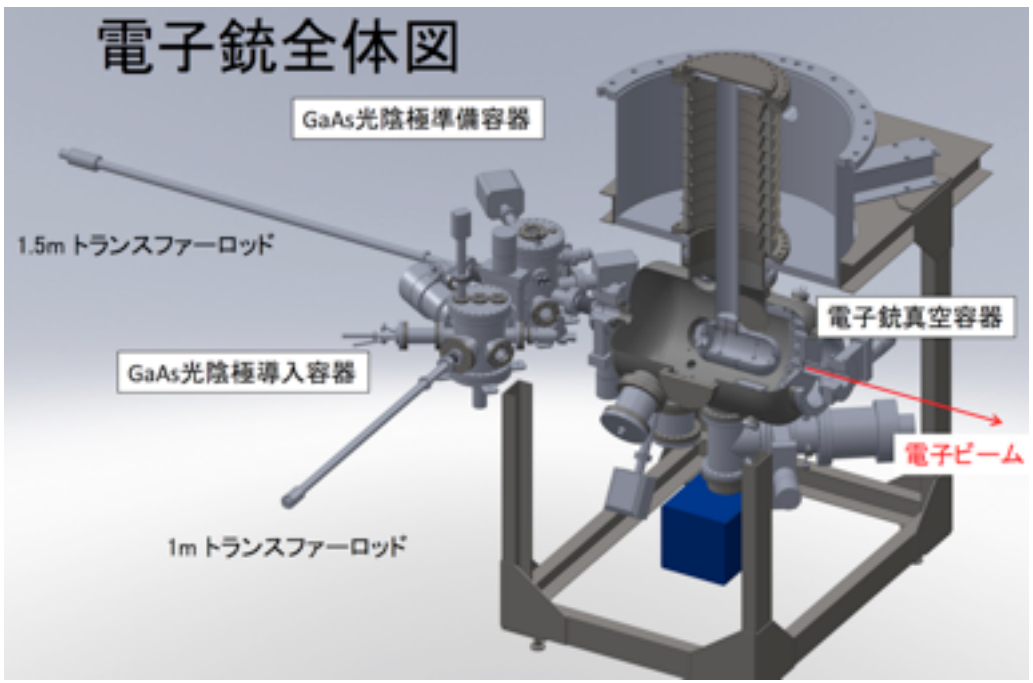


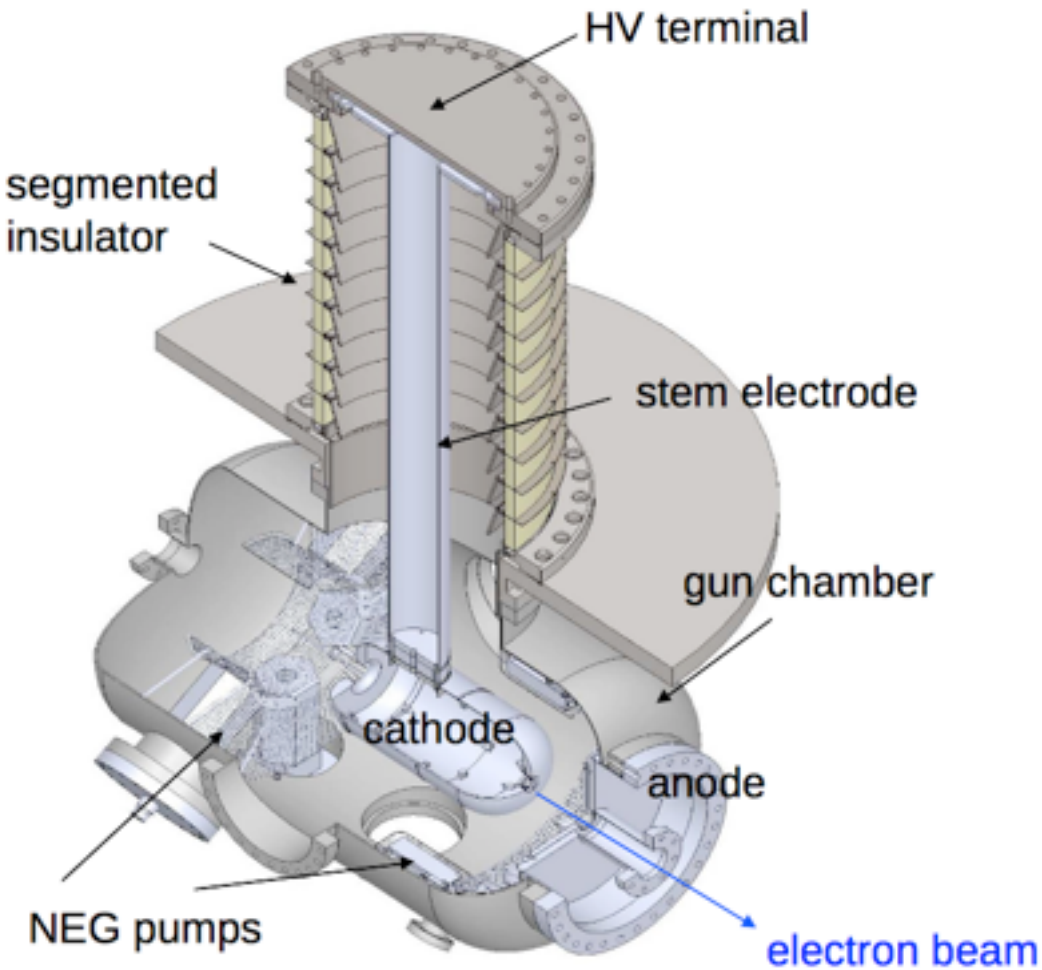
Parameters of the Compact ERL

	Parameters
Beam energy (upgradability)	35 MeV 125 MeV (single loop) 245 MeV (double loops)
Injection energy	5 MeV (10 MeV in future)
Average current	10 mA (100 mA in future)
Acc. gradient (main linac)	15 MV/m
Normalized emittance	0.1 mm·mrad (7.7 pC) 1 mm·mrad (77 pC)
Bunch length (rms)	1 - 3 ps (usual) ~ 100 fs (with B.C.)
RF frequency	1.3 GHz

Injector components (gun)

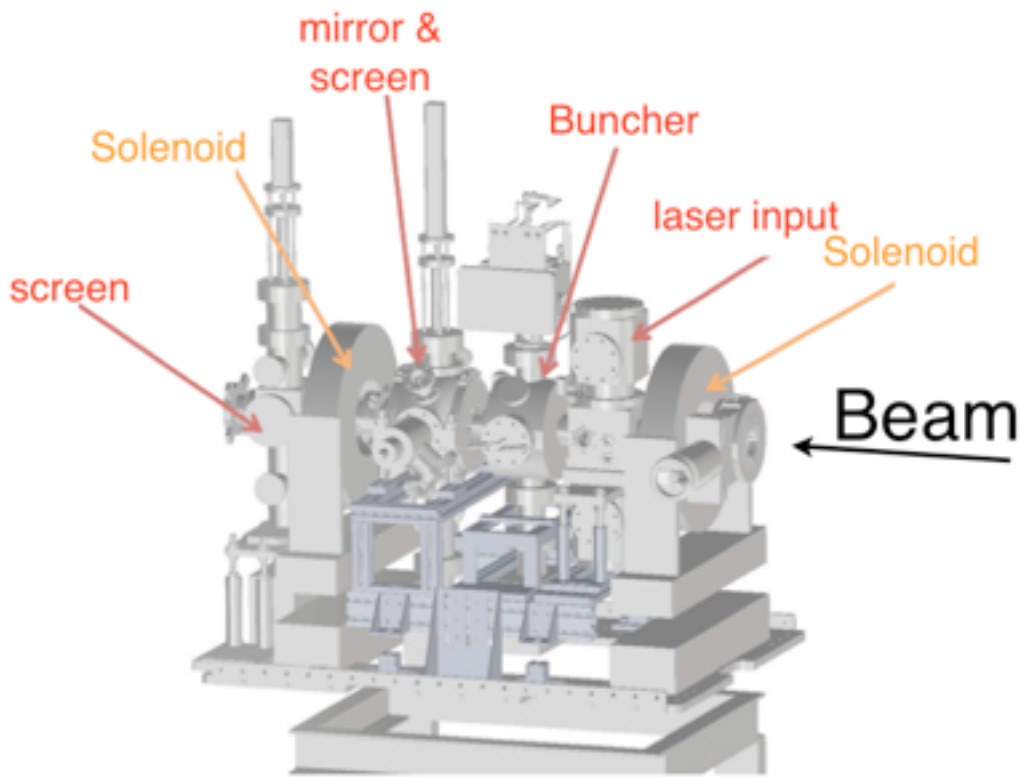
- Just to quickly remind our system
  - DC photo cathode gun, developed at JAEA
  - Operate at 390kV (can reach 500kV)
  - NEA-GaAs cathode





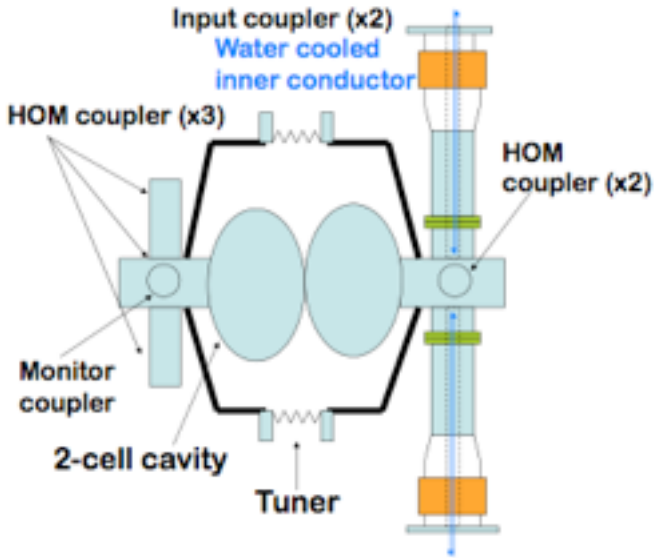
Injector components(low energy line)

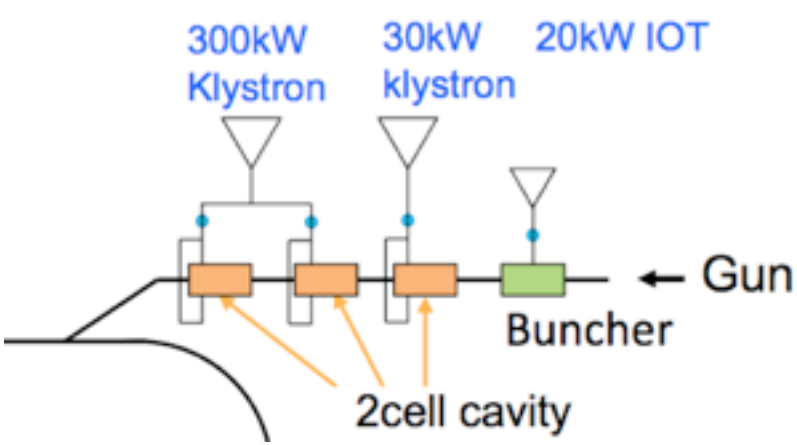
- Just to quickly remind our system
  - Space between the gun and the SC acc.
  - Trying to minimize the length of low energy beam transport line.
  - Needed instruments
    - Solenoids, Buncher, laser input, screen

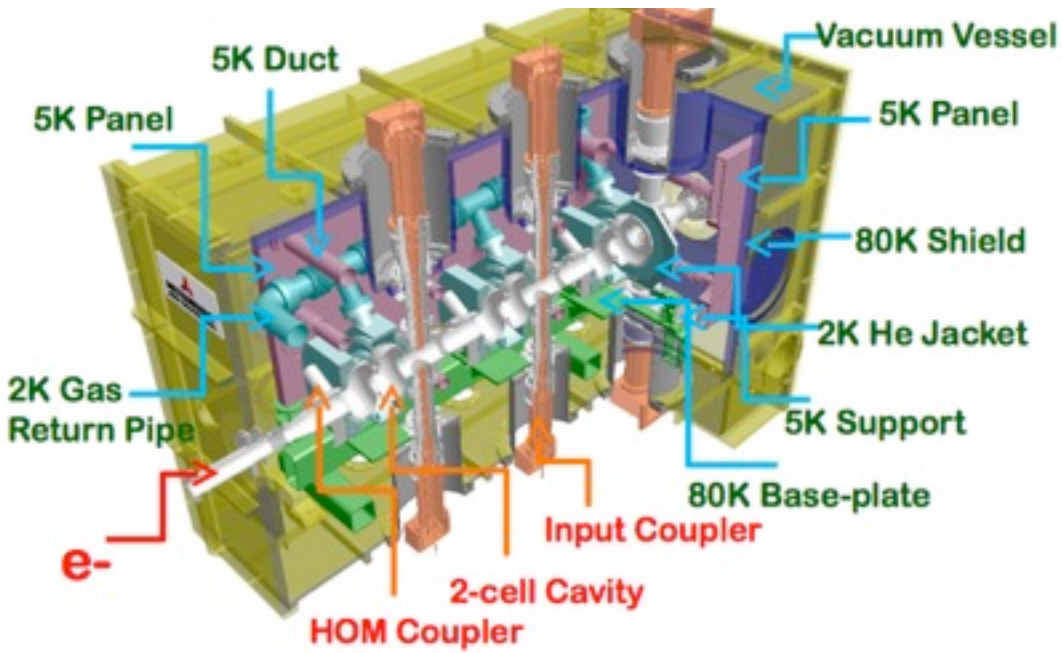


Injector components(SC accelerator)

- Just to quickly remind our system
  - Three, 2-cell cavities
  - Typically operate at 7 MV/m
  - All cavities operate at on-crest in this operation period.
  - 5.6MeV at the exit of accelerator







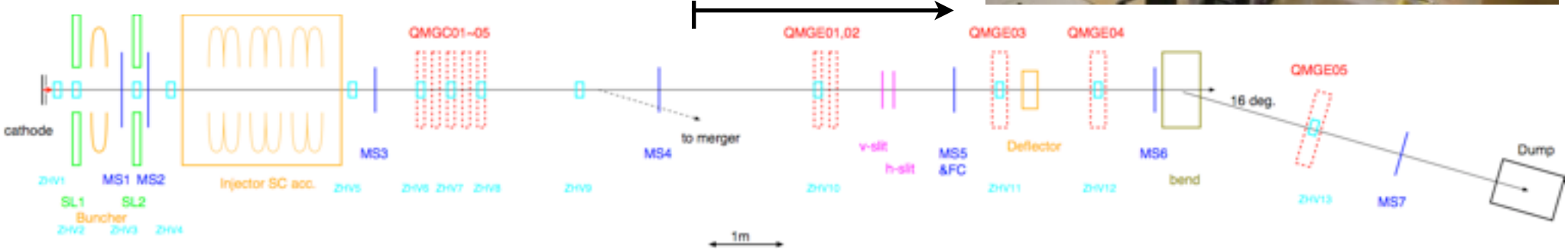
Injector and diagnostic line

- Beam diagnostic line for 5MeV beam
- What to measure : monitor
  - Beam current: Faraday cup
  - Beam energy: Corrector magnets
  - Profile: Ce:YAG Screens
  - Position: Quad mags BBA
  - Emittance: Slit scanners
  - Bunch length: RF deflector
  - Energy spread: Screen at dump line

designed parameter at merger(7.7pC/bunch)

parameter		
γ	10.84	全エネルギー 5.54MeV
σ_γ	0.0184	エネルギー拡がり 10.2keV
$\epsilon_{n,x}$	0.28 μm	規格化エミッタンス (水平)
$\epsilon_{n,y}$	0.21 μm	規格化エミッタンス (垂直)
σ_x	0.33 mm	RMS ビームサイズ (水平)
σ_y	0.20 mm	RMS ビームサイズ (垂直)
σ_z	0.64 mm	RMS バンチ長
σ_t	2.13 ps	RMS バンチ長
β_x	5.61 m	Twiss parameter
β_y	1.58 m	
α_x	0.071	
α_y	1.622	

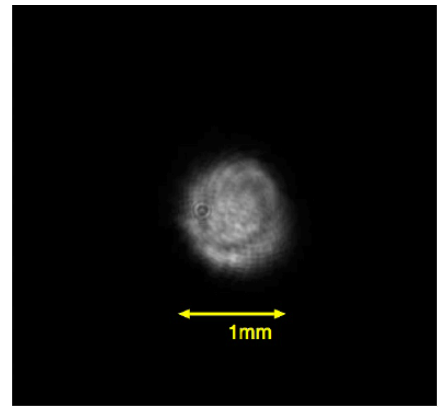
diagnostic line

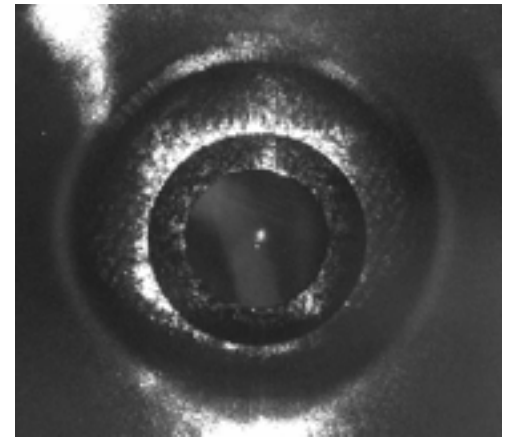


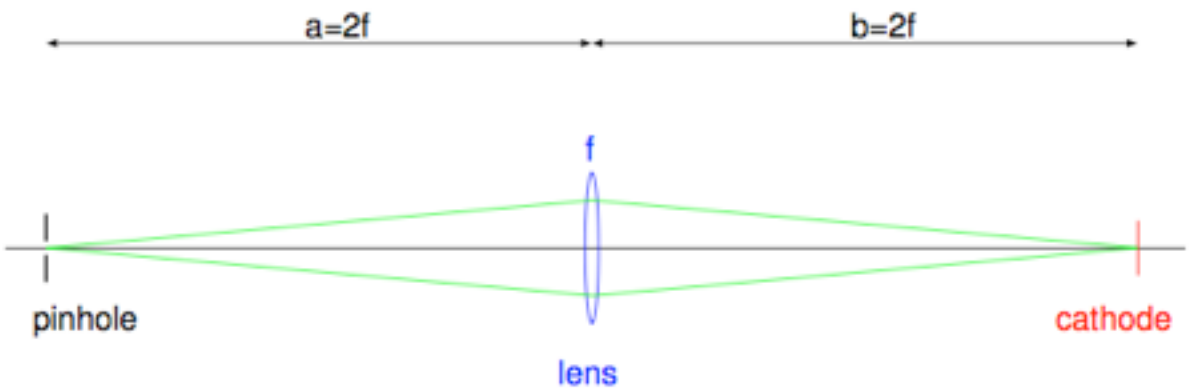
Laser spot on photo cathode

- Before beam operation, laser spot on the cathode was directly checked with a camera.
  - (Impossible if it is an ideal mirror surface, but possible in reality.)
  - Adjusted to be center of the cathode.
- Laser spot profile
  - Imaging a pinhole, designed to be a flat circular distribution.
  - Not perfect, but seems ok.

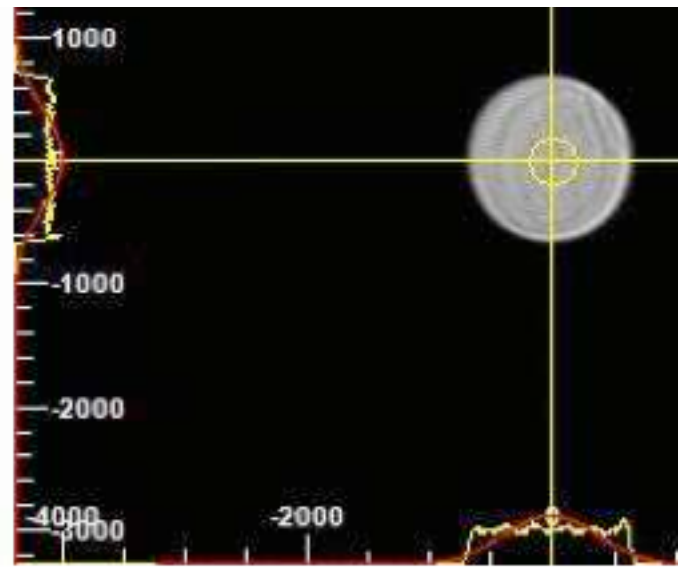
at beam operation





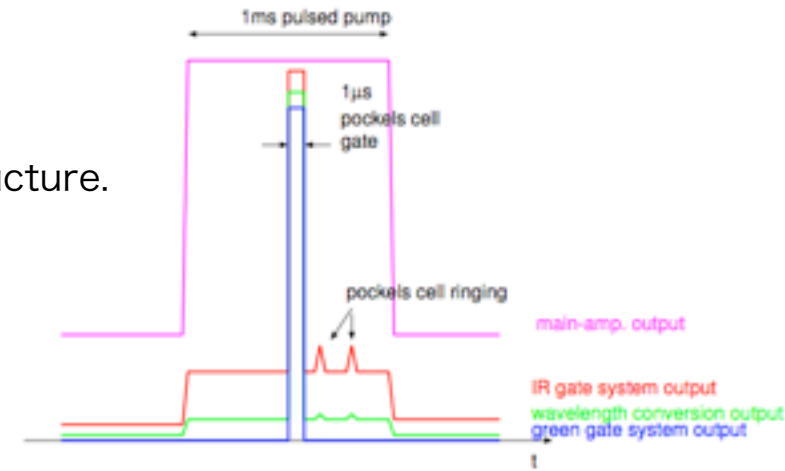


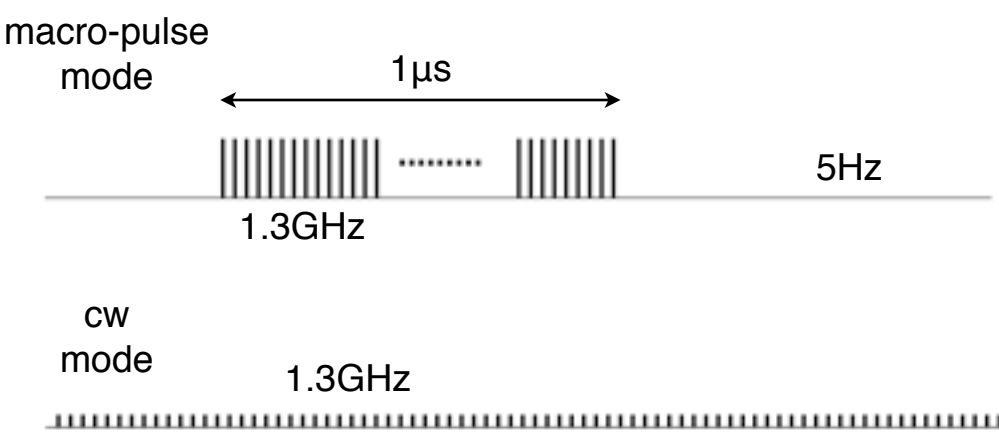
in an ideal case

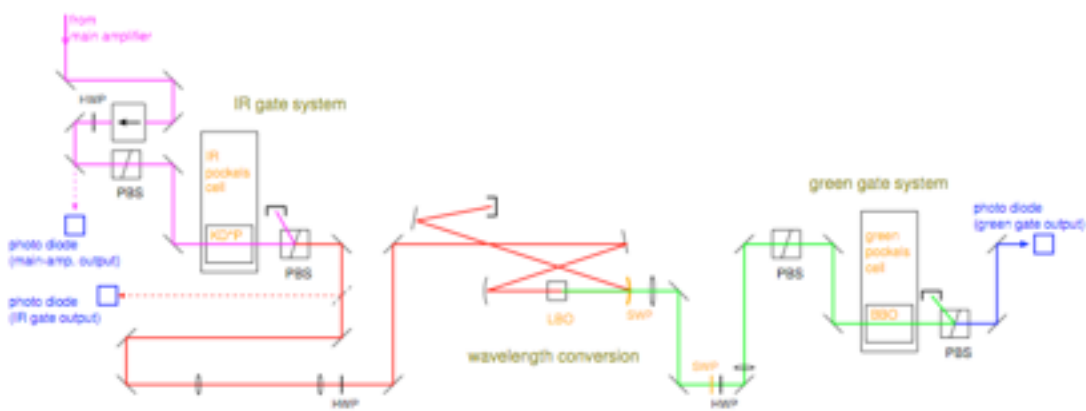


Operational mode for commissioning

- Handling CW beam is difficult at first.
  - Can not use destructive monitor.
  - Small loss can be a fatal damage.
- Macro-pulse mode for commissioning.
  - Can use screen monitors, you can move beam as you like
  - Accelerator system works CW, only laser works gated structure.
- Typical structure at tuning/measurement
  - 1.3GHz, 1μs (1300 bunches), 0~10mA, 5Hz

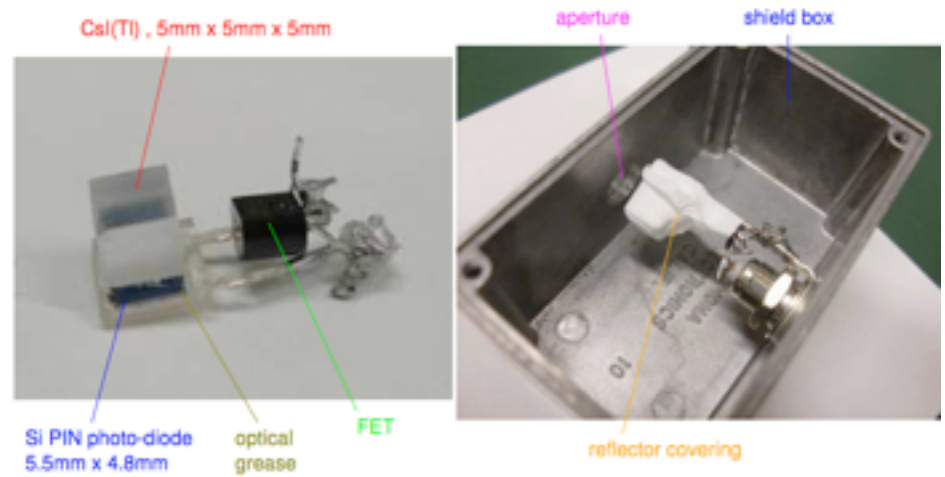


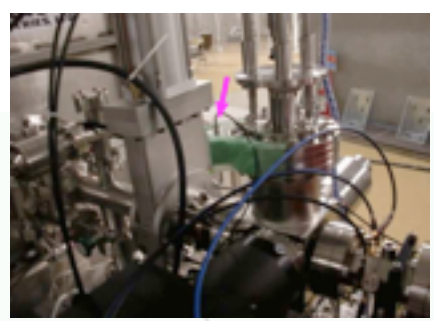




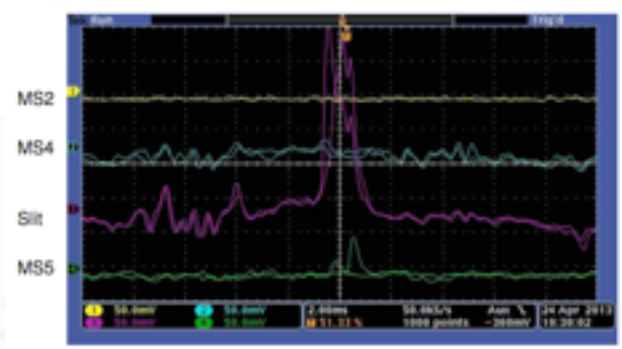
First beam transport

- Loss monitors were spread over the beam line.
  - cheap detector of CsI and photo-diode
- We could tell where the beam reaches.
- It turned out to be a reliable tool for the very first time.

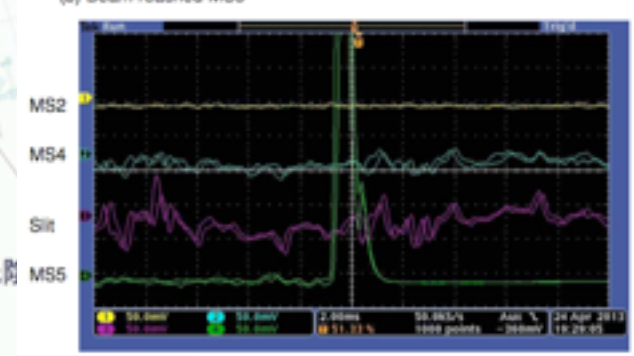




(a) When beam could not reach MS5

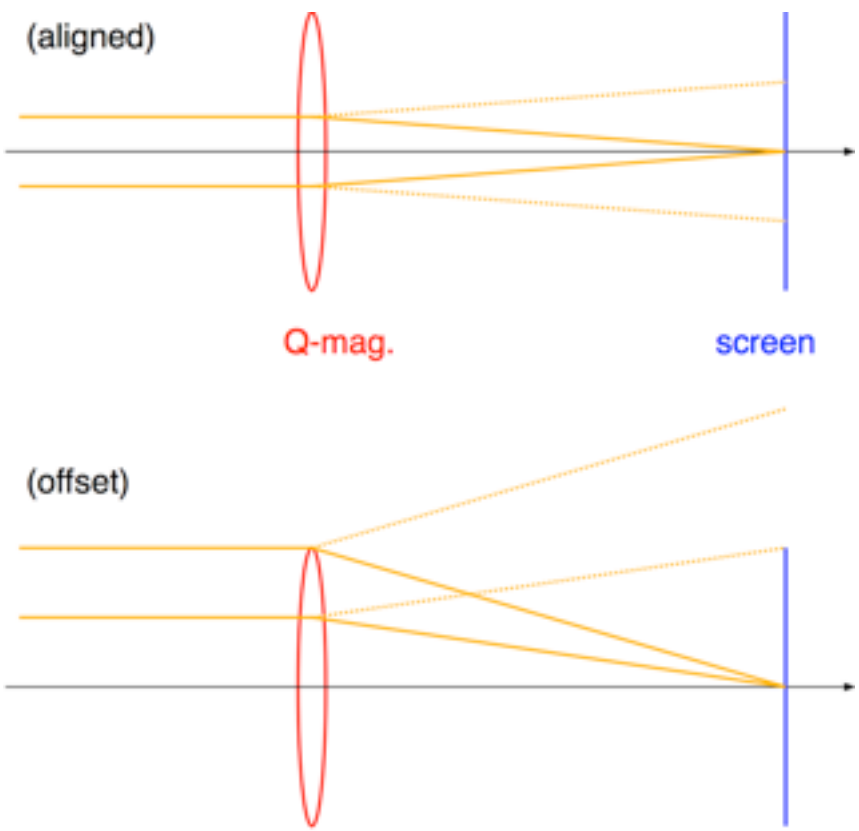


(b) Beam reached MS5



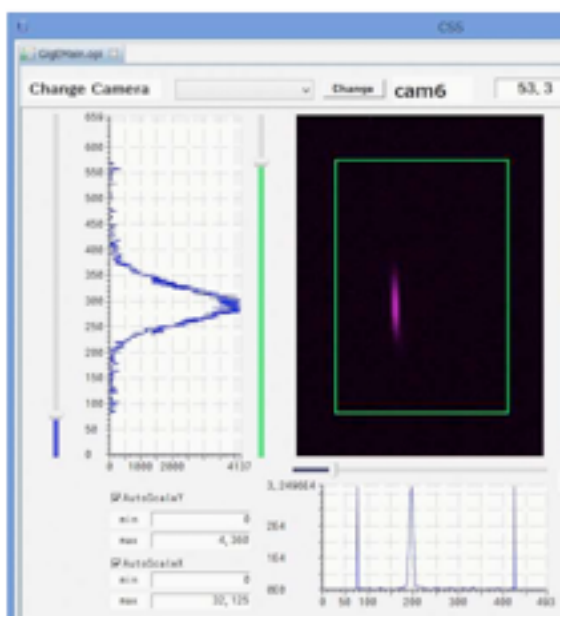
Beam orbit tuning

- BPM did not work at low charge, beam tuning was done using screens.
- Once beam was seen on a screen, orbit tuning was straight forward.
  - Beam based tuning of Quads and Solenoids
  - Varying the magnet, and adjust the upstream correctors
  - <1mm including alignment errors

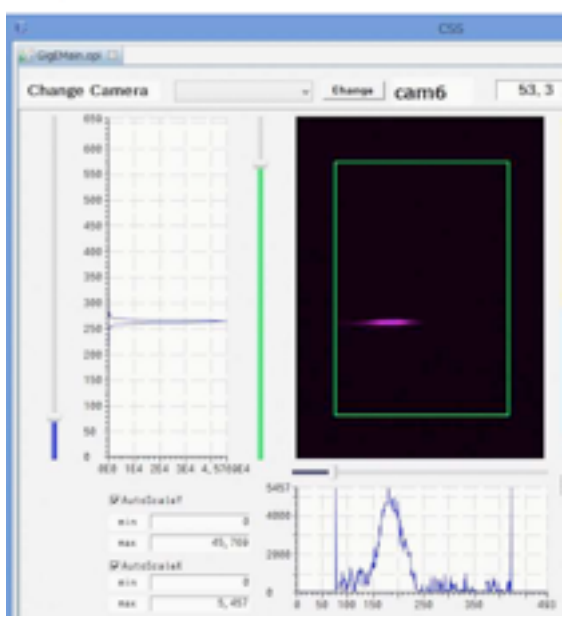


example: QMGE01 BBA

QMGE01=0.2A



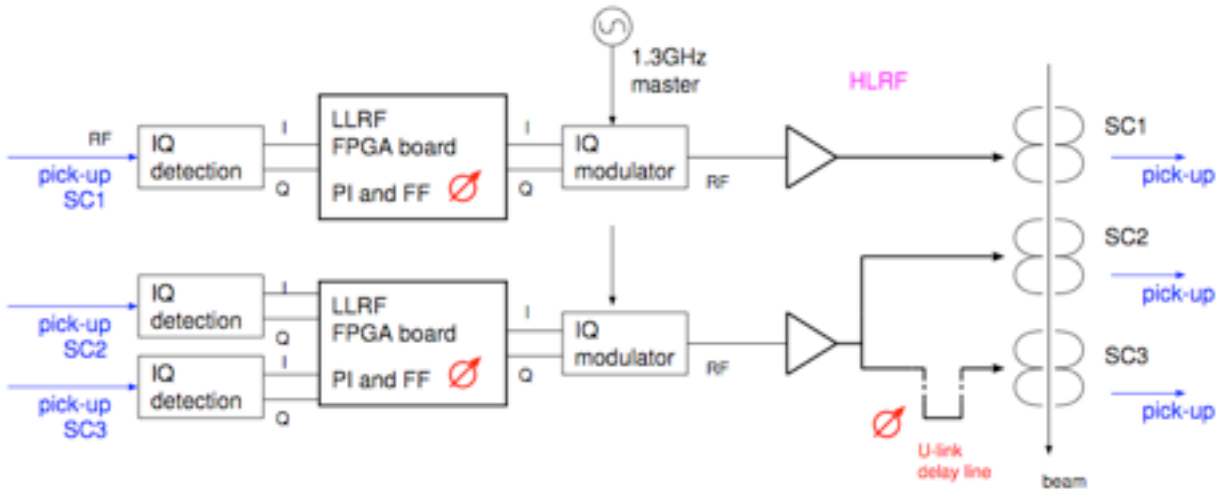
QMGE01=-0.15A

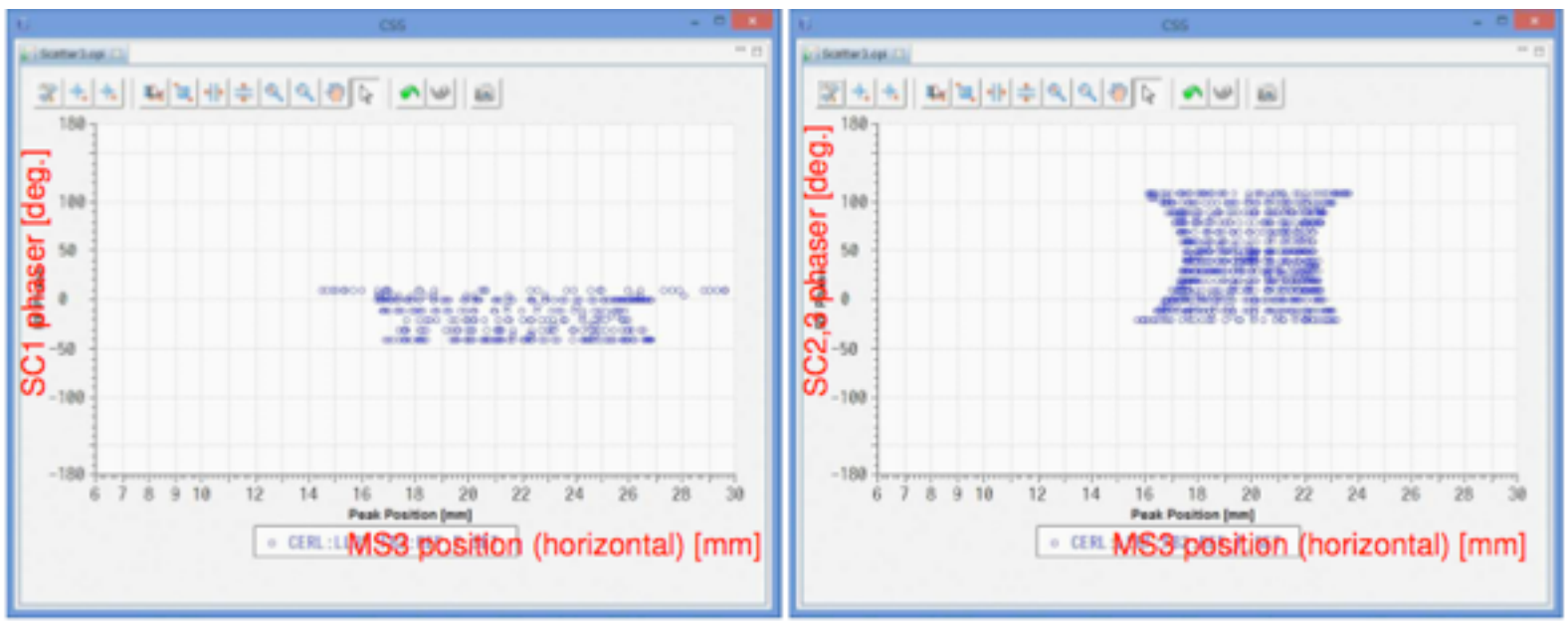


MS6で測定

Acc. phase tuning

- There are three acc. cavities.
- At the very beginning, you need to find accelerating phase.
- Varying (shaking) corrector and scan RF phase. You can find the phase of maximum energy.



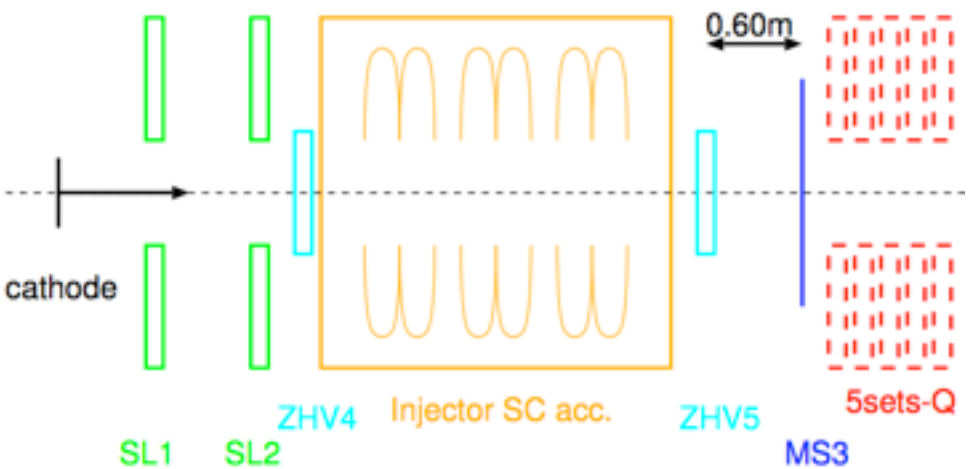


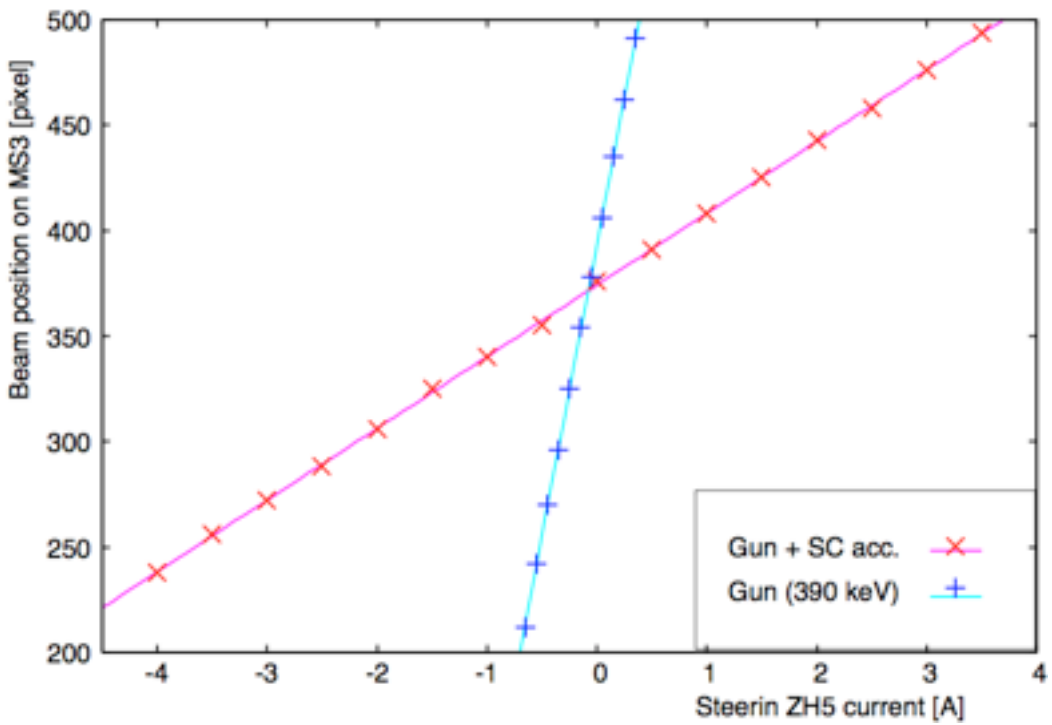
SC1 7MV/m, SC2,3 OFF

SC1 7MV/m, SC2,3 7MV/m

Beam energy confirmation

- After all the cavities were set to be on-crest, we needed to confirm beam energy after acceleration
- Use gun voltage as a reference. (It is calibrated with a reference register.)
  - Measure steering kick with a screen.
  - Using a same set of steering-screen pair for SC acc. on/off measurement, systematic errors are cancelled.
- 5.6 MeV kinetic energy confirmed.

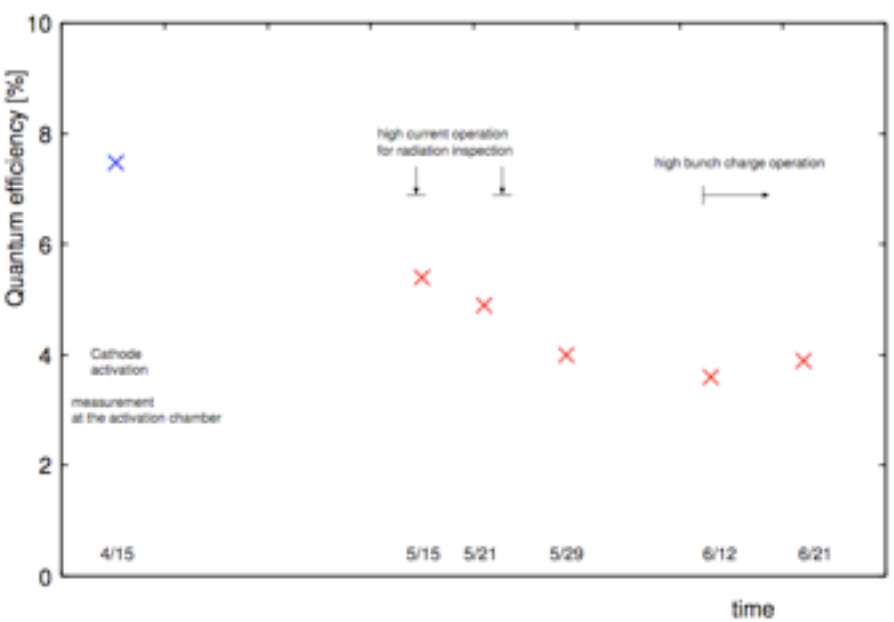


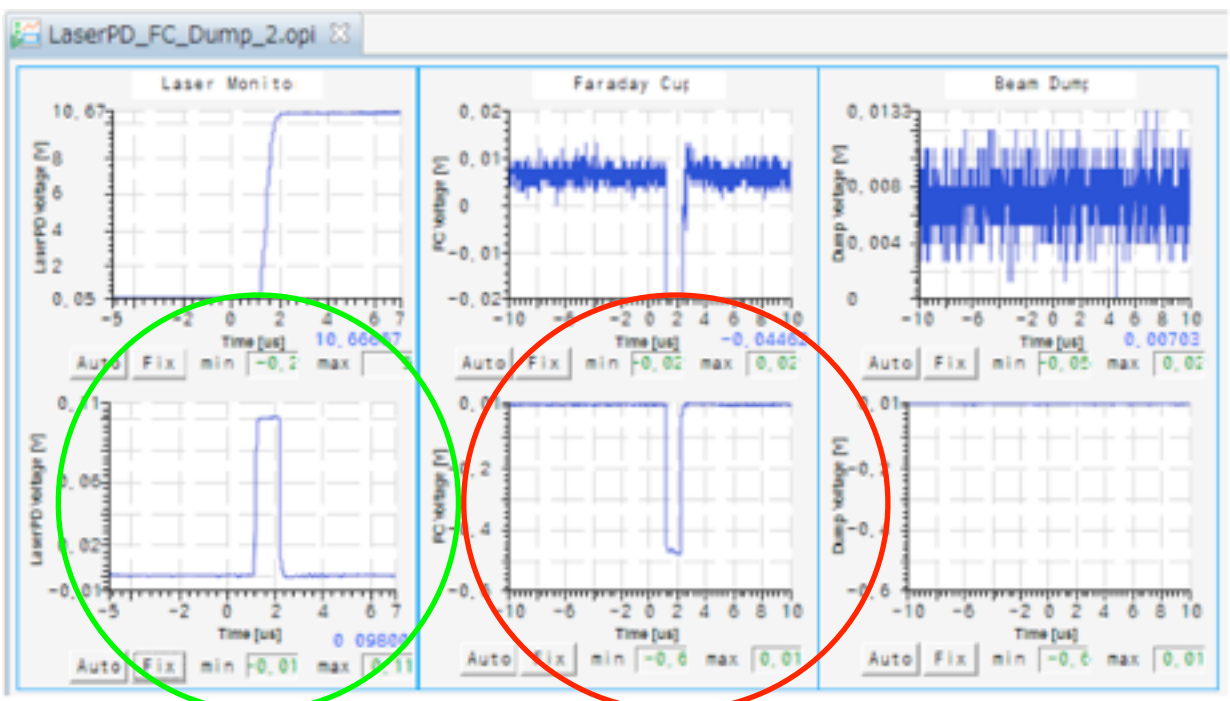


Beam current measurement

- Faraday cup in the diagnostic line
  - 50Ω readout, 0.5V corresponds to 10mA beam.
- Comparing laser power and beam current, you can tell Q.E.
  - 3.5% after more than 1 month of operation (low charge operation)

$$I[\mathrm{mA}] = \frac{\lambda[\mathrm{nm}]}{124} \cdot P[\mathrm{W}] \cdot QE[\%]$$



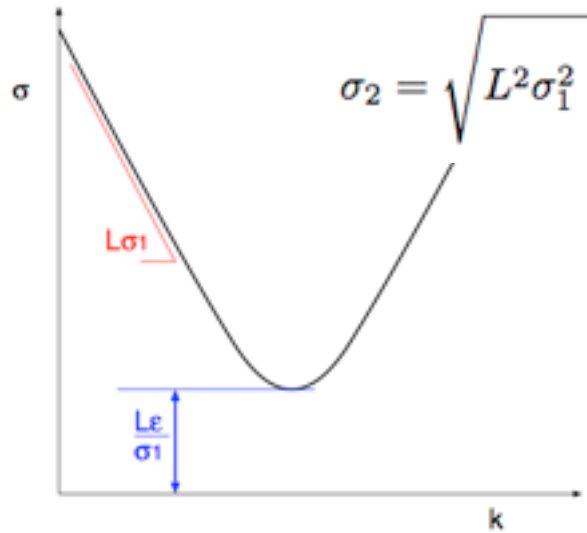


Laser power monitor

Faraday cup

Emittance measurement at gun

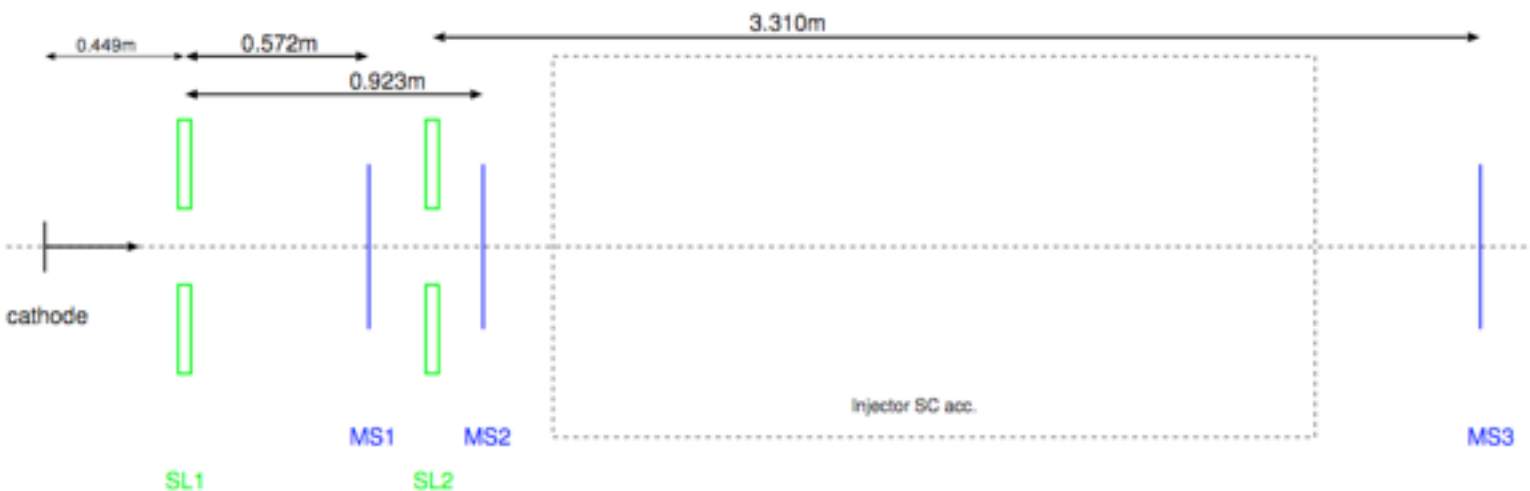
- Waist scan (Solenoid)
- Input
  - K from magnetic measurement
  - L from geometry
- In order to check systematics, measurements were repeated with several sets of solenoid and screen.
- This measurement was done at very low charge.



$$\sigma_2 = \sqrt{L^2\sigma_1^2\left(k - (\frac{1}{L} - \frac{\alpha_1}{\beta_1})\right)^2 + \frac{L^2\epsilon^2}{\sigma_1^2}}$$

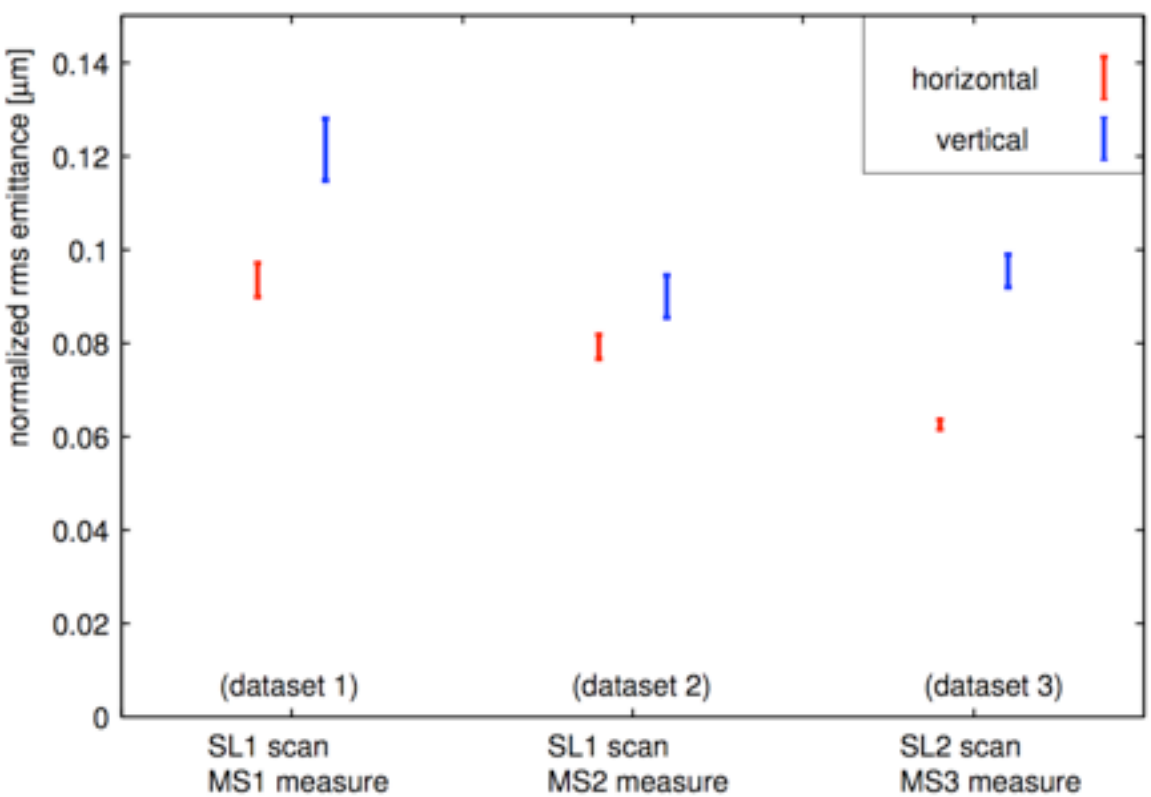
$$y = \sqrt{a(k-b)^2 + c}$$

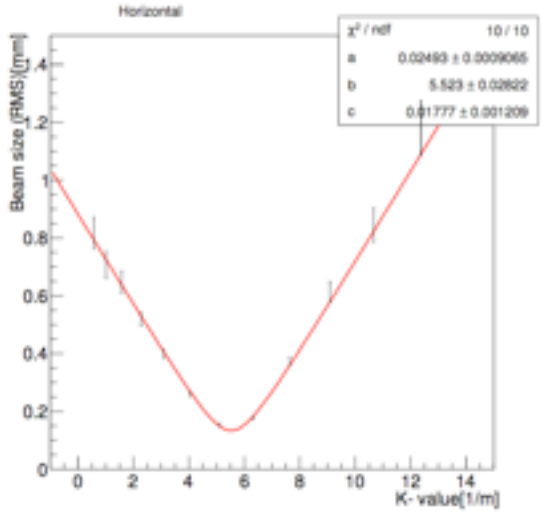
$$\epsilon_n = \gamma\beta\frac{\sqrt{ac}}{L^2}$$

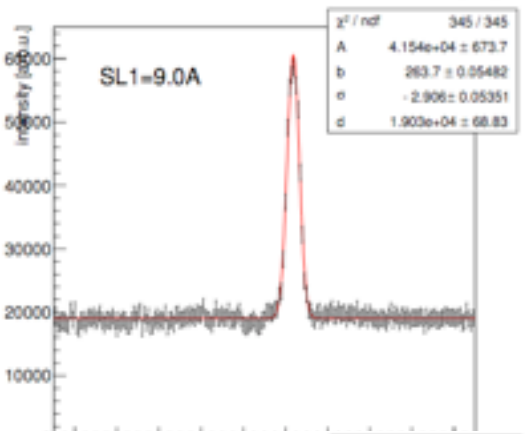


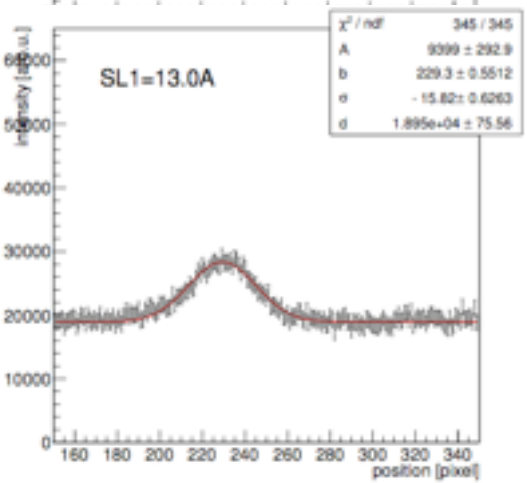
Gun emittance result

- Beam image rotates while changing the solenoid. So, horizontal and vertical have no exact meaning.
- Anyway, normalized emittance 0.07 μm (+-10%).
- We believe the cathode keeps good quality.



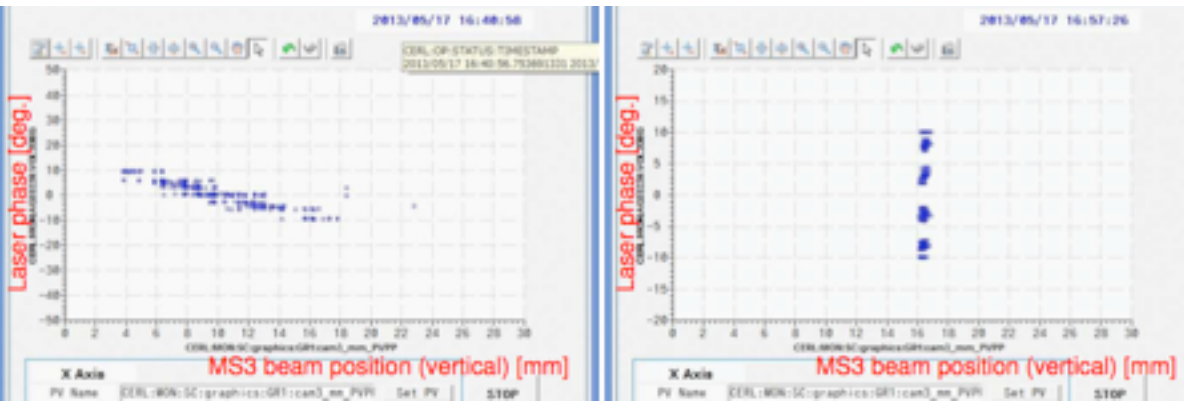


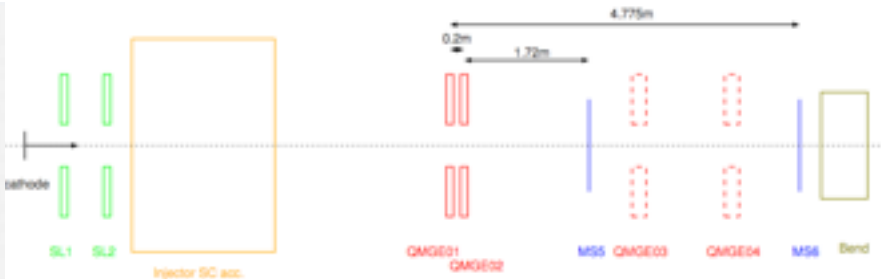


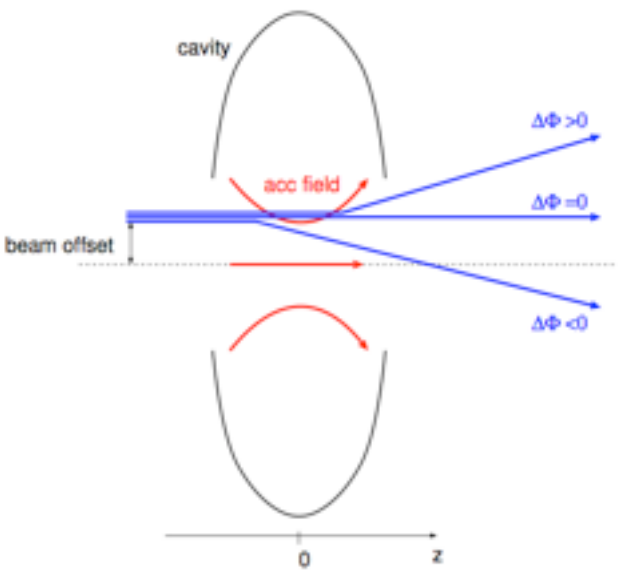


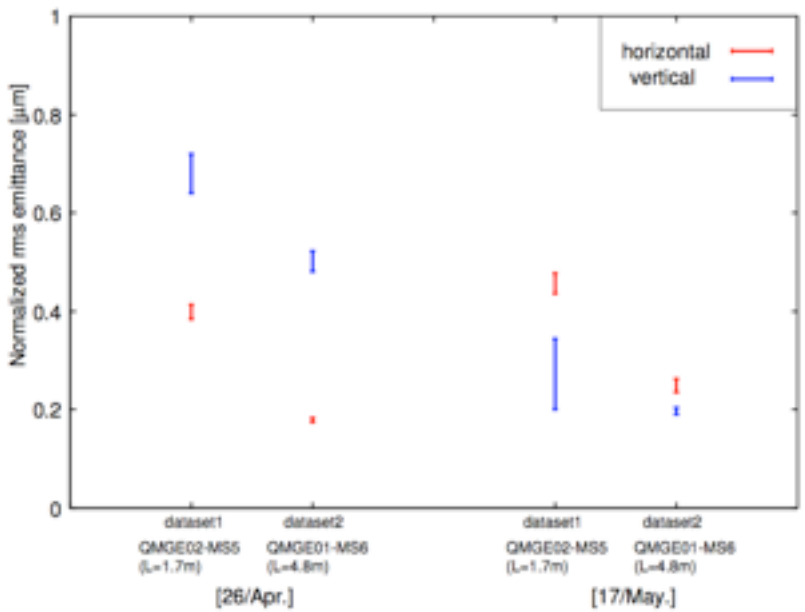
Emittance at the diagnostic line

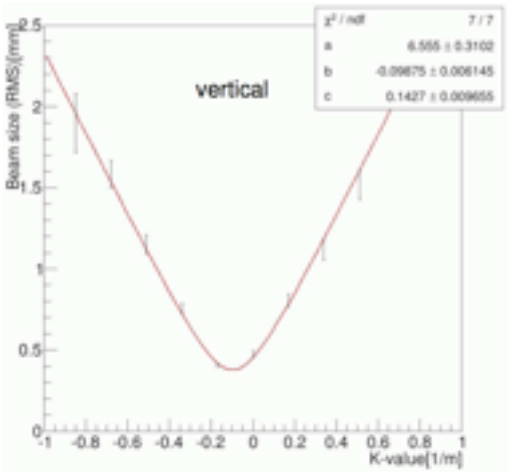
- Waist scan by Quads. Measurement at low charge.
- Turned out orbit in acc. cavity affect the emittance.
  - Beam based orbit tuning of cavities improved the emittance to 0.2 μm, still factor 2 to improve.
  - Since there are three cavities in the cryo module, they can not be perfectly aligned in a line.





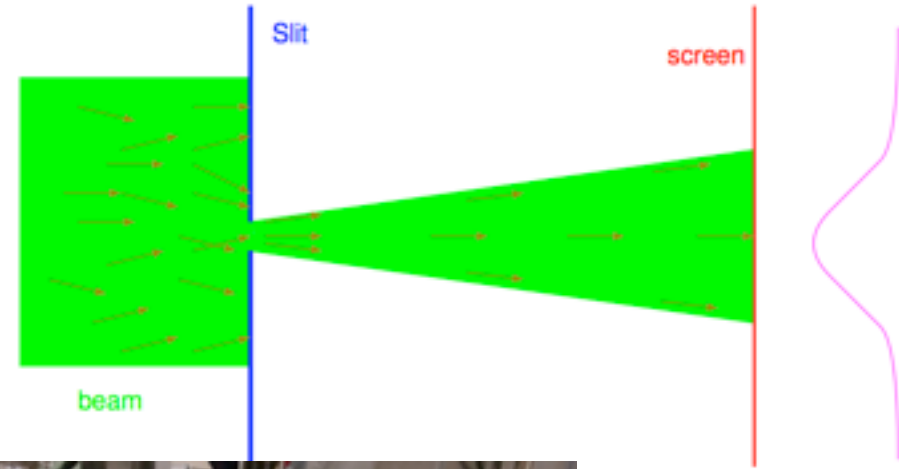


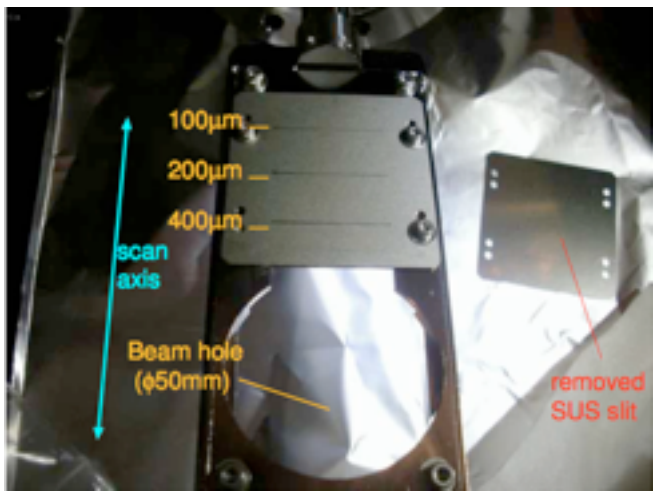


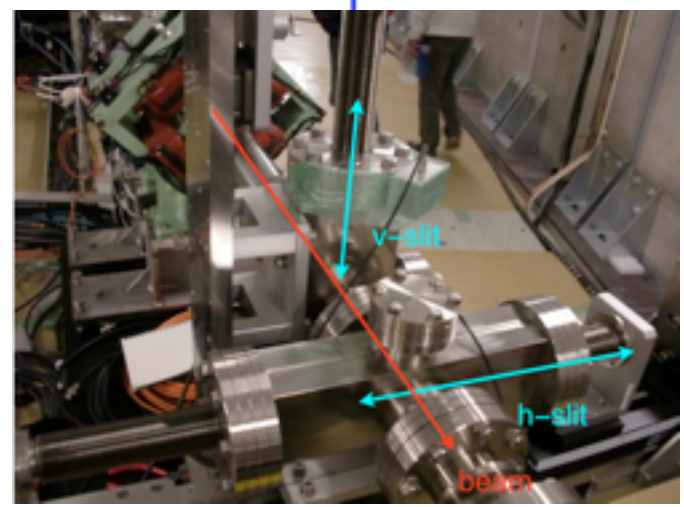


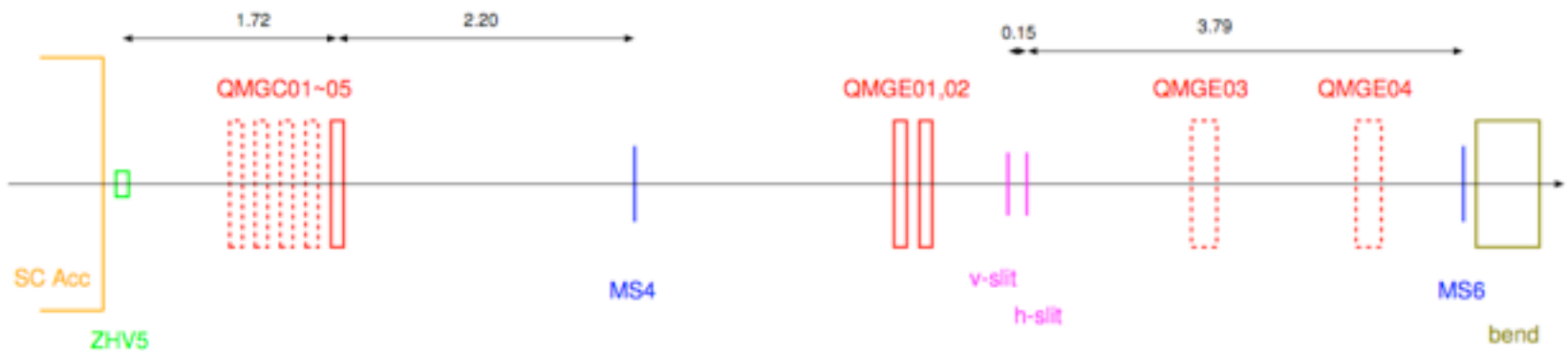
Emittance measurement (slit)

- Slit scan for high bunch charge beam
  - Quad scan is affected much by space charge
  - Slit converts a beam to a low charge beamlet, can be measured through a long drift space.
- 100μm tungsten slits



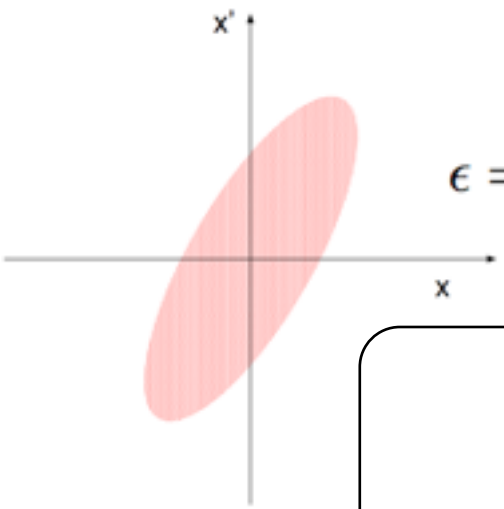






Slit scan result

- Scanning the slit position (x) , density map I(x,x') was obtained.
- Emittance ε was calculated from I(x,x') by the definition.
- To check the measurement system, results of quad scan and slit scan for the same beam are compared.
- 0.2 μm normalized emittance at the diagnostic line (low charge), factor 2 increase compared with the upstream of acc.



$$\epsilon = \sqrt{\overline{x}^2\overline{x'}^2 - (\overline{xx'})^2}$$

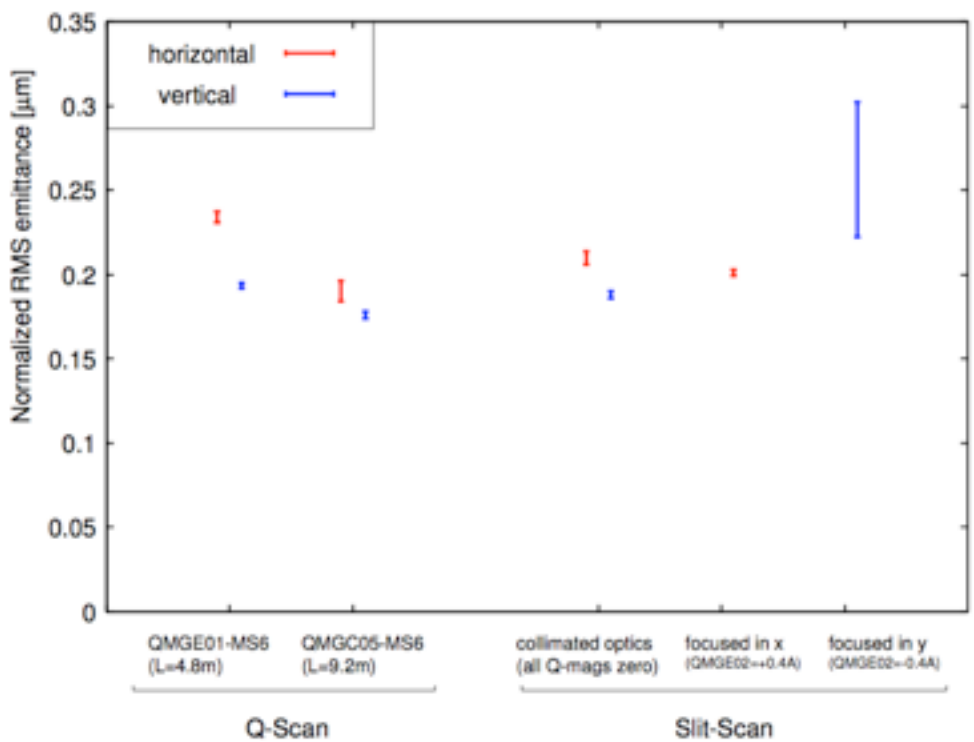
$$\overline{x} = \frac{\sum_{x,x'} I(x,x') \cdot x}{\sum_{x,x'} I(x,x')}$$

$$\overline{x'} = \frac{\sum_{x,x'} I(x,x') \cdot x'}{\sum_{x,x'} I(x,x')}$$

$$\overline{x}^2 = \frac{\sum_{x,x'} I(x,x') \cdot (x-\overline{x})^2}{\sum_{x,x'} I(x,x')}$$

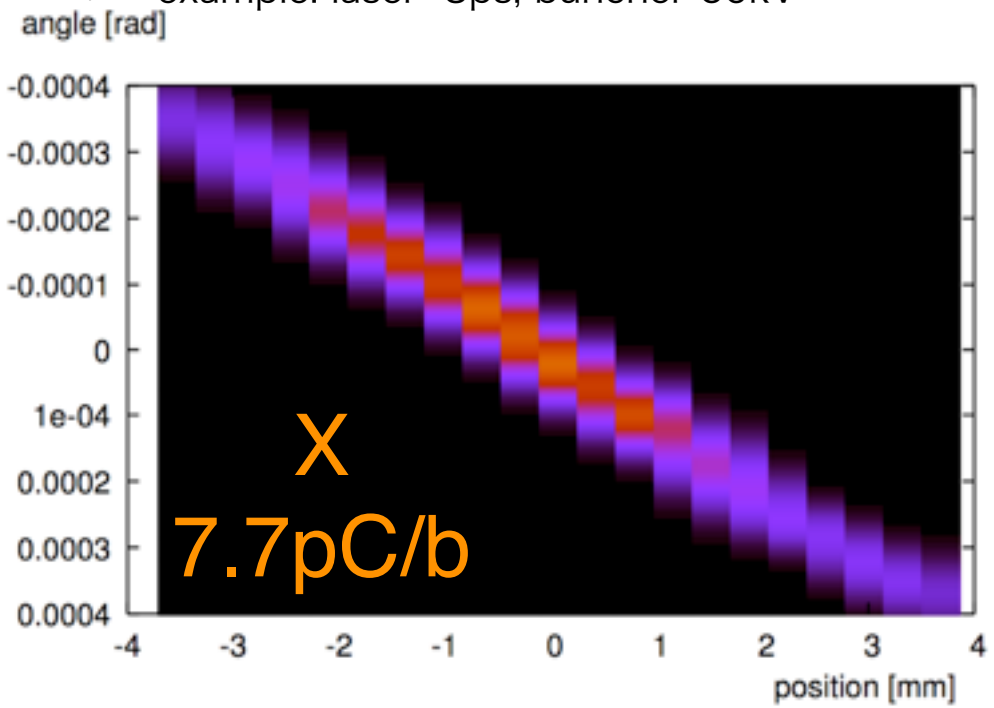
$$\overline{x'}^2 = \frac{\sum_{x,x'} I(x,x') \cdot (x'-\overline{x'})^2}{\sum_{x,x'} I(x,x')}$$

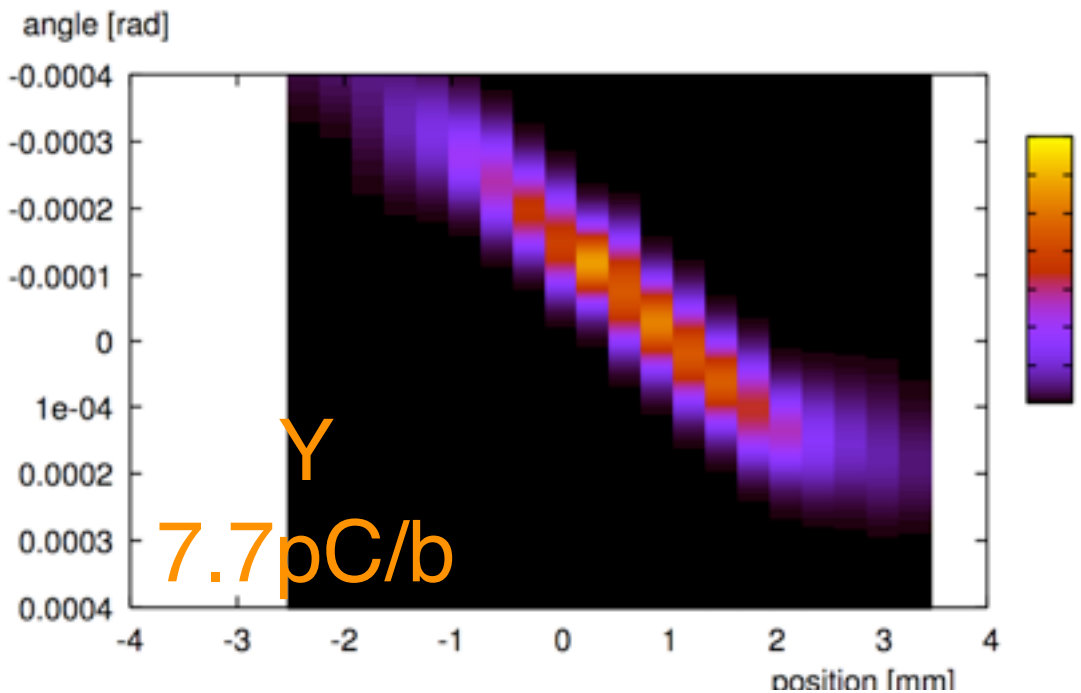
$$\overline{xx'} = \frac{\sum_{x,x'} I(x,x') \cdot (x-\overline{x})(x'-\overline{x'})}{\sum_{x,x'} I(x,x')}$$

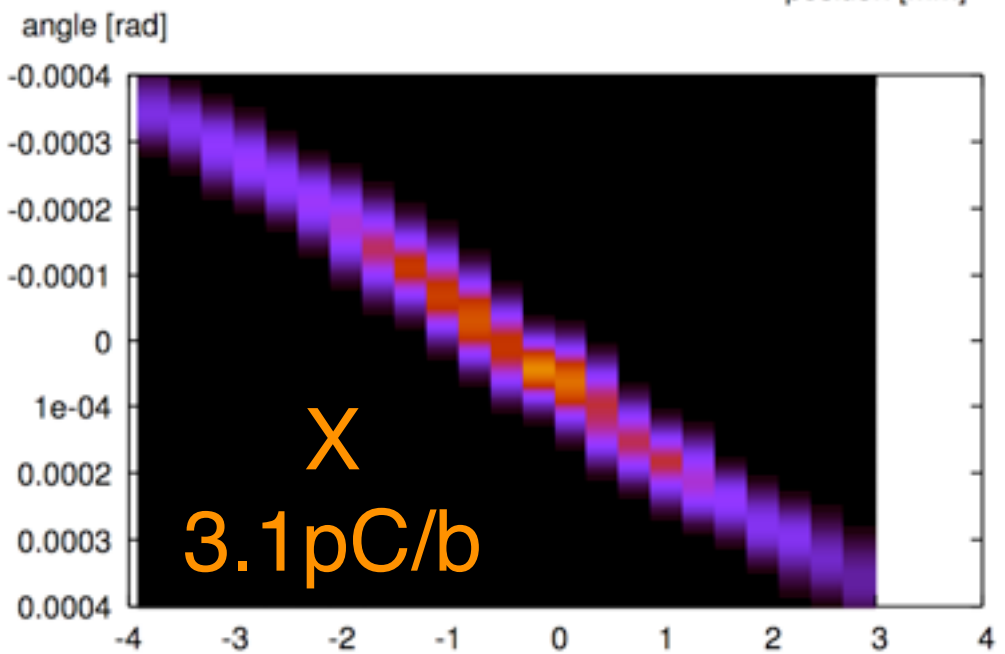


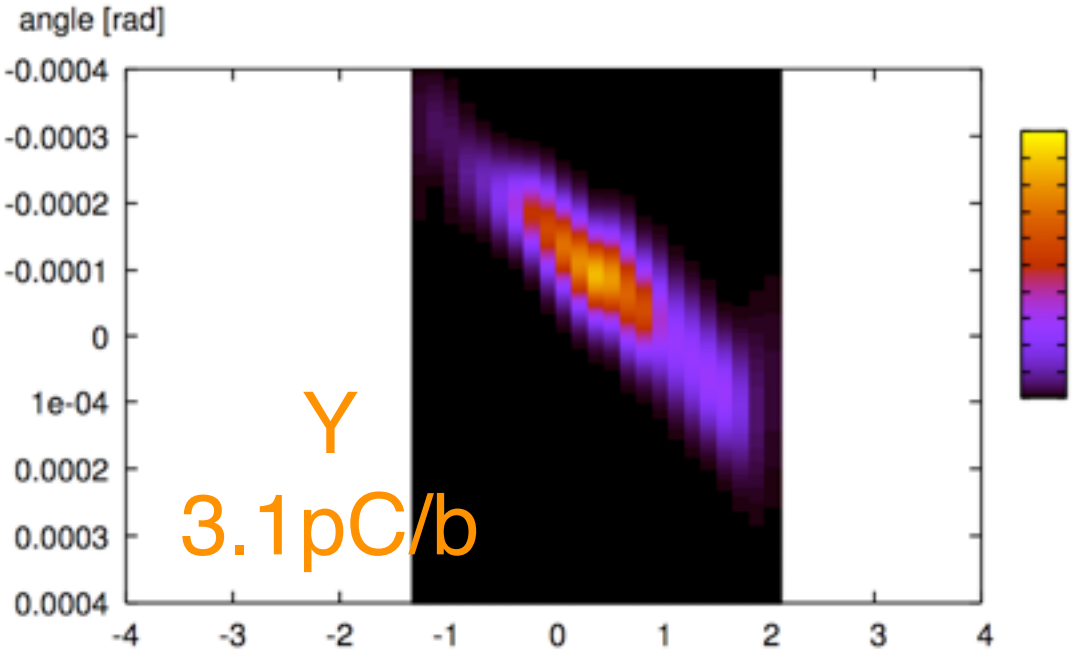
Emittance result at high charge

- example: laser 3ps, buncher 50kV



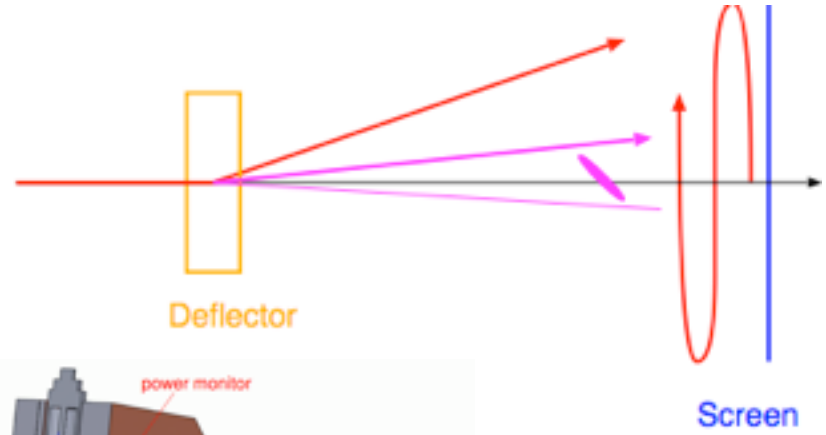


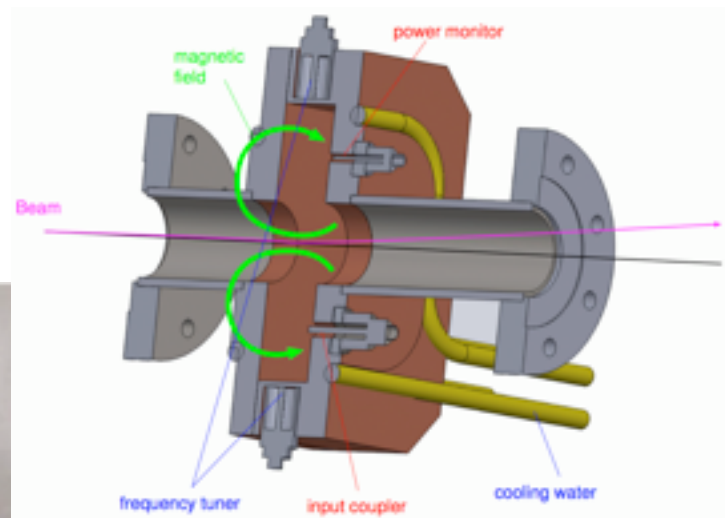


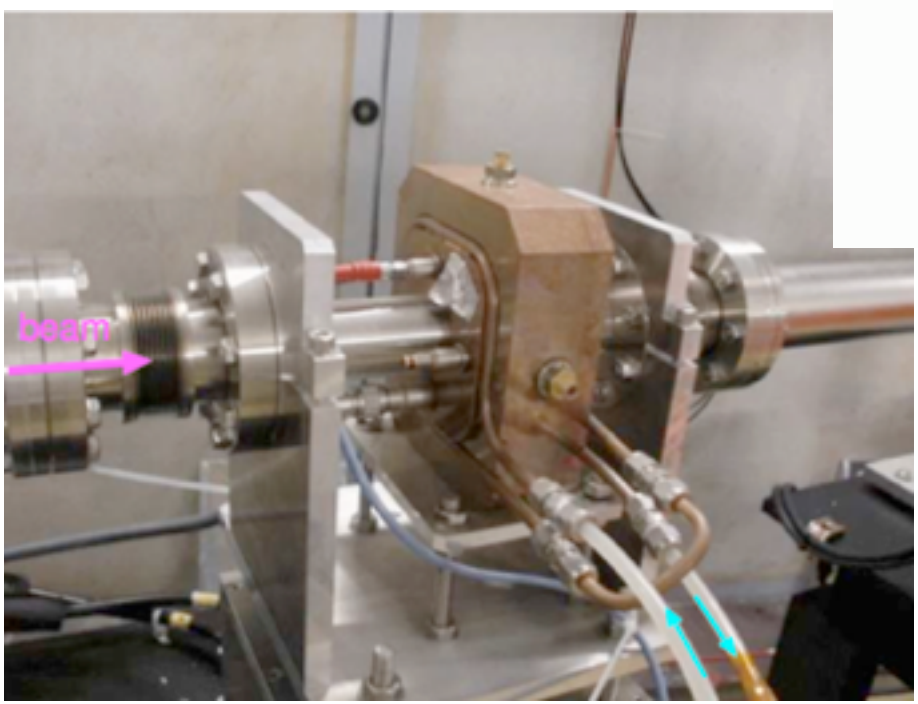


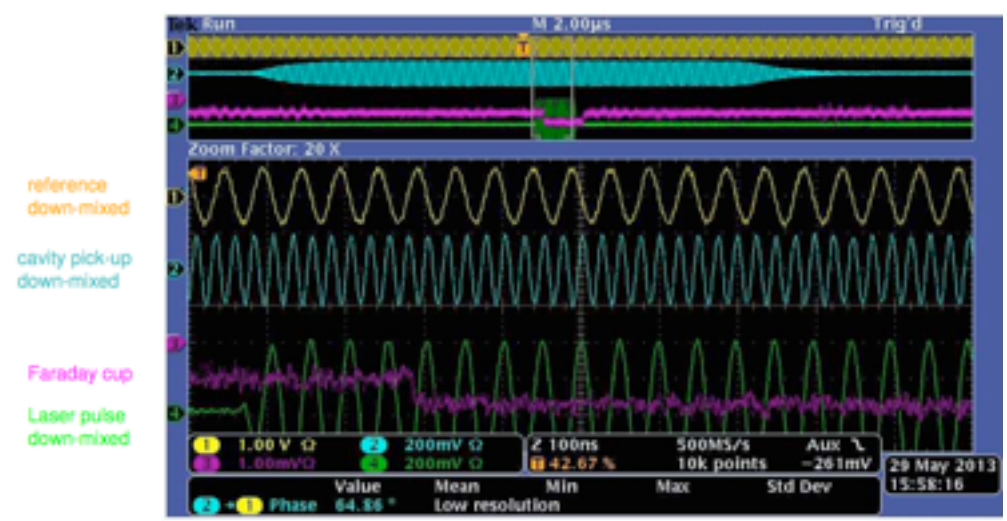
Bunch length measurement

- RF deflector
  - 2.6GHz dipole mode
  - Q-loaded 7000 (time constant 0.4μs)
  - 10μs, 600W pulsed operation
  - Kick in vertical direction



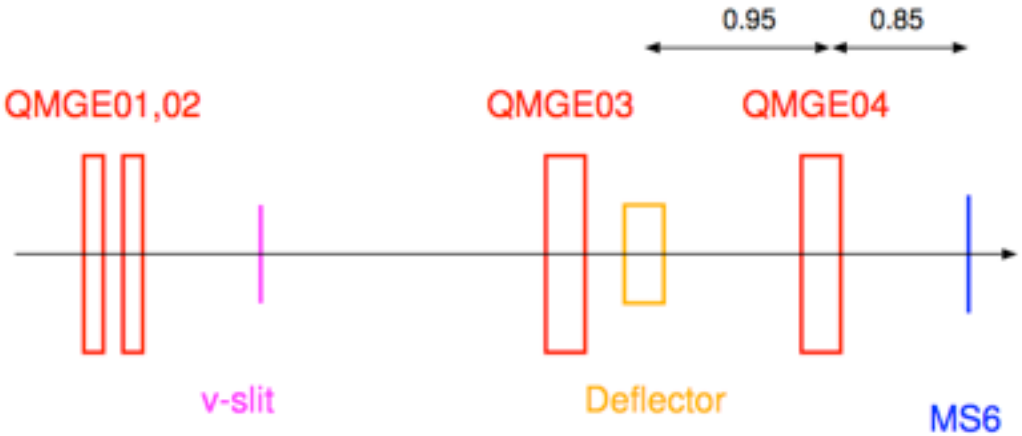


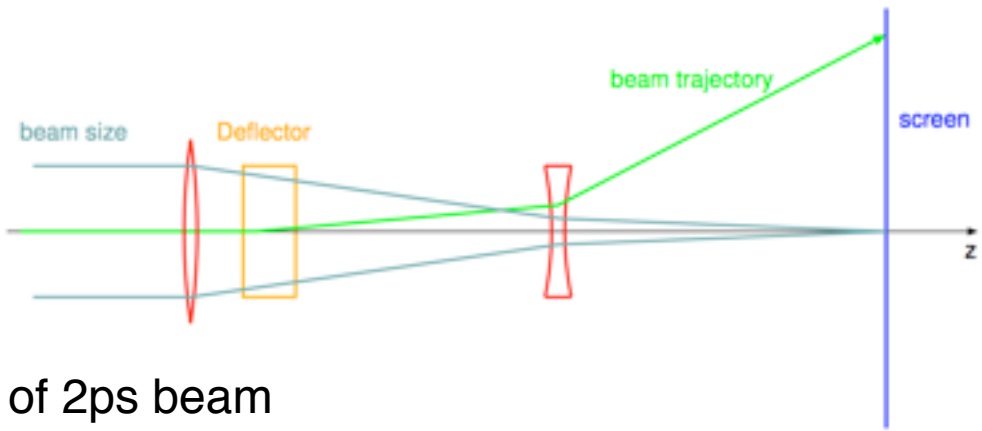




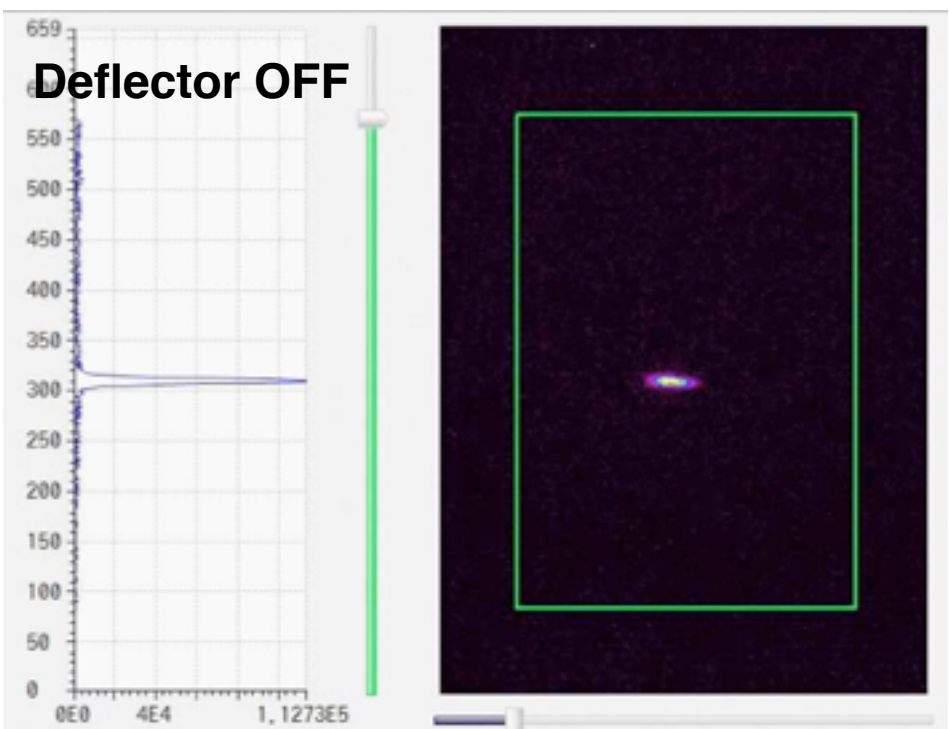
Bunch length measurement

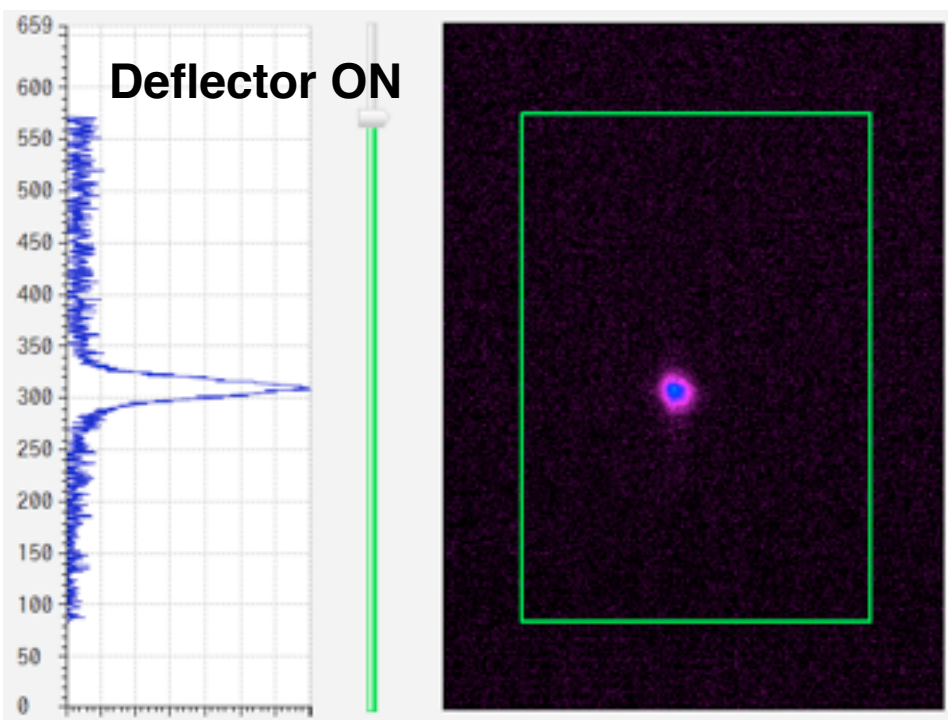
- Special defocusing optics for improving resolution in a limiting distance.
- 0.7ps resolution (can be better)





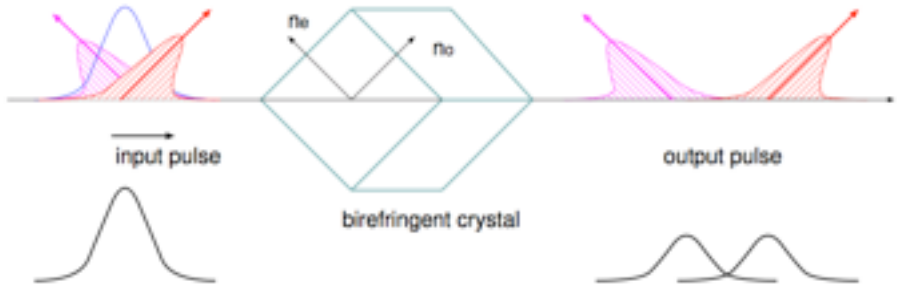
example of 2ps beam



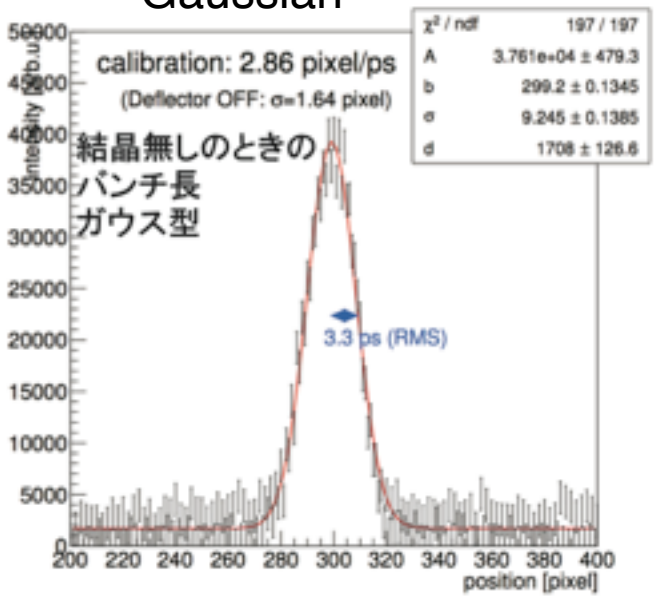


Laser pulse duration

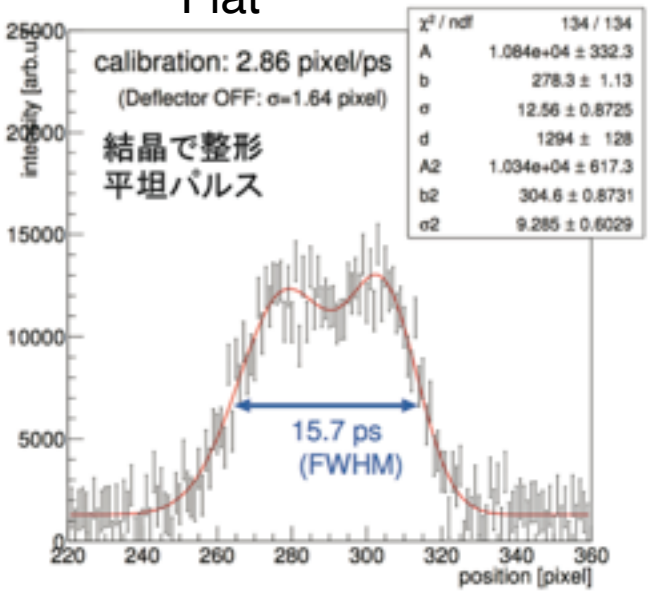
- At space-charge dominated case, emittance optimization can be done by laser shape.
  - Flat time structure is preferable than gaussian.
  - 16ps flat pulse is assumed in the simulation
- Laser pulse
  - 3.4 ps rms gaussian
  - 16 ps flat-like structure by pulse stacking
- Confirmed by beam measurement at buncher off condition

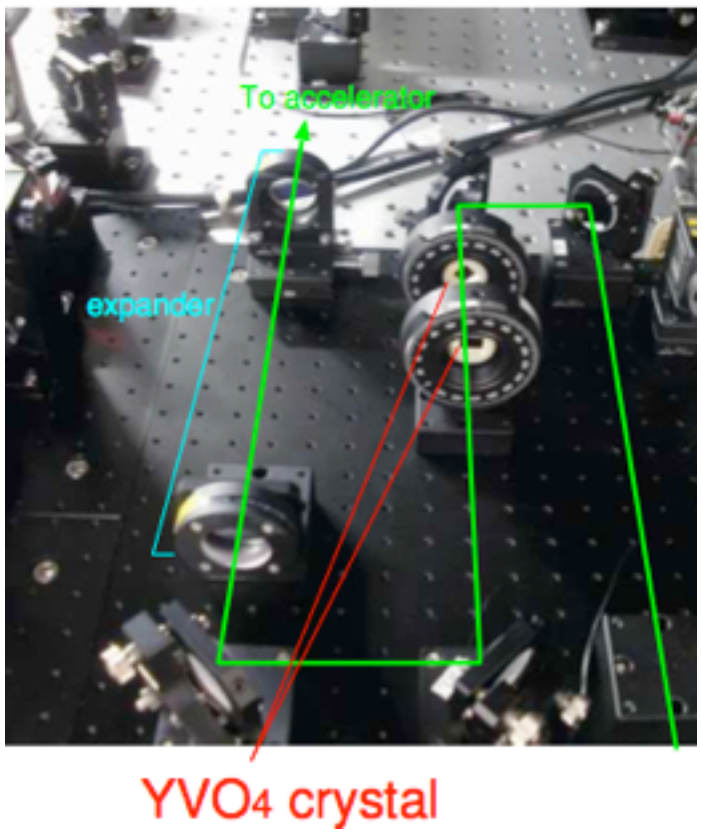


Gaussian



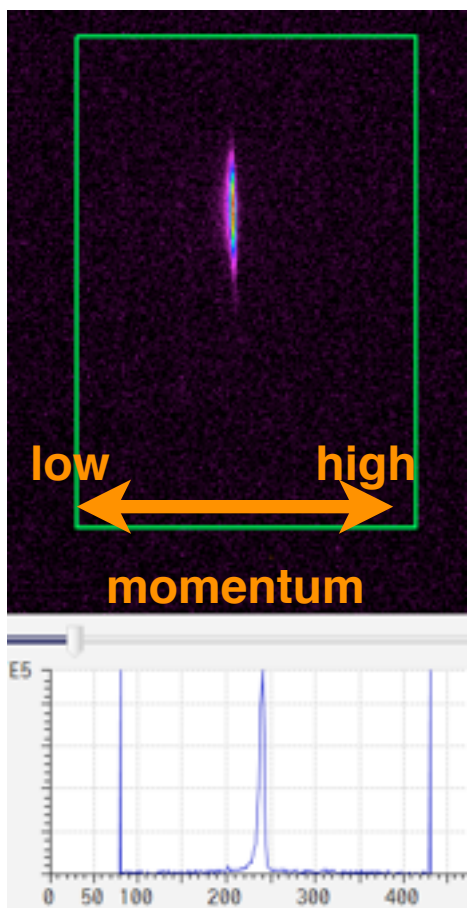
Flat

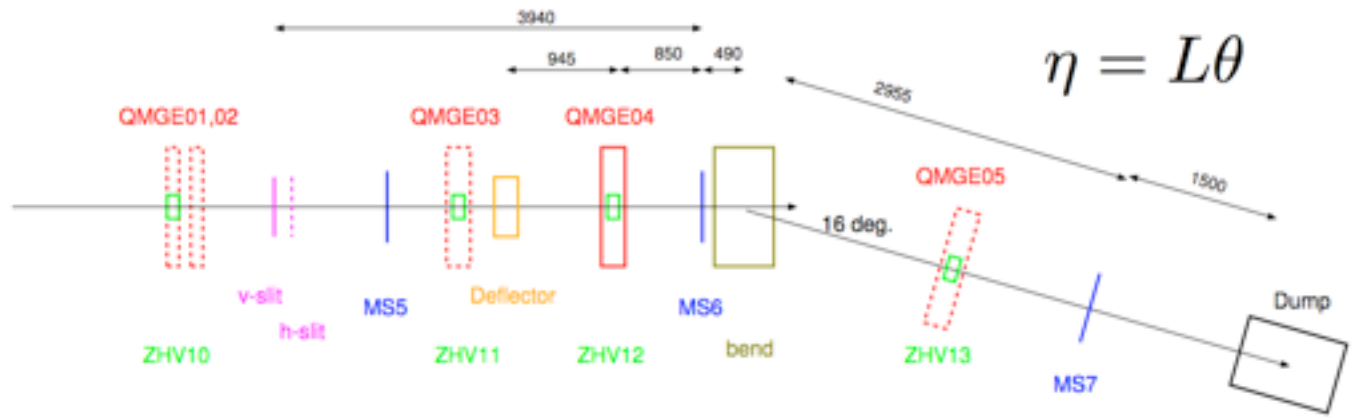




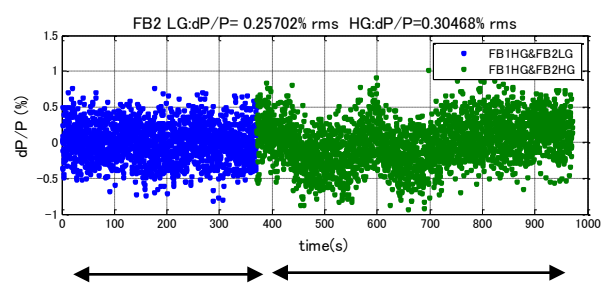
Energy spread

- Dispersion at dump line was for energy spread measurement
  - η =0.83m at the screen MS7
  - Beam focus by a quad at upstream of the bending, QMGE04
- Momentum jitter was improved to be 6x10^-5 after phase optimization.





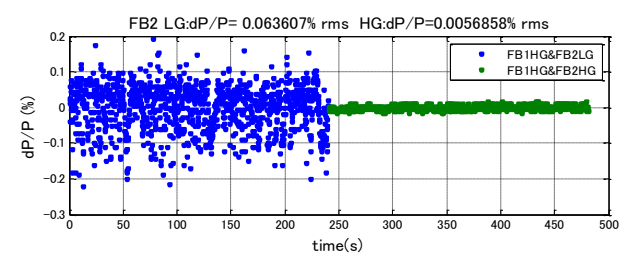
Before phase fine tuning



FB1: high gain
FB2: low gain

FB1: high gain
FB2: high gain

After fine tuning of on-crest

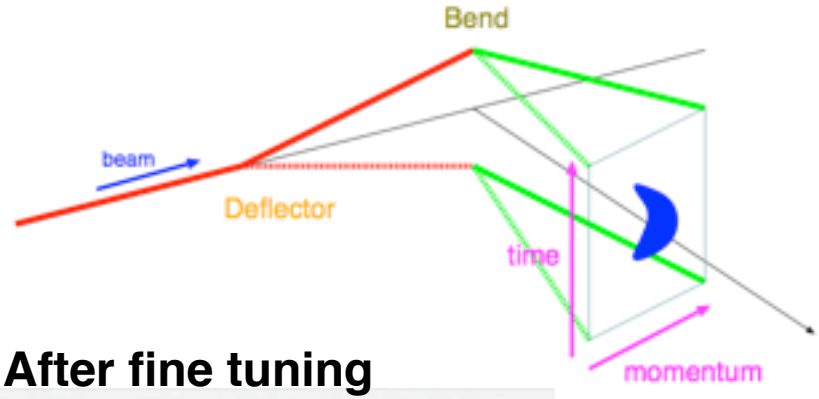


FB1: high gain
FB2: low gain

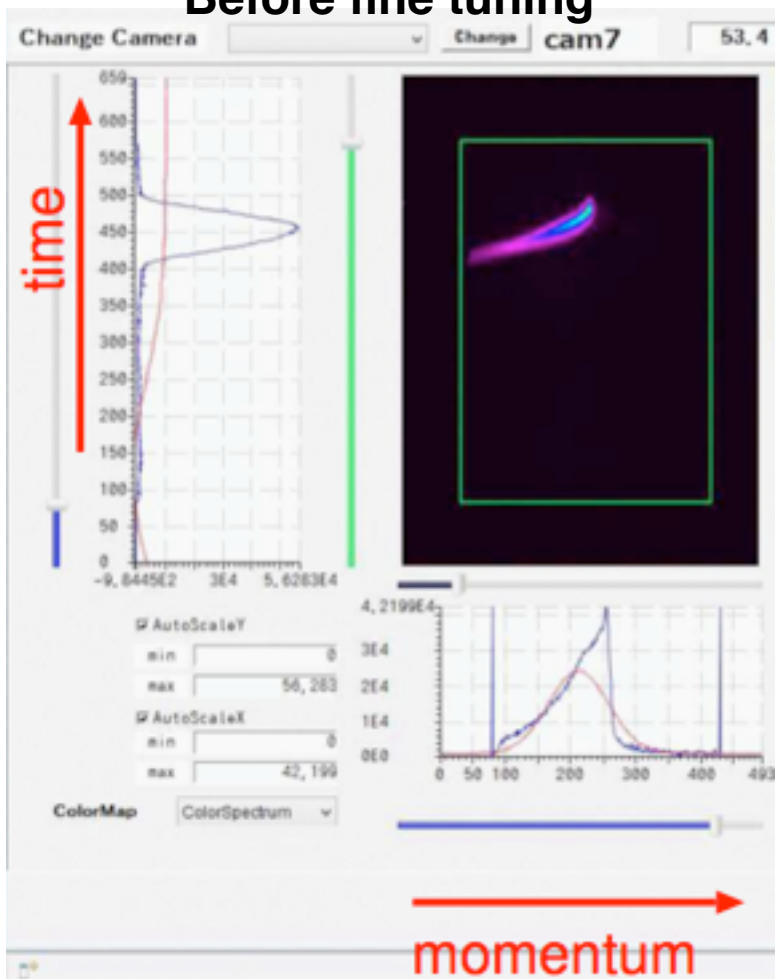
FB1: high gain
FB2: high gain

Longitudinal phase space

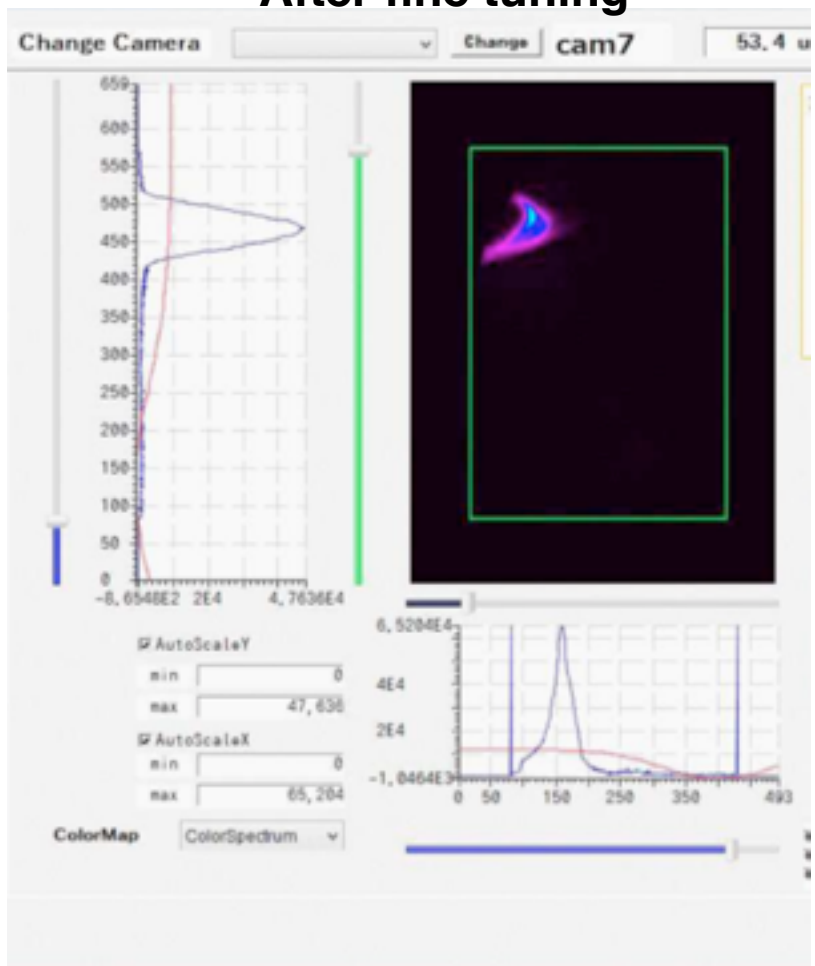
- Combine bunch length and energy measurements.
  - Deflector kicks in vertical
  - Bend kicks in horizontal
- Easily confirm on-crest condition



Before fine tuning



After fine tuning



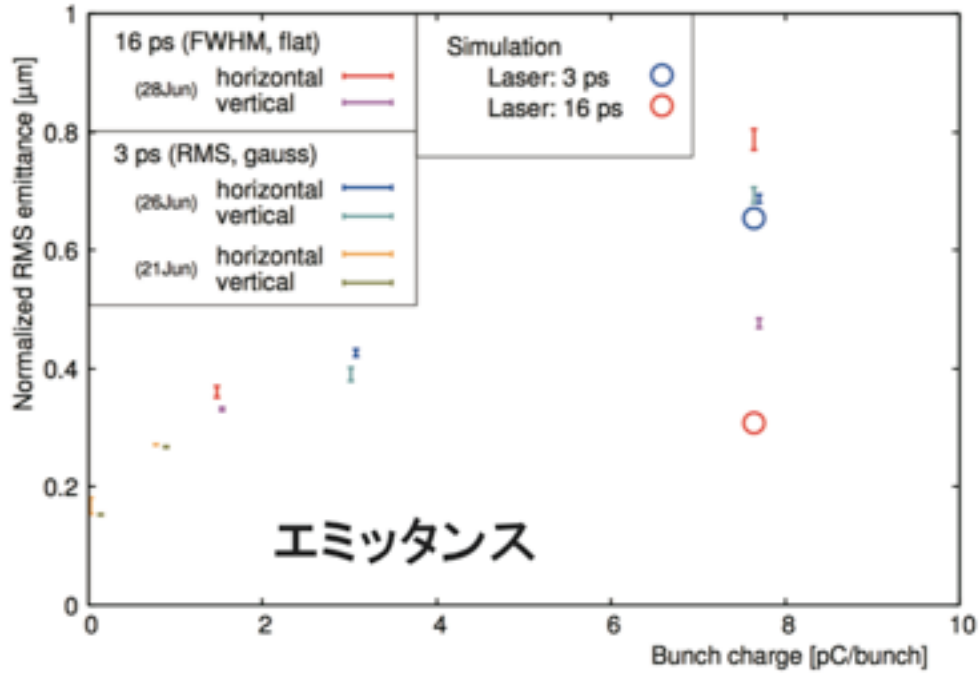
Beam measurement

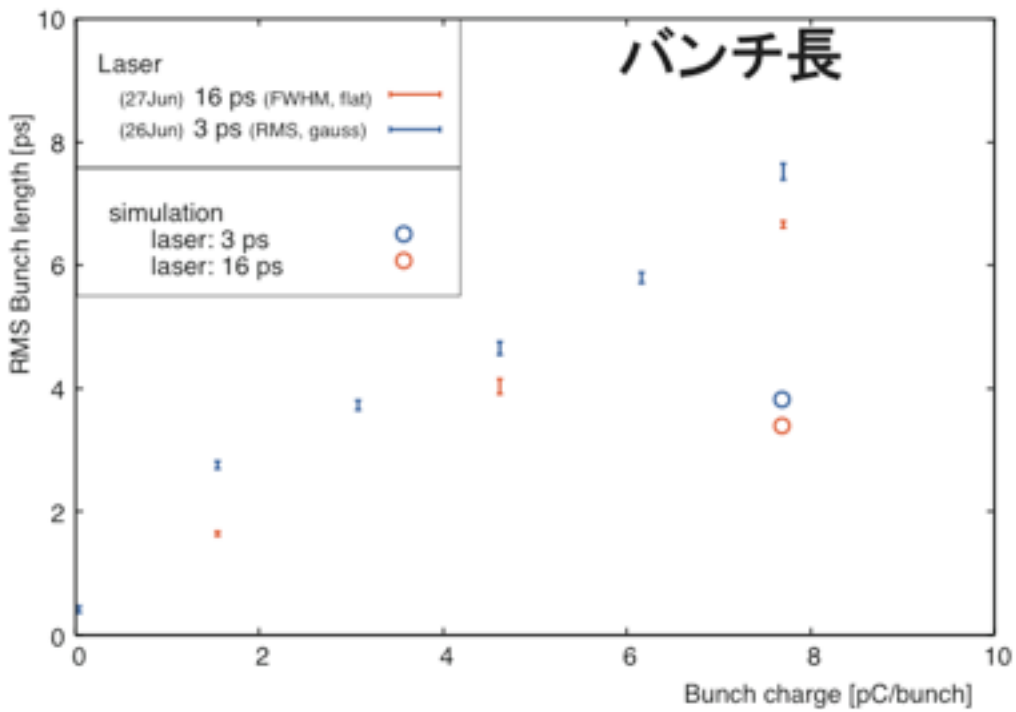
- Most of the first commissioning period was for debugging components.
- Finally at the last week, there was a chance to take systematic data in a fixed beam condition.
- At bunch charge 7.7pC, emittance, bunch length, energy spread were measured.

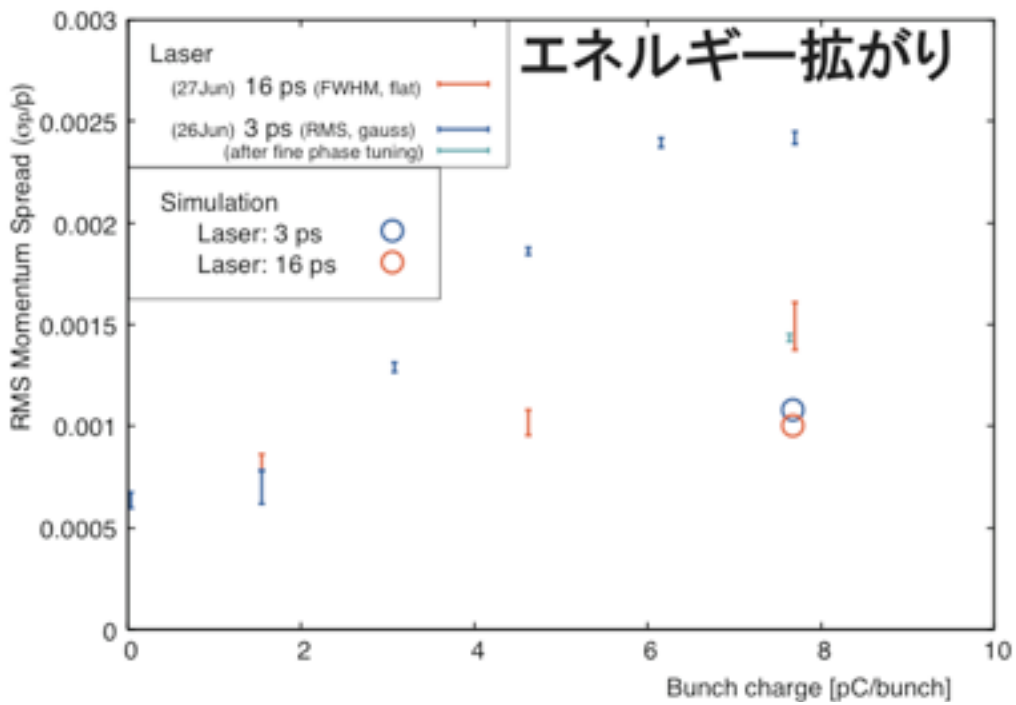
	日付	バンチ電荷 [pC/b]	レーザー時間幅 [ps]	バンチャー電圧 [kV]	SL1 [A]	SL2 [A]	測定内容
A	6/21	0.02, 0.77	3 (RMS, gauss)	40	7.2, 8.7	3.0	エミッタンス
B	6/26	3.1, 7.7	3 (RMS, gauss)	50	8.3	4.99	エミッタンス
B	6/26	0.03~7.7	3 (RMS, gauss)	50	8.3	4.99	バンチ長
B	6/26	0.03~7.7	3 (RMS, gauss)	50	8.3	4.99	エネルギー拡がり
C	6/27	0.03~7.7	16 (FWHM, flat)	50	8.3	4.99	バンチ長
C	6/27	0.03~7.7	16 (FWHM, flat)	50	8.3	4.99	エネルギー拡がり
D	6/28	1.5,7.7	16 (FWHM, flat)	50	8.3	4.99	エミッタンス

Beam performance results

- Not too terrible. Relieved as a first commissioning.
  - At 7.7 pC/bunch
    - 0.8μm emittance
    - 7ps (RMS) bunch length
    - 0.15% (RMS) energy spread
- Apparent discrepancy from simulation.





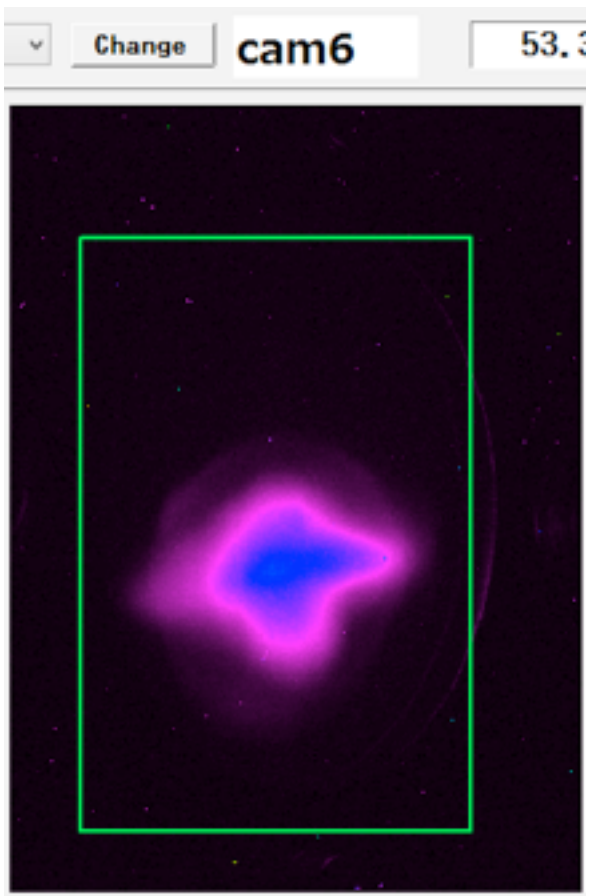


Beam profile at high charge

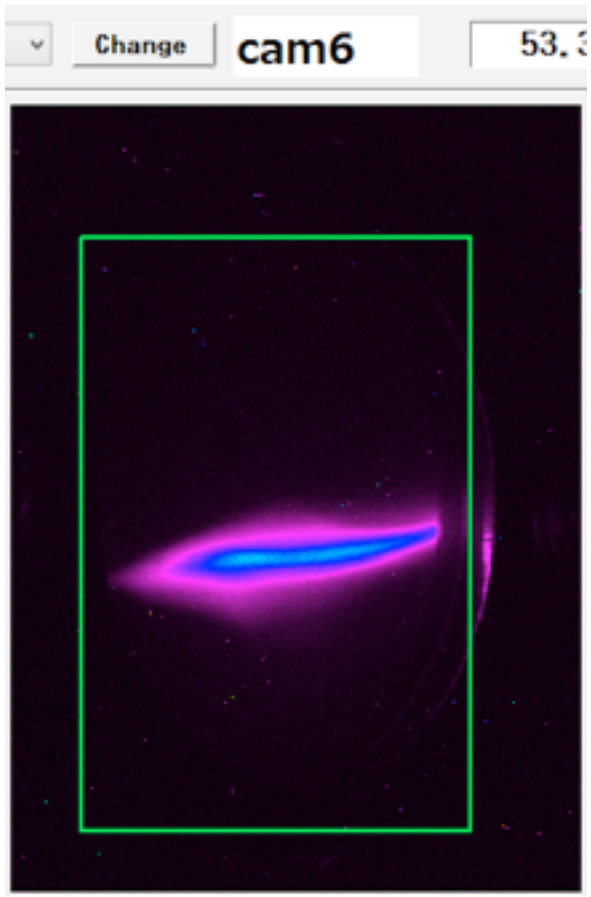
- Profile distortion at high bunch charge
- All quads are turned off, so it should be a round beam
- Distortion seen especially at high charge and high buncher voltage...

emittance measurement

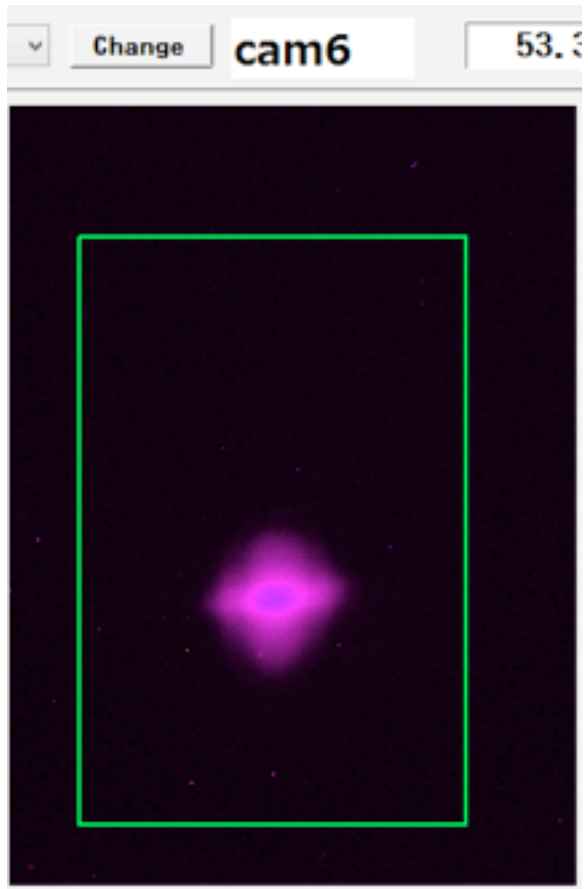
7.7pC/bunch
buncher 50kV



7.7pC/bunch
buncher 75kV



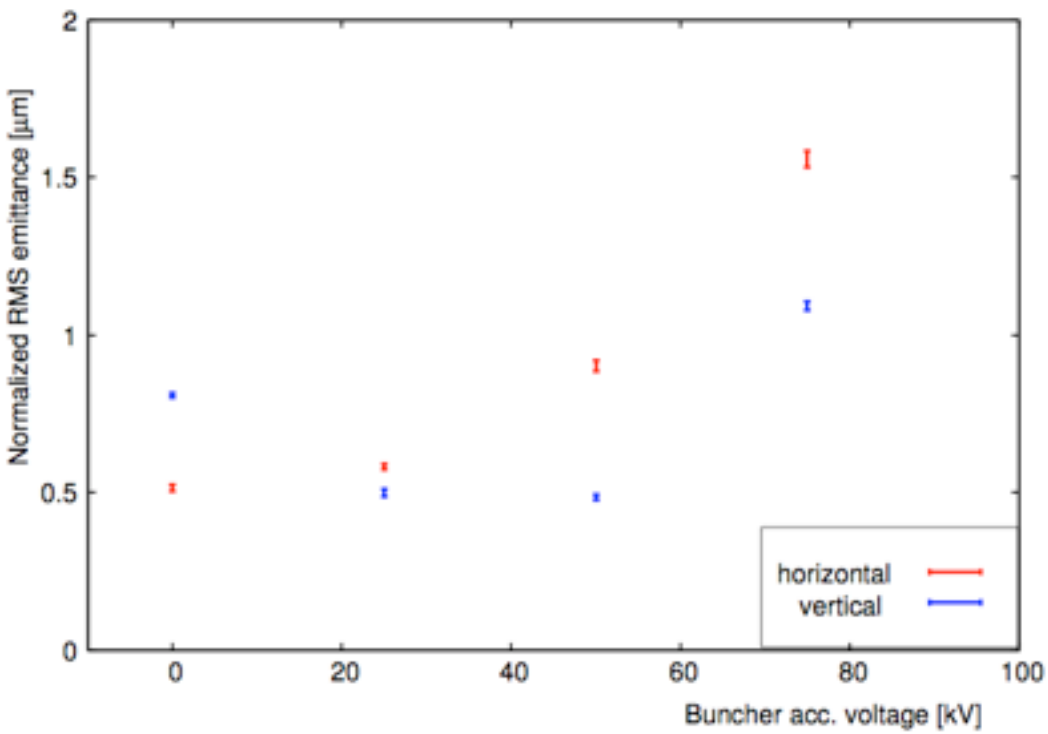
1.5pC/bunch
buncher 75kV



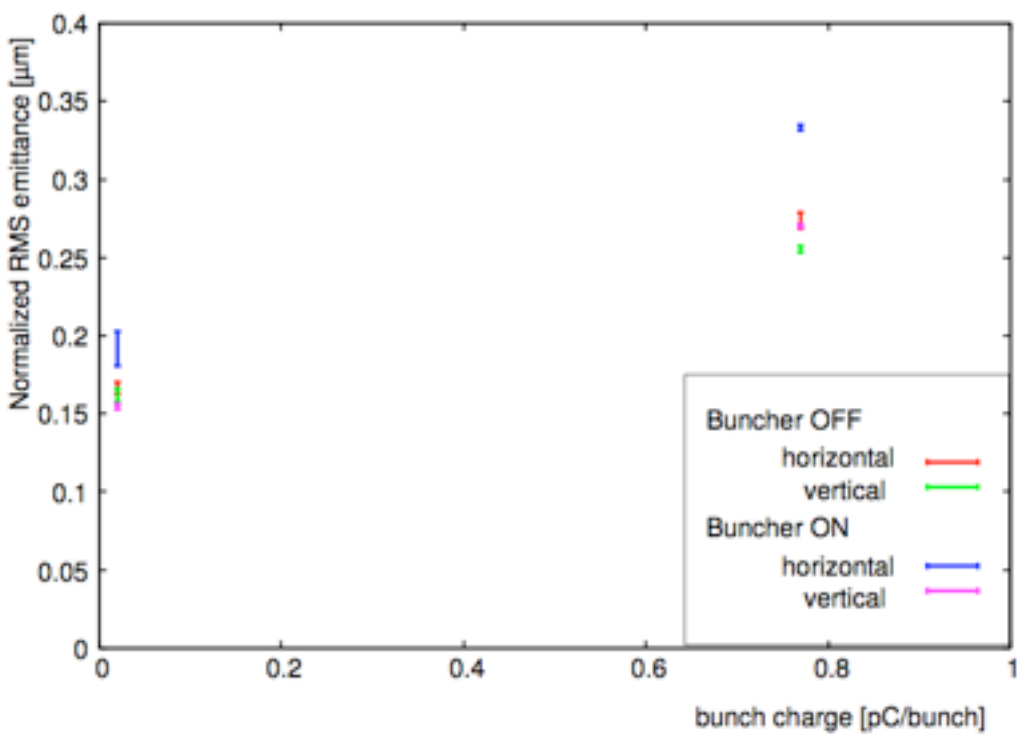
Some trials

- Buncher voltage changes the emittance.
- No significant effect of buncher on/off at low charge.
- It seems there is something at high charge AND high buncher voltage.

7.7pC/bunch
change buncher voltage



at low charge

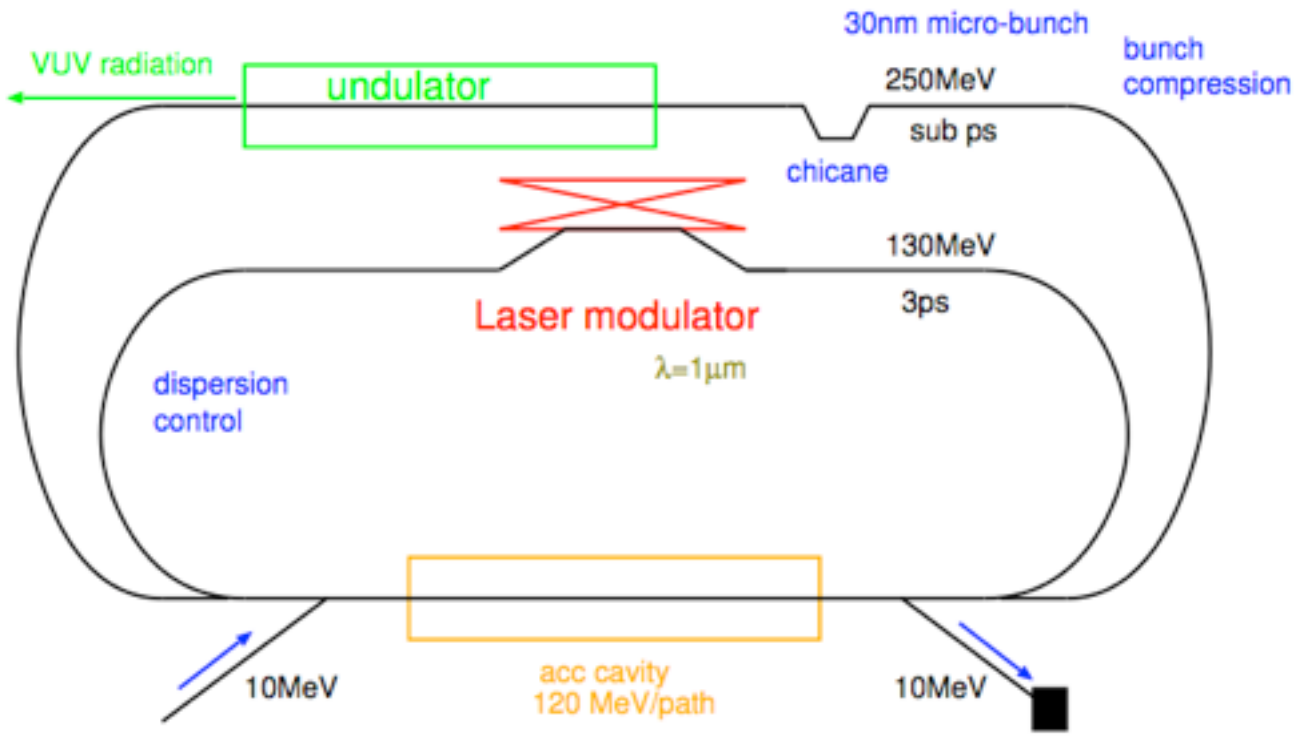


Summary of commissioning

- Operation
  - no significant trouble
  - quick start than expected, done most of the planned
- Beam performance result
  - normalized emittance
    - At gun 390keV, low charge, 0.1 μm
    - At diagnostic line 5.6MeV, low charge 0.2 μm
    - 7.7pC/bunch, 0.8 μm
  - bunch length
    - 7.7pC/bunch, 7ps(RMS)
  - energy spread
    - 7.7pC/bunch, 0.15%(RMS)
- Training
  - not much done...

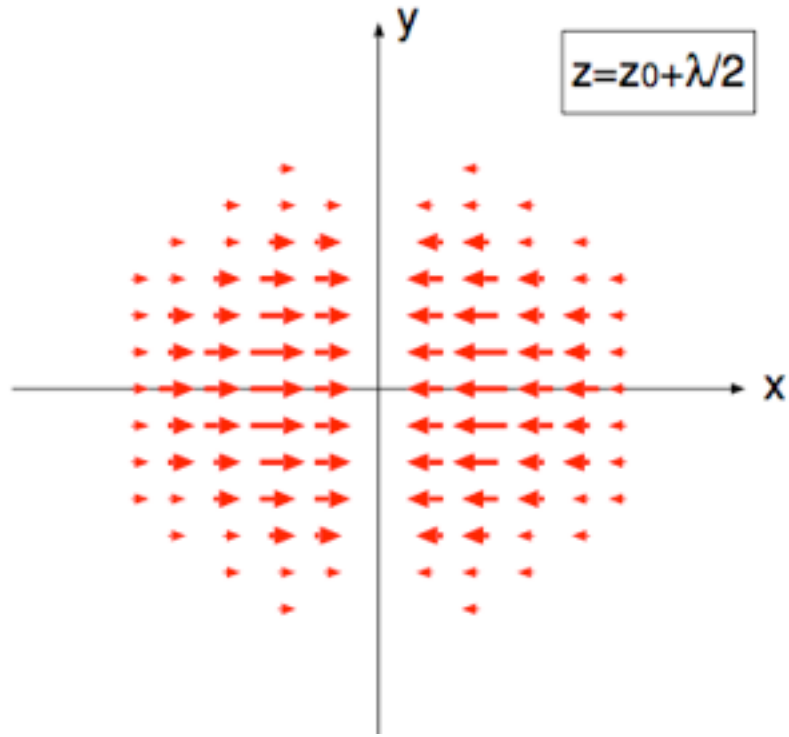
Future proposal at cERL

- 250MeV, 2-loop system was what originally planned
  - One possibility is a coherent VUV radiation source
  - CW, high repetition rate, seeded scheme
- Present situation
  - 20MeV 1-loop system
  - First priority is demonstration of a laser-Compton X-ray source.
  - High power optical cavity for Compton target will be established.
- This optical cavity technique can be used for seeding energy modulation
  - laser and beam are the same direction (difference from Compton configuration)



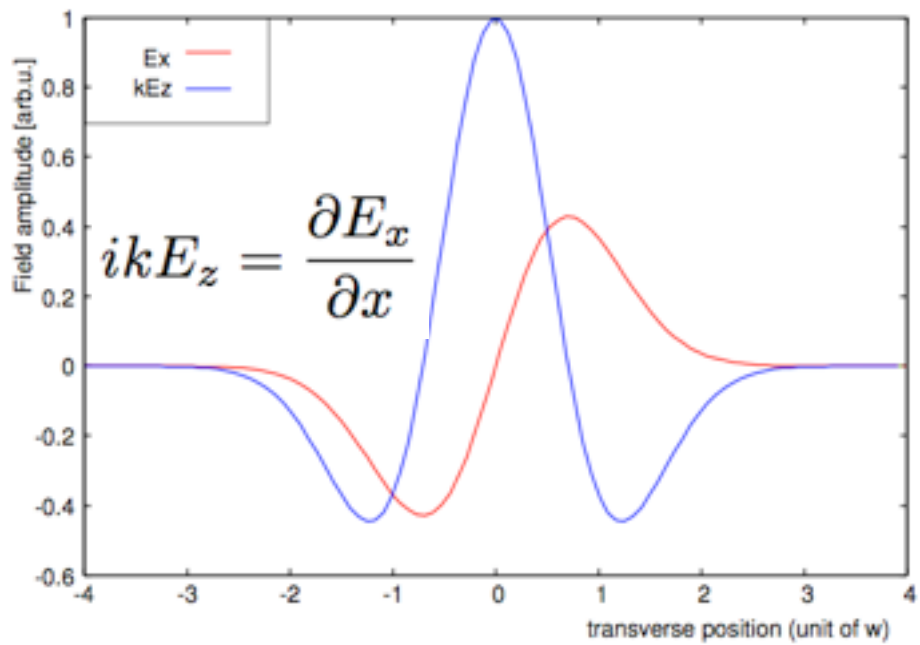
Energy modulator

- Higher transverse laser mode acceleration
  - Longitudinal field in laser light
  - Old laser acceleration idea
    - not powerful for an accelerator
    - but enough for giving energy modulation
- Optical cavity
  - high efficiency and continuous operation system
  - well defined transverse mode
  - no net loading
- Specification and configuration
  - Almost same as the laser-Compton case
  - 10MW peak, wavelength 1 μm, spot 100 μm
  - good enough for modulation of ~50keV, comparable with the initial energy spread



$$E_z = \frac{1}{kw_0^2}\sqrt{\frac{P}{c\epsilon_0}}$$

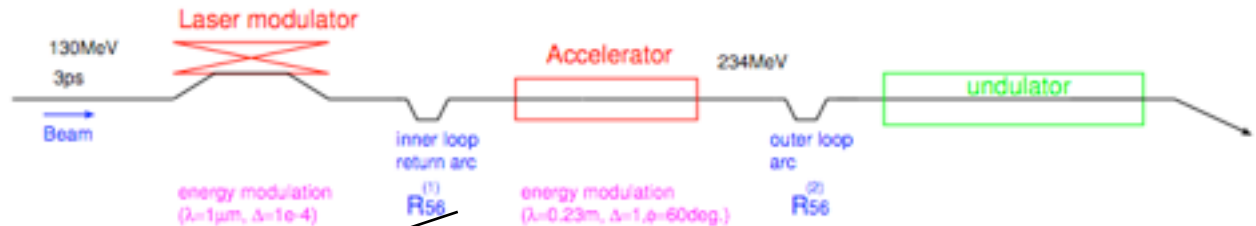
$$G = E_z \times 2z_0 = e\sqrt{\frac{P}{c\epsilon_0}}$$

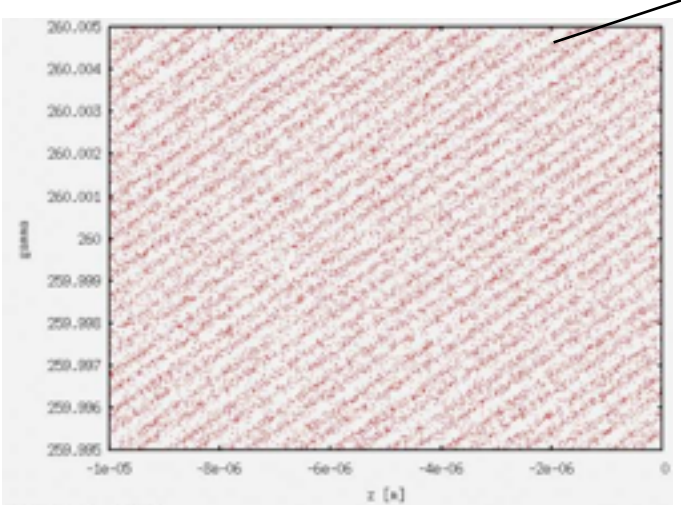


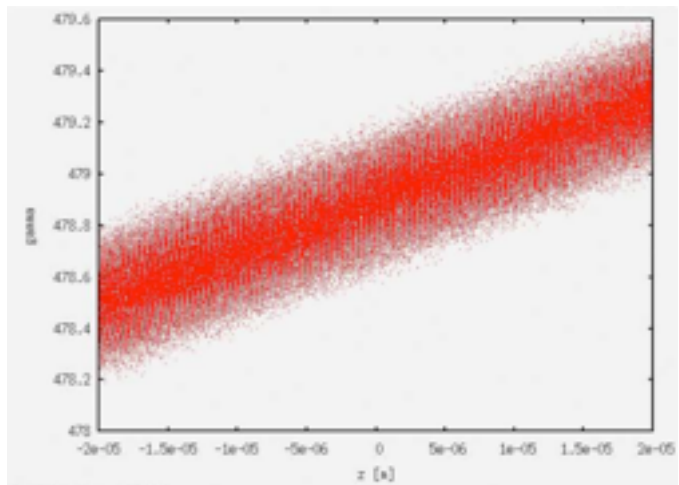
Example of calculation

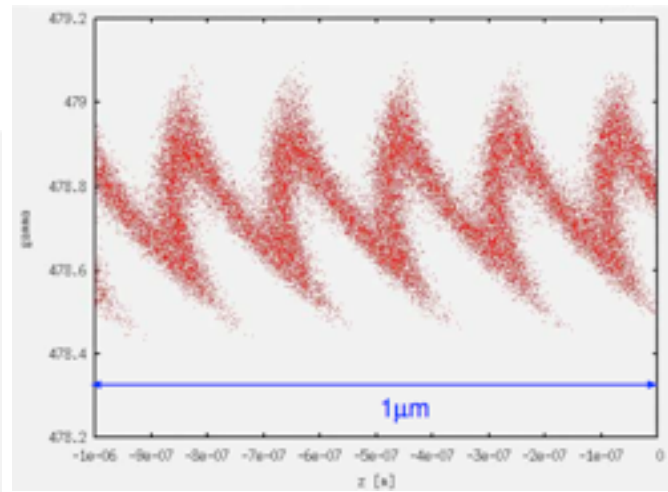
- Same as EEHG scheme
  - RF accelerator works as the second modulator

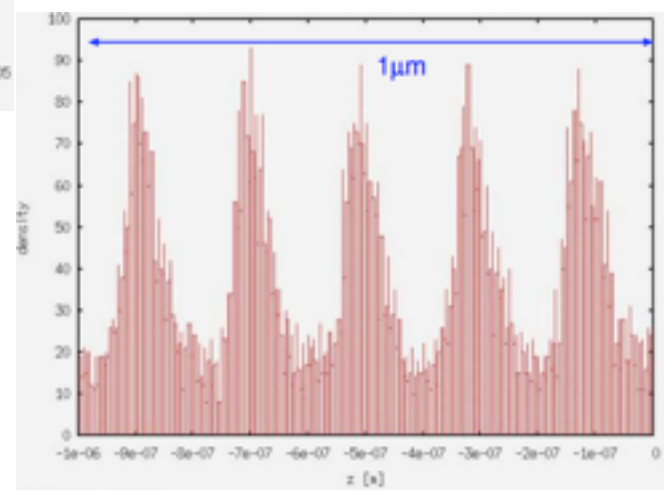
parameter	symbol	value
Beam energy	γ	260 (130 MeV)
Energy spread	$\Delta\gamma/\gamma$	5×10^{-5}
Bunch duration	σ_t	3 ps
Bunch repetition	f	1.3 GHz







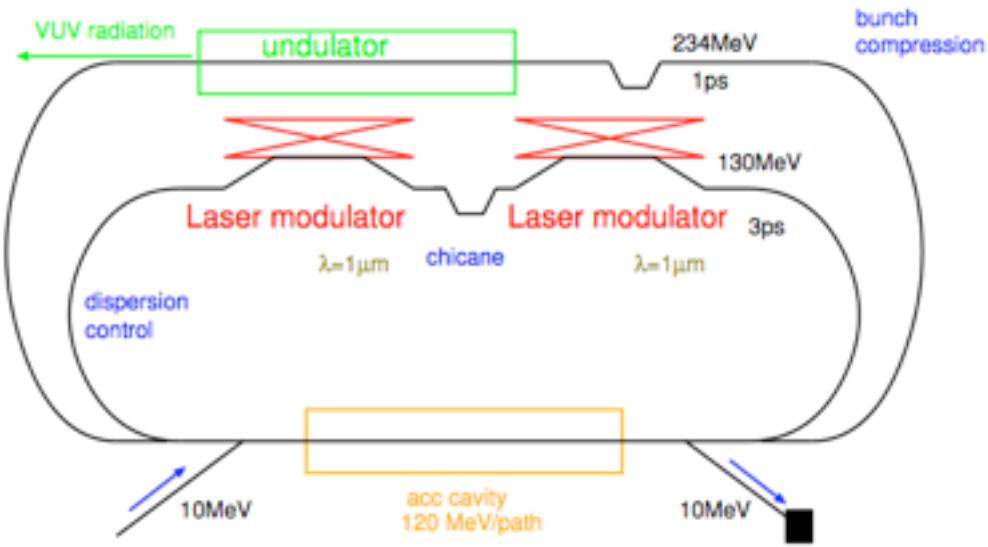


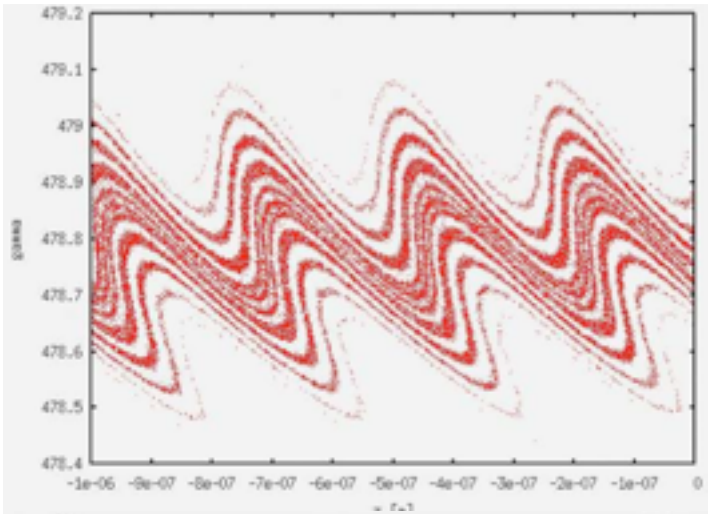


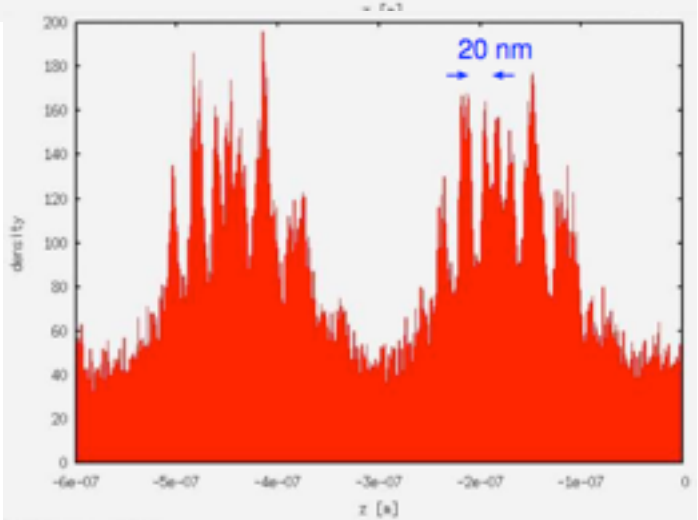
$R_{56}^{(1)}$ [mm]	$R_{56}^{(2)}$ [mm]	compression ratio
285	-55	1/5
512	-60	1/9

Example of calculation

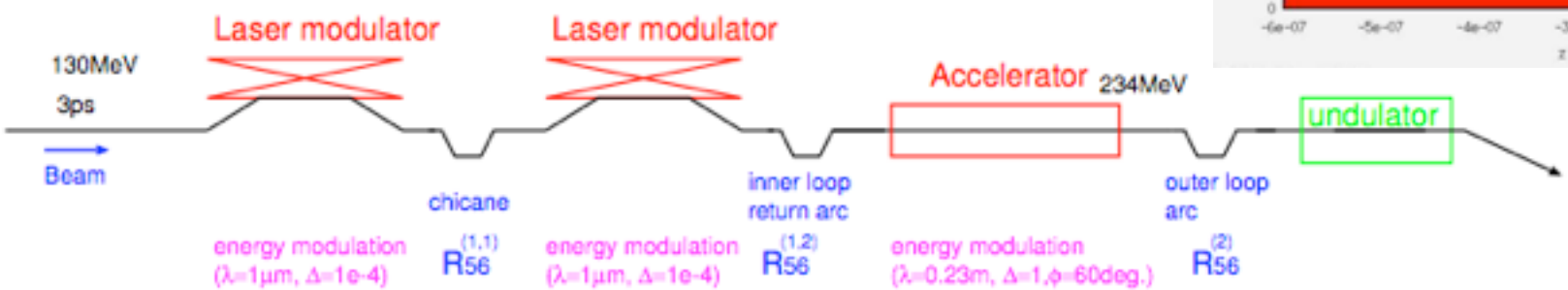
- Same as EEHG scheme
  - Three stage system







	$R_{56}^{(1,1)}$ [mm]	$R_{56}^{(1,2)}$ [mm]	$R_{56}^{(2)}$ [mm]	compression ratio
parameter	-20	186.5	-50	1/3.5



thanks