Status of KEK ERL test accelerator (cERL)

2013.2.20

at CERN

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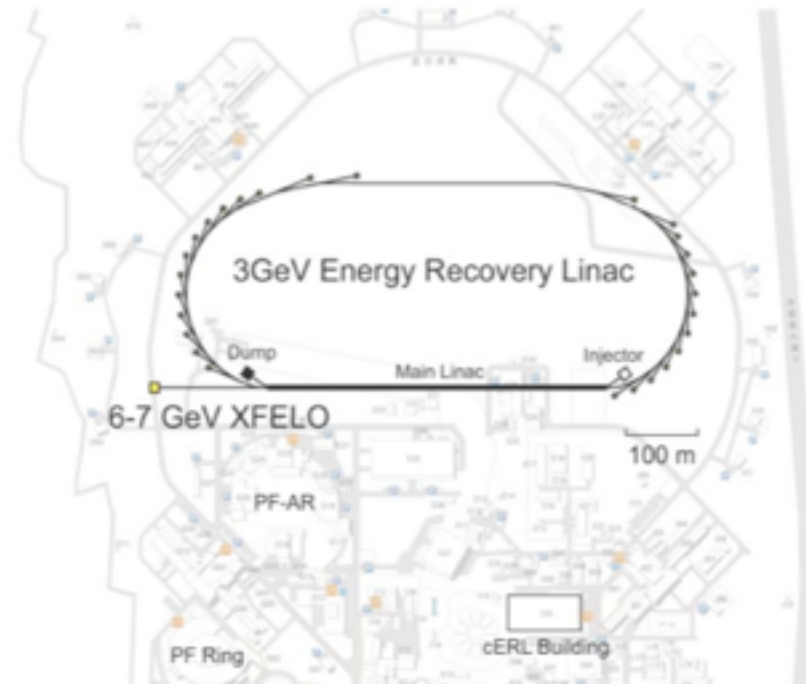
- Contents: quick review of overall status of compact ERL construction
  - Gun, Cryo, RF, Injector SC, Main SC, Loop
  - Beam commissioning preparation of Injector and Diagnostic line
  - Schedule

KEK ERL light source plan

- An ERL based machine has been planned as a next generation synchrotron light source. (operation 2020~)
- (Background of the story)
  - No attractive big project in KEK Tsukuba campus after superKEKB...
  - Existing light sources (PF) have already been too old...
- ERL as a light source
  - Advantage:
    - low emittance in horizontal and short bunch, as a linac based feature.
  - Disadvantage:
    - hard to increase average beam current. difficult to operate
  - overall, may be similar brightness as achievable with a conventional light source.
  - Technically new and challenging, challenging is good, lets start.
- Synergy with ILC



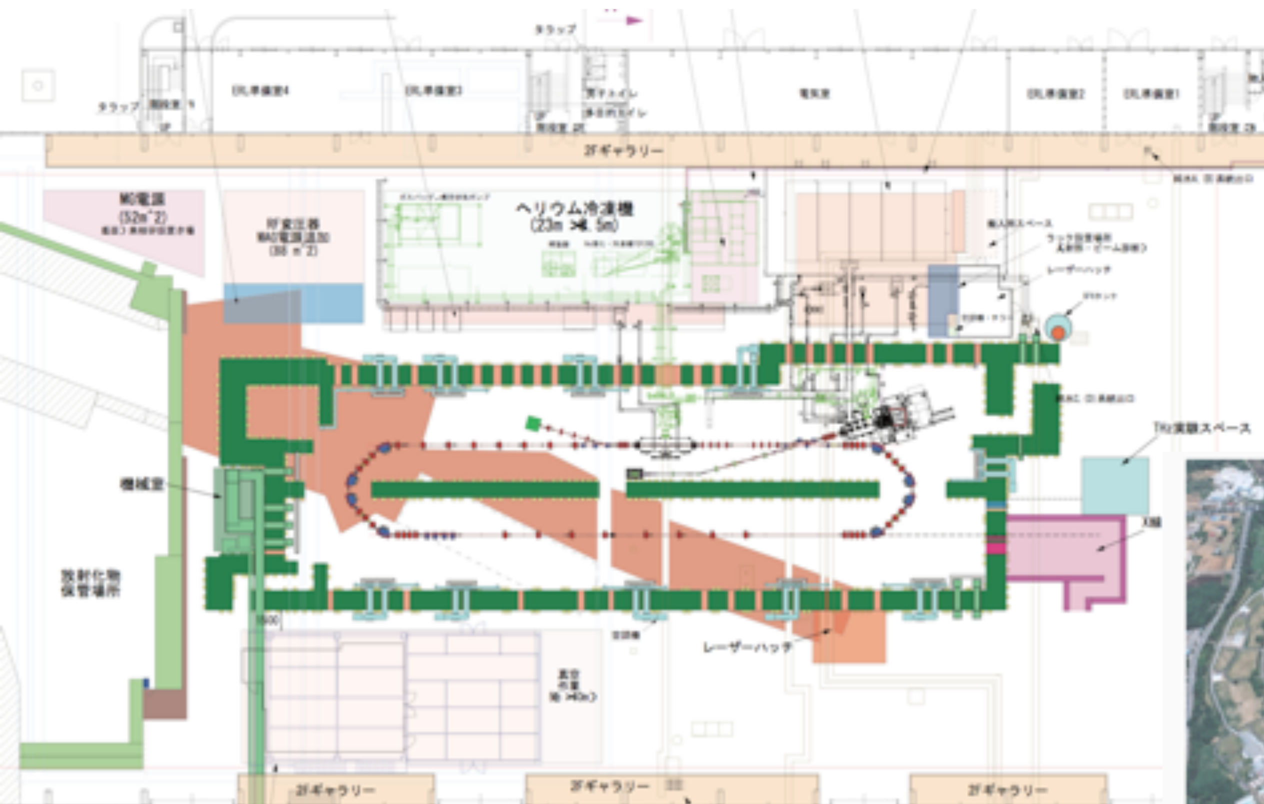
	Operation modes				
	High-coherence mode	High-flux mode	Ultimate mode	Ultra short-pulse mode	XFEL-O
Beam energy (E)	3 GeV				6-7 GeV
Average beam current (I_0)	10 mA	100 mA	100 mA	Typically, 77 μA (flexible)	20 μA
Charge/bunch (q_b)	7.7 pC	77 pC	77 pC	Typically, 77 pC (flexible)	20 pC
Repetition rate of bunches (f_{rep})	1.3 GHz	1.3 GHz	1.3 GHz	Typically, 1 MHz (flexible)	1 MHz
Normalized beam emittances (ε_{nx}, ε_{ny})	0.1 mm·mrad	1 mm·mrad	0.1 mm·mrad	To be investigated (typically, 1-10 mm·mrad)	0.2 mm·mrad
Beam emittances at full beam energy (ε_x, ε_y)	17 pm·rad	170 pm·rad	17 pm·rad	To be investigated (typically, 0.2-2 nm·rad)	15 pm·rad
Energy spread of beams; in rms (σ_E/E)	2×10^{-4}	2×10^{-4}	2×10^{-4}	To be investigated	5×10^{-5}
Bunch length; in rms (σ_t)	2 ps	2 ps	2 ps	100 fs	1 ps

compact ERL

- Before proposing a big machine, we started with a test ERL accelerator (compact ERL).
- Purpose of compact ERL is to restructure the ERL group, not only in the light source group, including experts in all KEK accelerator groups and also from outside of KEK, educate and training themselves while its construction process.

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



Facility Construction

2008.11

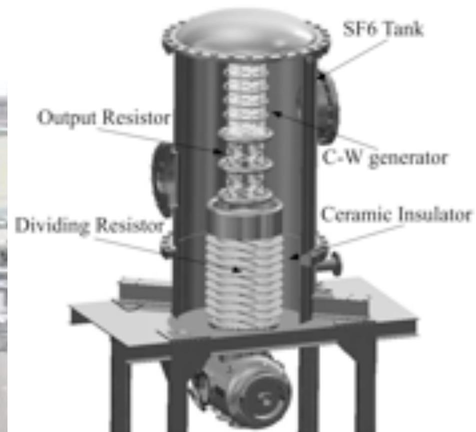
2010.4

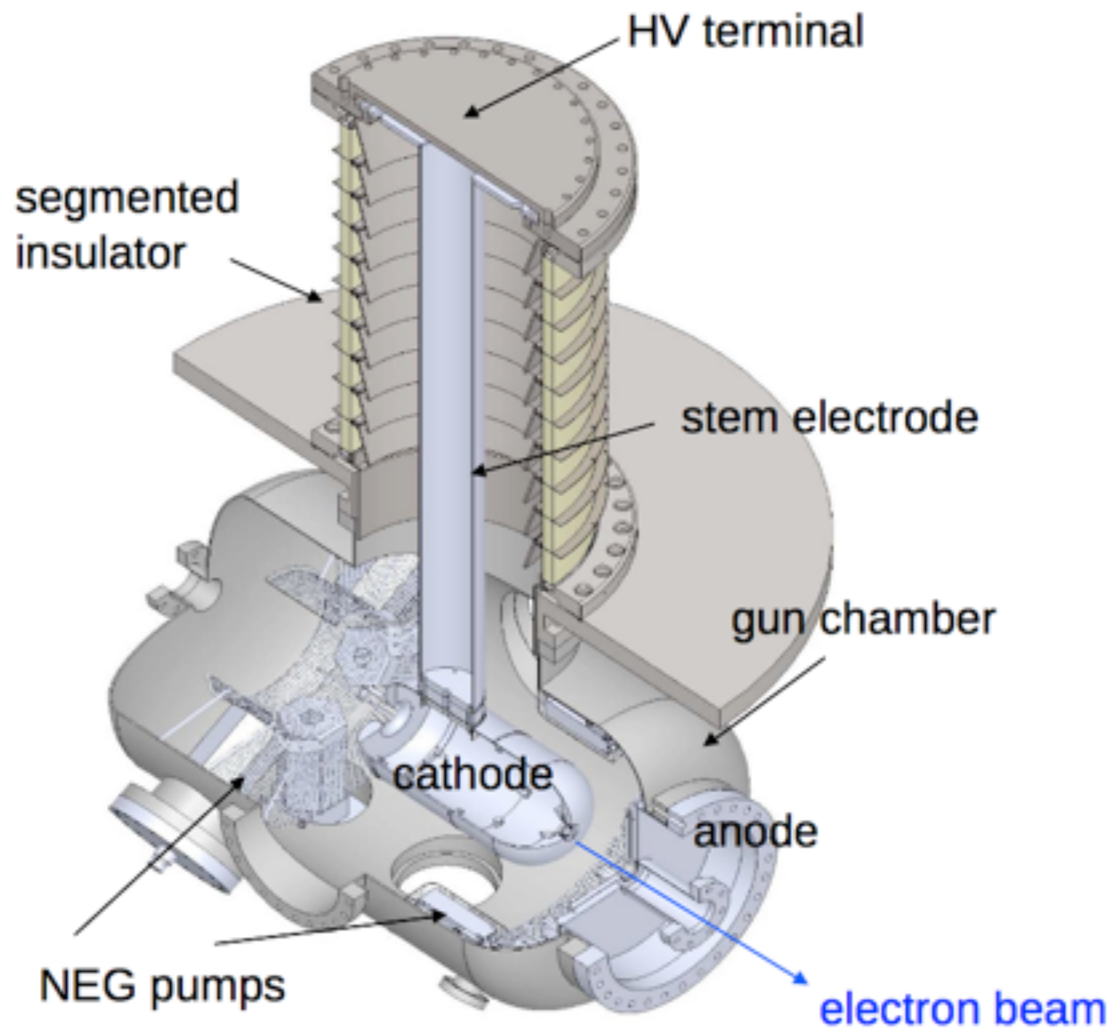
2012.4

2012.10

Electron Gun

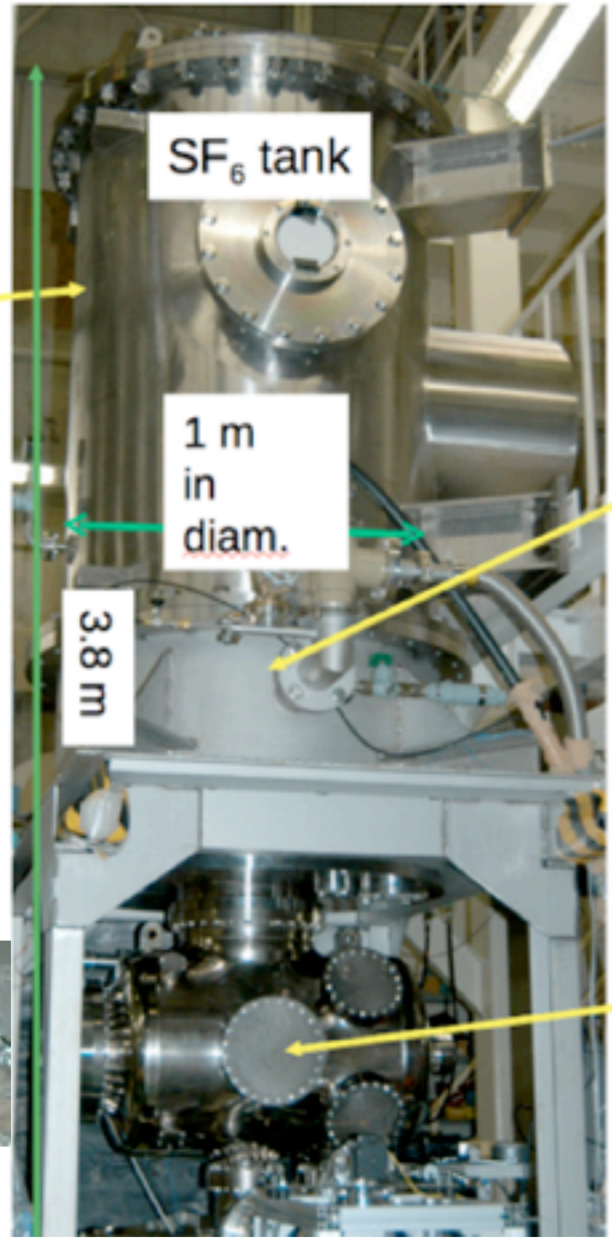
- 500kV (10MV/m), 10mA (7.7pC/b), n.emittance 0.1~1 μm is a reasonable target for R&D
- Photo-cathode DC gun scheme
- Challenge
    - stable operation of high voltage (ceramic, cathode)
    - cathode lifetime (>1000C for a week operation), vacuum and cathode damage
    - routine operation
- Development at JAEA
- Moved to KEK Oct.2012, then re-assembled.



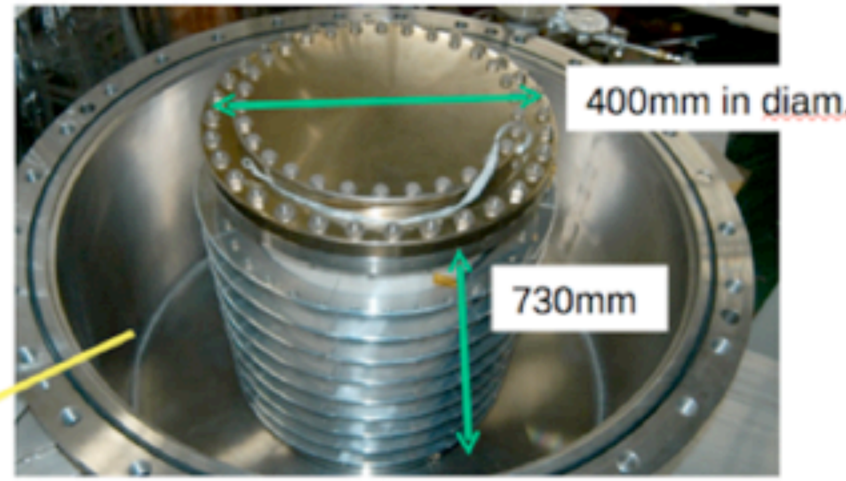


Electron Gun

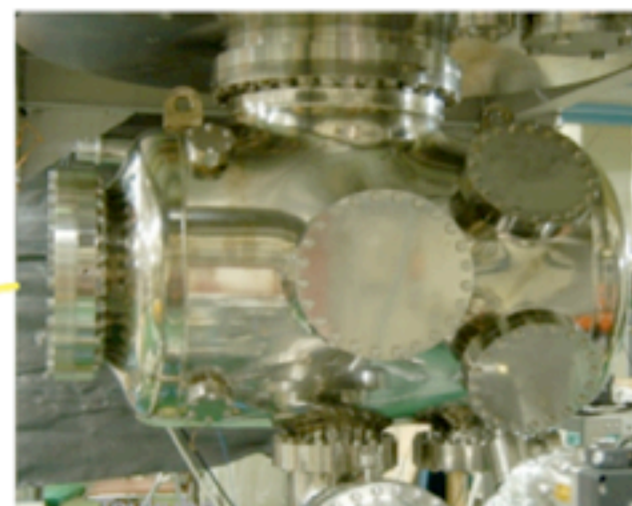
550kV Cockcroft Walton power supply



segmented insulator



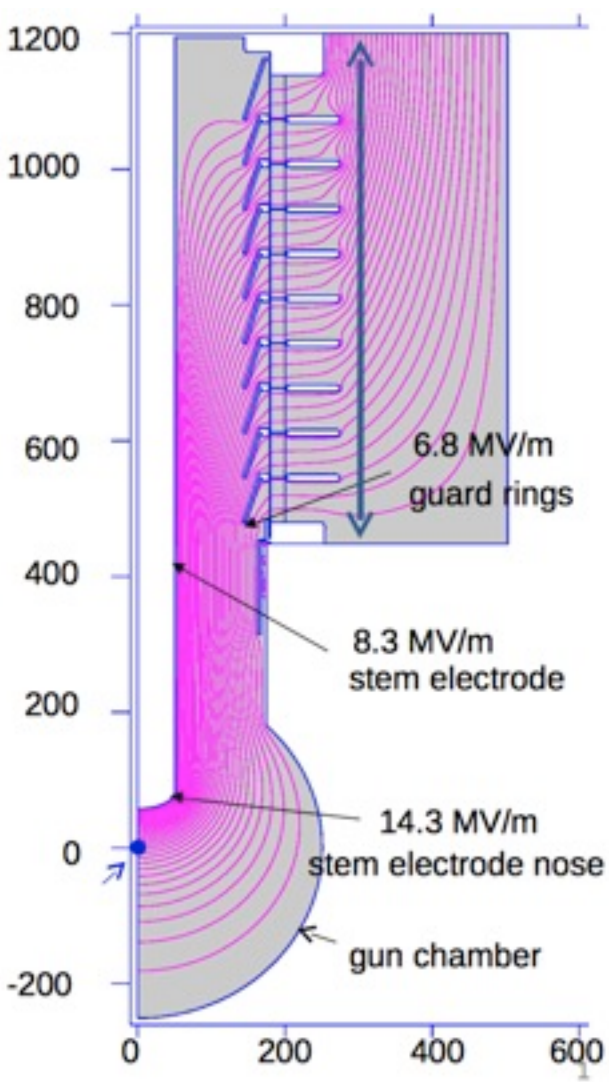
gun chamber made of titanium

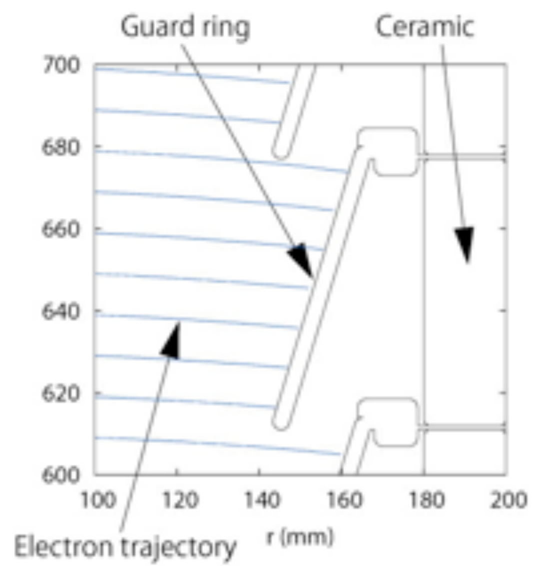


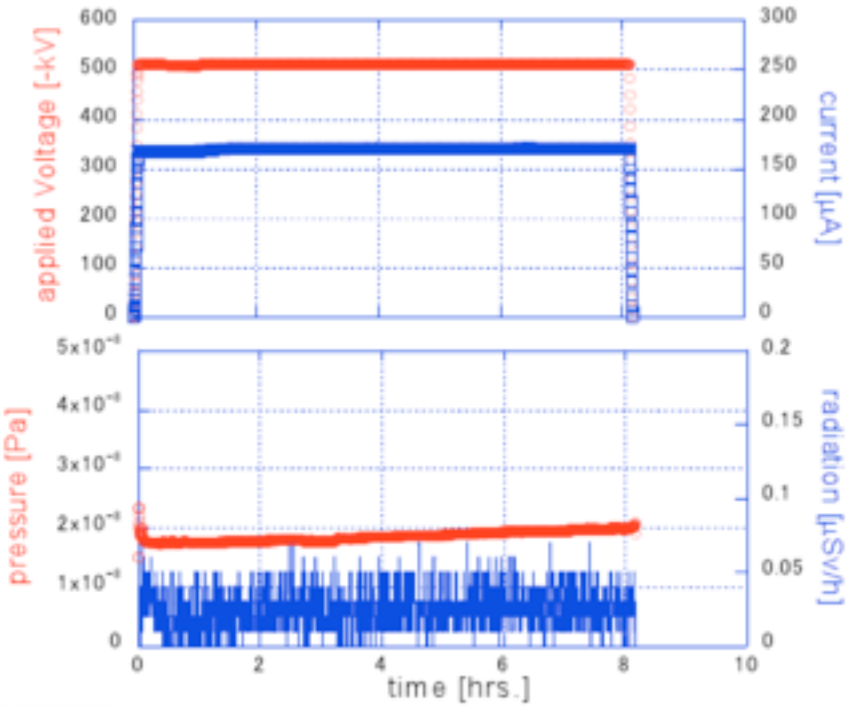
18000L/s of NEG in the gun chamber

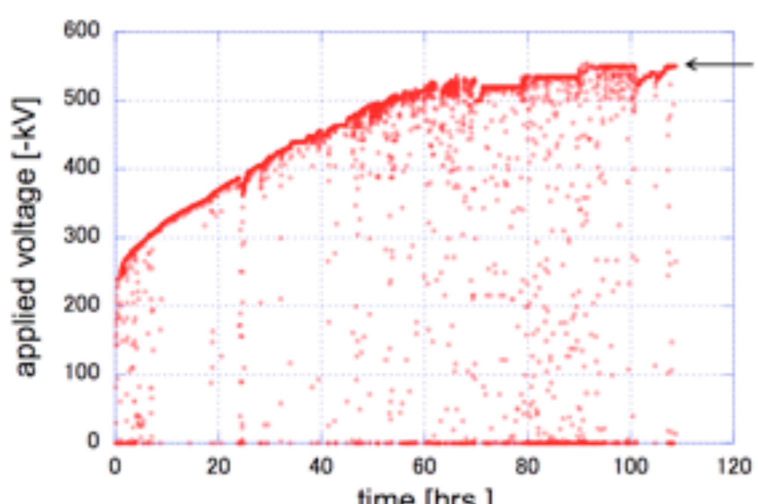
Gun High Voltage

- One big problem has been the damage of ceramic insulator
- Dark-current from high voltage support-rod hits the ceramic and it charges up
- Our solution: conventional approach, segmented ceramic and use guard-ring
- Successful test result (with ceramic & support rod, but without cathode)
    - 525kV, 8 hour kept



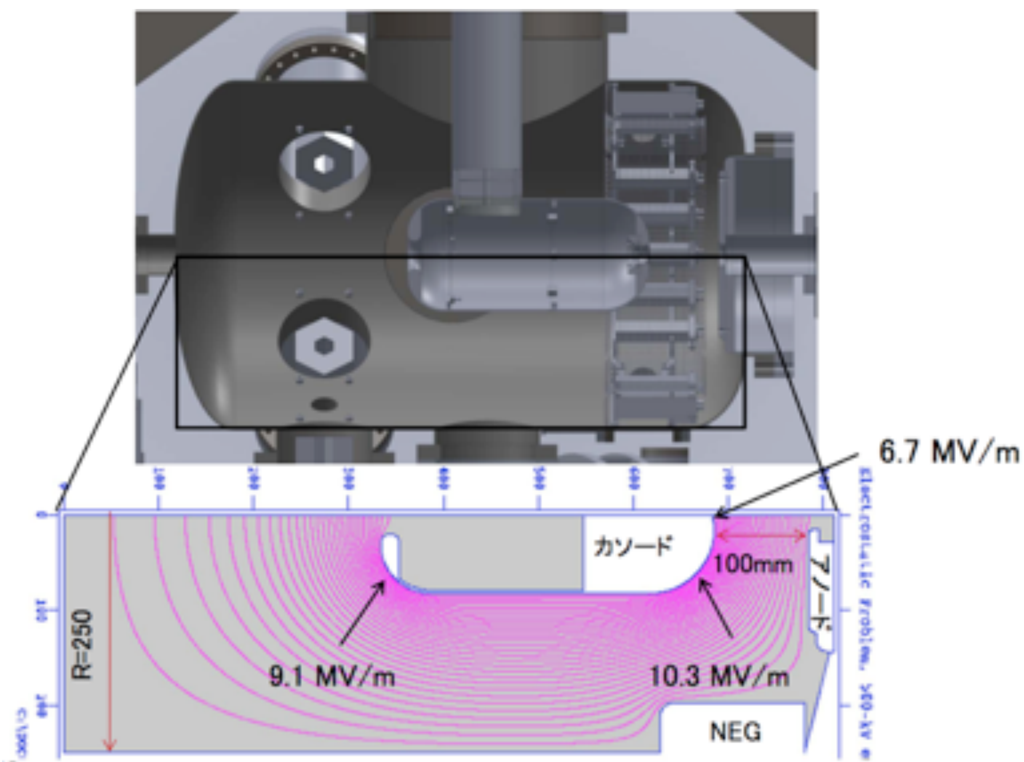


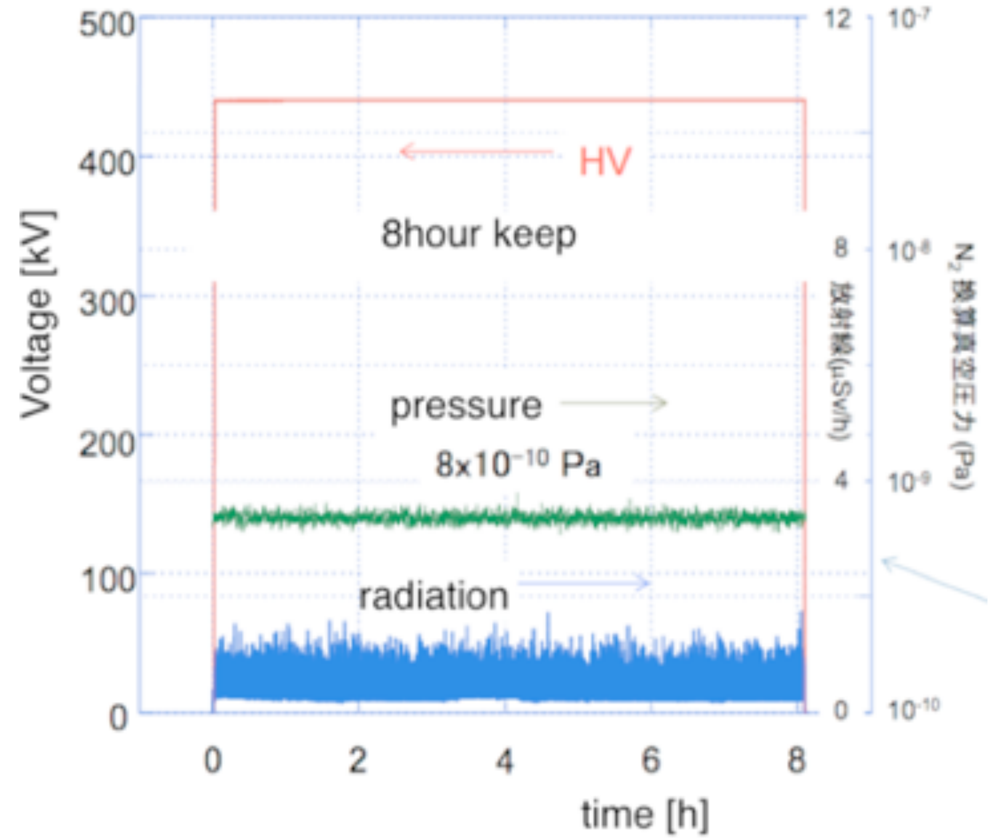




HV test (full system)

- Then, cathode, NEG, etc. are assembled
- Operation voltage limited ~440kV
- vacuum <10^-9 Pa realized
- Still problem remains
  - some time sudden radiation rise happens, after that cannot recover the operated HV. (emitter is produced on the cathode)
  - in that case, vacuum open and wiping the cathode is needed (>1 week stop).
  - dust on cathode?





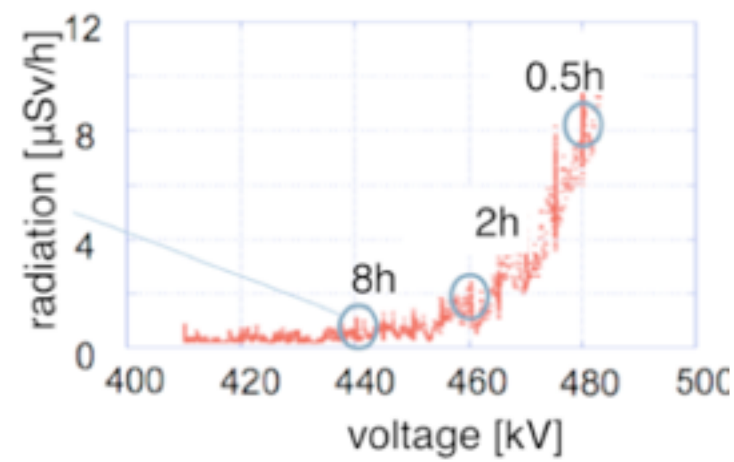
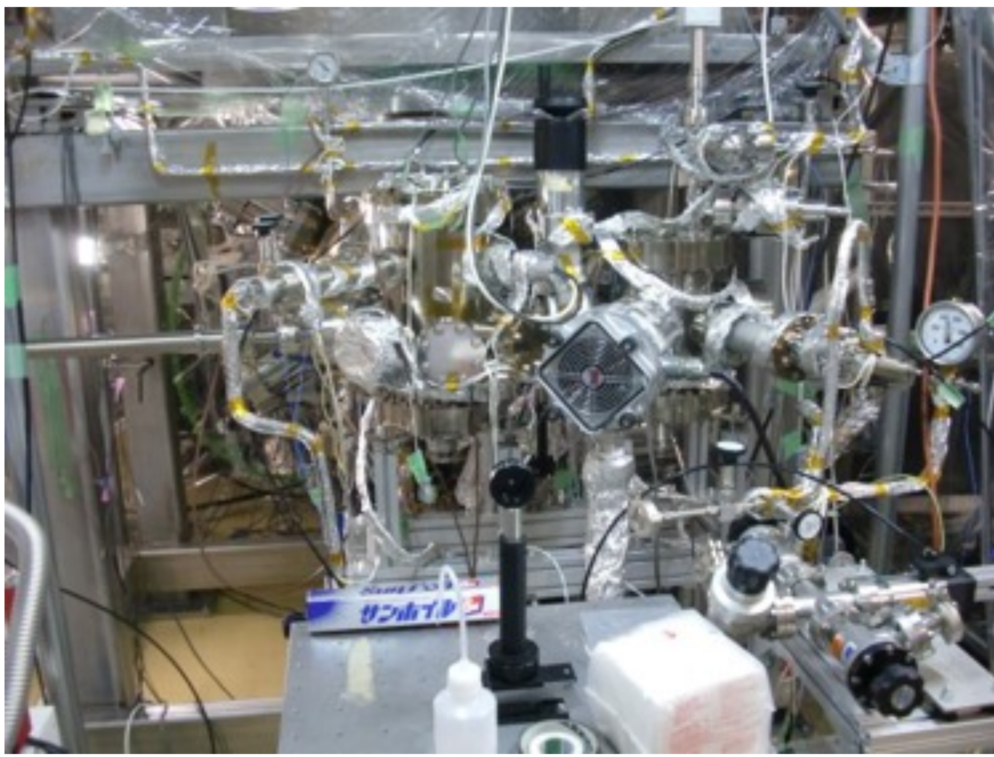


Photo cathode system

- NEA GaAs is chosen for low-emittance, high Q.E.
- In situ activation system, single cathode. (may be, need upgrading to multi-cathode handling later)
- Assembling cathode activation system is underway at KEK (final transfer-rod has not yet attached).
- Q.E.10% at 532nm checked



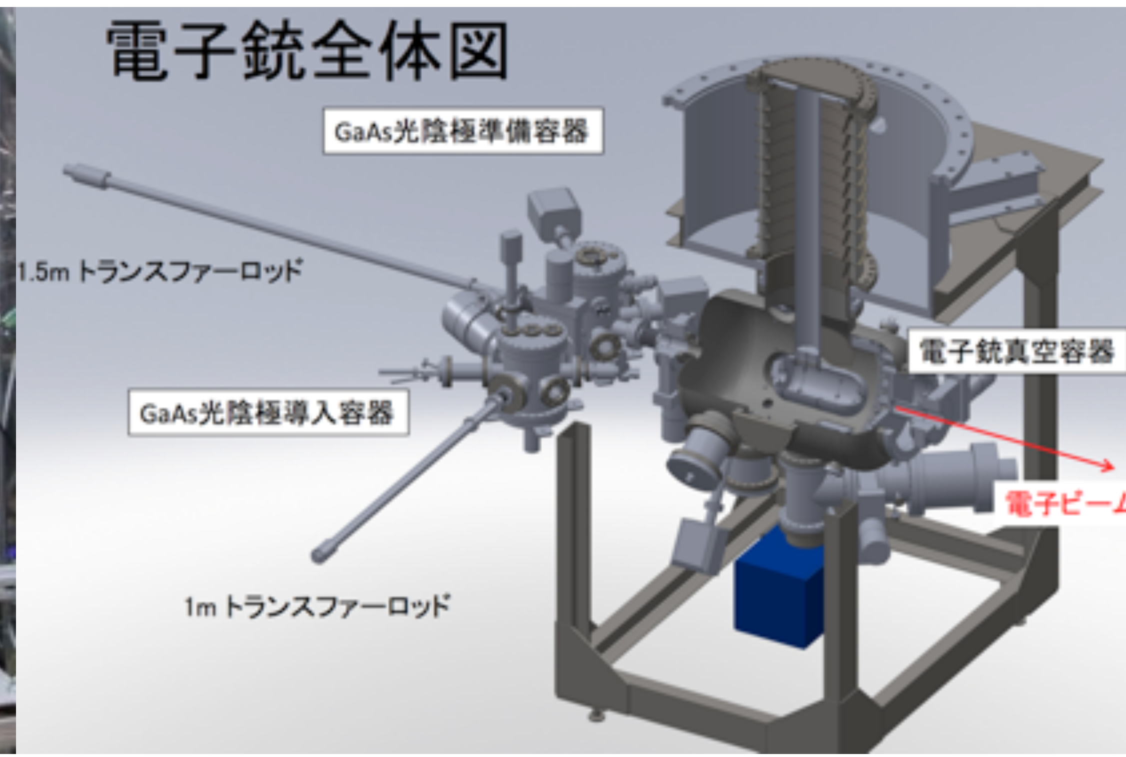
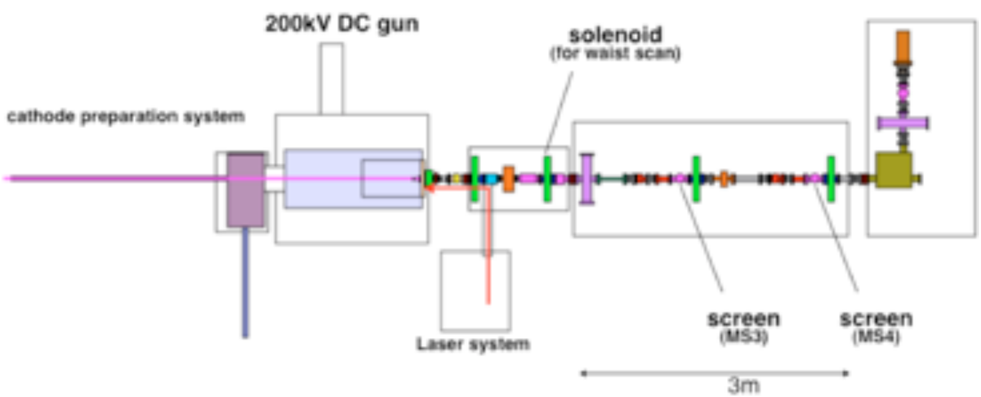
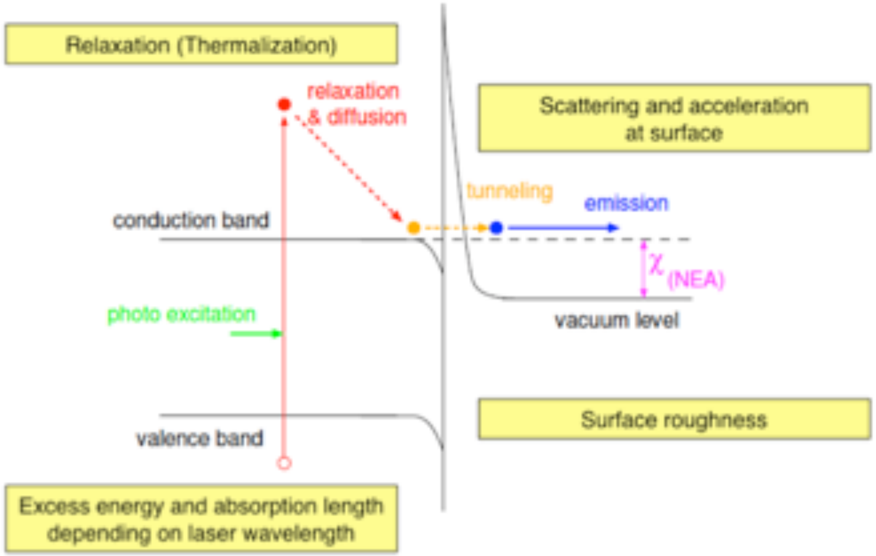
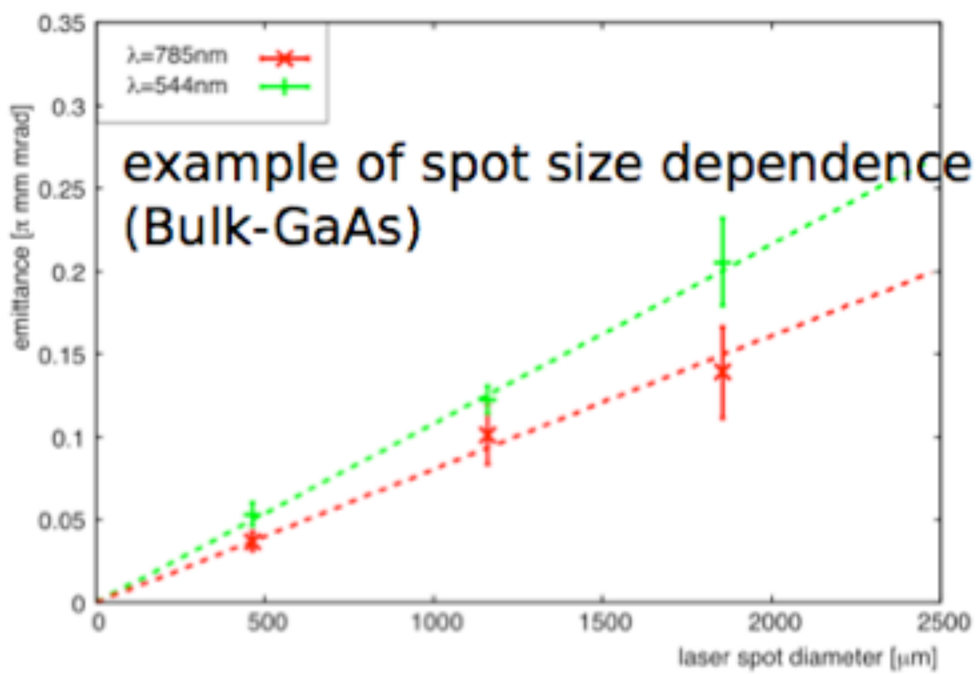


Photo-cathode study (emittance)

- Cathode material & laser wavelength are studied (intrinsic emittance or transverse energy)
- Due to relaxation in the crystal, fairly low emittance is achievable with green laser.
- Still a little higher than temperature limited.







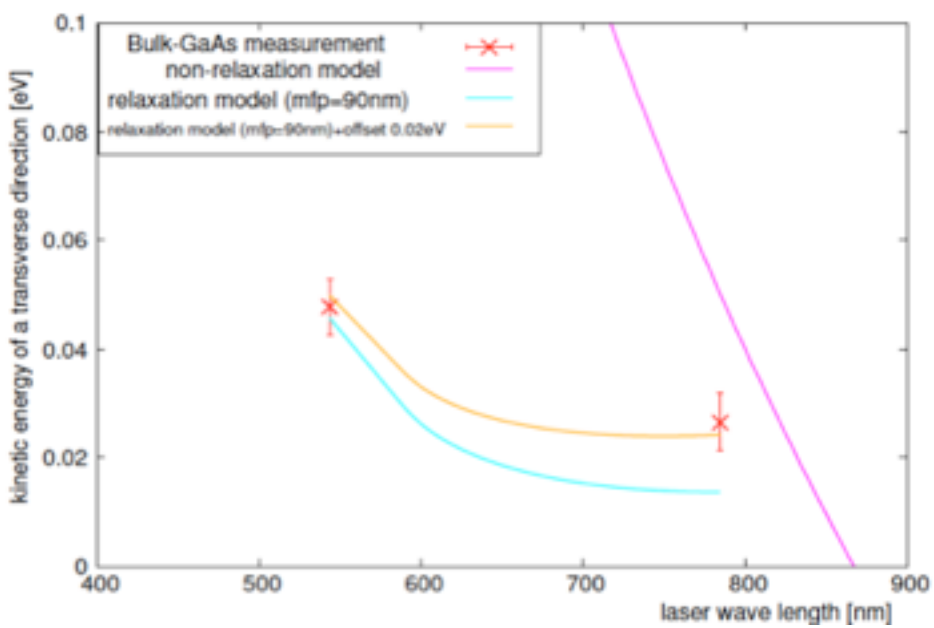
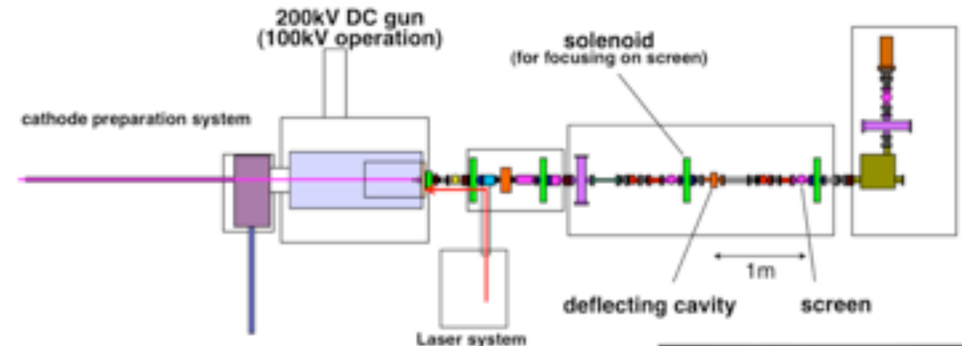
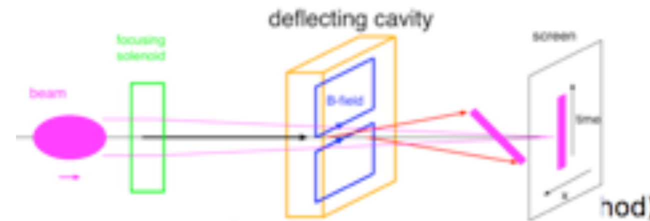
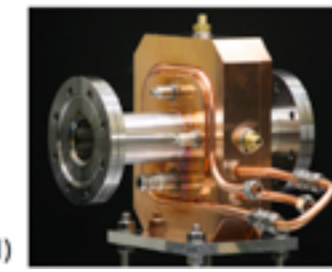


Photo-cathode study (temporal response)

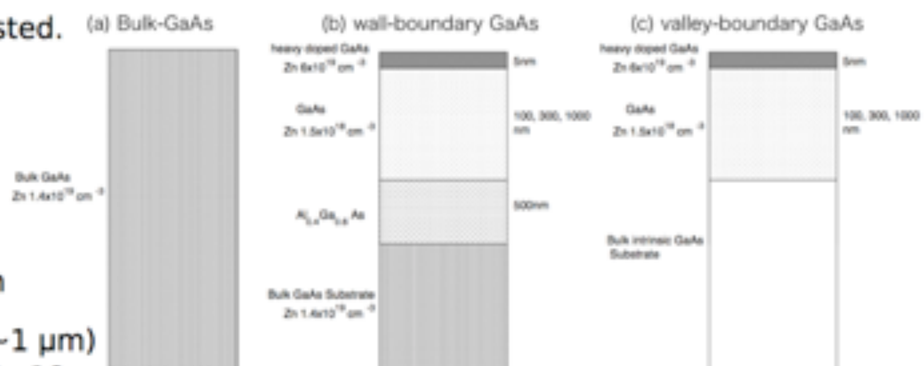
- Cathode response is measured using deflecting cavity technique
- Bulk GaAs turned to have long tail of ~100ps when 700~800nm laser illumination. This comes from the diffusion time in the crystal. Not good for projected emittance or beam loss.
- In the case of green laser (short absorption length), time response is quite fast.





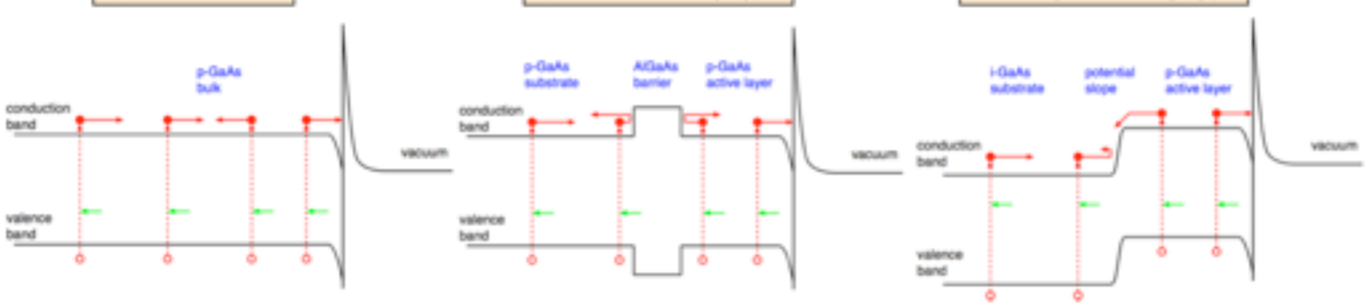


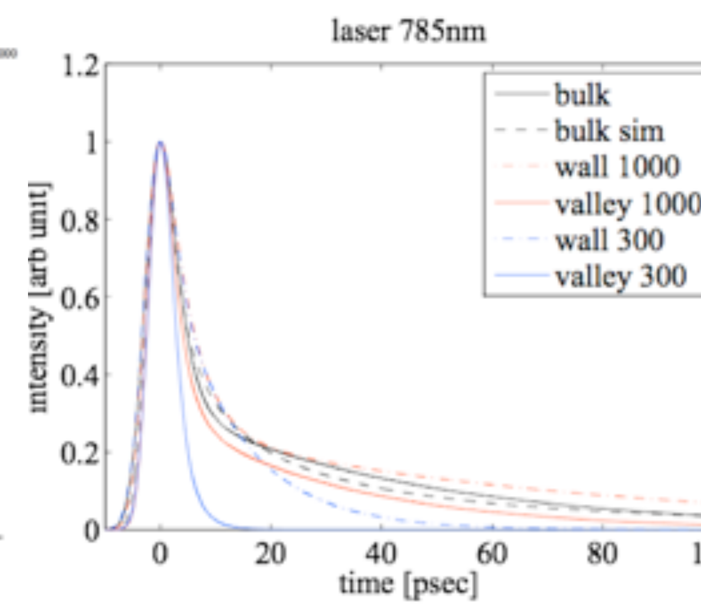
Three types of cathodes were tested.
(a) Bulk-GaAs (p-doped heavily)
(b) Thin p-GaAs active layer separated from substrate by a barrier potential (wall-boundary)
(c) Thin p-GaAs active layer on



Laser wavelength.
(1) 785nm (absorption length ~1 μm)
(2) 850nm (absorption length 3~10 μm)

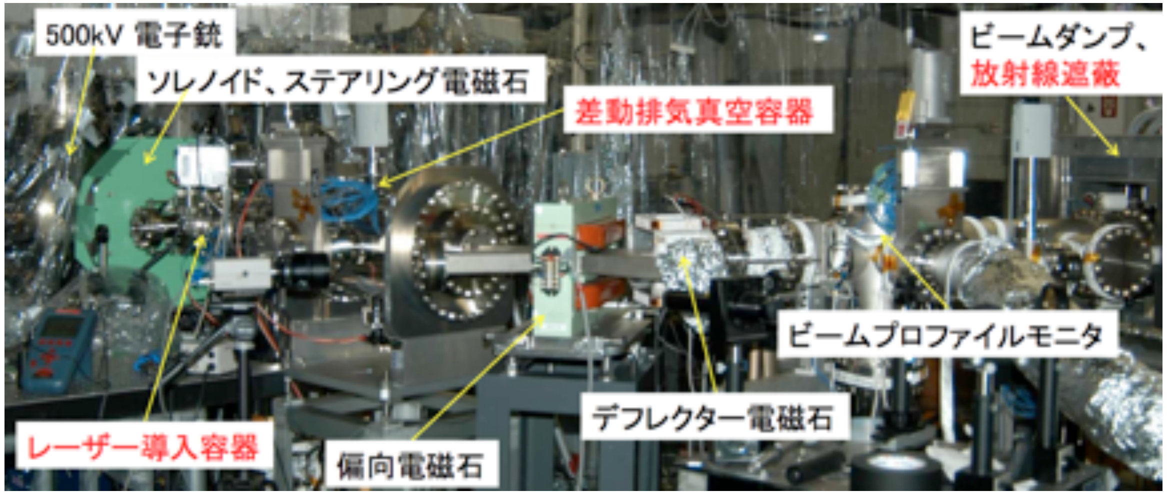
(a) bulk-cathode
(b) wall-boundary type
(c) valley-boundary type

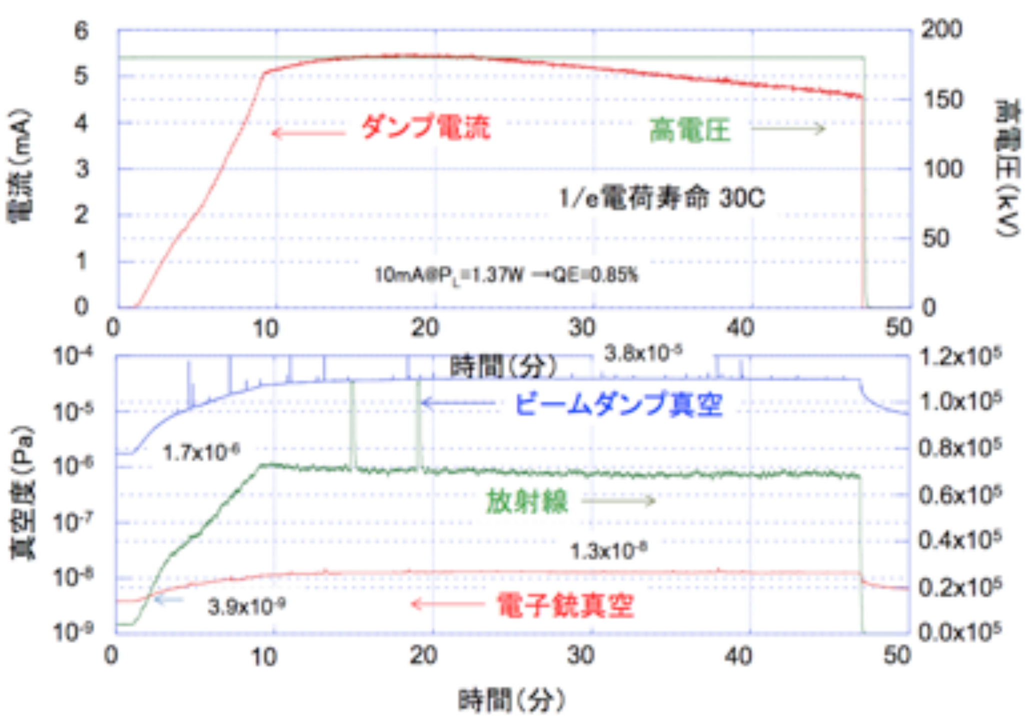


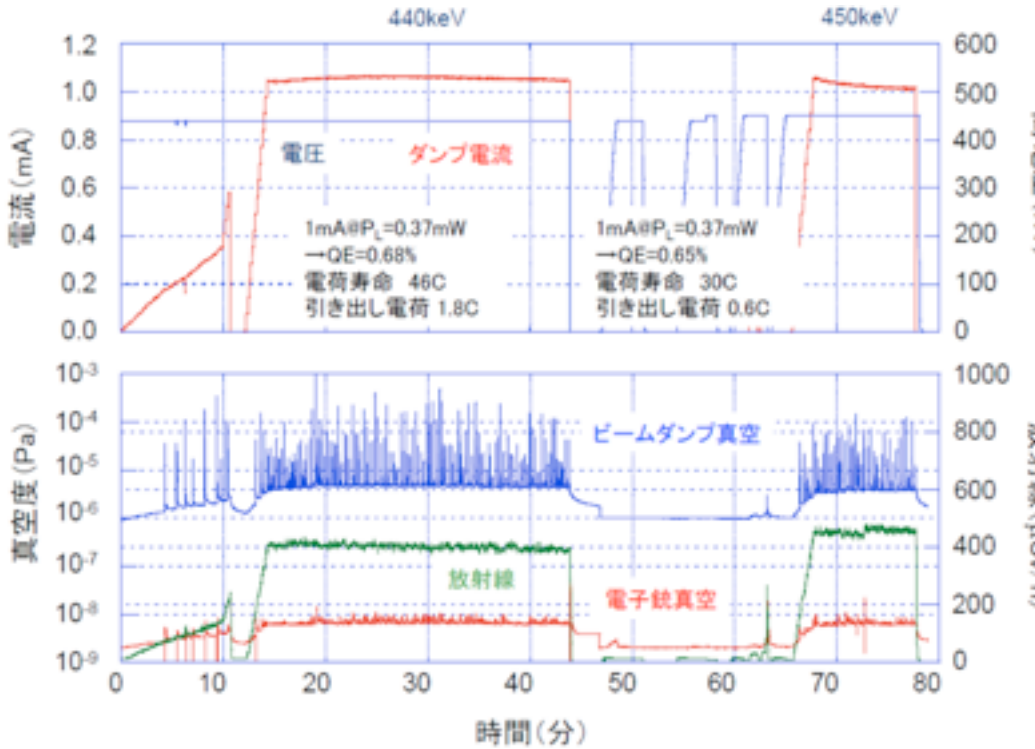


Gun beam result

- Beam emission experiment has done at JAEA (before moving to KEK).
- Achievement
  - 180keV, 10mA or 5mA (10min.)
  - 450keV, 1mA (30min.)
- Beam lifetime 1/e life 30C, 1 day for 1mA operation
  - This should depend on beam loss and dump
  - Anyway enough for the first commissioning of 1 μA.

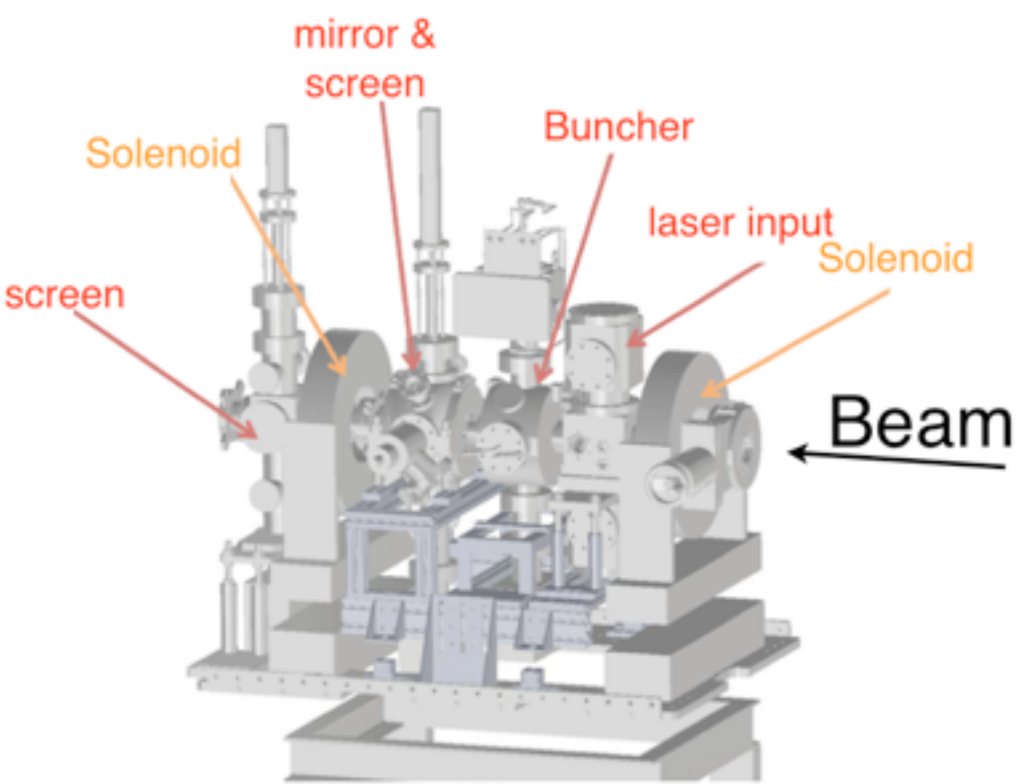


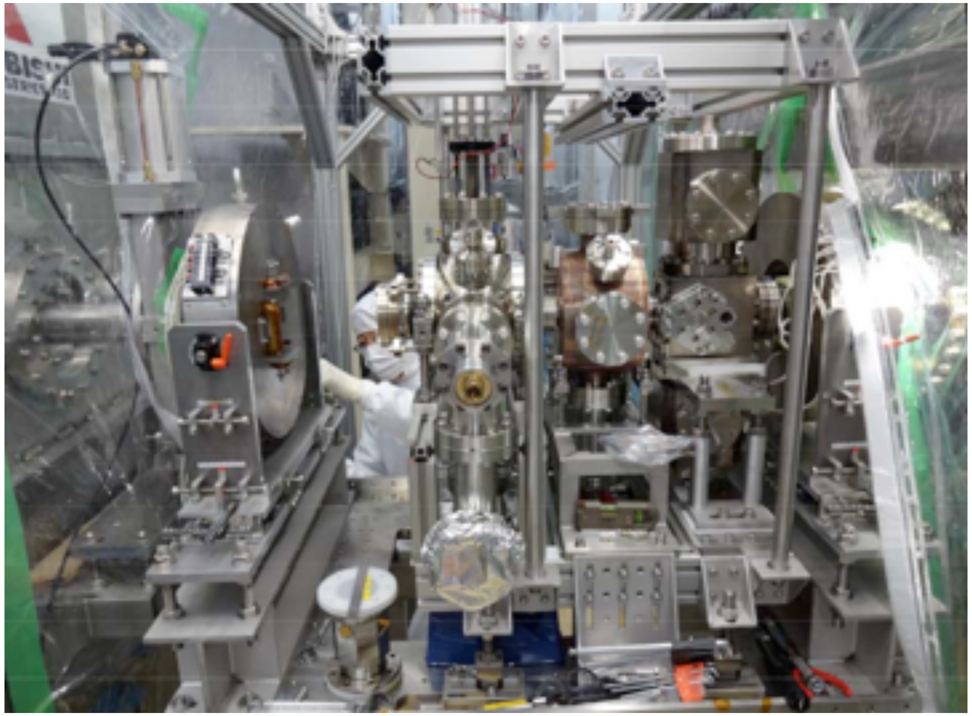




Injection line

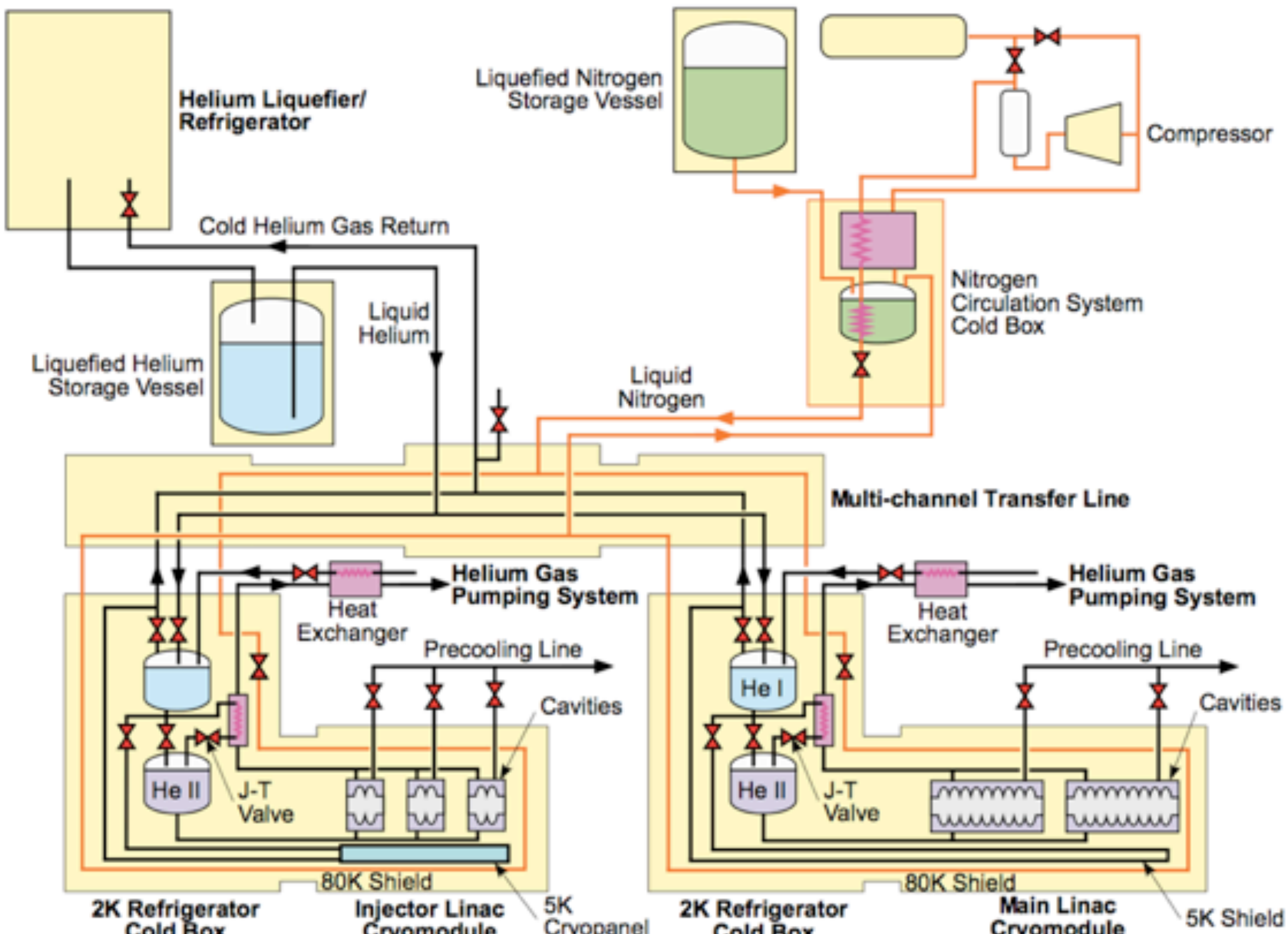
- 1m beam line between gun and SC accelerator
- low energy, space-charge dominated beam transport
  - Designed to be as short as possible, result in quite difficult to assemble.
- Complicated requirement
  - monitors, laser input, buncher
  - severe vacuum pressure requirement, 10^-9Pa.
- After all assembling 2~6x10^-9Pa realized.
  - Buncher high power test is underway, need to check actual pressure in operation.





Cryogenic system

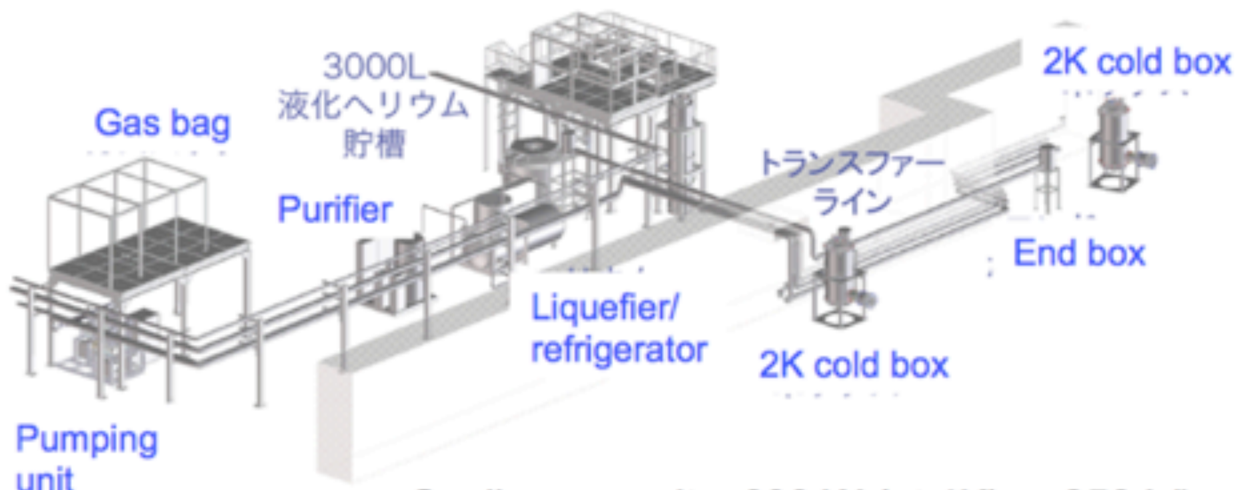
- Similar system as operating at STF.
- Seems just enough for 35MeV, 10mA. For beam upgrade, need upgrading.
- Cooling capacity: 600W(@4K), 250L/h, actually limited by pumping capacity 40W@2K
- After high power tests of each cavity (on going now), heat load will be known.
- Then, operation energy in full system should be discussed.



Cryogenic system

Overview of the system

Courtesy: H. Nakai



Cooling capacity: 600 W (at 4K) or 250 L/h

3000L liquefied helium storage vessel

2K cold box and end box

TCF200 helium liquefier/refrigerator

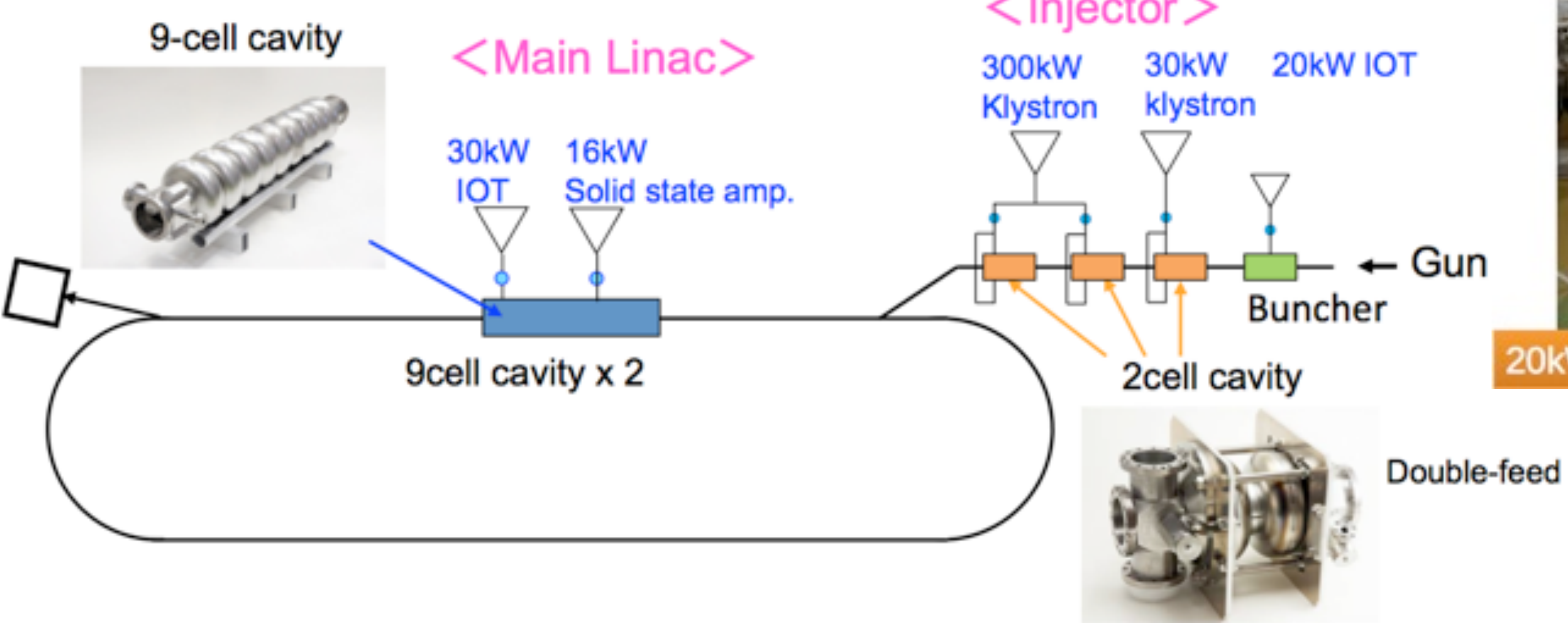
RF system

- Original design (100mA): 300kW Klystron for each Injector, 30kW IOT for Main linac
- Present situation for limited budget (10mA)


30kW CW IOT for main SCC


300kW CW Klystron for injector SCC

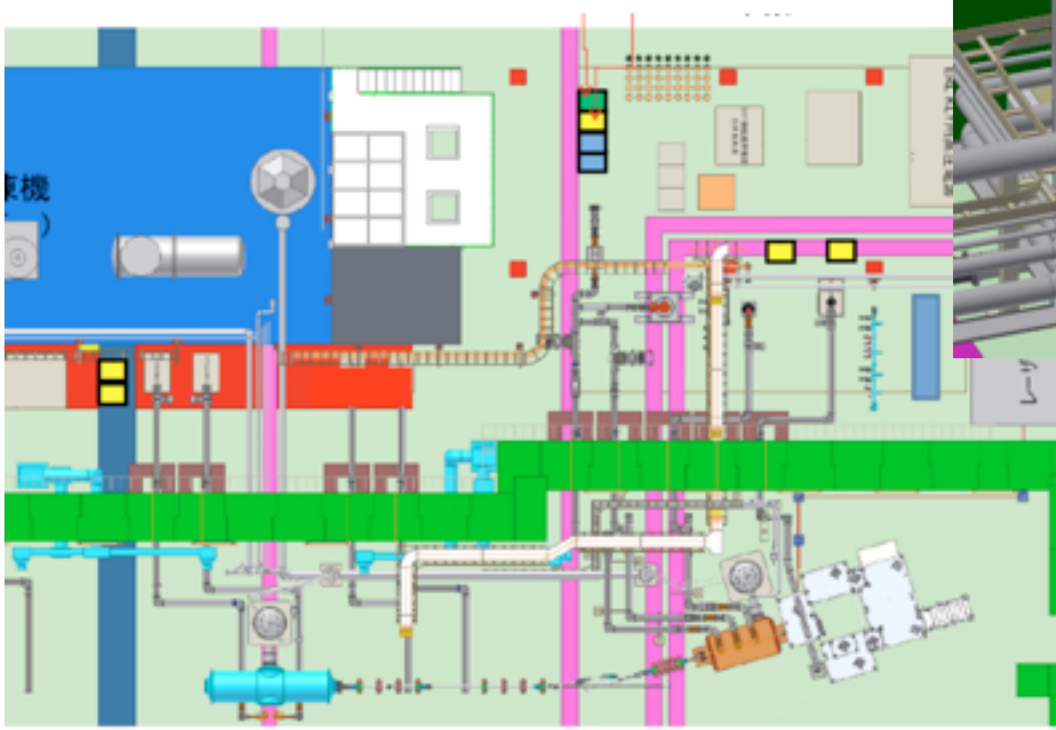

30kW CW Klystron for injector SCC

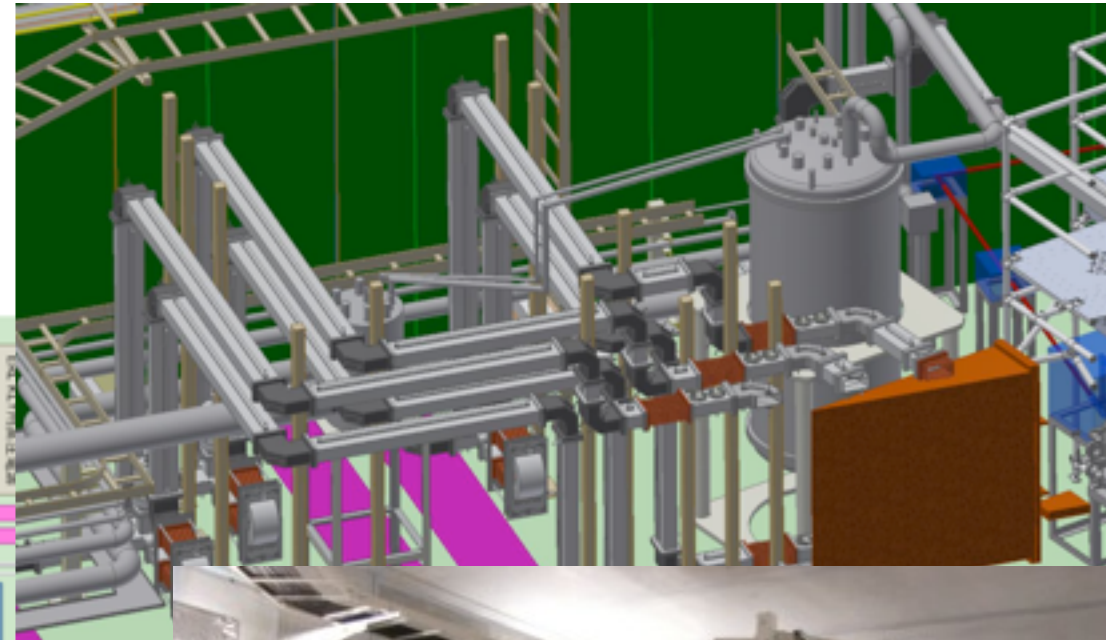



20kW CW IOT for buncher

RF distribution system

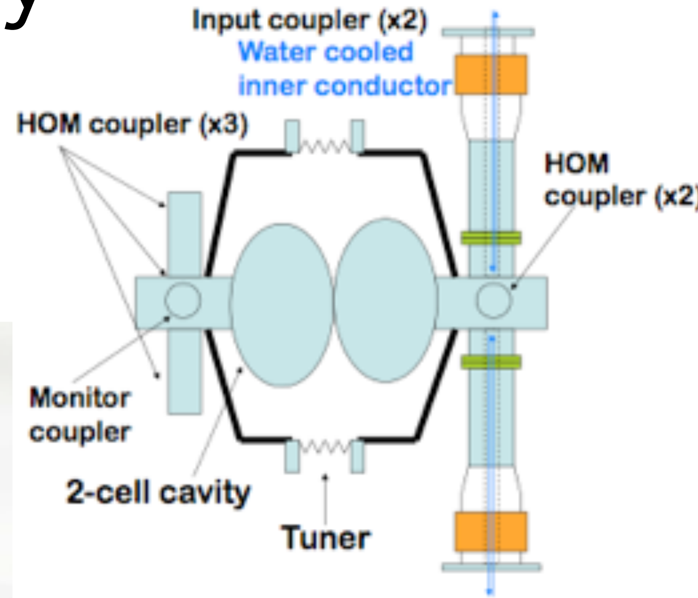
- Most time spent for “cERL construction meeting” is space and time sharing of the complicated area between groups.



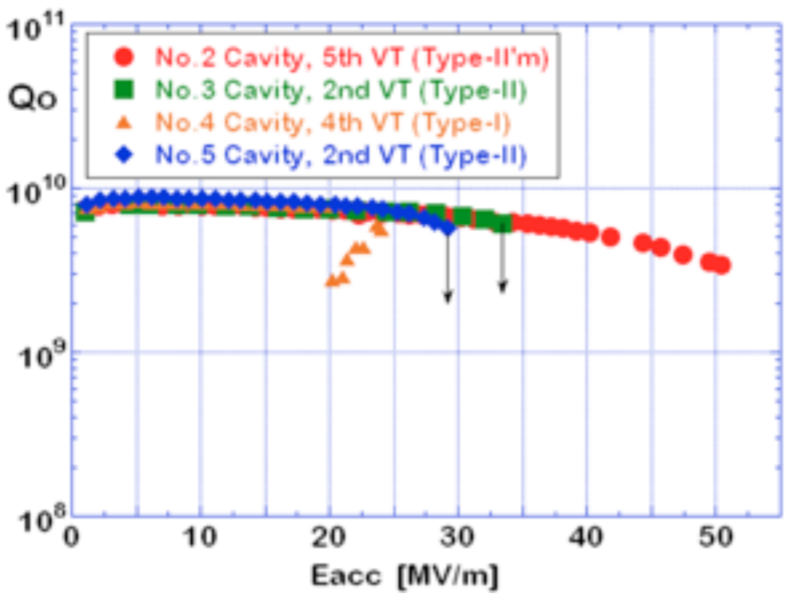


Injector SC cavity

- Three 2-cell cavities (500keV to 5MeV)
- Target: Accelerate to 10MeV (15MV/m at CW)
- Challenge
  - high power input coupler (100mA case, much relaxed at 10mA)
  - HOM coupler
- Vertical test result
  - >40MV/m reached
  - limited at 15MV/m by heat-up at HOM coupler



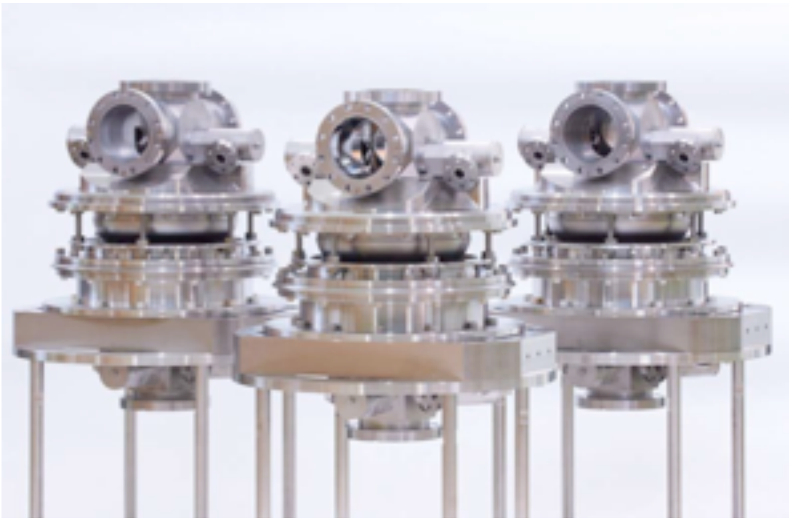
Cavity Vertical Tests Results (Final)

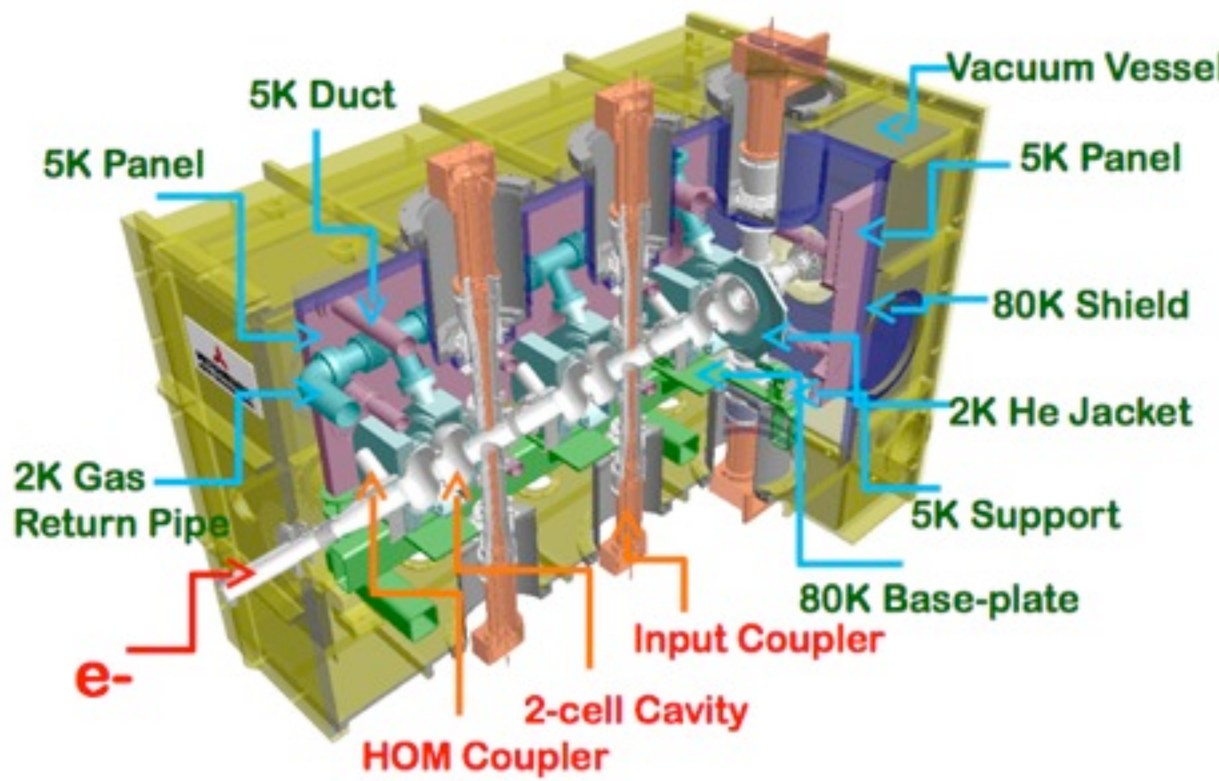


(Q_L /coupler, P_{rf} /coupler, I_{beam} = 10 mA, E_{beam} = 5 MeV)

	Cavity - I	Cavity - II	Cavity - III
Cavity	#3 cavity	#4 cavity	#5 cavity
Input coupler	#3 & #4 couplers	#5 & #6 couplers	#7 & #8 coupler
Operational gradient	6.5 MV/m (1.5 MV)	11 MV/m (2.5 MV)	11 MV/m (2.5 MV)
Loaded Q (Q_L)	10×10^5	4×10^5	4×10^5
Required RF Power	10 kW	20 kW	20 kW

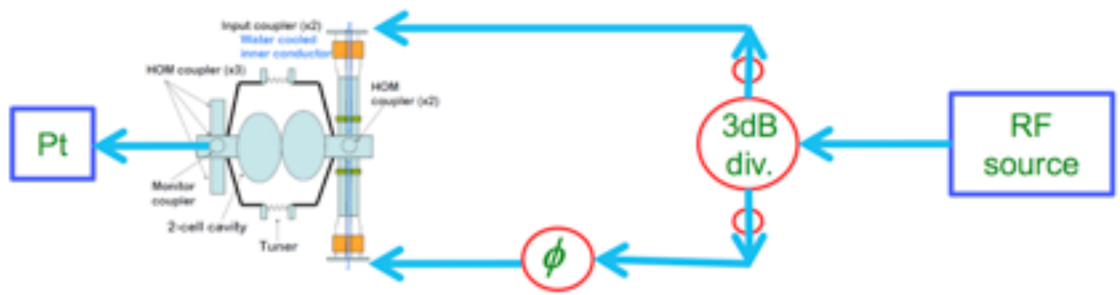
Injector SC cavity assembly

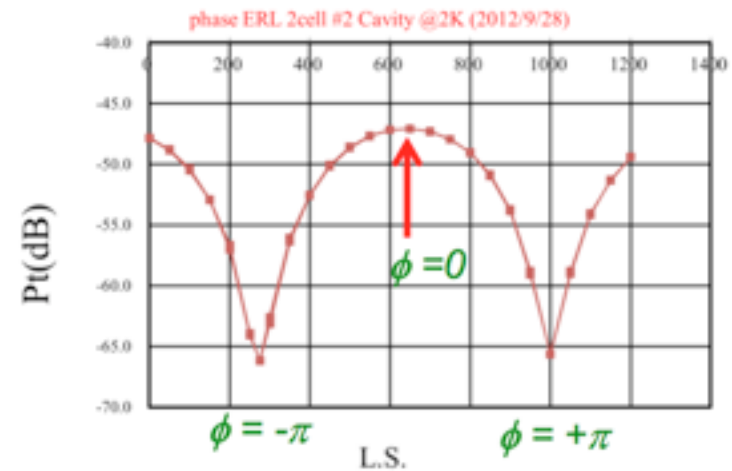


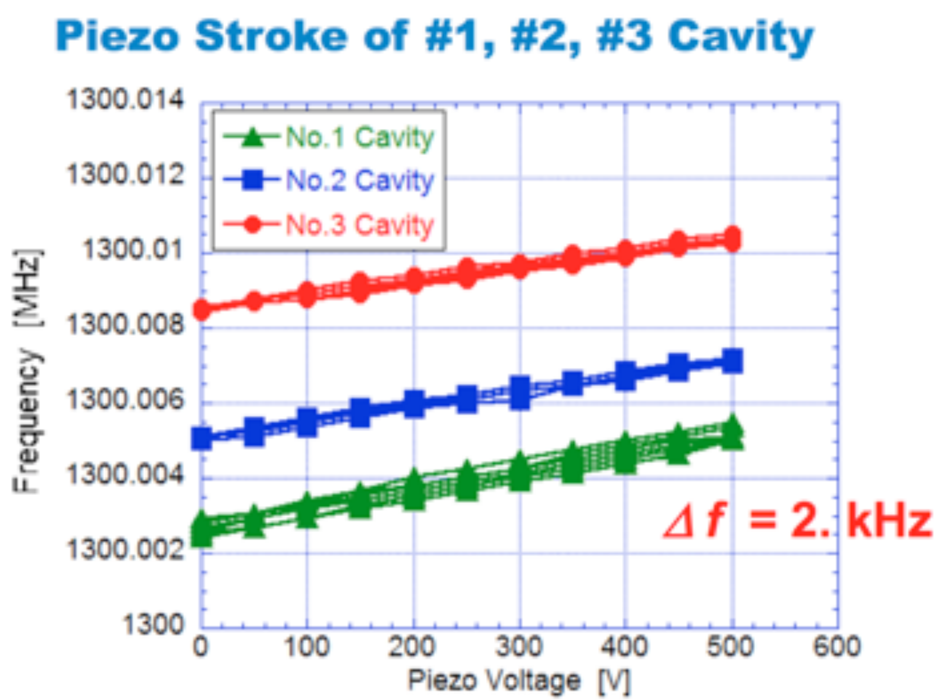


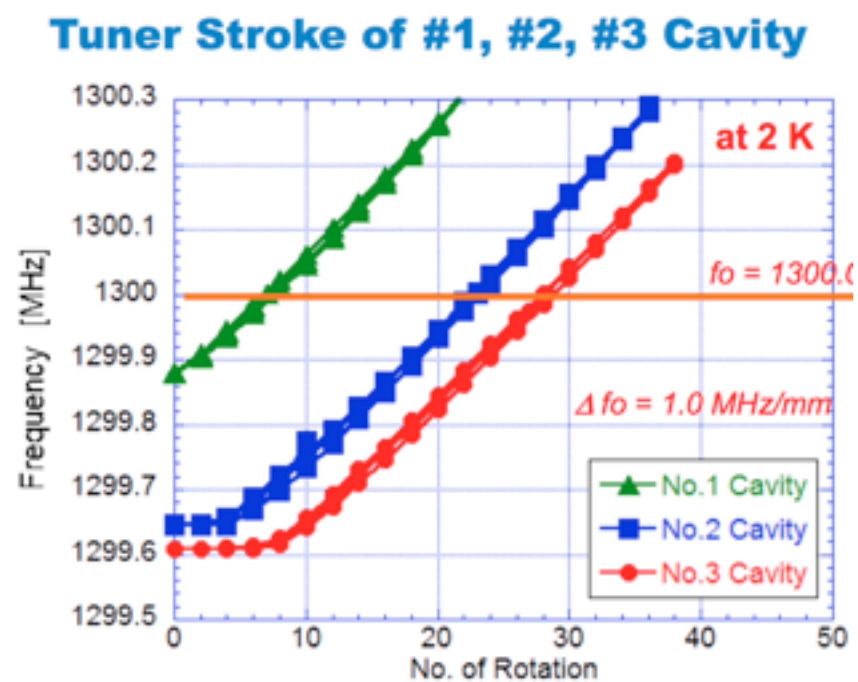
Injector SC system test

- Successfully cooled down to 2K
- Low RF power tests at 2K, good performance checked
- Now, high power test is underway



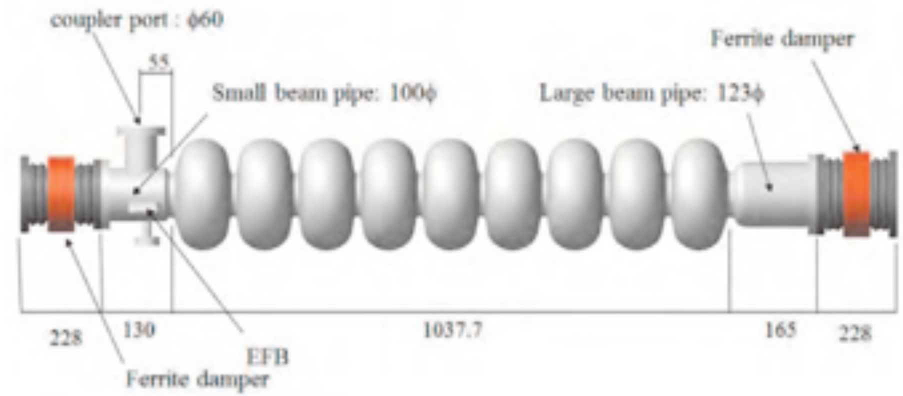






Main SC linac

- 9cell, 1.3GHz cavity, 15MV/m, tolerable for 200mA operation
- HOM management is the key
  - large beam pipe diameter, mode converter, absorber
- Vertical test has proven the specification

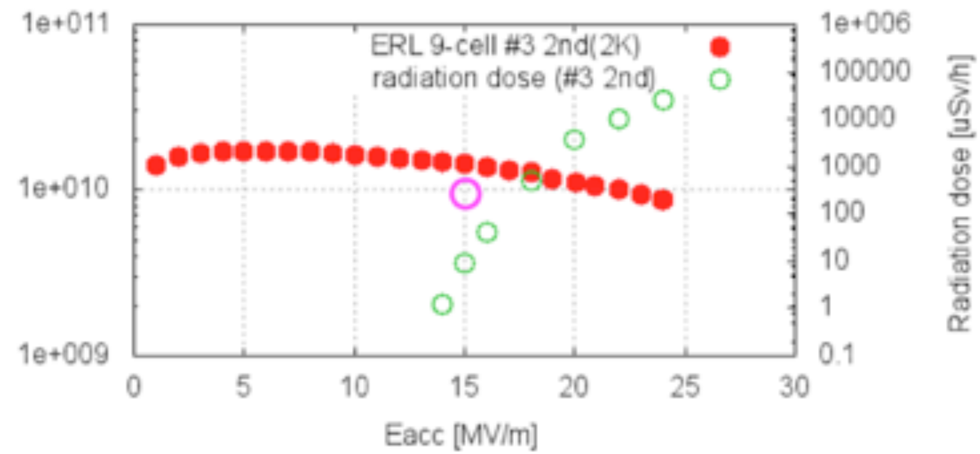


ERL 9-cell #3 cavity

- Field reached to 25 MV/m
- No limitation up to 25 MV/m
- Q > 1e10@15MV/m

•Satisfied cERL specification

•X-ray onset around 14 MV/m

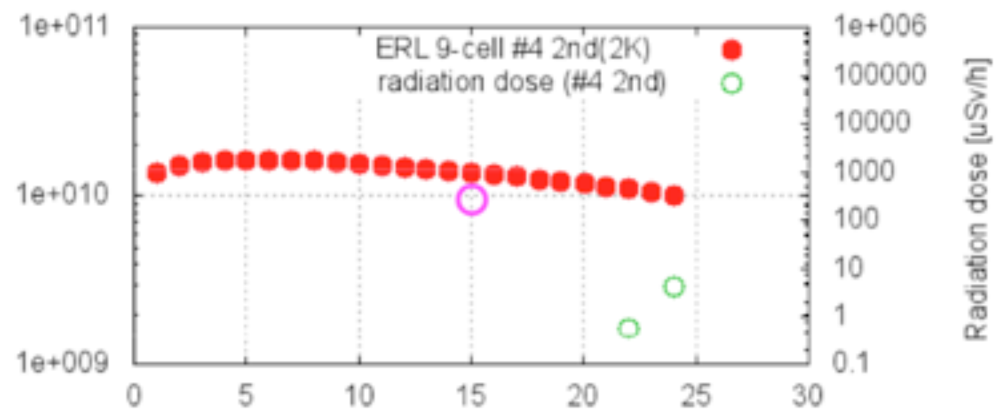


ERL 9-cell #4 cavity

- Field reached to 25 MV/m
- No limitation up to 25 MV/m
- Q > 1e10@15MV/m

•Satisfied cERL specification

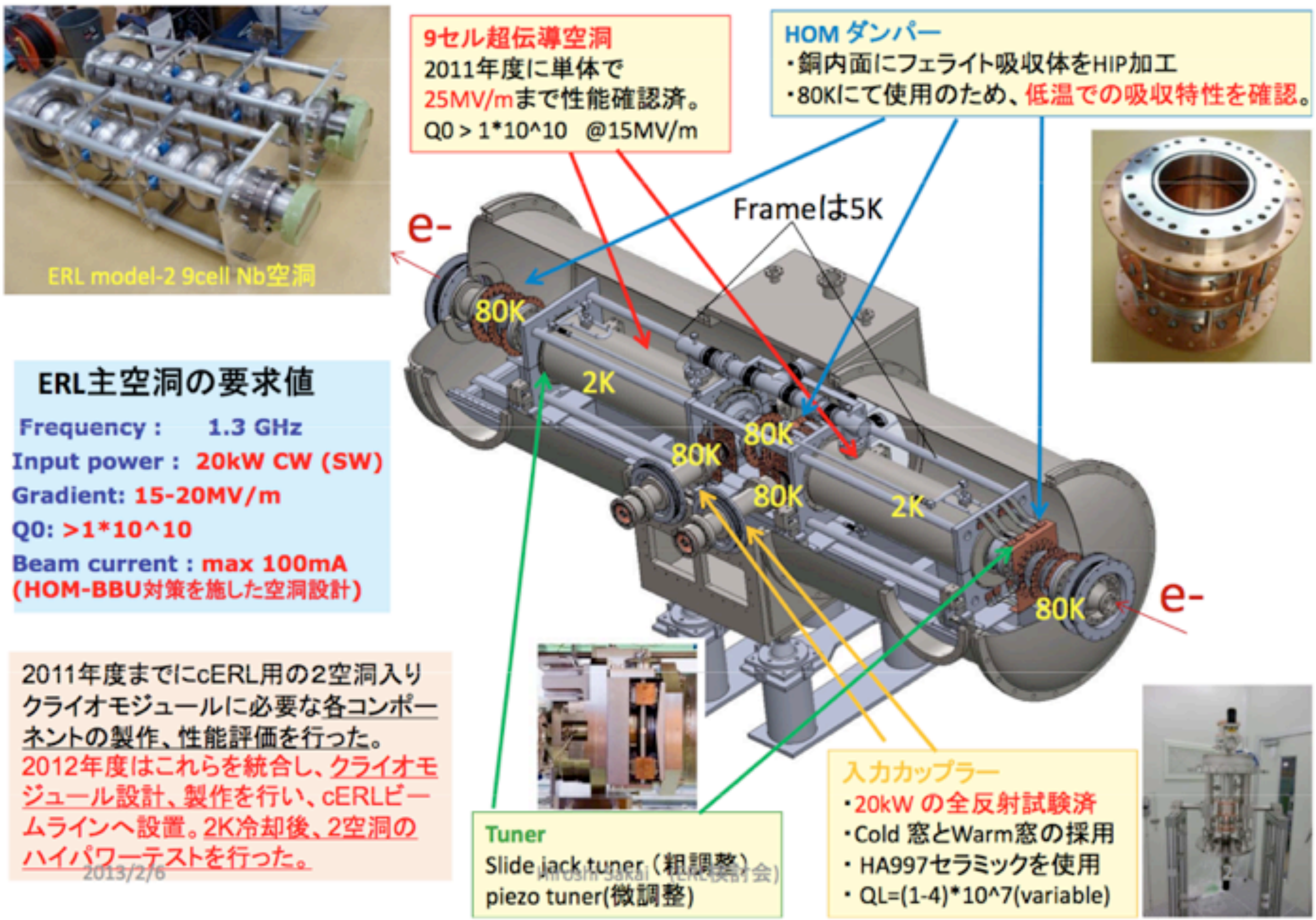
•X-ray onset around 22 MV/m



〇 はcERLの要求値

Main SC module

- Assembling as a system

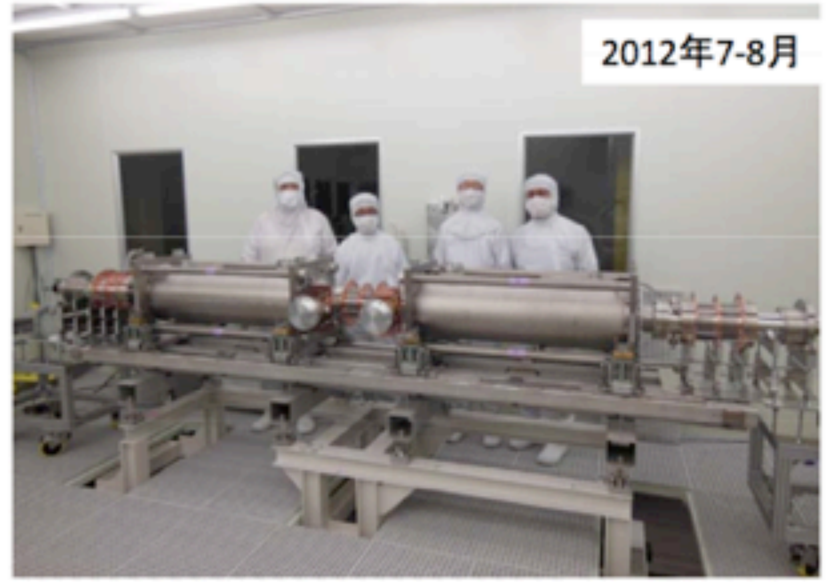


Main SC linac assembly

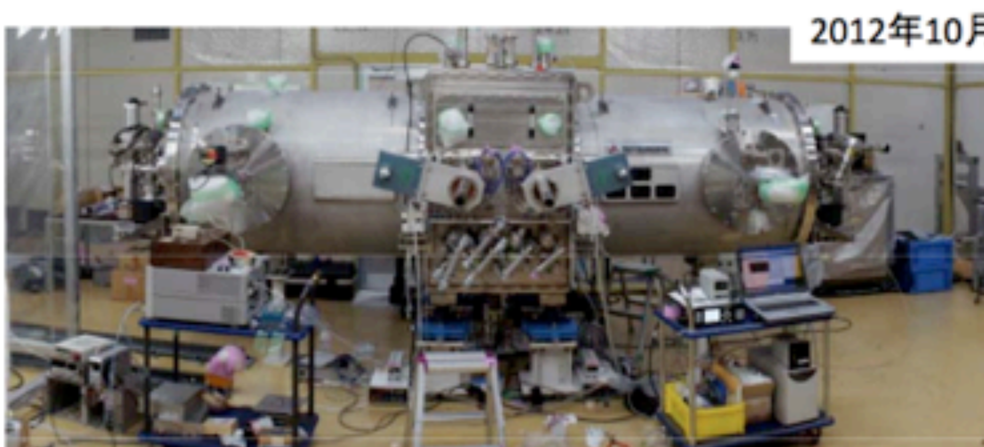
モジュールアッセンブリ（おさらい）

空洞単体での性能確認後、Ar封入した2台の空洞にHeジャケットを溶接。高圧ガス検査を行った後にKEKに。

超伝導空洞、HOMダンパー、入力カプラー窓などをクリーンルーム(class10)にてアッセンブリ@KEK



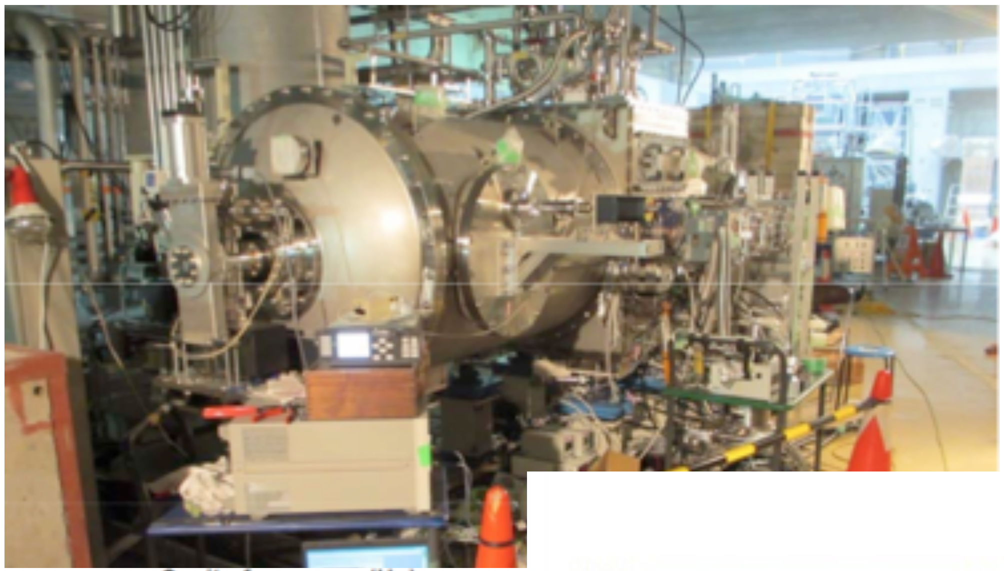
クリーンルームから出し、Heライン、磁気シールド、チューナー、センサー、熱シールドなどを装着。

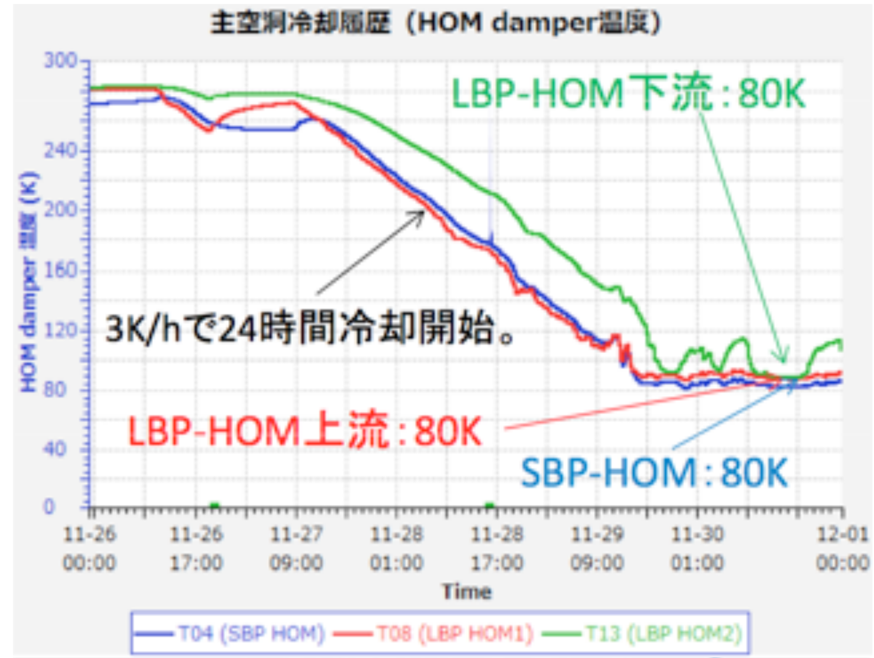


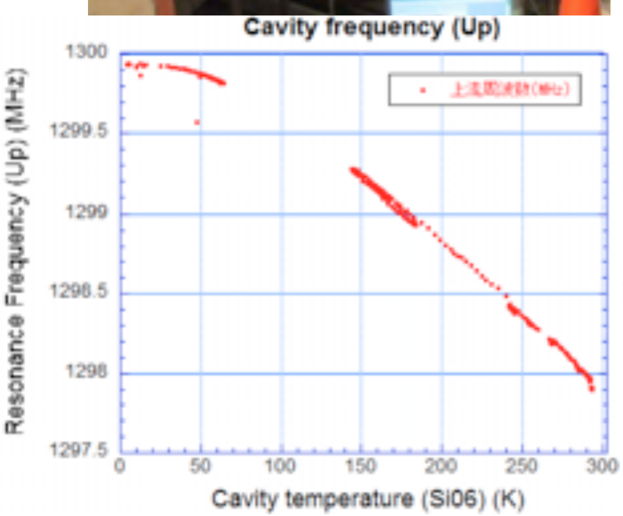
空洞のアラインメント後、断熱槽をかぶせ、ゲートバルブを取付、リークcheckを行い、アセンブリ完成。

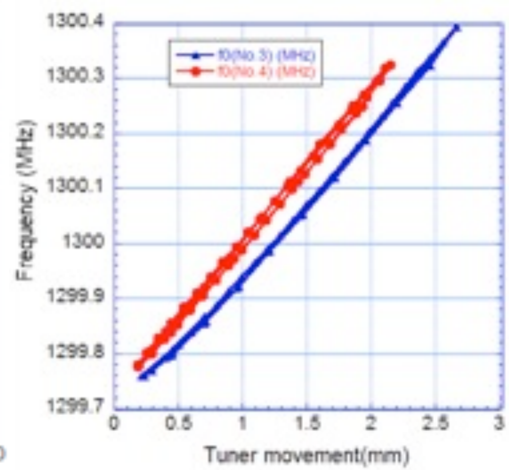
Main SC linac system test

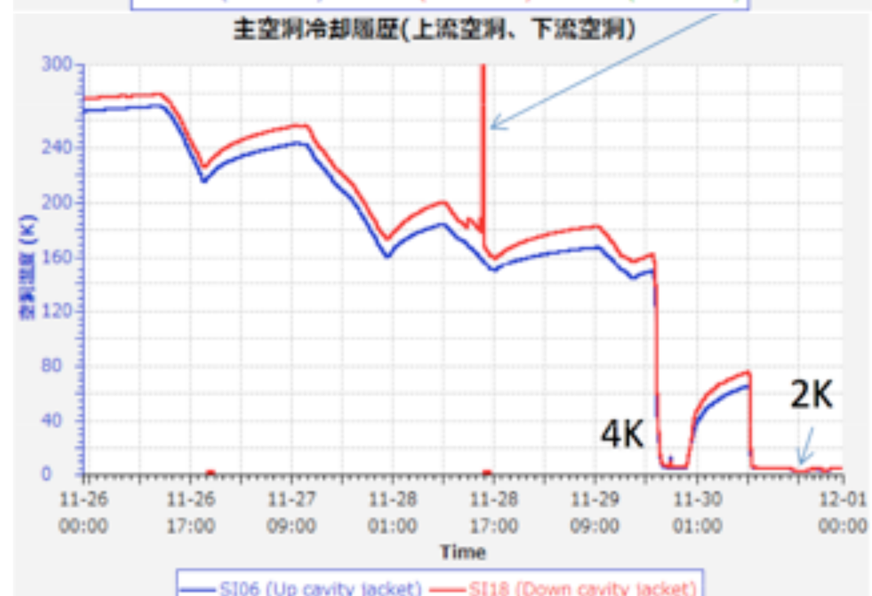
- Successfully cooling down to 2K
- Check that system works (tuner, coupler, HOM absorber...)





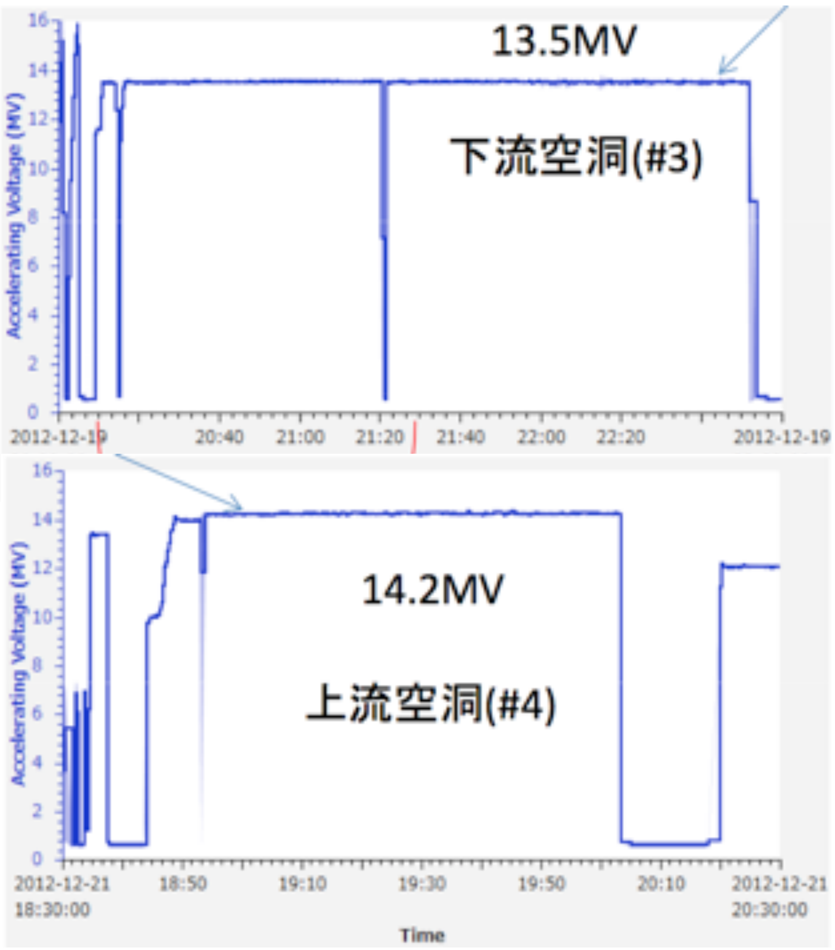


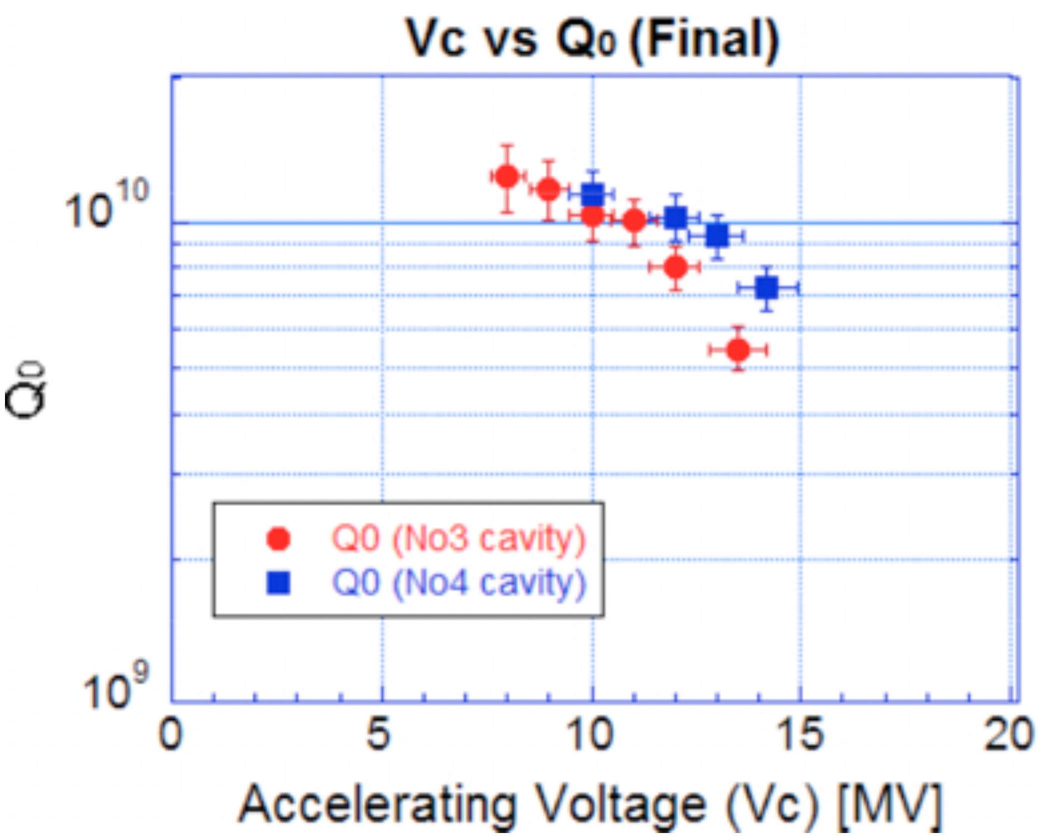




Main SC linac high power test

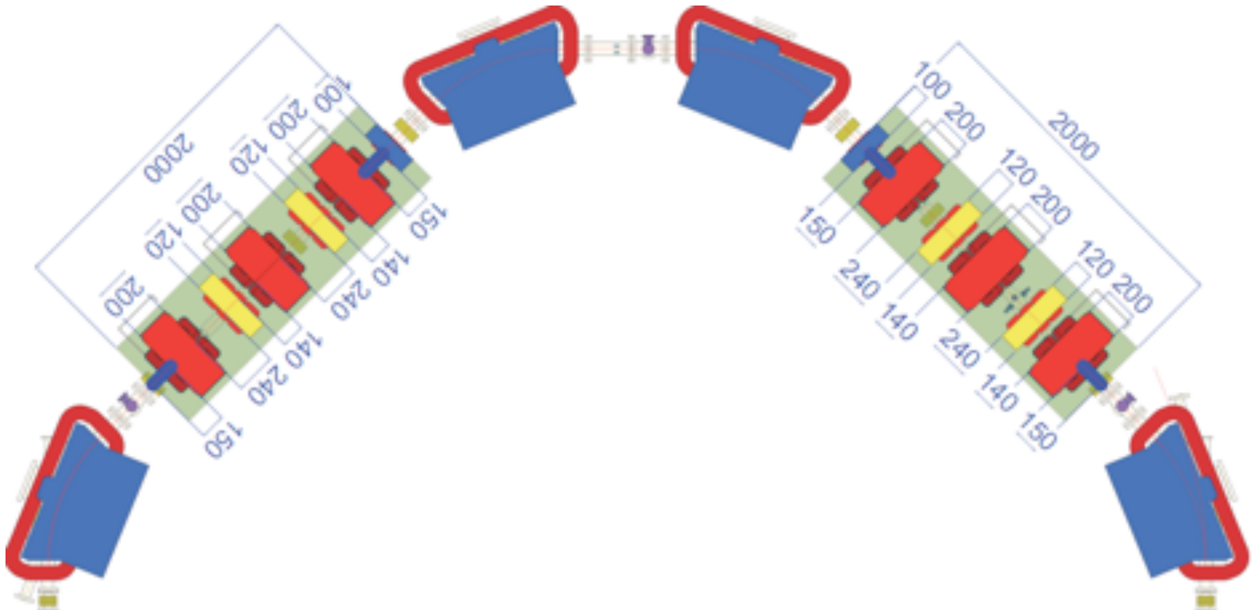
- Max. 16MV/m reached
- Operational limited at 13.5MV/m and 14.2MV/m, by cooling capacity.
  - more than expected field emission, radiation and heat load increase, 1uA of dark current
- Problems may be in assembling process. (reached to 25MV/m at vertical test)
- Need to decide operation beam energy of cERL
  - merger acceptance, total cryogenic load with injector, radiation, etc.

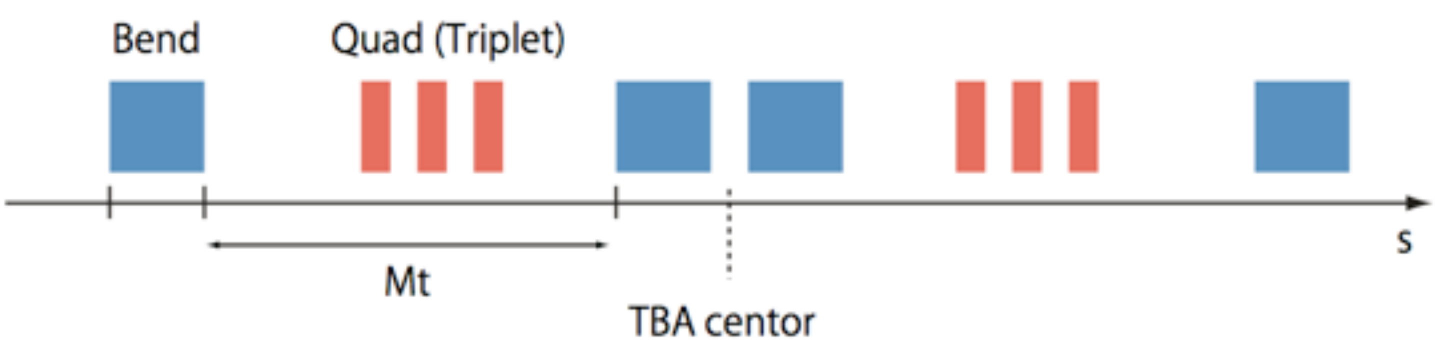




Return Loop Optics

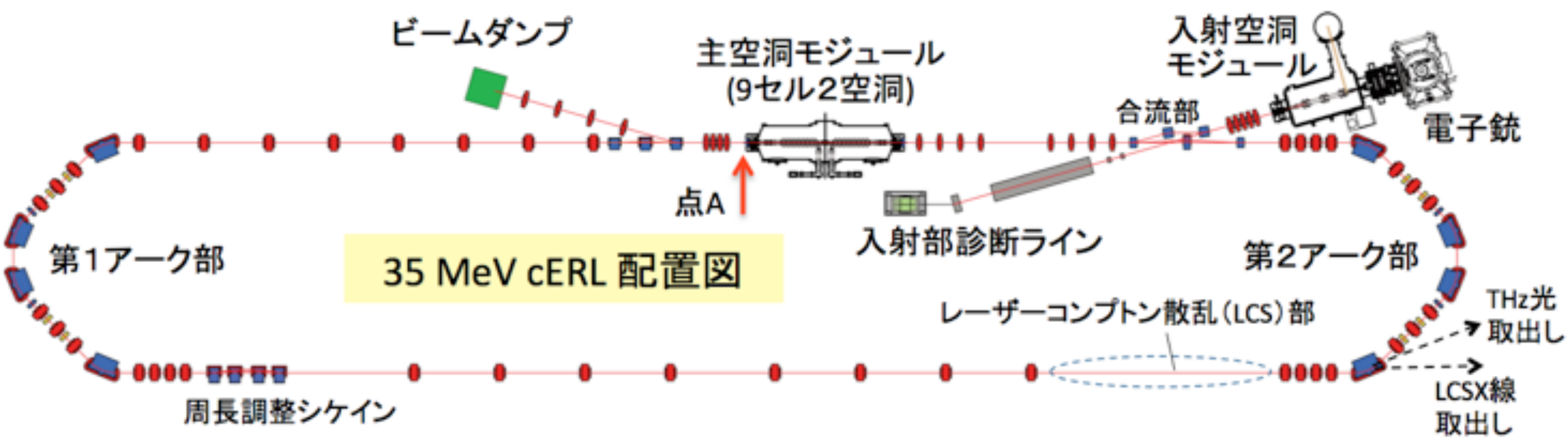
- Optics in Arc section
  - dispersion less and isochronous at straight line
  - symmetric TBA lattice chosen for compactness
  - size is determined by shield room size
  - actually not much to do, only one parameter left after Twiss parameters at input is given.

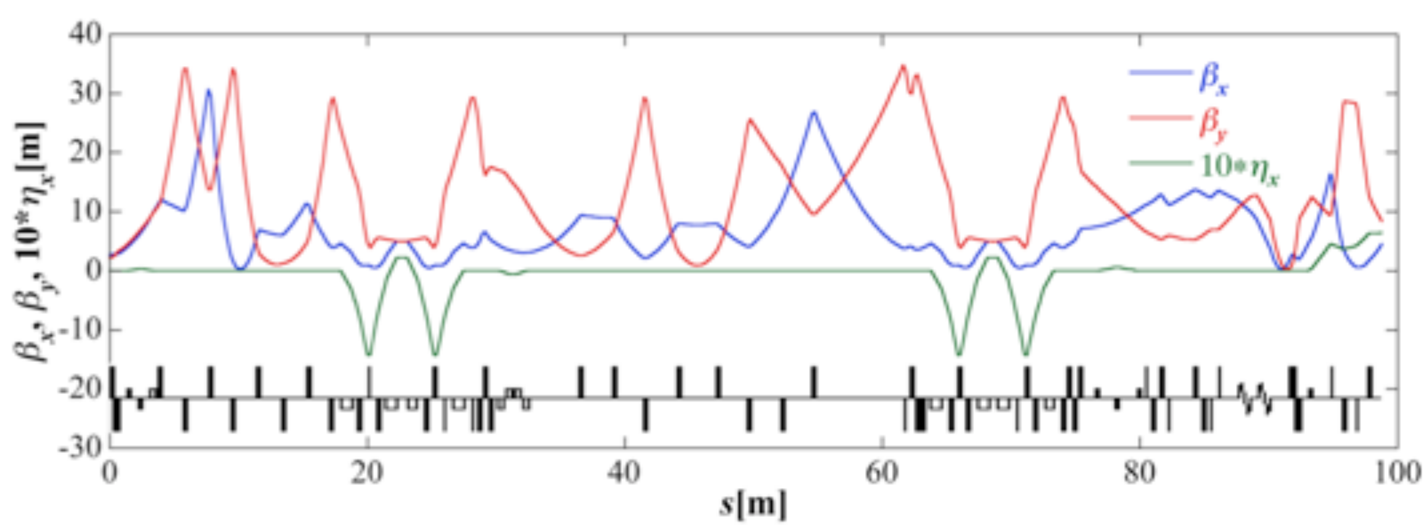




Return Loop Optics

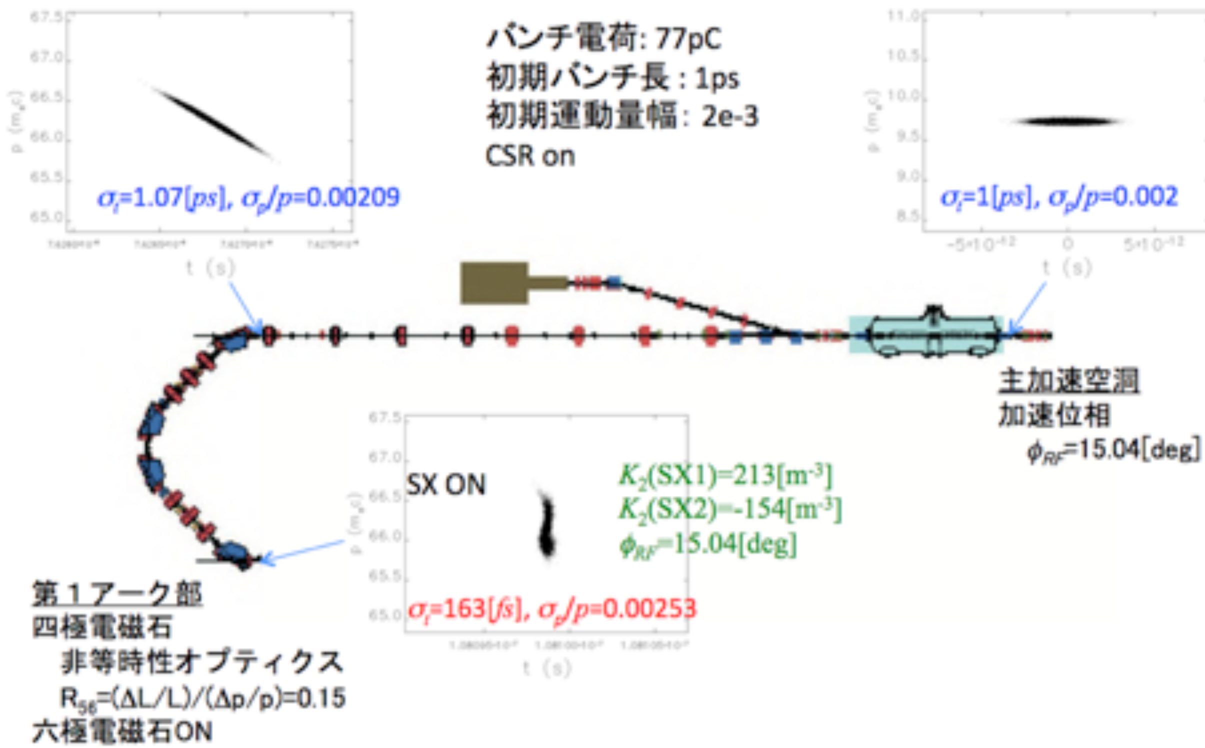
- Optics connection done with the input (after SC linac) to the damp
- Path length adjustment and tuning chicane (5mm) included
- At 10pC/bunch, space charge or CSR effect are not so strong.

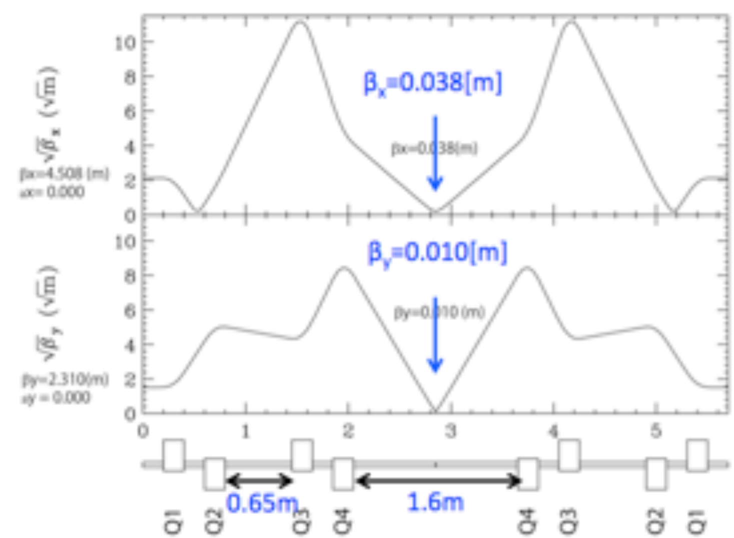


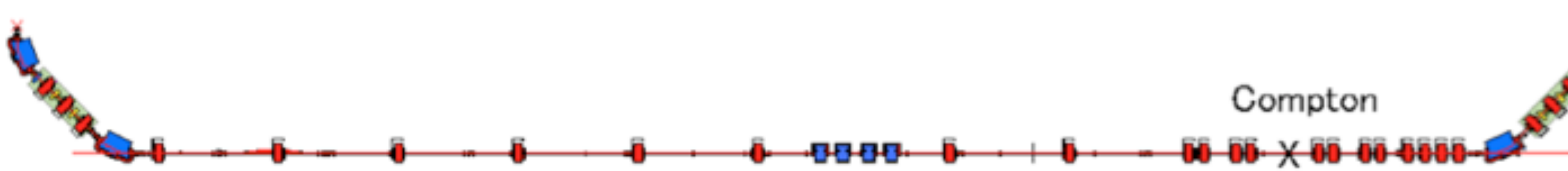


Possible operation

- Two optional operation modes proposed
  - Bunch compression to <0.2ps, for THz application.
  - Compton X-ray operation





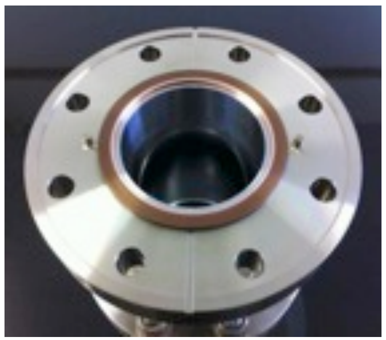


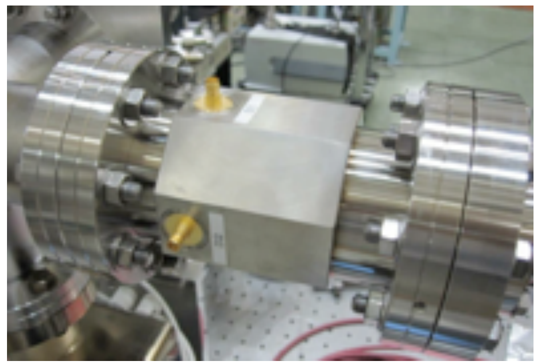
Return Loop Construction

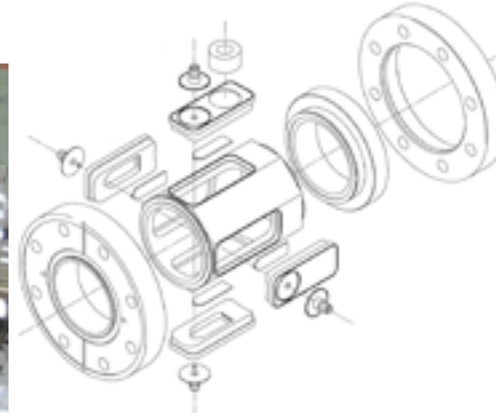
- Not yet. To be done in summer 2013.

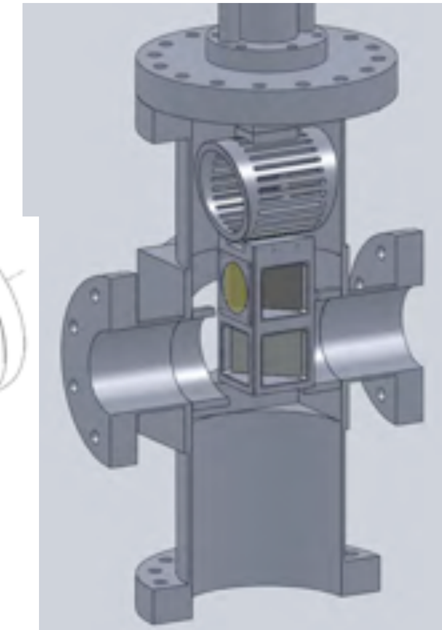
Return Loop Monitor

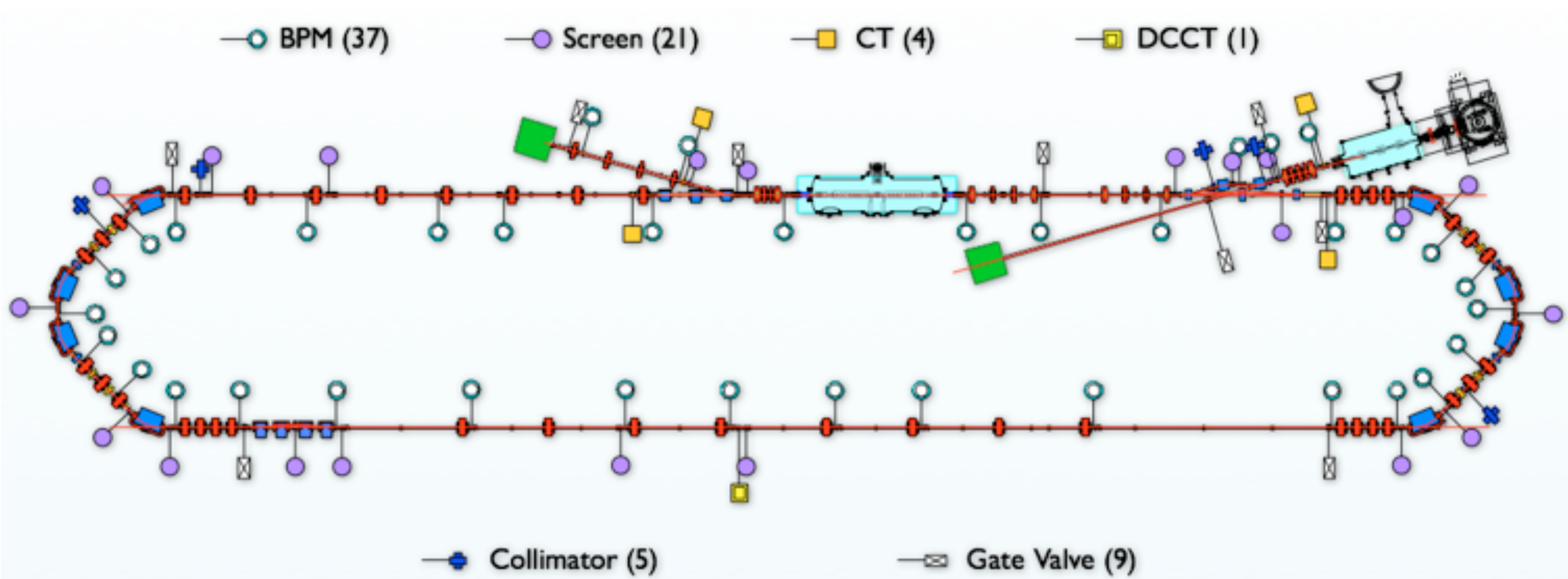
- Screen (CeYAG and OTR) monitor with shielding
- Strip line BPM (2.6GHz resonant strip-line)
- Bunch length (not prepared so far, CSR?)





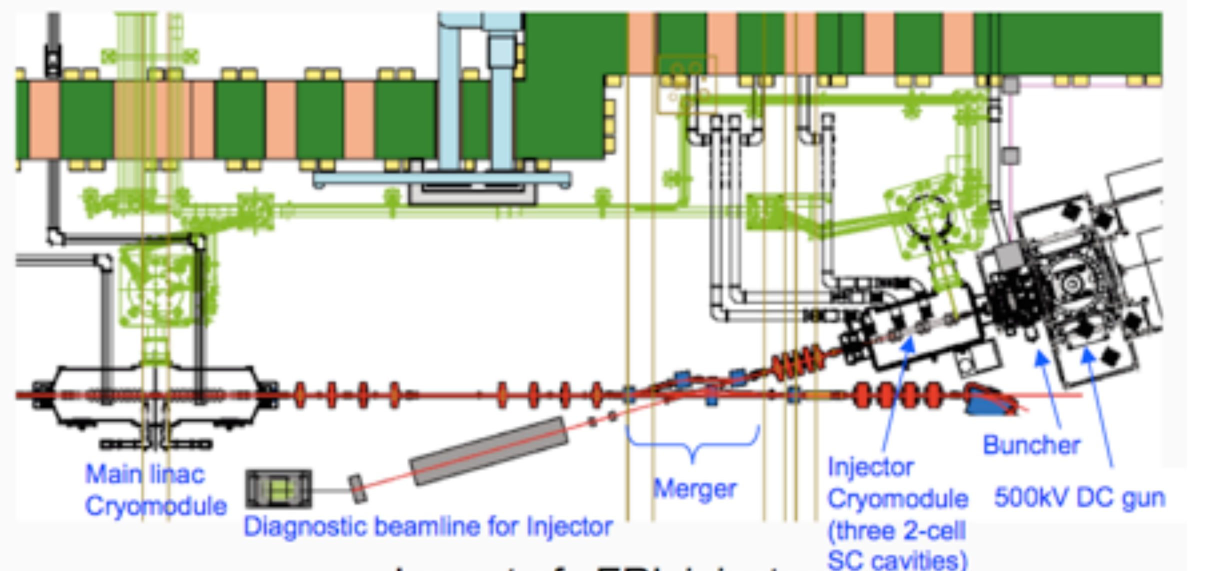




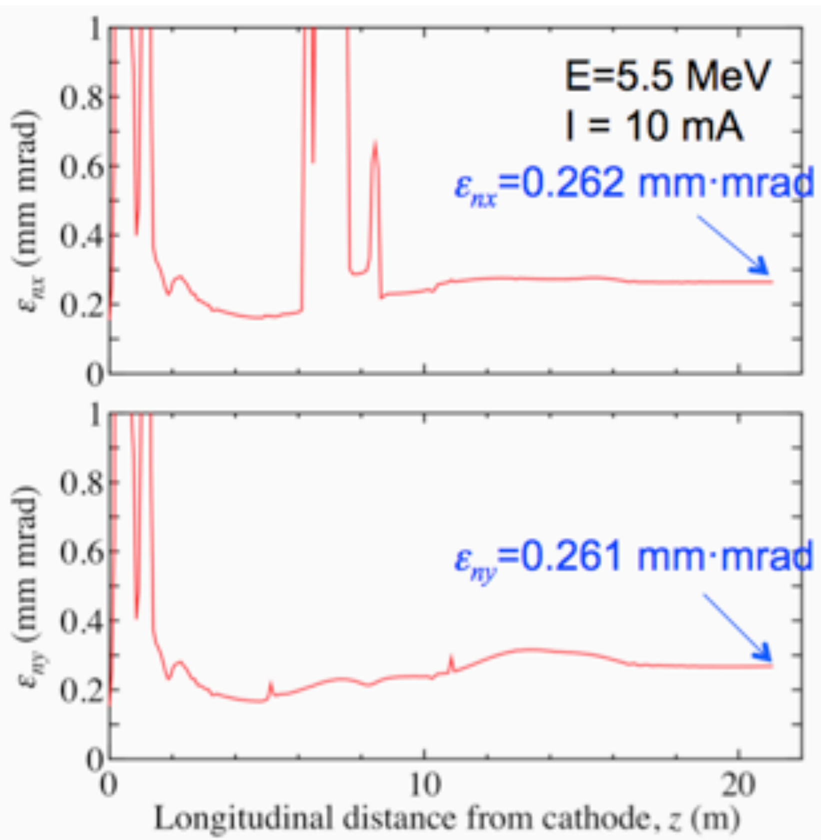


Injector Optics design

- Gun to main SC linac end simulation was done by macro-particle method including space-charge (GPT).
- 7.7pC/bunch
- Twiss parameter based on this calculation is given as an input of return loop calculation.



Layout of cERL injector.

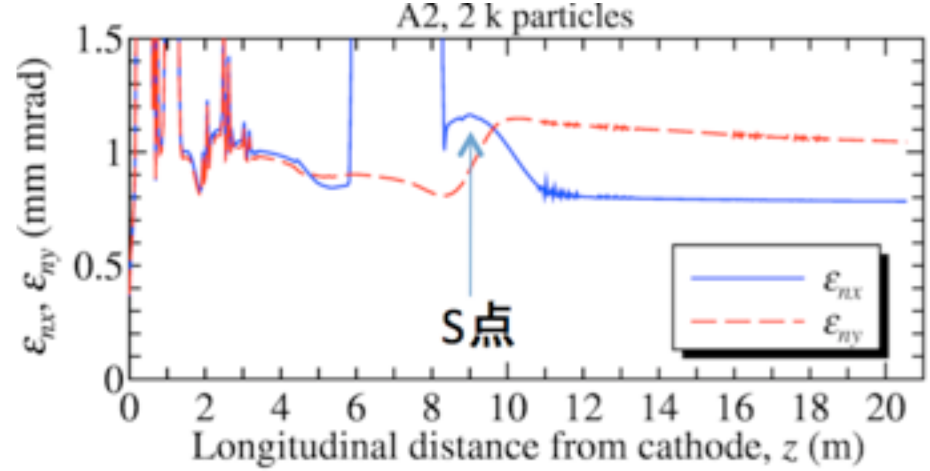


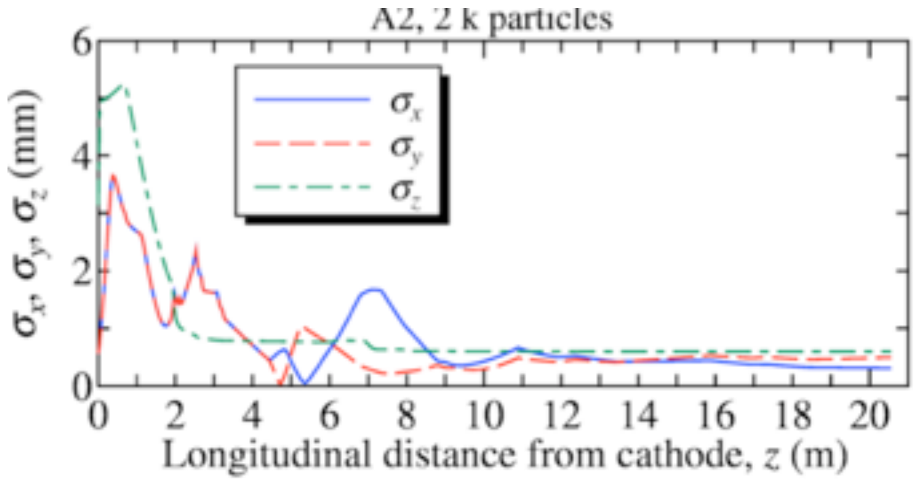
Injector parameters

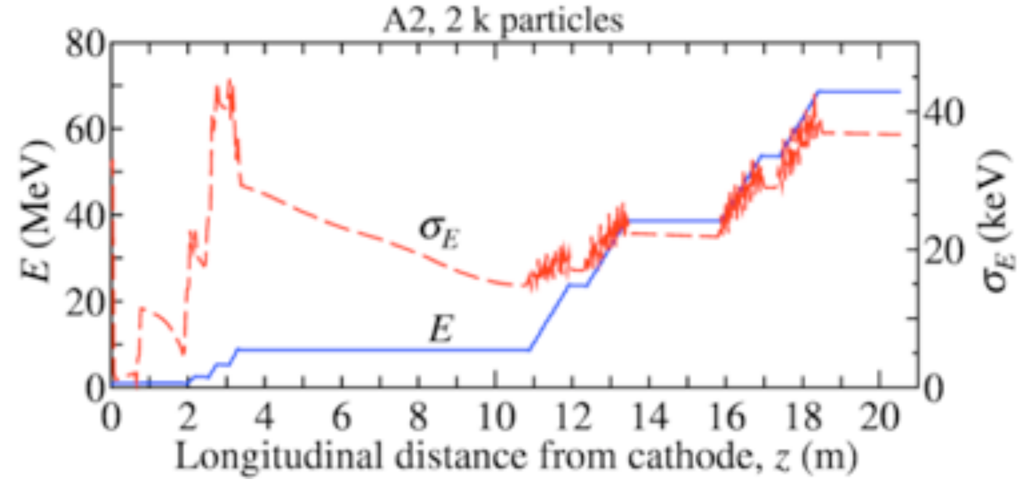
Parameter	Value
Gun DC voltage	500 kV
Beam energy of injector	5 MeV
Charge/bunch (Current)	7.7 pC (10mA)
Full width of laser pulse	16 ps
Spot diameter of laser	0.52 mm
Magnetic fields of solenoids #1, #2	0.0364, 0.0146 T
Voltage of buncher cavity	105 kV
Eacc of 1st, 2nd, and 3rd SC cavity	6.84, 7.53, 7.07 MV/m
Offset phase of 1st, 2nd, and 3rd cavity	29.9, -9.8, -10.0 degrees

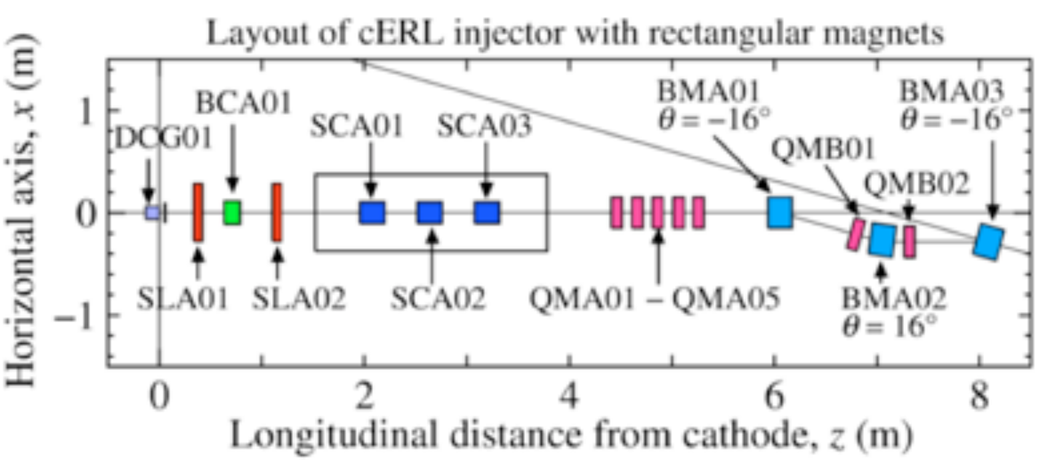
Injector Optics design

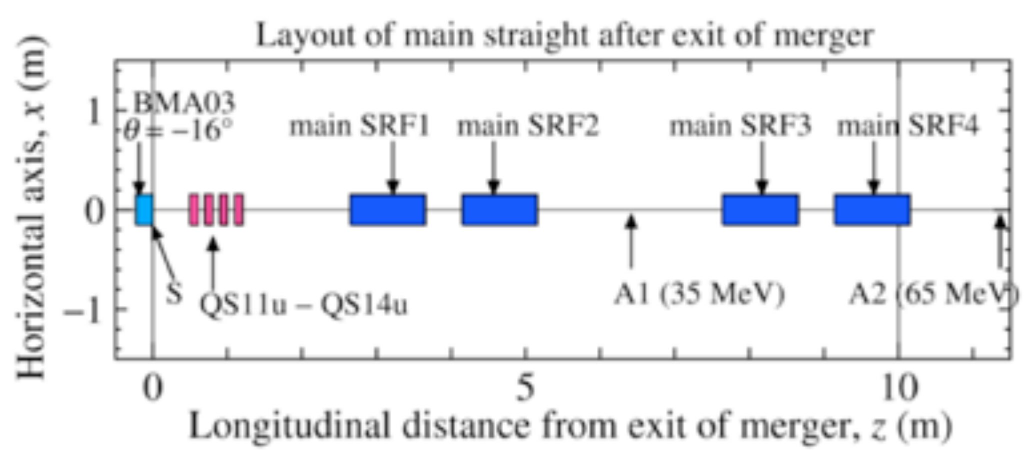
- For future upgrade, 80pC/bunch case is also considered.
- 10MeV injector energy (5MeV at present)
- normalized emittance <1 μm should be possible





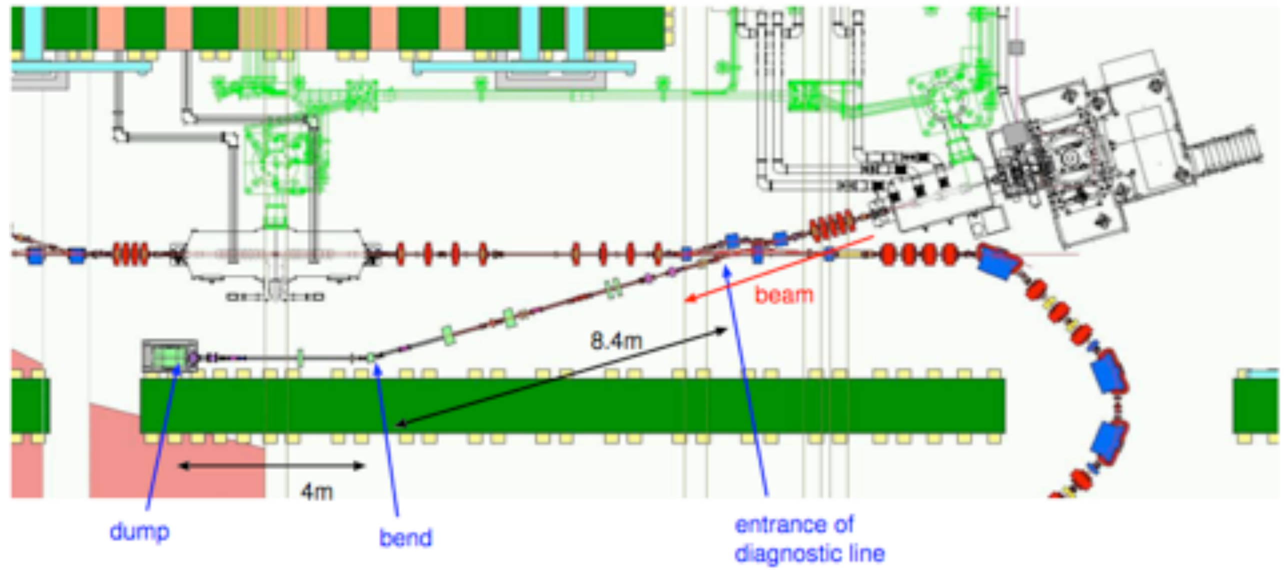


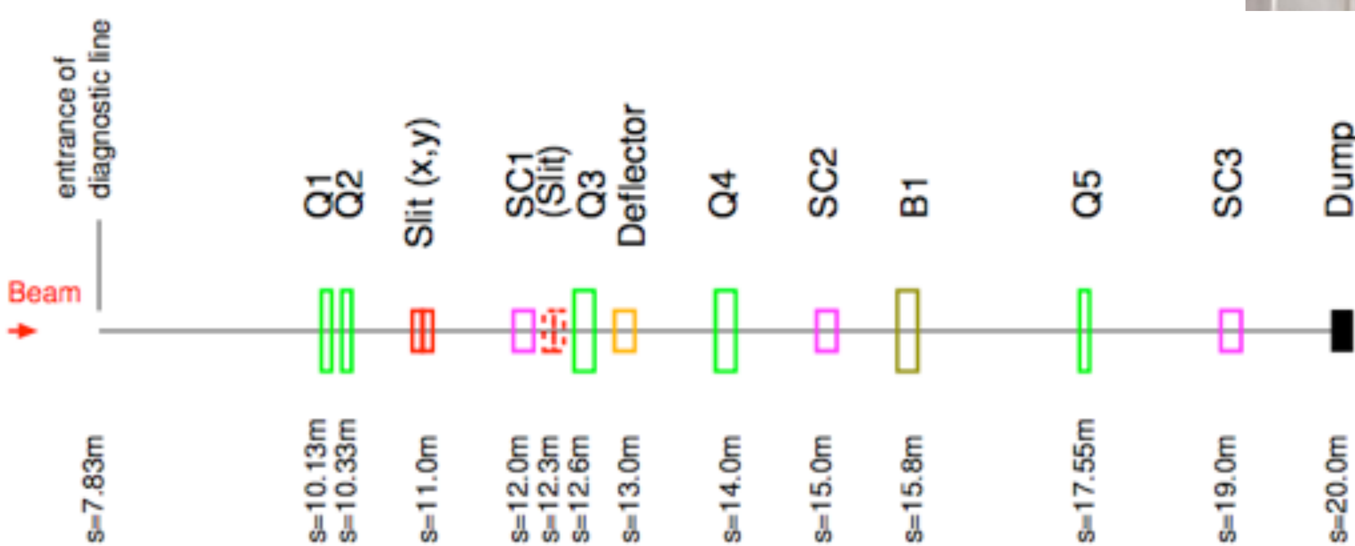




Injector Diagnostic line

- At the first commissioning, beam is sent to the straight line at 5MeV.
- Specification (to be allowed by radiation center): 6MeV, 1μA
  - 1fC/bunch, CW
  - 10pC/bunch, 1000bunch, 50Hz
  - 100pC/bunch, 1000bunch, 5Hz
- Beam diagnostics
  - Beam current (Faraday-cup and dump current)
  - Beam energy (after bending)
  - Emittance (Q-scan and Slit-scan)
  - Bunch length (RF deflection)





Emittance measurement

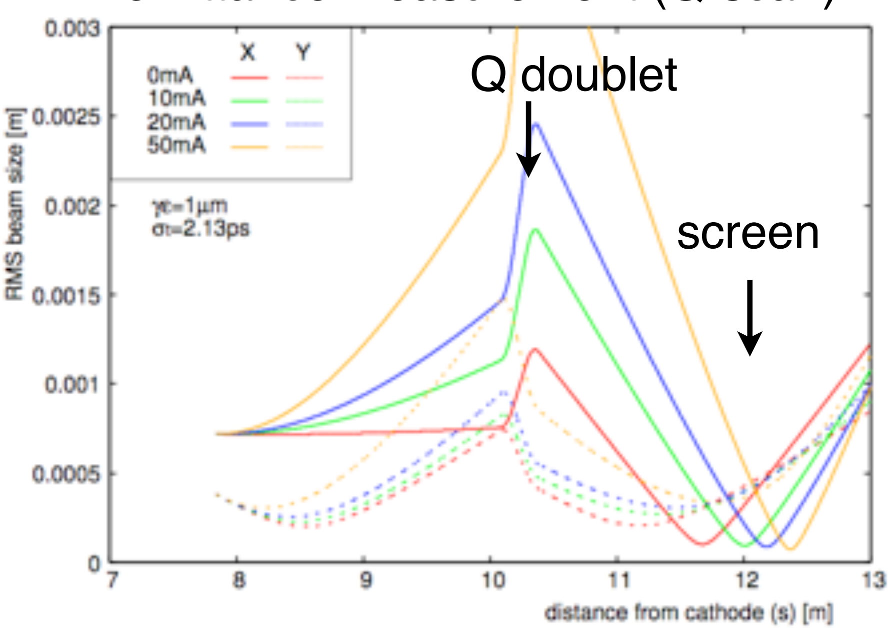
- Beam parameter at the entrance of the diagnostic line is given.
- Beam optics including space-charge effect was calculated using envelope equation
- Emittance measurement itself is difficult at 0.1 μm normalized emittance, too small divergence. Anyway as a first step, proving <1 μm is the target.

parameter		
Q	7.7 pC/bunch	バンチ電荷
f	1.3 GHz	バンチ繰り返し (ただしバースト運転)
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
$\epsilon_{n,x}$	1 μm	規格化エミッタンス (水平)
$\epsilon_{n,y}$	1 μm	規格化エミッタンス (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	Twiss parameter
α_x	0.071	Twiss parameter
α_y	1.622	Twiss parameter

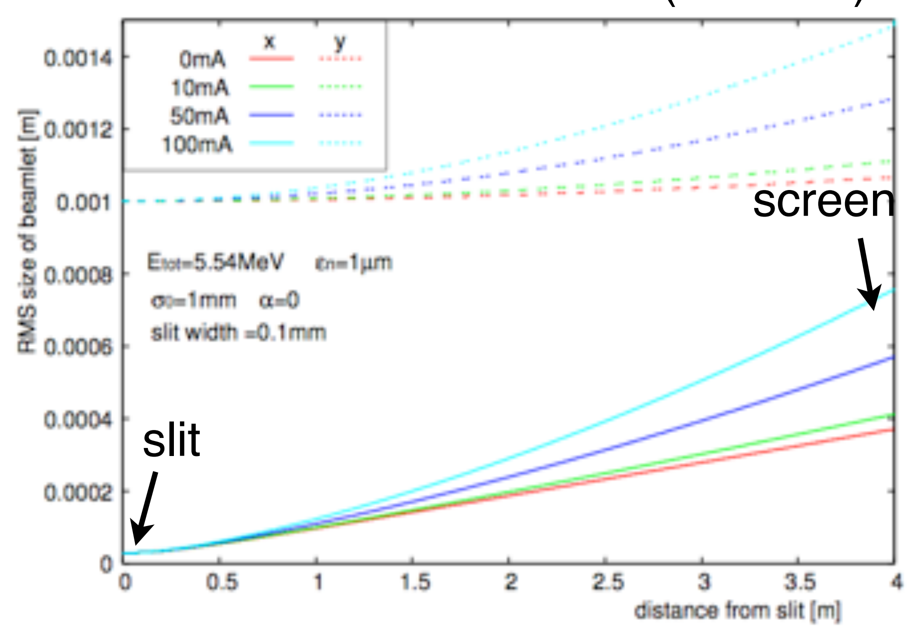
$$\sigma_x'' = \frac{I}{I_0\gamma^3(\sigma_x+\sigma_y)} + \frac{\epsilon_{n,x}^2}{\gamma^2\sigma_x^3} - K_x\sigma_x$$

$$\sigma_y'' = \frac{I}{I_0\gamma^3(\sigma_x+\sigma_y)} + \frac{\epsilon_{n,y}^2}{\gamma^2\sigma_y^3} - K_y\sigma_y$$

x-emittance measurement (Q-scan)

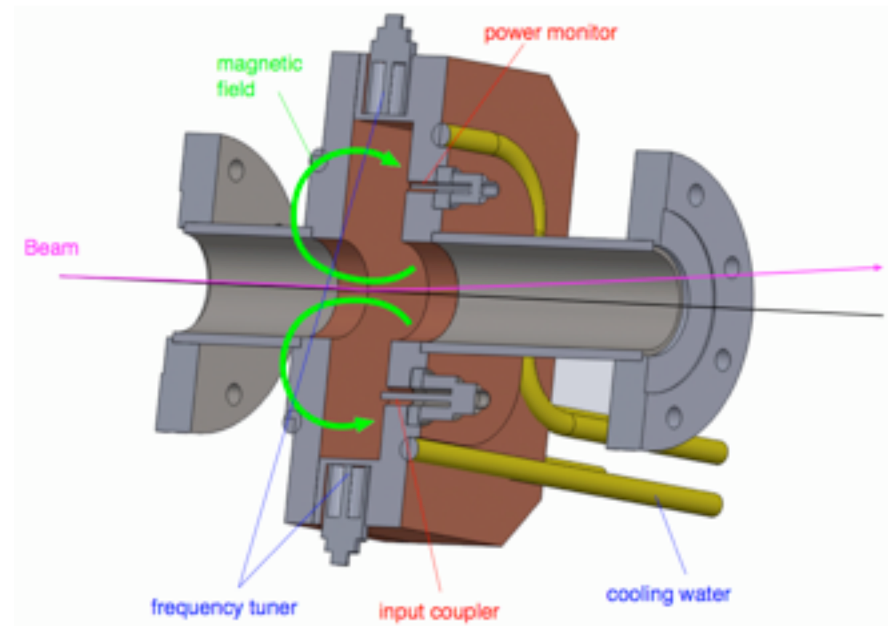


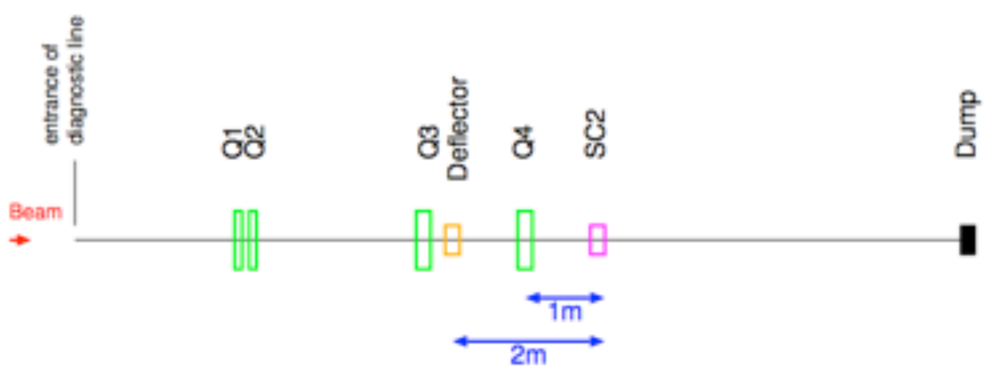
emittance measurement (slit-scan)

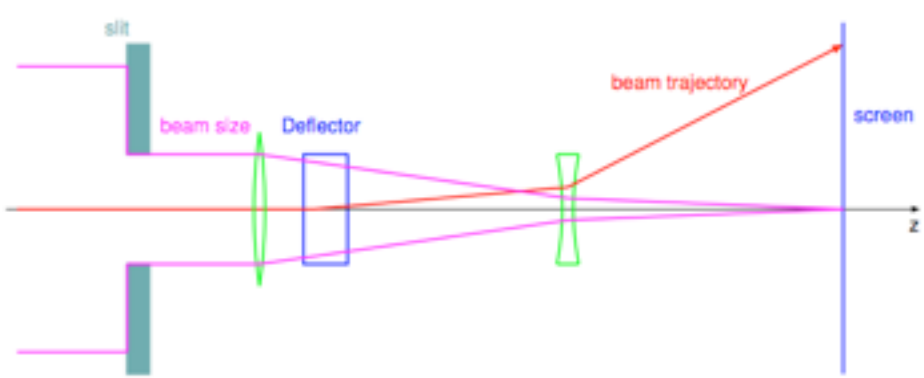


Bunch length measurement

- 2.6GHz, Dipole-mode deflector cavity
- Originally developed for 500 keV beam.
- Actually, kick angle is not so strong, some idea
  - higher power (pulsed) RF amp (40W->300W)
  - longer distance
  - diverging optics
- possible to measure 2ps bunch







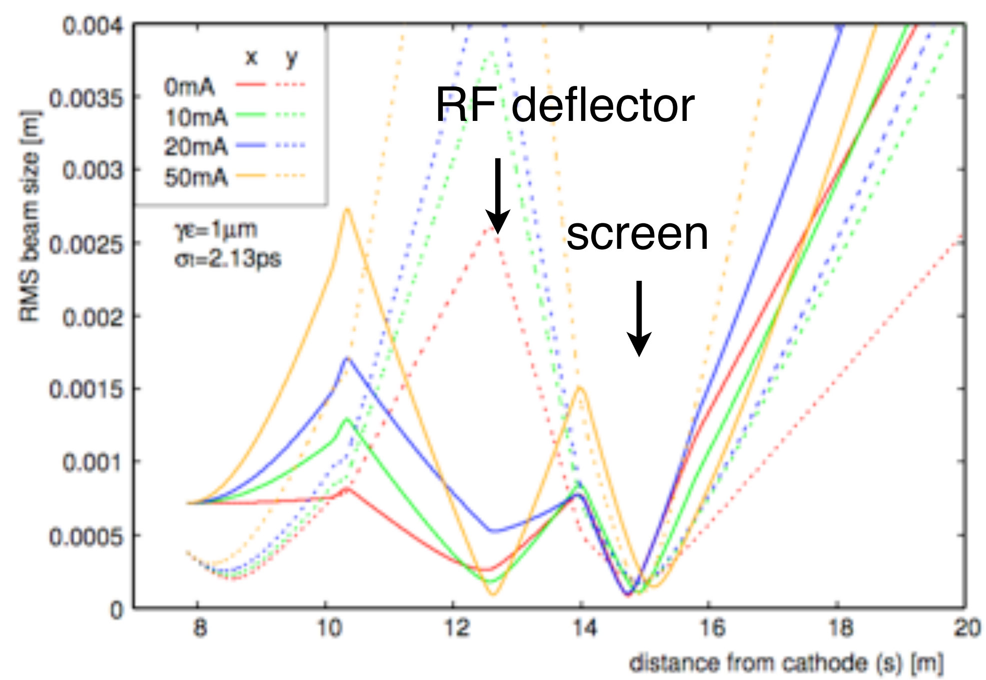
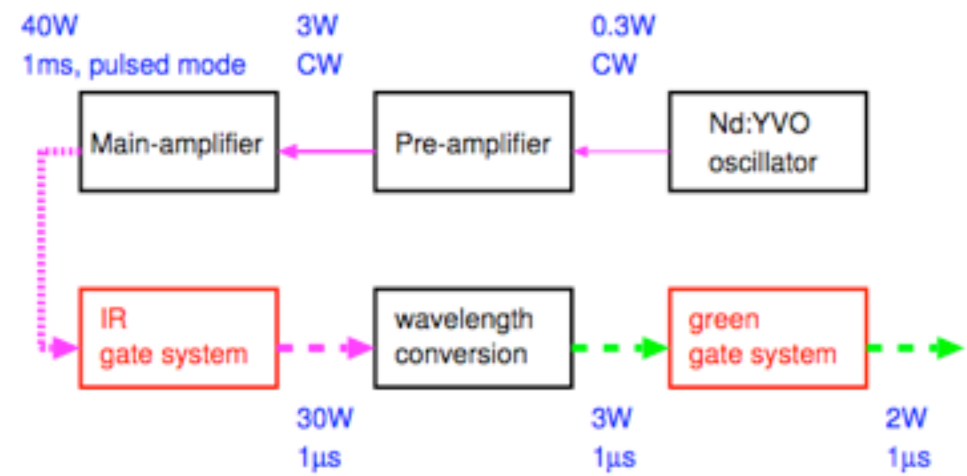
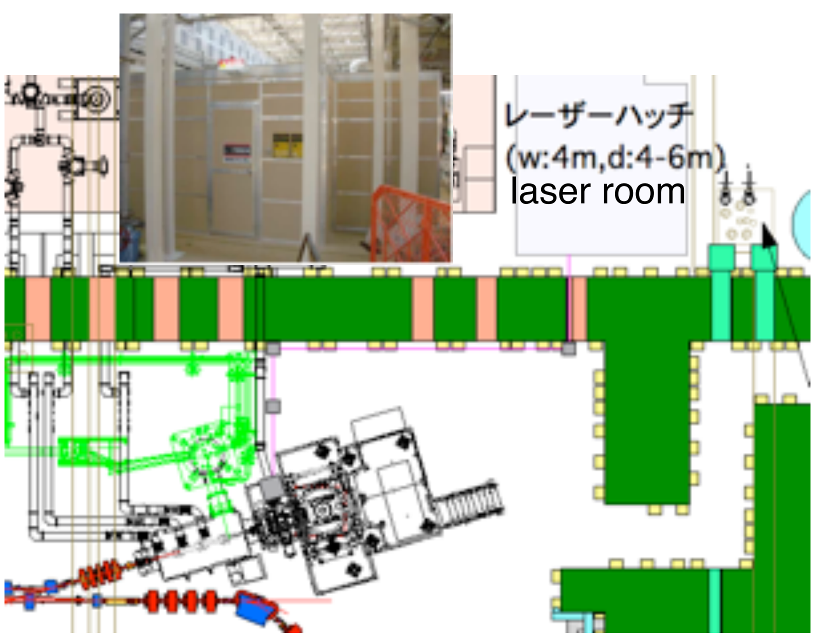


Photo-cathode laser

- Accelerator operates CW mode, Beam structure is controlled by laser
  - CW mode (1.3GHz continuous)
  - macro-pulse mode (for beam tuning)
- Laser specification
  - wavelength 532nm (<800nm for GaAs cathode)
  - 1.5W on cathode (assuming 1% Q.E.) for 10mA
  - pulse-width 16ps (2ps x 8stack)
- Laser system (efficiency is the key for high power)
  - Fiber based amplifier (efficiency)
  - cavity based SHG (efficiency)





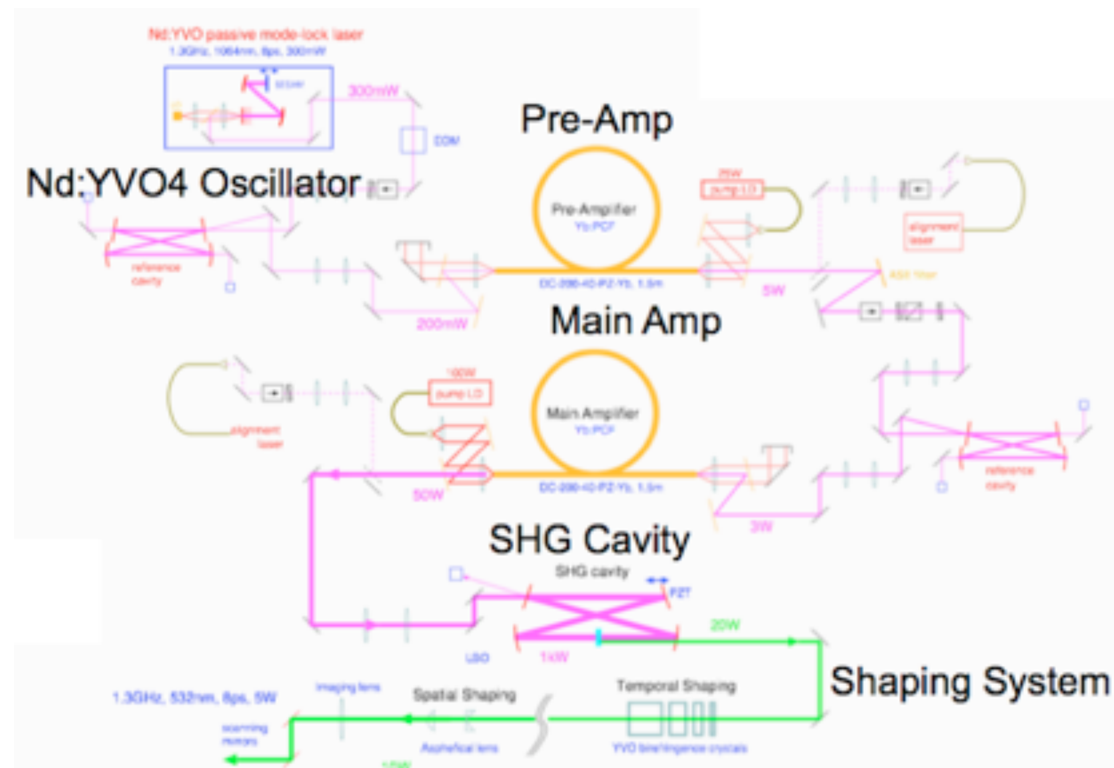
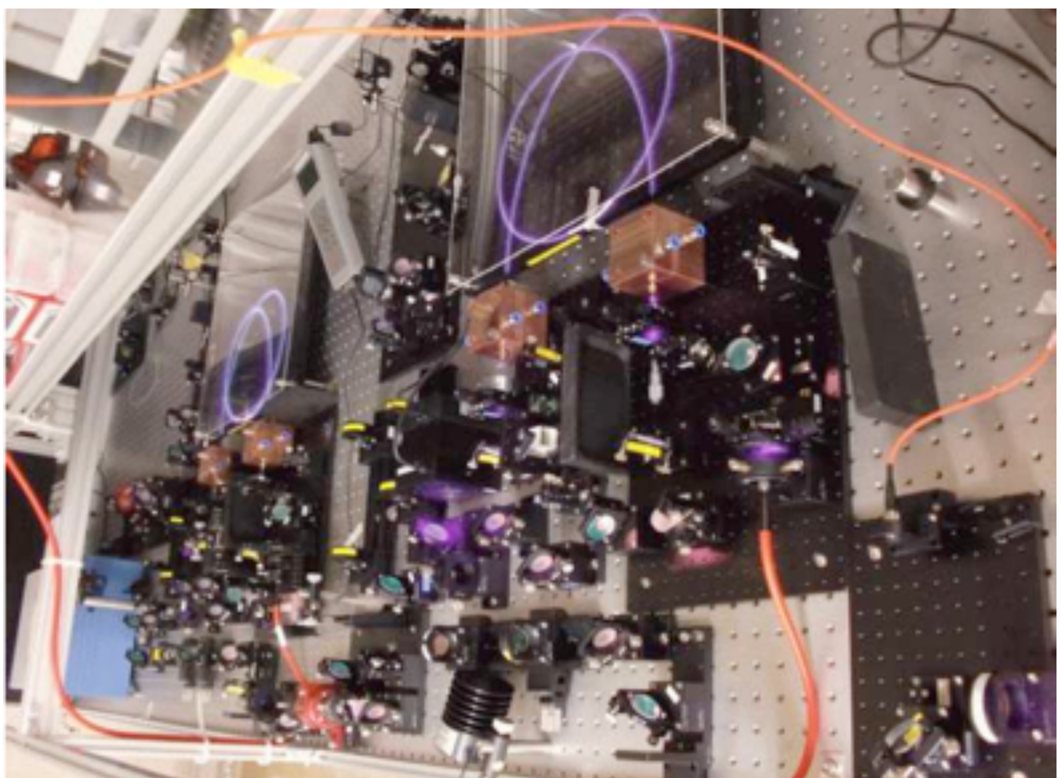
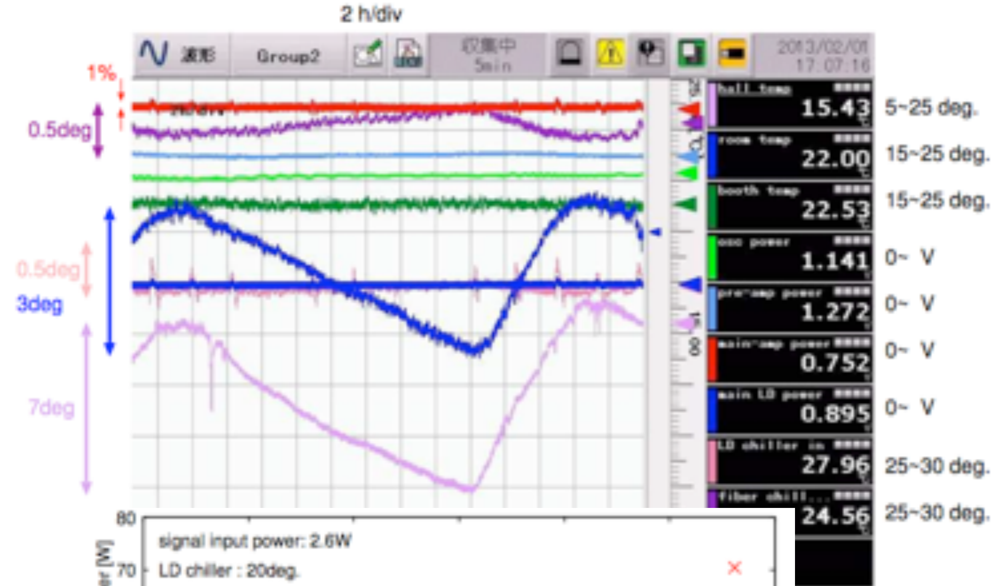
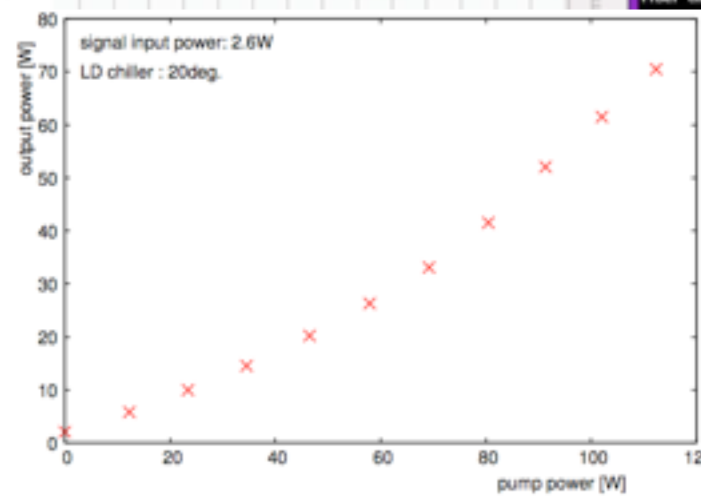


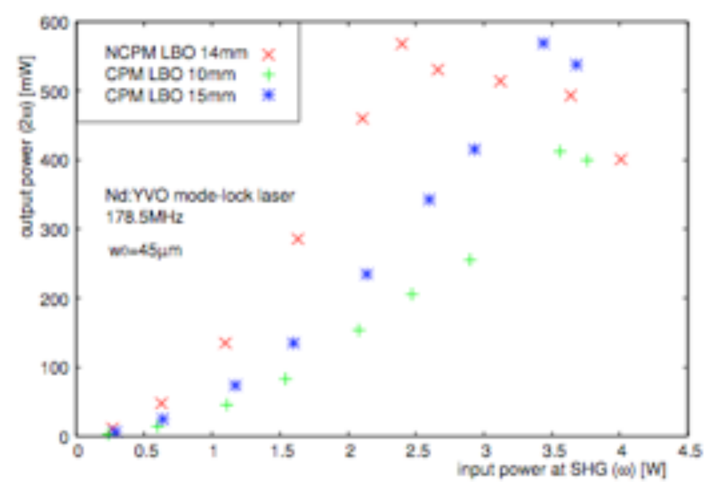
Photo-cathode laser

- Amplifier (1064nm)
  - 70W at two stage
  - power stability tested at 40W 1% stability for week
- Wavelength conversion (532nm)
  - bench tested, 20% efficiency
  - final setting-up, to be done soon
- Many things to do before operation
  - synchronization to acc. reference
  - transport and interlock (machine protection) system
  - control for beam operation



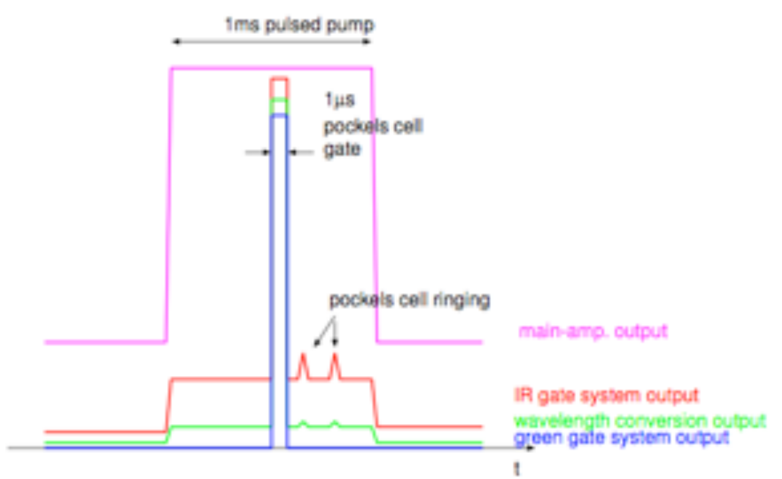


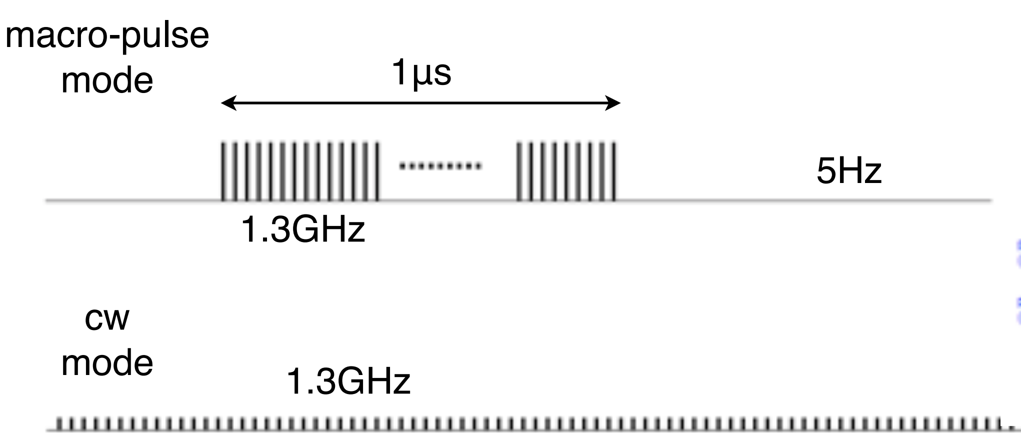


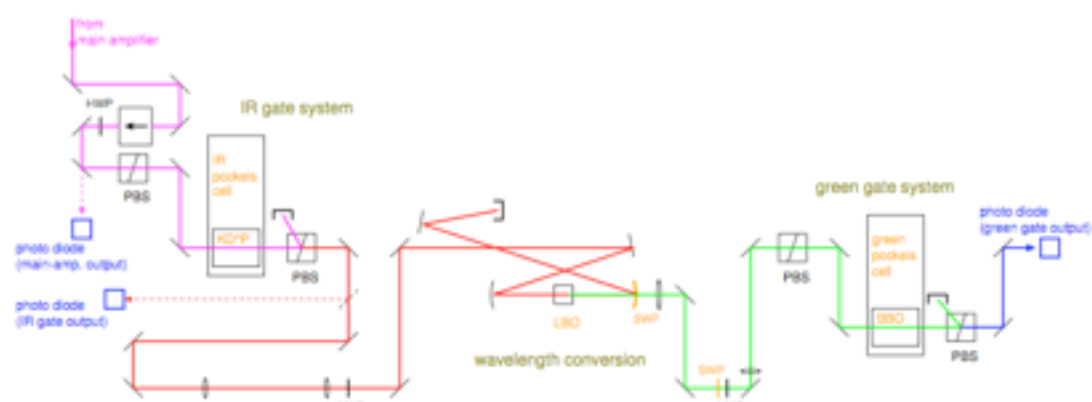


Operational mode

- Beam power specification (determined by radiation shield and bean control skill)
  - Target: 35MeV, 10mA
  - Initial specification: 6MeV, 1μA for diagnostic line
  - Next step: 35MeV, ??mA (to be decided after we experienced first beam)
- Beam tuning operation mode is necessary
  - need destructive beam measurement
  - same bunch charge as nominal but limited pulse number
  - no transient effect in accelerator system (loading negligible)
- Planned beam structure
  - 1.3GHz, 1μs (1300 bunch), 0~10mA, ~5Hz typical
  - 1μA continuous mode will be prepared(, but not much to do)
- Extinction ratio is important for macro-pulse mode (10^-9)

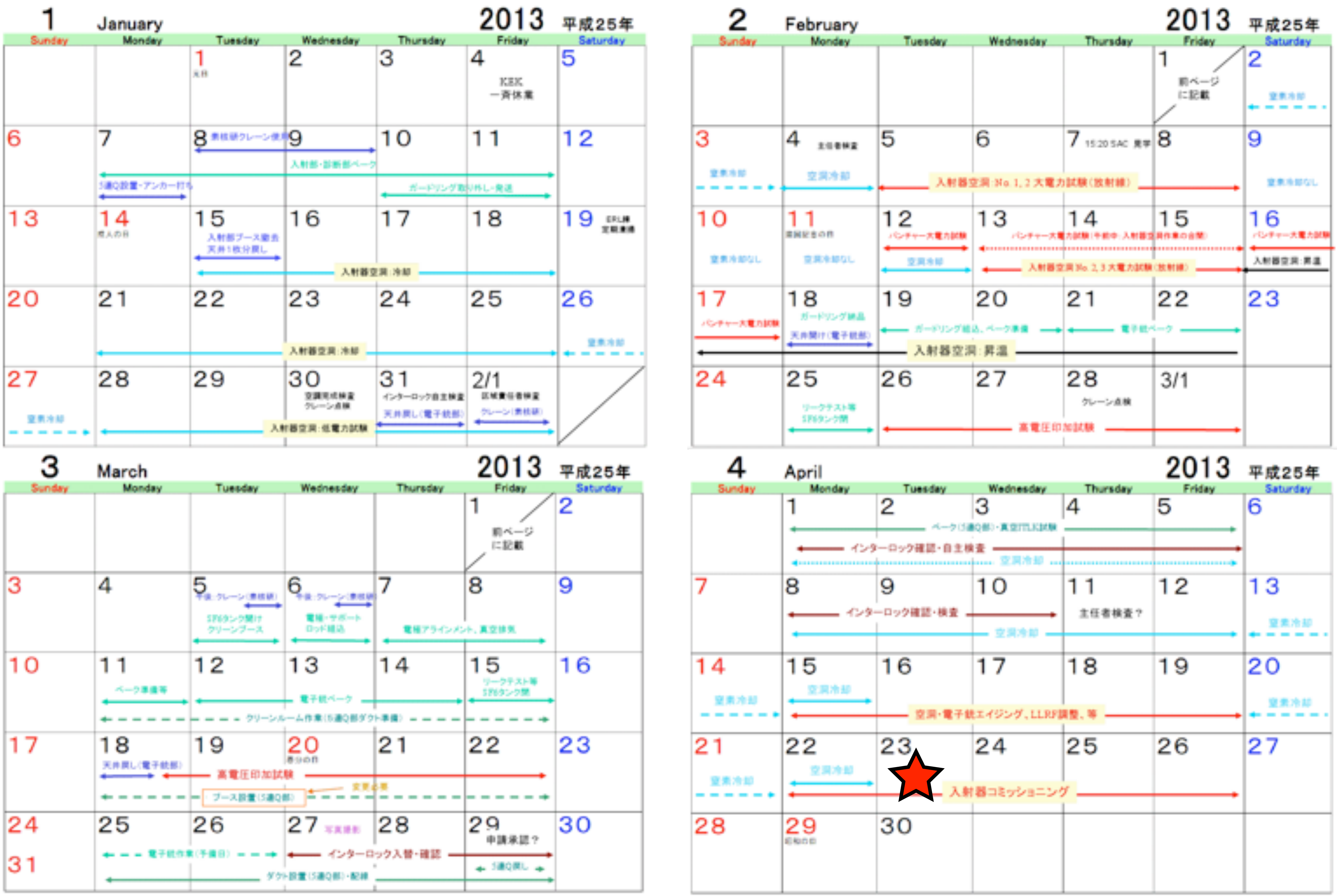






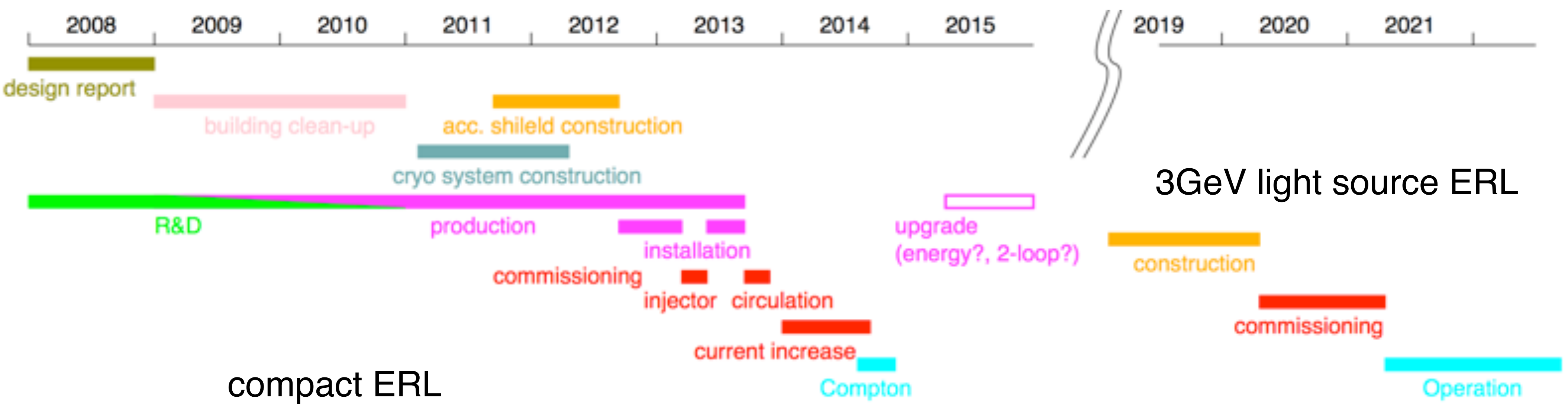
Working schedule

- Complicated working time sharing between groups…



Schedule

- At present, very busy time for preparing first beam.
- Commissioning is planned in two stages
  - first, injector (5MeV) and diagnostic line
  - after construction of loop in the summer, try circulation. but still at low current
  - beam loss and radiation may limit the allowed beam current
- First beam will be end of April 2013.
- 3GeV operation will be from 2021.



Thank you