European Workshop on Photocathodes for particle Accelerator Applications/EWPAA2017

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THE SEMICONDUCTOR PHOTOCATHODE FOR THE KEK SRF-GUN

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KEK

OUTLINE

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2. PHOTOCATHODE PROPERTIES
3. CAVITY DESIGN AND VERTICAL TESTS
    1. DUMMY CATHODE PLUG
    2. CATHODE PLUG
4. PLAN OF THE KEK SRF GUN #2
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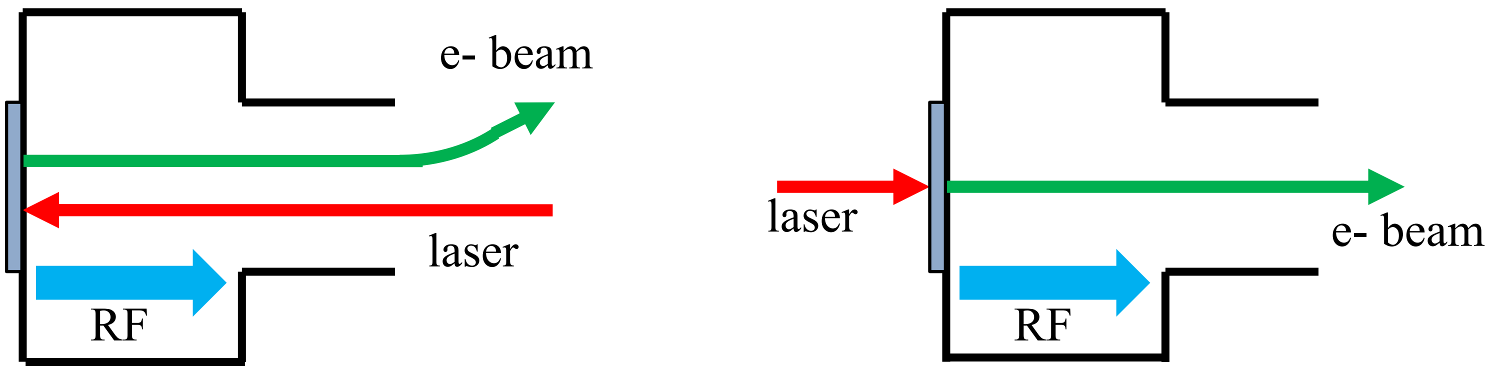
CONCEPT OF THE KEK SRF GUN

- KEK started SRF gun development from 2013 for future linac base accelerator.
- Feature of the KEK SRF gun is back side excitation type.
- Merits of the back side excitation:
  - Simple beam line structure.
  - Laser control could be more precisely because of the short focal length.
- Difficulty of the back side excitation photocathode development
  - Photocathode, transparent substrate and cathode plug need to withstand RF high voltage.

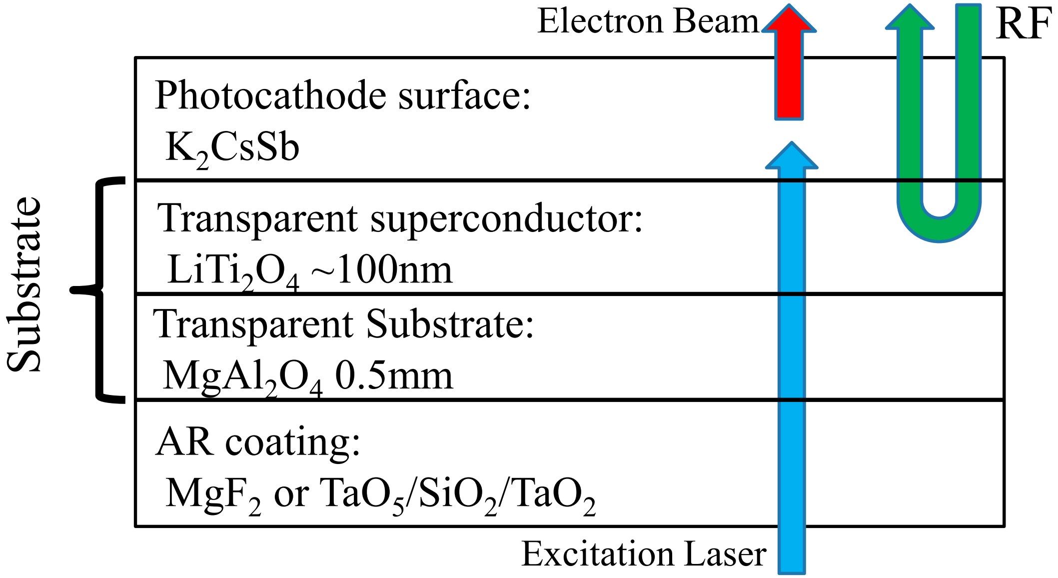
Front side excitation

Back side excitation

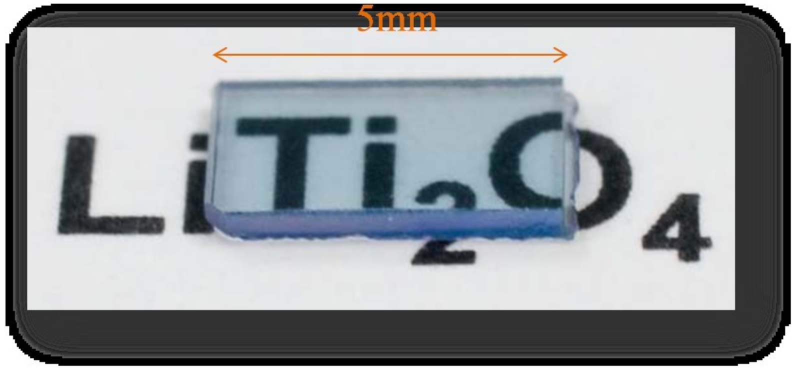


CONCEPT OF THE KEK PHOTOCATHODE

- There are 4 layers in the photocathode.
  1. Photocathode surface is K_2CsSb.
  2. The transparent superconductor $LiTi_2O_4$ can block the RF leakage and transmit the excitation laser.
  3. $MgAl_2O_4$ is the substrate for epitaxial growth of $LiTi_2O_4$.
  4. AR coating is a option for increasing laser efficiency.
- The photocathode performances were evaluated before by quantum efficiency, initial emittance and critical DC magnetic field.



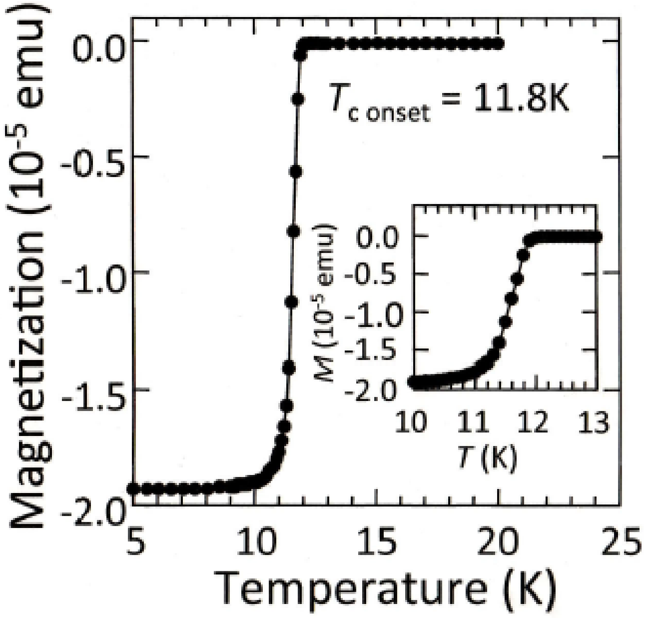
Photocathode substrate
($LiTi_2O_4$/ $MgAl_2O_4$)



PROPERTY OF THE PHOTOCATHODE SUBSTRATE

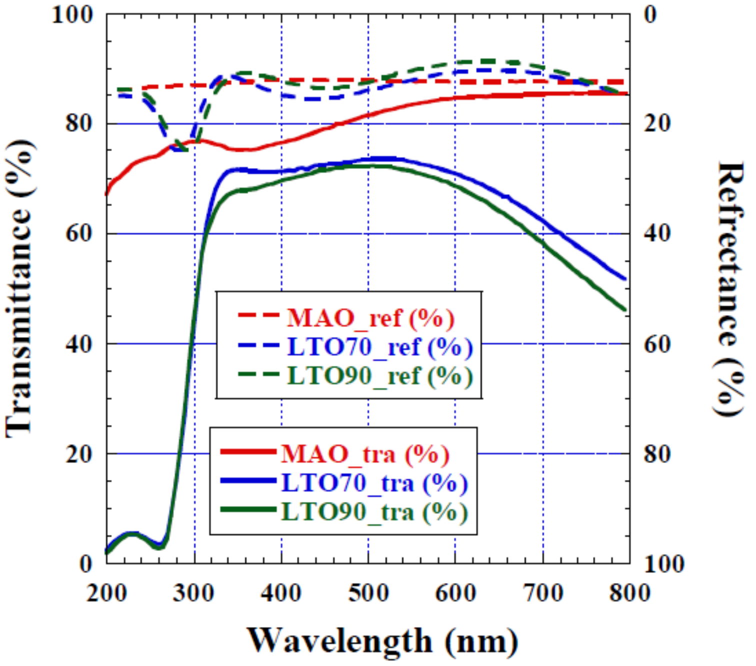
- Transition temperature is 11~13 K.
- Transmittance is 75 % at 530 nm.
  - Gap between transmittance and reflectance is absorption. Absorption is about 10 %.
  - There is not big difference between $LiTi_2O_4$ film thickness 70 nm and 90 nm.
    - The film thickness of LTO will be changed by prioritizing RF penetration depth.

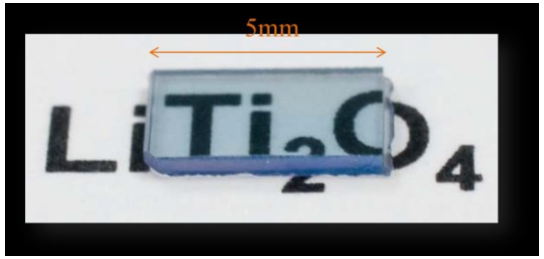
Transition temperature



Kumatani et al., APL 101,123103 (2012

Transmittance & Reflectance

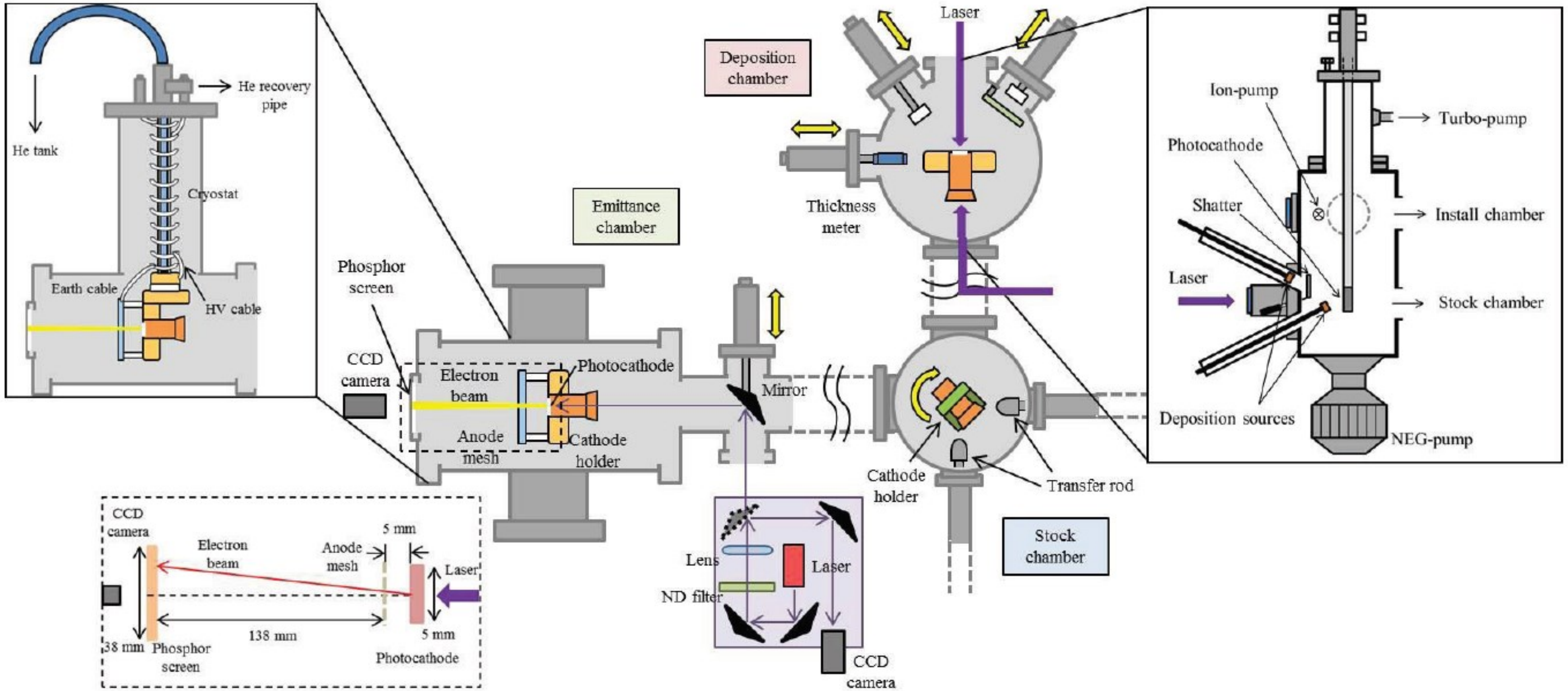


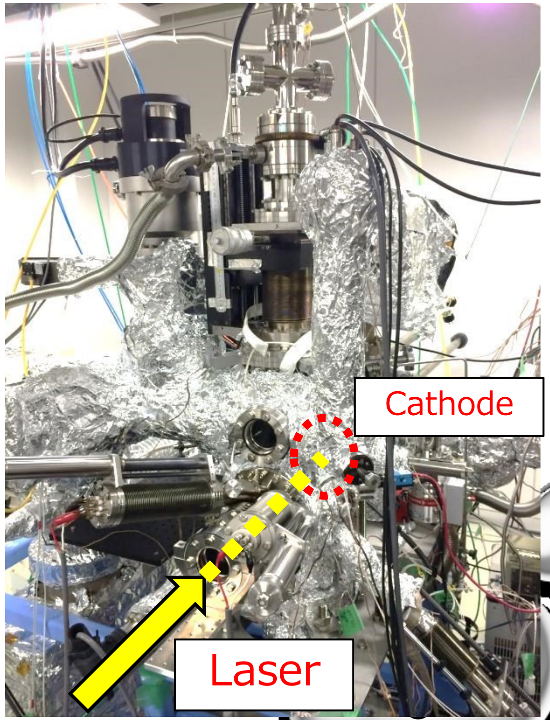


Parameter	Value
Tc mid	13.3 K
Resistivity	$3.3 \times 10^{-4}\ \Omega\mathrm{cm}$ (at R.T.)
Lattice constant	$a_{LTO} = 0.8405$ nm
Transmittance	75 % (at 530 nm)
Carrier density	$1.1 \times 10^{22}\ cm^{-3}$
Hall mobility	0.8 (280K), 6.0 (15K) $cm^2V^{-1}S^{-1}$

PREVIOUS PHOTOCATHODE EVALUATION CHAMBERS

- Now these chambers are disassembled to assemble KEK SRF gun #2.
- **Quantum efficiency**: QE was measured at deposition chamber. Xenon lamp were used to measure QE spectrum. Excitation light can be inject from back and front. Transmittance can be measured.
- **Initial emittance**: The photocathode can be cooled down to 6.7 K.
- **Critical magnetic field**: The photocathode was taken out from chamber and measured by SQUID MPMS7 (Quantum Design, Inc.)

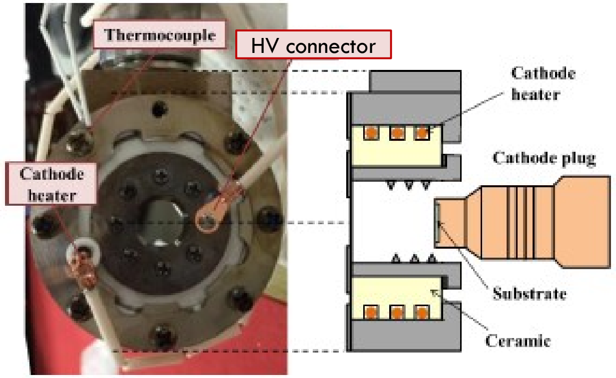


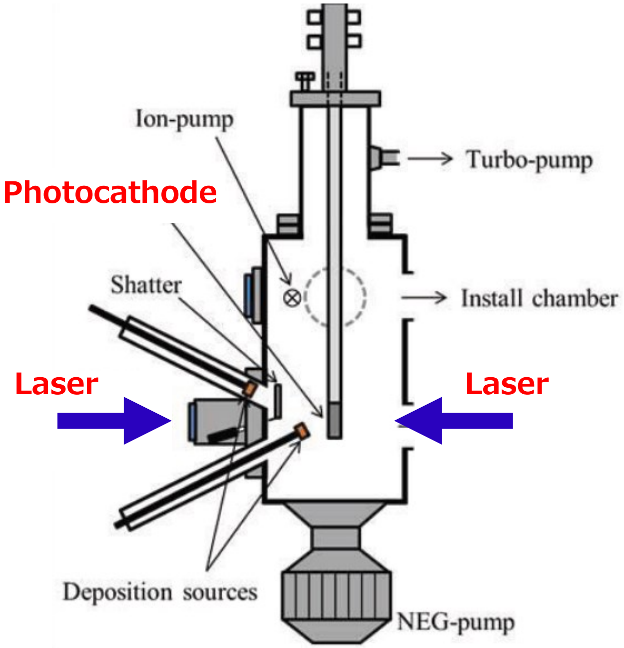


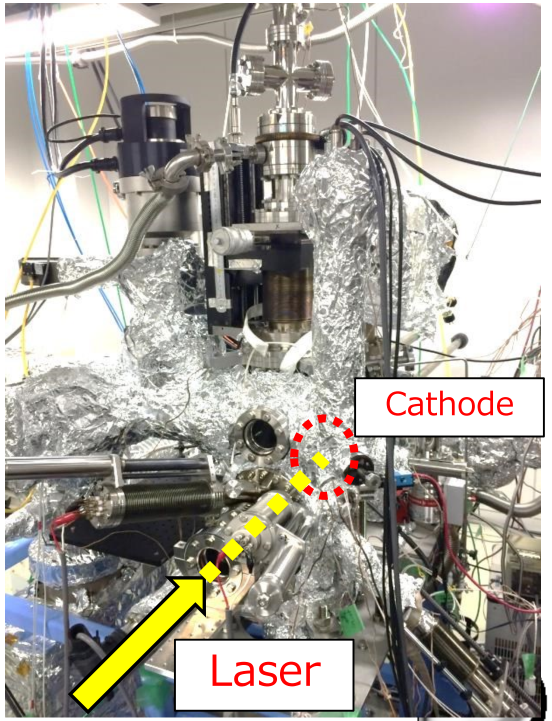
PHOTOCATHODE DEPOSITION CONDITION

- The photocathode deposition chamber has cesium (SAES), potassium (SAES) and bulk antimony evaporation sources.
- Laser and xenon lamp can inject from front and back side of the photocathode.
- Base pressure is 1×10^{-8} Pa.
- The chamber vacuum is $6 \times 10^{-8} \sim 1 \times 10^{-7}$ Pa during the deposition.

Procedure	Condition
Heat cleaning	~500 ^{o}C × 3 hours
Sb deposition	150^{o}C , Thickness 10nm (Transmittance decrease 20-30%)
K deposition	~120 ^{o}C, QE peak
Cs deposition	100 ^{o}C, QE peak



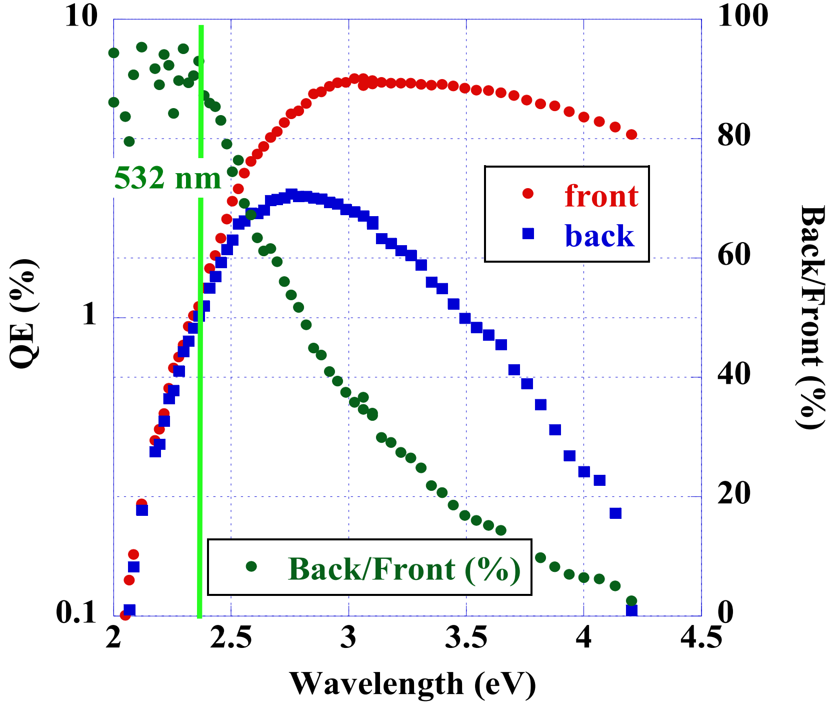




QUANTUM EFFICIENCY

- The threshold energy is 1.85±0.15eV. This is same value as other studies.
  ⇒ K_2CsSb deposition on the transparent superconductor was successful.
- The ratio of back and front side QE can't be explain by the transmittance of LTO.
  ⇒ We suspect Sb rich layer exists on the boundary.
- But It is not a problem for gun operation because we will use 532nm laser.
  - At 532nm, back side QE is 90% of the front side.

QE of the photocathode



Transmittance of the substrate

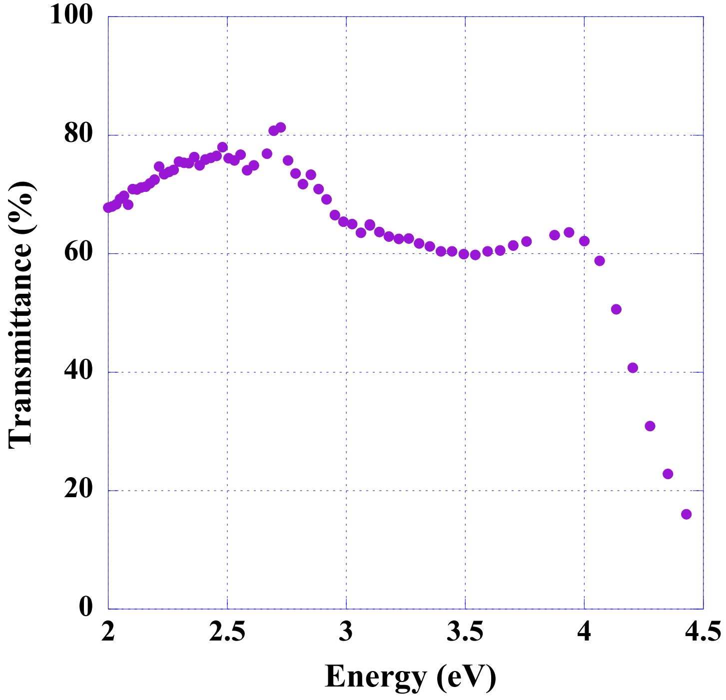
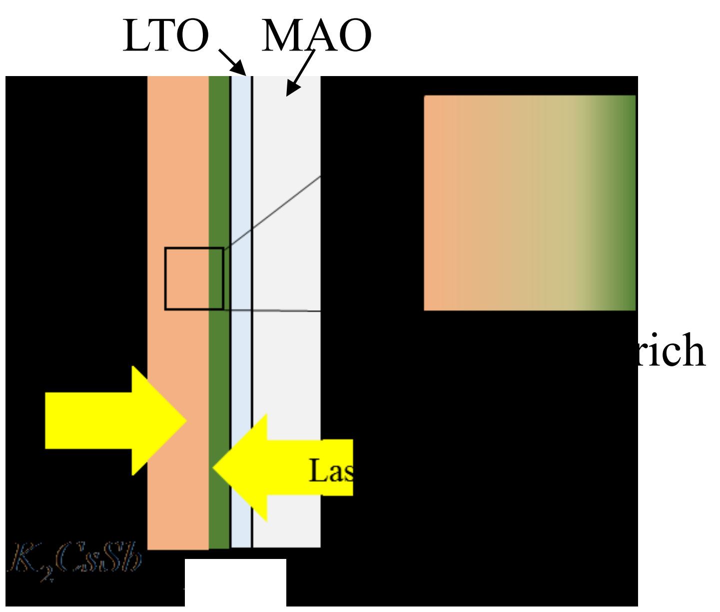
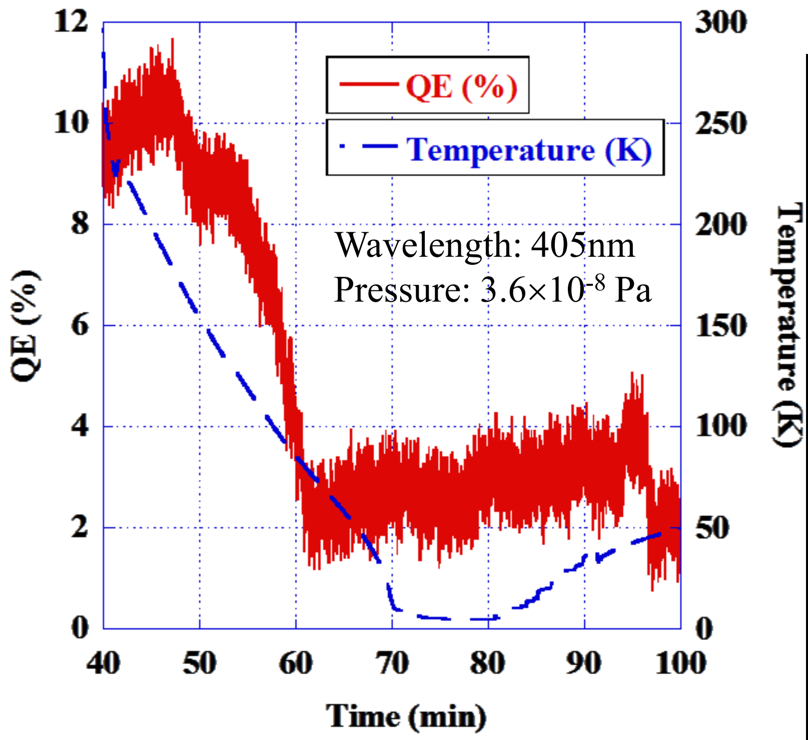


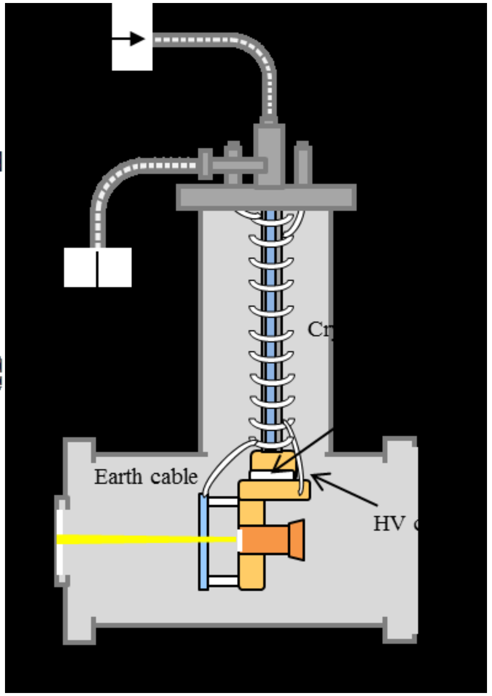
Image of the photocathode boundary

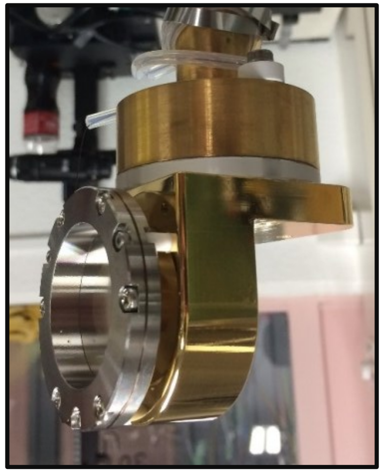


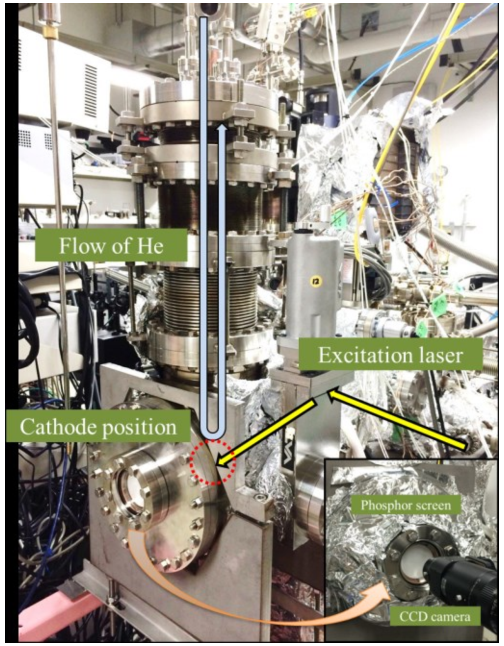
QE DEGRADATION AT LOW TEMPERATURE

- We transferred the photocathode to initial emittance measurement chamber which has a LHe small cryostat.
- QE was decreased during cooling.
  - We suspect residual gas was absorbed on the photocathode surface and increase the surface work function.
- Further study of photocathode performance at cryogenic temperatures and ways to improve this performance is essential for the photocathode development.





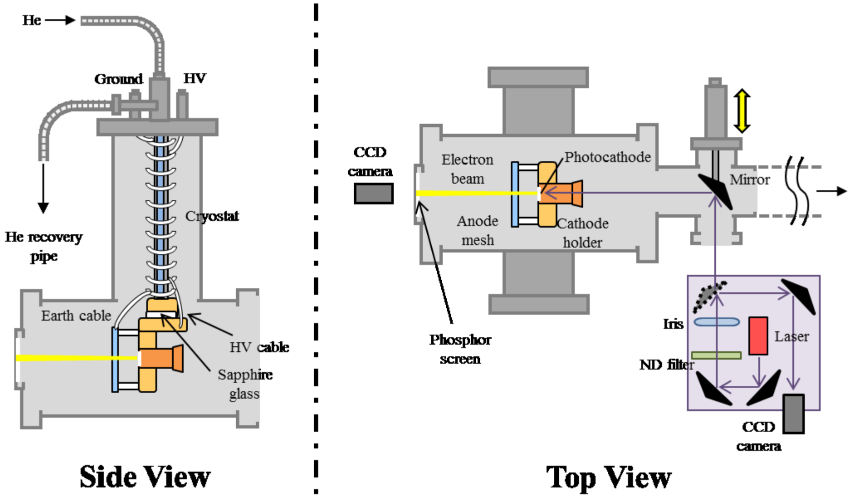


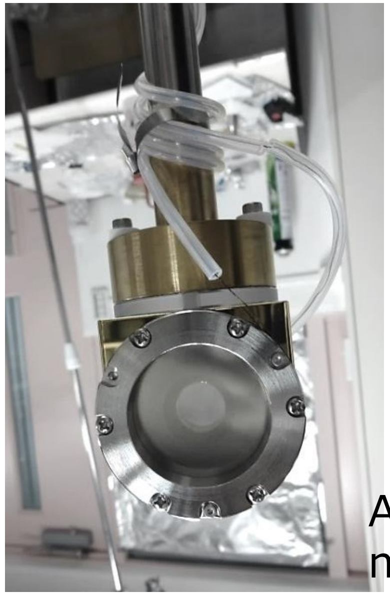


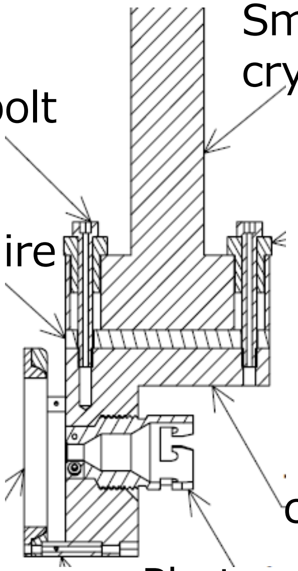
Initial emittance

- Initial emittance was calculated by measuring the expansion of beam size.
- Parallel plate DC gun consists of thin anode mesh and cathode block.
- Laser was inject from backside of the photocathode. laser spot side is Φ~0.1mm

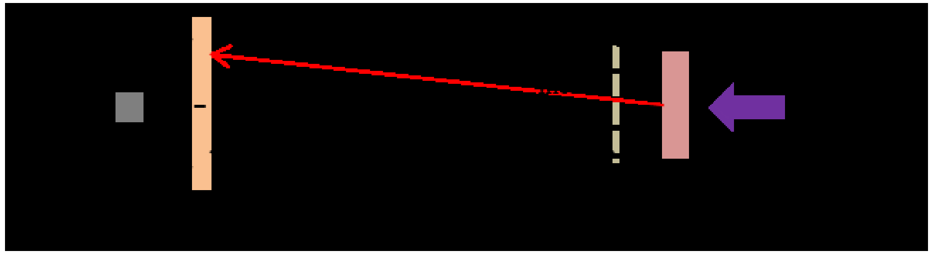
Initial emittance chamber scheme







Initial emittance measurement scheme and equation



$$\frac{\varepsilon_n}{\sigma_x} = \frac{1}{2g+d}\cdot\sqrt{\frac{2eV}{mc^2}}\cdot\langle r^2 - \sigma_x^2\rangle^{1/2}$$

Gap voltage (kV)

Beam radius

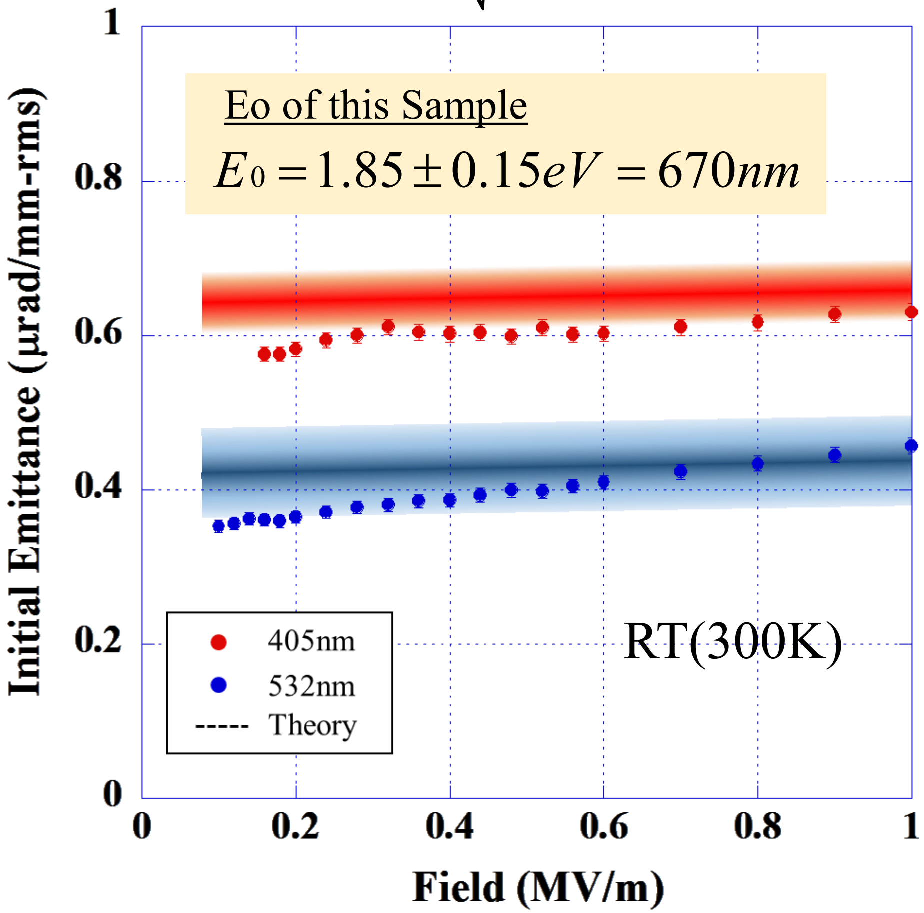
Laser radius

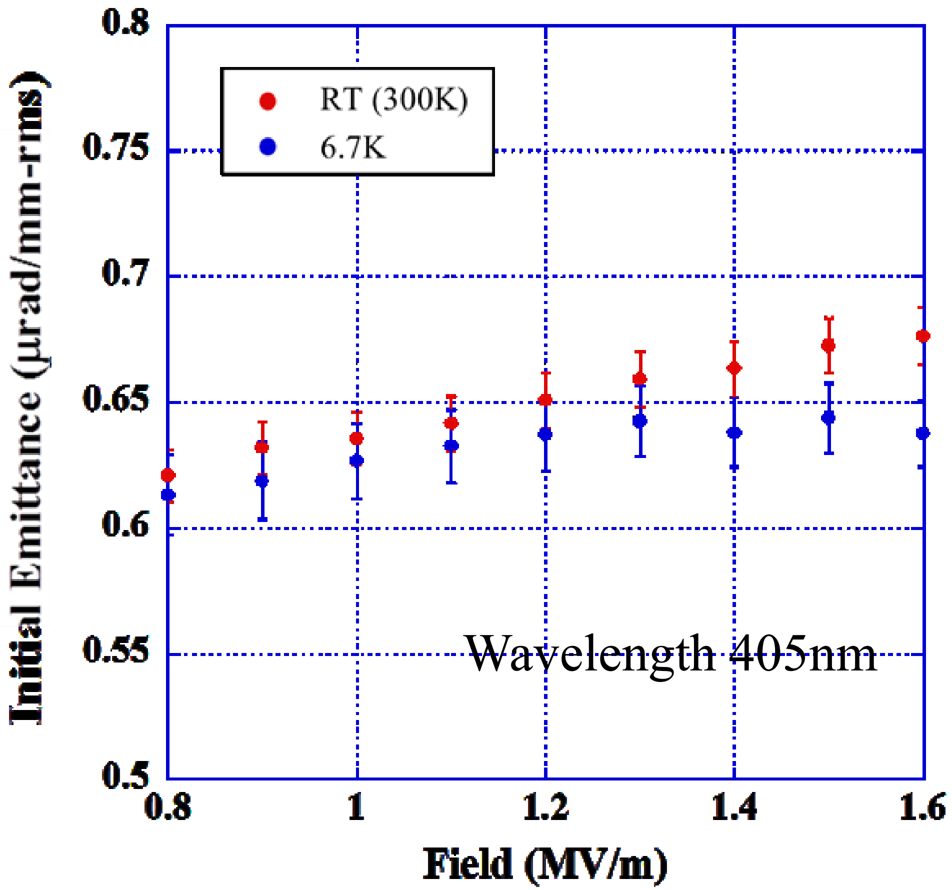
Initial emittance

- The measurement results at RT almost agree with theory.
- Initial emittance should be constant regardless of the electric field
    - The measured data is rising along with electric field.
    - We suspect anode was bended with electric field, because it is 20 μm thin film.

Theory: $\varepsilon_n = \frac{R}{2}\sqrt{\frac{2(\hbar\omega - E_0 + \phi_{sch})}{3mc^2} + \frac{2k_BT}{mc^2}}$

Shottky effect: $\phi_{sch} = \sqrt{\frac{eV}{4\pi\varepsilon_0}}$





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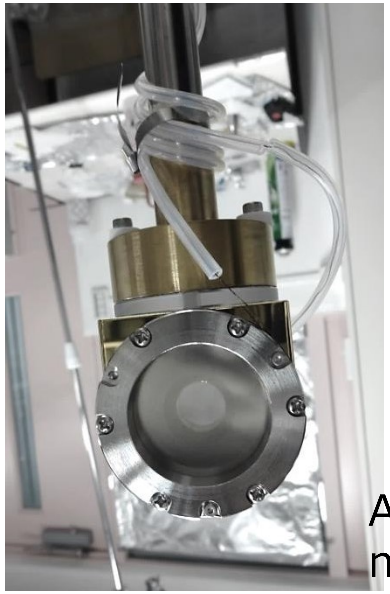
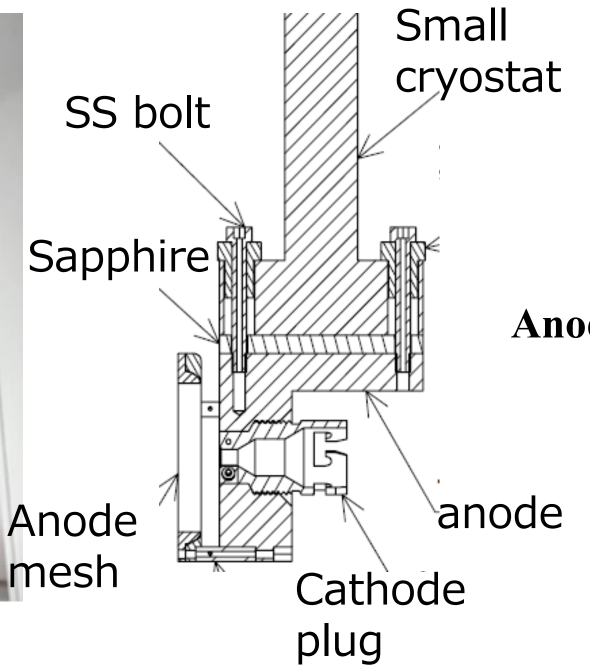
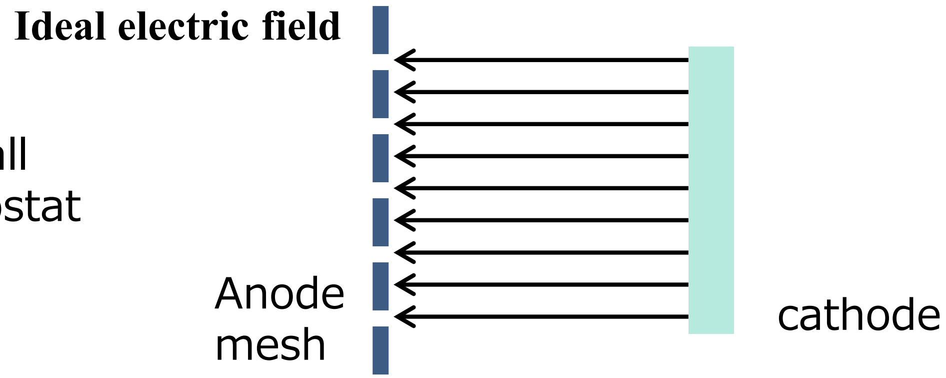
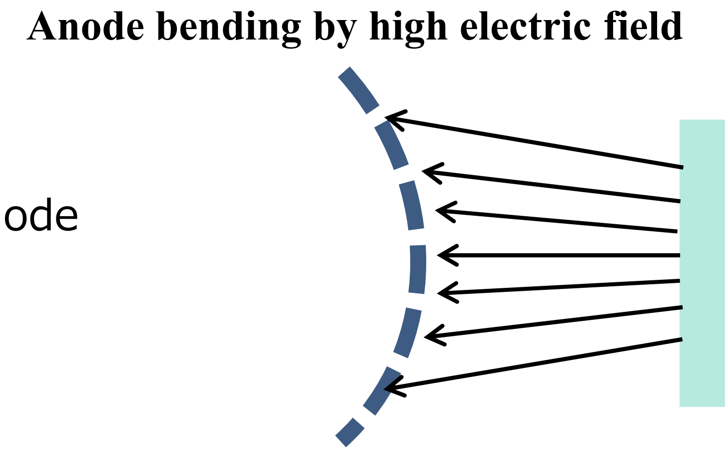








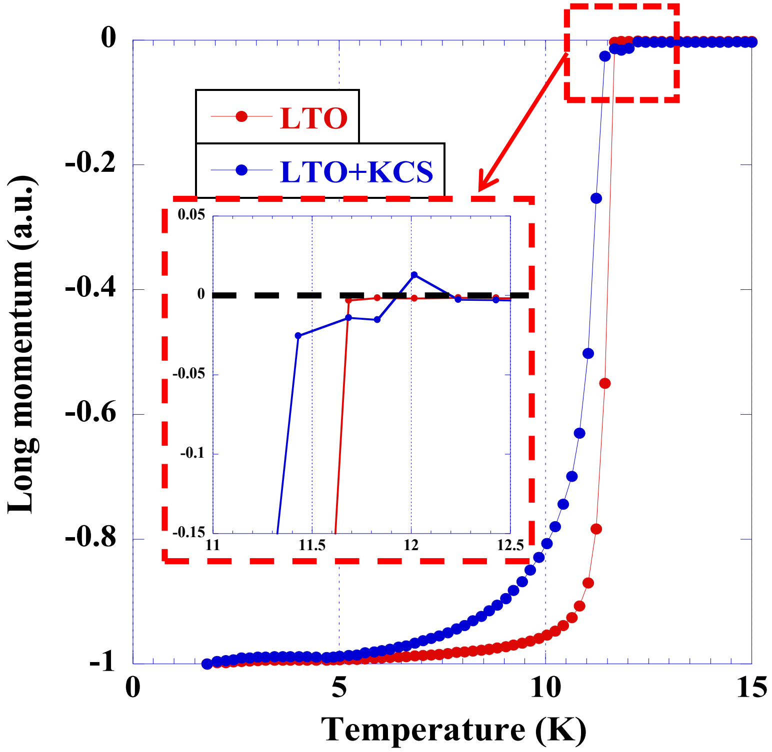
Divergence electric field is created

SUPERCONDUCTING PROPERTY OF THE PHOTOCATHODE

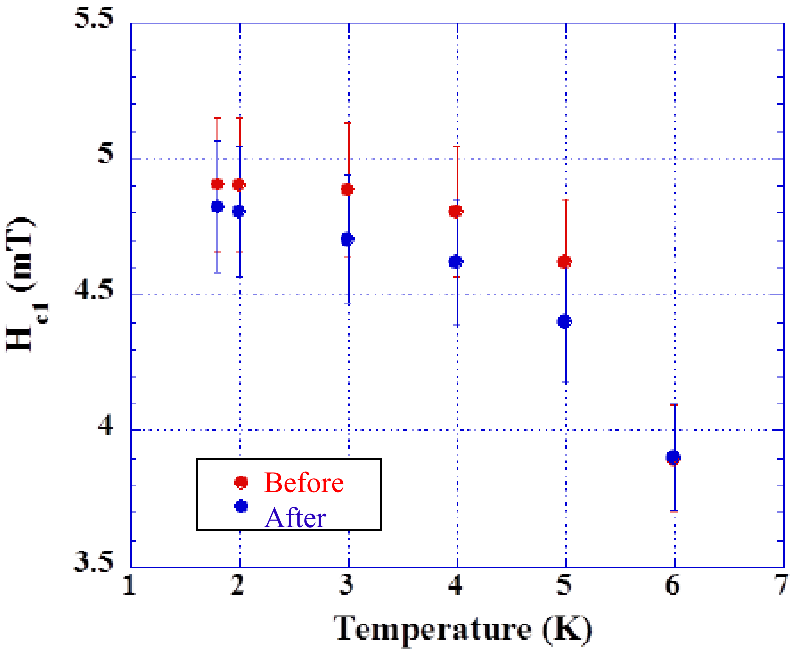
- The critical temperature and critical magnetic field were not changed before and after K_2CsSb deposition.
- Critical magnetic field is higher than the SRF gun operation.

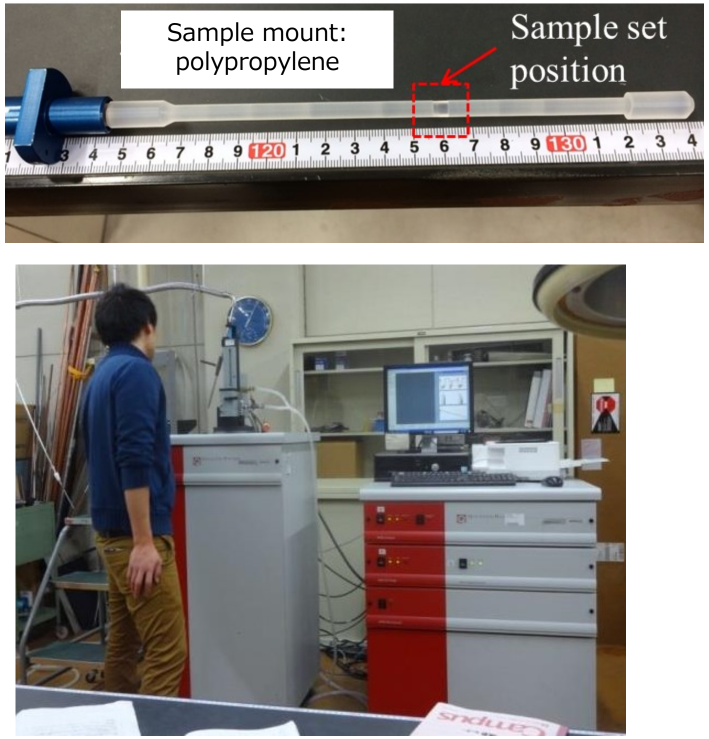
$T_c^{before\ deposition} = 11.7 \pm 0.1\ K$

$T_c^{after\ deposition} = 11.4 \pm 0.2\ K$



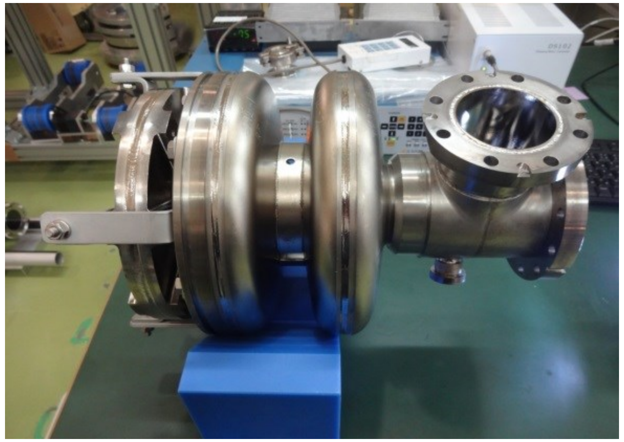
Target RF magnetic field is 3.3mT

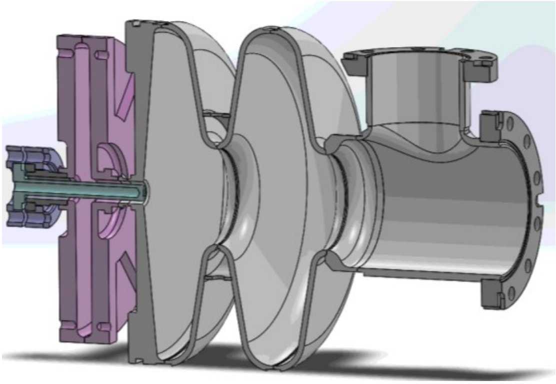


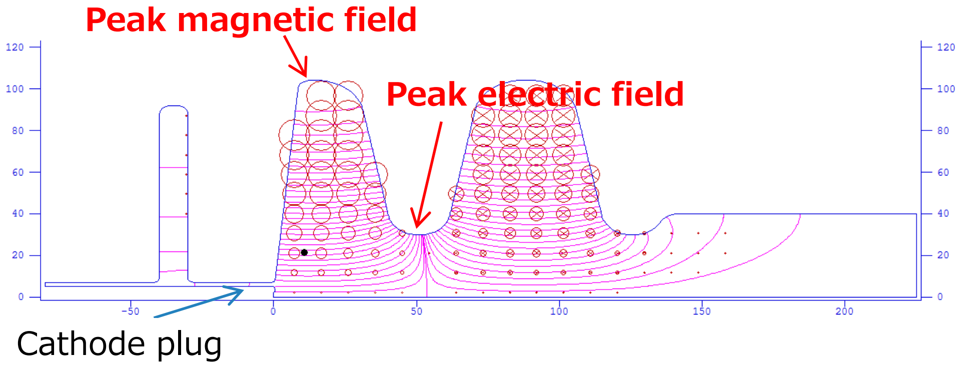


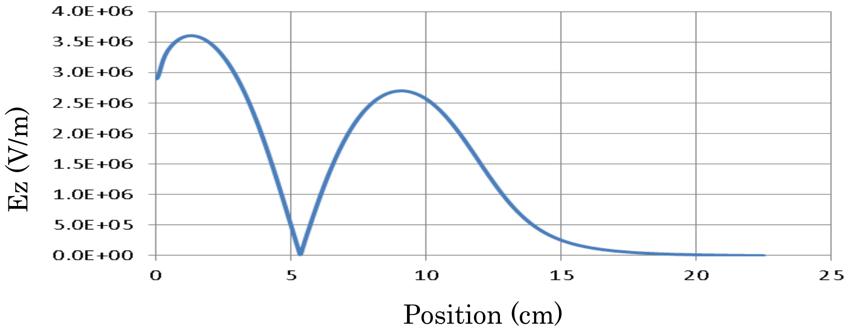
KEK SRF GUN #1

- KEK SRF gun #1 was designed to check basic RF parameters (maximum Esp, Qo).
  - 3 GeV KEK- ERL was selected as the target parameters.
- Slope of the cavity was designed to compensate the space charge effect.





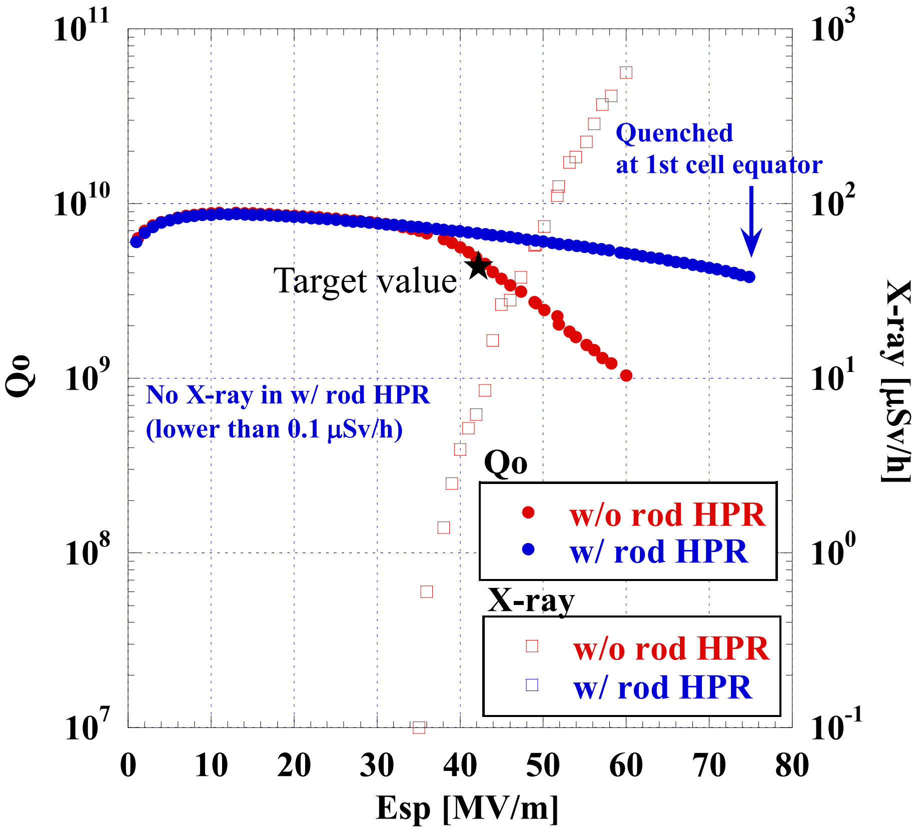


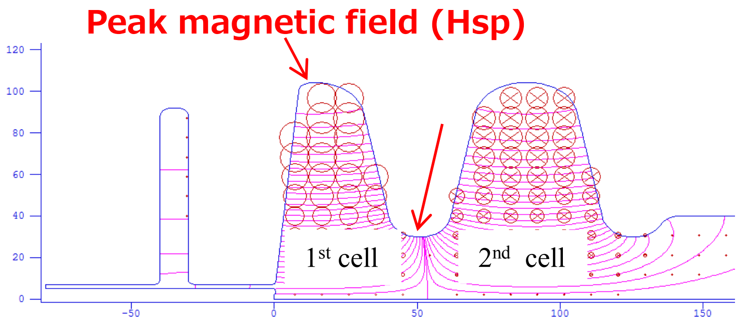


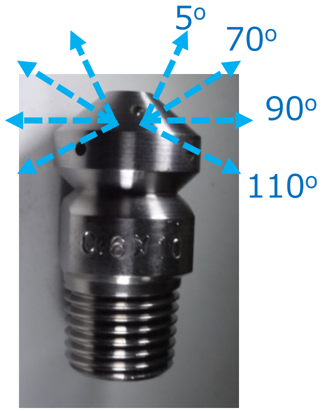
Parameter	Value
Beam energy	**2 MeV**
Bunch Charge	**77 pC**
Bunch length	**3 ps**
Projected emittance	**0.6 π mm.mrad**
Projected energy spread	**0.09%(1.84 keV)**
Peak electric field	**41.9 MV/m**
Peak magnetic field	95.2 mT
RF phase	55°
Geometrical Factor	135.6 Ω (TESLA 270 Ω)
Target surface resistance	30 nΩ (ILC target)
Target Q value	4.5×10^{9}
Target cavity loss	8 W

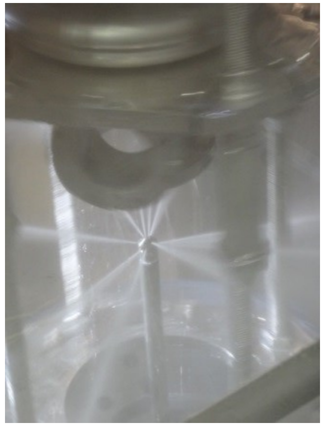
VERTICAL TESTS WITH DUMMY CATHODE PLUG

- The cathode plug cleaning is important to achieve high gradient
- After HPR, the peak surface electric field reached 75 MV/m and X-ray couldn't be observed.
- However HPR should not apply to the transparent superconductor because it is very thin and delicate.
  - We have to search other method for cleaning for example hydrogen cleaning or sputtering



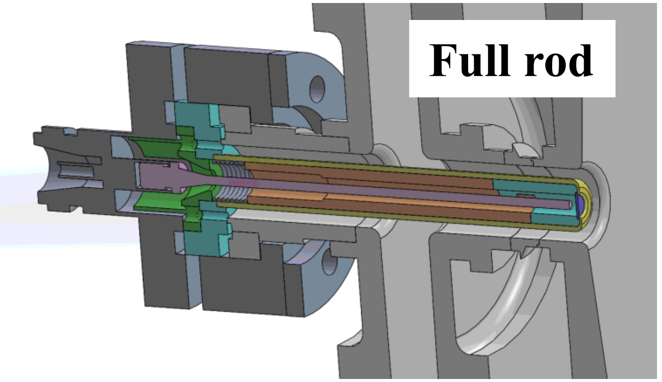


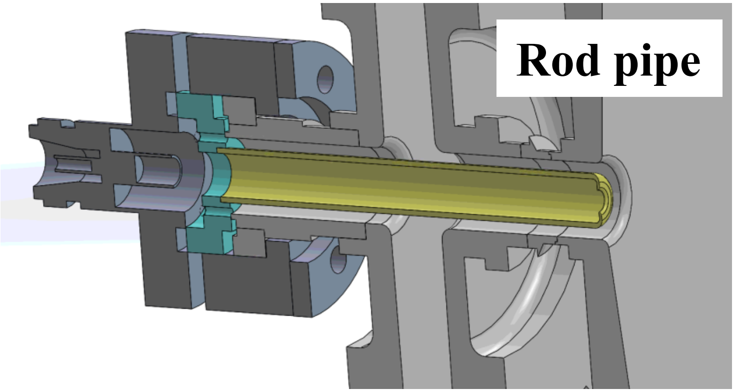


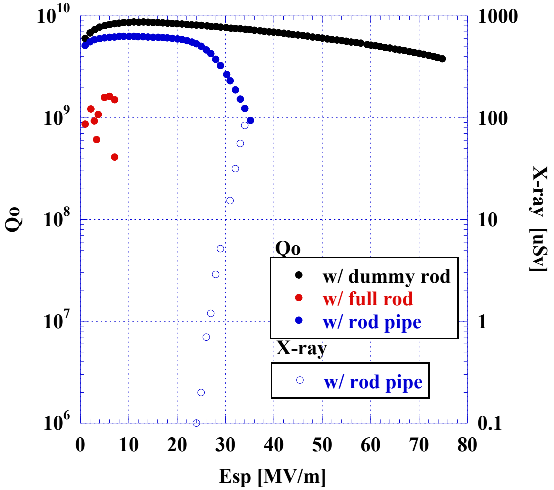


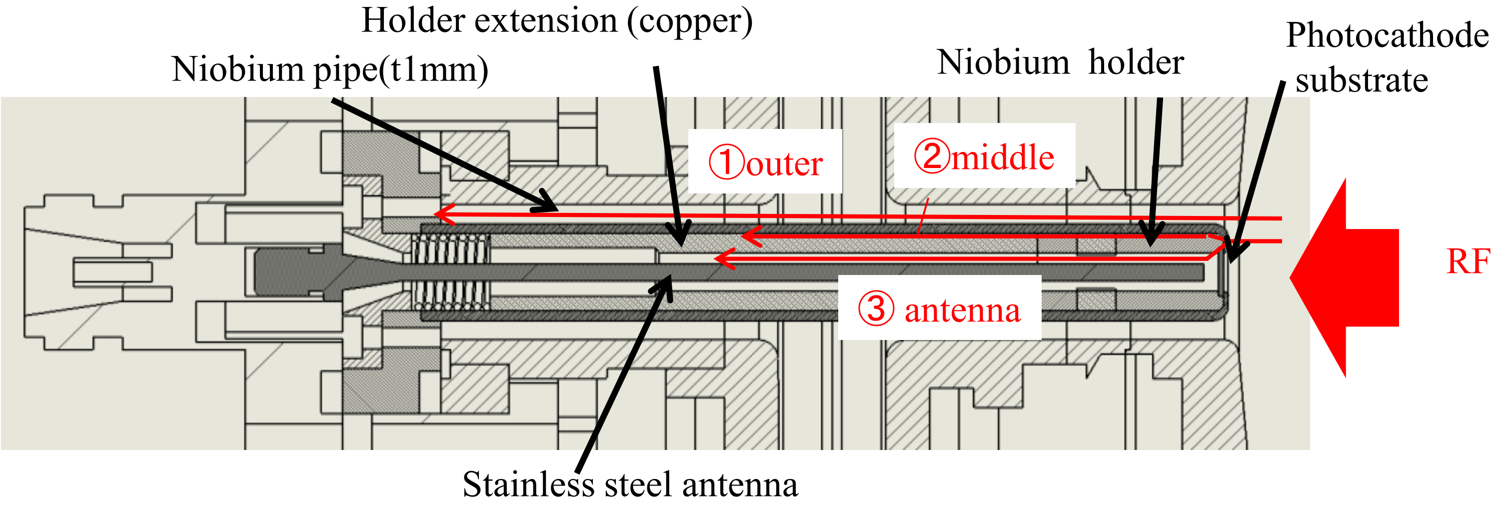
VERTICAL TESTS WITH CATHODE PLUG ASSEMBLY

- In order to test various photocathode substrate materials, new cathode rod which can mount 5mm square sample was fabricated.
- Q value of full rod was quite low. VT with rod pipe was almost same as the dummy rod.
    - We suspected RF loss at inner components (middle path).
        - RF passing through outer is reflected by choke and Q value of rod pipe.
        - Coupling of antenna was adjusted about 1E+11 at room temperature.
- We will use indium seal to protect RF leakage and enforce thermal contact. It might become a contamination source.









PLAN OF KEK SRF GUN #2

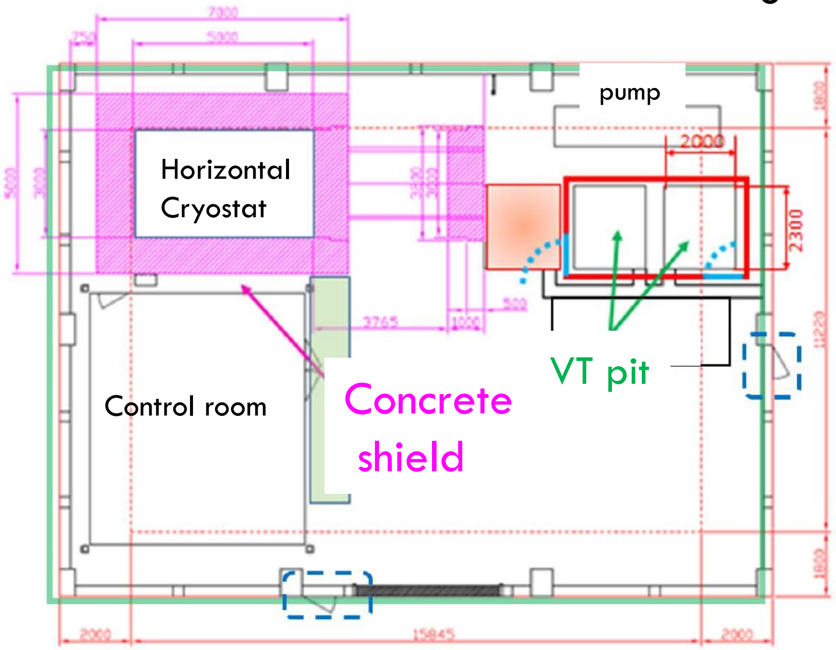
FY2017 (until 2018 March)

- Fabricate gun cavity with helium jacket and K_2CsSb photocathode deposition chamber individuality.

After FY2018

- Install cavity and cathode chamber to horizontal cryostat test area at KEK-ARE2

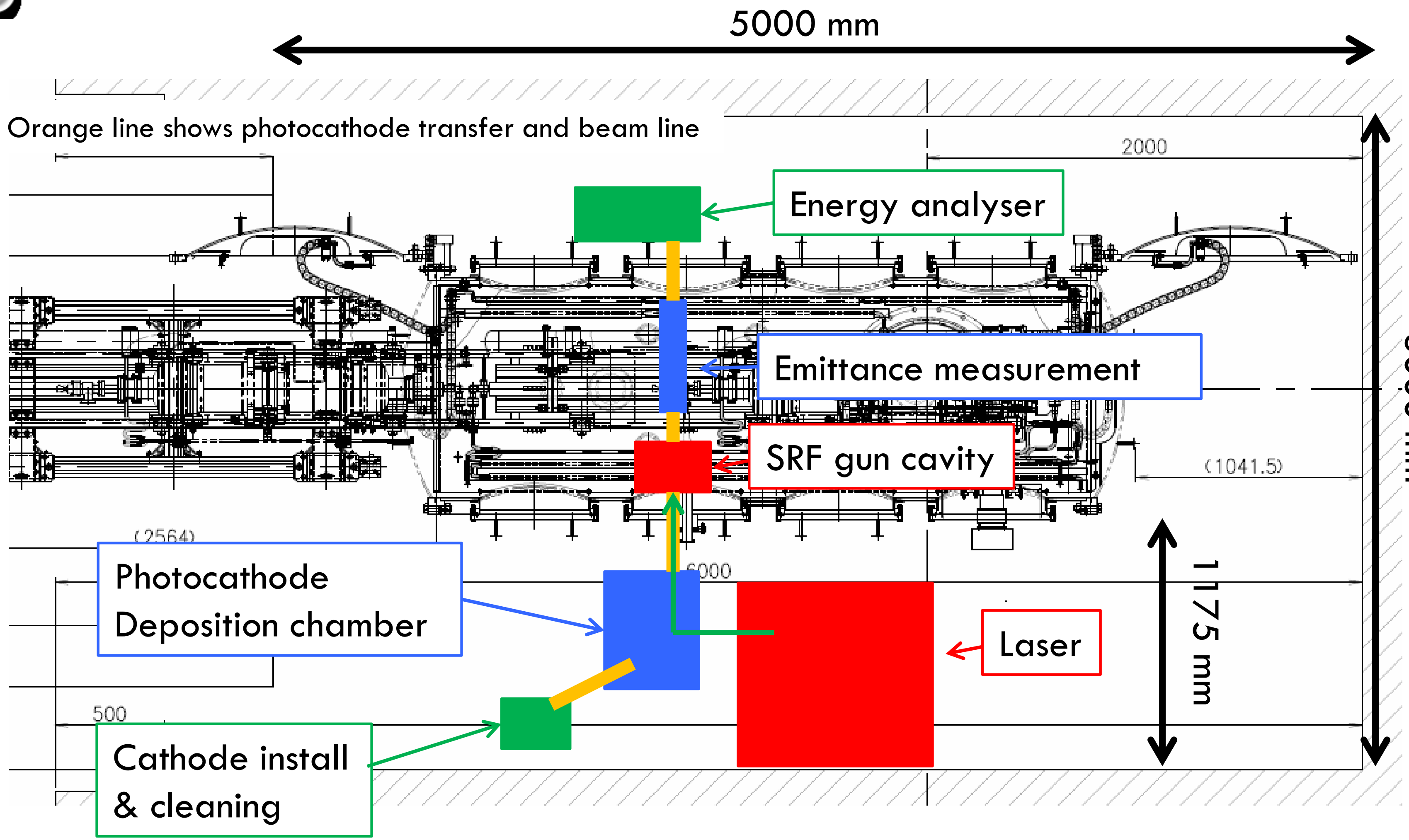
KEK-AR-East2 – 2nd SRF test building

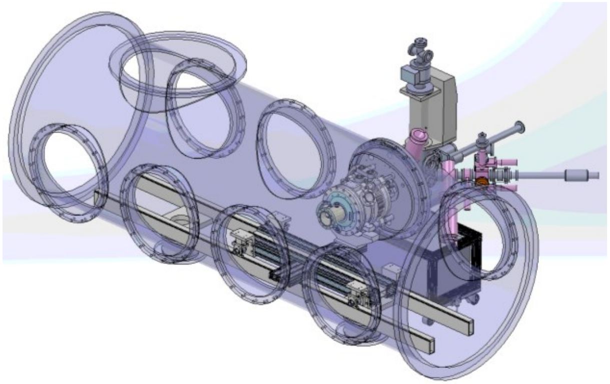


Horizontal Cryostat

LAYOUT OF KEK SRF GUN #2

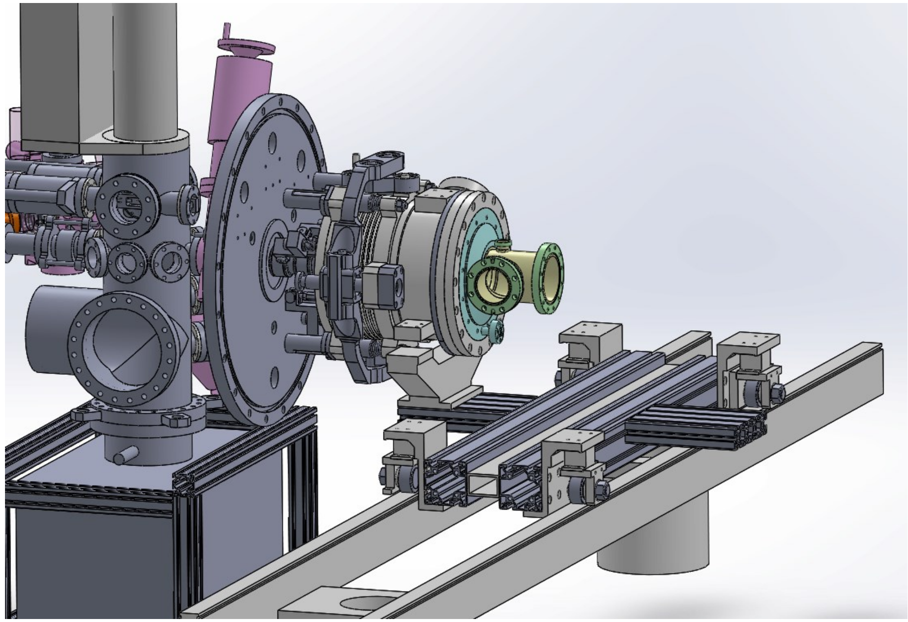
- Photocathode deposition chamber need to rebuild because the space is narrow.
- Gun cavity will be fabricate in house. Helium vessel will be fabricate in small factory.

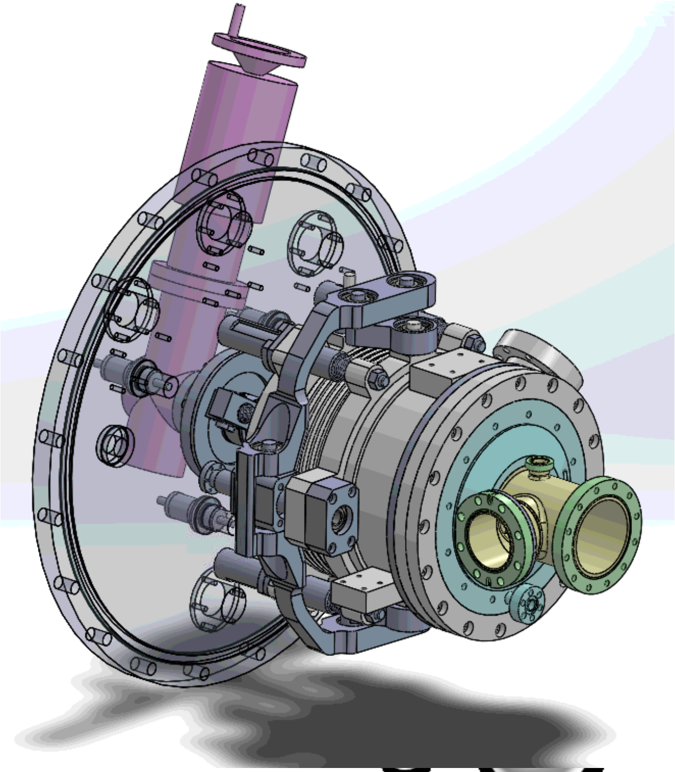


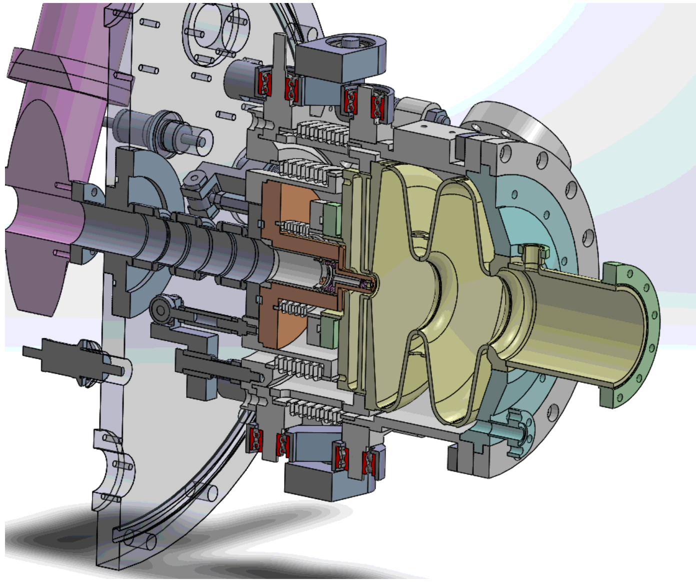


KEK SRF GUN #2 DESIGN

- He vessel is connected by flange with indium seal
  - because #2 cavity is out of high pressure gas safety law.
- He vessel material is stainless steal.
- Vessel was designed compatible with ILC as possible.

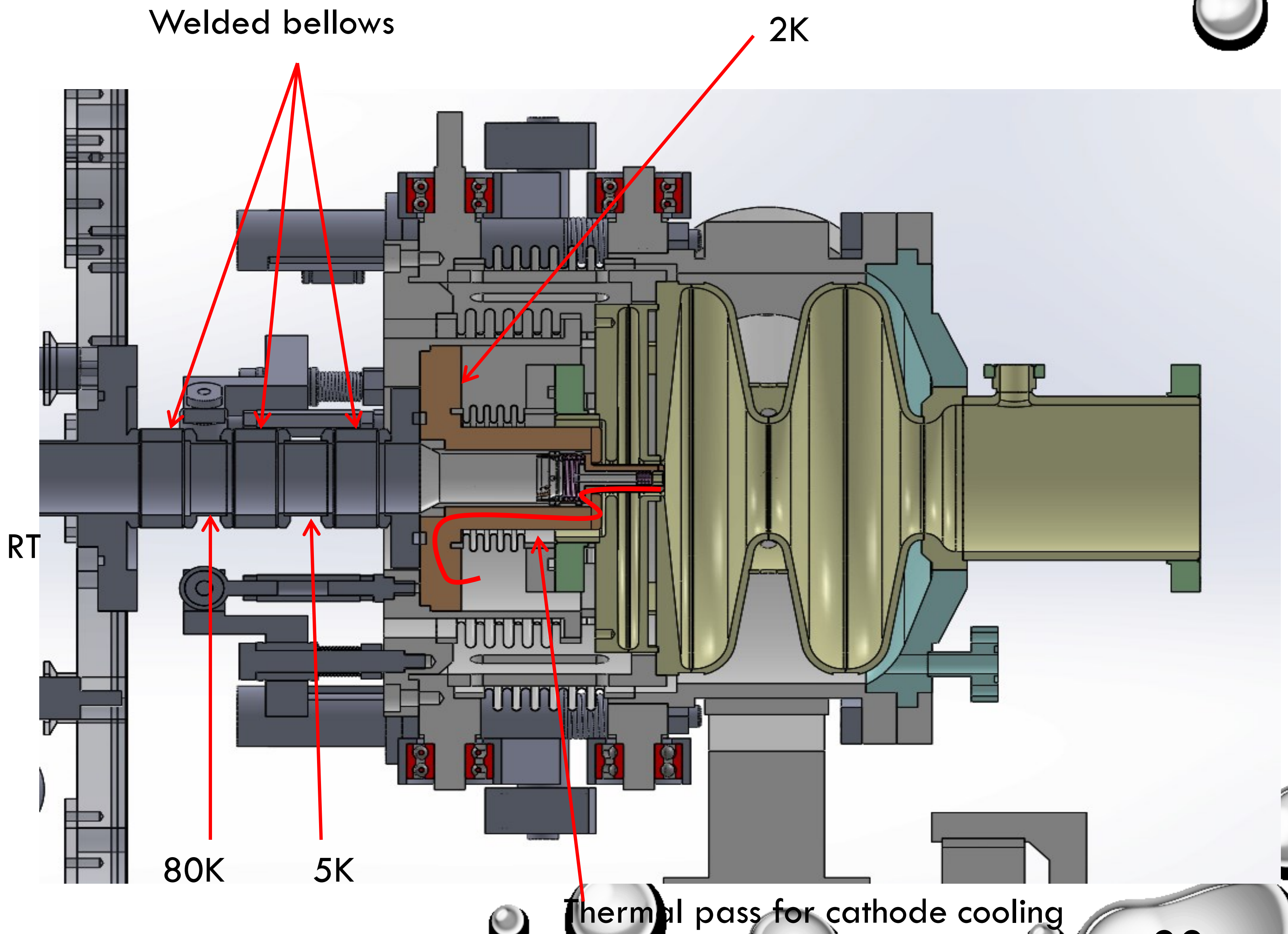






THERMAL STRUCTURE

- Photocathode will cool down about 2K
- Width between cavity and cryomodule should be narrowed to ensure the transfer rod space.



THERMAL CONDUCTIVITY OF THE CATHODE PLUG

- Photocathode will cool down about 2K.
- Main material is copper. Surface is covered with Nb (HIP)
- Thermal contact will be measured by test chamber.

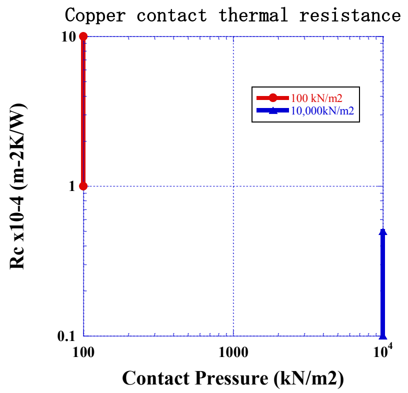
Simple model

$R_{plug\ holder}$
$=1/300[W/(m \cdot K)]/(1.2x10^{-4}[m^2])x(36x10^{-3}[m])=0.9[K/W]$
$R_{thermal\ contact}=10x10^{-4}[m^2K/W]/4.0x10^{-4}[m^2]=2.5\ [K/W]$
$R_{cathode\ plug}$
$=1/300[W/(m \cdot K)]/(1.7x10^{-3}[m^2])x(63x10^{-3}[m])=0.1[K/W]$
$R_{total}=0.9+2.5+0.1)=3.5[K/W]$

- RF loss on cathode plug ~0.3mW @43MV/m
- Cathode temp. ~1mK

$$Q = \frac{\Delta T}{R}$$

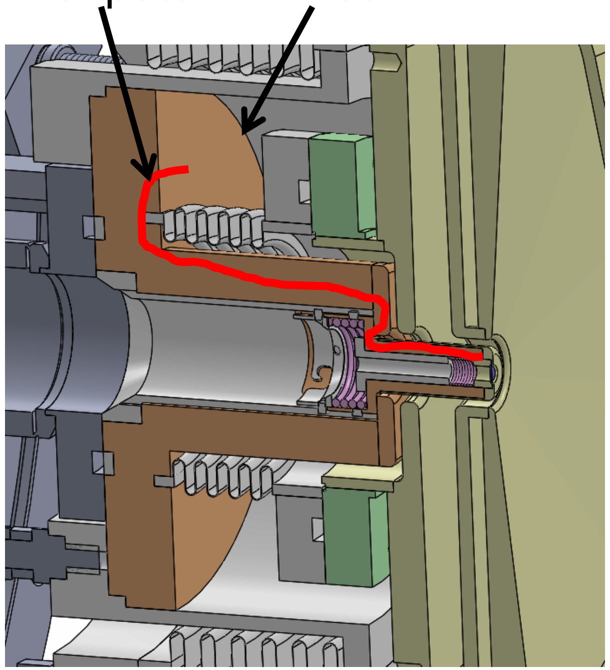
Heat flow : Q[W]
Thermal resistance: R[K/W]
Temperature gradient : ΔT [K]



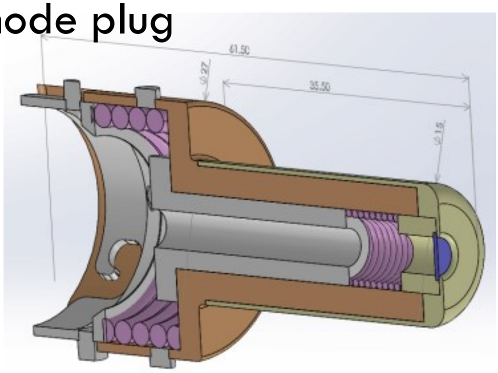
Solidworks database

Contact thermal resistance in vacuum : $Rcx10^{-4}(m^2K/W)$

Contact Pressure	100 kN/m²	10,000 kN/m²
Stainless steal	6-25	0.7-4.0
Copper	1-10	0.1-0.5
Magnesium	1.5-3.5	0.2-0.4
Aluminum	1.5-5.0	0.2-0.4



Cathode plug

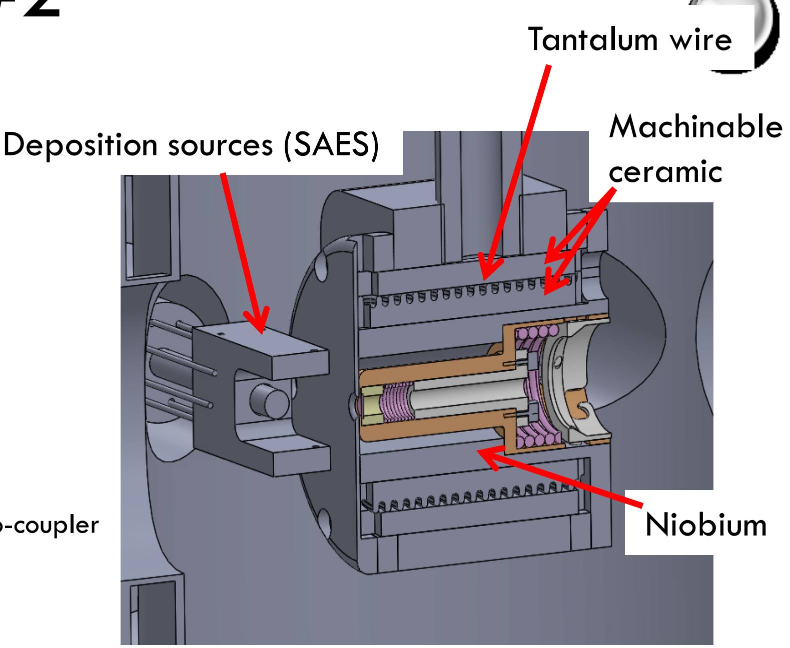


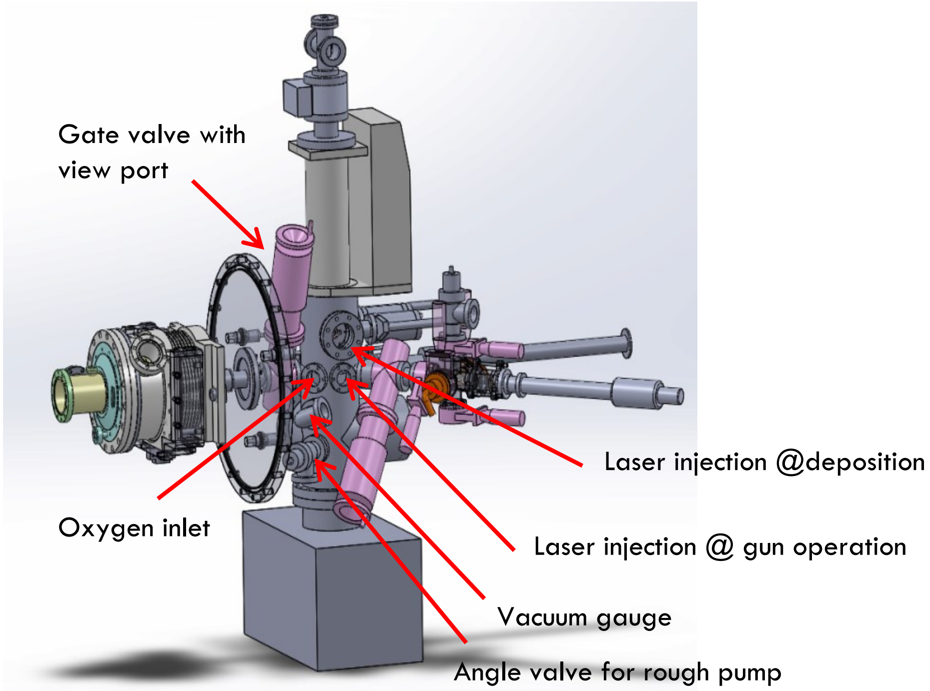
Catalog #	Wire dia.[mm]	Outer dia.[mm]	Free length[mm]	# of turn	Spring constant[N/mm]	Maximum load[N]	Maximum deflection[mm]
TB-3035			35	4.8	8.09	104.22	12.88
TB-3060	3.0	30	60	9	4.32	98.40	22.80
TB-3090			90	13	2.99	111.14	37.20

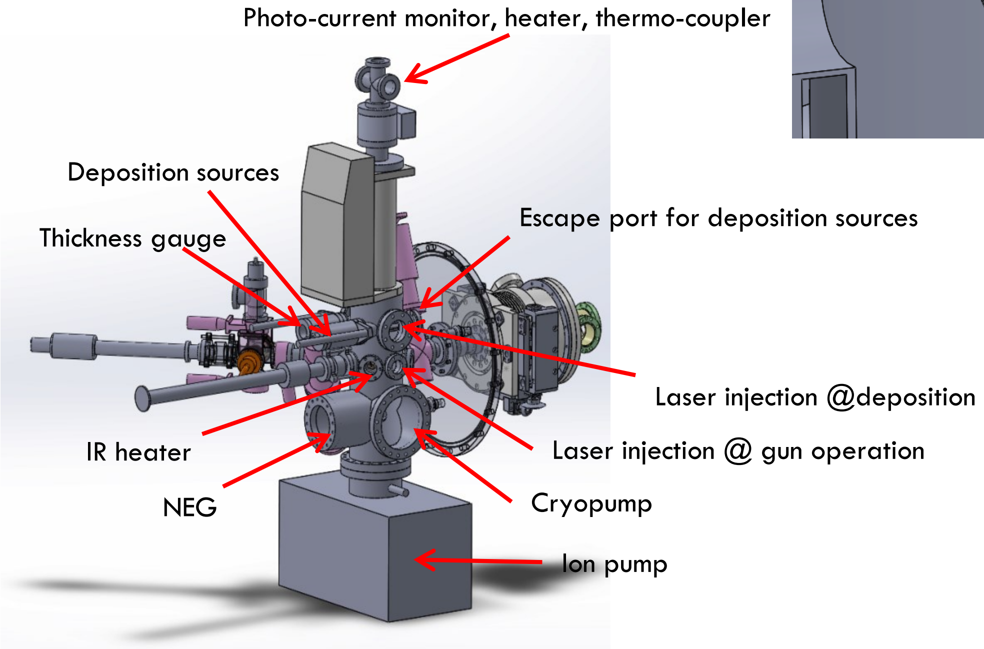
TOKUSHU BANE co., Ltd.

PHOTOCATHODE DEPOSITION CHAMBER FOR KEK SRF GUN #2

- Chamber resize is necessary because the horizontal cryostat area is narrow.

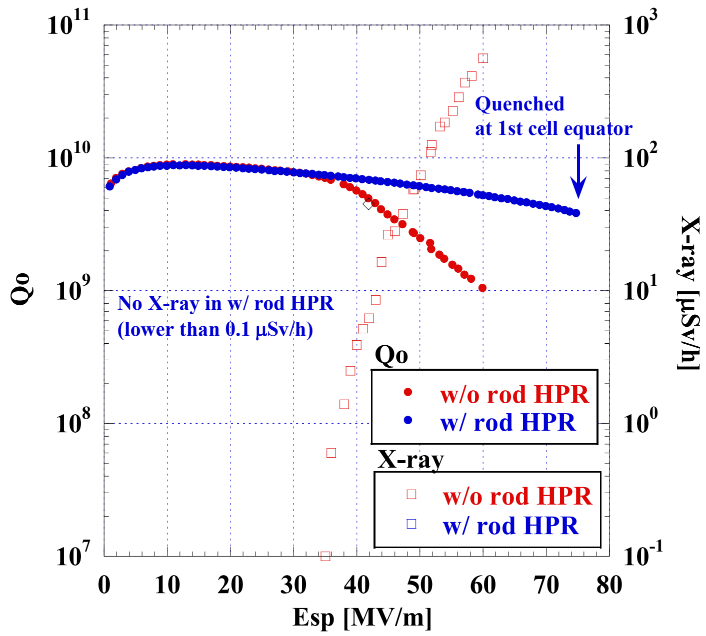


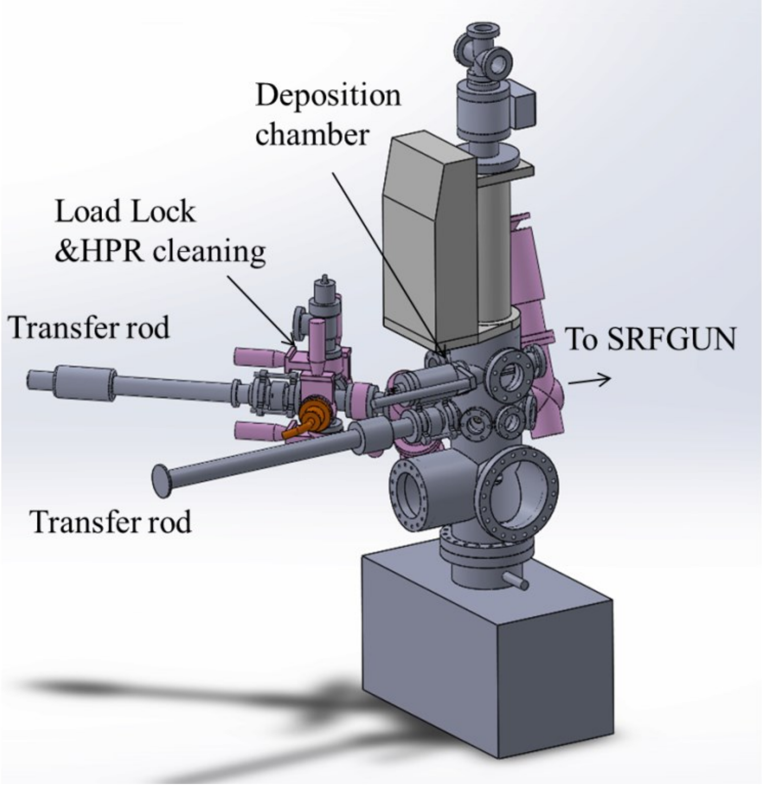


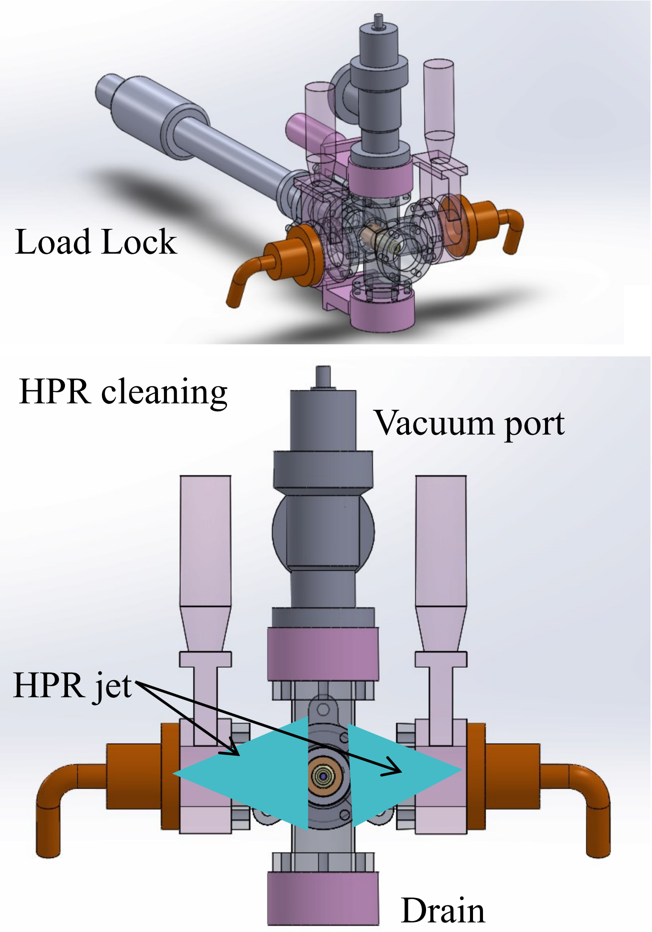


CATHODE INTRODUCING CHAMBER

- Applying the HPR to cathode plug is necessary for achieving high gradient
- How to clean the cathode plug is necessary more consideration
  - One idea is cleaning in the load lock chamber.







SUMMARY

- KEK SRF gun has been developed for 3GeV KEK ERL.

- Prototype #1 cavity was designed to check the RF parameters.
  - Target Esp is 42 MV/m, it correspond to Eacc = 20MV/m of TESLA cavity.
  - After HPR, the peak surface electric field reached 75 MV/m and X-ray couldn't be observed.
  - We have to search other method for cleaning because $LiTi_2O_4$ is thin and delicate.

- Basic properties of the photocathode using transparent superconductor were measured.
  - QE ratio from back side was 90% of front side at 532 nm.
  - Initial emittance almost agreed with theory.
  - Critical magnetic field satisfy the SRF gun operation.
  - QE decrease during cooling down.
  - Further study of photocathode performance at cryogenic temperatures and ways to improve this performance is essential for the photocathode development.

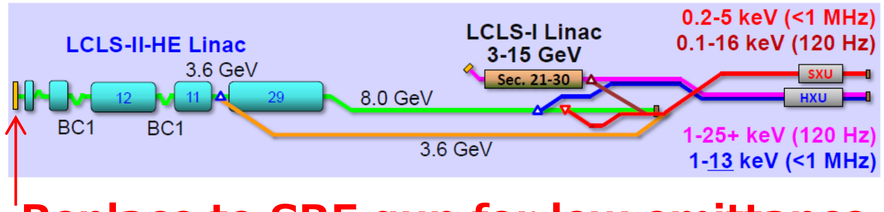
- SRF gun #2 design was started.
  - We will fabricate deposition chamber and gun cavity until March 2018.

BACKUP

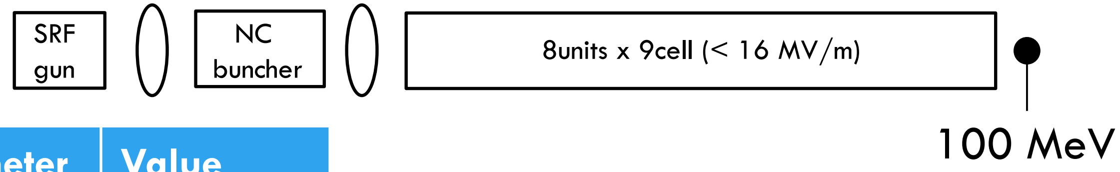
PLAN OF THE KEK SRF GUN

US-Japan collaboration Plan

1. Beam simulation
   - KEK: 1.3 GHz multi-cell cavity (KEK SRF gun #3)
     - #3 and #2 are different design because beam parameter is different.
   - SLAC: Quarter wave cavity
     - Both guns are designed for LCLS-II-HE. Compare both feature.
2. Evaluation of photocathode characteristics at low temperature.
3. Cathode design and cleaning for particle free operation.
4. Beam operation (SLAC)



Replace to SRF gun for low emittance.



Gun Parameter	Value
Beam energy	≧750 keV
Charge	20-300 pC
Rep. frequency	1 MHz

Beam parameter@ 100MeV, 100pC	value
emittance	0.1mm.mrad
Energy spread	$<10^{-3}$
Bunch length	~ 1ps

- Beam simulation is main topic for collaboration.
- KEK plans to start the simulation from October.

Tor Raubenheimer,"LCLS-II-HE FEL Facility Overview" , Workshop on Scientific Opportunities for Ultrafast Hard X-ray at High Rep. rate SLAC, September 26-27, 2016