Superconducting Accelerator for ERL based FEL EUV light source at KEK/Japan

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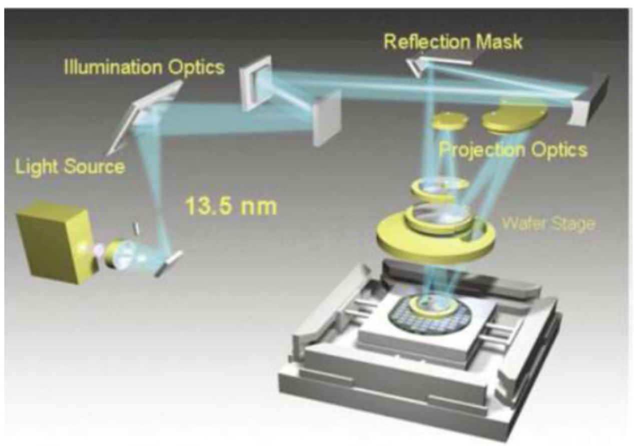
1. Introduction for high-power EUV Light source
2. Learn from cERL cryomodule
3. EUV main linac cavity & cryomodule design
4. Development for EUV main linac cavity
5. Summary

SRF2017@Lanzhou. (2017.Jul.17)

Introduction

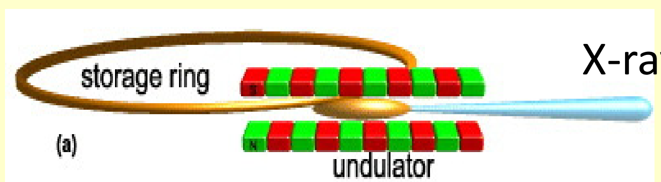
- 10-kW class EUV sources are required in the future for Next Generation Lithography

In order to realize 10-kW class EUV light source, ERL-FEL is the most promising light source (High repetition rate (≦1.3 GHz) and high current linac system).



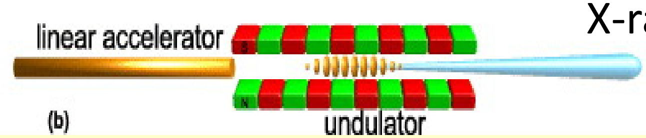
LPP of 13.5nm
→ 250W level now
Need breakthrough for higher EUV light (>1kW)

Breakthrough for EUV light by using FEL (with ERL)



X-ray pulse duration ~ 50 ps

Micro-bunching -> SASE lasing → high peak power



X-ray pulse duration ~ 10 fs

G. Dattoli et al., NIM-A (2001)

In case of normal conducting accelerator,
The repetition rate of FEL is less than 100Hz
→ High repetition with SC cavity is needed for kW laser

EUV/X-ray FELs

Low power → High power

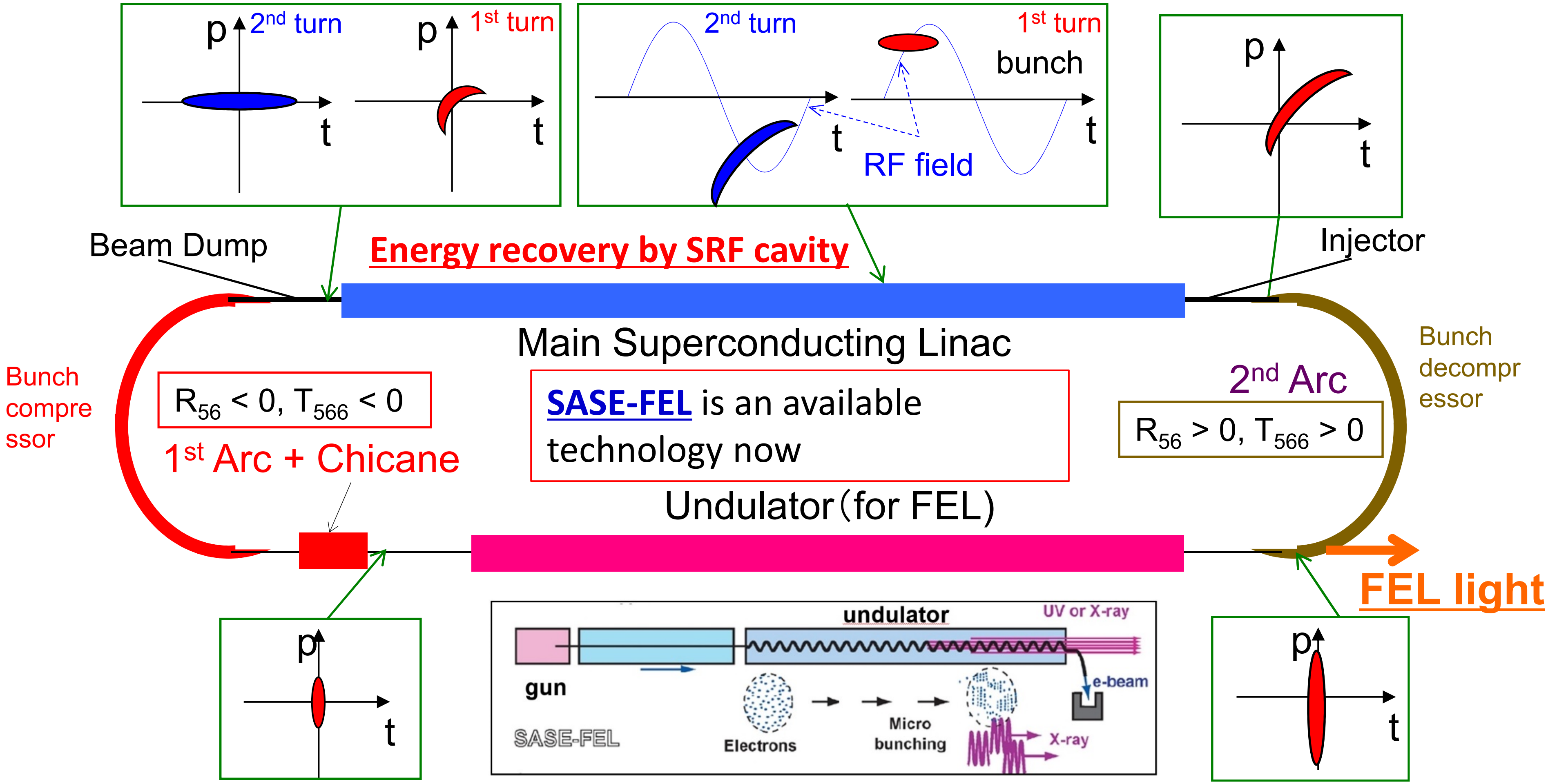
	LCLS	SACLA	FLASH	Euro-XFEL	LCLSII	EUV-FEL
Type of linac	Normal conducting		**Super conducting**			
Operation mode	Pulse		Long pulse		**CW**	
Country	US	Japan	Germany	Germany	US	-------
ERL scheme	No	No	No	No	No	**Yes**
Repetition rate	120	30～60	<5000	<27000	1M	**162.5M**
Beam energy (MeV)	14300	6000～8000	1250	17500	4000	**800**
Wavelength(nm)	0.15	0.08	4.2-52	0.05	~0.3	13.5
Pulse energy(mJ)	~10	~10	<0.5	~10	~1	~0.1
Average Power (W)	~1	~1	<0.6	~100	~1000	**>10000**
Beam dump power (W)	~1.5k	~0.5k	~6k	~0.5M	~1M	**~0.1M**
Status	Operation 2009	Operation 2011	Operation 2004	Construction 2017	Construction 2020	Planning

ERL helps to make high power CW FEL and reduce the beam dump power (important in future)

Design Concept for high repetition high current EUV-FEL

EUV Source (ERL)

- Target : 10kW power @ 13.5 nm, (800 MeV, 10mA)
- Use available technology (based on SASE-FEL) without too much development
- Make ERL scheme by cERL designs, technologies and operational experiences

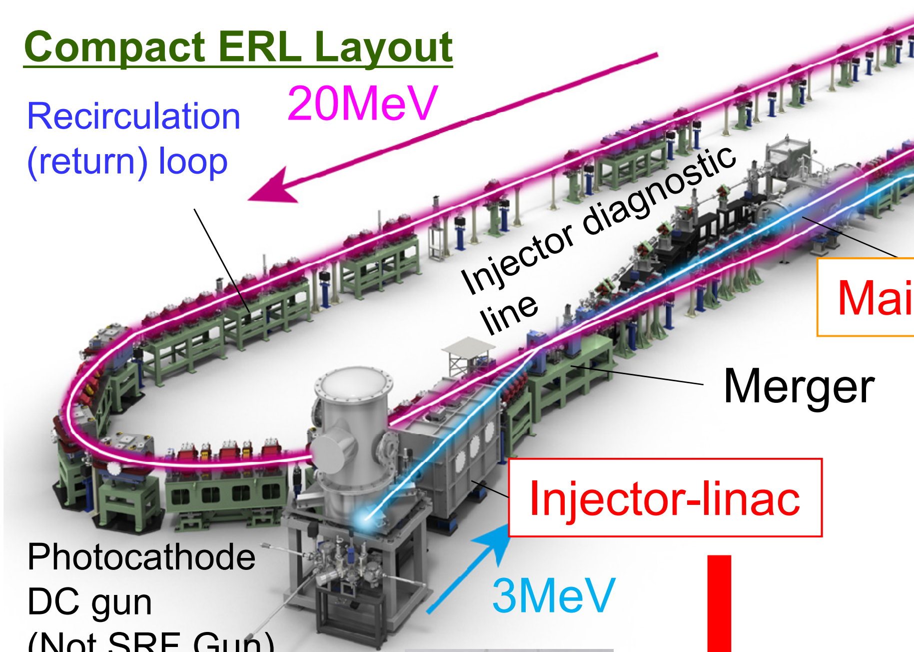


Energy recovery is needed for accelerating more than 10 mA to reduce beam dump and save RF power.
This operational experience with high current is studied in Compact ERL (cERL) at KEK

Learn from Comact ERL (cERL) in KEK (cERL cryomodules)

See details by [**K.Umemori ;"Long operational experience with beam in Compact-ERL cryomodules"** .July.20th 12:00 (THYA06)]

Compact ERL Layout



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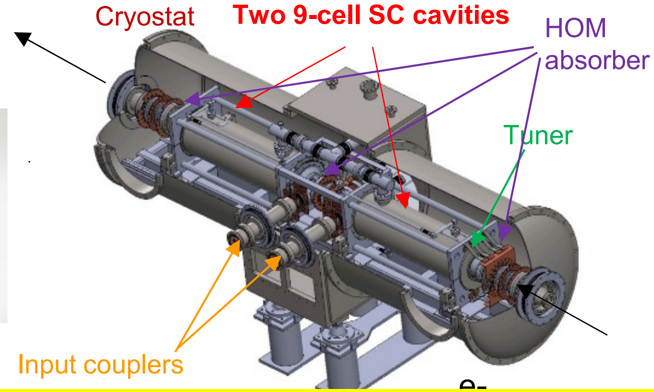
Main linac module

HOM damped (for 100mA circulation to suppress HOM-BBU in design)

9-cell cavity (ERL-model2)× 2

RF frequency:	1.3 GHz
Input power :	20kW CW (SW)
E_{acc}:	8.3 MV/m（operational）
Unloaded-Q:	$Q_0 > 1\times10^{10}$



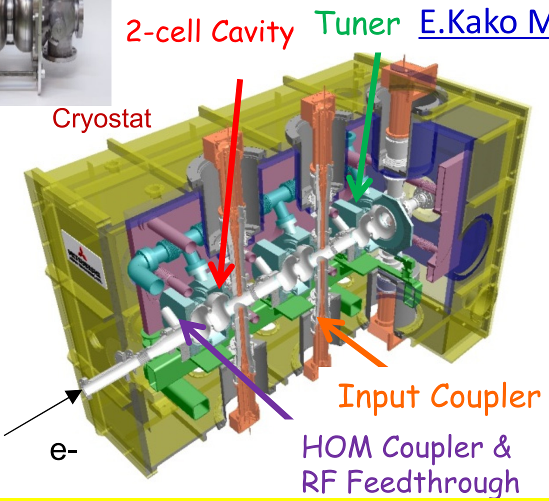
Requirement was satisfied at V.T. **Heavy F.E was met** @9-10MV/m after string assembly.

Injector module

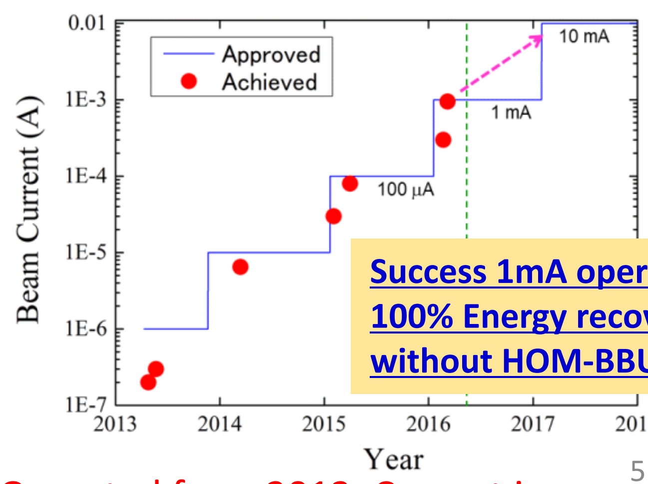
2-cell cavity × 3

Double coupler

RF frequency:	1.3 GHz
Input power :	
	10kW/coupler (10mA, 5MeV)
	180kW/coupler (100mA, 10MeV)
E_{acc}:	7.6MV/m（5MeV）
	15MV/m (10MeV)
Unloaded-Q:	$Q_0 > 1\times10^{10}$



Requirement was satisfied at V.T and for initial 10mA requirement .



Success 1mA operation
100% Energy recovery without HOM-BBU.

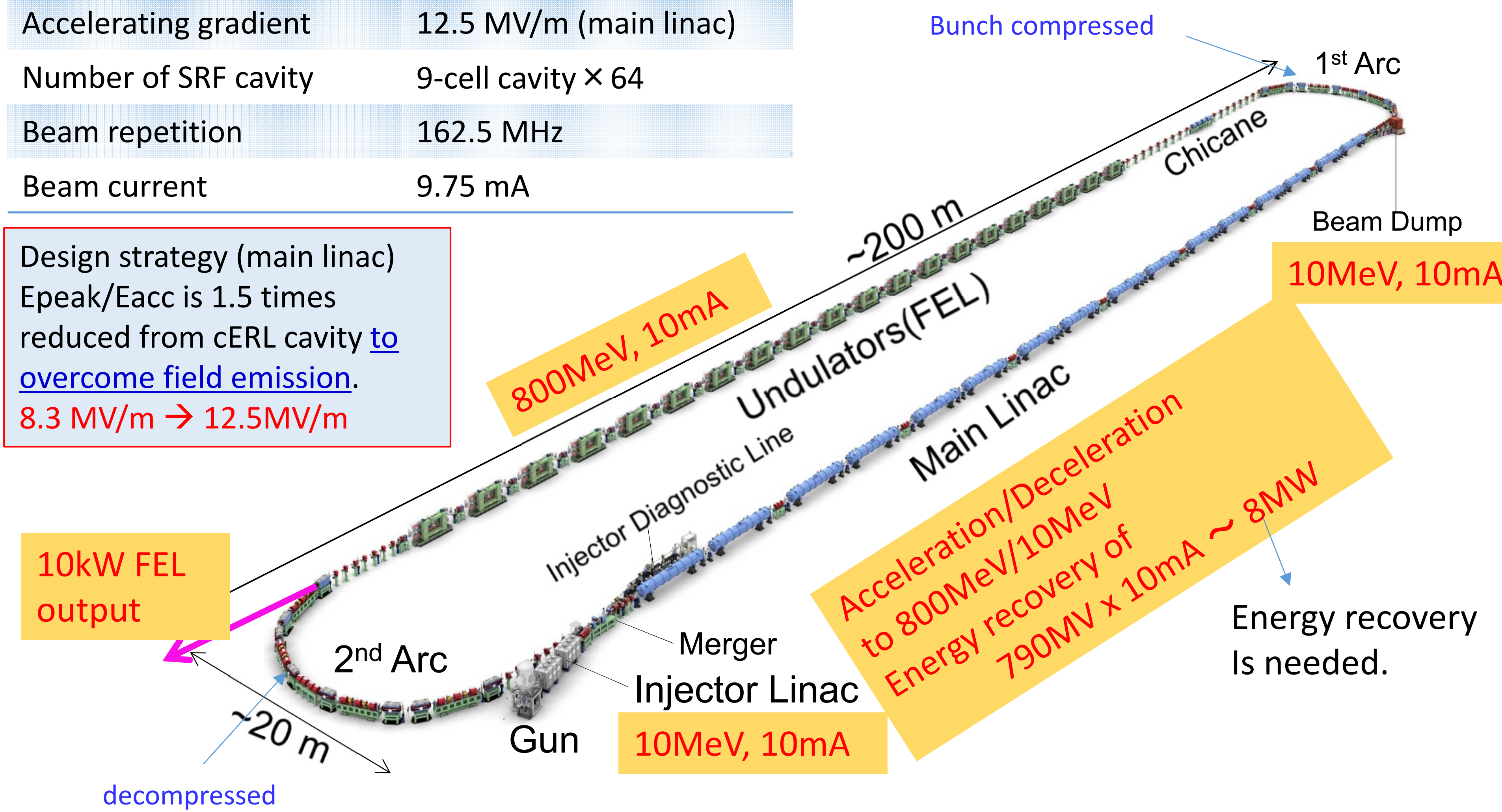
Operated from 2013. Current increased.

EUV-FEL Design

Parameter	Specification
Wavelength	13.5 nm
Output power	10 kW
Bunch chare	60 pC
Beam energy	800 MeV
Accelerating gradient	12.5 MV/m (main linac)
Number of SRF cavity	9-cell cavity × 64
Beam repetition	162.5 MHz
Beam current	9.75 mA

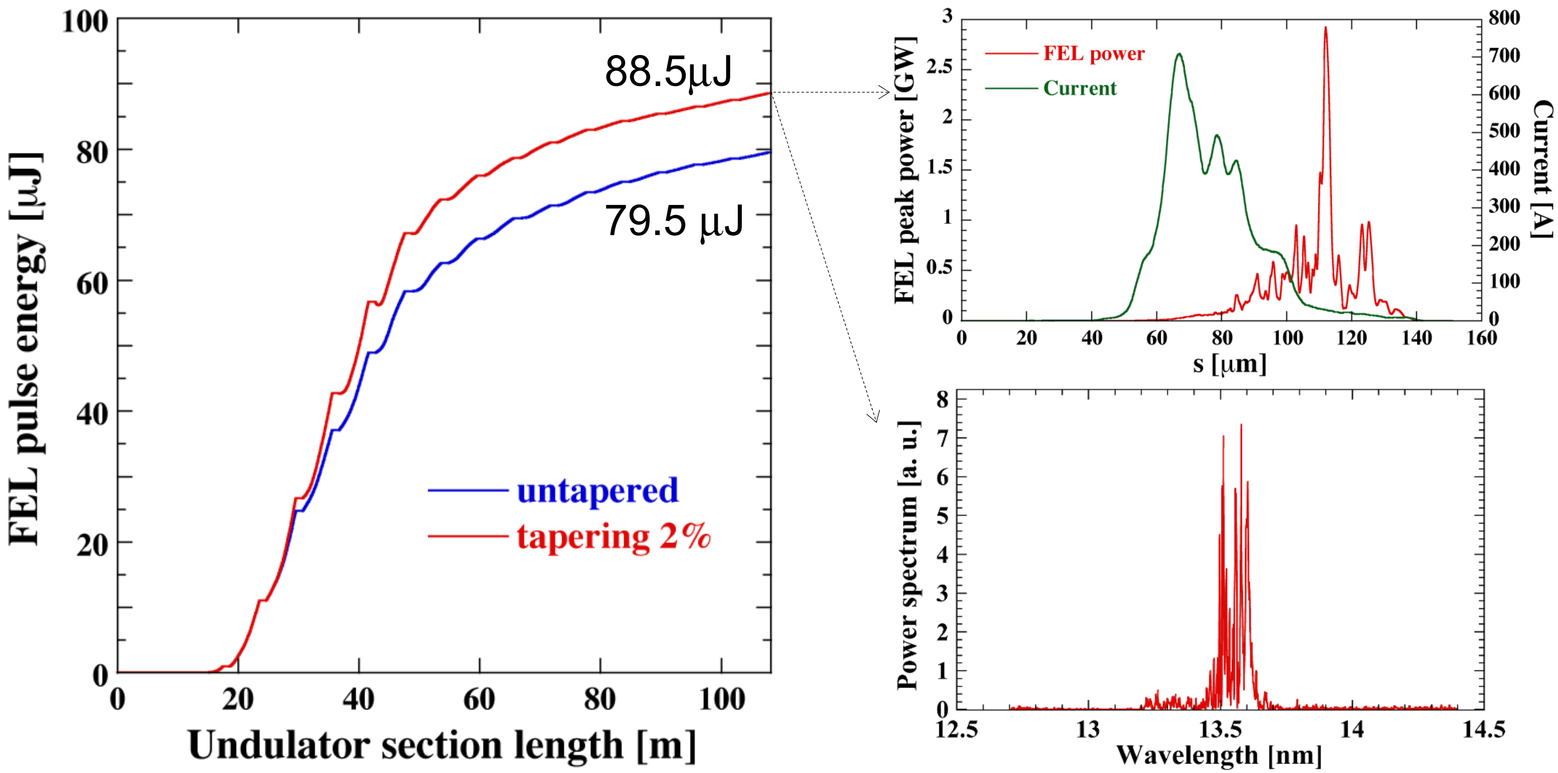
Presented by Norio NAKAMURA
ERL2015（https://www.bnl.gov/erl2015/ ）

Design strategy (main linac)
Epeak/Eacc is 1.5 times reduced from cERL cavity to overcome field emission.
8.3 MV/m → 12.5MV/m



FEL Performance by simulation

Electron beam parameters: **E=800 MeV**, **Q_b=60 pC**, f_b=**162.5**/325 MHz
Helical undulator parameters: K=1.652, λ_u=28 mm, L_u=4.9 m(18 units), L_g=1.12 m
Bunch compression scheme: 1st Arc(DBA), R_{56}=0.3115 m

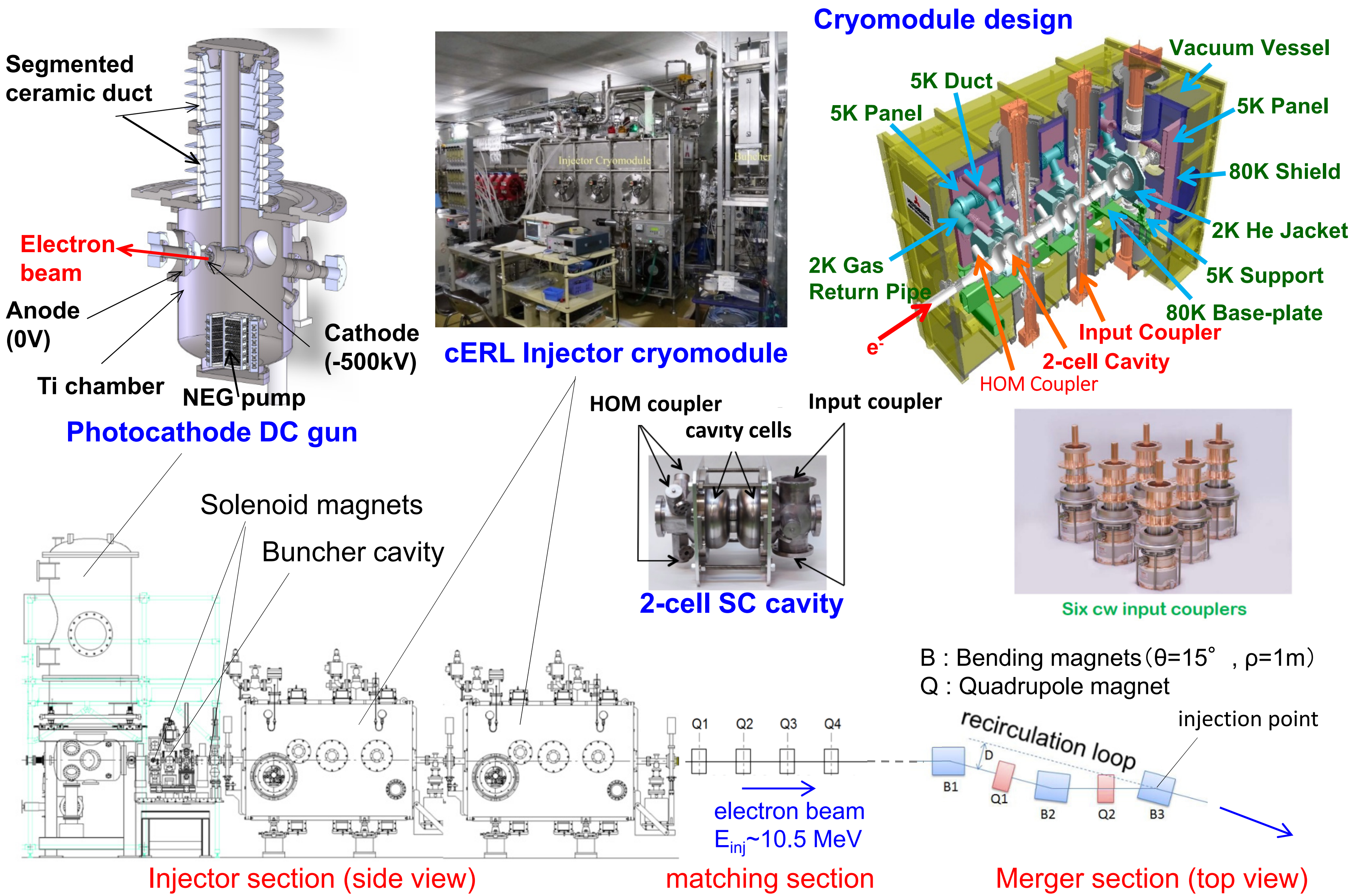


FEL power without tapering: **12.9**/25.8 **kW** @ **9.75**/19.5 **mA**
FEL power with 2% tapering: **14.4**/28.8 **kW** @ **9.75**/19.5 **mA**

10 kW class high power EUV light source is NOT just a dream!

Injector & Merger Design

ref. E.Kako “MOPB097” poster in SRF2017



Injector part of cERL will be used for EUV-FEL light source.

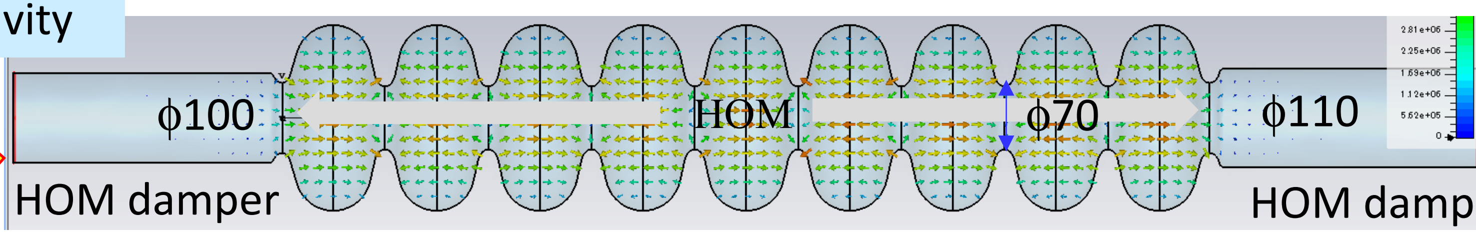
Design of Main Linac Cavity

How to overcome field emission

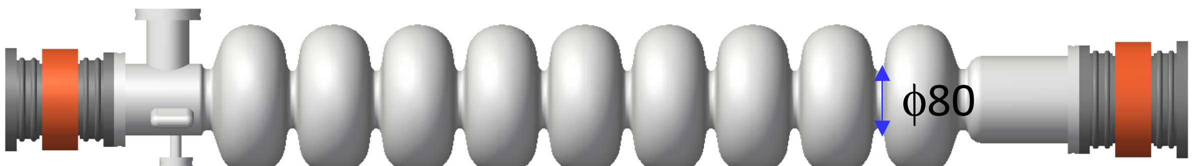
EUV cavity – TESLA-type 9-cell cavity + Large beam pipes(100ϕ & 110ϕ)

→ Only end cell was modified to match the impedance to beam pipe.

EUV cavity



cERL cavity (Model 2) – HOM damped cavity for 100mA operation



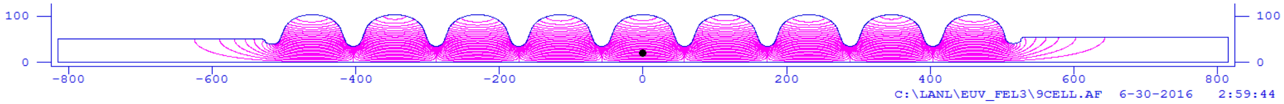
Parameters for acceleration mode

	ERL Model 2	EUV		ERL Model 2	EUV
Frequency	1300 MHz	**1300 MHz**	Iris diameter	80 mm	70 mm
R_{sh}/Q	897 Ω	**~1000 Ω**	$Q_o \times R_s$	289 Ω	～270 Ω
E_p/E_{acc}	3.0	**~ 2.0**	H_p/E_{acc}	42.5 Oe/(MV/m)	～42.0 Oe/(MV/m)

From cERL stable beam operation of 8.3 MV/m in 3 years with less trip ratio.
Stable operation at 12.5 MV/m seems achievable due to reduced E_p/E_{acc}.

Detailed calculated parameters of EUV main linac cavity

- Ep/Eacc is 2.0 because the center cell is TESLA shape.
- EUV monopole HOM is lower than cERL because the cERL was optimized for dipole HOMs



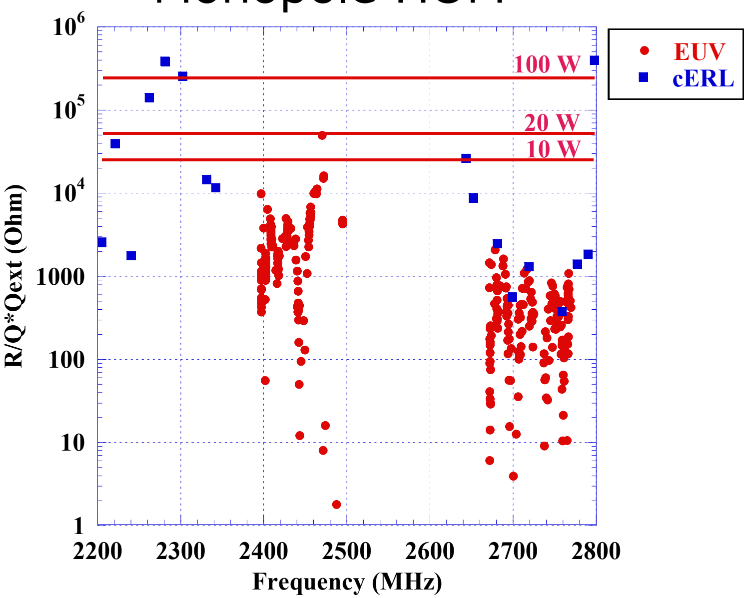
Acc.

Cavity Parameters	KEK-EUV	KEK-cERL	TESLA
Frequency (MHz)	1300	1300	1300
Iris diameter (mm)	**70**	**80**	**70**
R/Q (Ω)	1009	897	1036
G (Ω)	269	289	270
Ep/Eacc	**2.0**	**3.0**	**2.0**
Hp/Eacc (mT/(MV/m))	4.23	4.25	4.26
BBU limit	**>190 mA**	**~600 mA**	**~10 mA**

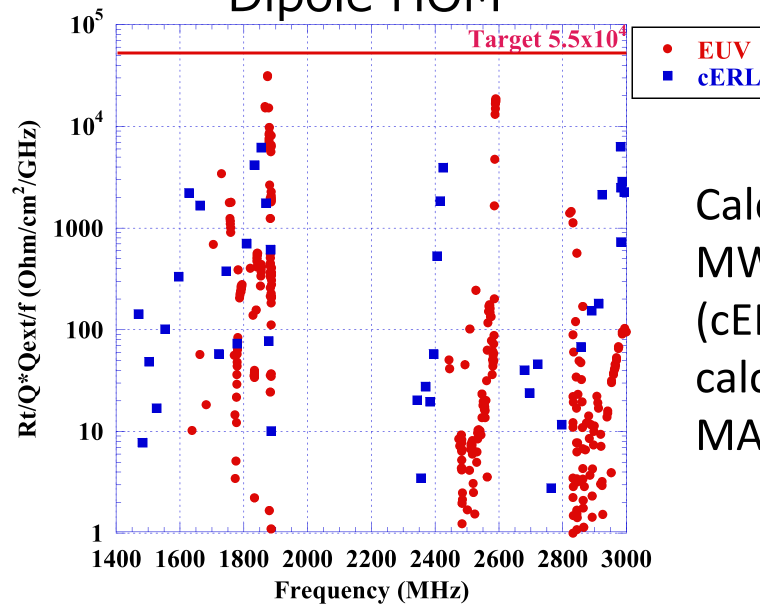
Calc by Superfish

Norio NAKAMURA ERL2015 (https://www.bnl.gov/erl2015/)

Monopole HOM



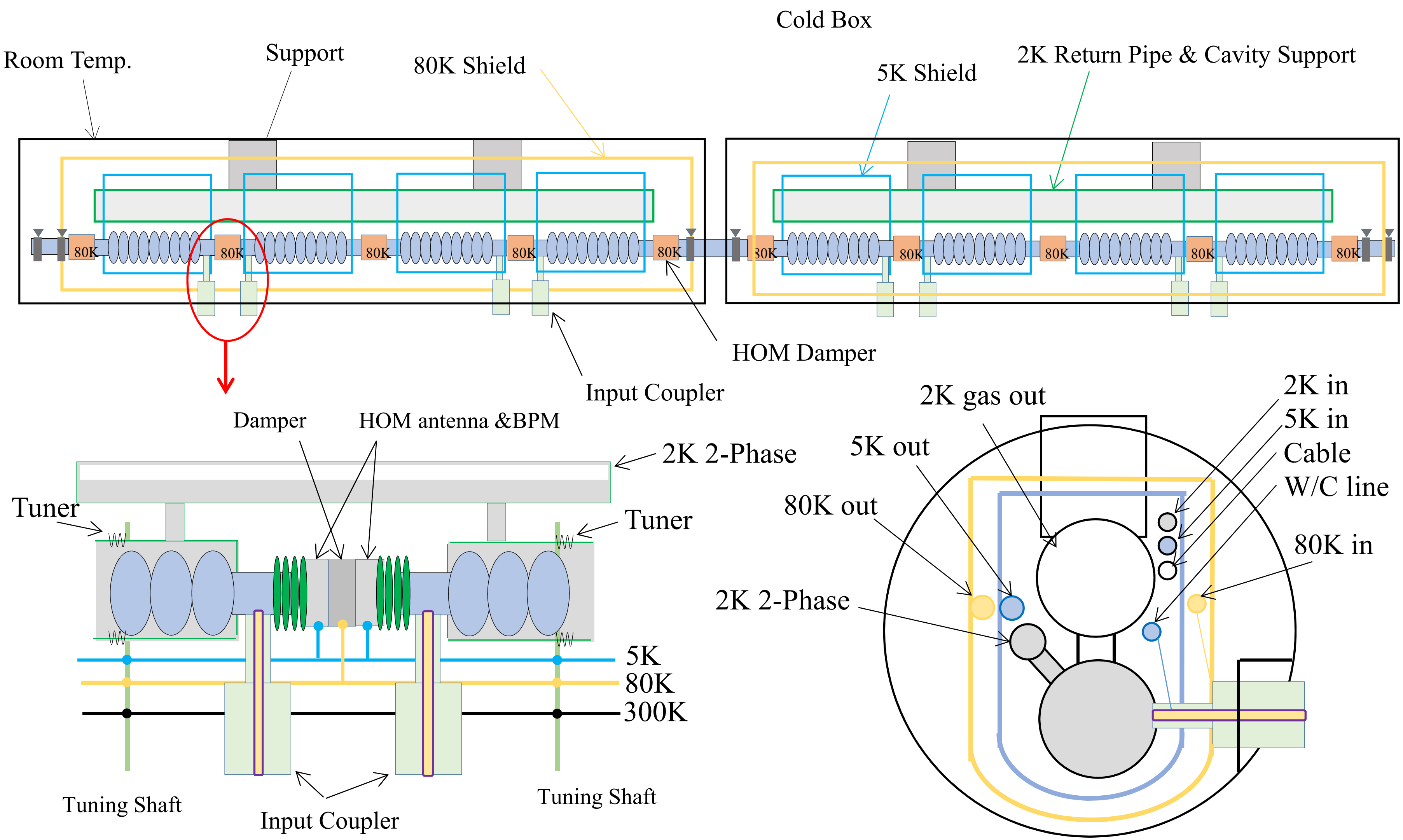
Dipole HOM



Calc by MW-Stdio (cERL case calc by MAFIA)

EUV cavity satisfied our requirement of 10 mA beam operation by keeping Ep/Eacc ~ 2.

Concepts of EUV main linac cryomodule



- EUV module consists 4 cavities and the design based on STF and ERL module.
- Coupler position is opposite direction each cavity, because the beam pipe sizes are different.
- Input coupler and tuner are same type of ERL and STF.
- HOM damper needs new development.

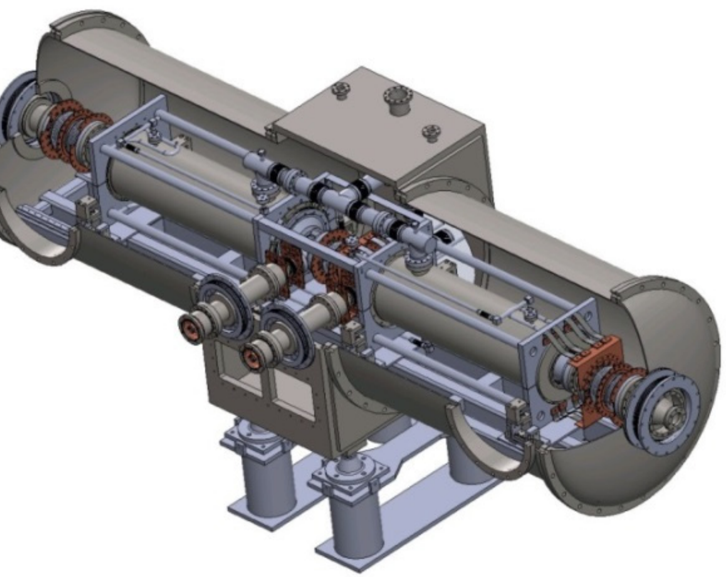
Detailed and Modified from cERL main linac cryomodule

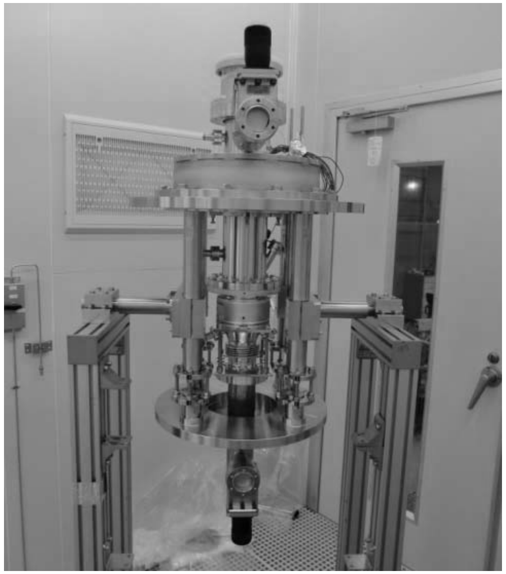
Input coupler

- cERL main linac coupler is working well up to CW 15 kW power (double windows)
- Qext=$2x10^7$ require 4~5 kW input power for Eacc=12.5 MV/m
- We could apply for EUV main linac cavity by using cERL main linac coupler.

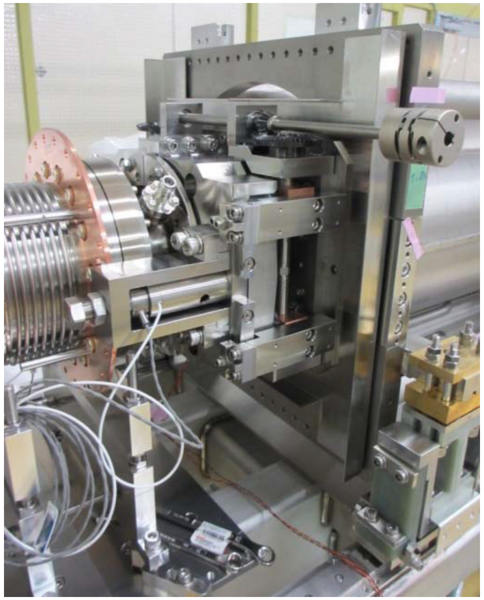
Frequency tuner

- Rough tuning by Slide-Jack tuner controlled by motor
  - Full stroke 3mm (~1MHz)
- Fine tuning by piezo tuner
  - Precision <nm
- Working very well at cERL and STF
- Apply for EUV



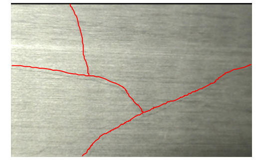


cERL Input coupler

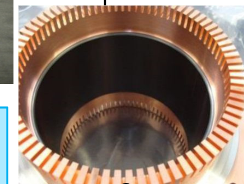


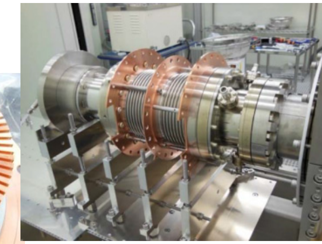
cERL Tuner

Test of HOM damper for EUV cavity



cERL HOM damper





HIP ferrite

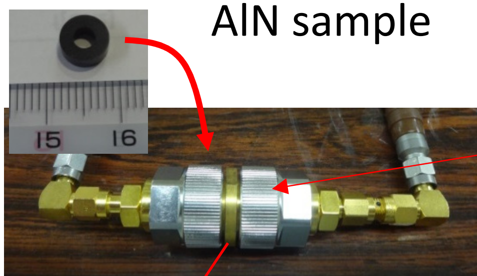
change

- cERL HOM absorber (ferrite) has cracks during cool down and not bakable ⇒ not good for SRF usage.
- AlN (Sienna Tec. : STL-150D) is a candidate for absorber.
  ⇒ AlN is already tested at Jlab and DESY
- We started the measurement of RF parameter @ low temperature, outgassing and testing the brazing.

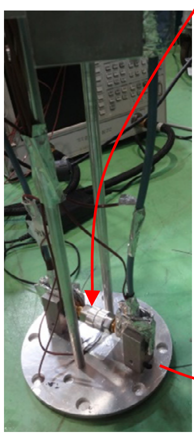
AlN ring

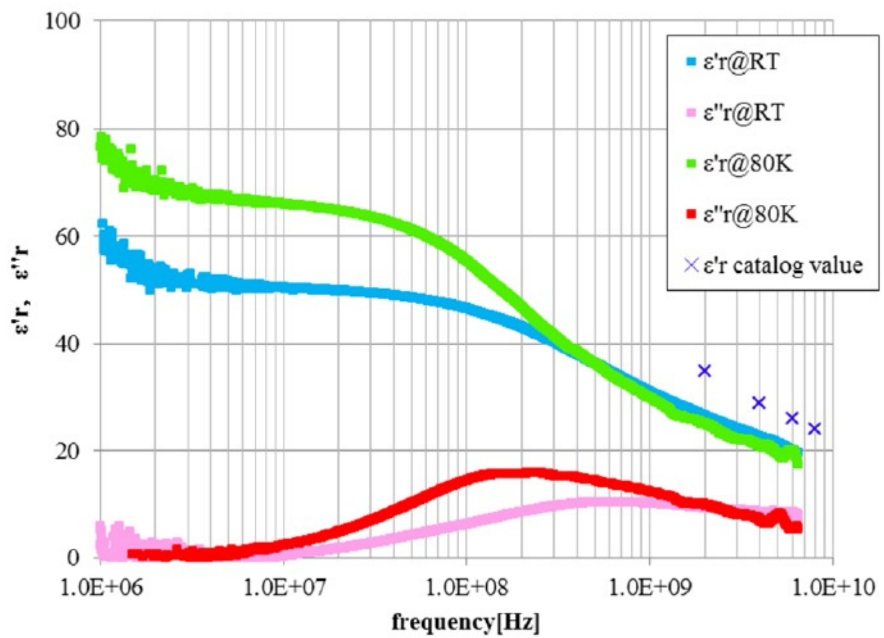
RF parameter measurement @ 80K

AlN sample



Cool to 80K



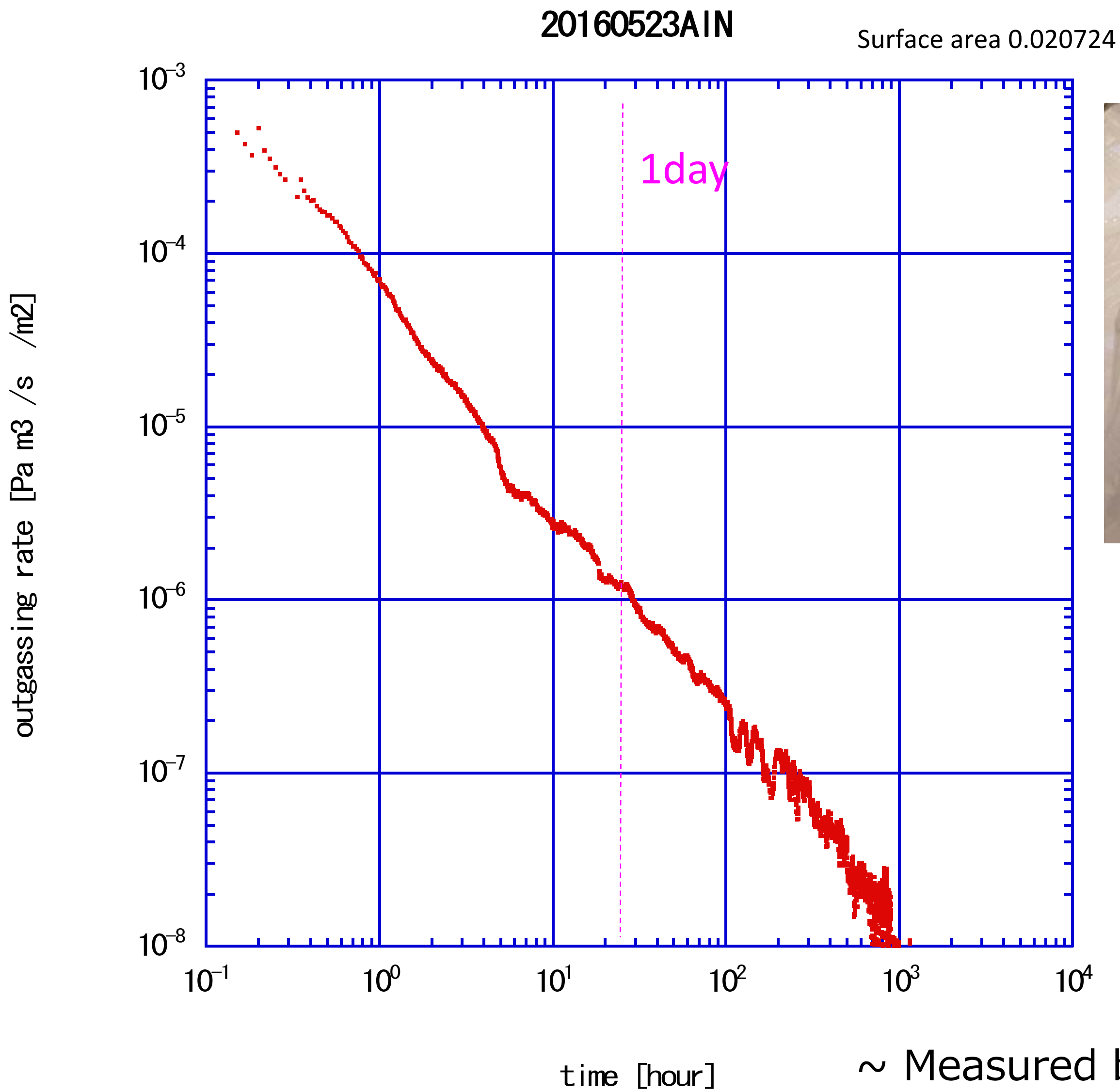


Little difference of epsilon of AlN between R.T and 80 K

We have enough absorption by using AlN material @80K.

Outgassing rate of AlN ring

Outgassing rate of AlN ring was measured after 48h x150 °C baking.
After 1000h, outgassing rate is lower than 10^{-8} Pa*m³/s/m²



AlN ring

cERL damper is not bakeable.
So water rinse is not allowed.

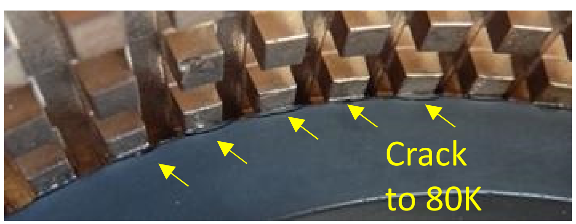
AlN (STL-150D) damper is bakeable and easy for cleaning.
<u>It is enough for installation inside the cryomodule</u>

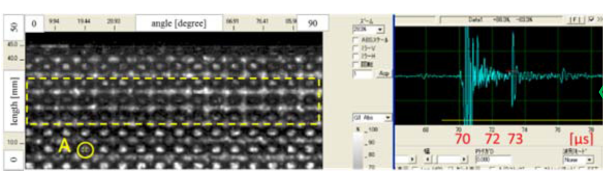
~ Measured by Shinji Terui (KEK)

Brazing test of AlN based HOM damper prototype

- Two AlN cylinder were brazed in the copper cylinder which has the comb pattern.
- Brazed by Silver at 750 degree under Hydrogen Furnace.
- We tried thermal test. Unfortunately, AlN cylinder is broken after first 80K thermal cycle.
- Ultrasonic testing in the water bath was done after brazing. AlN ring of 2nd prototype much tighter connected than that of 1st one. But not all area of AlN ring was connected.
- We need to search more tighter brazing condition including thermal cycle.

1st : Test piece of brazing

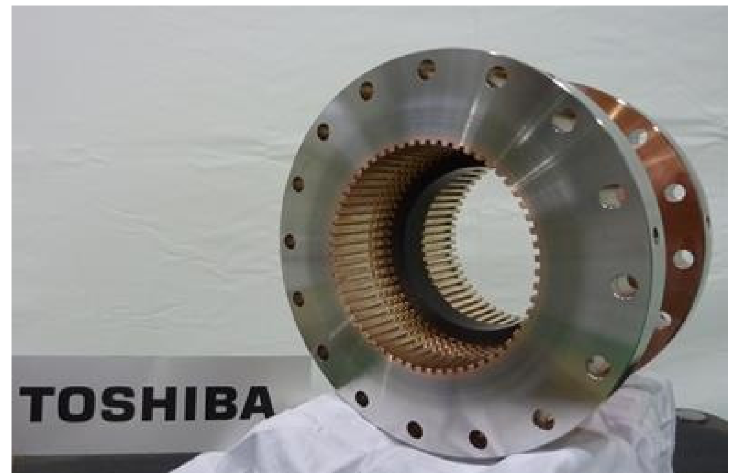




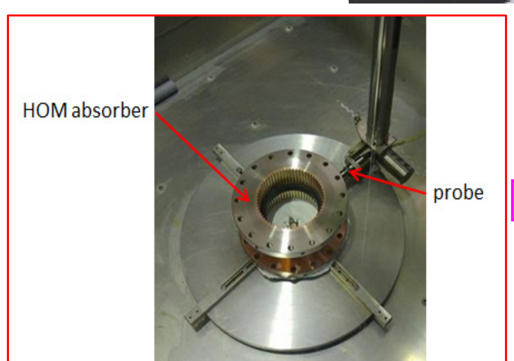
Connection was not tight and crack occurred under cooling to 80 K (but very fast (1 hour)).

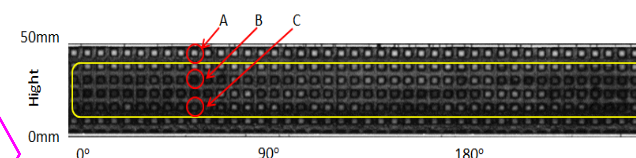
Same brazing condition but shape was optimized to fit AlN at center position.

2nd : HOM damper prototype



Ultra sonic test





2nd prototype is tighter connected. 60% area connected but not perfect.

T. Ota et al. , "Development of HOM absorbers for CW Superconducting cavities in Energy Recovery LINAC" (MOPB062))

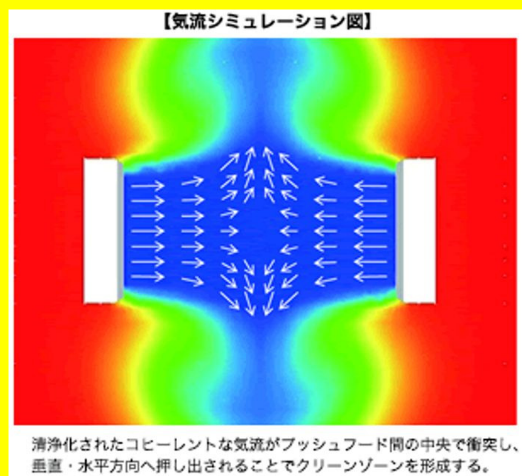
For reliable operation after assembly work

Toward the reliable operation,

- We made the horizontal test stand for testing the performance after cryomodule assembly including HOM damper, input coupler, tuner and magnetic shield.
- Furthermore, now we try to establish the local clean boose and slow pumping system in this horizontal test standto overcome field emission after string assembly.

Horizontal test stand was build and already carried out high power test in KEK .

For making very clean local boose



Slow pumping system

EUV-FEL Light Source Study Group for Industrialization

since 2015

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THE UNIVERSITY OF TOKYO
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Industrialization of High Power EUV light source based on ERL@KEK and FEL@QST

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By all Japan association to realize EUV-FEL light source

Summary

- EUV-FEL-ERL is promising to open the era to the highest EUV light source and can make more than 10 kW@ 13.5nm EUV light in design.

- We learned that most severe problem is field emission on long beam operation.
- EUV cavity has been designing by including cERL beam operation experience for EUV-ERL/FEL accelerator.
  - Cavity based on KEK-cERL +TESLA cavity to reduce Epk/Eacc.
    ⇒TESLA center cell + beam line damper with modified end-cell & beam pipe
  - This designed cavity could make 10 mA beam operated without HOM BBU instability and large HOM heat load with 12.5 MV/m accelerating field by extrapolated from cERL operation.
- Cryomodule has been designing based on STF+ERL cryomodule.
- HOM damper was newly developed for EUV cavity. We found AlN material is suitable for our cryomodule HOM damper on RF parameters and outgassing. Unfortunately, we did not find good brazing condition.
- For a reliable cryomodule operation, we made horizontal test stand for study of more reliable string assembly work to prevent the dust coming into the cavity.

- We also do the nitrogen doping/infusion work for future high-Q operation. (See poster; T. Konomi, et, al., "Trial of Nitrogen Infusion and doping by using J-PARC Furnace", THPB021 poster)

- Finally, all Japan association with KEK promote to build EUV-FEL light source.

Thank you for your attention!