HOM-BBU Simulation for KEK ERL Light Source

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2015.06.09
on ERL2015 Workshop
TULCLH2033

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  - KEK ERL Light Source Project
  - HOM-BBU in ERL
- Simulation Setup
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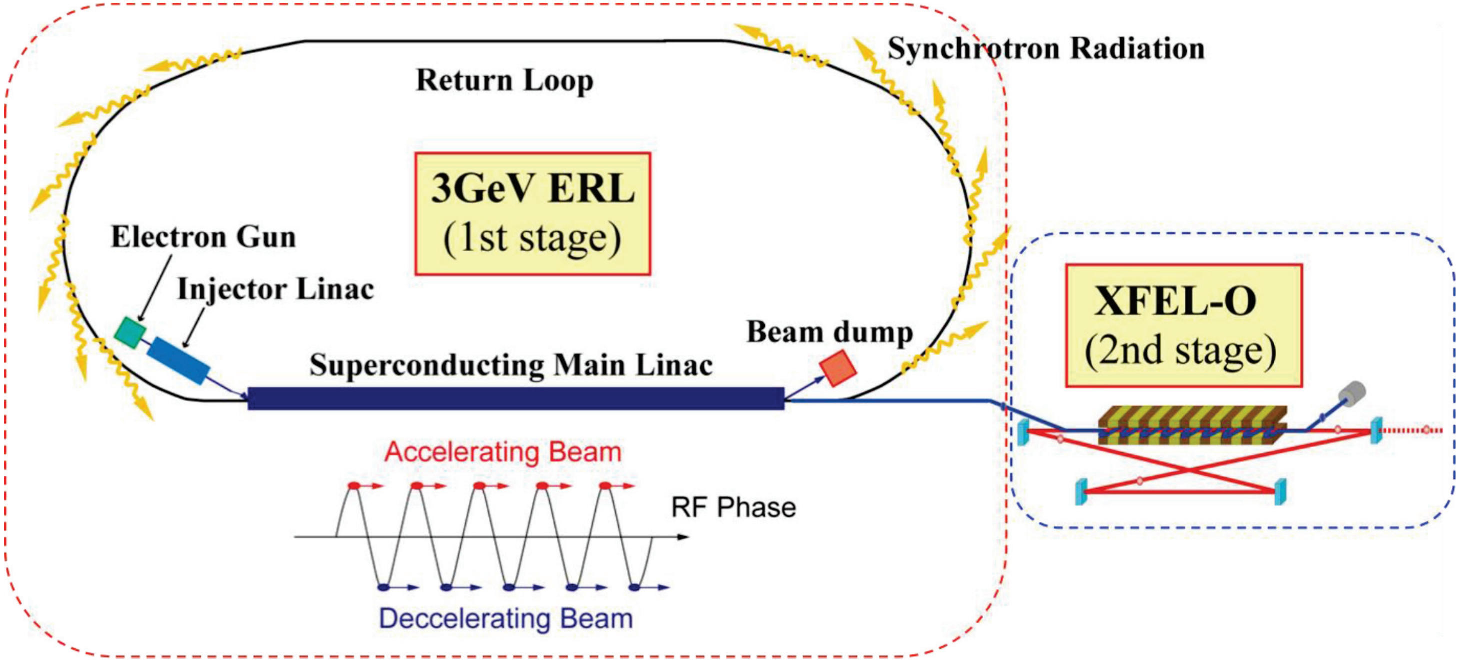
Introduction and Motivation

KEK ERL Light Source Project - PEARL

- **P**hoton Factory **E**RL **A**dvanced **R**esearch **L**aboratory
- Two stages
  - 1st stage: 3GeV ERL for VUV and X-ray SR light source
  - 2nd stage: 6-7GeV X-FEL Oscillator.

PEARL
Photon Factory



A schematic view of PEARL and the XFEL-O

KEK ERL Light Source Project - PEARL

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- Two stages
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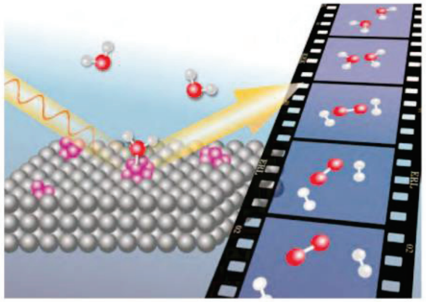
PEARL
Photon Factory

- Proposed as the successor of two operating SR sources at the Photon Factory of KEK [1], the 2.5GeV PF ring and 6.5GeV PF-AR.
- Conceptual Design Report has been published in 2012. [2]
- As a prototype machine, the compact ERL (cERL) is on going[3].

Energy Recovery Linac
Conceptual Design Report



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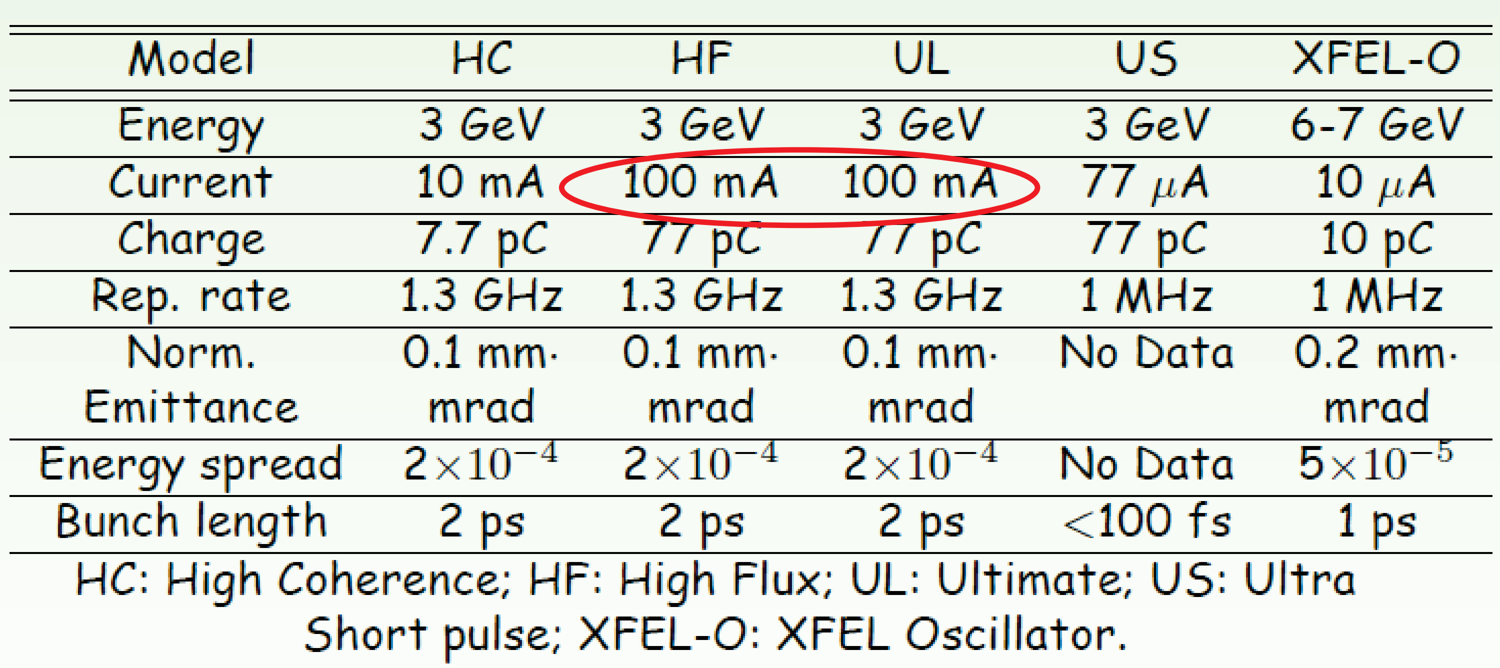
1. N.Nakamura, IPAC2012, tuxb02
2. Energy Recovery Linac Conceptual Design Report, KEK Report 2012-4(2012)
3. S.Sakanaka, This Workshop

KEK ERL Light Source Project - PEARL

- Photon Factory ERL Advanced Research Laboratory
- Two stages
  - 1st stage: 3GeV ERL for VUV and X-ray SR light source
  - 2nd stage: 6-7GeV X-FEL Oscillator.

Target Parameters of PEARL

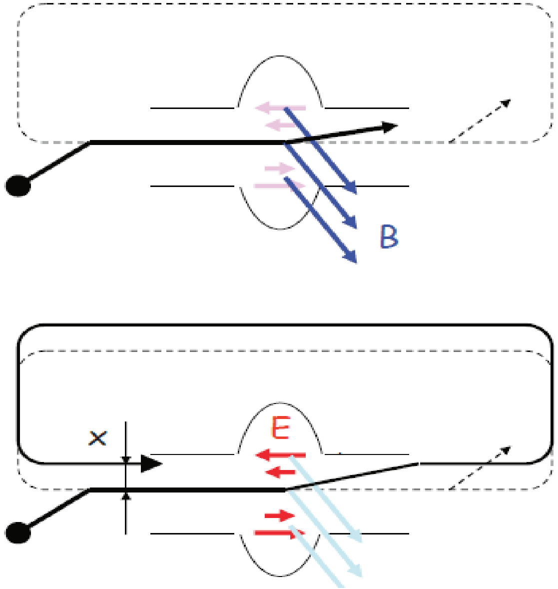


Model	HC	HF	UL	US	XFEL-O
Energy	3 GeV	3 GeV	3 GeV	3 GeV	6-7 GeV
Current	10 mA	100 mA	100 mA	77 μA	10 μA
Charge	7.7 pC	77 pC	77 pC	77 pC	10 pC
Rep. rate	1.3 GHz	1.3 GHz	1.3 GHz	1 MHz	1 MHz
Norm. Emittance	0.1 mm·mrad	0.1 mm·mrad	0.1 mm·mrad	No Data	0.2 mm·mrad
Energy spread	2×10^{-4}	2×10^{-4}	2×10^{-4}	No Data	5×10^{-5}
Bunch length	2 ps	2 ps	2 ps	<100 fs	1 ps

HC: High Coherence; HF: High Flux; UL: Ultimate; US: Ultra Short pulse; XFEL-O: XFEL Oscillator.

- Average beam current up to 100mA is expected for both High Flux and Ultimate Ring models.

HOM-BBU in ERLs



- HOM-BBU: a possible issue to limit the average beam current in an ERL.
- When BBU occurs, a positive feedback loop is established between electron beam and HOMs.
- The maximum average beam current to keep stability is the BBU threshold current.

- An analytical formula of BBU threshold current is [1]

$$I_{th} = -\frac{2V_b}{k\left(\frac{R}{Q}\right)Q_L} \cdot \frac{1}{M_{12}^* \sin(\omega T_r)},$$

$$M_{12}^* = R_{12}\cos^2\theta + (R_{14} + R_{23})\sin\theta\cos\theta + R_{34}\sin^2\theta$$

where $V_b = \frac{pc}{e}$ is the beam voltage; R/Q, Q_L, ω are the HOM shunt impedance, loaded quality factor and frequency; T_r is the recirculating time of electron bunch; R_{ij} are the transfer matrix element of the lattice.

[1] 1.Pozedev E., PRST-AB 8, 074401(2005).

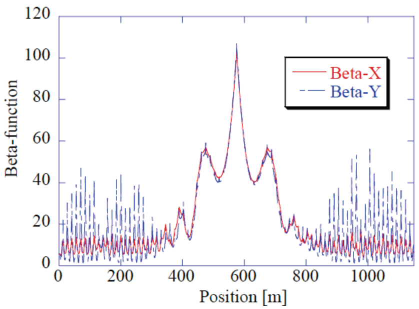
BBU Simulation Codes

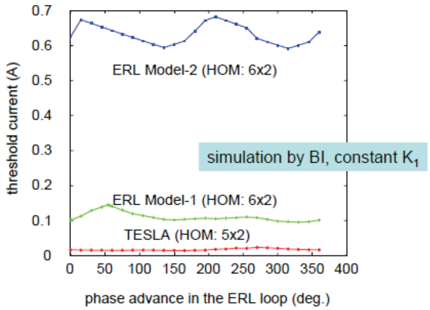
- The availability of analytical formula is limited:
    - Single cavity, single HOM.
    - $M_{12}^{*}\sin(\omega T_r) > 0 \Rightarrow I_{th} < 0$, not valid.
- For more complicated cases, numerical simulation needed.
- BBU simulation codes overview [1]:
    - MATBBU, TDBBU, ERLBBU (developed at JLab).
    - BI (by I. Bazarov at Cornell University), BMAD [2] (by D.Sagan at Cornell University).
    - BBU-R (developed at JAEA).
- Basic algorithm
    - Particle tracking (TDBBU, ERLBBU, BI, BBU-R).
    - Eigenvalue Solution [3] (MATBBU, BMAD).
- In the previous work on JLab ERL, simulation result (by various codes) agrees well with the experimental result [4].
- In this work, "BI" code [5] is used for simulation.

1. E.Pozdeyev, et al., NIM A 557(2006) 176-188
2. D.Sagan, NIM A 558(2006) 356-359
3. G. Hoffstaetter, I.Bazarov, PRST-AB 7,054401 (2004)
4. E.Pozdeyev, et al., NIM A 557(2006) 176-188
5. http://www.lepp.cornell.edu/~ib38/bbucode

Previous Studies on the BBU of KEK ERL project

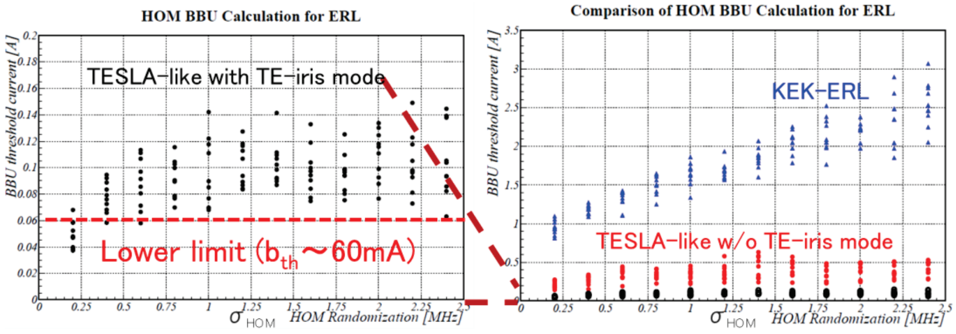
- R.Hajima, R.Nagai, ERL2007 [1], Analysis of HOM-BBU with newly designed cavities for 5GeV ERL design. E_{inj}=10MeV, E_{full}=5GeV, E_{acc}=20MV/m. “BI” and “BBU-R”

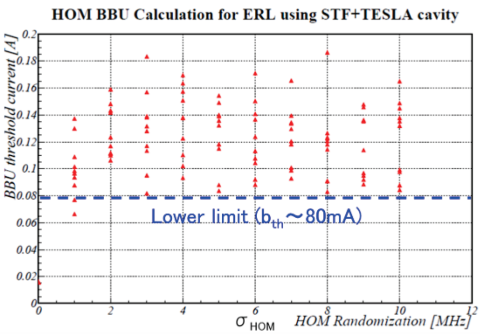




- BBU threshold of more than 600mA is possible with KEK-ERL model-2 cavity.
- 1.5A with 1MHz HOM frequency spread.

- K.Yamamoto, et al., 2011 [2], “BBU Simulation using HOM Randomization for Application of TESLA-like Cavity to KEK-ERL”, TE_{iris} mode most dangerous. “BI”





- In ERL CDR (2012), BBU threshold current was qualitatively estimated based on the simulation results of 5GeV design. Detailed simulations are not included in CDR (The motivation of this work).

1. R.Hajima, R.Nagai, in Proceedings of ERL2007, 133-138
2. K.Yamamoto, in Proceedings of ERL2011.

Simulation Setup

Lattice Setup for Simulation

- What are needed for simulation
  - Beam parameter (Bunch reptetition rate (1.3GHz), injection energy (10MeV), sufficient more bunch number(run time $t_{on} = 1 \times 10^{-4}$s, 130,000 bunches))
  - Lattice parameters (especially the linac lattice.)
  - HOM parameters (frequency, R/Q, Q_{ext}, polarization angle)
- 6 by 6 transportation matrix is used for "BI" lattice input file.
- Cavity matrix in Rosenzweig-Serafini's form [1] is used to take into account the cavity focusing. This helps the simulation closer to reality. [2]

$$M_{CAV} = \begin{bmatrix} \cos\alpha - \sqrt{2\cos(\Delta\phi)}\sin\alpha & \sqrt{8\frac{\gamma_i}{\gamma'}\cos(\Delta\phi)}\sin\alpha \\ -\frac{\gamma'}{\gamma_f}\left(\frac{\cos(\Delta\phi)}{\sqrt{2}} + \frac{1}{\sqrt{8}\cos(\Delta\phi)}\right)\sin\alpha & \frac{\gamma'}{\gamma_f}\left(\cos\alpha + \sqrt{2}\cos(\Delta\phi)\sin\alpha\right) \end{bmatrix}$$

where $\alpha \equiv \frac{1}{\sqrt{8\cos(\Delta\phi)}}\ln\left(\frac{\gamma_f}{\gamma_i}\right)$; $\gamma_i, \gamma_f, \gamma'$ are the Lorentz factor of injection energy, output energy and energy change, respectively. $\Delta\phi$ is the RF phase.

1. J. Rosenzweig, L. Serafini, Phys.Rev.E, 49(2), 1994.
2. I. Shin, et al., in Proceedings of PAC2011, WEP048.

Lattice Setup for Simulation

- Simulation were done for two different lattice designs.

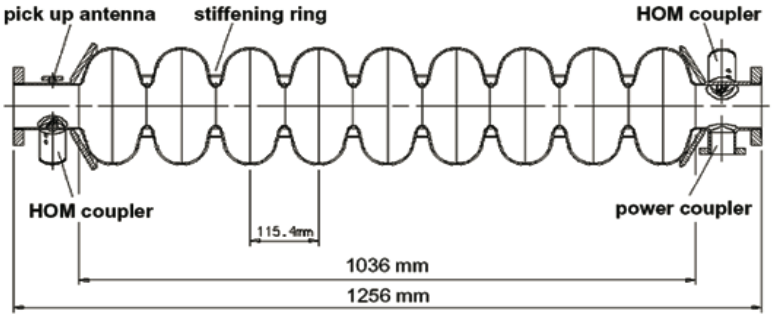
Tentative layouts of the two designs at KEK Tsukuba Campus

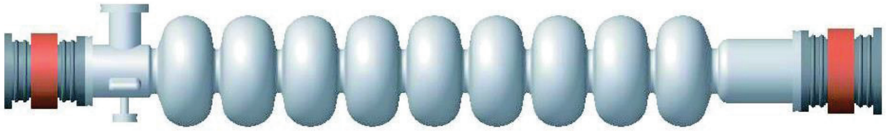
- Left: CDR design with 3.0GeV energy and 470m linac. Eacc=13.4MV/m.
- Right: New design with 3.4GeV energy and 630m linac. Eacc=12.5MV/m.

- Because of the field emission issue in KEK-ERL model-2 cavity, lower cavity gradient is more practical now.

HOM Parameters

- A 9-cell superconducting cavity modified from TESLA-type cavity to enhance the HOM damping is used for main linac.





- Left: 9-cell TESLA-type cavity [1];
- Diameter of iris D_{iris} =70mm.
- Diameter of beam pipe same as the iris diameter.
- Coaxial HOM coupler
- High cavity gradient.

- Right: 9-cell KEK-ERL model-2 cavity[2];
- Diameter of iris D_{iris} =80mm.
- Diameter of beam pipe 100mm(left) and 123mm(right).
- On-axis HOM damper.
- High average current.

1. TESLA TDR
2. T. Furuya, et al., in Proceedings of SRF2007, TUP39

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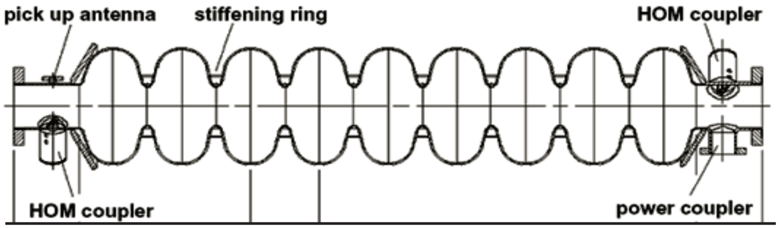
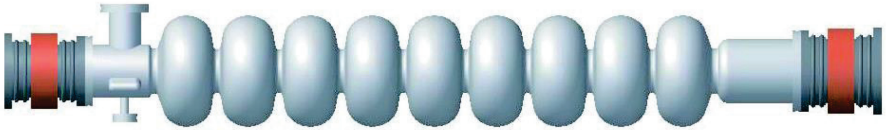




f	Q_e	R/Q	$\left(\frac{R}{Q}\right)Q_e/f$
(GHz)		(Ω/cm²)	(Ω/cm²/GHz)
1.707	5×10^{4}	11.21	3.28×10^{4}
1.734	2×10^{4}	15.51	1.79×10^{5}
1.869	5×10^{4}	6.54	1.75×10^{5}
1.874	7×10^{4}	8.69	3.25×10^{5}
1.880	1×10^{5}	1.72	9.15×10^{4}
2.575	5×10^{4}	23.80	4.62×10^{5}

Main dipole HOMs in TESLA-type cavity [1]

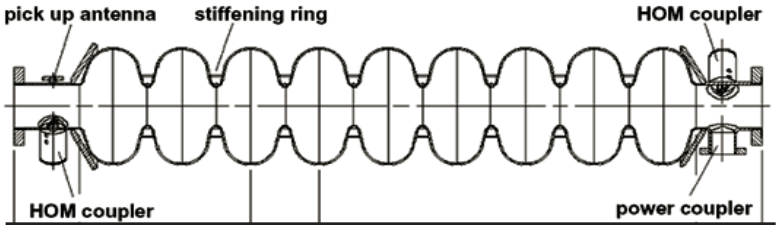
f	Q_e	R/Q	$\left(\frac{R}{Q}\right)Q_e/f$
(GHz)		(Ω/cm²)	(Ω/cm²/GHz)
1.835	1.101×10^{3}	8.087	4852
1.856	1.698×10^{3}	7.312	6691
2.428	1.689×10^{3}	6.801	4732
3.002	2.999×10^{4}	0.325	3246
4.011	1.141×10^{4}	3.210	9135
4.330	6.068×10^{5}	0.018	2522

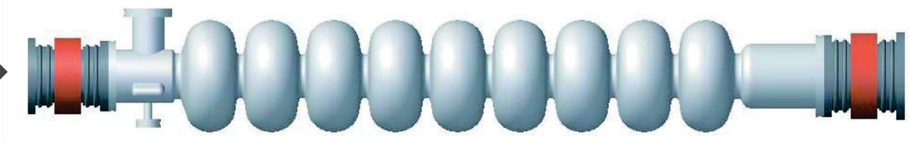
Main dipole HOMs in KEK-ERL model-2 cavity [2]

1. R. Wanzenber, TESLA Report 2001-33
2. R. Hajima, et al., in Proceedings of ERL2007, 133-138

HOM Parameters

- A 9-cell superconducting cavity modified from TESLA-type cavity to enhance the HOM damping is used for main linac.





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Main dipole HOMs in KEK-ERL model-2 cavity [2]

$$(R/Q)Q_{ext}/f < 1.4\times10^5\ (\Omega/\mathrm{cm}^2/\mathrm{GHz})$$

1. R. Wanzenber, TESLA Report 2001-33
2. R. Hajima, et al., in Proceedings of ERL2007, 133-138

Simulation Procedures

1. Threshold current vs. beam optics

$$I_{th} \propto \frac{V_b}{R_{12}} \cdot \frac{1}{\sin(\omega T_r)}$$

where

$$R_{12}(i \to f) = \sqrt{\frac{\beta_i \beta_f}{p_i p_f}} \sin \Delta\psi_{if}$$

The optics of the ERL is flexible, especially for the return loop. BBU threshold current with the change of betatron phase advance $\Delta\psi_{x,y}$ and the recirculating time T_r need to be considered.

2. Find out the most dominant HOM to BBU in the cavity.

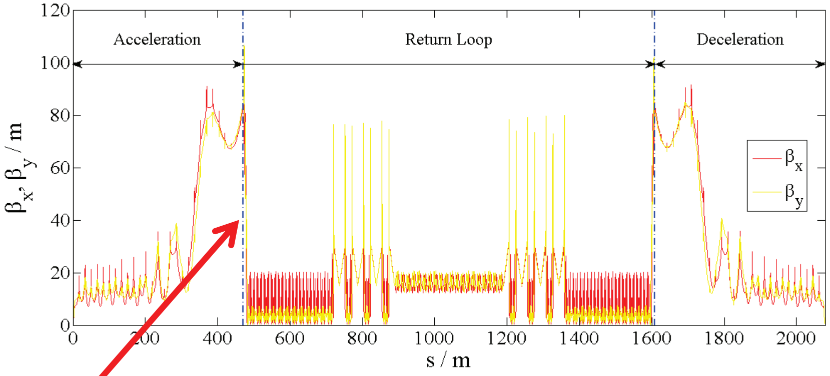
3. BBU threshold current with HOM randomization should be considered.

Simulation Results

Betatron Phase Advance Changes (1)

- 3.0GeV ERL design (CDR) [1]
  - 28 cryomodules×8cavities

    = 224 cavities in total
  - E_{inj}=10MeV.
  - E_{acc}=13.4MV/m.
  - E_{full}=3.01GeV.
  - Mirror-Symmetrical optics design applied.



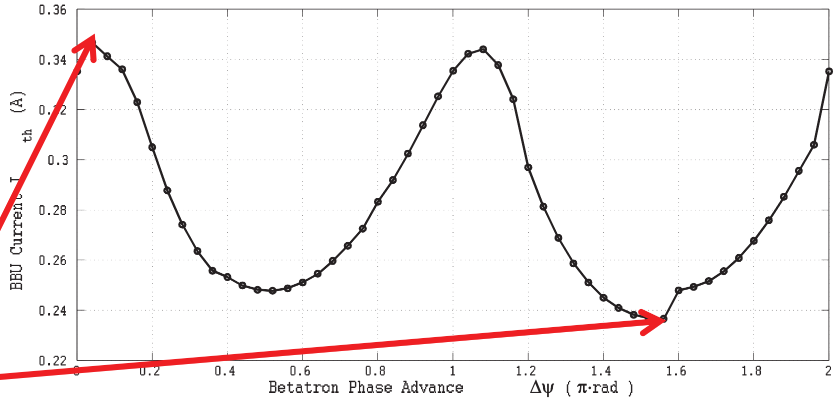
$\beta_{x,y}$ of the 3.0GeV linac design

- A matrix element is inserted to change the $\Delta\psi_{x,y}$ value in $[0, 2\pi]$ but without changing the twiss parameters and loop length.

- Simulation results:

  $I_{th,max} \approx 345mA$ at $\Delta\psi \approx 0.04\pi \cdot rad.$

  $I_{th,min} \approx 236mA$ at $\Delta\psi \approx 1.56\pi \cdot rad.$



I_{th} vs. Betatron phase advance $\Delta\psi$

[1] Lattice provided by M.Shimada

Betatron Phase Advance Changes (2)

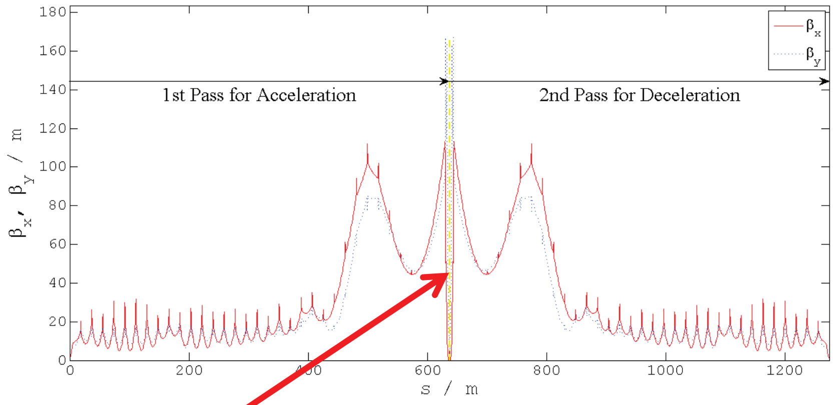
- 3.4GeV ERL design (NEW) [1]
  - 34 cryomodules×8cavities = 272 cavities in total
  - E_{inj}=10MeV.
  - E_{acc}=12.5MV/m.
  - E_{full}=3.41GeV.
  - Mirror-Symmetrical optics design applied. Return loop lattice has not fixed.

- A matrix element is inserted to change the $\Delta\psi_{x,y}$ value in $[0, 2\pi]$ but without changing the twiss parameters and loop length.

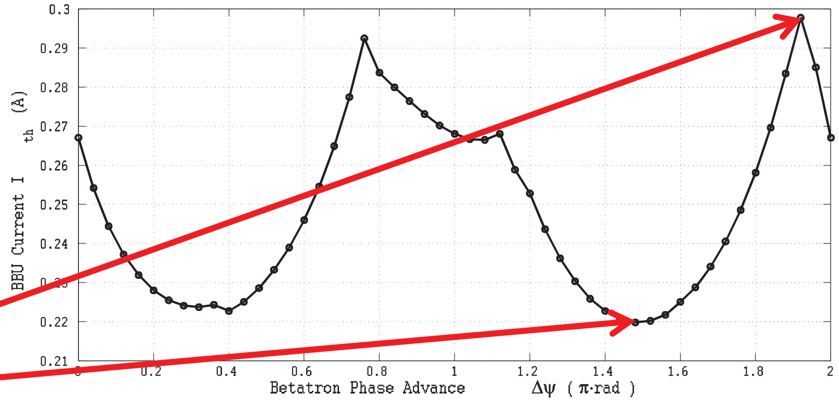
- Simulation results:

  $I_{th,max} \approx 298mA$ at $\Delta\psi \approx 1.92\pi \cdot rad.$

  $I_{th,min} \approx 220mA$ at $\Delta\psi \approx 1.48\pi \cdot rad.$



$\beta_{x,y}$ of the 3.4GeV linac design



I_{th} vs. Betatron phase advance $\Delta\psi$

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[1] Lattice provided by M.Shimada

Single Cryomodule Contribution to BBU

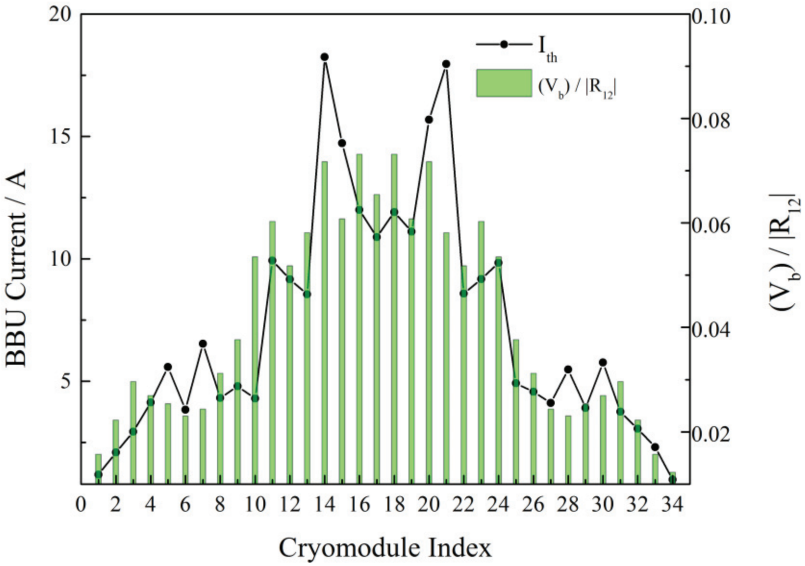
- When BBU occurs, which of the cavities contribute more to the instability?
- BBU simulated for each cryomodule separately, i.e., remove the HOM impedance of all the other cavities but keep the cavity matrix.
- Cryomodules at the lower energy sections (the start and the end of linac) clearly have smaller BBU current than those in the middle of the linac.

- Threshold dependency on beam energy and transportation

$$I_{th} \propto \frac{V_b}{R_{12}}$$

The distribution of BBU current is roughly consistent with the distribution of V_b/R_{12} in each cryomodule.

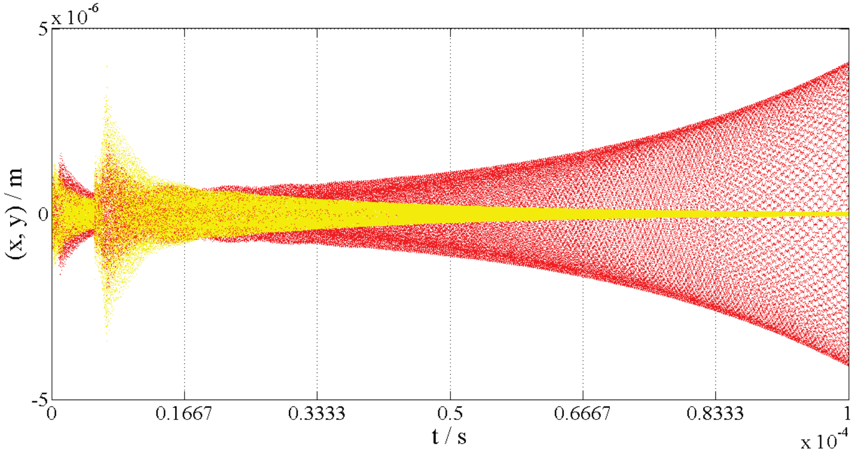
- BBU are easier to occur in those cavities at low energy sections.



- Possible to improve the BBU threshold current by optimizing the linac lattice to improve the BBU current in lower energy sections (future work).

Dominant Mode

- 3.0GeV ERL; $I_{th} = 236\text{mA}$ (the minimum value). A beam with current 238mA is used for a single track. Total beam-on time 1×10^{-4}s (130,000 bunches for 1.3GHz bunch repetition rate).
- The (x, y) coordinates at the exit of the linac on second pass (the dump) of each electron bunch are output. The trend of exponential growth occurs on x-coordinate and meanwhile y-coordinate is stable.



Transverse coordinates of each bunch of at the exit of the 2nd pass of linac.

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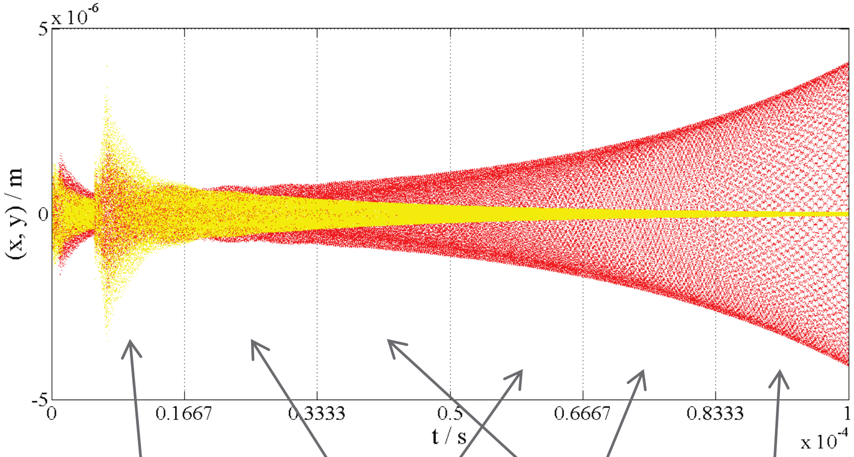
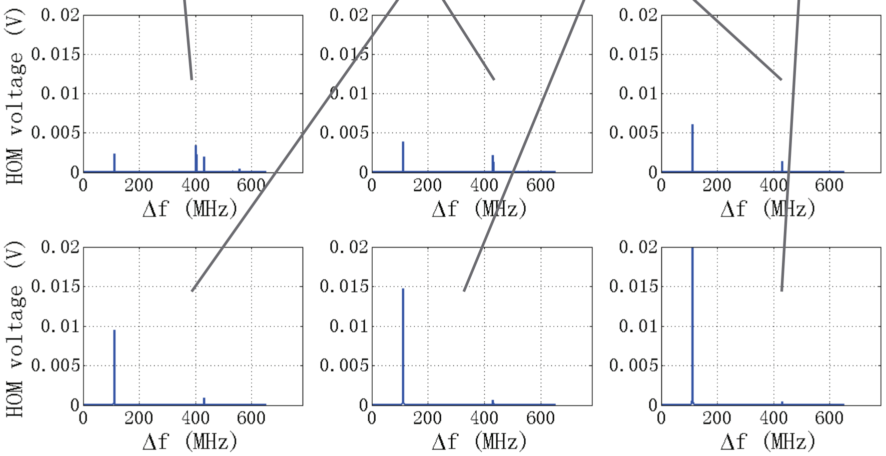
- The (x, y) coordinates at the exit of the linac on second pass (the dump) of each electron bunch are output. The trend of exponential growth occurs on x-coordinate and meanwhile y-coordinate is stable.
- FFT is done to the x-coordinate profile in different time zone in order to get the HOM spectrum



Transverse coordinates of each bunch of at the exit of the 2nd pass of linac.

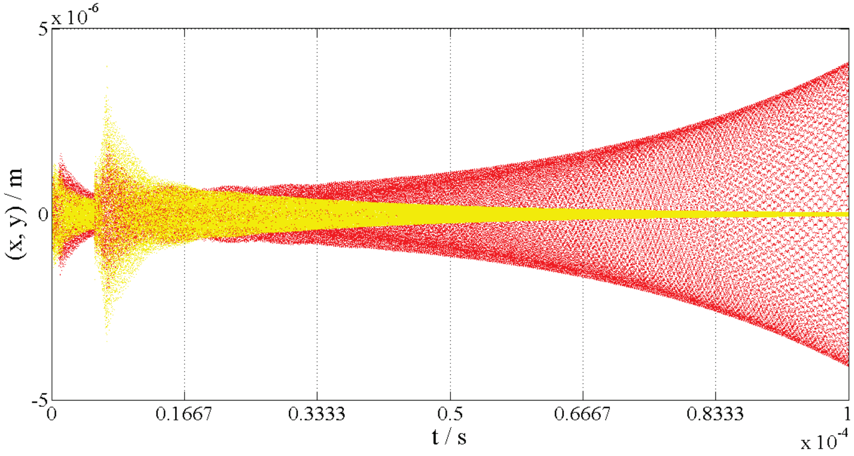


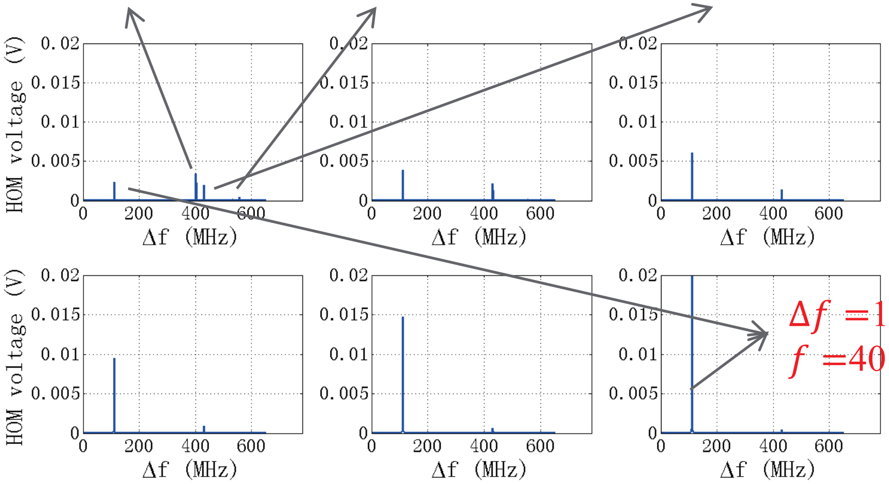
FFT of the transverse oscillation for different time zone

Dominant Mode

- The x-label of FFT results (Δf) is the minimum frequency deviation of HOM to the nearest harmonics of the bunch repetition rate (1.3GHz).

f	Δf	$\left(\frac{R}{Q}\right) Q_e / f$
(MHz)	(MHz)	(Ω/cm^2/GHz)
1835	535	4852
1856	556	6691
2428	172	4732
3002	402	3246
4011	111	9135
4330	430	2522





Δf =402MHz, f =3002MHz

Δf =556MHz, f =1856MHz

Δf =430MHz, f =4330MHz

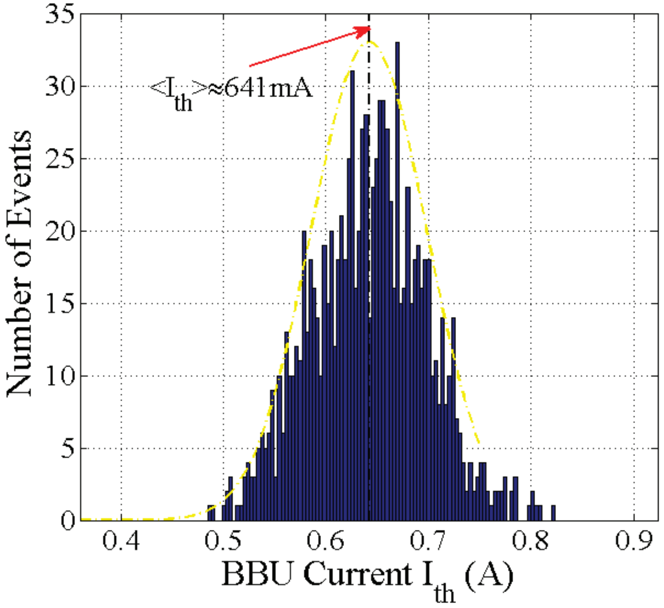
Δf =111MHz, f =4011MHz

- The dominant HOM in KEK-ERL model-2 cavity is the mode with f=4011MHz

HOM frequency Randomization (1)

- HOM frequency randomization was not included in the previous simulation.
- Simulation and experimental results ^{2} show a 1~2 MHz frequency spread for the HOMs in KEK-ERL model-2 cavity.

- BBU threshold simulated for 3.0GeV ERL. Lattice corresponds to the minimum I_{th} value (236mA) in $\Delta\psi$ scan.
- 1000 sets of HOM frequency data. In each set, the HOM frequency is Gaussian distributed among 224 cavities. The HOM spread is σ_f =1MHz.
- An approximately Gaussian distribution of BBU current resulted by Gaussian HOM frequency randomization.



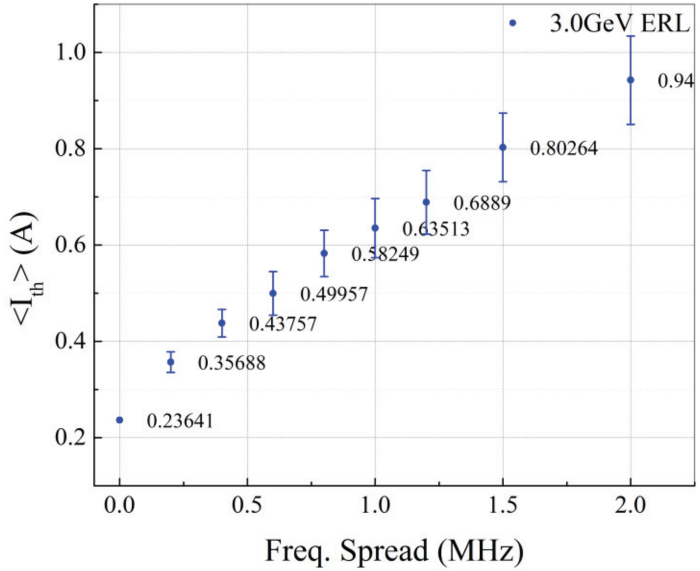
Histogram of the BBU current events

Average BBU current is 641mA for this simulation and the std. of BBU current is about 56mA.

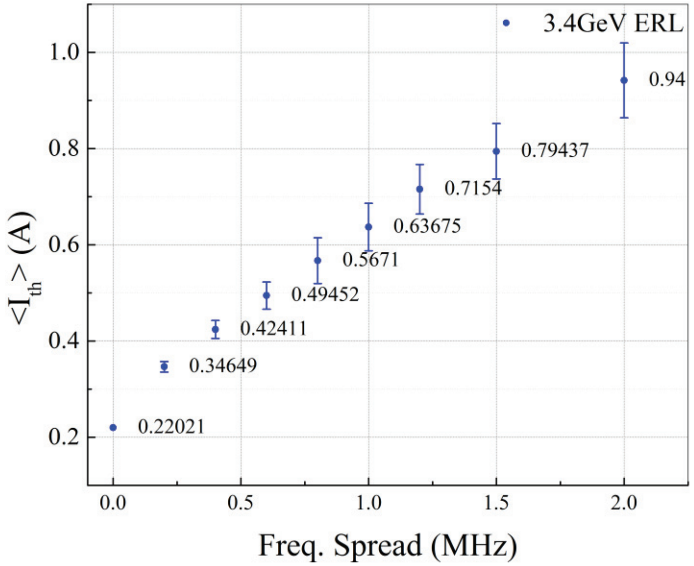
1. L. Xiao, et al., SLAC-PUB-12634 (2007)
2. M.Sawamura, et al., in Proceedings of ERL2011

HOM frequency Randomization (2)

- Average BBU current is used to represent the BBU threshold current with HOM frequency randomization.
- Simulation of 50 sets HOM frequency data for each σ_f, average BBU current is calculated with std., for both 3.0GeV and 3.4GeV ERL designs.



$< I_{th} >$ vs. σ_f for 3.0GeV ERL



$< I_{th} >$ vs. σ_f for 3.4GeV ERL

- Average BBU current increases almost linearly with the increase in σ_f. About 940mA is reached at σ_f =2MHz for both designs.

BBU Current vs. Return Loop Length Change

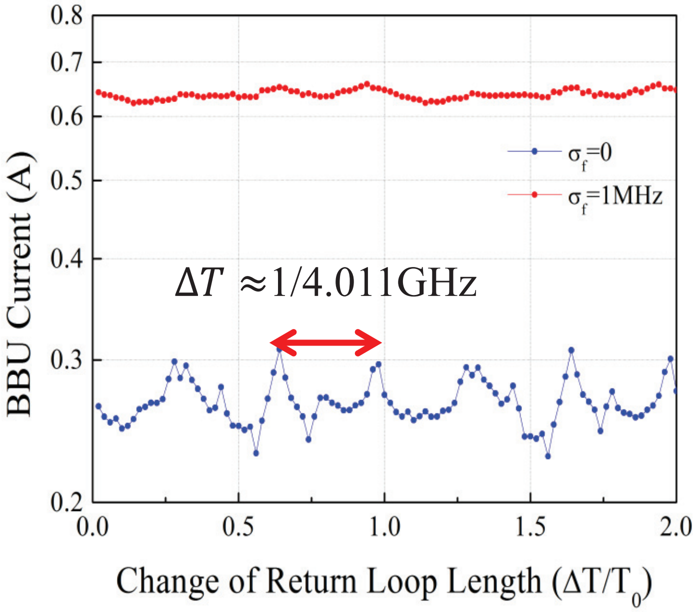
- BBU threshold dependency on return loop length

$$I_{th} \propto \frac{1}{\sin(\omega T_r)}$$

- Simulate the BBU current vs. the Change of the return loop length in unit of $\Delta T/T_0$, where T_0 is the time period of the accelerating mode (1.3GHz).

- For the case of $\sigma_f = 0$, a quasi-periodical variation of BBU current with return loop length change is observed. The interval of the two peaks of BBU current is determined by the mode with frequency 4.011GHz.

- For the case of $\sigma_f = 1\text{MHz}$, the phase correlation of the same HOM in different cavities is disturbed. Thus a higher BBU threshold current but without the quasi-periodical variation is observed.



Summary

Summary

- The HOM-BBU simulation results of KEK ERL light source are presented.

	3.0GeV ERL (CDR)	**3.4GeV ERL (NEW)**
No. of Cavity	28×8=224	34×8=272
Linac Length	470.4m	628.9m
E_{inj}	10MeV	10MeV
E_{acc}	13.4MV/m	12.5MV/m
E_{full}	3.01GeV	3.41GeV
I_{th} (σ_f=0)	236mA	220mA
I_{th} (σ_f=2MHz)	941mA	942mA

- With 9-cell KEK-ERL model-2 cavity, simulation results demonstrate BBU threshold current larger than 100mA for both designs. The most dominant HOM is the mode with frequency 4.011GHz.

- Future work:
    - Further optimization to the linac lattice and the betatron phase advance of return loop can be done to improve the BBU threshold current.
    - Optimization of the SC cavities to get higher gradient while keeping the HOM property.

Thank you for your attention!

This work is a cooperation with M.Shimada, N.Nakamura in KEK ERL group. Thanks to R.Hajima from JAEA, K.Umemori, K.Yamamoto and many other people in KEK ERL group. Special thanks to K.Ohmi, D.Zhou K.Sonnad for many useful comments.
Most of this work is finished during my Ph.D. candidate in the SRF group of Peking University. Also thanks to J-E.Chen, K.Liu, S.Huang, L.Feng and many other people in PKU SRF group.