Transverse beam breakup simulation for compact and Multi-GeV ERLs

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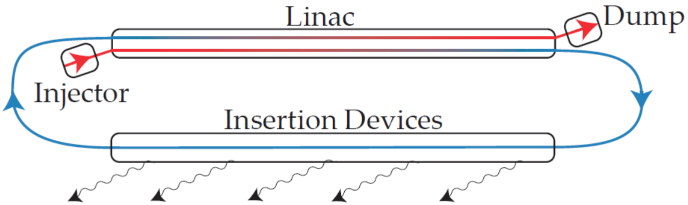
Outline

Abstract

In energy recovery linacs (ERLs), the transverse beam break-up (BBU) due to the HOMs of RF cavities may limit their capability of running at higher beam current. It is important to determine the BBU threshold via simulations while designing the ERLs. At Peking University, a compact ERL test facility is under construction, which will use two 9-cell TESLA-type RF cavities in the main linac. The BBU effect was simulated for the PKU-ERL test facility and the possibility of using 9-cell TESLA-type cavity on such a compact ERL was proved. At KEK, a multi-GeV ERL based synchrotron light source, extendable to a XFEL-O, is under design. The designed average current for the multi-GeV ERL is up to 100mA. The BBU effects were simulated with various design schemes. In this talk, I will briefly overview the progress of the compact ERL at PKU and the BBU theories and simulations codes. The BBU simulations for the compact ERL at PKU and the multi-GeV ERL at KEK will be presented as well.

Energy Recovery Linacs



Benfities

- Saving RF-power: High current.
- Good beam quality: not limited by the machine
- Reduce the energy dispose on the dump

$\Rightarrow$

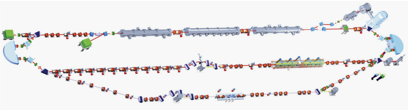
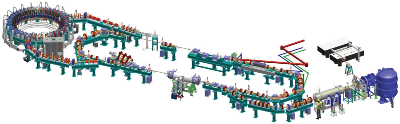
Applications

- Next generation light source;
- High power FEL and THz radiation source;
- other applications.

ERLs all over the World

Existed and Existing ERLs

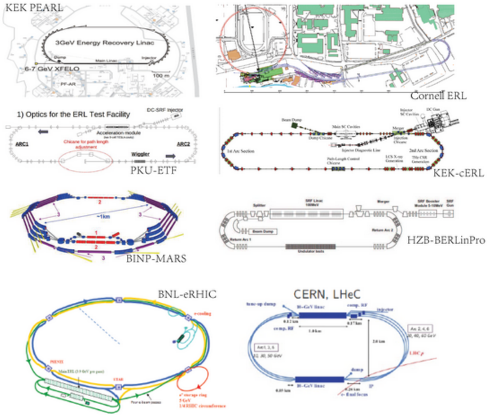
- 1965, proposed by M. Tigner.
- Realized by several laboratories during 1970s and 1980s as experiments.
- JLab(IR-FEL Demo@1998[1], IR-FEL Upgrade@2004[2], JLAMP@2012[3], CEBAF@2003[4]), JAERI(2001)[5], BINP(2004)[6], Daresbury(ALICE@2010)[7], ERL facilities after 1990s

Left: JLAMP@JLab; Right: ALICE@Daresbury

1. Benson, S., et al., NIM A, 429(1):27-32, 1999. 2. Neil, G., et al., NIM A, 557(1):9-15, 2006.
3. Douglas, G., et al., Proceedings of IPAC2012. 4. Bogacz, A., et al., Proceedings of PAC2003.
5. Hajima, R., et al., Proceedings of PAC2001. 6. Bolotin, V.P., et al., BINP-tech report, 2004.
7. Jackson, F., et al., Proceedings of IPAC2011.

ERLs all over the World



ERLs under construction or under design.[1]

1. Nakamura, N., Proceedings of IPAC2012

The ERL project at Peking University

PKU-ETF: Peking University ERL Test Facility

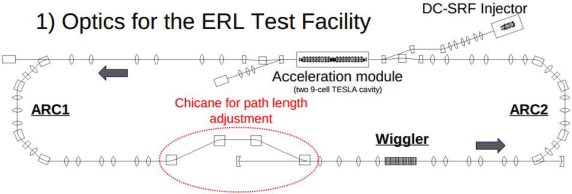
- First ERL project proposed in China.
- Superconducting accelerator technology; FEL/THz/ICS research; Other related technologies.

Two stages

- First stage: DC-SRF injector with THz beamline.
- Second stage: Energy recovery linac based on the DC-SRF injector.

The ERL project at Peking University

Parameters and lattice design



One of the lattice designs of PKU-ETF[1]

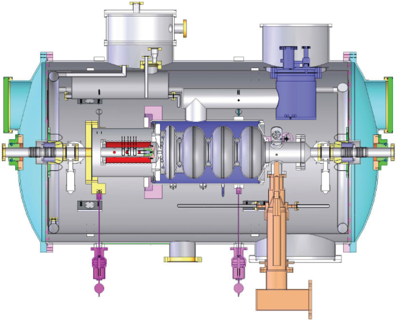
- DC-SRF injector; 2×9-cell TESLA-type cavities; Beamline; Undulator; etc.
- Macro pulse mode.

Energy	Bunch charge	Emittance	Bunch length
30MeV	60pC	4μm	4ps
Energy spread	rep. rate	pulse rep. rate	pulse length
0.32% (FWHM)	81.25/26MHz	10Hz	2ms

1. Huang, S., et al., Proceedings of ERL2011

The ERL project at Peking University

A key component: DC-SRF photoinjector[1]



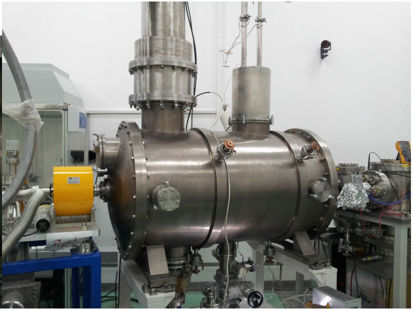
- Combination of a DC pierce gun and a 3.5-cell superconducting cavity.
- Two working modes
  - Marco pulse or continue wave mode for ERL.
  - Bunch compressor mode for coherent THz radiation.

- Now the THz mode is under commissioning[2]. Stable electron beam has been generated.

1. Zhu, F., et al., Proceedings of SRF2011 2. Liu, K., et al., Proceedings of SRF2013

The ERL project at Peking University

A THz radiation source based on the DC-SRF photoinjector[1]



- DC-SRF photoinjector(including the photocathode); Driving-Laser; Solid state microwave source;
- Beamline(Solenoid & Beam diagnostics); 10-period Wiggler; Beam dump; etc.
- LLRF control system & Control system based on EPICS.[3]

1.Thanks Feng Liwen for providing the pictures.
2. Wang, F., et al., arXiv.1405.1238

The ERL project at Peking University

upper left: The first 2K cryogenic system in China; upper right: Bruker Far Infra-red Spectrograph; bottom: PKU people and visitors in the control room.[1,2,3]

1. Thanks Feng Liwen for providing the pictures. 2. Huang, S.L., Proceedings of IPAC2013 3. Hao, J.K., Chinese Physics Letters, 30(8) 080702(2013)

Introduction of the ERL project at Peking University

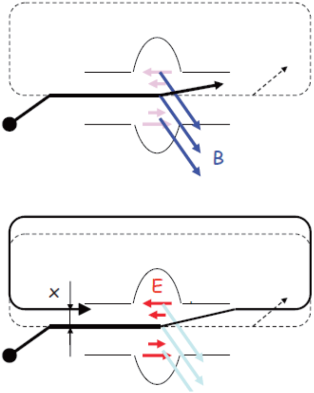
Theory and simulation code of ERL BBU

BBU simulation for compact ERL with 9-cell TESLA-type cavities

BBU simulation for a multi-GeV ERL light source

Summary

HOM-BBU in ERLs



- Positive feedback process between recoverying beam and HOMs in superconducting cavities.
- Limit the maximum beam current of ERL.
- 1977, first observed on the SCA at Stanford.
- 1986, SCA operates on ERL model.
  2004, observed on the IR-FEL upgrade at JLab.
  2007, JLab, CEBAF.
- Theoretical research by SLAC, JLab, Cornell Univ., etc..

BBU theory - Time Domain: Energy conservation

E. Pozdeyev, Phys.Rev.ST AB. 8, 074401 (2005).

Assumptions: Single HOM in single cavity; twice pass through linac; Energy loss negelected in two passes.

$$\begin{aligned}\frac{dU}{dt} &= \frac{dU_{beam}}{dt} - P_c = \langle \Delta U_1 + \Delta U_2 \rangle \cdot f_b - P_c \\ &= -\frac{V_a^2}{a^2}\left[I_b \frac{q}{\omega_n p} R_{12}^* \frac{\sin(\omega_n t_r)}{2} - \frac{1}{k_n^2 (R_d/Q) Q_L} \right] = 0\end{aligned}$$

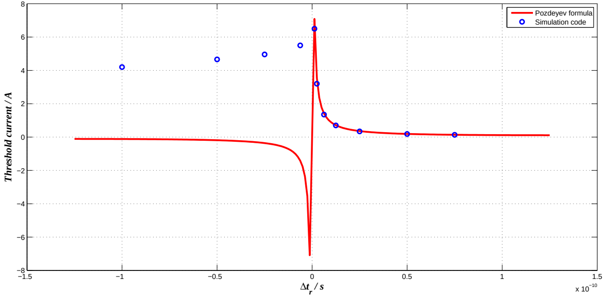
$$\Downarrow$$

$$I_{th} = -\frac{2V_b}{k(R_d/Q_0) Q_L R_{12}^* \sin(\omega t_r)}$$

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

- Not suitable for $R_{12}^* \sin\omega t_r \geq 0$.

BBU theory - Time Domain



Comparison of analytical formula with simulation code

- Analytical formula agrees well with simulation when $R^*_{12} \sin \omega t_r < 0$.
- When $R^*_{12} \sin \omega t_r \geq 0$, BBU threshold current is relatively high.

BBU theory - Frequency Domain

G. Hoffstaetter & I. Bazarov, Phys.Rev.ST AB. 7,054401 (2004).

Dispersion relation - A more general BBU threshold current formula.

$$\frac{1}{\mathrm{I_0}} = \frac{\mathcal{K}\left(\mathrm{e}^{\frac{\omega_\lambda \mathrm{t_b}}{2\mathrm{Q}_\lambda}}\mathrm{e}^{-\mathrm{i}\Omega \mathrm{t_b}}\right)\sin(\omega_\lambda \mathrm{t_b})}{1-2\left(\mathrm{e}^{\frac{\omega_\lambda \mathrm{t_b}}{2\mathrm{Q}_\lambda}}\mathrm{e}^{-\mathrm{i}\Omega \mathrm{t_b}}\right)\cos(\omega_\lambda \mathrm{t_b})+\left(\mathrm{e}^{\frac{\omega_\lambda \mathrm{t_b}}{2\mathrm{Q}_\lambda}}\mathrm{e}^{-\mathrm{i}\Omega \mathrm{t_b}}\right)^2}\frac{1}{\mathrm{e}^{-\mathrm{i}\Omega \mathrm{t_r}}}$$

where

$$\mathcal{K} \equiv \frac{\mathrm{t_b}(\mathrm{R_d}/\mathrm{Q_0})_\lambda \mathrm{k}_\lambda \omega_\lambda \mathrm{R}_{12}}{2\mathrm{V_b}}$$

- The smallest positive value of $\mathrm{I_0}$ to make $\mathrm{Im}(\Omega) = 0$ is the threshold current.

BBU simulation codes

For real cases, simulation codes required.

Two main algorithms:

- Tracking (Time domain): TDBBU, ERLBBU, BBU-R, bi
- Eigenvalue solution (Freq. domin): MATBBU, BMAD

Main approximations

- The kick effect of HOMs treats as thin lens;
- Point charge;
- Energy change negelected between two passes;
- Linear beam transportation.

BBU simulation codes

Comparison of BBU simulation codes

Name	TDBBU	ERLBBU	MATBBU	BBU-R	bi	Bmad
Developer	JLab	JLab	JLab	JAERI	Cornell	Cornell
Method	track	track	eigenvalue	track	track	eigenvalue
T/L	T	T	T	T	T/L	T
Dimensional	1D	2D	1D	1D	1D	1D
Polarization	X/Y	arbitray	X/Y	X/Y	arbitray	arbitray
Topology	arbitray	2	2	2	arbitray	2
Language	Fortran/C	C++/java	C	C	C++	Fortran

- Simulation results meet well with the experiment at JLab ERL-FEL[1]
- Here, the bi code, which was developed by I. Bazarov of Cornell Univ.,[2] is used.

1. Tennant C.D., Ph. D. Dessertion, 2006
2. bi, http://www.lepp.cornell.edu/ ib38/bbu/

Introduction of the ERL project at Peking University

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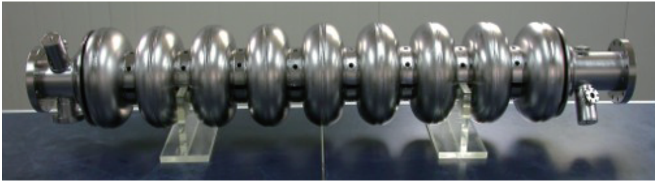
BBU simulation for compact ERL with 9-cell TESLA-type cavities

BBU simulation for a multi-GeV ERL light source

Summary

9-cell TESLA-type cavity@Peking University

- Relatively mature in shape design and manufacture technology.
- High R/Q and Q_0 value, high accelerating efficiency



Peking University has a lot of experiences on the manufacturing of 9-cell TESLA-type cavities.

- The first 9-cell TESLA-type cavity in China[1];
- The first 9-cell TESLA-type cavity to meet the basic requirement of ILC in China.

1. Lu, X.Y., et al., Chinese Physics Letter, 25(11) 3934(2008)

High-Order-Modes in TESLA-type cavity

- Several dipole HOMs with large value of R/Q and Q_L exist in 9-cell TESLA-type cavity.

Dipole HOMs with the largest value of $(R/Q)Q_L/f$ in TESLA-type cavity[1,2]

f [GHz]	Q_e	R_d/Q_0 [Ω/cm^2]	$(R/Q)Q_e/f$ [$\Omega/cm^2/GHz$]	Type
1.7074	5×10^4	11.21	3.28×10^5	TE_{111}
1.7343	2×10^4	15.51	1.79×10^5	TE_{111}
1.8687	5×10^4	6.54	1.75×10^5	TM_{110}
1.8738	7×10^4	8.69	3.25×10^5	TM_{110}
1.8799	1×10^5	1.72	9.15×10^4	TM_{110}
2.5751	5×10^4	23.80	4.62×10^5	TE_{121}

Question:
Can 9-cell TESLA-type cavity be used on compact ERLs like the PKU-ERL Test Facility?

1. TESLA TDR
2. Luo, X., et al., unpublished

BBU simulation – Modeling

Main parameters for simulation

- HOM parameters $(\mathrm{f}, \mathrm{R/Q}, \mathrm{Q_L}, \theta)$
- Beam parameters $(\mathrm{f_b}, \mathrm{E_{inj}})$
- Beamline parameters (Transport matrix, Recirculating time (length of beamline))

HOM parameters

- Each HOM has two polarization directions: $\mathrm{x}(0^\circ)$ and $\mathrm{y}(90^\circ)$.
- HOMs affact individually to the beam.

BBU simulation – Modeling

Beamline parameters

- Linear transfer matrix
- Transverse focusing effect included in cavity matrix – Rosenzweig-Serafini's form:

Rosenzweig-Serafini's form of the transfer matrix of a pure π mode cavity

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

- x-y phase space no coupling: $R_{14} = R_{23} = 0$

1. Rosenzweig, G., Serafini, L., Phys. Rev. E., 49(2):1599,1994

BBU threshold current VS. Betatron phase advance

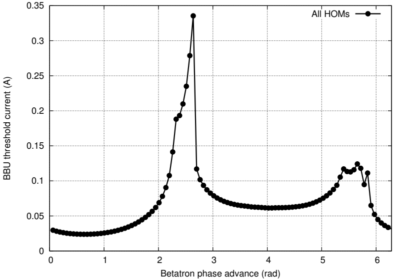
For x-polarized HOM: $R^*_{12} = R_{12}$

$$R_{12}(i \to f) = \gamma_i \sqrt{\frac{\beta_i \beta_f}{\gamma_i \gamma_f}} \sin \Delta\psi \approx p_i \sqrt{\frac{\beta_i \beta_f}{p_i p_f}} \sin \Delta\psi$$

$$I_{th} \propto -\frac{1}{R_{12}}$$

$$\Downarrow$$

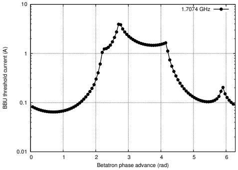
$$I_{th} \propto \frac{1}{\sqrt{\beta_1 \beta_2} \sin \Delta(\psi)}$$



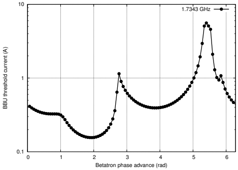
- $\Delta\psi$ clearly influences the BBU threshold current.
  - Maximum I_{th} about 330mA and minimum about 24mA.

The most threatening HOM in TESLA-type cavity

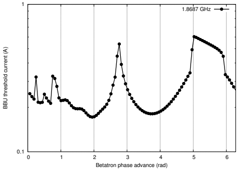
BBU threshold current when each HOM acts individually to the beam



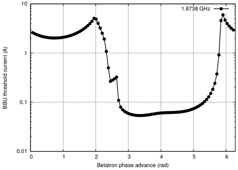
(a) 1.7074 GHz TE_{111}



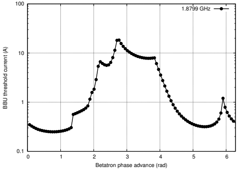
(b) 1.7343 GHz TE_{111}



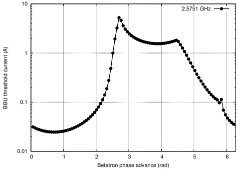
(c) 1.8687 GHz TM_{110}



(d) 1.8738 GHz TM_{110}



(e) 1.8799 GHz TM_{110}

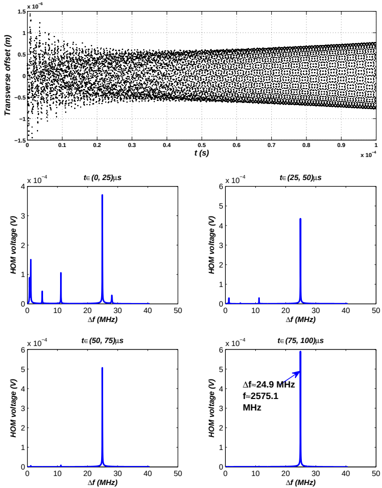


(f) 2.5751 GHz TE_{121}

- Most threatening HOMs in 9-cell TESLA-type cavity
  1.7074GHz(TE_{111}), 1.8738GHz(TM_{110}), 2.5751GHz(TE_{121})

The most threatening HOM in TESLA-type cavity

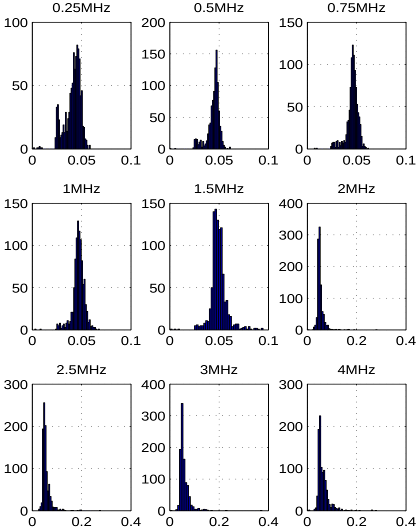
- $\Delta\psi = 0$, $I_{th} \approx 30$mA。
  $I_0 = 33$mA ,
  $t_{on} = 100\mu$s。
- x offset VS. time
  ⇓FFT
  Frequency spectrum evolution VS. time



- TE_{121} – like mode determines the BBU at last.

Influence of inhomogeneous HOMs

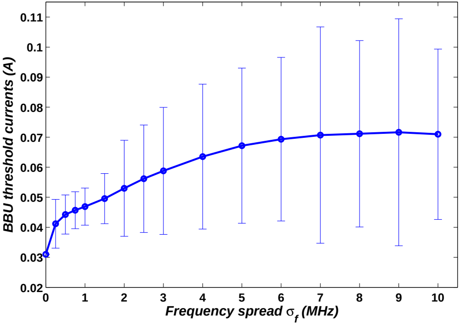
- Inhomogeneous of cavity shape during farbication leads to HOM spread between different cavities.[1]
- HOM frequency spread disturbs the phase between bunch and HOMs
- 1000 random seed of HOM frequency (Gaussian distribution)



1. Xiao, L., et al., Proceedings of PAC2007

Influence of inhomogeneous HOMs

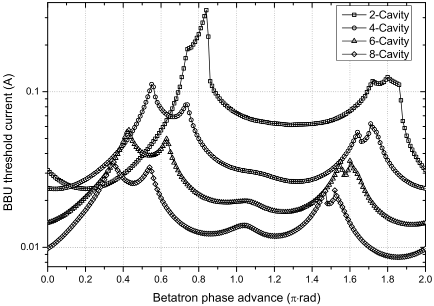
- σ_f: 0MHz-10MHz, 1000 Gasussian random seed of frequency at each σ_f.
- Average BBU threshold value increases with the σ_f increases.
- Changes slower after $\sigma_f > 6$MHz



- Due to the limited cavity number, large fluctuations of the threshold currents.

BBU threshold with different cavity numbers

- Higher energy requires more cavities.
- Same gradient; Same E_{inj}; Same t_r; Single module.



- 8×9-cell TESLA-type cavity: $I_{th,max}$ ≈35mA, $I_{th,min}$ ≈7mA.
- BBU threshold current drops clearly with the cavity number increases.

BBU superssion methods

- Improve HOM damping ability - High current superconducting cavities
  - 9-cell KEK-ERL cavity; 7-cell Cornell cavity; 7-cell CEBAF cavity; 5-cell BNL cavity......etc. [1]
- Improve the beam energy (Injection energy and accelerating gradient to reduce cavity number)
- Beam optics methods
  - Adjusting the betatron phase advance or the return loop length.
  - Inducing transverse phase space coupling: Rotation/Reflection.
- Beam-based feedback.

BBU superssion methods - Beam optics methods

Betatron phase advance adjusting

- Point-to-Point focusing: Adjusting betatron phase advance without influence the phase space match.
- JLab method: Phase Trombone[1,2]

$$\frac{\Delta\beta_n}{\beta_o^n} = \mp\sum_{k=1}^{N} P_k\beta_k^n \sin(2(\psi_o^n - \psi_k^n))$$

$$\Delta\alpha_n = \pm\sum_{k=1}^{N} P_k\beta_k^n(\cos(2(\psi_o^n - \psi_k^n)) - \alpha_o \sin(2(\psi_o^n - \psi_k^n)))$$

$$\Delta\psi_n = \pm\frac{1}{2\pi}\sum_{k=1}^{N} P_k\beta_k^n \sin^2((\psi_o^n - \psi_k^n)$$

1. Douglas, D., Proceedings of PAC1991
2. Douglas, D., JLAB-TN-04-017, 2004

BBU superssion methods - Beam optics methods

- Transverse phase space coupling method[1]

Reflection

$$M_{\mathrm{ref}} = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

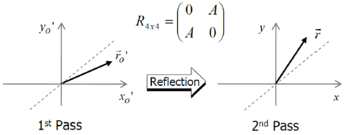
$$R_{12} = R_{34} = 0$$

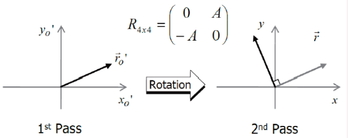
Rotation

$$M_{\mathrm{ref}} = \begin{pmatrix} 0 & I \\ -I & 0 \end{pmatrix}$$

$$R_{12} = R_{34} = 0$$

$$R_{14} + R_{23} = 0$$

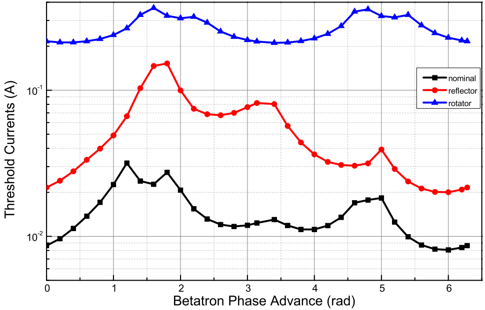




1. R.Rand & T. Smith, Particle accelerators, 2:1– 13, 1980

BBU superssion methods - Beam optics methods

- Efficiency of transverse phase space coupling.
- 8×9-cell TESLA-type cavity in a single cryomodule.



- BBU threshold current improves significantly. $I_{th}^{(norm)} < I_{th}^{(ref)} < I_{th}^{(rot)}$(with same $\Delta\psi$)
- Limitation: Sometimes transverse phase space coupling should be avoid.

BBU of ERL light source

ERL light source, BBU is much complex than compact ERLs

- Higher beam energy: MeV→GeV ⇒ Much more cavities.
- Average current up to 100mA ⇒ Stronger beam-HOM interaction.

KEK 3-GeV ERL light source——PEARL

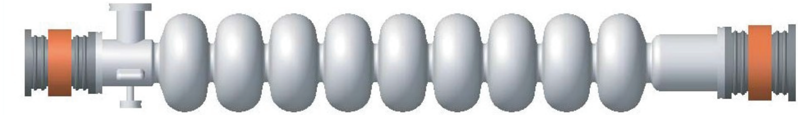
- 3-3.5GeV ERL light source & 6-7GeV XFEL-O
- BBU simulation for 5-GeV ERL design carried out in 2007[1].
- In the preliminary design report, preciesely simulation of the new design is not included.

BBU simulation for 3-GeV ERL

- 2 different ERL designs: 3.0-GeV (470m-linac); 3.4-GeV (630m-linac)[3]
- 9-cell KEK-ERL mode-2 superconducting cavity used.

1. Hajima, R. Proceedings of ERL2007
2. ERL preliminary design report(2012)
3. Lattice file provided by Miho Shimada

9-cell KEK-ERL mode-2 cavity



9-cell KEK-ERL mode-2 cavity

main HOMs in 9-cell KEK-ERL mode-2 cavity[1].

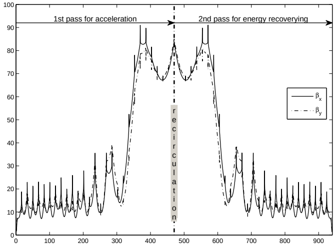
f [GHz]	Q_e	R/Q [Ω/cm^2]	$(R/Q)Q_e \cdot f$ [Ω/cm^2/GHz]
1.835	1.1010×10^3	8.087	4852
1.856	1.6980×10^3	7.312	6691
2.428	1.6890×10^3	6.801	4732
3.002	2.9990×10^4	0.325	3246
4.011	1.1410×10^4	3.210	9135
4.330	6.0680×10^5	0.018	2522

- 2007, 5-GeV ERL design: I_{th} ≈600mA[1].

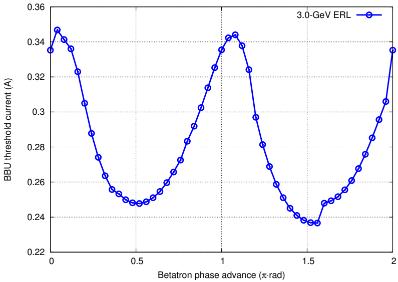
1. Sakai H., et al., Proceedings of ERL2007

1

3.0-GeV ERL design

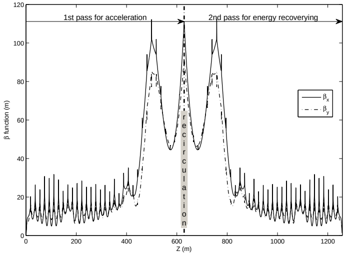


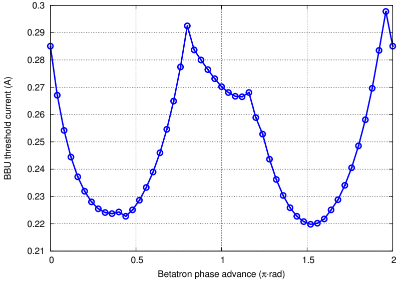
- 28 modules×8 cavities, E_{inj}=10MeV, E_{acc}=13.4MV/m, E_{full}=3.0GeV.
- β value at the end of linac is about 83m.



- $\Delta\psi \in [0, 2\pi]$, $I_{th,min}$ ≈240mA and $I_{th,max}$ ≈340mA.

3.4-GeV ERL design

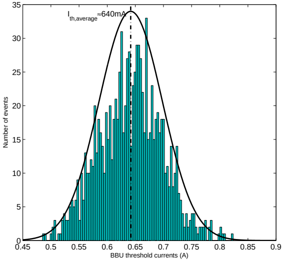




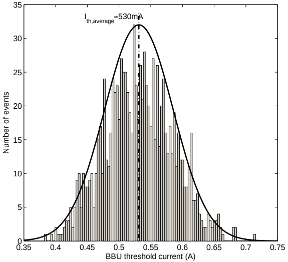
- 34 modules×8 cavities, E_{inj}=10MeV, E_{acc}=12.5MV/m, E_{full}=3.4GeV.
- β value at the end of linac is about 100m.
- $\Delta\psi \in [0, 2\pi]$, $I_{th,min}$ ≈220mA, $I_{th,max}$ ≈300mA

HOM frequency spread

- 1000 random seeds with $\sigma_{\mathrm{f}} = 1\mathrm{MHz}$



3.0-GeV ERL



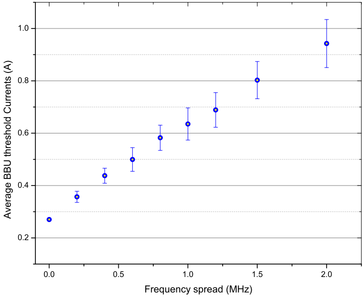
3.4-GeV ERL

$\sigma_{\mathrm{f}} = 1\mathrm{MHz}$

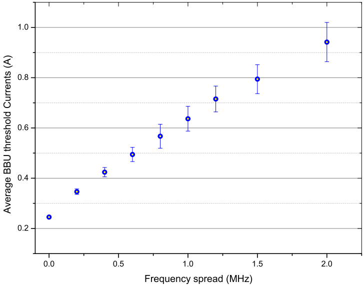
- $\overline{\mathrm{I}_{\mathrm{th}}^{(1)}} \approx 640\mathrm{mA}$, $\sigma_{\mathrm{I}}^{(1)} \approx 56\mathrm{mA}$, $\sigma_{\mathrm{I}}^{(1)}/\bar{\mathrm{I}}_{\mathrm{th}}^{(1)} \approx 8.75\%$
- $\overline{\mathrm{I}_{\mathrm{th}}^{(2)}} \approx 530\mathrm{mA}$, $\sigma_{\mathrm{I}}^{(1)} \approx 54.2\mathrm{mA}$, $\sigma_{\mathrm{I}}^{(1)}/\bar{\mathrm{I}}_{\mathrm{th}}^{(1)} \approx 10.2\%$

HOM frequency spread

- Average value of I_{th} VS. σ_f



3.0-GeV ERL

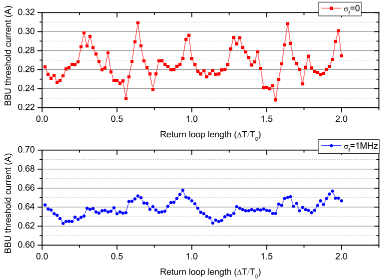


3.4-GeV ERL

- $\sigma_f = 2\text{MHz}$, $\bar{I}_{th} \approx 940\text{mA}$.

Return loop length

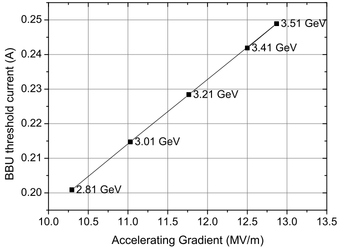
- In ERL, sometimes we need to adjust the length of return loop.



- The most threating mode: 4.011GHz.
- Quansi-periodic variation along with the path length variation when $\sigma_f = 0$.
- when σ_f=1 MHz, periodic variation almost disappears.

Comparison of different ERL designs

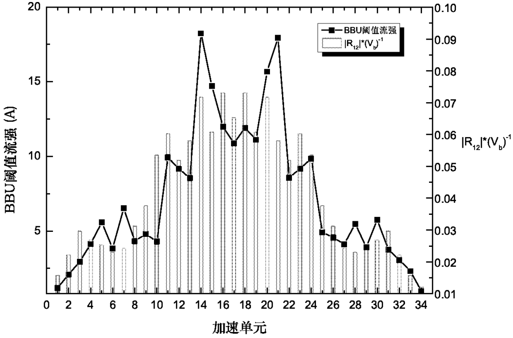
	3.4-GeV ERL	3.0-GeV ERL	5.0-GeV ERL
E_{inj}[MeV]	10	10	10
E_{full}[MeV]	3410	3010	4970
Modules	34	28	31
E_{acc}[MV/m]	12.5	13.4	20
$I_{th,min}(\sigma_f=0)$[mA]	220	240	580
$I_{th,average}(\sigma_f=2MHz)$[mA]	940	940	2.4e3



Thanks Dr. M. Shimada for providing lattice files

- Same cavity number; Different cavity gradient.
- $I_{th} \propto E_{acc}$.

Contribution of different cavity to BBU



The cavities at low energy section (the start and the end of the linac)

$$\frac{1}{\mathrm{I_{th}}} \propto \frac{\sqrt{\beta_1\beta_2}}{\sqrt{\mathrm{p_1 p_2}}} \sin\Delta\psi$$

Summary

BBU simulation for compact ERL with 9-cell TESLA-type cavities

- BBU threshold current of PKU-ETF is about 24mA, larger than the design average current.
- The most threatening mode in TESLA-type cavity is the TE_{121}-like mode with frequency about 2.57GHz.
- By applying beam optics methods, BBU threshold current can be improved significantly.

BBU simulation for multi-GeV ERL light source in KEK

- BBU threshold of both the two designs of KEK ERL light source is larger than the design value of average current.
- By improving the accelerating gradient, BBU threshold current can also be improved.

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KEK

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JAEA

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Thank you!