BBU Simulation of the KEK 3.5-GeV (modified) and 3.0-GeV Energy Recovery Linac Light Source

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ERL Beam Dynamics WG, KEK
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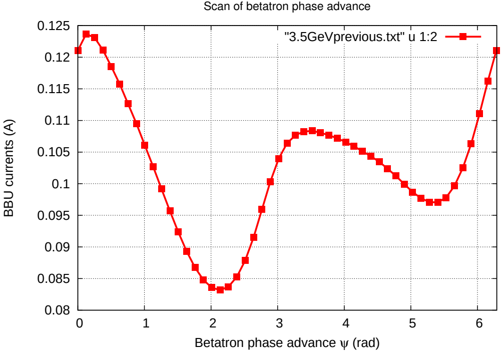
Outline

1. Previous results
2. Modified results of 3.5-GeV ERL and simulations results of 3.0-GeV ERL
   - 2 ERL schemes
   - Parameters
   - Threshold current simulation
   - HOMs randomization
3. Comparison and summary

- A BBU simulation result of a 3.5-GeV ERL light source scheme was presented in the previous ERL Beam Dynamic WG. *(Chen Si, ERL Beam Dynamics WG 84, 2013.09.25)*



- BBU threshold current is about 83mA. Previous result of 5-GeV ERL is 580mA, 7 times as the 3.5-GeV ERL
- Question: Why is the threshold current so small compared with the result of 5-GeV scheme?

Problems

- According to the analytical formula of BBU threshold current

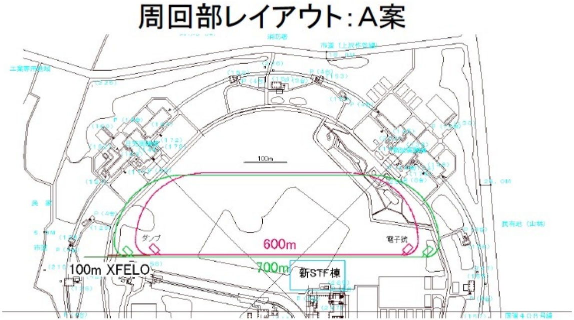
$$I_{th} = -\frac{2pc^2}{e\omega(\frac{R}{Q})Q_e T_{12}\sin(\omega T_r)} \qquad (1)$$

  The BBU threshold current is proportional to the beam energy and inversely proportional to the HOM parameters $(R/Q)Q_{ext}f$ and transport matrix element T_{12}.

- The input files of bi are checked carefully. It has been confirmed that the beam energy and HOM data are correct. Therefore, there must be some where in the linac has very large value of T_{12} and make the threshold current so small.

- The lattice input file of bi is in the form of 6 by 6 transfer matrix of each element. When translated the lattice file from elegant to bi, the sequence of quadrupole magnet was reversed by mistake. The quadrupole strength at the deceleration linac does not match the energy, which makes the T_{12} at the deceleration linac very large.

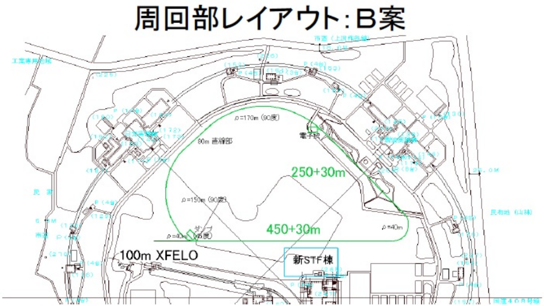
ERL designs - scheme A (3.5 GeV)



Miho Shimada, ERL Beam Dynamics WG 81, 2013.06.17

- 34 cryomodules, 8 cavities in each cryomodule;
- $E_{acc} = 12.5$ MV/m; Linac length $\sim$ 630m
- 10 MeV injection energy, 3.5 GeV full energy

ERL designs - scheme B (3.0 GeV)



Miho Shimada, ERL Beam Dynamics WG 81, 2013.06.17

- 28 cryomodules, 8 cavities in each cryomodule;
- E_{acc}=13.4 MV/m; Linac length $\sim$ 470m
- 10 MeV injection energy, 3.0 GeV full energy

- KEK-ERL mode 2 cavities are applied.
- 6 most threatening HOMs (with large value of $(R/Q)Q_{ext} \cdot f$) are chosen for simulation.*(R. Hajima, R. Nagai. Proceedings of ERL2007)*

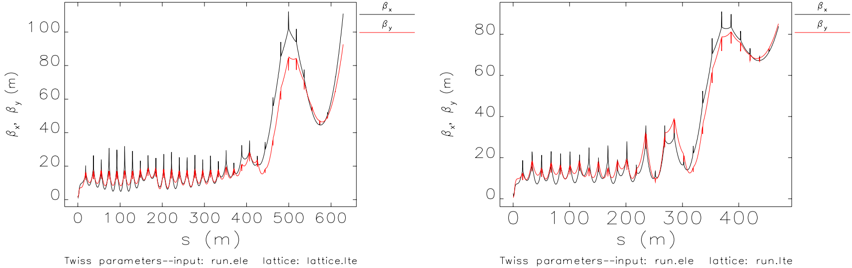
R/Q Ω	Q_{ext}	*freq.* GHz	$(R/Q)Q_{ext} \cdot f$ $\Omega\cdot$ GHz
54.680	1.1010E3	1.8350	1.1047E5
48.320	1.6980E3	1.8560	1.5228E5
26.260	1.6890E3	2.4280	1.0769E5
0.8210	2.9990E4	3.0020	7.3915E4
4.5420	1.1410E4	4.0110	2.0787E5
0.0219	6.0680E5	4.3300	5.7541E4

Table: HOM parameters of KEK-ERL 9-cell cavity

Lattice parameters

- Lattice design is flexible for ERL. We mainly concern about the arrival time(i.e. the length of return loop) and the T_{12} element of transport matrix.

$$T_{12}(i \to f) = \sqrt{\frac{\beta_i \beta_f}{p_i p_f}} \sin \Delta\Psi \tag{2}$$



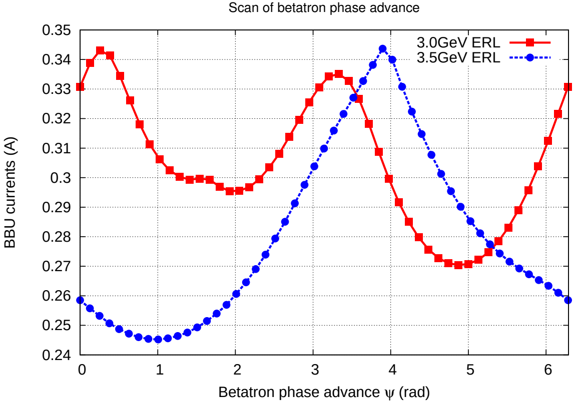
(a) β-function of the 3.5-GeV linac

(b) β-function of the 3.0-GeV linac

Figure: β-function in the linacs of two scheme

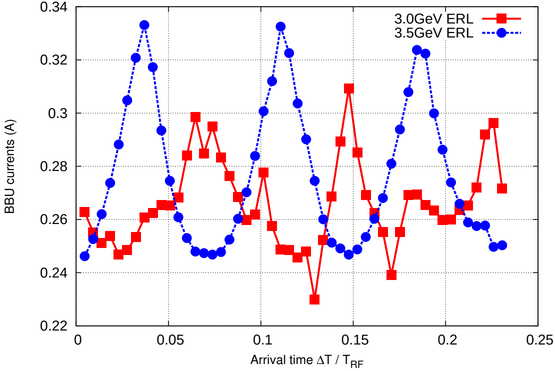
(Thanks Miho Shimada for providing the lattice file.)

Betatron phase advance (ψ) scan



- The BBU threshold currents (minimum value on the BBU current curve) are 240mA for 3.5-GeV scheme and 270mA for 3.0GeV scheme, respectively

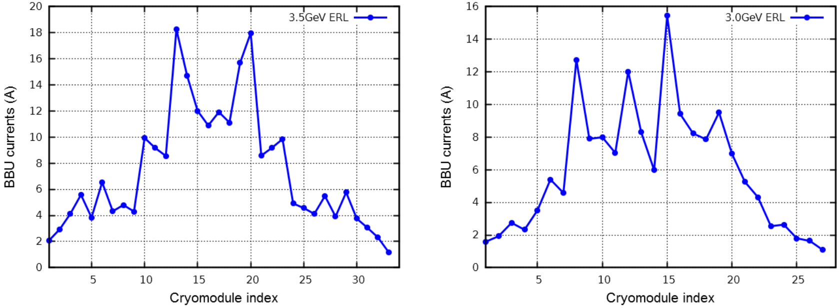
- Modify the length of recirculating loop. The value of $\sin \omega T_r$ will be changed. ΔT_r=1/1.3GHz.



- The time interval between two peaks of the curve is about 1/4.062GHz, which means the dominant HOM in this type of cavity is the mode with frequency near 4.062GHz.

Effect of single cryomodule

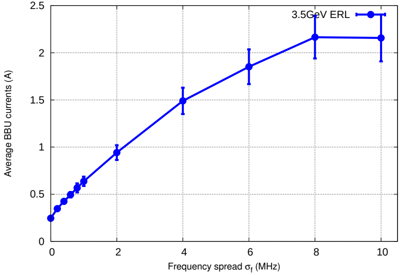
- In order to find out which cryomodules determine the BBU threshold current, the HOMs in only one cryomodule are kept while HOMs in other cryomodules are shut down.



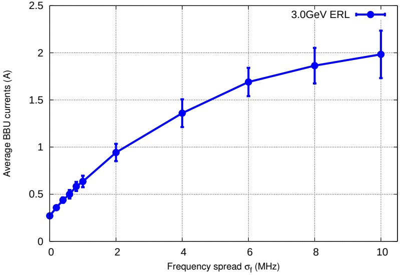
(a) 3.5-GeV ERL (b) 3.0-GeV ERL

- Applying a simple estimate formula of threshold current $\frac{1}{I_{th}} = \sum_{n=0}^{N_{mod}} \frac{1}{I_n}$, we can get $I_{th}^A = 129\text{mA}$; $I_{th}^B = 118\text{mA}$. while the simulation results with all HOMs open are $I_{th}^A = 240\text{mA}$; $I_{th}^B = 270\text{mA}$.

- 20 Gaussian random seed were generated for each value of σ_f.



(c) 3.5-GeV scheme



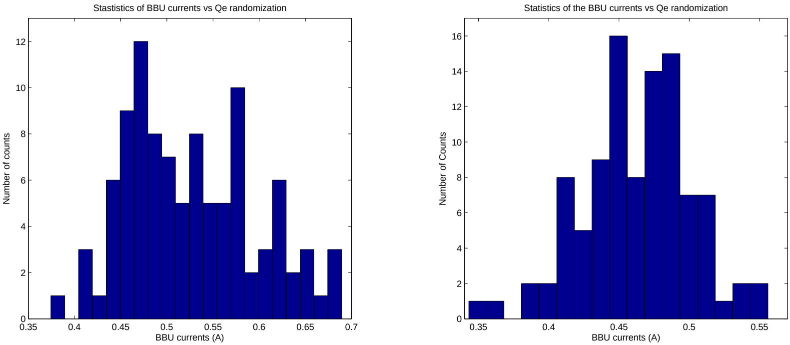
(d) 3.0-GeV scheme

Figure: HOM frequency randomization of two scheme

- The BBU threshold current can be significantly enhanced by introducing sufficient frequency randomization.

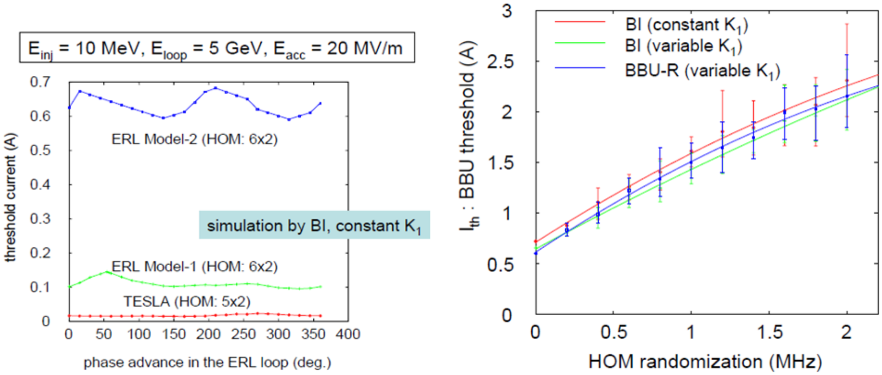
External quality factor (Q_{ext}) randomization

- 100 uniformed random seed from $0.1Q_{ext0}$ to $10Q_{ext0}$ and a Gaussian random seed of 2MHz frequency spread were applied. The initial values (no Q_{ext} spread) of threshold current are 0.95A for 3.5-GeV scheme and 1.06A for 3.0-GeV scheme.



(a) 3.5-GeV scheme (b) 3.0-GeV scheme

Figure: Q_{ext} randomization of two scheme. With 2MHz frequency spread



(a) Phase advance scan (b) Freq. randomization

Figure: Previous results of 5-GeV ERL*(R. Hajima, R. Nagai. Proceedings of ERL2007)*

- 31 cryomodules, 8 cavities in each cryomodule;
- E_{acc}=20 MV/m, 10 MeV injection energy, 5GeV full energy.

Comparison

Parameters	Units	3.5-GeV (A)	3.0-GeV (B)	5.0-GeV
E_{inj}	MeV	10	10	10
E_{full}	GeV	3.5	3.0	5.0
N_{mod}		34	28	31
E_{acc}	MV/m	12.5	13.4	20
$I_{th}(\sigma_f=0)$	mA	240	270	580
$I_{th}(\sigma_f=2\text{MHz})$	mA	940	940	2.4e3

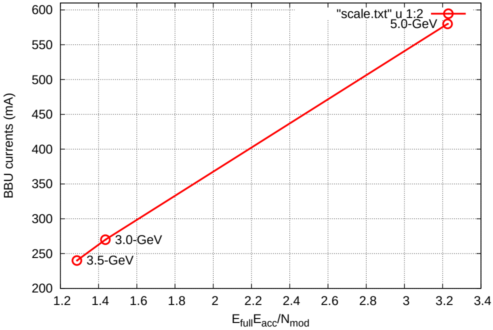
Scale

As is shown in the analytical formula of I_{th}

$$I_{th} = -\frac{2pc^2}{e\omega(\frac{R}{Q})Q_e M_{12}^* \sin(\omega T_r)}$$

where $T_{12} \propto \frac{1}{E_{acc}}$ [1]

So that $I_{th} \propto \frac{E_{full} \cdot E_{acc}}{N_{mod}}$



[1] *J. Rosenzweig, L. Serafini. Phys.Rev. E 49(2): 1599-1602, (1994)*

Summary

- BBU Threshold current of 3.5-GeV ERL (scheme A)
  - $I_{th}^{A} \approx$240mA, with σ_f=0;
  - $I_{th}^{A} \approx$940mA, with σ_f=2MHz;
- BBU Threshold current of 3.0-GeV ERL (scheme B)
  - $I_{th}^{B} \approx$270mA, with σ_f=0;
  - $I_{th}^{B} \approx$940mA, with σ_f=2MHz;

- Cavities at the lower energy section (the start of the acc. linac and the end of the dec. linac) contribute more to the threshold current. If HOMs in these cavities have larger quality factor, the threshold current will be smaller.

- Simulation results of BBU threshold current is well above the design value of average current (100mA) of KEK 3-GeV ERL light source.

The End