MODELING OF THE BEAM BREAK UP INSTABILITY IN BERLIN ENERGY RECOVERY LINAC PROJECT*

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Abstract

Helmholtz-Zentrum Berlin officially started Jan. 2011 the design and construction of the Berlin Energy Recovery Linac Project BERLinPro. The initial goal of this compact ERL is to develop the ERL accelerator physics and technology required to accelerate a high-current low emittance beam.

The conversion efficiency of an FEL is about 1% therefore superconducting ERL-based FEL machines look promising. One of the problems of superconducting ERL machines is the Beam Break Up (BBU) instability which limits the current.

In this work the threshold current of the BBU instability was calculated for the BERLinPro. The comparison of two 100 MeV linacs based on different type of superconducting cavities is made. Different methods of BBU suppression are investigated (e.g. the influence of solenoid, pseudo-reflector and quadruple triplets in the linac structure on the BBU threshold).

INTRODUCTION

Nowadays Helmholz-Zentrum Berlin has a project for the design and construction of the Berlin Energy Recovery Linac Project BERLinPro. The schematic layout of the facility is shown in Fig. 1. The main parameters of the BERLinPro are shown in Table 1.

Table 1: The Main Parameters of the BERLinPro

Parameter	Value
Max. beam energy	100 MeV
Average current up to	100 mA
Nominal bunch charge	77 pC
Max. repetition rate	1.3 GHz
Injection energy	7 MeV

One of the main problems of modern superconducting ERLs is the Beam Break Up instability. A theory of BBU instability in ERLs was presented in [1]. If an electron bunch passes through an accelerating cavity it interacts with dipole modes (e.g. TM110) in the cavity. First, it exchanges energy with the mode; second, it is deflected by the electro-magnetic field of the mode. After recirculation the deflected bunch interacts with the same mode in the cavity again which constitutes the feedback. If net energy transfer from the beam to the mode is larger than energy loss due to the mode damping the beam becomes unstable.

Stability of the beam against BBU depends on the transport properties of the magnetic system expressed by the transport matrix elements of the magnet system. For a single mode in a cavity it is easy to design a one turn optics which makes the constituted feedback negative. For high energy linacs the number of cavities is large and a detailed simulation of the optics is necessary. So, calculations and optimization of the BBU threshold current is a task closely related to modelling and optimization of magnetic optics of BERLinPro.

The threshold current for the transverse beam breakup may be estimated for the case of a single cavity and single mode as [2]

$$I_b = -\frac{2pc^2}{e\omega R_d m_{12}\sin(\omega T)}, \tag{1}$$

where p – is the beam momentum, ω – HOM frequency, R – the HOM impedance, m_{12} – the element of recirculation matrix, T – recirculation time, c,e – fundamental constants.

Another approach [3] gives estimation for a multipass ERL in the form

$$I_b \approx I_0 \frac{\lambdabar^2}{Q_a L_{eff}\sqrt{\sum_{m=1}^{2N-1}\sum_{n=m+1}^{2N}\frac{\beta_m\beta_n}{\gamma_m\gamma_n}}}, \tag{2}$$

where I_0- Alfen current, Q_a is the quality factor of HOM, $\lambdabar = \lambda/2\pi$, λ is the wavelength corresponding to the resonant frequency of the TM110 mode, γ_m is the relativistic factor at the m-th pass through the cavity, β_m – is the Twiss parameter, L_{eff} – is the effective length of the cavity. This expression shows that it is preferable to have low β-functions at low energies. It also indicates the limitation for the number of passes.

For a long linac with many cavities the current depends on the mode frequency spread from cavity to cavity and details of the magnetic optics. Special cavity design with strong suppression of HOMs can be one of the ways to achieve higher current.

More details on the multi-pass beam breakup in energy recovery linacs may be found in [2].

There are a number of existing software packages for modelling of accelerator optics and BBU. During this work we used the GBBU program written by E.Pozdeyev [2] and the Elegant particle tracking program [4].

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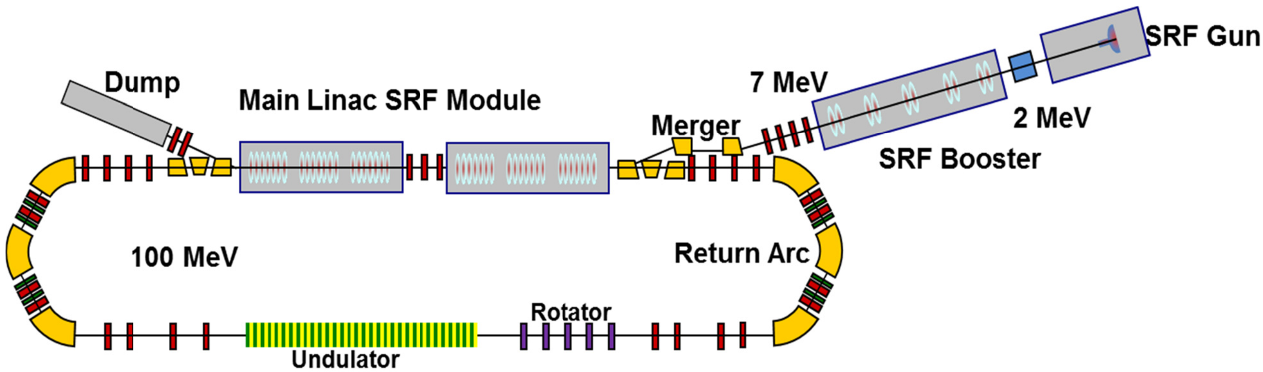

Figure 1: The scheme of BERLinPro.

BBU MODELLING

The BBU instability for 100 MeV linacs based on the standard TESLA-type cavities and new CEBAF-like design being pursued by HZB was compared [5].

100 MeV linac having 6 9-cell TESLA cavities with an accelerating gradient E ~16 MeV/m was assumed.

As a base for a new HOM-damped design of the cavities suitable for high current operation 5-cell CEBAF-type geometry is taken. The parameters of the cavity relevant for the BBU modeling were calculated at JLab [5]. We assume the same average accelerating gradient in the cavity (16 MeV/m). The CEBAF type linac requires 11 cavities to accelerate the beam to 100 MeV.

For the comparison of the two linacs, we scale the CEBAF cavity geometry to make the frequency of the accelerating monopole mode equal to that of the TESLA cavities (1.3 GHz). The frequencies of all other modes are scaled correspondingly. It should be mentioned, that the values of R/Q used in the modeling program GBBU are defined according to the book [6, equation (15.47)]. In this definition R/Q for dipole modes are in Ohm and not in Ohm/m^2 as in modeling programs like CST MWS or MAFIA. The additional conversion factor $(\omega_n/c)^2$ is frequency dependent. We took this factor into account when converting R/Q for both TESLA and CEBAF type cavities.

The frequency spread of the dipole modes due to fabrication accuracy is of the order of 10 MHz [7,8]. In the modeling we set the differences between the frequencies of the dipole modes for different cavities equal to 1 MHz.

Recirculator optics was assumed to be flexible. First we set the revolution matrix (from the end of the linac after acceleration to the beginning of the linac before the deceleration) to have equal betatron phase advances in x and y planes and scanned over the phase advance. The optics was assumed to be symmetrical with the β-function at the beginning and at the end equal to 30 m and α-function equal to 0.

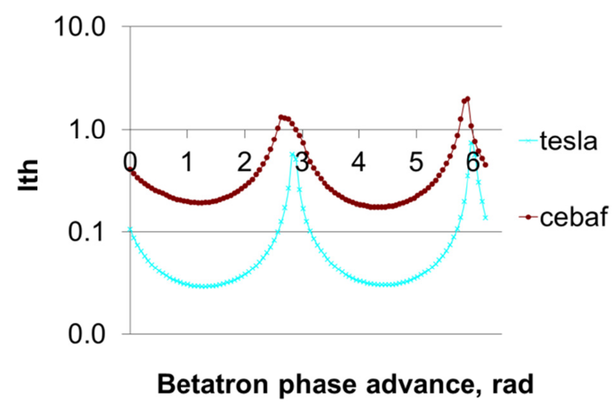

Figure 2: Comparison of the threshold currents for TESLA and CEBAF type linacs for BERLinPro.

In Fig. 2 the results of our modeling are presented. There was used the method "unity" in the GBBU program. With this method we can provide our own matrices of the linac structure, which were calculated by the Elegant program where the focusing in cavities was taken into account. The focusing in the linac is described in [9].

FREQUENCIES OVERLAPPING

In this paragraph we would like you to pay more attention to frequencies overlapping. If the differences between some cavities are smaller than the value A (5) than the HOMs of these cavities start to interact with each other which decreases the threshold current. As an example we will use the TESLA type linac in BERLinPro.

Let's assume:

$$f_i = f_0 + df_i, \tag{3}$$

f_i is the frequency of some HOM in a TESLA cavity, df_i has the Gaussian distribution – $\Phi_{0,\sigma}{}^2$ and i= 1..6 – is the number of a cavity, σ=1 MHz.

Let's find a probability P, when any pair of frequencies

$$|f_n - f_m| < A, \tag{4}$$

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overlap in the interval

$$A = \frac{f_0}{Q}, \tag{5}$$

This probability P is the same for the value

$$|x| = |df_n - df_m| < A, \tag{6}$$

because f_0 is constant. The value x has Gaussian distribution $\Phi_{0,2\sigma^2}$ due to the fact that if two independent values $X_1 \in \Phi_{\mu_1,\sigma_1^2}$ and $X_2 \in \Phi_{\mu_2,\sigma_2^2}$ then $X_1 + X_2 \in \Phi_{\mu_1+\mu_2,\sigma_1^2+\sigma_2^2}$.

And now the probability P_0 for fixed n,m may be found as:

$$\begin{aligned} P_0 &= F(0,2\sigma^2, A) - F(0,2\sigma^2, -A) = \\ &= 2F(0,2\sigma^2, A) - 1, \end{aligned} \tag{7}$$

where

$$F(\mu,\sigma^2,z) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{z} e^{-\frac{(t-\mu)^2}{2\sigma^2}} dt. \tag{8}$$

Now we need to find a probability that all pairs overlap. Here we use the Bernoulli's scheme:

$$\begin{aligned} P &= \sum_{k=1}^{n} C_n^k P_0^k (1-P_0)^{n-k} = \\ &= 1 - C_n^0 P_0^0 (1-P_0)^{n-0} = 1-(1-P_0)^n, \end{aligned} \tag{9}$$

where $n = C_6^2$ – the number of pairs.

Let's calculate the probability P for TESLA cavity for the mode with the highest Q (R/Q=86, Q=40000, f=1.7·10^9, A=42 kHz) and the lowest (R/Q=82, Q=5400, f=2.58·10^9, A=477 kHz). For the first mode the probability equals 0.224 and for the second 0.956.

To study the effect of overlapping, BERLinPro based on the TESLA cavities was modelled with randomly distributed frequencies of the HOMs. In Figs.3,4 the results are presented. The maximum threshold current from Fig. 2 was chosen I_{th} = 0.566 A. For the optics which corresponds to this current value were carried out a series of modelling when the frequencies of all HOMs of all cavities in the linac were generated randomly with Gaussian distribution with σ = 1 and 10 MHz.

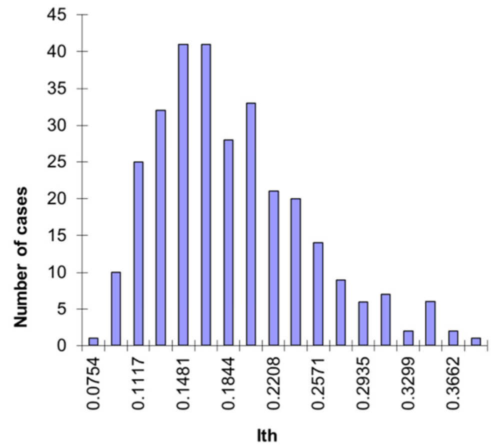

Figure 3: Results of BBU modelling for TESLA type linac. The optics was chosen correspondingly to the maximum current value from Fig. 2. σ = 1 MHz..

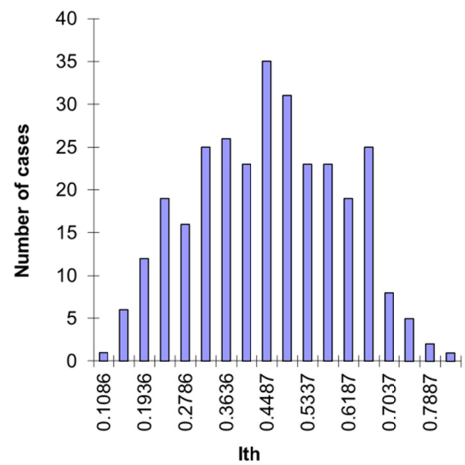

Figure 4 Results of BBU modelling for TESLA type linac. The optics was chosen correspondingly to the maximum current value from Fig. 2. σ = 10 MHz.

BBU SUPPRESSION

One of the methods to suppress BBU is to mix x and y planes of motion. To do this we put pseudo-reflector (rotator) or 90^0-solenoid in the long drift between two arcs of the main ring [10]. To calculate the influence of these elements on BBU we divided the matrix of the recirculation optics in two parts and put the matrix M_{rot} for solenoid or M_{pr} for pseudo-reflector (11).

To divide the effects of focusing and rotation of the solenoid we transform:

$$M_{sol} = M_f M_{rot} M_f, \tag{10}$$

where M_f contains the focusing of the solenoid and M_{rot} – matrix of 90^0- rotation.

$$M_{rot} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}, \; M_{PR} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}. \qquad (11)$$

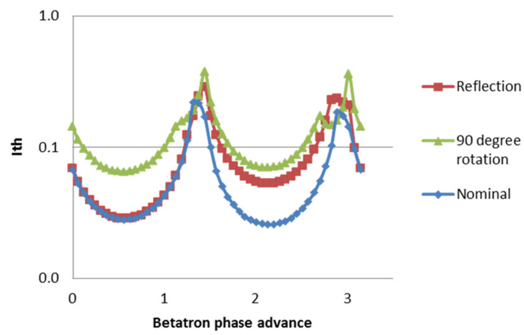

Figure 5: The results of BBU modelling for BERLinPro with rotator and solenoid.

Figure 5 shows the results of BBU modelling for BERLinPro based on TESLA cavities. Pseudo-reflector, solenoid or unity matrix is used. As you can see solenoid is more effective for BBU suppression but for a 100 MeV beam such solenoid is about 1 T·m.

Another way to improve BBU is to use an addition focusing in the linac structure. The linac, based on TESLA cavities was divided into two cryomodules with 3 cavity each. Between two cryomodules we put a triplet of quadruple lenses. The strength of quadruples was adjusted to have the lowest possible beta functions at the end of the linac. We set the revolution matrix to have a different betatron phase advances in x and y planes and scanned over the phase advances (30x30). The results of such modelling are presented in Fig. 6. The maximum threshold value was about 670 mA.

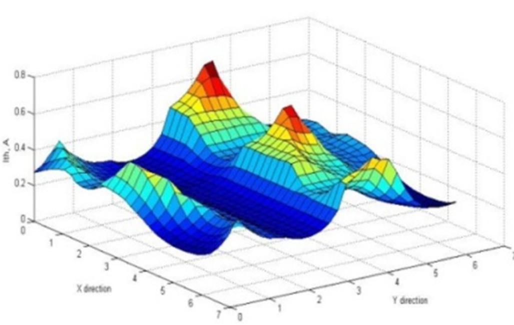

Figure 6: The results of 2D phase scan.

The example of optics layout modelled in the Elegant program and presented in Fig. 7.

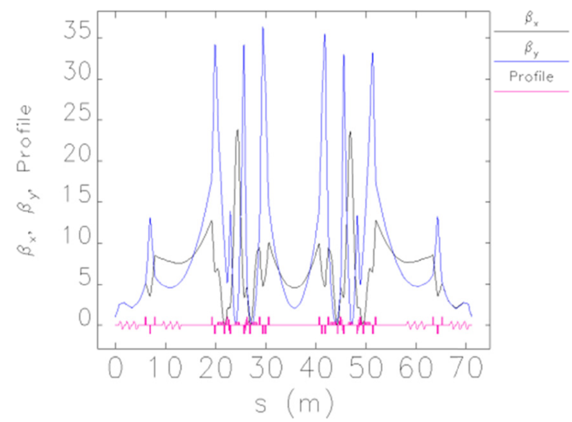

Figure 7: The optics of BERLinPro.

One more way to increase the threshold current is to change the length of the recirculation ring. It should be noted, that usually only one strongest HOM defines the threshold for a given optics. However, this method seems impractical, since the mode frequencies are not known exactly before the assembling of the linac.

REFERENCES

[1] G.H. Hoffstaetter, I.V. Bazarov, „Beam-breakup instability theory for the energy recovery linacs", Phys. Rev. ST AB 7, 054401 (2004).

[2] E. Pozdeyev, et al., "Multipass beam breakup in energy recovery linacs", NIM A 557 (2006) 176-188.

[3] N.A. Vinokurov et al., Proc. of SPIE Vol. 2988, p. 221 (1997).

[4] M. Borland, "Elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," APS LS-287, 2000.

[5] F. Marhauser et al., "JLAB high current cryomodule development" Proc. ERL Workshop 2009, Cornell University, U.S.

[6] H.Padamsee, J.Knobloch, T.Hays, "RF superconductivity for Accelerators", WILEY-VCH, 2008.

[7] http://tesla.desy.de/oracle/6i/CavityDB/GUI/view?config=app_hom_meas

[8] L.Xiao et al., "Modelling imperfection effects on dipole modes in TESLA cavity", Proceedings of PAC07, pp. 2454-2456.

[9] J. Rosenzweig, L. Serafini. "Transverse particle motion in radion-frequency linear accelerators." Phys. Rev. E, vol. 49, number 2 (2004).

[10] E. Pozdeyev, "Regenerative multipass beam breakup in two dimensions." Phys. Rev. ST AB 8, 054401 (2005).

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