MODELING OF THE BEAM BREAK UP INSTABILITY FOR BERLINPRO*

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Abstract

Following funding approval late 2010, 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.

In this work the threshold current of the Beam Break Up (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

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. TM_{110}) 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 and transfers energy. If the net energy transfer from the beam to the mode is larger than the 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 modeling and optimization of magnetic optics of BERLinPro.

The threshold current for the transverse beam breakup was estimated for the case of a single cavity and single mode and presented in [2]. Another approach [3] gives an estimation for a multipass ERL.

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.

There are a number of existing software packages for modeling 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].

BBU MODELING

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.

100 MeV linac having six 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.

The frequency spread of the dipole modes due to fabrication accuracy is of the order of 10 MHz [6,7]. 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 the 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.

In Fig. 2 the results of our modeling are presented. There we used the method “unity” in the GBBU program. With this method we can provide matrices of the linac structure, which were calculated using the Elegant where

*Work supported by German Bundesministerium für Bildung und Forschung, Land Berlin, and grants of Helmholtz Association VH-NG-636 and HRJRG-214.
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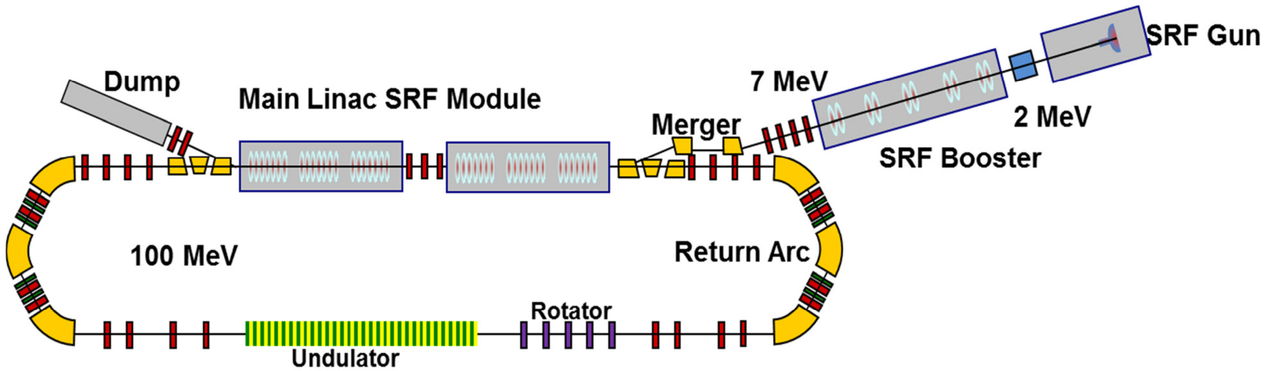

Figure 1: The scheme of the BERLinPro.

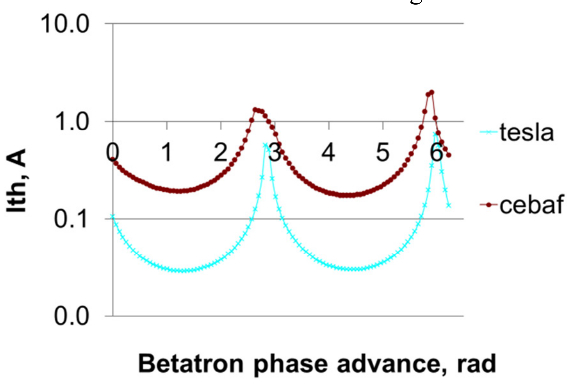

Figure 2: Comparison of the threshold currents for the TESLA and the CEBAF type linacs for BERLinPro.

the focusing in cavities was taken into account. The focusing in the linac is described in [8].

FREQUENCIES OVERLAPPING

In this paragraph we pay more attention to the frequencies overlapping. If the differences between some cavities are smaller than the value A (3) then 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:

$$f_i = f_0 + df_i, \tag{1}$$

where 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

$$|f_n - f_m| < A, \tag{2}$$

overlap in the interval

$$A = \frac{f_0}{Q}, \tag{3}$$

where Q is the quality factor of HOM.

This probability P is the same for the value

$$|x| = |df_n - df_m| < A, \tag{4}$$

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:

$$\begin{aligned} P_0 &= F(0,2\sigma^2, A) - F(0,2\sigma^2,-A) = \\ &= 2F(0,2\sigma^2, A) - 1, \end{aligned} \tag{5}$$

where

$$F(\mu,\sigma^2,z) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{z} e^{-\frac{(t-\mu)^2}{2\sigma^2}}\, dt. \tag{6}$$

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

$$\begin{aligned} P &= \sum_{k=1}^{n} C_n^k P_0^k (1-P_0)^{n-k} = \\ &= 1 - C_n^0 P_0^0 (1-P_0)^{n-0} = 1-(1-P_0)^n, \end{aligned} \tag{7}$$

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 simulated with randomly distributed frequencies of the HOMs. In Fig. 3 the results are presented. The maximum threshold current from Fig. 2 was chosen I_{th} = 0.566 A. For the betatrone phase which correspond to this current value, the series of simulations were carried out using randomly generated HOM frequencies assuming a Gaussian distribution with σ = 1 and 10 MHz.

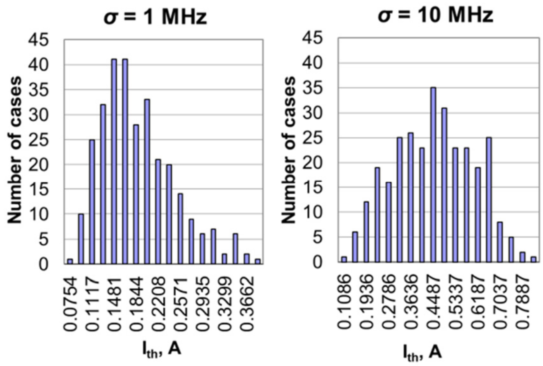

Figure 3: Results of BBU modeling for TESLA type linac. The optics was chosen correspondingly to the maximum current value from Fig. 2. σ = 1 and 10 MHz.

BBU SUPPRESSION

One of the methods to suppress BBU is to couple the x and y planes of motion. To do this we put a pseudo-reflector (rotator) or 90^0-solenoid in the long drift between two arcs of the main ring [9]. To calculate the influence of these elements on BBU we divided the

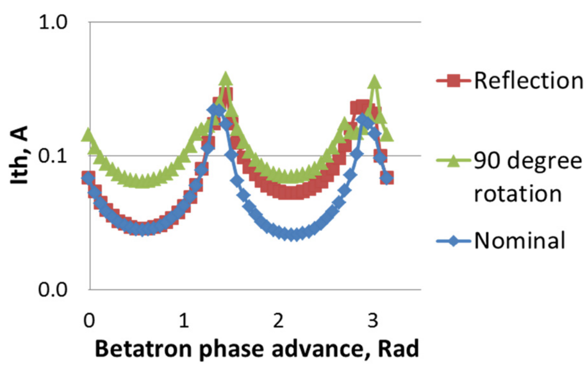

Figure 4: The results of BBU modeling for BERLinPro with pseudo-reflector and solenoid.

matrix of the recirculation optics in two parts and put the matrix M_{rot} for solenoid or M_{pr} for pseudo-reflector (9).

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

$$M_{sol} = M_f M_{rot} M_f, \qquad (8)$$

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

$$M_{rot} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}, \quad M_{PR} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}. \qquad (9)$$

Fig. 4 shows the results of BBU modeling 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 has a field of 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 quadrupole lenses. The strength of quadrupoles 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 modeling are presented in Fig. 5. The maximum threshold value was about 670 mA.

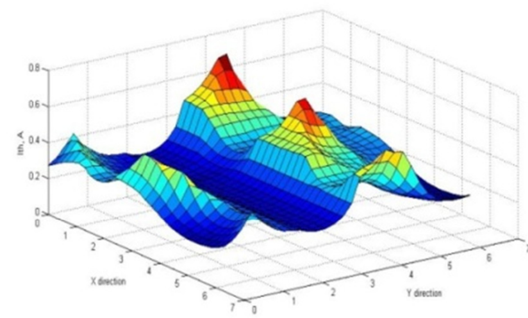

Figure 5: The results of 2D phase scan.

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.

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