PHASE-MODULATION SLED MODE ON BTW SECTIONS AT ELETTRA

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Abstract

The former linac sections used in the injector system of the Elettra Laboratory storage ring will be upgraded for use on the FERMI@Elettra project, a FEL user facility operating down to 3 nm. These seven accelerating sections are 3π/4 mode backward-travelling wave (BTW) constant-impedance structures, powered by 45 MW TH2132A klystrons couple to what was called a PEN (Power Enhancement Network), or more commonly referred to as a SLED system. Due to breakdown problems inside the sections, that was the result of high peak fields generated during conventional SLED operation, the sections experienced difficulties in reaching the design gradients. To lower the peak field and make the compressed pulse "flatter", phase-modulation of the SLED drive power option is investigated. This paper presents the results of this investigations with a detailed mathematically analysis.

MOTIVATION

The former linac sections used in the injector system of the Elettra Laboratory storage ring were designed and fabricated by CGR-MeV in late 1980's, and had not reached the designed energy-gain gradient with SLED since then. The problem was breakdown inside the sections associated with the very high peak-field inhered by conventional SLED operation. The end-scope view showed that there were indeed severe arcing traces in the first cells near the RF input port.

To lower the very high peak field inhered with conventional SLED, that is, to make a "flatter" compressed pulse and meanwhile to maximize the beam energy gain, the phase-modulation SLED option is encouraged to investigate further on the machine[1] in order to get optimised operation parameters.

PHASE-MODULATED PULSE OF P.E.N

For a typical power enhancement network (PEN), as shown in Fig. 1, the following equations describe the basic relation between the output power (field) E (to the accelerator structure) and the output of the klystron E_k:

$$T_c \frac{dE_c}{dt} + E_c = -\alpha E_k \tag{1}$$

$$E = E_c + E_k \tag{2}$$

where E_c is the emitted power (field) from the cavities, which is proportional to the field level (energy) inside the cavities; $T_c=2Q_0/\omega_0(1+\beta)$, the filling time of cavity; β is coupling factor of the cavity, $\alpha=2\beta/(1+\beta)$, ω_0 ($2\pi f_0$) is resonant frequency of cavity and Q_0 is unloaded quality factor of cavity.

In our case β=10, Q_0=190000, f=2998 MHz, T_c=1.834 μs.

We will calculate the field E during the three time intervals, denoted as A ($0<t<t_1$); B ($t_1<t<t_2$); and C ($t>t_2$).

During the time interval A, the PEN cavity fields and hence the emitted field vary as shown in Fig. 2, assuming E_k (A) = -1.

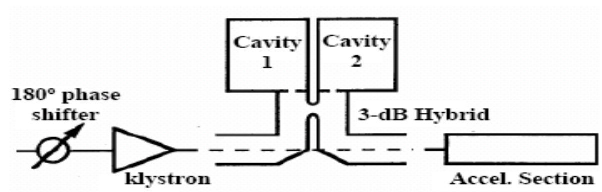

Figure 1: Sketch of power enhancement network P.E.N.

The usual way of operating the SLED system implies that, at a certain instant t_1 (usually t_1 should be more than 2~3T_c), the phase of the RF wave at the klystron output is reversed by 180º . This effect produces a much higher peak RF power at the input of accelerator, determined by all the parameters, but the waveform is far from "flat", as shown in fig.2. This high peak field may reach or exceed the breakdown threshold in the BWT structure S1-S7.

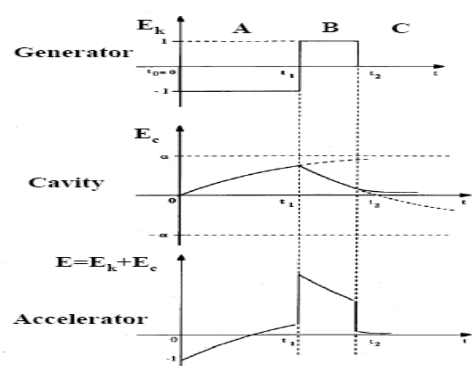

Figure 2: The waveform of conventional SLED.

To lower the very high peak field and make it toward more flatter we could run it in phase-modulation mode.

In stead of swooping of 180º at t_1 (conventional/normal SLED), it swoops of (180 º-φ_0) first, and then varies continuously to zero at time t_{1B}, ($t_1<t_{1B}\leq t_2$), and remains zero till the end of pulse, the time t_2 (RF off). This is phase-modulating SLED operation mode.

To be more general and flexible, we denote the time interval B in Fig. 2 into two periods, B_1 and B_2. B_1 denotes "from t_1 to t_{1B}", B_2 denotes "from t_{1B} to t_2".

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During interval B_1 there's phase modulation on klystron LLRF. And we have klystron output as following:

$E_k=e^{j180°}$, when $t<t_1$;

$E_k=e^{j\varphi(t)}$, when $t_1<t<t_{1B}$;

here **$\varphi(t)=\varphi_0+k(t-t_1)$, $k=-\varphi_0/(t_{1B}-t_1)$** (phase modulation on klystron drive, LLRF) (3)

$E_k= e^{j0°}$, when $t_{1B}<t<t_2$;

$E_k=0$, when $t>t_2$ (RF off)

Let us look what the waveform of RF delivered to the accelerator will be like with above E_k (klystron output) and exam the effect on the peak field and on the beam energy gain.

To do this analysis we need to solve the differential equation (1) with E_k as expressed above.

For $t<t_1$, $E_k=e^{j180°}$,

$$E_c(t)=\alpha*(1-e^{-t/T_c})$$

$$E(t)=E_c+E_k=\alpha*(1-e^{-t/T_c})-1 \qquad (4)$$

For $t_1<t<t_{1b}$, $E_k=e^{j\varphi(t)}$,

$$E_c(t)=$$

$$\frac{\alpha}{1+jkT_c}\left(e^{\frac{t_1-t}{Tc}}e^{j\varphi(t_1)}-e^{j\varphi(t)}\right)+\alpha*e^{\frac{t_1-t}{Tc}}-\alpha*e^{\frac{-t}{Tc}} \qquad (5)$$

For $t_{1b}<t<t_2$, $E_k= e^{j0°}$,

$$E_c(t)=$$

$$\alpha*\left(\frac{e^{\frac{t_1-t_{1B}}{T_c}}*e^{j\varphi_0}+jkT_c}{1+jkT_c}*e^{\frac{t_{1B}-t}{T_c}}-1+e^{\frac{t_1-t}{T_c}}-e^{-\frac{t}{T_c}}\right)$$

$$E(t)=E_c+E_k=1+$$

$$\alpha*\left(\frac{e^{\frac{t_1-t_{1B}}{T_c}}*e^{j\varphi_0}+jkT_c}{1+jkT_c}*e^{\frac{t_{1B}-t}{T_c}}-1+e^{\frac{t_1-t}{T_c}}-e^{-\frac{t}{T_c}}\right) \qquad (6)$$

For $t>t_2$, $E_k=0$ (RF off),

$$E(t)=E_c(t)=\alpha*e^{\frac{t_2-t}{T_c}}*$$

$$*\left(\frac{e^{\frac{t_1-t_{1B}}{T_c}}*e^{j\varphi_0}+jkT_c}{1+jkT_c}*e^{\frac{t_{1B}-t_2}{T_c}}-1+e^{\frac{t_1-t_2}{T_c}}-e^{-\frac{t_2}{T_c}}\right) \qquad (7)$$

It should point out that the condition of continuity of $E_c(t)$ at t_1, t_{1B} and t_2, must be satisfied -- because emitted cavity field can not change suddenly – in the solution of differential equation (1), that is,

when $\delta t \rightarrow 0$:

$E_c(t_1-\delta t)=E_c(t_1+\delta t)$; $E_c(t_{1B}-\delta t)=E_c(t_{1B}+\delta t)$;

$E_c(t_2-\delta t)=E_c(t_2+\delta t)$;

Taking the real part of E(t) from the expressions (4)-(7), it will get the waveform of RF pulse delivered to the load (accelerator section). Fig. 3 shows typical waveforms of sled output for various phase-modulations.

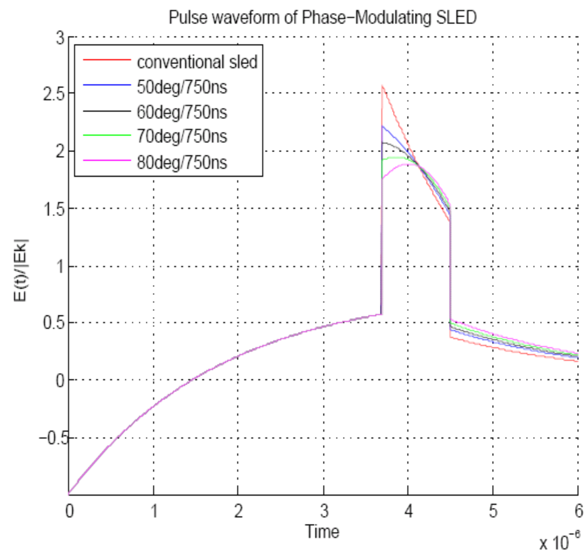

Figure 3: Waveforms of sled output for various p.m.

ENERGY GAIN CALCULATION

Our task is to find proper parameter, **$\varphi(t)= \varphi_0+k(t-t_1)$, $k=-\varphi_0/(t_{1B}-t_1)$,** with that parameter it will have lower high peak field and still have less or little loss on beam energy gain.

Let's find beam energy gain with RF waveform expressed in (4), (5), (6) and (7).

The accelerating section is a BTW constant-impedance structure, the measured attenuation factor of the sections τ = 0.611 Neper, and the measured filling time of the sections T_a=0.757 μs[2].

The field at any point z along the structure can be obtained from the field at the RF input port. Because it is a backward travelling wave structure, for convenience we take the downstream end (RF input port) as z=0, the upstream end of the section as $z=z_L$.

$$E_s(z,t)=E_s(0,t-\Delta t)*e^{-\frac{\tau}{z_L}z}$$

where,

$\Delta t=z/V_g$,V_g is group velocity, Δt is the time elapse of RF propagating to z from the input port

Notice that $z_L=V_g*T_a$, z_L is length of the section (6.15 m), T_a is the filling time of the section. Thus the field at any time t and any position z along the accelerating structure could be expressed in the form:

$$E_s(z,t)=E_s(0,t-\Delta t)*e^{-\frac{\tau}{T_a}\Delta t} \qquad (8)$$

The factor $e^{-\tau\Delta t/Ta}$ is the attenuation of field along the accelerator.

The energy gain V will be the integral of equation (8) over the entire section. Again, notice that in our case the

RF propagating direction is opposite to beam moving direction,

$$V = \int_{z_{up}}^{z_{dwn}} E_s(z,t)\,d(-z) \qquad (9)$$

Here, z_{up} denotes z upstream, $z_{dwn,}$ downstream. d(-z) means that the integral is done along opposite to +z direction.

Normalizing z with z_L, t and Δt with T_a (filling time of accelerator), that is,

$z'=z/z_L$, $z_{up}'=z_{up}/z_L$, $z_{dwn}'= z_{dwn}/z_L$; $t'=t/T_a$, $\Delta t'=\Delta t/T_a$; integral (8) will be written in form

$$V = \int_{z'_{dwn}}^{z'_{up}} E_s(0,t'-\Delta t') * e^{-\tau\Delta t'/Ta}\, dz' \qquad (10)$$

A simulation model is built up using of MATLAB simulink to calculate RF waveform E(t) given by expressions (4)-(7) and integral (10) to get the beam energy gain for various phase-modulations, **$\varphi(t)=\varphi_0+k(t-t_1)$,** where **$k= -\varphi_0/(t_{1B}-t_1)$.**

RESULTS

Figure 4, 5 present the results of peak field E and beam energy gain V for various options of phase-modulation vs. conventional/normal SLED.

Fig. 6 presents the picture of RF pulse and energy gain vs. time for phase-modulation and normal SLED.

In the past, the energy gain per section was around 140 MeV. This number was not limited by klystron's output. (45MW-klystron was operated at ~30MW). It was mainly limited by breakdown problem in accelerator structures.

By adopting phase-modulation mode it could lower the peak field and keep the energy-gain little compromised or even higher, with optimised operation parameters. Fig. 7 compares the result of phase-modulation with the data in past operation -- normal sled. At klystron output of 30 MW (4.5μs) with p.m. of 70º/750ns, as expressed in formula (3), the peak field would be ~12% lower, and the beam energy gain would be 10% higher compared to the data in the past runs. This means that it could reach ~165 MeV per section, still with no breakdown problem.

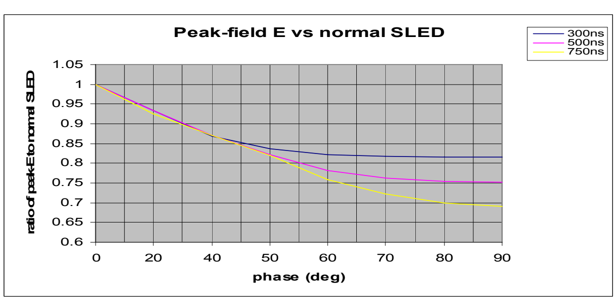

Figure 4: Effect of phase-modulation on peak E field.

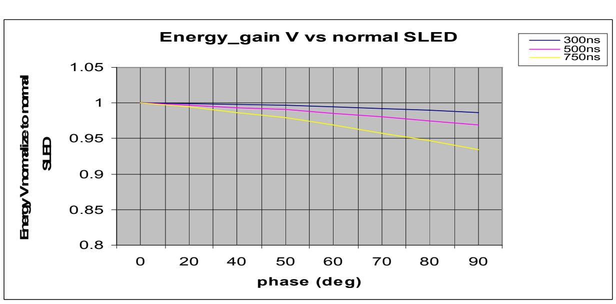

Figure 5: Effect of phase-modulation on energy gain.

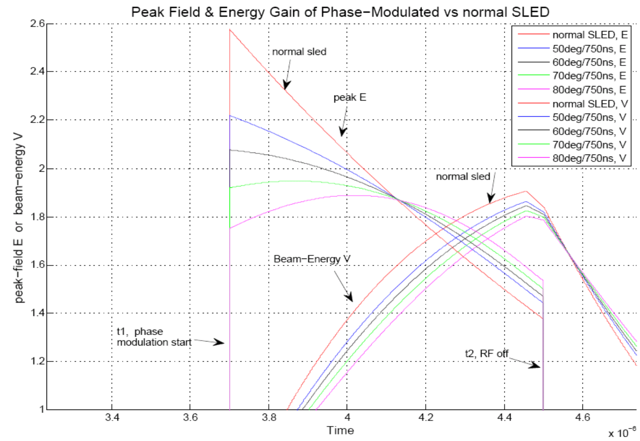

Figure 6: Peak field E & energy gain of phase-modulation vs. normal sled (peak field E is normalized to $|E_k|$ -- klystron output; energy gain is normalized to the one w/o sled).

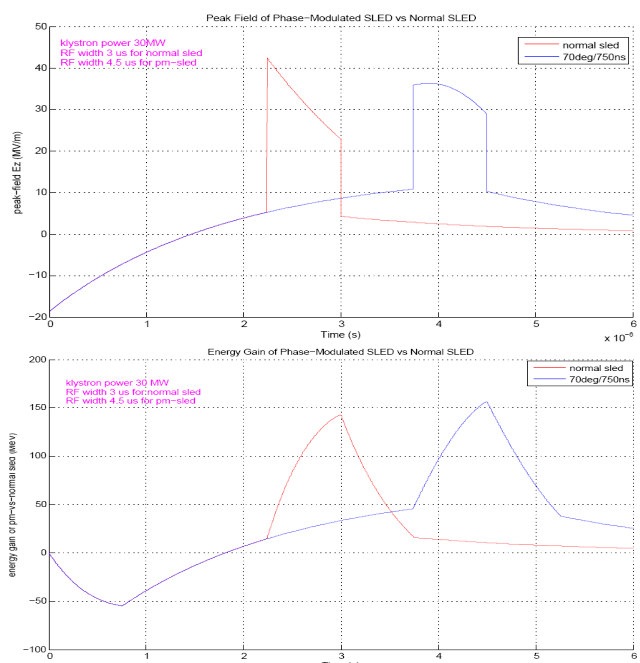

Figure 7:Peak-field & energy-gain for p.m. sled vs. normal sled.

REFERENCES

[1] C. Rossi, ST/M-TN-98/20.
[2] G. D'Auria, etc. ST/M-TN-91/15.