SINGLE PASS COLLIDER MEMO

AUTHOR: Karl L.F. Bane

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TITLE: CONFIGURING THE SLC LINAC FOR INJECTION INTO PEP*

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Introduction

From time to time the normal SLC physics program is to be interrupted so that beam can be delivered to PEP. In order that the switch to PEP injection (and the switch back again) can be accomplished quickly and easily the gun, the damping rings, the linac phase ramp, the energy profile of the linac klystrons for the scavenger bunch, and the entire positron production system are to be kept the same as in the SLC configuration. What mainly remains to be changed is the linac klystron profile for the leading two bunches - those going to PEP. The new klystron profile must be such that it leaves these two beams (1) with final energies that match that of the storage ring and (2) with final energy spectra that fit within the energy aperture of the PEP transfer line. In this note I discuss the conditions that need to be met in order to achieve these two goals.

Phasor Notation for the Linac Klystron Profile

In general, the final linac energy – at position ϕ within the beam – is given by

$$E_f(\phi) = E_0 + E_a(\phi) - E_{wake}(\phi) \quad , \quad (1)$$

with E_0 the initial energy, E_a the total energy gain from the klystrons, and E_{wake} the total energy loss due to wakefields. A negative phase is toward the front of the bunch, a positive phase is toward the back; the phase $\phi = 0$ locates bunch center. Similarly, the derivative of the energy (with respect to ϕ) at the end of the linac is given by

$$E'_f(\phi) = E'_a(\phi) - E'_{wake}(\phi) \quad . \quad (2)$$

The function $E'_f(\phi)$ is important in that it determines the final energy spectrum of the beam. Under normal SLC operation E_a is chosen to achieve the desired final beam energy and E'_a is chosen to approximately cancel the energy variation induced along the beam by the wakefield, leading to a narrowed spectrum.

We can easily keep track of both E_a and E'_a for any collection of klystron amplitudes and phases by using phasor notation. The total effect of all klystrons is given by the phasor:

$$\tilde{E}_a = |\tilde{E}_a|e^{i\phi_0} = e^{i\phi_r} \sum_i \hat{E}_i e^{i\phi_i} \quad , \quad (3)$$

with ϕ_r the setting of the phase ramp knob, a knob which globally shifts the klystron phases. Here $\hat{E}_i$ is the peak energy gain and ϕ_i is the central phase of the bunch in the section driven by Klystron i . (If Klystron i is turned off then $\hat{E}_i = 0$.) Note that the real part of $\tilde{E}_a e^{i\phi}$ is E_a , and its imaginary part is $-E'_a$.

We see from Eq. (3) that the magnitude of $\tilde{E}_a$ is given by

$$|\tilde{E}_a|^2 = \left(\sum_i \hat{E}_i \sin(\phi_i + \phi_r) \right)^2 + \left(\sum_i \hat{E}_i \cos(\phi_i + \phi_r) \right)^2 . \quad (4)$$

Its phase ϕ_0 , sometimes called the linac "average phase", is given by

$$\tan \phi_0 = \frac{\sum_i \hat{E}_i \sin(\phi_i + \phi_r)}{\sum_i \hat{E}_i \cos(\phi_i + \phi_r)} . \quad (5)$$

Switching from the SLC to the PEP Configuration

Under normal SLC operation a number of sectors at the front end of the linac are set to a phase $\phi_a > 0$, the rest to another phase $\phi_b < 0$, in order to gain the benefits of BNS damping. (The overall phase, of course, needs to be less than zero.) The phasors which represent a typical SLC klystron configuration are displayed in Fig. 1a. For the example shown the phase ramp $\phi_r = 0$; if it were nonzero the whole figure would be rotated about the origin by ϕ_r . Also shown in the plot is the phasor that gives the overall effect of the configuration, $\tilde{E}_a$. Its value in the plot roughly corresponds to that appropriate for a gaussian bunch with population $N = 2 \times 10^{10}$ and length $\sigma = .75$ mm.

In changing over from the SLC to the PEP configuration the following recipe (given to me by Marc Ross) is to be used:

- i) leave Sectors 2-14 unchanged,
- ii) turn off Sectors 15-19, 27, 28, 30,
- iii) backphase a number of klystrons (to be determined) in Sectors 22-26 and 29 to phase ϕ_c , while turning the rest off, and
- iv) set Sector 20 to phase $\phi_c + \pi/4$ and Sector 21 to $\phi_c - \pi/4$, so that they can be used as energy verniers.

Fig. 1. (a) Phasor representation of the klystrons in a typical SLC configuration, and (b) the corresponding PEP configuration which keeps $Im(\tilde{E}_a)$ unchanged. In this example the phase ramp $\phi_r = 0$.

Since the klystron on/off switches can be set differently for the scavenger than for the leading bunches (they arrive on different beam pulses), and since the scavenger bunch leaves the linac at the end of Sector 19 (before the first phase change), we see that this prescription allows the klystron profile seen by the scavenger beam to remain unchanged during configuration changes.

When switching from the SLC to the PEP configuration we want the real part

of $\hat{E}_a$ to change by the amount $E_{fP} - E_{fS}$, the difference between the two final energies. (The subscripts P and S represent, respectively, the PEP and the SLC configurations.) Given our recipe for the changeover, this condition implies that

$$(\hat{E}_{1P} + \sqrt{2} \hat{E}_{20}) \cos(\phi_c + \phi_r) = \hat{E}_{2S} \cos(\phi_b + \phi_r) + E_{fP} - E_{fS} \quad , \quad (6)$$

with $\hat{E}_{1P}$ the peak energy gain in Sectors 22-29 in the PEP configuration, $\hat{E}_{20}$ the peak gain in Sector 20 (assumed to be equal to the peak gain in Sector 21), and $\hat{E}_{2S}$ the peak gain in Sectors 15-30 in the SLC configuration. In Eq. (6) I have also assumed that the changeover from phase ϕ_a to phase ϕ_b occurs somewhere ahead of Sector 15.

When switching from the SLC to the PEP configuration we normally also want the imaginary part of $\tilde{E}_a - Im(\tilde{E}_a)$ – to remain unchanged. By fulfilling this second condition we keep the shape of the energy spectrum in the PEP configuration the same as in the SLC configuration. (Its width, however, will be increased by the factor E_{fS}/E_{fP} .) Therefore if, for example, the rms width of the distribution is minimized in the former configuration, it will also be so in the latter. In order to keep $Im(\tilde{E}_a)$ unchanged we require that

$$(\hat{E}_{1P} + \sqrt{2} \hat{E}_{20}) \sin(\phi_c + \phi_r) = \hat{E}_{2S} \sin(\phi_b + \phi_r) \quad . \quad (7)$$

Solving Eqs. (6) and (7) simultaneously we find that

$$\tan(\phi_c + \phi_r) = \frac{\hat{E}_{2S} \sin(\phi_b + \phi_r)}{\hat{E}_{2S} \cos(\phi_b + \phi_r) + E_{fP} - E_{fS}} \quad . \quad (8)$$

Eqs. (7) and (8) can be used to find the two unknowns ϕ_c and $\hat{E}_{1P}$. Note that in order to solve the problem we only needed to know the peak energy gain and

phases of the sectors to be modified, the phase ramp setting, and the final energies in the two configurations. The PEP klystron configuration that corresponds to the SLC configuration of Fig. 1a, and which leaves $Im(\tilde{E}_a)$ unchanged, is shown in Fig. 1b.

One other useful quantity, the sensitivity of the final energy to small changes in ϕ_c , is given by

$$\frac{\Delta E_{FP}}{\Delta \phi_c} \approx -(\hat{E}_{1F} + \sqrt{2} \hat{E}_{20}) \sin(\phi_c + \phi_r) \quad (\Delta \phi_c \text{ small}) \quad (9)$$

Narrowing the Energy Spectrum

If the final spectrum in the PEP configuration turns out to be wider than the acceptance of the PEP transfer line, we might want to decrease $Im(\tilde{E}_a)$. This will narrow the spectrum core at the cost of increasing the tail population (see, for example, Ref. 1). At higher currents, if we want to maximize the current injected into PEP, we will need to make such an adjustment. The value of $Im(\tilde{E}_a)$ can be decreased by increasing $\hat{E}_{1P}$. While doing this, however, we need to change ϕ_c so that Eq. (6) remains satisfied, in order that the beam's final energy remains unchanged. This procedure would be represented in Fig. 1b by moving the tip of $\tilde{E}_a$ downward along the dotted line.

There is a limit, however, to how far we can go by this procedure, since according to our recipe for switching between configurations we can use at most 6 sector's worth of klystrons to add up to $\hat{E}_{1P}$. From Fig. 1b we see that if we want to decrease $Im(\tilde{E}_a)$ beyond the limit given by this constraint we need to adjust - in addition to $\hat{E}_{1P}$ and ϕ_c - also the phase ramp ϕ_r . If we allow ourselves this extra degree of freedom we can, by following the same reasoning of this paper, derive

two equations analogous to Eqs. (6)-(7) that give the connections that need to be satisfied between the three unknowns. Note that in this case, in order to solve the problem, we need to know the peak gains and phases of *all* the klystrons in the linac.

Finally we should note that there is an alternative to decreasing $Im(\hat{E}_a)$ for narrowing the core of the spectrum. If we reduce the amplitude of the RTL compressor voltage we lengthen the bunch in the linac. And – over a certain range – as the bunch lengthens its spectrum will narrow (see, for example, Ref. 1).

A Numerical Example

According to a linac lattice listing of the SLC configuration (given to me by Mark Woodley), $\hat{E}_{25} = 25.1$ GeV and $\hat{E}_{20} \approx 1.7$ GeV. Suppose that the first 6 sectors of this model linac are set to $\phi_a = 20$ degrees, the rest to $\phi_b = -14.8$ degrees, and that $\phi_r = 0$. Also suppose that we have a gaussian beam with $N = 2 \times 10^{10}$ and $\sigma = .75$ mm. Then, according to the example listing, if the wakefield losses are included (.6 GeV) the beam in the SLC configuration will reach a final energy $E_{fS} = 47.4$ GeV. Furthermore, following the methods of Ref. 1. I find that the rms energy spread at the end of the linac equals 0.18%, and that the final energy distribution is double horned, with a horn spacing – containing 95% of the beam – of 0.38%.

In the PEP configuration, on the other hand, we want the beam to reach a final energy $E_{fP} = 13.5$ GeV; in addition we want it to fit within the energy acceptance of the transfer line to PEP. If we change configurations according to the recipe given in this paper, and satisfy Eqs. (7)-(8), then the shape of the final energy distribution will be unchanged, though its width will be increased by the factor $47.4/13.5 = 3.5$. The horn spacing, again containing 95% of the beam, will then

be 1.3%. Since the energy aperture of the PEP transfer line is 1.5%, following our prescription will result in essentially all the beam arriving at PEP.

Substituting the known quantities into Eqs. (7)-(8), we find that we require $\phi_c = -146$ degrees and $\hat{E}_{1P} = 9.1$ GeV. Since the back-phased sectors each contribute about 1.88 GeV, the requirement on $\hat{E}_{1P}$ can be achieved if we keep Sectors 22-25 fully powered, if in Sector 26 we keep 7 of its 8 klystrons on, and if we turn Sector 29 completely off. Fig. 2a shows the beam energy variation along the linac in the new configuration. The energy rises to 23.5 GeV in the middle of the linac, and ends up at 13.5 GeV. Fig. 2b gives the rms energy spread along the linac. This plot only gives the coherent part of the energy deviation. The incoherent part begins at 1% and drops as $1/E$. The dotted curve in the same frame, for comparison, gives the results in the SLC configuration.

Finally, we note also that Eq. (9) implies that the final energy of the beam will change by 0.1 GeV for a 1 degree error in ϕ_c . Since the acceptance of the transfer line to PEP is 1.5%, which at 13.5 GeV is equivalent to 0.2 GeV, we see that ϕ_c should be steady to a small fraction of 1 degree.

Acknowledgements

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References

1. Karl Bane, "Optimizing the Average Longitudinal Phase of the Beam in the SLC Linac", SLAC-AP-76, September 1989.

Fig. 2. The beam energy profile (a) and the rms energy spread (b) along the linac in the PEP configuration. The bunch population $N = 2 \times 10^{10}$ and the bunch length $\sigma_z = .75$ mm.