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AUTHOR: J. C. Sheppard

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TITLE: Required Energy Gain in the Linac *

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Introduction

The purpose of this note is to determine how much energy is required for each bunch at the end of the linac such that 100 GeV center of mass collision energy at the IP may be achieved. Once this has been ascertained it is possible to decide how much energy per station in the linac is needed, considering the effects of beamloading, shortened pieces of DLWG, and RF detuning. An appendix is included to cover a related topic: assuming lower bunch currents and lower collision energies, how many low power klystrons can remain in the linac? An attempt has been made to indicate what assumptions have been made so that the readers may try other assumptions to see what happens.

Linac Energy

In order to deliver 50.0 GeV beams to the IP it is necessary that the energy losses due to synchrotron radiation, resistive walls, and wakefields from discontinuities in the arcs and final focus system be considered. Energy loss, U , along an arc from the end of the linac may be expressed differentially in terms of the angle travelled, ϕ , and the initial beam energy, E_{Linac} , as¹

$$\frac{dU}{d\phi} = A(E_{Linac} - U)^4 + B \quad (1)$$

with $A = \frac{8.85 \times 10^{-4}}{2\rho} (GeV)^{-3}$ where ρ = the radius of curvature in a magnetic field and B is a linear loss term due to wakefields and the resistive wall. Ignoring B for the moment it is possible to show from (1) that the energy required at the end of the linac, E_{Linac} , to produce E_{IP} at the interaction point is given by

$$E_{Linac} = (E_{IP}^{-3} - 3\zeta \int \frac{d\phi}{\rho})^{-\frac{1}{4}} \quad (2)$$

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Table 1: Bend Parameters in the Arcs and FFS

Location	$\rho_i(m)$	ϕ_i
ARCN	279.378	236.12°
ARCS	279.378	225.55°
B6-FFS	119.129	0.912°
B5-FFS	119.129	0.426°
B4-FFS	119.129	0.912°
B3-FFS	133.424	1.047°
B2-FFS	133.424	2.094°
B1-FFS	133.424	0.994°
SE-FFS	3335.6	0.052°

where $\zeta = \frac{8.85 \times 10^{-8}}{2\pi} \left(\frac{m}{GeV^2} \right)$.

The integral in (2) may be replaced by a summation over the bend magnets. Table 1 lists the pertinent arc and FFS ϕ s and ρ s. Evaluation of $\int \frac{d\phi}{\rho}$ and substitution into (2) leads to

$$E_{Linac} = (E_{IP}^{-3} - 6.601 \times 10^{-7})^{-\frac{1}{3}} \quad (3a)$$

and

$$E_{Linac} = (E_{IP}^{-3} - 6.322 \times 10^{-7})^{-\frac{1}{3}} \quad (3b)$$

for the north and south arcs respectively. Substituting $E_{IP} = 50$ GeV into equations (3) yield $E_{Linac} = 51.456$ GeV for the north arc, and 51.391 GeV in the south arc. The energy loss due to resistive wall and arc BPMs is estimated to be about 27.5 MeV in each arc (approximately 2.5 MeV for wall losses² and the remainder for discontinuities due to some 500 arc and FFS BPMs³). Taxation in the form of extra synchrotron radiation caused by injection of higher energy beams into the arcs suggest the required E_{Linac} be augmented by approximately 30 MeV in order to compensate for the 27 MeV. It should be noted that integration of (1) including the linear loss term,

B, does not result in an expression from which E_{Linac} can be algebraically separated from E_{JP} .

Required Klystron Gain

For the purposes of determining the required energy gain in the linac it is assumed that beams of 51.500 GeV are required. In calculating the acceleration from the damping rings through sector 30, the effects of single bunch beamloading, random phase errors, Landau damping, and the necessity of keeping four klystrons in reserve are considered. In terms of linac parameters, E_{Linac} can be expressed as

$$E_{Linac} = G f A_3 \cos(\theta_3) - \Delta E_{BL} + E_{INJ} \quad (4)$$

wherein $G \equiv$ the energy gain from a standard linac girder (i.e. one which has 4-10' DLWG and is powered with a 50 MW tube in SLED II mode); $f \equiv$ an RF derating factor to account for random phase errors and deviations in water temperature and a myriad of other effects, all of which decrease the maximum gain from a station; $A_3 \equiv$ the equivalent number of klystrons available for acceleration at RF phase θ_3 ; $\Delta E_{BL} \equiv$ the average energy loss within a single bunch due to longitudinal wakefields plus the loss due to the passage of a prebunch, 60ns ahead in the linac; and $E_{INJ} \equiv$ the energy of the beam injected into sector two from a damping ring. Equation (4) allows one to determine the necessary G for a desired E_{Linac} given suitable assumptions for the values of the other quantities. G is given by

$$G = \frac{E_{Linac} + \Delta E_{BL} - E_{INJ}}{f A_3 \cos(\theta_3)} \quad (5)$$

E_{Linac} was determined above to be 51.500 GeV. For 5×10^{10} particles in a single bunch and $\sigma_x = 1\text{mm}$, $\Delta E \approx 1.30$ GeV from self-loading⁴ and $\Delta E \approx 0.890$ GeV due to the presence of the first bunch⁵ thereby bring the total energy loss from longitudinal wakefields to $\Delta E_{BL} \approx 2.190$ GeV. E_{INJ} is taken as the nominal 1.210 GeV. f is arbitrarily chosen to be 0.98. A_3 and θ_3 are discussed below.

For the case of Landau damping, a set of A_1 klystrons are operated at phase θ_1 at the beginning of the linac and the remaining A_2 tubes are run with phase θ_2 . The A_1 and A_2 represent an effective number of klystrons and are given as summations over a normalized gain coefficient:

$$A_1 = \sum_{i=1}^{I_1} a_i \quad (6a)$$

and

$$A_2 = \sum_{i=I_1+1}^{N-4} a_i \quad (6b)$$

where the $a_i \equiv 1.000$ for a standard girder with four 10' DLWGs and the $a_i < 1.000$ for the nonstandard girders which contain shortened or missing sections of DLWG. Table 2 lists the a_i for sectors two through thirty for the case of so-called flat RF and for the case of SLED II. SLED II is of interest for SLC running. In (6b) $N \equiv$ the total number of tubes in the linac; $N-4$ represents the scenario of operating with 4 klystrons in reserve. Thus, $A_3 \cos(\theta_3)$ is simply

$$A_3 \cos(\theta_3) = A_1 \cos(\theta_1) + A_2 \cos(\theta_2). \quad (7)$$

For the case⁶ of $N=232$, $I_1=24$, $\theta_1 = -30^\circ$, $\theta_2 = 16.8^\circ$ and the entries of Table 2, $A_1 = 23.492$ klystrons, $A_2 = 199.874$, and $A_3 \cos(\theta_3) = 211.743$ klystrons.

Substituting the aforementioned parameter values into (5), it is seen that

$$G = \frac{51.500 + 2.190 - 1.210}{(0.98)(211.743)} \text{GeV} = 0.253 \frac{\text{GeV}}{\text{Station}}.$$

Thus, the linac gain per station needs to be at least 253 MeV per girder in order to deliver a 50.0 GeV electron beam to the IP. The corresponding positron prebunch arrives at the IP with an energy of 50.6 GeV. Readers are invited to try other assumptions for parameters. The example above corresponds to the gain required to produce a 50 GeV electron bunch at the IP. By sliding the positron bunch to the crest of the

SLED waveform, a gain of $G = 247$ MeV per station will generate 50 GeV positrons at the IP. However the trailing electron bunch would arrive with an energy of about 43.4 GeV because of the loading due to the leading bunch and fall off of the SLED waveform, 60 ns after the peak.

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References

1. SLC Design Report, page 3-35.
2. J. Peterson, P.B. Wilson, CN-232 1983, have used Al conductivity versus SS used in CN-232.
3. Karl Bane, Private communication.
4. Karl Bane, Private communication; G. A. Loew, Private communication.
5. SLC Design Report, page 2-24.
6. J. T. Seeman, CN-278 1984

Table 2: Maximum Energy Gain at Special Locations

Location	$a_i \equiv \frac{\Delta E}{\Delta E_{nominal}}$ NONSLED	$a_i \equiv \frac{\Delta E}{\Delta E_{nominal}}$ SLED	Special Sections
2-1	0.778	0.842	a, 9.4', 7', 10'
2-2 to 2-8	0.982	0.982	3 x 9.4', 10.'
3-1 to 4-8	0.990	0.990	10', 9.4', 10', 10'
10-1	0.707	0.707	c, d
10-8	0.854	0.854	d
11-1	0.854	0.854	a
11-3	0.707	0.707	a, d
11-4	0.838	0.875	7'-A, B, D
11-5	0.946	0.945	7'-B
11-6	0.892	0.910	7'-A, D
11-7	0.946	0.945	7'-D
12-2	0.946	0.945	7'-A
12-3	0.946	0.945	7'-D
12-6	0.946	0.945	7'-A
13-4	0.946	0.945	7'-D
14-4	0.946	0.945	7'-D
19-4	0.946	0.945	7'-D
19-7	0.000	0.000	a, b, c, d
20-1	0.000	0.000	a, b, c, d
20-8	0.854	0.854	d
21-1	0.854	0.854	a
25-1	0.845	0.845	c, 0.95 x D
30-8	0.854	0.854	d
$\sum_{Girders} 1 = 44$	$\sum_{Girders} a_i = 39.319$	$\sum_{Girders} a_i = 39.430$	

1. ΔE is determined for specified configuration of DLWG.
2. $\Delta E_{nominal}$ refers to gain from a girder with four 10' sections.
3. Lower case a, b, c, d indicate missing sections.
4. Lengths indicate size of installed DLWG.
5. Assume 5% of input power to 25-1D goes to buncher.
6. The feeds to sections A and B on 10-2 are presently disconnected.

Appendix: 95.0 GeV Center of Mass at the IP

Question: How many XK-5 klystrons can remain in the linac such that 95 GeV center of mass IP collisions for 2 bunches of 2×10^{10} particles per bunch may still be achieved? It is assumed that 0.158 GeV of energy gain per klystron (i.e. 33 MW peak power) is available from the XK-5 tubes and 0.253 GeV is available from the new klystrons.

Answer: 46 tubes

The number of tube sockets which may be filled with low power tubes is given as A_{LP} :

$$A_{LP} = \frac{A_1 \cos(\theta_1) + A_2 \cos(\theta_2) - \frac{E_{Linac} + \Delta E_{BL} - E_{INJ}}{Gf}}{(1 - R) \cos(\theta_2)} \quad (1)$$

wherein R is the ratio of the energy gain from a low power klystron to the gain from a high powered tube and the other parameters have been defined in the previous note¹ as: A_1 and A_2 are the number of klystrons operating at RF phase θ_1 and θ_2 , respectively; E_{Linac} is the beam energy required at the end of the linac; ΔE_{BL} is the beam energy lost to longitudinal wakefields (this is taken as the sum of the intra-bunch loss and the effect from a bunch passage 60 ns ahead in the machine); E_{INJ} is the beam energy when reinjected from the damping ring; G is the peak energy gain from a high powered SLC klystron; and f is the klystron derating factor. To generate equation (1) it has been assumed that the XK-5 tubes are run at phase θ_2 .

For 2.5 μ s RF, the SLED multiplier is 1.379 at the peak and 1.364 at 60 ns before the peak. Given the typical energy gain formula, one can expect $\Delta E = 0.158$ GeV and 0.157 GeV from a 33 MW klystron at the peak and 60 ns before, respectively. The ratio of peak energy gains from 33 MW tubes and 50 MW tubes is given as R . For $G = 0.253$ GeV from the new klystrons, $R = 0.625$.

For a center of mass energy of 95.0 GeV choose $E_{IP} = 47.50$ GeV. Equations (3) in reference [1] then indicate one needs $E_{Linac} = 48.676$ GeV for the north arc and $E_{Linac} = 48.624$ GeV for the south arc. Select $E_{Linac} = 48.70$ GeV. For 2×10^{10} particles per bunch, $\Delta E_{BL} = 0.88$ GeV. $E_{INJ} = 1.21$ GeV, as always; $G \equiv 0.253$ GeV, and $f \equiv 0.98$. Using the value of 211.743 klystrons for $A_3 \cos(\theta_3)$ and $\theta_2 = 16.8^\circ$, substitution into (1) yields

$$A_{LP} = \frac{211.743 - \frac{48.700 + 0.876 - 1.210}{0.253 \times 0.98}}{(1.00 - 0.625) \cos(16.8^\circ)} = 46 \text{ tubes.}$$

The attached figure is a plot of equation (1) for beamloading energies corresponding to bunch currents of 0 particles, 2×10^{10} particles, and 5×10^{10} particles.

Low Power Tubes Versus IP Energy

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