ELECTRONS, THE ENERGY CRISIS AND THE POSSIBILITIES OF RF POWER

This note results from the convergence of a number of contingencies:

- A recent question by W. Panofsky as to the ultimate field gradients attainable in room temperature rf structures,
- The realization that Stage II-type or superconducting solutions are not economically or technically viable at SLAC,
- The fact that the cost of power at SLAC will probably double in the next five years,
- Uncertainties about funding of new construction projects,
- The uneasy feeling about SLAC becoming just an injector for storage rings.

Energy and RF Power Considerations

The energy of the present accelerator in the absence of beam loading can be calculated from the energy per girder (or per klystron) from

$$E_G\ (\text{MeV}) = 20\sqrt{P_K\ (\text{MW})} \tag{1}$$

where P_K is the peak output power of a klystron in MW. With an average of 240 klystrons operating at any given time, the total energy is

$$E_{SLAC}\ (\text{GeV}) = 4.8\sqrt{P_K\ (\text{MW})} \tag{2}$$

At the present time, there are approximately 80 klystrons (10 sectors) with 30 MW output and 160 klystrons (20 sectors) with 20 MW output. This results in a total connected RF power of 5600 MW or 23.3 MW per station. If we look at the conversion efficiencies involved in the production of this RF power, we see that we can write

$$P_K\ (\text{MW}) = \frac{\eta_{RF}\ \eta_{AC}\ P_{AC}\ (\text{MW})}{n_p\ \tau_{RF}} \tag{3}$$

where η_{RF} is the efficiency of the klystron
(presently 0.33 on the 20 MW klystrons and 0.40 on the 30 MW klystrons)

η_{AC} is a lumped efficiency which combines the substation, VVS, and modulator efficiencies
(presently ~ 0.60)

n_p is the number of pps

τ_{RF} is the flat top rf pulse length

(presently 2.5 μsec)

P_{AC} is the AC power consumed per klystron

(presently an average of $\sim$0.094 MW at 360 pps or $P_{T,AC}$ = 22.6 MW for 240 klystrons, not including positron source solenoid power. The actual total number of klystrons is 245 but for simplicity the number of 240 is used hereinafter.)

If we refer to Eqs. (1) and (2) and Fig. 1, we see that the following approximate results obtain:

P_K (MW)	E_G (MeV)	E_{SLAC} (GeV)	$P_{T,AC}$ (MW)
23.3	96.6	23.2	22.6
30	109.2	26.3	27 *
40	126.4	30.2	27 **
60	154	37	18 ***

* assuming η_{RF} = 0.40

** assuming η_{RF} = 0.53, 360 pps and all other parameters held constant

*** assuming η_{RF} = 0.60, 180 pps, neglecting power for possible electromagnets (extra 1 MW), and all other parameters held constant.

The various values of P_K in the table correspond to presently projected milestones in our klystron construction program. The upper two curves in Fig. 1 also give the effective and maximum E-fields (in kV/cm, right hand scale) in the SLAC disk-loaded waveguide structure. The maximum E-field is obtained from the relation $E_{MAX} / E_{EFF} = 2.2$ derived from a LALA calculation. Two special points are shown on the figure. One is a CERN data point (520 kV/cm) giving a maximum E-field in a practical electroformed structure. The other is a data point obtained by

R. Borghi and R. Baker with a short disk-loaded waveguide structure in a resonant ring, back in the "purple coffin days": it shows powers in excess of 200 MW circulating in the section (or > 800 MW per klystron with a four-way split) without electric breakdown. Thus, in principle, SLAC would be capable of yielding energies in excess of 135 GeV (assuming that the rectangular waveguide components do not break down!).

Beam Current Considerations

Combining Eqs. (2) and (3), we see that

$$E_{SLAC}\,(\mathrm{GeV}) = 4.8\sqrt{\frac{\eta_{RF}\,\eta_{AC}\,P_{AC}\,(\mathrm{MW})}{n_p\,\tau_{RF}}} \tag{4}$$

and

$$n_p\,(\mathrm{pps}) = \frac{23\,\eta_{RF}\,\eta_{AC}}{\tau_{RF}\,E^2_{GeV}}\;\frac{P_{T,AC}\,(\mathrm{MW})}{n_K} \tag{5}$$

where n_K is the number of klystrons. Now, clearly the number n_e of electrons/sec obtainable is simply

$$n_e = n_p \frac{i_{pk}\,\tau_i}{1.6\times 10^{-19}} \tag{6}$$

where τ_i is the beam pulse length and i_{pk} is the peak current. Thus

$$n_e = \frac{23\,\eta_{RF}\,\eta_{AC}}{E^2_{GeV}}\;\frac{\tau_i}{\tau_{RF}}\;\frac{P_{T,AC}\,(\mathrm{MW})}{n_K}\;\frac{i_{pk}}{1.6\times 10^{-19}} \tag{7}$$

Assuming for a moment that beam currents giving up to 10% beam loading are manageable both "BBU-wise* and spectrum-wise," we see that since $\Delta E/\Delta i \sim 36\,\mathrm{GeV/A}$,

* At 48 GeV, i.e., twice the present gradient, currents of ~160 mA are probably not unrealistic if one increases the focussing strength accordingly.

we should be able to obtain currents i_p (Amps) = E (GeV) / 360. Then

$$n_e = \frac{10^{19}}{1.6 \times 360} \; \frac{23}{E_{GeV}} \; \frac{\tau_i}{\tau_{RF}} \; \frac{\eta_{RF} \; \eta_{AC} \; P_{T,AC} \, (MW)}{n_K} \qquad (8)$$

For the present SLAC parameters, we get $n_e \sim 2.4 \times 10^{14}$ electrons/sec, or a peak current of 65 mA at 10% beam loading. Notice in passing that we consume 1 erg of energy to produce one ~20 GeV electron (our process is about 3% efficient).

The interesting fact is that while n_p, the number of pps varies as E^{-2}, n_e varies only as E^{-1}. Hence, if we did nothing except build klystrons at constant η_{RF} and $P_{T,AC}$ but with peak powers sufficient to double the energy, the number of pps would go down by 1/4, but the number of electrons would drop by only 1/2! The beam power would remain constant. Notice that strictly speaking, the above equations are not quite correct because the expressions giving energy vs. power should really contain a beam loading term of the form (-Ki), but this has been neglected since we are only considering currents up to 10% beam loading and the accuracy is sufficient for the sake of this argument.

What might be practical?

Now let us look at the future and see what possibilities we have. Short of actual power rationing, it is clear that power costs will gradually rise. A. Tseng, for example, predicts that the cost of power at SLAC will henceforth increase by 1 mil/KW-hr/year and, thus, will double in 5 years. If this is correct, our power bill in 1978 at 1973 consumption levels will be above 2 M$ for the accelerator-BSY-EFD complex. Assuming 600 shifts or ~5000 hours of operation per year at 27 MW, the yearly cost increase due to RF power alone * would be $135,000/year. What might we expect to do under those circumstances? What are the options, looking at Eqs. (4), (5), and (8)?

* At the present time, the accelerator at 360 pps together with the BSY and attending conventional facilities consume about 35 MW.

Let us assume that we set out to develop a 100 MW klystron operating at 400 KV and 55% efficiency. Further assume that the present $\eta_{AC} = 0.60$ cannot be improved upon and that we keep $\tau_i / \tau_{RF} = 1.6/2.5$ as in the past. The number of klystrons cannot be increased without incurring major costs and modifications including waveguides, instrumentation, phasing, drive, etc. For the total AC power to be converted into RF, $P_{T,AC}$, let us look at two hypotheses:

a) $P_{T,AC} = 27$ MW, i.e., no possible increase above and beyond the power consumption level required when all klystrons will be of the 30 MW type.

b) $P_{T,AC} = 32.5$ MW, i.e., a 20% increase above this level which entails some changes in the power supplies, V.V.S. and water system.

The consequences then are shown in the table:

	(a)	(b)
Total accelerator AC power, $P_{T,AC}$	27 MW	32.5 MW
Klystron power, P_K	100 MW	100 MW
Klystron efficiency	0.55	0.55
Energy per girder	200 MeV	200 MeV
Total SLAC no-load energy	48 GeV	48 GeV
Repetition rate, n_p	150 pps	180 pps
Number of electrons/sec for 10% beam loading	1.95×10^{14}	2.4×10^{14}
Equivalent peak current, i_{pk}	130 mA	130 mA

It is seen that the number of electrons per second does not compare unfavorably with the present levels of operation or with those of RLA. The 32.5 MW power consumption in case (b) is not overwhelming and is well within the level of 27 + 10 = 37 MW which must be considered for RLA operation, not including BSY modifications. As has been shown by Coward and Tseng for RLA, BSY improvements to accommodate the 40-50 GeV beams would require adding another 2-3 MW of AC power. Presumably a similar addition would be required here although the basic construction changes in the BSY would be relatively straightforward and the present configuration of the pulsed magnets could be preserved.

Cost

Since technical feasibility of a 100 MW klystron - 400 KV modulator system has not been established, it is hard to make a meaningful cost estimate. Olson has made a preliminary guess of 16 K$ per modulator for case (a) to upgrade our present units to 400 kV plus ~4 K$ per power supply for case (b), Lebacqz has guessed 30 K$ for a 100 MW klystron; say a total of 50 K$ per station for case (b) or $12 M total. To this one would have to add some focussing improvements on the accelerator (~$0.5 M), a BSY improvement fund ($2 M), and for case (b) some added funds for more AC-DC power facilities and water ($1.5 M).* Thus, a grand total of $13.5 M for (a) and $16 M for (b) might not be too unrealistic, not including R&D. In case no construction money could be made available for such a project, one would have to attempt to carry it out in a creeping A.I.-type fashion and make a gradual conversion much like the 40-60 MW conversion is envisaged now.

In view of these thoughts and possibilities, one might conclude in the present climate of uncertainty that starting an R&D program on a 100 MW - 400 KV klystron with its attendant waveguide tests would be a good long term bet. Meanwhile we should of course continue our daydreams about other RF power conversion tricks such as pulse compressors, overcoupled high-Q cavities or even laser devices, fully realizing that they are only daydreams at the present time.

*This number cannot be worked out with any accuracy without some actual work on the VVS.

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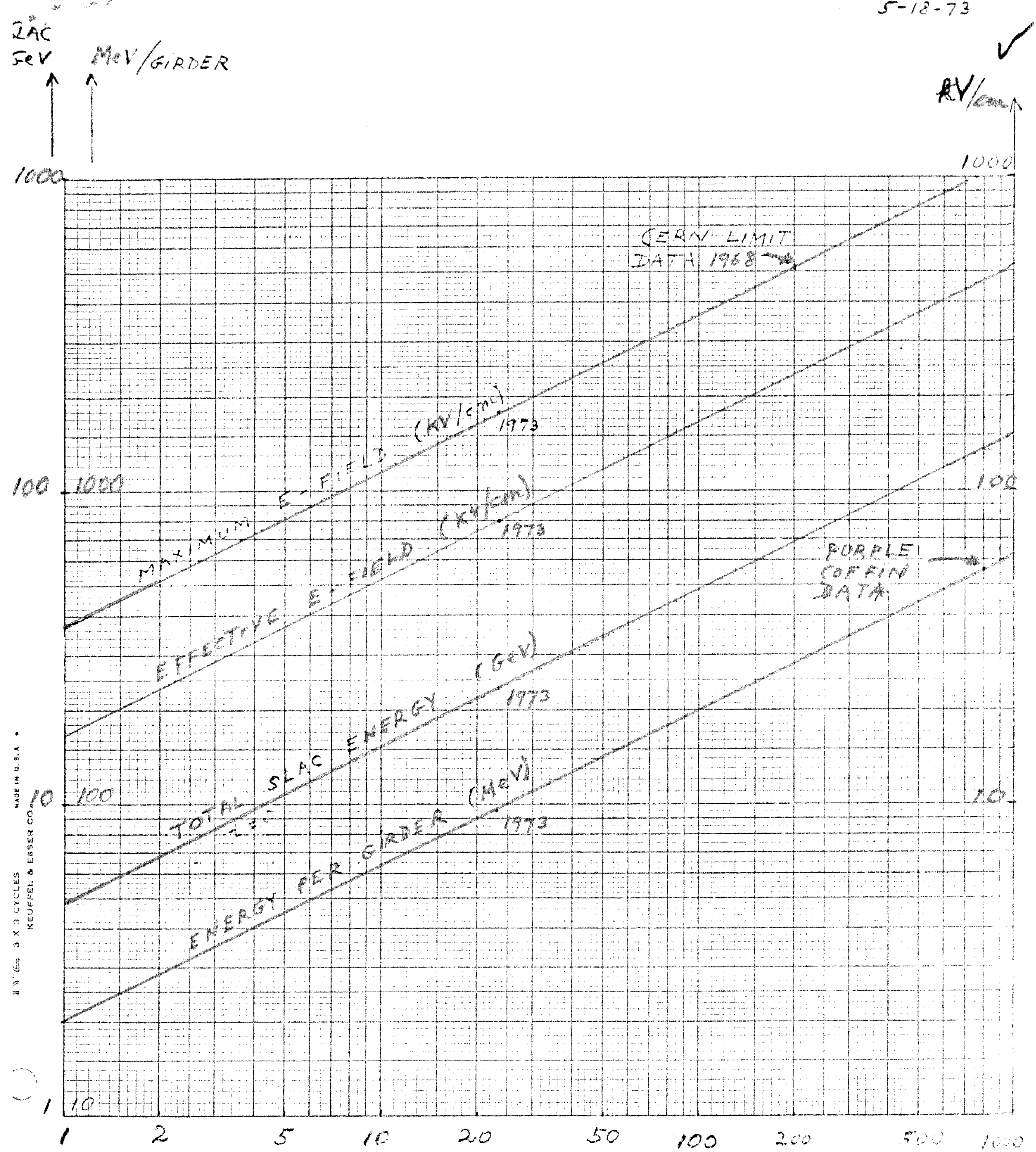

POWER PER KLYSTRON (MW)

FIG. 1