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ACCELERATOR TECHNOLOGY WORKING GROUP SUMMARY*

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ABSTRACT

A summary is presented of workshop deliberations on basic scaling, the economic viability of laser drive power for HEP accelerators, the availability of electron beam injectors for near-term experiments, and a few very general remarks on technology issues.

INTRODUCTION

This group was set up to aid the other groups in their deliberations. The membership is listed below.

J. Fraser, Los Alamos	R. Sheffield, Los Alamos
E. Gray, Los Alamos	J. Sheppard, SLAC
R. Jameson, Los Alamos	J. Simpson, Argonne
J. Lawson, Rutherford-Appleton	D. Sutter, DOE/OHENP
A. Ruggiero, Fermilab	L. Teng, Fermilab
S. Schriber, Los Alamos	R. Williams, UCLA
T. Smith, Stanford University	

In fact, the group did disperse most its efforts in interaction with the other groups. Specific contributions covered elsewhere in these proceedings include analysis by Sheppard of how to achieve better emittance using damping rings (looks favorable) or wigglers (pessimistic, because of excessive wiggler length and energy loss), and an outline by Fraser, Sheffield, and Gray on prospects for reducing electron beam source emittance using photo-emitters and advanced preaccelerators.

The following comments summarize other concerns of the group relevant to questions of basic scaling, the major influence of economics on the overall viability of high-gradient accelerators, availability of electron beams for acceleration tests, and a few observations on technology issues.

SCALING RELATIONSHIPS FOR HEP REQUIREMENTS

The basic scaling equations for High-Energy Physics (HEP) colliding beam requirements (relating energy, luminosity, disruption factor, beamsstrahlung) were reviewed by Lawson. It was concluded that the set of equations is consistent and mature, and that the same approach was taken at this meeting as was used at the Frascati Workshop on the Generation of High Fields for Particle Acceleration in October 1984. There has been some refinement in

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the treatment of disruption factor and beamsstrahlung recently, and it should also be noted that P. Wilson pointed out in his talk that one might do better with flat, rather than round, beams because the beamsstrahlung would be less.

ECONOMIC VIABILITY OF LASER DRIVE POWER FOR HEP ACCELERATORS

Major emphasis was placed on ensuring that the significance of efficiency and economics in achieving the HEP goals for colliding beams at high energies was appreciated by the proposers of the various schemes.

In particular, it is necessary to understand that achieving very high accelerating gradients alone is a far too simplistic prescription--very high gradients hold the lure of short machines, but without very significant attendant economic advantages, very high gradients would be unaffordable in a real machine.

A short example underscores the point: As a rule of thumb, the total construction cost of a facility is about half plant, engineering, design and installation, and about half technical equipment. The technical equipment in this case is some form of linear accelerator (linac); under the usual optimization procedure¹ for today's linacs, about half the cost is for the installed drive power and half is for the linear structure cost.

$$\text{Technical Equipment Cost} \sim (\text{Unit Power Cost})(\text{Power}) + (\text{Unit Length Cost})(\text{Length})$$

The amount of power required varies inversely with length; therefore, the two terms trade directly against each other, resulting in optimum cost when the terms are roughly equal.

Putting in some numbers helps illustrate the challenges involved in the factors in this simple equation. Richter, in his opening address, gave a range of electron beam power cases; take the case of 10-MW average power. It is important to note that the requirement is for average power, because of the need for adequate luminosity.

For beam breakup and energy-spread reasons, at the present time, it is felt for HEP colliders that no more than about 10% of the power in the accelerating structure can be converted into beam power. Further, in schemes where there is an added energy conversion step between beam and drive, for example from laser drive to plasma wave to accelerated beam, another 10% efficiency (at best) is encountered. Thus, the drive power requirement is between 100 MW and 1 GW; take 100 MW.

The present cost of conventional rf average power, up to frequencies of a few GHz, is about \$5/average watt. Various breakdown considerations indicate that the frequency of conventional linacs could be pushed up to a point of diminishing returns around 30 GHz, and it appears that the cost per average watt could be kept roughly the same up to that frequency. Then, the power cost term would be \$500M, and one would optimize the gradient (at around

100-200 MeV/m) against length to produce an equal length cost, for a total technical equipment cost of \$1B.

Laser drive power, on the other hand, is produced through a number of energy conversion steps, with resulting overall efficiencies (wall-plug to laser average power) of a few per cent at best, compared to 60-70% for rf. (The free-electron laser with energy recovery may reach a few tens of per cent, depending on the wavelength and power levels.) The laser technology group found that the present cost per average laser watt is about several hundred dollars and projected a possible reduction to about \$100/average watt after extensive development. Take the cost/average laser watt to be \$100. Then the cost of the power alone in our example would be \$10B, clearly unfavorable and with no possibility to recoup the situation by lower length costs.

One must therefore conclude that accelerator length is not the overriding problem, and that the HEP requirements challenge even conventional unit costs and efficiencies.

An appropriate problem ranking might be the following:

- Improve drive-to-beam efficiency
- Improve electric-to-drive efficiency
- Reduce unit power costs

This very cursory system analysis further strongly suggests that a balance be maintained between longer wavelength approaches and the laser accelerator approaches. Work on longer wavelength (~ 1 -cm) structures, transformer designs, rf breakdown, and related topics might well provide solutions appropriate to the next linear collider.

In a complementary fashion, the application of lasers to the HEP goals does address many basic physics and technology issues and is also well worth pursuing. Even while direct laser drive had to face the stringent economic realities at this meeting, new ideas on how lasers might be used were surfacing. Lasers produce peak power efficiently and might be used in that mode to provide the very strong focusing fields required, as suggested by Channell, or to provide electrical switching, as in the scheme outlined by Willis.

Also, the address of such topics (like how to achieve and use high gradients) could well be the priming influence for a new insight or breakthrough.

ELECTRON BEAM INJECTORS

Considerable interaction occurred in defining approaches and available equipment or facilities for providing the electron beams to be accelerated in near-term experiments. Table I shows the main properties of some of the prospects identified; beams could be provided at the GeV level (SLAC SLC Damping Ring, or Nuclear Physics Injector), 100 MeV from the Stanford Superconducting Accelerator, 22 MeV from ANL, and at low energies up to 10 MeV from the Los Alamos designed portable linac or commercial 9-GHz linacs from Schoenberg Radiation. One main tradeoff involved is whether one brings the linac injector to the rest of the experiment, or vice

Table I Electron beams for near-term experiments

	<u>Energy</u>	<u>Np</u>	ϵ (m·rad) (unnorm)	<u>γ</u>	<u>σ_x</u>	<u>$\Delta p/p, \%$</u>	<u>\$</u>
SLC Damping Ring	1 GeV	5×10^{10}	1.5×10^{-8}	2×10^3	3 μ m	0.1%	
SLAC NPI	1 GeV	2×10^9	1.5×10^{-7}	2×10^3			
	6 GeV	2×10^9	3×10^{-8}	1×10^4			
Stanford	1 GeV	(future; seeking users, will also have storage ring)					
Stanford Super-Conducting Linac	100 MeV (20-150)	5×10^7	2×10^{-8}	200		~ 0	Cost Recovery + \$500K?
ANL	22 MeV (+ witness pulse)	6×10^{10}	2×10^{-7}	40		0.5	Cost Recovery $\sim$ \$175/hour
Los Alamos FEL 1.3-GHz e ⁻ Linac Optical	10-20 MeV 9-100 μ m, high peak and average power	2×10^{10}	2×10^{-6}	40	1 mm	1-2	
Los Alamos 3-GHz Linac (portable--could be improved with photo-cathode)	6-10 MeV	2×10^8	3×10^{-6}	20	2 mm	10	\$500K
Schoenberg Radiation Linac	6 MeV	2×10^7	1×10^{-6}		2/3 mm	10	\$315K
9-GHz Linacs	4						\$265K
	1.5						\$150K

versa. Another is the energy gain to be achieved in the experiment relative to the injection energy.

Some further particulars are listed below.

SLAC Beams

(See layout, Fig. 1.)

SLAC: CID Gun	
Charge/bunch	8 to 16 nC (5 to 10 x 10 ¹⁰ e-/pulse)
Bunch length	30 ps FWHM
Number of bunches	2
Bunch separation	arbitrary in 5.6-ns increments
Emittance	$\gamma_e < 15 \times 10^{-5}$ m·rad
Energy	50 MeV
$\Delta E/E$	approximately 1% FWHM
SLC: Damping Ring Beams	
Bunch separation	61.6 ns
Emittance	$\gamma_e < 3 \times 10^{-5}$ m·rad
Energy	1.27 GeV
Energy spread	2.0% FWHM, typical 0.2% FWHM, uncompressed
Bunch length	3.5 mm nominal (12 ps) (14 mm uncompressed)
SLC: End of Linac	
Emittance	$\gamma_e < 3 \times 10^{-5}$ m·rad
Energy	1 to 51 GeV
$\Delta E/E$	>0.1% FWHM
Rep rate	180 Hz
Type of beams	e ⁺ and e ⁻
NPI Gun:	
Pulse length	≤ 1.6 μ s (4500 S-band bunches)
Charge/bunch	$\leq 2.2 \times 10^9$ e-/bunch, max* $\leq 2.2 \times 10^8$ e-/bunch nominal
Bunch length	5 ps FWHM
Emittance	$\gamma_e \leq 5 \times 10^{-5}$ m·rad
Energy	≤ 6 GeV
$\Delta E/E$	$\geq 0.1\%$ FWHM (single bunch) $\approx 0.7\%$ FWHM (multibunch pulse)

*This corresponds to maximum gun output and can only be transported through the linac for pulse lengths of several nanoseconds.

Fig. 1. Overall SLC layout. The figure indicates the general features of the SLAC linac. Emittance damping rings are located approximately 120 m downstream of the collider injector (CID). BL90 is a 14° off-axis extraction line situated about 1000 m from the gun. The dc bends associated with BL90 operate at beam energies up to 10 GeV. The Nuclear Physics Injector (NPI) is at the 2500-m point along the linac. As a point of reference, the SLC positron source is located at the 2000-m point. Overall the linac is 3 000 m long. There are three end stations at the end of the accelerator.

Stanford FEL Group

Stanford's FEL program is constructing a 1-GeV linac and storage ring, and is seeking users. Beam available in 1987.

Stanford HEPL Superconducting Linac

Average beam currents up to 400 μ A are available.

Two types of pulse trains:

1) every rf bucket filled, spaced at $1/1.3$ GHz = 769 ps; each pulse ~ 5 ps, peak current ~ 40 mA.

2) subharmonic operation - pulses at 110th subharmonic of 1.3 GHz = 85 ns, each pulse ~ 7 ps, peak currents to 4 A.

Beam emittance at 50 MeV ~ 10 mm-mrad normalized.

A cost-recovery operation is desired and, with \$500K up-front, a first-rate user facility could be set up.

HEPL also has a 40-MeV infrared (1.6μ m) FEL machine that delivers about 1/4-A average current during the 10- μ s pulse, with every bucket filled, and with emittance "equal to about half the Lawson-Penner criterion."

ANL Wake-Measurement Facility

Argonne has internal support to set up a multipurpose, user-oriented wake-field measurement facility around their 22-MeV high-peak-intensity linac. They hope to be able to start tests by the fall of 1985.

Linac Characteristics

Energy	22 MeV
Energy spread	± 100 keV
Pulse length	30 ps*
Peak current	1 kA
Rep rate	< 800 Hz
ϵ_x, ϵ_y	7×10^{-6} m-rad (Norm)
Intensity/pulse	9 nC

*Will be ~ 5 -10 ps this year

L-Band, subharmonic buncher

Use at present about 5-6 shifts/wk by CHEM, PHYS, HEP. Used 25 shifts/yr for stochastic cooling pickup devices and calibration.

Beam manipulations to provide the shock pulse followed by a full or reduced energy probe pulse are being studied, as indicated in Fig. 2.

Los Alamos FEL Facility

Although programmatically committed, the Los Alamos FEL accelerator could be considered for a variety of advanced accelerator concept studies starting in 1987. Synchronized, high-quality photon and electron bunches are available.

"REDUCED ENERGY"

USES: WAKE FUNCTIONS
Z/n MEAS
etc. —

"FULL ENERGY"

USES: WAKE FUNCTIONS
SHORT STRUCTURES

Fig. 2. Beam manipulations being studied for ANL wake measurement facility.

Electron Beam Parameters

Energy	10-20 MeV
Peak current	25-55 A
Energy spread	1-2%
Bunch length	40 ps
Pulse train	21.7 MHz for ~ 100 μ s
Emittance (Norm)	$8\pi \times 10^{-5}$ m $\cdot$ rad
(Unnorm)	$2\pi \times 10^{-6}$ m $\cdot$ rad
Number electrons/bunch	3×10^9 after improvements this year.

Optical Beam Parameters

Wavelength	9-35 μ m (extendible to 100 μ m)
Peak power	6 MW
Pulse length	30 ps
Pulse interval	46 ps
Macropulse	100 μ s
Rep rate	1 Hz
Strehl ratio	0.8-0.9 (99% transmission through hole)
Raman sidebands	0.3-2.0%

With a solenoidal or periodic channel emittance filter, it might be possible to provide more than 10^7 electrons/pulse in an emittance of about 10^{-8} m $\cdot$ rad.

Los Alamos 3-GHz Portable Linac

This machine was packaged into seven boxes, each transportable by one or two persons, for use in extreme environments. It is not available, but the design could be used to make more machines, either portable or not. Peak current is 100 mA during the 1- μ s pulse; at 3 GHz, the 30-ps micropulses occur every 330 ps.

Changing to a pulsed photoemitter cathode might improve the emittance by a factor of 10 and produce 4×10^{10} electrons/pulse, or 200-A peak current during the 30-ps pulse.

Schonberg Radiation MINAC

Inquires should be directed to Schonberg Radiation.
Address: 2560 Wyandotte Street, Mountain View, CA 94043.
Phone: (415) 964-6214.

TECHNOLOGY ISSUES

The focus of this meeting was on accelerator physics issues, rather than on accelerator technology, which will have to be addressed after some of the concepts are tested further. Thus, we do not attempt here to make lists of problems, but only summarize very briefly a few topics where preliminary discussions produced some insight that might be of general interest.

Staging/Matching

Some general considerations of the problems of staging led to the suggestion that "laser lenses" might be used to provide the extremely strong focusing needed for staging or in the final transport. Also, realization of the enormous focusing strengths inherent, for example in the plasma beat-wave scheme, led to discussion of the possibility of a continuous long channel. Staging and the interstage matching required to avoid spoiling the emittance will require much further study.

Electron Beam Emittance Reduction by Scraping (T. Himel, SLAC)

To test some accelerator concepts, one needs a very low emittance beam with a small energy spread. It has been suggested that such a beam could be obtained by scraping off all but 1 part in 10^6 of a high-quality SLAC beam. Can this be done without excessively large backgrounds from beam particles entering the edge of a collimator and scattering into the accepted region?

A study using the EGS electromagnetic shower simulation has been done by Hobey de Stabler at SLAC. Fifty-GeV electrons were incident a distance x from the edge of a copper collimator. The fraction of electrons with greater than 80% of their initial energy, which emerged from the edge of the collimator at any angle, was $0.4/(1 + x/2)^3$ where x is measured in micrometers.³ For example, 0.4 emerged when the beam was incident at the very edge ($x = 0$) but only 0.0009 emerged when the beam was incident 5 μm from the edge. The particles emerged at an average angle of 0.2 mrad. Hence the background caused by edge scattering from a collimator, followed by a crude momentum selection, will be less than 10% if the collimator hole has a radius greater than 20 μm .

Alignment and Control

A few very general remarks to keep in mind:

The design strategy for a machine will have to find a balance between the tolerances to be achieved in the initial construction and the instrumentation and correction elements that will sense the beam and put it on the proper orbit as the machine is tuned up and run. These days, it will be found that great advantage can be had from stressing the instrumentation and correction side. Instrumentation development using the beam or perhaps structure fields will be very important.

It is usually very difficult (expensive) to make precise corrections at the high-power levels in the system. Low-power correction elements should be added, or trim modulation provided using closed-loop control. Such control will be greatly aided by thorough understanding of the machine parameters through such modeling studies as reported in these proceedings by Karl Bane on wake-field effect compensation. Models like this are crucially important; they end up being built right into the computer control system and significantly ease requirements on the hardware.

The extremely small positional and timing tolerances will certainly require closed-loop control. Sensitivity to geological disturbances might be attacked by feedback methods, but the achievable bandwidth will be low. If the rep rate is not too high, sensing and setup of components on a shot-to-shot basis might be possible. Or perhaps a probabilistic, predictive approach to feedforward should be considered. Modern control practice has produced a wealth of information on such approaches, and one can readily imagine gaining several factors in the number of successfully colliding bunches in this manner. On the timing, present projects are requiring phase and amplitude tolerances of 0.1° and 0.1% at rf frequencies--a factor of 10 better for each over existing machines. Achieving this factor of 10 is a challenge, but probably it can be done. As indicated in the laser technology summary, optical regime timing to about $1\ \mu\text{m}$ pulse-to-pulse and to a few degrees phasing on the wave front appears possible. Phase-conjugation optics is also a possibility.

REFERENCE

1. R. A. Jameson, "New Linac Technology - for SSC, and Beyond?," 12th Int. Conf. on High Energy Accelerators, FNAL, August 1983, p. 497.