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LASERS FOR SWITCHED-POWER LINACS

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ABSTRACT

Laser-switched power sources for particle accelerators, just as with direct laser-driven accelerator schemes, place unique demands on the specifications of the invoked laser systems. We review the laser requirements for switched power sources of the types described in other chapters of this volume. The relative advantages and disadvantages of selected lasers are listed, and the appropriateness and scalability of existing technology is discussed.

INTRODUCTION

Laser-switched power sources for particle accelerators will have specifications that demand laser capabilities beyond what is currently available. Proof-of-principle demonstrations notwithstanding, the ultimate practicality of any of the schemes may well depend on the realities of laser development. It is interesting to note therefore that, in projecting from the laser requirements of a demonstration experiment to those of a scaled system, some schemes require fewer "leaps of faith" than others, those differences are probably equally as important as the feasibility of the scheme itself. Such considerations are dealt with in what follows. The fact that switched-power devices could potentially be used as powerful focusing or bending elements, wherein power-conversion efficiency, or gain, is essentially unimportant, also motivates us to examine these concepts.

As discussed elsewhere in this volume there are three specific switching approaches that have been considered at the workshop:

1) Photoconductive solid-state (semiconductor) switches.
2) Laser-initiated gas avalanche switches.
3) Vacuum photocathode switches.

All three of these mechanism would be applied to the same basic concept of voltage multiplication: the radial line transformer (RLT), or variations of that concept such as parabolic geometries or the linear voltage multiplier (LVM), which are discussed elsewhere in this volume. The original concept of the RLT was suggested by W. Willis [1] and, as applied to particle accelerator schemes, generally requires switching times on the order of picoseconds. This is the main reason why lasers, with their accompanying complications and expense, are invoked in the switching concepts. There are simply no other known mechanisms for such fast rise-time switching.

REQUIREMENTS

The above statements require some amplification. Table 1 lists the laser specifications that might be required for three different schemes. It should be noted that since many of the specifications of an imagined future-generation accelerator are not well defined, some of the laser specifications are consequently nebulous. Nonetheless, the intent is to bolster the argument that we already have a technology base from which it may be possible to extrapolate future development.

	Solid-state switches	Vacuum photocathode	Avalanche PD
λ	0.8-1.2 μm	0.2 - 0.5 μm	<0.2 - >1.0 (?) μm
τ	1 ps	1 ps	10 ps
PRF	100 Hz - 20 kHz	100 Hz - 20 kHz	100 Hz - 20 kHz
η	>5%	>5%	>5%

Table 1. Comparison of laser requirements for three different schemes for switched power accelerators. λ is the required wavelength, τ is the pulse duration and PRF stands for pulse repetition frequency and η is the electrical efficiency.

The required pulse repetition frequency (PRF) varies tremendously depending on the specific application. For example, when used to power an injector to a circular proton accelerator such as the ELOISATRON, a PRF as low as 100 Hz may be acceptable if the ring storage time is long enough. On the other hand, for an electron LINAC the PRF would have to be equal to the bunch rate, which may be on the order of 20 kHz For some types of lasers this would present serious limitations. The electrical efficiency, η, is set at >5% simply because a significantly higher standard would eliminate most laser systems from the outset.

In addition to the above required specifications are the obvious imperatives that the laser system be reliable and that the pulse be accurately synchronized to an external reference.

LASER SYSTEM CANDIDATES

Listed in Table 2 are several laser candidates that are selected for further examination; their applicability will be examined in more detail in the discussion that follows. There are certain classes of lasers that are simply beyond consideration because of limitations such as inappropriate wavelength as in the case of the highly developed CO_2 laser, or unacceptably low efficiency as in the case of the Ar-ion laser.

Type	Wavelength (nm)	Pulse Rep Freq	Efficiency
Excimers	248, 308, 351	up to ~1000	4-8%
Diode	800-1300	up to ~1GHz	30-40%
Diode-pumped Nd:YAG (harmonics)	1060, (532, 355)	<100Hz or ~100MHz	8% (2%)
RF-LINAC FEL	any	>100 kHz	20%

Table 2: Laser types to be considered.

Excimer lasers:
Currently excimer lasers represent the most efficient and powerful sources in the ultraviolet. Effective pulse repetition frequencies (PRF) in excess of 1 kHz with useful pulse energies, however, have not been demonstrated, and the multiplexing of a number of parallel units would be required to achieve higher PRF's. Nonetheless, high average powers (up to ~1kW) per unit are available. Efficiencies are moderate (4-8%, depending on the excitation method), and reliability limitations would demand extensive engineering for any accelerator application. Further, to maintain a reasonable extraction efficiency with picosecond pulses, a multiplexed train of pulses would have to be used to extract energy, and then the pulses would have to be redirected and/or combined optically in the appropriate manner for the application. This results in a rather complex and expensive optical system.

Diode lasers:
This type of laser is very interesting, particularly in the context of the photoconductive switch scheme for pulsed power. Very high efficiencies (for lasers!) are available, and the tunable near-infrared wavelengths are appropriate for the band-gaps of available semiconductor switch materials. Moreover, these tend to be comparatively high reliability devices, following the trend of solid-state electronics. Perhaps the most interesting feature, however, is the flexibility of manufacturing. In mass production the costs can be quite low, and one can imagine an integrated optics structure in

which a circular array of diode lasers and semiconductor switches are all produced on a monolithic substrate by photolithographic techniques. A conceptual illustration of such a structure is shown in Figure 1. The limitations are that the peak optical output power is limited - diode lasers are more suitable for continuous or modulated, rather than short pulse, operation - and that picosecond pulse lengths are fundamentally difficult to obtain. Nonetheless, recent advances [2] generate optimism about the potential for picosecond operation. Pulse energies and average power are also limited, but it is clear in a scheme such as illustrated that a multiplicity of lasing elements could make up for the limitations of single junctions.

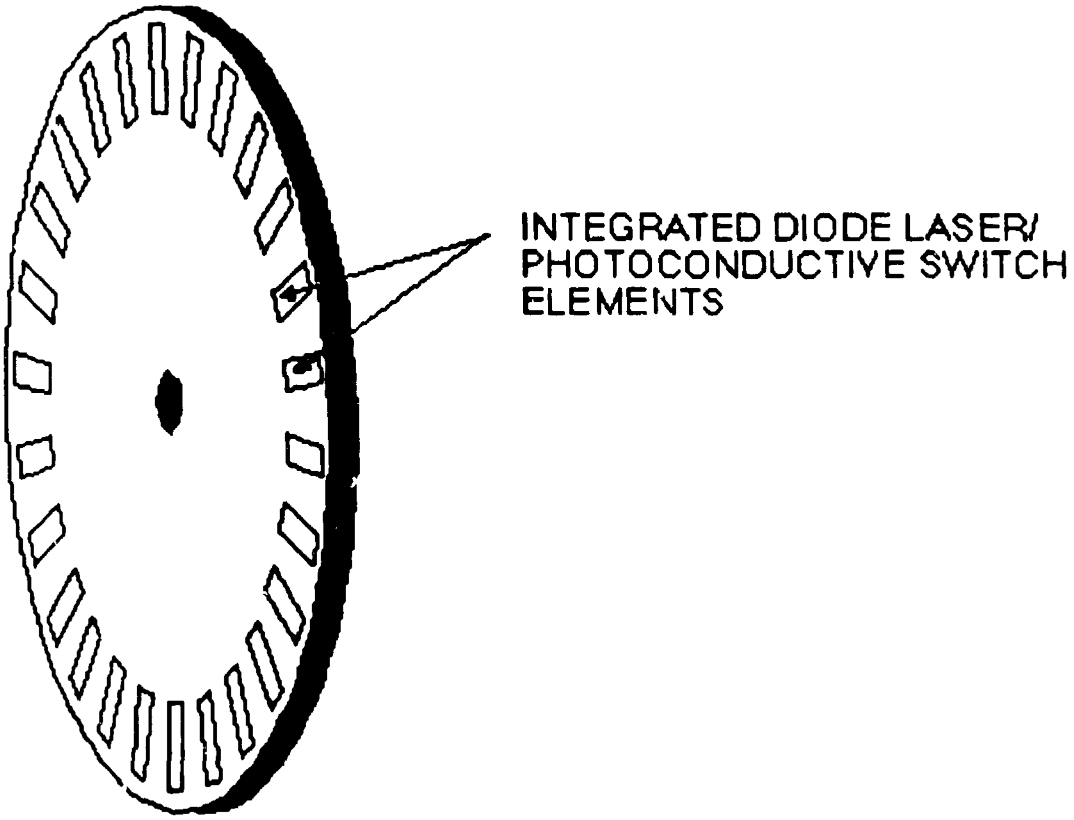

Figure 1. A monolithic integrated-optics structure incorporating diode lasers and photoconductive solid-state switches.

Diode-laser pumped Nd:YAG lasers:
Some of the limitations of diode lasers (e.g., low pulse energy, long wavelength) can be circumvented (at the cost of reduced efficiency) by the use of an intermediate storage medium. Currently this hybrid laser is also a rapidly developing technology, and considerable advances should be expected over the next couple of years. Again, the use of all solid-state components can be expected to result in high reliability. The storage medium, Nd:YAG, would limit pulse durations to tens of picoseconds or

longer, but other candidates exist that could yield pulse widths in the picosecond regime, or nonlinear optical components can be utilized to achieve picosecond pulse emission with Nd:YAG (passive components that should not affect reliability). Efficiencies in the 5-10% range obtain for the fundamental frequency (1.06 μm), but these are reduced to the 2-4% range for the harmonics (532, 355 nm).

Free-electron lasers:
It is perhaps ironic that the type of laser most likely to be usable for an actual accelerator power source would itself require an accelerator to operate. There are two classes of free-electron laser (FEL): those driven by an induction LINAC and those using an RF LINAC. The induction-LINAC FEL is not really appropriate for switched-power accelerator schemes because pulse durations under ~1 ns are essentially not feasible, and visible wavelengths are very difficult to achieve with acceptable efficiency. On the other hand, RF-LINAC driven FEL's can be expected to boast picosecond pulse durations and visible to near-UV wavelengths at efficiencies approaching 20%. But pulse repetition frequencies must in general be greater than ~10 MHz to avoid serious loss of efficiency, so any pulse power scheme requiring significantly lower PRF's would demand some adaptation and/or innovative thinking.

Innovative thinking may actually be at hand! The development of the "LASERTRON" concept [3,4] as an RF power source may result in an RF power source that can operate in a pulsed mode with efficiency comparable to klystrons operating continuously. It is entertaining to imagine the symbiotic relationship between laser and accelerator components that might obtain if a system were designed that took advantage of the benefits of each. A cartoon of one such conceptual system is shown in Figure 2.

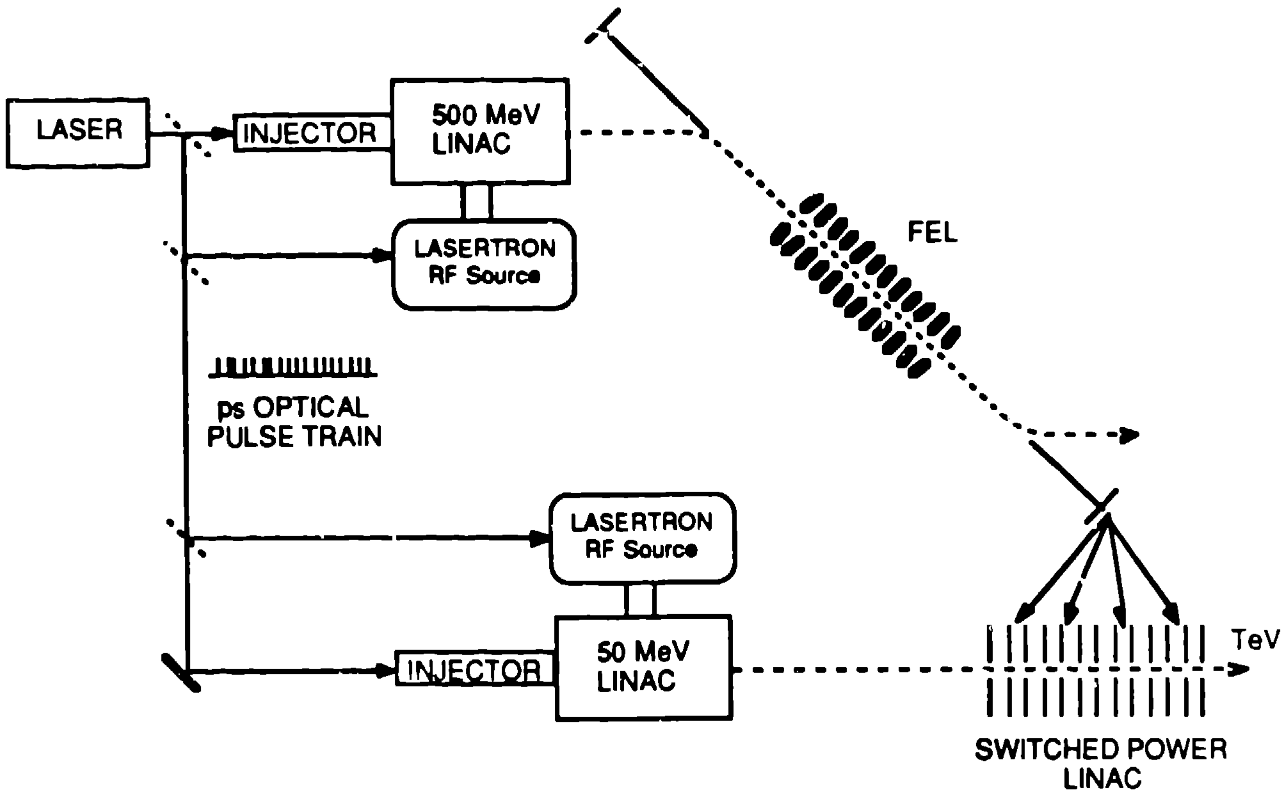

Figure 2. A symbiotic relationship among various laser and accelerator components when an FEL is used as the optical source for a switched-power accelerator scheme.

One of the major problems for the development of FEL's is the issue of optical damage. The inherent design results in a very large optical power density on vacuum windows and on the cavity mirrors. These problems may not be insurmountable, but they will certainly require further development. Nonetheless, for a scaled system the advantages of an FEL may make it the most promising candidate. The expected reliability is difficult to assess, but might be expected to be similar to that of LINAC's themselves.

ADVANTAGES AND DISADVANTAGES

The following lists of relative advantages and disadvantages refer mainly to the differences that obtain among the selected laser types. This does **not** serve as a comparison of laser-switched power and other methods of pulsed power.

ADVANTAGES	DISADVANTAGES
Excimer lasers:	
•UV wavelengths	•limited efficiency
•high average power •picosecond pulses demonstrated	•a continuous stream of pulses at rates exceeding ~1 kHz requires parallel operation of a number of units •efficiency drops for ps pulses, multiplexing required
Diode lasers:	
•High efficiency •Flexible rep rate •amenable to mass production and integrated optics techniques •high reliability	•limited to near-IR wavelengths •ps pulse generation difficult •low energy/pulse ⇒ many devices needed to operate in parallel
Diode-pumped SS lasers:	
•usable pulse energies	•pulse energy depends on rep rate: need to use parallel devices at higher rates •must use harmonics for visible/UV operation
•ps pulses obtainable	•limited efficiency (2-5% for visible/UV)
RF FEL:	
•very high average power •good efficiency •high rep rates easy	•low rep rates difficult
•ps pulses obtainable	•optical damage problems, requires development

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