ELECTRON ACCELERATORS WITH PULSED POWER DRIVES

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Abstract

Pulsed power driven accelerators can produce intense beams with diverse characteristics, ranging from extremely high peak power at low repetition rate to high average power with moderate beam current. The continuing development of highly reliable components for linear induction accelerators (LIAs) and free electron lasers (FELs) may enable one to use such accelerators as economical sources of microwave power to drive magnetic fusion reactors and high-gradient rf linacs. More recently, the technology of pulsed power driven accelerators has been extended to allow the acceleration of intense pulses with <5-ns duration.

Introduction

Thirty years ago, N. C. Christofilos proposed the Astron linear induction accelerator as a means of accelerating high current electron beams to energies beyond those possible with single stage high voltage diodes. Christofilos's idea aimed not only at higher voltage beams than diodes but, more significantly, at highly reproducible, long pulses of nearly constant voltage and current that could be generated at repetition rates of $\approx$1 kHz. Since then, evolving perceptions of needs in the defense and fusion research communities have shaped the development of pulsed power driven linacs and their component technologies. Although pulsed power components have found diverse applications, the multistage induction linac is, aside from flash x-ray production, still a technology waiting for Godot.

Several challenging, large-scale applications for induction linacs have been suggested over the past ten years based on the use of a free electron laser (FEL) to convert the electron beam energy to microwave radiation. Unlike flash x-ray production, the generation of microwaves at high average power requires operating the linac heavily beam loaded to maximize electrical efficiency. Heavy beam loading, in turn, places a premium on voltage regulation techniques in the accelerator drives.

High-Power Microwaves for Fusion

Driving tokomak reactors with tens of megawatts of rf power for electron resonance cyclotron heating (ERCH) will require powerful, highly reliable, highly efficient sources of microwaves. One means of generating high powers employs an FEL amplifier to transform the kinetic energy of a multimegavolt, high-current electron beam to high-peak-power microwaves. High average power is attained by repeating this process at a multikilohertz repetition rate.

The central frequency and frequency sweep of the microwave power are determined by the mean field, B_T, in the tokomak and its inhomogeneity, ΔB_T. The central resonance frequency of the n^{th} harmonic of the cyclotron resonance is

$$f_{in} = n\, f_{ec} = 28 \text{ GHz } n(B_T/1\text{ T})\,. \qquad (1)$$

Hence, 200–600 GHz microwaves can drive the fundamental and second harmonic modes in experimental tokomaks such as the Frascati Tokomak Upgrade (FTU), Alcator-C, or future power reactors. For power densities <100 kW/cm^2 the interaction of the electric field with the plasma is linear. For most regimes of operation of the LIA driven FEL (IFEL), however, the microwave field will exceed 30 kV/cm. Whether the nonlinear effects will modify the absorption in detrimental or beneficial ways is controversial. Nonlinear absorption can be eliminated if the FEL is driven by an rf-linac rather than an induction linac. An analysis [1] of the FEL scaling suggests, however, that the rf-linac approach will be much less efficient than the induction approach precisely in this frequency range. The remainder of this article examines the required performance and the progress in the technology of pulsed power driven linacs from the perspective of applications in magnetic fusion and high-energy physics.

High-Energy Physics

The design of high luminosity electron-positron colliders at TeV energies has concentrated on conventional disk-loaded waveguides with gradients $\approx$100 MeV/m. The accelerating gradient can be increased and the energy per meter of accelerator reduced by scaling the structure to high frequencies (10–30 GHz.) At t X-band, one can employ conventional klystrons plus rf-pulse compressors to power the collider. More speculative approaches might offer similar performance at a substantially lower cost. In the two-beam accelerator (TBA) [2], the kinetic energy of a high peak current beam produced with an induction linac is transformed to high peak power microwaves at 10–30 GHz with an FEL amplifier. In another variant [3] of the TBA most suitable for X-band, the relativistic electron beam excites klystron transfer cavities. An experimental study of relativistic klystrons by a SLAC/LLNL/LBL collaboration has shed considerable insight on the operation of high-gradient structures, but it has also exposed the difficulties of moving LIA technology into the realm of economic viability for linear colliders.

Pulsed power driven guns may allow one to design relatively compact sources of intense beams with subnanosecond duration for injection into rf linacs and storage rings. Two approaches for generating subnanosecond pulses are shock-line gridded induction guns and switched power guns with photo-cathodes.

FEL Constraints on Scaling Accelerator Design

To estimate the characteristics of the IFEL microwave generator, one can adopt the one-dimensional model [4] of Bonifacio, Narducci, and Pellegrini (BPN) for an optical FEL amplifier. As the microwaves for ERCH (100–1000 GHz) will be generated in highly overmoded waveguides, a quasi-optical model is a reasonable starting point. The BPN model scales FEL performance with a single dimensionless parameter,

$$\rho = \frac{1}{\gamma}\left(\frac{a_w \omega_p}{4\omega_w}\right)^{2/3}, \qquad (2)$$

where a_w is the dimensionless vector potential of the wiggler, ω_w is the wiggler frequency, and ω_p is the relativistic plasma frequency. The FEL relies on single pass growth from self-amplified spontaneous emission (SASE) starting from beam noise in a long undulator [4,5]. SASE growth from noise in agreement with the BPN predictions has been measured in a quasi-optical experiment at 140 GHZ at LLNL [6,7]. For FELs operating in the SASE mode, the geometrical emittance should be less than $(\lambda_{signal}/2\pi)$. The energy spread should be less than $\rho/4$.

One might expect the cost of the FEL to be minimized by minimizing the number of wiggler periods needed to obtain a specified energy extraction level. The experience of many FEL groups, however, suggests that the cost per meter of wiggler is roughly constant, independent of λ_w. Then one should minimize saturation length of the wiggler. For $a_w >> 1$, one can show that

$$L_{sat} \propto \left(\frac{\gamma^{7/9}}{I^{1/6}}\right)_{accel}\left(\frac{1}{B_w^{1/9}}\right)_{wig}. \qquad (3)$$

[1] Work partially performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Hence, with respect to the FEL converter, the cost is sensitive neither to the wiggler field nor to beam current in the accelerator. Low beam energy does minimize wiggler cost. This scaling, therefore, favors FELs operating at relatively low peak powers.

In contrast with the quasi-optical IFEL, rf linac-driven microwave sources are constrained by the slippage condition:

$$L_{slip} = N_w \lambda_s < \frac{1}{10} L_{bunch} \approx \frac{\lambda_{rf}}{100}, \tag{4}$$

which leads to a scaling of the number of wiggler periods,

$$N_w \propto \left(\frac{\gamma^{1/9}}{I^{1/6}}\right)_{accel} \left(\frac{1}{B_w^{1/9}}\right)_{wig} < \frac{1}{100}\left(\frac{\lambda_{rf}}{\lambda_s}\right). \tag{5}$$

Satisfying the slippage condition is sensitive neither to the accelerator operating point nor to the wiggler characteristics. For typical ERCH frequencies and for 320 MHz accelerating cavities, the right-hand side of Eq. (5) is at most ≈20. The amplifier may just reach saturation (2–4% efficiency); however, tapering will not be possible. In contrast, for powering high-gradient linacs operating at 10–30 GHz, one will be forced either to operate the FEL in the strong slippage, strong super-radiance regime in which conversion efficiency is low or to use a fundamental mode waveguide in which slippage is eliminated at the expense of greatly increasing the bandwidth of the microwave output. We conclude that pulsed power linacs are superior to rf linacs for driving FELs in the 10- to 1000-GHz frequency range for fusion and collider applications.

One potential drawback to decelerating the beam to minimum energy in a saturated (tapered) amplifier is that it maximizes the peak power of the output and limits the conversion efficiency due to space charge debunching of the FEL buckets. This approach also risks damaging the output waveguides due to the thermal fatigue induced in the first skin depth of the guide. The thermal fatigue can be eliminated [8] if the temperature rise due to shock heating is small enough that the deformation of the metal is elastic.

Alternatively, one may stop the conversion process after ≈10% of the beam energy has been extracted. At this point the microwaves would be separated from the electron beam, and the beam would pass through a set of induction modules to raise the average energy to the original value. The deceleration-acceleration cycle could be repeated indefinitely, as in the TBA, to yield a conversion efficiency approaching 90%. A further advantage of the reacceleration scheme is that the microwave signal is easily stretched in time. Thus the peak power can naturally be held below some specified maximum value set by beam-plasma considerations.

Recently, Hopkins et al. [9] studied the limitations of reacceleration in FEL-based microwave sources in the context of providing 17 GHz power to high-gradient accelerating structures. They find that after the third reacceleration, a large fraction of electrons is lost from the FEL bucket. Their work suggests that the FEL amplifier must be operated well into saturation to yield sufficient overall conversion efficiency. Calculations such as these must be repeated for the frequencies of interest for ERCH.

Design of Induction Linac Cells

The primary characteristics of induction accelerator cells for pulses <300 ns are the gap width, w, the inner radius of the ferrite in the cell, r_i, the radius of the beam pipe, b, and the volt-seconds of core material, toroids of ferrite (TDK PE-11), which has minimal core losses for saturation times <1 µs. The gap width and shape are selected to minimize the Q of the cell and the coupling impedance of the beam, $Z_\perp$, to transverse deflecting (beam breakup, BBU) modes [11] of the cell consistent with a conservatively chosen field stress, E_g, ≈125 kV/cm. The insulator, which separates the vacuum from the insulating fluid surrounding the cores, is set at an angle such that all TM cavity modes will pass through the insulator without reflection to be absorbed by the ferrite. The slight re-entrant design of the gap shields the insulator from stray beam electrons. Passing through the induction cavities, the beam excites wake fields that can amplify transverse displacements of the beam centroid arising from stray dipole fields, misalignments of the cathode, the focusing solenoids, or the accelerating cells themselves. The most damaging cavity modes are the TM_{1n0} modes with frequencies that are cut off by the beam pipe. These modes have a finite deflecting field, B_y, on the axis. Each mode is characterized by a frequency, ω_n, a quality factor, Q_n, and a transverse shunt impedance, $Z_\perp$. The shunt impedance and quality factor are related to the energy stored in the mode, U, and the deflecting field, B_y, by

$$\frac{Z_\perp}{Q} = \frac{\left[\int B_y dz\right]^2}{2\, U\, \omega}. \tag{6}$$

The TM_{1n0} modes are excited by the dipole moment of the beam current (proportional to I_{beam} times the transverse displacement). Caporaso's [11] analysis of the growth of the transverse displacement, ξ, uses a model in which the accelerating gaps are considered to be distributed continuously along the beam pipe to show that $\xi = \xi_o \exp(S)$, where

$$S \propto \frac{e\, I_{beam}}{mc^3} \frac{w}{b^2} F(N_g)\, \mathrm{Im}\, P_1(\omega)/B_z w E_{gap}, \tag{7}$$

where the function $F(N_g)$ depends on the dependence of the betatron wavelength upon beam energy. For constant solenoidal focusing $F(N_g)$ = Ng, whereas increasing the field strength to maintain a wavelength that is constant with energy yields $F(N_g)$ = Ln(Ng), where N_g is the number of gaps (proportional to the final beam energy) and B_z is the (effective) field strength of the magnetic transport. As $N_g = V_{beam}/V_{gap} = V_{beam}/wE_{gap}$, the growth of beam breakup modes is minimized by choosing the field stress in accelerating gaps to be as large as possible. Although the focusing strategy of ramping the magnetic field yields a slower functional dependence, minimizing the growth of transverse displacements requires one to employ the strongest practical focusing strength throughout the accelerator. In that case, Eq. (7) describes the appropriate scaling relation.

$P_1(\omega)$ is the geometrical part of the integrated deflection impulse per unit dipole current. $\mathrm{Im}[P_1(\omega)]$, which is $\pi/2$ out of phase with the beam excitation, controls the growth rate. For a gap shaped to approximate a perfectly matched radial line, $\mathrm{Max}(|\mathrm{Im}\, P_1(\omega)|) \approx 0.71 - 0.33$ (w/b) over the range 0.1< w/b <1. In LIAs built to date, b is several centimeters, and w/b is ≈0.3.

Applying these considerations to account for the constraints on beam transport imposed by control of BBU in the induction drive, one can assess the sensitivity of microwave power cost to variations in the I_{beam} in the IFEL. In particular, one should vary the solenoidal field of the accelerator with "tube" voltage, current, and beam pipe radius to allow three e-foldings in the beam breakup amplitude in the induction linac section of the IFEL. Then, Eq. (7) yields the scaling relation

$$B_z = 0.3\ \mathrm{kG} \left(\frac{V_{beam}}{12.5\ \mathrm{MeV}}\right)\left(\frac{I_{beam}}{3\ \mathrm{kA}}\right)\left(\frac{7.5}{b}\right)^2\left(\frac{125\ \mathrm{kV}}{E_{gap}}\right), \tag{8}$$

where E_{gap} is the field stress in the induction gaps.

The thickness of the solenoidal winding is linearly proportional to the field strength. Assuming a current density of 10^7 A/m^2 in the winding, one has $\Delta r(m) = B_z(T)/4\pi$. This value is added to the beam pipe radius, b, plus an additional 1 cm spacing to yield the inner radius of the ferrites, r_i, thus setting the linear dimension for scaling the size of the induction cell; i.e.,

$$r_i = 0.01 + b + B_z(T)/4\pi. \tag{9}$$

The accelerating voltage, V_{acc}, and the cell length, z, determine the outer radius of the cell via the law of magnetic induction,

$$V_{acc} T_p = \int_{r_i}^{r_o} \Delta B(r)\, dr\, dz \le \Delta B_{sat} A, \tag{10}$$

where A is the cross-sectional area of the ferrite, ΔB_{sat} is the total flux swing (0.6 Wb/m^2 for ferrite), and T_p is the pulse duration. Writing the cell length, z, in terms of the effective gradient, G (≈0.75 MeV/m), and the packing fraction for the ferrites, p (typically, 0.8), one can recast Eq. (10) as

$$r_o = r_i + (G\, T_p/p)/\Delta B, \tag{11}$$

where B is assumed to be roughly uniform throughout the core. To keep the net energy spread in the beam <ρ/4 for the microwave FEL, the accelerating voltage must be constant to within <0.5%. Such voltage regulation introduces difficulties in the accelerator drive circuits. In addition, the length of the cell and the properties of the ferromagnetic material are subject to an additional constraint. The region between the high voltage drive blade and the back wall of the induction cavity should be designed to be a constant impedance transmission line loaded with a high permeability material to slow the wave speed. Let the ferrite have a permeability, $\mu_r \mu_o$, and a permittivity, $\varepsilon_r\varepsilon_o$, where $\mu_r \approx 400$ and $\varepsilon_r \approx 12$ and the subscript o denotes the free space value. The wave speed in the ferrite loaded line is

$$v_{cell} = c/(\mu_r\varepsilon_r)^{1/2} \ . \tag{12}$$

Even if the transverse dimension of the cavity is sufficiently large to avoid a saturation wave forming in the core, the transit time in the longitudinal direction must equal or exceed the pulse length. That is,

$$z_{cell} \geq T_p(\mu\varepsilon)^{1/2} \ . \tag{13}$$

In an idealized toroidal core for which μ is constant prior to saturation, B(r) varies inversely with radius. To avoid saturation anywhere in the core, $B(r_i) \leq B_{sat}$. The shunt impedance of the cell and voltage in the gap are determined by both the inner and outer radii of the ferrite cores which have a maximum flux swing, $\Delta B_{ferrite}$:

$$Z_{shunt} = \frac{Z_o}{2\pi}\sqrt{\frac{\mu_r}{\varepsilon_r}}\ln\left(\frac{r_o}{r_i}\right) , \tag{14}$$

and from Eq. (11)

$$V_{gap} = \frac{c\ \Delta B_{ferrite}}{\sqrt{\mu_r\varepsilon_r}} r_i \ln\left(\frac{r_o}{r_i}\right) , \tag{15}$$

where Z_o is the impedance of free space, i.e., 377 Ω. The number of induction cells and the gap width are simply $N_{cell} = V_{beam}/V_{gap}$ and $w = V_{gap}/E_{gap}$, respectively.

The induction core serves only to limit the leakage current during the voltage pulse supplied by the drive circuit to a value independent of the magnitude of the beam current. Therefore, the cost of the IFEL can be minimized by maximizing the beam current consistent with the emittance constraints. In addition to minimizing capital costs, controlling operating costs provides a second important reason to try to operate at as high a current as practical in the IFEL (consistent with plasma physics constraints on peak power). As the beam current is raised (and as the beam pipe radius is reduced), the coupling efficiency, C, between the pulsed power drives and the beam improves as

$$C = \frac{Z_{shunt}}{Z_{shunt} + Z_{beam}} , \tag{16}$$

where the beam impedance is

$$Z_{beam} = {V_{gap}}/{I_{beam}} \ . \tag{17}$$

Minimizing operating costs also requires one to keep core magnetization (hysteresis) losses small. The same design consideration allows one to minimize beam energy variations during the pulse ($\Delta E/E$ < 1%). In practical terms, the magnetization current should not exceed 20% of the beam current;

$$I_m = \frac{1}{L}\int V_{acc}\, dt \leq 0.2\ I_{beam} , \tag{18}$$

where L, the inductance of the core, is given by

$$L = \frac{\mu}{2\pi} z \ln\left(\frac{r_o}{r_i}\right) . \tag{19}$$

The actual behavior of the cell is more complicated than that given by Eq. (18). The core housing and accelerating gap constitute a capacitance in parallel with the core inductance. The displacement current necessary to charge this capacitance produces an energy loss for short times that will be larger than the inductive losses. For pulse lengths <30 ns, these capacitive effects must be measured to arrive at an accurate assessment of the cell losses and voltage fluctuations due to variations in magnetization current.

For induction cells that are to be operated at repetition rates <5 Hz, the most economical power drives are Blumleins or Marx banks discharged by high-pressure gas spark gaps. This approach was followed for the ATA and FXR linacs at LLNL. More recently, SNLA and LANL have adopted this approach for the HERMES III x-ray simulator and DARHT radiography linacs, respectively. For linear colliders operating at repetition rates between 100–1000 Hz or for plasma heating requiring rates up to 5 kHz, the accelerator cells can be driven by magnetic pulse compressors [12]. The primary commutators used in the intermediate stores can be ceramic envelope thyratrons or branched arrays of silicon controlled rectifiers (SCR) as have been used by Birx [13] to drive magnetic compressors such as the SNOMAD-II at multi-kilohertz rates. SCRs seem to be particularly cost effective for pulsers delivering <100 J.

The cost implications of the FEL and accelerator models are shown in Figs. 1 and 2 for ERCH drives and relativistic klystrons, respectively. The scaling procedure follows [1, 14]. If the MTX experiment at LLNL shows that the plasma responds favorably to high peak powers, the costs of ERCH drives can be lowered dramatically. Currents >1.5 kA are not need for economic operation of IFEL drive. In contrast, the present 500 A operation of relativistic klystrons must be raised to ≈3 kA for these devices to have relevance to linear colliders.

<u>Constraints Imposed by Reacceleration in TBAs</u>

Although the single pass extraction efficiency of the FEL can be as high as 40%, the economics of powering TeV class linear colliders or of driving fusion reactors dictate that the beam-to-microwave conversion efficiency, h_{rf}, be raised to ≈70% or more. Such high efficiencies may be realized if it is possible to use induction cells to reaccelerate the beam that has passed through the wiggler or klystron converter cavity. Unfortunately, reacceleration of a bunched beam raises questions requiring both theoretical and experimental study. First, the bunch structure is likely to constrain the design of the accelerating gap to limit radiation into the gap either at the fundamental bunching frequency, which will deplete the energy of the beam or increase the energy spread beyond the acceptable limit, or at the frequencies of higher-order deflecting (beam-breakup) modes, which will spoil the emittance. If the beam is not to be subjected

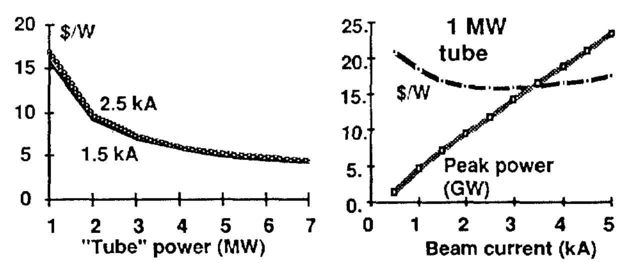

Figure 1. Cost of IFEL microwave power for ERCH at 240 GHz

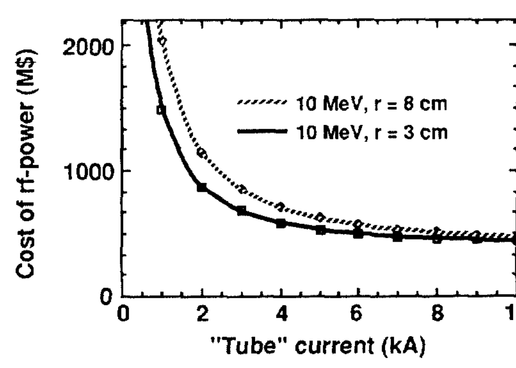

Figure 2. Cost of 4 TW of rf-power at 17 GHz for 1 TeV linear collider from relativistic klystrons

to large fluctuations in radius that will increase the emittance during the deceleration-acceleration cycle, the solenoidal field in the accelerator sections must be chosen to match the beam size set by the natural focusing in the wiggler. This restriction may not be consistent with the values of focusing needed to suppress the growth of transverse beam break-up instabilities.

Given specifications on the beam energy, current, pulse length and the requirement to minimize beam breakup for emittance preservation, the accelerator designer can choose two independent characteristics such as B_{max}, G, or r_i to minimize cost. Thereafter, all other accelerator characteristics will be specified by the scaling relations described above. Even this freedom of choice may be reduced for a system with re-acceleration.

To minimize the coupling of the high-frequency components of the beam current with the gap, one can set the transit angle factor in $P_1(\omega)$ equal to zero. The functional form of $P_1(\omega)$ is given in [11] as a transit time factor,

$$\mathrm{Tr}(\theta) = \left(\sin\frac{\theta}{2}\Big/\frac{\theta}{2}\right)^2 , \tag{20}$$

times a geometrical function describing the radial mode structure. Setting $\mathrm{Tr}(\theta) = 0$, one has $\theta = 2\pi n$, where n is an integer. Hence, the width of the gap, w, is $n\,\lambda_{rf}$. Combining this relation with Eq. (10), one finds that

$$r_i \ln\left(1 + \frac{G\ T_p}{p\ \Delta B\ r_i}\right) = \frac{n\,\lambda_{rf}\,E_{gap}}{\Delta B}\frac{\sqrt{\mu_r\varepsilon_r}}{c} . \tag{21}$$

Recalling the form of the BBU gain (kept to 2 e-foldings),

$$S_{bbu} = K_1\left[\frac{I_{beam}\ Q_{cell}\ V_{acc}}{B_z\ E_{gap}(r_i - B_z/4\pi)^2}\right] \approx 2 , \tag{22}$$

one writes the BBU constraint in terms of the total rf power, P_{rf}, required from the TBA,

$$r_i(\mathrm{cm}) = \left[\frac{K_1\ Q_{cell}\ P_{rf}}{2\ B_z\ E_{gap}\ \eta_{rf}}\right]^{1/2} + \left[\frac{B_z(T)}{4\pi}\right] . \tag{23}$$

Even the apparent freedom of choosing either r_i or B_z is probably illusory. As the beam passes from wiggler section to linac section to wiggler section, etc., preserving the emittance of the beam probably requires avoiding fluctuation in beam size. In the wiggler the betatron wavelength is set by the wiggler wavelength and a_w; $\lambda_\beta = \sqrt{2}(\gamma\,\lambda_w/a_w)$. Matching the mean value of λ_β in the wiggler and in the linac determines B_z in terms of B_w. Hence, in the two-beam accelerator, all of the induction linac characteristics are determined by the wiggler characteristics.

The response of induction cavities to bunched beams, as calculated by Whittum [15], supports the idea that for bunching at the very high frequencies needed for plasma heating, the transverse coupling impedance of the gap is very insensitive to the frequency of rf current of the beam. In that limit, the constraint on gap width for a system with re-acceleration will be absent. The requirement to hold the beam radius roughly constant will remain. Experiments on the re-acceleration of bunched beams are beginning at Pulse Sciences, Inc., at Agrora Hills, California.

Technological Progress in Pulsed Power Driven Linacs

The ETA-II at LLNL is the first pulsed power linac designed to drive an FEL at high average power. To this end, the energy sweep from head to tail of the 50-ns pulse was to be ±1%; the energy jitter from pulse to pulse, ±0.1%; a current of 3 kA at 6.75 MeV; and a brightness $>2 \times 10^9$ A m^{-2} rad^{-2}. Over the past three years, considerable effort has been directed toward eliminating the misalignments of the magnetic axis of each accelerating cell with respect to the mechanically aligned axis of the gaps. The misalignments plus energy sweep wind the beam into a corkscrew shape as the beam particles execute several cyclotron oscillations in the solenoidal field. The existing 4-Ω transmission lines that drive ten accelerator cells produce an energy spread of ±1% for ≈10 ns. These lines will feed a distribution box with 40-Ω output cables to drive individual cells. LLNL expects this change plus improved passive compensation networks to extend the voltage "flat top" to 50 ns. In the injector voltage, fluctuations lead to current fluctuations, which in turn lead to time-varying beam loading in the remainder of the linac. Bowles and Turner [16] have designed planar triode regulation cells to try to overcome this difficulty. Alignment of ETA-II has been dramatically improved [17] to ±200 μm with a low-energy electron probe that is feedback stabilized with respect to a reference laser beam.

Induction modules with small inner radius, SNOMAD-II, suitable for short pulses and for improving the economics of relativistic klystrons, have been developed by Birx. A small, 1-MeV test accelerator made with these components and powered by SCR-switched SNOMAD magnetic modulators is running at the Plasma Sciences Laboratory at MIT.

High-Current Beam Sources for Nanosecond Pulses

Rapid positron injection into low-energy colliders, such as phi factories, or into synchrotron light sources would be easier with electron beam sources of moderate emittance (10^{-3} m rad) and high peak current (≈1 kA). Kiloampere currents are difficult to provide from conventional rf guns without considerable beam manipulation and without high-voltage (≥0.5 MV) dc power supplies. Such hardware is both large and relatively expensive. An alternate idea, SNŌGUN, proposed by Birx and Barletta [13], combines SNOMAD technology with ferromagnetic shock lines and rf-bunching cells. The shock line is capable of generating a 50-kV, ≈100-ps pulse that drives an extraction grid. The grid pulse extracts ≈0.5 to 1.0 kA during the 500 kV peak of an anode-cathode pulse generated by SNOMAD induction cells summed by a metallic stalk. Solenoids in the cells transport the beam a short distance to an S-band bunching cavity, which provides longitudinal focusing for the beam prior to its injection into a conventional disk-loaded waveguide. By stacking two (or more) shock lines in parallel, a series of bunches can be injected into the rf linac with any temporal separation of <50 ns. For two-pulse operation, the induction cells need not have a flat top. All that is needed is that the pulses be reproducible to ≈1%.

Shock lines in parallel can be used directly with radial pulse transformers to produce electric fields well in excess of 100 MV/m for <100 ps. The center of the transformer can be fitted with a photo-cathode to produce trains of very low emittance beams. The basic approach is the same as switched power electron guns except that the photo-conductive switch and the switching laser pulse are absent.

Summary and Conclusion

The role of electron accelerators using pulsed power in fusion and in high-energy physics must still be considered as speculative. Nonetheless, the basic principles of operation are understood well enough to guide the development of the technology to be consistent with economics. Moreover, new concepts such as switched power guns or shock-line controlled guns may offer a compelling role for this technology.

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