Relativistic Klystron Two-Beam Accelerator

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A high-energy linear collider consisting of two beams, a driver beam of electrons and a high-energy beam, in which the intense low-energy driver beam is bunched, is analyzed theoretically. The low-energy beam is made to travel through resonant transfer cavities, in which it radiates microwave energy that is used to accelerate the second beam to very high energies. The low-energy beam is maintained at a constant energy by periodic induction-acceleration cavities.

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A two-beam accelerator in which an intense low-energy electron beam drives a high-energy beam was proposed five years ago.[1] In that version a free-electron laser was the device that removed energy from the low-energy beam.[2] Alternatively, as proposed by Panofsky, if the low-energy beam is bunched, and made to travel through resonant transfer structures, it will produce copious amounts of microwave energy and the free-electron laser (i.e., the undulator) is no longer needed.[3] The physical layout of this version, which we call the relativistic klystron two-beam accelerator (RK/TBA), is shown in Fig. 1 with a detailed drawing of a period of the device shown in Fig. 2. Parameters of a design for a 375-GeV on 375-GeV linear collider are given in Table I.

The RK/TBA is a very attractive candidate for large colliders since the three major components of the concept [rf accelerator, induction linear accelerator (linac), and klystron] are technologically well established. In addition, the induction linac is reliable and efficient ($\gtrsim 60\%$), and can be operated at high repetition rates (~ 1 kHz cw). The operating characteristics of induction linacs and microwave output cavities are well matched to rf accelerators operating at frequencies appropriate to linear colliders. The transverse instabilities of the driving beam, which are potentially disastrous because of the narrow beam pipes required for microwave cutoff, can be suppressed by Landau damping.

Optimization of rf frequency for large colliders is a much-studied subject. Since the achievable gradient increases with frequency and the energy stored in a collider decreases with frequency, one wants to design at high as a frequency as is possible. On the other hand, the rf structure is miniaturized at high frequencies. Similarly, a small beam pipe is required for the driving beam. This is because the transfer cavities work in a conventional klystron mode only if the beam pipe does not transmit the microwaves; i.e., if it is beyond cutoff. Cutoff in a round pipe, of radius b, is related to the wavelength λ by $\lambda = 2\pi b/2.405$. We compromise at λ approximately 2.6 cm and b at 6 nm.

Breakdown surface field, $\mathcal{E}_s$, as a function of frequency has been studied experimentally at 3, 6, and 9.3 GHz.[4] The data in this range can be fitted by $\mathcal{E}_s \approx (300\ \mathrm{MeV/m})[f/(3\ \mathrm{GHz})]^{0.88}$. The accelerating gradient, G, is related to $\mathcal{E}_s$ and to the geometry of the structure

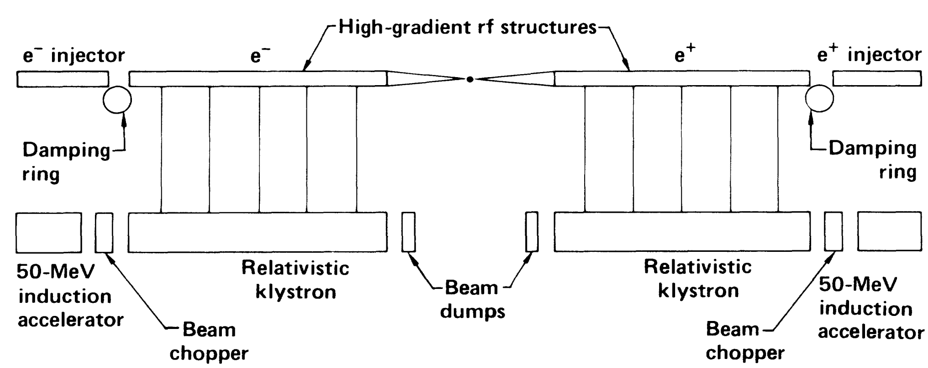

FIG. 1. A schematic drawing showing the layout of a relativistic klystron two-beam accelerator (RK/TBA).

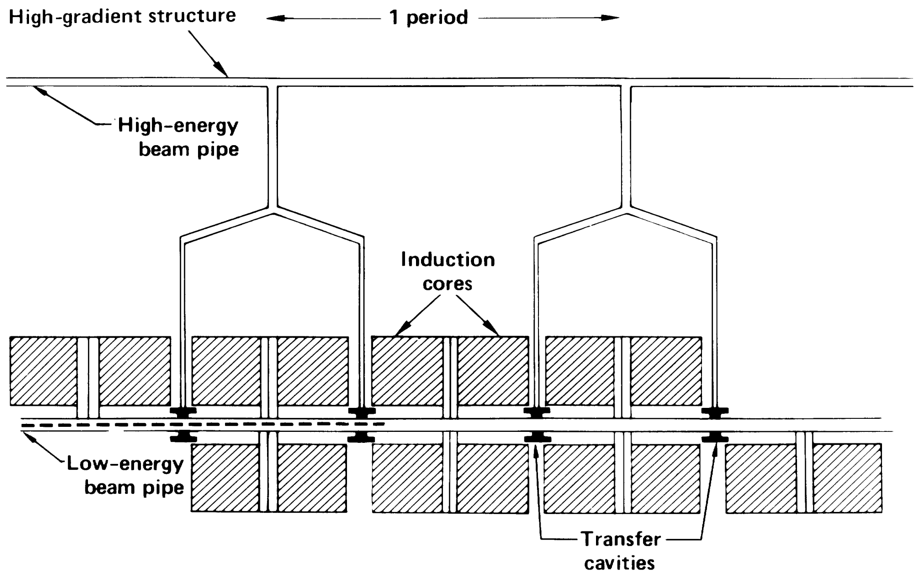

FIG. 2. A period of a RK/TBA showing the induction units (four per period in this version) and the transfer cavities.

(disk and washer, jungle gym, etc.), and is half of $\mathcal{E}_s$ in the Stanford Linear Accelerator (SLAC) structure, but a larger fraction of $\mathcal{E}_s$ in other structures. Thus at $\lambda \sim 3$ cm, G can be as much as 200 MV/m. At this gradient the required peak power P/l is greater than 1 GW/m. This requirement is easily met by induction modules.[5]

An additional feature of high-frequency rf accelerators is a strong reduction of filling time ($t_F \propto \lambda^{3/2}$). At $\lambda = 2.6$ cm, $t_F \gtrsim 100$ ns. This scaling is crucial since induction modules typically operate at peak power for relatively short times (~ 50 ns). The availability of high peak power and the constraints of short filling time from the induction cells are naturally matched to a high-gradient structure with a low attenuation parameter $\tau \equiv \omega t_F/Q$, where ω is the frequency, and Q the quality factor of the structure. Operation at low τ has the advantage of increased structure efficiency. The filling time is $t_F \equiv l/v_g$, where l is the distance between feeds and v_g is the group velocity. We choose to make v_g larger than in usual disk-loaded structures. This is accomplished by having a rather large beam hole, r_b, in the washer. Making a large beam hole r_b reduces the wake-field effects ($\sim r_b^{2.5-3.5}$) while only reducing the effectiveness of the accelerating structure somewhat ($\sim r_b^{0.3}$).

The parameters of the induction cells can be chosen by our noting that P_c/l, the peak power per unit length, is given by $P_c/l = N_c I_b V_c$, where N_c is the number of cells per unit length, V_c is the voltage on the induction cell, and I_b is the low-energy beam (peak) current. The accelerating voltage, V_c, is related to the field swing of the ferrite, $\Delta\beta$, by $V_c t_c = l_c(r_{0c} - r_{ic})\Delta B$, where t_c is the duration of the voltage pulse, and l_c is the length of the ferrite core whose radii are r_{ic} and r_{oc}. Cell designs must also be constrained to have adequately small hysteresis losses in the core.

The constraint of short voltage duration t_c comes from ferrite weight (cost) considerations and core loss requirements. The rf power requirements can be met with induction cells similar to those presently employed at the Advanced Test Accelerator at Lawrence Livermore National Laboratory, with $V_c = 250$ kV, and accelerating gradient of ~ 1 MV/m. We choose the electron beam current between 1 and 2 kA. One might be tempted to further reduce the voltage and increase the current, but is deterred from pushing to much higher currents primarily because of difficulties with constructing the transfer cavities, and difficulties with beam stability.

The transfer cavities are designed by noting that the peak power per unit length, P_t/l, is given by $P_t/l = I_t V_t N_t/2$, where N_t is the number of transfer cavities per unit length, V_t is the rf voltage across the cavity, I_t is the rf current that the beam induces in the cavity, and

$$I_t/V_t = (R/Q)^{-1}\{(1/Q)^2 + [2(f_0 - f)/f]^2\}^{1/2},$$

where Q is the quality factor of the transfer cavity, f_0 its resonant frequency, and R/Q a property of the cavity geometry. I_t depends on details of current waveform, radial couplings, etc.; in general, $I_t \approx I_b$ for reasonably well bunched beams. Determination of I_t and R/Q, f_0, as well as other resonant modes of the cavity, can most readily be done with standard computer codes; e.g., MASK and MAFIA.[6]

For simplicity of power transfer structure, the power output from a cavity should be comparable to the power needed to feed a single rf section. The rf voltage must stay below breakdown, and the impedance of the cavity must be attainable with reasonably simple geometry. For $I_b \approx 1$ to 2 kA, all of these requirements can be met

TABLE I. Parameters for a (375×375)-GeV design. The high-energy beam has a luminosity, $\mathcal{L}$, as a result of a repetition rate f_{rep} of the collider, a beam transverse rms transverse size σ_y, and a number of particles per bunch N. The collider has a length, exclusive of damping rings, of L. Each bunch has a rms length σ_z. The transverse size, σ_y, is consistent with the crossing-point focusing β^* and a normalized emittance ϵ_n. The beams disrupt each other, characterized by the disruption parameter D, and produce in each other a bremsstrahlung energy spread $\delta \equiv \Delta E/E$. All other symbols in the table are defined in the text.

Low-energy beam	Induction cells
$I_b = 1.6$ kA	$N_c = 4$ cells/m
$E = 50$ MeV	$t_c = 60$ ns
	$V_c = 250$ kV/cell
Transfer cavities	
$R/Q = 36\ \Omega$	High-energy beam
$Q = 20$	$E_f = 375$ GeV
$f_0 = 11.7$ GHz	$G = 215$ MeV/m
$N_t = 2$ cavities/m	$f_{rep} = 120$ Hz
$V_t \approx 1$ MV	$f = 11.4$ GHz
$b = 0.6$ cm	$L = 1.74$ km (each linac)
	$D = 2$; $H(D) = 5.6$
High-gradient structure	$\mathcal{L} = 1 \times 10^{32}$ cm^{-2} sec^{-1}
$t_F = 50$ ns	$\sigma_z = 1.9$ mm
$\tau = 0.257$	$\sigma_y = 0.5\ \mu$m
$l = 1$ m	$\beta^* = 3$ mm
$v_g/c = 0.067$	$\epsilon_n = 6.25 \times 10^{-5}$ mrad
$G = 215$ MV/m	$\delta = 21\%$
$P/l = 1.42$ GW/m	$N = 6.8 \times 10^{10}$
$f_0 = 11.7$ GHz	
$\mathcal{E}_s$ peak $= 537$ MV/m	

simultaneously.

The small beam pipe, coupled with the high current and the long distance of propagation, cause collective transverse instabilities of the intense low-energy beam to become potentially very serious. The resistive wall (RW) instability,[7] for example, has a characteristic length, L_{RW}, that is proportional to b^{-3}. For a 50-MeV, 1-kA beam of 50-ns duration propagating in a 6-mm radial copper tube with 3-kG solenoidal focusing, the growth length is $L_{RW} \approx 10$ m.

A more virulent transverse instability arises from the interaction of the beam with the cavities, i.e., the beam breakup (BBU) instability.[8] The transverse beam motion grows exponentially with a scale length L_{BBU}. With 3-kG solenoidal focusing, $L_{BBU} \approx 2$ m.

Both effects are prevented from occurring by Landau damping. If there is a spread in k_β^2 values, δk_β^2, such that

$$\delta k_\beta^2 \gamma > \pi [I_b/(17\ \mathrm{kA})](\omega_0 Z_\perp / L_g),$$

then there will be no growth in transverse beam position.[9]

A spread in k_β may be introduced if ion focusing is employed. This is done by propagating the low-energy intense beam through an ionized channel created in low-pressure gas by a preceding laser beam. The last has been shown to be very successful in transporting for many meters intense (10-kA) beams of various energies (5 and 50 MeV).[9] Landau damping is caused by the nonlinearities of the ion channel. It is possible to introduce enough nonlinearities to suppress the BBU instability totally with beam and channel parameters that are not very different from Advanced Test Accelerator operating parameters.

If ion focusing is used, one must be concerned with "beam head erosion" (the front of the beam is *not* focused and will expand radially) and with the spread, by diffraction, of the light beam. (The Rayleigh length, for typical parameters, is ~100 m.) The beam head erosion has been calculated to be tolerably small, while diffraction effects require a fresh laser beam (and hence a jog of the low-energy beam every 1 to 2 Rayleigh lengths).

An alternative strategy for Landau damping makes use of a spread in beam energy in a magnetic transport scheme. Although ion focusing may be less expensive than external magnet focusing, the latter is adequate and conceptually simpler. In a solenoid, k_β is inversely proportional to particle energy and, therefore, a spread in k_β occurs if there is a spread, $\delta\gamma$, in γ. If a low-energy bunch is made to travel through an inductively detuned cavity, then an energy variation from head to tail is induced. After the bunched beam has gone through a series of such cavities, a large energy spread will develop. Eventually, the bunch forms a stable bucket in phase space with particles performing synchrotron oscillations around the bucket center. For the parameter of the design, inducing adequate energy variation to suppress BBU is relatively easy. In addition, spatial variation in the solenoidal field could also contribute to a spread in k_β. The low-energy beam bunches will spread longitudinally because of space-charge forces. They will also spread because of finite transverse emittance effect. These effects are compensated by the same inductive detuning of cavities.

The RK/TBA requires a chopped beam. Starting from a uniform beam (i.e., a pulse of tens of nanoseconds), chopping can be accomplished at frequency f_0 with a slit and transverse deflection at a frequency $f_0/2$ (such as in an rf separator).

In the last analysis, the RK/TBA will be selected over the alternative of hundreds of power supplies (klystrons, lasertrons, gyrotrons, etc.) only if it is less expensive and/or simpler and more reliable. Preliminary studies[10] suggest that it will be cheaper, while the physics and engineering issues require laboratory studies. That work is now being planned.

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