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TITLE HIGH-BRIGHTNESS RF LINEAR ACCELERATORS

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HIGH-BRIGHTNESS RF LINEAR ACCELERATORS*

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INTRODUCTION

Soon after electrons and ions were discovered, production of practical generators of particle beams began, and a succession of machines were invented that could produce more energetic and more intense beams. Progress on the energy frontier is often charted from the 1930s in the form of the Livingston Chart, Fig. 1, showing that particle accelerator energy has increased by a factor of about 25 every 10 years. The corresponding cost per million electron volts has decreased by about a factor of 16 per decade (Lawson, 1982). The physics principles on which all of these devices work were deduced long ago; the energy increases were possible because of cost reductions from thorough exploitation of parameters, engineering perfection, systems integration, and advanced manufacturing methods (Voss, 1982).

At the same time, the development of more intense sources proceeded. Linear accelerators (linacs) are suited to intense sources because the beam can easily exit the machine.

Although technology to increase energy and intensity tended to be pursued separately in the past, recent applications have had to consider both, along with the ability to keep the beam very precisely confined, aimed, or focused. The figure of merit used is called brightness, defined (variously) as the beam power (sometimes only the beam current) divided by the phase space appropriate to the problem at hand. Phase space for the beam as a whole is six-dimensional, describing the physical size of the beam and the change in size with time or distance; the area projected on one plane is called emittance.

This discussion will concentrate on a particular kind of linear particle accelerator—the kind whose driving energy is provided by radio-frequency fields—that is well suited to producing high-brightness electron or ion beams. We will concentrate on the issue of high brightness and its ramifications.

CONTEXT OF LINEAR ACCELERATORS

It is useful to place the rf linac in context with other accelerators, using a classification proposed by Lawson (Lawson, 1982) to illustrate the physical principles used in various accelerator types. Figure 2 shows a division between machines where the accelerating field at a point varies harmonically and those in which it does not. These categories are then divided.

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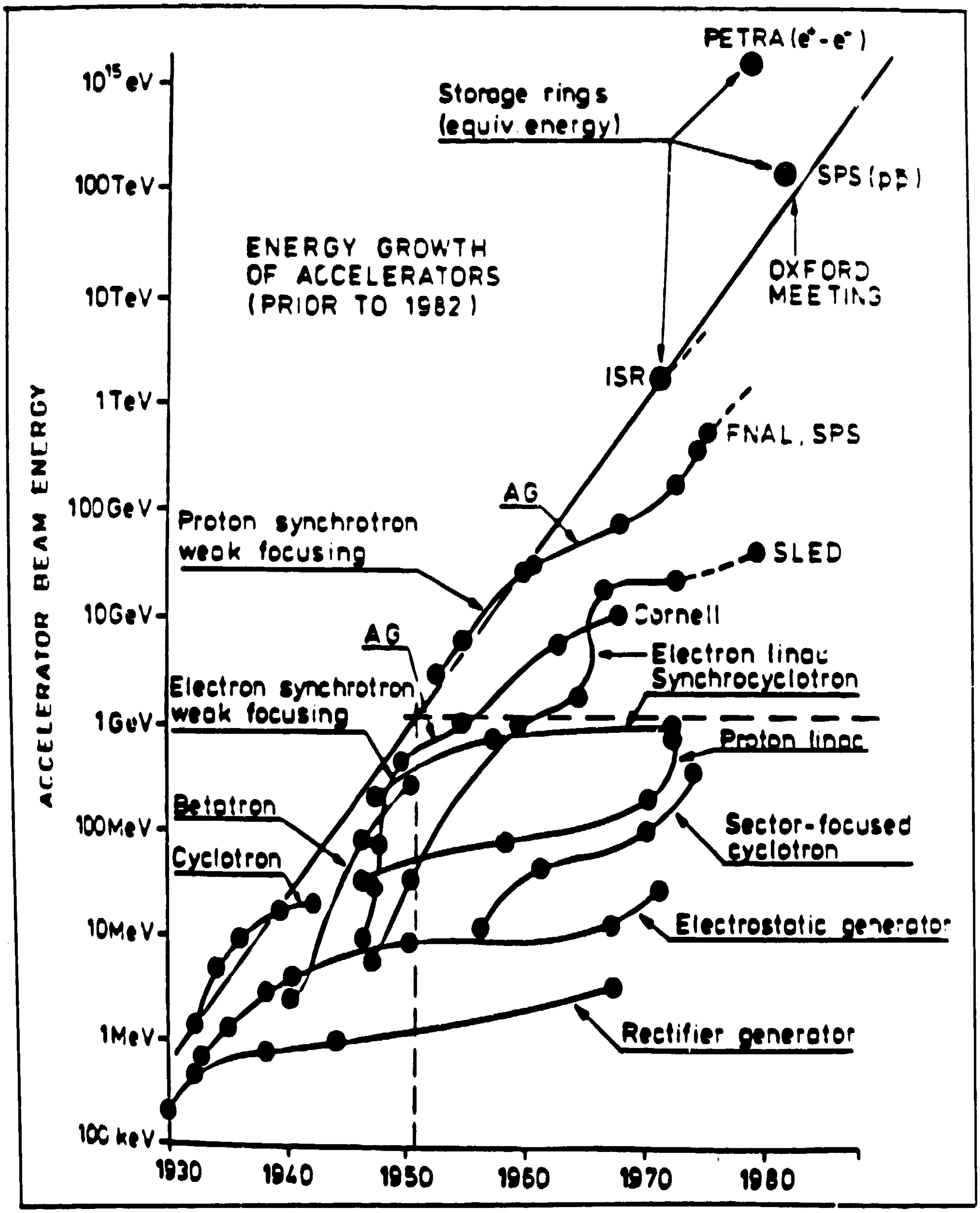


Fig. 1

The Livingston chart, showing the evolution of various types of accelerators with time.

ACCELERATING FIELDS	CATEGORY 1 ACCELERATED PARTICLES IN FREE SPACE		CATEGORY 2 ACCELERATED PARTICLES IN A MEDIUM
	CATEGORY 1.A NO FREE CHARGES IN SYSTEM	CATEGORY 1.B FREE CHARGES IN SYSTEM	
HARMONIC	• Linacs • Synchrotrons • Inverse Free-Electron Laser	• Linac plus rf Drive System	• Inverse Cherenkov • Beam-Wave • Laser Beat-Wave
NONHARMONIC	• Betatron • Induction Linac • Electrostatic Accelerator	• Ion-Drag Accelerator • Wake-Field Accelerator	• Ionization Front • Electron Ring

Fig. 2
Classification of accelerators used by Lawson.

depending on whether the particles move in free space or in a medium, which could be a plasma or an intense beam of a different kind of particle. The free-space category is subdivided, depending on whether the charges that produce the accelerating and focusing fields are all bound in metals or dielectrics or if they are free parts of a plasma or particle beam. In a generic sense, most applied accelerator systems today are in Category 1 and are based on classical electromagnetic (EM) physical principles. Category 2 basically involves plasma physics, which is much less tractable and has not led to significant practical application in accelerator technology.

As the beam brightness is raised, the particles cease to be acted upon by the EM fields independently but begin to feel the repulsive force of the other, like-charged, particles, and the total EM interaction becomes the collective effect of the whole ensemble of particles and fields. The limit at which the particle self-fields cancel the externally applied fields, called the space-charge limit, is where control is lost of the acceleration and/or focusing process, a condition obviously deleterious to brightness. Another basic limiting phenomenon, called beam breakup (BBU), occurs when the intense beam interacts electromagnetically with its surroundings, creating waves that interact back on the beam, causing it to be diverted or diluted.

For the Category 1 high-brightness linacs we are now building, we must consider these collective effects in the accelerated beam, but do not rely on them for acceleration, as would be the case in Category 2. As the need for brighter beams grows, we continue to explore the collective-effect boundary, requiring better understanding of plasma effects in the beam itself or as an efficient acceleration mechanism therefore, an understanding of plasma physics is becoming a prerequisite for workers in this field.

Before delving into some of the details of linear accelerators, let us look at some current applications that are strongly driving progress in rf linear accelerators.

APPLICATIONS STIMULATING RF LINAC DEVELOPMENT

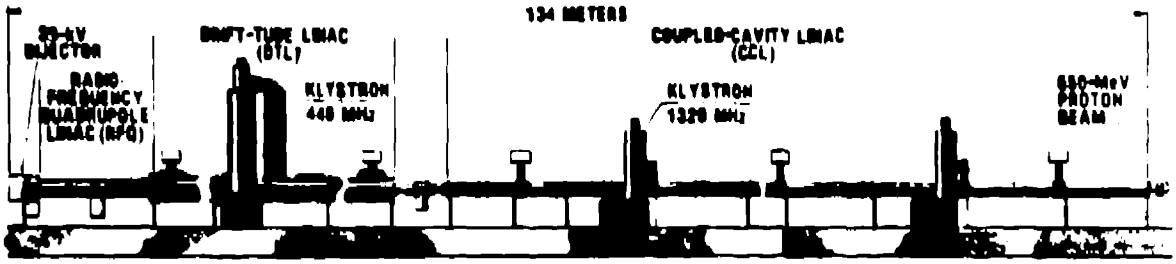
Physics Research

Nuclear and particle physics, and the increasingly blurred interface between these traditional fields, continue to stimulate linac development. The Los Alamos Meson Physics Facility (LAMPF) is the most intense operational proton linac in the world, producing a 1-mA average current at 800 MeV. LAMPF was recently upgraded to produce a bright H^- beam for injection into the new Proton Storage Ring. Both the Superconducting Super Collider (SSC) and the heavy-ion-collider facilities that will likely be the next generation of large ion accelerators probably will have linac-based injectors that use new techniques involving higher frequencies, higher accelerating gradients, radio-frequency quadrupole (RFQ) preaccelerators, and other advanced accelerator structures. Figure 3 shows such a machine and outlines the innovations that influence most new ion-linac initiatives now in progress.

In electron machines, a new US Continuous Electron Beam Accelerator Facility (CEBAF), Newport News, Virginia, is proposed, based on very recent advances in superconducting linac technology, to provide a high-intensity cw 200-μA, 4-GeV electron beam. Very high energy physics (HEP) machines now use colliding beams to reach the highest center-of-mass energies, and construction of an important proof of principle is nearing completion at SLAC's Linear Collider (SLC). Here, two intense beams will be collided at a spot about 1μm in diameter. The brightness figure of merit for these machines is called luminosity—a combination of brightness and the event rate and data collection characteristics of the physics experiment. In the long term, luminosity goals of $10^{33\text{-}34}$ $cm^{-2}s^{-1}$ at energies in the 3-TeV range are sought for electron colliders, compared to the design goal of 6×10^{30} $cm^{-2}s^{-1}$ at 50-GeV energy for the SLC. Control of BBU is important in the linac drivers for these colliders. Similar considerations influence the design of microtron electron accelerators (Fig. 4) and free-electron lasers (FELs) (Fig. 5). The microtron application also stresses development of room-temperature cw accelerating structures; the Los Alamos/NBS program produced an advanced 2400-MHz cw side-coupled structure capable of 2-MeV/m accelerating gradient.

Fusion

The Fusion Materials Irradiation Test (FMIT) project, now in abeyance, was to test materials in a neutron flux produced by a cw, 100-mA, 35-MeV linac accelerating a deuteron beam that would hit a molten lithium target, as outlined in Fig. 6. The cw, very high intensity nature of this linac presented great challenges in two major areas. Efficiency required operation near the space-charge limit while, at the same time, residual beam losses that would cause radioactivity build-up in the machine had to be minimized so that machine maintenance



MAJOR TECHNICAL INNOVATIONS

- HIGHER FREQUENCIES
- HIGHER GRADIENTS
- LOWER INJECTION ENERGY
- RFQ LINAC STRUCTURE
- POST-COUPLED DTL STRUCTURE
- PERMANENT-MAGNET QUADRUPOLE LENSES
- DISK-AND-WASHER CCL STRUCTURE
- COAXIAL BRIDGE COUPLERS
- DISTRIBUTED MICRO-PROCESSOR CONTROL

PROTON BEAM PARAMETERS

INJECTION ENERGY	30 keV
RFQ/DTL TRANSITION ENERGY	2.5 MeV
DTL/CCL TRANSITION ENERGY	125 MeV
FINAL ENERGY	650 MeV
PEAK BEAM CURRENT	28 mA
PULSE LENGTH	60 μs
REPETITION RATE	60 Hz
AVERAGE BEAM CURRENT	100 μA

PROTON LINAC PARAMETERS

	FREQUENCY	KYLSTRONS	GRADIENT
RFQ & DTL SECTION	440 MHz	1	6 MV/m
CCL SECTION	1320 MHZ	6	8MV/m

Fig. 3. PIGMI Program.

The Pion Generator for Medical Irradiations (PIGMI) program, sponsored by the National Cancer Institute, has resulted in an optimized design for a practical generator of negative pi-meson beams of sufficient intensity and quality for cancer therapy. Such a machine must be compact, reliable, of reasonable cost, and easy to construct, install, maintain and operate. Our component-development program could also be applied to a smaller deuteron, proton, or heavy ion accelerator suitable for providing neutrons or ions for therapeutic application. The technology is also applicable to machines for medical radioisotope production. Major innovations are listed. Collectively, these innovations contribute to a highly compact, efficient, and manageable device, compatible with typical hospital or isotope-production environments.

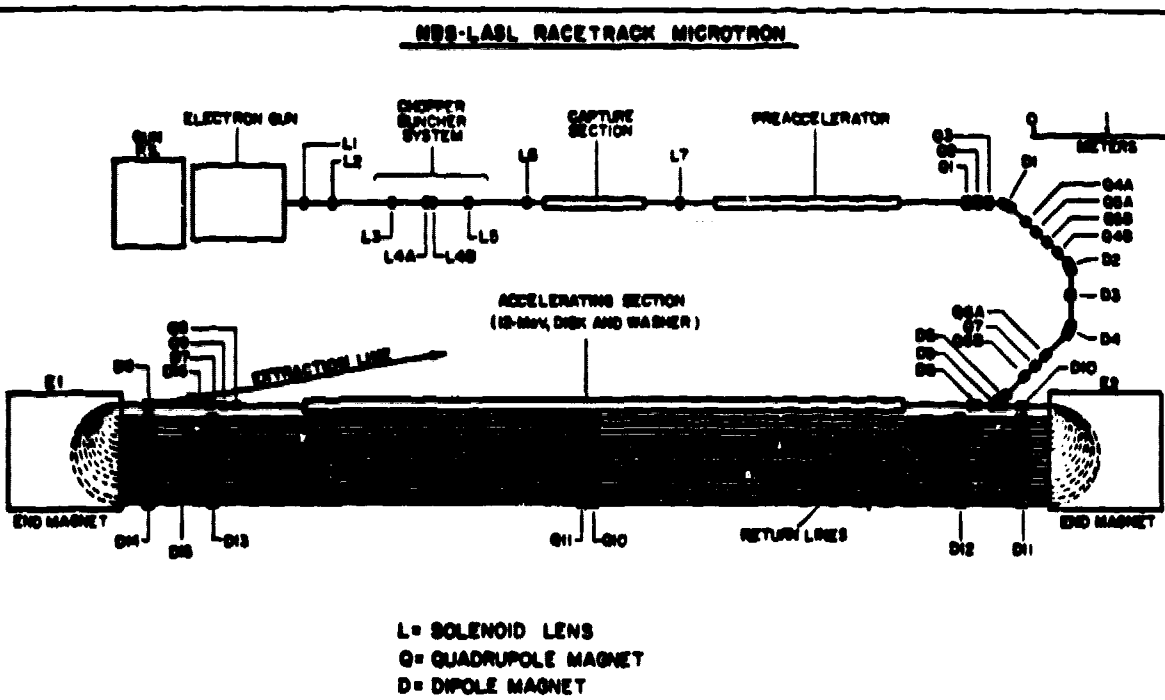


Fig. 4. The Racetrack Microtron.

The NBS/Los Alamos racetrack microtron (RTM) is a joint project of the National Bureau of Standards (NBS) and Los Alamos. The goal of this accelerator research project is to build the accelerator depicted above, using beam recirculation and room-temperature rf accelerating structures. This accelerator will be capable of accelerating a 550-μA electron beam to 185 MeV.

The portion of the project being done at Los Alamos includes development of the rf power source, the rf accelerating structure, and the control system. The rf power will be provided by a single 500-kW cw klystron operating at 2380 MHz. We have developed a side-coupled accelerating structure with sufficient water cooling to operate with an accelerating gradient of 2 MeV/m cw. This structure also features a high shunt impedance (efficiency) and sufficient cell-to-cell coupling for good accelerating field stability in structures up to 4 m long at 2380 MHz.

problems would not be too severe. The development work for this program contributed much to our present understanding of the dynamics of high-intensity linacs (Jameson, 1983; Jameson, 1982; and Hofmann, 1983) and a new accelerator type, the RFQ (Stokes et al., 1981). The other challenge was the engineering requirements of such a high power, cw system that must run with very high availability. A 2-MeV prototype accelerator was operated cw at 50 mA this spring.

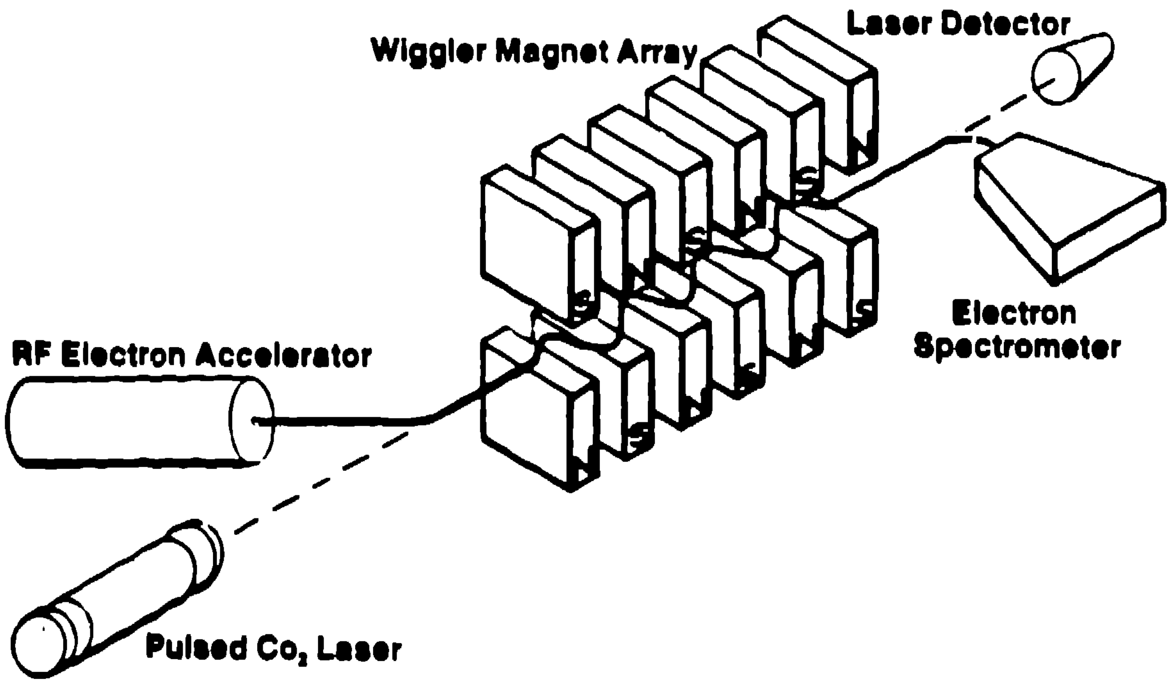


Fig. 5. The Free-Electron Laser.

The free-electron laser, shown here in a single-pass configuration, amplifies light from a laser as it passes through an arrangement of magnets called a "wiggler." This causes electrons from the accelerator to vibrate at a frequency that permits the laser to strip energy from the electrons and convert it to light. For increased efficiency, the wiggler designed by Los Alamos uses nonuniform spacing between the magnets to improve the efficiency by an order of magnitude.

In inertial confinement fusion, high-energy heavy ions might interact classically with the target, avoiding problems that have prevented laser, electron, or light-ion beams from achieving practical performance. However, the required heavy-ion accelerators would still be large and complex devices. Two approaches have been studied—the rf-linac/storage ring approach and the induction linac. The primary system requirement is for a very bright 6-D phase space because the beam must deposit its energy in a short time on a small target. Thus, the heavy-ion fusion (HIF) program has been a primary motivation toward understanding space charge and instability limits in both types of machines (Hoffman, 1983; Darmstadt report, 1982; Tokyo report, 1984; and Washington, D.C., report, 1986) and toward practical techniques for phase-space manipulation and control that will not spoil the brightness.

Industrial/Medical

As indicated in Fig. 3, high-brightness ion-linac technology is being applied to cancer treatment or radioisotope production. Advanced electron linacs are being considered for

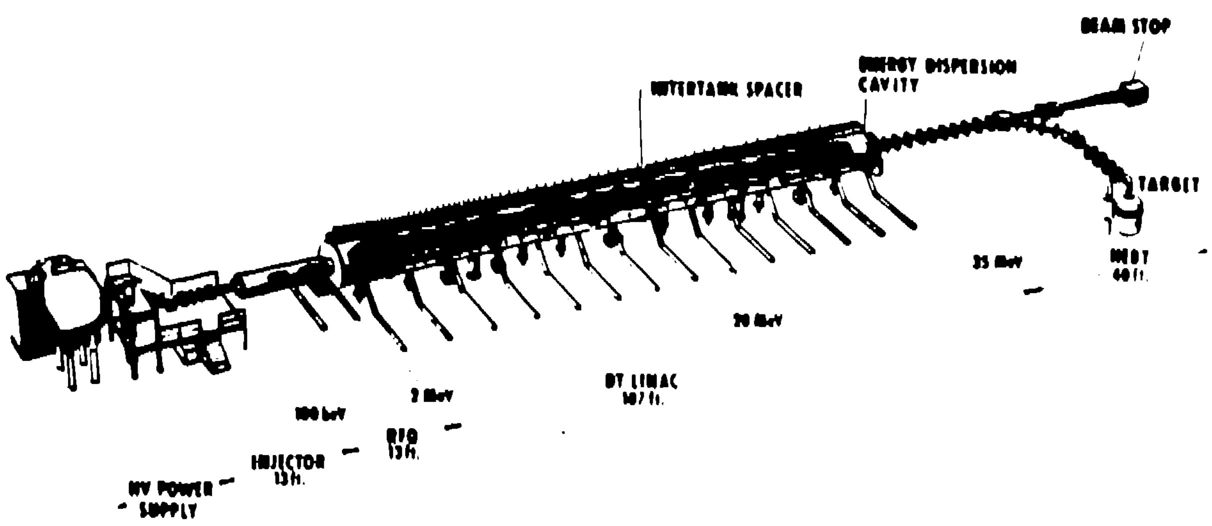


Fig. 6. The FMIT Accelerator.

A 35-MeV, 100-mA cw linear accelerator is being designed by the Los Alamos National Laboratory for the Fusion Materials Irradiation Test Facility to be built at the Hanford Engineering Development Laboratory, Richland, Washington. The 2-MeV first section of the accelerator has been built at Los Alamos and is being evaluated. The FMIT concept involves a linear accelerator that injects a 35-MeV beam of deuterons onto a flowing lithium target. Deuteron stripping produces a significant flux of 14-MeV neutrons that simulates the neutron flux from a fusion-reactor core.

radiography, free-electron lasers, and food processing. FELs present challenging demands on electron linac performance; considerably more intense beams with better emittance, compared with existing machines, are required, and this makes understanding and control of BBU phenomena essential for both beam acceleration and the energy-recovery beam-deceleration scheme now being tested at Los Alamos (Watson, 1985) (Fig. 7). Applications of rf-linac based FELs to infrared on ultraviolet light sources, process chemistry, and other industrial uses are under study.

Strategic Defense

The possibility of using particle beams for defense against nuclear weapons has resulted in increased attention to rf linac development (Jameson, SLAC report to be published). Neutral particle beams, which would be undeflected by the earth's electromagnetic fields, and FELs are being studied. Such systems require exceedingly bright beams and present overall system challenges of a new scope—in particular, the prospect for accelerator of substantial size operating in space. Beyond any defense application, this environment would afford many scientific and practical initiatives, and the techniques developed will influence all linac construction.

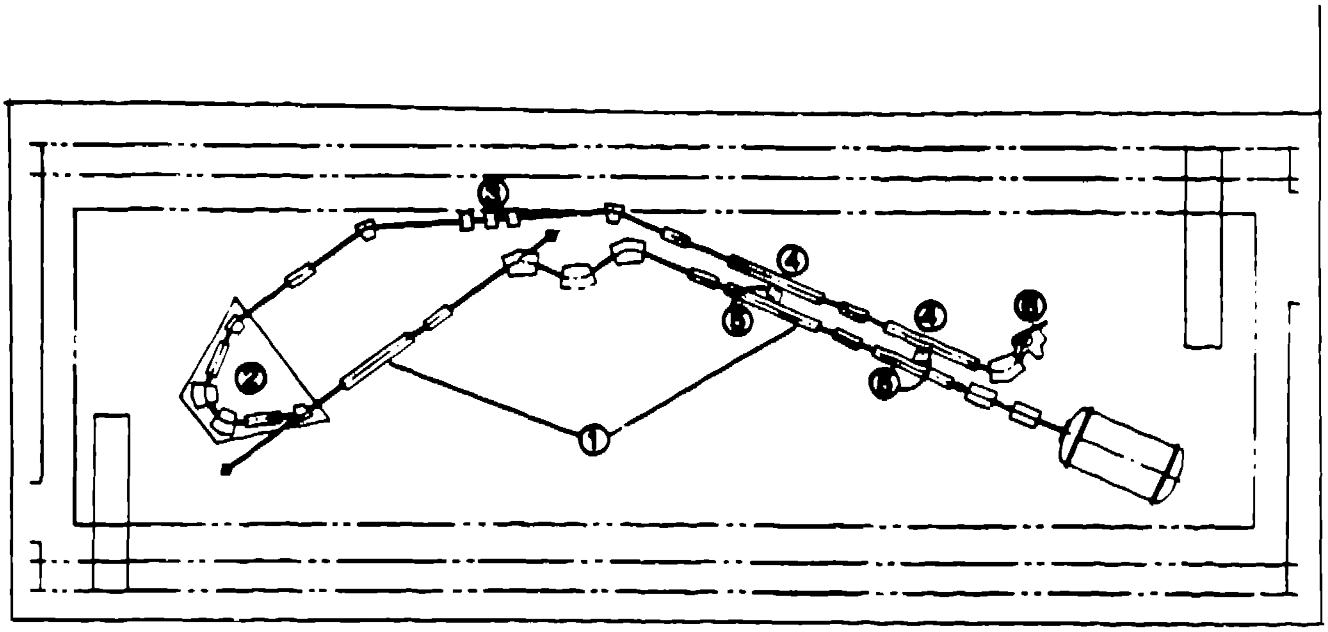


Fig. 7.

Los Alamos rf-linac-driven FEL energy-recovery experiment layout: (1) accelerator and FEL operating at two-fold increase in peak current; (2) isochronous 180° bend on translation table; (3) isochronous 60° bend; (4) two 1.8-m decelerator (energy-recovery) sections; (5) two variable rf bridge couplers; (6) beam dump for 2- to 3-MeV beam; (7) 20-MeV diagnostics.

BASICS OF LINAC BRIGHTNESS

So linac devices for a variety of applications have similar challenges, problems, and approaches to solutions—the basic problems of attacking the numerator or the denominator of the brightness equation. The numerator can be raised by brute force, but the large power requirements and engineering problems are formidable, and better system efficiency is a desirable research goal. Power scale-up may tend to spoil the beam quality because of intensity-related phenomena. Emittance preservation in each case also requires that aberration effects in the beam transport optics be avoided. Thus, a long-term development program in advanced linac-based drivers is required. We turn to a short outline of how linacs work (Humphries, 1986) and further development of the high-brightness theme.

As we have noted, rf linacs accelerate particles in a beam through a resonant interaction with external charge distributions and the coupling EM fields that transfer energy to the beam particles. The applied EM fields exert forces on the beam that we will vectorize as acting longitudinally along the beam direction to accelerate or decelerate it and, transversely, to confine the beam. At high enough beam currents, the self-consistent solution of the equations describing a particle's motion must account for the total field generated by the external charges and by fields generated by other particles. This is a nonlinear problem and can be handled in detail only by computer programs, using successive iteration. However, much of the useful design information comes from smoothed approximations of the detailed motion, dealing in particular with the rms properties.

In the resonant rf linac, the resonance properties of the circuit are used to obtain voltage amplification, and the time-varying fields are used specifically to influence the particle motion. In particular, particles must be at the right place at the right time to see an accelerating field, and this synchronism must be maintained over a long distance to produce high energy. In rf linacs, the energizing field is expressed as a sum of traveling waves, and one wave is made to travel near the average velocity of the particles. The truly synchronous particle would travel exactly along the axis with the wave, whereas particles with different phases or energies would oscillate around the synchronous particle, or if too far from synchronism, would be only jostled as the wave passed. As indicated in Fig. 8, (nonrelativistic) particles arriving earlier than the synchronous particle see a lower voltage, are accelerated less, tend to converge on the synchronous phase point φ_s, and so on; thus, there is a region of phase stability over some phases of the wave, known as the rf bucket, in which the particles oscillate around the synchronous particle. An approximate equation describing this phase oscillation is that of a nonlinear oscillator:

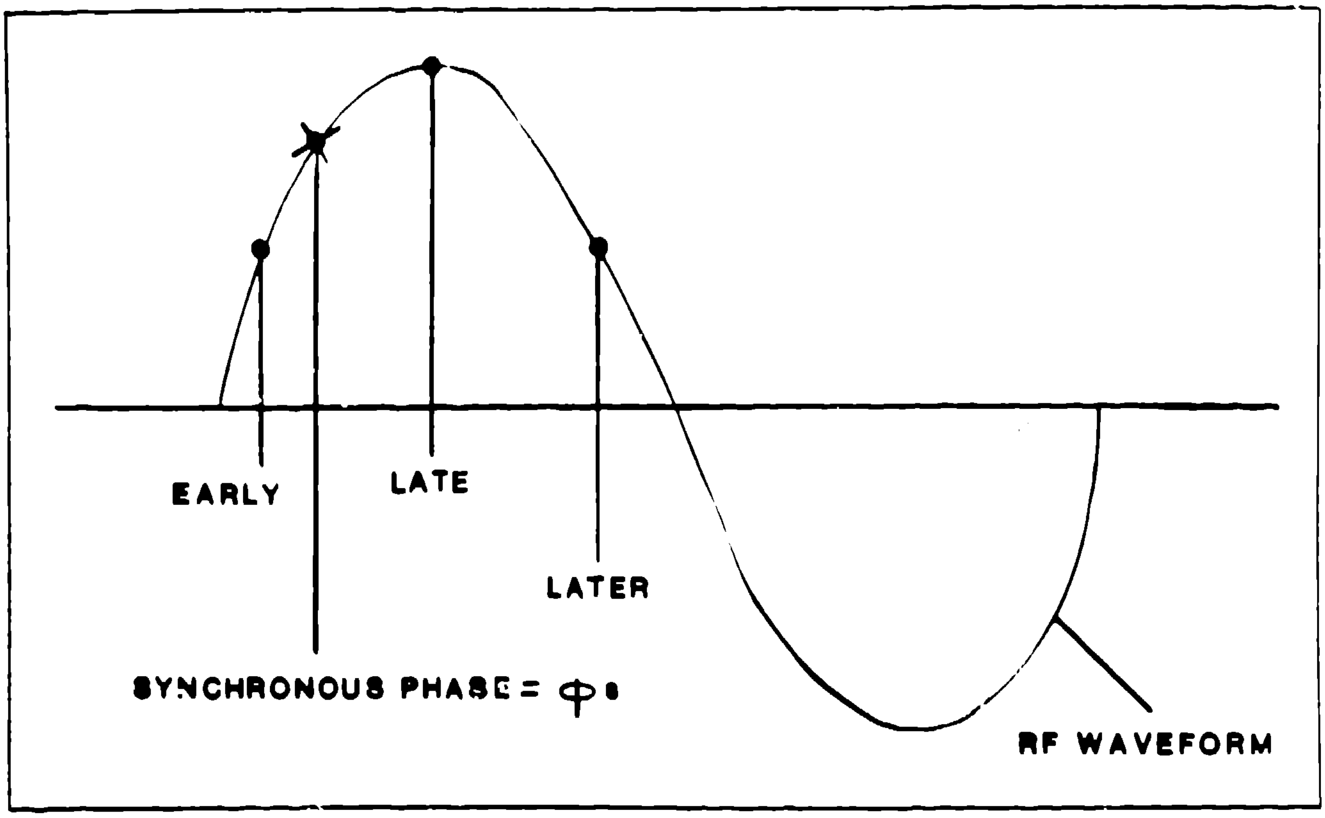


Fig. 8.
Time or equivalent position along rf wave.

$$d^2\varphi/dt^2 = -K_t(\sin\varphi - \sin\varphi_s) \ .$$

The solution for small-amplitude oscillations is harmonic, characterized by the phase advance σ^t of the oscillation over an accelerator system period. The particle with synchronous phase clearly also has a synchronous energy as well, and off-synchronous particles define oscillation trajectories around the synchronous particle in energy and phase. A plot of the displacement from synchronism is called the longitudinal phase space. The boundary within which particles oscillate stably is called the acceptance, as indicated in Fig. 9.

If the distribution of the beam particles, called the emittance, is congruent with the acceptance, as in A, the beam is said to be matched, with the particles moving on congruent orbits in the linear approximation. Particles injected in the shape B would sweep out a larger area in phase space, like C, and if nonlinear forces are present, the particles would eventually disperse to fill the area C (or worse). Thus, we have introduced the concepts of matching and emittance growth and have suggested that matching is to be desired and emittance growth avoided. With relativistic particles, assuming the wave travels at the speed of light c,

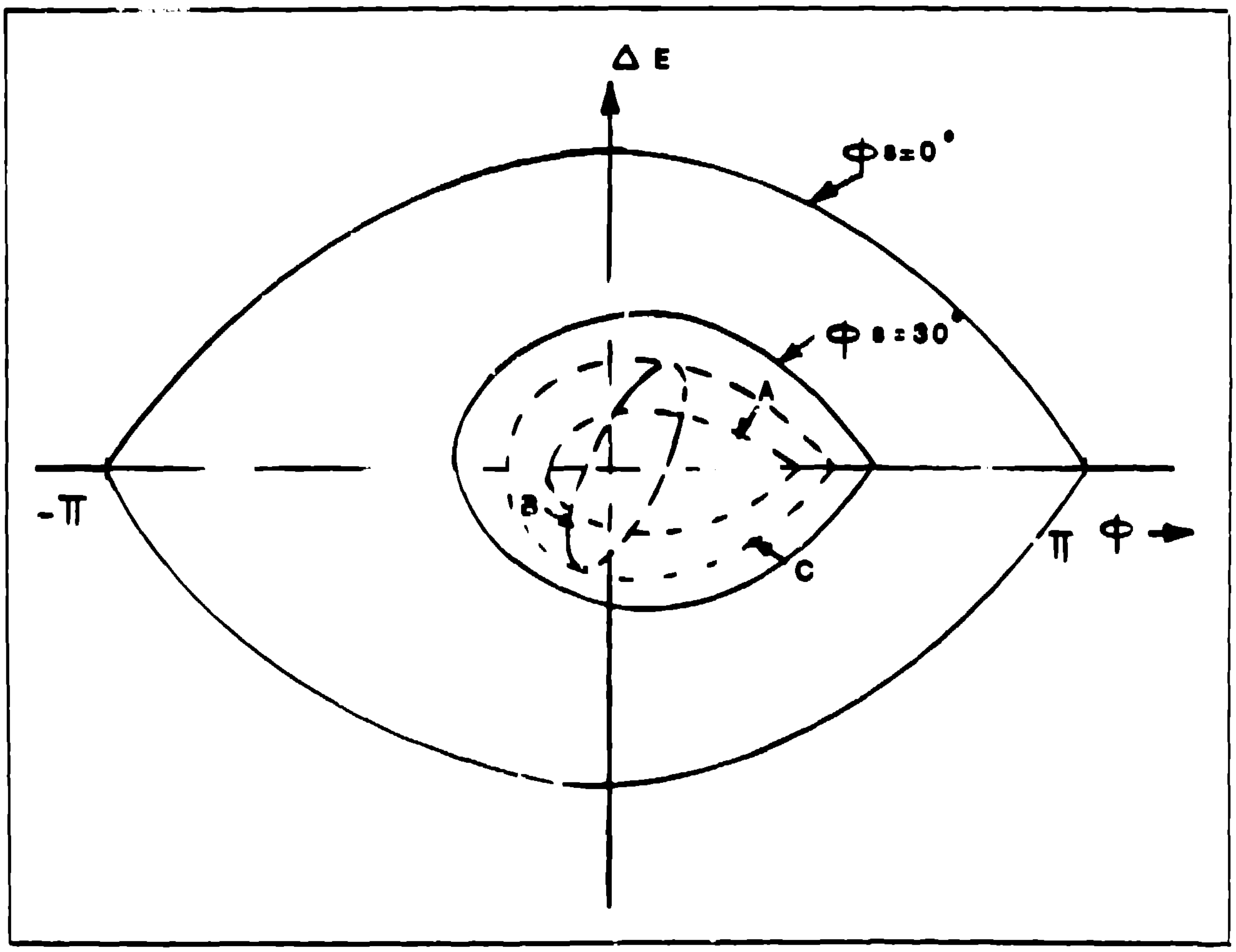


Fig. 9.
Longitudinal acceptance diagrams for different φ_s.

acceleration occurs if the phase is less than π, with a slippage until the particle reaches π because the particle is not quite at c. However, if the acceleration voltage is high enough, acceleration takes place so fast that the particles can be trapped in a bucket and carried to arbitrarily high energy. The solution is not oscillatory; because time dilation dominates, the particles monotonically approach a constant phase. We will have to differentiate between relativistic (electron) machines and nonrelativistic (ion) aspects as we go along.

The traditional physical structures for setting up the desired fields were basically configured to produce the longitudinal field. For short pulses, the electron linac structure is a simple pipe with periodic loading in the form of iris disks with a beam hole at the center, spaced to slow a traveling wave to match the beam velocity, as in Fig. 10. For longer pulses, a standing-wave structure is more efficient; in the structure of Fig. 11, the field can again be explained using the sum of traveling waves, one of which matches the beam, or by considering that the beam is only exposed to the field during the proper interval of the rf wave that results in acceleration. During the rest of the rf cycle, the beam is in the tunnel, or drift-tube, between cells, and does not feel the field.

In ion linacs, the traditional structure for energies above an MeV or so is called the Alvarez or drift-tube linac, Fig. 12; it operates as a standing-wave structure. Above 100 MeV or so, the drift-tubes become long and efficiency arguments require a transition to a higher frequency and a structure like that of Fig. 11.

In the transverse plane, the unavoidable existence in cylindrically symmetric rf linacs of the slow traveling wave's radial field components results in orbits that are transversely unstable when the longitudinal orbits are stable; therefore, ion linacs must use arrays of focusing elements to contain the beam. This focusing requirement introduces a host of new considerations but, for now, the essential point is that the added transverse focusing also has a periodic property. In electron rf linacs, the beam is traveling so fast that the radial defocusing is less apparent, and added transverse focusing elements are needed much less frequently. A new type

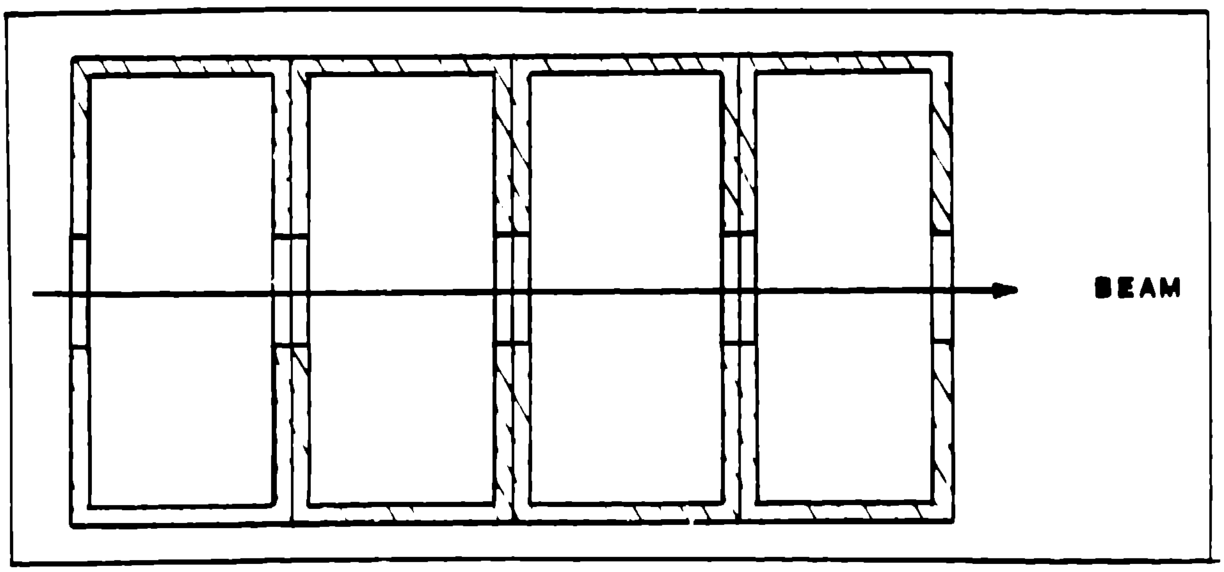


Fig. 10.
Iris-loaded waveguide for traveling-wave electron linac.

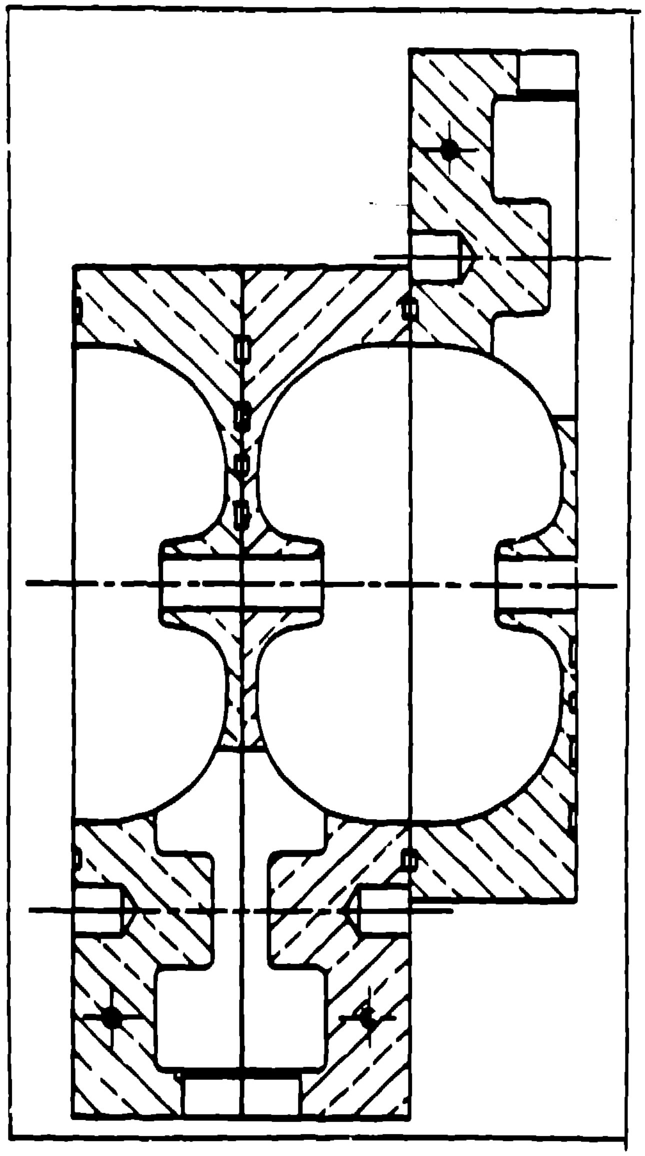


Fig. 11.
Standing-wave structure for electron linac.

of structure, the RFQ, has azimuthally asymmetric transverse fields and is basically a transverse focusing structure that is perturbed to set up a longitudinal accelerating component (Fig. 13). This structure uses the electrostatic focusing from the rf fields to provide both the focusing and acceleration and has great advantages for low-velocity ions in the tens of keV to few MeV range. The RFQ is also well described by the smoothed oscillator equations.

Off-axis particles oscillate in a transverse phase space characterized by position with respect to the axis and angle with (or velocity away from) the axis. Their motion can be described by a nonlinear oscillator equation similar to that of the longitudinal space, with a phase advance per accelerator transverse period of σ'. As with the longitudinal phase space, it is important to match the shape of the beam distribution to the shape of the transverse acceptance to avoid

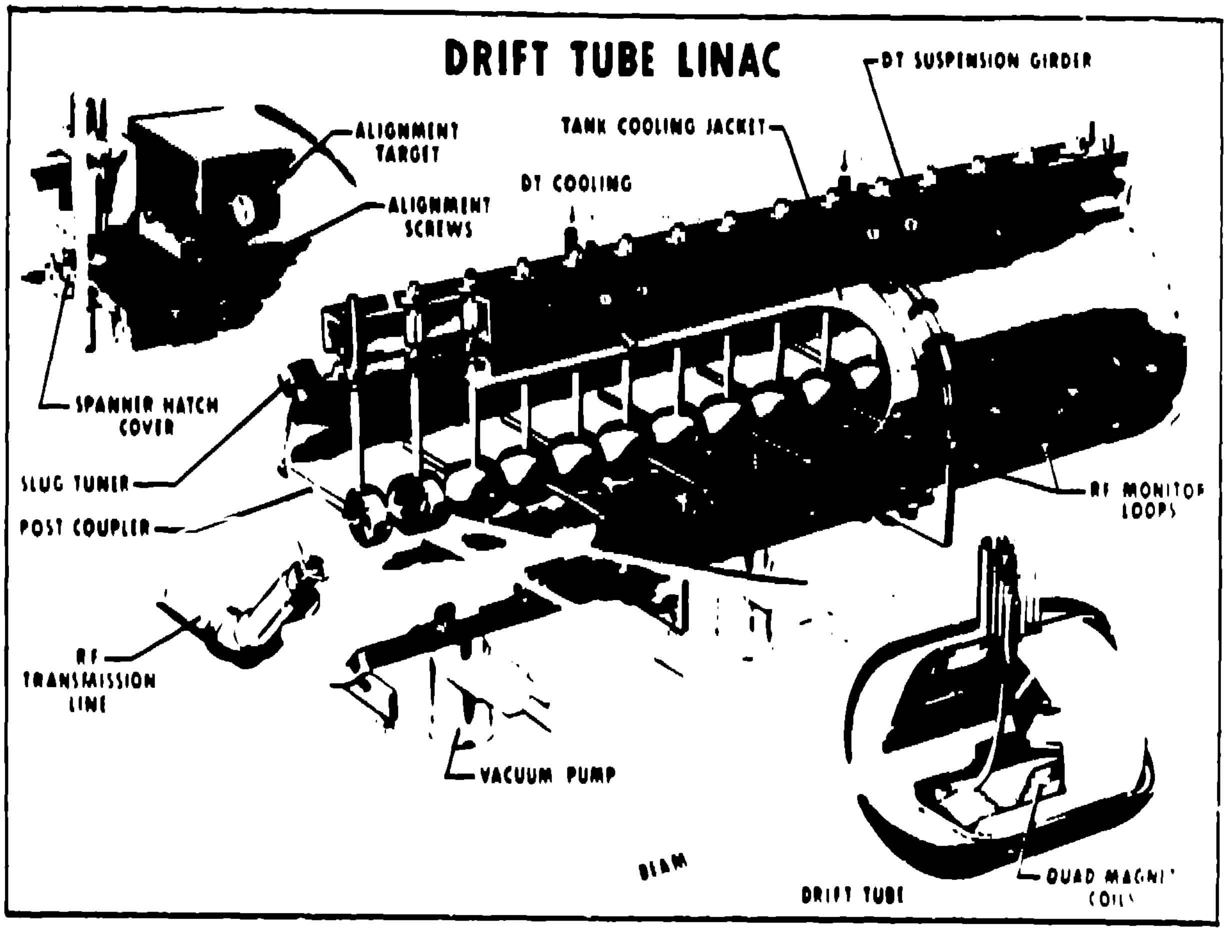


Fig. 12.
Alvarez or drift-tube linac.

emittance growth. Such growth leads to loss of brightness or (eventually) even to loss of particles, which not only reduces the transmitted current (further brightness loss) but also causes unwanted problems with heat dissipation or radioactivity build-up in the accelerator walls.

The characteristic phase advances σ^t and σ^l are not independent because of coupling between the transverse and longitudinal external fields and because the fields of the beam itself are also coupled between longitudinal and transverse. The equations for the phase advances have the forms

$$\sigma = \cos^{-1}\left[\cos\sigma_0 + f(\text{beam current, beam size a and b})\right] ,$$

where a is the average transverse rms beam radius; 2b is the physical rms bunch length; and σ_0 is the zero current phase advance, which in turn is a function of the structure geometry and the external fields, including the transverse and longitudinal couplings.

The rms space-charge forces in the beam directly cancel the rms external restoring forces, so the phase advances tend to zero as the current rises. We define the relation between space charge and external forces in terms of the phase advances as

Fig. 13.
The radio-frequency quadrupole (RFQ) accelerator.

$\mu_l = [1 - (\sigma^l/\sigma_0^l)^2]$ and $\mu_t = [1 - (\sigma^t/\sigma_0^t)^2]$.

Next we need to look at the idea of emittance a little more closely. Figure 14 indicates a collection of particles in transverse phase space that has some particle density distribution. The rms emittance* ε_{rms} of the distribution is given by

$$\varepsilon_{rms} = \left(\overline{x^2}\,\overline{x'^2} - \overline{xx'}^2\right)^{1/2} ,$$

which is the equation of an ellipse. The rms beam size is $a = \sqrt{\overline{x^2}}$ and the rms beam divergence is $a' = \sqrt{\overline{x'^2}}$. In a linear periodic system, the ellipse would have the same shape at similar points of each period; one convenient point is where the correlation terms vanish and the ellipse is upright. If an ellipse of the rms shape is fit through each particle in the distribution, an effective ε_{total} is found. While the actual area occupied by particles in phase space is conserved, the effective area is of more practical import because nonlinear effects tend to push particles out in diffusion or filamentation processes until they occupy the larger area. Because brightness is a key figure of merit, we see that it would be desirable to keep the maximum number of particles in the smallest rms area, or perhaps in the smallest total area.

$$\text{Brightness} \propto \frac{\text{current}}{\varepsilon_x \varepsilon_y \varepsilon_z} .$$

The accelerated beam can be no brighter than the input beam, but there are a number of processes that can make it worse. The study of these processes and attempts to control them have absorbed accelerator designers for many years. The difficulties of creating the particle beam and delivering it to the beginning of the rf linac are another whole story, fraught with poorly understood phenomena involving material properties and partially neutralized plasma effects. In the rf linac, the EM fields ensure that the beam plasma is nonneutralized.

The nonlinearities and couplings in the external fields have been thoroughly studied, and their control is a large part of the art of making practical accelerating structures. At present, configuration of the external field is done well enough that most particles are confined near the center of the phase-space diagrams where the motion is nearly linear, on average. It is important that the rms shape properties of the emittance be matched to the acceptance. The beam must be kept centered on the transverse axis and straight along it, and the longitudinal centroid must be at the synchronous phase and energy. Also, the rms-emittance shape and orientation of the longitudinal distribution must be right.

However, it was long a mystery that, even though the ellipse properties were matched in each plane, transverse rms emittance growths of a factor of 2-3 occurred in the low-velocity section of rf ion linacs with intense beams. The cause has been the subject of an intense search by a few people, with some real progress recently (Wangler and Guy, 1986; Guy and Wangler, 1986; Wangler et al., 1986; and Wangler, this Advanced Study Institute report). It had long been suspected (Lapostolle, et al., 1968) that some kind of energy balance, or equipartitioning,

*This is true rms emittance, without the factor of 4 used by some.

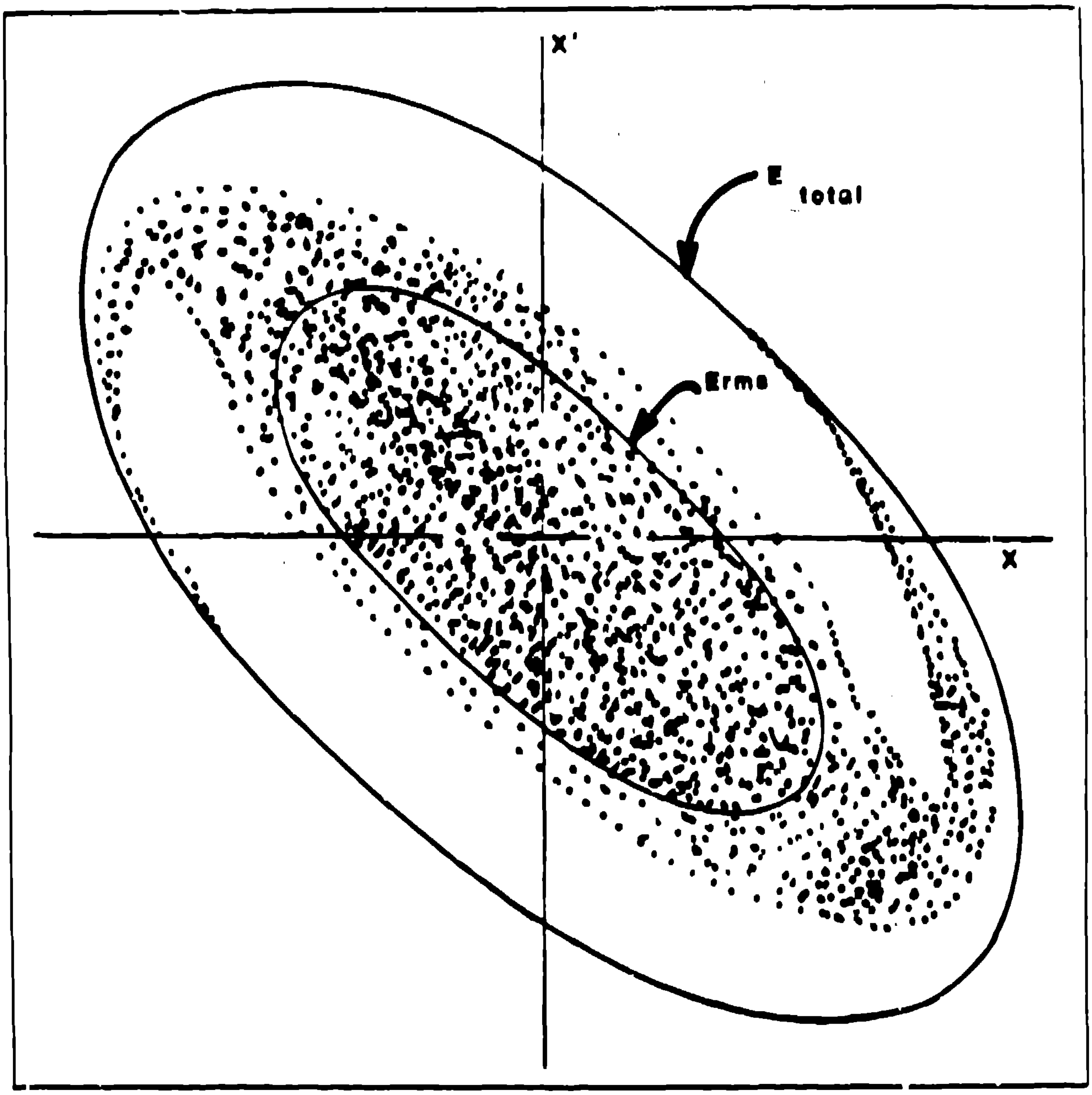


Fig. 14.
A particle distribution in x-x' transverse phase space.

between the degrees of freedom would ameliorate the growth, but the way to characterize the physics was very elusive. One breakthrough occurred (Jameson, 1981) when it was shown that a very simple rms equipartitioning requirement on a bunched injected beam could indeed produce remarkably small emittance growth, at least in a full-scale, nonlinear computer simulation of the linac. We will now outline the set of equations leading to these conditions.

A simple derivation for energy balance in a weakly coupled harmonic oscillator system requires equality of the average kinetic and potential energies in each degree of freedom;

$$<1/2\, mv_i^2> = <1/2\, k_i x_i^2> ,$$

where k_i is the appropriate force constant. If we characterize the motion in terms of the oscillation's phase advance σ_i over an accelerator system period $N\beta\lambda$, we can write the mean-square velocity as

$$<v_i^2> = \sigma_i^2 <x_i^2>/(N\beta\lambda)^2 .$$

At a location where the correlation $<x_i v_i>$ is zero, rms emittance is defined as

$$\varepsilon_i = <x_i^2>^{1/2} <v_i^2>^{1/2} ,$$

and the two equations that describe the motion of the particle envelopes follow directly:

$$\varepsilon_t = \sigma^t a^2/N\beta\lambda \text{ and } \varepsilon_\ell = \sigma^\ell b^2/N\beta\lambda .$$

It can be shown rigorously that these are the matched envelope equations ($\ddot{a} = \ddot{b} = 0$) for the rms envelope behavior of particle distributions in linearized periodic systems. The simultaneous solution of these two equations was a necessary condition for preventing emittance growth, but was not enough. If we require equal average energy in each of the coupled degrees of freedom, by equating

$$<v_i^2> = <v_j^2> \text{ and } \sigma_i^2 <x_i^2>/(N\beta\lambda)^2 = \sigma_j^2 <x_j^2>/(N\beta\lambda)^2 ,$$

we find

$$\frac{\varepsilon_t}{\varepsilon_\ell} = \frac{\sigma^t}{\sigma^\ell} = \frac{b}{a} .$$

Systems satisfying this equation and the envelope equations simultaneously will be both matched and equipartitioned. We have observed, in simulation studies of completely described accelerating channels, emittance growths of only about 20% over a large number of cells for linacs quite near the space-charge limit ($\mu_t = 0.9$) (Fig. 15).

The problem with earlier drift-tube linacs (DTLs) was that the injected longitudinal emittance was typically four to five times larger than the injected transverse emittance because of the way the particles came to be bunched around the synchronous phase. Ion beams are generated from sources with extraction voltages typically less than 50 kV; thus the ions are traveling very slowly, around $\beta = 0.001$, and are very nonrelativistic and susceptible to emittance growth phenomena. Large initial acceleration forces, although convenient in terms of length, are disruptive. It was long thought desirable to accelerate ion beams adiabatically, but this required excessive length. The compromise was to use a crude buncher system consisting of one or two rf cavities, separated by the proper drift lengths between the buncher cavities and the linac input to cluster as much of the initially dc beam as possible near the synchronous phase at the first linac cell. The bunching process itself leads to the too-large longitudinal emittance and also to transverse emittance growth. The RFQ accelerator mentioned is now the preferred method in most applications for converting the initially dc particle distribution into an appropriately bunched beam for further accelertion in a DTL. A fundamental advantage of the RFQ is that it focuses at all energies. When perturbations are added to produce longitudinal fields, short cell lengths with precisely controllable properties

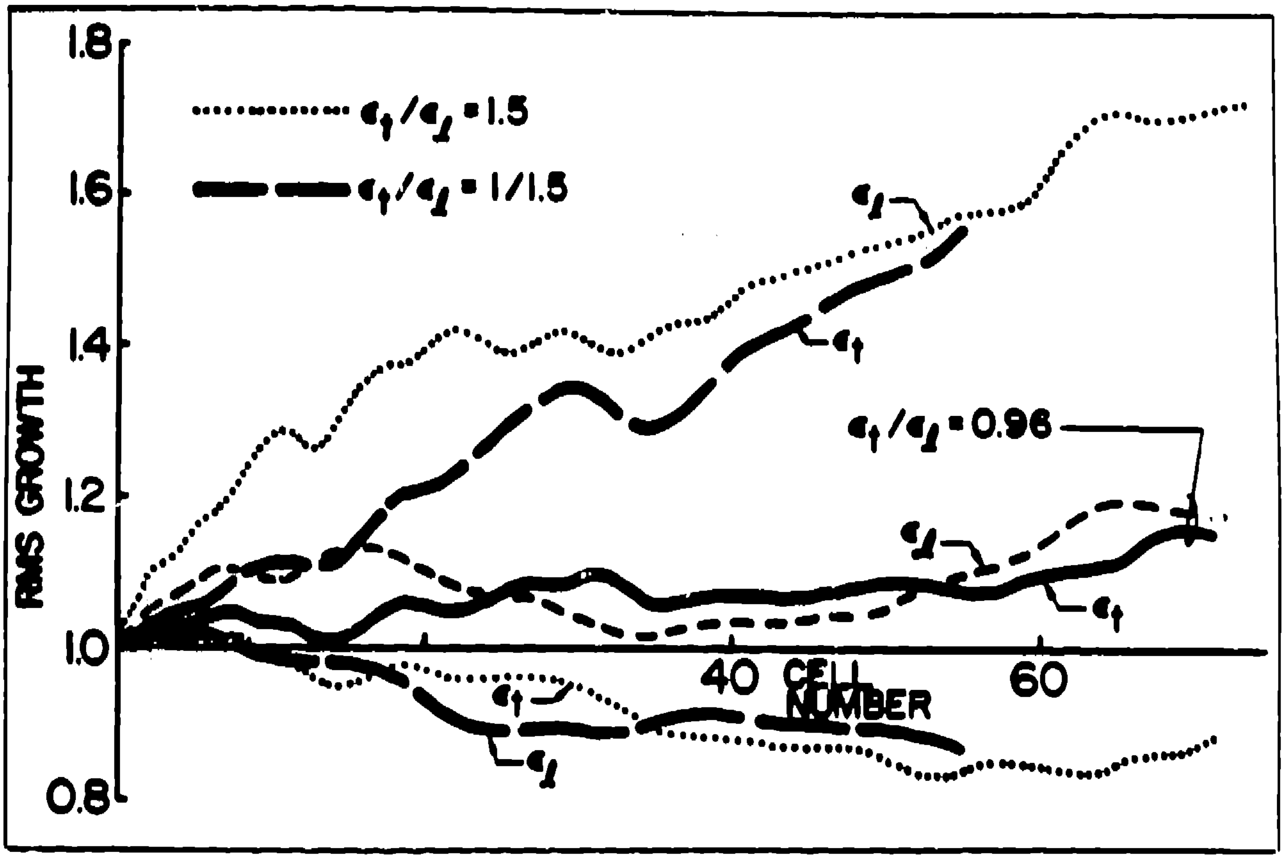


Fig. 15.
Rms emittance growth in 72-cell, constant μ_t = *0.9, constant* E_0 *linac. Initial* $\mu' \sim 0.8$. ϵ_t *and* ϵ_l *are transverse and longitudinal rms emittances; ratios are initial conditions at injection into linac.*

result, allowing many cells in a reasonable length and the capability to longitudinally bunch and accelerate the beam gently, keeping the emittance from growing very much. The RFQ can thus be used to capture the beam at the typical ion-source extraction voltage and deliver the beam to a drift-tube-type accelerator at about 2 MeV. Before the RFQ was invented, ion sources had to inject directly into drift-tube linacs in which the required magnetic focusing strength varies inversely with particle energy. Restrictions of space inside the drift tubes and on magnetic strength make it difficult to build drift tubes below about 700 keV; therefore, the ion-source beam was accelerated in a dc Cockcroft-Walton up to that energy. The RFQ system is dramatically smaller and much better in terms of beam dynamics properties.

It turns out, however, that we still cannot prepare beams as we would like at various points in the system without some unwanted side effect, for example, an overly long RFQ. Thus, we have had to continue looking for a more complete understanding of the detailed physical processes that lead to emittance growth. At this point in our discussion, we have noted that emittance growth can occur from the following.

- Nonlinear external forces: these forces particularly affect the longitudinal phase-space, but include important longitudinal/transverse coupling effects, and may be a dominant factor in processes that cause growth of the total emittance through the formation of halos at the beam edge.

- Mismatching: certainly the rms beam properties must be matched to the channel properties. At a deeper level, minimum emittance growth would require *all* beam properties, including those of the density distribution, to be perfectly balanced against the channel properties and to repeat each period—we do not understand how to do this yet.

- Missteering: the beam must start and stay on-axis and the longitudinal centroid must be at the synchronous energy and phase.

- Energy unbalance, or nonequipartitioning.

The fact that using rms equations to set up the injected beam and initial linac parameters resulted in low emittance growth held some important clues: the main ones being that

- these equations cover a large fraction of the problem if the conditions could be met in practice, and

- the equations involve only linear forces.

Linear space-charge forces result from uniform particle distributions in the beam. In the space-charge limit, the beam behaves like a plasma and arranges itself to shield the external field from the interior of the beam; inside the shielding layer, which is of an equivalent Debye-length thickness, the particle distribution is uniform. It was also often observed in computer simulations that, at high currents, the beam tended to homogenize. So it made sense to look at the difference between typical beam density distributions and uniform beams to look further at processes causing emittance growth. A differential equation was discovered (Wangler and Guy, 1986; Guy and Wangler, 1986; Wangler et al., 1986; and Wangler, this Advanced Study Institute report) that relates the rate of change of rms emittance and the rate of change of nonlinear field energy. The nonlinear

$$\frac{d\varepsilon^2}{dz} = -\,(\text{Constant})\,\frac{dU}{dz}$$

field energy corresponds to a residual field energy, available for emittance growth, of beams with a nonuniform charge density distribution, depending only on the shape of the distribution. The quantity U is the difference between the self-electric-field energies of the actual beam and the equivalent uniform beam with the same rms properties as the actual beam. Using the property that a matched beam near the space-charge limit stays the same size (laminar flow) and assuming the tendency to uniformity of the final charge density, the equation can be integrated and predictions made of the final emittance. Two effects are described: in the first, an adjustment of the beam's charge distribution occurs to match the external focusing forces. The redistribution occurs very quickly, within about one-fourth a plasma period, and results in transfer of the nonlinear field energy to particle kinetic energy and an approximately uniform beam distribution with a tail of about the Debye length at the edge of the beam. On a slower timescale, any unbalance in the kinetic energy from one coordinate direction to another also equilibrates, resulting in partial or complete kinetic energy equipartitioning. The degree of final equipartitioning is somewhat difficult to predict at this stage of the theory development; simulations show three distinct regions of behavior for a given initial distribution, departure from equipartitioning, and number of plasma periods.

1) Above a threshold in σ/σ_0, the (emittance-dominated) beam is stable and no kinetic energy transfer occurs for a uniform beam. For nonuniform beams above this threshold, only charge redistribution occurs.

2) At high current, with σ/σ_0 far below the threshold, the kinetic energy becomes completely equipartitioned for all initial charge distributions after a few plasma periods.

3) Between these regions is a transition region where the beam moves more slowly toward equipartitioning. An empirical equation for the equipartitioning rate has been derived, but more theoretical work is needed.

Dr. Wangler's lecture at this ASI (Wangler, this ASI report) will develop these topics in detail. Another cause of emittance growth is coherent modes that can be excited. Thresholds for these modes have been derived (Hofmann, 1981) and checked for periodic transport systems; the thresholds appear to be approximately correct for a variety of charge distributions and also for accelerator systems where the rms envelope approximations are valid (Jameson, 1982). In the recent simulation work (Guy and Wangler, 1986) described above, rather complicated behavior is seen near initial tune depressions corresponding to the coherent mode thresholds. In some cases, the beam seems to be attracted to integer or half-integer ratios of x and y tunes, which may result in partial kinetic energy change, in more transfer to the lower initial energy plane (overpartitioning), or even in kinetic-energy transfer from the lower energy plane to the higher. These effects require further study.

The equations can be used to estimate the minimum final emittance, corresponding to the initial conditions of the extreme space-charge limit where the initial emittances are zero. These estimates predict that the minimum final emittances depend on the initial nonlinear field energy but not on the degree of departure from initial equipartitioning. For bunched beams, the final emittances are predicted to scale as the beam current to the two-thirds power.

Simulation studies (Guy and Wangler, 1986) also suggest that uniform charge-density distributions are best for controlling the total beam emittance of the surrounding halo beam. We do not yet understand the mechanisms involved, but observe that the charge redistribution process, creating a shielded inner core and Debye-thickness shield, produces a halo that can extend to many standard deviations beyond the rms core. We have simulated nonstationary laminar beams (at the extreme space-charge limit) for which the initial total field is nonlinear, and have observed that particles initially at large radii in an initially Gaussian profile do not remain laminar but move into a halo.

Summarizing, the effort to understand single-channel current limits and emittance behavior has recently been successful in separating and elucidating several effects that can cause emittance growth. This work explains why a uniform beam distribution, kinetic energy balancing, and careful matching are desired and indicates that we must know how to avoid coherent instabilities. (The latter is easier in a linac where the parameters change as energy increases.)

We thus are returned, with greater confidence, directly to the challenge—how to produce such beams at the source and maintain them through the accelerator.

Equivalent problems govern the peak current and brightness that can be achieved in electron linacs. Electrons are very light and become essentially relativistic at around 1 MeV. Because electron sources typically start at lower voltages, it is still necessary to use great care, at the beginning of acceleration, in shaping the accelerating and focusing fields. However it is impractical to use many cells; thus, the strategy at this time is to accelerate very fast to the relativistic regime. Producing a cleanly bunched beam without longitudinal tails is important, and instead of an RFQ, which would be too long, photocathode sources such as the one shown in Fig. 16 are being developed. The cathode is driven by a laser synchronized to the rf waveform; electrons are emitted only during the desired time and are extracted directly by the rf wave in the cavity gap. The fields in the first few gaps are optimized to produce very rapid acceleration, typically 1 MeV per gap, but with as little brightness degradation as possible. Tailored solenoidal magnetic fields provide transverse focusing.

At higher energies, beam breakup effects (Gluckstern, 1986; Gluckstern, 1985; and Wilson, 1986) limit the available brightness in the electron* linac or electron transport lines, for example, in an FEL. The intense bunch shock excites fields at discontinuities in the channel as it travels along, generating transverse and longitudinal EM "wake fields." These can affect the particle distribution within the bunch; for example, the fields excited by the head of the bunch can contain components that steer the tail of the bunch away from the axis or cause the tail to

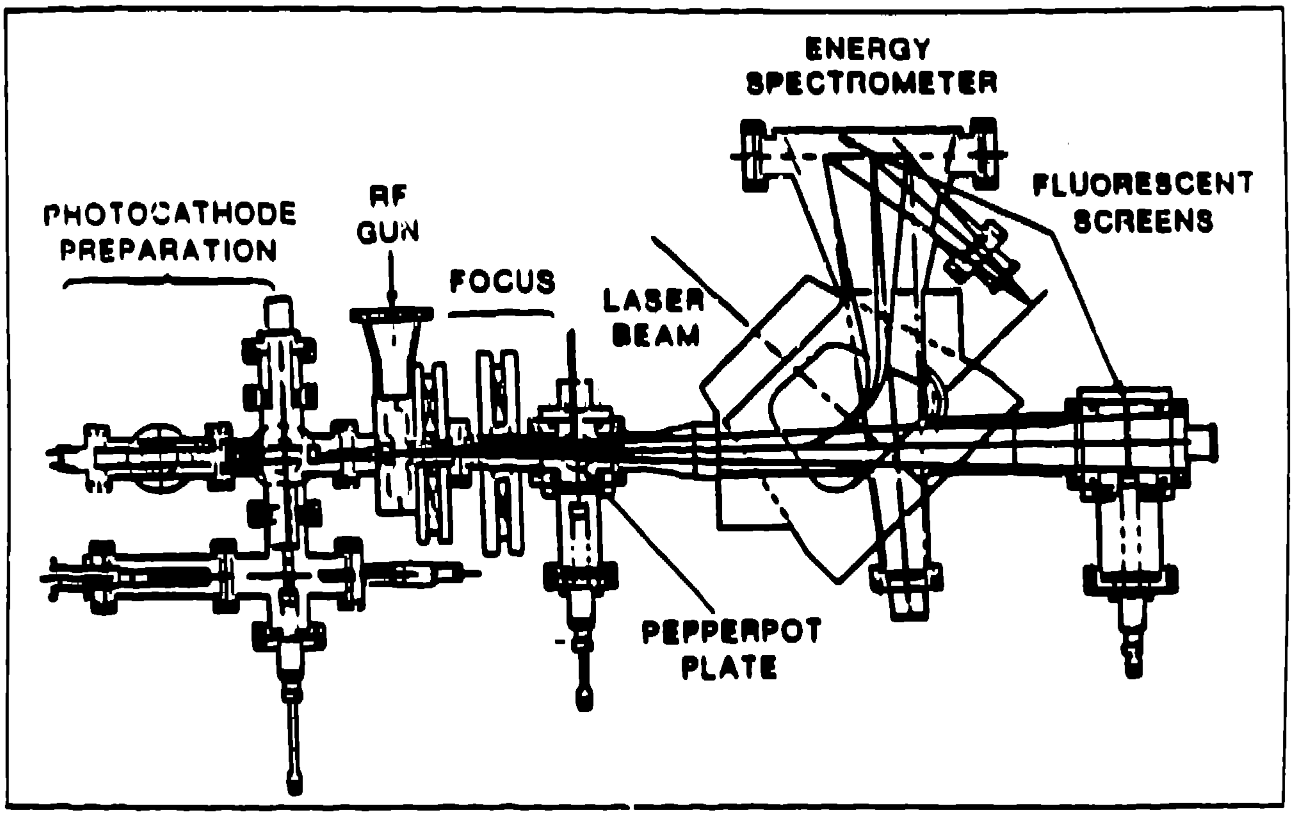


Fig. 16.
Laser-driven photocathode and rf-cavity injector-development experiment at Los Alamos.

*In ion systems, other limits, for example on focusing strengths, come into play before BBU effects become important. At ultrarelativistic energies and high intensities, BBU phenomena would also be important for ion beams.

gain or lose energy relative to the head. At the cavity gaps, the wake fields can build up resonantly and affect subsequent bunches, and the effects can be aggravated if the bunches are arriving at intervals corresponding to structure resonances. In recirculating devices such as the microtron, the resonances associated with the circulation time add another, severe, constraint to the achievable current. The avoidance of beam breakup depends on a detailed knowledge of the modes that can be excited in the system and on development of techniques to suppress their excitation. These techniques include smooth walls wherever possible, perturbations to break the symmetry of unwanted nodes, special consideration to allow bad modes to quickly dissipate their energy through Q-spoiling or propagation to external loads, and other techniques. The design is complicated by the 3-D nature of the problem and the difficulty of analysis. There have been considerable advances in the past few years in the understanding and theoretical treatment of the problem, and the advent of 3-D cavity codes (Weiland, 1986) will make detailed design more tractable.

HIGH-BRIGHTNESS ECONOMICS

Having discussed the need for and characteristics of high-brightness beams, and having posed the challenge of needing uniform charge distributions in ion-beam systems, the rest of this discussion will focus on another fundamental challenge facing accelerator designers—the economic feasibility of higher brightness machines. As indicated earlier, the cost for construction and operation of higher energy machines for HEP has become so large that the SSC may be the last of its type. In this case, the economic constraint is stronger than the technical constraint because the technical approach of the SSC would allow higher energy. The electron-positron collider machines like SLC also have heavy power demands, spurring efforts to get higher brightness by striving for very small emittances. Reducing emittance is necessary, but at some point the cost for further reduction will rise and require a balance to be struck with other system costs. The need for more efficient machines has become a major consideration.

Efficiency could have several aspects. The most common requirement is to achieve more beam energy, or current, or brightness, or power, per dollar cost. However, in some applications, more beam power per unit weight or unit volume might be more important than the cost. In all cases, higher conversion efficiencies from the prime power source to beam power are needed. It may be difficult to make a good estimate of the ultimate system efficiency of a new scheme until after prototypes have been tested, but the need for efficiency should always be kept in mind. As an example, a discussion of the rf linac is useful.

Tigner shows in Fig. 17 (Tigner, 1982) an evolution of a conventional linac circuit that guides us from today's separate linac structure and microwave tubes to a coupled source and accelerator structure and, finally, to a fully integrated system in which the transformer action between a low-voltage/high-current driving beam is integrally coupled to a high-voltage/low-current accelerated beam.The idea is to force consideration of the overall system efficiency, beam power divided by prime power, as the product of power conversions through the system.In Fig. 17.a., typical present-day efficiencies would be about

$\gtrsim$ 97%, energy-reservoir to rf-source dc input;
50-70%, rf source, dc to rf;
~90%, coupling-network, rf source to accelerator structure;
60-80%, accelerator-structure losses;
1-10%, structure to beam;
0.1-10% overall system efficiency.

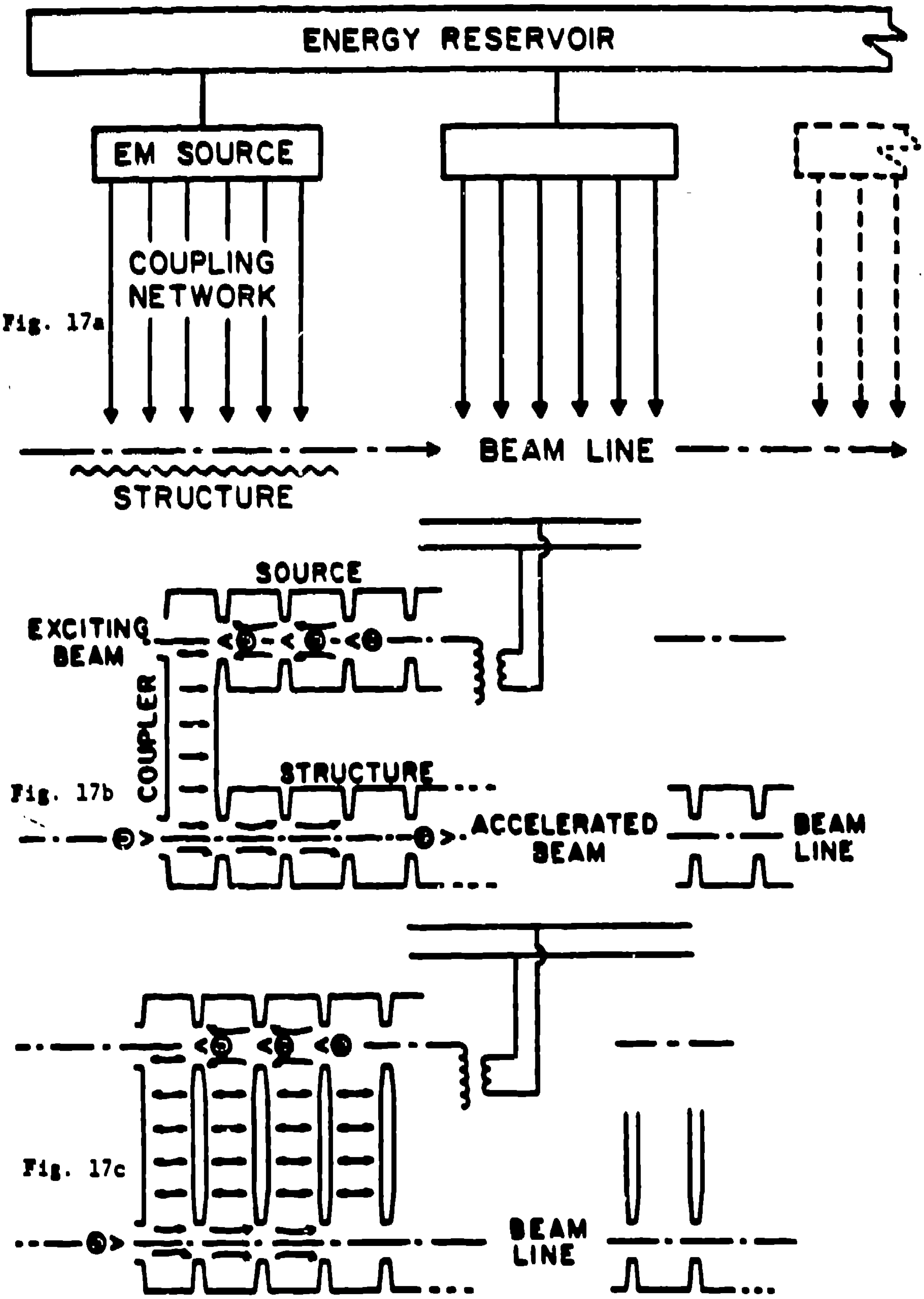


Fig. 17.
An evolution of a conventional linac circuit to a two-beam system.

Accelerator structure losses result from field multiplication in the structure; more multiplication causes more dissipation and lower efficiency; the converse requires high peak input power and gives higher group velocity. Structures today with group velocities around 0.01 c achieve about 60% efficiency; new structures might use group velocities of 0.1-0.2 c and have around 80% efficiency, but would take several times more peak power to achieve the same accelerating gradient (for example, several gigawatts for 100 MeV/m).

The structure-to-beam efficiency is the ratio of energy gained to energy stored, per unit length of structure. This efficiency is limited from ~1 to 10% by beam breakup and phase-space dilution effects.

Multiplying yields overall efficiencies from less than a percent to 6-10%, with the larger numbers requiring development. Further inefficiencies usually result from the beam to the desired output, for example, in a HEP event rate, or a loss in stripping to a different charge state. The progression from Fig. 17.a. to 17.c. is to suggest that a more tightly coupled system might raise or eliminate some of the serial efficiencies. Practical schemes with significantly better efficiency are as yet elusive. It is useful to consider some of the basic tradeoffs in the conventional system to establish a frame of reference.

First, however, a basic note of caution on what are sometimes called tradeoff studies, or scaling studies, or system studies. A practical aid to keeping a fresh outlook is to emphasize that the solution to a given, specific problem does not need to be a generic solution; in fact, the solution sought will be determined as much by the *constraints* imposed as by the basic principles. A classic example occurred some years ago in the HIF studies: in trying to determine how much power could be transported through a focusing channel, one analysis showed beam emittance entering in the numerator and another in the denominator! A scholarly and well-written explanation and resolution was written by M. Reiser (Reiser, 1978), who clearly showed how the choice of constraints and fixed or variable parameters could so drastically shape the result. The danger, of course, is that an improper statement of the problem prevents the needed insight. Reiser's article should be regarded as part of the "Art of War" (Tzu, 1971) of the accelerator designer. Another example was the revelation (Jameson, 1981) that high-intensity rf linac beams, which also required small emittance, should use higher rf frequency rather than moving to lower frequencies as was commonly supposed.

RF Power and Accelerator Structure Tradeoffs

We can use a simple linac costing relationship to elaborate the relative influence of the rf power and accelerator-structure subsystem efficiencies mentioned above and development directions that should be taken.

Basic linac costs are given by

$$\text{Cost} = R(P_{cu} + P_b) + SL + AC(\hat{P}_{cu} + \hat{P}_b) \,,$$

where R = cost/peak rf watt;
P_{cu} = accelerator-structure peak power that is due to losses;
P_b = beam peak power;
S = structure cost/unit length;
L = accelerator length;
AC = ac unit power cost; and
$\hat{P}_{cu}$ and $\hat{P}_b$ are structure and beam average power, equal to peak power times duty factor.

The first two terms represent capital investment; the last term adds in the operating cost over the expected life.

$$P_{cu} \propto (E_0L)^2/ZL \propto (\Delta W)^2/ZL \ ,$$

where E_0 is accelerating gradient/unit length;
Z is effective structure shunt impedance/unit length (includes transit time and synchronous phase-angle factors);
ΔW is the desired, fixed, particle-energy gain of the linac; and
$P_b = (\Delta W)$(beam current).

Substitution shows the structure power cost varies inversely with length, whereas the structure cost varies directly with length. Therefore, there is a strong tradeoff between accelerating gradient and length, and choice of the maximum achievable accelerating gradient is not *a priori* desirable. Ignoring the operating cost, differentiation with respect to length yields the optimum length, and thus gradient, for lowest cost:

E_0 opt $= (SZ/R)^{1/2}$, independent of ΔW;

$L_{opt} = \Delta W(R/SZ)^{1/2}$;

$C_{opt} = \Delta W[2(SR/Z)^{1/2} + RI]$, linear in ΔW.

At the optimum, $RP_{cu} = SL$. Folding in operating cost will push the optimum E_0 down and optimum L up.

We need to examine the cost equation further to see more of the influencing factors. It is reasonable to expect that we would want to exploit the accelerator structure to some physical limit, even though the cost relation warns us to be careful. The applicable physical limit will depend on the application and could be, for example, removal of average waste power, voltage breakdown, surface damage that is due to high peak power, magnetic field limitations, space-charge limit on current, and so on. Typical proton rf linacs today might be designed at around 440 MHz for the RFQ/DTL, and around 1320 MHz (X3) for the high-beta stage. In this frequency range, a limiting factor comes from the electric-field sparking limit as defined by the Kilpatrick Limit (KL), a frequency scaling for allowable peak surface field based on an ion-multipactoring model and empirical determination of constants known as the Kilpatrick Criterion (Kilpatrick, 1957):

$$f = 1.643\, E^2 \exp -(8.5/E) \ .$$

The field E_{KP} thus found is multiplied by a "bravery factor" to determine the actual allowed peak surface field by accounting for the influence of modern techniques in raising the sparking limit; E_{KP} is 20 MV/m at 440 MHz and 32 MV/m at 1320 MHz.

The experience factor $K = E/E_{KP}$, by which E_{KP} may be multiplied for modern structures, appears to be as high as 2.5 to 3.0 for RFQs, and up to 2.0 for DTL and SSC structures. Thus, for our 1320-MHz coupled-cavity linac (CCL), we can consider peak surface fields of up to about 64 MV/m.

All the peak surface field, however, cannot be used for acceleration—geometry factors in practical structures reduce the effective gradient on-axis by some factor. This factor can be minimized but usually at some cost, say in shunt impedance Z or transit-time factor, which would directly offset the increased accelerating gradient E_0. For example, one structure with many desirable properties is called the disk-and-washer (DAW) type (Fig. 18). The addition of noses around the beam hole increases the transit-time factor, at some loss in shunt impedance, and increases the peak-surface-field to accelerating-field ratio (E/E_0) from 1.94 with no nose to 5.37 with full nose. The Vaguine structure has a somewhat better efficiency in using peak surface field as accelerating field, with the Chalk River structure intermediate.

The fabrication cost/unit length S of all these high-β structures is roughly the same, $50-100 K/m. The tradeoffs among shunt impedance (~50-100 MΩ/m), transit time (0.8-0.92), and other detailed factors are also not dramatic. Therefore, the gradient versus length-cost tradeoff must dominate the choice of optimum gradient. Figure 19 illustrates this result, showing the cost curves for a linac that was designed as an injector for the proposed SSC, and relating E, E_{KJ}, and E_0 for the four structures. The cost minima are all at about $20 M and require an accelerating gradient of ~20 MeV/m. The available E_0 (30-40 MeV/m) at K = 2 of the more efficient structures cannot be used economically, but the 20 MV/m E_0 giving the cost minimum is available below the sparking limit. The less efficient structures cannot reach the cost minimum without sparking, although this is not too serious because the cost minima are broad. Another look at the cost equation shows the optimum $E_0 \propto (SZ/R)^{1/2}$; thus, we could use a higher accelerating gradient if we could get the effective structure shunt impedance up or the unit rf power cost down.

A great deal of rf accelerating structure development has occurred at frequencies ≤3 GHz, and it is unlikely that major increases in shunt impedance can be achieved. Also, as with structure cost, the cost per peak rf watt at low duty factor is relatively independent of frequency in this frequency range, at about $0.01-0.015/watt. The cost of rf power is beginning to be looked at, and some details are given in a later lecture at this school. Both tube and solid-state approaches are pushing toward higher conversion efficiency at better weight and volume ratios.

Figure 19 indicates that a point design accelerating gradient of only 8 MeV/m was selected. We had already concluded for economic reasons that only half of the 40-MV/m available from the Vaguine structure could be used; why did we limit the design by more than another factor of 2? The answer is in the emittance growth arguments of the preceding discussion. In this particular study, we used a conventional DTL that incorporated no special provisions for preparing a beam that would stay equipartitioned across the DTL/CCL interface. We studied the emittance growth resulting from direct injection into the CCL as a function of the CCL accelerating gradient, with that gradient held constant along the CCL. Unacceptable growth occurred above 8 MeV/m. The cost impact of operating at this nonoptimum gradient would be significant. More recently, we have devised workable recipes for injecting at a low gradient with approximate equipartitioning, then raising the gradient to the cost optimum level at a controlled rate that causes little emittance growth, which can be done at either an RFQ/DTL or a DTL/CCL interface and can result in a cost and/or length advantage. (If length were more important than cost, appropriate weights could be assigned.)

Full optimization is seen to be a complicated nonlinear optimization problem with many constraints. More and more attention is being given these days to finding advanced methods of acceleration that would be more efficient and cost less, particularly in the field of HEP because

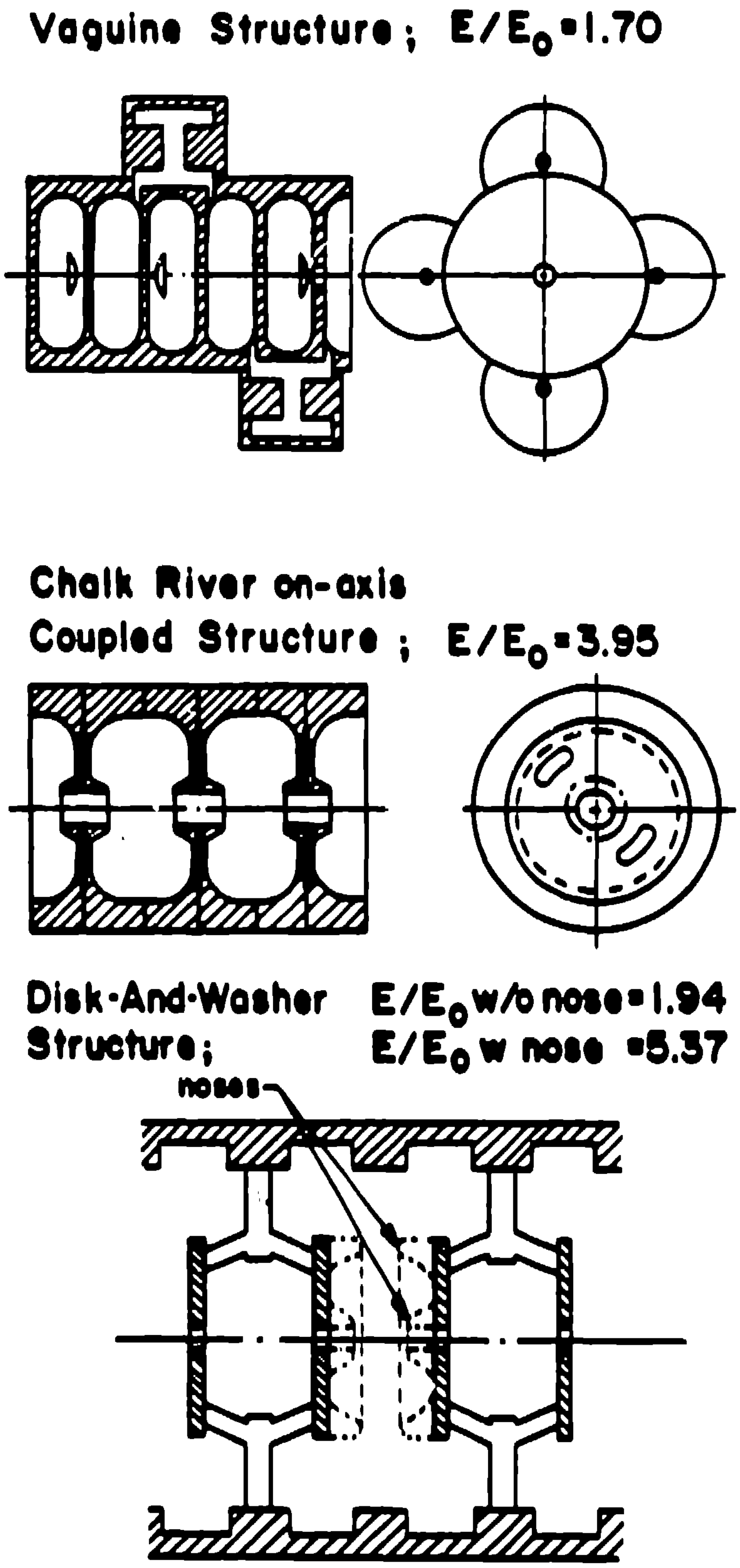


Fig. 18.

Cross sections of four CCL types: the DAW with and without nose, the Chalk River on-axis coupled structure (McKeown and Schriber, 1981) and the Vaguine structure (Vaguine, 1977). E/E_0 is the ratio of peak surface field to accelerating gradient.

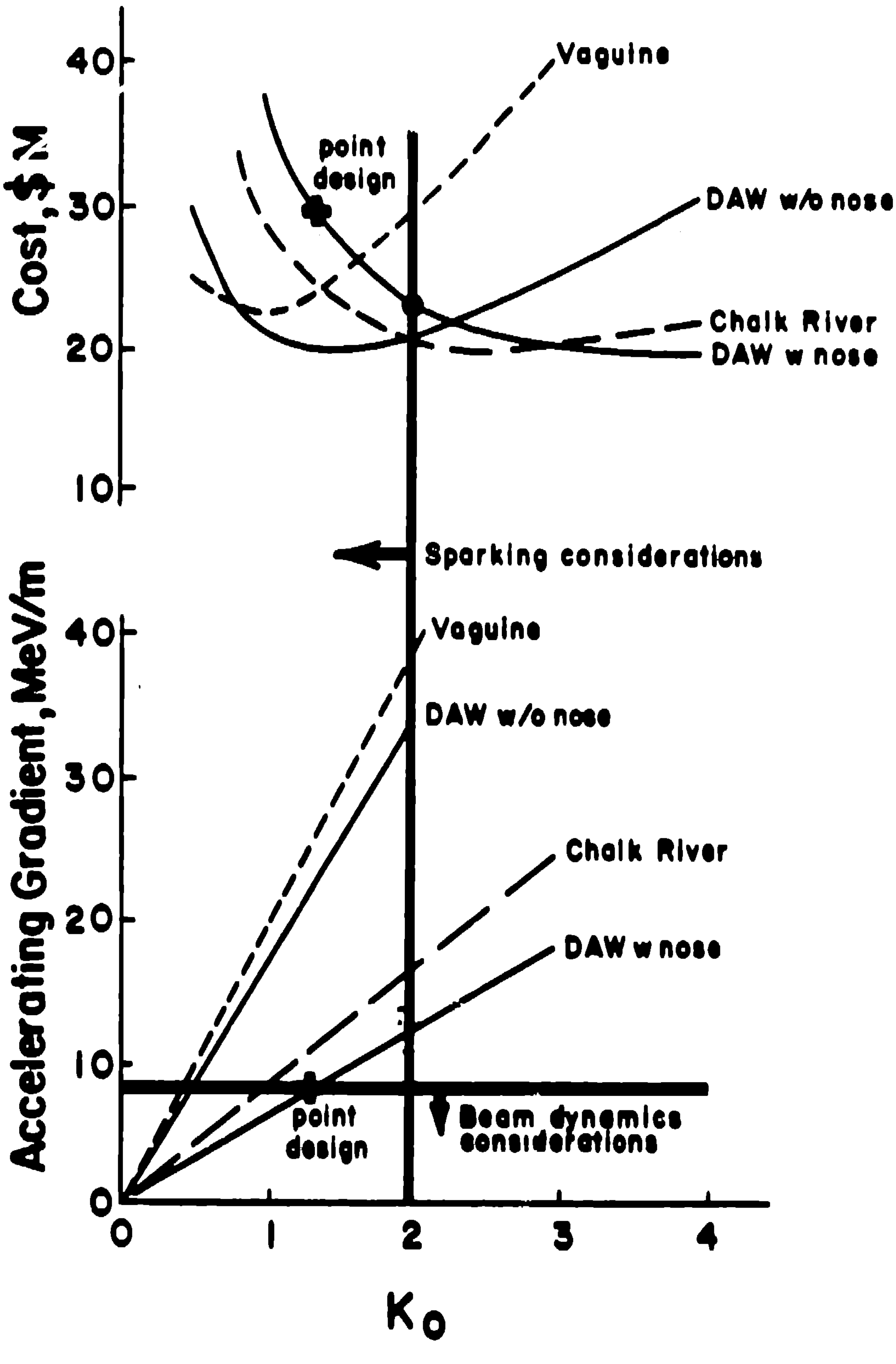


Fig. 19.

Cost estimate for the SSC 2.5-GeV injector linac as a function of K, the ratio of peak-surface-field E in the CCL accelerating structure to the Kilpatrick Limit E_{KP} = 32 MV/m at 1320 MHz, and the CCL accelerating gradient E_0 as a function of K. Curves for the four CCL geometries of Fig. 18 are plotted.

of the cost barrier to ever higher energy machines. Ideas involving laser drives have so far come up short because lasers are considerably less efficient than rf sources on an average power basis. At this point, it appears that scaling rf linac technology might be the best bet until some kind of collective-effect accelerator is mastered.

The most important physical limits on accelerating gradient in an rf linac as a function of wavelength are indicated on Fig. 20. A frequency around 30 GHz may be at about the point of diminishing returns, and there a gradient of a few hundred MeV/m may be possible, assuming that other constraints do not intervene.

The linac structure at these frequencies would be only a centimeter or so in diameter, and the rf power requirements at a few hundred MeV/m would be a few hundred MW/m; thus only very short pulse machines might be considered, but this might be all right for HEP requirements. An innovative research program (Sessler, 1986) is under way to see if a system will work that uses distributed induction-linac modules and single-pass FEL amplifiers to generate rf for the linac structures, prototypes of which have been fabricated. If the system operates successfully, and if one assumes that the linac structure cost is still in the range of \$50-100K/m, then the rf cost per peak watt would have to be reduced to around 5×10^{-4} \$/rf watt to make optimal use of a 200-MeV/m accelerating gradient. It appears that such costs are not out of the question.

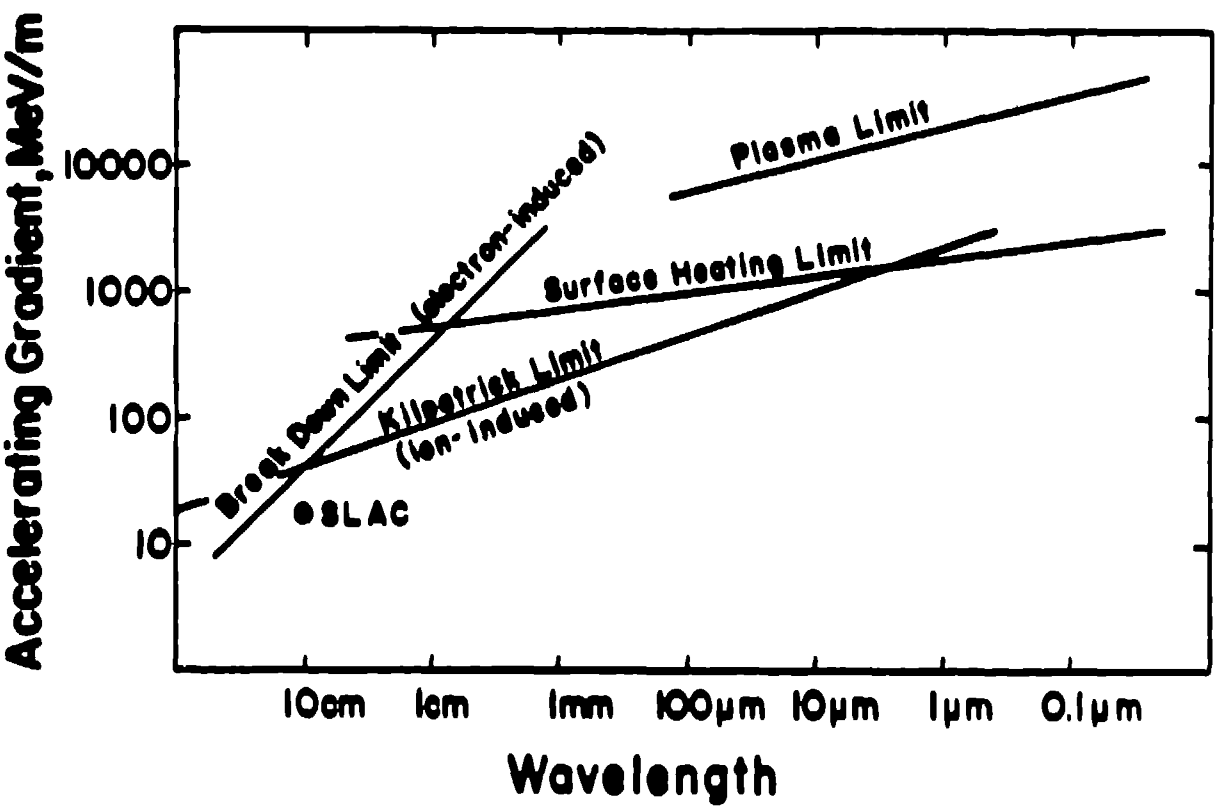


Fig. 20.
Approximate limits on accelerating gradient, for structures with assumed ratio of peak surface field to accelerating gradient equal to 2, vs wavelength. Kilpatrick-Limit line also assumes peak surface field of twice KL.

CONCLUSION AND ACKNOWLEDGMENTS

The field of particle accelerators, and linacs in particular, is rich in challenge and subtlety. This has been only an overview in simple terms, describing a few key issues on the basic requirements for bright beams and some of the economic impacts of brightness on accelerator design. It is hoped that the treatment might reveal something of the thrill of addressing an unresolved problem, the satisfaction of solving it, and the posing of future work that might be addressed by newcomers. It is my privilege to discuss here the knowledge accumulated by many colleagues; the many discussions are gratefully acknowledged.

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