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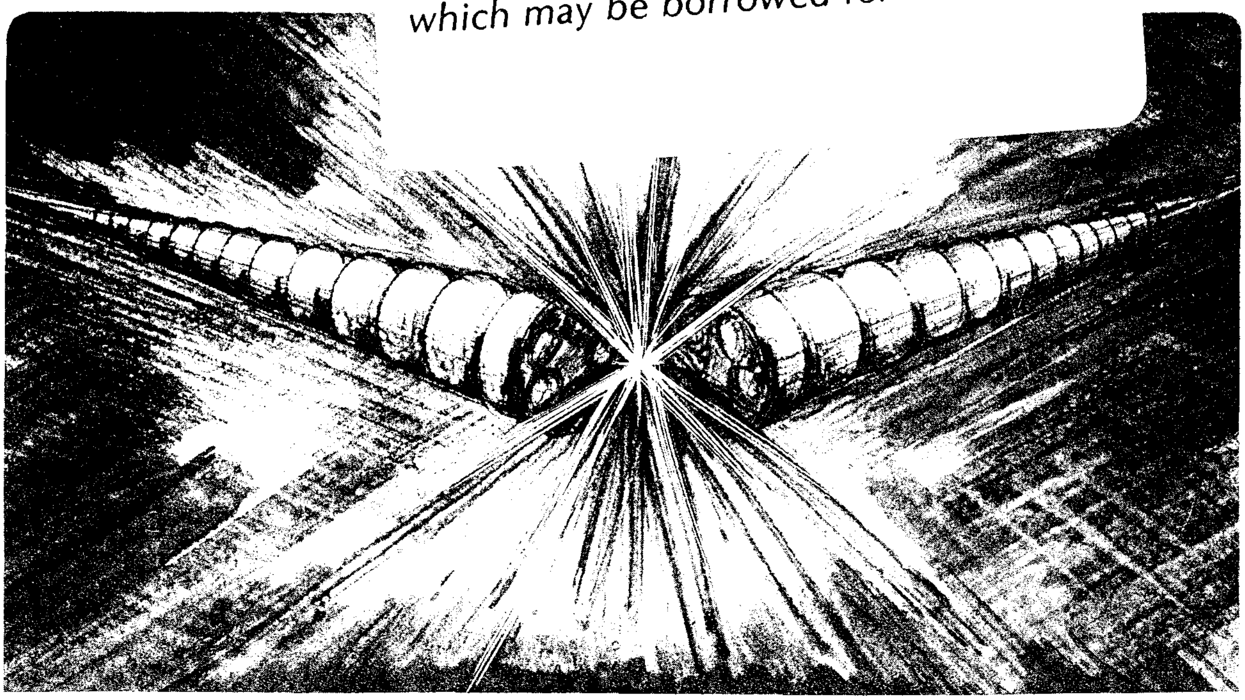

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THE TWO-BEAM ACCELERATOR*

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A Two-Beam Accelerator, in which one of the beams is an intense low energy beam made to undergo free electron lasing and the other beam is a compact bunch of high energy electrons, is shown to be an interesting possibility for a linear collider.

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A linear collider of the next generation will, presumably, have an energy considerably in excess of the 50 GeV x 50 GeV Stanford Linear Collider.[1] A high accelerating gradient is required in order to keep the length of the linear collider modest but since both the stored energy and the power needed to overcome resistive losses go as the square of the gradient, one finds that the power consumption of such a device is excessive. Thus (since the stored energy varies as the inverse square of the frequency) one is forced to consider higher frequencies than the 2.8 GHz of SLAC. Power sources in the 30 GHz range, suitable for a collider, do not yet exist, although a number of possibilities need to be explored (such as photo-cathode klystrons, multi-beam klystrons, and gyrotrons).[2] One additional possibility is a free electron laser.[3]

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Once a free electron laser is considered as a power source it is but a small step to configuring the linac as a two-beam device. One of the beams is an intense low energy beam which is made to undergo wiggles and hence becomes a source of microwave energy for a normal high-gradient slow-wave structure in which a second beam is accelerated to high energy. The low energy beam has its energy periodically replenished by induction accelerator units. Thus one is led to a configuration having two structures connected by rf pipes as was explored in Ref. 3. This Dual Structure is shown in Fig. 1a.

In fact, it is possible to do all of this in a Single Structure, as will be demonstrated below. We believe a Composite Structure is the preferred realization and, hence, this will be the primary subject of this communication. Figure 1 shows schematics of these three possible realizations of the Two-Beam Accelerator (TBA).

In order to have a Single Structure, which has the advantage of not needing the "connecting pipes" and hence being compact and also potentially less expensive, we need to satisfy a number of criteria:

1. It must operate in a large beam pipe (in order to accommodate the low energy beam) and hence must have an "overmoded" structure.

2. The structure must be a slow-wave structure in order to resonantly accelerate the high energy beam.

3. There must be a longitudinal field at the high energy beam.

4. There must be no deflecting transverse fields at the high energy beam.

5. There must be a transverse field at the low energy beam (for FEL action).

6. There must be no vertically deflecting field at the low energy beam.

7. The ratio of the longitudinal field at the high energy beam to the transverse field at the low energy beam must be of the order of unity (otherwise the device will not produce a high gradient and the whole concept is defeated).

We can achieve all of these criteria with a TM_{21} mode in a loaded waveguide. The high energy beam will have a resonant velocity $v = \omega/k_g$, while the low energy beam has a resonant velocity $v = \omega/(k_g + k_w)$, where $(2\pi/k_w)$ is the wiggler wavelength, $(2\pi/k_g)$ is the rf field wavelength in the waveguide, and ω is the frequency of the mode. In Fig. 2 we show the geometry of such an accelerator. The ratio of fields (criteria #7), in a guide of dimensions a x b, and having guide wavelength λ, is:

$$R \equiv \frac{|\mathscr{E}_z|_{max}}{|\mathscr{E}_x|_{max}} \approx \frac{\pi a}{2}\left(\frac{\lambda}{2\pi}\right)\left(\frac{4}{a^2} + \frac{1}{b^2}\right) ,$$

and when $b << a$: $$R \approx \left(\frac{\lambda}{4b}\right)\left(\frac{a}{b}\right). \qquad (1)$$

For typical dimensions a x b = 6 cm x 2 cm, and λ = 1 cm we find R = 3/8.

Some typical parameters for the Single Structure might be obtained as follows: We seek a final energy of 375 GeV, and believe that one can obtain a gradient of 250 MeV/m.[4] The low energy beam has an energy of 3 MeV, a pulse length of 67 ns, and a current of 500 A. (All of these parameters are well within current technological capabilities.) Going through a 10 cm wavelength wiggler this beam can be made to generate a field in the TM_{21} mode which has the requisite longitudinal field at the high energy beam and has a transverse field of 431 MV/m at the center of the waveguide. This field corresponds to an energy density of 1.1×10^6 J/m^3 or, if the field has a group velocity close to c, a power flow of 6.6×10^{11} W. It should also be noted that in the Single Structure the high energy beam will be subject to the wiggler magnetic field, and hence undergo synchrotron radiation. This effect, although not fatal to the concept, nevertheless must be considered.[5] Another concern is beam loading effects.[6]

The Composite Structure avoids the above concerns and, hence, is the subject of the remainder of this communication. In Fig. 3 we show the geometry of a Composite Structure. In this realization the fields are built up in the slow-wave structure by means of a directional coupler, which becomes central to the realization. We shall give, below, the concept upon which such a coupler is designed.

We want to point out that a low energy beam undergoing FEL action in a waveguide resonating in the TM_{21} mode will also interact with a longitudinal electric field component. A non-zero longitudinal field allows one to easily couple to an accelerating structure. Looked at from this point of view the "connecting pipes" in the Dual Structure served the extremely important purpose of "turning around" the transverse field of the FEL to a longitudinal accelerating field.

In designing the FEL portion of a TBA we need to consider the resonance condition

$$k_w - \left(\frac{\omega}{c} - k_g\right) - \frac{\omega}{2c\gamma^2}\,(1 + K^2/2) = 0 \quad , \tag{2}$$

where γ is the relativistic energy parameter, K is the wiggler parameter given by

$$K = \left(\frac{eB}{mc^2 k_w}\right) , \tag{3}$$

and B is the wiggler field strength. All other parameters are fundamental parameters ($e = |e|$). We can manipulate Eq. (3) into the form

$$\gamma^2 = \frac{k\ (1 + K^2/2)}{2\left[k_w - \frac{(2\pi)^2}{2k\lambda_c^2}\right]} \ , \tag{4}$$

where the free space wavelength is $(2\pi/k)$, and we have introduced the cutoff wavelength of the mode in question, λ_c, by means of

$$\left(\frac{2\pi}{\lambda_c}\right)^2 = \left(\frac{\omega}{c}\right)^2 - k_g^{\ 2} \ . \tag{5}$$

The choice of waveguide dimensions and shape for the FEL portion of the TBA is determined by the size of the low energy beam and the proximity of modes other than the desired mode. Size considerations need to be made, and suffice it to say that a guide of 2 cm x 6 cm is adequate. Mode-mode interaction, by means of the electron beam, is a very complicated subject and has been studied by one of us (JSW) at great length. Roughly, one can say that it is necessary, in order to reduce mode-mode effects to have the unwanted modes separated from the mode one desires by 10% in $\Delta\gamma/\gamma$. In rectangular waveguides there is degeneracy between the TM modes and the TE modes. This degeneracy is removed if the waveguide is deformed. An elliptical waveguide, with an aspect ratio of 1/3 appears to be adequate for our purposes.

We present data on waveguides, both rectangular and elliptical, in Table I. For a rectangular guide the cutoff wavelength is

$$\lambda_c = \frac{2}{\left[\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2\right]^{1/2}} \ , \tag{6}$$

where a and b are the full widths of the guide, and m and n are the mode numbers of the mode in question. For an elliptical guide of minor radii a x b, the TM_{21} mode cutoff, which must be evaluated by infinite series or numerically, is $\lambda_c = 0.9761$ a.[7] As can be seen from Table I, the elliptical guide separates the TM_{21} mode from all other modes except the TE_{11} mode. (Note that, following Larsen, we use the mode notation of rectangular geometry.[8]) We believe that this degeneracy is acceptable, for the TE_{11} mode is odd about the median plane and hence will hardly couple to the electron beam.

Analysis of an FEL operating in a waveguide and resonating with the TM_{21} mode can proceed by assuming an ideal wiggler field:

$$\underset{\sim}{B}_w = B_0 (\cos k_w z)\, \hat{y} \quad , \tag{7}$$

The electron velocity in this field is

$$v_x = c \frac{K}{\gamma} \sin k_w z \quad , \tag{8}$$

$$v_z = v_{z0} - \frac{c}{4} \left(\frac{K}{\gamma}\right)^2 \sin 2 k_w z \quad , \tag{9}$$

where v_{z0} is the initial electron velocity in the longitudinal (z) direction. The coupling between the electron and an electromagnetic wave is

$$\frac{d\gamma}{dt} = - \frac{e}{mc^2} \underset{\sim}{v} \cdot \underset{\sim}{\mathscr{E}} \quad , \tag{10}$$

assuming that the electromagnetic wave hardly affects the particle trajectory. The TM_{21} mode, in a rectangular pipe (which is an adequate approximation for this purpose), has electric fields

$$\mathscr{E}_x = \mathscr{E}_0 \left(\cos \frac{2\pi x}{a}\right) \left(\cos \frac{\pi y}{b}\right) \cos (k_g z - \omega t) \quad ,$$

$$\mathscr{E}_z = \mathscr{E}_0 R \left(\sin \frac{2\pi x}{a}\right) \left(\cos \frac{\pi y}{b}\right) \sin (k_g z - \omega t) \quad , \tag{11}$$

where ω is the frequency of the mode and R is the quantity defined in Eq. (1). Thus, ignoring quadratic terms and taking y = 0,

$$\frac{d\gamma}{dt} = -\left(\frac{e\mathscr{E}_0}{mc}\right)\left(\frac{K}{\gamma}\right)\left[\sin k_w z \cos(k_g z - \omega t) - \left(\frac{2\pi R}{k_w a}\right)\cos k_w z \sin(k_g z - \omega t)\right] . \tag{12}$$

Defining the resonant phase ψ,

$$\psi = (k_w + k_g)\, z - \omega t \quad , \tag{13}$$

and keeping only resonant terms,

$$\frac{d\gamma}{dt} = -\frac{1}{2}\left(\frac{K}{\gamma}\right)\left(\frac{e\mathscr{E}_0}{mc}\right)\left(1 - \frac{2\pi R}{k_w a}\right)\sin\psi \ . \tag{14}$$

From this expression one can see that FEL action in the TM_{21} mode is modified significantly from that in free space. The factor of correction due to the z component of the electric field, is approximately 50%.

The coupling between the FEL, in its elliptical guide, and the high-gradient structure is designed using the theory of directional couplers. One can start from the analysis for a traveling wave resonant ring, "break" the ring and stretch it out so as to have a linear structure. Thus the couplers must be spaced by a distance ℓ, where ℓ is chosen so that there is resonance between the wave in the FEL and the phase velocity of a wave in the high-gradient structure. The latter is designed to be c, while the former, since the FEL is overmoded, is somewhat larger than c. For the TM_{21} mode, and with the dimensions we have adopted, ℓ = 16.4 cm (or an integral multiple of this).

The coupler is constructed with small holes, spaced by a quarter wavelength, i.e., 0.25 cm. One can have a number of such holes before the two waves are significantly out of phase, reducing the coupling per hole. Permitting a maximum phase deviation of $\pm$ 25° leads to a design having 9 holes.

Energy in the high-gradient structure will be dissipated by resistive loss at a rate $\alpha = 2\omega/Q$ which for $Q = 4000$ is $10^8 \mathrm{sec}^{-1}$. Energy will be fed into this structure through the couplers. We may write

$$W = C \int_{-\mathscr{L}/c}^{0} P e^{-\alpha(t - t')} dt' \quad , \tag{15}$$

where W is the energy in the high-gradient structure, just as the low-energy beam, of length $\mathscr{L}$, passes by and P is the power in the FEL. In writing this formula we assume that the group velocity in the high-gradient structure is sufficiently large to spread the energy W over the distance, ℓ, between couplers. The coefficient, C, is the power coupling coefficient per (9 hole) coupler. The energy W can be expressed in terms of the electric field, $\mathscr{E}$, in the high-gradient structure. We can perform the integral in Eq. (15), assuming that the power P is independent of time, which is approximately true, and obtain

$$P = \frac{\mathscr{E}^2 \ell}{C\, r \left[1 - e^{-\alpha \mathscr{L}/c}\right]} \quad , \tag{16}$$

where we have introduced the shunt impedance r.

The FEL must have an amplification rate such that the power gain per meter ΔP(w/m) is

$$\Delta P = \frac{C}{\ell} P = \frac{\mathscr{E}^2}{r \left[1 - e^{-\alpha \mathscr{L}/c}\right]} \quad . \tag{17}$$

Taking $\ell = 16.4$ cm, $r = 130 \frac{M\Omega}{m}$, $\alpha = 10^8 \mathrm{sec}^{-1}$, $C = .15$, $\mathscr{E} = 250$ MV/m we have $P = 550$ Mw, $\Delta P = 550$ M w/m. Note that the maximum coupled power is only about 90 MW per 9-hole coupler. The length of the low-energy beam, $\mathscr{L}$, is taken to be 6 m. The design of a Composite Structure TBA now follows that done by Prosnitz.[9] Design parameters are presented in Table II. Note that it appears possible to obtain a 300 GeV x 300 GeV collider in 2 x 1.5 km and with a repetition rate of 1 kHz the luminosity of the collider is greater than $10^{32}\text{cm}^{-2}\text{sec}^{-1}$.

The very concept of the TBA rests, of course, upon the FEL. The operation of the FEL must be routine. Since FELs are still at the development stage it may seem visionary to even contemplate a TBA. The recent developments of FELs make realization of a TBA more immediate than one would, at first thought, appreciate. In particular, the Lawrence Berkeley Laboratory/Lawrence Livermore Laboratory Group has made significant progress towards developing a single-pass linear FEL in the 34.6 GHz range and their first results are, indeed, encouraging.[10] And, also very relevant, is the experiment performed by the Naval Research Laboratory Group with a helical FEL operating in the 35 GHz range and giving 17 MW with a total gain of 50 dB in 72 cm of FEL and a conversion efficiency of more than 3%.[11]

Note that for the TBA we need a FEL power level of 550 Mw and a gain of 10 dB/m. The gain already achieved by the NRL Group is more than adequate, while the power level can be achieved, by scaling their results at constant conversion efficiency, to a current of 1 kA at 6 MeV. Theoretical computations on FELs and on-going experiments indicate that conversion efficiencies of 25% are achievable.[12]

There are many aspects of the Composite Structure TBA which still need to be analyzed. Of a fundamental nature is the operation of a "steady state" FEL. To this end, experimental realization will surely be necessary. Also, one must study transverse focusing of both the low energy beam and the high energy beam. Although we believe this to present no difficulties, we have not yet designed a structure with the necessary focusing. The important subject of breakdown, i.e., what field gradient can actually be achieved in practice, must also be studied experimentally. Finally, there are questions of instabilities involving either one or both beams and other (unwanted) modes of the waveguide. (These could, for example, involve transverse motion.)

All in all, however, the TBA seems to offer the possibility of realizing, with due regard to economics, a high energy and high luminosity linear collider.

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Table I

Mode Designation	Rectangular Guide $\lambda_c/(a/2)$	$\frac{\delta\lambda_c}{\lambda_c}$	$\frac{\Delta\gamma}{\gamma}$	Elliptical Guide λ_c/a	$\frac{\delta\lambda_c}{\lambda_c}$	$\frac{\Delta\gamma}{\gamma}$
TM_{21}	1.1	–	–	.98	–	–
TE_{21}	1.1	–	–	(.86)	(.2)	(> .1)
TM_{22}	.63	–.43	–	(.7)	(.3)	(> .1)
TE_{20}	2.0	.80	.27	1.8	.86	.44
TM_{12}	.66	–.40	–	.63	–.35	–
TE_{12}	.66	–.40	–	(.8)	(.2)	(> .1)
TM_{11}	1.3	.14	.10	1.2	.22	.23
TE_{11}	1.3	.14	.10	1.0	.03	.05
TE_{02}	.67	–.40	–	.63	–.35	–
TE_{01}	1.3	.20	.13	1.2	.25	.25
TE_{10}	4.0	2.6	.34	3.3	3.7	.54

Table I Cutoff wavelengths, the fractional change in cutoff wavelengths compared to the TM_{21} mode, and the fractional change in resonant energy (Eq. 4) ($\Delta\gamma = \gamma_{mn} - \gamma_{21}$) for various modes, in a rectangular waveguide and in an elliptical guide of aspect ratio 1/3. (Data taken from Ref. 7)

Table II

Accelerator	
Average Gradient	250 MV/m
Frequency	30 GHz
Length	1500 m
Pulse Repetition Rate	1 kHz
Input rf Power/Unit Length, avg.	550 MW/m
Peak rf Power	91 MW
Stored Energy/Unit Length	10 J/m
Luminosity	$10^{32} cm^{-2} sec^{-1}$
Low Energy Beam	
Initial Beam Energy	3 MeV
Peak Current	500 A
Bunch Length	6 m
Beam Power	1.5 GW
Beam Energy	30 J
High Energy Beam	
Final Beam Energy	300 GeV
Peak Current	4.8×10^3A
Bunch Length	1 mm
No. Electrons/Bunch	10^{11}
$\Delta E/E$	0.10
Bunch Radius	1.0 μm

Table II Parameters for a Two-Beam Accelerator employed in a collider.

FIGURE CAPTIONS

Fig. 1 Three realizations of the Two-Beam Accelerator (TBA), Besides the obvious difference in geometry, in the Dual Structure the Free Electron Laser (FEL) operates in the usual manner with a purely transverse field (TE_{01}) while in the other two realization there is also a longitudinal field in the FEL (TM_{21}). An induction unit replenishes the energy of the low-energy beam, thus the low-energy beam becomes essentially a power transformer.

Fig. 2 A TBA Single Structure showing the details of a TM_{21} mode and how one could configure the geometry. In Fig. (2a) is shown the TM_{21} mode in an unloaded (smooth) guide. Fig. (2b) shows the loading fins and position of the low-energy and high-energy beams. Fig. 2(c) shows how the wiggler and induction units are deployed.

Fig. 3 A TBA Composite Structure showing, in Fig. (3a) a transverse section and in Fig. (3b) a longitudinal section. Note, in the longitudinal section, the directional coupler which takes energy from the FEL and transmits it to the high-gradient column. The diagram shows two FELs so as to feed the high-gradient column symmetrically.

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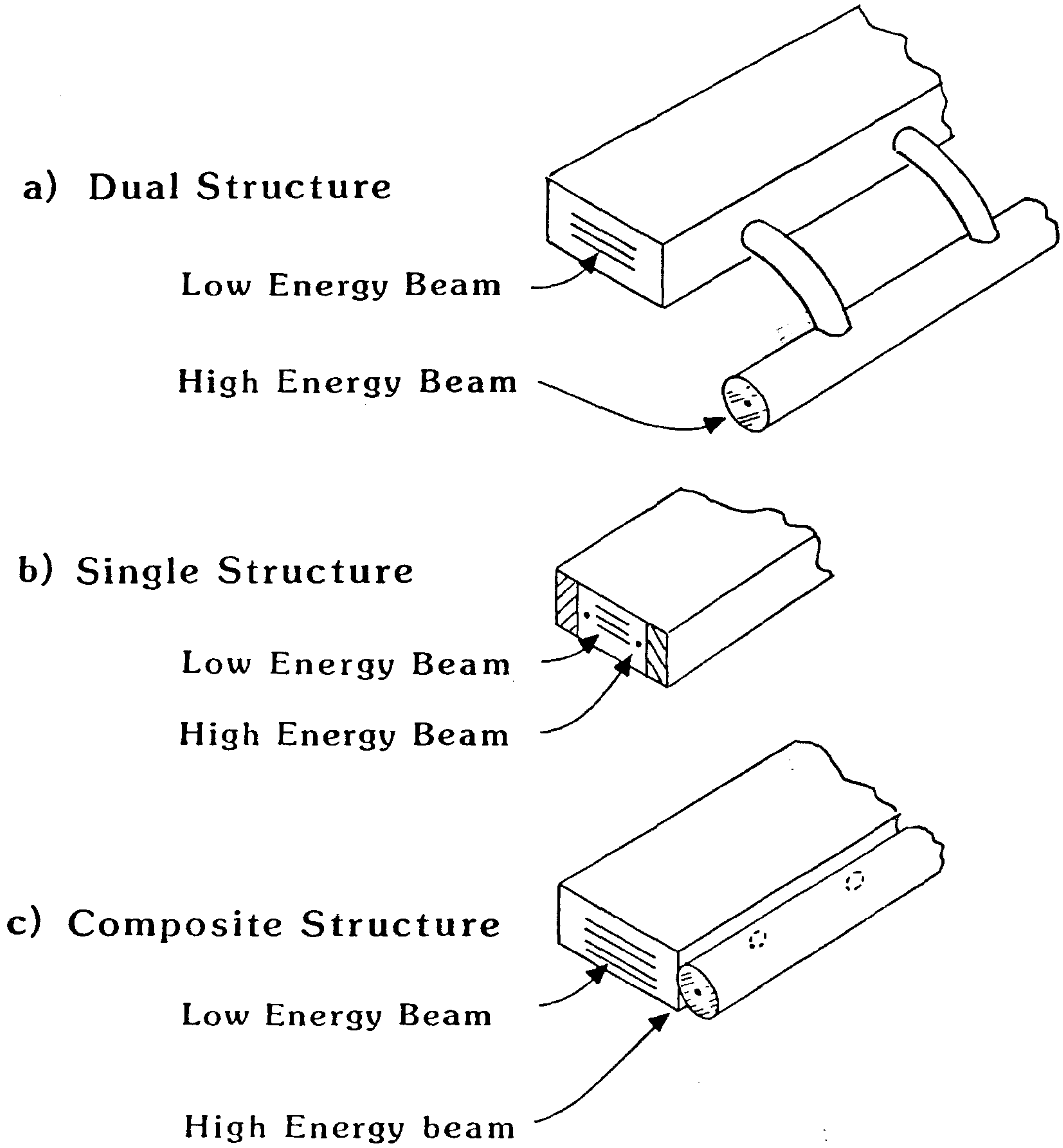
a) Dual Structure
Low Energy Beam
High Energy Beam
b) Single Structure
Low Energy Beam
High Energy Beam
c) Composite Structure
Low Energy Beam
High Energy beam

Figure 1

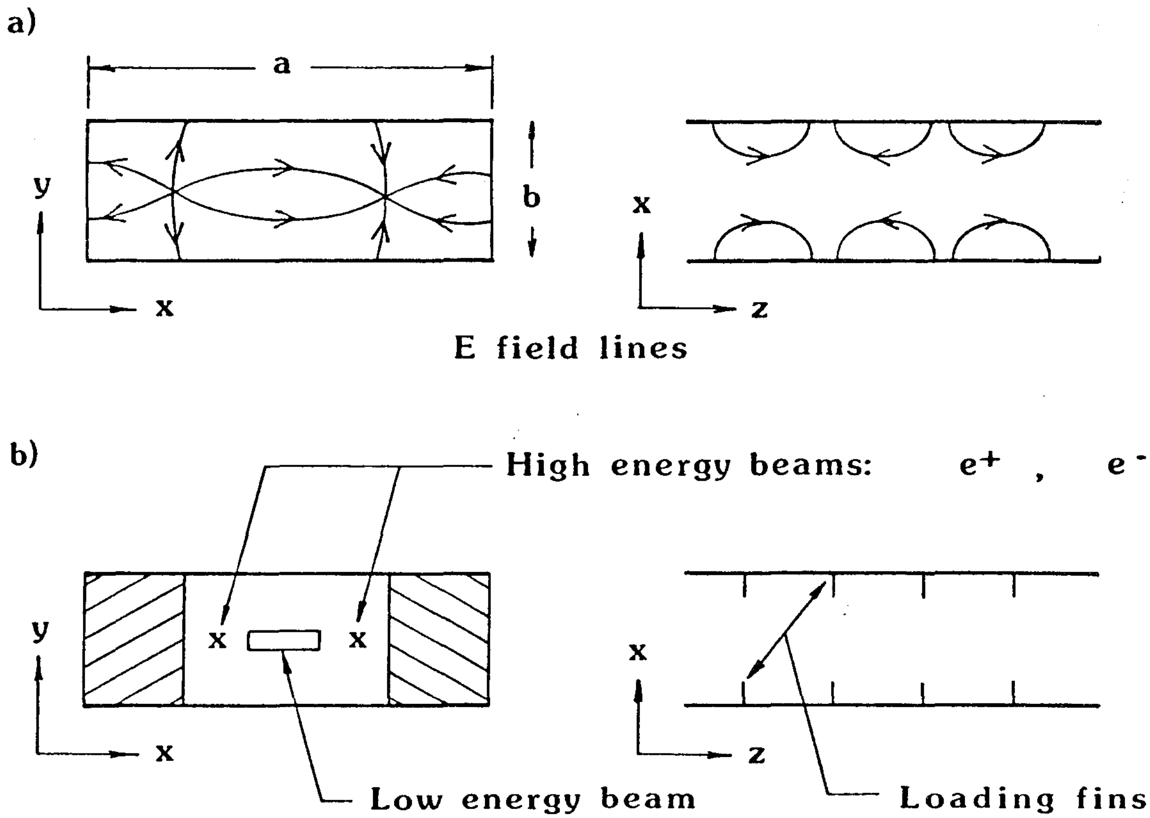
a)
a
b
y
x
x
z
E field lines
b)
High energy beams: e+ , e-
y
x
x
x
x
z
Low energy beam
Loading fins

Figure 2

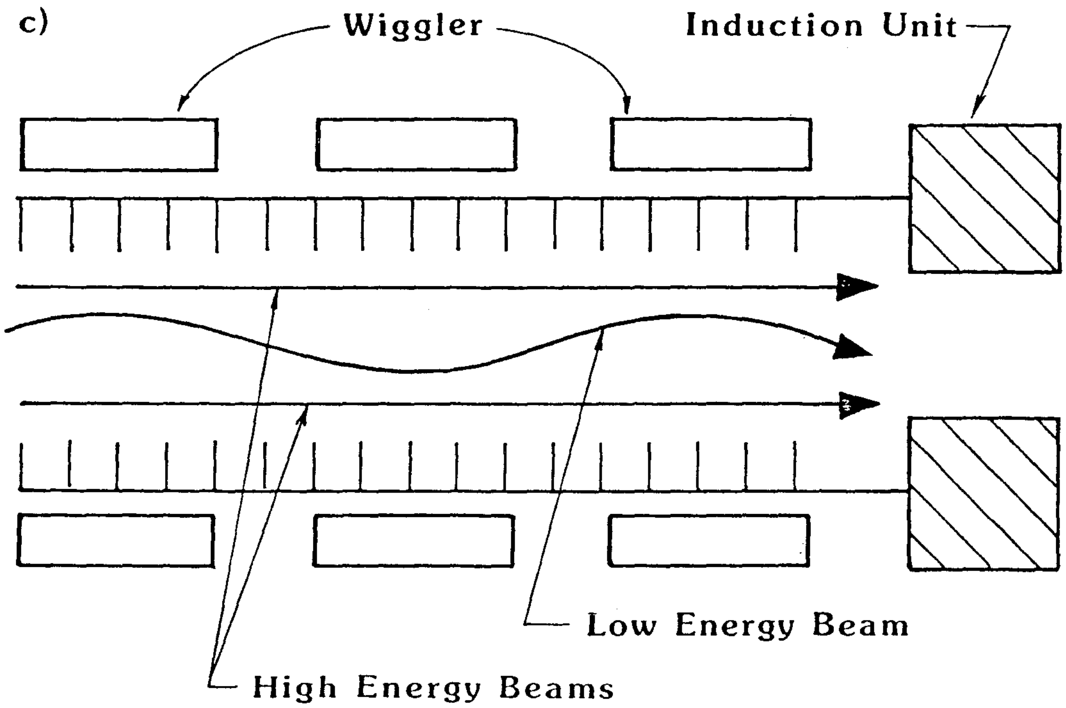

Figure 2

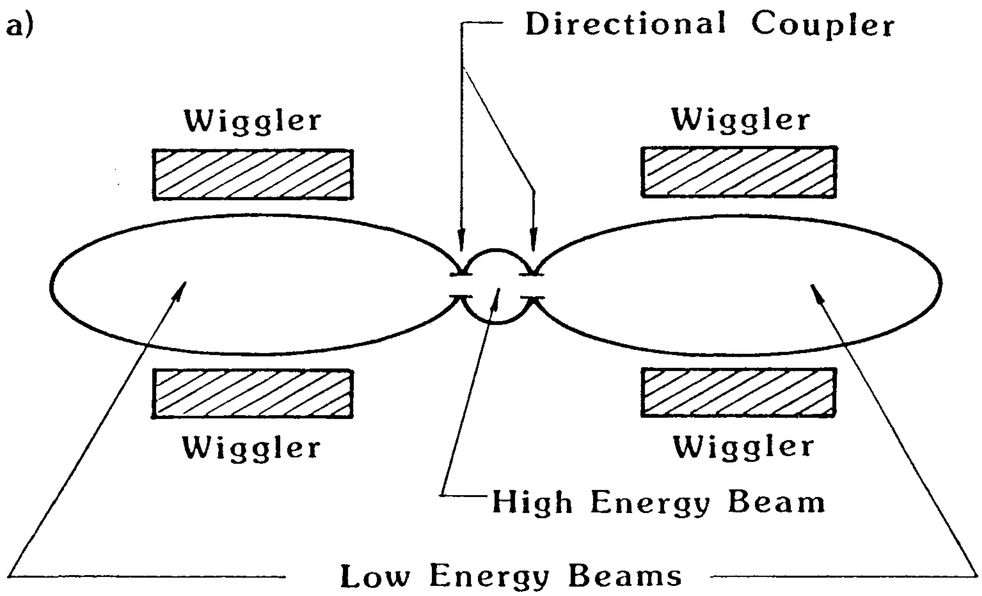
a)
Directional Coupler
Wiggler
Wiggler
Wiggler
Wiggler
High Energy Beam
Low Energy Beams

Figure 3

b)

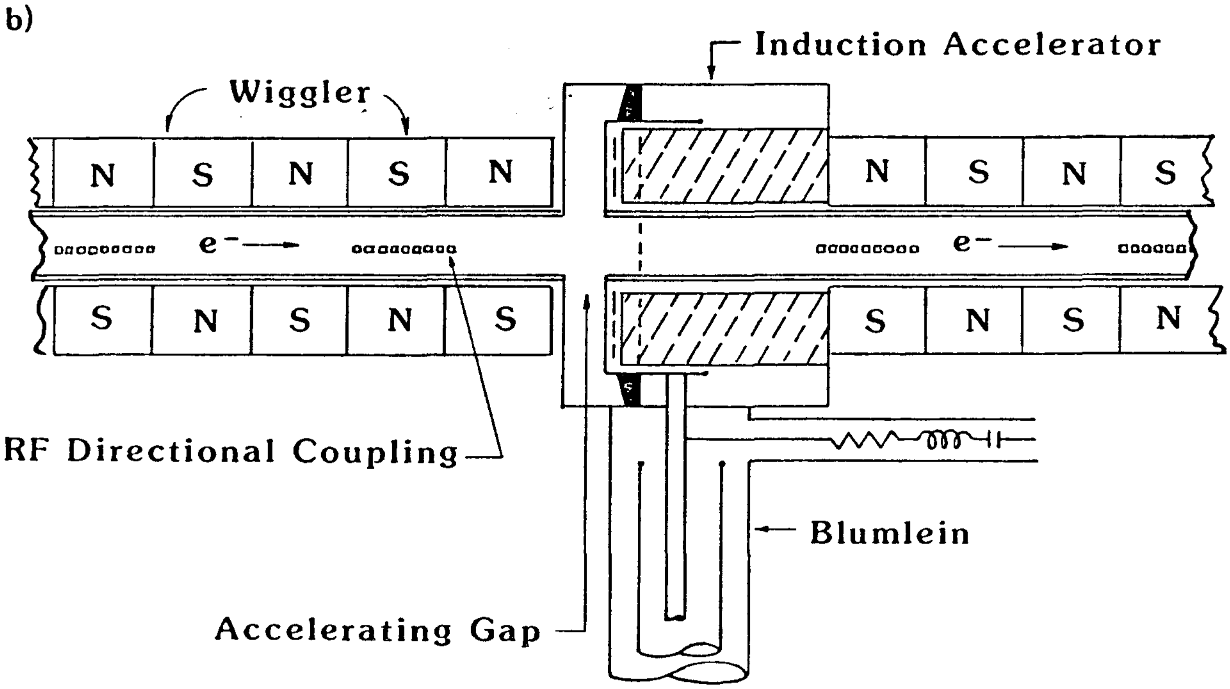
Induction Accelerator
Wiggler
N
S
N
S
N
N
S
N
S
e⁻
e⁻
S
N
S
N
S
S
N
S
N
RF Directional Coupling
Blumlein
Accelerating Gap

Figure 3