LBL-31006
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

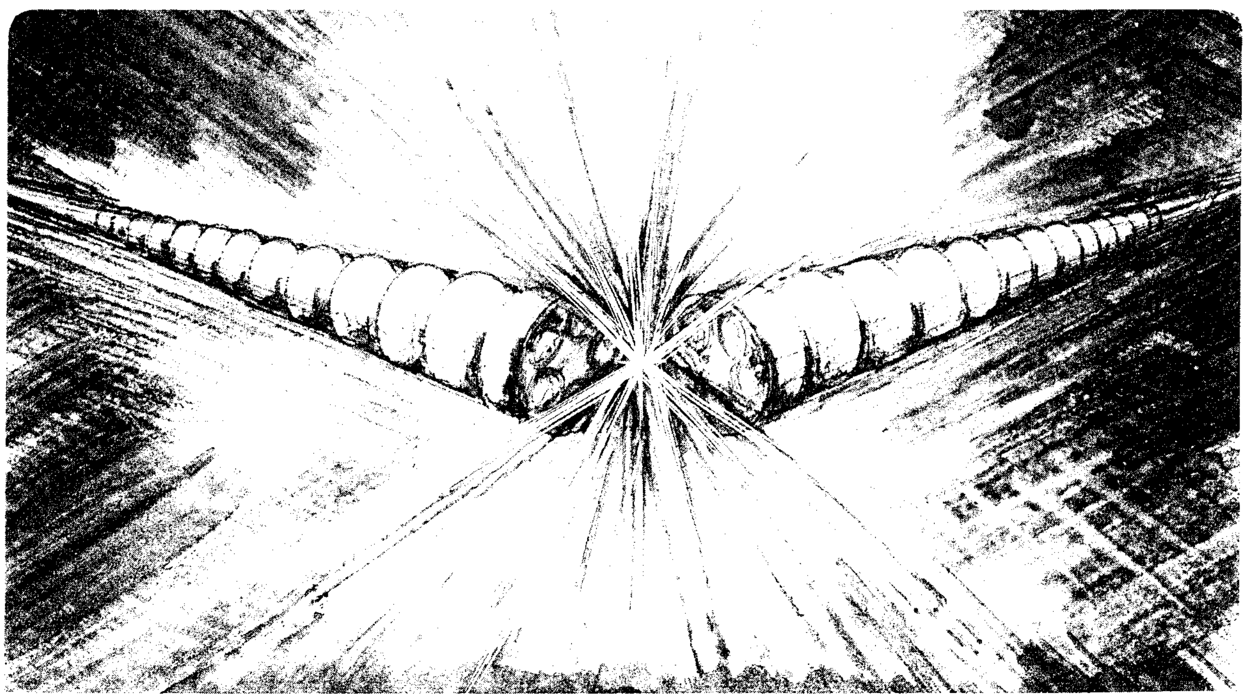
Accelerator & Fusion Research Division

Submitted to Physical Review Letters

Radio-Frequency Beam Conditioner for Fast-Wave Free-Electron Generators of Coherent Radiation

A.M. Sessler, D.H. Whittum, and L.-H. Yu

July 1991



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

LBL-31006

RADIO-FREQUENCY BEAM CONDITIONER FOR FAST-WAVE FREE-ELECTRON GENERATORS OF COHERENT RADIATION*

Andrew M. Sessler and David H. Whittum**
Lawrence Berkeley Laboratory, University of California,
Berkeley, California 94720

Li-Hua Yu
Brookhaven National Laboratory, Upton, New York 11973

July 1991

* Work at LBL was supported by the U.S. Department of Energy under Contract Number DE-AC03-76SF00098; work at BNL was supported by the U.S. Department of Energy under Contract Number DE-AC02-76CH00016; work at KEK was supported by the Japan Society for the Promotion of Science and the National Laboratory for High Energy Physics (KEK).

** Present address: Accelerator Division, National Laboratory for High Energy Physics, KEK, 1-1 Oho, Tsukuba, Ibaraki, 305, Japan.

RADIO-FREQUENCY BEAM CONDITIONER FOR FAST-WAVE FREE-ELECTRON GENERATORS OF COHERENT RADIATION

Andrew M. Sessler and David H. Whittum[a]
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
Li-Hua Yu
Brookhaven National Laboratory, Upton, New York 11973

July 1991

A method for conditioning electron beams is proposed, making use of the TM_{210} mode of microwave cavities, to reduce the axial velocity spread within the beam, in order to enhance gain in resonant electron beam devices, such as the free-electron laser (FEL). Effectively, a conditioner removes the restriction on beam emittance. The conditioner is analyzed using a simple model for beam transport and ideal RF cavities. Analysis of an FEL is employed to evaluate performance with reduced axial velocity spread. Examples of FELs are presented showing the distinct advantage of conditioning.
PACS numbers: 42.55.Tb, 41.80.Ee, 52.75.Ms

The performance of fast-wave resonant electron devices for the production of coherent radiation, such as free-electron lasers (FEL) or cyclotron auto-resonant masers (CARM), is limited by the intrinsic spread in longitudinal velocity of the electrons.[1,2,3,4] For the purpose of this note we limit the discussion to FELs. In practice, to limit the spread in longitudinal velocity the energy spread and the emittance of the electron beam are carefully limited. In fact, it is the very difficulty of reducing these two features of a beam, while still maintaining high beam current, which produces the limit on gain in fast wave devices. Often electron beam sources have the feature that the energy spread of the particles is exceedingly small. In this work, we shall consider only this situation.

Small energy spread, alone, is not enough to make a fast-wave device work optimally, for the non-zero angular spread of the beam, measured by its emittance, produces longitudinal velocity spread; i.e., "effective energy spread". However, one can consider a device, placed between the accelerator producing the electron beam and the fast-wave coherent radiation generator, that "conditions the beam"; i.e., converts the beam to particles all moving with the same longitudinal velocity. Such a device need not "cool" the beam; i.e., the phase volume after the device can equal that before the device, but it builds upon the fact that the beam has a very small energy spread and "pushes phase space around"; i.e., introduces a tight correlation between transverse oscillation energy and total particle energy. In this note we analyze the performance of such a device, and show that it can significantly increase the gain in fast-wave devices.

In Ref (1) it is shown that FEL behavior is governed by the equation

$$\left[\Omega - q_{11} + \nabla_\perp^2 + U\left(\Omega, q_{11}, r\right)\right] E = 0 \ , \tag{1}$$

$$U = 4\gamma_0^3 \rho^3 \int \frac{d\gamma}{\gamma^2} \int \frac{d^2p \ \dfrac{\partial f_0}{\partial \gamma}\left(\gamma, p^2 + k^2 r^2\right)}{\Omega - \left(1 + q_{11}\right)\left[2\left(\dfrac{\gamma - \gamma_0}{\gamma_0}\right) - \dfrac{1}{4}\left(p^2 + k^2 r^2\right)\right]} \ , \tag{2}$$

provided

$$\frac{k_\beta}{\rho k_w} << 1 \quad . \tag{3}$$

In this formula, E is the electromagnetic field, the wiggler wave number is k_w, the betatron wave number is k_β, and the central beam energy is $\gamma_0 mc^2$. Resonance at the signal wave number k_r occurs when $\gamma = \gamma_r$. The FEL parameter is ρ and q_{11} is the Fourier transform variable of $\xi = (k_r + k_w)\, Z$ - $v_0\, t$. The variables $k = k_\beta / k_w$, $r = \sqrt{2k_s k_w}\, R$, R is the radial coordinate, and $p = dr/d(k_w z)$.

The usual inequalities for FEL behavior are obtained from Eq. (1) by requiring that the energy spread and the emittance effect are small. Thus $2\,(\gamma\text{-}\gamma_0)/\gamma_0 << 2\rho$, $(1/4)\,(k^2r^2+p^2) << 2\rho$, or

$$\frac{\sigma}{\gamma} << \rho \ , \tag{4}$$

$$\varepsilon << \left(\frac{\lambda_s}{2\pi}\right)\left(\frac{\rho k_w}{k_\beta}\right) , \tag{5}$$

where $\varepsilon = k_\beta R^2$, the emittance, and σ, the energy spread, have been introduced. Eq. (1) now becomes

$$\left[\Omega - q_{11} + \nabla_\perp^2 - \frac{(2p)^3}{\Omega^2}\, W(r) \right] E = 0 \ , \tag{6}$$

where $W_{(r)}$ is dependent only upon r.

Transverse effects can be ignored if $\nabla_\perp^2 << 2\rho$, which is

$$L_{Ray} >> L_{Gain} \tag{7}$$

where $L_{Ray} = k_s R^2$ and $L_{Gain} = 1/2\rho k_w$. The usual inequalities are Eqs. (3), (4), (5), (7), which result from taking $f_0 = f_0\left((\gamma-\gamma_0)/\gamma_0, (1/4)\,(p^2+k^2r^2)\right)$ having a small spread in its two arguments.

For a conditioner we have

$$f = f_0\left(2\left(\frac{\gamma-\gamma_0}{\gamma_0}\right) - \frac{1}{4}\left(p^2 + k^2r^2\right), \frac{1}{4}\left(p^2 + k^2r^2\right)\right), \tag{8}$$

still having a small spread in its two arguments, but now we have introduced a correlation between total energy and transverse energy. In this case it is obvious, from Eq. (2), that there is no longer a restriction on transverse energy. Thus FEL behavior is only limited by the inequalities Eqs. (3), (4) and (7). In the microwave range, where there is a wave guide, only the conditions of Eqs. (3) and (4) remain.

A device, or "conditioner", that introduces a correlation between transverse oscillation amplitude and particle energy is shown in Fig. 1. It consists of a focusing FODO channel and suitably phased RF cavities operating in the TM_{210} mode. For a FODO channel, and in the thin-lens approximation, in the absence of RF cavities a matched beam will have maximum $\langle x^2\rangle_+$ at the focusing lenses and minimum $\langle x^2\rangle_-$ at the defocusing lenses where, in terms of the lens strength f and separation L we have

$$\langle x^2\rangle_\pm = 2f\,\varepsilon_x\sqrt{\frac{2f \pm L}{2f \mp L}} \equiv \varepsilon_x\,\beta_\pm\ , \tag{9}$$

where ε_x is the beam emittance. The orthogonal $\langle y^2\rangle$ will be exactly the same, but $\langle y^2\rangle$ will be largest at the defocusing lenses.

Since in the TM_{210} mode, at the appropriate phase, there is predominantly E_z, and no deflecting fields (we ignore fringe fields), to a good approximation a particle passing through the RF cavity at the focusing lens has its transverse motion unaffected, but gains energy $\Delta\gamma_+ = \alpha\,(x^2 - y^2)$, with α a constant that depends on cavity parameters. Similarly, with a 180° phase change, at the defocusing lens $\Delta\gamma_- = -\alpha\,(x^2 - y^2)$. It is clear that in passing through N periods of a conditioner, a particle of initial amplitude of oscillation characterized by emittance ε and initial phase φ_{0x} and φ_{0y} will gain energy

$$\Delta\gamma = \alpha\varepsilon \sum_{n=1}^{\infty} \left\{\beta_+ \sin^2\left[n\mu + \varphi_{0x}\right] - \beta_- \sin^2\left[n\mu + \varphi_{0y}\right]\right\}$$

$$- \alpha\varepsilon \sum_{n=1}^{\infty} \left\{\beta_- \sin^2\left[n\mu + \mu/2 + \varphi_{0x}\right] - \beta_+ \sin^2\left[n\mu + \mu/2 + \varphi_{0y}\right]\right\} \qquad (10)$$

where μ, the phase advance for a period is given by $\cos\mu = 1 - \frac{1}{2}L^2/f^2$. If the conditioner has an infinite number of periods, is "perfect", then

$$\Delta\gamma\big|_{perfect} = \alpha\varepsilon\left(\beta_+ - \beta_-\right)N \ . \qquad (11)$$

There results an averaging over oscillations, as we expected, so that energy, $\Delta\gamma$, is exactly correlated with amplitude of oscillation, ε. The requirement for a conditioner is given by Eq. (8) and results in

$$\alpha = \left(\frac{\gamma k_s k_\beta}{2k_w}\right)\left[\frac{1}{N\left(\beta_+ - \beta_-\right)}\right], \qquad (12)$$

where the first factor only contains FEL parameters, and the second only conditioner parameters.

In practice, a conditioner has only a finite number of periods. How many periods are necessary to obtain a rather good averaging; i.e., for particles to be mostly at the extreme of oscillations when going through the RF cavities? A bit of analysis shows that for N periods the *maximum* deviation of $\Delta\gamma$ is:

$$\left|\frac{\Delta\gamma}{\Delta\gamma|_{perfect}} - 1\right| \le \left|\frac{\sin N\mu}{N \sin \mu}\right| \left[\cos^2\frac{\mu}{2} + \frac{4f^2}{L^2}\sin^2\frac{\mu}{2}\right]^{1/2} , \tag{13}$$

so that the spread in energy drops off inversely with N and can be made zero if $N\mu$ is a multiple of π. As a good practical example, L = 50 cm, f = 100 cm, μ = 0.505, β_+ = 258 cm, β_- = 155 cm, and for N = 6 we have $\Delta\gamma/\Delta\gamma|_{perfect} = 5.2 \times 10^{-2}$ so that with only 6 periods the induced correlation is good to 5%, which for the examples given is a negligible correction.

A complete analysis of an FEL with conditioner, such analysis taking into account energy spread, emittance and focusing of the electron beam, and the diffraction and guiding of the radiation, may be given following the work of Yu, Krinsky and Gluckstern.[5] In fact, the analysis results in the same scaling laws. The only change is to delete the term 3is (κ/D) $(k_r\varepsilon)$ in Eq. (10) of Ref. 5. Now Fig. 1 of Ref. 5 is replaced with Fig. 2 of this Letter. Thus the e-folding length of the electric field, L_G, is given by

$$\frac{1}{L_G k_w} = D\, G\left[k_r\varepsilon, \frac{\sigma}{\gamma D}, \frac{k_\beta}{k_w D}, \frac{\omega-\omega_r}{\omega_r D}\right] , \tag{14}$$

where, in terms of the wiggler parameter K, and the beam current I

$$D = \left[\frac{4eZ_0}{\pi m c^2} \frac{K^2}{1 + K^2} \frac{I}{\gamma_0} \right]^{1/2} [JJ] \ , \tag{15}$$

and the factor $[JJ]$, a difference of Besel functions is given in Ref. 5, but is close to unity. The dependence of G upon its first three arguments is given in Fig. 2. For all cases the detuning was taken as zero; i.e., $[(\omega - \omega_r)/\omega_r D] = 0$. (The gain was close to optimum for zero detuning.) With the formula for L_G and Fig. 2 one can readily evaluate the performance of an FEL with conditioned beam.

Some examples of a conditioner are given in Table I. The examples have been arrived at by using the scaling laws and then checked by numerical simulation (they gave the same result). The parameters of the examples are all realistic; the beam current, energy spread, and emittance in the examples corresponds to less demanding performance than that of the LANL photo cathode gun.[6] The amount of conditioning required, $\Delta\gamma|_c$, which is the average energy increment across the beam, is given by $\Delta\gamma_c = k_s k_\beta \varepsilon_n / 2\ k_w$, and is indicated in Table I. It can be seen that gain from conditioning is considerable; for example, in the infra red (10 μm) example the gain length is reduced by a factor of 5, while in the ultra-violet example the energy of the beam is reduced by a factor of 3 (thereby reducing the cost of the accelerator by essentially the same factor) while the gain length is reduced by more than a factor of 2 (thus reducing the cost of the wiggler by this factor). The saving in cost is even larger than these numbers indicate, for with the shorter wiggler, magnet errors are less important and therefore manufacturing tolerances are reduced.

In the analysis of this paper, and in all the examples, the betatron wavelength λ_β has been determined by the "natural" focusing of the FEL. That doesn't have to be the case and, in particular, ion focusing (the use of a plasma) can be used to decrease λ_β.[3] Such reduction is quite advantageous, for FEL performance, but is limited by the very condition, on the emittance, that a conditioner removes.

If λ_β is reduced by an ion channel, one can design a conditioner so that the average longitudinal velocity spread across the beam is zero, but there will still be oscillations (at frequency $2k_\beta c$) in the longitudinal velocity. In Table II we have presented examples whose performance has been evaluated under the assumption that longitudinal velocity modulations are unimportant. (Numerical simulation confirms the essential correctness of the assumption.) The example of the 30 Å FEL operates in the "water window" where wet biological samples are transparent and where an intense coherent source would be of great interest for imaging. Presumably such a short wavelength FEL is obtained by seeding a 1000 Å FEL at (say) 3000 Å with an excimer or dye laser and then cascading FELs. The second example in Table II, based upon the proposed Brookhaven National Laboratory VUV Facility, is a set of parameters which might be used to experimentally study conditioning and ion focusing. Operation at very short wavelengths requires two things which have not yet been achieved, but which appear to be possible; namely, operation of a conditioner and operation of an FEL with ion focusing.

This work was supported by the U.S. department of Energy under Contract Numbers DE-AC03-76SF00098 and DE-AC02-76CH00016, the Japan Society for the Promotion of Science, and the National Laboratory for High Energy Physics (KEK).

References

(a) Present address: Accelerator Division, National Laboratory for High Energy Physics, KEK, 1-1 Oho, Tsukuba, Ibaraki, 305, Japan.

1. Li-Hua Yu and Samuel Krinsky, Physics Letters A 129, 463 (1988).

2. C. Pellegrini, Nuclear Instruments and Methods in Physics Research A 272, 364 (1988); Li-Hua Yu and Samuel Krinsky, Ibid, A 272, 436.

3. W.A. Barletta and A.M. Sessler, Proceedings of the INFN International School on Electromagnetic Radiation and Particle Beams Acceleration, Varenna, Italy, North-Holland Physics, 211 (1989); K. Takayama and S. Hiramatsu, Phys. Rev. A 37, 143 (1988).

4. K.D. Pendergast, B.G. Danby, R.J. Temkin and J.S. Wurtele, IEEE Trans. on Plasma Science 16, 122 (1988); D. Whittum, A.M. Sessler, and J. Dawson, Phys. Rev. Lett. 64, 2511 (1990).

5. L.-H. Yu, S. Krinsky and R.L. Gluckstern, Phys. Rev. Lett. 64, 3011 (1990).

6. Richard L. Sheffield, Proc. of the 1989 IEEE Particle Accelerator Conference 2, 1098, Chicago, IL, March 20-23, 1989; D.W. Feldman et al, "Performance of the Los Alamos HIBAF Accelerator at 17 MeV", Proceedings of the 12th International FEL Conference, Sept. 1990, Paris (to be published).

Table I. Parameters for a 10 μm, 300 Å and 500 Å FEL, with, and without, a conditioner. For each case the wiggler wavelength (λ_w) was varied and determined so that the growth length (L_G) was minimum.

	10 μm FEL	10 μm FEL with conditioner	3000 Å FEL	3000 Å FEL with conditioner	500 Å FEL	500 Å FEL with conditioner
Electron Beam Energy $\gamma_0 mc^2$ (MeV)	54.2	54.2	483	153	1004	304
Electron Beam Peak Current I (A)	300	300	300	300	300	300
Electron Beam Normalized Emittance ε_n (rms) (m)	$8\text{x}10^{-4}\pi$	$8\text{x}10^{-4}\pi$	$5\text{x}10^{-5}\pi$	$5\text{x}10^{-5}\pi$	$2\text{x}10^{-5}\pi$	$2\text{x}10^{-5}\pi$
Electron Beam Betatron Wave-length λ_β (m)	8.91	8.91	20.1	12.4	33.5	19.2
Electron Beam Radius (rms) (mm)	4.6	4.6	0.58	0.81	0.33	0.46
Electron Beam Energy Spread σ/γ (rms)	$4.4\text{x}10^{-4}$	$4.4\text{x}10^{-4}$	$4.4\text{x}10^{-4}$	$4.4\text{x}10^{-4}$	$4.4\text{x}10^{-4}$	$4.4\text{x}10^{-4}$
Wiggler Wave-length $2\pi/kw$ (cm)	8.0	8.0	4.8	2.8	3.7	2.0
Maximum Magnetic Field B (T)	0.25	0.25	1.0	0.52	1.26	0.66
Power e-folding Length $L_G/2$ (m)	7.95	1.58	3.09	1.38	4.64	2.12
Beam conditioning (rms) $\Delta\gamma_c/mc^2$ (MeV)	---	0.12	---	0.61	---	0.67

Table II. Parameters for a "water window" FEL assuming one can have ion focusing and a conditioned beam. Parameters are also given for an experiment at the proposed BNL facility.

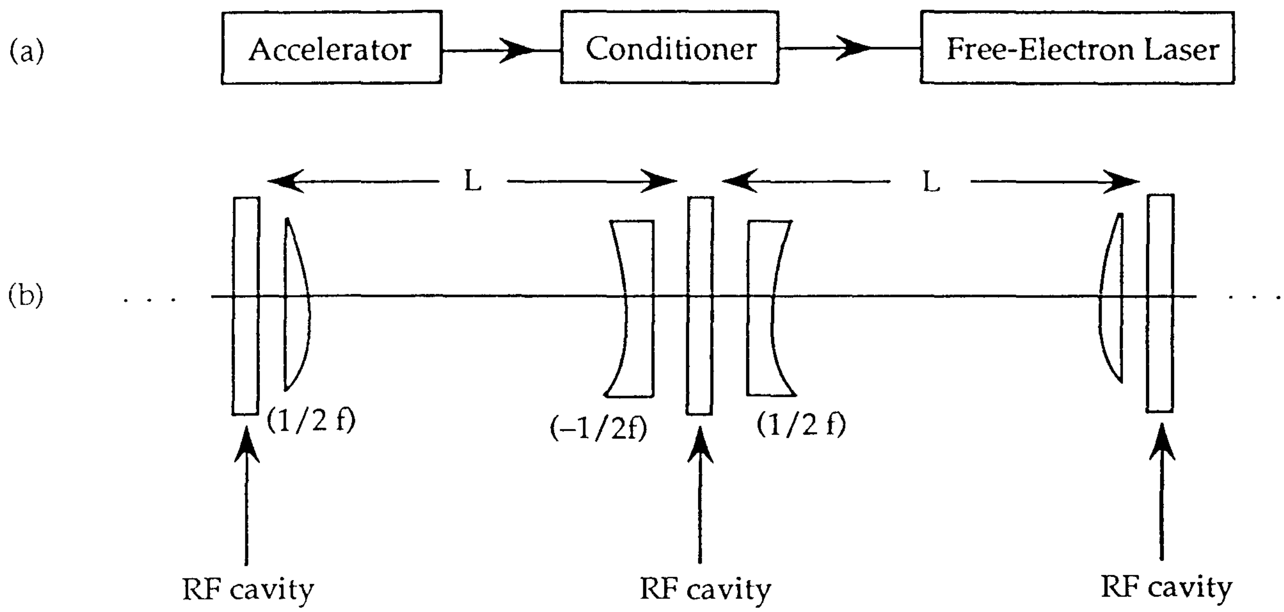
	30 Å FEL	30 Å FEL with plasma focusing and conditioning	VUV facility 1000 Å FEL	Experiment 1000 Å FEL with plasma focusing and conditioning
Electron Beam Energy $\gamma_0 mc^2$ (MeV)	1562	1240	250	250
Electron Beam Peak Current I (A)	80	80	300	30
Electron Beam Normalized Emittance ε_n (rms) (m)	$2\times10^{-6}\,\pi$	$2\times10^{-6}\,\pi$	$8\times10^{-6}\pi$	$8\times10^{-6}\pi$
Electron Beam Betatron Wavelength λ_β (m)	82.9	0.62	14.0	0.23
Electron Beam Radius (rms) (mm)	0.13	0.013	0.27	0.035
Electron Beam Energy Spread σ/γ (rms)	4.4×10^{-4}	4.4×10^{-4}	4.4×10^{-4}	4.4×10^{-4}
Wiggler Wavelength $2\pi/k_w$ (cm)	2.3	2.0	2.2	2.2
Maximum Magnetic Field B (T)	0.79	0.66	0.75	0.75
Power e-folding Length $L_G/2$ (m)	25.6	1.54	1.07	0.76
Beam conditioning (rms) $\Delta\gamma_c/mc^2$ (MeV)[(a)]	---	17.3	---	6.2

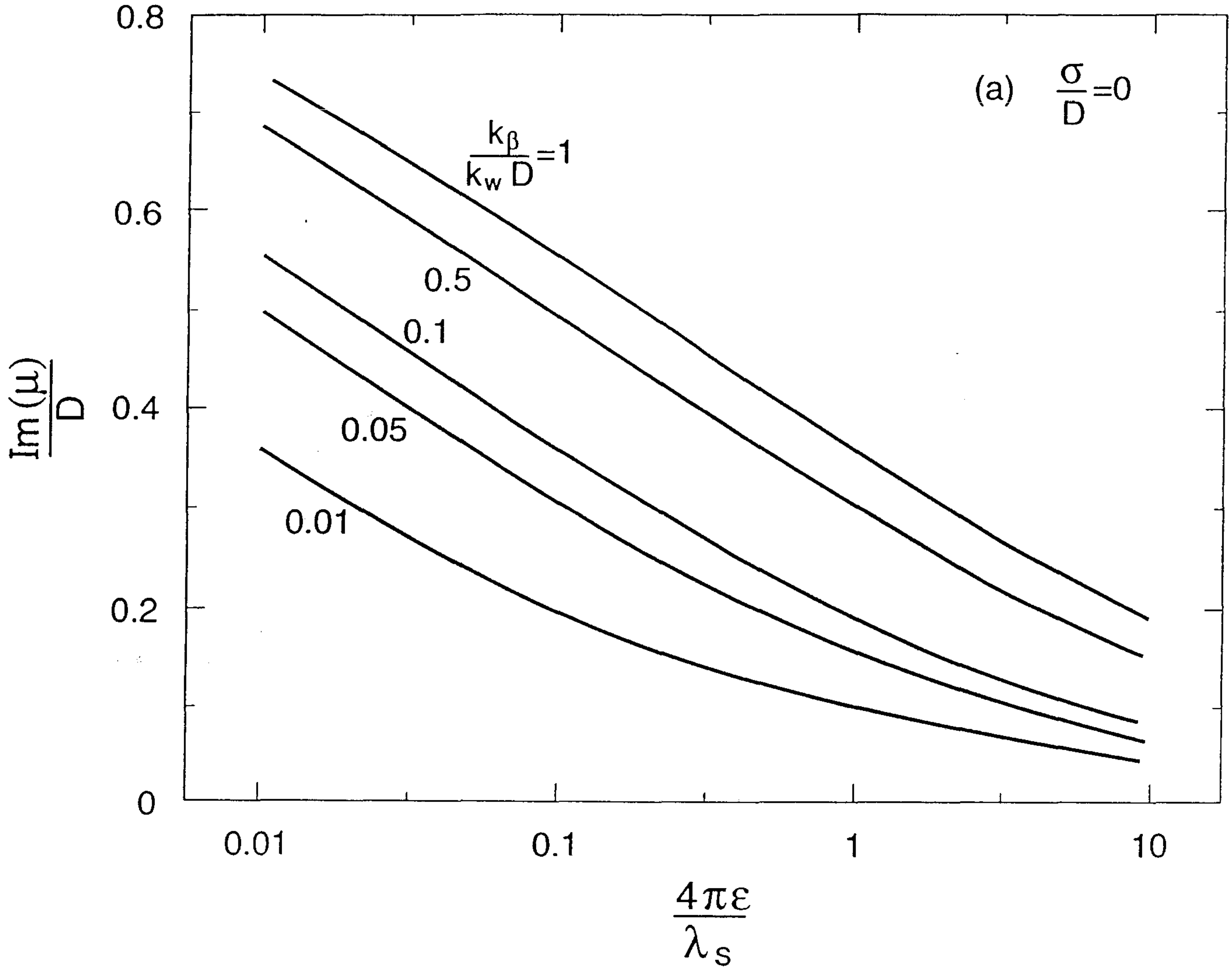
[(a)] For strong ion focusing, $\Delta\gamma_c$ is given by 1/2 of the formula used in Table I.

Figure Captions

Fig. 1. A diagram showing the location of the beam conditioner (1a), and then showing one period of the conditioner (1b). A period consists of two focusing lenses (each of strength $f/2$), two defocusing lenses (each of strength $-f/2$), and three RF cavities each operating in the TM_{210} mode.

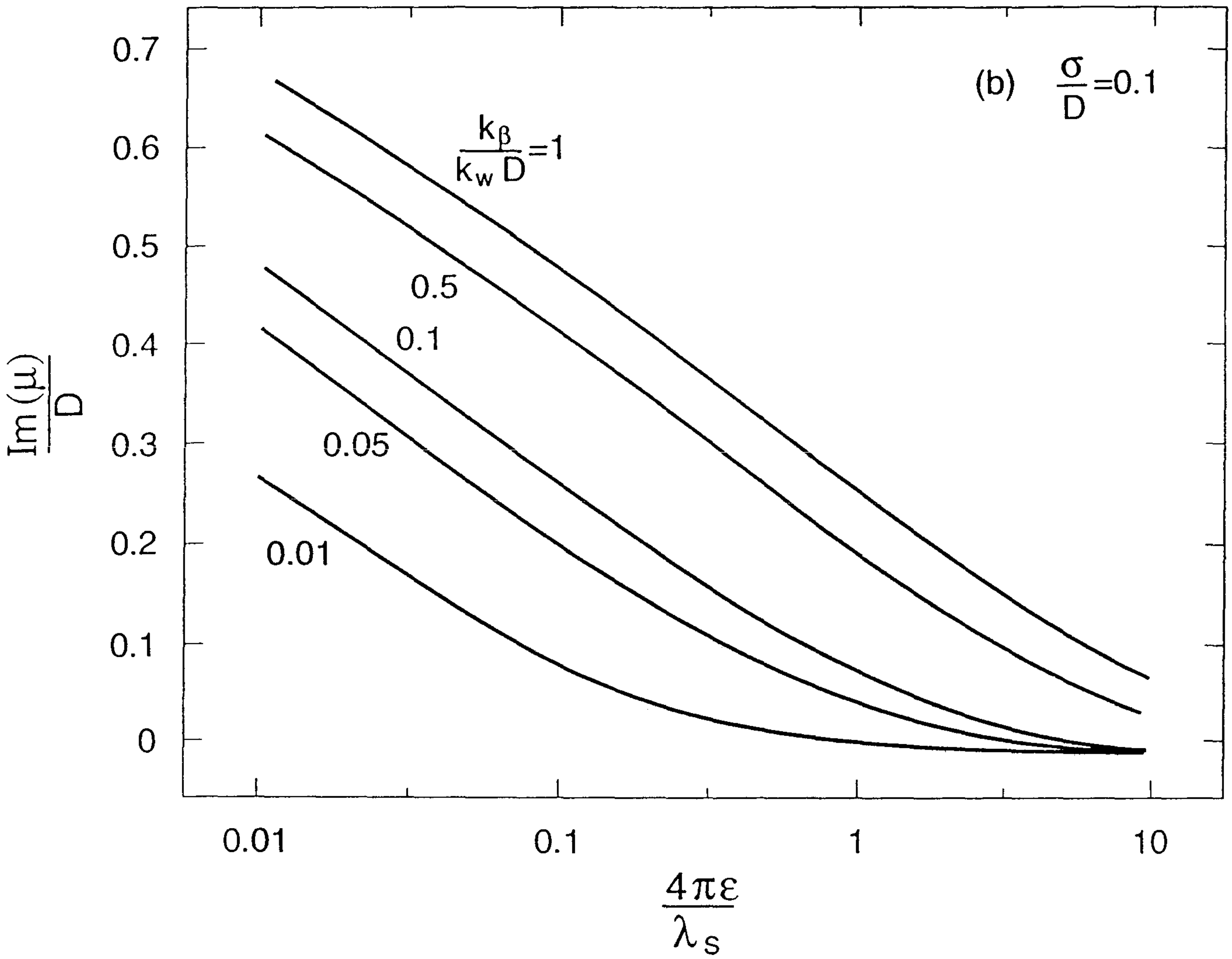
Fig. 2. Scaling functions versus scaled emittance for several values of $k_\beta/k_w D$ corresponding to scaled energy spreads (a) $\sigma/D = 0$, (b) $\sigma/D = 0.1$ and (c) $\sigma/D = 0.2$.


(a)
Accelerator
Conditioner
Free-Electron Laser
(b)
L
L
(1/2 f)
(−1/2f)
(1/2 f)
RF cavity
RF cavity
RF cavity

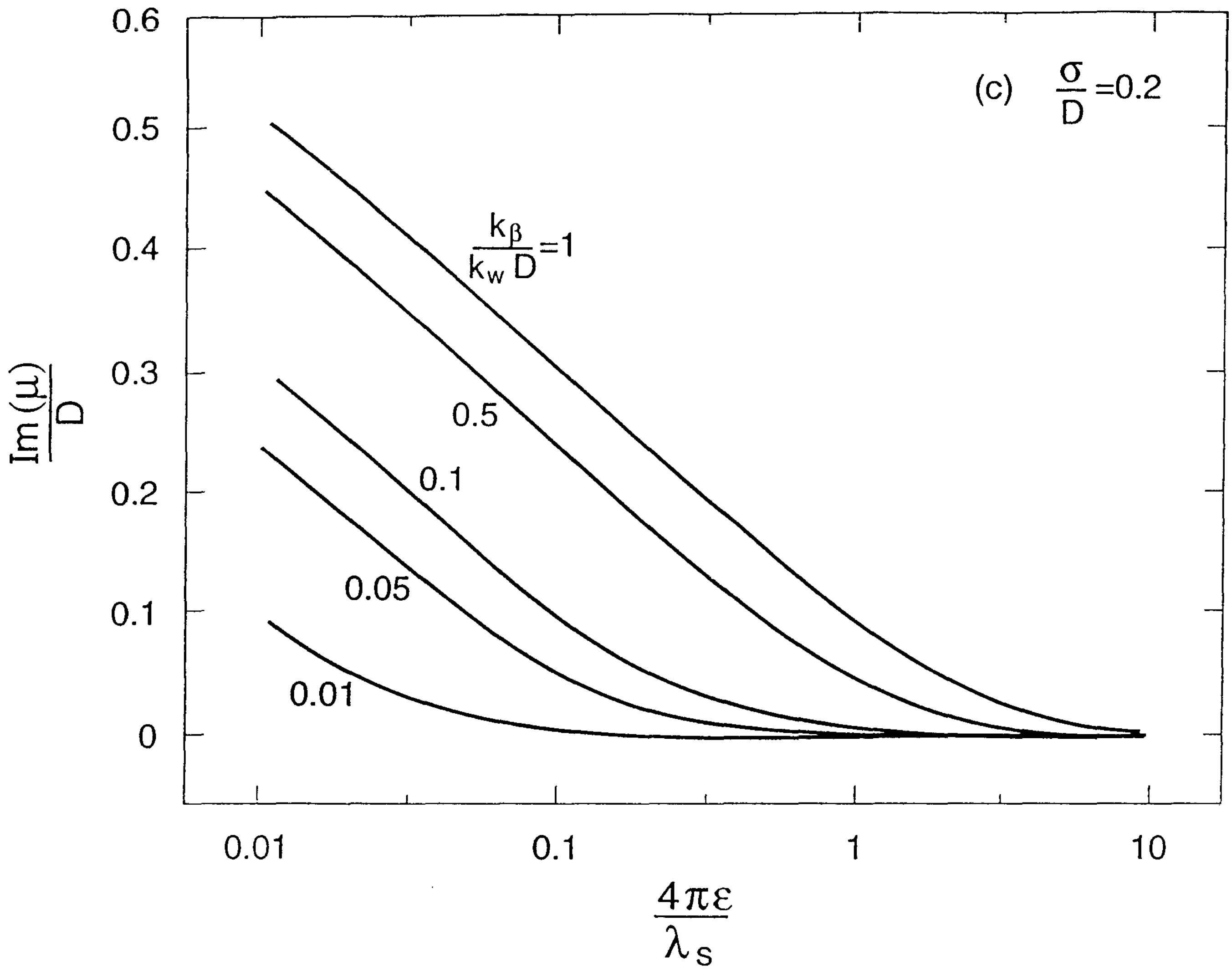


0.8
0.6
0.4
0.2
0
0.01
0.1
1
10
(a) $\frac{\sigma}{D}=0$
$\frac{k_\beta}{k_w D}=1$
0.5
0.1
0.05
0.01
$\frac{\mathrm{Im}(\mu)}{D}$
$\frac{4\pi\varepsilon}{\lambda_s}$

XBL 917-6088


(b) $\frac{\sigma}{D}$=0.1
$\frac{k_\beta}{k_w D}$=1
0.5
0.1
0.05
0.01
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
$\frac{Im(\mu)}{D}$
0.01
0.1
1
10
$\frac{4\pi\varepsilon}{\lambda_s}$

XBL 917-6090



(c) $\frac{\sigma}{D}=0.2$
$\frac{k_\beta}{k_w D}=1$
0.5
0.1
0.05
0.01
$\frac{Im(\mu)}{D}$
0.6
0.5
0.4
0.3
0.2
0.1
0
0.01
0.1
1
10
$\frac{4\pi\varepsilon}{\lambda_s}$

XBL 917-6089