ELECTRON BEAM CONDITIONING FOR FEL APPLICATIONS*

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Argonne National Laboratory

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OUTLINE

- FEL resonance & why we need conditioning?
- Electron dynamics
  - Wiggle & betatron motion
- Examples
  - Conditioning using external fields
  - Self conditioning
- Summary

FEL RESONANCE

- FEL interaction governed by electron-ponderomotive wave phase

$$\psi(t) = \int_0^t d\tau\,[\omega - (k + k_w)\,v_z(\tau)]$$

$(\omega \approx ck \;\&\; k_{\mathrm{w}} = 2\pi/\lambda_{\mathrm{w}})$

- Resonance is *not* smeared if

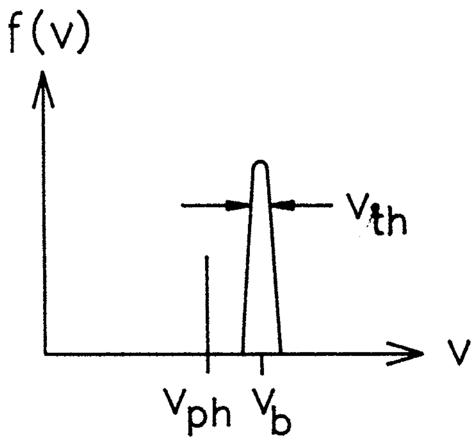
$$\frac{|\delta v_z|}{v_z} << \frac{\text{wavelength}}{\text{e} - \text{folding length}}$$

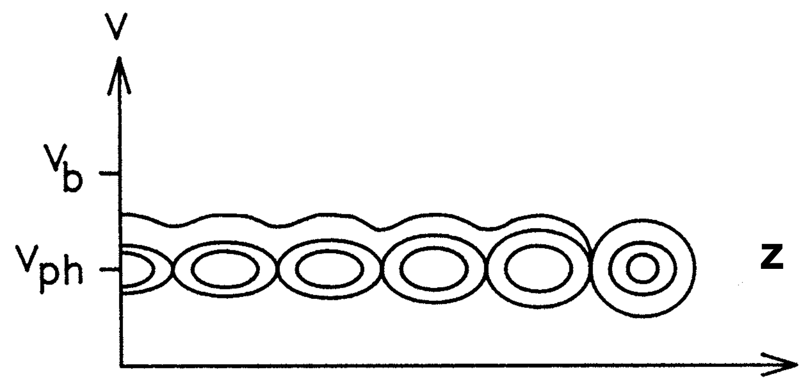
$\Rightarrow$ *Bunching on optical scale*

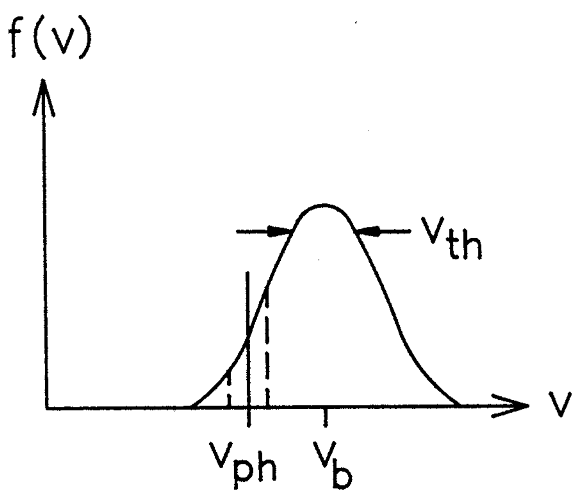
BEAM INTERACTION WITH PONDEROMOTIVE WAVE

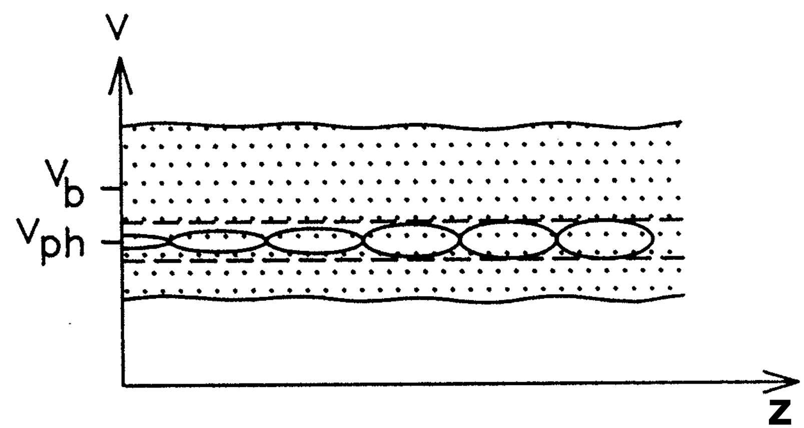
cold beam vs. warm beam

Velocity Distribution	Phase Space









WHY WE NEED CONDITIONING?

- FEL interaction:
  - Cold beam regime: coupled +ve & -ve energy modes ⇒ exponential growth
  - Warm beam regime: inverse Landau damping

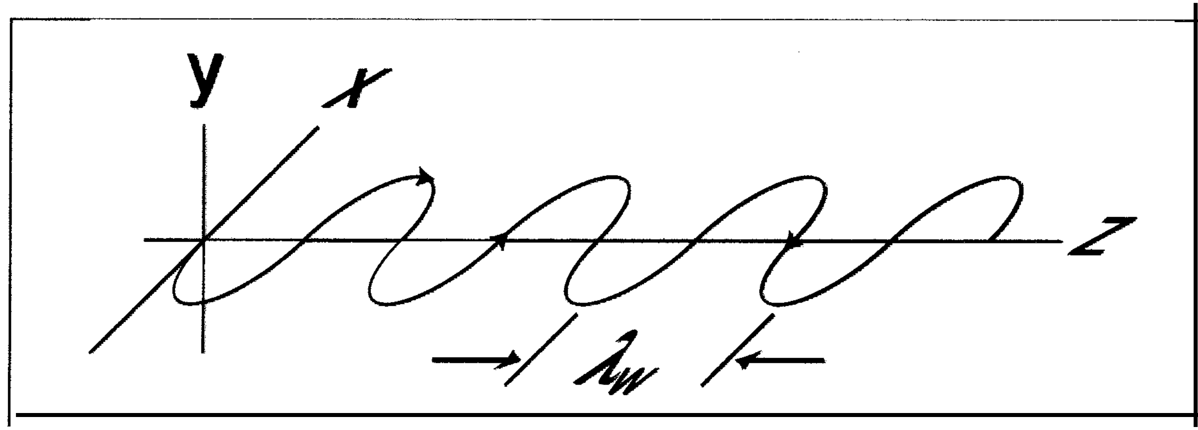
- Efficient operation limits emittance & energy spread; e.g.
  - High energy, short wavelength ($1 < \lambda[\text{Å}] < 3000$) FELs*
  - Low voltage, compact FELs

* *Committee on free electron lasers & other advanced coherent light sources,* National Research Council, 1994

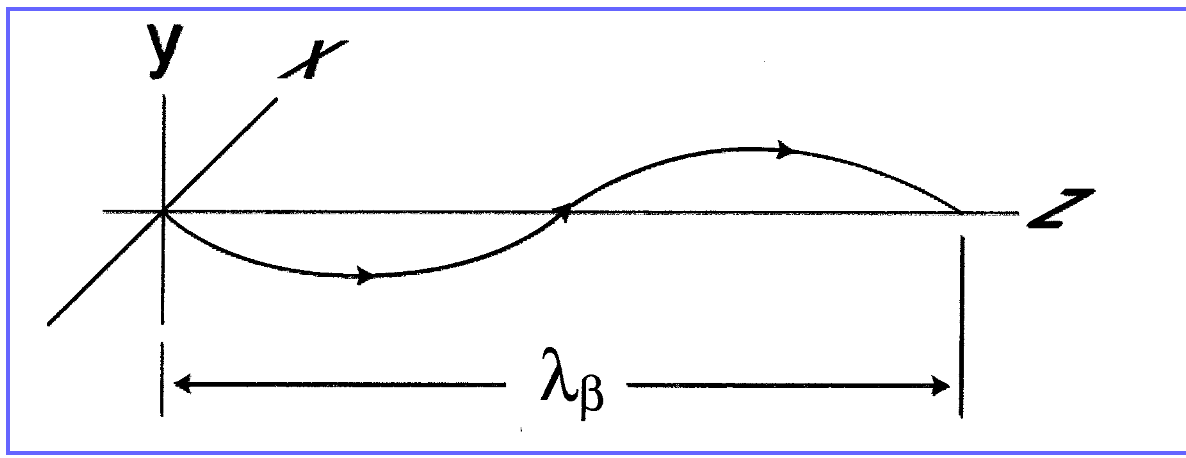
WIGGLE & BETATRON MOTION

$$\mathbf{A}_w = A_w \cosh(k_w y)\sin(k_w z)\mathbf{e}_x$$

Wiggle motion in horizontal plane



Betatron motion in vertical plane



VELOCITY SPREAD

- Axial velocity

$$\beta_z = \beta_{z0} + \delta\beta_z$$

- Common axial velocity

$$\beta_{z0} = 1 - \frac{1 + a_w^2/2}{2\gamma_0^2}$$

- Deviation in axial velocity

$$\delta\beta_z = \frac{1 + a_w^2/2}{\gamma_0^2}\frac{\delta\gamma}{\gamma_0} - \frac{1}{2}k_{\beta 0}^2 y_\beta^2 + \frac{k_{p0}^2}{2\beta_{z0}\gamma_{z0}\gamma_0^{1/2}} y_\beta^2$$

Energy spread

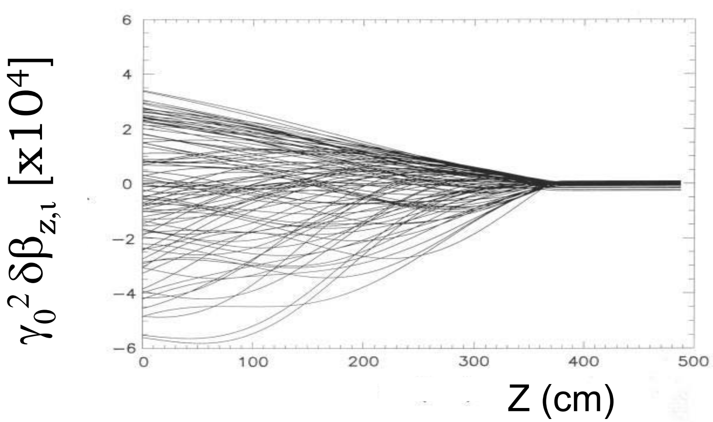
Betatron oscillation

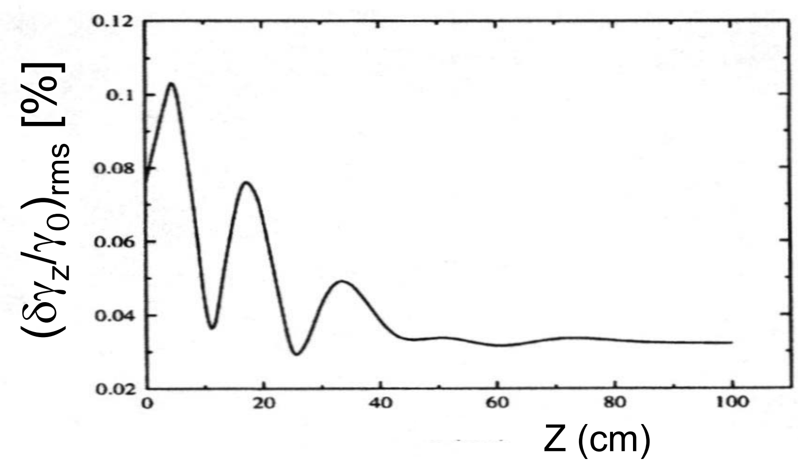
Space charge

BEAM CONDITIONING WITH EXTERNAL FIELDS

- Remove axial velocity spread by introducing correlation between betatron amplitude & energy
- Conditioning with periodic array of FODO channels & *cavity* modes, *waveguide* modes or *laser beam*

	10 μm	Conditioned	3000 Å	Conditioned	500 Å	Conditioned
$mc^2\gamma_0$ (MeV)	54	54	483	153	1004	304
ε_n (m)	$8\times10^{-4}\pi$	$8\times10^{-4}\pi$	$5\times10^{-5}\pi$	$5\times10^{-5}\pi$	$2\times10^{-5}\pi$	$2\times10^{-5}\pi$
λ_β (m)	8.9	8.9	20	12	34	19
λ_w (cm)	8.0	8.0	4.8	2.8	3.7	2.0
B (T)	0.25	0.25	1.0	0.52	1.26	0.66
$L_G/2$ (m)	8.0	1.6	3.1	1.4	4.6	2.1
$mc^2\Delta\gamma_c$ (MeV)		3.6		2.0		2.1
$mc^2\gamma_c$ (MeV)		54		51		51
N		10		20		50
N_c		1		10		10
L_c (m)		10		20		50





Sessler *et al.*, Phys. Rev. Lett. **68**, 309 (1992); Sprangle *et al.*, Phys. Rev. Lett. **70**, 2896 (1993); Liu & Neil, Phys. Rev. Lett. **70**, 3557 (1993)

SELF CONDITIONING

- Betatron oscillations due to wiggler gradients

$$y'' = -\tfrac{1}{2}\left(\frac{a_w k_w}{\gamma_0 \beta_{z0}}\right)^2 y \equiv -k_{\beta 0}^2 y$$

- With self-electric & -magnetic fields

$$y'' = -k_{\beta 0}^2 y + \frac{k_p^2}{\gamma_0 \gamma_{z0}^2 \beta_{z0}^2} y$$

$$k_\beta = k_{\beta 0}(1 - SFP)^{1/2}$$

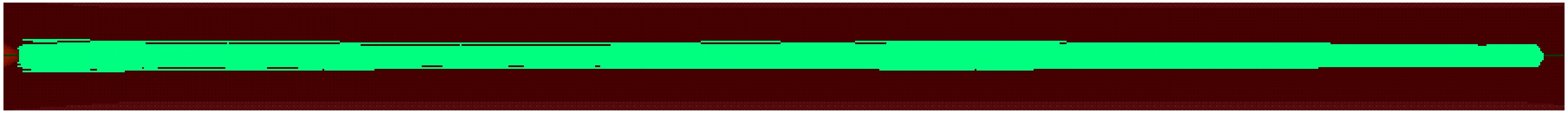
- *Self field parameter* $SFP \equiv \left(\frac{k_{p0}/k_{\beta 0}}{\beta_{z0}\gamma_{z0}\gamma_0^{1/2}}\right)^2,$ cf *Brillouin flow*

BEAM ENVELOPE SIMULATION

•Betatron oscillations in vertical plane with *no* space charge

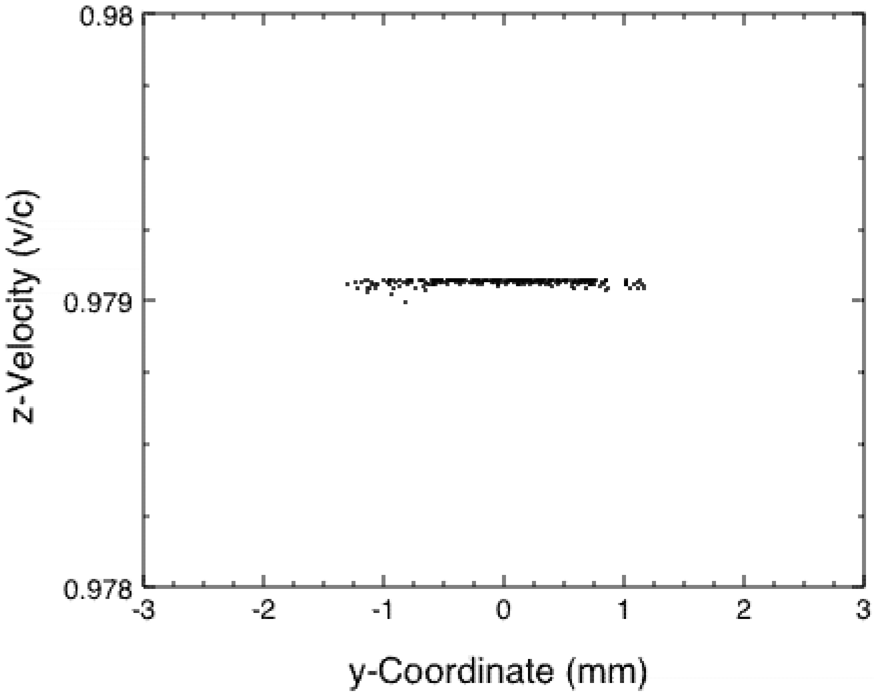
$$\delta\beta_z \approx -\frac{1}{2}k_\beta^2 y_\beta^2 \ , \qquad k_\beta = k_{\beta 0}(1\text{-}SFP)^{1/2} \ , \qquad SFP = \left(\frac{k_p / k_{\beta 0}}{\beta_{z0}\gamma_{z0}\gamma_0^{1/2}}\right)^2$$

•Betatron oscillations in vertical plane with space charge

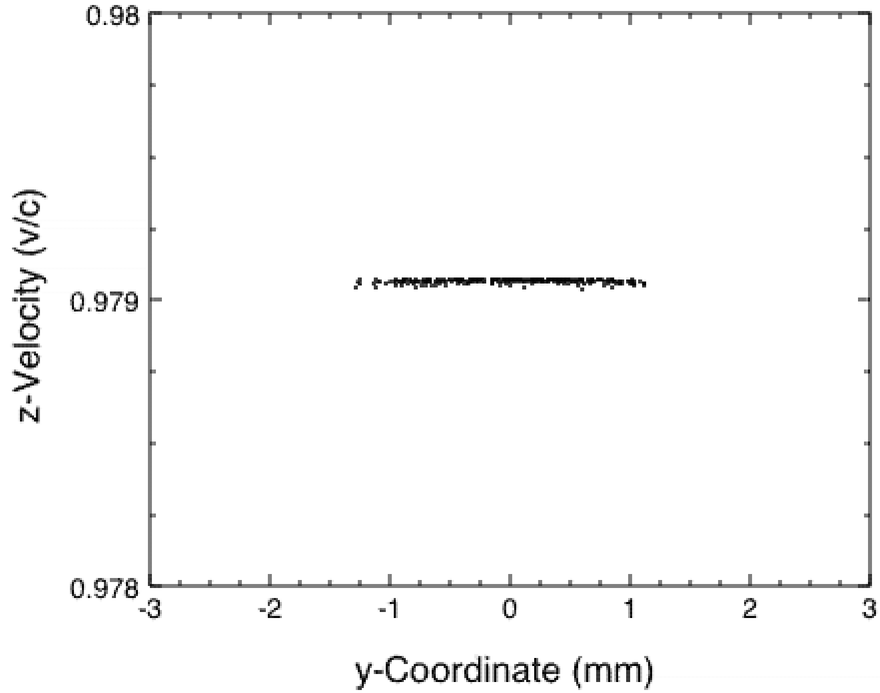


WIGGLER FLOW

•Current = 0

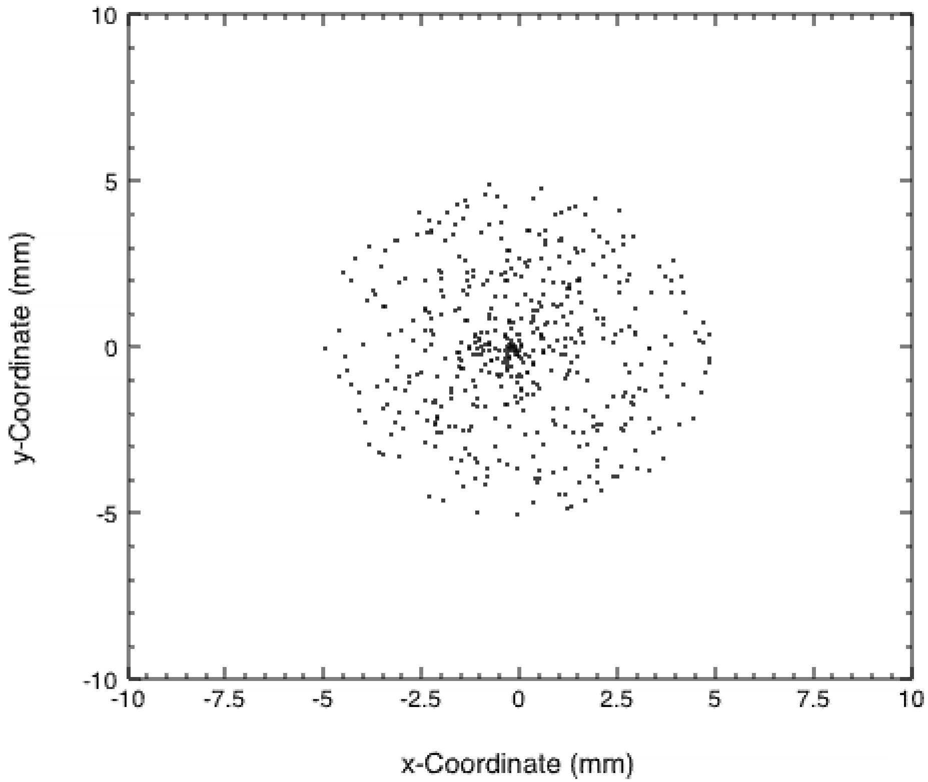


•Current = 210 A



BRILLOUIN FLOW

- Current = 120 A



CONDITIONING: SUMMARY

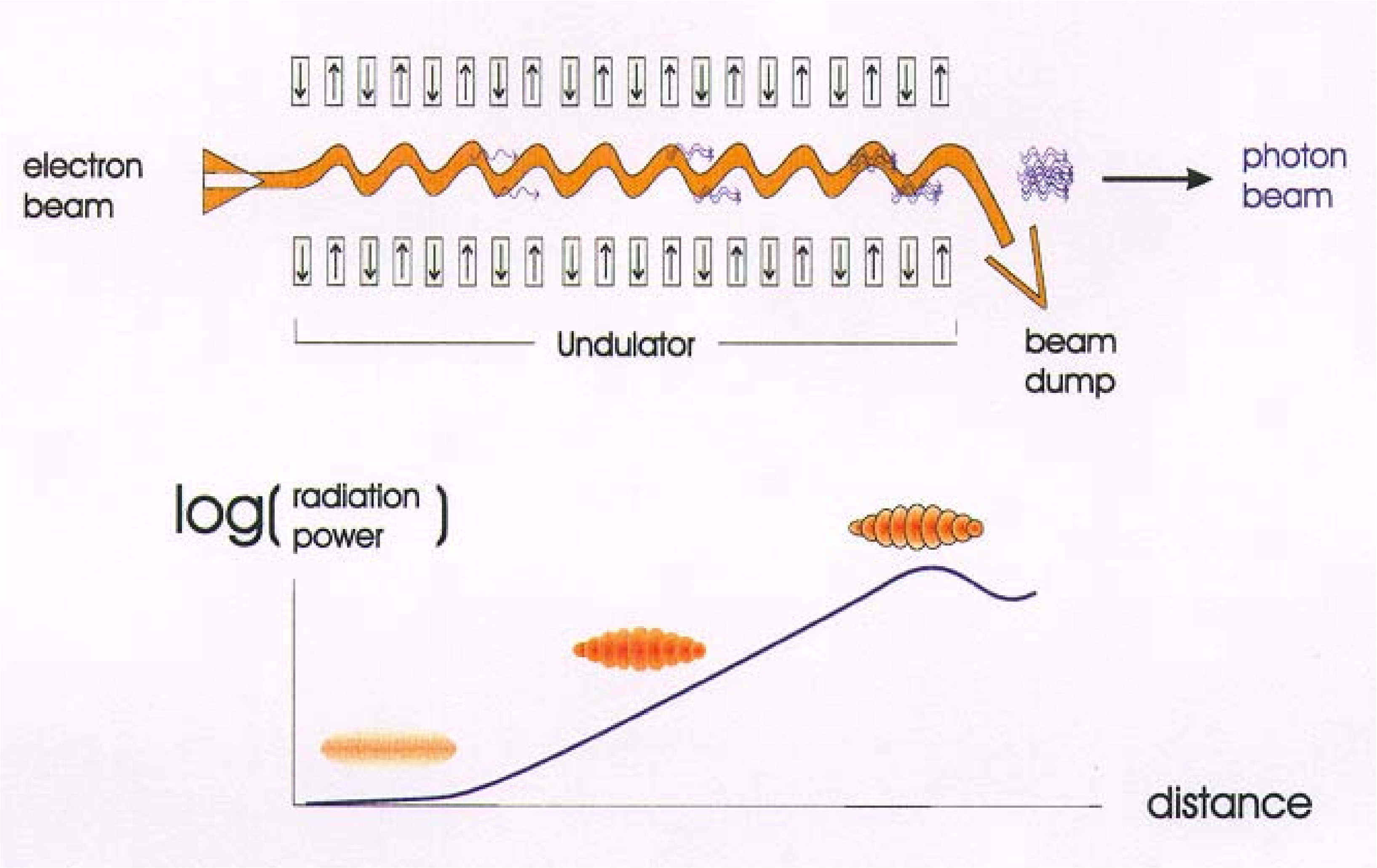
- Conditioning improves electron beam quality for FELs

- For short wavelengths conditioning requires external fields

- For low-voltage, high-current FELs self-conditioning appears to be possible

Back-up View Graphs

SELF AMPLIFIED SPONTANEOUS EMISSION*



*tesla.desy.de

ELECTRON DYNAMICS

- Axial velocity

$$\beta_Z \approx 1 - \frac{1}{2\gamma^2} - \frac{\beta_\perp^2}{2}$$

- Wiggler field

$$\mathbf{A}_w = A_w \cosh(k_w y)\sin(k_w z)\mathbf{e}_x$$

- Transverse velocity

$$\boldsymbol{\beta}_\perp = \frac{a_w}{\gamma}(1 + k_w^2 y^2 / 2)\sin(k_w z)\mathbf{e}_x + \frac{dy}{dz}\mathbf{e}_y$$

BEAM CONDITIONING WITH CAVITIES

- Remove axial velocity spread by introducing correlation between betatron amplitude & energy
- Conditioning with periodic array of FODO channels & *cavities* excited in TM_{210} mode (~5 GHz)

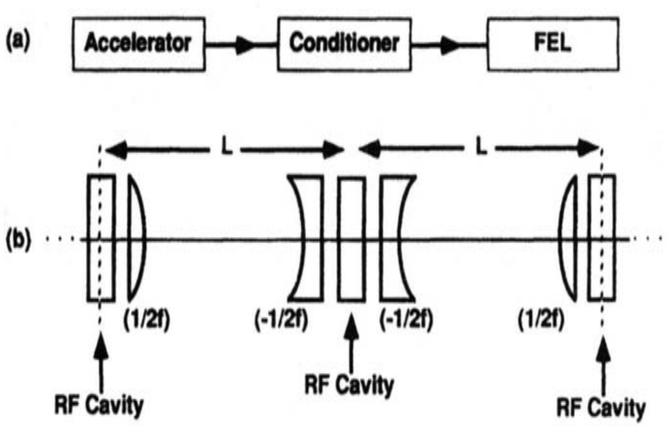


TABLE I. Parameters for several example FEL designs, with and without a conditioned beam. Current is fixed at $I \sim 300$ A, with energy spread $\sigma/\gamma \sim 4.4\times10^{-4}$. In each case k_w was varied to minimize L_G.

	10 μm	Conditioned	3000 Å	Conditioned	500 Å	Conditioned
$mc^2\gamma_0$ (MeV)	54	54	483	153	1004	304
ε_n (m)	$8\times10^{-4}\pi$	$8\times10^{-4}\pi$	$5\times10^{-5}\pi$	$5\times10^{-5}\pi$	$2\times10^{-5}\pi$	$2\times10^{-5}\pi$
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$L_G/2$ (m)	8.0	1.6	3.1	1.4	4.6	2.1
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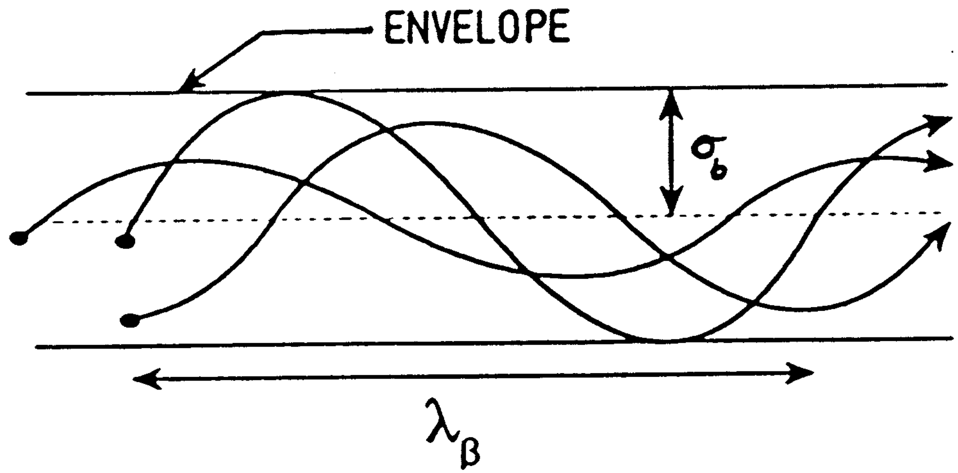
N_c		1		10		10
L_c (m)		10		20		50

[1)]Sessler *et al.*, Phys. Rev. Lett. **68**, 309 (1992)

ELCTRON BEAM ENVELOPE



- Spread $\delta\beta_z \approx -\frac{1}{2}k_\beta^2 y_\beta^2$

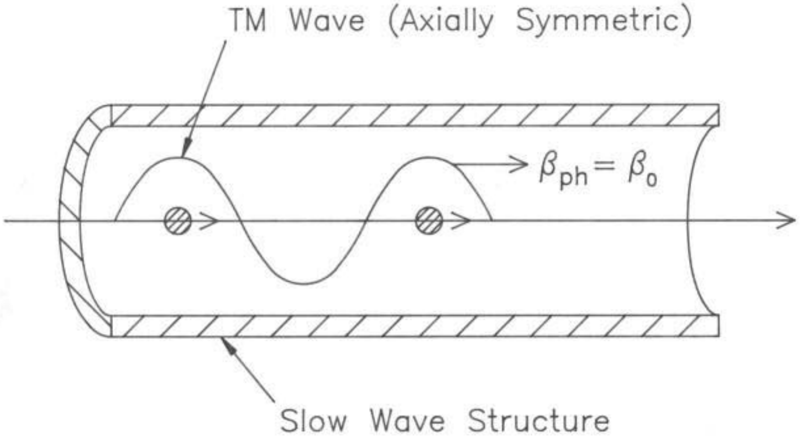
- Matched beam $k_\beta \sigma_b^2 = \varepsilon$

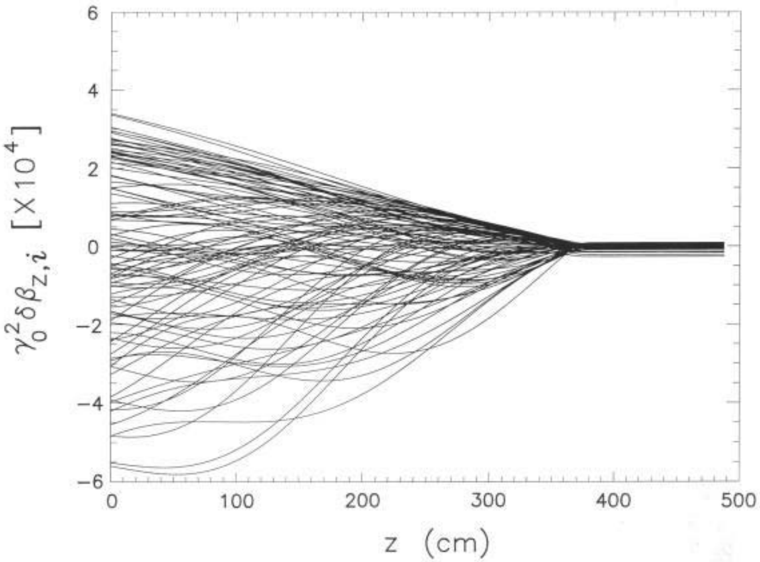
$$|\delta\beta_z| < \frac{1}{2}k_\beta \varepsilon$$: surprise

$$k_\beta = \frac{a_w k_w}{\sqrt{2}\beta_{z0}\gamma_0}(1 - SFP)^{1/2}$$

BEAM CONDITIONING IN WAVEGUIDE

- Introduce correlation between betatron amplitude & energy
- Conditioning with TM *waveguide* mode (~15 GHz)

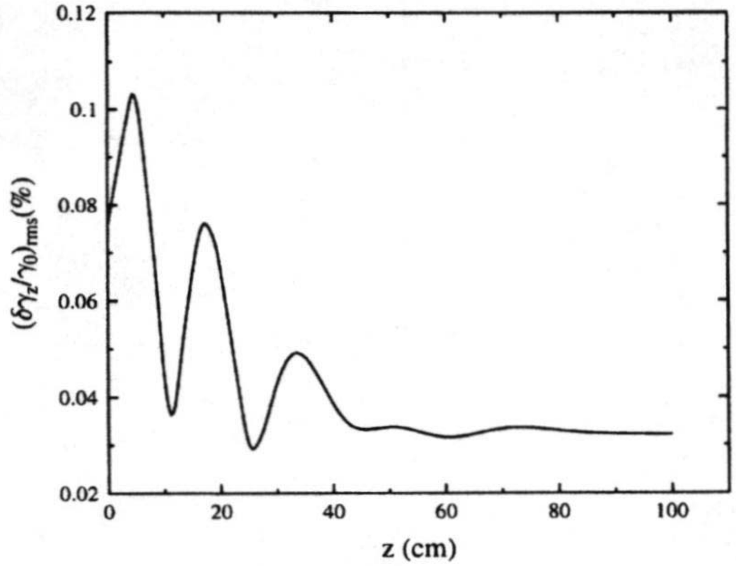




[1)]Sprangle *et al.*, Phys. Rev. Lett. **70**, 2896 (1993)

BEAM CONDITIONING WITH LASER BEAM

- Introduce correlation between betatron amplitude & energy
- Conditioning with TEM_{10} Gaussian *optical* beam (~1 or 10 μm laser)



[1)]Liu & Neil, Phys. Rev. Lett. **70**, 3557 (1993)

BEAM QUALITY

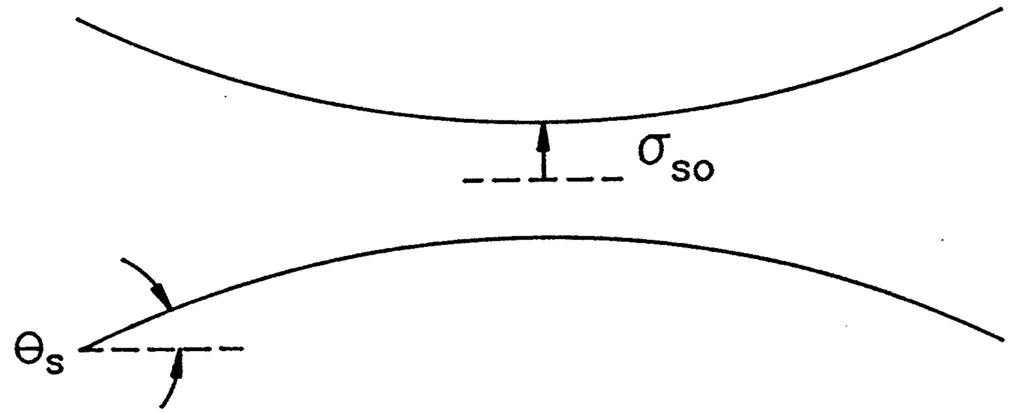
- FEL interaction dominated by axial velocity
- Adopt scaled thermal velocity S is measure of beam quality

$$S \equiv \frac{v_{th,z}}{< v_z > - v_{ph}}$$

- v_{ph} depends on FEL parameters, including electron density
  - Warm beam regime: $S \geq 1$
  - Cold beam regime: $S << 1$

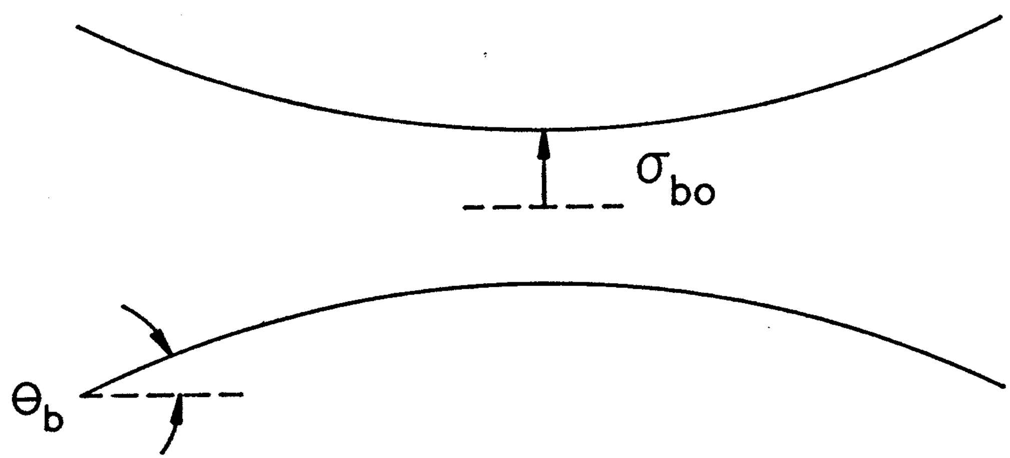
EMITTANCE & DIFFRACTION

Optical beam expands
due to *diffraction*
$\Delta k \Delta x \approx 1$



•wave

Electron beam expands
due to *emittance*
$\Delta \beta \Delta x \approx \varepsilon$



VLASOV-MAXWELL MODEL

- Wiggler & optical fields

$$\mathbf{A}_w = A_w \cosh(k_w y)\sin(k_w z)\mathbf{e}_x$$

$$\mathbf{A}_s = \tfrac{1}{2} A_s(y,z)\exp[i(kz-\omega t)]\mathbf{e}_x + c.c.$$

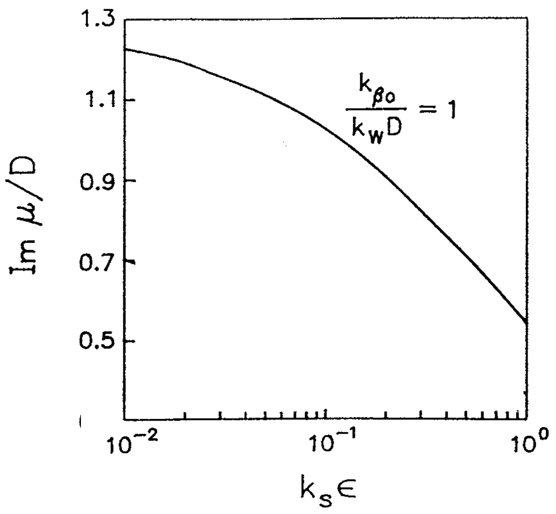
- Electron distribution function

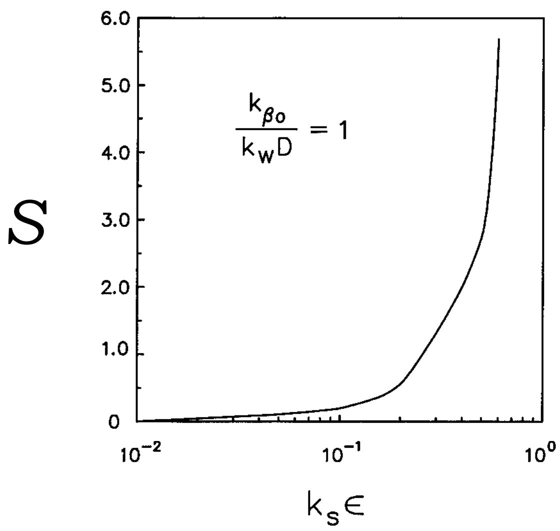
$$F(E,P_x,J) = \frac{I_b/(\beta_{z0}I_0)}{2\pi mcr_e\varepsilon_N}\frac{\exp[-(E-E_0)^2/(\sigma_\gamma mc^2)^2]}{\sqrt{\pi}\sigma_\gamma mc^2}$$
$$\times\delta(P_x)\exp(-k_{\beta 0}J/mc\varepsilon_N k_\beta)$$

$J = \iint dy dp_y/2\pi$: ⊥ phase space area

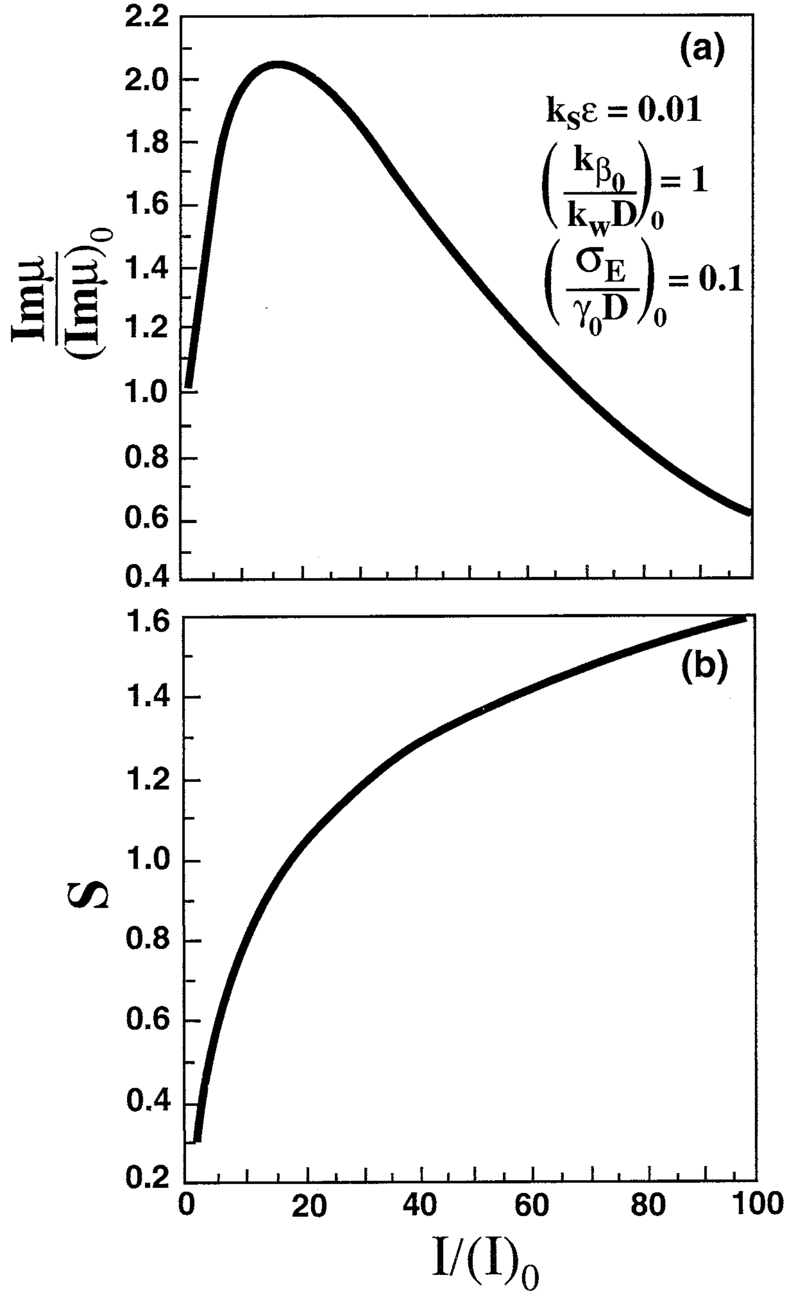
- Integrate over unperturbed orbits

EFFECT OF EMITTANCE





BEAM COMPRESSION (cont.)



COMPACT FELs

- One approach to compact X-Ray FELs is to use a low-voltage (10's MV) beam with an ultra-intense laser as wiggler; $\lambda \approx \lambda_w /(4\gamma^2)$

- Space charge effects can be limiting factor in this approach

COMPACT FEL (cont.)

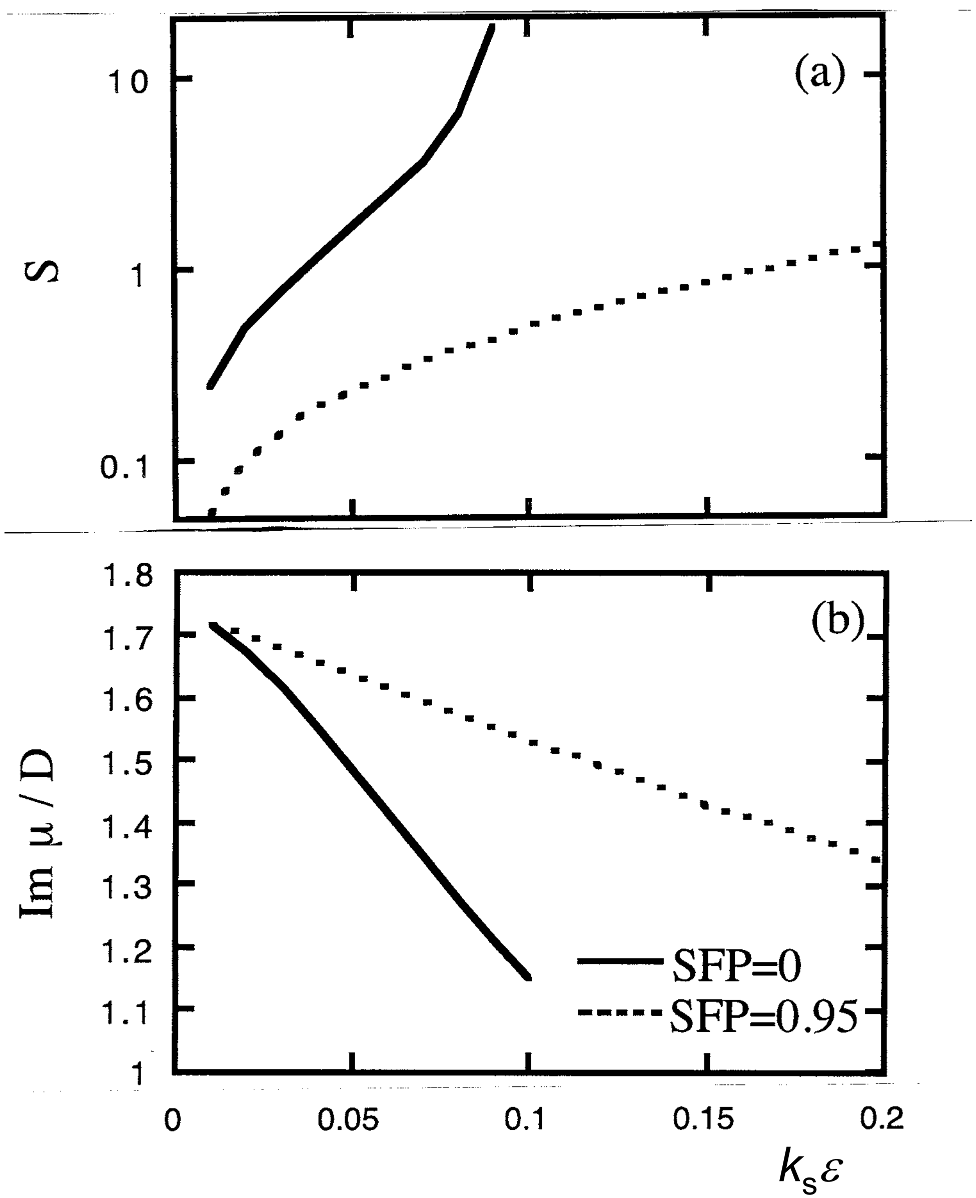
- Scaled thermal velocity including space charge

$$S = \frac{\left\{ 2\left(\frac{\sigma_\gamma}{\gamma_0}\right)^2 + \left[\frac{k_\beta}{k_w} k_s \varepsilon\right]^2 \right\}^{1/2}}{\eta}$$

- η: 'cold' beam efficiency
- Emittance & energy spread add up in quadrature
- Self fields reduce effect of emittance

$$k_\beta \to 0, SFP \to 1$$

COMPACT FEL (cont.)



SUGGESTED READING

- T.M. O'Neil & J.H. Malmberg, *Transition of dispersion roots from beam-type to Landau-type solutions*, Phys. Fluids **11**, 1754 (1968). **Change in topology of dispersion relation with S**

- C.W. Roberson & P. Sprangle, *A review of free electron lasers*, Phys. Fluids B **1**, 3 (1989). **Review of FELs – the first 10 years**

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- C.W. Roberson, K.W. Gentle & P. Neilsen, Phys. Rev. Lett. **26**, 226 (1971)
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- J.R. Thompson, Phys. Fluids **14**, 1532 (1971)
- T.J. Orzechowski, *et al.*, Phys. Rev. Lett. **57**, 17 (1986)

SCALED THERMAL VELOCITY

- Scaled thermal velocity including space charge

$$S = \frac{\left\{2\left(\frac{\sigma_\gamma}{\gamma_0 D}\right)^2 + \left[\frac{k_{\beta 0}}{k_w D} k_s \varepsilon (k_\beta / k_{\beta 0})\right]^2\right\}^{1/2}}{\beta_{z0}\left[-\frac{\Re\mu}{D} + \frac{1-\omega/\omega_s}{D}\right] - \frac{k_{\beta 0}}{k_w D} k_s \varepsilon (k_\beta / k_{\beta 0})}$$

- $k_\beta = k_{\beta 0}(1\text{-}SFP)^{1/2}$

- SFP = $\left(\frac{k_p / k_{\beta 0}}{\beta_{z0}\gamma_{z0}\gamma_0^{1/2}}\right)^2$

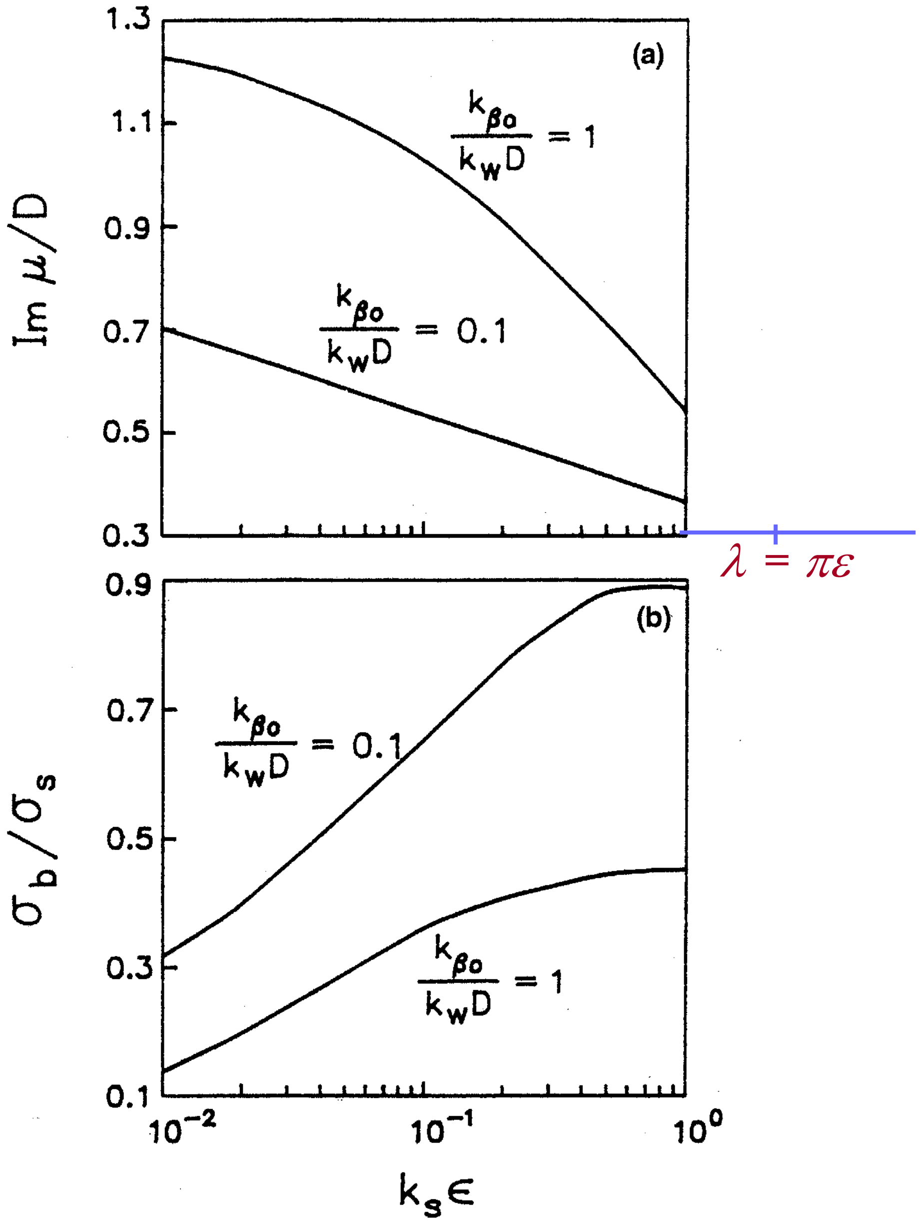
SCALED PARAMETERS

- $k_{\beta 0}/k_w D$: wiggler parameter
- μ/D: growth rate & wavenumber shift
- $(1-\omega/\omega_s)/D$: detuning
- $k_{\beta 0}\zeta_R$: Rayleigh range
- $k_s \varepsilon$: emittance; $k_s \approx 2\gamma^2 k_w$
- $\sigma_\gamma/\gamma_0 D$: energy spread

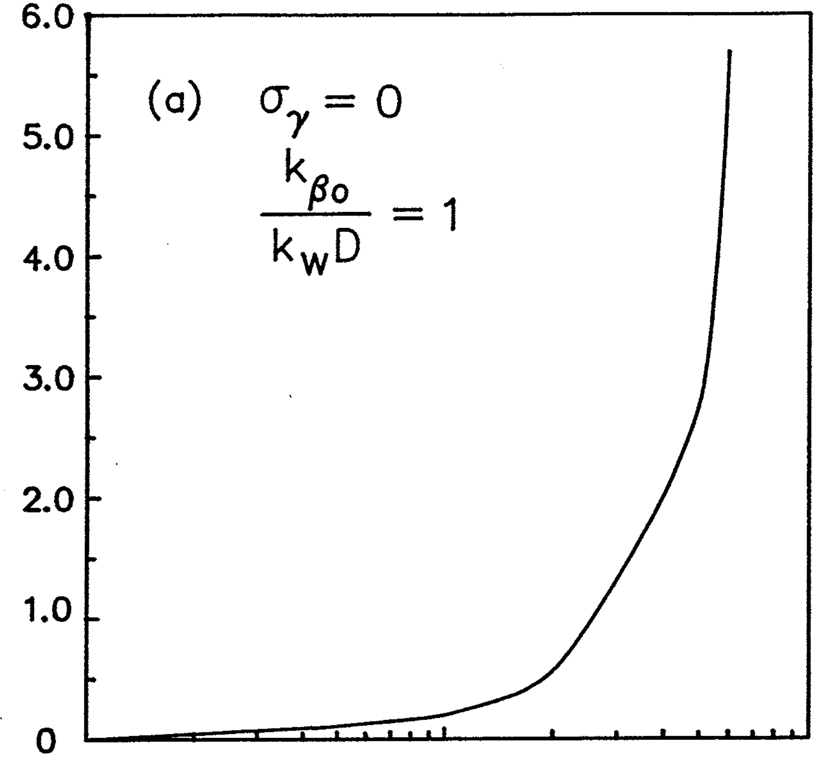
$$D = \left[\left(\frac{2\pi}{k_{\beta 0} k_s}\right)^{1/2} \frac{I_b}{I_A} \left(\frac{a_w k_s f_B}{2 k_w \gamma_0^2 \beta_{z0}^2} \right)^2 (1 + a_w^2/2) \right]^{1/2}$$: *3-D Pierce Parameter*

I_b: current, I_A: Alfven current

EFFECT OF EMITTANCE



EFFECT OF EMITTANCE



SCALED PARAMETERS

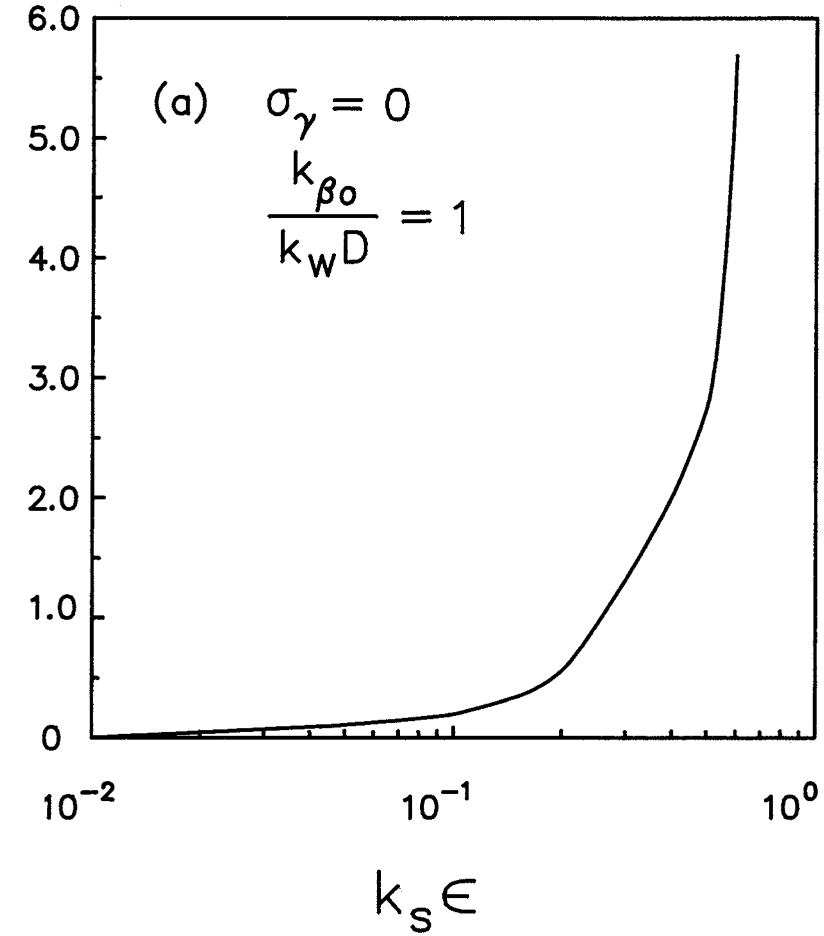
- $k_{\beta 0}/k_w D$: wiggler parameter
- μ/D: growth rate & wavenumber shift
- $k_s \varepsilon$: emittance
- $\sigma_\gamma/\gamma_0 D$: energy spread

$k_s \approx 2\gamma^2 k_w$

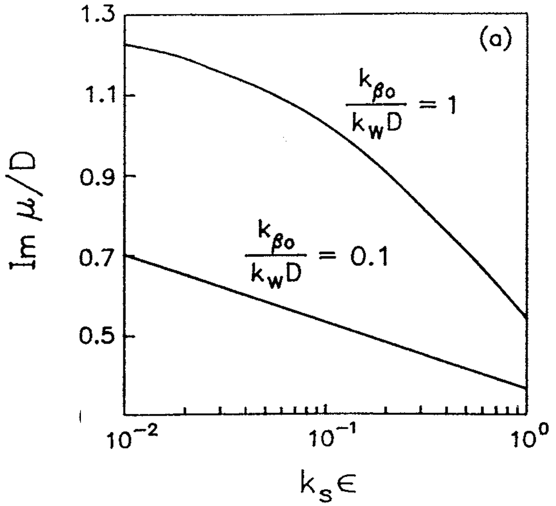
$$D = \left[\left(\tfrac{2\pi}{k_{\beta 0} k_s}\right)^{1/2} \tfrac{I_b}{I_A} \left(\frac{a_w k_s f_B}{2 k_w \gamma_0^2 \beta_{z0}^2} \right)^2 (1 + a_w^2/2) \right]^{1/2}$$

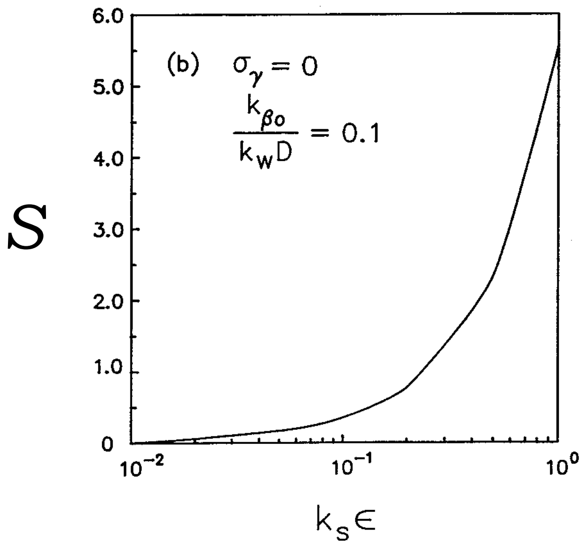
: *3-D Pierce Parameter*

I_b: current, I_A: Alfven current


6.0
5.0
4.0
3.0
2.0
1.0
0
(a) σγ = 0
kβo / kwD = 1
10−2
10−1
100
ksϵ

EFFECT OF EMITTANCE





BACKGROUND

- 2-stream instability is collective process driven by free energy of streaming particles
  - Cold beam: coupled +ve & -ve energy modes in plasma ⇒ exponential growth
  - Warm beam regime: inverse Landau damping ⇒ growth; real part of *DR* not modified

- O'Neil & Malmberg found scaled thermal velocity $S \equiv (v_{th}/v_b)(2n_0/n_b)^{1/3} = v_{th}/(v_b - v_{ph})$ to be a useful measure of transition between these regimes

- We adopt *S* as a measure of beam quality in high gain FELs

BEAM QUALITY (cont.)

- $\beta_{\mathrm{th,z}}$ comes from spread, $\delta\beta_z$, of individual electrons

- $\delta\beta_z$ is due to
  - Betatron oscillations & emittance
  - Intrinsic energy spread
  - Space charge effects

VLASOV-MAXWELL MODEL

- Wiggler & optical fields

$$\mathbf{A}_w = A_w \cosh(k_w y)\sin(k_w z)\mathbf{e}_x$$

$$\mathbf{A}_s = \tfrac{1}{2} A_s(y,z)\exp[i(kz-\omega t)]\mathbf{e}_x + c.c.$$

- Electron distribution function

$$F(E,P_x,J) = \frac{I_b/(\beta_{z0}I_0)}{2\pi mcr_e\varepsilon_N}\frac{\exp[-(E-E_0)^2/(\sigma_\gamma mc^2)^2]}{\sqrt{\pi}\sigma_\gamma mc^2}$$

$$\times\delta(P_x)\exp(-k_{\beta 0}J/mc\varepsilon_N k_\beta)$$

$J = \iint dy dp_y/2\pi$: ⊥ phase space area

- Lasing wavelength $\lambda_s = \dfrac{\lambda_w(1+a_w^2/2)}{2\gamma_0^2}$

- Integrate over unperturbed orbits