Conditioned Beams: Principle and Consequences

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1. Introduction

- The energy and longitudinal position of particles are often correlated to good advantage. This is done for bunch compression and in the final focus region of linear colliders.
- Here we consider energy correlated with transverse amplitude
- The idea behind a "beam conditioner" is to introduce a correlation between beam amplitude and energy to improve the performance of an FEL
- Reference: A.M. Sessler, D.W. Whittum, and L.-H. Yu, " Radio-frequency beam conditioner for fast wave free electron generators of coherent radiation", Physical Review Letters **66**, 309 (1992).

2. Concept

- Resonance condition for FEL requires a specific average velocity: after each undulator period, electrons fall behind the laser field by exactly one wavelength.
- The usual resonance condition assumes zero emittance. Adding correlations of transverse amplitude with energy brings more particles into resonance.
- For a zero amplitude particle, the typical angle is K/γ, where K is the normalized strength of the undulator.
- Then $$\frac{v_z^2}{c^2} = 1 - \frac{1}{\gamma^2} - \frac{\bar{v}_\perp^2}{c^2} \simeq 1 - \frac{1+K^2}{\gamma^2}$$
- Slippage after one undulator period should be λ:

$$\lambda = \Delta z = \left(1 - \frac{v_z}{c}\right)\lambda_w \simeq \frac{1}{2}\left(1 - \frac{v_z^2}{c^2}\right)\lambda_w = \frac{1+K^2}{2\gamma^2}\lambda_w$$

2. Concept (Continued)

- This is the basic resonance condition. For large γ, the angle and $v_\perp/c$ are roughly the same.

- For non-zero emittance, the average angle in terms of the normalized emittances is:

$$\langle \theta_\epsilon^2 \rangle \simeq \frac{2\pi(\epsilon_{Nx} + \epsilon_{Ny})}{\gamma \lambda_\beta}$$

- Here $\lambda_\beta = 2\pi\beta_x = 2\pi\beta_y$

- The angles from the emittances and undulator are uncorrelated, and add in quadrature.

- Modified equation for v_z: $$\langle \theta_\epsilon^2 \rangle + \frac{v_z^2}{c^2} \simeq 1 - \frac{1+K^2}{\gamma^2}$$

2. Concept (Continued)

- To have uniform v_z requires an energy shift $\Delta\gamma$ from the zero emittance case to balance out the emittance term:

$$\frac{2\pi(\epsilon_{Nx} + \epsilon_{Ny})}{\gamma\lambda_\beta} \simeq \langle\theta_\epsilon^2\rangle = \frac{1+K^2}{\gamma^2}\frac{2\Delta\gamma}{\gamma}$$

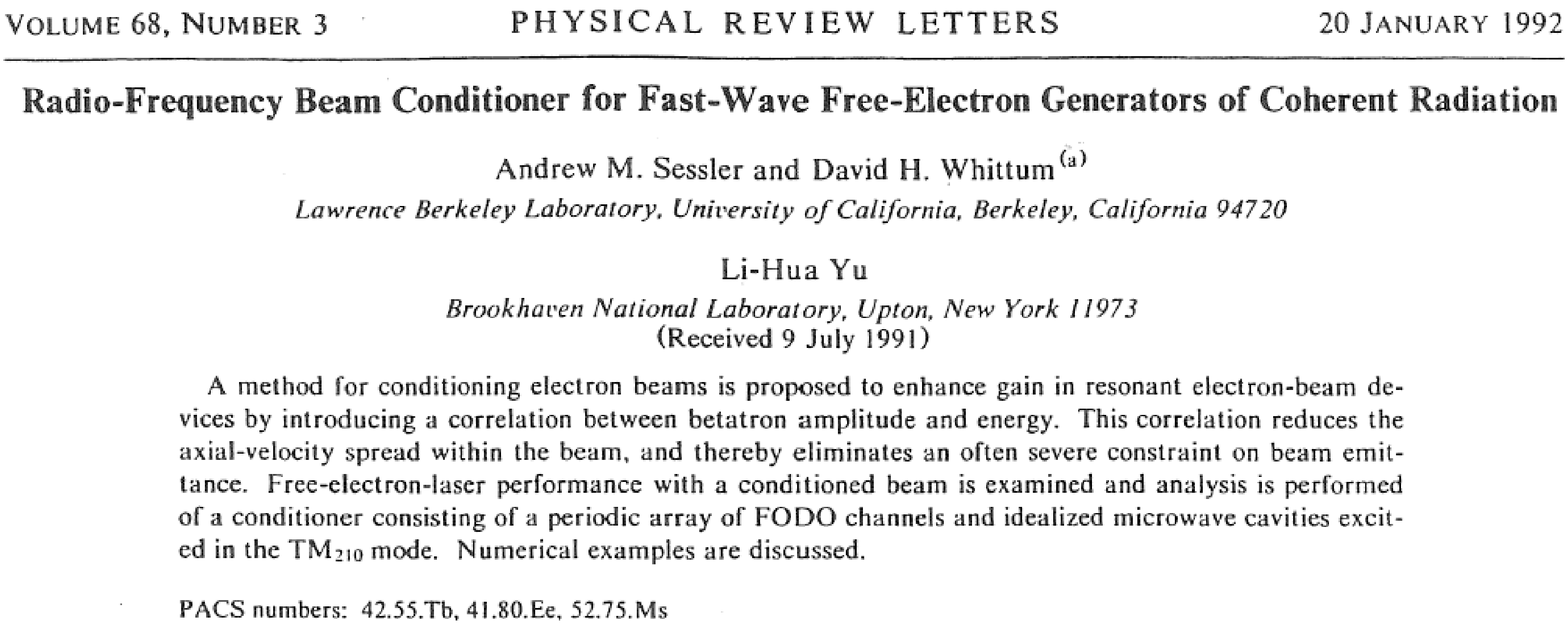
- Note $\Delta\gamma/\gamma << 1 \quad \Rightarrow \quad \lambda_\beta >> \pi\gamma(\varepsilon_{Nx} + \varepsilon_{Ny})/(1+K^2)$

- Using the resonance condition and taking $\varepsilon_{Nx}=\varepsilon_{Ny}=\varepsilon_N$,

$$\Delta\gamma = \pi\frac{\lambda_w}{\lambda}\frac{\epsilon_N}{\lambda_\beta}$$

- If the gain length $\leq \lambda_\beta$, no averaging over betatron oscillation: then what matters is the peak angle, near axis, where the fields are strongest.
- This doubles the conditioning required.

3. Historical material



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

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A method for conditioning electron beams is proposed to enhance gain in resonant electron-beam devices by introducing a correlation between betatron amplitude and energy. This correlation reduces the axial-velocity spread within the beam, and thereby eliminates an often severe constraint on beam emittance. Free-electron-laser performance with a conditioned beam is examined and analysis is performed of a conditioner consisting of a periodic array of FODO channels and idealized microwave cavities excited in the TM_{210} mode. Numerical examples are discussed.

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3. Historical material (Continued)

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 $\sigma/\gamma \sim 4.4 \times 10^{-4}$. 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)	$8\times10^{-4}\pi$	$8\times10^{-4}\pi$	$5\times10^{-5}\pi$	$5\times10^{-5}\pi$	$2\times10^{-5}\pi$	$2\times10^{-5}\pi$
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

3. Historical material (Continued)

These results assume a point bunch. For a finite bunch length l, there will in addition be a small sweep in energy from head to tail, $\Delta\gamma_l = -(\theta^2/2)\Delta\gamma_c$, where $\theta = \omega_c l/c$ and ω_c is the cavity angular frequency. More significantly, from the Panofsky-Wenzel theorem one expects a radio-frequency quadrupole (RFQ) effect with a phase-dependent focal length of order $f_l \sim \gamma/2al$. As a result the beam head and tail will have slightly different lattice parameters and will be mismatched upon injection. We will consider only the limit $f_l \gg f$, where this effect is small. In general one expects that this effect can be eliminated with proper matching at the conditioner entrance and exit, for example, with an RFQ [12].

We were correct about the work not applying to finite bunches. We were incorrect to think RFQ could fix the matching, but Andy Wolski will tell us how to match.

3. Historical material (Continued)

We find that while the potential improvement in FEL performance is great, the simple conditioner we have considered here is inadequate. For example, for a 30-Å FEL, with $I \sim 80$ A, $mc^2\gamma_0 \sim 1240$ MeV, $\varepsilon_n \sim 2\times10^{-6}\pi$ m, $\lambda_w \sim 2$ cm, $B \sim 0.66$ T, and plasma density $n_p \sim 1.5\times10^{13}$ cm^{-3}, we find extremely high gain, $L_G/2 \sim 2.1$ m (without conditioning $L_G/2 \sim 26$ m). However, $mc^2\Delta\gamma_c \sim 17$ MeV and the corresponding conditioner would be several hundred meters long [17].

The broader conclusion from this kind of analysis is that conventional microwave linacs and focusing lattices are not optimally designed as FEL drivers. We have in some sense demonstrated this "by construction," albeit a simple construction; we are optimistic that more sophisticated conditioner designs will make feasible more compact conditioners, and ultimately high-gain FEL operation in the x-ray regime.

4. Applications

- Simulations using GENESIS, with energy-amplitude correlations added to the particle loading subroutines. All runs use amplifying mode, with initial seed - obtain gain length and saturation.

- The conditioning parameter κ is defined as

$$\Delta\gamma = \kappa \times (J_x + J_y),$$

where J_x is the *normalized* action, with $< J_x > = \varepsilon_{Nx}$

- In the paraxial limit, with $\gamma >> 1$,

$$J_x \simeq \frac{1}{2}\gamma \left[\frac{2\pi x^2}{\lambda_\beta} + \frac{\lambda_\beta}{2\pi} \left(\frac{v_x}{c} + \frac{2\pi\alpha x}{\lambda_\beta} \right)^2 \right]$$

4. Applications (Continued)

- Proper conditioning requires $\kappa \simeq \frac{\pi}{\lambda_\beta} \frac{\lambda_w}{\lambda}$
- Interpretation of conditioning parameter:
  - for $\kappa = 1\ \mu m^{-1}$, a beam with $\varepsilon_{Nx} = \varepsilon_{Ny} = 2\ \mu m$ has $\Delta\gamma = 4$,
  - i.e. an electron at typical amplitude has 2 MeV more energy than a particle at zero amplitude.
- Specific examples are given below.
- In the following plots,
  - red = nominal case
  - green = 2 x emittance
  - black = largest emittance
  - points = unconditioned, lines = conditioned
- Conditioned beams are optimized at smaller beta functions, leading to further improvements.
  - Indicated on plots by '+'s overlapping a line

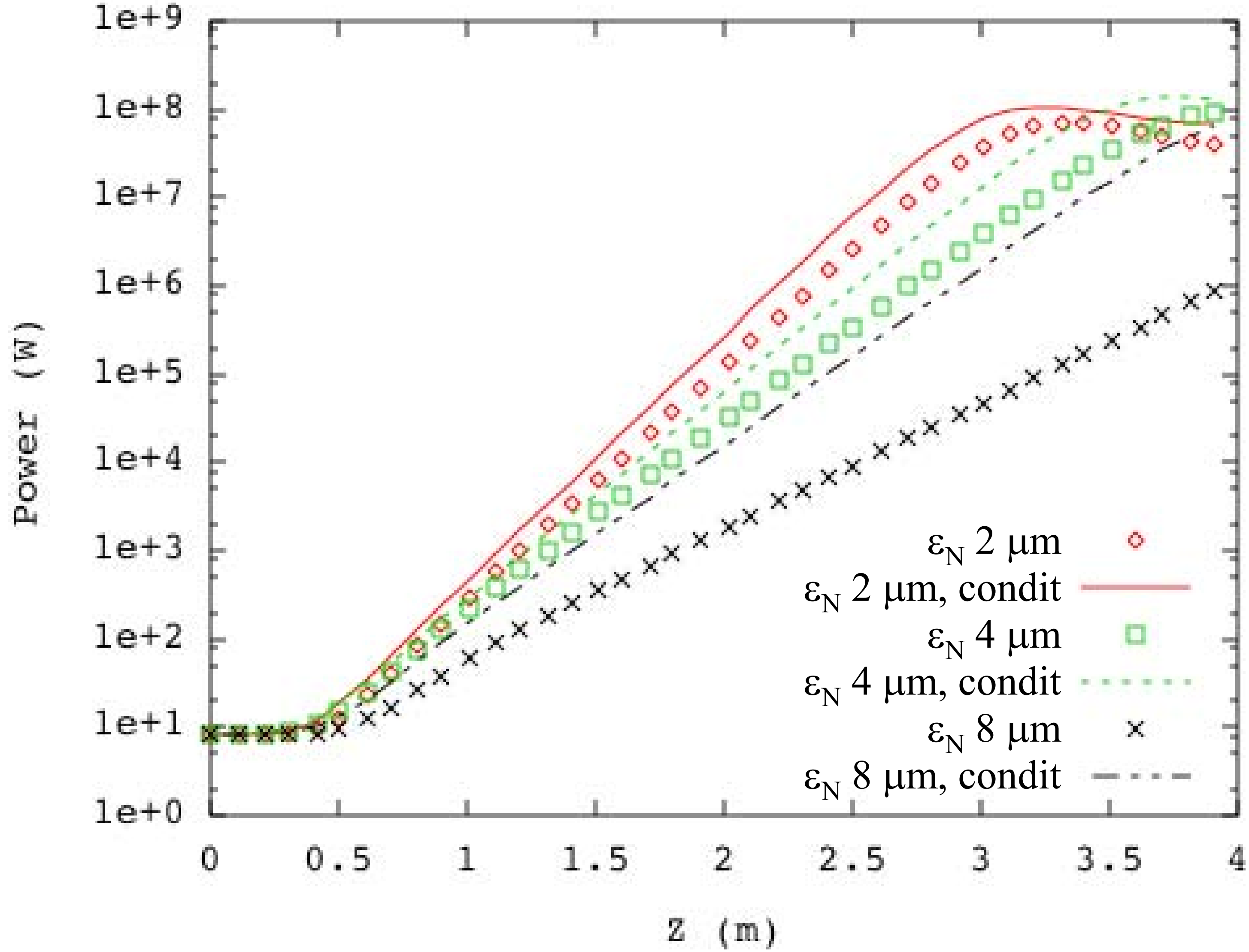
VISA

- Parameters:
  - radiation wavelength 0.84 μm
  - 70 MeV, $\Delta\gamma/\gamma = 8 \times 10^{-4}$
  - 2.1 μm emittance
  - peak current 240 A
  - undulator: $\lambda_w = 1.8$ cm, $K = 0.89$

- $\lambda_\beta \approx 1.8$ m, matched $\kappa = 0.036\ \mu m^{-1}$

- Not limited by emittance, conditioning has little effect until reach 4x nominal emittance. Optimum gain length ~ 16 cm.

VISA Results ($\lambda_\beta \equiv 1.8$ m)



Soft X-rays

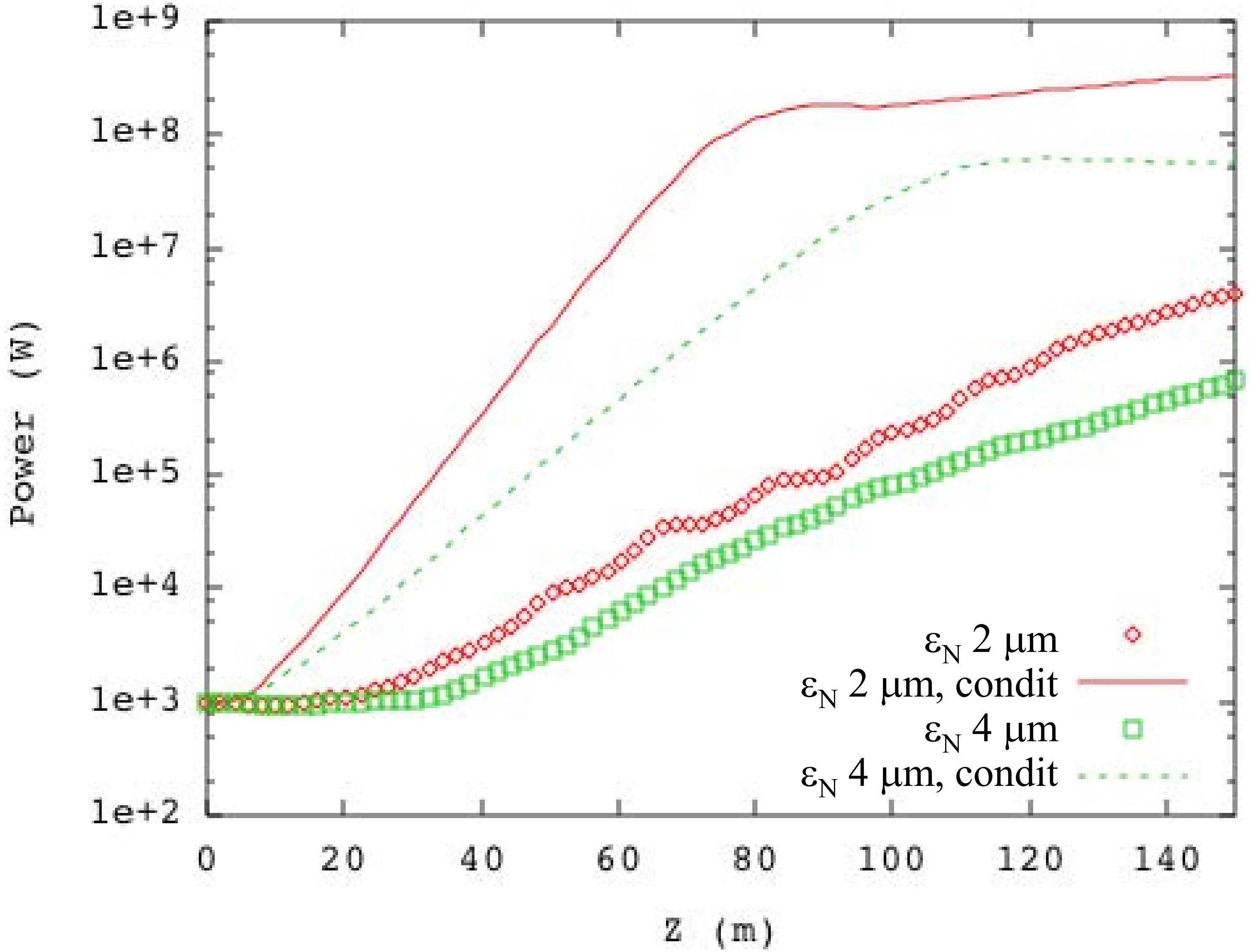
- An example for 1 nm wavelength (1.24 keV)

- Parameters:
  - radiation wavelength 1 nm
  - 2.5 GeV, $\Delta\gamma/\gamma = 4 \times 10^{-4}$
  - 2 μm emittance
  - peak current 500 A
  - undulator: $\lambda_w = 2.5$ cm, $K = 0.96$

- $\lambda_\beta \approx 30$ m, matched $\kappa = 2.6\ \mu\text{m}^{-1}$

- Best value for gain length: 13 m.

Soft X-rays ($\lambda_\beta \equiv 30$ m)

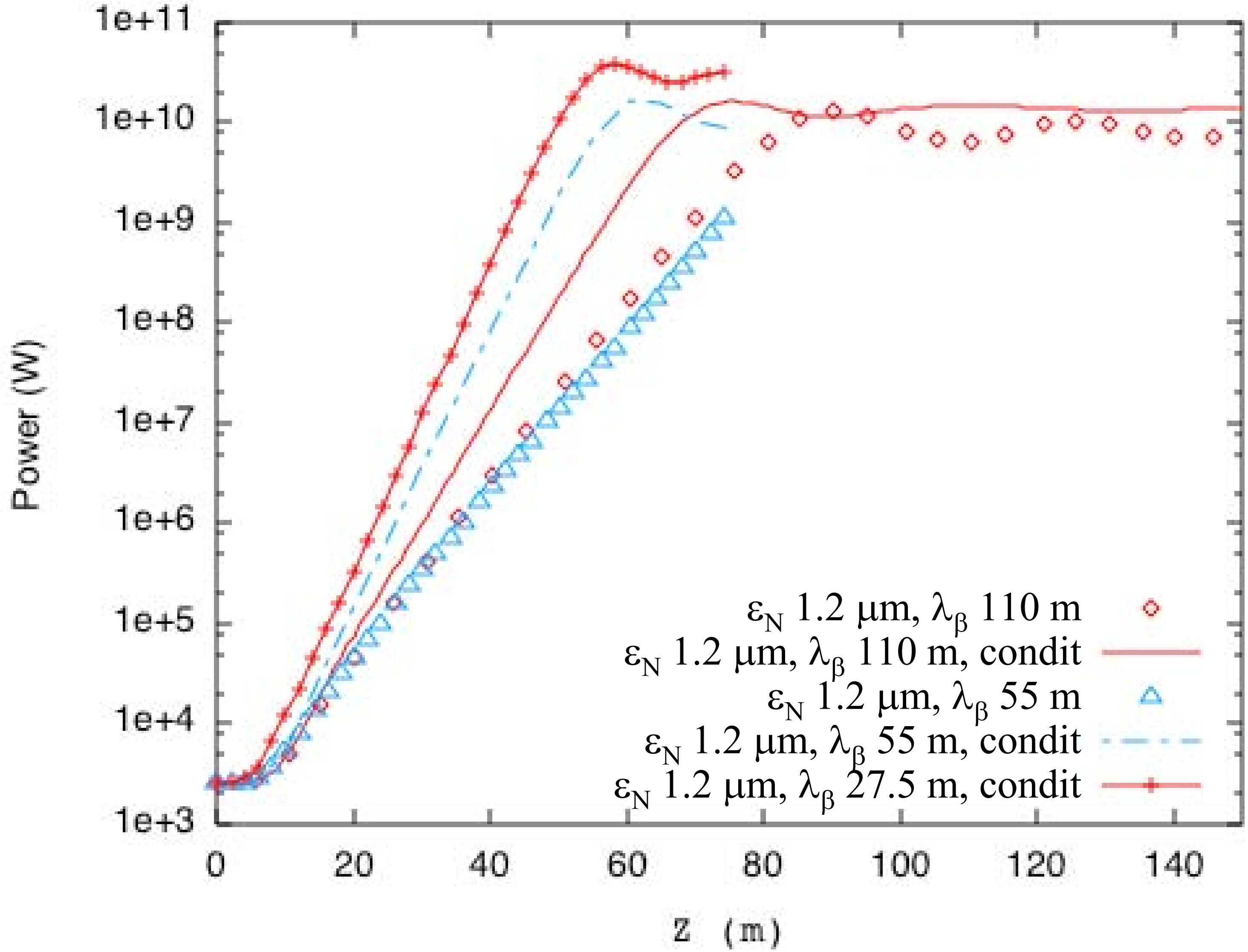


LCLS

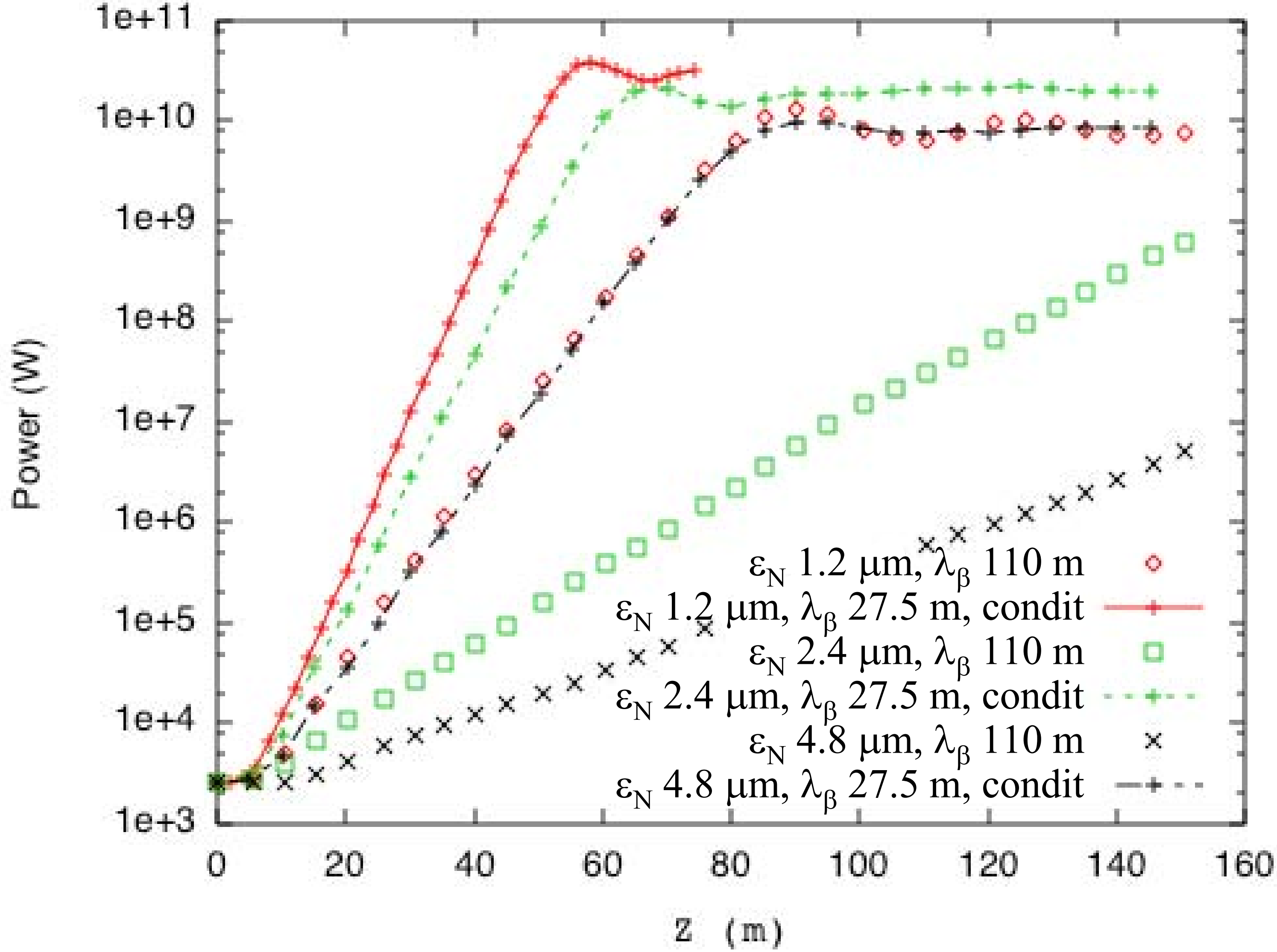
- Parameters:
  - radiation wavelength 1.5 Å
  - 14.3 GeV, $\Delta\gamma/\gamma = 1 \times 10^{-4}$
  - 1.2 μm emittance
  - peak current 3.4 kA
  - undulator: $\lambda_w = 3$ cm, $K = 2.62$

- $\lambda_\beta \approx 110$ m, matched $\kappa = 5.8\ \mu\text{m}^{-1}$

LCLS, vary beta function



LCLS, vary emittance, optimal λ_β



LCLS Results

- Conditioned beam improves with stronger focusing, both in gain length and saturated power, while uncorrelated beam does not.

- At $\lambda_\beta \approx 27.5$ m, matched $\kappa = 23.2\ \mu m^{-1}$, and gain length is 2.5 m.

- Uncorrelated beam has much worse performance at higher emittances.

- With 4 x emittance, conditioned beam has same performance as nominal, uncorrelated beam, with gain length of 5 m.

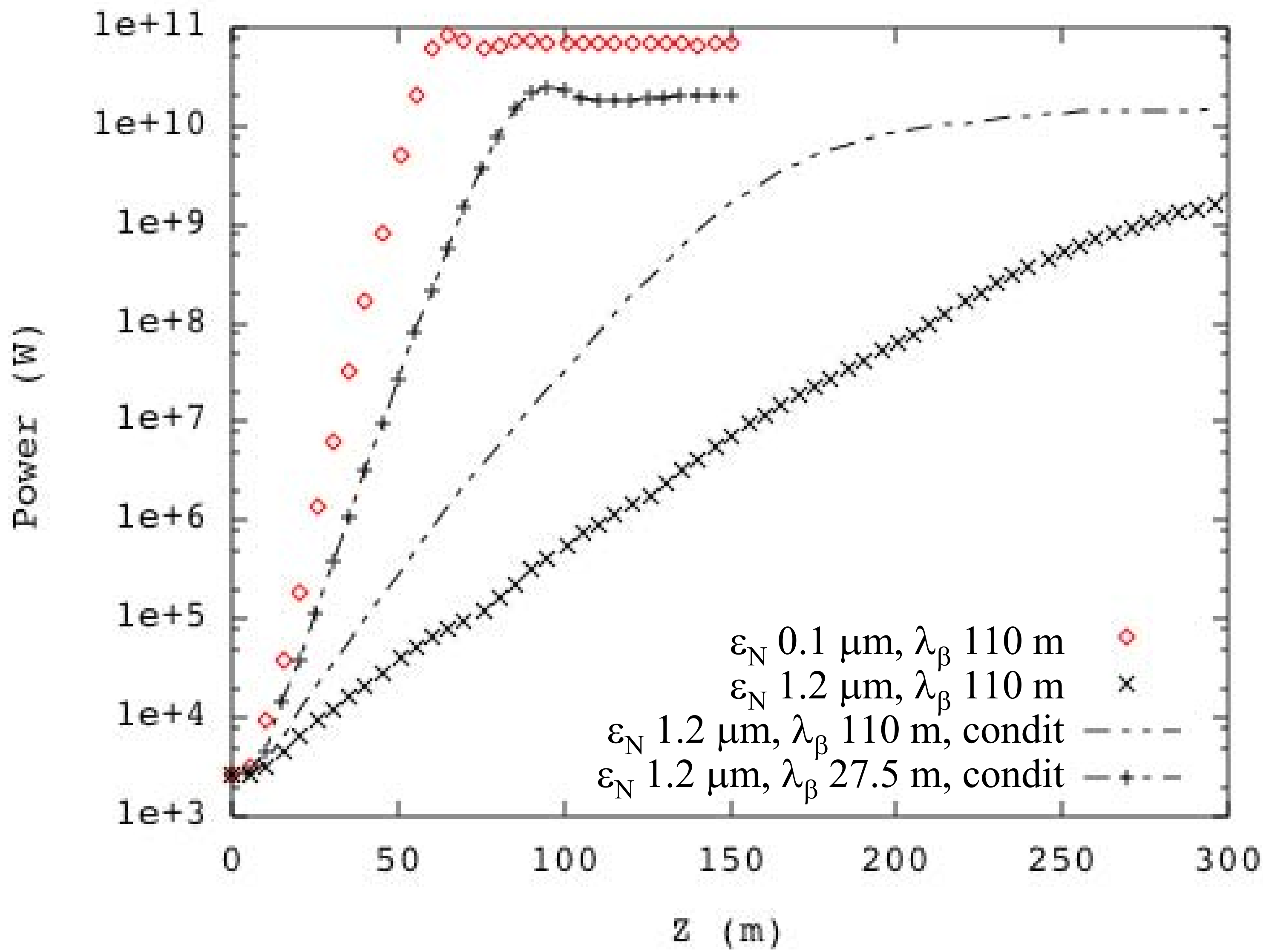
Greenfield FEL

- Possible scheme to achieve highly energetic (30 keV) photons, radiation wavelength 0.4 Å
- Low and high energy options.
- Both cases have peak current of 3.5 kA.
- Nominal emittance 1.2 μm, but consider emittances as low as 0.1 μm.
- Nominal $\lambda_\beta \approx 110$ m in both cases.

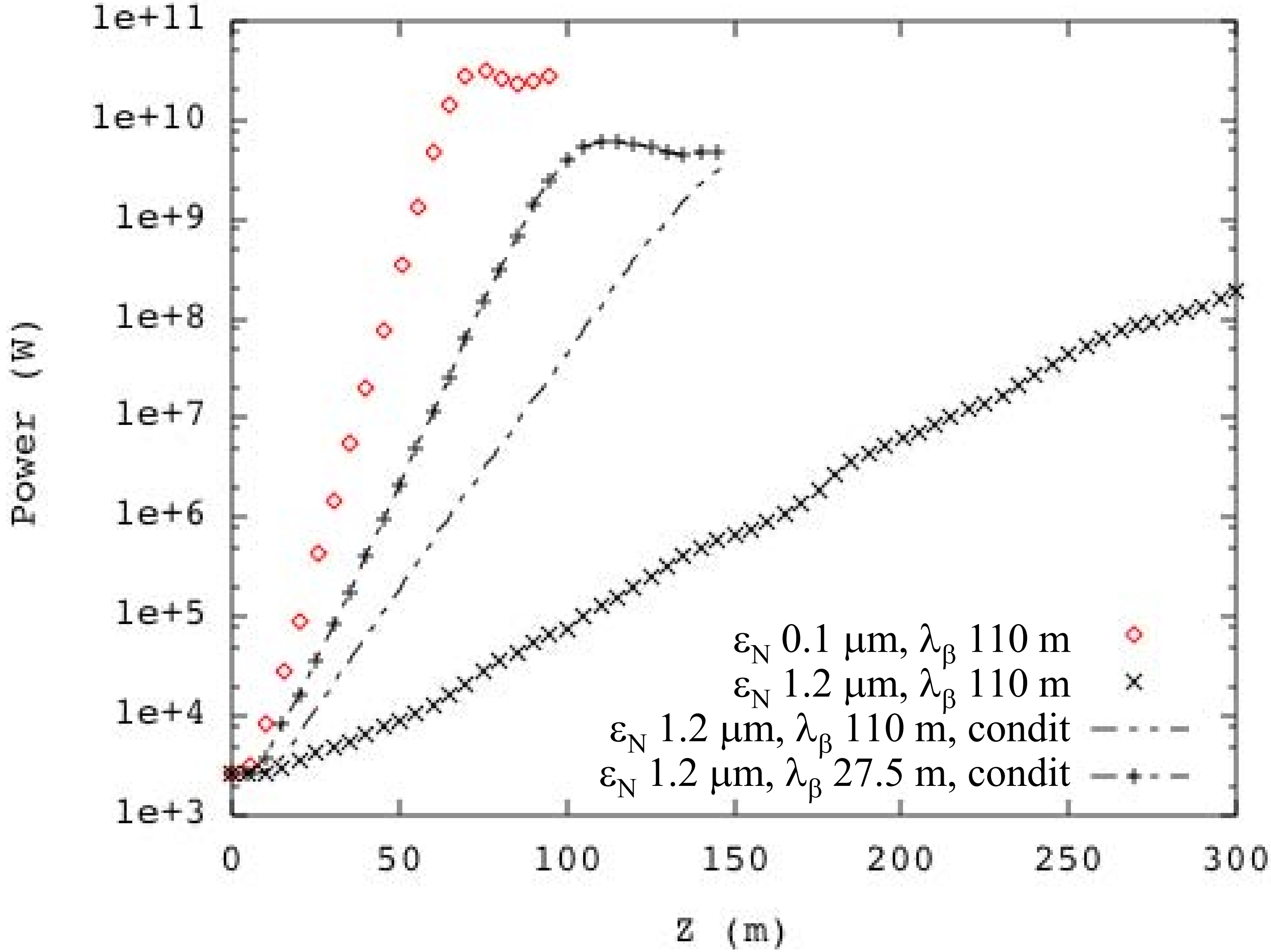
- High energy parameters:
  - 27.8 GeV, $\Delta\gamma/\gamma = 1 \times 10^{-4}$
  - undulator: $\lambda_w = 3$ cm, $K = 2.62$

- Low energy parameters:
  - 12.1 GeV, $\Delta\gamma/\gamma = 1.2 \times 10^{-4}$
  - undulator: $\lambda_w = 3$ cm, $K = 0.71$

Greenfield FEL at 28 GeV



Greenfield FEL at 12 GeV



Greenfield FEL Results

- In both cases:
  - at $\lambda_\beta \approx 110$ m, matched $\kappa = 22\ \mu m^{-1}$
  - if conditioned, better at $\lambda_\beta \approx 27.5$ m, $\kappa = 88\ \mu m^{-1}$.

- At 28 GeV:
  - for $\varepsilon_N = 0.1\ \mu m$, gain length ≈ 3 m
  - for $\varepsilon_N = 1.2\ \mu m$, conditioned with small beta function, gain length ≈ 5 m
  - slightly lower saturation level

- At 12 GeV:
  - for $\varepsilon_N = 0.1\ \mu m$, gain length ≈ 3.2 m
  - for $\varepsilon_N = 1.2\ \mu m$, conditioned with small beta function, gain length ≈ 6 m
  - lower saturation level

Summary

Beam conditioning is a technical challenge but can enhance FEL performance:

- reduces sensitivity to beam emittance
- allows stronger focusing in undulator
- simulations show gain lengths a factor of two shorter, higher saturated power
- applicable to wide range of FEL designs