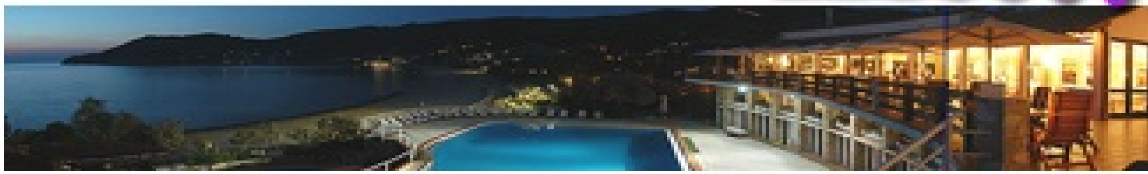
FEL Frontiers 07



Steady state analysis of short-wavelength, high-gain FELs in a large storage ring

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September 13, 2007 (Elba, Italy)

Talk Outline

- Introduction and motivation for this study
- Steady state analysis of a high-gain FEL on rings
- PEP as a potential future light source
- 3D SASE and seeded studies for PEP
- Lasing with injector beams
- Summary

Introduction

- Rapid development in linac-based, short-wavelength FELs

- Hard x-ray FELs (LCLS, SCSS, European XFELs) are on the horizon

- FEL community is looking ahead for second-generation short-wavelength FELs (seeded or self-seeded, attosecond pulses, compact,…)

- Many scientific applications (x-ray spectroscopy, inelastic x-ray scattering, lensless imaging…) demand high-average power and high-repetition rate sources

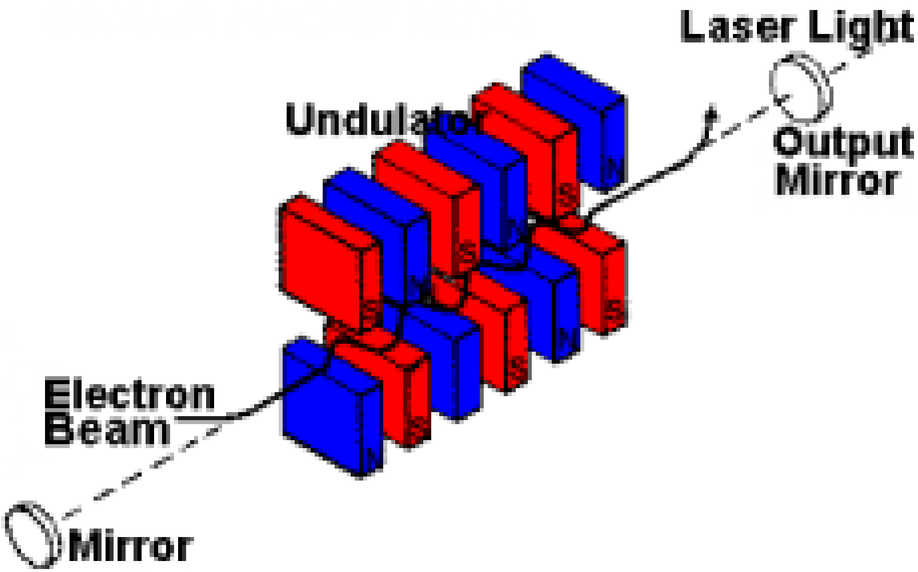
- SC CW linac + high rep. rate injector are still under R&D

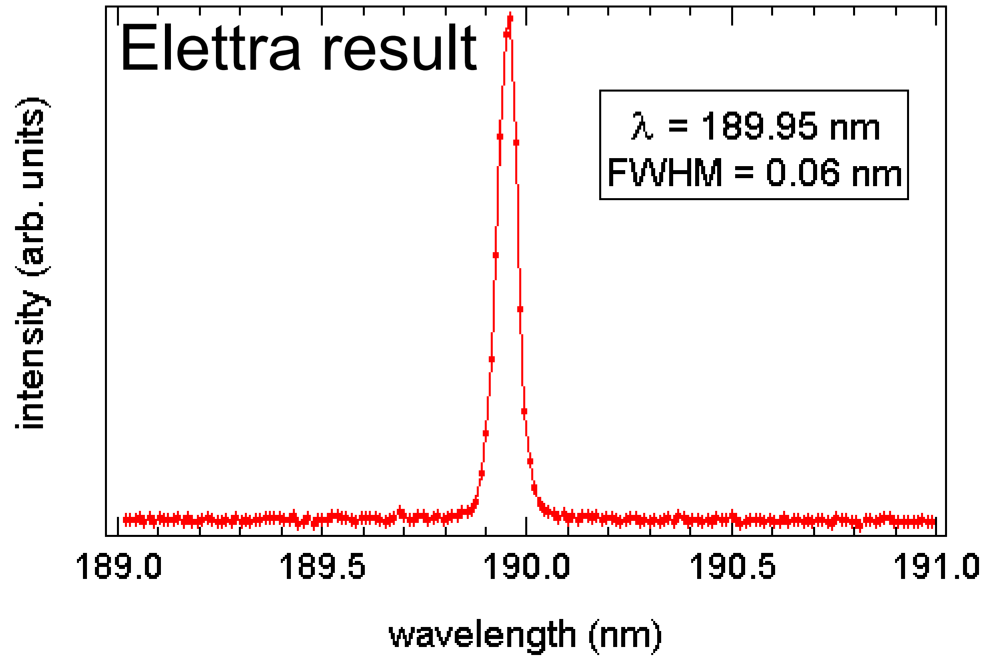
What about our friendly, reliable storage rings?

Storage Ring FELs

➢ SR FELs have operated successfully in the low-gain regime using optical cavities.

➢ Wavelength range limited by mirror reflectivity, to about 200 nm (Duke, Elettra,…)

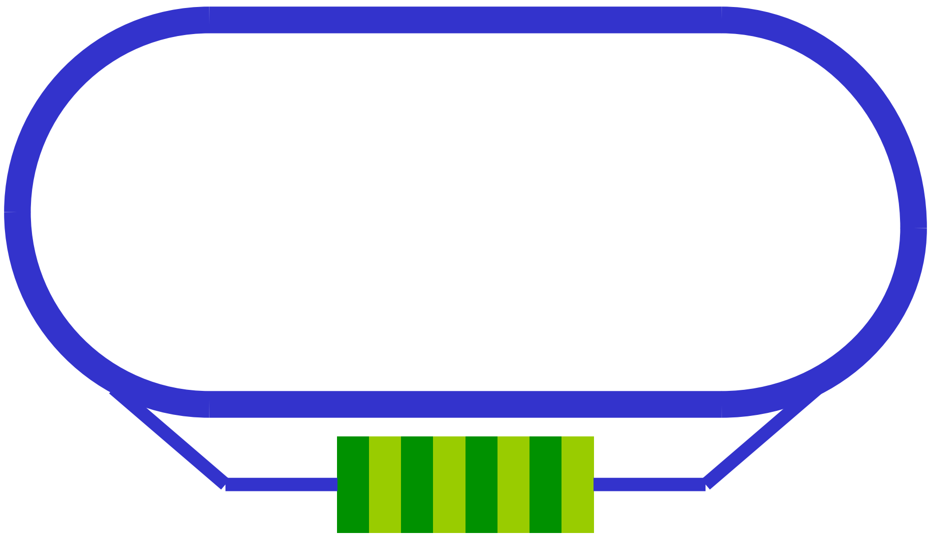




➢ Harmonic generation may push wavelength to ~100 nm

High-gain FEL on rings

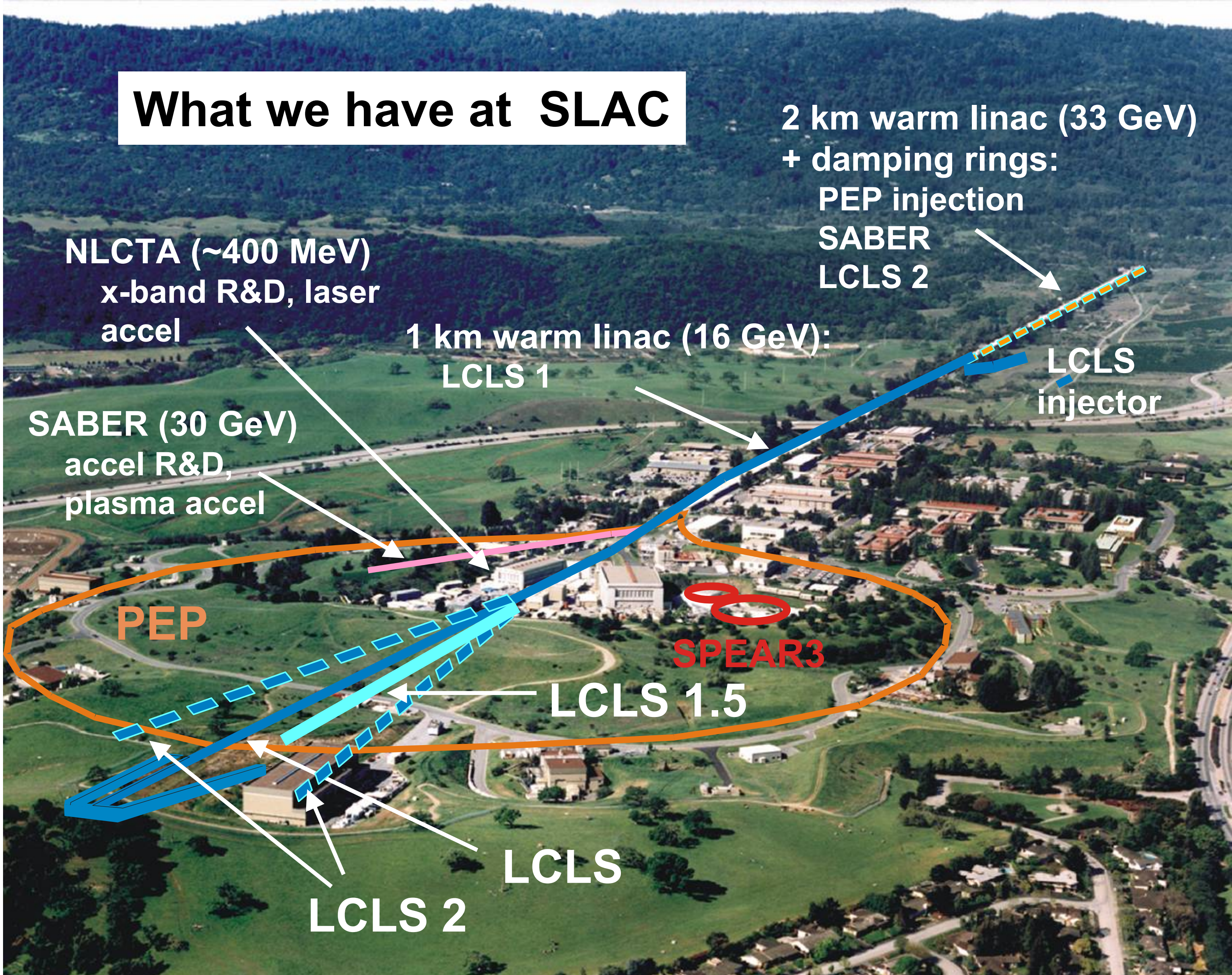
➢ Early discussions (1985 ~ 1990) of mirrorless, high-gain FELs in a storage ring involve a special bypass to provide the FEL interaction about once every damping time



➢ Bypass has complex technology issues. At low rep. rate, SR beams cannot compete with peak brightness of linac beams

➢ Can stored beams lase on a turn-by-turn basis without a bypass in a high-gain configuration?

What we have at SLAC



From R. Hettel

Task Force on the Future of SSRL

- Co-chairs: Bob Hettel and Ingolf Lindau
- Members from SSRL, LCLS, Beam Physics, Accelerator Technology Research, Advanced Accelerator Research + expert consultants

Bane, Karl	Dolgashev, Valery	Pellegrini, Claudio
Brennan, Sean	Hastings, Jerry	Safranek, James
Cai, Yunhai	Huang, Xiaobiao	Seeman, John
Chao, Alex	Huang, Zhirong	Tantawi, Sami
Colby, Eric	Merdji, Ahmed	Terebilo, Andrei
Corbett, Jeff	Nosochkov, Yuri	

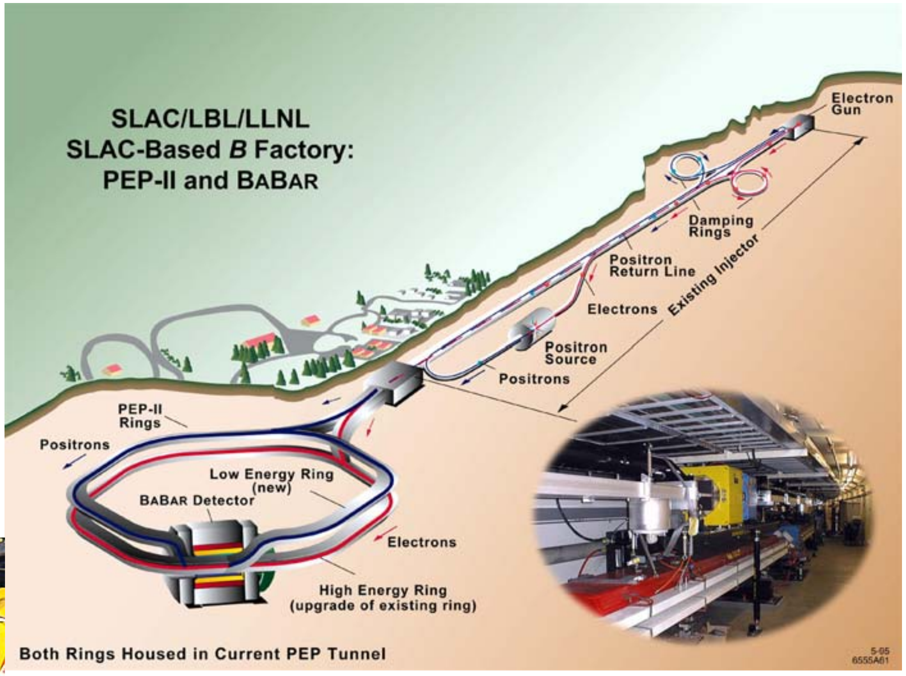
Charge:

- Explore enhanced opportunities with SPEAR3 ring
- **Explore PEP as a new generation light source**
- Explore “green-field” developments
- Report in 2007

From R. Hettel

PEP as a Future Light Source?

- 2 rings:
  - 3 GeV (4 GeV max), 3 A (LER)
  - 9 GeV (~11 GeV max), 2 A (HER)
- 2200 m circumference
- High-brightness injector
- Advanced rf and feedback systems
- PEP II will shut down after 2008 run



JD_138 Straight Section showing the LER above the HER 03/11/98

- 6 long straight sections (110 m, rf can be moved or removed)
- "Missing dipole" scheme in arcs could create more straight sections

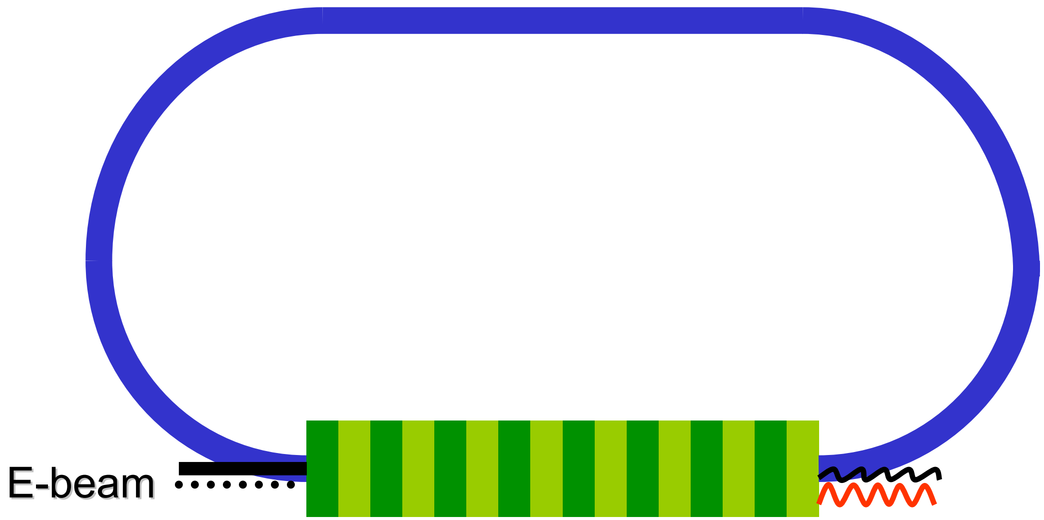
From R. Hettel

Steady state analysis

- FEL interaction modulates electron energy ➔ microbunching + increased energy spread

- At short wavelengths, microbunching is washed out in a fraction of one turn by momentum compaction + E-spread

- FEL-induced energy spread can be treated as diffusion, adds to quantum excitation, decreases next-turn FEL efficiency and leads to a new equilibrium



1D Model

- For a beam with a Gaussian energy spread σ_δ

$$L_G \approx L_{G0}\left[1+\left(\frac{\sigma_\delta}{\rho}\right)^2\right], \quad L_{G0}=\frac{\lambda_u}{4\sqrt{3}\pi\rho}$$

- Beam energy spread increases during the high-gain process

$$\Delta(\sigma_\delta^2)_{FEL} \approx 2\frac{\rho P}{P_{beam}}$$

$$\text{SASE power } P \approx \frac{1}{9}P_n \exp\left(\frac{z}{L_G}\right)$$

- Coupled FEL + ring dynamics determined by

$$\frac{d\sigma_\delta^2}{dt} = \underbrace{-\frac{\sigma_\delta^2}{\tau_s}}_{\text{damping}} + \underbrace{\frac{\sigma_{\delta 0}^2}{\tau_s}}_{\text{QE}} + \underbrace{\frac{\Delta(\sigma_\delta^2)_{FEL}}{T_0}}_{\text{FEL interaction}}$$

Equilibrium behaviors

- Introduce scaled variables $\sigma=\sigma_\delta/\rho$, $n=t/T_0$, $N_d=\tau_s/T_0$

$$\frac{d\sigma^2}{dn} = \frac{\sigma_0^2-\sigma^2}{N_d} + \frac{2P}{\rho P_{beam}}$$

- For a short undulator, FEL induced-energy spread negligible

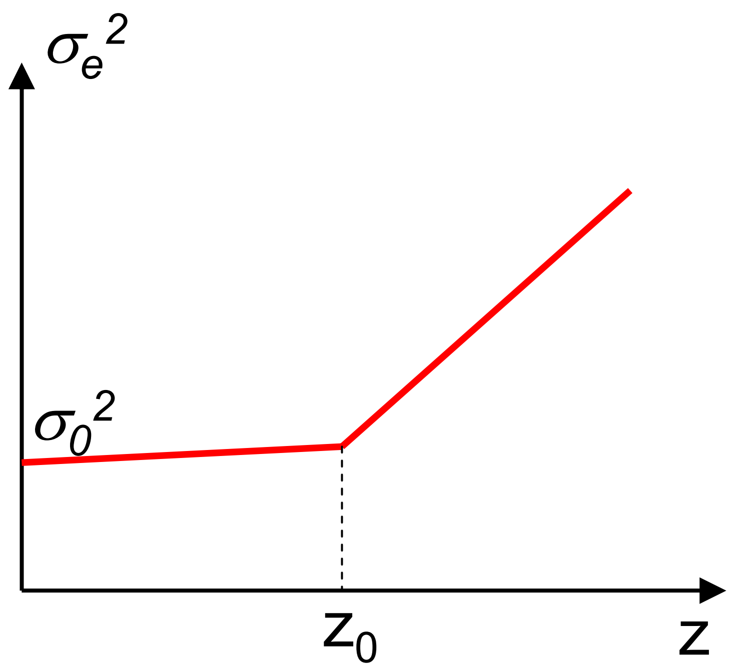
$$\sigma_e = \sigma_0$$

$$P_e = \frac{1}{9} P_n \exp\left[\frac{z}{L_G(\sigma_0)}\right]$$

- For a longer undulator

$$\sigma_e^2 = \sigma_0^2 + a(z - z_0)$$

$$P_e = \frac{\rho P_{beam}}{2N_d} a(z - z_0)$$



Estimate maximum equilibrium power

- For a sufficiently long undulator, a rough estimate of the maximum equilibrium power

$$P_e^{max} \sim P_{beam} \frac{\sigma_{\delta 0}^2}{\rho N_d}$$

- FEL saturation power $P_{sat} \sim \rho P_{beam}$

$$\frac{P_e^{max}}{P_{sat}} \sim \left(\frac{\sigma_\delta}{\rho}\right)^2 \frac{1}{N_d}$$

e.g., $\sigma_{\delta 0}=10^{-3}$, $\rho \sim 10^{-3}$, and $N_d=10^3$ ➔ $\frac{P_e^{max}}{P_{sat}} \sim 10^{-3}$

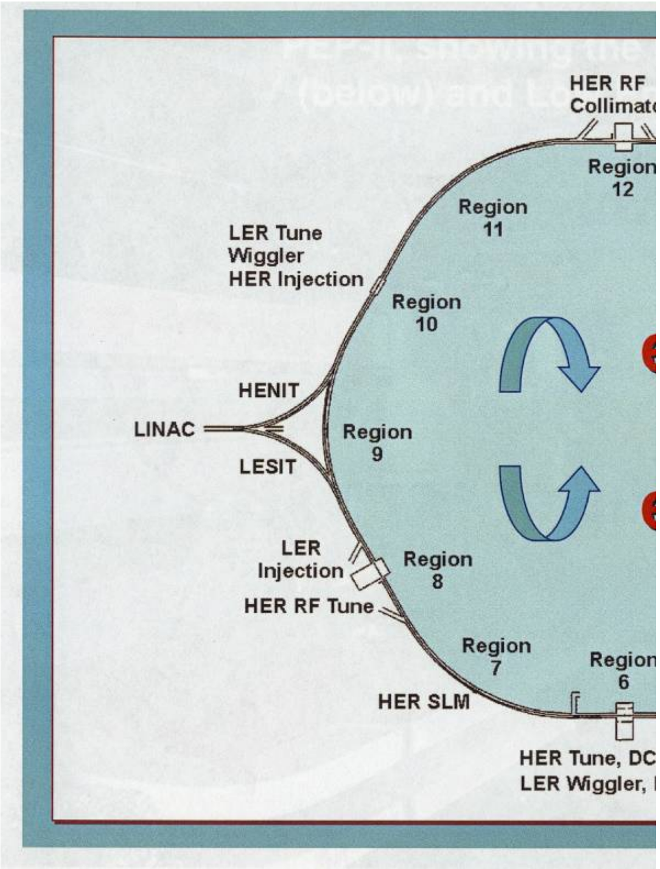
- P_{sat} is 5 to 6 orders magnitude above shot noise power P_n

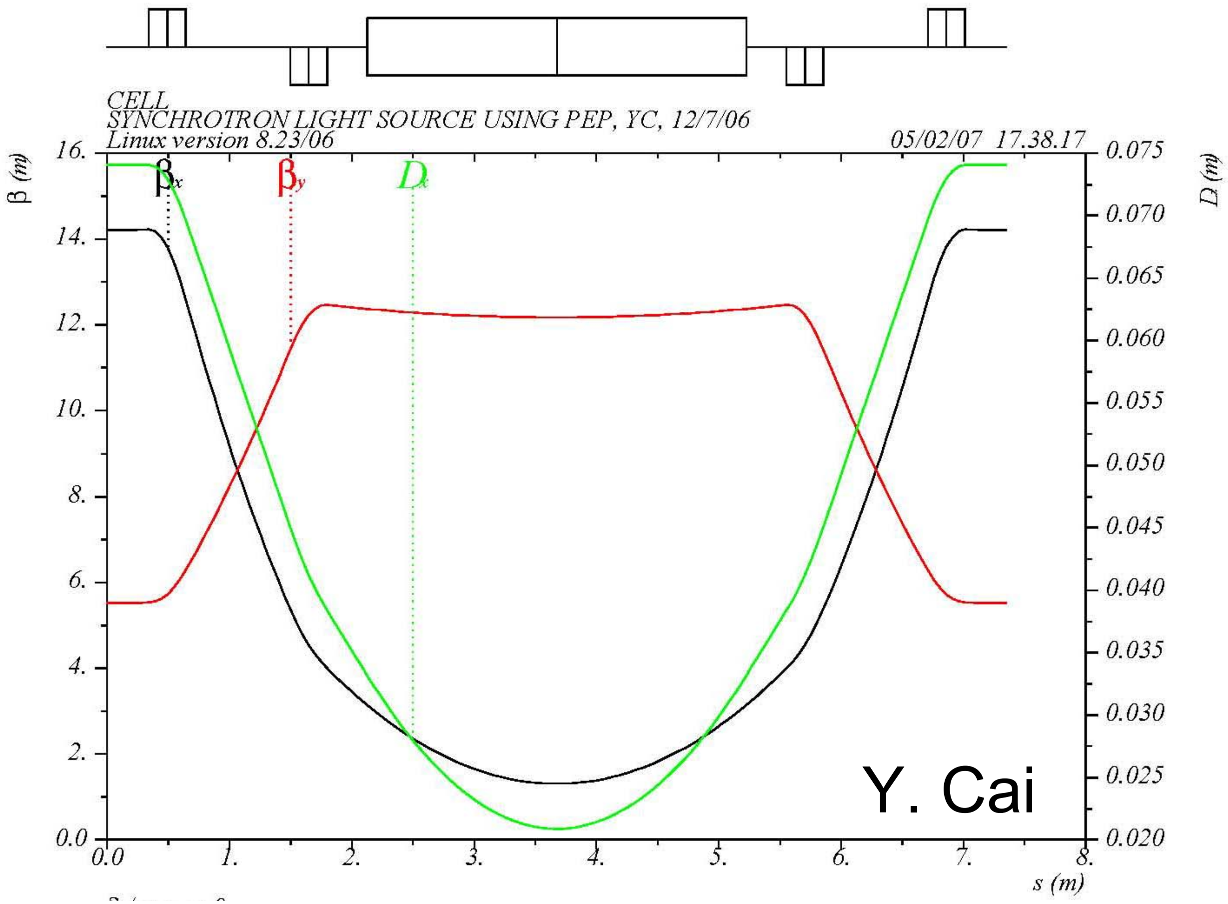
$$\frac{P_e^{max}}{P_n} \sim 10^2 \text{ to } 10^3 \text{ !}$$

PEP as a future light source

- Major lattice rebuild option: pack arcs (~1500 m) with as many Theoretical Minimum Emittance (TME) cells as possible

- Use long straights (6 X 110 m) for damping wigglers, IDs





Ultra-low emittance PEP ring

- 4.5 GeV Parameters

Description	Without wiggler	With wiggler
Energy E(Gev)	4.5	4.5
Circumference (m)	2200	
Horizontal emittance (nm-rad)	0.10	0.05
Damping time τ_x (ms)	177	15
Tunes, ν_x, ν_y, ν_s	88.57, 38.64, 0.0065	99.57, 39.64, 0.0087
Momentum compaction α_c	6.96×10^{-5}	6.86×10^{-5}
Bunch length σ_z (mm)	1.45	3.13
Energy spread σ_e/E	3.90×10^{-4}	1.14×10^{-3}
Natural chromaticities ξ_x, ξ_y	-143.4, -62.5	-175.6, -72.4
Energy loss per turn (Mev)	0.37	4.34
RF Voltage (MVolt)	5	10

With stored current ~1 A,

average brightness: **$>10^{22}$** for spontaneous hard x-ray source

CSR instability

- High peak current essential for short-wavelength FELs

- Threshold current typically determined by microwave instability at wavelengths shorter than bunch length (~3 mm)

- CSR impedance from dipoles dominates at sub-mm wavelengths

- CSR instability threshold for a coasting beam model (Stupakov/Heifets, PRST, 2002)

$$\frac{I_{th}}{I_A} = \frac{\gamma \alpha_c \sigma_\delta^2 C}{2(\pi R \lambda^2)^{1/3}}$$

C = 2200 m, R = 98 m, I_A = 17 kA

Current threshold determined by the longest CSR wavelength

Peak current

- Vacuum chamber shielding cuts off CSR above λ_s. According to Warnock parallel plate model

$$\lambda_s = \frac{2^{5/2} b^{3/2}}{\sqrt{\pi} R^{1/2}}$$

- Current threshold at $\lambda = \lambda_s$

$$\frac{I_{th}}{I_A} = \frac{\gamma \alpha_c \sigma_\delta^2 C}{2^{8/3} b}$$

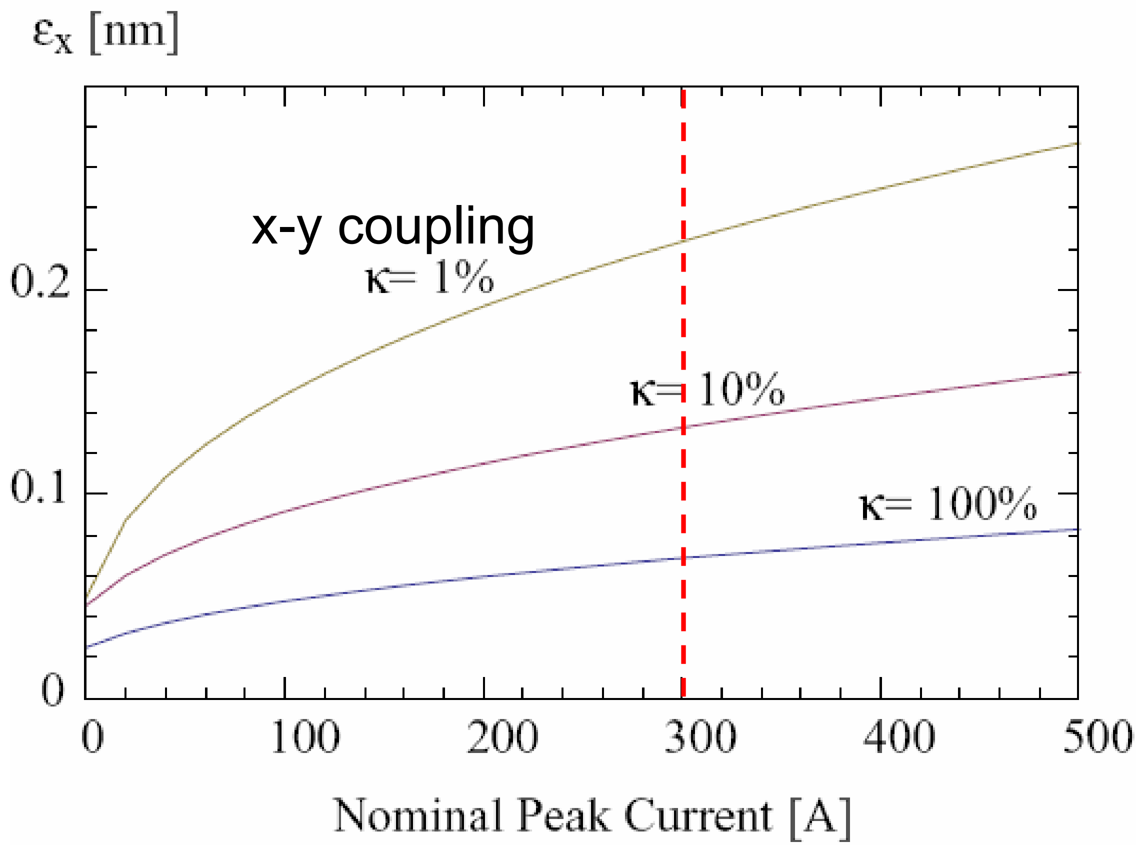
e.g., half height b = 2 cm, R = 98 m, λ_s = 0.9 mm

- Use "with wiggler" set of parameters ➔ I_{th} = 230 A

- TME lattice can be adjusted slightly to accommodate a more aggressive peak current at 300 A (1 mA average current). Total charge per bunch ~7.5 nC

Intrabeam scattering (IBS)

➢ At high bunch density, IBS degrades emittance (not much on energy spread) (K. Bane's simplified IBS model)



➢ Full coupling yields the smallest horizontal emittance

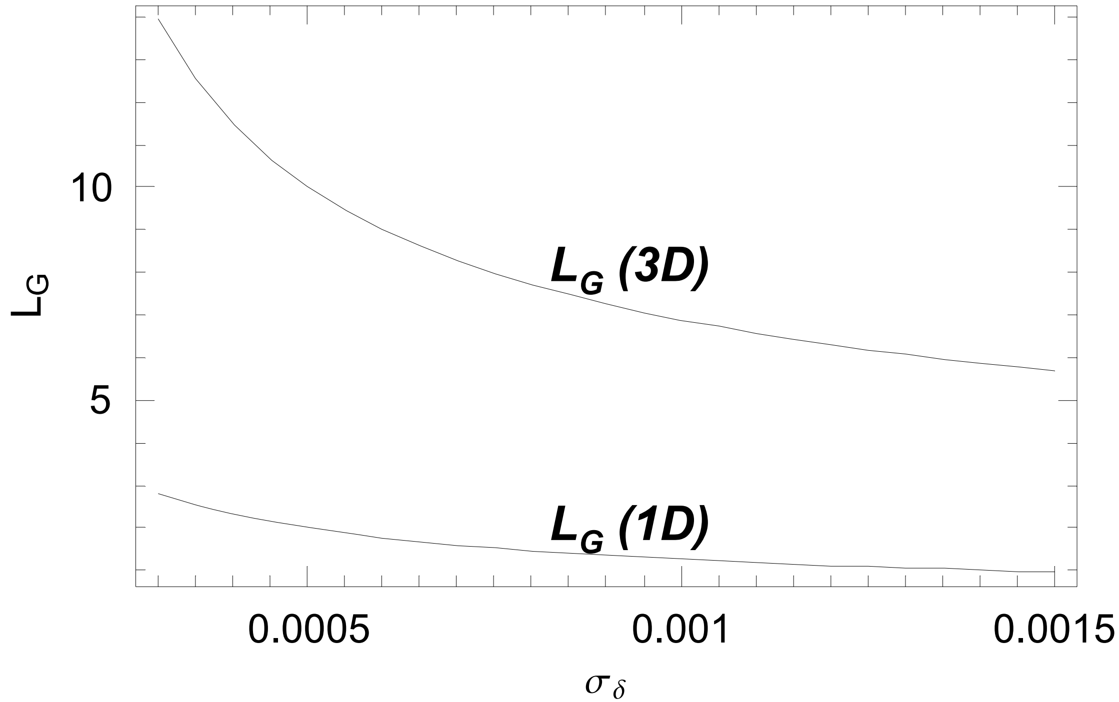
+ FEL prefers a round beam ➔

choose full coupling for FEL studies

Role of energy spread

Assume $I \sim \sigma_\delta^2$ from instability scaling

Electron energy	4.5 GeV
Norm. emittance in x/y	0.6 μm
Peak current	300 A
Bunch length	10 ps
Energy spread	0.114%
Undulator period	6 cm
Undulator parameter	7.05
Undulator beta	4 m
Peak magnetic field	1.26 T
FEL wavelength	10 nm



- FEL gain prefers larger energy spread with a higher current
- Increasing energy spread (via wigglers) is more effective than bunch compression ($I \sim \sigma_\delta$)

3D calculation

- Use Ming Xie to account for 3D effects, and gain length dependence on energy spread
- Include peak current drop due to energy spread increase and bunch lengthening
- For 3D with large energy spread, SASE induced E-spread

$$\Delta(\sigma_\delta^2)_{FEL} \approx 2\frac{\rho P}{P_{beam}}$$ agrees w/ simulations

$$\text{SASE power } P \approx P_n \exp\left(\frac{z}{L_G}\right)$$

- Coupled FEL + ring dynamics still determined by

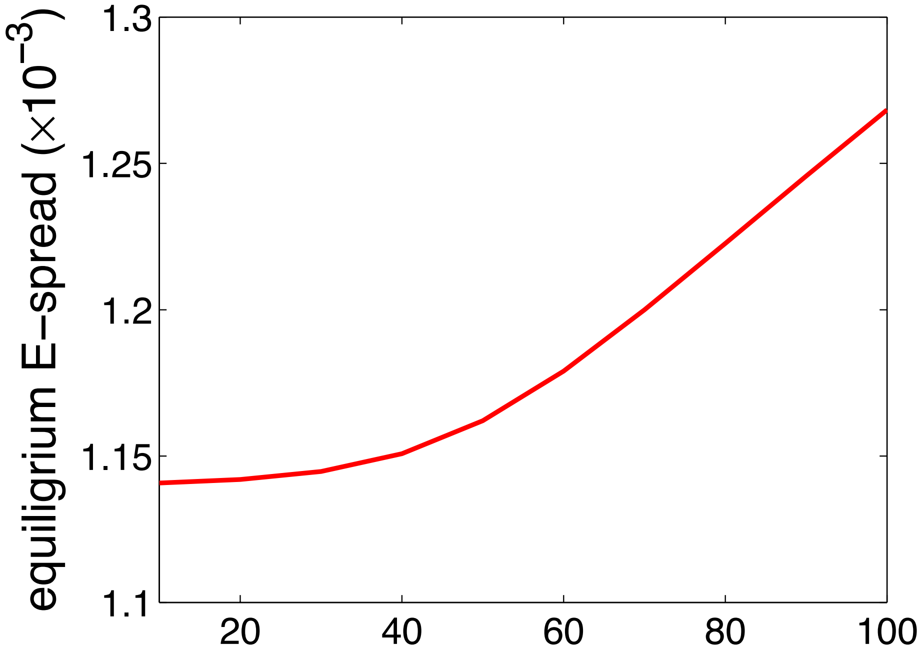
$$\frac{d\sigma_\delta^2}{dt} = -\frac{\sigma_\delta^2}{\tau_s} + \frac{\sigma_{\delta 0}^2}{\tau_s} + \frac{\Delta(\sigma_\delta^2)_{FEL}}{T_0}$$

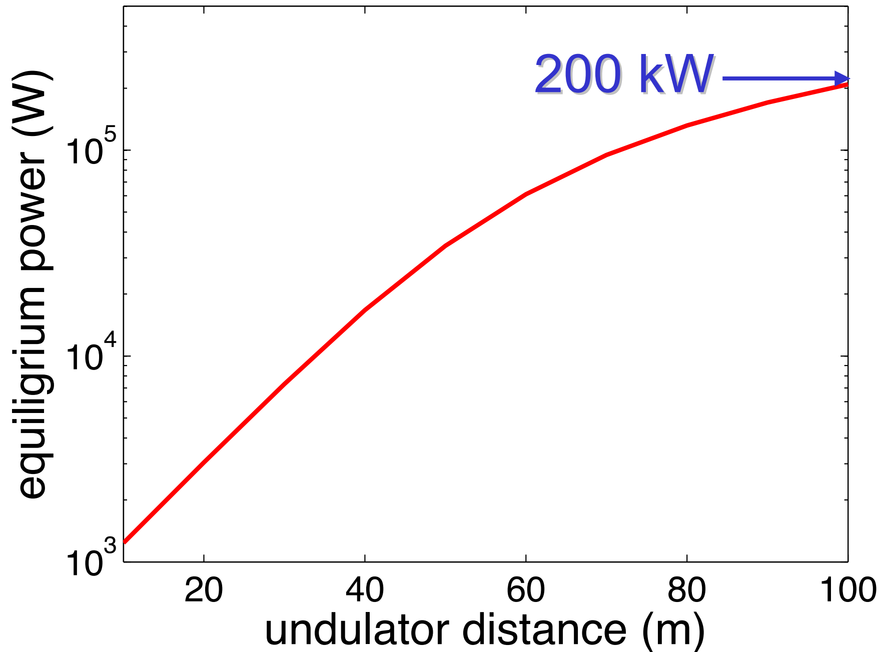
damping QE FEL interaction

Steady-state SASE at 3 nm

- PEP Low-emittance lattice with damping wigglers (IBS included)

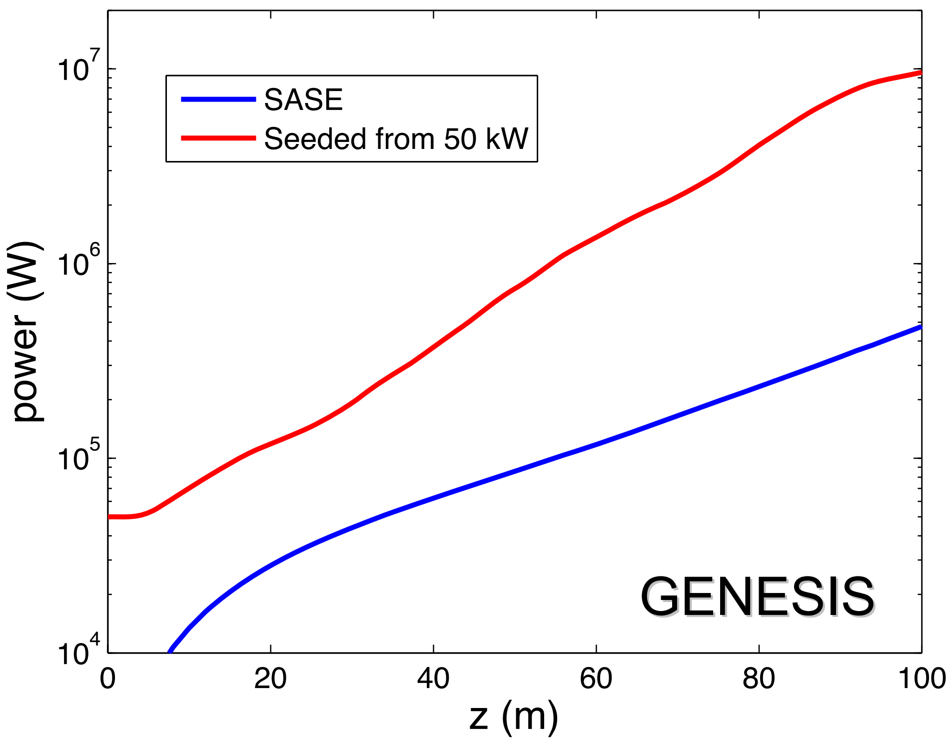
Electron energy	4.5 GeV
Norm. emittance in x/y	0.6 μm
Peak current	270 A
Bunch length	~10 ps
Energy spread	0.126%
Undulator period	5 cm
Undulator parameter	4.3
Undulator length	100 m
average beta	~4 m
FEL wavelength	3.3 nm

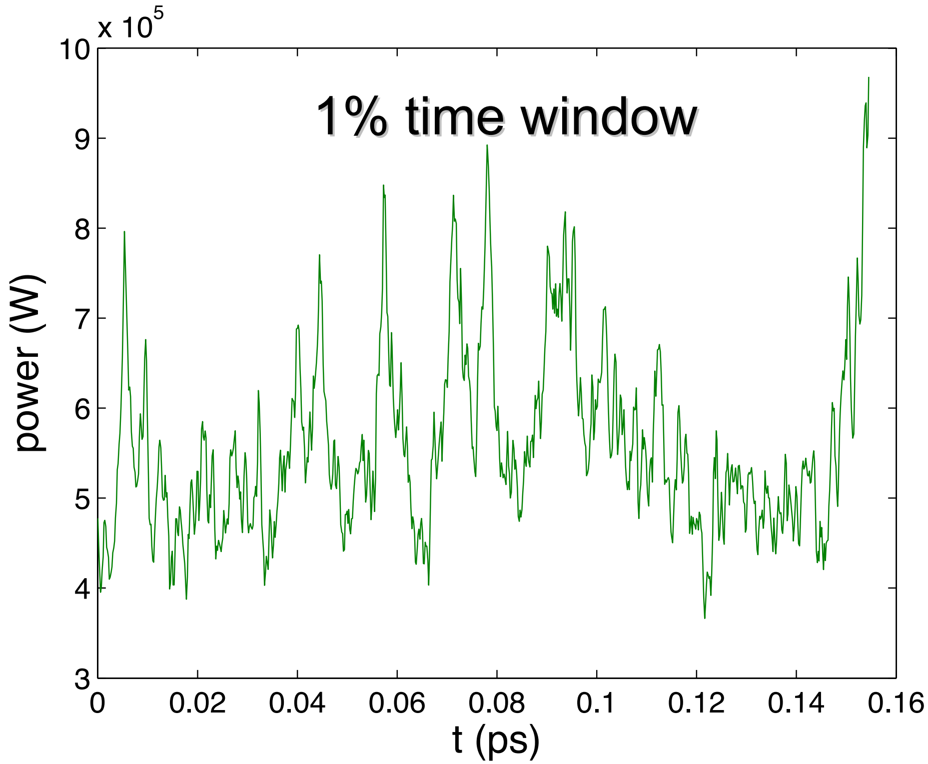




Gain and brightness enhancement

- ➢ Spontaneous power in 0.1% BW is ~1 kW at 3 nm
- ➢ Gain enhancement of ~200, confirmed by seeded simulations





- ➢ Average power 0.7 W at 136 kHz rep. rate per bunch, 700 W for 1000 bunches (1 A average current)

- ➢ Brightness increases by the same factor at soft x-ray regime

HHG: Energy output in the XUV

- Standard laser energy ~ 10 mJ :

  → XUV ~10μJ (100nm)

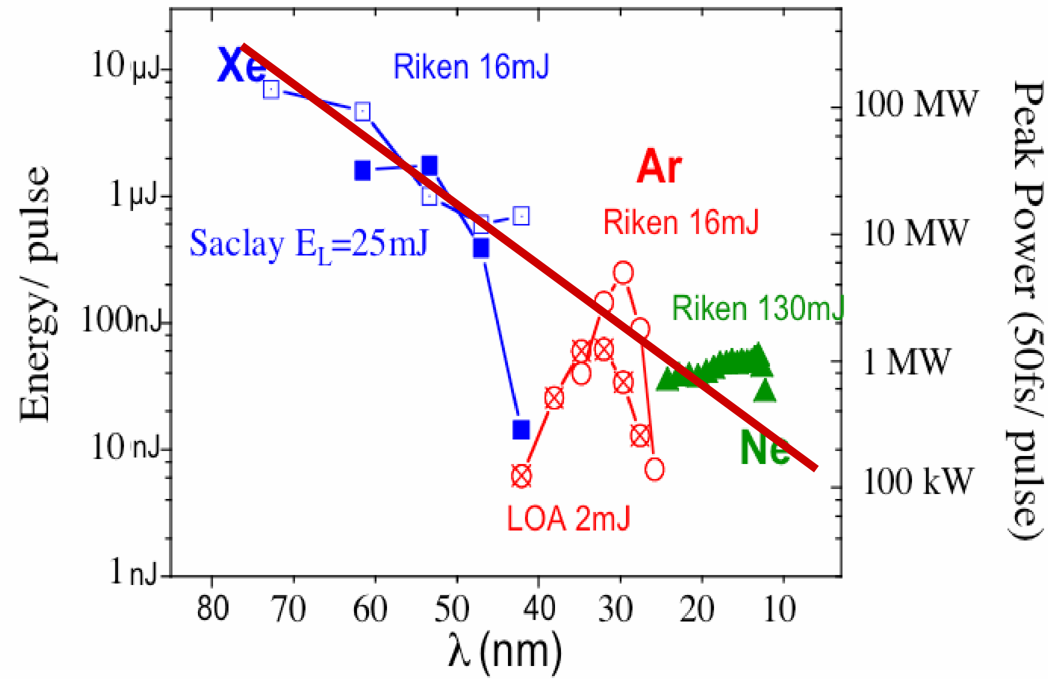
  to 10nJ (10 nm)

- Higher XUV output:

  →Scaling laser energy

  at constant intensity

  ~1J → E_{XUV} x100



- **Water window:**
  - 2.7 nm with 40 fJ/pulse *(Chang et al., PRL79 (1997))*
  - 1 nm with 100 fJ/pulse *(Seres et al., Nature 433 (2005))*

- Shorter wavelength:
  - Longer IR wavelength *(Chang et al., PRA 65 (2001), SPAM/OHIO PRL to be published)*
  - HHG from ions *(Milosevic et al. PRA63 (2000))*
  - **HHG on solid target** *(DROMEY et al. Nature phys. 338 (2006))*

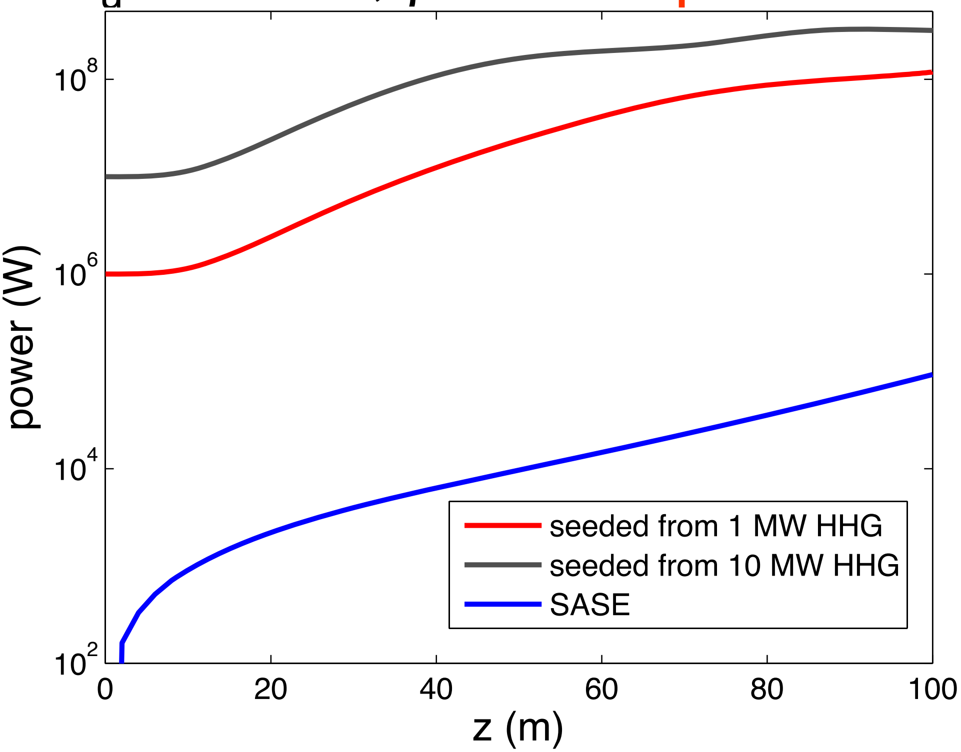
from M. Labat's talk

Seeding with HHG

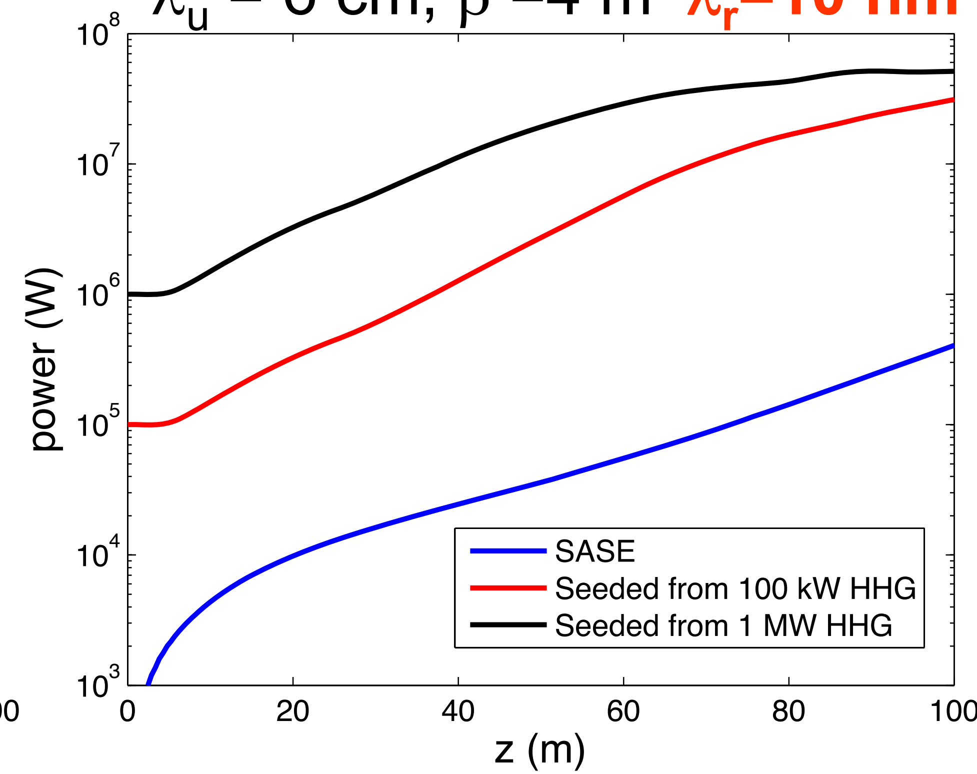
- ➢ HHG affects only a small portion (10-50 fs) of the e-beam at a low repetition rate ➔ negligible impact on ring dynamics

- ➢ Equilibrium determined by interplay of SASE with damping/excitation

λ_u = 10 cm, β =6 m **λ_r=30 nm**



λ_u = 6 cm, β =4 m **λ_r=10 nm**



➢ SASE power three orders of magnitude above spontaneous

Other beam dynamic issues

➢ Undulator peak field ~ 1 T for 100 m long is itself an excellent damping wiggler due to broadband spontaneous emission

➔ no need for large amount of damping wigglers

➔ remaining damping wigglers should be adjustable in field strengths to compensate for tuning the gap (to vary K)

➢ Full gap g ~ 1 cm for 5-6 cm undulator period, transverse resistive wall (~ g^{-3}) may cause multi-bunch instability

➔ Preliminary analysis for 1 A current shows it may be cured by a narrow-band feedback system

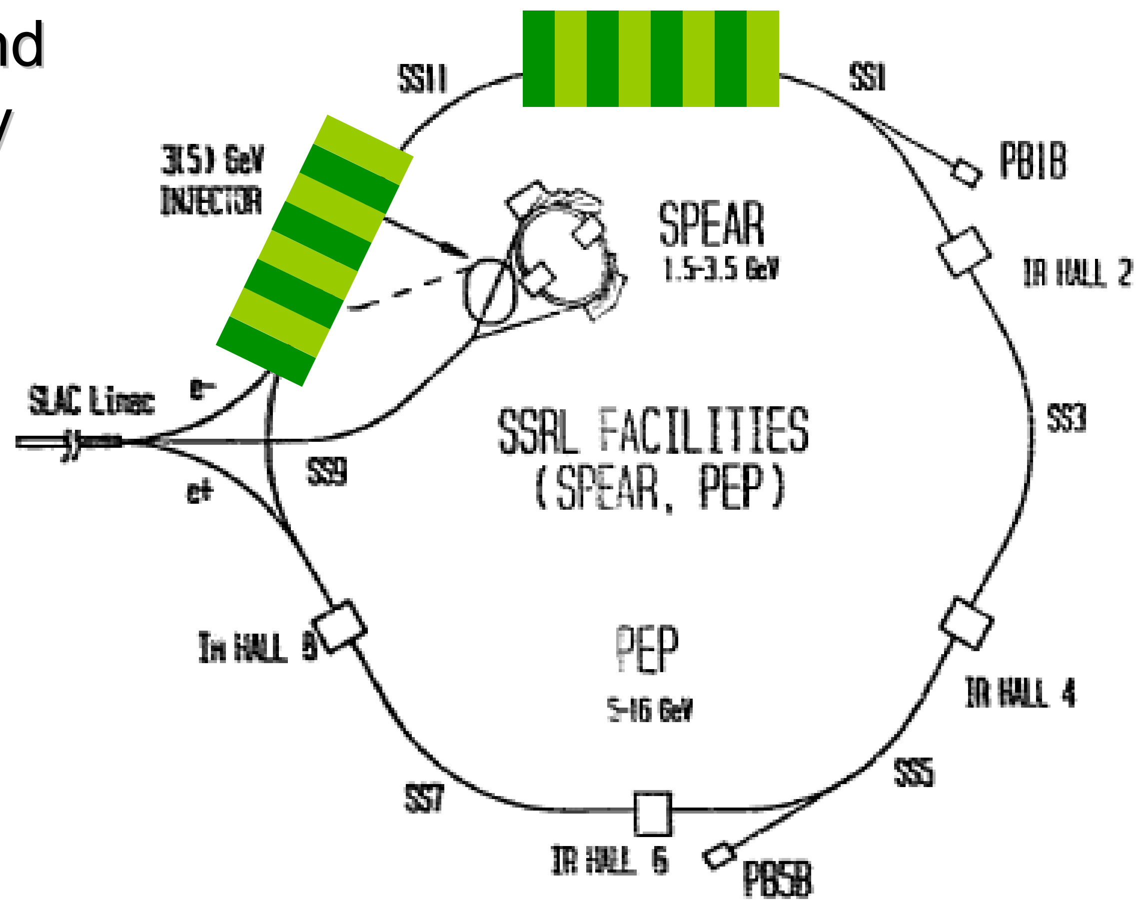
……

Short bunch using injected beams

➢ PEP ring may also be fed by a high-brightness injector

➢ First (or two arcs) may be made isochronous to maintain short bunch of injected current

➢ Lattice compatibility and kicker issues under study



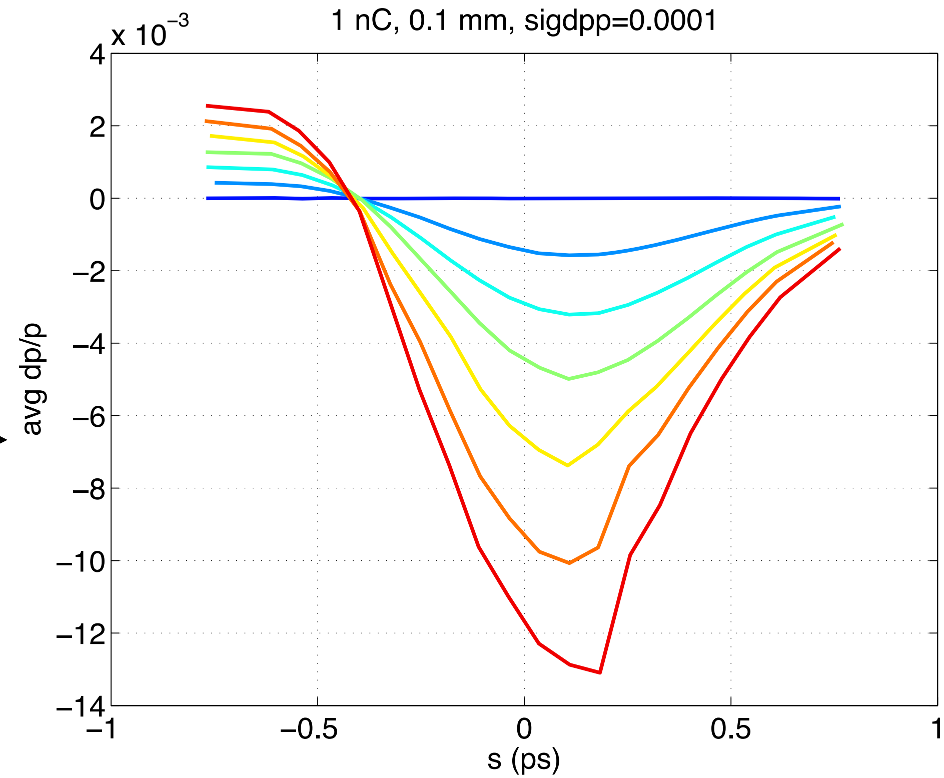
Tracking with Elegant

Photoinjector + 4.5 GeV linac

Normalized emittance	1.2 μm
Pulse length, FWHM	0.8 ps
Peak current	~1 kA
Eenergy spread, RMS	10^{-4}
Charge	~1 nC

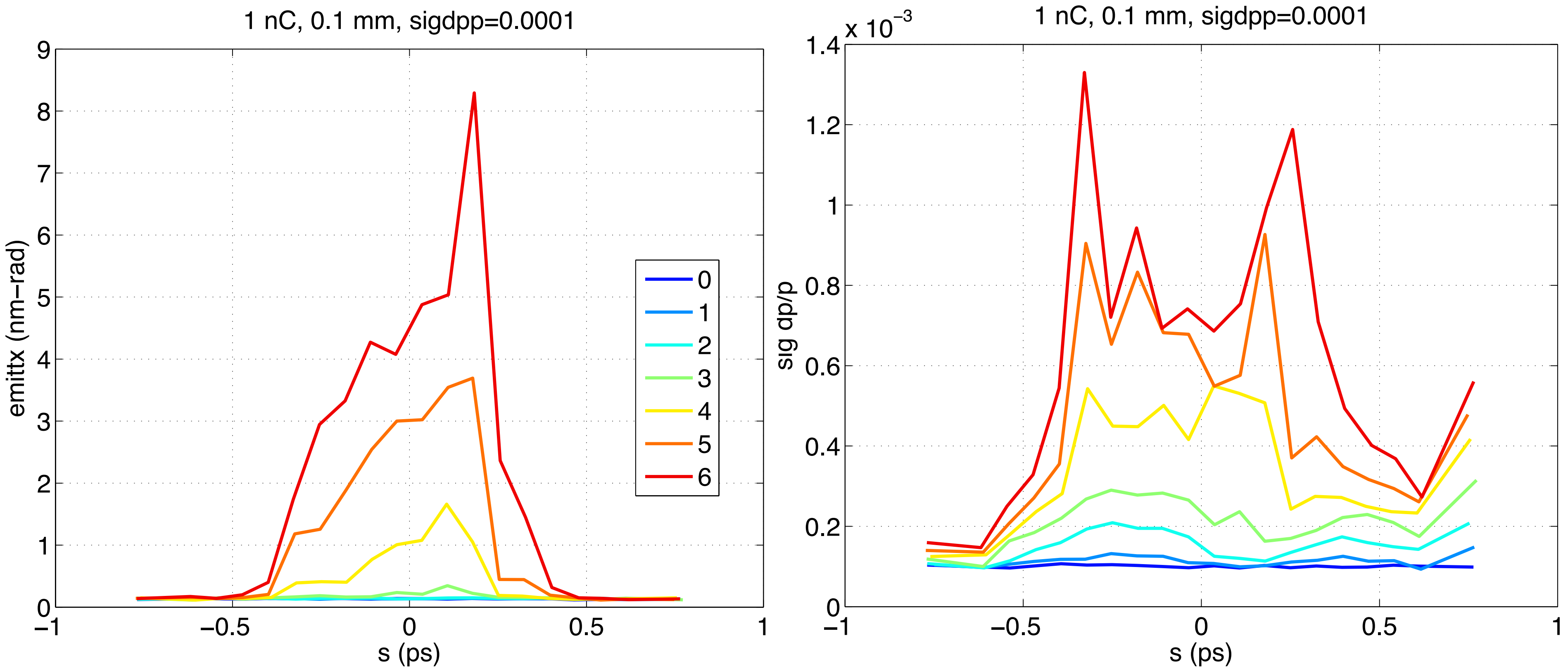
+ Low-alpha PEP lattice

Correlated energy spread due to CSR



Courtesy Xiaobiao Huang

Slice emittance and slice energy spread

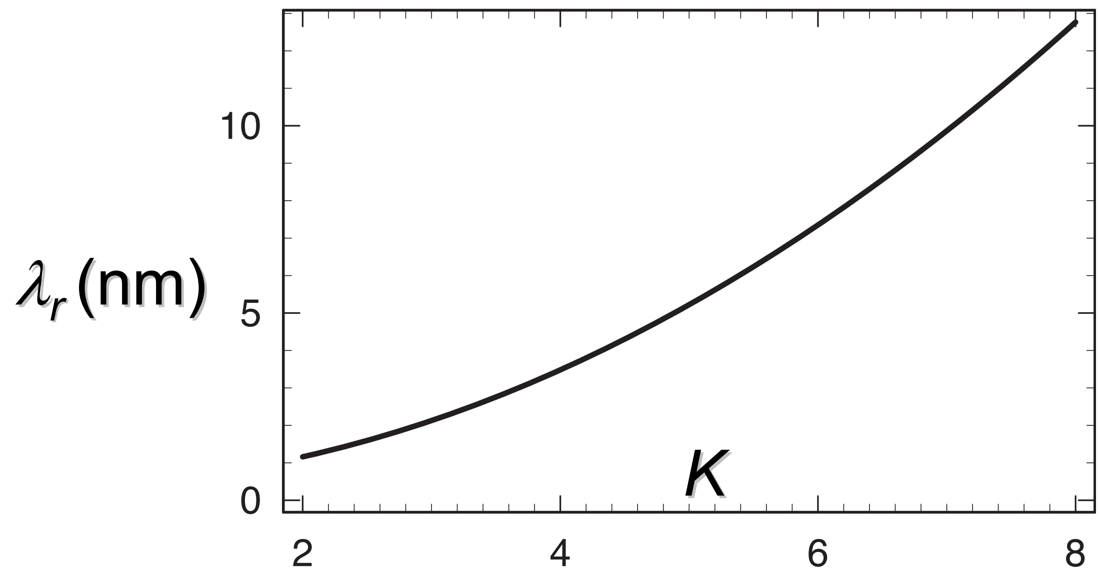


- ➢ Slice emittance and energy spread appears to be kept at the initial level after the first two arcs
- ➢ Signature of microbunching instability at later arcs

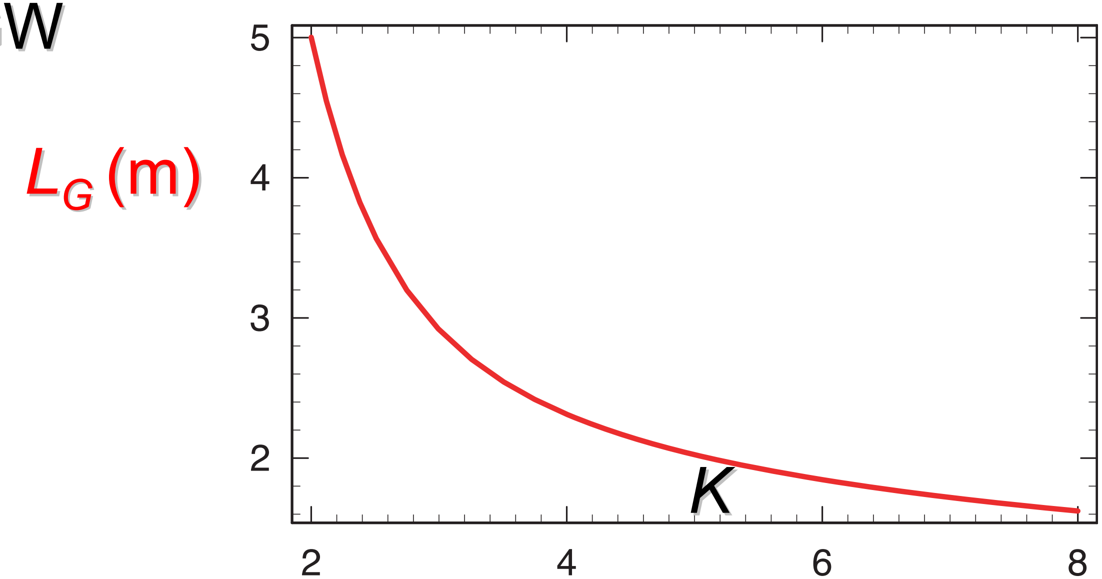
Courtesy Xiaobiao Huang

Lasing with injected beams

- FEL wavelength λ_r = 1-10 nm, λ_u = 6 cm, β = 7 m



- Saturation power ~ GW



Summary

- For a low emittance PEP ring with sufficient current, high-gain, unsaturated FEL at EUV/soft x-ray regime is feasible on a turn-by-turn basis, with modest degradation in beam qualities

- A bypass is not necessary for short-wavelength FELs

- Steady-state SASE increases the average brightness by two to three orders of magnitude over spontaneous source at these radiation wavelengths

- HHG sources can be applied to obtain 10-50 fs, saturated radiation pulses at available rep. rate

- Long undulators in first two straights may also be used for injected beam lasing

Concluding remarks

- This is part of an initial exploratory study on PEP as a light source, not a design study

- Suggestions and novel ideas are appreciated

Acknowledgments

M.-E. Couprie, Y. Hao, X. Huang, I. Lindau, A. Merdji, and L.-H. Yu for many stimulating discussions