Incoherent Radiation as a Seed for Free Electron Laser

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Outline

- Free electron laser(FEL)
  - FEL configurations
  - Different seeding schemes
- SPARC project
- Betatron radiation
- The resonance condition
- Simulation setup
  - White radiation
  - Electron beam
- Results
  - FEL growth and bunching
  - Saturation lengths
  - Temporal Output
- Conclusion

Free Electron Laser(FEL)

- A Free Electron Laser is a source of coherent light
  - Relativistic electron beam
  - Undulator (periodic magnets)
  - Oscillatory motion → radiation
  - Coherent amplification
  - Laser-like source
  - Tunable λ

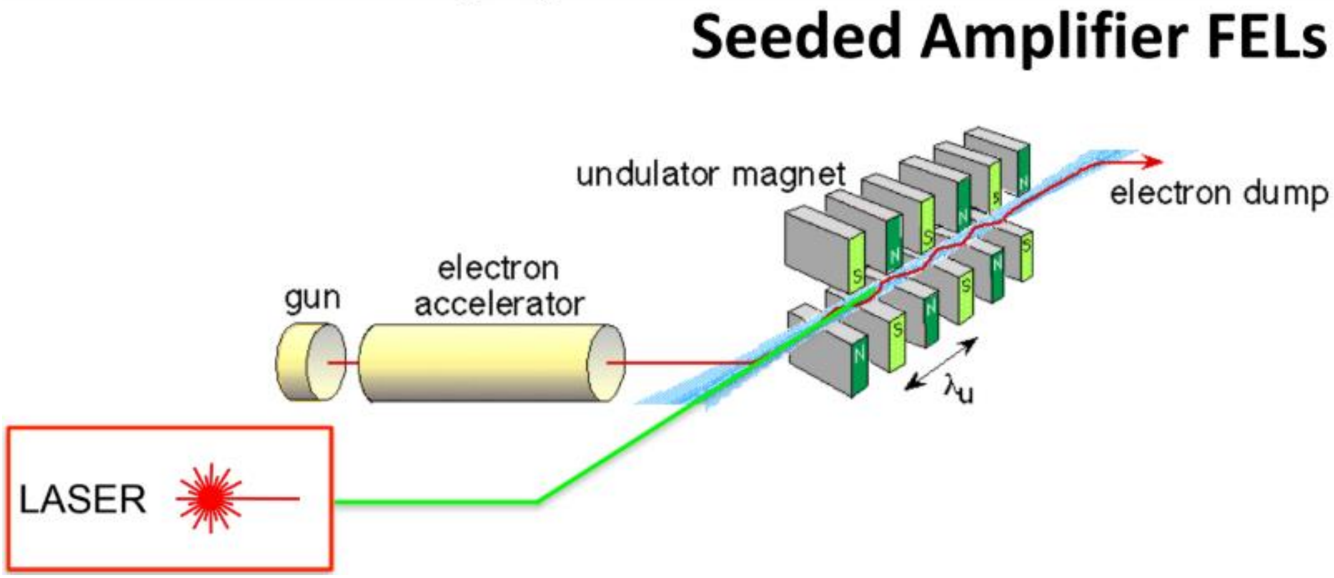


Figure adapted from L. Giannessi, "Corso Fisica del FEL CONDIVISO," Lecture slides

FEL Configurations

Oscillator FEL

- Uses mirrors → optical cavity
- Works at IR–THz wavelengths
- Applications: spectroscopy, materials science

Storage Ring FEL

- Uses electron storage ring (like synchrotrons)
- e- bea,
- Moderate intensity, high repetition rate
- Applications: spectroscopy, user experiments

Single-Pass High-Gain FEL

- Based on linac
- No mirrors → fresh beam each pass
- Works at X-ray wavelengths
- Applications: ultrafast science, molecular movies, plasma studies

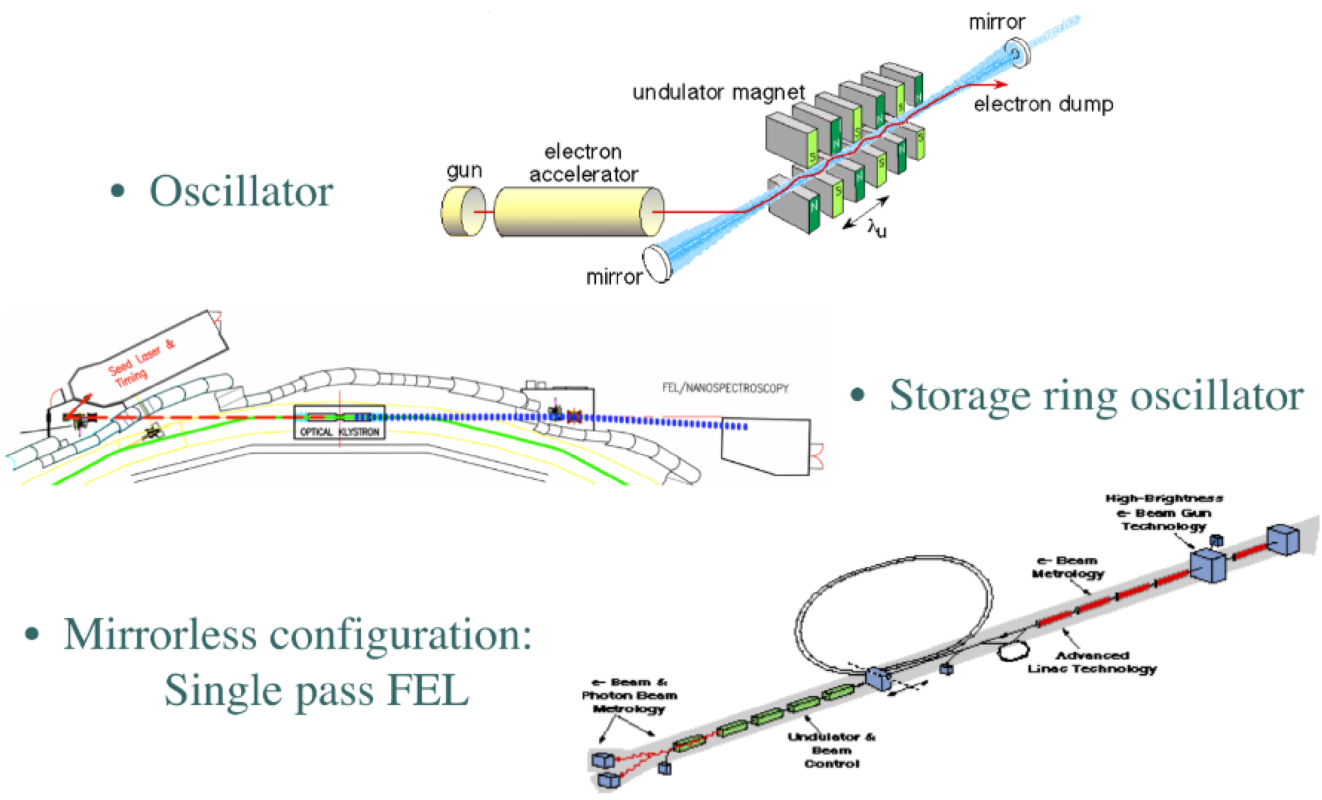


Figure adapted from L. Giannessi, "Corso Fisica del FEL CONDIVISO," Lecture slides

SASE vs Seeding

SASE FEL

- Starts from shot noise (spontaneous emission)
- Needs high beam energy & long undulators
- Requires high beam quality: small emittance, short bunches
- Limited temporal coherence, strong fluctuations

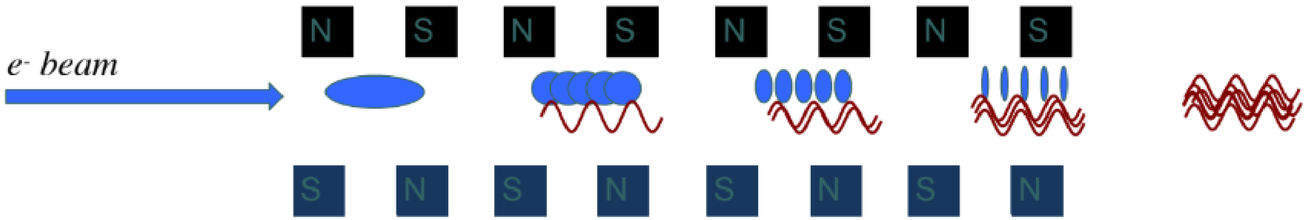


Figure adapted from L. Giannessi, "Corso Fisica del FEL CONDIVISO," Lecture slides

Seeded FEL

- Starts from coherent input field
- Efficient energy exchange → density modulation
- Improved coherence, stability, reproducibility
- Enables shorter undulators than SASE
- Limited by the seed wavelenght for X-ray range

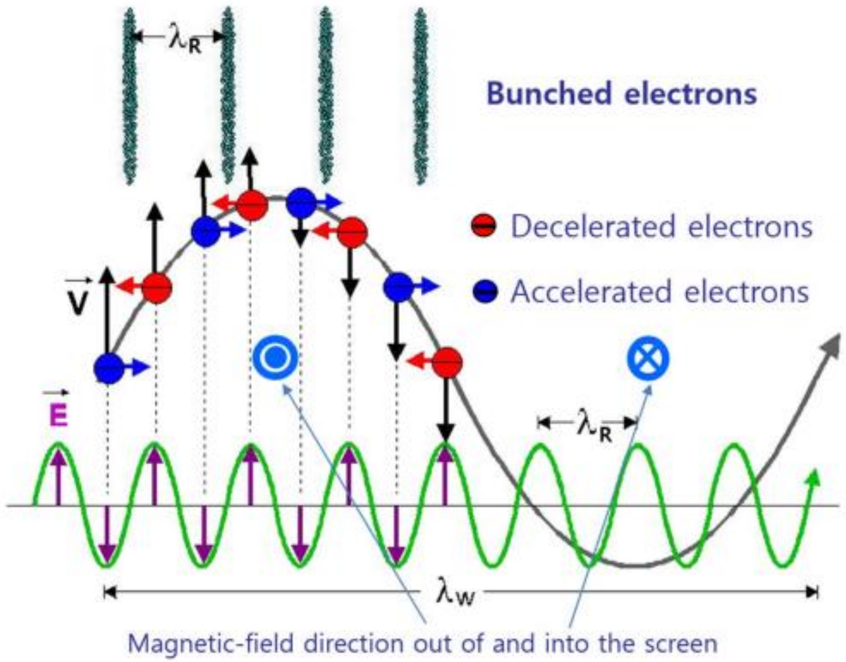
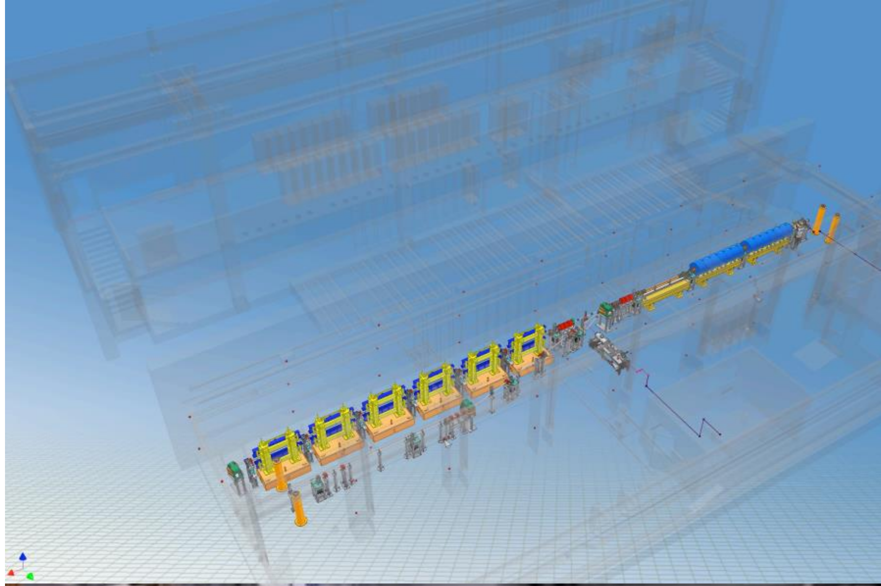


Figure adapted from Y. U. Jeong, K.-H. Jang, S. Bae, V. Pathania, J. Mun, K. Lee, "Prospects of a terahertz free-electron laser for field application," J. Korean Phys. Soc., 80, 195–205 (2022)

SPARC

- SPARC (Frascati, Italy): Sorgente Pulsata ed Amplificata di Radiazione Coerente
- **First lasing:** 2009 at 150 MeV electron beam energy
- **Modes:** Operated in both **SASE** and **seeded FEL** configurations
- **Spectral range:**
  - SASE: visible (≈ 500–800 nm)
  - Seeded mode: extended to 36–400 nm
- **Research focus:**
  - FEL gain dynamics and saturation studies
  - Superradiance and beam manipulation experiments
  - Benchmarking of simulation codes (GENESIS 1.3, etc.)
- One of the first European FEL user facilities demonstrating both SASE and external seeding, paving the way toward FERMI and future plasma-based FELs.



Quantity	Symbol	Value
Undulator period	λ_u	2.80 cm
Undulator parameter (planar)	K	1.281
Resonant wavelength	λ_r	826 nm
Mean beam energy	E_0	$\approx$ 89.75 MeV
Peak current	I_{pk}	200 A
Energy spread	σ_E/E_0	0.097% ($\sigma_E \approx$ 0.087 MeV)
Normalized emittance (x/y)	$\epsilon_{n,x}/\epsilon_{n,y}$	2.24 / 1.59 mm·mrad

Figures adapted from L. Giannessi et al., Self-amplified spontaneous emission for a single pass free-electron laser, Phys. Rev. ST Accel. Beams 14, 060712 (2011)

Betatron Radiation

Plasma accelerators (LWFA/PWFA):

- Compact, high-gradient drivers → future FEL technology

Formation (inside plasma bubble):

- Driver bunch expels plasma electrons → **ion cavity (“bubble”)**
- Witness bunch oscillates transversely in plasma focusing fields
- Oscillatory motion → emits **betatron radiation**

Properties:

- Broadband X-rays, femtosecond duration, naturally synchronized
- High brightness, forward-directed
- Spectral overlap with FEL resonance → potential seed

Challenges:

- Radiation is incoherent, fluctuating
- Difficult to transport, monochromatize, and couple into undulator

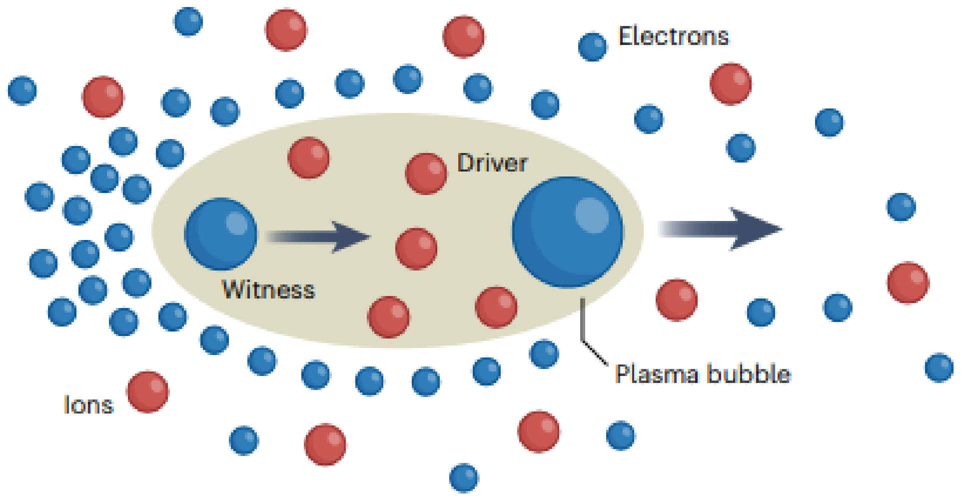


Figure adapted from M. Galletti et al., “Prospects for free-electron lasers powered by plasma-wakefield-accelerated beams,” Nature Photonics

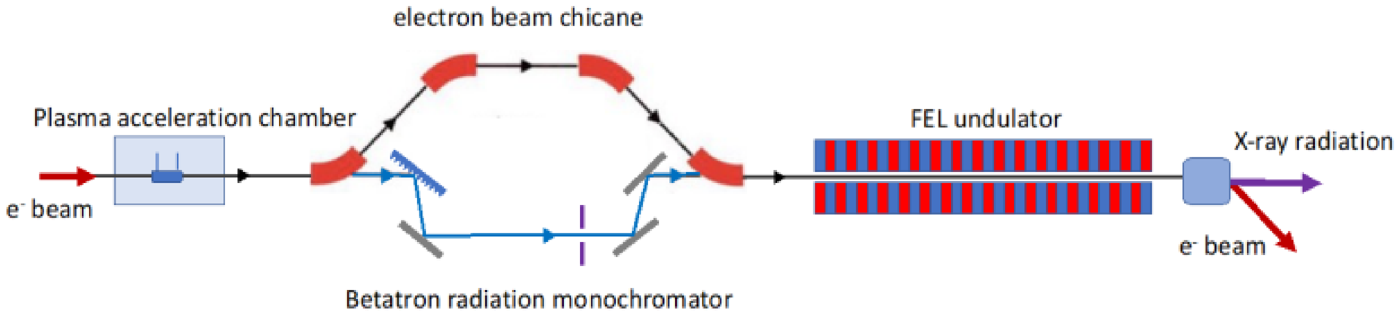


Figure adapted from A. Ghigo et al., “Free electron laser seeded by betatron radiation,” NIM A 909 (2018)

The Resonance Condition

- **λ_r**: FEL resonant wavelength
- **λ_u**: undulator period
- **γ**: electron beam energy (Lorentz factor)
- **K**: undulator strength parameter
- **θ**: observation angle

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

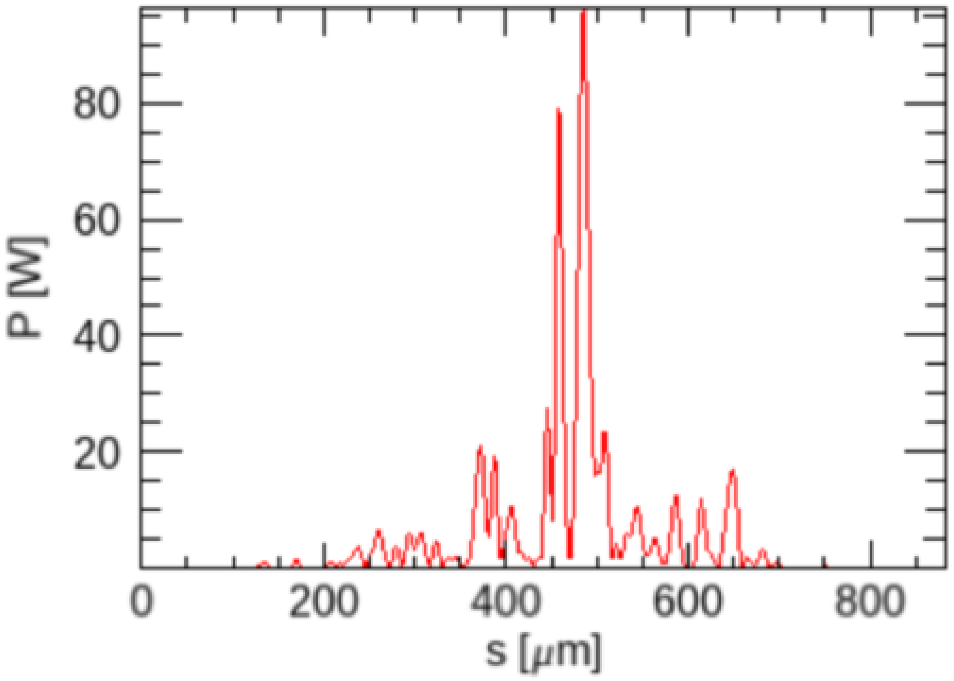
Key points:

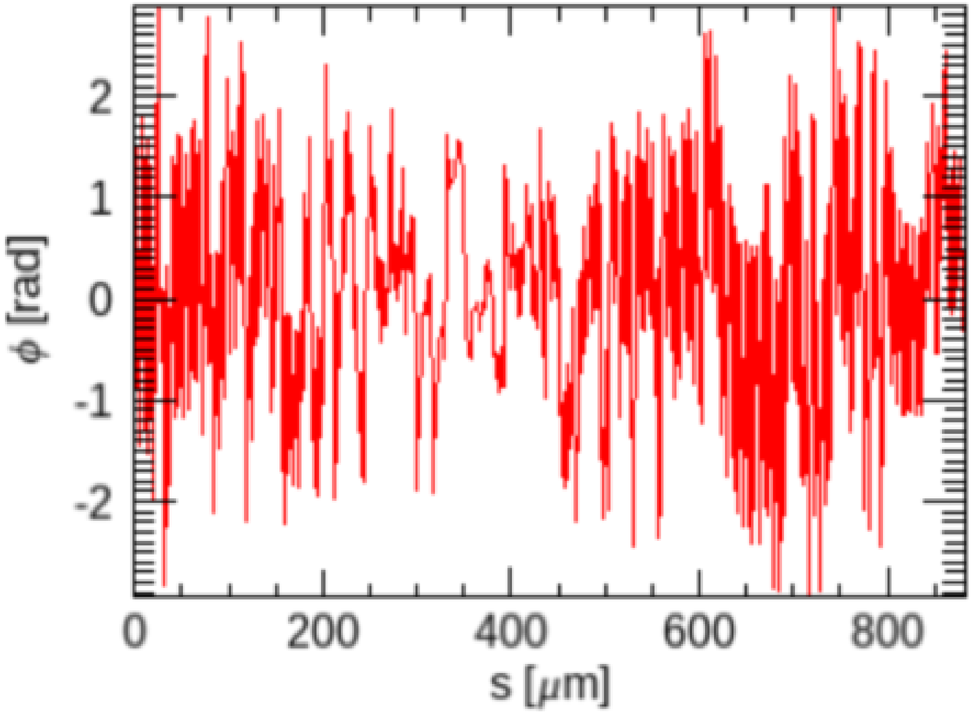
- Determines wavelength of emitted radiation
- Tunable via beam energy, λ_u, or K
- Resonance condition must match seed spectrum (e.g., white light overlap)
- Bandwidth tolerance ~ $\rho\, \lambda_r$ (Pierce parameter)
- Beam quality ($\Delta\gamma/\gamma$, emittance) → shifts / broadens resonance

- At resonance, radiation phase stays synchronized with oscillating electrons
- Enables constructive interference → exponential gain
- Tunable knobs: beam energy (γ), undulator period (λ_u), K parameter

White Radiation

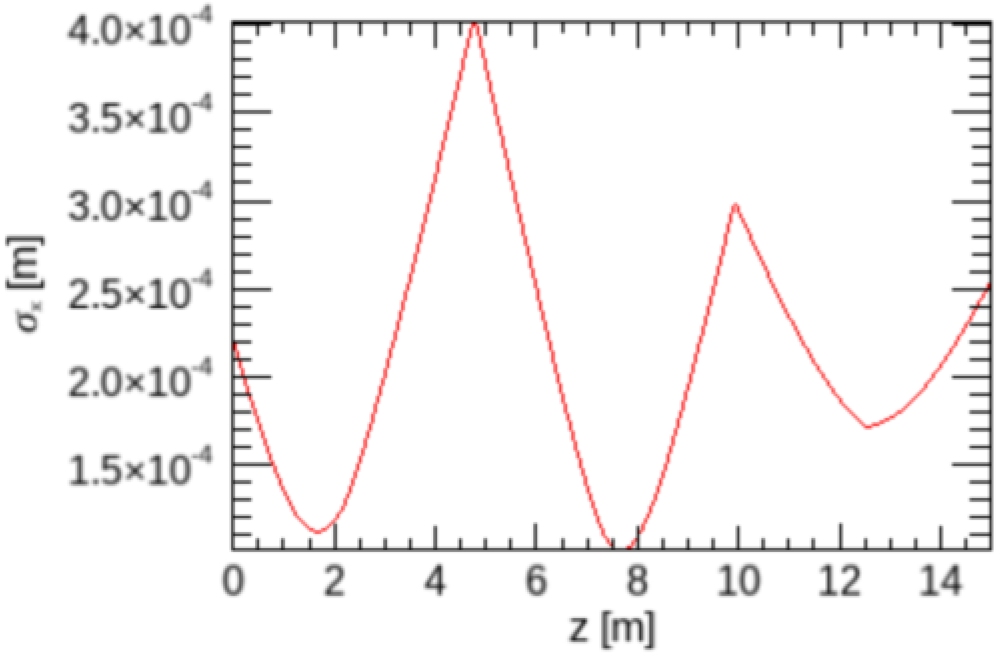
- **Motivation**: Betatron radiation = promising seed but incoherent, fluctuating, hard to test directly
- **Approach**: Use synthetic white radiation → broadband and controllable
- **Generation**: Created power profile with random fluctuations + random phase distribution to mimic incoherence
- **Control knobs**: spectrum width, temporal envelope, arrival time (tunable in simulations)
- **Application**: Injected into SPARC FEL beamline in GENESIS → compared against SASE case under identical beam/undulator conditions
- **Goal**: Test if incoherent broadband seeds can trigger FEL amplification and improve temporal properties

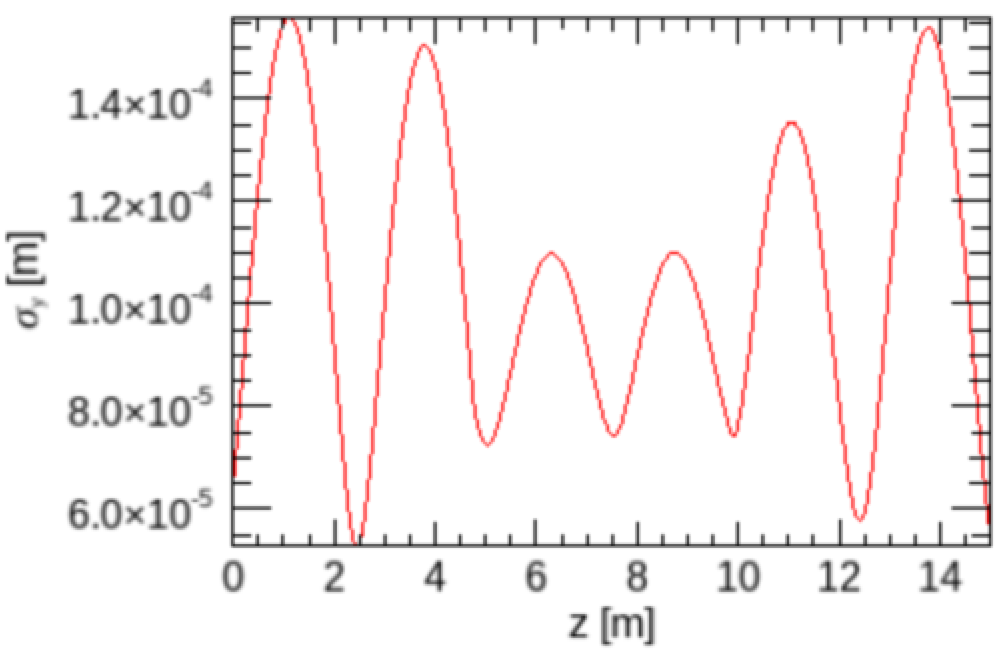




Electron Beam

- **Energy spread (Δγ/γ)** → too large → destroys resonance overlap → reduces gain
- **Emittance** → transverse beam quality; high emittance → larger divergence → weaker coupling to radiation field
- **Peak current** → higher current → stronger FEL gain
- **Bunch length** → must overlap with slippage length; too short → limits amplification
- **Energy stability** → jitter broadens spectrum, reduces reproducibility





Simulation Parameters

- **Undulator period (λu = 2.8 cm):** Sets fundamental FEL resonance; relatively long → IR wavelength output.
- **K = 1.28:** Moderate undulator strength → balances radiation wavelength and coupling efficiency.
- **Resonant wavelength (λr = 826 nm):** Matches accessible diagnostics at SPARC → convenient for benchmarking simulations.
- **Beam energy (~90 MeV):** Requires precise beam quality to achieve gain.
- **Peak current (2 kA):** High enough to enter high-gain regime despite moderate energy.
- **Normalized emittance (~2 / 1.6 mm·mrad):** Critical for transverse coherence.

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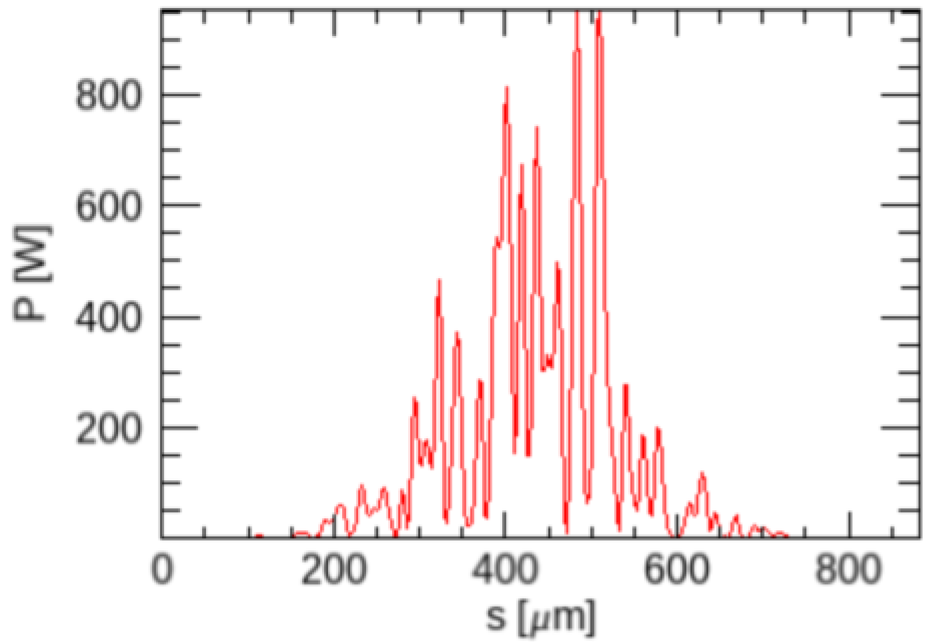
White Radiation Properties

- **Fractional bandwidth ~5%** → mimics broad, incoherent source like betatron/white light.
- **Coherence time ~60 fs** → much shorter than electron bunch length → realistic for incoherent seed.
- **Coherence length ~18 μm** → ensures overlap with electron bunch slices.
- **Entrance waist ~2.3×10^{-4} m** → chosen to match beam transverse size.
- **Peak power scan (1–1000 W)** → allows studying FEL sensitivity to seed strength.

Quantity (symbol)	Value
Fractional bandwidth (Δ)	0.04708 (4.708%)
Coherence time (τ_c)	5.85×10^{-2} ps (58.5 fs)
Coherence length (ℓ_c)	17.54 μm
Time window (T)	2.945 ps
Entrance optical waist (w_0)	$\approx 2.3 \times 10^{-4}$ m

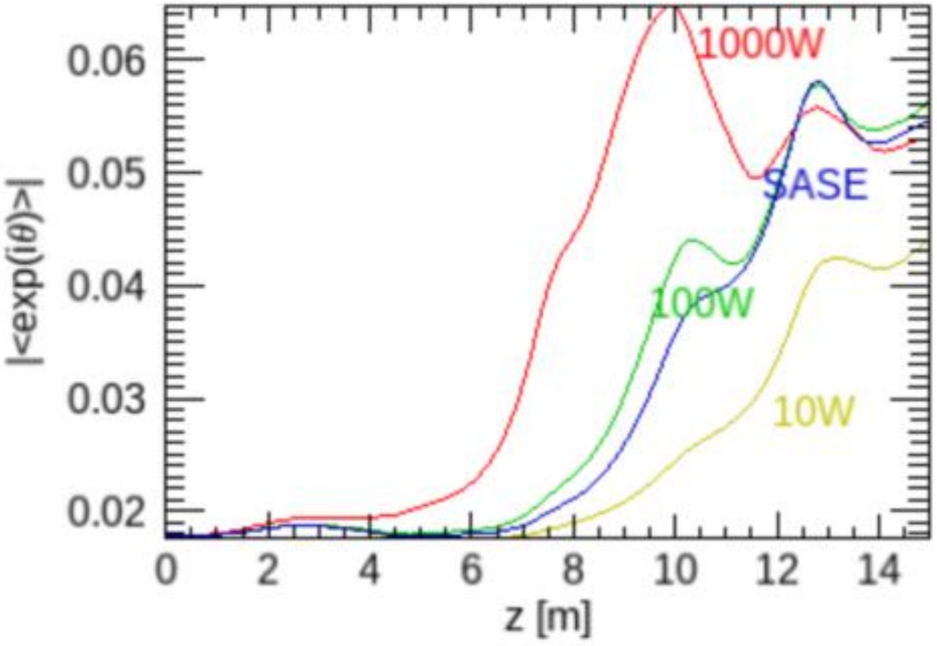
Peak power P_{pk} (W)	Total energy U_{seed} (J)	U_{seed} (pJ)	$t_{eff} = U_{seed}/P_{pk}$ (ps)
1	2.83×10^{-13}	0.283	0.283
10	2.28×10^{-12}	2.28	0.228
100	2.11×10^{-11}	21.1	0.211
1000	2.33×10^{-10}	233	0.233

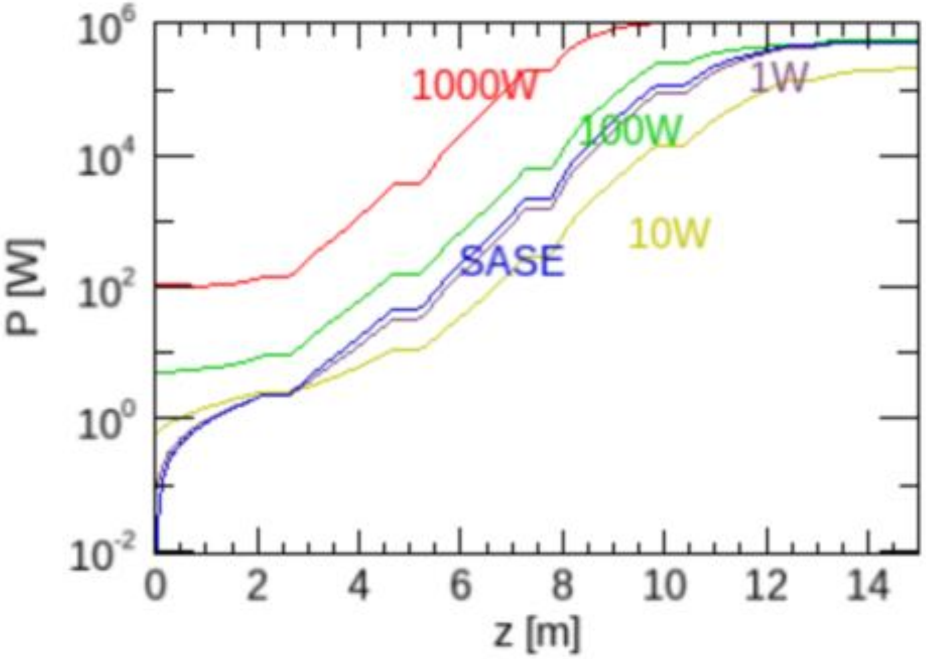


FEL Growth & Bunching

- Radiation amplification starts from shot noise (SASE) or from a seed field.
- Weak seeds (1 W, 10 W): no clear advantage over SASE, sometimes degraded growth.
- Moderate seeds (100 W): earlier growth, stronger bunching, narrower spectrum.
- Strong seeds (1000 W): fastest saturation, highest bunching, single-peak spectrum.
- Clear correlation: higher seeding → earlier saturation & improved coherence.

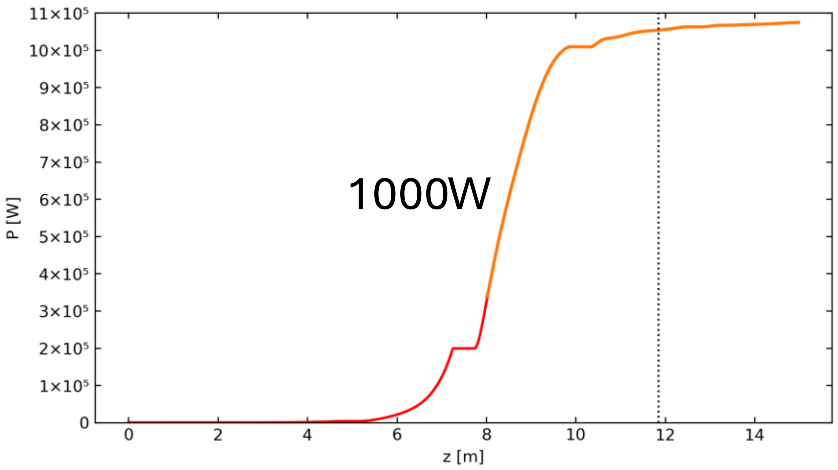
Case	P_{sat} (W)	b_{max}	Spectrum
SASE	$\sim 5 \times 10^5$	~ 0.05	Broad, noisy
1 W	$\sim 5 \times 10^5$	~ 0.05	Broad, noisy
10 W	$\sim 2 \times 10^5$	< 0.05	Irregular, degraded
100 W	$\sim 7 \times 10^5$	~ 0.055	Narrower
1000 W	$\sim 1 \times 10^6$	> 0.06	Narrow, single peak

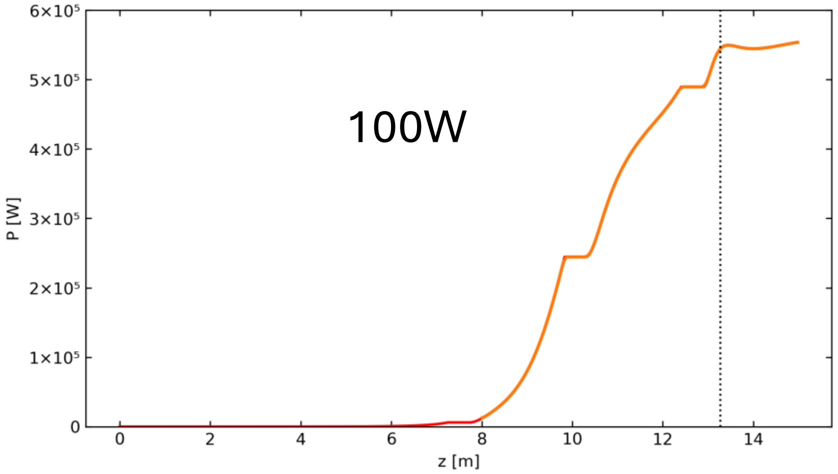


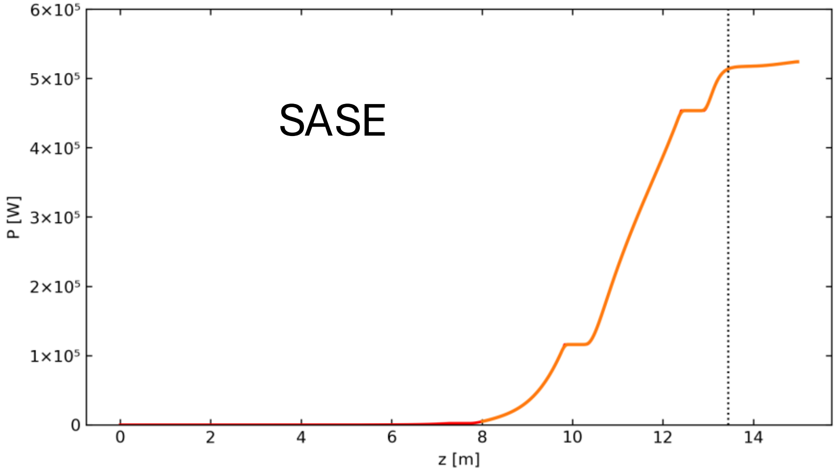


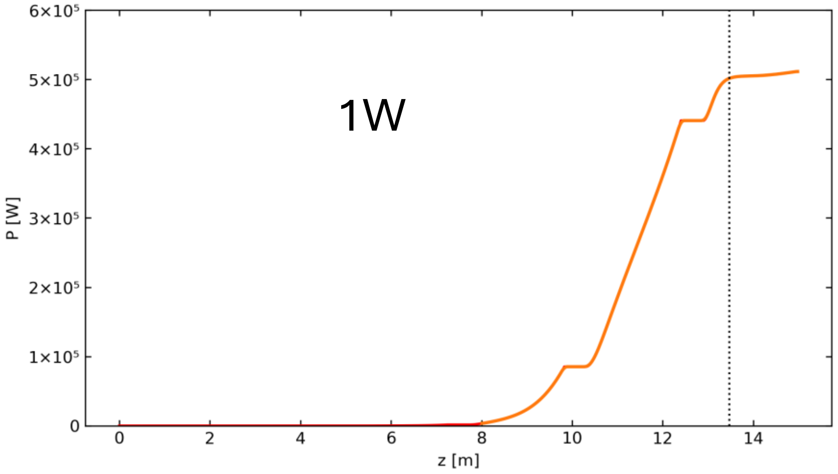
Saturation Lengths

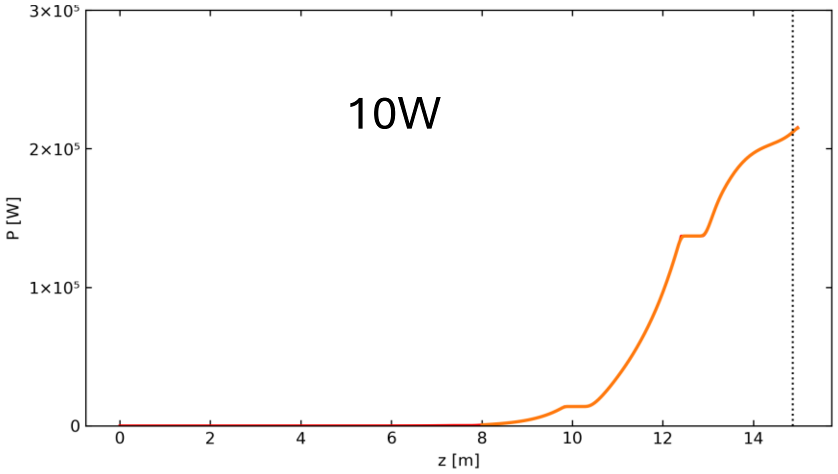
- SASE: saturation after ~13–14 m, noisy growth.
- 1 W seed: nearly identical to SASE → negligible impact.
- 10 W seed: weaker growth, delayed saturation → insufficient seeding.
- 100 W seed: earlier saturation, stronger output.
- 1000 W seed: fastest saturation, highest power.
- General trend: increasing seed power → shorter Lsat and improved efficiency.





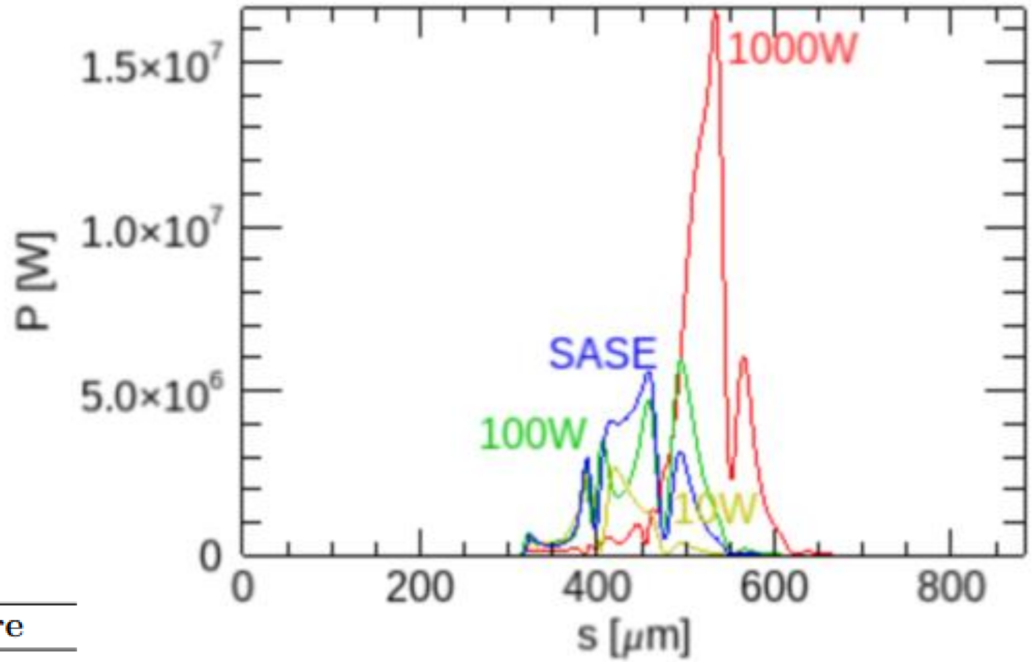






Temporal Output

- SASE/1W → noisy multi-spike structure.
- 10W → weaker output, irregular temporal profile.
- 100W → shorter pulse with fewer spikes, more stable.
- 1000W → clean, dominant single spike with highest power.
- Stronger seeds improve temporal coherence, reduce fluctuations, and shift the system toward more stable lasing.



Case	L_{sat} [m]	P_{sat} [W]	Δt_{FWHM} [fs]	Δs_{FWHM} [μm]	Temporal structure
SASE	~ 13.4	$\sim 5\times10^5$	~ 205	~ 50	Multi-spike, noisy
1 W	~ 13.47	$\sim 5\times10^5$	~ 206	~ 61.9	Multi-spike, noisy
10 W	~ 14.87	$\sim 2\times10^5$	~ 151	~ 45.3	Multi-spike, weaker
100 W	~ 13.27	$\sim 6\times10^5$	~ 108	~ 32.5	Fewer spikes, shorter pulse
1000 W	~ 11.84	$\sim 1\times10^6$	~ 146	~ 43.9	Dominant single spike

Conclusion

- **SASE baseline** reproduces expected noisy, multi-spike structure with broad spectrum.
- **White-light seeding** explored as an alternative seed source:
- Low seed powers (1–10 W) show limited improvement or degraded performance.
- Intermediate seeding (100 W) yields shorter pulses, earlier saturation, and improved coherence.
- Strong seeding (1000 W) produces clean single-spike temporal structure, but with spectral broadening.
- **Key trend:** Increasing seed power reduces saturation length and improves temporal coherence.
- **Outlook:** White radiation, despite limitations in spectral control, is a valuable test-bed for alternative FEL seeding strategies, especially for betatron seeded cases.