The Physics of Electron Sources

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Applications of Modern Electron Sources

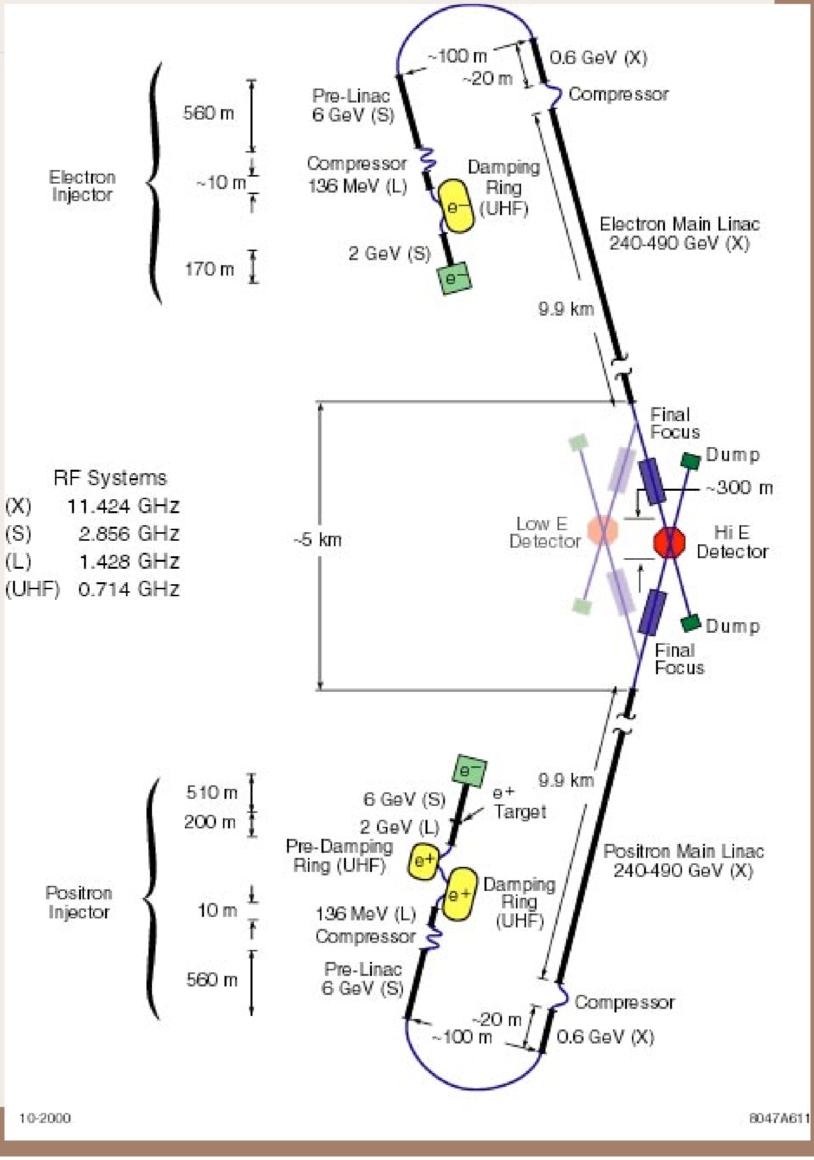
- Advanced applications demand extremely high quality beams
  - High charge (>10^9 electrons)
  - Short pulse (ps to fs)
  - Very cold: little spread in momentum, transverse angle (low emittance)
- High energy physics
  - Linear colliders
  - Advanced accelerators
- Light sources
  - High gain free-electron lasers
  - Inverse Compton scattering X-ray sources

Next generation linear collider

- Electrons and positron collisions at >250 GeV
- How does electron source impact design?
- *Luminosity* requires
  - High repetition rate
  - Bunch trains
  - Large number of electrons per pulse
  - Low emittance

$$\mathbf{L} = \frac{N_{e+} N_{e-} f_c}{4\pi\sigma_x\sigma_y} = \frac{\gamma N_{e+} N_{e-} f_c}{4\pi\sqrt{\beta_x^*\beta_y^*}\cdot\sqrt{\varepsilon_{x,n}\varepsilon_{y,n}}}$$

- Electron (and positron) spin polarization needed
  - Physics reach of machine



NLC electron beam parameters at damping ring entrance

PARAMETER NAME	SYMBOL	VALUE
Bunch Spacing	τ_s	1.4 ns
Particles/Bunch	N_{e-}	0.8×10^{10}
Number of Bunches	N_b	190
Repetition Rate	f_{rep}	120 Hz
Energy	E	1.98 GeV
Bunch Length	σ_z	10 mm (max.)
Bunch-to-Bunch Pop. Uniformity		2%
Emittance (norm. rms)	ε_n	100 mm-mrad
Polarization	p_{e-}	80 %

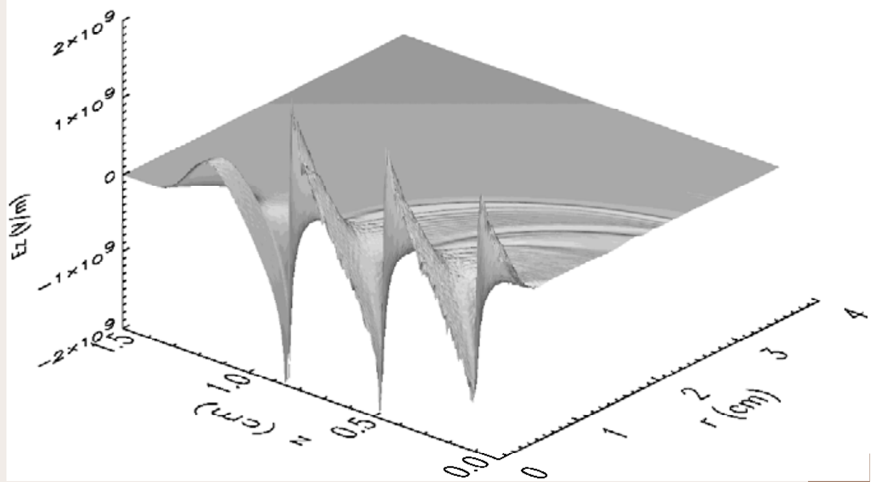
Advanced Accelerators I: Wakefield Accelerators

- Use coherent (generalized Cerenkov) to excite waves in media
  - Plasma
  - Dielectric
  - Periodic structures
- Beam excitation must have correct frequency content
  - Multi-bunch (~klystron)
  - *Short* single bunch $k_z \sigma_z \leq 2$
- Cerenkov scaling for very high fields

$$eE_{z,dec} = e^2 N_b \int \frac{n(k)-1}{n(k)} dk$$

$$\Rightarrow e^2 N_b k^2 \cong 4 e^2 N_b \sigma_z^{-2}$$

- Emittance important at low energies

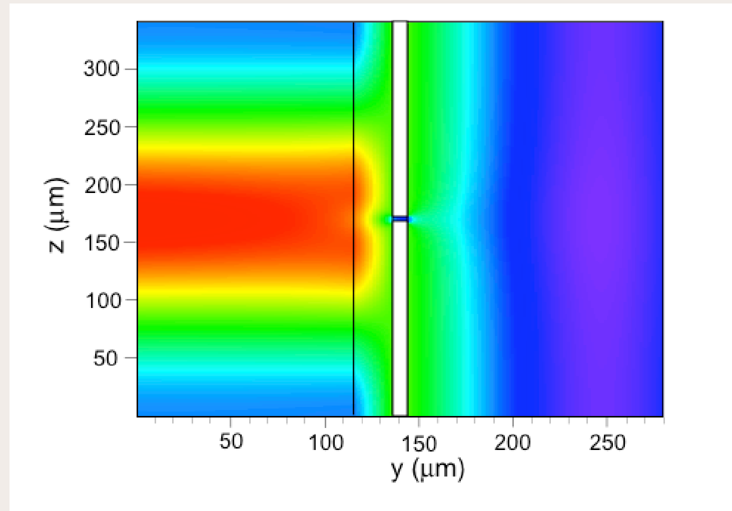


Example: Simulation of ~GV/m *plasma wakefield accelerator* longitudinal fields. Beam located near z =1.3 cm, σ_z=0.5 mm, σ_r=0.7 mm; N_b=10^{11}.

Advanced Accelerators II: Optical Accelerators

- Optical to quasi-optical accelerators under investigation
  - Use lasers or other coherent sources
  - Scale the RF accelerator to μm-mm wavelengths
- Very high fields
  - Short time scales
  - Short length scales
- Beams demanding
  - Microbunched injection
    - Small charge/μbunch (pC)
  - *Very* small emittances

$$\varepsilon_n \leq 10^{-8} \text{ m-rad.}$$



Example: Simulation of resonant THz dielectric accelerator, with 250 micron aperture.

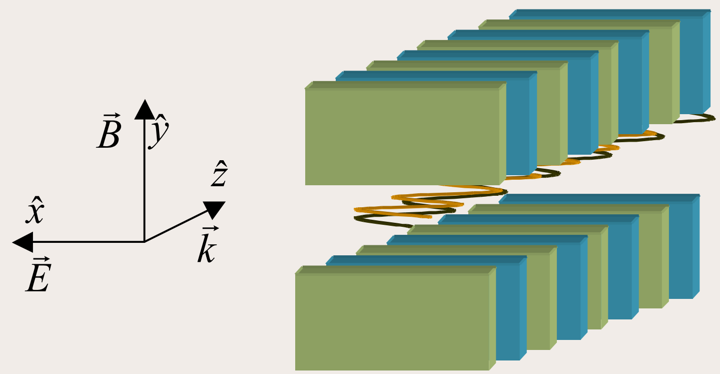
Beam-based Light Sources I: The Free-electron Laser

- Electromagnetic field coherently enhanced by undulator radiation
- Resonance condition: electron slips one λ_r for every λ_u

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left[1 + a_u^2\right] \qquad a_u = 2\pi\, eB_{u,rms}/\lambda_u m_e c^2$$

- Coherence: radiation cone (γ^{-1}) angular overlap

$$\varepsilon_n \leq \frac{\lambda_r \gamma}{4\pi} = \frac{\lambda_u}{8\pi\gamma}\left[1 + a_u^2\right]$$



Schematic of undulator with periodicity λ_u, interaction of electron beam with radiation field.

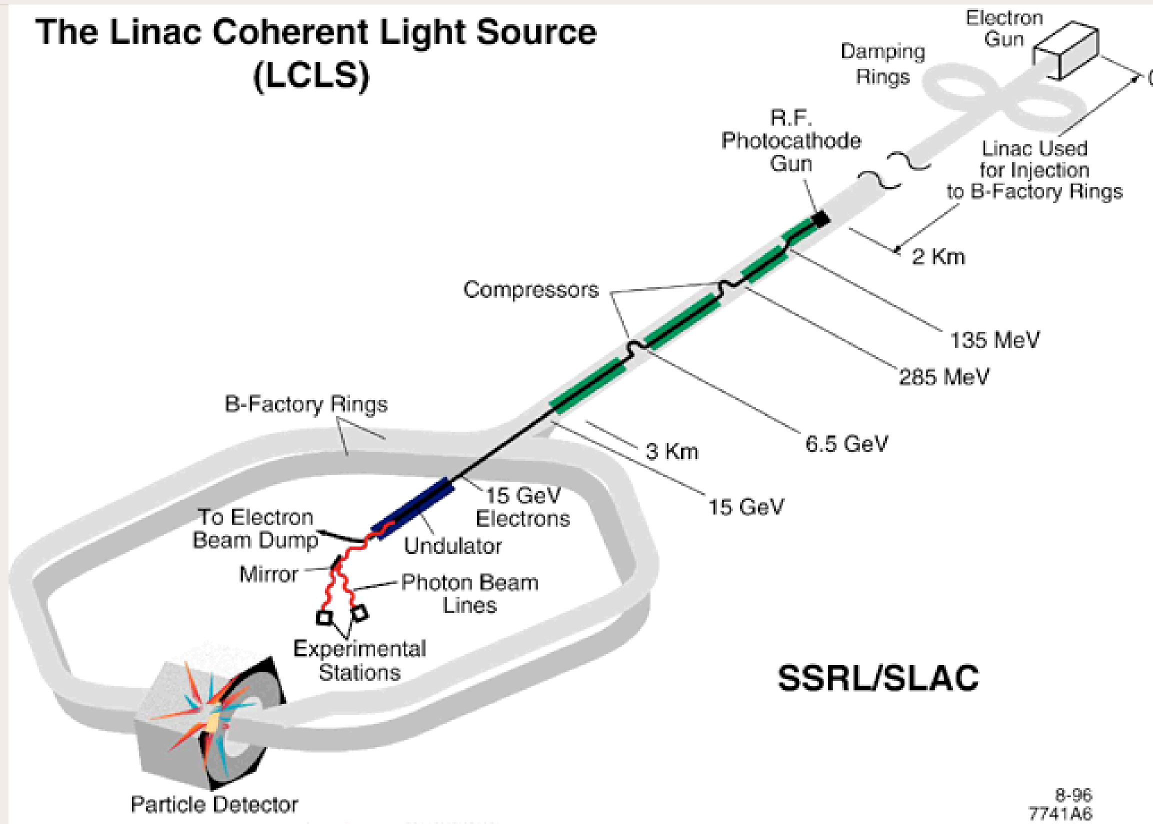
Amplification is *instability*, based on cold, dense beam. Gain: $G \propto \exp(z/L_g)$

$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

$$\rho = \left[\frac{a_u}{4k_u}\right]^{2/3}\left(\frac{4\pi e^2 n_b}{\gamma^3}\right)^{1/3} \propto a_u^{2/3}\left(\frac{B_e}{\gamma}\right)^{1/3}$$

$$B_e = \frac{2I}{\varepsilon_{x,n}\varepsilon_{y,n}}$$

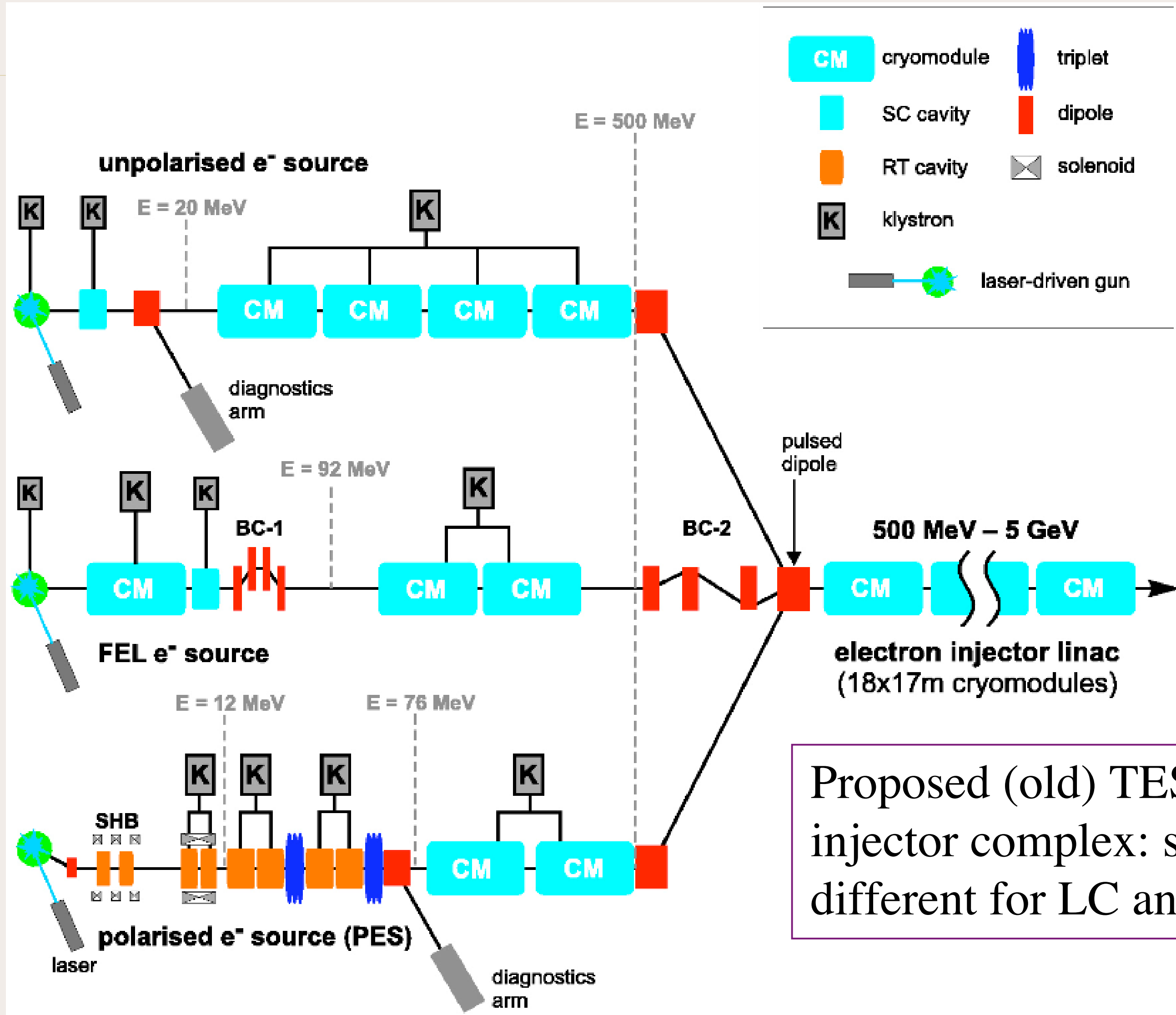
X-ray SASE FEL



E=14 GeV
λ_r=1.5 Å

- Based on SASE (self-amplified, spontaneous emission) instability
- Very high brightness demanded: $\varepsilon_n \le 2 \cdot 10^{-6}$ m-rad, $I = 4$ kA

HEP and FEL Marriage?



Proposed (old) TESLA injector complex: sources are different for LC and FEL