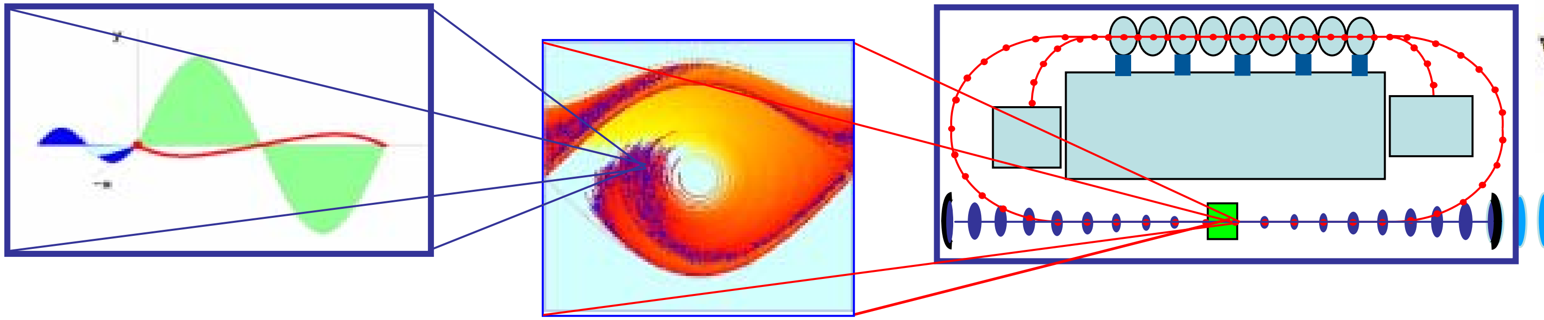

Short Rayleigh Length Free Electron Lasers

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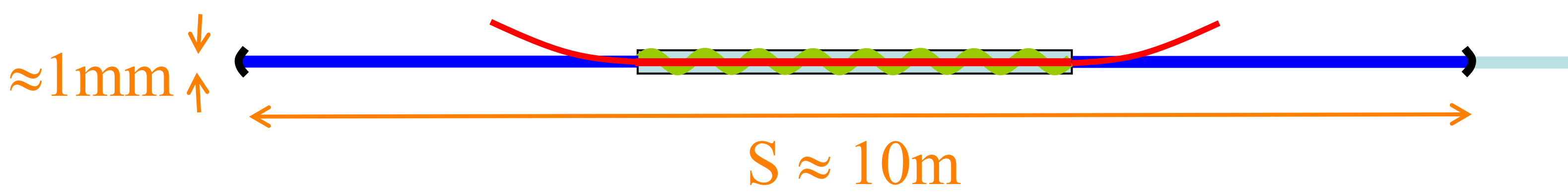
- **Acknowledgements:** NPS students over last 8 years, Alan Todd (AES), and George Neil & Steve Benson (Jlab)
- **Motivation:** consider compact FEL oscillators
  - Scientific laboratories want compact FELs
  - Industrial & military applications need compact FELs
  - Assume “compact” means mirror separation $S < 12$ m
  - Mirror damage at intensities $I > 1 \rightarrow 10 \text{kW/cm}^2$
  - Typical FEL design: $\perp$ size $\approx$ 1mm, $\parallel$ length $\approx$ 10m

=> mirror damage limits optical power !!



FEL Design Examples

- **Assume:** Compact FEL mirror separation: $S \approx 12$ m
  - Mirror damage at intensities like $I > 1 \rightarrow 10\text{kW/cm}^2$
  - Diffraction of mode radius $w(z) = w_0(1+z^2/Z_0^2)^{1/2}$

    where optical Rayleigh length is $\mathbf{Z_0 = \pi w_0^2 / \lambda}$
  - Typical FEL interaction gives $w_0 \approx 2r_b \approx 1\text{mm}$
  - Resonator output coupling (10%): $Q_n \approx 10$

- **Example 1:** desired wavelength $\lambda \approx 1\mu\text{m}$ (infrared)
  - FEL interaction: $w_0 \approx 2r_b \approx 1\text{mm} \Rightarrow Z_0 \approx 3\text{m}$
  - Mode area at mirror ($z \approx S/2 \approx 6\text{m}$) is $A \approx 0.15\text{cm}^2$

  Therefore: FEL power limited to $P_{out} < 150\text{W}$

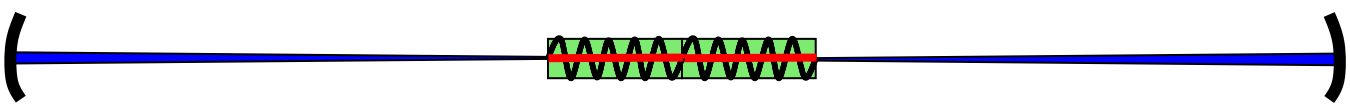
- **Example 2:** desired wavelength $\lambda \approx 0.1\mu\text{m}$ (UV)
  - FEL interaction: $w_0 \approx 2r_b \approx 1\text{mm} \Rightarrow Z_0 \approx 30\text{m}$
  - Mode area at mirror ($z \approx S/2 \approx 6\text{m}$) is $A \approx 0.03\text{cm}^2$

  Therefore: FEL power limited to $P_{out} < 3\text{W}$

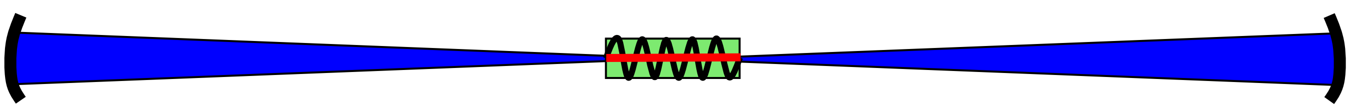
Short Rayleigh Length FEL Concept

- Alter a basic design rule: $Z_0 \approx 0.5L$

  where L is undulator length, typically $L \approx$ meters
- Short Rayleigh Length (SRL) reduces mirror intensity
- Determine SRL by adjust mirror radius of curvature
- FEL interaction altered with SRL mode:
  - rapidly changing optical amplitude and phase - bad !
  - accelerated bunching in more intense optical fields - good !
- Conventional FEL:



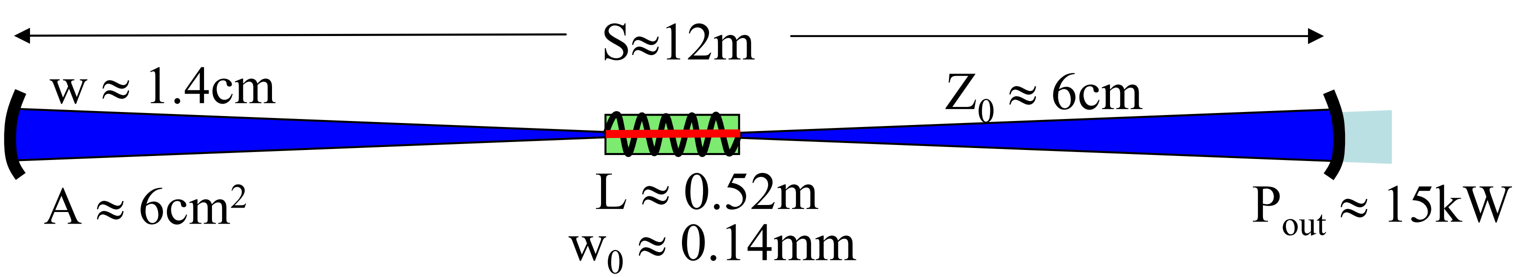
- Short Rayleigh Length FEL*:



* NIM A **393**, 262 (1997)

A Short Rayleigh Length FEL Design

- SRL expands mode and protects mirrors
- Expanding mode requires shorter undulator length L
- Shorter L requires adequate peak current in micropulse
- **Example SRL FEL:**
  - Undulator: $N \approx 22$, $L \approx 52\text{cm}$, $\lambda_o \approx 2.36\text{cm}$, $K \approx 1$
  - Electron Beam: $E_b \approx 80\text{MeV}$, $I_{peak} \approx 400\text{A}$, $r_b \approx 0.06\text{mm}$
  - Optical: $\lambda = \lambda_o(1+K^2)/2\gamma^2 \approx 1\mu\text{m}$
  - Resonator: $S \approx 12\text{m}$, $Z_0 \approx 6\text{cm}$, $w_0 \approx 0.14\text{mm}$, $Q_n \approx 4$
  - At mirror: $w \approx 1.4\text{cm}$, $A \approx S^2\lambda/4Z_0 \approx 6\text{cm}^2$, **$P_{out} \approx 15\text{kW}$**

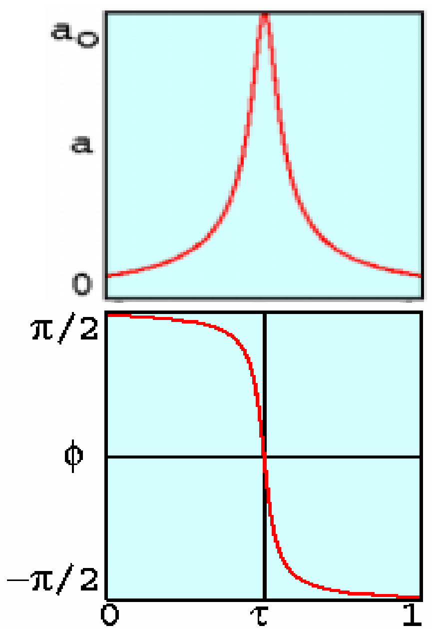


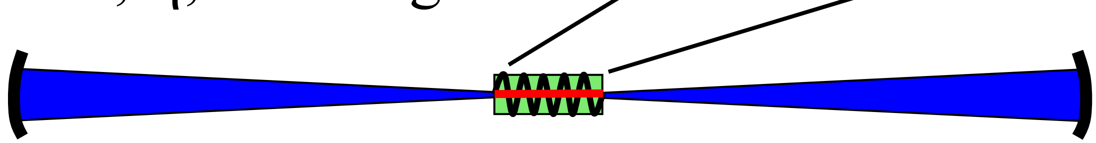
FEL Interaction with a Short Rayleigh Length Mode

$$a(\tau) = \frac{a_0}{(1+(\tau-\tau_w)^2/z_0^2)^{1/2}}$$

$$\phi(\tau) = -\tan^{-1}((\tau-\tau_w)/z_0)$$

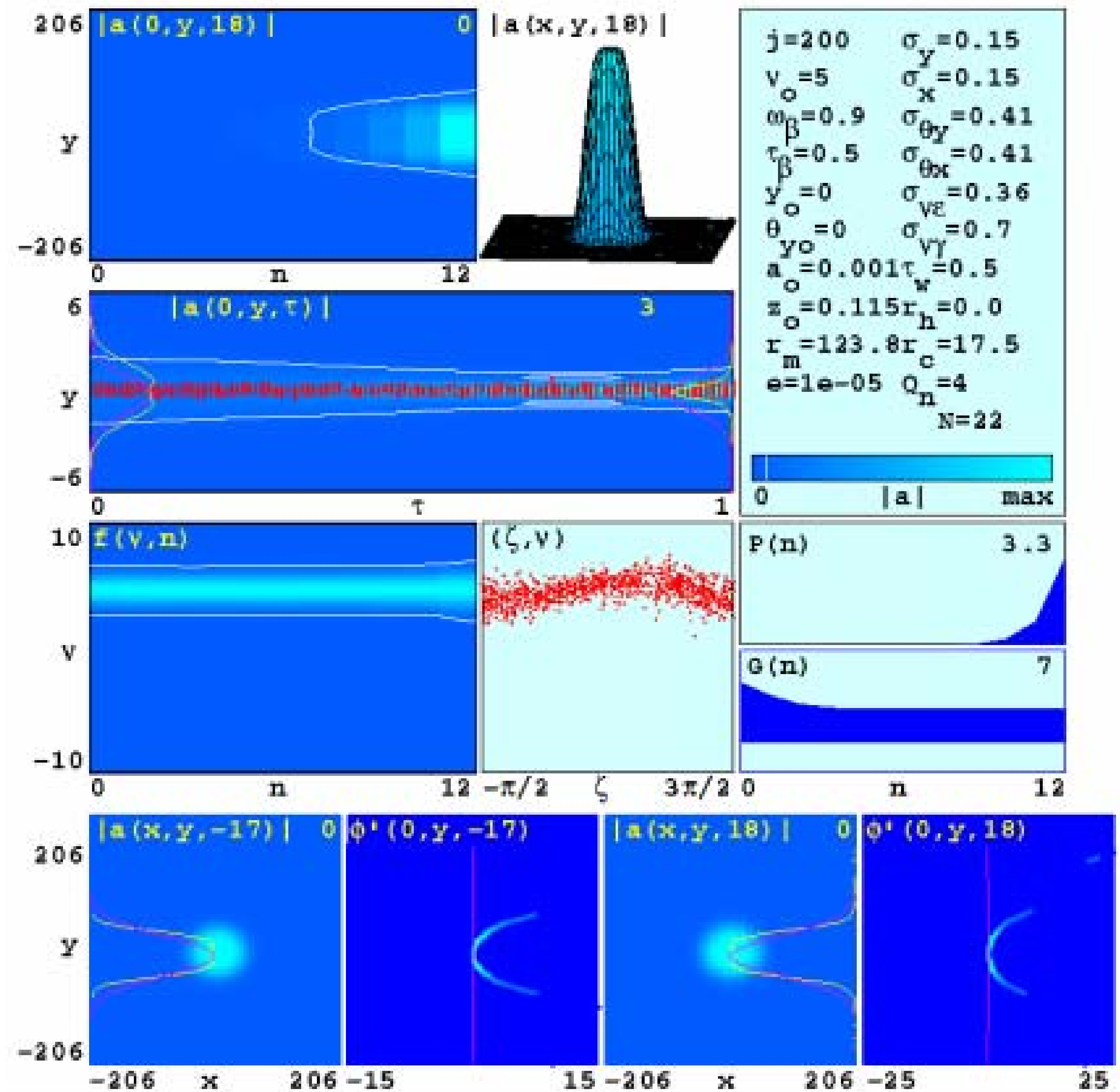
- Electrons interact with field along undulator from $\tau = ct/L = 0 \rightarrow 1$
- Electrons "see" intense optical field $a(\tau_w)$ and phase $\phi(\tau_w)$ at mode focus τ_w
- Rapidly changing field reduces FEL interaction, but surprisingly OK
- Examine FEL interaction: r_b, N, Z_0
- Examine FEL gain, G, in weak fields
- Examine FEL extraction, η, in strong fields





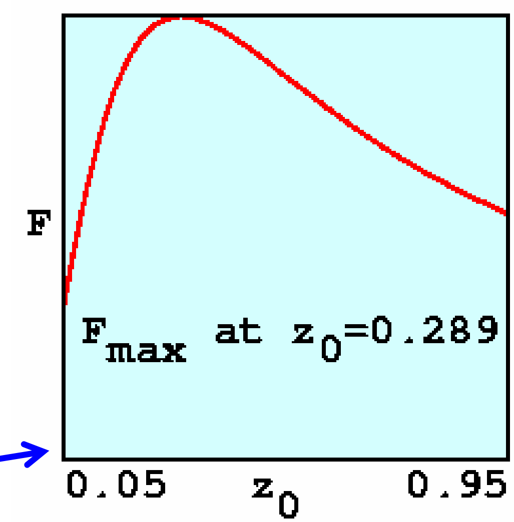
Multimode FEL Simulations

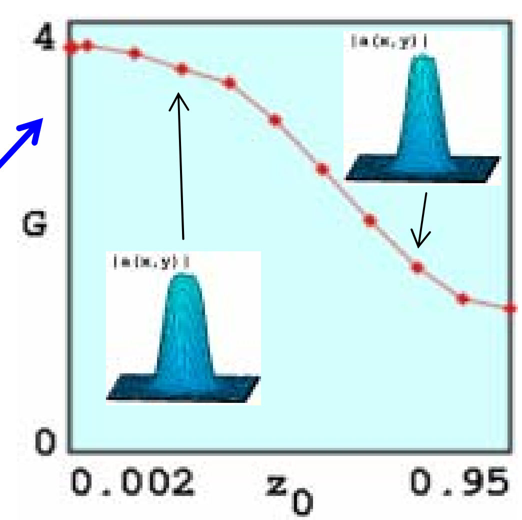
- Simulation follows:
  - Many ⊥ modes
  - Optical diffraction
  - Betatron motion
  - Energy spread
  - Mirror vibration
  - Beam alignment
  - Self-consistent
  - SVAP approx.
- Note:
  - mode shape
  - mode in undulator
  - mode at mirrors
  - steady-state gain
- See Poster: MOPOS65



Vary Rayleigh Length

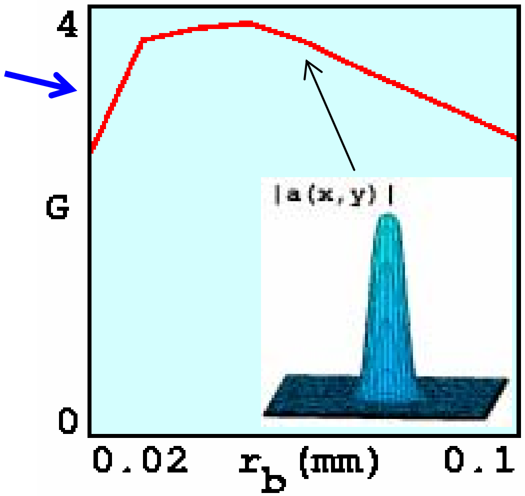
- Vary $Z_0 = 2.6$cm to $Z_0 = 49$cm
- Normalized Rayleigh length $z_0 = Z_0/L$
- Mode area at mirrors is $A_{S/2} \propto 1/z_0$
  as desired to reduce mirror intensity
- Mode area at waist is $A_0 \propto z_0$
- Mode area averaged over undulator is
  $\langle A \rangle \propto [z_0 + 1/(12z_0)] \propto 1/F$ (above)
- Simple theory: $G \propto F$ (filling factor)
- G_{max} at $z_0 = (12)^{-1/2}$; $Z_0 = L/(12)^{1/2}$
- Simulation allows many optical modes:
  - Gain G increases for small z_0 values **!!**
- **Small Z_0 $\Rightarrow$ still good gain !!**
- **Can save mirrors with good gain !!**





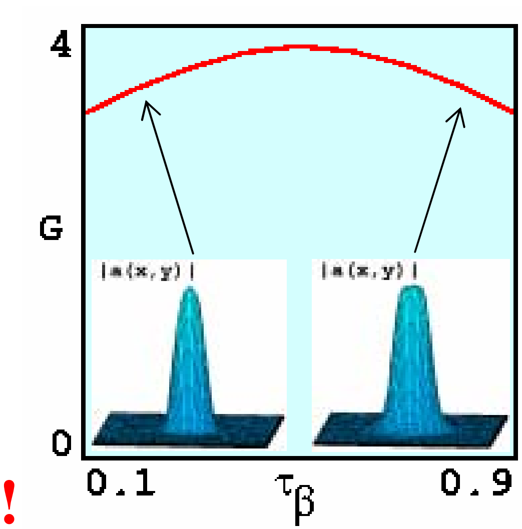
Vary Electron Beam Focus

- **Keep beam inside focused optical mode**
- Emittance $\varepsilon_n = \gamma r_b \theta_b \approx 3$mm-mrad
- For large r_b , beam is outside mode
- For small beam focus $r_b \Rightarrow \theta_b$ bigger



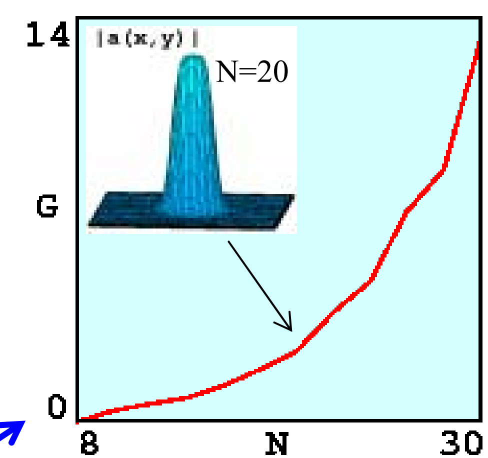
r_b small, θ_b big r_b big, θ_b small

- Electron beam focus optimum
  at middle of undulator $\tau_\beta = 0.5$
  (with optical mode centered at $\tau_w = 0.5$)
- **So, focus electron at optical mode waist !!**

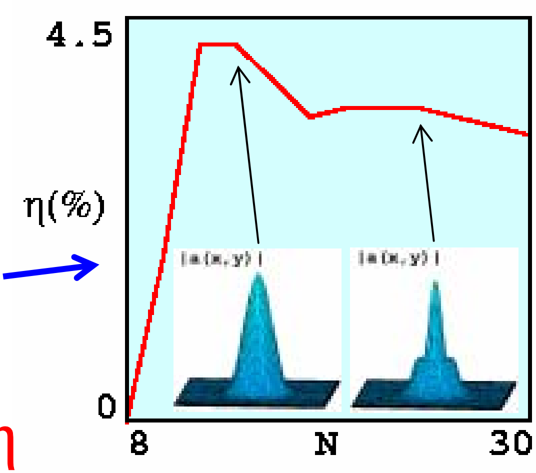


Vary Undulator Length N

- Vary N from 8 to 30 periods
- Undulator period fixed at $\lambda_o \approx 2.36$cm
  to give $\lambda \approx 1\mu$m optical wavelength
- Undulator gap is $g \approx 1$cm
- Mode scraping not an issue for small N's



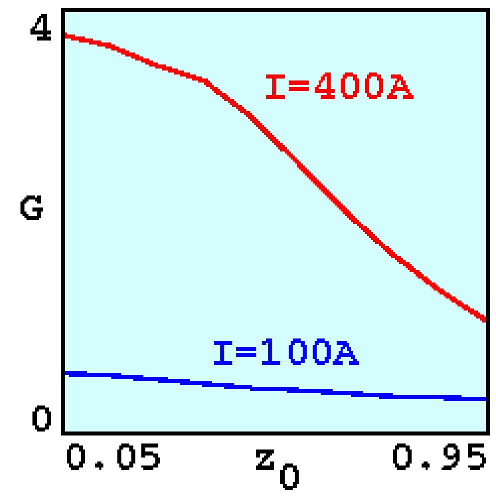
- N > 8 needed for $G > 1/Q_n$, "threshold"
- Gain increases rapidly with increasing N



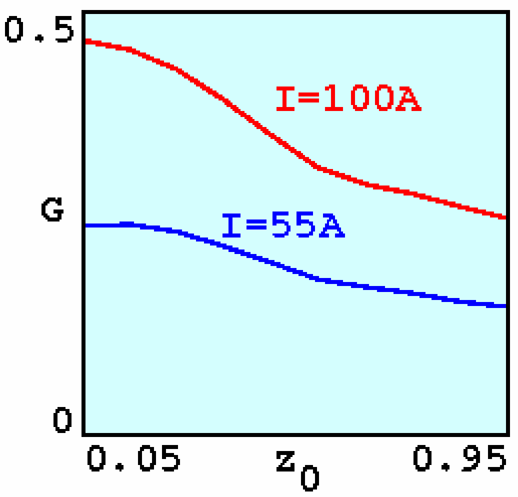
- Extraction $\eta \approx 4.3\%$ peaks at $N \approx 12 - 14$
- Extraction decreases as $\approx 1/2N$
- Use N = 22 in design: **BIG Gain, good η**
- See Poster: MOPOS66

Short Rayleigh Length FELs

- Reduce peak current I = 400A to I = 100A
- Still SRL is a better FEL design option !!



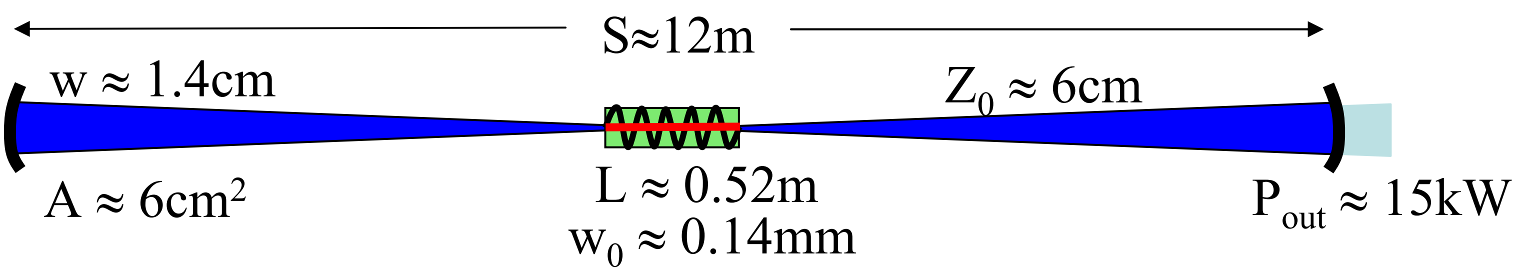
- **New example SRL FEL:**
- Same Undulator: N≈22, L≈52cm, K≈1
- Resonator: S≈12m , Z_0≈6cm, **Q_n≈20**
- Same Optical wavelength: λ≈1μm
- New Electron Beam: E_b ≈ 80MeV,
  ε_n ≈ 10mm-mrad (typical emittance)
  r_b ≈ 0.1mm (beam focal radius)
  I_{peak} ≈ 100A, and **I_{peak} ≈ 55A**
- SRL gives better FEL gain in each case



- **Appears that SRL FEL is just a better design !!**

Conclusions: SRL Advantages & Issues

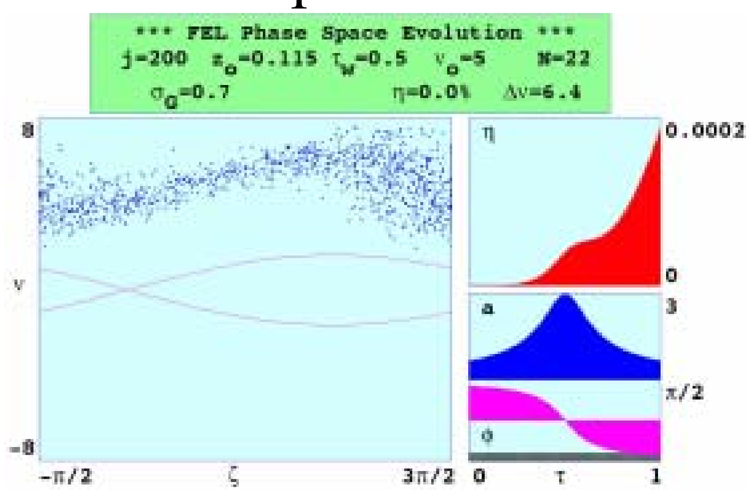
- Short Rayleigh Length (SRL) optical mode ⇒ 2 advantages
  - reduces optical intensity on resonator mirrors at smaller S
  - single optical wavefront amplified ⇒ excellent beam quality
- **Issues:** (See Poster: THPOS59)
- Electron Beam - Optical Mode Alignment is **delicate**:
  - Electron beam ($r_b \approx 60\mu m$) < optical mode ($w_o \approx 140\mu m$)
  - But, FELs now hold beam to tolerance of $0.1 r_b \approx 6\mu m$!!
- Optical Resonator Mirror Alignment is **delicate** :
  - Mirror must "aim" mode back to small waist $\approx w_o$ over $\approx S$
  - So, allowed mirror tilt $\Delta\theta \approx w_o/S \approx$ a few μradians
  - But, FELs now hold to ≈ 0.1μradians ⇒ **Active Alignment !!**



SRL FEL Phase Space

- Show phase space evolution for weak & strong fields
- Separatrix “balloons” to “pull down” bunched electrons
- Electron bunching mechanism is **NOT** conventional
- Note optical amplitude sharp focus and phase shift

weak optical fields



strong optical fields