Establishing Lasing in the FEL*

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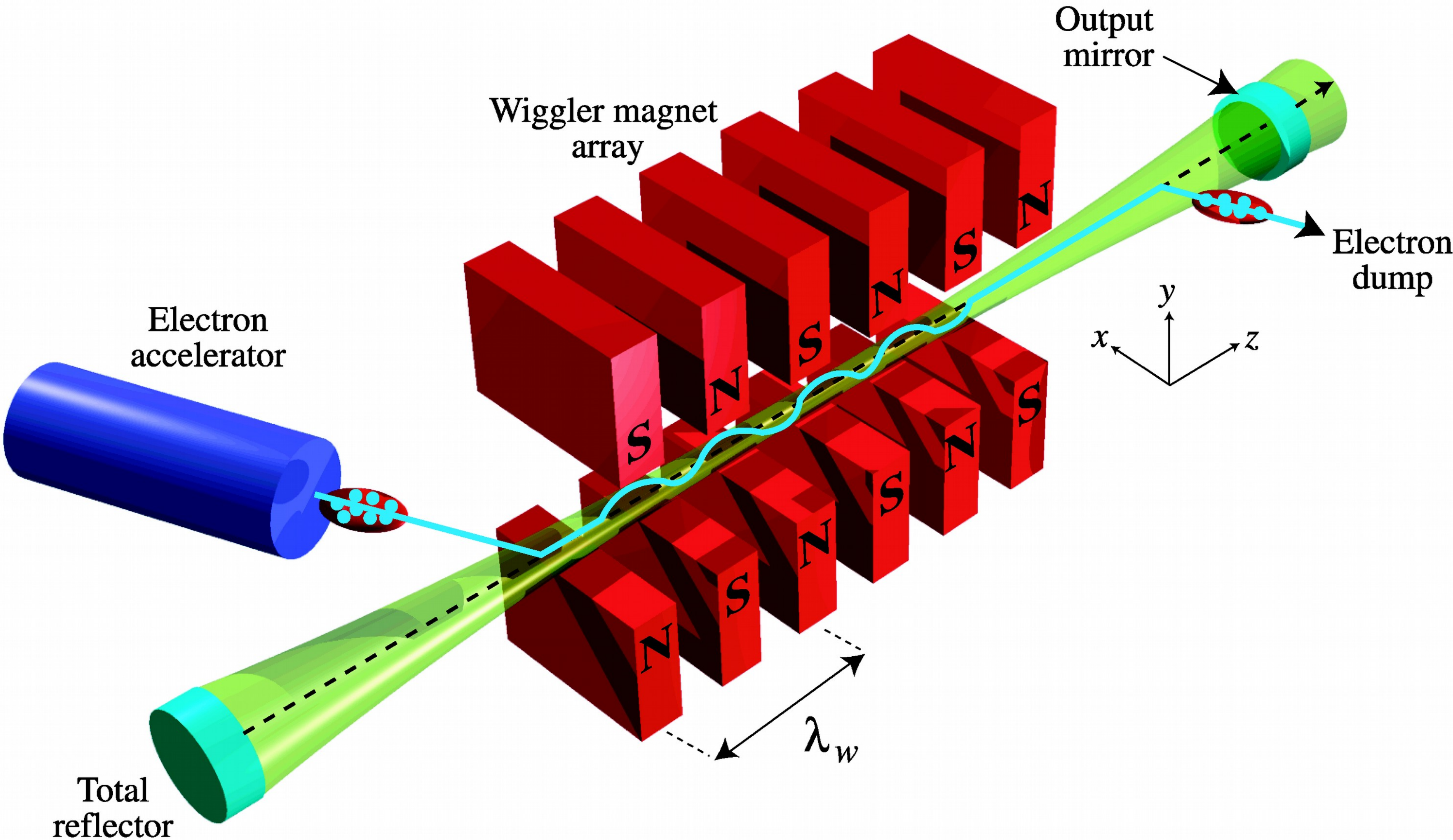
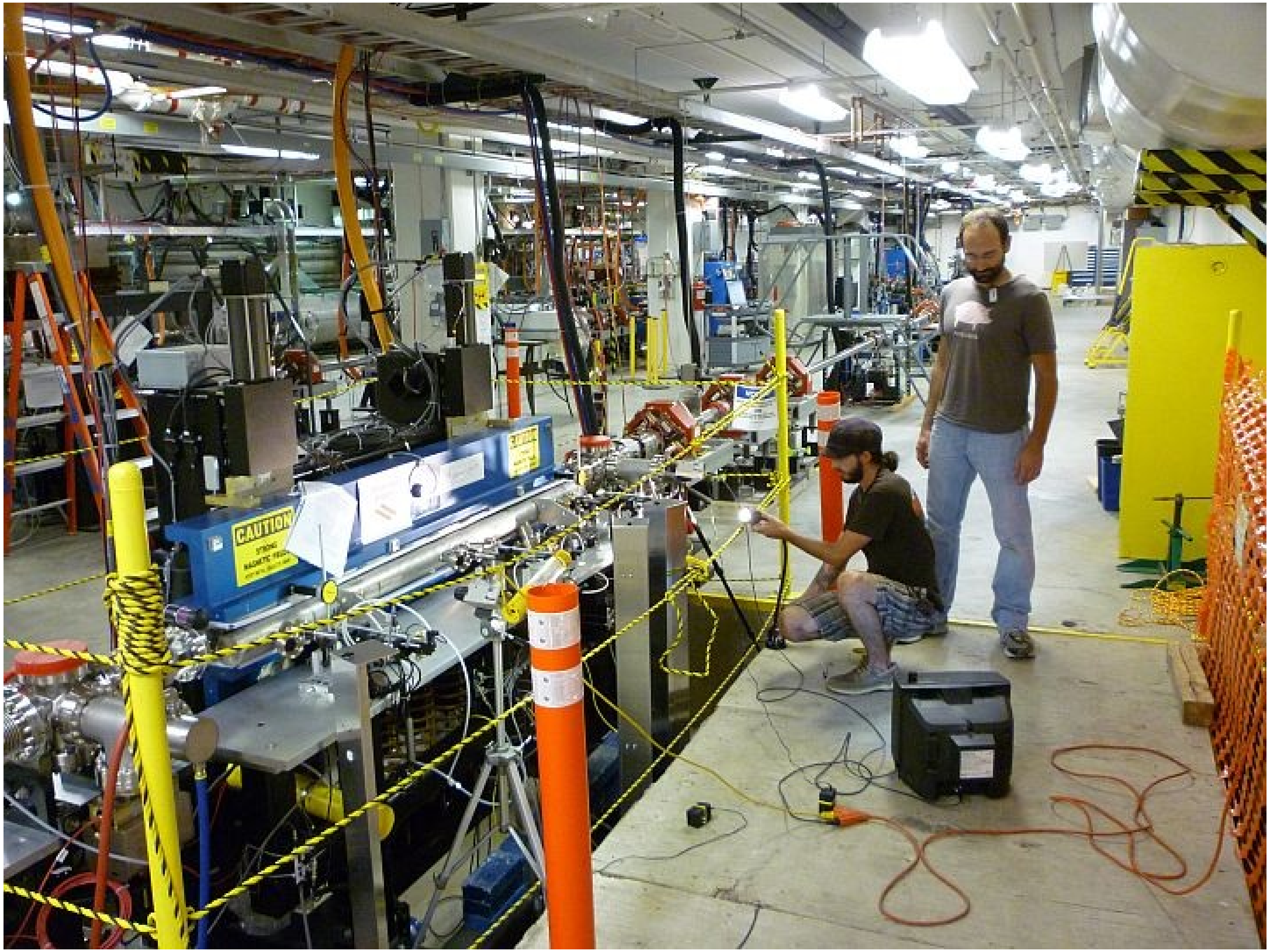
Ideal FEL



Output mirror
Wiggler magnet array
Electron dump
Electron accelerator
y
x
z
S
N
S
N
S
N
S
N
S
N
S
N
λ_w
Total reflector

Real FEL

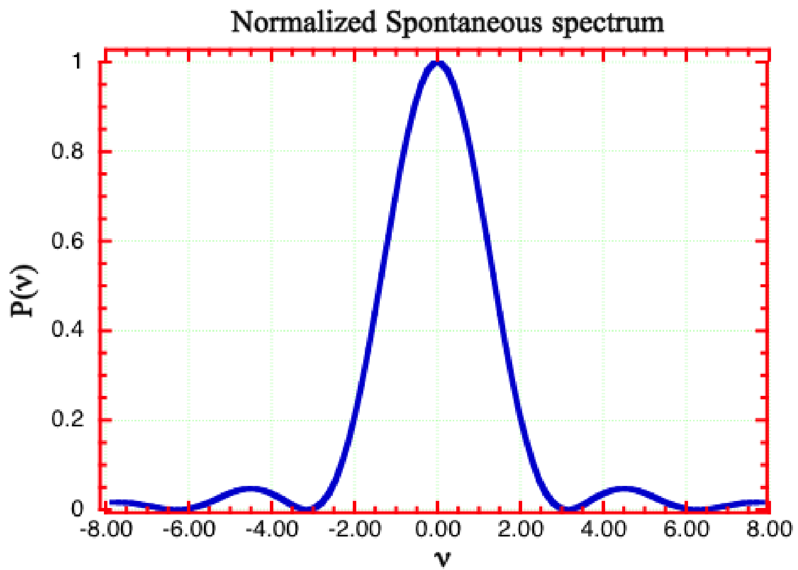


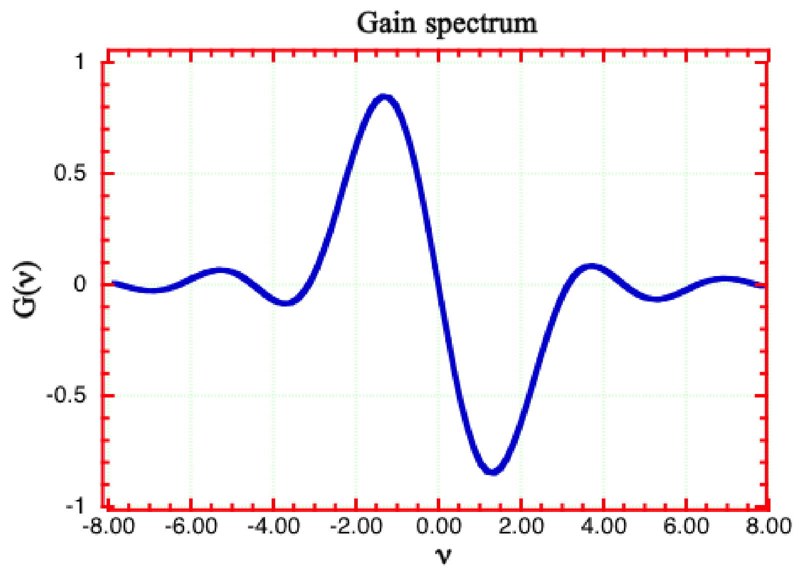
Spontaneous radiation and Gain

- The spectrum of the spontaneous radiation is just:

$$P(\nu) = P_0 \left(\frac{\sin^2(\nu)}{\nu^2} \right)$$

- The width is inversely proportional to the number of wiggler periods and the height is proportional to the square of the number of wiggler periods.
- The gain is proportional to the slope of the spontaneous radiation so it is proportional to the cube of the number of periods.





What do you have to do to establish lasing?

- The electron beam has to have small energy spread and transverse emittance and a good longitudinal match (high peak current).
  - Miniphase and optimize vernier cavity to get close to optimal longitudinal match.
  - Match to get beta function waists equal to about 40% of the wiggler length at the center of the wiggler.
- The optical cavity has to be aligned with its optical axis coincident with the wiggler axis.
  - Can check with cavity enhancement.
- The electron beam has to be aligned along the wiggler axis and overlapped with the optical mode. (remember they are both really small!!!)
- The cavity length has to be within a few microns of synchronous length or no gain occurs.

A few numbers for the 400 nm UVFEL

Remember the optical mode waist vs. position:

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R} \right)^2} \quad \text{and} \quad R(z) = z\left[1 + \left(\frac{z_R}{z}\right)^2\right] \quad \text{with} \quad z_R = \frac{p w_0^2}{\lambda}$$

In our case *z*R = 93 cm and the wavelength is 400 nm so

$$w0 = 344\ \mu\text{m}$$

The minimum beta function is supposed to be 80 cm so the electron beam size is about (assuming 5 mm-mrad emittance)

$$\rho = \rho_0 \exp\left[-r^2/(2s(z)^2) \right] \quad \text{and} \quad s^2(z) = \frac{\beta_{x0} e_{nx}}{g} \left(1 + \left(\frac{z}{\beta_{x0}} \right)^2 \right)$$

$$\sigma x = \sigma y = 123\ \mu\text{m}$$

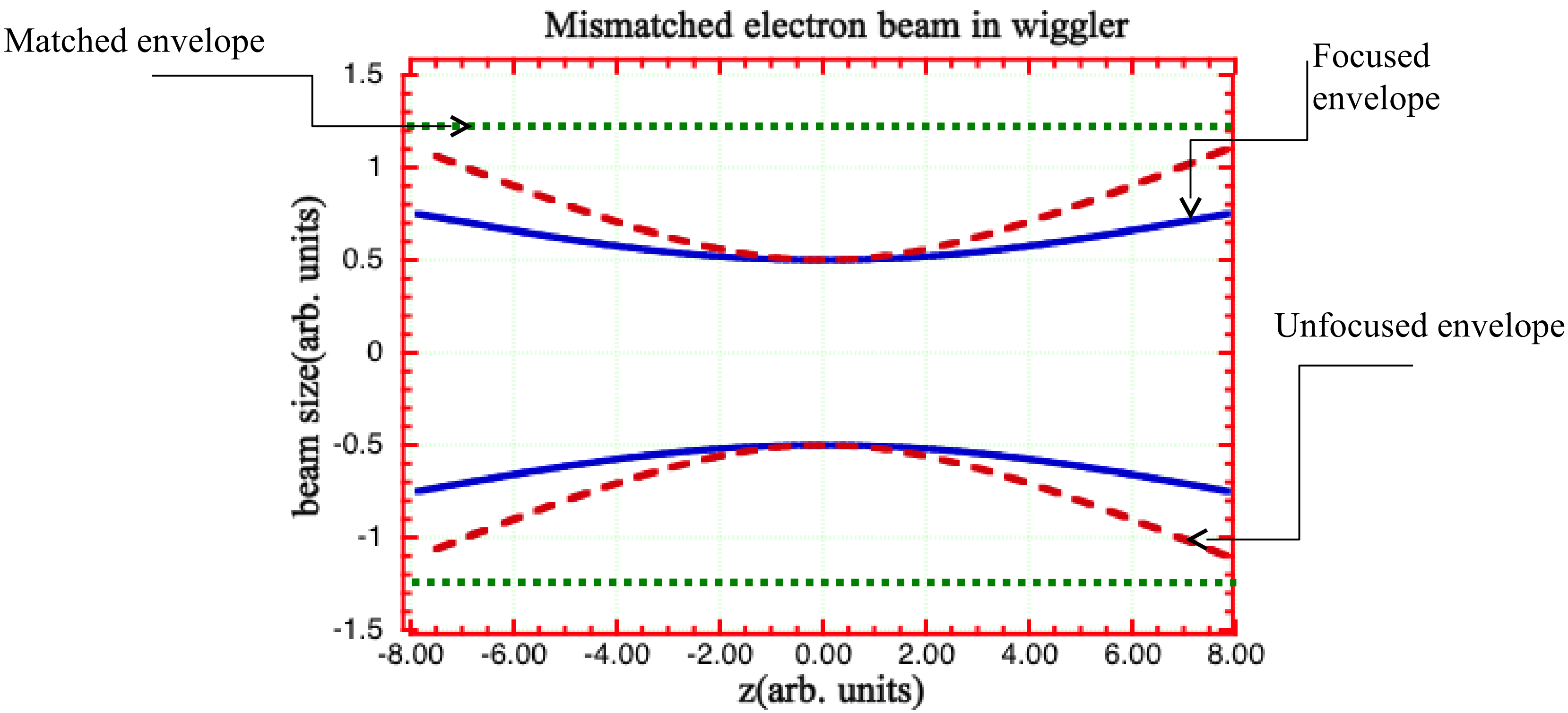
The mirror piezos move the mirrors at the rate of ~15 μrad/V

A corrector change of 10 G-cm steers a 135 MeV beam by 22 μrad

The wiggler vertical betatron phase advance is 66.7°. This means that the beam moves 78% of the amount vertically as horizontally at the end of the wiggler

Weak focusing case

- For a matched betatron period much longer than the wiggler it might be better to focus the beam in the wiggler center to improve the filling factor.



Allowed offsets

- Everything so far has concentrated on distributions. What if the whole beam moves?
  - Angular shift: Want the angular shift to be less than the mode divergence so we want

$$q_e < \sqrt{\frac{\lambda}{p z_R}}$$

  - As an example for 400 nm and *z*R=93 cm we want the angle error to be less than 370 μrad.
  - Position shift: Want the transverse position to be smaller than half the waist size (mode jumps if you exceed this) so

$$Dx < \sqrt{\frac{z_R \lambda}{4p}} \text{ or for previous parameters } Dx < 170\, mm$$

  - If I steer at the wiggler entrance the horizontal offset will dominate the angular error. ~40 G-cm will steer 170 μm at wiggler center. This changes the angle by ~90 μrad.

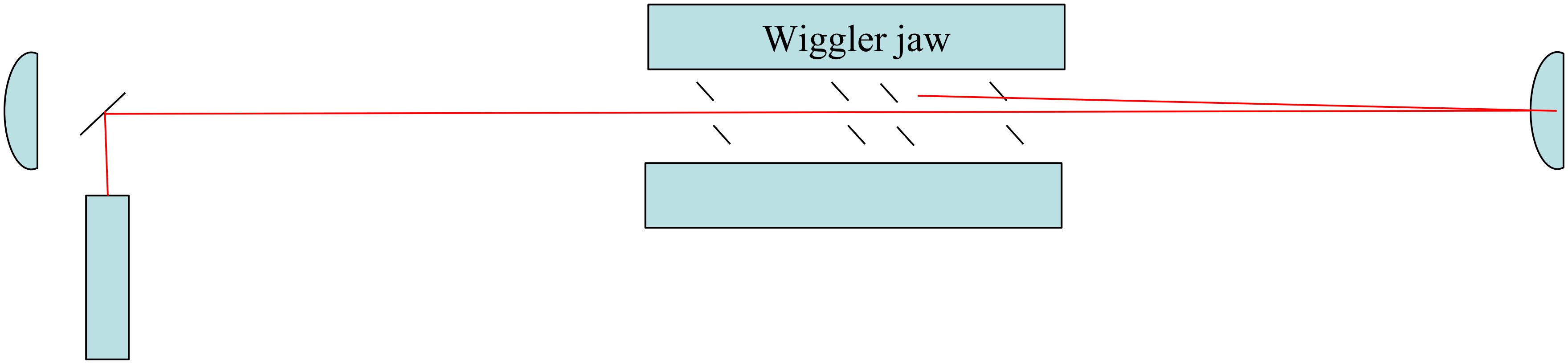
Mirror Steering

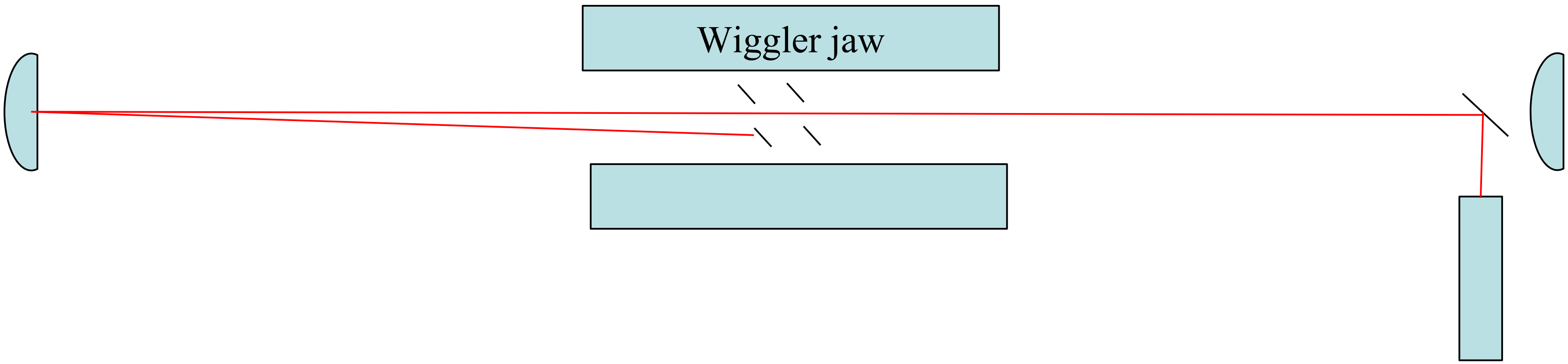
- The mode rotates by about M/2 times the steering of one mirror. The magnification is defined as:

$$M = \left(1 + \left(\frac{L}{2 z_R}\right)^2\right)$$

- For a 32 meter cavity with a 93 cm Rayleigh range the magnification is 296 so the mode rotates by 148 times the mirror steering.
- So the mode moves about 2.4 mm on the mirror for a 1 μrad steering.
- This means that the mode will miss the mirrors for a shift of less than 10 μrad.

Aligning the cavity

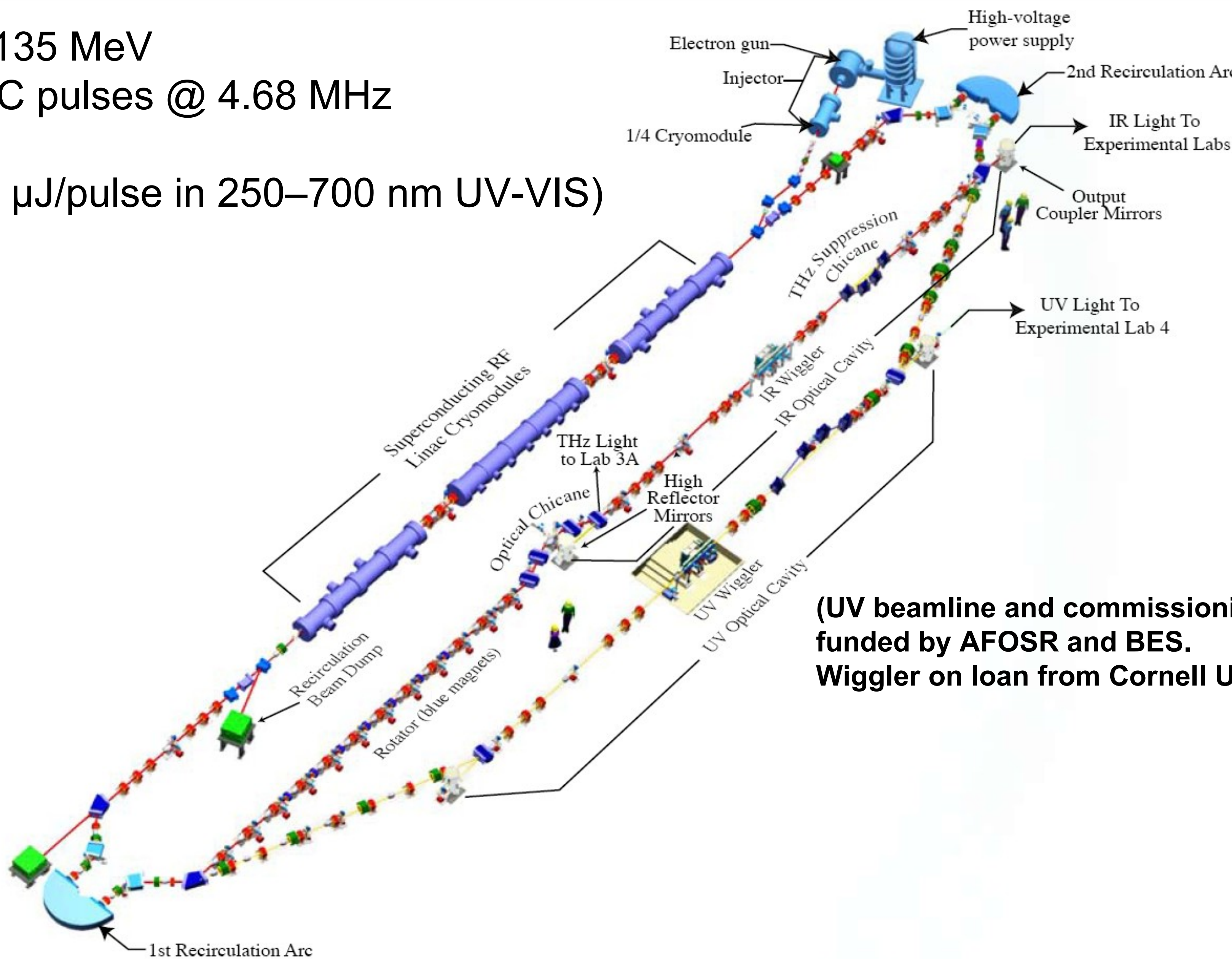




UV Demo Beamline Layout

E = 135 MeV
67 pC pulses @ 4.68 MHz

(>20 μJ/pulse in 250–700 nm UV-VIS)



(UV beamline and commissioning funded by AFOSR and BES. Wiggler on loan from Cornell U.

Very High Gain Seen at 400 nm

Conclusions

- For optimum laser performance three things are required

1. The electron beam should be as small as possible compared to the optical mode and should be inside the optical mode.
2. The detuning spread must be less than about $\pi/4$ from all effects.
3. The beam must be stable. The parameters should vary by no more than about 1/10 of their spreads.

If any of these things are not true the FEL will let you know!