MULTI-BEAM FREE-ELECTRON LASERS*

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WHY MULTI-BEAMS?

Multiple beams have been proposed for applications such as microwave tubes, heavy ion inertial fusion drivers and other cases where single beam systems may have difficulties

FEL ISSUES:

- **Coherent Synchrotron Radiation (CSR)** during pulse compression

  A compression factor of 20-30 or more is needed to reach the peak currents necessary for the LCLS. The use of multiple beams/injectors would increase the available charge and reduce the compression factor, thereby reducing the CSR.

- **Emittance Reduction in the Injectors**

  Less charge per bunch is needed from each injector. This would reduce the emittance of the beams from each injector, and reduce the projected gain length.

- **Increased Charge Extraction and Peak Currents**

  Increased peak currents would reduce the gain length. For the LCLS, this could mean substantial reductions in the projected (about 100 m) wiggler line.

HOW MULTI-BEAMS?

- Liouville's Theorem forbids "overlay" of the beams in a common phase space volume (exclusion principle)
  - must be "combined" in regions relevant to end-users (*i.e.*, transversely for colliders, transversely and in phase for FELs), but
  - must have separation (adequate to introduce devices producing the merge) in at least one phase space variable
- Required separation depends on method of merge
  - Nonlinear methods (chaos) more effective but error sensitive

CONFIGURATIONS & PROCEDURE

• **MEDUSA*** is a 3-D, polychromatic FEL simulation code that has been modified to treat multi-beam FELs. Two configurations have been incorporated into the model:

- Multiple beams whose centroids are offset from the axis of symmetry.
- Multiple beams that are offset in energy/phase but which are propagating along the axis of symmetry.

In either case, each beam is assumed to carry $1/N$ times the total beam current. For the LCLS example assuming a total peak current of 3400 A, this means that current in each beam in a 4-beam system would be 850 A.

*H.P. Freund, S.G. Biedron, and S.V. Milton, IEEE J. Quantum Electron. **QE-36**, 275 (2000).

SAMPLE FEL UNDER STUDY

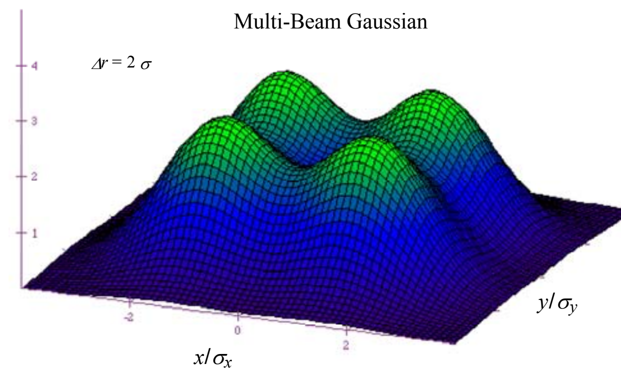
For the present examination of multiple-beam FELs, we consider the LCLS. However, it is important to note that the concept is also relevant to high-power FEL oscillators and amplifiers. The parameters we use are:

Average Beam Energy	14.35 GeV
Total Beam Current	3400 A
Normalized Emittance	1.5 mm-mrad
Energy Spread	0.006 %
Wiggler Type	Planar: Parabolic Pole Face
Wiggler Period	3.0 cm
Wiggler Amplitude	13.2 kG (on-axis peak)

OFFSET IN SPACE

In this case, we envision merging otherwise identical beams from multiple injectors to produce a composite, *partially*-overlapping beam which is symmetric about the axis of symmetry. Questions of interest are:

• What is the effect of reducing the current density as the aggregate beam expands while holding the total current fixed. For propagation in a waveguide, it is the total current which is important.



What is the sensitivity to reductions in current density when the radiation is optically guided?

• How can such a composite beam be produced? At the present time, we don't know how to do this, so interest in this concept is largely academic, and addresses the former question.

OFFSET IN SPACE

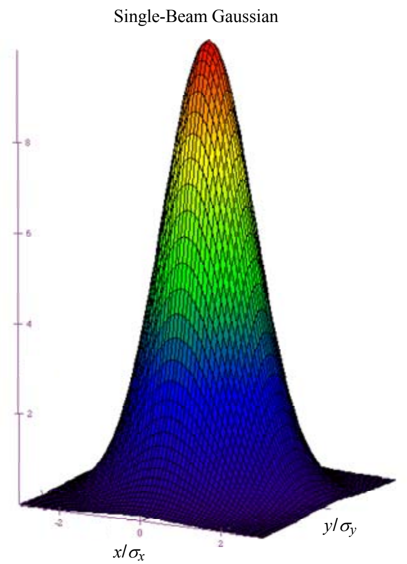
The effect of lower current densities, for fixed total current, can be illustrated by reference to a simple, modified 1-D dispersion equation

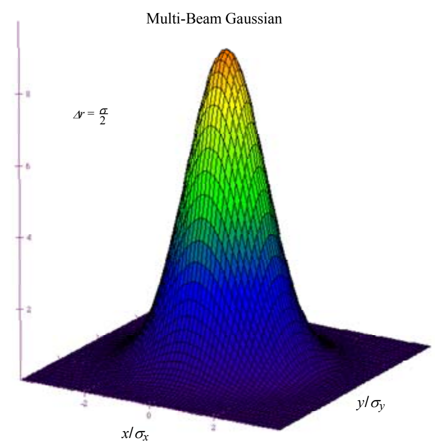
$$\left[\omega^2 - (k + k_w)c^2 - \frac{\omega_b^2}{\gamma_b}\right]\left[(\omega - k\mathrm{v}_b)^2 - \frac{\omega_b^2}{\gamma_b\gamma_z^2}\right] = ff\,\frac{2K^2}{1+K^2}\,\frac{\omega_b^2}{\gamma_b}\,c^2k_w^2$$

$$\text{filling-factor} = \frac{A_b}{A_{em}} \qquad \text{square plasma frequency} = \frac{I_b}{A_b}$$

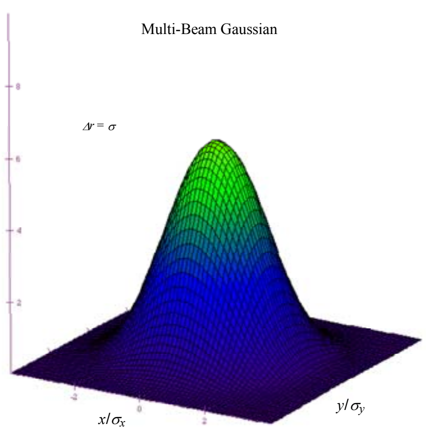
Coupling coefficient depends on the ratio of the current to the radiation spot size. This is weakly dependent on the beam area which impacts the coupling coefficient through optical guiding of the radiation pulse in an amplifier or SASE FEL. The resonator controls to spot size in oscillators.

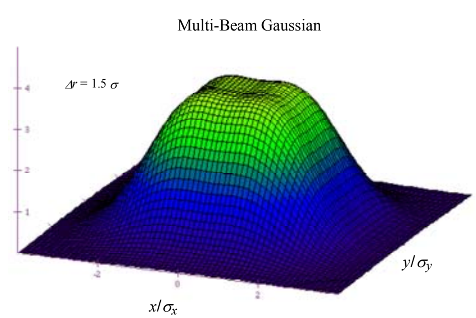
OFFSET IN SPACE

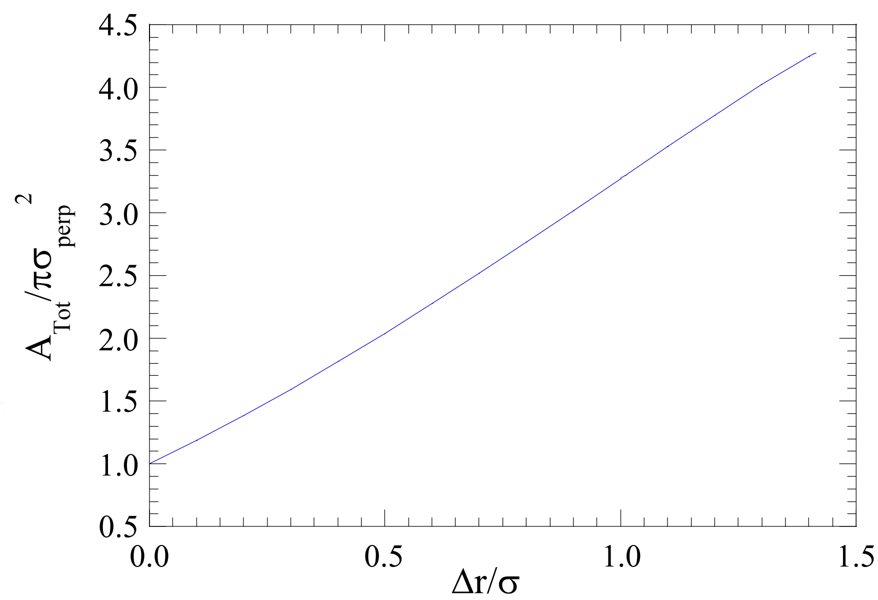




As the separation of the four beams increases, the peak current and current density decrease and the total area enclosed by the beams increases.

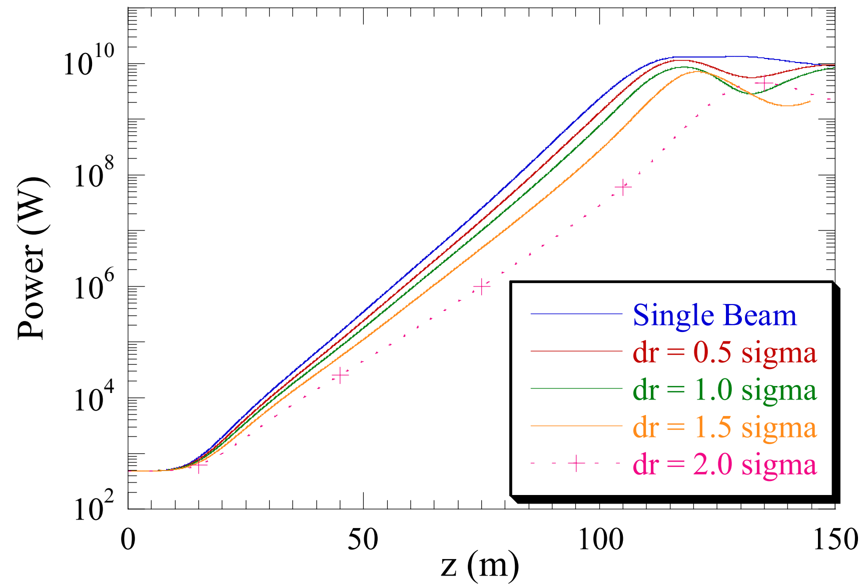


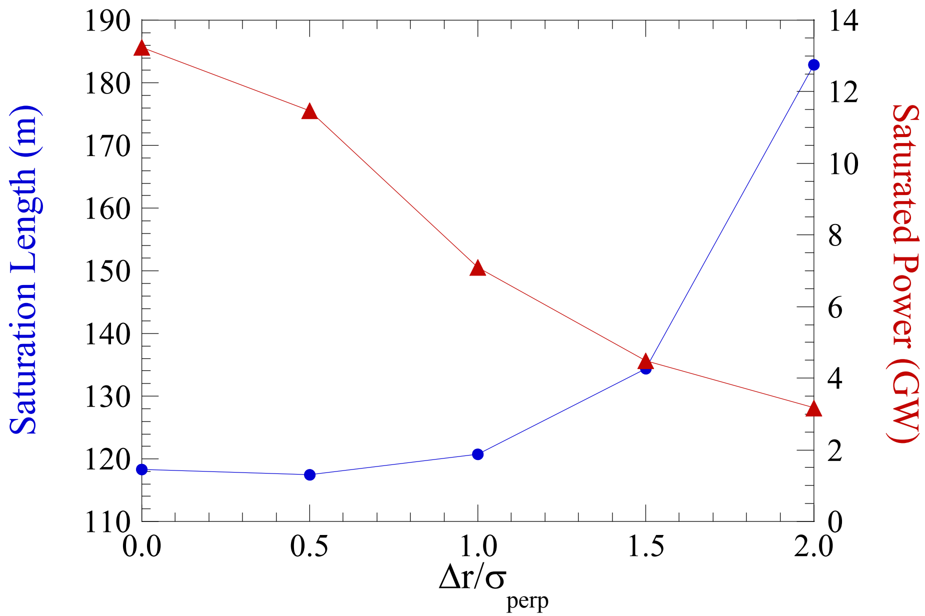




OFFSET IN SPACE

As the beam separation increases, the reduction in performance (gain length and saturated power decrease slowly up to $\Delta r/\sigma_{\text{perp}} = 1$. The decline is more rapid for higher degrees of separation.





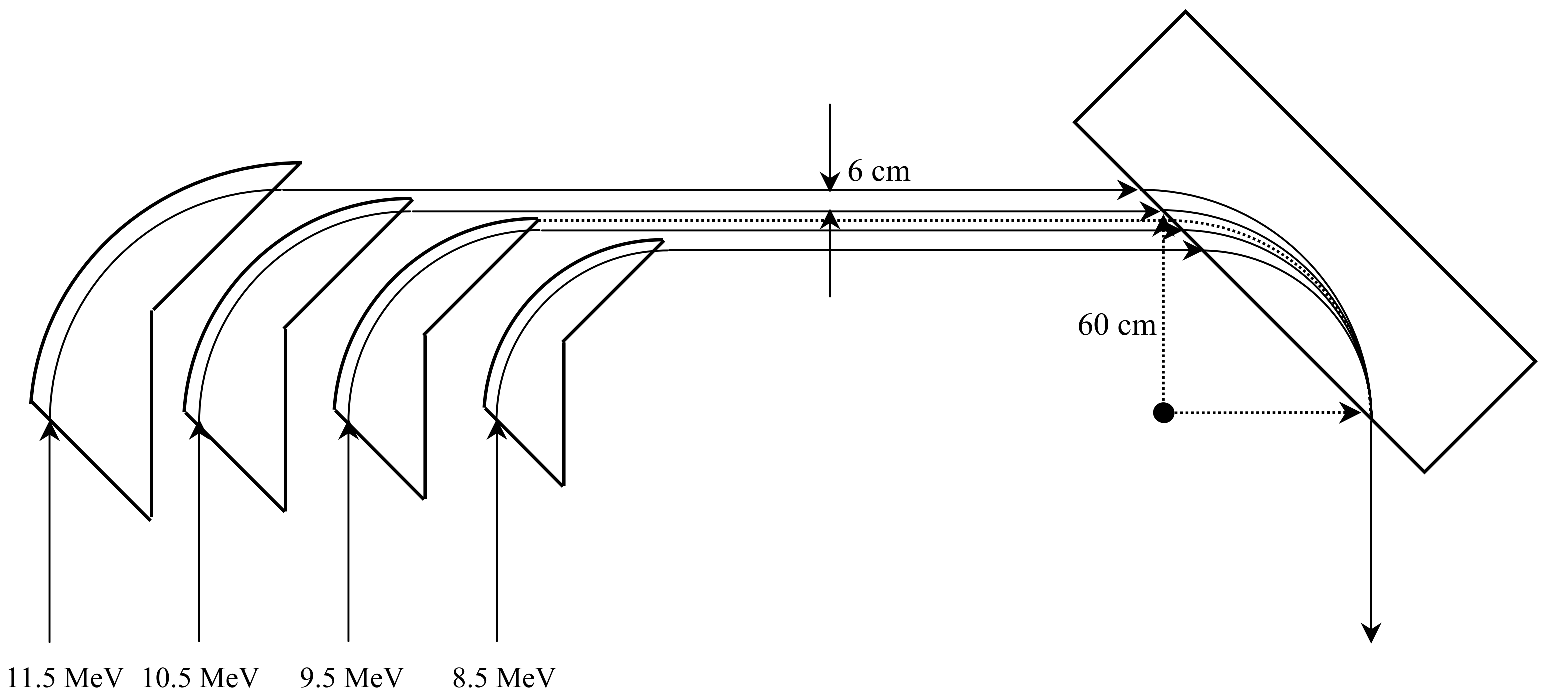
We conclude that optical guiding can counter the effect of decreasing current densities over a substantial range of operating parameters.

ENERGY/PHASE STACKING

- Linear methods can be used to combine beams in analogy with energy stacking for storage ring injection
  - multiple injectors at different (but close) energies provide high brightness beams with modest charge/bunch
  - magnetic combiners merge beams transversely and adjust their relative phase to form beam of high-charge macrobunches
  - further acceleration damps relative energy displacements amongst the beams
  - acceleration phase, downstream compaction can be used to control downstream properties of macrobunch & configure it for users

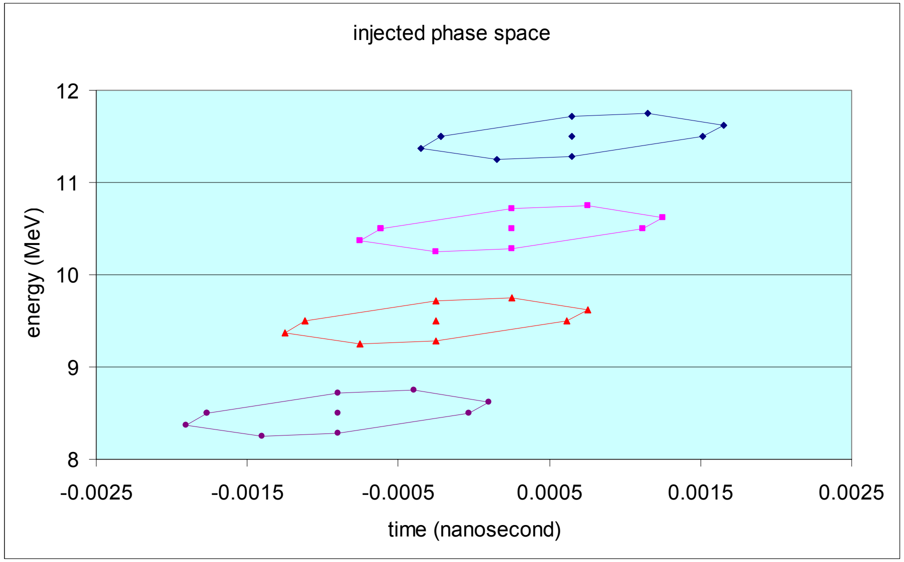
EXAMPLE: INJECTOR SUITE WITH MIRROR-BEND ACHROMAT BASED COMBINER

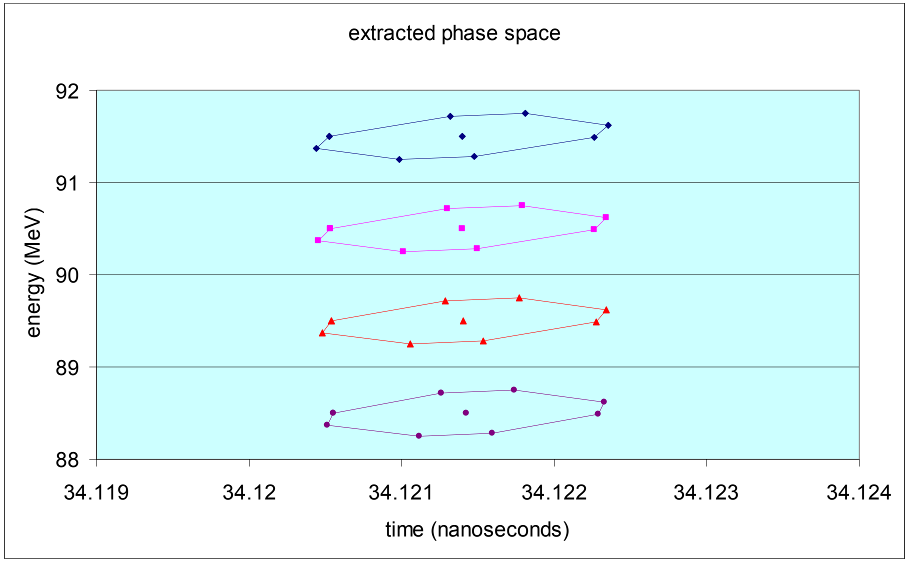
- Suite of 4 injectors at ~10 MeV
- Mirror bend achromats based on 90^{o} bends generate dispersion (= bend radius), moderate momentum compaction
- Energy offset amongst beams (1 MeV) provides dispersive separation, allows transverse merge of beams using single common dipole



ENERGY STACKING

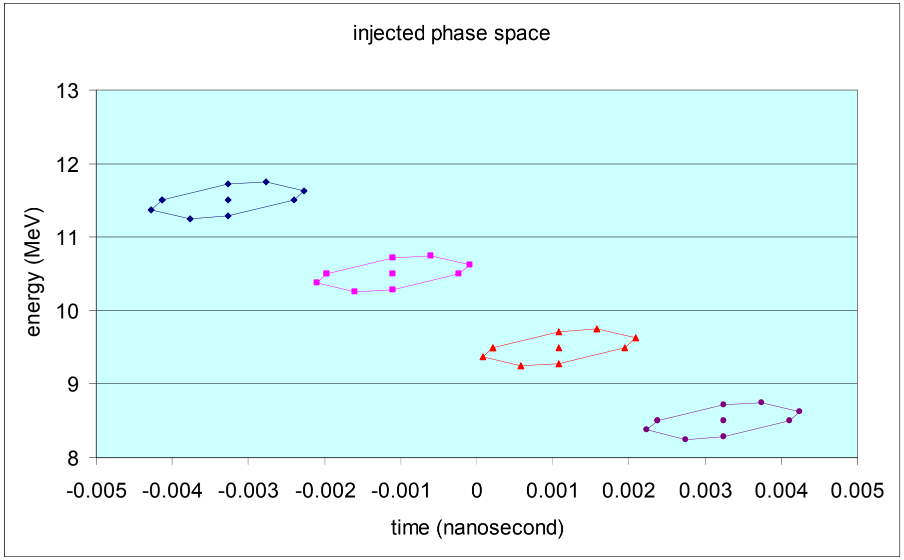
- four bunches (8.5, 9.5, 10.5, 11.5 MeV) merged, accelerated on crest through 80 MeV
- initial phases adjusted to compensate time-of flight differences
- produces short, energy-stacked macrobunch (high peak current)

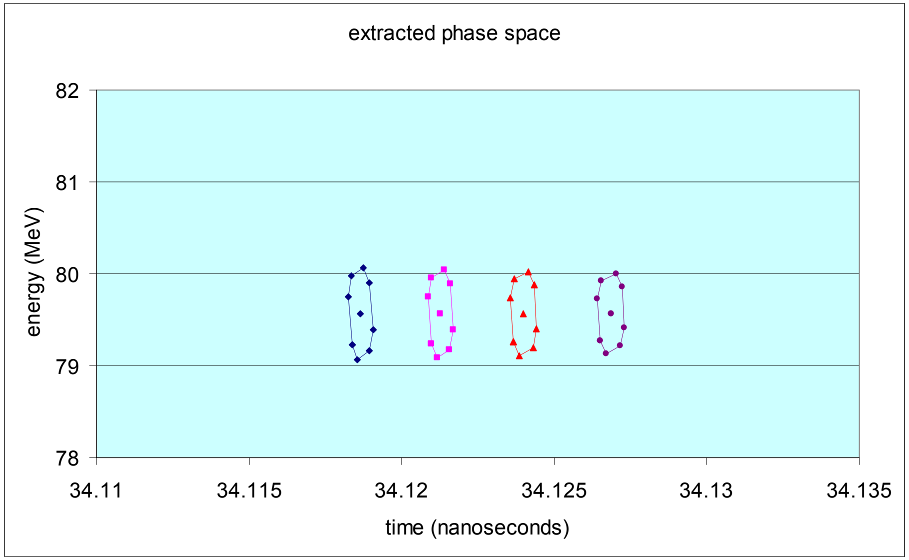




PHASE STACKING

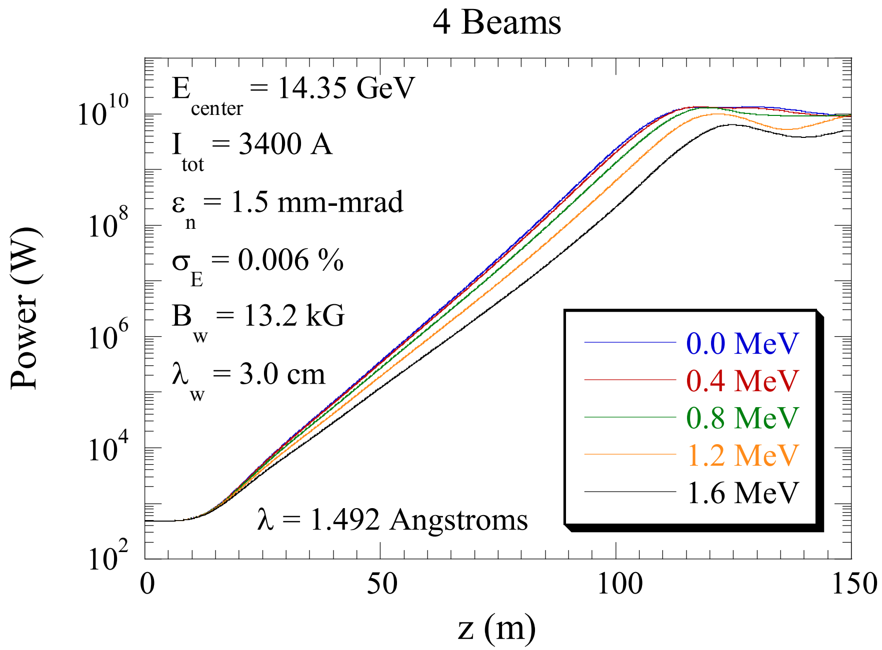
- four bunches (8.5, 9.5, 10.5, 11.5 MeV) merged, accelerated 30^o off-crest through 80 MeV
- initial phases adjusted to produce energy compression amongst bunches
- Compaction used at end of linac to rotate bunches upright
- Produces phase-stacked macrobunch with small energy spread

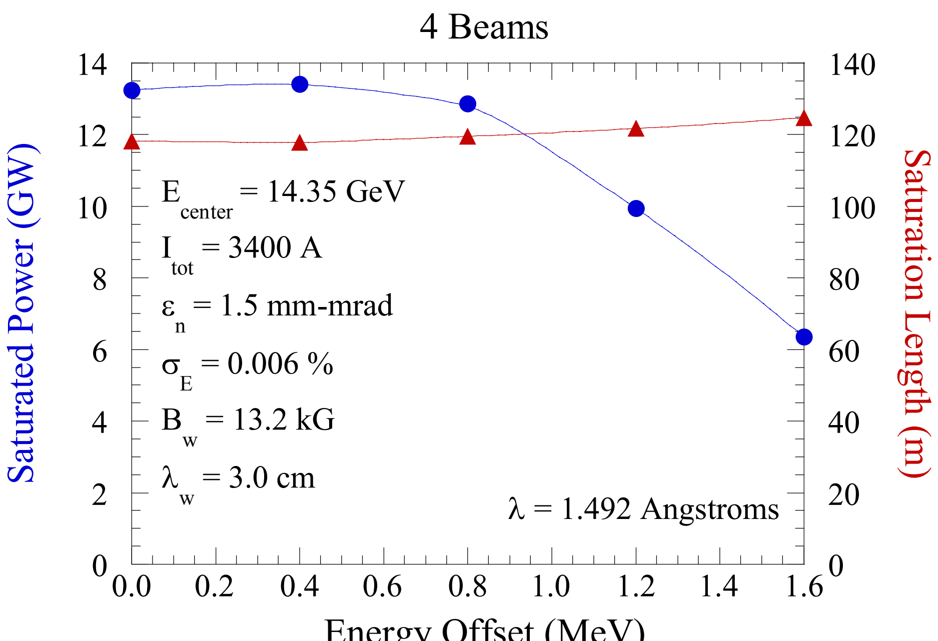




ENERGY STACKING

Consider 4 beams with energies offset symmetrically about the center value of 14.35 GeV and currents of 850 A.

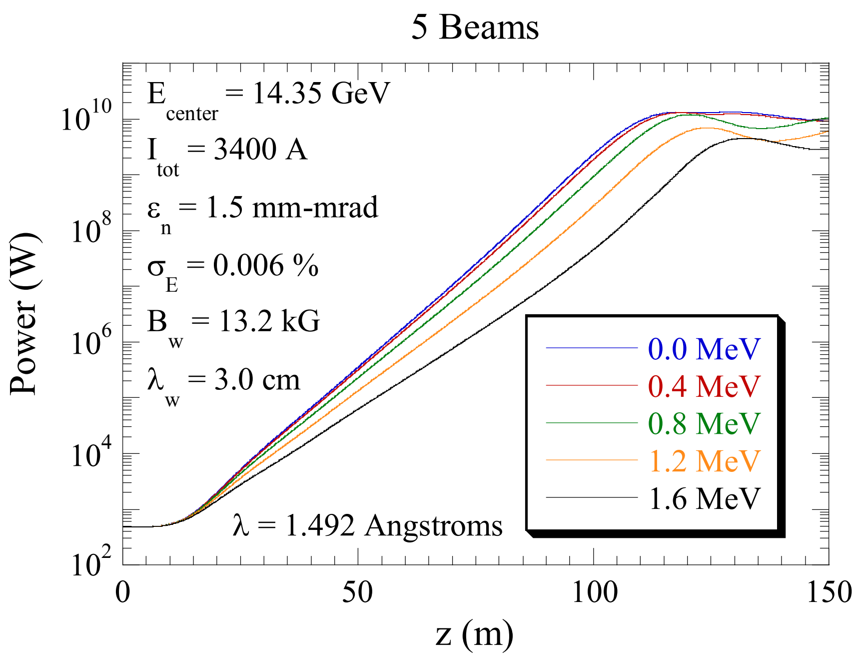


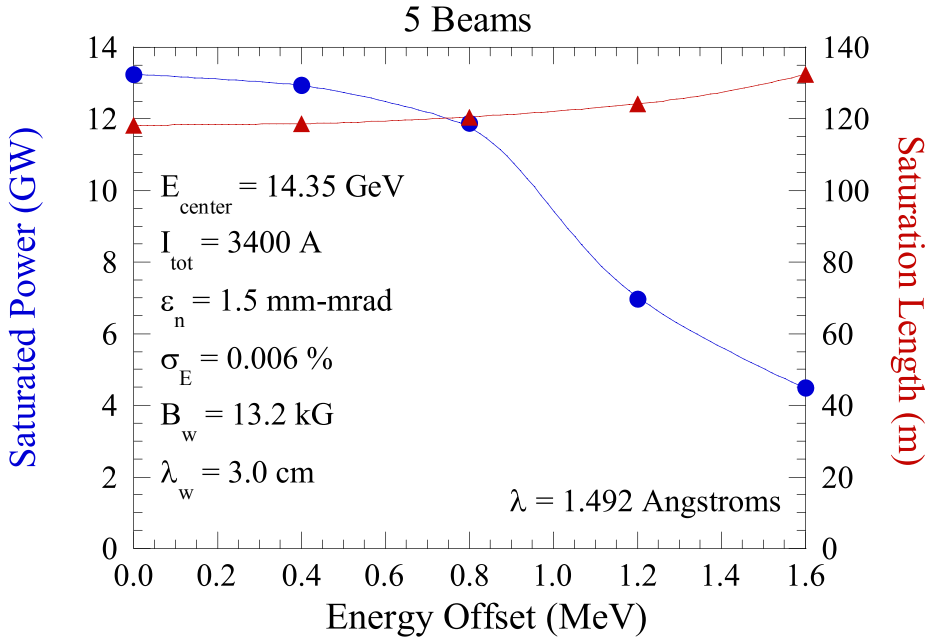


Performance depends weakly on the energy offset up to energies of about 1.0 MeV – comparable to thermal energy spread of the beams

ENERGY STACKING

Consider 5 beams with energies offset symmetrically about the center value of 14.35 GeV and currents of 680 A.





As in the case of 4 beams, we find that the performance is weakly sensitive to the energy separation up to about 1.0 MeV.

ENERGY STACKING

- Note that no effort has been made to use either peak currents higher than the 3400 A target or beam qualities superior to the 1.5 mm-mrad emittance or 0.006% energy spread.

    - Such parameters depend upon specific design issues.
    - Previous performance results can be improved with higher peak currents and better beam quality.

- Open questions include the effect of the bends in the energy stacking technique on CSR and beam quality.

    - This is under study now

    - If difficulties are found, then it is possible to combine the beams using bends shallower than 90 degrees.

SUMMARY & CONCLUSIONS

- Combination of beams with an offset in energy appears to offer performance advantages for many FEL applications:
  - Use of multiple beams permits higher total charge
    - Less bunch compression is needed lessening effects of CSR.
    - Higher peak currents may be achievable. This translates into shorter wigglers and higher saturated powers.
  - If the total charge desired is held fixed, then less charge is needed from each injector and lower emittance may be possible. This translates into higher saturated powers and shorter wigglers.
- Single injectors with the performance required for many applications have not yet been demonstrated. Use of multiple beams may be needed to achieve these desired goals.
- The disadvantage is increased cost/complexity of the injectors and beamline needed to combine the beams. This is offset by the reduced cost of the shorter wiggler and higher output powers.