High Gradient High energy gain Inverse Free Electron Laser at BNL

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Outline

- IFELs.
- BNL & UCLA. IFEL background.
- A proposal for an experiment at the ATF
- What can we do next?

Why you don’t want to hear anymore about IFELs

- Complicate experiment. State of the art requirements on laser and magnet technology.
- Synchrotron losses at high energy. NOT feasible for HEP multi-TeV machines.
- Gradient is energy dependent.
- Dwarfed by results of laser/plasma and beam/plasma schemes.

Why IFELs (again…)?

- IFEL scales ***ideally well*** for mid-high energy range (50 MeV – ***up to few GeV***) due to
  - high power laser wavelengths available (10 um, 1 um, 800 nm)
  - permanent magnet undulator technology (cm periods)

- Simulations show high energy/ high quality beams with gradients 350 MeV/m achievable with current technology!
  - 70 MeV/m gradient already demonstrated at UCLA
  - 70 % trapping already demonstrated at BNL.
  - ***Preservation of e-beam quality/emittance*** and high capture simulated

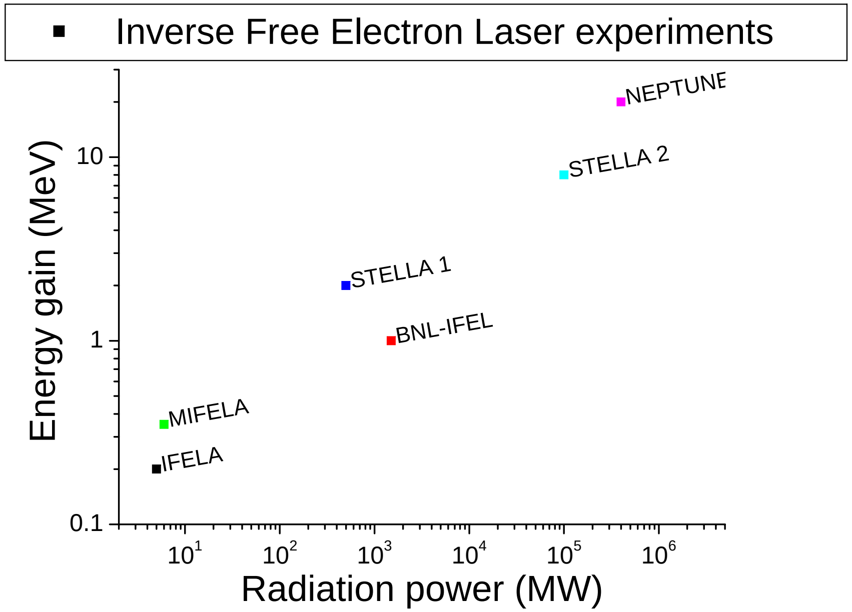
- ***Microbunching:*** still the preferred interaction for longitudinal phase space manipulation at optical scale

- ***Efficient*** mechanism to transfer energy from laser to electrons

- Anybody cares for a ultracompact 1-2 GeV injector?
  - Injector + (phase-locking) microbuncher for other kinds of advanced accelerators
  - Injector for advanced light sources (ICS or FELs)

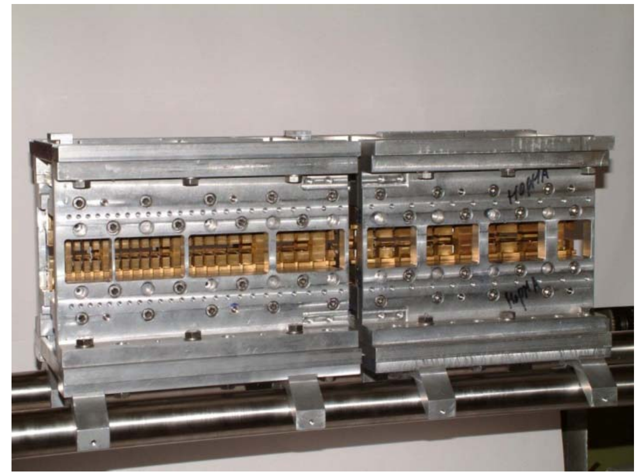
From proof-of-principle to 2nd generation IFEL experiments

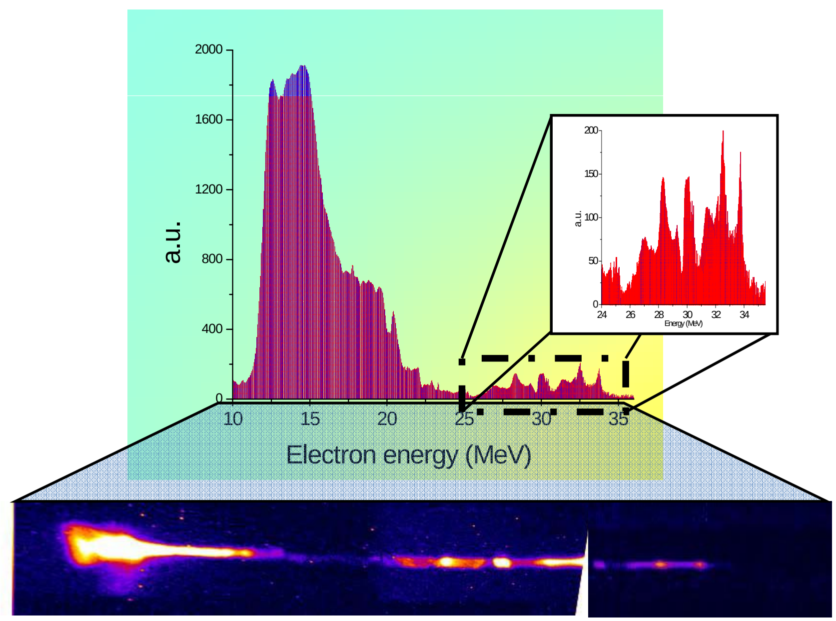
- Proof-of-principle experiments successful
- Upgrade to significant gradient and energy gain
  - Technical challenges:
    - very high power radiation
    - strong undulator tapering
  - Physics problems:
    - include diffraction effects in the theory
    - beyond validity of period-averaged classical FEL equation



UCLA Neptune IFEL

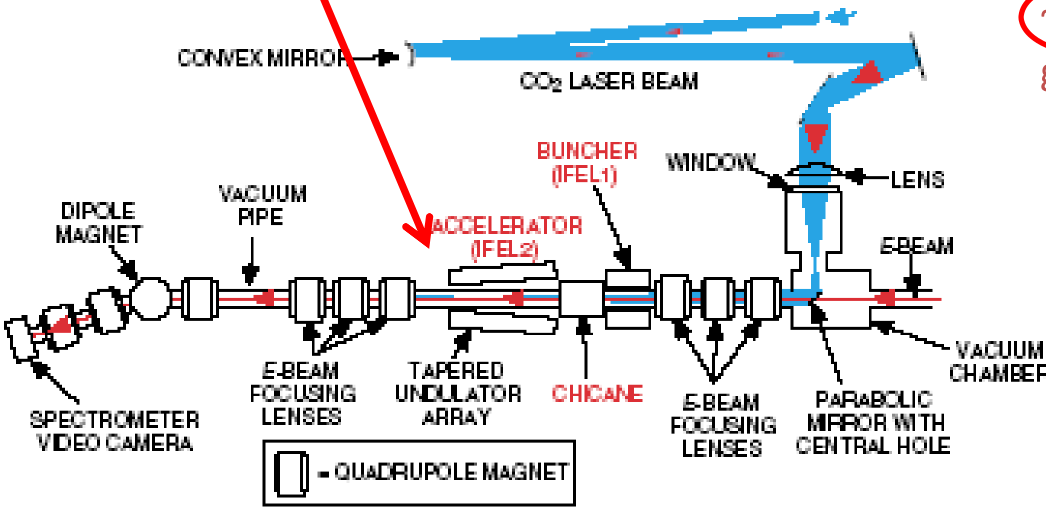
- 0.5 TW 10.6 μm laser
- Strongly tapered (period and amplitude) Kurchatov undulator
- Highest recorded IFEL acceleration
    - 15 MeV beam accelerated to over 35 MeV in 25 cm
    - Accelerating gradient ~70 MeV/m !
    - Observation of higher harmonic IFEL interaction !



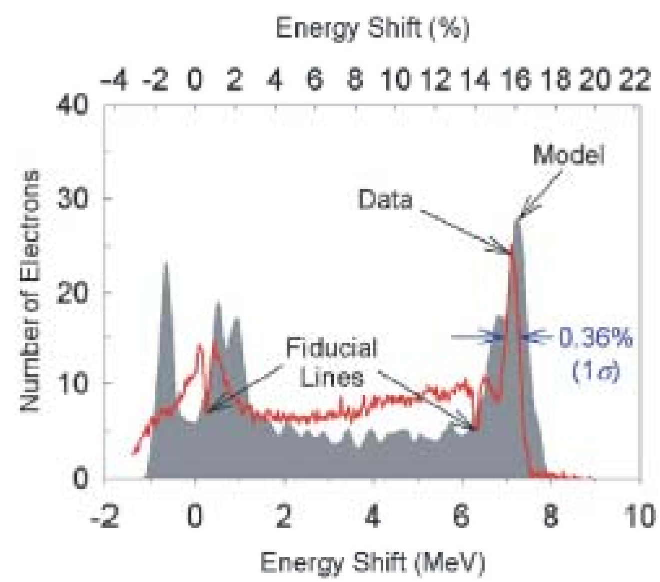


STELLA2 experiment

Gap-tapered planar undulator (no period tapering).



80 % of electrons accelerated,
energy spread less than 0.5 % FWHM
~30 GW@ λ = 10.6 μm,
gain up to 17 % of initial beam energy



W. Kimura et al. First demonstration of high trapping efficiency and narrow energy spread in a laser accelerator,
PRL, 92, 154801 (2004)

Current IFEL projects

Not much going on besides UCLA:

Microbunching experiment at Neptune (7th harmonic)

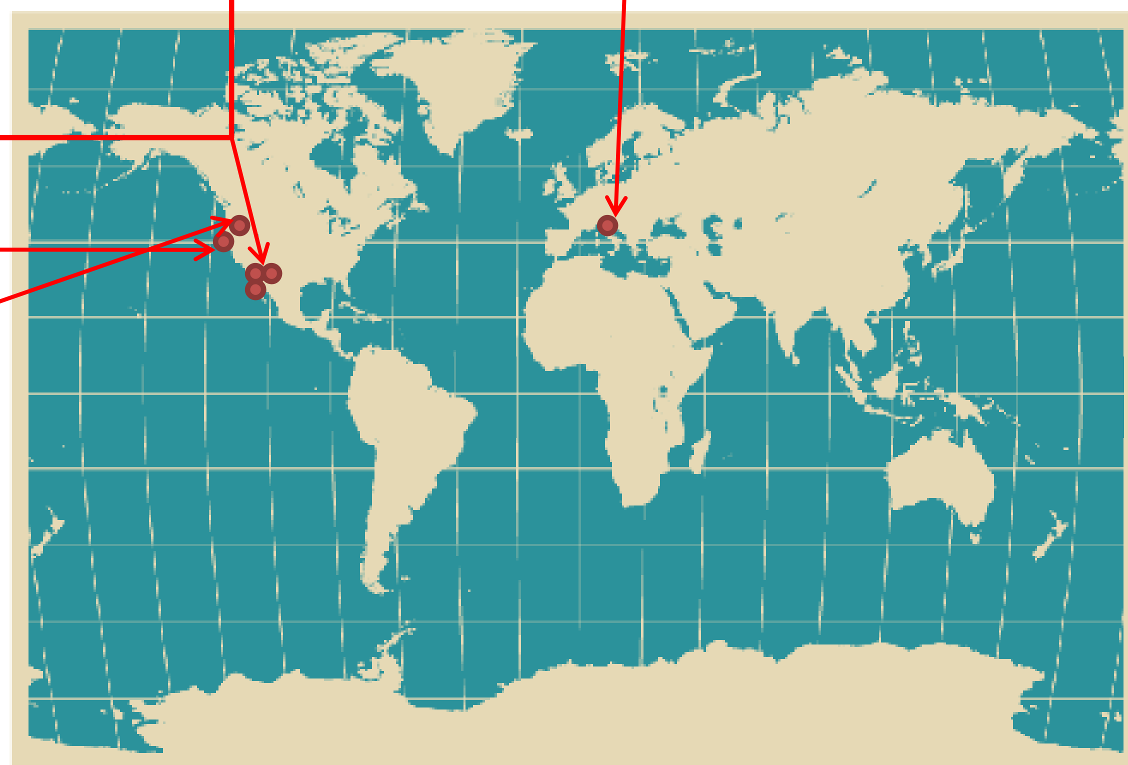
Helical bunching experiment at Neptune (again harmonic coupling, interesting beam modes)

Permanent magnet helical undulator development

Prebunching at 800 nm at SLAC

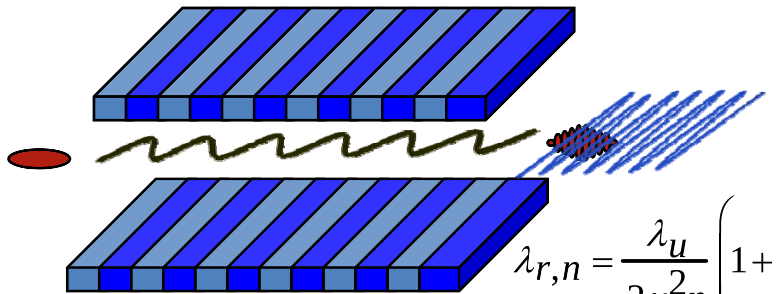
Proposal for experiment at LLNL
ICS driver

Proposal for experiment at SPARC-PLASMON-X (Italy)
Driver for FEL-based light source



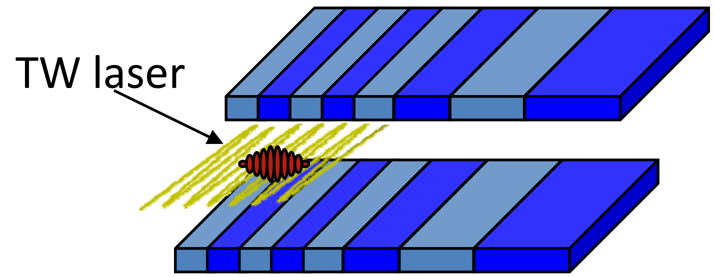
IFEL Interaction

In an FEL energy in the e-beam is transferred to a radiation field



$$\lambda_{r,n} = \frac{\lambda_u}{2\gamma^2 n}\left(1+\frac{K^2}{2}\right)$$

In an IFEL the electron beam absorbs energy from a radiation field.



Undulator magnetic field to couple high power radiation with relativistic electrons

$$K_l = \frac{eE_0}{mc^2 k} \qquad K = \frac{eB}{mck_w}$$

$$\gamma_r^{\,2} \cong \frac{\lambda_w}{2\cdot\lambda}\cdot\left(1+\frac{K^2}{2}\right)$$

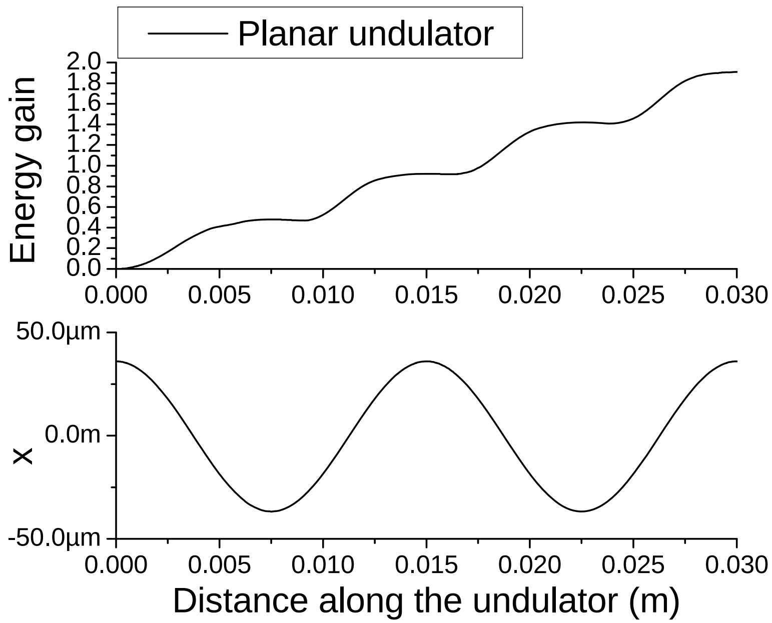
Significant energy exchange between the particles and the wave happens when the resonance condition is satisfied.

Helical interaction

Works at least two times better.

Interaction with circularly polarized laser always on

Factor x 2.5 extra gradient



Planar

$$\frac{\partial \gamma}{\partial z} = kK_l \frac{JJ(K)}{2} \cdot \frac{K}{\gamma} \sin(\psi)$$

vs.

Helical

$$\frac{\partial \gamma}{\partial z} = kK_l \cdot \frac{K}{\gamma} \sin(\psi)$$

BNL IFEL experiment

The experiment main goal is to achieve energy gain and gradient significantly larger than what possible with conventional RF accelerators to propose IFEL as a viable technology for mid-high energy range accelerators.

This can be achieved using the existing ATF e-beam and high power CO2 laser system

TOGETHER WITH

Helical geometry.

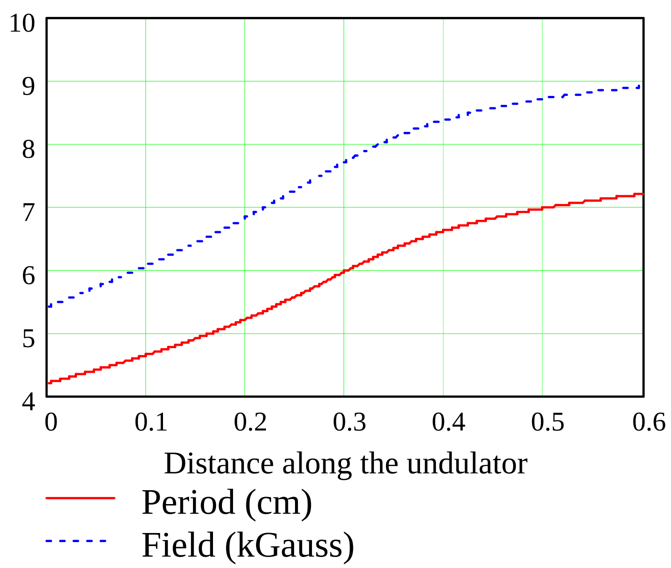
Permanent magnet double tapered undulator.

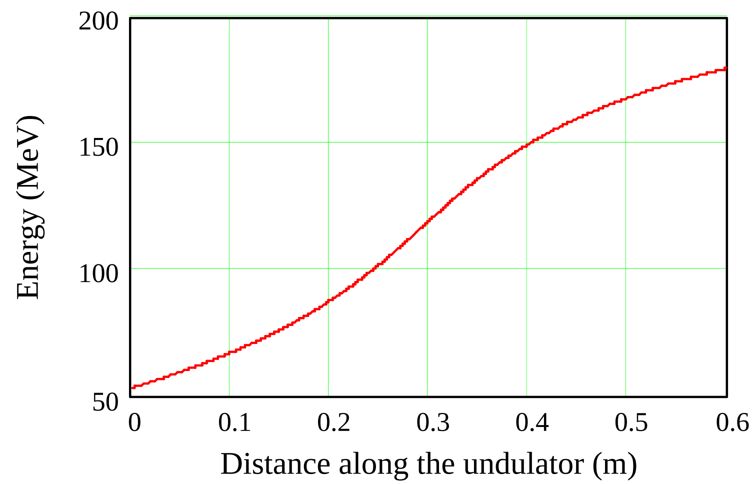
Parameter	Fixed Value
Initial *e*-beam energy	50 MeV
Laser wavelength	10 um
Laser peak power	0.5 TW
Nominal length of wiggler, L_w	60 cm
Rayleigh range	9 cm
Laser focal spot size (w)	550 um
Location of laser waist inside wiggler	30 cm
Undulator length	60 cm

Table 1. Parameters for BNL high gradient high energy gain IFEL experiment

Optimized tapering design

Keep resonant phase constant ($\pi/4$)
Keep into account limitation of permanent magnet undulator. Relatively large gap.
Assume B = B (λ_w).
Find optimum tapering i.e. $\lambda_w(z)$

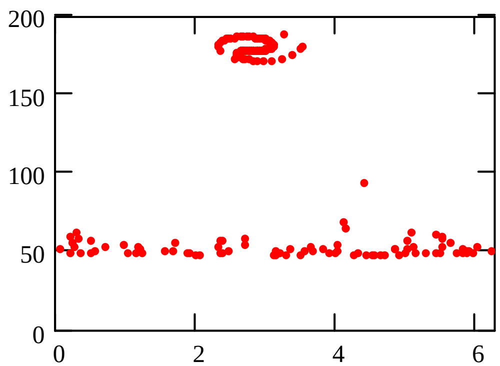


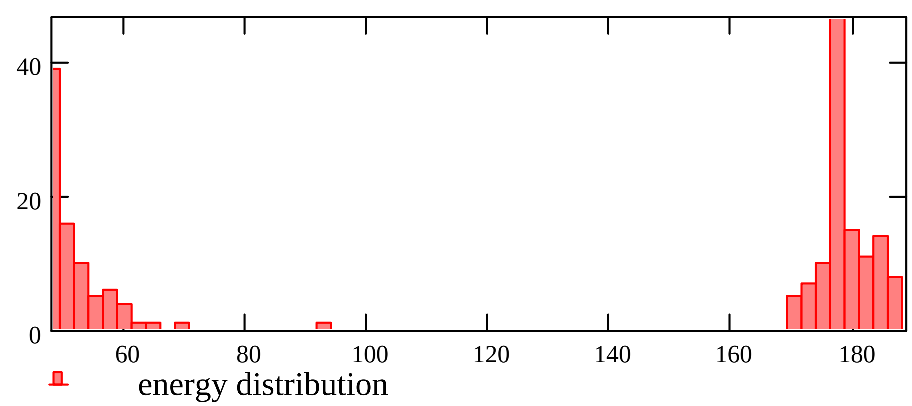


Parameter	Initial	Final
Undulator gap	1.0 cm	1.0 cm
Undulator period	4.2 cm	7.1 cm
Magnetic field amplitude	5.5 kG	8.9 kG

Output beam characteristics

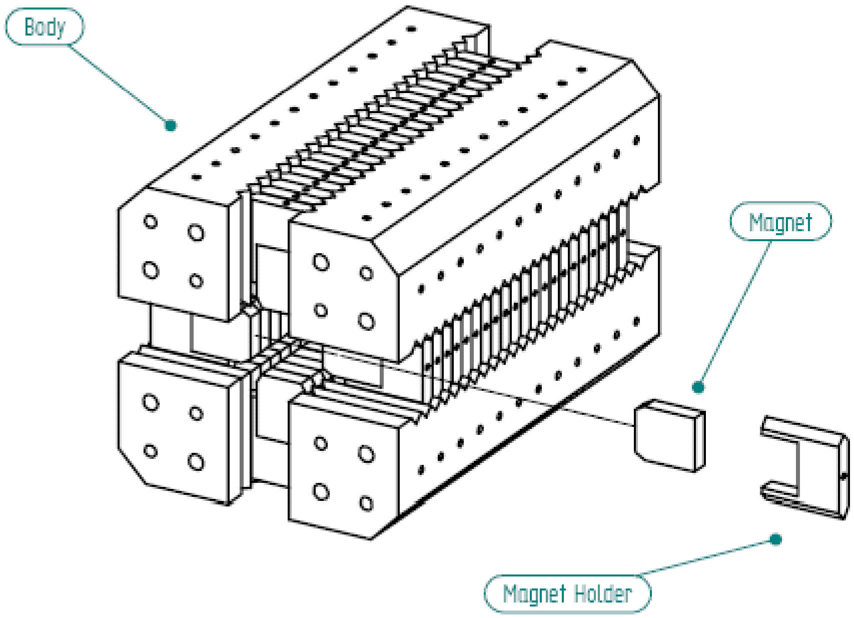
Longitudinal phasespace and final energy spectrum

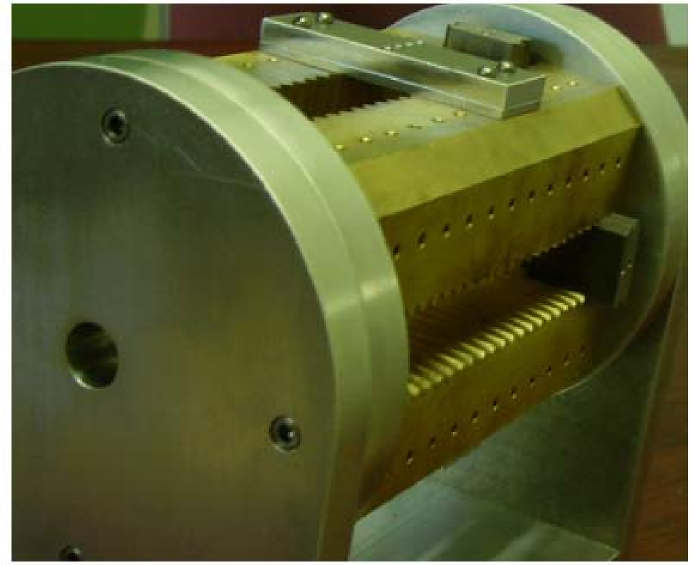




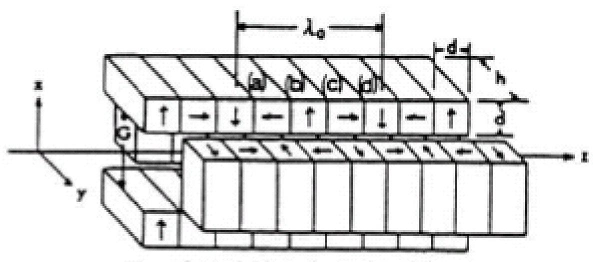
Parameter	Fixed Value
Final *e*-beam energy	180 MeV
Microbunching spacing	10 um
Microbunch length	1.5 um
Beam energy spread	2 %
Total energy gain	130 MeV
Avg energy gradient	220 MeV/m

Permanent magnet helical undulator

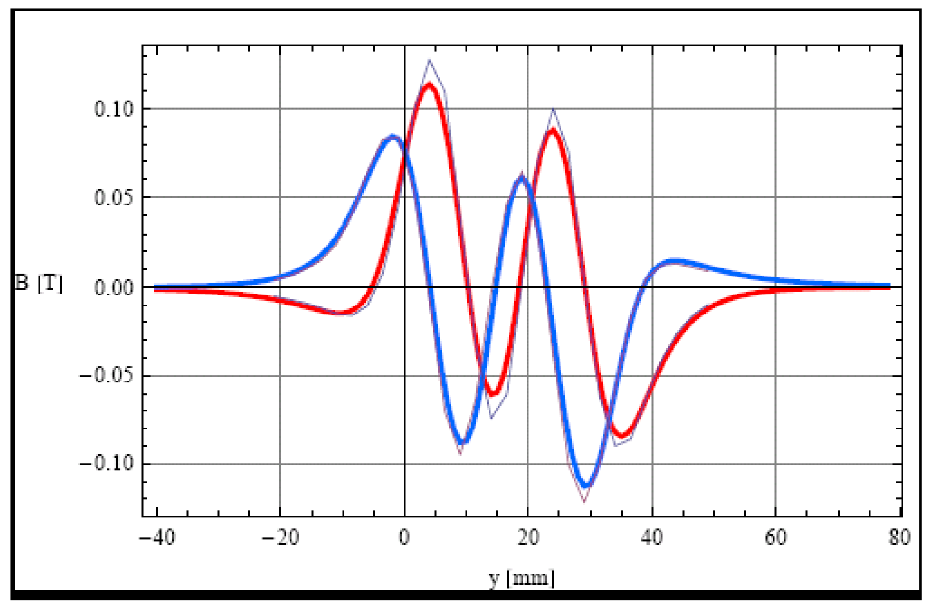




- Helical permanent magnet undulator.



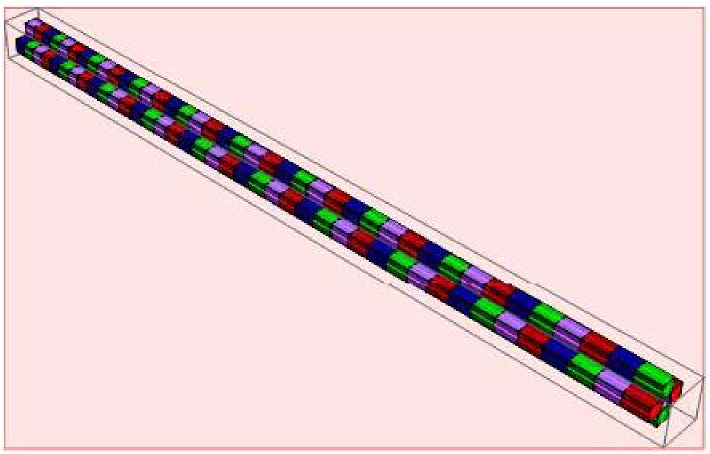
- RADIA modeling
- Prototype (10 cm, not tapered) built
- 30 cm unit being assembled
- Preliminary measurements in very good agreement with RADIA predictions.



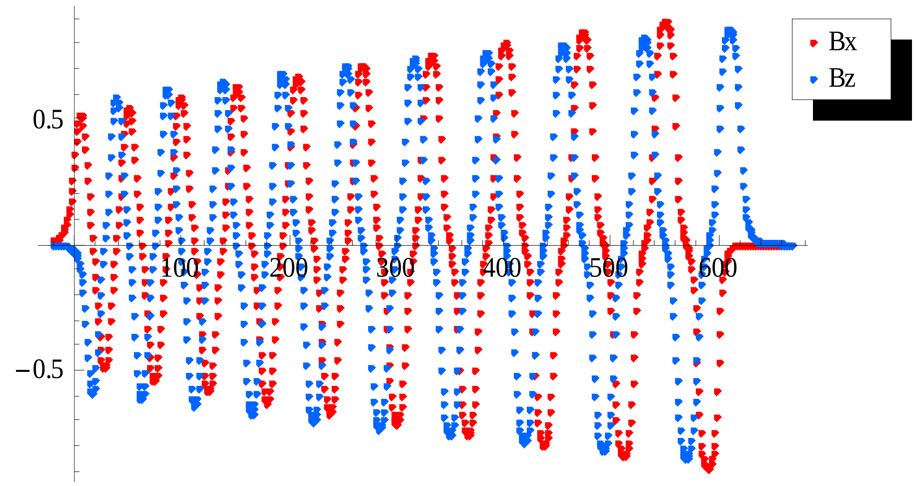
Piece-wise tapering approximation.

Same mechanical design based on bronze rails to hold the magnets.
Use permanent magnets of different thickness for the different periods.

3D RADIA model



On-axis magnetic field



Harmonics appear when the gap is very small compared to the period length.
To be further investigated.

Future plans

- Pre-Bunching.
  - Use a STELLA-like pre-buncher to improve the capture efficiency and the output beam quality.

- Measure beam quality after laser acceleration.
  - So far the experiments have been limited to longitudinal diagnostics (energy spectrometer, microbunching). Need a measurement of transverse beam quality.

- One of the main critics to IFEL (and laser acceleration in general) is the limit on the repetition rate.
  - At BNL-ATF it could be possible to try multi-bunch, laser-recirculation (same as ICS schemes).