Case 5: FEL Driven by Plasma Injector

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on behalf of Group 10

Group 10		
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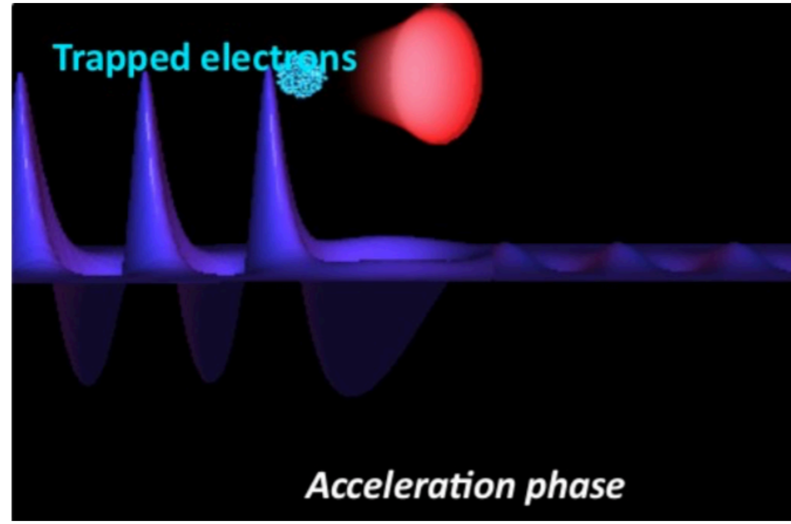
Overview

LPAs electron beam

- High energy: 1GeV
- High peak current : 10kA
- Low emittance: 0.2mm.mrad
- Energy spread : few % level



T. Tajima and J. M. Dawson, Phys. Rev. Lett. 43, 267 (1979).

Goal

- Development of compact FELs (radition: GW, fs, coherence)

Overview

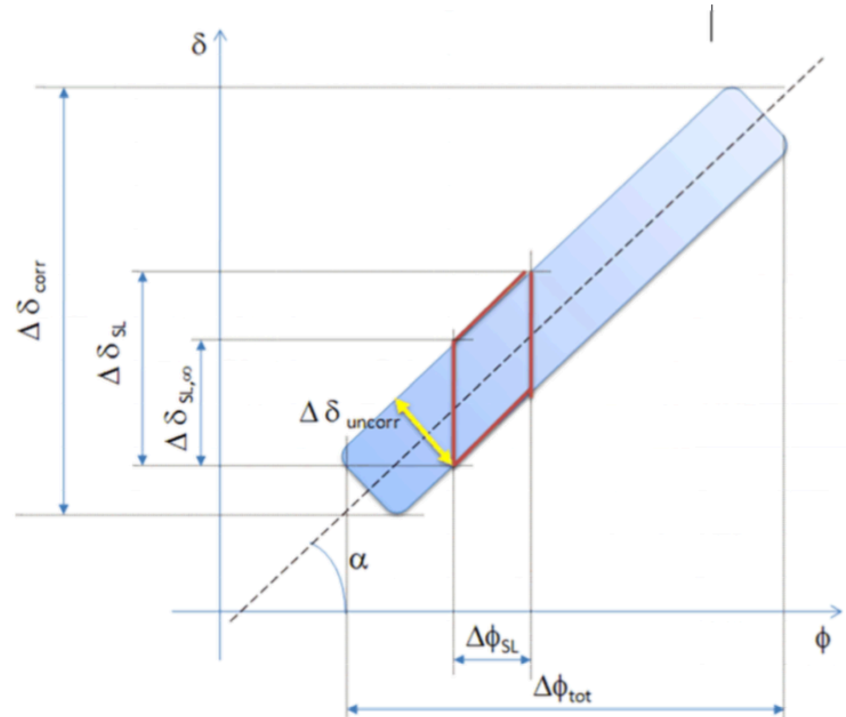
Challenge

- large energy spread of short-wavelength FEL amplification

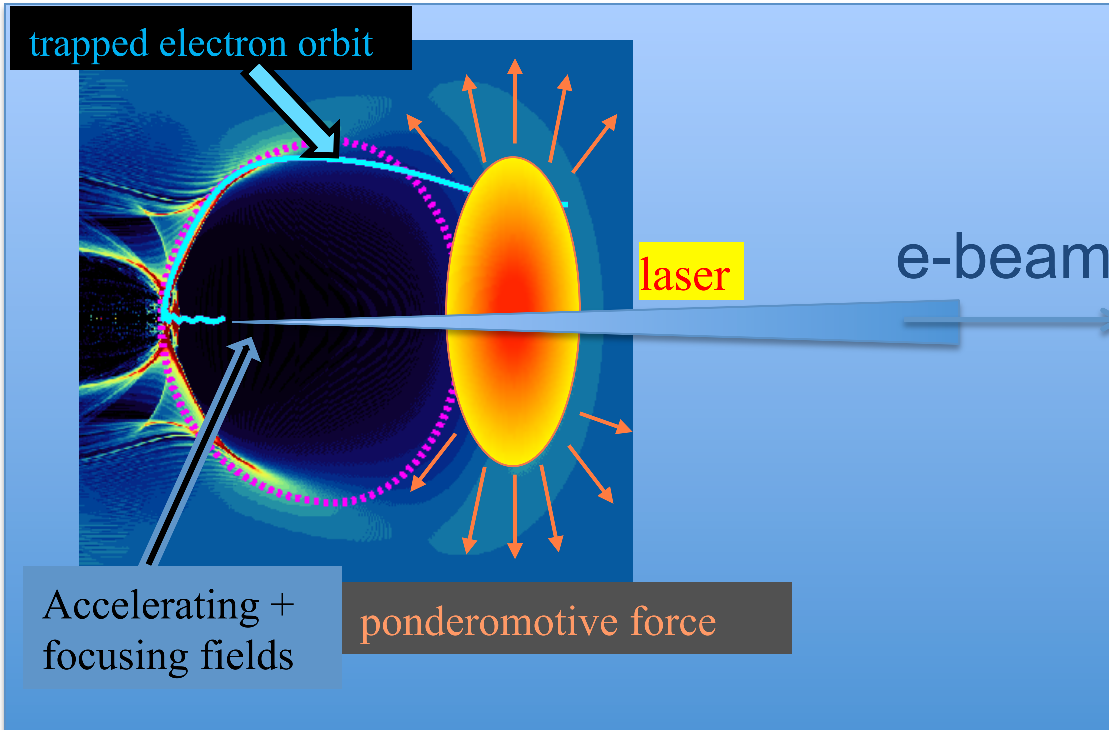
Beam manipulation to reduce slice energy spread :

- High peak current
- Longitudinal decompression
- Transverse gradient undulator,

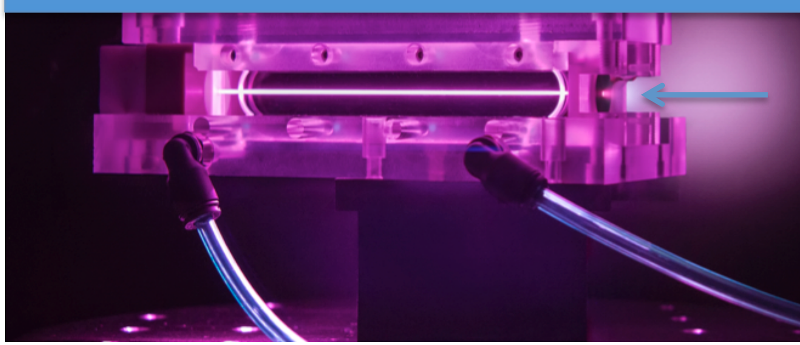
  (It will be presented by Tao ☺)

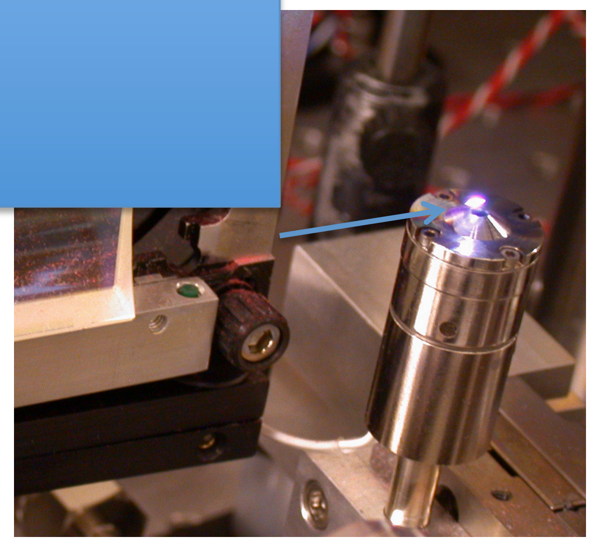


Laser Plasma Accelerator: laser pulses on a gas target



Gas Targets
Gas jet, gas cell,
discharged guiding channel
1mm to 10cm in length
density ~10^{16}-10^{18} cm^{-3}

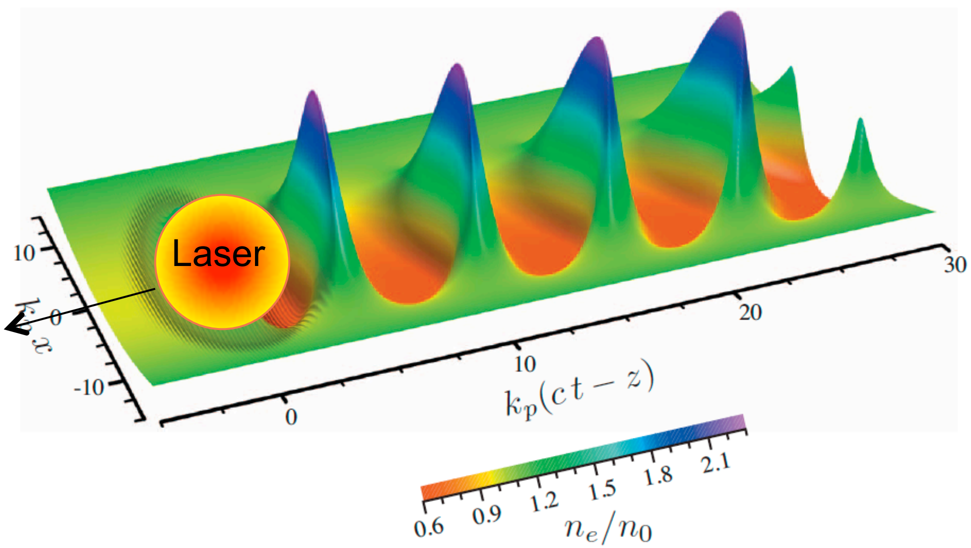




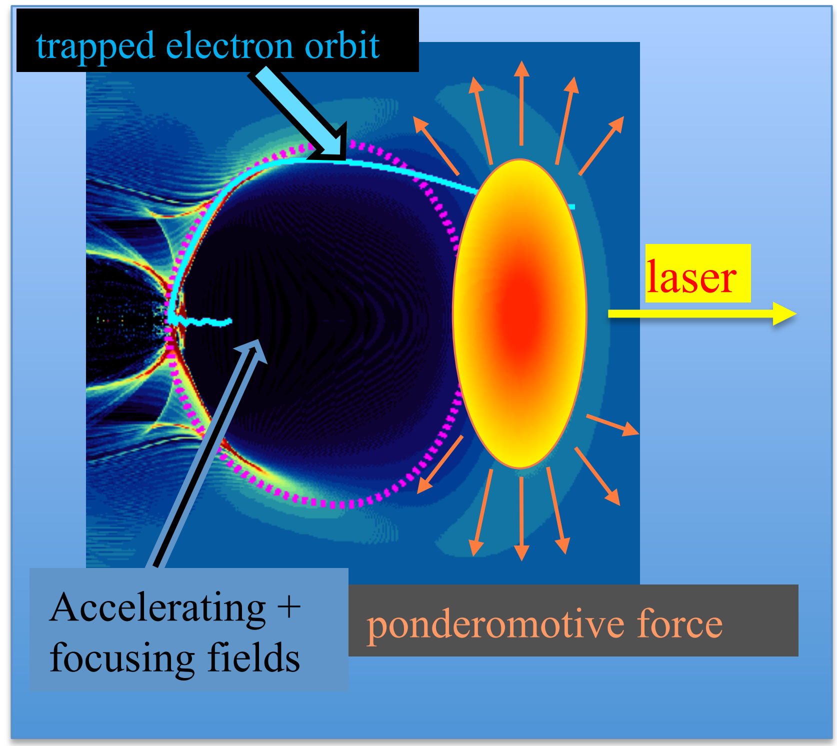
W. Leeman

Laser plasma accelerators (LPAs) are compact and produce femtosecond relativistic e-beams

- Ionization
- Ponderomotive push → charge separation
- Ions pull back electrons → charge oscillation
- Strong accelerating fields propagate w/ laser
- Electrons externally- or self-injected
- Acceleration to GeV in mm's



B.A. Shadwick et al., IEEE PS. 2002



T. Tajima and J.Dawson, PRL, 43, 267 (1979)
Esarey et al., RMP 81, 1229 (2009)

FEL application: LPA 6D electron beam brightness comparable to conventional sources

Beam brightness: $$B_{6D} = \frac{N}{\epsilon_{nx}\epsilon_{ny}\epsilon_{nz}} \approx \frac{(I/I_A)}{r_e \epsilon_n^2 \sigma_\gamma} = b_6 \lambda_c^{-3}$$

LPA (~cm)			LCLS (~km)
ε_N = 0.1 micron 1 GeV 1-3% energy spread I = 3 kA (~10 fs)	$b_6 \sim 10^{-12}$	$b_6 \sim 10^{-12}$	ε_N = 0.4 micron 13.6 GeV 0.01% energy spread I = 3 kA

- FEL application requires post-LPA e-beam phase-space manipulation (redistribution)
  - Emittance exchange
  - Phase-space redistribution:
    - Longitudinal decompression (with tapered undulator)
    - Transverse dispersion (with transverse gradient undulator)

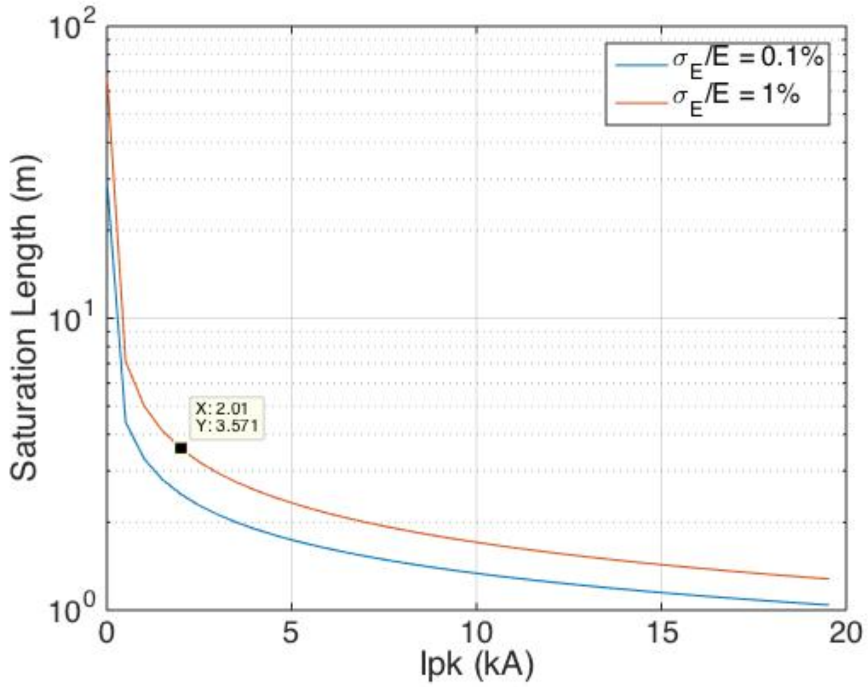
The proposed electron beam and machine parameters

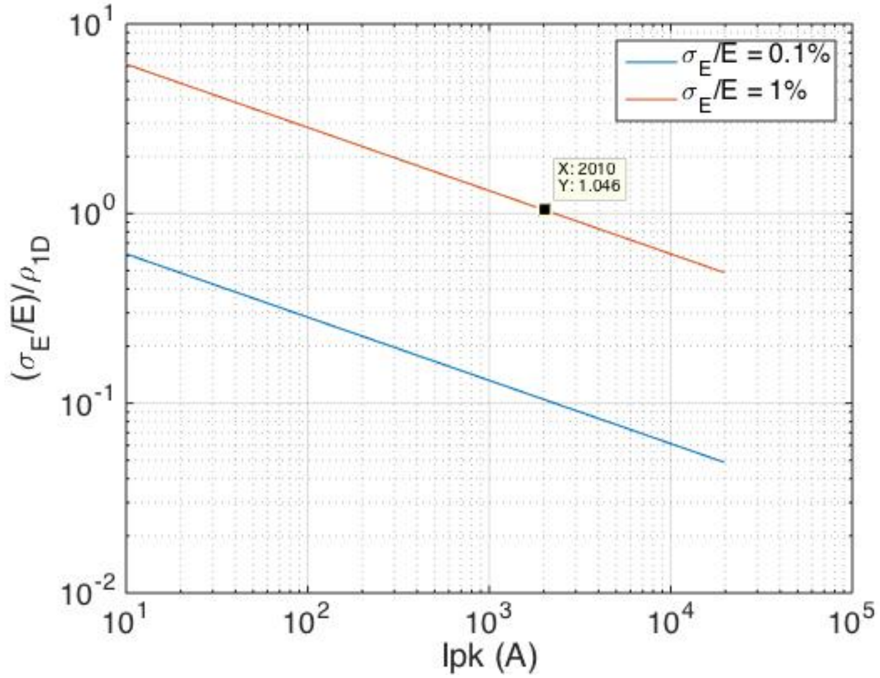
Power gain model used:	Xie			Input data set:	none
Beam parameters:					
Beam Energy [GeV] :	0.300	Norm. Emittance [mm mrad]:	0.2	Energy Spread [MeV] :	3
Bunch charge [nC] :	0.04	Peak Current [kA] :	10	Beam Power [TW] :	3
Beam size [mu] :	26.339	bunch length [mu] :	0.479	#Bunches/sec. :	1
Undulator parameters:	Type :	Hybrid with NdFeB		Geometry :	planar
Period [mm] :	19	K-rms parameter :	0.9	Length [m] :	4
Peak field [T] :	0.718	Gap [mm] :	6.89	Bessel factor J0-J1 :	0.876
FODO period [m] :	4	Quadrupole gradient [T/m] :	10	Quadrupole Length [m] :	0.1
Quadrupole focal length [m] :	0.999	Average beta-function [m] :	2.033	beta_max/beta_min :	120.783
Radiation parameters:					
Radiation wavelength [nm] :	50.06	Photon Energy [eV] :	24.776		

finalize

1D rho parameter (Bonifacio) :	0.01441	1D gain length [m] :	0.06		
3D rho parameter :	0.005046	**3D gain length [m] :**	**0.173**	**Saturation length [m] :**	**3.48**
Shotnoise power [W]:	140.641	**Saturation power [GW] :**	**8.481**	Power at undulator exit [GW] :	8.511
Electrons per wavelength:	10429167	Effective Energy spread :	3.927	Diffraction parameter :	2.1
Spotsize at exit (FWHM) [mu] :	62.02	Divergence (FWHM) [murad]:	356.18	Bandwidth (FWHM) [%] :	1.19
Pulse duration (FWHM) [fs] :	1.88	Photons per Pulse :	0.043E14	Autocorrelation time [fs] :	9.329
Peak Flux [#/sec] :	21.394E26	Peak Brilliance* :	3.415E30	Pulse Energy [mJ] :	0.017
Average Flux [#/sec] :	0E18	Average Brilliance* :	0E21		
SR Energy loss [MeV] :	0.0001	SR Energy spread [MeV] :	0		

Higher peak current to overcome the impact of 1% energy spread





Disadvantage: Space charge force !

U.S. DEPARTMENT OF ENERGY

Space charge effect

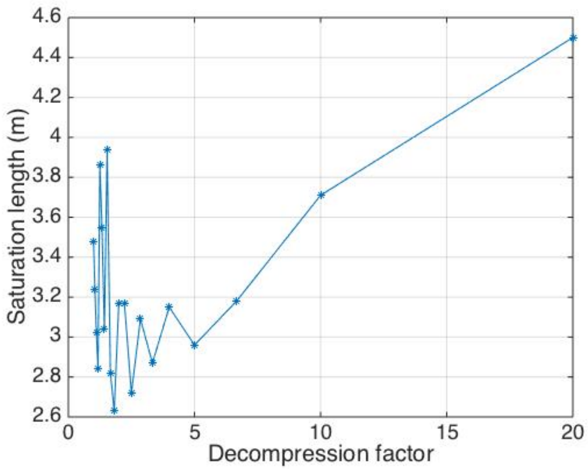
- The major space-charge induced effect on the bunch scale is the buildup of a longitudinal energy chirp.
- Electrons at the bunch head get accelerated while electrons at the bunch tail get decelerated. This energy modulation can reduce the efficiency of the FEL process.
- To maintain the FEL performance the width of the detuning range traversed by a photon during one gain length has to be smaller than the Pierce parameter

Dispersion of e-beam will mitigate slice energy spread

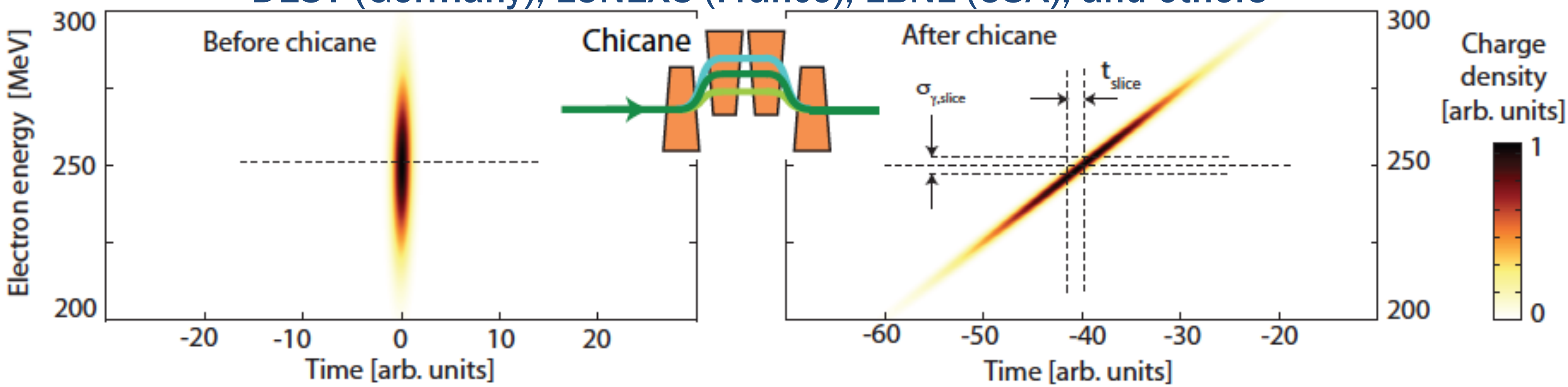
Key requirements

- Sub-% energy spread required for lasing slice
- Disperse/stretch electron beam

(although, gain length ~ $I_{pk}^{-1/3}$ ~ $n^{1/3}$)



DESY (Germany), LUNEX5 (France), LBNL (USA), and others

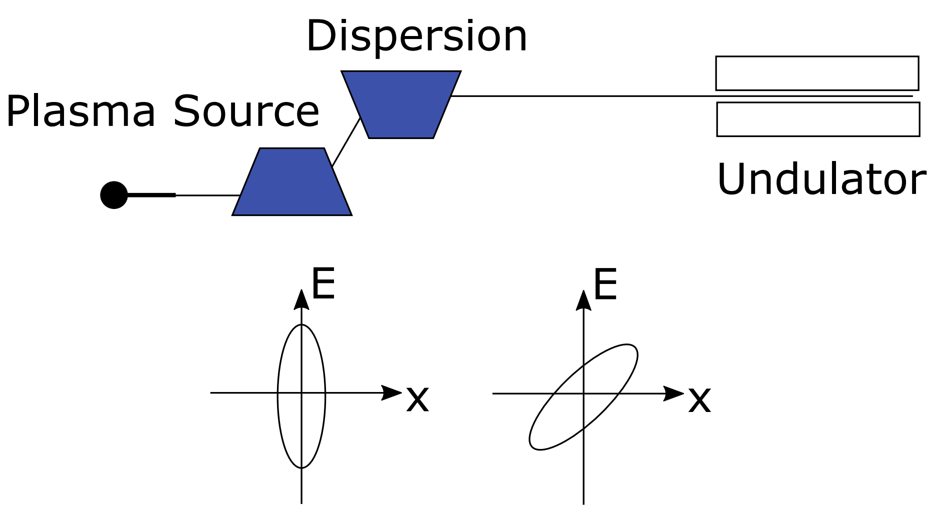


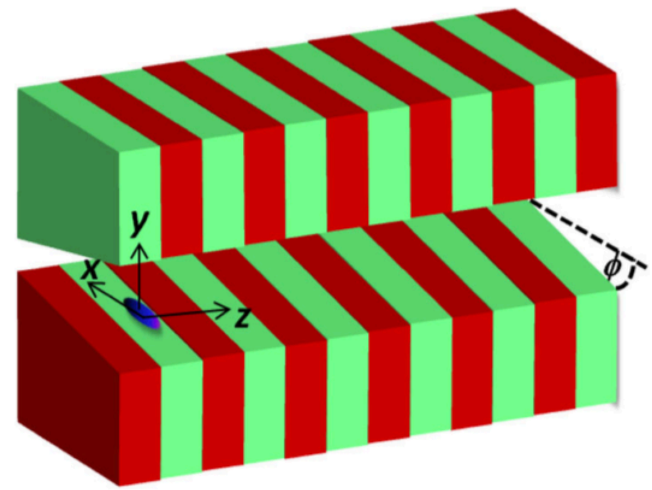
Schroeder *et al.* FEL Proc. (2012), Maier *et al.* PRX 2, 0311019 (2012), Schroeder *et al.* FEL Proc. (2013)

Transverse Gradient Undulator

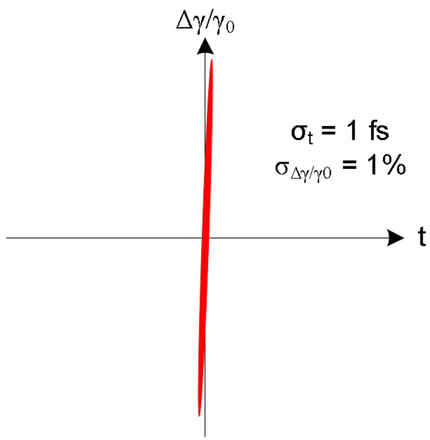
TGU to reduce the sensitivity to electron energy variation for FEL oscillator

Higher energy electrons are dispersed to the higher filed region to match FEL resonant condition.





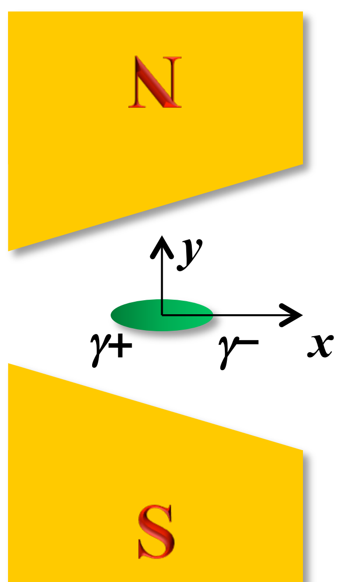
Stretching the bunch transversely



$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

- Such a big energy spread cause different wavelength;
- How to compensate? K varied with energy also.

$$x = \eta\frac{\Delta\gamma}{\gamma_0} \qquad \frac{\Delta K}{K_0} = \alpha x$$

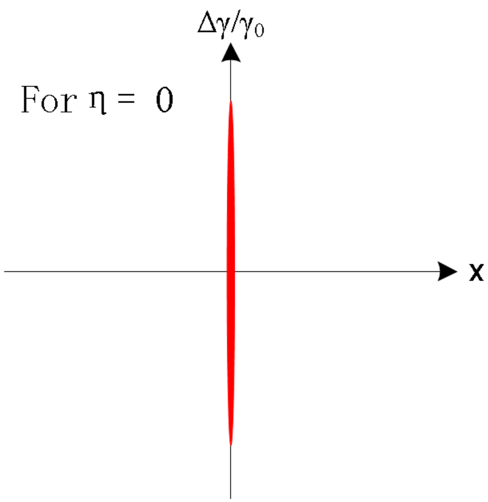


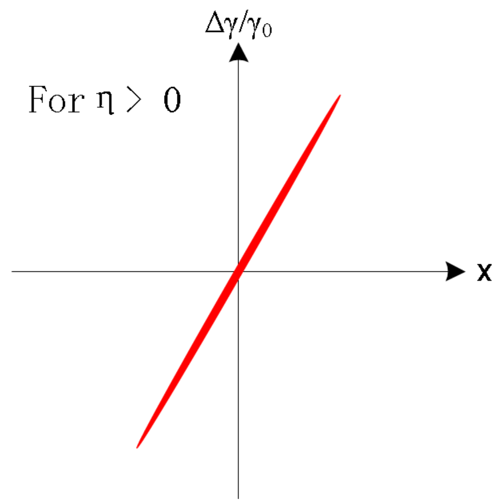
- Transverse Gradient Undulator (TGU) introduced at dispersion section. Resonance can be satisfied for all beam energies if

$$\eta = \frac{2 + K_0^2}{\alpha K_0^2}$$

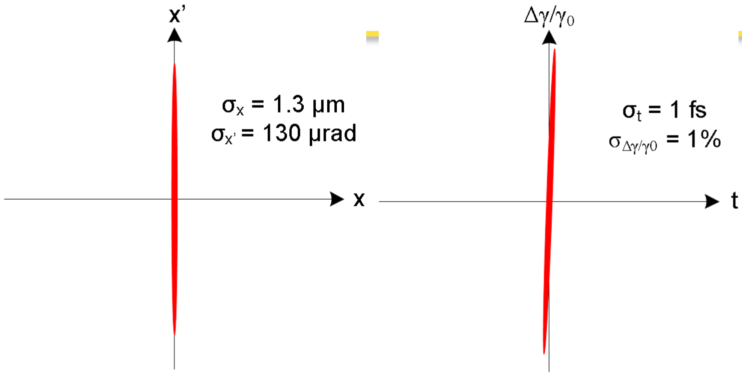
- The influence of energy spread can be well compensated by TGU placed at finite dispersion;
- But the beam cross sectional area changed. In comparision with energy spread, such an impact is more slightly;

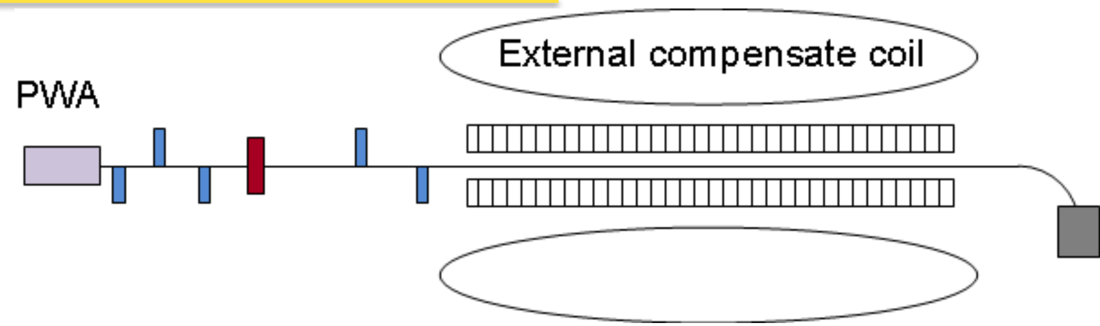
$$\rho = \frac{1}{2\gamma}\left[\frac{I}{I_A}\left(\frac{\lambda_u K f_B}{2\pi\sigma_x}\right)^2\right]^{1/3}$$



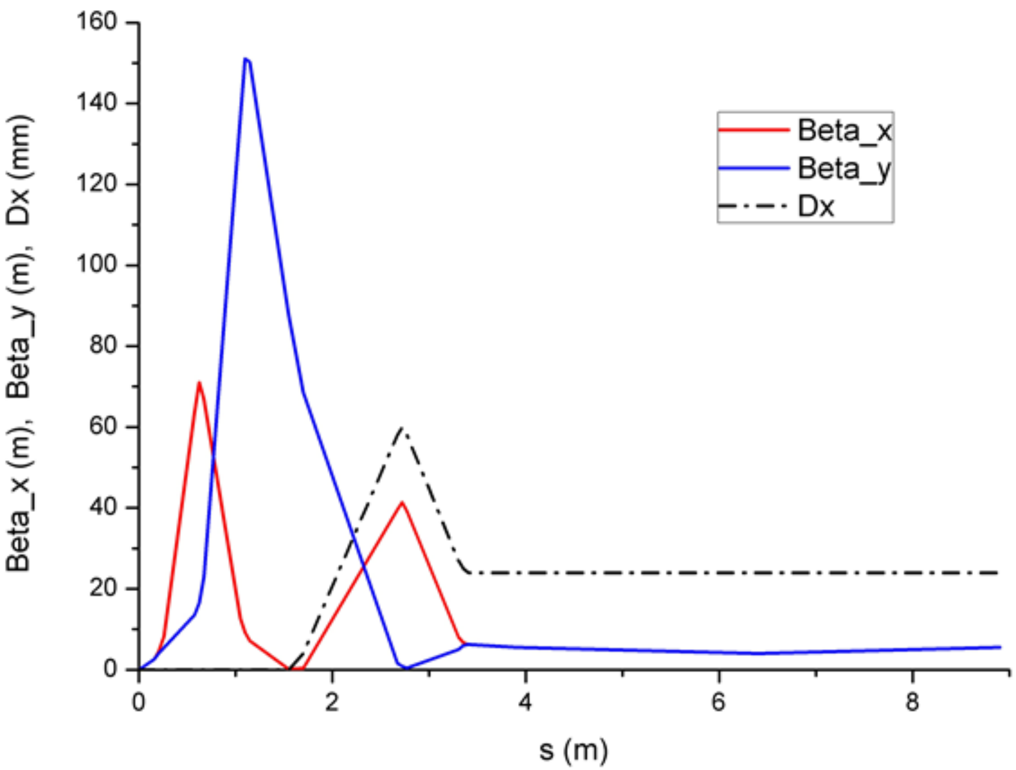


- The design of TGU-FEL is a compromise between FEL performance and undulator technique & beam transport.





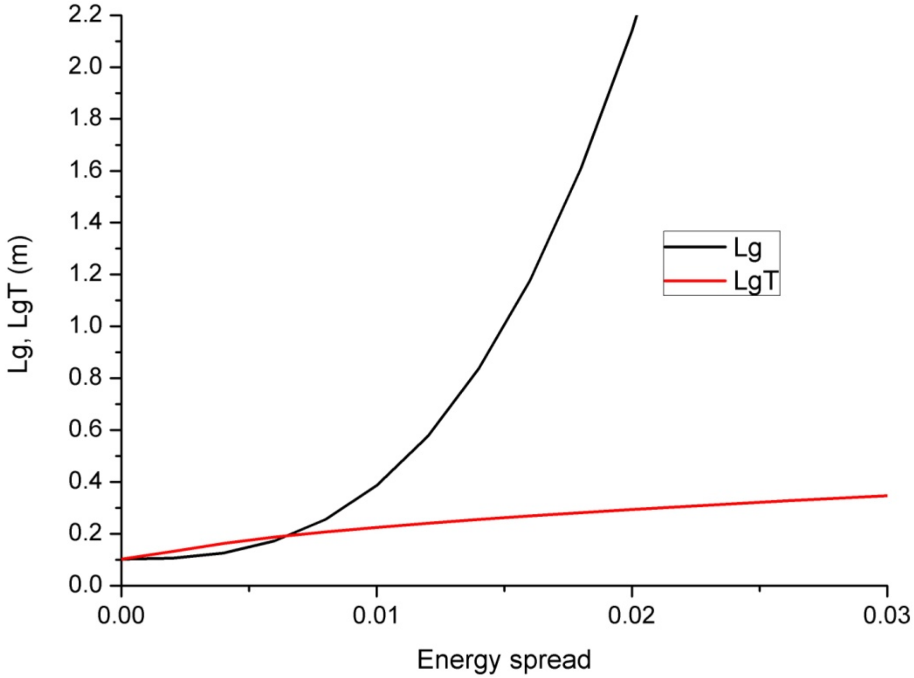
- 5 quadrupoles + 1 bending magnet used to tranport electron beam;
- 5m long transverse gradient undulator, the average beta function is ~4.5m, the dispersion is 0.024m;
- External coil used to compensate 1st and 2nd magnetic field integral caused by the TGU.



Beam Parameters used for TGU

Parameter	value
Beam energy (MeV)	300
Normalized transverse emittance (μm)	0.1
Peak current (kA)	5
Rms energy spread	1%
Injection Twiss parameter β (m)	0.01
Undulator type	Hybird
Undulator length (m)	5
Undulator period (mm)	20
Average beta function in TGU (m)	4.5
Horizontal dispersion η in TGU (m)	0.024
TGU maximun transverse gradient α (m^{-1})	100
External compensate field (gauss)	2
TGU gap adjust range (mm)	7.8 ~ 4.8
Undulator parameter K	1.2 ~ 2.2
Central peak field (T)	0.64 ~ 1.18
(nm)	

Gain length suppression using TGU



PRL **109,** 204801 (2012) PHYSICAL REVIEW LETTERS week ending 16 NOVEMBER 2012

Compact X-ray Free-Electron Laser from a Laser-Plasma Accelerator Using a Transverse-Gradient Undulator

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Compact laser-plasma accelerators can produce high energy electron beams with low emittance, high peak current but a rather large energy spread. The large energy spread hinders the potential applications for coherent free-electron laser (FEL) radiation generation. We discuss a method to compensate the effects of beam energy spread by introducing a transverse field variation into the FEL undulator. Such a transverse gradient undulator together with a properly dispersed beam can greatly reduce the effects of electron energy spread and jitter on FEL performance. We present theoretical analysis and numerical simulations for self-amplified spontaneous emission and seeded extreme ultraviolet and soft x-ray FELs based on laser plasma accelerators.

$$\rho_T = \rho\left(1 + \frac{\eta^2\sigma_\delta^2}{\sigma_x^2}\right)^{-1/6}$$

$$L_G^T \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho_T}\left[1 + \left(\frac{K_0^2}{2+K_0^2}\right)^2 \frac{\alpha^2\varepsilon_x L_u}{2\rho_T^2}\right]$$

- Gain length Lg calculated from Ming Xie model (without TGU);
- Gain length LgT calculated from the upper formula (with TGU);
- For our case, the gain length is ~ 0.25m, the saturation length is ~ 5m.

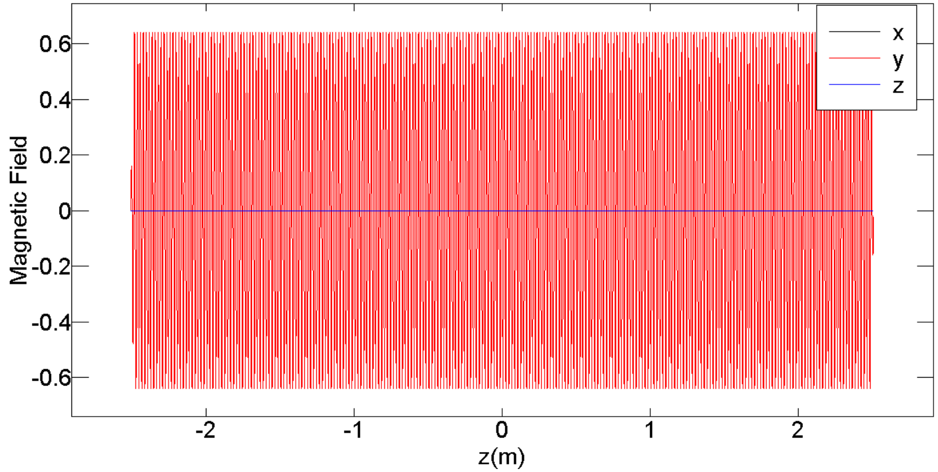
Transverse Gradient Undulator

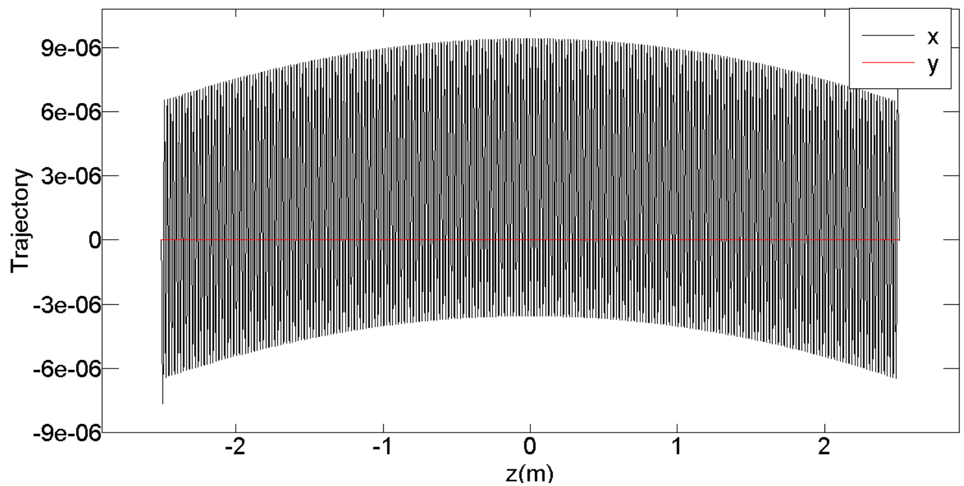
$$\alpha = 2\phi \frac{1}{K_0}\frac{\partial K_0}{\partial y} = 2\phi\left(\frac{5.47}{\lambda_u} - 3.6\frac{g}{\lambda_u^2}\right)$$

Halbach-type hybird undulator with cant angle

e.g., $\phi = 14$ deg, $\lambda_u = 2$ cm, g =7.8mm

= 100 m^{-1}





Compensated by 2 gauss external magnetic field

Summary of suggested schemes for mitigation of energy spread

Schemes	Comments
Longitudinal decompression	Compromise between peak current drop and energy spread suppression
Higher Peak current	Space charge effects and loss of emittance control. Increase of FEL parameter but dependence is too weak!
Transverse decompression	The beam can lase independently in the different transverse locations and hence looses spatial coherence. This will lead to a multimode beam that is less focusable and has reduced coherent flux.

Thank you slide!

- Thank you Sven for fruitful discussions! ☺

Thanks for your attention!

Appendix

Case 5 –FEL driven by Plasma Injector

- Goal: ***Use the output from a plasma injector to drive an FEL in the UV range.***

- Background: The non-linear regime of a laser driven plasma channel can generate a relativistic electron beam with small emittance but rather large energy spread. They can potentially shorten the classical RF injector and accelerator of FEL facilities down to a few meters.

- Approach: Experiments have shown promising beam parameters with a current of hundreds of Amperes, small emittances of about 100 to 200 nm but an relative energy spread of 1% at a beam energy of several hundreds of MeV. The practical limit to apply the beam to an FEL is its large energy spread.

Case 5 - Tasks

- With an expected energy spread of about 1% discuss the methods to over come this limitation by
  1. Stretching the bunch longitudinally, where the energy spread decreases linearly with the decompression but the FEL parameter only with its cubic root
  2. Stretching transversely with dispersion and apply a transverse gradient to the undulator field.

- Propose possible configuration of the machine layout for both methods. Discuss possible limitation in the wavelengths with any of the methods.

- An alternative approach is to generate much higher peak current to overcome the impact of 1% energy spread. What is the minimum current to allow lasing at 300 MeV and a wavelength of 50 nm. Discuss the impact on longitudinal space charge.

FEL equations

Spread in the average beam energy →

- spread in resonant condition and degrading FEL gain

$$\lambda_r = \frac{\lambda_u}{2\gamma_0^2}\left(1 + \frac{K_0^2}{2}\right).$$

High-Gain FEL requirements:

$$\sigma_\delta = \frac{\sigma_\gamma}{\gamma_0} \ll \rho = \left[\frac{1}{16}\frac{I_0}{I_A}\frac{K_0^2[\mathrm{JJ}]^2}{\gamma_0^3\sigma_x^2 k_u^2}\right]^{1/3},$$