

*Compact FEL Devices: The Quest for new design  
solutions*

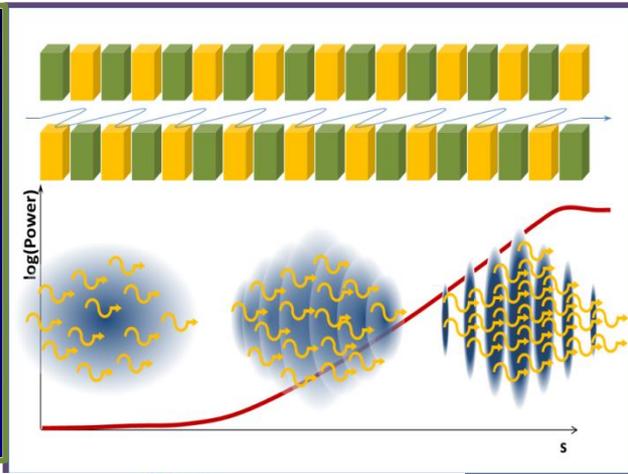
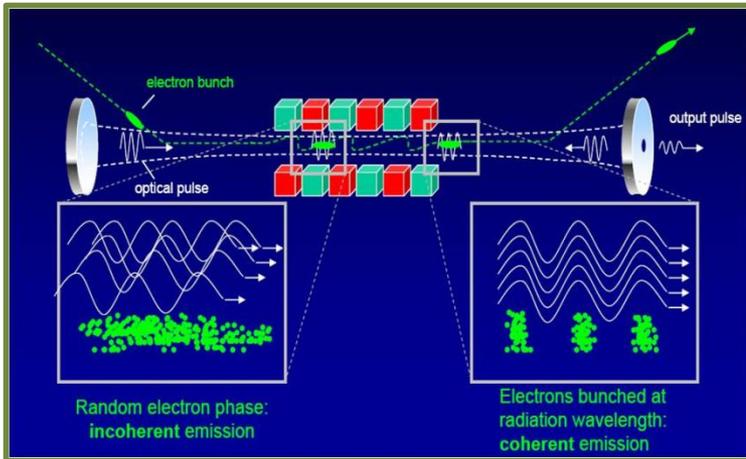
*G. Dattoli*

*ENEA FRASCATI FSN DIVISION*

*Alessandro Curcio and Federico Nguyen*



# FEL Oscillator or SASE



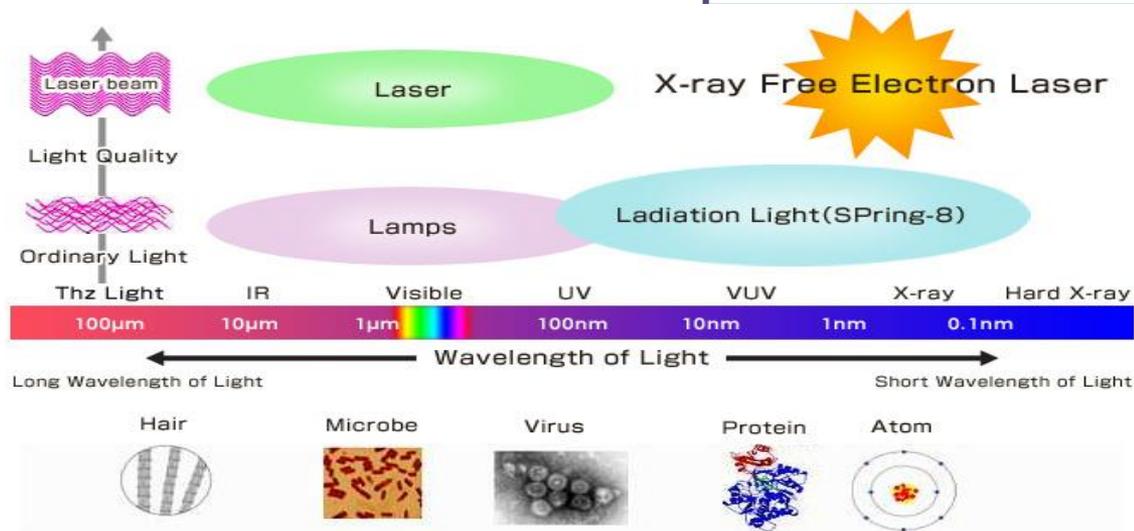
$I \cong$  Kilo - Ampères

$E \cong GeV$

$P_E \cong 10^3 GW$

$P_L \leq 0.1 - 1GW,$

$\sigma_\tau \cong 10 fs$



$I \cong$  Few Ampères

$E \cong$  Few Tens of MeV

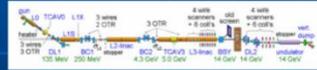
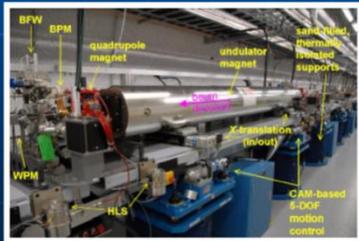
$P_E \cong$  Tens of MW

$P_L \leq 0.1MW,$

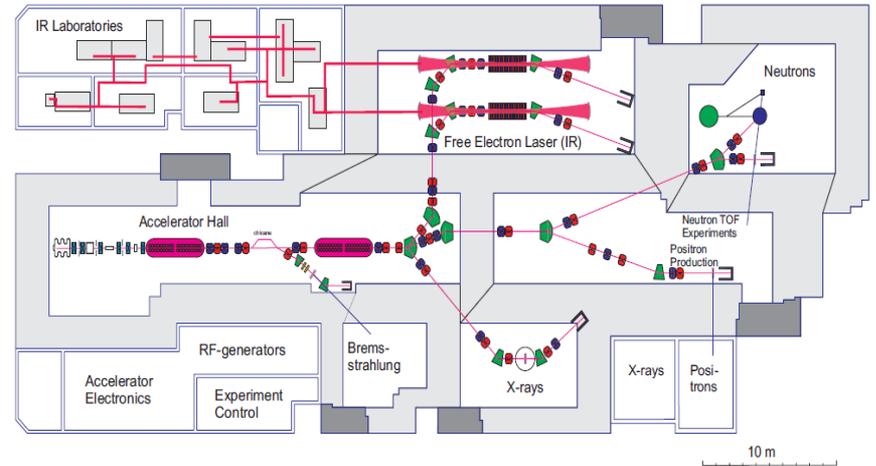
$\sigma_\tau \cong ps$

# Two Paradigmatic Examples

## LCLS at SLAC



1 km

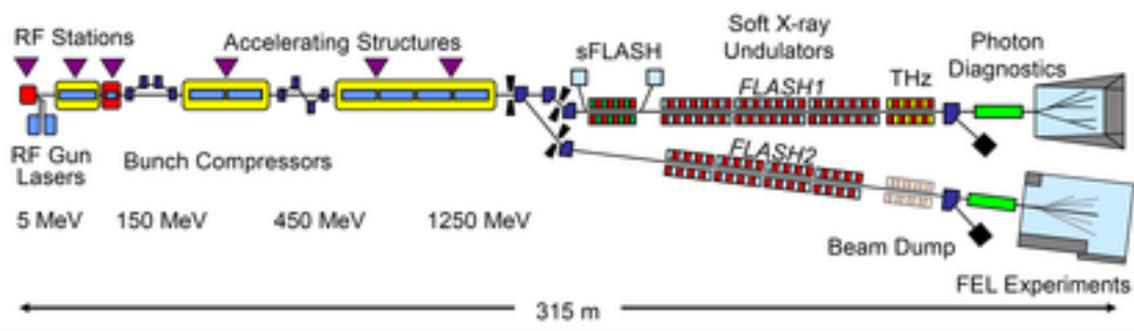
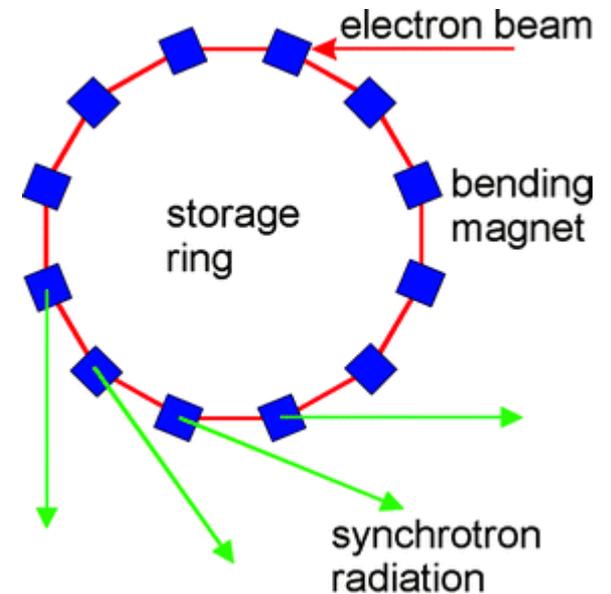
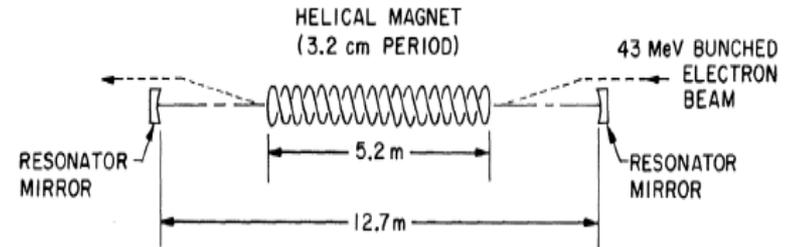
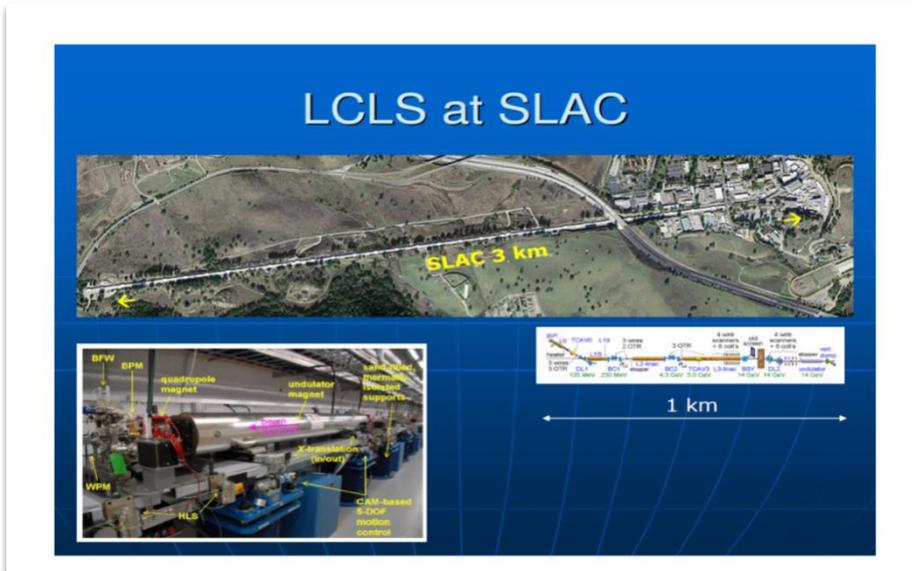


10 m

Figure 1: Layout of the radiation source ELBE.

# What's the Price to be Payed?

Size and Costs...few experimental lines



# *What about money?*

## FEL size and cost

	Wavelength	Energy	Size [m]	Cost [M\$]
<b>IR</b>	2-10 $\mu\text{m}$	10-40 MeV	3-10	1-5
	EUV 13.5 nm	0.5-1 GeV	40	30-50
<b>X</b>	0.15 nm	15 GeV	500-1000	1000

# *Reduce cost and size: The problem is of public domain...*

Fundamental physics seems to have an insatiable appetite for bigger, more expensive machines. There may, though, be a way to shrink them radically

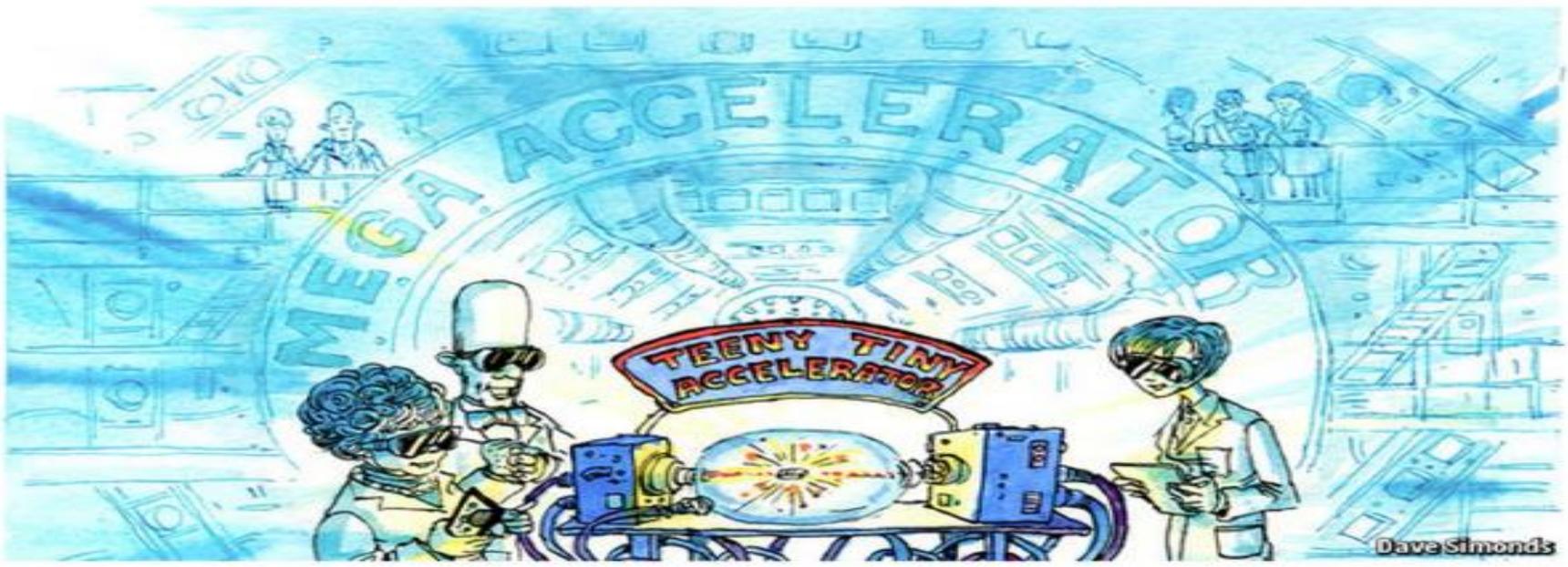
Oct 19th 2013 | From the print edition

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512

 Tweet

55



BIG science tends to get bigger with time. The first modern particle accelerator, Ernest Lawrence's cyclotron, was 10cm across and thus fitted comfortably on a benchtop. It cost (admittedly at 1932 prices) \$25. Its latest successor, the Large Hadron Collider (LHC), has a diameter of 8.6km (5.3 miles) and does not even fit in one country: it straddles the border between France and Switzerland, near Geneva. It cost \$5 billion. Clearly, this is a trend that cannot continue. And two groups of physicists – one American and one German – think they

*Cannot continue for longer time*

# The Challenges

- *A) Reduce the costs*
- *B) reduce the sizes*
- *C) Improve the «light» coherence properties*
- *D) Increase the number of experimental stations*

- *..... The Strategy*

- *A) Reduce the undulator length using exotic devices*
- *(Laser Wave undulators, R.F. Undulators,....)*
- *B) Reduce the size of the accelerator using different accelerating schemes*
- *(High gradient, Plasma accelerators,...)*

# The solution stays in a nut shell

- Remind that there are crucial parameters which allow a very quick understanding of the design parameters

$$\rho \cong \frac{8.36 \cdot 10^{-3}}{\gamma} \cdot \left[ J \left[ \frac{A}{m^2} \right] \cdot (\lambda_u [m] K f_b(\xi))^2 \right]^{\frac{1}{3}},$$

$$f_b(\xi) = J_0(\xi) - J_1(\xi), \quad \xi = \frac{1}{4} \frac{K^2}{1 + \frac{K^2}{2}}, \quad J = \frac{\hat{I}}{2\pi\sigma^2}$$

$$\lambda = \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right), \quad L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho}, \quad L_s \cong 20L_g$$

$$K = 0.7, \lambda_u = 2 \text{ mm}, \lambda \cong 10 \text{ nm}$$

$$\hat{I} \cong 1 \text{ kA}, L_s = 10 \text{ m} \rightarrow$$

$$\rightarrow \gamma \cong 5 \cdot 10^2, \rho \cong 1.84 \cdot 10^{-4},$$

$$J \cong 4 \cdot 10^9, \sigma \cong 2 \cdot 10^{-4}$$

- $\varepsilon \cong \frac{\lambda}{4\pi} \rightarrow \varepsilon_n \cong 0.4 \text{ mm} \cdot \text{mrad}$

# PM Undulators

Halbach configuration undulator parameters :

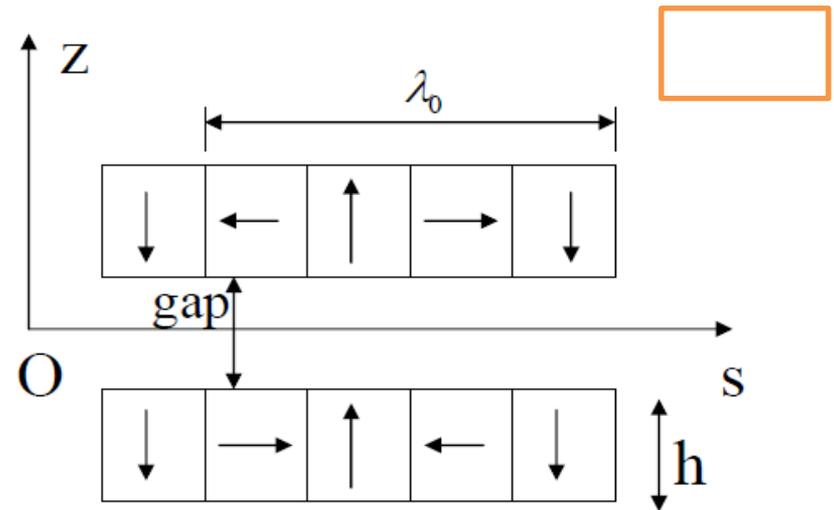
$$B_0 = 2B_r \frac{\sin\left(\frac{\pi}{M}\right)}{\frac{\pi}{M}} \left[ 1 - \exp\left(-\frac{2\pi h}{\lambda_u}\right) \right] \exp\left(-\frac{\pi g}{\lambda_u}\right)$$

$M$  number of blocks per period

$h$  magnet height

$g$  gap

$B_r$  remanent field



$$K = 0.7, \lambda_u = 2 \text{ mm}$$

- *Are these reliable parameters???*

$$K = \frac{eB_0\lambda_u}{2\pi m_e c^2} = \frac{\lambda_u[\text{cm}]B_0[\text{KG}]}{10.71}$$

$$\rightarrow B \cong 3.75 \text{ T}$$

$$B_0 \sim 1.8B_r \exp\left(-\pi \frac{g}{\lambda_u}\right)$$

$$g \cong 2.19 \text{ mm}$$

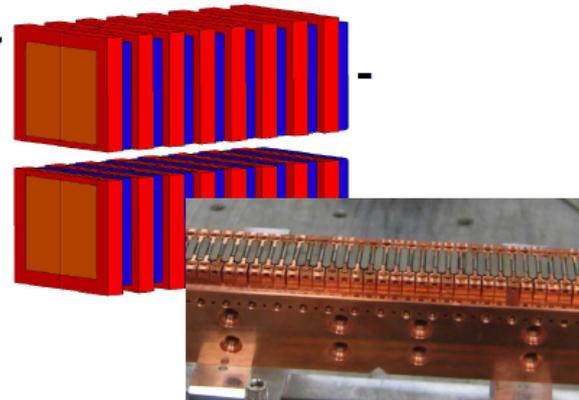
Courtesy of J. Rosenzweig

# What's next: the 5<sup>th</sup> generation ultra-com

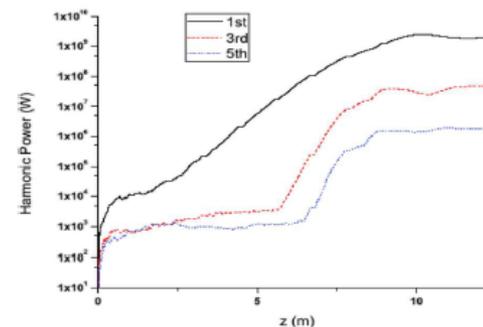
- **High brightness beam (HBB)**
  - low charge (pC), ultrashort pulses
  - Ultralow emittance

J.B. Rosenzweig, et al., *Nucl. Instruments Methods A*, 593, 39 (2008)

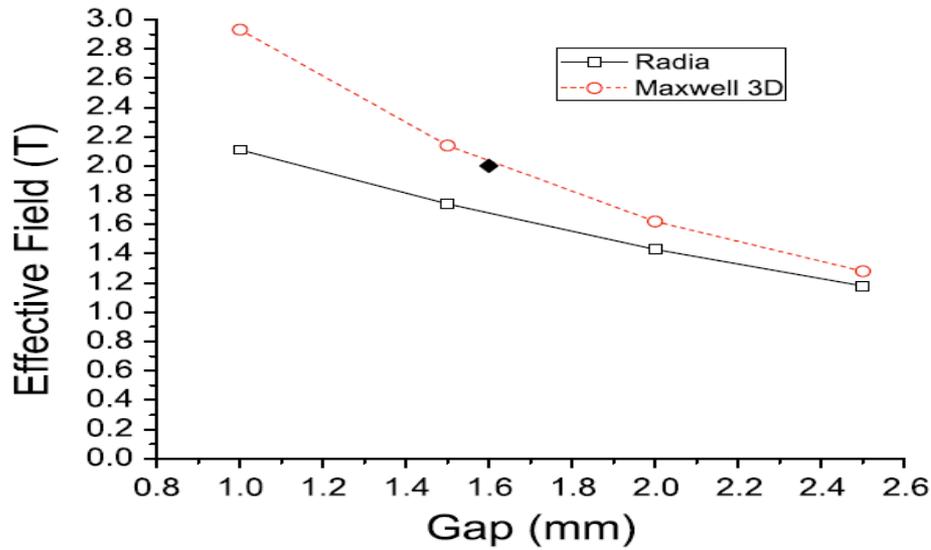
- **High field, short  $\lambda$  undulator**
  - With HBB, large  $\lambda$ , short  $L_g$
- **Lowers e- energy needed to reach short wavelength**
  - Ex: 2 GeV hard X-ray FEL
  - *Much smaller accelerator, undulator*
- **Utilize high gradient accelerators to shrink the FEL dramatically**



Hybrid cryo-undulator: Pr-based, SmCo sheath;  $\lambda = 9$  mm up to 2.2 T



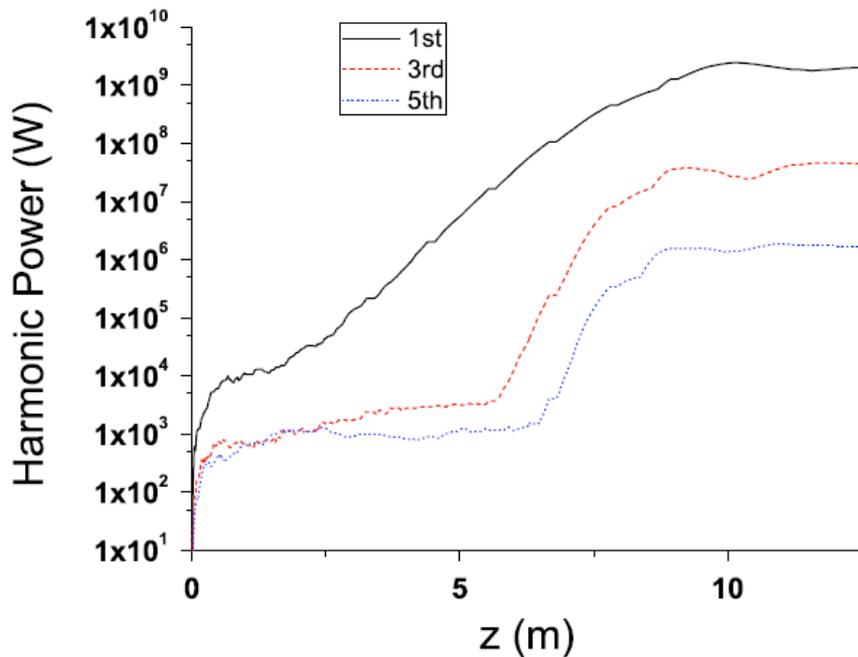
# High field cryogenic undulators



$$B \cong 8e \frac{0.6 \cdot \pi g}{\lambda_u}$$

# What does compact mean?

- SPARX (O'Shea et al. PRSTAB (2010))



$$\varepsilon_f \cong 1.8 \text{ keV}$$

$$I = 700 \text{ A}$$

$$\sigma_z \cong 0.48 \text{ fs}$$

$$\rho \cong 1.4 \cdot 10^{-3}$$

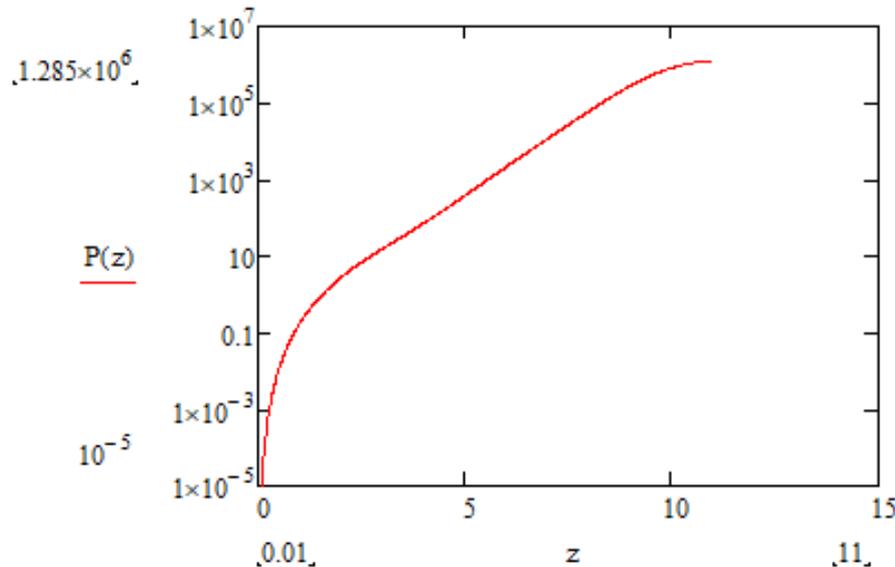
$$\sigma_\varepsilon \ll \frac{\rho}{2} \rightarrow 7 \cdot 10^{-4}$$

$$L_g \cong L_g^{(0)} \left( 1 + 0.185 \sqrt{\frac{3}{2}} \cdot \tilde{\mu}_\varepsilon^2 \right)$$

$$\frac{\Delta L_g}{L_g^{(0)}} \cong 0.185 \sqrt{\frac{3}{2}} \cdot \tilde{\mu}_\varepsilon^2, \tilde{\mu}_\varepsilon = 2 \frac{\sigma_\varepsilon}{\rho}$$

# Saturation 10 m!!

Including Energy spread, diffraction, ...



$$P(z) = \frac{P_0}{9} \frac{B(z)}{1 + \frac{P_0}{9P_F} B(z)}$$

$$B(z) = 2 \left[ \cosh\left(\frac{z}{L_g}\right) - e^{z/2L_g} \cos\left(\frac{\pi}{3} + \frac{\sqrt{3}z}{L_g}\right) - e^{-z/2L_g} \cos\left(\frac{\pi}{3} - \frac{\sqrt{3}z}{L_g}\right) \right]$$

$$L_g \cong L_g^{(0)} \left( 1 + 0.185 \sqrt{\frac{3}{2}} \cdot \tilde{\mu}_\varepsilon^2 \right)$$

$$\frac{\Delta L_g}{L_g^{(0)}} \cong 0.185 \sqrt{\frac{3}{2}} \cdot \tilde{\mu}_\varepsilon^2, \tilde{\mu}_\varepsilon = 2 \frac{\sigma_\varepsilon}{\rho}$$

# Alternative Solutions?

- *Wave Undulators*

$$K \approx 0.85 \cdot 10^{-5} \lambda[m] \sqrt{\left( I \left[ \frac{W}{m^2} \right] \right)}$$

$CO_2$

- $I \left[ \frac{W}{m^2} \right] \cong 8 \cdot 10^{19}, K = 0.76$

$f = 91.392 \text{ GHz}$

$\lambda_u = 1.75 \text{ mm}$

Gap = 4.9 mm

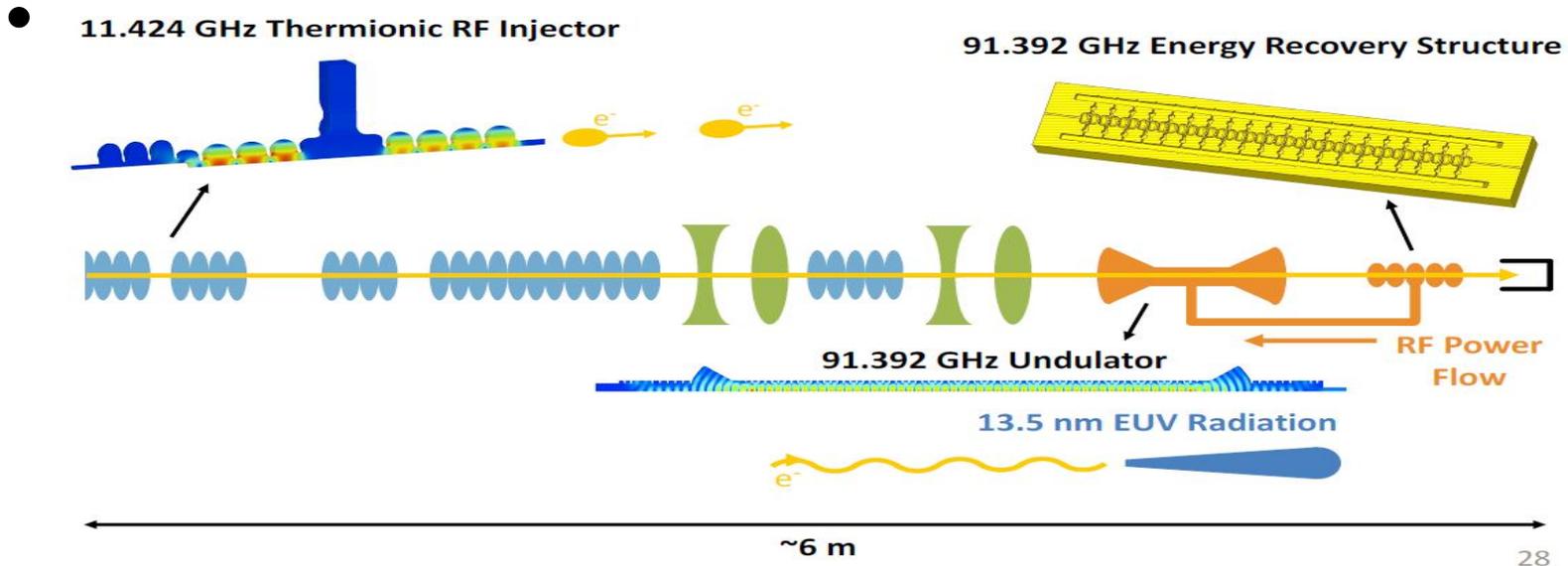
Beam Pipe 0.87 mm

- *RF Undulators*



$K = 0.1$

# Towards A Compact Device



## A Compact Linac-Driven EUV Light Source utilizing a Short-Period Microwave-Driven Undulator

Filippos Toufexis\* - [ftouf@stanford.edu](mailto:ftouf@stanford.edu),  
C. Limborg-Deprey, V.A. Dolgashev, S.G. Tantawi  
SLAC National Accelerator Laboratory  
\*Also at Electrical Engineering, Stanford University

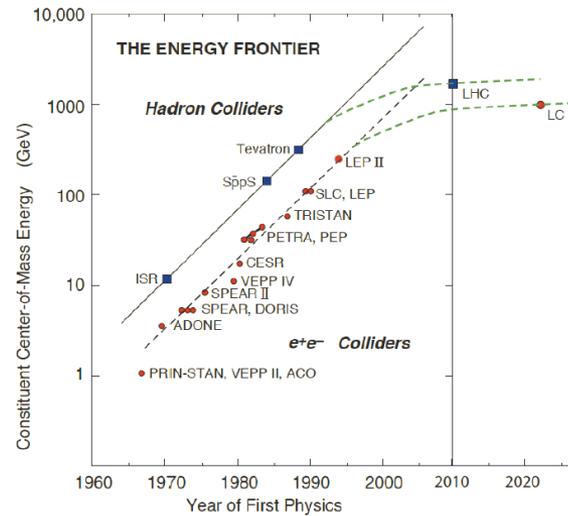
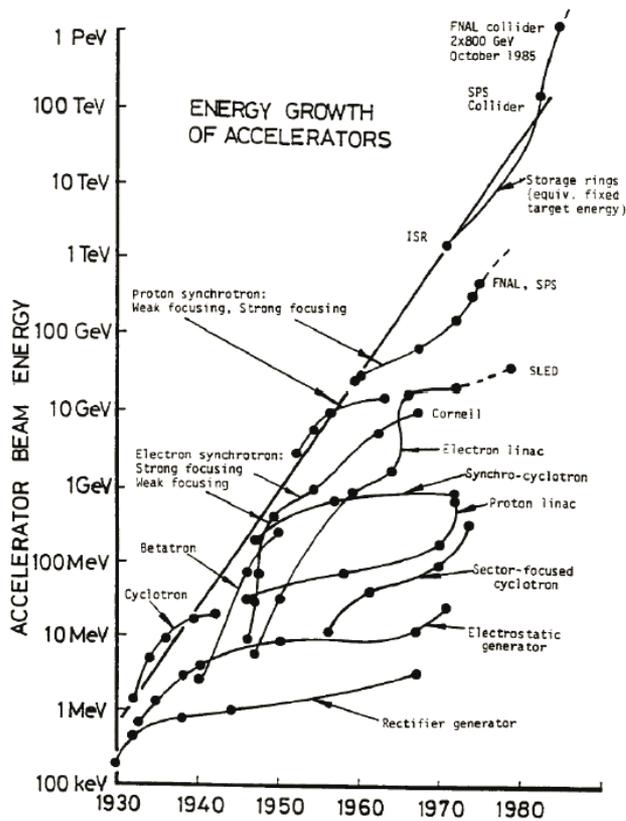
2017 International Workshop on EUV Lithography  
June 14, 2017

# A few parameters

- $E = 129.6 \text{ MeV}$   
 $Q = 20.34 \text{ pC}$   
 $\sigma_{xy} = 151 \text{ }\mu\text{m}$   
 $\sigma_z = 124 \text{ fs}$   
 $\varepsilon_n = 4.4 \text{ mm mrad}$   
 $\Delta E = 0.15 \%$

<b>Input Power</b>	<b>1.4 MW</b>
<b>Periods</b>	<b>66</b>
<b>K</b>	<b>0.1</b>
<b>Peak B</b>	<b>0.61 T</b>
<b>Peak E</b>	<b>181.6 MV/m</b>
<b>Period</b>	<b>1.75 mm</b>
<b>Temp Rise</b>	<b>44°C / 250 nsec</b>

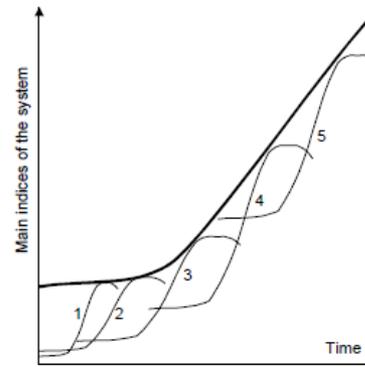
# Livingston Plot and Saturation of technologies



## Livingston Chart 2010

Progress has slowed in pushing the energy frontier

No longer proceeding along at the rate of development seen over the previous 60 years

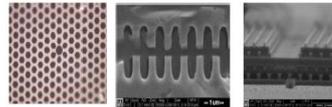


Successive substitutions of new systems for old ones following the law of Ideality growth.

# Is the future coming? JF so where is it going?



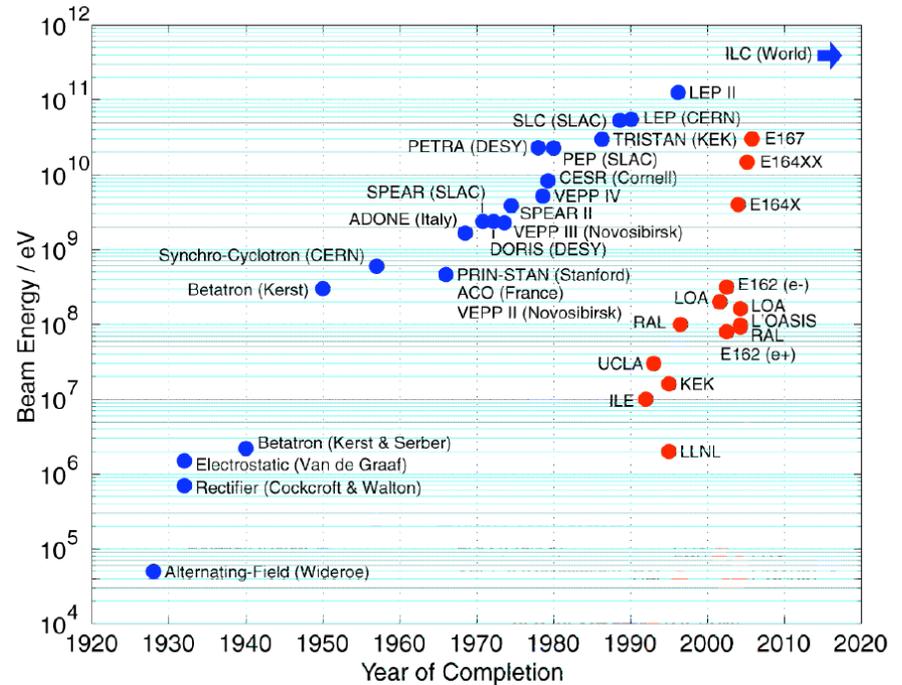
30 MV/m  $\lambda = 10$  cm  
 gradient wavelength  
 1-2 GV/m  $\lambda = 1-10 \mu\text{m}$   $\times 10^{-4}$



Goal: lower cost, more compact, higher gradient

laser-driven microstructures

- **lasers:** high rep rates, strong field gradients, commercial support
- **dielectrics:** higher breakdown threshold  $\rightarrow$  higher gradients (1-5 GV/m), leverage industrial fabrication processes



- The effective accelerating length is

# LPA-Parameters

$$\Delta E_{Acc} \left[ \frac{GeV}{m} \right] \cong 96 \sqrt{\frac{n_0 [cm^{-3}]}{10^{18}}},$$

$n_0 [cm^{-3}] \equiv$  plasma density

$$\Delta E [GeV] \cong 3.23 \cdot 10^{-3} \left( \frac{\omega_l}{\omega_p} \right)^2$$

$$L_{eff} \cong \gamma_p^2 \lambda_p [m]$$

$$\lambda_p [m] \cong 33.7 \cdot 10^{-6} \sqrt{\frac{10^{18}}{n_0 [cm^{-3}]}}$$

$\lambda_p \equiv$  plasma wavelength

$$\omega_p [Hz] \cong 5.6 \cdot 10^{13} \sqrt{\frac{n_0 [cm^{-3}]}{10^{18}}}$$

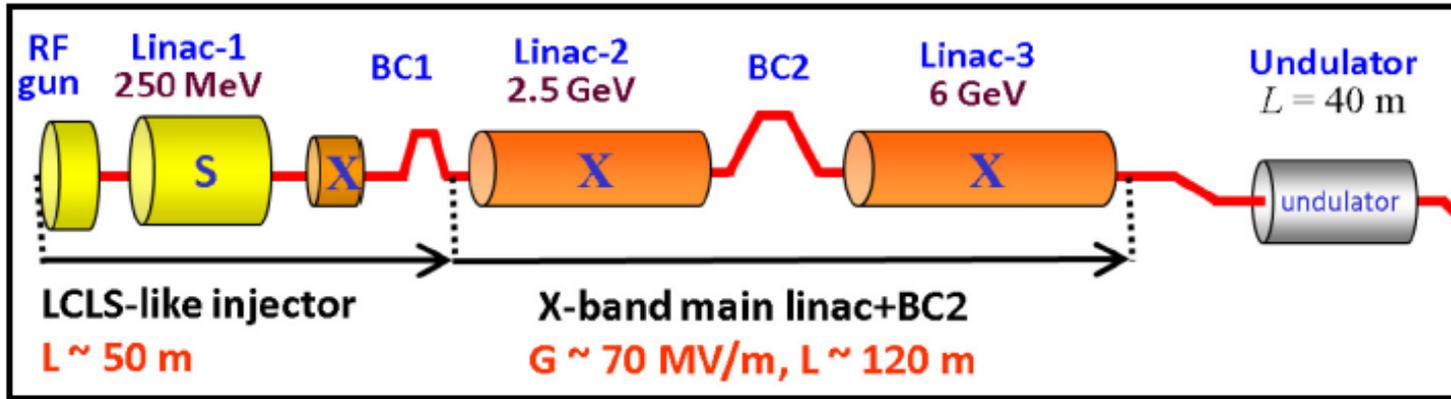
$\omega_p \equiv$  plasma frequency

$$\gamma_p = \frac{1}{\sqrt{1 - \beta_p^2}} = \frac{\omega_l}{\omega_p}$$

$$\beta_p = \left( 1 - \left( \frac{\omega_p}{\omega_l} \right)^2 \right)^{\frac{1}{2}}$$

$\omega_l \equiv$  laser frequency

# An exercise: X-Band LINAC (70 MeV/m)

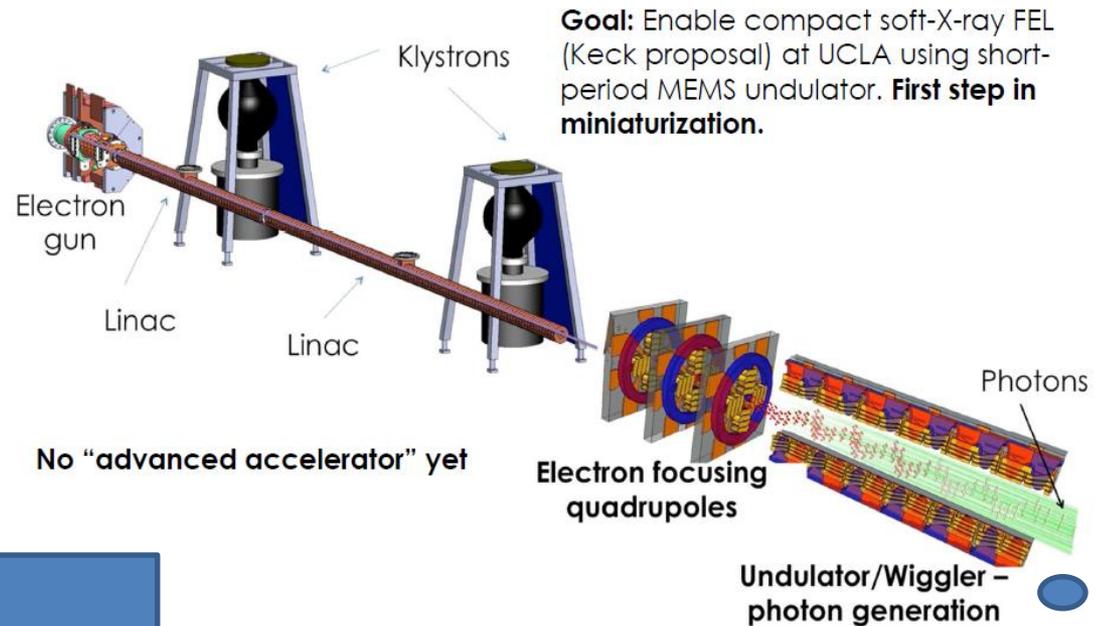


SLAC-PUB-14276

Chris Adolphsen, Zhirong Huang, Karl L.F. Bane, Zenghai Li, Feng Zhou, Faya Wang, and  
Christopher D. Nantista

Parameter	symbol	LCLS	X-band FEL	unit
Bunch Charge	$Q$	250	250	pC
Electron Energy	$E$	14	6	GeV
Emittance	$\gamma_{e,x,y}$	0.4-0.6	0.4-0.5	$\mu\text{m}$
Peak Current	$I_{pk}$	3.0	3.0	kA
Energy Spread	$\sigma_E/E$	0.01	0.02	%
Undulator Period	$\lambda_u$	3	1.5	cm
Und. Parameter	$K$	3.5	1.9	
Mean Und. Beta	$\langle\beta\rangle$	30	8	m
FEL wavelength	$\lambda_t$	1.5	1.5	$\text{\AA}$
Sat. Length	$L_{sat}$	60	30	m
Sat. Power	$P_{sat}$	30	10	GW
FWHM Pulse Length	$\Delta T$	80	80	fs
Photons/Pulse	$N_\gamma$	2	0.7	$10^{12}$

# Towards «Bonsai» FEL



# Pathway to a Compact SASE FEL Device

G. Dattoli,<sup>1</sup> E. Di Palma,<sup>1</sup> V. Petrillo,<sup>2</sup> J.V. Rau,<sup>3</sup> E. Sabia,<sup>1</sup>  
 I. Spassovsky,<sup>1</sup> S.G. Biedron,<sup>4</sup> J. Einstein,<sup>4</sup> and S.V. Milton<sup>4</sup>

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<sup>2</sup> Università degli Studi di Milano, via Celoria 16, 20133 Milano, Italy

<sup>3</sup> Istituto di Struttura della Materia, ISM-CNR, Via del Fosso del Cavaliere, 100-00133 Rome, Italy

<sup>4</sup> Colorado State University

- *Wave undulators: Use a laser instead of a magnetic device*

## The State of the art: ATF experiment

M. N. Polyanskiy, I. V. Pogorelsky and V. Yakimenko

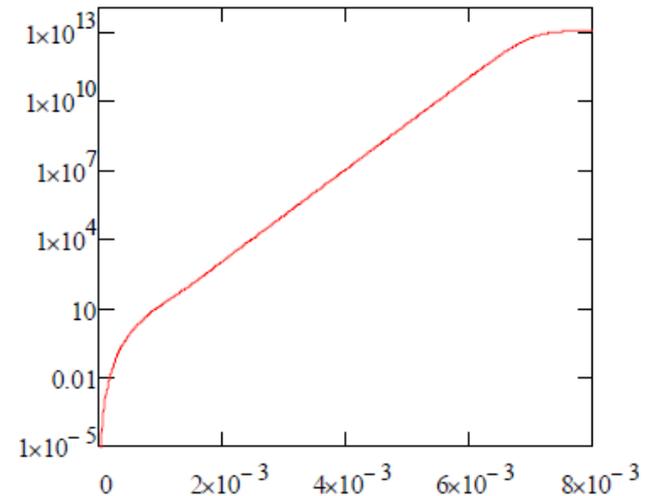
Optics Express 7717, Vol. 19, April 11 (2011)

V. Yakimenko, CO<sub>2</sub> Laser Based undulator for a compact SASE FEL

Talk delivered at "Laser and Plasma Accelerators Workshop 2011"

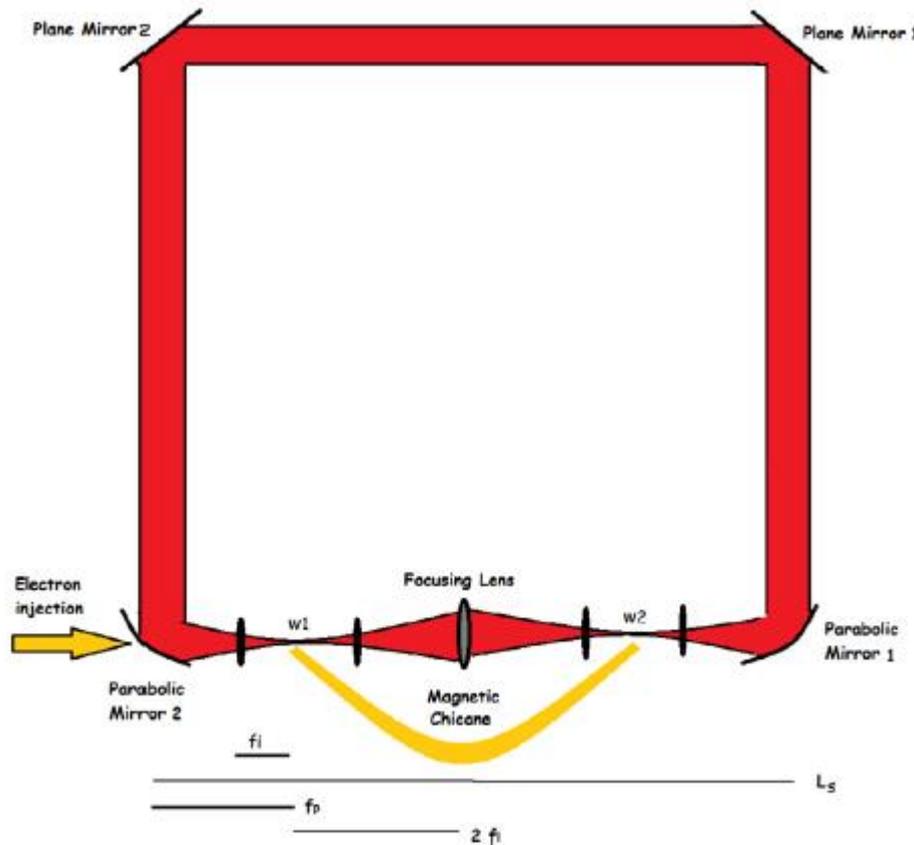
Brookhaven (New York) June 20-21 (2011)

<b>Electron beam</b>	
<b>E[Mev]</b>	77.3
<b>I[A]</b>	$1.5 \cdot 10^3$
$\frac{E}{E_x} \rho_c$	8.6
$E_x [keV] = \hbar \omega_c$	10
<b>Laser Energy [J]</b>	30
<b>Laser duration [ps]</b>	30



# A Super Compact FEL device

A. Curcio et Al. Opt. Commun. (2017)



CO<sub>2</sub> laser ( $\lambda_0 = 10.6 \mu\text{m}$ ),

$$I_p = 4.2 \times 10^{18} \text{ W/m}^2,$$

$$40 \text{ J} \quad 300 \text{ ps}$$

$$P_L = 130 \text{ GW}$$

$$20 \text{ MeV}$$

$$I_e = J \Sigma_e = 3 \text{ kA}$$

...

