Wave Undulators and SASE FEL DEVICES

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Thanks to
Vittoria Petrillo
And
Gulietta Rau

outline

(1) History of FEL Sources

(2) The idea of "Wave Undulators"

(3) Scaling Relations For SASE wave undulator devices

(4) Theoretical feasibility

(5) Technological feasibility

(6) An outlook to future

(1) History of FEL sources

- 1932 Kapitza-Dirac effect
- 1968-Pantell, Soncini, Puthoff stimulated amplification of CO2 laser via stimulated Compton Backscattering
- 1971 Madey, proposal of Free Electron laser and use of the WW approximation to treat the undulator magnetic field as a wave field
- 1983 Dobsiach, Meystre, Scully, Use of wave undulator in FEL
- 1985 Ciocci, Dattoli, Walsh, Analysis of the Feasibility of a FEL oscillator using a wave undulator
- 1987 J. Gea Banacloche, G. T. Moore, R. R. Schlicher, M. O. Scully, H. Walther
- 1993 Cha Mei Tang, B. Hafizi, S. K. Ride…
- 1999 Dattoli, T. Letardi, L.R. Vazquez, FEL SASE WAVE undulators
- 2006 Bacci, Ferrario, Maroli, Petrillo, Serafini
- 2012 Dattoli, Petrillo, Rau Feasibility of wave SASE FEL undulators

FEL COMPTON DEVICES

- The idea is even older than that based on Magnetic undulators

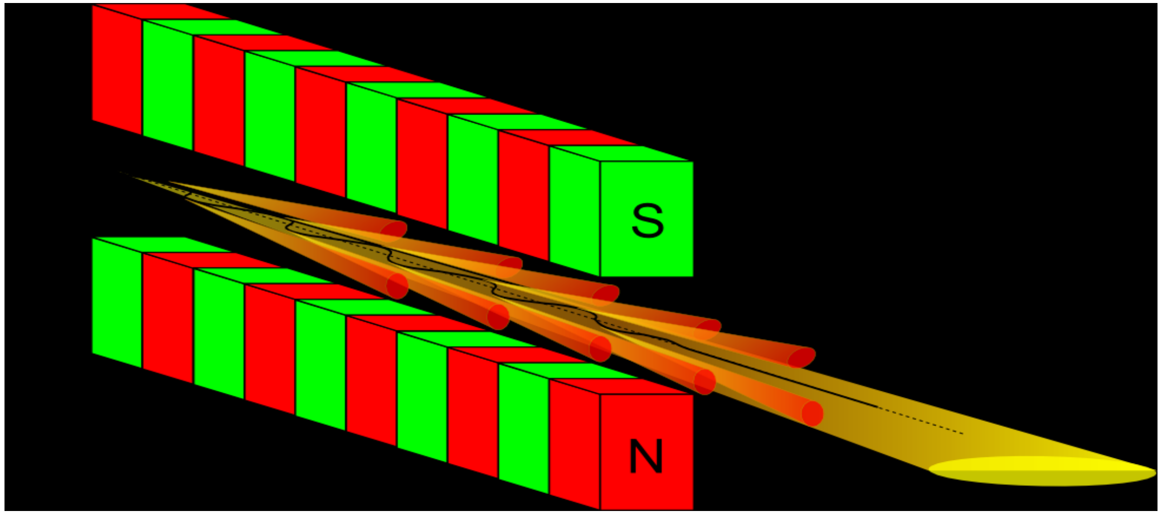
the electron-undulator interaction is treated by the use of

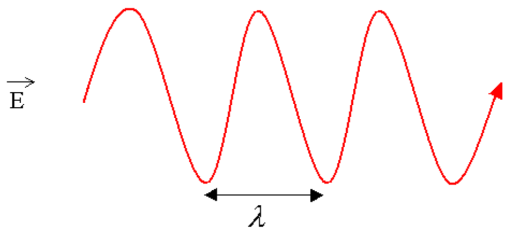
Weiszacker-Williams

method of virtual quanta

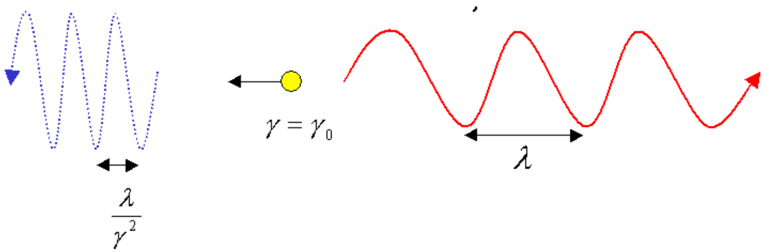
- The emission by electrons inside the undulator is considered as
- The Compton backscattering of pseudo undulator photons,
- The undulator is viewed as an electromagnetic wave with wavelength twice the period of the undulator itself

FEL and Compton Backscattering





$$\gamma_0 = \frac{1}{\sqrt{1-{v_0}^2/c^2}} = 1 + \frac{K.E.}{mc^2}$$



W.W. Approximation

The undulator is a collection of pseudophotons
(J. M. J. Madey, J. Appl. Phys. (1971)
G. Dattoli and A. Renieri, Laser Handbook Vol. IV (1985))

$$\lambda^* = 2\lambda_u,$$

$$I_u\left[\frac{W}{m^2}\right] \cong 1.385\frac{10^{10}}{\left(\lambda_u[m]K\right)^2}$$

$$\lambda_s = \frac{1-\beta}{1+\beta}\lambda^* = 2\frac{1-\beta}{1+\beta}\lambda_u \cong \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right),$$

$$K \propto B_0\lambda_u$$

FEL-BSC

- Transverse motion and Wave intensity

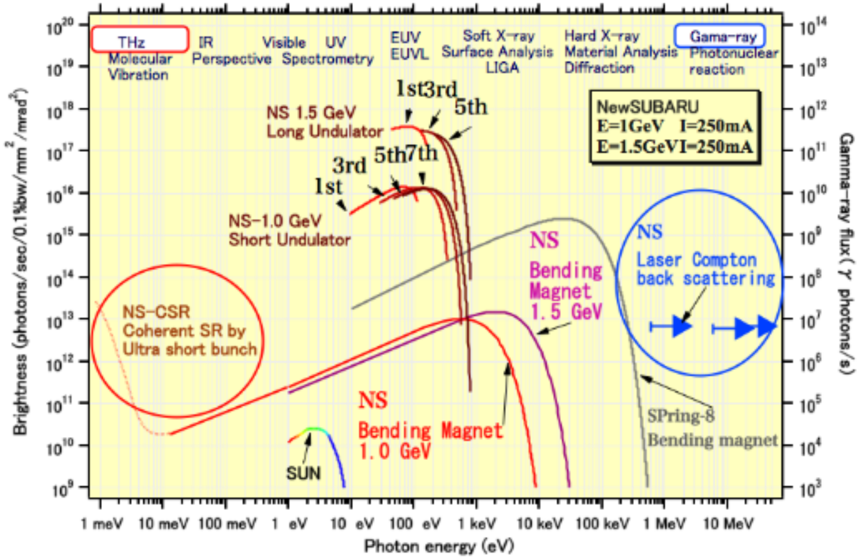
$$\lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \Rightarrow \frac{\lambda_u}{2\gamma^2}\left(1+bI\right)$$

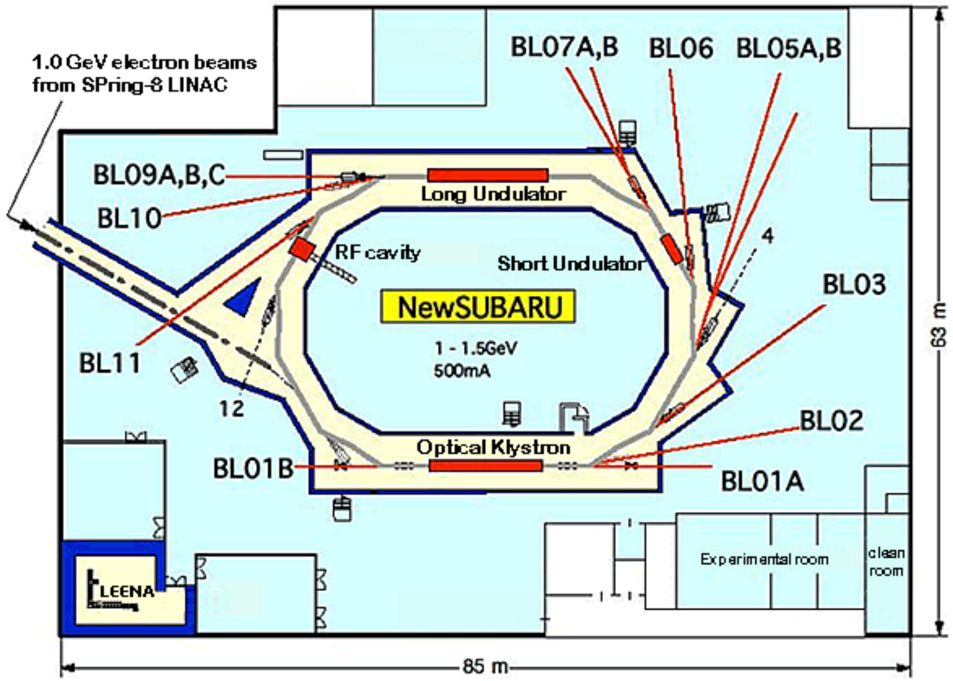
Mass Intensity Dependent corrections

Sngupta 1952, Brown and Kibble (1964)

An integrated way of conceiving light sources

- From THz to gamma rays (New Subaru)





The FEL largely relies on the BCS analogy
The Question therefore is: Why not replace the magnetic undulator with a wave field?

What are the problems ?
Enough Laser Intensity and Beam Qualities to Ensure The necessary Gain

THE FEL KEY PARAMETERS

$$\lambda \cong \frac{\lambda^*}{4\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$K \approx 0.85 \cdot 10^{-5} \lambda^*[m]\sqrt{\left(I\left[\frac{W}{m^2}\right]\right)}, K \cong 1 \Rightarrow \lambda^*[m] \cong 10^{-5},$$

$$I\left[\frac{W}{m^2}\right] \cong 10^{20}$$

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

$$f_b(\xi) = J_0(\xi) - J_1(\xi),\ \xi = \frac{1}{4}\frac{K^2}{1+\frac{K^2}{2}},$$

Link e-beam and laser parameters

$$J\left[\frac{A}{m^2}\right] I\left[\frac{W}{m^2}\right] f_b^2 \cong 2.35 \cdot 10^{16} \frac{(\gamma\, \rho)^3}{\lambda^*[m]^4}$$

The condition links the various parameters and can be exploited to evaluate the ranges of the laser wave intensity and beam current density necessary to achieve FEL operation. The operating conditions become more demanding with the decrease of the laser undulator wavelength due to the dependence on

$$\lambda^*[m]^{-4}$$

…

- Gain Length

$$L_g[m] \cong \frac{\lambda^*[m]}{8\pi\sqrt{3}\rho}$$

- full saturated power

$$P_F \cong \sqrt{2}\rho\, P_E$$

- Saturation length (about 10 Gain Length)

$$L_S[m] \cong \frac{\lambda^*[m]}{4\rho}$$

FEL SASE POWER EVOLUTION

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

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

$$P_F\left[MW\right] \cong \frac{1.2 \cdot \sqrt{2} \cdot 10^{16}}{f_b^2} \frac{(\gamma\,\rho)^4}{I\left[\frac{W}{m^2}\right] \lambda * \left[m\right]^4} \Sigma\left[m^2\right]$$

CO_2 laser

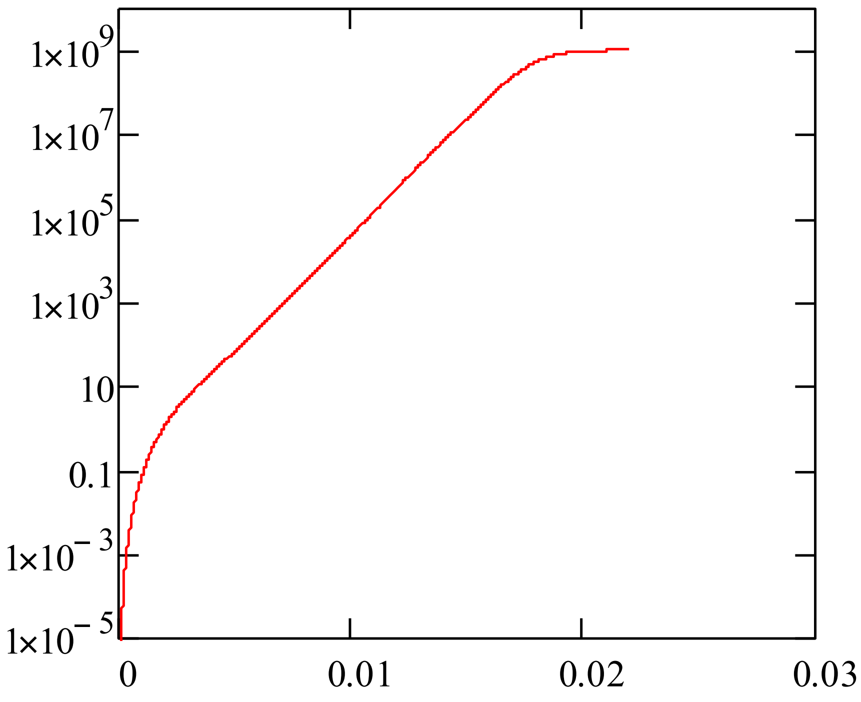
$$E \cong 25\,MeV$$

$$I\left[\frac{MW}{m^2}\right] \cong 8\cdot 10^{19} \Rightarrow K \cong 0.76 \Rightarrow \lambda \cong 1.34\,nm,$$

$$J\left[\frac{A}{m^2}\right] \cong 10^{11} \Rightarrow \rho \cong 3\cdot 10^{-4} \Rightarrow L_g \cong 7.7\,mm$$

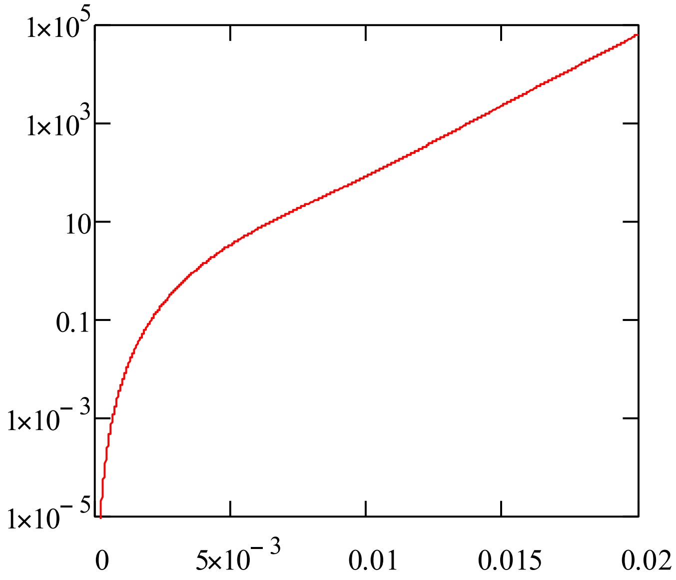
$$Z_R \cong 5\cdot 10^{-3}\,m \Rightarrow L_s \cong 1-2\,cm, E_L[J] \cong 260!!!$$

$$I[A] \cong 5\cdot 10^3$$



FEL Intensity growth vs. pulse length (in *m*), corresponding to power density of

$$I\left[\frac{W}{m^2}\right] \cong 10^{19} \Rightarrow 32J$$



Beam Quality Effects
Energy Spread

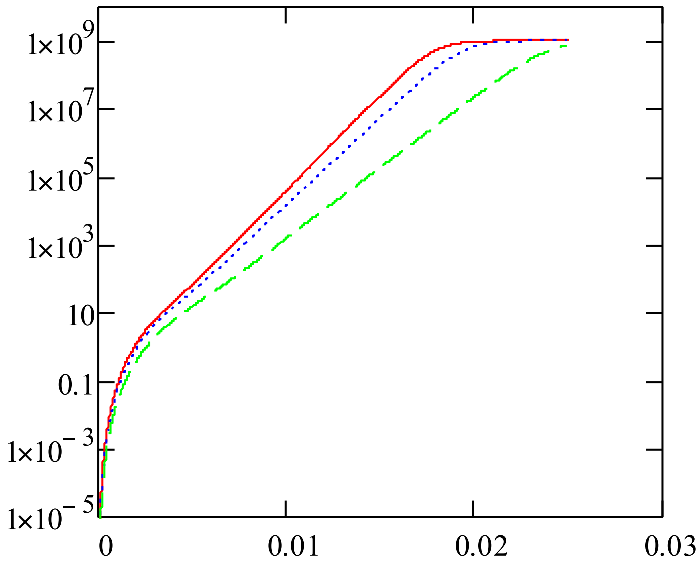
$\sigma_\varepsilon = 0,$ continous line

$\sigma_\varepsilon = 5 \cdot 10^{-5}$ dot line

$\sigma_\varepsilon = 10^{-4}$ dash line

$$\overline{L}_S \cong \left(1 + 0.185 \cdot \frac{\sqrt{3}}{2} \tilde{\mu}_\varepsilon^2\right) L_S,$$

$$\tilde{\mu}_\varepsilon = 2 \cdot \frac{\sigma_\varepsilon}{\rho}$$



Problems…

- The transverse shape of the laser wave should be as flat as possible to allow a proper matching with the e-beam and avoid problems of line broadening due to the intensity inhomogeneity
- further inhomogeneous broadening is associated with the relative bandwidth of the wave laser

$$\frac{\Delta\omega}{\omega} \leq \rho \Rightarrow \Delta\omega \cong 2\pi \frac{c}{L_S} \cong \frac{4\pi c \rho}{\lambda}$$

$$\Rightarrow \frac{\Delta\omega}{\omega} \cong 2\rho$$

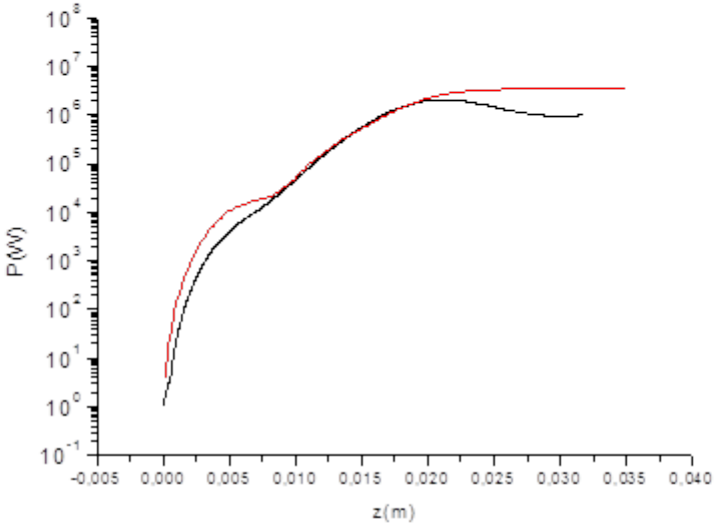
CO_2

$$I\left[\frac{W}{m^2}\right] \cong 1.34 \cdot 10^{19},\ J\left[\frac{A}{m^2}\right] \cong 5 \cdot 10^{11}$$

Electron beam	
Energy	60 MeV
Length (longitudinal) (rms)	1 mm
Transverse size (rms, micron)	25
Relative energy spread	10^{-4}
Emittance (micro-meter rad)	0.6
Gain Length	2.83 mm
Pierce parameter	2.81 10^{-4}
Laser pulse	
Wave Length (micronns)	10 mm
W_0	50 mm
K	0.3

Comparison with the numerical Analysis

- CO2 laser

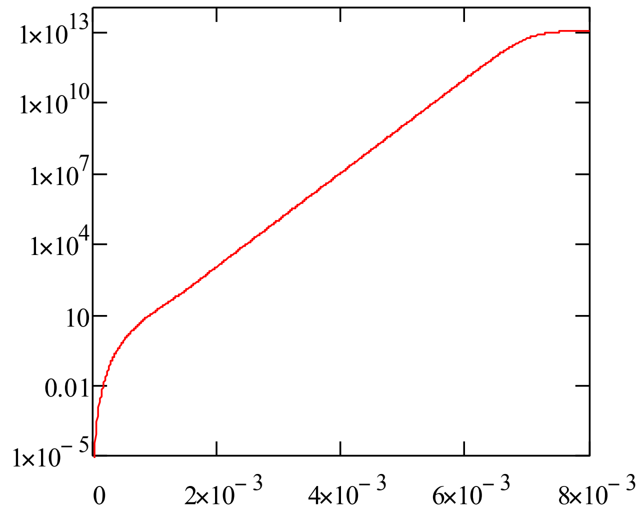


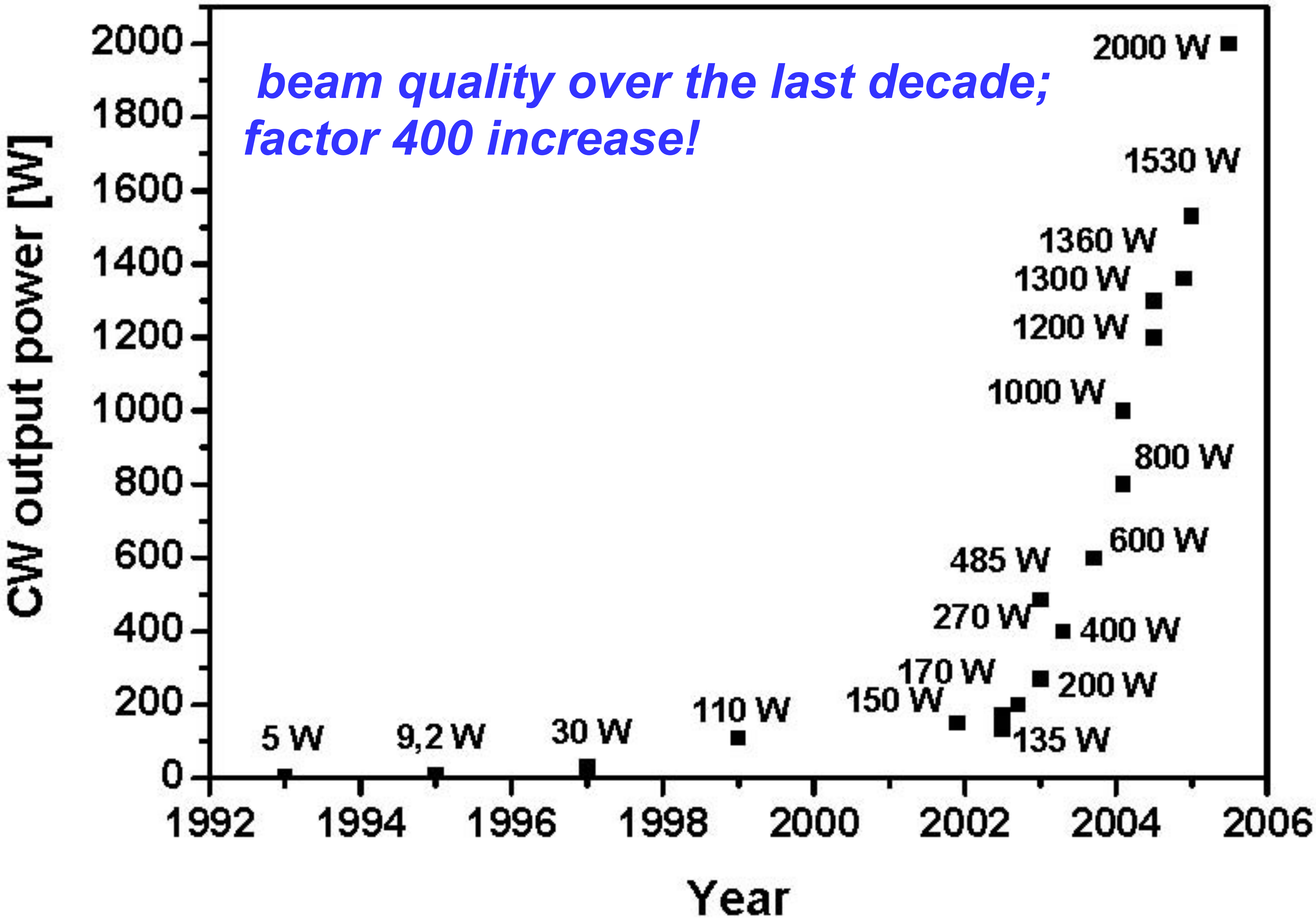
The State of the art: ATF experiment

M. N. Polyanskiy, I. V. Pogorelsky and V. Yakimenko
Optics Express 7717, Vol. 19, April 11 (2011)
V. Yakimenko, CO_2 Laser Based undulator for a compact SASE FEL
Talk delivered at "Laser and Plasma Accelerators Workshop 2011"
Brookhaven (New Jork) June 20-21 (2011)

Electron beam	
E[Mev]	**77.3**
I[A]	$1.5 \cdot 10^3$
$\frac{E}{E_X}$ $\rho,$ $E_X\left[keV\right] = \hbar\omega_s$	**8.6** **10**
Laser Energy [J]	**30**
Laser duration [ps]	**30**

Power density evolution vs. longitudinal coordinate For The ATF proposal





Source: Fiber Based High Power Laser Systems,
Jens Limpert, Thomas Schreiber, and Andreas Tünnermann

Conclusion

- Photoinjector
  - there are ideas (UCLA: X band bunching injector)
  - "twenty years after (1.6cell BNL/SLAC/UCLA gun)" team is needed
- CO_2 laser
  - technology is close
  - likely to be developed due to other applications
  - Self chirping in plasma and longitudinal shaping ar not demonstrated
- Diagnostics
  - Development and testing is crucial

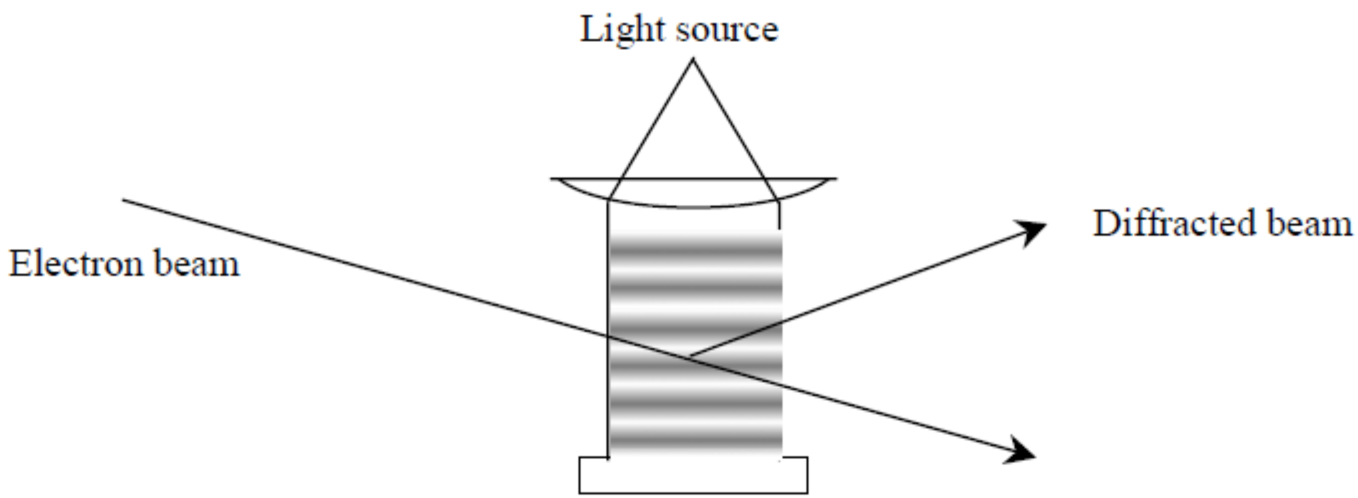
Compton X-ray sources

Lyncean Technologies (Ron Ruth & Co.), Palo Alto
HIGS, Duke University
BNL-ATF
KEK-ATF
BINP ROKK-1M facility
Spring-8
LLNL/UCLA (PLEIADES)
ALS, LBNL
NIRS Chiba/U. Tokyo/KEK – coronary arteriography
…

rapidly evolving field with huge synergy!

Kapitza Dirac Effect

- K-D



laser system based on realistic technology