All Optical FEL

A challenging, next generation radiation source: realistic feasibility considerations.

Andrea R. Rossi*
INFN - Milan

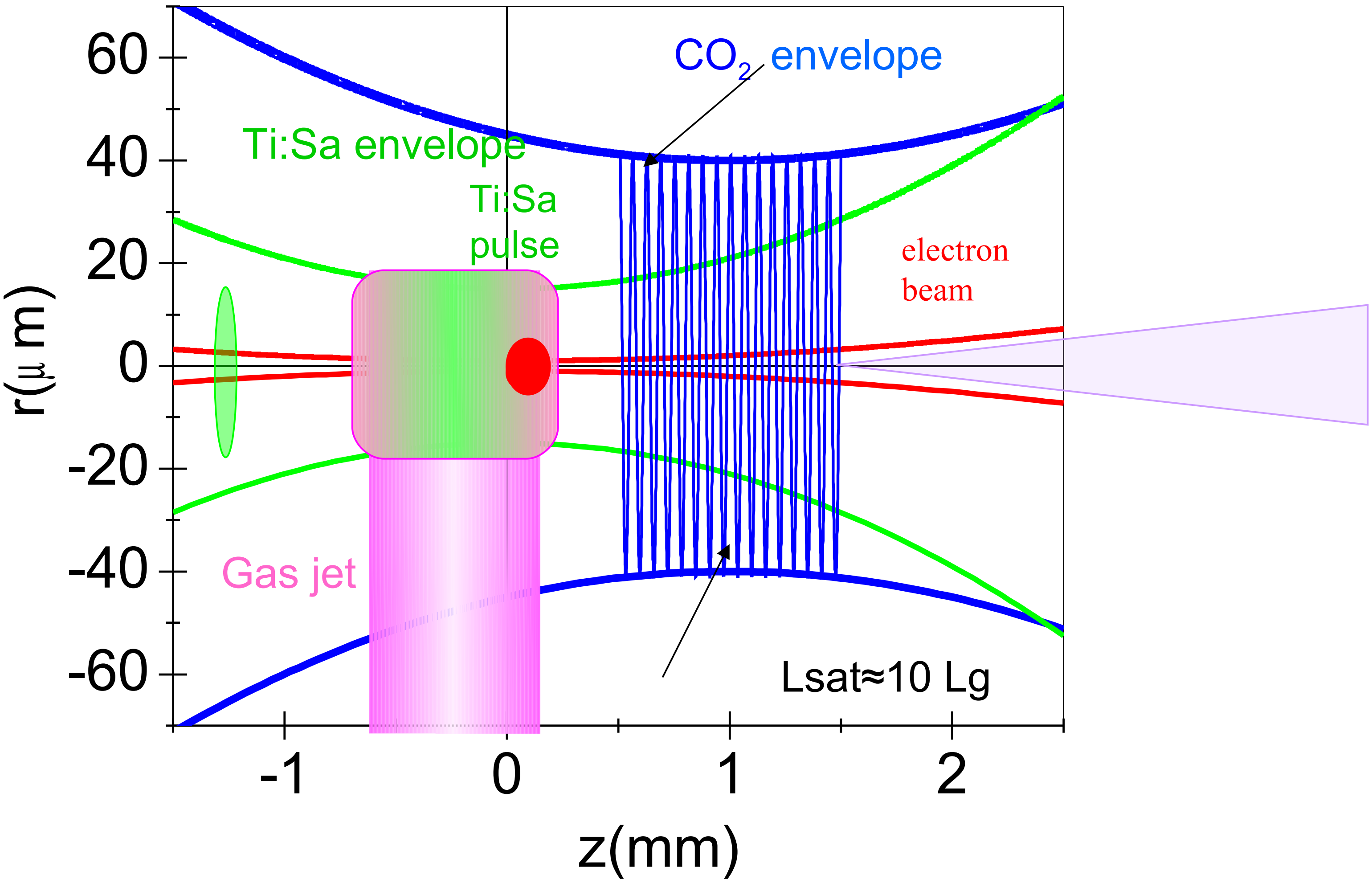
Istituto Nazionale
di Fisica Nucleare

* andrea.rossi@mi.infn.it

Sources for Plasma Accelerators and Radiation Compton with Lasers And Beams

All Optical FEL in a nutshell

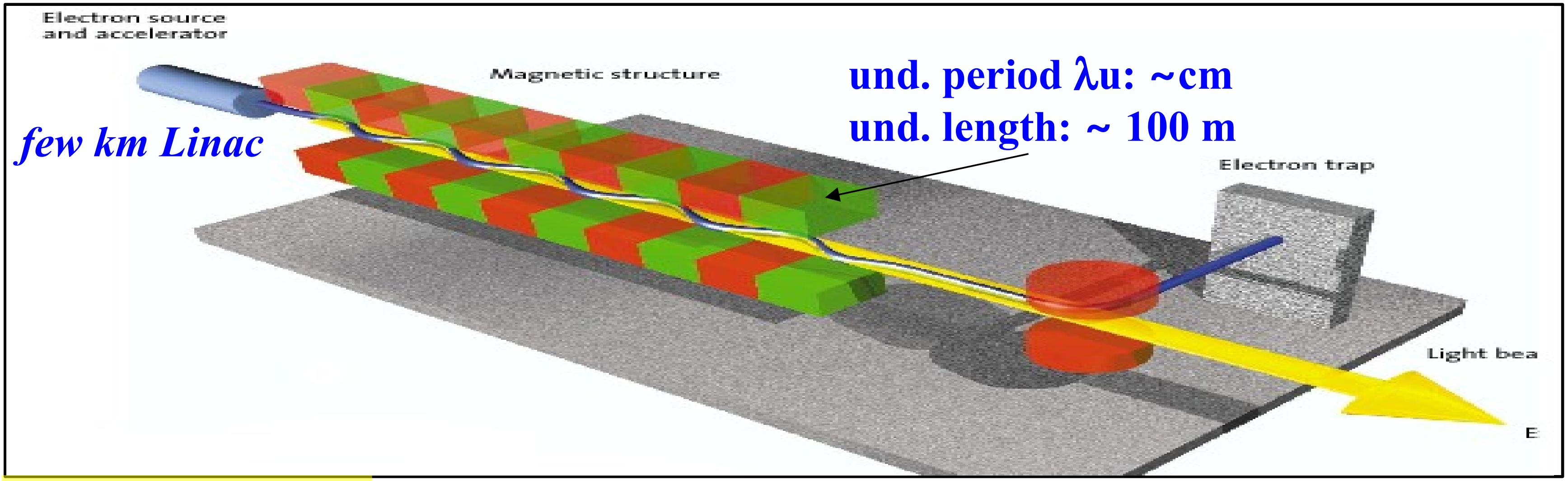
"Simply" collide a plasma generated beam with an electromagnetic undulator (laser):



From FEL to AOFEL

Scale down linac AND undulator sizes (and costs)!

10-25 GeV electrons, few kA beam current



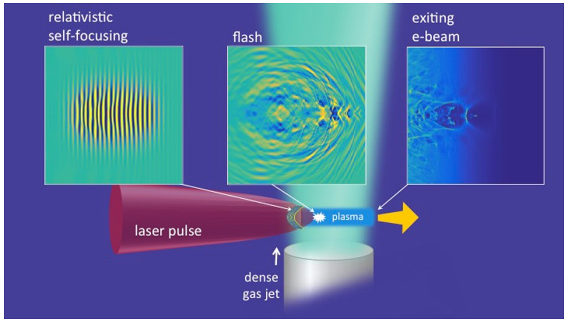
few km Linac

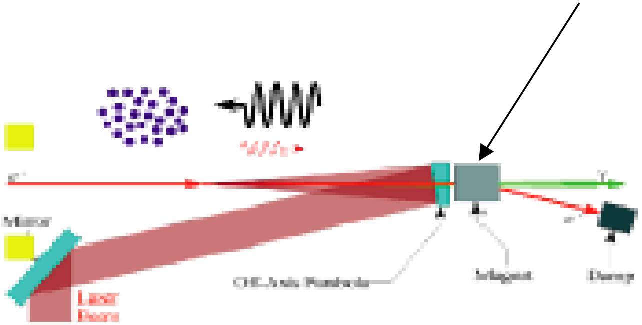
und. period λu: ~cm
und. length: ~ 100 m

100-0.5 Å photons
(0.5 Å~ 24 KeV)

laser λ: ~ 1- 10 μm
interaction area ~ few cm

30-150 MeV electrons, tens of kA beam current





~ few cm Linac

AOFEL: e.m. undulator

RESONANCE CONDITIONS:

Magnetostatic undulator

$$\lambda_R = \boxed{\lambda_u} \frac{\left(1 + a_w^2 / 2\right)}{2\gamma_0^2}$$

Example : for λ_R=.1nm, λ_υ=3cm and $a_w \approx 1$

$\Longrightarrow$ E $\simeq$ 7.5 GeV

AOFEL: e.m. undulator

RESONANCE CONDITIONS:

Magnetostatic undulator

$$\lambda_R = \boxed{\lambda_u}\,\frac{\left(1 + a_w^2/2\right)}{2\gamma_0^{\ 2}}$$

Example : for λ_R=.1nm, λ_υ=3cm and $a_w \approx 1$

$\Longrightarrow E \simeq 7.5$ GeV

Electromagnetic undulator

$$\lambda_R = \boxed{\lambda_u}\,\frac{\left(1 + a_0^2/2\right)}{4\gamma_0^{\ 2}}$$

Example : for λ_R=.1nm, λ_u=0.8μm and $a_0 \approx 0.3$*

$\Longrightarrow E = 22 \sim 23$ MeV

Example : for λ_R=.1nm, λ_u=10 μm and $a_0 \approx 0.3$*

$\Longrightarrow E = 82 \sim 83$ MeV

* for many practical reasons, $a_0 \lesssim 1$

AOFEL: electron bunch

FEL PIERCE PARAMETER:

RF linac

$$\rho = \frac{1}{2\gamma}\left[\frac{I_b}{I_A}\left(\frac{\lambda_u \kappa}{2\pi\sigma_x}\right)^2\right]^{\frac{1}{3}}$$

Example : for λ_R=.1nm, λ_υ=3cm and $a_w \approx 1$

$\gamma \approx 16000$, $\sigma \approx 50\ \mu m$, $I_b \approx 3\ kA$

$\Longrightarrow \rho \approx 3 \times 10^{-4} \Longrightarrow L_g \approx 4.6\ m$

$$L_g = \frac{\lambda_u}{4\sqrt{3}\pi\rho}$$

AOFEL: electron bunch

FEL PIERCE PARAMETER:

$$\rho = \frac{1}{2\gamma}\left[\frac{I_b}{I_A}\left(\frac{\lambda_u \kappa}{2\pi\sigma_x}\right)^2\right]^{\frac{1}{3}}$$

$$L_g = \frac{\lambda_u}{4\sqrt{3}\pi\rho}$$

RF linac

Example : for λ_R=.1nm, λ_υ=3cm and $a_w \approx 1$

$\gamma \approx 16000$, $\sigma \approx 50\ \mu m$, $I_b \approx 3\ kA$

$\Longrightarrow \rho \approx 3 \times 10^{-4} \Longrightarrow L_g \approx 4.6\ m$

Plasma acceleration (internal injection)

Example : for λ_R=.1nm, λ_u=0.8μm and $a_0 \approx 0.3$

$\gamma \approx 45$, $\sigma \approx 1\ \mu m$, $I_b \approx 30\ kA$

$\Longrightarrow \rho \approx 1.2 \times 10^{-3} \Longrightarrow L_g \approx 31\ \mu m$

Example : for λ_R=.1nm, λ_u=10 μm and $a_0 \approx 0.3$

$\gamma \approx 165$, $\sigma \approx 1 \mu m$, $I_b \approx 30\ kA$

$\Longrightarrow \rho \approx 1.8 \times 10^{-3} \Longrightarrow L_g \approx 270\ \mu m$

AOFEL: electron bunch

FEL PIERCE PARAMETER:

RF linac

$$\rho = \frac{1}{2\gamma}\left[\frac{I_b}{I_A}\left(\frac{\lambda_u \kappa}{2\pi\sigma_x}\right)^2\right]^{\frac{1}{3}}$$

Example : for $\lambda_R = .1 nm$, $\lambda_\upsilon = 3 cm$ and $a_w \approx 1$

$\gamma \approx 16000$, $\sigma \approx 50\ \mu m$, $I_b \approx 3\ kA$

$\Longrightarrow \rho \approx 3 \times 10^{-4} \Longrightarrow L_g \approx 4.6\ m$

Plasma acceleration (internal injection)

$$L_g = \frac{\lambda_u}{4\sqrt{3}\pi\rho}$$

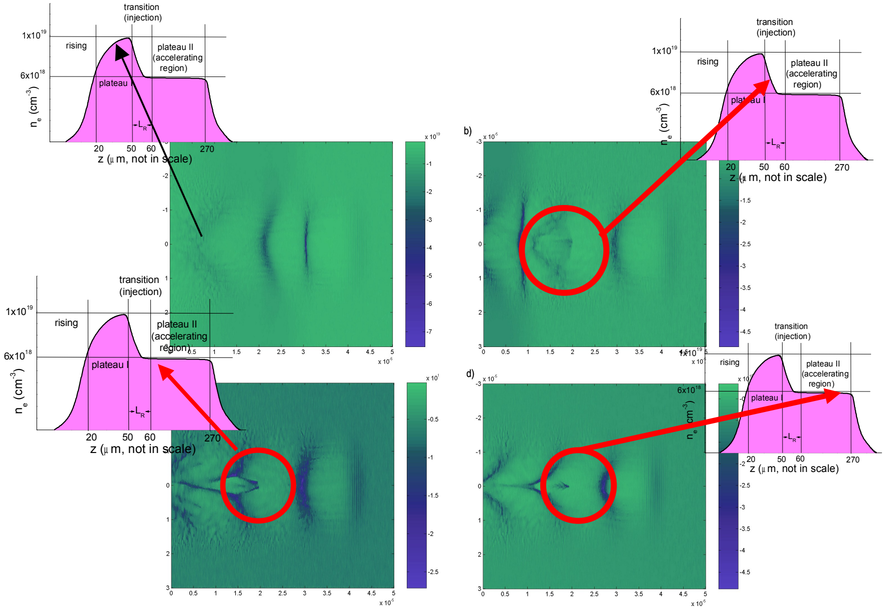
Example : for $\lambda_R = .1 nm$, $\lambda_u = 0.8 \mu m$ and $a_0 \approx 0.3$

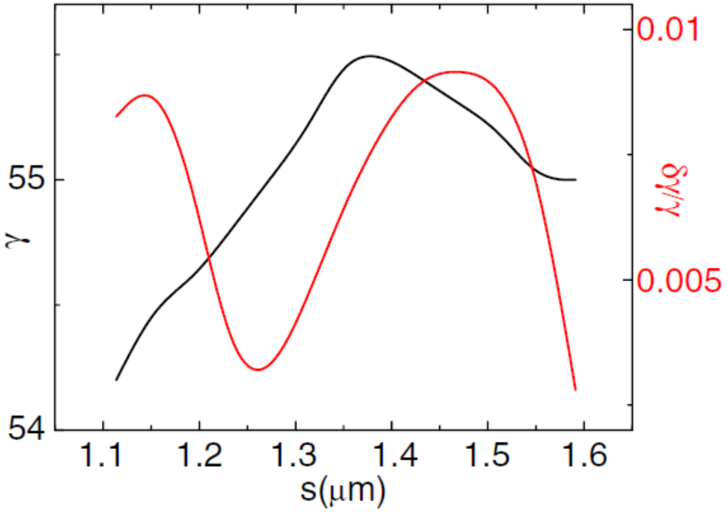
assuming $w_0 = 30 \Longrightarrow E_L < 6$ J, $P_L < 3$ TW @ sat

Example : for $\lambda_R = .1 nm$, $\lambda_u = 10\ \mu m$ and $a_0 \approx 0.3$

assuming $w_0 = 100 \Longrightarrow E_L < 3$ J, $P_L < 0.2$ TW @ sat

AOFEL: is it really feasible?



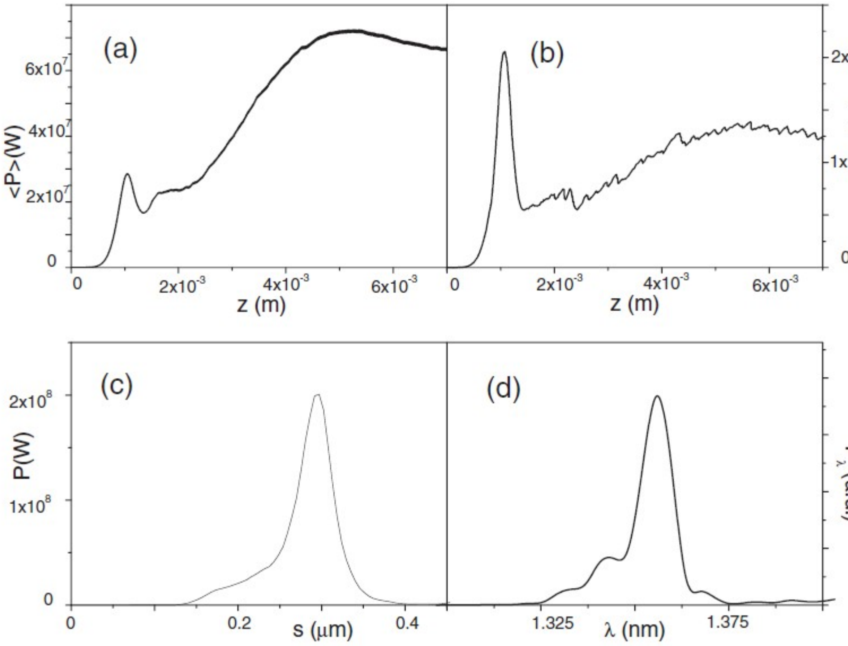


PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **11**, 070703 (2008)

Ultrahigh brightness electron beams by plasma-based injectors for driving all-optical free-electron lasers

V. Petrillo,[1,2] L. Serafini,[1] and P. Tomassini[1,3]

[1]*INFN-Milan, Via Celoria 16, 20133, Milano, Italy*
[2]*Università degli Studi di Milano, Dipartimento di Fisica, Via Celoria 16, 20133, Milano, Italy*
[3]*CNR-ILIL, Via G. Moruzzi, 1, 56124, Pisa, Italy*
(Received 27 March 2008; published 29 July 2008)

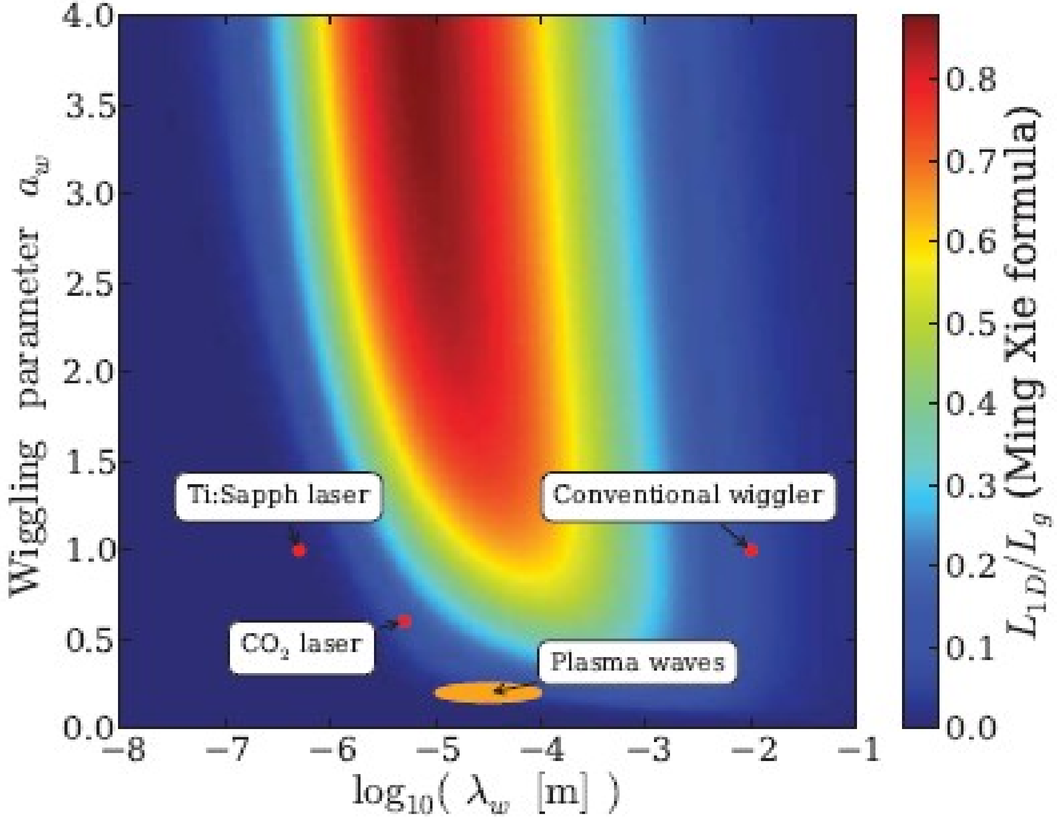


$\epsilon_n = 0.3\ \mu\text{m},\ \sigma_x = 0.5\ \mu\text{m}$

AOFEL: is it really feasible?

Table 1: Parameters of the Electron Bunch

γ	$\Delta\gamma$	$\epsilon_{n,\perp}$	I	σ_x
20	0.2	0.3 mm.mrad	10 kA	1 μm

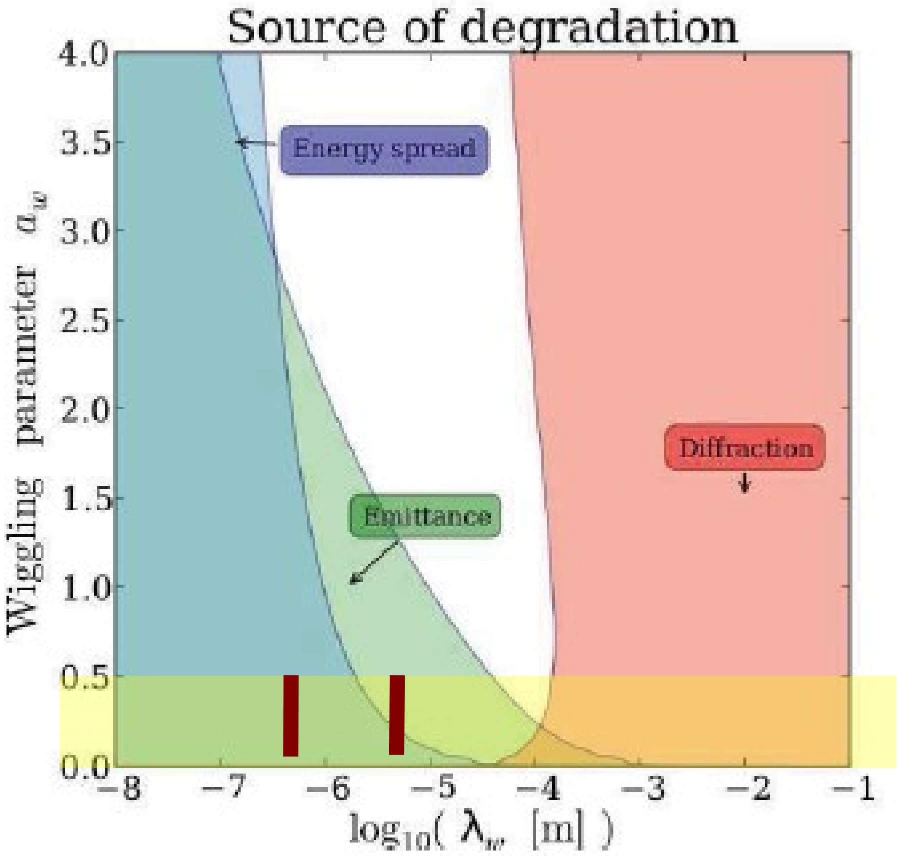


This study shows that the idea of such a laser-plasma wiggler seems realistic. This scheme requires a challenging bunch quality ($\Delta\gamma/\gamma = 0.01$ and $\epsilon_{n,\perp} = 0.3$ mm.mrad for electrons at 10 MeV), which has not yet been observed in experiments. However, in the light of some simulations [2, 6], such a bunch quality does not seem beyond reach.

THPD48 Proceedings of FEL2012, Nara, Japan

NUMERICAL STUDY OF AN FEL BASED ON LWFA ELECTRONS AND A LASER-PLASMA WIGGLER *

R. Lehe†, G. Lambert, A.F. Lifschitz, V. Malka, J.-M. Rax
LOA, Chemin de la Hunière, 91761 PALAISEAU, FRANCE
X. Davoine, CEA, DAM, DIF, 91297 ARPAJON, FRANCE



AOFEL: is it really feasible?

Lets add transverse dimension (Ming Xie, NIM A, 445, 59 (2000)):

$$L_{g3D} = (1+\eta)L_{g1D}$$

$$\eta = 0.45\eta_d^{0.57} + 0.55\eta_\epsilon^{1.6} + 3\eta_\gamma^2 + 0.35\eta_\epsilon^{2.9}\eta_\gamma^{2.4} + 51\eta_d^{0.95}\eta_\gamma^3 + 5.4\eta_d^{0.7}\eta_\epsilon^{1.9} + 1140\eta_d^{2.2}\eta_\epsilon^{2.9}\eta_\gamma^{3.2}$$

$$\eta_d = \frac{\lambda_R}{4\pi\sigma_x^2}L_{g1D}$$

$$\eta_\gamma = \frac{4\pi}{\lambda_L}\frac{\delta\gamma}{\gamma}L_{g1D}$$

$$\eta_\epsilon = \frac{4\pi}{\lambda_R}\frac{\epsilon_n^2}{\gamma^2\sigma_x^2}L_{g1D}$$

$$\eta_d, \eta_\gamma, \eta_\epsilon < 1$$

AOFEL: a closer look at diffraction issues

Radiation diffraction:

$$\eta_d = \frac{\lambda_R}{4\pi\sigma_x^2} L_{g1D} < 1 \Rightarrow \frac{\lambda_L^2}{(4\pi)^2\sqrt{3}\gamma^2\sigma_x^2} \approx \frac{\lambda_L^2}{270\gamma^2\sigma_x^2} < \rho$$

AOFEL: a closer look at diffraction issues

Radiation diffraction:

$$\eta_d = \frac{\lambda_R}{4\pi\sigma_x^2} L_{g1D} < 1 \Rightarrow \frac{\lambda_L^2}{(4\pi)^2\sqrt{3}\gamma^2\sigma_x^2} \approx \frac{\lambda_L^2}{270\gamma^2\sigma_x^2} < \rho$$

TiSa

$$\eta_d \approx 1.2 \times 10^{-6}$$

CO_2

$$\eta_d \approx 1.5 \times 10^{-5}$$

AOFEL: a closer look at diffraction issues

Radiation diffraction:

$$\eta_d = \frac{\lambda_R}{4\pi\sigma_x^2} L_{g1D} < 1 \Rightarrow \frac{\lambda_L^2}{(4\pi)^2\sqrt{3}\gamma^2\sigma_x^2} \approx \frac{\lambda_L^2}{270\gamma^2\sigma_x^2} < \rho$$

TiSa

$$\eta_d \approx 1.2 \times 10^{-6}$$

CO_2

$$\eta_d \approx 1.5 \times 10^{-5}$$

However this contribution is correctly evaluated if the beam dimension is roughly constant (i.e. there is a focusing channel). Otherwise the radiation diffracts as the electron beam, so this term would be included in the emittance term (later on).

AOFEL: a closer look at diffraction issues

Radiation diffraction: **?**

$$\eta_d = \frac{\lambda_R}{4\pi\sigma_x^2} L_{g1D} < 1 \Rightarrow \frac{\lambda_L^2}{(4\pi)^2\sqrt{3}\gamma^2\sigma_x^2} \approx \frac{\lambda_L^2}{270\gamma^2\sigma_x^2} < \rho$$

AOFEL: a closer look at energy spread issues

Radiation diffraction: **?**

Beam energy spread:

$$\eta_\gamma = \frac{4\pi}{\lambda_L}\frac{\delta\gamma}{\gamma}L_{g1D} < 1 \Rightarrow \frac{\delta\gamma}{\gamma} < \sqrt{3}\rho$$

Well known relation.

AOFEL: a closer look at energy spread issues

Radiation diffraction: **?**

Beam energy spread:

$$\eta_\gamma = \frac{4\pi}{\lambda_L}\frac{\delta\gamma}{\gamma}L_{g1D} < 1 \Rightarrow \frac{\delta\gamma}{\gamma} < \sqrt{3}\rho$$

Well known relation.

assuming

$$\frac{\delta\gamma}{\gamma} = 10^{-3}$$

TiSa

$$\eta_\gamma \approx 0.5$$

CO_2

$$\eta_\gamma \approx 0.3$$

AOFEL: a closer look at energy spread issues

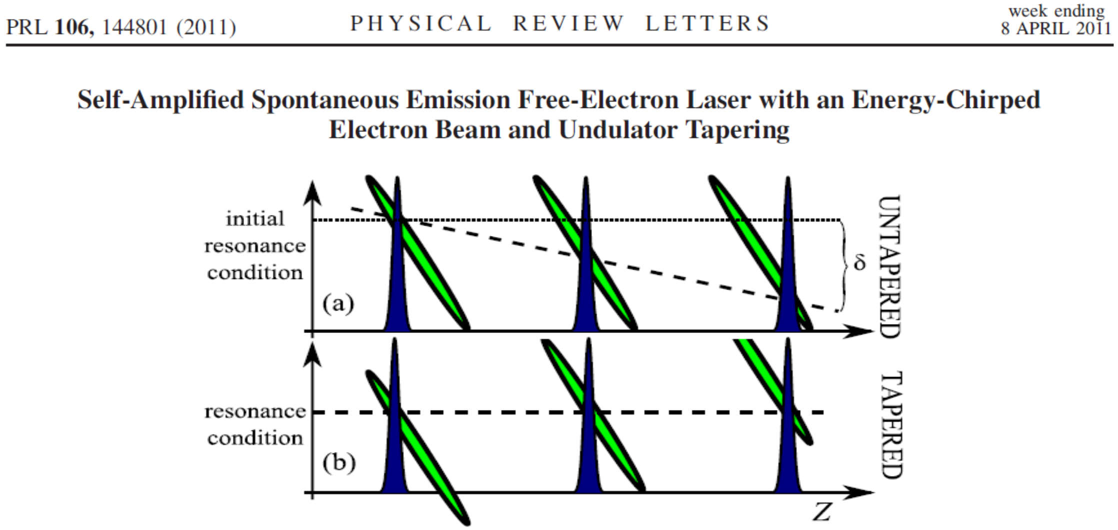
Radiation diffraction: **?**

Beam energy spread:

$$\eta_\gamma = \frac{4\pi}{\lambda_L}\frac{\delta\gamma}{\gamma}L_{g1D} < 1 \Rightarrow \frac{\delta\gamma}{\gamma} < \sqrt{3}\rho$$

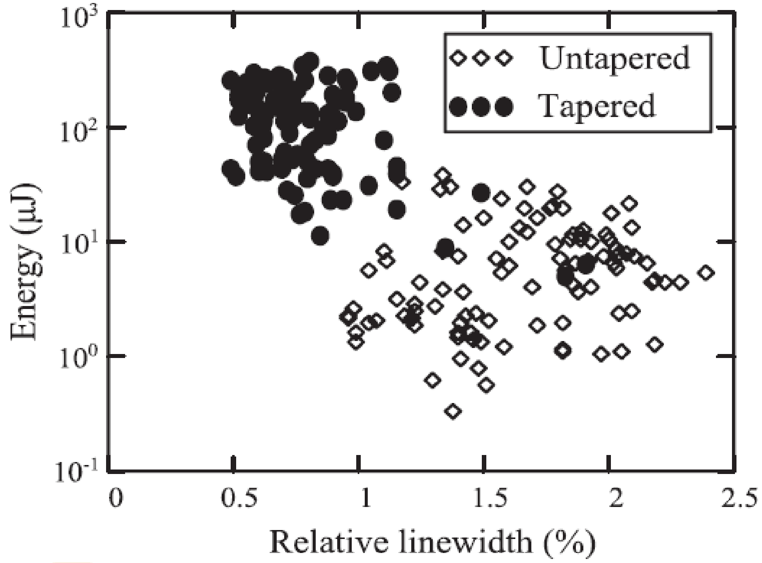
Well known relation.

Challenging for a whole plasma beams. However, it suffices to hold true for slices and simulations give similar results. Since bunches produced by bubble regime do possess a linear chirp, it is possible to **Chirp & Taper** by chirping the laser pulse



PRL **106,** 144801 (2011) PHYSICAL REVIEW LETTERS week ending 8 APRIL 2011

Self-Amplified Spontaneous Emission Free-Electron Laser with an Energy-Chirped Electron Beam and Undulator Tapering



AOFEL: a closer look at energy spread issues

Radiation diffraction: **?**

Beam energy spread:

$$\eta_\gamma = \frac{4\pi}{\lambda_L}\frac{\delta\gamma}{\gamma}L_{g1D} < 1 \Rightarrow \frac{\delta\gamma}{\gamma} < \sqrt{3}\rho$$

Well known relation.
Moreover, producing hard X-rays (1 - 12 KeV) with relatively low energy electrons (few tens of MeV) means

$$\frac{h\nu_R}{m\gamma c^2} \approx 10^{-3} - 10^{-4}$$

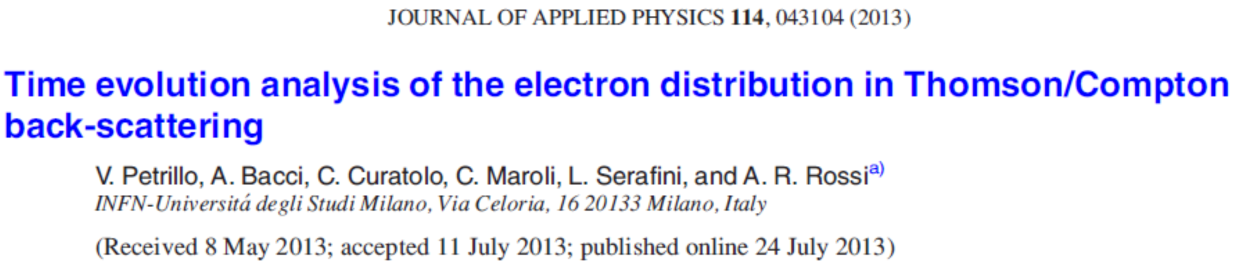
AOFEL: a closer look at energy spread issues

Radiation diffraction: **?**

Beam energy spread:

$$\eta_\gamma = \frac{4\pi}{\lambda_L}\frac{\delta\gamma}{\gamma}L_{g1D} < 1 \Rightarrow \frac{\delta\gamma}{\gamma} < \sqrt{3}\rho$$

So electrons may go out of resonance very soon....

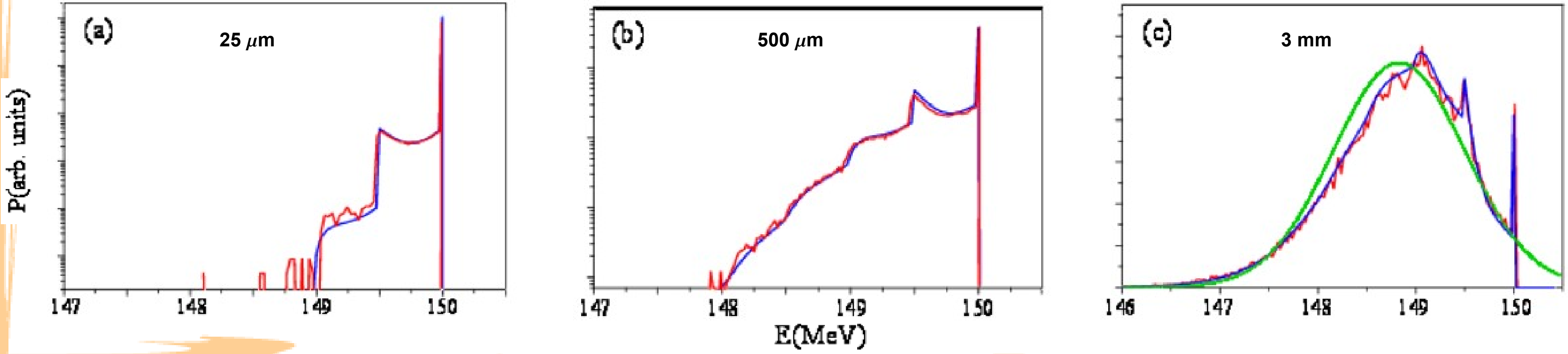


JOURNAL OF APPLIED PHYSICS **114**, 043104 (2013)

Time evolution analysis of the electron distribution in Thomson/Compton back-scattering

V. Petrillo, A. Bacci, C. Curatolo, C. Maroli, L. Serafini, and A. R. Rossi[a)]
INFN-Universitá degli Studi Milano, Via Celoria, 16 20133 Milano, Italy

(Received 8 May 2013; accepted 11 July 2013; published online 24 July 2013)



AOFEL: a closer look at energy spread issues

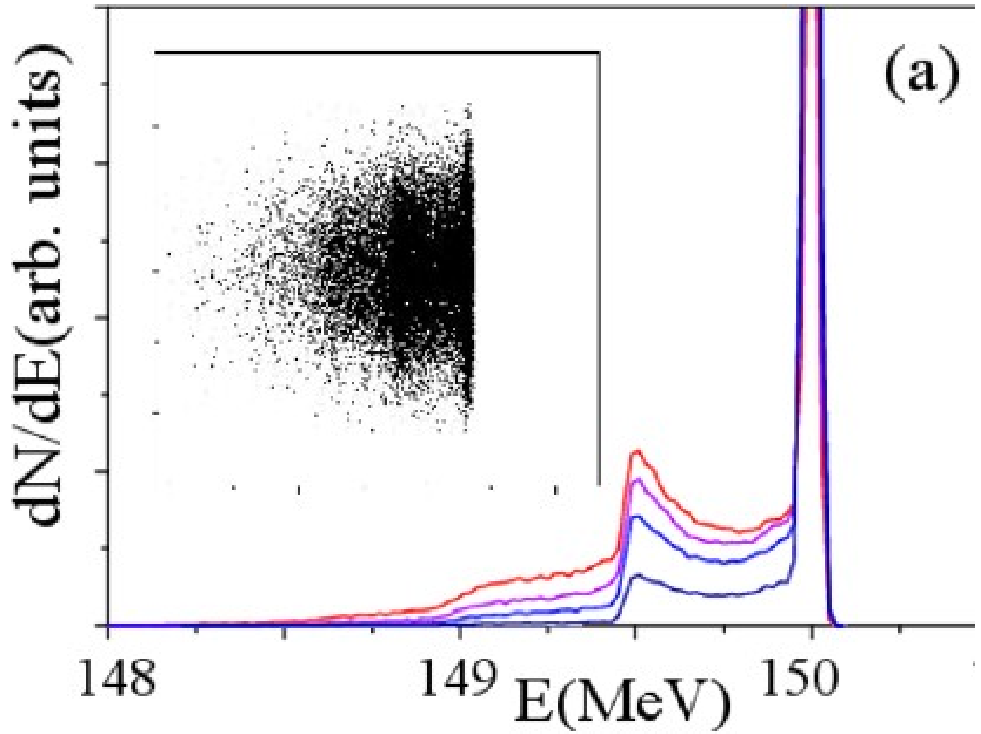
Radiation diffraction: **?**

Beam energy spread:

$$\eta_\gamma = \frac{4\pi}{\lambda_L}\frac{\delta\gamma}{\gamma}L_{g1D} < 1 \Rightarrow \frac{\delta\gamma}{\gamma} < \sqrt{3}\rho$$

So electrons may go out of resonance very soon....

$\Delta E/E = 10^{-4}$



AOFEL: a closer look at energy spread issues

Radiation diffraction: **?**

Beam energy spread: **OK?**

AOFEL: a closer look at emittance issues

Radiation diffraction: **?**

Beam energy spread: **OK?**

Beam emittance:

$$\eta_\epsilon = \frac{4\pi}{\lambda_R}\frac{\epsilon_n^2}{\gamma^2\sigma_x^2}L_{g1D} < 1 \Rightarrow \frac{4}{\sqrt{3}}\frac{\epsilon_n^2}{\sigma_x^2} = \frac{4}{\sqrt{3}}\sigma_{px}^2 < \rho$$

AOFEL: a closer look at emittance issues

Radiation diffraction: **?**

Beam energy spread: **OK?**

Beam emittance:

$$\eta_\epsilon = \frac{4\pi}{\lambda_R}\frac{\epsilon_n^2}{\gamma^2\sigma_x^2}L_{g1D} < 1 \Rightarrow \frac{4}{\sqrt{3}}\frac{\epsilon_n^2}{\sigma_x^2} = \frac{4}{\sqrt{3}}\sigma_{px}^2 < \rho$$

$$\sigma_x = \sqrt{\frac{2}{\gamma}\frac{\epsilon_n}{k_p}}$$

@ source

AOFEL: a closer look at emittance issues

Radiation diffraction: **?**

Beam energy spread: **OK?**

Beam emittance:

$$\eta_\epsilon = \frac{4\pi}{\lambda_R}\frac{\epsilon_n^2}{\gamma^2\sigma_x^2}L_{g1D} < 1 \Rightarrow \frac{4}{\sqrt{3}}\frac{\epsilon_n^2}{\sigma_x^2} = \frac{4}{\sqrt{3}}\sigma_{px}^2 < \rho$$

After some manipulations:

$$\epsilon_n \lesssim \frac{1}{4}\left(\frac{I_b}{I_A}\right)^{1/4}\sqrt{\frac{a_0\lambda_R}{k_p}}$$

$a_0 < 1$

or...

$$\epsilon_n[\mathrm{nm}] \lesssim \frac{3.7}{(n_0[\times 10^{18}\mathrm{cm}^{-3}])^{1/4}}$$

AOFEL: a closer look at emittance issues

Radiation diffraction: **?**

Beam energy spread: **OK?**

Beam emittance:

$$\eta_\epsilon = \frac{4\pi}{\lambda_R}\frac{\epsilon_n^2}{\gamma^2\sigma_x^2}L_{g1D} < 1 \Rightarrow \frac{4}{\sqrt{3}}\frac{\epsilon_n^2}{\sigma_x^2} = \frac{4}{\sqrt{3}}\sigma_{px}^2 < \rho$$

After some manipulations:

$$\epsilon_n \lesssim \frac{1}{4}\left(\frac{I_b}{I_A}\right)^{1/4}\sqrt{\frac{a_0\boxed{\lambda_R}}{k_p}}$$

$a_0 < 1$

or...

$$\epsilon_n[\text{nm}] \lesssim \frac{3.7}{(n_0[\times 10^{18}\text{cm}^{-3}])^{1/4}}$$

....

AOFEL: a closer look at emittance issues

Radiation diffraction: **?**

Beam energy spread: **OK?**

Beam emittance: **Extremely challenging!**

AOFEL: a closer look at emittance issues

Radiation diffraction: **?**

Beam energy spread: **OK?**

Beam emittance: **Extremely challenging!**

HARDLY verified for plasma beams **@ source!**

This is our core business and THE problem to solve for driving AOFEL!

There comes the need to **adiabatically** (i.e. at constant emittance) **defocus the beam while keeping energy spread as low as possible.** This works because

$$\eta_\epsilon < 1 \Rightarrow \epsilon_n < \frac{3^{1/4}}{2}\sqrt{\rho}\sigma_x \propto \sigma_x^{2/3}$$

AOFEL: a closer look at emittance issues

Radiation diffraction: **?**

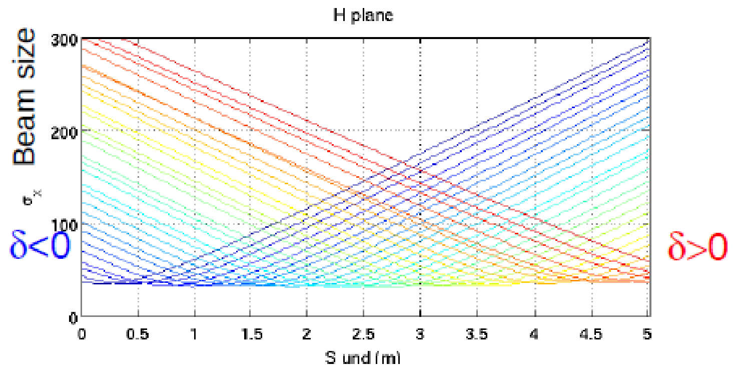
Beam energy spread: **OK?**

Beam emittance: **Extremely challenging!**

HARDLY verified for plasma beams **@ source!**

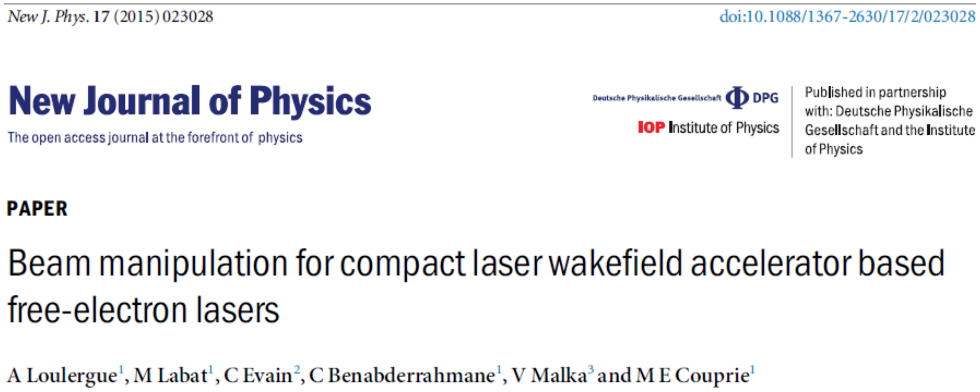
This is our core business and THE problem to solve for driving AOFEL!

Also, this would allow for an easier beam manipulation with conventional beam optics. In turn, we could employ advanced beam techniques like **supermatching** if need be.



<= undulator =>

Courtesy A. Loulergue



New J. Phys. 17 (2015) 023028 doi:10.1088/1367-2630/17/2/023028

New Journal of Physics

The open access journal at the forefront of physics

Deutsche Physikalische Gesellschaft DPG

IOP Institute of Physics

Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

PAPER

Beam manipulation for compact laser wakefield accelerator based free-electron lasers

A Loulergue[1], M Labat[1], C Evain[2], C Benabderrahmane[1], V Malka[3] and M E Couprie[1]

AOFEL: a closer look at emittance issues

Radiation diffraction: **?**

Beam energy spread: **OK?**

Beam emittance: **Extremely challenging!**

HARDLY verified for plasma beams **@ source!**

For example, if we can magnify the beam 50x we get, for both situations considered

$$\boxed{\epsilon_n \lesssim 0.3\mu\mathrm{m}}$$

still challenging, but possible at least “slice”!

AOFEL: a closer look at emittance issues

Radiation diffraction: **Extremely challenging!**

Beam energy spread: **Extremely challenging!**

Beam emittance: **Extremely challenging!**

What do we pay for defocusing? A decrease in $\rho \approx \sigma_x^{-2/3}$!

This requires the energy spread to be lower by one order of magnitude...

$$\boxed{\epsilon_n \lesssim 0.3\mu\mathrm{m}}$$

$$\boxed{\frac{\delta\gamma}{\gamma} \lesssim 10^{-4}}$$

challenging, but maybe possible at least “slice”!

Adiabatic defocusing: state of the art

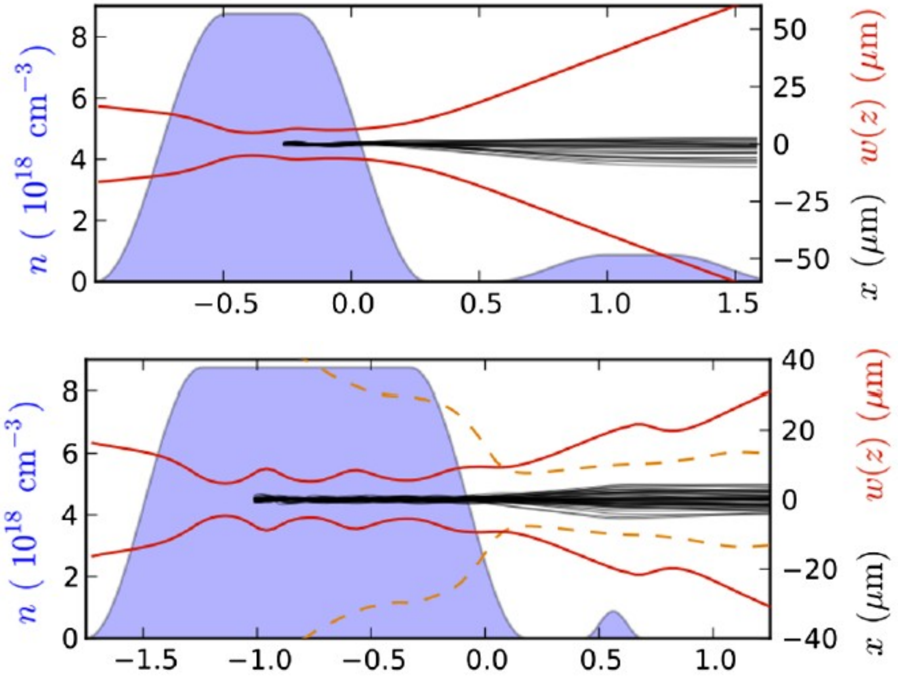
Stand alone, **active** or **passive** plasma lenses...

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 17, 121301 (2014)

Laser-plasma lens for laser-wakefield accelerators

R. Lehe,* C. Thaury,† E. Guillaume, A. Lifschitz, and V. Malka
Laboratoire d'Optique Appliquée, ENSTA-CNRS UMR7639-École Polytechnique, Chemin de la Hunière, 91761 Palaiseau, France

(Received 26 June 2014; published 12 December 2014)

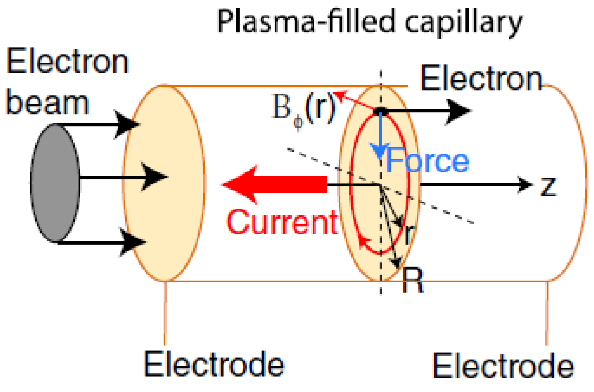


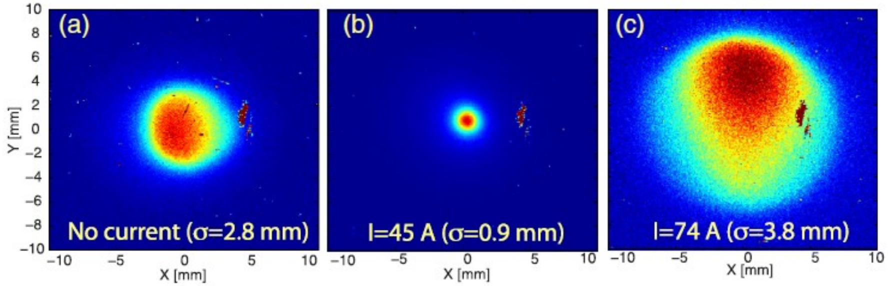
PRL 115, 184802 (2015) PHYSICAL REVIEW LETTERS week ending 30 OCTOBER 2015

Active Plasma Lensing for Relativistic Laser-Plasma-Accelerated Electron Beams

J. van Tilborg,[1] S. Steinke,[1] C. G. R. Geddes,[1] N. H. Matlis,[1] B. H. Shaw,[1,2] A. J. Gonsalves,[1] J. V. Huijts,[1] K. Nakamura,[1] J. Daniels,[1] C. B. Schroeder,[1] C. Benedetti,[1] E. Esarey,[1] S. S. Bulanov,[1] N. A. Bobrova,[3] P. V. Sasorov,[4] and W. P. Leemans[1,2]
[1]*Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720, USA*
[2]*Department of Physics, University of California, Berkeley, California 94720, USA*
[3]*Institute of Theoretical and Experimental Physics, Moscow 117218, Russia*
[4]*Keldysh Institute of Applied Mathematics, Moscow 125047, Russia*

(Received 8 June 2015; published 28 October 2015)

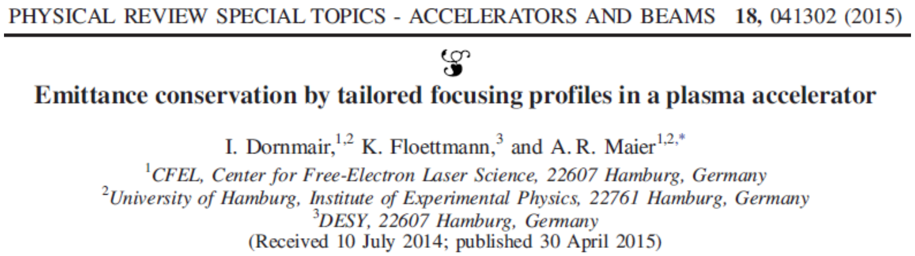




Experimental data!

Adiabatic defocusing: state of the art

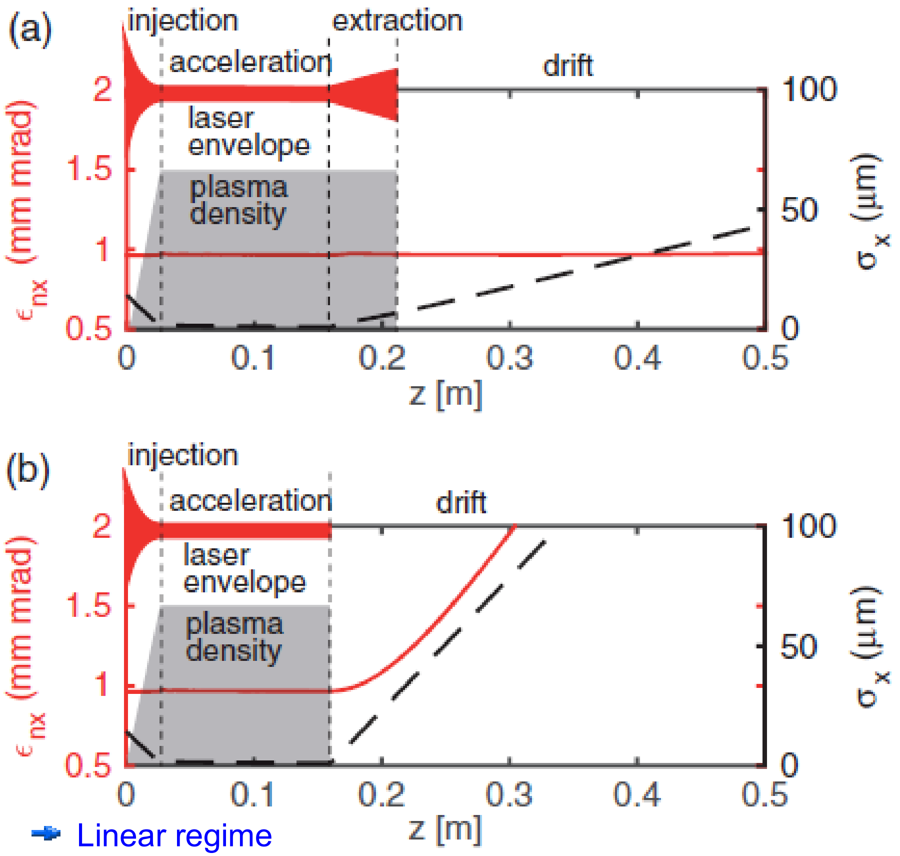
Integrated, **passive** plasma lenses...



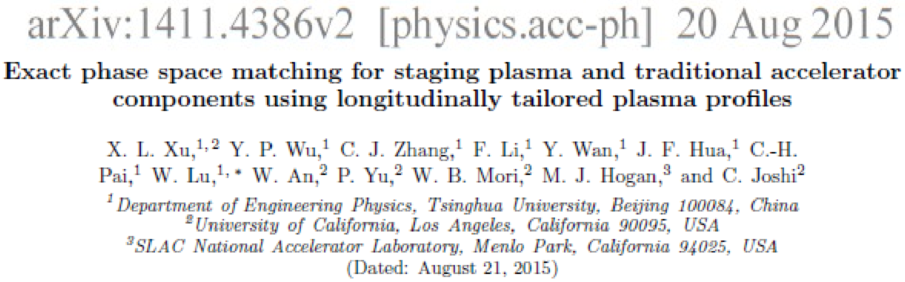
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **18,** 041302 (2015)

Emittance conservation by tailored focusing profiles in a plasma accelerator

I. Dornmair,[1,2] K. Floettmann,[3] and A. R. Maier[1,2,*]
[1]*CFEL, Center for Free-Electron Laser Science, 22607 Hamburg, Germany*
[2]*University of Hamburg, Institute of Experimental Physics, 22761 Hamburg, Germany*
[3]*DESY, 22607 Hamburg, Germany*
(Received 10 July 2014; published 30 April 2015)



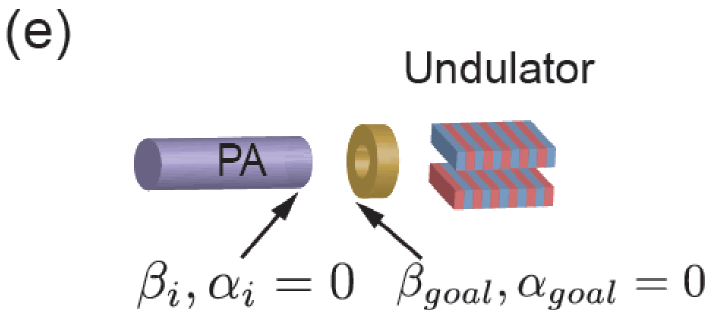
- Linear regime
- Negligible beam loading

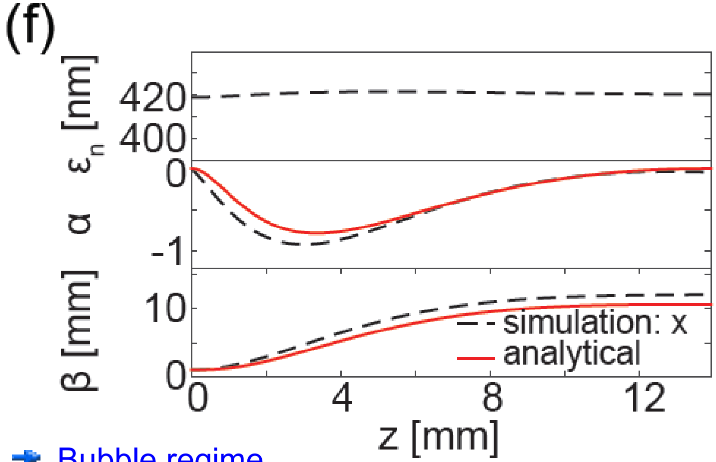


arXiv:1411.4386v2 [physics.acc-ph] 20 Aug 2015

Exact phase space matching for staging plasma and traditional accelerator components using longitudinally tailored plasma profiles

X. L. Xu,[1,2] Y. P. Wu,[1] C. J. Zhang,[1] F. Li,[1] Y. Wan,[1] J. F. Hua,[1] C.-H. Pai,[1] W. Lu,[1,*] W. An,[2] P. Yu,[2] W. B. Mori,[2] M. J. Hogan,[3] and C. Joshi[2]
[1]*Department of Engineering Physics, Tsinghua University, Beijing 100084, China*
[2]*University of California, Los Angeles, California 90095, USA*
[3]*SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
(Dated: August 21, 2015)

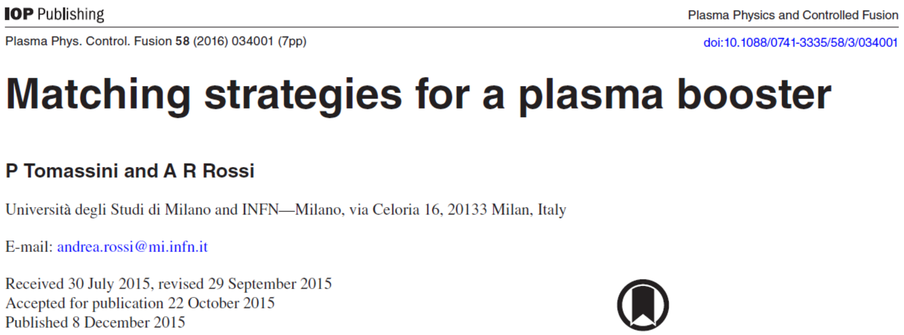




- Bubble regime
- Small beam loading

Adiabatic defocusing: state of the art

Integrated, **passive** plasma lenses...



IOP Publishing Plasma Physics and Controlled Fusion
Plasma Phys. Control. Fusion **58** (2016) 034001 (7pp) doi:10.1088/0741-3335/58/3/034001

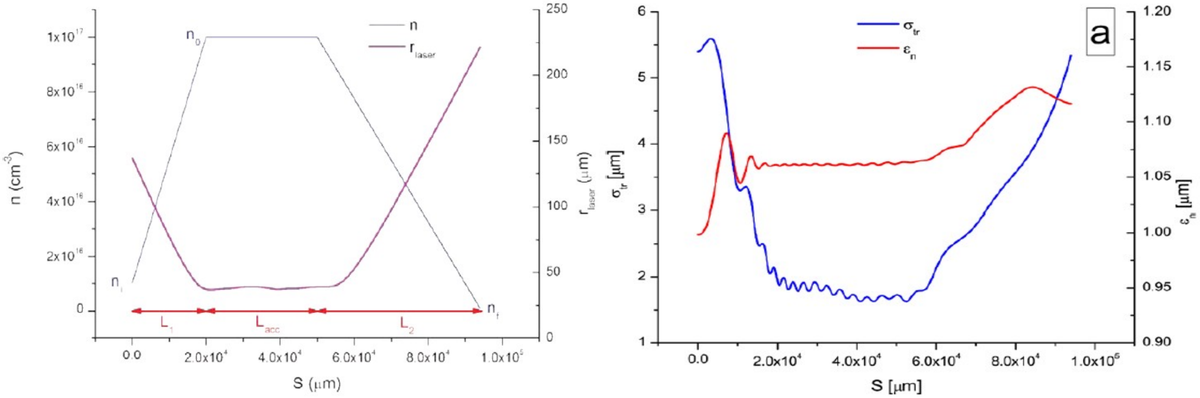
Matching strategies for a plasma booster

P Tomassini and A R Rossi

Università degli Studi di Milano and INFN—Milano, via Celoria 16, 20133 Milan, Italy

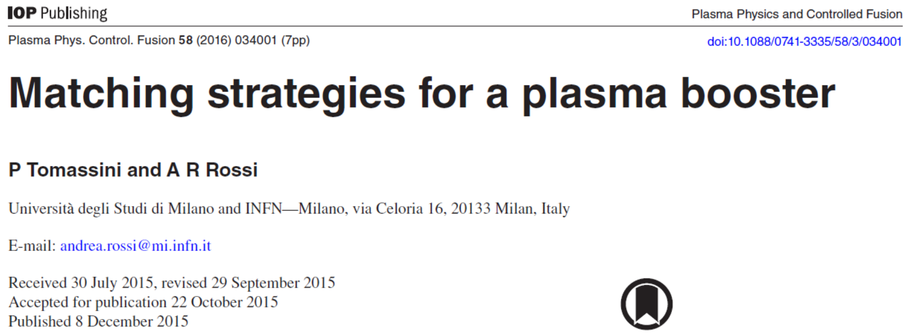
E-mail: andrea.rossi@mi.infn.it

Received 30 July 2015, revised 29 September 2015
Accepted for publication 22 October 2015
Published 8 December 2015



Adiabatic defocusing: state of the art

Integrated, **passive** plasma lenses...



IOP Publishing Plasma Physics and Controlled Fusion

Plasma Phys. Control. Fusion **58** (2016) 034001 (7pp) doi:10.1088/0741-3335/58/3/034001

Matching strategies for a plasma booster

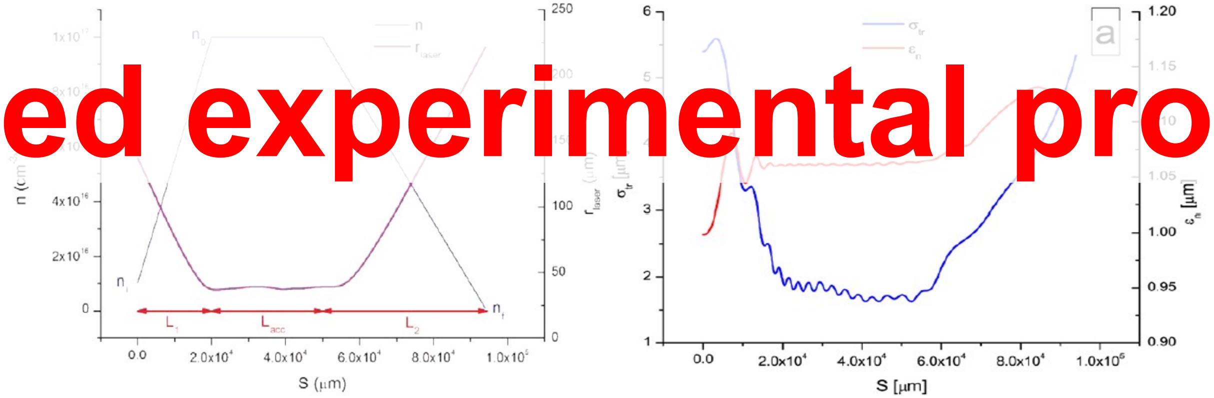
P Tomassini and A R Rossi

Università degli Studi di Milano and INFN—Milano, via Celoria 16, 20133 Milan, Italy

E-mail: andrea.rossi@mi.infn.it

Received 30 July 2015, revised 29 September 2015
Accepted for publication 22 October 2015
Published 8 December 2015

Need experimental proof!



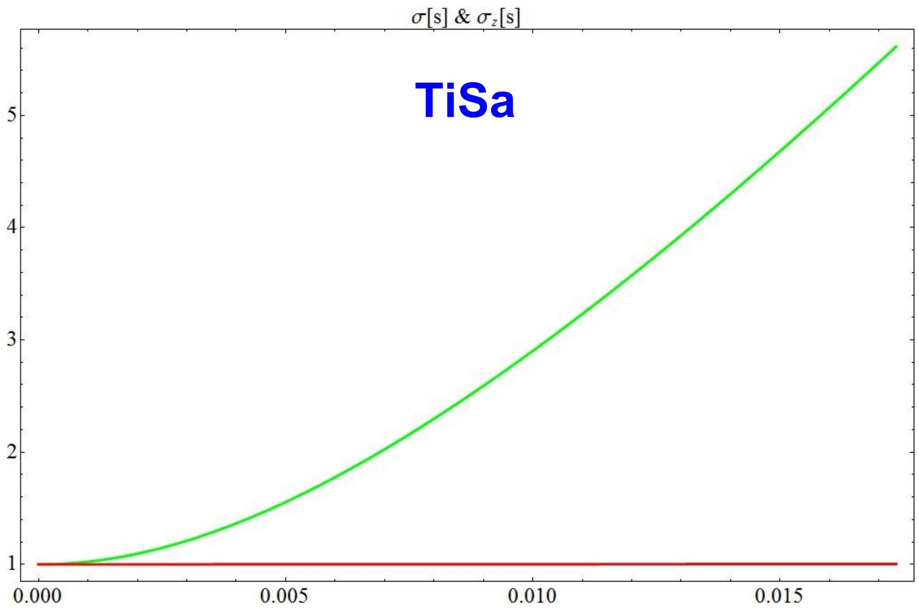
AOFEL: beam dynamics

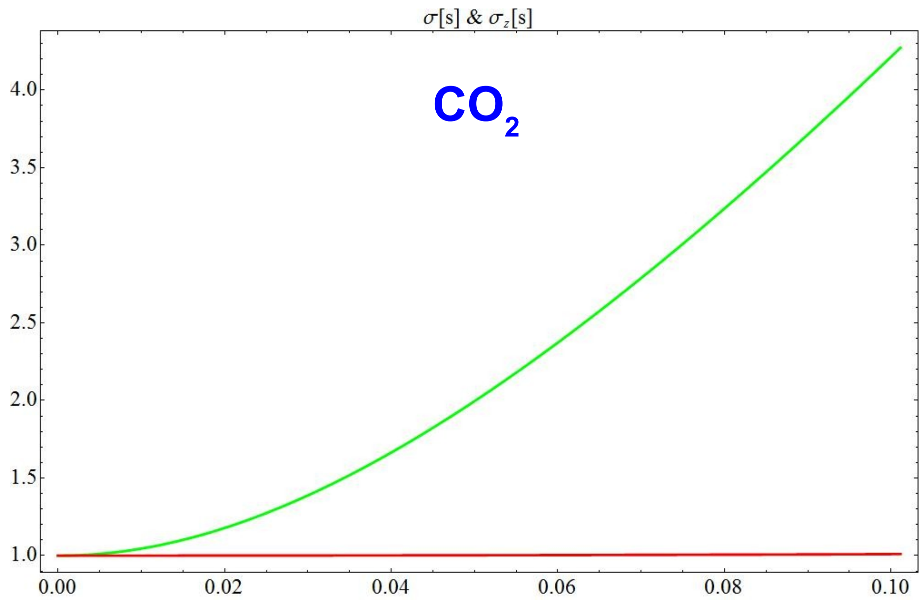
With the given beam parameters we have

$$\rho^{(\mathrm{TiSa})} = 1.0 \times 10^{-4} \quad L_g^{(\mathrm{TiSa})} = 0.8\mathrm{mm}$$

$$\rho^{(\mathrm{CO_2})} = 1.6 \times 10^{-4} \quad L_g^{(\mathrm{CO_2})} = 5.1\mathrm{mm}$$

Beam diffraction (by solving coupled envelope equations): σ_x green, σ_z red





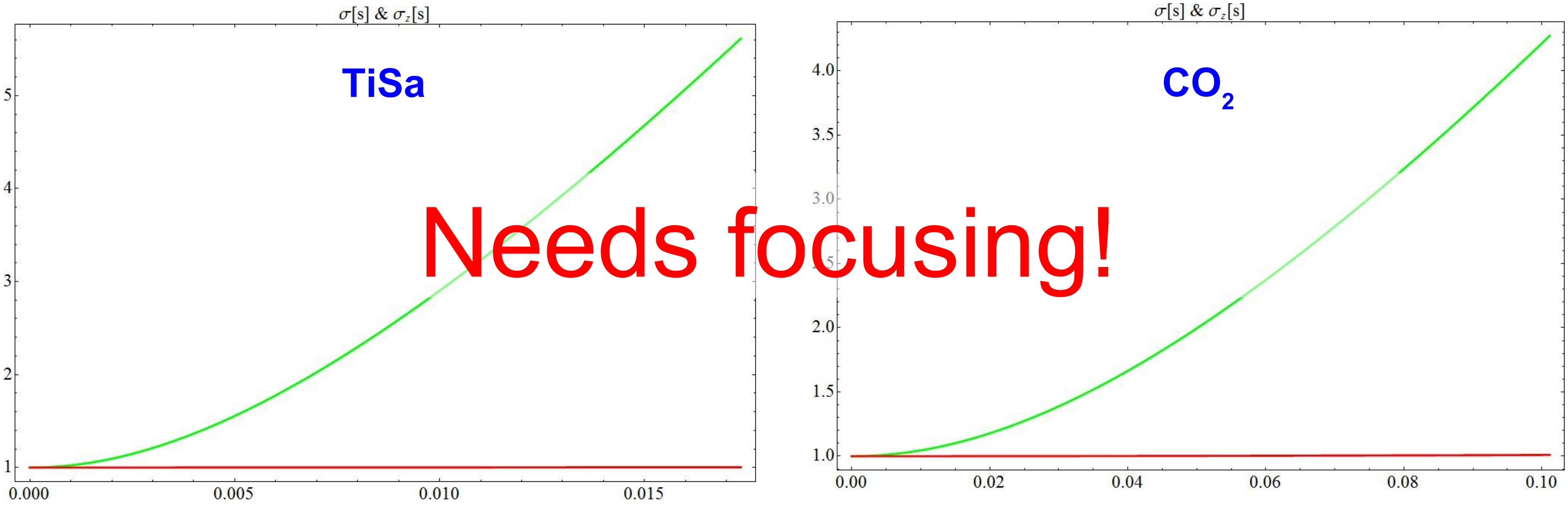
AOFEL: beam dynamics

With the given beam parameters we have

$$\rho^{(\mathrm{TiSa})} = 1.0 \times 10^{-4} \quad L_g^{(\mathrm{TiSa})} = 0.8\mathrm{mm}$$

$$\rho^{(\mathrm{CO_2})} = 1.6 \times 10^{-4} \quad L_g^{(\mathrm{CO_2})} = 5.1\mathrm{mm}$$

Beam diffraction (by solving coupled envelope equations): σ_x green, σ_z red



Needs focusing!

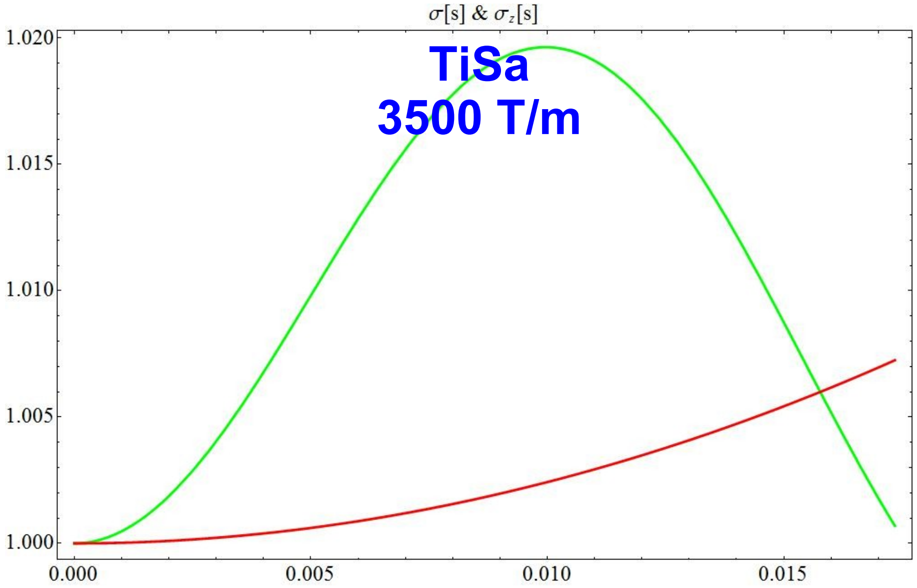
AOFEL: beam dynamics

With the given beam parameters we have

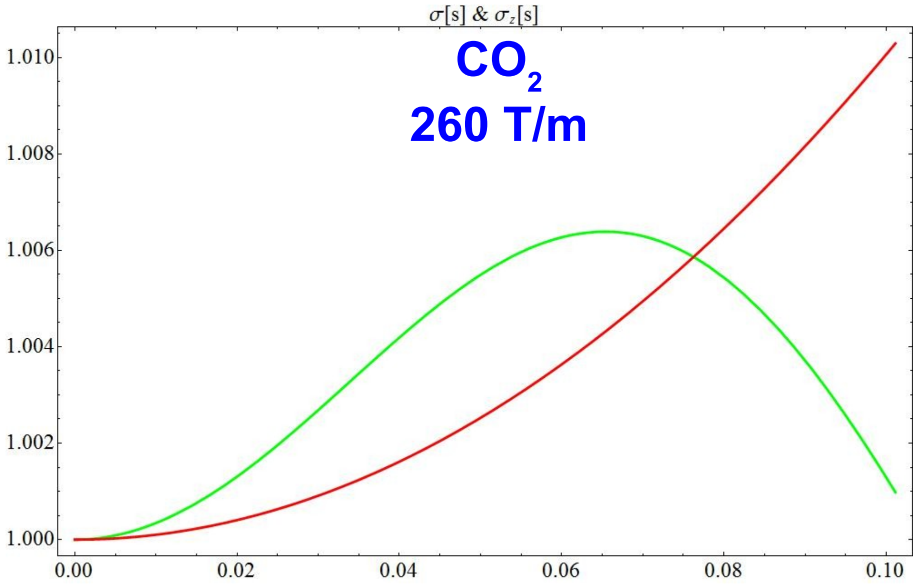
$$\rho^{(\mathrm{TiSa})} = 1.0 \times 10^{-4} \quad L_g^{(\mathrm{TiSa})} = 0.8\mathrm{mm}$$

$$\rho^{(\mathrm{CO_2})} = 1.6 \times 10^{-4} \quad L_g^{(\mathrm{CO_2})} = 5.1\mathrm{mm}$$

Assuming focusing (uniform focusing channel, discharge capillary): σ_x green, σ_z red



TiSa
3500 T/m



CO_2
260 T/m

Feasible with more conventional devices: PMQ

AOFEL: laser diffraction

Laser diffraction (assuming longitudinal flat top):

$$\frac{d\lambda_R}{\lambda_R} \lesssim \rho \Rightarrow \begin{cases} \dfrac{\sigma_x^2}{w_0^2} \lesssim \dfrac{\rho}{a_0^2} \sim 10^{-2} \\ \dfrac{|\Delta z|}{Z_R} \lesssim \dfrac{\sqrt{\rho}}{a_0} = \dfrac{\sigma_x}{w_0} \sim 10^{-1} \end{cases}$$

The first requirement also enforces the condition for preventing electrons defocusing by ponderomotive force, since

$$K_{\mathrm{def}} \propto \frac{\sigma_x^2}{w_0} \left(\frac{a_0}{w_0 \gamma} \right)^2$$

The second requirement is determined by the first. In general, it is sufficient for attaining saturation if emittance and energy spread are reasonably good.

AOFEL: laser diffraction

Laser diffraction (assuming longitudinal flat top):

$$\frac{d\lambda_R}{\lambda_R} \lesssim \rho \Rightarrow \begin{cases} \dfrac{\sigma_x^2}{w_0^2} \lesssim \dfrac{\rho}{a_0^2} \sim 10^{-2} \\ \dfrac{|\Delta z|}{Z_R} \lesssim \dfrac{\sqrt{\rho}}{a_0} = \dfrac{\sigma_x}{w_0} \sim 10^{-1} \end{cases}$$

This means that, generally speaking, we **DO NOT NEED** to guide the laser!

AOFEL: laser diffraction

Laser diffraction (assuming longitudinal flat top):

$$\frac{d\lambda_R}{\lambda_R} \lesssim \rho \Rightarrow \begin{cases} \dfrac{\sigma_x^2}{w_0^2} \lesssim \dfrac{\rho}{a_0^2} \sim 10^{-2} \\ \dfrac{|\Delta z|}{Z_R} \lesssim \dfrac{\sqrt{\rho}}{a_0} = \dfrac{\sigma_x}{w_0} \sim 10^{-1} \end{cases}$$

However, with present beam parameters, we need

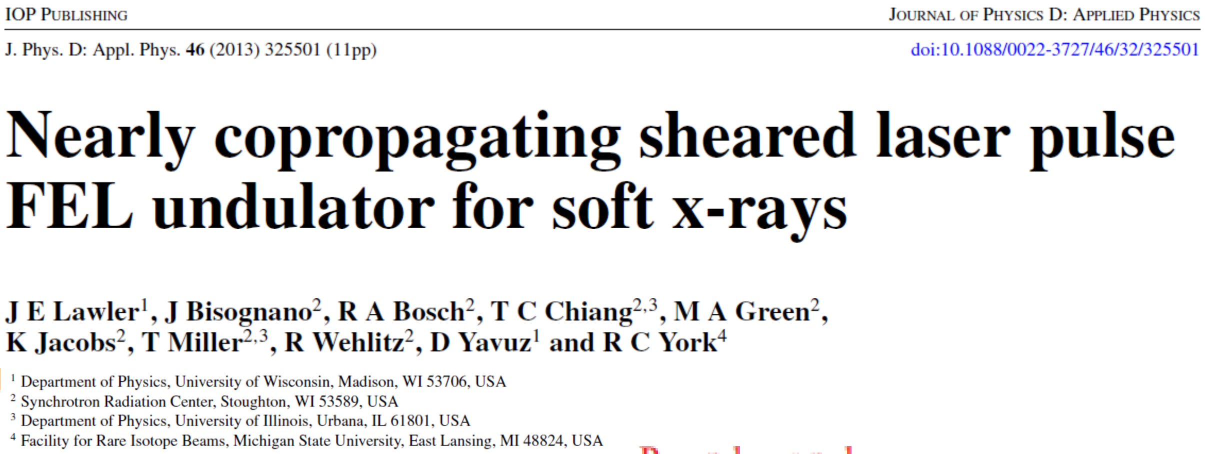
$$P^{(\mathrm{TiSa})} \approx 4.5\mathrm{TW} \quad P^{(\mathrm{CO_2})} \approx 16\mathrm{TW}$$

$$E^{(\mathrm{TiSa})} \approx 250\mathrm{kJ} \quad P^{(\mathrm{CO_2})} \approx 5.5\mathrm{kJ}$$

….

AOFEL: an alternative scheme 1

Allows to relax laser power/energy requirements and employ higher energy e-beams

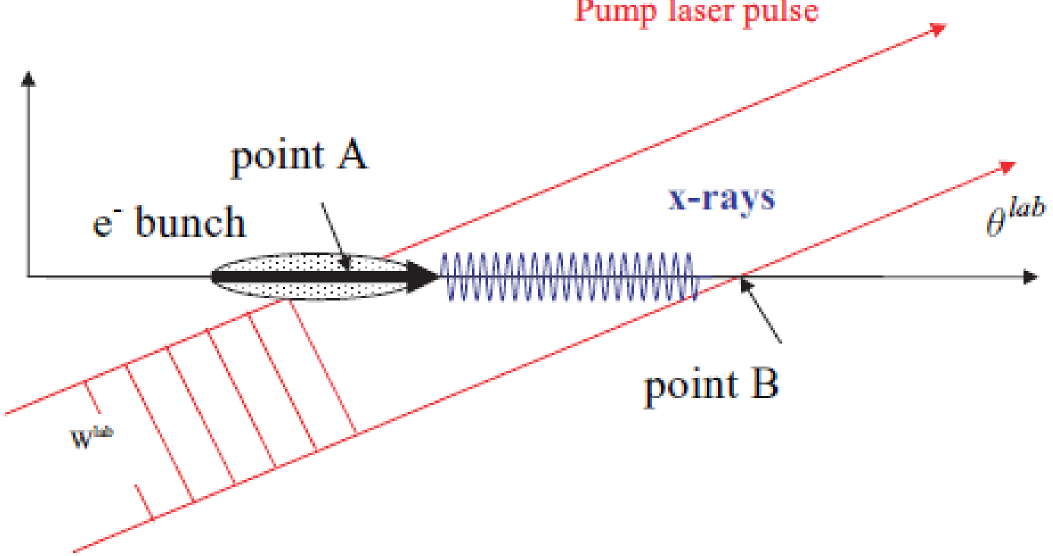


IOP Publishing Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. **46** (2013) 325501 (11pp) doi:10.1088/0022-3727/46/32/325501

Nearly copropagating sheared laser pulse FEL undulator for soft x-rays

J E Lawler[1], J Bisognano[2], R A Bosch[2], T C Chiang[2,3], M A Green[2], K Jacobs[2], T Miller[2,3], R Wehlitz[2], D Yavuz[1] and R C York[4]

[1] Department of Physics, University of Wisconsin, Madison, WI 53706, USA
[2] Synchrotron Radiation Center, Stoughton, WI 53589, USA
[3] Department of Physics, University of Illinois, Urbana, IL 61801, USA
[4] Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA



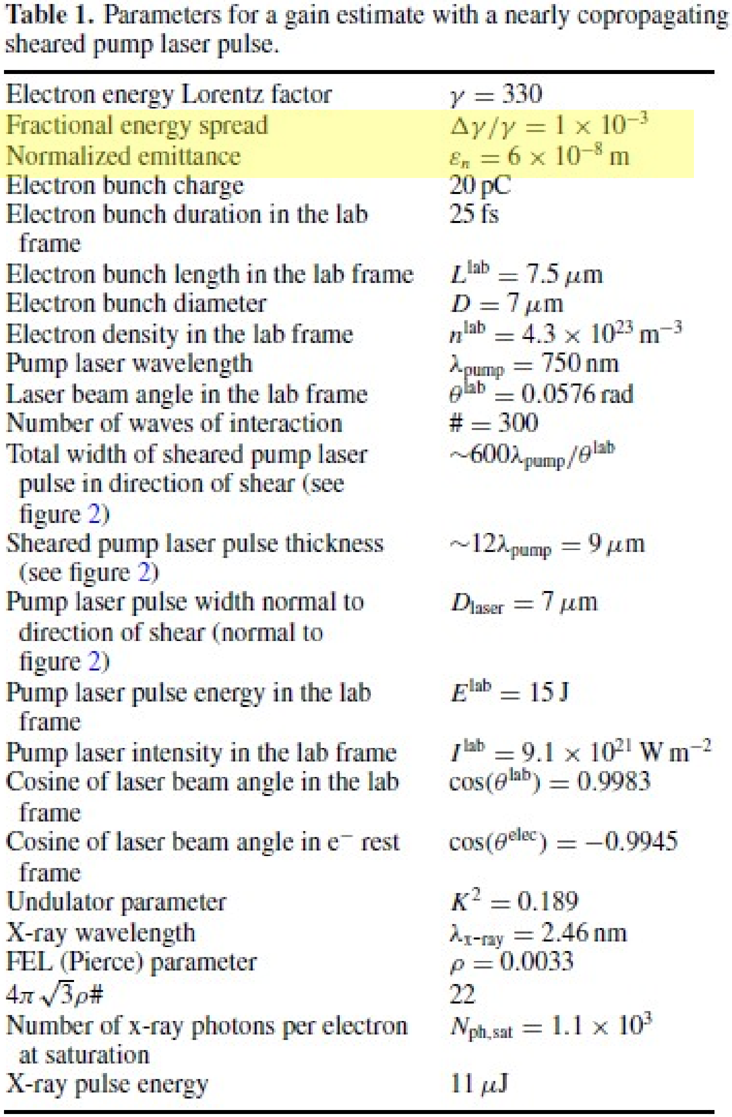


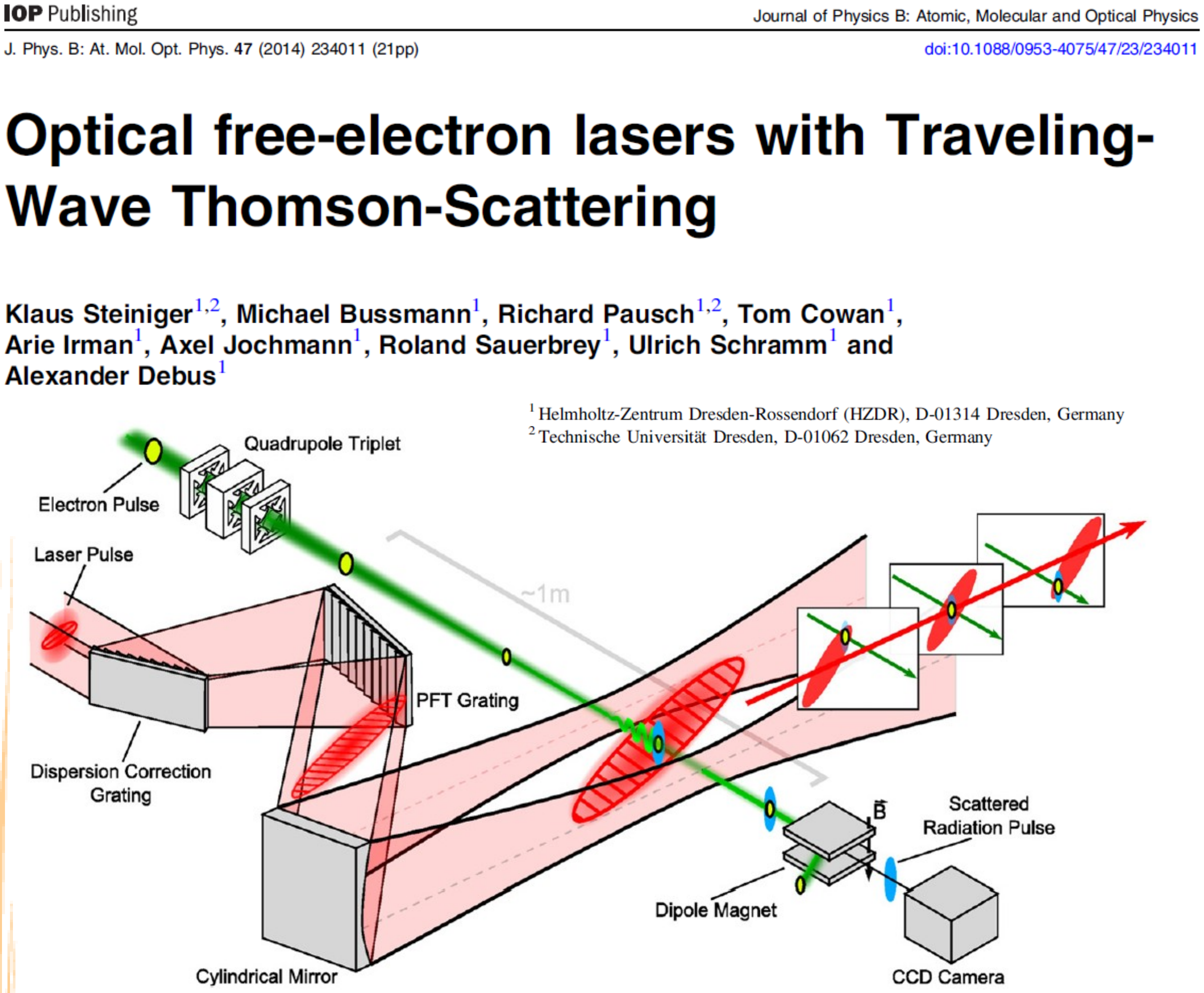
Table 1. Parameters for a gain estimate with a nearly copropagating sheared pump laser pulse.

Electron energy Lorentz factor	$\gamma = 330$
Fractional energy spread	$\Delta\gamma/\gamma = 1 \times 10^{-3}$
Normalized emittance	$\varepsilon_n = 6 \times 10^{-8}$ m
Electron bunch charge	20 pC
Electron bunch duration in the lab frame	25 fs
Electron bunch length in the lab frame	$L^{\rm lab} = 7.5\ \mu$m
Electron bunch diameter	$D = 7\ \mu$m
Electron density in the lab frame	$n^{\rm lab} = 4.3 \times 10^{23}$ m^{-3}
Pump laser wavelength	$\lambda_{\rm pump} = 750$ nm
Laser beam angle in the lab frame	$\theta^{\rm lab} = 0.0576$ rad
Number of waves of interaction	$\# = 300$
Total width of sheared pump laser pulse in direction of shear (see figure 2)	$\sim 600\lambda_{\rm pump}/\theta^{\rm lab}$
Sheared pump laser pulse thickness (see figure 2)	$\sim 12\lambda_{\rm pump} = 9\ \mu$m
Pump laser pulse width normal to direction of shear (normal to figure 2)	$D_{\rm laser} = 7\ \mu$m
Pump laser pulse energy in the lab frame	$E^{\rm lab} = 15$ J
Pump laser intensity in the lab frame	$I^{\rm lab} = 9.1 \times 10^{21}$ W m^{-2}
Cosine of laser beam angle in the lab frame	$\cos(\theta^{\rm lab}) = 0.9983$
Cosine of laser beam angle in e$^-$ rest frame	$\cos(\theta^{\rm elec}) = -0.9945$
Undulator parameter	$K^2 = 0.189$
X-ray wavelength	$\lambda_{\rm x\text{-}ray} = 2.46$ nm
FEL (Pierce) parameter	$\rho = 0.0033$
$4\pi\sqrt{3}\rho\#$	22
Number of x-ray photons per electron at saturation	$N_{\rm ph,sat} = 1.1 \times 10^3$
X-ray pulse energy	11 μJ

Still, requires unavailable e-beam quality.

AOFEL: an alternative scheme 2

Allows to relax laser power/energy requirements and employ higher energy e-beams



IOP Publishing Journal of Physics B: Atomic, Molecular and Optical Physics

J. Phys. B: At. Mol. Opt. Phys. 47 (2014) 234011 (21pp) doi:10.1088/0953-4075/47/23/234011

Optical free-electron lasers with Traveling-Wave Thomson-Scattering

Klaus Steiniger[1,2], Michael Bussmann[1], Richard Pausch[1,2], Tom Cowan[1], Arie Irman[1], Axel Jochmann[1], Roland Sauerbrey[1], Ulrich Schramm[1] and Alexander Debus[1]

[1] Helmholtz-Zentrum Dresden-Rossendorf (HZDR), D-01314 Dresden, Germany

[2] Technische Universität Dresden, D-01062 Dresden, Germany

Parameter	LWFA x-ray
Resonant wavelength [nm]	0.2
Interaction angle [°]	4.2
Undulator wavelength [μm]	372
Electron energy [MeV]	500
Peak current [kA]	5.0
Bunch duration (rms) [fs]	2.4
Bunch charge [pC]	26
Bunch radius [μm] (rms)	12
Norm. emittance [mm mrad]	0.30
Rel. energy spread	0.03%
Undulator parameter a_0	0.26
Laser power [TW]	1765
Transv. intensity profile stability	1.9%
Gain length [cm]	5.41
Saturation length [cm]	86.5
Peak x-ray power [MW]	791

Still, requires unavailable e-beam quality.

So, what could we do?

Two options:

1) **Assume** we can produce beams with **nm emittance** and **0.01% order energy spread** and **reduce beam current** to few hundreds Amps. Then beam dynamics becomes easier and we can operate an FEL with power of few tens MW and an energy of some fractions of μJ needing a CO_2 laser with some tens of GW power and some J energy.

So, what could we do?

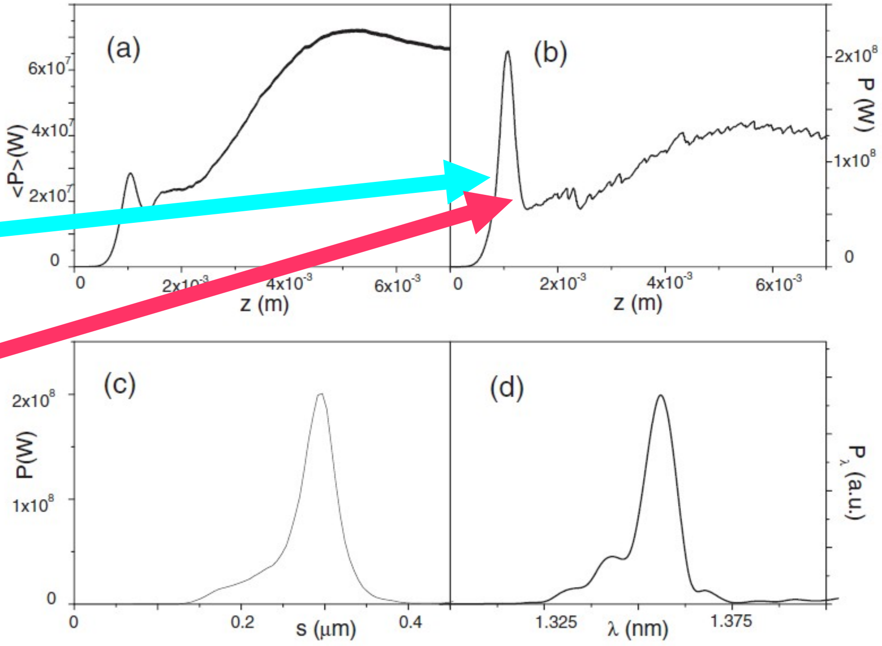
Two options:

1) **Assume** we can produce beams with **nm emittance** and **0.01% order energy spread** and **reduce beam current** to few hundreds Amps. Then beam dynamics becomes easier and we can operate an FEL with power of few tens MW and an energy of some fractions of μJ needing a CO_2 laser with some tens of GW power and some J energy.

1) Go along with **what we have** in term of beams and **give up saturation**. Back to the beginning:

i. Growth starts

i. Growth is killed by 3D effects and beam dynamics



Maybe also ...

- Pursue the construction of mm wavelength undulators, much like in

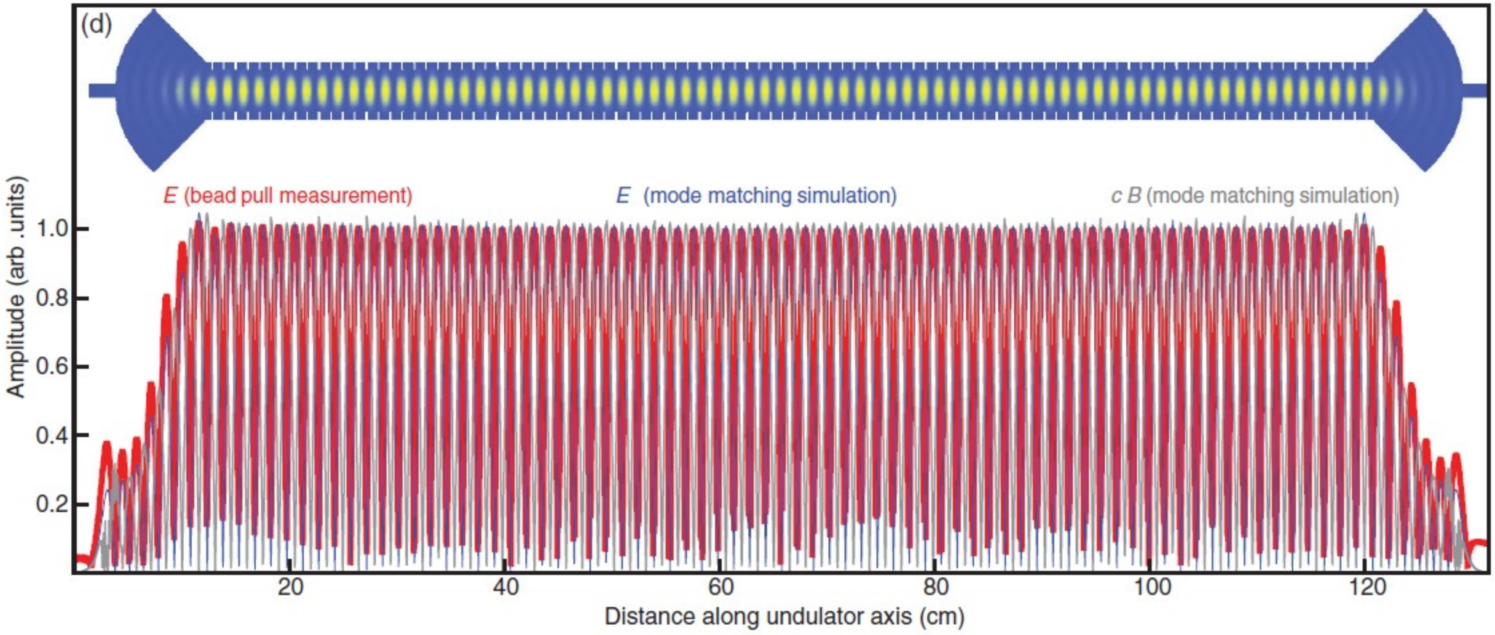
PRL **112,** 164802 (2014) PHYSICAL REVIEW LETTERS week ending 25 APRIL 2014

Experimental Demonstration of a Tunable Microwave Undulator

Sami Tantawi, Muhammad Shumail,* Jeffery Neilson, Gordon Bowden, Chao Chang,†
Erik Hemsing, and Michael Dunning
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

(Received 15 November 2013; published 23 April 2014)

Static magnetic undulators used by x-ray light sources are fundamentally too limited to achieve shorter undulator periods and dynamic control. To overcome these limitations, we report experimental demonstration of a novel short-period microwave undulator, essentially a Thomson scattering device, that has yielded tunable spontaneous emission and seeded coherent radiation. Its equivalent undulator period (λ_u) is 13.9 mm while it has achieved an equivalent magnetic field of 0.65 T. For future-generation light sources, this device promises a shorter undulator period, a large aperture, and fast dynamic control.



Conclusions

- All Optical FEL seems to still be out of reach despite all the progresses attained since its first proposal.

Conclusions

- All Optical FEL seems to still be out of reach despite all the progresses attained since its first proposal.
- At present, we would need laser with lots of J energy and W power. It is good to push research on high power, high energy lasers, but this does not help in spreading FELs by reducing costs. Also, detuning due to recoil should be better evaluated

Conclusions

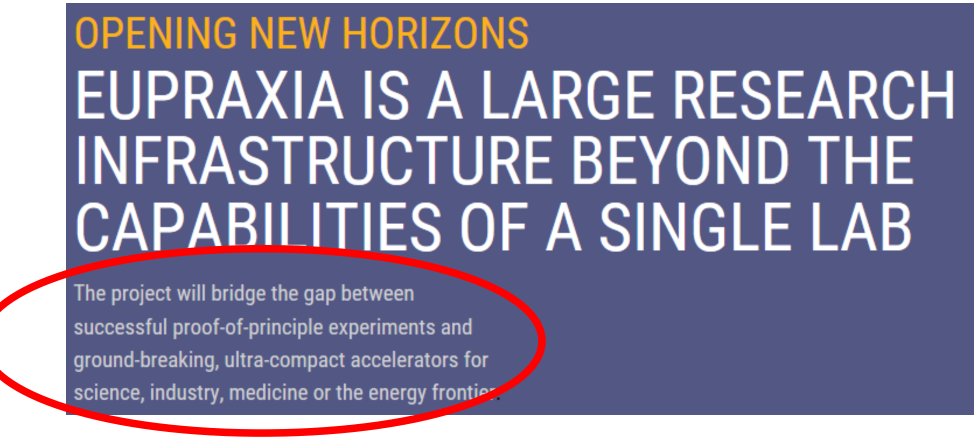
- All Optical FEL seems to still be out of reach despite all the progresses attained since its first proposal.
- At present, we would need laser with lots of J energy and W power. It is good to push research on high power, high energy lasers, but this does not help in spreading FELs by reducing costs. Also, detuning due to recoil should be better evaluated
- We MUST go on improving plasma beam quality and their control and manipulation by conventional and innovative techniques. Then we will completely exploit the full potential of plasma based acceleration.

Conclusions

- All Optical FEL seems to still be out of reach despite all the progresses attained since its first proposal.
- At present, we would need laser with lots of J energy and W power. It is good to push research on high power, high energy lasers, but this does not help in spreading FELs by reducing costs. Also, detuning due to recoil should be better evaluated
- We MUST go on improving plasma beam quality and their control and manipulation by conventional and innovative techniques. Then we will completely exploit the full potential of plasma based acceleration.
- The EuPRAXIA project was conceived to reach exactly those goals:

NOVEL FUNDAMENTAL RESEARCH

COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY



OPENING NEW HORIZONS

EUPRAXIA IS A LARGE RESEARCH INFRASTRUCTURE BEYOND THE CAPABILITIES OF A SINGLE LAB

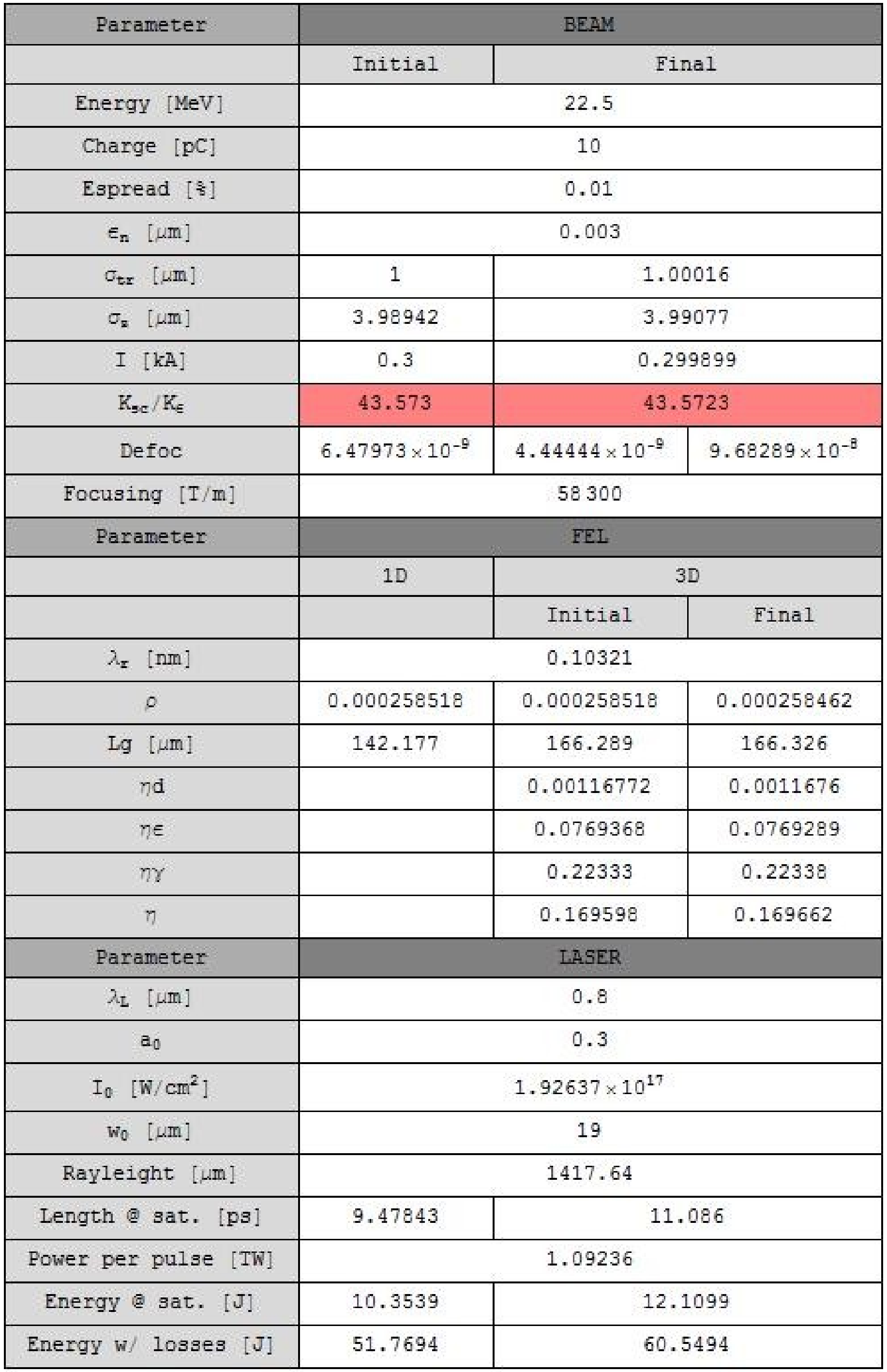
The project will bridge the gap between successful proof-of-principle experiments and ground-breaking, ultra-compact accelerators for science, industry, medicine or the energy frontier.

http://www.eupraxia-project.eu/

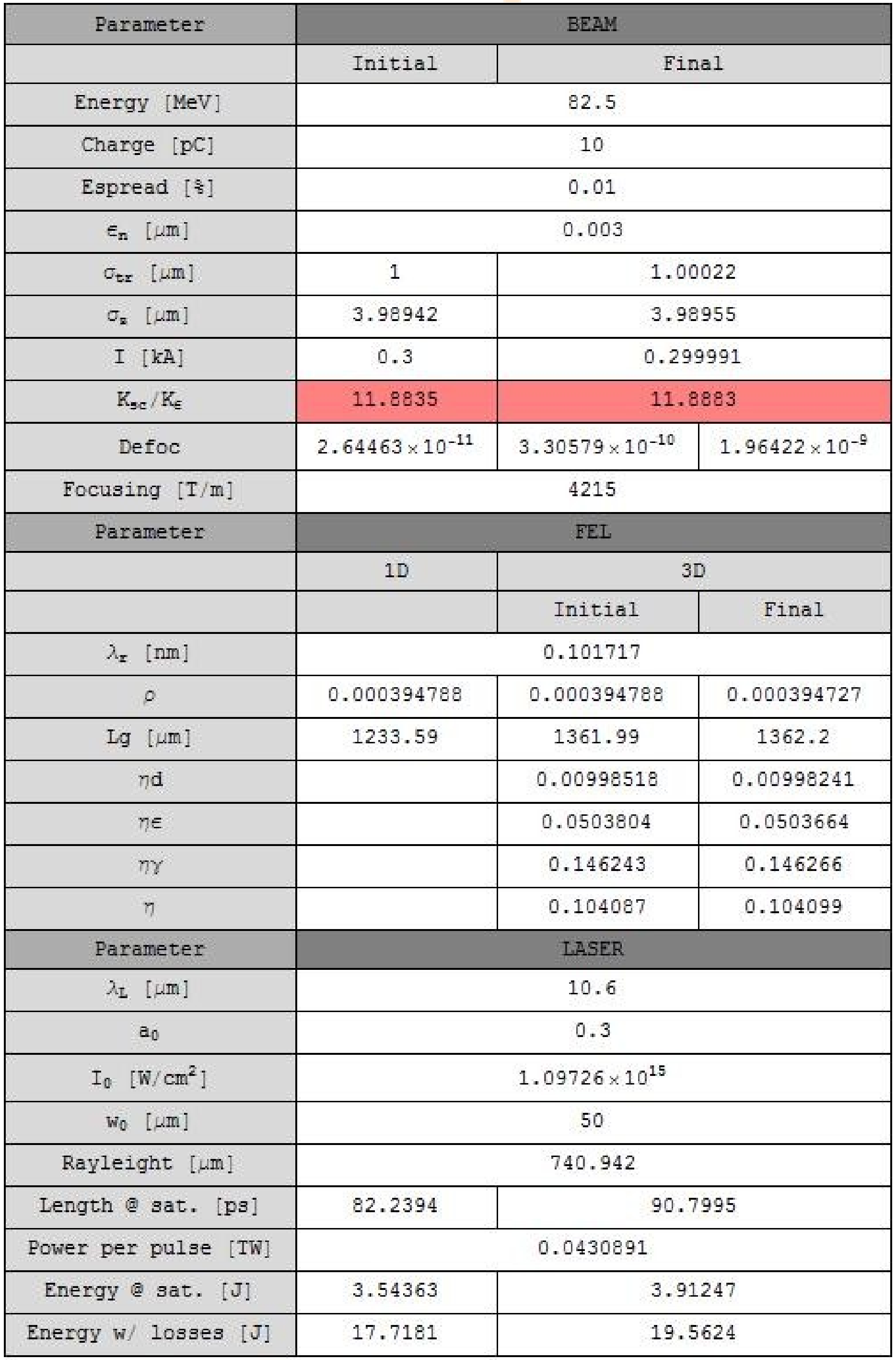
Thanks for your attention

… and a special thank you to Vittoria Petrillo for enlightening discussions and invaluable advices!

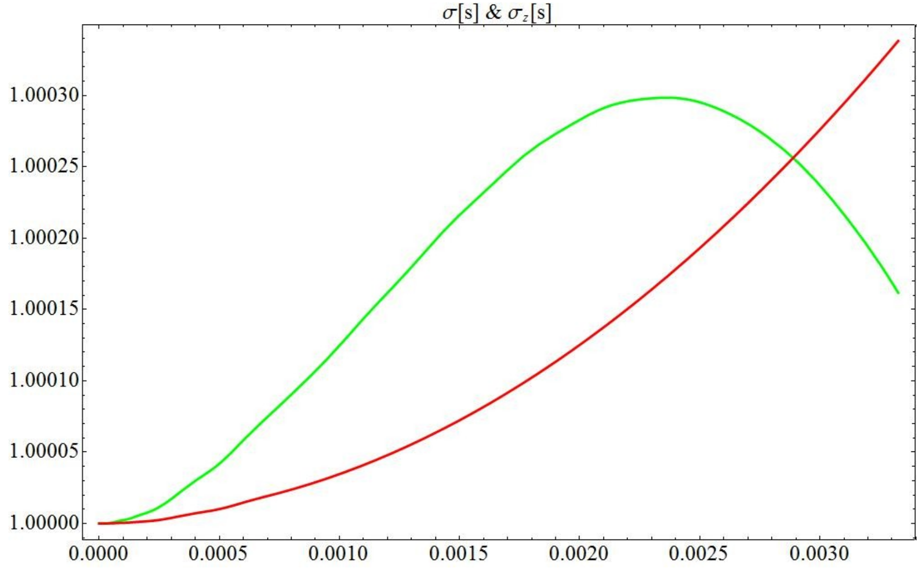
Backup slides

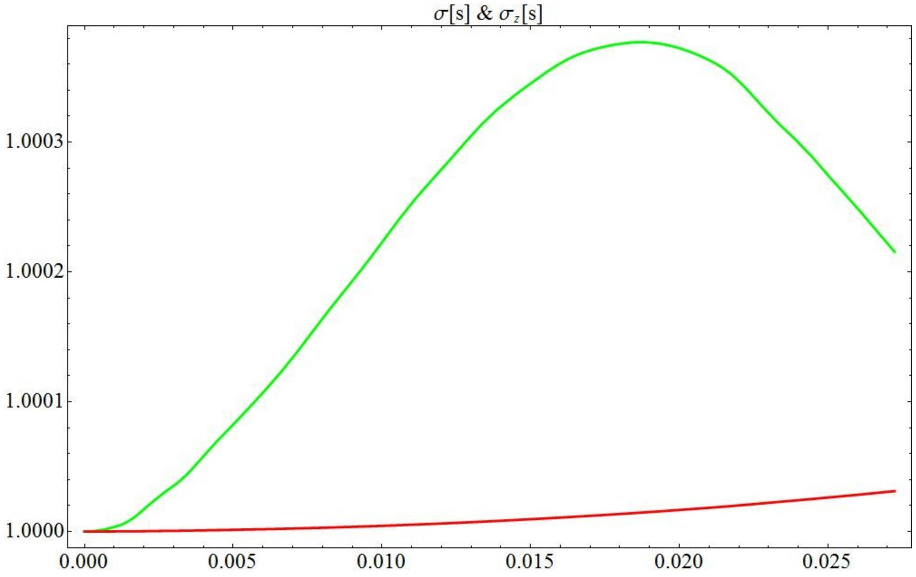


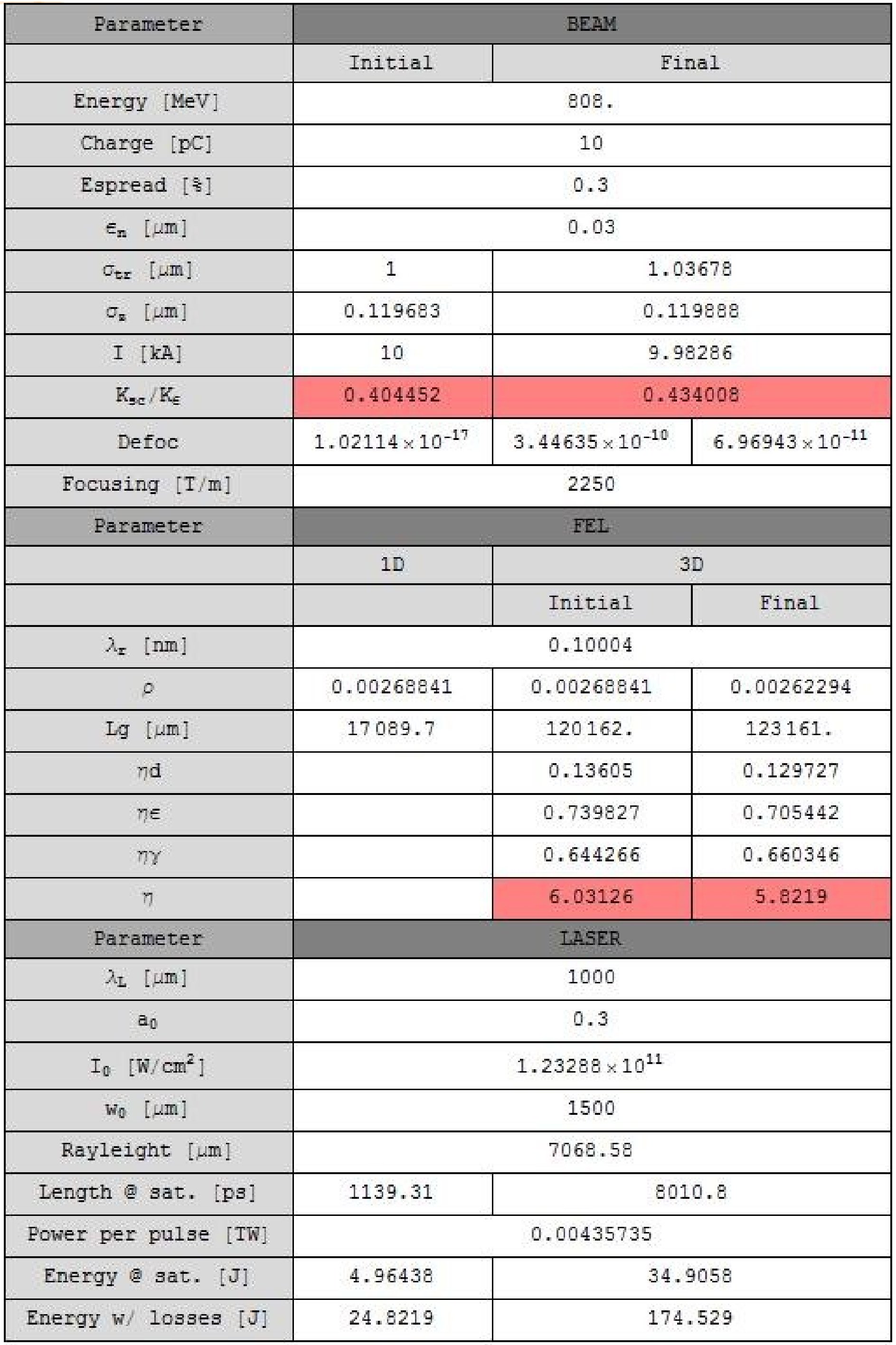
Parameter	BEAM		
	Initial	Final	
Energy [MeV]	22.5		
Charge [pC]	10		
Espread [%]	0.01		
ϵ_n [μm]	0.003		
σ_{tr} [μm]	1	1.00016	
σ_z [μm]	3.98942	3.99077	
I [kA]	0.3	0.299899	
K_{sc}/K_ϵ	43.573	43.5723	
Defoc	6.47973×10^{-9}	4.44444×10^{-9}	9.68289×10^{-8}
Focusing [T/m]	58300		
Parameter	FEL		
	1D	3D	
		Initial	Final
λ_r [nm]	0.10321		
ρ	0.000258518	0.000258518	0.000258462
Lg [μm]	142.177	166.289	166.326
ηd		0.00116772	0.0011676
$\eta\epsilon$		0.0769368	0.0769289
$\eta\gamma$		0.22333	0.22338
η		0.169598	0.169662
Parameter	LASER		
λ_L [μm]	0.8		
a_0	0.3		
I_0 [W/cm^2]	1.92637×10^{17}		
w_0 [μm]	19		
Rayleight [μm]	1417.64		
Length @ sat. [ps]	9.47843	11.086	
Power per pulse [TW]	1.09236		
Energy @ sat. [J]	10.3539	12.1099	
Energy w/ losses [J]	51.7694	60.5494	



Parameter	BEAM		
	Initial	Final	
Energy [MeV]	82.5		
Charge [pC]	10		
Espread [%]	0.01		
ϵ_n [μm]	0.003		
σ_{tr} [μm]	1	1.00022	
σ_z [μm]	3.98942	3.98955	
I [kA]	0.3	0.299991	
K_{sc}/K_ϵ	11.8835	11.8883	
Defoc	2.64463×10^{-11}	3.30579×10^{-10}	1.96422×10^{-9}
Focusing [T/m]	4215		
Parameter	FEL		
	1D	3D	
		Initial	Final
λ_r [nm]	0.101717		
ρ	0.000394788	0.000394788	0.000394727
Lg [μm]	1233.59	1361.99	1362.2
ηd		0.00998518	0.00998241
$\eta\epsilon$		0.0503804	0.0503664
$\eta\gamma$		0.146243	0.146266
η		0.104087	0.104099
Parameter	LASER		
λ_L [μm]	10.6		
a_0	0.3		
I_0 [W/cm^2]	1.09726×10^{15}		
w_0 [μm]	50		
Rayleight [μm]	740.942		
Length @ sat. [ps]	82.2394	90.7995	
Power per pulse [TW]	0.0430891		
Energy @ sat. [J]	3.54363	3.91247	
Energy w/ losses [J]	17.7181	19.5624	


$\sigma[s]$ & $\sigma_z[s]$
1.00030
1.00025
1.00020
1.00015
1.00010
1.00005
1.00000
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030


$\sigma[s]$ & $\sigma_z[s]$
1.0003
1.0002
1.0001
1.0000
0.000
0.005
0.010
0.015
0.020
0.025



Parameter	BEAM		
	Initial	Final	
Energy [MeV]	808.		
Charge [pC]	10		
Espread [%]	0.3		
ϵ_n [μm]	0.03		
σ_{tr} [μm]	1	1.03678	
σ_z [μm]	0.119683	0.119888	
I [kA]	10	9.98286	
K_{sc}/K_ϵ	0.404452	0.434008	
Defoc	1.02114×10^{-17}	3.44635×10^{-10}	6.96943×10^{-11}
Focusing [T/m]	2250		
Parameter	**FEL**		
	1D	3D	
		Initial	Final
λ_r [nm]	0.10004		
ρ	0.00268841	0.00268841	0.00262294
Lg [μm]	17089.7	120162.	123161.
ηd		0.13605	0.129727
$\eta\epsilon$		0.739827	0.705442
$\eta\gamma$		0.644266	0.660346
η		6.03126	5.8219
Parameter	**LASER**		
λ_L [μm]	1000		
a_0	0.3		
I_0 [W/cm^2]	1.23288×10^{11}		
w_0 [μm]	1500		
Rayleight [μm]	7068.58		
Length @ sat. [ps]	1139.31	8010.8	
Power per pulse [TW]	0.00435735		
Energy @ sat. [J]	4.96438	34.9058	
Energy w/ losses [J]	24.8219	174.529