EAAC2025

Design of high-brightness electron beams with MP-LWFA for FEL in the water-window [and Thomson/Compton sources]

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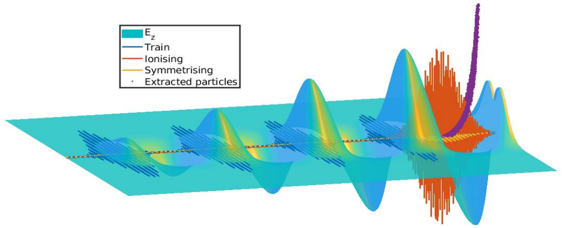
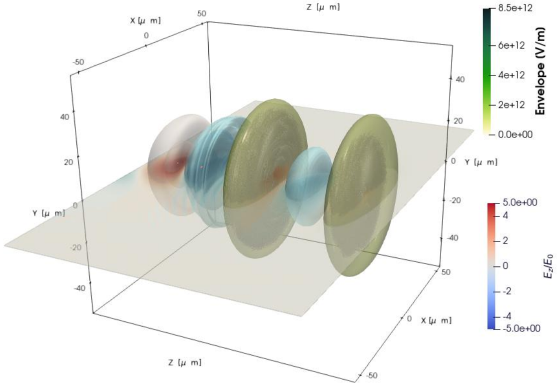
1. ELI-NP, HH-IFIN
2. Istituto Nazionale di Ottica – CNR
3. INFN - Pisa
4. ELI-ALPS
5. University of Oxford
6. INFN - Milano

Outlook

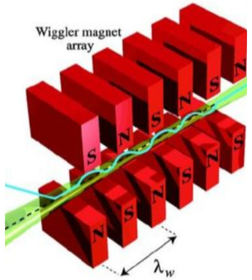
1. The Resonant Multi-Pulse Ionization injection (ReMPI)



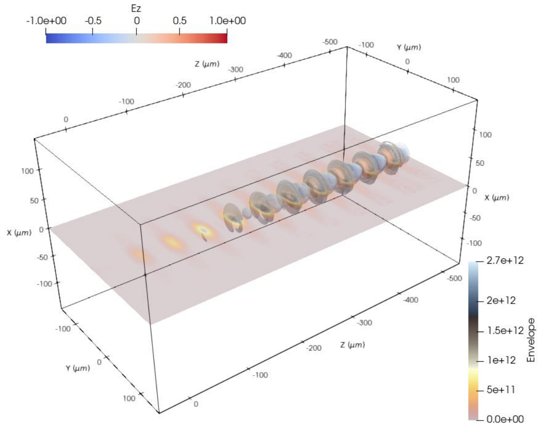
2. High-brightness **340as long** 2.2GeV **10Hz** beams with a simplified ReMPI setup



3. Preliminary FEL simulations in the water-window with the **10Hz** 2.2GeV ReMPI beam



4. High-brightness **kHz**, >1GeV beams with a P-MoPA/ReMPI scheme



The Theory@LDED group

The group is part of **LDED** (Department Head: **Domenico Doria**)

Theory@LDED

Performs theory and simulation researches (mostly) for LDED

- Nuclear Physics
- Laser Solid
- LWFA/DLA
- Radiation and secondary sources

Paolo Tomassini
Head of Research

C-J Yang (Jerry)
Young Researcher

Vojt
Young Rese

a Budriga
rcher *

F. Avella et al., **Laser fields reconstructor for initialization of experimental laser profiles in Particle In Cell simulations**, Poster, Wed. 24th 7-9 PM

Dragana Dreghici
Ph. D. student

Bogdan Corobean
Ph. D. student

Federico Avella
Ph. D. student **

Maxim Andronic
Master Student

* Part Time, **In Co-Tutoring with CNR-INO/L.A. Gizzi

Beam Quality

- **Compactness** in phase-space (low energy spread, divergence…)
- High charge or high current
- **Linear correlation** in the transverse x-u_x and y-u_y planes (low emittance)

Normalized emittance

$$u = p/mc \qquad \epsilon_n^2 = \langle x^2 \rangle \langle u_x^2 \rangle - (\langle x \cdot u_x \rangle)^2$$

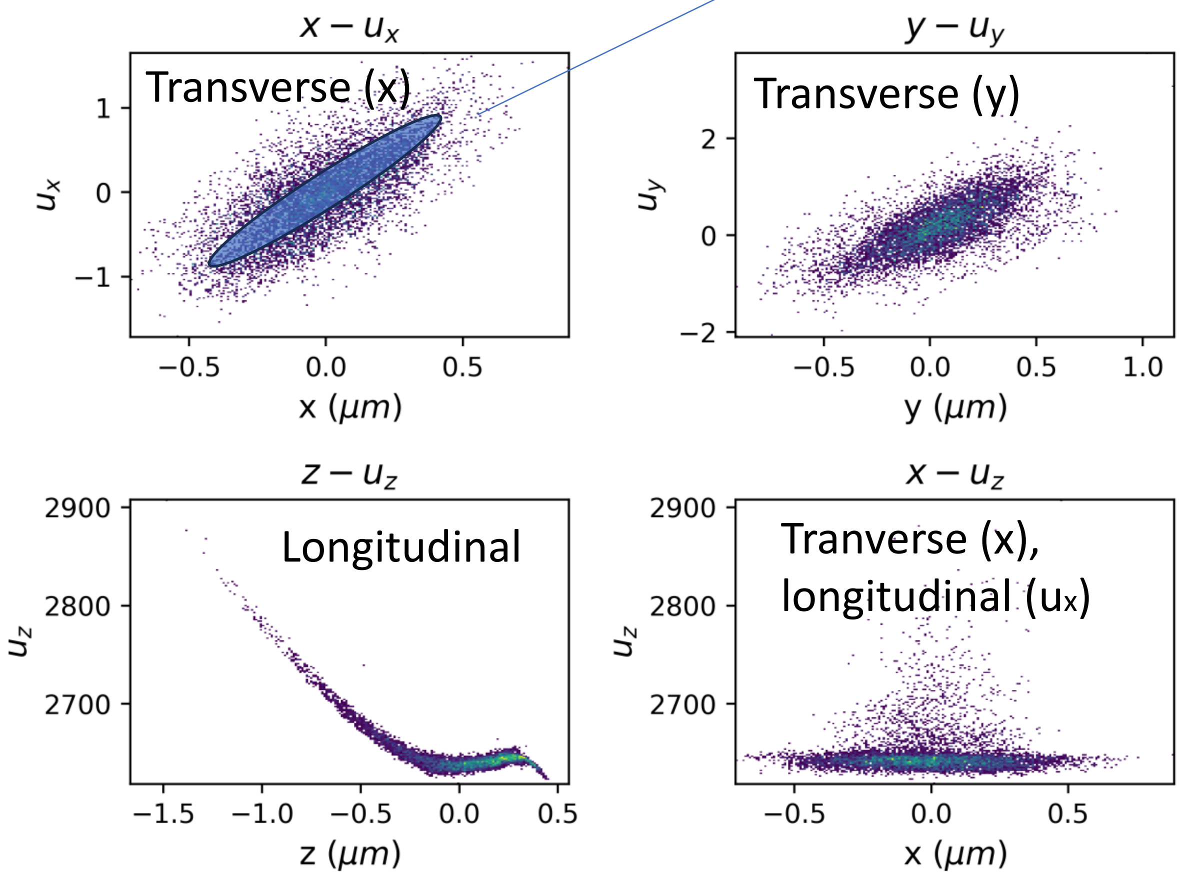
Normalized Brightness (5D)

$$B_{n,5D} = \frac{2}{\pi^2} \frac{I}{\epsilon_{n,x} \epsilon_{n,y}} \quad A/(m \times rad)^2$$

Normalized Brightness (6D)

$$B_{n,6D} = \frac{B_{n,5D}}{\delta E/E}$$

$$B_{n,6D} = \frac{B_{n,5D}}{\delta E/E/0.1\%}$$



We start from the Two-Color ionization injection

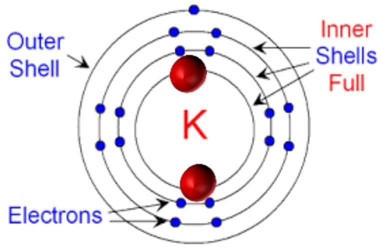
Two-color injection [L. L. Yu et al. PRL 112 (2014)] is a very **promising scheme aiming at generating extremely low-emittance bunches but requires two [sinchronized] laser systems**: a long-wavelength (e.g. CO_2) for wake driving and a short (e.g a frequency doubled Ti:Sa) for electron extraction.

$a = eA/mc^2 = \frac{eE}{mc^2 k_0} \rightarrow a \propto E\lambda$

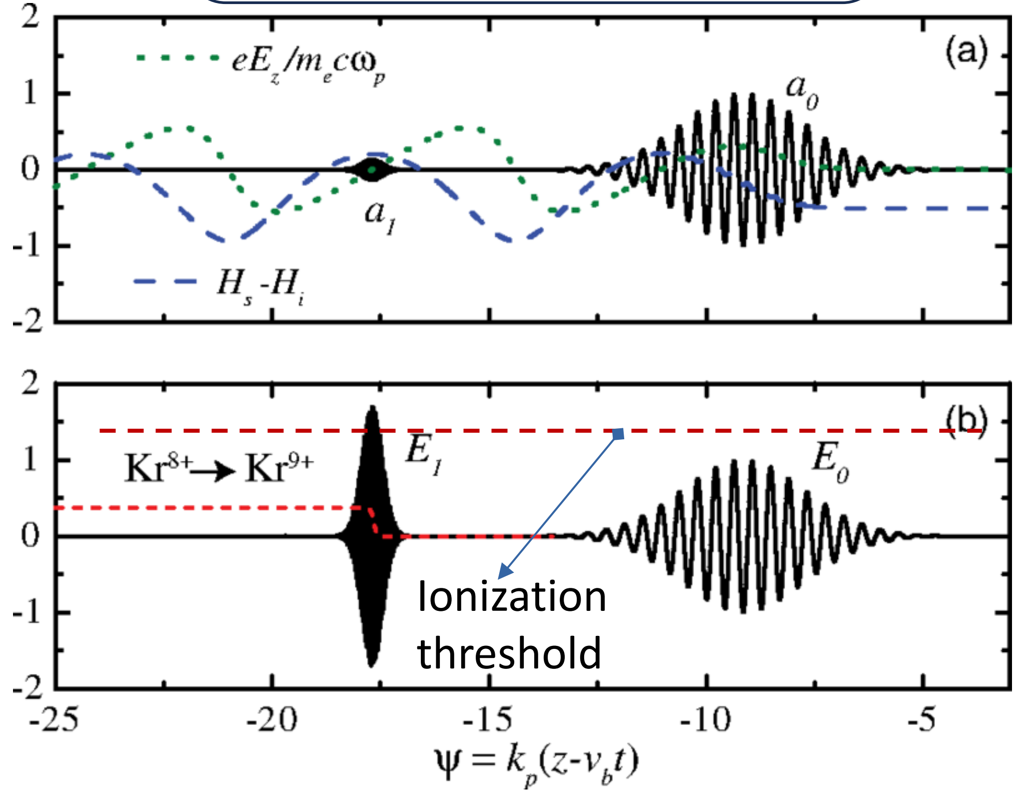
Ponderomotive Force

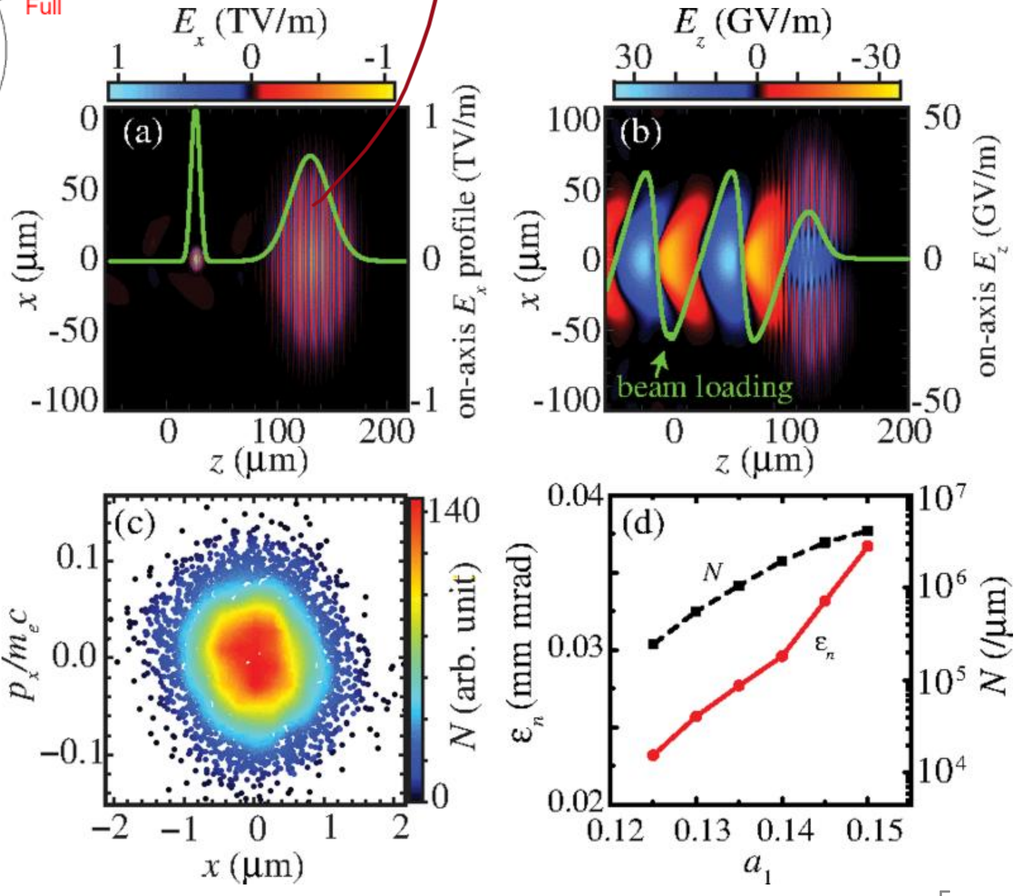
$\vec{F}_p \propto \vec{\nabla} a^2$

$a_0 = max(a)$



Needs to have a large a0 to drive the wakefield



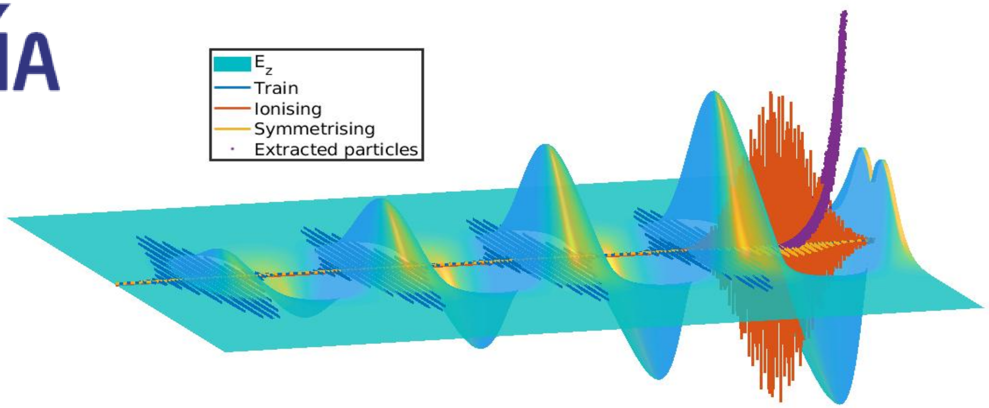


The Resonant Multi-Pulse Ionization injection (ReMPI) scheme

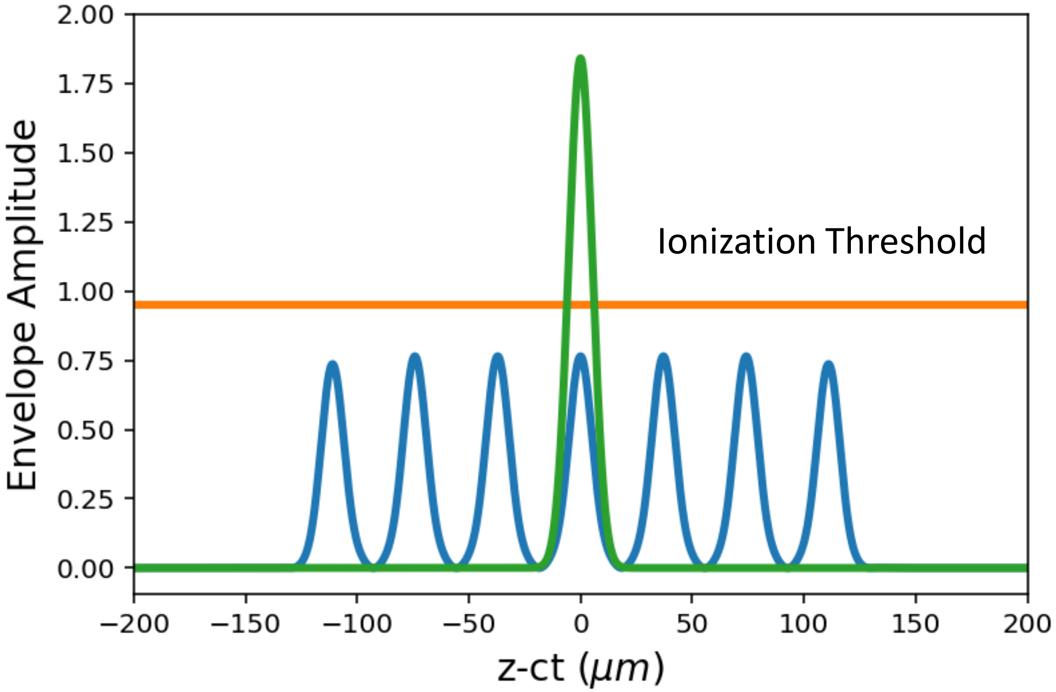
PHYSICS OF PLASMAS **24**, 103120 (2017)

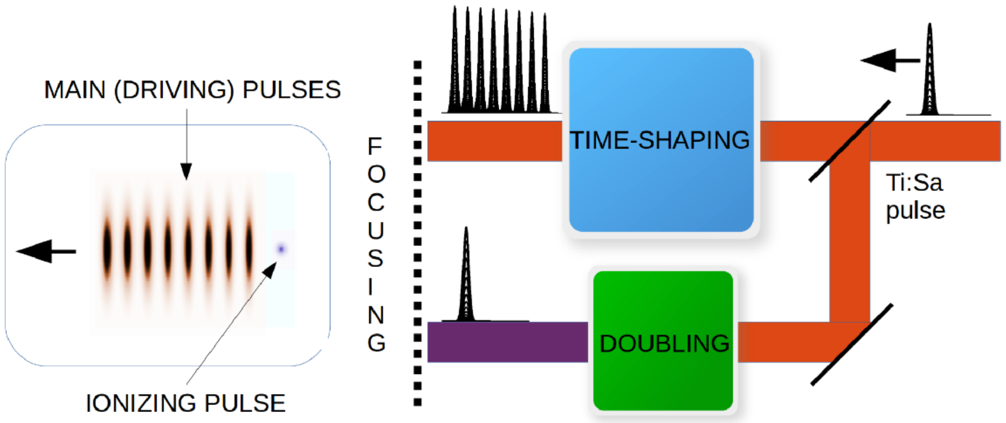
The resonant multi-pulse ionization injection

Paolo Tomassini,[1,a)] Sergio De Nicola,[2,3] Luca Labate,[1,4] Pasquale Londrillo,[5]
Renato Fedele,[2,6] Davide Terzani,[2,6] and Leonida A. Gizzi[1,4]
[1]*Intense Laser Irradiation Laboratory, INO-CNR, 56124 Pisa, Italy*
[2]*Dip. Fisica Universita' di Napoli Federico II, 80126 Napoli, Italy*
[3]*CNR-SPIN, Napoli, 80126 Napoli, Italy*



ReMPI **requires one "driver" pulse train** made with a sequence of sub-[ionization] threshold amplitude pulses.





ReMPI is flexible. Examples of earlier works

Theory @ LDED

Injector for multistage LWFA

30pC, 150MeV, 1.6% , 0.23 μmrad

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 111302 (2019)

EuPRAXIA

High quality electron bunches for a multistage GeV accelerator with resonant multipulse ionization injection

Paolo Tomassini,[1,*] Davide Terzani,[1] Luca Labate,[1,2] Guido Toci,[3] Antoine Chance,[4] Phu Anh Phi Nghiem,[4] and Leonida A. Gizzi[1,2]

[1]*Intense Laser Irradiation Laboratory, INO-CNR, Via Moruzzi 1, 56124 Pisa, Italy*
[2]*INFN, Sect. of Pisa, Largo Bruno Pontecorvo 3, 56127 Pisa, Italy*
[3]*INO-CNR, Largo Enrico Fermi 2, 56125 Firenze, Italy*
[4]*CEA-Irfu, Centre de Saclay, Université Paris-Saclay, 91191 Gif sur Yvette, France*

Single stage 5GeV accelerator

30pC, 5GeV, 1% (proj) , 0.04% (slice) 0.08 μmrad

High-quality 5 GeV electron bunches with resonant multi-pulse ionization injection

P Tomassini[3,1], D Terzani[1], F Baffigi[1], F Brandi[1], L Fulgentini[1], P Koester[1], L Labate[2,1], D Palla[1] and L A Gizzi[2,1]

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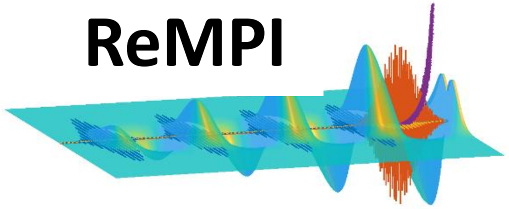
Plasma Physics and Controlled Fusion, Volume 62, Number 1
Special Issue Featuring the Invited Talks from the 46th EPS Conference on Plasma Physics, Milan, 8-12 July 2019
Phys. Control. Fusion **62** 014010

EuPRAXIA

ReMPI



Beams for FEL or Thomson backscattering X/gamma

30pC, 4.5GeV, 0.9% (proj) , 0.03% (slice) 0.08 μmrad

Brilliant X-ray Free Electron Laser driven by Resonant Multi Pulse Ionization Injection accelerator, P. Tomassini et al. Proc. FEL conference 2022

EuPRAXIA

Beams for Thomson Back Scattering sources

5pC, 1GeV, 0.8% (proj) , 0.08 μmrad

High-quality electron bunch production for **high-brilliance Thomson Scattering sources**
P. Tomassini et al., SPIE 2017
https://doi.org/10.1117/12.2266938

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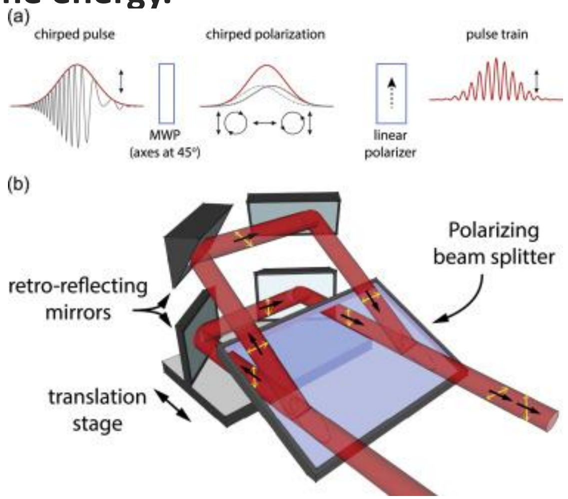
ReMPI brick 1: Multi-Pulse generation

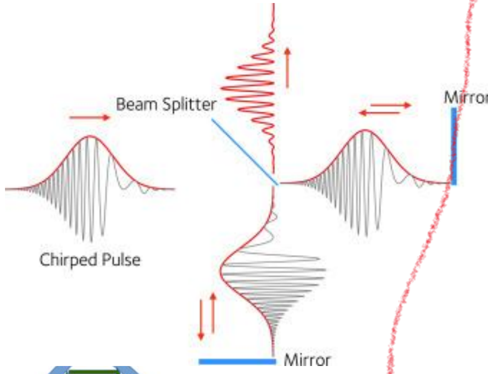
Theory@LDED

- **The multi-pulse approach to LWFA has been proposed so far [D. Umstadter et al, PRL 72, (1994)]. A multi-pulse train can generate plasma waves with larger amplitude than those driven by a single pulse with the same energy.**

Three possible pulse-shaping schemes have been proposed very recently

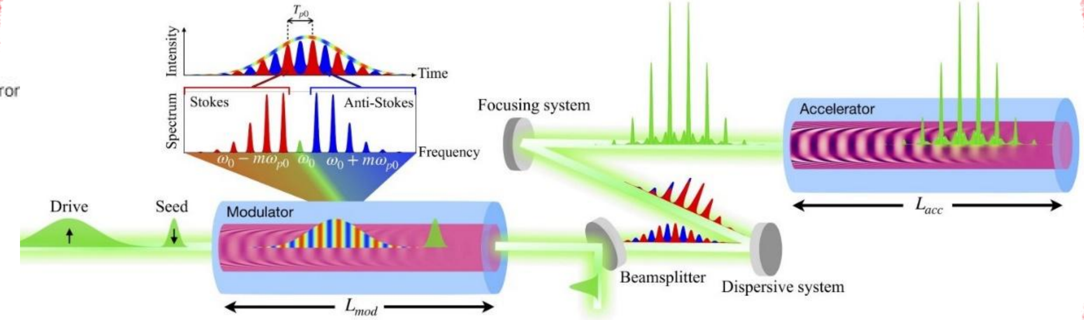


[J. Cawley et al, PRL 2017]
[R.J. Shallow et al, NIM A 2016]

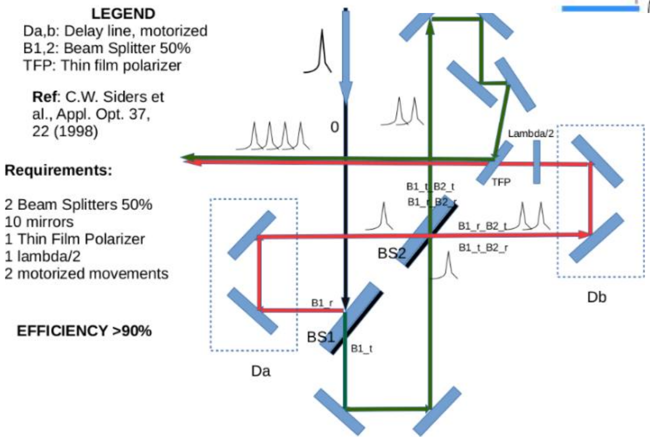


P-MOPA

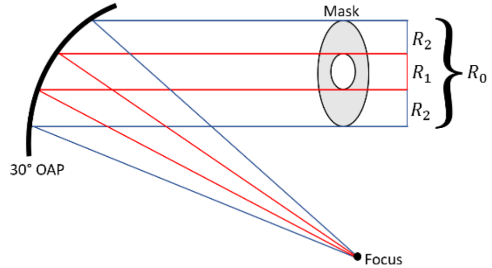
[O. Jakobsson et al., PRL **127** (2021)]
J. J. van de Wetering et al., PRE **109** (2024)]



Older methods include either multiple beam-splitters setup or phase masks



[W. Siders et al., Appl. Opt, 37 (22) 1998]



[G. Vantaggiato et al., NIMA 2018]
[A. Marasciulli et al., CLEO conf. 2021]
[A. Marasciulli et al., Appl. Optics , 2023]

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ReMPI brick 2: Accurate ionization model for the extracted electron statistics

Theory@LDED

High Power Laser Science and Engineering, (2022), Vol. 10, e15, 16 pages.
doi: 10.1017/hpl.2021.56

HIGH POWER LASER SCIENCE AND ENGINEERING

RESEARCH ARTICLE

Accurate electron beam phase-space theory for ionization-injection schemes driven by laser pulses

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[1] *Intense Laser Irradiation Laboratory, INO-CNR, Pisa, Italy*
[2] *ELI-NP, Magurele, Ilfov, Romania*
[3] *Maison de la Simulation, CEA, USR 3441, Gif-sur-Yvette, France*
[4] *INFN, Sect. of Pisa, Pisa, Italy*
(Received 31 August 2021; revised 25 October 2021; accepted 26 November 2021)

Highly accurate modeling of the 6D phase-space for tunnel-ionisation extracted electrons (ADK theory).

Single-cycle detailed description of the phase-space and whole bunch emittance

Also valid in the deep-saturation regime

$$\rho \equiv \frac{3E}{2E_a}\left(\frac{U_H}{U_I}\right)^{3/2} = a/a_c = \Delta^2$$

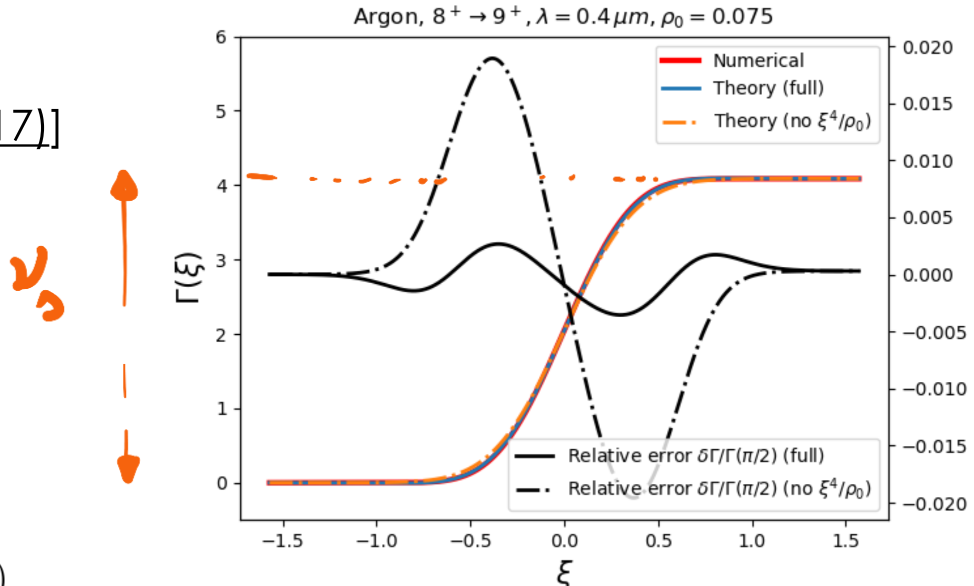
$$W = C \times \rho^\mu e^{-\frac{1}{\rho}} \quad \rho = \rho_0|\cos(\xi)|$$

ADK rate rewritten as in [P. Tomassini et al., PoP 24, 103120 (2017)]

$$\frac{1}{n_{0,i}}\frac{dn_e}{d\xi} = -\frac{\partial}{\partial_\xi} e^{-\Gamma(\xi)},$$

$$\Gamma(\xi) \equiv \frac{1}{k_{0,x}}\int_{-\pi/2}^{\xi} dx W(x)$$

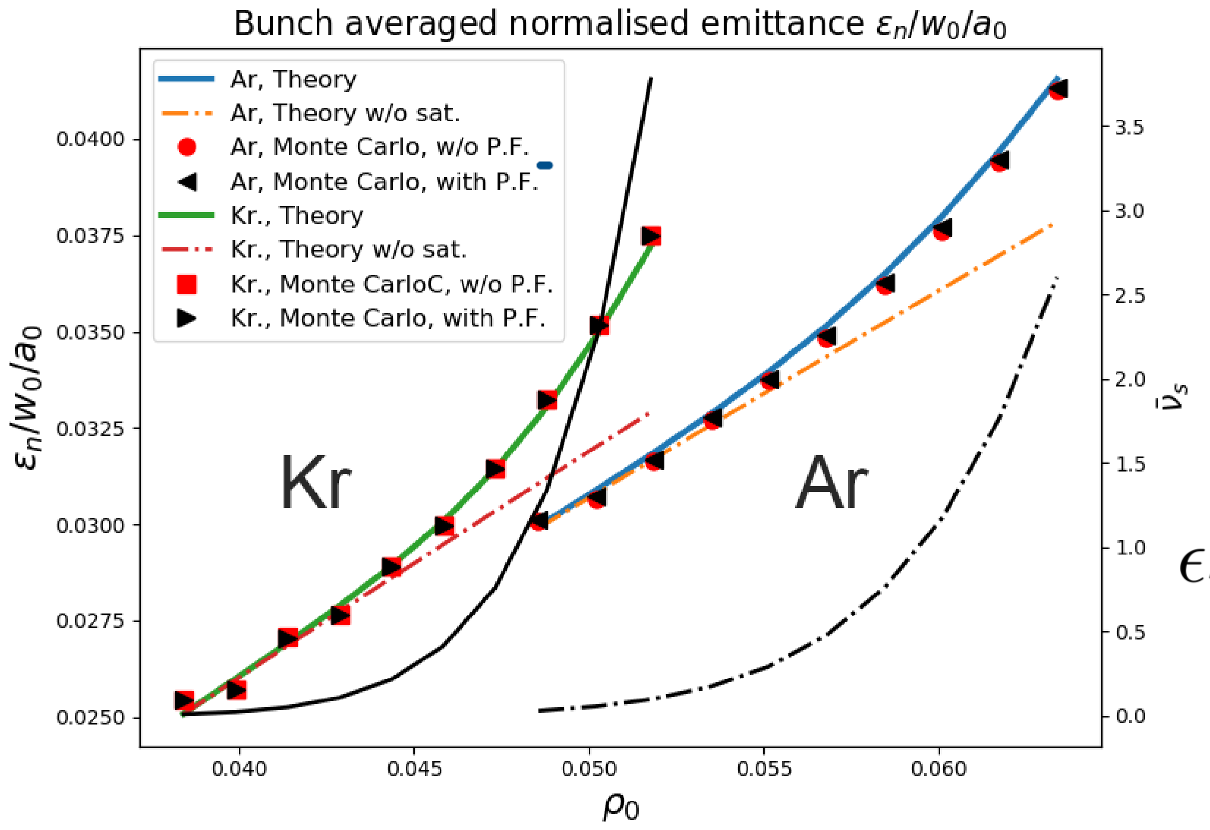
$$= \frac{k_{ADK}}{k_0}\rho_0^\mu \int_{-\pi/2}^{\xi} dx (\cos x)^\mu e^{-\frac{1}{\rho_0 \cos x}} \simeq \nu_s(\rho_0)\mathcal{G}\left(\frac{\xi}{\sqrt{2\rho_0}}\right) \quad (1)$$



Advanced theory outcomes for a whole electron beam

P. Tomassini et al, HPLSE 10 e15 (2022)

$$\rho_0 \equiv \frac{3E}{2E_a}\left(\frac{U_H}{U_I}\right)^{3/2} = a_0/a_c = \Delta_0^2$$



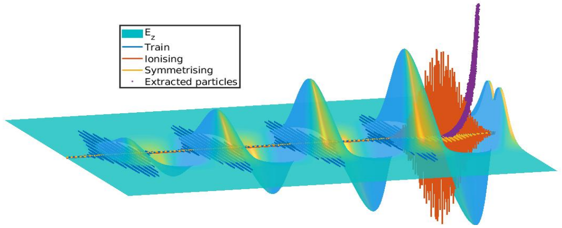
Minimum obtainable *«thermal» normalised emittance*

$$Ar^{8^+\to 9^+} \quad \rho_0 = a_{0,i}/a_c = 0.062$$

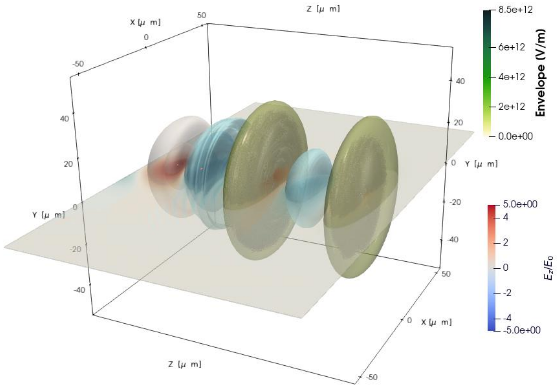
$\lambda_i = 0.4\mu m$	$\lambda_i = 0.2\mu m$
$a_c = 7.41$	$a_c = 3.71$
$a_{0,i} = 0.46$	$a_{0,i} = 0.23$
$w_0 = 4.0\mu m$	$w_0 = 4.0\mu m$
$\epsilon_n\|_{th} = 72nm\, rad$	$\epsilon_n(min) = 37nm\, rad$

Outlook

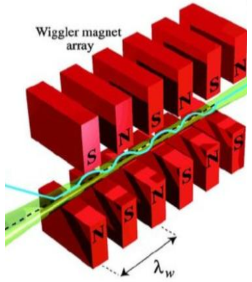
1. The Resonant Multi-Pulse Ionization injection (ReMPI)



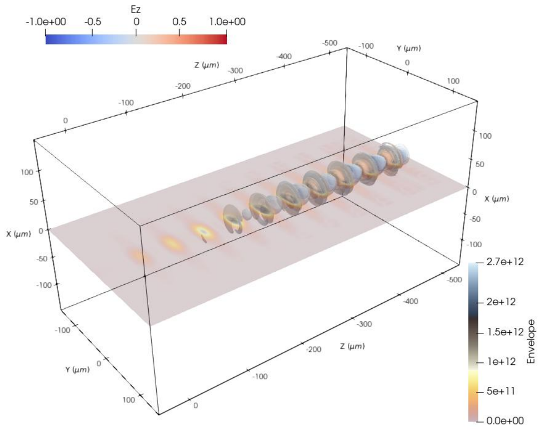
2. High-brightness **340as long** 2.2GeV **10Hz** beams with a simplified ReMPI setup



3. Preliminary FEL simulations in the water-window with the **10Hz** 2.2GeV ReMPI beam



4. High-brightness **kHz**, >1GeV beams with a P-MoPA/ReMPI scheme



High-brightness 340as long 2GeV 10Hz beams with a simplified ReMPI setup

eli nuclear physics

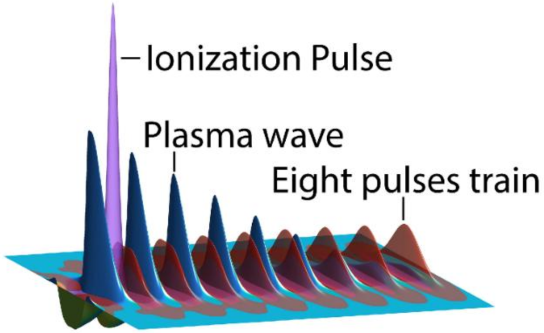
The first Free Electron Laser compliant version of ReMPI for 5GeV suffered from “gigantism”.

8 pulses

(1PW, EuPRAXIA)

EuPRAXIA

Scheme selected and included in the CDR



Theory @ LDED

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30 pC

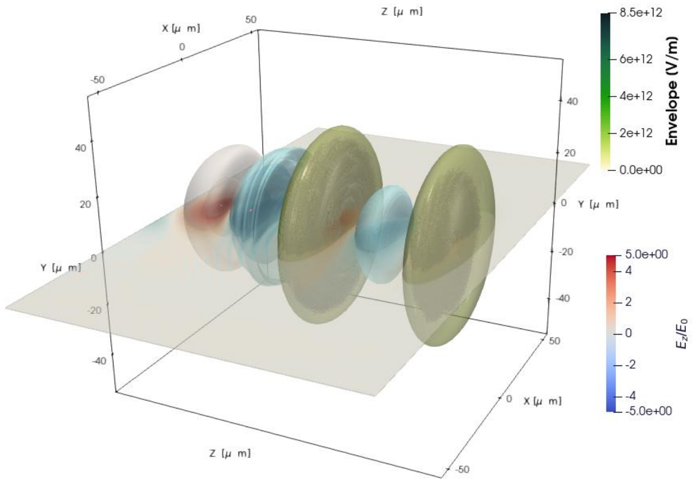
$$\epsilon_n \simeq 80nmrad$$

P. Tomassini et al., High-quality 5GeV electron bunches with the resonant multi-pulse ionization injection, PPCF P 62 (2020) 014010

P. Tomassini et al., BRILLIANT X-RAY FREE ELECTRON LASER DRIVEN BY RESONANT MULTI-PULSE IONIZATION INJECTION ACCELERATOR, proc. FEL 2022 conference, Trieste.

(200/300TW)

2 pulses



3-30 pC

$$\epsilon_n \simeq 80nmrad$$

*P. Tomassini et al.,”*Ultra-High-Brightness and tuneable attosecond-long electron beams with the Laser Wake Field Acceleration*”,* [*https://www.researchsquare.com/article/rs-6889281/v1*](https://www.researchsquare.com/article/rs-6889281/v1) *(submitted)*

High-brightness 340as long 2GeV 10Hz beams with a simplified ReMPI setup

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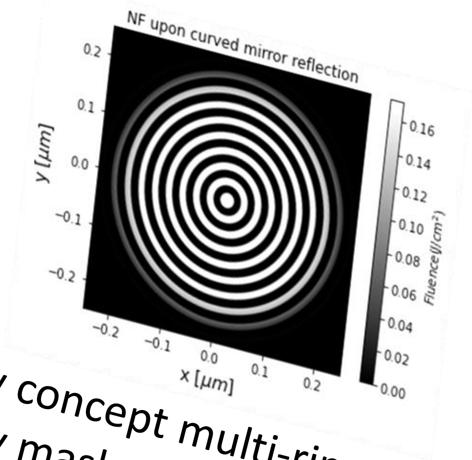
eli attosecond



New concept multi-ring delay mask splitting (Tomassini/Labate/Gizzi)

6J,23fs Ti:Sa

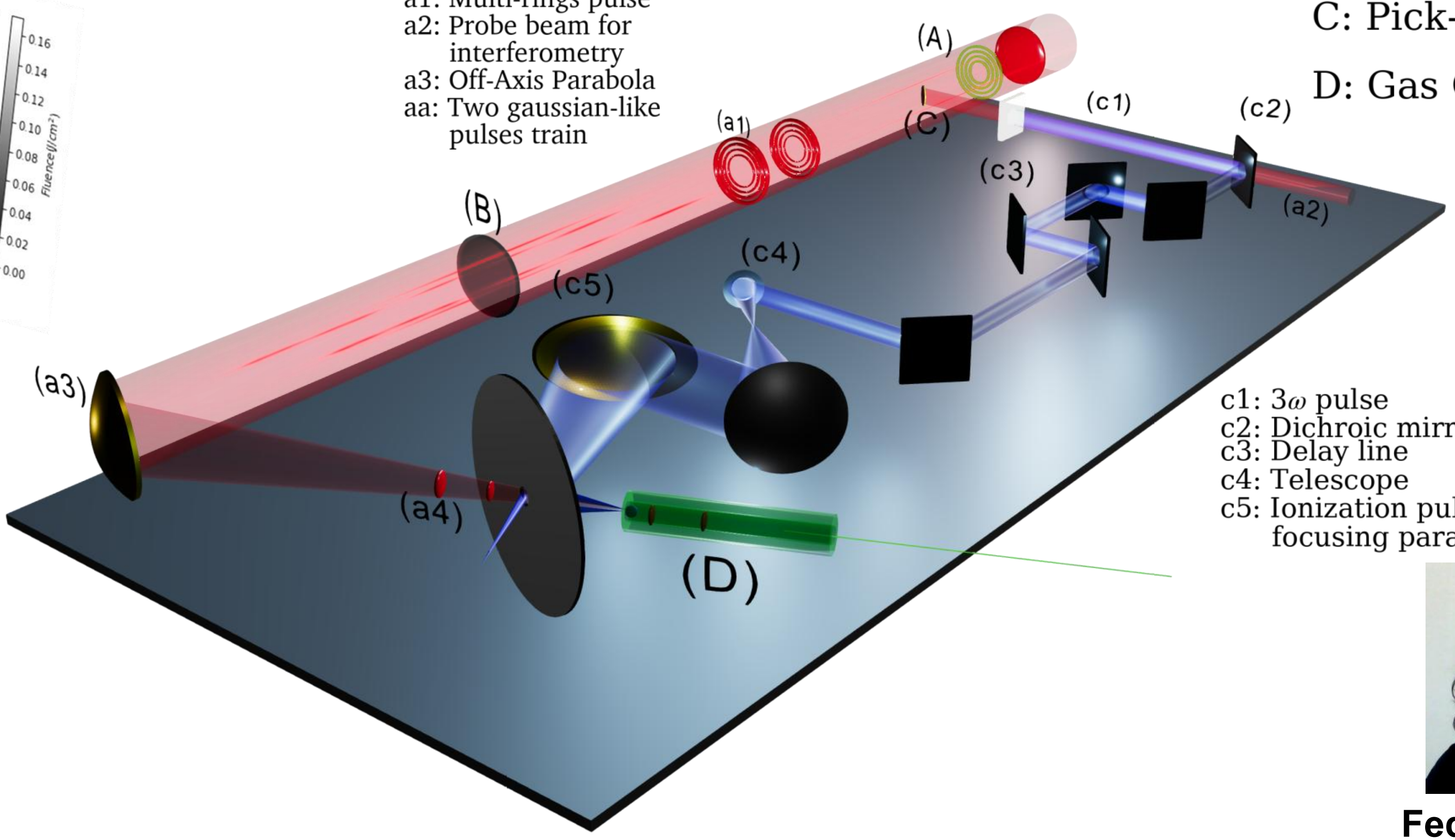
A: Delay Mask

B: $\lambda/4$ plate

C: Pick-off Mirror

D: Gas Cell

a1: Multi-rings pulse
a2: Probe beam for interferometry
a3: Off-Axis Parabola
aa: Two gaussian-like pulses train



c1: 3ω pulse
c2: Dichroic mirror
c3: Delay line
c4: Telescope
c5: Ionization pulse focusing parabola

Federico Avella
Ph. D. student@INO
(co tutoring)

P. Tomassini et al.,"Ultra-High-Brightness and tuneable attosecond-long electron beams with the Laser Wake Field Acceleration", *https://www.researchsquare.com/article/rs-6889281/v1 (submitted)*

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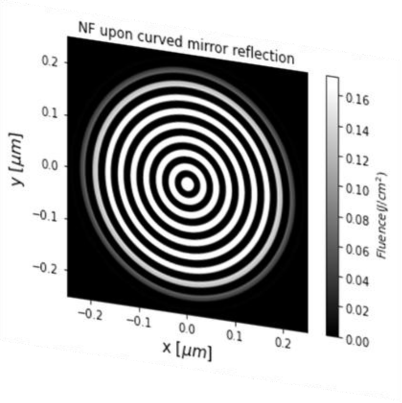
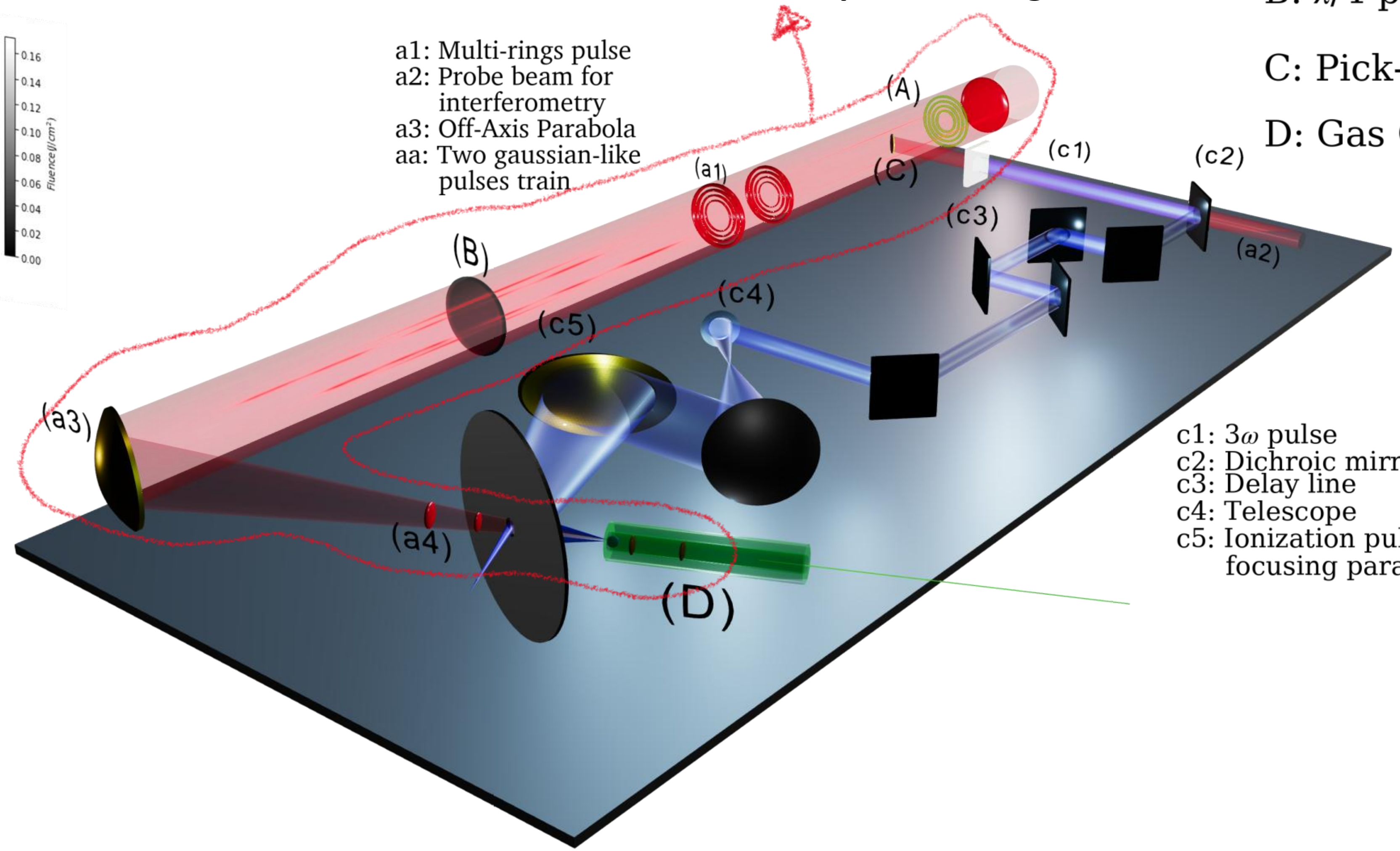
Theory @ LDED
eli attosecond



Stable driver pulse train generation



A: Delay Mask

B: $\lambda/4$ plate

C: Pick-off Mirror

D: Gas Cell

c1: 3ω pulse
c2: Dichroic mirror
c3: Delay line
c4: Telescope
c5: Ionization pulse focusing parabola

Federico Avella
Ph. D. student@INO
(co tutoring)

P. Tomassini et al.,"Ultra-High-Brightness and tuneable attosecond-long electron beams with the Laser Wake Field Acceleration"*, https://www.researchsquare.com/article/rs-6889281/v1 (submitted)*

REMINDER High-fidelity PIC simulations with structured pulses

Virtual Lab Infrastructure **LP4PIC package (Laser to PIC interface)**

SG @ ELI-NP Simulation Group

(P. Tomassini, F. Avella)

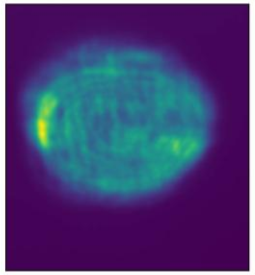
TO PIC (OUTPUT)

Federico Avella
Ph. D. student@INO
(co tutoring)

Solve the Helmoltz equation for the propagation

$$2ik_0\partial_z \hat{E}(x,y,z) = \nabla_\perp^2 \hat{E}(x,y,z)$$

INPUT



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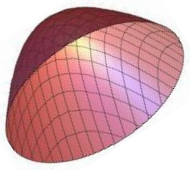
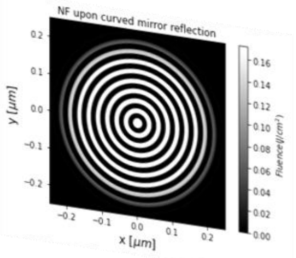


NF Image

+

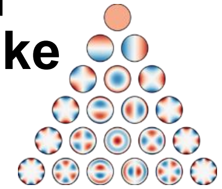
Add Masks



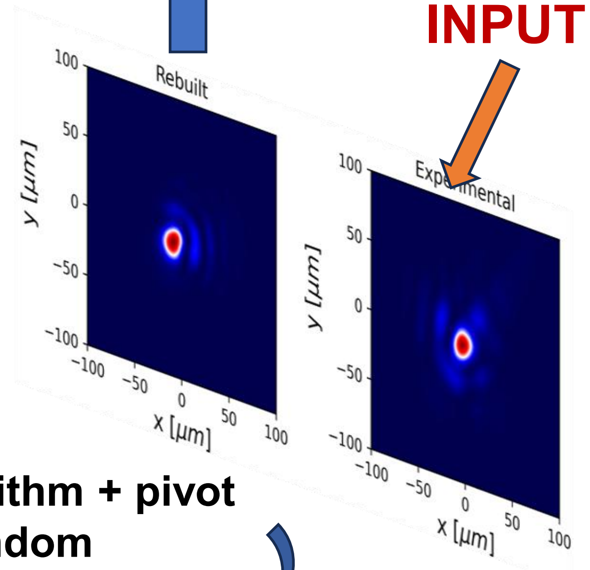
+

Add aberrations

Z=[z_1,…, z_N]
List of Zernike Polinomial coefficients



INPUT



F. Avella, P. Tomassini et al., "Automatic reconstruction of the laser transverse intensity and phase structures near the focal plane for advanced Particle In Cell modelling", to be submitted **on J. Comp. Physics**

Optimization

1. Genetic algorithm + pivot preceded by random sampling of the Nth dimensional space

2. Gerchberg-Saxton loop

Theory @ LDED

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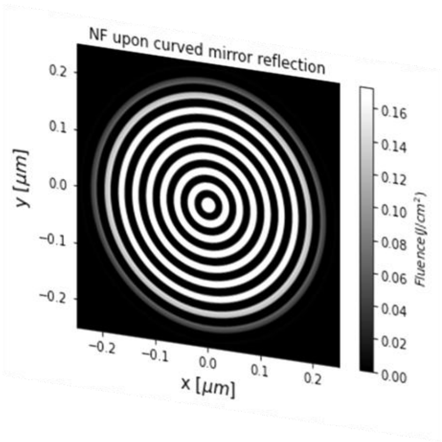
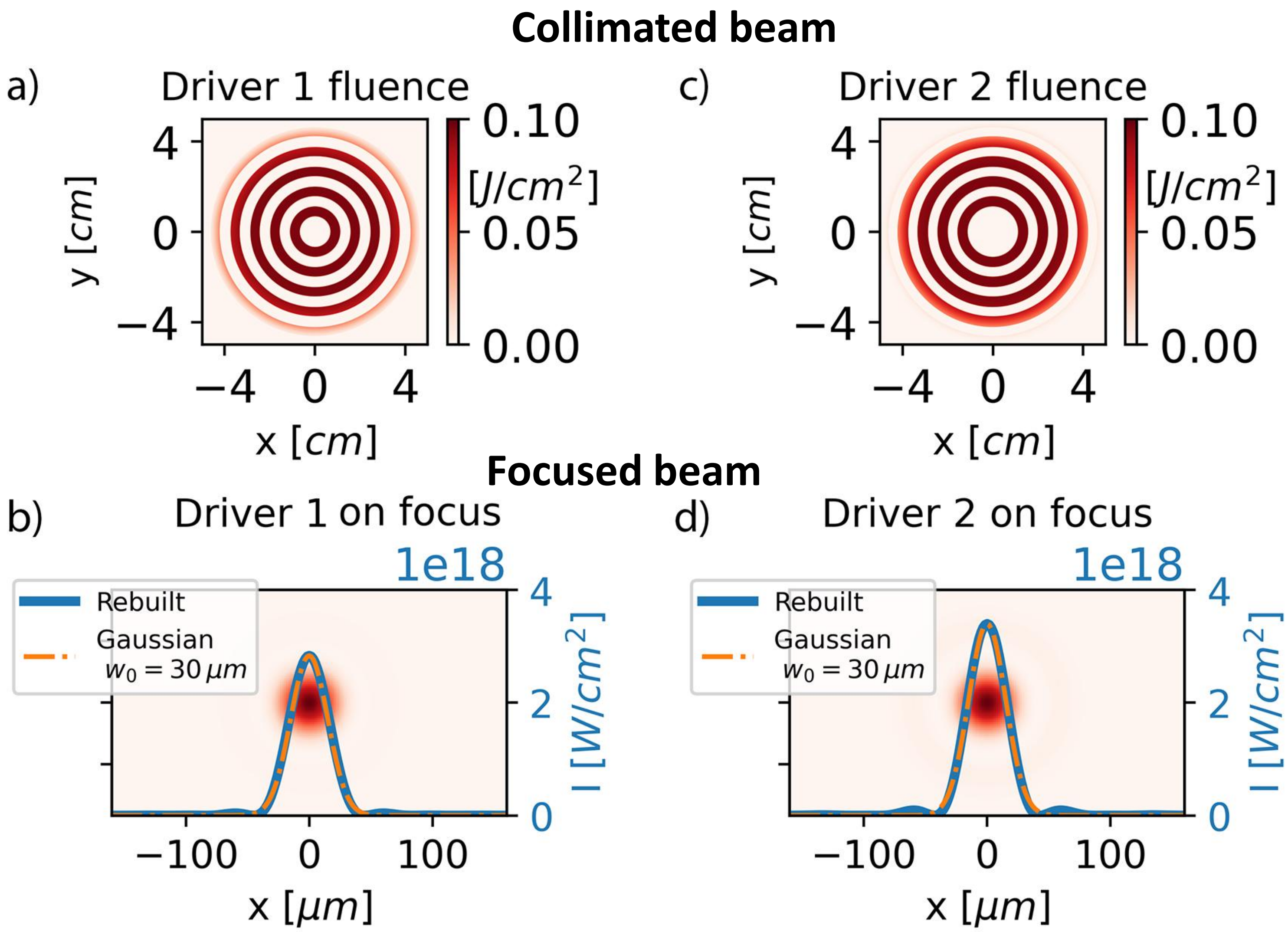
Theory @ LDED

eli attosecond

Stable driver pulse train generation

Federico Avella
Ph. D. student@INO
(co tutoring)





P. Tomassini et al.,"Ultra-High-Brightness and tuneable attosecond-long electron beams with the Laser Wake Field Acceleration", https://www.researchsquare.com/article/rs-6889281/v1 *(submitted)*

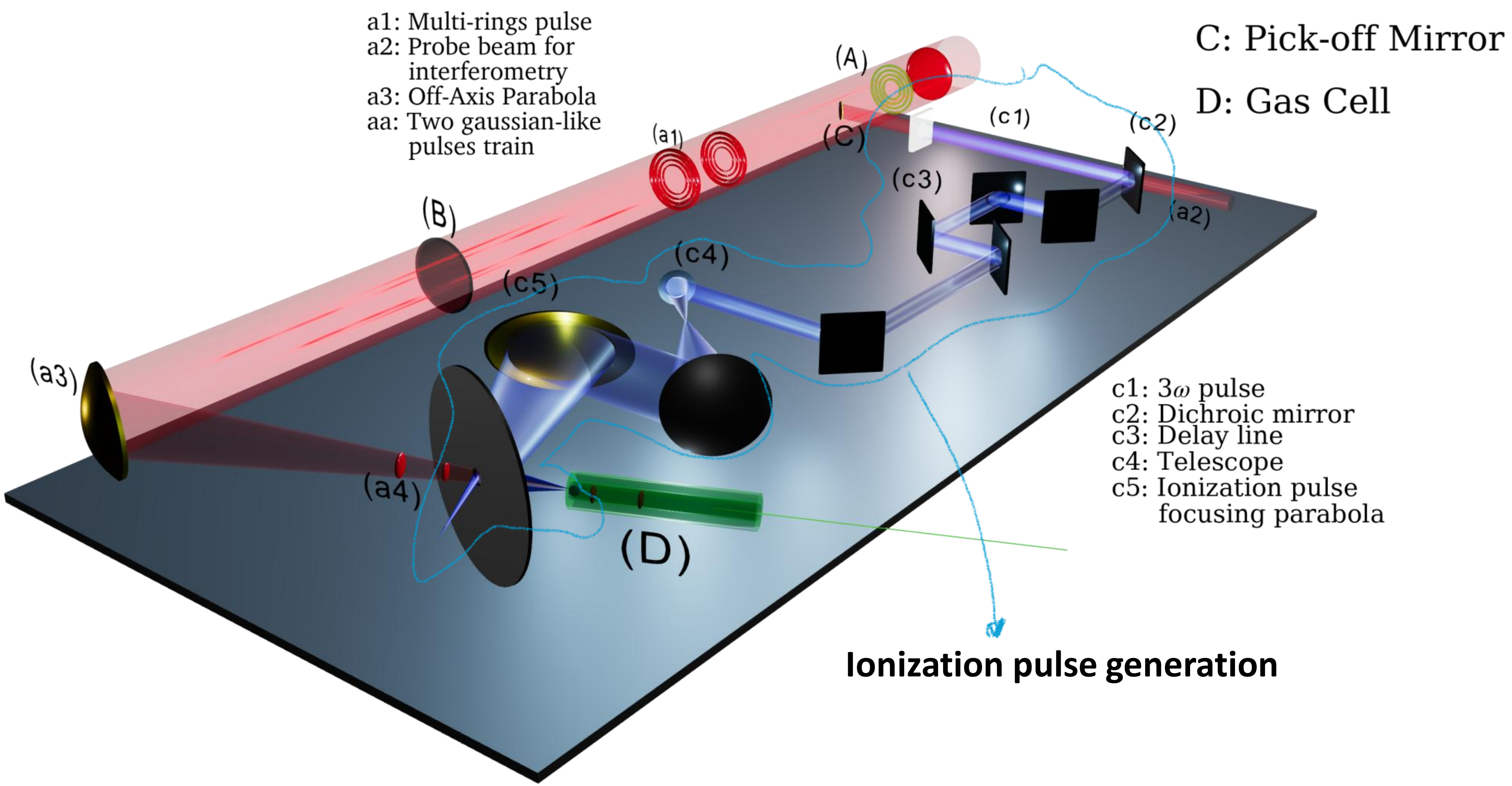
High-brightness 340as long 2GeV 10Hz beams with a simplified ReMPI setup

A: Delay Mask

B: $\lambda/4$ plate

C: Pick-off Mirror

D: Gas Cell

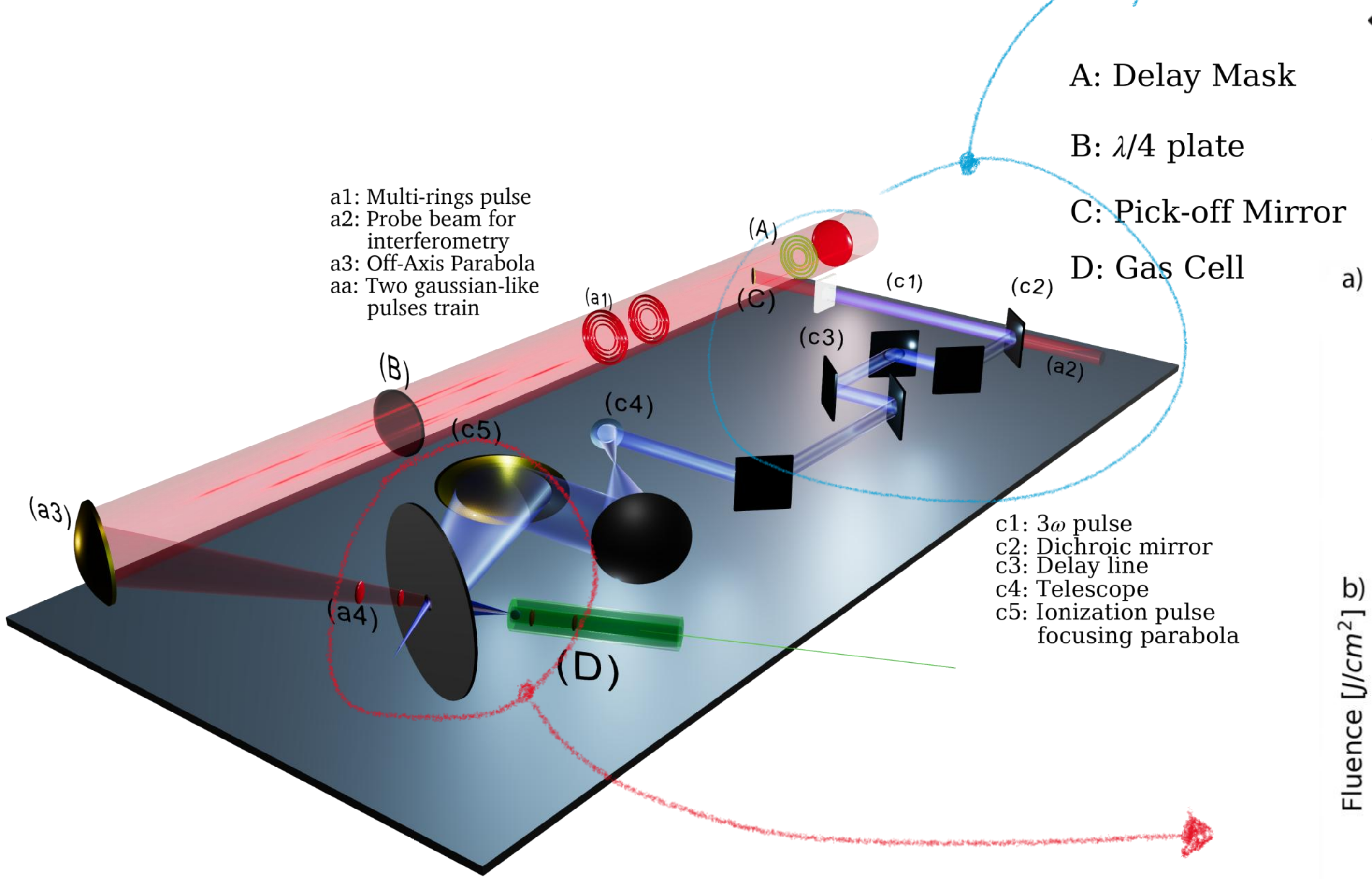


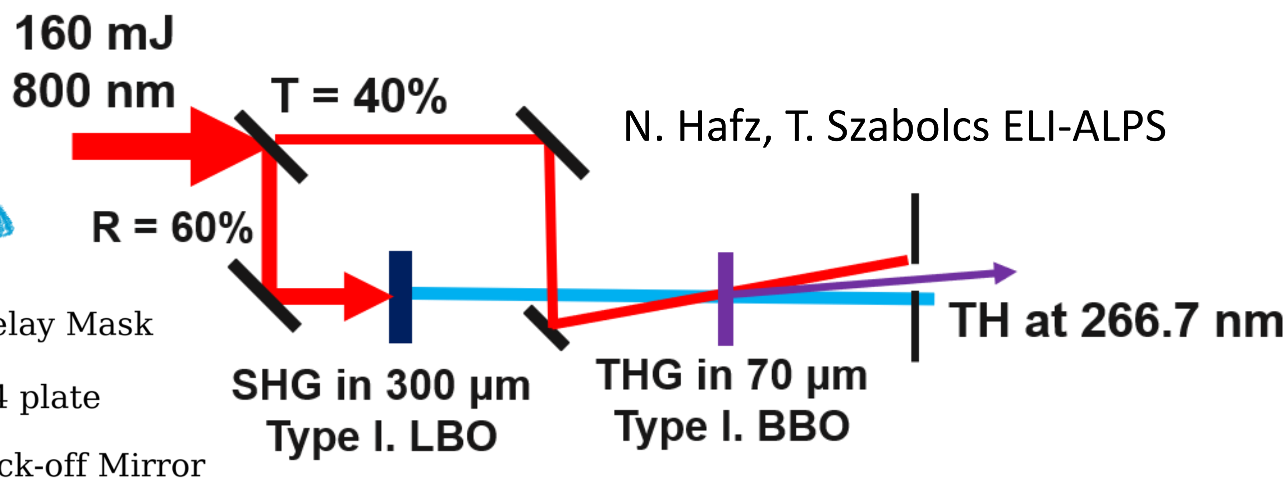
Ionization pulse generation

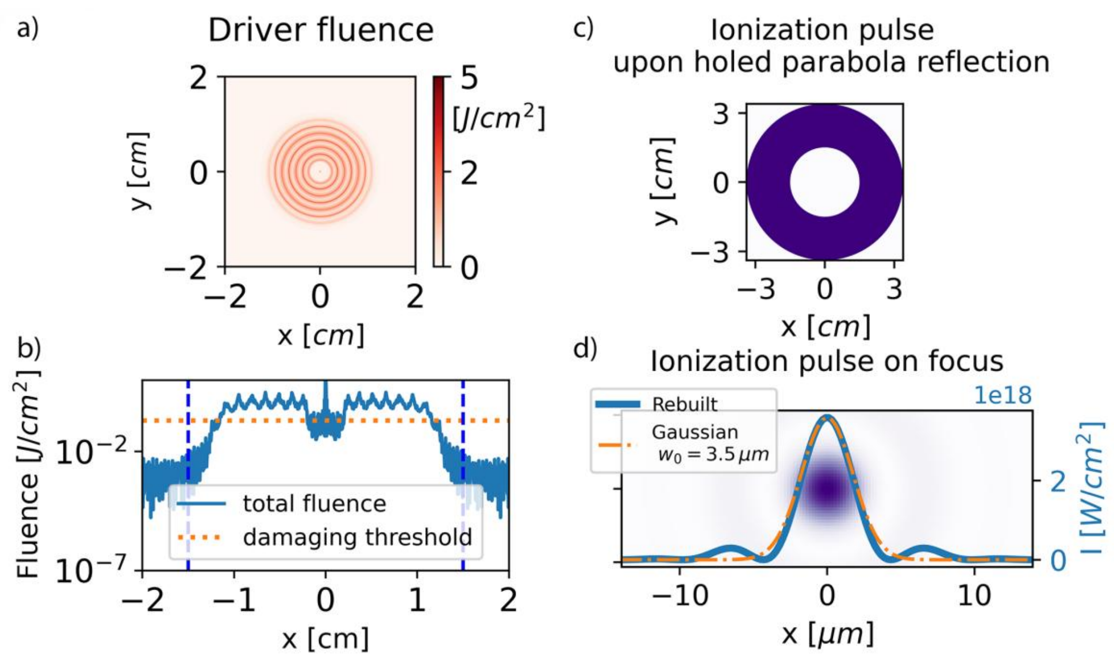
*P. Tomassini et al.,"*Ultra-High-Brightness and tuneable attosecond-long electron beams with the Laser Wake Field Acceleration*", https://www.researchsquare.com/article/rs-6889281/v1 (submitted)*

CNR INO CONSIGLIO NAZIONALE DELLE RICERCHE ISTITUTO NAZIONALE DI OTTICA — Theory @ LDED — eli attosecond

Ionization pulse generation





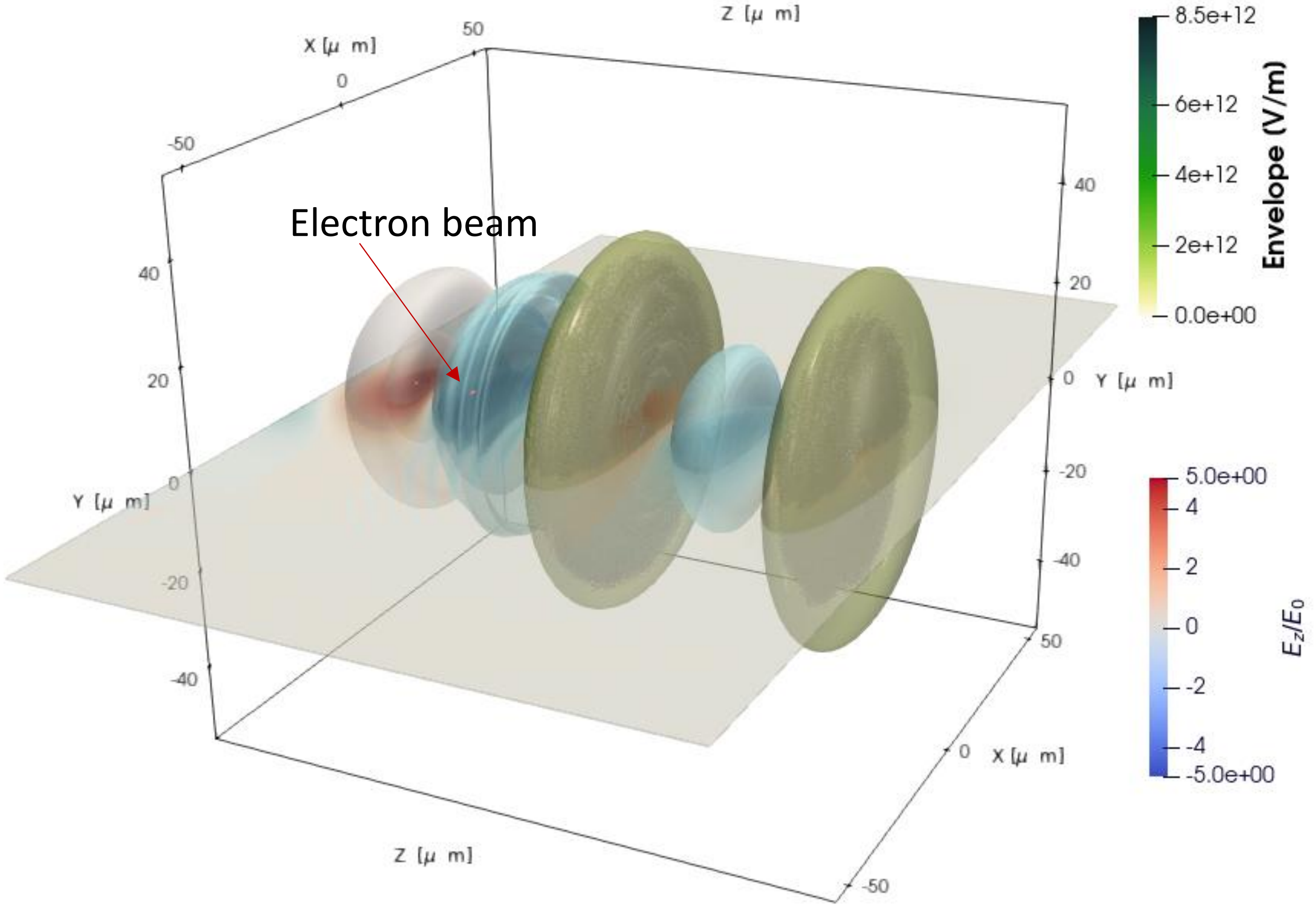


Ionization pulse on focus

P. Tomassini et al.,"Ultra-High-Brightness and tuneable attosecond-long electron beams with the Laser Wake Field Acceleration", https://www.researchsquare.com/article/rs-6889281/v1 *(submitted)*

High-brightness 340as long 2GeV 10Hz beams with a simplified ReMPI setup

CNR INO CONSIGLIO NAZIONALE DELLE RICERCHE ISTITUTO NAZIONALE DI OTTICA · Theory @ LDED · eli attosecond



SINGLE Ti:Sa 200TW/300TW laser system, Circularly Polarised pulses

DRIVER
- 2x 23fs FWHM pulses, w0=30 μm
- Total 5.6 J on TEM00,

IONIZATION
- 1x 30fs FWHM ionization pulse **in III** harmonics,
- w0=3.5 μm, on TEM00, 20mJ

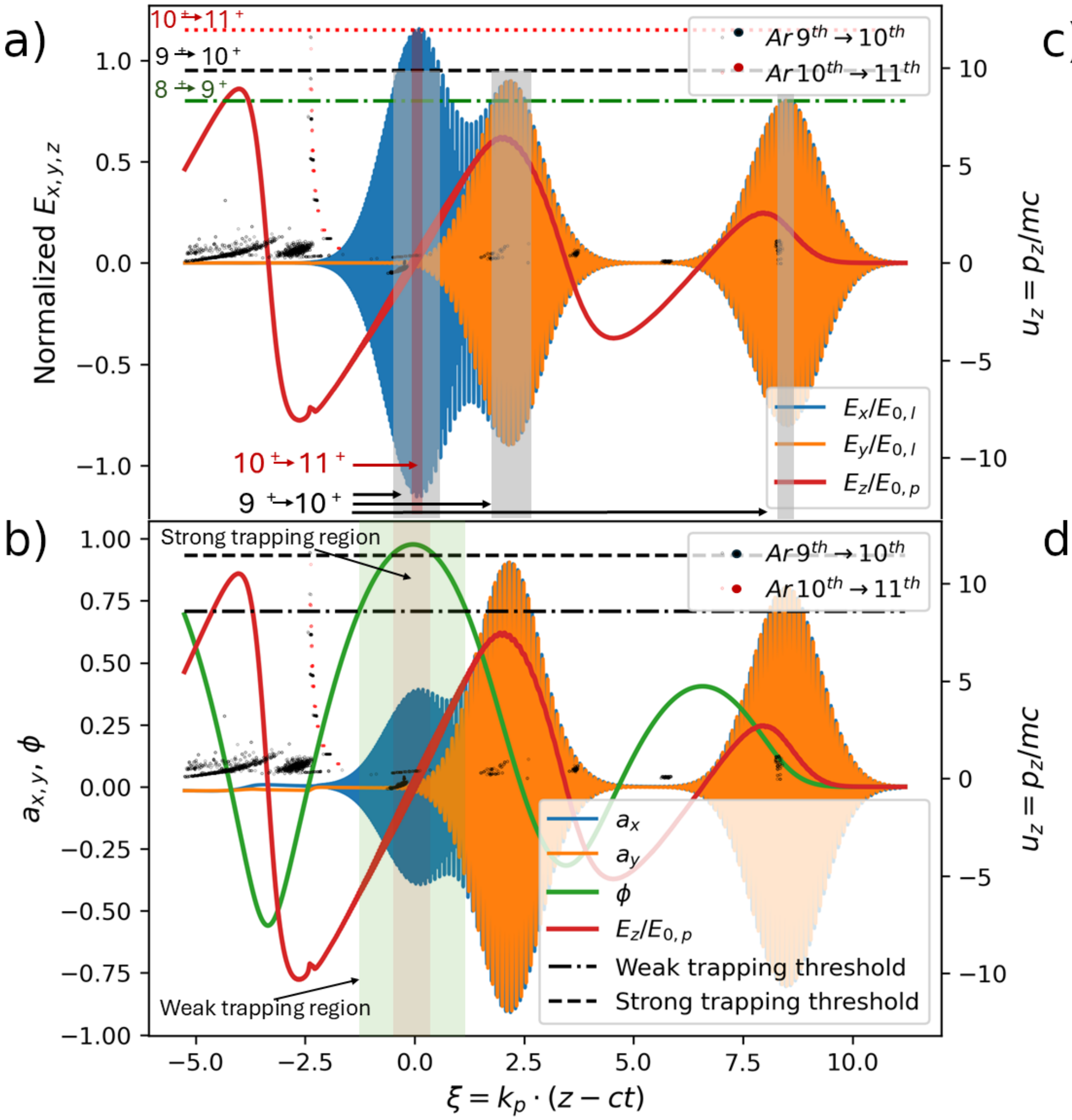
TARGET
- **n0=0.75e18 1/cm^3,**
- **100%Ar 1mm (injection)**
  100%He 30mm accelerating structure, guided pulse with radially parabolic density profile

q3D (FB-PIC) simulations:
Nm=3 angular modes
dz=10nm, dr=25nm, dt =4.6as
Lorentz Boost (γ =10)
48H100, ELI-NP cluster

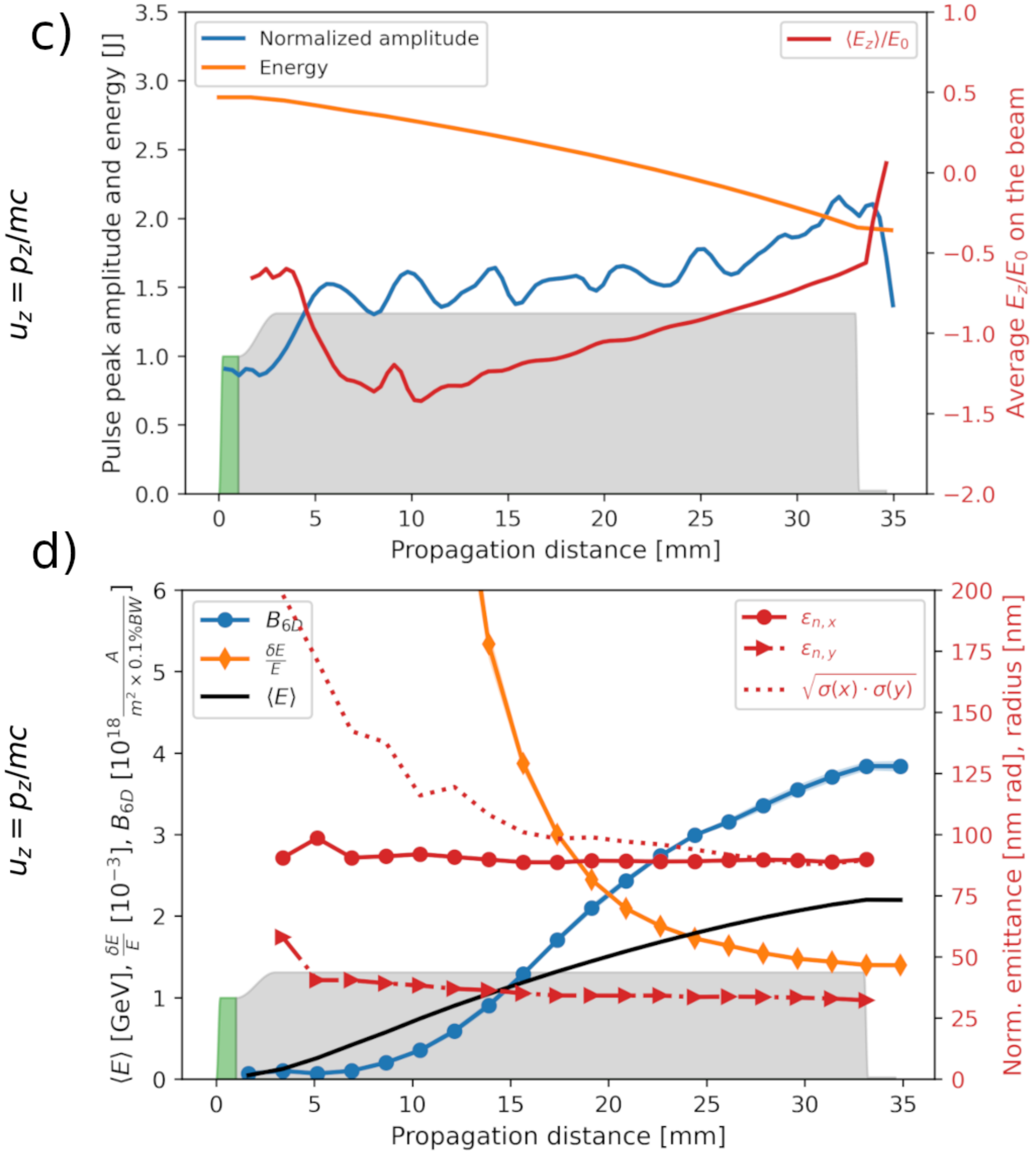
*P. Tomassini et al.,"*Ultra-High-Brightness and tuneable attosecond-long electron beams with the Laser Wake Field Acceleration*", https://www.researchsquare.com/article/rs-6889281/v1 (submitted)*

High-brightness 340as long 2GeV 10Hz beams with a simplified ReMPI setup

Dark current free beams

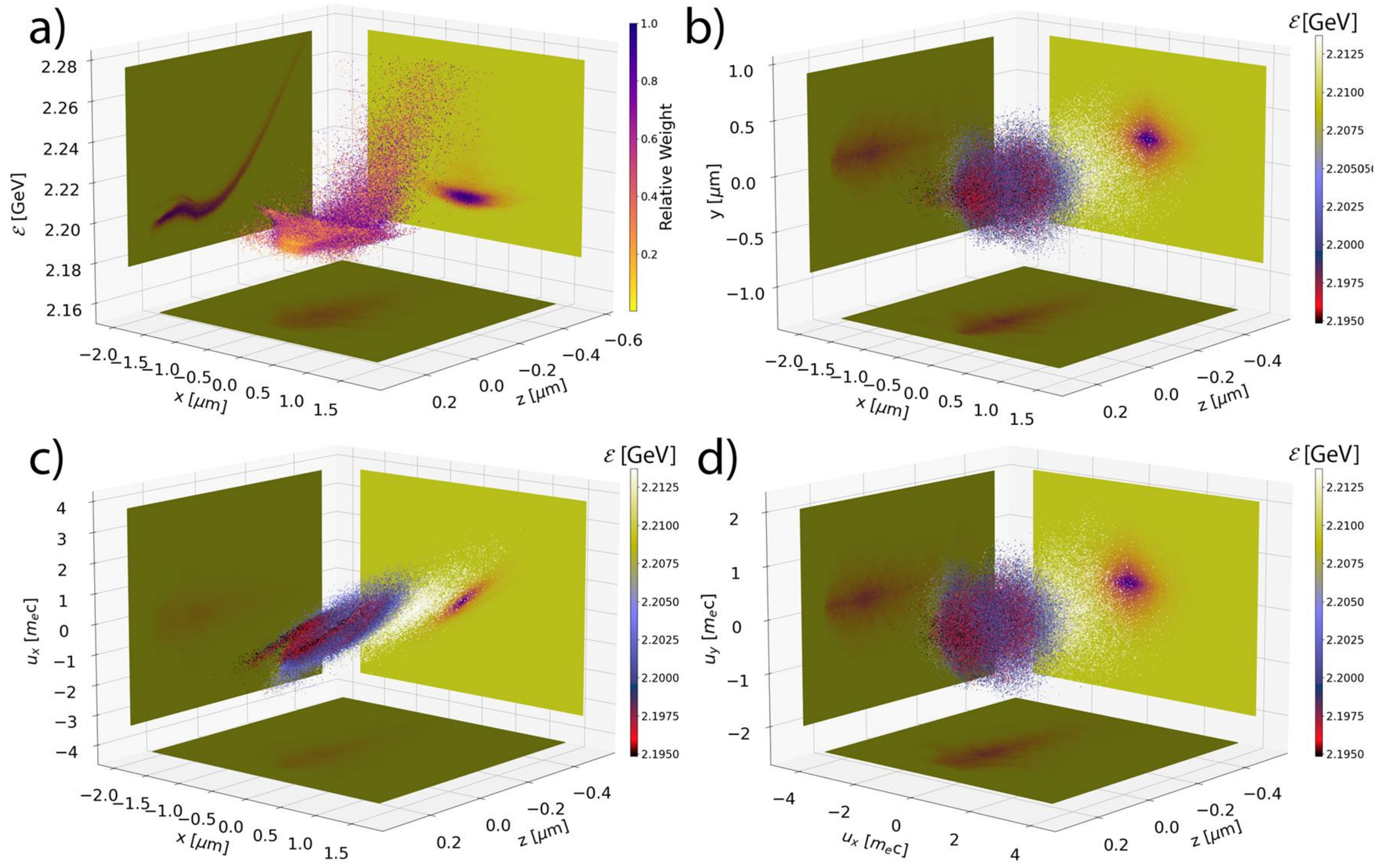


Laser/beam evolution



High-brightness 340as long 2GeV 10Hz beams with a simplified ReMPI setup

Final electron beam



Projected quality

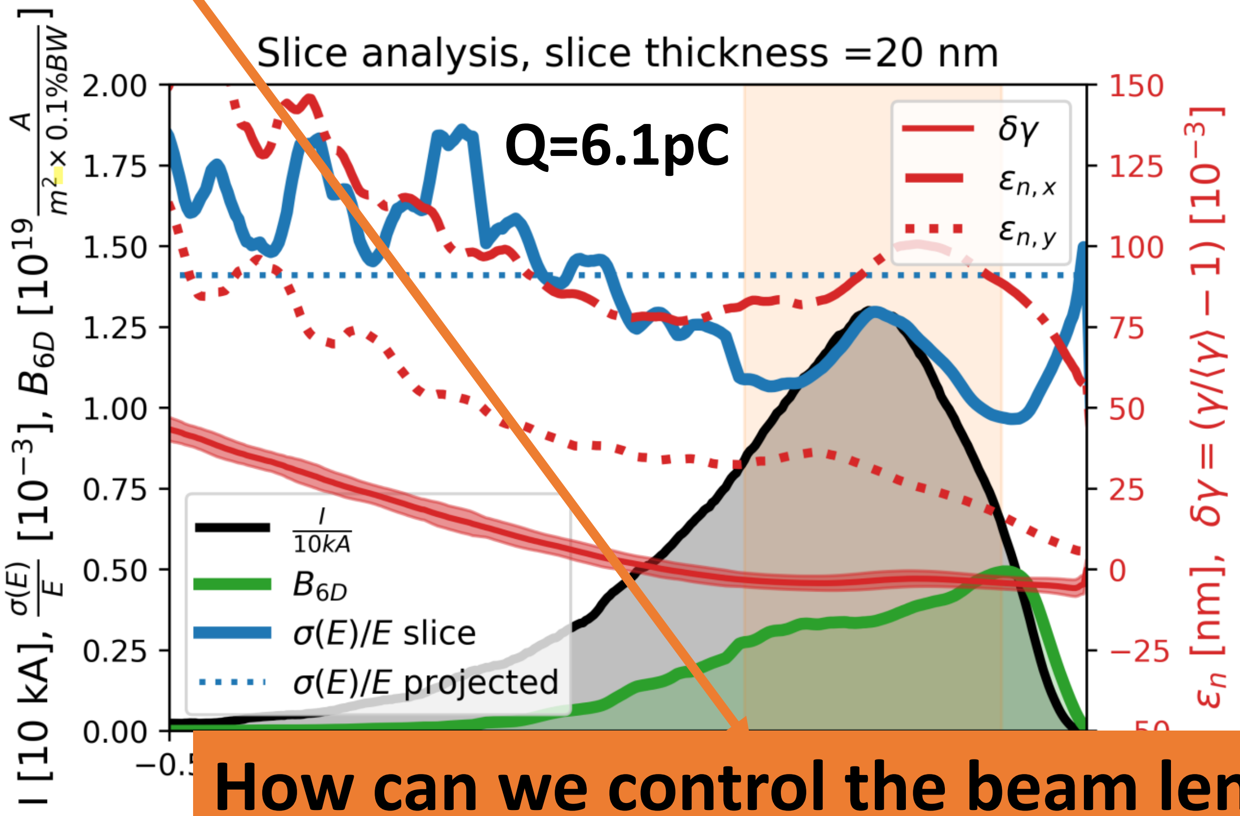
Duration (rms)	350 as
Brightness 6D	$4\ 10^{18} A/m^2 0.1\%BW$
δE/E (rms)	0.14%
Norm. Emittance	$\epsilon_{n,x} = 90nm$ $\epsilon_{n,y} = 32nm$
Current	12kA
Charge	6.1 pC

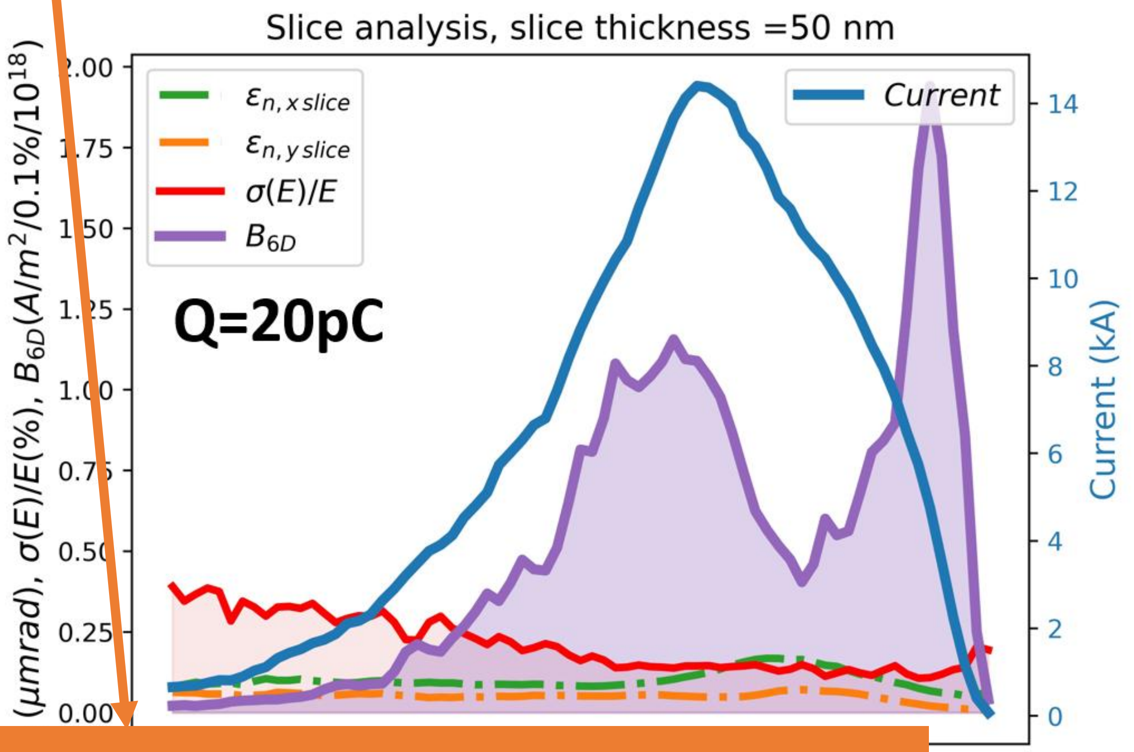
*P. Tomassini et al.,"*Ultra-High-Brightness and tuneable attosecond-long electron beams with the Laser Wake Field Acceleration*",* https://www.researchsquare.com/article/rs-6889281/v1 *(submitted)*

High-brightness 340as long 2GeV 10Hz beams with a simplified ReMPI setup

Duration (rms)	Projected Brighthess 6D	δE/E (rms)
350 as	$4\ 10^{18} A/m^2 0.1\% BW$	0.14%

Duration (rms)	Projected Brighthess 6D	δE/E (rms)
600 as	$5 \cdot 10^{17} A/m^2/0.1\%$	0.7%





How can we control the beam length? How short a beam can be?

FEL-oriented

Theory@LDED

Thomson BS oriented

P. Tomassini et al.,"Ultra-High-Brightness and tuneable attosecond-long electron beams with the Laser Wake Field Acceleration"*,* *https://www.researchsquare.com/article/rs-6889281/v1 (submitted)*

Fine tuning of the beam length in two-color/ReMPI/trojan-horse schemes

nuclear physics — Theory @ LDED

Article

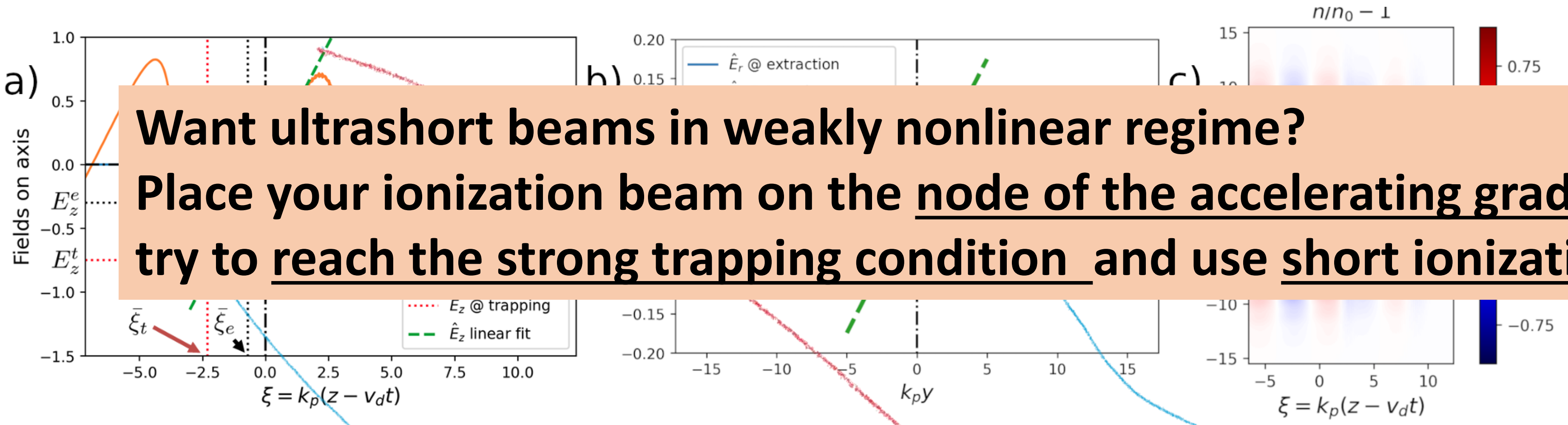
Attosecond Pulses from Ionization Injection Wakefield Accelerators

Paolo Tomassini [1,2,*], Vojtech Horny [1] and Domenico Doria [1]

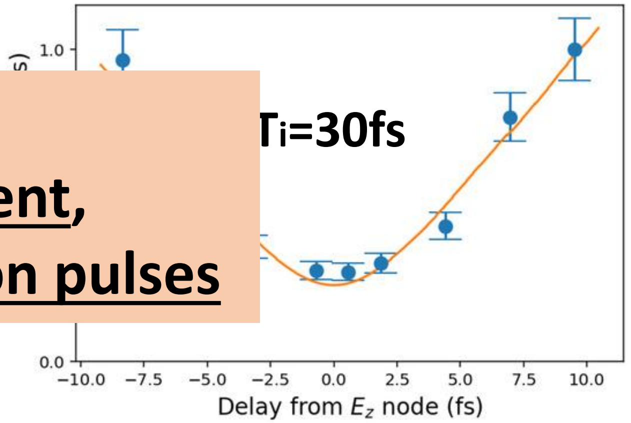
https://doi.org/10.3390/instruments7040034

Proc of PAHBB San Sebastien 2023 [Ed. A. Chianchi, M. Galletti]

Just by tuning the distance between the node of the accelerating gradient and the peak of the ionization pulse we can vary the length of the trapped beam.



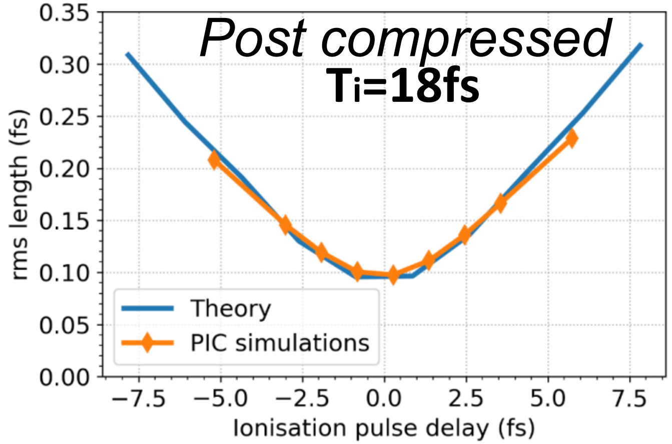
Want ultrashort beams in weakly nonlinear regime?
Place your ionization beam on the node of the accelerating gradient, try to reach the strong trapping condition and use short ionization pulses



$$\sigma(\delta z_f) \gtrsim \frac{k_p \rho_0}{\sqrt{2} E_z^t} \left\{ (\partial_\xi \hat{E}_z^e)^2 \left[\frac{1}{4} + \left(\frac{\bar{z}_e}{\sqrt{\rho_0} L_i} \right)^2 \right] L_i^4 + (\partial_{k_p r_e} \hat{E}_r^e)^2 w_{0,i}^4 \right\}^{1/2}$$

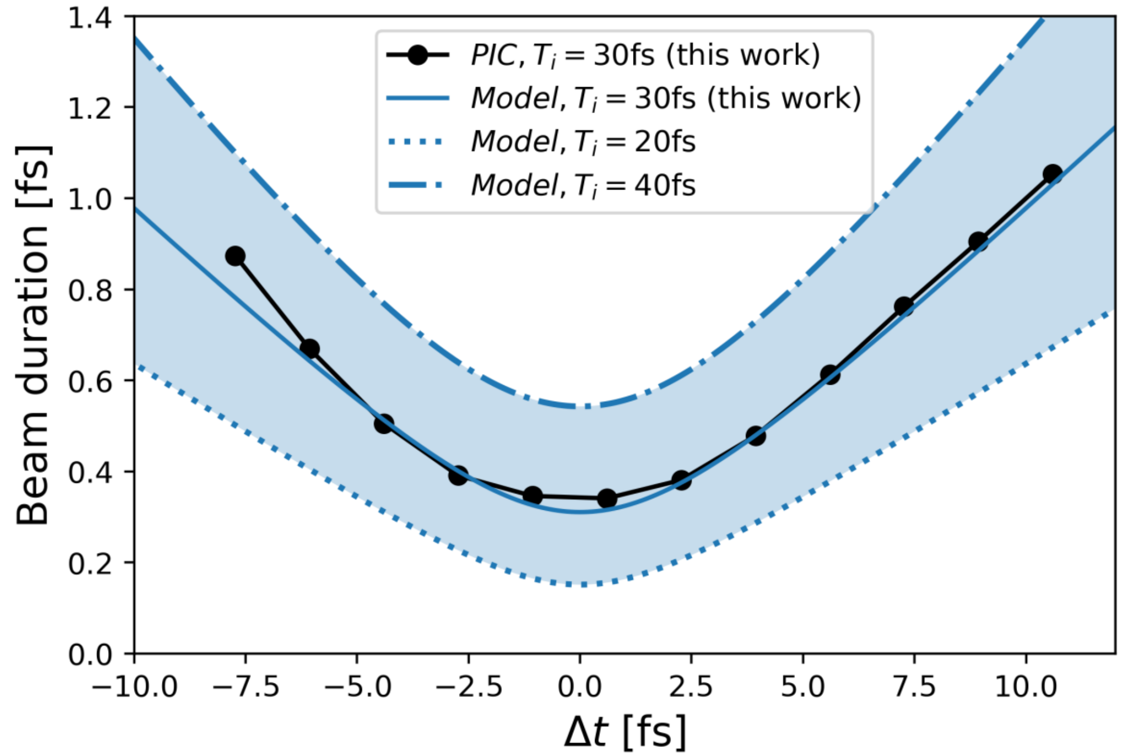
$$\rho_0 \equiv \frac{3E}{2E_a} \left(\frac{U_H}{U_I} \right)^{3/2} = a_0/a_c = \Delta_0^2$$

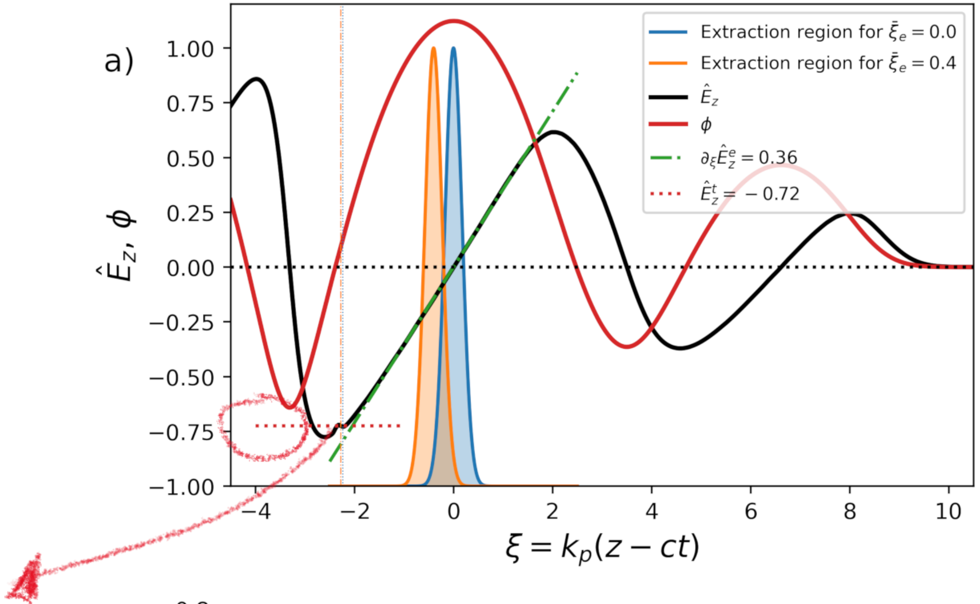
Ionization parameter



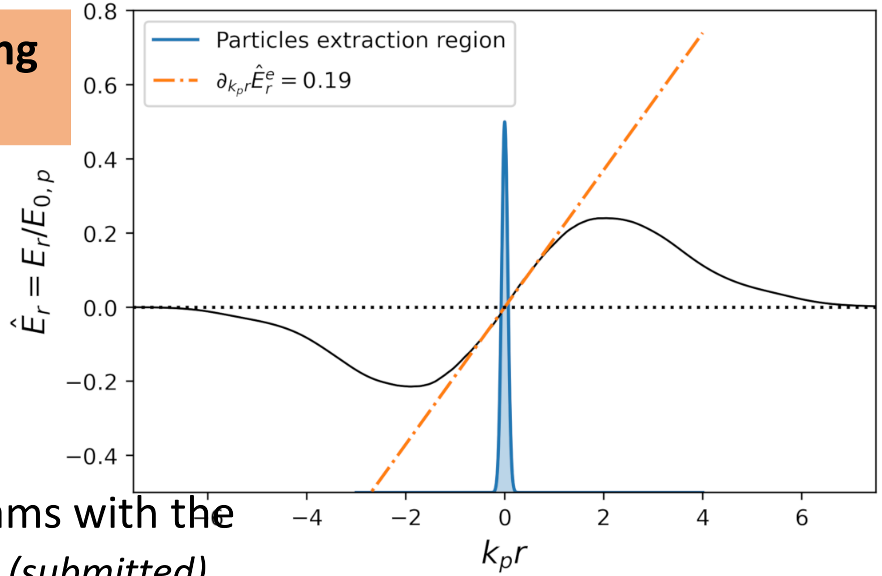
Tuneability of the FEL-oriented beam e-beam duration

$$\hat{E}_z = E_z/E_0;\; E_0 = mc\omega_p/e$$





Strong trapping reached



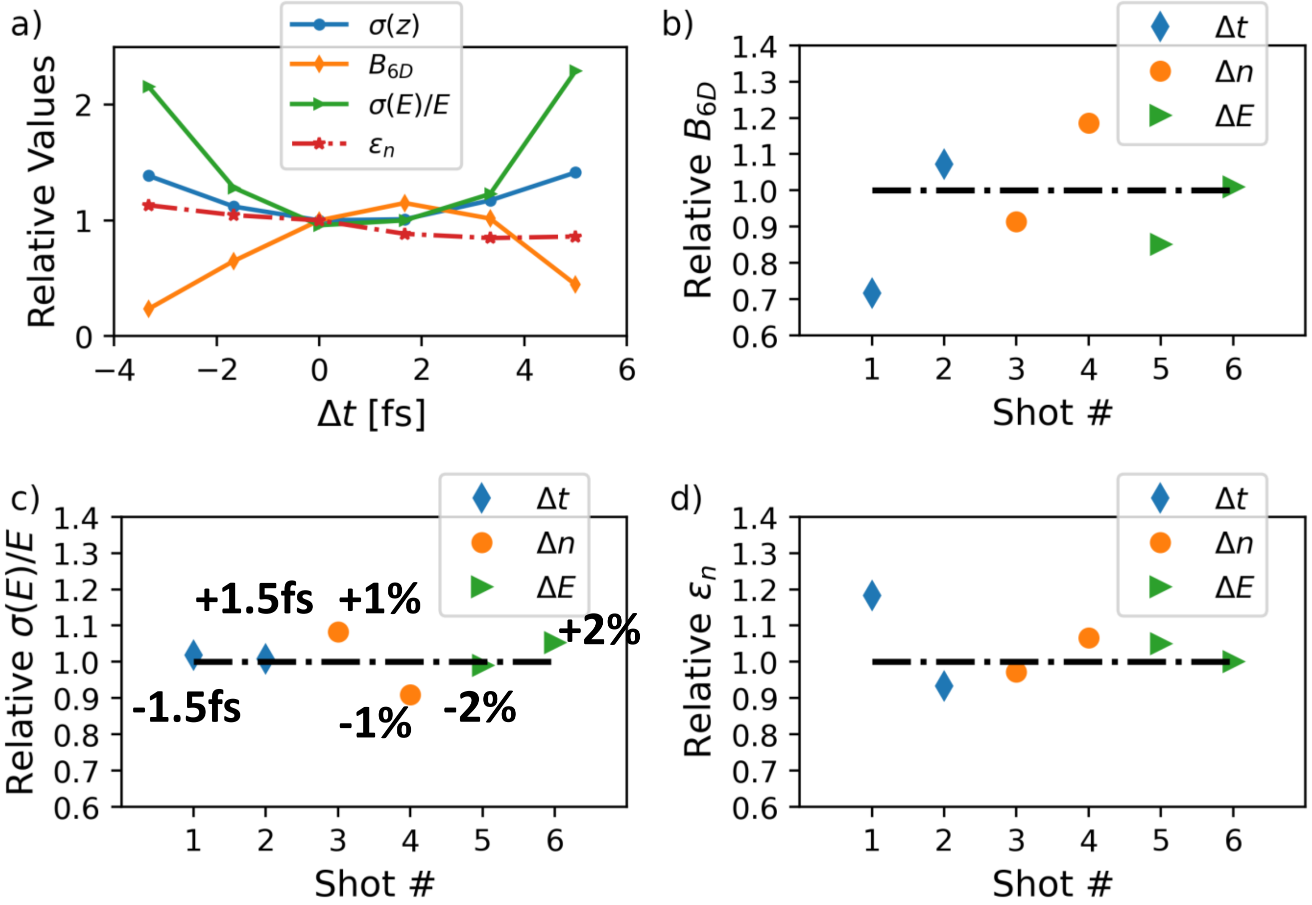
$$\sigma(\delta z_f) \gtrsim \frac{k_p\rho_0}{\sqrt{2}E_z^t}\left\{(\partial_\xi \hat{E}_z^e)^2\left[\frac{1}{4}+\left(\frac{\bar{z}_e}{\sqrt{\rho_0}L_i}\right)^2\right]L_i^4 + (\partial_{k_p r_e}\hat{E}_r^e)^2 w_{0,i}^4\right\}^{1/2}$$

P. Tomassini et al.,"Ultra-High-Brightness and tuneable attosecond-long electron beams with the Laser Wake Field Acceleration", *https://www.researchsquare.com/article/rs-6889281/v1 (submitted)*

Partial stability study. A full stability study should be performed during the experiment preparatory phase, with the actual laser parameters and guiding channel design. This would also include transverse pointing jitter effects.

Base quality parameters

Duration (rms)	350 as
Brightness 6D	$4\ 10^{18} A/m^2 0.1\%BW$
δE/E (rms)	0.14%
Norm. Emittance	$\epsilon_{n,x} = 90nm$ $\epsilon_{n,y} = 32nm$
Current	14kA
Charge	6.1 pC



Δt: driver to ionization-pulse delay variation

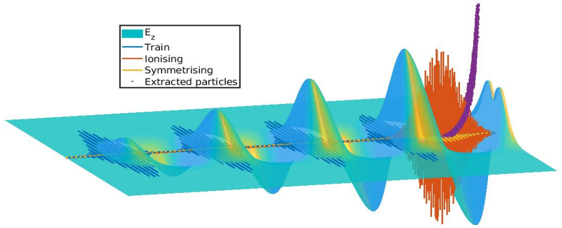
Δn: background density variation

ΔE: Laser pulse energy variation

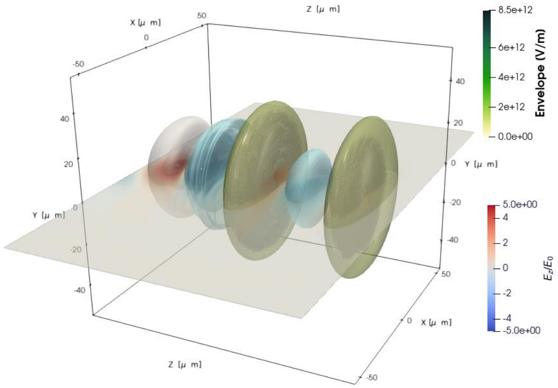
*P. Tomassini et al.,"*Ultra-High-Brightness and tuneable attosecond-long electron beams with the Laser Wake Field Acceleration*", https://www.researchsquare.com/article/rs-6889281/v1 (submitted)*

Outlook

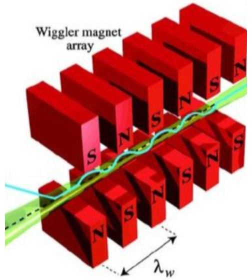
1. The Resonant Multi-Pulse Ionization injection (ReMPI)



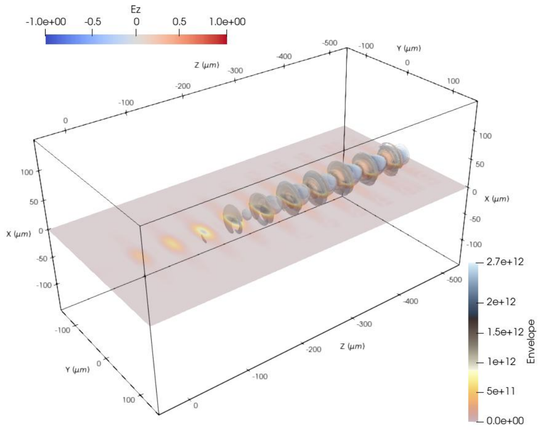
2. High-brightness **340as long** 2.2GeV **10Hz** beams with a simplified ReMPI setup



3. Preliminary FEL simulations in the water-window with the **10Hz** 2.2GeV ReMPI beam



4. High-brightness **kHz**, >1GeV beams with a P-MoPA/ReMPI scheme



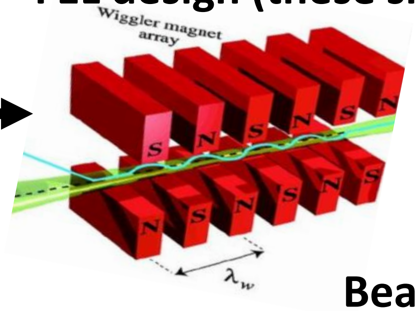
INFN Istituto Nazionale di Fisica Nucleare

Preliminary simulations of the FEL performances, **no beam transport simulations made at this stage. They will be part of a near term start-to-end simulation**

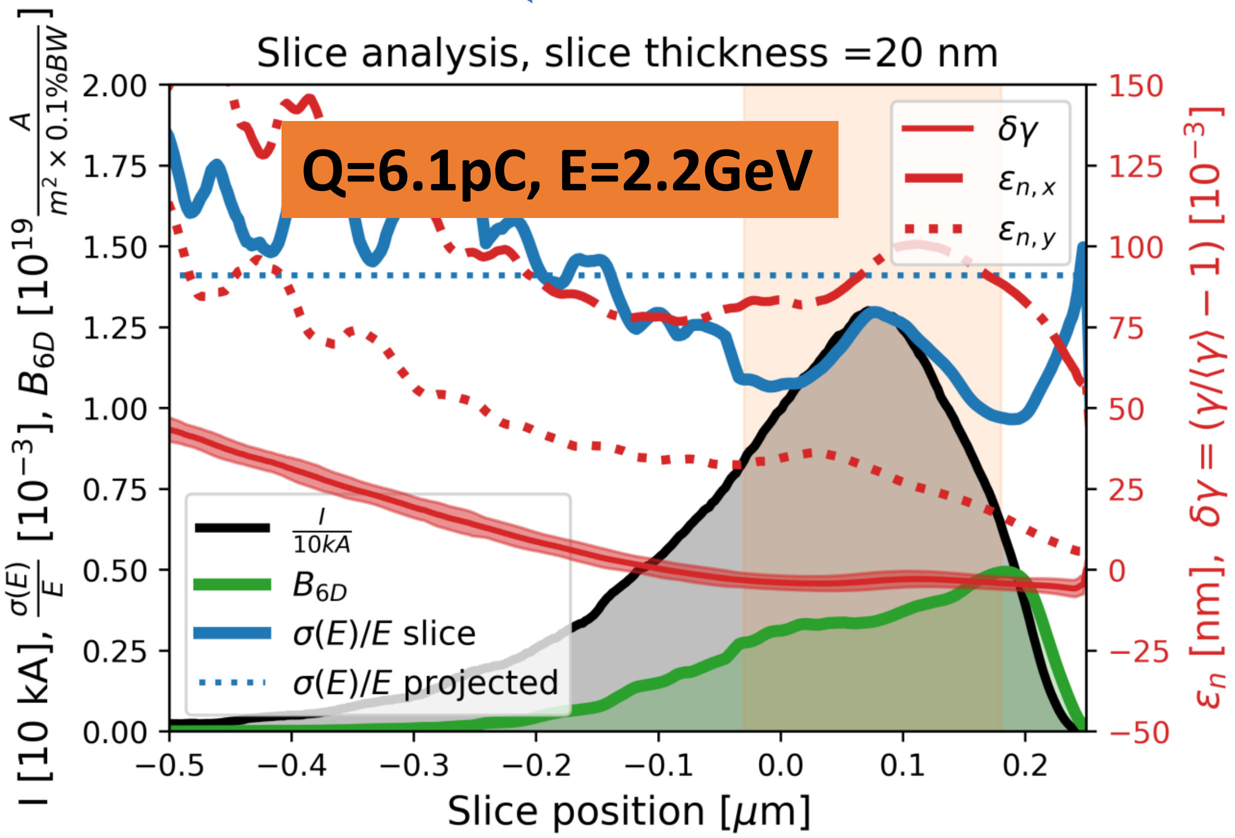
eli nuclear physics

2.2GeV → Beam Transport (TBD) → **FEL design (these slides)**

LPA



V. Petrillo/L. Serafini/INFN-MI

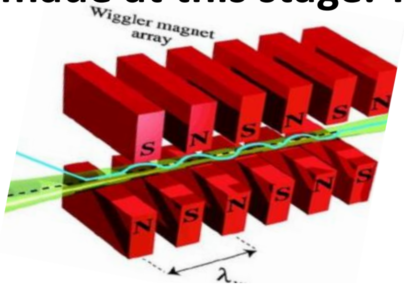


Beam quality

Duration (rms)	**350 as**
Peak Brightness 6D	$5\ 10^{18} A/m^2 0.1\%BW$
δE/E @peak (rms)	0.12%
Norm. Emittance@ peak	$\epsilon_{n,x} = 150nm$ $\epsilon_{n,y} = 80nm$
Peak Current	13kA

Preliminary FEL simulations in the water-window with the **10Hz** 2.2GeV ReMPI beam

Preliminary simulations of the FEL performances, **no beam transport simulations made at this stage. They will be part of a near term start-to-end simulation**



FEL design, simulations obtained with GENESIS1.3

V. Petrillo/L. Serafini/INFN-MI

$$K_u = \frac{eB_0}{k_u m_e c} \qquad \lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{1}{2}K_u^2\right)$$

$$\rho^3 = \frac{I}{4I_A}\frac{\gamma K_u^2 [JJ]^2 (K_u^2)}{(1 + K_u^2/2)^2 (k_r \sigma_x)^2}$$

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

$$\epsilon_n < \gamma\lambda_r/4\pi$$ **Pellegrini criterion**

The SPARC/X SASE-FEL Projects 343

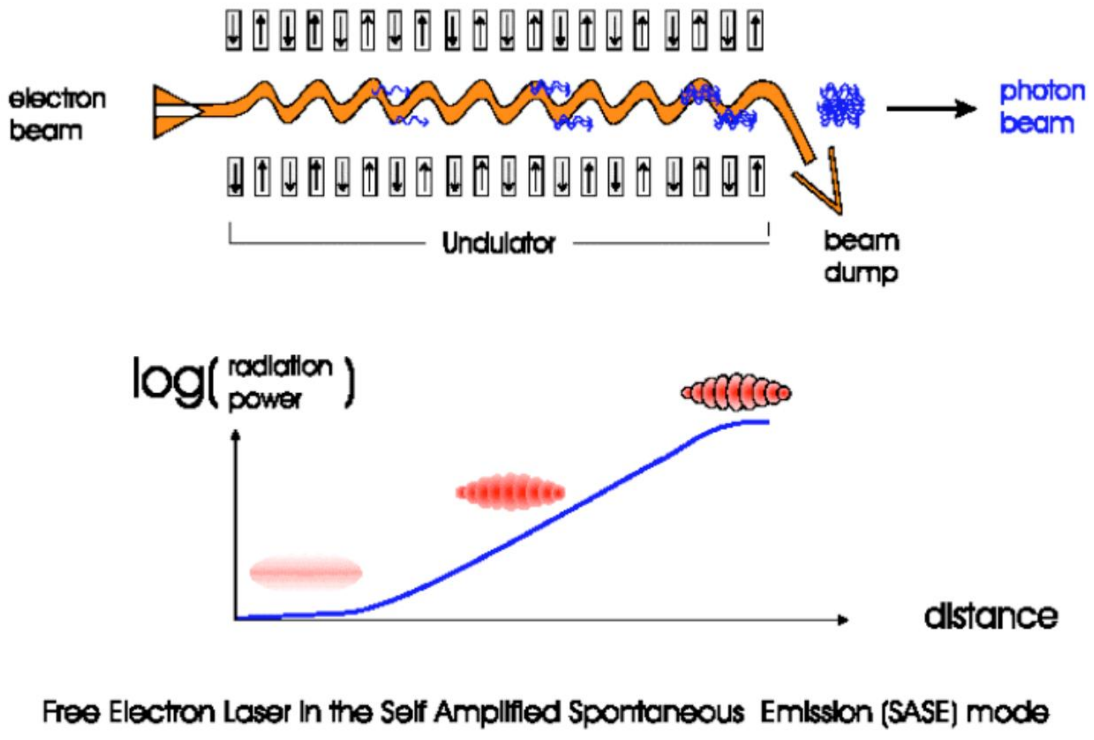
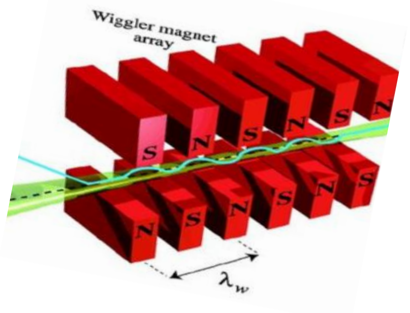


Fig. 2. Schematic Diagram of a Single-Pass Free Electron Laser (FEL) operating in the Self-Amplified-Spontaneous-Emission (SASE) mode [TESLA Design Technical Report, March 2001]. The bunch density modulation (micro-bunching), developing in parallel to the radiation power, is shown in the lower part of the figure. Note that in reality the number of slices is much larger.

Preliminary simulations of the FEL performances, **no beam transport simulations made at this stage. They will be part of a near term start-to-end simulation**



FEL design, simulations obtained with GENESIS1.3

V. Petrillo/L. Serafini/INFN-MI

Due to the very small emittance the beam can be focused to a small waist.
A preliminary value of **w=27 μm** and a tapered undulator with period $\boldsymbol{\lambda_u = 3.5cm}$ were used (based on estimations of beta function, ρ, and saturation length, goal radiation wavelength in the middle of the water-window).

<u>Best slice</u>: $\boldsymbol{\rho_{3D}}\ [5 \times 10^{-3}] \geq \boldsymbol{\delta E/E}\ [1.5 \times 10^{-3}]$ (SASE condition met)

$\boldsymbol{\epsilon_{n,x}}\ [150\ \text{nm}[< \boldsymbol{\gamma\lambda_r/(4\pi)}$ [1050nm]

(Pellegrini criterion easily satisfied)

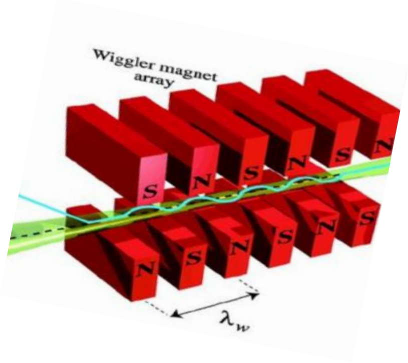
$$K_u = \frac{eB_0}{k_u m_e c} \qquad \lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{1}{2}K_u^2\right)$$

$$\rho^3 = \frac{I}{4I_A}\frac{\gamma K_u^2 [JJ]^2 (K_u^2)}{(1 + K_u^2/2)^2 (k_r \sigma_x)^2}$$

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

$$\epsilon_n < \gamma\lambda_r/4\pi$$ **Pellegrini criterion**

Preliminary FEL simulations in the water-window with the **10Hz** 2.2GeV ReMPI beam

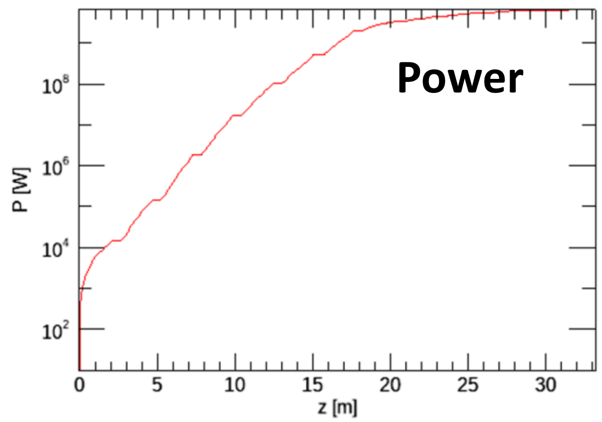


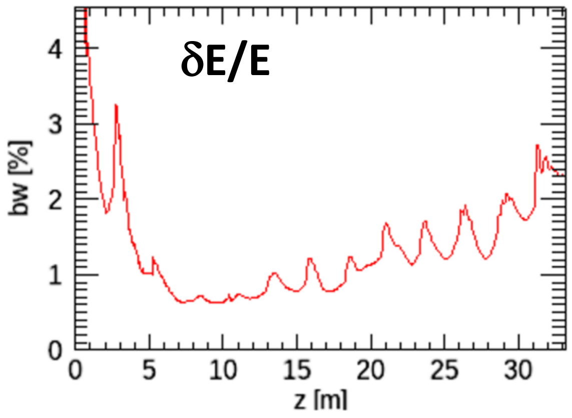
Preliminary simulations of the FEL performances, **no beam transport simulations made at this stage. They will be part of a near term start-to-end simulation**

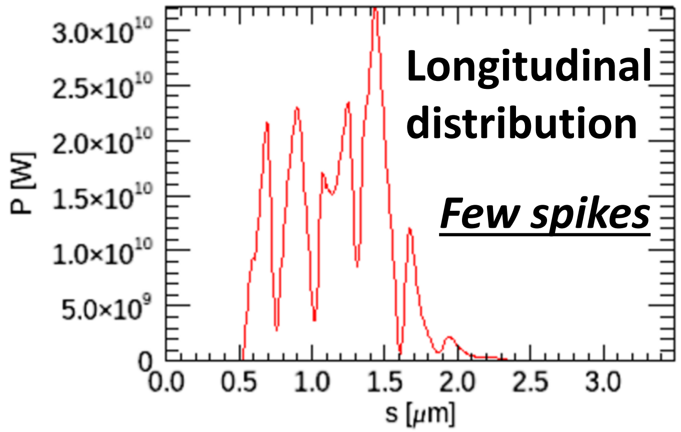
FEL design, simulations obtained with GENESIS1.3

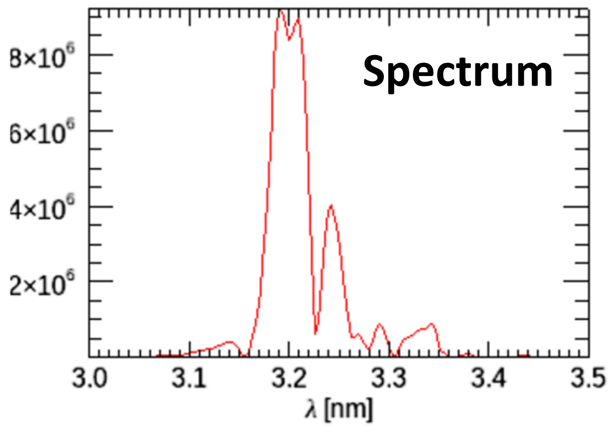
V. Petrillo/L. Serafini/INFN-MI

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









$\lambda_u = 3.5cm$ **K =1.7**

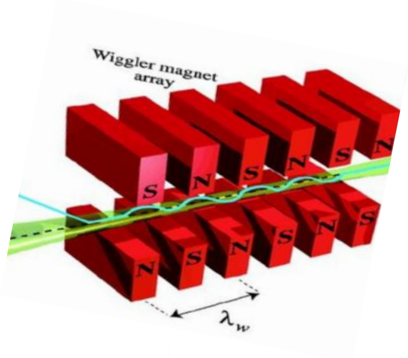
Radiated energy =**75 μ J**

Nγ = **1.2×10^{12} photons/shot**

Bandwidth: **1.5 % at 3.2 nm.**

Undulator length = **20m**

Undulator gradient **- 1.2×** $\mathbf{10^{-3}T/m}$

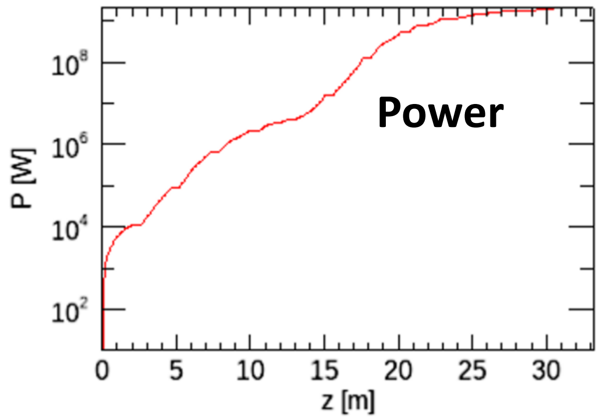


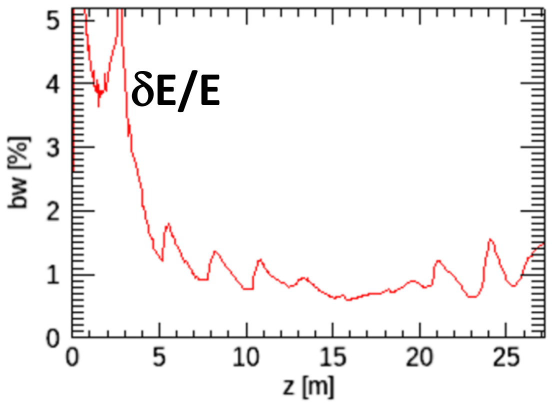
Preliminary simulations of the FEL performances, **no beam transport simulations made at this stage. They will be part of a near term start-to-end simulation**

FEL design, simulations obtained with GENESIS1.3

V. Petrillo/L. Serafini/INFN-MI

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





$\lambda_u = 3.5cm$ **K =1.4**

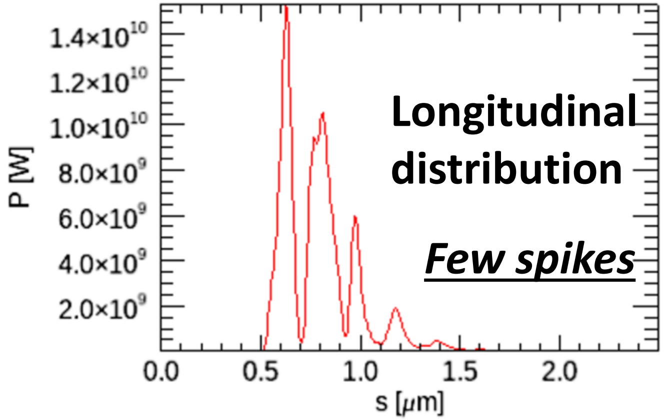
Radiated energy =**17 μ J**

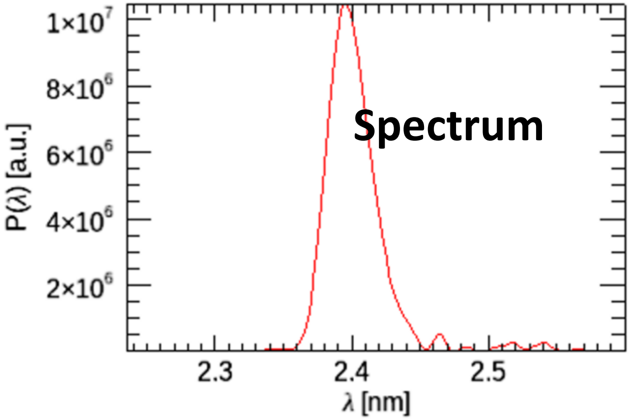
Nγ = **0.2×10^{12} photons/shot**

Bandwidth: **1 % at 2.4 nm**.

Undulator length = **20m**

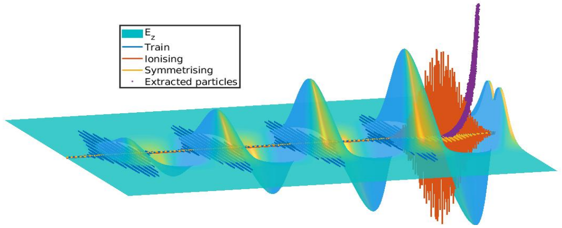
Undulator gradient **- 1.2× $10^{-3}T/m$**



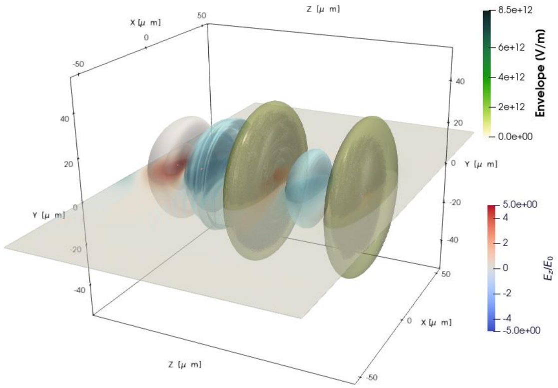


Outlook

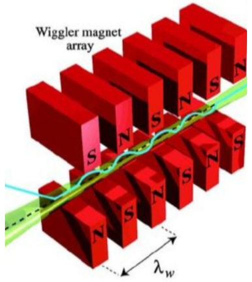
1. The Resonant Multi-Pulse Ionization injection (ReMPI)



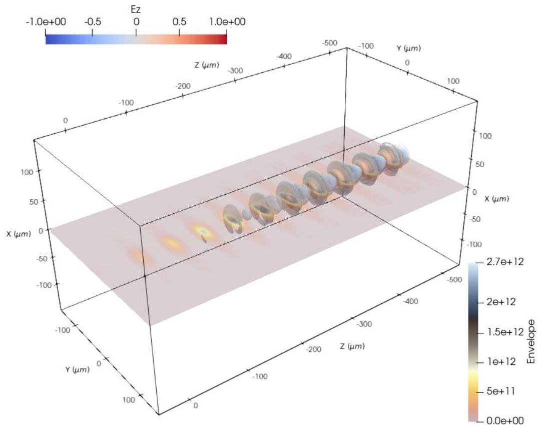
2. High-brightness **340as long** 2.2GeV **10Hz** beams with a simplified ReMPI setup



3. Preliminary FEL simulations in the water-window with the **10Hz** 2.2GeV ReMPI beam



4. High-brightness **kHz**, >1GeV beams with a P-MoPA/ReMPI scheme



P-MOPA@ReMPI. The P-MOPA modulation scheme

Induces a modulation of a long (ps scale) pulse by using a “seed” short pulse.

1. The final modulation amplitude is larger than that achieved with the self-modulation instability

2. The **phase** of the modulated pulses is determined by the position of the seed pulse, thus **making the generation of the subsequent LWFA structure reproducible**

PHYSICAL REVIEW LETTERS **127,** 184801 (2021)

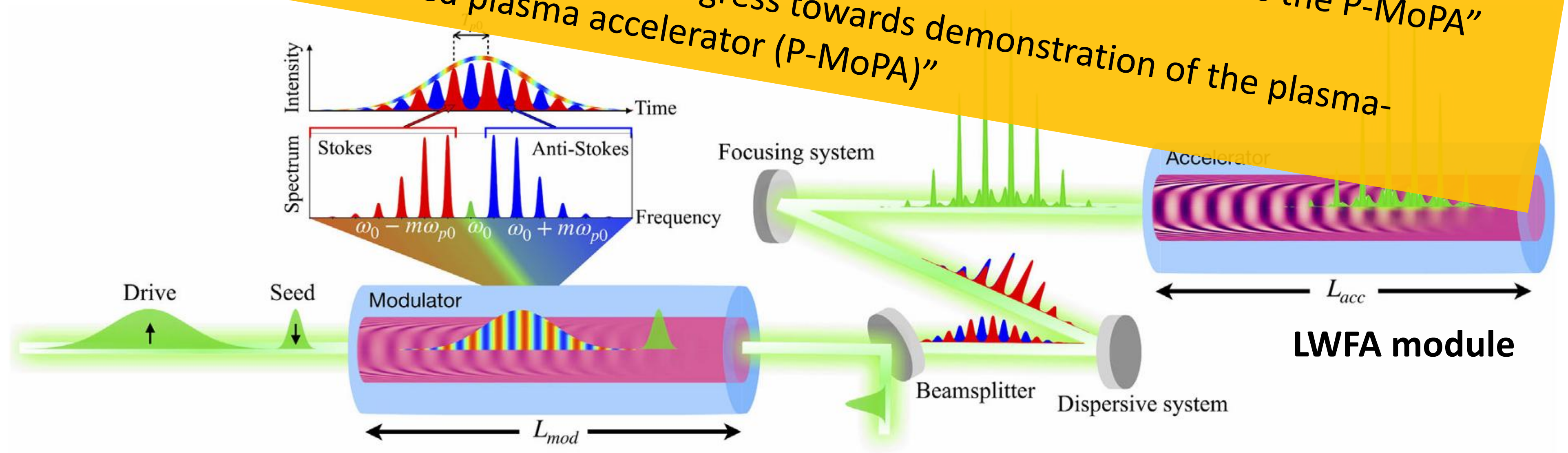
Related presentations/poster about P-MoPA

Mon poster: **Roman Walzcak** “Potential applications of P-MoPAs”

Tue: **Stefan Karsch** “Towards better electrons for applications…”

Wed poster: **Sebastian Kalŏs** “Experimental progress towards the P-MoPA”

Wed: **Simon Hooker** ”Progress towards demonstration of the plasma-modulated plasma accelerator (P-MoPA)”



LWFA module

P-MOPA modulator module

P-MOPA@ReMPI Conceptual Configuration

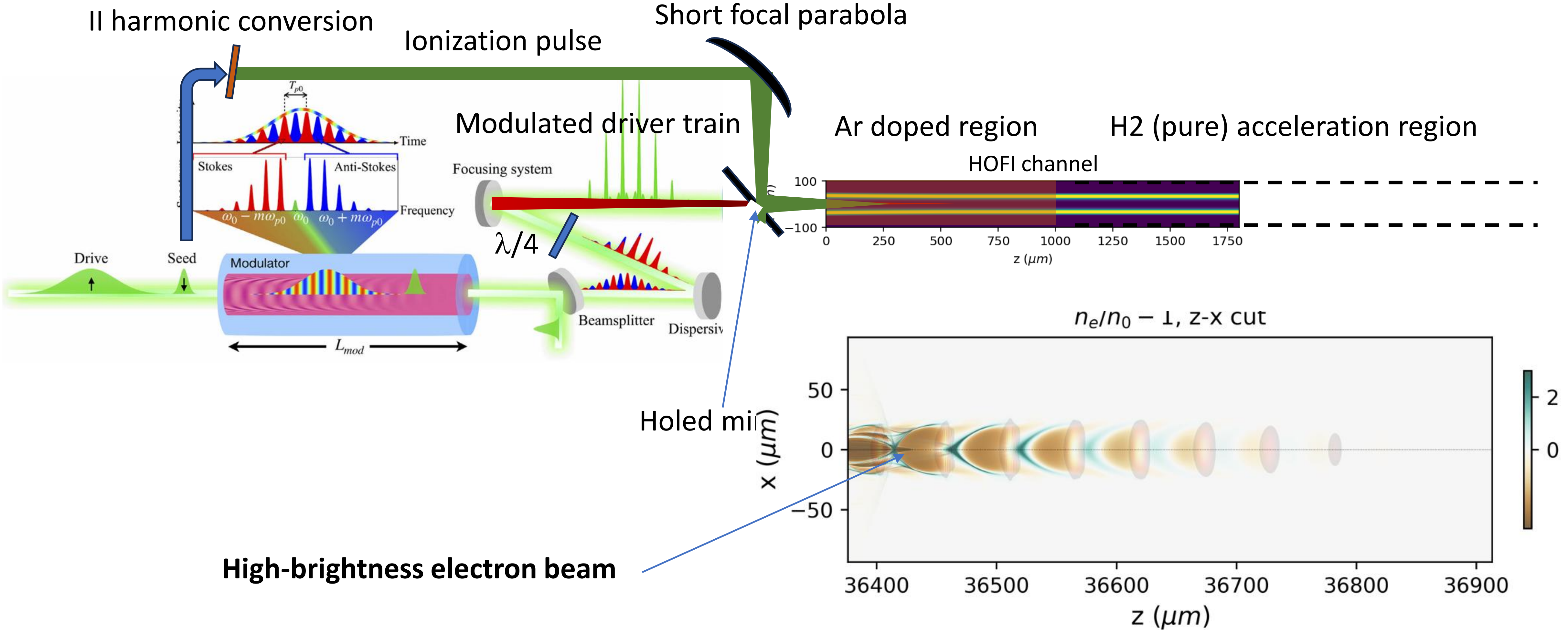
Theory@LDED

P-MOPA driver pulse modulation + ReMPI conceptual setup

PHYSICAL REVIEW LETTERS 127, 184801 (2021)

PHYSICS OF PLASMAS 24, 103120 (2017)

The resonant multi-pulse ionization injection

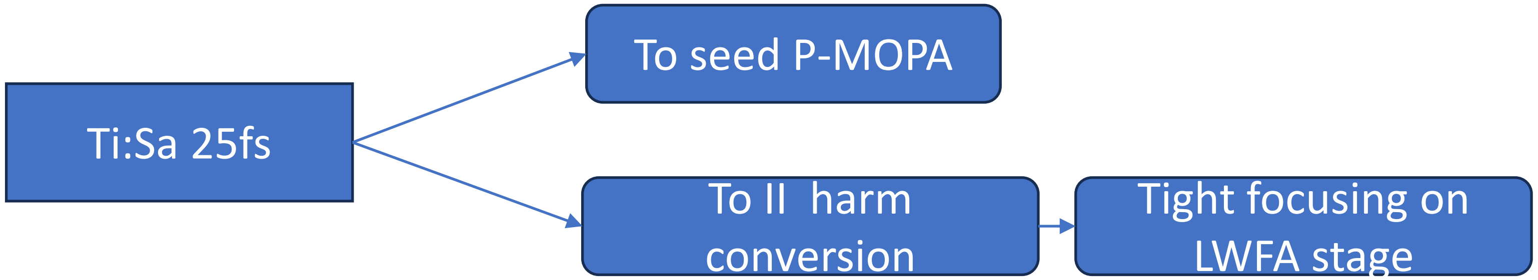


P-MOPA@ReMPI Particle extraction+injection

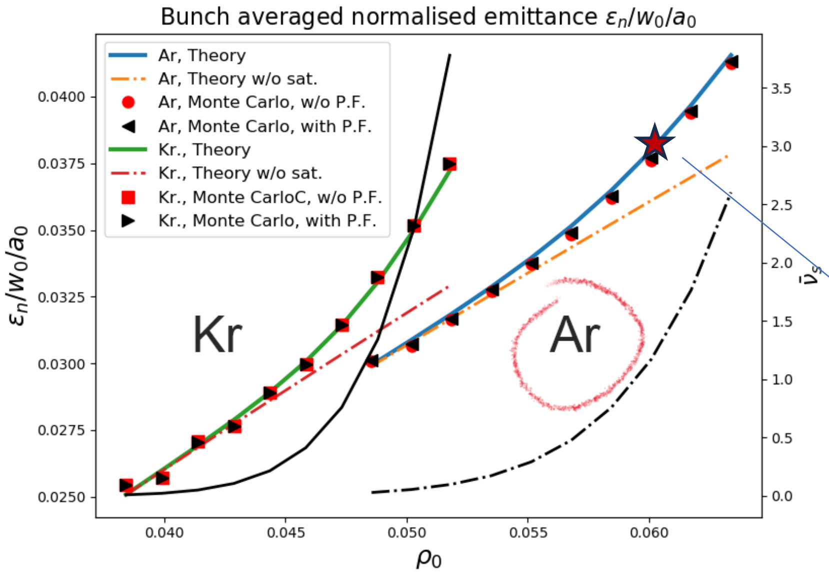
Theory @ LDED

Simplest configuration: ionization pulse in II harm of the Ti:Sa

<u>The ionization pulse and the seed must come from the same pulse</u>



The jitter between the two is critical. It's only due to micro vibrations, so **it should be maintained below 1μm rms**



[P. Tomassini et al, HPLSE 10 e15 (2022)]

$$Ar^{8^+\to 9^+} \quad \lambda_i = 0.4\mu m$$

$$a_c = 7.41 \quad a_{0,i} = 0.46$$

Expected minimum emittance in the ionization pulse plane

$$\epsilon_n \simeq 85nmrad$$

Reaching the minimum possible value of the emittance means making the transverse forces linear (and with almost constant radial gradient on the beam).

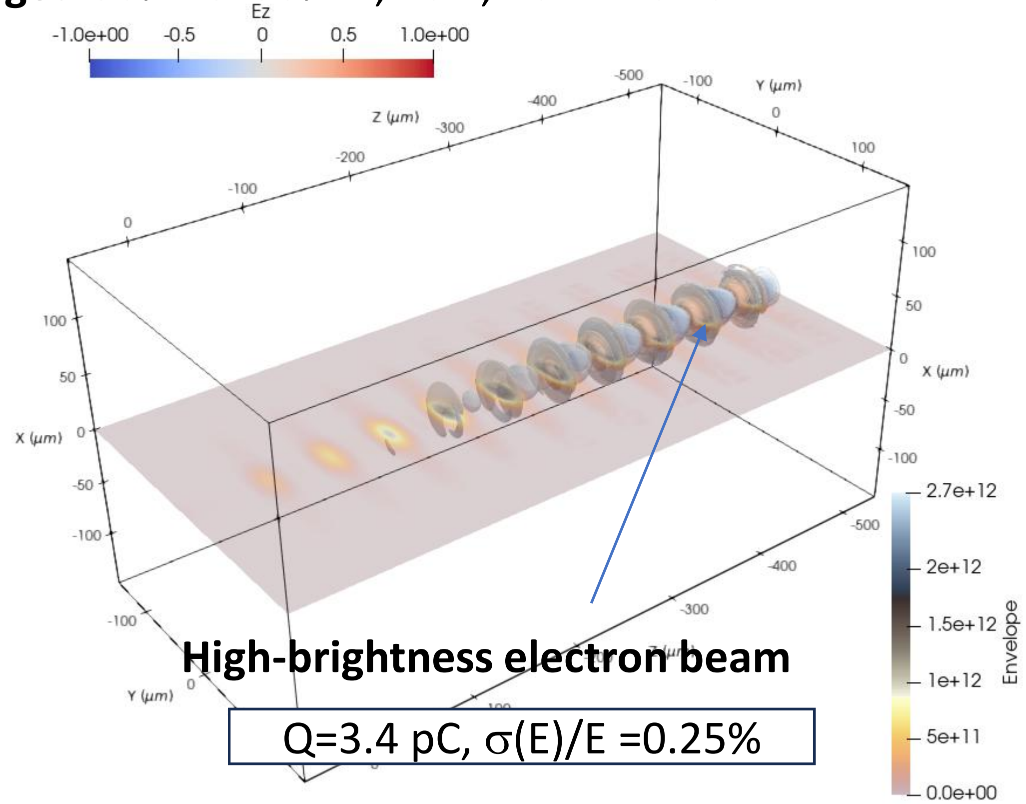
P-MOPA@ReMPI

Theory @ LDED

Driver: TEM00, 2.1J , w0 = 25 μm, β_mod =1.2, **CP**

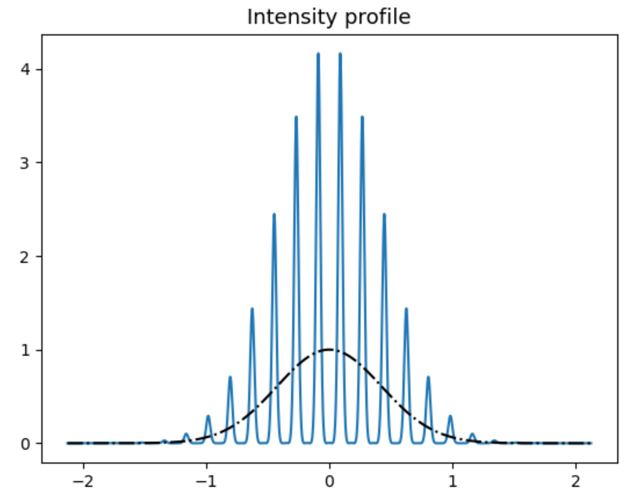
Ionization: TEM00, II harm of Ti:Sa, w0 = 4.5 μm, 27.5 fs FWHM, 50mJ, a0i = 0.48

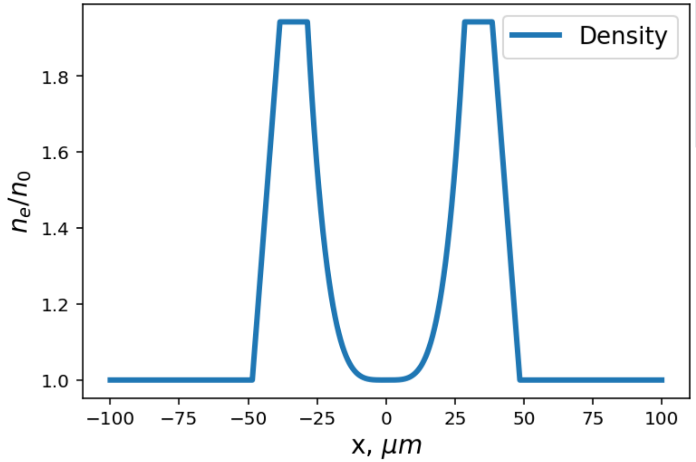
Target: 50%He+50%Ar, 7cm, n0=4x$10^{17}$$cm^{-3}$



High-brightness electron beam

Q=3.4 pC, σ(E)/E =0.25%





HOFI plasma density radial profile

Numerical parameters FBPIC, q3D

R= 5*w0 = 125 μm
dz = λ/40
dr = λ /12

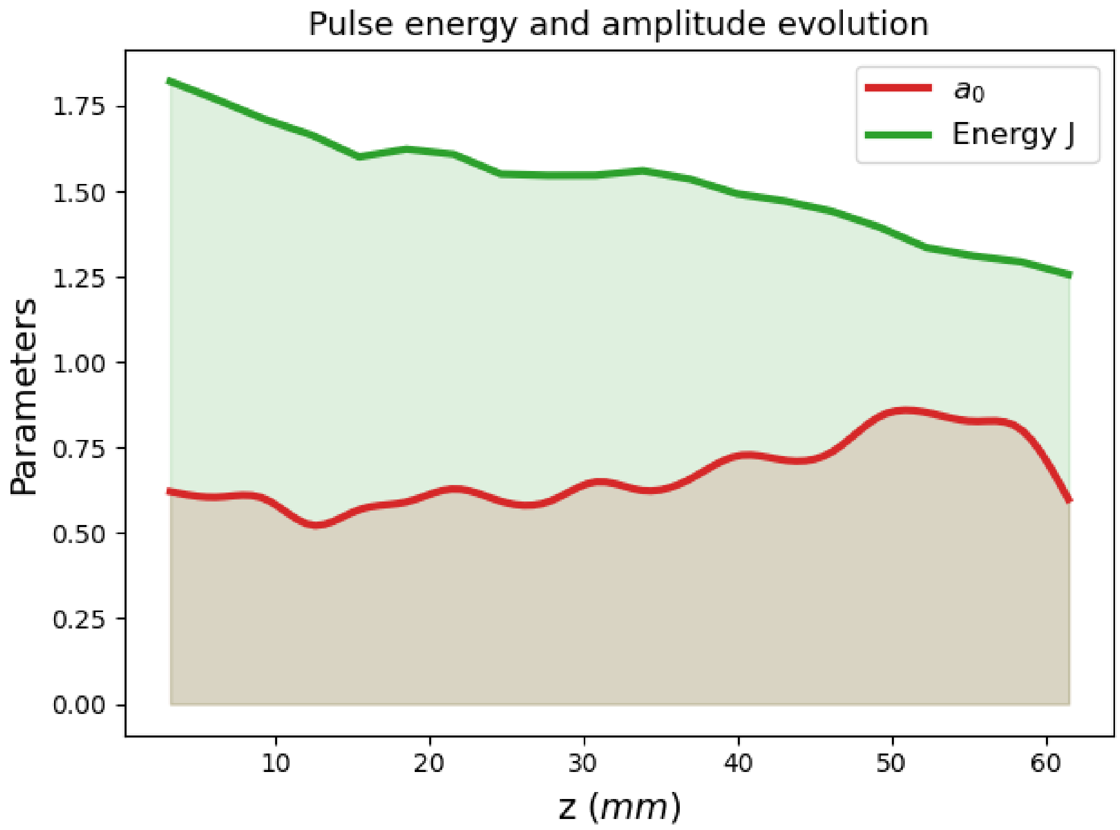
Nθ = 2

18h run on 48xH100 (ELI-NP cluster)

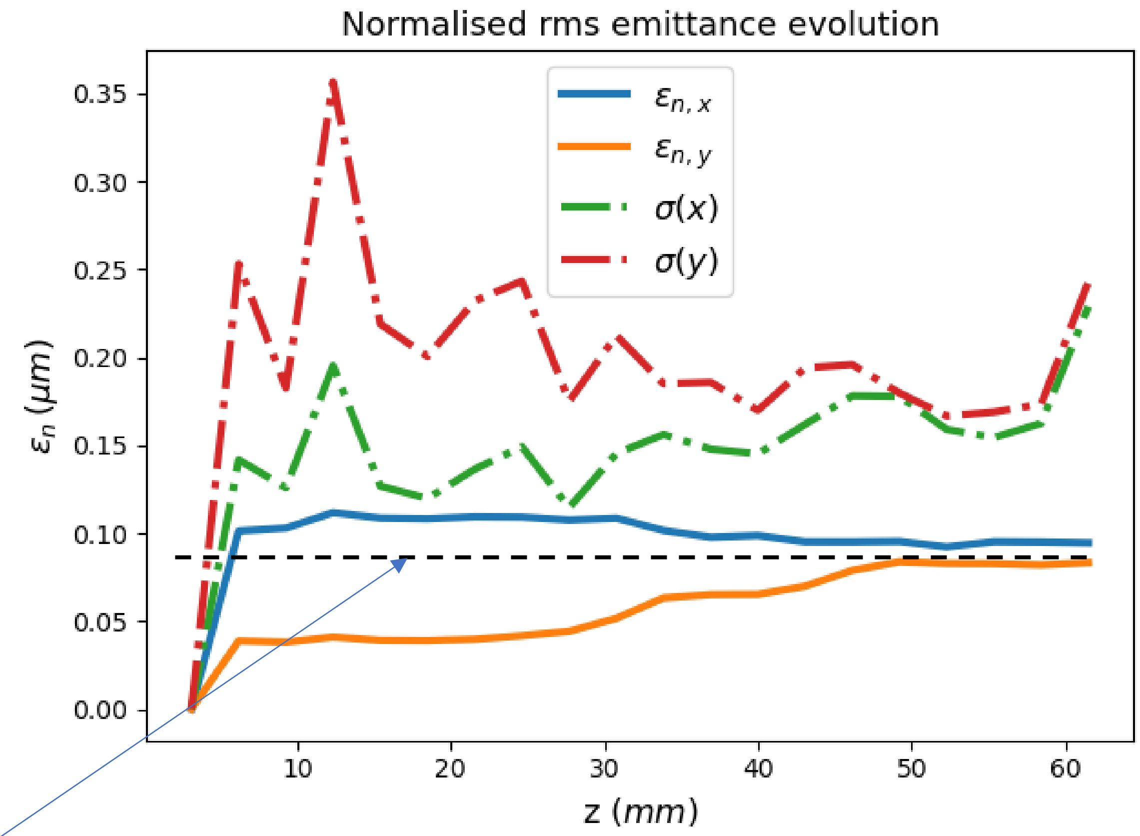
P-MOPA@ReMPI

Theory@LDED

Driver train energy (in the simulation window) and peak amplitude evolution



Electron beam transverse size and emittance evolution

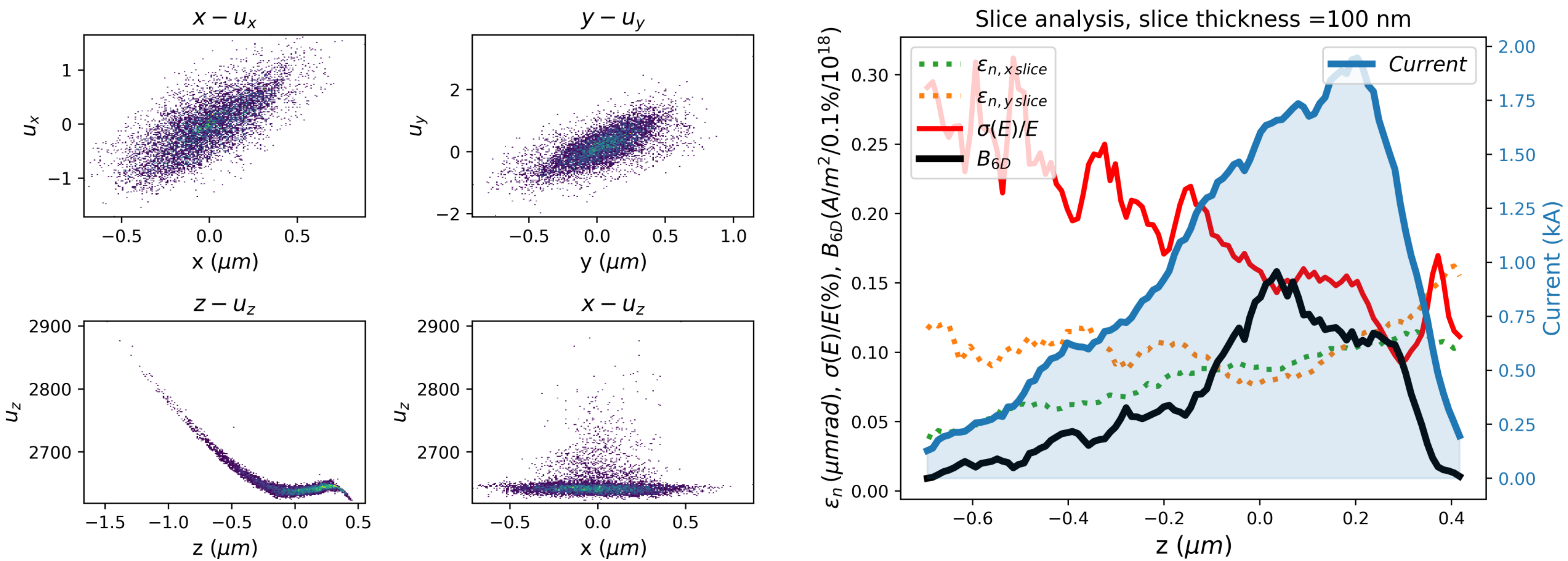


Expected value from *P. Tomassini et al, HPLSE 10 (2022)*

P-MOPA@ReMPI

Theory@LDED

Q=3.4 pC, σ(E)/E =0.25%, transverse normalized emittance 90nm rad



TBS sources with the low charge beam, good quality

Theory@LDED

Towards TBS kHz sources [first TBS simulations, not optimized yet]

TBS laser **0.5J** (from the same original pulse, 2.5J -> 0.5J TBS, 2J P-MOPA)

$$\Psi \equiv \gamma \cdot \theta_c$$

Normalized acceptance
EXTREMELY USEFUL parameter

$$\text{if } \Psi \ll 1 \Rightarrow N_{Acc}(\Psi) \simeq \delta\omega/\omega \simeq \Psi^2$$

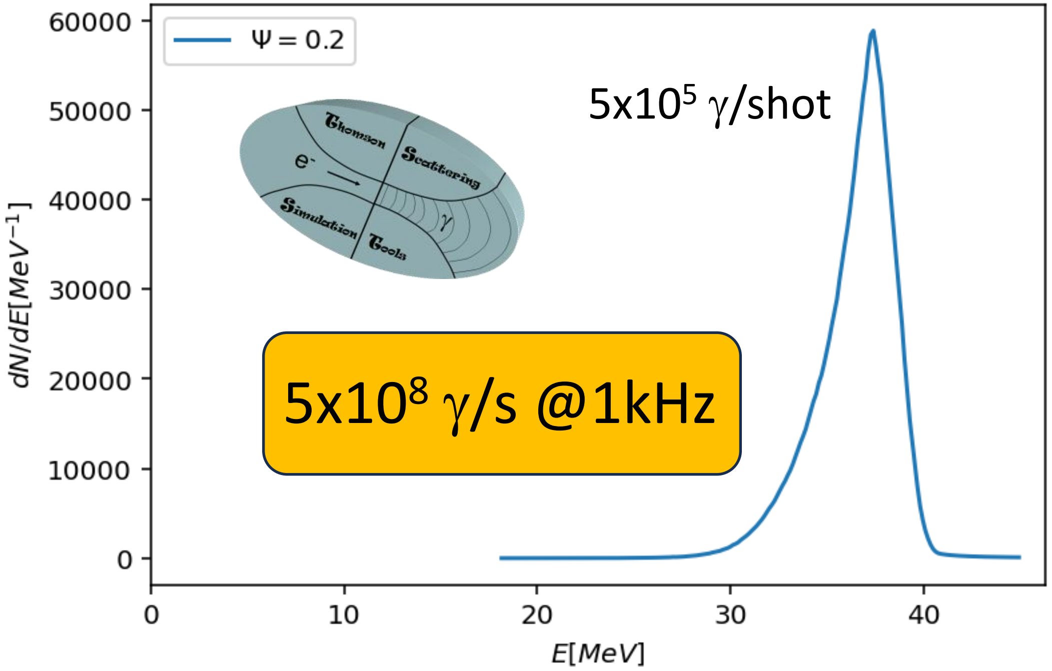
After beam transport and final focus optics:

$$(\delta\omega/\omega)_{min} \simeq \sigma(u_\perp)^2 + 2\frac{\delta\gamma}{\gamma} + a_0^2/2 \sim 10\%$$

$$\rightarrow \psi^2 \approx 0.1 \rightarrow \psi \lesssim 0.3$$

[P. Tomassini et al., APB 80 (2005)]

We have only 3.4pC (should be improved up to 10pC)



Conclusions

1. The simplified ReMPI scheme employing a 300 TW Ti:Sa system and two driver pulses only was designed to work in conjunction with a (brand new) multi-ring phase masks splitting technique.

2. The optimization procedure led to the (quite stable) generation of a **350as** long **and tuneable**, 2.2GeV beam with **FEL compliant quality** and Brightness:

$$\mathrm{B6D} = 4\mathrm{x}10^{18} A/m^2 0.1\% BW$$

3. Preliminary FEL simulations confirmed that the beam is **suitable for driving a water-window X-ray source**

4. Preliminary results about the mixed PMoPA/ReMPI schemes shows that **kHz rep.rate high quality beams can be generated** in this way

Thank you for your attention!

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