Bright attosecond electron beams and brilliant gamma ray sources with the Resonant Multi-Pulse Ionization Injection

Paolo Tomassini

Theory @ LDED

Head of the ELI-NP Simulation Group

ELI-NP, Magurele, LDED, Romania

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IMPULSE

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Lecz Zsolt (ELI-ALPS, Szeged, Hungary)
Domenico Doria (ELI-NP, Magurele, Romana)

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Outlook

1. **The two-color ionization injection and the Resonant Multi Pulse Ionization Injection (ReMPI) schemes**

2. Earlier results with ReMPI

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3. Attosecond high-brightness beams with ReMPI and 250TW Ti:Sa systems

4. Towards Compton/Thomson sources

5. Conclusions

The two-color ionization injection

PRL 112, 125001 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

Two-Color Laser-Ionization Injection

L.-L. Yu,[1,2,3] E. Esarey,[1] C. B. Schroeder,[1] J.-L. Vay,[1] C. Benedetti,[1] C. G. R. Geddes,[1] M. Chen,[3] and W. P. Leemans[1,2]
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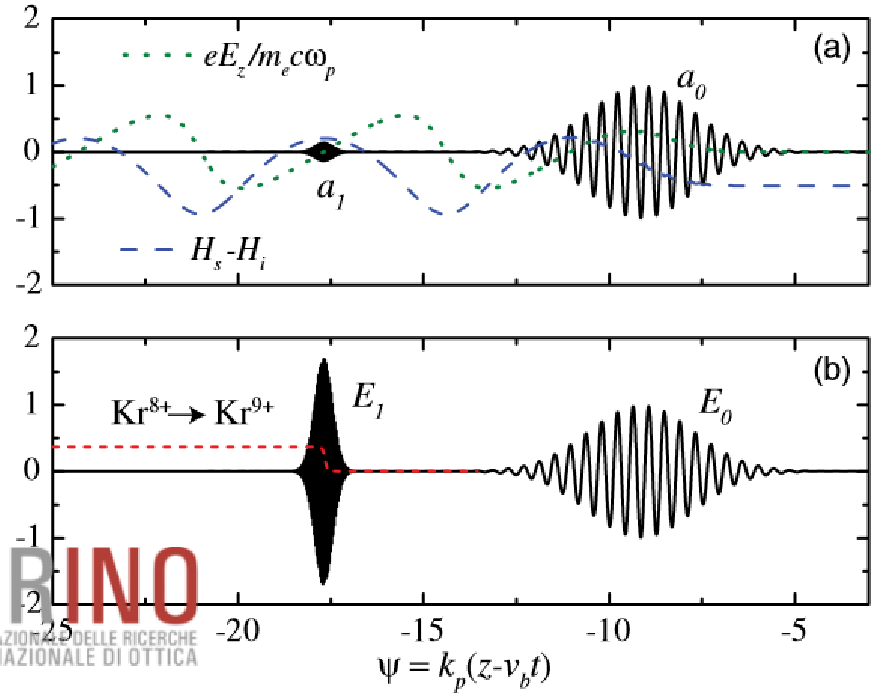
(Received 31 July 2013; published 24 March 2014)

A method is proposed to generate femtosecond, ultralow emittance ($\sim 10^{-8}$ m rad), electron beams in a laser-plasma accelerator using two lasers of different colors. A long-wavelength pump pulse, with a large ponderomotive force and small peak electric field, excites a wake without fully ionizing a high-Z gas. A short-wavelength injection pulse, with a small ponderomotive force and large peak electric field, copropagating and delayed with respect to the pump laser, ionizes a fraction of the remaining bound electrons at a trapping wake phase, generating an electron beam that is accelerated in the wake.

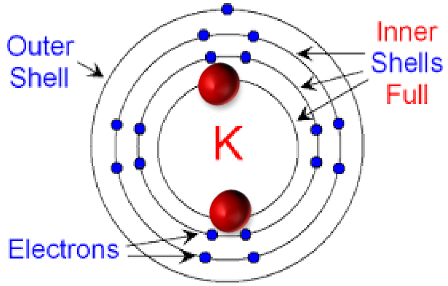
DOI: 10.1103/PhysRevLett.112.125001 PACS numbers: 52.38.Kd, 52.25.Jm

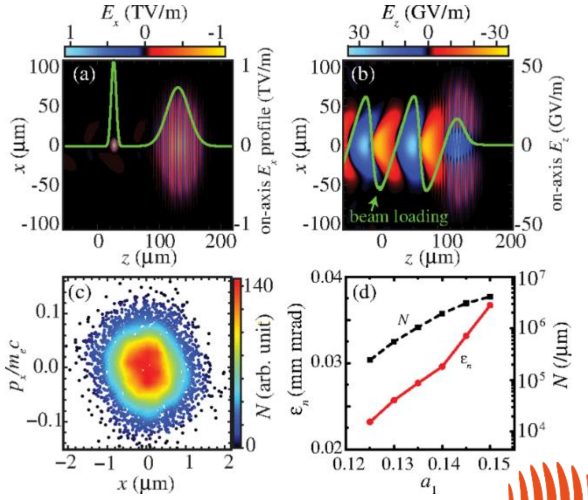


It uses two lasers systems:
A long wavelength ($\lambda > 5$ µm) pulse excites the plasma wave and the short wavelength one ($\lambda <= 0.4$ µm) extracts electrons by field ionization from an high-Z dopant.

It allows for very low emittance bunches (few tens of nm rad).

However, to date, its experimental feasibility is limited from the lacking of commercial high power, ultrashort and long wavelength laser systems.





The Resonant Multi-Pulse Ionization injection (ReMPI

Theory @ LDED

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]
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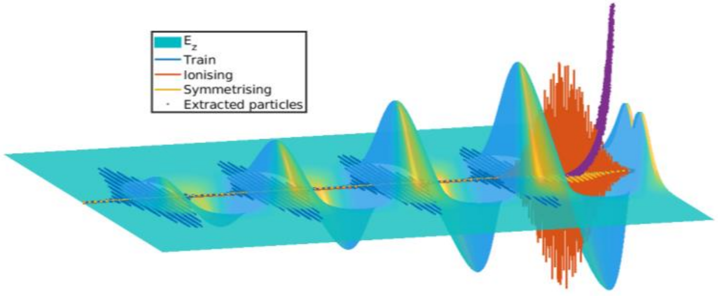
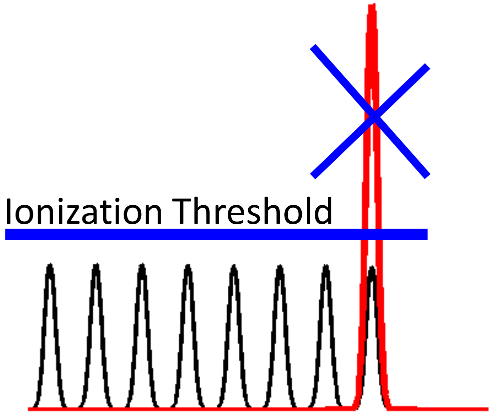
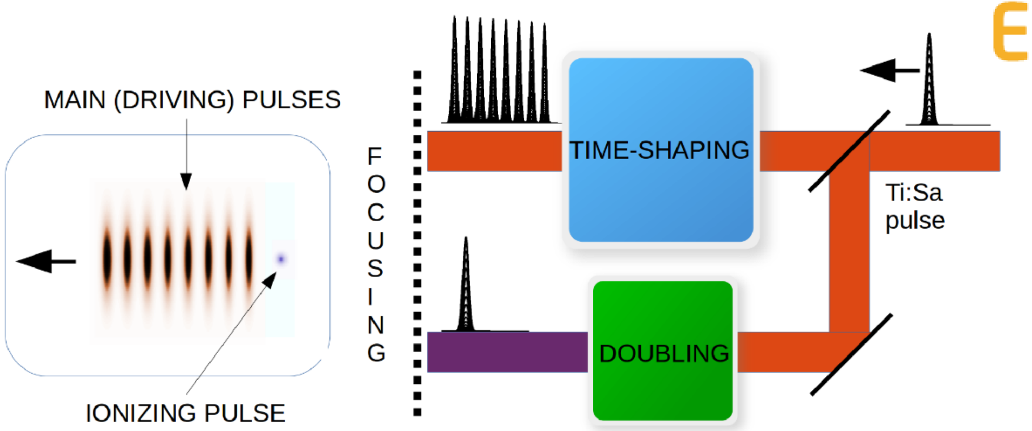
[3]*CNR-SPIN, Napoli, 80126 Napoli, Italy*



- ReMPI **requires one** short-pulse (e.g Ti:Sa) laser system. It works also with multiple lases systems
- Since a unique very large-amplitude Ti:Sa pulse would fully ionize the atoms (Ar8+ in our selected example), **the pulse is shaped as a resonant sequence** of sub-threshold amplitude pulses.





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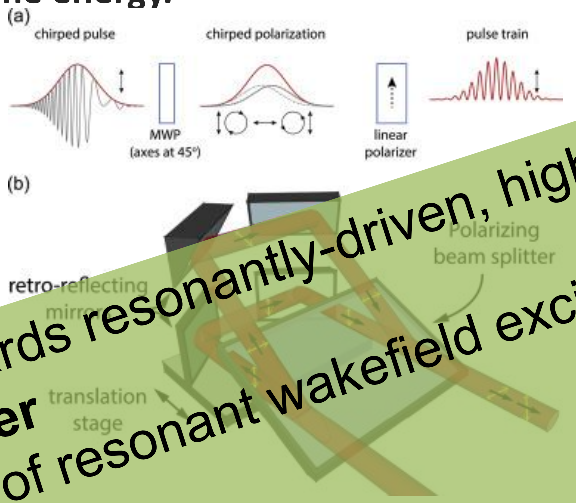
Active work on multi-pulse generation

Theory @ LDED

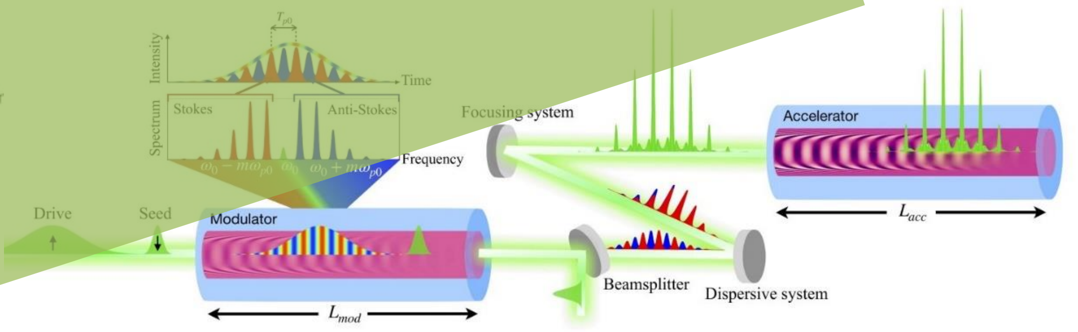
- The multi-pulse approach to LWFA has been proposed so far [D. Umstadter et al, PRL 72, (1994)]. A multi-pulse train can generate plasma waves with larger amplitude than those driven by a single pulse with the same energy.

Three pssible pulse-shaping schemes have been proposed very recently

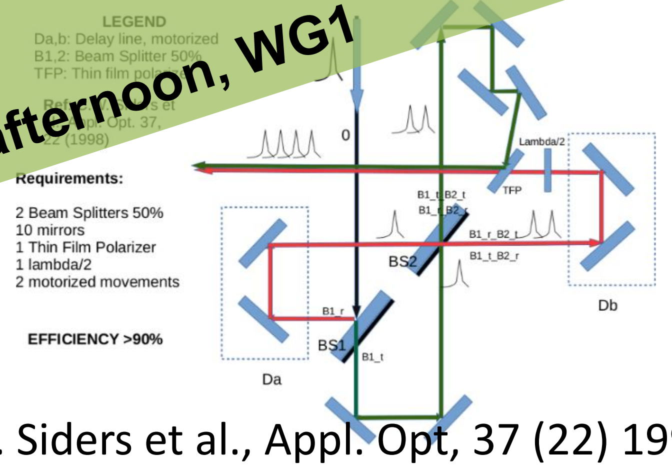


[J. Cawley et al, PRL 2017]
[R.J. Shalloo et al, NIM A 2016]

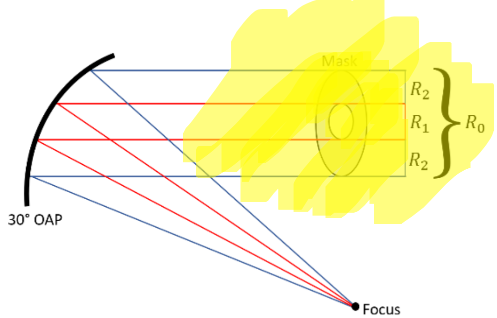
[O. Jakobsson, et al. PRL **127** (2021)]



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]

Progress towards resonantly-driven, high-repetition-rate GeV-scale plasma accelerators
Simon Hooker
Observation of resonant wakefield excitation by pulse trains guided in long plasma channels
Linus Feder
held on Monday afternoon, WG1

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Trapping conditions

Conserved Hamiltonian in 1D+QSA

$$\mathcal{H}(\psi,\gamma) = \gamma(1-\beta\beta_{ph}) - \phi(\psi)$$

$$\psi \equiv k_p(z-\beta_\phi ct)$$

[E.Esarey & M. Pillov, PoP **2** 1432 (1995)]

$$E_{norm} = E_z/E_0;\ E_0 = mc\omega_p/e$$

$$\mathcal{F} \equiv \frac{1}{2} E_{norm}|^2_{max}$$

$$(1+\phi_{Max,min}) = \mathcal{F} \pm \beta_{ph}\sqrt{(1+\mathcal{F})^2-1}$$

$$2|\beta_{ph}|\sqrt{(1+\mathcal{F})^2-1} \geq 1-1/\gamma_{ph}$$

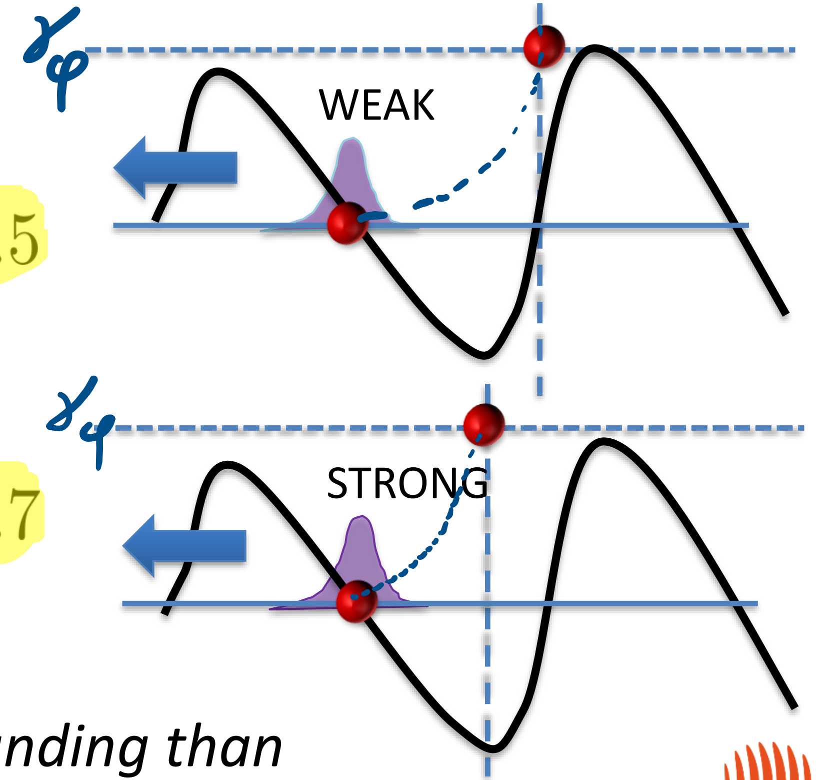
Weak (standard) trapping threshold

$$E_{norm} \simeq 0.5$$

Strong trapping threshold

$$\mathcal{F} + |\beta_{ph}|\sqrt{(1+\mathcal{F})^2-1} \geq 1-1/\gamma_{ph}$$

$$E_{norm} \simeq 0.7$$



[Tomassini et al.; Phys. Plasmas 24 (2017)]

Strong trapping condition is more demanding than the standard «weaker» one

Highly accurate 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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[2] ELI-NP, Magurele, Ilfov, Romania
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[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

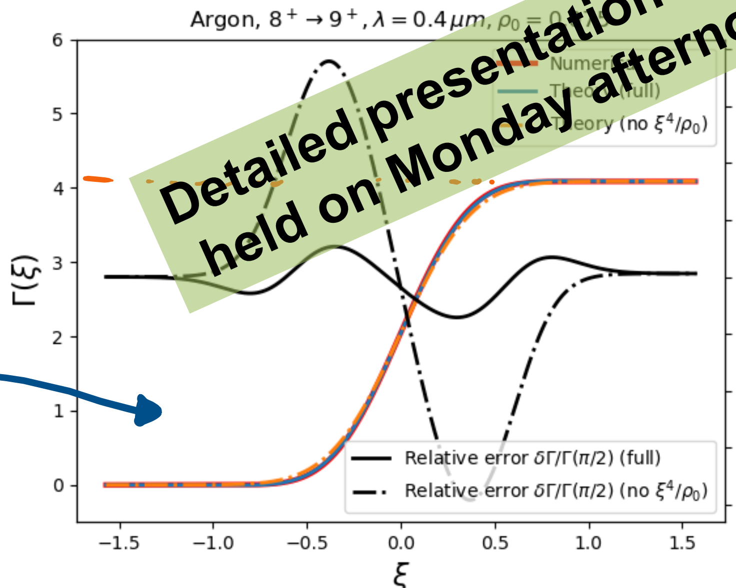
$$\rho \equiv \frac{3E}{2E_a}\left(\frac{U_H}{U_I}\right)^{3/2} = a/a_c = \Delta^2$$

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

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

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

$$\Gamma(\xi) \equiv \frac{1}{k_{0,x}}\int_{-\pi/2}^{\xi} dx W(x) = \frac{k_{ADK}}{k_0}\rho_0^\mu \int_{-\pi/2}^{\xi} dx (\cos x)^\mu e^{-\frac{1}{\rho_0 \cos x}} \simeq \nu_s(\rho_0)\mathcal{G}\left(\frac{\xi}{\sqrt{2\rho_0}}\right)$$



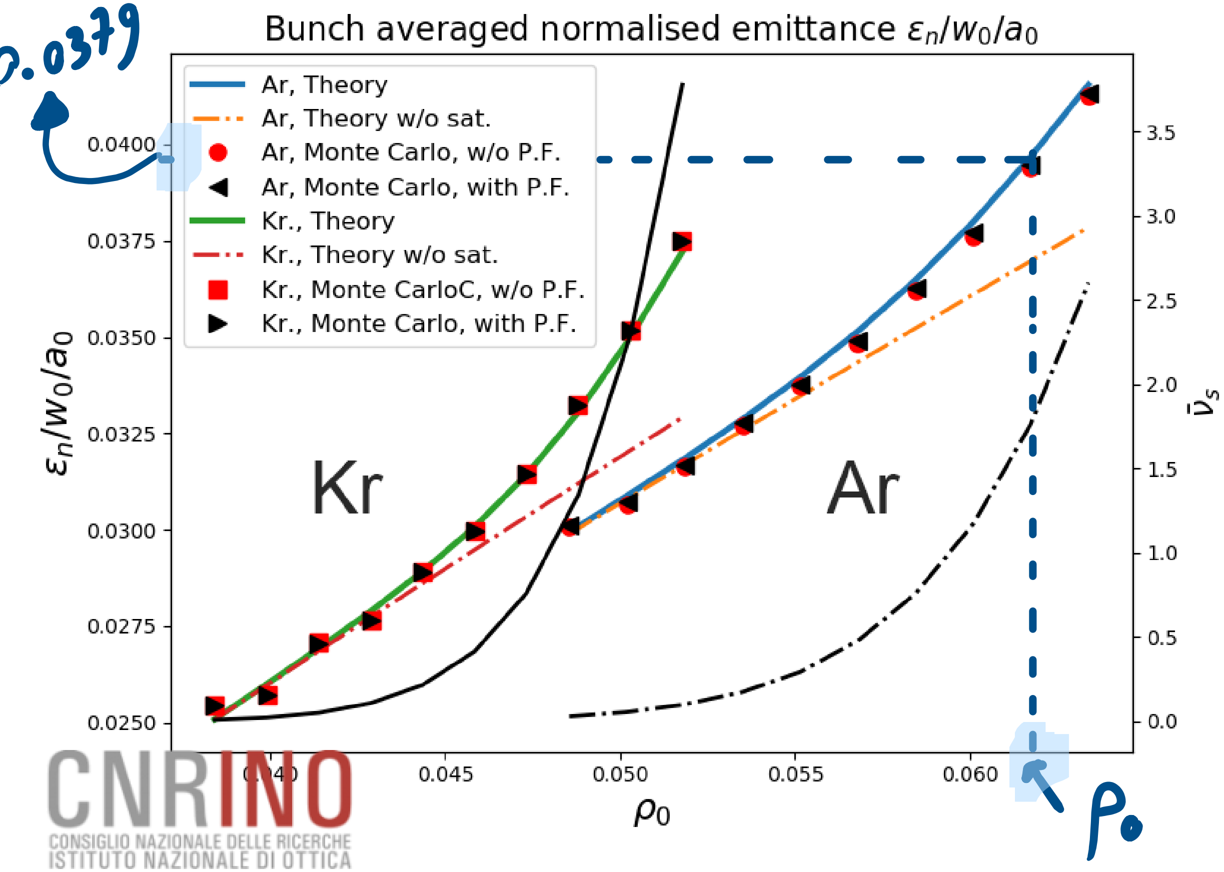
Detailed presentation of the theory held on Monday afternoon, WG3

Advanced theory outcomes for a whole electron beam

Theory @ LDED

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*

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

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

IV harm. IV harm.

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Outlook

Theory @ LDED

1. The two-color ionization injection and the Resonant Multi Pulse Ionization Injection (ReMPI) schemes
2. **Earlier results with ReMPI**
3. Attosecond high-brightness beams with ReMPI and 250TW Ti:Sa systems
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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]

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[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 Gizz

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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

ısma Phys. Control. Fusion **62** 014010

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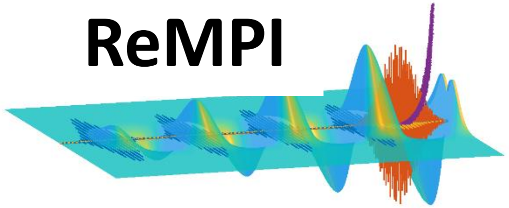
ReMPI



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

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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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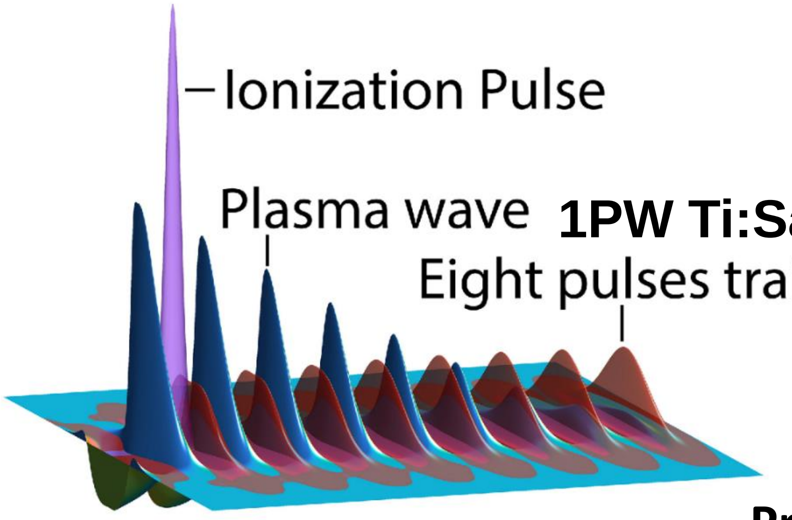
High-brightness 5GeV beams for EuPRAXIA

Theory@LDED

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

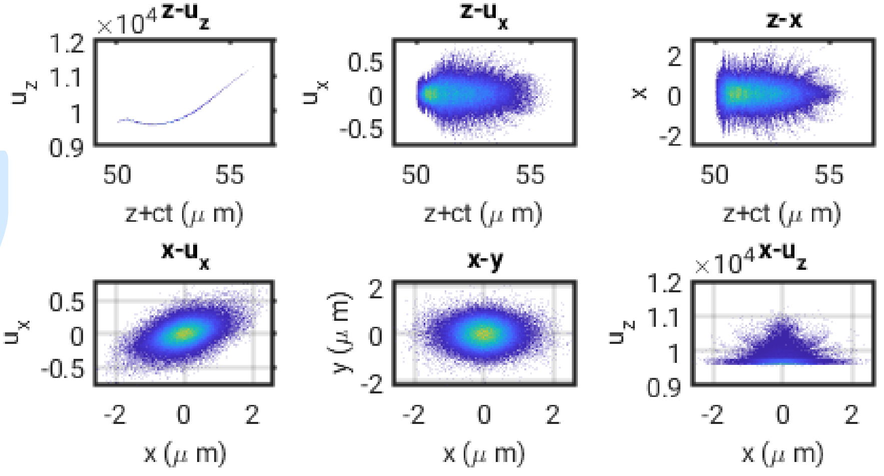
R. Assman et al., EuPRAXIA CDR , EPJ 229, 675 (2020)

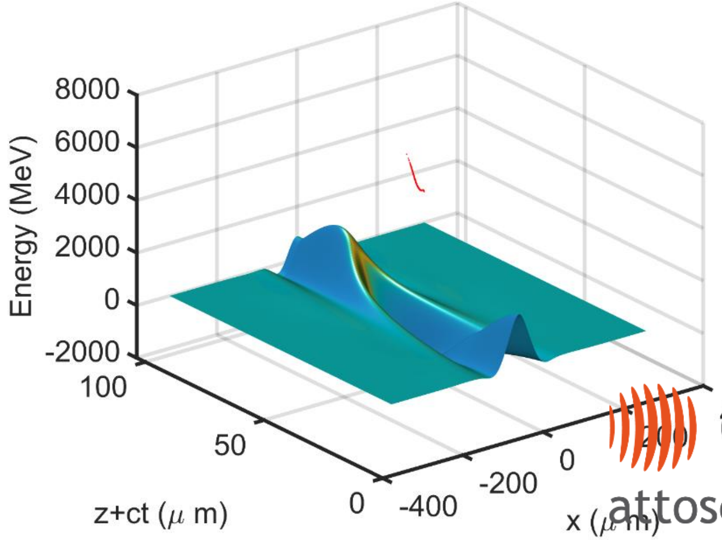


1PW Ti:Sa driver

Projected beam quality

$$B_{n,6D} \approx 4 \times 10^{17} A/m^2/0.1\%$$





Projected

dE/E	ε_n	Q	I peak
0.9% **(92% of the charge)** 1.8 % (tail included)	0.085 mm mrad	32 pC	3.5 kA

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Slice analysis

dE/E SLICE	ε_n SLICE	Q	I peak
0.05% (**min**)	**<0.08 mmmrad**	30 pC	3.5 kA

The slice analysis is FEL oriented
and reveals outstanding peak values

$$B_{n,5D} = \frac{2I}{\epsilon_{n,x}\epsilon_{n,y}}$$

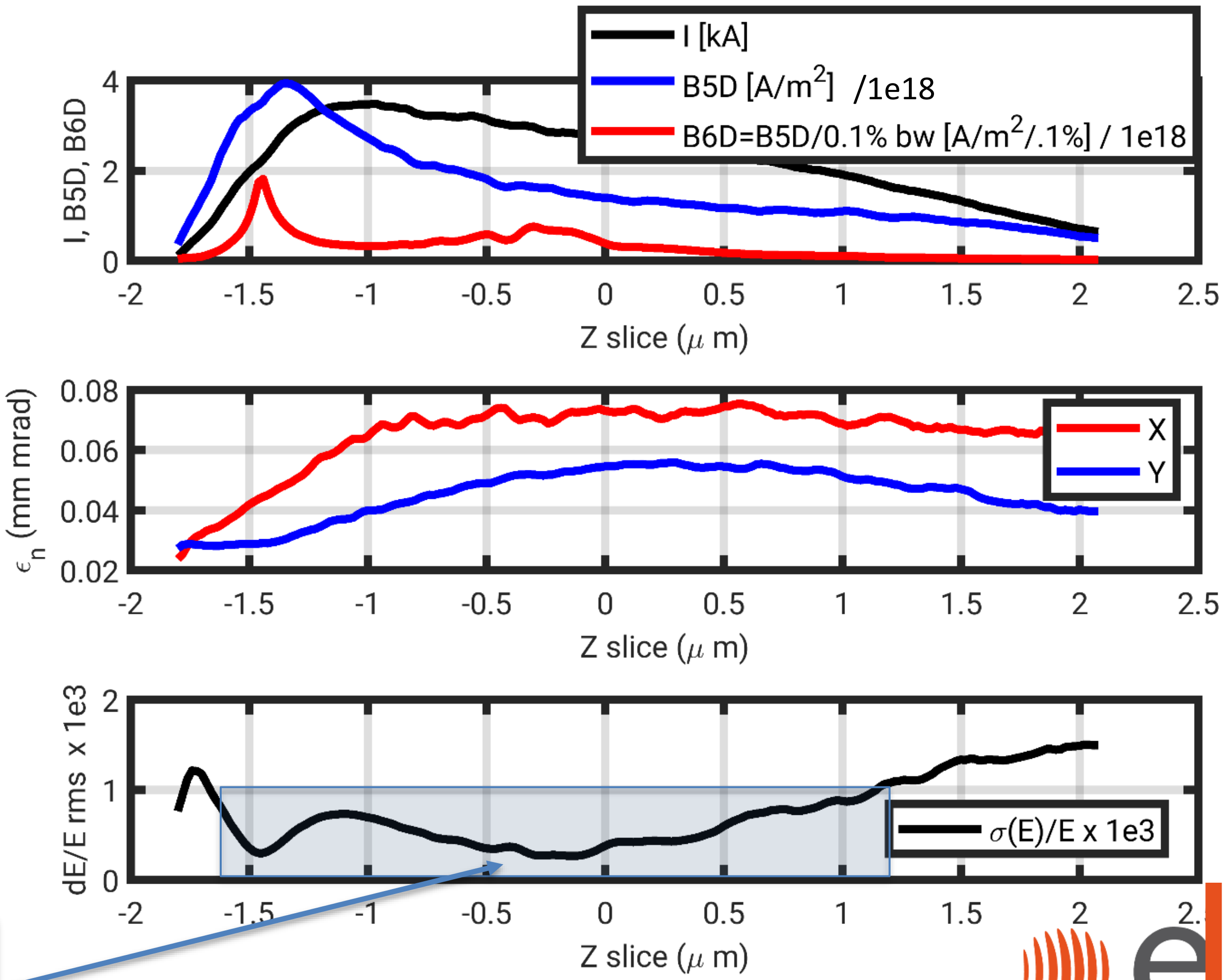
Peak

$$B_{n,6D} \approx 2 \times 10^{19} A/m^2/0.1\%$$

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

Slice averaged

$$B_{n,6D} \approx 4 \times 10^{18} A/m^2/0.1\%$$



About **90%** of the slices have σ(E)/E<0.1%

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High-brightness 5GeV beams for EuPRAXIA

PROJECTED 6D brightness

$$B_{n,6D} \approx 4 \times 10^{17} A/m^2/0.1\%$$

SLICE 6D brightness

The slice analysis is FEL oriented and reveals outstanding peak and slice average values

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

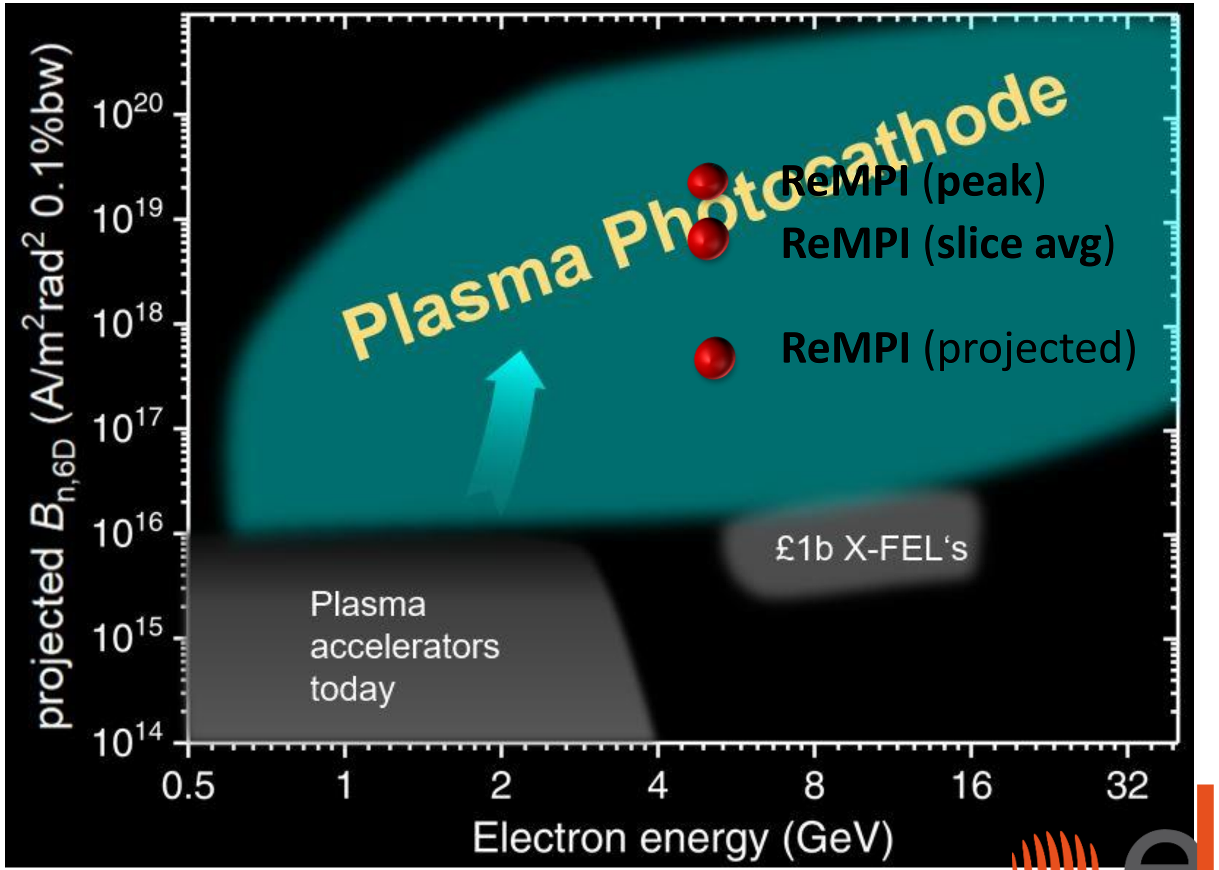
Peak

$$B_{n,6D} \approx 2 \times 10^{19} A/m^2/0.1\%$$

Slice averaged

$$B_{n,6D} \approx 4 \times 10^{18} A/m^2/0.1\%$$

https://pwfa-fel.phys.strath.ac.uk



Outlook

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Where we want to go: high-brightness 1.7GeV ultrashort beams with 250TW Ti:Sa

Examples of (projected) Beam Brightness performances

https://pwfa-fel.phys.strath.ac.uk

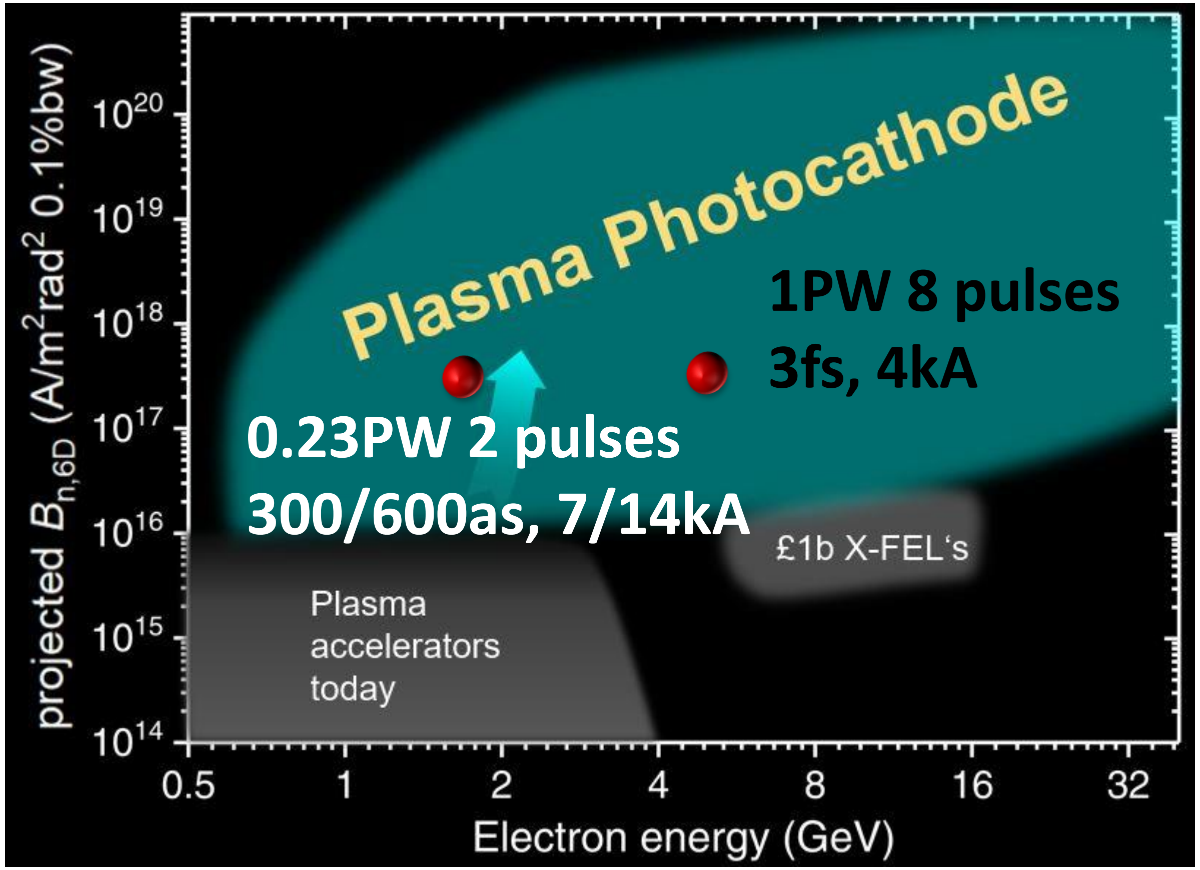
$$B_{n,5D} = \frac{2I}{\epsilon_{n,x}\epsilon_{n,y}} \qquad B_{n,6D} = \frac{B_{n,5D}}{\delta E/E/0.1\%}$$

Projected beam brightness

$$B_{n,5D} \approx 4 \times 10^{18} A/m^2$$

$$B_{n,6D} \approx 4 \times 10^{17} A/m^2/0.1\%$$

300/600as high-brightness 1.7GeV beam with 200 TW Ti:Sa laser



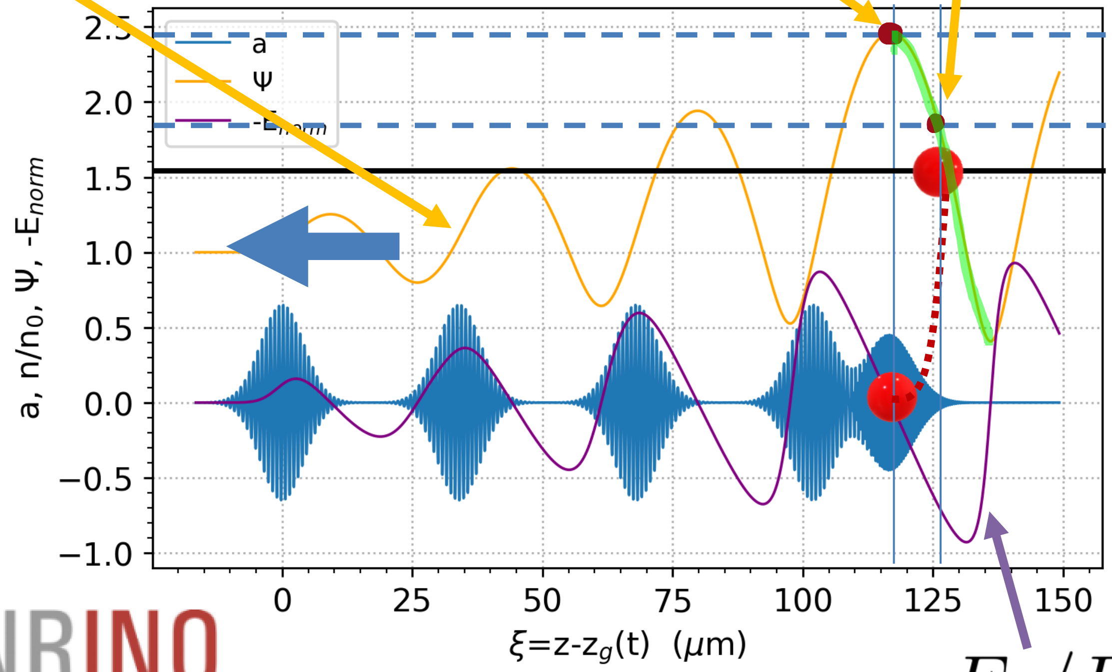
Fine tuning of the beam length in two-color/ReMPI/trojan-horse schemes

Theory @ LDED

In Two Color and ReMPI ionization injection schemes the extraction of the electrons from the dopant occurs in a controlled way. **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.**

$\psi = 1 + \phi$

$\Psi(\xi_e) \quad \Psi(\xi_t)$



E_z/E_0

$$\mathcal{H}(\eta,\gamma) = \gamma(1-\beta\beta_{ph}) - \phi(\eta)$$

$$\eta = k_p(z-z_g) = k_p \cdot \xi$$

$$\gamma_\perp^2 = 1 + u_\perp^2 = 1 + (a - a_{ex})^2$$

$$\phi(\xi_{tr}) = \phi(\xi_e) - 1 + \gamma_\perp(\xi_{tr})/\gamma_\phi$$

@ trapping *@ extraction*

$$\xi_{tr} = \phi^{-1}(\phi(\xi_e) - 1 + \gamma_\perp(\xi_{tr})/\gamma_\phi)$$

nuclear physics

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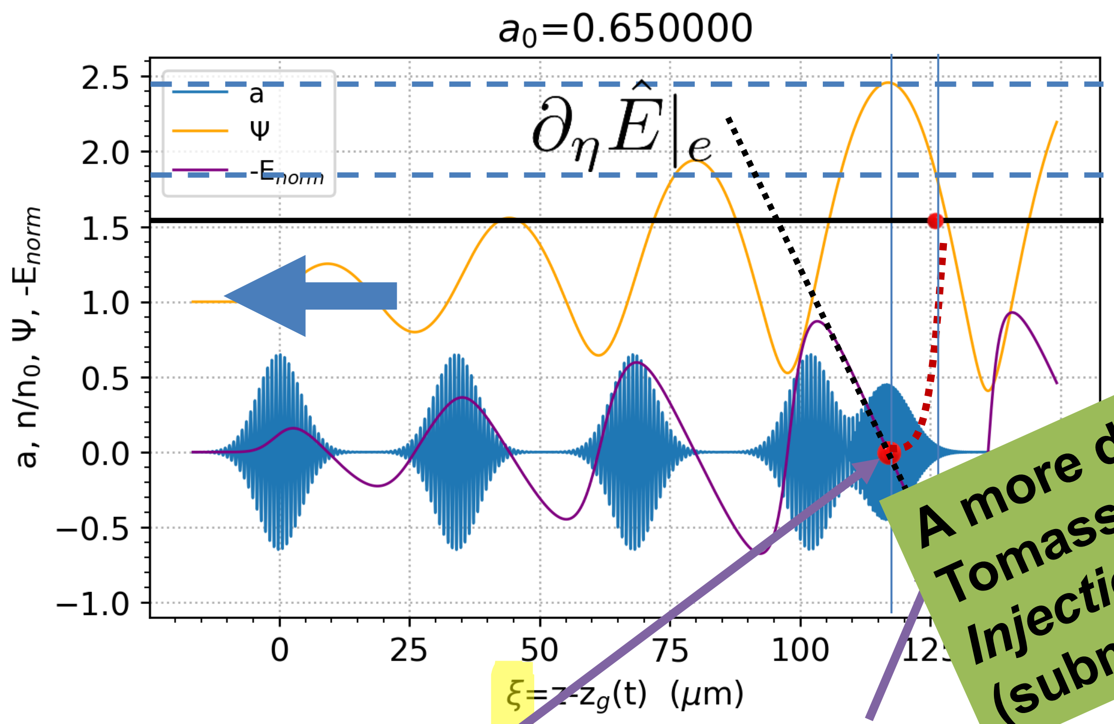
Fine tuning of the beam length in two-color/ReMPI/trojan-horse schemes

Theory@LDED

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.



$$\hat{E}_e = \frac{E_z|_e}{E_0} \qquad \hat{E}_t \doteq \frac{E_z|_t}{E_0}$$

$$\hat{E} = E_z/E_0 = -\frac{\partial \phi}{\partial \eta} \qquad \eta = \dots$$

We consider the electrons ...
the pulse of FWHM l... ...urated
regime the ext... ...n gaussian
variable ...

$$\dots \sqrt{\frac{\rho_0}{4 \log 2}}$$

... positions can be evaluated in the limit
... as

$$\sigma_{\xi_t} \simeq \sigma_{\xi_e} \frac{1}{\hat{E}_t} \sqrt{\hat{E}_e^2 + \frac{1}{2} k_p^2 (\partial_\eta \hat{E}|_e)^2 \sigma_{\xi_e}^2}$$

A more deltailed model including 3D effects is available on P. Tomassini et al., *“Attosecond pulses from Ionization Injection Wake Field Accelerators”*, DOI 10.20944/preprints (submitted)

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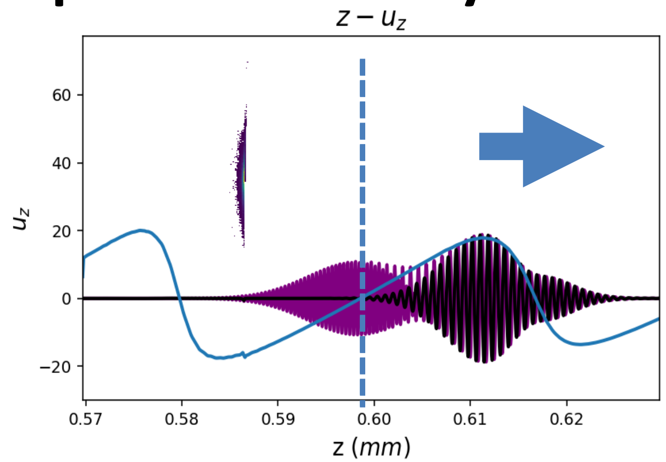
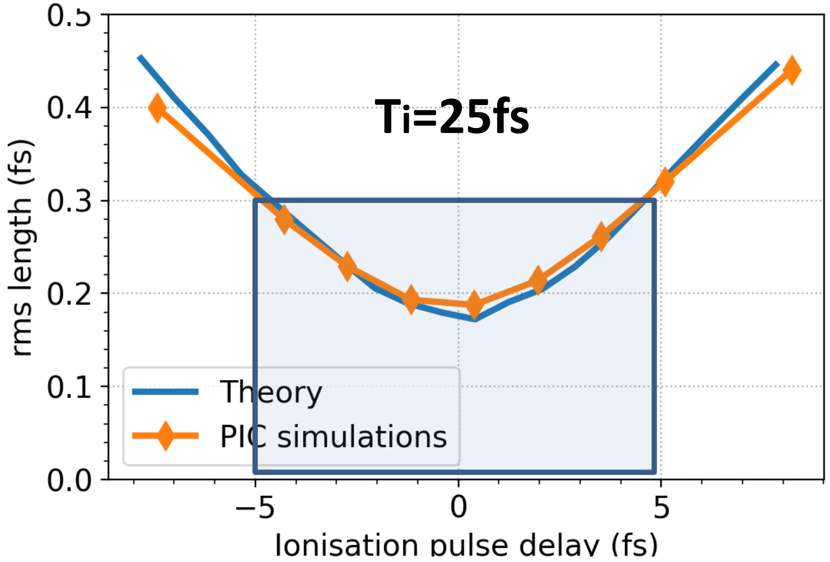
Fine tuning of the beam length in two-color/ReMPI/trojan-horse schemes

Theory@LDED

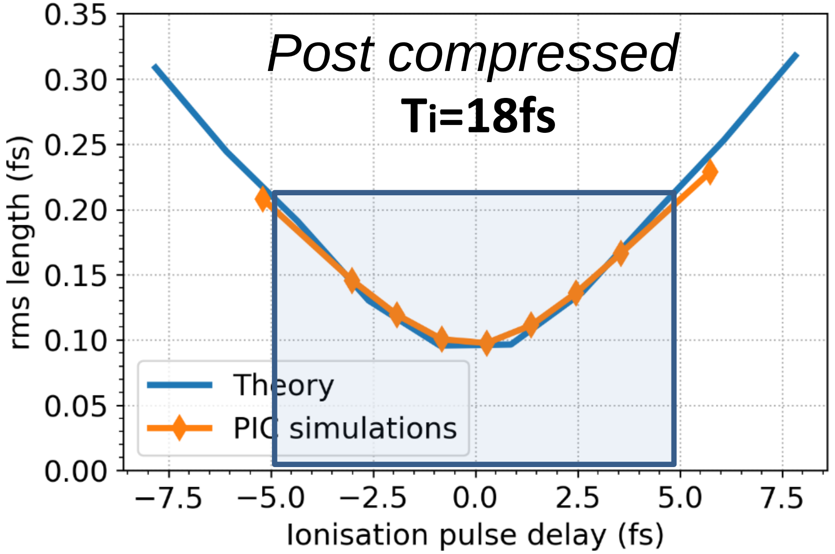
Scan of the beam length as a function of the ionization pulse position. **The "zero position" corresponds to a delay which places the pulse on the node of the accelerating gradient**



- **SINGLE Ti:Sa 200TW laser system, Circularly Polarised pulses**
- 4x 23fs FWHM pulses, w0=45 μm , total 5J on TEM00,
- 1x 25fs or 18fs FWHM ionization pulse **in II** harmonics, w0=3.5 μm
- 100%Ar (8+) plasma, n0=5e17 1/cm^3
- **PIC simulations with the quasi-3D FB-PIC code. Resolution λi/24 and λi/8 in the longitudinal and transverse directions**



Timing jitter below 3fs rms



Simplifying ReMPI

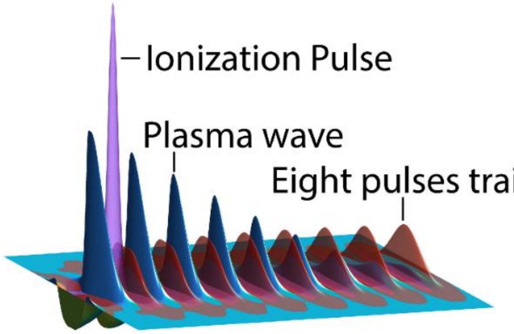
Theory@LDED

The first FEL compliant version of ReMPI for 5GeV suffered from "gigantism".

Eight pulse, with complex evolution due to the propagation into an evolving wakefield

8 pulses

(1PW, EuPRAXIA)

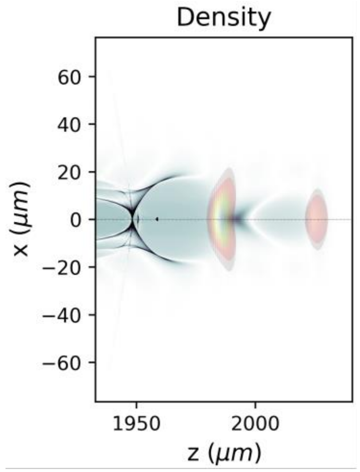


30 pC

$$\epsilon_n \simeq 80nmrad$$

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.



(200TW)

2 pulses

5-30 pC

$$\epsilon_{n,x} \simeq 120nmrad$$
$$\epsilon_{n,y} \simeq 60nmrad$$

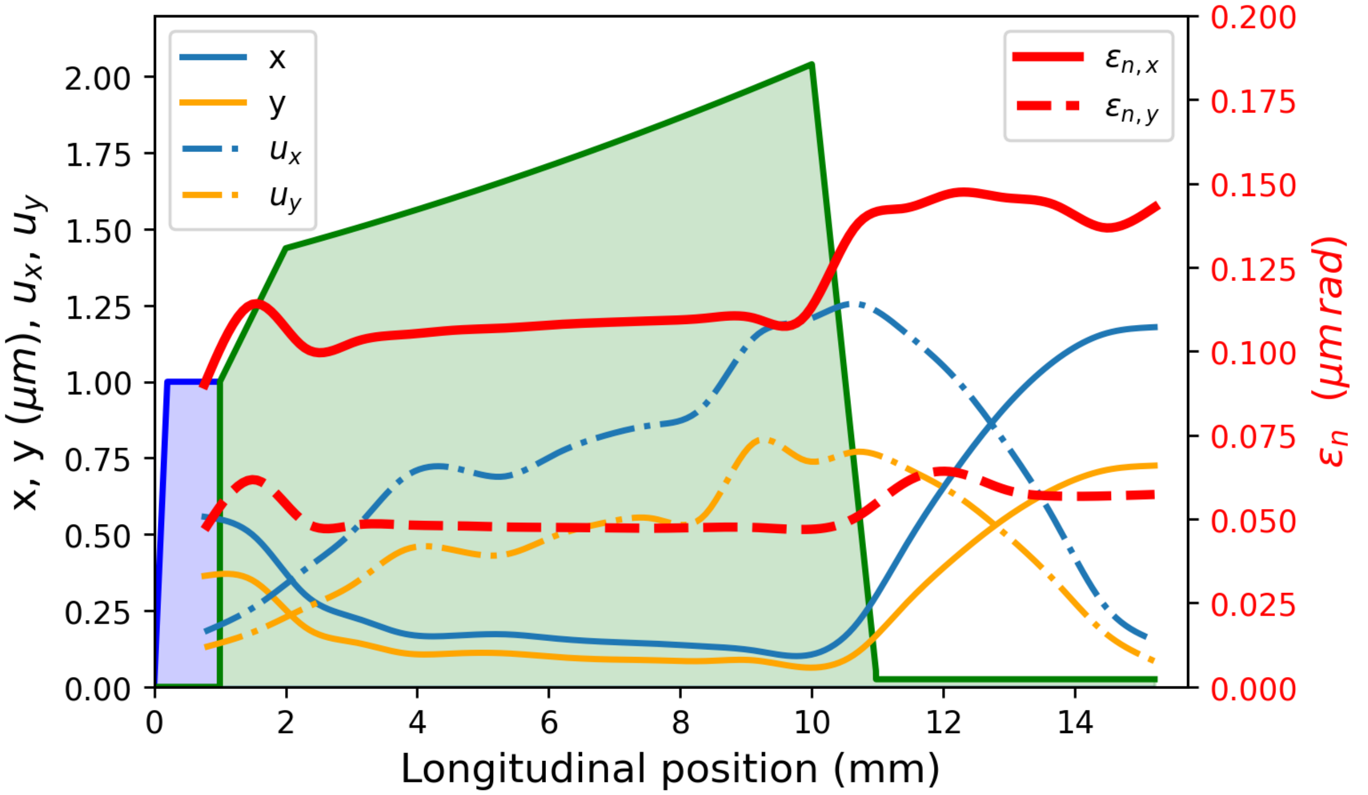
P. Tomassini et al., High-Brightness e-beams with the ReMPI scheme employing two driver pulses, in preparation

Flexible attosecond source

Theory @ LDED

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

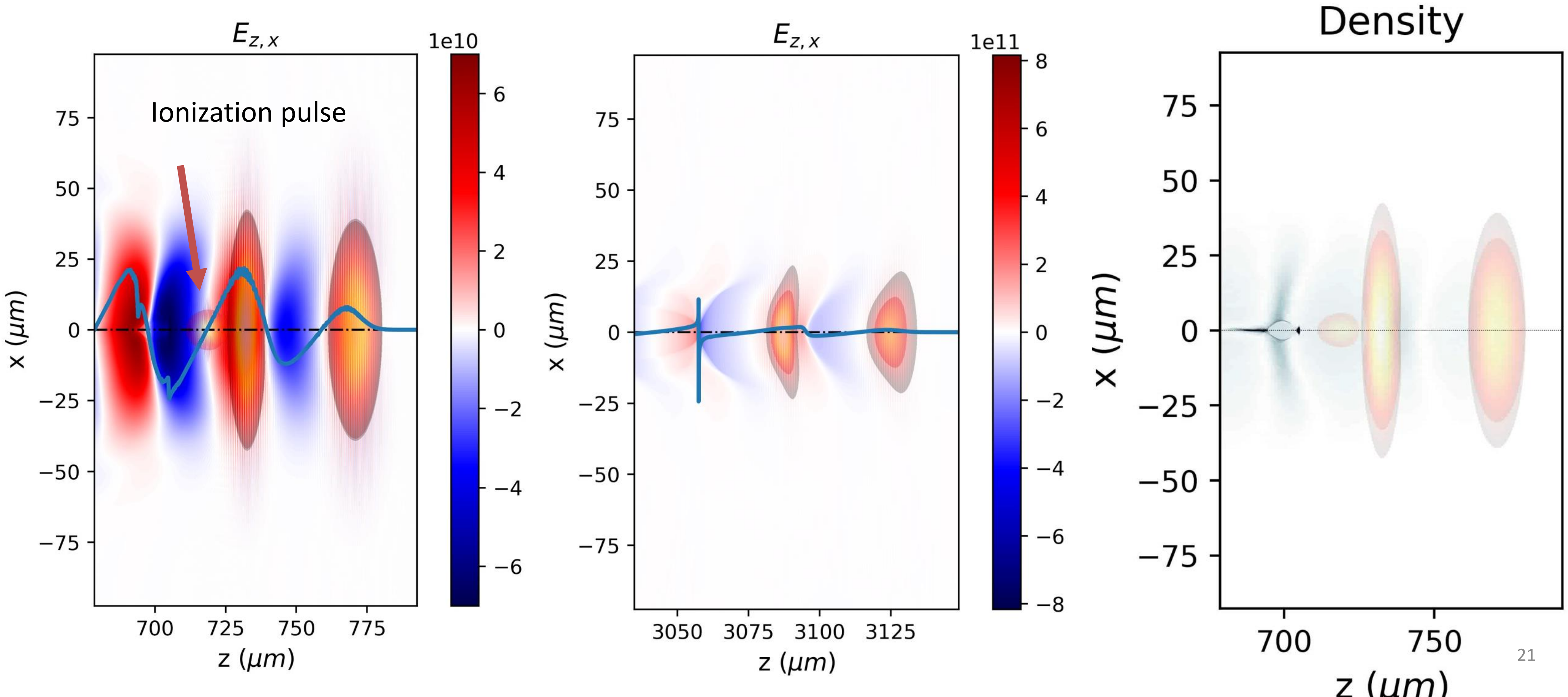
- 2x 23fs FWHM pulses,   w0=30 μm ,   total 4.2J on TEM00,
- 1x 30fs FWHM ionization pulse **in III** harmonics, w0=3.5 μm, on TEM00, 20mJ



- **100%Ar (8+) plasma, n0=0.75e18 1/cm^3,**
- **1mm plateau + 100He 10mm accelerating structure, guided pulse with radially parabolic density profile**

Plasma lens after the downramp to reduce beam divergence

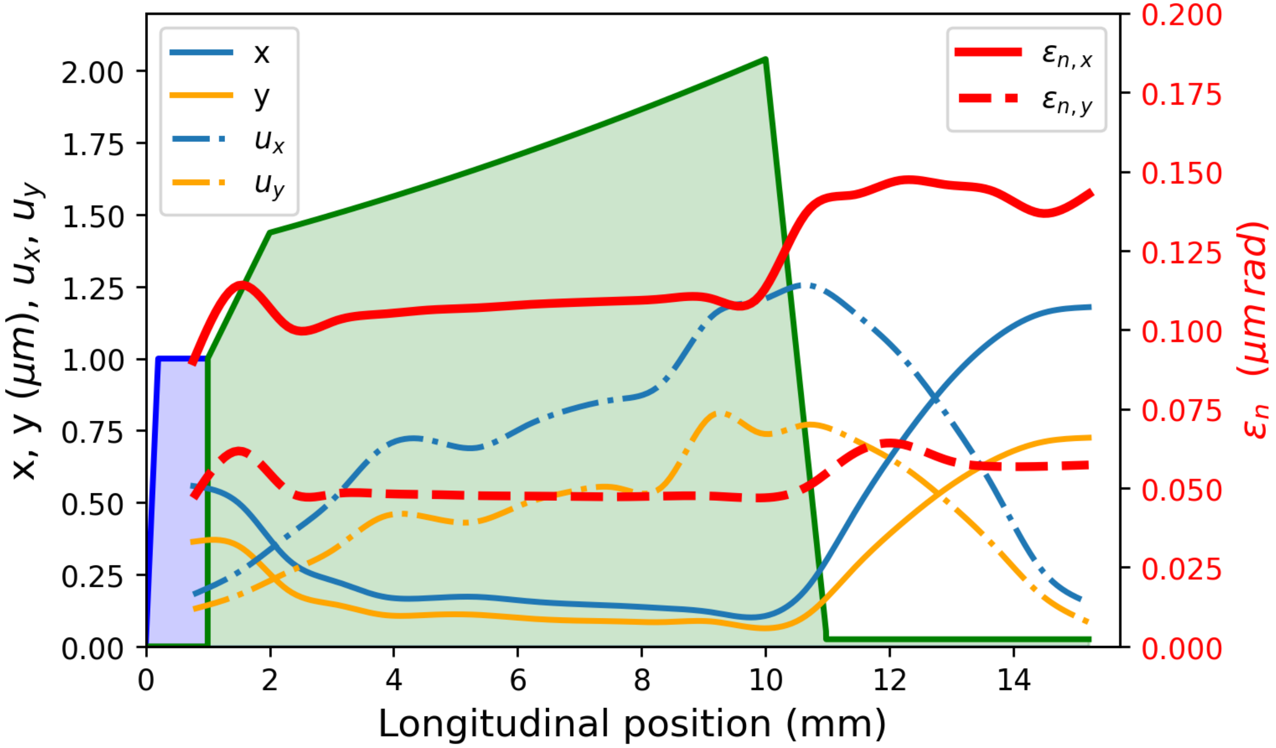
Flexible attosecond source

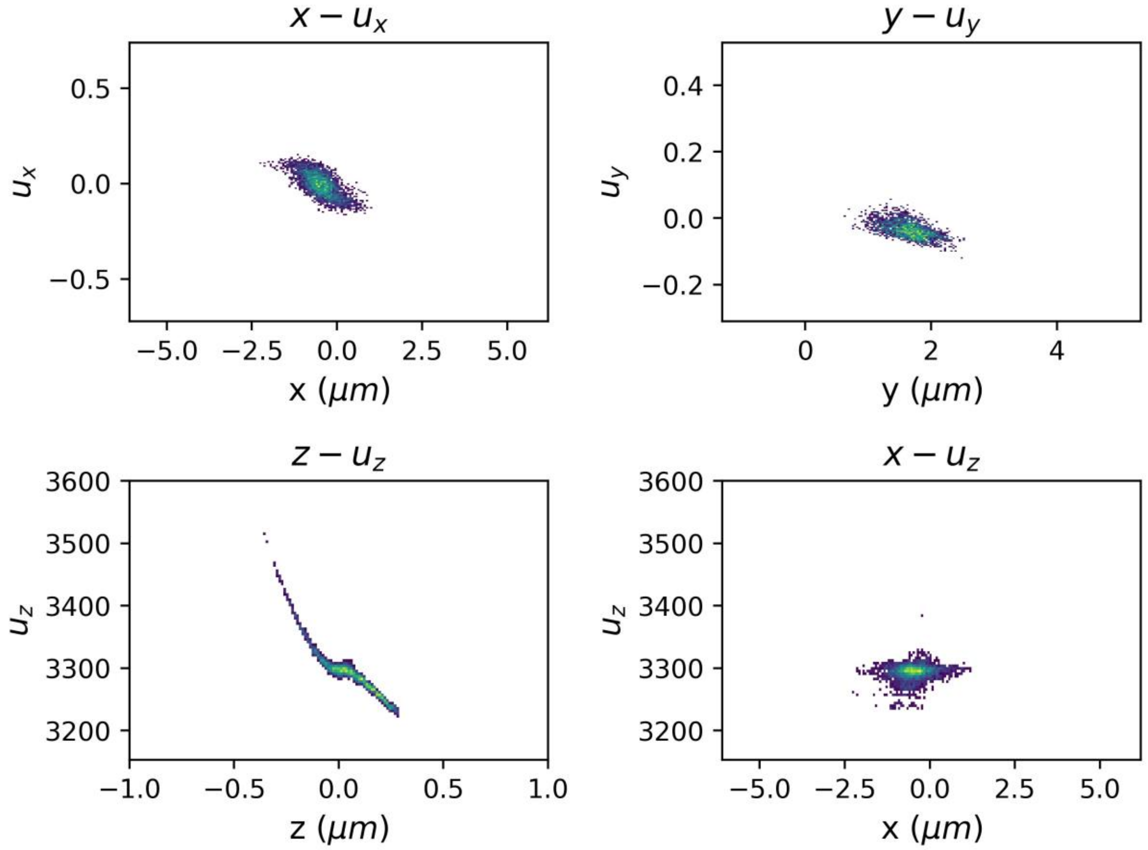


Flexible attosecond source

Theory @ LDED

Q=18pC





Final beam phase space

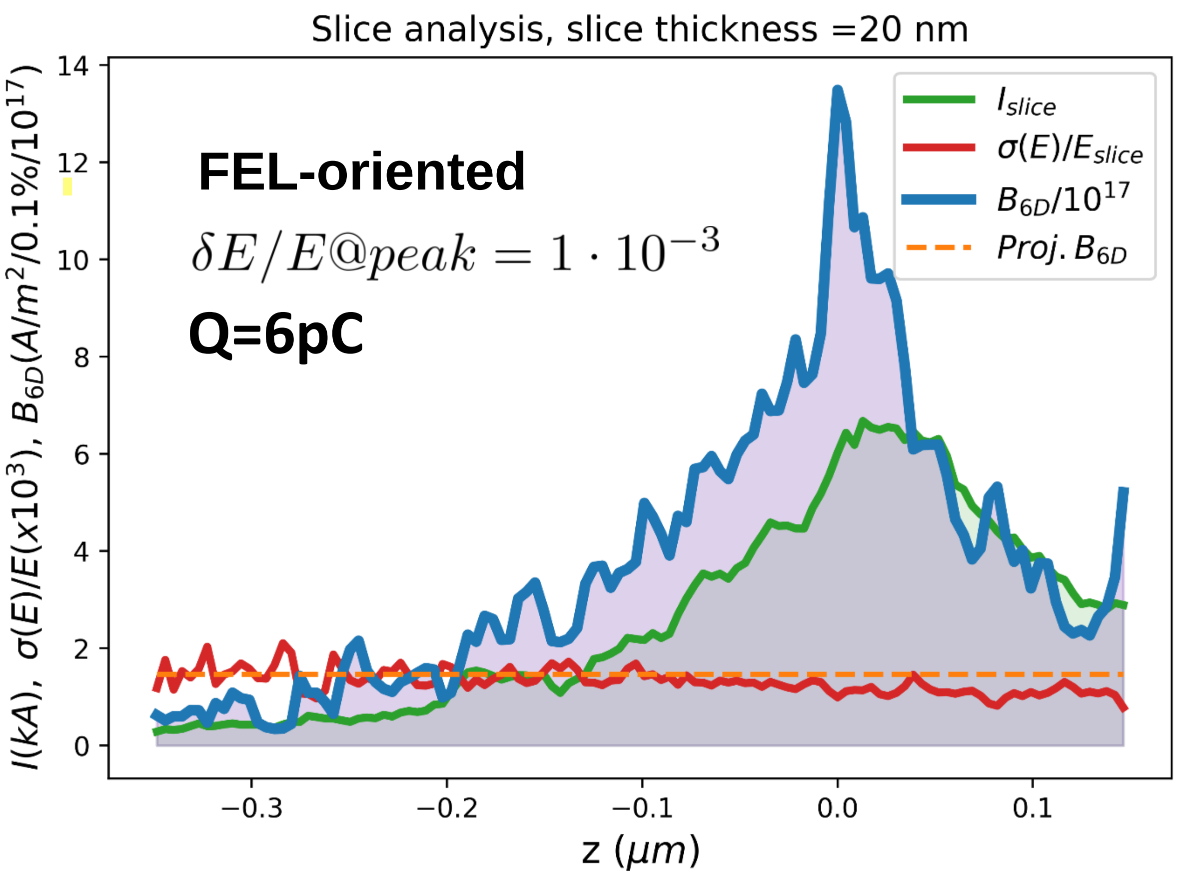
The downramp shape needs to be optimized

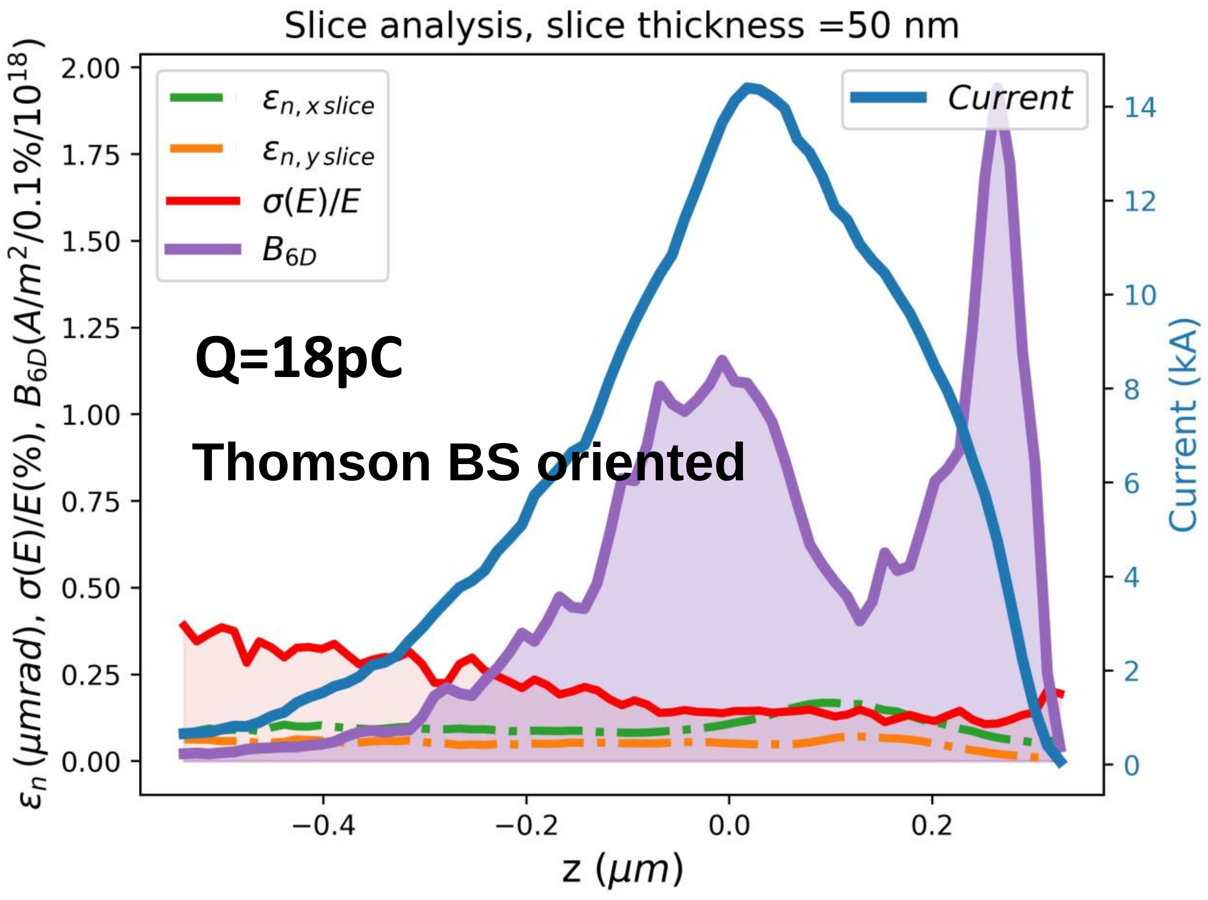
Flexible attosecond source

Theory @ LDED

Duration (rms)	Projected Brighthess 6D	δE/E (rms)
250 as	$1.5 \cdot 10^{17} A/m^2/0.1\%$	0.6%

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





Outlook

1. The two-color ionization injection and the Resonant Multi Pulse Ionization Injection (ReMPI) schemes

2. Earlier results with ReMPI

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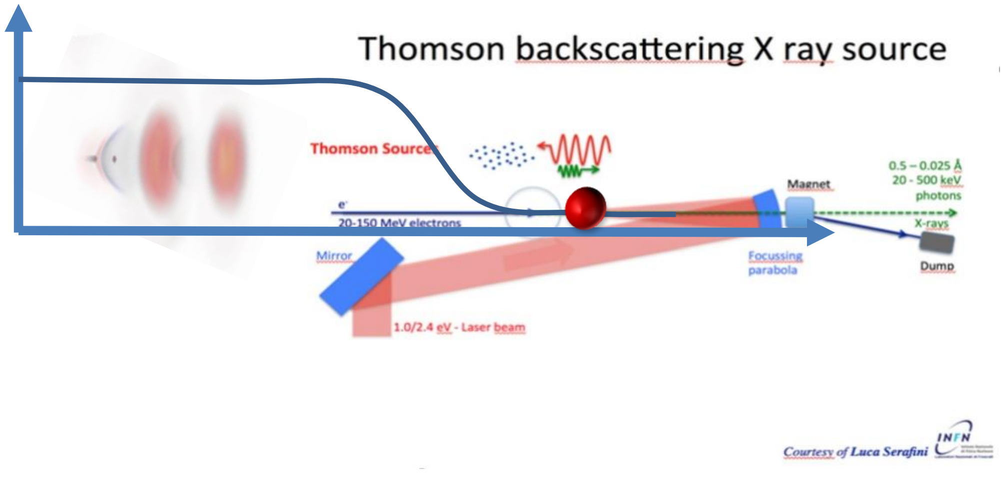
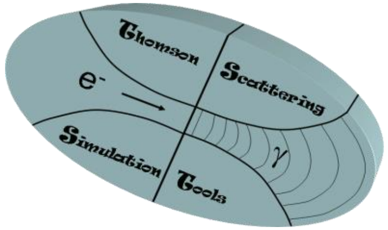
3. Attosecond high-brightness beams with ReMPI and 250TW Ti:Sa systems

4. **Towards Compton/Thomson sources**

5. Conclusions

Attosecond long X/γ sources with the Thomson backscattering process





Thomson Scattering Simulation Tools (TSST) is a semi-analytic code employing the analytic Thomson Scattering theory in [P. Tomassini et al., Appl. Phys. B 80 (2005)]

Projected beam quality

σ(E)/E	Q	σ(u perp.)	σ(x perp.)	σ(z long.)
0.7%	18pC	0.12	0.15 μm	0.2μm

Counterpropagating pulse Yb:YAG (1.053 μm)

Energy	Duration	W0	A0
1J	2ps	12.5 μm	0.2

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

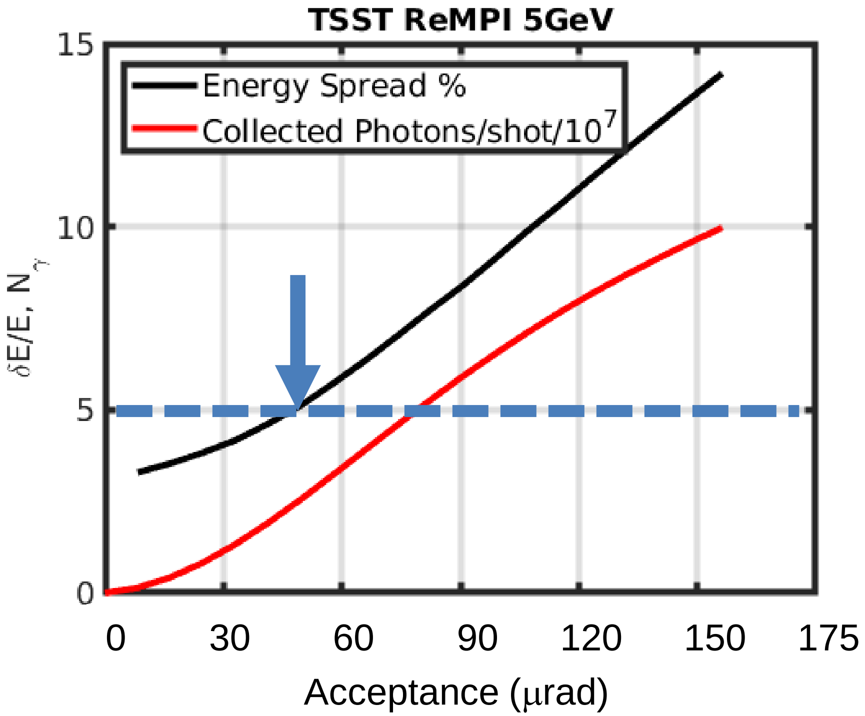
Normalized acceptance
EXTREMELY USEFUL parameter

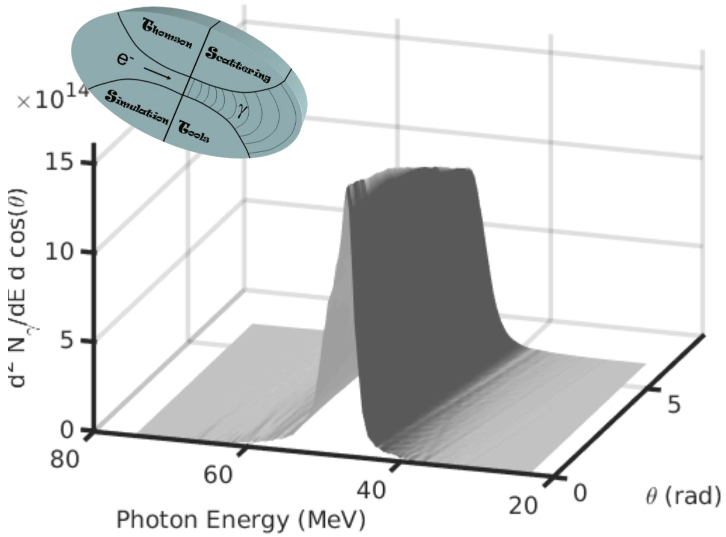
$$\text{if } \Psi \ll 1 \Rightarrow N_{Acc}(\Psi) \simeq \delta\omega/\omega \simeq \Psi^2$$

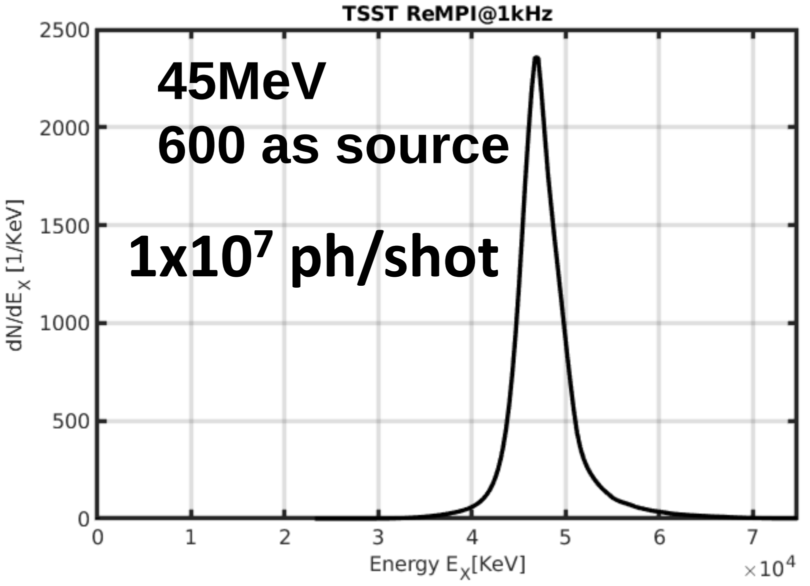
$$(\delta\omega/\omega)_{min} \simeq \sigma(u_\perp)^2 + 2\frac{\delta\gamma}{\gamma} + a_0^2/2$$

$$(\delta\omega/\omega)_{min} \approx 3\%$$

Attosecond long X/γ sources with the Thomson backscattering process







The peak brilliance is

$$B_\gamma = \frac{\#photons}{rms\,duration}\frac{1}{Area \times divergence^2 \times BW(0.1\%)}$$
$$= \frac{1\times10^7}{0.6\times10^{-15}s}\frac{1}{\pi(0.15\times10^{-3}mm)^2\times(50mrad)^2\times50}$$
$$= 1\times10^{30}\frac{ph}{s\,mm^2\,mrad^2\,0.1\%BW}$$

Conclusions

- ReMPI needs a pulse shaping with (approximately) equal intensity pulses. This is not straightforward . **Any collaboration on this side is welcome**

- ReMPI is very flexible and it can be employed to generate **high-brightness e-bunches**

- By tuning the delay between the ionization pulse and the driver, the beam length can be adjusted in a wide interval. **100's** as bunches can be generated in this way

- The time jitter between the ionization and the driver pulses is a critical parameter.

A few fs rms jitter are acceptable for attosecond bunches generation

- **The simplified scheme with two driver pulses and short-ultrashort e-beams should still be explored, <u>for now only "high density -> low energy" working points have been optimized</u>. For them, a full transport + undulator analysis is needed**

An experimental demonstration of the two-pulses case is now on the table at **CNR-INO and ELI-NP (collaborations with Victor Malka, Nasr Hafiz and other colleagues started on this purpose)** nuclear physics

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Theory @ LDED

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INFN-MI/PI
ENEA
ELI-ALPS
WEIZMANN

attosecond

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Thank you for your attention!