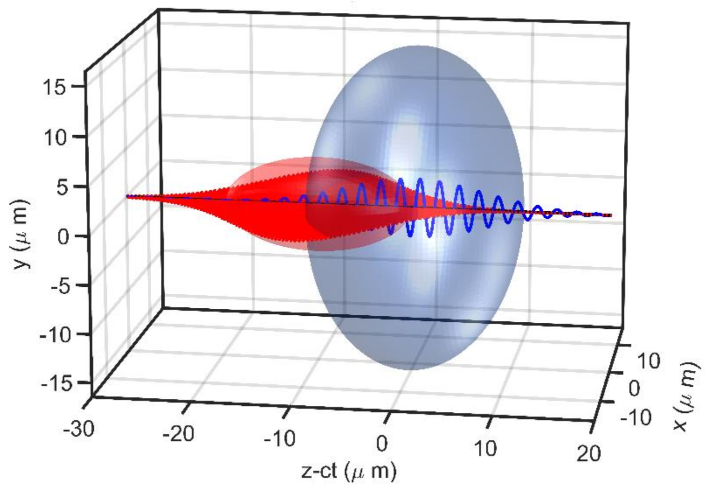

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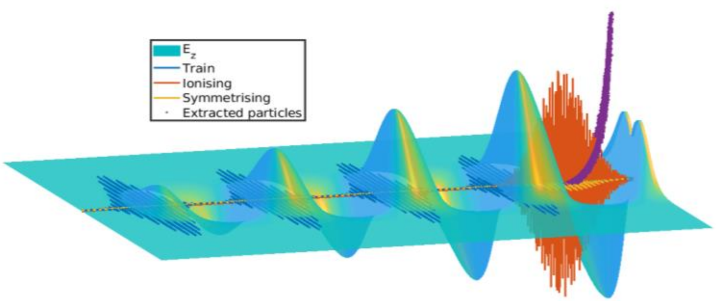

EuPRAXIA

Ultra-low emittance round beams with multi-pulse ionization injection schemes

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In collaboration with

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CEA, France

Preamble: High-quality two-color injection

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

Two-Color Laser-Ionization Injection

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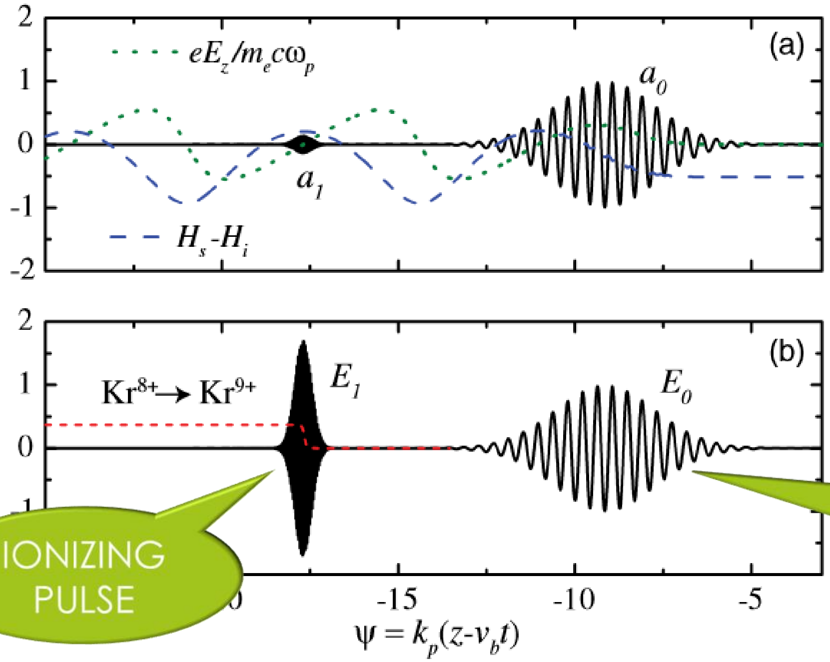
(Received 31 July 2013; published 24 March 2014)

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

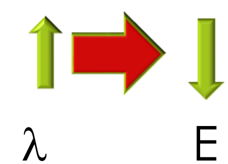


It uses two lasers systems:
A **long wavelength** (λ>5 μm) pulse excites the plasma wave and the **short wavelength** one (λ<0.4 μm) extracts electrons by field ionization from an high-Z dopant.
It allows for very low emittance bunches.

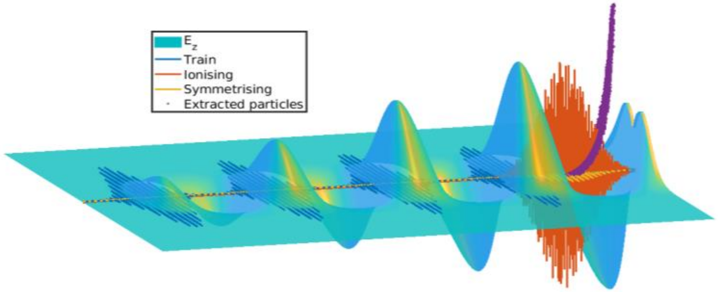
The ionisation pulse is **linearly polarised** so as to strongly reduce the beam emittance

Emittances of the order of a **few tens of nm** could be obtained with this scheme

A very asymmetric beam is generated



The high-quality ReMPI scheme



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

The resonant multi-pulse ionization injection

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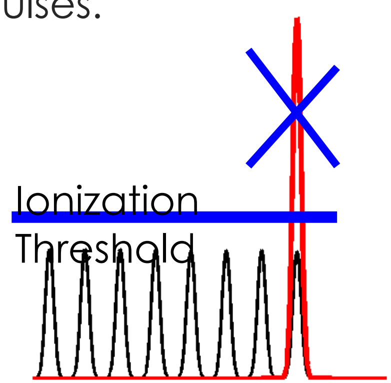
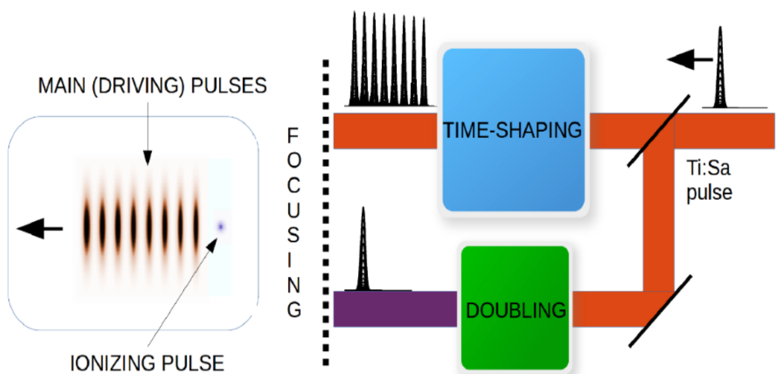
In ReMPI the wakefield driver is a train of resonant, sub-threshold pulses. It may be implemented lwith just **one** short-pulse (e.g Ti:Sa) laser system.

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.





As in two-color, emittances of the order of **tens of nm** could be obtained with this scheme

A very asymmetric beam is generated, as the ionisation pulse is linearly polarised

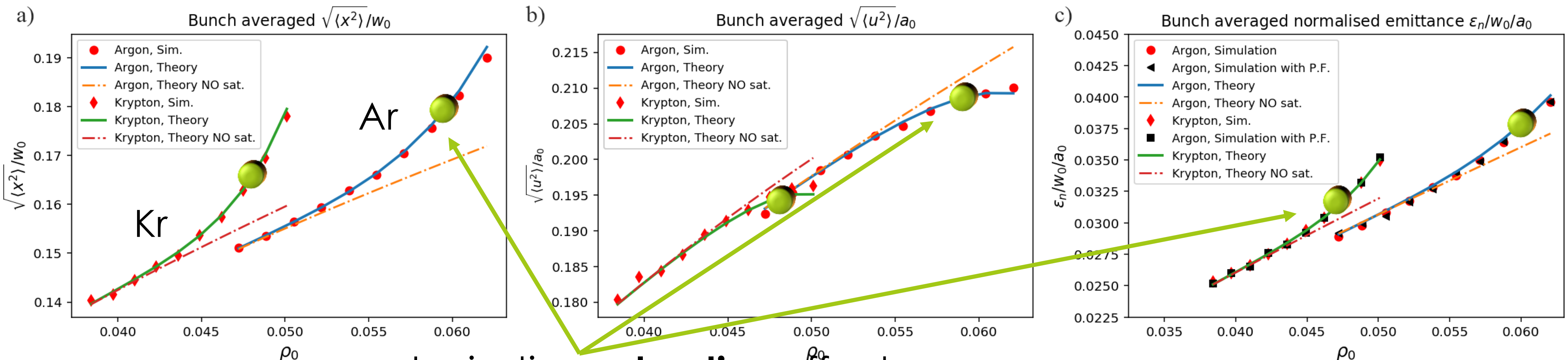
Single pulse field (tunnel) ionisation theory (I)

[1] C. Schroeder et al., Thermal emittance from ionization-induced trapping in plas. accel., PRAB 10130 (2014)

[2] P. Tomassini et al . Accurate theory of tunnel ionization emittance with a single laser pulse,., in prep.

Based on the work n [1] and with the aim of obtaining a very accurate theory for a **single cycle** or the **whole bunch ionisation**, we developed a model including Δ_0^4 correction terms and **exponential contributions due to the onset of saturation effects.**

Errors **below 1%** are obtained with $Kr^{8^+ \to 9^+}$ and $Ar^{8^+ \to 9^+}$ processes.



$$\rho_0 = \sqrt{\Delta_0}$$
$$T = 10fs$$
$$w_0 = 5\mu m$$

Ionisation **saturation** effects on

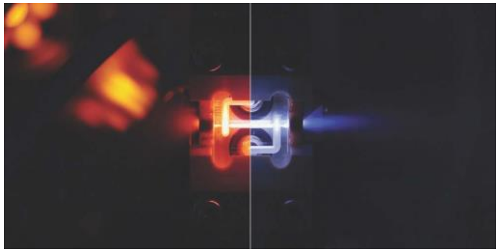
$$\Delta_0 = \left(\frac{2E_{0,x}}{3E_a}\right)^{1/2} \left(\frac{U_H}{U_I}\right)^{3/4} \ll 1$$

Emittance ϵ_{nx}

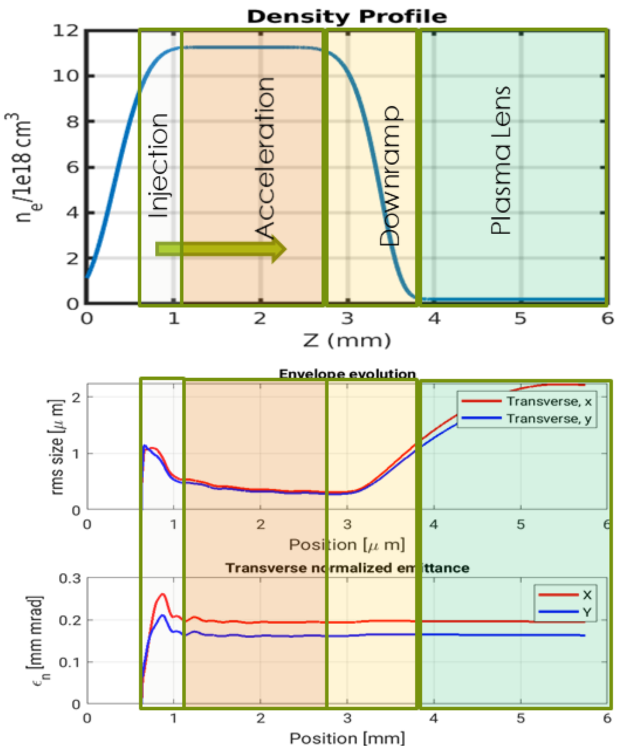
The new theory can be applied in **laser-envelope codes**, so as to accurately mimic the ionisation process (with <1% error) **without the need of a very large resolution.**

ROUND vs FLAT beams

Active plasma lens



Courtesy of CERN: Image: KSjøbæk/CLEAR



P. Tomassini et al., High quality electron bunches for a multistage GeV accelerator with resonant multipulse ionization injection PRAB 22 11 (2019)

	FLAT	ROUND
Matching betatron oscill.	**Impossible** to match: x and y sizes evolve differently	**Matchable**
Beam loading control/energy spread minim.	**Impossible** to match: x and y sizes evolve differently	**Matchable**
UP/DOWN ramps	**Impossible** to match in both directions	**Matchable**
Simulation complexity	**Very large**. Full 3D codes are necessary (even in an optimisation stage)	**Small**. Cylindrical or quasi-cylindrical codes can be employed
PLASMA LENSES	**Impossible** to match in both directions	**Matchable**

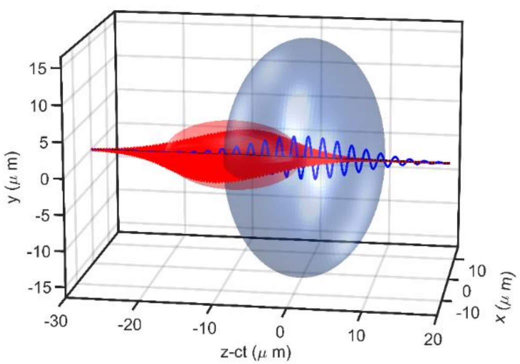
Only HQ round beams are candidates for staging.

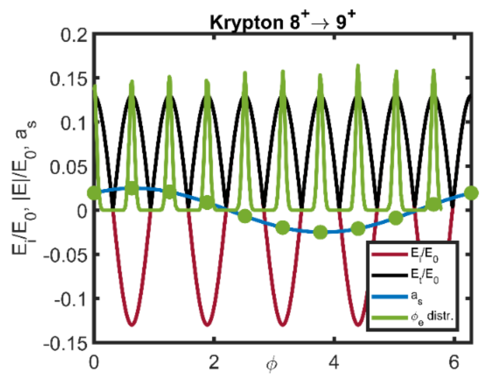
Double pulse field (tunnel) ionisation theory and axially symmetric beams

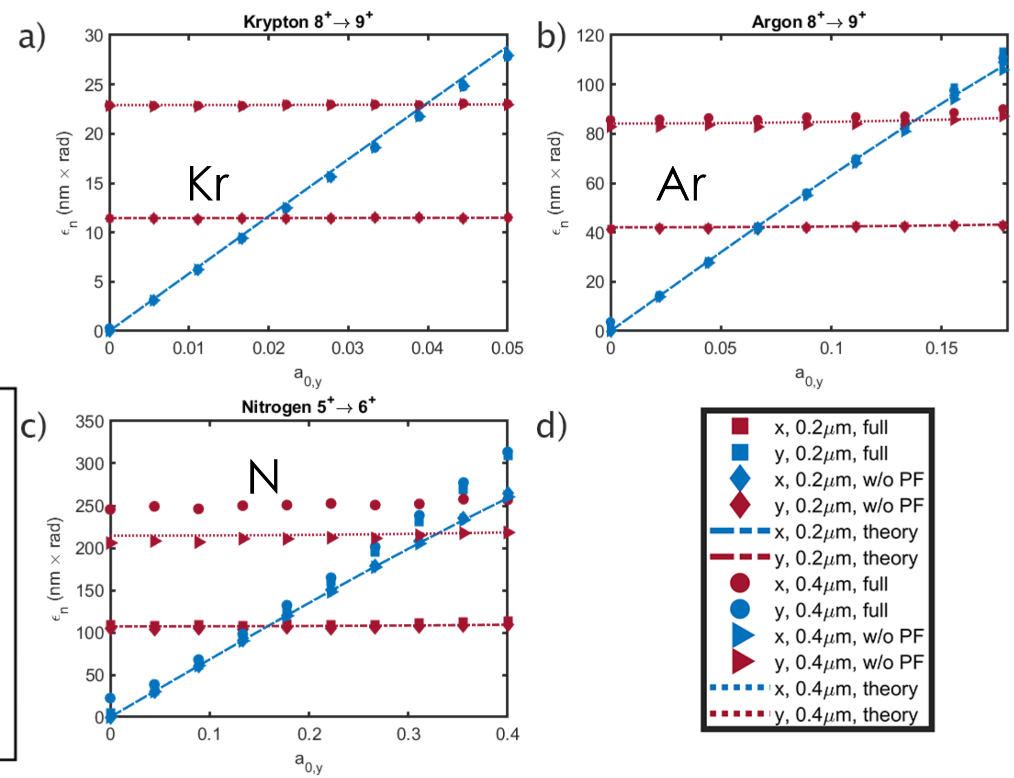
[4] Axially symmetric high-quality electron beams generation with single or multi-pulse ionization injection schemes, P. Tomassini et al., in prep.

Two (even partially) overlapped, perpendicularly polarised pulses with different wavelengths can be fruifullly employed to obtain **round beams**, still **preserving the beam qualiy** offered by the two-color and ReMPI schemes. The idea has been presented in [1-4], and an *accurate prediction* of the single-cycle or whole bunch properties will published in [4]

$$w_0 = 5\mu m \;\; T = 15fs$$



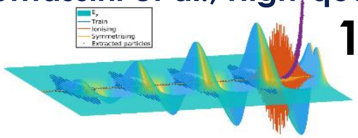




[1] P. Tomassini et al., High-quality 5GeV electron bunches with the resonant multi-pulse ionization injection, PPCF 62 (1) (2019)
[2] P. Tomassini et al., High quality electron bunches for a multistage GeV accelerator with resonant multipulse ionization injection, PRAB 22 (2019)
[3] R. Assman et al., EuPRAXIA Conceptual Design Report Eur. Phys. J ST (2020)

FEL-quality 5GeV round beams with ReMPI

P. Tomassini et al., High-quality 5GeV electron bunches with the resonant multi-pulse ionization injection, PPCF 62 (1) (2019)

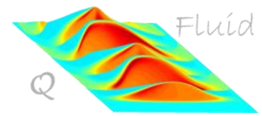


1PW Ti:Sa pulse needed. Argon as dopant+20cm capillary

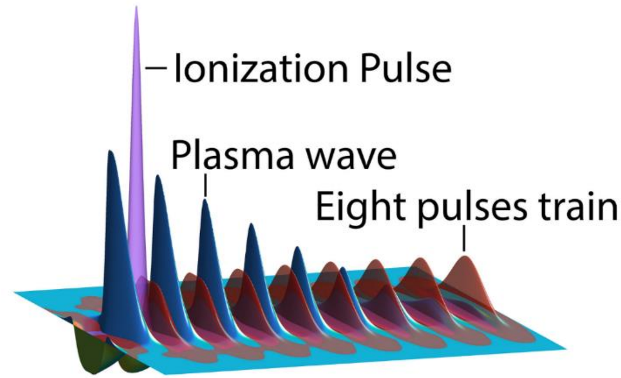
The ionisation pulse is **partially overlapped** with the **last pulse** of the train and a (quasi) round beam of emittances

$$\epsilon_{nx} \simeq 75nm \times rad \qquad \epsilon_{nx} \simeq 65nm \times rad$$

is produced. Slice analysis reveals that a **FEL compliant 5GeV** beam is produced



QFluid4.5
(laser-envelope)
simulations



Simulation Parameters

«Injector» gas jet (50%He,50%Ar)

Up/Down ramps	Plateau	Atomic Density	Background density
2mm	5mm	2.75 10^16 1/cm^3	2.2 10^17 1/cm^3

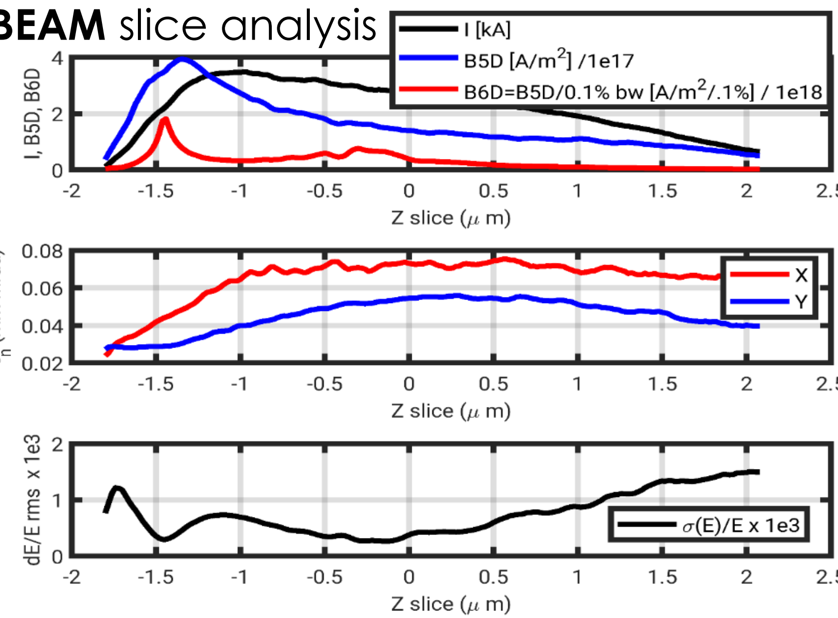
«booster» capillary (100% He)

Up/Down ramps	Plateau	Atomic density	Background plasma density	Channel depth for guiding
2mm	22 cm	1.1 10^17 1/cm^3	2.2 10^17 1/cm^3	90% of the matched value

Ionization pulse, 4^th harmonics of the Ti:Sa pulse

Wavelength	Energy	Duration	Waist
0.2 μm	0.06J	45 fs	4 μm

FINAL BEAM slice analysis



My tentative answers (1/4)

P1 **! Everything is «on my opinion», I omit to repeat it to save space !**

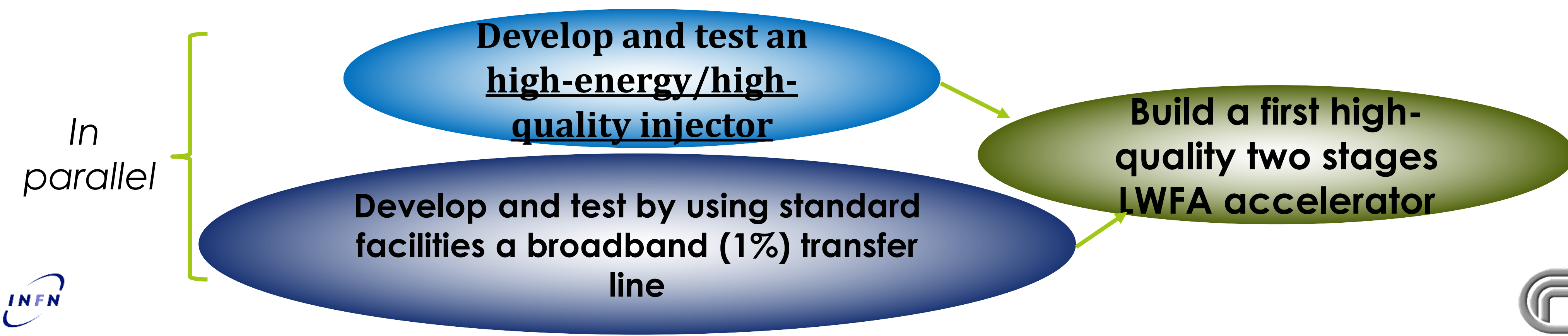
1) **Where do you see HEP applications of advanced accelerators in 30 years?** //
2) **What intermediate physics applications/steps do you see until a HEP linear collider?**

Applications (in addition to the medical one)

- **High-field physics and polarized particles** are very interesting option.
- **Atto-seconds probing** is also very interesting because it's not available with standard accelerators. For example **Two-color** and **ReMPI** schemes can provide **sub-fs beams**. They can be employed directly as probes or used to generate sub-fs X/gamma beams.

Steps (in addition to the positron counterpart)

- The critical step is **staging**, of course. In particular, **preserving beam emittance** is the most challenging physical and technical issue. We need to **step-up the first stage final energy to a GeV scale** so as to have the chance of being able to control emittance growth during the downramp+optics+upramp sections. Therefore an interesting **first steps** chain in pure LWFA could be



My tentative answers (2/4)

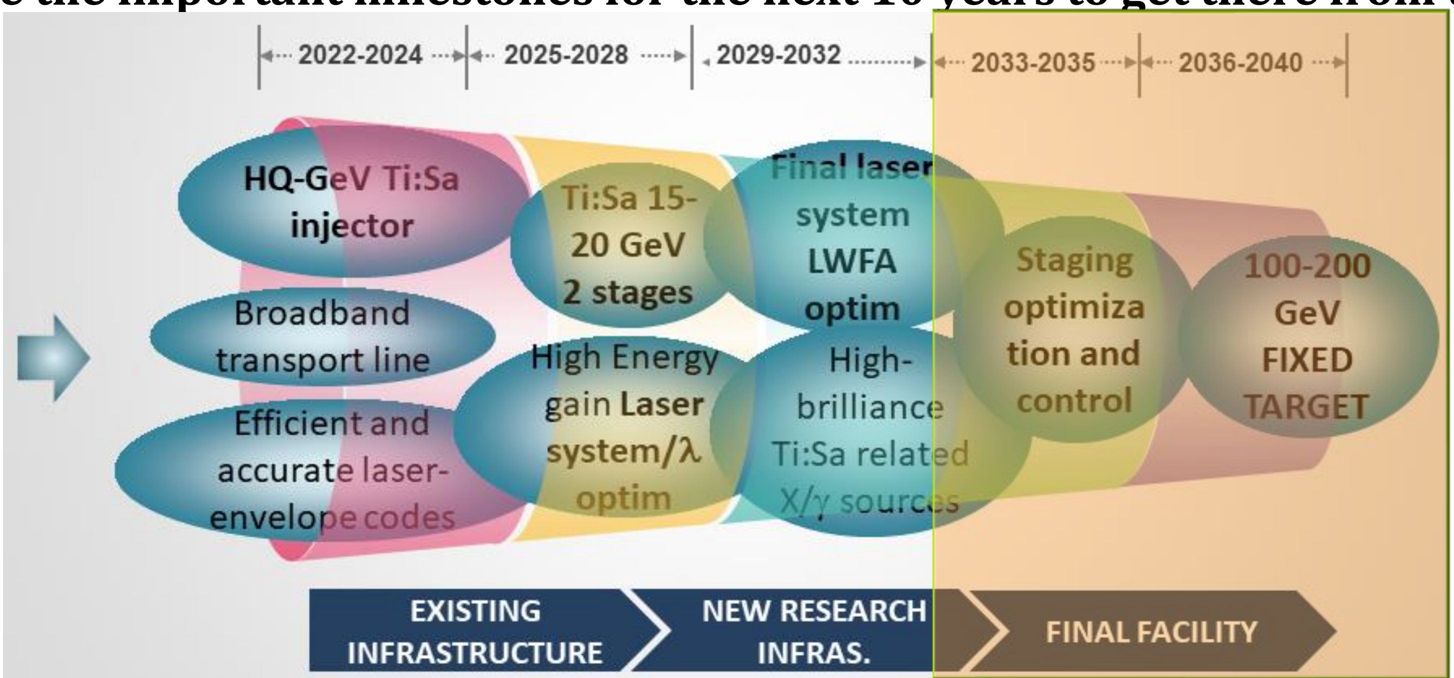
3) **What is the synergy with related fields?** Apart from the obvious speed-up of **laser system development** I see a deep link with the related **High-Brilliance X/gamma sources development.**

4) What is the role of your work here?

I'm working on **high-quality injectors since 2003** (first numerical demostration of density downramp as a low-emittance injector). My main (current) contribution is on **ReMPI optimisation** and on the development of an **accurate theory of beam emittance** with ionisation injection schemes. I'm also proposing a simple way to obtain **round beams** with very low emittances.

P2

1) **What are the important milestones for the next 10 years to get there from today?**



My tentative answers (3/4)

2) What additional support is needed to achieve these? //
3) What should be proposed as deliverables until 2026? Please list in order of priority.

a**.** Demonstration that the **main ingredients** of a HEP (electron) accelerator are physically understood and technically controlled. This means that a GeV-scale high-quality (<100nm rad, round, <1% energy spread) LWFA injector should be tested in an **existing 1PW Ti:Sa facility** [ELI-NP? ELI-Beamlines?...]. At the same time, by using the information from Simulations and preliminary tests on the obtained bunch, we need to demonstrate that the beam exit from the injector stage + (plasma lens ?) + standard beam optics + plasma upramp sections can be managed **sufficiently well to maintain the beam quality** [SPARC-LAB? DESY?....]

b. Demonstration that a GeV class FEL quality compliant and stable beam can be generated with a single stage LWFA [ELI-NP? ELI-Beamlines?...].

c. Demonstration that active control of beam phase jitter can be achieved [DESY?]

4) Is the R&D work for each of those deliverables already funded and, if not, what additional resources / support would be needed? //

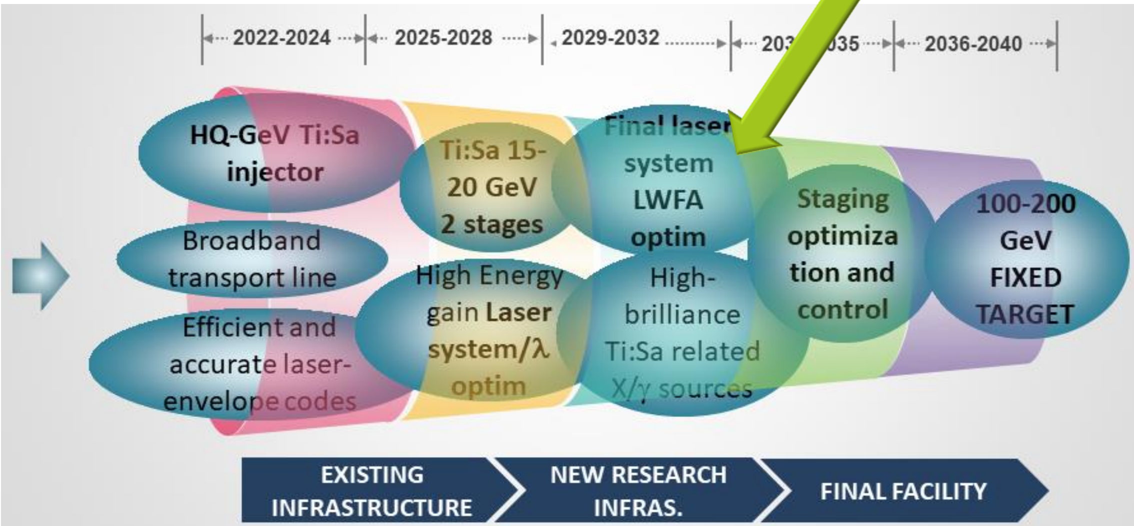
My tentative answers (4/4)

P3

1) What key R&D needs can be achieved in existing R&D facilities?

- Ti:Sa LWFA demonstration module , Beam transport line, Active beam phase control

NOTE: Once the optimal laser technology has been selected, a **light research infrastructure** to test the new system (including LWFA tests) is needed.



2) What is the role of the already planned future facilities in Europe and world-wide? //

3) What can be done with the existing and planned funding base? //

4) Is a completely new facility needed?

Yes

5) Are additional structures needed beyond existing networks and projects, e.g. a design study for a collider or an advanced accelerator stage?//