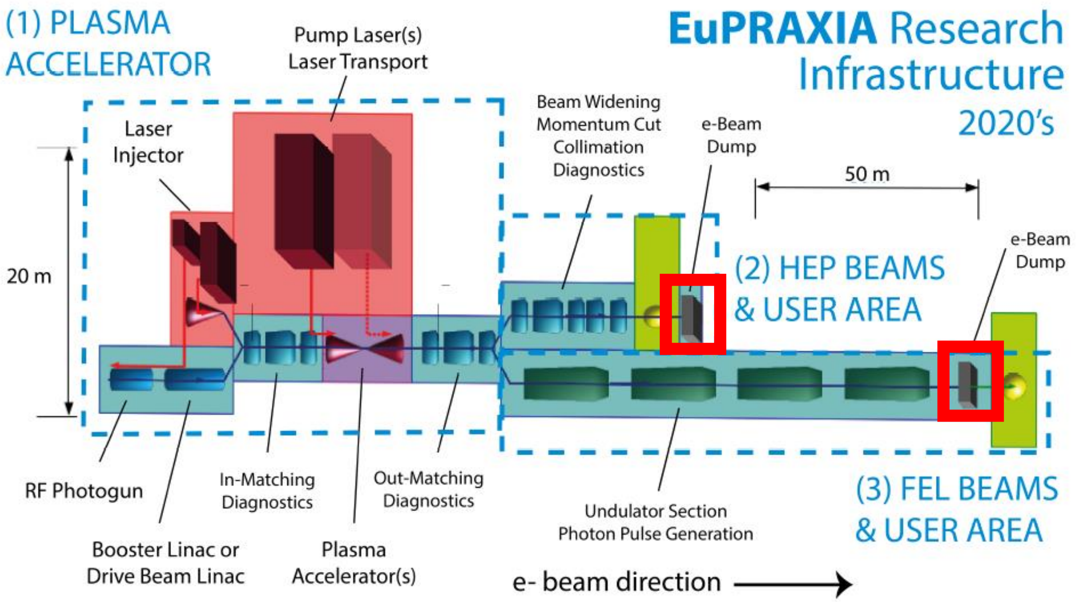
Pilot Applications of Electron Plasma Accelerators Workshop

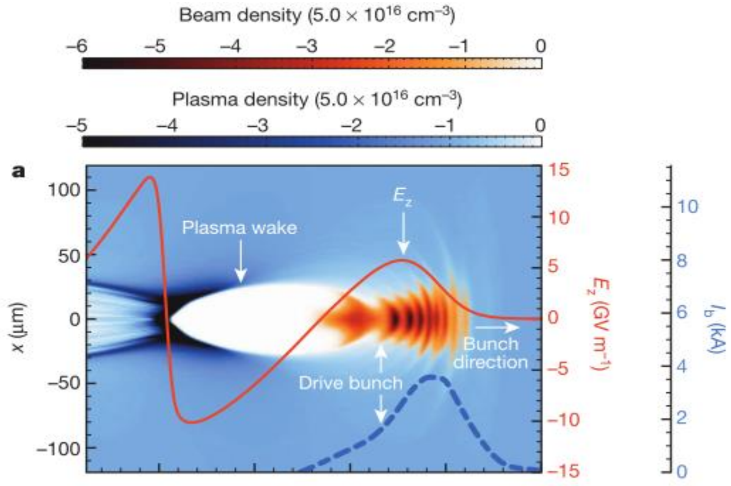
Paul Scherkl and Bernhard Hidding

Scottish Centre for the Application of Plasma-Based Accelerators SCAPA,
Department of Physics, University of Strathclyde
& The Cockcroft Institute

identify pilot applications for plasma accelerators both **in high energy physics (HEP**), particle accelerator technology, but also in other fields of science and accelerator technology. In particular, this workshop aims at defining design **beam parameters** required by applications of electron beams to be delivered by the **future European plasma accelerator research facility EuPRAXIA**

***Pilot* applications**





M. Litos et al., Nature 512, 035001, 2014

Simplest plasma wakefield geometry: **electron beam propagating in plasma**

Beam excites plasma oscillations → energy transfer to plasma

Acceleration/deceleration on GeV/m level

1. Broadening of spectral distribution → medical and **space radiation** applications

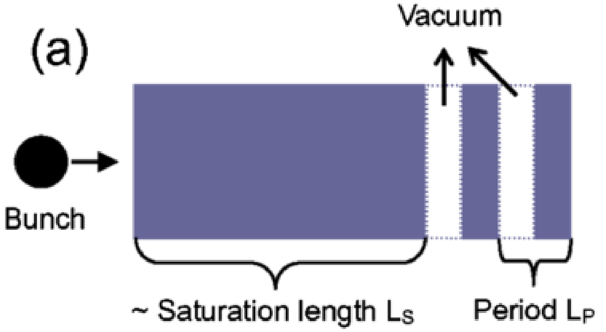
   See P. Delinokolas' talk later today

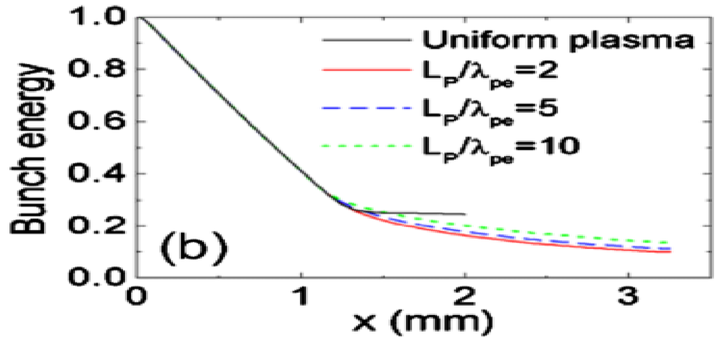
2. Controlled **deceleration** of electron beam: **plasma beam dump**

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **13**, 101303 (2010)

Collective deceleration: Toward a compact beam dump

H.-C. Wu,[1] T. Tajima,[1,2] D. Habs,[1,2] A. W. Chao,[3] and J. Meyer-ter-Vehn[1]

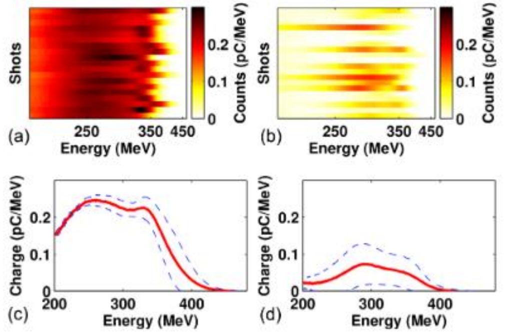


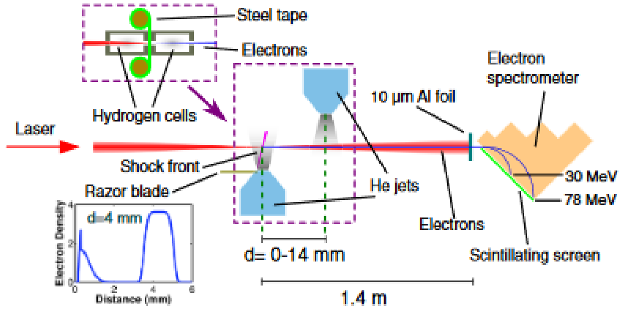


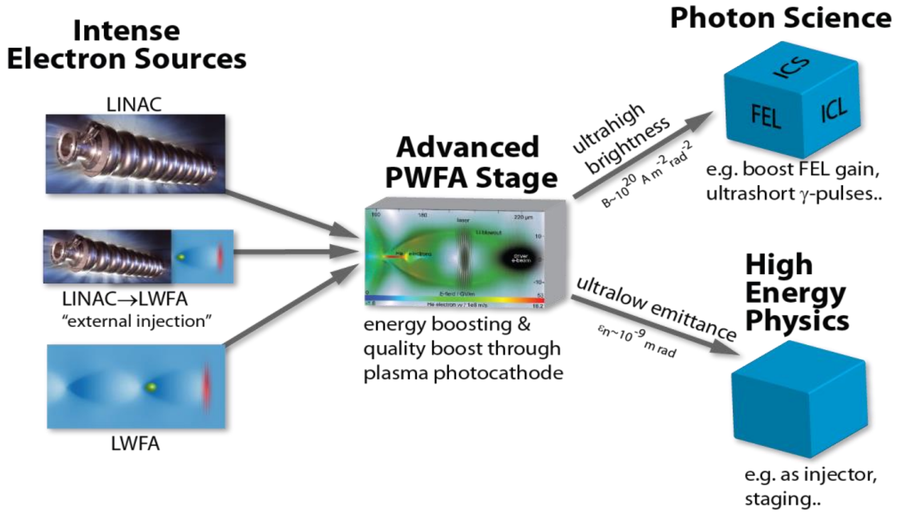
PRL **117**, 144801 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Collective Deceleration of Laser-Driven Electron Bunches

S. Chou (周紹暐),[1,2,*] J. Xu (徐建彩),[1,3] K. Khrennikov,[2] D. E. Cardenas,[1,2] J. Wenz,[2] M. Heigoldt,[2] L. Hofmann,[1,2] L. Veisz,[1,4] and S. Karsch[1,2]



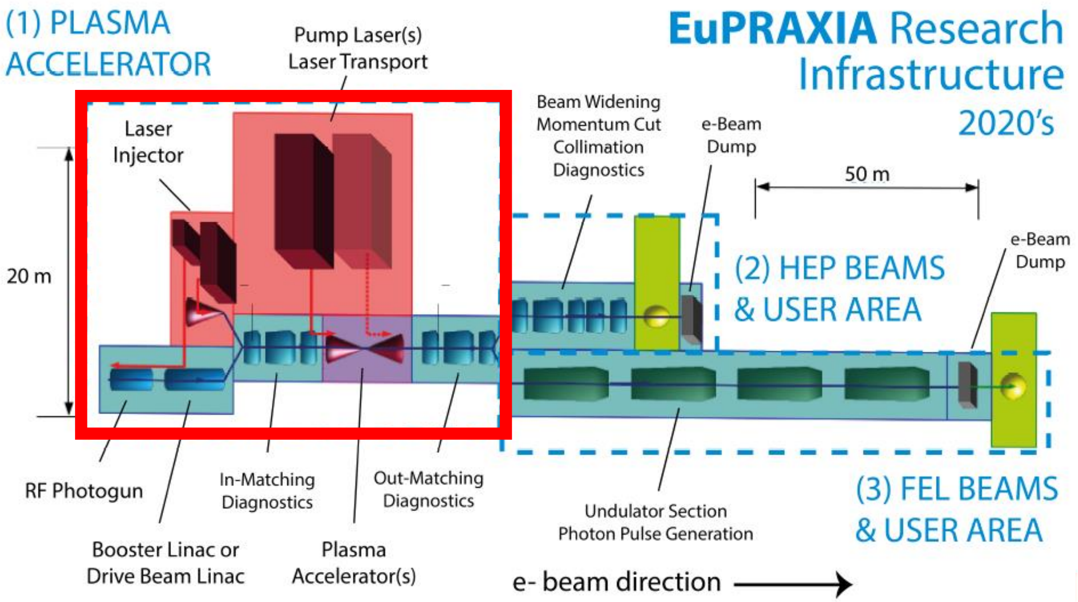


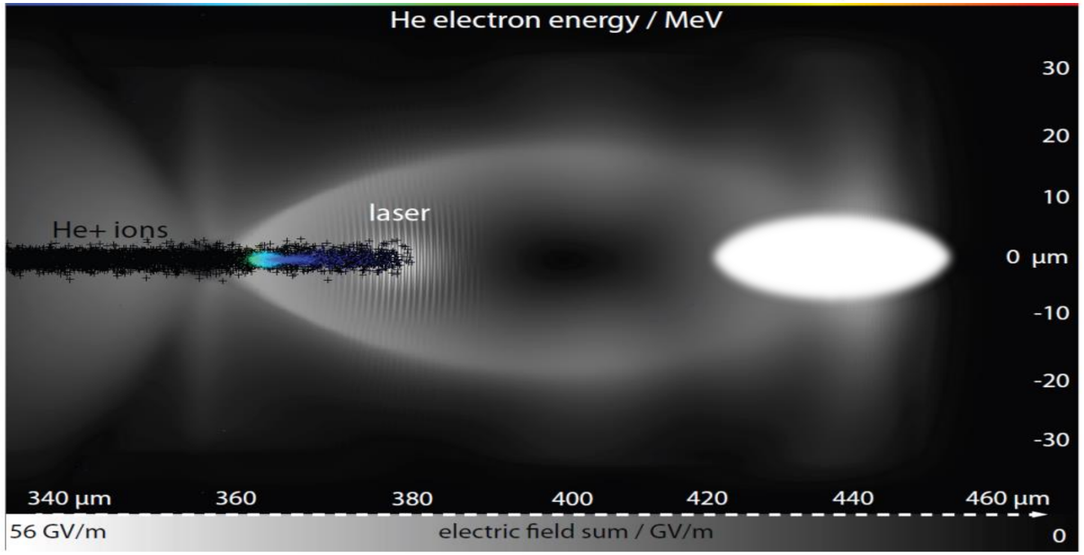


All experiments and applications require beam dump

- Sufficient shielding
- Highly reduced contamination/radioactivation
- Small spatial footprint
- **Synergies with plasma acceleration!**

Easy setup, decent early-on application





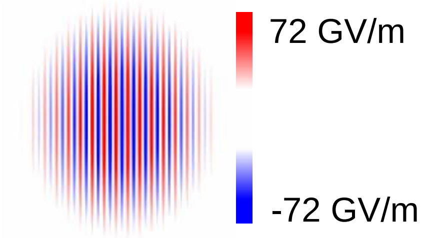
B. Hidding et al., PRL 108, 035001, 2012,Y. Xi et al., PRSTAB 2013, DE patent 2011, US patent 2012

Stable phase relation:

Dephasing-free acceleration to GeV levels

Trojan Horse method

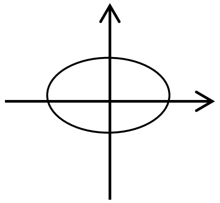
Laser kick contrib. to norm. emittance:



$$E_0 = a_0 \frac{2\pi m_e c^2}{e\lambda}$$

$$\sigma_{p_r}/(mc) \;\approx\; a_0/2$$

residual momentum



$$\sigma_{\mathrm{r,He}} \approx w_0/\sqrt{2}$$

source size

$$\epsilon_n = \gamma\sigma_x\sigma_\theta \propto a_0 {w_0}^2$$

→ ***normalized emittance ε_n down to 10^{-9} m rad***

Schroeder et al., PRSTAB 17, 101301 (2014)

HEP Applications

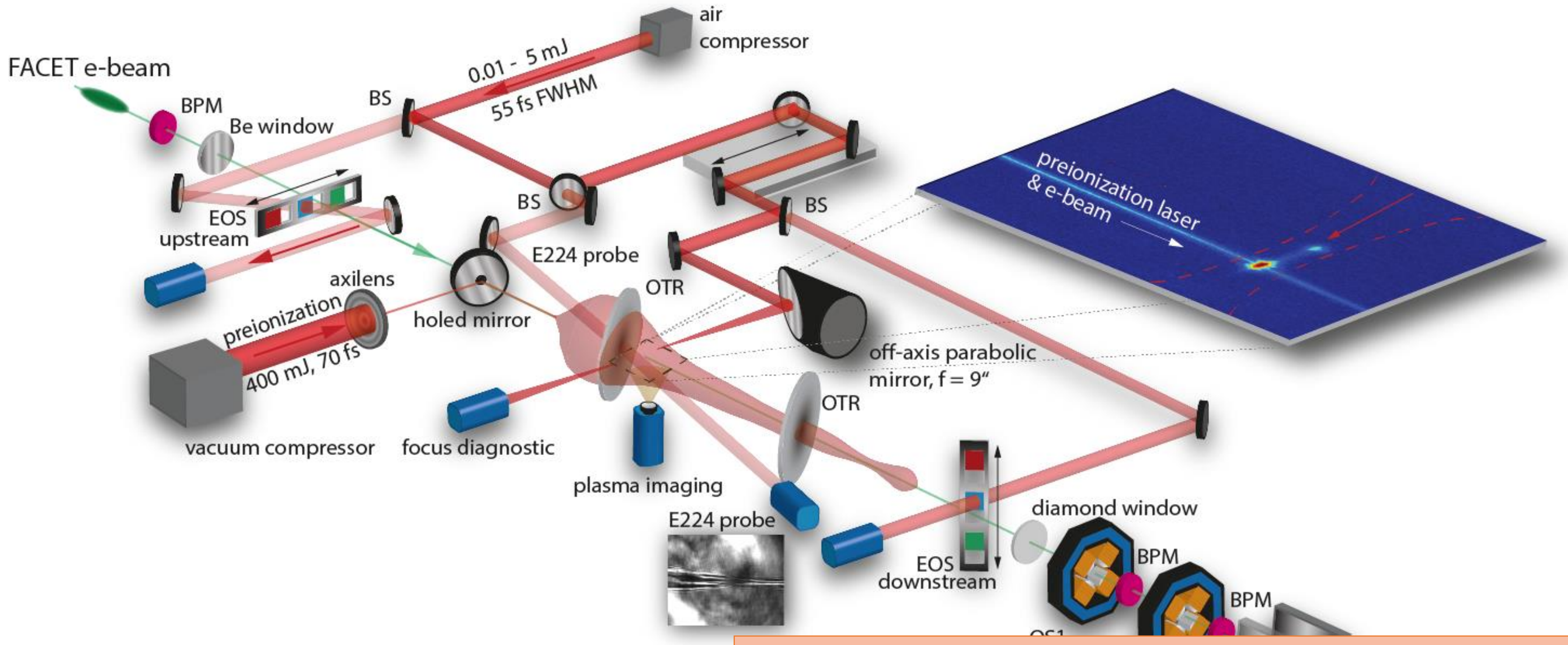
$$L = \frac{fN^2}{4\pi\sigma_x\sigma_y}$$

Radiation sources

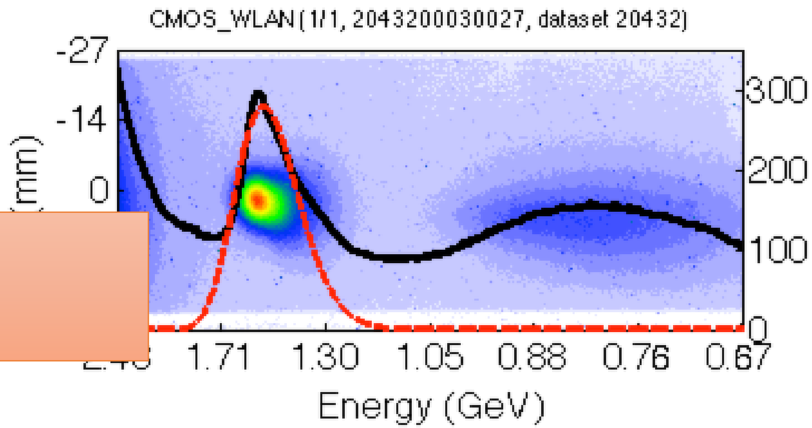
$$b_6 = \frac{I_p}{\frac{\varepsilon_n^2}{0.1\%}\frac{\delta W}{W}}$$

fs beams, kA-scale currents
(typical for plasma accelerators)

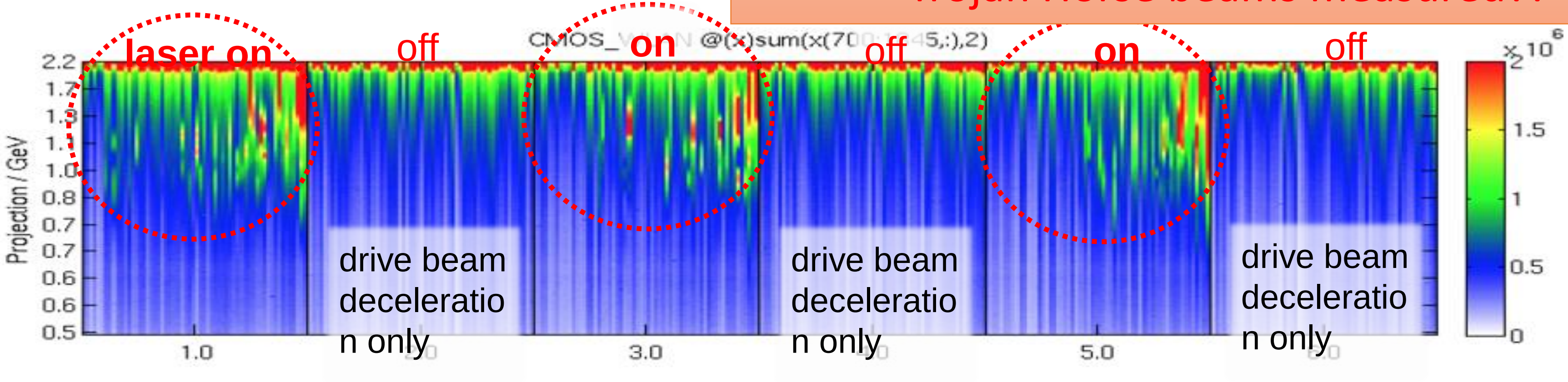
2015/2016: Full Trojan Horse setup



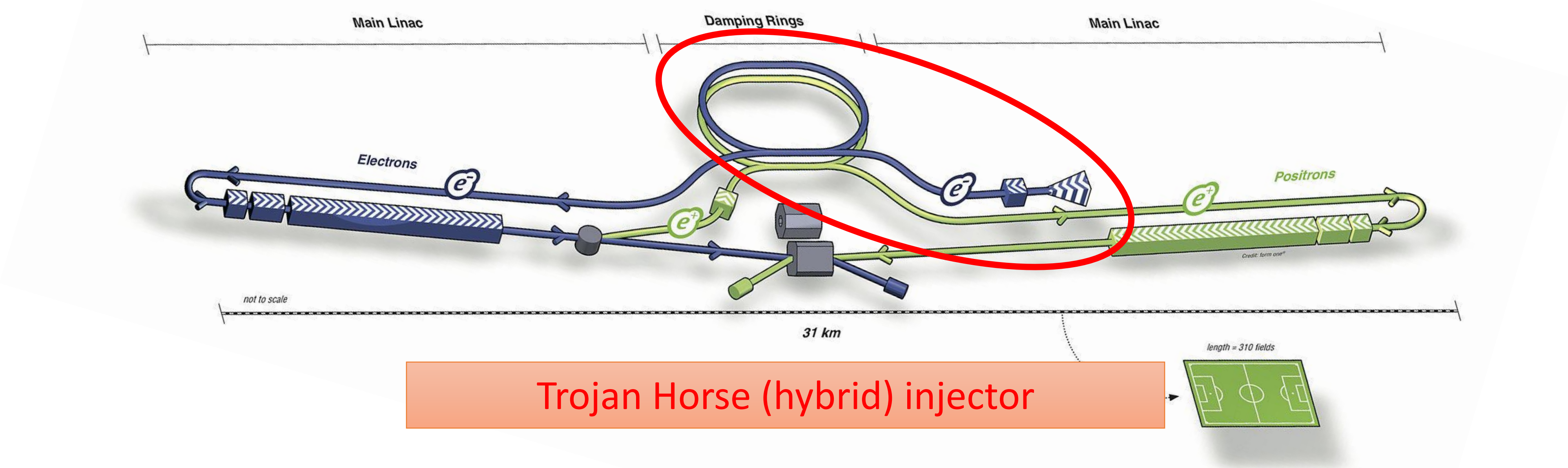
Injected witness bunch accelerated to 0.5 to 3 GeV :



Laser-triggered injection works
Trojan Horse beams measured?!



Plasma accelerator for high energy physics (HEP)



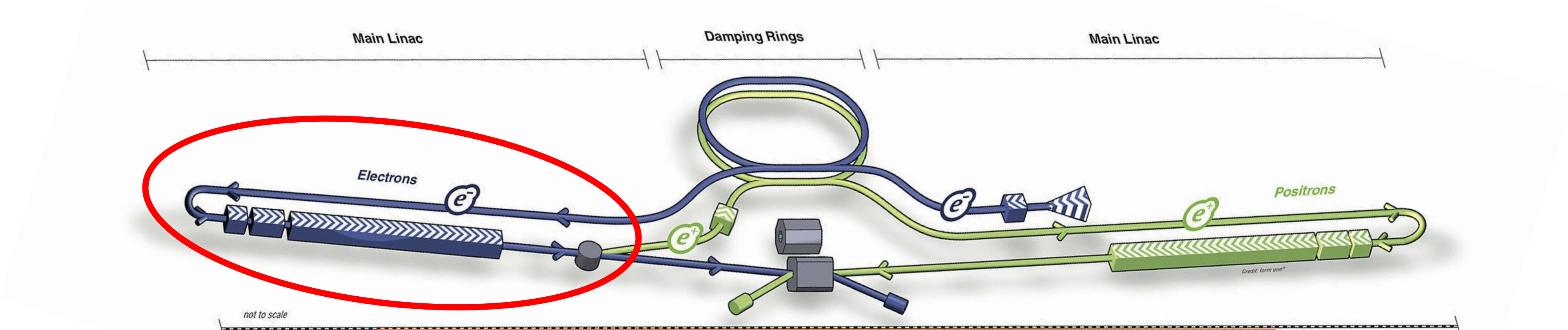
Trojan Horse (hybrid) injector

Ultra-low emittance → high luminosity

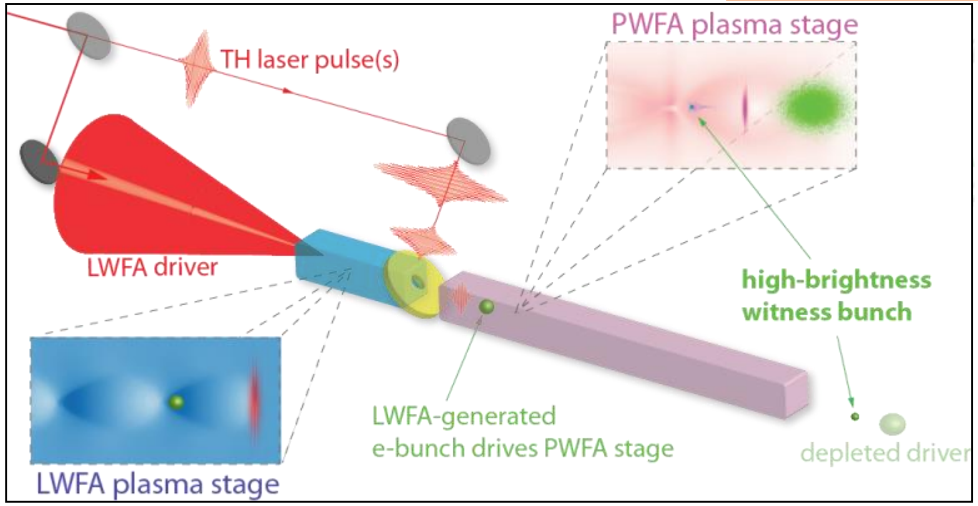
$$L = \frac{f N^2}{4\pi \sigma_x \sigma_y}$$

No damping rings → much smaller footprint

Plasma accelerator for high energy physics (HEP)



Stacked hybrid accelerators towards HEP energies



B. Hidding et al. J. Phys. B: At. Mol. Opt. Phys. 47 (2014) 234010

Benefits from huge progress in LWFA community:

- **Stable prodution of GeV beams**
- Extremely high **currents**
- **Plasma lens** for refocusing/matching S. Kuschel et al., PRAB 19, 071301 (2016)

+

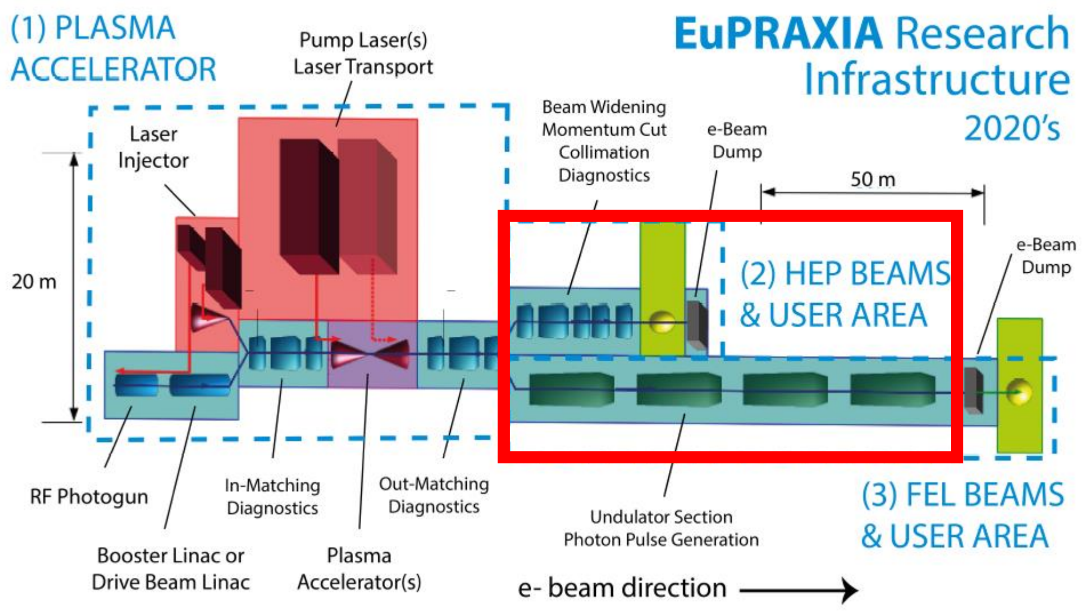
Dephasing-free acceleration from PWFA

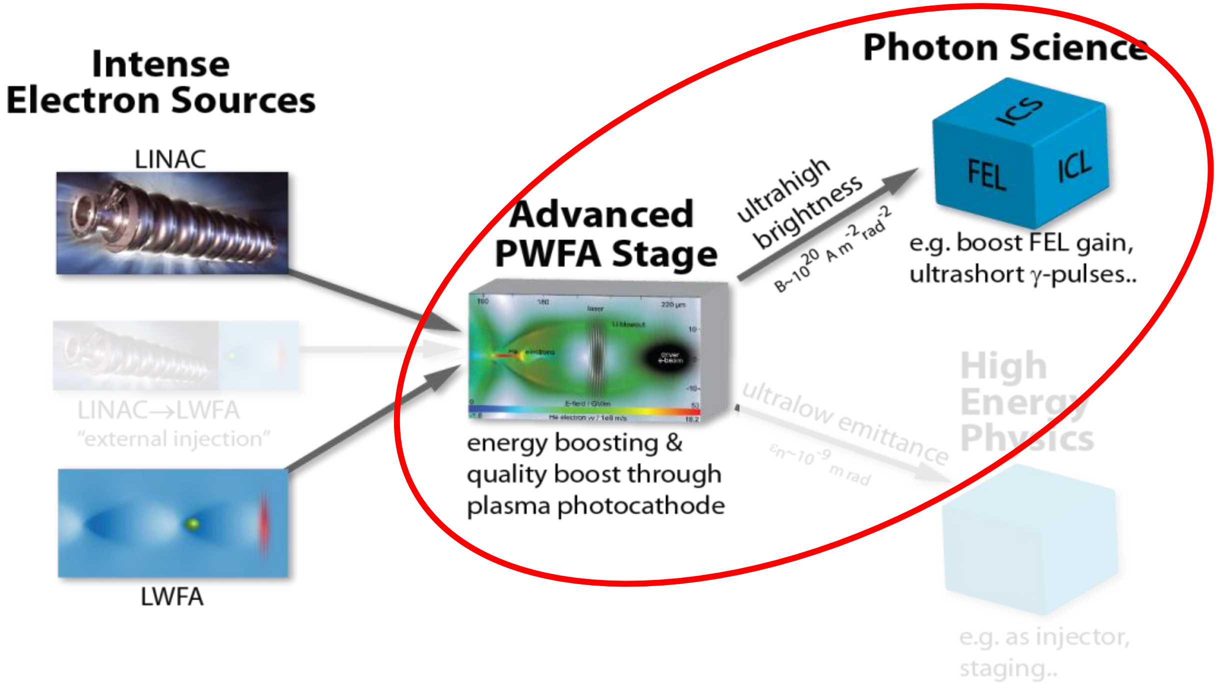
Dark current-free G. G. Manahan et al. (PRAB 19, 011303 (2016)

WP14 Hybrid Laser-Electron-Beam Driven Acceleration

WP lead: Bernhard Hidding WP deputy: Alberto de la Ossa

LWFA: self-injection vs ionization injection





Radiation sources open new opportunities for research, experiments, and commercialization

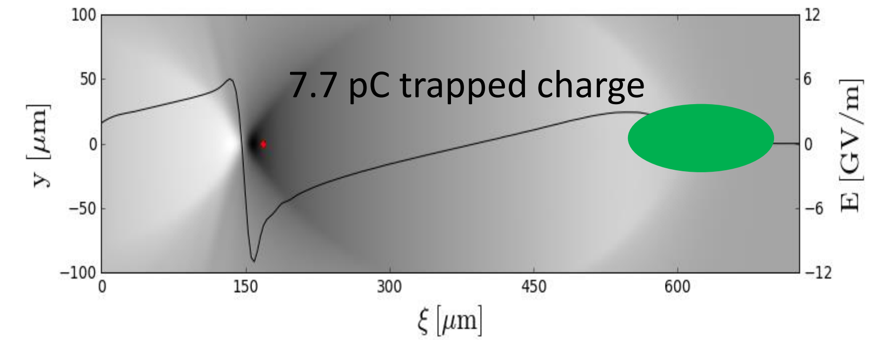
However: they rely on high-quality beam injector/accelerator

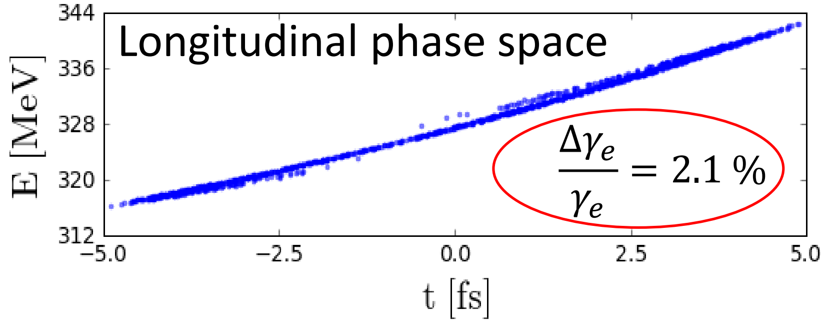
$$b_6 = \frac{I_p}{\frac{\varepsilon_n^2}{0.1\%}\,\frac{\delta W}{W}}$$

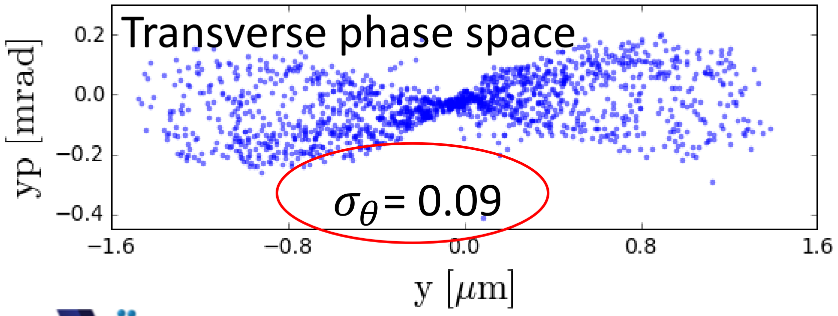
Progress in beam brightness as basis for novel radiation schemes
S. Di Mitri, Photonics 2015, 2, 317-341

High 6D brightness required!

Trojan Horse for monochromatic inverse Compton scattering





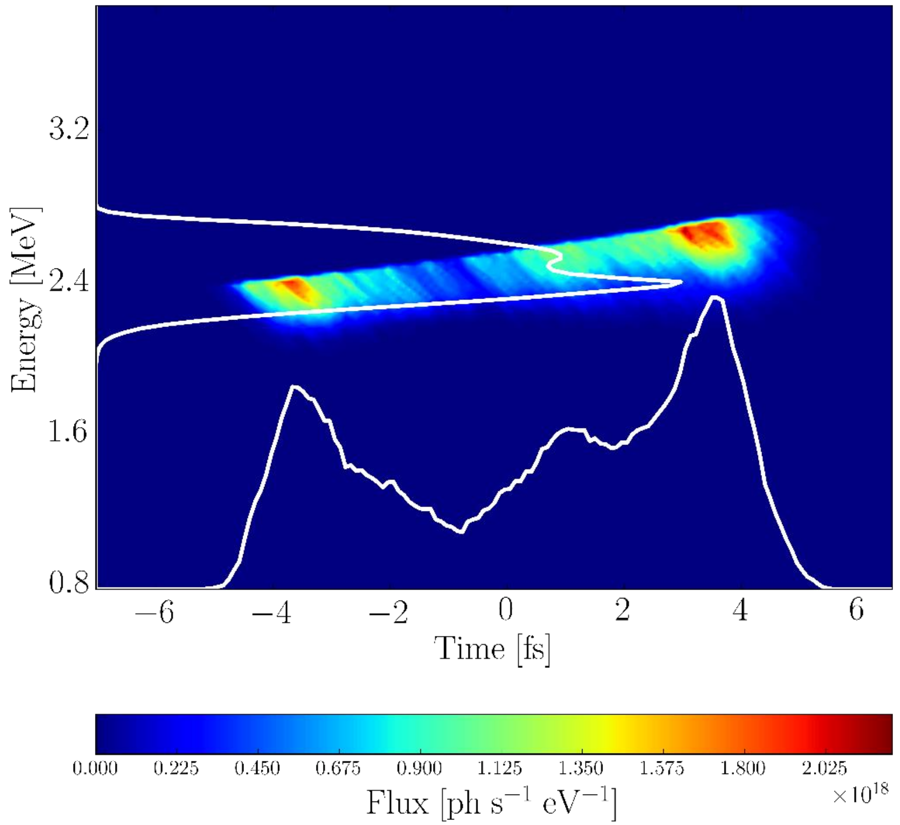


$$\frac{\Delta\omega}{\omega} \propto 2\frac{\Delta\gamma_e}{\gamma_e}$$

Electron beam energy spread: <u>offset</u>
Here: 2.1 %

$$\frac{\Delta\omega}{\omega} \propto \frac{(\gamma_e\sigma_\theta)^2}{4}$$

Electron beam divergence couples with energy



$E = 2.5$ MeV

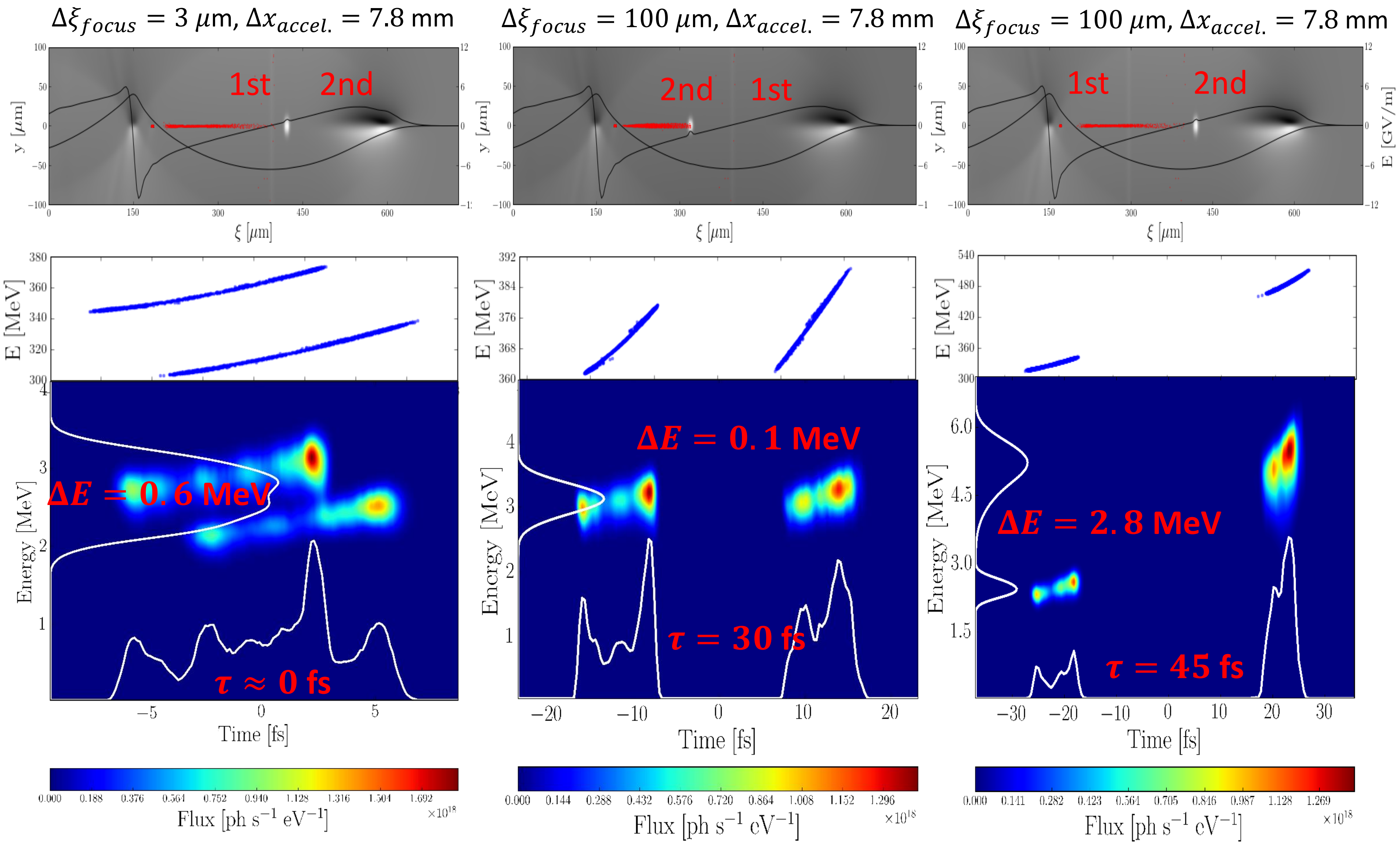
$\frac{\Delta\omega}{\omega} \approx 6.9\ \%$

State-of-the-art:
tens of percent!

$7x10^{6}$ photons/pulse $\tau = 2.8$ fs

3D particle-in-cell code Vsim/VORPAL, Nieter et. al., Journal of Computational Physics 196 (2004) 448–473
3D incoherent scattering simulations: COMPTON, Brown et. al., PRSTAB, 7, 060703 (2004)

Synchronized multicolor radiation



- Energy tunable
- Delay tunable
- Narrow bandwidth

P. Scherkl, to be published soon…

3D time-resolved FEL simulations with high-brightness TH cathode

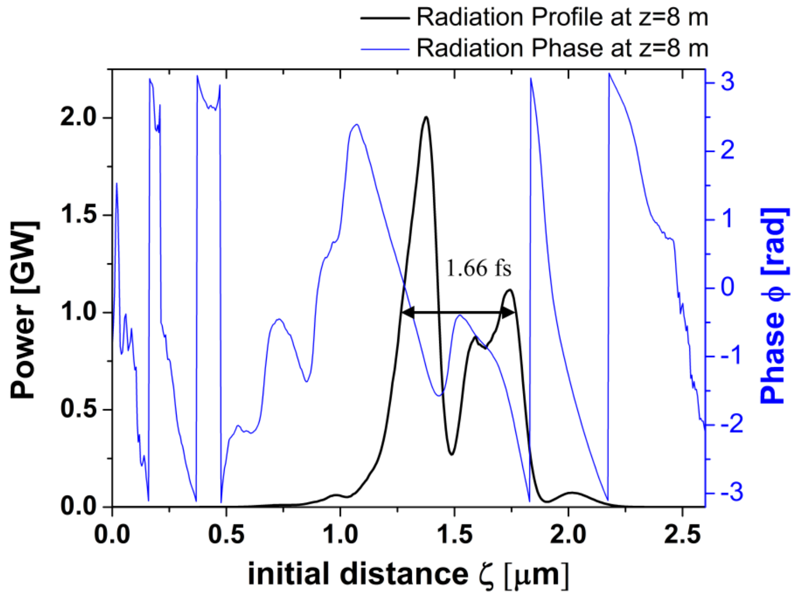
e.g. designed to probe water dissociation

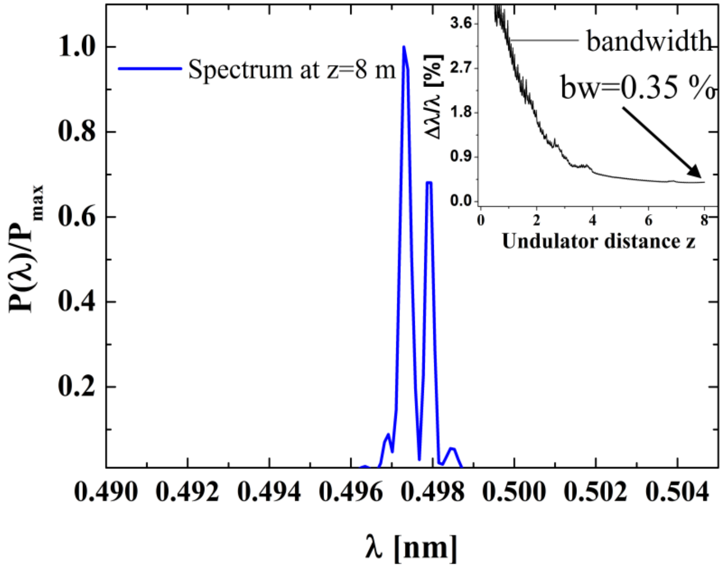
Bunch properties	
E_{mean} [MeV]	1404.3
$\sigma_{z,rms}$ [μm]	2.6
σ_η	0.03%
I_{peak} [kA]	2.0
ϵ_n [nm rad]	43.9
β [m]	7.3

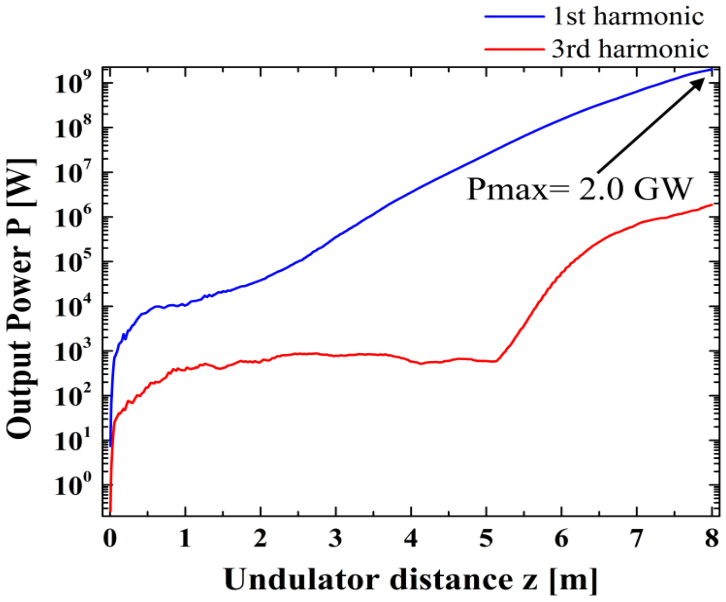
Undulator

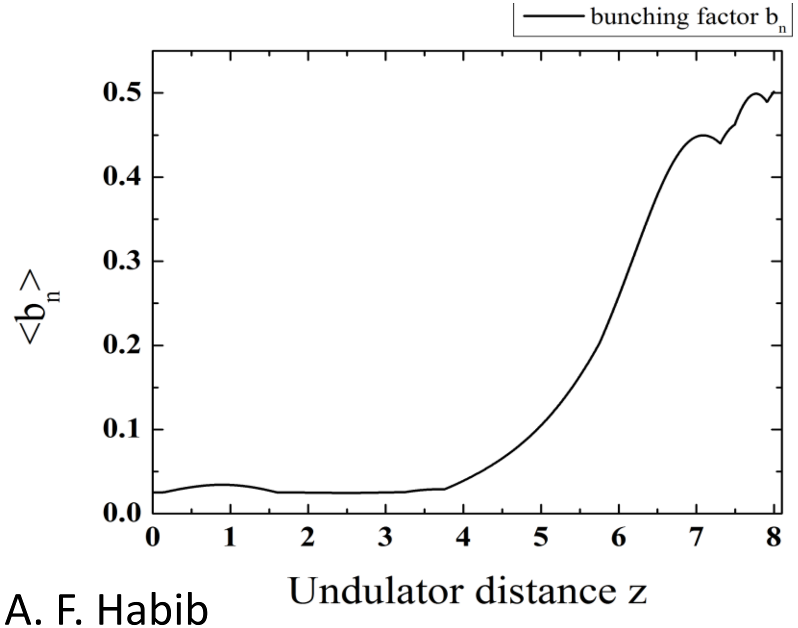
K	0.7	natural focusing
λ_u [mm]	6	cryogenic
λ_r [nm]	0.49	planar
L_u [m]	8	

Theoretical prediction [2]	
P_{sat} [GW]	3.28
L_{sat} [m] → $20L_{g,3D}$	6
ρ	0.001
L_c [nm]	26
$\frac{\Delta\lambda}{\lambda} \sim \frac{\lambda_r}{2\pi L_c}$ [%]	0.3



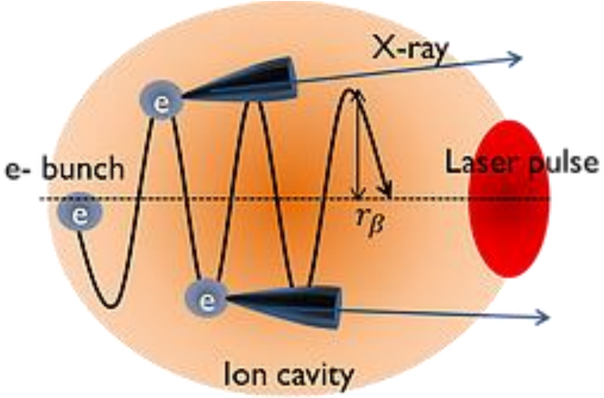




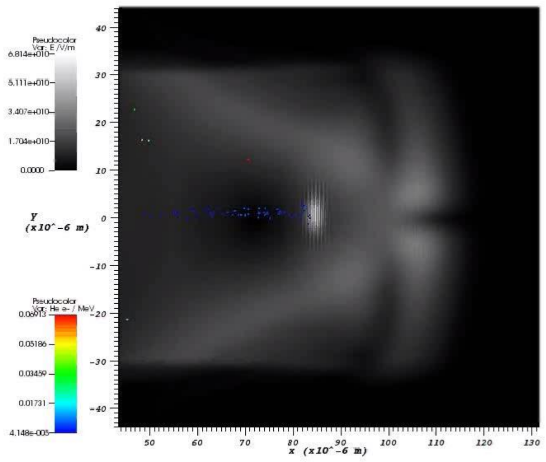


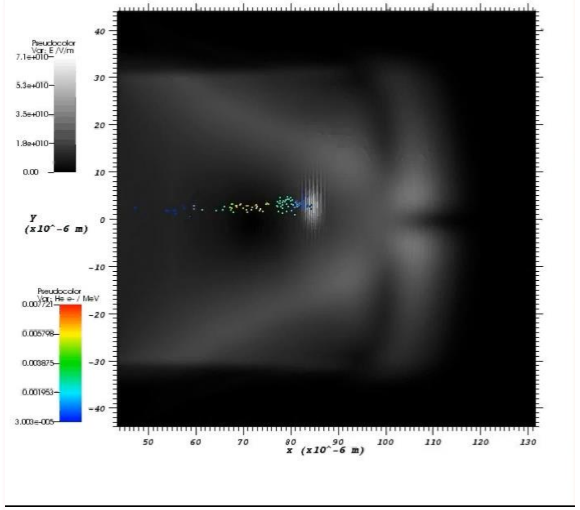
Courtesy A. F. Habib

Plasma-undulators: (enhanced) betatron radiation, Ion Channel Laser



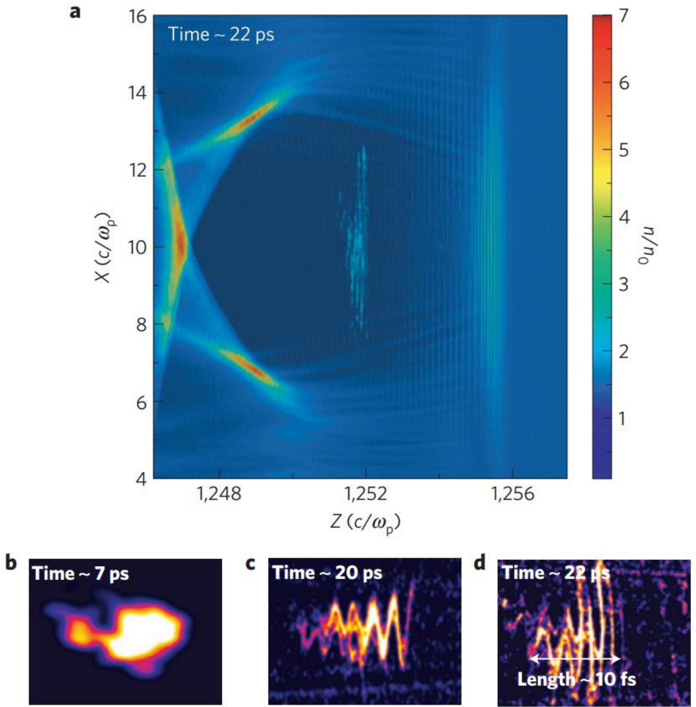
Betatron radiation, fig. from IPAL

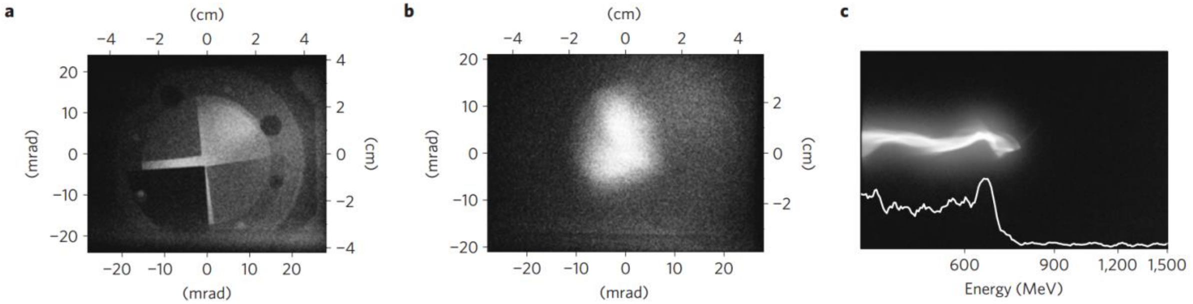


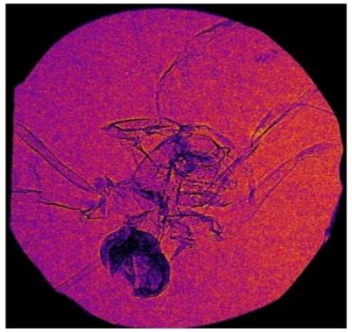


B. Hidding, PRL 2012

S. Cipiccia et al., "**Gamma-rays from harmonically resonant betatron oscillations in a plasma wake**", Nat. Phys. 7, 867-871 (2011)







Cipiccia *et al.*, J. Appl. Phys. **111**, 063302 (2012);
Cipiccia *et al.*, Rev. Sci. Instrum. **84**, 113302 (2013)
Ersfeld *et al.*, New Journal Physics. (2014)

Summary

Plasma-based beam dump as pilot application

- **Collective deceleration** instead of scattering and shower
- **No radioactivation** of dump, **reduced spatial footprint**
- Synergies with other plasma-based applications

Hybrid **injector** can produce 5 GeV beams

- Ultra-low emittance
- High luminosity as ultimate goal → HEP
- High brightness → **radiation sources**

Radiation sources based on hybrid injector produce **high-quality radiation**

- **Narrow bandwidth** ICS on MeV level
    - Even synchronized pulses possible
- **Compact and powerful FEL** applications
- Potentially even Ion Channel Laser