A Personal Perspective on the Status and Prospects for Plasma Accelerator Based Light Sources

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Outline

- **Key physics of Plasma based wakefield accelerator (PBA)**
- **Current status of high quality PBA experiments**
- **PBA based Betatron/Compton sources**
- **PBA based FEL**
- **Summary**

Plasma Based Wakefield Acceleration

- Laser or beam Pulse

- Trailing beam

Wake

Very large gradient (~10-100GV/m) + small structures (~10-100um)

T.Tajima and J.M. Dawson PRL (1979) **LWFA**
P.Chen, J.M. Dawson et.al. PRL (1983) **PWFA**

Significant Progress in Past Decade

Real Challenge for Plasma Based Acceleration

From “Acceleration” to “Accelerator”

- **Understand the physics:**

Systematic understanding of all the relevant physics

- **Develop the technology:**

Lasers,plasma sources and structures, diagnostics .....

- **Find the applications:**

Science (light sources, colliders),industry,medical applications ......

Key physics issues for a plasma accelerator

- ☐ **The structure issue:**

Wake excitation for given drivers ……

- ☐ **The energy spread and efficiency issue:**

Beam loading, pulse shaping, transformer ratio ……

- ☐ **The stability issue:**

Driver evolution, matching, guiding, instabilities ……

- ☐ **The injector issue:**

Self-injection, high quality controlled injection ….

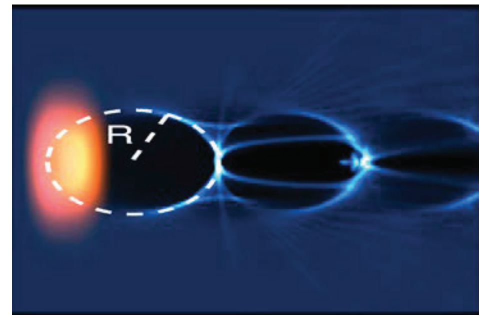
- ☐ **The overall design and staging issue:**

Parameter optimization for a plasma based accelerator to match the requirements on beam quality, staging,external injection ….

An ideal regime for electron acceleration

the Blowout/Bubble Regime

Driven by an electron beam: ***nb>np***



Driven by a laser pulse: ***a0>~2***

Main advantages:

- ☐ Uniform acceleration across the transverse slice
- ☐ Ideal uniform focusing force for electron beam

Beam driver:
Rosenzweig et al., PRA 1991;
Lu et al., PRL 2006;

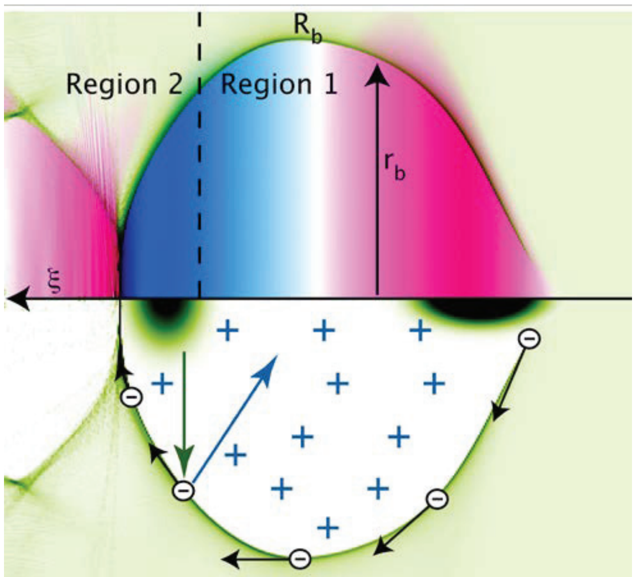
Laser driver:
Mori et al., PAC proceedings 1991;
Pukhov et al., APB 2002
Lu et al., PRSTAB 2007

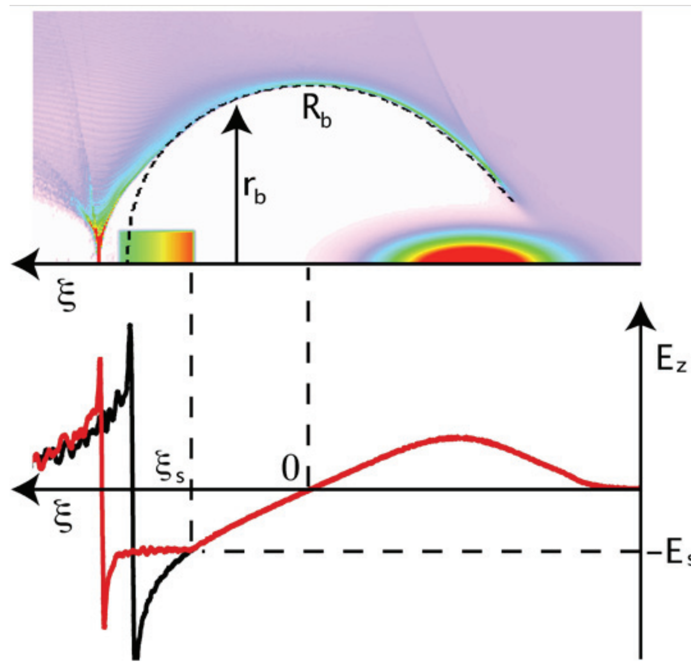
Key questions for high quality electron acceleration

- Can uniform and high efficiency acceleration be achieved?
- Can the driver (laser or particle beam) propagate stably to form a stable structure?
- For beam drivers, can a good transformer ratio (TR) be achieved stably?
- Can very high quality beams (low energy spread, high current,low emittance) be generated in PBA?
- Can different sections of accelerators be properly staged with well preserved quality?

High efficiency uniform acceleration: Beam loading

High efficiency + Uniform acceleration





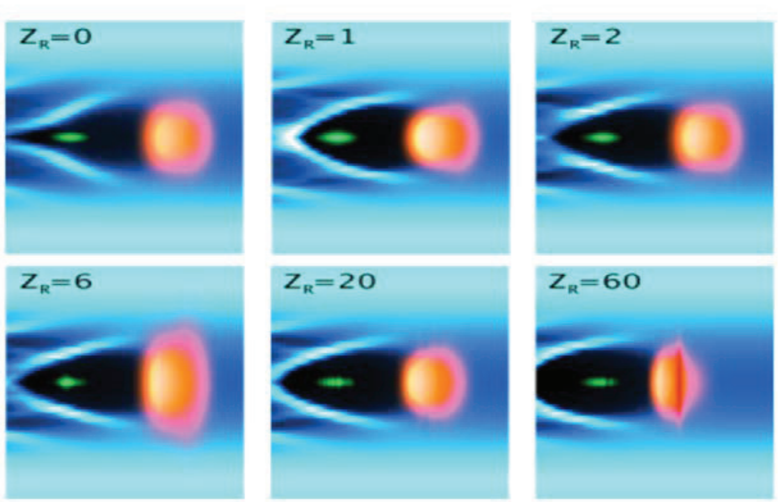
- For beam driver, there is no dephasing between bunches
- For laser driver, dephasing reduces the overall efficiency

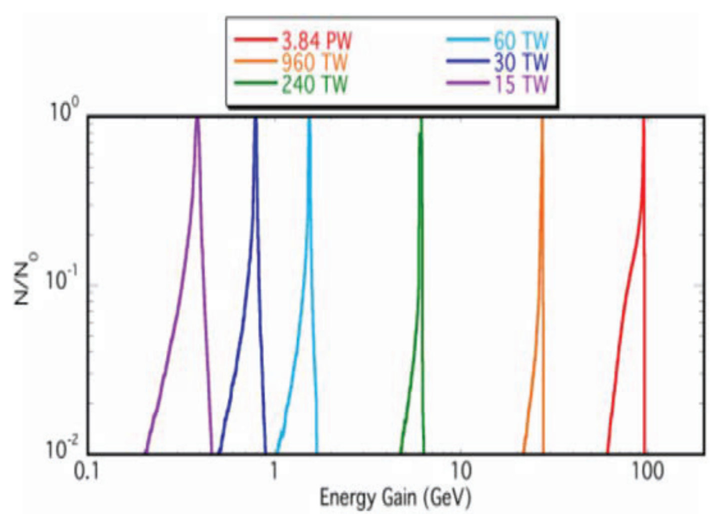
W. Lu et al., PRL (2006), M. Tzoufras, et al., PRL (2008)

Matched channel guided LWFA with external injection

0.5-1600GeV single stage design of a0=2

$\frac{\langle \Delta W \rangle}{\text{GeV}}$	$\frac{P}{\text{TW}}$	$\frac{\tau}{\text{fs}}$	$\frac{w_0}{\mu\text{ m}}$	$\frac{n_p}{\text{cm}^{-3}}$	$\frac{L_\phi}{\text{m}}$	$\frac{\langle E_z \rangle}{\text{GeV/m}}$	$\frac{\sigma_z}{\mu\text{m}}$	$\frac{N}{10^{10}}$
0.4	15	35.6	10.68	2E+18	0.0068	59.08	1.5	0.05
1.6	60	71.2	21.36	5E+17	0.0542	29.54	3	0.1
6.4	240	142.4	42.72	1.25E+17	0.4333	14.77	6	0.2
25.6	960	284.8	85.44	3.13E+16	3.4663	7.385	12	0.4
102.4	3840	569.6	170.9	7.81E+15	27.731	3.693	24	0.8
409.6	15360	1139.2	341.8	1.95E+15	221.84	1.846	48	1.6
1638.4	61440	2278.4	683.5	4.88E+14	1774.8	0.923	96	3.2





Lu et al., PRSTAB 2007, Martins et al., Nat. Phys. 2010, Tzoufras et al., JPP 2012

A 40cm long LWFA achieving 6.4GeV by a 34J laser

Efficiency 5.5%, energy spread ~1%, charge 0.32nC

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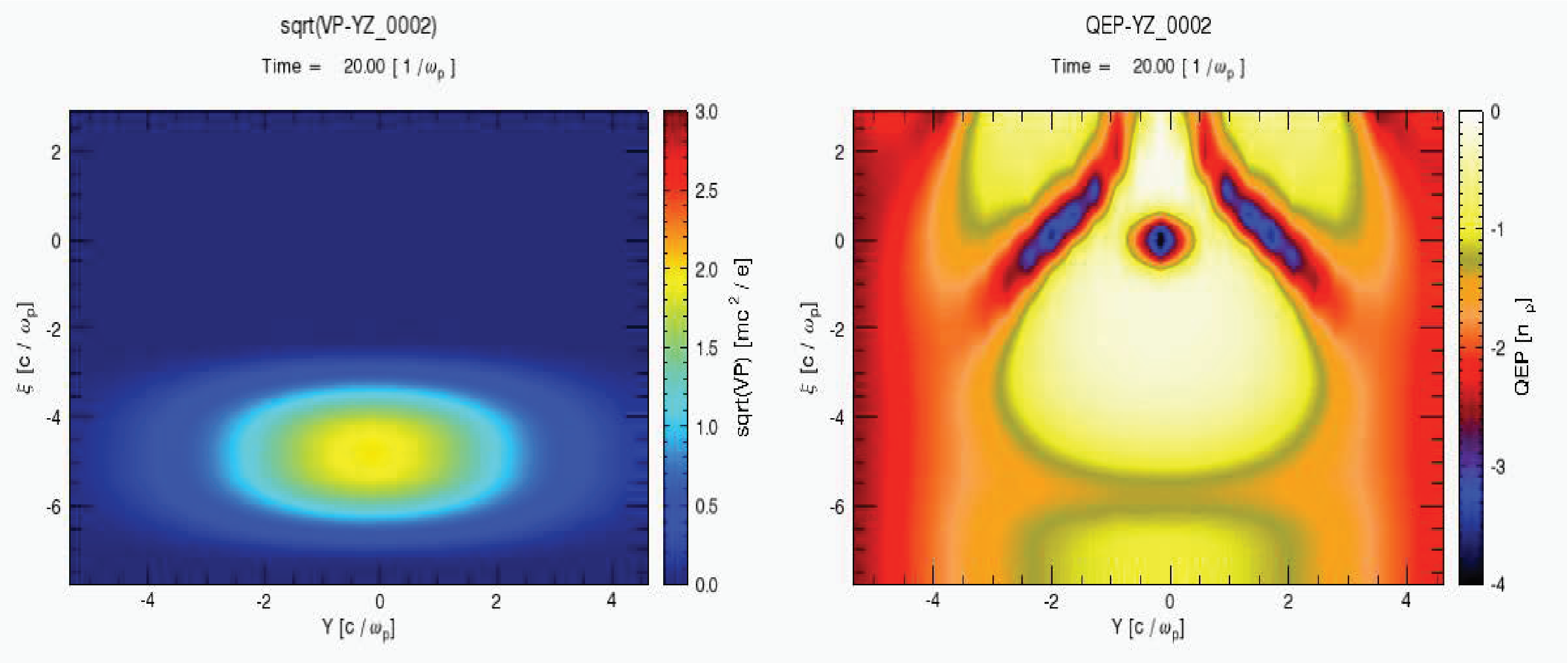

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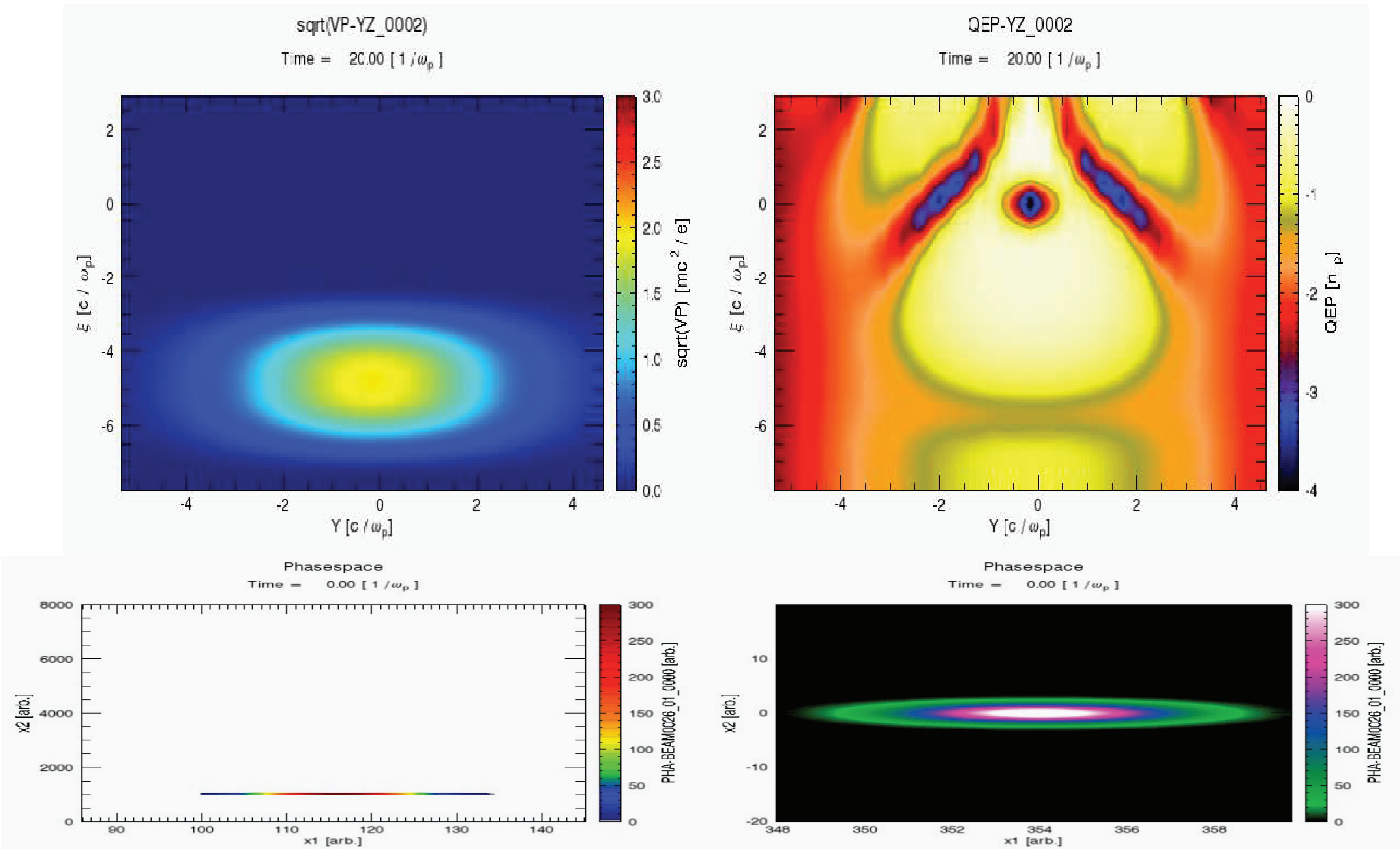

High brightness injection schemes

		I [kA]	Emittance [nm]	Energy Spread [MeV]	B [A/m^2/rad^2]
Ionization Injection[1]	Trojan Horse	0.3	40	several	7e17
	Downramp-assisted Trajan Horse	1	20	2.2	9e18
	Transverse colliding	0.4	8.5/6	0.2, 0.012 (slice)	1.7e19
	Two-color: Longi.	0.3	50	1~2	2.5e17
	Two-color: Trans.	0.03	60	1, 0.03 (slice)	2e16
Downramp Injection[2]	Laser (10^{19} cm^{-3})	9	10	0.3	2e20
	Beam (2.8e18 cm^{-3})	10	30	0.5	2e19

[1]B. Hidding et al., PRL 108, 035001 (2012); A. Knetsch et al., arXiv:1412.4844v1; F. Li et al., PRL 111, 015003 (2013); L. L. Yu et al., PRL 112, 125001 (2014); X. Xu et al., PRST-AB 17, 061301 (2014).
[2]FACET-II Proposal V6 (2013); J. Grebenyuk et al., NIMA 740, 246 (2014); X. Xu et al., PRAB 20, 111303 2017

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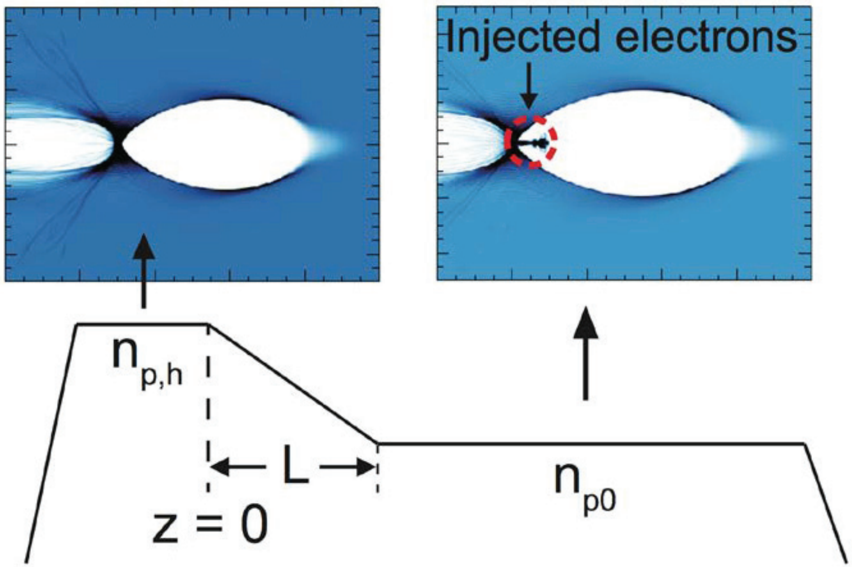
Bright electron beam generation on a density downramp

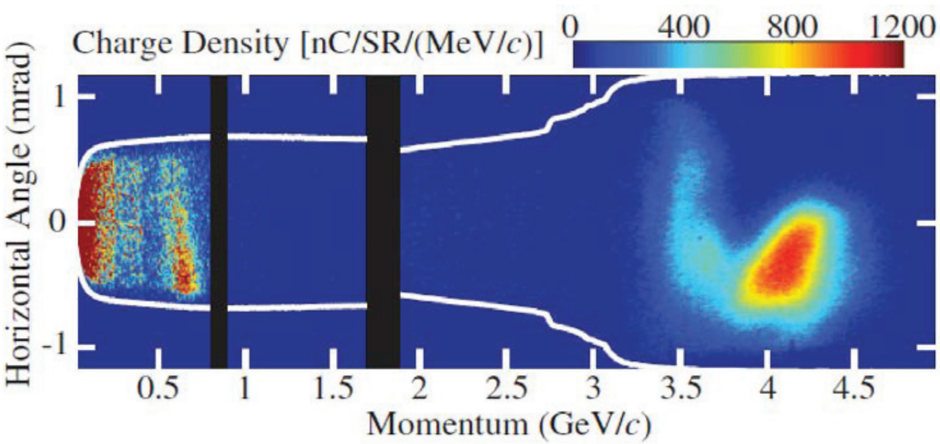


Under proper driver and plasma condition, Electron beams with high current (~10kA), low emittance (~10nm rad) and low slice energy spread (~0.3MeV) may be generated!

- 1D downramp injection process analyzed: **Bulanov PRE (1998), Suk PRL (2001)**
- Theory and simulation of transverse dynamics of injection process **X. Xu et al., PRAB 20, 111303 (2017)**

Energy gain

LWFA

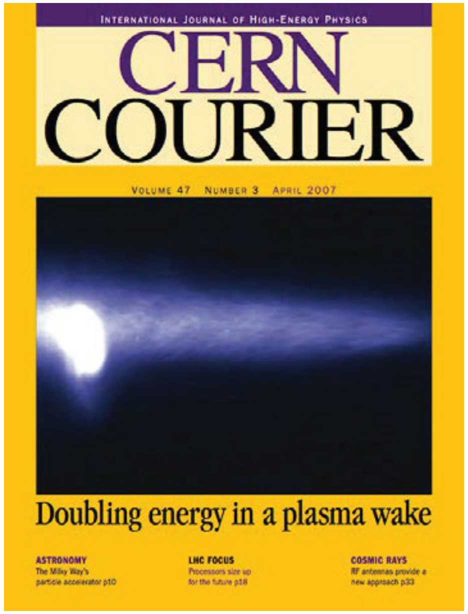


LBNL BELLA:

4.25GeV, 6pC, 0.3mrad rms divergence

Leemans et al.,PRL 113, 245002 (2014)

PWFA



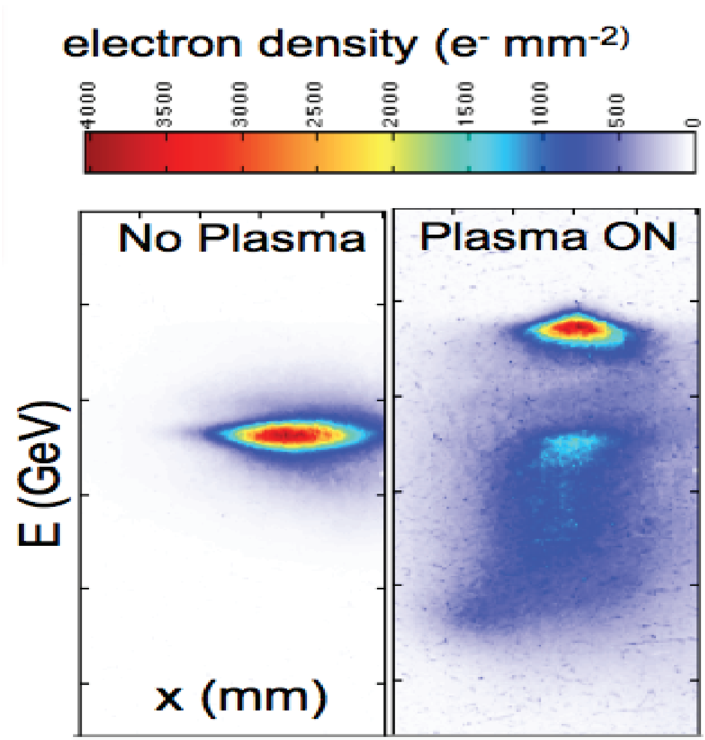
SLAC FFTB

42GeV gain

Blumenfeld et al., Nature 15, 445, (2007)

High efficiency PWFA

~30% energy conversion efficiency with 2% energy spread

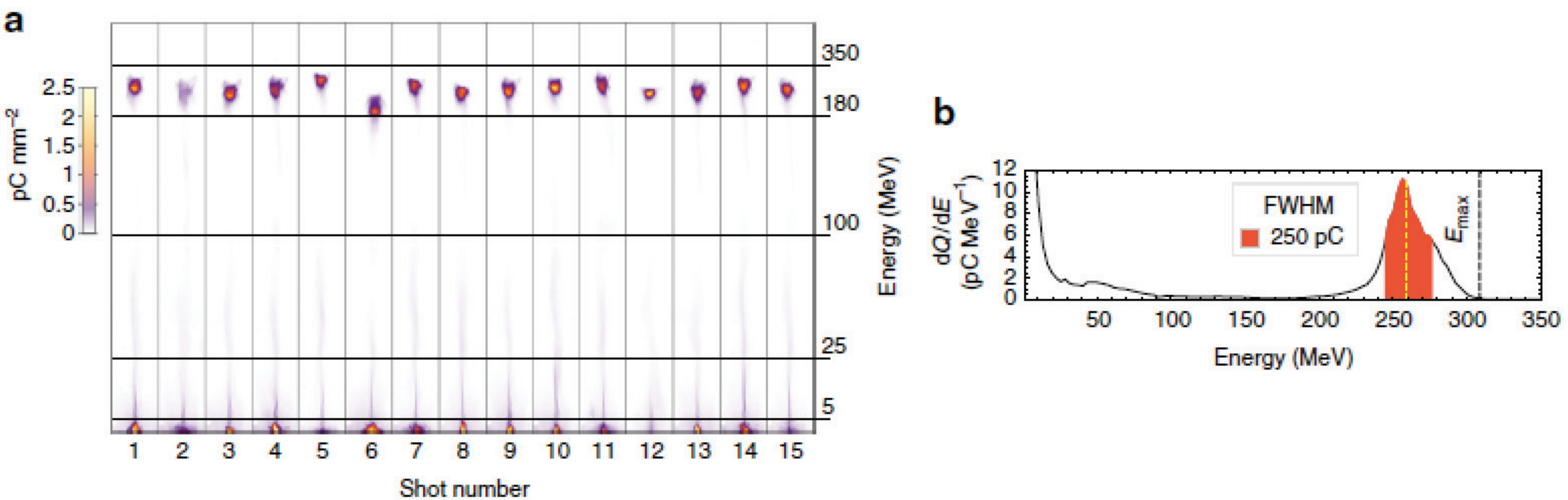


SLAC FACET

Nature 2014

High charge LWFA

~0.25nC charge within a mono-energetic peak



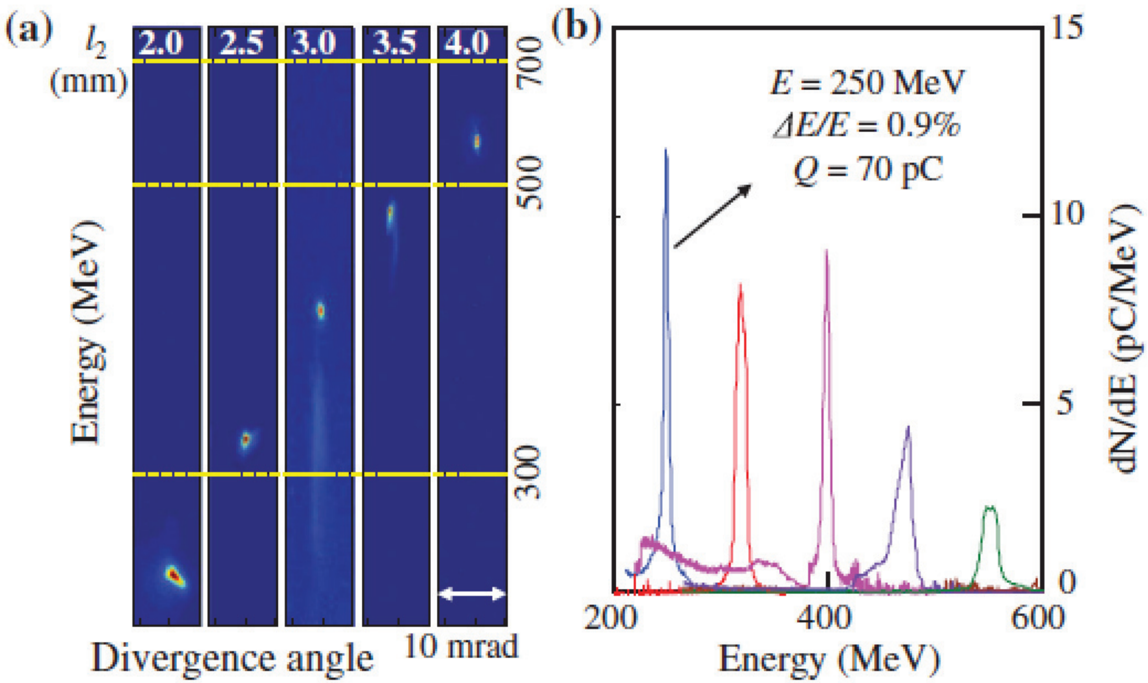
Couperus

Couperus et al., Nat. Comm. 2017

HZDR

Energy spread

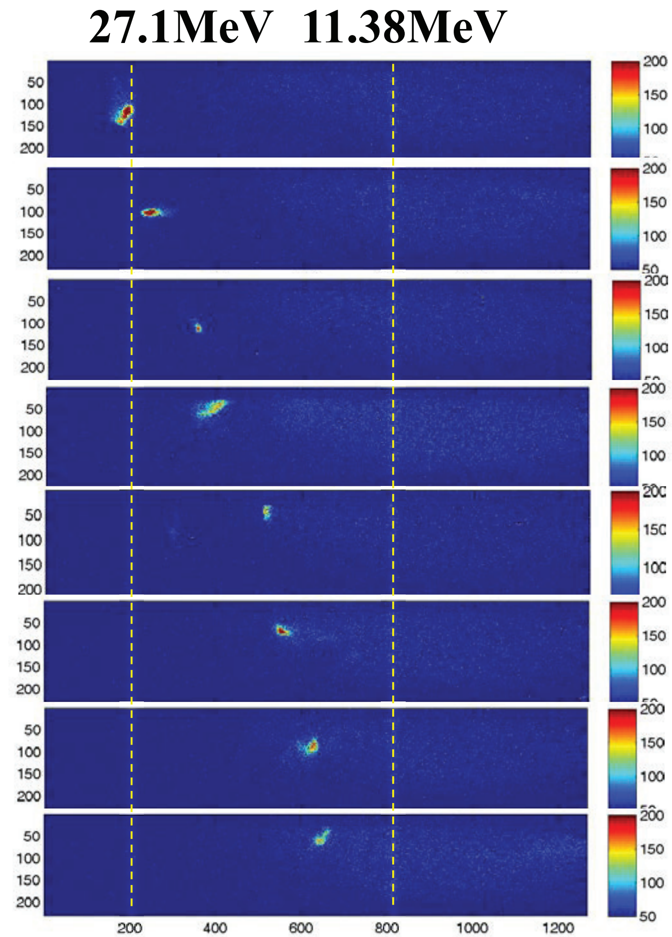
~1% relative energy spread



SIOM

Wang et al., PRL 117, 124801 (2016)

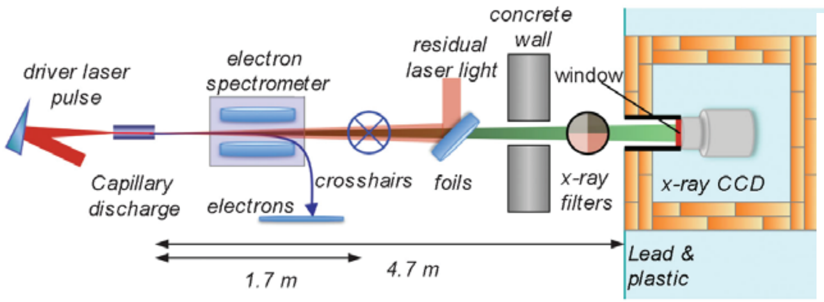
~0.2MeV absolute energy

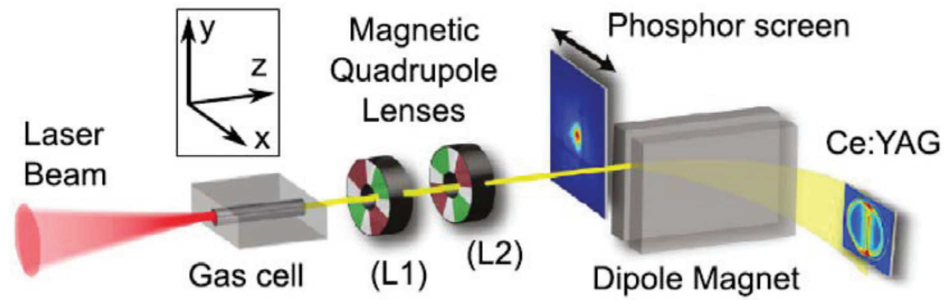


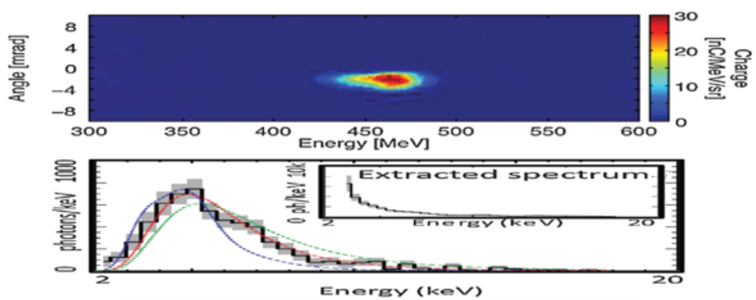
THU

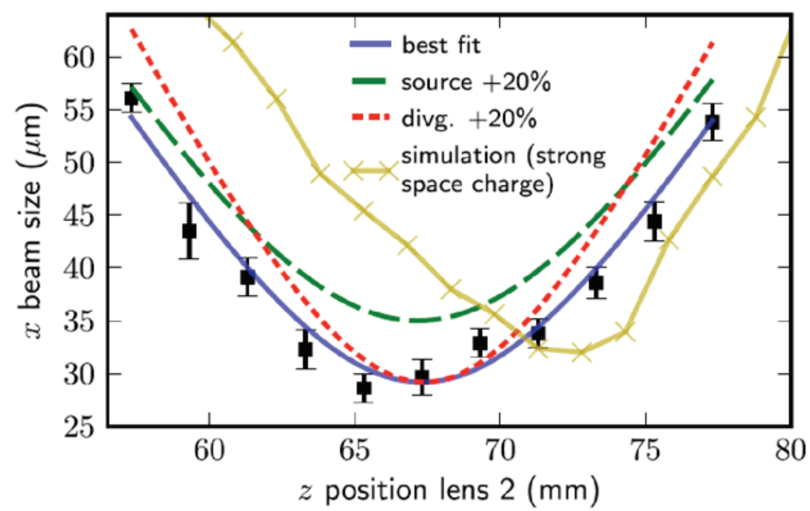
Lu et al., IPAC 2014

Emittance







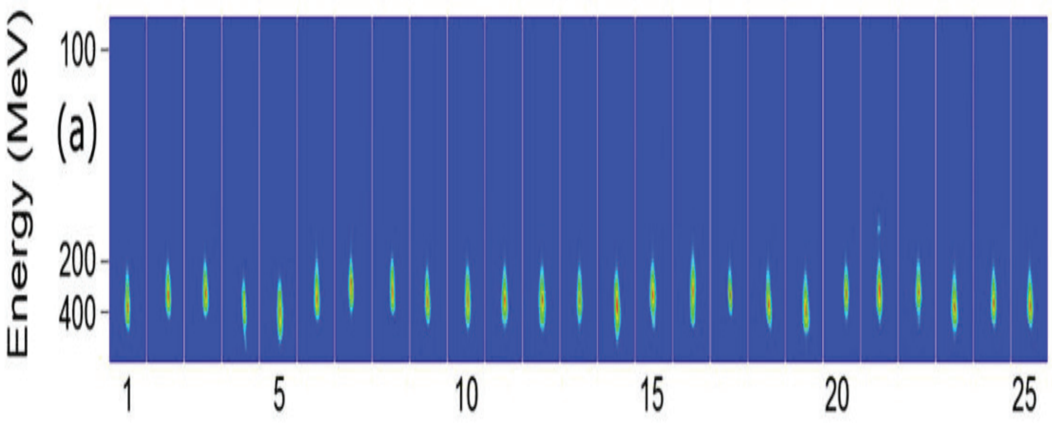


~0.1mm mrad normalized emittance deduced from Betatron X ray measurement

LBNL:
G. R. Plateau, et al., Phys. Rev. Letts. 109, 064802 (2012)

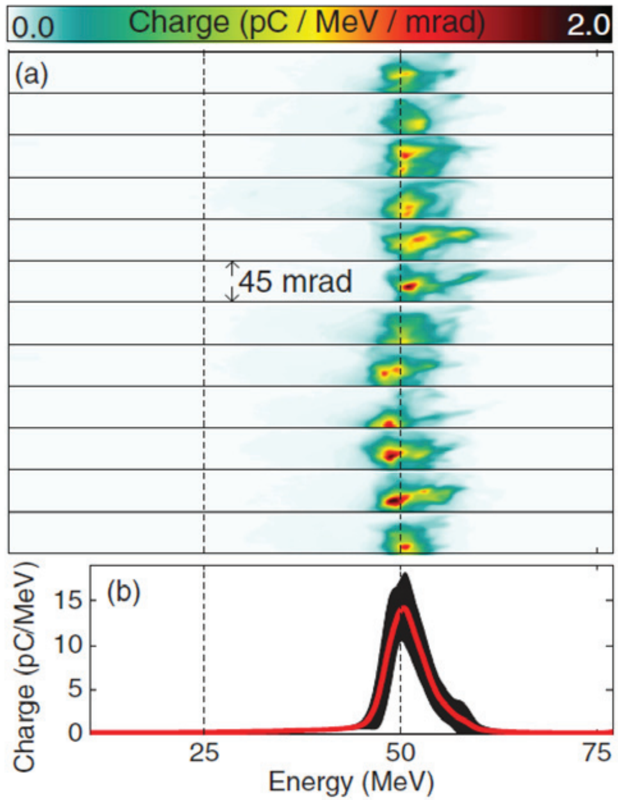
0.2 mm mrad normalized emittance measured using single shot Quad scan
LMU/MPQ:
Weingartner et al., PRSTAB 15, 111302, 2012

Repeatability



35fs 55TW laser wakefield acceleration

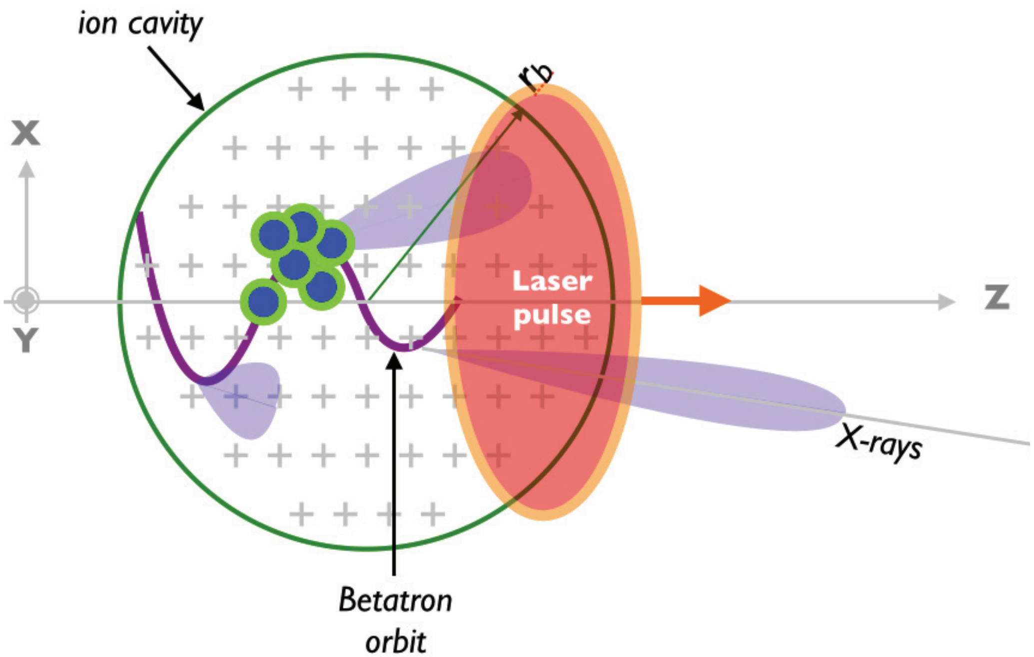
S. Banerjee, et al., Phys. Rev. ST Accel. Beams 16, 031302 (2013)



Shock front downramp injection

Buck et al., PRL 110, 185006 (2013)

Betatron X-ray Source



$$\lambda_u[\mu\text{m}] = 4.72 \times 10^{10}\sqrt{\gamma/n_e[\text{cm}^{-3}]},$$

$$K = 1.33 \times 10^{-10}\sqrt{\gamma n_e[\text{cm}^{-3}]}r_\beta$$

$$\hbar\omega_c[\text{eV}] = 5.24 \times 10^{-21}\gamma^2 n_e[\text{cm}^{-3}]r_\beta[\mu\text{m}]$$

Source Characteristics:

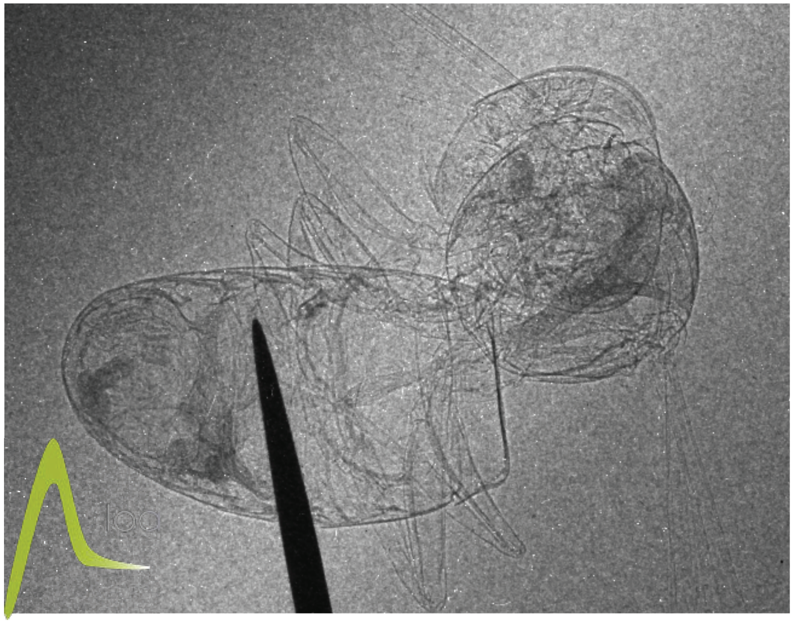
- $10^{8\text{-}9}$ photons/shots
- angular spread: 10’s mrad
- ultrashort: <10 fs
- broadband: 1-100 keV
- source size: ~few microns

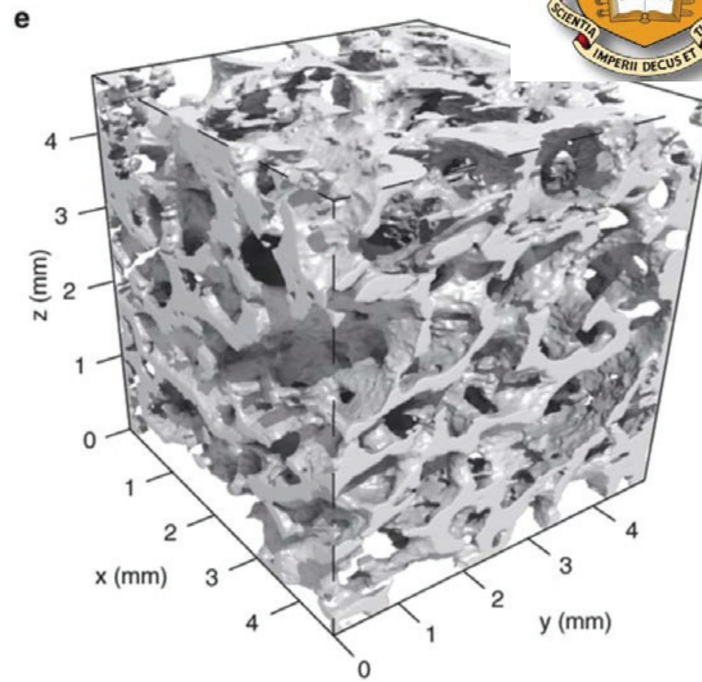
Applications:

- PBA diagnostics
- Phase contrast image
-fs X-ray diffraction and absorption

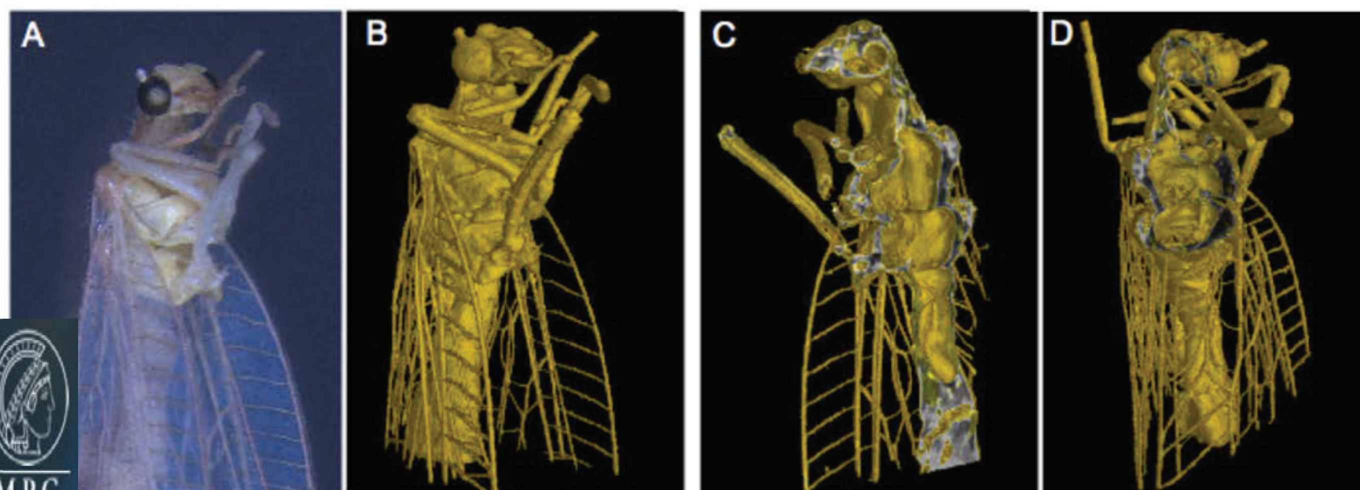
Bone tomography

Phase contrast image of a bee

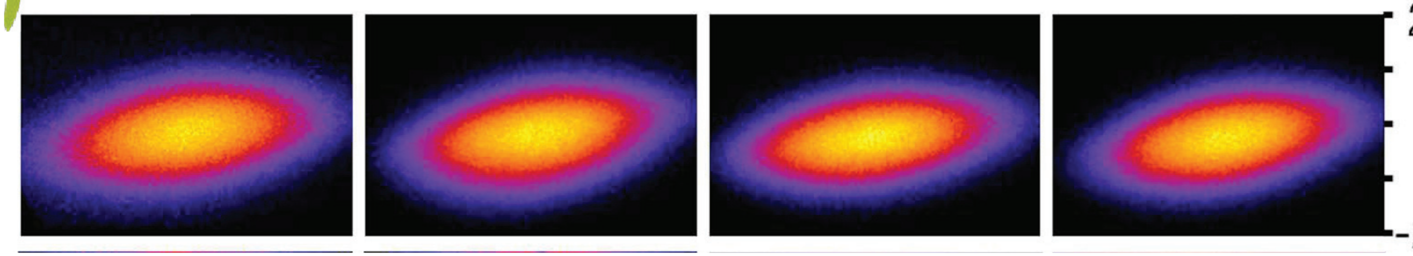


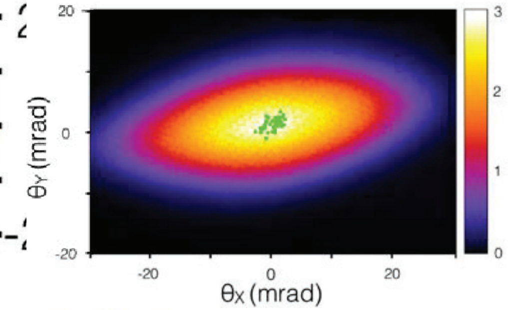


Tomography of a fly (Phase contrast)

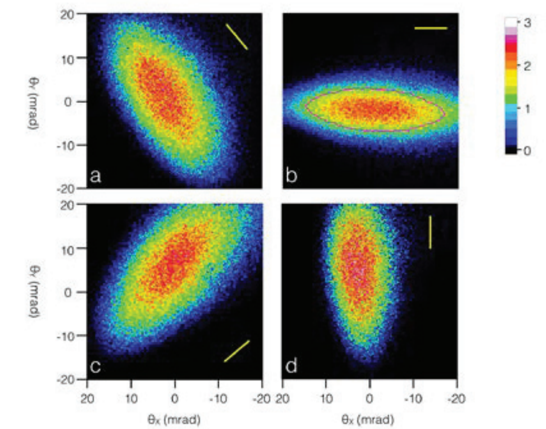


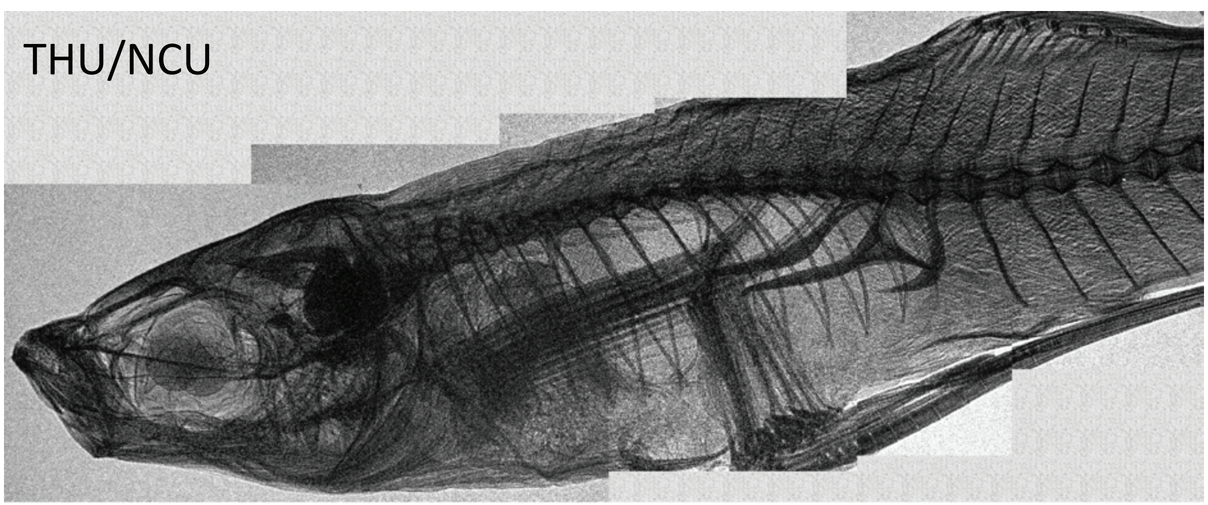
Stable and polarized Betatron radiation using ionization injection



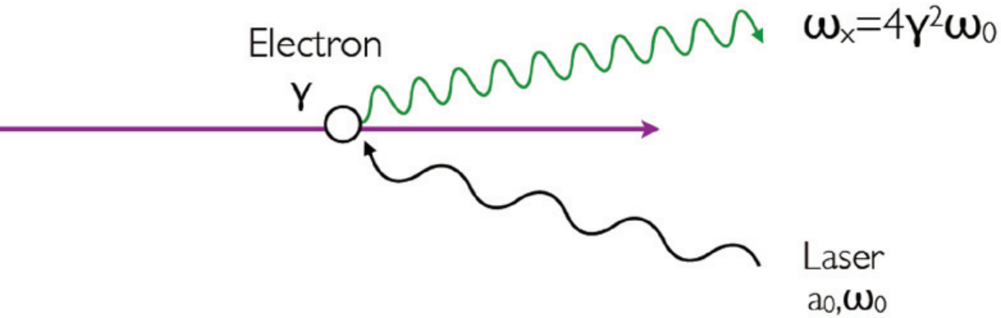


Pointing stability: 10% of the beam diameter
Beam shape: 100% reproducible
Energy stability (standard deviation): 10% of the mean energy
Flux stability (standard deviation) : 15% of the mean flux
Polarization degree: ~ 80%



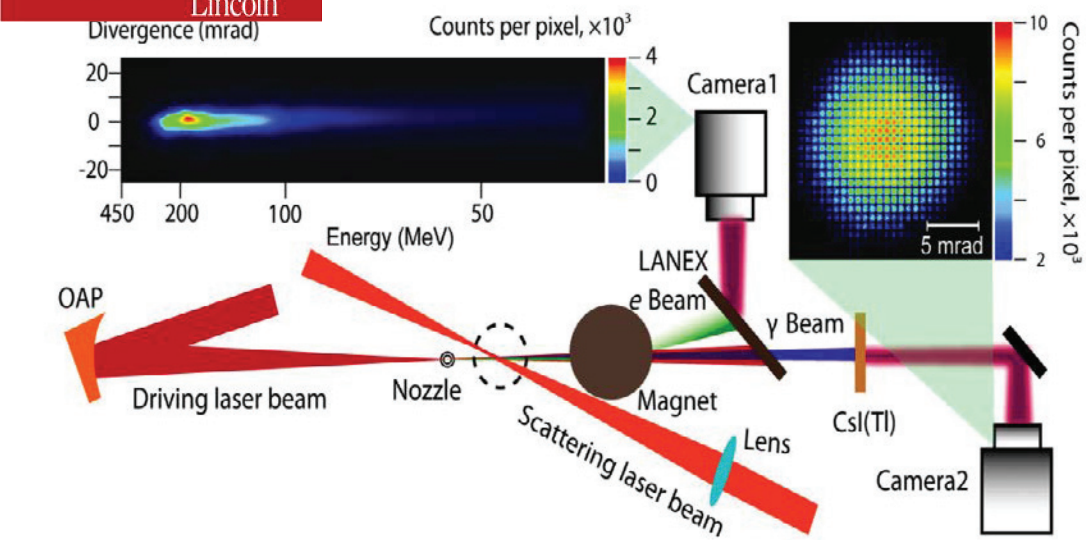


PBA Based Compton Source

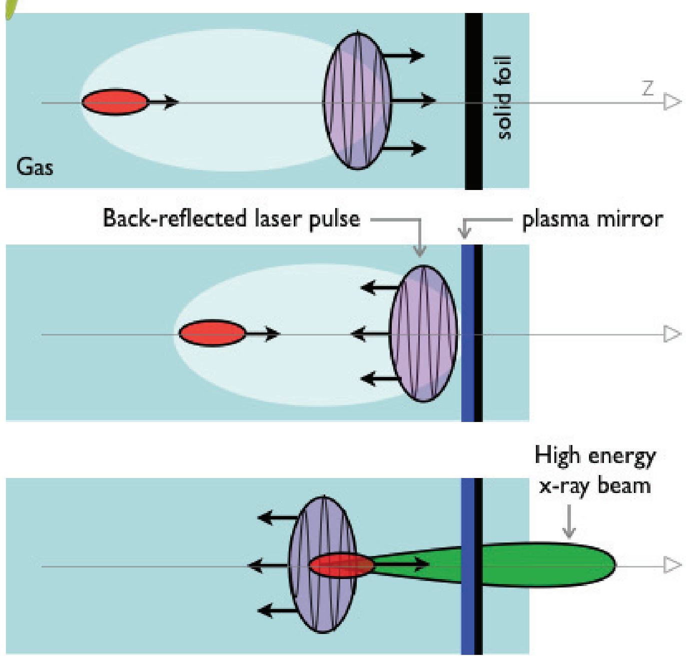


- $10^{8\text{-}9}$ photons/shot
- angular spread : 10's mrad
- ultrashort: 10's fs
- broadband: quasi-mono-energetic
- source size: ~1 microns

Two beam scheme



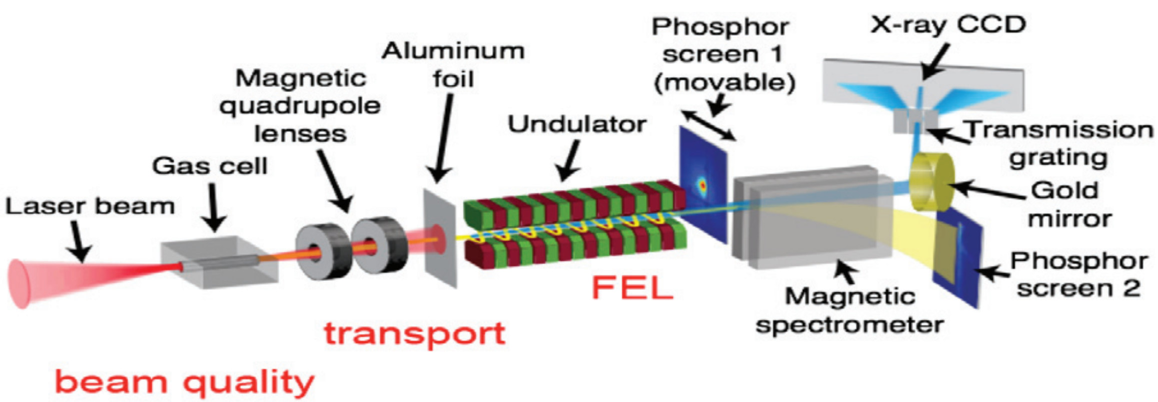
Plasma mirror scheme



PBA Based FEL

The current key challenges for PBA based FELs is mainly due to the special beam features of PBA :

- Relatively large energy spread (~1%), leading to very large gain length (0.1% level is preferred)
- Small beam sizes with relatively large angular spread (~1mrad), together with 1% level energy spread, leading to large emittance growth during the transport to undulator
- Relatively large fluctuation in energy and pointing, making it hard to tune the beam optics



Current LWFA based programs

TGU based:

SIOM/SINAP

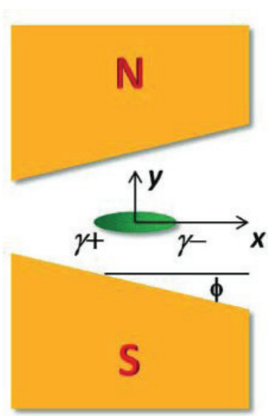
Jena/KIT

Chican decompression for energy spread reduction

SOLEIL/LOA: COXINEL

LAOLA

LBNL (with APL)



Z. Huang et al., PRL 109, 204801, 2012

Currently most these programs are mainly working on Equipment preparation,installation and beam transport tuning

The near term goal is to observe FEL gain

M E Couprie *et al* 2016 *Plasma Phys. Control. Fusion* **58** 034020
J. Van Tiblorg et al.,
AIP Conference Proceedings **1812**, 020002 (2017);

SOLEIL/LOA: COXINEL
Aiming at observing FEL gain (10MW level)

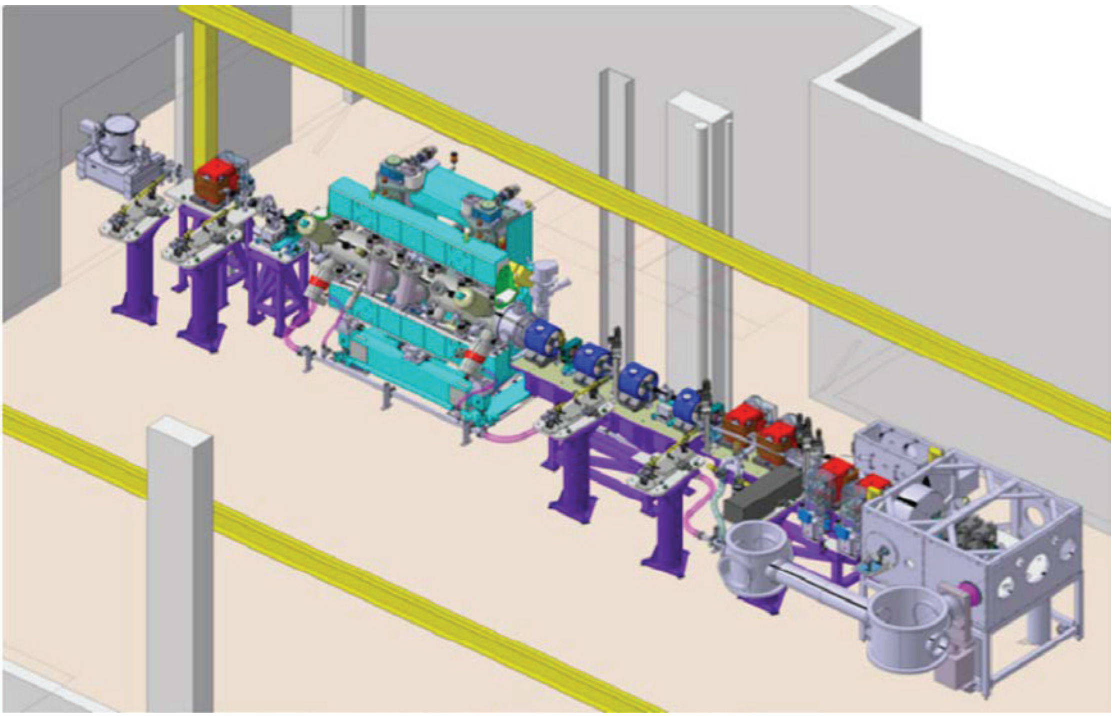
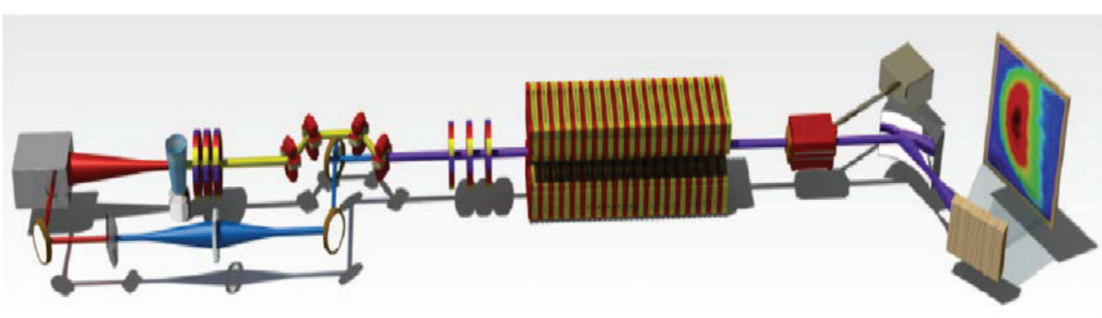
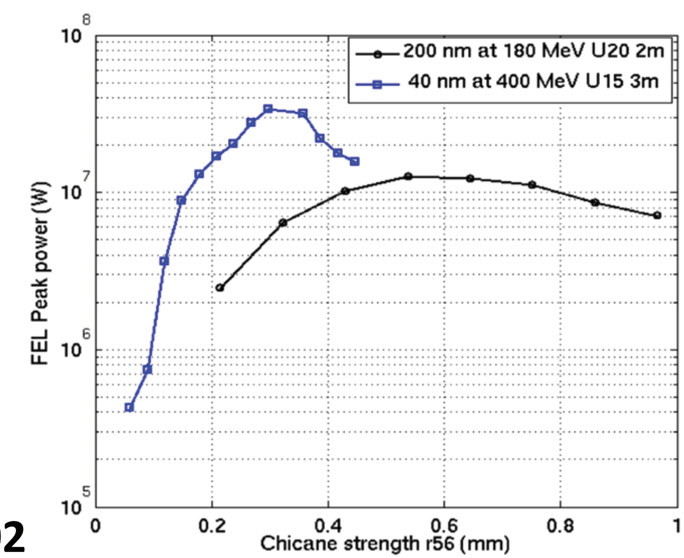


Table 1. Main COXINEL electron parameters at 180 MeV.

Electron characteristics		Cell exit	Undulator entrance
Energy	MeV	180	180
Normalized emittance total	π.mm.mrad	1	2.4
Normalized emittance slice		1	1.3
Divergence	mrad	1	20
Size	μm	1	60 (slice)
Duration	fs	3.3	36
Charge	pC	34	
Peak current	kA	4	0.5
Energy spread total	%	1	1.1
Energy spread slice	%	1	0.13



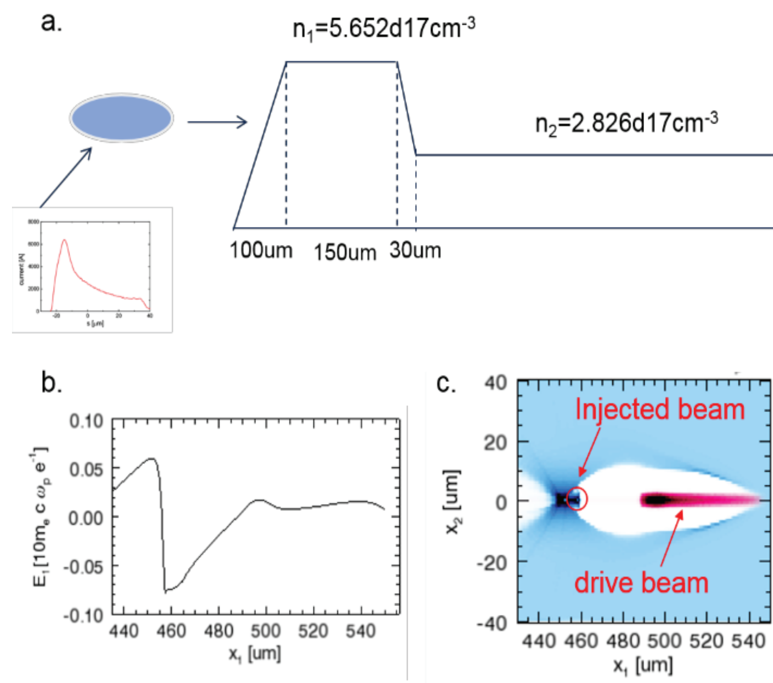


M E Couprie *et al* 2016 *Plasma Phys. Control. Fusion* 58 03402

Planned PWFA based programs

- FACETII (no Undulator) SLAC
- Flash Forward (Undulator planned) DESY
- SXFEL-PWFA (SINAP/THU) (Undulator installed)

SXFEL facility in Shanghai



S. Huang et al., IPAC proceeding 2017

A HTR PWFA (TR=4) with high brightness injection campaign is planned at SXFEL in 2017-2019

Summary

- The physics of plasma based wakefield acceleration has been well established over the decades, and stable, efficient, high quality acceleration of electron beams are within reach in future
- Synchrotron like Light sources based on PBA (Betatron and Compton sources) are well passing the proof of principle stage, further optimization and application are on-going
- FEL based on PBA are very challenging and active research area, currently with many dedicated groups adopting different schemes , aiming at achieving observation of FEL gain
- Further improving the beam quality (especially the energy spread down to 0.1% level) and stability are the key for the success of FEL based on PBA

Thank you for your attention!