470th Heraeus Seminar – Bad Honnef – December 14th, 2010

Prospects of Plasma Acceleration @ DESY

J. Osterhoff, E. Elsen, F. Stephan, R. J. D. Miller,
K. Floettmann, B. Schmidt, R. Brinkmann

Plasma Accelerator Science in Hamburg - Staff

Brand new: first activities started in *September 2010*

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Plasma Acceleration Group

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postdoc starting in January 2011

2 postdocs t.b.a. (UHH, DESY)
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→ We are looking for excellent and motivated postdocs and (PhD-)students...

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~600 k€ until Dec 2012

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

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HELMHOLTZ | ASSOCIATION
Accelerator Research and Development

not done deal yet,
but looks promising

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start-up grand

UHH

e.g. funding for a ~100 TW class laser

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5.0 M€ until 2015

Alexander von Humboldt Stiftung/Foundation

e.g. funding for a ~100 TW class laser

Plasma Accelerator Science in Hamburg - Collaborations

internal network

Plasma Accelerator Group
University and DESY in Hamburg

R. Brinkmann
Director Accelerators (DESY Hamburg)

- General support

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- Ultrafast beam diagnostics
- Laser to beam sync

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- RF-gun and gun-laser R&D
- Beam dynamics
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Plasma Accelerator Group
University and DESY in Hamburg

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R. Brinkmann *Director Accelerators (DESY Hamburg)*	- General support
B. Schmidt *FLA (DESY Hamburg)*	- Ultrafast beam diagnostics - Laser to beam sync
F. Stephan *PITZ (DESY Zeuthen)*	- RF-gun and gun-laser R&D - Beam dynamics - LPA Boosting
K. Flöttmann *REGAE & MPY group (DESY Hamburg)*	- Gun and accelerator R&D - Beam dynamics - LPA Boosting
R.J.D. Miller *REGAE (CFEL, University of Hamburg)*	- High-power IR-laser techn.

Plasma Accelerator Science in Hamburg - Collaborations

internal network

Plasma Accelerator Group
University and DESY in Hamburg

HPC infrastructure,
simulations

I. Agapov
HPC (DESY Hamburg)

P. Wegner
HPC (DESY Zeuthen)

R. Brinkmann
Director Accelerators (DESY Hamburg)

- General support

B. Schmidt
FLA (DESY Hamburg)

- Ultrafast beam diagnostics
- Laser to beam sync

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PITZ (DESY Zeuthen)

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REGAE & MPY group (DESY Hamburg)

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- Beam dynamics
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REGAE (CFEL, University of Hamburg)

- High-power IR-laser techn.

Plasma Accelerator Science in Hamburg - Collaborations

external network

Plasma Accelerator Group
University and DESY in Hamburg

Plasma Accelerator Science in Hamburg - Collaborations

external network

→ talk yesterday

Plasma Accelerator Science in Hamburg - Collaborations

external network

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University and DESY in Hamburg

Helmholtz internal →

HZDR

U. Schramm (~~FZD~~ Rossendorf)
experiments, gas-target development

→ talk yesterday

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e.g. *applications, diagnostics*

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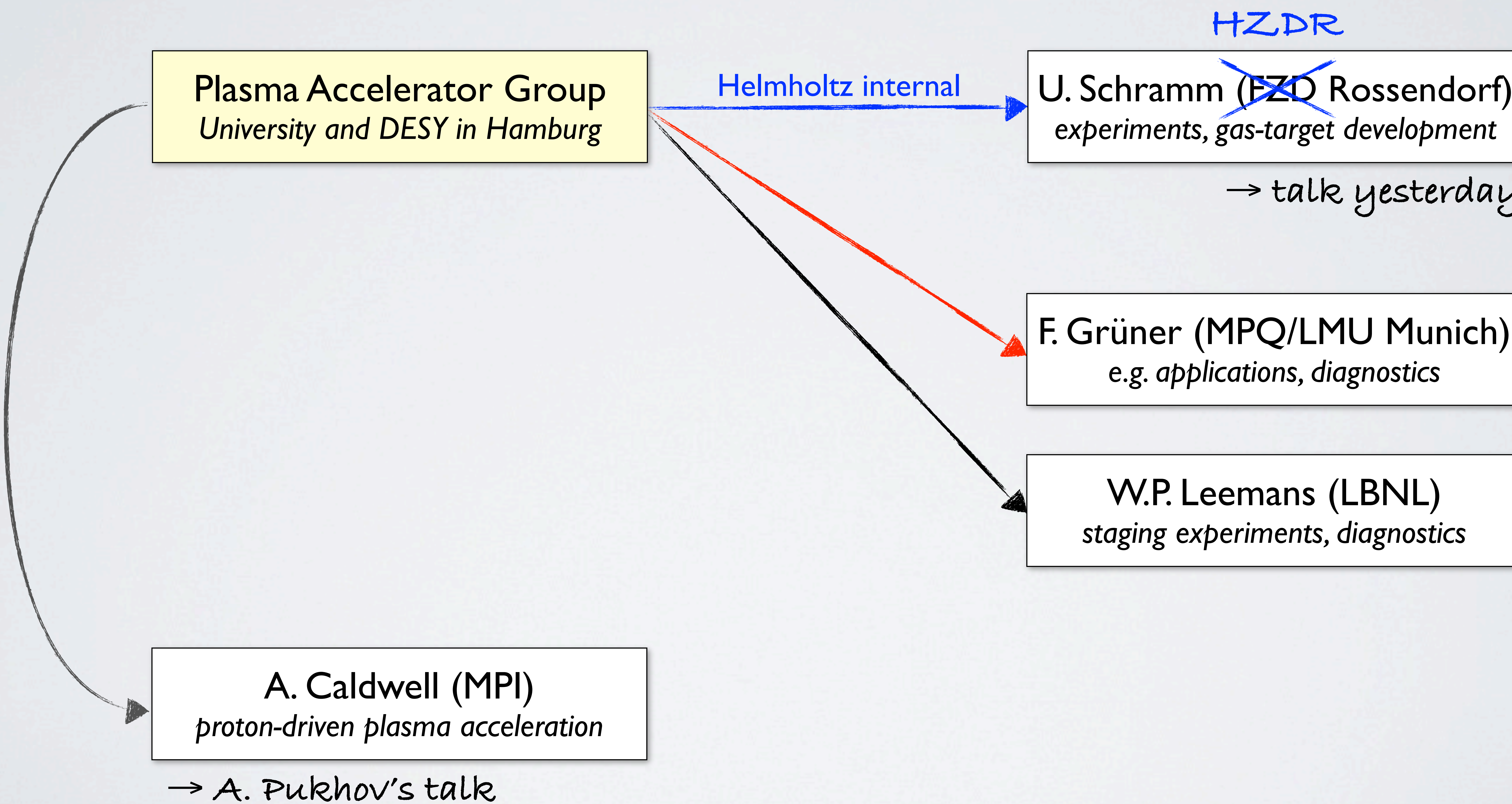
W.P. Leemans (LBNL)
staging experiments, diagnostics

Plasma Accelerator Science in Hamburg - Collaborations

external network



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external network

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HZDR

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experiments, gas-target development

→ talk yesterday

Collaboration
contract

L.O. Silva (IST Lisbon)
full access to latest OSIRIS PIC code

not only code access,
but work on common projects

F. Grüner (MPQ/LMU Munich)
e.g. *applications, diagnostics*

W.P. Leemans (LBNL)
staging experiments, diagnostics

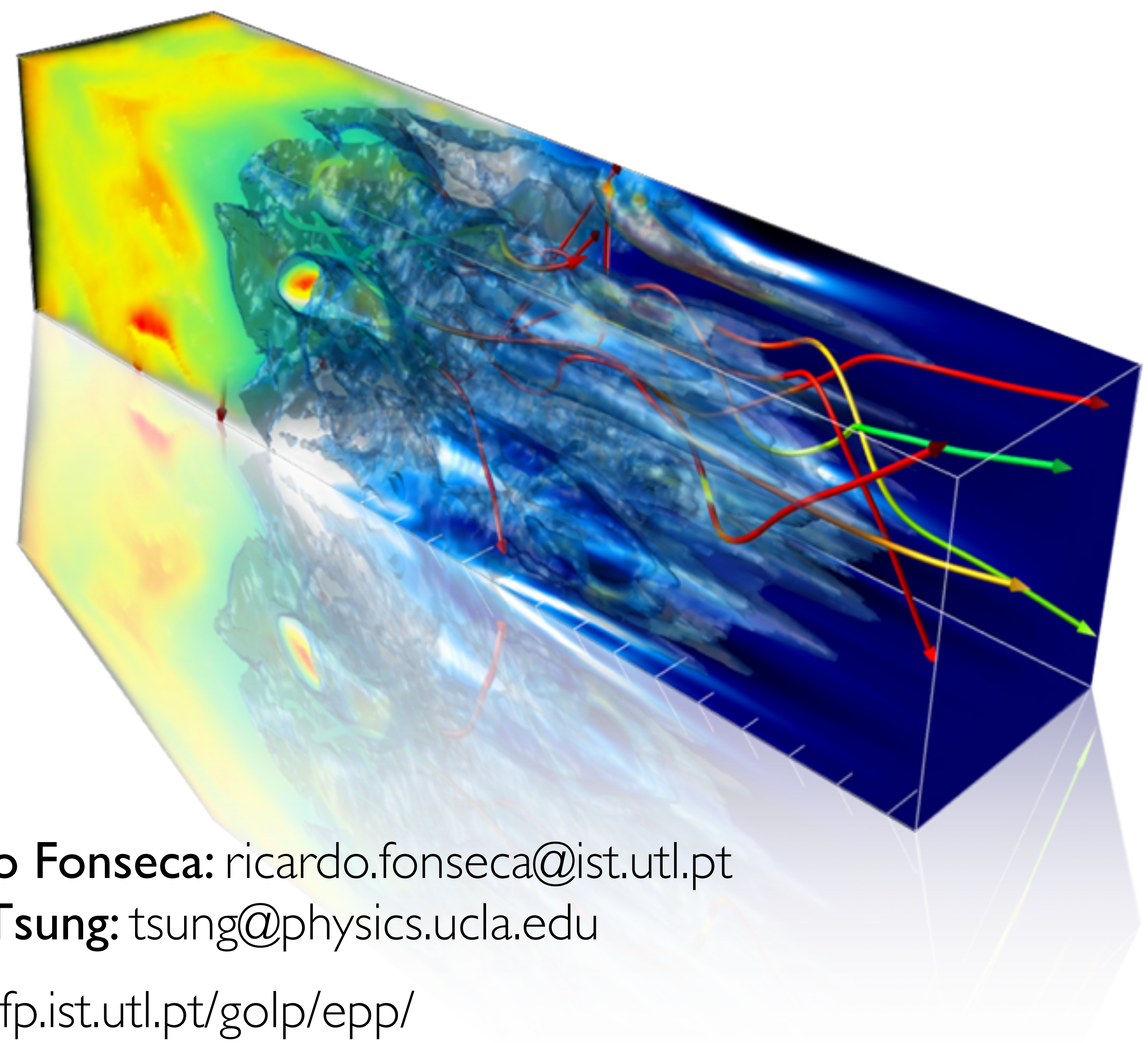
A. Caldwell (MPI)
proton-driven plasma acceleration

→ A. Pukhov's talk

OSIRIS 2.0

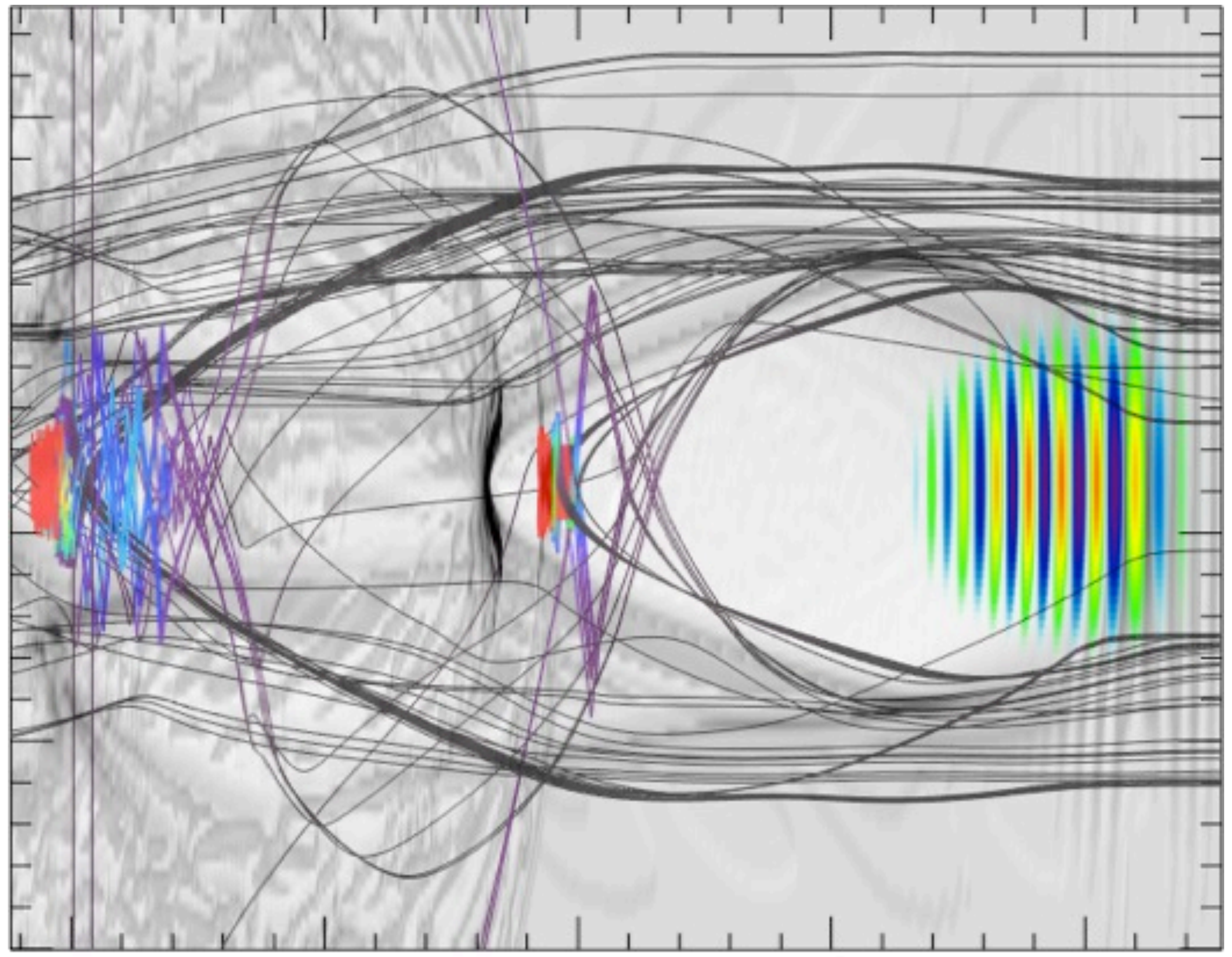
osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST



Ricardo Fonseca: ricardo.fonseca@ist.utl.pt
Frank Tsung: tsung@physics.ucla.edu

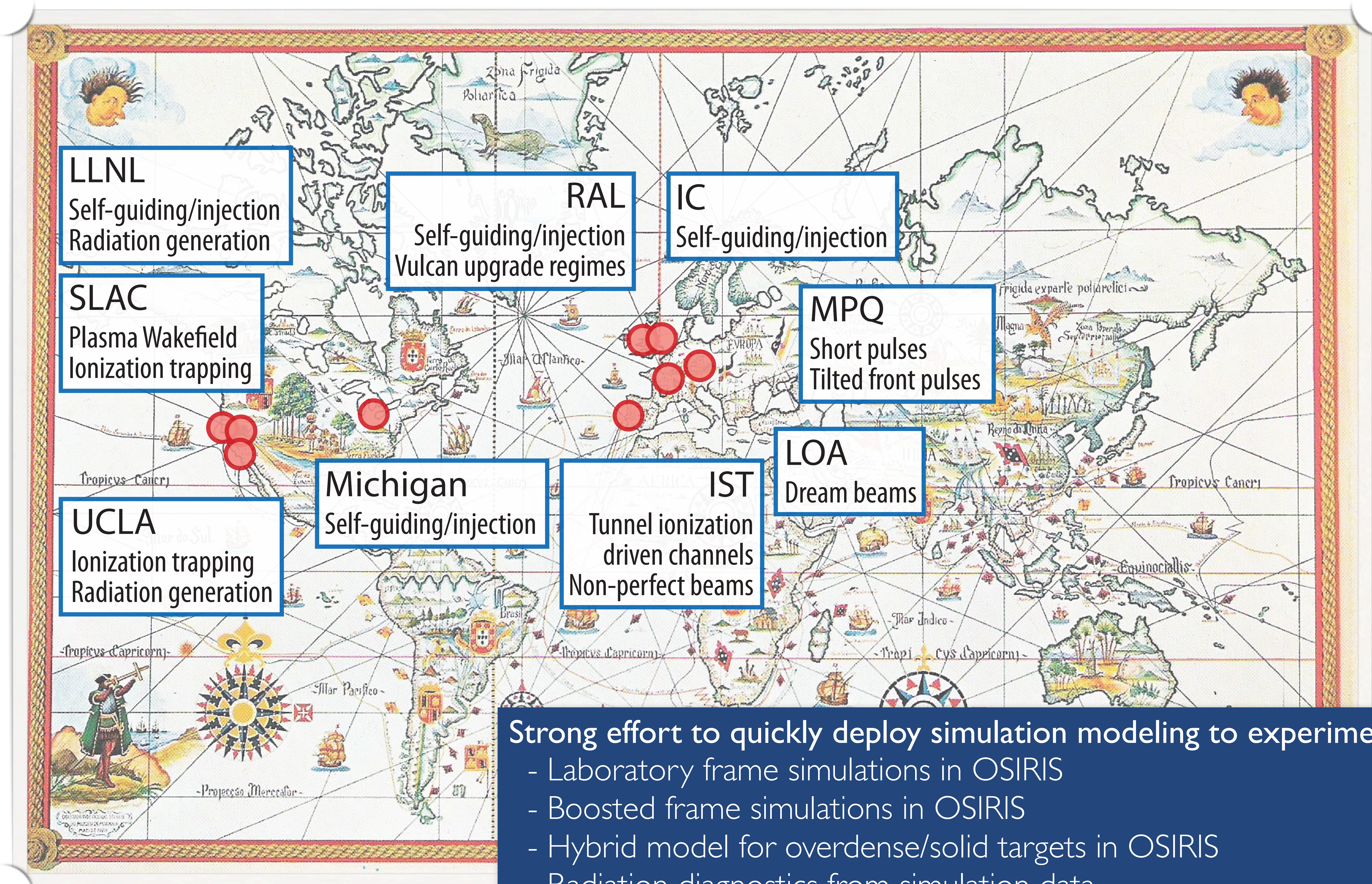
http://cfp.ist.utl.pt/golp/epp/
http://exodus.physics.ucla.edu/



New Features in v2.0

- Bessel Beams
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- PML absorbing BC
- Optimized higher order splines
- Parallel I/O (HDF5)
- Boosted frame in 1/2/3D

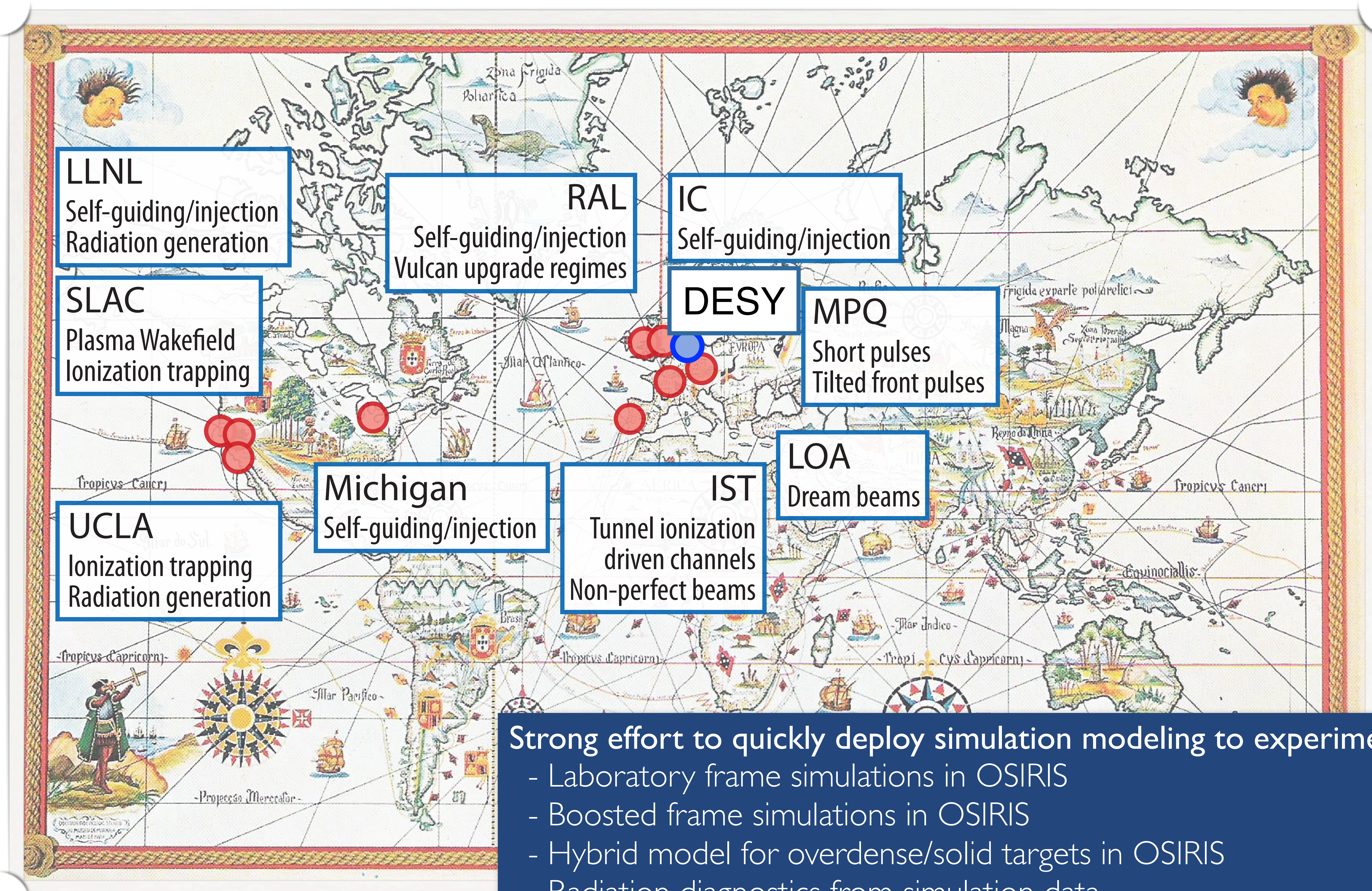
OSIRIS has been used to model many experiments



Strong effort to quickly deploy simulation modeling to experimental teams

- Laboratory frame simulations in OSIRIS
- Boosted frame simulations in OSIRIS
- Hybrid model for overdense/solid targets in OSIRIS
- Radiation diagnostics from simulation data

OSIRIS has been used to model many experiments



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Plasma Accelerator Science in Hamburg - Goals

Laser-driven
plasma acceleration

Beam-driven
plasma acceleration

Plasma Accelerator Science in Hamburg - Goals

Laser-driven
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Beam-driven
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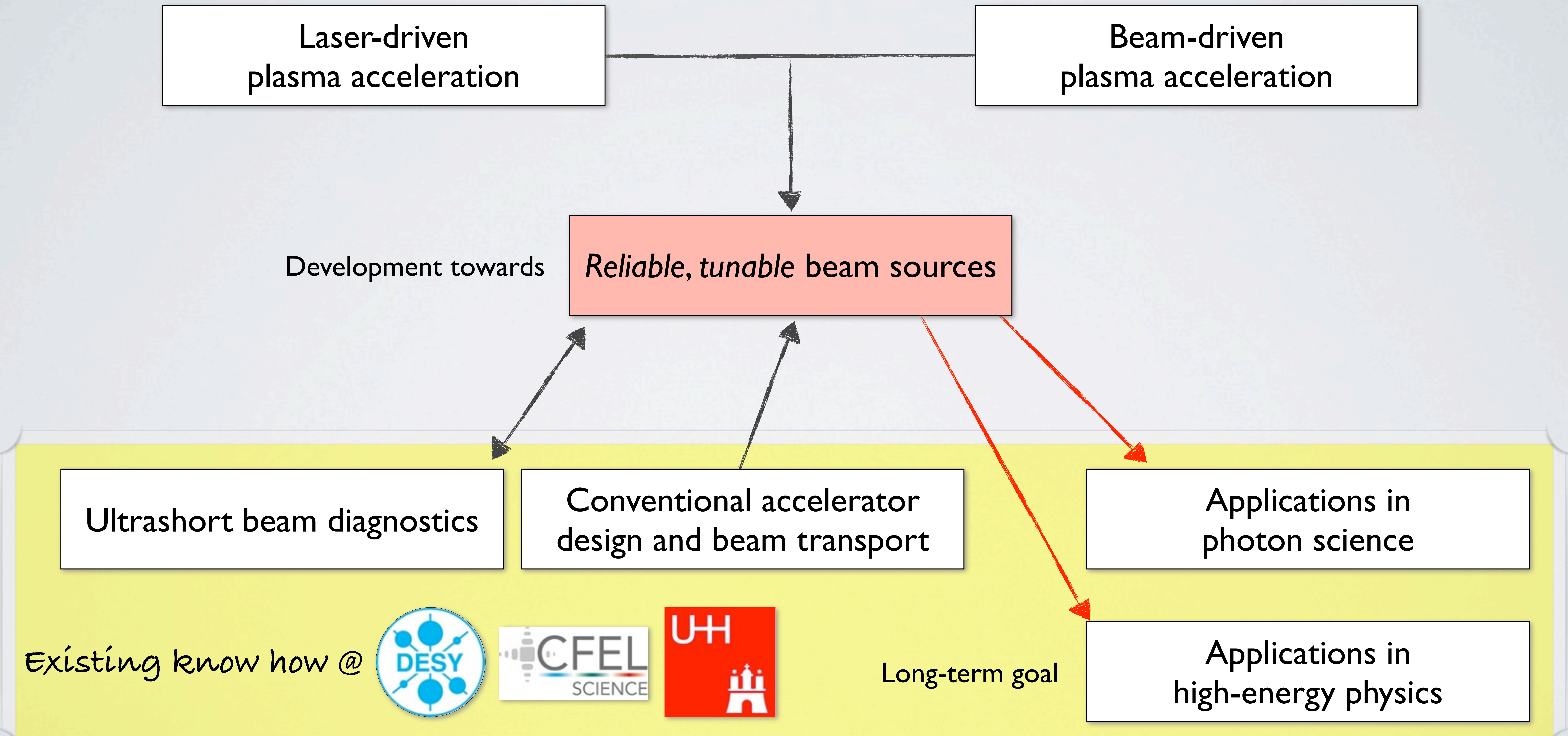
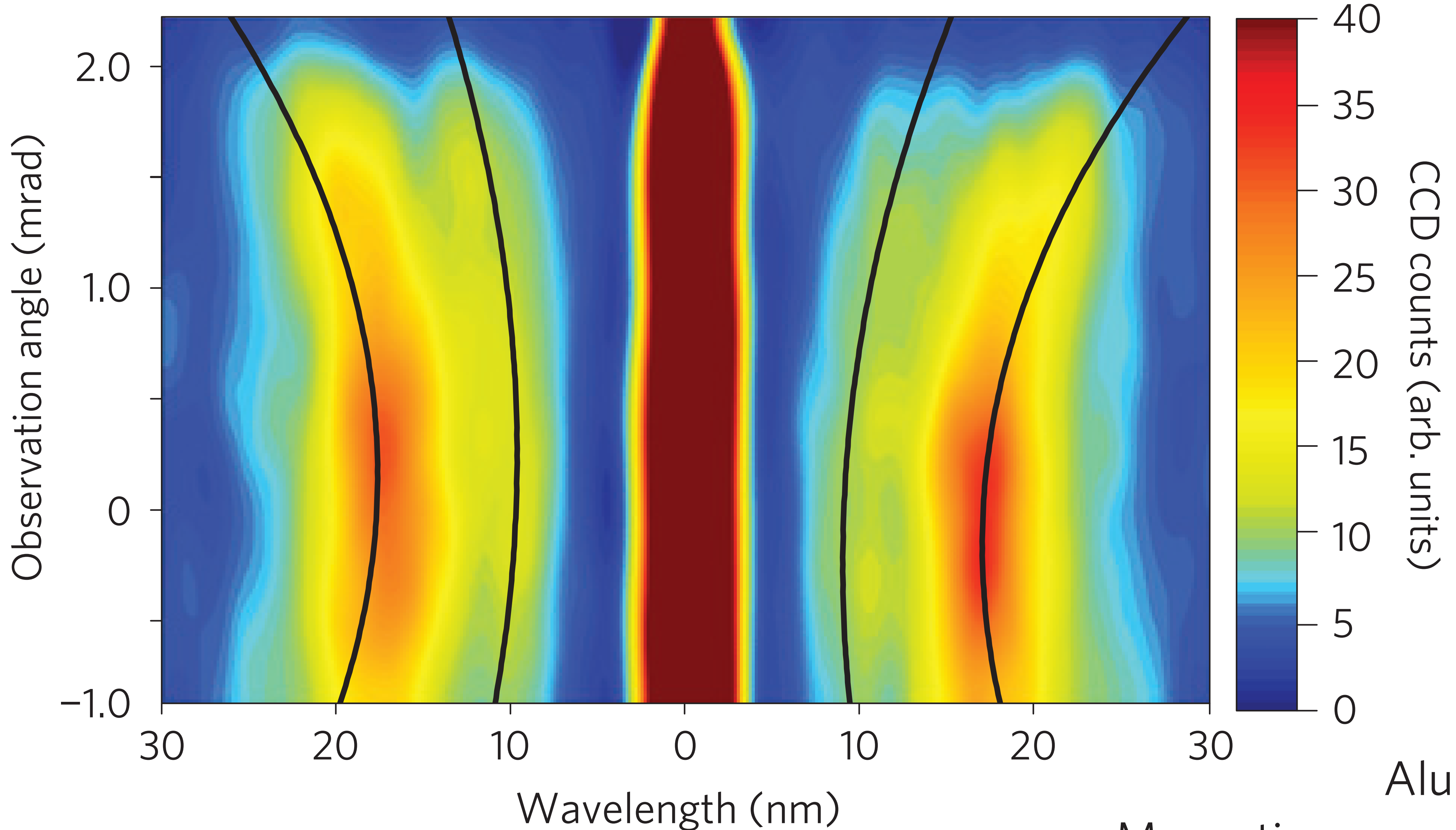
Development towards *Reliable*, *tunable* beam sources

Plasma Accelerator Science in Hamburg - Goals



Stability key in XUV-emission from an LPA driven undulator

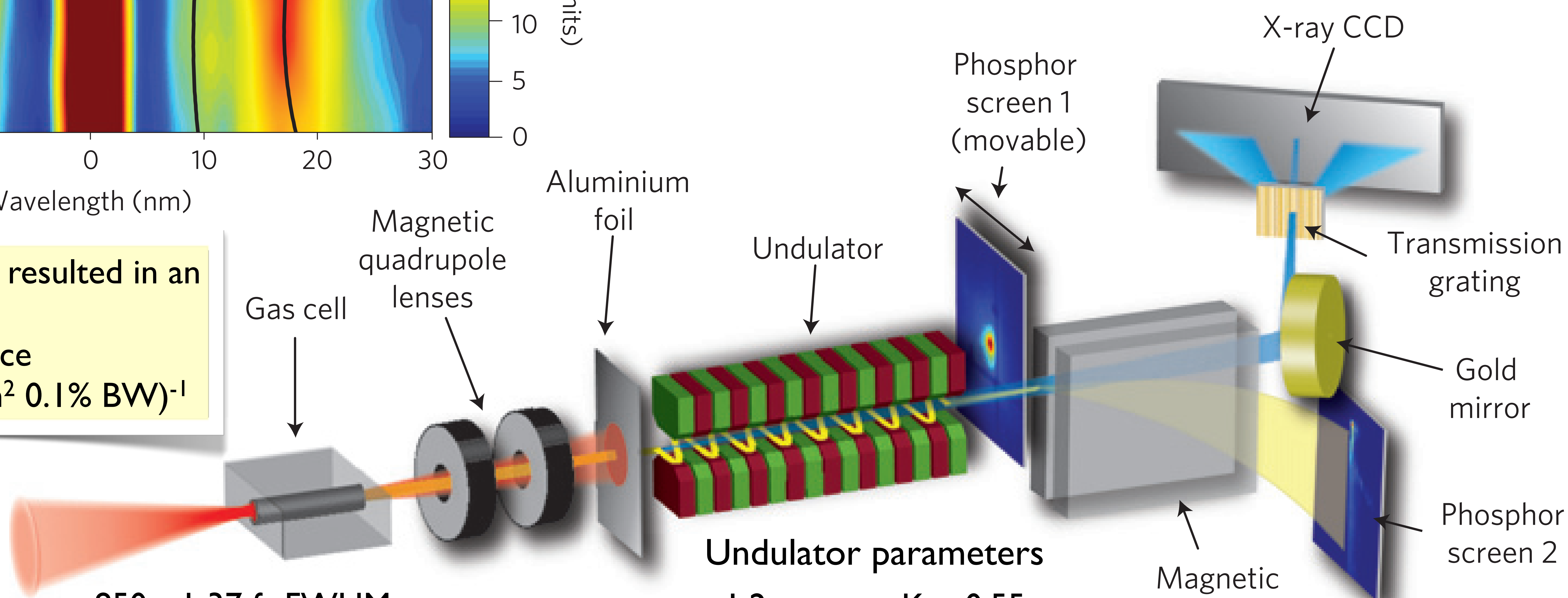
M. Fuchs *et al.*, Nature Physics 5, 826 (2009)



Resonance condition:

$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\Theta^2\right)$$

- **70%** of all laser shots resulted in an undulator XUV signal
- Estimated peak brillance 1.3×10^{17} (s mrad^2 mm^2 0.1% BW)$^{-1}$



Laser pulse parameters

850 mJ, 37 fs FWHM
23 µm focus FWHM

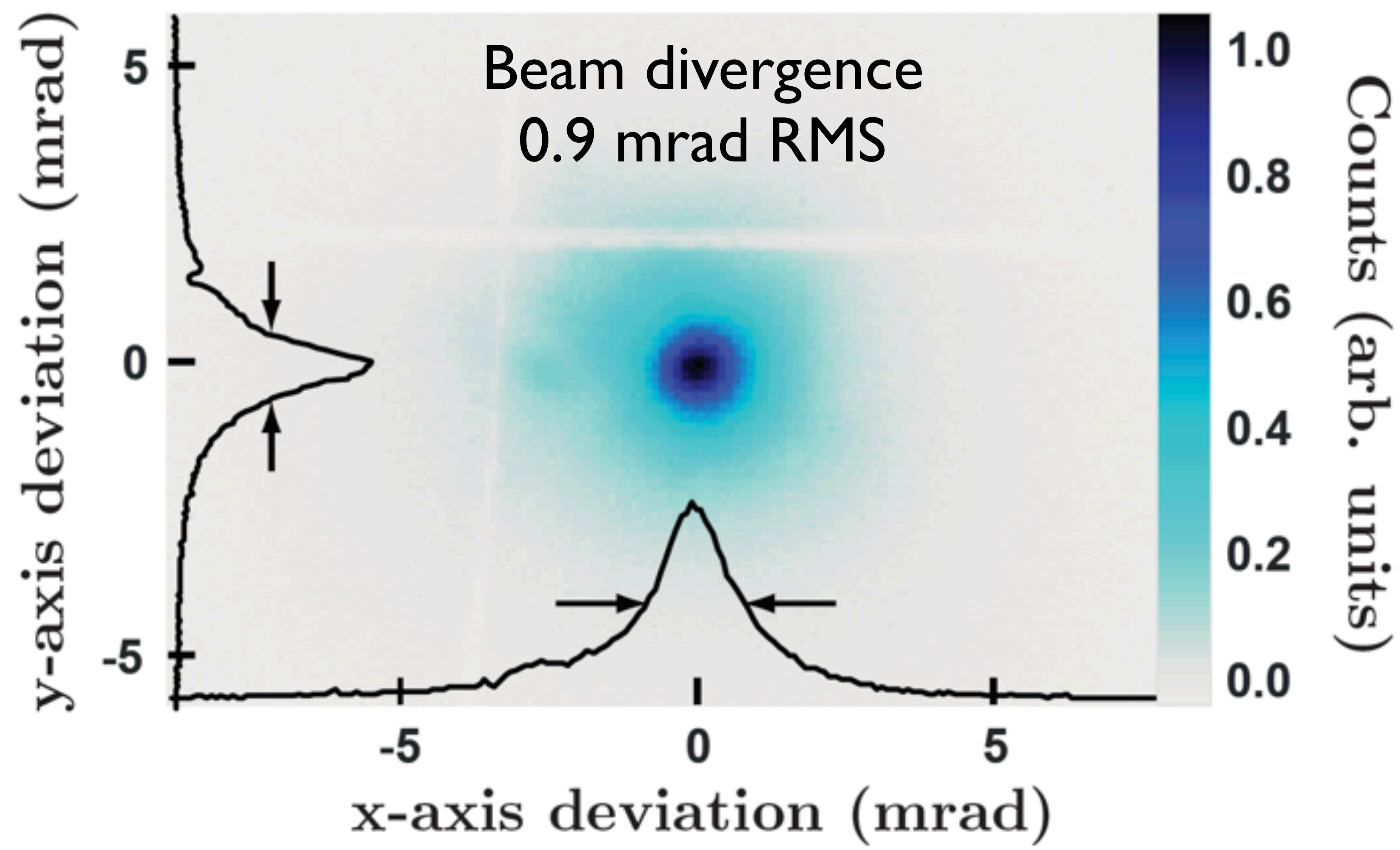
Undulator parameters

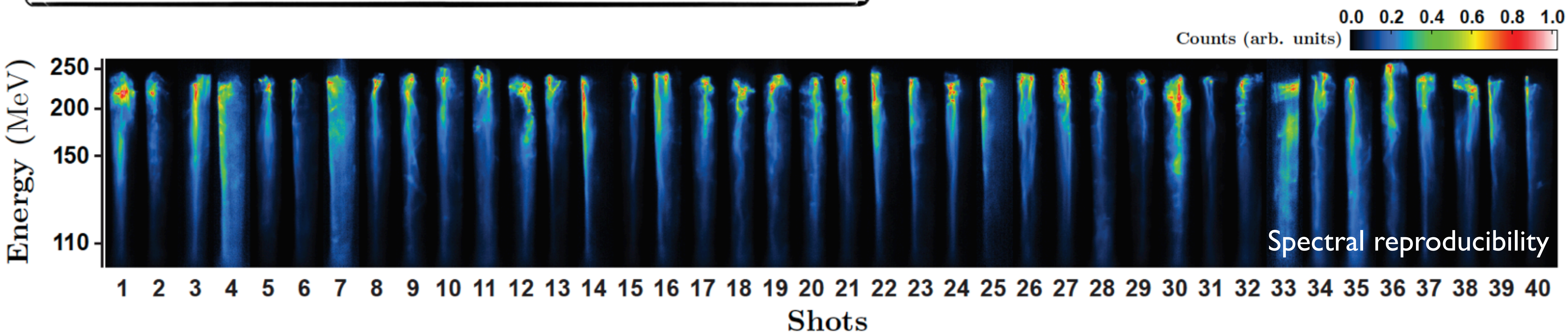
1.2 mm gap, K = 0.55
λ_u = 5 mm, 60 periods

A steady-state-flow gas cell stabilizes plasma conditions

Acceleration results	Gas cell	
Peak energies	220 MeV	
Energy fluctuations	± 2.5 %	✓ LWFA record
Energy spread	> 2 % RMS	
Peak charge	~ 10 pC	
Charge fluctuations	±16 %	✓ LWFA record
Divergence	0.9 mrad RMS	✓ LWFA record
Pointing stability	1.4 mrad RMS	✓ LWFA record
Injection	~ 100 %	*…in 2008*

J. Osterhoff *et al.*,
Phys. Rev. Lett. 101, 085002 (2008)





Strategy towards stable electron-beam sources

Electron beam fluctuations originate from

variations in
laser pulse parameters
(spatial and temporal energy profiles, pointing)

$\longleftrightarrow$

amplified through
nonlinear processes

(laser self-modulation effects, wavebreaking)

variations in
plasma parameters
(mainly three-dimensional density profile)

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Strategy towards stable electron-beam sources

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(laser self-modulation effects, ~~wavebreaking~~)

develop stable, tailored
plasma sources

a) mildly nonlinear wake → no dark current
b) control of phase space population
by controlled injection:

- density downramp injection {*Bulanov et al., Phys. Rev. E 58, R5257 (1998); Geddes et al., Phys. Rev. Lett. 100, 215004 (2008)*}
- well-localized ionization injection {*Umstadter et al., Phys. Rev. Lett. 76, 2073 (1996); Pak et al., Phys. Rev. Lett. 104, 025003 (2010)*}
- counterpropagating laser pulses {*Esarey et al., Phys. Rev. Lett. 79, 2682 (1997); Faure et al., Nature 444, 737 (2006)*}
- external beam injection {*Dewa et al., Nucl. Instrum. & Methods Phys. Res. A 410, 357 (1998); Dorchies et al., Phys. Plasmas 6 2903 (1999)*}

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use resonant laser pulses
below critical power

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~~(laser self-modulation effects,~~ ~~wavebreaking)~~

maximize laser stability
→ *will have dedicated laser engineer working on this issue*

use resonant laser pulses
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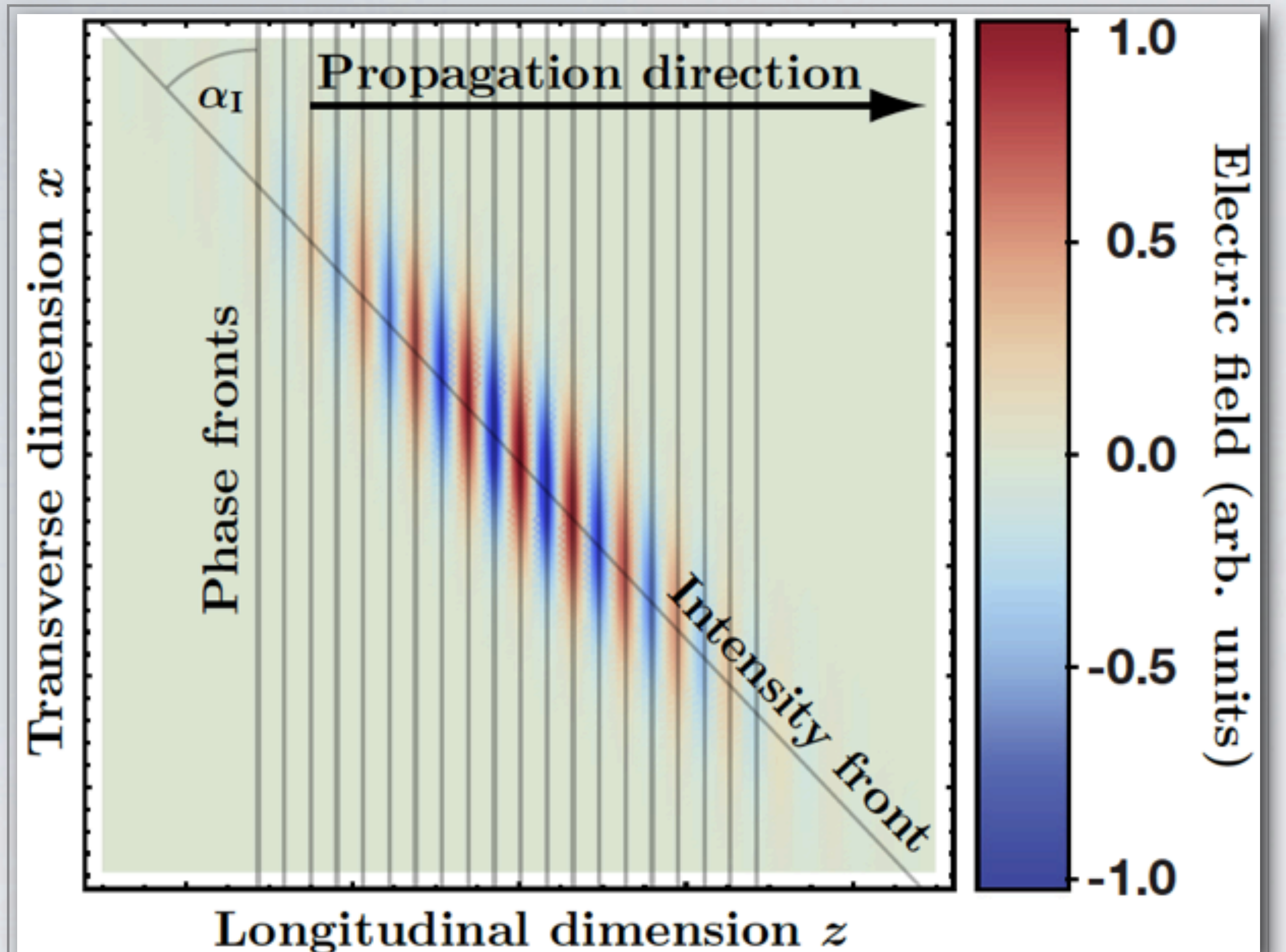
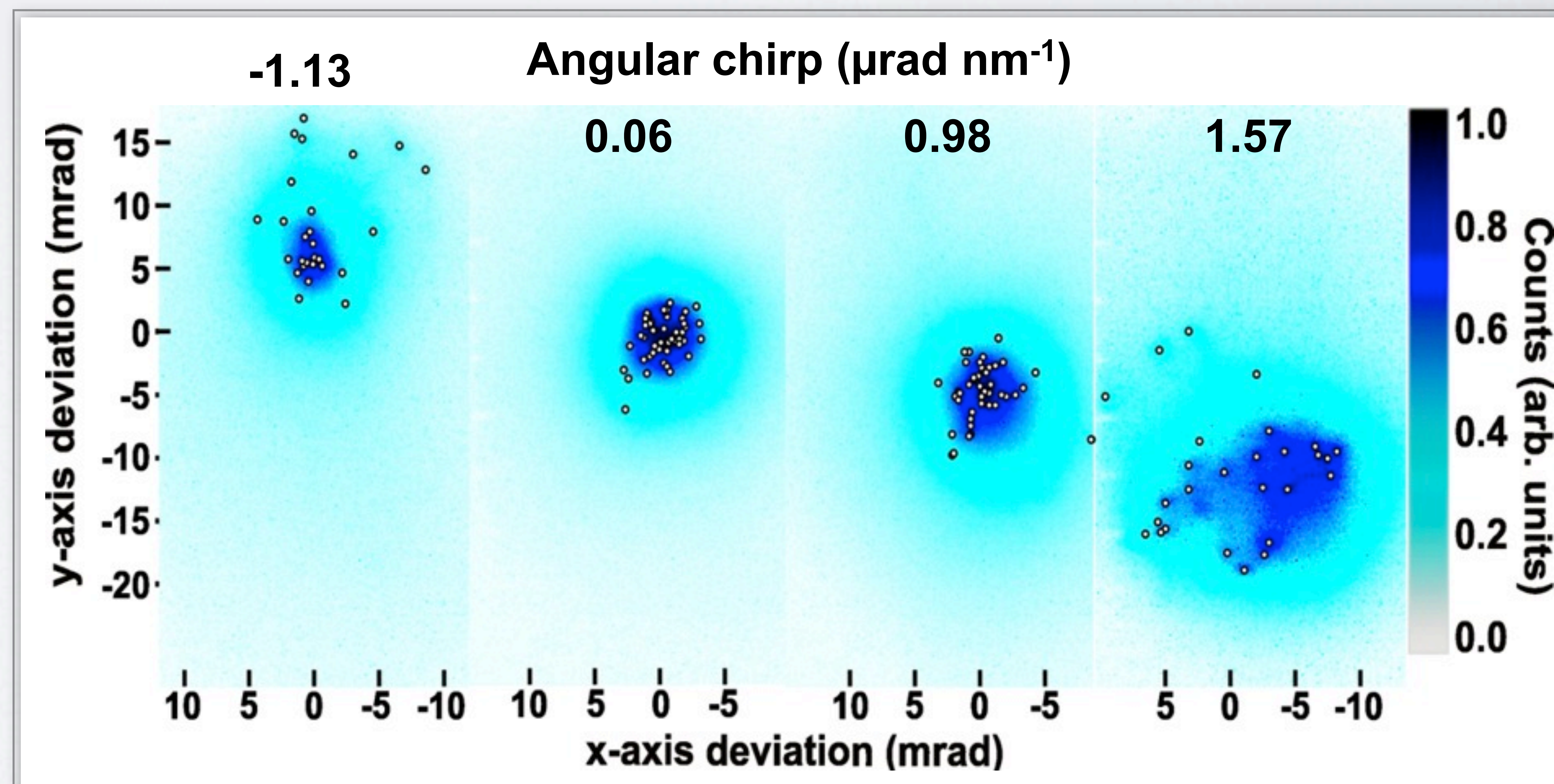
Eliminating laser intensity-front tilt increases stability



A. Popp *et al.*, Phys. Rev. Lett. 105, 215001 (2010)

Intensity or pulse-front tilt usually originates from laser angular chirp (AC) caused by an imperfect stretcher/compressor alignment

- hard to diagnose
- small amounts of AC have large effect on the stability of LPAs



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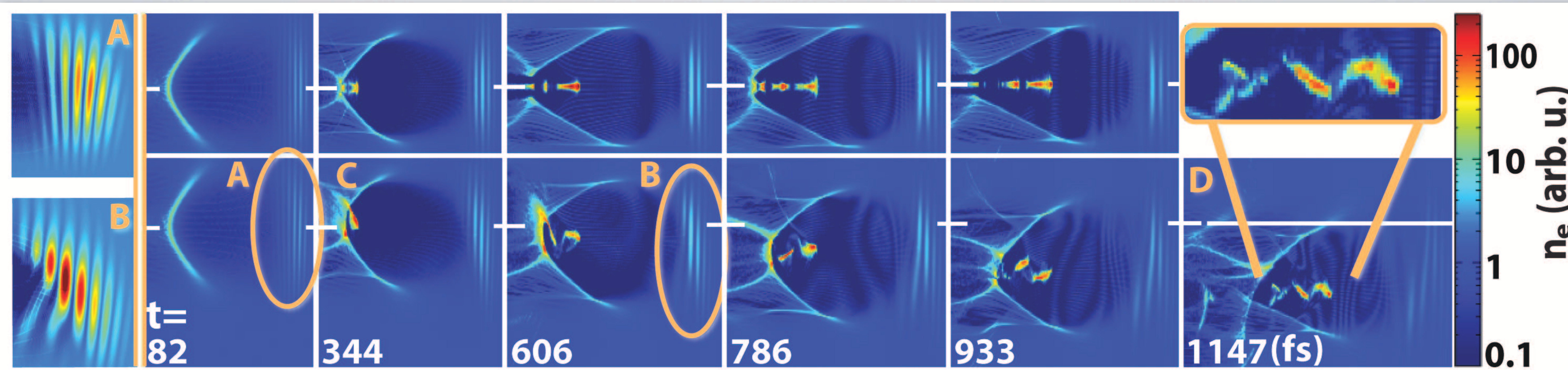

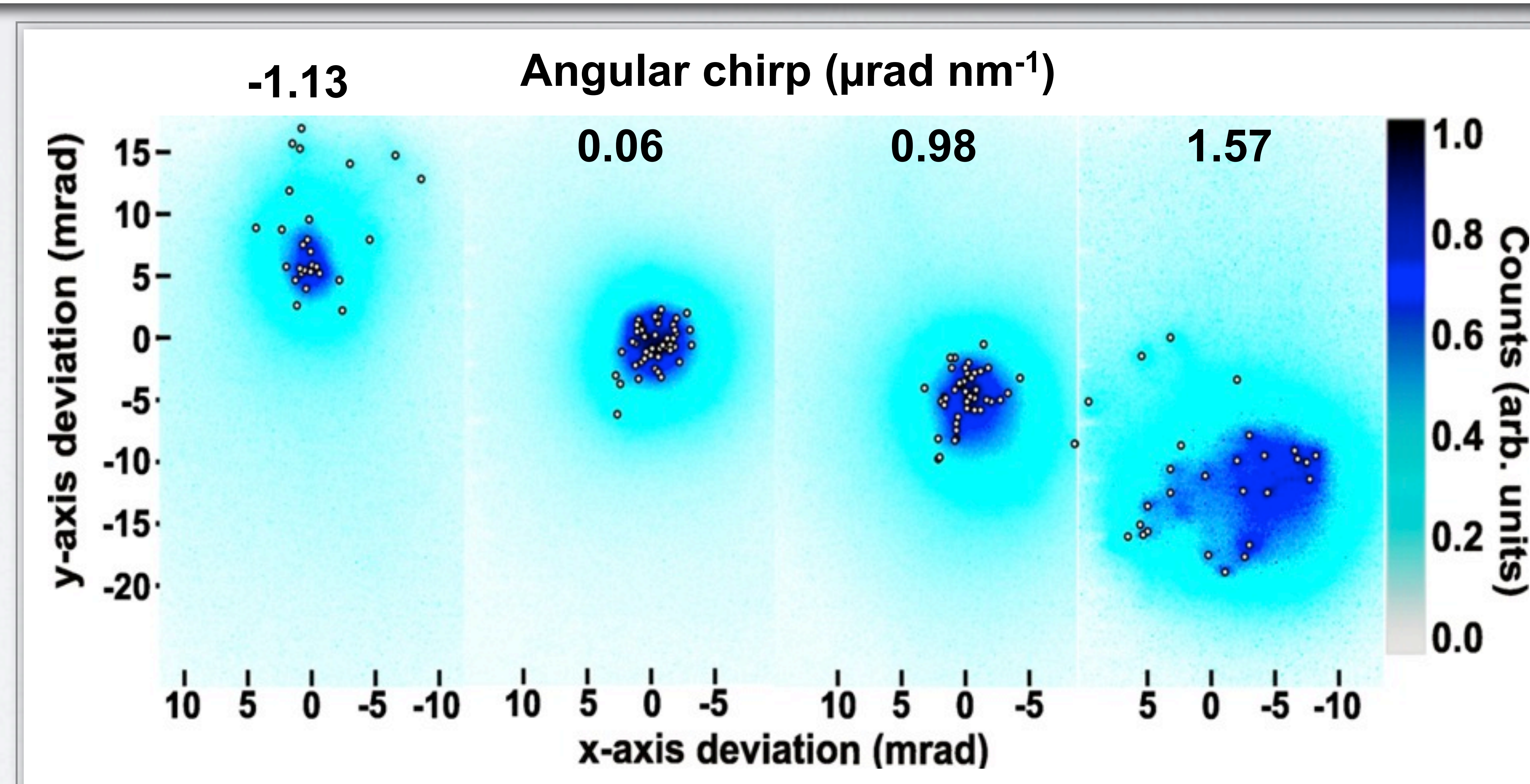

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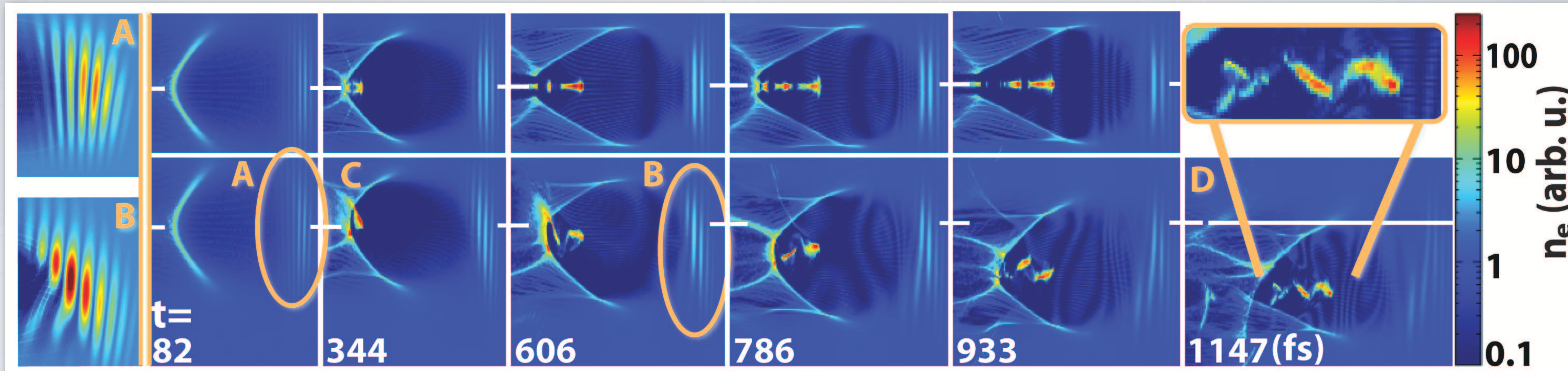

Collective beam oscillations
→ way to tailor betatron radiation?
→ useful for beam cooling?

Proposed plasma acceleration activities at DESY

<u>From the start:</u>

Laser-driven plasma acceleration

Photon science applications (FELs, hard x-ray sources)

Post-acceleration of beams from conventional sources

Novel beam diagnostics to measure pulse duration, slice energy spreads

<u>Long-term:</u>

Beam-driven plasma acceleration

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details follow...

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Long-term:

Beam-driven plasma acceleration

details follow...

External beam injection offers control and reliability

Post-acceleration of tailored beams from conventional sources in a plasma allows to

- start from a well-characterized, 6d-tunable (space and momentum), stable electron beam
  → shaped and chirped beams to control beam-loading effects and final energy spread
- fine-tune the plasma-wave phase-space population
  → gives control over charge, emittance, energy spread
- operate the wake in a mildly nonlinear regime ($a_0 \approx 1$) and prevent dark-current generation
- accelerate positrons

External beam injection offers control and reliability

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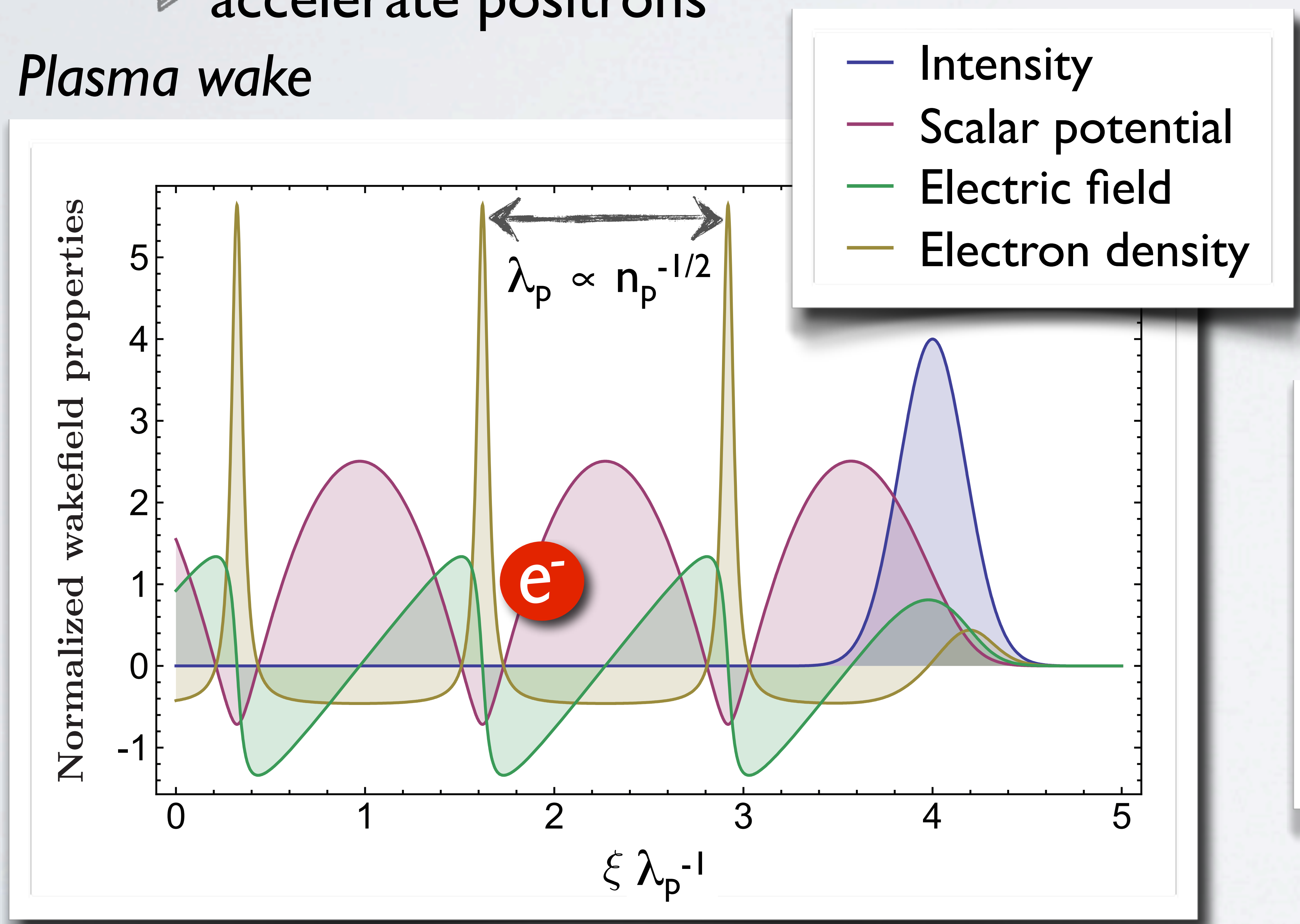
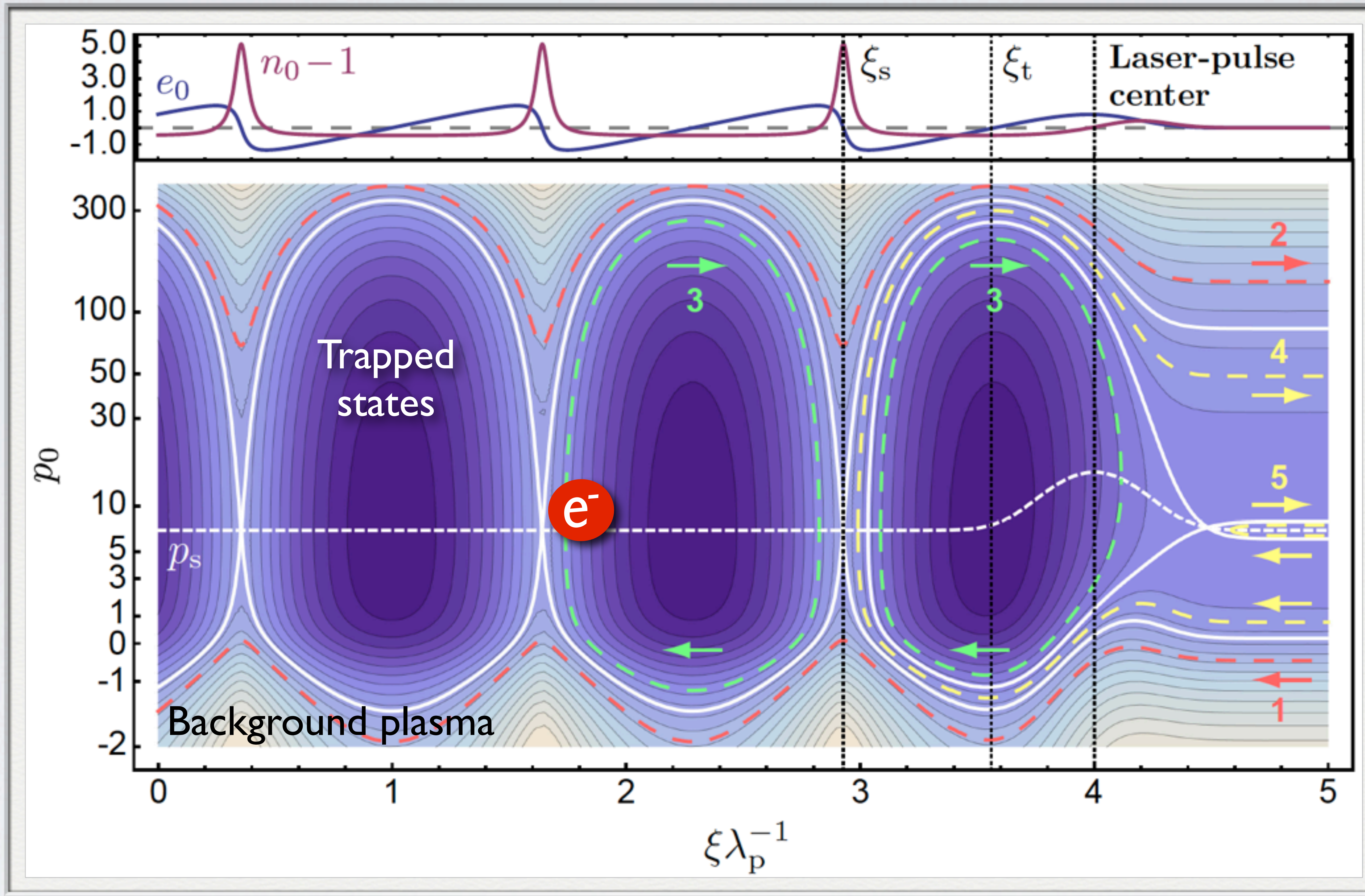
Plasma wake



Requirements:

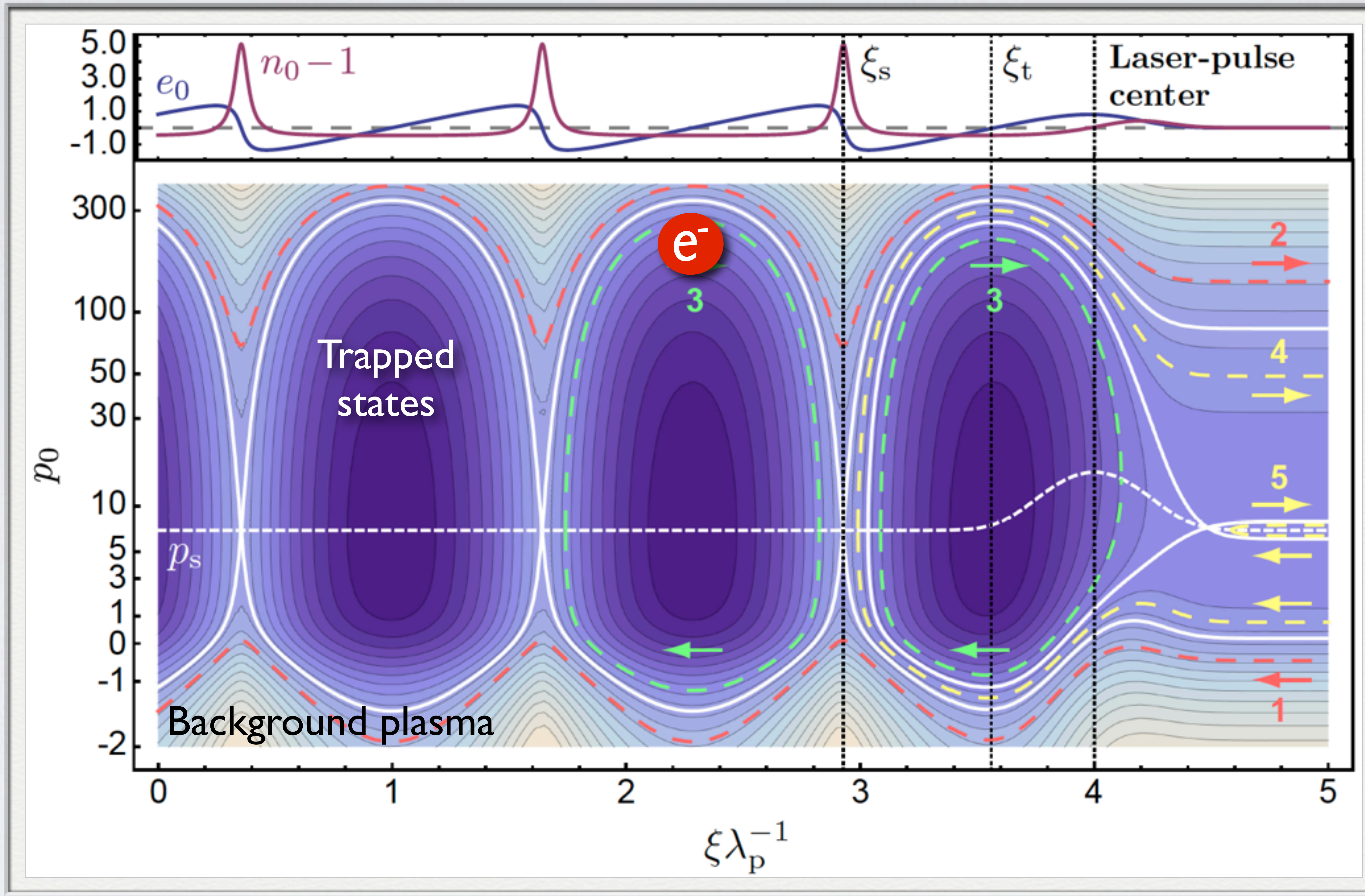
- Spatial and temporal matching
  → electron bunch length must be a fraction of λ_p
  → transverse size must be smaller than transverse wake
- Spatial and temporal overlap jitter must be small

Possible experiments: mapping of wake phase space



Time-delay scan between laser pulse and electron beam allows for sampling of wake phase space

Possible experiments: mapping of wake phase space



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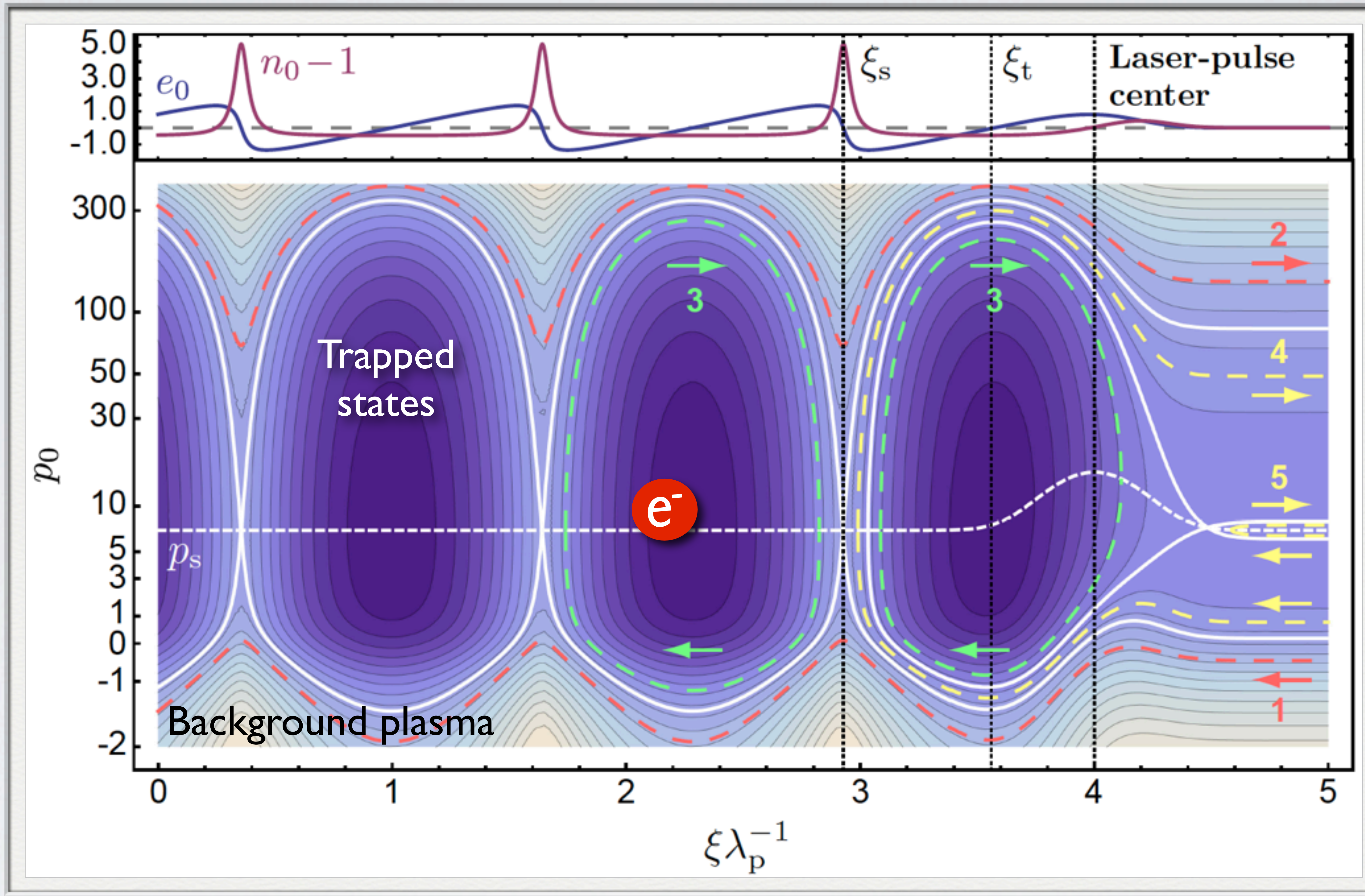

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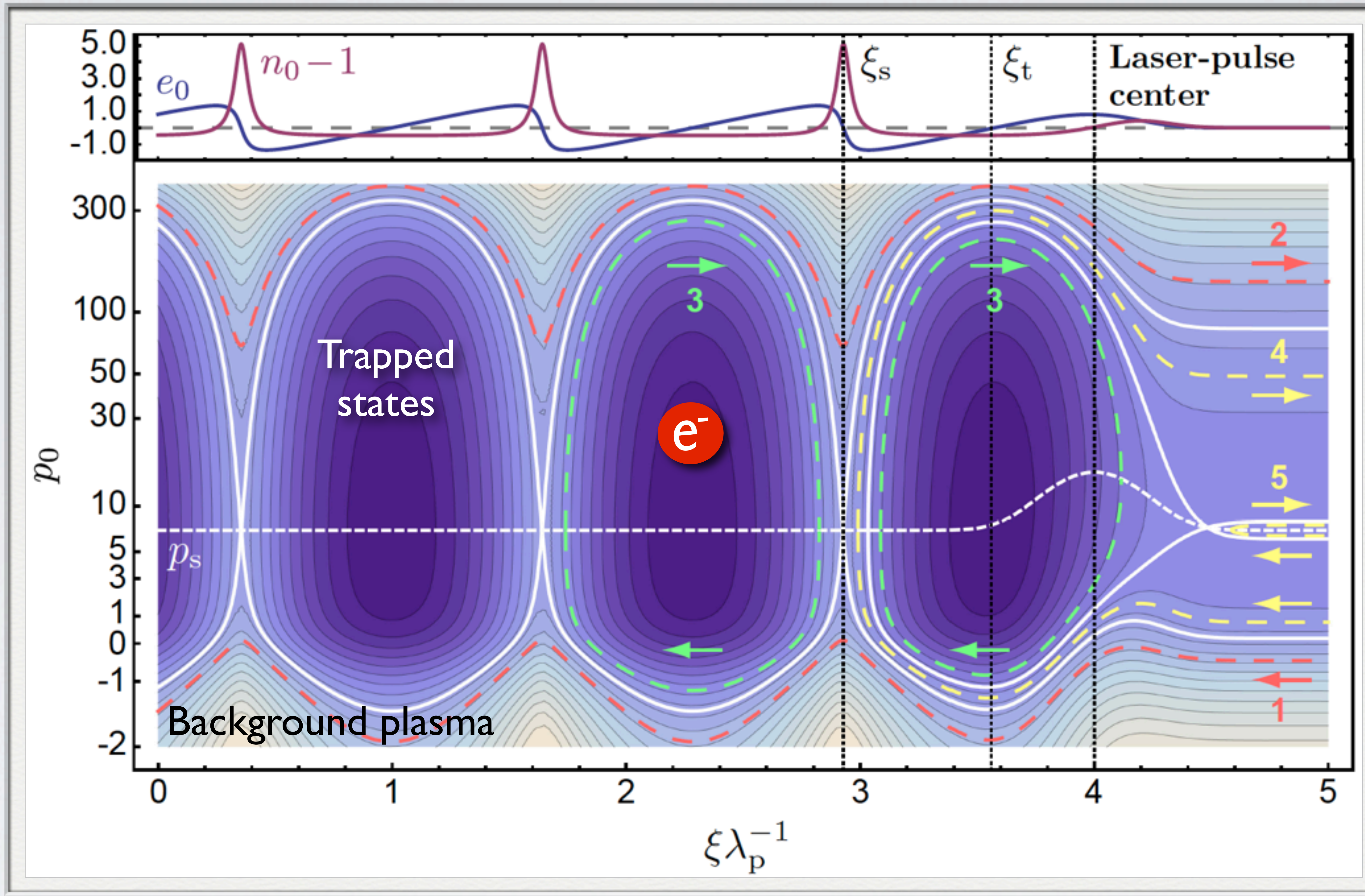
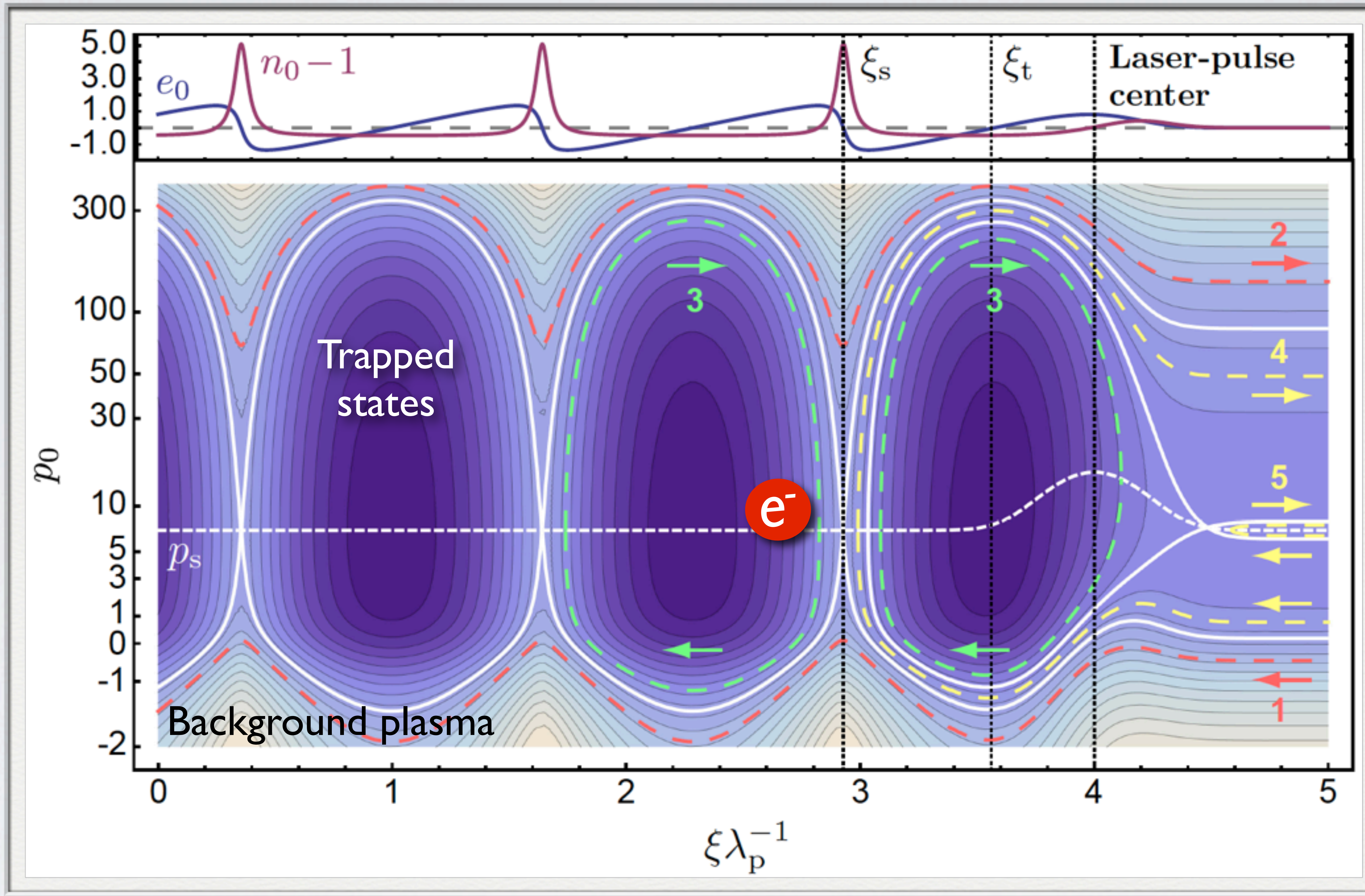


Time-delay scan between laser pulse and electron beam allows for sampling of wake phase space

Possible experiments: mapping of wake phase space



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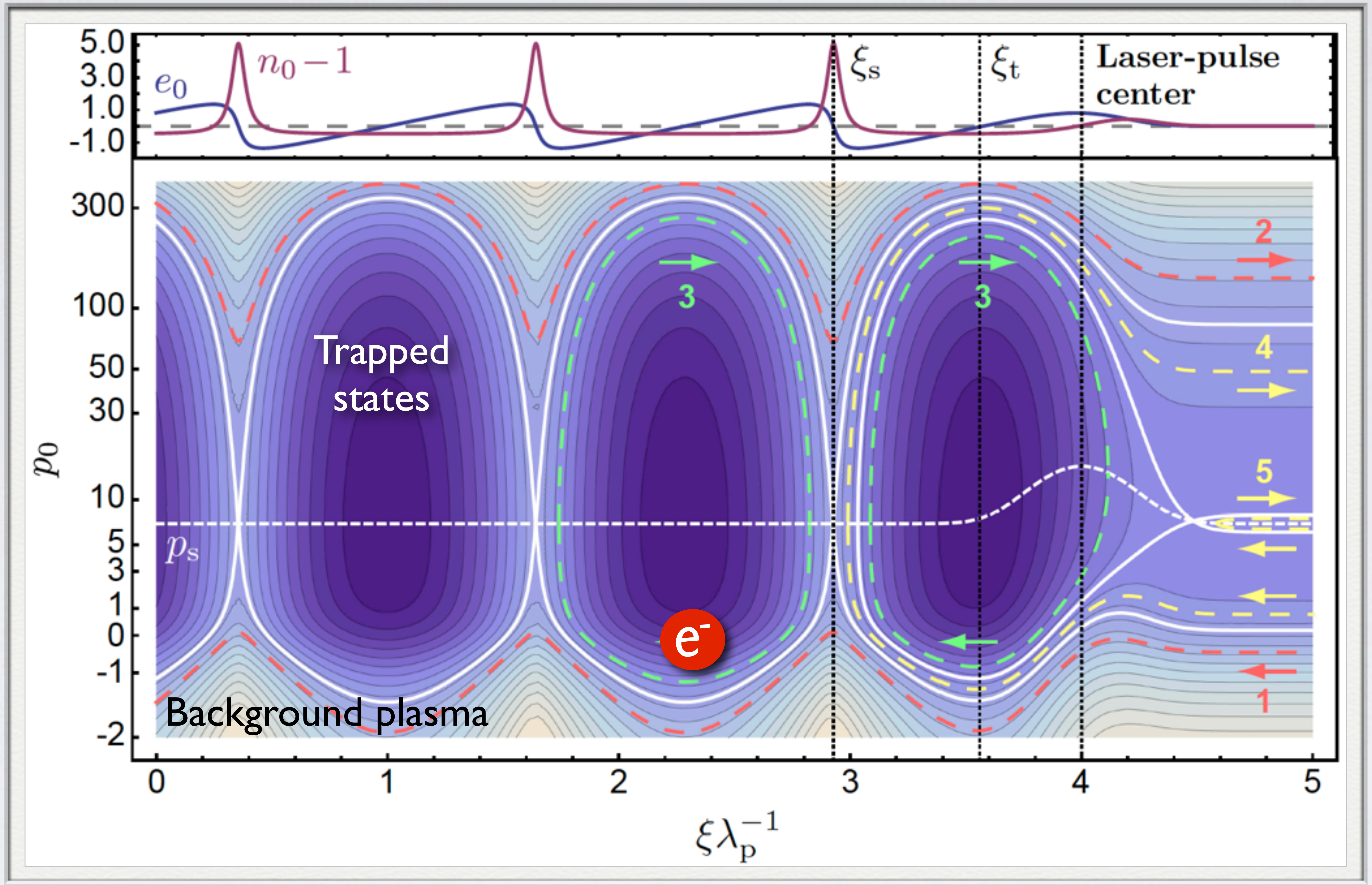
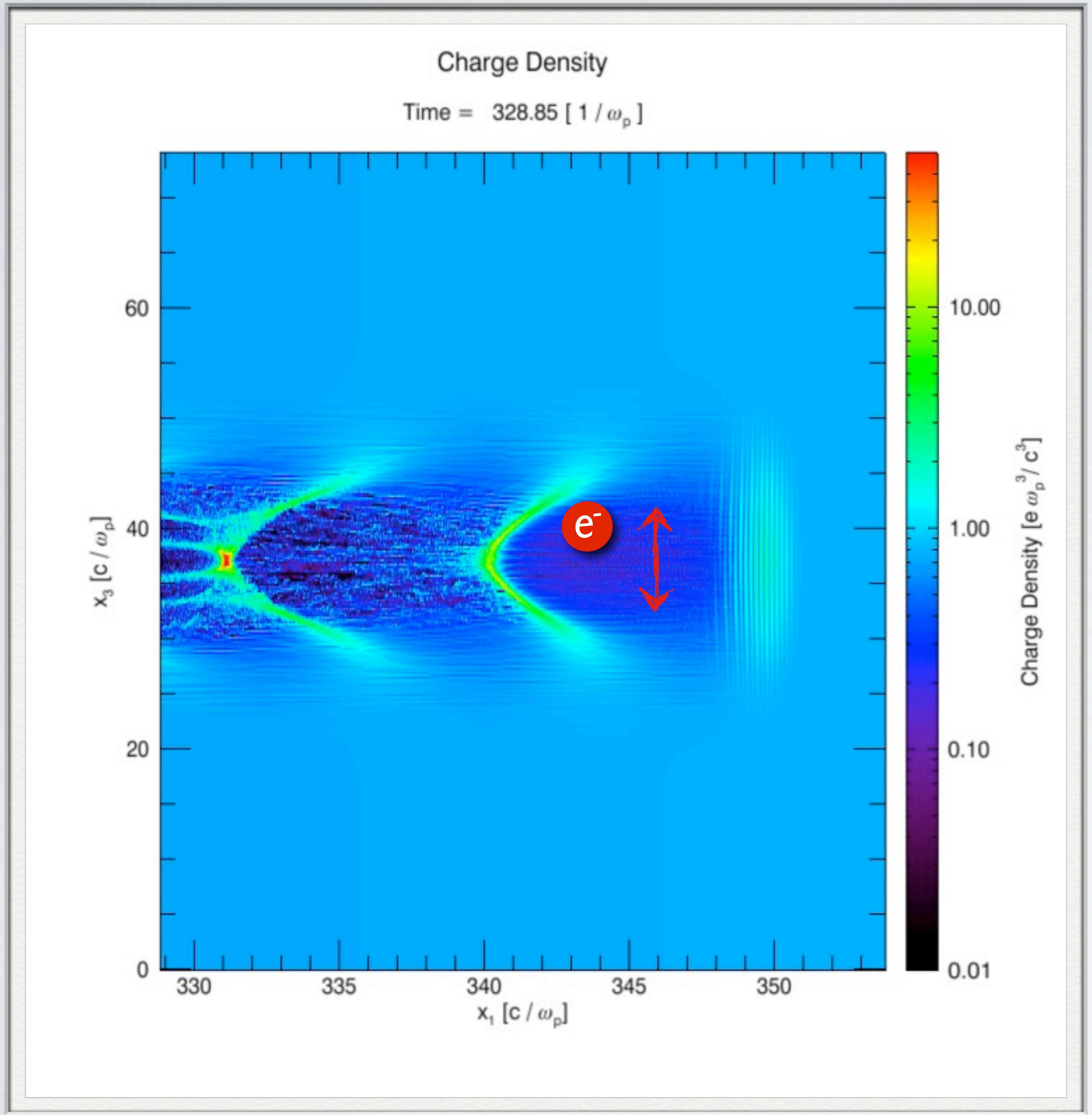


Time-delay scan between laser pulse and electron beam allows for sampling of wake phase space

Possible experiments: tailored betatron radiation source



Control transverse offset between laser pulse and electron bunch for tailored betatron sources

$$K_\beta = \gamma k_\beta \boxed{r_\beta}$$ tunable

$$\omega_\beta = ck_\beta \qquad \omega_\beta = \frac{\omega_\mathrm{p}}{\sqrt{2\gamma}}$$

will affect the emitted photon spectrum

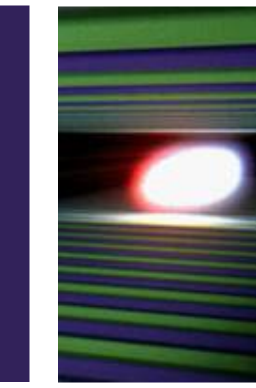
External injection needs carefully prepared e$^-$-beams

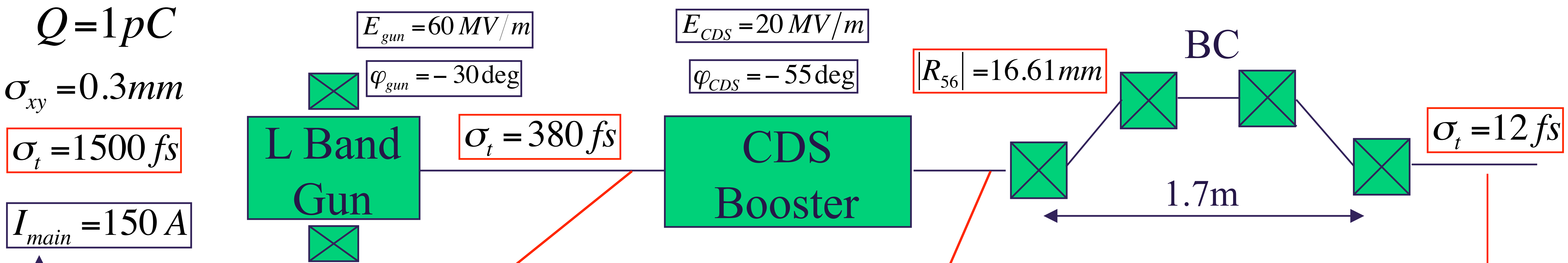
DESY offers extensive know how in beam-to-laser synchronization and short-pulse accelerator design

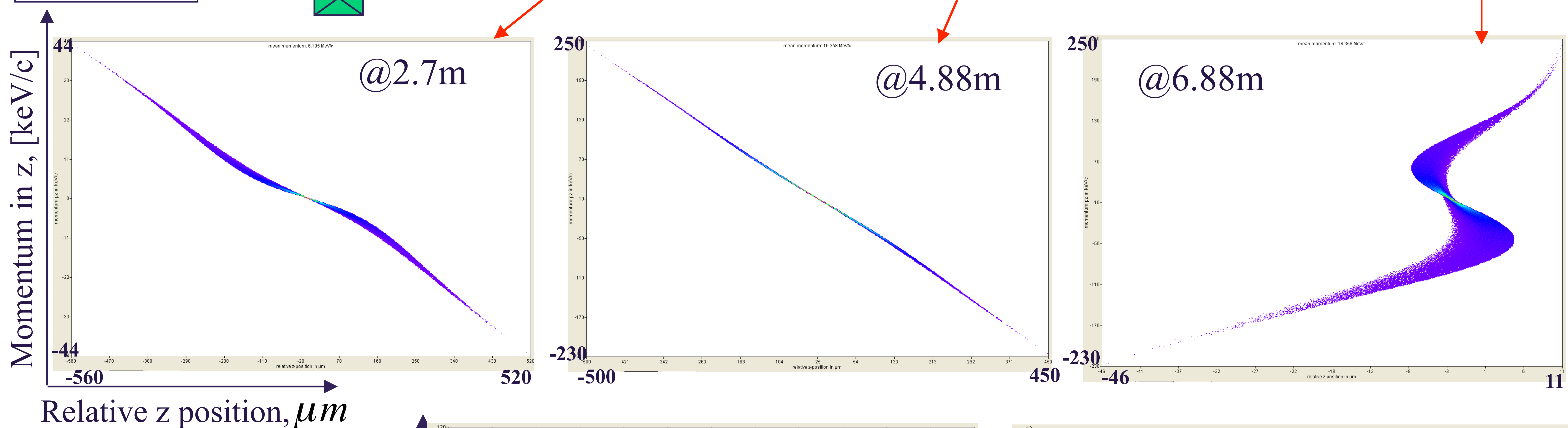
Available machines

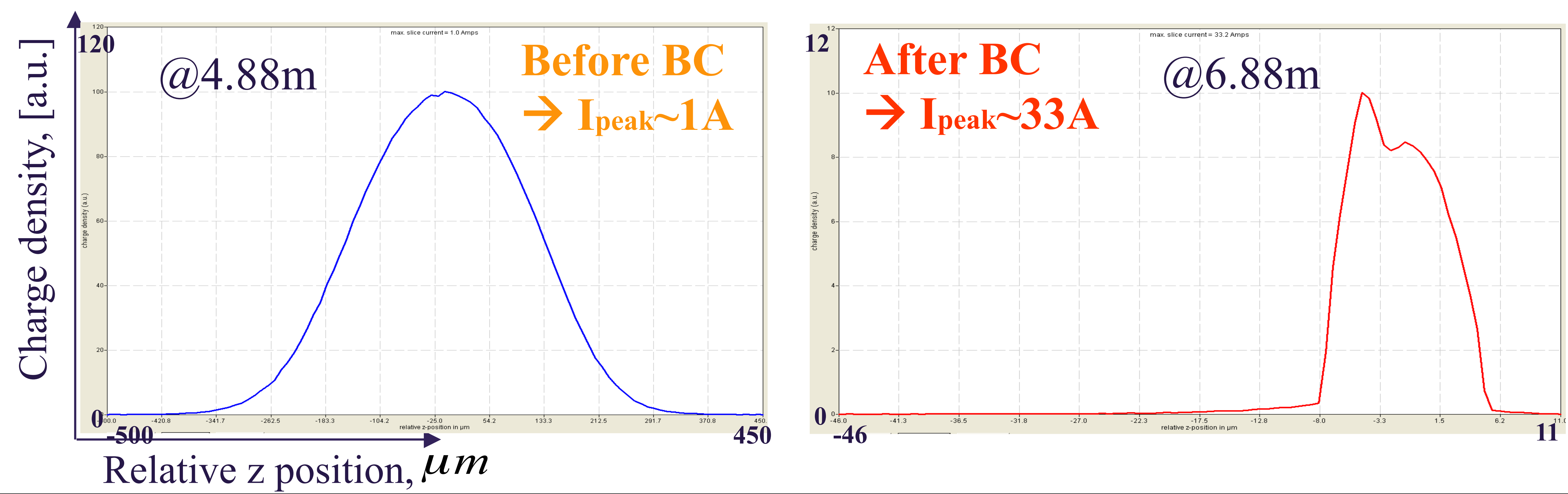
- FLASH at 1.2 GeV → S. Schreiber's talk
  short bunch operation in preparation, laser synchronized to within 40 fs and improving
- PITZ at 20 MeV
  short bunch operation with ~10 fs should be possible, laser synchronized
- REGAE at 5 MeV
  explicitly being built for laser-sync'ed, short bunch operation of ~10 fs at low charge

Schematic layout for bunch compression at PITZ



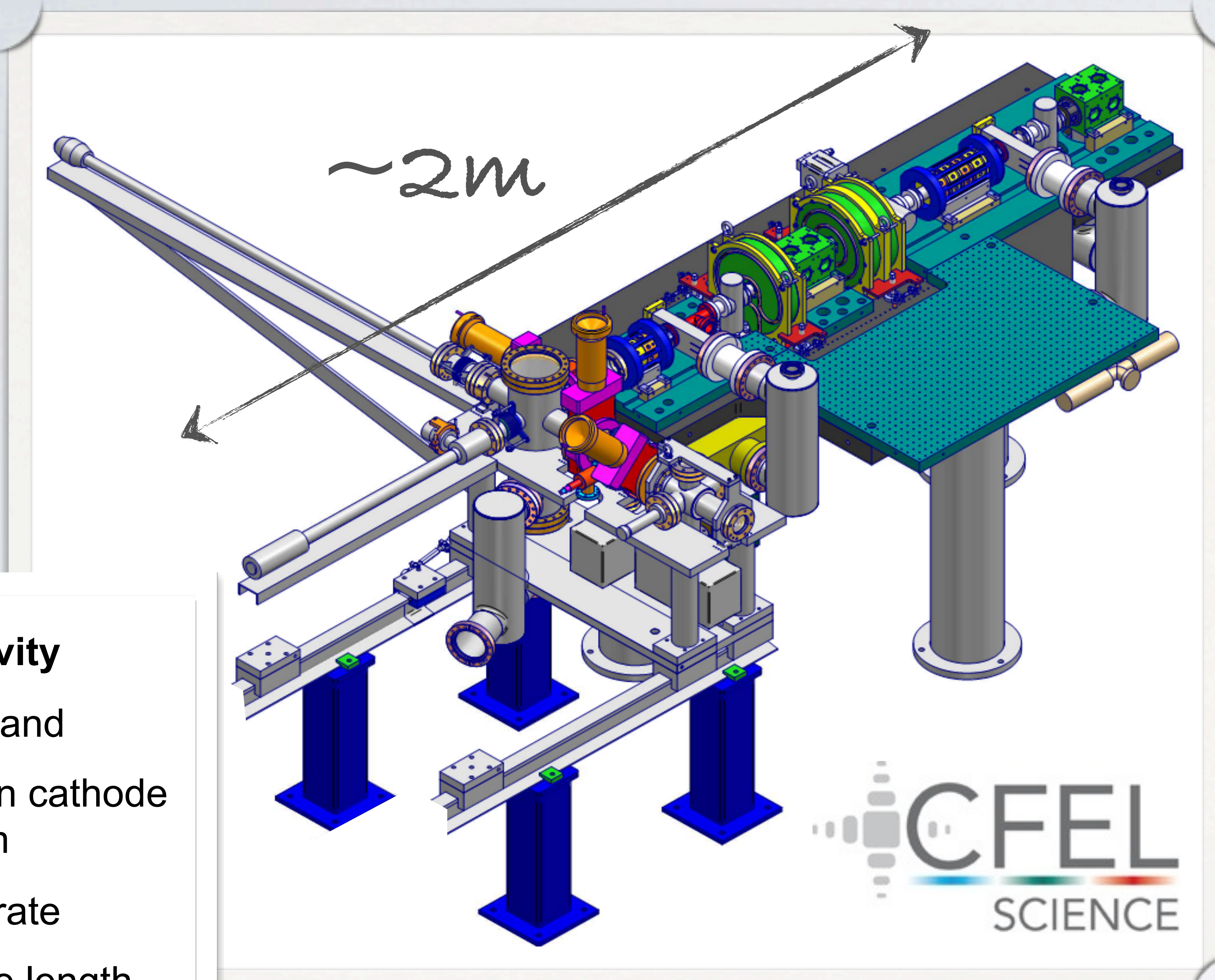






Studies are ongoing

Optimization of REGAE beam dynamics is ongoing



Relativistic Electron Gun for Atomic Exploration (REGAE)

Parameters for previous beam dynamic simulation

- transversely uniform distribution, longitudinally uniform
- Charge: 80 fC ($5 \cdot 10^5$ electrons)

$$\sigma_x^{cath} = 7\ \mu m$$
$$\sigma_t = 0.5\ ps$$
$$E_{kin} = 0.1\ eV$$

Rf-gun cavity

3 GHz S-Band

Gradient on cathode ≥ 110MV/m

50 Hz rep rate

~5 µs pulse length

Buncher cavity

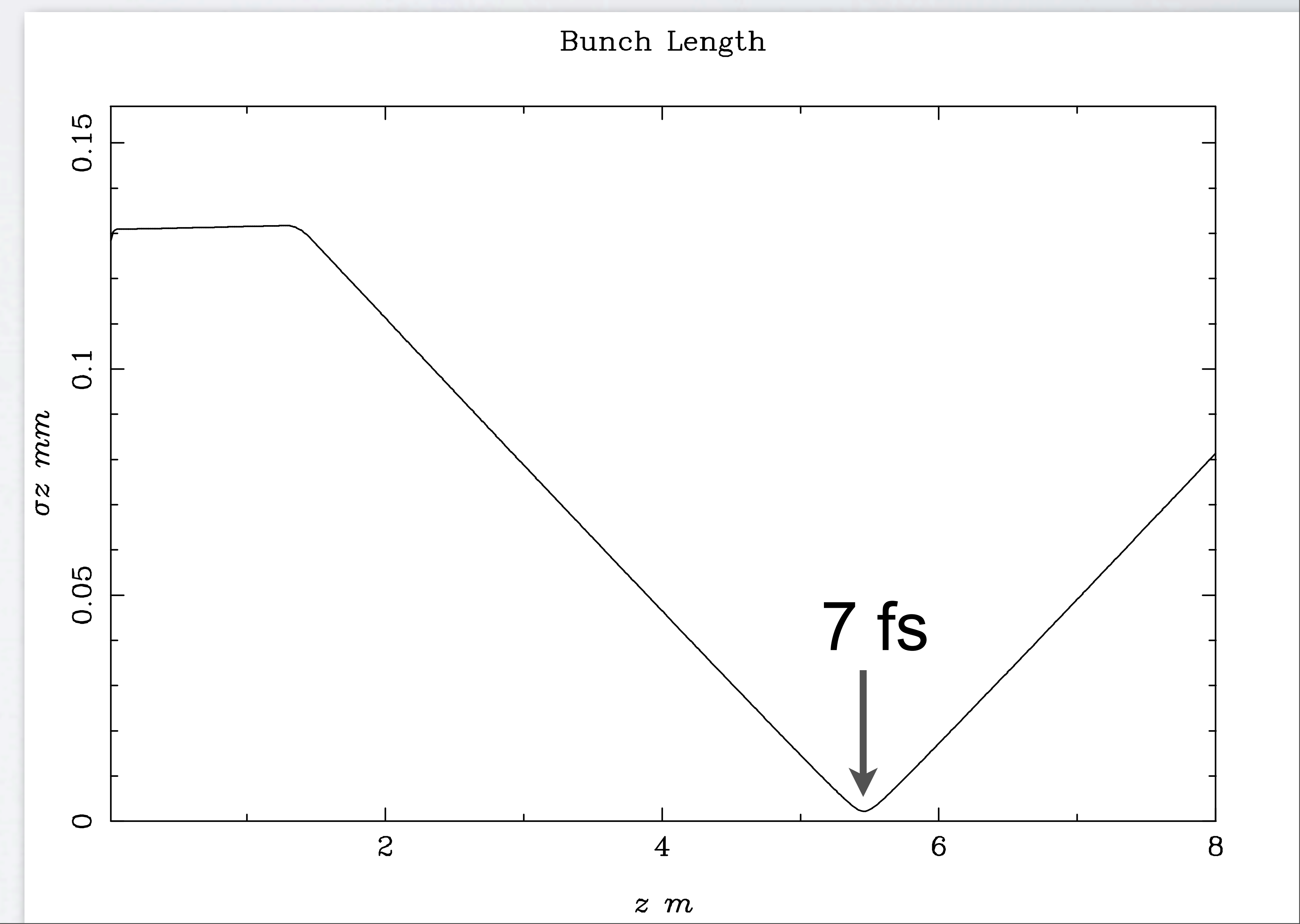
3 GHz S-Band

3-cell

average Gradient ~15-20 MV/m

Synchronized to a

- kHz Ti:sapph laser system
- tunable IR laser system



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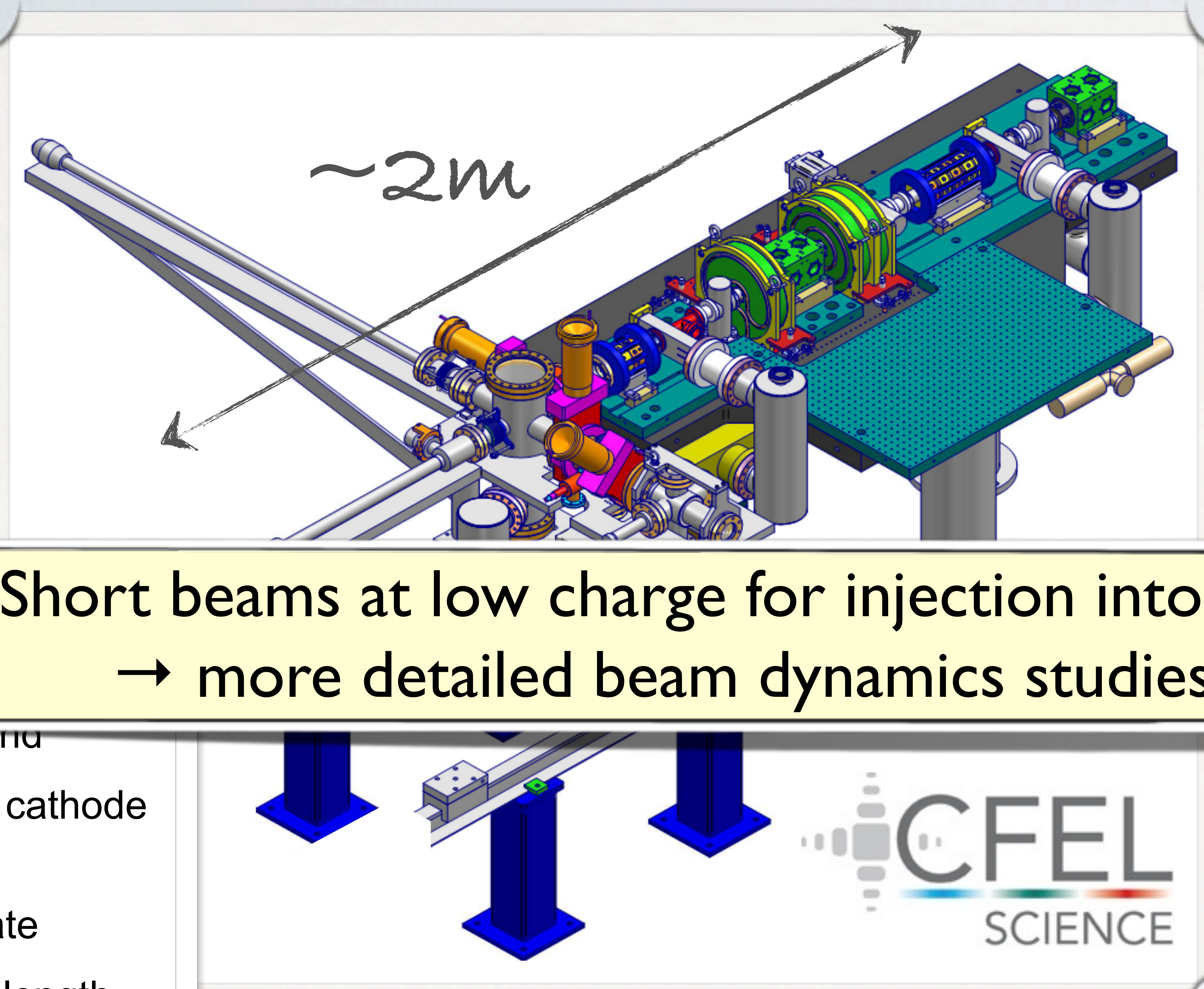

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$\sigma_t = 0.5\ ps$

l eV

Short beams at low charge for injection into a laser plasma booster seem feasible
→ more detailed beam dynamics studies of PITZ and REGAE are needed

Rf-gun ca

3 GHz S-Band

Gradient on cathode ≥ 110MV/m

50 Hz rep rate

~5 μs pulse length

Buncher cavity

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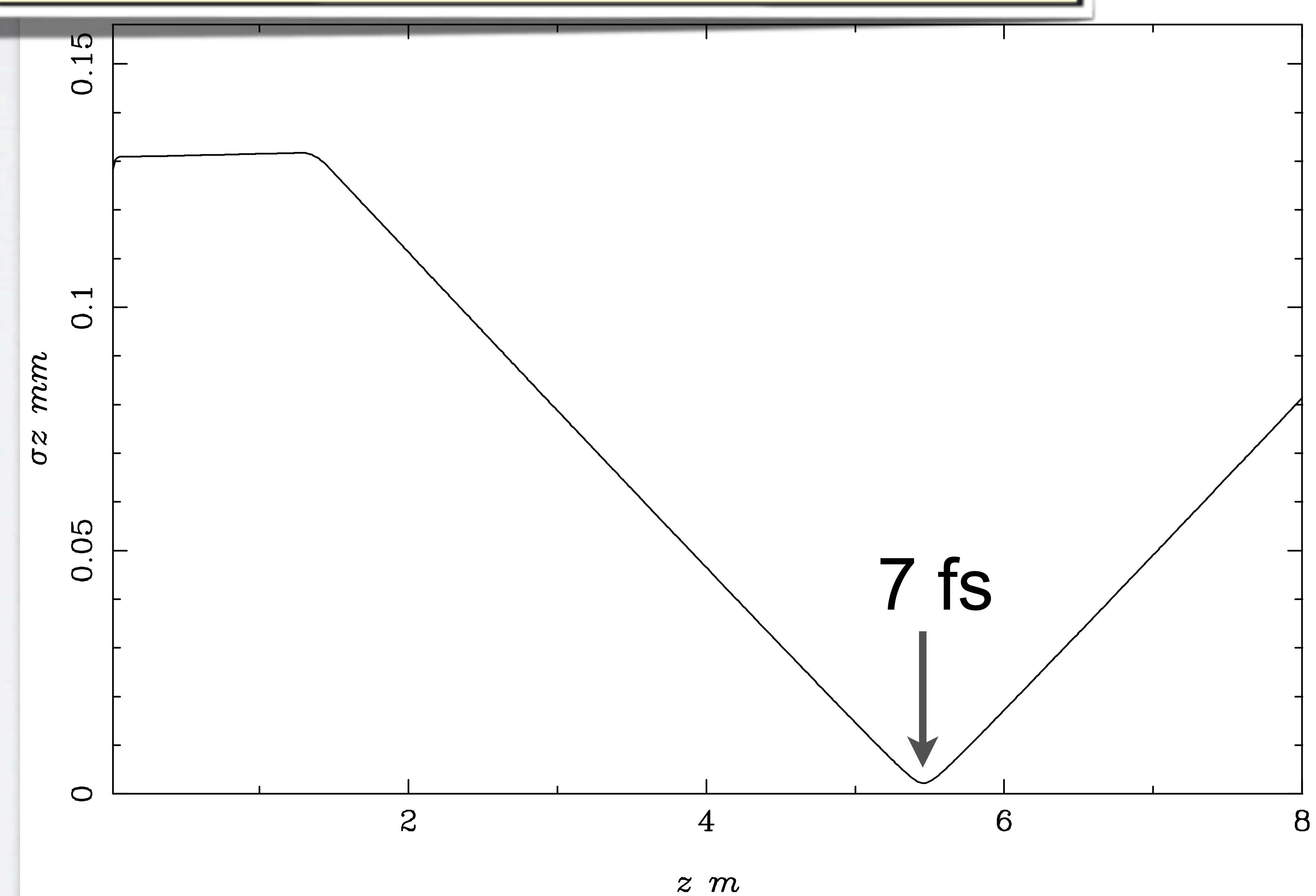


First PIC simulations show promising results

Laser pulse properties

$a_0 = 1.7$

$\lambda = 800$ nm

$\tau = 30$ fs FWHM

w = 60 µm FWHM

Plasma background density

$n = 1\times10^{17}$ cm^{-3}

Electron beam properties

$\tau = 10$ fs RMS

$\sigma_{trans} = 10$ µm

Q = 1 pC

E = 5 MeV

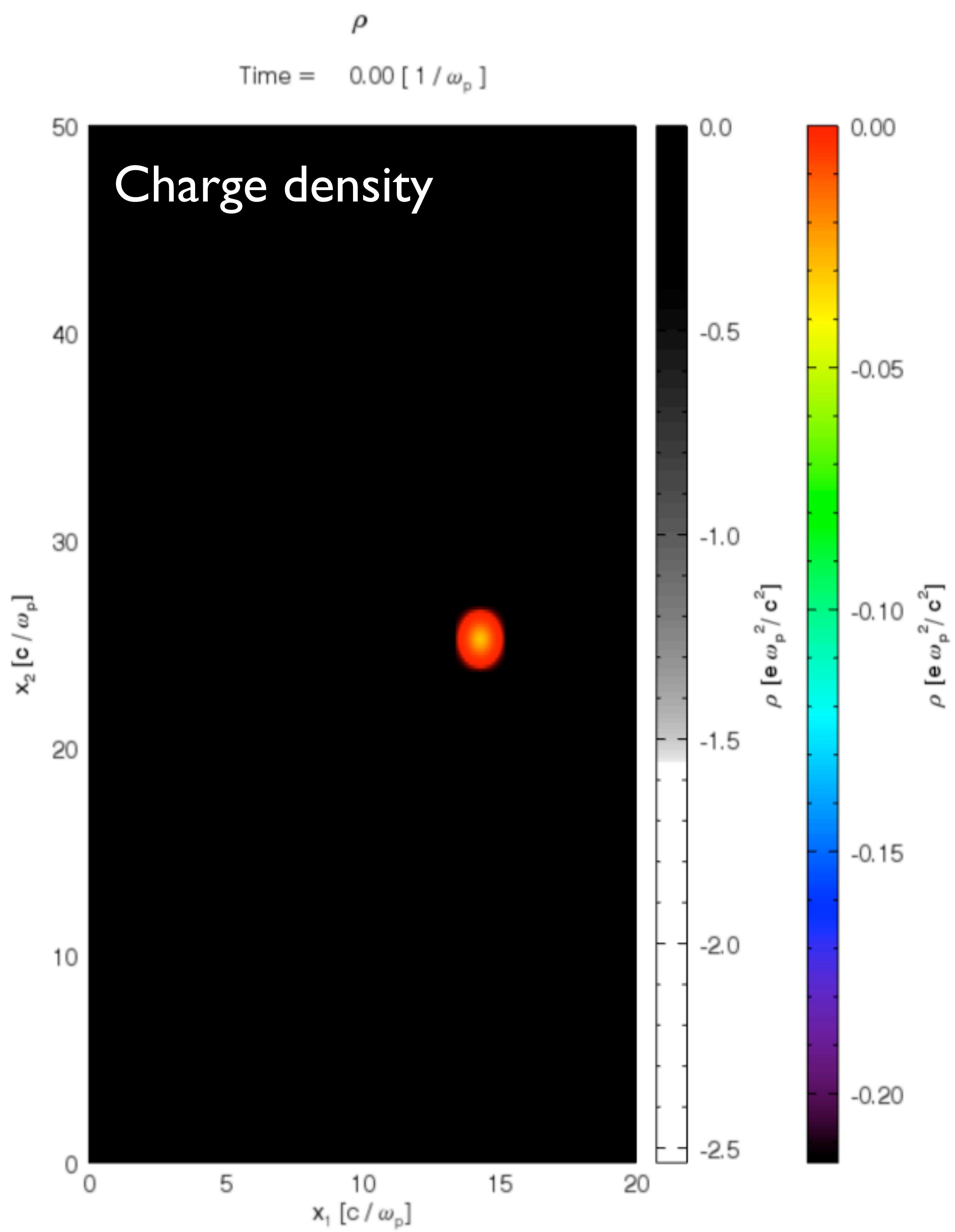
$\Delta E = 33$ keV

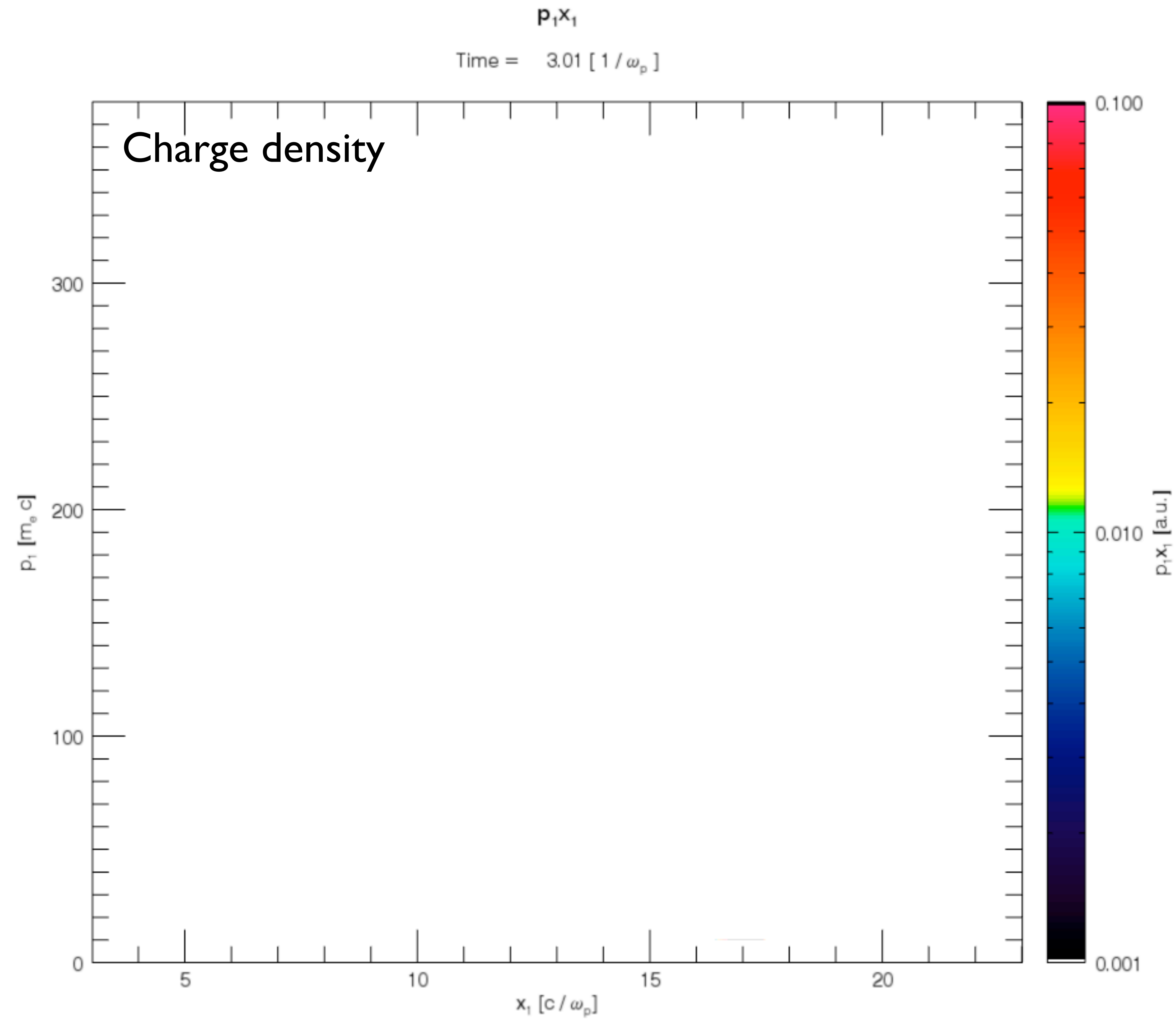
…first 24 mm in 2d space

First PIC simulations show promising results

Charge density

First PIC simulations show promising results





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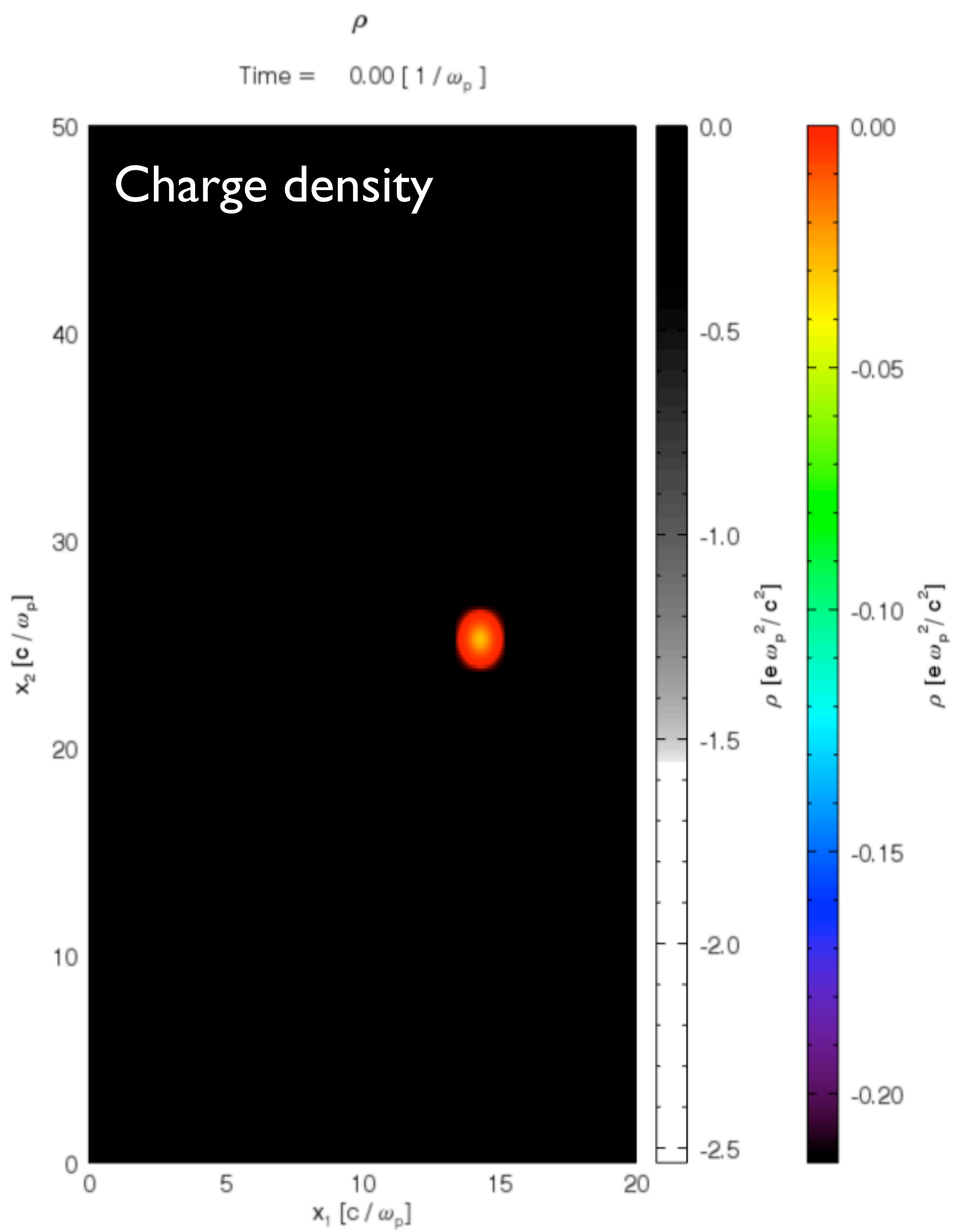
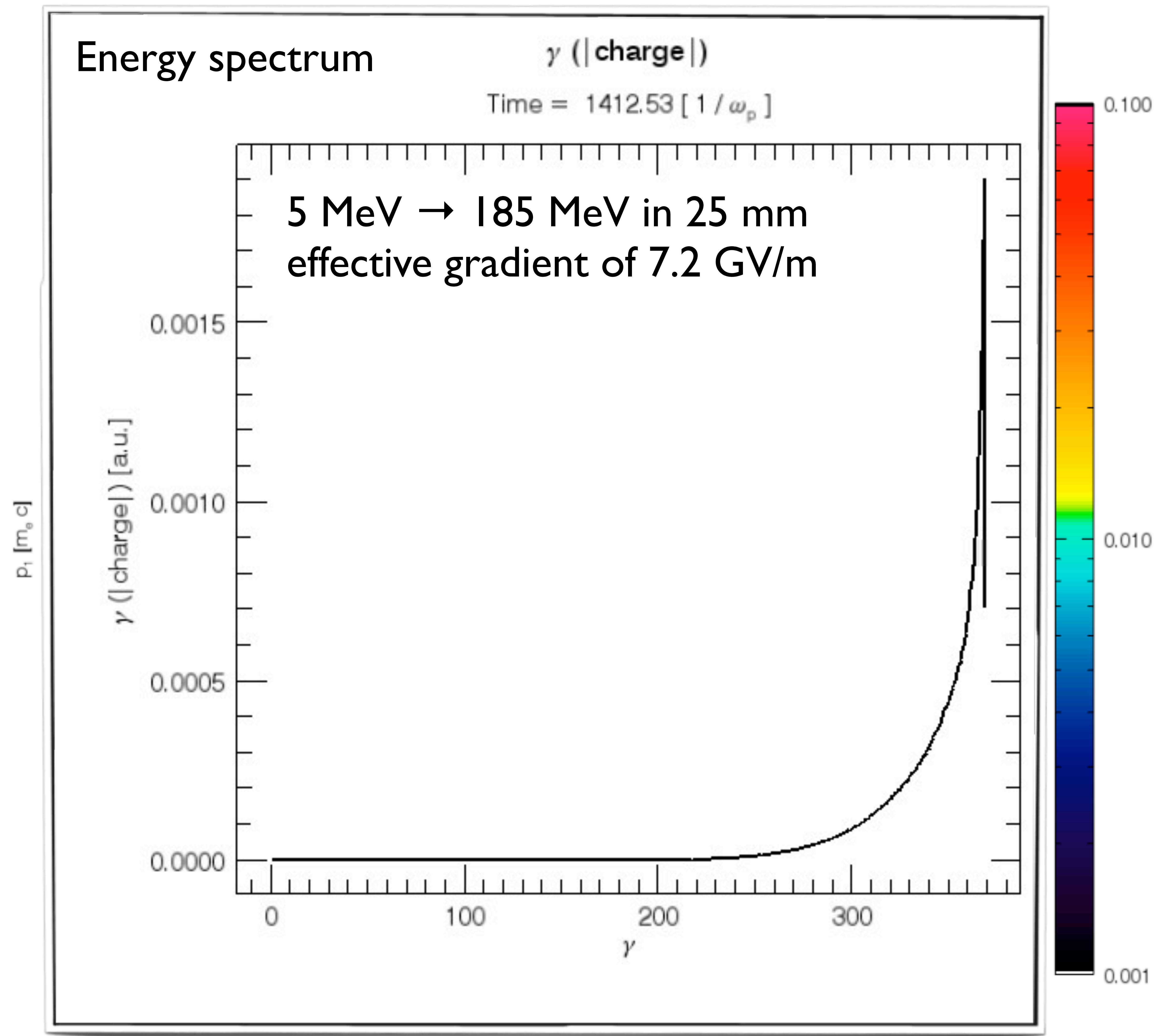
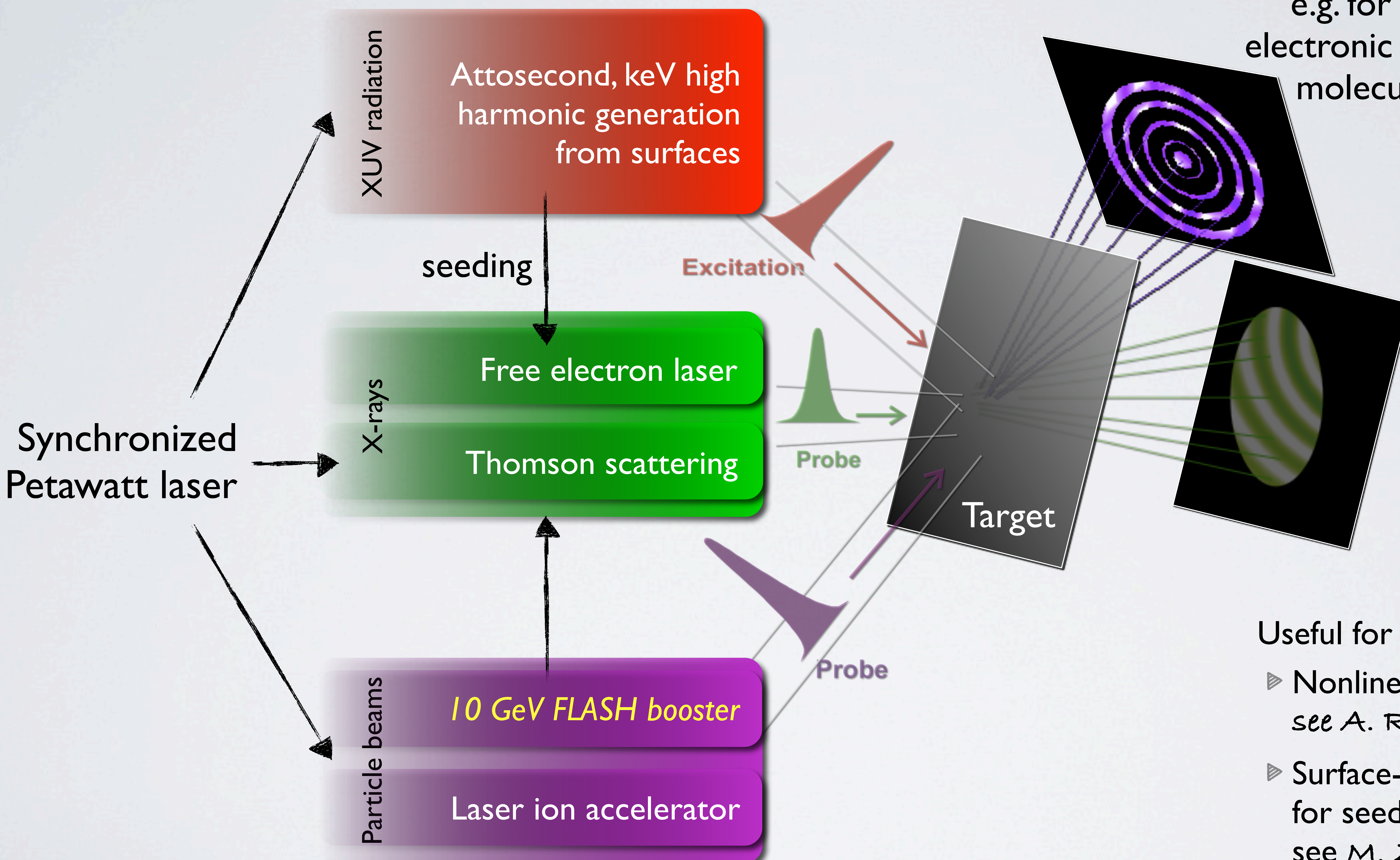




A Petawatt laser opens up new possibilities at FLASH

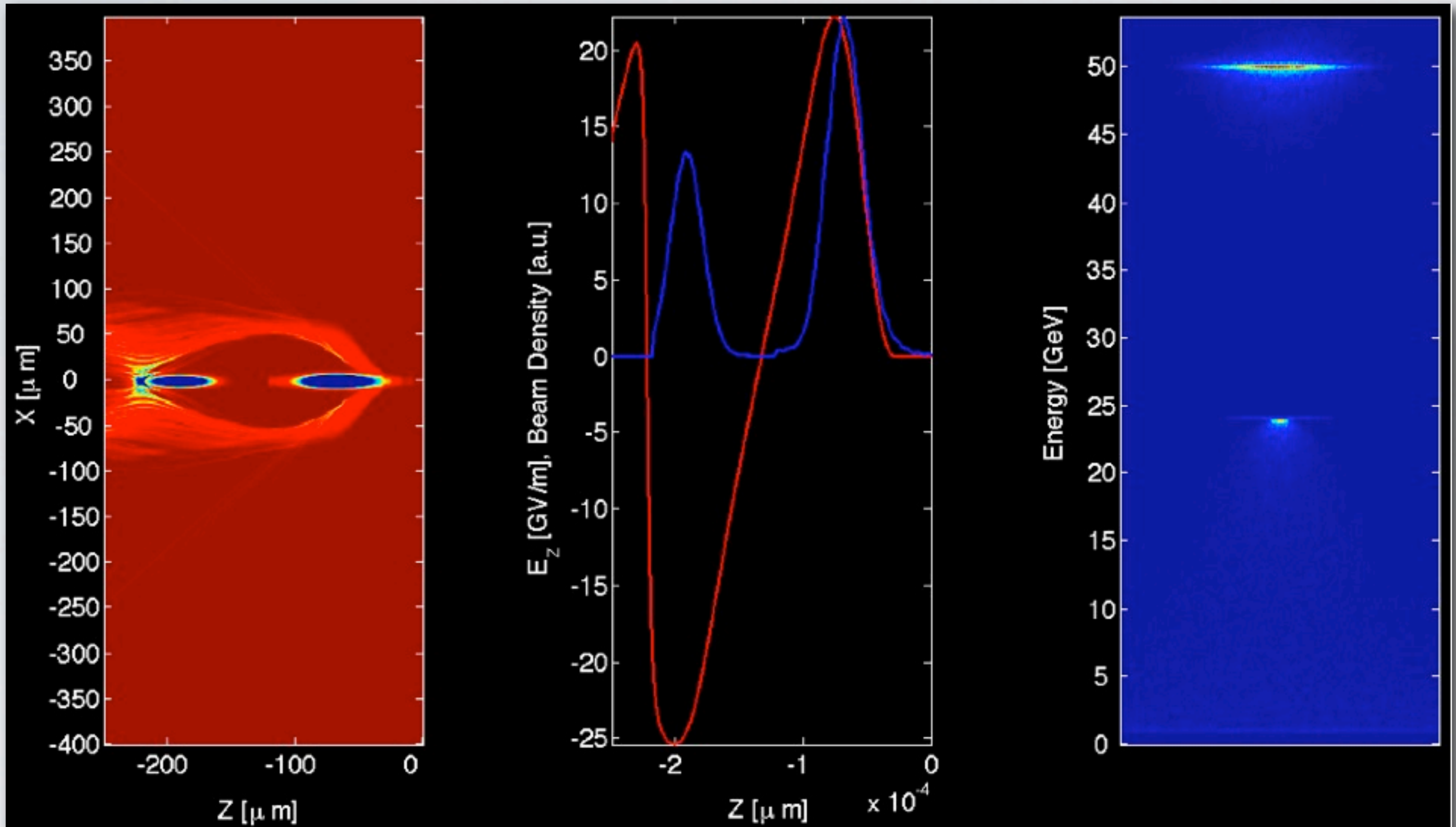
e.g. for 4D imaging of electronic motion in atoms, molecules and solids



Useful for other projects:

- Nonlinear QED
  see A. Ringwald's talk
- Surface-HHG generation for seeding of FELs
  see M. Zepf's talk

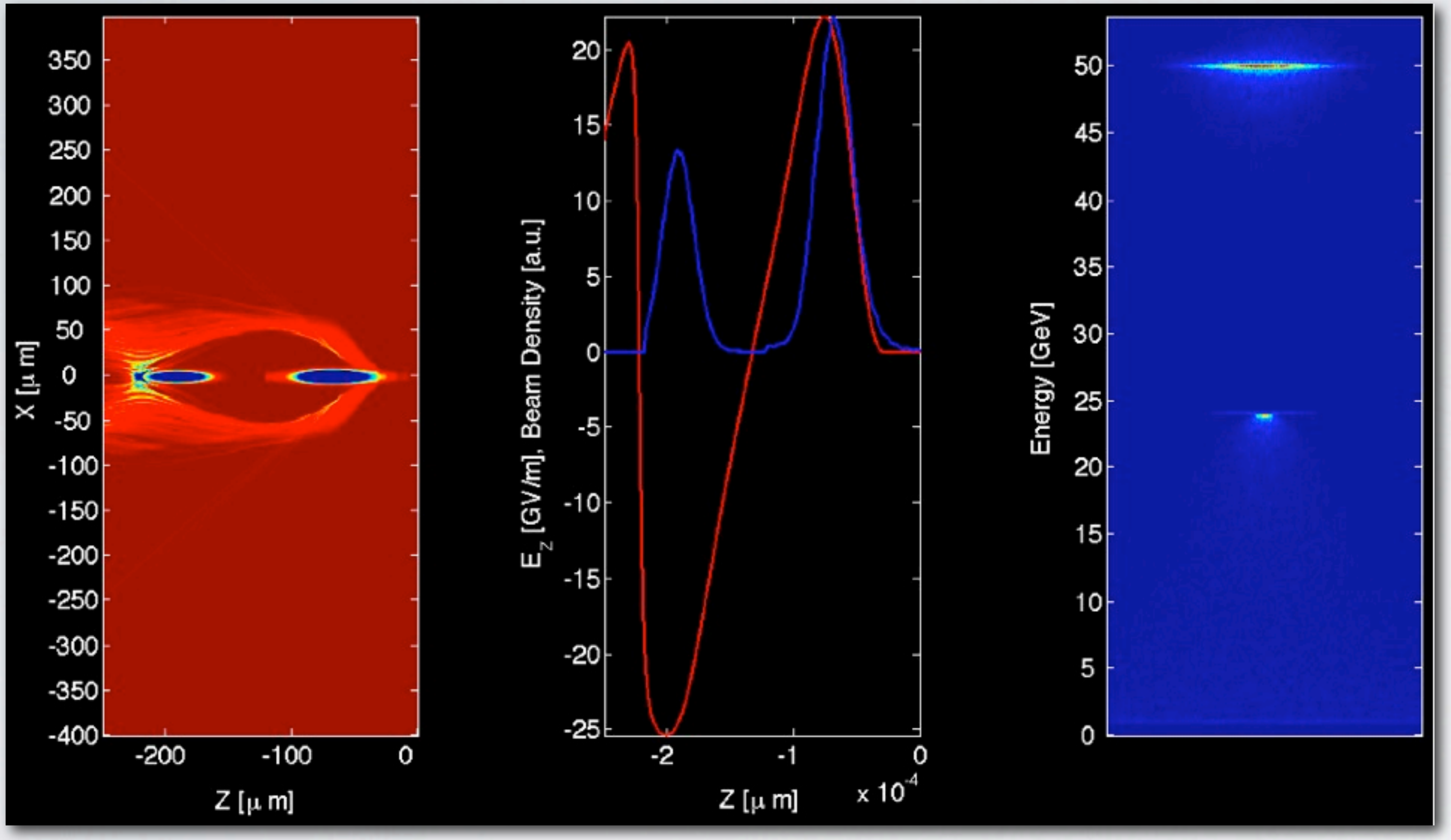
The FLASH beam as a *driver* for plasma acceleration?



simulations by the FACET team at SLAC

→ use short, stiff, high average power electron beams to excite plasma wake, second beam to witness energy gain

The FLASH beam as a *driver* for plasma acceleration?



simulations by the FACET team at SLAC

→ use short, stiff, high average power electron beams to excite plasma wake, second beam to witness energy gain

Why investigate beam-driven plasma acceleration?

High-energy physics applications will not be realized with lasers in the foreseeable future…

Proposal: FLASH beam as a *driver* for plasma acceleration

FLASH facility ideally suited for beam-driven plasma acceleration

A FLASH plasma accelerator project would
- advance plasma accelerator science
- rely on and hence advance
  - short-pulse beam operation
  - short-pulse beam diagnostics
  - temporal pulse-shaping capabilities (also interesting for FEL operation)

FACET at SLAC in operation until 2016/17, when LCLS II is finished → Timeframe when FLASH plasma accelerator could come online 2014/15

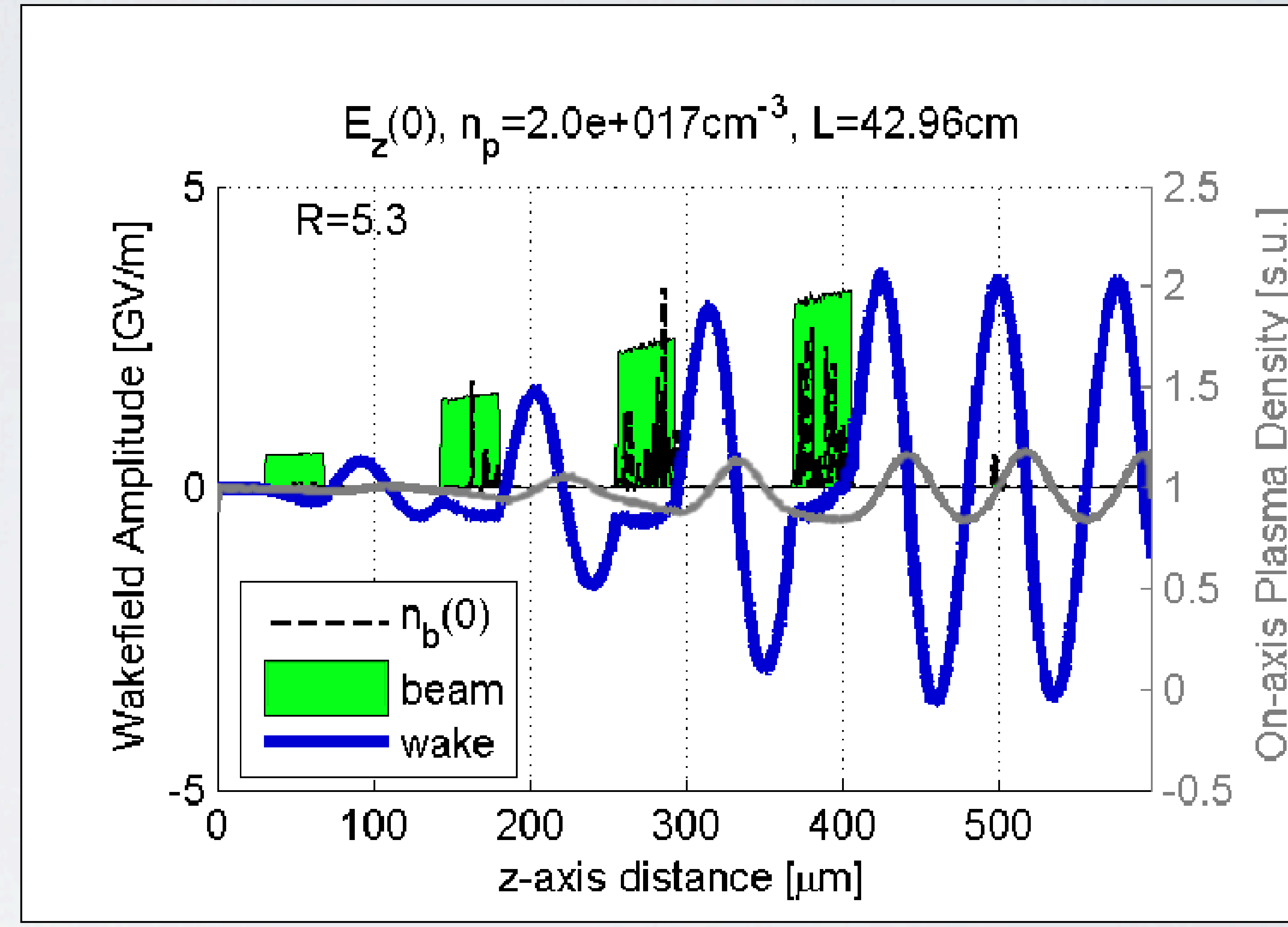
Investigate electron pulse shaping techniques for BPA

Simulations of a High-Transformer-Ratio Plasma Wakefield Accelerator Using Multiple Electron Bunches

Efthymios Kallos[a], Patric Muggli[a], Thomas Katsouleas[a], Vitaly Yakimenko[b] and Jangho Park[b]

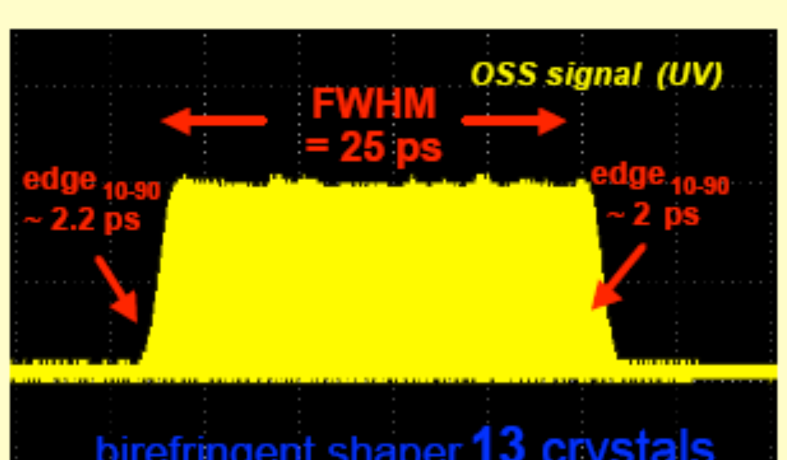
[a]*University of Southern California, Los Angeles, CA 90089*
[b]*Brookhaven National Lab, Upton, NY 11973*

Multi-electron bunch generation by tailoring gun-laser profile in time and appropriate beam compression in a chicane

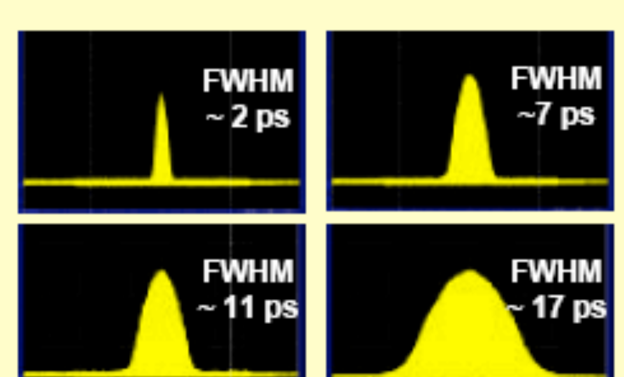


Further development of the Yb:YAG laser

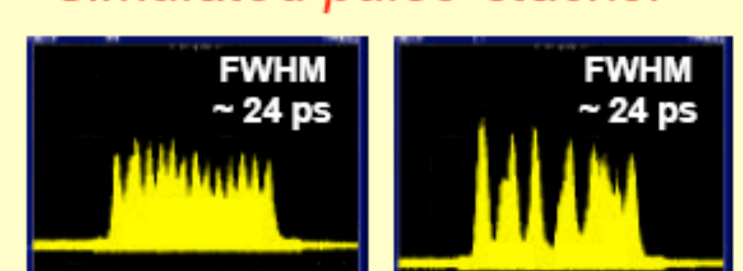
+ Yb:YAG laser has large flexibility in pulse shape



Gaussian:



Simulated pulse-stacker



Joint PITZ@DESY and MBI gun-laser pulse-shaping project into this direction

I. Will *et al.*, Opt. Exp. 16, 14922 (2008) and Nucl. Instrum. Meth. Phys. Res. A 594, 119 (2008)

Summary

DESY efforts have just started to pursue and advance plasma acceleration science towards:

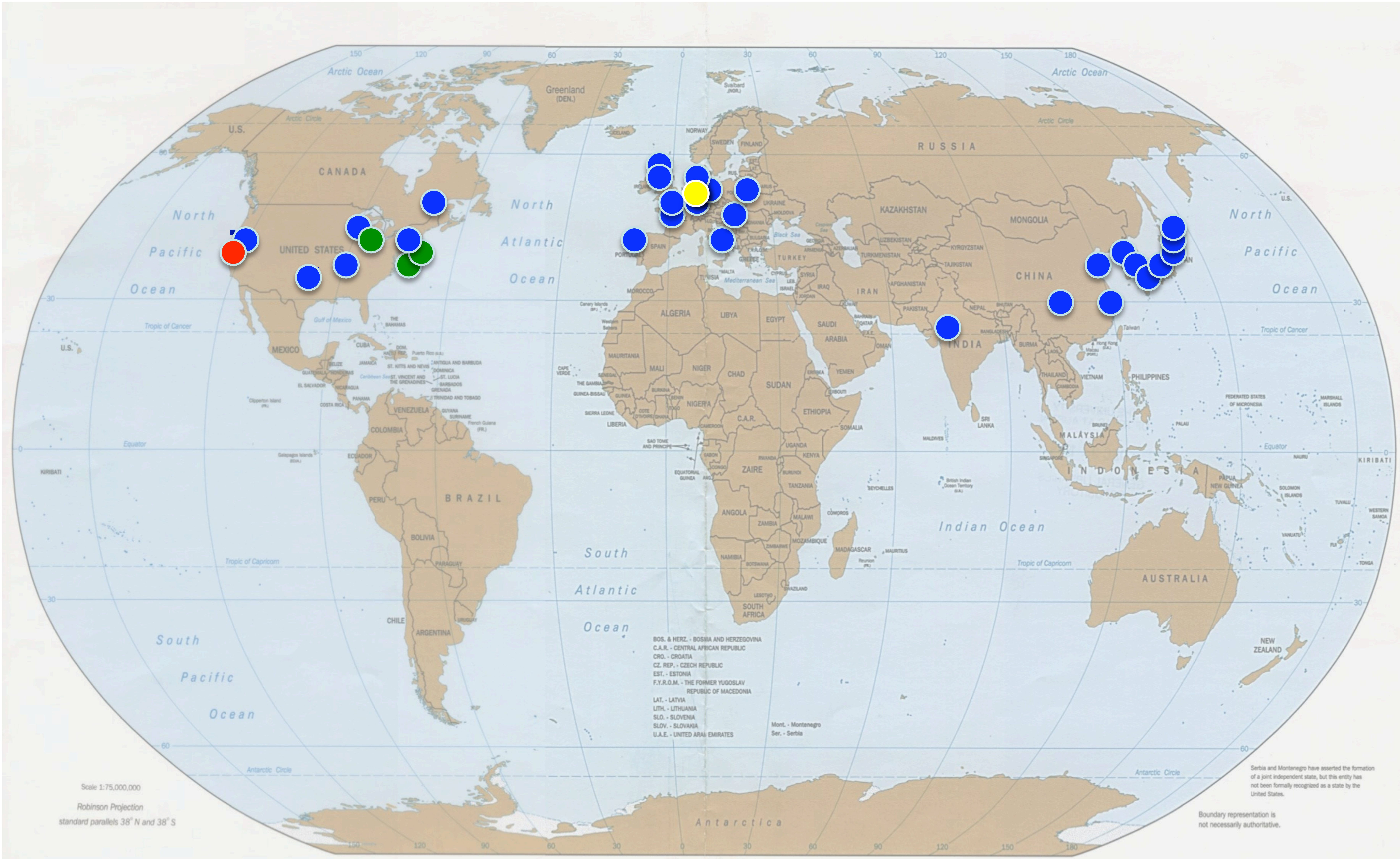
- Laser-plasma boosting of conventional, high-quality electron beams
- Standalone laser-plasma acceleration *(not presented here)*
- Electron-beam driven plasma acceleration

DESY is one of few places worldwide with simultaneous know how in RF-gun and short-pulse accelerator design, short-pulse beam diagnostics, laser to beam synchronization, and photon science

→ great possibilities for and synergies with plasma acceleration

Plasma accelerators: A Global Community

original slide by C. Joshi



Laser & beam-driven Wake Expts + RF-accelerator science

Laser Wake Expts

Electron Wake Expts

e-/e+ hi γ Wake Expts

European Network on Novel Accelerators (EuroNNAc)

- Initiative by EuCARD, CERN, DESY, École Polytechnique
- Coordinators: R. Assmann, J. Osterhoff, H. Videau
- Scope: "Plasma wakefield acceleration and direct laser acceleration of electrons and positrons"
  (which includes laser, electron, proton drivers)
- Presently forming organization committee
- Network is open to all interested parties in Europe!
- Network invites main actors in Asia/US for discussions and decisions!
- EuroNNAc should bring together:
  Big science labs and smaller R&D labs (difference in priorities and possibilities)
  Different driver technologies
- Goals: build network and prepare significant FP8 proposal for big novel accelerator(s) in 2013

EuroNNAc Workshop will be held May 2-6, 2011 at CERN

http://www.cern.ch/euronnac

More details → R. Assmann's talk yesterday

Thank you for your attention!