FACET-II

Facility for Advanced Accelerator Experimental Tests

FACET-II Science Overview

FACET-II Summer Intern Program

Doug Storey | Associate Staff Scientist | Advaced Accelerator Research Department

Summer 2025

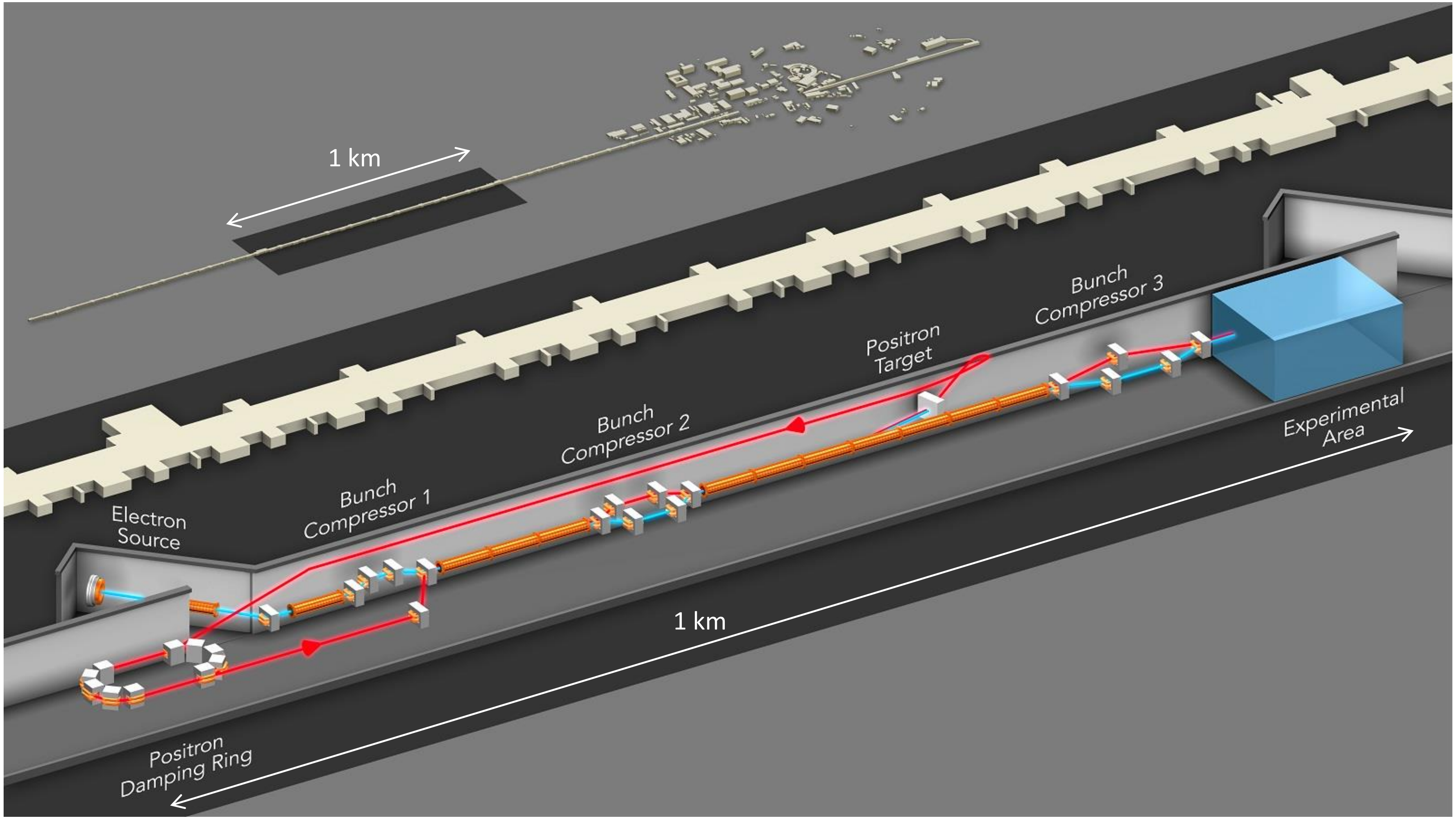
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

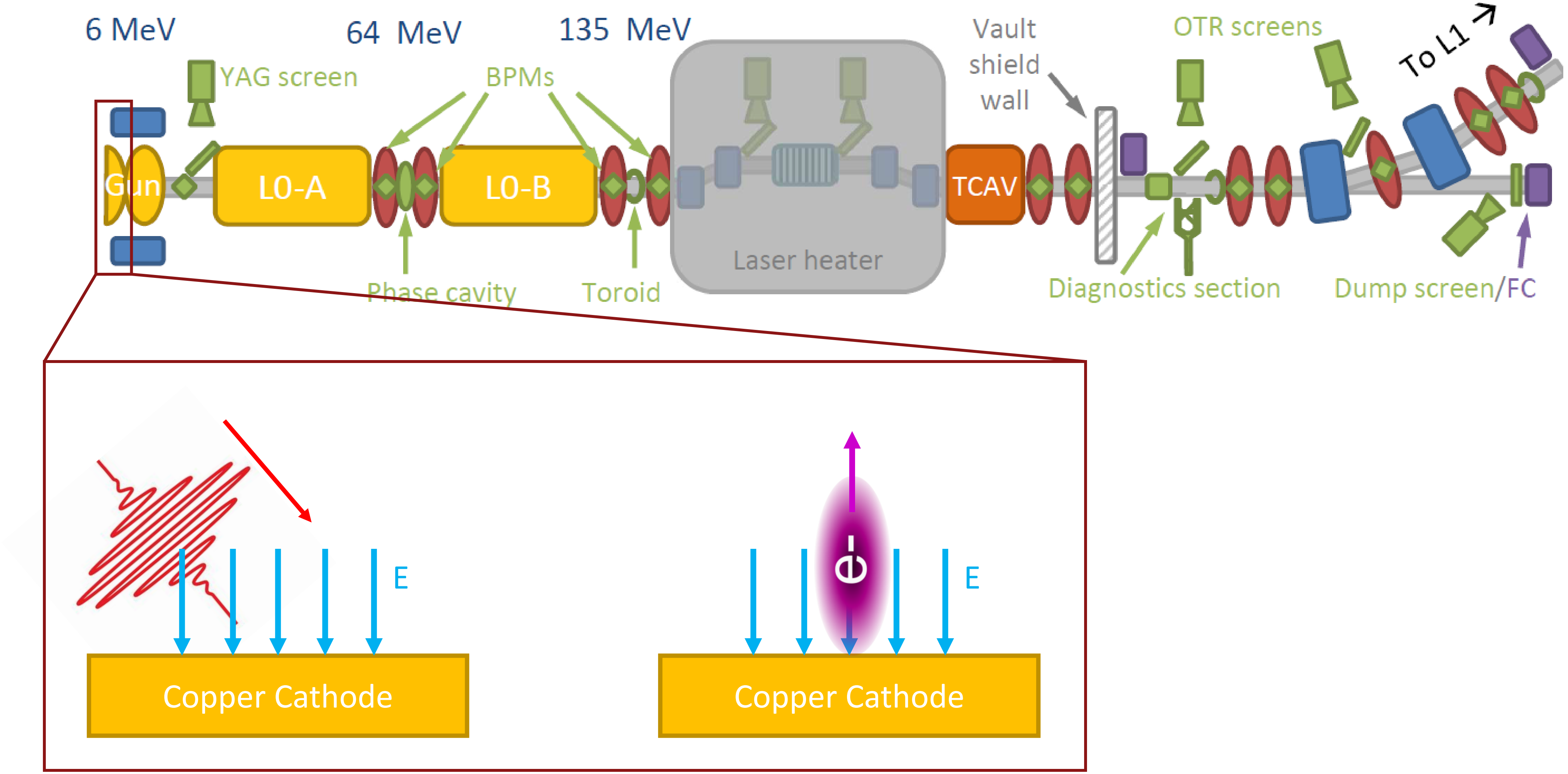
An introduction to the FACET-II accelerator

Some of us are here – B052

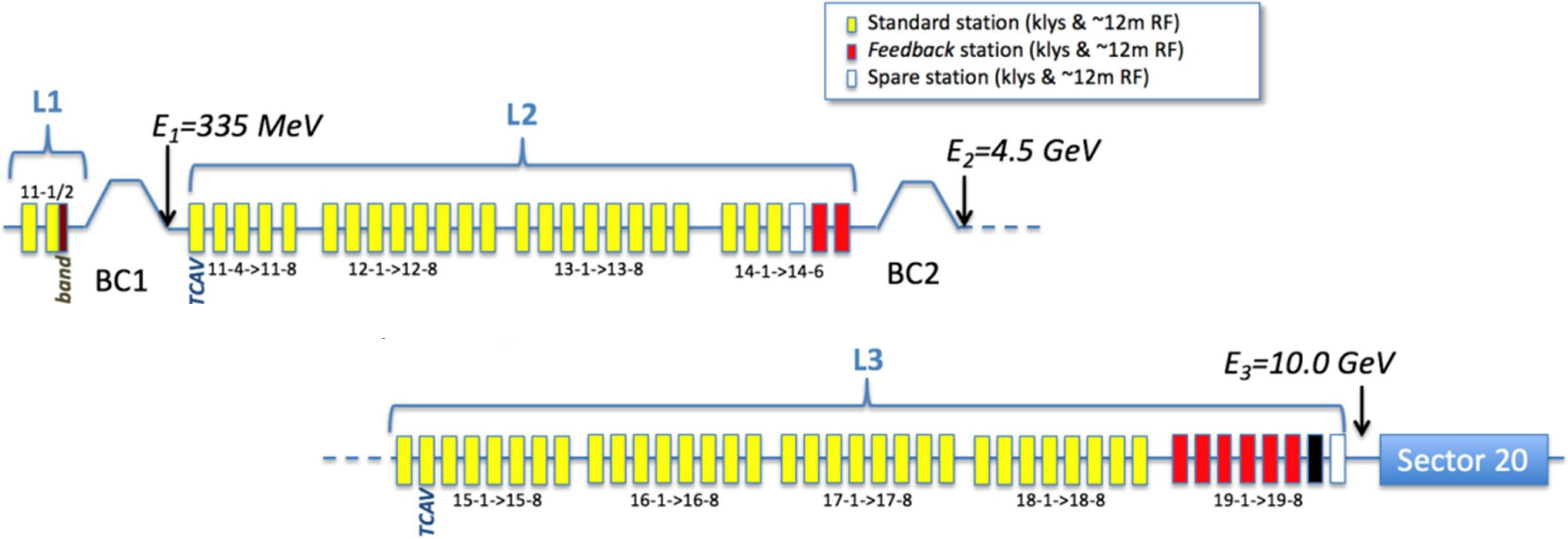
Accelerator layout



A very traditional injector…

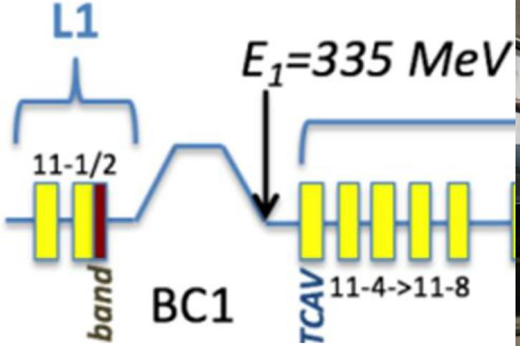


More very traditional "LINAC" and bunch compressors



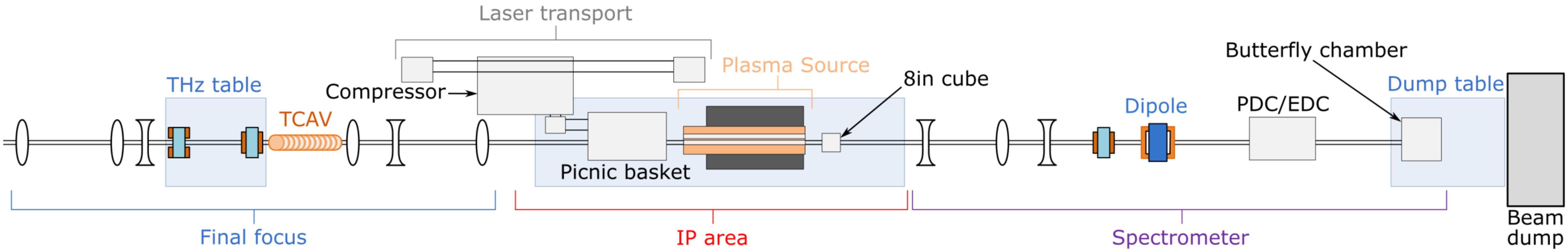
But - FACET-II is not traditional in that it produces very high peak current beams

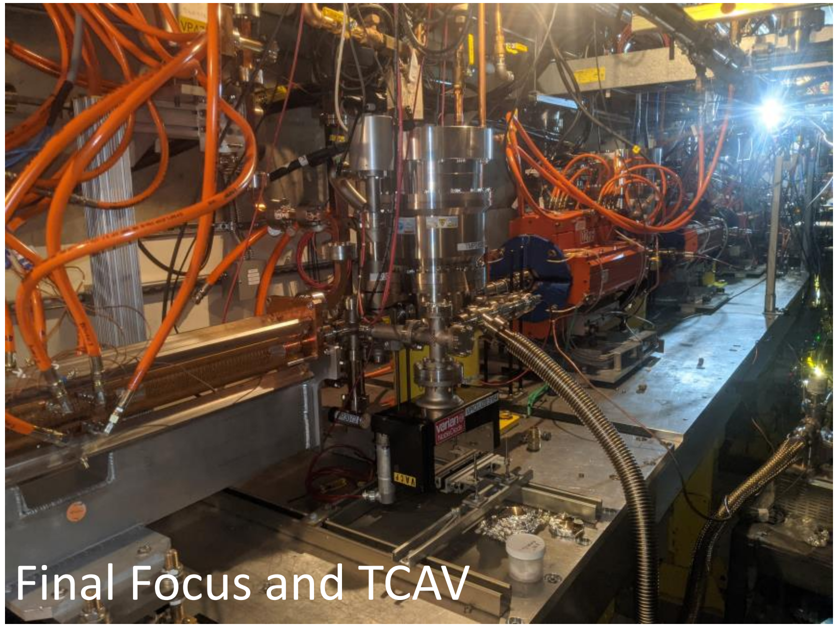
More very traditional “LINAC” and bunch compressors

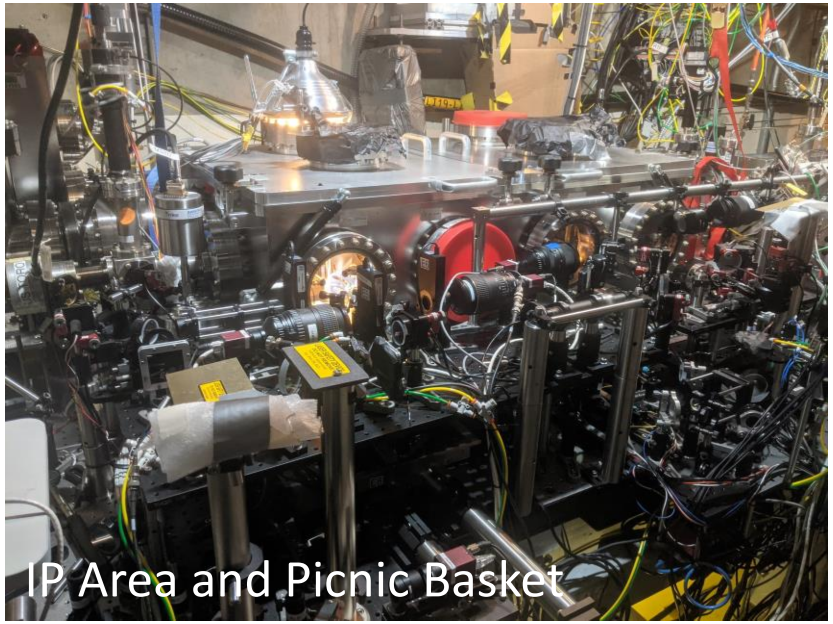


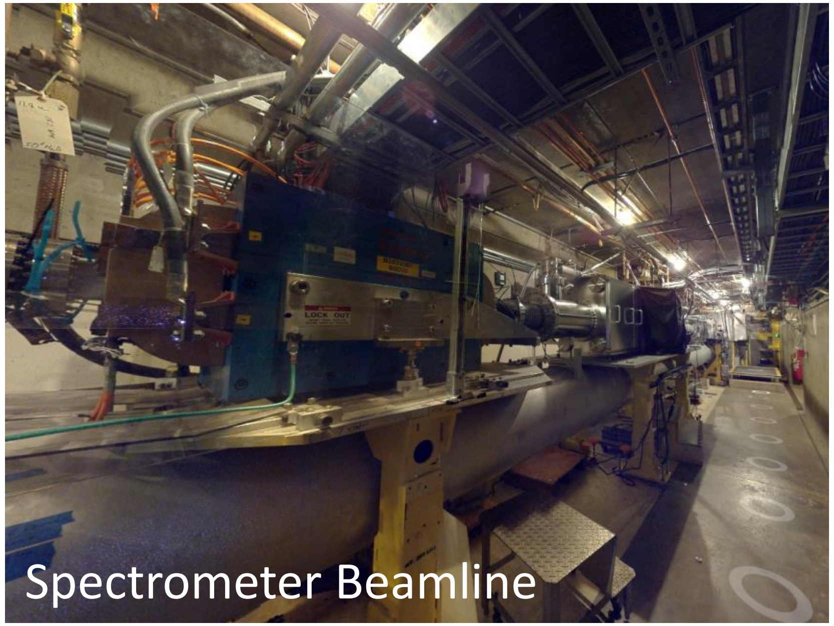
FACET-II accelerator

Overview of the experimental area




Final Focus and TCAV


IP Area and Picnic Basket


Spectrometer Beamline

FACET-II is a user facility – scientists propose experiments

- Many experiments are underway, and even more planned: https://facet-ii.slac.stanford.edu/accepted-proposals

Plasma wakefield acceleration

X-ray source application of PWFA

Strong field quantum electrodynamics

Strong field physics

Accelerator diagnostics

Proposal No.	Title
E-300 / E-301	Plasma wakefield acceleration
E-302	Transverse instabilities in PWFA
E-308	Extreme focusing with a passive thin plasma lens
E-325	Automatic tuning for PWFA optimization
E-304	Density down ramp injection in PWFA
E-31x	Plasma injection (Trojan horse, Plasma torch, Dragon tail)
E340	Wakeless regime in plasma accelerators
E-338	Attosecond XUV/X-ray sources driven by PWFA
E-320	Strong field QED
E-332	Near field CTR based focusing of beams – laser-less SFQED
E-305	Beam filamentation and bright gamma ray bursts
E-336	Beam interactions with carbon nanotube materials
E-339	PetaVolts/meter plasmonics in materials
E-315	Plasma afterglow attosecond metrology
E-324	Optical visualization of plasma wakefield acceleration
E-326	Non-intercepting beam diagnostics
E-327	Virtual diagnostics for phase space prediction
E-331	Neural network-based tuning
E-341	6D phase space reconstruction of beams

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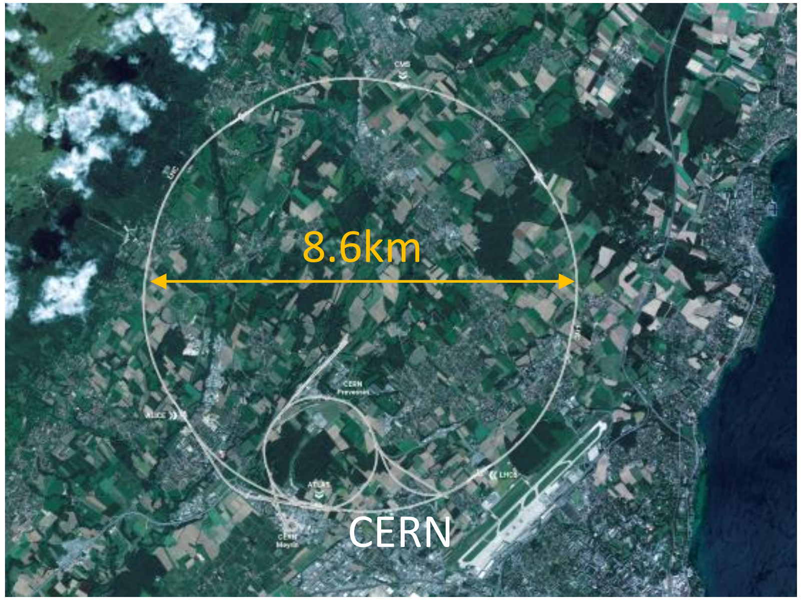
Plasma wakefield acceleration

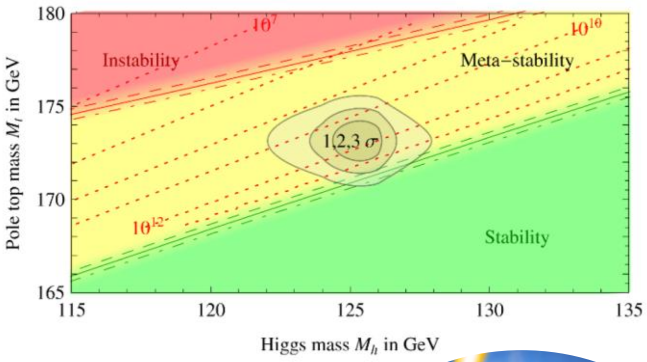
- Accelerators are useful, but large and expensive
- Make them smaller and more efficient to build more, or more powerful

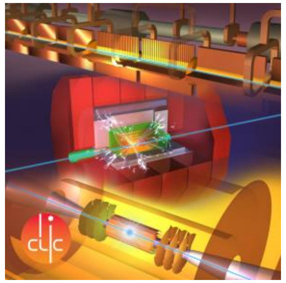
LHC: 27km accelerator
€7.5 billion



Colliders

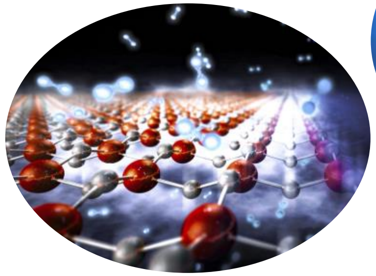
Precision Higgs and top quark studies



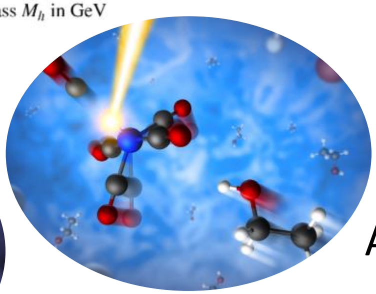


Physics beyond the standard model

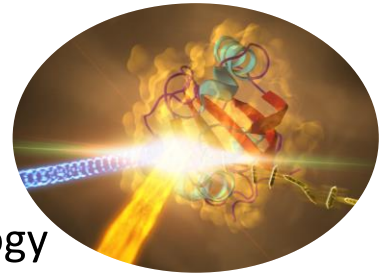
Light sources



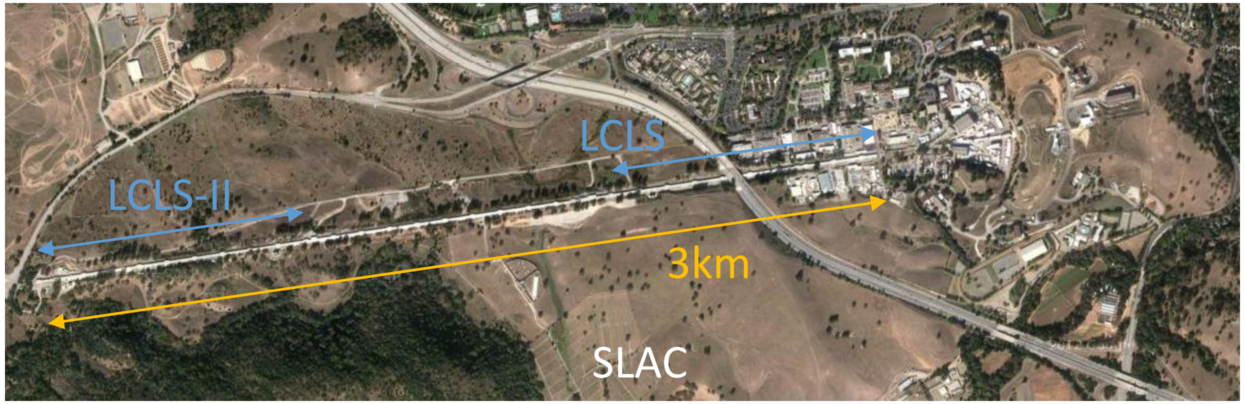
Condensed matter



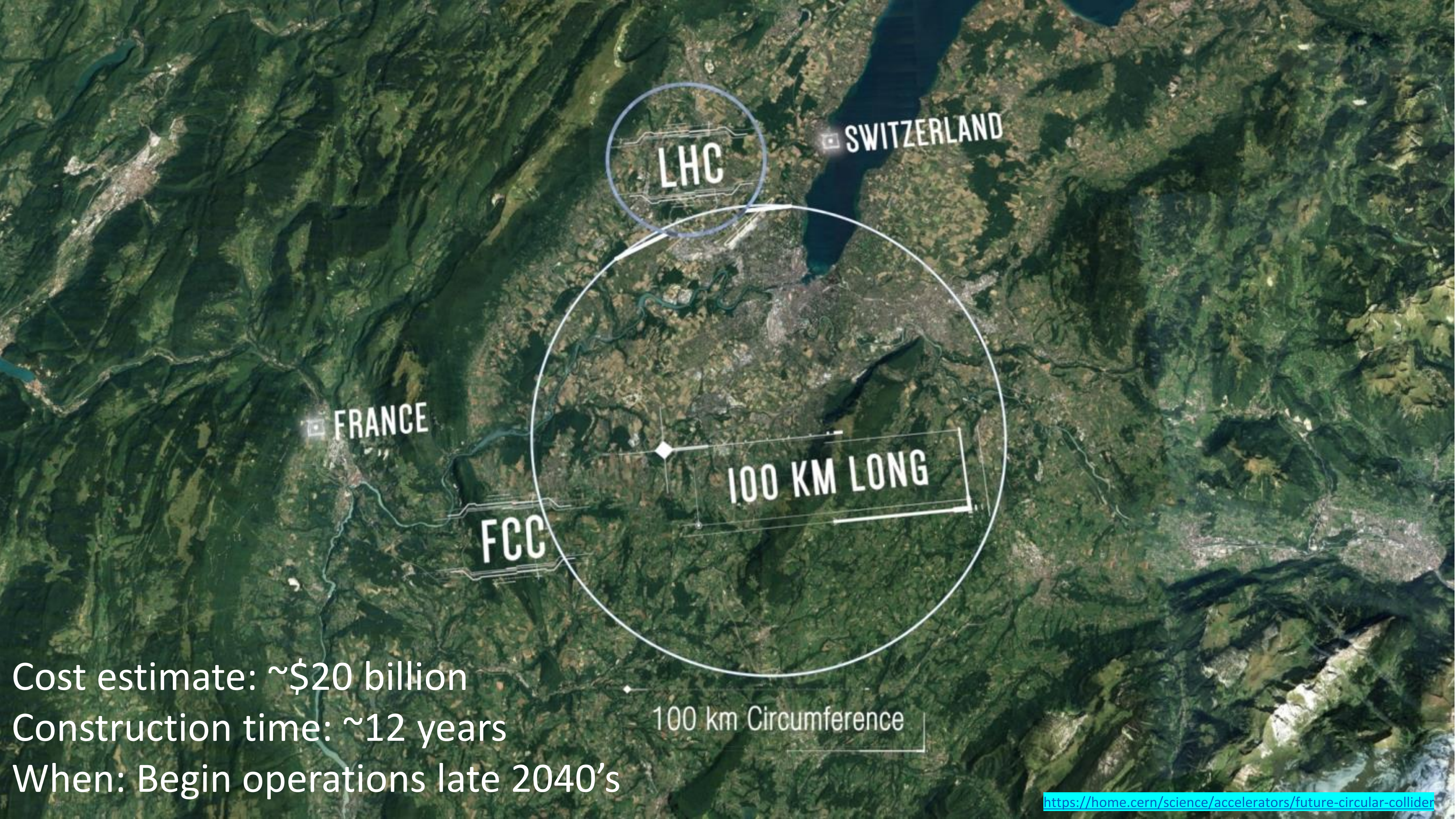
AMO



Biology



LCLS FEL: 2x 1km accelerators
$1 billion for LCLS-II

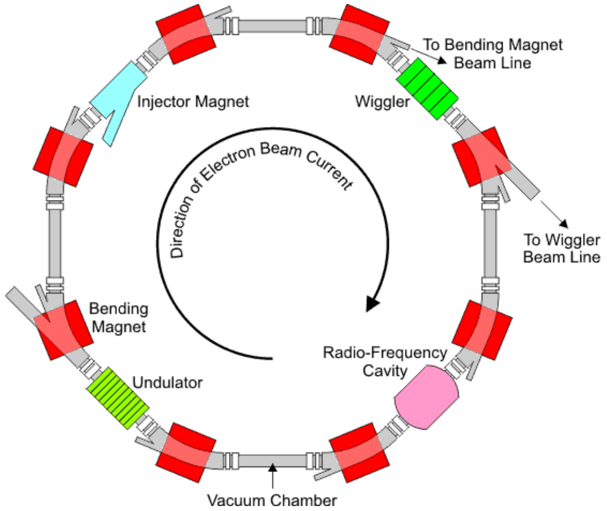


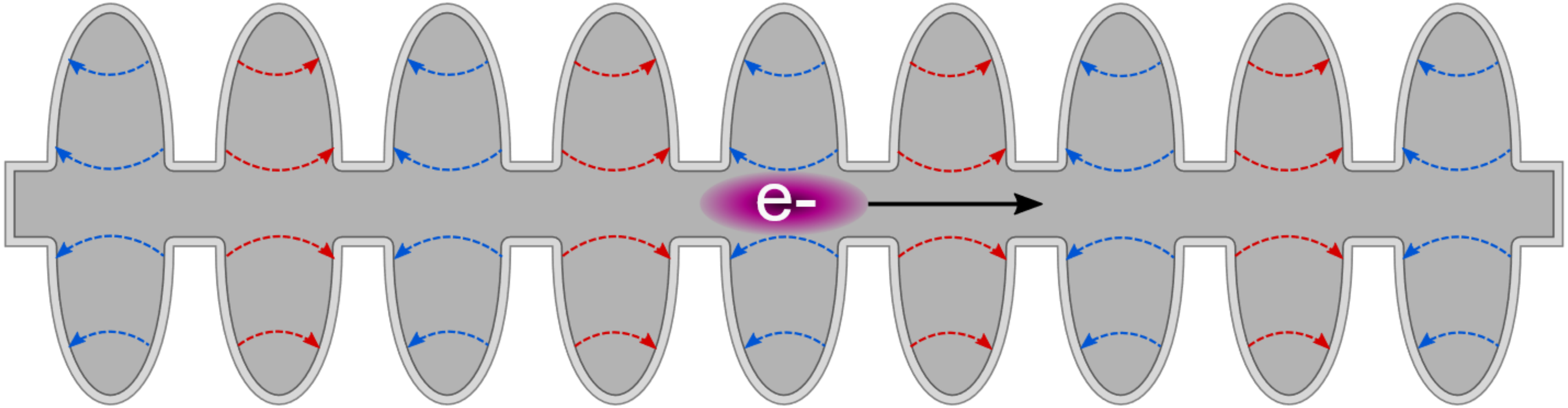
Cost estimate: ~$20 billion
Construction time: ~12 years
When: Begin operations late 2040’s

https://home.cern/science/accelerators/future-circular-collider

Why are high energy accelerators so large?

Circular proton accelerators are limited by the magnetic field of the bending magnets.



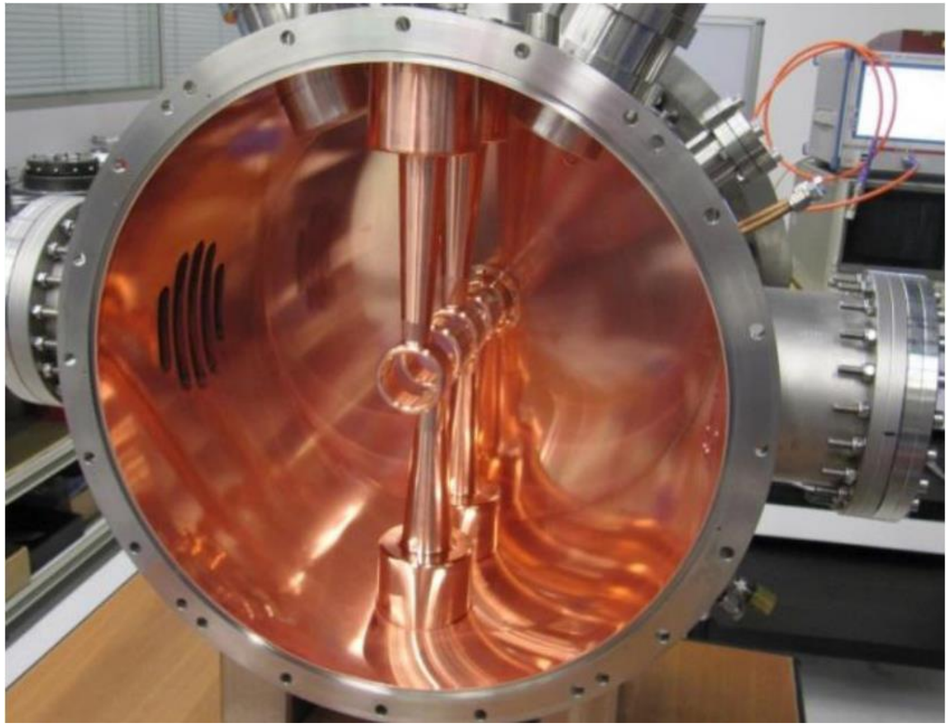


The largest field in conventional RF cavities is ~50 MV/m.
The limit is breakdown of the cavity.

SLAC linac is 22 MV/m.

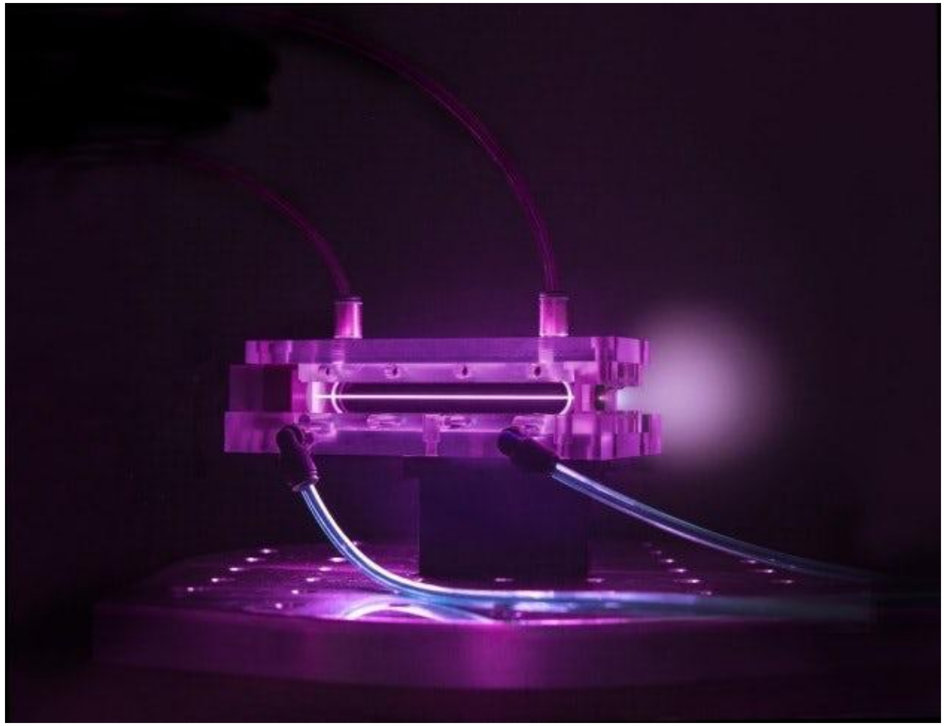
Cockcroft *et al.* (1999)

Plasma-based accelerators won’t breakdown



Metallic cavities contain and shape EM waves

Max accelerating field $\mathcal{O}(10s - 100\ \mathrm{MeV})$



Generates fields by charge separation and plasma currents

Max accelerating field $\mathcal{O}(10s - 100s\ \mathrm{GeV/m})$

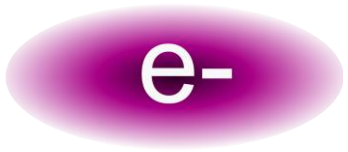
D. Gavela *et al*. IPAC Proceedings (2014) and Berkeley Lab Laser Accelerator BELLA

Plasma wakefield acceleration

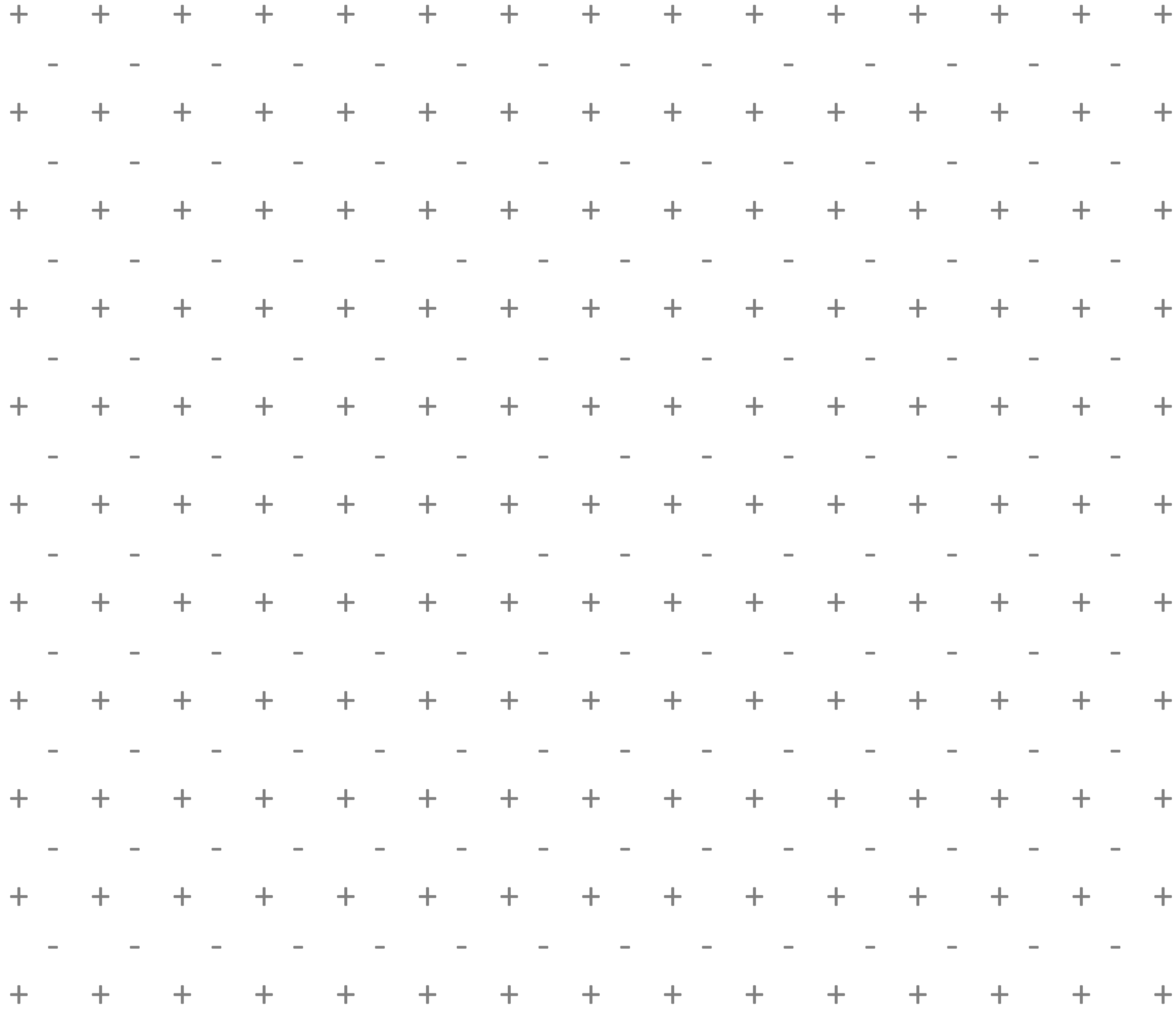
0.5nC
10GeV
5J

Witness Beam

1.5nC
10GeV
15J



Drive Beam

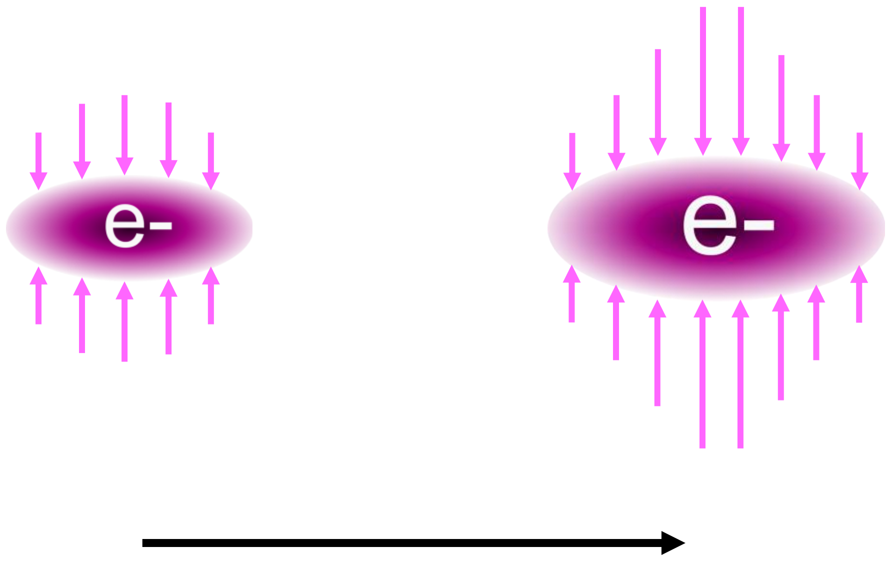


Both beams travel to the right at about c

$\gamma_b \gg 1$

Plasma wakefield acceleration

The electron beams have strong, radial electric fields



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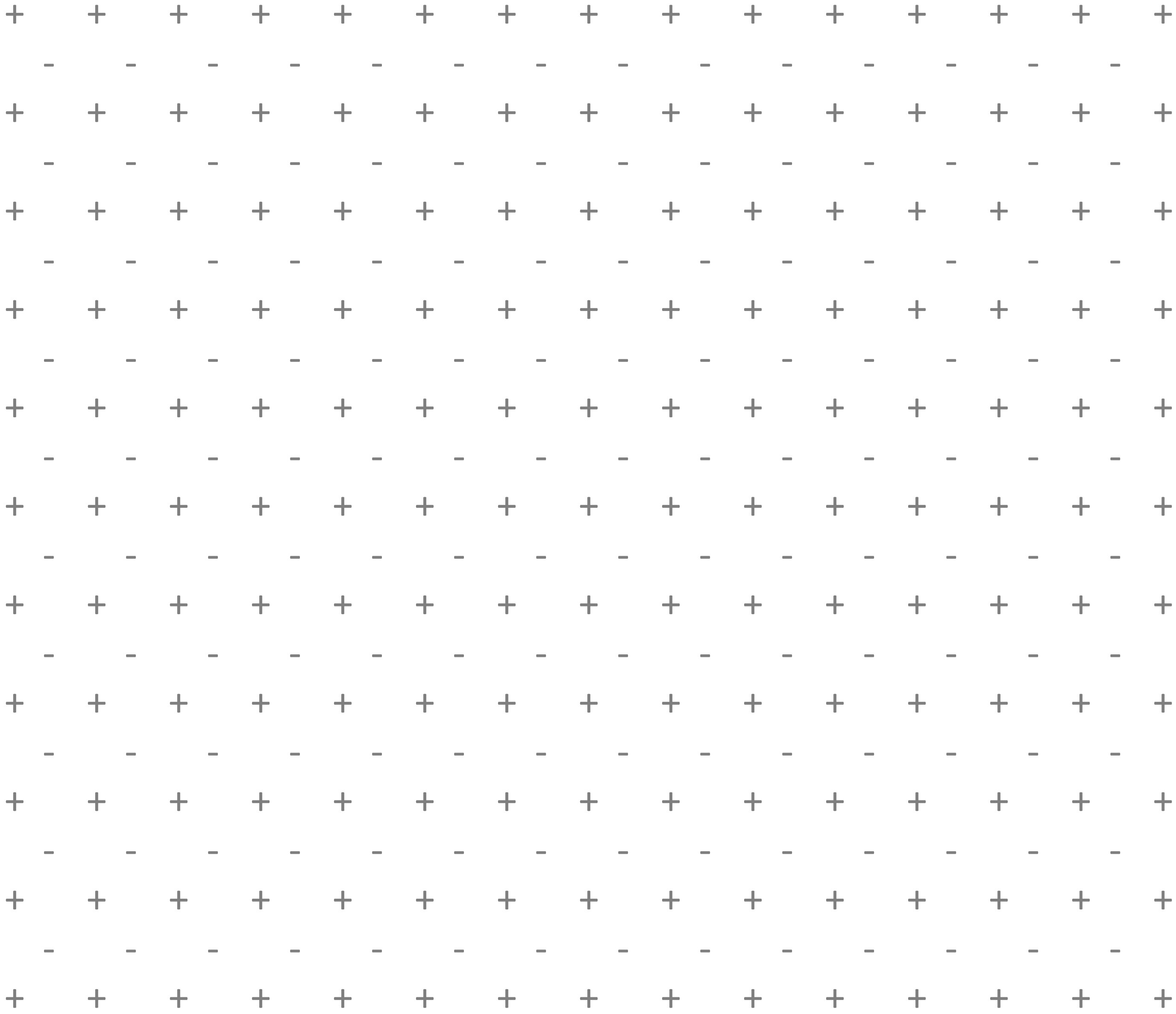
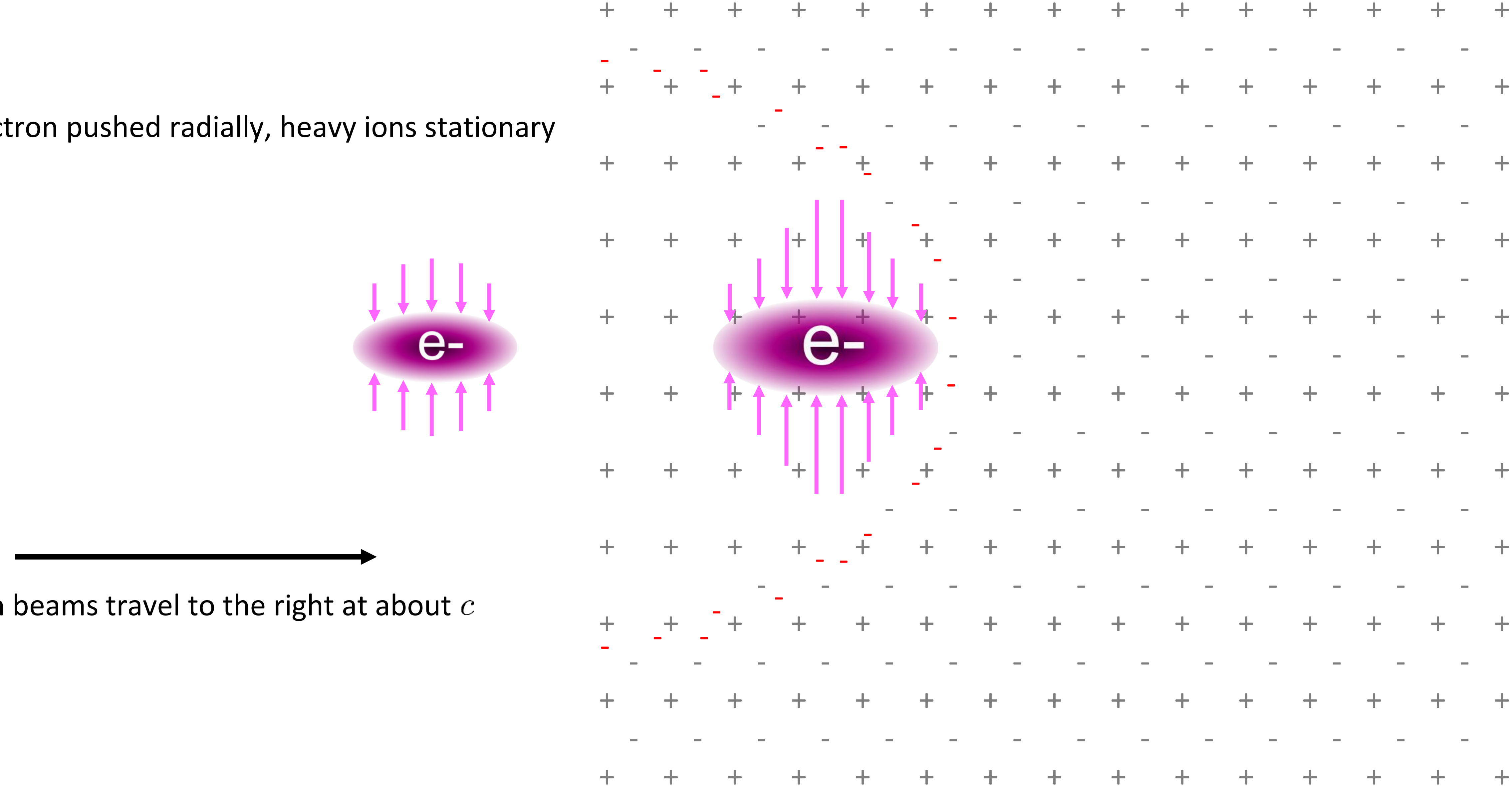


Plasma wakefield acceleration

Light electron pushed radially, heavy ions stationary



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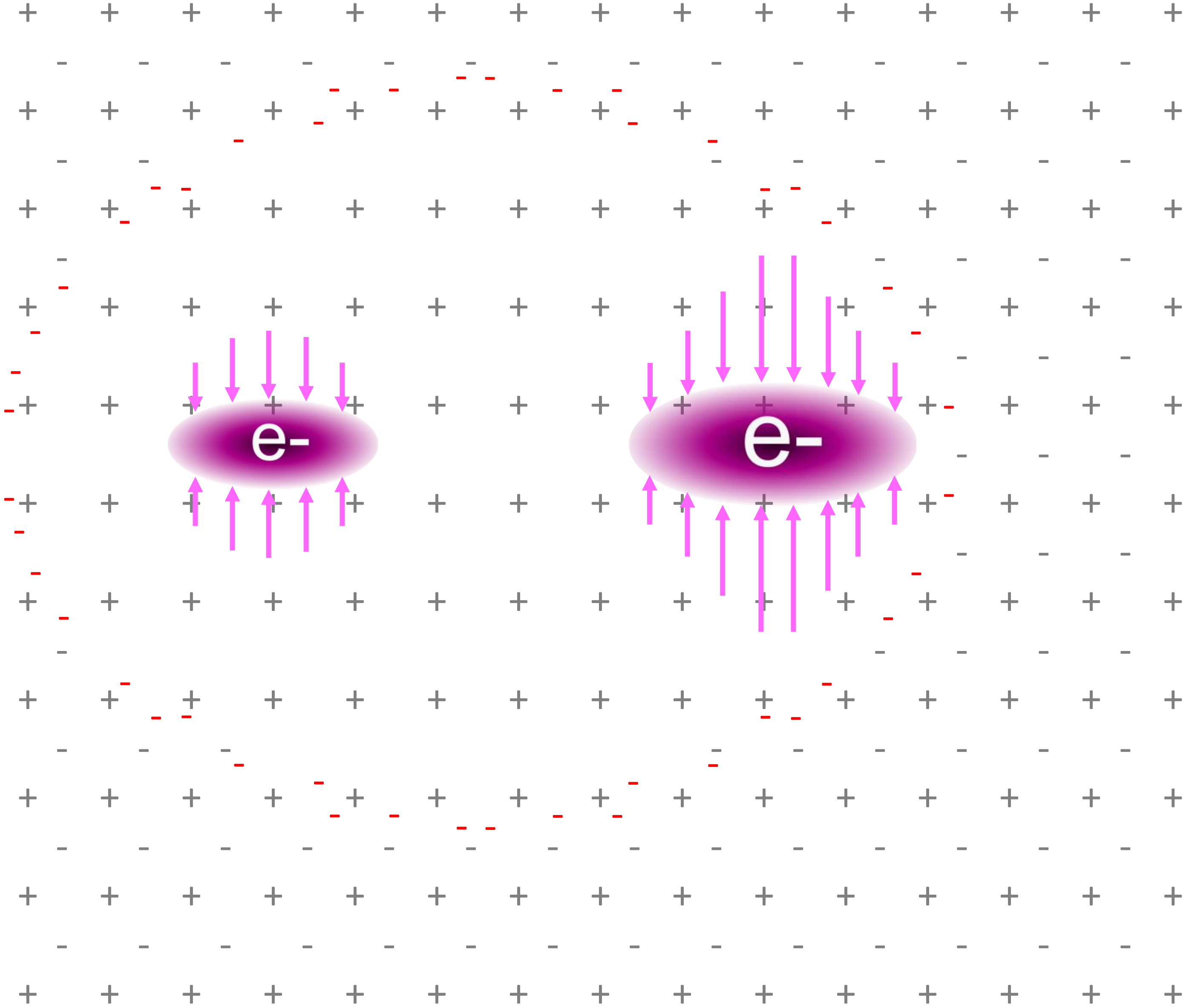
Plasma wakefield acceleration

Electrons return to the axis, attracted by the ions



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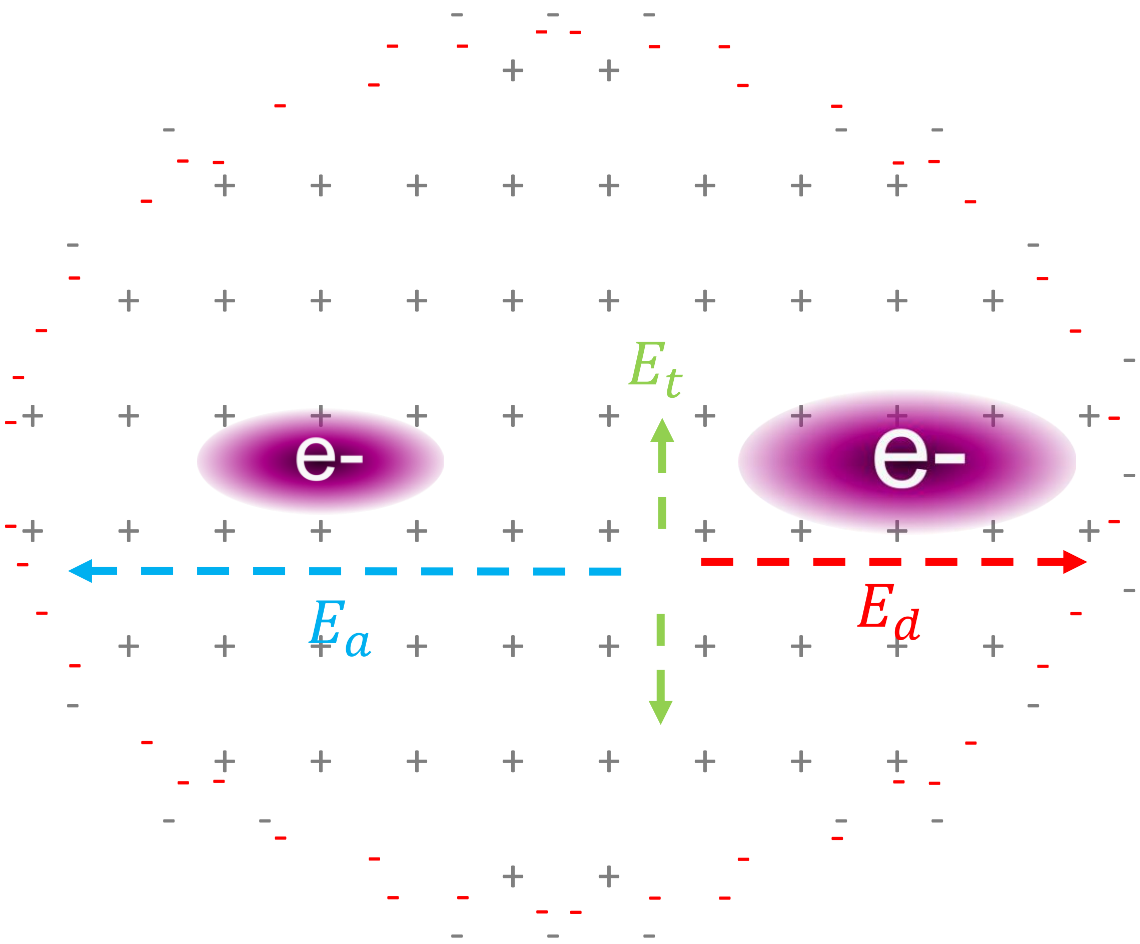
Plasma wakefield acceleration

Electrons return to the axis, attracted by the ions



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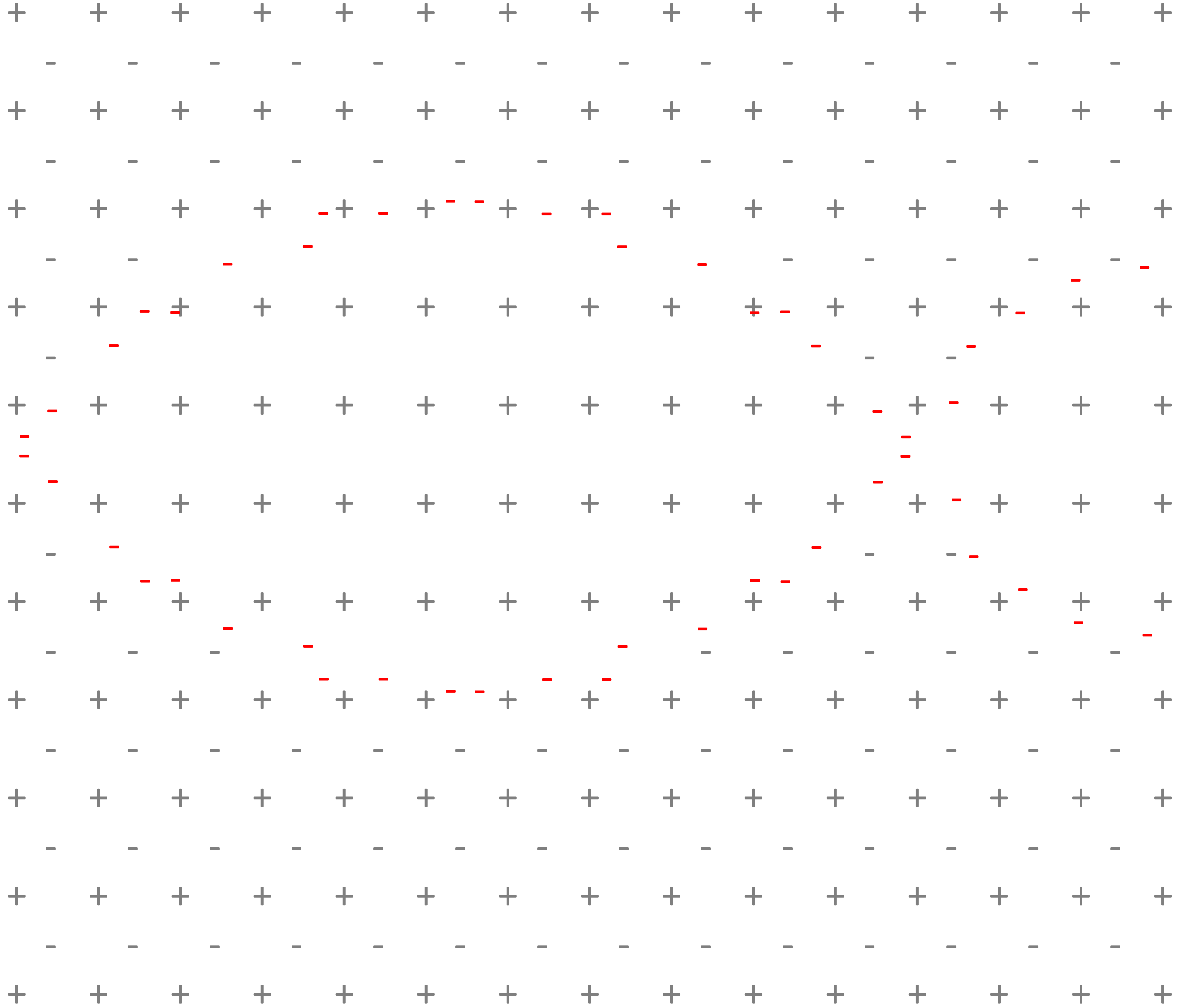
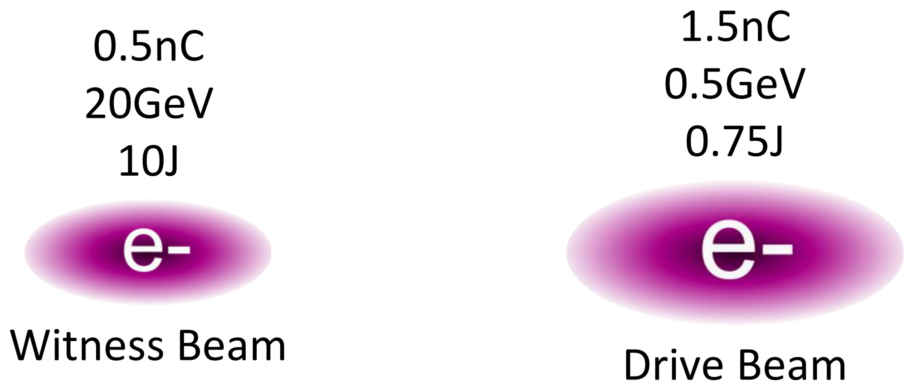
Plasma wakefield acceleration





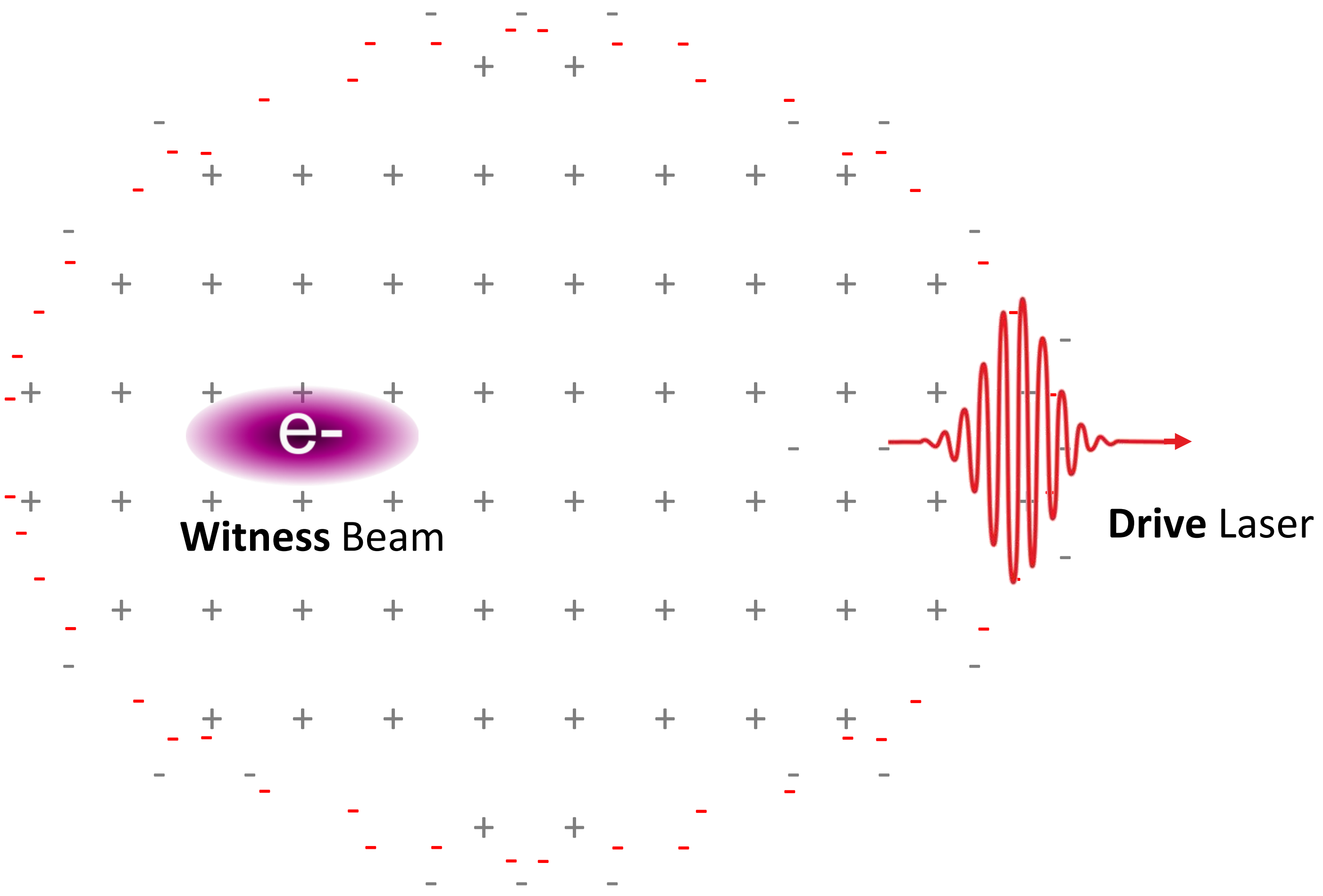
Drive beam lost 14.25J, witness beam gained 5J
Efficiency: 5/14.25 = 35%

Plasma wakefield accelerator transfers energy from the drive beam to the witness.

Aside – Laser Wakefield Accelerator

For laser plasma wakefield acceleration
Replace the drive electron bunch with an intense laser pulse

(Not directly within the scope of FACET science)



Both beams travel to the right at about c

How strong are the fields?

- Size of the plasma wave scales as

$$\lambda_p = 2\pi c\sqrt{\frac{m_e\epsilon_0}{n_e e^2}}$$

At ~1e16 cm^{-3} density → λ_p~100's μm

- Electric field scales as

$$E \approx 100\sqrt{n[10^{18}\,\mathrm{cm}^{-3}]}[\mathrm{GV/m}]$$

At ~1e16 cm^{-3} density → E~ 10's GV/m

There is a GV/m in there!
Reminder: conventional linac is maybe 50 MV/m.
1 km accelerator in 1m.

State of the art conventional vs. plasma

Parameter	Conventional (LCLS)	Plasma Based
Energy	10 GeV	9 GeV ✓
Gradient	22 MeV/m	50 GeV/m ✓
Charge	0.25 nC	0.1 nC ✓
Energy Spread	0.1%	0.13% ✓
Emittance	1 um-rad	2.75 um-rad ✓

State of the art conventional vs. plasma

Parameter	Conventional (LCLS)	Plasma Based	Other Parameters
Energy	10 GeV	9 GeV ✓	Emittance? We don't talk about that
Gradient	22 MeV/m	50 GeV/m ✓	6% energy spread, 6 pC
Charge	0.25 nC	0.1 nC ✓	0.1 nC
Energy Spread	0.1%	0.13% ✓	45 MeV gain on a 1 GeV beam
Emittance	1 um-rad	2.75 um-rad ✓	35 MeV gain on a 1 GeV beam

Experiments have only achieved 3 at a time!

Total efficiency is low in experiments.

Scientific goals for PWFA at FACET-II

- Start with ~1.5nC drive beam and 0.5 nC witness beam
- High total efficiency
  - Deplete all the energy from the drive beam
  - Accelerate the witness beam to high energy
- Emittance preservation
  - Beam quality doesn't degrade during acceleration
- Reasonable energy spread
  - Better than a couple percent

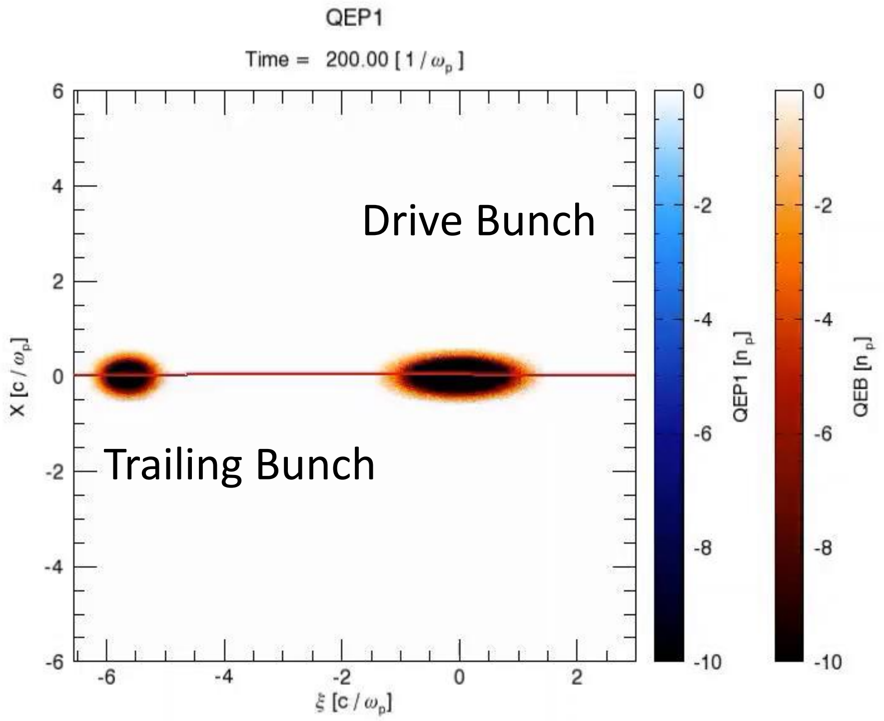
- Put it all together

Ideal PWFA at FACET-II

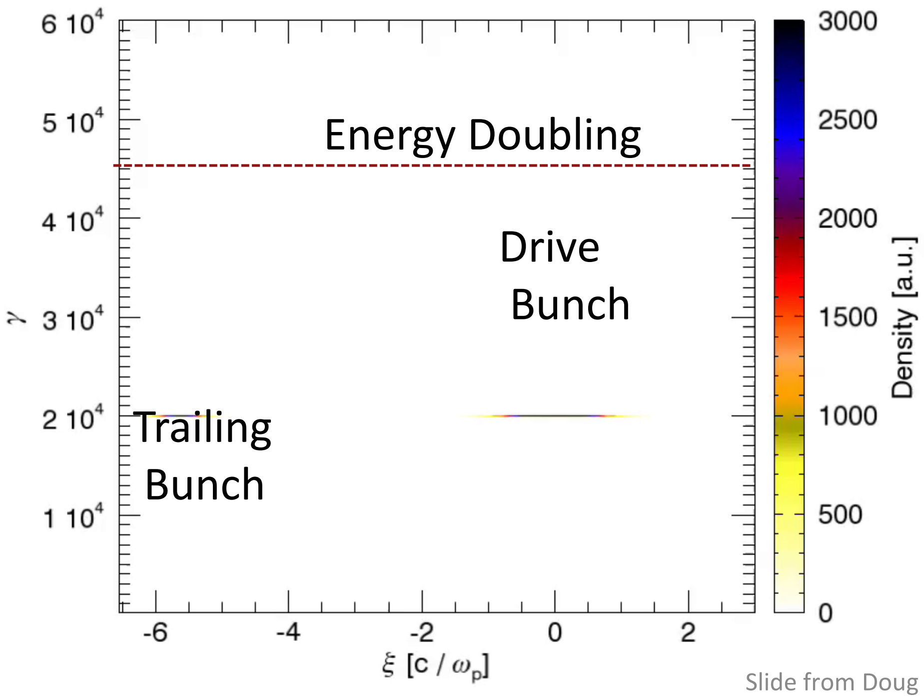
Energy Doubling (10 to 20+ GeV) with:

- <1% Energy Spread,
- Pump Depletion and > 40% pump to trailing bunch energy transfer efficiency,
- while minimizing emittance growth

Plasma and beam density with on-axis Ez line out:



Energy evolution of drive and trailing bunches:

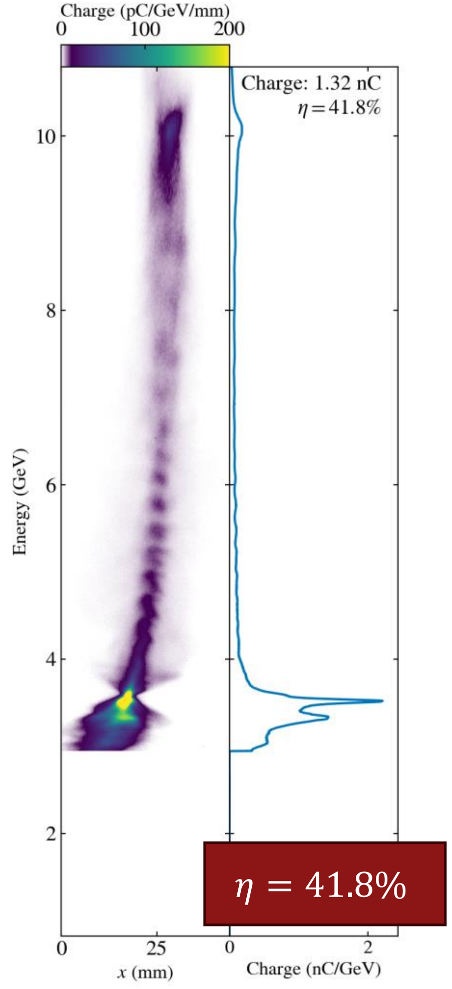


C. Joshi, et al., Plasma Physics and Controlled Fusion 60 (2018) 034001

Slide from Doug Storey

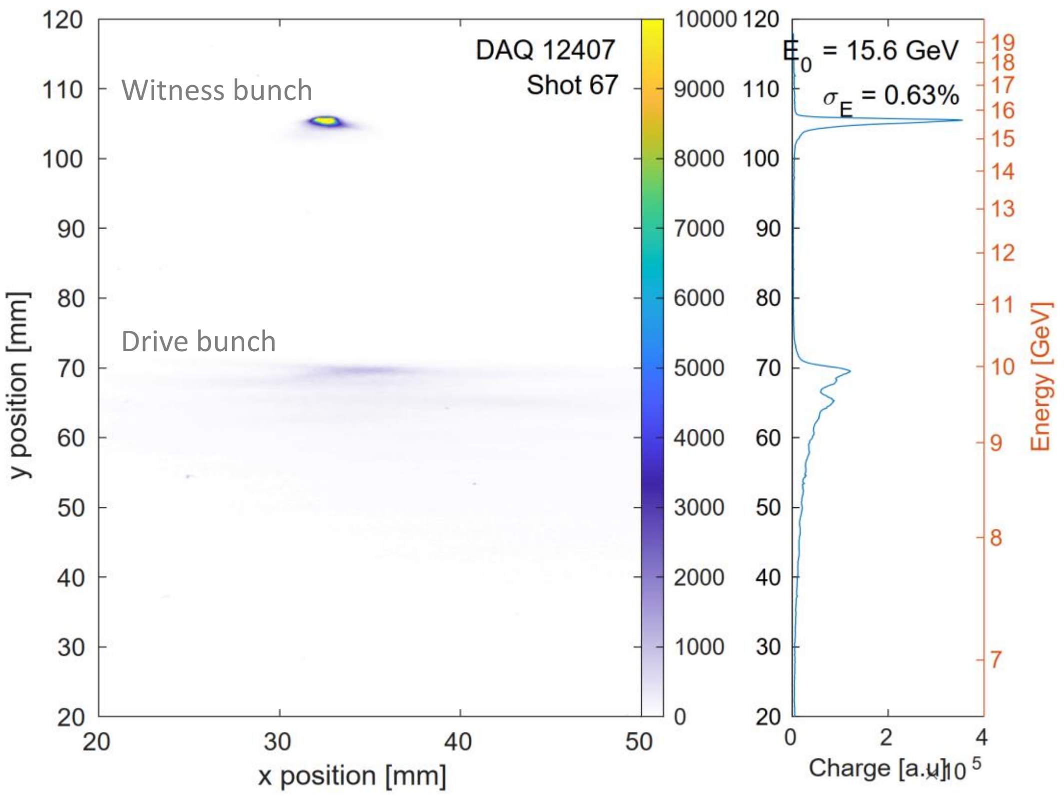
What have we achieved so far at FACET-II?

>40% of drive bunch energy transferred to plasma



- Single drive bunch started at 10 GeV
- Decelerated down to ~3 GeV

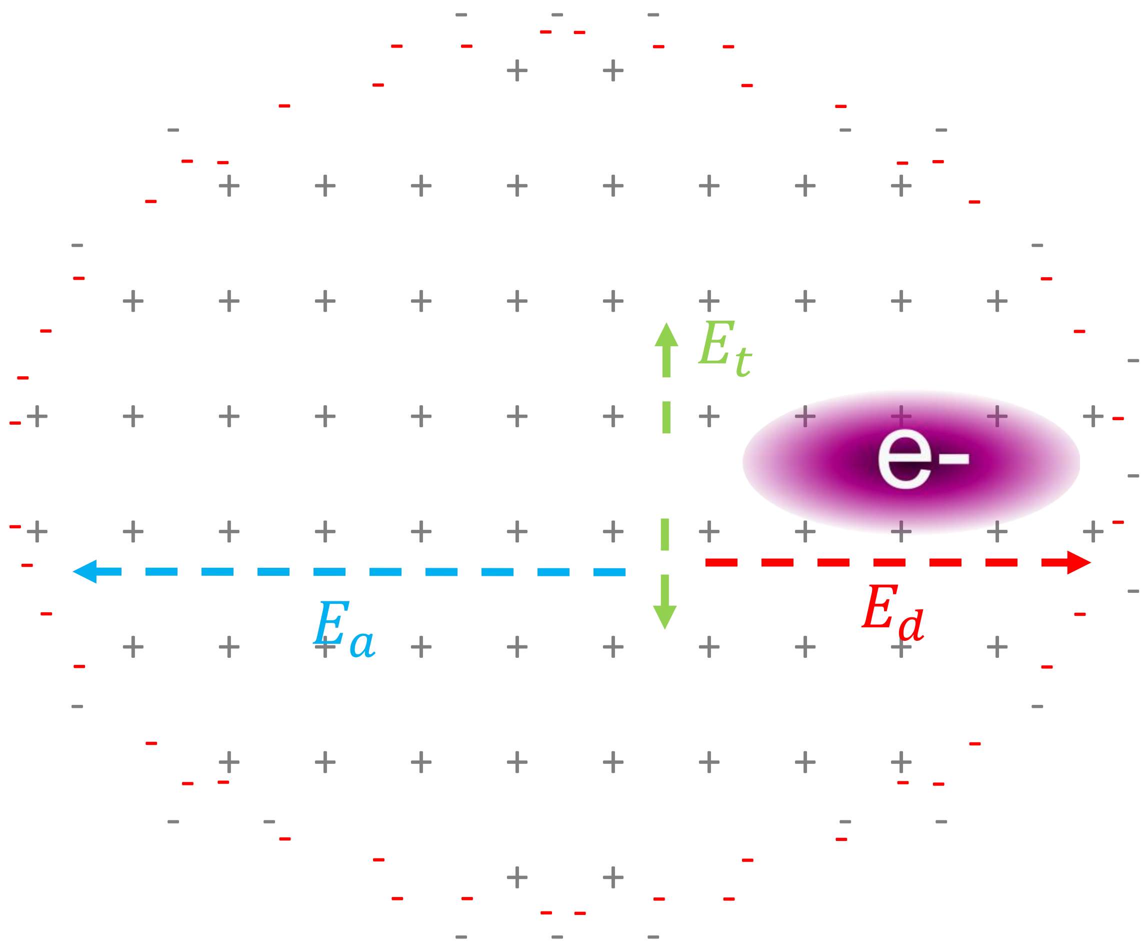
Witness accelerated by ~6 GeV
Energy spread of <1%
Total energy transfer efficiency ~10%



- Drive and witness pair started at 10 GeV
- Witness accelerated to 15.6 GeV in 40cm!

Other things that can be done with PWFA – injection

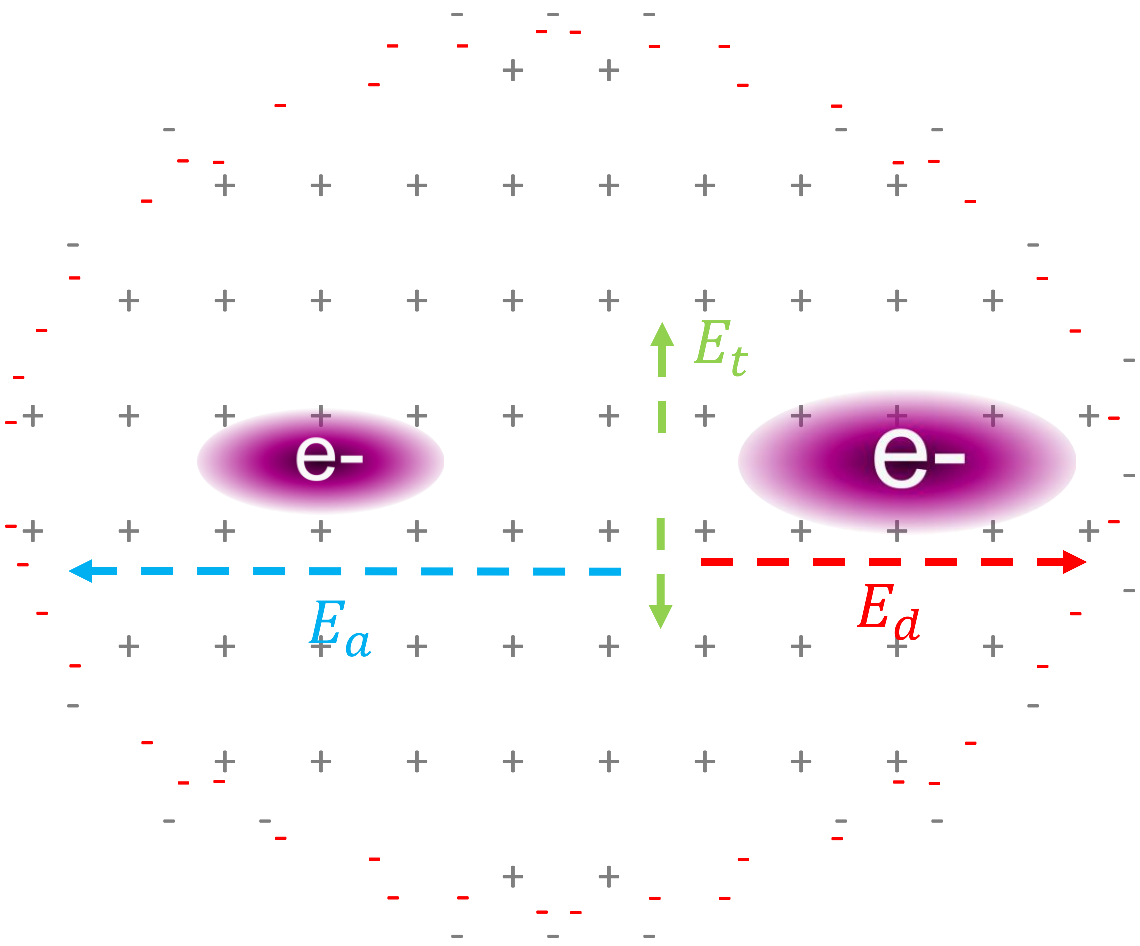
Only have the drive beam to start



Both beams travel to the right at about c

Other things that can be done with PWFA – injection

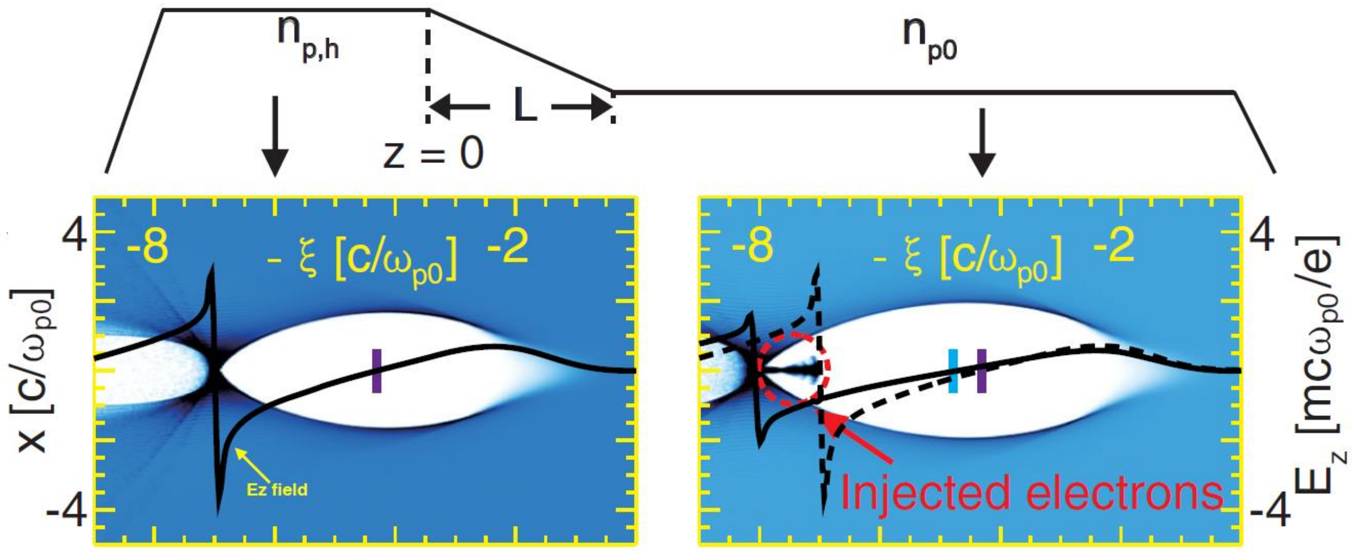
Create a second electron beam in the wake



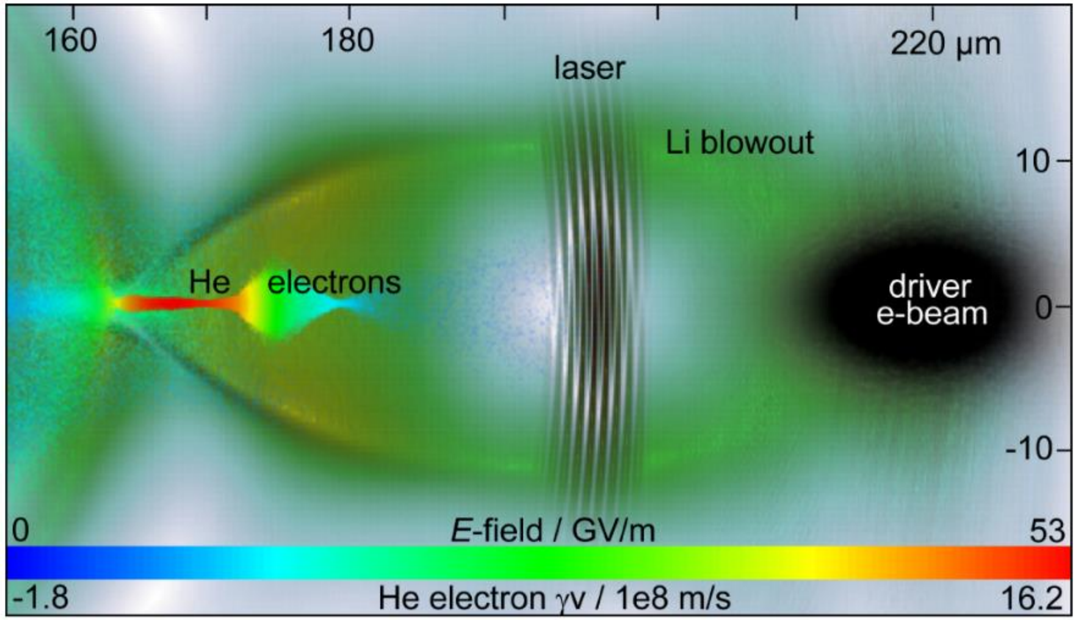
Both beams travel to the right at about c

Many ways to create an electron beam in the wake

- Electron beams typically have very nice properties



"Density downramp" injection

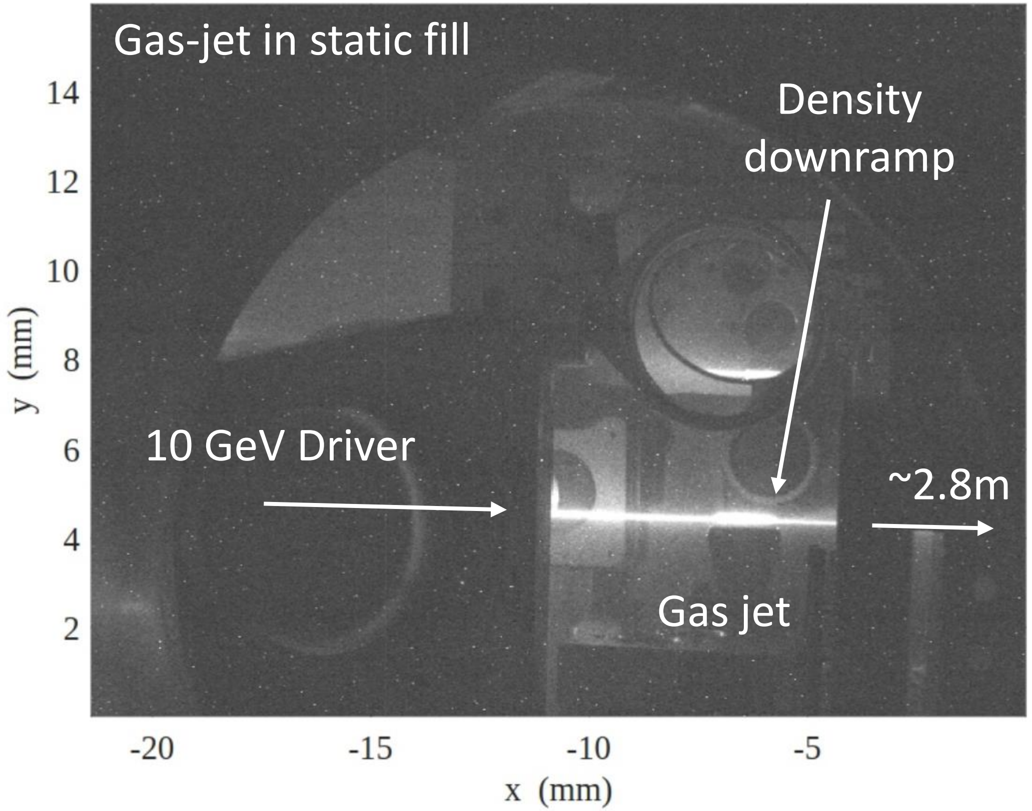


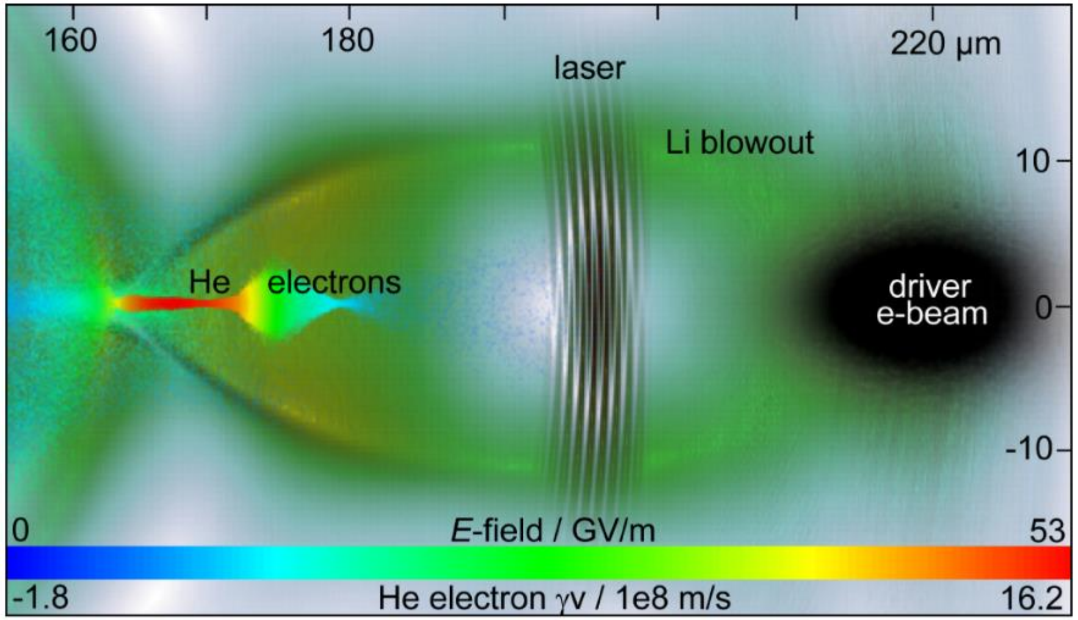
Mixed gas injection

Goal of injection experiments: make nice beams!

Many ways to create an electron beam in the wake

- Electron beams typically have very nice properties



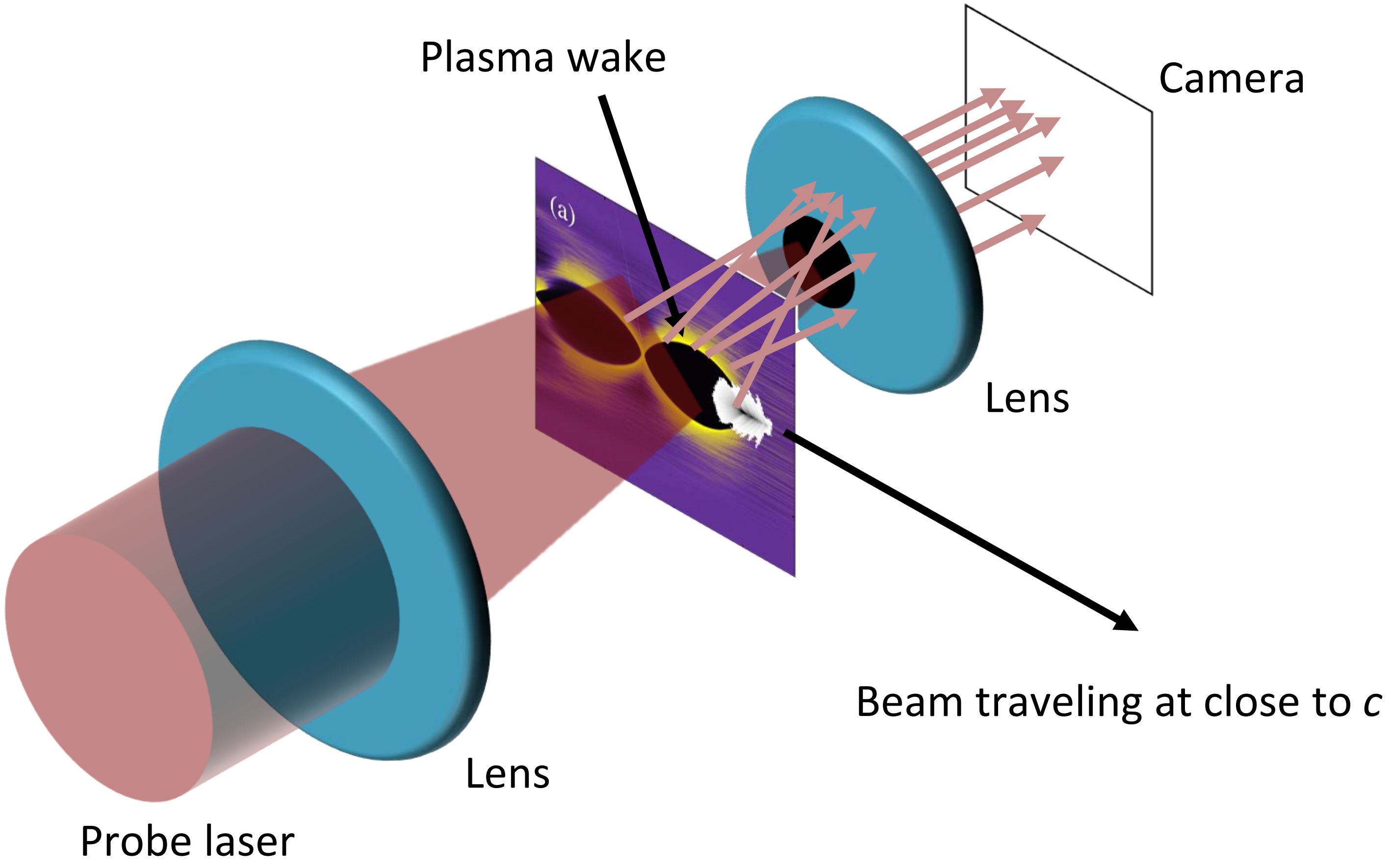


Mixed gas injection

Goal of injection experiments: make nice beams!

Can we see these plasma wakes?

- Yes – with a technique called dark-field shadowgraphy



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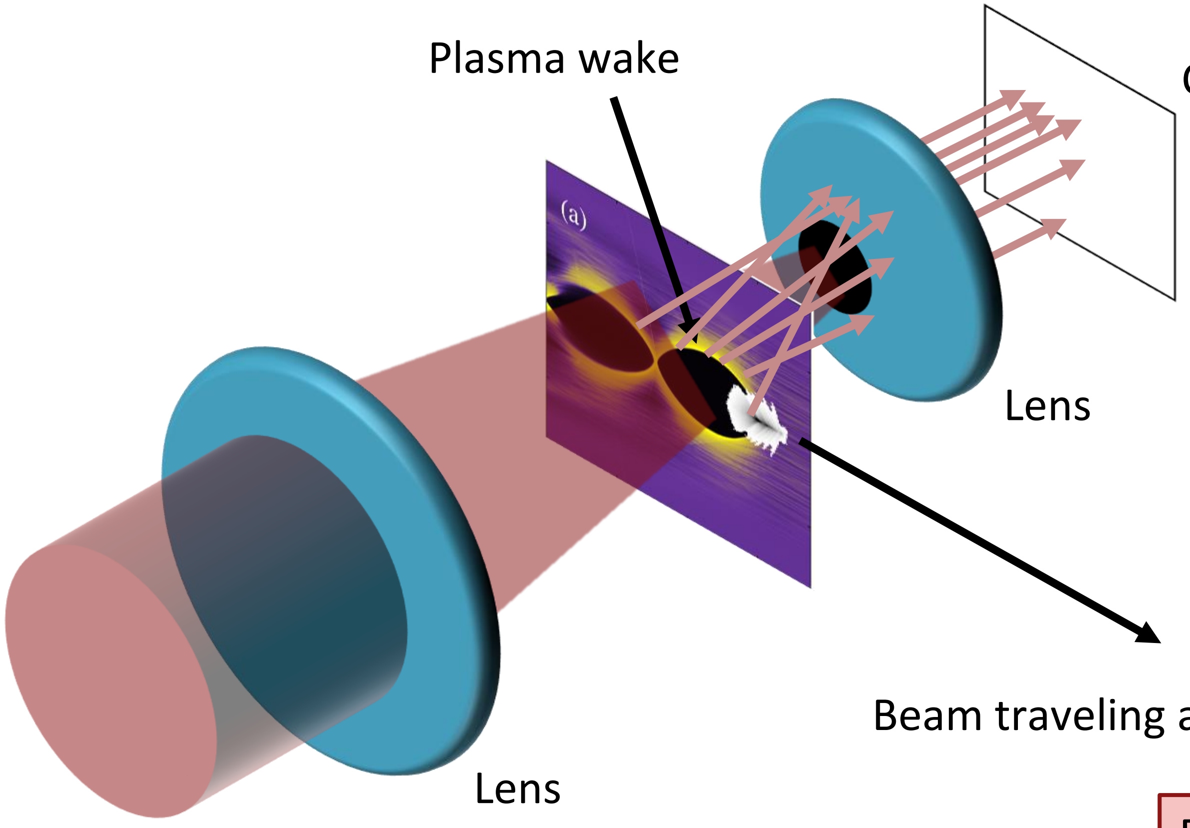
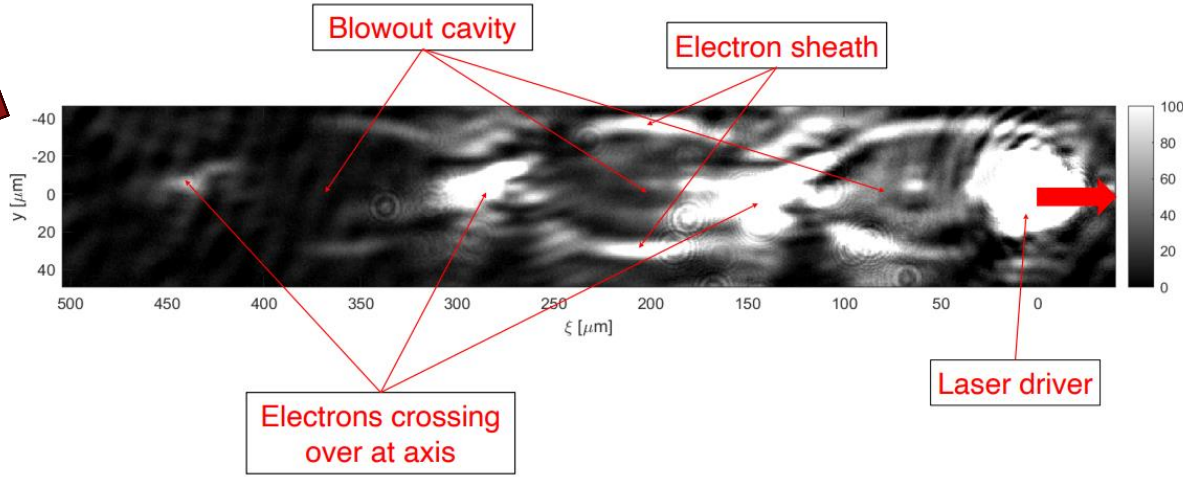
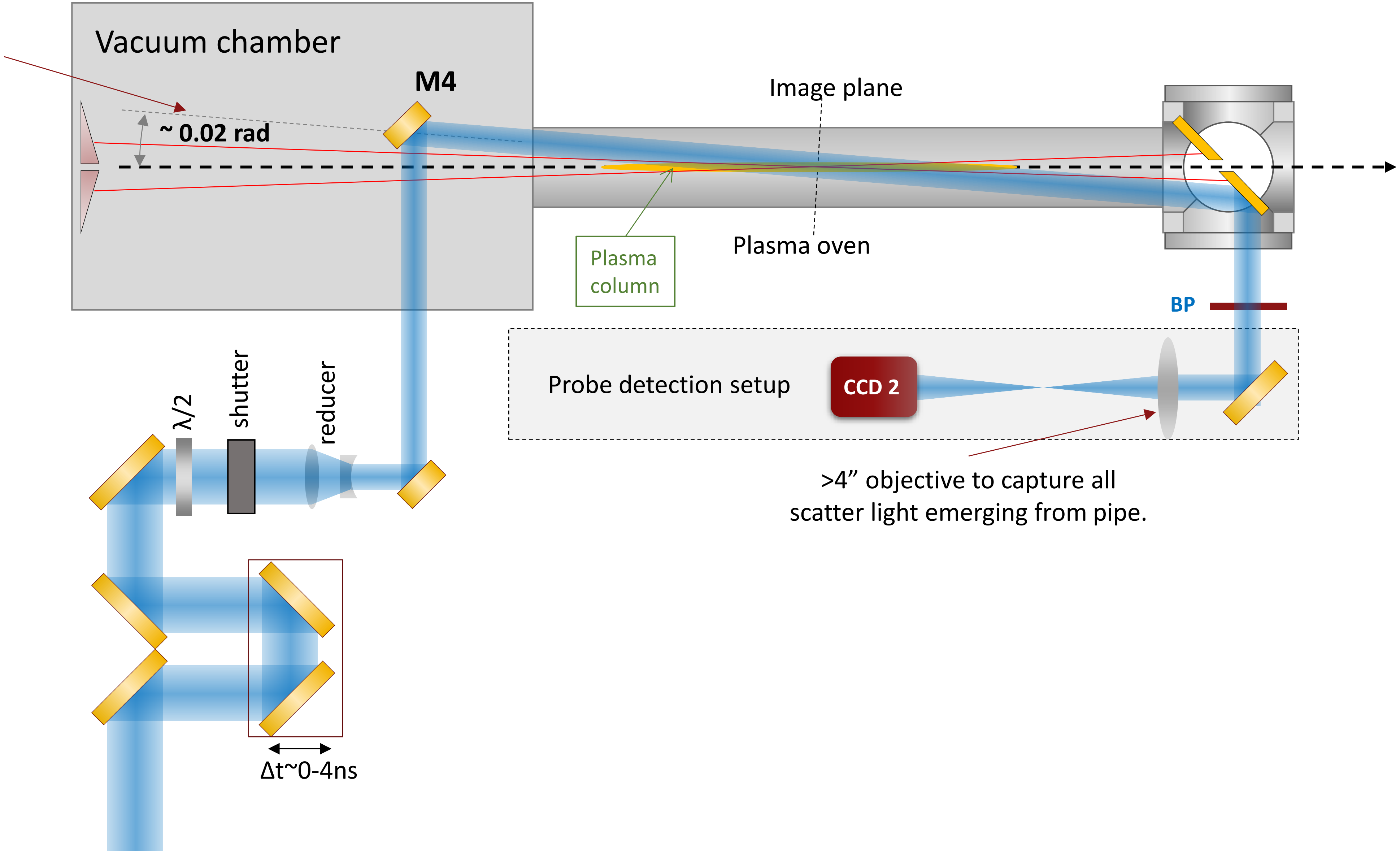


Plasma bubbles in laser plasma accelerator



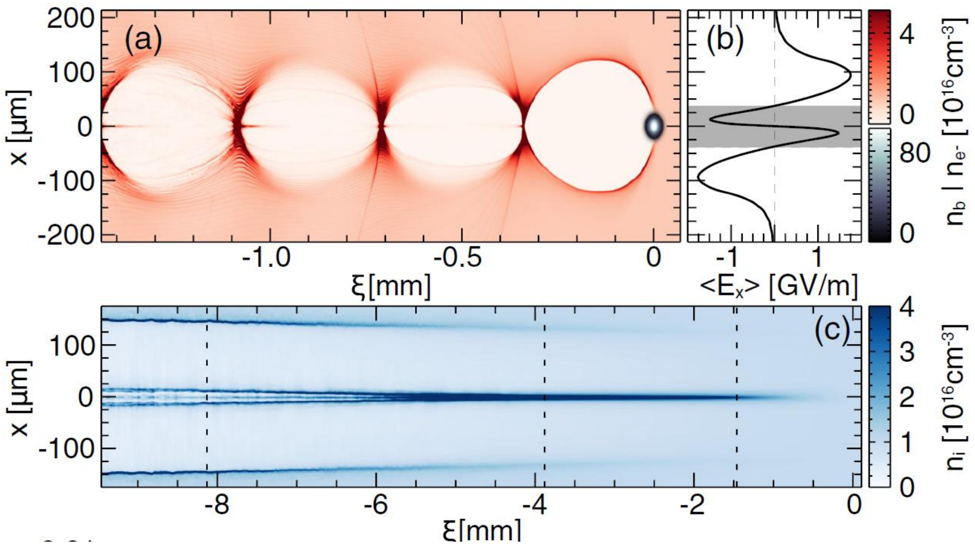
Probe laser can be used to take snapshots of the wake

Optical measurements of plasma evolution

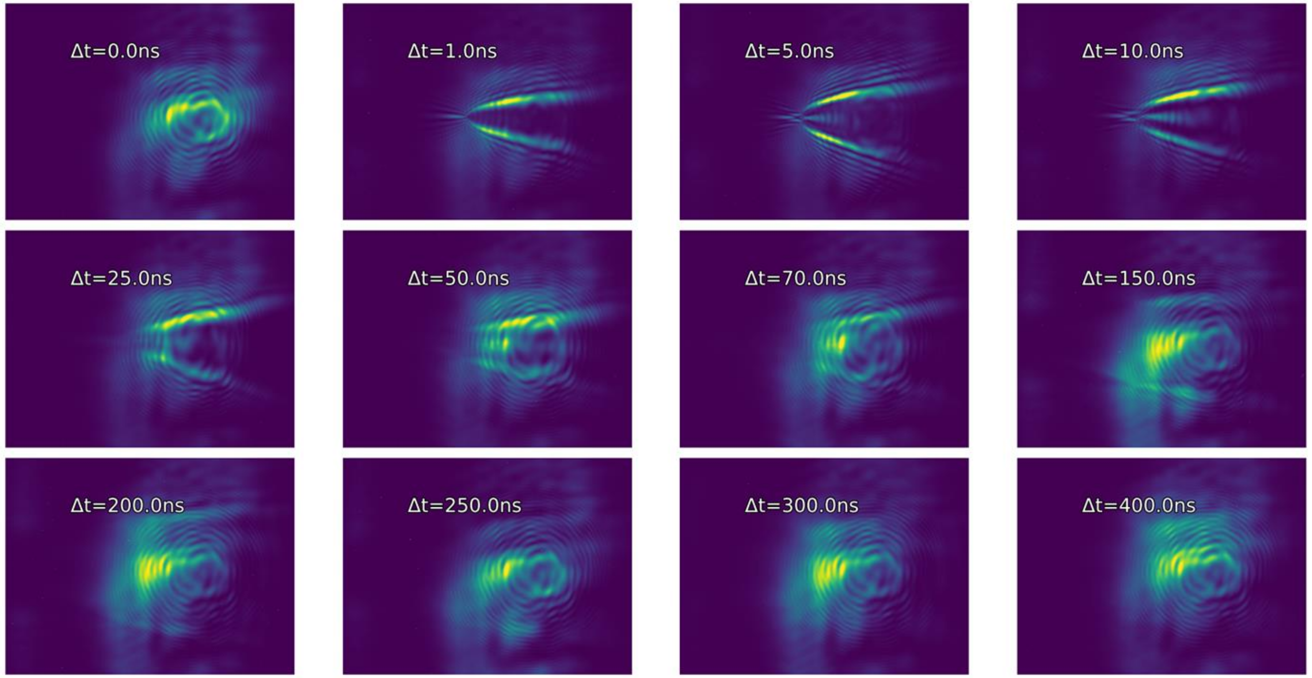


Optical measurements of plasma evolution

- Determines how long one needs to wait to send the next bunch into the plasma – limits repetition rate

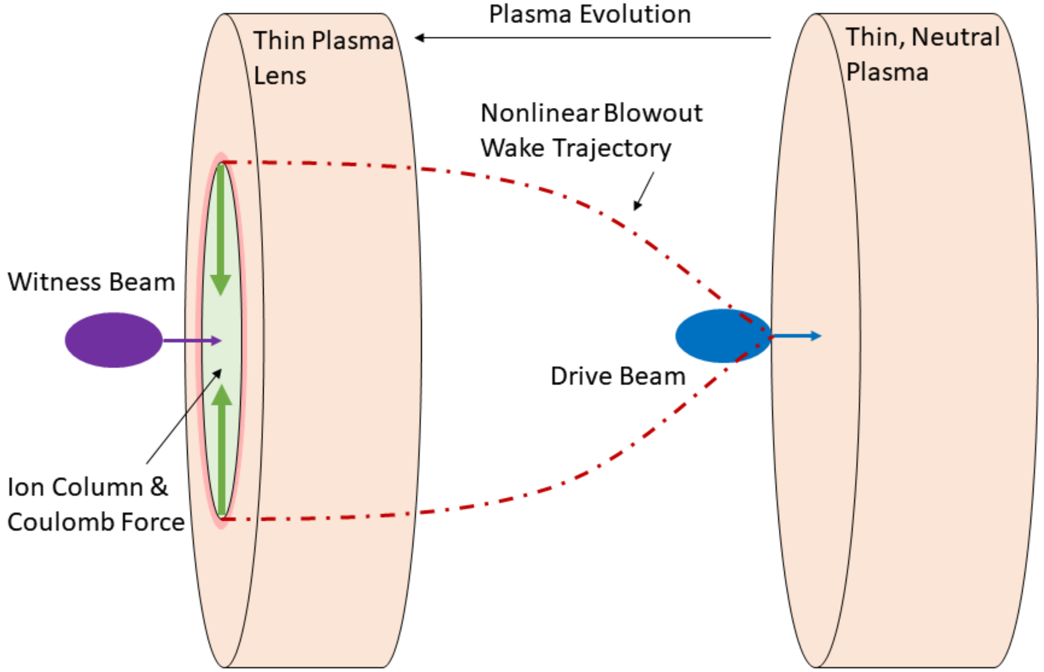


Goal: measure evolution of the plasma long after the PWFA electron beams have passed



Wake evolution in Argon plasma

Other things that can be done with PWFA – plasma lens



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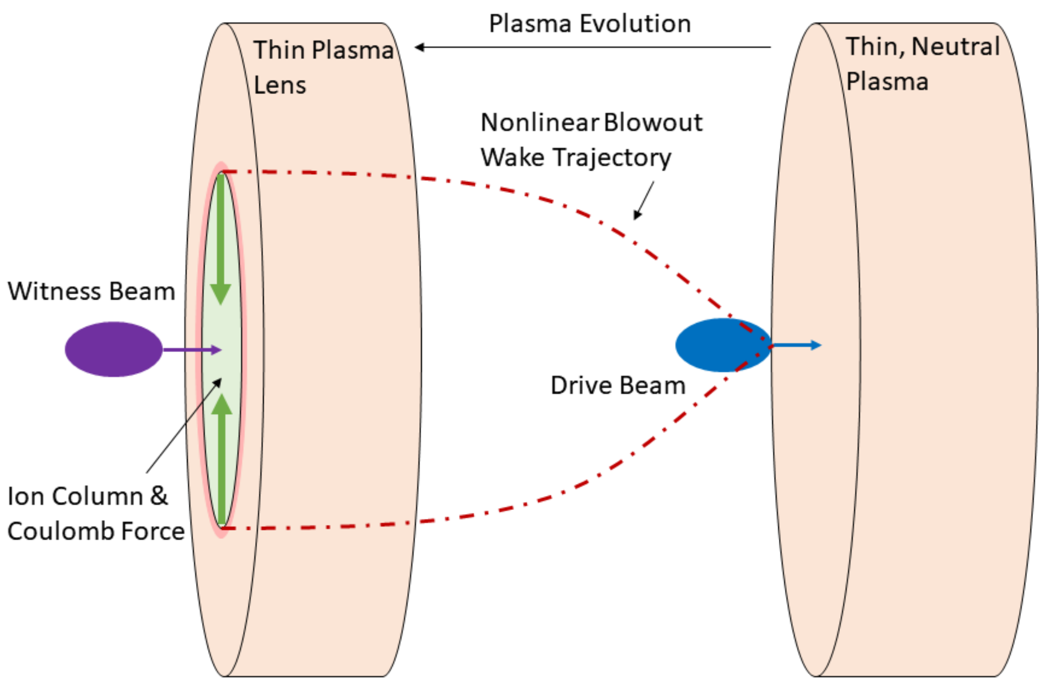
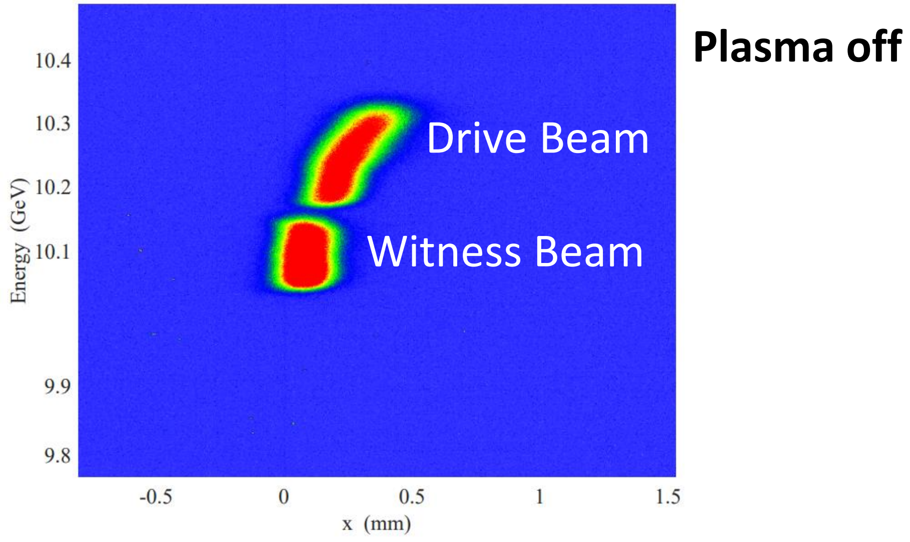
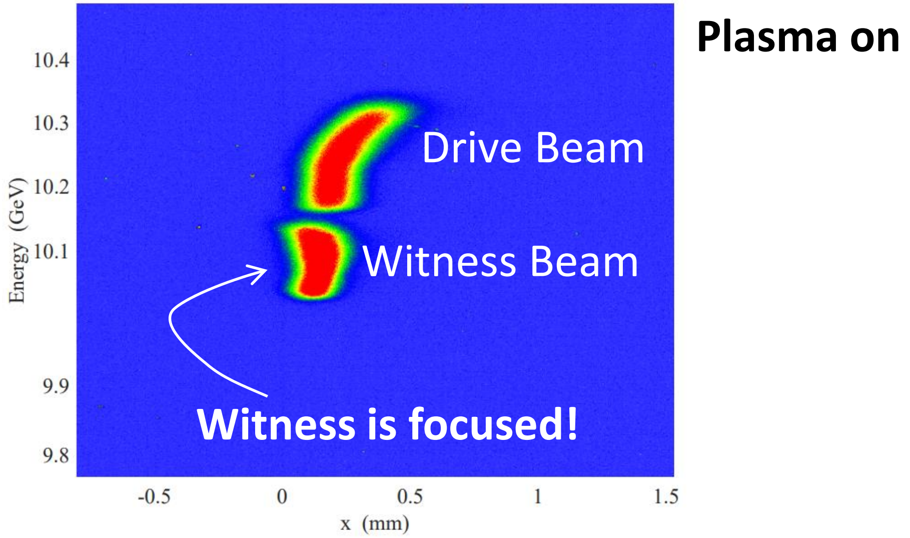


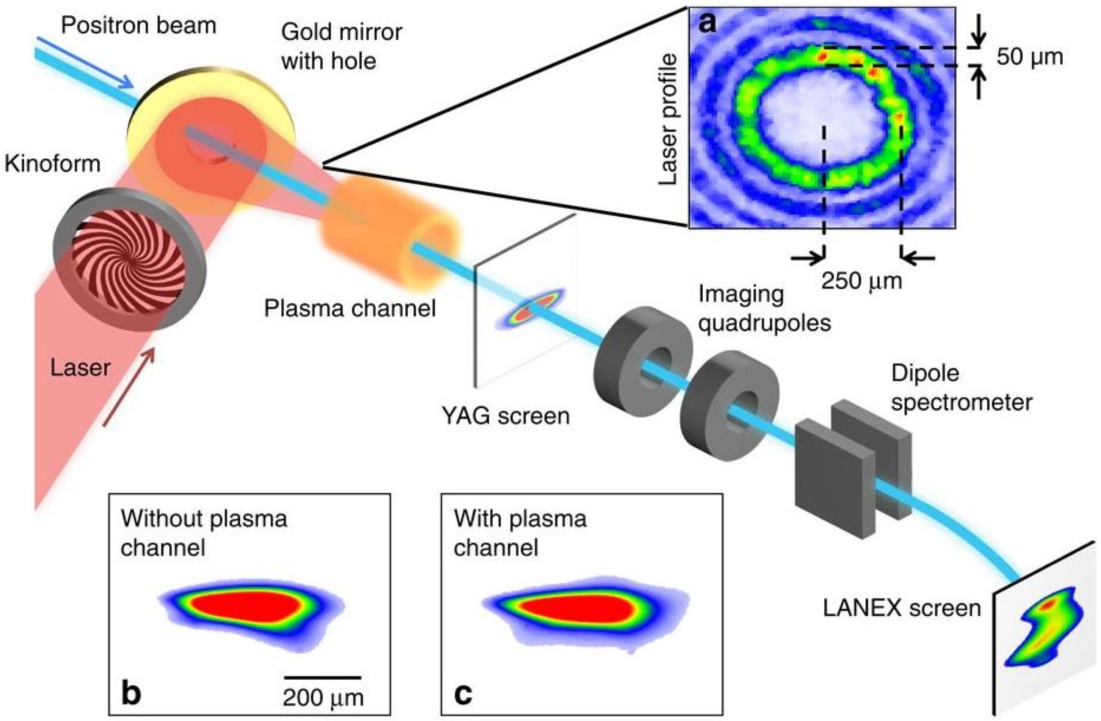
First goal is to observe strong focusing matching theory.
Second goal is to probe fundamental limits to focusing.

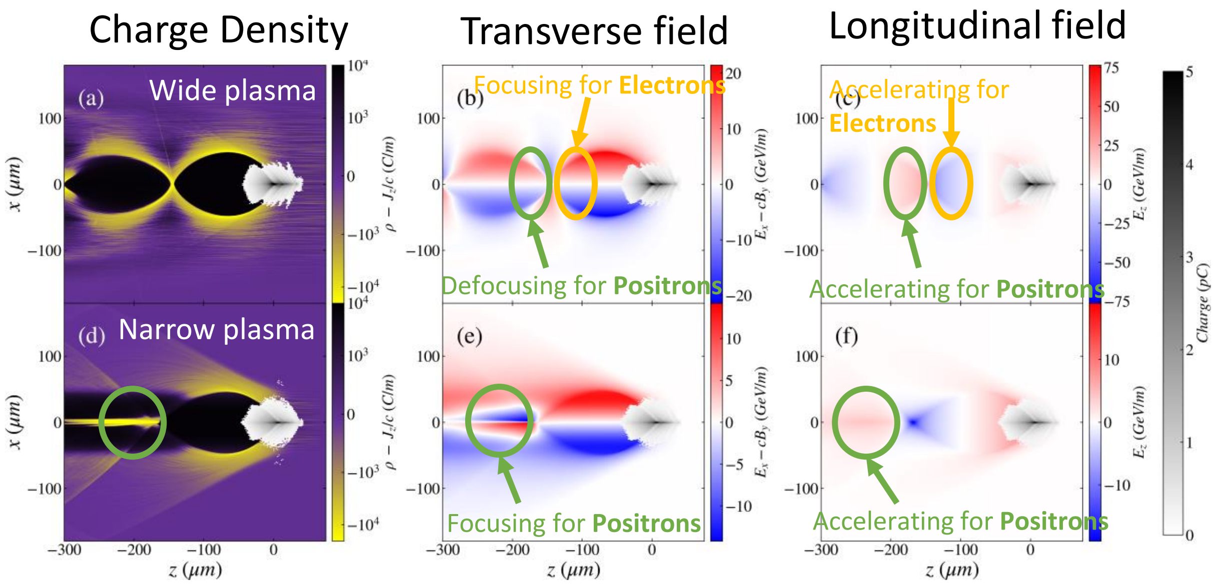




Other things that can be done with PWFA – positrons

Various ideas for how to accelerate positrons with plasma





V. Lee, CU Boulder

Gessner, *et al.*, Nature Communications **volume 7**, Article number: 11785 (2016)

FACET-II is a user facility – scientists propose experiments

- Many experiments are underway, and even more planned: https://facet-ii.slac.stanford.edu/accepted-proposals

Plasma wakefield acceleration

X-ray source application of PWFA

Strong field quantum electrodynamics

Strong field physics

Accelerator diagnostics

Proposal No.	Title
E-300 / E-301	Plasma wakefield acceleration
E-302	Transverse instabilities in PWFA
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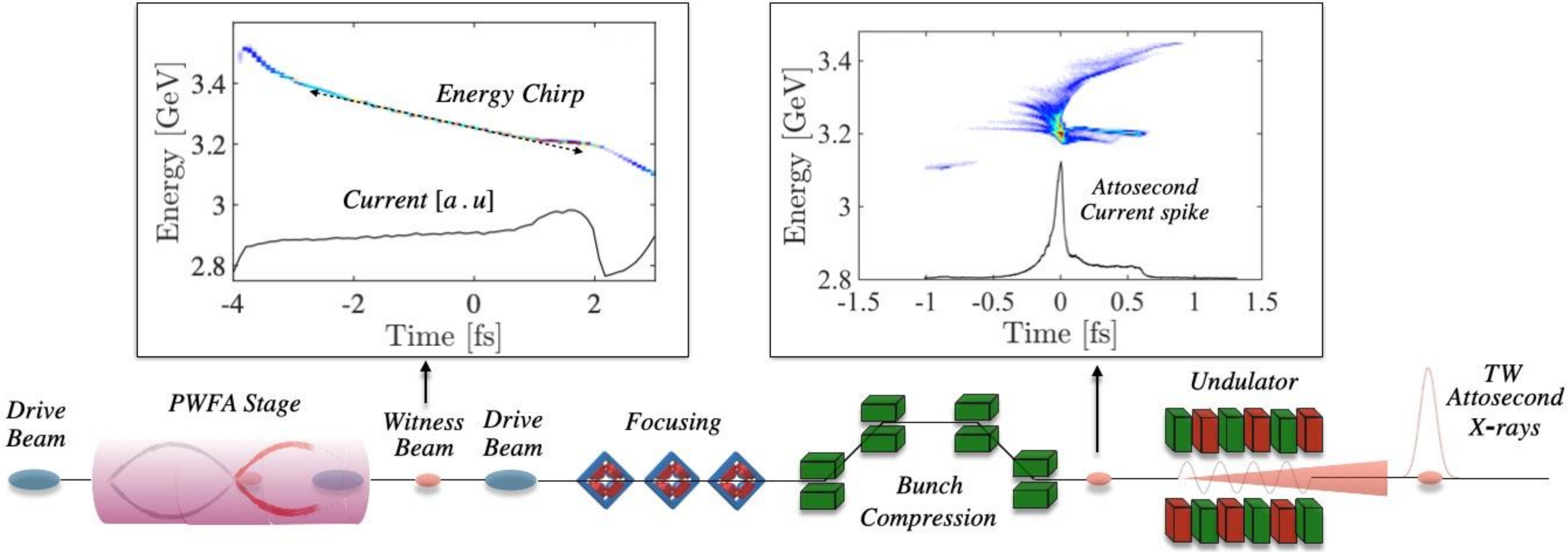
E-326	Non-intercepting beam diagnostics
E-327	Virtual diagnostics for phase space prediction
E-331	Neural network-based tuning
E-341	6D phase space reconstruction of beams

Application of PWFA beam – attosecond X-ray source



C. Emma et al., APL Photonics, 6, 076107 (2021)

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Plasma wakefield acceleration (E-300 / E-301 through E340)

X-ray source application of PWFA (E-338)

Strong field quantum electrodynamics (E-320, E-332)

Strong field physics (E-332 through E-339)

Accelerator diagnostics (E-315 through E-341)

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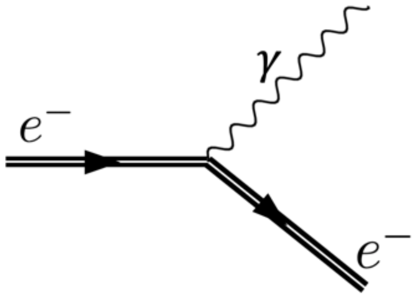
Strong field QED

- In the presence of a strong field – i.e. exceeding the Schwinger critical field: $E_s = \frac{m^2 c^3}{e\hbar} \sim 10^{18} \frac{V}{m}$

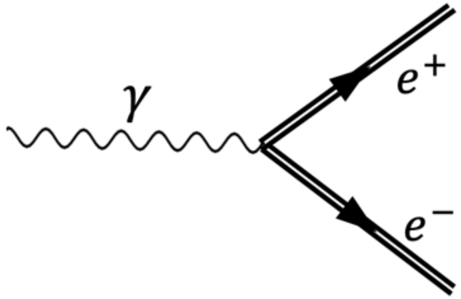
Non-linear inverse Compton scattering :

$$e^- + n\omega \rightarrow e^- + \gamma$$



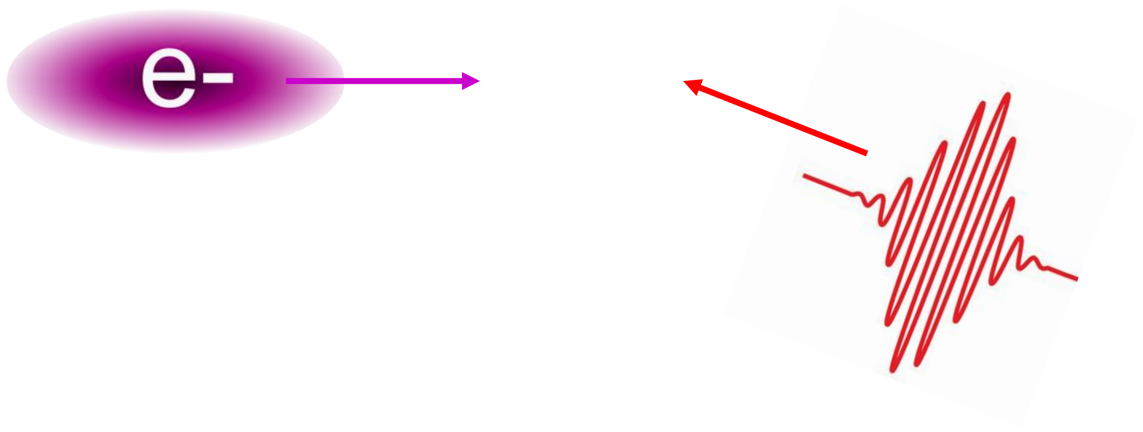
Non-linear Breit-Wheeler pair creation :

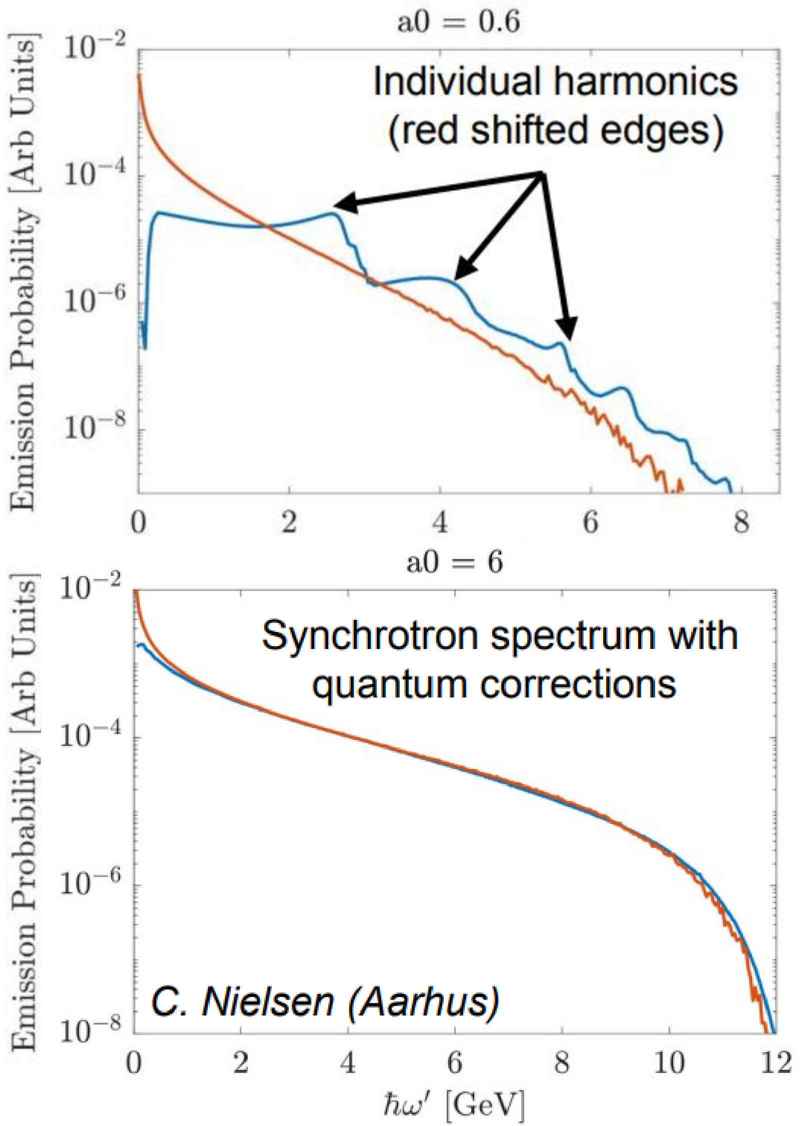
$$\gamma + n\omega \rightarrow e^- + e^+$$



So… How do you get these "strong fields" anyways?

Collide a relativistic electron beam with a laser

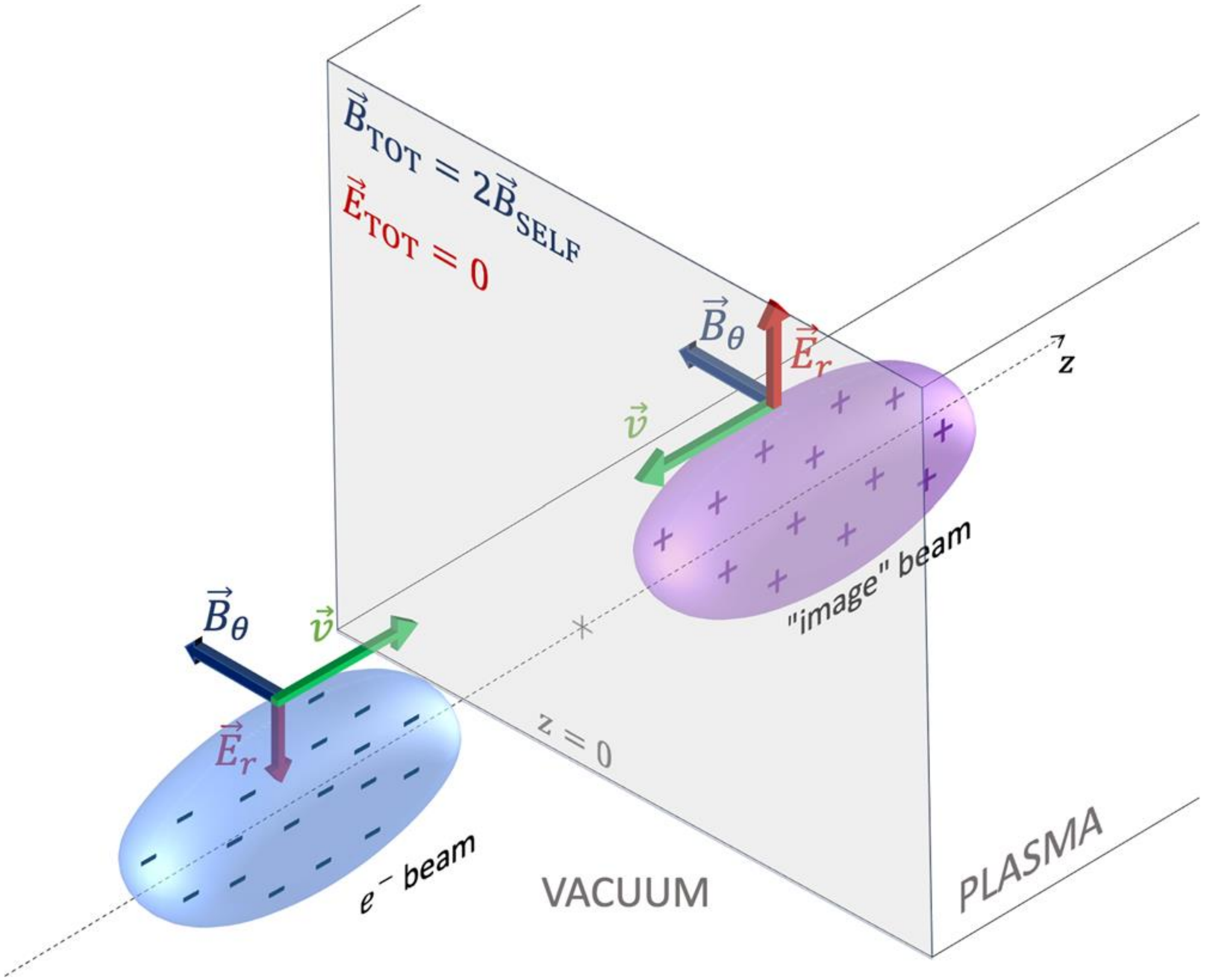




Observe energy spectrum of electrons showing inverse Compton scattering.
Observe positrons from "vacuum" pair production.

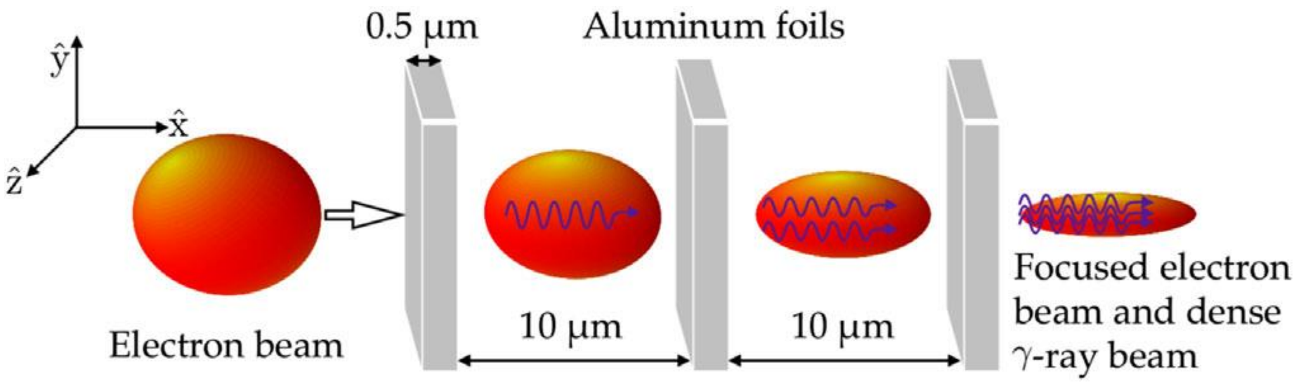
Or - collide a super small electron beam with a plasma

- Reflected self fields exceed Schwinger field in the beam rest frame



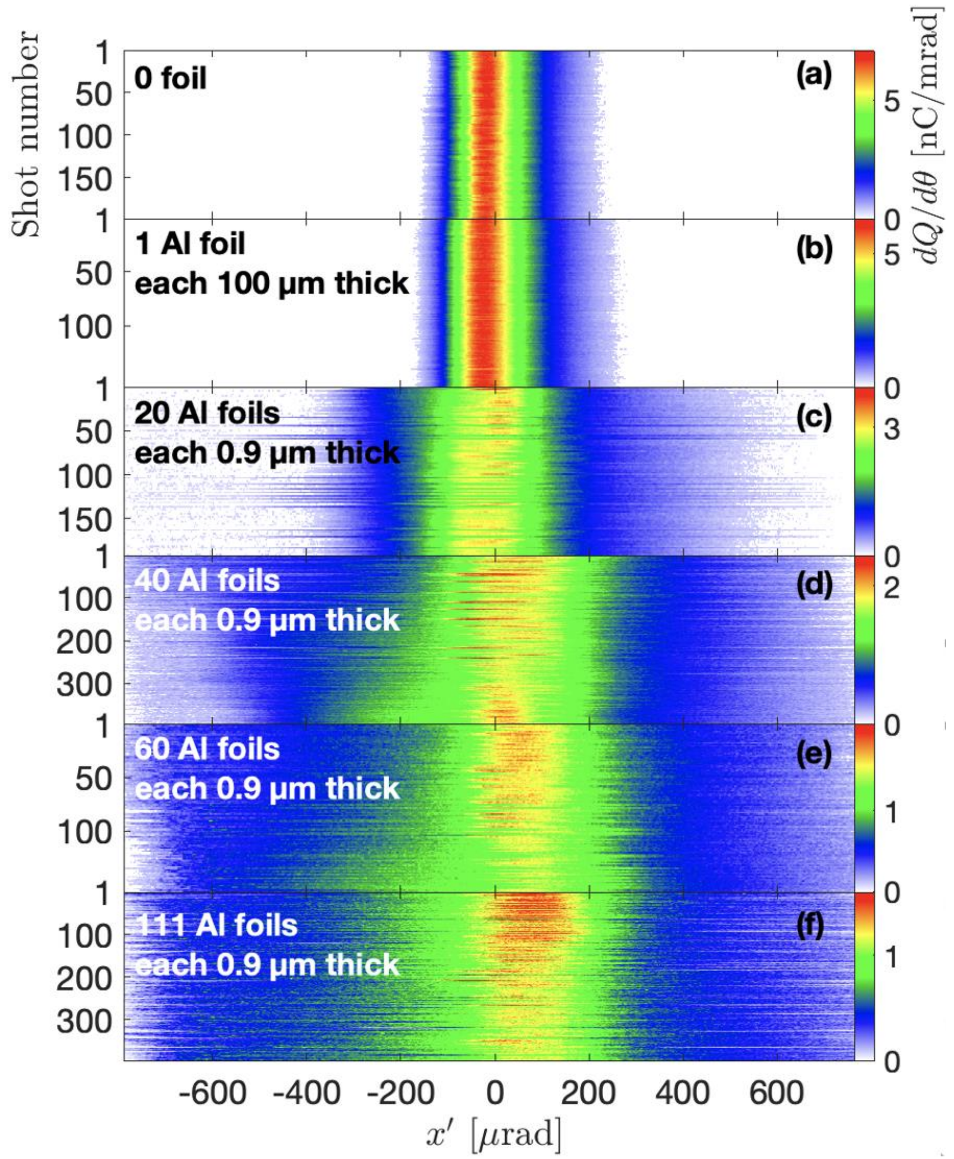
A. Matheron, et al., Commun Phys (2023)

Reaching beam sizes necessary for SFQED studies



~10 µm spot size

<1 µm spot size



Demonstrate focusing of the beam to small sizes by colliding with multiple foils.

Emission of intense, collimated gamma ray beam

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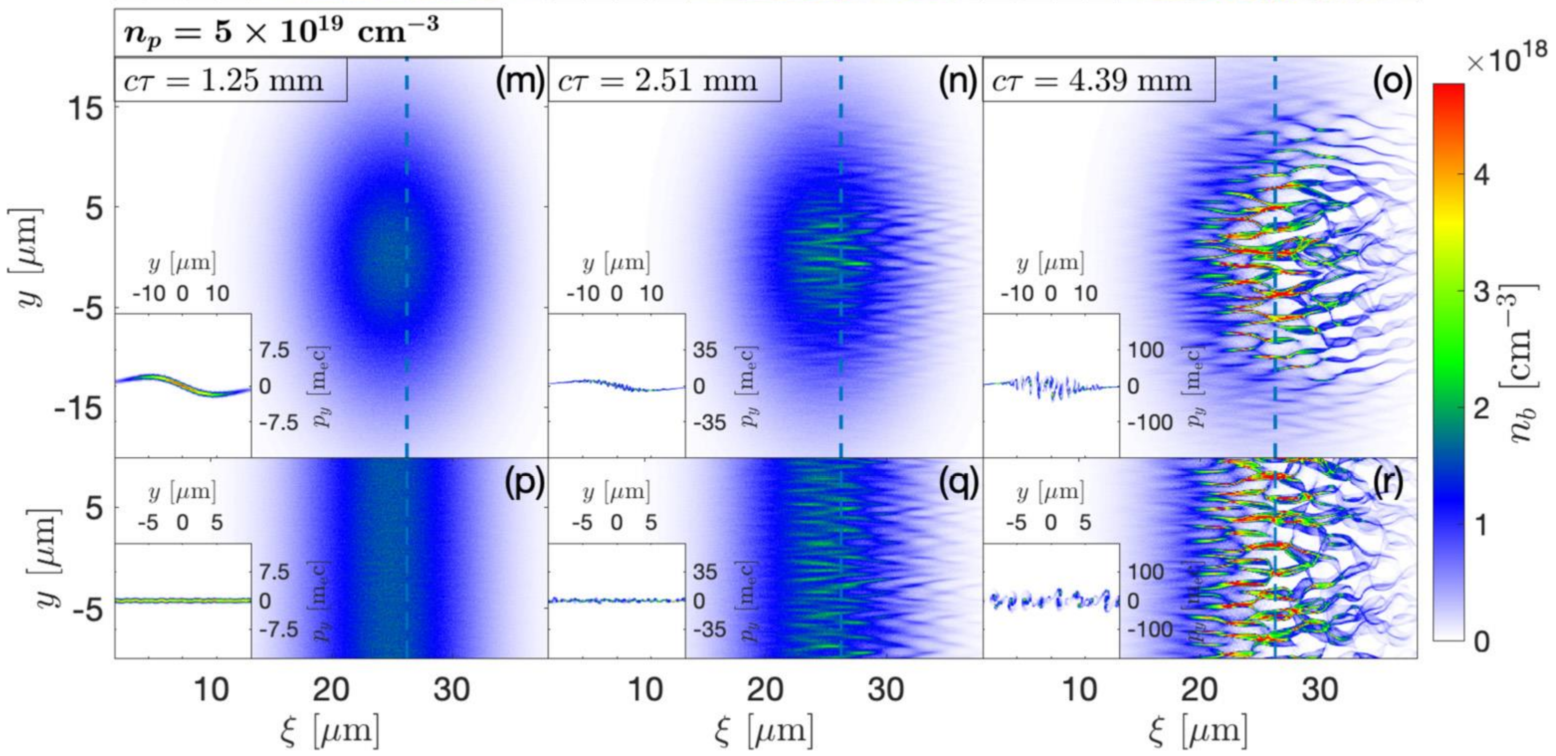
Beam filamentation instability

- Relativistic plasma instability



Goals: Understand relativistic kinetic plasma instabilities. Generate bright gamma rays from the instability.

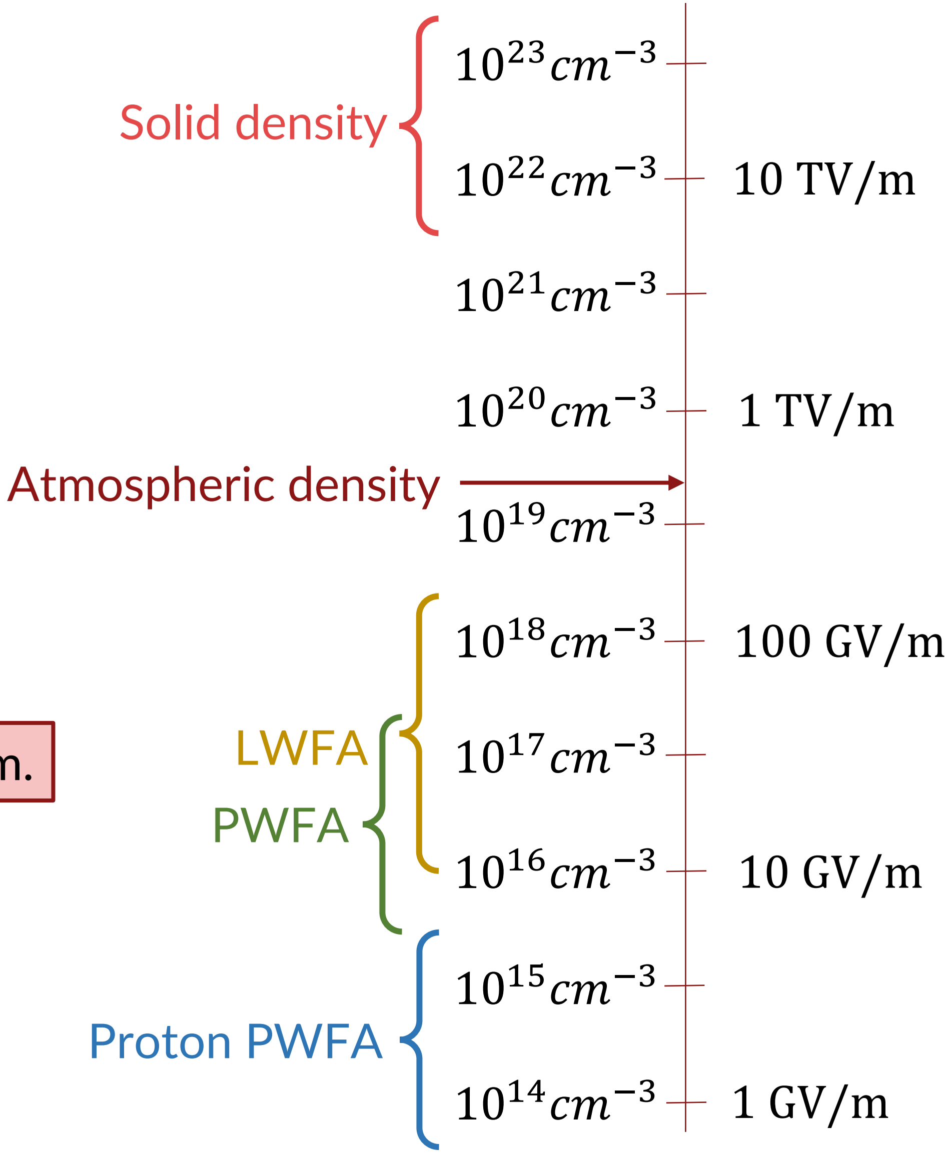
PWFA at solid material densities – very strong wakefields

- The accelerating field in a wakefield accelerator scales as

$$E[\mathrm{GV/m}] = m_e \omega_p c/e \approx 100\sqrt{n_0[10^{18}\mathrm{cm}^{-3}]}.$$

- Most PWFA/LWFA is done in ionized gas plasma sources at densities much less than atmospheric
- Solids are 4-5 orders of magnitude more dense
- Drive a wake in a solid density plasma, get 2 orders of magnitude stronger fields than an LWFA

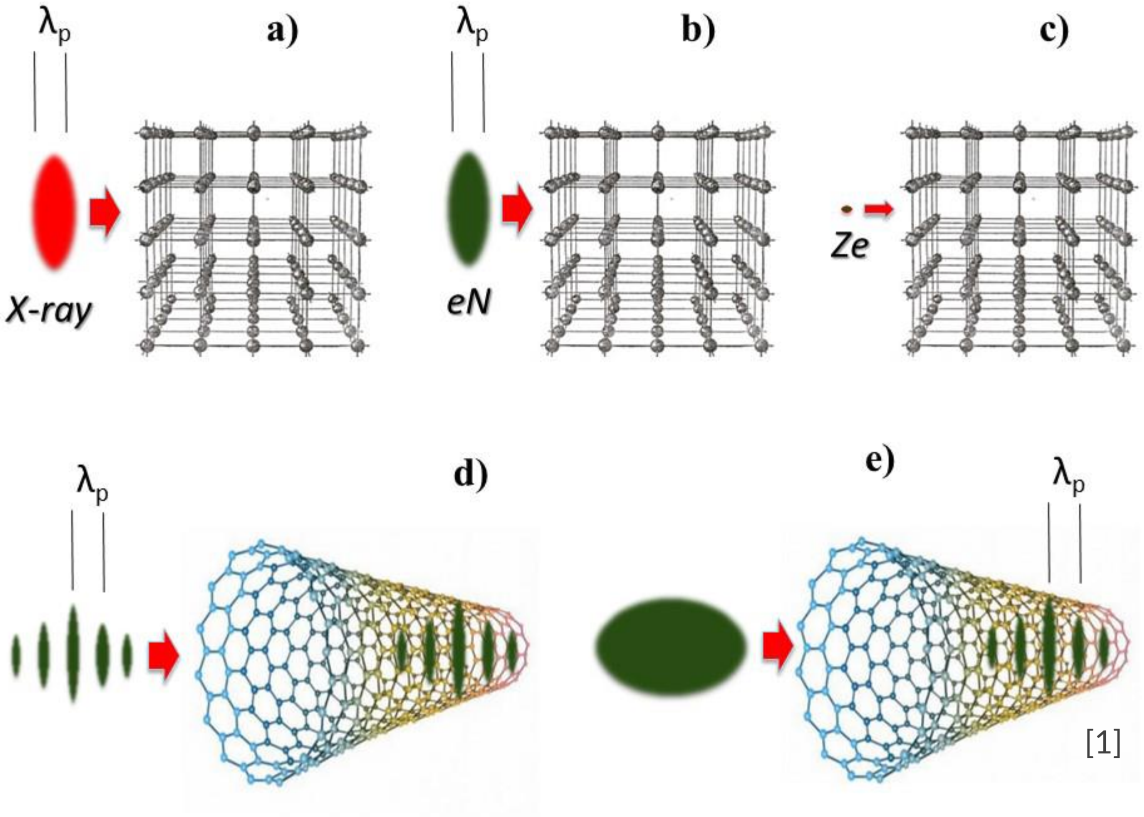
Solid density wakefield accelerators could produce fields of 10 TV/m.



Need a solid density nanostructure to provide the electrons

- At solid densities, scattering from plasma ions becomes significant

Acceleration in in a nanostructure provides high density plasma and limits scattering off the solid's ions.



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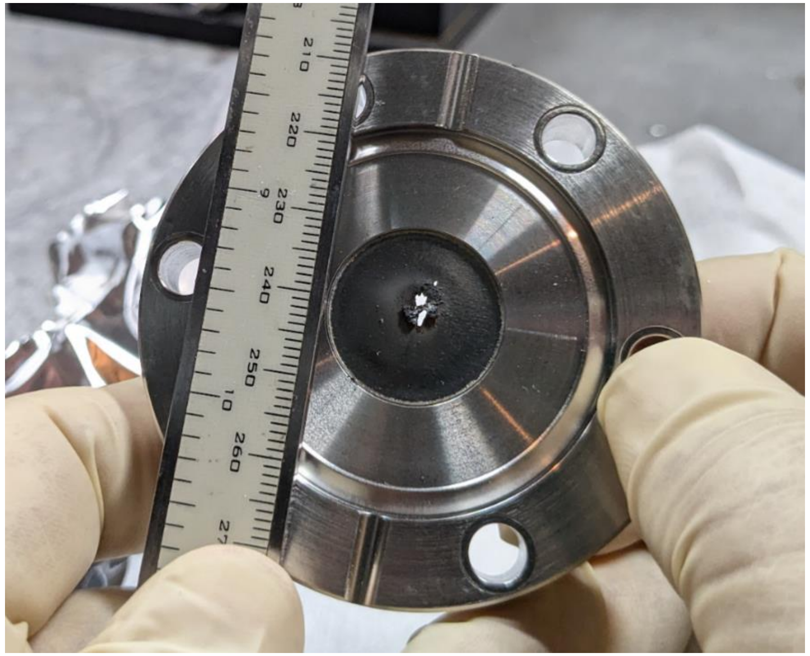
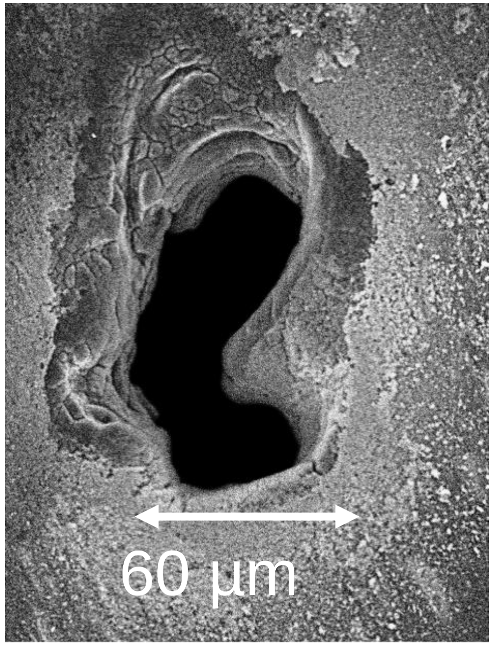
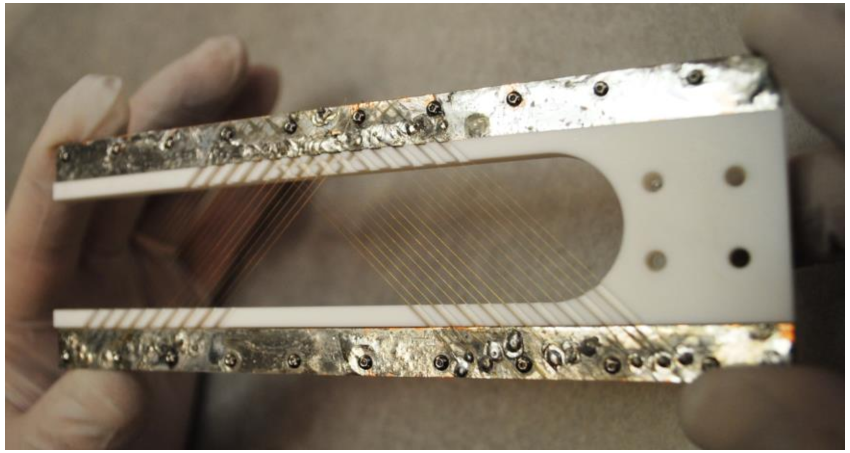
The FACET-II beam destroys most things placed in it

- Lots of standard beam measurements require inserting something into the beam
- Difficult anywhere near the electron beam focus



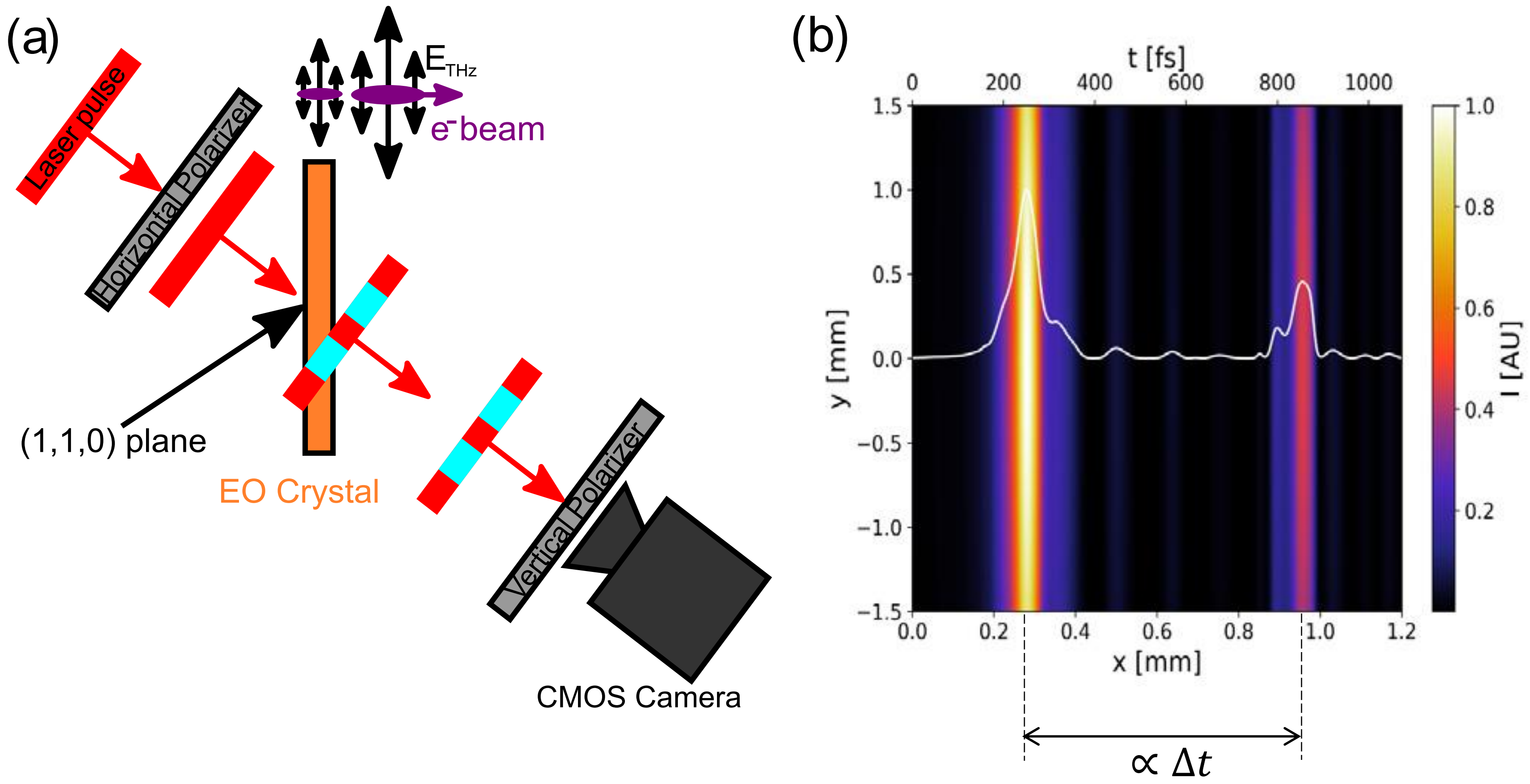




New wire scanner card

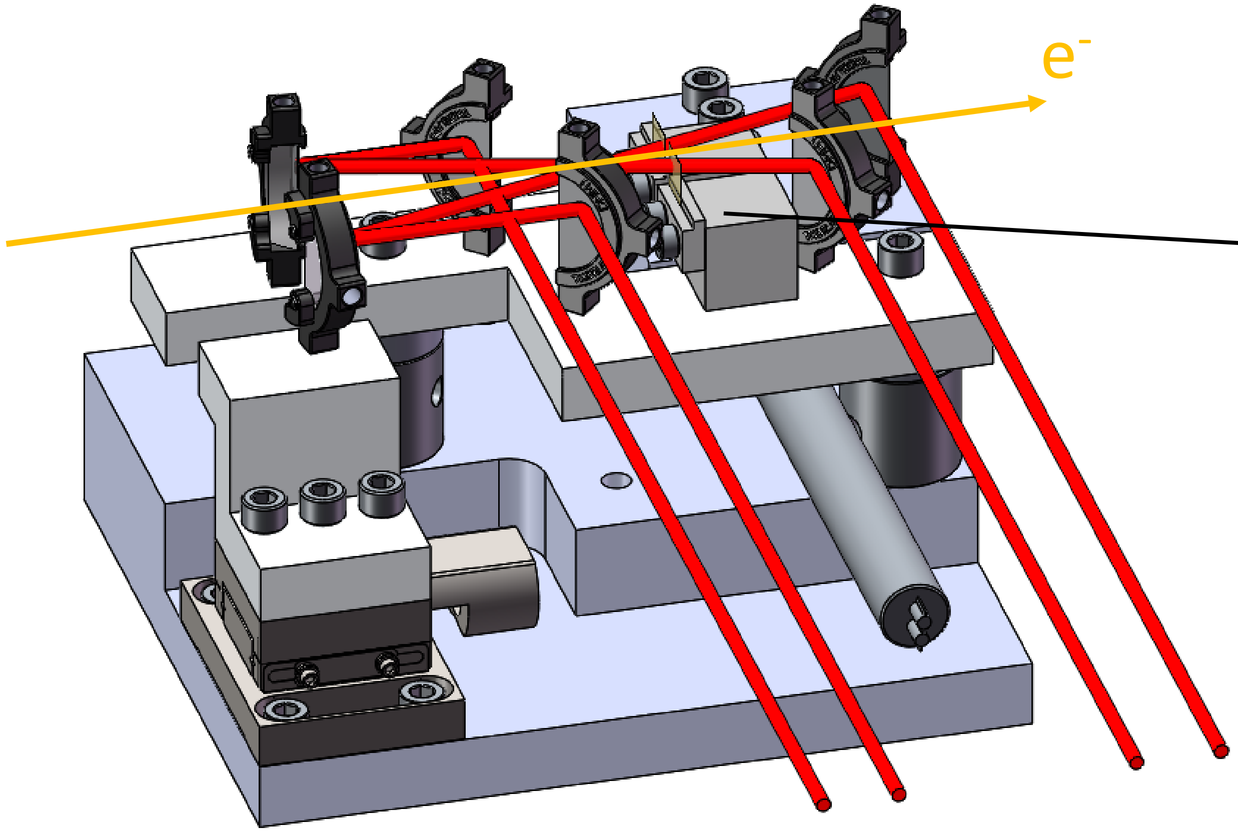
Wire scanner card halfway through a run

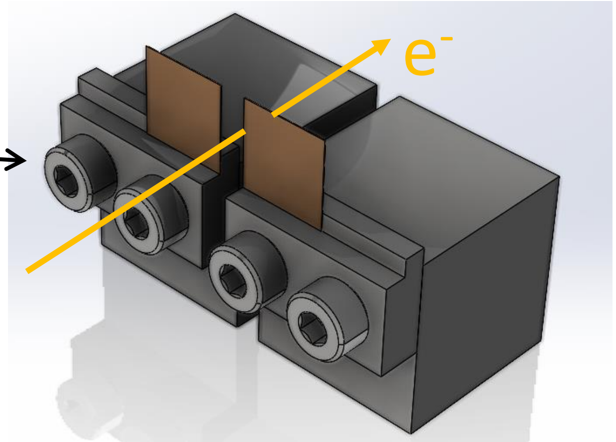
Electro-optic sampling based diagnostic



Tells you how far apart (in time) the bunches are

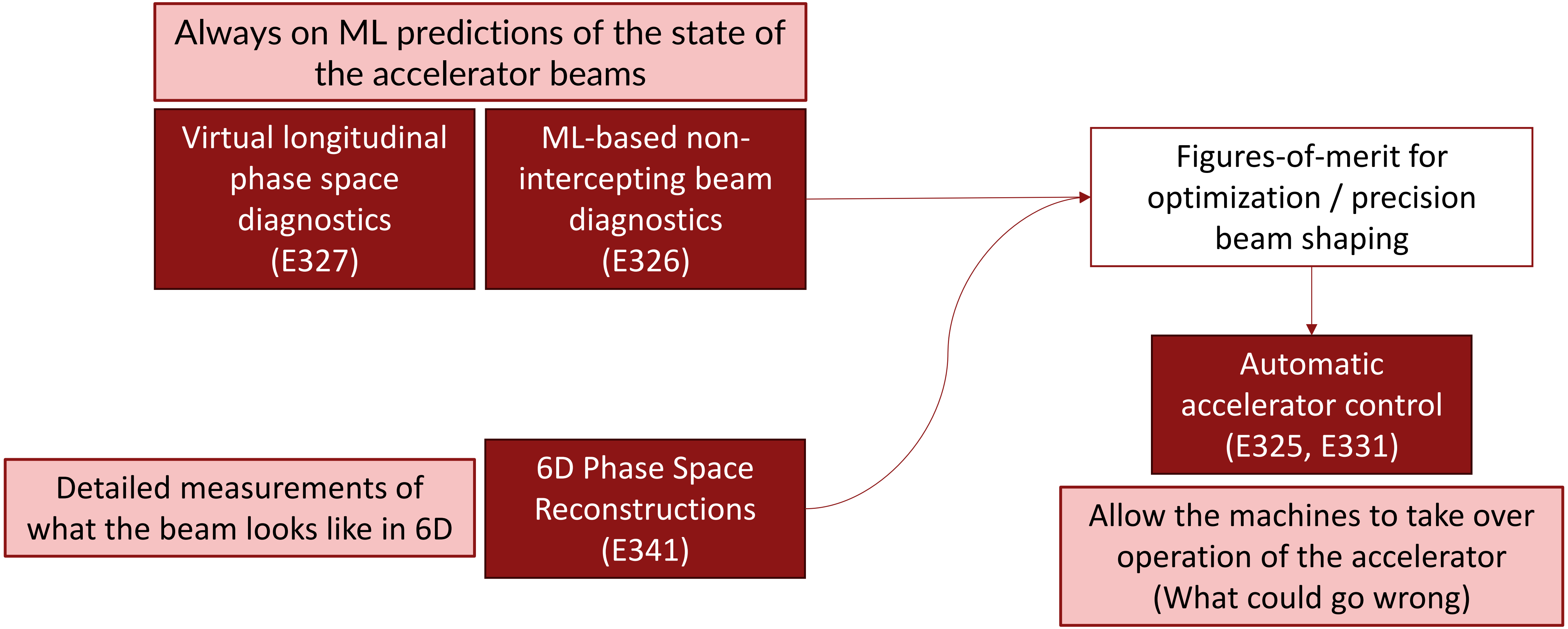
Two of them to measure the position of the beam



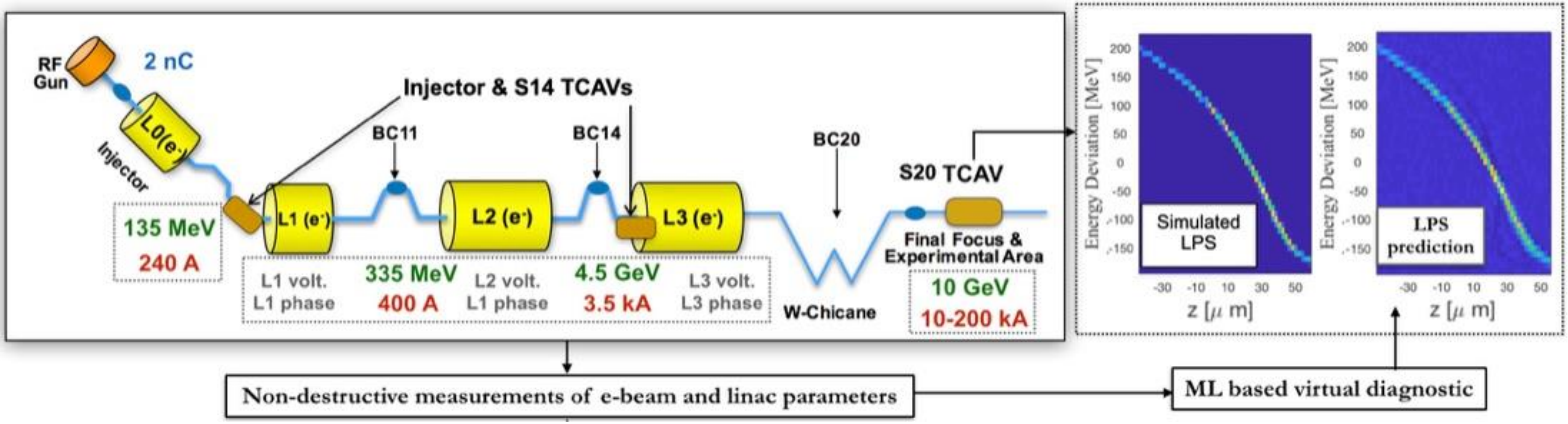


Relative signal in the two crystals tells you transverse position of the beam

Machine Learning at FACET-II

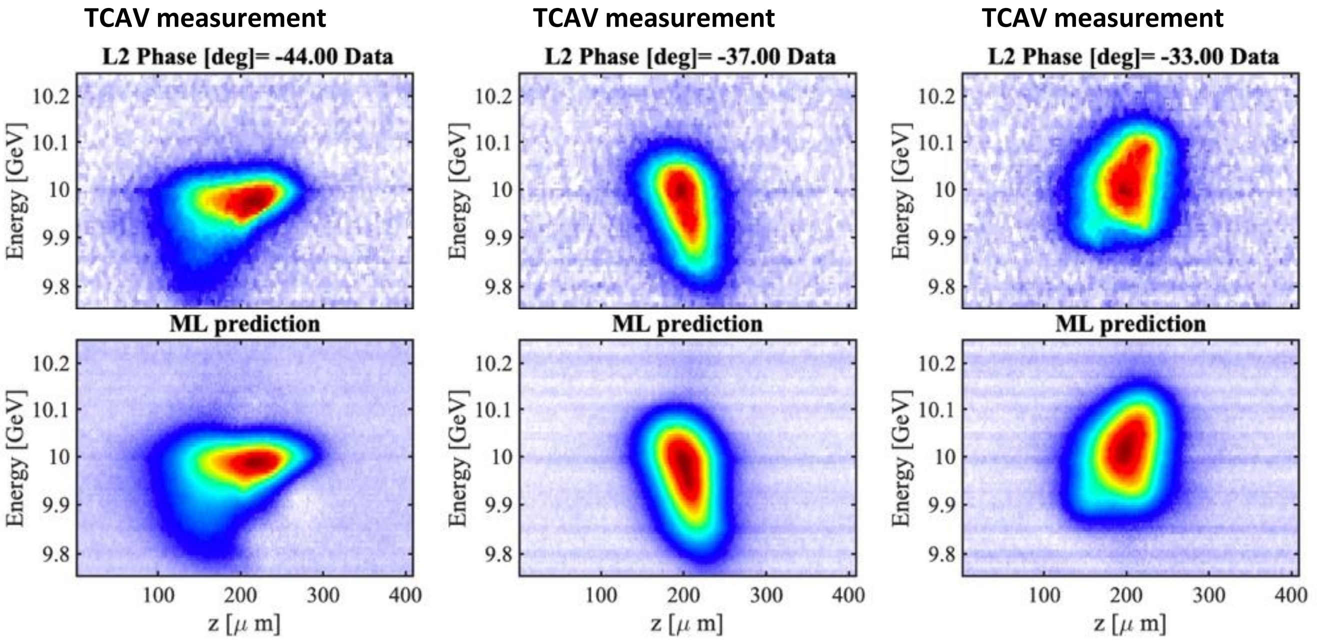


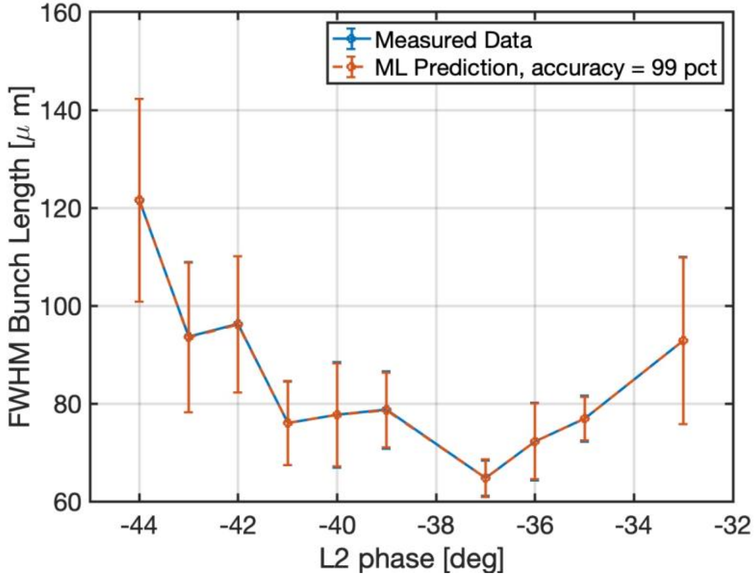
Virtual diagnostic for longitudinal phase space prediction



C. Emma and A. Edelen et al.,PRAB 21 112802 (2018)

Virtual diagnostic for longitudinal phase space prediction

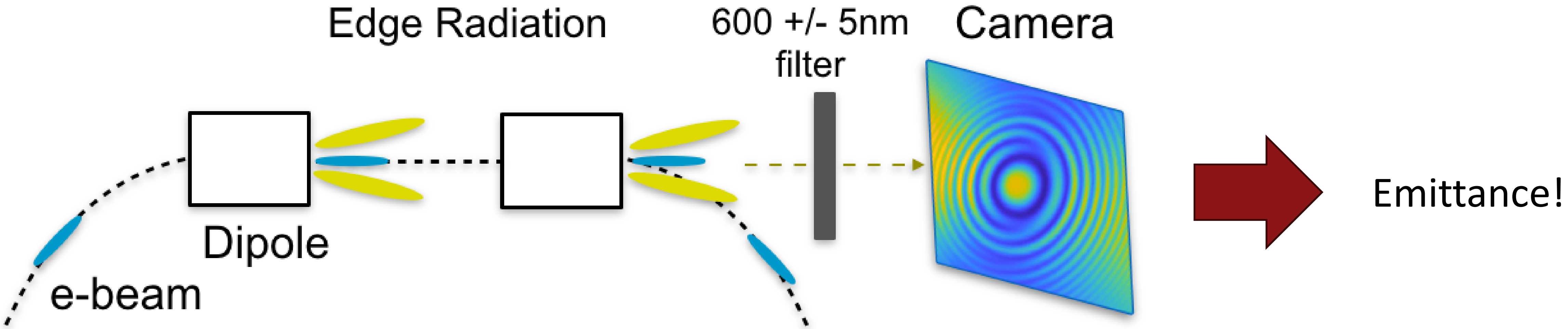




Use nondestructive measurements to reconstruct a destructive measurement.

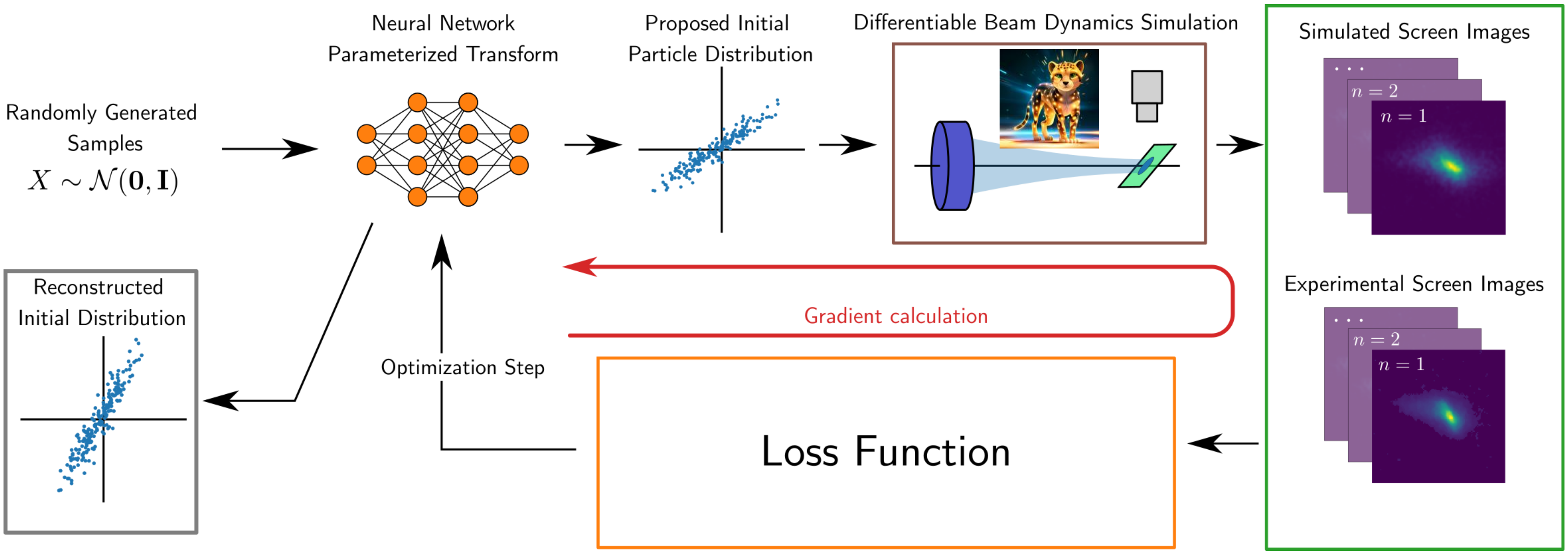
C. Emma and A. Edelen et al.,PRAB 21 112802 (2018)

Edge radiation diagnostic



Single shot non-destructive measurement of beam quality

6D phase space reconstruction of beam distributions



Roussel, Ryan, et al. PRL (2023)

ML based accelerator diagnostics tool to allow for much more detailed information of complex beams

Summary

- FACET-II
  - High current beams
  - Multiple bunches for PWFA

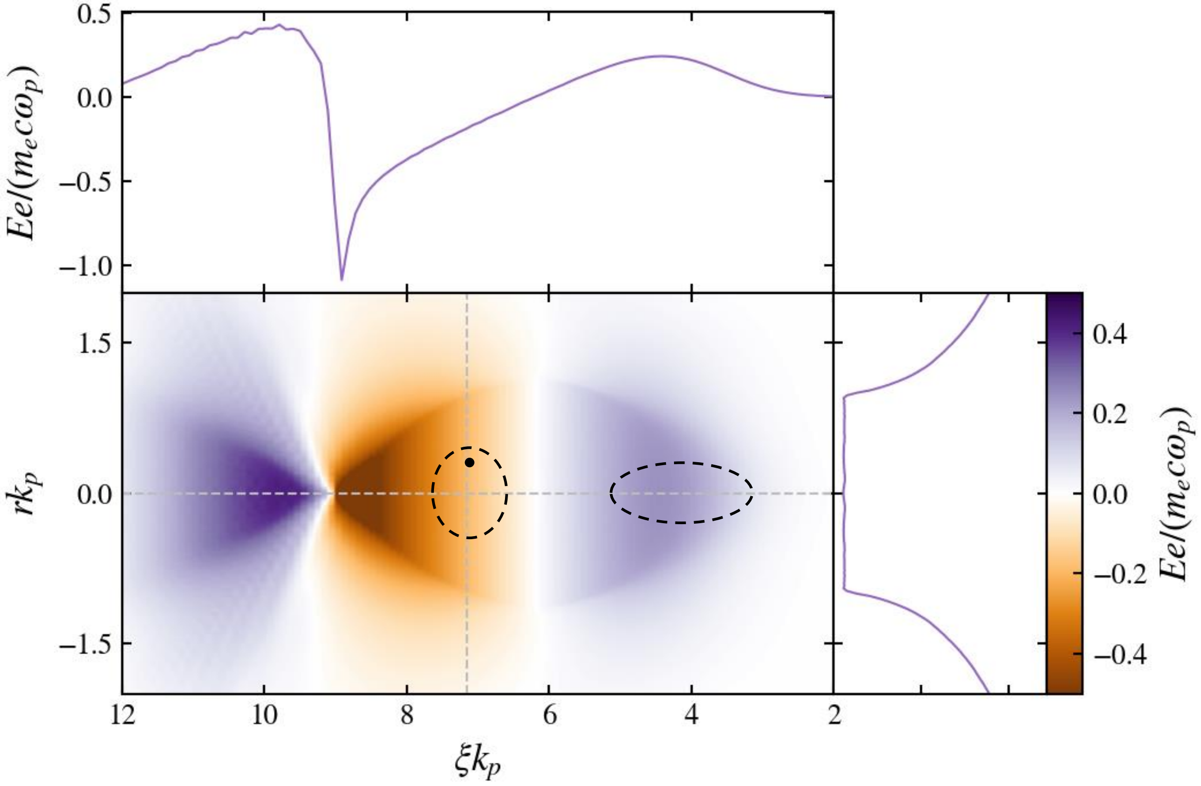
- Science program
  - Plasma wakefield acceleration
  - X-ray light sources
  - Strong field physics
    - Strong field quantum electrodynamics
    - Material interaction
    - Relativistic plasma instabilities
  - Accelerator diagnostics
    - Nondestructive diagnostics
    - Machine learning applied to accelerator diagnostics and control

Much more information can be found here:
https://facet-ii.slac.stanford.edu/

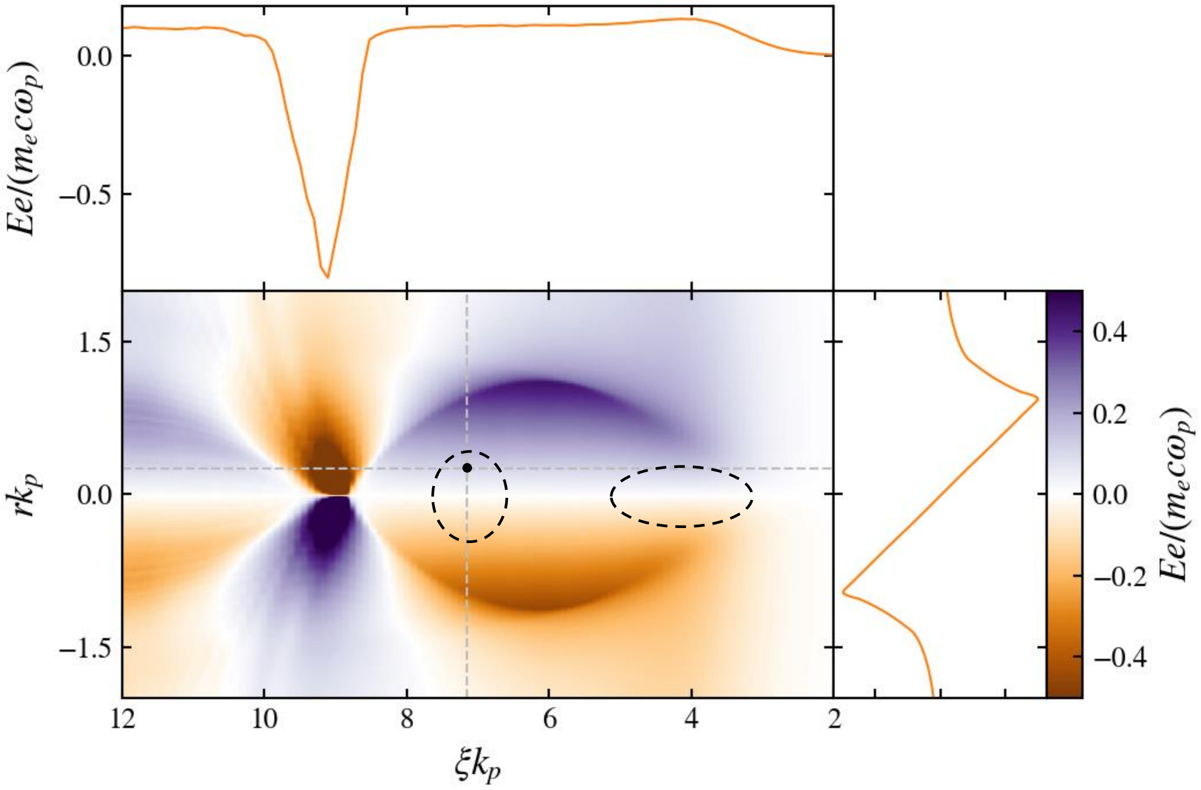
Questions?

Fields in the non-linear regime

Longitudinal electric field



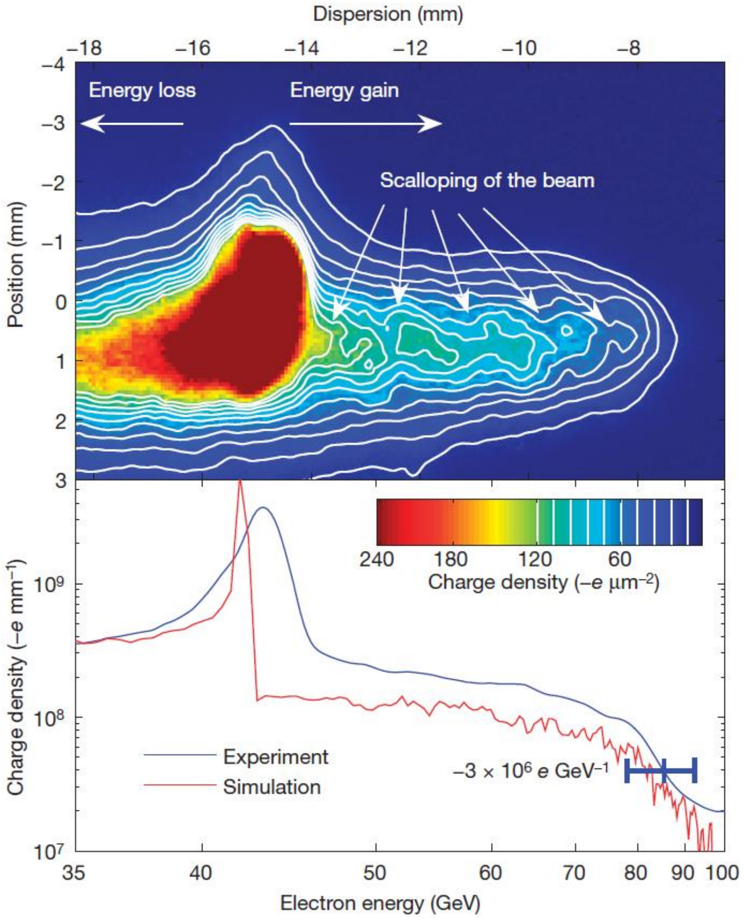
Transverse focusing field



Transverse focusing forces are linear in r.

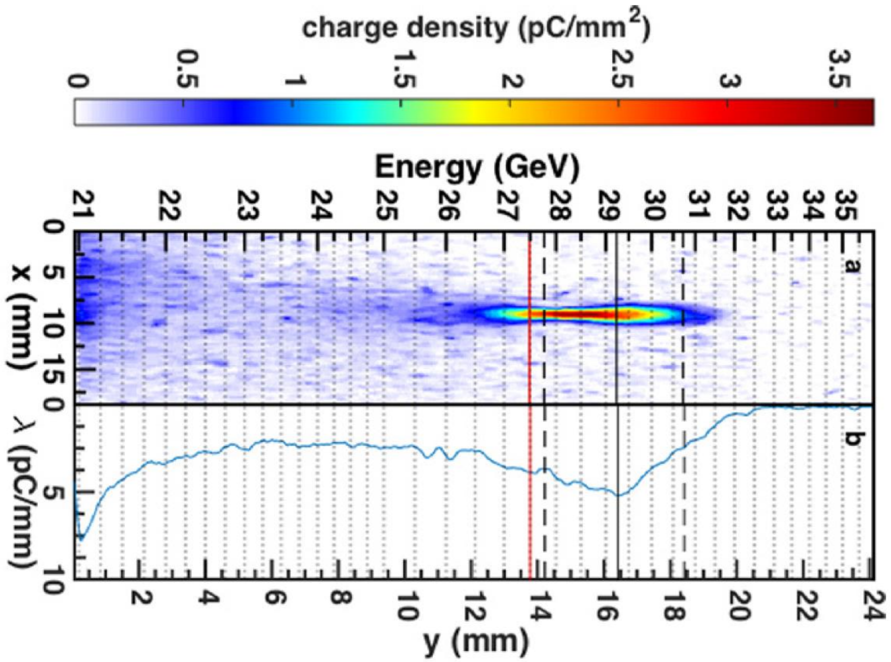
Plasma has demonstrated large gradients

52 GeV/m



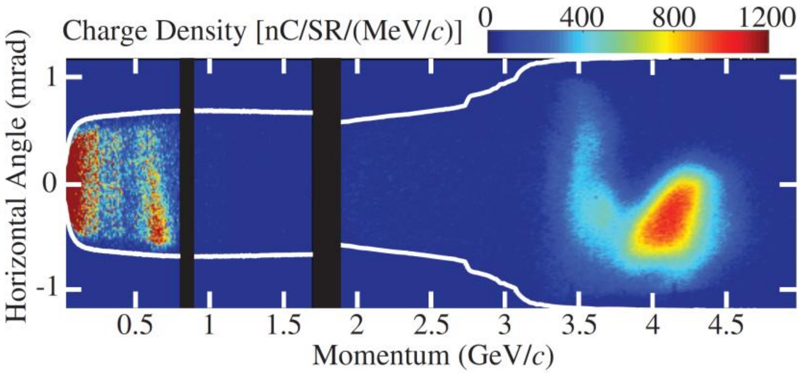
I. Blumenfeld, et al. *Nature* **445** 741 (2007)

6.9 GeV/m



M. Litos, et al. *Plas. Phys. Cont. Fusion* **58** 034017 (2016)

47 GeV/m



W.P. Leemans, et al. *Nat. Phys.* **113** 245002 (2014)

Gradients of 50 GeV/m have been demonstrated.

Energy and gradient aren't the only story, quality matters!

No cares if you can't make an XFEL/collider out of it!

Luminosity

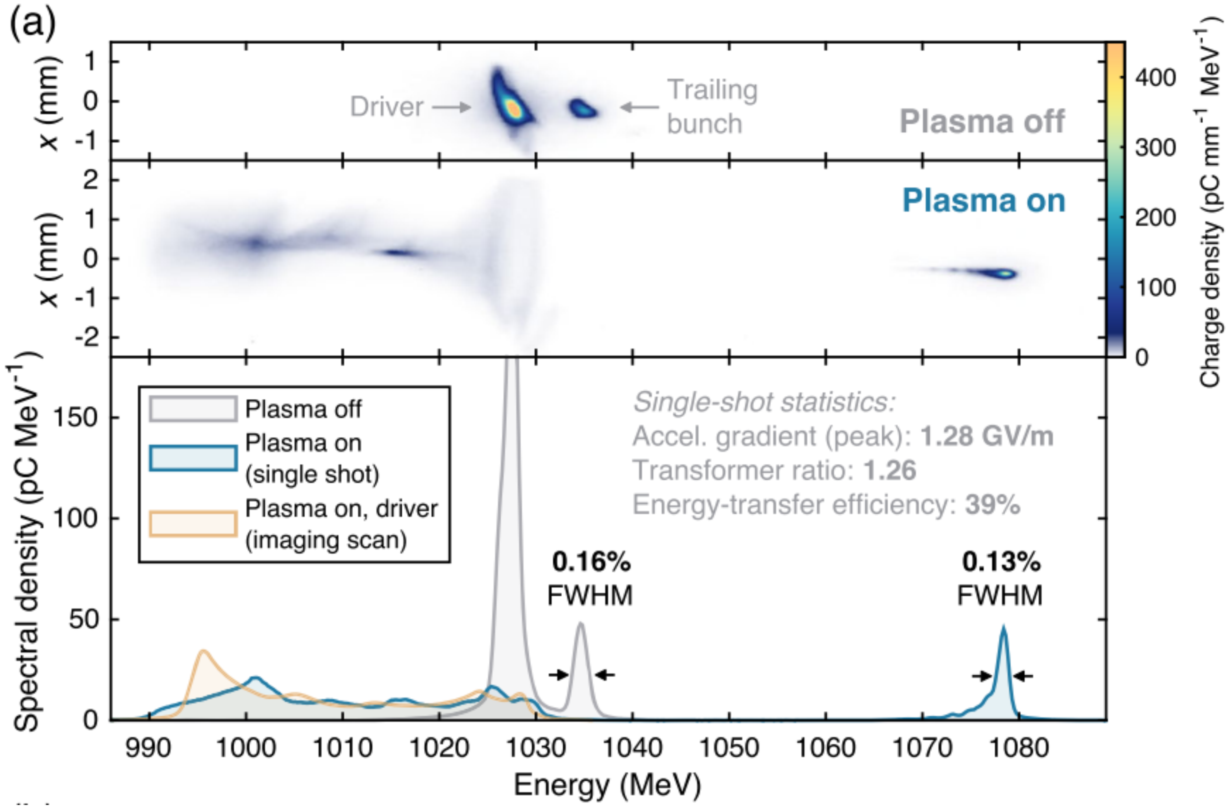
$$\mathcal{L} \propto \frac{Q_1 Q_2}{\sqrt{\beta_x \beta_y \epsilon_x \epsilon_y}}$$

Need:

- Lots of charge
- Low energy spread
- Small emittance
- High efficiency

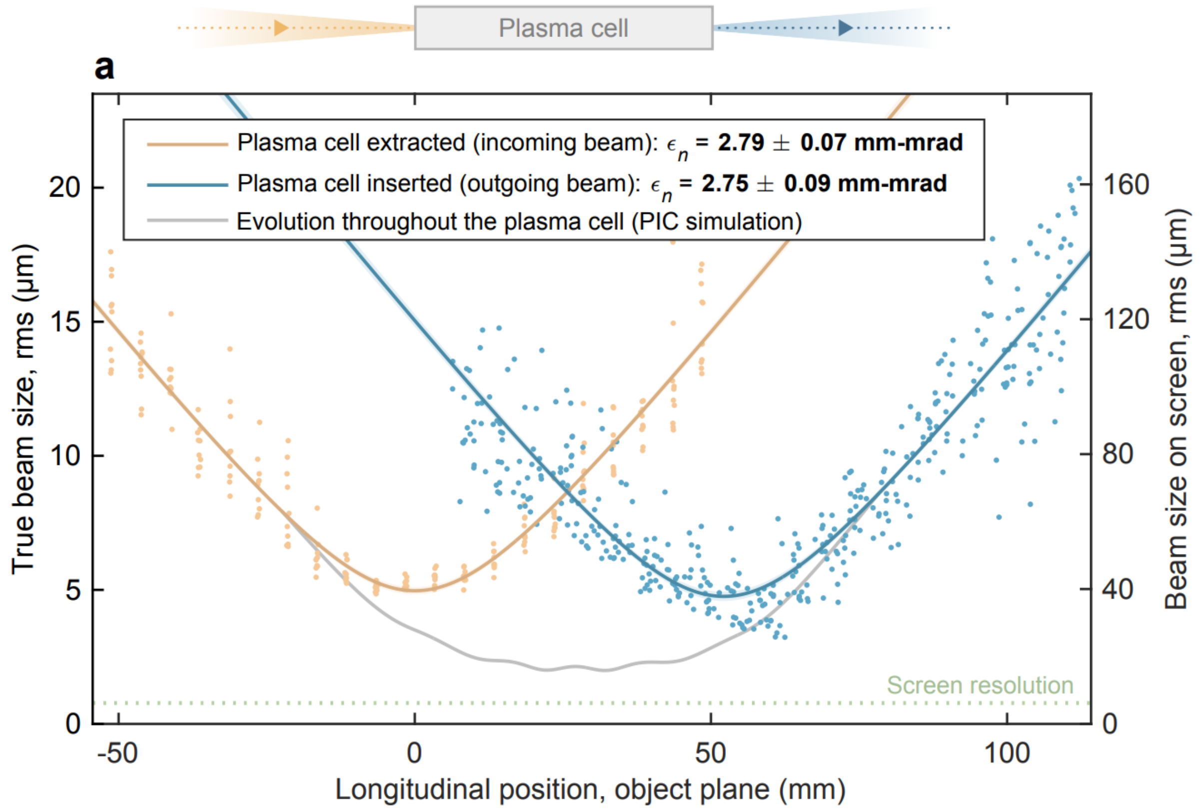
Each of these have been demonstrated

0.13% energy spread



Lindstrom, et al. *Phys. Rev. Lett.* **126** 014801 (2021)

2.75um-rad emittance



Lindstrom, et al. Preprint, (2022)

Chromatic emittance growth in a plasma

In a nonlinear plasma accelerator, the ion column exerts a linear, radial focusing force on the beam.

Motion in an ion column:

$$x'' + \frac{\gamma_b'}{\gamma_b} x' + k_\beta^2 x = 0$$

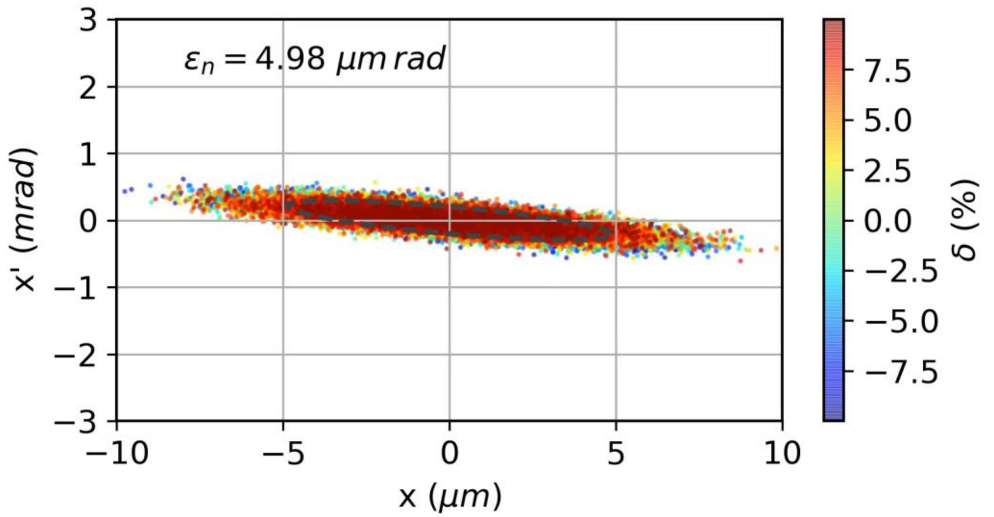
Oscillation frequency depends on particle energy:

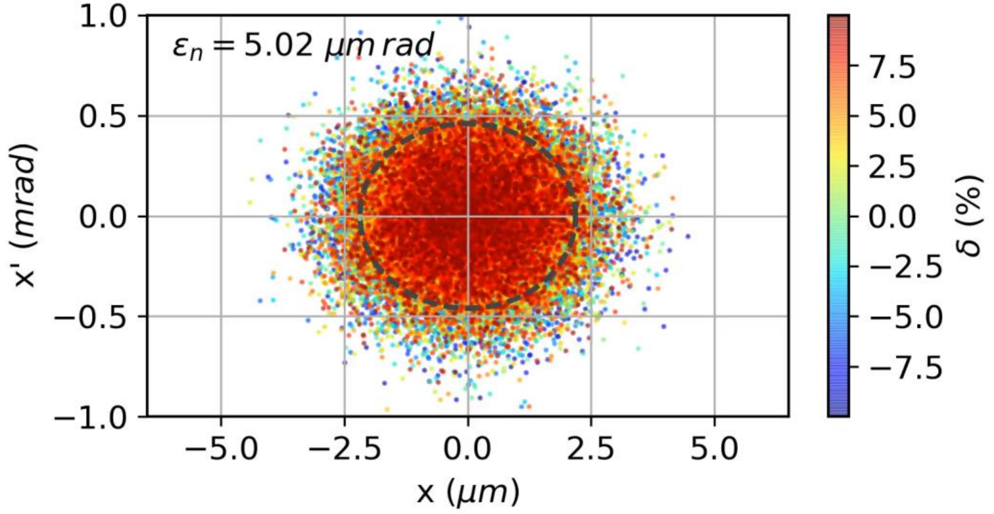
$$k_\beta \propto 1/\sqrt{\gamma_b}$$

Chromatic phase spread causes projected emittance growth for an electron bunch in an ion column.

Emittance growth is minimized when different energy particles overlap in phase space – matched beam.

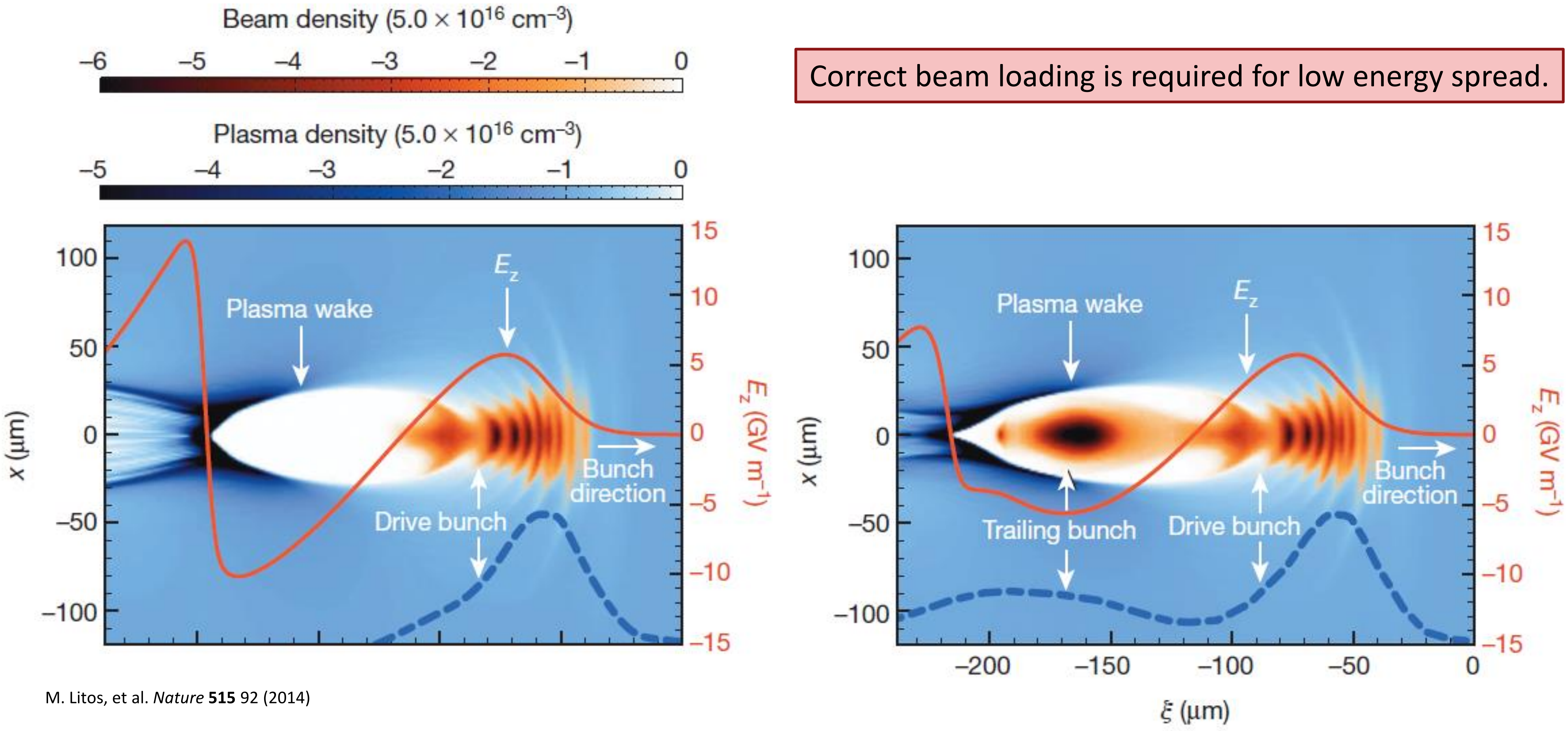
Emittance growth is a major problem that must be solved in order for plasma-based accelerators to be useful.





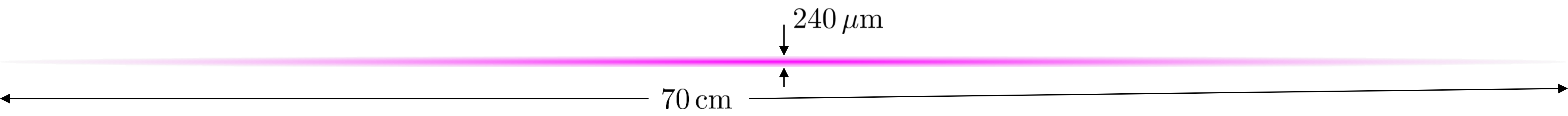
Beam loading

Correct beam loading is required for low energy spread.



M. Litos, et al. *Nature* **515** 92 (2014)

Plasma source

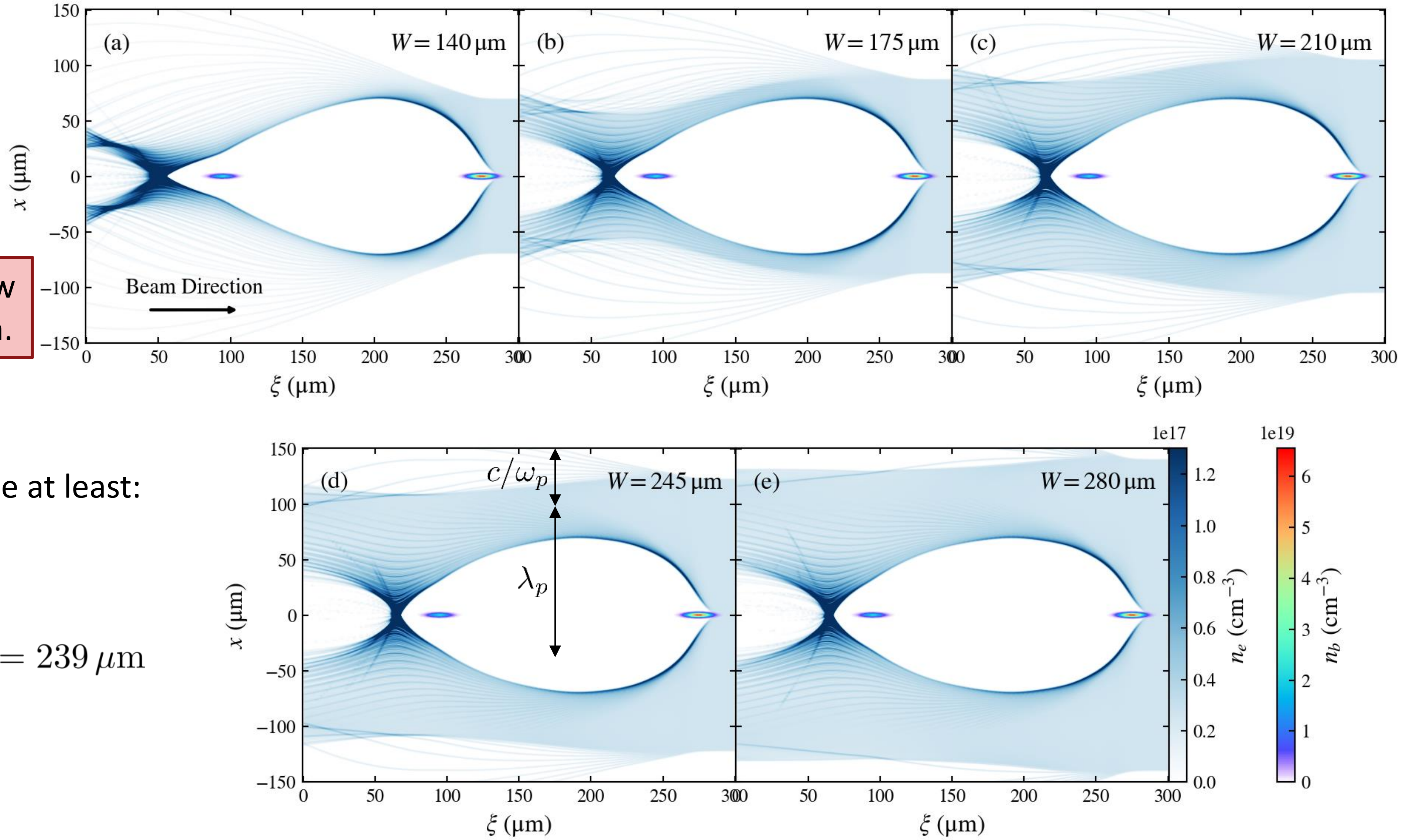


Parameter	Requirement
Density	$3.4 \times 10^{16}\,\mathrm{cm}^{-3}$
Length	$48\,\mathrm{cm}$
Width	$239\,\mu\mathrm{m}$
Entrance Ramp	$\beta^*/\beta_m = 10$
Exit Ramp	$\beta^*/\beta_m \approx 10$

Using Gaussian ramps, the entrance ramp length is $\sigma_{ent} = 4.9\,\mathrm{cm}$

Lots of work to create a good plasma source

Lots of work to figure out how to make/optimize the plasma.

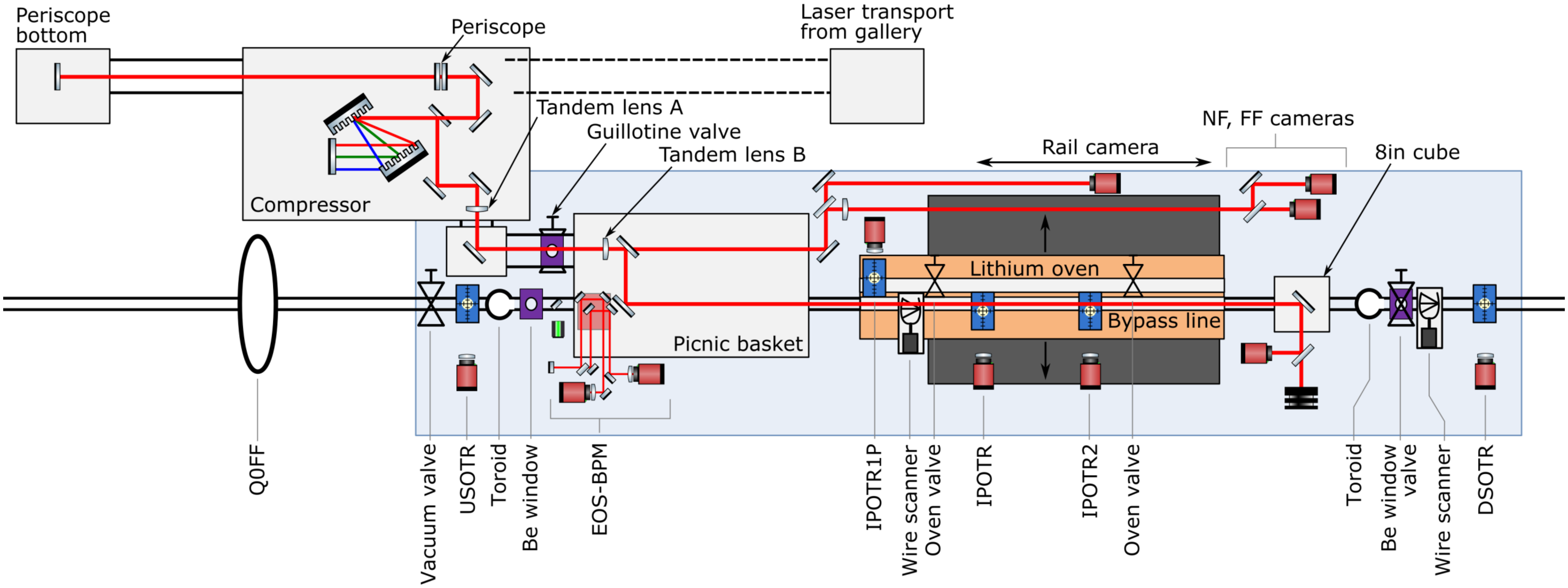


Plasma width needs to be at least:

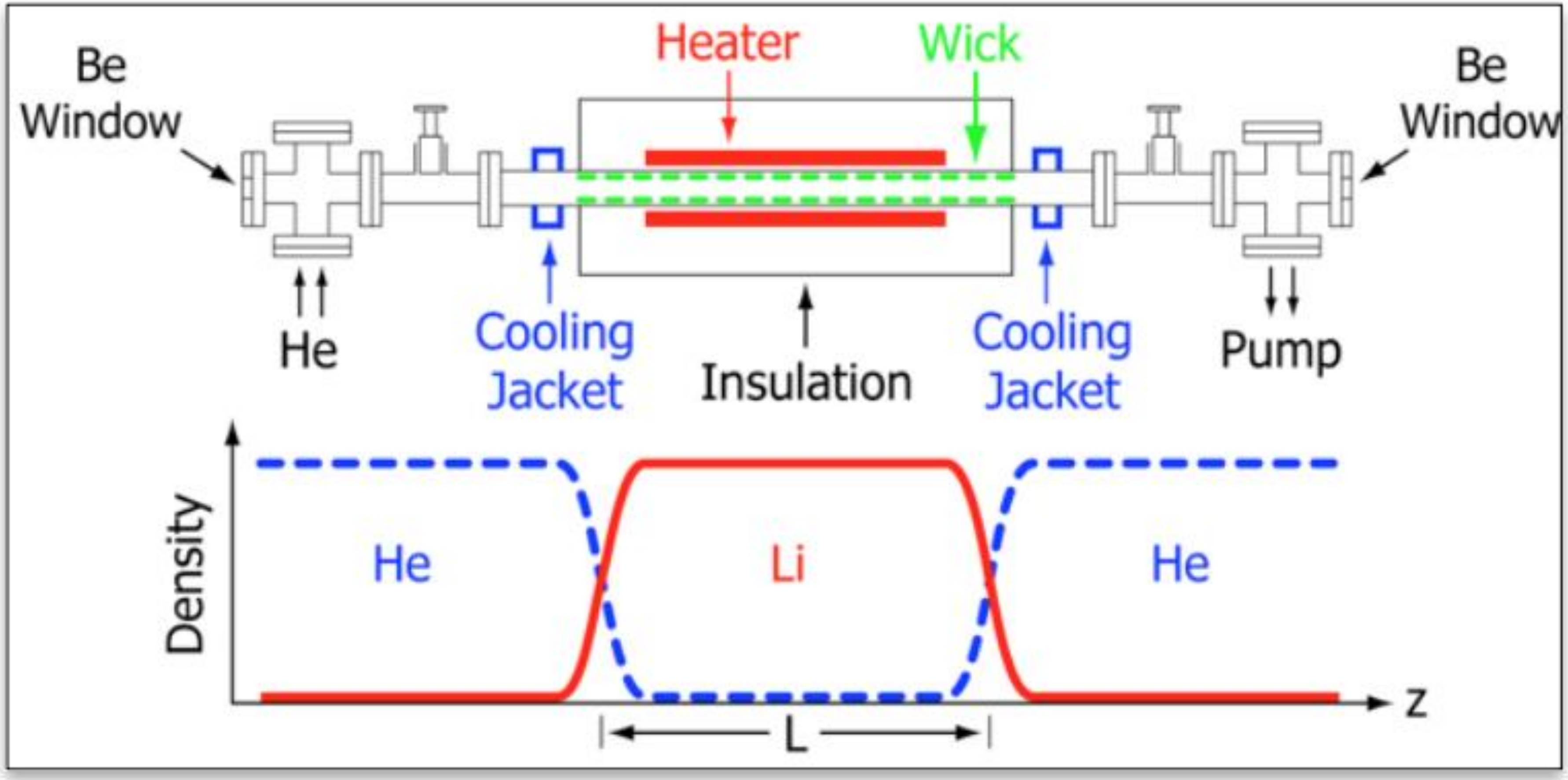
$$W = \lambda_p + 2\frac{c}{\omega_p}$$

At $3.5 \times 10^{16}\,\mathrm{cm}^{-3}$, $W = 239\,\mu\mathrm{m}$

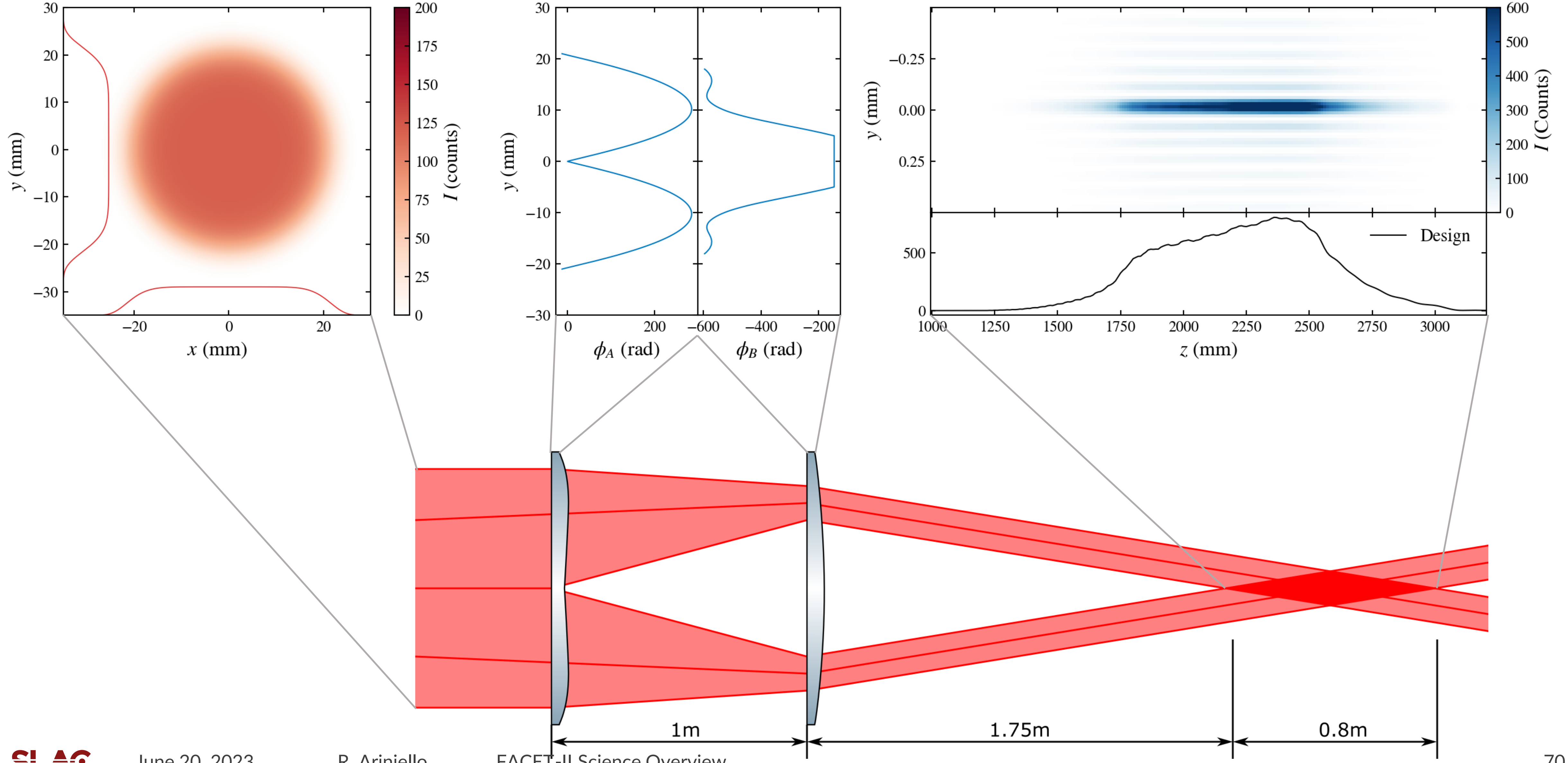
IP area – where the PWFA happens



Lithium vapor oven



Laser ionized plasma sources



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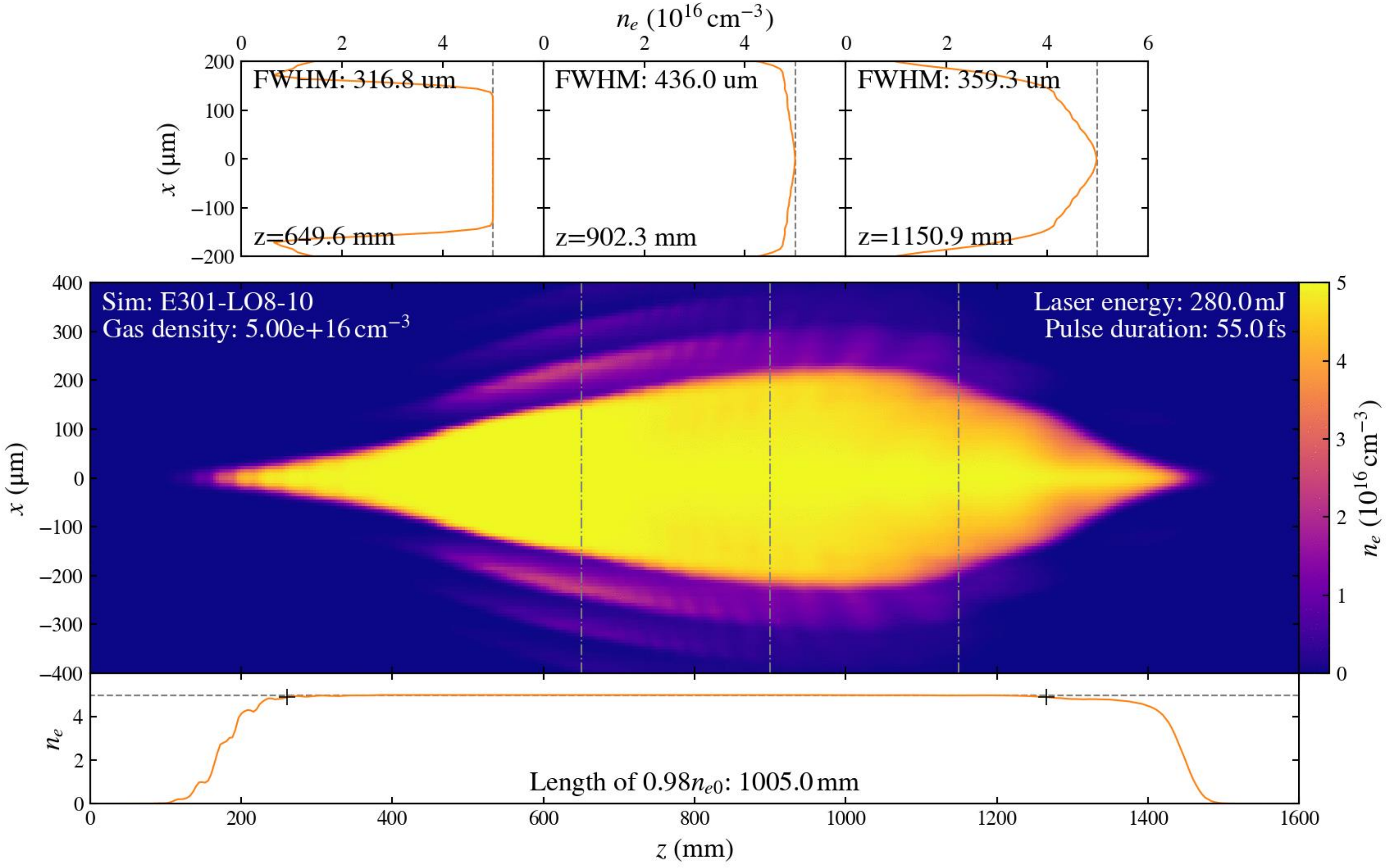
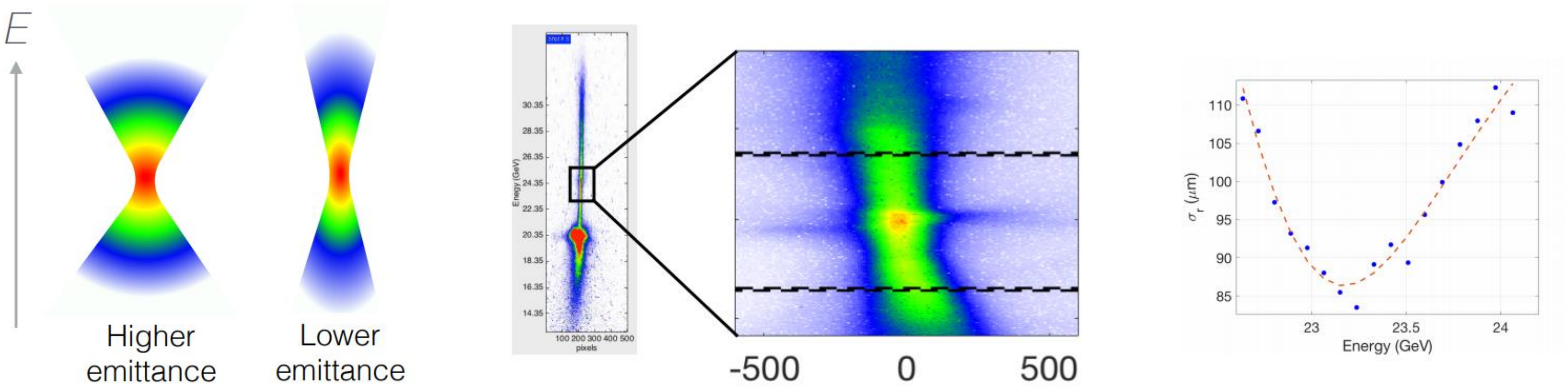


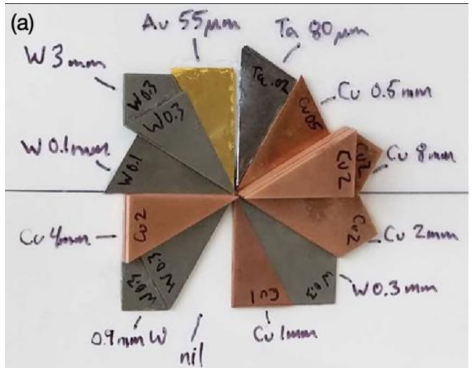
Diagnostics – butterfly technique



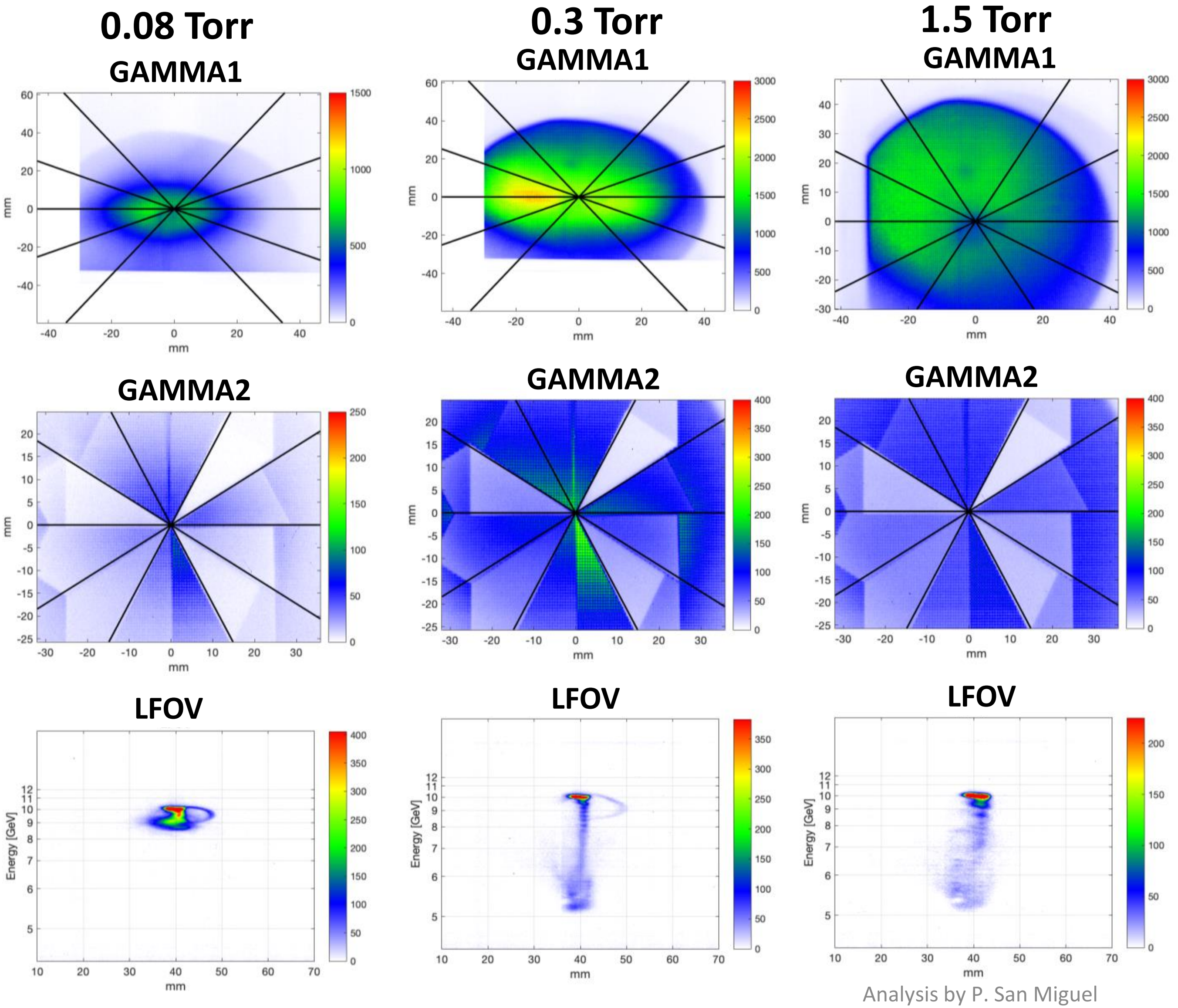
C. A. Lindstrom, 2016 FACET II Science Workshop

Diagnostics – gamma and x-ray

- GAMMA1 detector measures intensity and angular profile
  - DRZ scintillator or CsI crystal array
- GAMMA2 provides spectral info by measuring conversion signal behind filters
  - Filter set:
  - DRZ scintillator immediately sits behind



- Provides information on matching dynamics, trailing bunch offsets, etc



Analysis by P. San Miguel

Slide from Doug Storey