Bright Radiation Source based on Plasma-micro-bunched Diamond Beam

James Holloway

University College London, London, UK

PhD Supervisors:

Professor Matthew Wing

University College London, London, UK

Professor Peter Norreys

University of Oxford, Oxfordshire, UK

Central Laser Facility, Rutherford Appleton Laboratory, UK

Synchrotron Facilities Worldwide

Image Source: http://www.veqter.co.uk/residual-stress-measurement/synchrotron-diffraction

Synchrotron Facilities Europe

Image Source: http://www.veqter.co.uk/residual-stress-measurement/synchrotron-diffraction

Synchrotron Facilities Europe

Electron beam length
Proton beam length

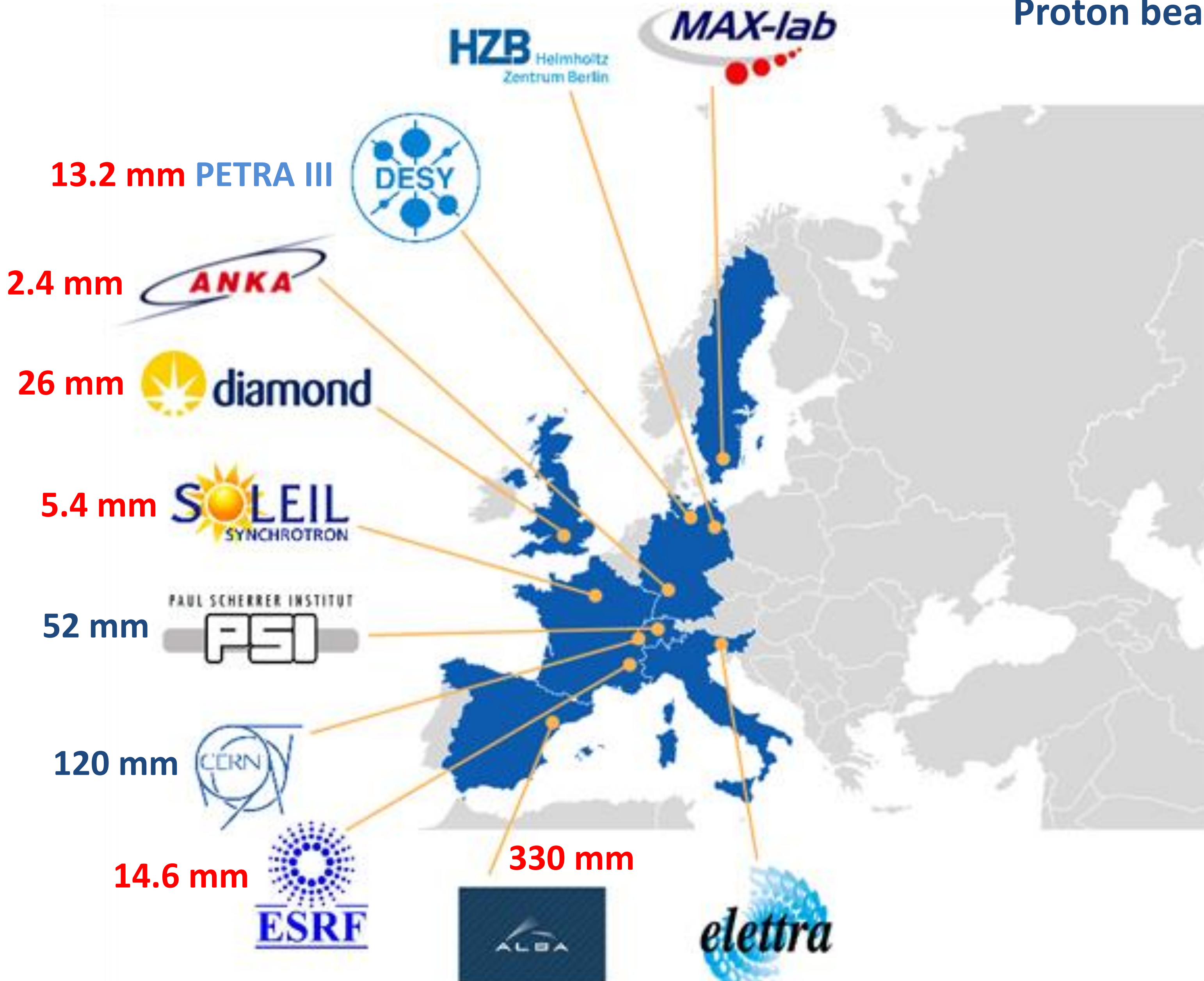


Image Source: http://www.veqter.co.uk/residual-stress-measurement/synchrotron-diffraction

The Goal

- Use existing facilities' beams to drive PWA
- Accelerate higher energy beams using PWA
- Generate harder X-rays from 3rd generation light sources

The Problem

- These beams are too long to drive effective wakefields
- Existing beam lines have limited space
- Longitudinal compression via magnetic chicanes takes considerable space and expense

$\sigma_{ideal} = \lambda_p / (\pi\sqrt{2})$

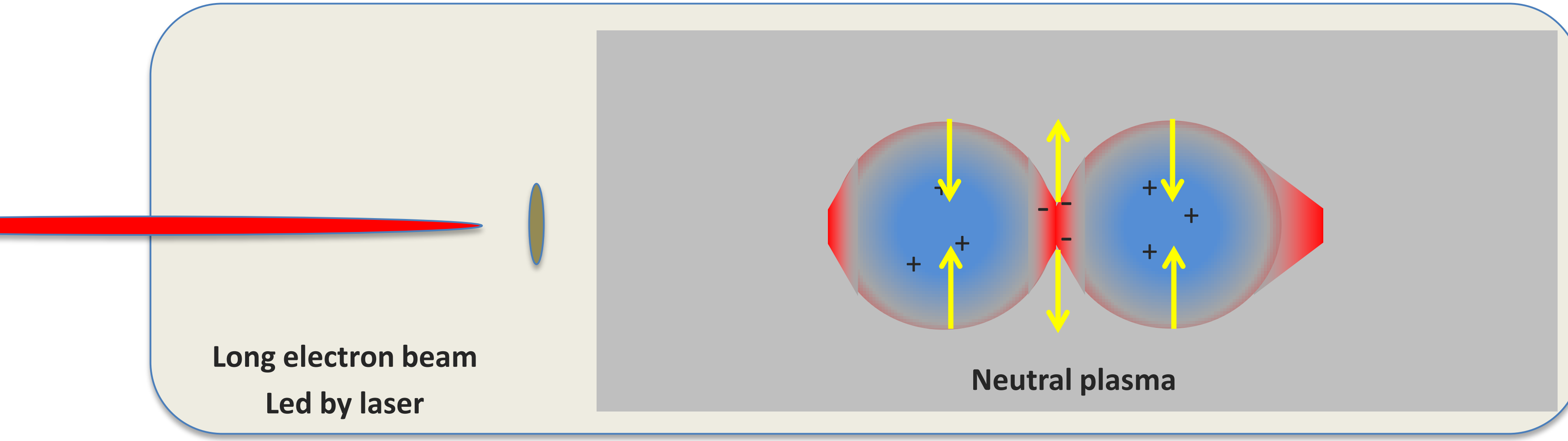
Need beam lengths of:

$\sigma_z < 1$ mm

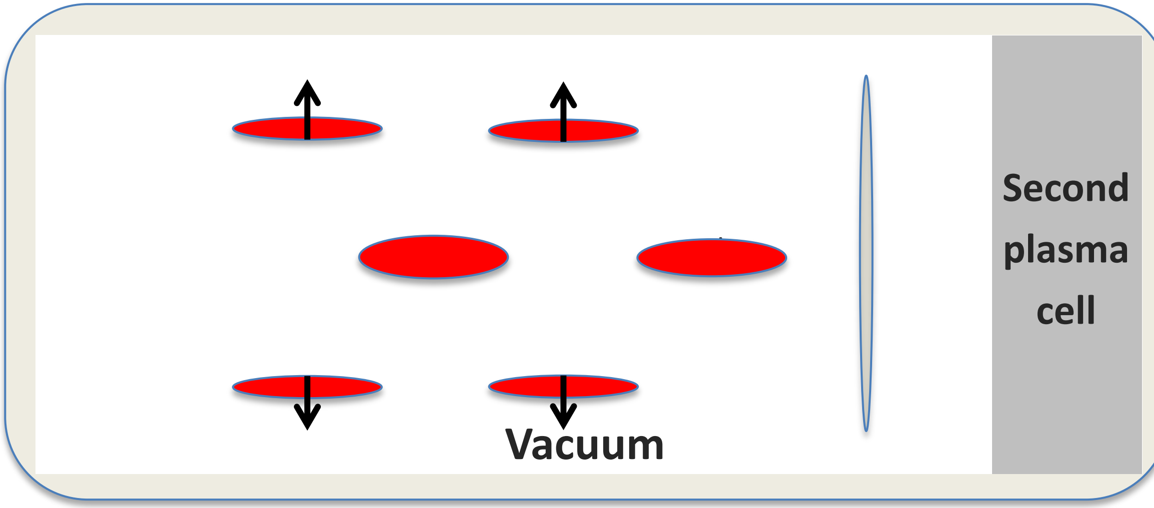
The Solution

- Micro-bunch beams to make them an effective wakefield driver

Micro-Bunching Via Wakefield Kick and Drift Space

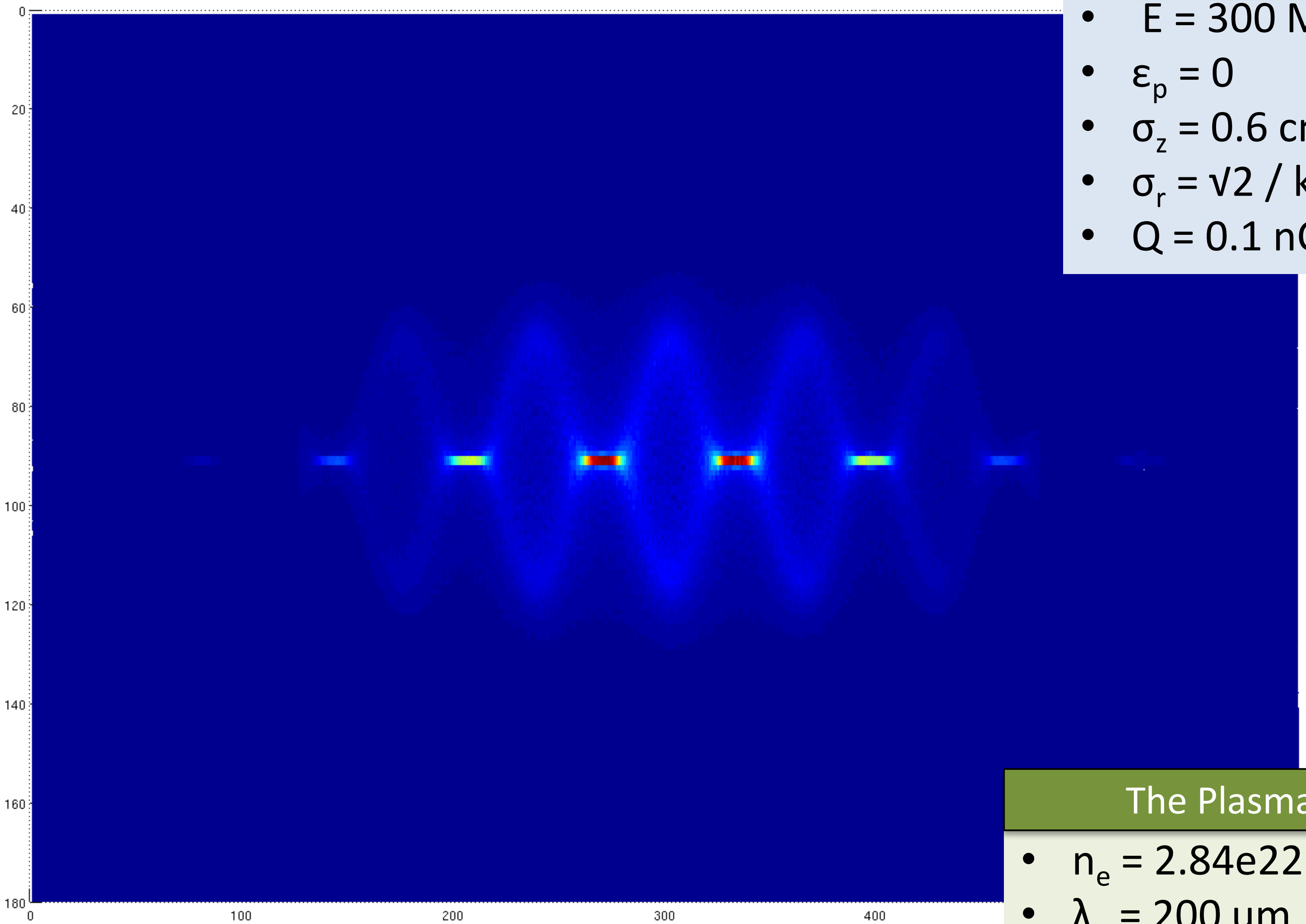


- Strong transverse kick from laser wakefield
- **Propagate beam through vacuum**
- Pass micro-bunches into second plasma stage when on-axis number density maximised



Micro-bunched driver beam.

Beam number density. 51 mm of propagation



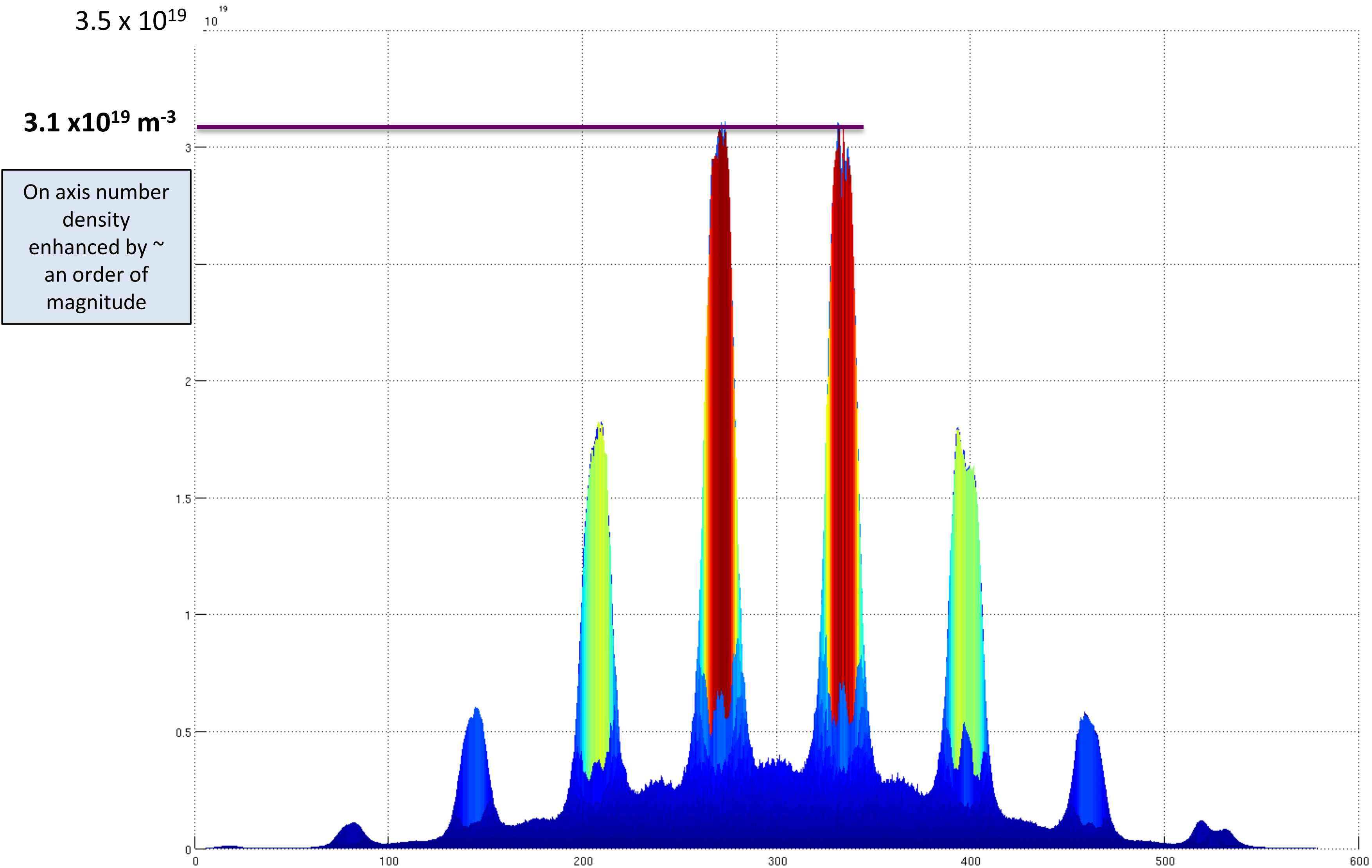
Electron beam

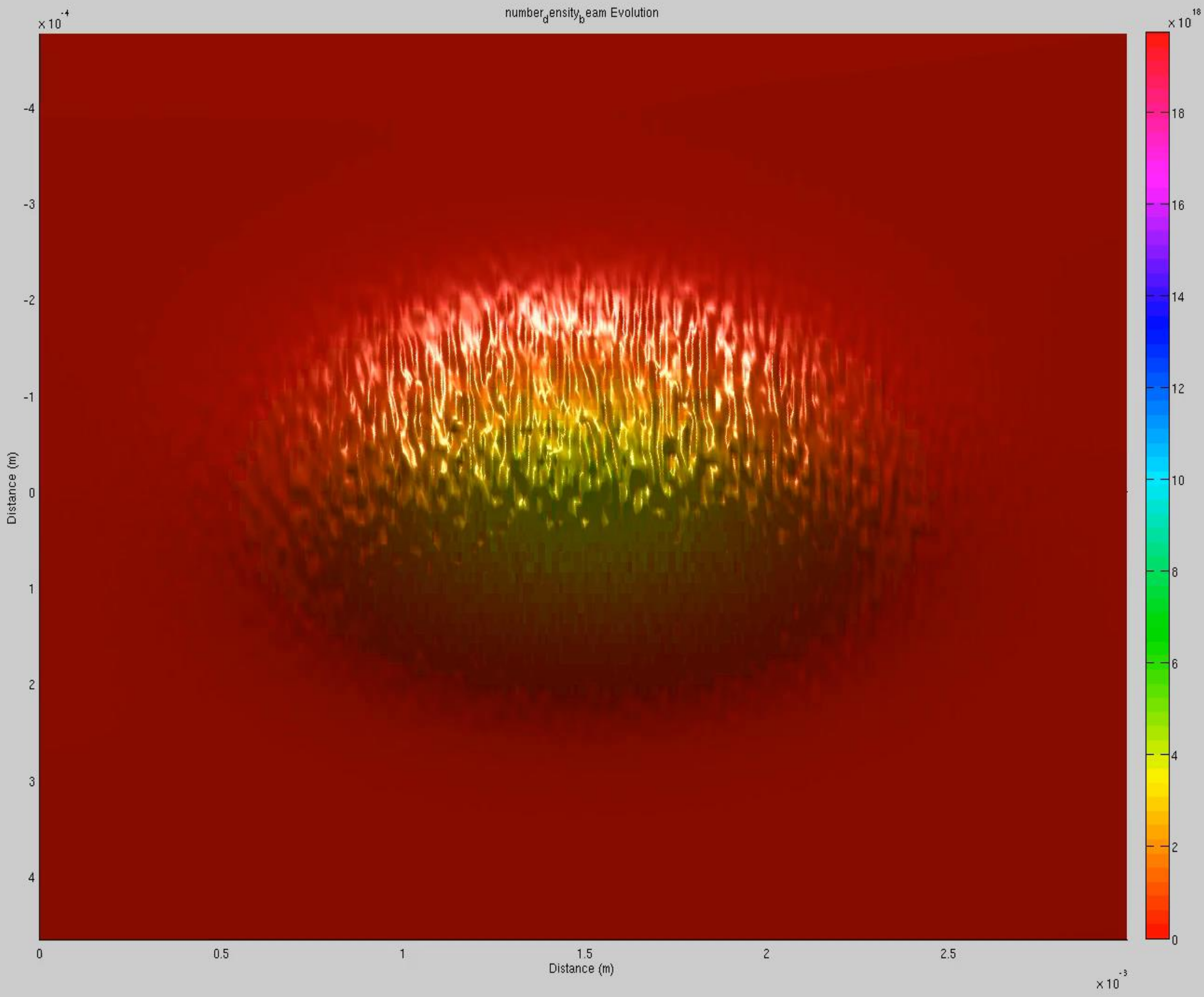
- $E = 300$ MeV
- $\varepsilon_p = 0$
- $\sigma_z = 0.6$ cm
- $\sigma_r = \sqrt{2} / k_p$
- $Q = 0.1$ nC

The Plasma

- $n_e = 2.84e22\ m^{-3}$
- $\lambda_p = 200$ um
- $E_r = 1\ GVm^{-1}$

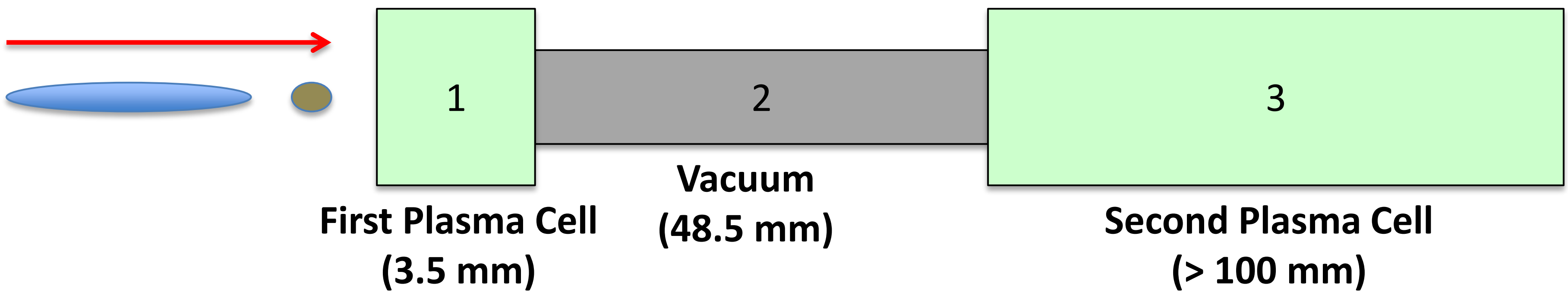
Beam number density. 51 mm of propagation





number_density_beam Evolution
× 10^-4
-4
-3
-2
-1
0
1
2
3
4
Distance (m)
0
0.5
1
1.5
2
2.5
Distance (m)
× 10^-3
× 10^18
18
16
14
12
10
8
6
4
2
0

The ‘Drift Space’ Design



1) The long beam given transverse momentum by strong wakefield.

2) Micro-bunches form as half e- defocused, other half focused

3) At the moment the beam has achieved best micro-bunching*, pass into the second plasma cell.

Electron beam

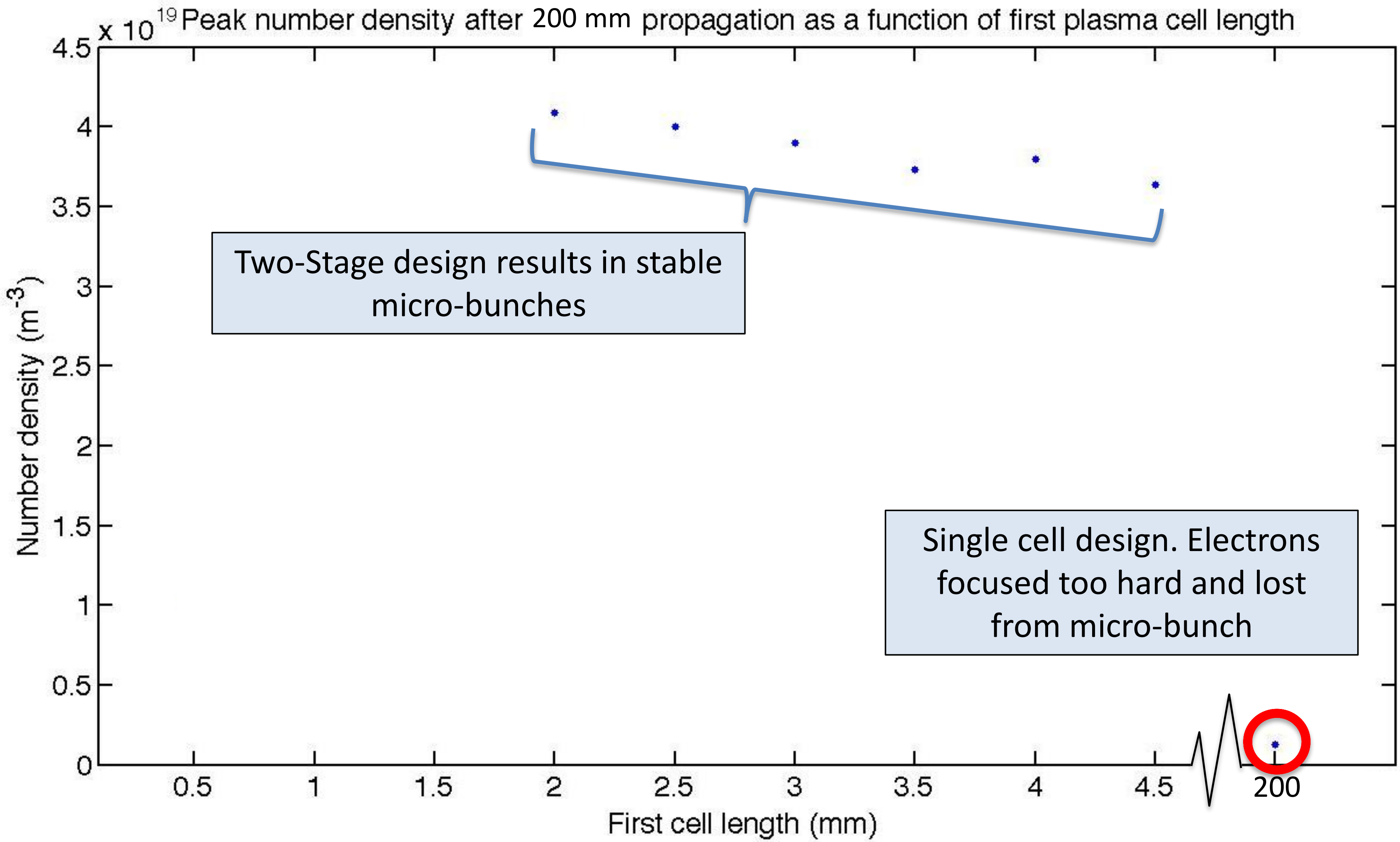
- E = 300 MeV
- $\varepsilon_p = 0$
- $\sigma_z = 0.6$ cm
- $\sigma_r = \sqrt{2} / k_p$
- Q = 0.1 nC

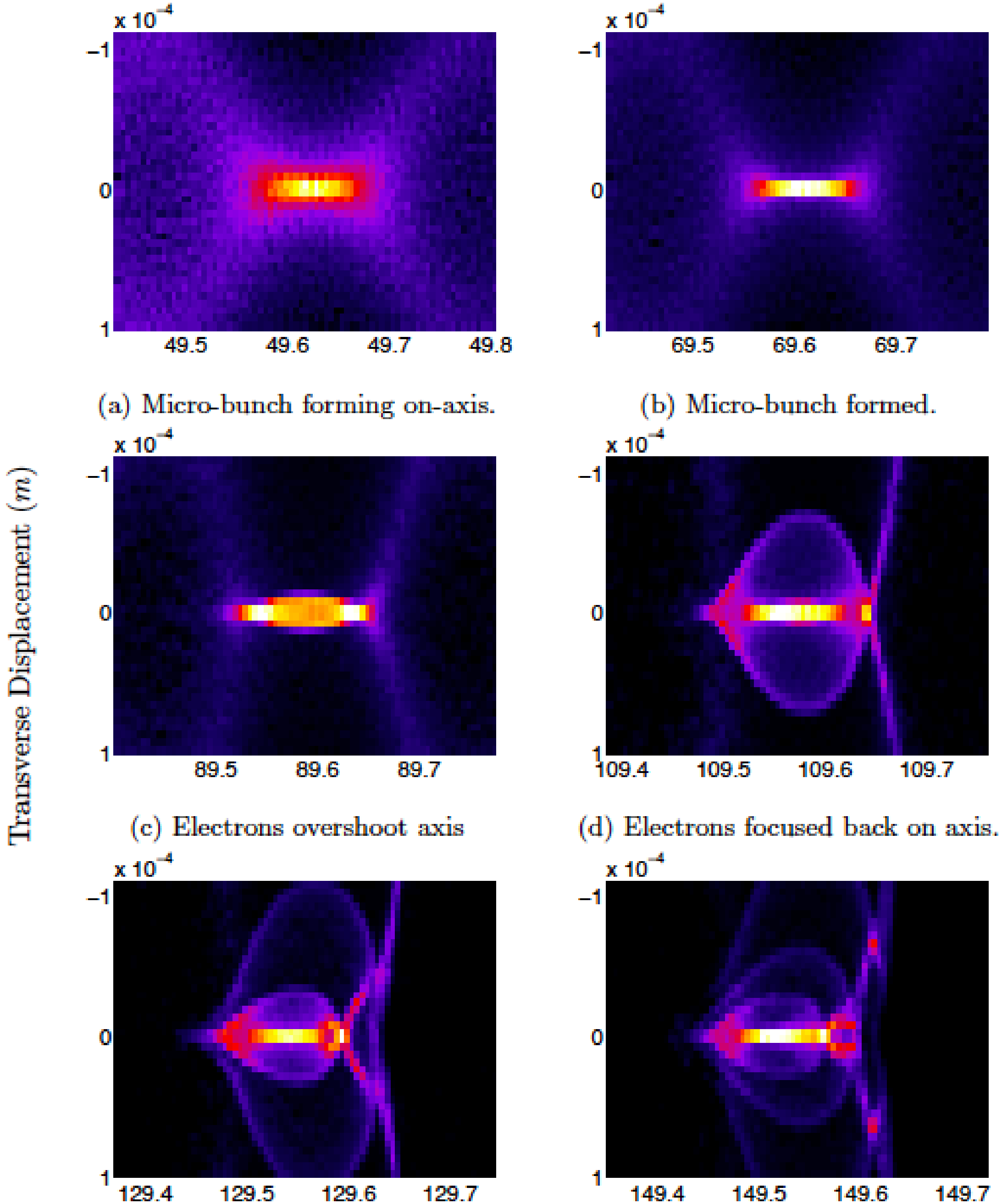
The Plasma

- $n_e = 2.84e22\ m^{-3}$
- $\lambda_p = 200$ um
- $E_r = 1\ GVm^{-1}$

- First plasma cell analogous to lens
- Longer first cell results in a stronger focus and shorter vacuum needed
- However strong focus results in higher emittance micro-bunches

Effects of First Cell length





(a) Micro-bunch forming on-axis.

(b) Micro-bunch formed.

(c) Electrons overshoot axis

(d) Electrons focused back on axis.

(e) Second undulation.

(f) Third undulation.

Distance from start of first plasma stage (mm)

The Diamond Light Source

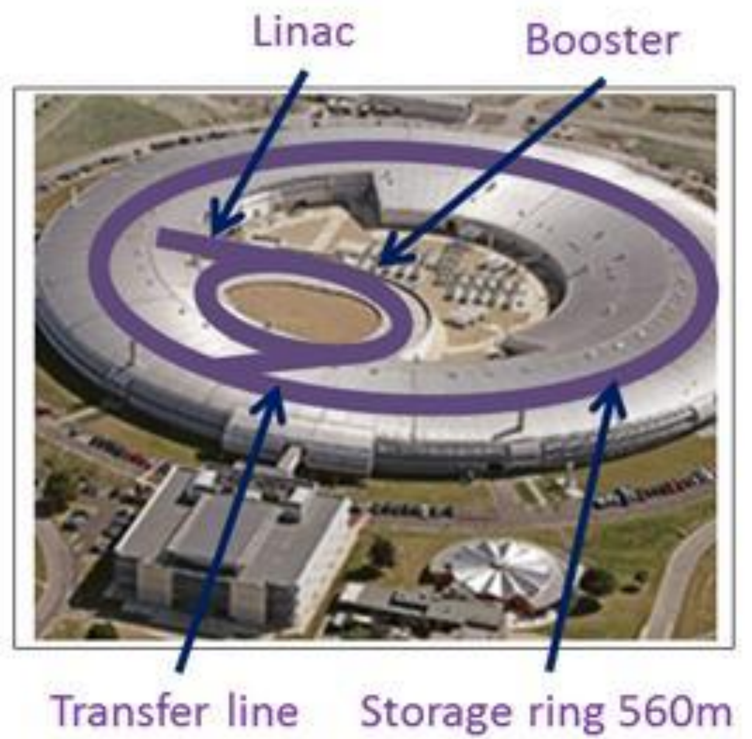
The Diamond light source at RAL uses a 3 GeV electron beam to generate soft x-rays.

Beam length: σ_z = 26 mm

Too long to effectively drive a wakefield!
(λ_p ~ 100um).

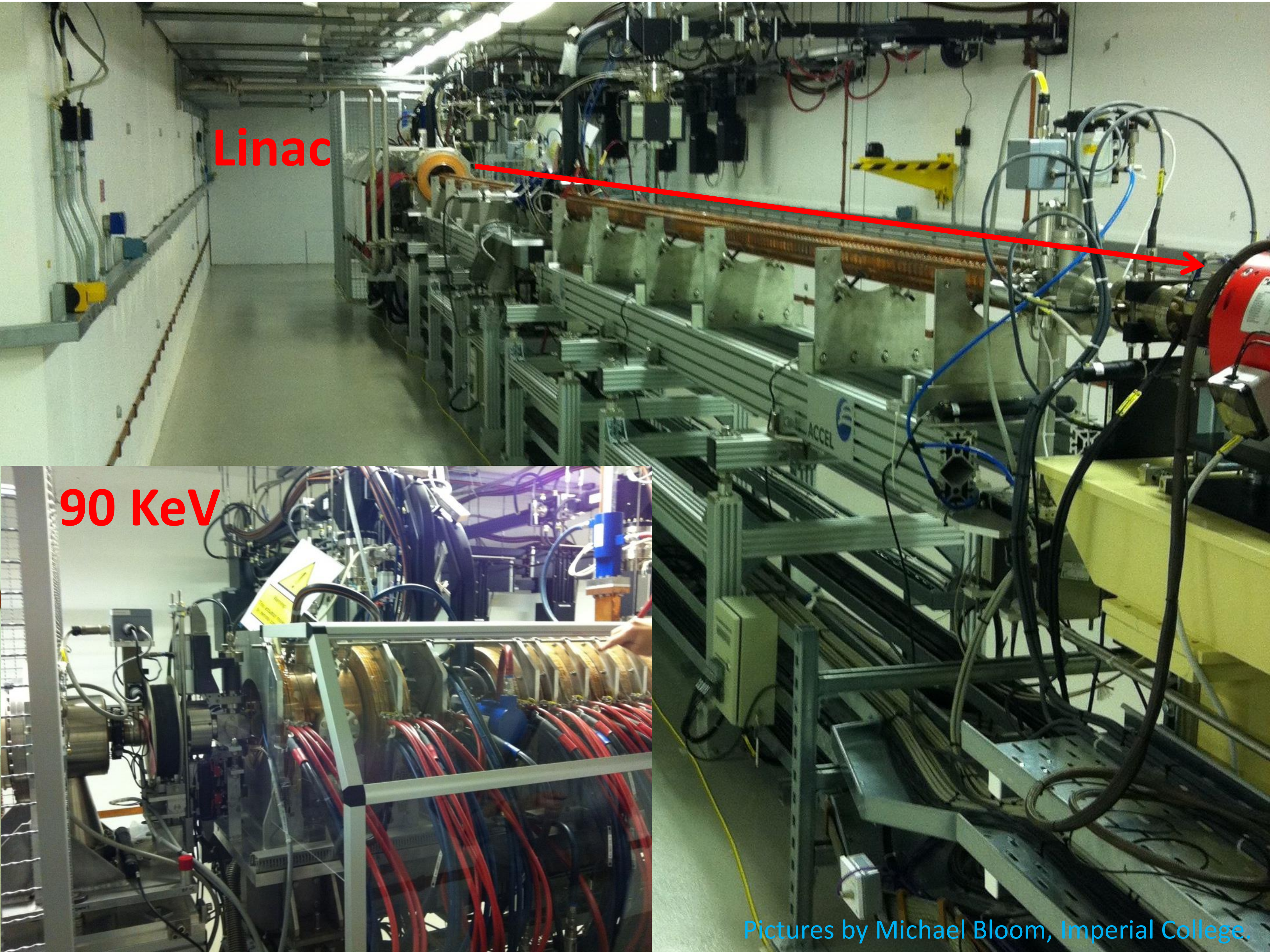
A proof of principle experiment has been proposed
to micro-bunch the beam using a laser-driven wakefield. The beam can then drive a PWA to:

- Create a higher energy electron beam
- Create a poor mans FEL using betatron oscillations within the wake



Diamond Booster Beam

- E = 3 GeV
- ε = 140 nm rad
- σ_z = 26 mm
- Q = 2 nC


Linac
90 KeV
ACCEL
Pictures by Michael Bloom, Imperial College.


Booster
158m circumference
Pictures by Michael Bloom, Imperial College.

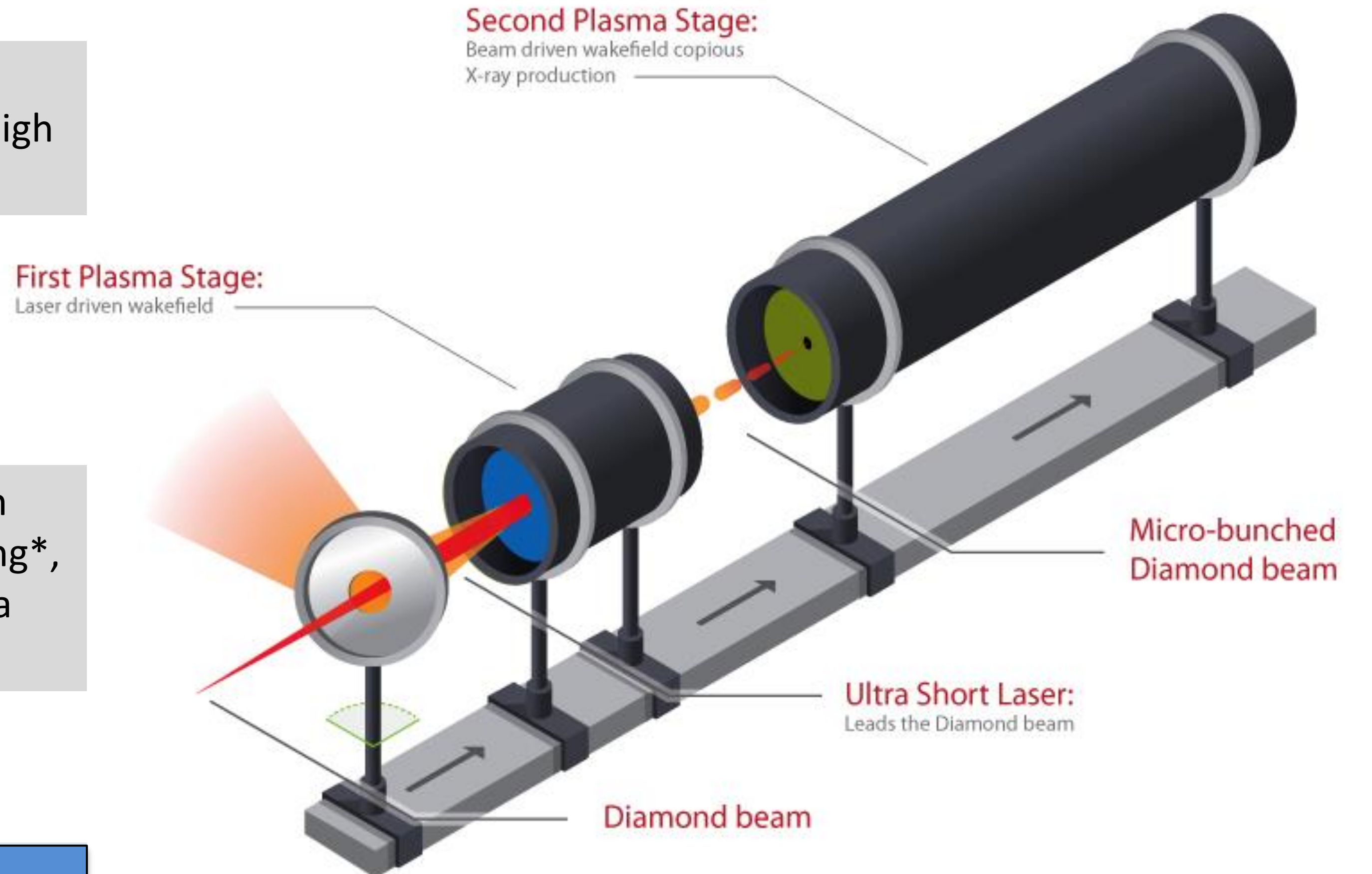

Transfer
Line
Pictures by Michael Bloom, Imperial College.

The 'Drift Space' Design

1) The long beam given transverse momentum by high amplitude wakefield.

2) Micro-bunches form as half e^- defocused, other half focused.

3) At the moment the beam has achieved micro-bunching*, pass into the second plasma cell.

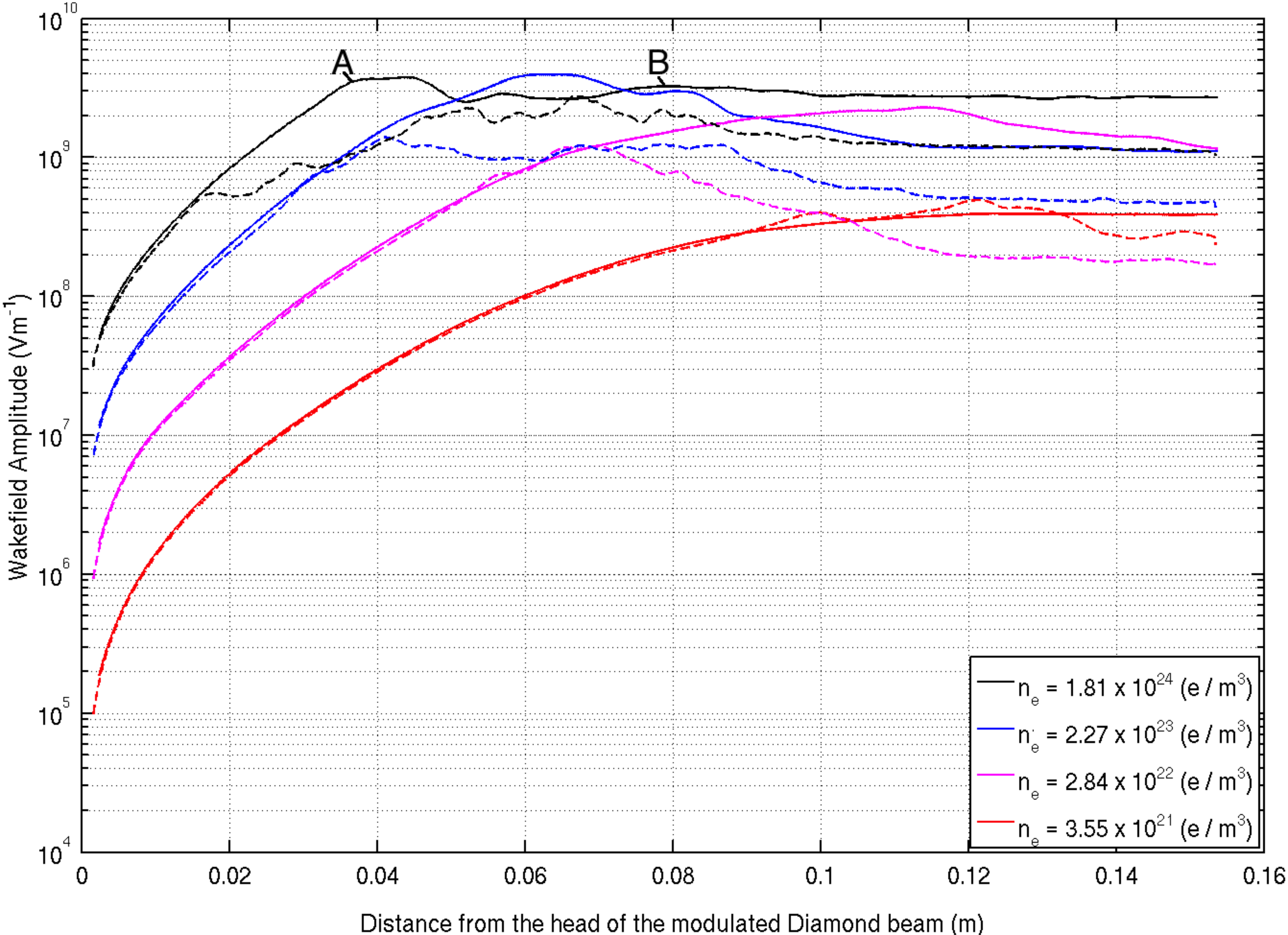


Electron beam

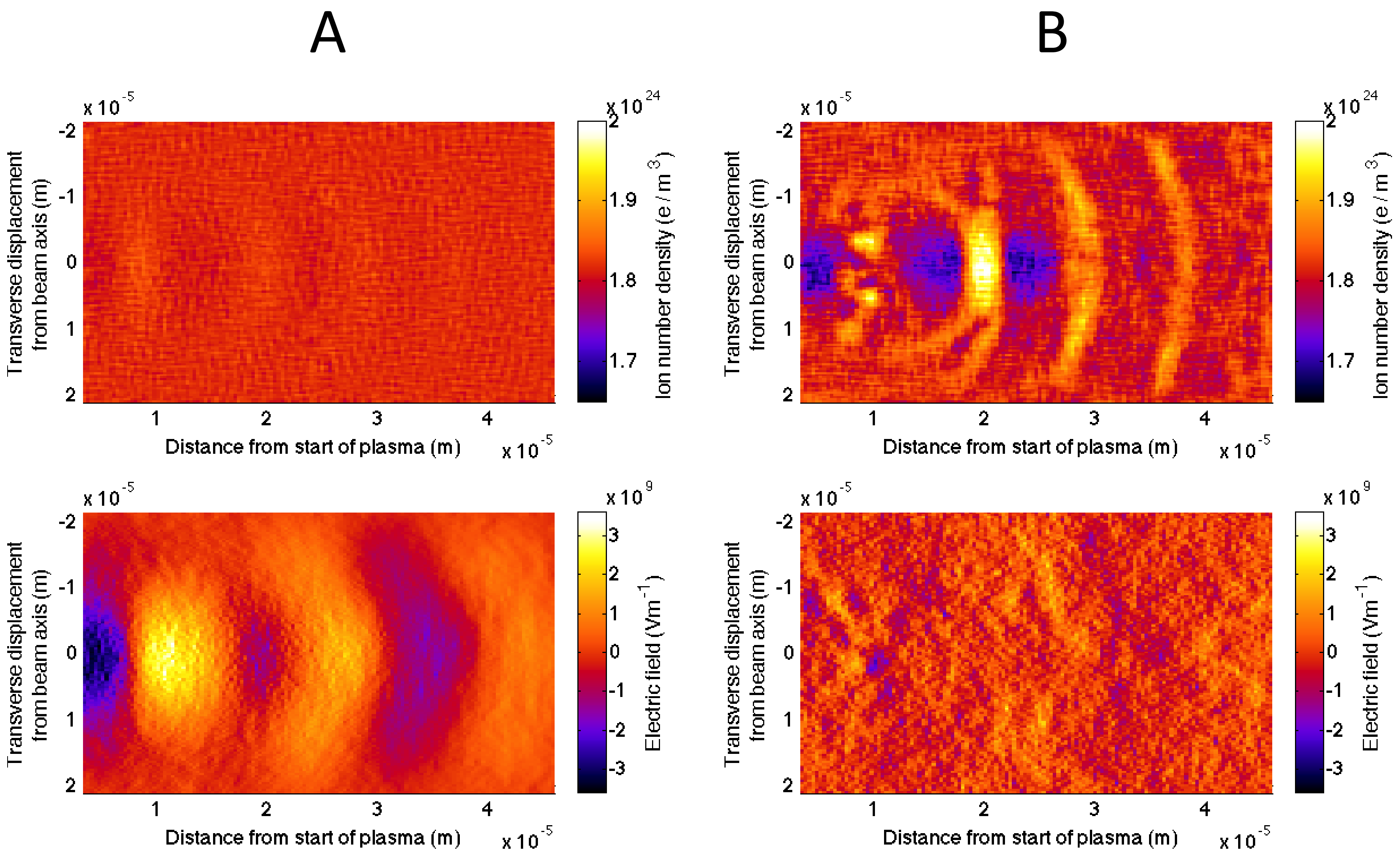
- $E = 300$ MeV
- $\varepsilon_p = 0$
- $\sigma_z = 0.6$ cm
- $\sigma_r = \sqrt{2} / k_p$
- $Q = 2$ nC

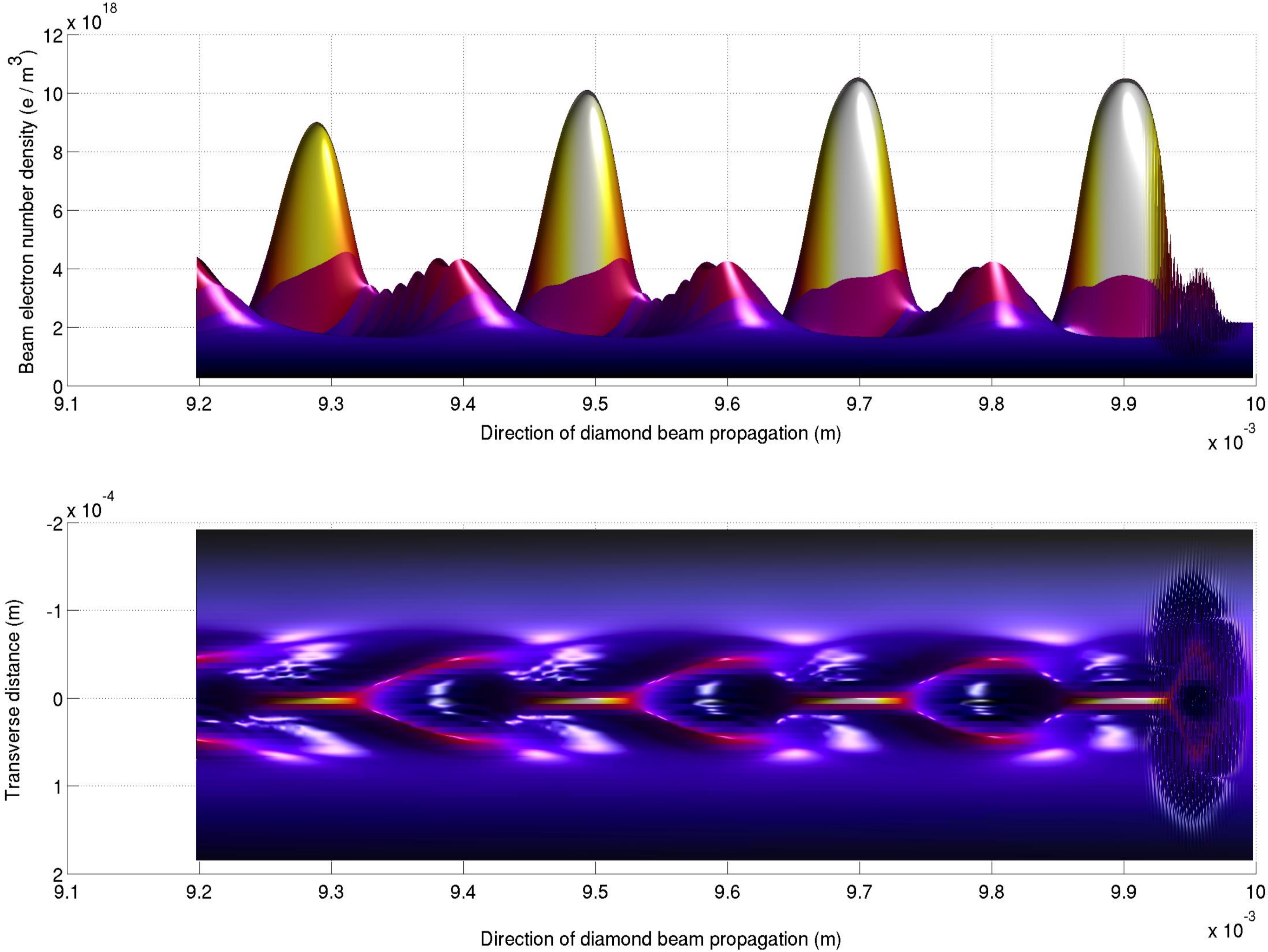
The Plasma

- $n_e = 1.11e22\ m^{-3}$
- $\lambda_p = 300$ um
- $E_r = 1\ GVm^{-1}$

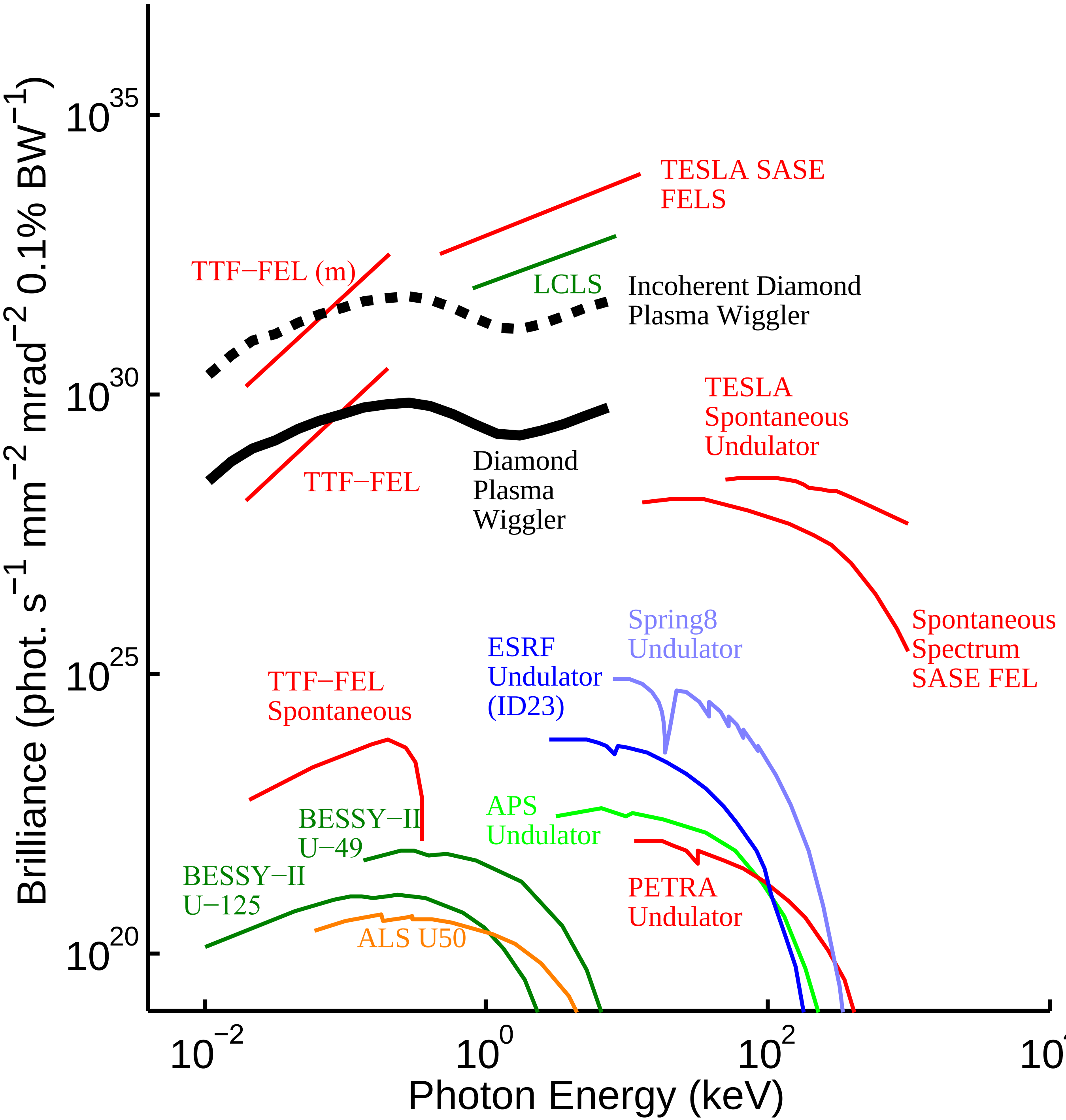


A
B
Wakefield Amplitude (Vm^{-1})
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
Distance from the head of the modulated Diamond beam (m)
n_e = 1.81 x 10^{24} (e / m^3)
n_e = 2.27 x 10^{23} (e / m^3)
n_e = 2.84 x 10^{22} (e / m^3)
n_e = 3.55 x 10^{21} (e / m^3)


A
B
x 10^-5
Transverse displacement from beam axis (m)
Distance from start of plasma (m)
x 10^24
Ion number density (e / m^3)
x 10^9
Electric field (Vm^-1)



x 10^18
12
10
8
6
4
2
0
Beam electron number density (e / m^3)
9.1
9.2
9.3
9.4
9.5
9.6
9.7
9.8
9.9
10
Direction of diamond beam propagation (m)
x 10^-3
x 10^-4
-2
-1
0
1
2
Transverse distance (m)
9.1
9.2
9.3
9.4
9.5
9.6
9.7
9.8
9.9
10
x 10^-3
Direction of diamond beam propagation (m)



Brilliance (phot. s^{-1} mm^{-2} mrad^{-2} 0.1% BW^{-1})
10^{35}
10^{30}
10^{25}
10^{20}
10^{-2}
10^{0}
10^{2}
10^{4}
Photon Energy (keV)
TESLA SASE FELS
TTF−FEL (m)
LCLS
Incoherent Diamond Plasma Wiggler
TESLA Spontaneous Undulator
TTF−FEL
Diamond Plasma Wiggler
Spring8 Undulator
ESRF Undulator (ID23)
Spontaneous Spectrum SASE FEL
TTF−FEL Spontaneous
BESSY−II U−49
APS Undulator
BESSY−II U−125
PETRA Undulator
ALS U50

Acknowledgements

Professor Matthew Wing
University College London, London, UK

Professor Peter Norreys
University of Oxford, Oxfordshire, UK
Central Laser Facility, Rutherford Appleton Laboratory, UK

Professor Robert Bingham
University of Strathclyde, Glasgow, UK
Central Laser Facility, Rutherford Appleton Laboratory, UK

Doctor Raoul Trines
Central Laser Facility, Rutherford Appleton Laboratory, UK

Computing resources provided by STFC's e-Science facility, SCARF and DiRAC.

Concluding

- Many existing particle beam facilities
- Can treat these beams and make them suitable to drive PWA
- Two-stage drift-space design achieves this over short distances
- PWA can generate higher energy electrons and in turn generate harder X-rays form existing infrastructure
- PWA can generate X-rays directly from micro-bunch oscillations
- Ion motion can be a problem!

Thank you for listening