

Particle-Driven Plasma Wakefield Acceleration

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Particle-Driven Plasma Wakefield Acceleration

1. The energy frontier
2. What is PWA?
3. The drive beam
4. SLAC experiment
5. AWAKE experiment
6. Self modulation
7. Diamond experiment

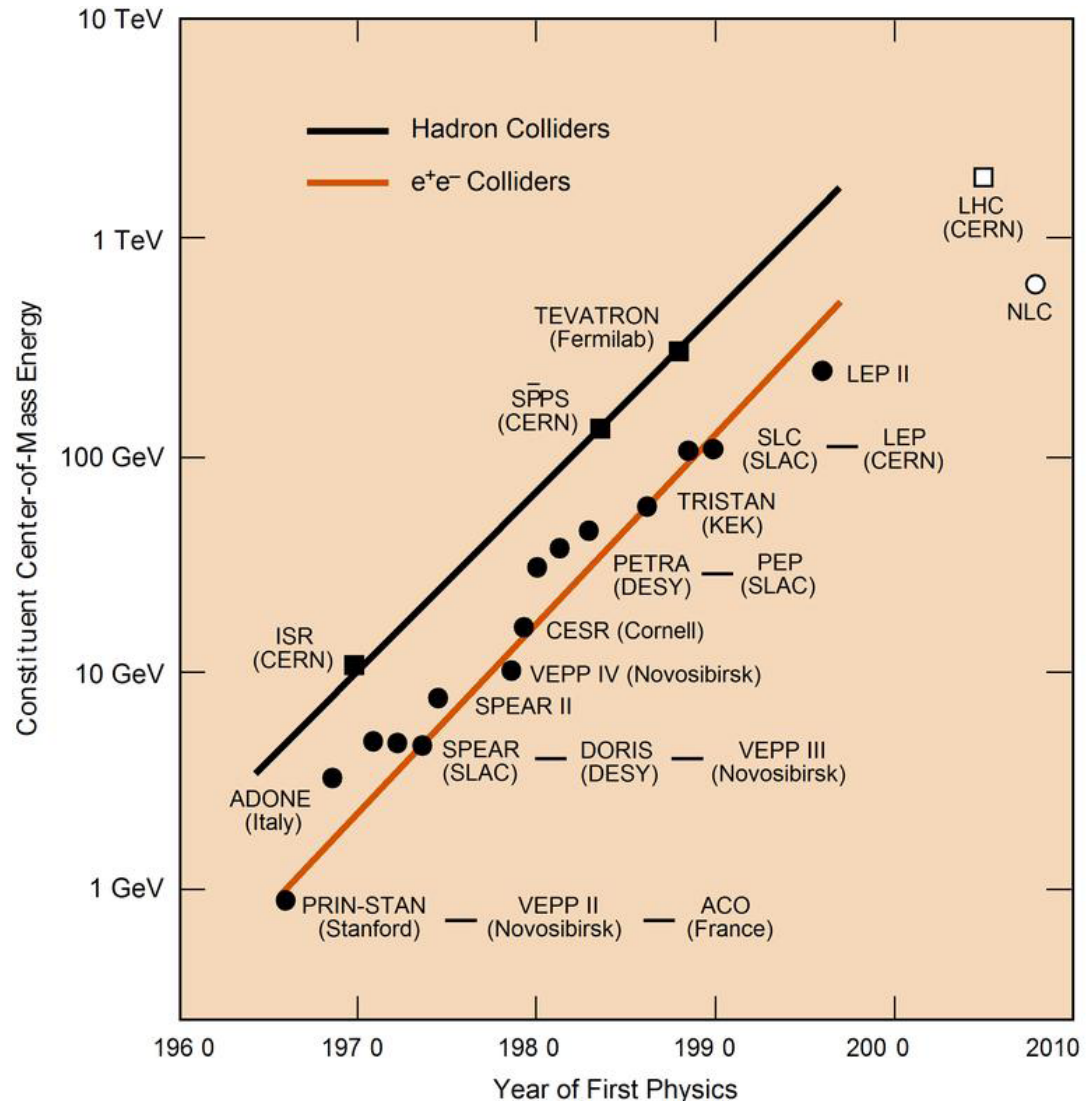
The Energy Frontier

Conventional Accelerators:

- Accelerate particles within a metal cavity.
- Accelerated using an alternating electric field.
- Electric fields greater than $\sim 100 \text{ MVm}^{-1}$ will ionize the metal itself.
- --> To reach higher particle energies one has to increase the length over which the particles are being accelerated.

Plasmas can support higher electric fields.

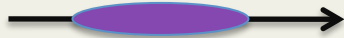
A plasma of number density $n_e = 10^{16} \text{ cm}^{-3}$ can support electric fields of $E = 10 \text{ GVm}^{-1}$.



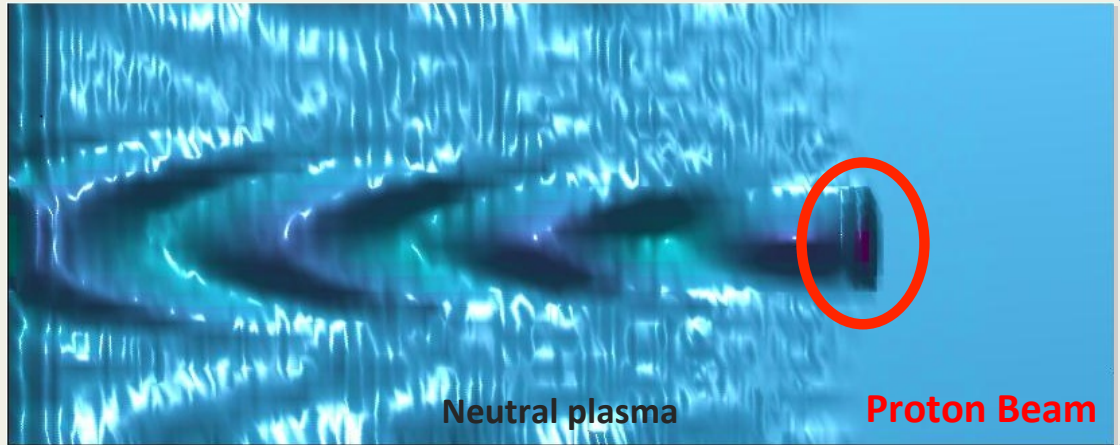
The Livingston plot shows the switch on time of hadron and lepton colliders at the energy frontier as a function of achieved energy.

What is PWA?

Novel particle acceleration technique



Short proton beam

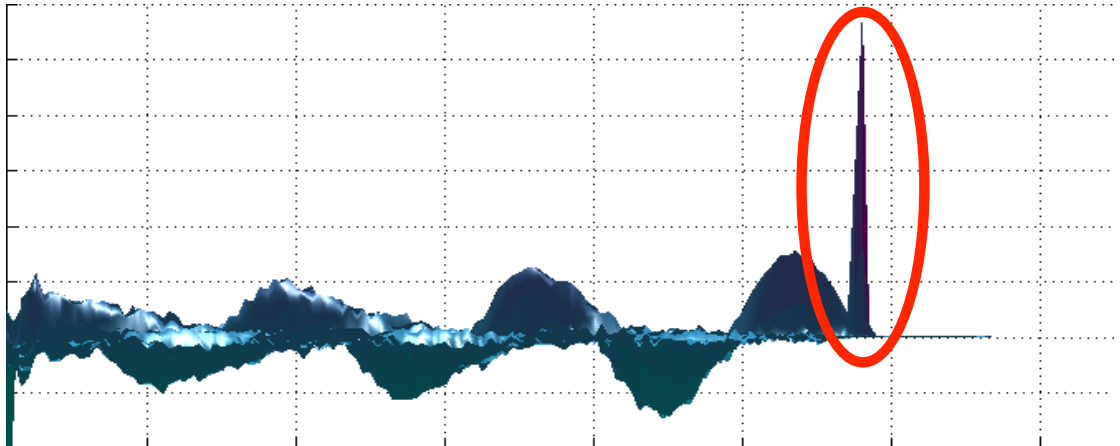


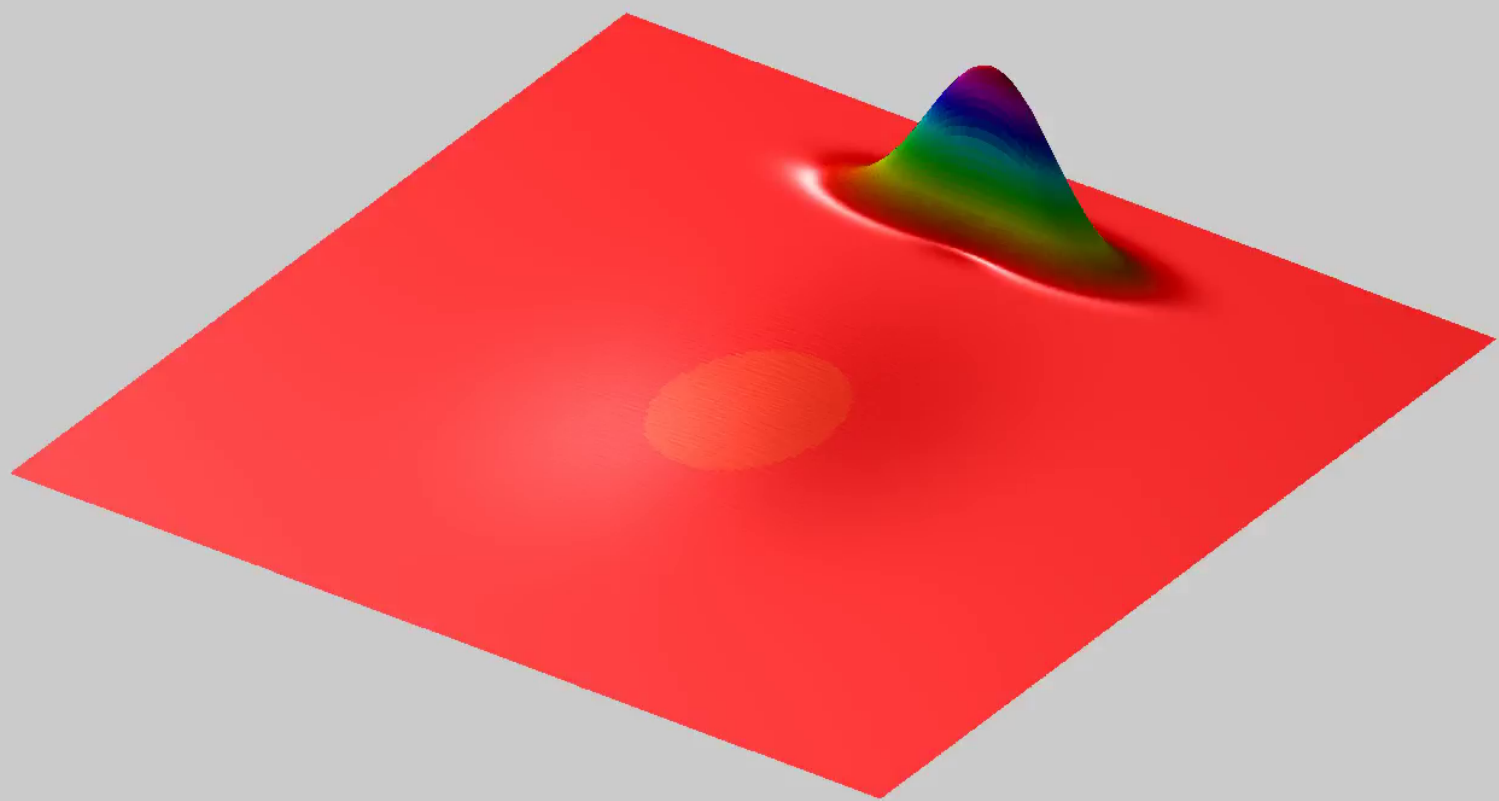
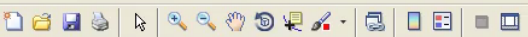
Neutral plasma

Proton Beam

Can also drive wakefields with:

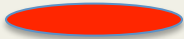
- Electrons
- Photons
- Positrons
- Muons (in principle)





Driving a strong wakefield

Short electron beam



Oscillates at the
plasma frequency

Displaced from
equilibrium position
provides displacement



Twice as long
electron beam



Second half
resists return journey!

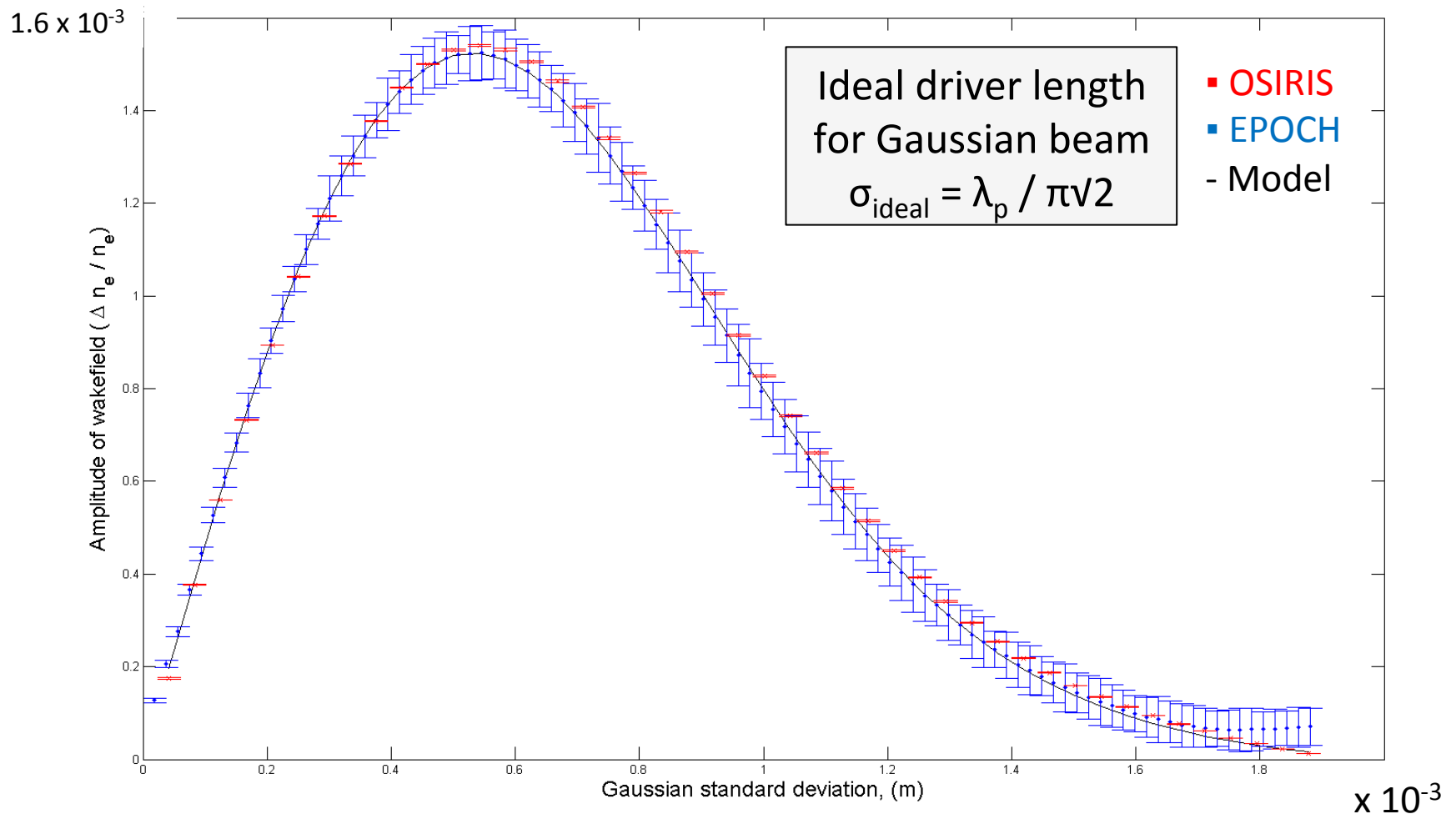
First half
provides displacement

No oscillation



Driver beam length important!

Driving a strong wakefield



The beam length of a driving beam plotted against the amplitude of the resulting wakefield. Data are from simulations using the PIC codes OSIRIS (red) and EPOCH (blue). The theoretical model is plotted as the black line. Both sets of error bars represent 95% confidence.

The SLAC Experiment

Simulation of the experiment using the code QuickPIC.

Stanford Linear Accelerator Center.

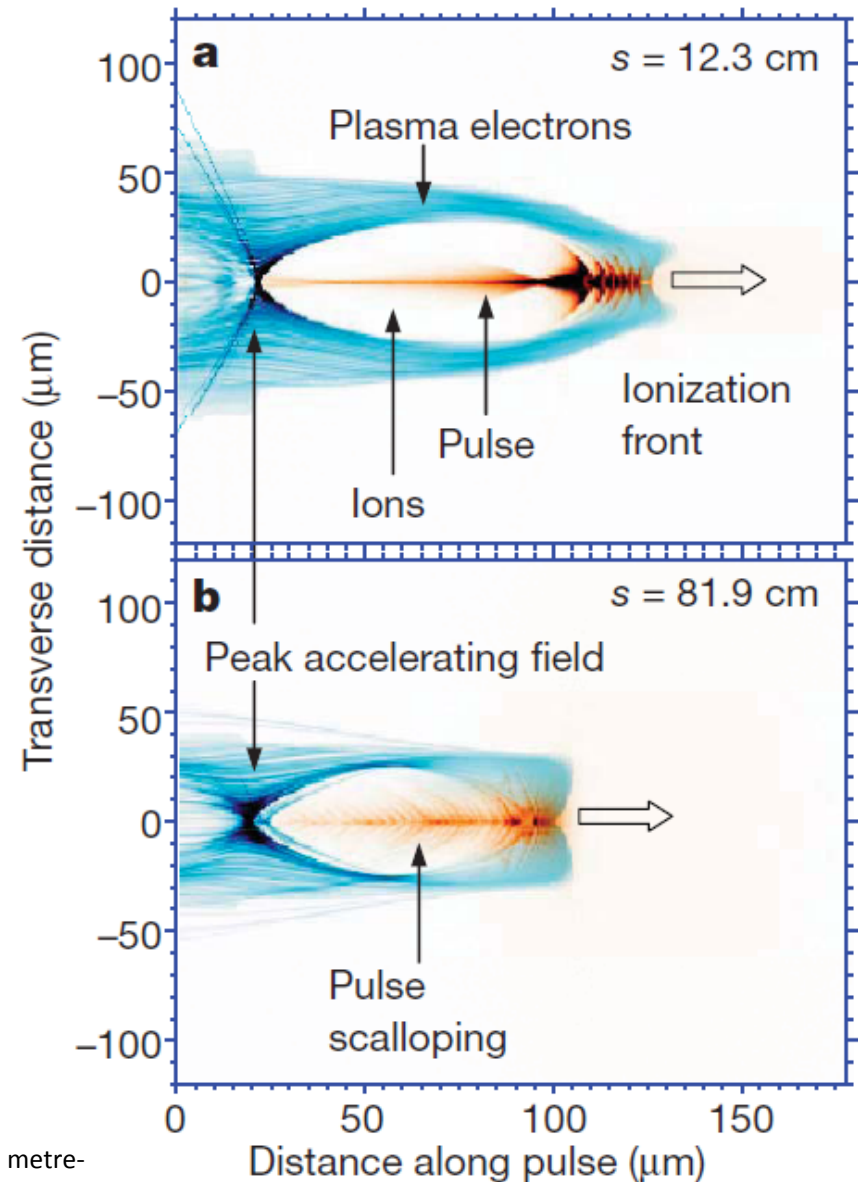
Most of the beam electrons lose energy driving the plasma wave, but some electrons in the back of the same beam are accelerated.

SLAC Beam

- $E = 42 \text{ GeV}$
- $\sigma_z = 15 \mu\text{m}$
- $Q = \sim 2 \text{ nC}$

Plasma Parameters

- Length = 85cm
- $n_e = 2.73 \times 10^{23} \text{ m}^{-3}$
- $\lambda_p = 57 \mu\text{m}$

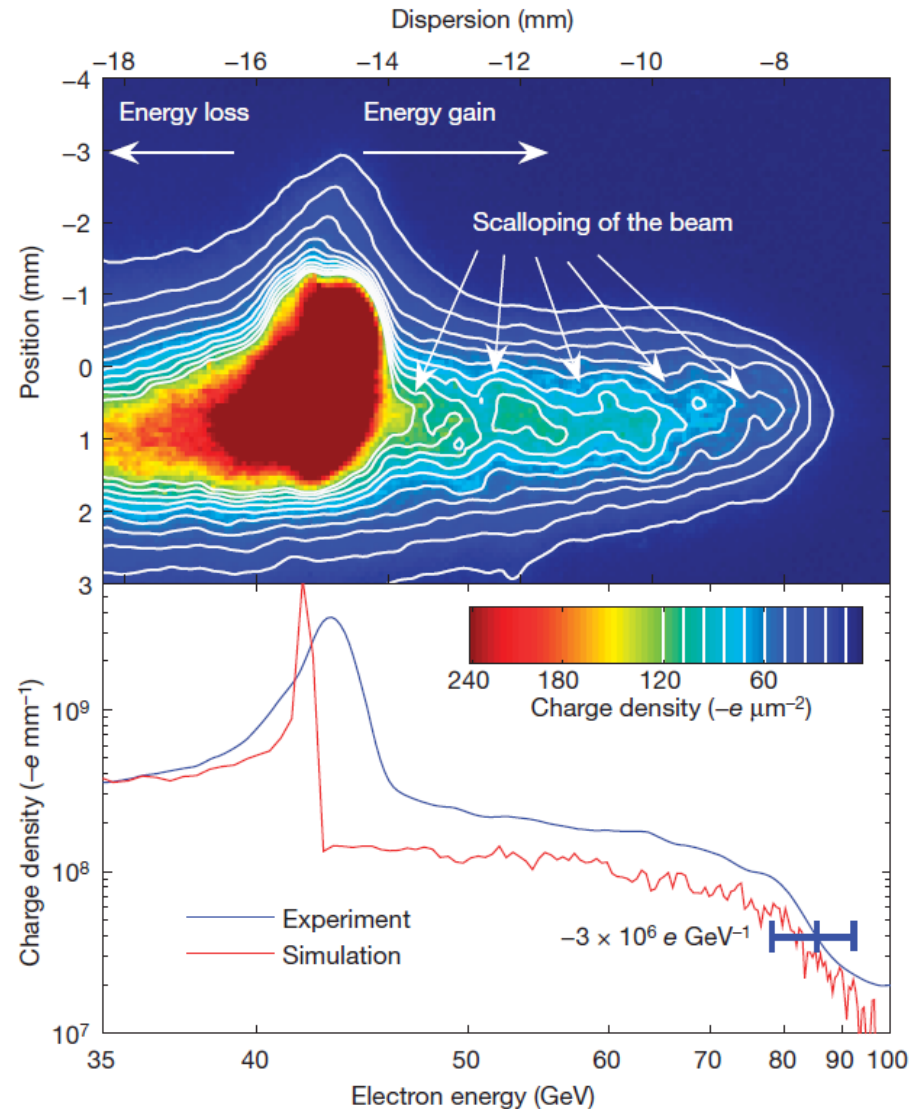


The SLAC Experiment

Achieves a wakefield of 52 GVm^{-1}
84 GeV electron beam generated.

The SLAC beam's original length is 6mm.
Was reduced by a factor of 500 over three
stages of compression.

They achieved energy gain of the 3-km-long
SLAC accelerator in less than a metre!
Although the luminosity was greatly reduced.



The AWAKE Experiment

The Super Proton Synchrotron beam at CERN Feeds the LHC.

Collaboration led by Allen Caldwell aims to use the SPS beam to drive PWA.

Initial goal is to observe the energy gain of 1 GeV in 5 m plasma.

A plan for reaching 100 GeV within 100 m plasma will be developed based on the proof of principle experiment.

- A laser pulse drives a wakefield that modulates the SPS beam into micro bunches.
- These micro bunches then act back on the wakefield, reinforcing it.
- e- then injected into wakefield and accelerated.

The uncompressed SPS beam will be used in the first experiment. It has a beam length of $\sigma_z = 12$ cm. Far longer than the λ_p .

Solution: Increase wakefield driving ability using self-modulation.

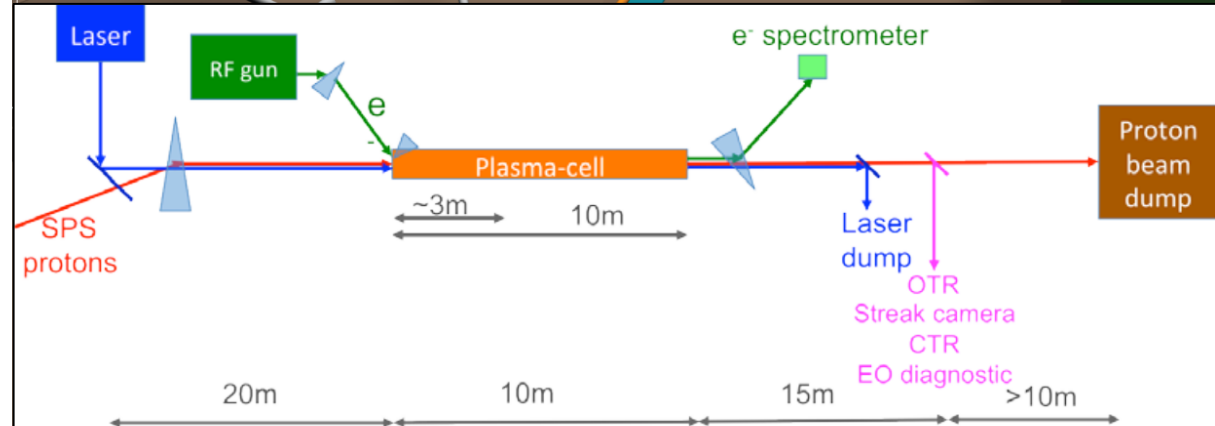
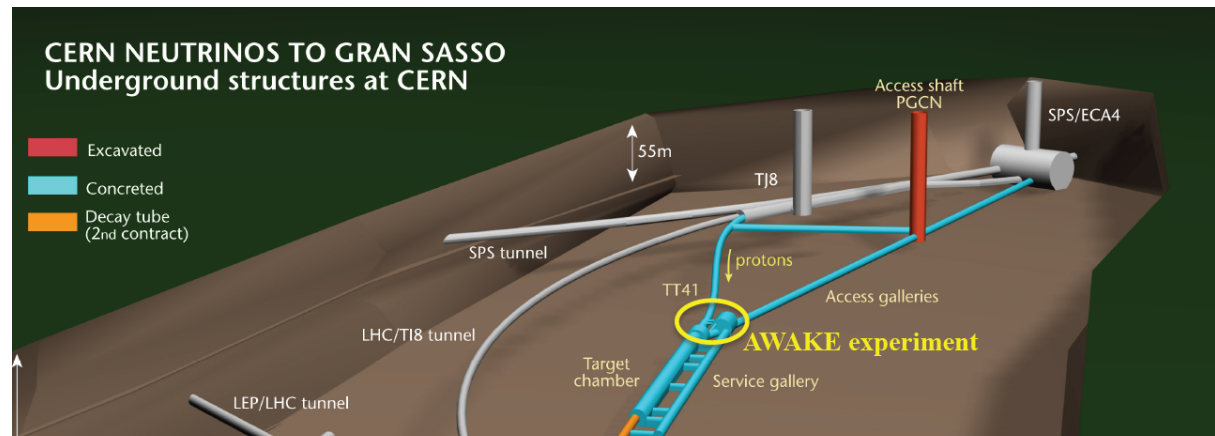
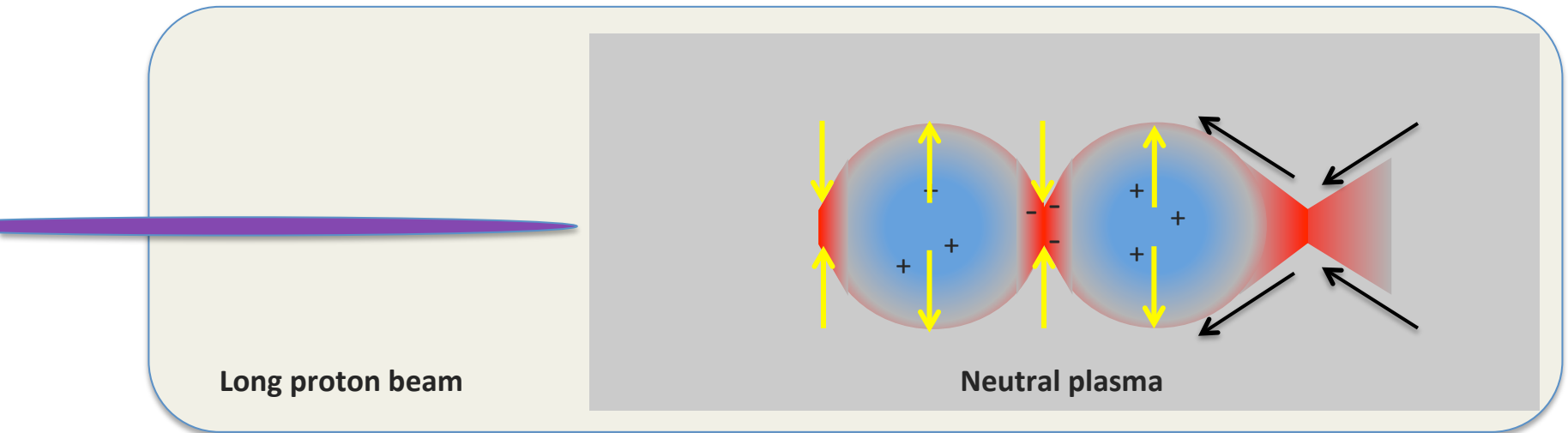


Figure 1: General layout of the AWAKE experiment.

The Self-Modulation Instability

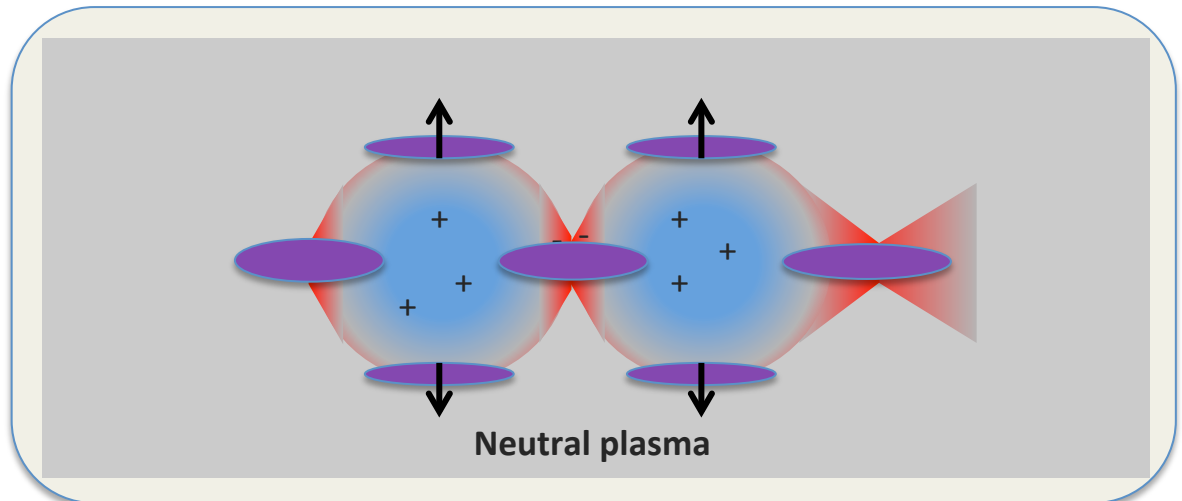
Affects long drive beams.



- Microbunches are spaced λ_p apart.
- Charge density increased.
- Micro bunch lengths are much closer to the ideal driver length of:

$$\sigma_{\text{ideal}} = \lambda_p / \pi v^2$$

These properties then allow the modulated beam to drive a wakefield much more effectively.



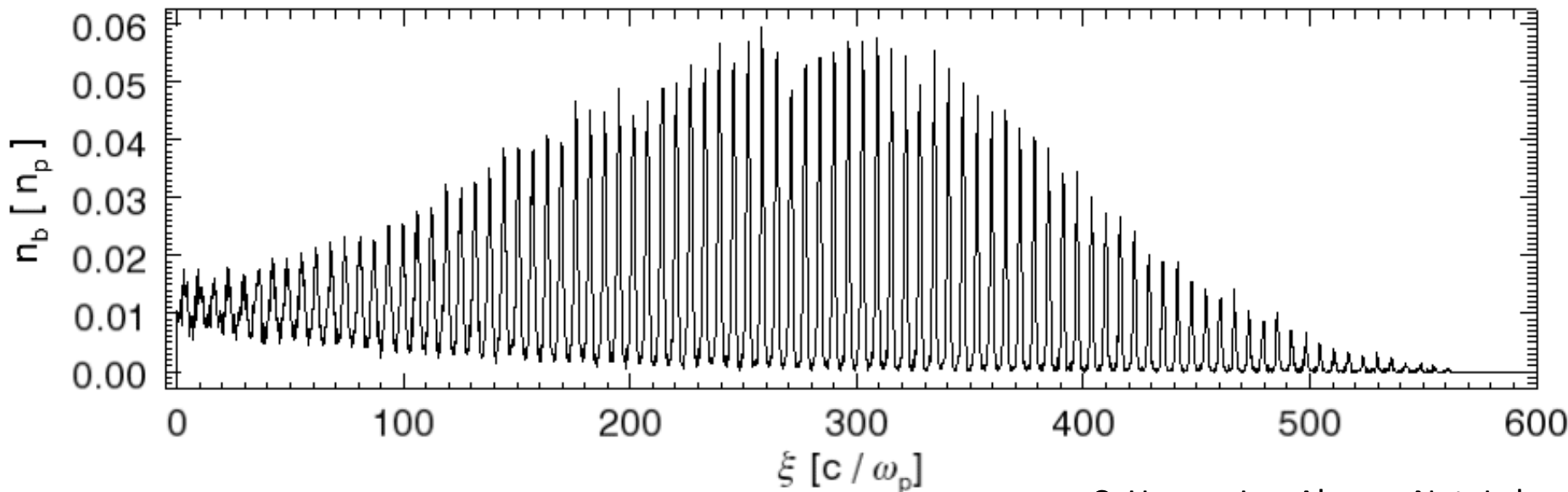
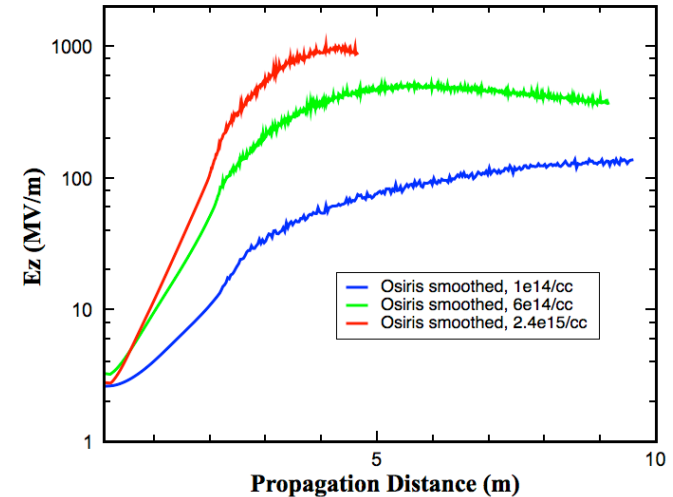
Self-modulated driver beam

The AWAKE Experiment

Collaboration led by Allen Caldwell aims to use the SPS beam to drive PWA.

Initial goal is to observe the energy gain of 1 GeV over 10m plasma.

A plan for reaching 100 GeV within 100 m plasma will be developed based on the proof of principle experiment.



The AWAKE Experiment

What can be achieved in the long term?

PWAs can accelerate witness beams to twice* the energy of the drive beam.
High energy proton beams are available and simulations show the SPS beam can accelerate an electron beam to 600 GeV over 600m.

Drive p⁺ Beam

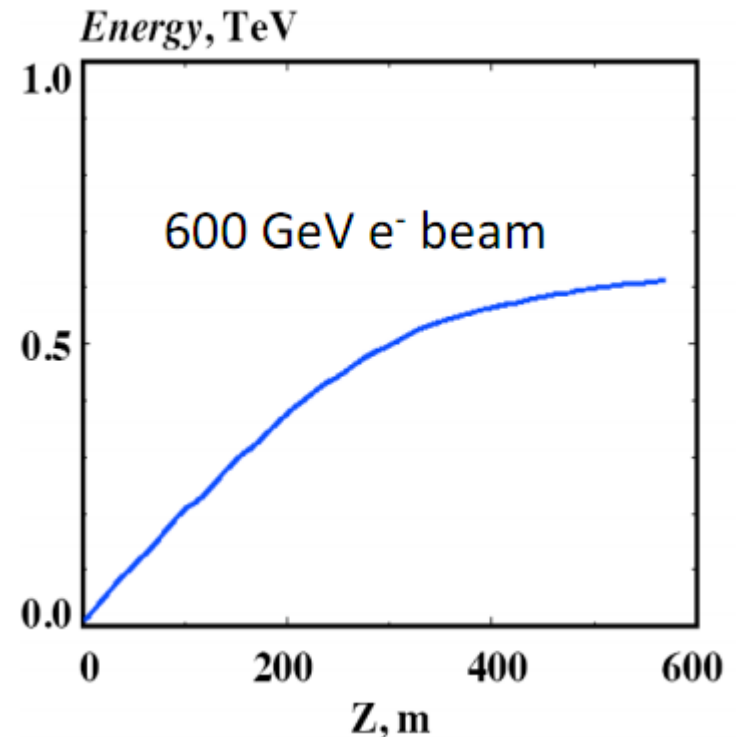
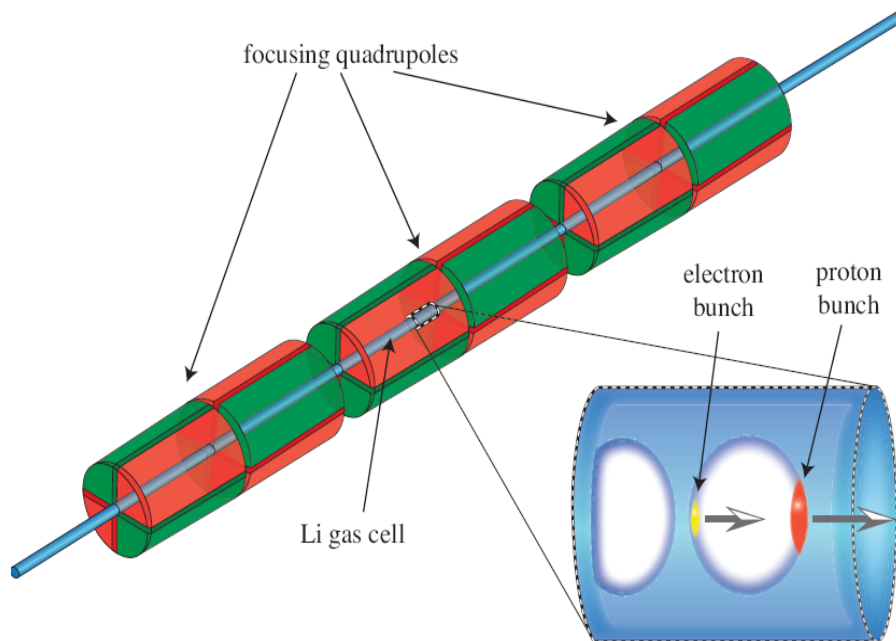
- $E = 1 \text{ TeV}$
- $N_p = 10^{11}$
- $\sigma_z = 100 \text{ } \mu\text{m}$,
- $\sigma_r = 0.43 \text{ mm}$
- $Q = 0.1 \text{ nC}$
- $\sigma_\theta = 0.03 \text{ mrad}$
- $\Delta E/E = 10\%$

Witness e⁻ Beam

- $E = 3 \text{ GeV}$
- $\epsilon_p = 0$
- $\sigma_z = \sqrt{2} / k_p$
- $\sigma_r = \sqrt{2} / k_p$
- $Q = 0.2 \text{ nC}$

The Plasma Cell

- $n_e = 6 \times 10^{14} \text{ cm}^{-3}$
- Field : 1000 T/m
- Mag length: 0.7 m
- $L = 600 \text{ m}$



Numerical simulation of PD-PWA demonstrating energy gains of 600 GeV by electrons

The Diamond Light Source

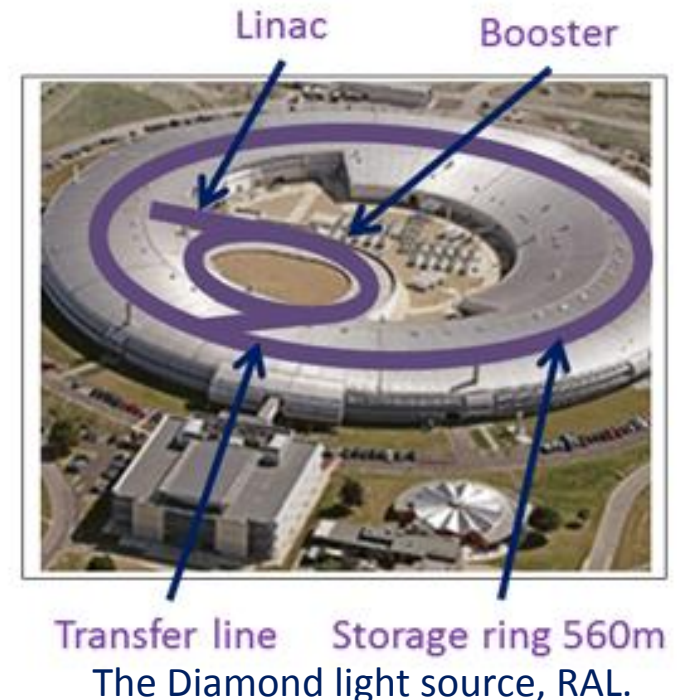
The Diamond light source at RAL uses a 3 GeV electron beam to generate soft x-rays. Beam length: $\sigma_z = 2.6$ cm \rightarrow **too long to effectively drive a wakefield**. ($\lambda_p \sim O(100\mu\text{m})$).

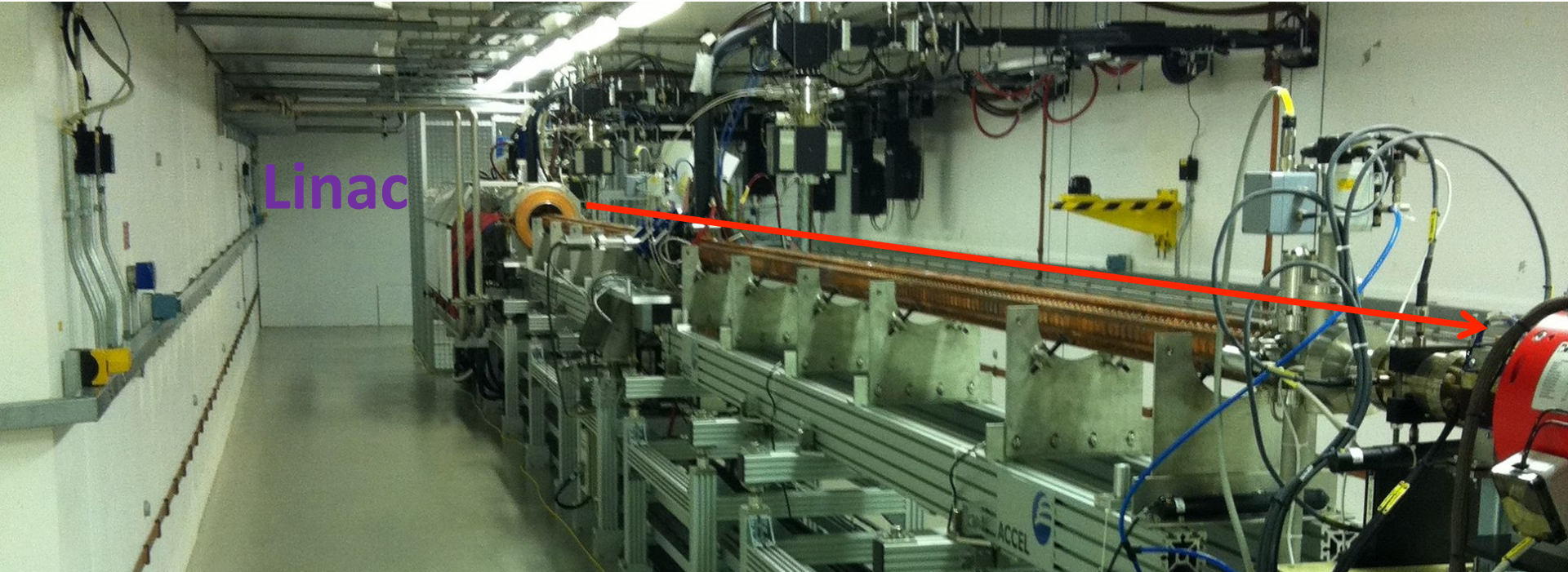
A proof of principle experiment has been proposed to micro bunch the beam using the self modulation instability, with the future intent to use the treated beam to:

- Create a higher energy electron beam
- **Create a poor mans FEL using betatron oscillations within the wake**
- Imprint the modulated profile onto a proton beam, seeding the modulation onto the proton beam

Diamond Booster Beam

- $E = 3$ GeV
- $\epsilon = 140$ nm rad
- $\sigma_z = 2.6$ cm
- $Q = 2$ nC





Pictures by Michael Bloom, Imperial College.



Booster

158m circumference

Transfer
Line

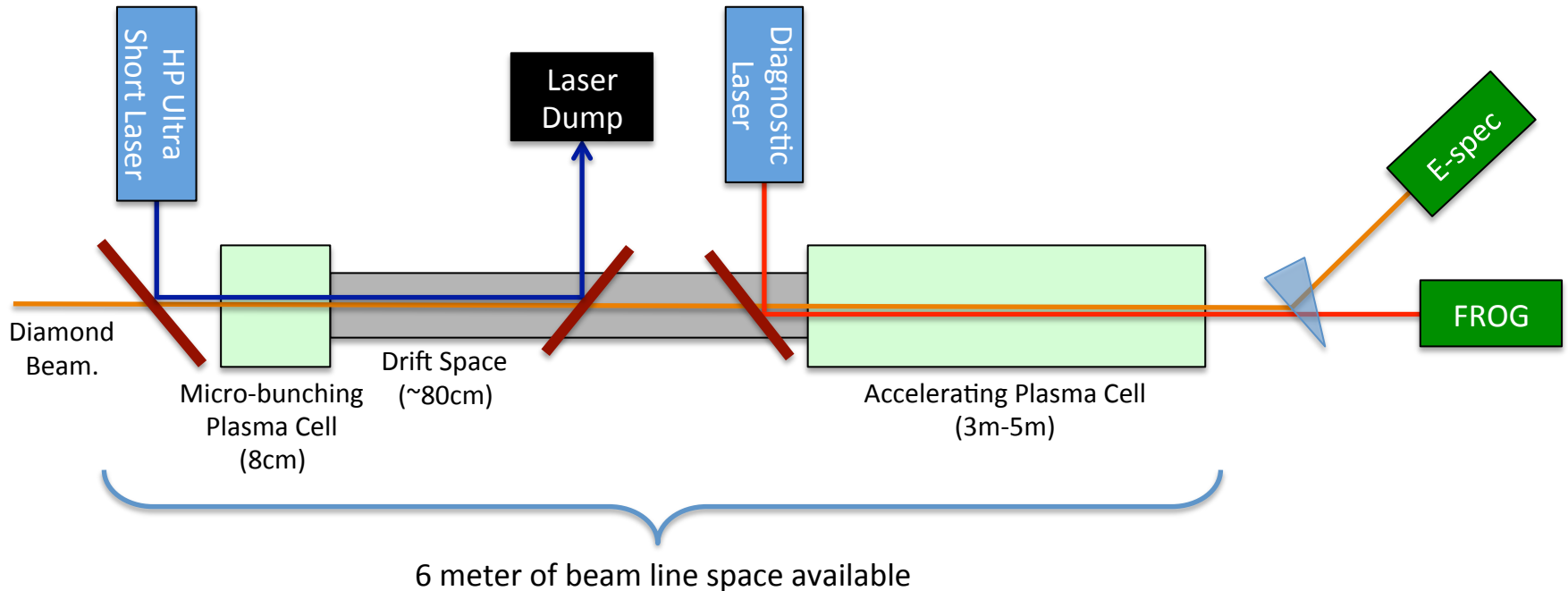


1

Storage Ring



Proposed Set Up



Diamond Beam Parameters

- $E = 3 \text{ GeV}$
- $\varepsilon_p = 140 \text{ nm mrad}$
- $\sigma_E / E = 0.0007$
- $\sigma_z = 2.6 \text{ cm}$
- $Q = 2 \text{ nC}$

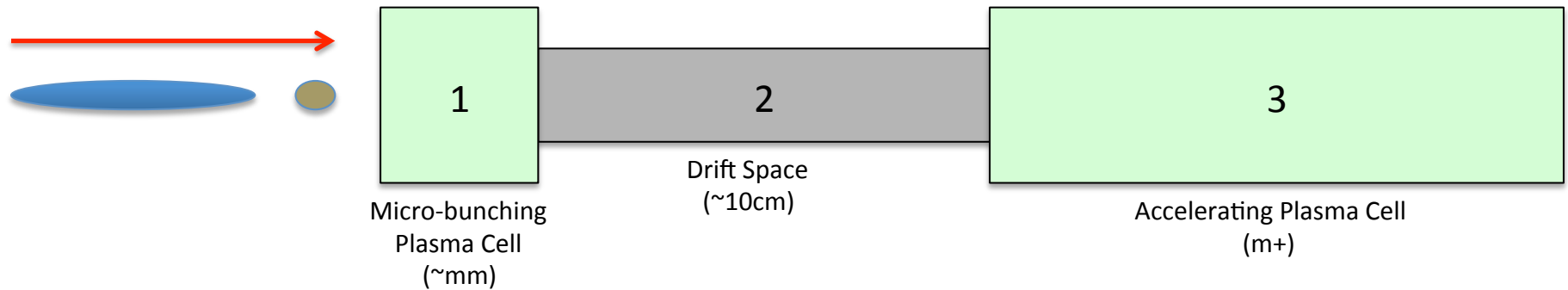
HP Ultra Short Laser

- $\lambda = 1.06 \text{ }\mu\text{m}$
- $\sigma_r = 20 \text{ }\mu\text{m}$
- $E = 1 \text{ J}$
- $I = 1e16 \text{ Wcm}^{-2}$
- $\tau = 50 \text{ fs}$

Plasma Parameters

- $N_e = 1.11e23 \text{ cm}^{-3}$
- $\lambda_p = 100 \text{ }\mu\text{m}$
- Element = Xenon
- Cell = ~Discharge

Achieving High Quality Modulation



1) The witness beam has transverse momentum imparted on it by the wakefield provided by the ideal driver. Leaves the Micro-bunching cell without significant modulation.

2) Micro-bunches form as transverse momentum causes electrons in the beam to drift into position.

3) At the moment the beam has achieved best micro-bunching*, it passes into the accelerating plasma cell.

Diamond-esque beam

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

Ideal e- driver

- $E = 3 \text{ GeV}$
- $\epsilon_p = 0$
- $\sigma_z = \sqrt{2} / k_p$
- $\sigma_r = \sqrt{2} / k_p$
- $Q = 0.2 \text{ nC}$

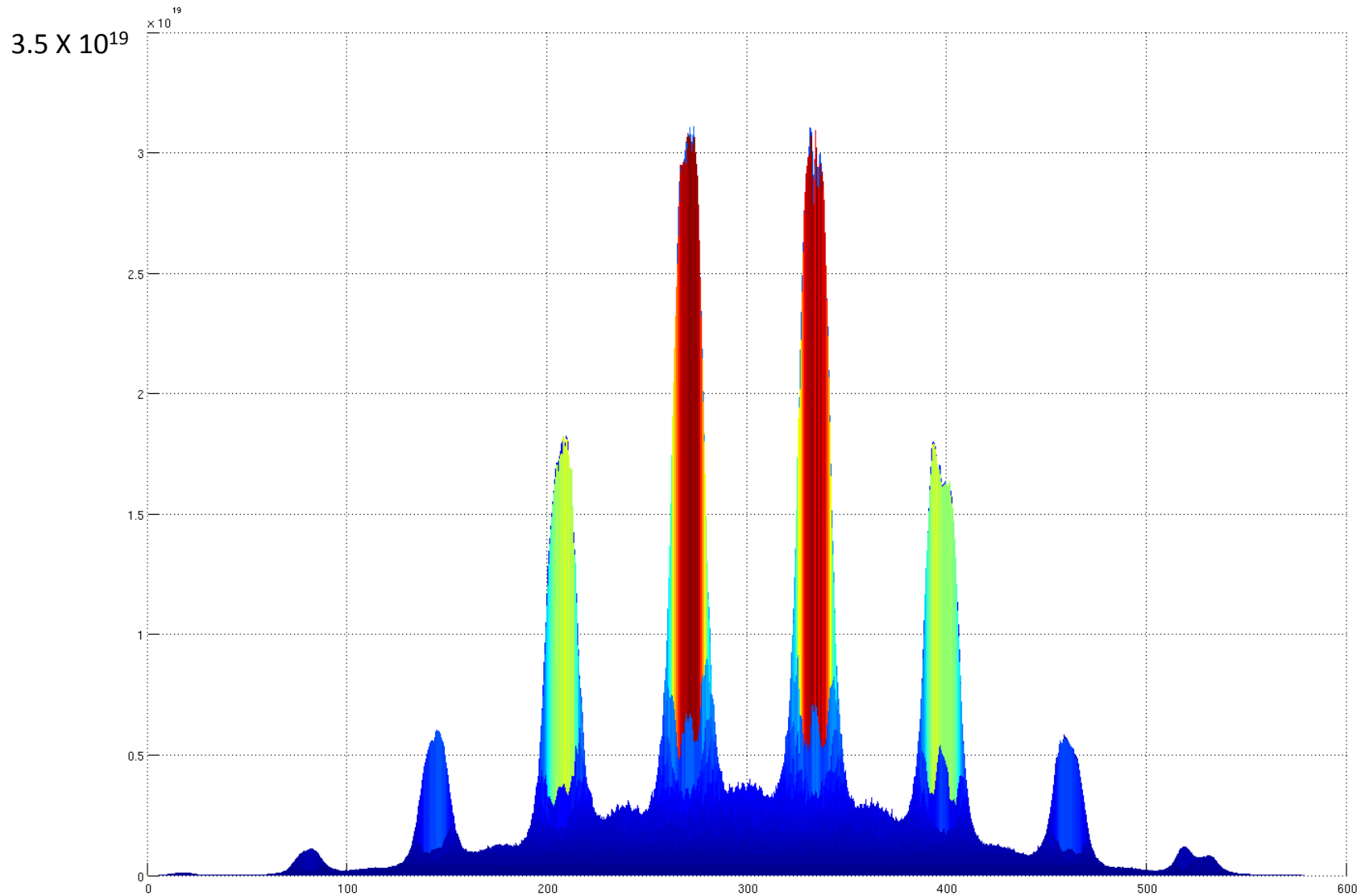
The Plasma

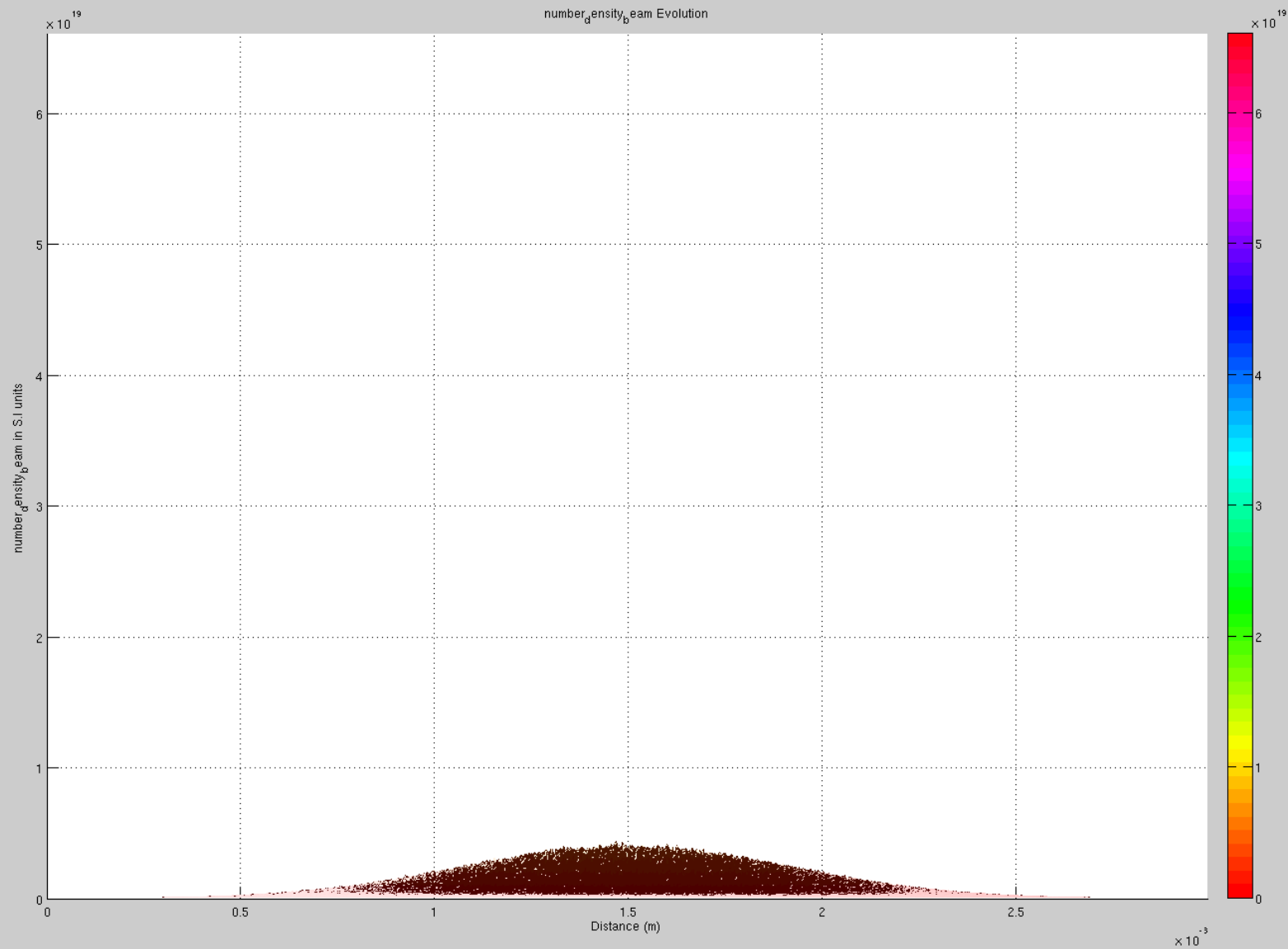
- $0.5 \text{ mm} \times \text{run \# of plasma in micro bunching cell.}$
- $n_e = 1.11 \text{e}22 \text{ m}^{-3}$
- $\lambda_p = 300 \text{ um}$

Effects of drift space

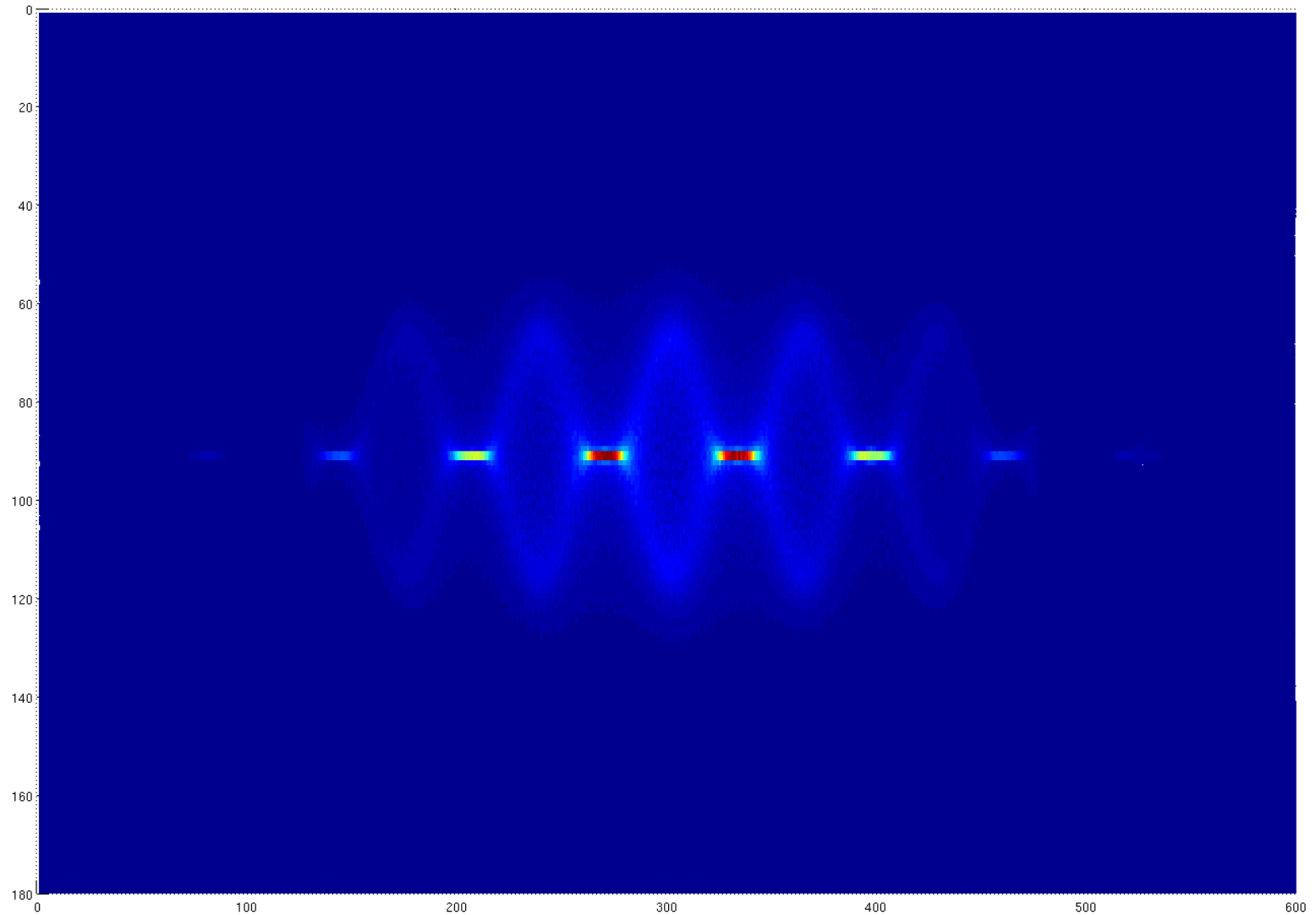
Run #	Cell Length (mm)	Drift Length (mm)	Peak Nd @ 260mm (e19)
5	2.5	65.5	4.09
6	3.0	57.0	4.00
7	3.5	48.5	3.90
8	4.0	42.0	3.73
9	4.5	37.5	3.80
10	5.0	32.0	3.64
No Drift	∞	0.0	0.13

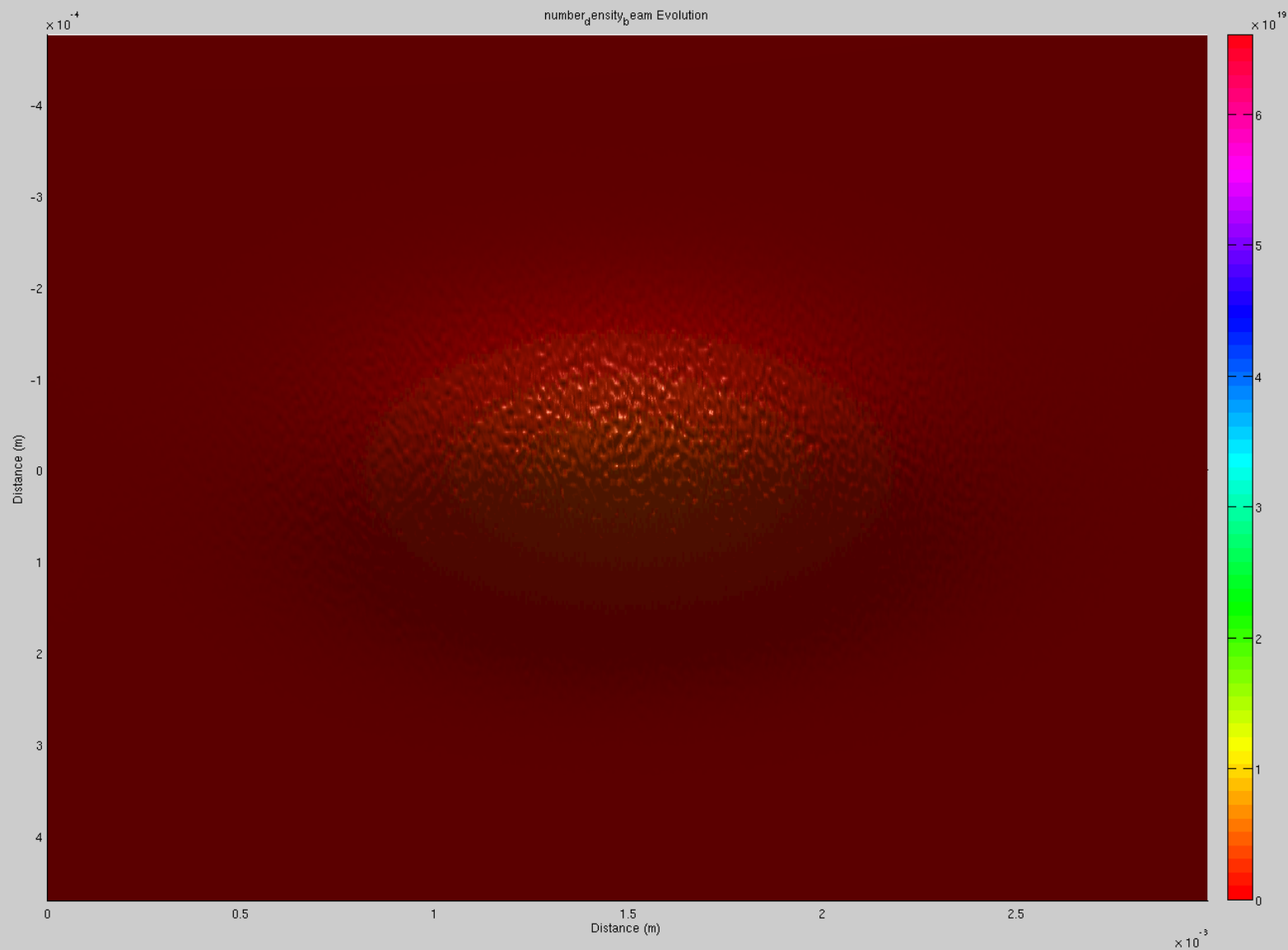
After 93mm of propagation.



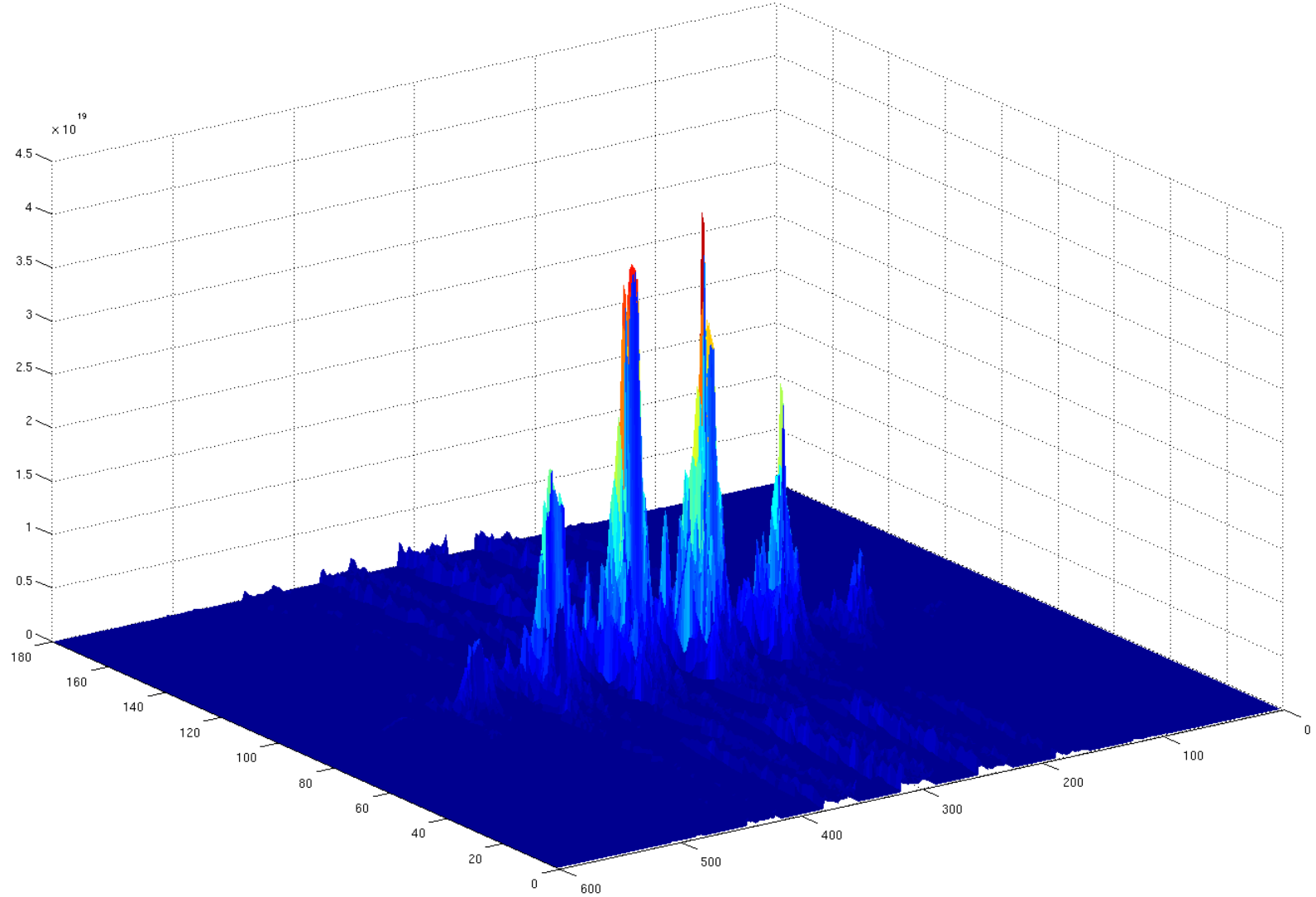


After 93.6mm of propagation





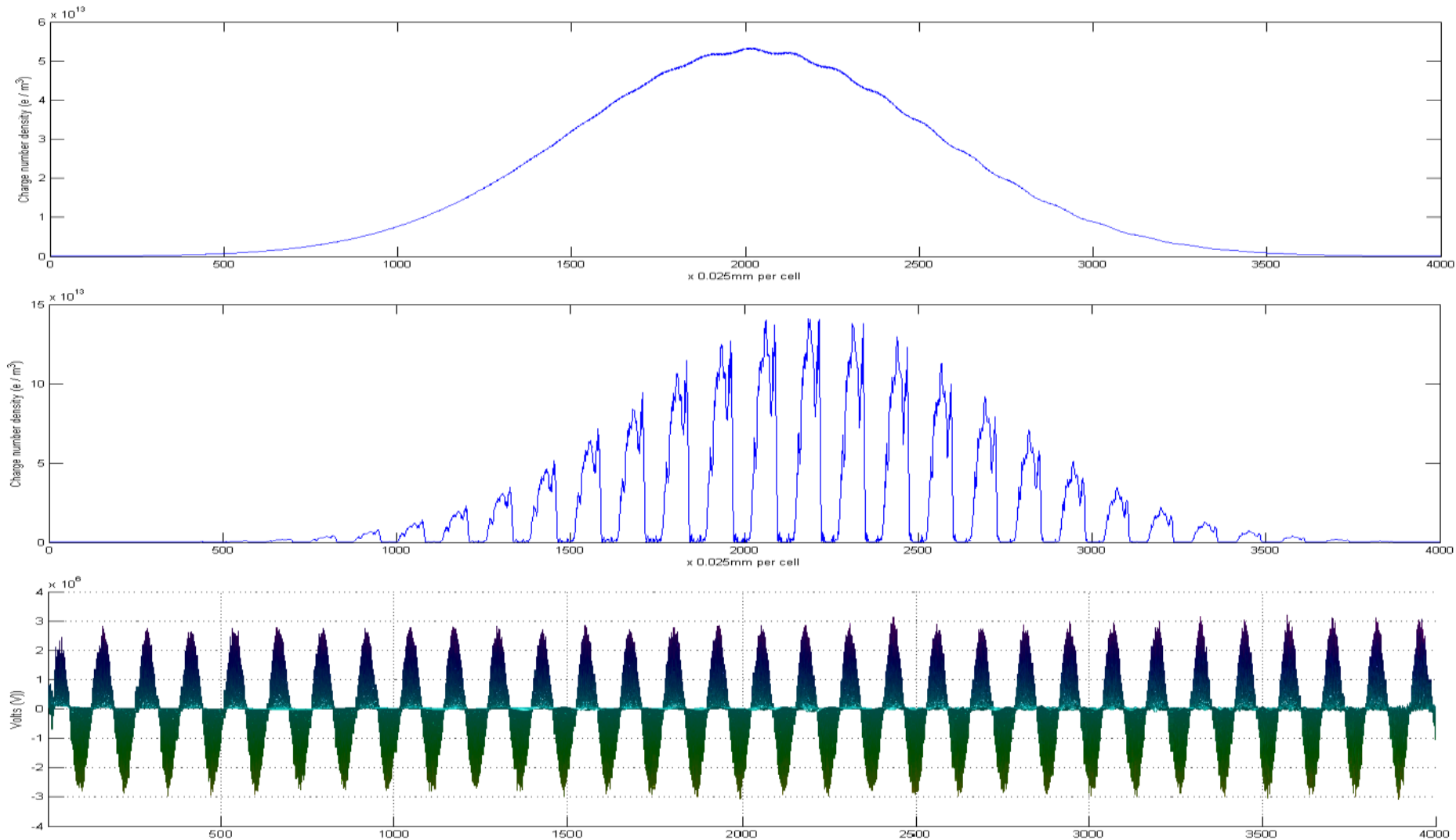
After 93.6mm



Micro-bunched Diamond Beam

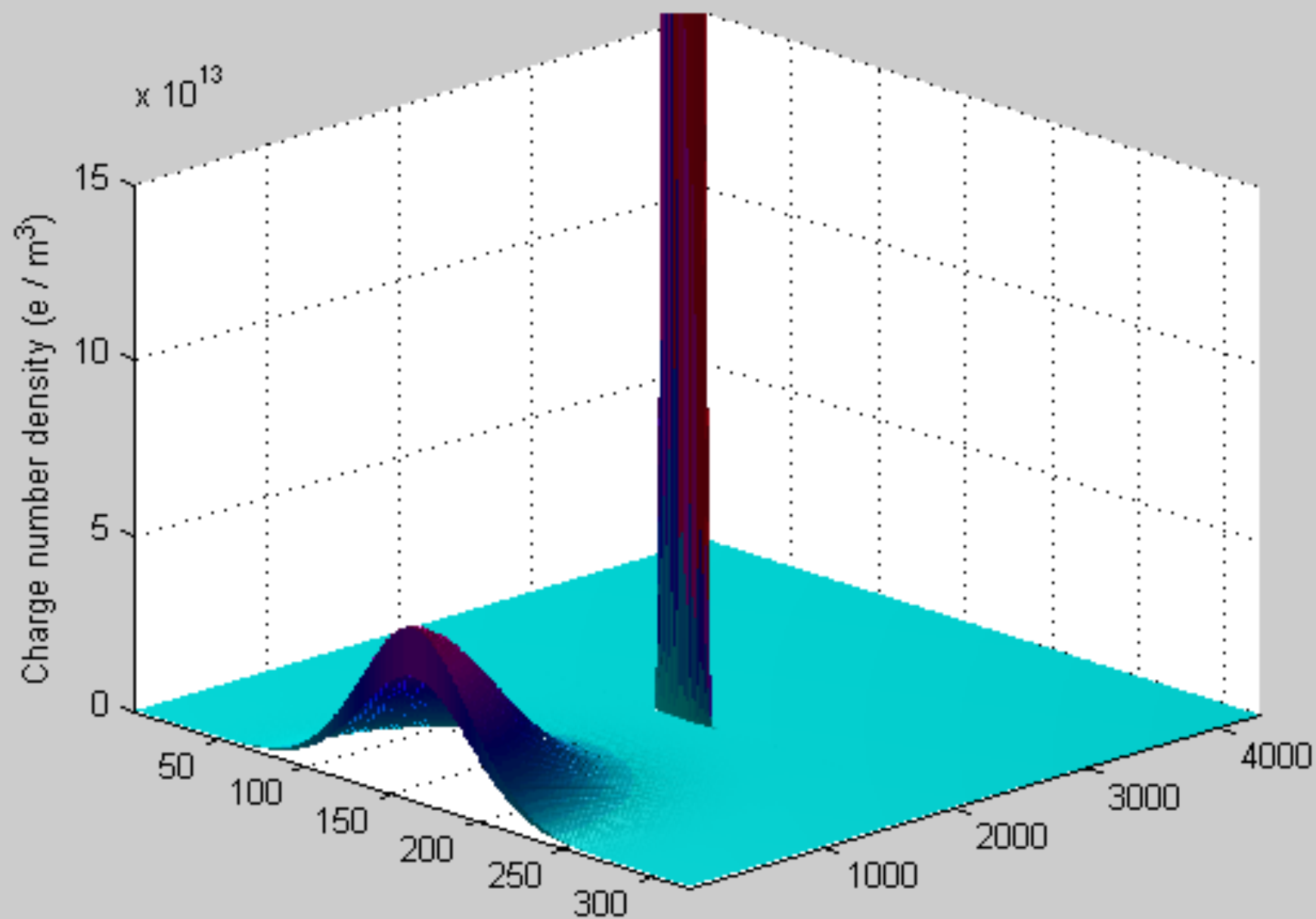
Initial wakefield driven by ultra short e- pulse: $\sigma_r = \sigma_z = 0.144$ mm. Charge = 2 nC.

Diamond beam then co-propagates with the wakefield and becomes micro bunched.



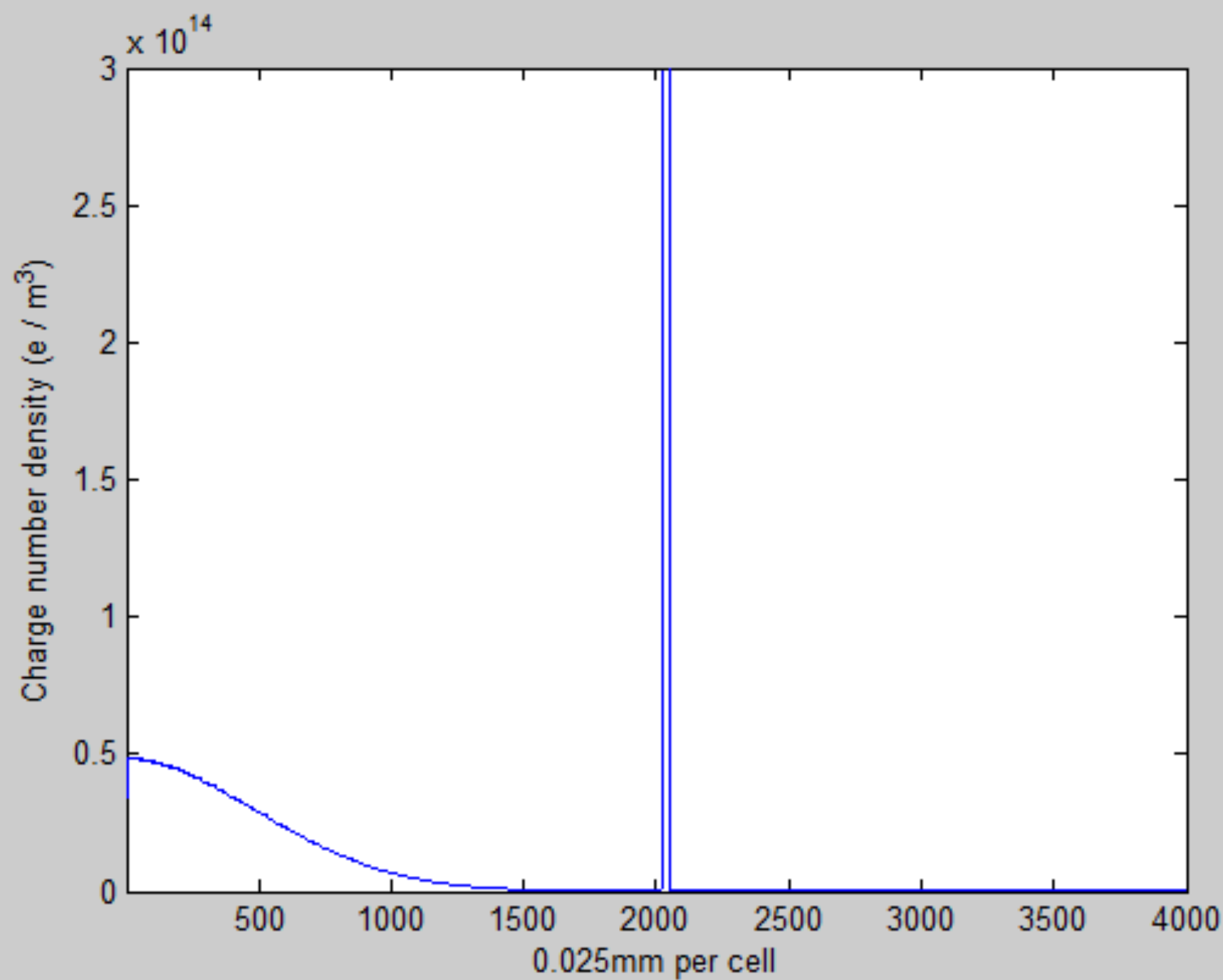
Simulation of the Diamond beam propagating with a wakefield.

$E = 3 \text{ MVm}^{-1}$

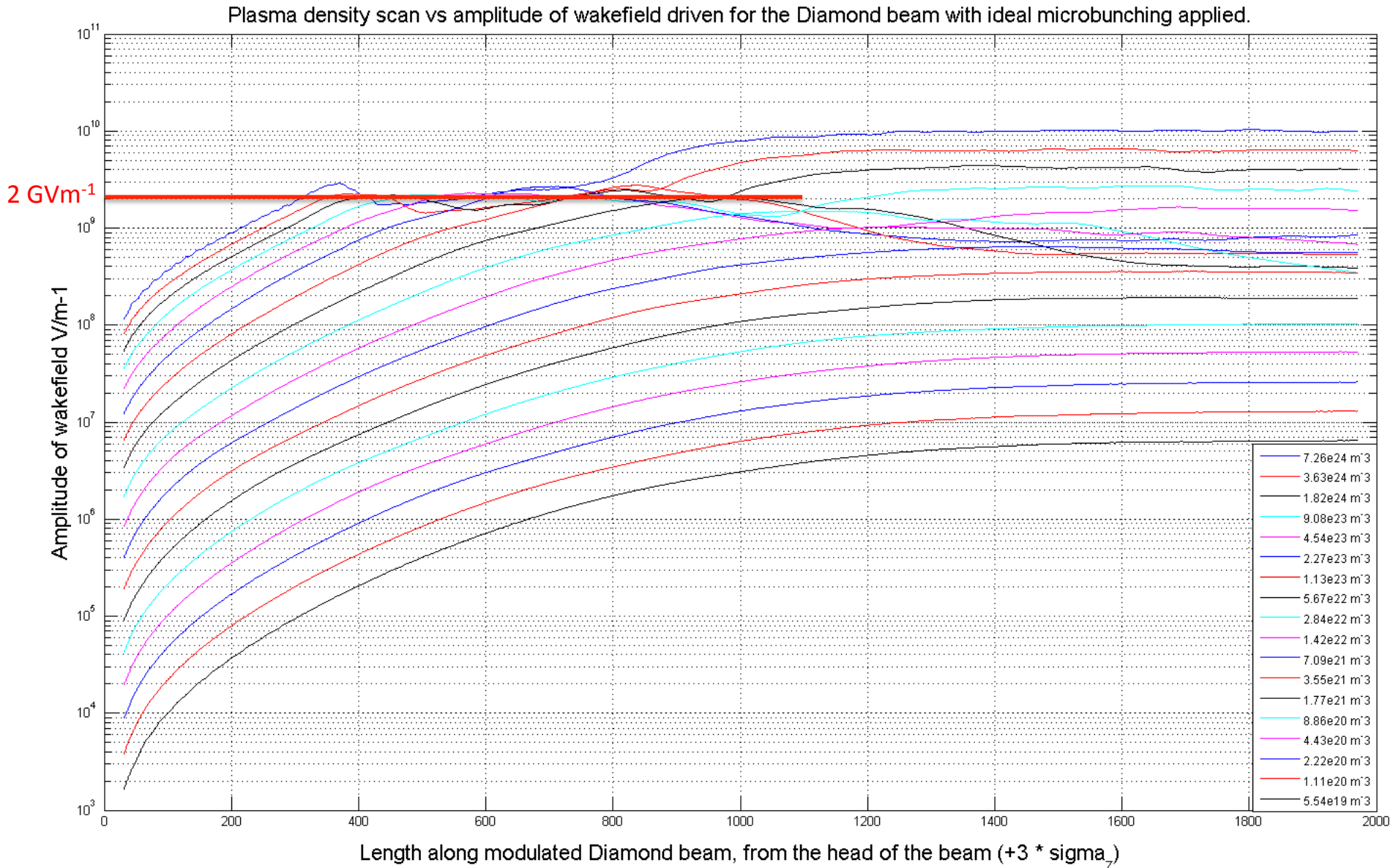


Rear View. 0.025mm per cell

Side View. 0.025mm per cell



The catch with long beams: Ion motion



Conclusions

- Conventional accelerator technology reaching its limitations (E fields)
- Plasma Wakefield Acceleration is a possible next step. Achieves high E fields (50+ GVm⁻¹)
- Simulations show conventional beams can be used to drive PWA
- Approved AWAKE experiment and planned Diamond will demonstrate this

Thank you for listening

Simulations

Simulations so far:

- Untreated Diamond beam from the booster
 - > Drove a weak wakefield
- Cooled beam (2.7 nm rad) from the storage ring
 - > Drove a weak wakefield
- Radially compressed beam – using quadrupole
 - > Filamentation instability dominated
- Cut beam
 - > Drove a weak wakefield. $E = 70 \text{ KVm}^{-1}$
- Seeded beam – using an ideal driver

Diamond Booster Parameters

- $E = 3 \text{ GeV}$
- $\varepsilon = 140 \text{ nm rad}$
- $\delta E / E = 0.0007$
- $\sigma_z = 2.6 \text{ cm}$
- $Q = 2 \text{ nC}$

Typical simulation parameters:

- 4320×320 grid. $\sim 10^7$ particles
- 127 cores over 4 days
- $n_e = 1.11 \times 10^{20} \text{ m}^{-3}$
 - > $\lambda_p = 3.17 \text{ mm}$

Simulations

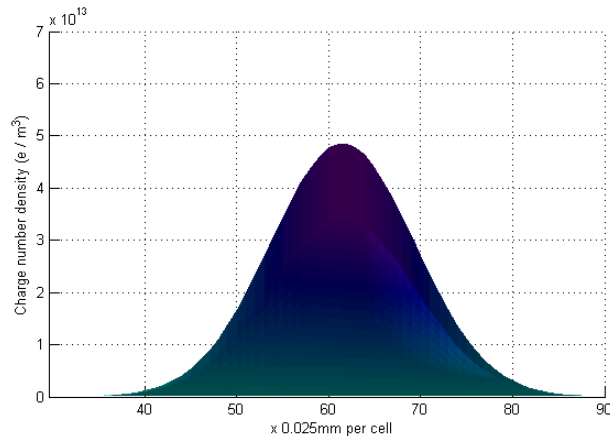
The untreated Diamond beam:

- Energy 3 GeV
- Geometric emittance 140 nm rad
- Rms relative energy spread 0.0007
- Rms bunch length 2.6 cm
- Charge up to 2 nC

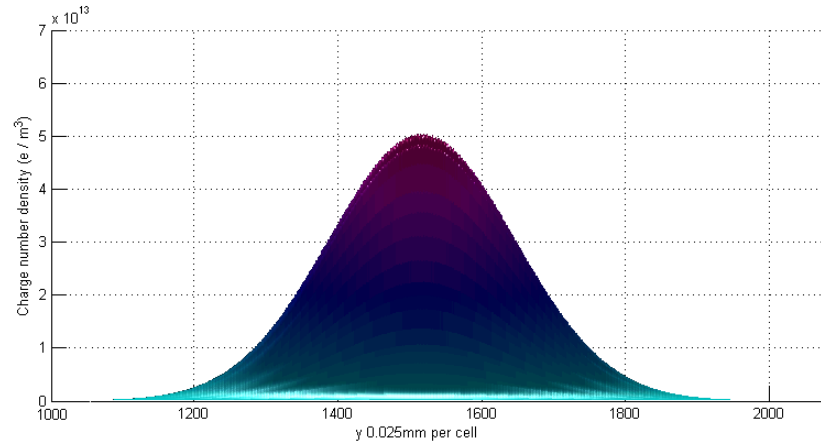
Set:

--> $\sigma_r = 1.58 \text{ mm}$
 $T = 1 \times 10^8 \text{ K}$

Rear view

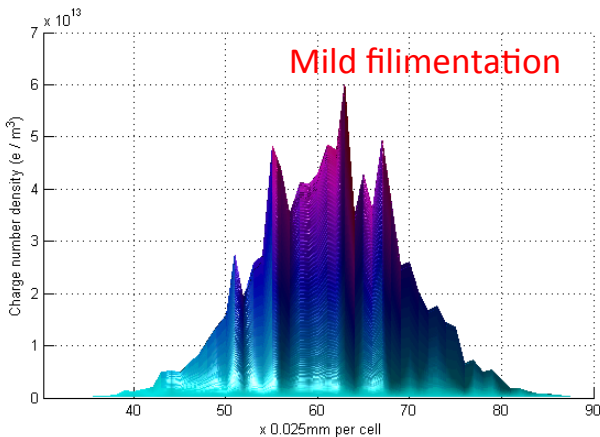


Side View

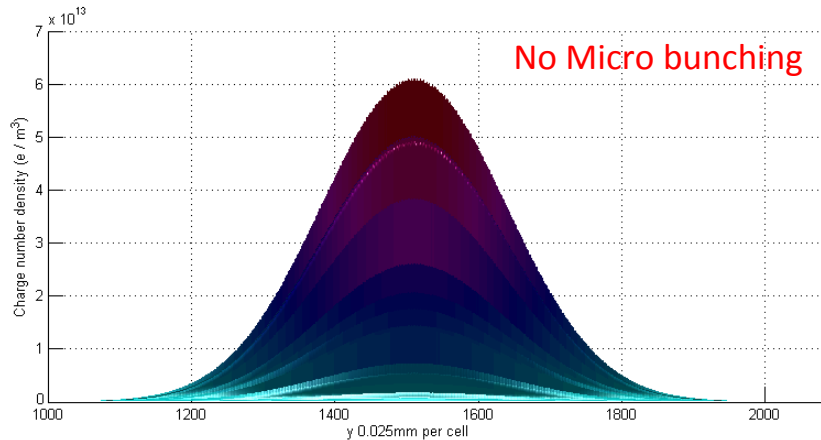


Before:

Mild filamentation



No Micro bunching



After:

Simulation of the untreated Diamond beam.

Simulations

Radially compressed Diamond beam. -> Higher charge density drives a stronger wakefield.

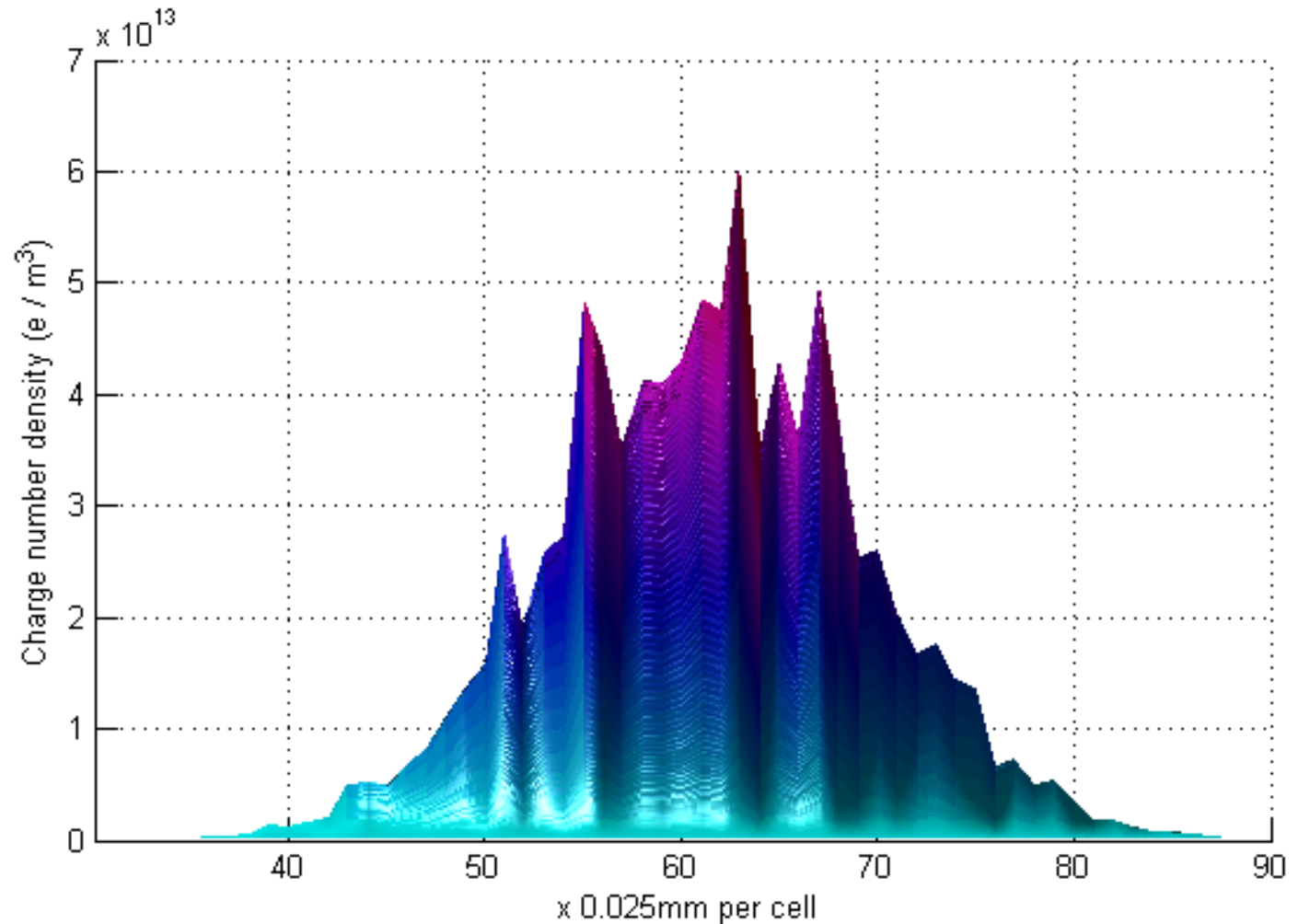
Set:

--> $\sigma_r = 0.158 \text{ mm}$

$T = 1 \times 10^{10} \text{ K}$

Filamentation
destroys the beam.

Cannot compress
smaller than
 $\sigma_r \sim 1.58 \text{ mm}$.



Simulation of the untreated Diamond beam.

Upcoming Simulations

Next set of simulations:

- Small parameter scan over intensities of seeding laser pulse
- Modulated Diamond bunch into second plasma stage
- Modulated Diamond bunch co-propagating with non-modulated proton bunch.
- Inject witness electron beam and use motion to calculate synchrotron radiation

Laser Parameters:

- $\lambda = 1 \mu\text{m}$.
- Spot size = $\sim 50 \mu\text{m}$ Diameter
- $I = 10^{13} - 10^{15} \text{ Wcm}^{-2}$
- Pulse length $\sim 500 \text{ fs}$

If our simulations demonstrate modulation of the Diamond beam is feasible and we secure the beam time and the funding then this experiment should go ahead in 2012.

Diamond Recent Results

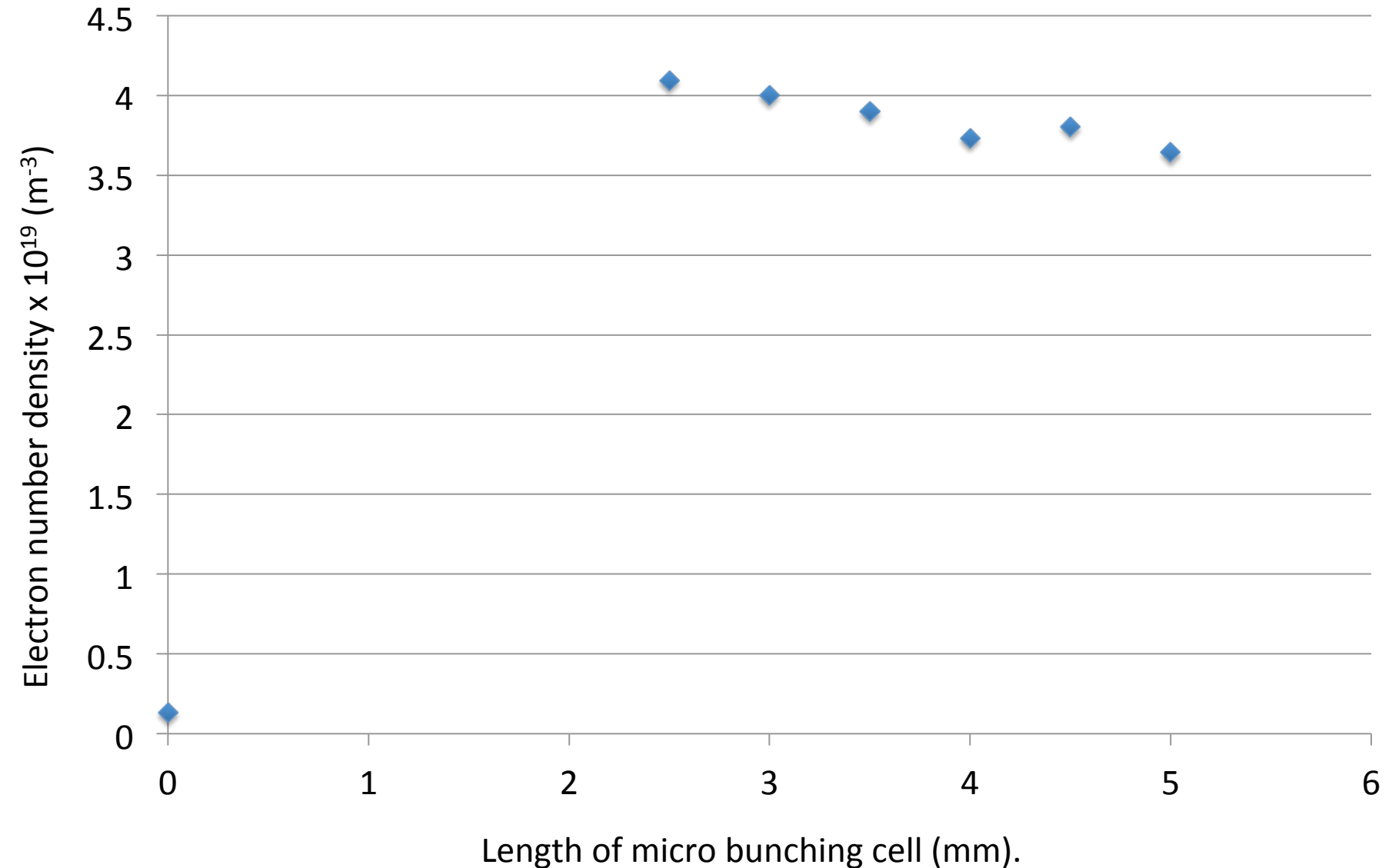
- High Quality Modulation
- Seeding Laser Scan
- Transverse Diamond Compression Scan*
- Plasma Density Scan
- DiRAC



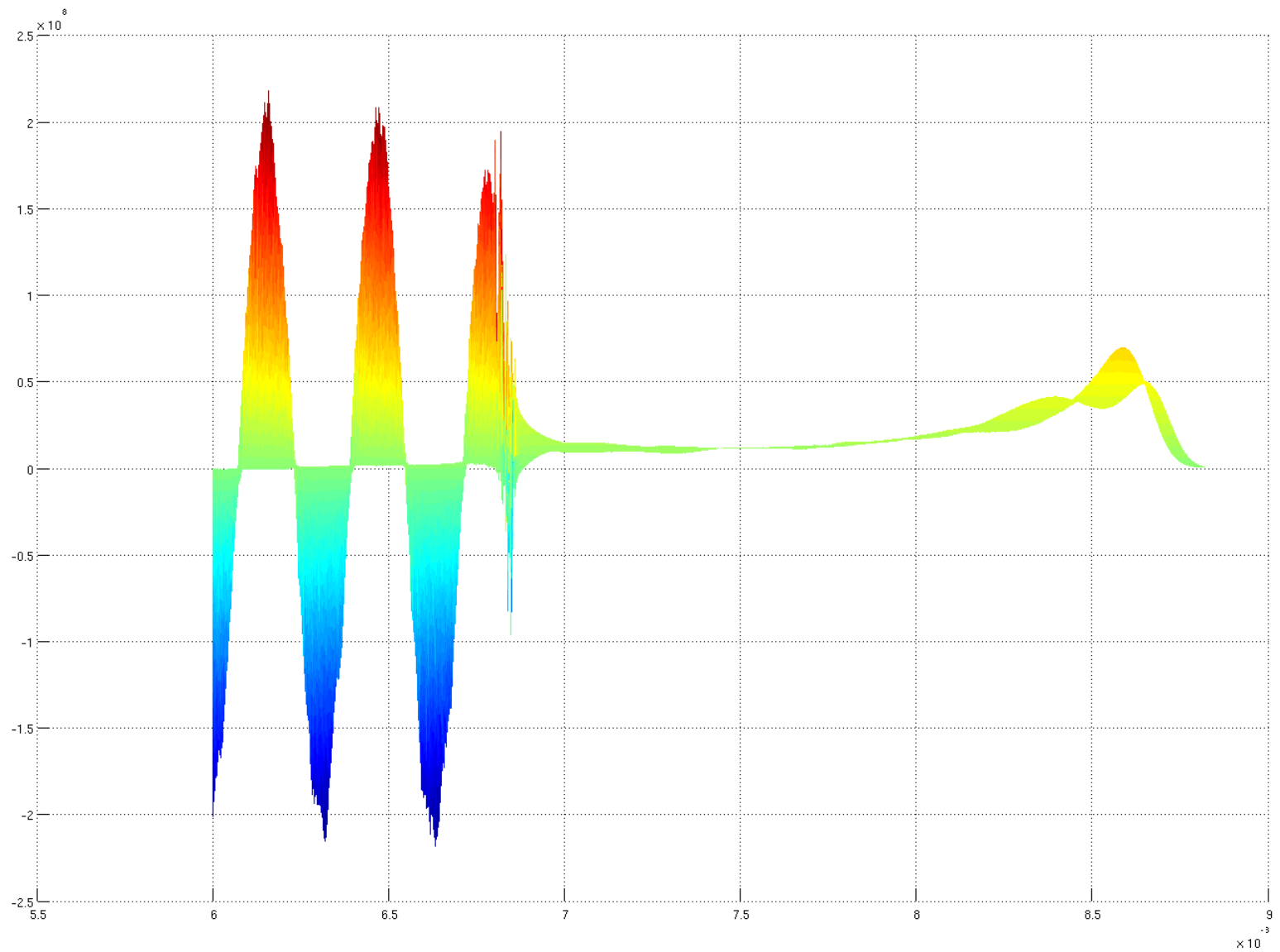
UCL

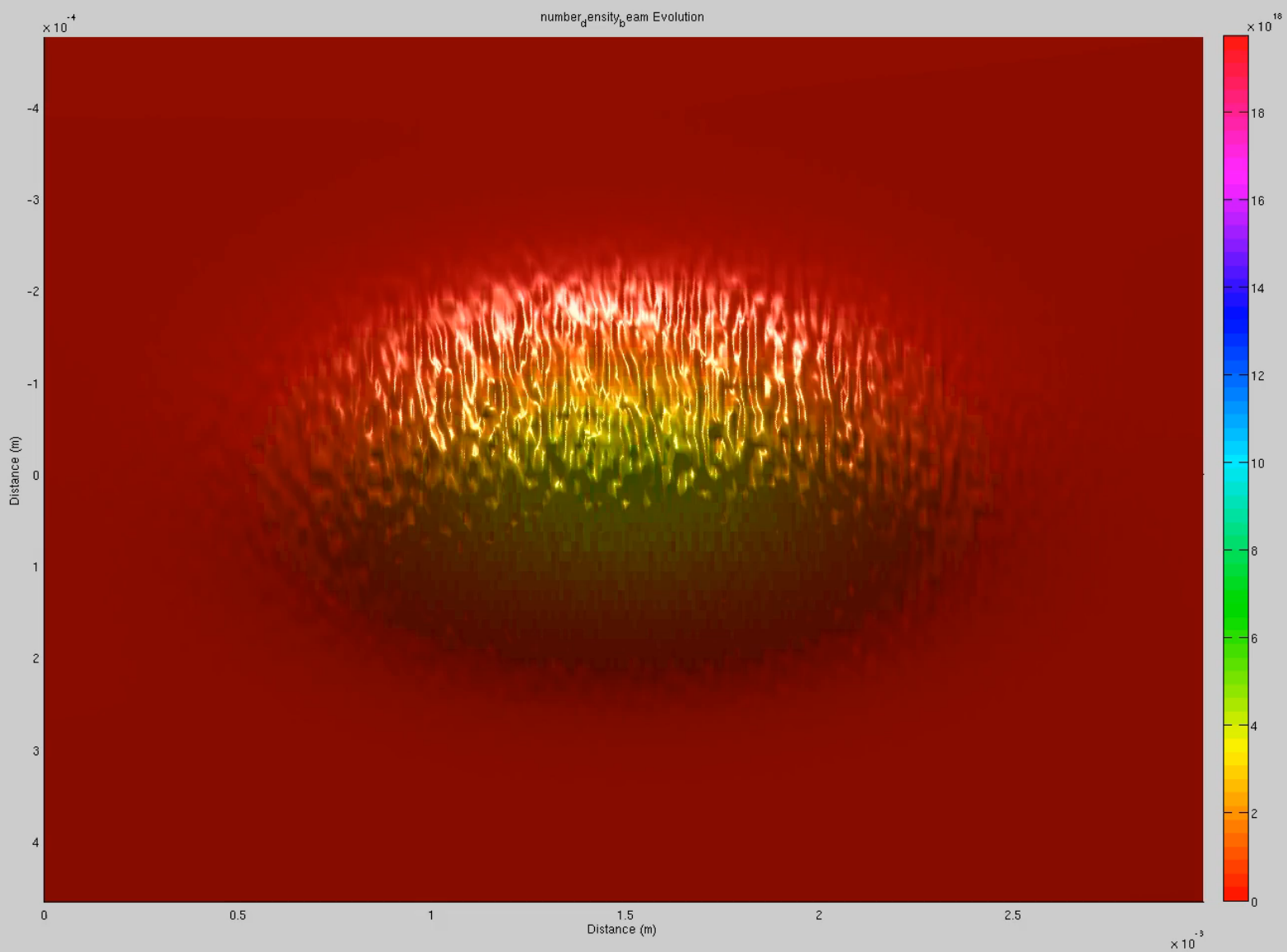
The Scan:

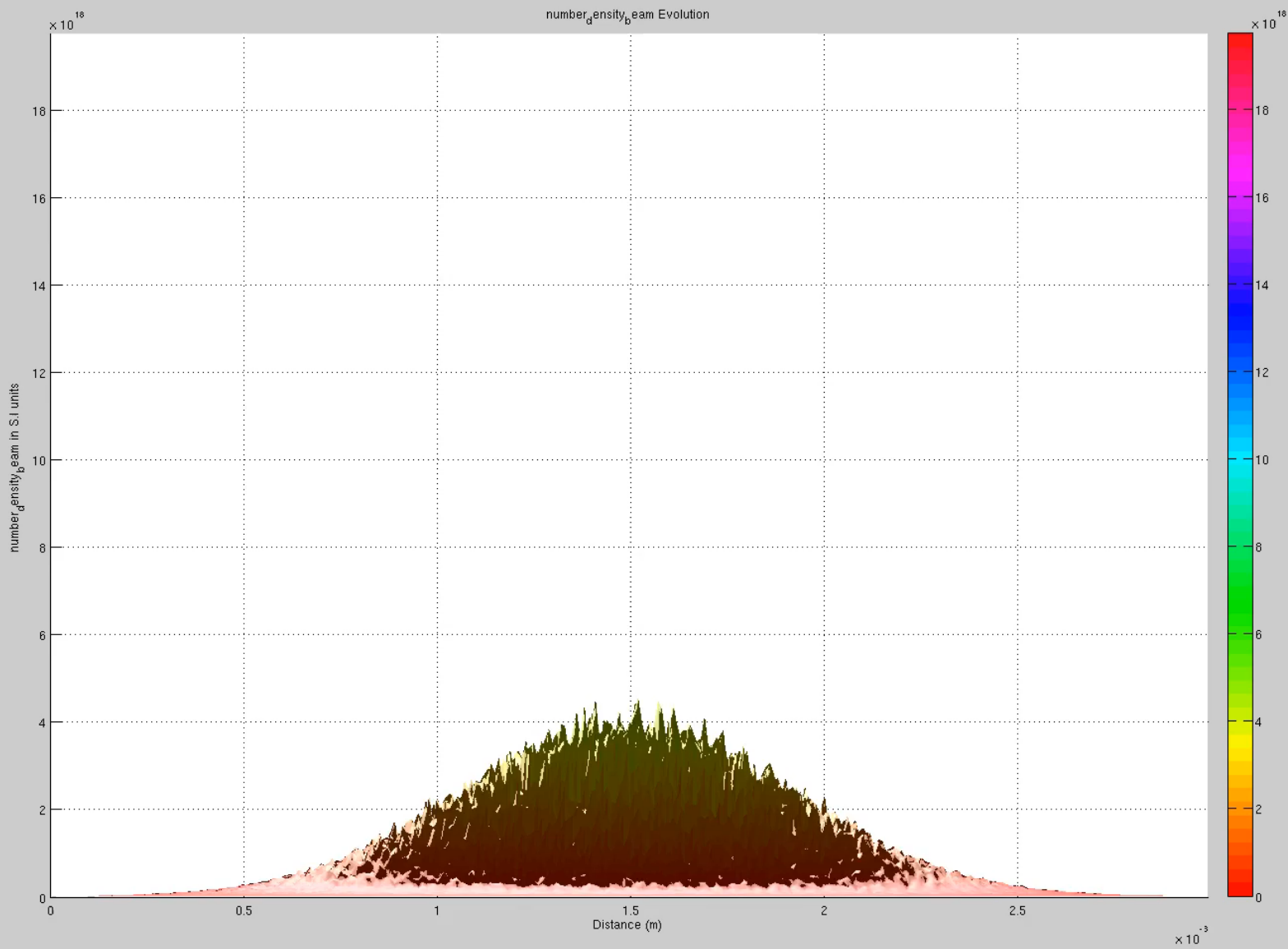
Peak N_d of micro bunched beam after 260mm of total propagation



0003.sdf – 7.8mm







The Plasma

		Interstellar plasma	Lightning	Inertial confinement fusion
Interstellar plasma	$n_e \text{ (m}^{-3}\text{)}$	10^5	10^{24}	10^{32}
Lightning	$E_{\text{max}} \text{ (Vm}^{-1}\text{)}$	30	10^{11}	10^{15}
Inertial confinement fusion	$\lambda_p \text{ (m)}$	3×10^2	3×10^{-5}	3×10^{-9}

$$\omega_p = (ne^2/m\epsilon_0)^{1/2}$$

Plasma frequency

$$E = \frac{\omega_p m_e c}{e}$$

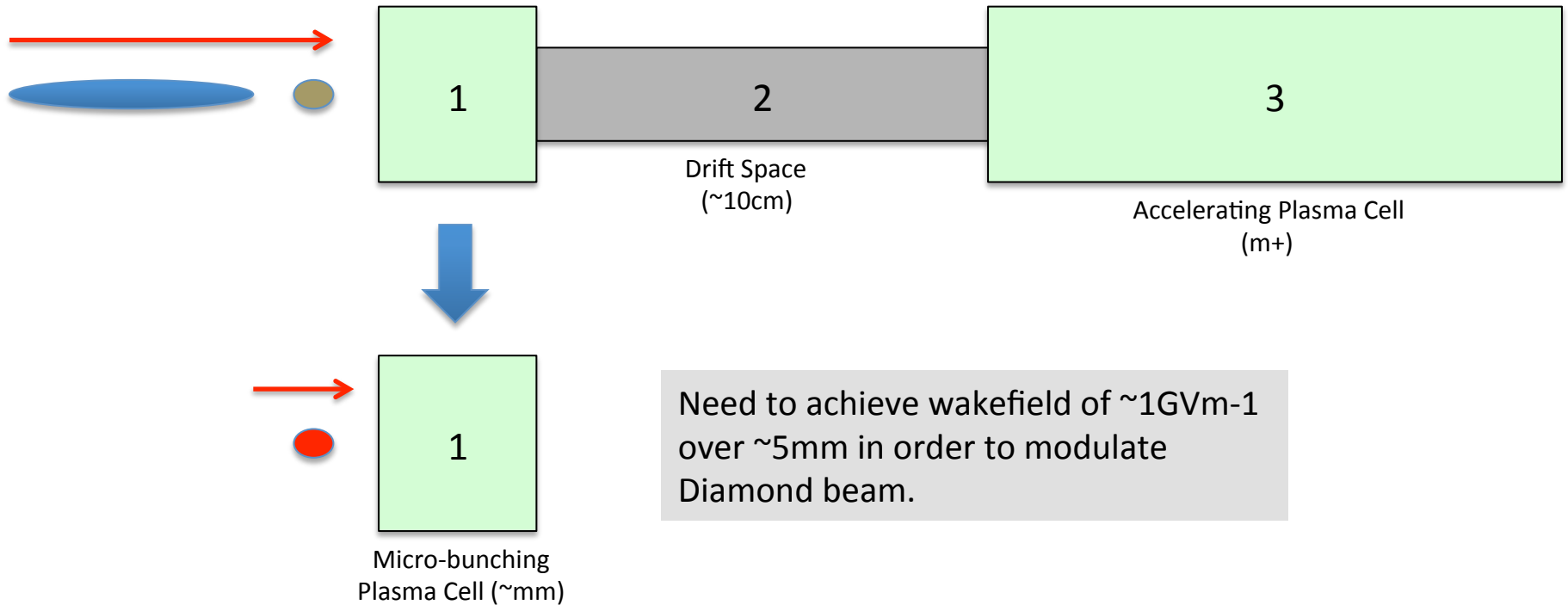
Maximum supportable E field

The SPS Experiment

- A spare SPS tunnel for demonstration experiment located
- Large group of interested institutes
- Letter of Intent to CERN accepted
- Develop technical plan required by July 2012
- Build components/installation of beamline til mid-end 2014
- Start experimentation 2015



Laser Seeding Scan



Ideal e- driver

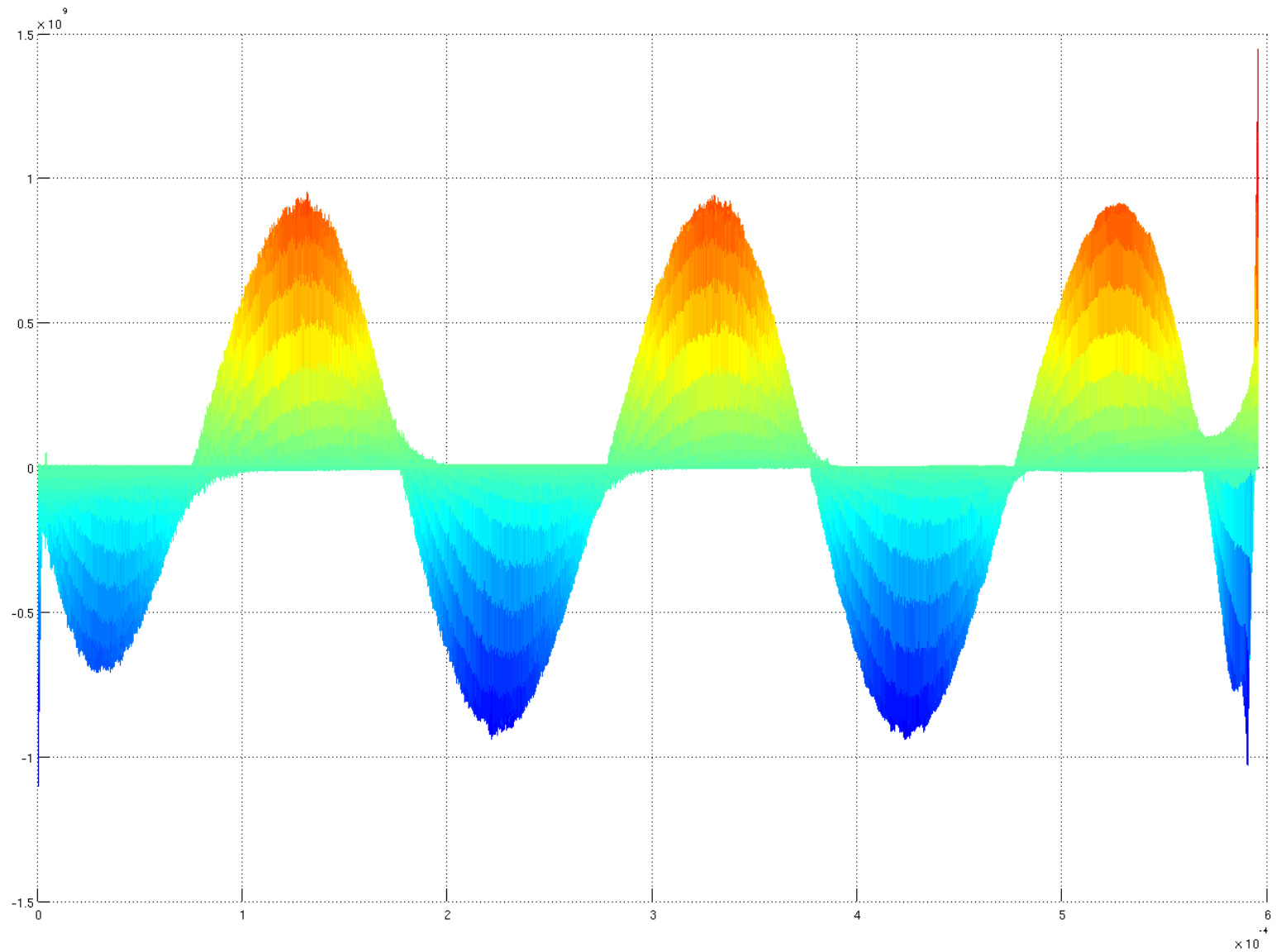
- $E = 1, 0.5, 0.2 \text{ J}$
- $\lambda_p = 1.06 \text{ } \mu\text{m}$
- $\sigma_z = 50 \text{ fs}$
- $\sigma_r = \sqrt{2} / k_p$
- $n_e = \text{Scan}$

Three short density scans:

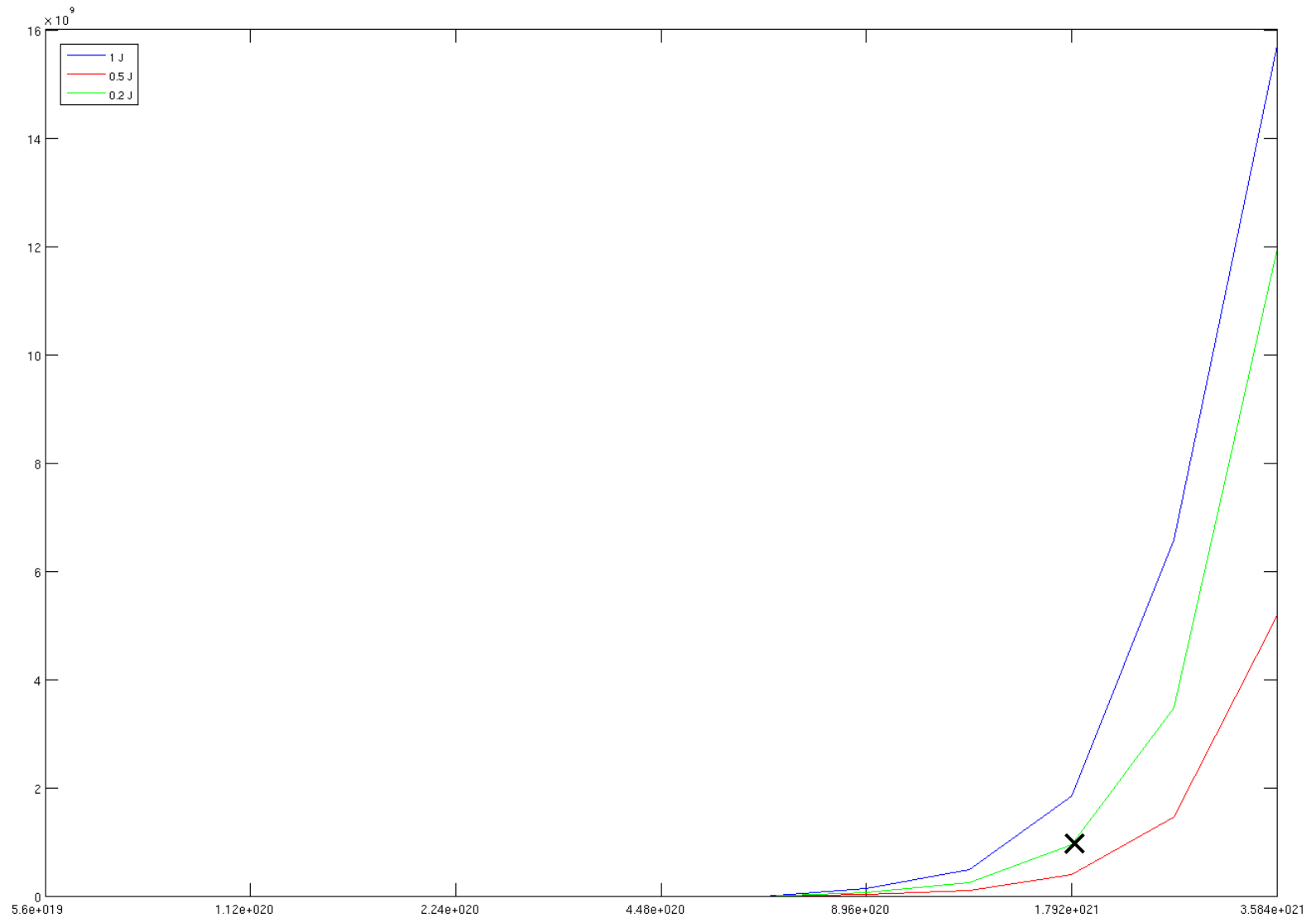
Use a 1J, 0.5J and 0.2J laser to drive wakefields in varying densities of plasma.

0.5J

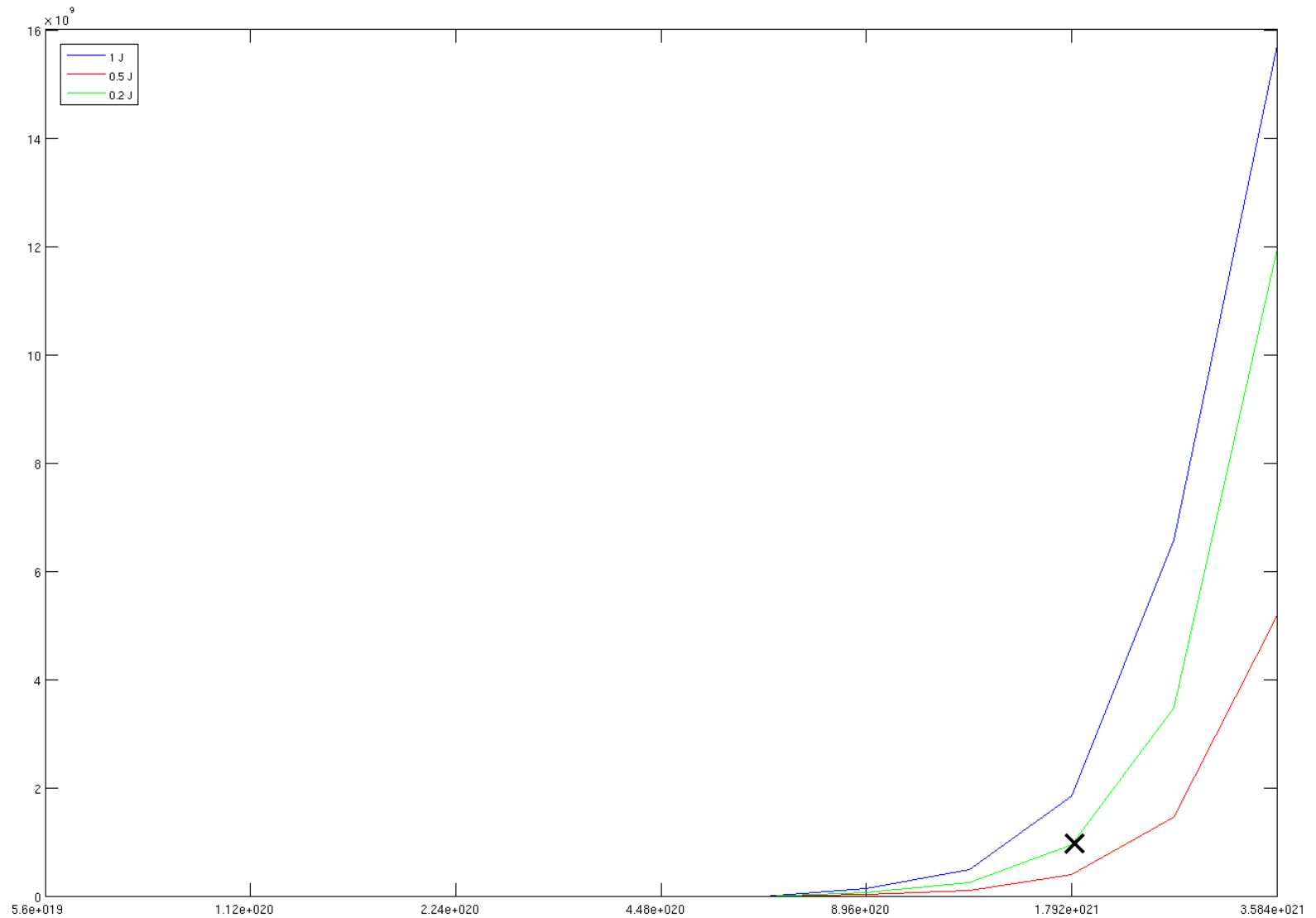
Laser Seeding Scan



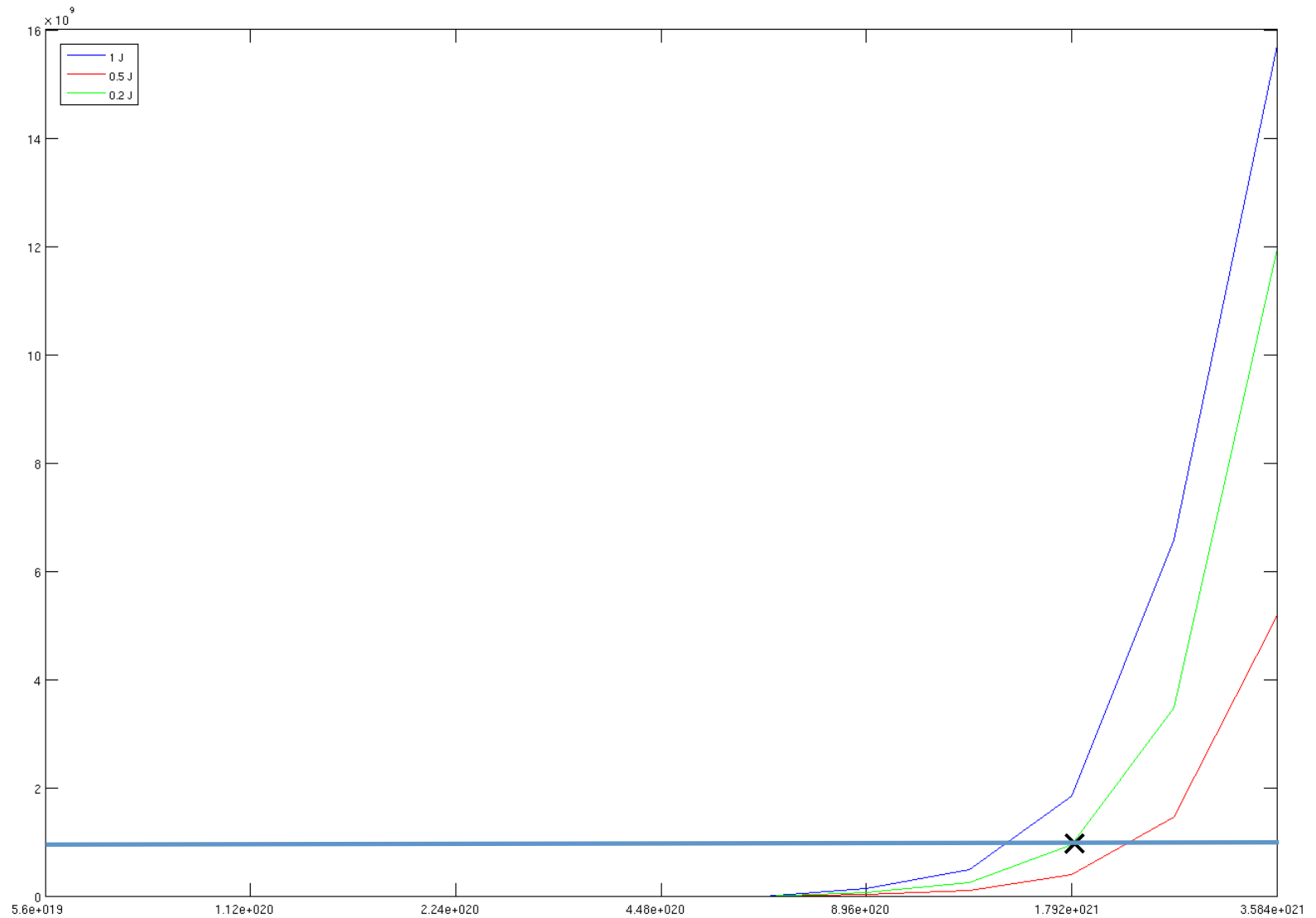
Laser Seeding Scan



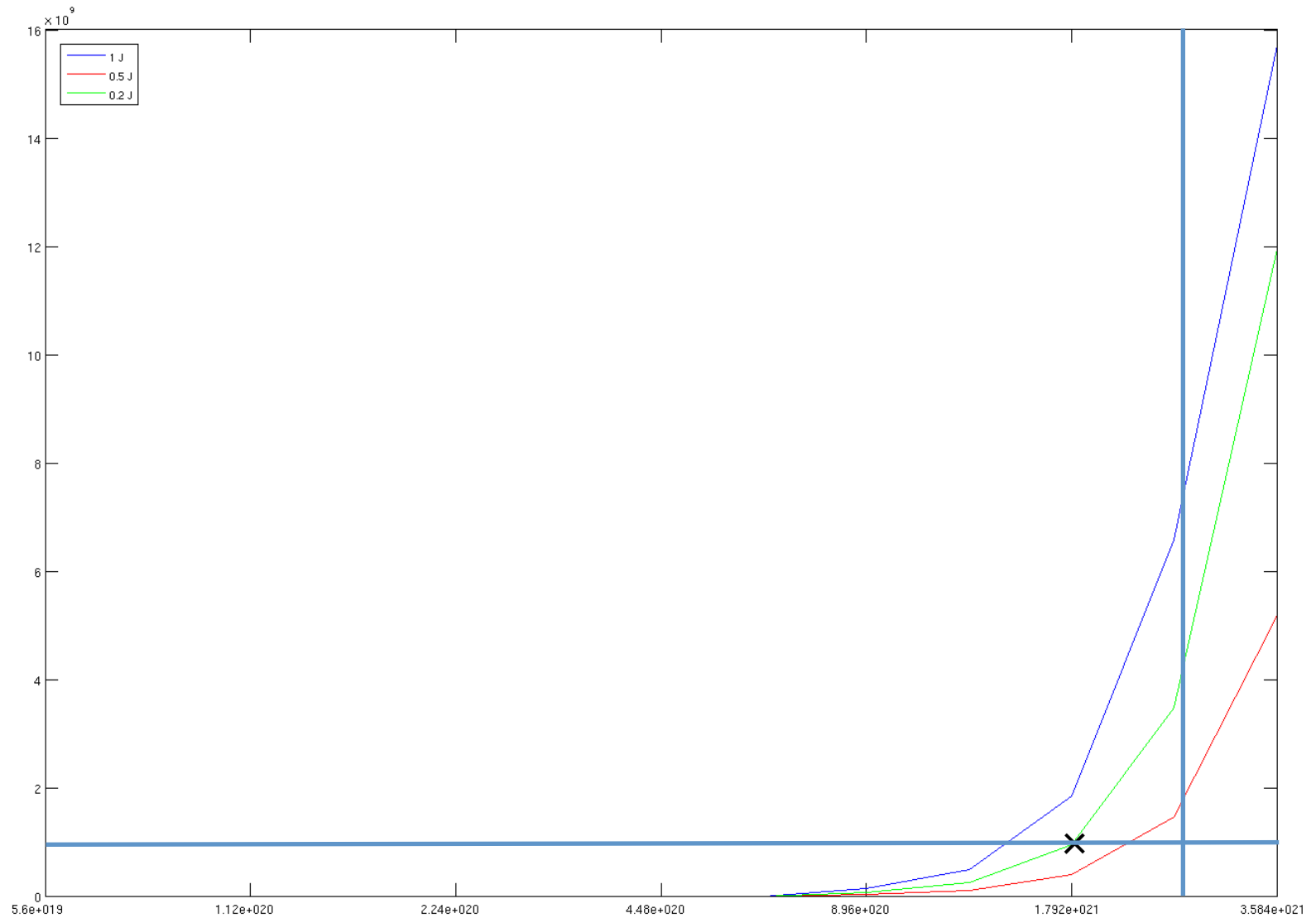
Laser Seeding Scan



Laser Seeding Scan



Laser Seeding Scan



Laser Seeding Scan

