Micro-bunching Conventional Particle Beams To Drive Plasma Wakefield Acceleration

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Synchrotron Facilities Worldwide

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

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Electron beam length
Proton beam length

13.2 mm PETRA III
2.4 mm ANKA
26 mm diamond
5.4 mm SOLEIL SYNCHROTRON
52 mm PSI
120 mm CERN
14.6 mm ESRF
330 mm MAX-lab

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 from 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

\[ \sigma_{\text{ideal}} = \frac{\lambda_p}{\pi \sqrt{2}} \]

Need beam lengths of:
\[ \sigma_z < 1 \text{ mm} \]

The Solution

• Micro-bunch beams to make them an effective wakefield driver
Micro-Bunching Via Self Modulation

- Seed instability
- Wakefield modulates beam
- Beam drives harder wakefield
- Feedback mechanism
- Takes time for instability to saturate

This is not the scheme I use

Micro-bunched beam.
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

**Diagram:**
- Long electron beam Led by laser
- Neutral plasma
- Second plasma cell
- Vacuum!

Micro-bunched driver beam.
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
- $E_r = 1$ GV m$^{-1}$

**The Plasma**
- $n_e = 1.11e22$ m$^{-3}$
- $\lambda_p = 300$ um

**Notes**
- 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
Beam number density. 51 mm of propagation
Beam number density. 51 mm of propagation

On axis number density enhanced by ~ an order of magnitude

$3.5 \times 10^{19}$

$3.1 \times 10^{19} \text{ m}^{-3}$
Beam number density. 200 mm of propagation
Effects of First Cell length

Two-Stage design results in stable micro-bunches

Single cell design. Electrons focused too hard and lost from micro-bunches
The Diamond Light Source

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

Beam length: $\sigma_z = 26$ mm

Too long to effectively drive a wakefield! ($\lambda_p \sim O(100\text{um})$).

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
- $\varepsilon = 140$ nm rad
- $\sigma_z = 26$ mm
- $Q = 2$ nC
Linac Pictures by Michael Bloom, Imperial College.

90 KeV

Pictures by Michael Bloom, Imperial College.
Booster Pictures by Michael Bloom, Imperial College.

158m circumference
Transfer Line

Pictures by Michael Bloom, Imperial College.
The Diamond Experiment

Several slides of tour of Diamond!

Storage Ring

Pictures by Michael Bloom, Imperial College.
Diamond Conceptual Layout

Diamond Beam Parameters
- $E = 3$ GeV
- $\varepsilon_p = 140$ nm mrad
- $\sigma_E / E = 0.0007$
- $\sigma_z = 2.6$ cm
- $Q = 2$ nC

HP Ultra Short Laser
- $\lambda = 1.06$ um
- $\sigma_r = 20$ um
- $E = 1$ J
- $I = 1e16$ Wcm$^{-2}$
- $\tau = 50$ fs

Plasma Parameters
- $N_e = 1.11e23$ cm$^{-3}$
- $\lambda_p = 100$ um
- Element = Xenon
- Cell = ~Discharge

6 meter of beam line space available
Diamond beam micro-bunched by 1 GVm$^{-1}$ WF
The Catch With Long Beams: Ion Motion

Plasma density scan vs amplitude of wakefield driven for the Diamond beam with ideal microbunching applied.

Amplitude of wakefield V/m-1

Length along modulated Diamond beam, from the head of the beam (±3 * sigma_m) (m)
Can alleviate with high Z plasmas

Plasma density scan vs amplitude of wakefield driven for the Diamond beam with ideal microbunching applied.

4 GV/m
Acknowledgements

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Computing resources provided by STFC’s e-Science facility, SCARF
• Many existing particle beams out there
• 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 betatron oscillations
• Ion motion is a problem!

Thank you for listening