09/02/2021 **Plasma Beam Dump** — 10114980 — 1st Meeting w/ Guoxing Xia

LHC → Proton-proton collisions involve quarks

ILC ↴ ILC is a linear collider over 10km, 30-50km
Positron - electron collisions provide clearer picture as they are fundamental

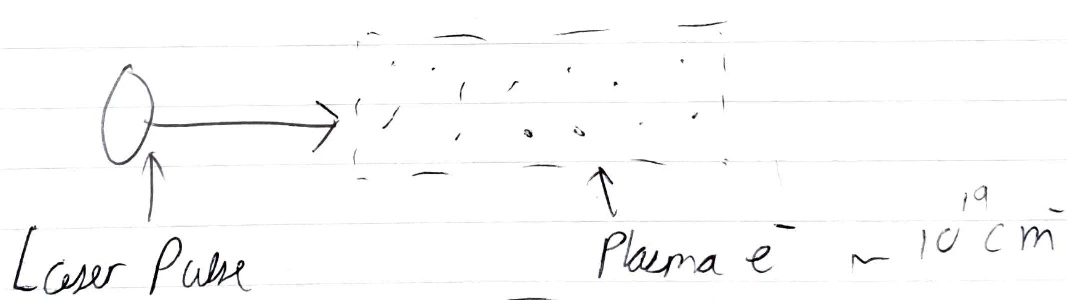
↳ But $e^+ - e^-$ produces "secret" radiation which is a problem!

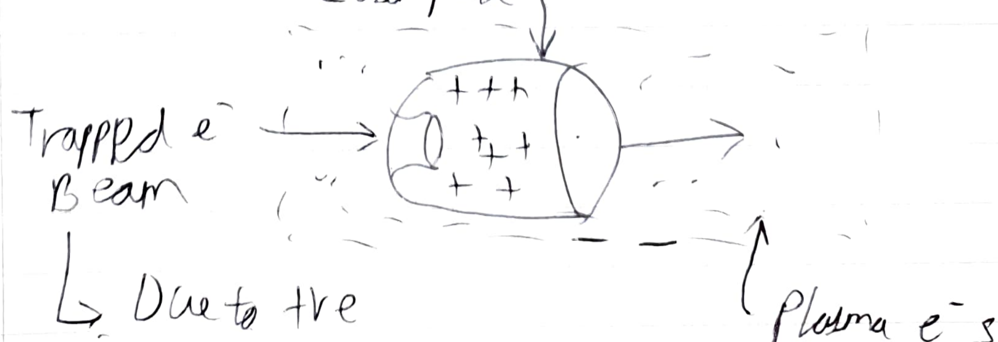
Plasma Accelerator

↳ Accelerating field in plasma is 3-4 orders of magnitude higher than conventional accelerators

Laser Plasma Acceleration

↳

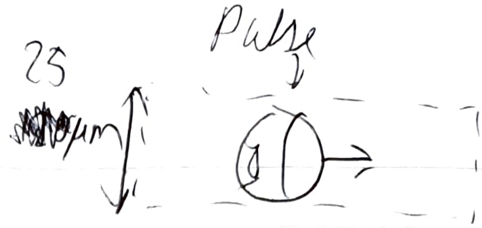




↳ Due to the ions attracting e^-

Bubble ~ 35 µm

lasts 120 fs



Plasma accelerator

↳ Can shrink to 9cm D

↳ Save money and space building large particle accelerators

↳ Tabletop accelerator

Plasma Accelerator

↳ Produces lots of high energies

↳ After collisions, still lots of high energy!

↳ Dump the plasma beam in a material to absorb energy

Conventional Beam dump design:

- Stainless steel pressure vessel
- 11m length
- 10 bar pressure, 100% Safety margin
- 155°C Water temp.

What about using a plasma beam dump?

Plasma beam dump offers high decelerating gradients in a low density medium.

$$E_{WB} = \frac{m_e c \omega_p}{e} = 9.6 \sqrt{\frac{n_e}{10^{22}}} \text{ GV m}^{-1}$$

For $n_e = 10^{18}$ cm^{-3}

$E_{WB} = 96$ GV m^{-1}

- Compared with stopping power in solid material e.g. ILC beam dump 250 GeV in 11m ~ 23 GV m^{-1}
- Plasma density is orders of mag. lower than solid e.g. graphite ~ 10^{23} cm^{-3}
- Plasma dump can also be applied to e^+, μ^- with high decelerating gradient

Motivation ⇒ Find optimum parameters to maximise beam energy loss in plasma

Next week: Discuss the background Physics

This Week
Objectives: Read up papers sent by Guoxing.
literature

11/02/2021

Literature

Bonatto et al. paper

↳ "Compact disposal of high energy electron beams using passive or laser driven plasma decelerating stage"

LPA = Laser-driven Plasma Accelerator

PIC = Particle-in-Cell

LPAs provide compact way to produce high-energy e^- beams → particle accelerators!

↳ But disadvantage is the high energy beam needs to be disposed

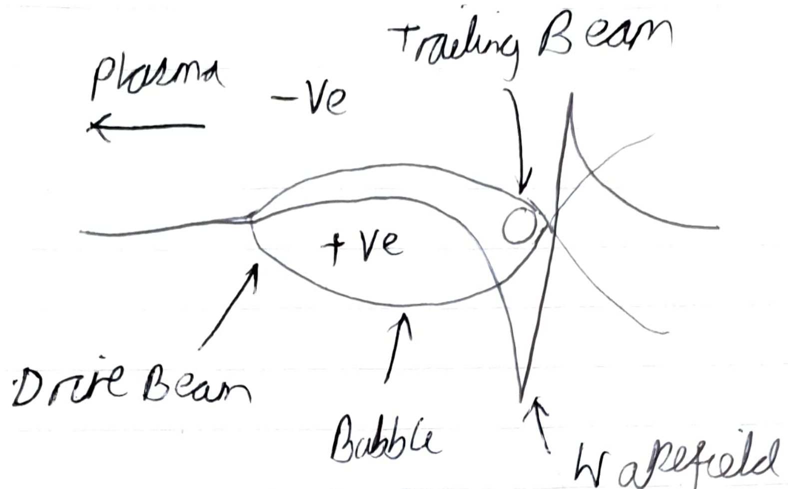
↳ Conventional beam dumps inefficient

↳ Plasma beam dump can decelerate high energy e^- beams to <u>non-relativistic</u> speeds in just a few <u>cms</u>!

Passive Dumping: Highly relativistic e^- beam propagates in an initially quiescent plasma, exchanging energy with self-excited wakefield

Active Dumping: Beam propagates in the wake of a laser pulse, experiencing a net E field that is a superposition of the self excited and laser driven wakefields

Wakefeild Excitation



The wakefeild is a "Charge disturbance"

Consider 1D
↳ If amplitude of wakefeild is small compared to cold non-rel. wave breaking E feild

$$\boxed{E_0 = \frac{c m_e \omega_p}{e}}$$

Where $\omega_p = k_p c = \sqrt{\frac{4\pi n_0 e^2}{m_e}}$

e^- Plasma Frequency

n_0 = Background e^- Plasma density

Active dumping → Better at reducing beam energy than passive dumping

Guoxing Xia et al.

↳ "Plasma Beam Damps for EuPRAXIA Facility"

Active Plasma Beam Dump = APBD

Passive Plasma Beam Dump = PPBD

PPBD

↳ • Head of bunch experiences no decelerating field due to finite response time of plasma
- Particles at bunch tail experience a decelerating field

↳ BUT eventually becomes non-rel. and fall behind rest of the bunch & reaches an accelerating phase of wakefield

↳ Beam re-acceleration! → BAD! We need to decelerate!

Counter Beam Re-acceleration:

↳ • Insert foils in plasma to absorb re-accelerated particles
- Tailor plasma density along beam propagation direction to change relative phases of wakefield along beam driver
- Use ~~ABD~~ APBD!
  ↳ An excited wakefield is employed in plasma prior to beam propagation. Such laser driver & beam driver wakefields flatten decelerating field along bunch.
    ↳ Prevents formation of reacceleration fields

BUT APBD much more complex to implement.

LWFA - Laser Wakefield Accelerator
PWFA - Plasma Wakefield Accelerator

<u>Wu et al.</u>

"Collective deceleration: toward a compact beam dump"

→ Conventional beam dump based on ionization/radiation loss mechanisms are cumbersome, costly and result in radiological hazards

With plasma beam dump
↳ required plasma density is low so hazardous radioactivation due to individual nuclear collisions significantly reduced

↳ More important for particle Energies > GeV where heavy secondary particles e.g. μ^- are produced and need more stopping power

→ Uniform plasma deceleration ineffective a certain distance
↳ Need a structure tailored plasma to further e^- deceleration

Bethe - Bloch formula for Stopping Power:

$$\boxed{-\left(\frac{dE}{dx}\right)_I = \left(\frac{F}{\beta^2}\right)\left[\ln\left(\frac{2m_e \gamma^2 v^2}{I}\right) - \beta^2\right]}$$

Change in Electron kinetic energy w.r.t. distance into medium

$$\boxed{F = \frac{4\pi e^4 n_{e,m}}{m_e c^2} = e^2 K_{pe,m}^2}$$

γ = Relativistic Factor

$n_{e,m}$ is e^- density in stopping material

$K_{pe,m} = \omega_{pe,m}/c$ is plasma wavenumber

$\beta = \frac{v}{c}$ normalised e^- velocity

I represents a specific average of excitation and ionisation potentials in atom

→ Electron energy absorbed by excitation/ionisation of bound e^- in atoms of stopping material

Collective Deceleration

Collective Stopping Power for wakefield deceleration of e^- bunch

↳ $$\boxed{-\left(\frac{dE}{dx}\right)_{coll-wave\ break} = m_e c\, \omega_{pe}\left(\frac{n_b}{n_e}\right)}$$

n_b = e^- bunch density

n_e = plasma density

⇒ In Principle, energies from decelerated beams deposited in form of organised plasma wakefields unlike heat energy in conventional dump, may be recycled into electricity !

↳ Save energy by reusing it to accelerator

↳ ALSO mitigates cooling plasma problem

16/02/2021 — 2nd Meeting w/ Gaoxing Xia + Niki Vitoratou (Post-doc)

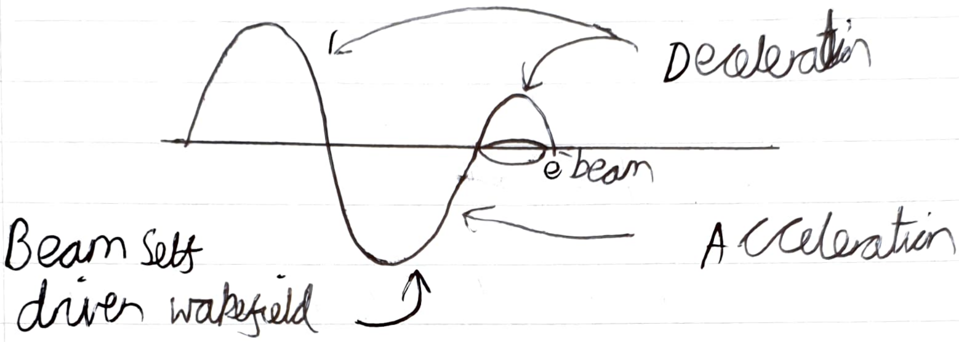
Main Goal: Find a way to deposit more energy into a plasma dump

Transverse – Focus/defocus

Longitudinal – Accelerates/decelerates

Passive Plasma Beam Dump

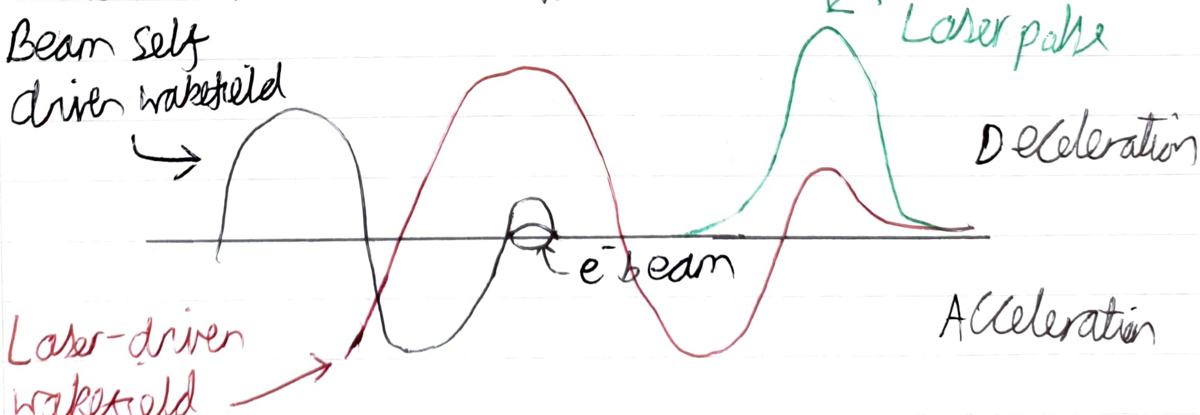
↳ Beam self driven wakefield



If e^-s ~~beam~~ falls behind bunch, it experiences a reacceleration! → Energy loss saturation!

Active Plasma Beam Dump

↳ Beam + laser driven wakefield



If e^-s ~~beam~~ falls behind bunch, the laser driven wakefield flattens reacceleration → No reacceleration!

Motivation: Plasma/Laser wakefield accelerators have vastly increased in specs, energy, and tech

↳ Resulted in higher energy beams which means conventional beam dumps become far more costly

↳ Therefore need an alternative approach (plasma beam dump) to keep up with the advancing PWFA technology

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How a Wakefield Accelerator Works

Using Electron Beam:

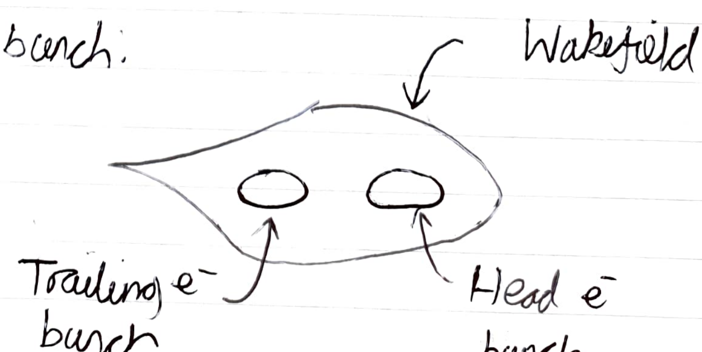
The head of the bunch of e^- propagates through a plasma and drives a "wake" of charge

The wake is driven out of the path of incoming e^- hence creating a charge imbalance that pulls it crashing back in behind the passing e^- bunch

This effect creates a strong longitudinal field that accelerates particles in the back of the bunch.

↳ Energy from the particles in the head bunch is transferred to those in the back, through the plasma wake

2 electron bunch:



Energy is transferred from the head e^- bunch to the trailing e^- bunch

↳ The trailing e^- bunch is also focussed

Jakobsson, O. et al.

↳ "Tailored plasma-density profiles for enhanced energy extraction in passive plasma beam dumps"

Plasma wakefield accelerators provide accelerating gradients up to hundreds of GVm^{-1} → ~10^3 larger than those in conventional RF cavities

Recent Results for Laser/Plasma Wakefield Accelerator

→ Guiding of 850TW laser pulse through 20 cm long pre-formed plasma channel at BELLA centre, yielding 5pC e^- bunch at 7.8 GeV

→ Final Focus Test Beam facility at SLAC demonstrated a fraction of a 42 GeV e^- beam had its energy doubled by its self driven wakefield, producing accelerating gradient of ~52 $GeVm^{-1}$ in 85 cm long plasma

→ 400 GeV proton bunch as a driver to demonstrate trapping and acceleration of e^- in AWAKE experiment at CERN

Beam Dump

Conventional dumps are metre-long water cooled metal/graphite blocks. → Stopping power via Bethe-Bloch formula

↳ Lots of nuclear radioisotopic hazards produced

Plasma Beam Dump

Consists of relatively low density plasma
↳ radionuclide hazard reduced

Dumps with uniform plasma density eventually reach an energy loss saturation due to particle reacceleration

↳ Instead can tailor a non uniform plasma density against longitudinal beam profile

Active damping → ~95% total beam energy loss

Passive damping → ~ 60 - 70% Total beam energy loss

→ Particles at head of bunch preserve their initial energy
→ Particles trailing behind undergo reacceleration

Tailored Plasma Density ✳

⇒ In linear to quasilinear regime, transverse & longitudinal wakefield components out of phase by ~ $\pi/2$
↳ max accelerating field behind bunch occurs at the point where transverse field changes from focusing to defocusing

⇒ reacceleration of non-rel. particles falling behind bunch result in them attaining rel. energies just before defocusing region
↳ ~~increase plasma density resulting in shortening of plasma wavelength, moving defocusing region towards head of bunch~~

⇒ As bunch continues to lose particles, it forms a secondary bunch of re-accelerating particles behind head of bunch, just in front of defocussing region

↳ Hence increasing plasma density results in shortening of plasma wavelength, moving defocusing region towards head of bunch and over re accelerating particles

↳ These particles rapidly ejected in transverse direction, hence avoiding beam energy loss saturation

NOTE: In uniform plasma density, saturation can also eventually be overcome by defocusing of particles in secondary bunch (reacceleration peak), when its charge is large enough

↳ But does include ejection of particles with energy above initial energy with no major beam energy reduction

S_{chirp} = The distance at which the first beam particles i.e. those experiencing higher amplitude decelerating wakefield have reached non rel. velocities and start falling behind

↳ Hence reach an acceleration phase and we reach an energy loss saturation

Different Plasma Density Profiles investigated:

- Uniform
- Multi-staged uniform
- Linearly increasing
- Constant Rate of wavelength change

⇒ ~~Defocusing causes transverse ejection?~~

Bonatto et al.

↳ "Advances in plasma-based beam dump modelling"

Important ~~Ro~~ Measurement is $\frac{\gamma(s)}{\gamma_0}$

↳ Ratio of relativistic factor at distance s into plasma to relativistic factor at s=0

Saturation Distance s^*

$$\boxed{s^* = \frac{\gamma_0}{k_p E_{z,max}/E_0}}$$

$k_p = \omega_p/c$ is plasma wavenumber

$\omega_p = \left(\frac{n_0 e^2}{m_e \varepsilon_0}\right)^{1/2}$ plasma frequency

$E_0 = \frac{c m_e \omega_p}{e}$ Cold non-relativistic wavebreaking electric field

$s^* =$ The distance at which particles under max wakefield $E_{z,max}$ reach condition $\frac{\gamma(s)}{\gamma_0} \ll 1$ (non-relativistic velocity) and suffer phase slippage

Reacceleration Problem

⇒ Wu et al. proposed use of vacuum regions & periodic thin foils to eliminate reacceleration

⇒ Hanahoe et al. explored linear/quadratically increasing plasma-density profiles to defocus particles from reacceleration peaks (causing ejection)

↳ vessel shaped foil wrapped around plasma cell to stop ejected particles

⇒ Jakobsson et al. explored role played by rate of plasma wavelength change with respect to propagation distance

↳ Changing plasma density n controls plasma wavelength $\lambda \propto \frac{1}{\sqrt{n}}$

↳ Hence move location of acceleration/deceleration and focusing/defocusing phases of wakefield

Hanahoe et al.

↳ "Simulation study of a passive plasma beam dump using varying plasma density"

Conventional Dump

↳ Large Electron-Positron Collider (LEP) uses 2m aluminium dump to stop 100 GeV e^- beam

↳ ILC proposed water dump stops 500GeV beam in 11m

↳ decomposition generates H_2 or O_2 gas that needs to be removed

Stopping power - Average loss of energy with distance

↳ At high energies, losses dominated by bremsstrahlung

T_c = Critical Energy

↳ Where energy loss due to Bremsstrahlung equal to losses due to other factors

$$\boxed{T_c = \frac{800\text{ MeV}}{Z + 1.2}}$$

Atomic Number of Stopping material

Stopping power due to radiation

$$\boxed{-\frac{dT}{dx} = Z\alpha \frac{4e^4 n_e}{mc^2}(\gamma - 1)\ln\left(183 Z^{-1/3}\right)}$$

$n_e = e^-$ density of stopping material

⇒ Passive dump is unable to decelerate head of bunch due to finite plasma response time

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18/02/2021

To mitigate reacceleration peaks in passive dump

↳ Change plasma density $n_0 \to n_1 \to n_2$

∴ Reacceleration Peak is

decelerated if $\left(\frac{3}{2}\right)^2 \leq \frac{n_1}{n_0} \leq \left(\frac{5}{2}\right)^2$

defocused if $1 \leq \frac{n_1}{n_0} \leq 4$

We want to decelerate peak so magnitude of reacceleration is reduced.

We want to defocus peak so reaccelerated particles can be transversely ejected.

(*) → This is with EuPRAXIA beam parameters

$\sigma_\xi = \sigma_r = 5\ \mu m$

Charge = 30 pC

Energy = 1 GeV

RMS Energy Spread $\frac{\sigma_E}{E} = 1\%$

Angular Divergence $= 10^{-5}$ rad

+ Plasma Density $= n_0 = n_{beam} = 10^{17}\ cm^{-3}$

23/02/2021

Meeting with · Gaoxing Xia
- Sanjeev Kumar (Post doc)
- Niki Vitoratou (post doc)

Write down ~~EU~~ FLASH Forward beam parameters

$[N_0, E_0, \sigma_r, \sigma_z]$

$$\boxed{n_b = \frac{N_0}{(2\pi^{3/2})\,\sigma_r^2\,\sigma_z}}$$

Calculate beam density from parameters

Beam Density

have roughly

We ~~want roughly~~ $n_p \simeq n_0$

$$n_p \sim n_b \begin{cases} n_p \sim 10 n_b \\ n_p \sim n_b \\ n_p \sim 0.1 n_b \end{cases}$$

σ_r = transverse width

σ_z = longitudinal width

Plasma Density $= n_p$

$$\boxed{E_{acc} = 244 \frac{N_0}{4 \times 10^{10}} \left(\frac{600\,\mu m}{\sigma_z}\right)^2 MeV\,m^{-1}}$$

$E_{acc} \sim E_{dec}$

$$\boxed{L \sim \frac{E_0}{E_{dec}}}$$

*Put these parameters into the beam code and run the simulation!

* Request access into Computer with email

* Download application for FBPIC

→ Mention Gaoxing Xia + Cockcroft institute

Beam parameters constant

↳ But plasma density is a variable

* Installed FBPIC into anaconda spyder

via

```
conda install numba scipy h5py mkl
conda install -c conda-forge mpi4py

pip install fbpic
```

* Requested access to CSF by emailing its-ri-team@manchester.ac.uk

25/02/2021

Literature - W.Lu et al.

~~[illegible]~~ "Limits of linear plasma wakefield theory for electron or positron beams"

Linear Theory

→ Green's function solution for the plasma response to an arbitrary relativistic charge bunch

↳ Form $\rho_b = \rho_\perp(r)\,\rho_{\parallel}(\xi)$

Where $\boxed{\xi = z - ct}$

$$\boxed{E_z(r,\xi) = Z'(\xi)R(r)}$$

$$Z'(\xi) = -4\pi \int_{\xi}^{\infty} d\xi' \rho_{\parallel}(\xi') \cos(k_p(\xi - \xi'))$$

$$R(r) = \frac{k_p^2}{2\pi} \int_0^{2\pi} d\theta \int_0^{\infty} r' dr' \rho_\perp(r') K_0(k_p|\underline{r} - \underline{r}'|)$$

Where K_0 is the zero-order modified Bessel function

→ we evaluate these expressions for a Gaussian longitudinal profile

↳ $\rho_{\parallel}(\xi) = q n_b e^{-\xi^2/2\sigma_z^2}$ at a position along the axis where $\xi << -\sigma_z$

Result is

$$E_z(0, \xi) = \left(\sqrt{2\pi}\, \frac{q}{e} \frac{mc\omega_p}{e} \frac{n_b}{n_p}\right)\left(k_p \sigma_z e^{-k_p^2 \sigma_z^2/2}\right) R(0) \cos(k_p \xi)$$

Where

$$R(0) = k_p^2 \int_0^\infty r' dr' \rho_\perp(r') K_0(k_p r')$$

For wide beams, i.e. $\rho_\perp = 1$ for $r' = 0$ and remains close to unity for r' much larger than k_p^{-1}, $R(0) \simeq 1$

For fixed bunch length σ_z and normalised beam density n_b/n_p, expression for E_z maximised at $\varepsilon = \frac{eE}{mc\omega_p} = \frac{2\sqrt{\pi}}{e}$

$$\frac{n_b}{n_p} \simeq 1.3 \frac{n_b}{n_p} \text{ for } k_p \sigma_z = \sqrt{2}$$

↳ well known 1D result

⇒ Summary

Proper expression for the wake amplitude from narrow bunches

↳ $k_p \sigma_r \ll 1$

$$E_{zM} \simeq (236\ \text{MeV m}^{-1})\left(\frac{q}{e}\right)\left(\frac{N}{4\times10^{10}}\right) \times \left(\frac{0.06\,\text{cm}}{\sigma_z}\right)^2 \ln\left(\sqrt{\frac{10^{16}\,\text{cm}^{-3}}{n}}\ \frac{50\,\mu\text{m}}{\mu_r}\right)$$

σ_r = Transverse Beam Width
σ_z = Longitudinal beam width

FLASH Forward Beam Parameters

e^- Beam

Macro. rep. rate	1-10 Hz	
Micro rep. rate	0.040-3 MHz	
Bunch Charge	50-800 pC	
Energy	400-1250 MeV	
Bunch Length	50-6000 fs	rms
Chirp	-0.5 - +0.5	% rms
Transverse emittance	1-3 mm mrad	rms proj.
Focal Spot Size	5x5 (spec.) 30x30 (meas.)	µm x µm
Energy Resolution	0.02 %	

Laser Beam

Nominal energy	550 mJ
Peak Power	25 TW
Pulse Length	>30 fs
Wavelength Range	770 – 830 nm
Focal length (ionis. & trans.)	18, >0.5 m
Time jitter	~100 (~10) fs
Polarisation	linear/circular

Plasma Sources

Gas flow	<20 mbar l/s
Gas Species	variable & mixed
density range (windowless, w/end caps)	$< 5\times10^{17}$, $< 1\times10^{20}$ cm^{-3}
Cell length & diameter	<500, <10 mm
Transverse ionis. injection length	~10 μm
Ignition methods	laser, high voltage discharge
Discharge	25 kV, 400 ns, 4.1 nF

02/03/2021

MPhys Meeting

With Guoxing Xia
Niki Vitoratou post doc

~~wave breaking limit~~ →

Plasma wakefield comes from electron acceleration

Can use either $MV\,m^{-1}$ → E field strength
or $MeV\,m^{-1}$ → Accelerating gradient
BOTH CORRECT!

1 GeV beam   10 GeV m^{-1} gradient

↳ $\frac{1 \text{ GeV}}{10 \text{ GeV m}^{-1}}$ = 10 cm long plasma

Chat => FBPIC link to Github

↳ Download Scripts and check them out

Handroe Thesis Notes Chapter 6

Plasma Beam Dumps work via Collective forces

↳ as opposed to random interactions in conventional beam dumps

↳ Particles in plasma oscillate coherently and thus achieve high decelerating gradients even at low plasma density

↳ Since plasma response is Collective, it is possible to recover electricity from plasma

↳ Conventional dump, energy recovery limited to low grade heat

↳ Recovery of electricity also lowers cooling requirements for the plasma dump

Passive Dump:

Saturation Length = L_{sat}

↳ Rate of energy loss of bunch dramatically decreases

$$\boxed{L_{sat} \simeq \frac{T_0}{eE_{dec}}}$$

Beam Initial Energy: T_0
Max decelerating Gradient : E_{dec}

Approx. the propagation length at which max decelerating gradient E_{dec} decelerates a portion of the beam to non-rel velocity

(NOTE - ACTIVE DUMP - wakefield created by preceding laser, whole of the bunch is thus decelerated)

LIMITS

Active - • Available laser pulse puts limit on max energy absorption

Passive - • Length of dump
• Continuing ability of the decelerating bunch to drive plasma wakefield

Stopping Power of a plasma beam depends on bunch parameters

↳ but limited by wavebreaking field

$$\boxed{E_{wb} = \frac{m_e c \omega_p}{e}}$$

Wb field depends on e^- plasma freq. ω_p

→ Essentially, E_{wb} is the maximum decelerating gradient of the plasma

Note: Decelerating gradient of plasma beam dump is independent of mass of particle being decelerated

↳ as opposed to conventional beam dump where stopping power is inversely proportional to particle mass

⇒ Bremsstrahlung is a method of energy loss in plasma beam dump

↳ but reduced factor of ratio of densities of plasma & conventional dump

↳ Pair production of muons may occur due to bremsstrahlung but stopping power of muons same as e^- in plasma dump (no dependence on mass)

Energy loss due to Bremsstrahlung can be neglected

↳ Stopping power $\simeq 30\ keV\ m^{-1}$

↳ very small relative to wakefields

Reacceleration → Wu et al. Suggested foil after L_{sat}

↳ However foil experiences extreme conditions that leads to damage overtime which dump is expected to operate

↳ Vary plasma density to defocus low energy particles & prevent reacceleration

↳ Much greater durability than foil

Low plasma density → Focusing region
High plasma density → defocusing region

High plasma density defocuses witness particles as transverse E field overcomes bunch B field

↳ Defocusing region of wakefield therefore lies behind accelerating region

↳ Force low energy portion of bunch through defocusing region to expel them

↳ If accelerating gradient is low enough, particles can pass accelerating region into defocusing region. Stop them from slipping to wakefield

↳ Shift plasma wakefield relative to bunch to pass low energy particles into defocus region

↳ Achieved by increasing plasma density to shorten plasma wavelength

Stepped Plasma Density Increase

→ Once a significant portion of decelerated particles reach defocusing, density is increased to shift particles into defocusing region

↳ Expelled particles must be sufficiently low so they are easily absorbed by walls / end of beam dump.

↳ Unclear how to do this in practice

Gradual Plasma Density Increase

↳ Density increase must be sufficiently fast so decelerated particles pass reacceleration and into defocusing region before they regain excessive energy

↳ Functional form should give roughly constant rate of plasma wavelength change with distance propagated by bunch

↳ Linear / quadratic forms

Linear Plasma

Rate of change of plasma wavelength w.r.t. position

↳ $$\boxed{\frac{d\lambda}{dz} = \frac{\pi c e^2 n_f}{\varepsilon_0 l m_e}\left[\frac{e^2 n_i\left(1 + \frac{n_f}{n_i}\frac{z}{l}\right)}{\varepsilon_0 m_e}\right]^{-3/2}}$$

- Initial Plasma Density n_i
- Final plasma Density n_f

↳ Length l

$\Rightarrow$ In linear, defocusing region $\frac{\lambda_p}{4}$ behind max deceleration region

$\Rightarrow$ Prop. distance Δz over which λ_p changes by $1/4$ can be estimated assuming rate of change of λ_p is constant, energy gain ΔT is average $E_{acc} \times \Delta z$

$$\boxed{\Delta T = E_{acc} \Delta z = E_{acc} \frac{\lambda_0}{4} \left(\frac{d\lambda}{dz}\right)^{-1}}$$

λ_0 is initial plasma wavelength $(z=0)$

$\Rightarrow$ More rapid change in plasma density, less energy gained by decelerated particles

↳ But density must remain low enough to be achievable & generate high decelerating field

$\Rightarrow$ Practicalities of achieving vary plasma density not investigated in death

↳ But stepped plasma densities achieved in beam & laser driven PWFA experiments using gas jet source

↳ But only for ~ mm plasma

Does not work for plasma ~ m

09/03/2021

Zoom Meeting with Gaoxing Xia
Niki Vitoratou

→ FBPIC

↳ tried running lwfa_script.py

↳ Completed in 16:43 but no graphics?

Niki sent a Github link about openPMD

↳ Need to explain about FBPIC in report!

⇒ only work in 400-600MeV e⁻ beam to shorten dump
↳ (up to 1.2GeV)

↳ Gaoxing will give us parameters, plot the energy change

↳ $\frac{E}{E_0}$ on y axis, Propagation distance on x axis

⇒ Small tail at end is the saturation energy due to reacceleration!

⇒ Contact Linbo about FBPIC simulations

Gaoxing sent link in chat about FBPIC

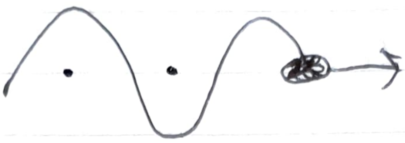
↳ Read & understand literature!

↳ It is a reliable code

Need access to machines by week 6

↳ Resend email chasing up on inquiry → Mention GuoXing

→ FLASHForward is a more realistic beam



PWFA

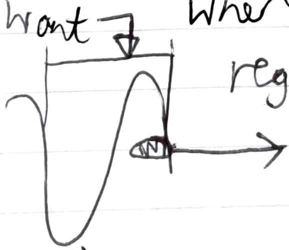
LWFA

↳ Sharper than PWFA

Most lose energy & decelerate

Some particles gain energy

We want → Where particles stay in deceleration region



λ_p

$$\boxed{\lambda_p \simeq 1\,mm \sqrt{\frac{1\times10^{15}\,cm^{-3}}{n_p}}}$$

Plasma Density

We change the region of particles by altering λ_p which is dependent on n_p.

⇒ Github openPMD has tutorials to understand it

16/03/2021

Zoom Meeting with	Guoxing Xia Niki Vitoratou

Still don't have access to CSF – need to consider using own laptop

Guoxing sent an example of previous student report
↳ read it!
↓
FLASHforward beam DESY website.

Checkout code from laptop → Contact Linbo for help

Worst case scenario → use MATlab write your own code

Niki has set up teams group → Registered on TEAMS.
↳ start on introduction ?

→ 1 section in report about FLASHForward

How does FBPIC work?

↳ Simulates the self-consistent interaction of charged particles & EM fields

Charged particles represented by macroparticles
↳ this lumps together several physical particles

Fields represented on a grid.
↳ Time evolution of system is discrete time steps

How it works: at each timestep

Particles Push
update $\underline{x}_i$ & $\underline{p}_i$

$$\dot{\underline{x}}_i = \underline{v}_i$$

$$\dot{\underline{p}}_i = q(\underline{E} + \underline{v}_i \times \underline{B})$$

Charge/Current Deposition
Calculate ρ, $\underline{j}$ from $\underline{x}_i$ & $\underline{v}_i$

Field Solver
Update $\underline{E}$, $\underline{B}$ using $\underline{j}$

$$\frac{\partial \underline{B}}{\partial t} = -\underline{\nabla} \times \underline{E}$$

$$\frac{\partial \underline{E}}{\partial t} = c^2 \underline{\nabla} \times \underline{B} - \mu_0 c^2 \underline{j}$$

Field Gathering
Interpolate $\underline{E}$, $\underline{B}$ onto $\underline{x}_i$

Normal PIC uses Cartesian grid $(x y z)$

↳ FBPIC uses Cylindrical Coordinates (ρ, ϕ, z) because it is more efficient

This is represented by a set of 2D radial grids, each grid represents an azimuthal mode (m)

m=0 represents fields independent of θ

m=1 represents fields varying proportionally to $\cos\theta / \sin\theta$

$m \geq 2$ represents fields varying proportionately to $\cos(m\theta) / \sin(m\theta)$

↳ Takes into account further departures from cylindrical symmetry

=> Usually only need 2 modes, 3 modes may be needed for nonlinear effects

↳ Using a few 2D grids as opposed to full 3D grids uses a lot less memory

↳ Computational cost increases with m

Macroparticles deposit their charge and current on each 2D radial grid and gathers the sum of the fields from each grid.

NOTE: due to cylindrical coordinates, macroparticles initialised far from the axis have a larger weight (represent more particles)

↳ Weight is denoted in output → Account for this

Analytical Integration

→ Standard PIC, Maxwell equations discretised using finite-differences

↳ But can lead to spurious numerical dispersion in EM waves propogation and numerical growth of emittance for relativistic beams

→ FBPIC fourier transforms the fields and solves the fields in spectral space

↳ derivatives more precisely calculated

↳ algorithm becomes dispersion free in all directions

⇒ Due to the FT, field solver has no Courant limit, Δt can be freely chosen

↳ Courant Limit: Time step in numerical analysis of explicit time integration schemes must be less than a certain time otherwise results will be incorrect

⇒ Common to choose $\Delta t = \frac{\Delta z}{c}$, Δz is resolution along z

⇒ At each timestep, FBPIC transforms fields into spectral space, advances in time and transforms back to real space

Due to cylindrical coords, spectral transform is a FT along z, Hankel transform along r

?

Hankel Transform:

↳ Expresses a function $f(r)$ as the weighted sum of an infinite number of Bessel functions of the first kind $J_\nu(kr)$

Computational Cost

FT cost scales as $N_z \log(N_z)$

HT scales as N_r^2 → HT may dominate Computational time if large number of gridpoints used along r.

→ FBPIC also removes problem of spurious Cerenkov radiation which appears in finite difference

17/03/2021

OpenPMD is a visualiser for our FBPIC code

↳ discrete vector fields on a mesh $\underline{E}(\underline{r})$
discrete scalar fields on a mesh $T(\underline{r})$
particle property position $\underline{r}_i$

→ physical quantities are records

=> Actual Components stored in multi dimensional arrays inside those records

↳ Position x is a component not a record

Each Record must fulfill these attributes:

→ Unit SI: Conversion factor to SI units
→ Unit Dimension: Parsable dimensionality
→ Time/TimeUnitSI: Iteration != time

Unit Dimension:
- Automate unit description
- as powers of 7 base SI units
  ↳ e.g. Vm^{-1} is $L^{1.0}\,M^{1.0}\,Time^{-3.0}$

Base SI units:

Electrical Current ⇒ Ampere [A]
Thermodynamic Temp. ⇒ Kelvin [K]
Amount of Substance ⇒ Mole [mol]
Luminous Intensity ⇒ Candela [Cd]
Length ⇒ Metre [m]
Mass ⇒ Kilogram [kg]
Time ⇒ Second [s]

To handle Petabytes of data

↳ Use parallel community file formats
e.g. PHDF5 .h5 (parallel/strided, uncompressed)
↳ (strided some elements are present to save space)

↳ Asked Linbo for help about certain things in Microsoft Teams

23/03/2021

Meeting with	Guoxing Xia Niki Vitoratou Sanjeev Kumar

↳ Get visual results in the 2 weeks of Easter break

↳ After, change parameters, maybe tailor plasma density to reduce

→ Ziqian Xiang Paper

Plasma is ionised gas → non uniform due to spatial distribution of generating source and under govern of diffusion

→ E & B fields produced by plasma but this will influence behaviour of plasma ions in it

↳ Fields induce ion displacement, which can then also change the field

↳ Response is always ahead of our calculation

⇒ Use fluid model in which individual particle is neglected and we treat plasma as a fluid of $\bar{e}$s & fluid of +ve ions

↳ Lorentz & Coulomb force interactions only, no collisions

$\bar{e}$ Bunch Assumption

→ Assume $\bar{e}$ speed $v \simeq c$ as FLASH Forward beam is 400-1250 MeV

→ Initial bunch has constant density

↳ Assume effective electron bunch is invariant

$$\boxed{\begin{aligned} \underline{\nabla} \cdot \underline{E} &= -4\pi \rho_{perturb} + 4\pi \rho_0 \\ \underline{\nabla} \times \underline{E} &= -\frac{1}{c} \dot{\underline{B}} \\ \underline{\nabla} \times \underline{B} &= \frac{4\pi}{c} \underline{j} + \frac{1}{c} \dot{\underline{E}} \end{aligned}}$$

? not same units as Maxwell equations

→ $\underline{\nabla} \times \underline{E} = -\dot{\underline{B}}$ $\quad \underline{\nabla} \cdot \underline{E} = \frac{\rho}{\varepsilon_0}$?

↳ implies $\frac{1}{\varepsilon_0} = 4\pi$?

↳ Email Gaoxing!! ⇒ CGS units ?

→ Assumption that unperturbed plasma has no contribution to E field, only perturbed generates $\underline{E}$ & $\underline{B}$

↳ $n_{plasma} = n_{perturb} + n_{unperturb}$

Density of individual $\bar{e}$ Propagating

↳ $\rho_e = q\,\delta(\underline{X} - \underline{v}_b t) = q\,\delta(r)\,\delta(\underline{Z} - v_b t)$

↳ Dirac delta, so charge only exists in certain points

$\underline{x}$ = Longitudinal Displacement of e^-

$\underline{r}$ = Transverse displacement in cylindrical
$\underline{z}$ = for axial displacement

↳ equation of motion for electron

$F = m \frac{dv_b}{dt}$ $\qquad$ $F = -eE$

↳ $$\boxed{\frac{dv_b}{dt} = \frac{-eE}{m}} \quad ①$$

=> Change of plasma density in local area equal to divergence of the flux into, minus flux out of

↳ Continuity equation for Plasma

$$\frac{\partial n_{Plasma}}{\partial t} + \nabla \cdot j = 0$$

$n_{plasma} = n_{perturbed}$

$$\boxed{\frac{\partial n_{perturbed}}{\partial t} + \nabla \cdot j = 0} \quad ②$$

Sub ① into differential of ② over time, subbing gradient of E with z.

↳ $n_{pe} = \omega^2 \frac{q}{ev_b} \sin\left(\omega\left(t - \frac{z}{v_b}\right)\right) \Theta\left(t - \frac{z}{v_b}\right)$

Take Curl of $\underline{\nabla} \times \underline{E} = -\frac{1}{c}\dot{\underline{B}}$ & Combine with $\underline{\nabla} \times \underline{B} = \frac{4\pi}{c} j + \frac{1}{c}\dot{\underline{E}}$, with Continuity equation

↳ $$\boxed{\frac{\partial J_1}{\partial t} = -e\, n_{upe} \frac{\partial V}{\partial t} = \frac{e^2 E\, n_{upe}}{m}}$$

J_1 = Current density from that e^-

↳ $$\frac{\partial^2 E}{\partial t^2} - c^2 \underline{\nabla}^2 \underline{E} = -\omega \underline{E} - c^2 \underline{\nabla}\left(-4\pi e n_{pe} + 4\pi \rho_0\right)$$

↳ Cylindrical $\underline{\nabla}^2$ written as $\underline{\nabla}_\perp^2 + \partial_z^2$, $dz = c\,dt$

↳ $$\left(\nabla_\perp^2 - k_p^2\right)\underline{E} = \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} + \underline{\nabla}\left(-4\pi e n_{pe} + 4\pi \rho_0\right)$$

$$= 4\pi \omega^2 \frac{e}{c} \cdot \underline{\nabla}\left(\delta(\underline{r})\,\Theta\left(t - \frac{z}{c}\right)\right) \sin\left[\omega\left(t - \frac{z}{c}\right)\right]$$

If $k_p^2 = \frac{\omega^2}{c^2}$, and only consider longitudinal fraction

$$\boxed{\left(\nabla_\perp^2 - k_p^2\right) E_z = \frac{4\pi \omega^2 e}{c} \cdot \delta(r)\,\Theta\left(t - \frac{z}{c}\right) \cos\left(\omega\left(t - \frac{z}{c}\right)\right)}$$

↳ Kelvin-Helmholtz equation using green's function & continuity methods for E_z

$$\boxed{E_z = 2 e k_p^2 K_0(k_p r)\,\Theta\left(t - \frac{z}{c}\right)\cos\left(\omega\left(t - \frac{z}{c}\right)\right)}$$

K_0 is zeroth order Bessel function of 2nd kind

Now e^- beam with density $\rho(r, \theta, z-ct)$

$$E_z(r, \theta, \xi) = -\int_{-\infty}^{\xi} d\xi' \int_0^{\infty} dr' \int_0^{2\pi} d\theta' \, 2k_p^2 \rho_b(r', \theta', \xi') \, K_0(k_p|r-r'|)\cos(k_p(\xi - \xi'))$$

in comoving frame

30/03/2021.

→ Energy Loss

$\xi = z - ct$ Co-moving Co-ordinates
r = Radial Distance
$s = ct$ Propogation distance

$\gamma = e^-$ energy

↳ Energy Loss $\boxed{\frac{d\gamma}{ds} \cong -k_p \frac{E_z}{E_0} \quad \text{as } v \simeq c}$

Where $\boxed{k_p^2 = \frac{\omega^2}{c^2}}$ plasma wavenumber

E_z = Longitudinal component of beam driven wakefield

$E_0 = c m_e \omega_p / e$ Wave-breaking E field

↳ Max E field in cold & non-relativistic plasma in linear region

NOTE : $n_{beam} << n_{plasma}$ Linear Region

$n_{beam} \simeq n_{plasma}$ Quasilinear Region

$n_{beam} >> n_{plasma}$ Non linear Region

Linear theory works well in quasilinear & linear region

→ in this project we use $n_{beam} \simeq n_{plasma}$

↳ So linear theory is accurate enough

To get γ

↳ $$\int_{\gamma_0}^{\gamma} d\gamma' = \int_0^s -k_p \frac{E_z}{E_0} ds'$$

$$\gamma - \gamma_0 = -k_p s \frac{E_z}{E_0}$$

$$\therefore \boxed{\gamma(\xi, r) = \gamma_0 - k_p s \frac{E_z}{E_0}}$$

$$\text{Also} \int_{U_0}^{U} dU' = \int_V dV \, \gamma(\xi, r) \frac{n_b}{n_0}$$

$$U - U_0 = \int_V dV \, \gamma(\xi, r) \frac{n_b}{n_0}$$

$\gamma = -k_p s \frac{E_z}{E_0}$

$$U = U_0 - k_p s \int_V dV \left(E_z/E_0\right)\left(n_b/n_0\right)$$

$$U_0 = \int_V dV \, \gamma_0 \, n_b/n_0 = \gamma_0 \int_V dV \frac{n_b}{n_0}$$

$$\boxed{\frac{U}{U_0} = 1 - \frac{k_p s \int_V dV (E_z/E_0)(n_b/n_0)}{\gamma_0 \int_V dV \, n_b/n_0}}$$

$$\Rightarrow U = \int_V dV \, \gamma(\xi, r) \frac{n_b}{n_0}$$

Sub in $\gamma(\xi, r)$

$$U = \int_V dV \left(\gamma_0 - k_p s \frac{E_z}{E_0}\right) \frac{n_b}{n_0}$$

$$U = \int_V dV \, \gamma_0 \frac{n_b}{n_0} - \int_V dV \, k_p s \frac{E_z}{E_0} \frac{n_b}{n_0}$$

$$U = U_0 - \int_V dV \, k_p s \frac{E_z}{E_0} \frac{n_b}{n_0}$$

$$\frac{U}{U_0} = 1 - \frac{\int_V dV \, k_p s \frac{E_z}{E_0} \frac{n_b}{n_0}}{\int_V dV \, \gamma_0 \frac{n_b}{n_0}}$$

$$\Rightarrow \boxed{\frac{U}{U_0} = 1 - k_p s \frac{\int_V dv \frac{E_z}{E_0} \frac{n_b}{n_0}}{\gamma_0 \int_V dv \frac{n_b}{n_0}}}$$

↳ Linear decreasing function of distance

06/04/2021

Collective Stopping Power for Wakefield deceleration of e^- bunch

$$↳ \boxed{-\left(\frac{dE}{dx}\right)_{\text{coll-wavebreak}} = m_e c \omega_{pe} (n_b/n_e)} \quad *$$

ω_{pe} = Plasma frequency

* Is exact resonant excitation of a wakefield with bunch length $\sigma_L / \lambda_{pe} \approx 0.5$

Transverse size $\sigma_T / \lambda_{pe} \geq 0.3$, density ratio $\frac{n_b}{n_e} < 10$

→ Ajman trying to run sim on his Laptop, I work out derivations

↳ LinBo very helpful!

↳ Unable to run sim, Aiman's laptop does not have enough memory.

→ Use $n_b \simeq n_e$

Ratio of collective deceleration in plasma & Bethe - Bloch stopping power

↳ $$\boxed{\begin{aligned} R &= \frac{(dE/dx)_{\text{coll-wave break}}}{(dE/dx)_{ind}} \\ &\simeq \frac{m_e c \omega_{pe} \beta^2}{F\Lambda} \\ &= \frac{n_e}{n_{e,m}} \frac{\lambda_{pe}}{r_0} \frac{\beta^2}{2\pi\Lambda} \end{aligned}}$$

Λ is log term of $(dE/dx)_{ind}$

↳ With typical numbers

↳ $R \simeq 1000$

↳ plasma dump is 10^3 larger in stopping power

Also: Radioactivating hazard reduced by $\left(\frac{n_e}{n_{e,m}}\right)$ due to gas tenuity

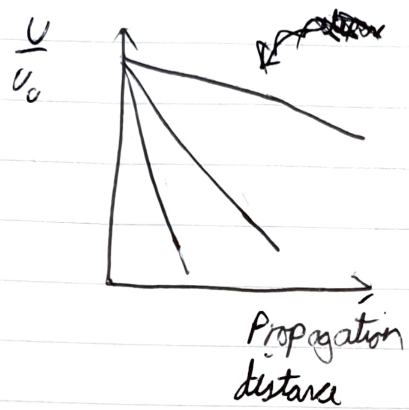
↳ R increases as we use energies > GeV and muons account

13/04/2021

Meeting with Guoxing Xia
Sanjeev Kumar

↳ Change particle per cell number, not total particles

↳ Analytical solution only accounts for linear, does not model simulation for after saturation L_{sat}



larger gradient ⟹ larger deceleration in smaller distance

⟹ Parameter scanning

<u>Thesis</u>

↳ Introduction
  ↳ Conventional beam dump
  ↳ Plasma beam dump

↳ Plasma Beam Dump
  ↳ Basic theory
    ↳ Higher deceleration field, equation to compare
↳ FLASH forward beam
  ↳ Based on this parameters
  ↳ Energy loss derivations / curve

↳ Assume $n_b = n_p$ ⇒ quasilinear regime

↳ Section 3/4

↳ Derivations of passive case

↳ Future considerations

↳ Conclusion

16/04/2021

↳ Scaling down simulation so can run on Aman's laptop

↳ Take every lower limit of FLASH forward beam parameters

↳ $k_{p_0} = \dfrac{\omega_{p_0}}{c}$

$$\omega_{p_0} = \sqrt{\frac{n_0 e^2}{\varepsilon_0 m_e}}$$

→ Changed $N = 1{,}000{,}000$ to $N = 1{,}000$

↳ Linbo said too small, lots of numerical noise period

↳ Changed back to 1,000,000

⇒ Can reduce diag period to see only a few periods, reduce sim time

↳ sim Time ≃ 18+ hours !! ☹

⇒ Start to ~~...~~ write code on plotting $\frac{U}{U_0}$ against Propagation distance

$$\boxed{\frac{U(s)}{U_0} = 1 - \frac{s\,\pi^3 k_p^2 L \left(\frac{n_b}{n_0}\right)\cos^2\left(\frac{k_p L}{2}\right)}{\gamma_0\left(\pi^2 - k_p^2 L^2\right)^2}}$$

↳ From compact disposable Bonatto

L = Beam Length

$$\gamma_0 = \gamma(s=0)$$

S: Propagation Distance

k_p: Plasma Wavenumber $k_p = \frac{\omega_p}{c}$, $\omega_p = \sqrt{\frac{n_0 e^2}{\varepsilon_0 m_e}}$

L_{sat}: Saturation Length $L_{sat} = \frac{U_0}{e E_{dec}}$

$$E_{acc} \simeq E_{dec}$$

$$E_{acc} = (236\ \mathrm{MV/m})\left(\frac{q}{e}\right)\left(\frac{N}{4\times10^{10}}\right)\left(\frac{0.06\ \mathrm{cm}}{\sigma_z}\right)^2 \ln\left(\sqrt{\frac{10^{16}\ \mathrm{cm}^{-3}}{n_b}}\ \frac{50\ \mu\mathrm{m}}{\sigma_r}\right)$$

n_b: Beam density $n_b \simeq n_0$

n_0: Plasma Density $n_b \simeq n_0$

γ_0: Lorentz factor at $s=0$ ⇒ use $\gamma_0 = 500$

$$\boxed{\lambda_p \simeq 1\ \mathrm{mm}\sqrt{\frac{1\times10^{15}\ \mathrm{cm}^{-3}}{n_0}}}$$ Plasma wavelength

$$L_{sat} = \frac{U_0}{eE_{dec}} \leftarrow 6eV$$

e: C, E_{dec}: Vm^{-1} $\qquad C \cdot Vm^{-1} = eVm^{-1}$

$$E_{dec} = \frac{m_e c \omega_p}{e}$$

$$= \frac{[kg][ms^{-1}][s^{-1}]}{[C]}$$

$1V = 1\,kg\,m^2\,s^{-3}A^{-1}$

$$= kg\,m\,C^{-1}s^{-2}$$

$$= \frac{1\,kg\,m^2\,s^{-3}A^{-2}}{\cancel{1kg}\,\cancel{m^2}\,\cancel{s^{-3}}A^{-2}} \cancel{kg}\,\cancel{m}\,C^{-1}\,\cancel{s^{-2}}$$

$$= 1V \cancel{s^{-1} A^{2} C^{-1}}$$

$\boxed{\text{NOTE!! } L \text{ is Length of Beam!}}$

22/04/2021

$\rightarrow$ coding $\frac{U}{U_0}$ against Prop. distance

$$\Rightarrow n_b = \frac{N_0}{(2\pi^{3/2})\sigma_r^2 \sigma_z}$$

4PM meeting with: Guoxing Xia
Sanjeev Kumar

↳ email Dr Conor Fitzpatrick to confirm interview date

↳ Do quick estimate of calculations before doing code

$$\boxed{n_b = \frac{N}{(2\pi)^{3/2}\sigma_r^2 \sigma_z}}$$

σ_z = Bunch length

Use smaller values for e^- beam!

↳ lower parameters

↳ Prepare for next meeting with a presentation / 2/3 slides

24/04/2021

Parameter Ranges:

e^- charge: 50 - 800 pC
e^- Energy U_0: 400 - 1250 MeV
e^- Bunch Length: 50 - 6000 fs

Plasma density n_0: 5e17 - 1e20 cm^{-3}
5e23 - 1e26 m^{-3}

⇒ Everything on lowest parameter except plasma density

↳ at 5e23 → energy ratio goes negative

27/04/2021

MPhys meeting with Gaoxing Xia
Sanjeev Kumar

N_0 is Particles per bunch

NOT Plasma Density
or No. of macroparticles

$$\boxed{N_0 = \frac{q}{e}}$$

q = Bunch charge

↳ Graph looks Great

Need ~ 8 pages by next week!
↳ derivations

→ Coding!

Introduction - FLASH Forward Beam
- Derivations

↳ Future Considerations

$$\cancel{\frac{V}{V_0} = 1 - k_p \varsigma \left(\frac{n_b}{n_0}\right) \frac{\left(1 - \cos(k_p L)\right)}{\gamma_0 L}}$$

$\cancel{\frac{n_b}{n_0}}$

$$\boxed{\frac{V}{V_0} = 1 - \varsigma \frac{k_p \int d\xi \left(E_z/E_0\right) \frac{n_b}{n_0}}{\gamma_0 \int d\xi \, n_b/n_0}}$$

$$\frac{E_z}{E_0} = -k_p \int_\infty^{\xi} d\xi' \cos k_p(\xi - \xi') \left[n_b/n_0 + a^2/2 \right]$$

$$a = c\omega_p$$

$$\cancel{F = Ea}$$

$$E = \frac{F}{e} = \frac{ma}{e} = \frac{m_e a}{e}$$

$$\int_0^L d\xi \, \frac{n_b}{n_0} \sin(\pi \xi / k_p L)$$

$$\left[-\frac{n_b}{n_0} \cos(\pi \xi / k_p L) \frac{k_p L}{\pi} \right]_0^L$$

$$= -\frac{n_b}{n_0} \frac{k_p L}{\pi} \left[\cos\left(\frac{\pi}{k_p}\right) - 1 \right]$$

$$\cancel{k_p L = 2\pi}$$

$$= -\frac{n_b}{n_0} \frac{k_p L}{\pi} \left[\cos\left(\frac{\pi}{k_p}\right) - 1 \right]$$

$$\int_{\infty}^{\zeta} \cos\left[k_p(\zeta - \zeta')\right] d\zeta'$$

$$\cancel{\left[\frac{1}{k_p} \sin\left[k_p(\zeta - \zeta')\right]\right]}$$

$$\boxed{= -\frac{1}{k_p} \sin\left[k_p(\zeta - \zeta')\right]}$$

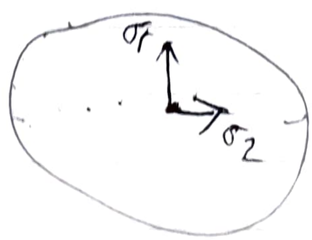
$$y = k_p(\zeta - \zeta')$$

$$\frac{dy}{d\zeta'} = -k_p$$

$$x = \cancel{\cos}\ \sin y \qquad \frac{dx}{dy} = \cancel{-\sin}\ \cos y$$

$$\frac{dx}{d\zeta'} = \frac{dx}{dy}\frac{dy}{d\zeta'}$$

$$= \cancel{-\sin}\ \cos y \cdot -k_p$$



$$-\frac{1}{k_p} \sin\left[k_p(\zeta - \zeta')\right]$$

04/05/2021

Meeting with Guoxing Xia
Sanjeev Kumar

→ Send email to Bonatto to ask about definite integral

↳ $\int_{\infty}^{\xi} \cos[k_p(\xi - \xi')] d\xi'$

→ Change beam energy, fix plasma density

→ Change bunch charge, fixed other parameters

→ ~~Fix~~ Vary plasma density, fix other parameters

abonatto@gmail.com
Alexandre Bonatto

q, v_0, L, n_0, n_b

After L_{sat} → Bunch extends length → reacceleration

07/05/2021

Variable v_0 - Fix All other parameters

↳ γ_0 varies

↳ $\frac{v_0}{v_0}$ varies ✓

q, L, n_0, n_b

Variable q → Fix all other parameters

↳ Variable N

↳ Variable beam density n_b

↳ Variable E_{dec}

↳ Variable $\frac{U}{U_0}$ ✓

U_0, L, n_0

Vary plasma ~~density~~ ~~N_0~~ beam length L

↳ variable $\frac{U}{U_0}$ ✓

q, U_0, n_0, n_b

Vary plasma density n_0

↳ variable ω_p λ_p

↳ $\boxed{k_p \longrightarrow \frac{U}{U_0}}$

↳ E_{wb}

↳ L_{sat} ✓

↳ $\boxed{\text{Variable } \frac{U}{U_0}}$

q, U_0, L, n_b

↳ L_{sat} does not change!

↳ cancels out.

5e23 − 1e26

Ideal bunchlength = 30 μm

Ideal bunchcharge = 100 pC

ideal U_0 = 400 MeV

Ideal n_0 = 5e23

3e8 x = ~~30~~ e-6

x = 1e-13

~~3e8L =~~

3e8x = 30e-6

x = 100e15

11/05/2021

$\boxed{\text{MPhys Zoom Meeting with Guoxing Xia, Sanjeev Kumar}}$

↳ showed Final graphs of varying parameters

↳ Final Parameters: $\boxed{\begin{array}{l} q = 100\,pC \\ L = 30\,\mu m \\ U_0 = 400\,MeV \\ n_0 = 5\times10^{23}\ m^{-3} \end{array}}$

Max Deceleration Field = 30.5 GVm^{-1}