Interaction of intense proton beam pulses with granular and powdered materials at HiRadMat

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Motivations

• Investigate potential for granular materials to withstand intense pulsed proton beams
  – Investigate practical phenomena for granular targets or collimators
    • E.g. disruption of granular material
      – open and contained
      – in vacuum and in helium

• Consider potential for future experiments as probe for fundamental physics
  – E.g. astrophysical plasmas (c/o Bob Bingham @ RAL)
Fluidised tungsten powder research at RAL for highest pulsed beam powers (e.g. neutrino factory)

Objective: continuous plug flow

1. Suction / Lift
2. Load Hopper
3. Pressurise Hopper
4. Powder Ejection and Observation
Continuous recirculation demonstrated

- Mass in pressurised discharge hopper
- Pressure cycling of chute and discharge hopper
- Suction line pressure variation during recycling
Tungsten powder experiments at HiRadMat (HRMT10 and 22)
Disruption of granular tungsten in vacuum

- $2 \times 10^{11}$ POT
- 20 mbar pressure
- Observed eruptions up to a few m/s
- Lift dependant on particle size (below)

Sub-45 $\mu$m spherical tungsten granules
Disruption of granular tungsten in vacuum
Higher lift in vacuum than in helium

Lift clearly has a non-aerodynamic origin
- Force chains?
  - Offline experiments do not support
- Electrostatic effect?
Proton Beam Interaction with Tungsten Powder Target

- Some secondary protons generated by the beam interaction stop in the target.
- Many more secondary electrons are accelerated by the proton beam.
- Secondary electrons only travel a short distance in the target, those formed near the surface of the sample are able to escape the material, leaving a positive charge layer.
Breakdown of charge gradients between particles

- Breakdown likely in atmospheric pressure helium
  - $\rightarrow$ lower lift
- unlikely at 20 mbar (mechanical vacuum)
  - $\rightarrow$ higher lift

**FIG. 14.** Paschen’s law curves for breakdown voltage in helium at 1 bar and at 20 mbar.
Simulations vs observations

Reasonable agreement between charge induced lift simulations and observations
‘Filamentation’ in lift of mixed powder

- Filamentation observed in previously disturbed surface for HRMT10
- Not observed in HRMT22 which had a ‘sweeper’ between beam shots

Other measurements:
- LDV used to measure surface vibrations of trough
- Observations made of primary and secondary wall
  - To separate effects of powder and secondary particles
- Measurements inconclusive
Two high speed image frames of 1 ms duration, the first one is before the beam pulse ($3 \times 10^{12}$ PoT) and the second one captures the beam pulse and shows a high intensity light output. The beam is impinging the sample from the left hand side. N.B. In the next frame after the beam pulse the light level returns to that shown in the first frame.
What is origin of optical radiation produced during proton beam interaction with tungsten powder?

- Generation of transition radiation as electron shower passes between granular solid and vacuum
- Generation of Bremsstrahlung radiation as the path of secondary electrons is affected by the charged grains

FLUKA simulation showing photons generated during beam interaction with tungsten powder – what wavelength are the photons?
High Energy LabAstro

Particle Astrophysics And Cosmology

Possible applications to astrophysical plasmas

c/o Bob Bingham

Interaction of energetic ion beams with granular material

Ionises medium:
Accelerates electrons: these leave the target setting up a space charge.

Generates radiation:
- EMP from THz to γ-rays
- Optical transition radiation
- Bremsstrahlung
- Cherenkov light? (ref HRMT30, 32)

Magnetic field generation:
- Weibel Instability?
Introduction

• Drivers for Experiments
  – Lasers - terawatt, petawatt deliver $\sim 10^{19-21}$ W/cm$^2$ - future $\sim 10^{22}$ W/cm$^2$
  – Electron beam Proposed ORION Facility at SLAC can deliver $\sim 10^{20}$ W/cm$^2$
  – Z-pinch experiments generate 1.8 MJ of soft X-rays in a few cubic centimeters of volume in 5-15 nanoseconds.
  – Proton beam- high energy 440GeV- HiRadMat - $10^{14}$ W/cm$^2$
• In contrast, supernovae release $\sim 10^{46}$ J of energy in a few seconds
  – 99% of which is in the form of neutrinos, representing $\sim 10^{34}$ W/cm$^2$.
  – Gravitational waves $\sim 10^{31-32}$ W/cm$^2$
• γ-ray bursts release $\sim 10^{44-45}$ J within seconds.
Connection to Extreme Astrophysical Conditions

- Extremely high energy events, such as ultra high energy cosmic rays (UHECR), neutrinos, and gamma rays
- Very high density, high pressure, and high temperature processes, such as supernova explosions and gamma ray bursts (GRB)
- Super strong field environments, such as that around black holes (BH) and neutron stars (NS)


“Detailed understanding of acceleration and propagation of the highest-energy particles ever observed demands a coordinated effort from plasma physics, particle physics and astrophysics communities”
Three Categories of LabAstro
- Using Lasers and Particle Accelerators as Tools

1. Calibration of observations
   - Precision measurements to calibrate observation processes
   - Development of novel approaches to astro-experimentation
     *Impact on astrophysics is most direct*

2. Investigation of dynamics
   - Experiments can model environments not previously accessible in terrestrial conditions
   - Many magneto-hydrodynamic and plasma processes scalable by extrapolation
     *Value lies in validation of astrophysical models*

3. Probing fundamental physics
   - Surprisingly, issues like quantum gravity, large extra dimensions, and spacetime granularities can be investigated through creative approaches using high intensity/high density beams
     *Potential returns to science are most significant*
Investigation of the dynamics of jet production and its interaction with the environment has been limited to the observed radiation spectrum.

Key Questions:

- How does the central engine create collimated relativistic out-flow?
- How do jets remain highly collimated and propagate over thousands of light years?
- What mechanisms power the observed non-thermal emission?
- Can jet dynamics lead to the acceleration of UHE cosmic rays?
Dense Proton HE Beam Source with U.I. Lasers

(a) Laser pulse
- Relativistic electron cloud
- Proton beam
- Aluminum foil
- Film pack

(b) Proton energy, megaelectronvolts (MeV)
- 6.5
- 8.5
- 10.2
- 11.6
- 13.0
- 14.2
- 16.4
- 18.4
- 19.3

Or proton beam?

(Ref: S&T, Dec. issue, 2003, LLNL)
Fig. 20. Artistic picture on what happens when an ultra-intense laser is irradiated on a gold foil attached by uranium on the rear side. The generated high-energy electrons produce $\gamma$-rays, which consequently lead to pair creation, photo-nuclear activation, and photo-nuclear-fission.
Relativistic Jets (2D Sim.)

M87 - Virgo
Supermassive BH
Optical/radio
/X-ray jet

HH111 - HST: WFPC2 visible
Investigation of Jet-Plasma Interactions

• Dynamics of jet evolution:
  - Collimation: MHD provides a possible mechanism but is highly unstable; self-magnetic field pinching: plasma lensing?
  - Bow-shocks and “knots”: importance of plasma instabilities and magnetic fields

• Simulating jet dynamics:
  - Jet-plasma interaction: study acceleration, radiation and polarization; cross-check with observations.

Shock waves created in a plasma diagnostic lasers.
GRB “Standard model”
--- GRB Internal/External Shock Model ---

fireball

prompt emission

afterglow

internal shock
(collision of shells)

external shock

ISM
X-rays
optical
radio

\[ \Gamma_2 \rightarrow \Gamma_1 \]
The Weibel instability

... current filamentation ...
... $B$ - field produced ...

\[
\begin{align*}
\Gamma_{\text{max}}^2 & \simeq \frac{\omega_p^2}{\gamma} \left( 1 - 2\sqrt{2} \frac{\gamma_\perp}{\gamma} \right), \\
\kappa_{\text{max}}^2 & \simeq \frac{1}{\sqrt{2} \gamma_\perp c^2} \left( 1 - \frac{3}{\sqrt{2}} \frac{\gamma_\perp}{\gamma} \right).
\end{align*}
\]

\[
\tau \simeq \frac{\gamma_\text{sh}^{1/2}}{\omega_p}, \quad \lambda \simeq 2^{1/4} \frac{c\gamma_\text{sh}^{1/2}}{\omega_p}.
\]

$\lambda \sim 10^3 n_{10}^{-1/2}$ cm, $\tau \sim 10^{-8} n_{10}^{-1/2}$ s$^{-1}$

Produced magnetic field:
* sub-equipartition
* small-scale (<<Larmor)

Relativistic Electron Flow is Unstable and Weibel Instability becomes Nonlinear to Form Structured Magnetic Field in a Very Short Time

Lee & Lampe, PRL 31, 1390 (1973)

(1) This may explain structured B-field in GRB.

(2) This inhibits the energy transport in FI.
3D PIC simulations:
- electron-positron pairs
- relativistic
- $10^9$ particles
The Weibel instability in brief

Linear regime

... current filamentation ...  
... $B$ - field produced ...

$$ B(t) \sim B_0 \exp(t/\tau) \quad \tau = 2\pi / \omega_p \quad \sim 10^{-3} \text{ s} $$

Saturation

... current filamentation inhibited...  
... isotropization of particle velocities ...

$$ \lambda / \rho_L \sim 1 \quad \varepsilon_B \sim (\gamma_{th}+1) / \left[ 2^{3/2} \gamma_{th} \right] \sim 0.5 $$

Nonlinear regime

... filament coalescence instability ...  
... 2D gas of filaments ...

$$ \lambda(t) \sim c t $$

Kinetic energy is converted into magnetic field energy

Magnetic fields scatter particles and provide effective collisions, $\lambda_{mfp} \sim c / \omega_p$

Magnetic field scale grows linearly, $\tau_{coal} \sim c / \lambda$

Weibel Instability

- Important for understanding of magnetic fields in astrophysics
- Can we trigger filamentation of the proton beam or (more likely) secondary particles by interaction with a granular or non-uniform target material?

Possible diagnostics:
- Gamma ray / X-ray Spectrometer
- Ceramic scintillator screen
Summary

• Future experiments on granular materials at HiRadMat may address questions such as:
  – Can beam induced shock waves be generated in a granular medium and propagated to a container wall?
    • If so, what is the mechanism (force chains?) and can it be measured?
  – What is the mechanism of powder filamentation observed at a free powder surface?
  – What are the source(s) and spectrum of the observed electromagnetic radiation flash?
  – Can filamentation of (the primary proton beam or) secondary charged particles be generated and observed in a granular medium?
  – Can HiRadMat be used as a probe for lab astrophysics e.g. for calibration/validation of models?
Extra slides
2 phase CFD with coupled Poisson's equation

\[ \nabla^2 \varphi = \frac{q}{\varepsilon}, \]

Poisson's equation to find potential field as a function of the deposited charge pattern

\[ E = -\nabla \varphi. \]

Electric field simply determined from the gradient of potential

\[ M_{\beta\text{charge}} = qE. \]

Coulombic force applied to the particle phase in the momentum equation