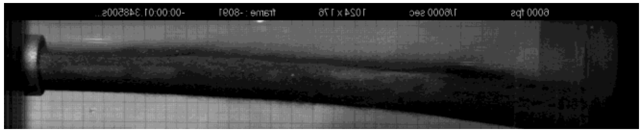
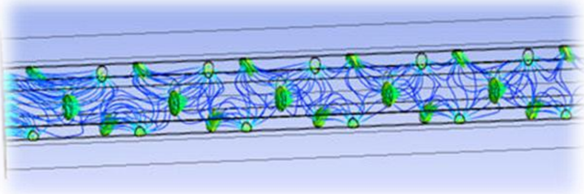
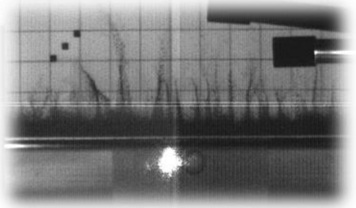
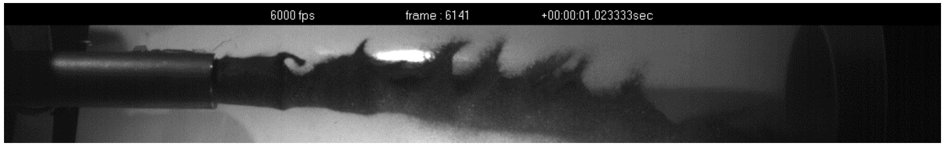




Interaction of intense proton beam pulses with granular and powdered materials at HiRadMat



Chris Densham, Tristan Davenne, Robert Bingham, Peter Loveridge , Dan Wilcox, Mike Fitton, Joe O'Dell
(STFC Rutherford Appleton Lab)
Ilias Efthymiopoulos, Nikolaos Charitonidis, Adrian Fabich (CERN), Ottone Caretta (UKAEA Culham Laboratory)

11 July 2019

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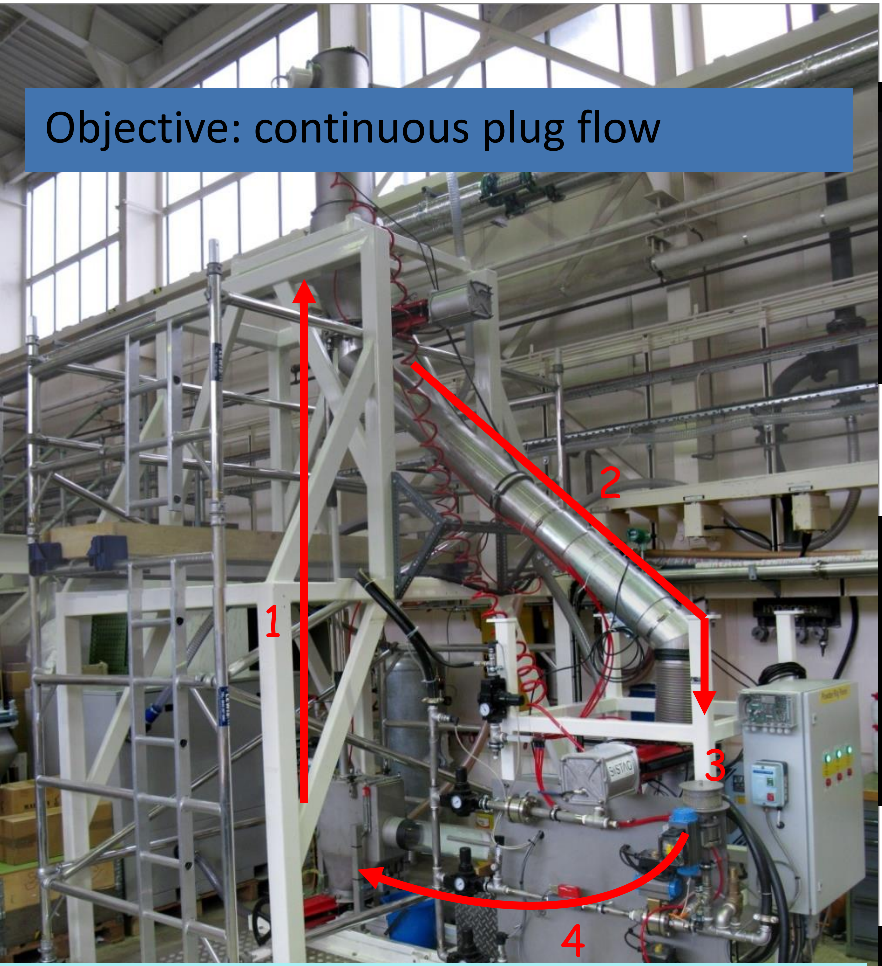
Motivations

- 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)

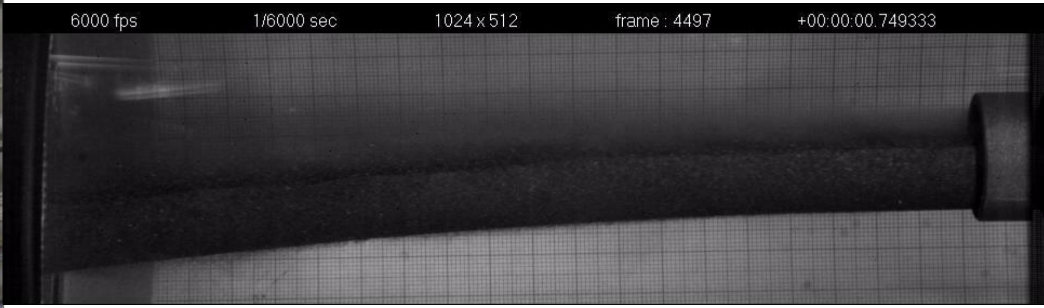
Fluidised tungsten powder research at RAL for highest pulsed beam powers (e.g. neutrino factory)



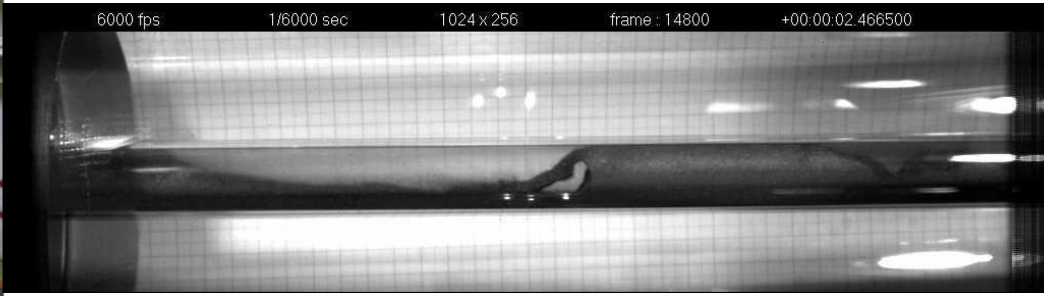
Objective: continuous plug flow

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

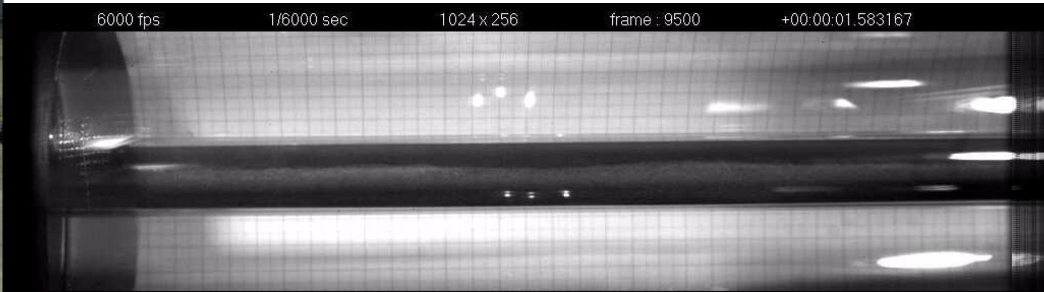
Open jet:



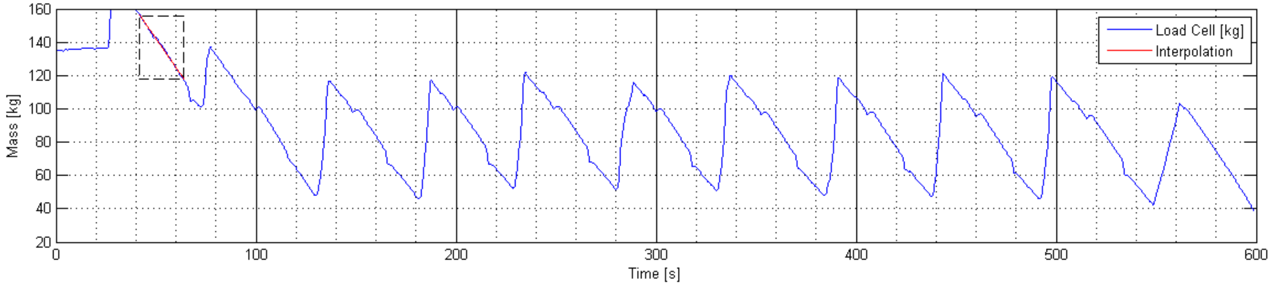
Contained discontinuous dense phase:



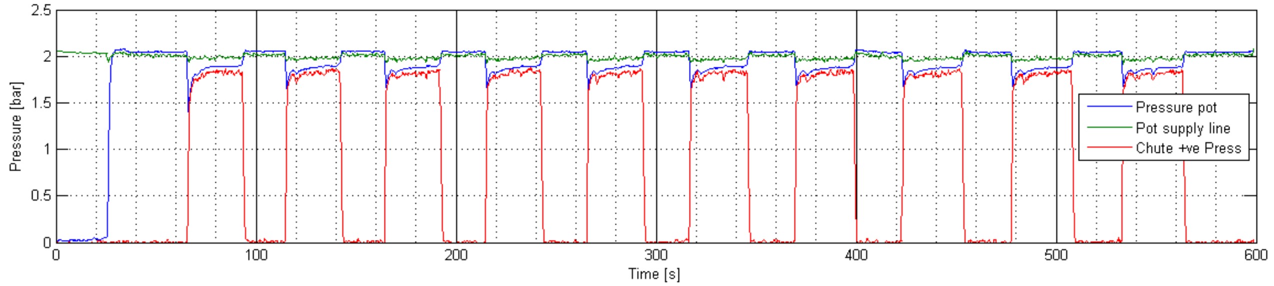
Contained continuous dense phase:



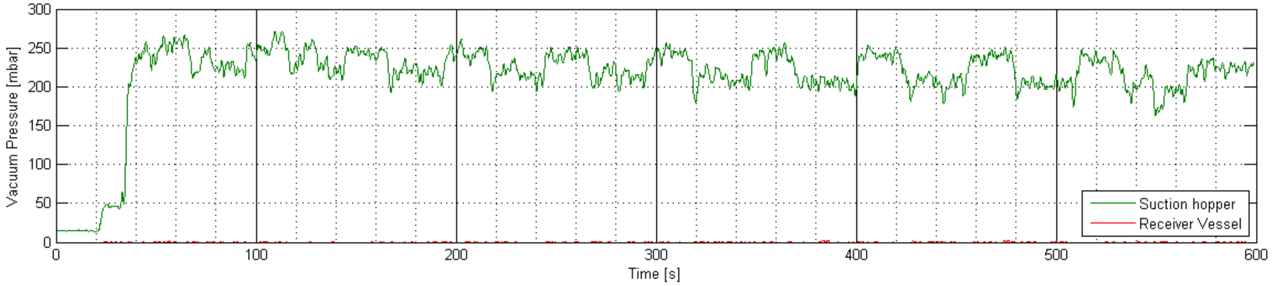
Continuous recirculation demonstrated



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)

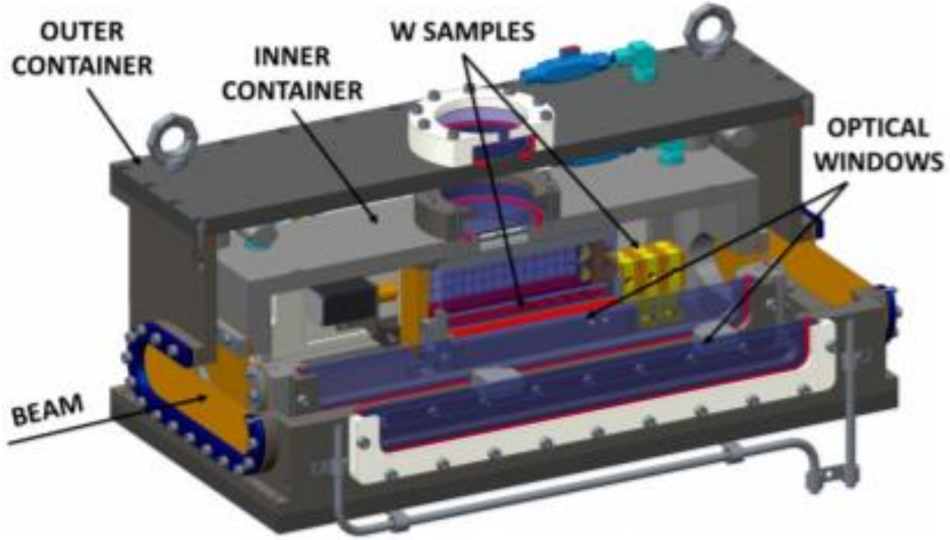


FIG. 2. Section drawing of the tungsten powder rig.

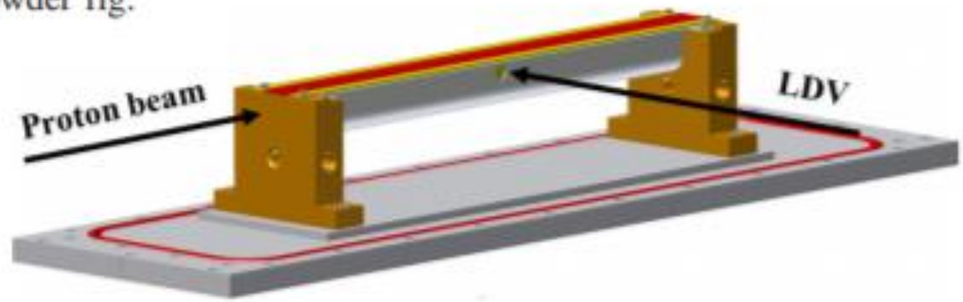
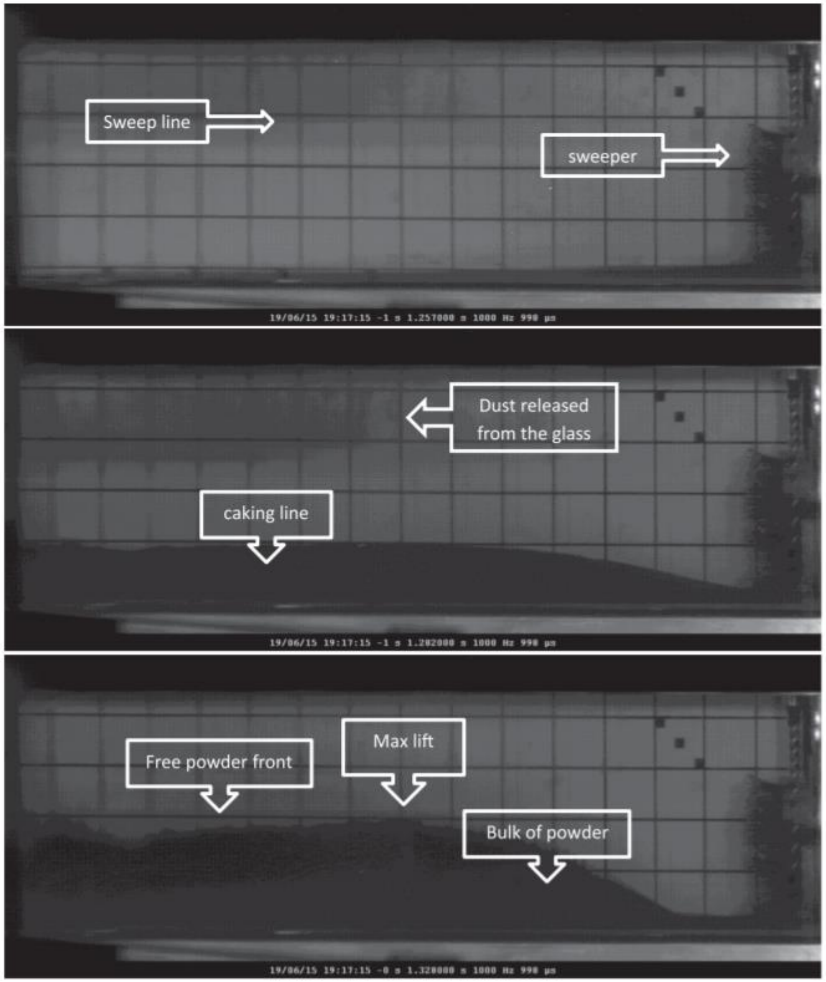


FIG. 3. Tungsten powder trough.

Disruption of granular tungsten in vacuum

ETTA *et al.* PHYS. REV. ACCEL. BEAMS **21,** 033401 (2018)



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

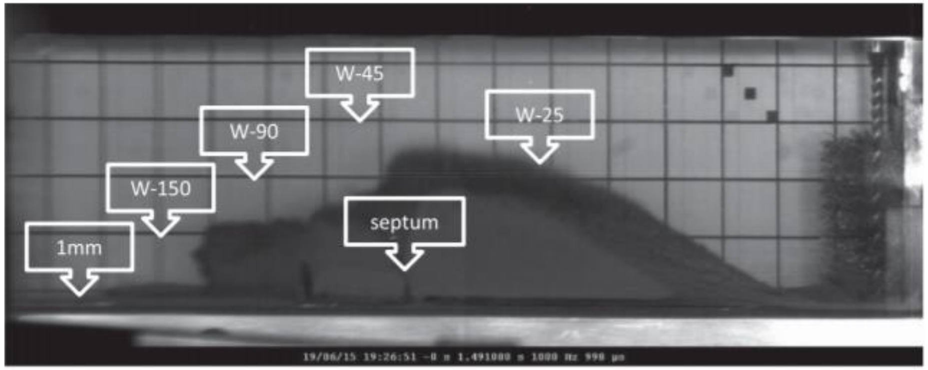


FIG. 19. Septa separated multisize experiment R1-28. 2×10^{11} POT. The beam impinges from the right.

Sub-45 µm spherical tungsten granules

Disruption of granular tungsten in vacuum

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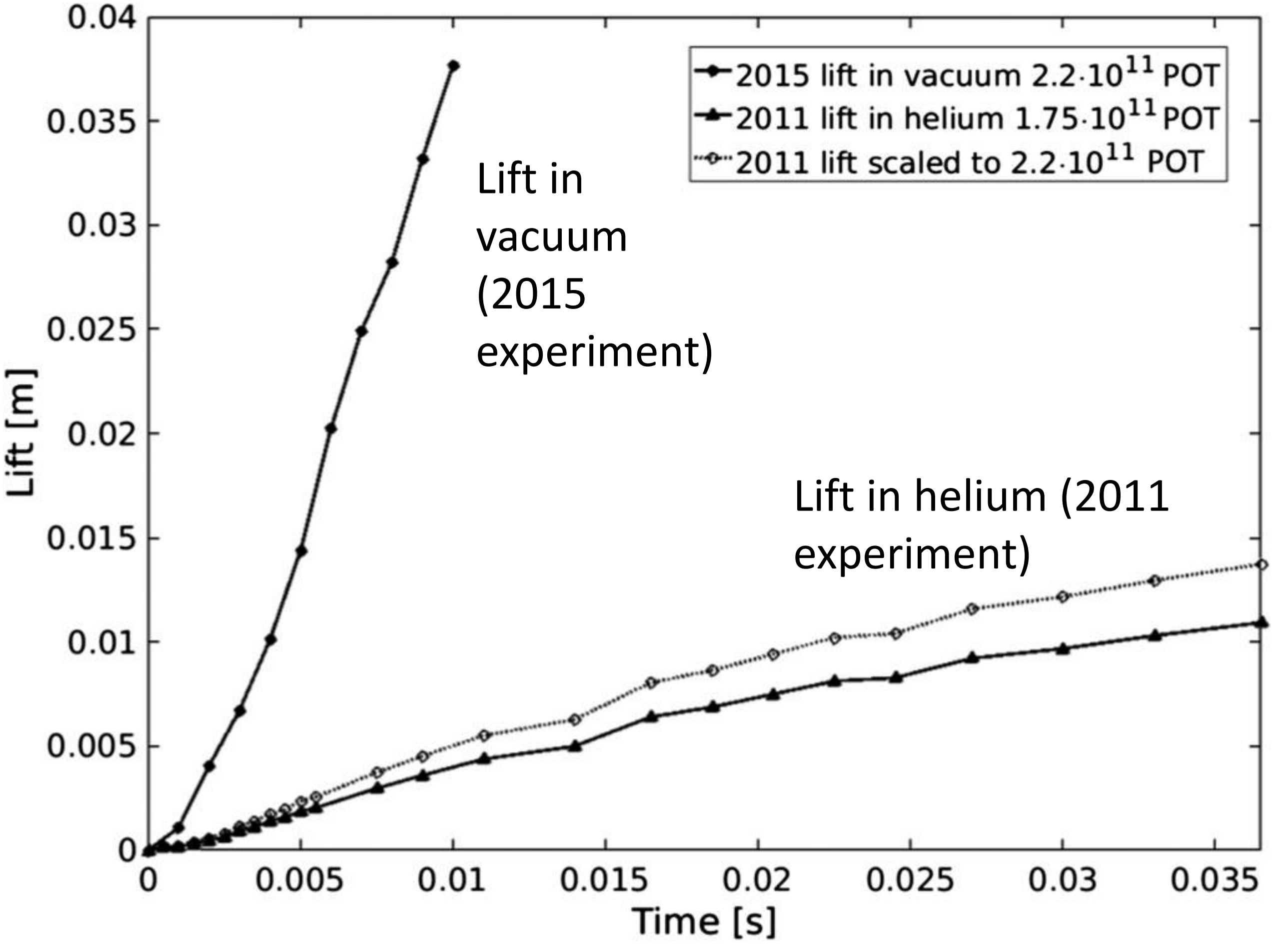
Higher lift in vacuum than in helium

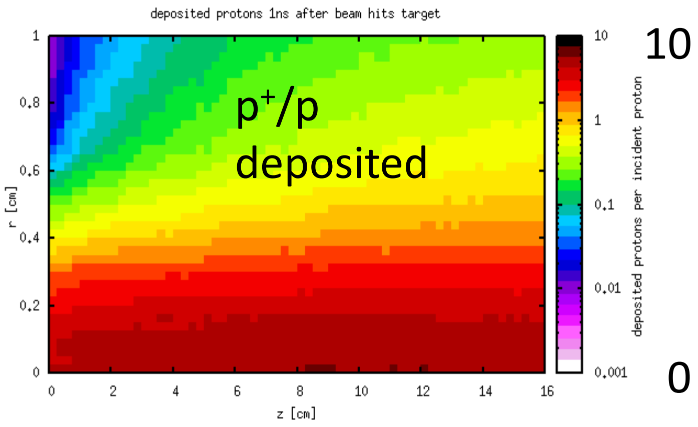


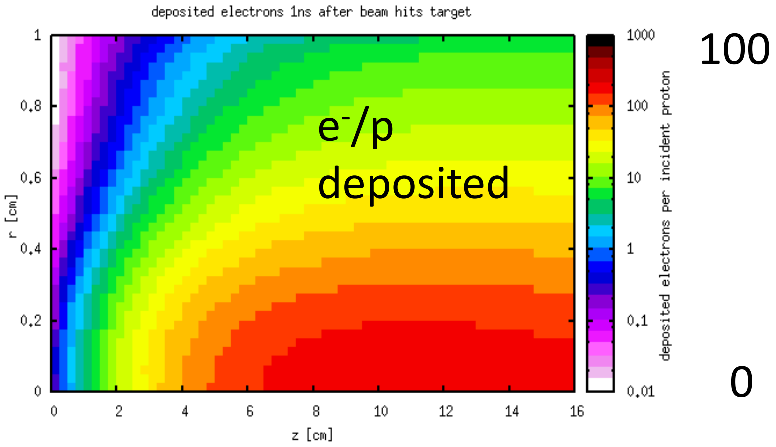
Lift clearly has a non-aerodynamic origin

- Force chains?
  - Offline experiments do not support
- Electrostatic effect?

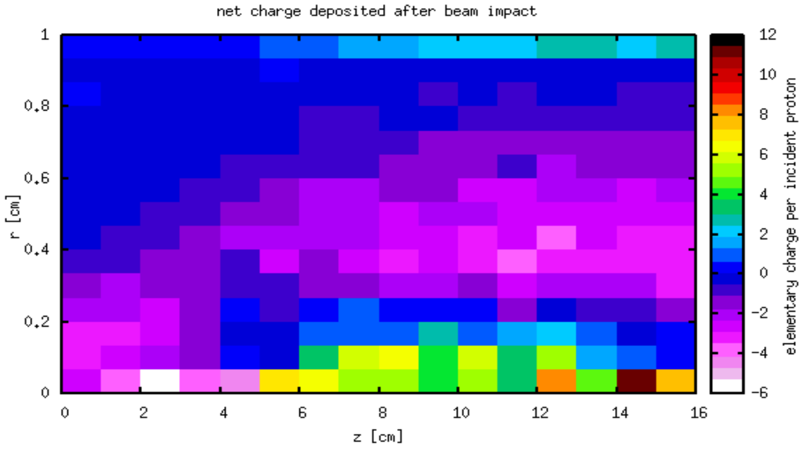
Proton Beam Interaction with Tungsten Powder Target

- 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

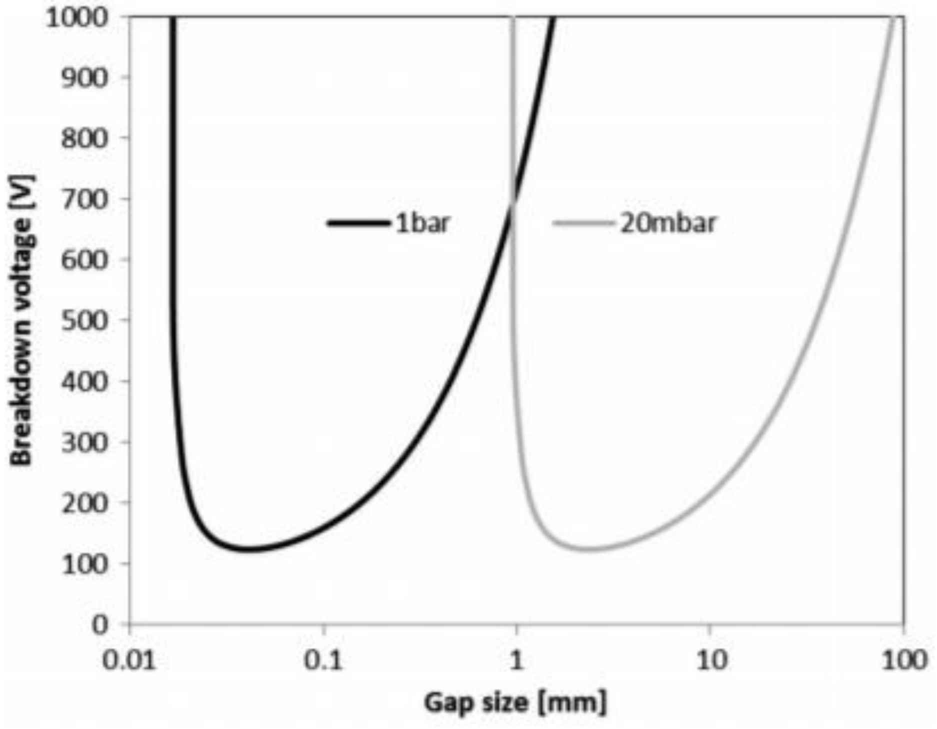


FIG. 14. Paschen's law curves for breakdown voltage in helium at 1 bar and at 20 mbar.

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

Simulations vs observations

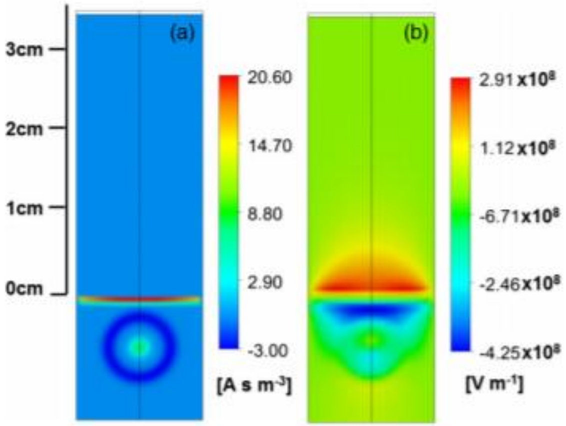


FIG. 16. Simulated deposited charge density on the solid powder phase (a) and resultant vertical electric field (b) immediately following a beam pulse of 3×10^{12} protons.

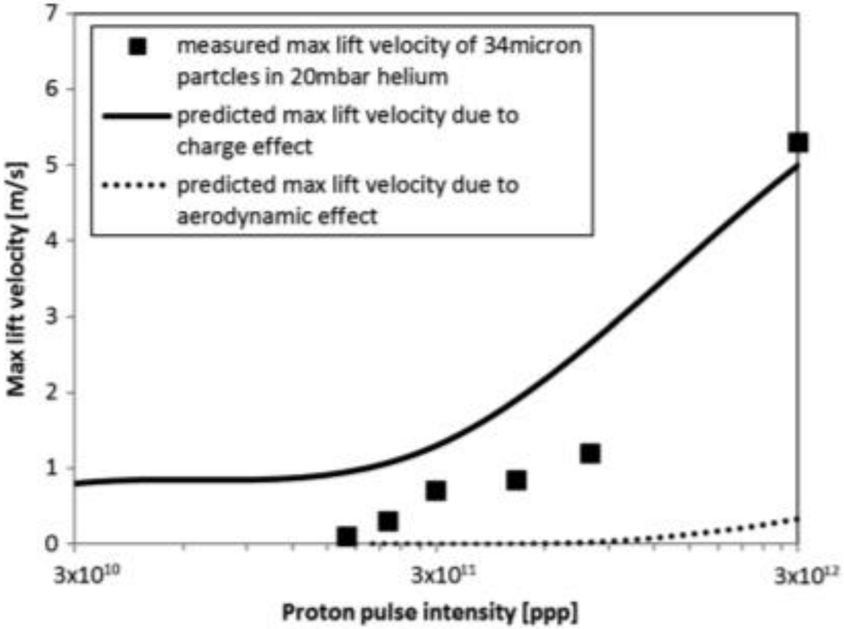


FIG. 21. Maximum lift velocity, comparing measurements with predictions from charge and aerodynamic models; helium pressure = 20 mbar; mean particle diameter = 34 μm.

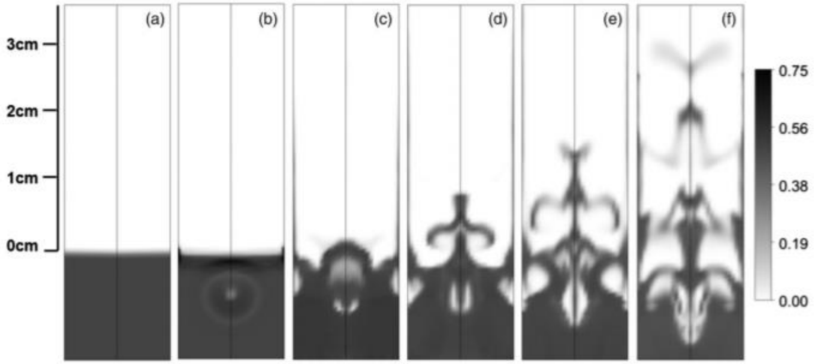
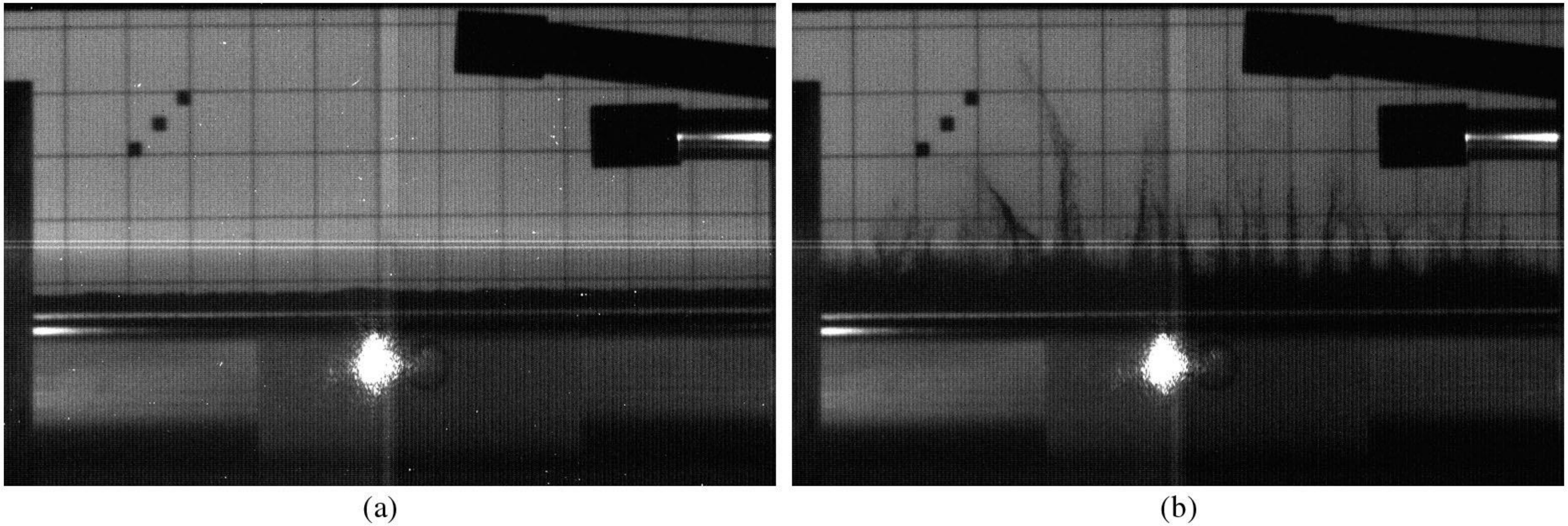


FIG. 17. Simulation of charge induced lift of 34 micron diameter tungsten particles, tungsten volume fraction at plane AA at indicated time intervals after a beam pulse with 3×10^{12} protons; $a = 1$ μs, $b = 0.1$ ms, $c = 1$ ms, $d = 2$ ms, $e = 3$ ms, and $f = 5$ ms.

Reasonable agreement between charge induced lift simulations and observations

'Filamentation' in lift of mixed powder


(a) (b)

- 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

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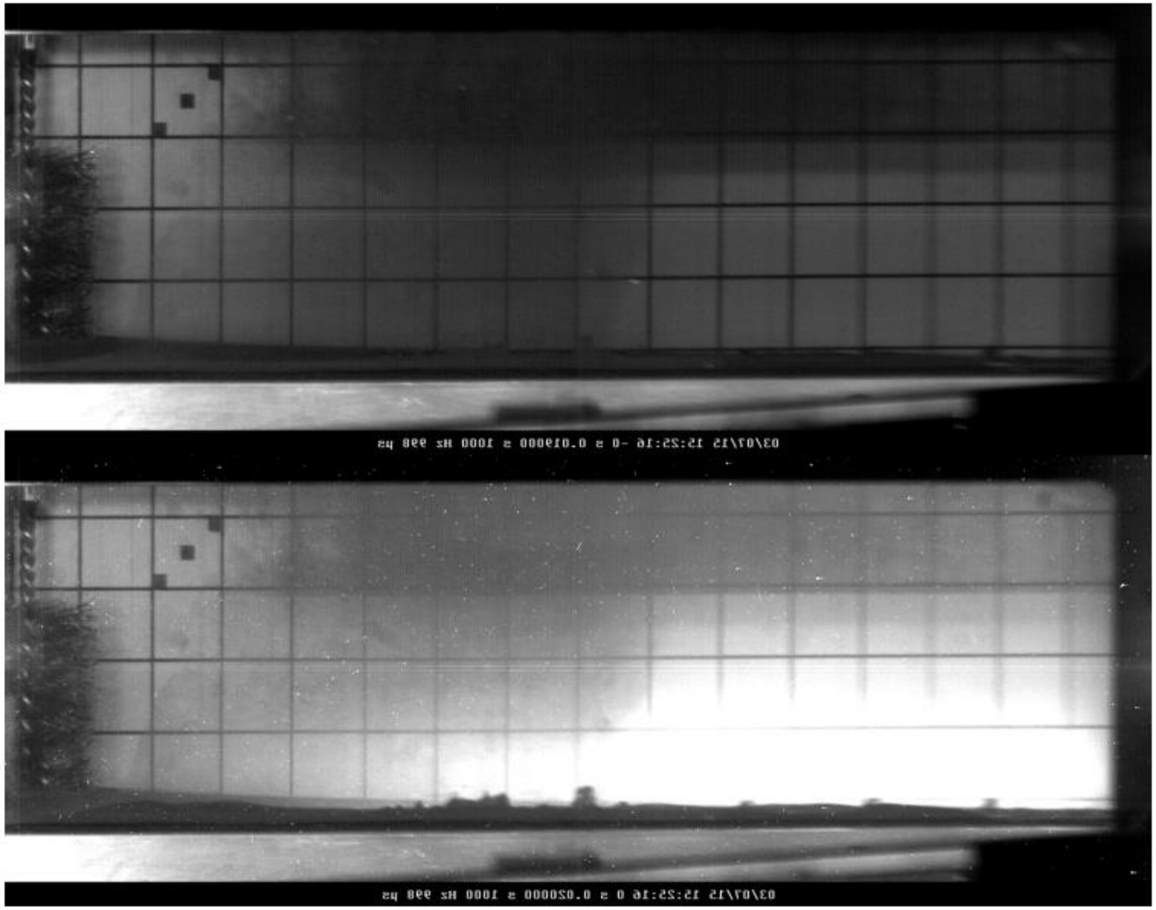
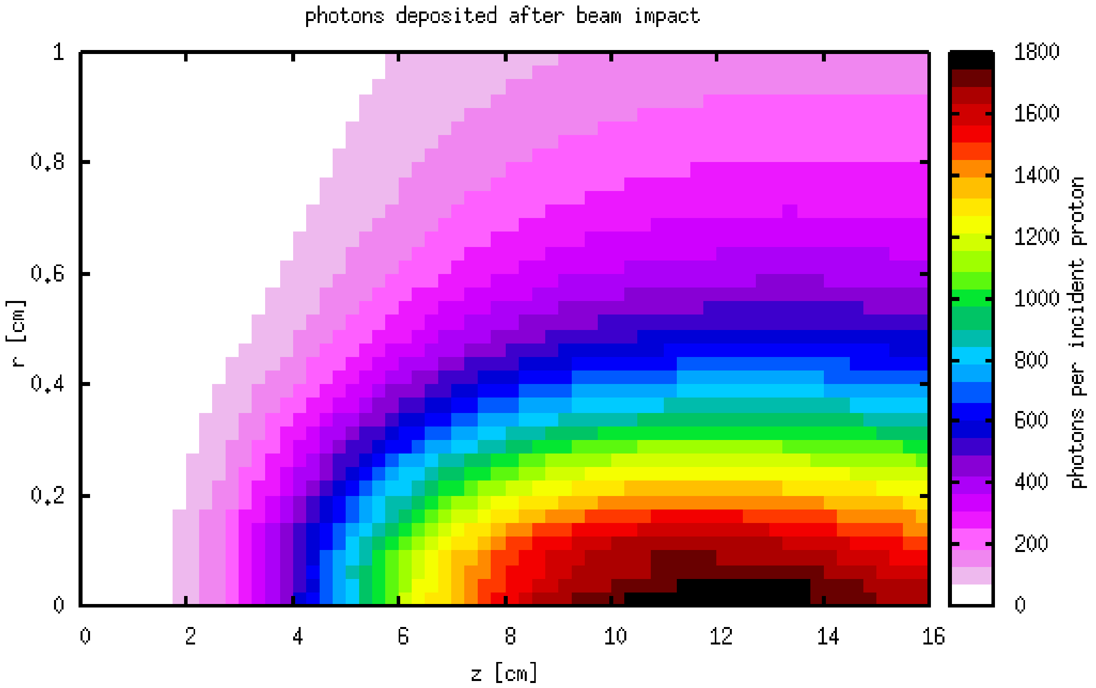
Photon flash captured after beam pulse



Two high speed image frames of 1 ms duration, the first one is before the beam pulse (3×10^{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 media



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

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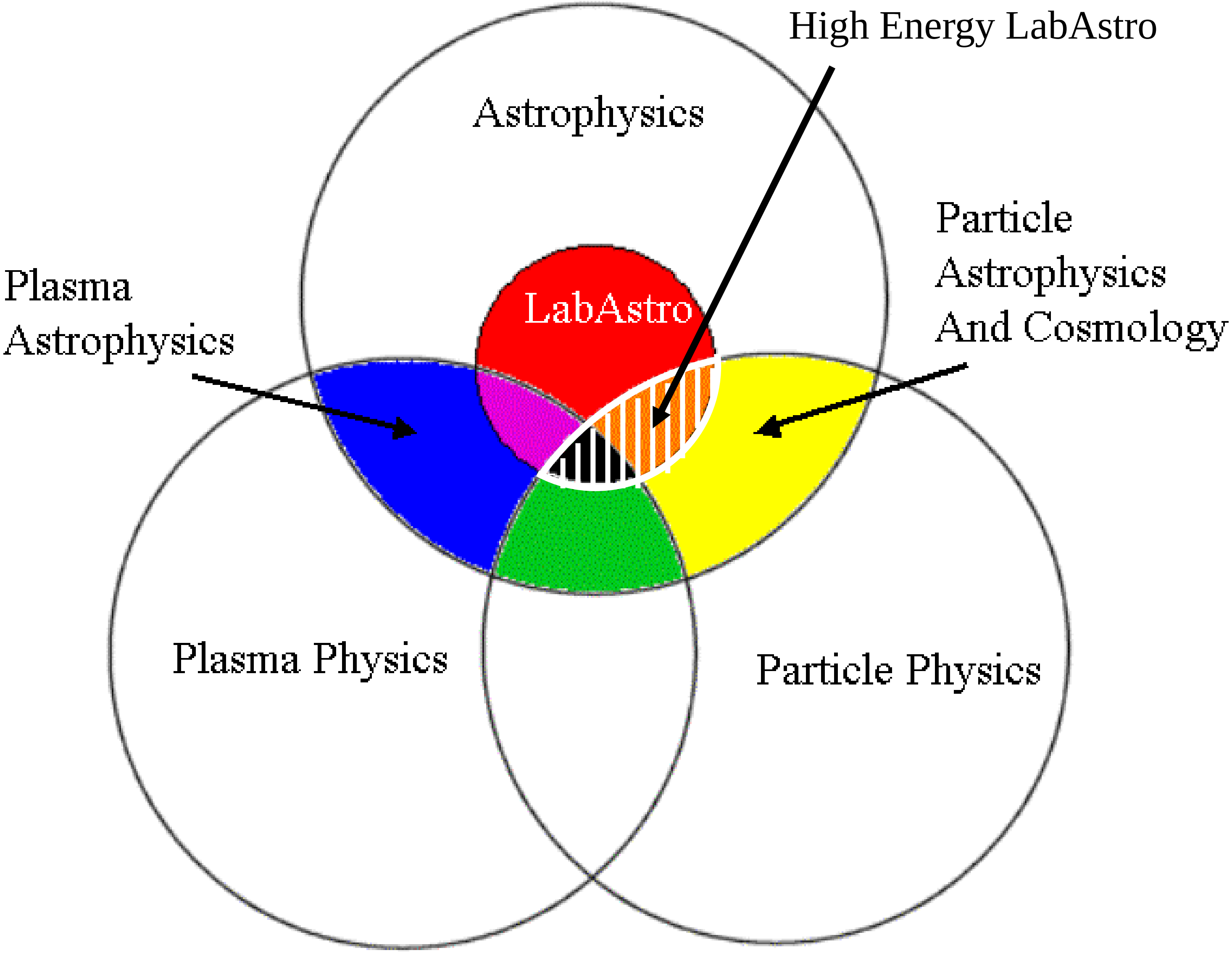
LABORATORY ASTROPHYSICS



High Energy LabAstro

Astrophysics

Particle
Astrophysics
And Cosmology

Plasma
Astrophysics

LabAstro

Plasma Physics

Particle Physics

P. Chen, *AAPPS Bull.* 13, 3 (2003).

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 ~10^{19-21} W/cm^2 - future ~10^{22} W/cm^2
  - Electron beam Proposed ORION Facility at SLAC can deliver ~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, supernovæ release ~10^{46} J of energy in a few seconds
  - 99% of which is in the form of neutrinos, representing ~10^{34} W/cm^2.
  - Gravitational waves ~10^{31-32} W/cm^2
- γ-ray bursts release ~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)

(US) NRC Davidson Committee Report (2003) "**Frontiers in High Energy Density Physics**" states:

*"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

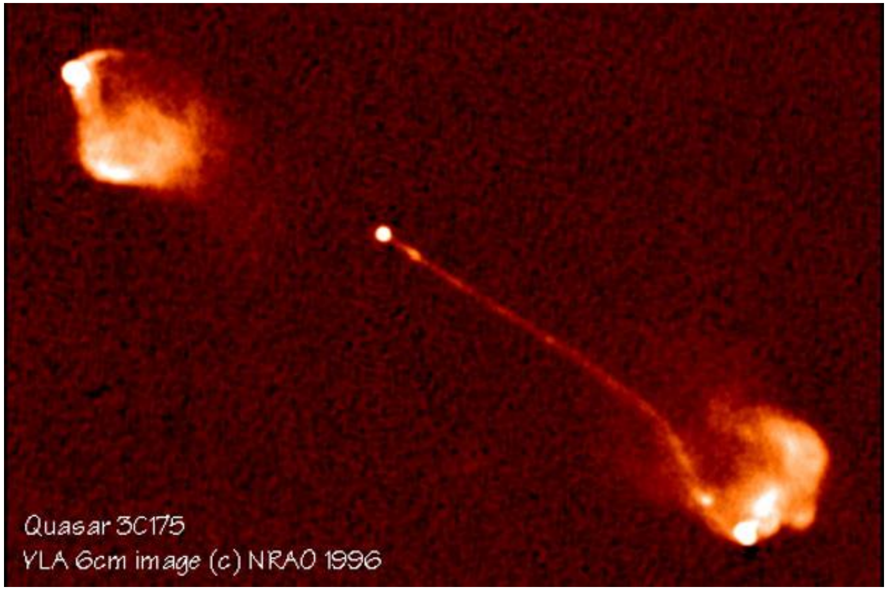
   Potential returns to science are most significant

Astrophysical Jet Dynamics

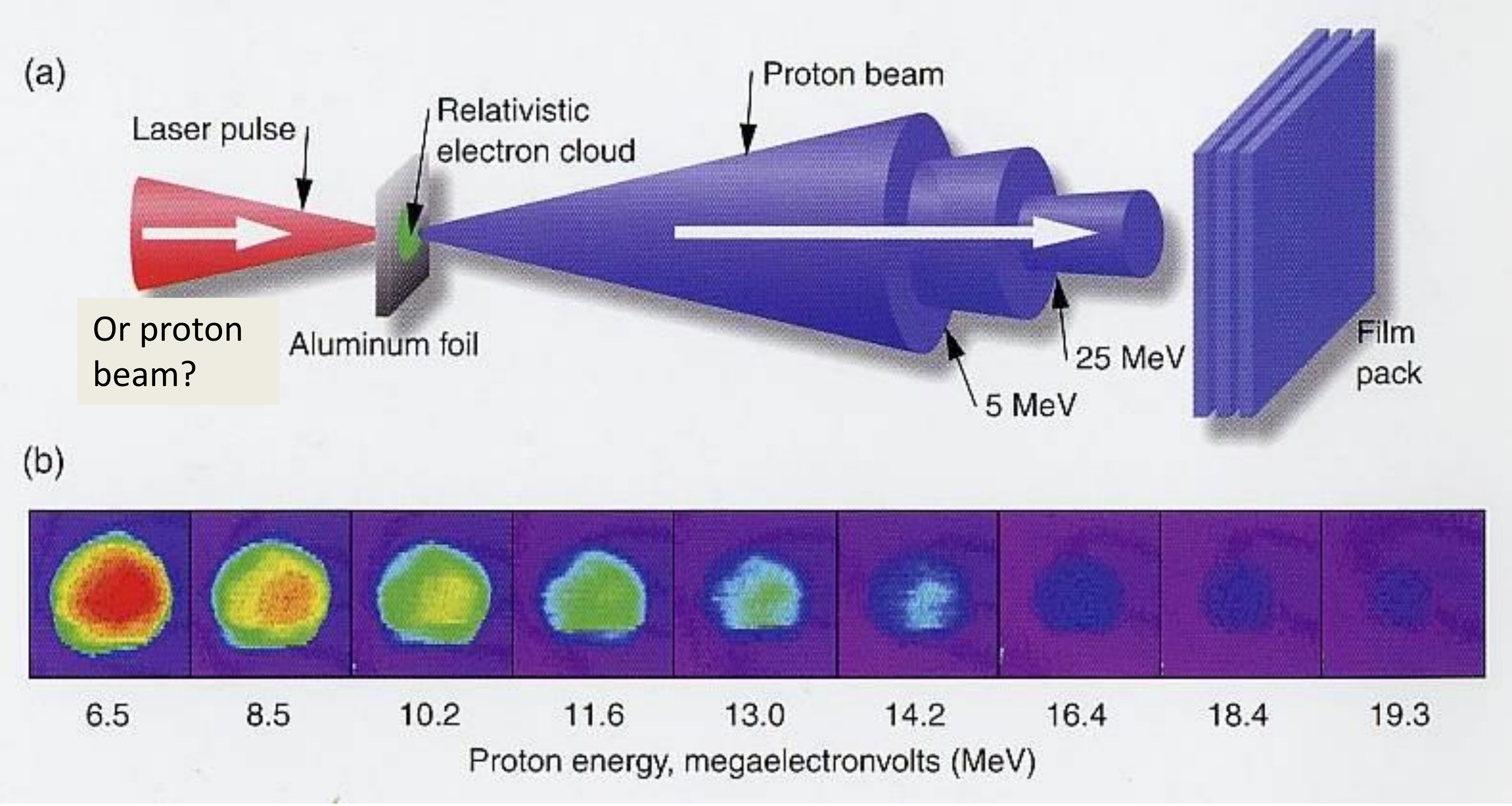
Investigation of the dynamics of jet production and its interaction with the environment has been limited to the observed radiation spectrum.

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?


Quasar 3C175
YLA 6cm image (c) NRAO 1996

Dense Proton HE Beam Source with U.I. Lasers



Or proton beam?

(Ref: S&T, Dec. issue, 2003, LLNL)

Gamma-Ray Production & Photonuclear Processes

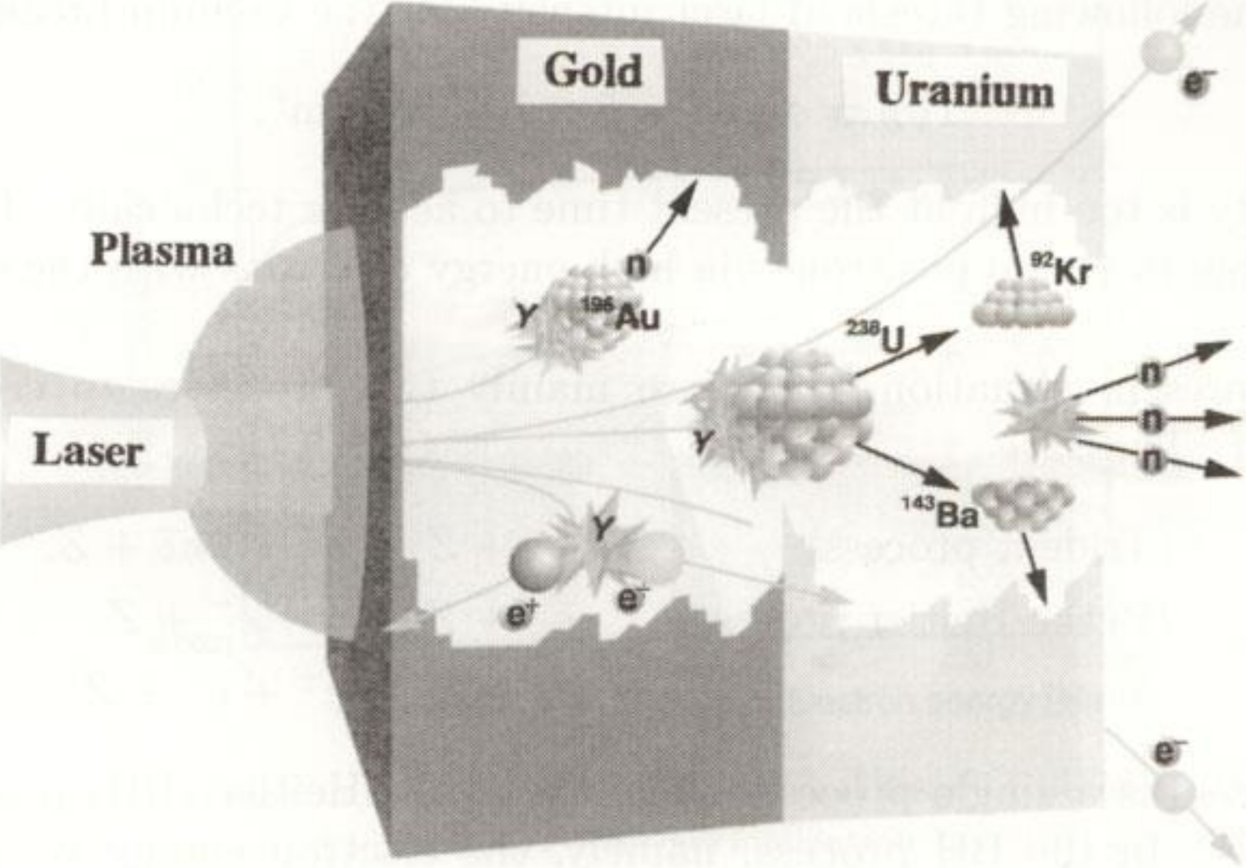
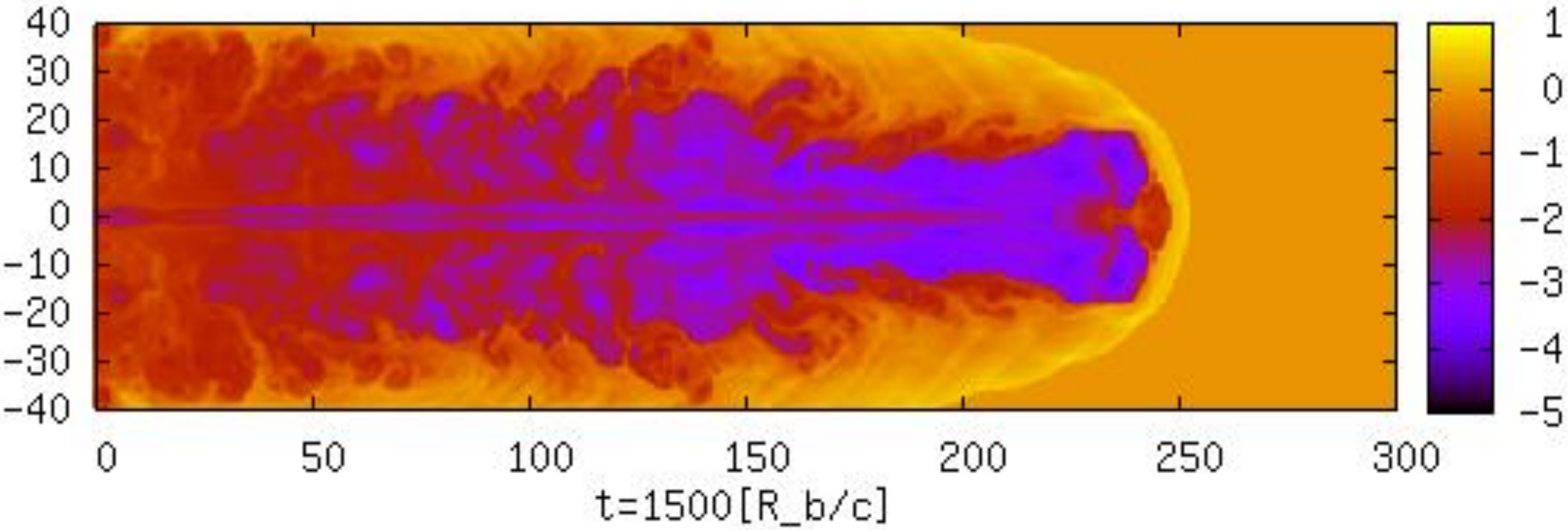
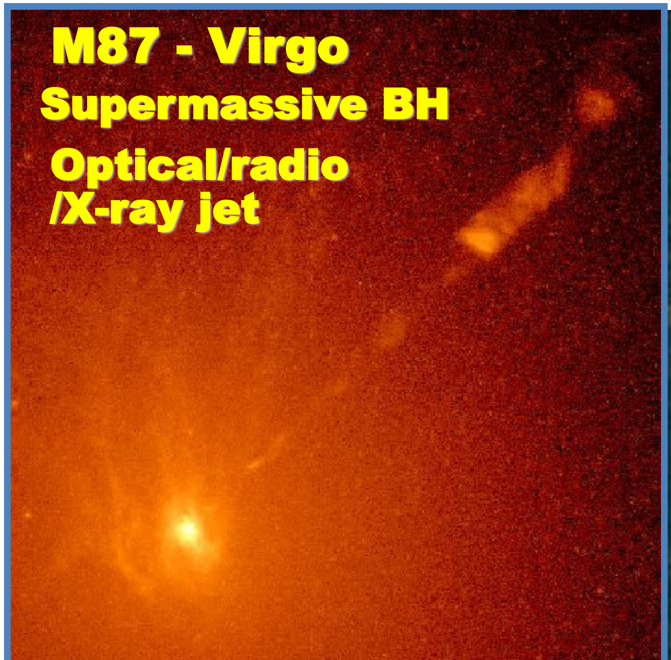


Fig. 20. Artistic picture on what happens when an ultra-intense laser is irradiated on a gold foil attached by uranium on the rear side. The generated high-energy electrons produce γ-rays, which consequently lead to pair creation, photo-nuclear activation, and photo-nuclear-fission.

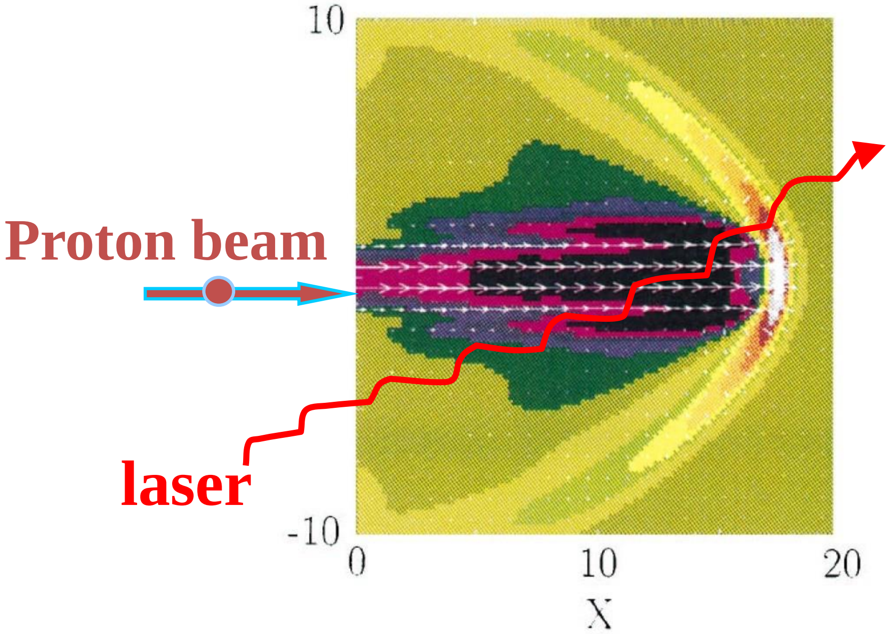
Relativistic Jets (2D Sim.)





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.

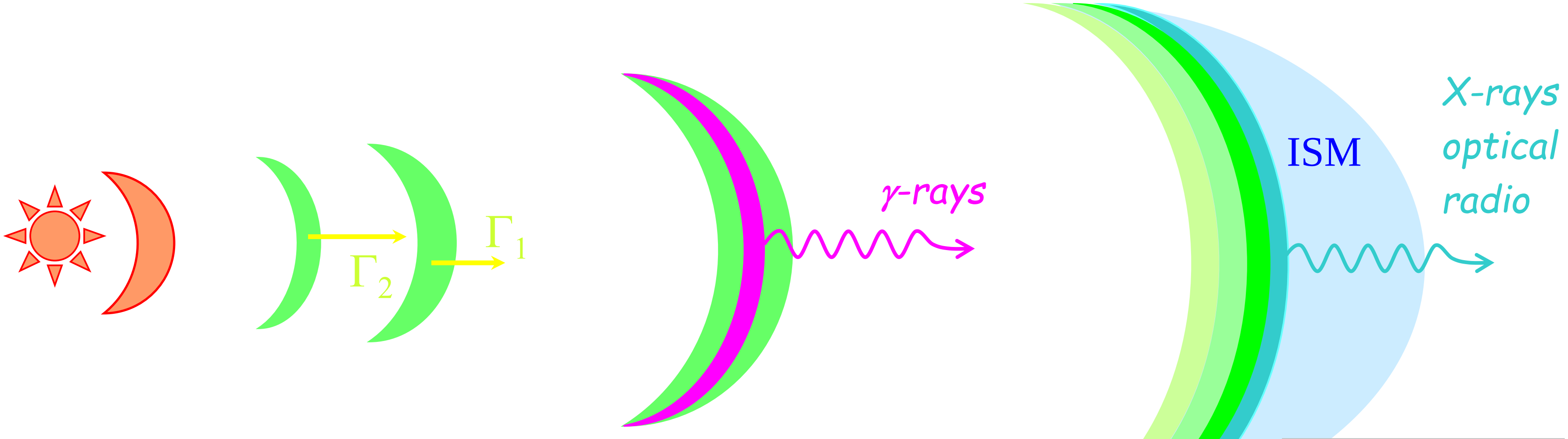


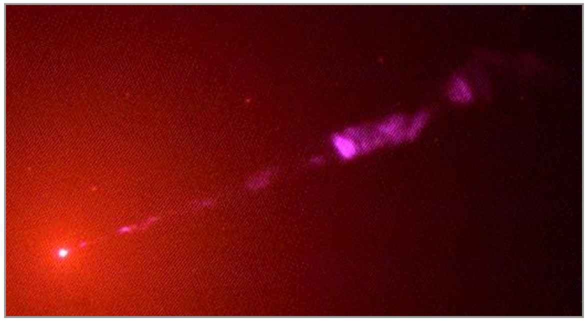
Shock waves created in a plasma diagnostic lasers.

GRB “Standard model”

--- GRB Internal/External Shock Model ---

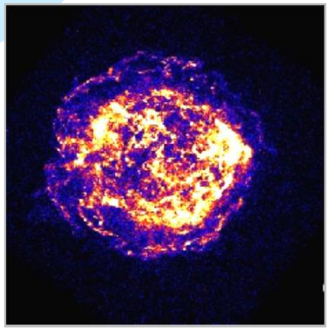
fireball *prompt emission* *afterglow*



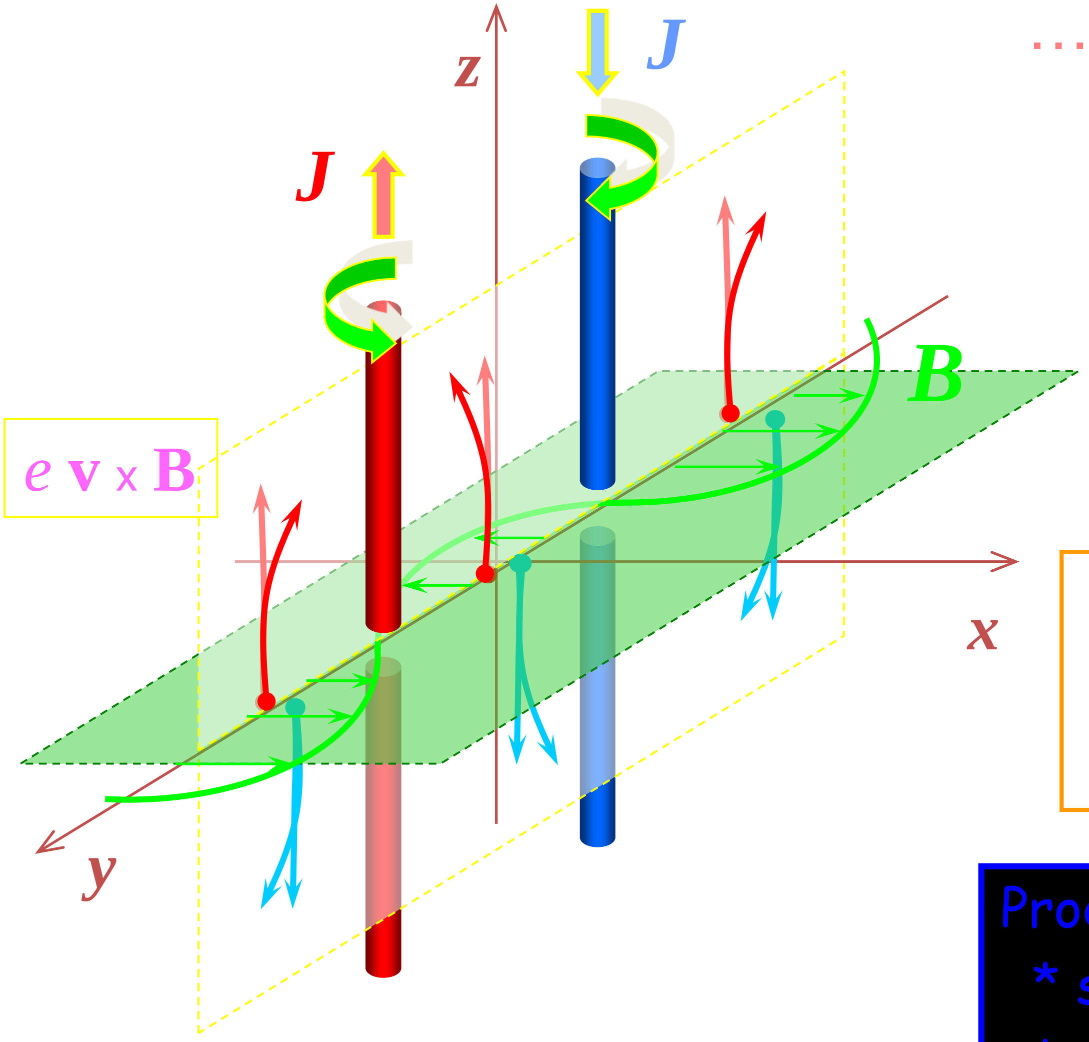


internal shock
(collision of shells)

external shock



The Weibel instability



(Medvedev & Loeb, 1999, ApJ)

… current filamentation …

… *B* - field produced …

$$\Gamma^2_{\max} \simeq \frac{\omega_p^2}{\gamma}\left(1 - 2\sqrt{2}\,\frac{\gamma_\perp}{\gamma}\right),$$

$$k^2_{\max} \simeq \frac{1}{\sqrt{2}}\,\frac{\omega_p^2}{\gamma_\perp c^2}\left(1 - \frac{3}{\sqrt{2}}\,\frac{\gamma_\perp}{\gamma}\right).$$

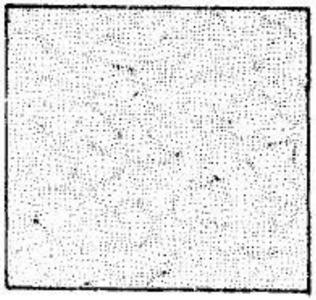
$$\tau \simeq \frac{\gamma_{\rm sh}^{1/2}}{\omega_p}, \qquad \lambda \simeq 2^{1/4}\,\frac{c\bar{\gamma}^{1/2}}{\omega_p}.$$

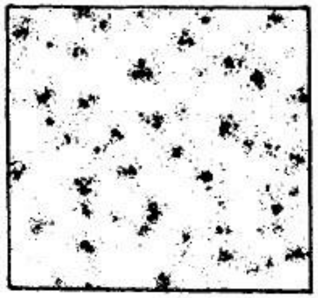
$\lambda \sim 10^3\, n_{10}^{-1/2}$ cm, $\tau \sim 10^{-8}\, n_{10}^{-1/2}$ s^{-1}

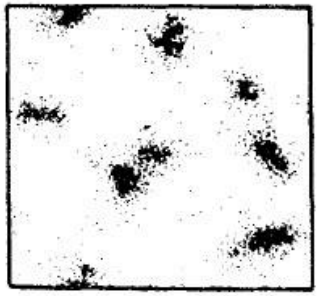
Produced magnetic field:

- * 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


T=40


T=60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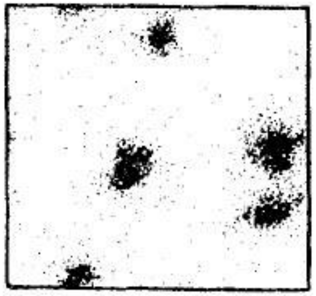
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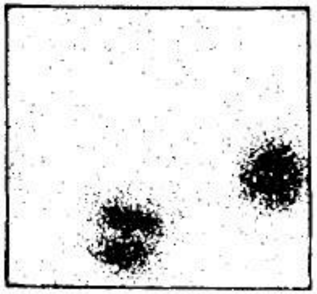
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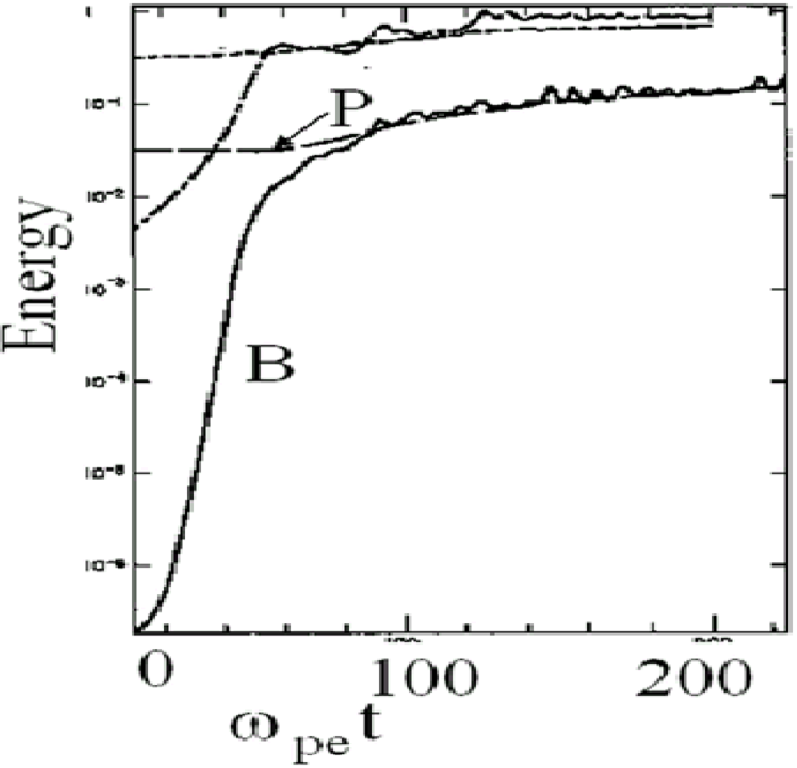


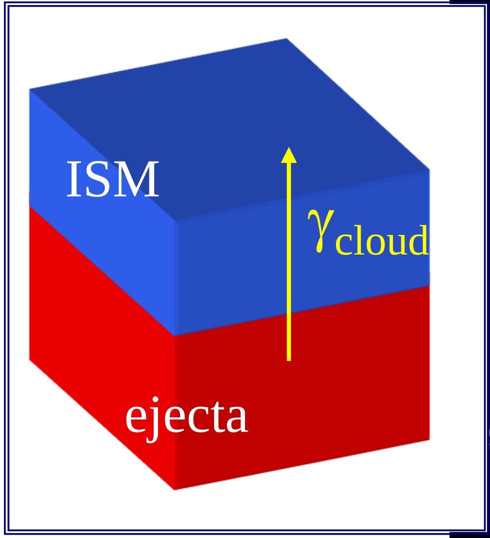
Lee & Lampe, PRL **31**, 1390 (1973)

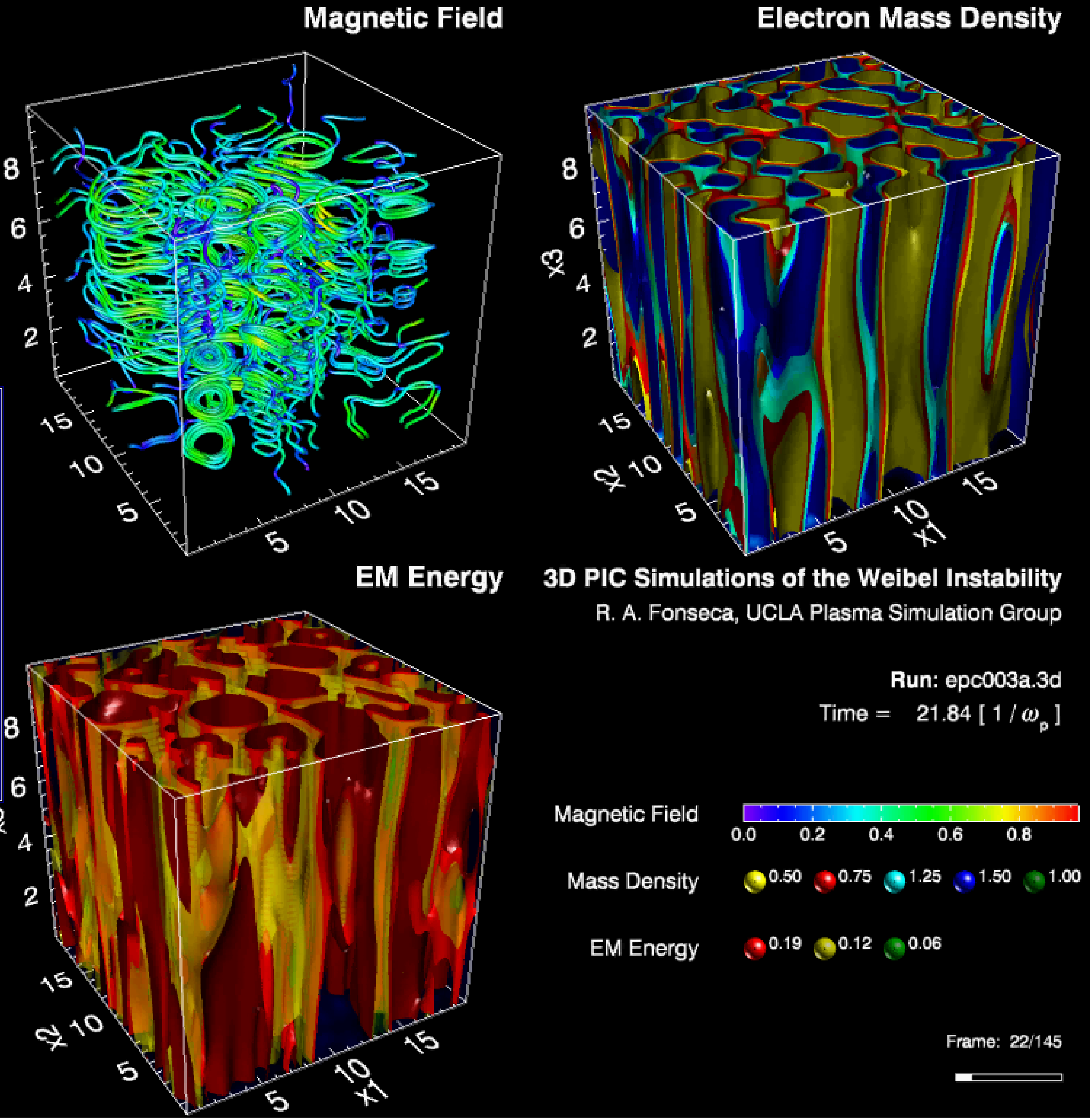
(1) This may explain structured B-field in GRB.

(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 …

$B(t) \sim B_0 \exp(t/\tau)$

$\tau = 2\pi / \omega_p$

$\sim 10^{-3}$ s

$\lambda = 2\pi c / \omega_p$

$\sim 10^{7}$ cm

Kinetic energy is converted into magnetic field energy

Saturation

… current filamentation inhibited…

… isotropization of particle velocities …

$\lambda / \rho_L \sim 1$

$\varepsilon_B \sim (\gamma_{th}+1) / [\, 2^{3/2} \gamma_{th} \,] \sim 0.5$

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

Nonlinear regime

… filament coalescence instability …

… 2D gas of filaments …

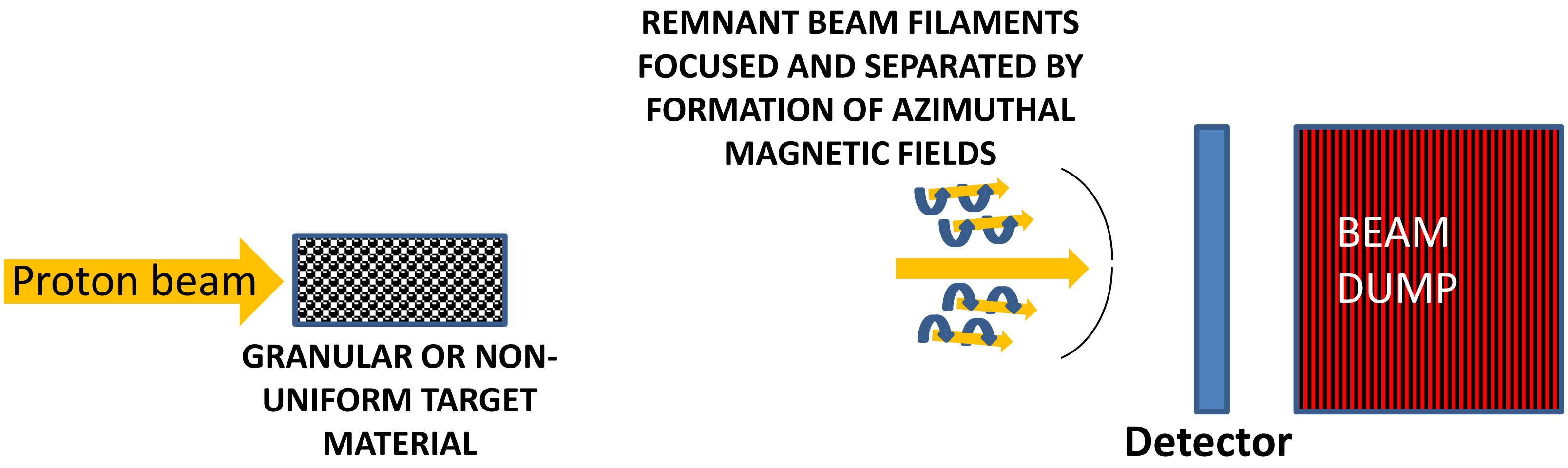
$\lambda(t) \sim c\, t$

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

(Weibel, PRL, 1959; Medvedev & Loeb, ApJ, 1999, Medvedev, et al 2004)

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?



REMNANT BEAM FILAMENTS FOCUSED AND SEPARATED BY FORMATION OF AZIMUTHAL MAGNETIC FIELDS

Proton beam

GRANULAR OR NON-UNIFORM TARGET MATERIAL

Detector

BEAM DUMP

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
$\boldsymbol{E} = -\nabla \varphi.$	Electric field simply determined from the gradient of potential
$M_{\beta \mathrm{charge}} = q\boldsymbol{E}.$	Coulombic force applied to the particle phase in the momentum equation