Laboratory Astrophysics Working Group Summary

Pisin Chen
Stanford Linear Accelerator Center
Stanford University

- Introduction
- Calibration of Observations
- Investigation of Dynamics
- Probing Fundamental Physics
- Summary

SABER Workshop
March 15-16, 2006, SLAC

LabAstro WG Participants

P. Chen (KIPAC) (Chair)
C.-W. Chen (KIPAC/NTU) (Scientific Secretary)
C.-C. Chen (KIPAC/NTU) (Scientific Secretary)
E. do Couto e Silva (KIPAC)
C. Field (SLAC)
R. Fiorito (UMD)
Wei Gai (ANL)
J. S.-T. Ng (KIPAC)
R. Noble (SLAC)
C. Pellegrini (UCLA)
K. Reil (KIPAC)
B. Remongton (LLNL)
P. Sokolsky (Utah)
A. Spitkovsky (KIPAC)
D. Walz (SLAC)

G. Barbiellini (Rome) (in absentee)

LabAstro Working Group Program

March 15 (Wed.)

WG Parallel Session 1 (11:00-12:00)

Pierre Sokolsky (Utah), "Some Thoughts on the Importance of Accelerator Data for UHE Cosmic Ray Experiments"

Pisin Chen (KIPAC, SLAC), "ESTA: End Station Test of ANITA"

WG Parallel Session 2 (13:30-15:00)

Robert Bingham (RAL, UK), "Tests of Unruh Radiation and Strong Field QED Effects"*

Anatoly Spitkovsky (KIPAC, SLAC), "Pulsars as Laboratories of Relativistic Physics,"

Eduardo de Silva (KIPAC, SLAC), "Can GLAST Provide Hints on GRB Parameters?"

WG Parallel Session 3 (15:30-17:00)

Robert Noble (SLAC), "Simulations of Jet-Plasma Interaction Dynamics"*

Johnny Ng (KIPAC, SLAC), "Astro-Jet-Plasma Dynamics Experiment at SABER"

Kevin Reil (KIPAC, SLAC), "Simulations of Alfven Induced Plasma Wakefields"

* Absent

LabAstro Working Group Program

March 16 (Thur.)

WG Parallel Session 4 (08:30-10:00)

Bruce Remington (LLNL), "Science Outreach on NIF: Possibilities for Astrophysics Experiments"

Bruce Remington (LLNL), "Highlights of the 2006 HEDLA Conference“

G. Barbiellini (Rome), (presented by Silva) “Stochastic Wakefield Particle Acceleration in GRB”

Round Table Discussion, "Considerations of Labaratory Astrophysics"

WG Summary Preparation (10:20-12:00)

Three Categories of LabAstro

-Using Lasers and Particle Beams 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/density beams

→ *Potential returns to science are most significant*

1. Calibration of Observations

Some Thoughts on Laboratory Astrophysics for UHE Cosmic Rays

Pierre Sokolsky
University of Utah

SABRE Workshop

SLAC, March, 2006

UHE Cosmic Ray detection (N, gamma, neutrino)

- Indirect - Extensive Air Shower in atmosphere or solid/liquid.
- Energy not directly measured - surrogate such as air fluorescence, cherenkov radiation, radio emission, electron/muon density at surface is measured instead
- Depending on surrogate, calibration or validation of detailed modeling of EAS cascade is required.

SLAC has been a leader in calibration experiments FFTB!

- LPM effect
- Askaryan effect
- FLASH - air fluorescence

Are there other such?

- Follow-up on FLASH - increase precision, effects of impurities
- ANITA radio detection efficiency tests
- Validation of low energy electromagnetic shower codes at large Moliere radii.
- Atmospheric EAS radio detection - what is the balance of Askaryan vs Earth’s magnetic field effects? - Possible controlled experiment producing shower in dense material with B field?

Radio signals from EAS in Air

- Mechanism is Askarian + curvature of charged particles in Earth's B field (coherent geosynchrotron radiation).
- Exact balance not well known
- First convincing demonstration by French and German groups (LOPES with Kascade-Grande, CODALEMA) - coincidence with particle ground arrays.
- May be the next big step??

Issues, continued

- Low energy shower modeling validation

  - GEANT, FLUKA predictions for e, gamma and hadron subshowers - very significant for understanding muon content of EAS, even at EHE
- High energy interaction models

  - pp cross-section, p-air cross section

  - pion and kaon multiplicities, forward direction physics - important for Xmax composition measurement

ESTA: End Station Test of ANITA
A SLAC-ANITA Collaboration

Pisin Chen
Kavli Institute for Particle Astrophysics and Cosmology
Stanford Linear Accelerator Center
Stanford University

- Introduction- Neutrino Astrophysics
- Askaryan Effect
- ESTA
- Future Outlook

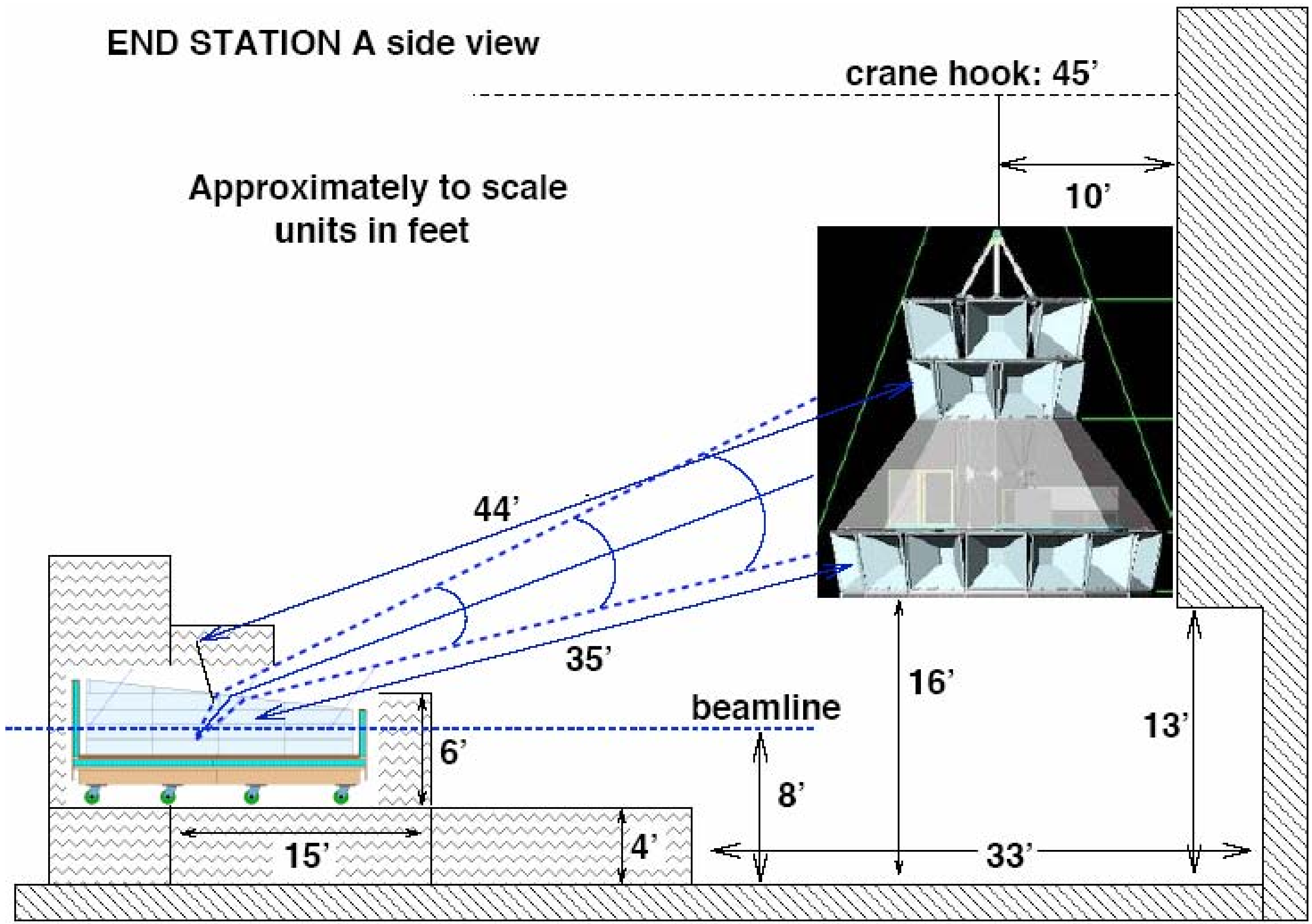
SABER Workshop
March 15-16, 2006, SLAC

ANITA: Antarctic Neutrino Transient Antenna

ESTA: End Station Test of ANITA

SLAC-ANITA Collaboration

Expected date: June 2006



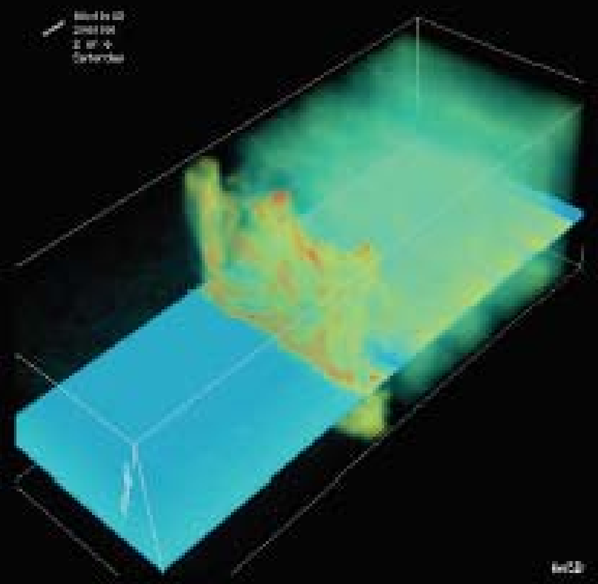
2. Investigation of Dynamics

Relativistic Collisionless Shocks: Shock Structure and Particle Acceleration

Anatoly Spitkovsky (KIPAC, Stanford)

Outline:

1. *Shocks in astrophysics: expectations of composition, structure and shock properties*
2. *3D shock modeling -- simulation setup*
3. *Unmagnetized shocks in pair plasma*
4. *Magnetized shocks in pair plasma*
   a) *Perpendicular*
   b) *Oblique*
5. *Shocks in electron-ion plasma*
   a) *Magnetized*
   b) *Unmagnetized*
6. *Conclusions*



3D PIC results are generally consistent with work by

Silva, Mori et al
Nishikawa et al
Hededal, Frederiksen, Nordlund et al

Shocking astrophysics

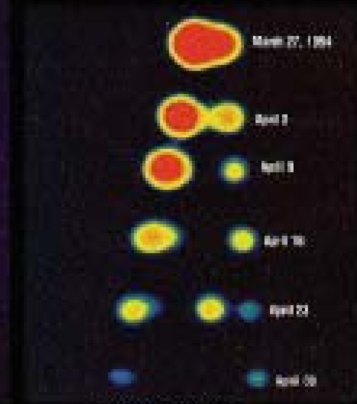
Relativistic collisionless shocks in astrophysics

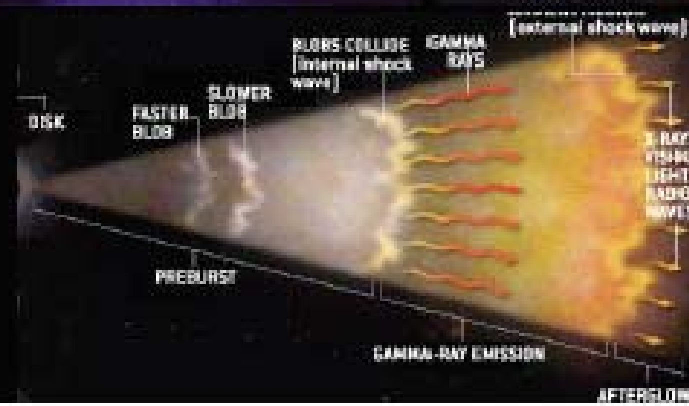
- *Pulsars + winds (plerions, J0737) $\gamma \sim 10^6$*
- *Extragalactic radio sources $\gamma \sim 10$*
- *Gamma ray bursts $\gamma > 100$*
- *Galactic superluminal sources $\gamma \sim$ few*
- *Sources for UHE CR?*

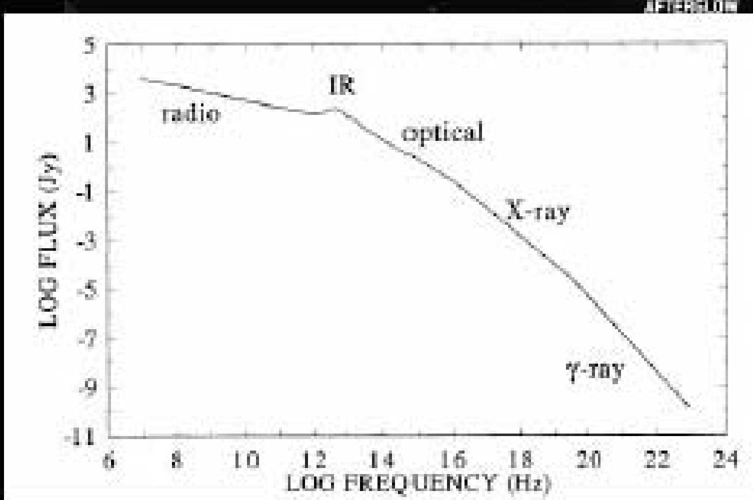
Open issues:

- *What is the structure of collisionless shock waves?*
- *Particle acceleration -- Fermi mechanism? Something else?*
- *Generation of magnetic fields (GRB shocks, primordial fields?)*

By using direct ab-initio numerical simulations of collisionless shocks we can place constraints on astrophysical models of composition and structure of relativistic outflows in nature.



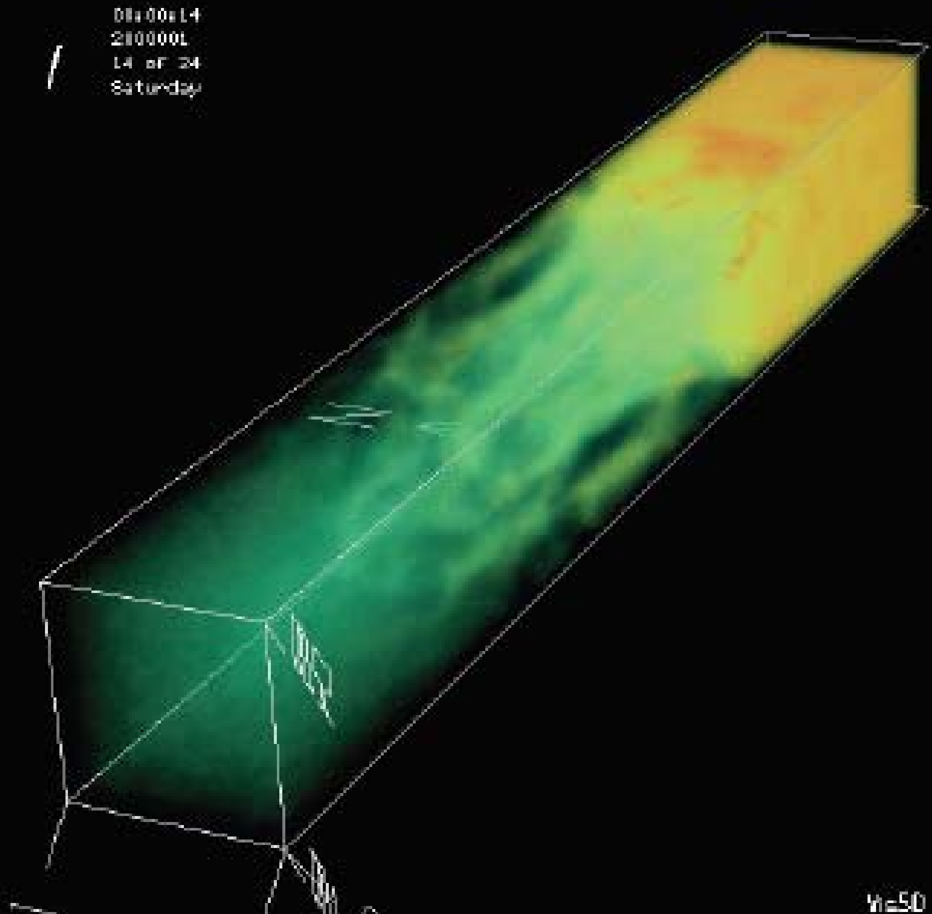


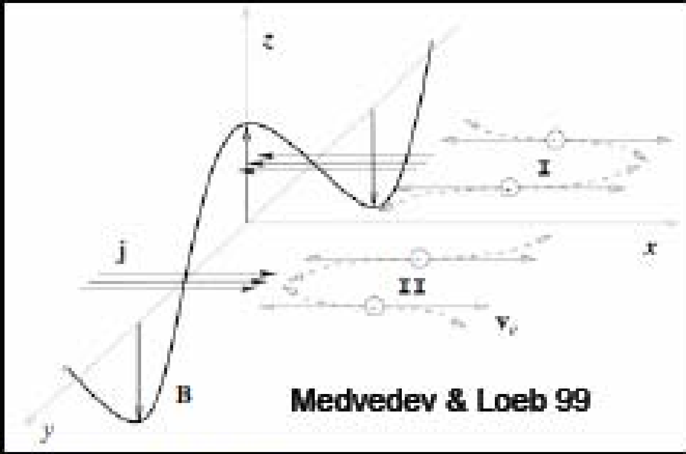


Unmagnetized pair shock

Why does a shock exist?

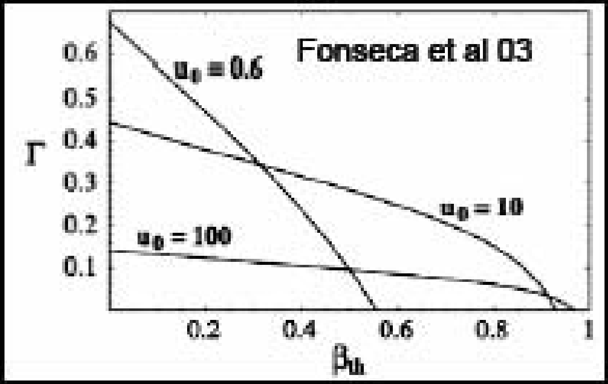
Particles are slowed down either by instability (two-stream-like) or by magnetic reflection. Electrostatic reflection is important for nonrelativistic shocks and when ions are present.





Weibel instability

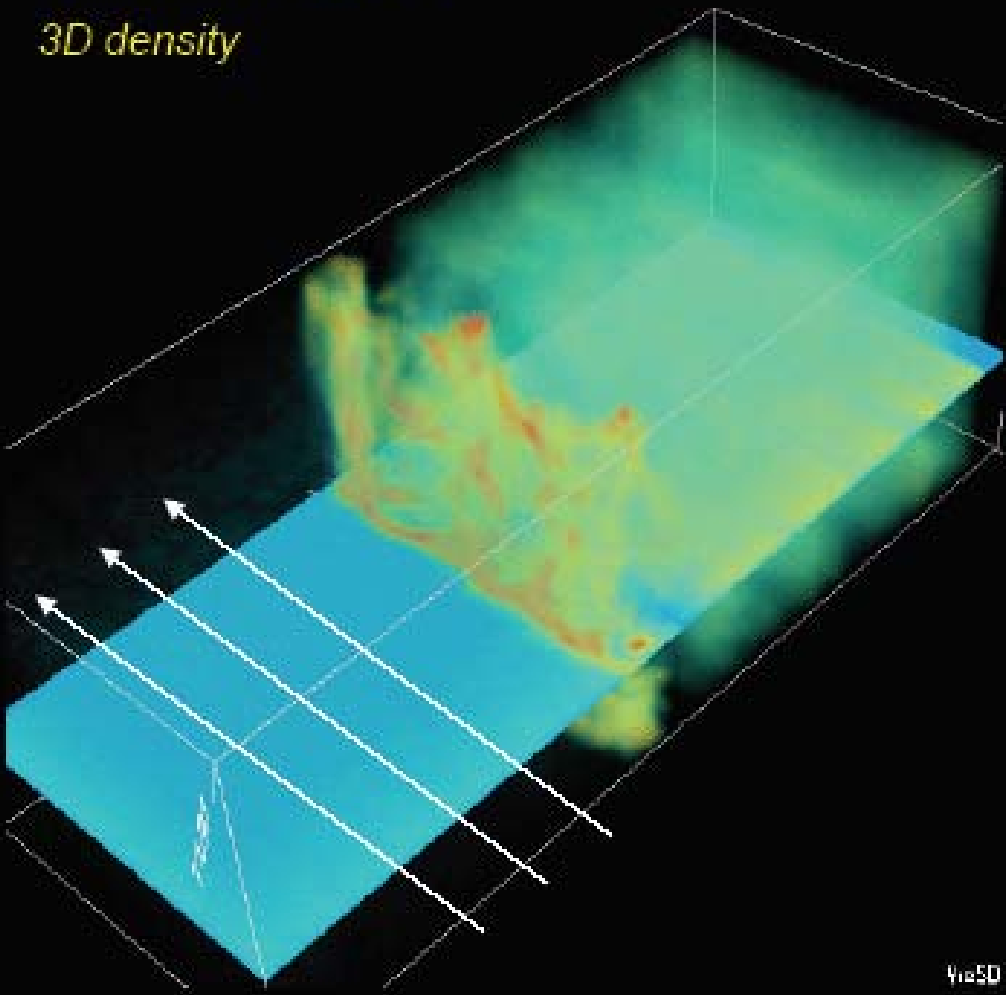
Spatial growth scale c/ω_p; timescale $10/\omega_p$



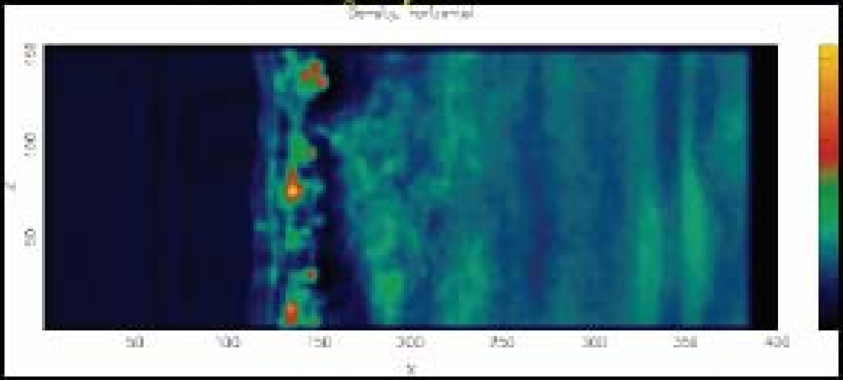
Magnetized perpendicular pair shock

Shock structure σ=0.1

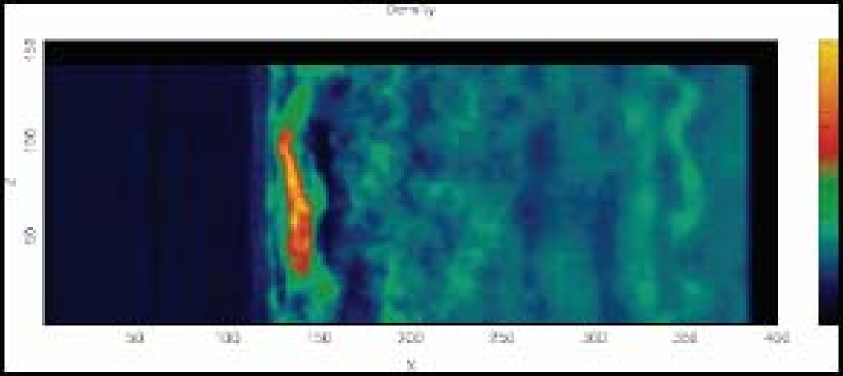
3D density



Plane of v_x-B_y



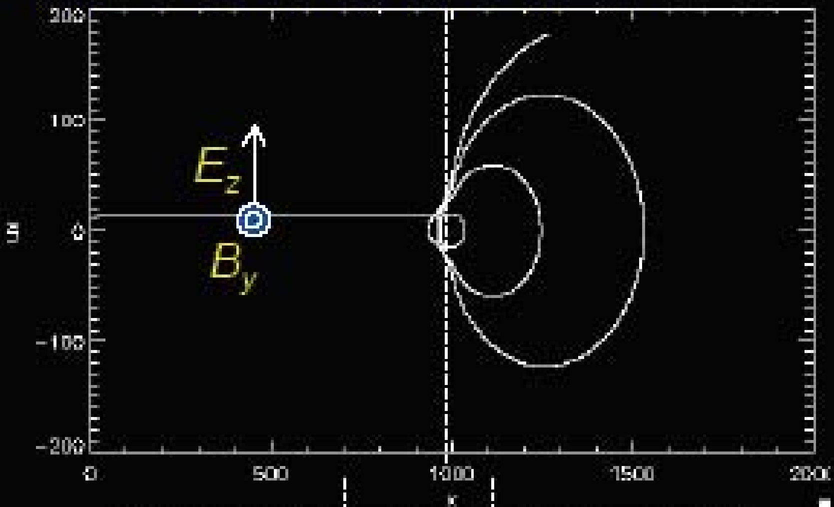
Plane of v_x-E_z

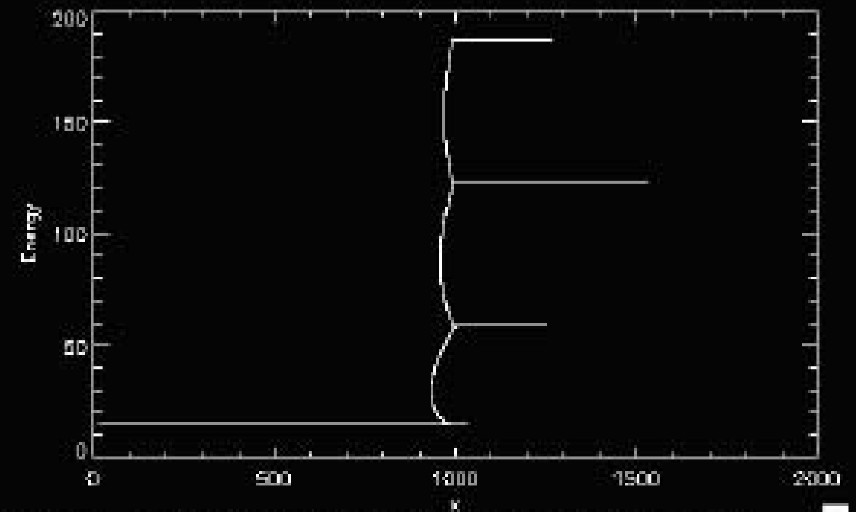


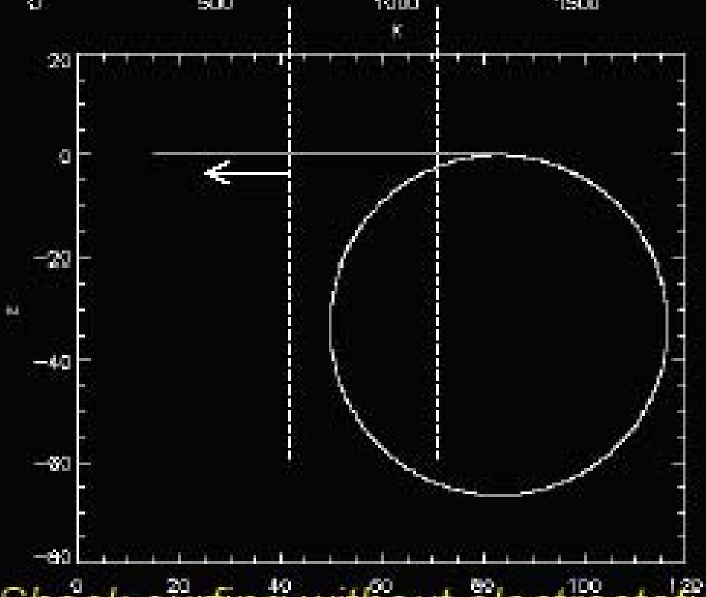
Shock is clearly magnetized -- anisotropy with respect to B.

Shock acceleration failure

Is it the injection problem? Perhaps high-energy preaccelerated particles will have easier time crossing the shock?







In order to outrun a moving shock, need

$$v_{sh} T < r_L = c/\omega_c$$

$$\frac{T_L}{2} < T < \frac{3T_L}{4} \qquad T_L = \frac{2\pi}{\omega_c}$$

$$v_{sh} < \frac{c/\omega_c}{\pi/\omega_c} = \frac{c}{\pi}$$

Shock surfing without electrostatic trap will only work in nonrelativistic shocks!

Can we constrain GRB shock parameters using the Gamma Ray Large Area Space Telescope?

Eduardo do Couto e Silva
SLAC/KIPAC

SABER Workshop – Mar 15, 2006

The Main Questions

- Is there any connection between the SABER program and the GRB science with GLAST?
  - Can we create an environment similar to that of the shock dissipation phase in GRBs?
    - see poster (*Stochastic wake field particle acceleration in Gamma-Ray Bursts*, *Baribiellini et al*)

GLAST Observatory : Overview

GLAST will measure the direction, energy and arrival time of celestial γ rays

Principal Investigator: Peter Michelson

LAT
will record gamma-rays in the energy range
~ 20 MeV to >300 GeV

GBM
will provide correlative observations of transient events in the energy range
~10 keV – 25 MeV

Observing modes

All sky survey

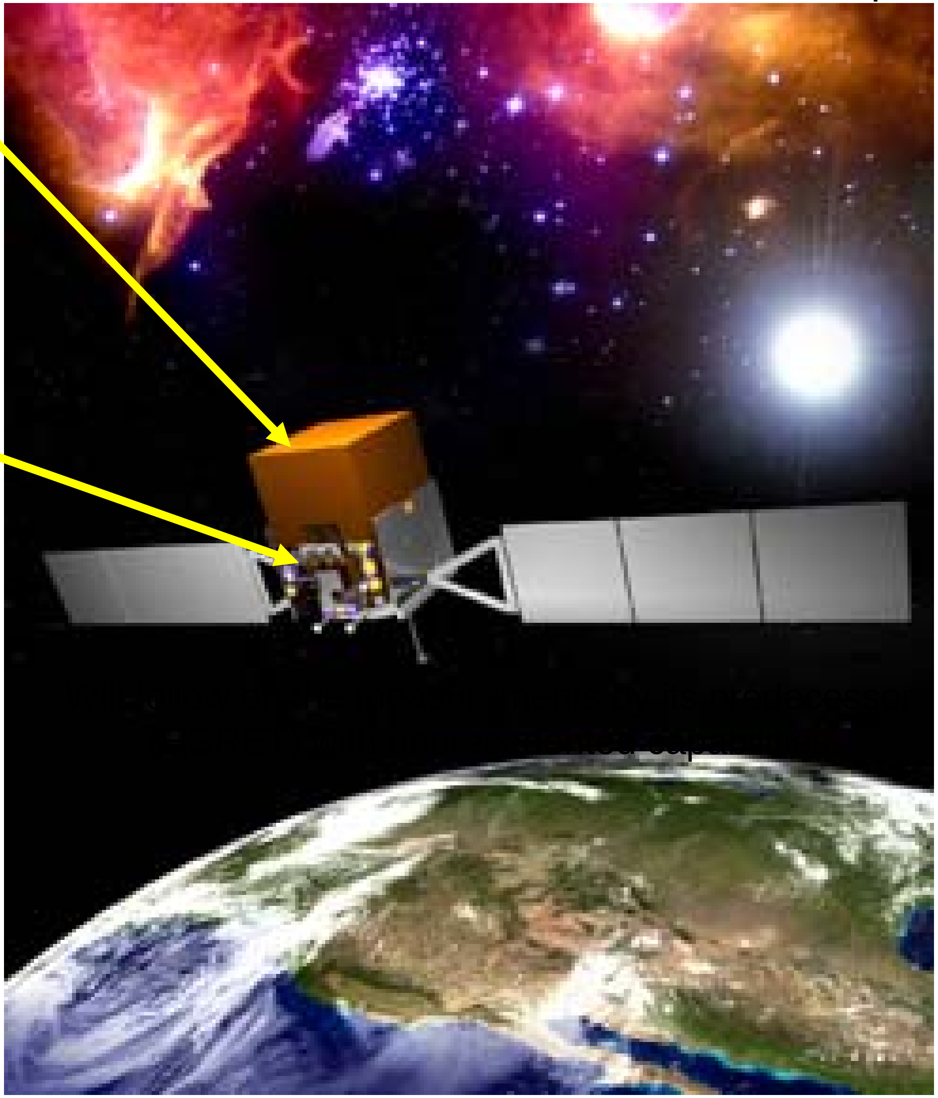
Pointed observations

Re-pointing Capabilities

Autonomous

Rapid slew speed

(75° in < 10 minutes)



Orbit

565 km, circular

Inclination

28.5°

Lifetime

5 years (min)

Launch Date
Sep 2007

Launch Vehicle
Delta 2920H-10

Launch Site
Kennedy Space Center

Back to the Main Questions

- Is there any connection between the SABER program and the physics interests of GLAST?
  - Can we simulate in the laboratory an environment similar to that of the shock dissipation phase in GRBs?
  - Can we quantify the relative importance of magnetic fields during the shock dissipation phase in GRBs?
  - A deeper question:
    - Are B fields generated locally or at the central engine?

Simulation of Relativistic Jet-Plasma Interactions

Johnny Ng and Bob Noble

Stanford Linear Accelerator Center

SABER Workshop, Laboratory Astrophysics WG
SLAC, March 15-16, 2006

Issues and Questions

- What are the plasma microphysics that cause particle acceleration and deceleration, and radiation in jet-plasma interactions?

- What are the parameters for scaled lab experiments that can explore this physics, benchmark the codes, and connect this plasma physics to the astrophysical observations?

- Real astrophysical outflows are larger than anything we can simulate with a PIC code. We focus on the physics at the **plasma wavelength scale**.

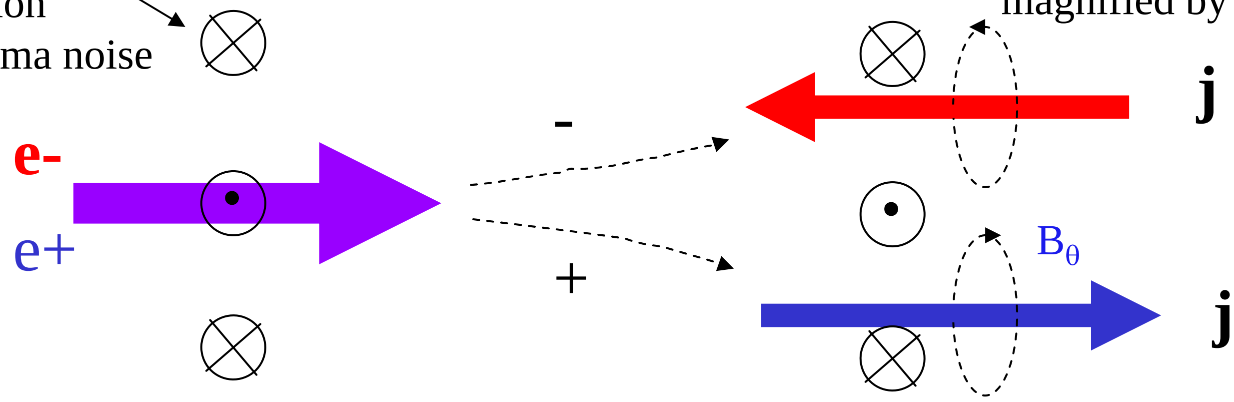
Streaming Neutral Plasma Systems: Plasma Filamentation

Weibel instability (1959) is the spontaneous filamentation of the jet into separate currents and the generation of associated azimuthal magnetic fields.

small $B_\perp$ field perturbation from plasma noise

magnetic field perturbation magnified by filaments

Mass flow but j_e=0



… then hose, pinch, streaming instabilities!

Davidson and Yoon (1987)
Weibel growth rate:

$$\Gamma = f(\beta_\perp, \beta_z)\ \omega_{p(b)} / \gamma^{1/2}$$

$\sim (n/\gamma)^{1/2}$

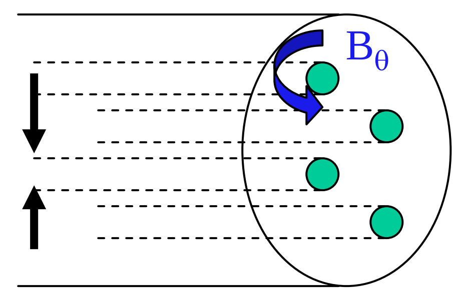
typ. f $\leq$1

Transverse scale size:

$$d = g(\beta_\perp, \beta_z)\ c/\omega_{p(b)}$$

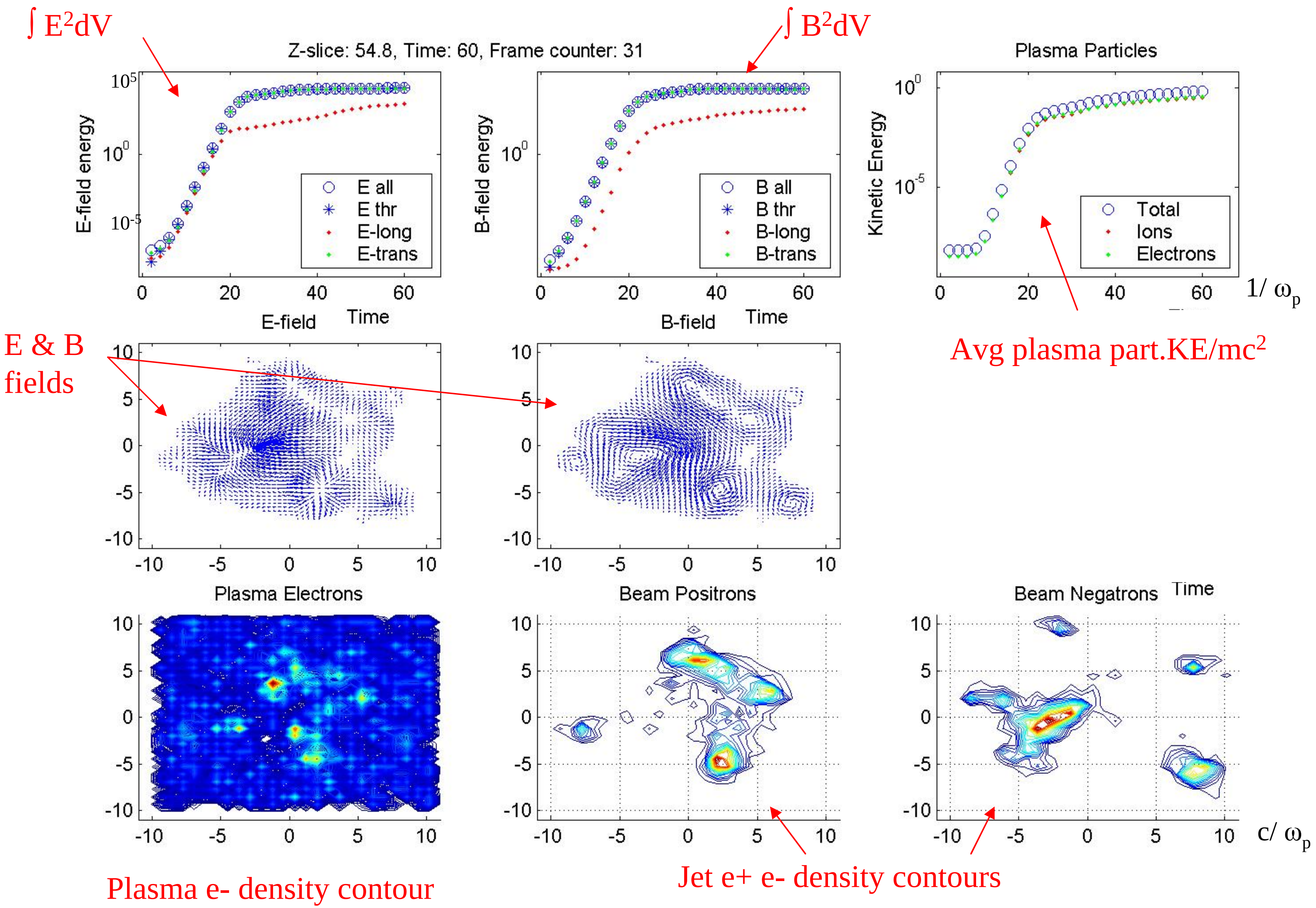
$\sim (1/n)^{1/2}$

typ. g $\geq$1



Past simulations: Saturated EM energy density/particle KE density ~ 0.01 – 0.1

Illustrative Case: gamma =10, jet/plasma density = 10



Summary of Simulation Results

1. General results:
   - We observe the correct $(n/\gamma)^{1/2}$ scaling of the Weibel instability growth rate, transverse filament size of few skin depths, and approximately the correct absolute growth rate.
   - Neutral jets in **unmagnetized** plasmas are remarkably unstable**.** One expects stability to improve if a background longitudinal B field existed.
2. Plasma filamentation sets up the jet for other instabilities.
   - Separation of electron and positron filaments.
   - Separating positron filaments generate large local E_Z
   - Charge filaments excite longitudinal electrostatic plasma waves

- We observe two local acceleration mechanisms:
  - Inductive "Faraday acceleration"
  - Electrostatic Plasma Wakefield acceleration.

⇒ **Robust general result: only requires Weibel filamentation**

Acceleration in Relativistic Jet-Plasma Interactions at SABER

Johnny S.T. Ng

Stanford Linear Accelerator Center

Stanford University

SABER Workshop, March 15-16, 2006, SLAC.

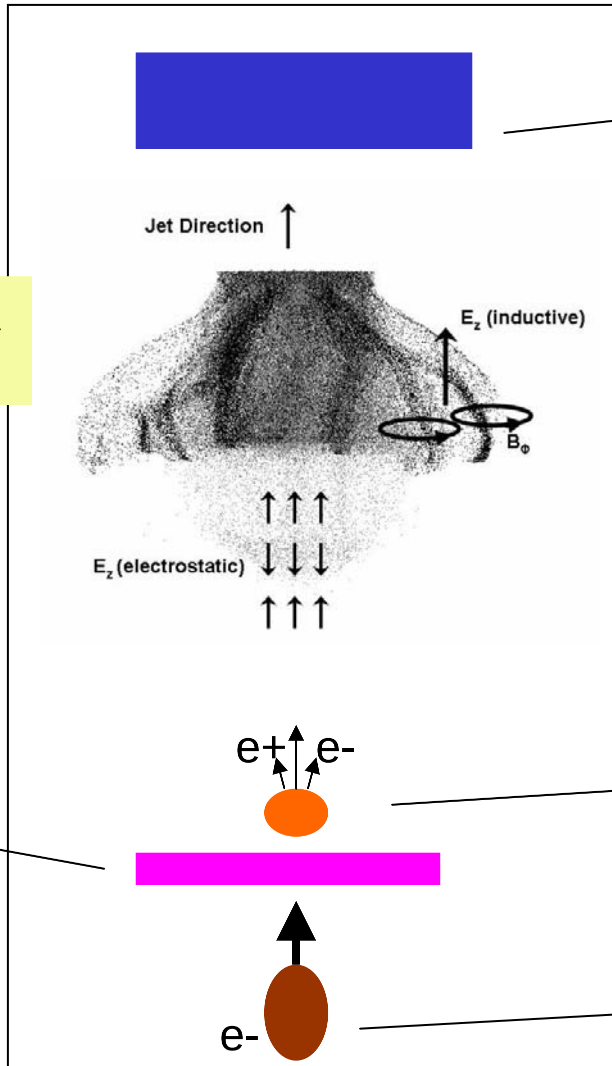
Cosmic Acceleration at SABER

- Create a relativistic electron-positron plasma “jet” by showering a high energy beam in solid target
- Investigate acceleration mechanisms in jet-plasma interactions over a scale of tens of collisionless skin-depths
- Current simulation techniques can accurately resolve physics on this scale (see Bob Noble’s talk)

Applicable to astronomical collisionless plasmas

Important tests of our ability to simulate these effects in astronomical environments

Schematic Layout of Experiment



Particle and radiation detectors

Magnetic field diagnostics

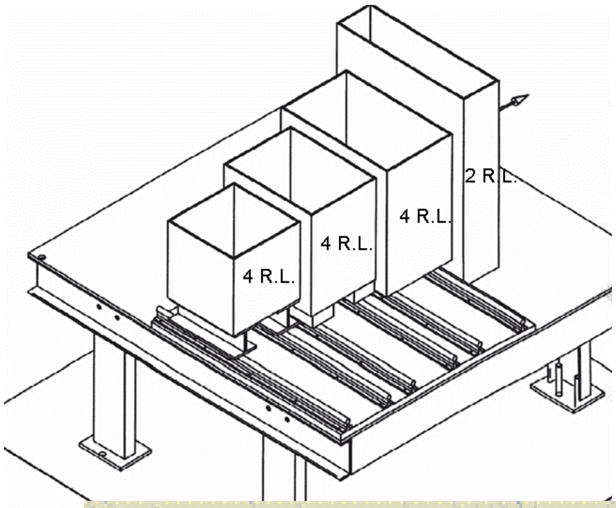
Jet-plasma interaction:
- Inductive acceleration
- Wakefield acceleration

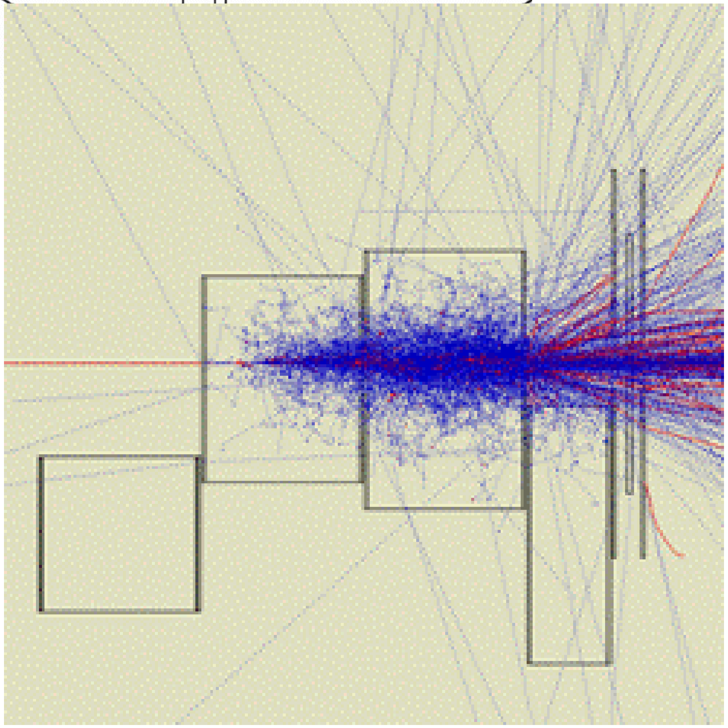
Solid target

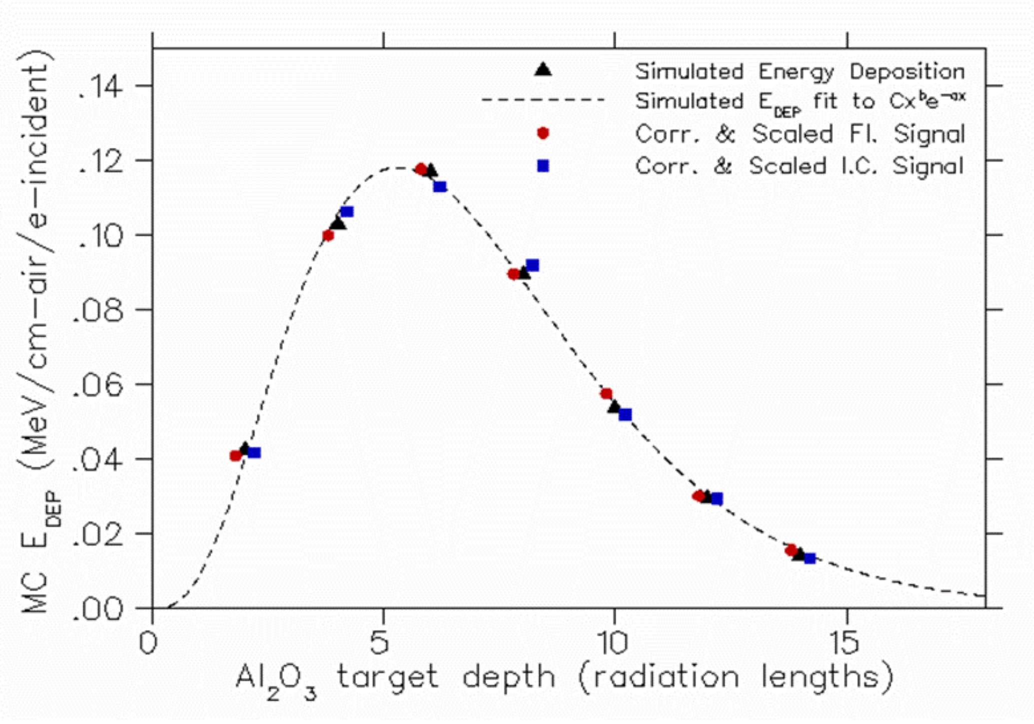
Electron-positron
plasma jet (10-100 MeV)

High-energy-density e- beam

FLASH Experiment: Thick Target







General Requirements for Jet-plasma Experiment at SABER

- Beam:
  - Energy above 10 GeV
  - N_e = 2 to 4 x 10^{10}
  - Size: σ_{xy} = 10 to 50 μm, σ_z = 40 μm
  - Energy density ~ 10^{16} J/m^3 !
- Facility infrastructure:
  - Radiation shielding: 6 to 7 X_{rad} target
  - Space to mount experiment: 4 m by 10 m
  - Beam line diagnostics (toroids, BPM, OTR)
- Beam time:
  - Program will last 3 to 5 years
  - 3-week runs, total 2 months per year

Measurement Parameters

- Filamentation:
  - Image jet down stream; micron resolution required
  - Magnetic field diagnostics based on Faraday rotation: sensitivity? Electron and positron filaments cancellation?
- Acceleration:
  - Electron and positron energy spectrum
- Radiation:
  - Spectra and angular dependence

Summary

- SABER is unique: high-energy-density beams providing relativistic plasma jets

"To understand the acceleration mechanisms of these [UHECR] particles, a better understanding of relativistic plasmas is needed"

"Laboratory work [thus] will help to guide the development of a theory of cosmic accelerators, as well as to refine our understanding of other astrophysical phenomena that involve relativistic plasmas."

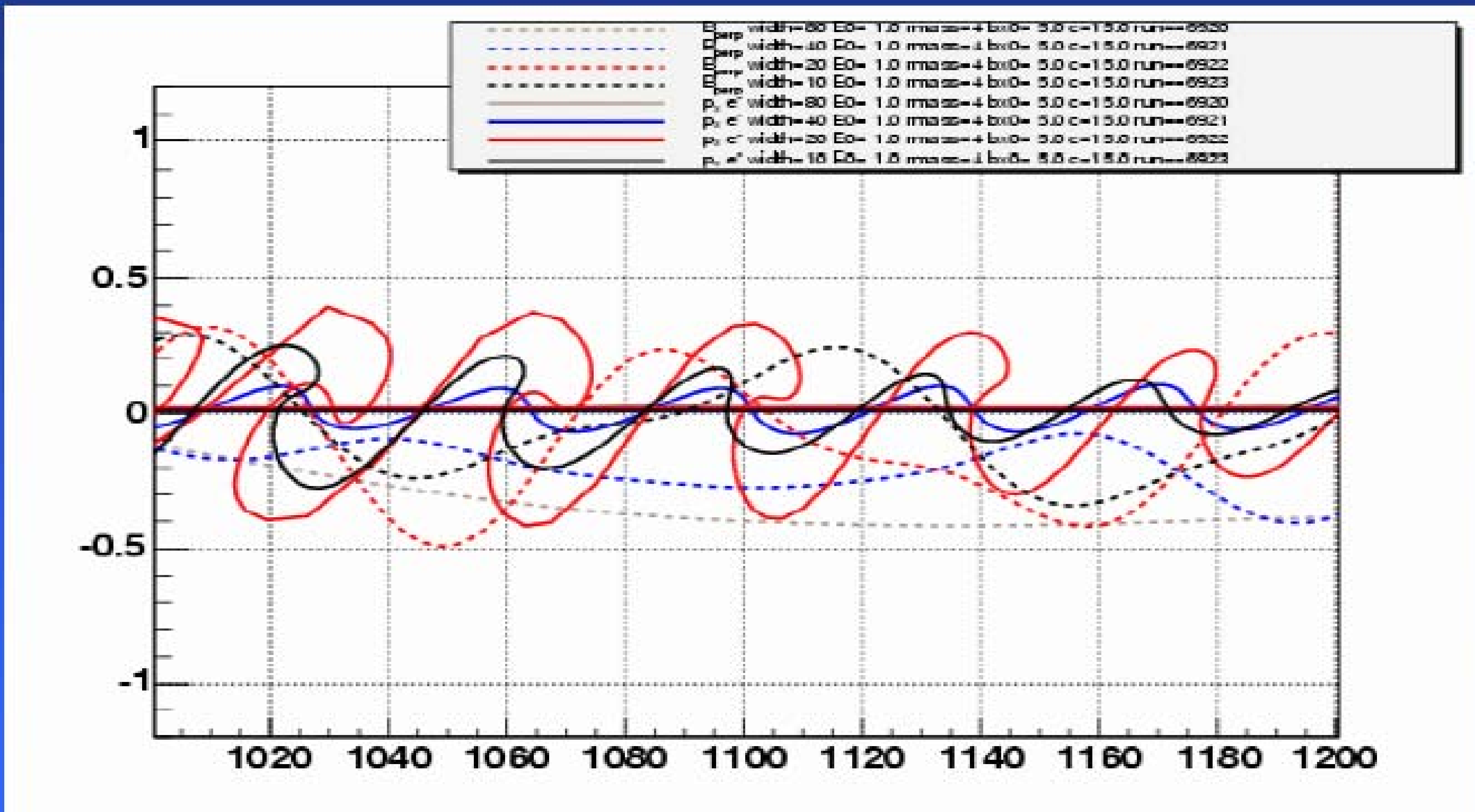
Turner Committee on the Physics of the Universe:
"Eleven Science QuestionsFor the New Century", NRC, 2003

An Astrophysical Plasma Wakefield Accelerator

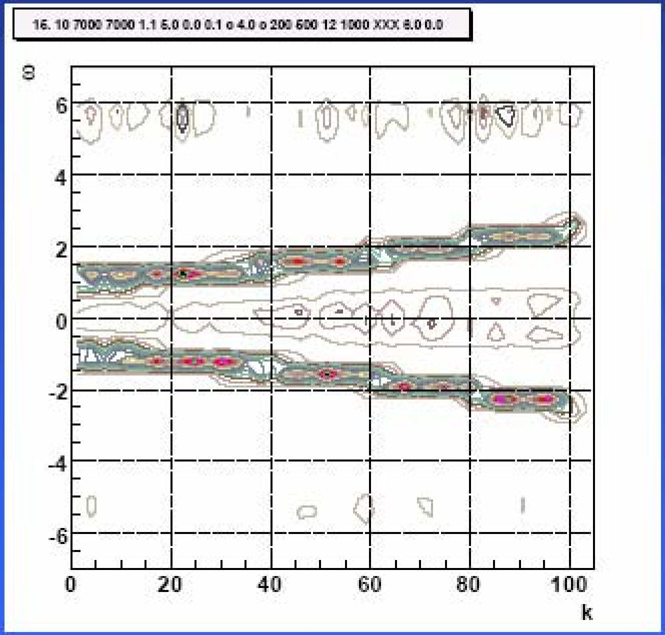
Alfven Wave Induced

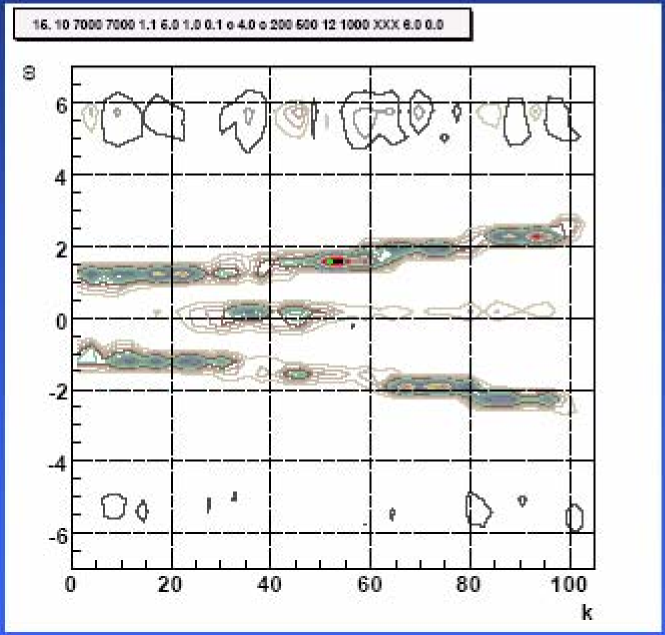
Plasma Wakefield Acceleration

R_{mass}=4 T=400 ω_p^{-1} (Zoomed)

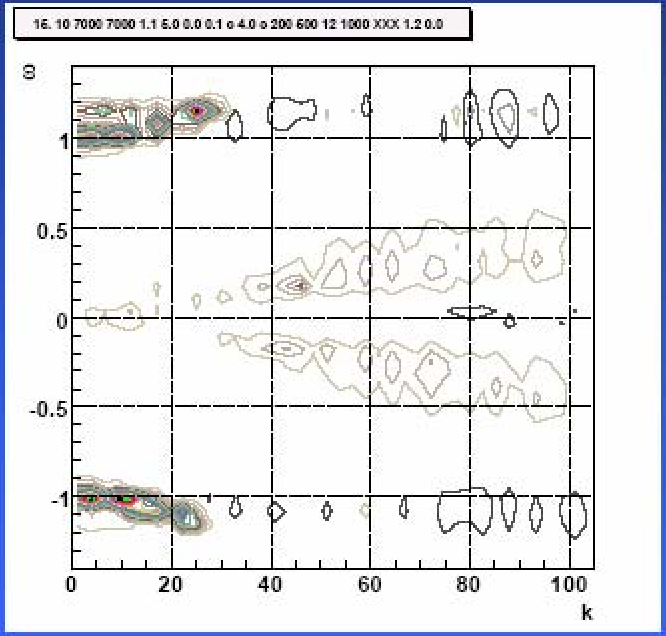


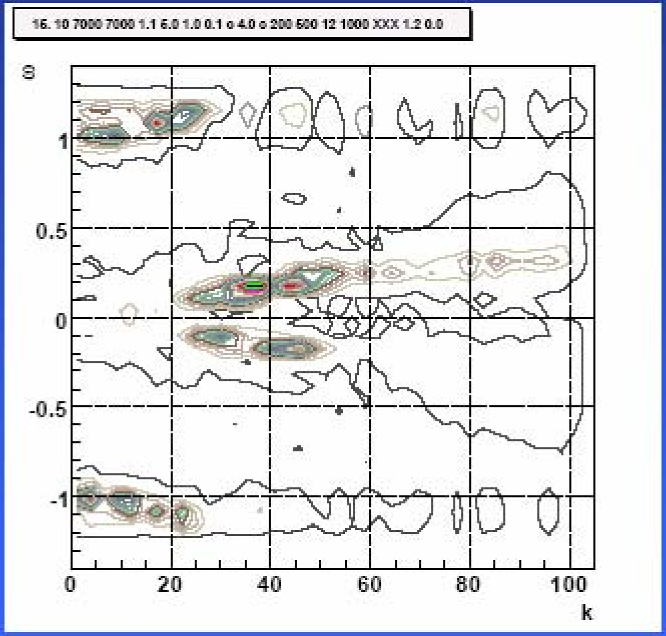
Dispersion Relation



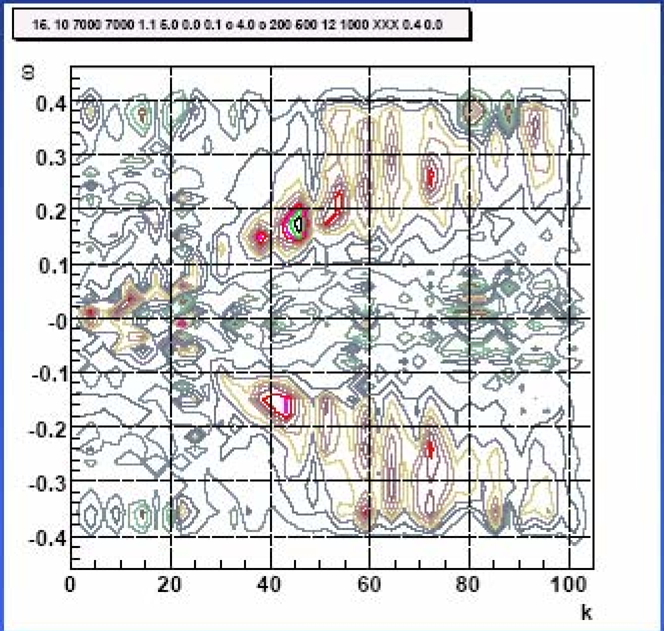


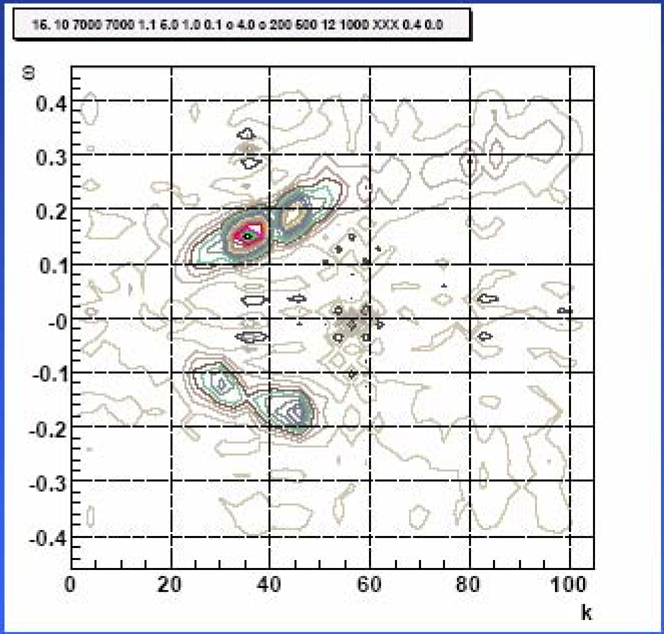
Dispersion Relation





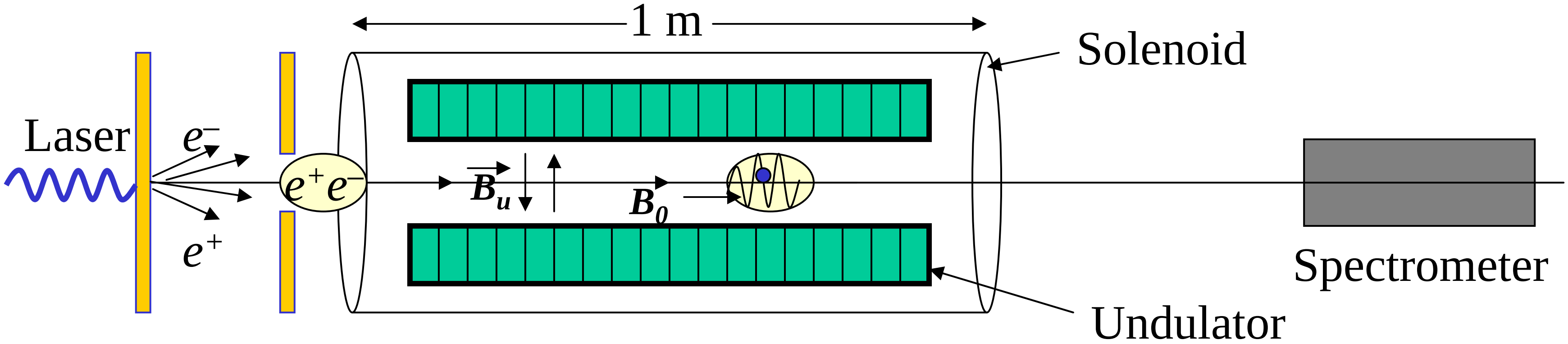
Dispersion Relation





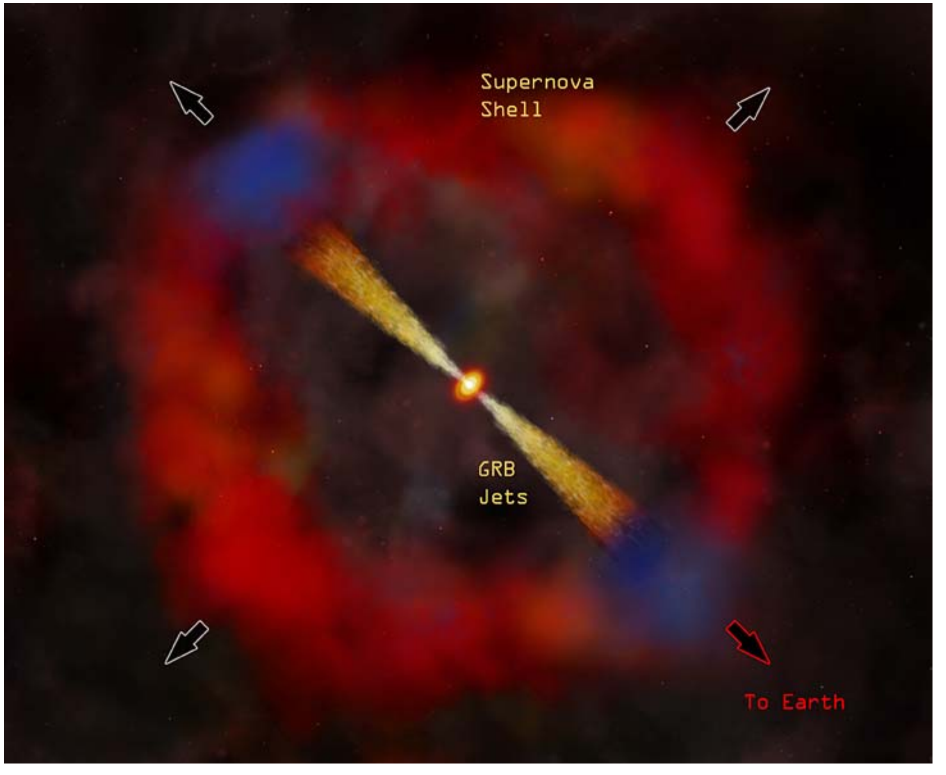
Alfven-Shock Induced Plasma Wakefield Acceleration

(Chen, Tajima, and Takahashi, PRL, 2001)



- Generation of Alfven waves in relativistic plasma flow
- Inducing high gradient nonlinear plasma wakefields
- Acceleration and deceleration of trapped e^+/e^-
- Power-law (n ~ -2) spectrum due to stochastic acceleration

Stochastic Wake Field particle acceleration in GRB



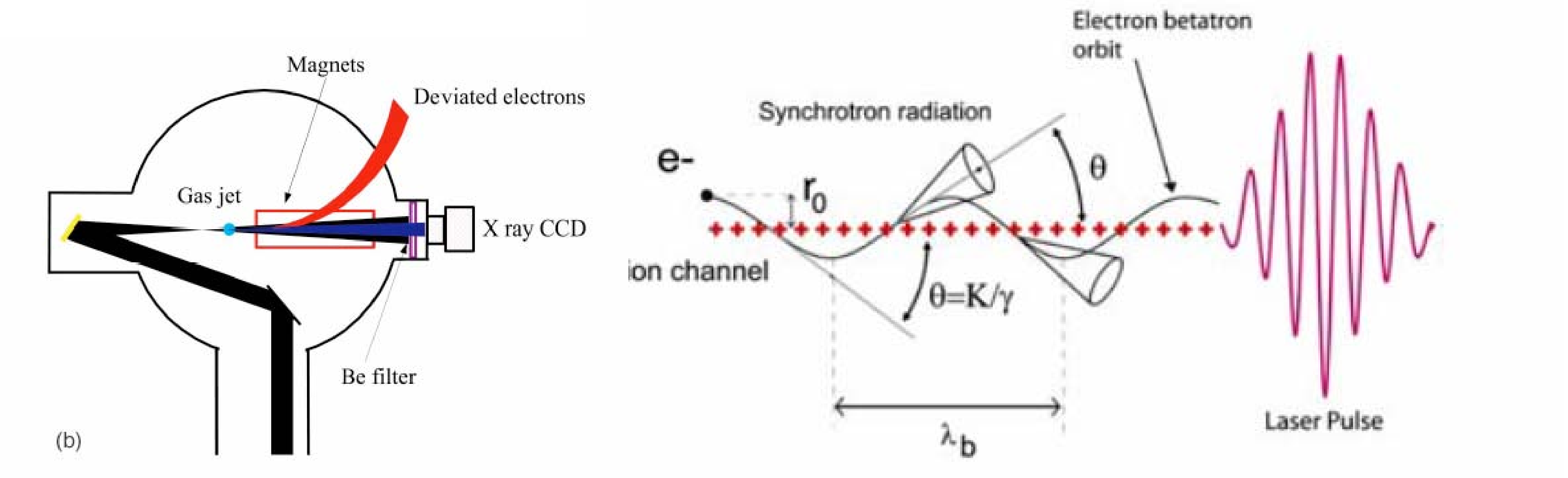
(image credits to CXO/NASA)

G. Barbiellini[(1)], F. Longo[(1)], N.Omodei[(2)], P.Tommasini[(3)], D.Giulietti[(3)], A.Celotti[(4)], M.Tavani [(5)]

Gamma-Ray Bursts in laboratory

WakeField Acceleration

(Ta Phuoc et al. 2005)



Laser Pulse $t_{laser} = 3\ 10^{-14}$ s

Laser Energy = 1 Joule

Gas Surface = 0.01 mm^2

Gas Volume Density = 10^{19} cm^{-3}

Power Surface Density $\sigma_W = 3\ 10^{18}$ W cm^{-2}

SABER proposal

- Proposal for SABER
  - Create a pulsed beam to very scaling relations of density
    - not focused on a particular model
  - Measure the X-ray spectrum vs the density of the plasma.
- Experimental Set-up (beam parameters)
  - Laser Pulse tlaser
    - 3^{10-14} s
  - Laser Energy

Science outreach on NIF: possibilities for astrophysics experiments

Presentation to the SABER workshop,
Stanford Linear Accelerator Center,
March 15-16, 2006

Bruce A. Remington
Group Leader, HED Program
Lawrence Livermore National Laboratory

We are implementing a plan for university use of NIF

fy05	fy06	fy07	fy08	fy09	fy10	fy11	fy12

Start 3 university teams

Develop full-NIF univ. use proposals

Add 1-2 university teams/year

Select, prepare for 1st univ. use experiment

Start university experiments (goal: ~10% of NIF shots)

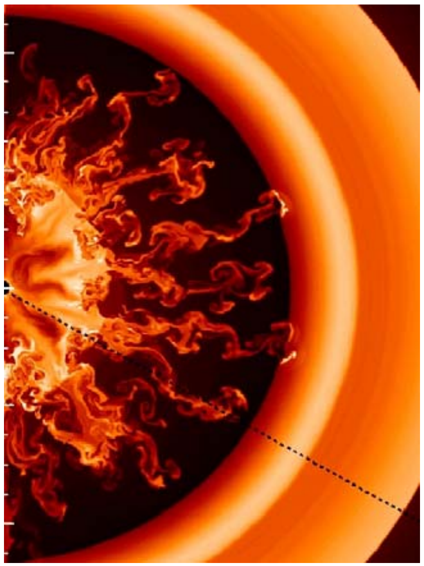
Issues:

- **funding for the universities**
- **targets**
- **coordination with the other facilities**
  - **- Omega/NLUF, Z/ZR, Jupiter, Trident, …**
- **proposal review committee**
  - **- assess science impact, facility capability, readiness**

Intro

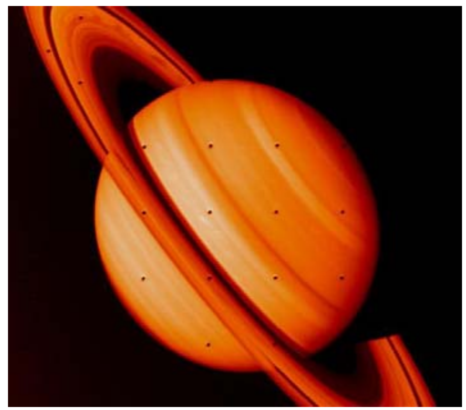
Three university teams are starting to prepare for NIF shots in unique regimes of HED physics

Astrophysics - hydrodynamics



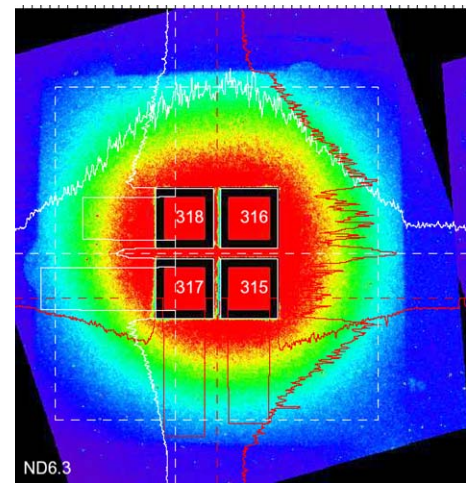
Paul Drake, PI, U. of Mich.
David Arnett, U. of Arizona,
Adam Frank, U. of Rochester,
Tomek Plewa, U. of Chicago,
Todd Ditmire, U. Texas-Austin
LLNL hydrodynamics team

Planetary physics - EOS



Raymond Jeanloz, PI, UC Berkeley
Thomas Duffy, Princeton U.
Russell Hemley, Carnegie Inst.
Yogendra Gupta, Wash. State U.
Paul Loubeyre, U. Pierre & Marie Curie, and CEA
LLNL EOS team

Nonlinear optical physics - LPI



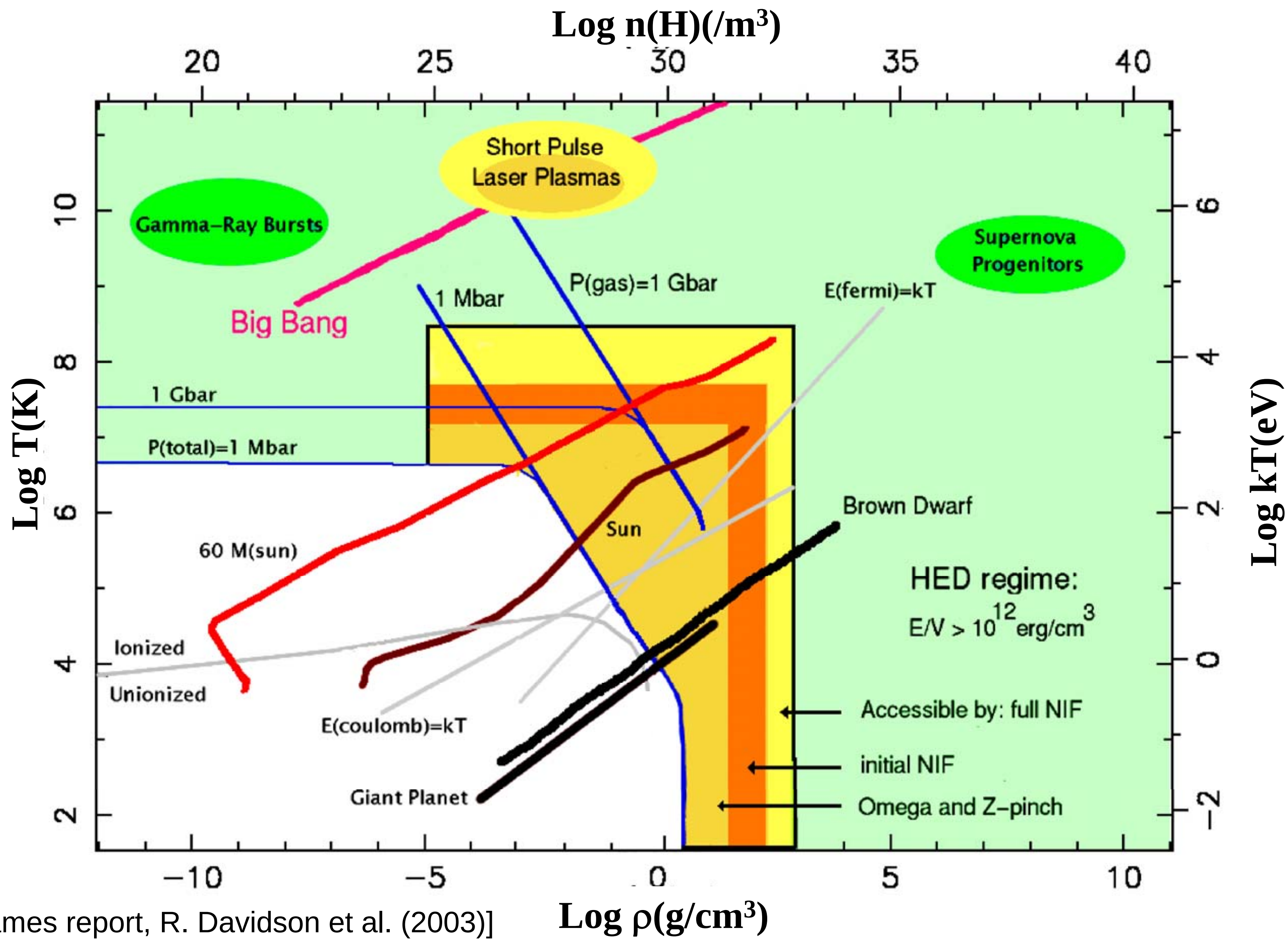
Chan Joshi, PI, UCLA
Warren Mori, UCLA
Christoph Niemann, UCLA NIF Prof.
Bedros Afeyan, Polymath
David Montgomery, LANL
Andrew Schmitt, NRL
LLNL LPI team

Highlights from HEDLA-06

Presentation to the SABER workshop,
Stanford Linear Accelerator Center,
March 15-16, 2006

Bruce A. Remington
HED Program
Lawrence Livermore National Laboratory

High energy density (HED) implies large Energy/Volume, which is the prevailing condition in high energy astrophysics



[NRC X-Games report, R. Davidson et al. (2003)]

Some highlights from HEDLA06

Peter Celliers: EOS of dense He showing reflectivities, 5% ionization thermally generated
Ray Smith: ICE drive on laser to 2 Mbar at Omega along a quasi-isentrope
Jonathan Fortney, Gilles Chabrier: planetary interior structure sensitive to EOS models, experiments
Jim Hawreliak: dynamic diffraction of shocked Fe showing $\alpha-\varepsilon$ transition at 120 kbar in sub-nsec
Barukh Yaakobi: dynamic EXAFS of shocked Fe showing $\alpha-\varepsilon$ transition at 120 kbar in sub-nsec
Marcus Knudson: EOS of water, showing refreeze (Dan Dolan)
Michel Koenig: absolute EOS msmt capability for Al, using Kα radiography

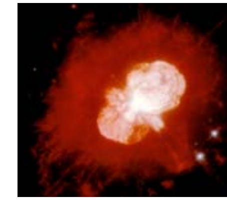
Tomek Plewa: "solved" the core-collapse SN1987A problem?
Carolyn Kuranz: deep nonlinear Omega experiments relevant to SN1987A
Lebedev, You, Kato: magnetic tower jets on Z-pinch, Cal Tech plasma simul. chamber, astrophys.
Marc Pound: synthetic observations of Eagle Nebula models to compare with actual observations
Amy Reighard: ρ/ρ_0 = 50 in radiative shock in Xe gas at Omega laser
Freddy Hansen: radiative shock precursor launches new shock
Gianluca Gregori: XTS to get Te, Ti, ne, Z in HDM and WDM

Steve Rose: photoionized plasmas (of Fe): models that put in all the levels poorly better than models that put in only some of the levels well (leaving out others). Showed Z distribution (Au, Fe) vs exp'ldata, w/, w/o rad. and/or dielectronic recomb/autoioniz
Jim Bailey: exp'l opacity of Fe at conditions approaching those of the solar radiative zone

Scott Wilks: PW experiments to reach high temperatures (200-300 eV) in solid-density Cu targets
Sebastien Le Pape, B = 500 MG using proton deflectometery
Karl Krushelnick: B = 750 MG using high harmonics cutoffl; speculation of reconnection signature
Dmitri Ryutov, John Castor, Gordienko: scaling in collisionless, intense laser experiments regime
Mikhail Medvedev: Weibel instability in GRB models and in intense laser experiments
Richard Klein: proposed NIF astro. exp. to achieve Te = 5 keV in $(1mm)^3$ solid density
Anatoly Spitkovsky: pulsar winds and wind shocks

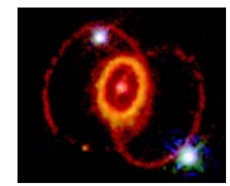
HED laboratory astrophysics allows unique, scaled testing of models of some of the most extreme conditions in the universe

- **Stellar evolution: opacities (eg., Fe) relevant to stellar envelopes; Cepheid variables; sellar evolution models; OPAL opacities**



- **Planetary interiors: EOS of relevant materials (H_2, H-He, H_20, Fe) under relevant conditions; planetary structure - and planetary formation - models sensitive to these EOS data**

- **Core-collapse supernovae: scaled hydrodynamics demonstrated; turbulent hydrodynamics within reach; aspects of the "standard model" being tested**



- **Supernova remnants: scaled tests of shock processing of the ISM; scalable radiative shocks within reach**

- **Protostellar jets: relevant high-M-# hydrodynamic jets; scalable radiative jets, radiative MHD jets; collimation quite robust in strongly cooled jets**

- **Black hole/neutron star accretion disks: scaled photoionized plasmas within reach**

Round-Table Discussion

1) Parameters very similar to FFTB - perhaps shorter
2) No laser thus far - users need to get it done - or at least let organizers know of needs
3) Calibration experiments (PS) - three categories.
4) Showering, poor beam is available first.
5) U Chicago - Airfly Paulo - result
6) Livermore charged particle in 1980s air fluorescence measures Simon Yu -
7) Radio detection ... issues saber can address?
8) Why no radio coherence at Corisika
9) Radio at SABER?
10) Studying Askaryan at different frequencies ()

Cosmic Particle Aceleration

"How do cosmic accelerators work and what are they accelerating?"

- Generally agreed by the LabAstro WG as the best niche of SABER in contributing to Laboratory Astrophysics in the "astro-dynamics" category.

- Most appropriately by way of jet-dynamics studies.

Astro-Jet Dynamics

Weibel instabilities -
GRB people
JNg et al moving forward with this.
Saber - a lot of different kinds of jets e+e- - other models - single component models Differentiate different models.
Differentiatability vs plausability
Prioritize - users have to do this
Techinical issues - different jet types - different location, etc

e-p+ jets

Issues Related to SABER

- Laser and/or e-beam probe
- e-p+ jets?
- Softer beams allow more things
- e164-e167 diagnostics exist.... Are they available for use?
- Are the developed diagnostics going to be generally available tools?