Preparations toward first WDM experiments

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for the

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August 9, 2006

7th VNL-PAC
Introduction

• Progress on WDM-related beam diagnostics and measurements since previous VNL-PAC
  - High resolution electrostatic energy analyzer
  - Gas-based beam diagnostic to measure beam & gas cloud

• Planned WDM experiments

• Target concepts for WDM experiments
  - New WDM diagnostics and target chamber
Ion beams provide an excellent tool to generate homogeneous, volumetric warm density matter.

- Warm dense matter (WDM)
  - $T \sim 0.1$ to 10 eV
  - $\rho \sim 0.01 - 1 \times$ solid density

- Techniques for generating WDM
  - High power lasers
  - Shock waves
  - Pulsed power (e.g. exploding wire)
  - Intense ion beams

- Some advantages of intense ion beams
  - Volumetric heating: uniform physical conditions
  - High rep. rate
  - Any target material

Workshop on Accelerator-Driven Warm Dense Matter Physics, Pleasanton CA, Feb. 22-24, 2006 provided important feedback.

- Purpose: to discuss WDM science and applications, explore opportunities for accelerator-based experimental WDM (drivers, science and applications), diagnostics, computer codes

- Presented and discussed plans for WDM experiments.

- Encouraging input from ~70 scientists from US, Germany, Japan. Disciplines include accelerator physics, laser physics, pulsed power, equation of state, ion stopping, physics of liquid metals, hydrodynamics, target physics and computational physics

A high-resolution electrostatic energy analyzer (EEA) measures beam energy as a function of time.

Applications

- Longitudinal beam energy spread for drift compression experiments
- Charge exchange at source temperature anisotropy instability
- Energy errors in head and tail, beam energy ripples and longitudinal space charge waves
- Independent measure of gas production at the wall using multiple beam ionization states
- WDM: beam energy loss and charge state measurements

Energy distribution in PLIA experiment
Gas cloud from metal target inserted into HCX beam emits light by excitation of gas molecules by beam ions.

Fast RGA measurements indicate the gas cloud is predominantly (>80%) H₂ gas.

Gas cloud expands with constant slope \( \sim 1.5 \text{ mm/µs} \)

Mean gas velocity during beam pulse is \( v_{\text{bar}}/4 \sim 0.5 \text{ mm/µs} \) for H₂ at 20 C.

White light imaged by CCD camera

Position

Location of plate

Time
Comparison with simple 1-D model for expansion of desorbed gas into a vacuum.

- Density distribution for a dense cloud of desorbed gas is given by

\[ n(x, t) = n_0 \left( 1 - \frac{\gamma - 1}{\gamma + 1} \frac{x}{t} \right)^{2/(\gamma - 1)} \]

Where \( x \) is normalized to the sound velocity \( c_s \) at the surface, \( t \) is normalized to pulse length \( \tau \), and \( \gamma = 1.4 \) is the ratio of specific heats. Sibold and Urbassek, Phys. Fluids A 4, 165 (1992).

- Gas cloud expands and cools: contours of constant density are straight lines in both model and experiment.

- At late times \( t > \tau \), the shape of the model distribution depends on gas wall reflection.

Experimental and model (H₂, 20 C) density profile of gas cloud near the wall at 1 µsec intervals during beam pulse.
“Optical Faraday cup” may be a self-healing diagnostic of beam current and profile obtained by imaging gas cloud.

- Optical flux is
  
  \[ I = h\nu A(\pi a_b^2)N^* \]

  where \( N^* \) is the density of the excited state.

  \[
  \frac{dN^*}{dt} = \left( \frac{J}{e} \right) n_g - (A + Bn_g)N^*
  \]

- Emission is independent of gas density if gas cloud density is high enough. [F. M. Bieniosek, et.al., Optical Faraday Cup for Heavy Ion Beams, Proc 2005 Particle Accelerator Conf.]
Near-term experiments provide opportunity to gain experience with diagnostics on WDM targets.

Initial diagnostics will be simple or extensions of existing capabilities
- Electrical resistivity, optical absorption provide information on target temperature and phase transitions
- Stopping power
- Visible light emission
- Laser probes

Compressed NTX beam pulse

![Diagram of ion beam setup with probe laser, current input, voltage taps, sample, and glass substrate. Diagram includes probe laser specular reflection, self emission (out of plane), and probe laser transmission.](image)
WARM DENSE MATTER EXPERIMENTS
PROTOTYPE TARGET CHAMBER

FINAL FOCUS
SOLENOID
TARGET
LOAD LOCK

DIAGNOSTICS
PORTS
TARGET
MANIPULATOR

PLASMA
INJECTION

VACUUM
PUMPING

TARGET

The Heavy Ion Fusion Science Virtual National Laboratory

8/8/2006
HIFS-VNL PROTOTYPE WDM TARGET MODULE
(Size: 5.66 cm wide, 2.29 cm high)

Target Foil  Debris Enclosure  Full Diagnostics Access from Side, Back, and Front

Voltage  Current

Current  Voltage  Electrical Contacts

Testing target manipulator
Limitations and issues with respect to prototype target chamber:

- Only 2 to 3 target modules can be in vacuum using the prototype chamber
- Load lock system required to load additional target modules

Issues to explore with prototype chamber:
- Electrical circuit and connections using target module
- Motion issues with target module. How to pick up target module from target rack and how to position it.
- Refine module design
- Interface with beam and target diagnostics
- Influence of pulsed magnet and plasma source
## What WDM experiments can we do in the next 5 years?

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target temp.</th>
<th>NDCX-1 or HCX</th>
<th>NDCX-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transient darkening emission and absorption experiment</td>
<td>Low (0-0.4 eV)</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>Thin target dE/dx, energy distribution, charge state, and scattering in a heated target</td>
<td>Low</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>Measure target temperature using a beam compressed both radially and longitudinally</td>
<td>Low</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>Positive - negative halogen ion plasma experiment</td>
<td>&gt;0.4 eV</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>Two-phase liquid-vapor metal experiments</td>
<td>0.5-1.0</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>Critical point measurements</td>
<td>&gt;1.0</td>
<td>?</td>
<td>v</td>
</tr>
</tbody>
</table>
1. Check WDM atomic models using transient darkening of glass at low temperature to use in future work.

In quartz, electrons excited from 2s, 2p (ground state) to 3s leave holes in ground state to absorb photons in both cases. Measure decay rate of excited electrons by studying decay of absorption and emission rates.

Significance: interpret WDM data, possible temperature measurement, fast switching of optical properties
Simple model of transient darkening reproduces experimental observation.

- Optical attenuation is measured quantity: 
  \[ f = \exp \left( - \sum_j \int N_j \sigma_j dx \right) \]

- Equation for concentration of 2s-2p holes \( N_+ \) and 3s-3p electrons \( N_- \) is 
  \[ \frac{dN_{\pm}}{dt} = S(t) - \alpha N_+ N_- - \beta_{\pm} N_{\pm} \]

- Source rate \( S(t) \) is proportional to the beam flux; loss rate coefficients \( \alpha, \beta \) depend on temperature

- Model fits Lyons fiber attenuation data for certain parameters (e.g. \( \sigma, \alpha \)) not uniquely determined

- Model results can be used to design/interpret further experiments; e.g. results should depend on probe wavelength.
Initial measurements on HCX show adequate optical emission to proceed with transient darkening experiment.

Optical emission: image and time response

Liquid nitrogen cooled target for emission and absorption experiments
2-3. We will develop diagnostic techniques in parallel with improving beam capability.

- Thin foil target interaction experiments can be done using NDCX beam compressed longitudinally and transversely.
  - Collect transmitted beam downstream of target in a Faraday cup
  - Use energy analyzer, time-of-flight to measure energy distribution
  - Use scintillator to measure beam scattering in foil

Significance: ion scattering near Bragg peak of theoretical interest at cold and warm temperatures.
C. Deutsch, G. Maynard. Low velocity ion stopping of relevance to the US beam-target program, Hirschegg Workshop, Jan. 2006
M. Murillo, et.al., Determining dE/dx in warm dense matter using nonequilibrium molecular dynamics, WDM Workshop, Pleasanton, Feb. 2006

- Example of diagnostic development: several ways to measure temperature
  - Hydrodynamic release: x-rays, lasers, optical imaging
  - Electrical conductivity
  - Optical emission: fast optical pyrometer
List of diagnostic equipment on order.

- Fast (2.5 GHz) oscilloscopes (at present we are limited to 500 MHz BW – too slow for nsec pulses)
- Fiber Doppler VISAR system
- Hamamatsu streak camera system
- Other (light collection optics, target manipulator, target chamber, …)
- We have one Princeton Instruments PI-MAX camera with 1-ns time resolution – in future we may need another.
4. As target temperatures reach $T=0.4$ eV or higher, new WDM regimes become accessible.

- Positive-negative ion halogen experiment ($T > 0.4$ eV) [see L.R. Grisham, et.al., HIF 2006 Symposium]
  - This experiment explores the expected unique properties of a dense electron-free positive-negative ion halogen plasma
  - Diagnostics include beam energy loss, target temperature, etc.

  **Significance:** novel state of matter, unusual conductivity properties

- Target temperatures surpassing 1 eV open up further WDM regimes
  - Liquid-vapor metal experiments
  - Critical point measurements
We plan joint experiment in FY 07 at GSI (Darmstadt, Germany) to study heating of porous targets.

• **Motivation:**
  - Porous media are of great interest to HEDP/WDM and have important practical applications.
  - Short range of low-energy beams forces short pulse (1 ns) and fast diagnostics - low density porous targets reduce need for very fast pulse by increasing hydro expansion time of target.

• **Modeling support effort connects experimental measurements to physics of porous target - e.g. HYDRA (LLNL); other codes under development.**
Proposal for experiment S320 approved by GSI PPAC advisory committee.

- Replace target foil with porous material.
- Study effect of pore size on target behavior using existing diagnostics.
- Sample targets: LLNL (Au, 60 nm), Mitsubishi (Cu, 50 micron).
Conclusion

• Ion beams provide an excellent tool to generate homogeneous, volumetric WDM.

• Development plan uses existing accelerators and pulse compression technique developed in HIFS-VNL. We are designing a target chamber, and acquiring target diagnostics.

• Initial experiments have been specified; path forward identified; first transient darkening modeling and measurements underway.