Preparations toward first WDM experiments

F.M. Bieniosek

Lawrence Berkeley National Laboratory

for the

Heavy Ion Fusion Science Virtual National Laboratory (HIFS-VNL)

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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 ~ 0.1 to 10 eV
  - ρ ~ 0.01 -1 * 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

Al target

Short pulse ion beam

Example: Ne+

Enter foil

Exit foil
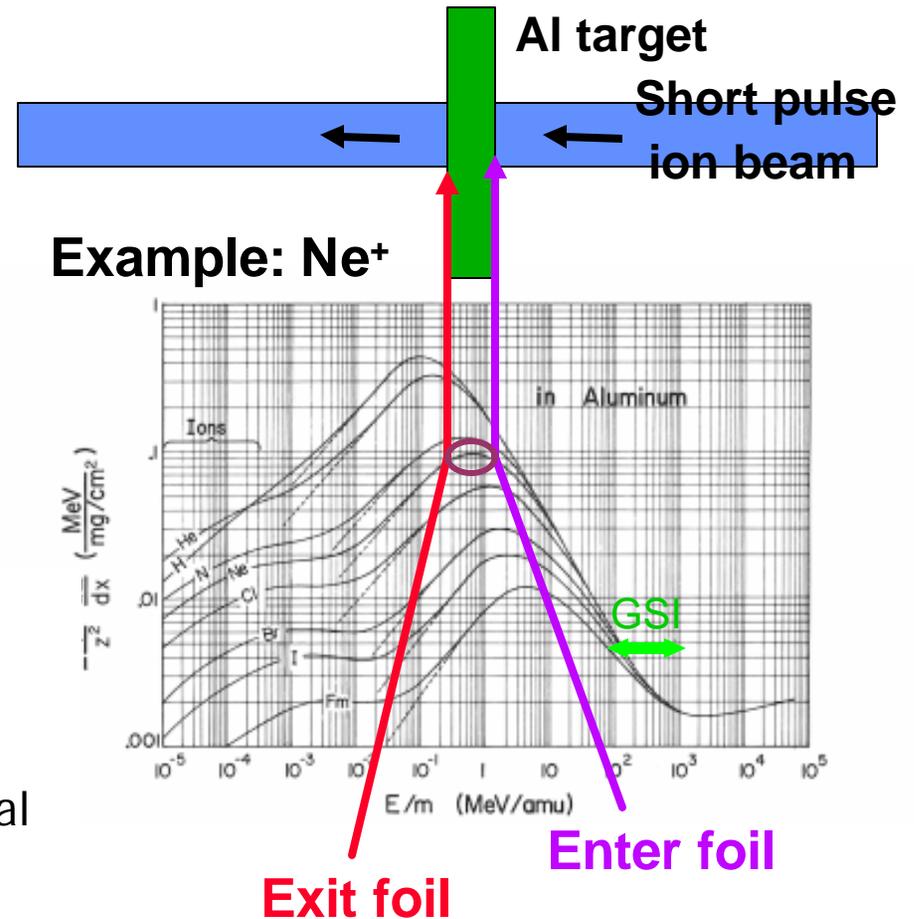
L. Grisham, Phys. Plasmas 11 (2004) 5727.

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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

- Workshop proceedings at http://ilsa.llnl.gov/wdm/.

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

detector

Sector field

Multipole corrector

Entrance slit

← beam

Aperture and fringe field corrector

Energy distribution in PLIA experiment
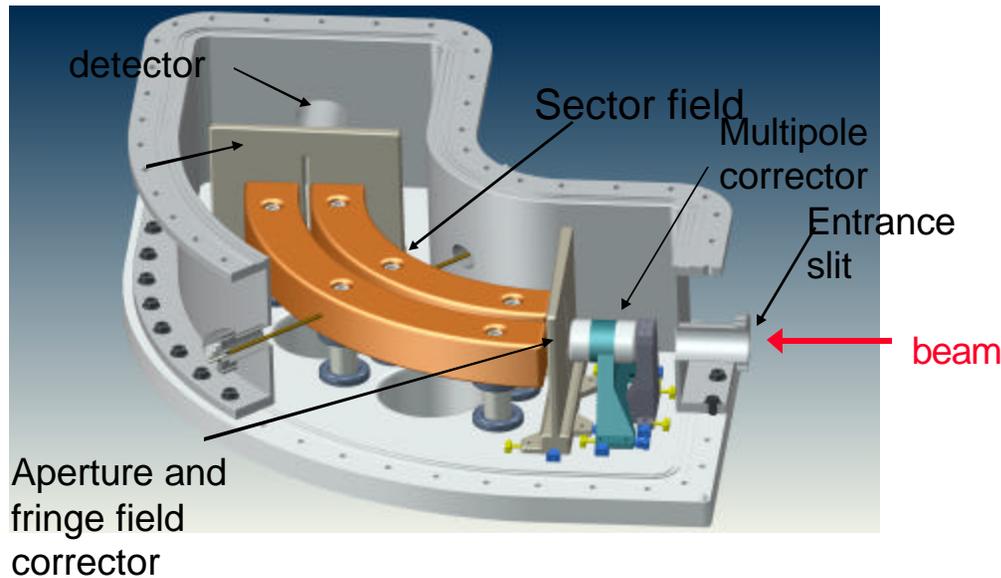
Applications

-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**

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%) H_2 gas.

Gas cloud expands with constant slope ~ 1.5 mm/ μs

Mean gas velocity during beam pulse is

vbar/4 ~ 0.5 mm/μs for H_2 at 20 C.

Position

Location of plate →

White light imaged by CCD camera

<-beam pulse->

Time →

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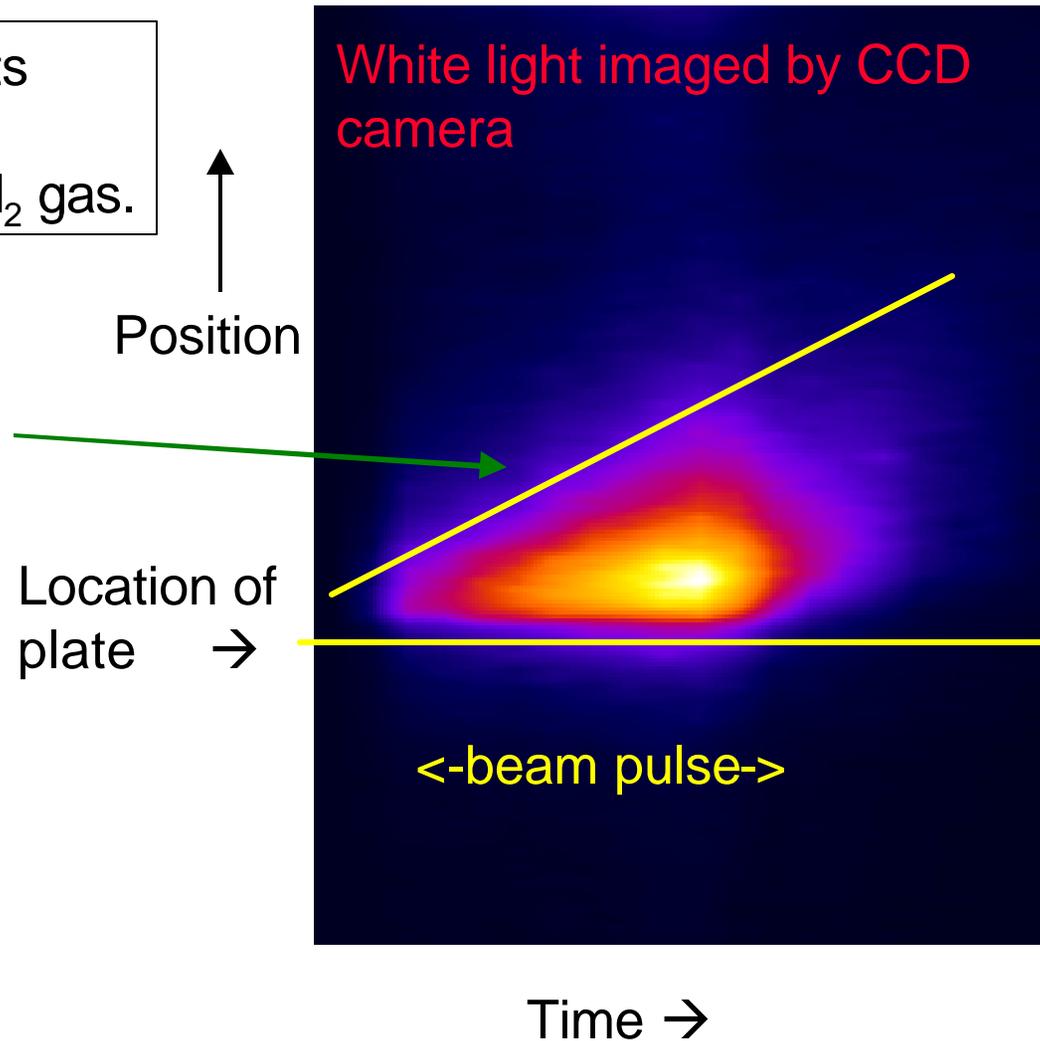
Comparison with simple 1-D model for expansion of desorbed gas into a vacuum.

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

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

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

Experimental and model (H_2, 20 C) density profile of gas cloud near the wall at 1 μsec intervals during beam pulse.

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

- **At late times t > t, the shape of the model distribution depends on gas wall reflection.**

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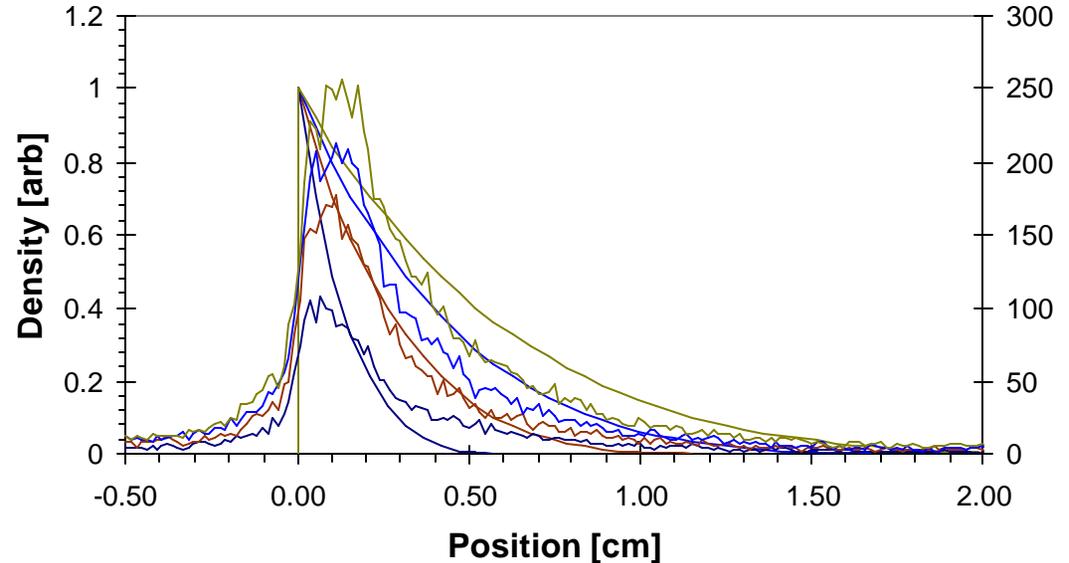
"Optical Faraday cup" may be a self-healing diagnostic of beam current and profile obtained by imaging gas cloud.

- **Optical flux is**

$$I = h\mathbf{n}A(\mathbf{p}a_b^2)N^*$$

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.]**


3 cm

scintillator

3 cm

hole plate

PPPL 8

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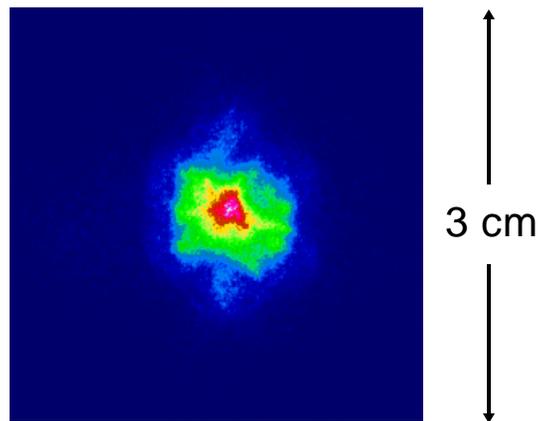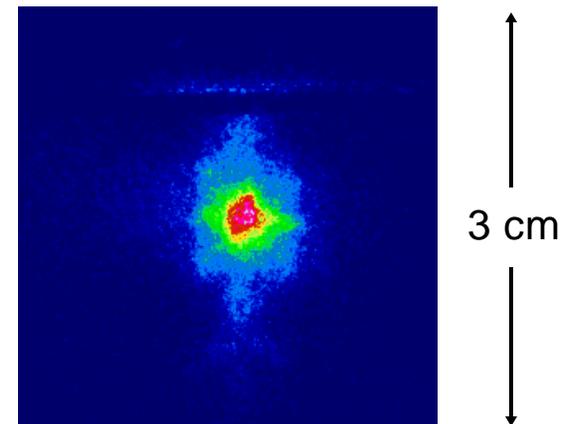
Near-term experiments provide opportunity to gain experience with diagnostics on WDM targets.

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
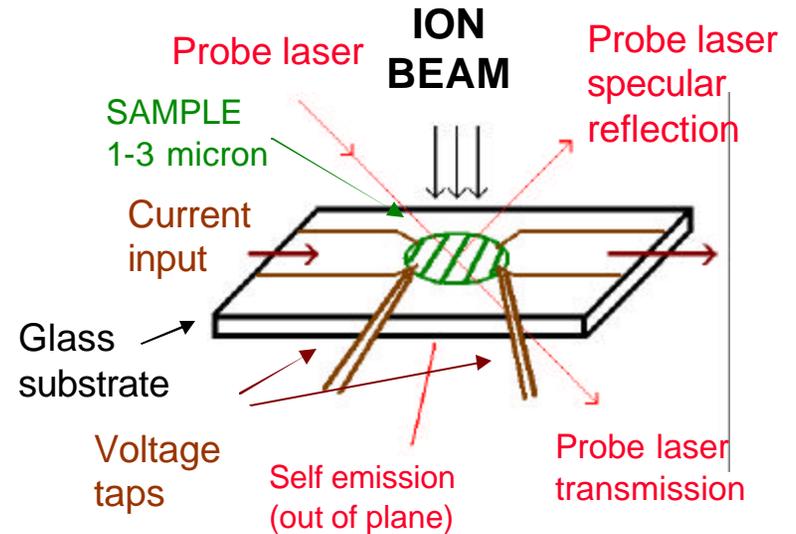
Compressed NTX beam pulse ➡
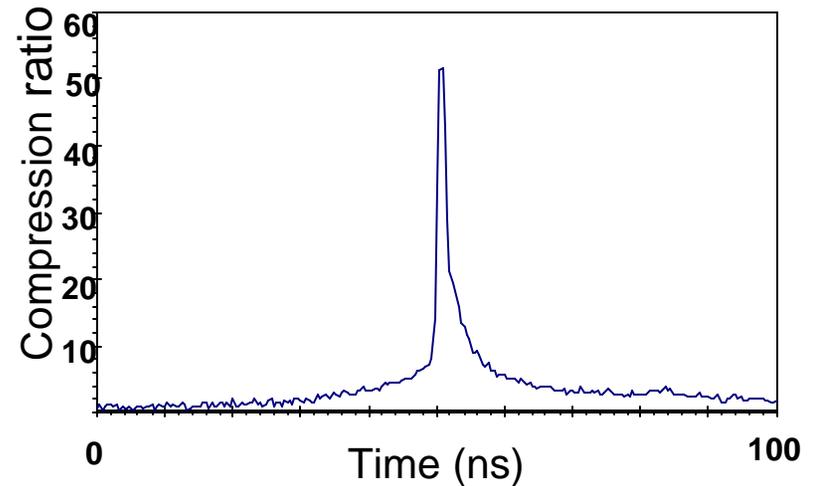
WARM DENSE MATTER EXPERIMENTS
PROTOTYPE TARGET CHAMBER

DIAGNOSTICS PORTS

TARGET LOAD LOCK

TARGET MANIPULATOR

FINAL FOCUS SOLENOID

PLASMA INJECTION

VACUUM PUMPING
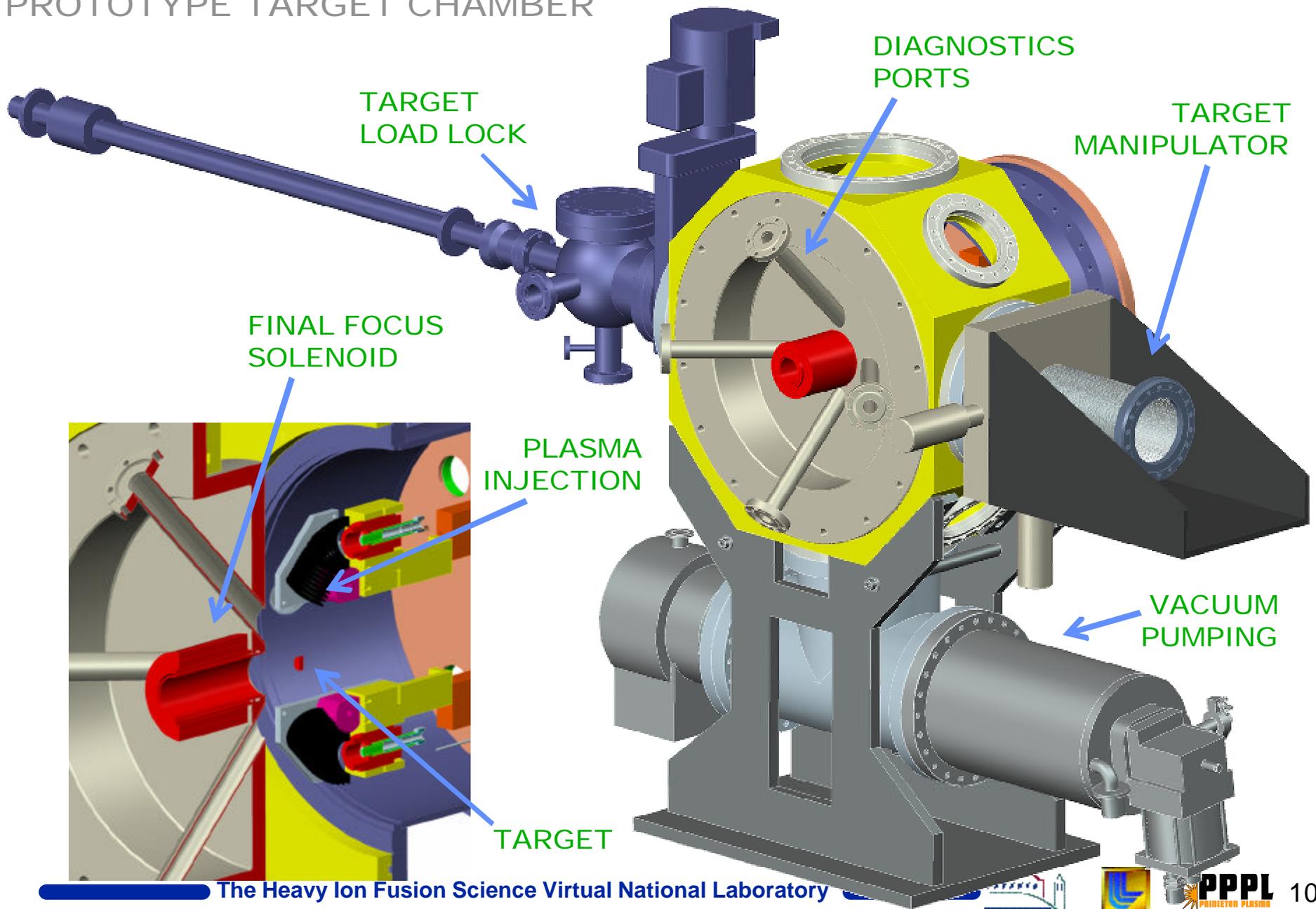
TARGET

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
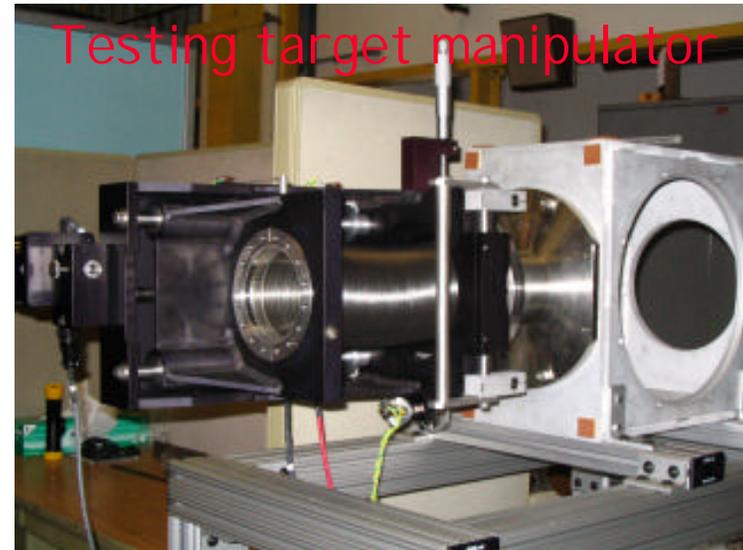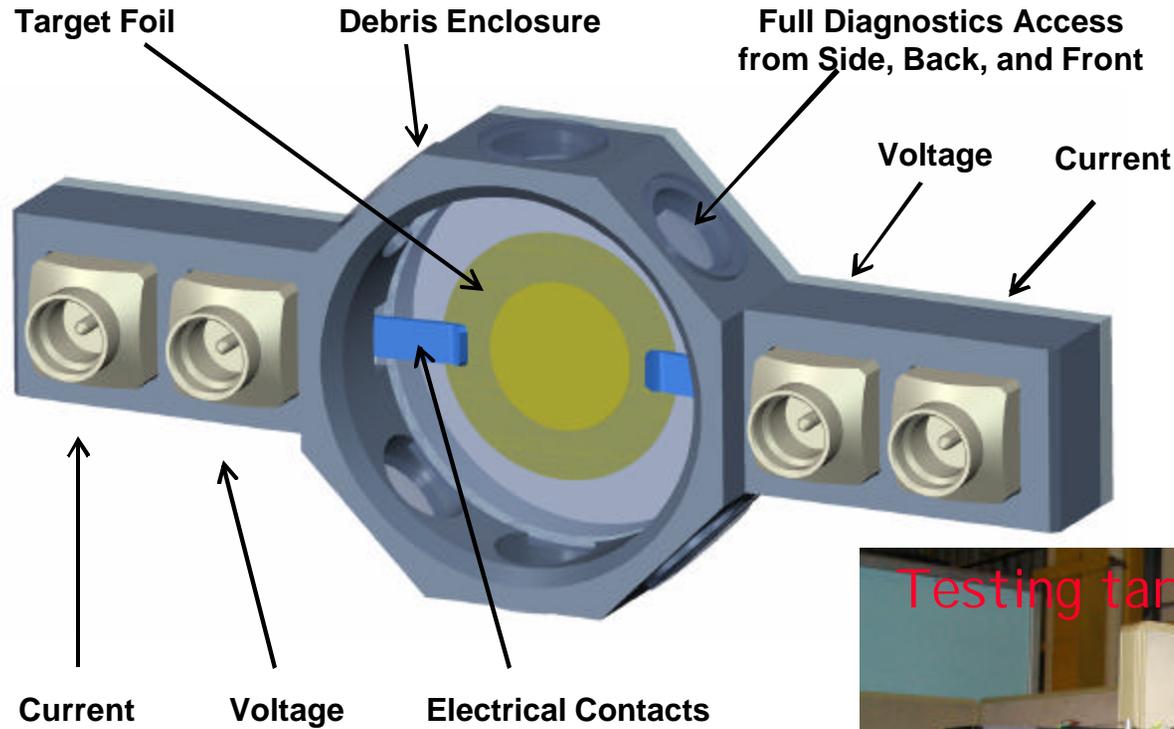
Limitations and issues with respect to prototype target chamber:

- **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?

	Target temp.	NDCX–1 or HCX	NDCX–2
Transient darkening emission and absorption experiment to investigate previous observations in the WDM regime	**Low (0-0.4 eV)**	v	
Thin target dE/dx, energy distribution, charge state, and scattering in a heated target	**Low**	v	
Measure target temperature using a beam compressed both radially and longitudinally.	**Low**	v	
Positive - negative halogen ion plasma experiment	**>0.4 eV**	v	v
Two-phase liquid-vapor metal experiments	**0.5-1.0**	v	v
Critical point measurements	**>1.0**	?	v

time

1. Check WDM atomic models using transient darkening of glass at low temperature to use in future work.

P. Lyons, SPIE 541 (1985)

FIBER ITT T303
PCS SUPRASIL
λ = 600 nm
D = 250K Rad

e-beam excitation

D.F. Price, et.al., PRL 75, 252 (1995)

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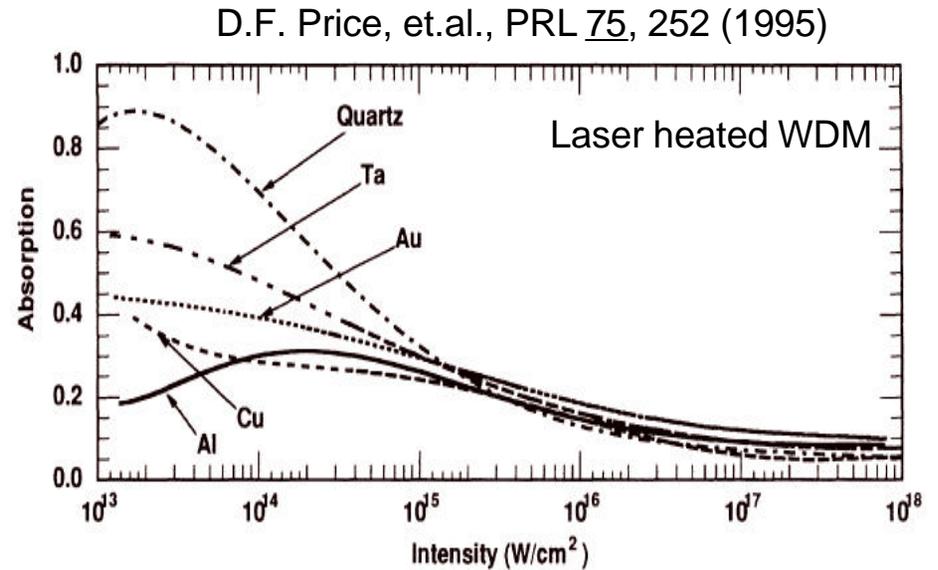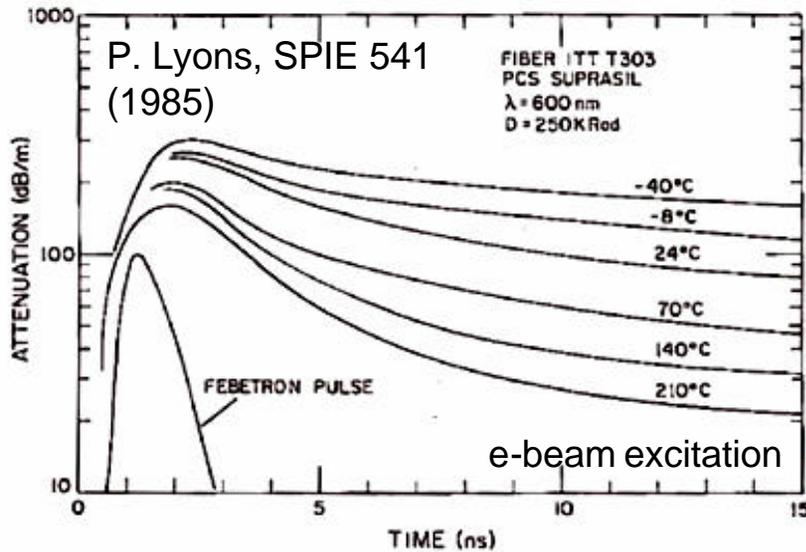
In quartz, electrons excited from 2s, 2p (ground state) to 3s leave holes in ground state to absorb photons in both cases. Measure decay rate of excited electrons by studying decay of absorption and emission rates.

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:** $f = \exp\left(-\sum_j \int N_j s_j \, dx\right)$

- **Equation for concentration of 2s–2p holes N$_+$ and 3s–3p electrons N$_-$ is**

$$\frac{dN_\pm}{dt} = S(t) - aN_+N_- - b_\pm N_\pm$$

- **Source rate S(t) is proportional to the beam flux; loss rate coefficients a, b depend on temperature**

- **Model fits Lyons fiber attenuation data for certain parameters (e.g. s, a) not uniquely determined**

- **Model results can be used to design/interpret further experiments; e.g. results should depend on probe wavelength.**

8/8/2006

Initial measurements on HCX show adequate optical emission to proceed with transient darkening experiment.

quartz

diamond

060511190

1MeV beam on diamond and quartz

from quartz
From diamond

at the tail

IntDens(au)

Delay (ns)
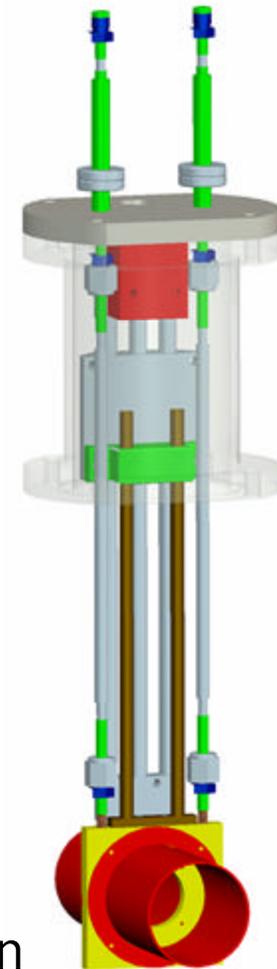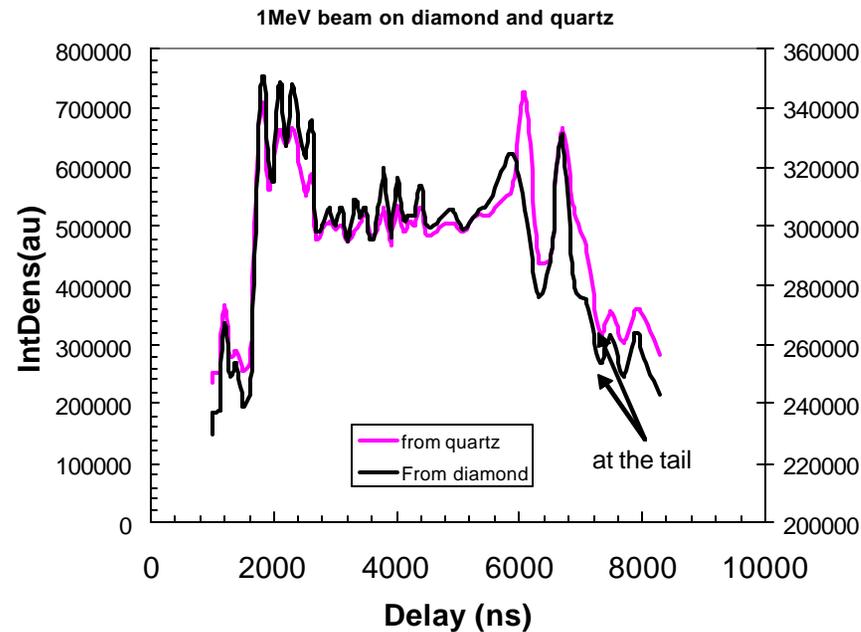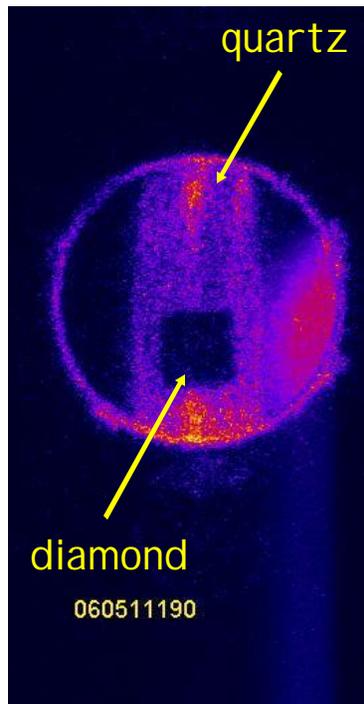
Optical emission: image and time response

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.
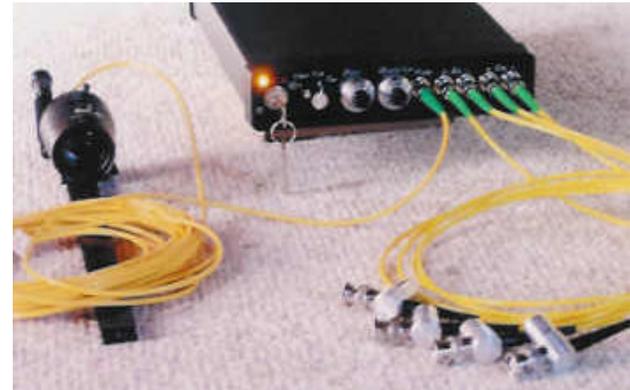
4. As target temperatures reach T=0.4 eV or higher, new WDM regimes become accessible.

- **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.

Target design / **Target Implementation**

Brass container

Sapphire

Target foil

Tungsten diaphragm
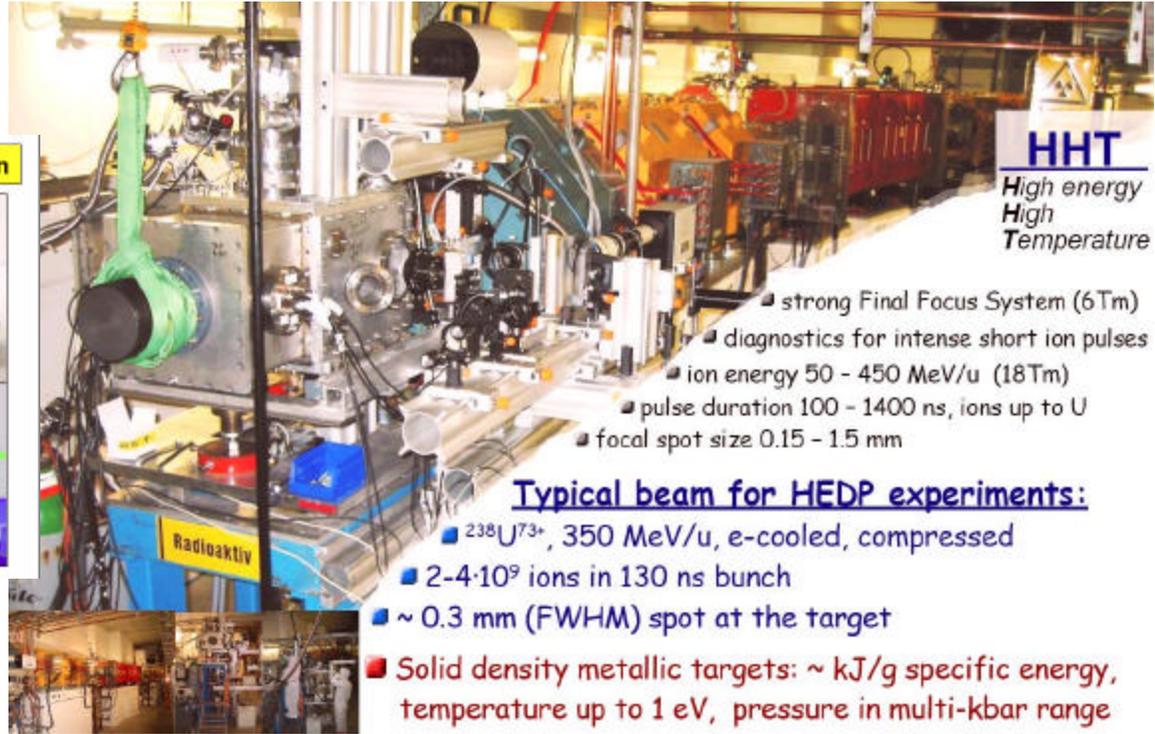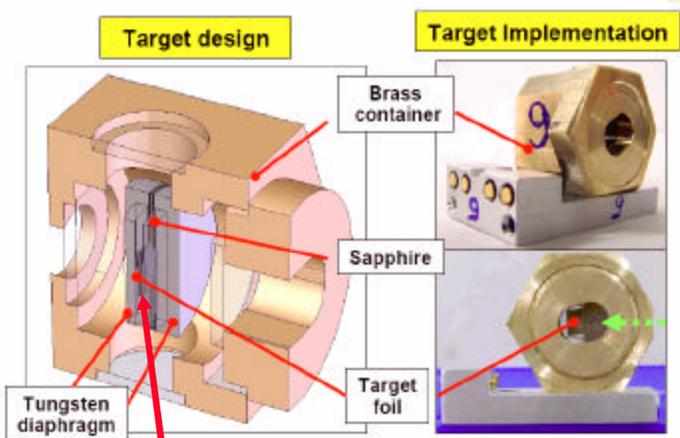
HHT
High energy High Temperature

- strong Final Focus System (6Tm)
- diagnostics for intense short ion pulses
- ion energy 50 – 450 MeV/u (18Tm)
- pulse duration 100 – 1400 ns, ions up to U
- focal spot size 0.15 – 1.5 mm

Typical beam for HEDP experiments:
- $^{238}U^{73+}$, 350 MeV/u, e-cooled, compressed
- $2-4 \cdot 10^9$ ions in 130 ns bunch
- ~ 0.3 mm (FWHM) spot at the target
- Solid density metallic targets: ~ kJ/g specific energy, temperature up to 1 eV, pressure in multi-kbar range
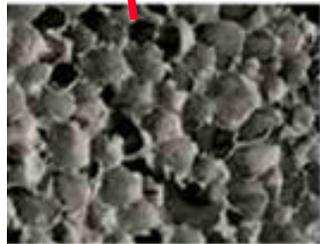
- Replace target foil with porous material.
- Study effect of pore size on target behavior using existing diagnostics.
- Sample targets: LLNL (Au, 60 nm), Mitsubishi (Cu, 50 micron).

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.