Beam-Driven Target Experiments

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for the HIFS-VNL

Workshop on Accelerator Driven Warm Dense Matter Physics

Four Points Sheraton

Pleasanton, CA

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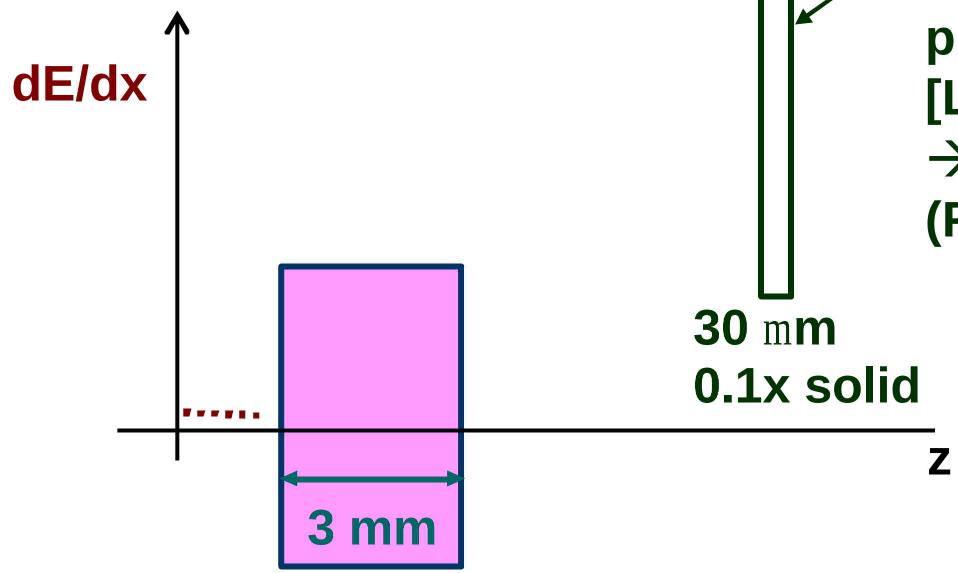
Overview

- Existing accelerator facilities and experimental technique for achieving WDM conditions in the laboratory
- Plans for WDM and WDM-related experiments
- Diagnostic development and target chamber

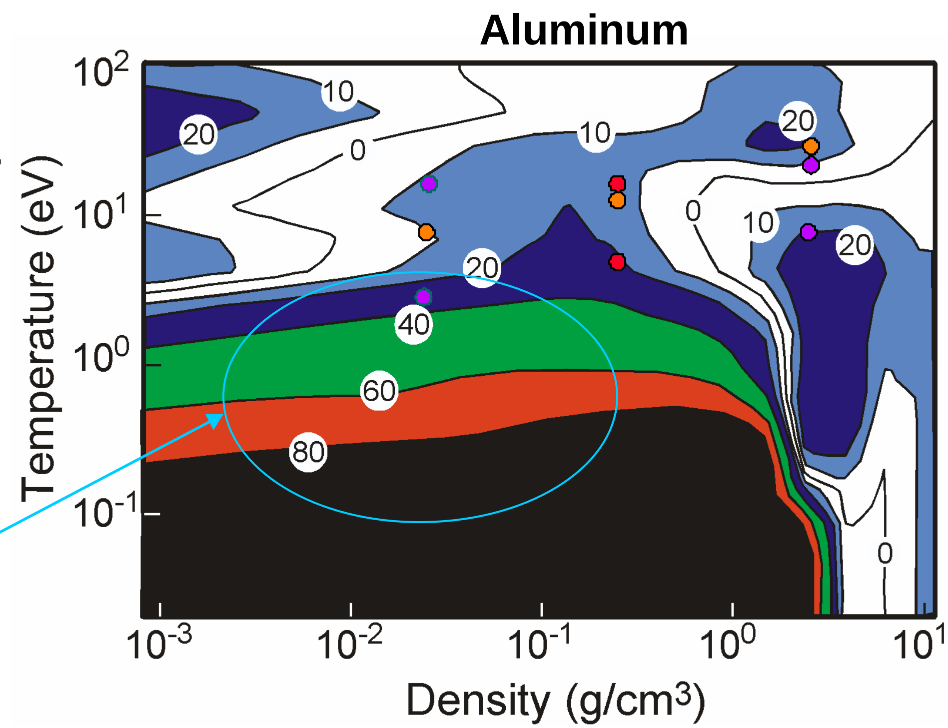
We pursue neutralized compression of short pulses for warm dense matter experiments at the peak of dE/dx.

Ion energy loss rate in targets



Maximum dE/dx *and* uniform heating at this peak require short (~ 1 ns) pulses to minimize hydro motion.
[L. R. Grisham, Physics of Plas.,2004].
→Te > 10 eV @ 20J, 20 MeV
(Future US accelerator for HEDP)

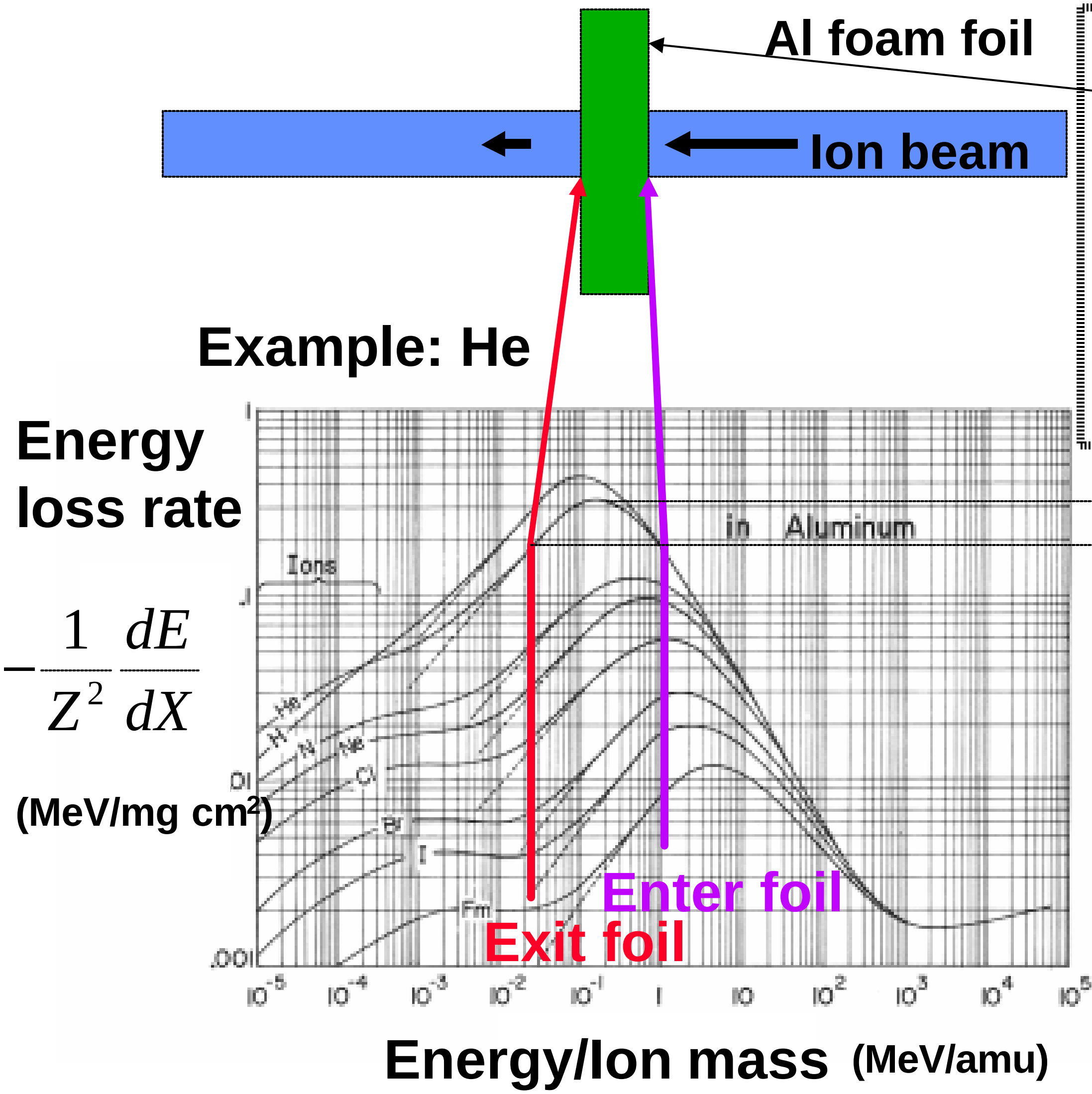
GSI: 40-100 GeV heavy Ions→
thick targets→ Te ~ 1 eV per kJ

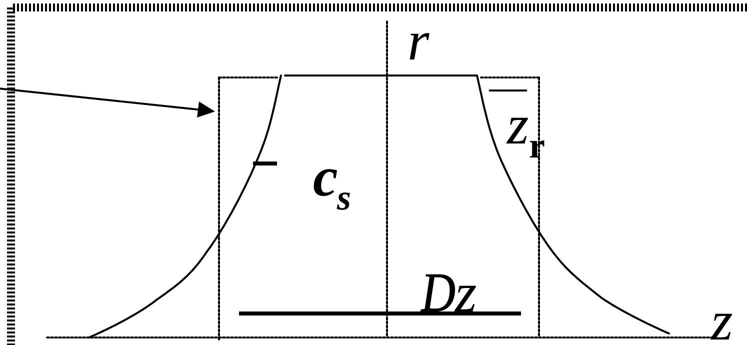


Dense, strongly coupled plasmas @ 10^{-2} to 10^{-1} *x* solid density are potentially interesting areas to test EOS models (Numbers are % disagreement in EOS models where there is little or no data)

(Courtesy of Richard Lee, LLNL)

Our strategy for WDM studies is to maximize uniformity and the efficient use of beam energy by placing center of foil at Bragg peak





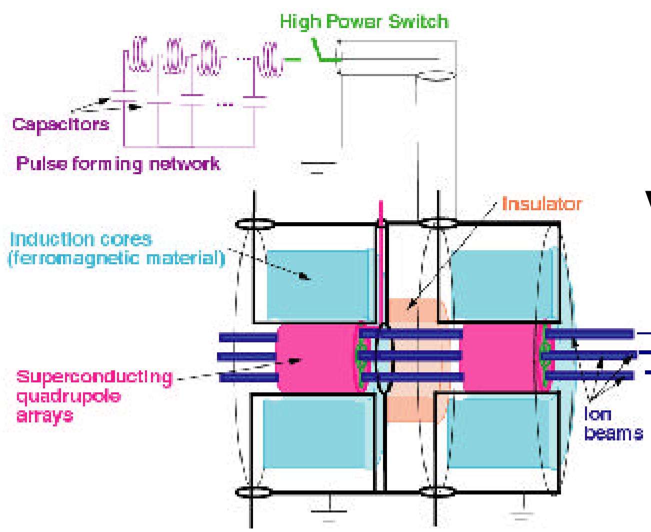
Rarefaction wave propagates inward at c_s (with c_s increasing with time)

DdE/dX µ DT

- Ion energy and mass chosen so that "Bragg peak" falls within foil maximizing uniformity
- Pulse duration must be short enough so that rarefaction wave does not reach center of foil during pulse

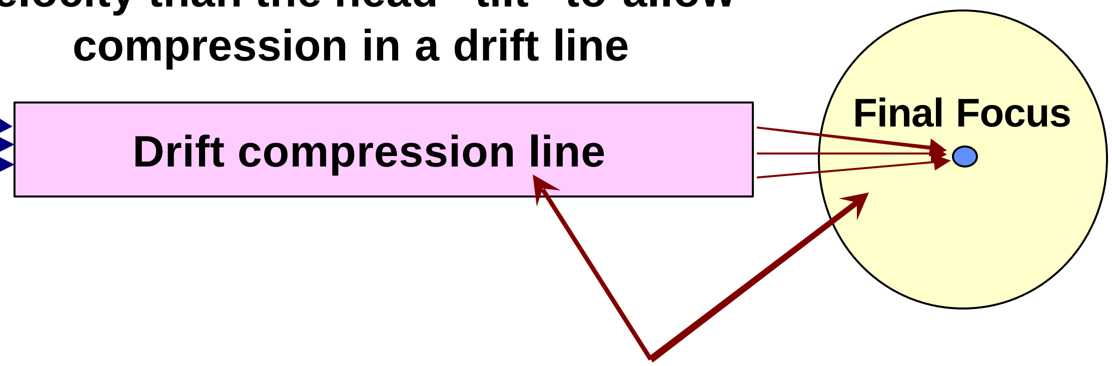
Drift compression of low cost, low energy ion beams (0.1 to 1 MeV/u) to the short pulses required to drive warm dense matter targets near the peak in dE/dx requires plasma neutralization of space charge.

Induction acceleration/ velocity "tilt" @ t_{pulse} ~100 to 200 ns



Bunch tail has a few percent higher velocity than the head "tilt" to allow compression in a drift line

Near term Warm Dense Matter targets require ~ 1-2 ns pulses



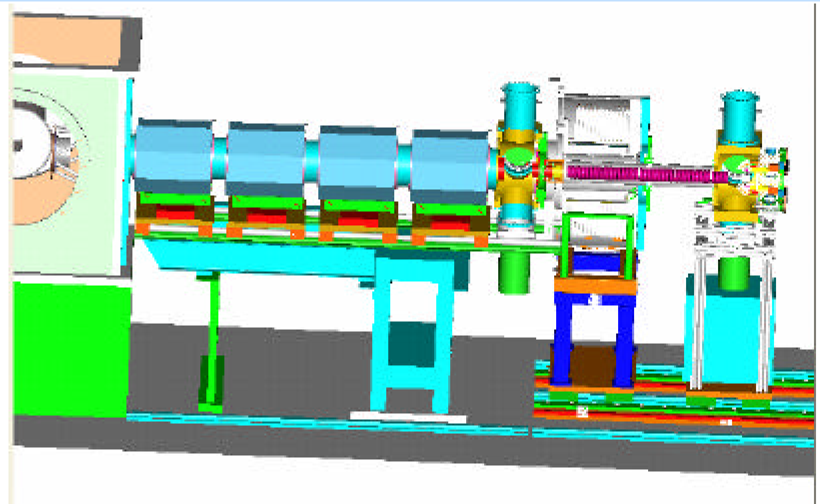
High beam perveances > 10^{-3} <u>requires</u> plasma neutralization of space charge during drift compression <u>and</u> final focus to target.

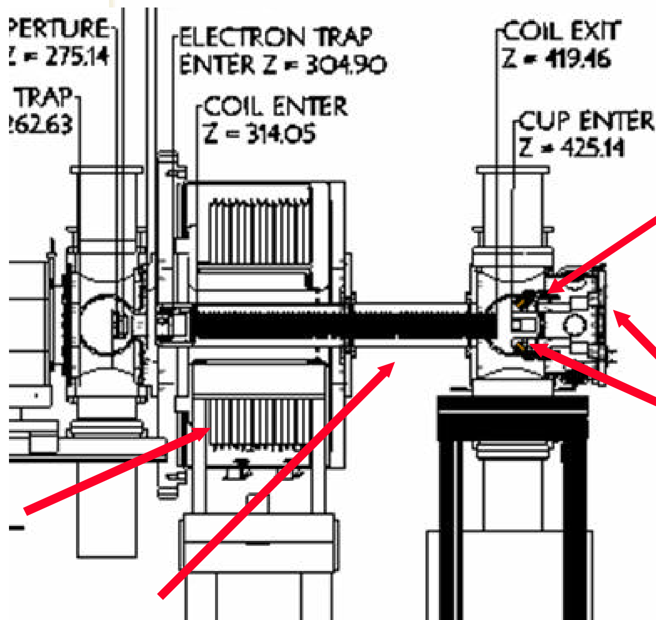
→Partial neutralization by electron cloud ingress was found to be unavoidable anyway!

By focusing the NDCX-1 beam in both longitudinal and transverse dimensions, significant localized heating on nsec time scale can be achieved.

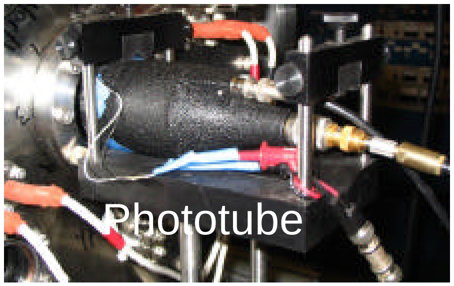
- **Beam has been focused to about 2 ns longitudinally and about 1 mm transversely. When these can be achieved simultaneously, experiments with localized heating become possible.**

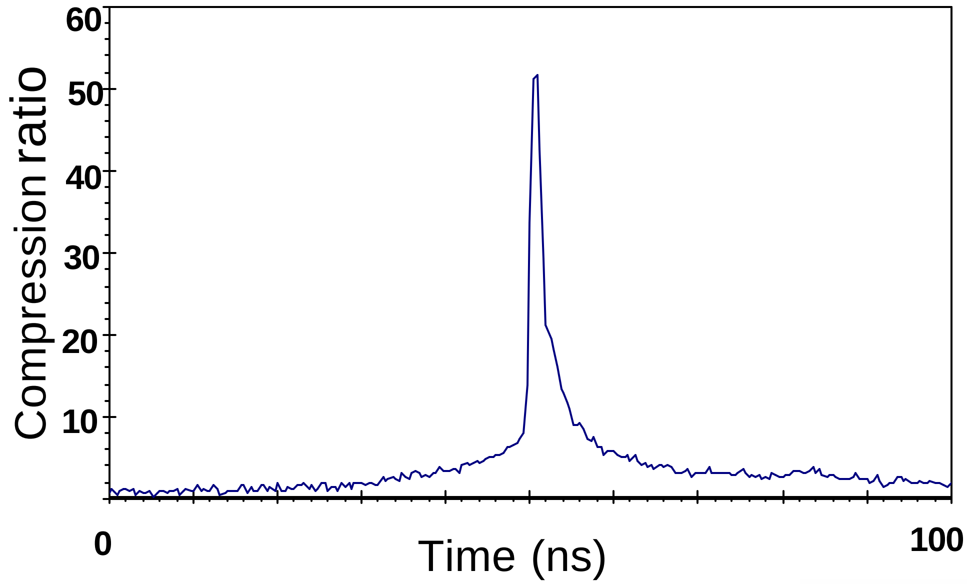
- **Layout of the experimental configuration at the target and diagnostic area. Existing diagnostics: fast Faraday cup, optical (scintillator and hole plate).**

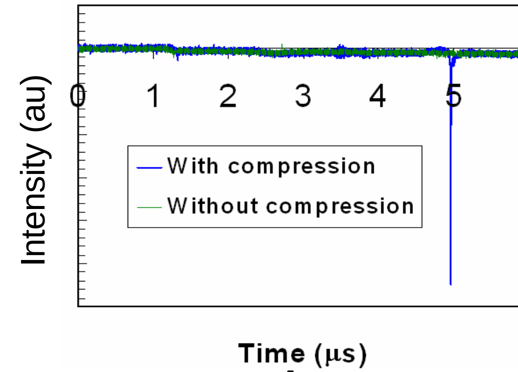




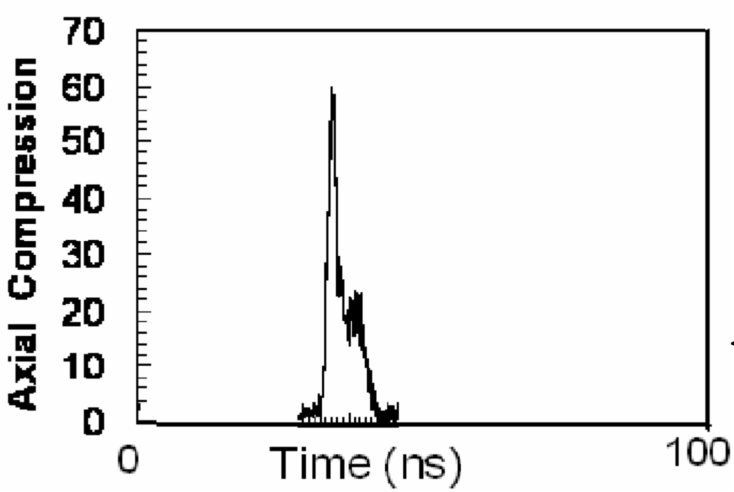
50 Fold Beam Compression achieved in neutralized drift compression experiment





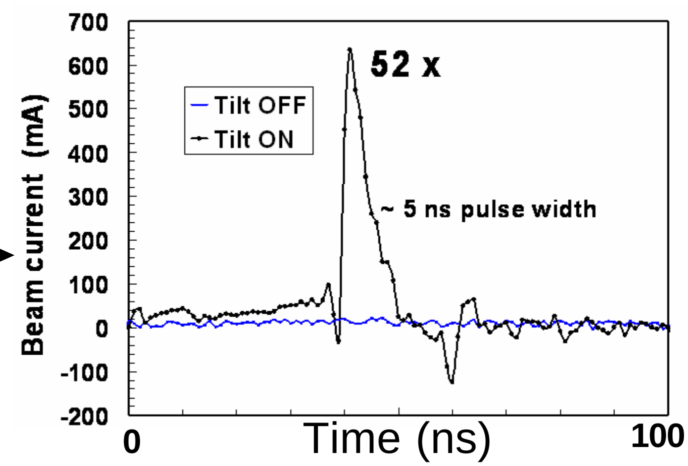


Optical data

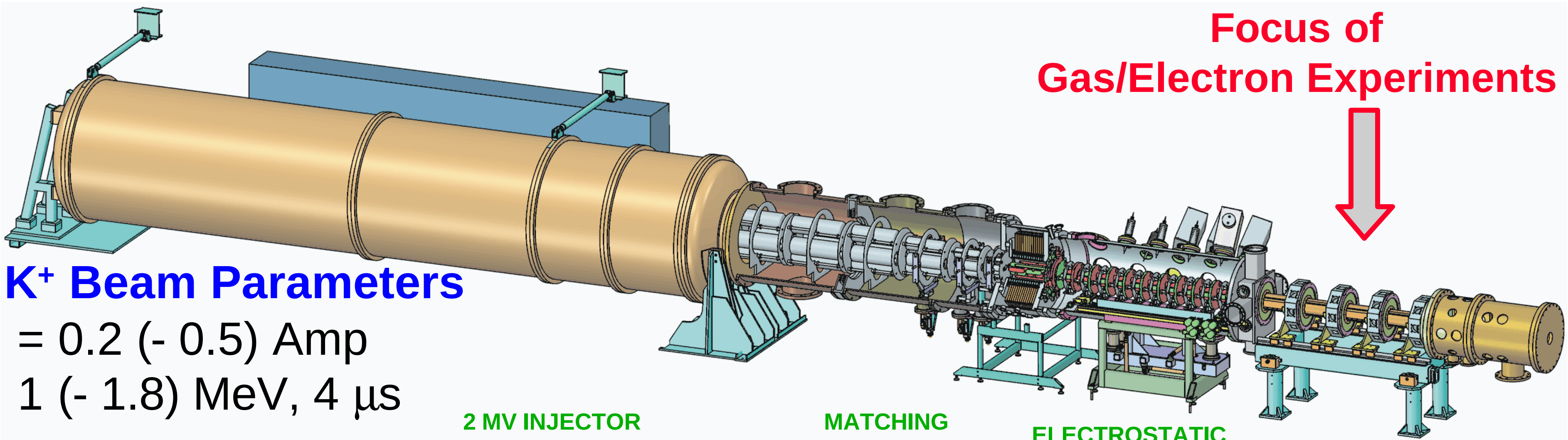


Corroborating data from Faraday cup

LSP simulation



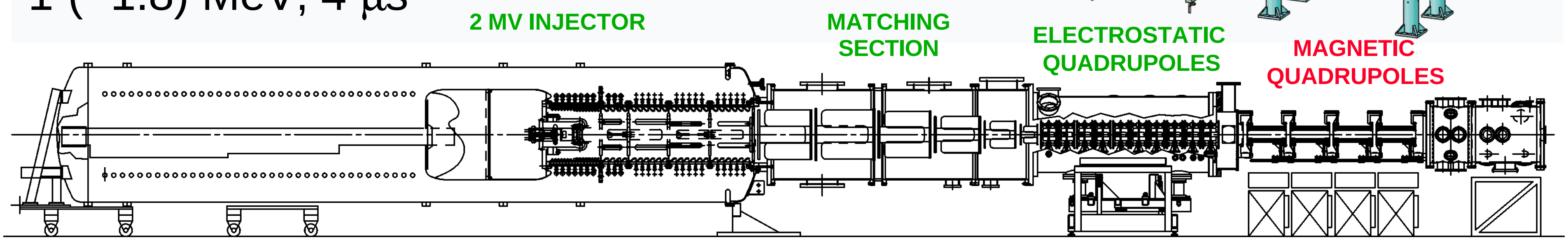
The High Current Experiment (HCX) is exploring beam transport limits and gas-electron effects.



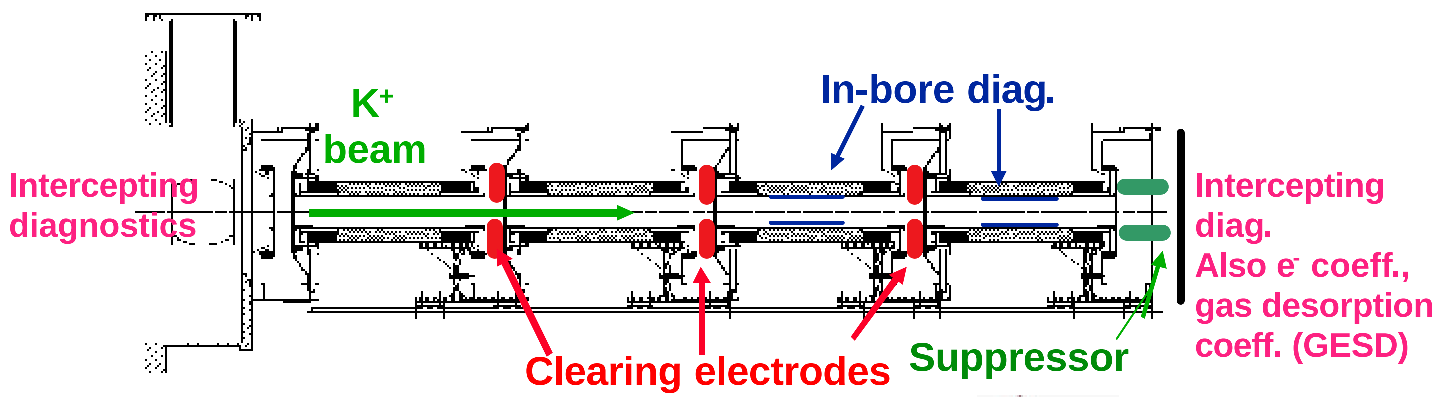
K^+ Beam Parameters

I = 0.2 (- 0.5) Amp

1 (- 1.8) MeV, 4 μs



4 magnetic quadrupoles, many diagnostics



Achievable target temperature with existing accelerators: NDCX beam compressed longitudinally and radially, and HCX as is.

E_i=400 kV,   dE/dX ~ 4.37 MeV-cm^2/mg

I = 20 mA x 60   (factor of 4 less than optimum)

τ= 2 ns

r_{spot} = 1 mm   (factor of 2 less than optimum)

==> I E_i t / p r_{spot}^2 = 0.96 mJ/0.031cm^2 = 0.031 J/cm^2

kT=0.19 eV (Edep/1 J/cm2) (1 MeV/Ebeam)(dE/dX/2 MeVcm2/mg) (Atarg/27)
=0.19 x (0.031) (1/0.4) (4.37/2) (1)
= 0.032 eV = ~350 K increase in T (factor of 2.4 to 3.6 higher at spot center)
-> ~ 0.1 eV (at spot center) (Alternatively, at 4 μs 33 x 0.032--> < 1 eV)

(Alternatively: HCX, E_i= 1.6 MeV, I = 0.364 A, t = 4 ms, dE/dX= 6.97 MeV-cm^2/mg, r_{spot} = 10 mm, E_iTt/pr_{spot}^2 =2.3 J/3.1cm$^{2=}$0.74J/cm^2)

kT=0.19 eV (Edep/1 J/cm2) (1 MeV/Ebeam)(dE/dX/2 MeVcm2/mg) (Atarg/27)
=0.19 x (0.74) (1/1.6) (6.97/2) (1)
< 0.31 eV (expansion over microsecond timescale will limt T to lower value)

Note that for Al: Melting point= 933 K=0.08 eV; Boiling point=2793 K = 0.24 eV

Can we reach temperatures ~0.4 eV range in the near term?

Spreadsheet-based estimate (J Barnard) for K+ beam compressed to 2-ns pulse length:

NDCX: For a 0.5 mm final radius (using a 5 T final focusing solenoid), and 4 x existing current of NDCX, target temps reach ~0.3 eV for compression ratio = 50.

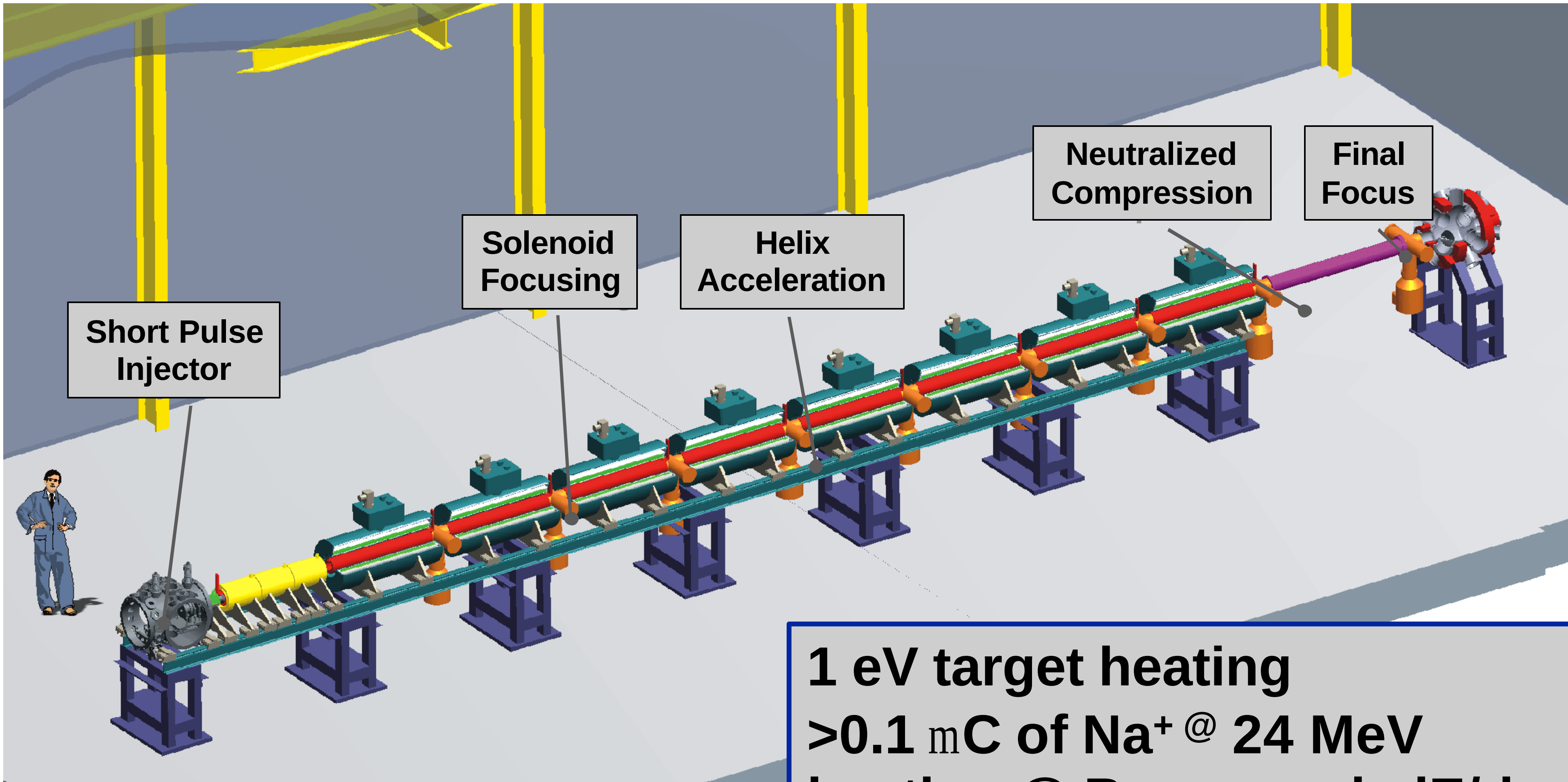
HCX: For a 1. 1 mm final radius (using 5 T final focusing solenoid) compression ratio of 25, target temp of 0.5 eV can be achieved for compression ratio = 25.

Note: EVEN if T reached, large T and r gradients will exist (but still much smaller than for equivalent laser targets).

Our goal is to develop a user facility for ion beam driven HEDP, with several important characteristics.

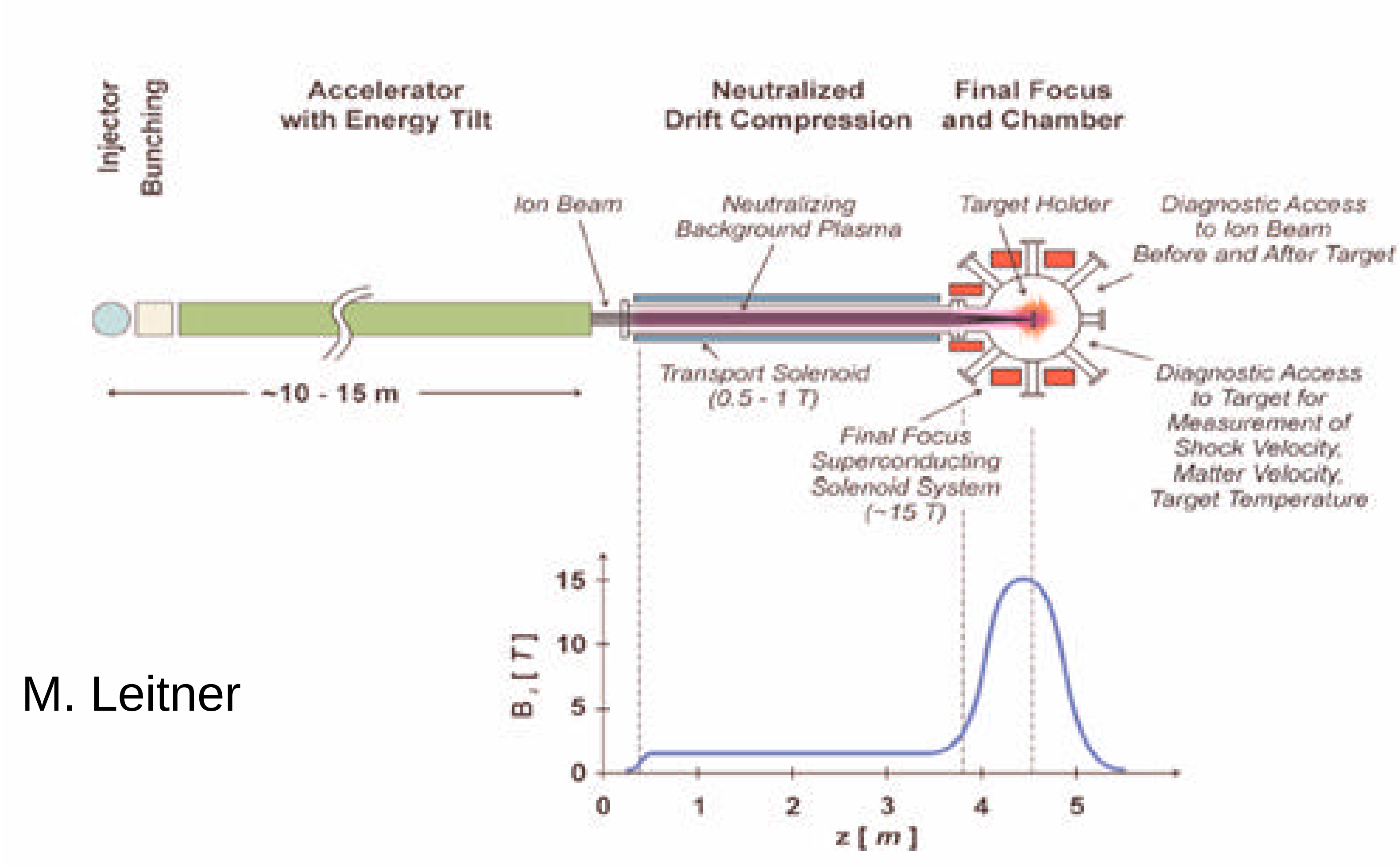
- **Precise control and uniformity of energy deposition**
- **Large sample sizes compared to diagnostic resolution**
- **Pulse length limited by target depth: short beam pulses and low mass density preferred**
- **A benign environment for diagnostics**
- **Potential for high shot rates and multiple beamlines/target chambers**
- **Low accelerator cost**

NDCX-II: a short pulse high gradient accelerator for ion-driven HEDP and IFE is being evaluated



1 eV target heating
>0.1 mC of Na^{+} @ 24 MeV
heating @ Bragg peak dE/dx

A strong solenoid will be required to focus the beam to mm spot sizes – target chamber access will be limited.

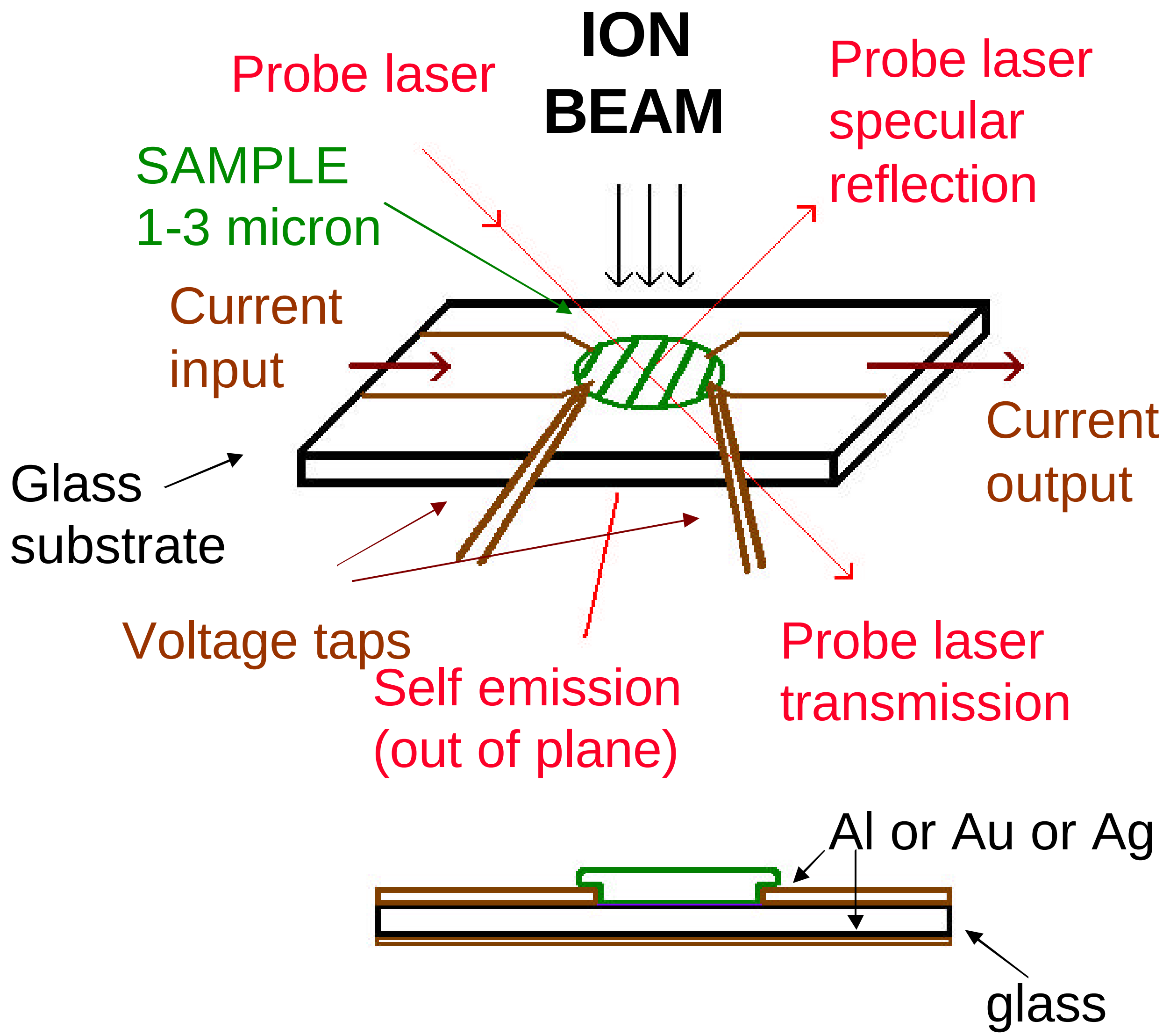


M. Leitner

Schematic drawing of a solenoid final focus system for HEDP studies on NDCX-II.

Conceptual design of a generic WDM target for reproducible manufacture (original sketch R. More).

- **Target to be mounted on a remote positioner/ carousel target changer.**
- **Simple optical/electrical diagnostics as indicated**
- **Attention to**
  - **Dimension and position**
  - **Inductance**
  - **Optical transmission**



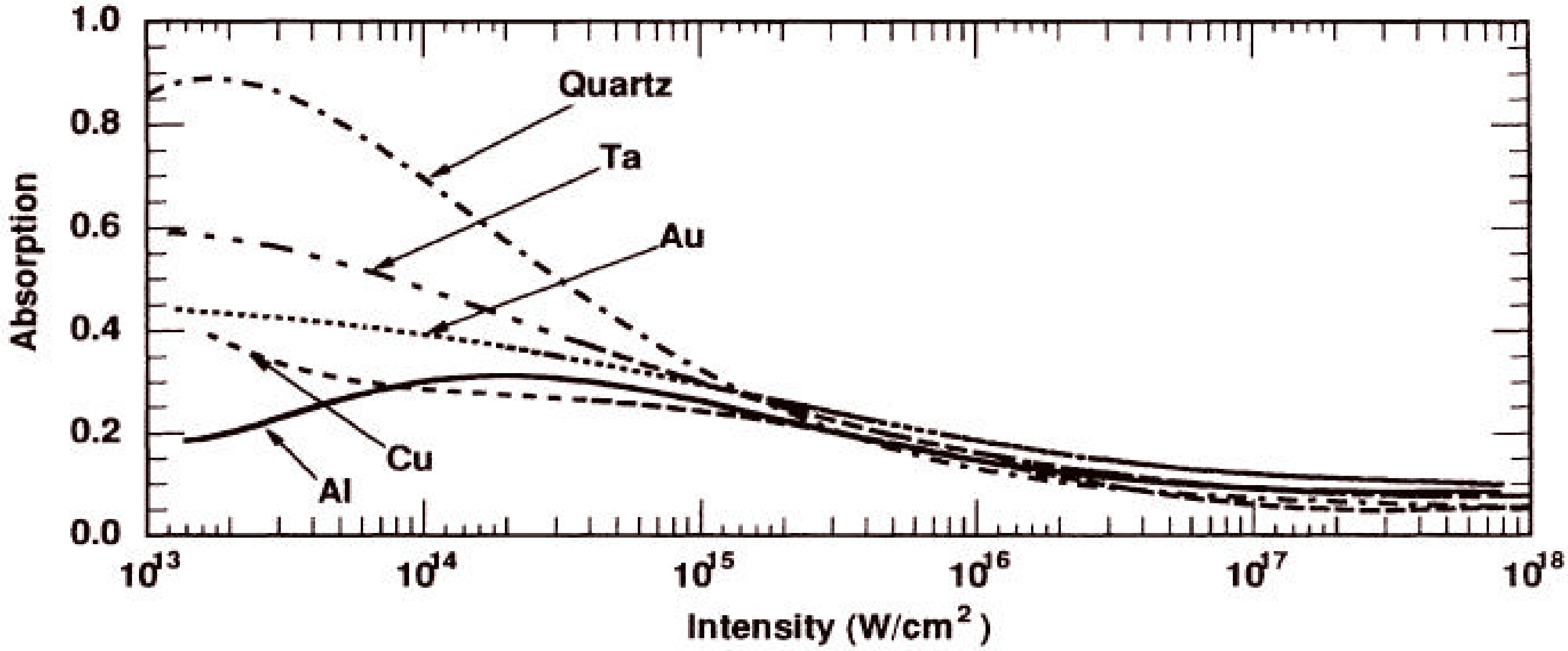
A WDM Study Group explored what experiments we could do in near future (next 5 years).

The study group finds that experiments can begin with the current HCX and NDCX and prepare for NDCX 2 in a series of experiments.

List of experiments:

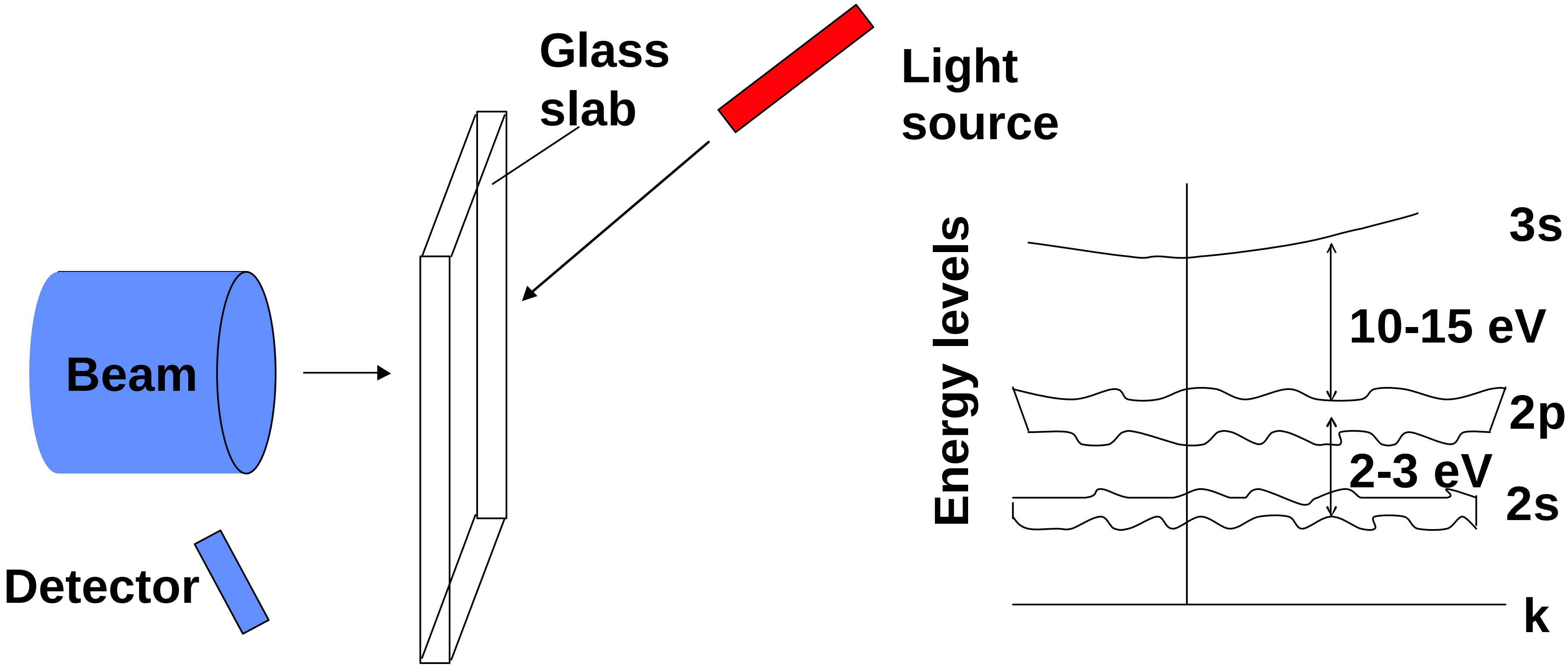
1. Transient darkening emission and absorption experiment (on HCX and if necessary NDCX)
2. Experiment to measure target kT using a beam compressed both radially and longitudinally (on NDCX or HCX)
3. Positive - negative halogen ion plasma experiment (kT >~ 0.4 eV) (on NDCX with focusing solenoid, or pulse compressed HCX with focusing solenoid)
5. Two-phase liquid-vapor metal experiments (kT > 0.5 - 1 eV for Sn) (on NDCX with focusing solenoid or pc HCX w/ foc. sol., or NDCX-2)
6. Critical point measurements (kT > 1 eV for Sn) (possibly only on NDCX-2)

Enhanced optical absorption of quartz is an indicator of WDM conditions (R. More).



Laser-driven WDM "black glass" experiment:
D.F. Price, et.al., PRL 75, 252, 1995

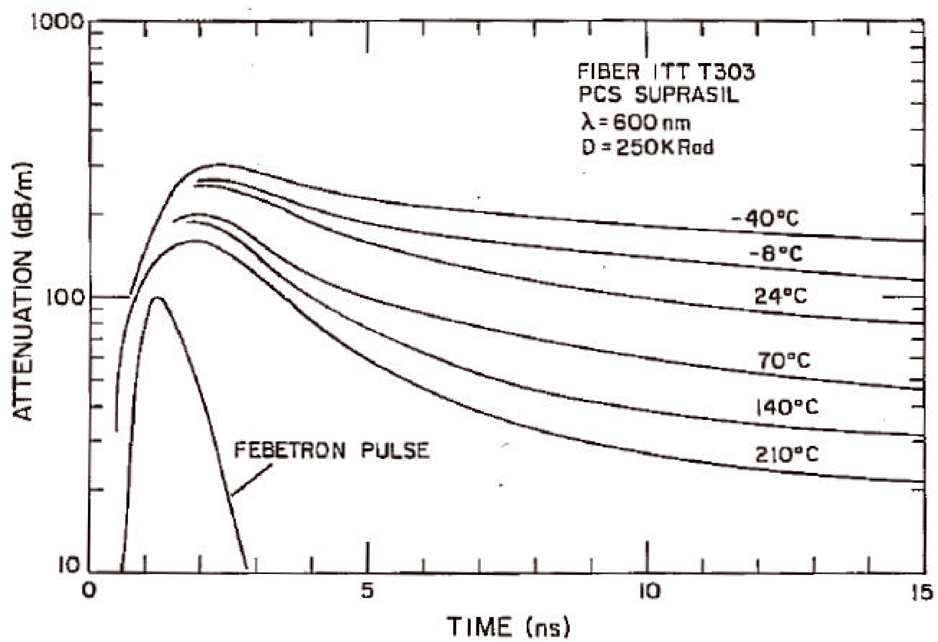
Transient darkening "black glass" experiment at low temperature will help confirm unusual behavior of glass under WDM (high T) conditions



In glass, at room temperature 2s and 2p bands are filled. At WDM conditions (~1 eV) some electrons are excited to 3s band, leaving holes in 2p band, allowing absorption by optical photons (black glass). This experiment will excite electrons out of 2p using ion beams again leaving holes and possibility of measuring decay rate out of 3s state by observing both decay of absorption and emission rates.

Transient darkening experiment can be done using existing HIFS-VNL accelerators and a glass target.

- **Transient scintillator darkening has been observed in quartz optical fibers – underlying physics not well understood.**
- **"Black glass" observations on SiO_2, Al_2O_3, MgF_2 targets in laser and reactor experiments can be studied by ion-beam excitations of 2s-2p electrons. Experiment involves measuring emission and absorption of quartz or sapphire for room temperature and cryogenic targets.**



P. Lyons, Fiber optics in transient radiation fields, SPIE 541, 89 (1985)

Suggestion from V. Fortov (via G. Logan): study metal spall strength for fast deformations.

This is a field of great practical interest in the strength of materials.

Are we are in the relevant regime?

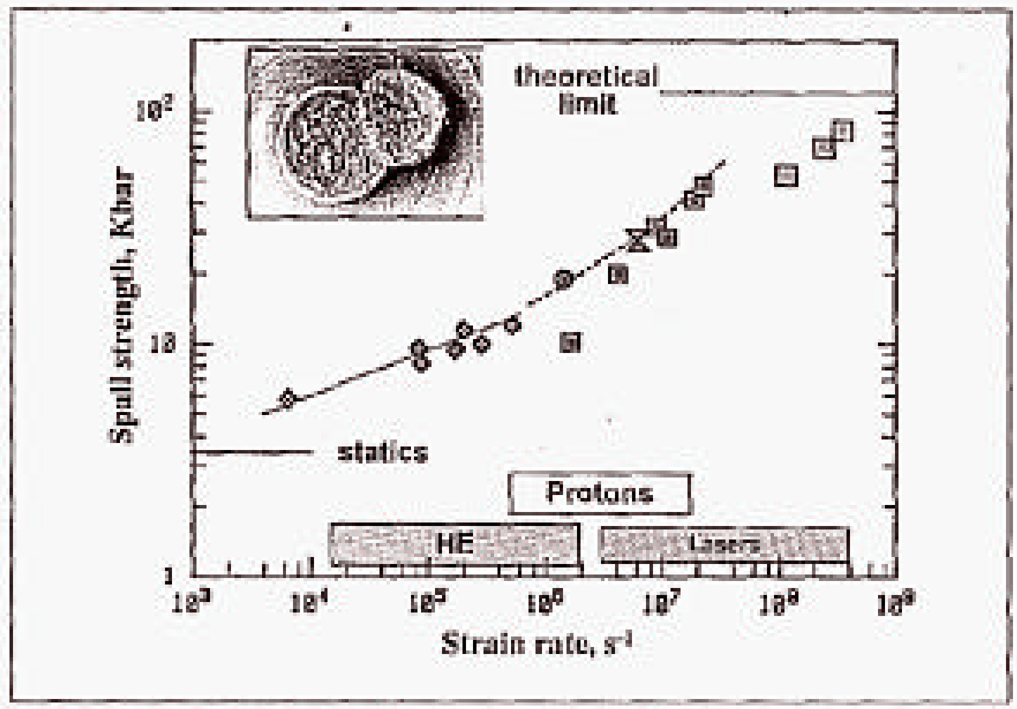


Fig. 15. Aluminium-magnesium alloy spall strength at fast deformations [8,41].

V. Fortov, Intense shock waves and extreme states of matter

Near-term experiments provide opportunity to gain experience with WDM diagnostics while developing accelerator technology.

- **Initial diagnostic needs are to measure temperature and expansion velocity to study heating and phase transitions in ice, foam, or gas-jet targets.**
- **Fast optical pyrometry**
  - **Image optically thick target at 2 or more wavelengths using fast gated camera or fast phototube**
- **Laser VISAR [velocity interferometer system for any reflector]**
  - **Use Doppler-interferometric technique to measure rarefaction waves and hydrodynamic expansion of the target**
- **Gas jet targets can be diagnosed using schlieren techniques, optical emission spectroscopy**
  - **Gas jets up to atmospheric density may be created in a compact laboratory arrangement**

Requirements to field scientifically interesting WDM experiments.

- More intense beams from NDCX-2 provide higher enthalpy targets in a relatively benign environment for diagnostics
- Simultaneous measurement with a number of diagnostics requires careful experiment design
- Need for reproducibility; compatibility of diagnostics with superconducting solenoid, neutralizing plasma
- Other diagnostic tools
  - Stopping power – measure beam energy and charge state after passing through the target
  - Laser reflectometry and polarimetry
  - Electrical resistivity measurements (metal to insulator, insulator to metal)
  - Electron beam flash x-ray shadowgraphy (backlighter)
  - Laser-produced x-ray backlighter

Diagnostic development

- A diagnostic of immediate interest is a fast optical pyrometer
  - 6 channel, 1 ns time resolution for measurements up to 6000 K, as developed at GSI
  - Detector may be a series of fast phototubes or streak camera
- VISAR laser Doppler system
- Ion beam current and profile diagnostic
- Other diagnostics, e.g. EUV/soft x-ray spectrometer

HEDgeHOB collaboration will study HEDP generated by heavy ion beams: GSI-Darmstadt.

GSI group will be testing a number of target diagnostics in coming years:

- **Fast pyrometry**
- **Target emission spectrometry**
- **Laser interferometry**
- **Electrical conductivity measurements**
- **Ion and proton radiography**
- **Energy loss and Bragg-peak contrast radiography**
- **Energy loss and charge state diagnostics**
- **Backlighting with HEPW (high energy petawatt) laser**
- **Radiography using intense bursts of x-rays**
- **Thomson x-ray scattering**

TECHNICAL PROPOSAL FOR DESIGN, CONSTRUCTION, COMMISSIONING AND OPERATION OF THE:

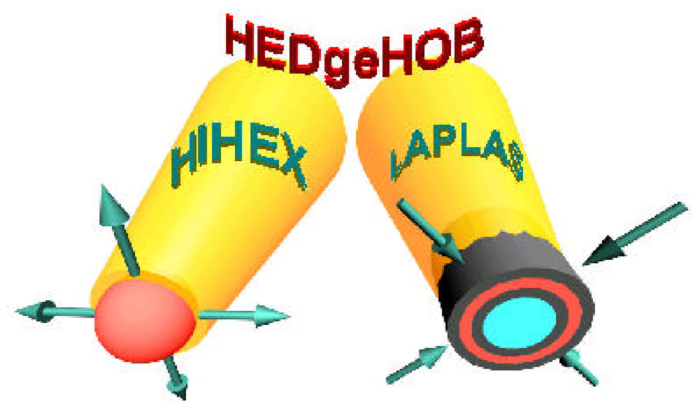
HEDgeHOB

High Energy Density Matter Generated by Heavy Ion Beams

STUDIES ON HIGH ENERGY DENSITY MATTER WITH INTENSE HEAVY ION AND LASER BEAMS AT FAIR

HEDgeHOB Collaboration

January 14, 2005



High energy heavy ion beams at energy >> Bragg peak generate long thin WDM regions.

Proposed HIFS-VNL collaborative experiment at GSI

Opportunities for experimental collaboration

- **Foams are of interest to HIFS-VNL and others:**
  - **Extend range of low energy heavy ion beams to reduce hydro expansion time**
  - **Study issues of relaxation and homogenization as filaments expand into voids**
  - **Foams are also of interest in heavy-ion IFE targets**
- **Proposed experiment uses metal foams (~10-30% solid density metal) to study effect of pore size using dE/dx and other diagnostics:**
  - **initial experiments can be done non-destructively at low intensity; later experiments in WDM regime.**
- **GSI is equipped to make these measurements at existing facility**
- **what are the important physical parameters and quantities to measure?**

Conclusion

- **Existing accelerator facilities and techniques**
  - NTX – neutralized beam profile reduced to mm
  - NDCX – 50x longitudinal compression to date
  - Target temperatures in the ~0.4 eV range appear achievable in near term
  - NDCX-2 will explore higher temperate WDM matter

- **Plans for WDM and WDM-related experiments**
  - Planned experiments to begin with transient darkening, include joint foam target studies at GSI

- **Diagnostic development and target chamber**
  - Much work is required in these areas