Ion-beam-driven warm dense matter experiments

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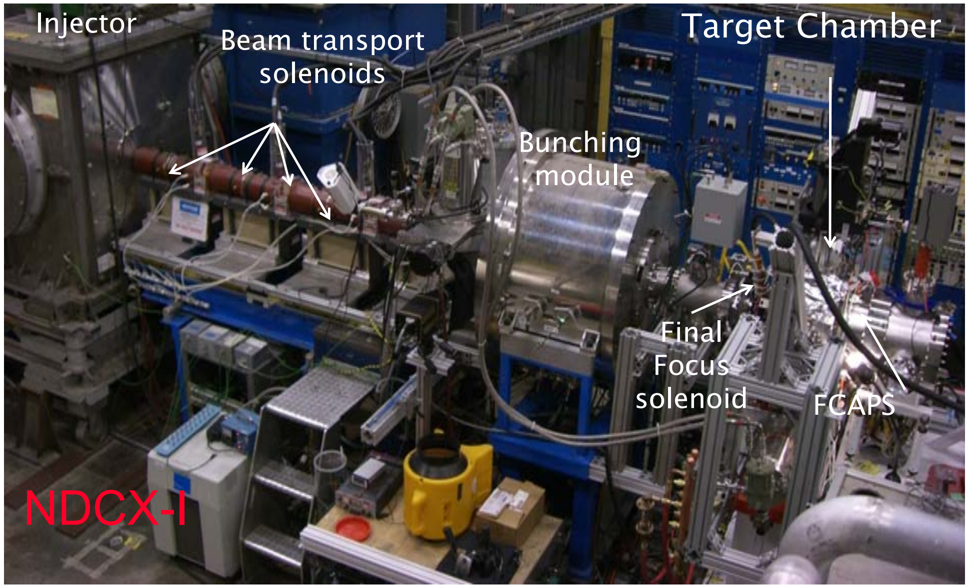
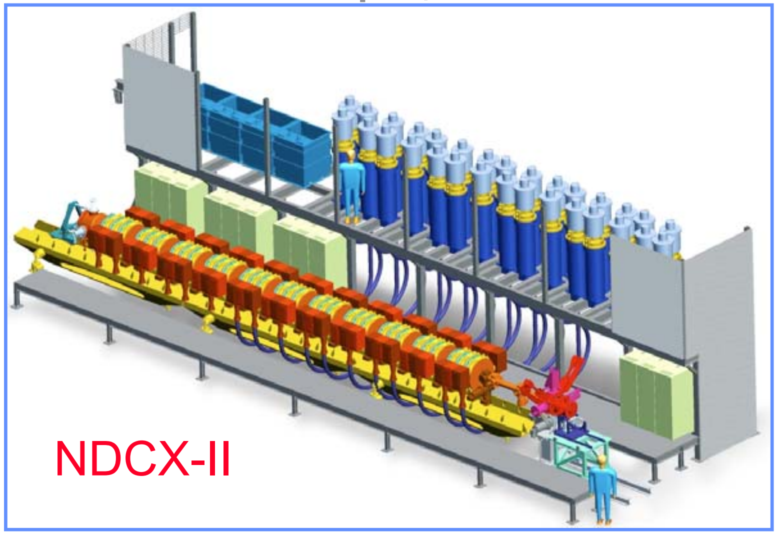
[1]LBNL, [2]LLNL, and HIFS-VNL



IFSA 2009, San Francisco, CA
Sep. 9, 2009



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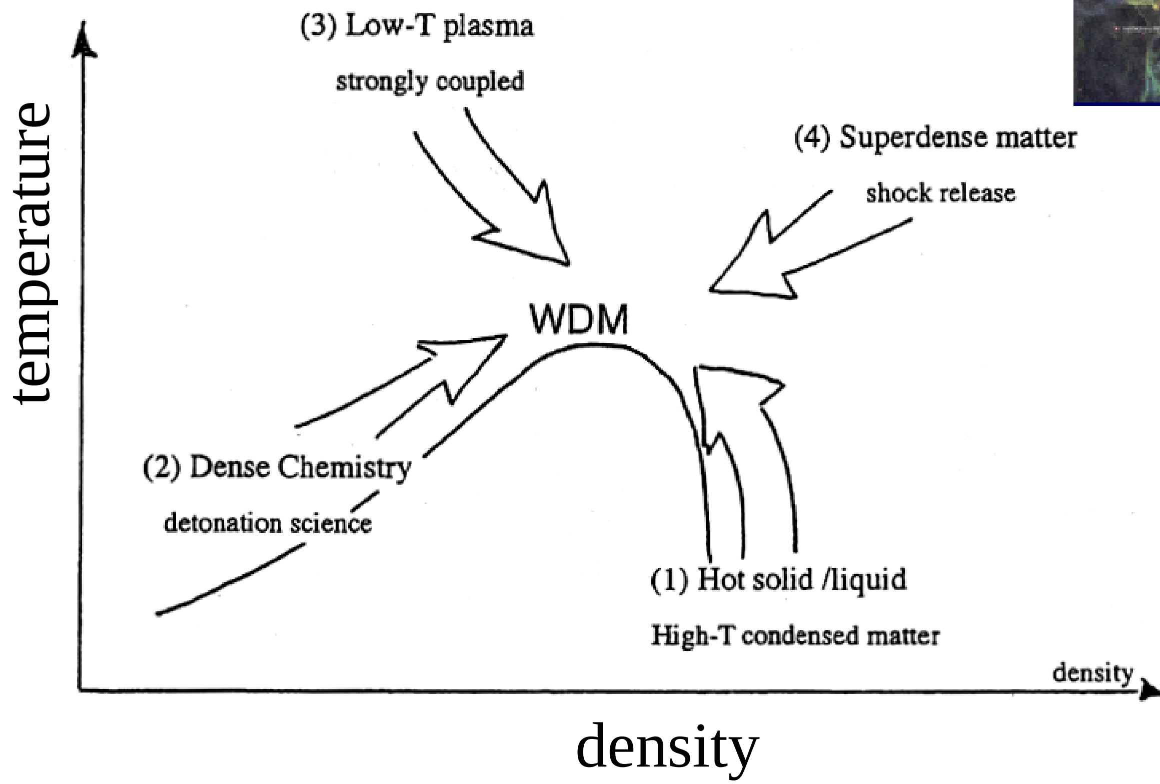
NDCX facility and HIFS-VNL staff at LBNL

The WDM regime is at the meeting point of several distinct physical regimes - a scientifically rich area of High Energy Density Physics.

From R. More, Warm Dense Matter School, LBNL, Jan. 10-16, 2008.
http://hifweb.lbl.gov/wdmschool/



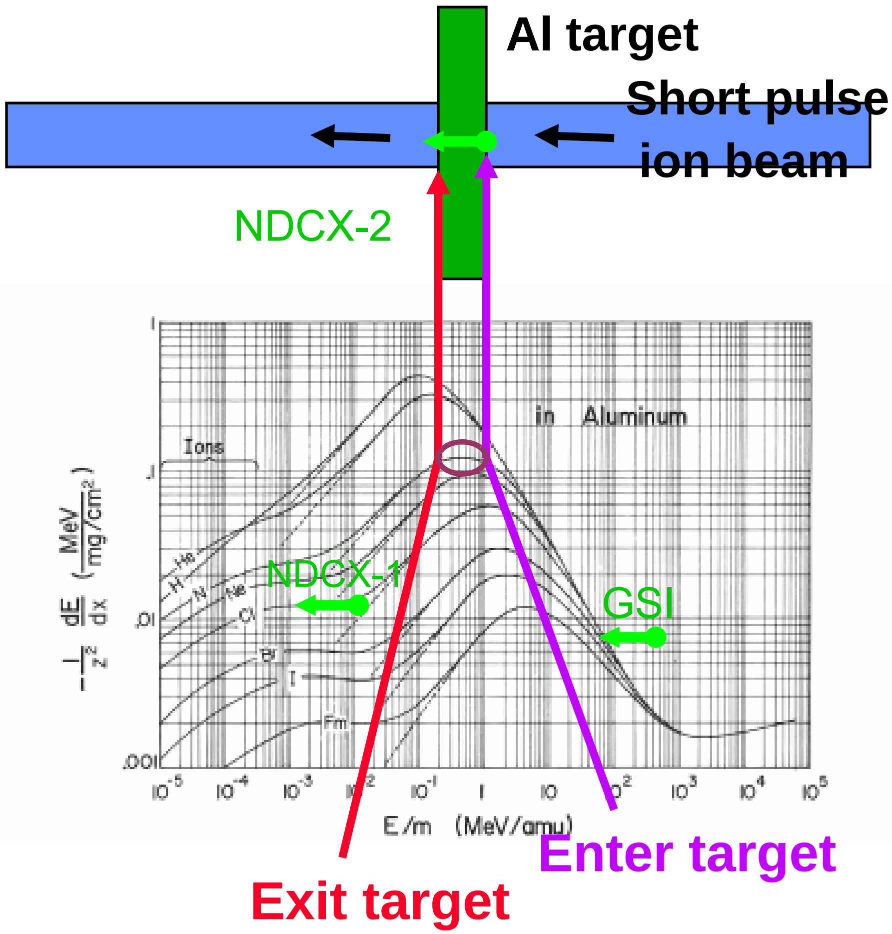
Unknown properties:
EOS ($p(\rho,T)$, $E(\rho,T)$)
Liquid-vapor boundary
Latent heat of evaporation
Evaporation rate
Surface tension
Work function
Electrical conductivity
dE/dX for hot targets

Phenomena:
Metal-insulator transition
Phase transitions?
Plasma composition?

Interesting phenomena at: $0.01\ \rho_{solid} < \rho < 1.0\ \rho_{solid}$
and $0.1\text{ eV} < T < 10\text{ eV}$

Ion beams provide a tool for generating homogeneous warm dense matter.

- Warm dense matter (WDM)
  - T ~ 0.1 to 10 eV
  - ρ ~ 0.01 -1 * solid density
- Uniform energy deposition near flat portion of dE/dx curve, e.g. nuclear stopping plateau (NDCX-I); Bragg peak (NDCX-II)
- Characteristics include
  - Precise control of energy deposition
  - Sample size ~micron depth, 1 mm diameter
  - Ability to heat any target material
  - Benign environment for diagnostics



L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, **A7**, 233 (1970)

NDCX I is laying the groundwork for NDCX II.

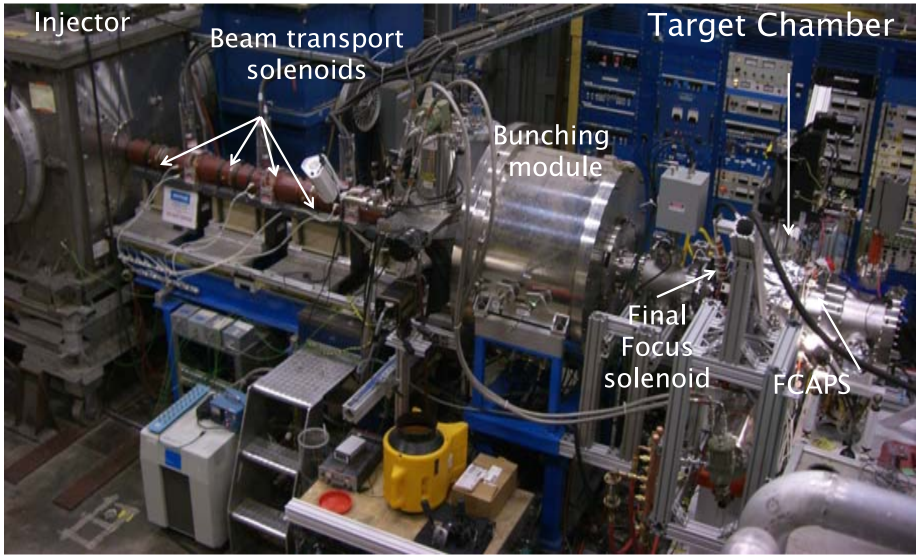
NDCX I

0.35 MeV,

0.003 μC

2 ns

Now



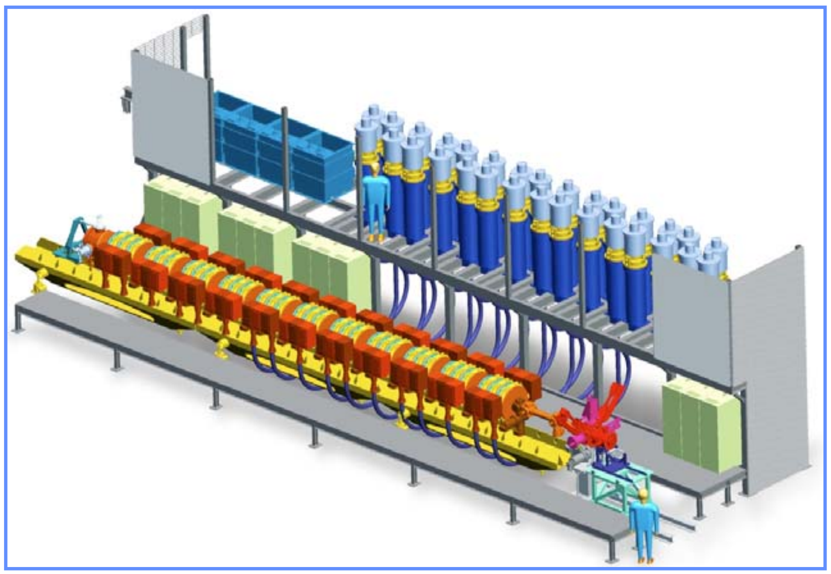
- **Explore liquid/vapor boundaries at T ~ 0.4 eV**
- **Evaporation rates/ bubble and droplet formation**
- **Test beam compression physics**
- **Develop diagnostics**

NDCX II

3 - 6 MeV, 0.03 μC

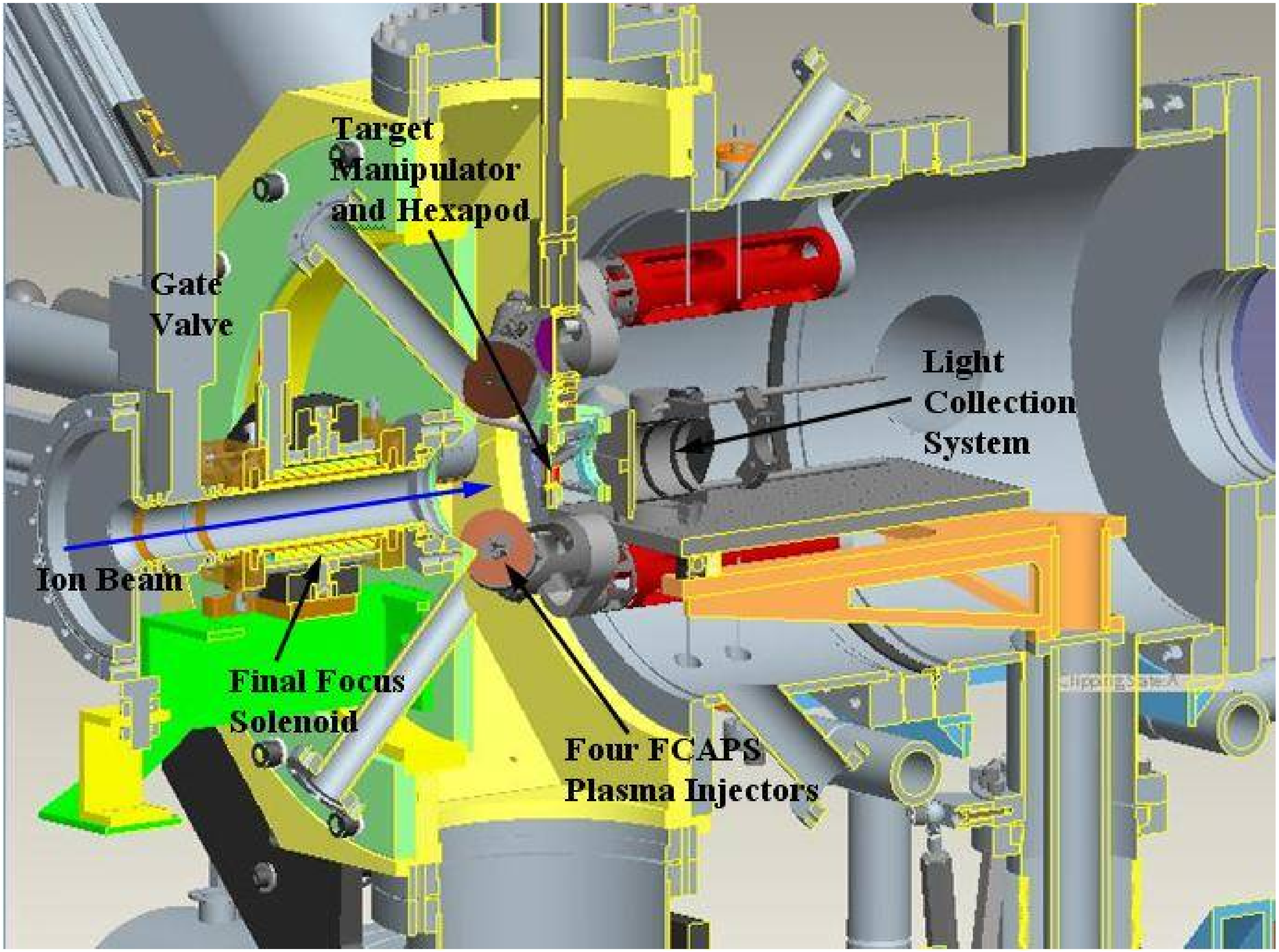
1 ns

Completion date: 2012



- **Bragg peak heating**
- **T ~1-2 eV in planar targets (higher in cylindrical/spherical Implosions)**
- **Ion$^+$/Ion$^-$ plasmas**
- **Critical point; complete liquid/ vapor boundary**
- **Transport physics**
- **HIF coupling and beam physics**

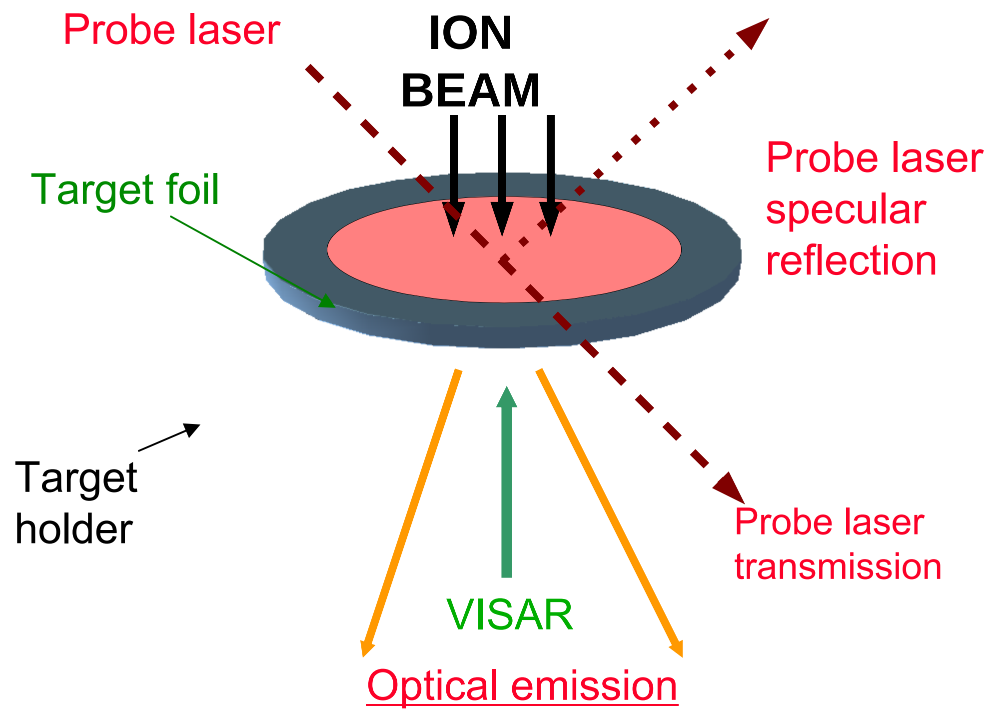
Warm dense matter target chamber contains target, neutralizing plasma, and target diagnostics.



Experiments include WDM target and beam diagnostics.

Initial diagnostics include

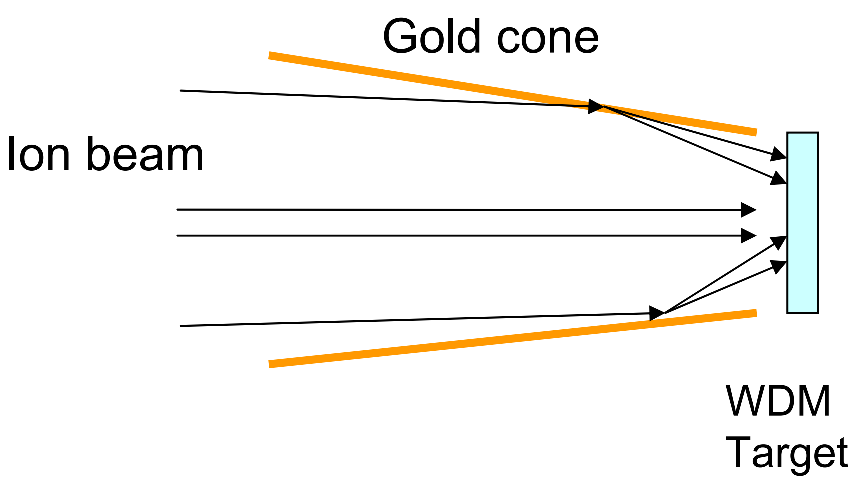
- Optical emission, especially high speed optical pyrometer
- High speed I-CCD cameras
- Streak camera
- Optical spectrometer
- Beam transmission
- VISAR probe
- Electrostatic energy analyzer

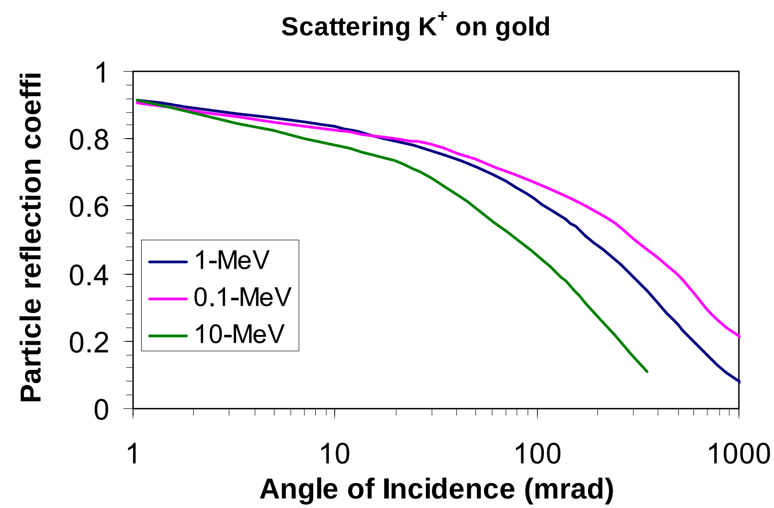


<u>Initial set of targets (foils with mesh backing)</u>

- 350-nm Al
- 150 nm Au
- 120 nm Pt
- 400 nm Si
- 400 nm C

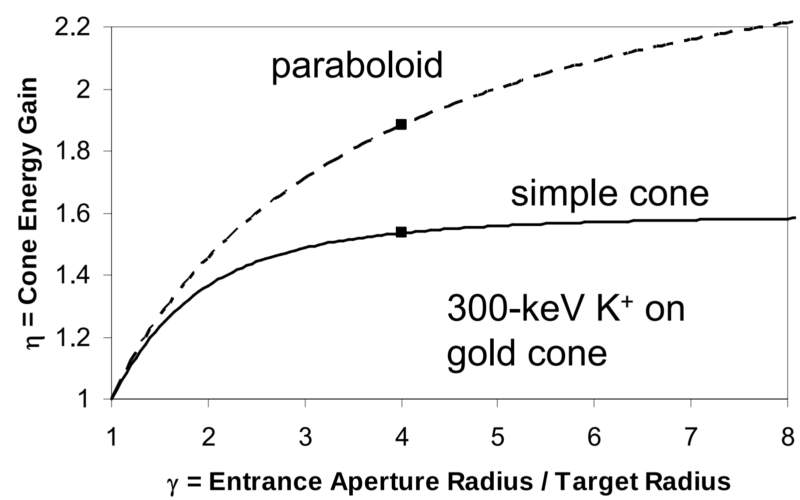
Gold cone concentrates ion beam energy density on target.



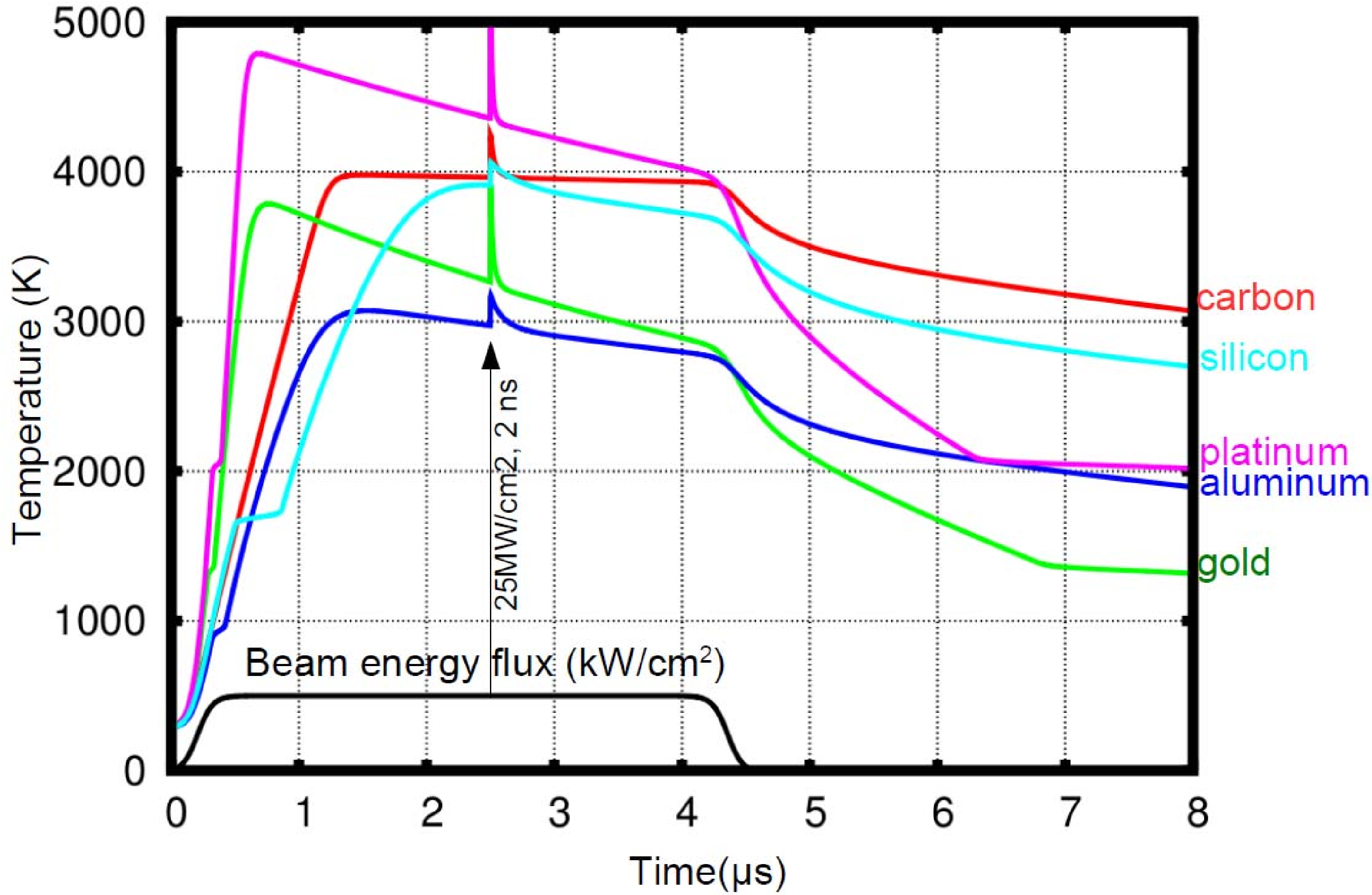


TRIM calculations for a single reflection

- **Cone acts as grazing incidence mirror. Enhanced ion intensity using cone has been demonstrated.**
- **Space charge neutralization of beam electric field by presence of walls, electron production may improve final focus on target.**
- **Cone shields target from unwanted heating by edge of beam.**

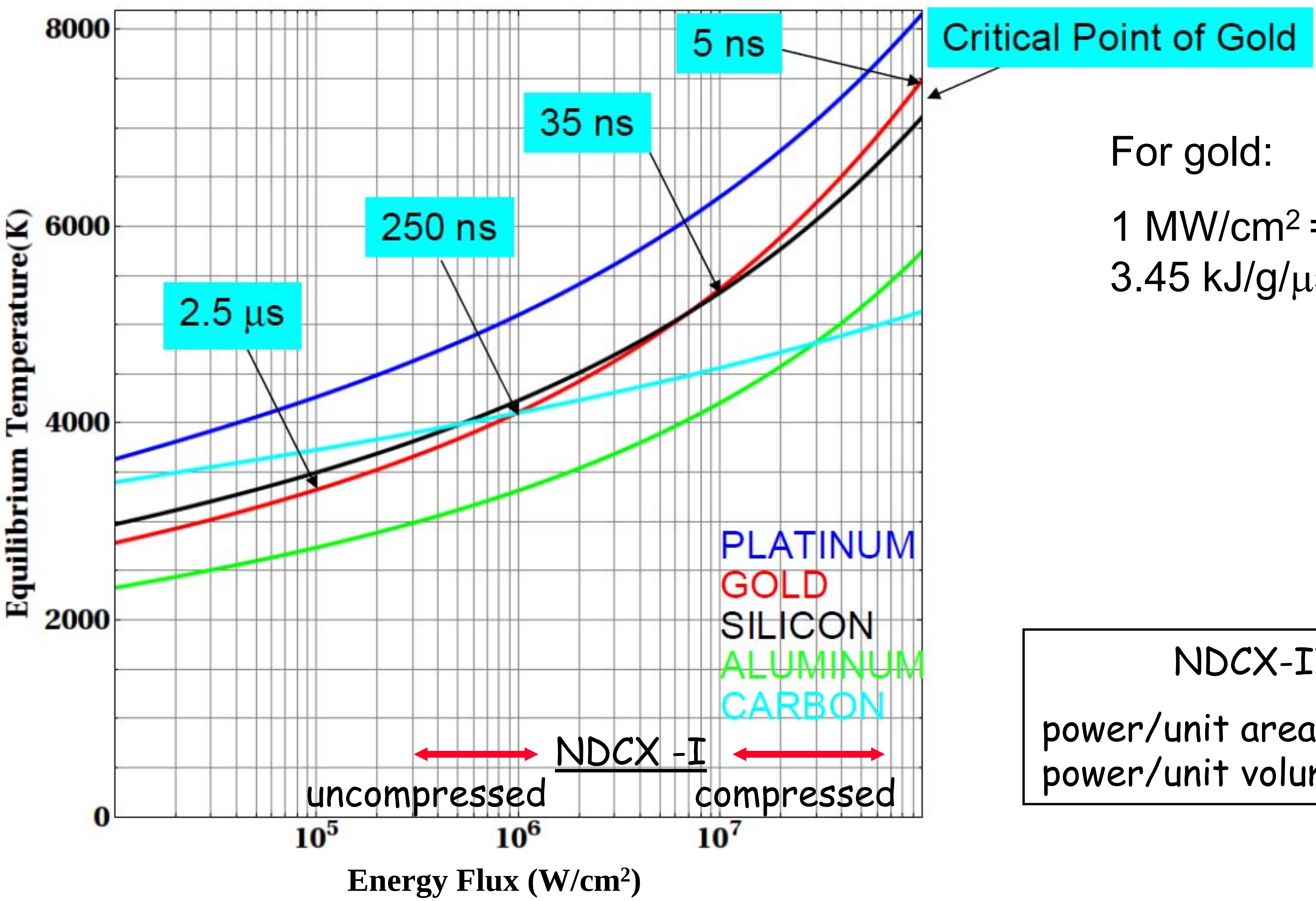


Equilibrium model predicts target heating using NDCX-I beam at 500 kW/cm².



Model of target heating predicts T ~ 0.3 - 0.6 eV using NDCX-I beam; T ~ 1 - 2 eV using NDCX-II beam.

Times indicate time required to reach equilibrium.



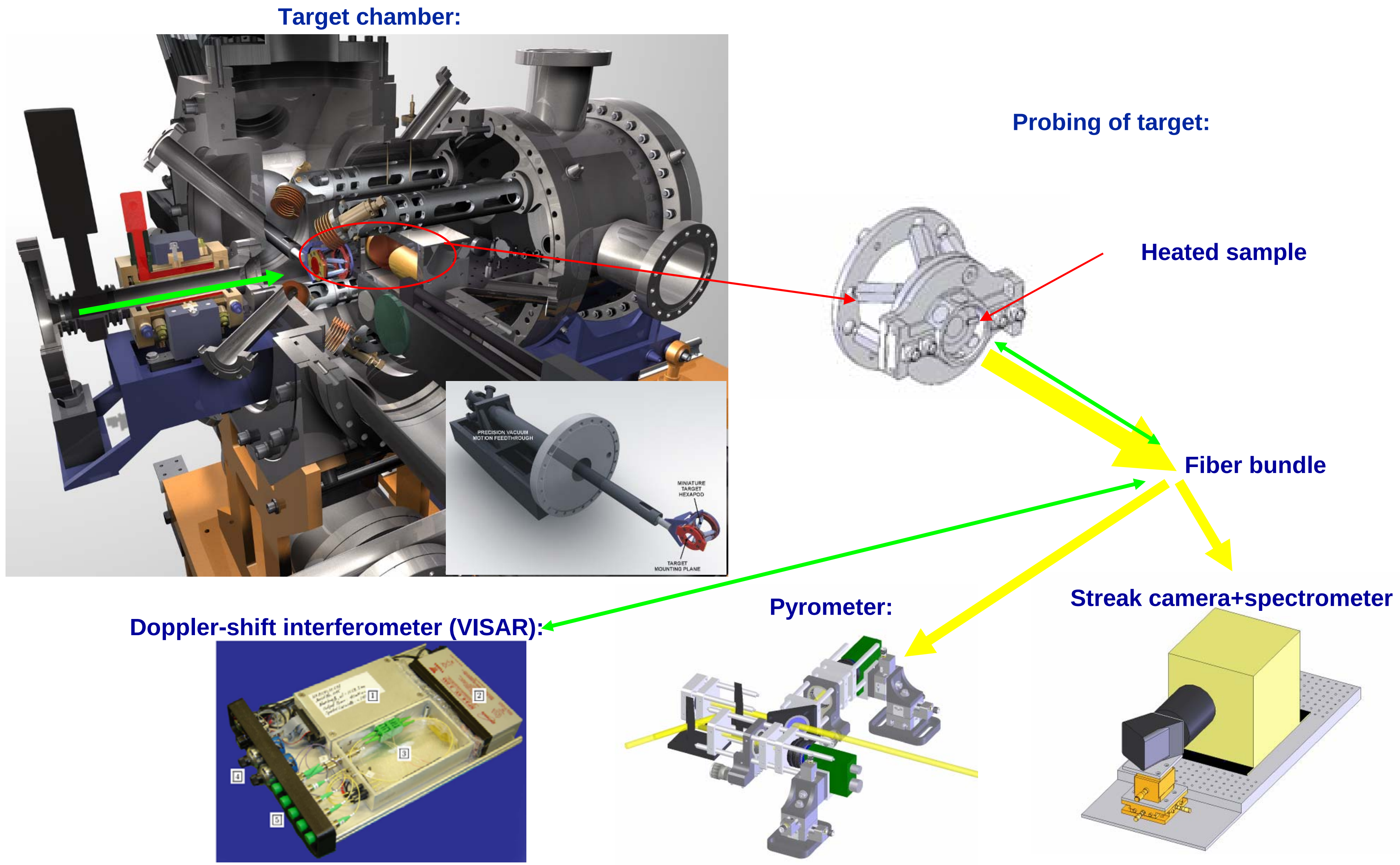
For gold:

1 MW/cm^2 = 3.45 kJ/g/μs

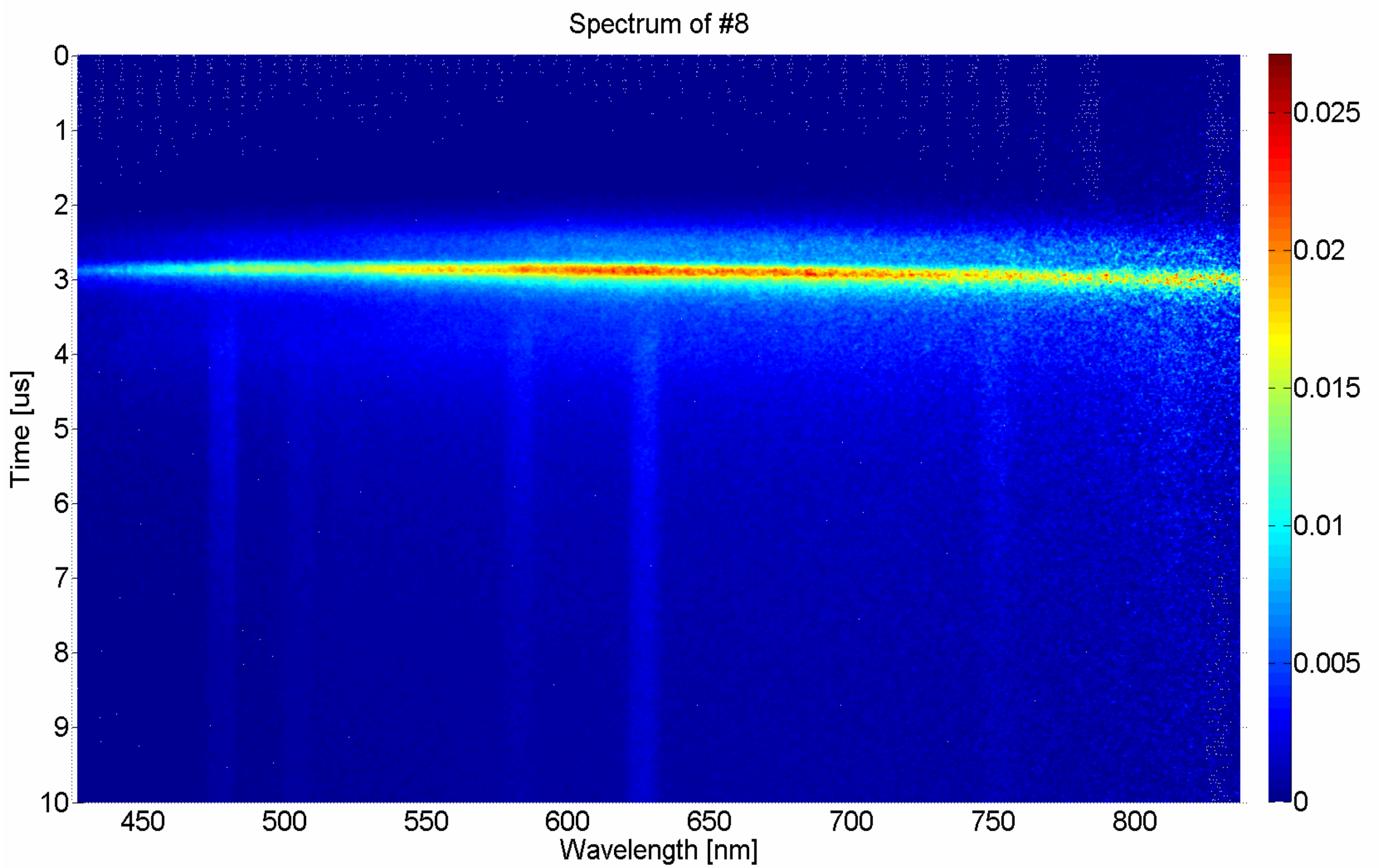
NDCX-II:

power/unit area x 100
power/unit volume x 10

Optical probing of target

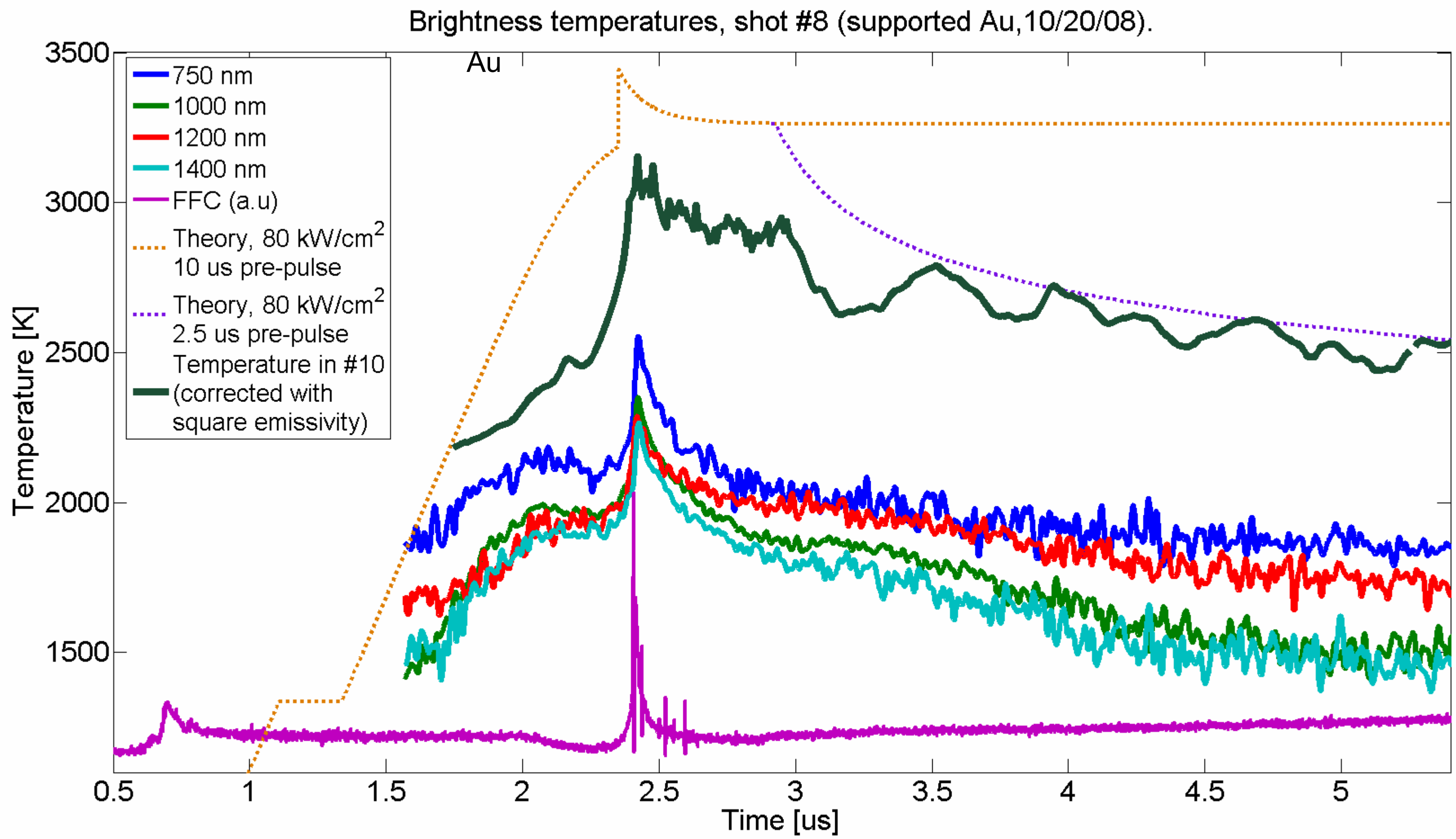


Typical data in foil targets shows heating from the prepulse and compressed pulse.



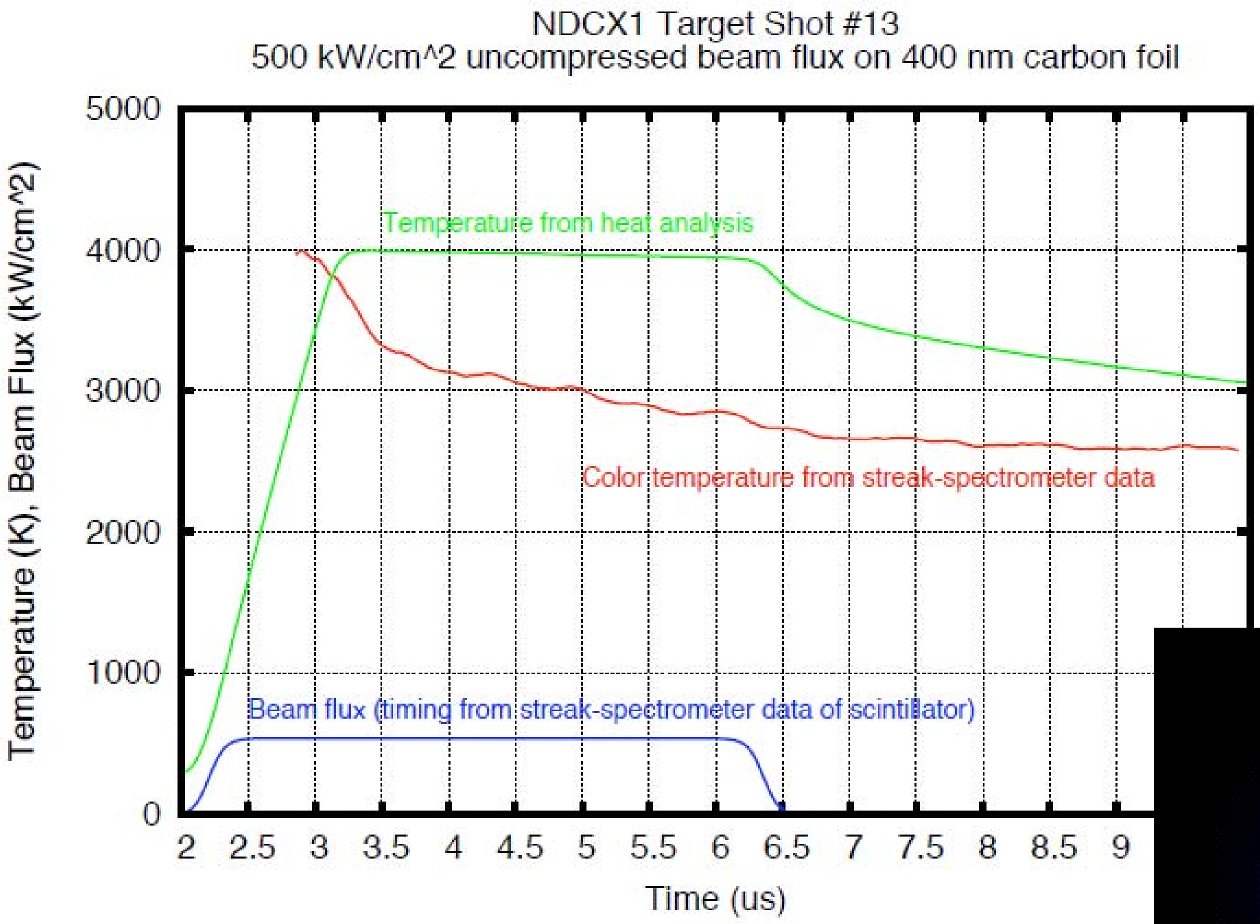
Streak - spectrometer data in Au target showing transition from continuum emission to emission lines from heated gold

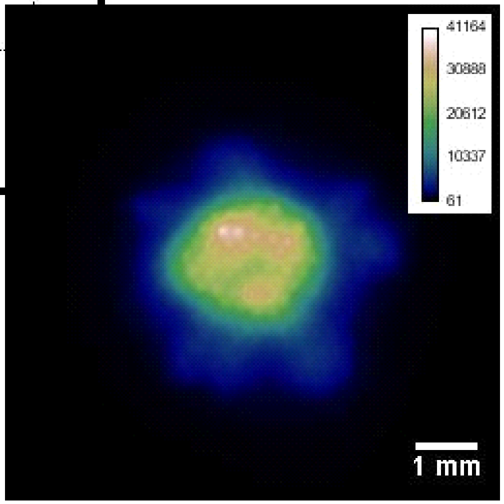
Gold targets are initially heated to about 3000 K and show drop in brightness temperature after ~3 μs.



Actual beam power ≥ 200 kW /cm^2

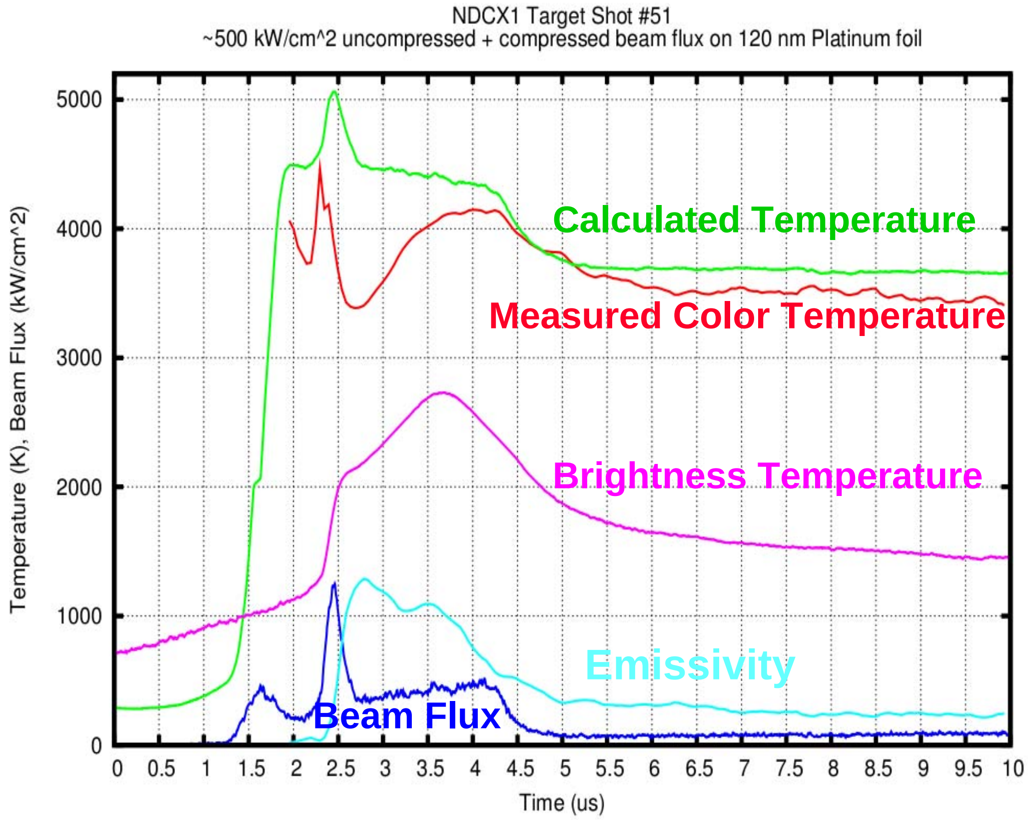
Carbon foil streak-spectrometer data and comparison with simple model.

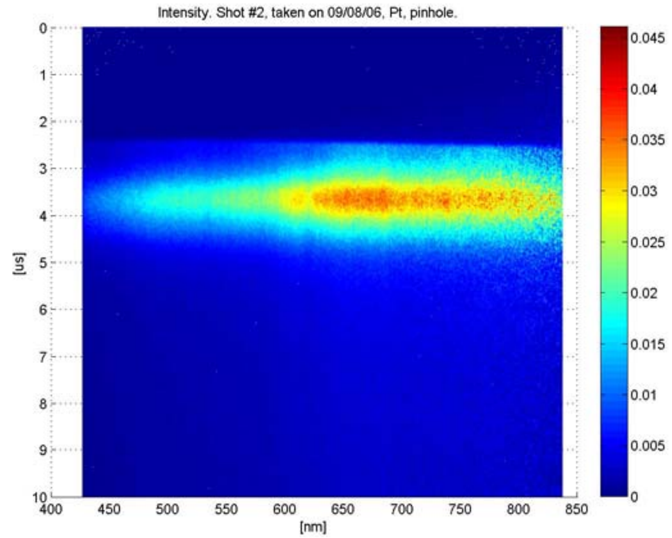


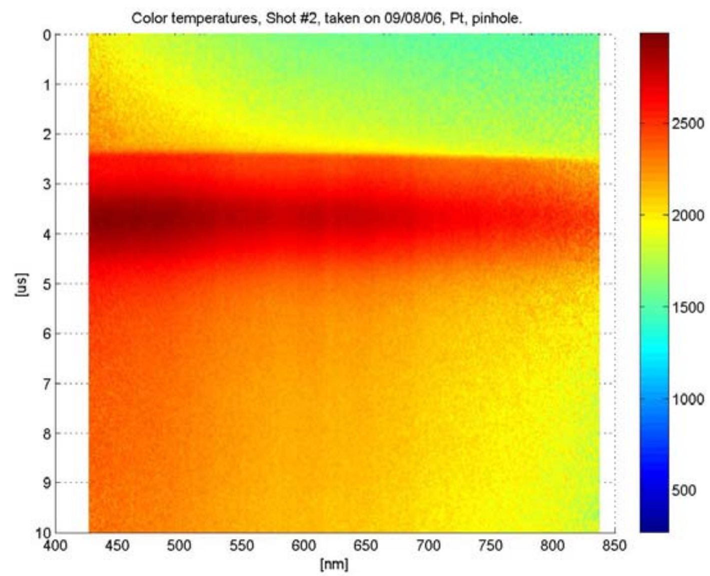


Platinum foil streak-spectrometer data

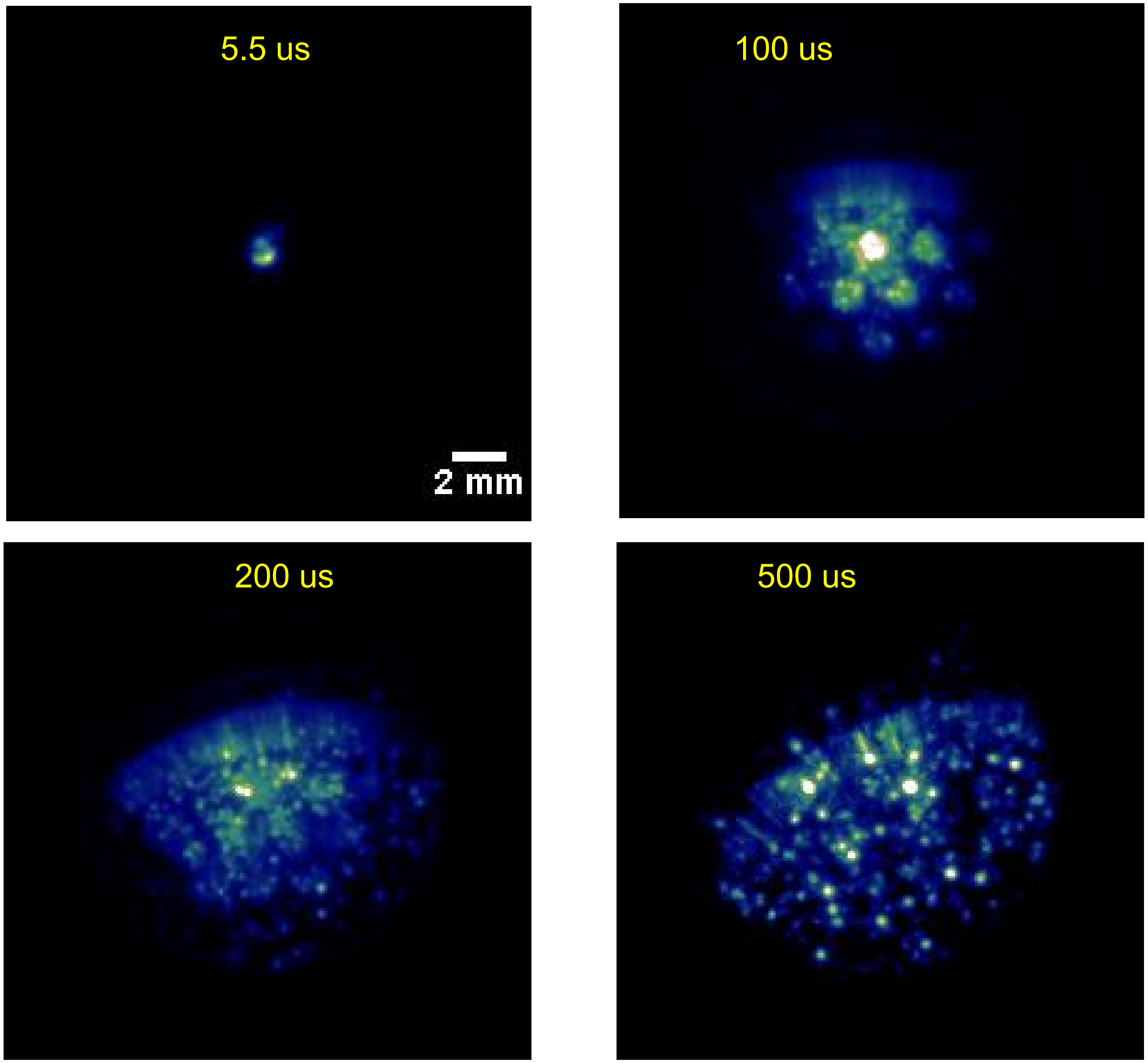
Shot#51, compressed pulse delay 1 μs



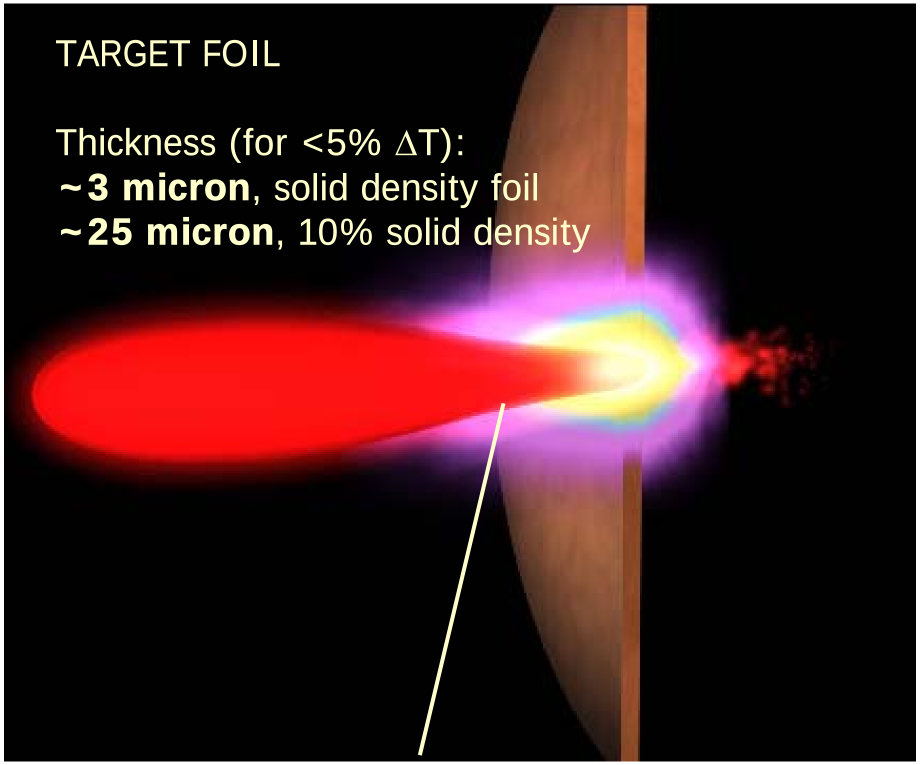


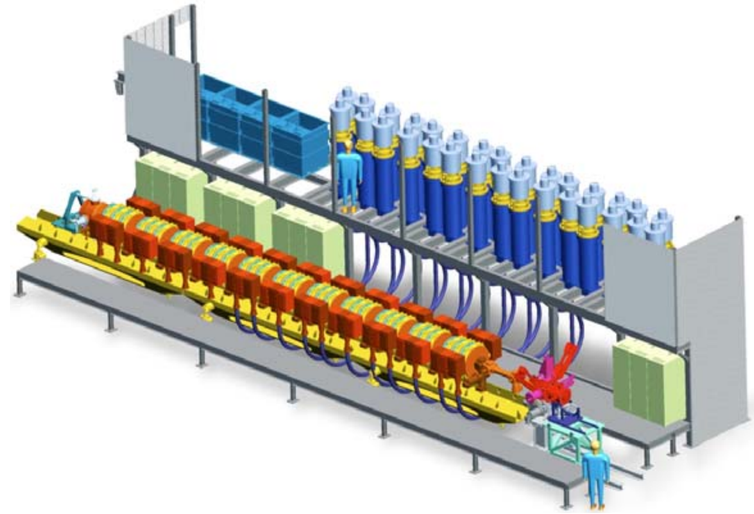


Shower of hot debris fragments after end of shot suggests droplet formation.



NDCX-II driver for >1 eV WDM target heating.





- Ion$^+$ / Ion$^-$ plasmas
- Critical point; complete liquid / vapor boundary
- HIF coupling and driver physics
- Cylindrical / spherical implosions
- Beam physics

TYPICAL DESIGN PARAMETERS FOR LITHIUM ION BEAM BUNCH

Final Beam Energy:	**2.8 MeV**	
Final Spot Size :	**<1 mm diameter**	
Final Bunch Length:	**<1 ns** (≅ <1 cm)	
Total Charge Delivered:	**0.03 micro-Coulomb**	(~ 2×10^{11} particles or I_{max} ~ 42 A)
Normalized Emittance:	**0.4 pi-mm-mrad**	

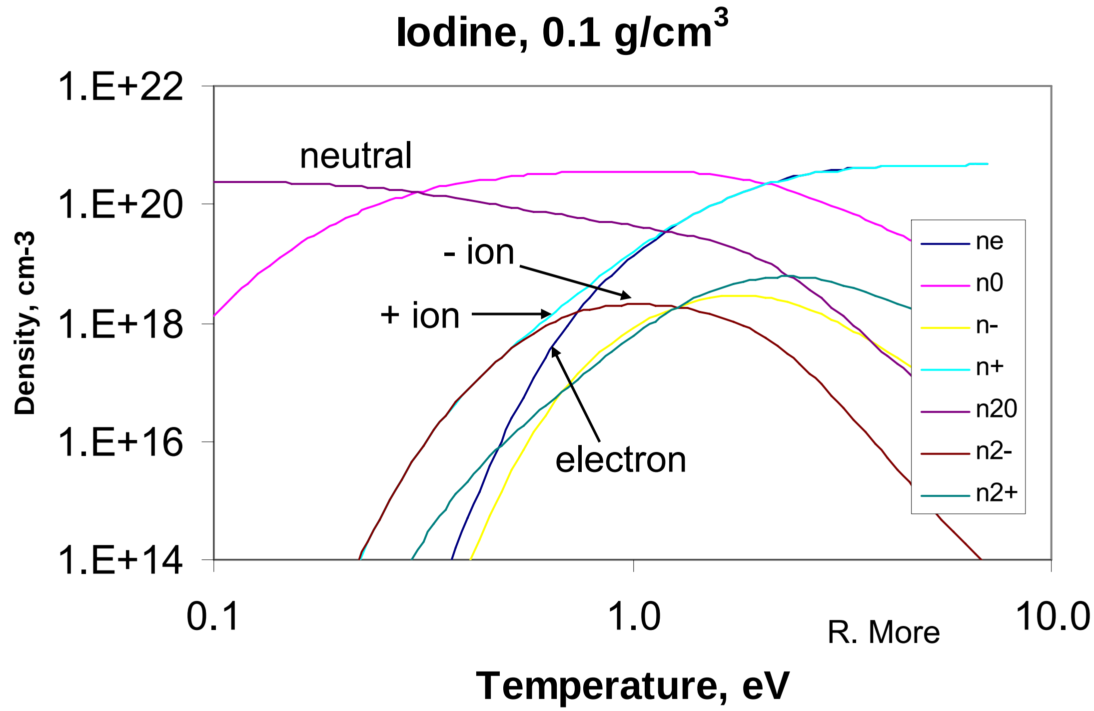
Summary

- Ion beams provide a new tool with unique properties to generate homogeneous WDM.
- We have developed and tested targets, target diagnostics, and a target chamber, as part of a new HEDLP user facility for studying WDM physics.
- NDCX-I provides a test bed for target physics studies, target diagnostics development, and ion beam compression studies.
- Upgrades in beam tuning, bunch compression, etc. are expected to yield higher temperature in NDCX-I WDM targets.
- Future experiments with NDCX-I and NDCX-II will explore aspects of WDM physics including high electron affinity targets, porous targets, beam-target coupling, etc.

Extra slides

Experiment in high electron affinity targets (halogen)

Electron affinity:	
Au	2.3 eV
I	3.1
Br	3.4

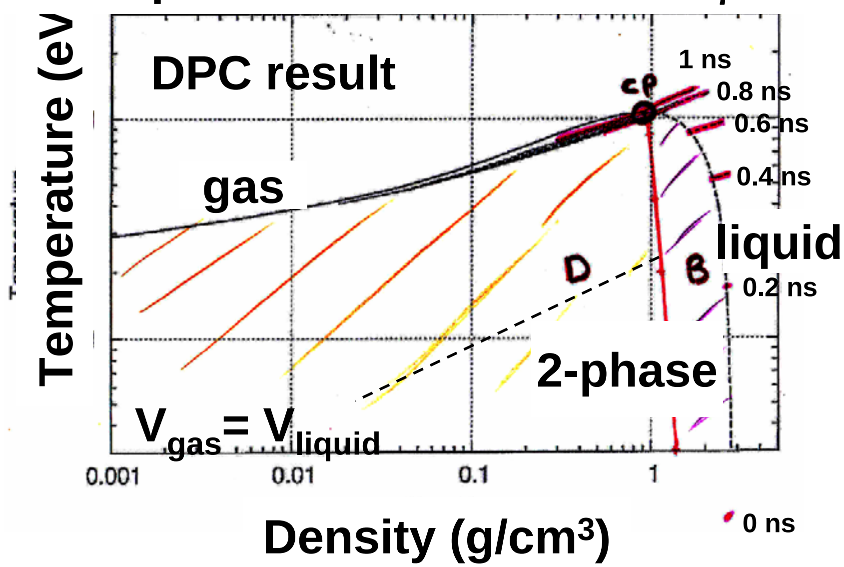


H Yoneda, et al., Phys. Rev. Lett. 2003, 91, 75004.

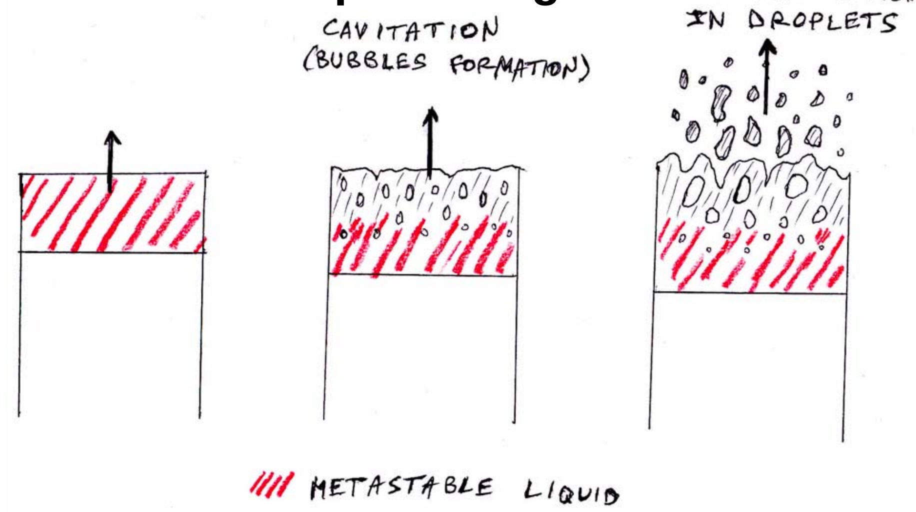
- **Unusual material – dominated by +/- ions**
- **narrow temperature range; e.g. 0.4 to 0.7 eV for iodine at 0.1 g/cc.**
- **radiation from charge exchange**
- **expect conduction by charge transfer**
- **unequal mobility for electrons and holes**
- **Other: optical behavior, metal-insulator transition**

Formation of droplets during expansion of foil is being investigated using a kinetic code

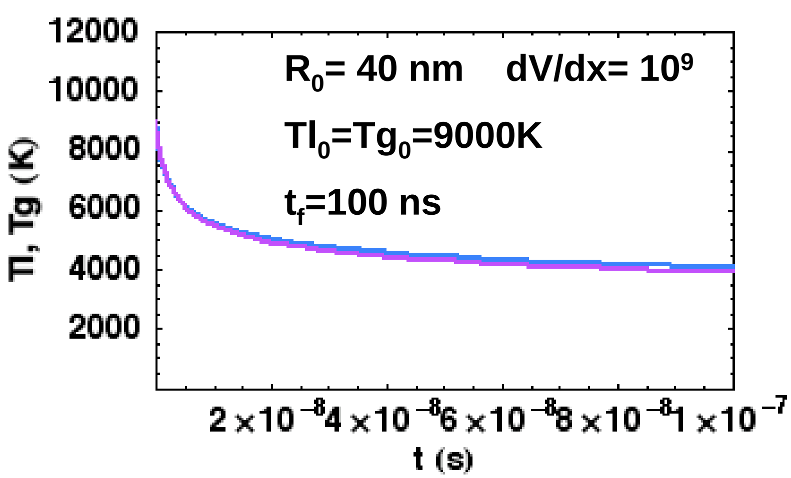
Example of evolution of foil in ρ and T

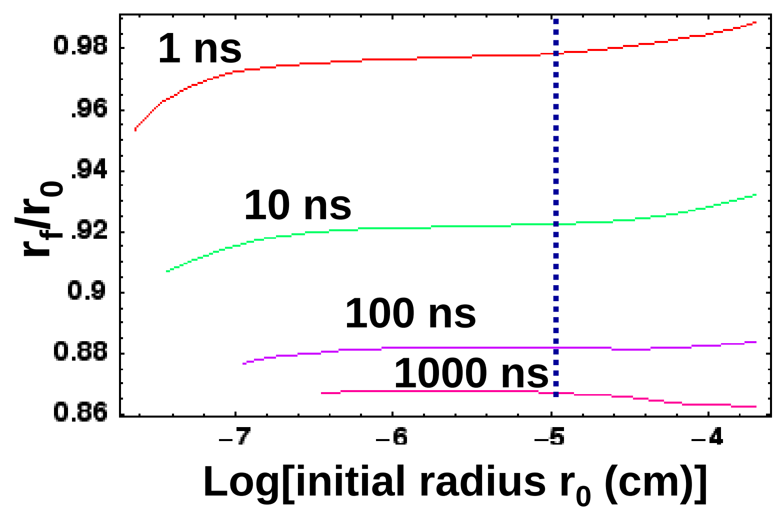


Foil is first entirely liquid then enters two phase regime.

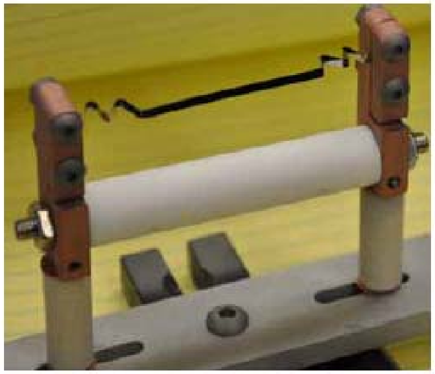


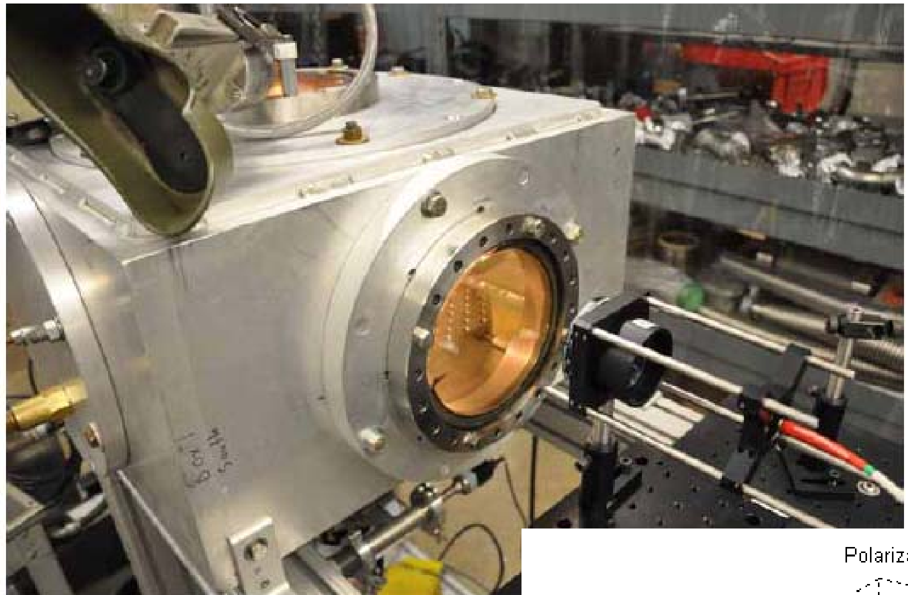
(Ref: J. Armijo, master's internship report, ENS, Paris, 2006; Armijo et al APS DDP 2006, and in prep.)





We are investigating the polarization of optical emission, for possible application to improved pyrometer diagnostic.





Optical polarization experiment using a hot tungsten filament.