Accelerator Optimization with Applications to Warm Dense Matter*

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(with thanks to F.M. Bieniosek[2], R.C. Davidson[3], A. Friedman[1], L. Grisham[3], B. G. Logan[2], M. Marinak[1], R. More[2], G.E. Penn[2], P. Santhanam[2], P.A. Seidl[2], D.R. Welch[4], J. S. Wurtele[2], S. S. Yu[2])

1. LLNL 2. LBNL 3. PPPL 4. ATK

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Outline

I. What is the warm dense matter regime that is of interest?

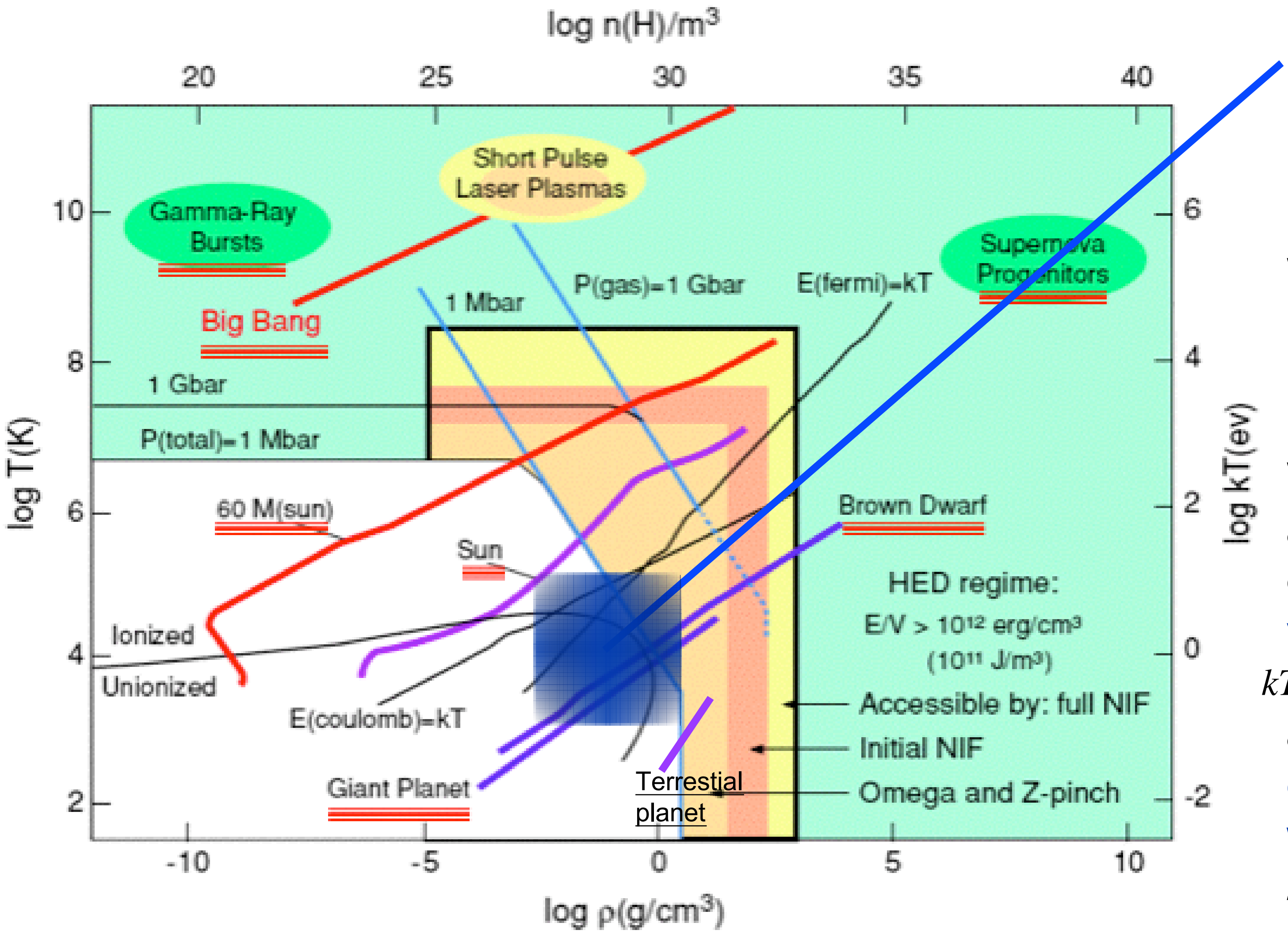
II. What are the requirements on the beam?

III. What are the requirements on the accelerator?

IV. What are some plans for near term experiments?

The ρ - T regime accessible by beam driven experiments lies square in the interiors of gas planets and low mass stars

Figure adapted from "Frontiers in HEDP: the X-Games of Contemporary Science:"



Accessible region using beams

Region is part of Warm Dense Matter (WDM) regime

WDM lies at crossroads of degenerate vs. classical

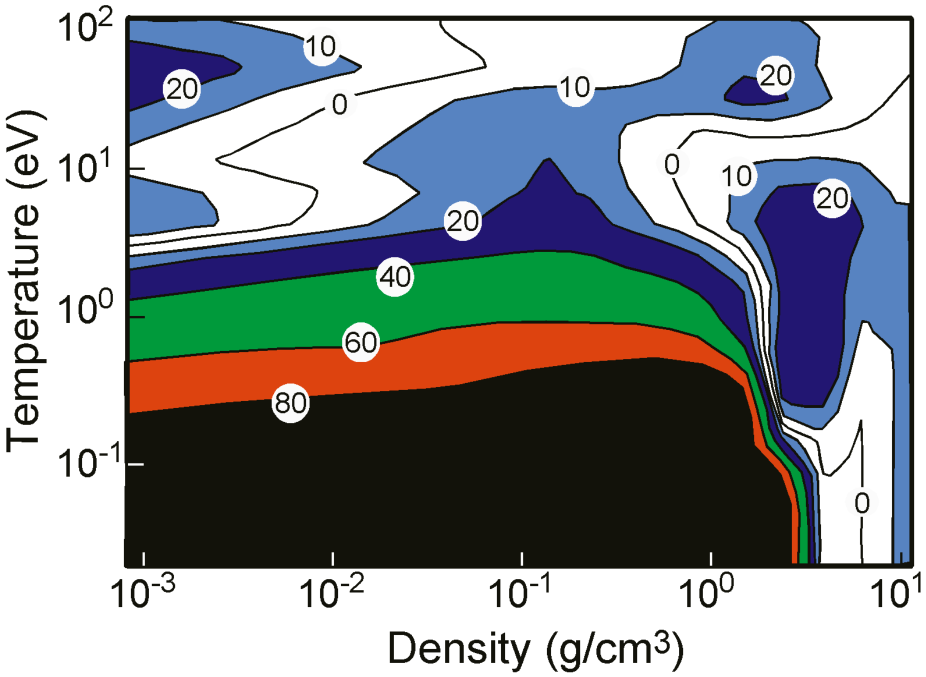
$$kT = \hbar^2(3\pi^2 n_e)^{2/3}/(2m_e)$$

and strongly coupled vs. weakly coupled

$$kT = Z^{*2}e^2 n_i^{1/3}$$

Equation of state in Warm Dense Matter regime has large uncertainties

Contours of difference in pressure for two different commonly used Equations of State for Aluminum:



WDM is interesting (more difficult) because it is neither a classical plasma, nor is it solid state condensed matter physics.

Figure courtesy Richard Lee, LLNL.

A user facility for ion beam driven HEDP will have unique characteristics

Precise control of energy deposition

Uniformity of energy deposition

Large sample sizes compared to diagnostic resolution volumes

Relatively long times to achieve equilibrium conditions

A benign environment for diagnostics

High shot rates (10/hour to 1/second)

Potential for multiple beamlines/target chambers;

Basic Requirements

Temperature T > ~ 1 eV to study Warm Dense Matter regime

Mass Density $\rho \sim 0.01$ to 1.0 times solid density

Strong coupling constant $\Gamma \sim 1$

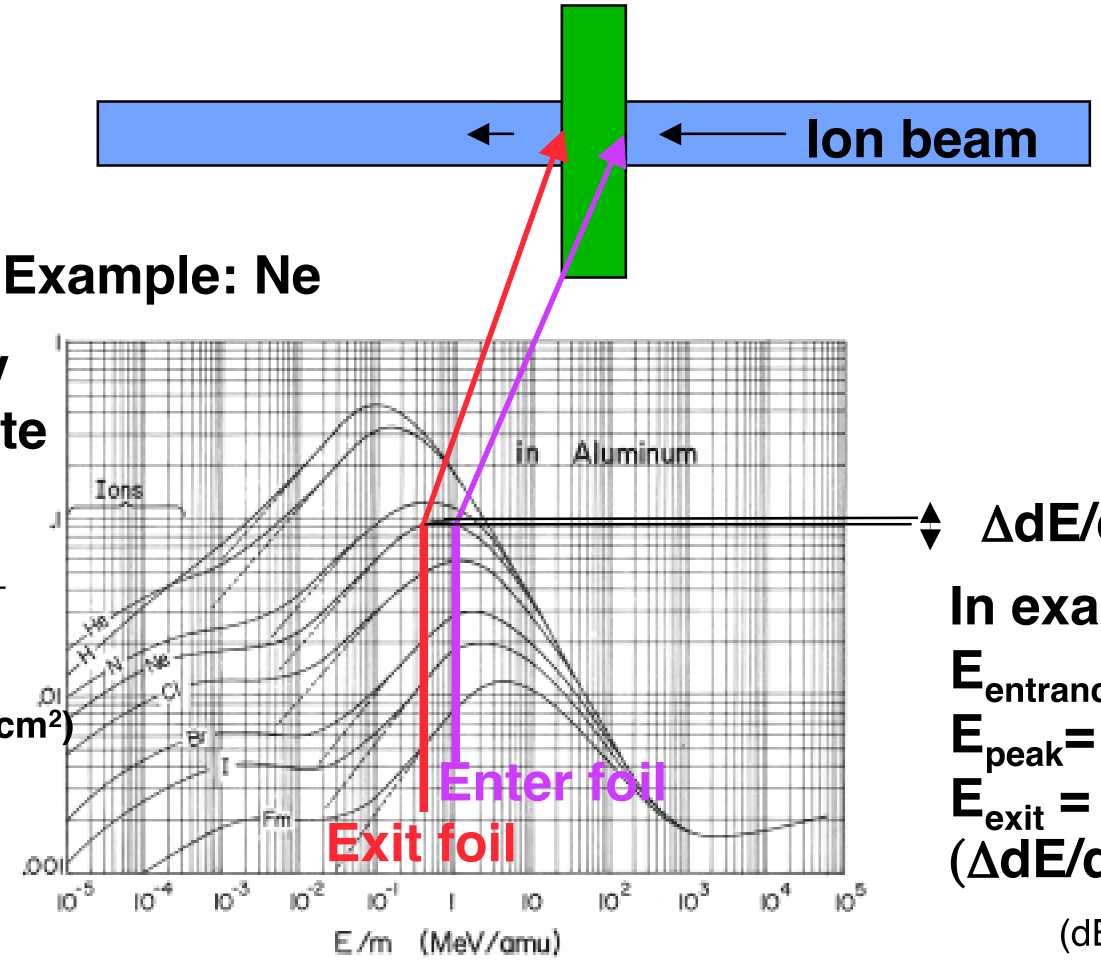
For isochoric heating: Δt must be short enough to avoid cooling from hydrodynamic expansion

Uniformity: $\Delta T/T < \sim 5\%$ (to distinguish various equations of state)

Low accelerator cost is a strong consideration, in present environment

Strategy: maximize uniformity and the efficient use of beam energy by placing center of foil at Bragg peak

In simplest example, target is a foil of solid or “foam” metal



Energy loss rate

$$-\frac{1}{Z^2}\frac{dE}{dX}$$

(MeV/mg cm^2)

Energy/Ion mass (MeV/amu)

fractional energy loss can be high and uniformity also high if operate at Bragg peak (Larry Grisham, PPPL)

$\Delta dE/dX \propto \Delta T$

In example,
$E_{entrance}$=1.0 MeV/amu
E_{peak}= 0.6 MeV/amu
E_{exit} = 0.4 MeV/amu
$(\Delta dE/dX)/(dE/dX) \approx 0.05$

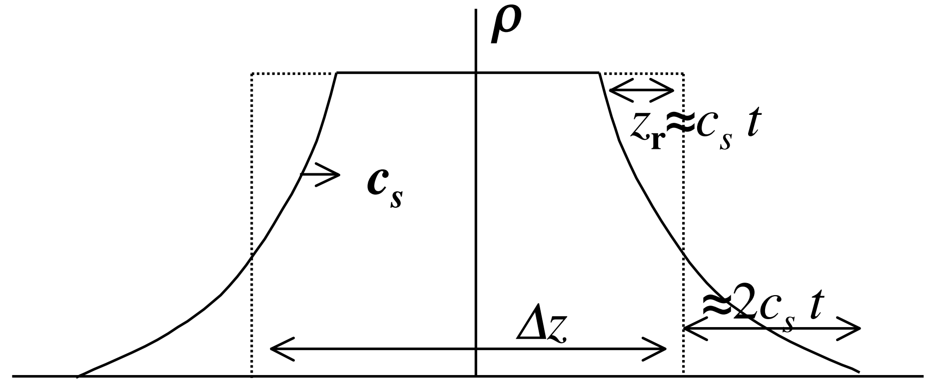
(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, **A7**, 233 (1970))

We set requirements on beam pulse based on target disassembly time

Here: τ_{pulse} = pulse duration

z_{r} = distance, such that diagnosable portion of heated target remains

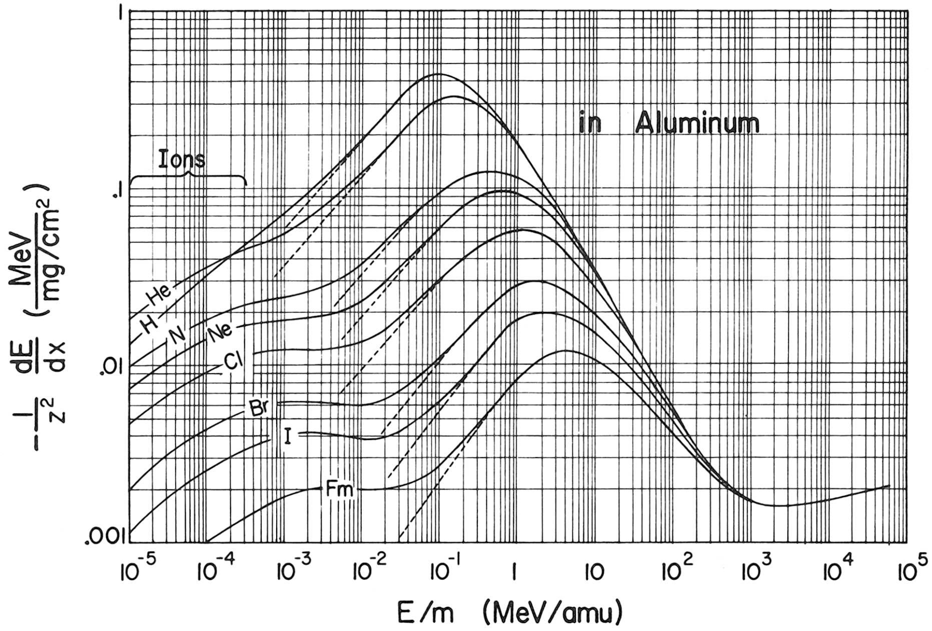
c_{s} = sound speed

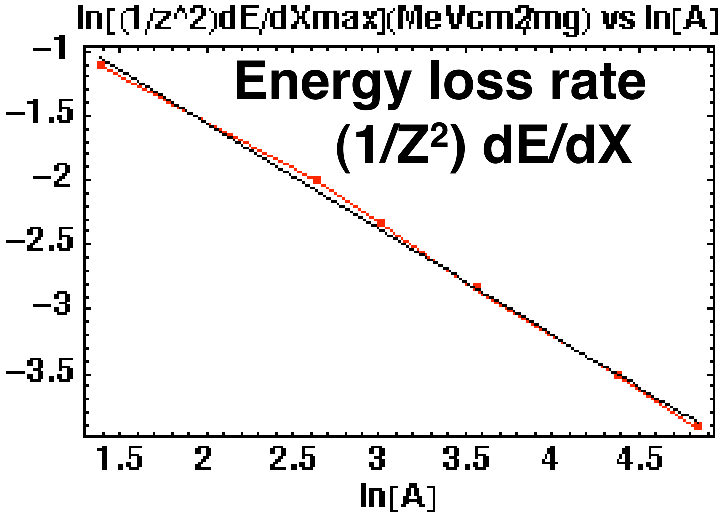


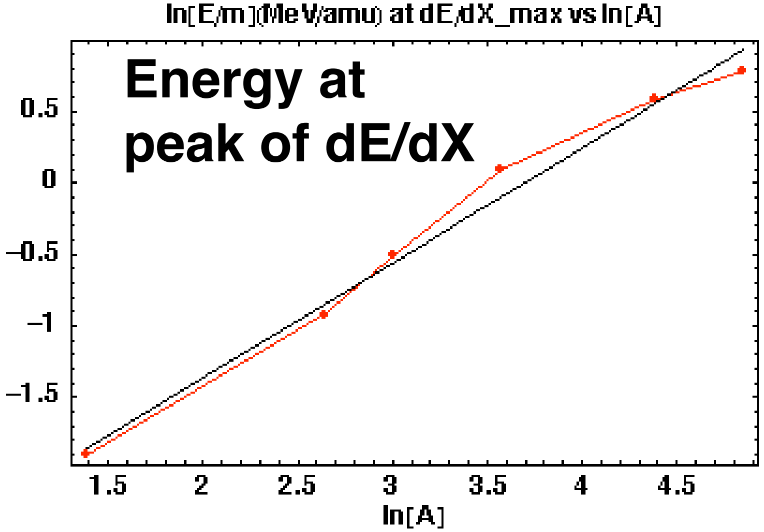
Rarefaction wave propagates inward at c_s (with c_s increasing with time)

The heating pulse should be delivered in a time short compared to the time it takes for a rarefaction wave to reach an interior point, such that a significant portion of the target has reached maximum temperature.

Increasing ion mass, increases energy of Bragg peak, and energy loss rate at Bragg peak







For 4 < A < 126 (He -> I):

Energy at maximum dE/dX:

$E_{dEdXmax} \sim 0.052$ MeV $A^{1.803}$

Energy loss rate at maximum dE/dX:

$(1/Z^2)dE/dX_{max} \sim 1.09$ (MeVcm²/mg) $A^{-0.82}$

$dE/dX_{max} \sim 0.35$ (MeVcm²/mg) $A^{1.07}$

Some scalings

E (at dE/dX_{max}) $=\sim 11.5$ MeV $(A/20)^{1.803}$ **(ion energy at peak in dE/dX)**

$\Delta E/E = \sim < 0.50$ **(for a 5% change in dE/dX, half width in energy)**

$Z = 2\Delta E/(\rho\, dE/dX) = \sim 4.8\ \mu\ \ (A/20)^{0.733}(\rho_{al}/\rho)$ **(width of foil for 5% change)**

Energy density U increases with higher ρ, larger A:

$$U = \frac{2N_{ions}\Delta E}{\pi r^2 Z} = 1.2\times 10^{11}\frac{\mathrm{J}}{\mathrm{m}^3}\left(\frac{N_{ions}}{10^{12}}\right)\left(\frac{1\ \mathrm{mm}}{r}\right)^2\left(\frac{\rho}{\rho_{al}}\right)\left(\frac{A}{20}\right)^{1.07}$$

Temperature kT depends weakly on ρ, and increases with A:

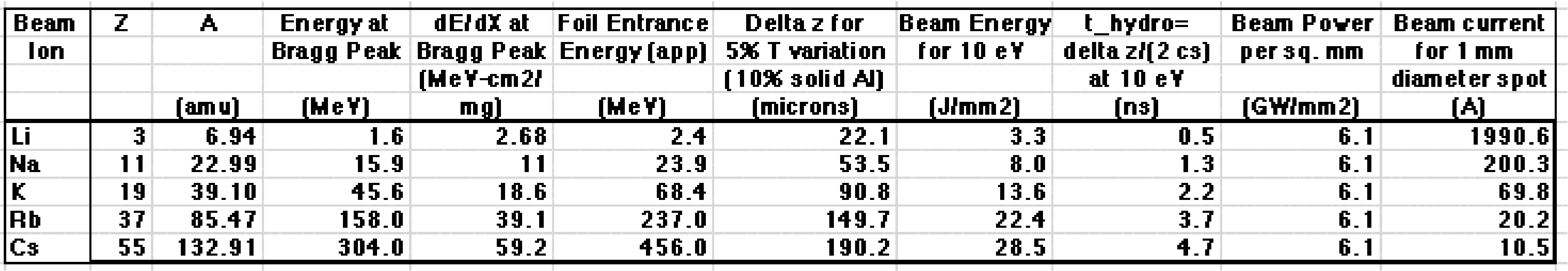
$$kT \approx \frac{2A_{\mathrm{targ}}m_H}{3(Z^*_{\mathrm{targ}}+1)}\left(\frac{U}{\rho}\right) \approx 2.5\ \mathrm{eV}\left(\frac{N_{ions}}{10^{12}}\right)\left(\frac{1\mathrm{mm}}{r}\right)^2\left(\frac{3.4}{Z^*_{\mathrm{targ}}+1}\right)\left(\frac{A}{20}\right)^{1.07}$$

Hydro time t_{hydro} increases with lower ρ, and weakly with larger A:

$$t_{hydro} = Z/c_s = \frac{Z}{\sqrt{\gamma(\gamma-1)U/\rho}} = 1.1\times 10^{-9}\mathrm{s}\left(\frac{10^{12}}{N_{ions}}\right)^{1/2}\left(\frac{r}{1\ \mathrm{mm}}\right)\left(\frac{\rho_{al}}{\rho}\right)\left(\frac{A}{20}\right)^{0.198}$$

Various ion masses and energies have been considered for Bragg-peak heating

Beam parameters needed to create a 10 eV plasma
in 10% solid aluminum foam, for various ions
(10 eV is equivalent to ~ 10^{11} J/m^3 in 10% solid aluminum)



Beam Ion	Z	A (amu)	Energy at Bragg Peak (MeV)	dE/dX at Bragg Peak (MeV-cm2/mg)	Foil Entrance Energy (app) (MeV)	Delta z for 5% T variation (10% solid Al) (microns)	Beam Energy for 10 eV (J/mm2)	t_hydro= delta z/(2 cs) at 10 eV (ns)	Beam Power per sq. mm (GW/mm2)	Beam current for 1 mm diameter spot (A)
Li	3	6.94	1.6	2.68	2.4	22.1	3.3	0.5	6.1	1990.6
Na	11	22.99	15.9	11	23.9	53.5	8.0	1.3	6.1	200.3
K	19	39.10	45.6	18.6	68.4	90.8	13.6	2.2	6.1	69.8
Rb	37	85.47	158.0	39.1	237.0	149.7	22.4	3.7	6.1	20.2
Cs	55	132.91	304.0	59.2	456.0	190.2	28.5	4.7	6.1	10.5

Accelerator to achieve WDM is challenging -- explores new beam physics regimes

Consider:

20 MeV Ne^+ beam, Δt = 1 ns, N_{ions}=1.0 x 10^{13} particles

Then:

β~ 0.045;

Bunch length $l_b = \beta c\ \Delta t$ = 1.4 cm

Line charge = eN_{ions} / l_b=110 μC/m

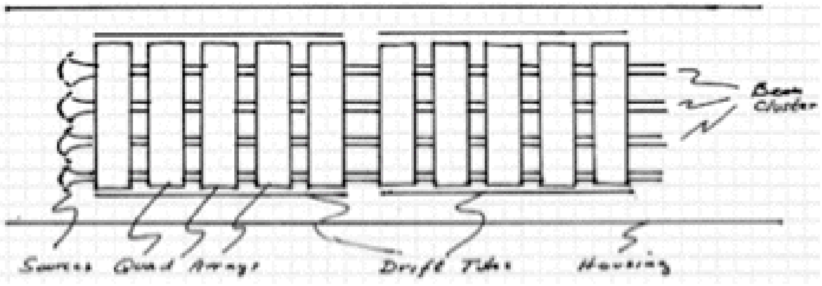
$E_z \sim eN_{ions}/4\pi\varepsilon_0\, l_b^2$ ~ 75 MV/m

So just to keep beam together requires substantial electric field. (1-2 MV/m typical "limit" in induction linac). So instead: use plasma to neutralize beam during final focus and drift compression

Ideas for accelerator configurations for HEDP emerged from HIF VNL “brainstorming” meetings and workshop(October 2004)

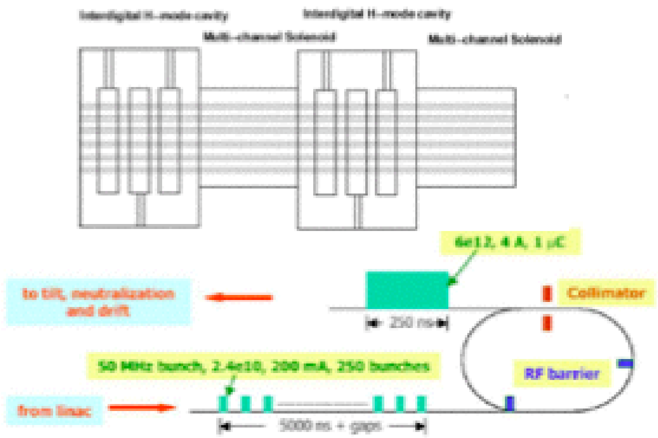
workshop proceedings: http://hifweb.lbl.gov/public/hedpworkshop/toc

Drift-Tube Linac



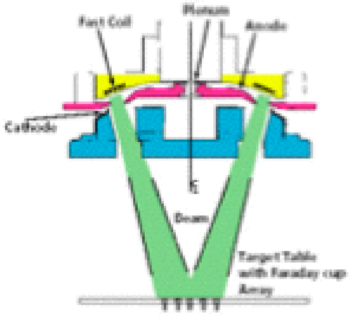
Faltens, *WS Proceedings*

RF Linac, w/ or w/o stacking ring



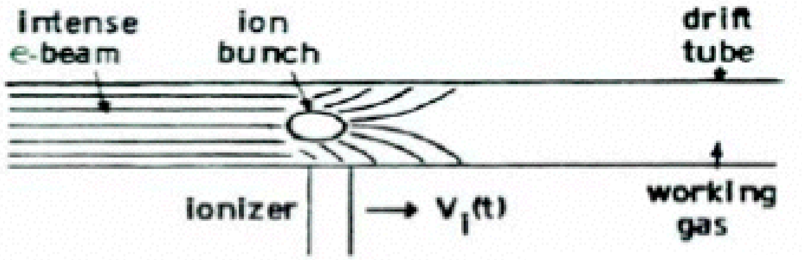
Staples, Sessler, Ostroumov, Chou, and Keller, ***WS Proceedings***

Single-gap diode



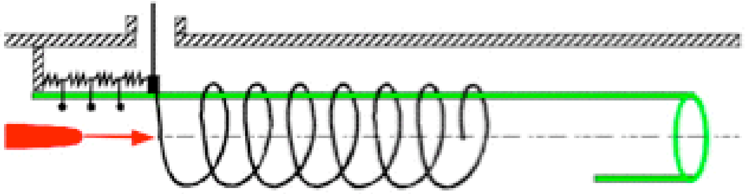
Olson, Ottinger, and Renk, *WS Proceedings*

Ionization Front Accelerator



Welch, Rose, & Olson, ***WS Proceedings***

Pulse-Line Ion Accelerator



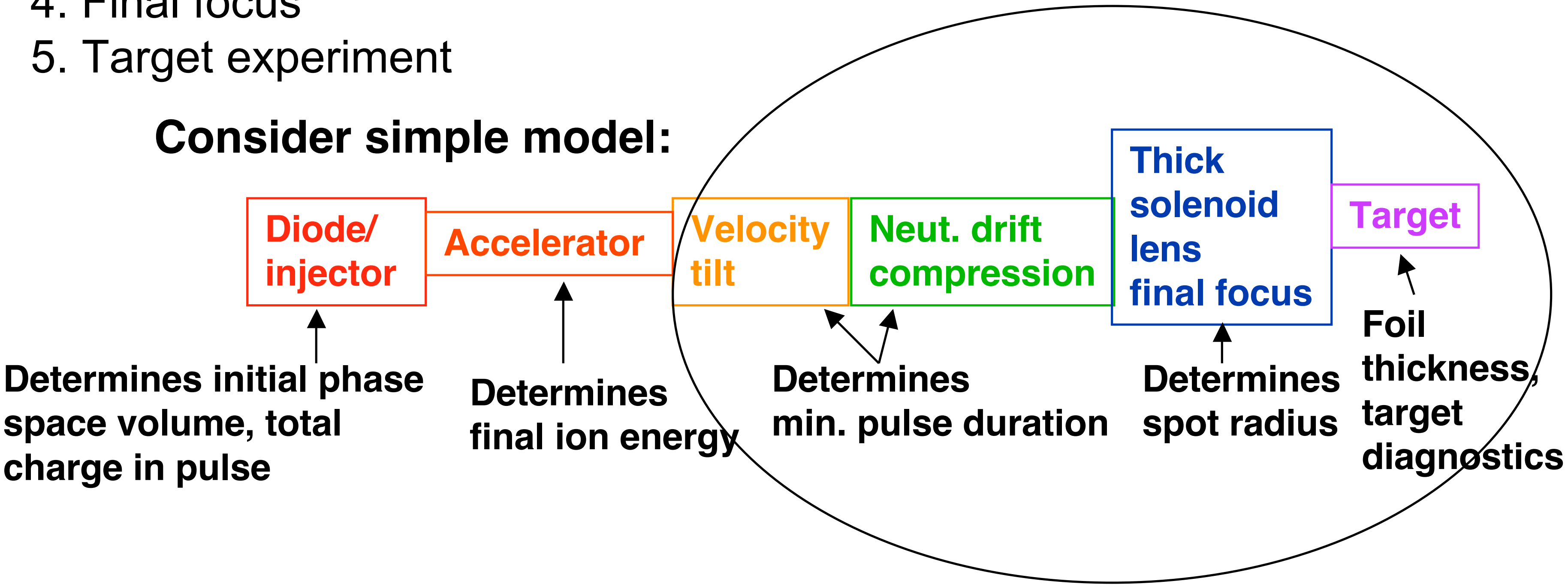
Briggs, ***WS Proceedings***

How do you connect the requirements to achievable parameters?

What are the requirements on the longitudinal and transverse emittance, and imposed velocity tilt?

1. Source/ Injector
2. Accelerator
3. Drift compression
4. Final focus
5. Target experiment

Consider simple model:



Diode/ injector

Accelerator

Velocity tilt

Neut. drift compression

Thick solenoid lens final focus

Target

Determines initial phase space volume, total charge in pulse

Determines final ion energy

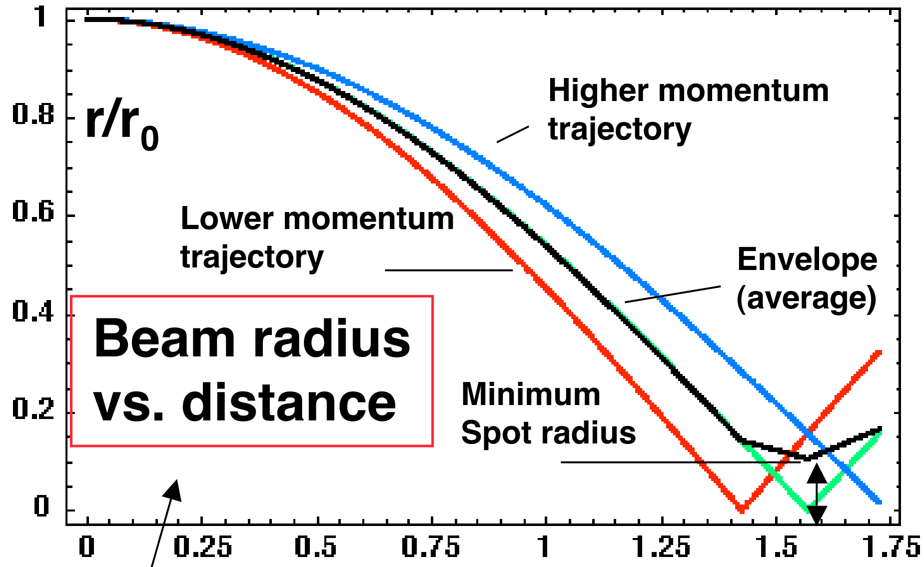
Determines min. pulse duration

Determines spot radius

Foil thickness, target diagnostics

The short pulse time and small spot radius place tight constraints on longitudinal and transverse emittance

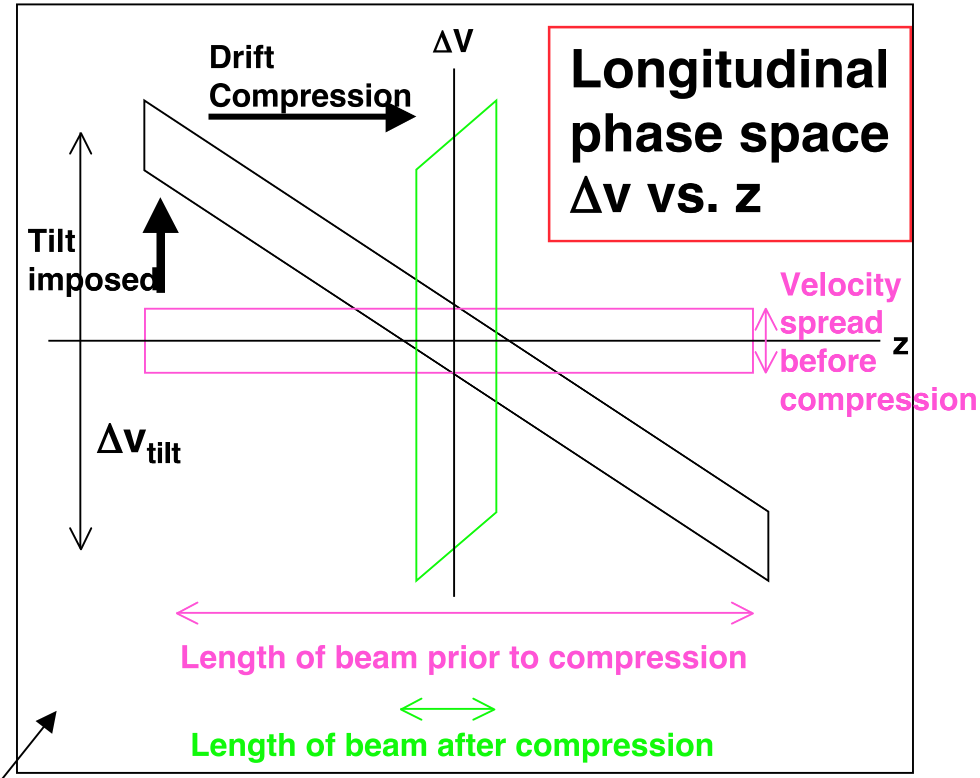
Transversely, spot radius determined by emittance + chromatic aberrations



$$r_{spot}^2 = \frac{4\varepsilon^2 f^2}{\pi^2 r_0^2} + \frac{\pi^2 r_0^2}{4}\left\langle \frac{\delta p^2}{p^2}\right\rangle_{\substack{after\\ compress}}$$

$$\left\langle\frac{\delta p^2}{p^2}\right\rangle^{1/2}_{\substack{after\\ compress}} = C\left\langle\frac{\delta p^2}{p^2}\right\rangle^{1/2}_{\substack{before\\ compress}} = \eta\left(\frac{\Delta v}{v}\right)_{tilt}$$

Longitudinally, phase space undergoes rotation during drift compression; $<\delta v/v>$ limits final bunch length



C = ratio of initial to final bunch length;
η = conversion factor from tilt to rms (~0.22 - 0.29)

Increasing velocity tilt decreases pulse duration but increases spot radius

If $r_{spot}^2 = \frac{4\varepsilon^2 f^2}{\pi^2 r_0^2} + \frac{\pi^2 r_0^2}{4}\left\langle\frac{\delta p}{p}\right\rangle^2_{\substack{after\\ compress}}$ **then optimum initial beam radius** r_{0_opt} **which minimizes** r_{spot}**:**

$$r^2_{0\_opt} = \frac{4\varepsilon f}{\pi^2\langle\delta p/p\rangle_{\substack{after\\ compress}}}$$

Minimum spot radius at r_{0_opt} **is then:**

$$r^2_{spot\,\min} = 2\varepsilon f\left\langle\frac{\delta p}{p}\right\rangle_{\substack{after\\ compress}}$$

$$\left\langle\frac{\delta p^2}{p^2}\right\rangle^{1/2}_{\substack{after\\ compress}} = C\left\langle\frac{\delta p^2}{p^2}\right\rangle^{1/2}_{\substack{before\\ compress}} = \eta\left(\frac{\Delta v}{v}\right)_{tilt}$$

At maximum compression

$$r^2_{spot\,\min} = 2\eta\varepsilon f\left(\frac{\Delta v}{v}\right)_{tilt}$$

$$\Delta t_{\substack{after\\ compress}} = \frac{\Delta t_{\substack{before\\ compress}}\left\langle\frac{\delta p^2}{p^2}\right\rangle^{1/2}_{\substack{before\\ compress}}}{\eta\left(\frac{\Delta v}{v}\right)_{tilt}}$$

Example: for $\Delta v/v_{tilt} = .1$, $\varepsilon_N = 2$ **mm-mrad,** $\beta = 0.047$
$f = 0.4$ **m,** $\eta = 0.29$ **==>** $r_{spotmin} = 1.0$ **mm**
For $\Delta t = 20\ ns$ **and** $\delta p/p_{rms} = 0.1\%$ **(both before compression)**
yields $\Delta t = 0.7\ ns$ **(after compression).**

The optimum spot radius is limited by the transverse and longitudinal emittance

$$r^2_{spot\,\min} = 2\varepsilon f\left(\frac{\Delta v}{v}\right)_{tilt} = \frac{f\varepsilon_{nx}\varepsilon_{nz}}{\sqrt{3}\beta^3 c\tau}$$

Here $\varepsilon_{\mathbf{nx}}$ = normalized transverse emittance
and $\varepsilon_{\mathbf{nz}}$ = normalized longitudinal emittance = $\varepsilon_{nz} \equiv 12\beta\left(\langle z^2\rangle\langle z'^2\rangle - \langle zz'\rangle^2\right)^{1/2} \approx \sqrt{12}\beta^2\left\langle\frac{\delta p^2}{p^2}\right\rangle^{1/2} c\tau$
f **= focal length = 0.7 m for B=15 T, 23.5 MeV Na**
τ **= final bunch duration = 1 ns**
β**= final ion velocity/**c

Example: for $\Delta v/v_{tilt} = .1$, $\varepsilon_N = 2$ **mm-mrad,** $\beta = 0.047$
$f = 0.4$ **m,** $\eta = 0.29$ **==>** $r_{spotmin} = 1.0$ **mm**
For $\Delta t = 20\ ns$ **and** $\delta p/p_{rms} = 0.1\%$ **(both before compression)**
yields $\Delta t = 0.7\ ns$ **(after compression)**

Tradeoffs between pulse duration and velocity tilt yield different requirements on initial $\langle \delta p/p \rangle$ and ε_N

For r_{spot}= 1 mm, Δt =1 ns pulse on target, 24 MeV Na beam:

Pulse duration (before drift compression) (ns)	Compression ratio C	Velocity tilt (Head to tail) dv/v_tilt	Maximum rms velocity spread dp/p_rms (befor drift comp)	Maximum emittance unnormalized 4 rms (mm-mrad)	Maximum normalized emittance 4 rms (mm-mrad)	Beam radius at solenoid entrance Ro (m)	Neutralized Drift length (m)	Maximum rms velocity spread dp/p_rms (at injector)
20	20	0.05	7.22E-04	49.5	2.3	0.031	5.34	1.98E-03
20	20	0.1	1.44E-03	24.7	1.2	0.016	2.67	3.97E-03
20	20	0.2	2.89E-03	12.4	0.6	0.008	1.34	7.93E-03
50	50	0.05	2.89E-04	49.5	2.3	0.031	13.77	1.98E-03
50	50	0.1	5.77E-04	24.7	1.2	0.016	6.89	3.97E-03
50	50	0.2	1.15E-03	12.4	0.6	0.008	3.44	7.93E-03

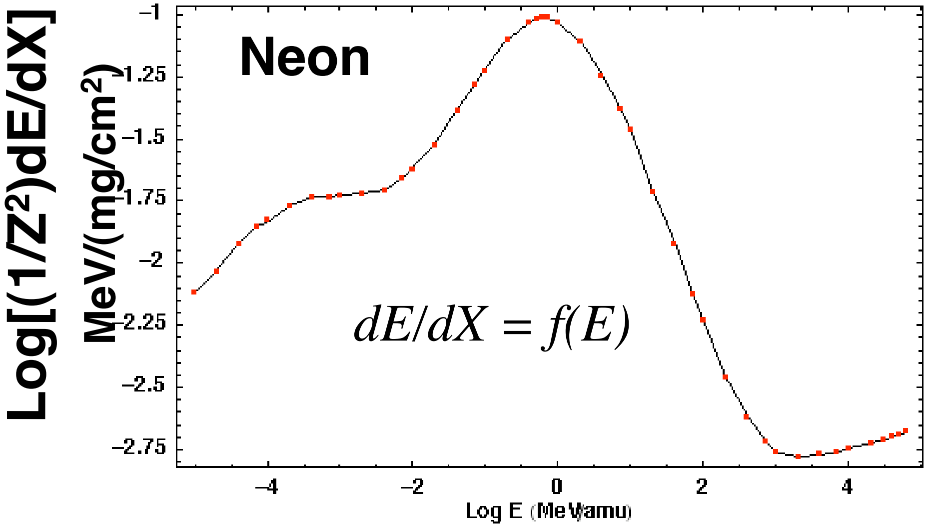
For r_{spot}= 2 mm, Δt =1 ns pulse on target (WITH adiabatic lens)

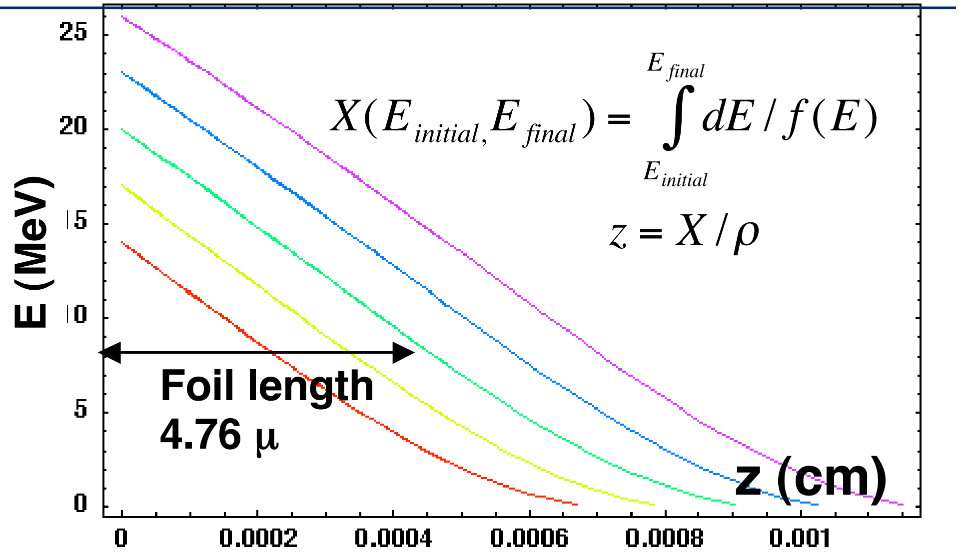
With adiabatic plasma lens, additional factor of two radial compression can be achieved, with large momentum acceptance

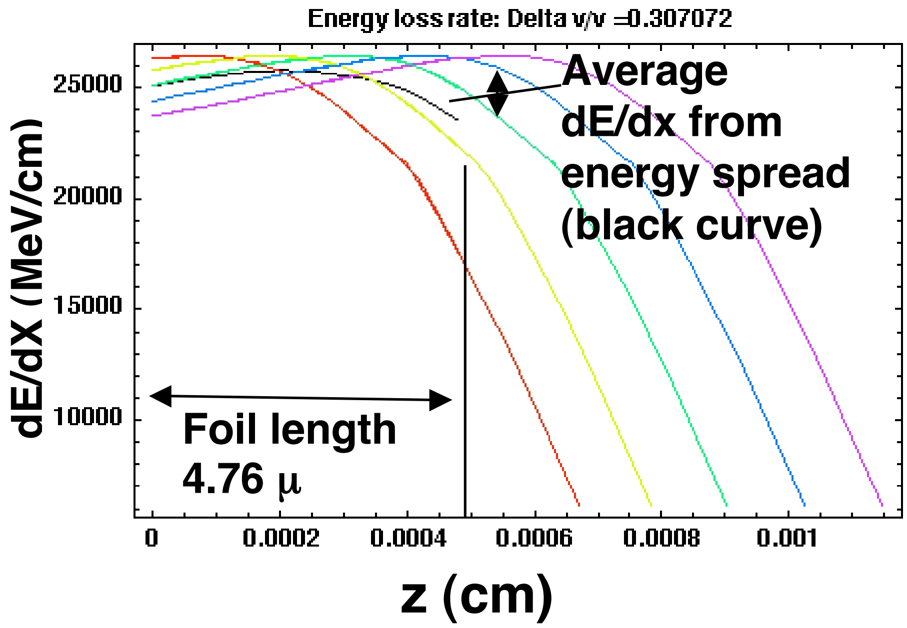
Pulse duration (before drift compression) (ns)	Compression ratio C	Velocity tilt (Head to tail) dv/v_tilt	Maximum rms velocity spread dp/p_rms (befor drift comp)	Maximum emittance unnormalized 4 rms (mm-mrad)	Maximum normalized emittance 4 rms (mm-mrad)	Beam radius at solenoid entrance Ro (m)	Neutralized Drift length (m)	Maximum rms velocity spread dp/p_rms (at injector)
20	20	0.05	7.22E-04	197.8	9.3	0.062	5.34	1.98E-03
20	20	0.1	1.44E-03	98.9	4.6	0.031	2.67	3.97E-03
20	20	0.2	2.89E-03	49.5	2.3	0.016	1.34	7.93E-03
50	50	0.05	2.89E-04	197.8	9.3	0.062	13.77	1.98E-03
50	50	0.1	5.77E-04	98.9	4.6	0.031	6.89	3.97E-03
50	50	0.2	1.15E-03	49.5	2.3	0.016	3.44	7.93E-03

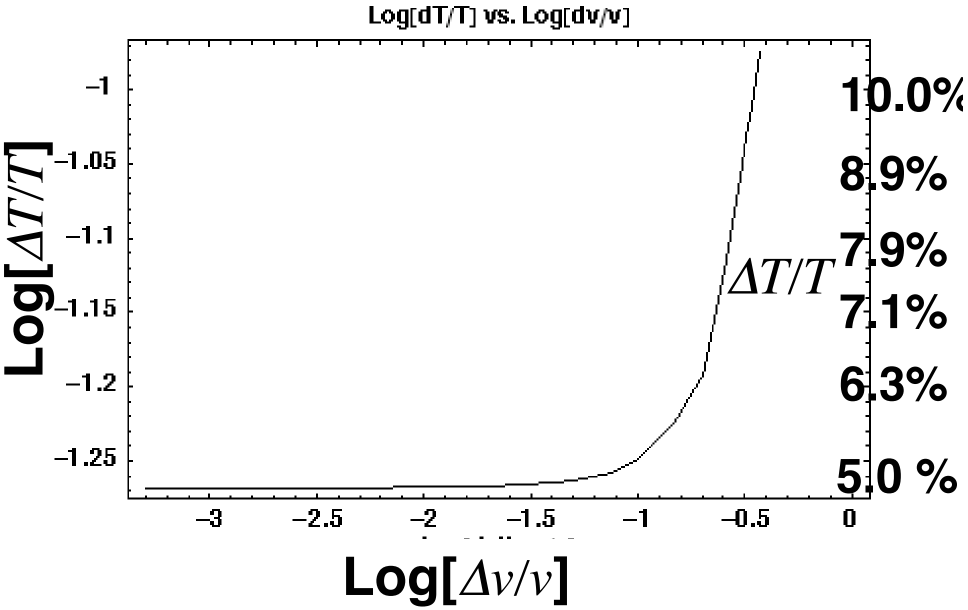
(Injector requirements based on 0.5m, 1 MV pulse with conservation of longitudinal emittance from injector to final focus).

The effect of a velocity spread on temperature uniformity is relatively benign









Parameters of experiments in the NDC sequence leading to a user facility (IBX/NDC)

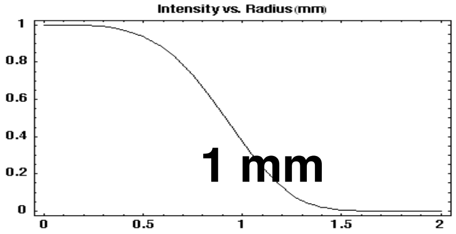
	NDCX-I	NDCX-II		NDCX-III (IBX-NDC)	
Ion Species	K^+	Na^+	Li^+	Na^+	Li^+
Total Charge (μC)	0.002	0.1	0.3	0.3-1.0	1.0
Final Ion Energy (MV)	0.4	23.5	2.4	23.5	2.4
Final Pulse Duration (ns)	2	1	1	1	1
Final Spot Radius (mm)	0.5-1.0	1	1	1	1
Total pulse energy (J)	0.0008	2.4	0.72	7.1-24	2.4
Expected Target Temp (eV)	0.05 - 0.1	2 - 3	1 - 2	5-10	3

We have begun using the 3D LLNL code HYDRA[1] for our target studies

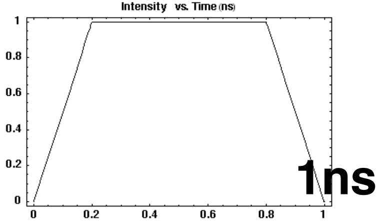
-- A state-of-the-art radiation transport/ hydrodynamics code by M. Marinak and collaborators

-- Initial explorations of ion beam interaction with foil targets:

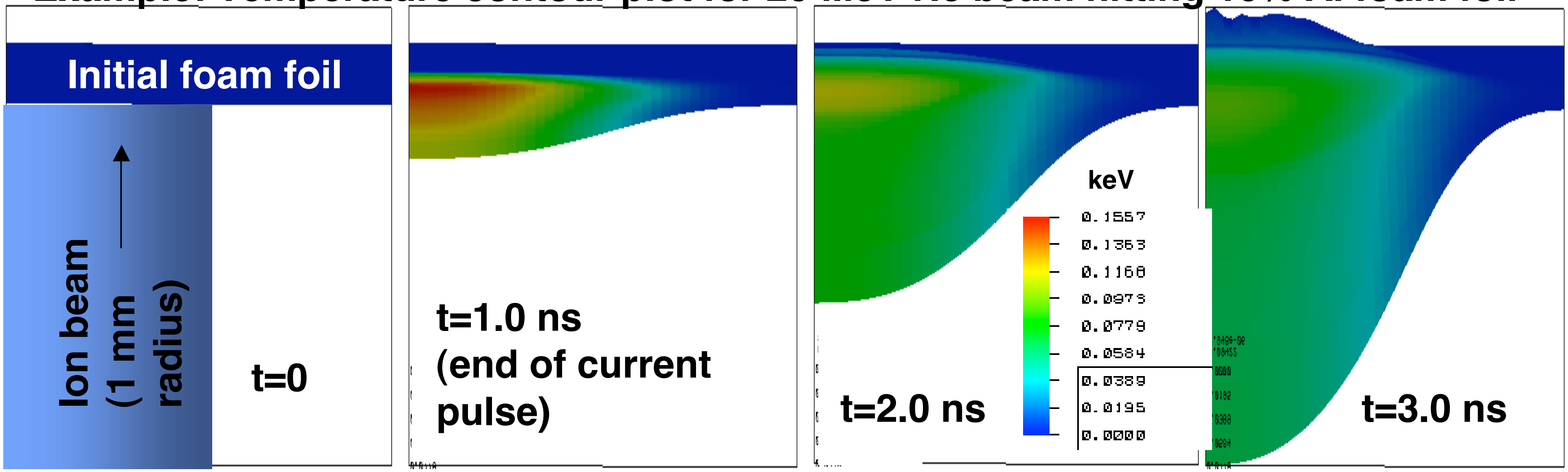
Power vs. radius:



Power vs. time:



Example: Temperature contour plot for 20 MeV Ne beam hitting 10% Al foam foil

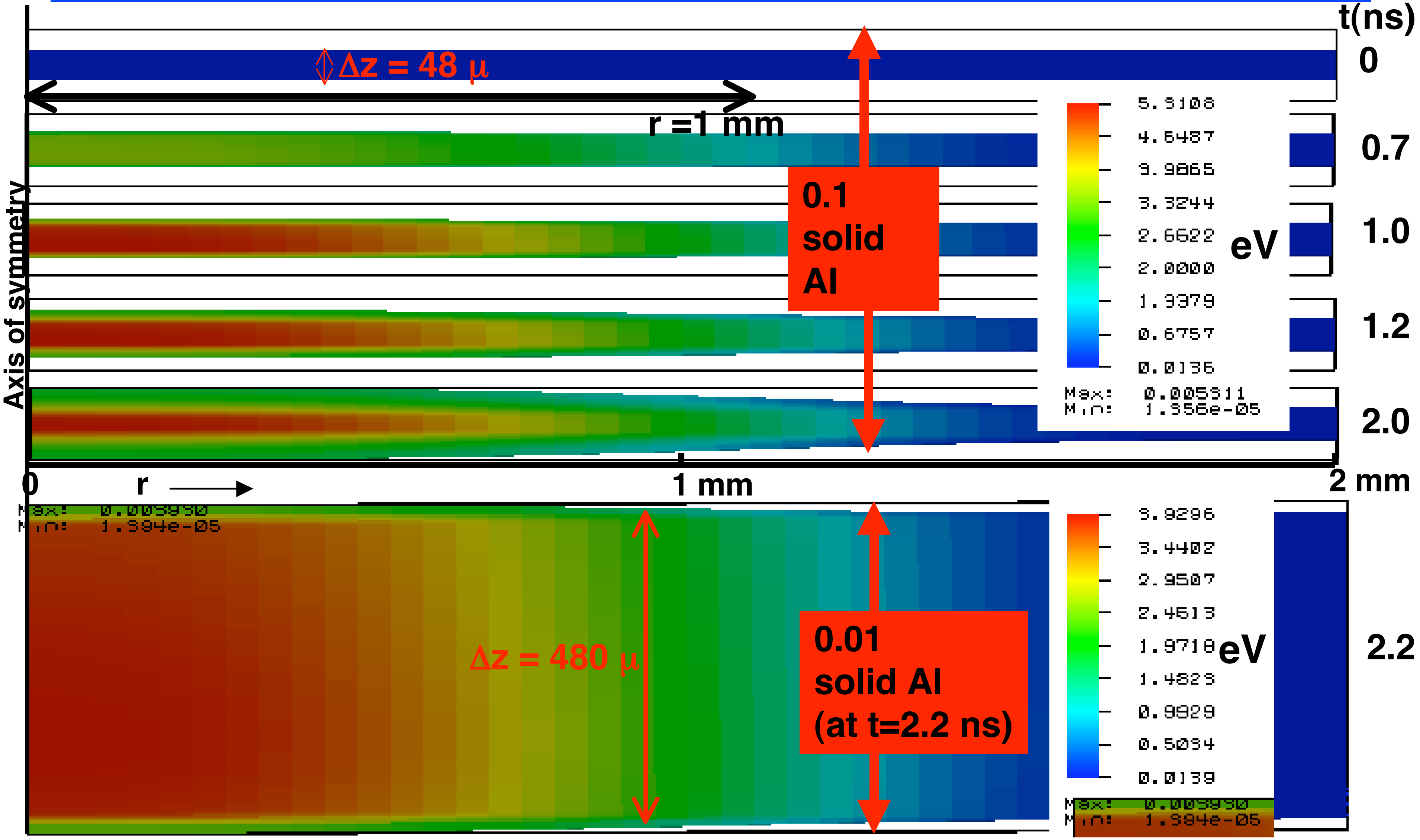


r=0 r=r_b

(2D,l [r-z], time-dependent simulations)

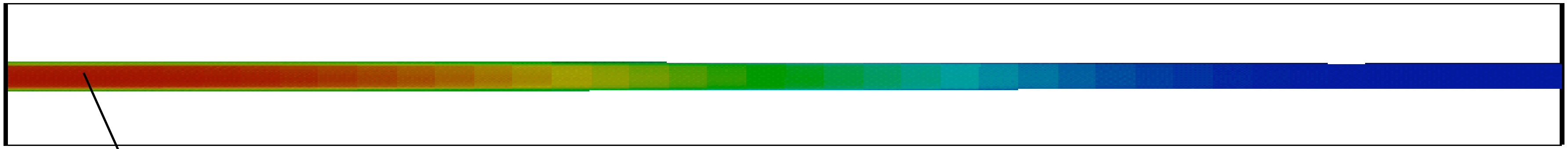
(Intensity 100 x higher, foil 3 x thicker for demo purposes)

Initial simulations of Hydra confirm temperature uniformity of targets at 0.1 and 0.01 times solid density of Aluminum

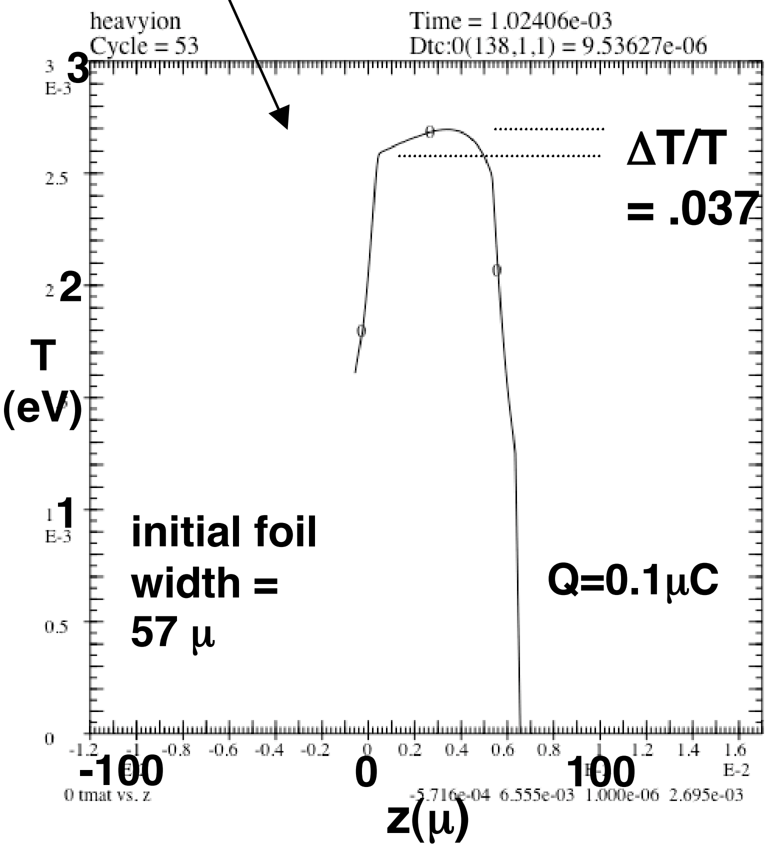


(simulations are for 0.3 μC, 20 MeV Ne beam -- IBX/NDC parameters from workshop).

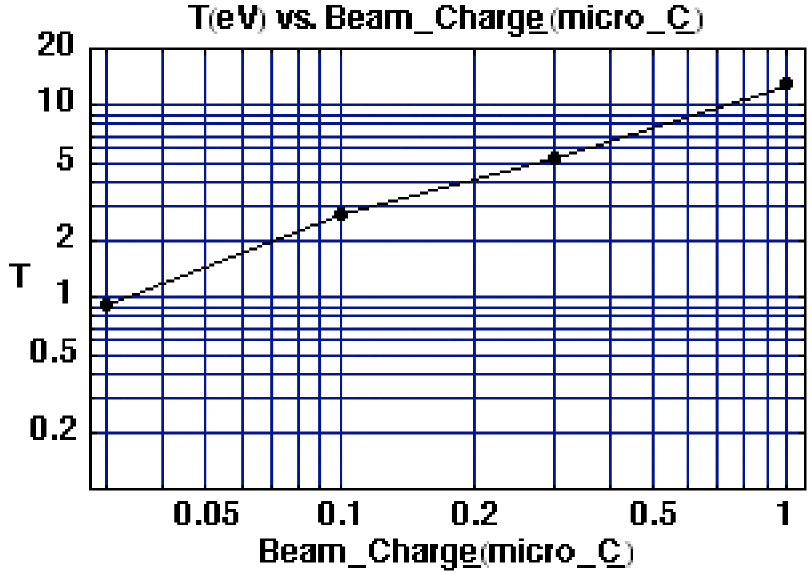
For NDCX-II parameters, temperatures of a few eV could be achieved with high uniformity



t=1ns



Variation of target temperature with total beam charge *Q*



(HYDRA results using QEOS, in Al 10% solid density; 23.5 MeV 1 mm Na$^+$ ion beam)

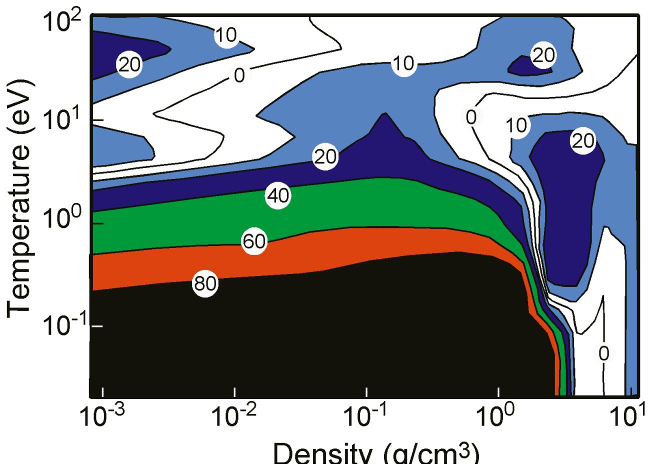
New theoretical EOS work meshes well with experimental capabilities we will be creating

Large uncertainties in WDM region arise in the two phase (liquid-vapor) region

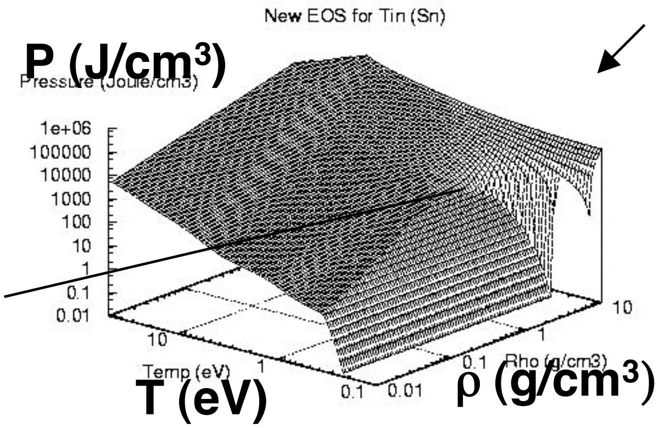
Getting two-phase regime correct will be main job for WDM

R. More has recently developed a new high quality EOS for Sn.

Interesting exactly in the ~1.0 eV regime.



Plot of contours of fractional pressure difference for two common EOS (R. Lee)



Critical point unknown for many metals, such as Sn

New EOS (*cf* R. More, T. Kato, H. Yoneda, 2005, in prep.)

EOS tools for this temperature and density range are just now being developed.

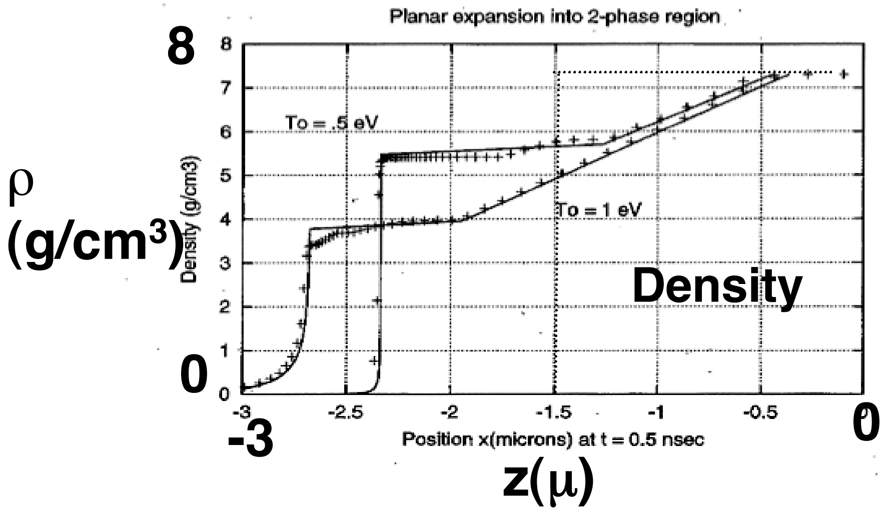
New EOS predicts a sharp density cliff which may facilitate detection and help determine metallic critical points

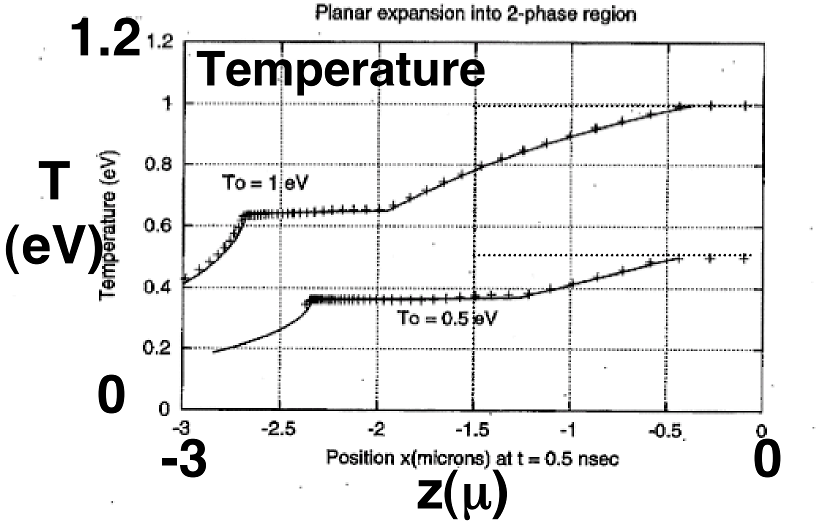
R. More has used a new EOS in his own 1D hydro calculations.

EOS based on known energy levels and Saha equation (in contrast to QEOS, which uses “average” (Thomas Fermi) atom model

Two phase medium results in temperature and density plateaus with cliffs

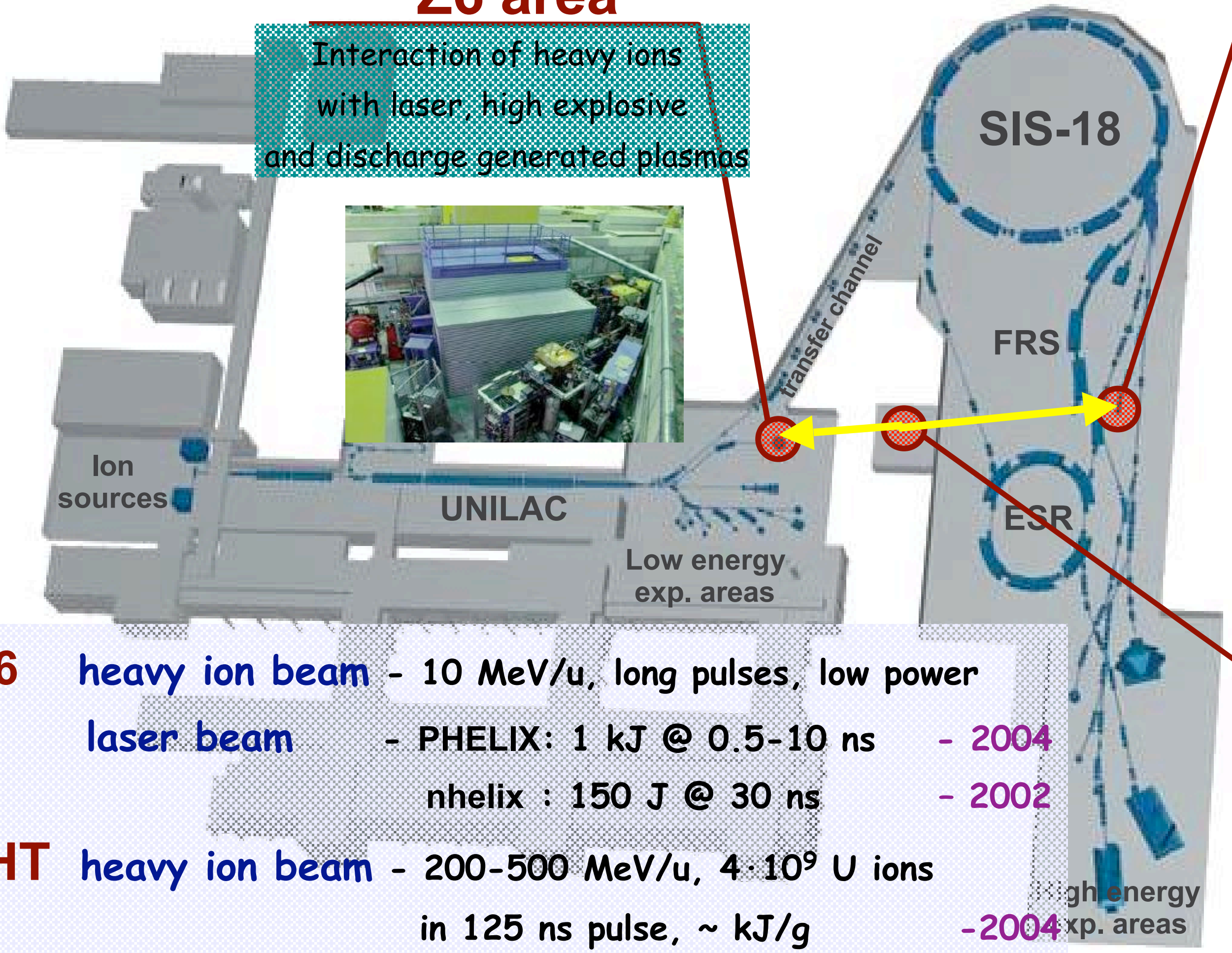
Initial distribution





Example, shown here is initialized at T=0.5 or 1.0 eV and shown at 0.5 ns after “heating.” Expect phenomena to persist for longer times and distances, but still to be explored.

Ion beam stopping experiments at GSI can explore differences between foam and solid dE/dX rates

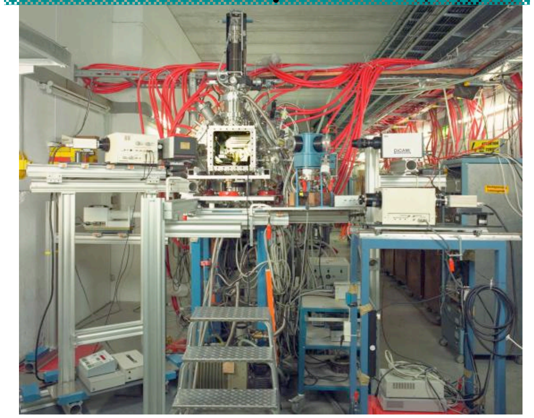


Z6 area

Interaction of heavy ions with laser, high explosive and discharge generated plasmas

HHT area

HED matter generated by intense heavy-ion beams



PHELIX

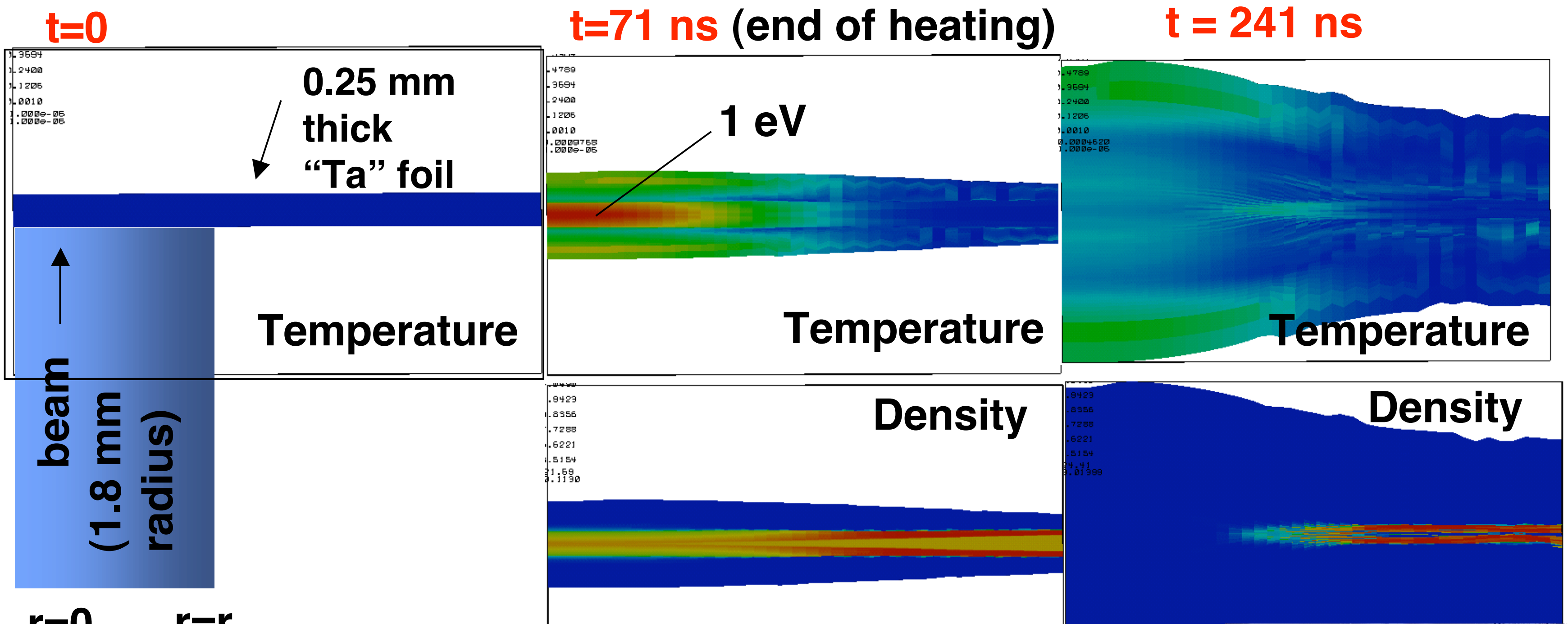
Petawatt High-Energy Laser for Ion-Beam Experiments

Z6	heavy ion beam	- 10 MeV/u, long pulses, low power	
	laser beam	- PHELIX: 1 kJ @ 0.5-10 ns	- 2004
		nhelix : 150 J @ 30 ns	- 2002
HHT	heavy ion beam	- 200-500 MeV/u, $4\cdot10^9$ U ions	
		in 125 ns pulse, ~ kJ/g	-2004
	laser beam	- PHELIX: 0.5 kJ @ 0.5 ps (PW)	-2006
		1-5 kJ @ 10 ns	

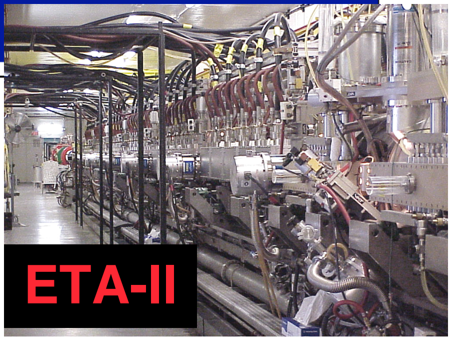
(slide courtesy D. Hoffmann)

Target experiments on ETA II, could almost instantly, provide target experience in interesting regime

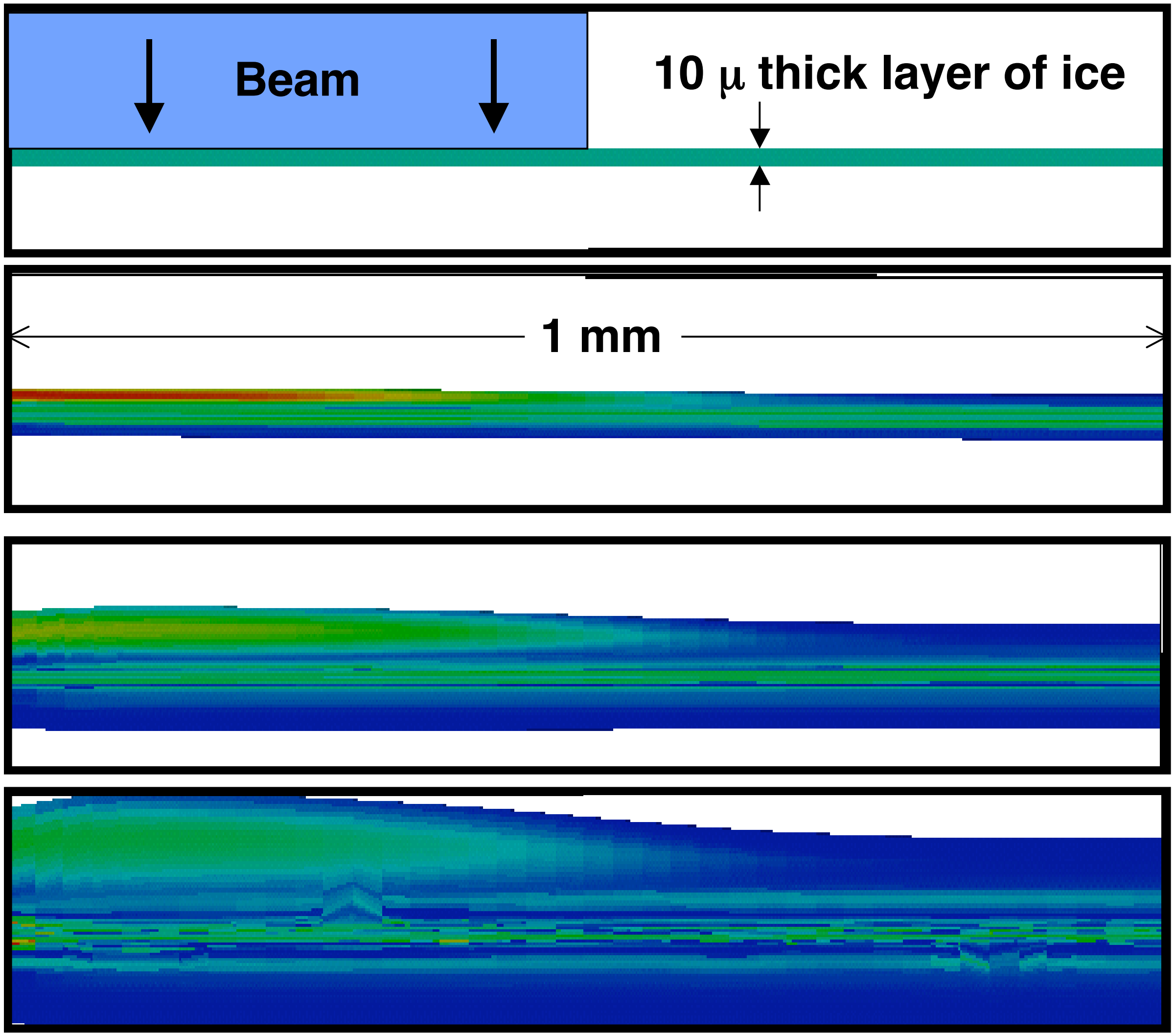
Example: “Tantalum-like” foil, with equivalent 40 GeV proton beam



- ETA II parameters: 5 MeV e-, 2 kA, 50 ns,
- Need to adapt electron beam deposition to include scattering (would be covered by LBNL LDRD)
- Seeking ways to fund project



Experiments to test diagnostics, explore hydro motion and test EOS could be carried out on NDCX I



t =
0 ns

2 ns
(end
of
heating)

5 ns

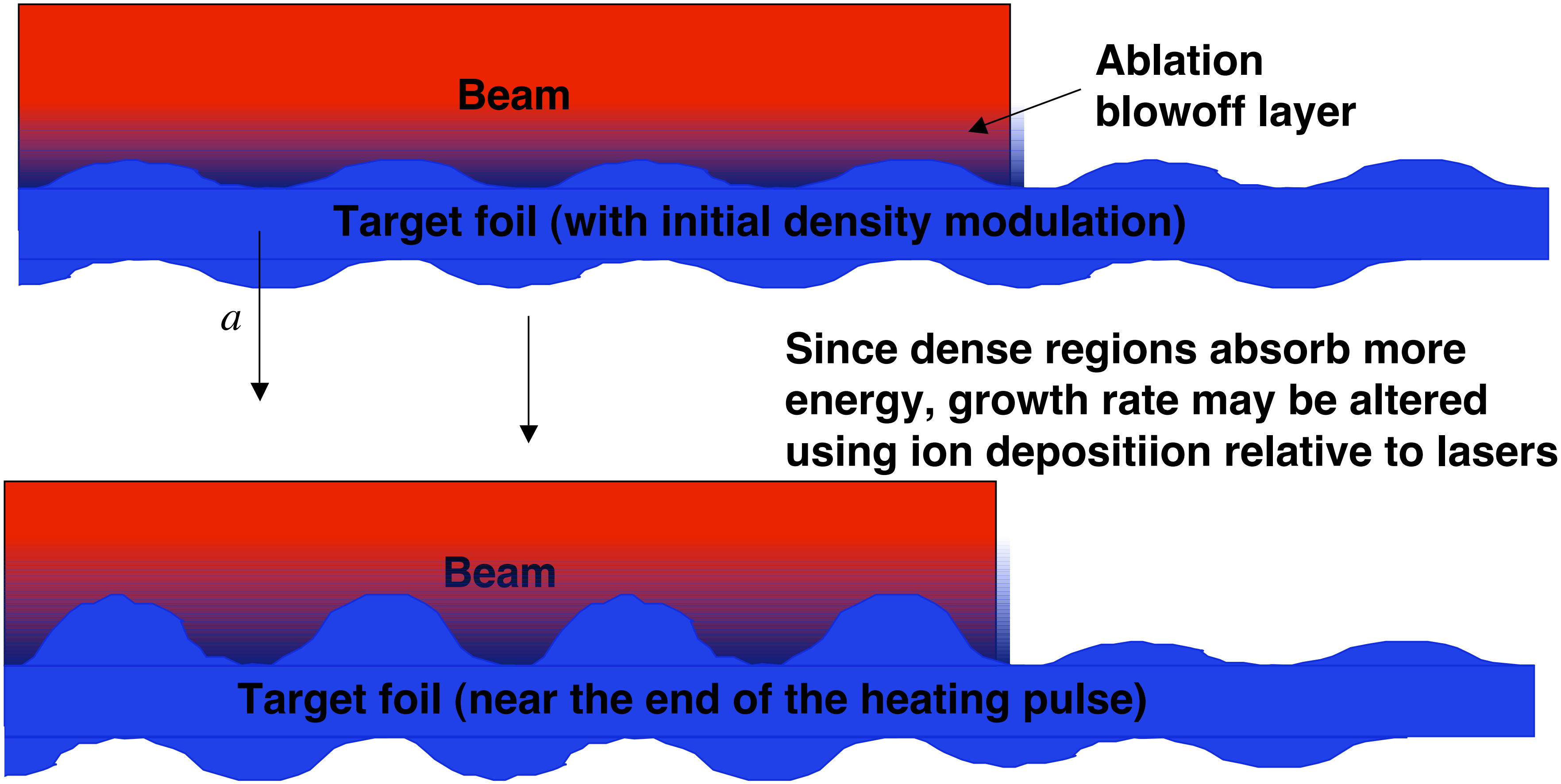
9 ns

Beam parameters:
0.5 mm radius
1 A K^+
2 ns

Target parameters:
10 μ thick layer of ice (possibly on top of solid surface--not included in simulation)

Maximums:
T = 0.07 eV
P=0.027 Mbar
= 2.7GPa (at 3 ns)

Energy deposition using ion beams may alter the growth rate of the Rayleigh-Taylor instability relative to lasers



Since dense regions absorb more energy, growth rate may be altered using ion depositiion relative to lasers

Growth rate γ **(for laser deposition) :** $\gamma \approx (k\,a/(1 + k\,L))^{1/2} - \alpha\,k\,V_a$**, where** k **is the wave number of the perturbation,** a **is the acceleration rate,** L **is the density-gradient scale length,** α **is a constant between** 1 **and** 3, V_a **is the velocity of the ablation front (Lindl, 1998)**

We have begun establishing target requirements for WDM studies and translating to requirements on the accelerator

We are quantitatively exploring the tradeoffs involved in focusing the beam in both space and time

We are using a state-of-the-art rad-hydro simulation code to evaluate targets for WDM study

Several potential experiments are being considered including:

- -- dE/dX experiments in foams and solids at GSI
- -- EOS/conductivity experiments on ETA-II
- -- NDCX-I experiments heating condensed ices
- -- Two-phase experiments on NDCX-II, IBX/NDC
- -- Rayleigh-Taylor experiments on NDCX-II, IBX/NDC

Future simulations and calculations will simulate in detail many of these potential experiments

Phase 2: 10 A, 100-ns He beam at end of accelerator

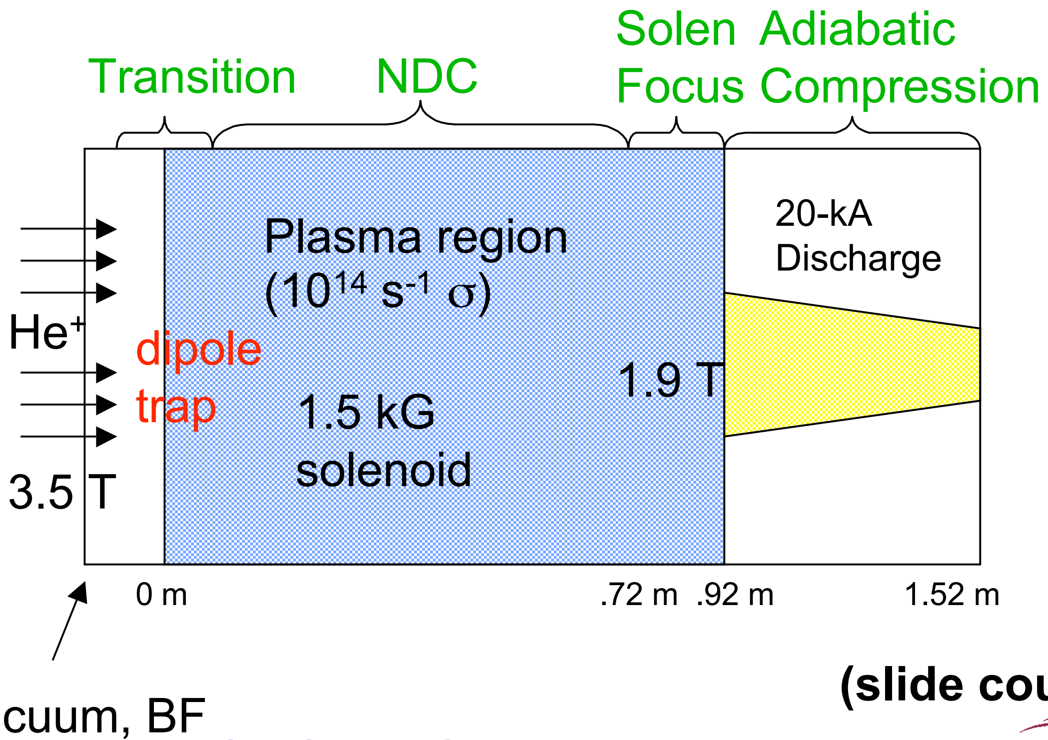
Compressed from 1-A 1-μs beam in accel-decel injector

ε=1.2π-mm-mrad, r=2cm, .75 J

60-cm long adiabatic discharge channel (20 kA); 10 mm to 1 mm radius

67% energy tilt from 500-1000 keV in 100 ns

Need to compress 100x and focus to 1-mm spot to achieve "HEDP"



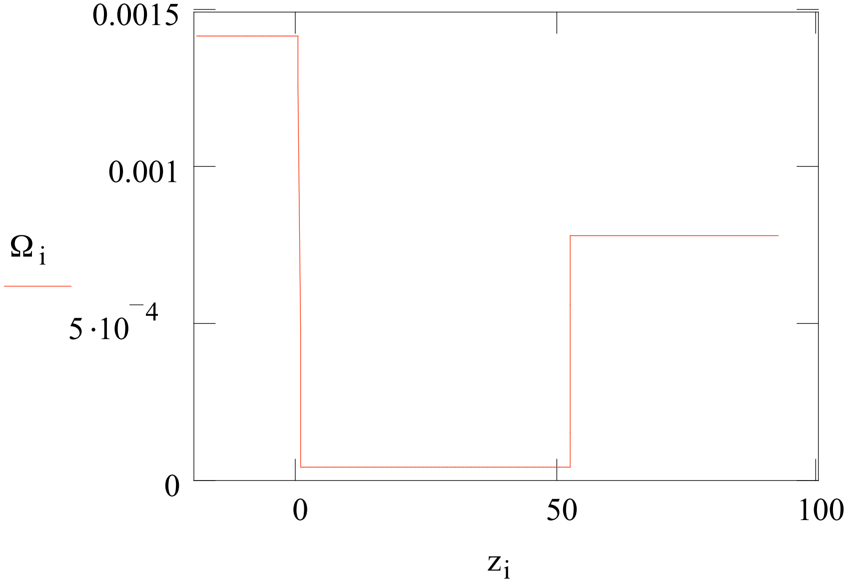
(slide courtesy D. Welch)

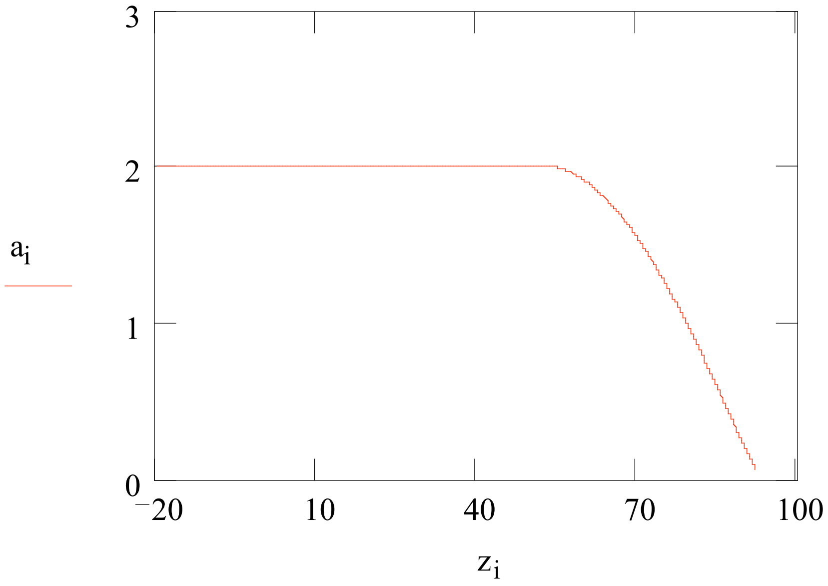
Envelope solution for Brillouin Flow and Neutralized Drift Compression

(slide courtesy D. Welch)

Solution for 750 keV He$^+$

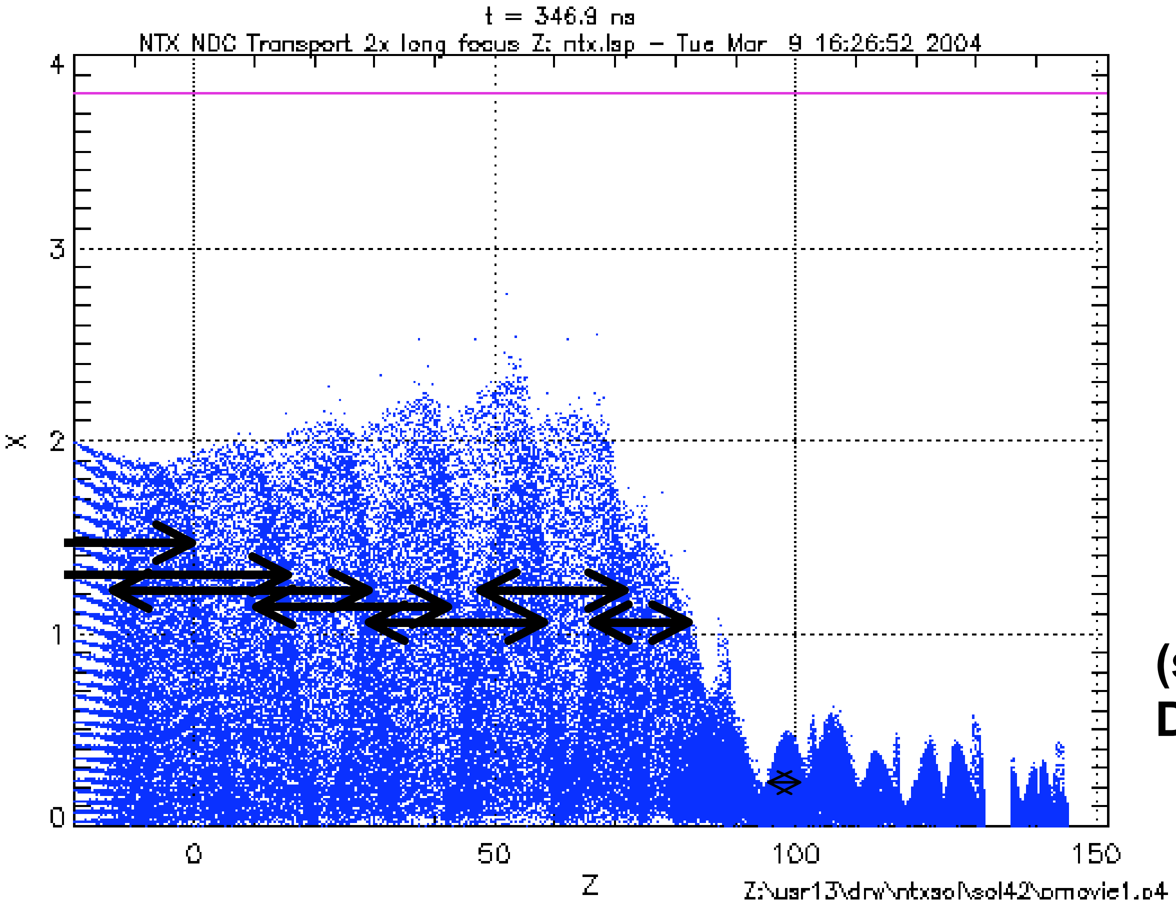
Long 1.9-T,40 cm focusing coil at z = 52-92 cm





Snapshots of Beam Transport

Beam relaxes longitudinally due to incomplete neutralization
Longitudinal "overfocus" to z = 139 gave shortest pulse at z =152



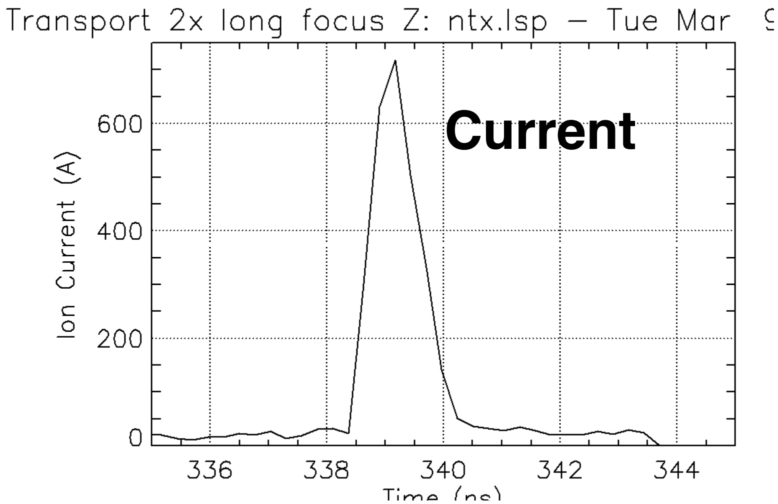
(slide courtesy D. Welch)

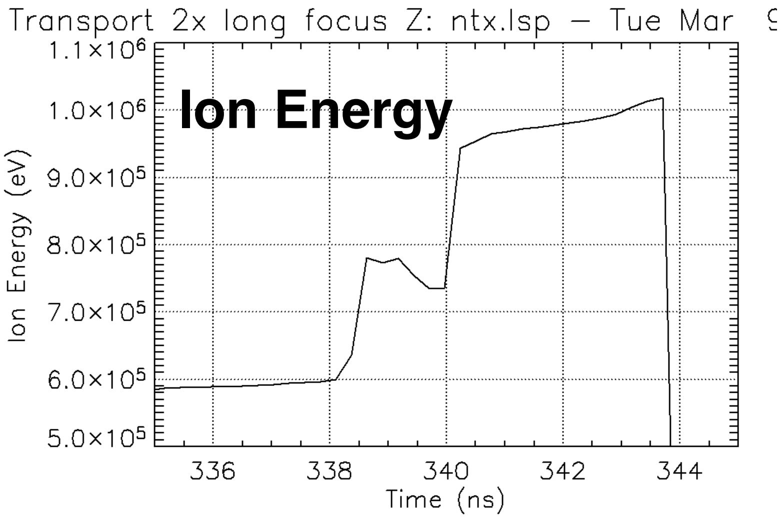
Possible to compensate for less than ideal neutralization

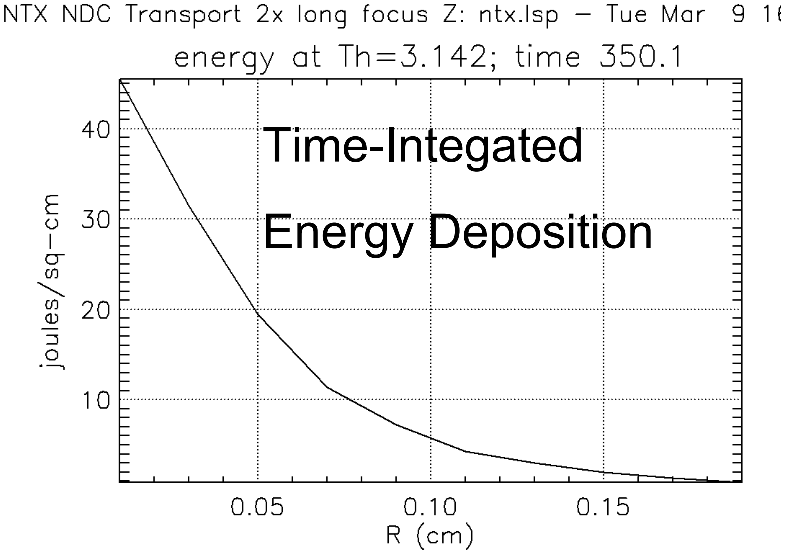
Beam compresses to WDM conditions

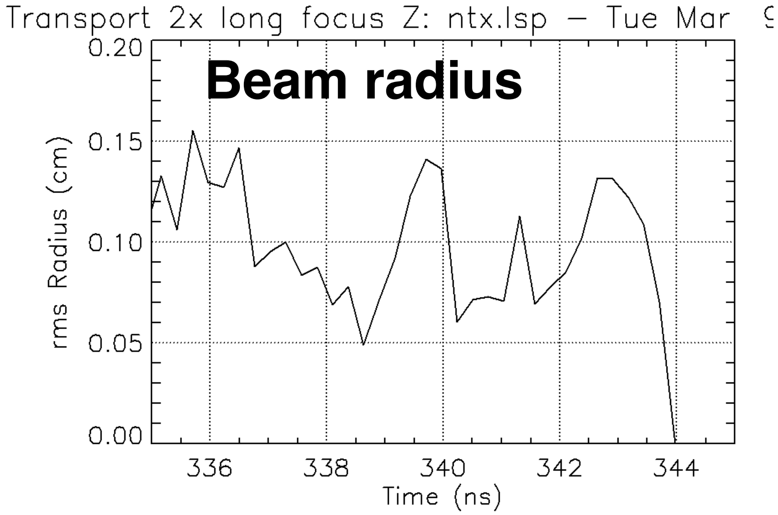
< 1 ns, < 1 mm pulse on target z = 152 cm
Compressed to .75 kA, 75x

(slide courtesy D. Welch)









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
- ❐ requires a laser reflectometer

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

Goal is to field scientifically interesting WDM experiments within 4-5 years.

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, plasma lens

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 backlighter (“Febetron”)**
- **Laser-produced x-ray backlighter (potential collaboration with Wim Leemans group at LBL)**