Ion-Beam-Driven HEDLP Research Opportunities and Connections to the January 2009 FESAC Report on High Energy Density Laboratory Plasmas

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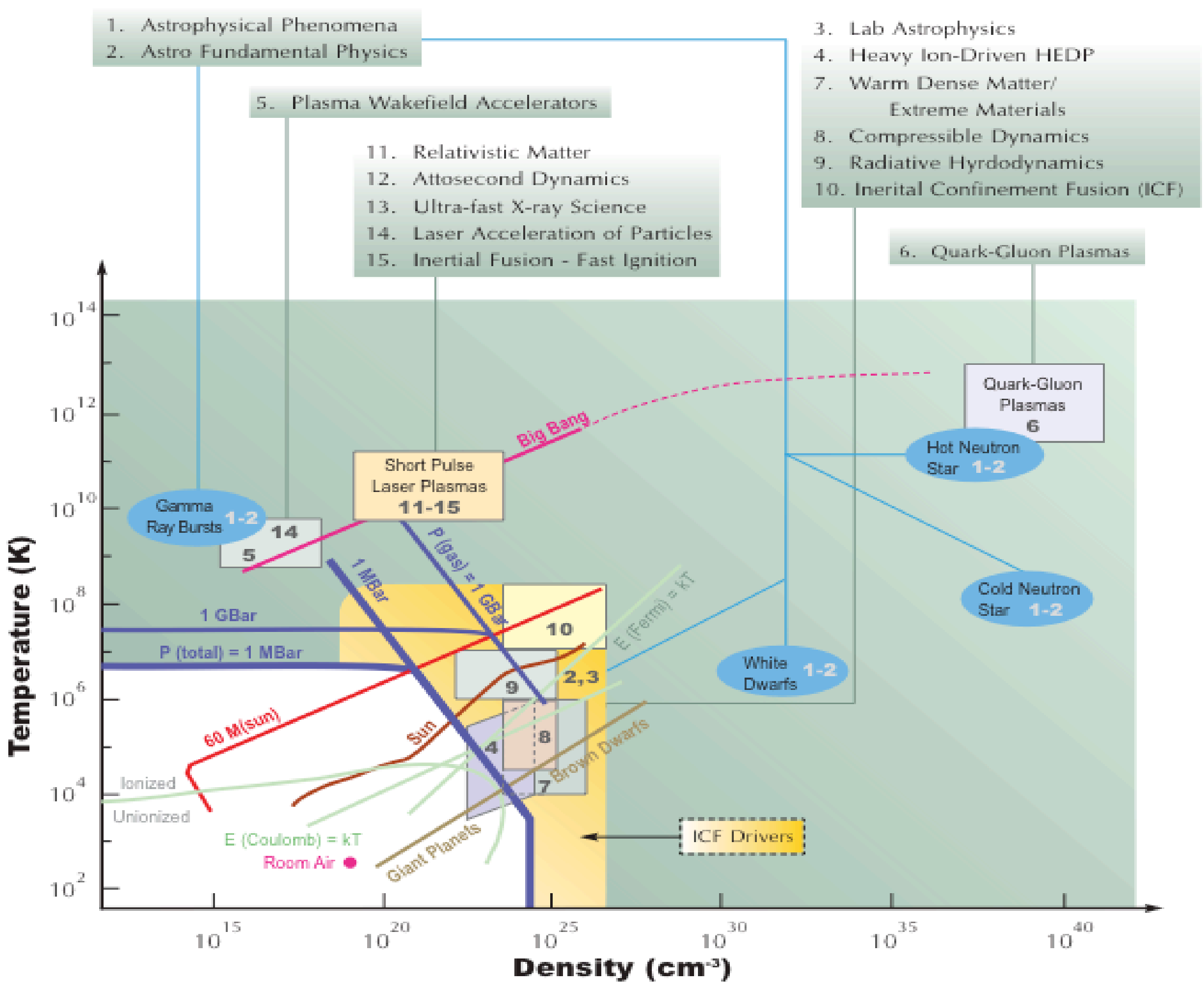
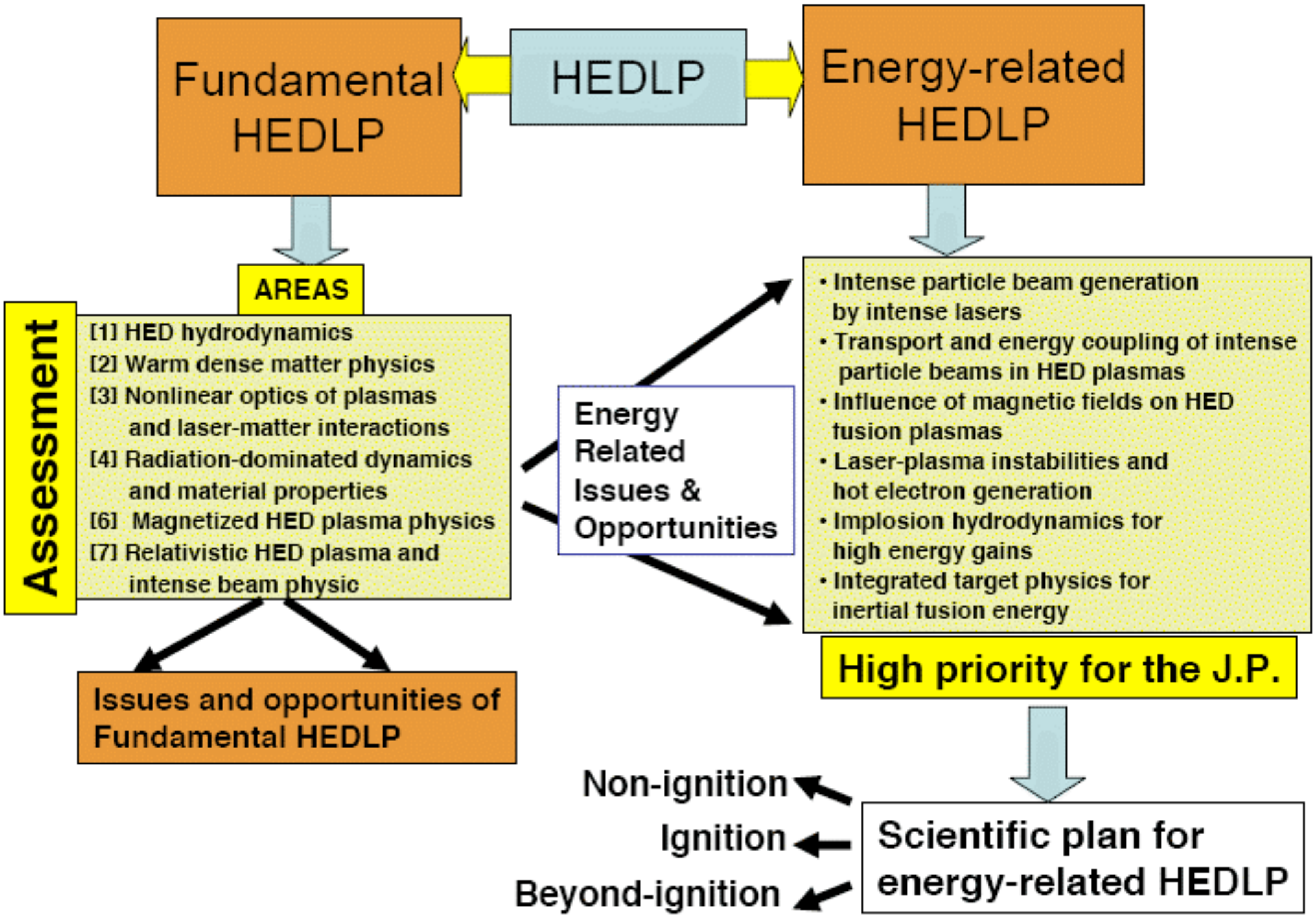
Map of the HED Universe



To address the charge the FESAC HEDLP panel took a two-prong strategy



High Priority Issues for Energy-Related HEDLP Science

HEDLP scientific issues that are essential to the achievement of high gains and improved inertial fusion energy concepts should be given a high priority within the Joint HEDLP Program. *All of these high-priority issues are either not addressed or are only partially addressed by the NNSA-ICF program. Out of fourteen, six high-priority scientific issues are identified that can be addressed by the Joint Program with existing facilities (Excerpted from FESAC HEDLP Panel Report):*

1. **Intense particle-beam generation by ultra-intense lasers.** *Science question:* What are the essential features of the energetic particles generated by intense lasers interacting with plasmas, and how does intense light affect the plasma dynamics?
2. **Transport and energy coupling of intense particle beams in high energy density plasmas.** ***Science question:*** **How are intense charged-particle beams transported in and how does their energy couple to HED plasmas?**
3. **Influence of magnetic fields on high energy density fusion plasmas.** *Science question:* How do magnetic fields, either spontaneous or induced, affect the behavior of HED fusion plasmas, and how can they be utilized to improve the prospects for inertial fusion energy?
4. **Laser-plasma instabilities and hot-electron generation.** Science *question:* How do laser-plasma instabilities reflect light, how do they generate energetic electrons, and how can they be controlled?
5. **Implosion hydrodynamics for high gains.** *Science question:* How can HED plasmas be assembled to the densities and pressures required for maximizing the fusion-energy output?
6. **Integrated target physics for inertial fusion energy.** ***Science question:*** **What are the optimal target designs to achieve high gains with good stability and efficient driver coupling?**

Energy-Related HEDLP Science*

Issue: Transport and Energy Coupling of Intense Charged Particle Beams in HED Plasmas*

Question: How are intense charged-particle beams transported in and how does their energy couple to HED plasmas?

Priority level: (1) High

Description: The underlying physics of transporting intense charge-particle beams in plasmas is of great interest for fast-ignition and heavy ion fusion research. ---------

----- At the beam currents and densities envisioned for electron fast ignition and heavy ion fusion, collective processes and beam-plasma interactions affect transport and focusing. ----------

* Pages 78 - 80, HEDLP FESAC Panel Report (2009)

Issue: Transport and Energy Coupling of Intense Charged Particle Beams in HED Plasmas*

Question: How are intense charged-particle beams transported in and how does their energy couple to HED plasmas?

Priority level: (1) **High**

Description: - *Continued* - ***Collective beam-plasma interaction processes***

----- In heavy ion fusion, collective processes can play an important role in (a) the acceleration and transport regions of the one-component driver beam, (b) the compression region where neutralizing background plasma is introduced to help focus the intense ion beam longitudinally and transversely onto the target, and (c) to a lesser extent in the target region, where classical beam dominate. Depending on the region of beam propagation, **these collective processes can include the electrostatic Harris instability driven by thermal-energy anisotropy of the beam ions, electrostatic two-stream instabilities associated with beam interactions, the resistive hose instability, and the multi-species electromagnetic Weibel (filamentation) instability** associated with beam analytical studies and advanced numerical simulations using particle-in-cell (PIC) and nonlinear delta-f codes, and comparisons with present-day experiments, a very good understanding of these collective interaction processes, including the process of charge neutralization by background plasma, is being developed. Operating regimes to eliminate or minimize the deleterious effects of collective instabilities are being identified. **As the beam density and current continue to increase in the next-generation experiments, the collective interaction processes will become correspondingly much more intense be increasingly important to develop and implement ever-more-accurate integrated modeling capabilities and experimental diagnostic techniques. ------**

Issue: Transport and Energy Coupling of Intense Charged Particle Beams in HED Plasmas*

Question: How are intense charged-particle beams transported in and how does their energy couple to HED plasmas?

Priority level: (1) **High**

Description: - *Continued -* ***High beam-target coupling efficiency***

----- the **most important frontier research issue for heavy-ion beam-target coupling is the effect of increasing the beam velocity in time (velocity ramping up from the head to the tail of the drive pulse), either to keep the ion range constant while the target heats up (for indirect drive), or to increase the ion range several times in direct drive to sufficiently keep ion-energy deposition close to the imploding ablation front.** The latter effect can greatly increase the hydro-coupling efficiency (and target gain) in direct drive, but can also steepen the pressure gradients behind the ablation front, increasing the growth rates of hydrodynamic instabilities. Resolution of this issue requires detailed 2-D hydro-code calculations and experiments.----

The Joint Program should support all six areas of fundamental science

The Joint Program should support all six areas of fundamental HEDLP science. Priority should be given to discovery-driven research efforts of high intellectual value that are expected to advance the field, explore its practical and scientific potentials, stimulate the interest of graduate students, and attract scientists from other disciplines.

Area/Criterion	(1)*	(2)**	(3)***	(4)****
HED hydrodynamics	High	Marginal	Medium	High
Radiation-dominated dynamics and material properties	High	Medium	High	Medium
Magnetized HED plasma physics	High	Medium	High	High
Nonlinear optics of plasmas	High	Medium	Medium	High
Relativistic HED plasma and intense beam physics	High	High	Medium	High
Warm dense matter physics	Medium	Marginal	High	High
*Criterion (1): Importance to the fundamental understanding and development of high energy				
**Criterion (2): Potential for important practical applications				
***Criterion (3): Potential for resolving major issues in other fields of science				
****Criterion (4): Readiness for progress in the next five/ten years				

NDCX I is laying the groundwork for the next step: NDCX-II

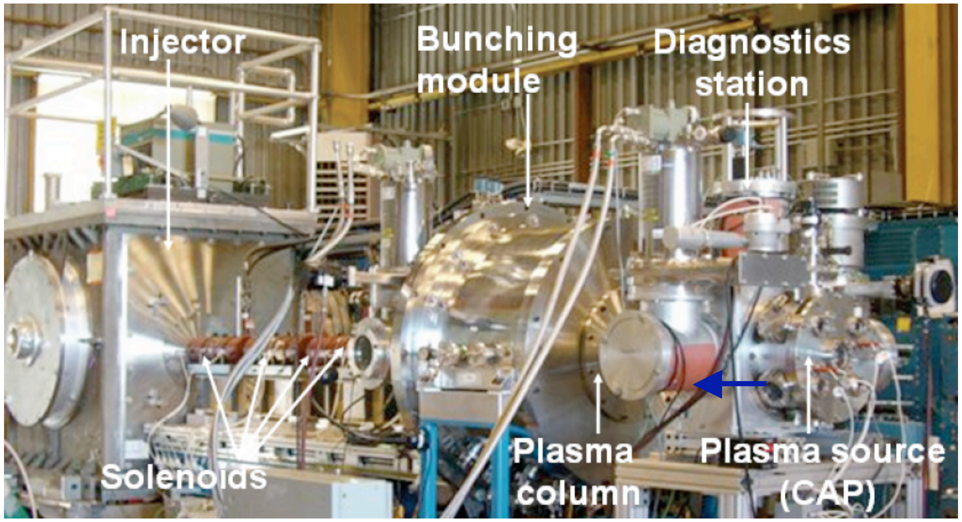
→

NDCX I

0.35 MeV,

0.003 μC

Now



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

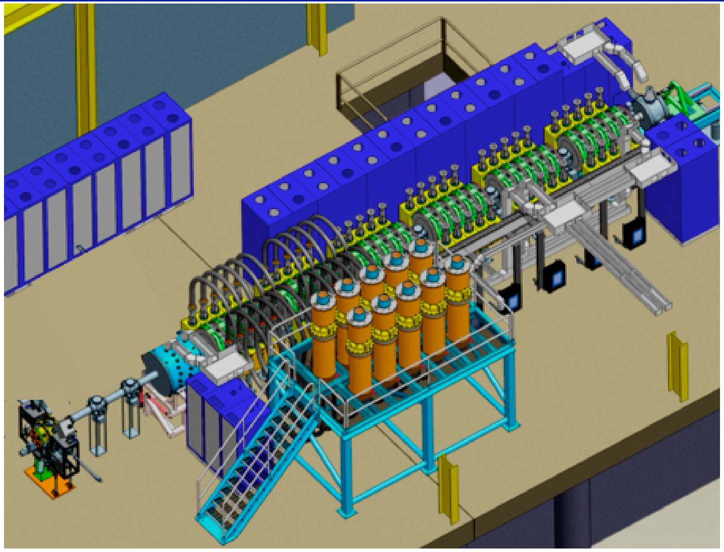
→

NDCX II

3 - 6 MeV,

0.03 μC

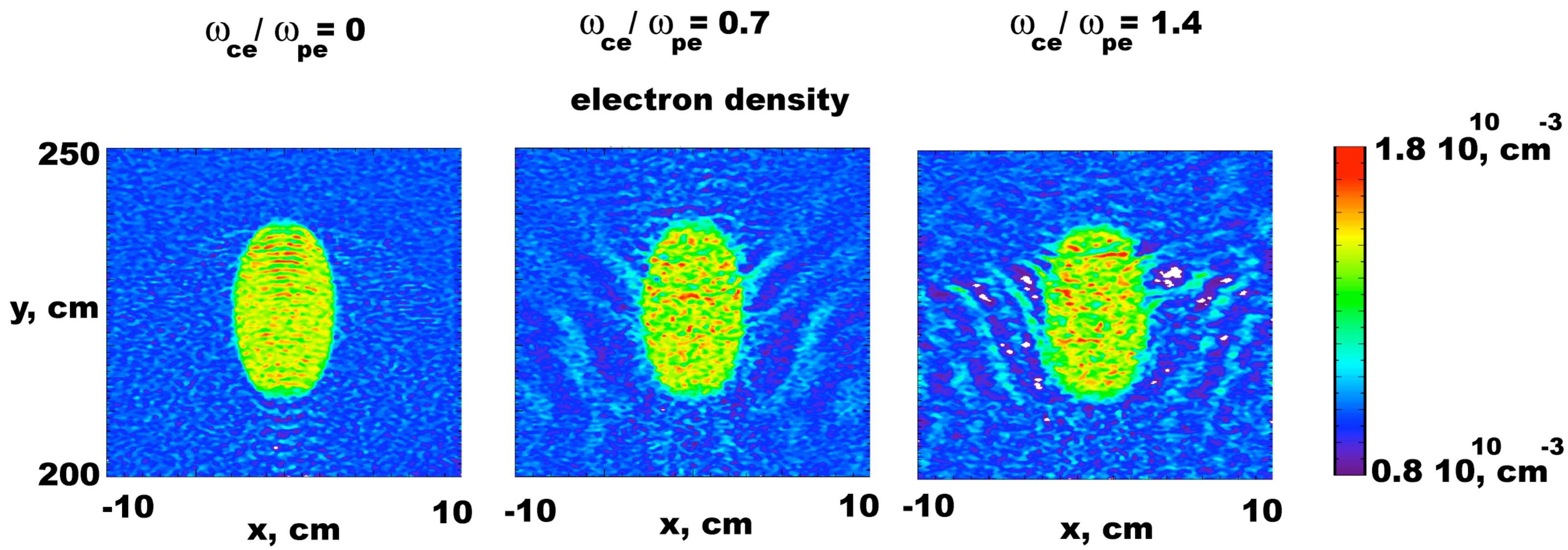
Completion date: 2011



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

Analytical studies show that the solenoidal magnetic field influences the neutralization by plasma if $\omega_{ce}>\beta\omega_{pe}$

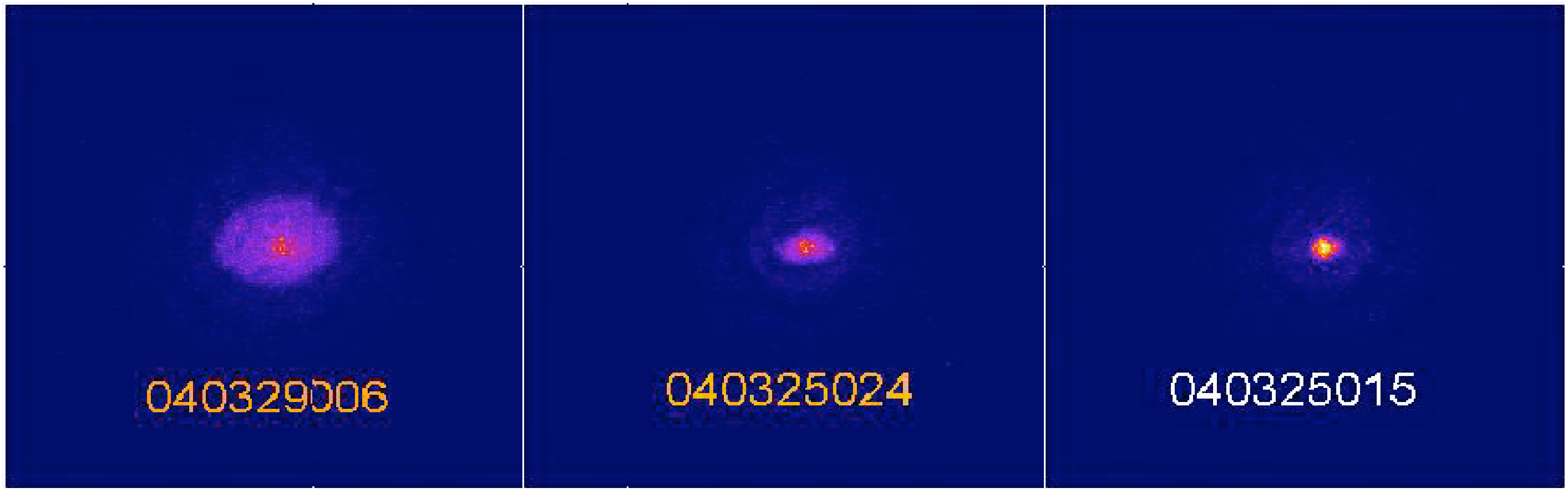
Plots of electron charge density contours in (x,y*)* space, calculated in 2D slab geometry using the LSP code with parameters: Plasma: $n_p=10^{11}cm^{-3}$; Beam: $V_b=0.2c$, 48.0A, r_b=2.85cm and pulse duration τ_b=4.75 ns. A solenoidal magnetic field of 1014 G corresponds to $\omega_{ce}=\omega_{pe}$.



- In the presence of a solenoidal magnetic field, whistler waves are excited, which propagate at an angle with the beam velocity and can perturb the plasma ahead of the beam pulse.

I. D. Kaganovich et al., Phys. Rev. Lett. 99, 235002 (2007); E. A. Startsev et al., Phys. Plasmas15, 062107 (2008).

Measurements on the Neutralized Transport Experiment (NTX) demonstrate achievement of smaller spot size using volumetric plasma*



Neither plasma plug nor volumetric plasma.

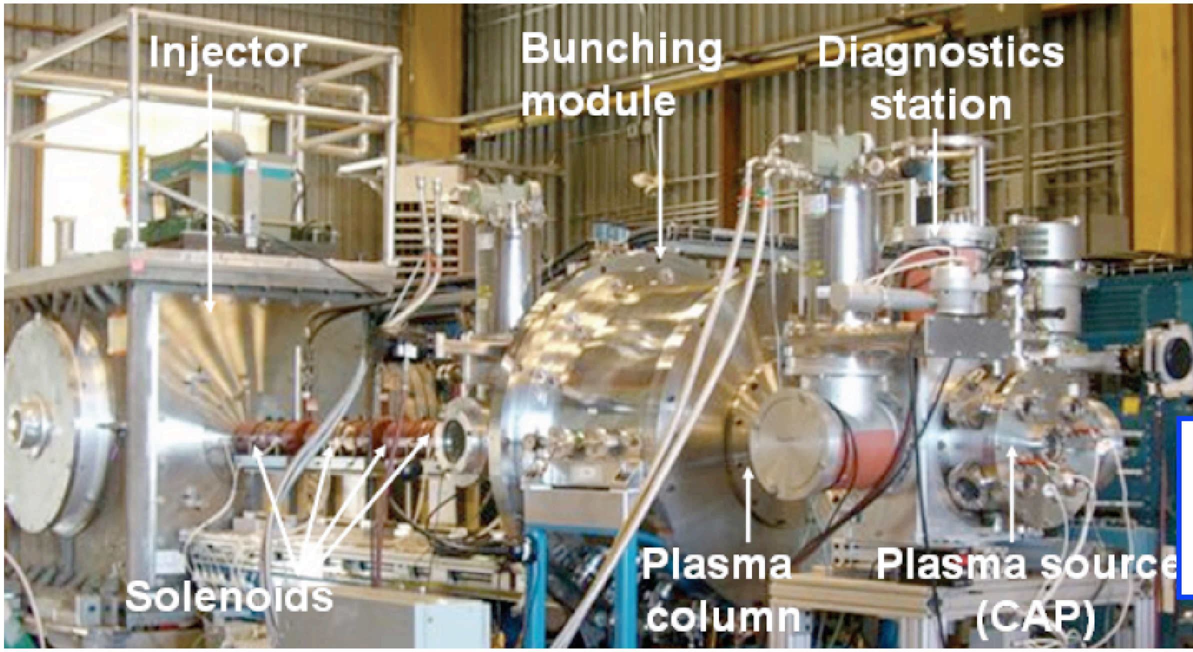
Plasma plug.

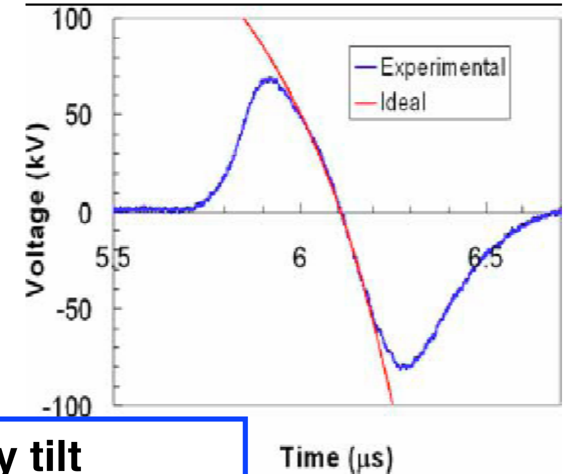
Plasma plug and volumetric plasma.

Ion species: K^+
Energy: $E_0 \leq 400$ keV
Current: $I_0 < 80$ mA
Beam radius: $r_b \sim 1\text{-}2$ cm
Temperature: $T_b \sim 0.2$ eV

*** P. K. Roy, S. S. Yu et al. ,Phys. Rev. Lett. 95, 234801 (2005).**

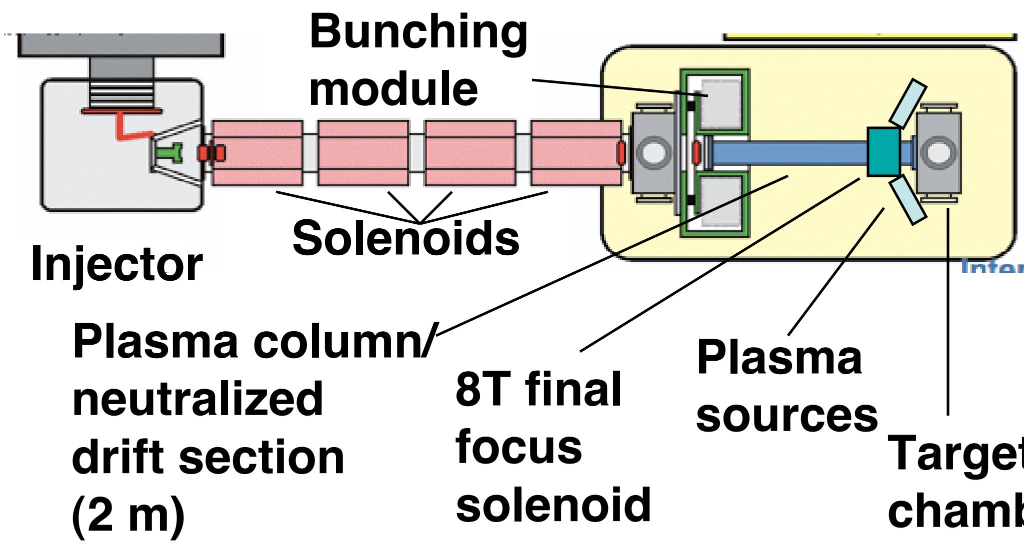
NDCX-1 has demonstrated > factor 60 pulse compression, and simultaneous transverse focus

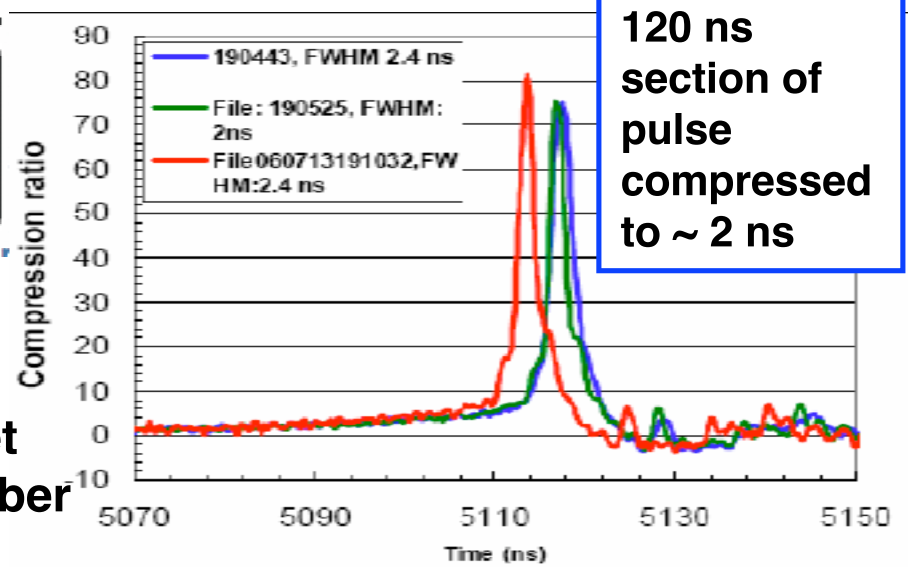




Velocity tilt accelerates tail, decelerates head

(Like chirped pulse compression)



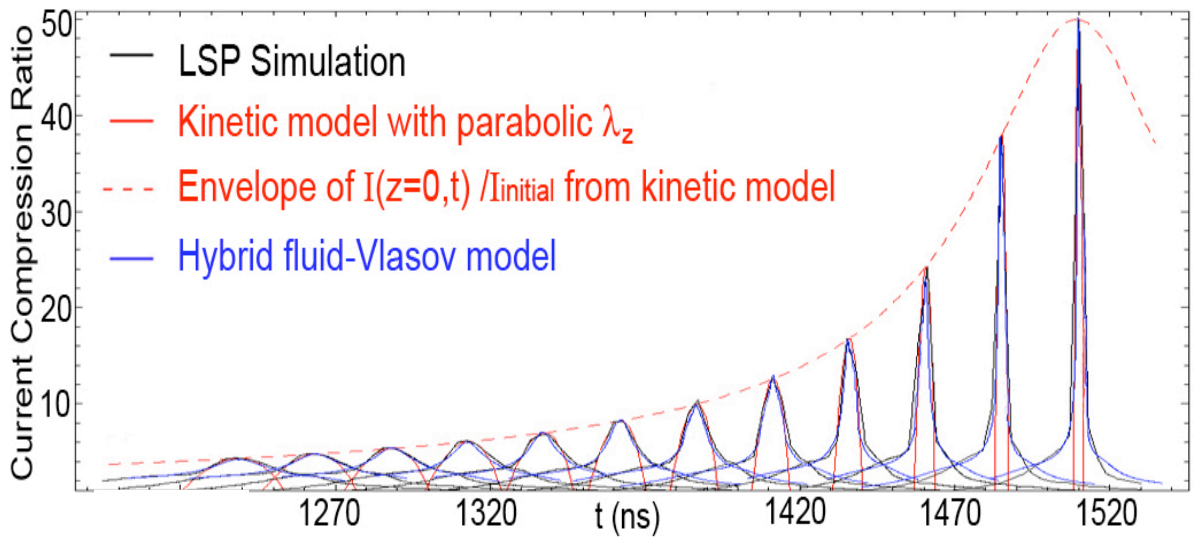


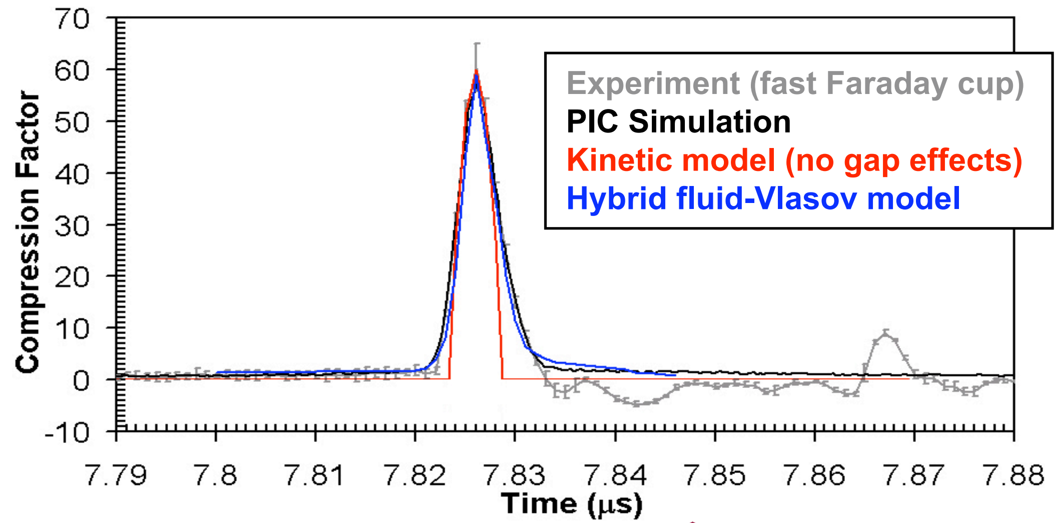
120 ns section of pulse compressed to ~ 2 ns

Theoretical models and PIC simulations give excellent agreement with with longitudinal current compression measured in NDCX - I

Parabolic waveform of main compression peak is described well by kinetic model

Deviation from ideal (linear) tilt waveform produce pedestals around main parabolic peaks





A. B. Sefkow and R.C. Davidson, Phys.Rev. ST Accel. & Beams 10, 100101 (2007); A. B. Sefkow et al., Phys. Plasmas 16, 056701 (2009).

Multispecies Two-Stream Instability

- A small axial momentum spread of the beam ions and the plasma ions leads to a reduction in the growth rate of the two-stream instability.

- In regimes where it occurs, the two-stream instability is likely to lead to a longitudinal heating of the plasma electrons in the nonlinear regime.

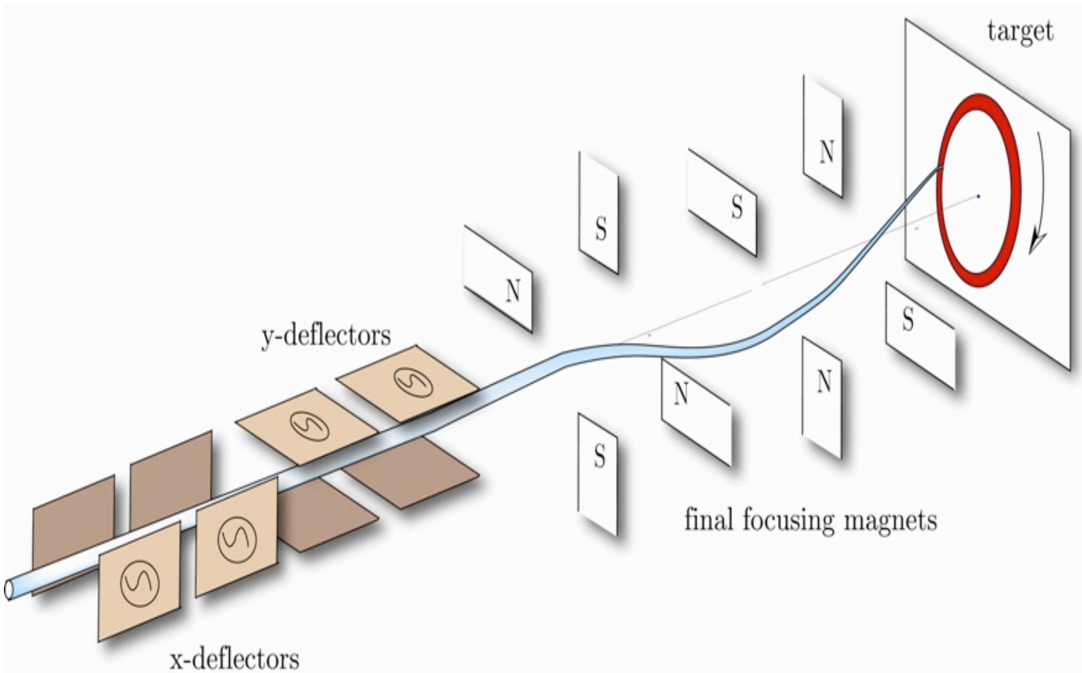
- For sufficiently small beam radius (in units of the plasma electron collisionless skin depth), the effects of finite transverse geometry have an important influence on detailed stability properties.

- A longitudinal velocity tilt can significantly reduce the growth rate of the electron-ion two-stream instability.

R.C. Davidson et al., Nuclear Instruments and Methods in Physics Research A606, 11 (2009).

A deflecting *wobbler* field may be an effective technique for beam smoothing, uniform energy deposition, and instability suppression

- Application of a deflecting wobbler field is being investigated as an effective beam smoothing technique.
- The wobbler field also enables the uniform deposition of beam energy onto an annular region on the target.
- It is also expected to suppress and/or mitigate the Rayleigh-Taylor instability.



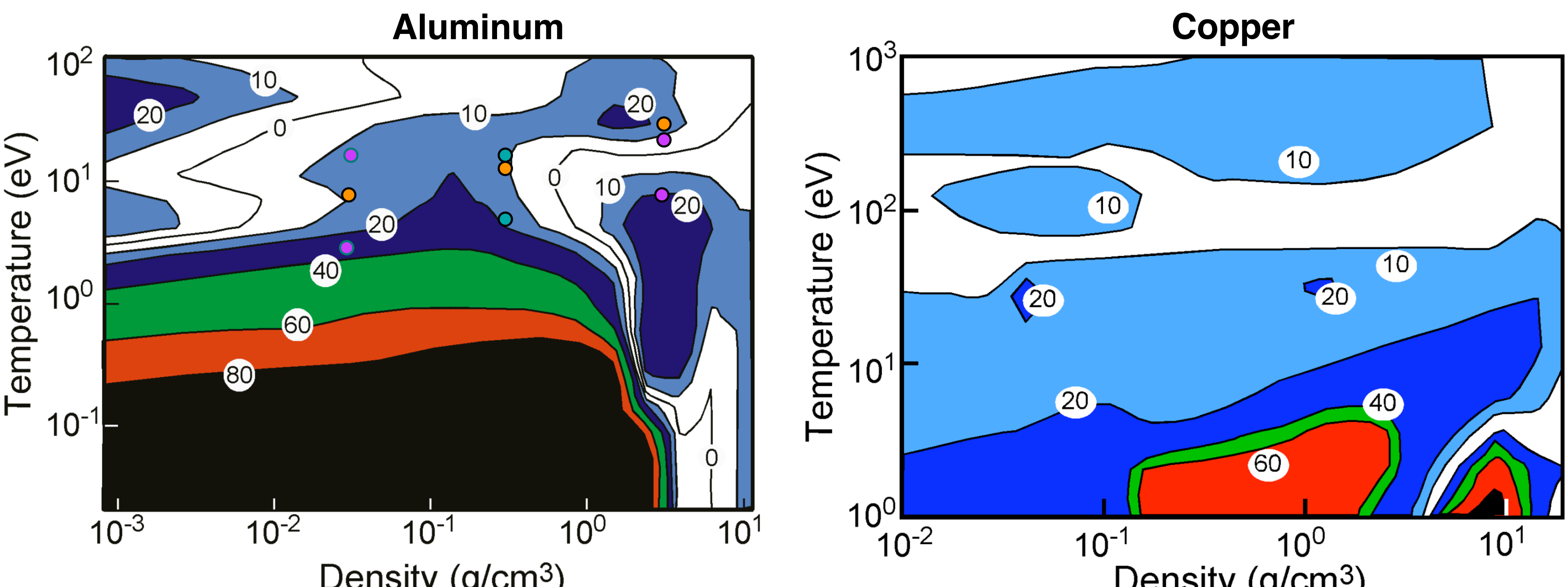
We have identified a series of high-leverage warm dense matter experiments that can begin on NDCX-I at Temperature < 1 eV and be extended to higher energy densities in NDCX-II

	Target Temp.	NDCX-I	NDCX-II
Metallic foam experiments at GSI	~0.5 eV		
Measure target temperature using a beam compressed both radially and longitudinally	Low	√	
Thin target dE/dx, energy distribution, charge state, and scattering in a heated target	Low	√	
Positive - negative halogen ion plasma experiment	>0.4 eV	√	√
Two-phase liquid-vapor metal experiments	0.5-1.0	√	√
Critical point measurements	>1.0	?	√
Ion deposition and coupling experiments	>1.0		√
Collapsing bubble experiments	>1.0		√

time

In Warm Dense Matter regime large errors exist in the equation-of-state even for the most studied materials

Contours of % differences in pressure for two commonly employed equations of state



- **EOS Differences > 80% are common**
- **Measurements are essential for guidance**
- **Where there is data the models agree!!**
  - **Data is along the Hugoniot - single shock ρ-T-P response curve**

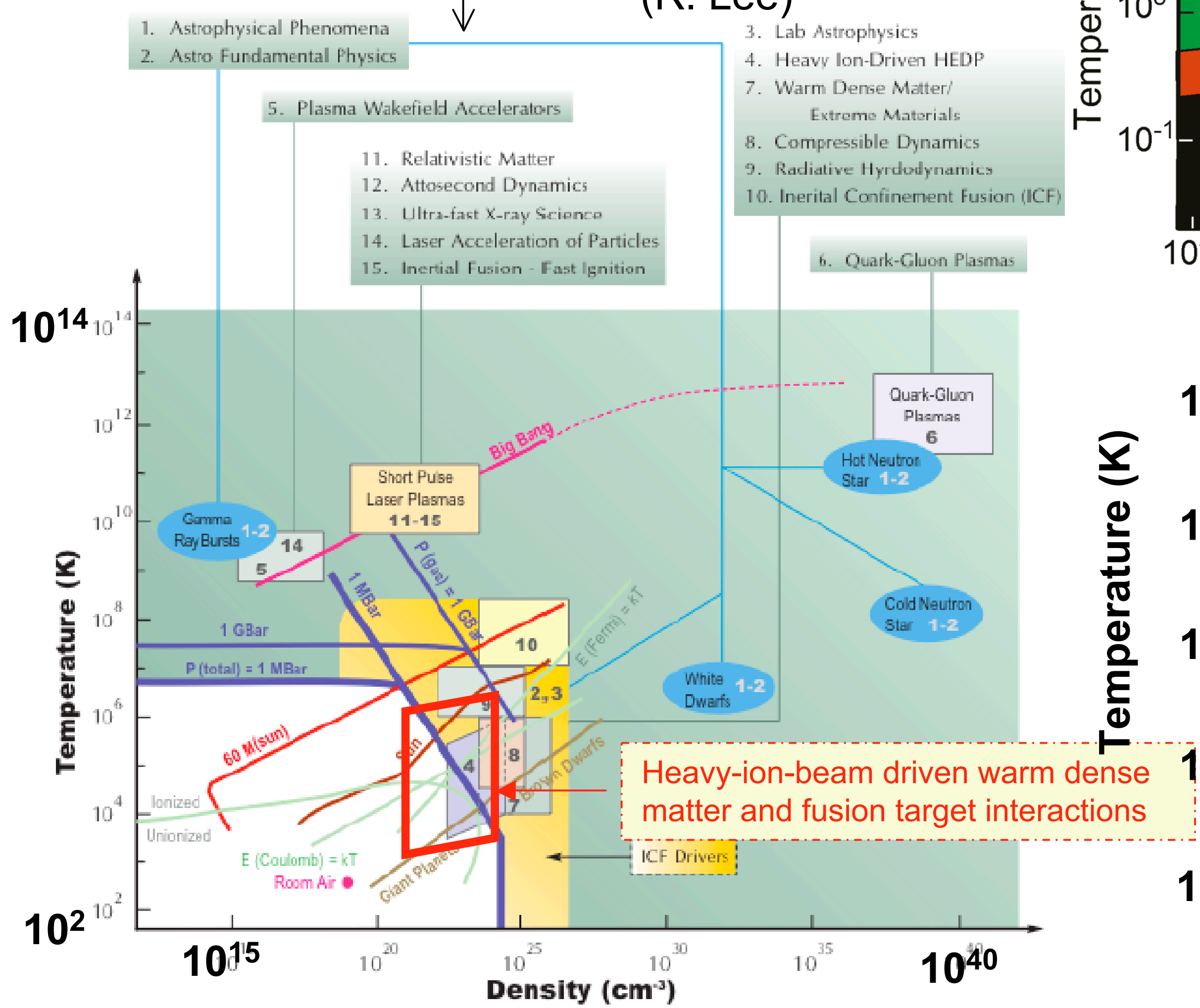
(Slide courtesy R. Lee)

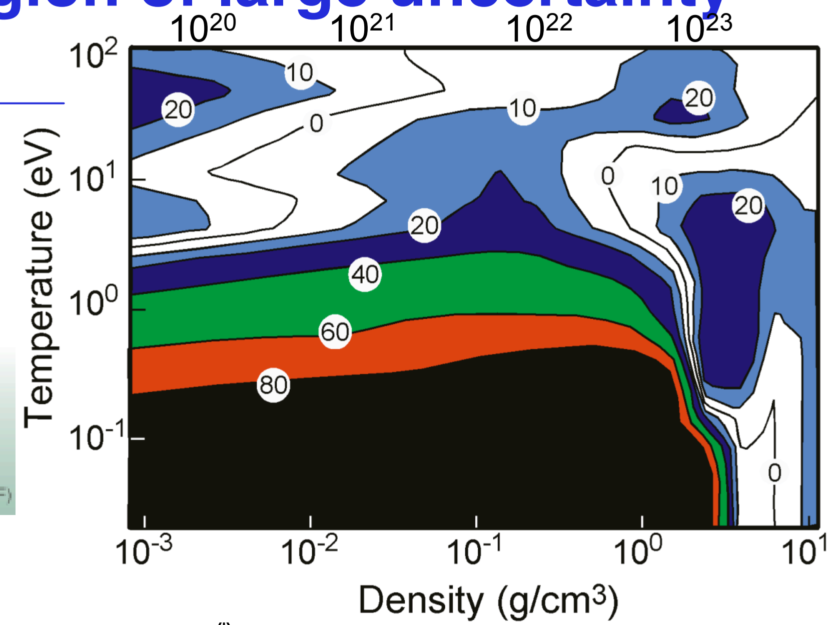
Back-up Viewgraphs

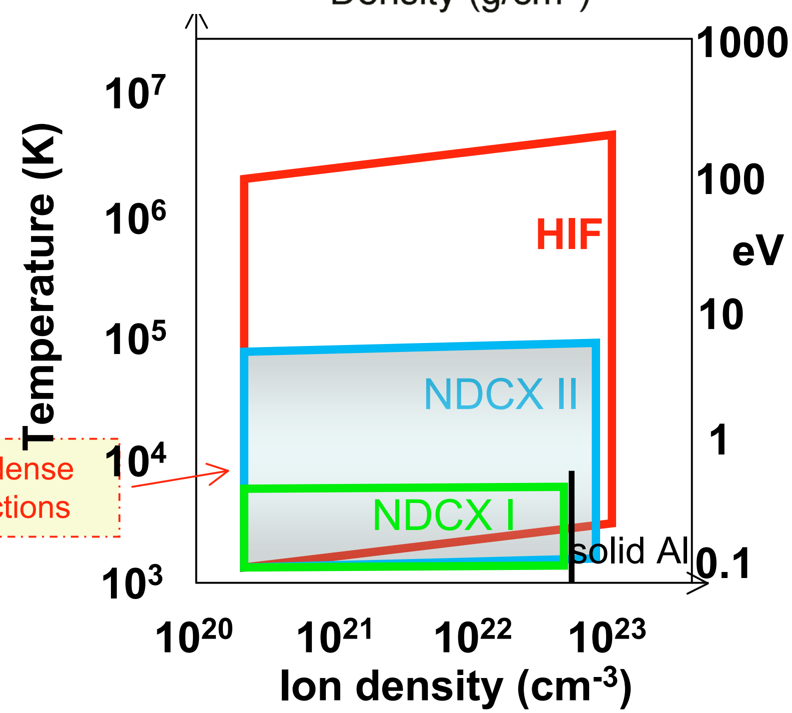
NDCX II covers WDM region -- a region of large uncertainty in EOS

Density - Temperature universe

EOS pressure variance for 2 eqs. of state in Al (R. Lee)







From National HEDP Task Force Report, 2004.

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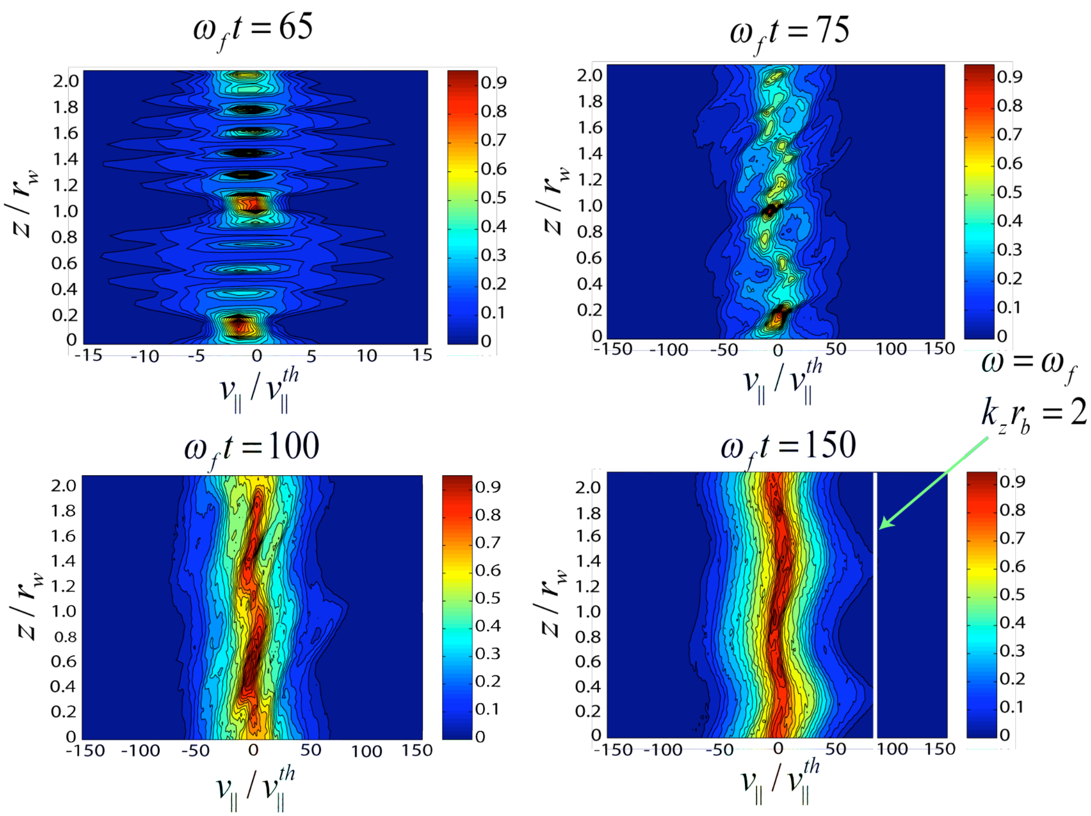
- Influence of magnetic fields on HED fusion plasmas
- Laser-plasma instabilities and hot electron generation
- Implosion hydrodynamics for high energy gains
- Integrated target physics for inertial fusion energy

Strong Harris instability for beams with large temperature anisotropy

- Moderate intensity → largest threshold temperature anisotropy.
- BEST simulations show nonlinear saturation by particle trapping.



Longitudinal particle trapping by a broadband spectrum of fast-growing waves with zero real frequency governs the nonlinear saturation.

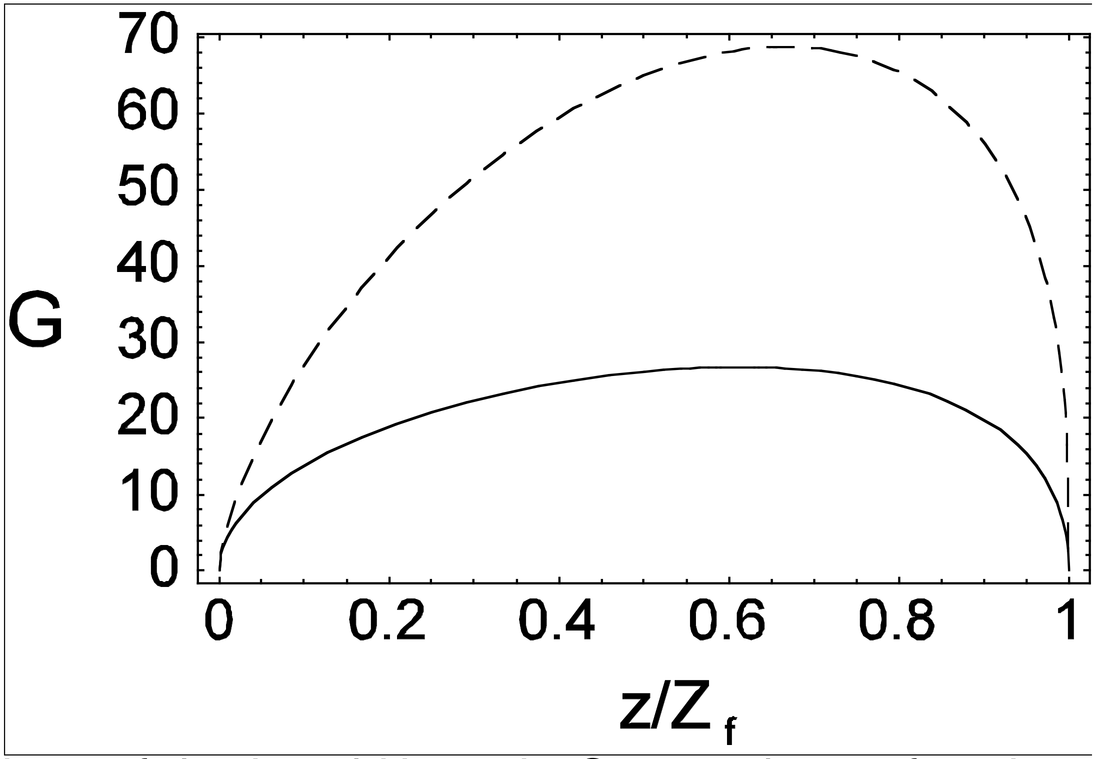
The nesting and overlapping of particle resonances in longitudinal phase space leads to the fast randomization of the trapped-particle distribution and to longitudinal heating of the beam.

Nonlinear interactions shift the wave spectrum to long wavelengths.

E. A. Startsev et al., Phys.Plasmas 14, 056705 (2007); Nucl. Instr. Meth. Phys. Res. A, in press (2009).

Parameters: $s_b = 0.9$ and $T_{\parallel b} / T_{\perp b} = 0.0001$

A longitudinal velocity tilt can significantly reduce the growth rate of the electron-ion two-stream instability



Comparison of the instability gain G plotted as a function of axial distance for ion beam with velocity tilt (solid curve) and without velocity tilt (dashed curve).

R.C. Davidson et al., Nucl. Instr. Meth. Phys. Research, in press (2009); E. A. Startsev and R. C. Davidson, Nucl. Instr. Meth. Phys. Research A577, 79 (2007).