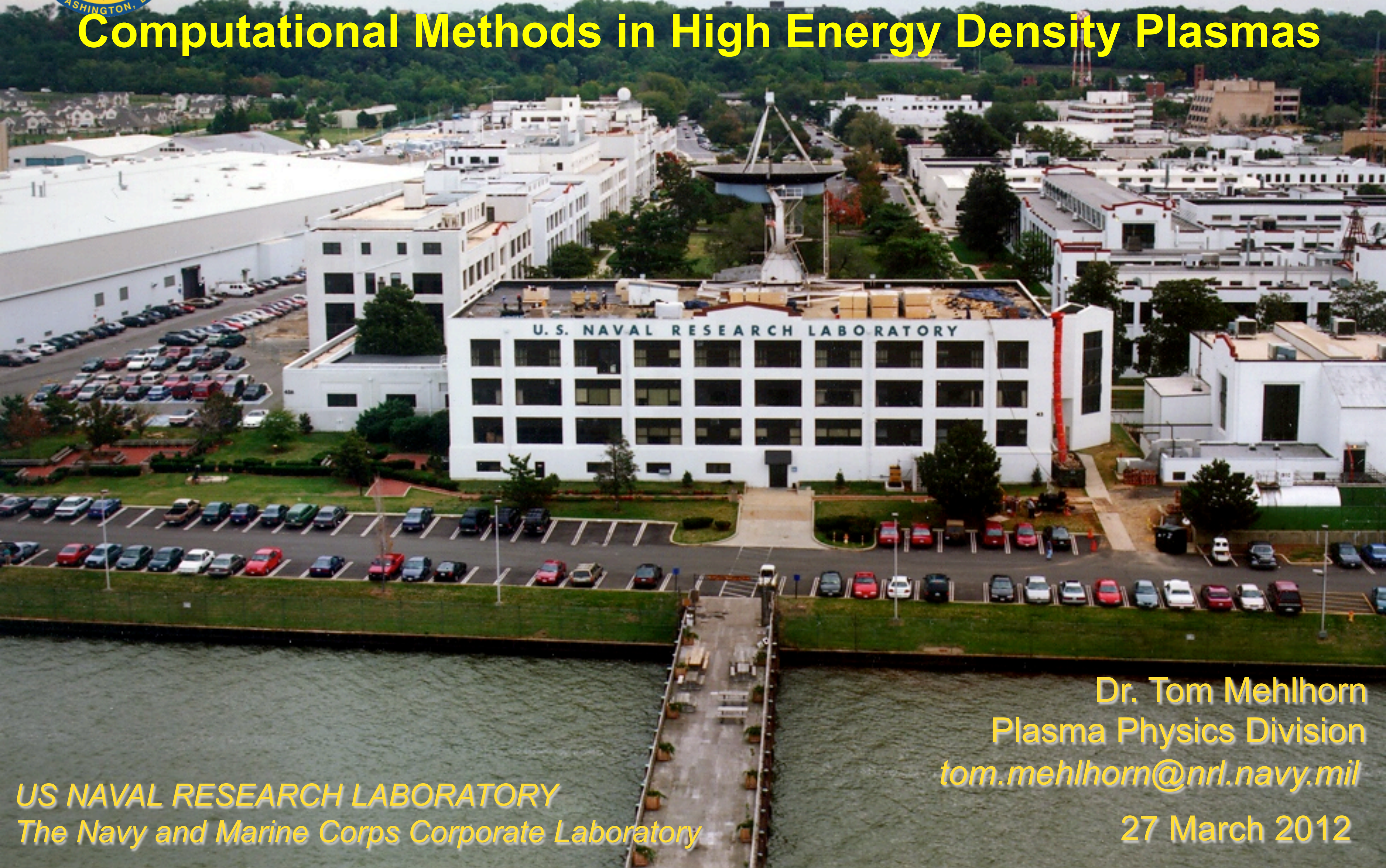
The Role of Non-Local and Non-Equilibrium Physics in High Energy Density Plasmas

IPAM - UCLA

Computational Methods in High Energy Density Plasmas



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27 March 2012

US NAVAL RESEARCH LABORATORY
The Navy and Marine Corps Corporate Laboratory

Thanks to the many NRL researchers who have contributed to this talk

Plasma Physics Division

<u>1. Non-LTE in radiation-dominated K-shell Z-pinches:</u>

Dr. Arati Dasgupta
Dr. John Giuliani
Dr. Ward Thornhill

Ref: J.W. Thornhill, J.L. Giuliani, A. Dasgupta, et al., IEEE Trans. Plasma Sci., 38, 606 (2010).

<u>2. Non-local electron transport in laser fusion</u>

Dr. Wally Mannheimer
Dr. Andy Schmitt

Ref: W. Manheimer, D. Colombant and V. Goncharov, Phys. Plasmas, **15**, 083103, 2008

<u>3. Non-equilibrium physics in clusters irradiated by ultra-short pulsed laser (USPL)</u>

Dr. Jack Davis
Dr. George Petrov
Dr. Lina Petrova

Ref: G.M Petrov, J. Davis, Phys. Plasmas 15, 056705 (2008)

Atomic physics and non-LTE Effects

J. Davis, R. Clark, M. Blaha, & J. Giuliani, Lasers & Part Beams 19, 557-577 (2001)

NRL has a distinguished history

THOMAS A. EDISON

"GOVERNMENT SHOULD MAINTAIN A GREAT RESEARCH LABORATORY TO DEVELOP GUNS, NEW EXPLOSIVES AND ALL THE TECHNIQUE OF MILITARY AND NAVAL PROGRESSION WITHOUT ANY VAST EXPENSE."

THOMAS A. EDISON,
THE NEW YORK TIMES MAGAZINE
SUNDAY, MAY 30, 1915

A WORLD-CLASS LABORATORY

- Idea followed the sinking of the Lusitania in 1915
- Secretary Josephus Daniels Established Naval Consulting Board with Edison Chair, meeting October 7, 1915
- August 29, 1916 Congress appropriates funds to establish the Lab
- Delayed by WW-I, Assistant Secretary of the Navy, Theodore Roosevelt, Jr. Commissions the Lab at Bellevue site on July 2, 1923

Primarily In-house Research to support Navy and Marine Corps needs

Plasma Physics is one of 18 NRL Research Divisions

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Acoustics
Remote Sensing
Oceanography
Marine Geosciences
Marine Meteorology
Space Science

VXS-1, Patuxent River, MD

Systems Directorate
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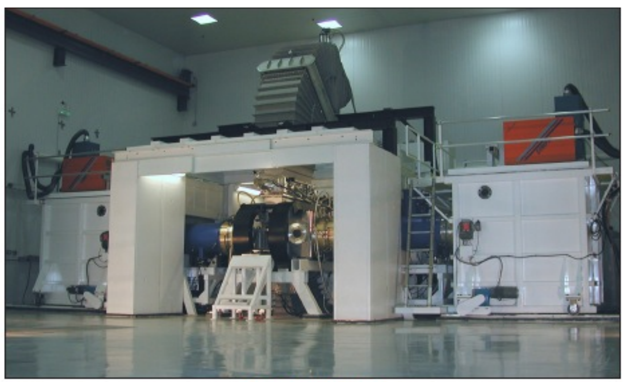

Electra Laser Facility

Material Science & Component Technology
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Material Science and Technology
Laboratory for Computational Physics & Fluid Dynamics
Plasma Physics
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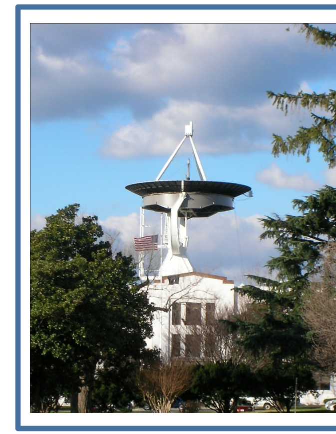

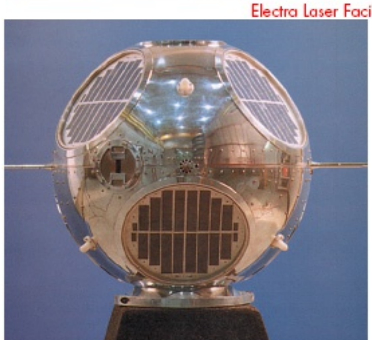

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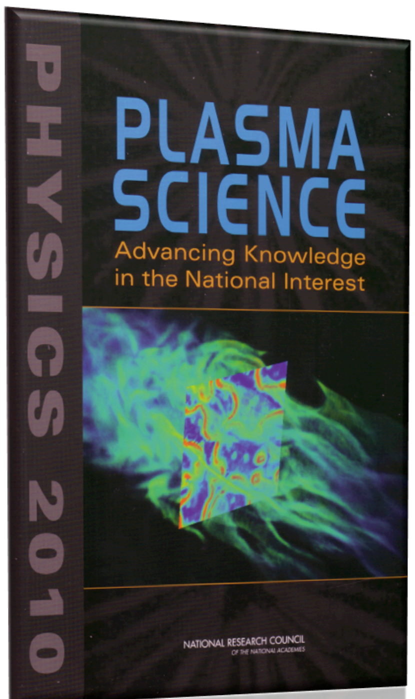
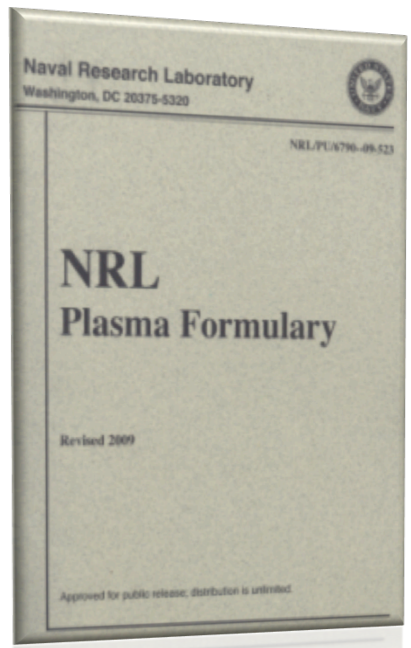
Spacecraft Engineering

Ex-USS Shadwell, Mobile, AL

Plasma Physics Division

NRL has world-wide recognition in plasma physics & related technologies





Non-LTE and non-local phenomena underlie High Energy Density (HED) plasmas

LTE

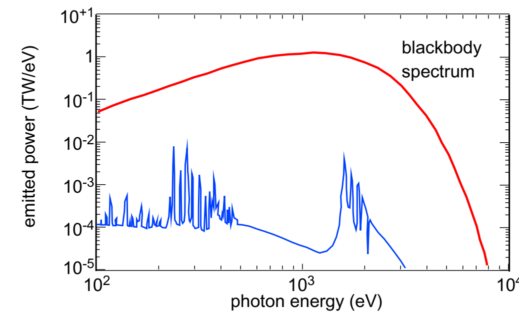
(Local Thermodynamic Equilibrium)

internal energy of a plasma
(thermal + excitation + ionization)
determined by local
density and temperature

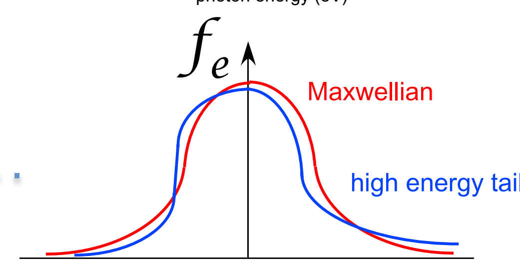
non-LTE

internal energy of a plasma
also depends on gradients
and thereby non-local

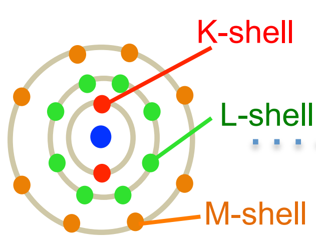
blackbody radiation spectrum .... $\lambda_{\gamma,mfp} > \frac{\rho}{\nabla\rho}$ ....



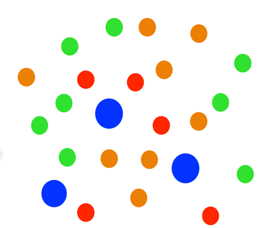
heat conduction = $\kappa\nabla T$ .... $\lambda_{e,mfp} > \frac{T}{\nabla T}$ ....



isolated atom

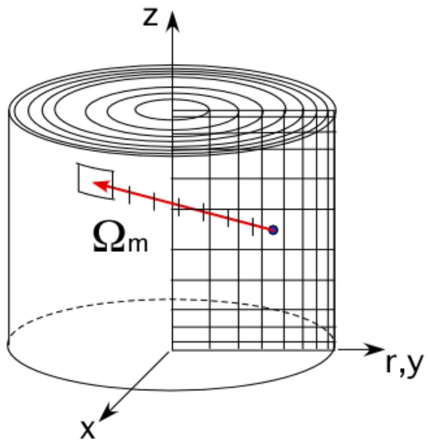


...... $\mathcal{E}_{laser} = \nabla\phi > \frac{e}{a_B^2}$ ....

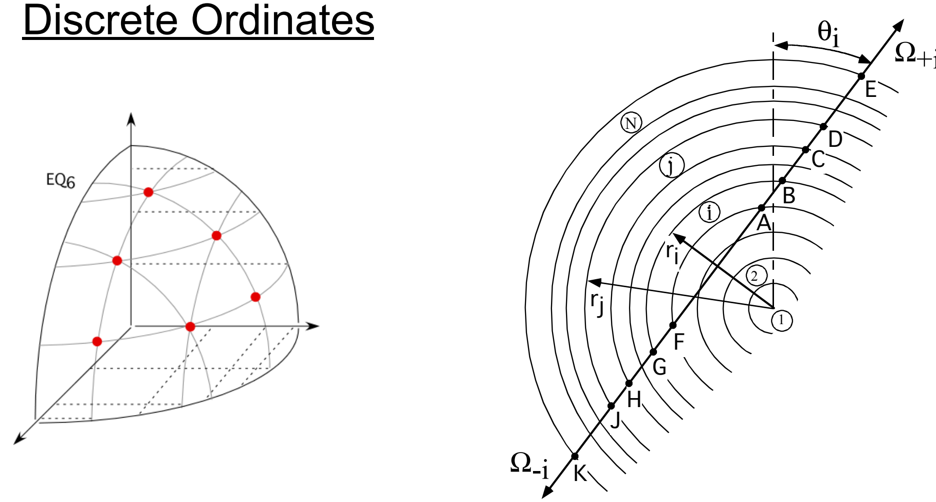


Non-local means spatial dependence, requiring some form of transport model

Raytracing



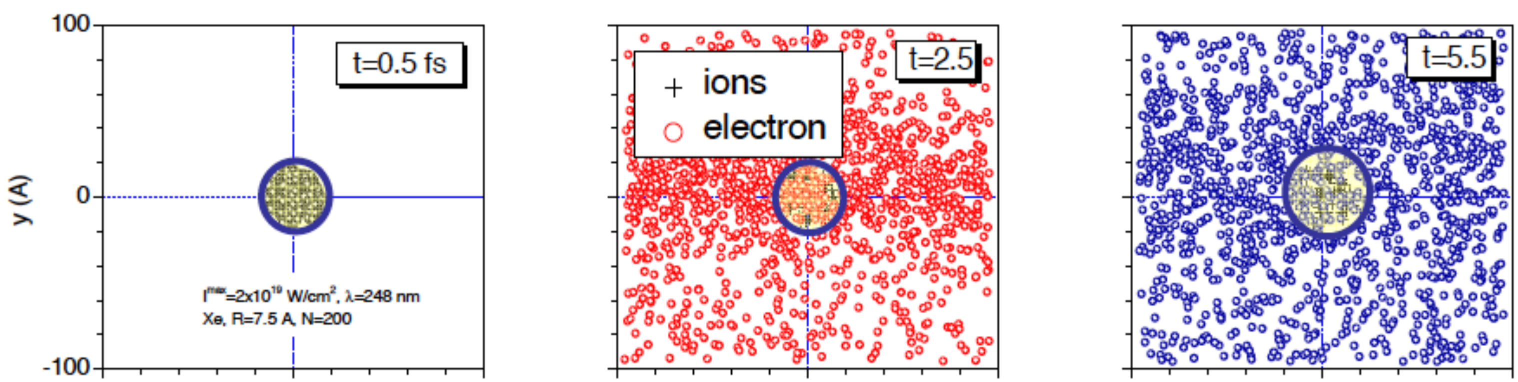
Discrete Ordinates



Vlasov model

$$V \bullet \nabla f - \frac{eE}{m} \bullet \nabla_V f_m = -\nu_e(V)\left(f - f_m\right) + \frac{\nu_i(V)}{2}\left[\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial}{\partial\theta} + \frac{1}{\sin^2\theta}\frac{\partial^2}{\partial\phi^2}\right] f$$

Molecular Dynamics



Z pinches: magnetically imploded plasma producing intense radiation

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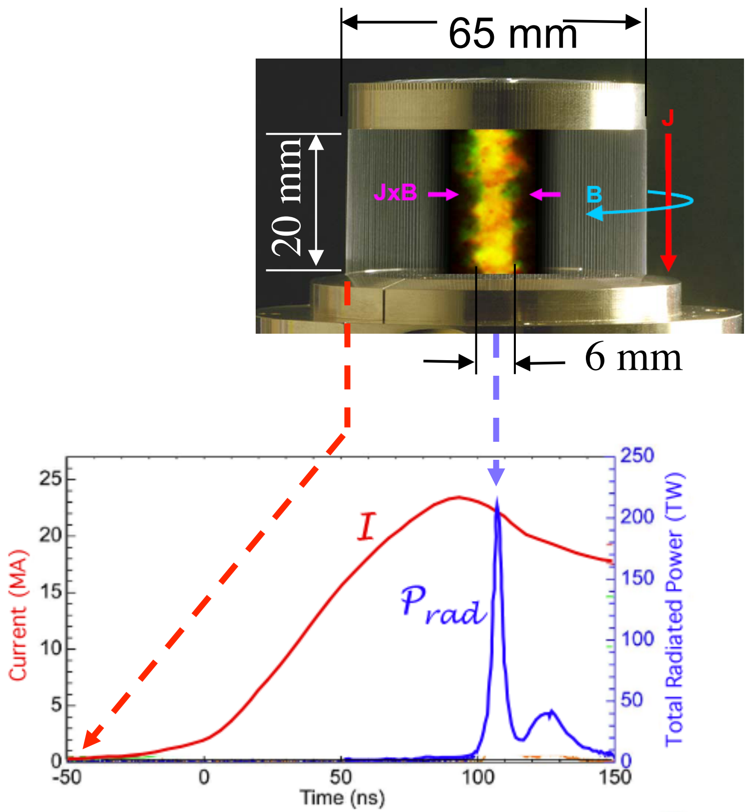
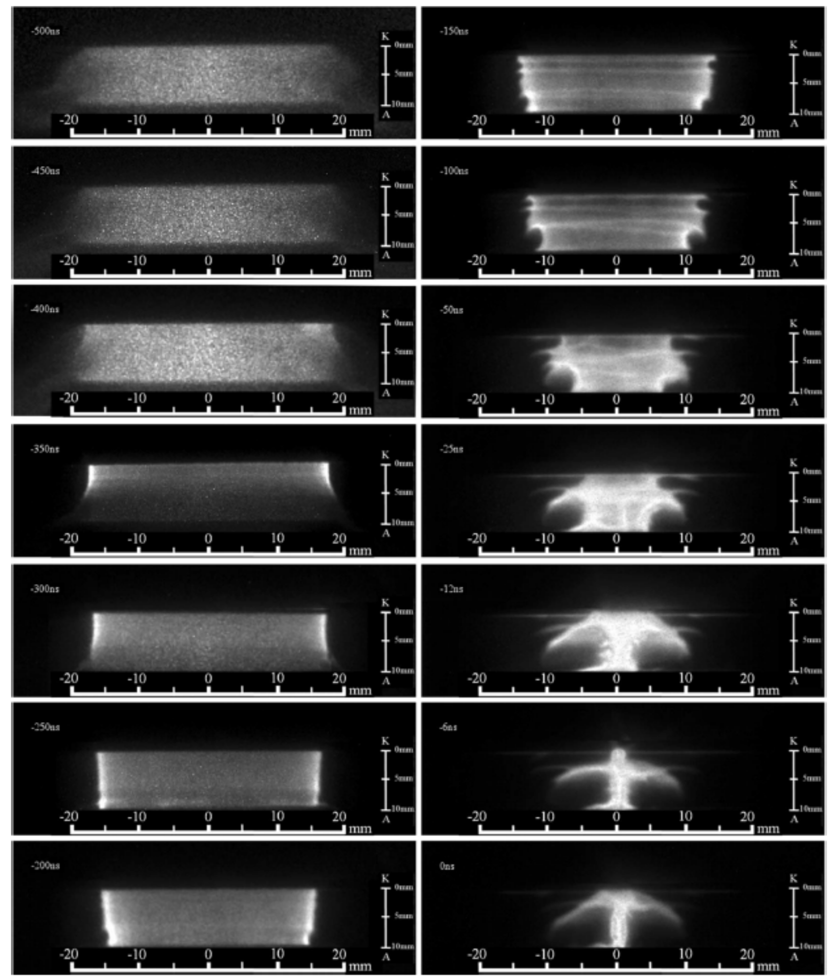
wire array



gas puff



Osin, et al., *IEEE TPS*, **39**, 2392 (2011)

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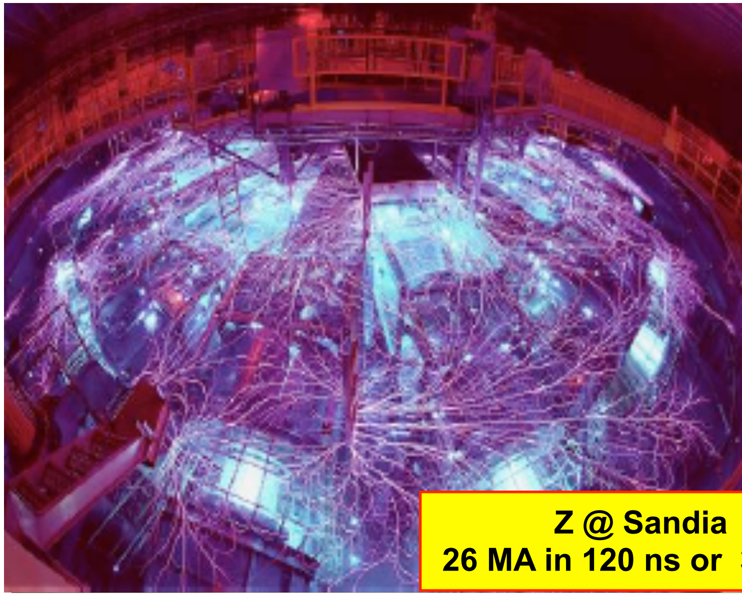
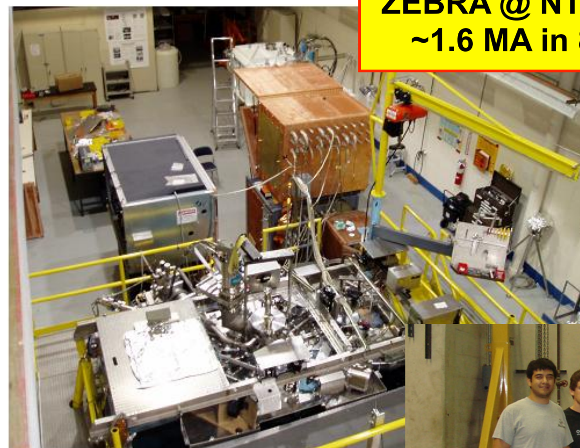
Z-pinch research in MHD and radiation production in is internationally active

34 m



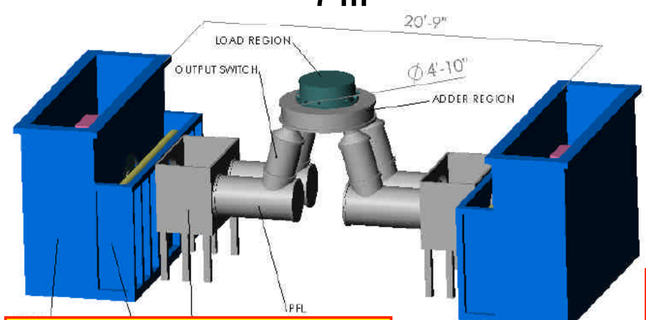
Z @ Sandia
26 MA in 120 ns or 300 ns



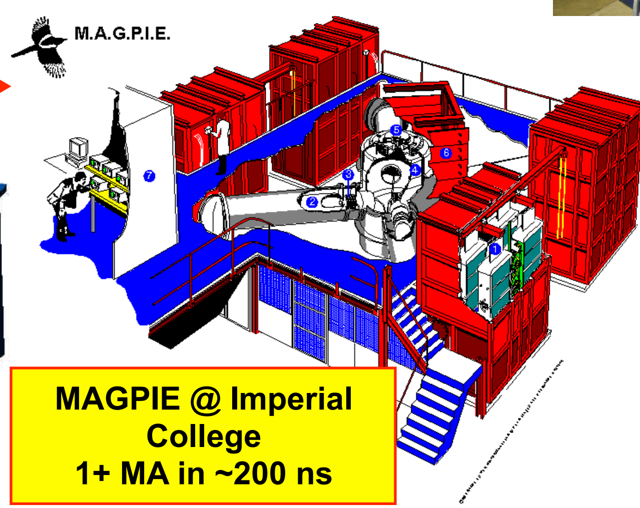
ZEBRA @ NTF, UNR
~1.6 MA in 80 ns

MAIZE @ U Michigan
1 MA LTD

7 m



COBRA @ Cornell
~1 MA in 100 or 200 ns



MAGPIE @ Imperial College
1+ MA in ~200 ns

2 m

WIS @ Israel
~0.5 MA in 500 ns

Advanced simulations of Z-pinch loads require an integrated physics approach

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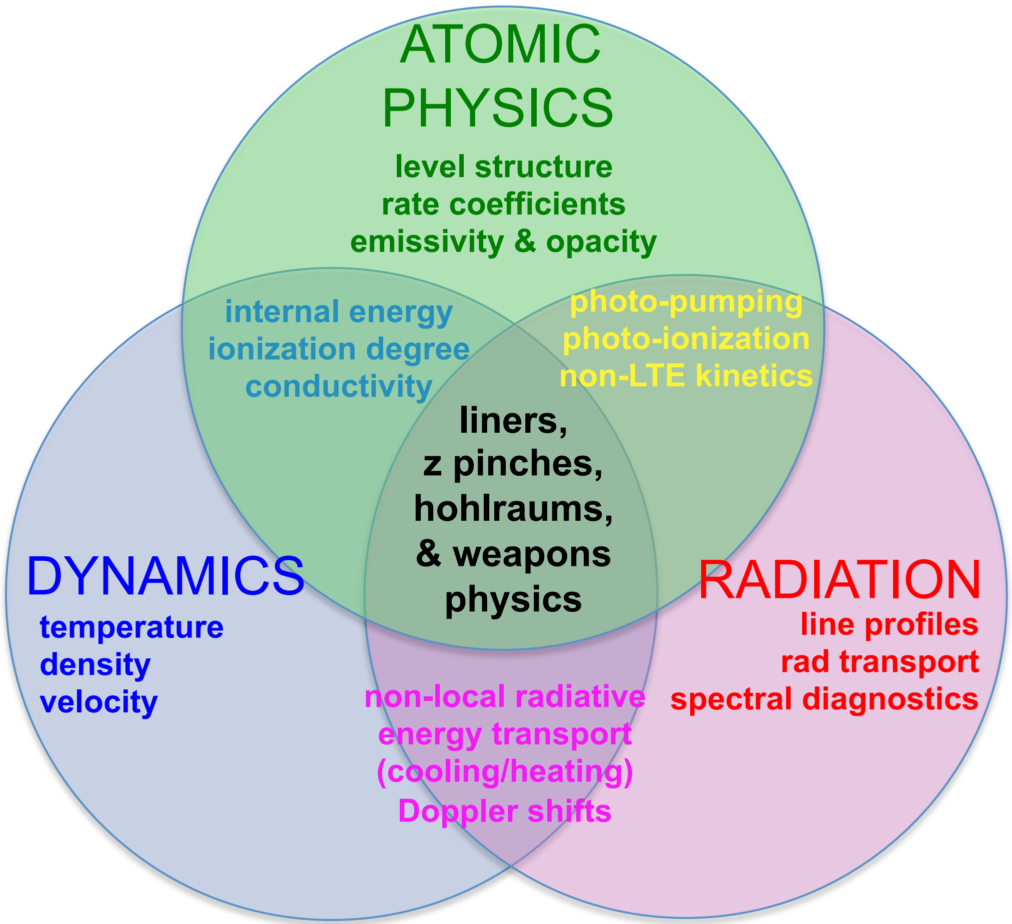

products:

- ❑ Verification tests for non-LTE radiation & MHD codes.
- ❑ Validation of simulations through yields & synthetic spectra.
- ❑ Interpretation of plasma conditions from spectral & imaging diagnostics.
- ❑ Predictions for next generation pulse power machines.

Non-LTE/non-local physics is important in radiation-dominated Z-pinch plasmas

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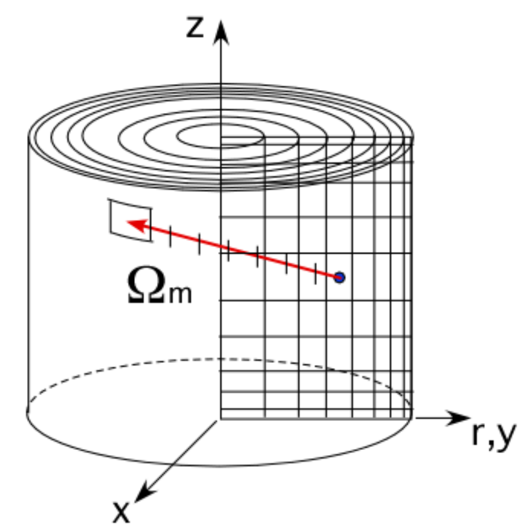
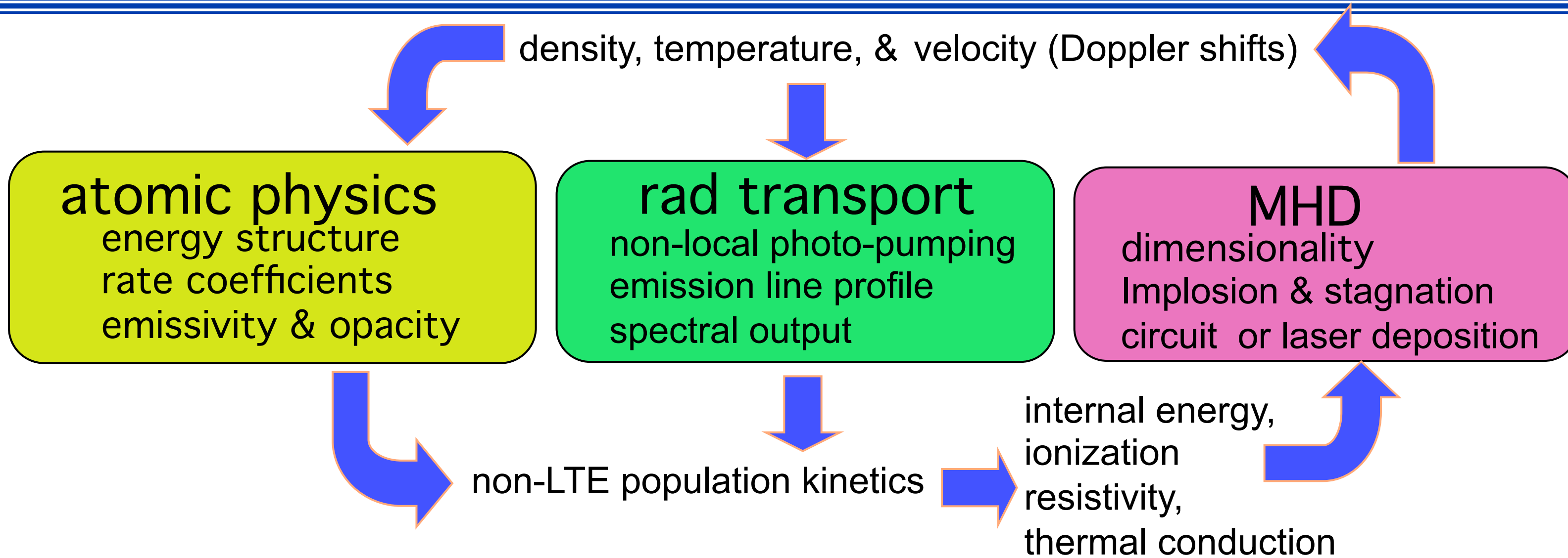
Radiation transport: The collection of processes in which radiation is emitted within a medium, and is subsequently absorbed elsewhere within the medium, or else escapes without further interaction

Effects:

- Emitted radiative power from an optically thick medium is reduced by reabsorption
- Energy is redistributed within the medium, resulting in localized heating or cooling
- Photoexcitation and/or photoionization results in enhancement of the medium's degree of excitation and ionization
- Boundary effects of the radiation field create gradients in ionization and excitation even if temperature and density are uniform
- Spectral line or continuum features of varying optical depth can provide valuable diagnostics of , e.g., temperatures, densities, and their gradients



In non-LTE radiation couples non-locally to populations & energy, affecting MHD



Bound-bound emission
$$\varepsilon_{b-b}(\omega) = \frac{h\nu}{4\pi} L(\omega) A_{UL}^{z,a} N_L^{z,a}$$

Bound-free emission
$$\varepsilon_{f-b} \approx \text{const}\left(\frac{E_H}{kT}\right)^{3/2} g_{f-b}\, e^{-\frac{h\nu}{kT}} N_e \sum_{n,z,a} \frac{z^4}{n^3} e^{\frac{z^2 E_H}{n^2 kT}} N_a^z$$

Free-free emission
$$\varepsilon_{f-f}(\omega) \approx \text{const}\left(\frac{\mathrm{E_H}}{\mathrm{kT}}\right)^{1/2} g_{f-f}\, e^{-\frac{h\nu}{kT}} N_e \sum_{z,a} z^2 N_a^z$$

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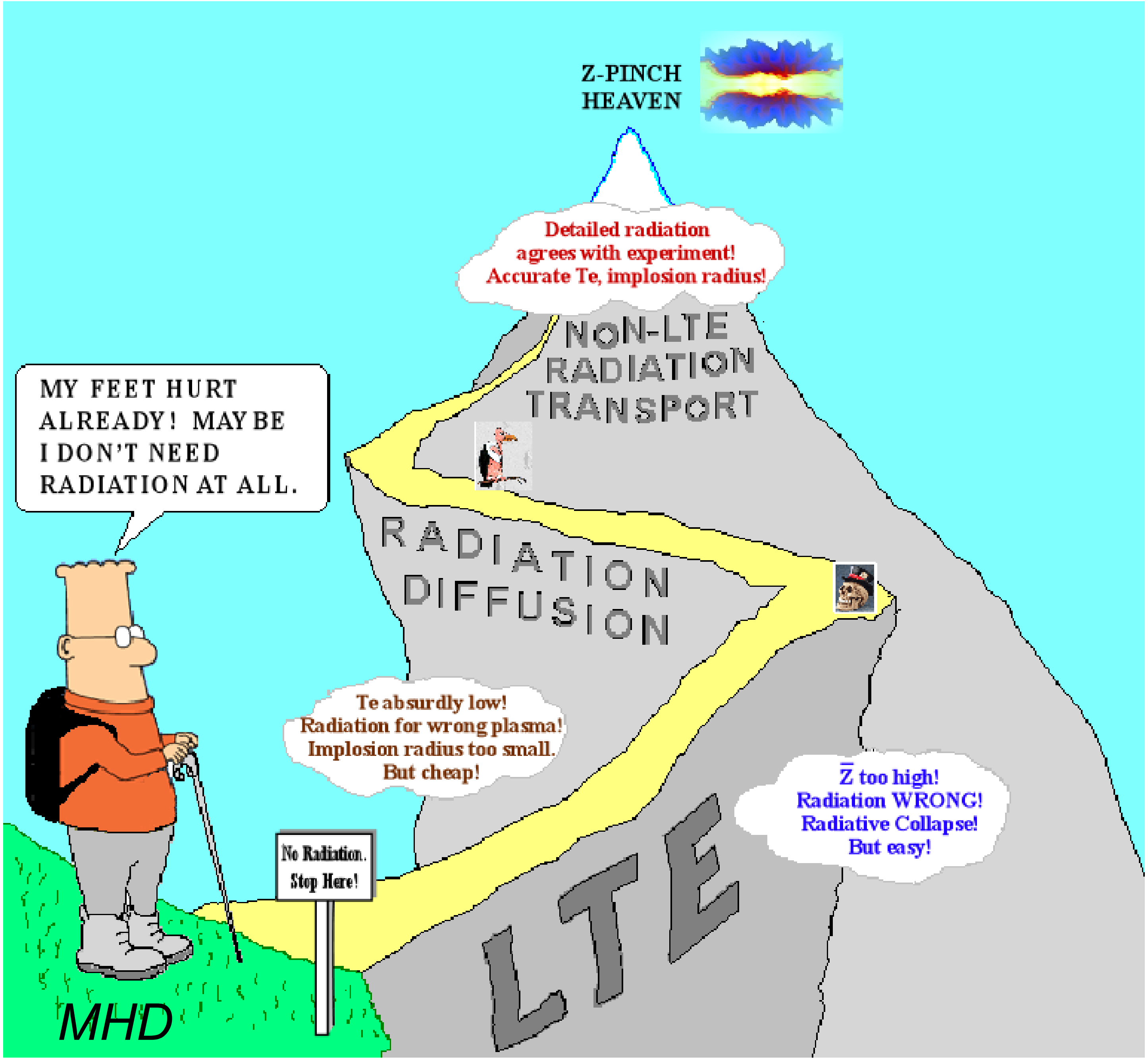
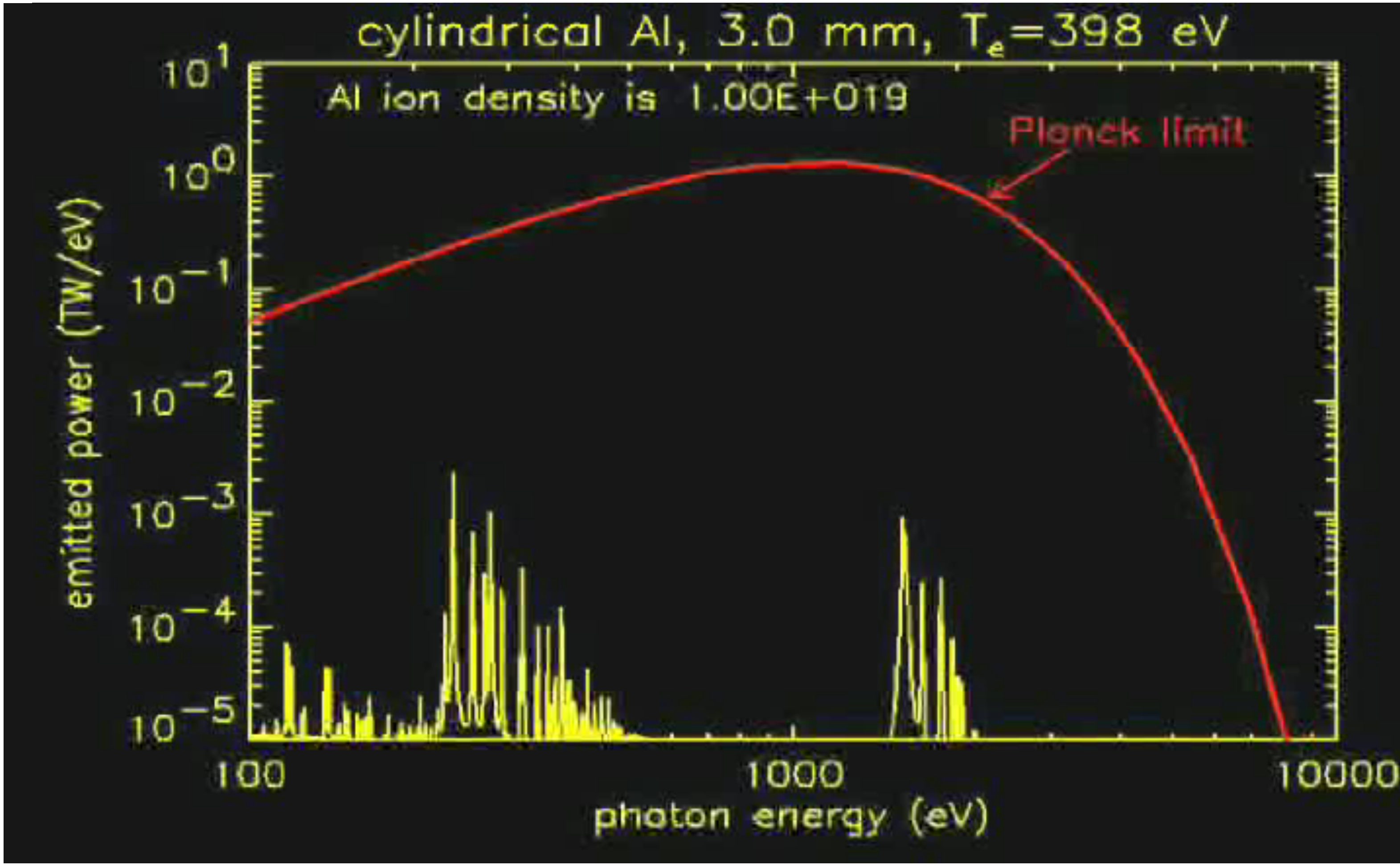
In LTE ion populations are independent of radiation, which is not necessarily Planckian,

- Local Thermodynamic Equilibrium (LTE) means that the ionization state distribution and bound state populations are given by the Saha and Boltzmann equations, respectively, evaluated at the local temperature and density.
  - The particles which dominate the population kinetics must have a Maxwellian velocity distribution, *and*
  - The population kinetics must be dominated by collisional processes, or the medium must be effectively thick
- In HED plasmas radiation is an important energy term:
  - Simple emission model can be used if radiation is Planckian
  - *else* frequency-dependent emission model required (e.g. multi-group diffusion, S_n, or IMC)


Z-PINCH
HEAVEN
Detailed radiation agrees with experiment! Accurate Te, implosion radius!
NON-LTE RADIATION TRANSPORT
MY FEET HURT ALREADY! MAYBE I DON'T NEED RADIATION AT ALL.
RADIATION DIFFUSION
Te absurdly low! Radiation for wrong plasma! Implosion radius too small. But cheap!
$\bar{Z}$ too high! Radiation WRONG! Radiative Collapse! But easy!
No Radiation. Stop Here!
LTE
MHD

Animation to show the transition between an LTE & non-LTE plasma



For a plasma of fixed temperature and size the LTE radiation is given by the blackbody spectrum. For a non-LTE plasma the radiation increases with the density until collisions dominate the kinetics, eventually going to the LTE limit.

Detailed atomic structure + kinetic rates are fundamental data to non-LTE plasma models

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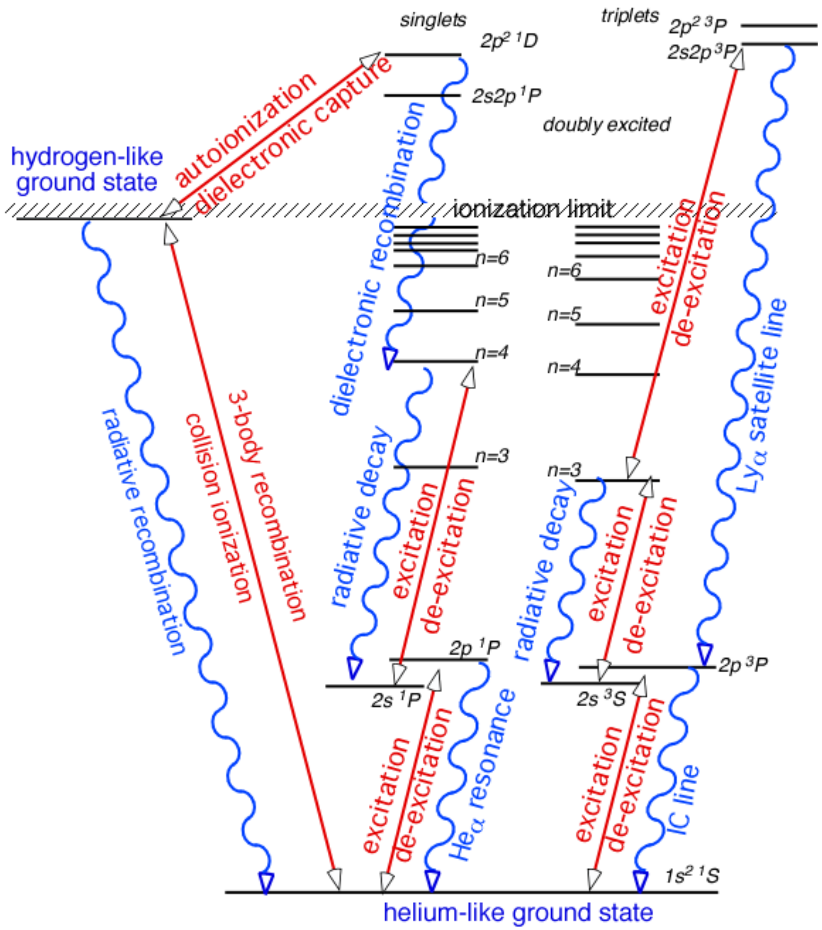
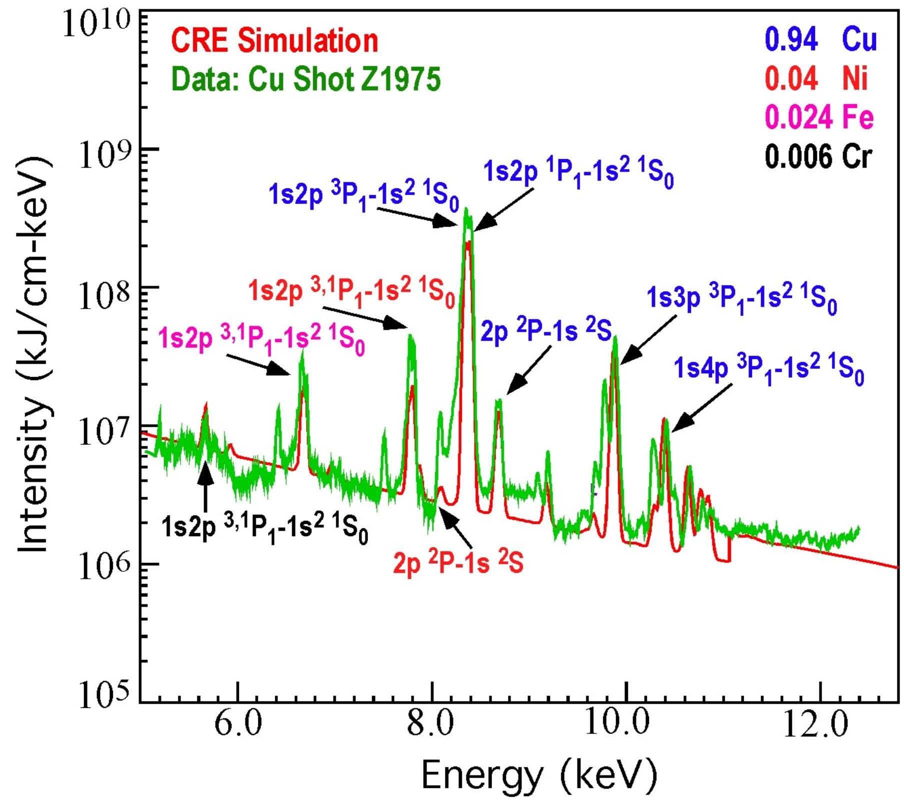


Dasgupta, R. W. Clark, et al., *AIP #1161*, **207** (2009)
Dasgupta, J. G. Giuliani, et al., *IEEE TPS*, **38**, 598 (2010)



The simulated and experimental K-shell spectra reveal plasma conditions in the emitting region are T_e~3.5 keV and n_e ~ 3×10^{22} cm^{-3}.

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Radiative transfer equation and its' formal solution

Medium characterized by j_ν, k_ν

Incident $I_\nu(0)$ → $I_\nu(s_0)$

Viewpoint at $s=s_0$

$$\frac{dI_\nu}{ds} = j_\nu - k_\nu I_\nu \left(-\frac{1}{c}\frac{\partial I_\nu}{\partial t}\right)$$

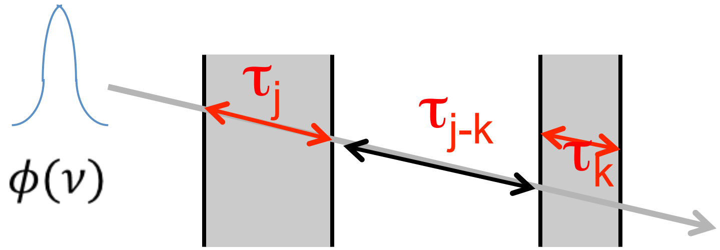
$$I_\nu(s_0) = I_\nu(0)e^{-\tau_\nu(0)} + \int_0^{s_0} j_\nu(s)e^{-\tau_\nu(s)}ds \qquad \tau_\nu(s_0) = \int_s^{s_0} k_\nu(x)dx$$

emission coefficient, j_ν, is the radiative power emitted per unit volume, per unit frequency interval, per unit solid angle.

absorption coefficient, k_ν, is the product of the absorption cross section at frequency ν and the local density of absorbers

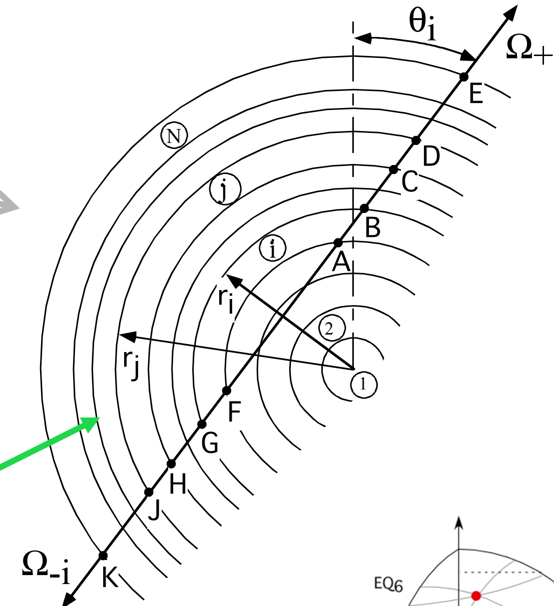
Optical depth τ_ν, is the line integral of the absorption coefficient along the path

Non-local radiation transport requires ray tracing between zones

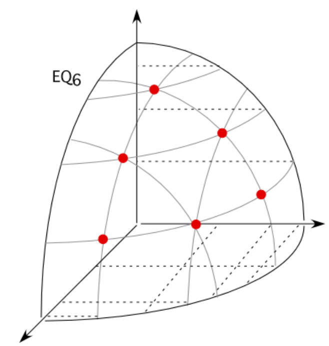


multi-frequency:
coupling coefficient between cells j and k
at frequency ν = $P_{\nu,esc}(\tau_j,\tau_{j-k}) - P_{\nu,esc}(\tau_j,\tau_{j-k}+\tau_k)$

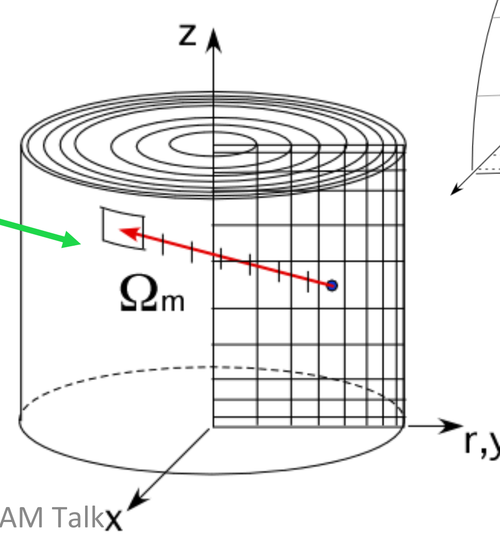
by frequency average $P_{esc} = \int \phi(\nu) e^{-\tau_o \phi(\nu)/\phi(\nu_o)} d\nu$



1D planar, cylindrical, spherical ray trace
by angle average with a unique ray per cell



But higher dimensional problems,
even 2D R-Z, require transport in 3D.



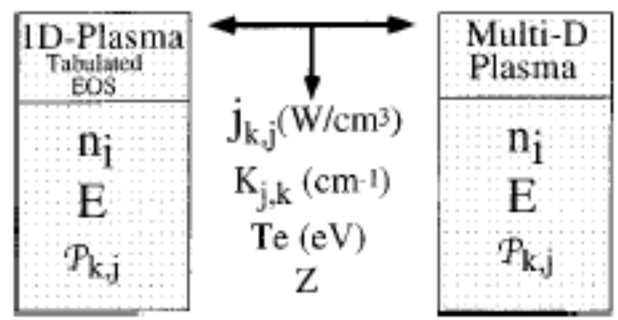
Apruzese, *JQSRT*, **34**, 447 (1985)
Apruzese, Giuliani, *JSQRT*, **111**,134 (2010)

In multi-dimensional simulations advanced approaches to non-LTE are required

LTE tables the plasma ionization & radiation depend only on the local density and temperature.

In non-LTE the plasma ionization & radiation also depend upon the optical depth of each emission line and the photo-pumping from distant regions.

The Tabular Collisional-Radiative Equilibrium (TCRE) model incorporates these features using a three parameter look-up: density,
internal energy (E), and
probability-of-escape ($P_{k,j}$).

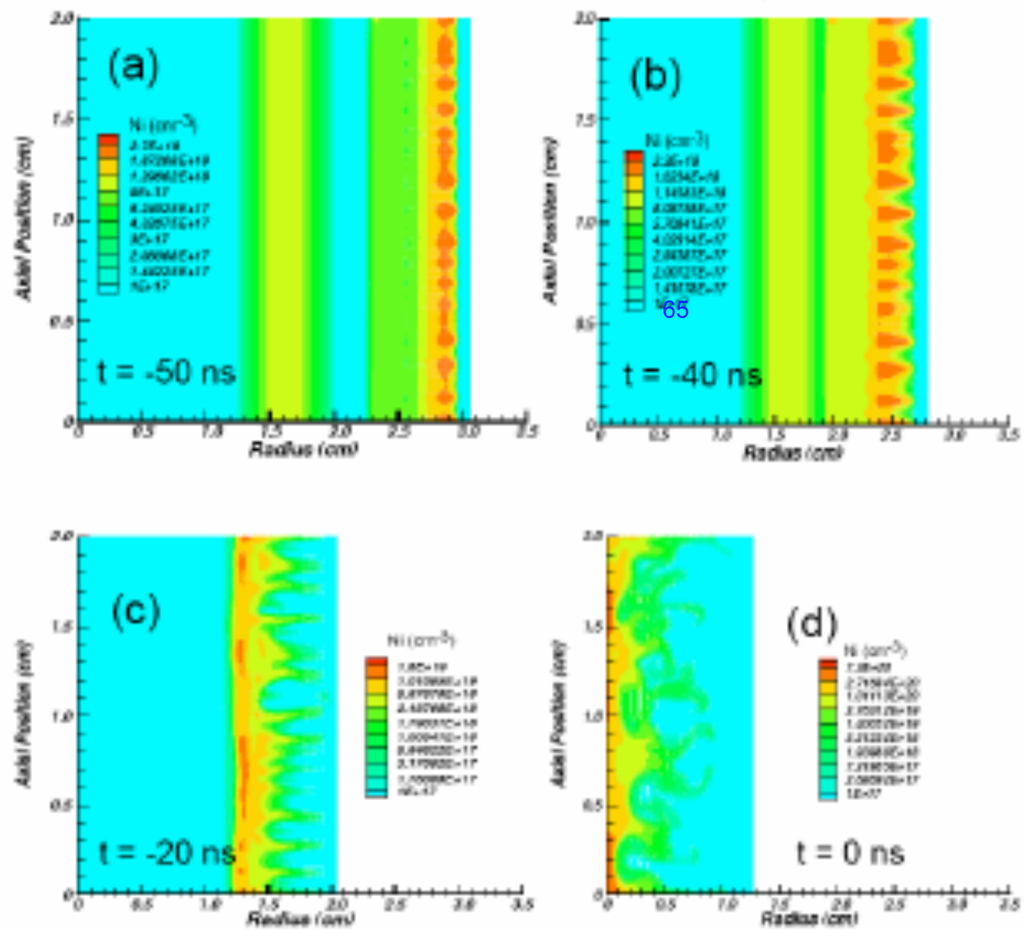


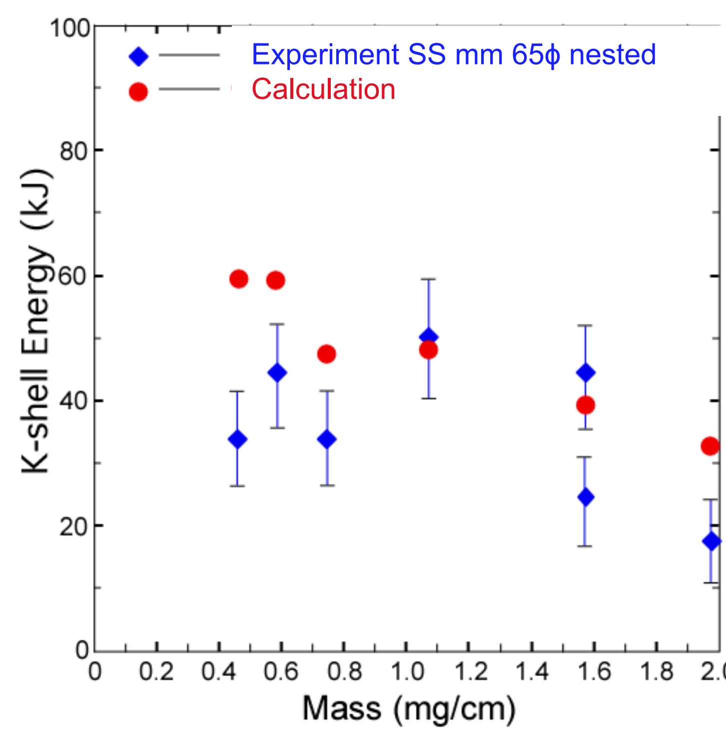
Properties determined from exact solutions of a uniform plasma.

Thornhill, Apruzese, et al., *PoP*, **8**, 3480 (2001)

Combine resistive MHD (MACH2) in R-Z with TCRE to match SS K-shell yields

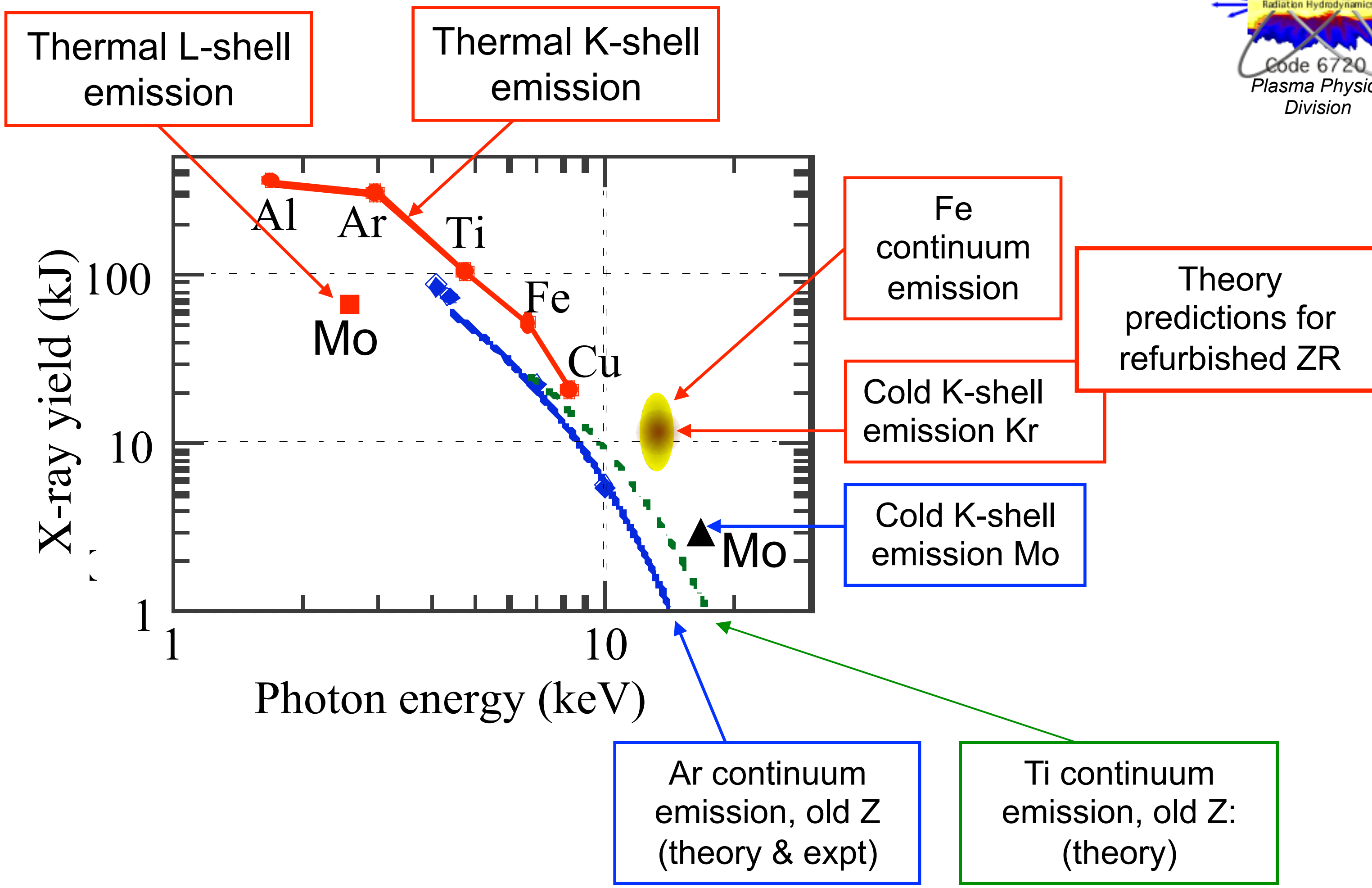
Nested double SS wire array load (M_{tot} = 2.5 mg, R = 55 mm) on refurbished Z (Z1860/61)





Thornhill, Giuliani, et al., *IEEE TPS*, 3**8**, 606 (2010)
Thornhill, Chong, et al., *PoP,* **14**, 063301 (2007)

Advanced simulations also applied in a predictive mode seeking photons >10 keV



Velikovich, Apruzese, Davis, et al.,*IEEE TPS,* **38**, 618 (2010).

Matching synthetic spectra to observed K-shell data provide averaged plasma conditions

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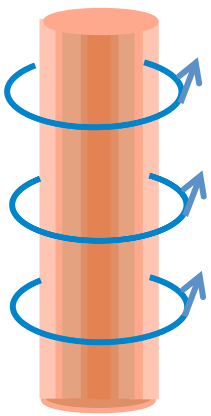
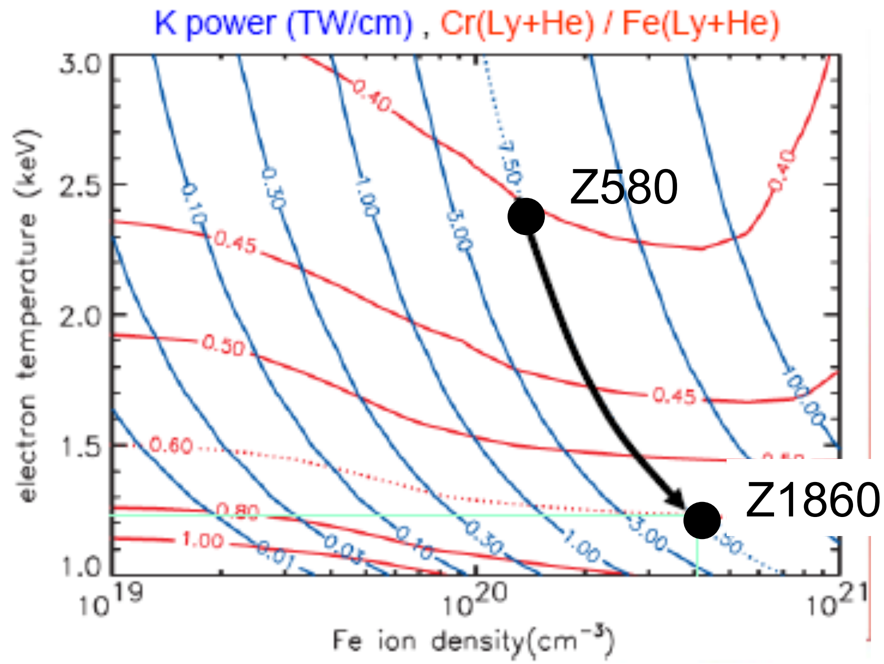
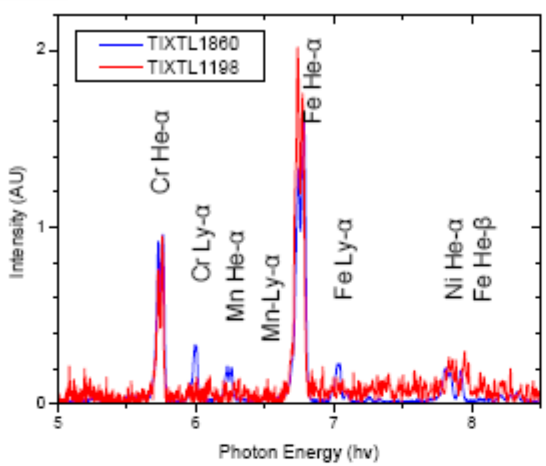


Calculate synthetic spectra from a static cylindrical plasma. Use absolute power and line ratios to form a diagnostic plane.



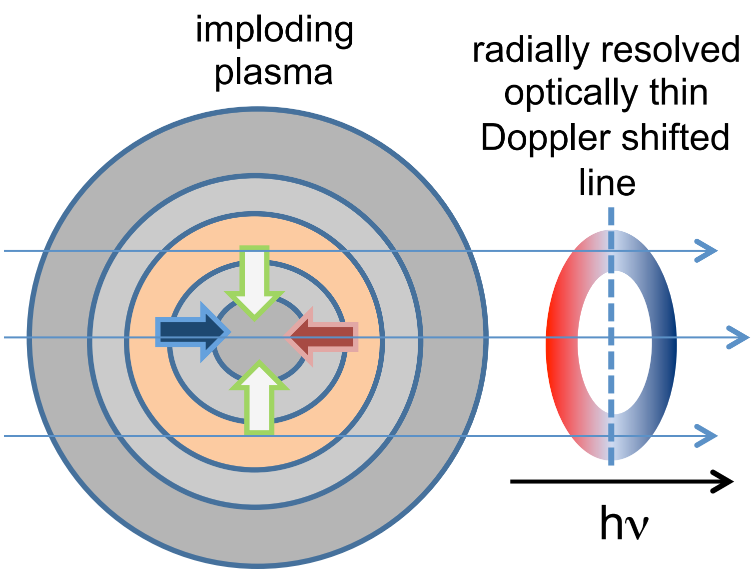
calc powers and ratios from experimental spectra SS

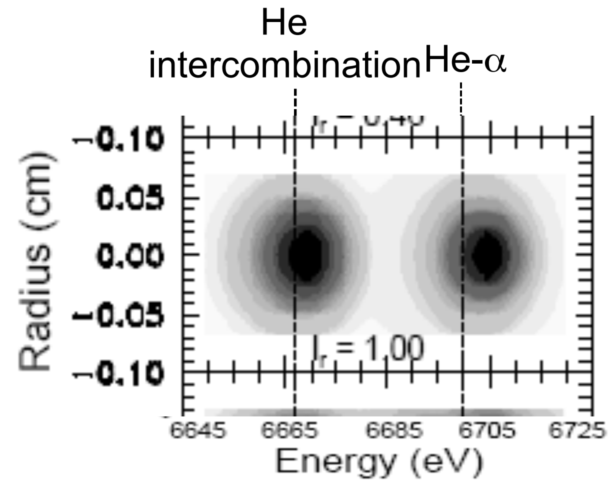


	Z580	Z1860
Pinch size	~1.2mm	0.9mm
Cr/Fe	~0.4	0.6
K-shell P	7.5TW/cm	7.5TW/cm
N_i (cm^{-3})	1.2×10^{20}	4×10^{20}
T_e (keV)	2.6	1.25

Deeney, Apruzese, Coverdale, et al., *PRL,* **93**, 155001 (2004).

Line opacity and Doppler shifts due to motion interact to give spectral features

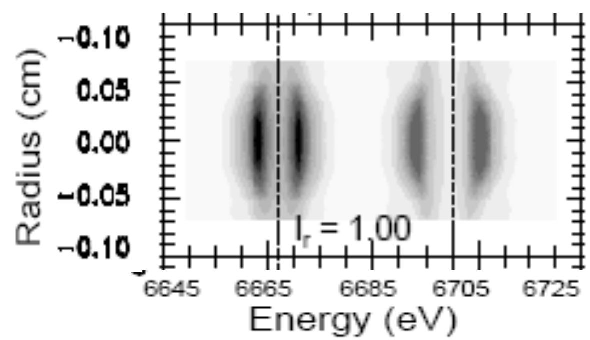




simulated spectra

with Doppler

Opacity interplays with Doppler shift to offset the lines.



without Doppler

"self-reversal" at line center due to absorption

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Comparison of radial and temporal resolved synthetic spectra with data

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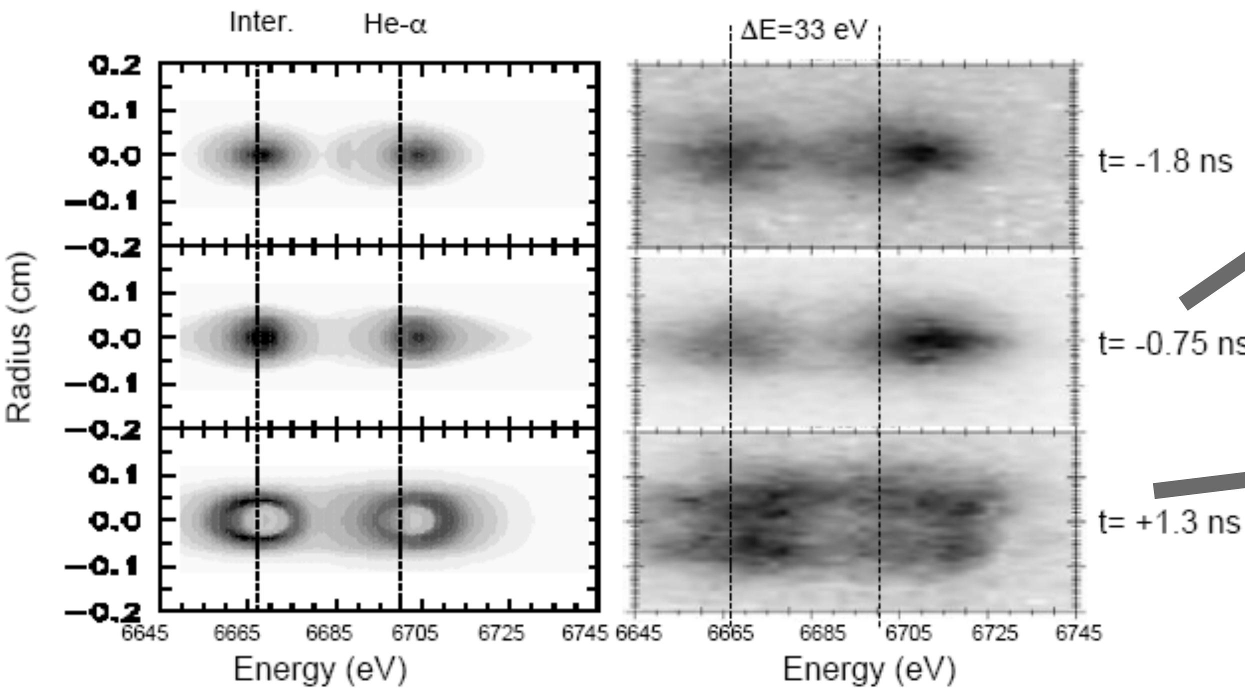
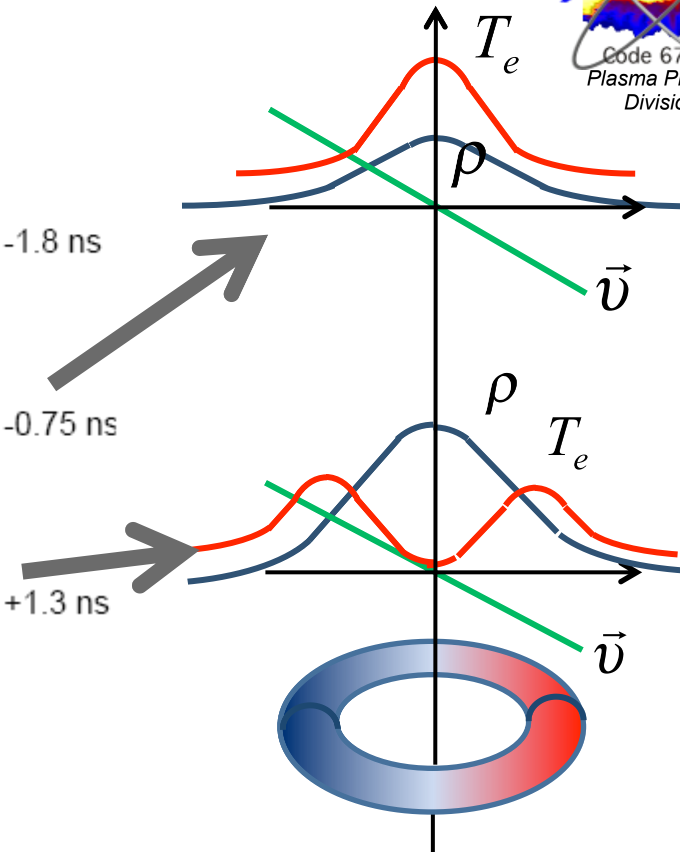
synthetic from TCRE-MACH2 simulation with Doppler

observed Fe spectra for Z1861 at stagnation





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t=0 corresponds to the peak K-shell power.

(Absolute energy dispersion on spectra to be finalized by B. Jones)

rapid radiative cooling in center produces a torus of He-like plasma

Sandia National Laboratories

NRL is the world leader in direct drive inertial confinement fusion with KrF lasers

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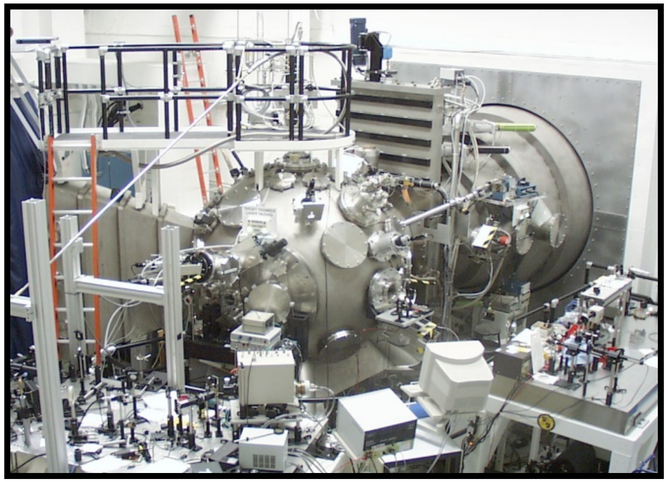
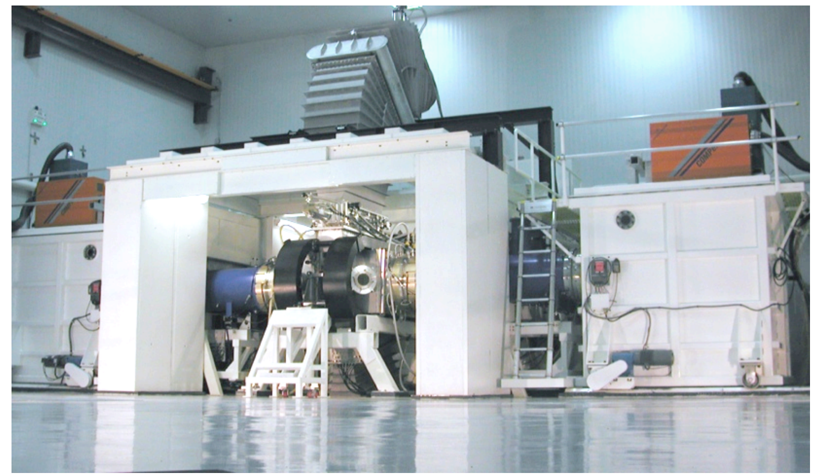
Nike Laser Target Chamber

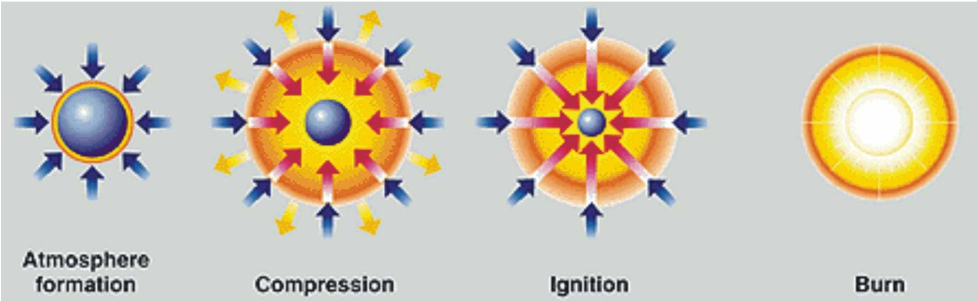


Electra 5 Hz electron-beam-pumped KrF laser

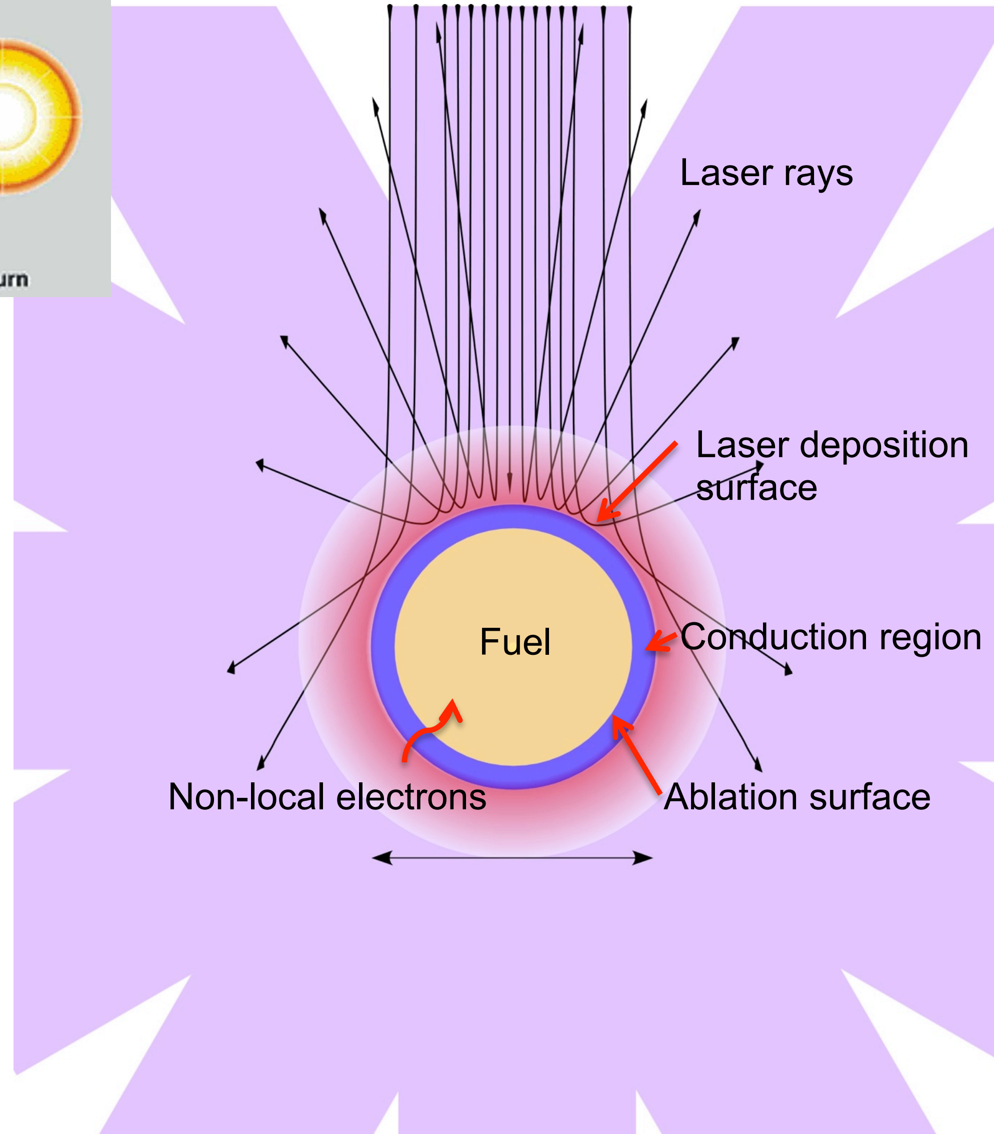


- **Laser facilities**
  - NIKE: 3 kJ KrF laser (0.25 μm, 4 ns) S. Obenschain
  - Electra KrF laser development facility (700 J, 5 Hz) J. Sethian
- **Research activities:**
  - ICF Target physics – Laser plasma interactions, RT instabilities, shock ignition
  - Laser Science – High power KrF, repetitive KrF and solid-state pulsed power
- **Vision:**
  - Contribute to future US Inertial Fusion Energy program

Non-local electron transport is important for direct-drive ICF targets

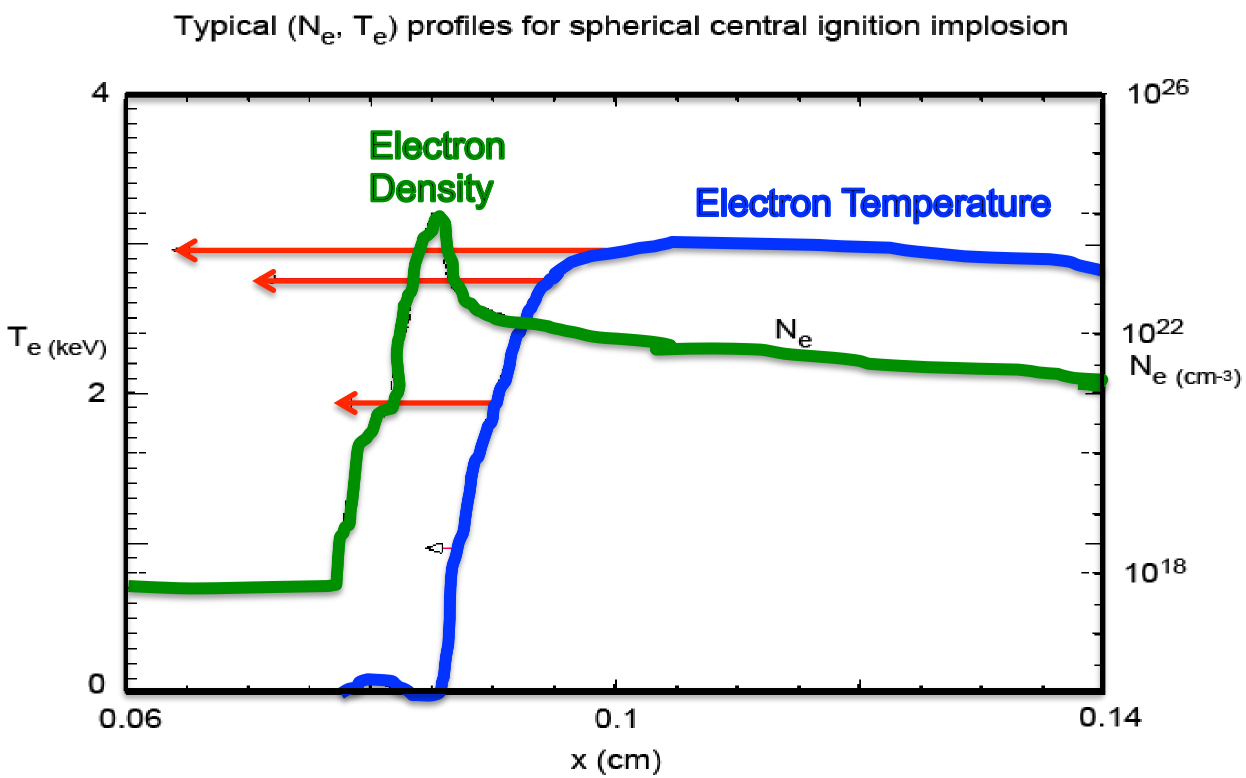


- Laser energy deposited at critical surface (Inverse Bremsstrahlung)
- Electron thermal conduction transports energy to ablation surface
- Normal diffusion ($q = -\kappa \nabla T$) invalid when thermal gradients between hot corona and cold fuel become too large
- Insufficient electrons to carry heat flux – transport becomes “flux limited”
- Generation of high-energy electrons with low collisionality can lead to energy deposition into fuel (preheat) – “non-local transport”



Question: Why is there a problem with classical transport?

Answer: Because classical transport assumes mean free path of energy carrying electrons is small compared to gradient scale length.



Red arrows are electron mean free path for energy = $10T_e$

Why do we care about electron transport in ICF?

Direct Drive:

- Shock timing depends on electron transport
- Preheat from hot electrons increases adiabat & decreases compression (stabilizes RT?)

Indirect Drive:

- High flux model with f=0.15 gives cooler plasma in NIF hohlraum – changes laser-plasma growth rates
- "Hohlraum energy balance, as measured by x-ray power escaping the LEH, is quantitatively consistent with revised estimates of backscatter and incident laser energy combined with a more rigorous non-local-thermodynamic-equilibrium atomic physics model with greater emissivity than the simpler average-atom model used in the original design of NIF targets"*

*Town, R. P. J., M. D. Rosen, et al. (2011). "Analysis of the National Ignition Facility ignition hohlraum energetics experiments." Physics of Plasmas **18**(5): 056302-056308.

Many hydrocode models use a flux limiter on electron thermal conduction

- Don't expect the flux to be greater than nmv_e^3, so many codes have a model to limit it to $q < fnmv_e^3$
- $f_e = \min(k_e dT/dx; \mathbf{f}_L nvT)$ or smoother harmonic mean
- A properly chosen flux limit in a fluid simulation can almost always reproduce a single experimental result.

High Flux Model (HFM) gives better agreement with NIC hohlraum data

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- "The HFM contains two principal changes from the standard model:
  - 1) It uses a detailed configuration accounting (DCA) atomic physics non-local-thermodynamic-equilibrium (NLTE) model, and
  - 2) It uses a generous electron thermal flux limiter, f = 0.15, that is consistent with a non-local electron transport model.

- Both elements make important contributions to the HFM's prediction of a hohlraum plasma that is cooler than that predicted by the standard model, which uses an NLTE average atom approach, and a value of f = 0.05 for the flux limiter. This cooler plasma is key in eliminating most of the discrepancies between the NIC data and revised expectations based on this new simulation model."

Rosen, M. D., H. A. Scott, et al. (2011). "The role of a detailed configuration accounting (DCA) atomic physics package in explaining the energy balance in ignition-scale hohlraums." High Energy Density Physics 7(3): 180-190.

But there are many problems with a using a simple flux limiter

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- mfp > scale length, so energy advances ahead of front:
  - $q < fnmv_e^3$ means $T>[q/f]^{2/3}m^{1/3}$
- Too low a flux limit gives too high a temperature (e.g. NIF hohlraum & impact on SRS threshold)
- It certainly cannot predict preheat, as this is absent from a flux limit formulation.
- Can one pick a flux limit to agree with more than one measurement?
- How do you pick f anyway?

Beyond diffusion – the NRL velocity-dependent Krook (VDK) model

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- Collision term in Vlasov Equation:

$$V \bullet \nabla f - \frac{eE}{m} \bullet \nabla_V f_m = -\nu_e(V)\left(f - f_m\right) + \frac{\nu_i(V)}{2}\left[\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial}{\partial\theta} + \frac{1}{\sin^2\theta}\frac{\partial^2}{\partial\phi^2}\right]f$$

Can solve analytically for q, it describes BOTH flux limitation and preheat.

VDK Solution for energy flux

Classical like flux but with reduced coefficient (flux limitation)

$$q = -\int_{0}^{\Xi_{cr}} d\Xi\,\alpha(\Xi)\frac{\partial T}{\partial x}\left(\equiv K\frac{\partial T}{\partial x}, K < K_{sp}\right) - \int_{-\infty}^{\infty} dx' \int_{\Xi_{cr}}^{\infty} d\Xi \frac{\alpha(x',\Xi)}{2\lambda(x',\Xi)}\frac{\partial T}{\partial x'}\exp - \left|\int_{x'}^{x}\frac{dx''}{\lambda(x'',\Xi)}\right|$$

nonlocal effect (preheat)

(Ξ is a particle energy)

Flux limitation and preheat are two sides of the same coin.

1-D VDK results in good agreement with Fokker-Planck , flux limiter under predicts Te @ front

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FP: Matte, Ref 10

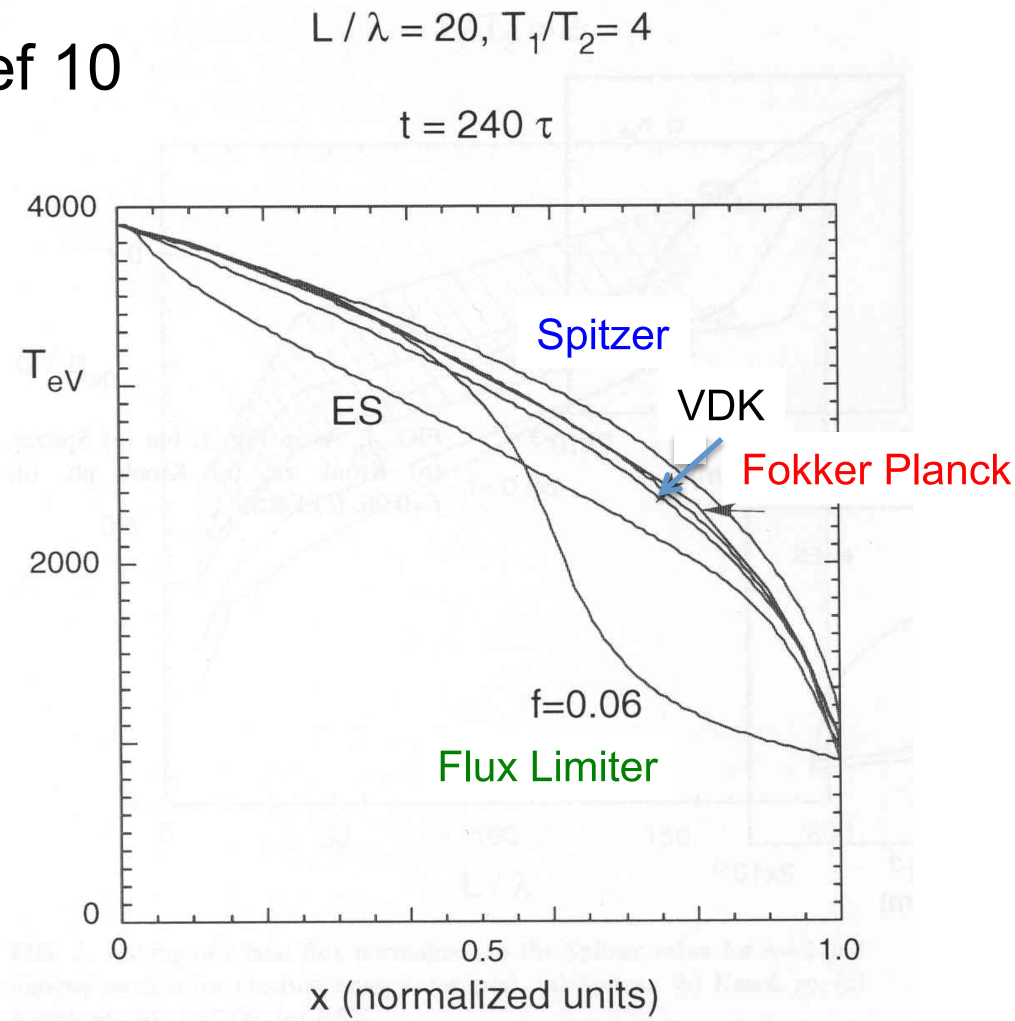

FIG. 6. As in Fig. 5(a), but at $t=240\tau$.

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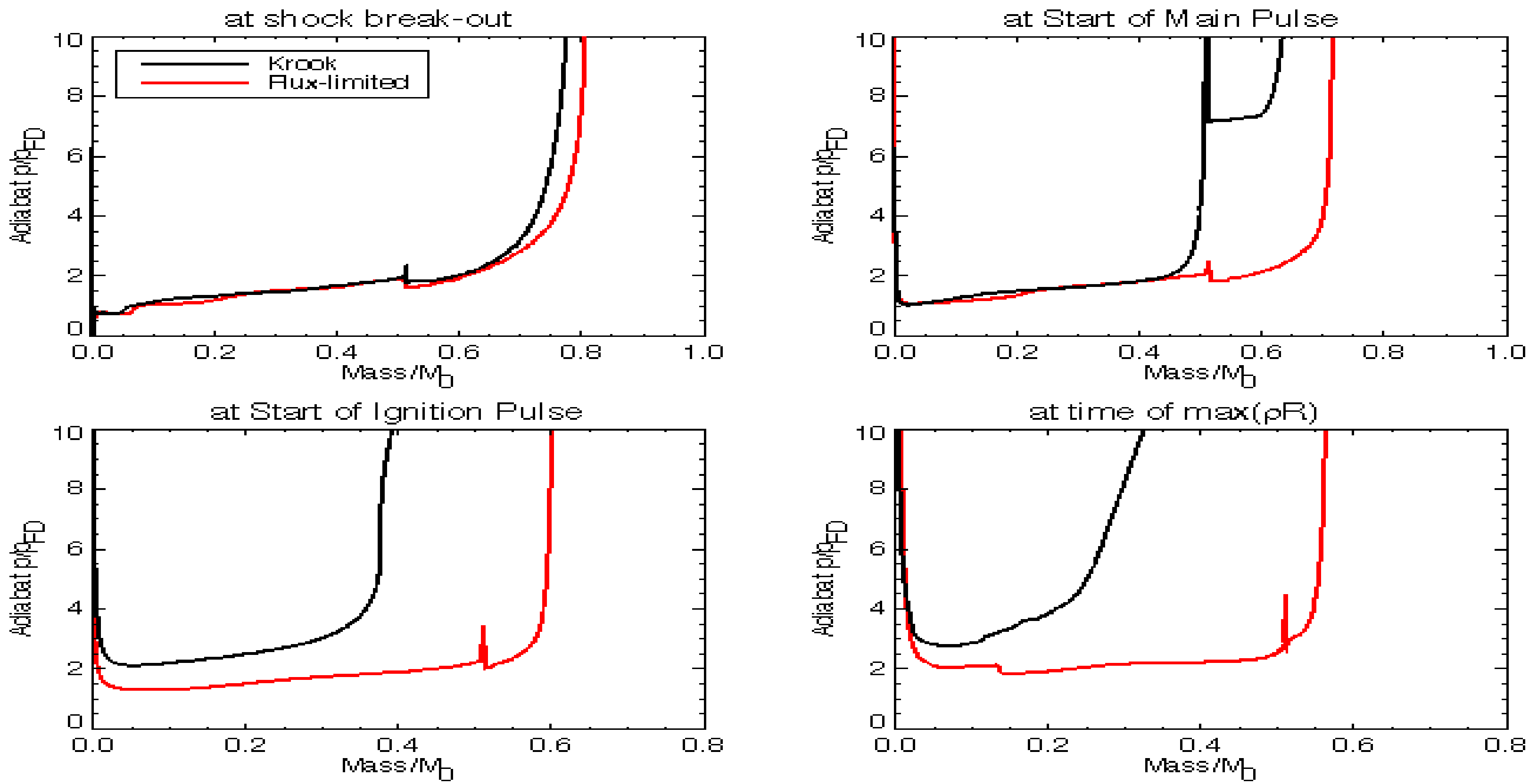
Application of Krook model to KrF shock ignition target implosion



- Comparison of shock ignition target calculations for VDK and f=0.075.
- Absorption increased from 85% to 90%, but gain drops from 140 to 100 due to preheat. (Ref 6)
- Increased alpha might in outer part of fuel might give rise to further RT stability.

Applying the Krook theory in two-dimensions is more challenging

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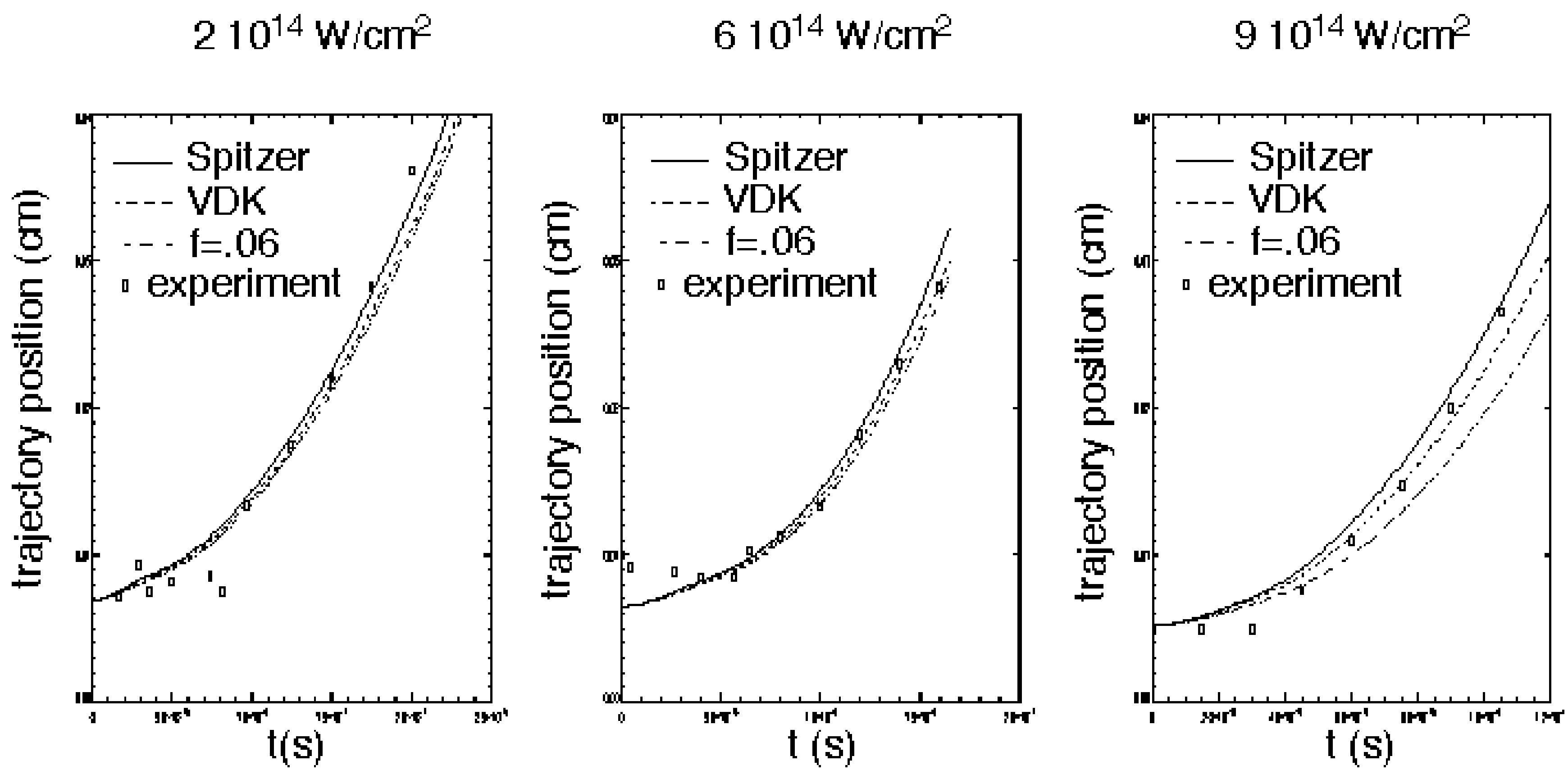
<u>Approach presently implemented and in testing:</u>

- Assume single collision frequency and solve first order equation. Solution same in 1-, 2-, or 3-D, but have to sum over angles to get q.
- Let 1-D Legendre solution guide how to select collision frequency.
- If there is a dominant direction (i.e. r for spherical, z for foil acceleration), the result reduces to decoupled non-local diffusion in each direction.
- The result can be implemented densely (i.e. at every point in each direction) or sparsely, (i.e. at a subset of point with interpolation).

Note: Fokker Planck not numerically tractable – 1) too many orders of magnitude to resolve, 2) only valid for large Λ, but Λ is small in many regions of a laser plasma

Comparison of 2-D theory and experiment at the three irradiances on Omega @UR-LLE



Impact of non-local transport greater with increasing laser irradiance

Velocity Dependent Krook best compromise between physics and numerical practicality

- Treats both flux limitation and preheat.
- Has proper treatment of both high and low velocity electrons.
- Shows a significant effect on laser pellet design, but certainly is not a show stopper.
  - So far we found redesigned pellet has reduced gain, but not by much (~10-25%).
- There may also be stabilizing effect on RT which we are examining now.

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10. J. Matte and J. Virmont, Phys Rev Let 49, 1936 (1982)

Reference on Fokker Planck:

- Mehlhorn, T. A. and J. J. Duderstadt (1980). "A discrete ordinates solution of the Fokker-Planck equation characterizing charged particle transport." Journal of Computational Physics **38**(1): 86-106.

Ultra-Short Pulsed Lasers (USPL) – from physics to applications

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Fusion energy
Detection of SNM
Material dynamics under extreme conditions
Affordable cancer radiotherapy

↑

Advances in other fields of physics (e.g. nuclear physics)

↑

Compact, high-current particle accelerators

↑

Generation of extreme matter, new probes, new tools

↑

Advances in physics:
understanding on relativistic laser-matter interactions

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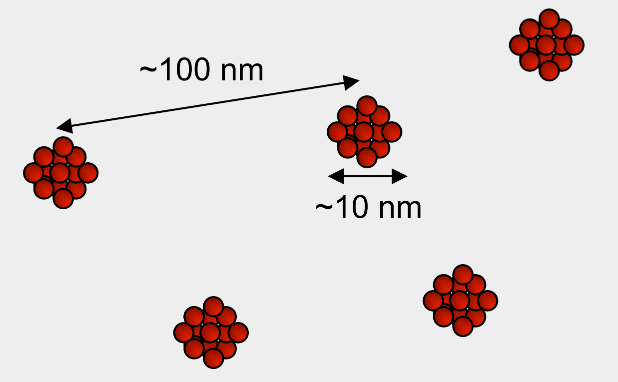
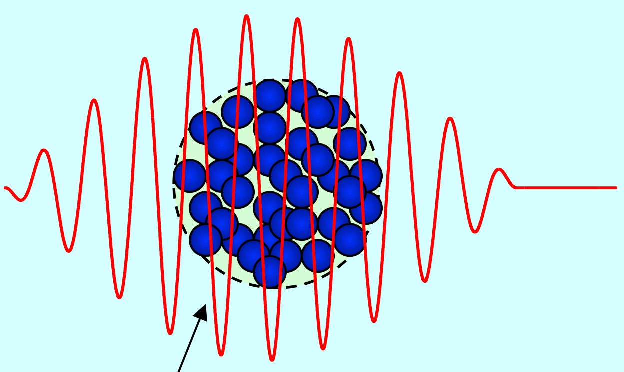
Laser cluster interactions: creation of hot dense plasma

Cluster media



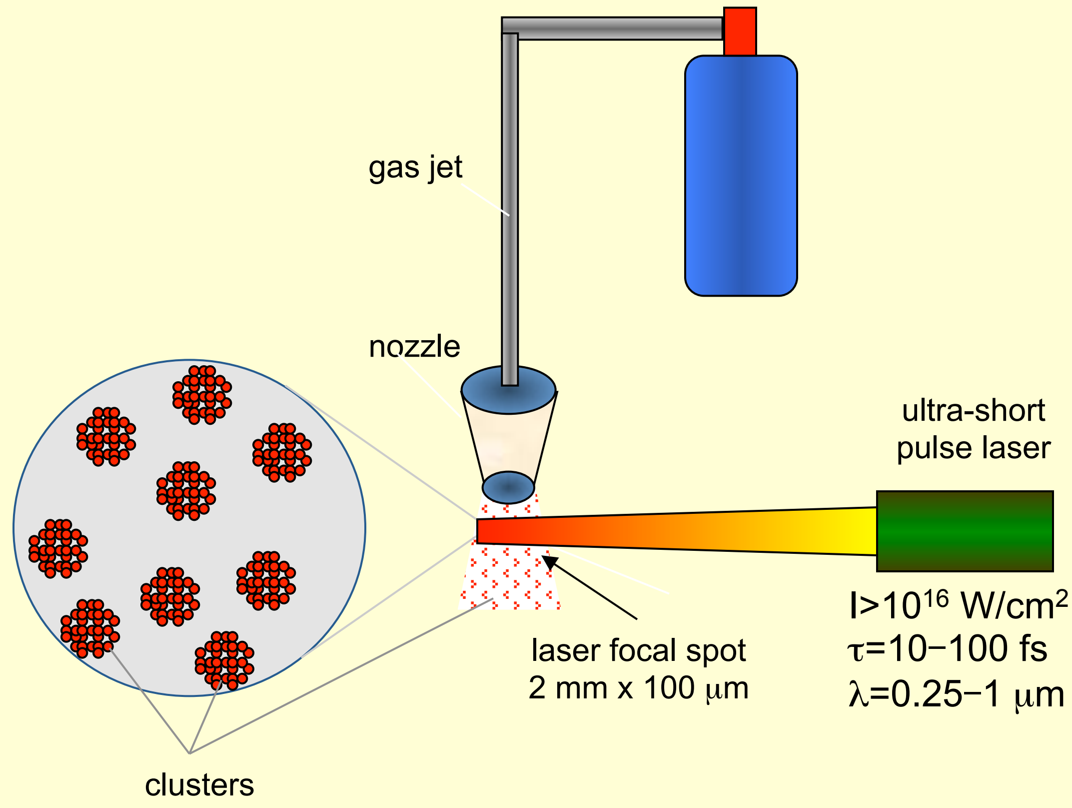
The cluster media is 99.9% space

Cluster irradiated by a laser



Laser electric field ~10^{12} V/m !

Cluster formation



High-pressure gas jet goes through a nozzle and expands in vacuum. The gas cools and forms tiny droplets (clusters). These clusters are irradiated by a high-intensity ultrashort pulse laser

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Laser cluster interactions: creation of extreme state of matter

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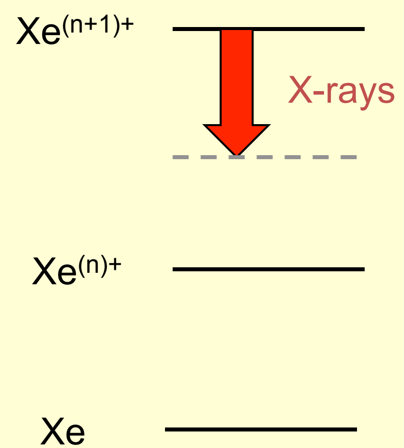
Typical cluster parameters

Atom density	~5x10^{22} cm^{-3} (solid density)
Cluster size	~10 nm
Cluster volume	~10^{-18} cm^3
Absorbed energy	~0.1 nJ
Absorbed energy density	~10^8 J/cm^3
Interaction time	~100 fs
State of matter	fully ionized, highly charged
Radiation emission	X-rays (1-100 A)

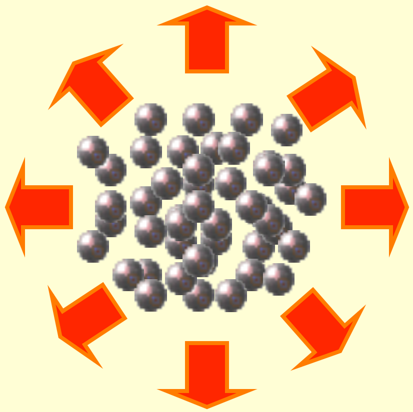
Absorbed energy density ~ 10^8 J/cm^3

Cluster dynamics

Formation of highly charged ions and X-ray generation

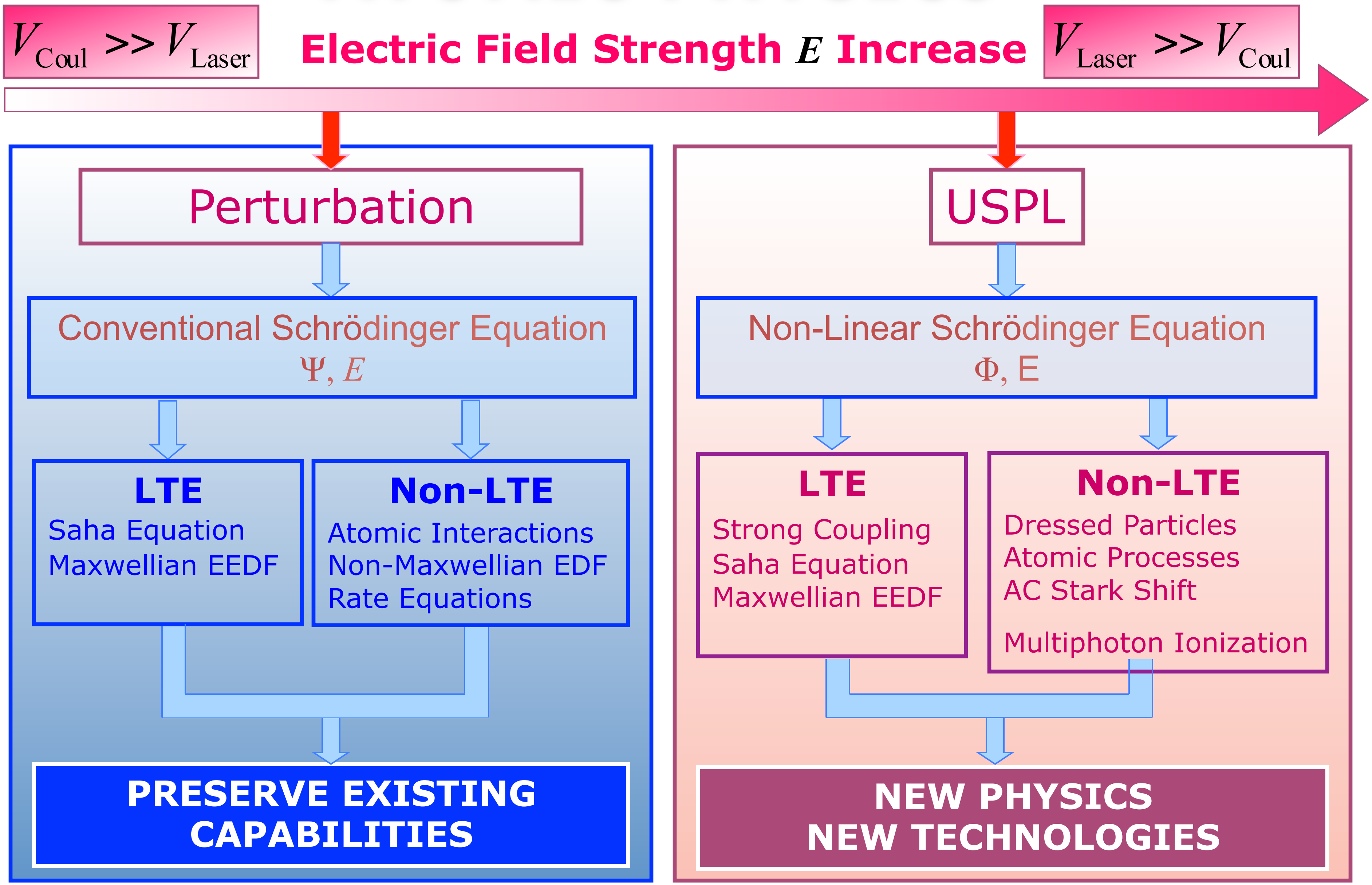


Cluster explosion & generation of high-energy particles



- ❑ **Laser-cluster interactions create extreme conditions and lead to high-energy density laboratory plasma.**
- ❑ **The cluster dynamics is highly non-local and non-equilibrium due to the impact of the enormous electromagnetic fields of the laser (electric field > 10^{12} V/m).**
- ❑ **Enhanced energy absorption leads to highly charged ions and X-ray generation**

ATOMIC PHYSICS



Simulating laser cluster interactions: synergy of particle simulations & atomic physics

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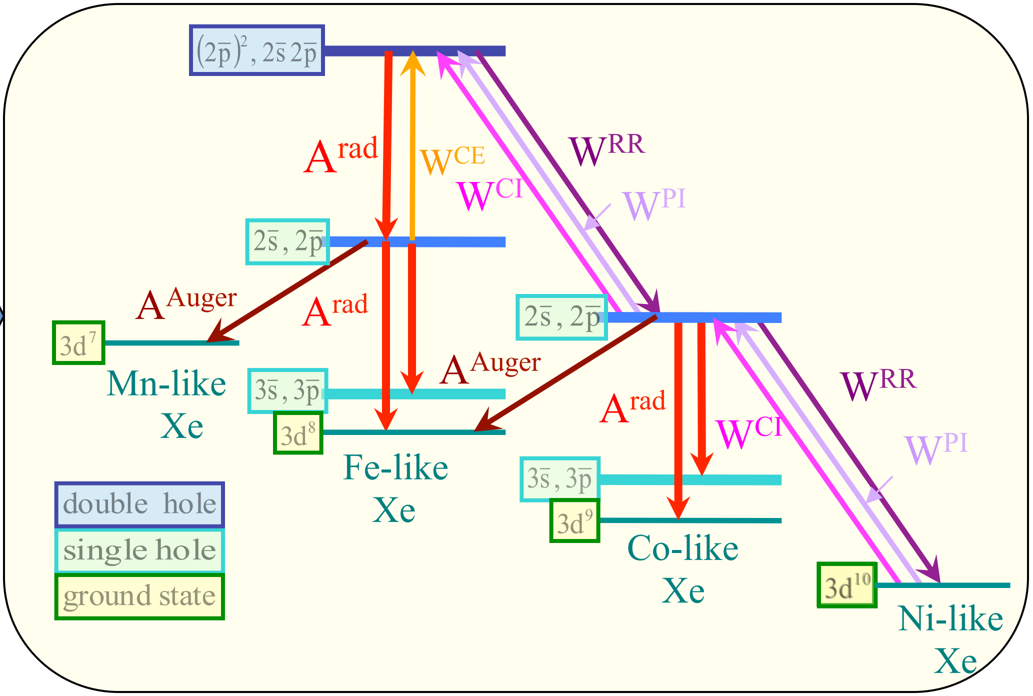
Molecular Dynamics of Xe Clusters:
Particle Equations
Tunneling Ionization
Collisional Ionization

- Energy Absorption
- Cluster Expansion
- Electron & Ion Densities
- Electron & Ion Temperatures

Atomic Physics (FAC):
Energy Levels
Transition Probabilities
Photoionization Cross Sec
Auger Rates



Ionization Dynamics:
Rate Equations
Population Level Dynamics

- X-ray radiation and spectra
- X-ray gain

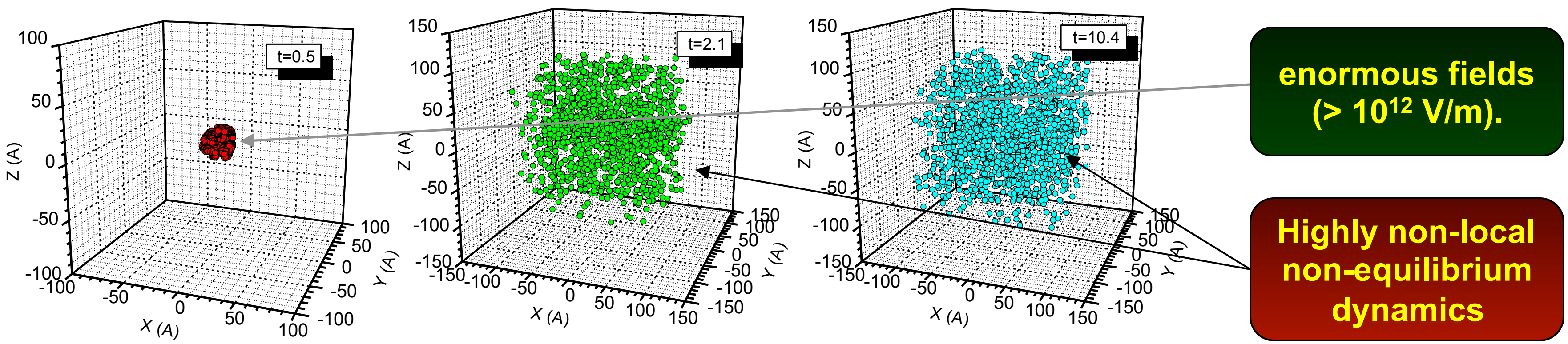
NRL Radiation Hydrodynamics Code 6720 Plasma Physics Division

Coupling of particle simulations to atomic physics

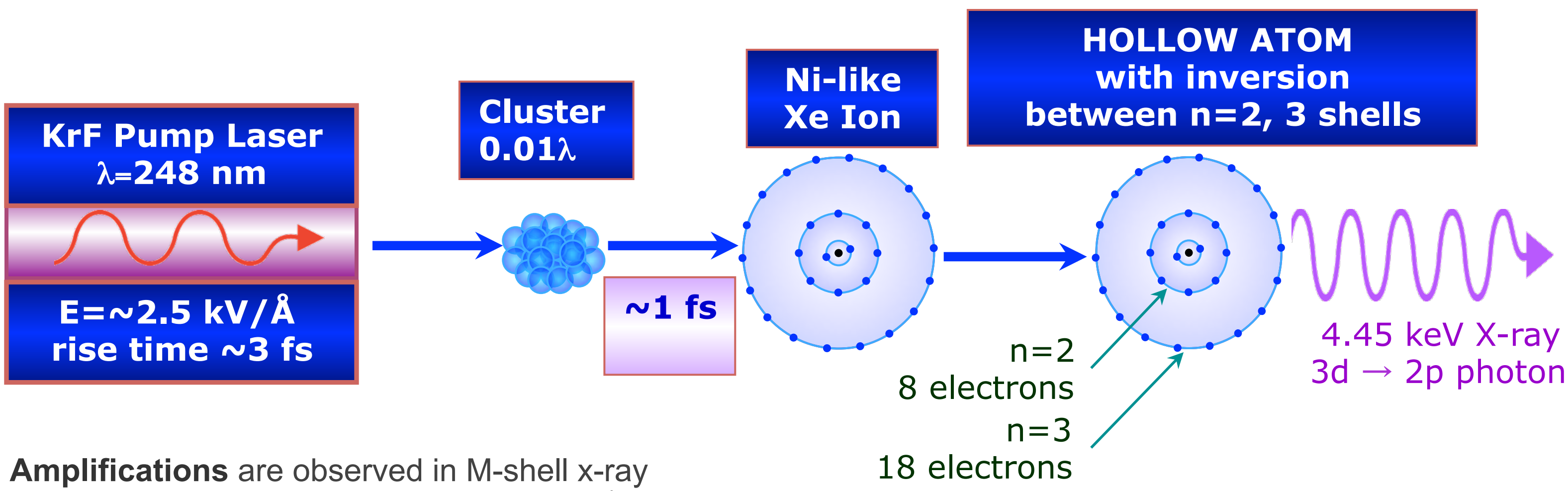
Plasma Physics Division

❑ Molecular dynamics simulation of small Xe clusters

N =20 atoms/cluster, I_{laser}^{max}=2x10^{19} W/cm^2, t=8 fs



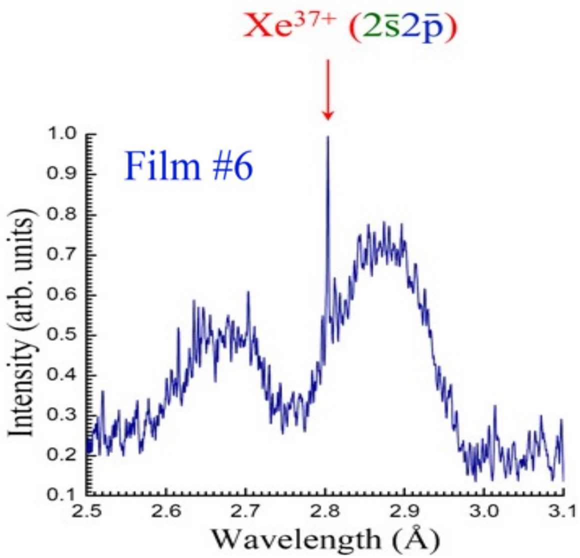
❑ Atomic physics of small Xe clusters

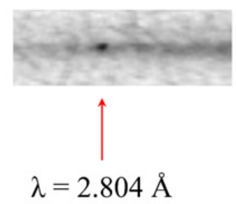


Amplifications are observed in M-shell x-ray emissions with short wavelengths (~2.5-3 Å).

NRL Radiation Hydrodynamics Code 6720 *Plasma Physics Division*

Measured and simulated spectra from highly charged Xe



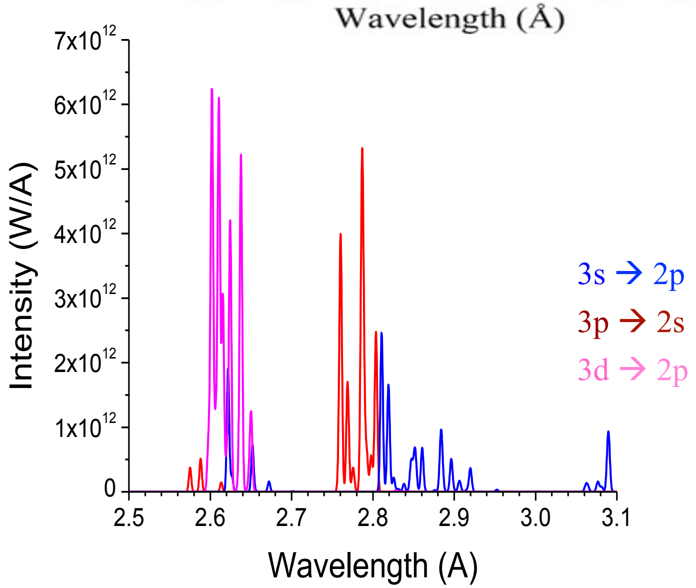


Xe^{37+} (2s̄2p̄) Double-Hole Line Amplification

Xe^{37+} (2s̄2p̄) $2s2p^63s^23p^6 \leftarrow 2s2p^53s^23p^63d$

Ref: A. B. Borisov, J. Phys. B, **38** 3935–3944 (2005)

Recorded time-integrated spectrum from a plasma channel with a mica equipped von Hamos spectrograph demonstrating amplification on the *(*2s2p*)* Xe^{37+} double-vacancy array at λ=2.804 A. The magnitude of the amplification represented by the narrow line at λ= 2.804 A is estimated to be ~10^6.



Calculated oxygen-like xenon snapshot spectrum from small Xe clusters. Simulation parameters:

Ion density: $2x10^{20}$ cm^{-3}
Ion temperature: 4 keV
Electron temperature: 40 keV

Non-LTE and non-local phenomena underlie High Energy Density (HED) plasmas

LTE

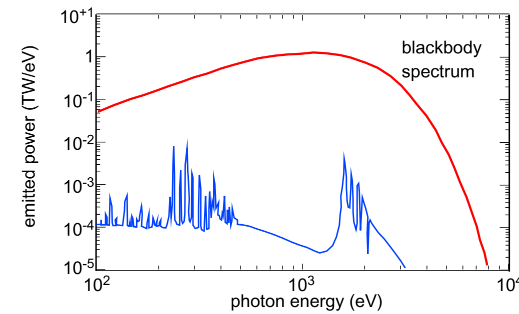
(Local Thermodynamic Equilibrium)

internal energy of a plasma
(thermal + excitation + ionization)
determined by local
density and temperature

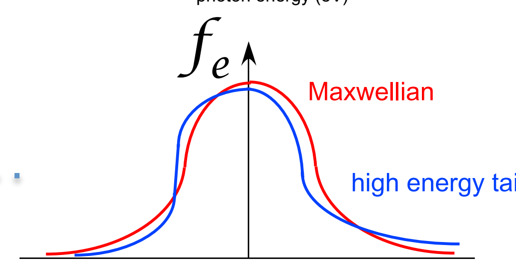
non-LTE

internal energy of a plasma
also depends on gradients
and thereby non-local

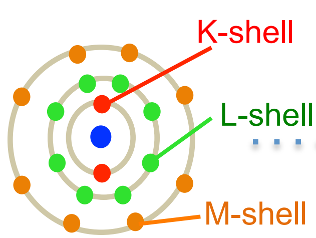
blackbody radiation spectrum .... $\lambda_{\gamma,mfp} > \dfrac{\rho}{\nabla\rho}$ ....



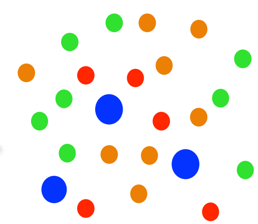
heat conduction = $\kappa\nabla T$ .... $\lambda_{e,mfp} > \dfrac{T}{\nabla T}$ ....

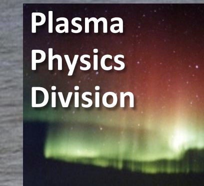


isolated atom



...... $\mathcal{E}_{laser} = \nabla\phi > \dfrac{e}{a_B^2}$ ....





Thank you for your attention

Are there any questions?

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Workshop Goals

- Scientific Overview
- The physics of hot, dense plasmas is a field rich with physics and mathematics, spanning many different length and time scales. To accurately simulate hot, dense plasmas requires resolving the physics of hydrodynamics, radiation and electron transport, atomic physics, burn physics, wave-wave interactions, wave-particle interactions and particle-particle interactions, to name a few processes.
- To perform such a calculation that resolves such physics at all these length and time scales remains computationally unfeasible even with an exascale capability. Thus, it is important to differentiate between the physics that must be fully resolved, and the physics that can be included with a reduced model description in a fully integrated simulation. These fully integrated simulations including reduced model descriptions can then be validated through experiment.
- The goals of this workshop are:
- to identify key physics components in integrated simulations of hot, dense plasmas
- to identify critical computation issues at the different length and time scales
- to propose reduced model descriptions that can be experimentally validated
- to define experiments critical to an integrated simulation of hot, dense plasmas
- to promote new collaborations
- to engage young scientists
- It is the goal of this workshop to bring together mathematicians, computer scientists, and physicists, who work in the area of hot dense plasmas. We expect this workshop will to attract junior as well as senior participants.
- This workshop will include a poster session; a request for posters will be sent to registered participants in advance of the workshop.

The Role of Non-Local and Non-Equilibrium Physics in High Energy Density Plasmas

There is a large class of problems in high energy density plasmas where the approximations of locality and equilibrium are invalid. In this talk I will consider three different systems: 1) K-shell Z-pinch radiation sources are not in LTE (local thermal dynamic equilibrium) and where non-local line radiation transport affects the plasma dynamics; 2) in laser generated plasmas, the mean free path of the heat conducting electrons can be greater than the temperature gradient scale length and the classical, local model can be invalid; and 3) when atomic clusters are irradiated by high-intensity ultrashort laser pulses the electric field of the laser is orders of magnitude greater than the Bohr electric field associated with the atoms, the ionization kinetics is time dependent (non-equilibrium), and all the tools and methodologies used in the isolated atom regime are negated. Simulating HED plasmas in LTE and where local transport is valid can be challenging to algorithms, databases, and computational hardware. Including these non-local and non-equilibrium effects is even more formidable, requiring trade-offs to be made between physics fidelity and computationally practicality. The choice of computational algorithm (e.g. hydrodynamics, particle-in-cell, or molecular dynamics; or diffusion, Krook, or Fokker Planck) is highly dependent upon the specific problem and degree of non-locality. This talk will provide an overview of each of these systems and their applications, the role of non-local and non-equilibrium physics, the computational physics challenge of including these effects, and a roadmap for future improvements.

References:

J.W. Thornhill, J.L. Giuliani, A. Dasgupta, et al., IEEE Trans. Plasma Sci., 38, 606 (2010).

G.M Petrov, J. Davis, Phys. Plasmas 15, 056705 (2008)

W. Mannheimer: APS DPP 2011: http://meetings.aps.org/link/BAPS.2011.DPP.YI3.3

In collaboration with A Dasgupta, J Davis, J Giuliani, W Mannheimer, and G Petrov, L Petrova, W Thornhill