Charged-particle stopping power in dense plasmas

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Lawrence Livermore National Laboratory

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Charged-particle transport is important microphysics for fusion scenarios and understanding basic plasmas

- Energetic charged particles lose energy via Coulomb collisions with background electrons and ions, and coupling to plasma waves, as they move through a plasma (dE/dx)

- Stopping power in high-energy-density plasmas has been a challenging problem for both theory and experiment, especially in degenerate/strongly-coupled plasmas and/or near the maximum in dE/dx ('Bragg peak')

- In the past few years several new experiments have provided strong constraints on dE/dx at relevant conditions and are distinguishing stopping models

Outline

- **Review of theoretical models and motivation**
- Overview of parameter space
- First measurement of dE/dx in warm-dense-matter plasma
- Accelerator beams through laser-generated plasmas
- Exploding pusher D^3He self-emission
- Shock-compressed WDM on NIF
- Summary and future problems

Energy balance in ICF depends on transport properties mediated by charged-particle interactions (dE/dx is one)

Paul Grabowski

$$\frac{\partial T_i}{\partial t} = \frac{1}{C_{vi}}\left[\dot{S}_i - \left(P_i + q + \frac{\partial I_i}{\partial v}\right)\frac{\partial v}{\partial t} - A_{ie}(T_i - T_e) + \frac{v}{r^2}\frac{\partial}{\partial r}\left(r^2 K_i \frac{\partial T_i}{\partial r}\right)\right],$$

$$\frac{\partial T_e}{\partial t} = \frac{1}{C_{ve}}\left[\dot{S}_e - \left(P_e + \frac{\partial I_e}{\partial v}\right)\frac{\partial v}{\partial t} - A_{er}(T_e - T_r) + A_{ie}(T_i - T_e) + \frac{v}{r^2}\frac{\partial}{\partial r}\left(r^2 K_e \frac{\partial T_e}{\partial r}\right)\right],$$

$$\frac{\partial T_r}{\partial t} = \frac{1}{C_{vr}}\left[-\left(P_r + \frac{\partial I_r}{\partial v}\right)\frac{\partial v}{\partial t} + A_{er}(T_e - T_r) + \frac{v}{r^2}\frac{\partial}{\partial r}\left(r^2 K_r \frac{\partial T_r}{\partial r}\right)\right].$$

Equation of state

Radiation

T-relaxation

Thermal conduction

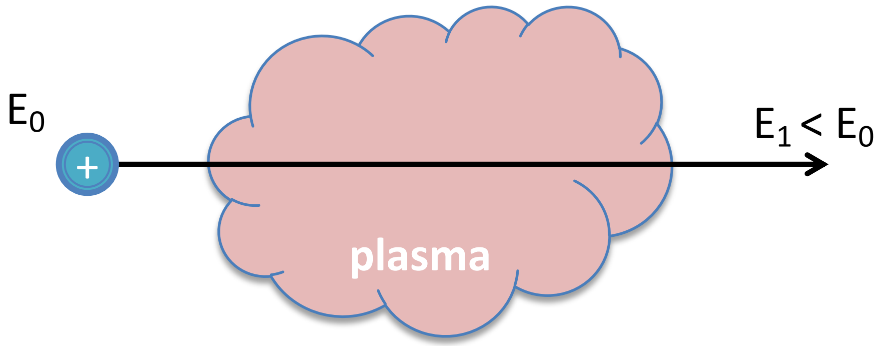
Stopping power

Not Shown:
Electrical conduction
Diffusion

Mediated by charged particle interactions

Stopping power is a fundamental transport property and important for applications (ICF)

dE/dx: energy loss rate from a projectile to the plasma particles:



In addition to a fundamental measurement, stopping power is important for fusion self-heating and burn, and some alternative fusion concepts (heavy-ion drivers, proton fast ignition)

Stopping power is simple in 'ideal' plasmas, but becomes complex when other effects are important

For a fast projectile in a low density high-temperature plasma, you can quickly derive a textbook/Spitzer type of stopping power based on binary collisions between a 'test' particle (t) and field particle (f):

$$\Delta E = \frac{(\Delta p)^2}{2m_f} \qquad \Delta p = \frac{2m_f v_t}{\sqrt{1+(b/r_0)^2}} \qquad r_0 = \frac{Z_f Z_t e^2}{m_f v_t^2}$$

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$$\Delta E = \frac{2(Z_t Z_f e^2)^2}{m_f v_t^2}\frac{1}{b^2+r_0^2} \qquad \frac{dE}{dx} = -\left(\frac{Z_t e}{v_t}\right)^2 \omega_{pf}^2 \log\Lambda$$

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$$\log \Lambda = \int_0^{b_{max}} \frac{bdb}{b^2 + r_0^2} = \frac{1}{2} \log\left(1 + \frac{b_{max}^2}{r_0^2}\right)$$

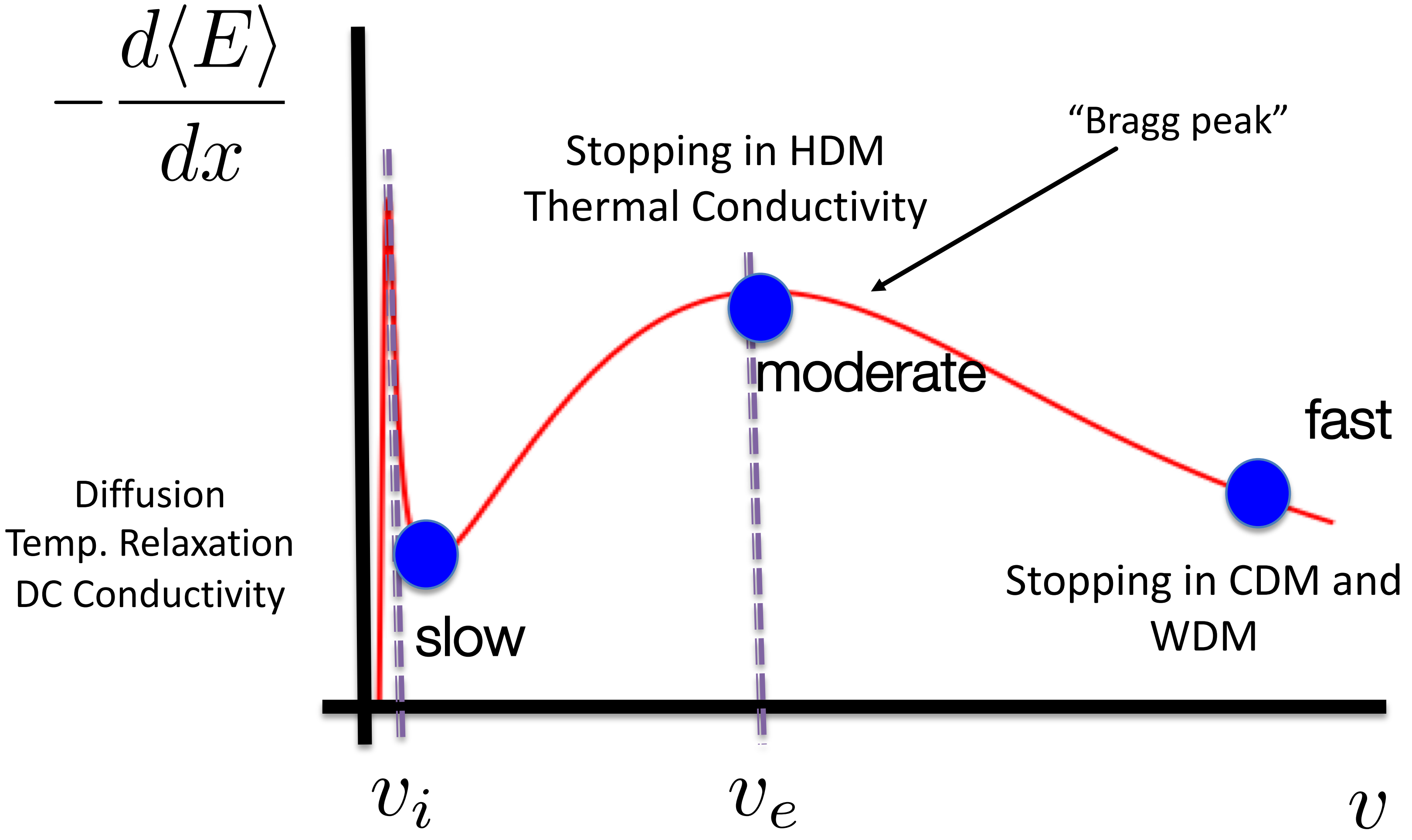
$$\log \Lambda = \log\left(\frac{\lambda_D}{b_{min}}\right)$$

This breaks down when:

- Restrictions on plasma particle states (bound electrons, degeneracy)
- Non-uniformity in the plasma (strongly-coupled systems)
- Collective effects of the plasma
- Projectile velocity comparable to the thermal velocity (Bragg peak)

Schematic of the stopping power:

Paul Grabowski



General categories of theories:

- Lenard-Balescu: Weak interactions, dynamical many-body effects. **Maynard-Deutsch (MD)**[1]
- Boltzmann: Binary approximation, employ a known, numerically-generated, or experimentally-measured cross section. + basic 'collective effects', get **Li-Petrasso (LP)**[2]
- Gould-Dewitt: **T-Matrix**[3] gives low velocity limit to infinite order, essentially a combination of Lenard-Balescu and Boltzmann

$$\frac{\partial\langle E\rangle}{\partial t} = \frac{\partial\langle E\rangle}{\partial t}^{\text{static}}_{\text{T-Matrix}} + \frac{\partial\langle E\rangle}{\partial t}^{\text{dynamics}}_{\text{Born}} - \frac{\partial\langle E\rangle}{\partial t}^{\text{static}}_{\text{Born}}$$

- **Brown-Preston-Singleton**[4]: Uses dimensional continuation analysis to cancel small and large k Coulomb divergences (weakly-coupled non-degenerate)

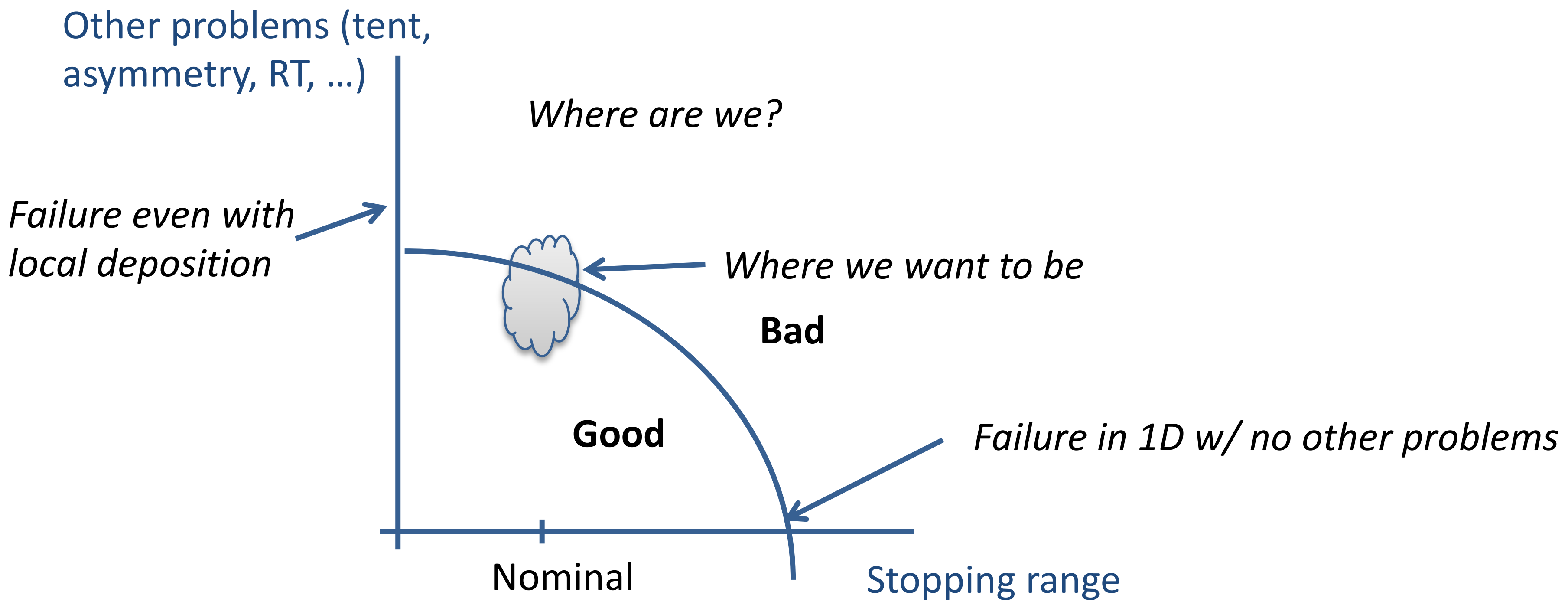
$$\frac{\partial E}{\partial t} = \lim_{D\to 3^-} \frac{\partial E}{\partial t} + \lim_{D\to 3^+} \frac{\partial E}{\partial t}$$

1: G. Maynard, C. Deutsch, Phys. Rev. A (1982)
2: C.K. Li, R.D. Petrasso., Phys. Rev. Lett. (1993)
3: D.O. Gericke et al., Phys. Lett. A (1996)
4: L.S. Brown et al., Phys. Reports (2005)

For ICF, we want to know the DT-α range to about 10-15%

Steve Haan

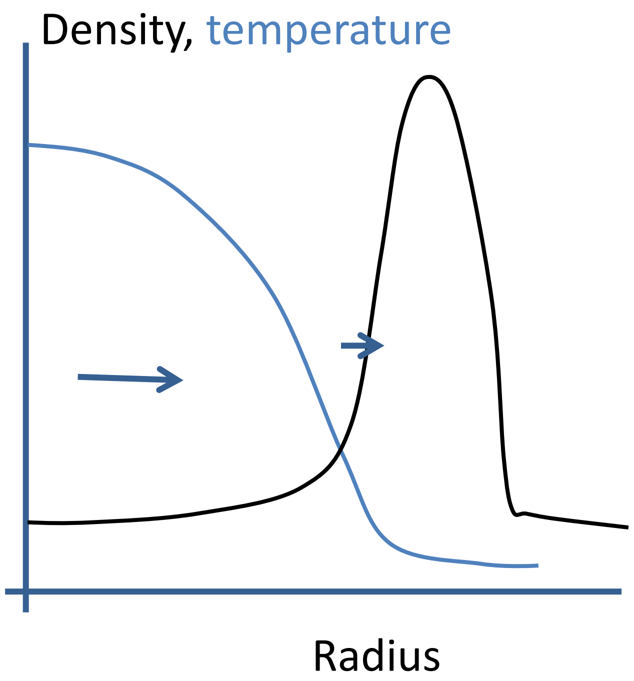
Energy required to get ignition is roughly linear with stopping range



Other assumptions include partition to electron/ion populations and modification of DT reactivity

Stopping in colder denser material does not matter to getting ignition

Steve Haan



We need the α's to stop in the hot, relatively low-density hot-spot

They DO stop when they get to the edge of the hot-spot

The only leverage could be the shape of the profile as it affects deceleration Rayleigh-Taylor, but for ±50% multipliers the profile looks the same until burn is robust, if it ever is

Stopping in the colder denser fuel CAN matter to higher order processes that can be used as diagnostics

Uncertainty in dE/dx (α range):
>25%: "LIFE" changing
10-20% Important but not dominant
<10%: "Good enough"

More generally we are interested plasmas that are non-equilibrium, multispecies and involve a variety of radiative, atomic and thermonuclear processes

Characteristics of hot dense radiative plasmas:

- Non-equilibrium (multi-temperature)
- Multi-species
  - Low Z ions (p, D, T, He3..)
  - High Z impurities (C, N, O, Cl, Xe..)
- Atomic and radiative processes
  - Photoionization
  - Electron impact ionization
- Thermonuclear (TN) burn
- Hydrodynamic mixing and turbulence
- Transport effects
  - Conductivity
  - Viscosity

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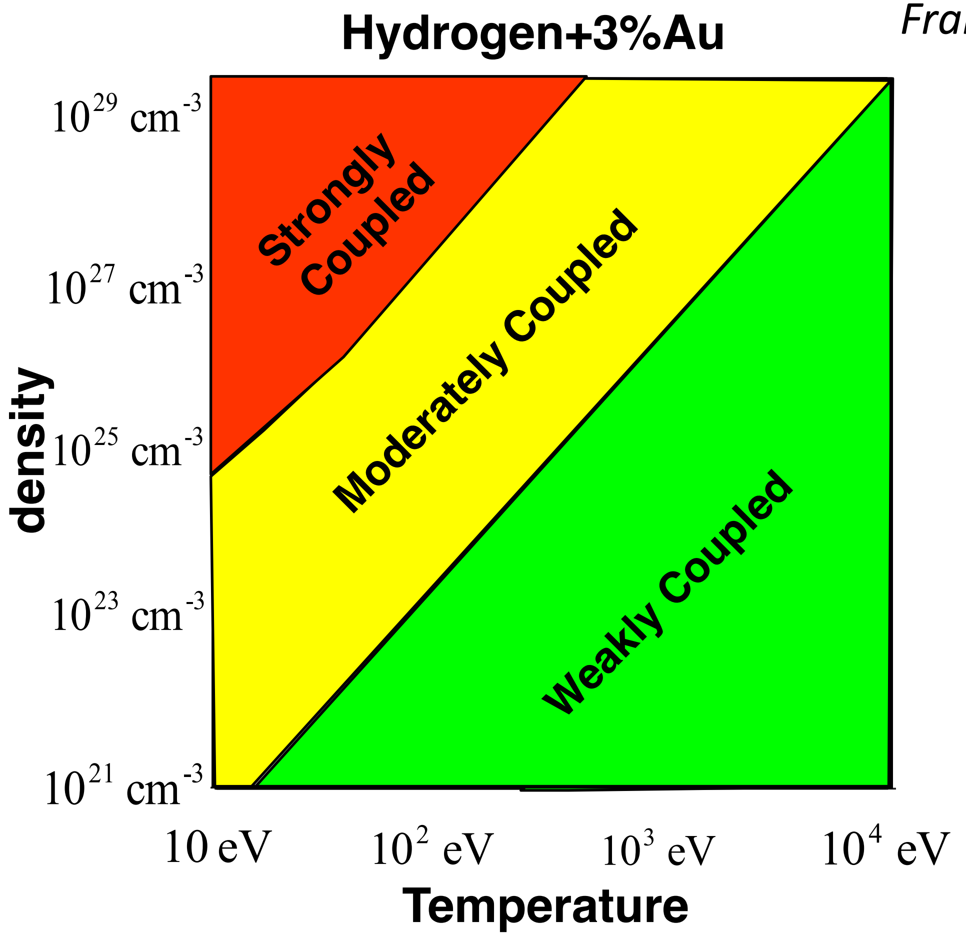

Iso-contours of Γ_{ei}

Codes that model HED rely on models that need to be validated with experimental data and underwritten by high fidelity physics codes

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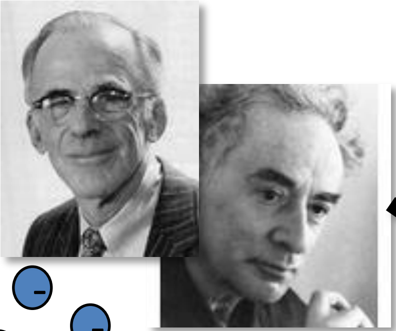
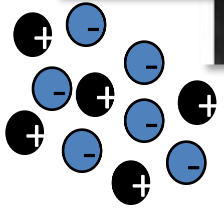
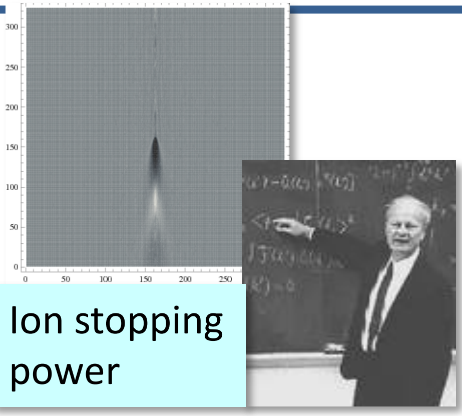


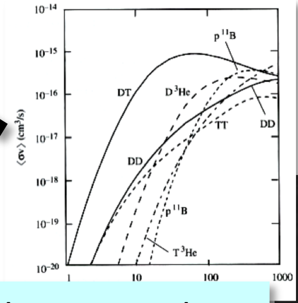


Electron-ion coupling

Design codes



Ion stopping power



Thermonuclear reactions

Conduction, diffusion, viscosity

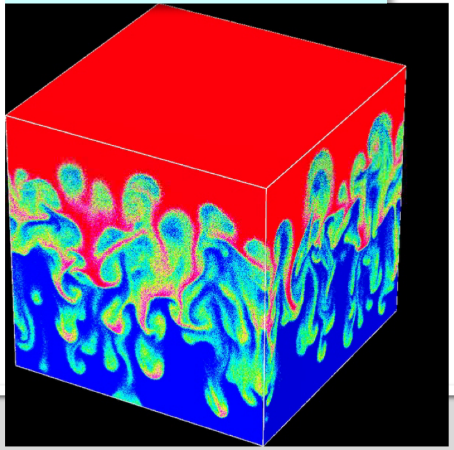
An electron conductivity model for dense plasmas

Y. T. Lee and R. M. More
University of California, Lawrence Livermore National Laboratory, Livermore, California 94550

(Received 5 July 1983; accepted 12 December 1983)

An electron conductivity model for dense plasmas is described which gives a consistent and complete set of transport coefficients including not only electrical conductivity and thermal conductivity, but also thermoelectric power, and Hall, Nernst, Ettinghausen, and Leduc–Righi coefficients. The model is useful for simulating plasma experiments with strong magnetic fields. The coefficients apply over a wide range of plasma temperature and density and are expressed in a computationally simple form. Different formulas are used for the electron relaxation time in plasma, liquid, and solid phases. Comparisons with recent calculations and available experimental measurement show the model gives results which are sufficiently accurate for many practical applications.

Turbulence and mix



Programmatically relevant HED experiments are driven by asking what matters and how accurate do I need the physics?

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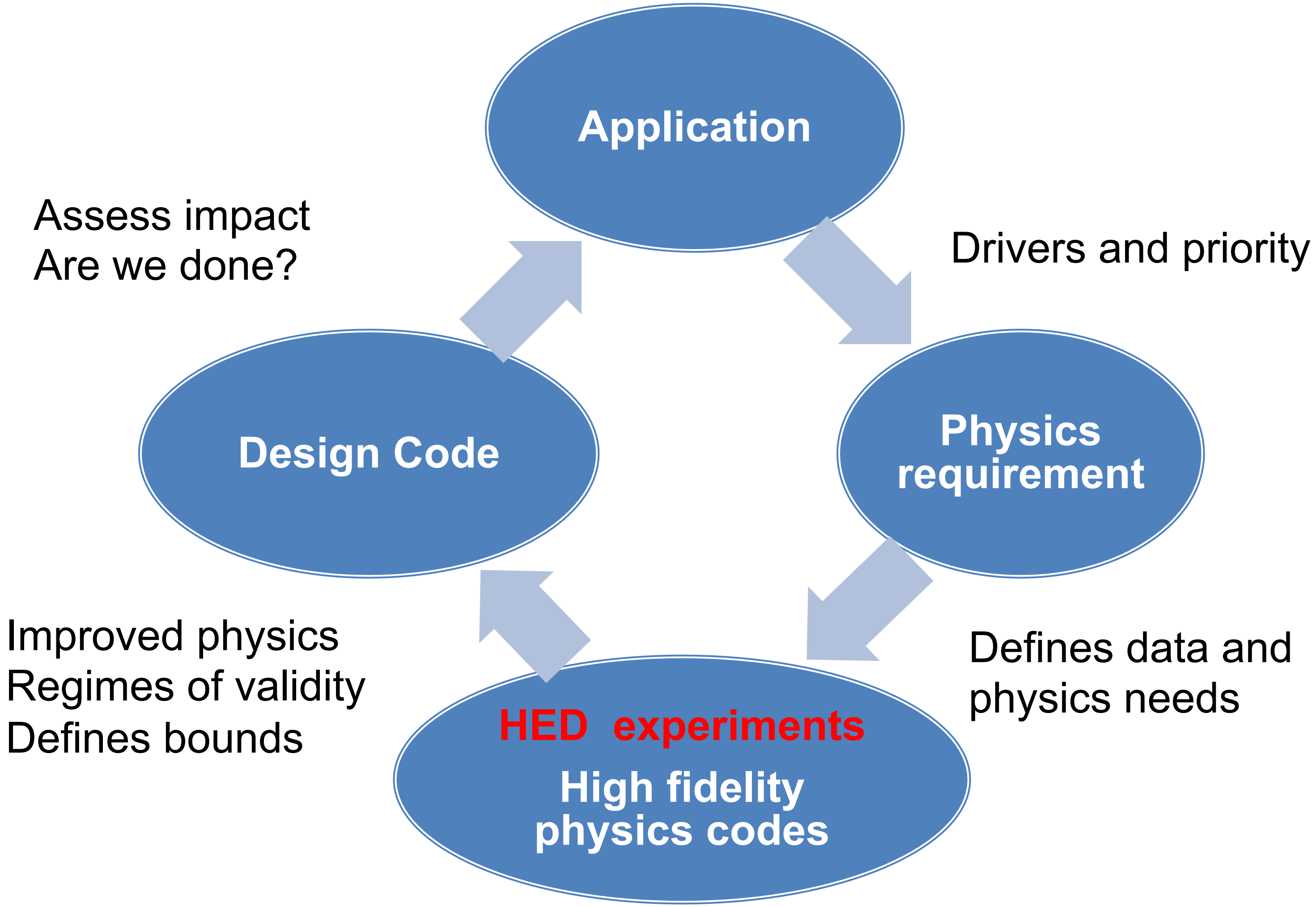

How should we use HED experimental capabilities to validate models and advance our understanding of burn physics?

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- Stewardship
  - Design codes underwritten by data and theory provide the basis

- HED experiments and programmatic applications
  - *What constitutes a programmatically relevant experiment?*
  - HED experiments must confirm, refute or improve our computations
  - Programmatically relevant data must
    - Validate a model or set of equations
    - Improve a model or set of equations
  - Prioritization of areas of investigation is critical
    - …not everything matters
    - Relevant regimes are important

Validate dE/dx models in some relevant regimes

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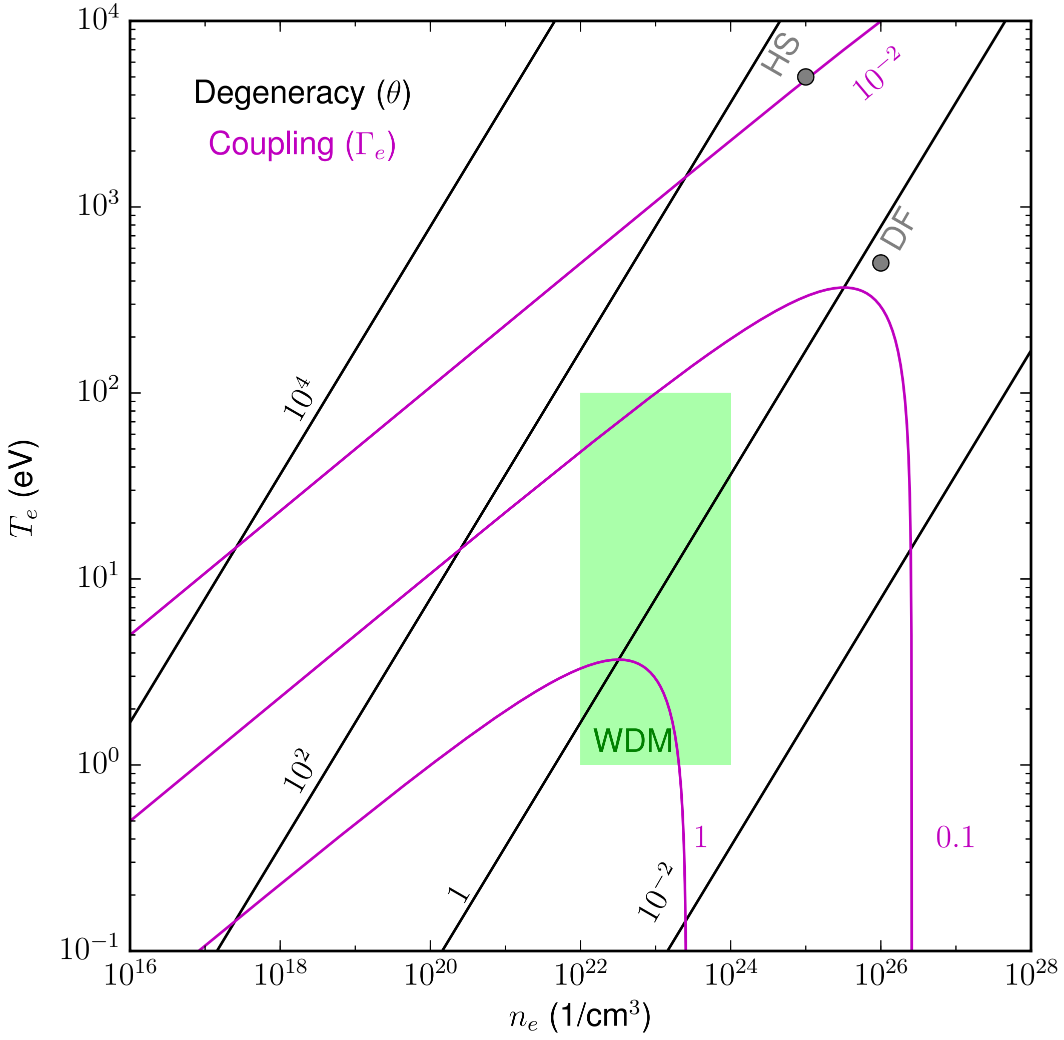
Overview of experimental parameter space:



$$\theta = \frac{k_B T_e}{E_F} \qquad \Gamma_e = \left(\frac{4\pi}{3}\right)^{1/3} \frac{e^2 n_e^{1/3}}{k_B T_e + E_F}$$

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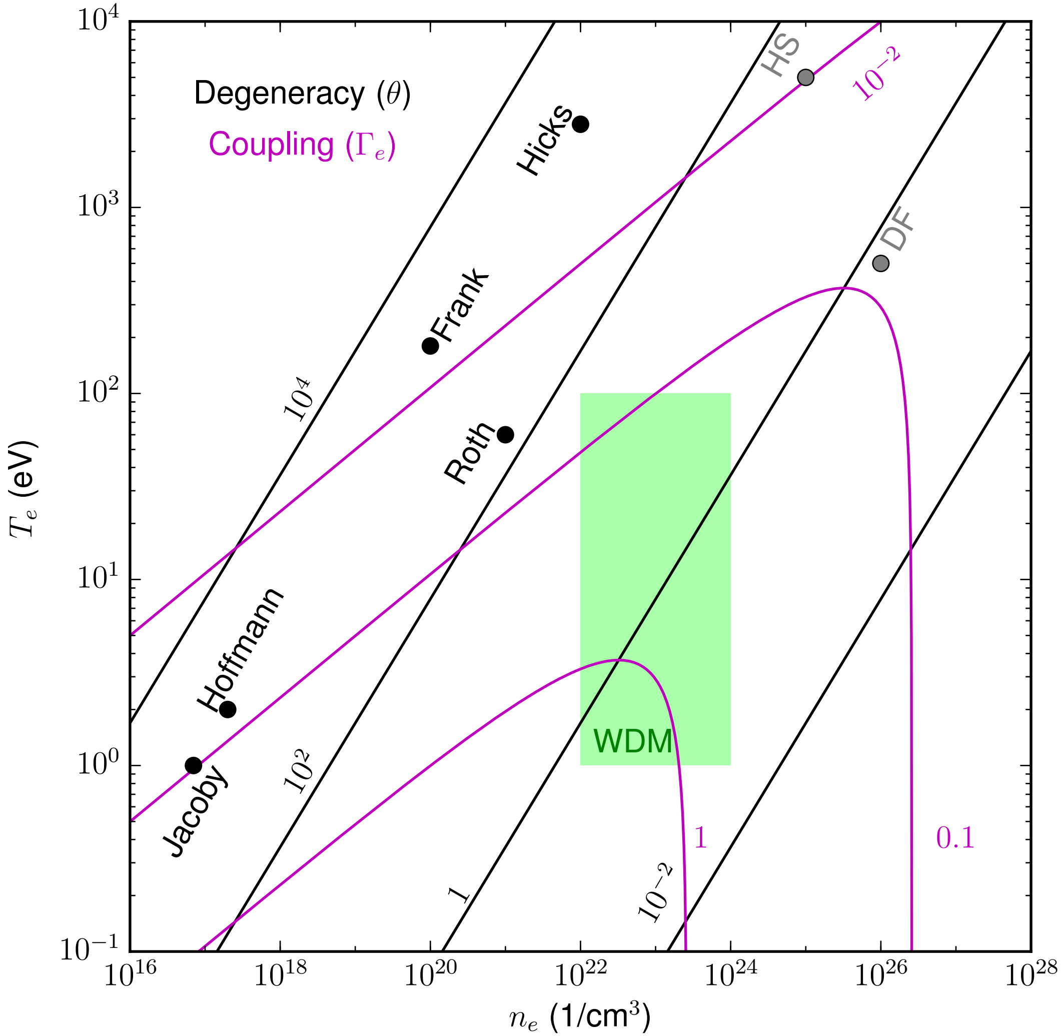

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"Old" Work

D.H.H. Hoffman et al., PRA 42 (1990)
J. Jacoby et al., PRL 74 (1995)
M. Roth et al., EPL 50 (2000)
D.G. Hicks et al., PoP 7 (2000)
A. Frank et al., PRL 110 (2013)

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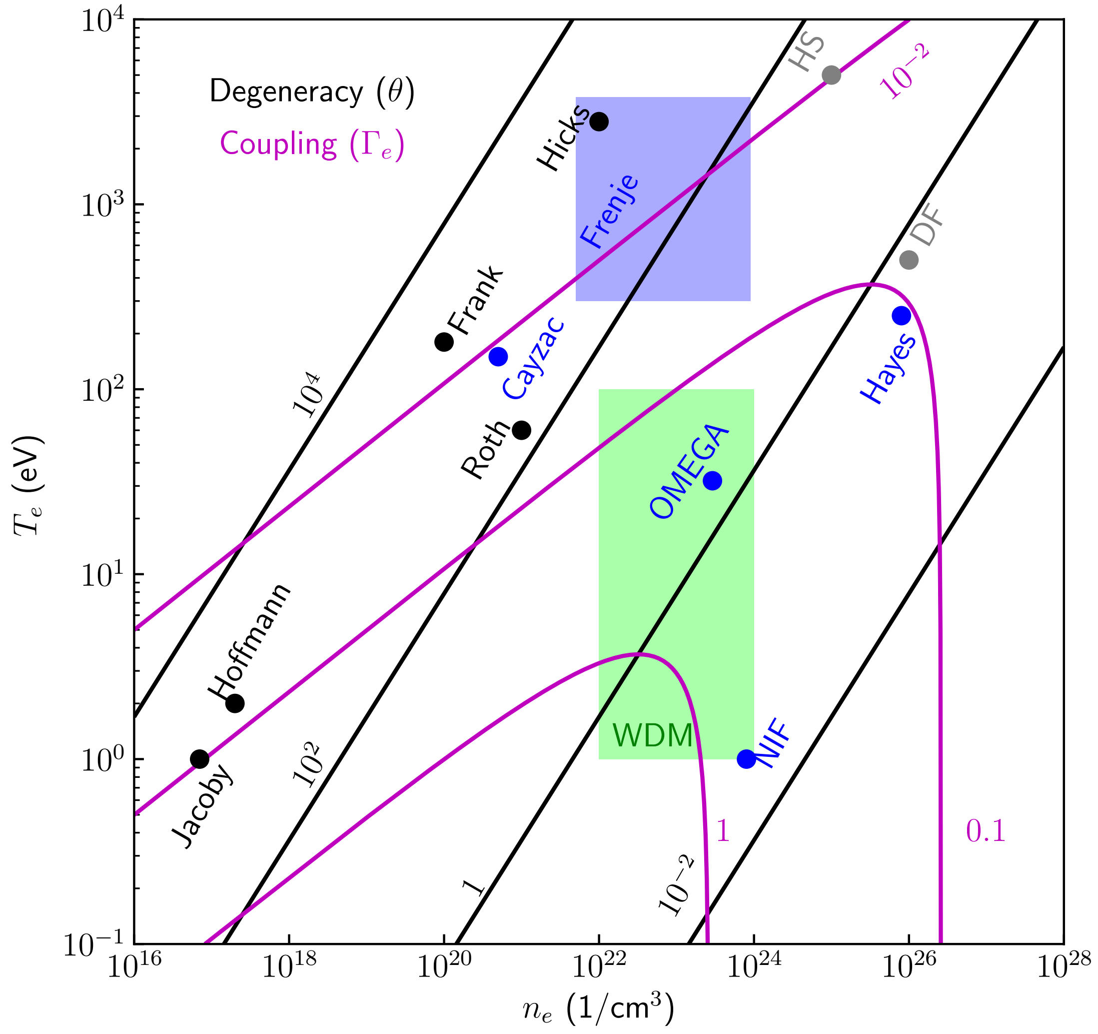

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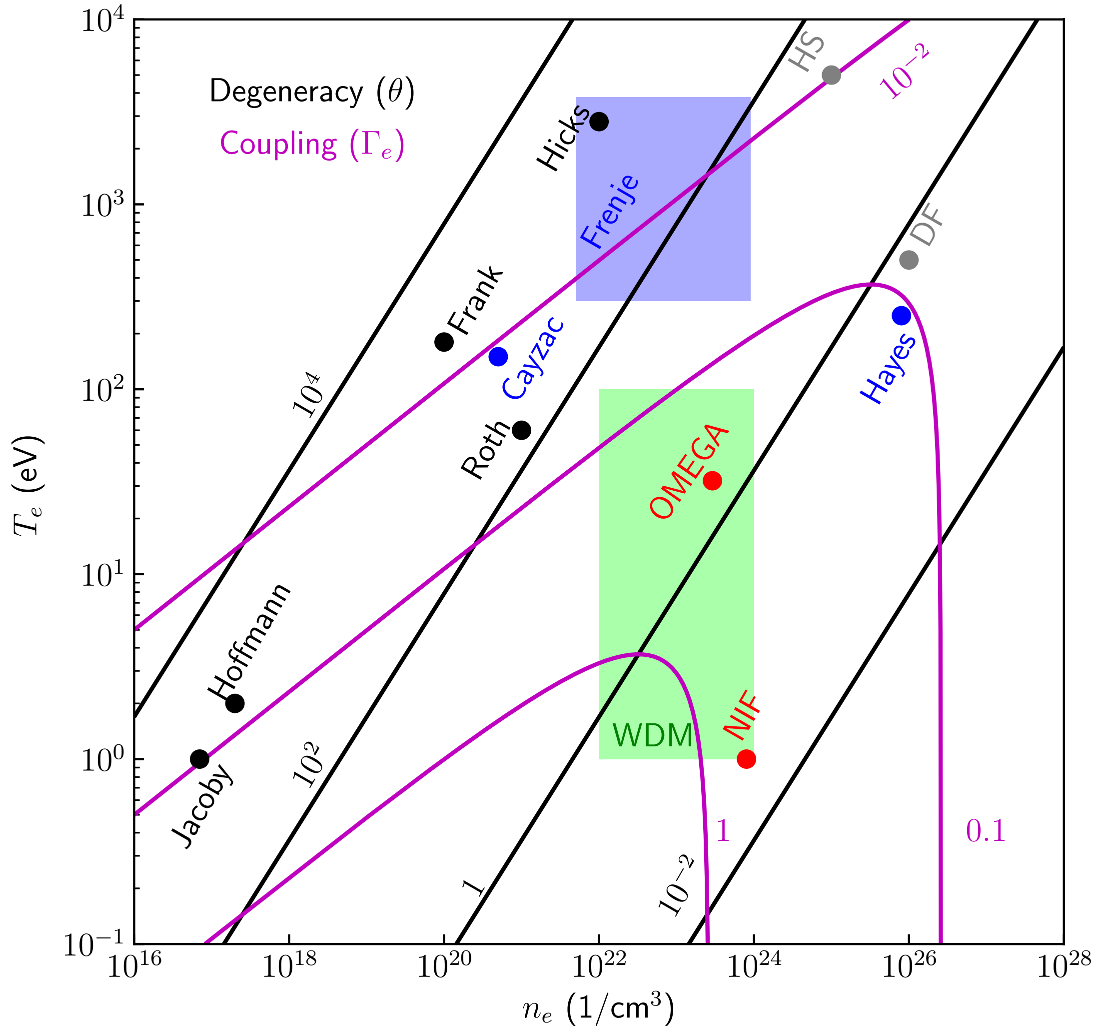
A. Frank et al., PRL 110 (2013)

"Recent" Work

W. Cayzac et al., PRE 92 (2015)
Nature Comms (2017)
J. Frenje et al., PRL 114 (2015)
PRL 122 (2019)
A. Zylstra et al., PRL 114 (2015)
A.C. Hayes et al., PoP 22 (2015)

Overview of experimental parameter space:



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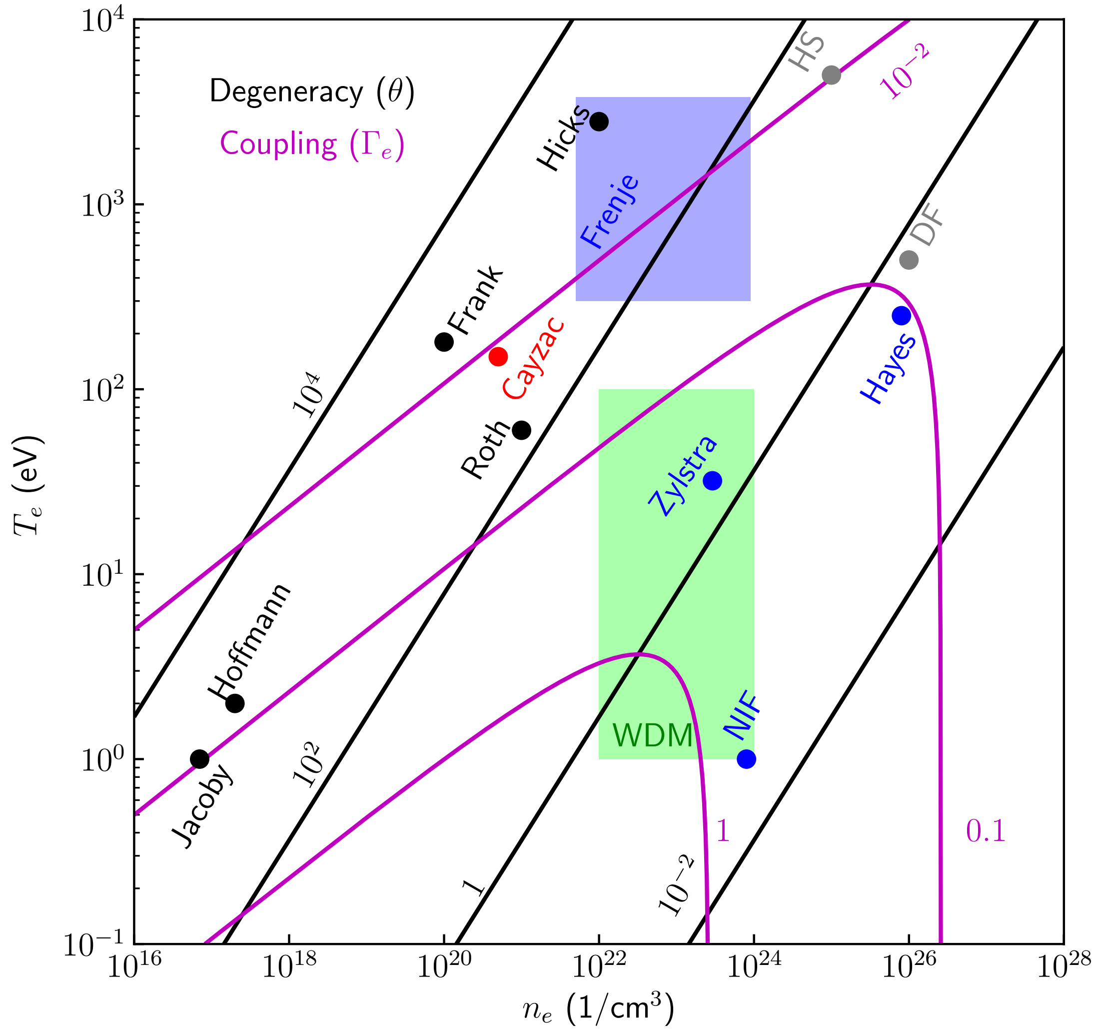
Fully Ionized

Partially Ionized

Overview of experimental parameter space:



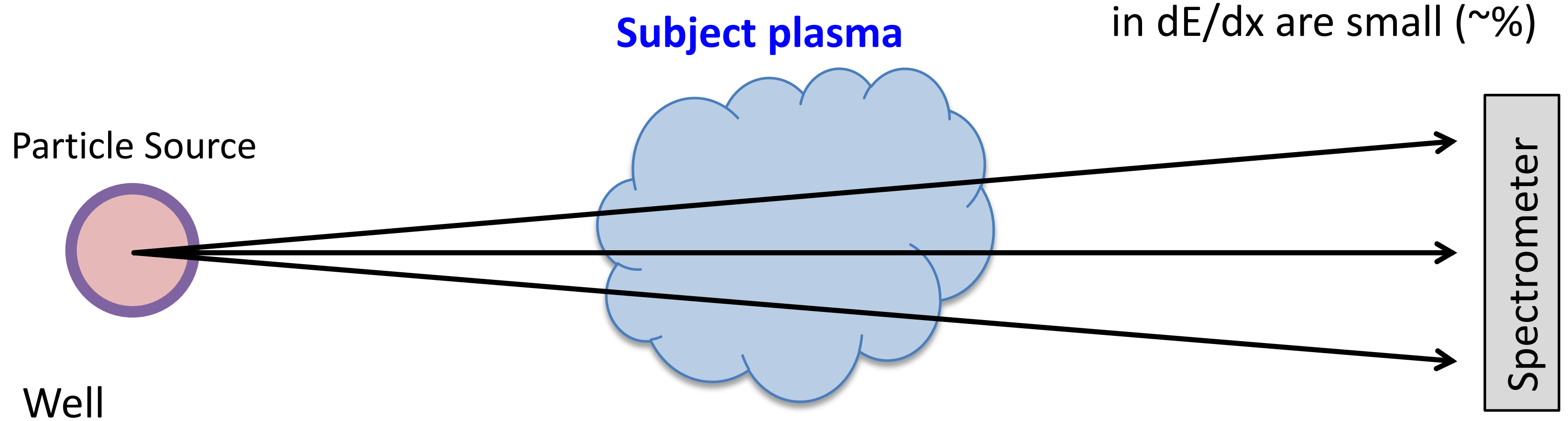
$$\theta = \frac{k_B T_e}{E_F} \qquad \Gamma_e = \left(\frac{4\pi}{3}\right)^{1/3} \frac{e^2 n_e^{1/3}}{k_B T_e + E_F}$$

Light-ion probe

Heavy-ion probe

Measuring the stopping power requires three key 'pieces' of an experiment:

- At some conditions, expected differences in dE/dx are small (~%)



- Well characterized
- Ideally monoenergetic, isotropic

- Well characterized conditions (known n_e, T_e)
- Uniform
- Quiescent over particle probing
- No spurious electromagnetic fields
- Relevant

- Accurate and precise.
- Ideally *direct*, or a well-understood *indirect* measurement

Usually have to make some tradeoffs…

In recent years a number of relevant stopping power experiments have been conducted:

- Published:
  - Fast protons in WDM
  - D3He self emission from exploding pushers (Frenje)
  - Inferred dE/dx from RIF neutrons (Hayes)
  - Accelerator beam ions through laser-generated plasma (Cayzac)

- Experiments/analysis in progress:
  - Inferred dE/dx from secondary neutrons (Sayre/Cerjan)
  - Expanded studies of WDM dE/dx (Lahmann)
  - dE/dx in compressed implosion shells (McEvoy)
  - Shock-compressed WDM on NIF

- Less than successful attempts (on my part):
  - TNSA protons in isochoric heated WDM on OMEGA EP
  - Quasi-monoenergetic heavy ions on Trident through shock-heated plasma

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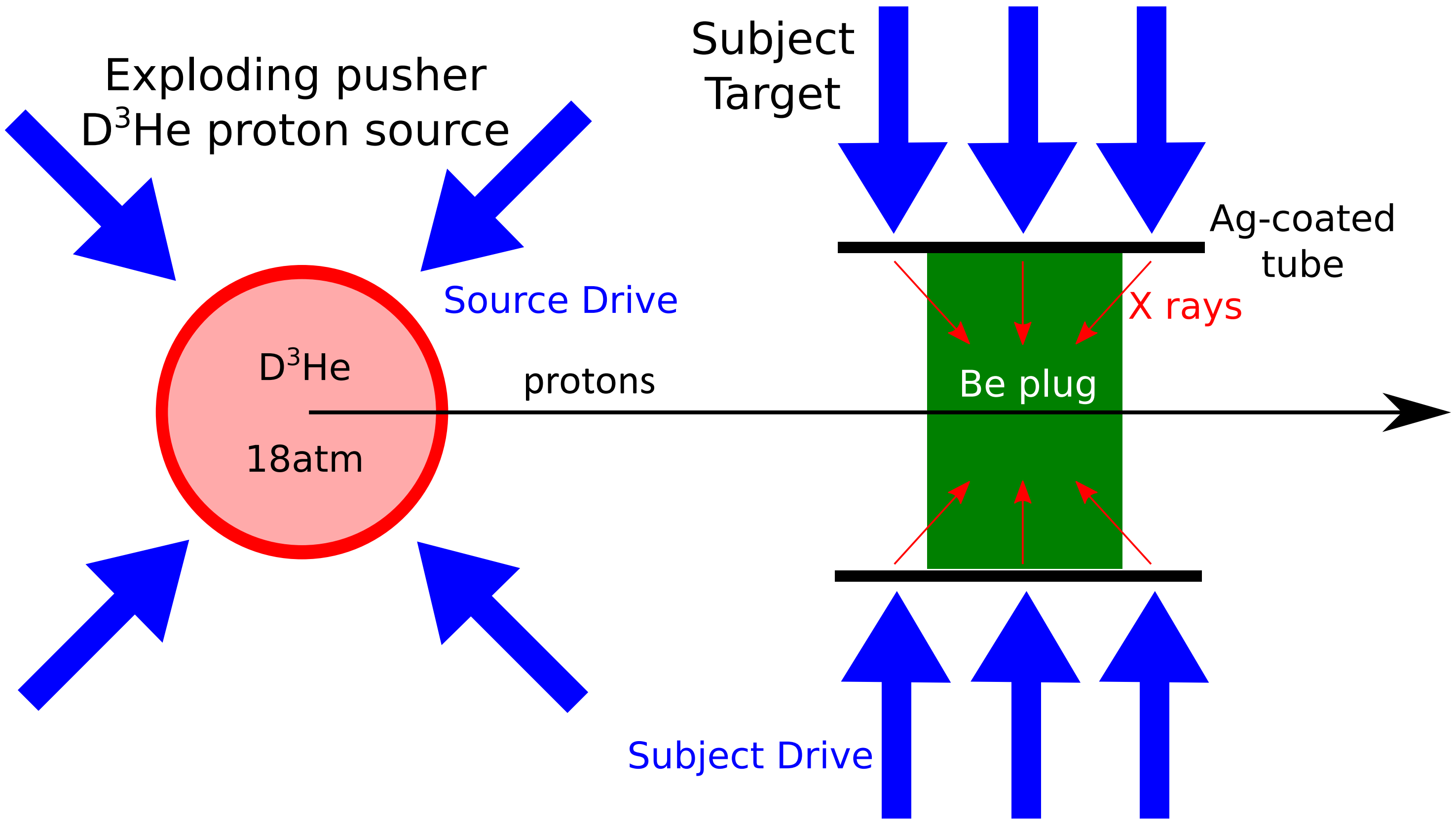
On OMEGA, D^3He protons were used to probe isochorically-heated Be to measure dE/dx

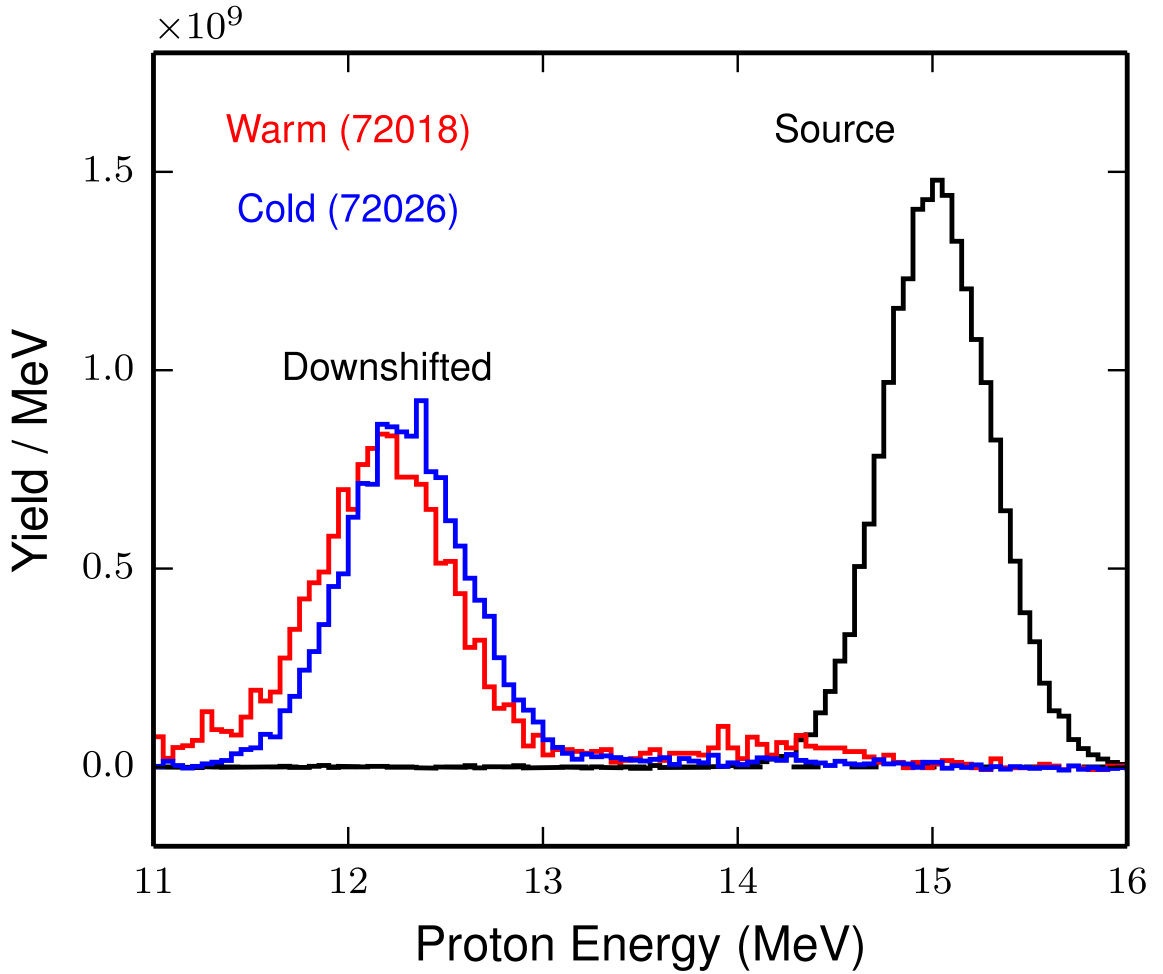


Plasma state:
T_e ~ 32 eV
Z* ~ 2.4
θ ~ 2
Γ_e ~ 0.3

Some drawbacks: T_e and Z* not the best characterized, $v_p \gg v_{te}$.

A.B. Zylstra et al., PRL 114, 215002 (2015)

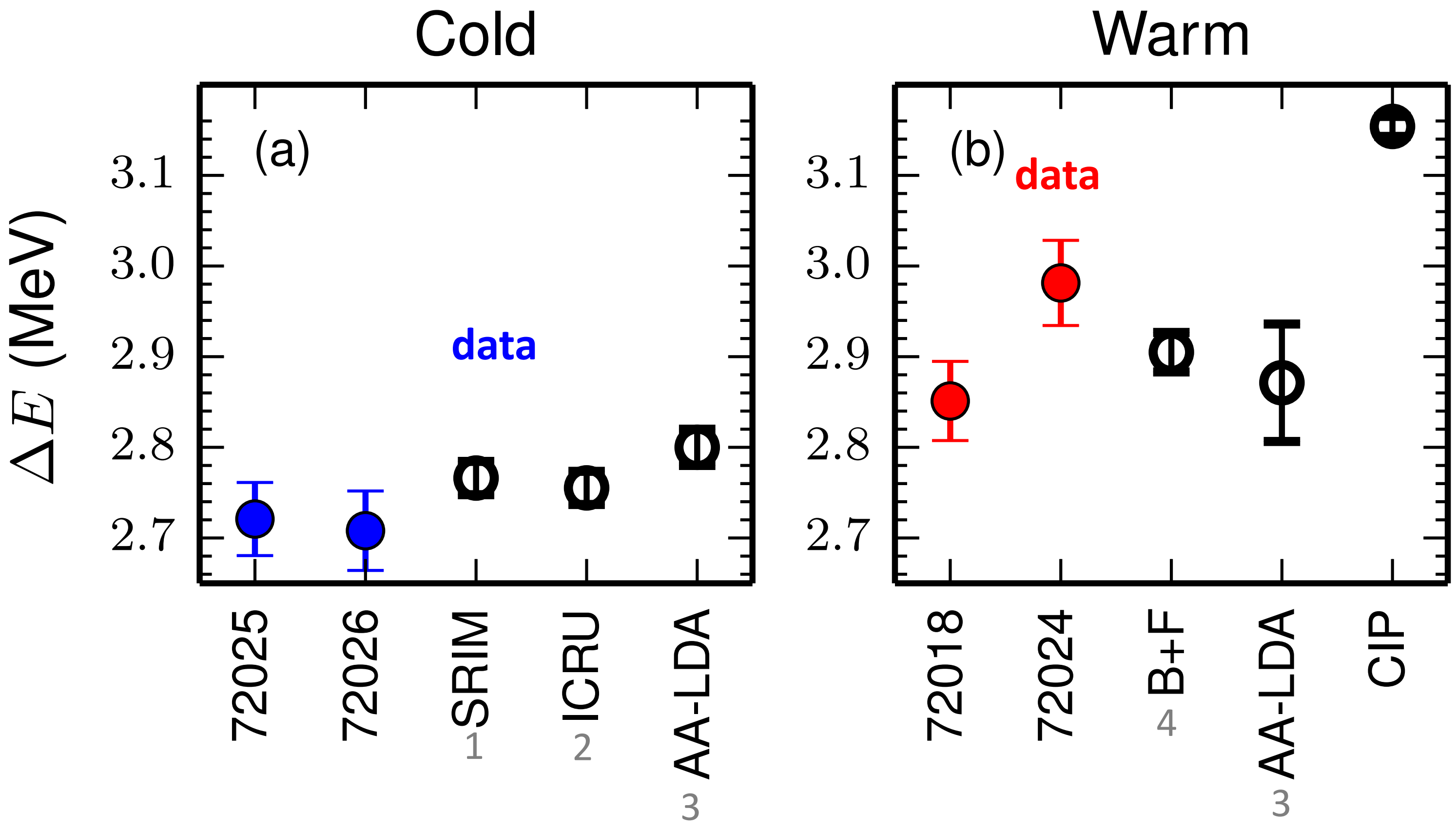
Proton spectroscopy shows an enhanced stopping power in WDM compared to cold



High-precision spectroscopy[1] allows a 1% ΔE measurement[2] using this technique

1: F.H. Seguin et al., RSI 83, 10D908 (2012)   2: A.B. Zylstra et al., PRL 114, 215002 (2015)

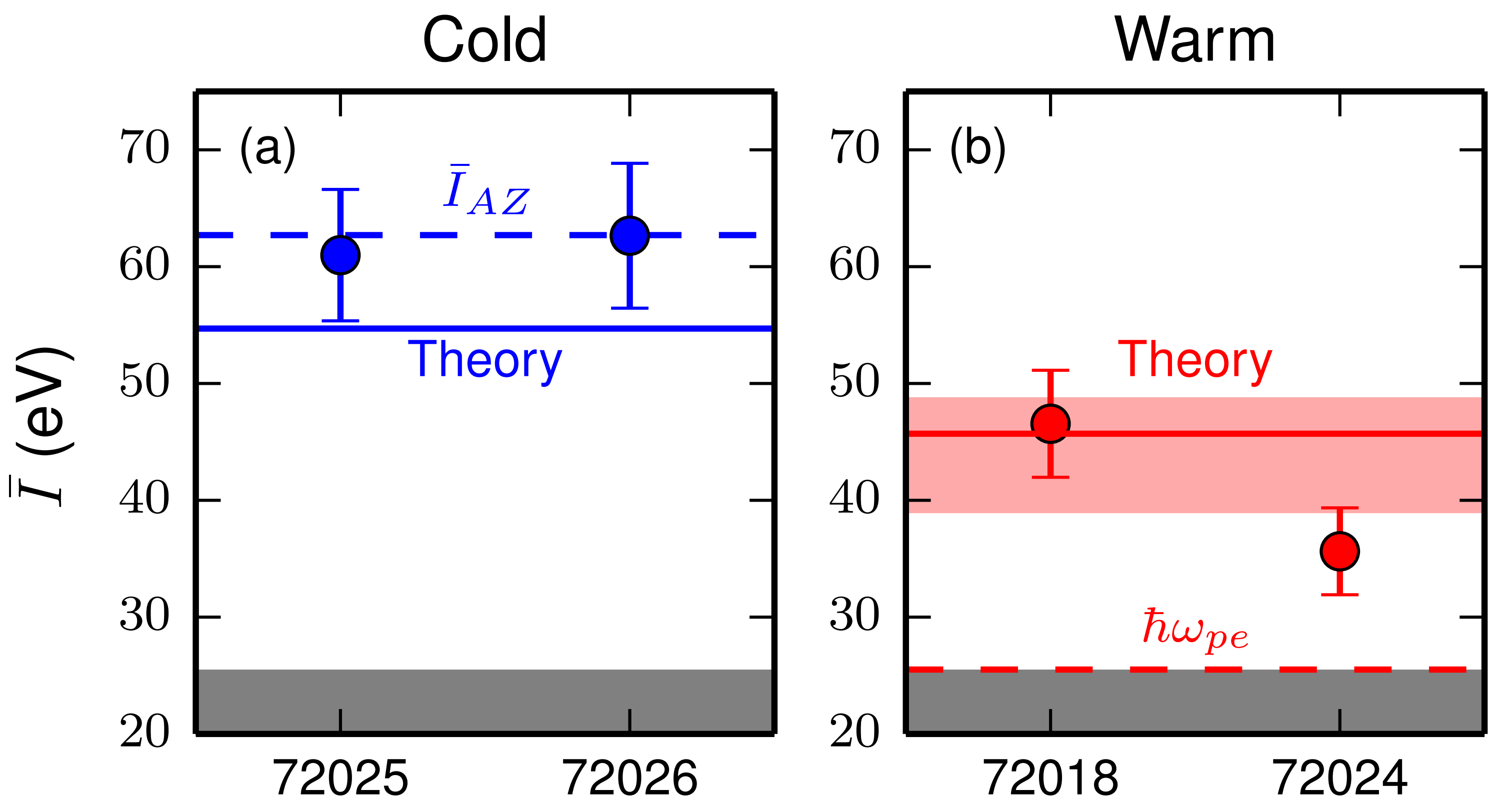
The measured energy downshifts show good agreement with our best theoretical models



Models:
B+F: Bound + Free
AA-LDA: Average-atom Local Density Approximation
CIP: Classical Ideal Plasma

1: H. Andersen and J. Ziegler, (Pergamon, New York, 1979).
2: ICRU Report 49 (1993).
3: S. B. Hansen et al., Phys. Rev. E 72, 036408 (2005).
4: G. Zimmerman, LLNL report, UCRL-JC-105616 (1990).

Using a Bethe-style stopping power constrains WDM electronic structure models



$$\frac{dE}{dx} = -\frac{4\pi Z_t^2 e^4}{m_e v_t^2} n_e \ln\left[\frac{2m_e v_t^2}{\bar{I}}\right]$$

These LDA models are used for general calculations of collisional transport phenomena in WDM

H. Andersen and J. Ziegler, (Pergamon, New York, 1979). S. B. Hansen et al., Phys. Rev. E 72, 036408 (2005).

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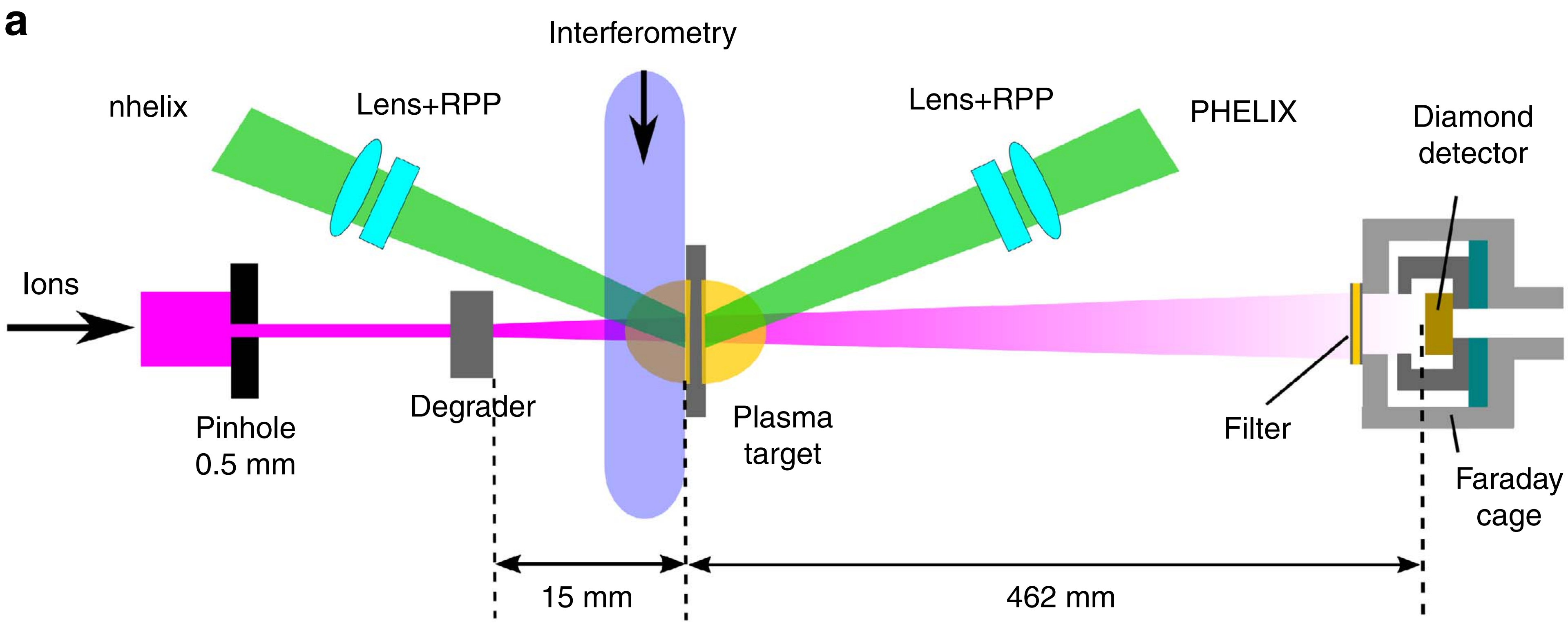
A group at GSI developed a novel beam-plasma stopping power experiment

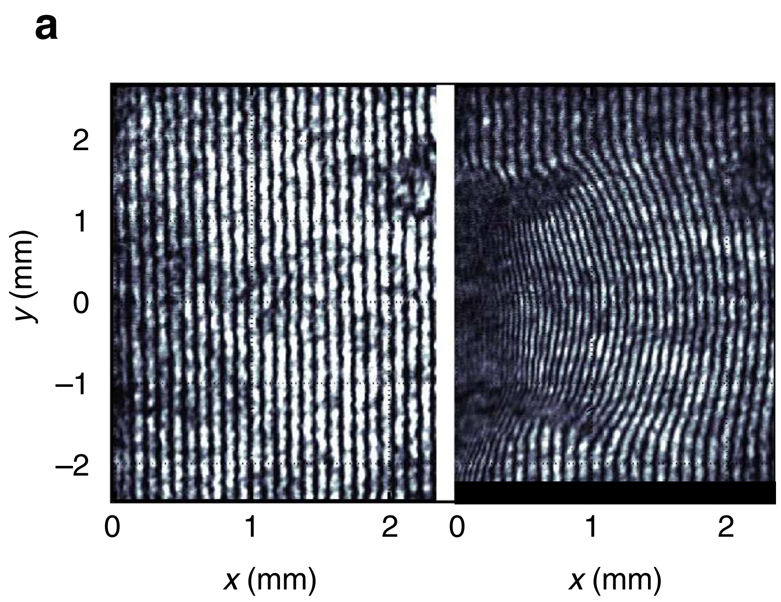


Limited to low-pressure plasmas by beam bunch duration (setting confinement timescale)

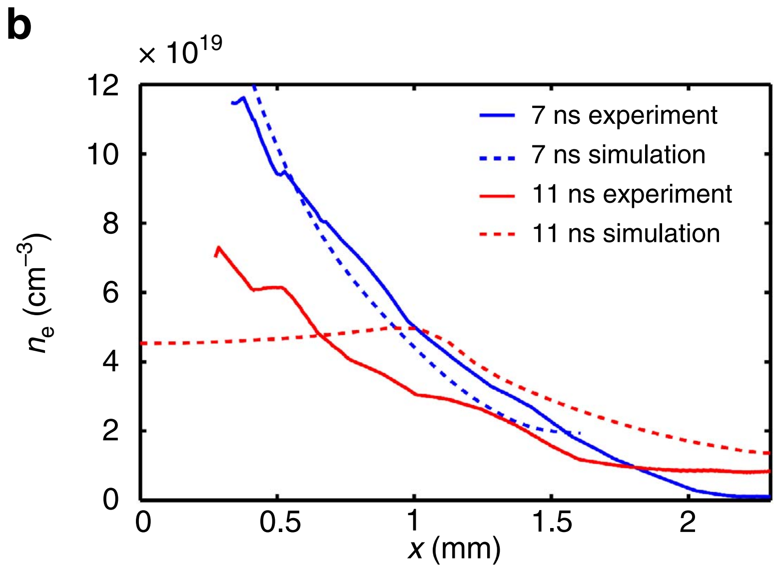
W. Cayzac et al., Nature Communications 8, 15693 (2017)

Uniformity of plasma conditions is a 'con' of this technique and requires modeling for interpretation:

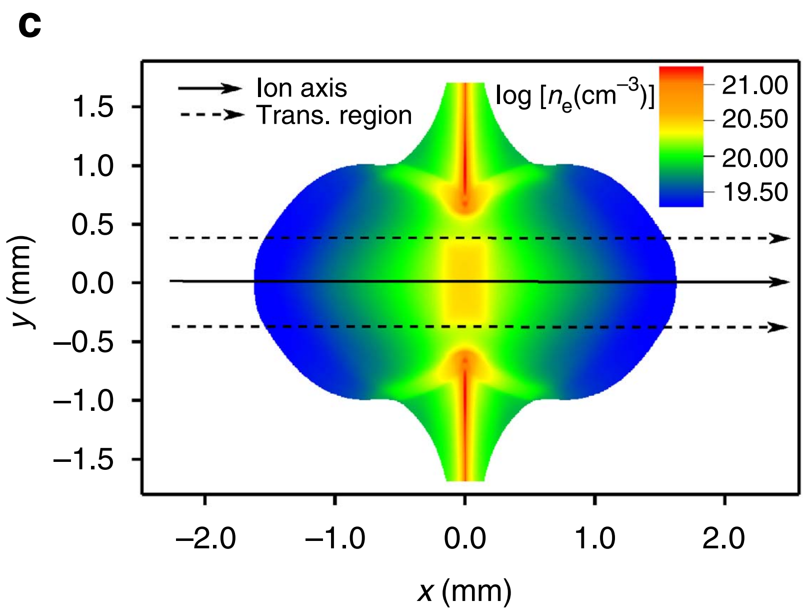
Interferometry:



Plasma profile:



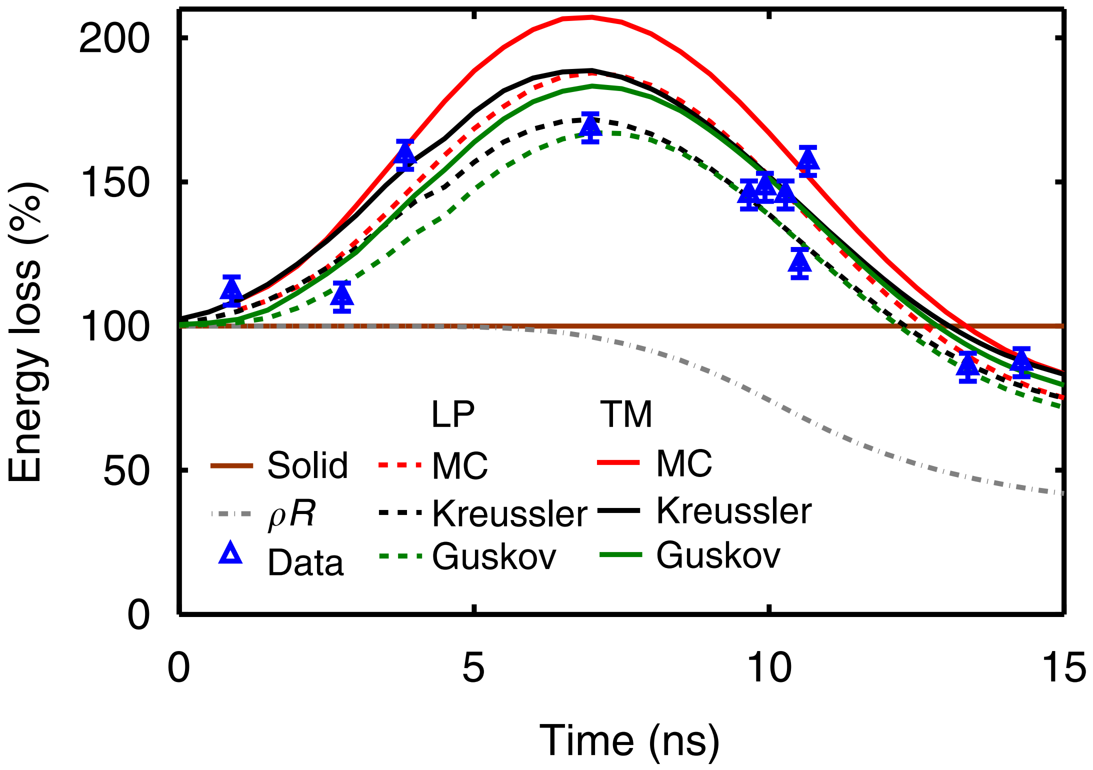
2-D simulation:



W. Cayzac et al., Nature Communications 8, 15693 (2017)

A unique aspect is the ability to use novel projectile ions:

Argon projectile ions at a velocity ratio v_p/v_{eth} ~ 3.1

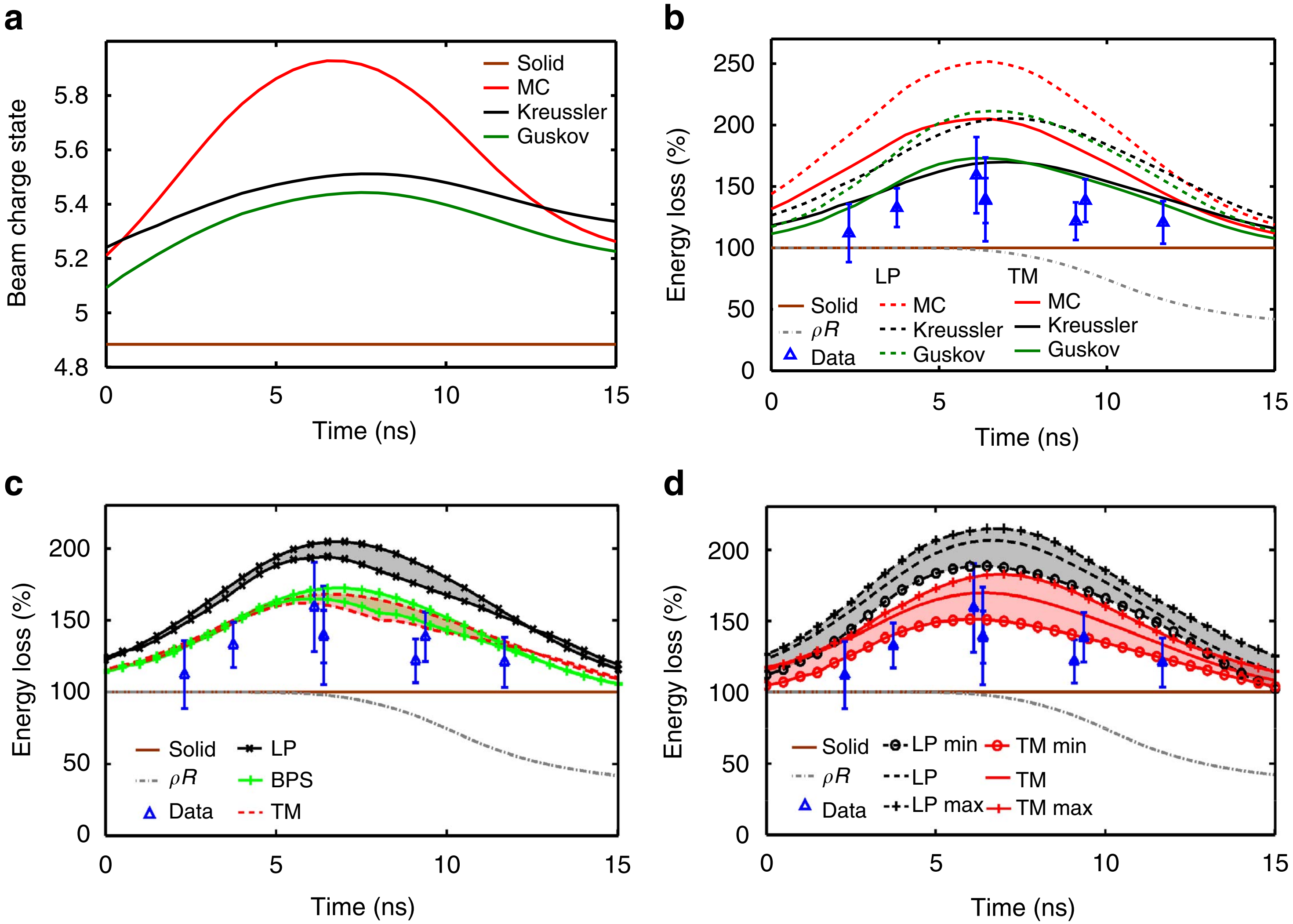


A complication for higher-Z ions is charge exchange in the plasma

W. Cayzac et al., Nature Communications 8, 15693 (2017)

With N beam and uncertainty analysis, the GSI data can begin to discriminate theories near the Bragg peak:

Nitrogen beam:



W. Cayzac et al., Nature Communications 8, 15693 (2017)

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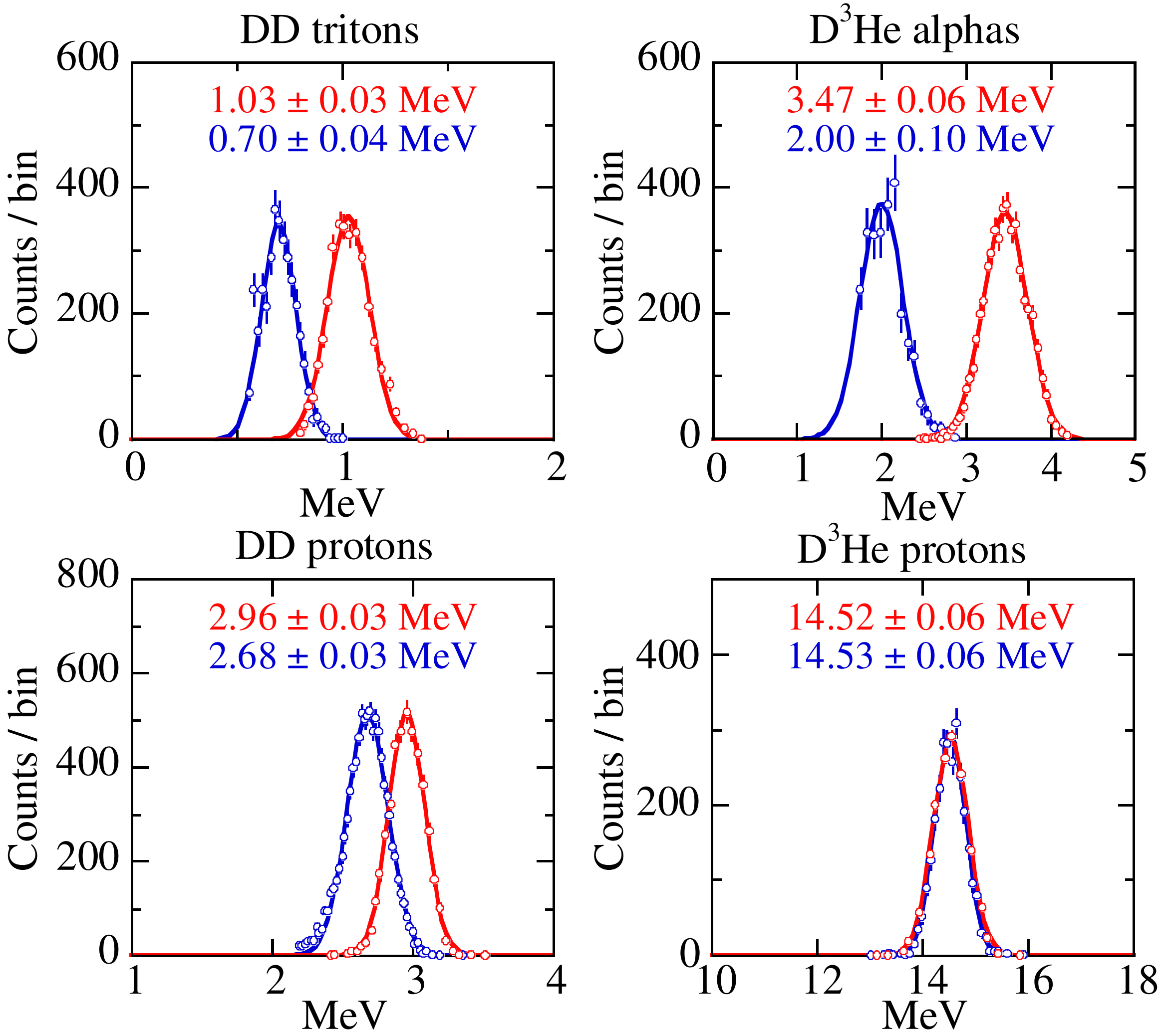
Recently Johan et al. at MIT developed a platform to look at the D3He self-emission particle downshifts:

Cold Implosion
Hot Implosion

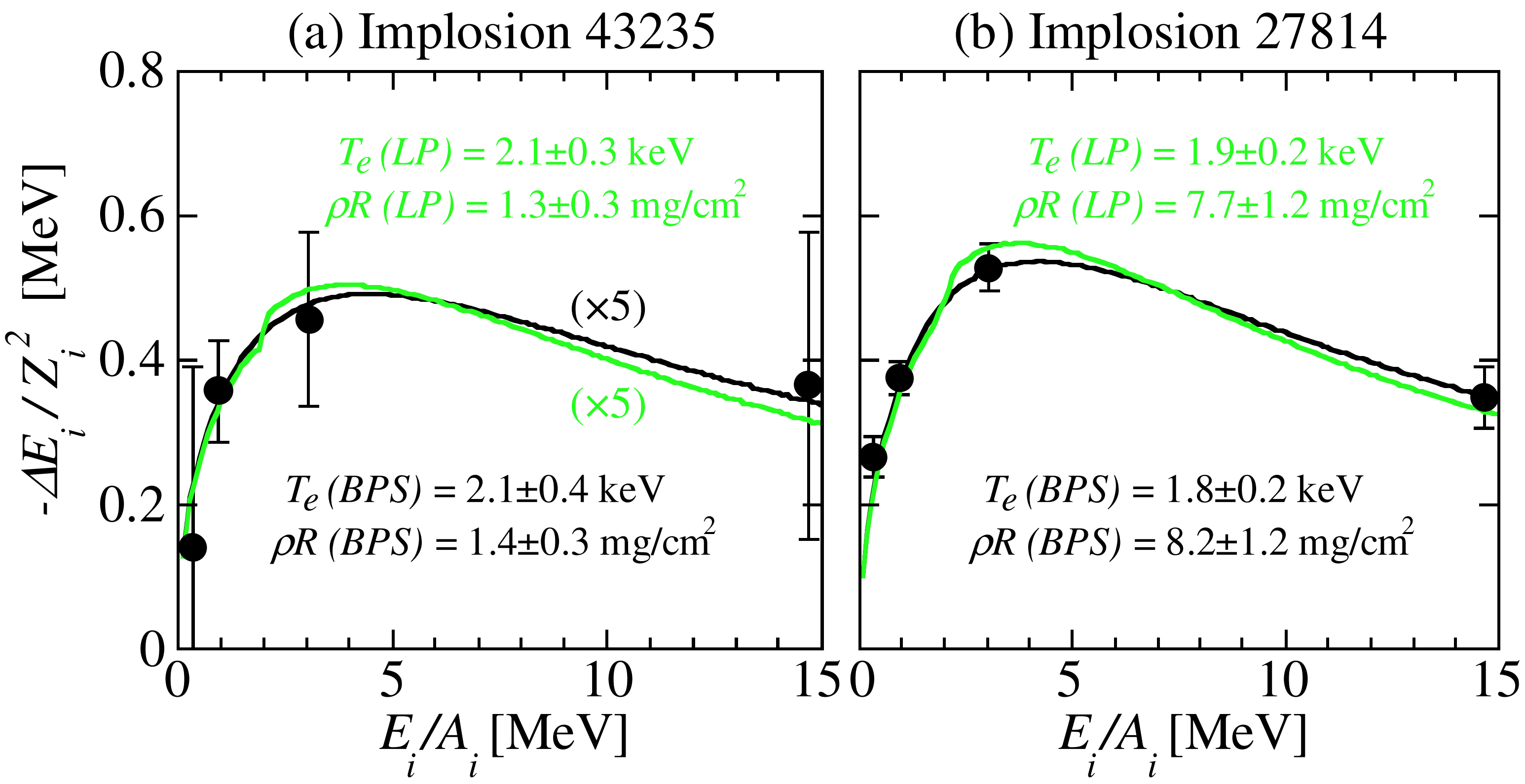
$$D + D \rightarrow t(1.01\ \text{MeV}) + p(3.02\ \text{MeV}),$$

$$D + {}^3\text{He} \rightarrow {}^4\text{He}(3.71\ \text{MeV}) + p(14.63\ \text{MeV}),$$

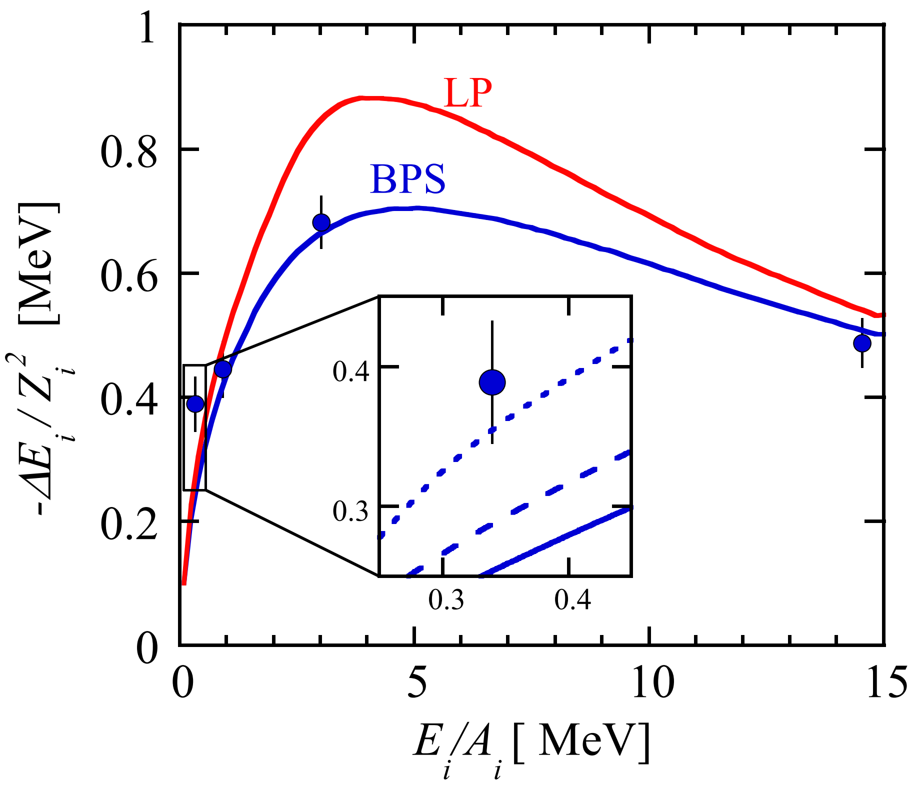


J.A. Frenje et al., Phys. Rev. Lett. 115, 205001 (2015)

Early experiments could not discriminate models because neither T_e or ρR were independently constrained:



With an independent constraint on ρR, newer data agrees well with BPS until the lowest velocity:



This is probably the best constraint on hot-spot relevant dE/dx, but there is a discrepancy with BPS at low projectile velocity.

Outline

- Review of theoretical models and motivation
- Overview of parameter space
- First measurement of dE/dx in warm-dense-matter plasma
- Accelerator beams through laser-generated plasmas
- Exploding pusher D^3He self-emission
- **Shock-compressed WDM on NIF**
- Summary and future problems

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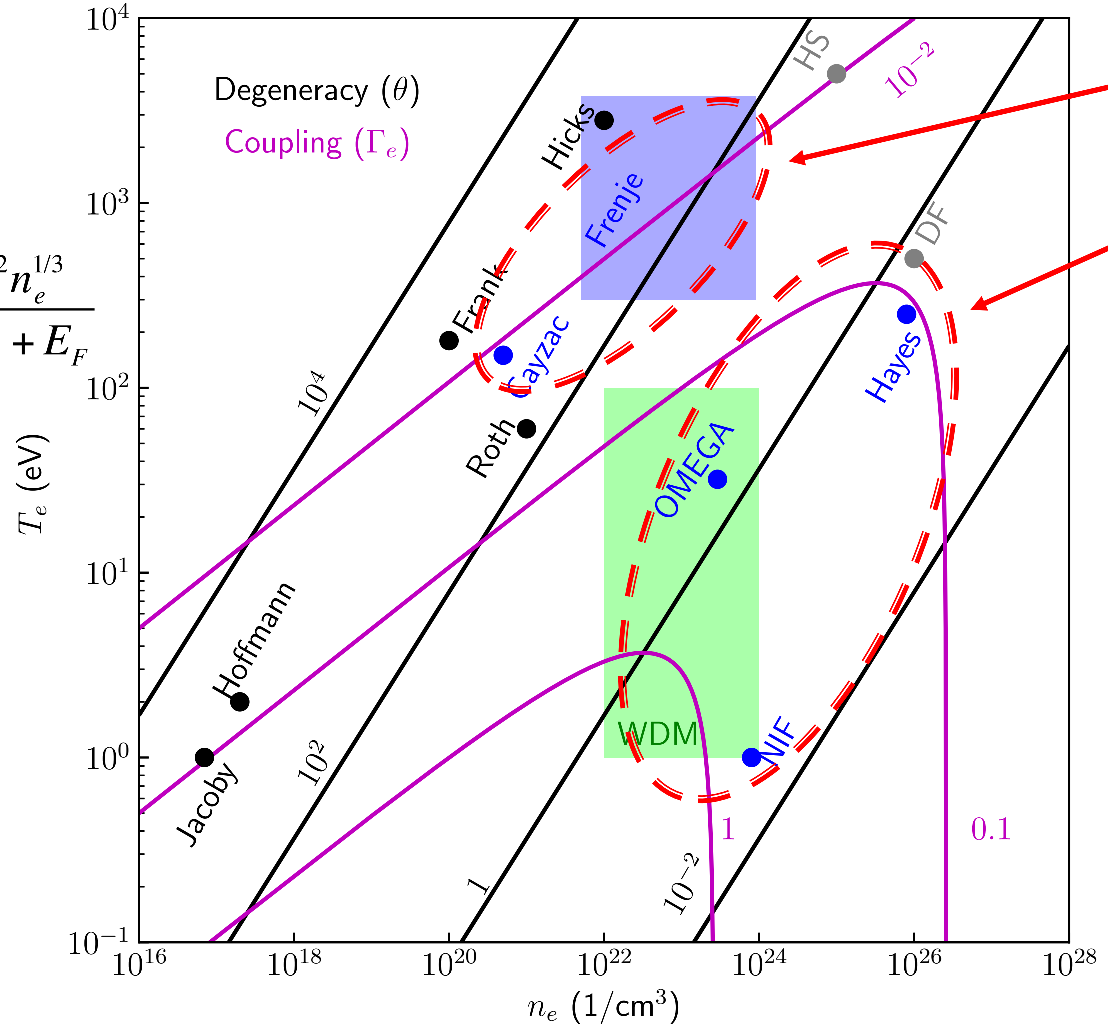
- **Summary and future problems**

Return to the parameter space:

$$\theta = \frac{k_B T_e}{E_F}$$

$$\Gamma_e = \left(\frac{4\pi}{3}\right)^{1/3} \frac{e^2 n_e^{1/3}}{k_B T_e + E_F}$$



BPS does pretty good

Zimmerman MD parameterization does pretty good

+ we know BPS and MD are pretty close for HS conditions, so we expect them to be pretty good models for ICF

"Recent" Work

W. Cayzac et al., PRE 92 (2015)
Nature Comms (2017)
J. Frenje et al., PRL 114 (2015)
PRL 122 (2019)
A. Zylstra et al., PRL 114 (2015)
A.C. Hayes et al., PoP 22 (2015)

Some missing topics (mostly experimental) that could be explored:

- Highly inhomogeneous plasmas (e.g. low-Z / high-Z mixture)
- Charge exchange between projectile and plasma
- Ion stopping in a hot-spot relevant plasma (and ion/electron partition)
- Dense beam effects and modification of plasma (spatial or distribution)
- Measurements near the Bragg peak in WDM plasmas

↓ *Difficulty?*

Stronger theoretical link between dE/dx measurements and other transport properties

A summary of the last few years of dE/dx experiments:

- Benchmark data is now available in WDM regime (for fast particles) and more is coming:
  - NIF data in strongly-coupled/highly-degenerate C and Be
  - New OMEGA data on Be and other materials (B. Lahmann, MIT)
- Data suggest that several models (BPS, MD, TM) do an good job for hot-spot dE/dx
  - In particular the Cayzac/Frenje data show there isn't a major discrepancy
  - My opinion is we're close to validating these models at the level desired for ICF
  - Low-velocity point from Frenje 2019 paper should be resolved
  - A more rigorous UQ analysis than my hand-waving could be done, comparing all theories to all data, to estimate the actual model uncertainty at hot-spot conditions

2016 Santa Fe report: **Intrinsic and Transport Properties Common Challenge 4:** Stopping power: Understanding DT-α stopping is essential for modeling hot spots, burning plasmas, and credible scaling

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