Studying Particle Transport using Nuclear and X-ray Diagnostics for Discovery Science and Inertial Confinement Fusion at OMEGA and the NIF

P. J. Adrian

High Energy Density Physics Division
Plasma Science and Fusion Center, MIT

SSGF
June 28, 2023

Collaborators and Sponsors

M. Gatu Johnson
J. Pearcy
T. Evans
S. Dannhoff

G. D. Sutcliffe
T. Johnson
F. H. Seguin
C. K. Li
R. D. Petrasso
J. Frenje

B. Bachmann
H. Sio
B. Lahmann
P. E. Grabowski
F. Graziani
H. Whitley
C. Scullard
L. X. Benedict

N. Kabadi
J. Katz
C. Stoeckl
A. Sorce
C. Sorce
V. Glebov
S. Regan
H. G. Rinderknecht
R. Betti
A. Lees

R. Mancini,
E. Galladro-Diaz

R. Florido

Supported by DOE/NNSA CoE DE-NA0003868
and by DOE/NNSA SSGF DE-NA0003960

Thesis Work Portfolio

- Project 1 : Implementation and use of an X-ray Imaging Spectrometer (XRIS)
- Project 2 : Studies of ion-electron energy exchange

} Today

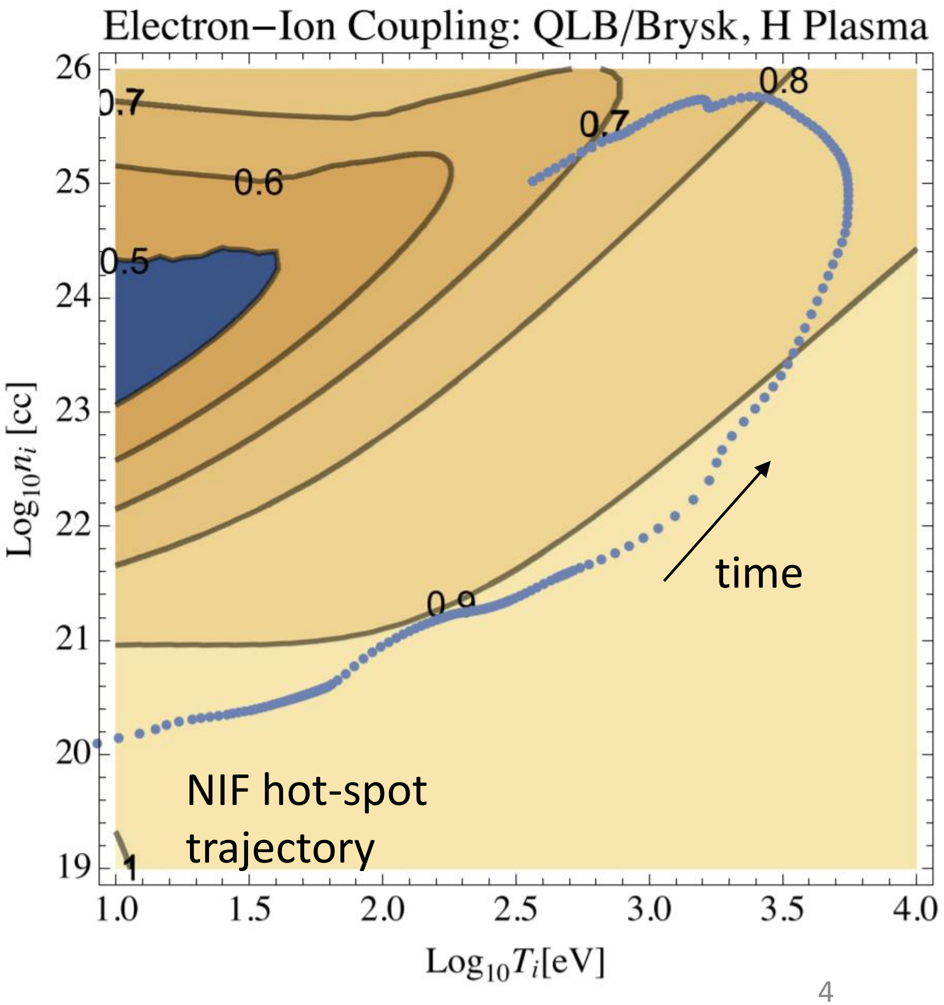
- Project 3 : Use of directional neutron spectroscopy of DT-n in SymCaps to diagnose hot-spot asymmetry
- Project 4 : Studies of diffusive mix during the shock-phase of inertial confinement fusion (ICF) implosions
- Project 5 : Studies of non-Maxwellian electron distributions in the coronal plasma of ICF implosions

HEDP and ICF codes require accurate models of the ion-electron (i-e) exchange. There's a paucity of experimental data to validate the different models

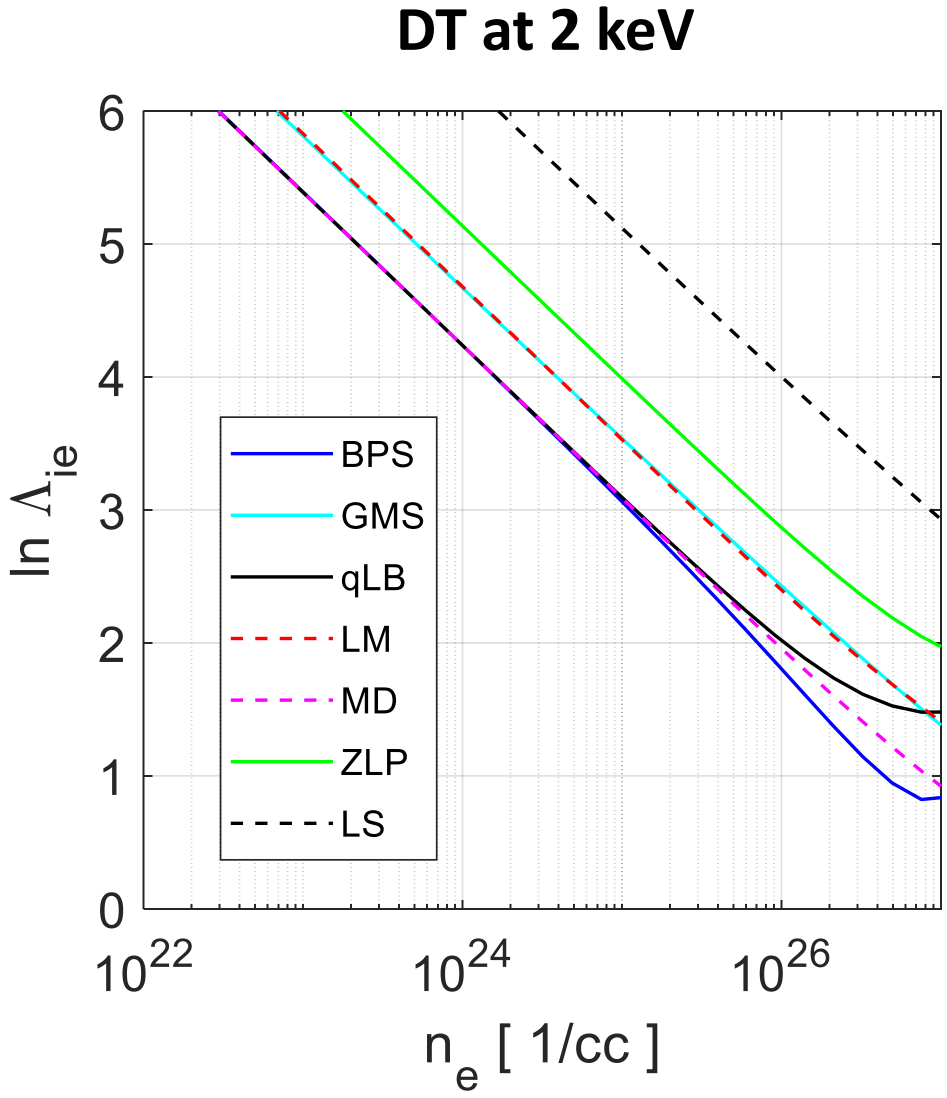
- Recent example : the implementation of a new i-e model in the ARES code at LLNL
- C. Scullard *et. al. [1]* derived an in-line evaluation of a quantum Lenard-Balescu (qLB) formulation of the i-e model that was used to replace the Brysk formulation
- The two models differ by 10-30% over the evolution of a NIF scale hot-spot

[1] C. Scullard *et. al.*; PRE (2018)

Figure from S. Bergeson *et. al.* (2019)



Several formulations of the Coulomb logarithm governing the i-e energy exchange exist for HEDP and ICF



$$\sigma_{ie} \propto \ln \Lambda_{ie}$$

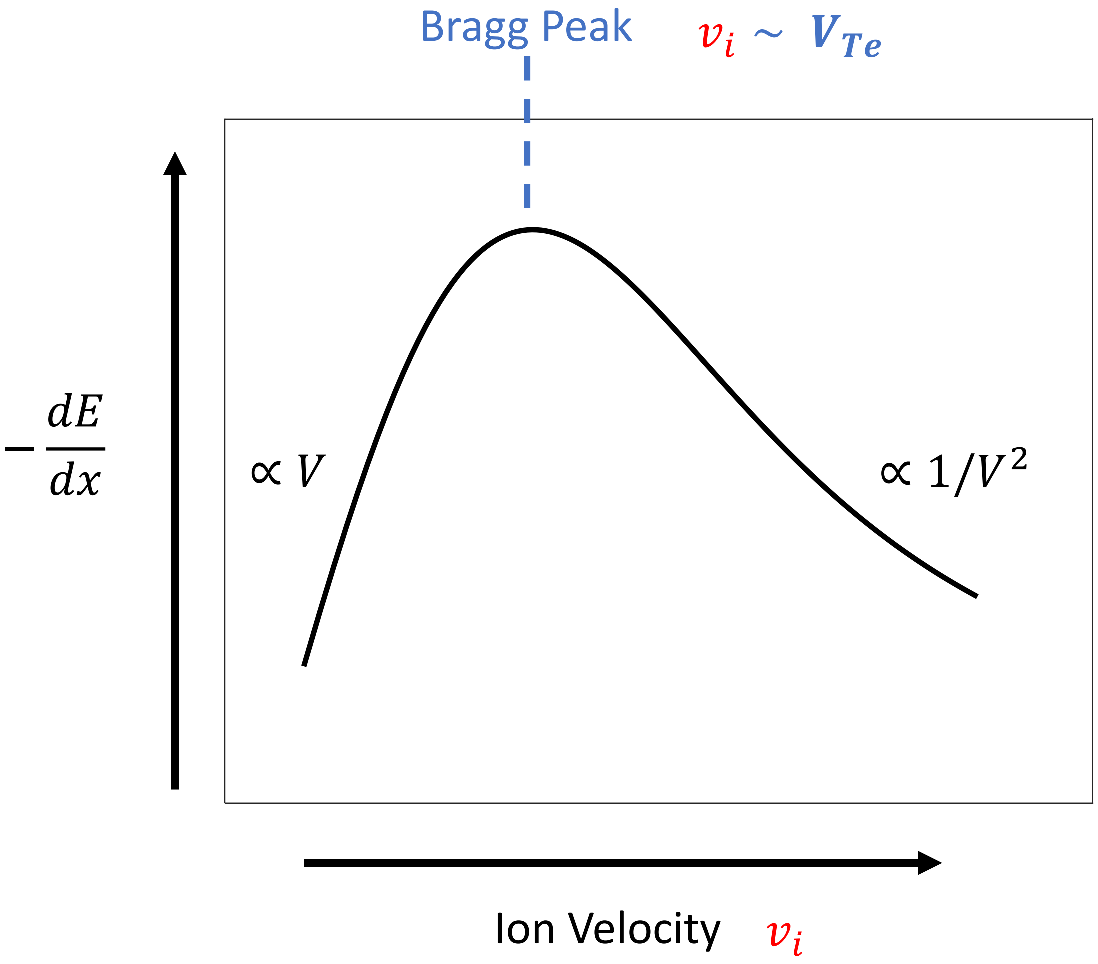
Ion-electron energy transfer cross section

Ion-electron Coulomb Logarithm

Formulation	**Used in**
Landau-Spitzer (LS)	FLASH
Zylstra-Li-Petrasso (ZLP)	
Maynard-Deutsch (MD)	Monte Carlo transport at LLNL [1]
Lee-More (LM)	LILAC, DRACO, and FLASH
quantum Lenard-Balescu (qLB)	ARES at LLNL
Gericke-Murrillo-Schlanges (GMS)	
Brown-Preston-Singleton (BPS)	LILAC

[1] George B. Zimmerman. “Monte Carlo methods in ICF”. In: AIP Conference Proceedings 406.1 (Apr. 1997)

Ion-electron energy exchange was probed using a novel method based on low-velocity-ion stopping, developed by myself and collaborators



The energy loss of ions below the average-electron thermal speed (V_{Te}) is given by:

$$\frac{dE}{dx}\Big|_{v_i \ll v_{Te}} = -\boldsymbol{\nu_{ie}}\, m_i v_i$$

$$\boldsymbol{\nu_{ie}} \propto \sigma_{ie}$$

that only depends on V_{Te} when $v_i \ll v_{Te}$

The coefficient for the ion-electron stopping has been shown to be the same as the ion-electron energy exchange coefficient [1,2,3]

$$\left.\frac{dE}{dx}\right|_{v_i \ll v_{Te}} = -\,\boldsymbol{\nu_{ie}}\, m_i v_i$$

$$\frac{dT_e}{dt} = \boldsymbol{\nu_{ie}}(T_e - T_i)$$

Equilibration measurement via low-velocity ion stopping power measurements

[1] D. O. Gericke et al; PRE (2002)
[2] D. O. Gericke et al; PRE (2001)
[3] Daligault PoP (2016)
[4] D. J. Bernstein, *et. al. PoP* (2019)

Previous works have used low velocity stopping to look at equilibration in Molecular Dynamics simulations [4]

Energy loss $\Delta\mathbf{E}$ of the low-velocity ions, electron temperature T$_e$(r), and density n$_e$(r) profiles were measured to infer a Coulomb Logarithm $\boldsymbol{ln\ \Lambda}$

Working in the low velocity limit, $v_i < v_{Te}$, the stopping power,

$$\left.\frac{dE}{ds}\right|_{v_i<v_{Te}} = -\boldsymbol{\nu_{ie}}\, m_i v_i$$

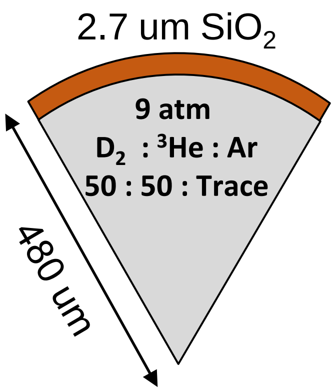
The energy loss $\mathbf{\Delta E}$ is related to the ion-electron energy exchange rate $\boldsymbol{\nu_{ie}}$:

$$\boldsymbol{\Delta E} \approx -m_i\ V_i\ \int \boldsymbol{\nu_{ie}}\, ds$$

$$\boldsymbol{\nu_{ie}} \propto \frac{n_e}{T_e^{\frac{3}{2}}}\ \ln\Lambda$$

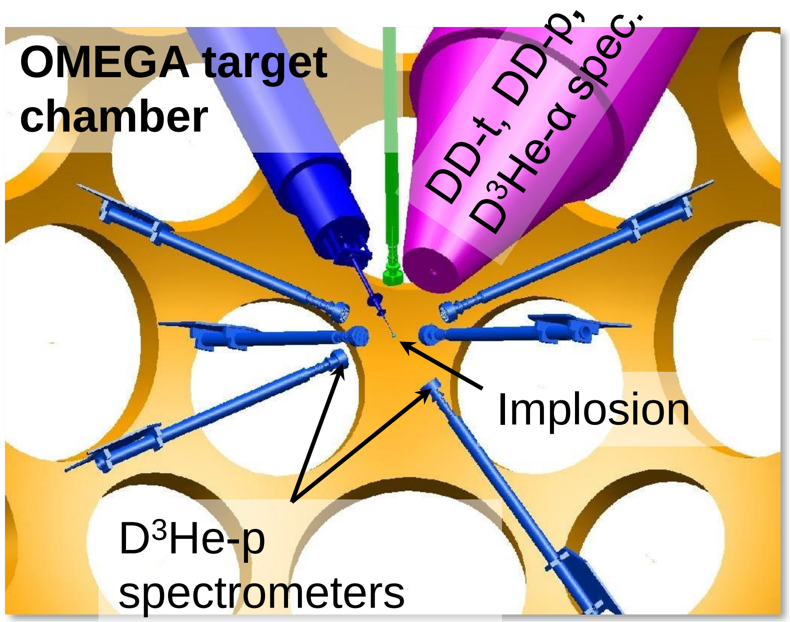
$$\ln\Lambda \propto \frac{\Delta E}{\int \frac{n_e}{T_e^{3/2}}\, ds}$$

Shock-driven, D^3HeAr gas-filled, thin-glass implosions are used for these studies



$$D + D \rightarrow \ p\,(3.0\,MeV) + \ T\,(1.0\,MeV)$$

$$D + {}^3He \rightarrow \alpha\,(3.7\,MeV) + p\,(14.7\,MeV)$$



Key Diagnostics	→	Key Measurements
Multi-Monochromatic Imager	→	$n_e(r)$ and $T_e(r)$
Streaked X-ray Spectrometer	→	$n_e(t)$ and $T_e(t)$
Particle X-ray Temporal Diagnostic	→	$D^3He(t)$ and DD(t)
Charged Particle Spectrometer	→	ΔE for DD-t, D^3He-α

Experiment

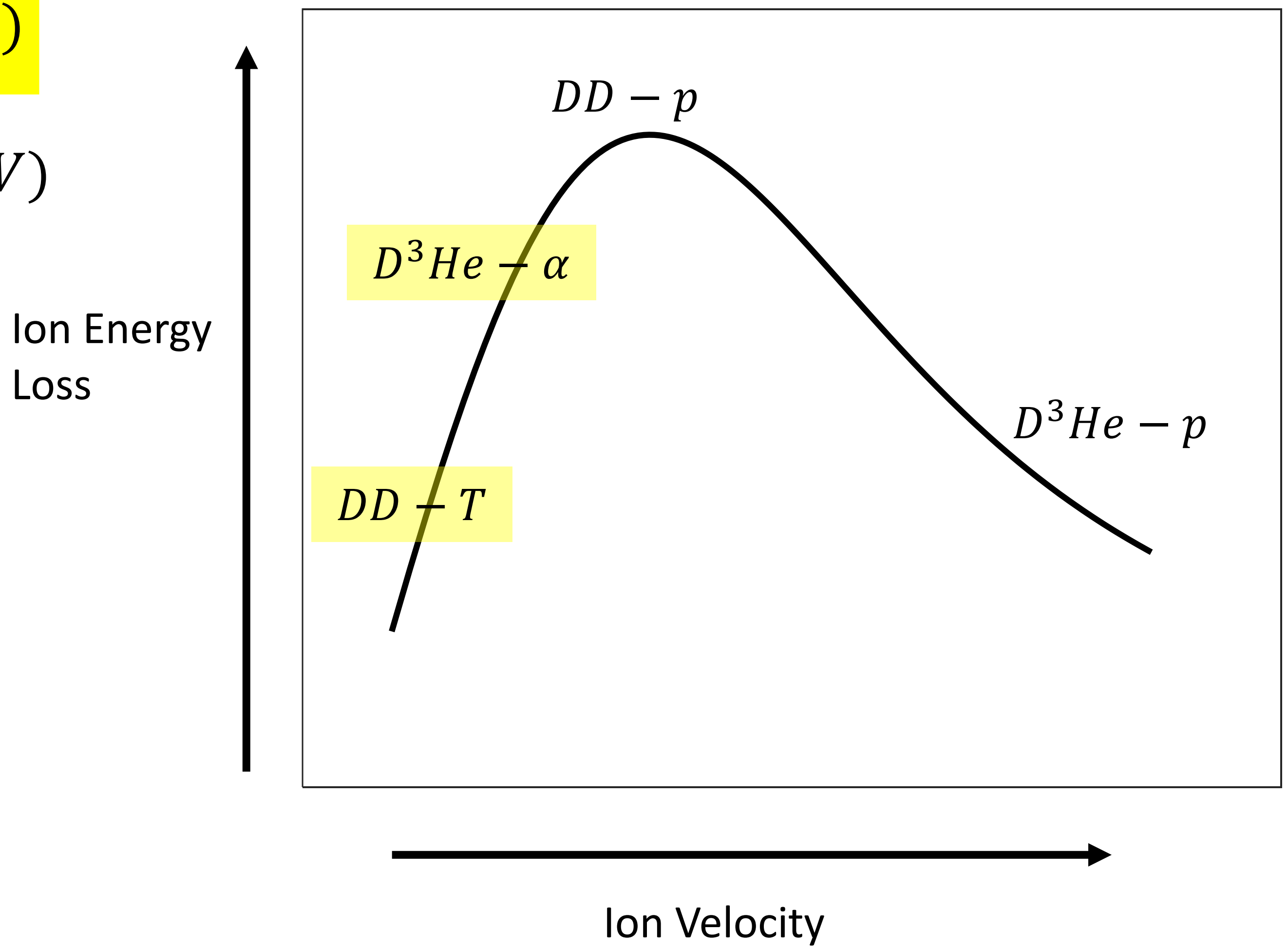
In these experiments, DD and D³He reactions produce DD-T's and D³He-α's with velocities below the Bragg Peak

Fusion Reactions

$$D + D \rightarrow \; p\,(3.0\;MeV) + T\,(1.0\;MeV)$$

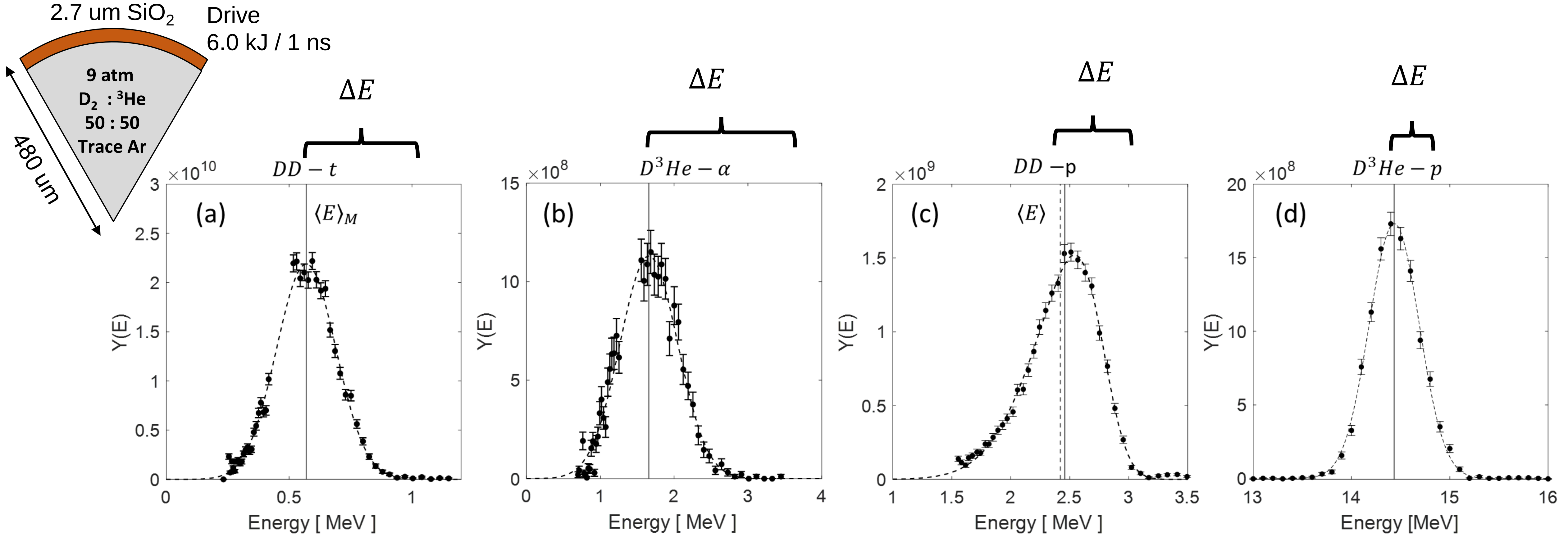
$$D + {}^{3}He \rightarrow \alpha\,(3.7\;MeV) + p\,(14.7\;MeV)$$

The velocity of DD-T's and D³He-α's contains information about the i-e **energy exchange** of the imploded plasma



Experiment

The energy loss ΔE of the fusion products were measured with several Charged Particle Spectrometers[1] (CPS)

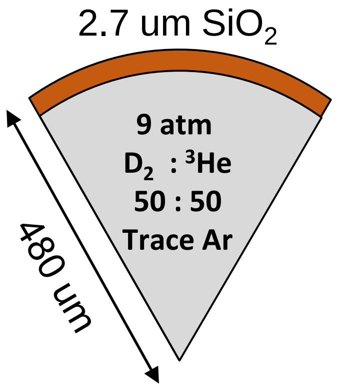


P J Adrian et al; *In situ calibration of charged particle spectrometers on the OMEGA Laser Facility using 241Am and 226Ra sources* RSI (2022)

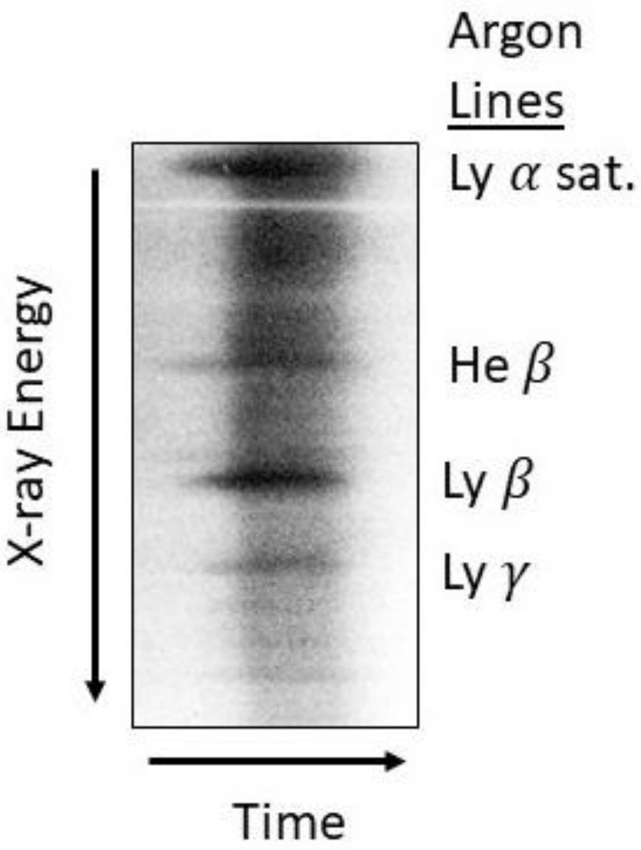
[1] F. H. Séguin et al., Rev. Sci. Instrum. 74, 975 (2003).

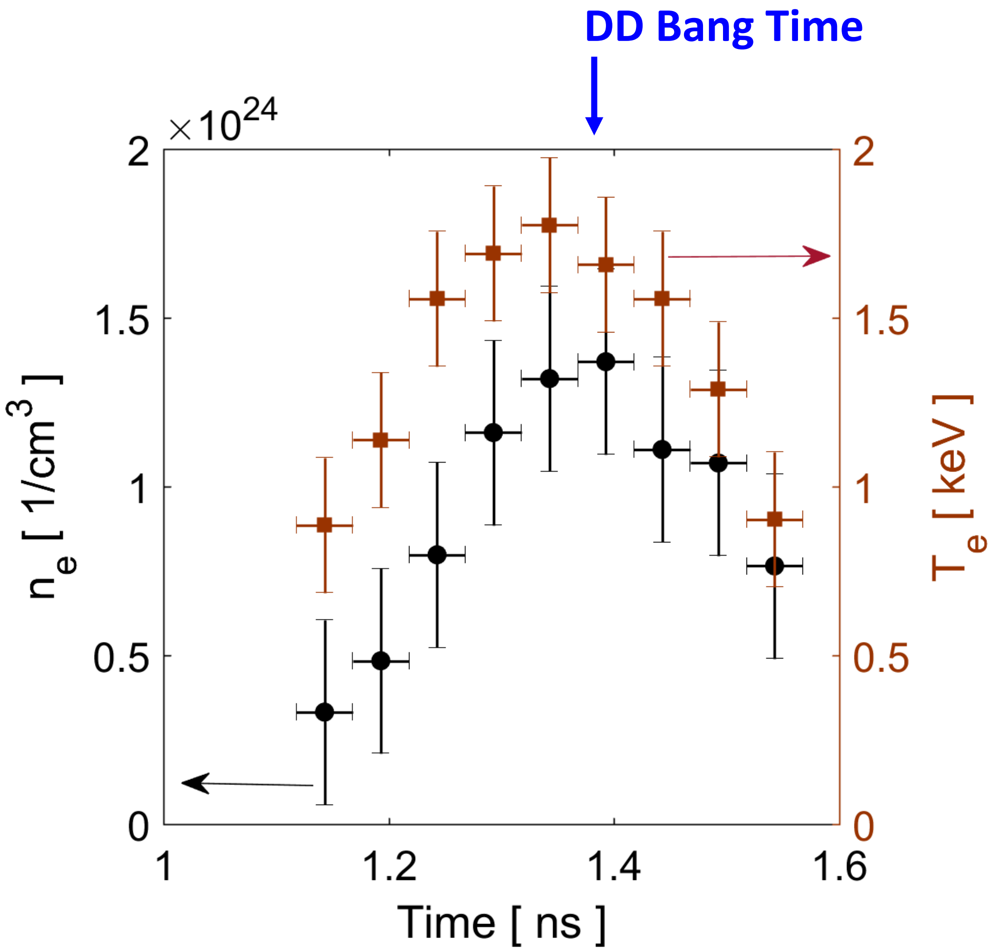
Experiment

The evolution of $T_e(t)$ and $n_e(t)$ were diagnosed with a time-resolving x-ray spectrometer setup to probe the Argon lines



Drive
6.0 kJ / 1 ns

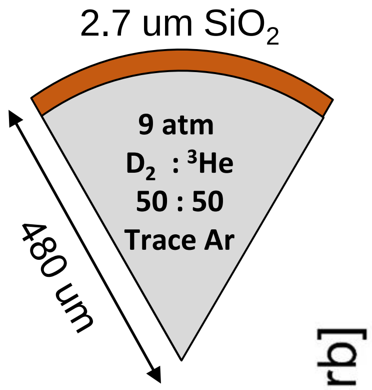




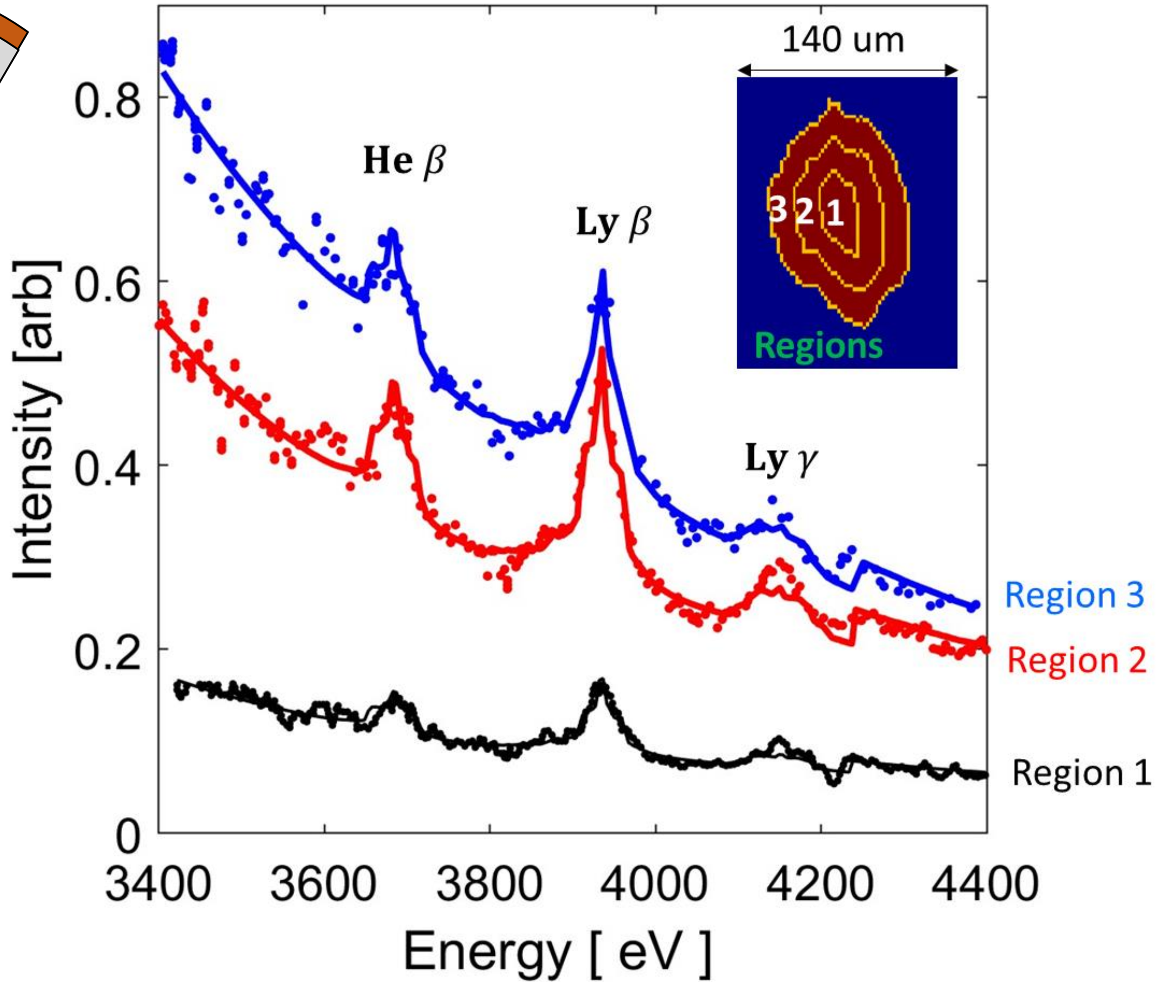
The Argon lines were modeled with ABBKO population kinetics code to extract the plasma conditions
Analysis done by R. Florido

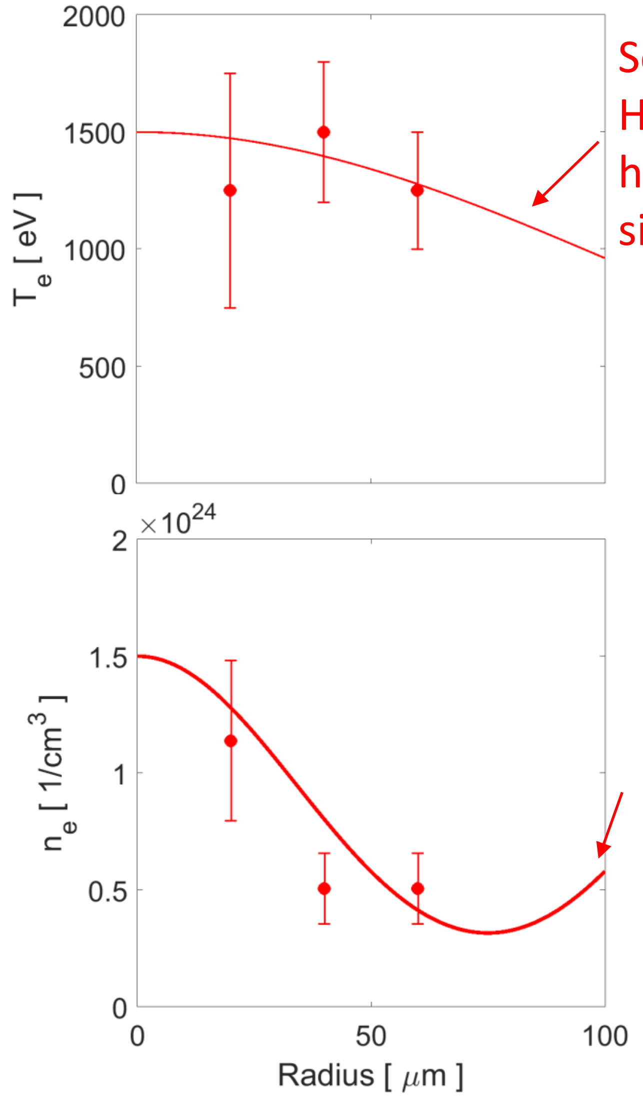
R. Florido et al; PHYSICAL REVIEW E 80, 056402 (2009)

The Argon line emission is described with a non-LTE population kinetics model to experimentally constrain $n_e(r)$ and $T_e(r)$



Drive
6.0 kJ / 1 ns





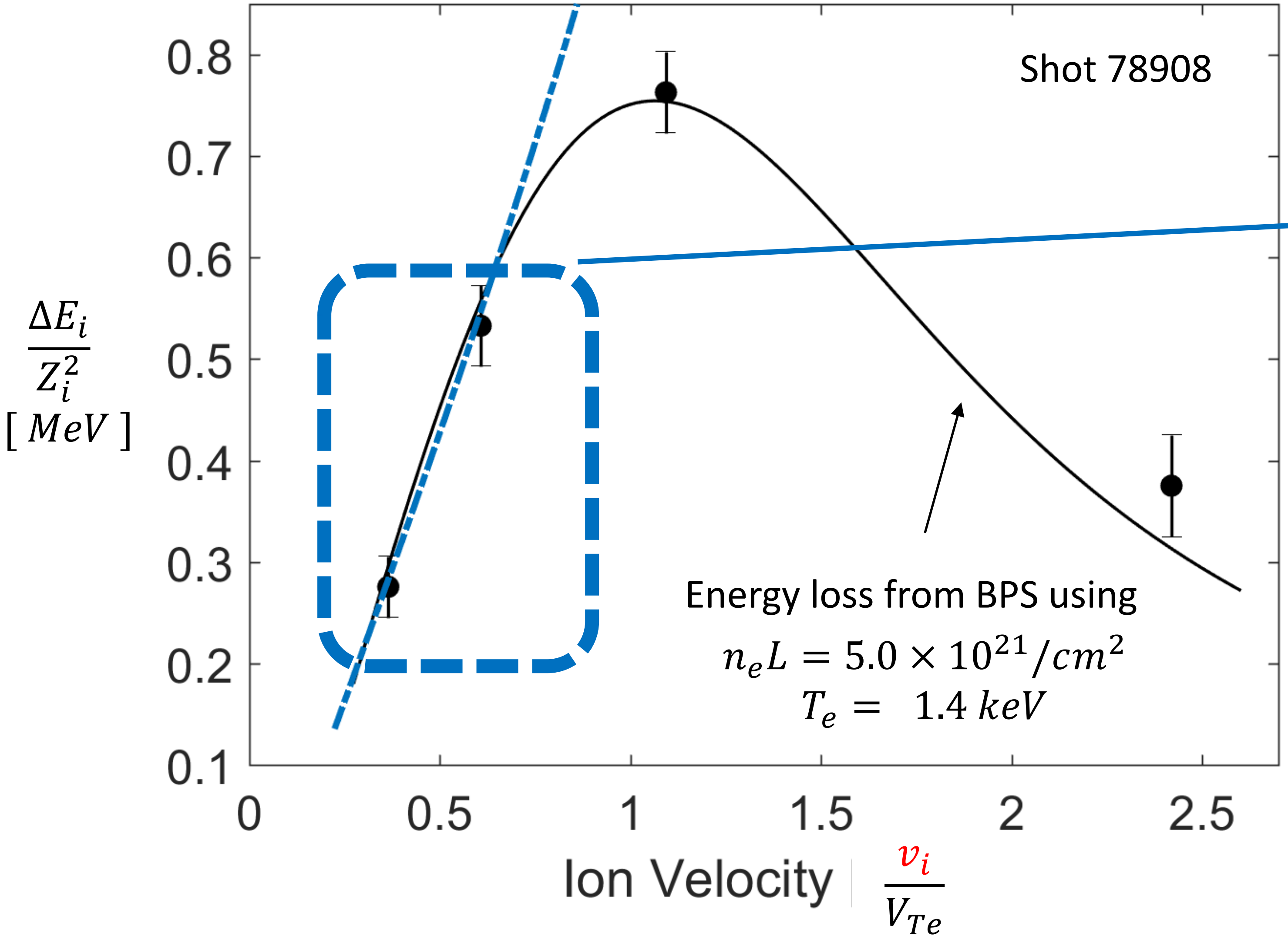
Scaled HYADES hydro simulation

Scaled HYADES hydro simulation

T. Nagayama, et al, Phys. Plasmas 21, 050702 (2014).

Analysis done by R. Mancini

Measured energy loss and plasma conditions were used to construct an energy loss curve from which the Coulomb Logarithm $ln\ \Lambda$ was determined

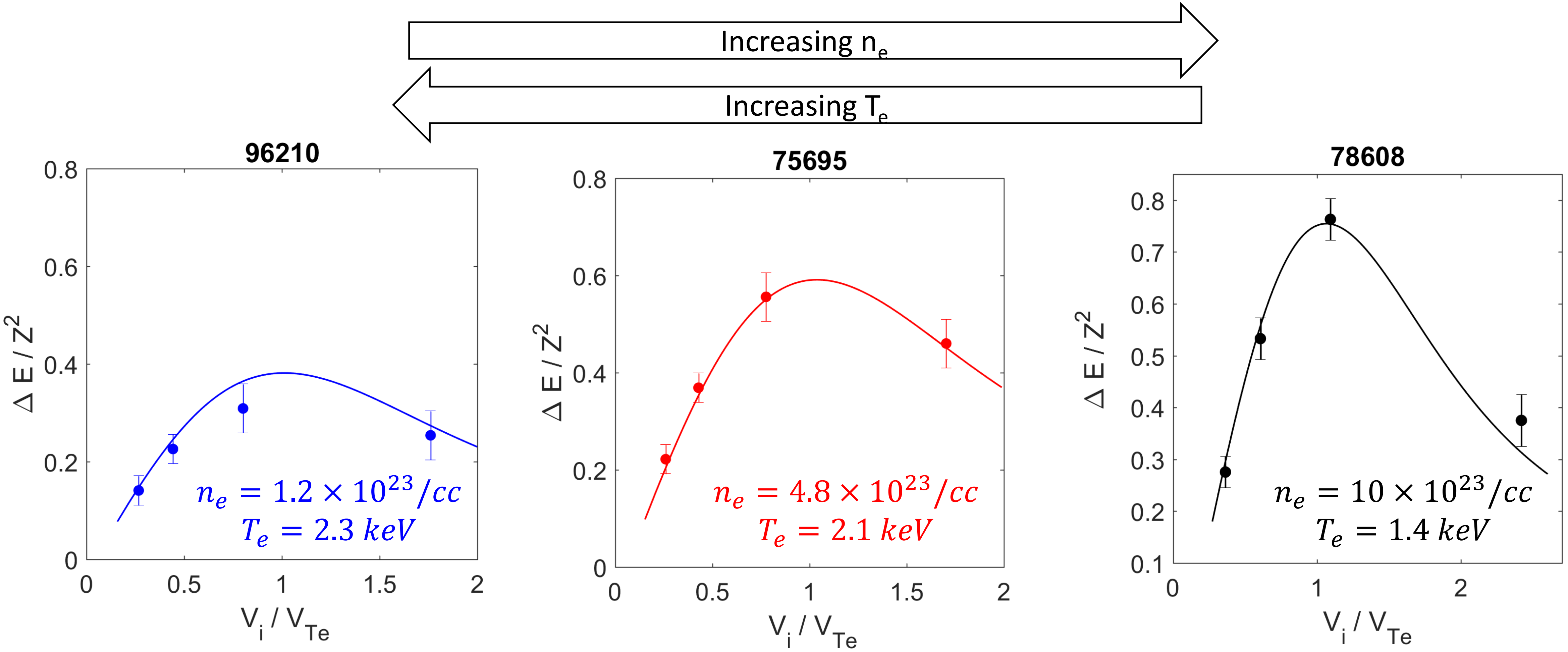


$$\ln \Lambda = const \times \frac{\Delta E}{\int \frac{n_e(s)}{T_e^{\frac{3}{2}}(s)} ds}$$

$$\ln \Lambda = 3.8 \pm 0.6$$
$$n_e \ = 2.1 \pm 0.4 \times 10^{24}/cm^3$$
$$T_e \ = 1.4 \ \pm 0.2\ keV$$

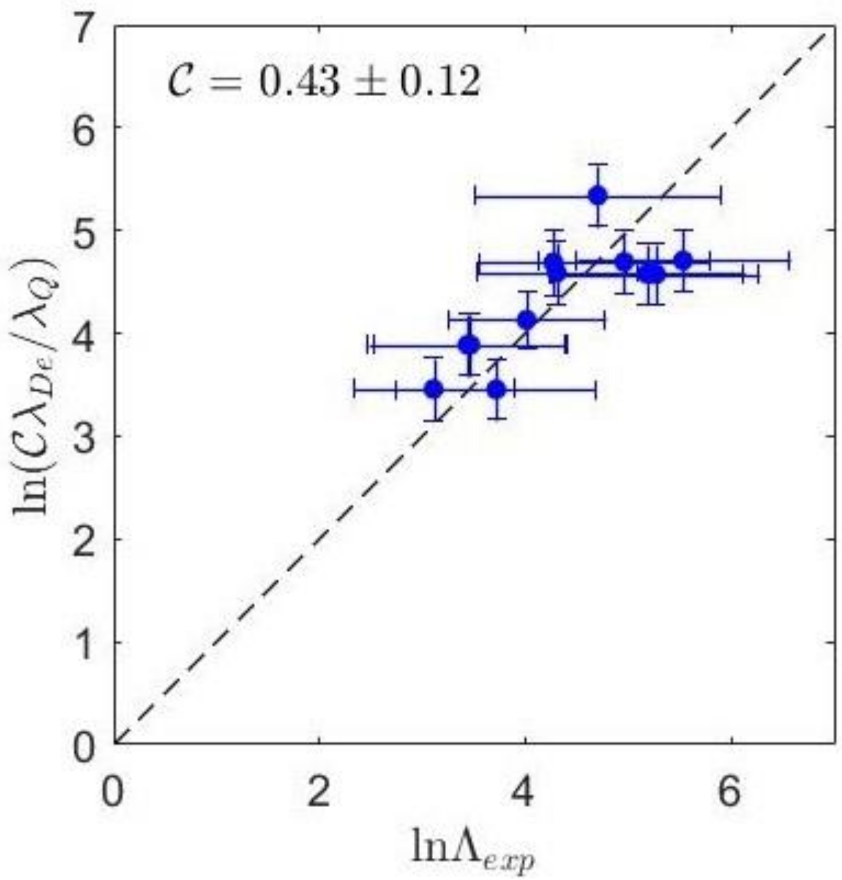
Results

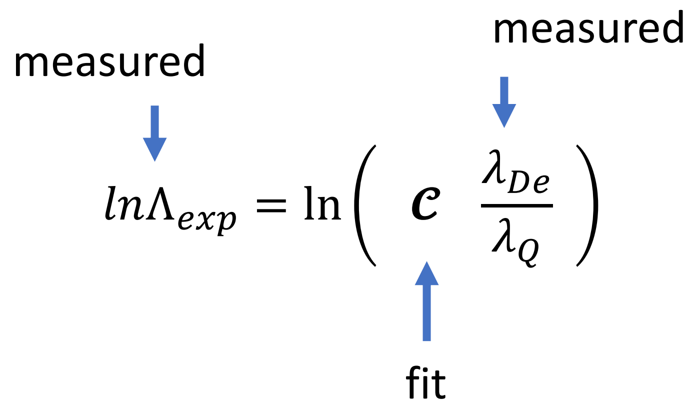
Capsules and laser drive were varied to scan electron density and temperature



The measurements of $\ln\Lambda_{\mathrm{exp}}$ and plasma conditions were used to constrain the $\mathcal{C}$ factor

$\ln(\mathcal{C}\ \lambda_{De}/\lambda_Q)$





measured

measured

$$ln\Lambda_{exp} = \ln\left(\boldsymbol{\mathcal{C}} \ \frac{\lambda_{De}}{\lambda_Q} \right)$$

fit

- λ_{De} - Debye length
- λ_Q - Debroglie wavelength
- $\boldsymbol{\mathcal{C}}$ – order unity correction factor

Measurements of ion-electron energy exchange in HEDP and ICF were conducted at OMEGA and the results were used to differentiate state-of-the-art models

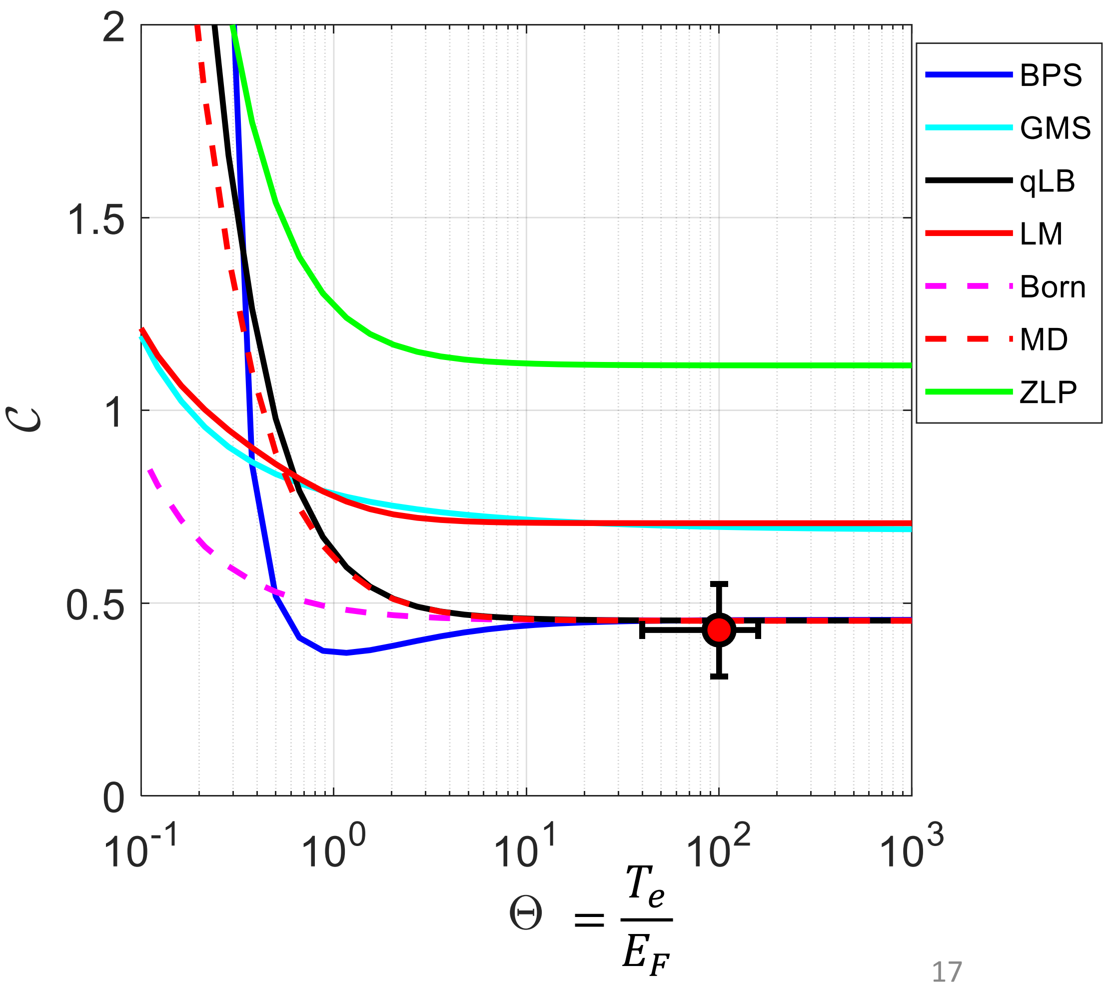
P J Adrian et al; Phys. Rev. E. **106**, L053201 (2022)

- Implosion experiments were conducted to generate plasma conditions:

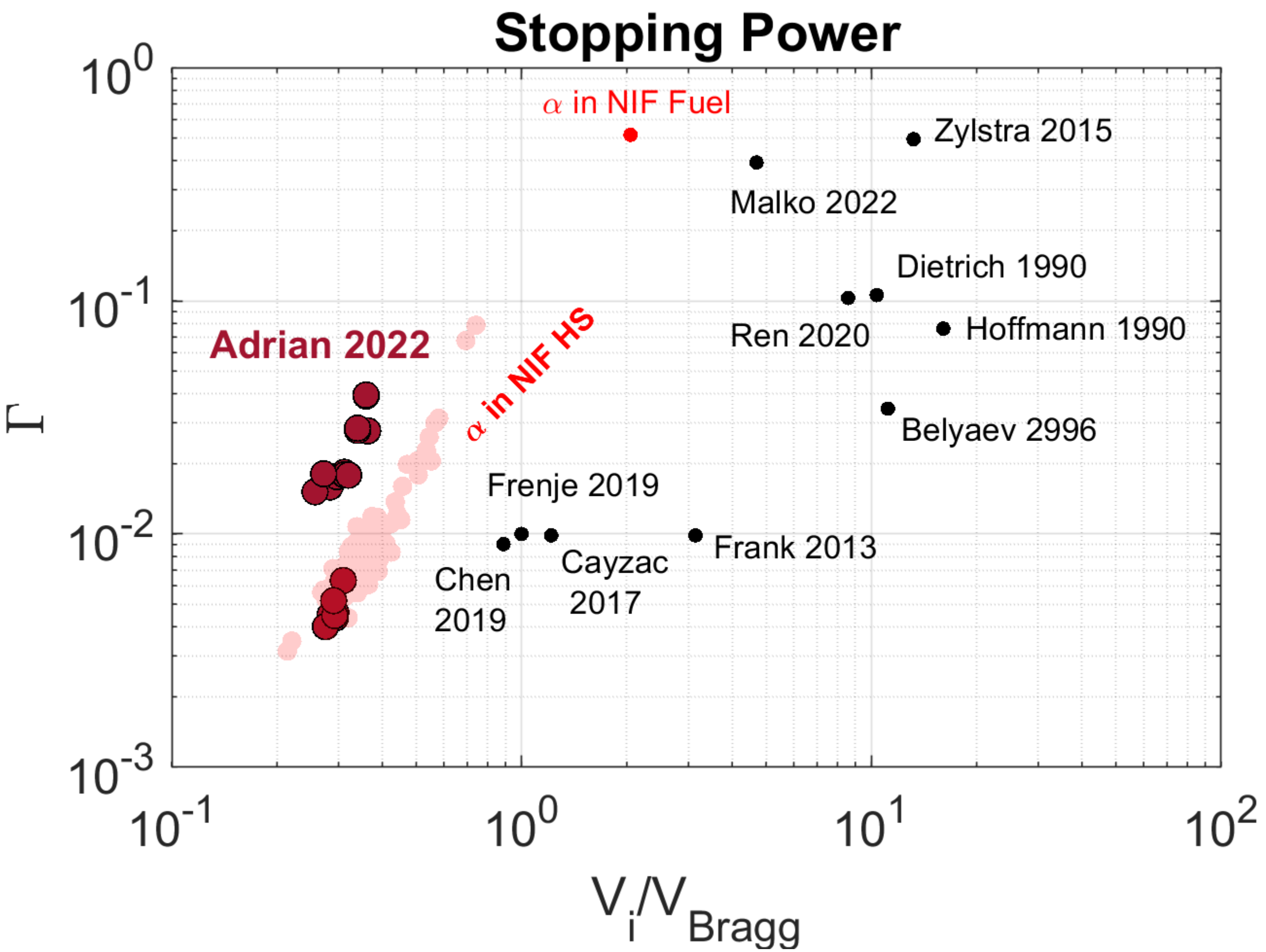
$$n_e \ \sim 1 - 20 \times 10^{23}\ /cc$$
$$T_e \ \sim 1.4 - 2.4\ keV$$

- Measurements were conducted to determine
-
  1. $\ln\Lambda \propto ln\frac{\lambda_{De}}{\lambda_Q} \rightarrow \text{quantum diffraction}$
  2. The correction factor $\mathcal{C} = 0.45 \pm 0.14$ (due to small angle scattering approximation)

- The results support BPS, quantum Lenard Balescu and quantum Fokker Planck equilibration models



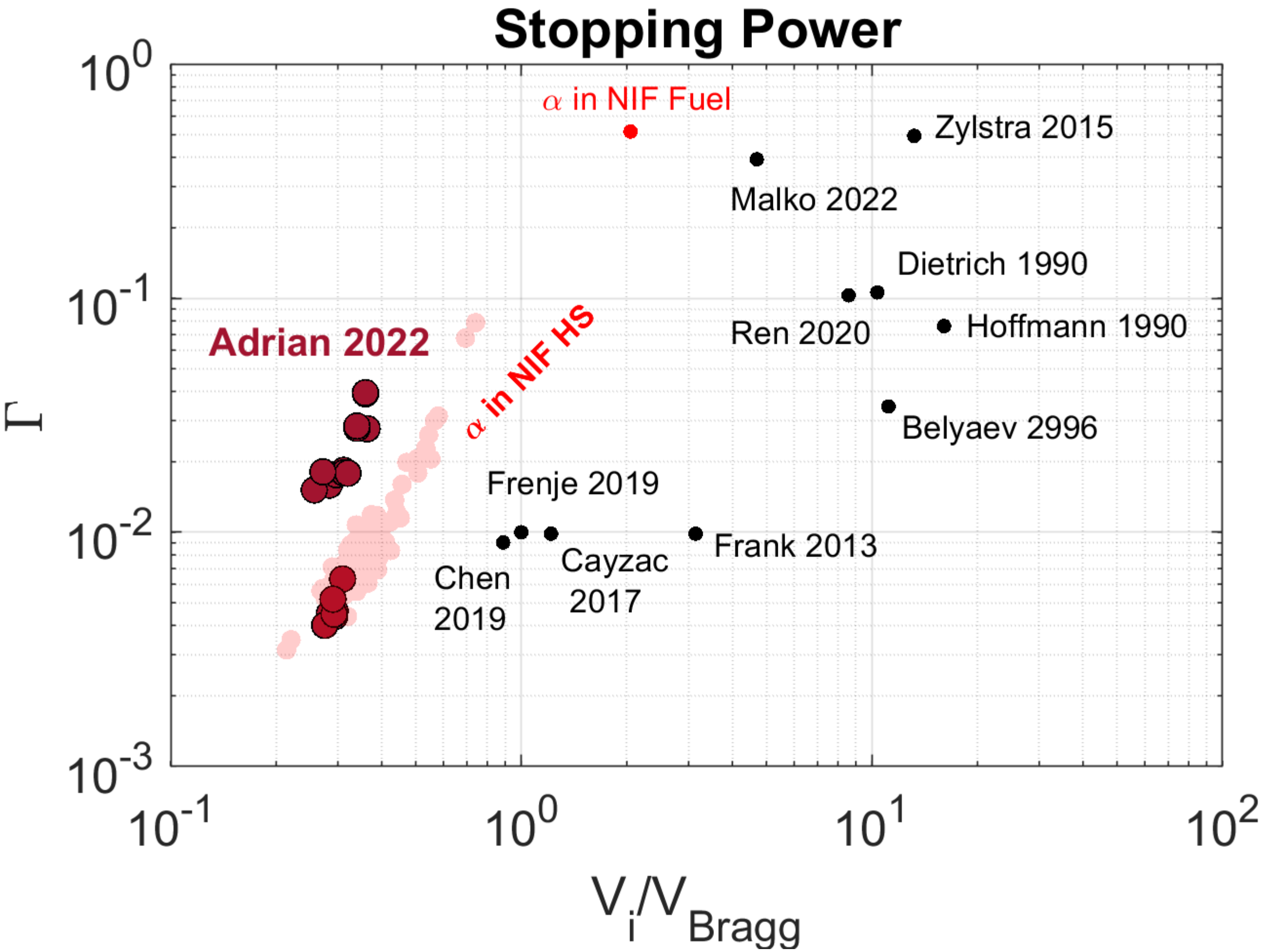
This work studied ion stopping below the Bragg Peak, which is highly relevant to alpha particle stopping in ignition experiments



Conclusions and Future Work

- Ion stopping and ion-electron equilibration were probed at hot-spot relevant conditions
  - The data validated models of the Coulomb Log recently implemented in simulations
  - P J Adrian et al; Rev. Sci. Instrum. **93**, 113534 (2022)
  - P J Adrian et al; Phys. Rev. E. **106**, L053201 (2022)

- Future work will involve studies of more coupled and degenerate HEDP
  - Relevant to alpha stopping in NIF Fuel



Stewardship Science Graduate Fellowship enabled me to pursue novel research in close collaboration with the national labs

- I have published papers with co-authors from: LLNL, LANL, SNL
    - Studying ion-electron energy exchange
    - Development of x-ray imaging spectrometer at OMEGA
    - Calibration methods for charged particle spectrometers at OMEGA

- 20+ coauthored publications
    - Ignition paper (2022)
    - Magnetized implosions
    - Alternative hohlraums

- Practicum : LLNL
    - Developing new experimental techniques to study shock physics for equation-of-state measurements