

Transport Analysis of ST40 High Performance Discharges

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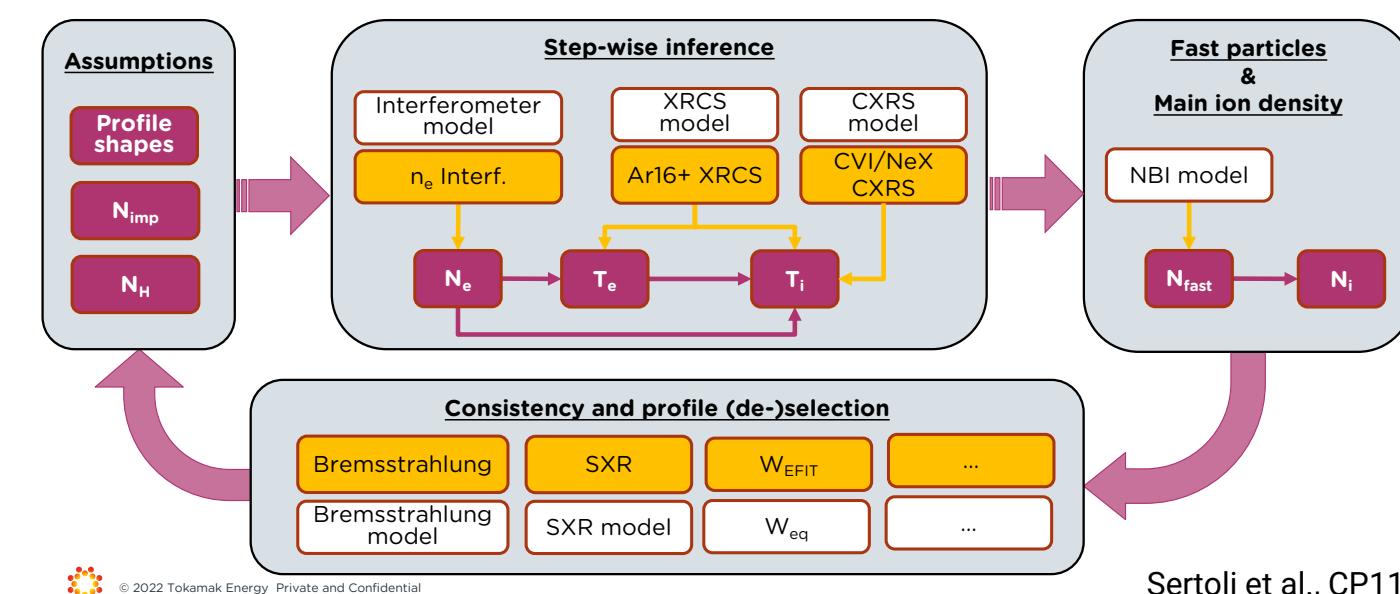
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Abstract

The main fusion element of the ST40 tokamak, owned and operated by Tokamak Energy, Ltd., UK, is to attain fusion-relevant ion temperatures (100M Kelvin) in a small, compact spherical tokamak. These temperature levels have been achieved at higher aspect ratio, but only in much larger devices with very high heating power levels. ST40 has a major radius of 40 cm, plasma currents up to 800 kA, toroidal fields up to 2.2 T, and it is heated by up to 2 MW of deuterium neutral beam injection. 2.2 T is the highest toroidal field in a spherical tokamak to date. Near central impurity ion temperatures in excess of 100M K (~8.6 keV) have recently been achieved and reported in ST40 for both hydrogen and deuterium thermal plasmas. Temperature and density profiles, and their uncertainties in these ST40 plasmas have been inferred from experimental and modeling constraints in the absence of full profile measurements. TRANSP has been used to analyze the transport properties of these high-performance plasmas and confirm the hydrogenic temperature levels. While slightly lower than the impurity ion temperature level, hydrogenic temperatures do reach and exceed the 100M K level. Despite the high central ion temperatures, both ion and electron transport are large, and the ion temperature exceeds neoclassical levels in the outer region of these plasmas. The TRANSP results are being used as a basis for both gyrokinetic studies of the source of these turbulence levels as well as for studying fast ion driven instability observations.

Integrated data analysis workflow to produce sets of kinetic profiles consistent with experimental constraints

- Step-wise inference of **kinetic profiles** for a given set of trialed profile shapes and initial assumptions
- No full kinetic profile measurements during this period of operation

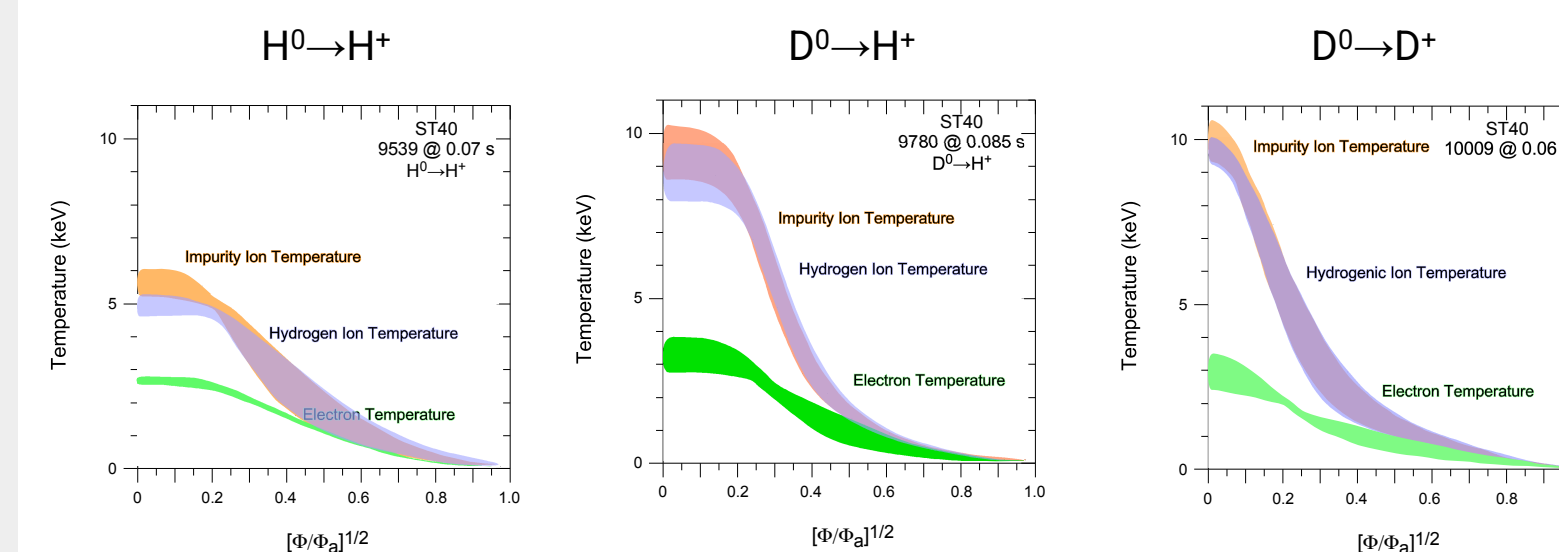


Sertoli et al., CP11.00014

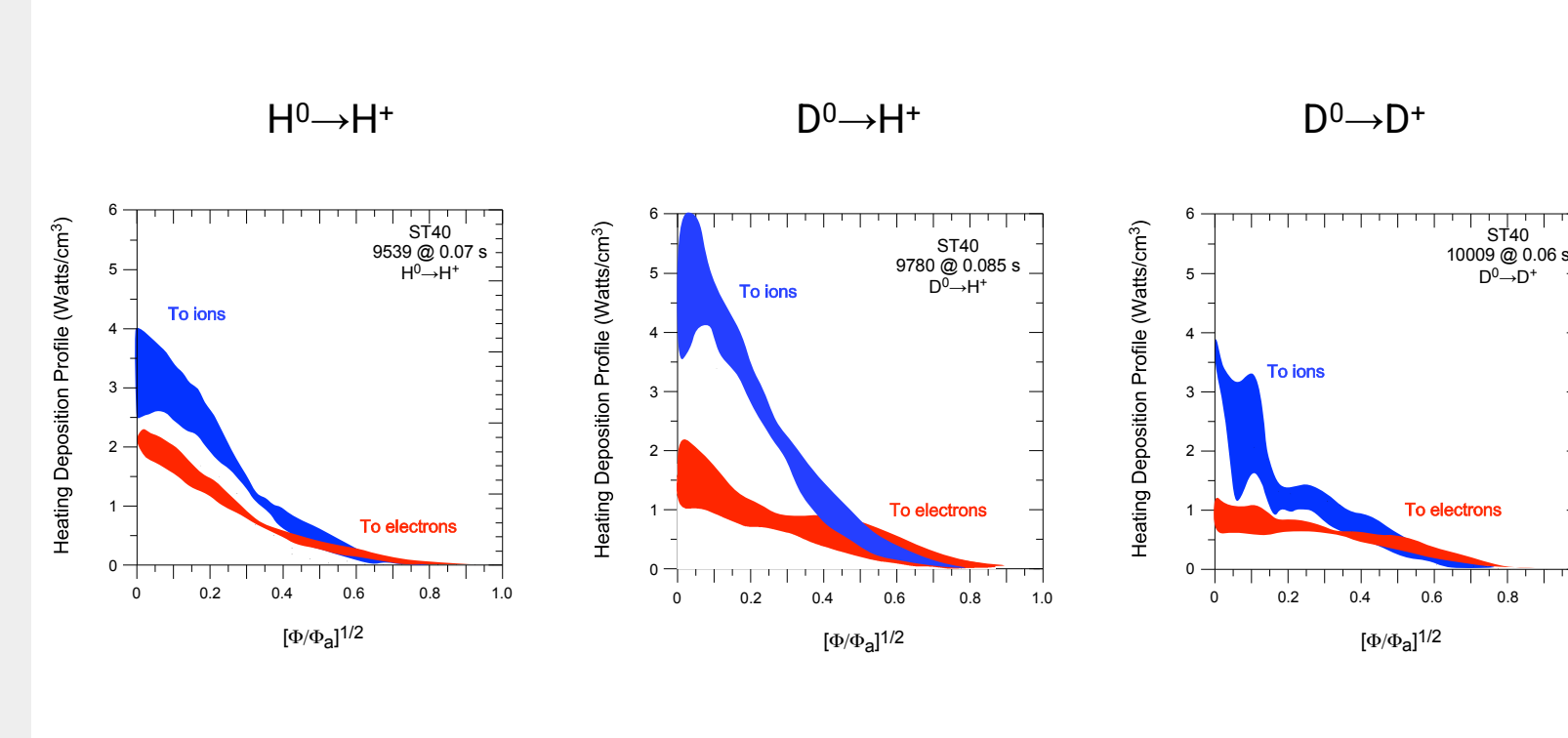
Hydrogenic temperatures slightly lower than impurity temperatures

- 100M C (~8.4 keV) exceeded in D⁰-D⁺ discharge
- Similar results for other high T_i D⁰-D⁺ discharges (T_i ~0.5 keV lower in 10014)

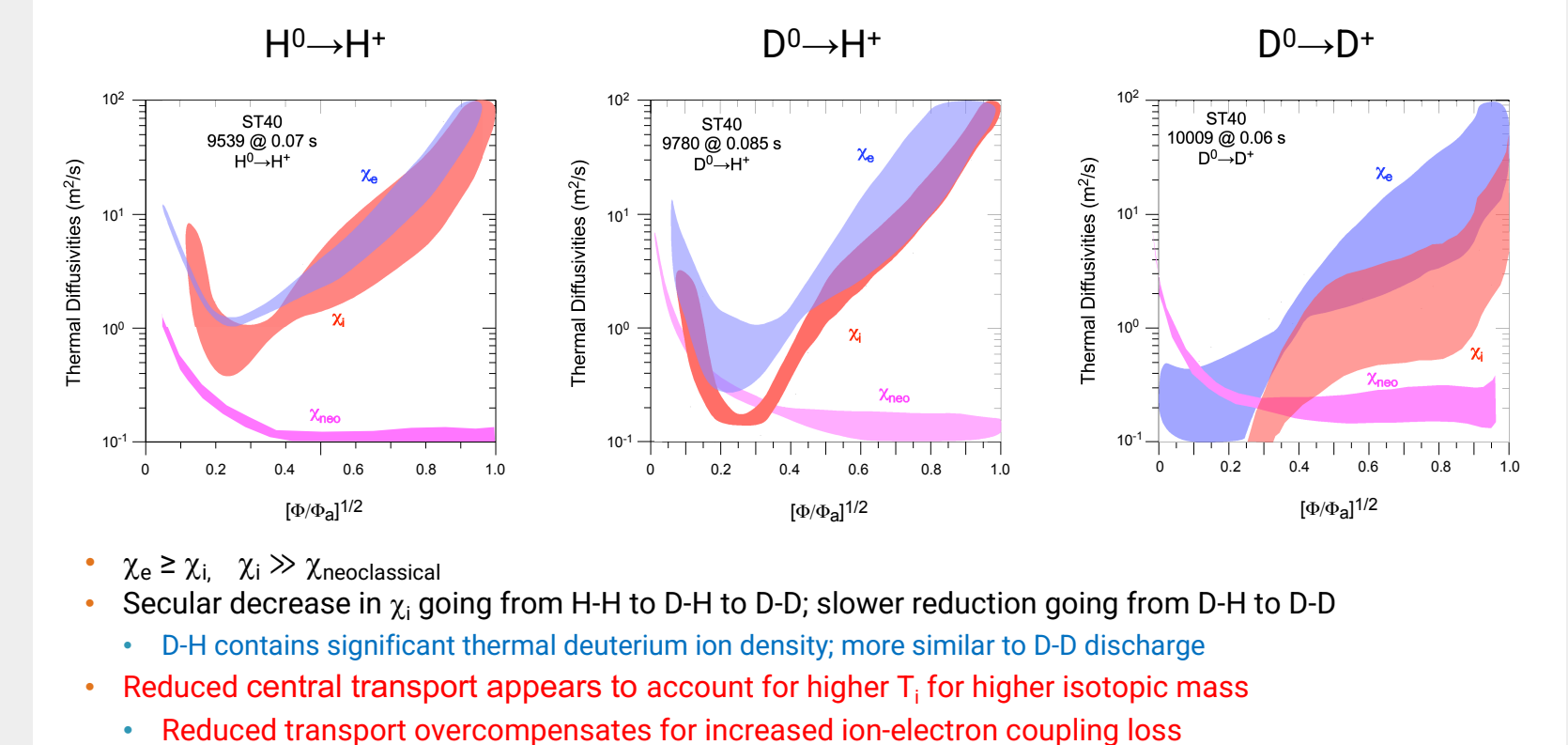
Increase of T_i seen with increasing isotopic mass



Predominant ion heating by beams for all isotopic mass

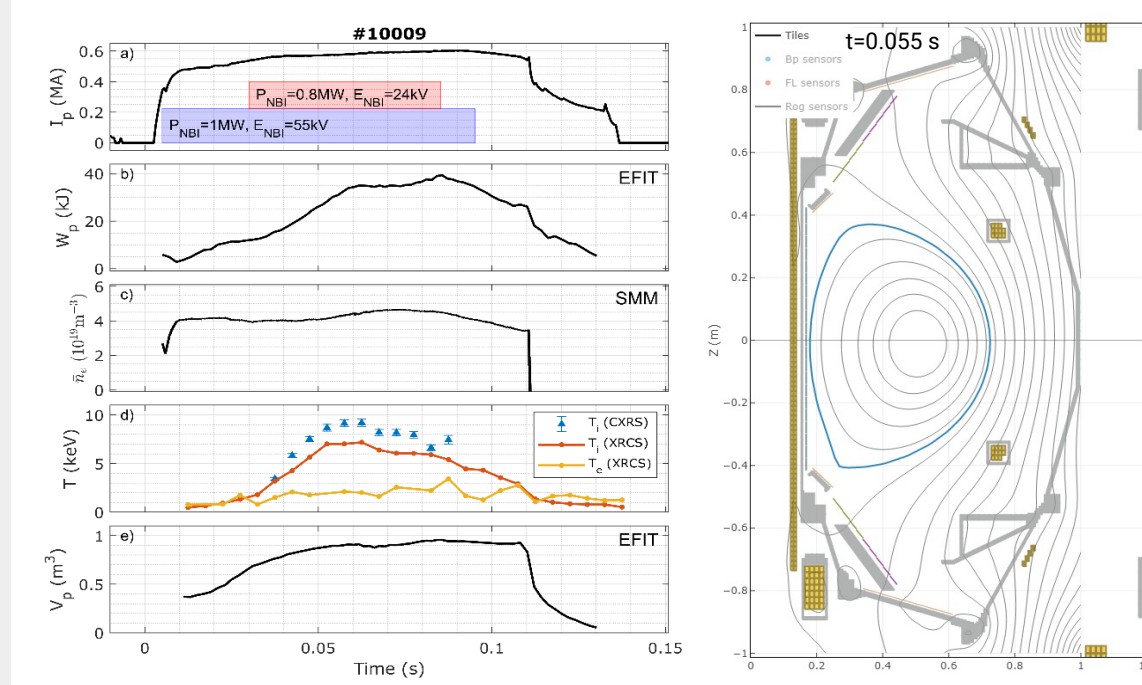


Clear reduction in ion thermal diffusivity with increasing isotopic mass



- $\chi_e \geq \chi_i$, $\chi_i \gg \chi_{neoclassical}$
- Secular decrease in χ_i going from H-H to D-H to D-D; slower reduction going from D-H to D-D
- D-H contains significant thermal deuterium ion density, more similar to D-D discharge
- Reduced central transport appears to account for higher T_i for higher isotopic mass
- Reduced transport overcompensates for increased ion-electron coupling loss

Plasma evolution and equilibrium of D⁰-D⁺ high T_i discharge

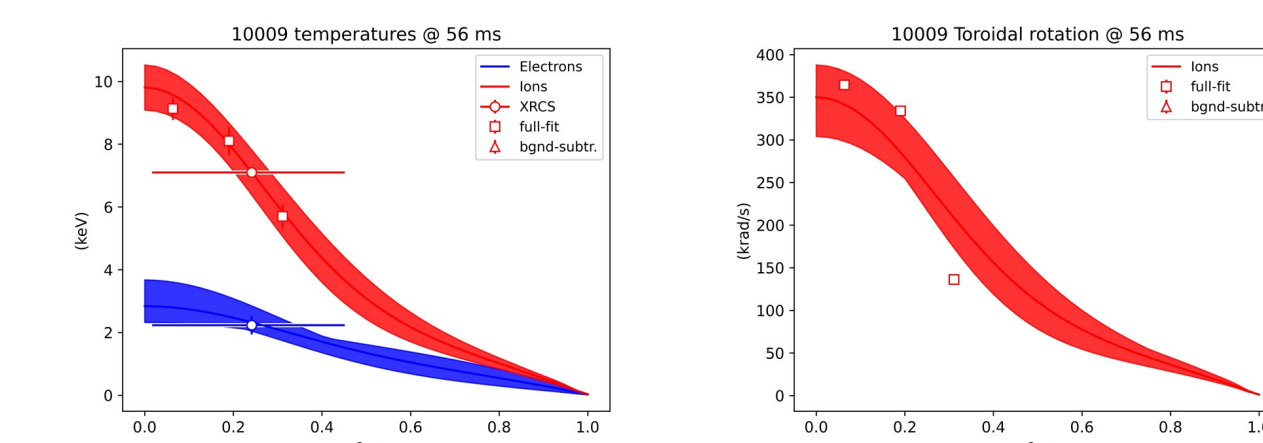


Thomas et al., Y102.00005, Romanelli et al., G003.00011

We will compare transport characteristics of high T_i discharges with differing isotopic mass

Example of IDA profiles

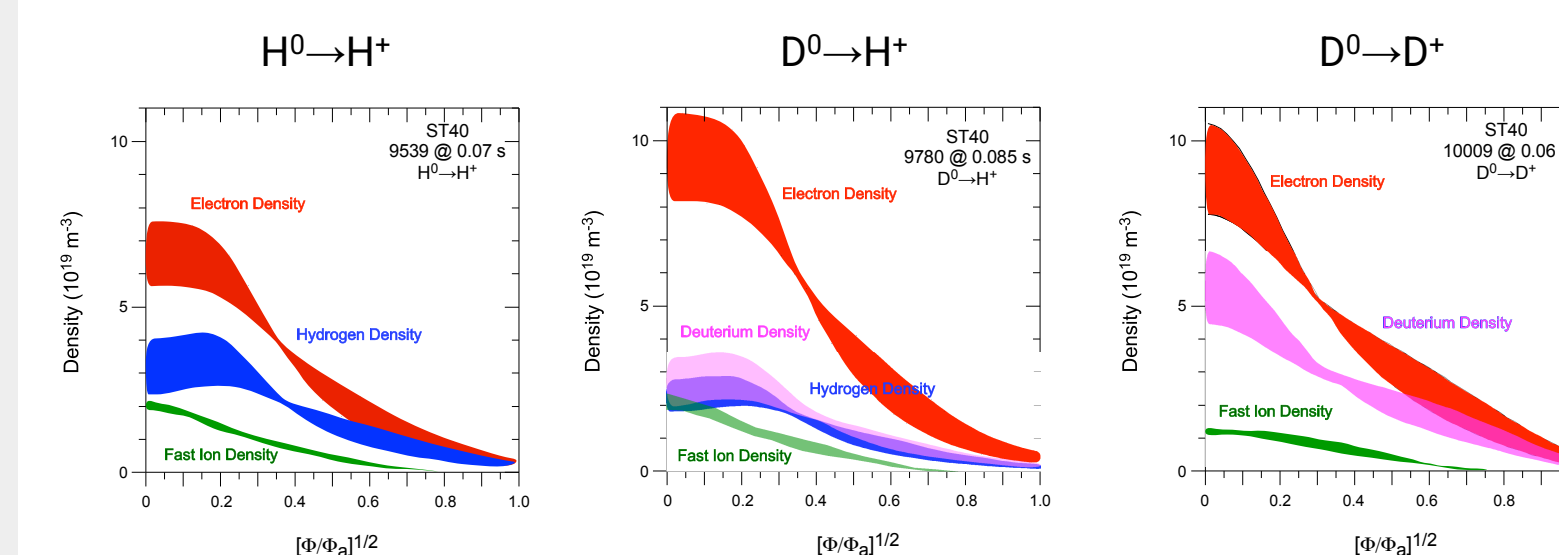
Range of profiles consistent with the measurement constraints from the He-like Ar X-ray crystal spectrometer, CVI charge exchange spectroscopy, near-infrared and sub-millimeter interferometers, EFIT stored energy.



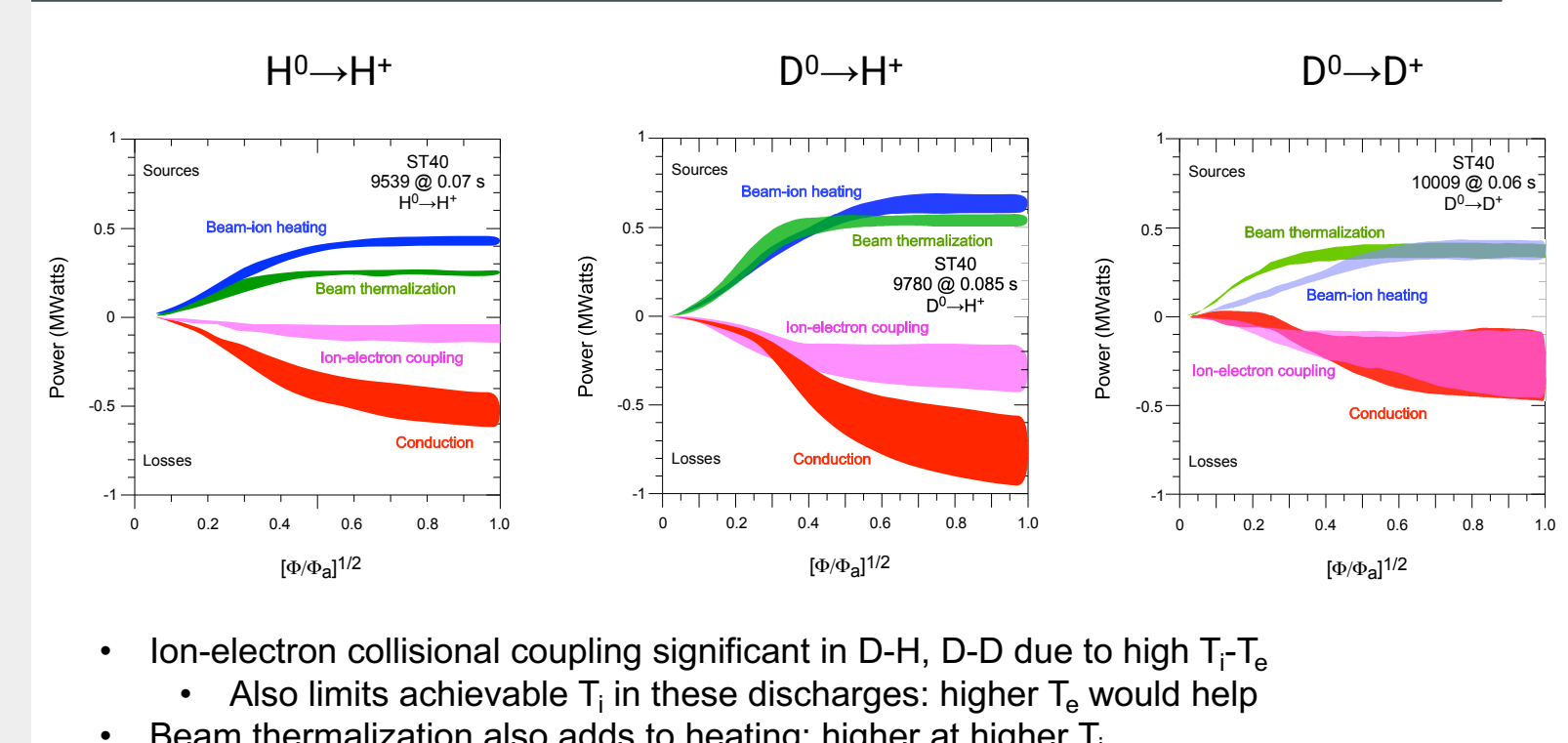
Ion temperature shown is impurity ion temperature

Compare discharges with similar line-averaged densities

- Dilution in thermal ion density due to fast ion density for lower isotopic mass
- Significant thermal deuterium density in D-H discharge due to beam thermalization
- Not much difference in temperatures between D-H and D-D (see previous slide)



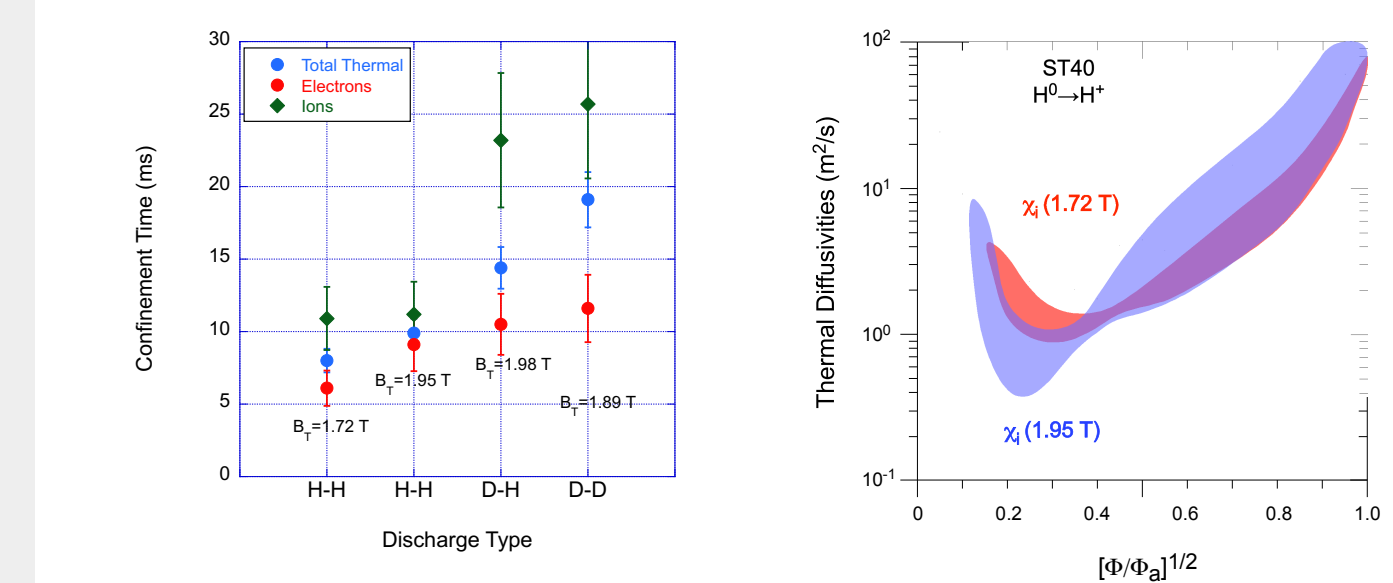
Thermal conduction primary loss mechanism in ions



- Ion-electron collisional coupling significant in D-H, D-D due to high T_i-T_e
- Also limits achievable T_i in these discharges: higher T_e would help
- Beam thermalization also adds to heating; higher at higher T_i

Confinement increase/transport reduction may account for higher T_i with increasing isotopic mass, and with higher B_T (for H-H discharges)

- Increase in confinement time in all channels with isotopic mass, B_T
- Reduced core ion thermal transport at higher B_T



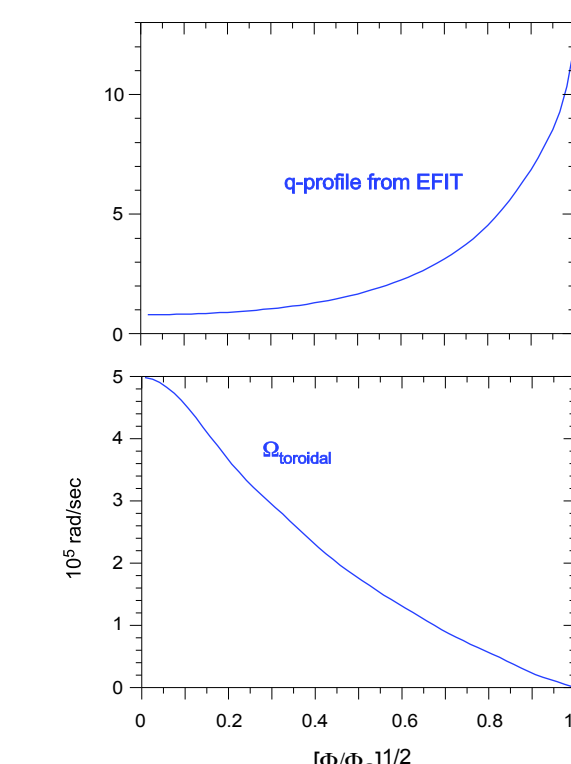
High T_i discharge parameters ("hot ion mode" with T_i >> T_e)

Shot	9520	9539	9780	10009
Time of interest (s)	0.09	0.07	0.085	0.06
Type	H ⁰ →H ⁺	H ⁰ →H ⁺	D ⁰ →H ⁺	D ⁰ →D ⁺
a (m)	0.25	0.26	0.26	0.28
R (m)	0.42	0.44	0.47	0.49
I _p (kA)	507	537	544	580
B _T (T)	1.72	1.95	1.98	1.89
κ	1.46	1.44	1.36	1.42
n _e (m ⁻³)	4.4 x 10 ¹⁹	3.5 x 10 ¹⁹	5.0 x 10 ¹⁹	4.4 x 10 ¹⁹
P _{inj} (MW)	1.51	1.48	1.80	1.60

TRANSP used to determine hydrogenic temperature and transport coefficients

- Measured T_i and inferred profiles based on **impurity** measurements
- TRANSP determines **hydrogenic temperature from power balance**
- Use different sets of consistent profiles inferred from IDA to determine hydrogenic temperatures, power flows, transport coefficients, confinement times
- Use EFIT outer boundary and internal equilibria
 - Compared to TRANSP calculation of internal equilibrium – little impact on calculated hydrogenic temperatures
- Assume Z_{eff} = 2.1 – 2.3 (flat profile), consistent with preliminary measurements
- Also tested by inputting inferred carbon and argon profiles – little impact on results

q and rotation profiles used in TRANSP calculations

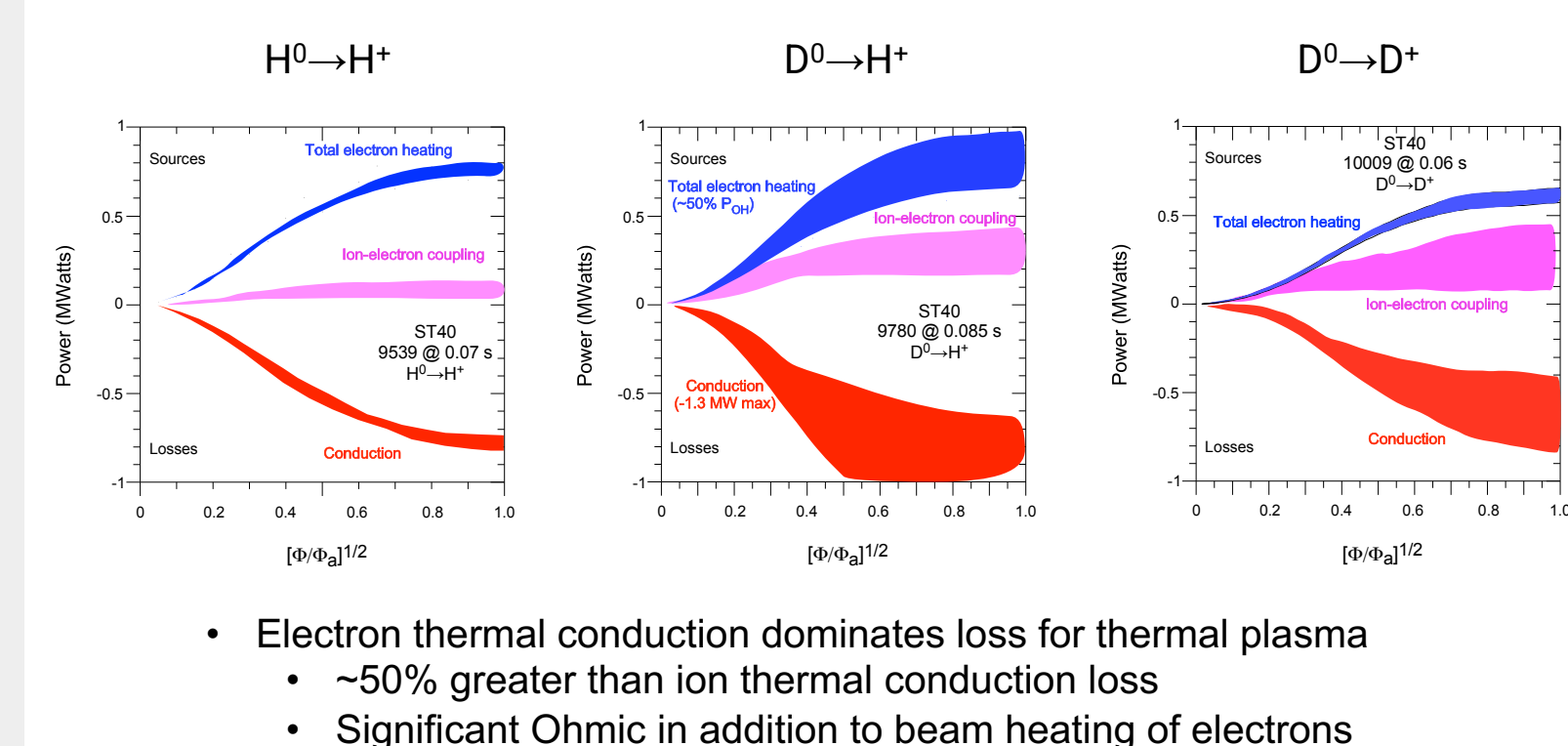


q-profile (and internal equilibrium used for TRANSP runs calculated by EFIT

Rotation profile shape determined from IDA; consistent with experimental constraints

TRANSP results not significantly sensitive to minor variations in Ω_{toroidal}

Electron power balance (volume integrated)



- Electron thermal conduction dominates loss for thermal plasma
- ~50% greater than ion thermal conduction loss
- Significant Ohmic in addition to beam heating of electrons

Summary

- ST40 is a compact Spherical Tokamak whose operating toroidal field is more than twice greater than any other ST
- Experiments have been carried out in ST40 in hot-ion mode plasmas (T_i >> T_e) to obtain measured impurity temperatures in excess of 100M K (8.6 keV)
- High T_i ST40 plasmas have been analyzed using the TRANSP code to determine the hydrogenic temperature and basic transport properties
 - Inferred kinetic profile sets satisfying a number of experimental constraints were used since full profile measurements were not yet available
 - The inferred range of profiles reflects the uncertainty in these profiles as well as the resulting transport properties
- Hydrogenic temperatures are also found to be in excess of 100M C for D-D discharges
 - Lower T_i for lower isotopic mass discharges; higher T_i at higher B_T for same isotopic mass
- Electrons are the primary loss channel through thermal conduction, as reflected in the transport coefficients
- Ion transport in these hot-ion mode plasmas is >> neoclassical transport levels
 - Reduction in core ion transport with increasing isotopic mass at constant B_T, and
 - Reduction in core transport with increasing B_T at same isotopic mass
 - appear to account for higher T_i's for each respective case
- More comprehensive transport analyses will be carried out with full profile measurements during the next period of operation (CY23)