Modeling of deuterium and carbon radiation transport in Super-X and snowflake divertor plasmas in MAST-U tokamak

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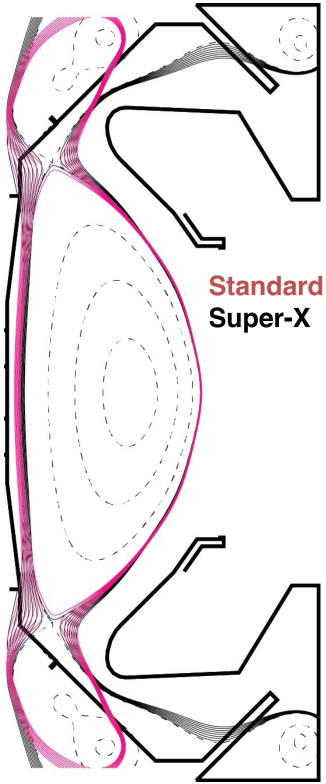
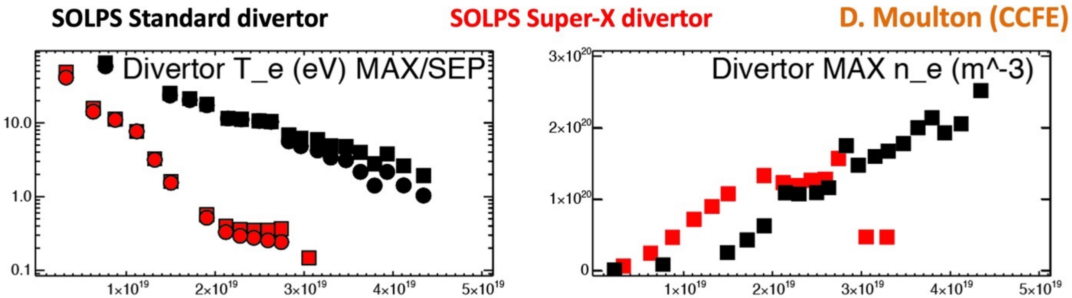
Deuterium Lyman and carbon radiation transport in MAST-U advanced divertor configurations do not significantly affect plasma parameters

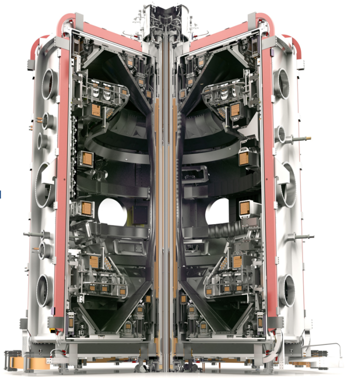
- SOLPS and UEDGE plasma models with CRETIN radiation transport calculations show
  - In near-term Super-X divertor configuration (input power 2.5 MW), Ly-α radiation is modestly trapped in high density (radiative, detached) cases, Ly-β and Ly-γ radiation is not trapped
  - C III and C IV resonant line radiation is not trapped
  - Weak impact of Ly-α trapping on plasma parameters and detachment threshold – Super-X appears to detach at much lower upstream density than standard divertor
  - No impact in snowflake divertor configurations



— At higher power (5MW), stronger Ly-α trapping is observed in SXD and is subject to future work



MAST-U tokamak Program plans significant research in divertor physics area



- MAST-U – medium size mega-ampere class spherical tokamak in Culham Centre for Fusion Energy, Culham, UK
  - First plasma 29 October 2020

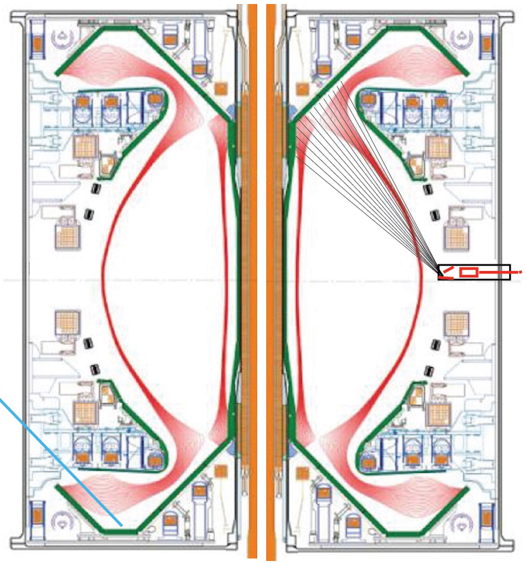
- MAST-U research objectives
  1. Adding to the knowledge base for ITER
  2. Testing alternative divertor concepts
  3. Exploring the case for a future fusion device based on a Spherical Tokamak

- Key elements of LLNL research program on MAST-U
  - Divertor detachment and snowflake divertor physics experiments
  - Two divertor diagnostics (VUV and UV-VIS spectrometers) are being installed
  - LLNL numerical codes used in support of planned experimental research
    - Atomic processes and radiation transport in divertors with CRETIN and UEDGE (this IAEA FEC Poster 746)
    - Multi-fluid transport code UEDGE modeling of snowflake divertor configurations (A. I. Khrabryi, IAEA FEC Poster 771)

Parameter / System	Upgrade
Toroidal Field	Up to 0.75 T (at R = 0.85m)
Plasma Current	Up to 2 MA
Pulse Length	Up to 5 s
In-vessel Coils	20
Ex-vessel PF Coils	4
NBI injection	1 on-axis, 1 off-axis Total power up to 5 MW
RMP coils	Two rows of 4 + 8 in-vessel coils
Divertor	Graphite tiles Standard, Super-X, snowflake and other magnetic configurations

Two LLNL spectrometers (VUV and UV-VIS) are being installed to support divertor research on MAST-U

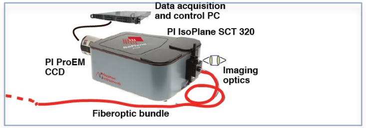
- **SPRED VUV spectrometer for Super-X divertor studies**
  - Carbon ionization balance between and during ELMs
  - Deuterium ionization / recombination balance, rate and T_e from Lyman series
  - Lyman and carbon line opacities
  - Divertor T_e from C II, C III, C IV line ratios
  - Improved divertor P_{rad} analysis
  - Radiative divertor impurity radiation (CD_4, N_2, Ne, Ar)
  - Benchmarking of UEDGE and Cretin models



Divertor SPRED: McPherson Model 251 vacuum ultraviolet spectrograph, 2 gratings, MCP image intensifier, Princeton Instruments ProEM 1600x200 CCD camera

DIBS: Princeton Instruments Isoplane SCT-320 spectrograph, 3 gratings, Acton reflective imaging optics, 26 input UV/Vis fibers, Princeton Instruments ProEM 1600x400 CCD camera

- **Imaging UV spectrometer DIBS for standard and advanced divertor configuration studies (strike points, X-point)**



  - C II, C III, C IV, Balmer line emission profiles
  - Vol. recombination rate and profile from Balmer lines
  - T_e from Balmer series and PR continuum
  - n_e from Balmer line Stark broadening at low T_e
  - Benchmarking of UEDGE and Cretin models

Radiation transport is important in astrophysical and laboratory plasmas

- Radiation transfer equation couples radiation field to material (plasma) properties

$$(\Omega \cdot \nabla) I(r,\Omega,v,t) = -\kappa(\nu)\left(I(r,\Omega,v,t) - \frac{n(r,t)A_{21}}{NB_{12}} \right)$$

- Characteristic form (along *s*) $\frac{dI_\nu}{d\tau_\nu} = -I_\nu + \frac{j_\nu}{\kappa_\nu}$
- Optical depth

$$\tau_\nu = \int_0^L \kappa_\nu \, \rho \, dx$$

- Specific intensity [erg/(s cm^2 rad^2 Hz) $I_\nu = \frac{dE_\nu}{cos\theta \; dA \; d\omega \; dt \; d\nu}$
- Mean intensity $J_\nu = \frac{1}{4\pi} \oint I_\nu d\omega$ Flux $F_\nu = \oint I_\nu cos\theta d\omega$

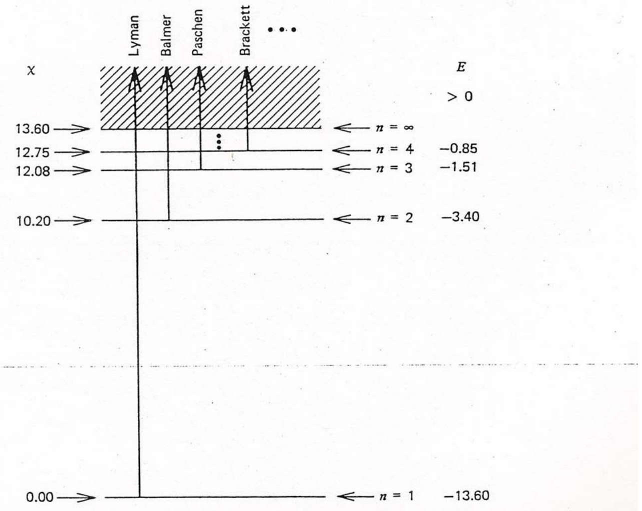


Fig. 8.1. This simplified energy level diagram for hydrogen shows the quantum numbers, n, binding energy, E, and the excitation potential, χ, in electron volts for the first four levels and the continuum.

Figure from D. Gray, The observation and analysis of stellar photospheres

Radiation transport is important in high density tokamak divertors

- Hydrogen Lyman line opacities measured in tokamak divertor experiments
  - Alcator C-Mod, JET (Terry J.L., et al. PoP 5 1759 (1998), Maggi C.F.. et. al. JNM 266 867 (1999))
- The modeling* shows potential importance for high-density tokamak divertors
  - Lyman line radiation absorption in divertor plasmas changes n=2+ level populations
    - Lead to enhanced ionization due to opacity-indiced ionization from n=2+ levels
  - Ionization balance (n_e, n_i, n_d) is modified
  - Lyman series emission and radiated power modified
  - Inner-outer divertor plasma asymmetry modified
  - **Upstream n_e (p_e) threshold for detachment may be modified (increased)**

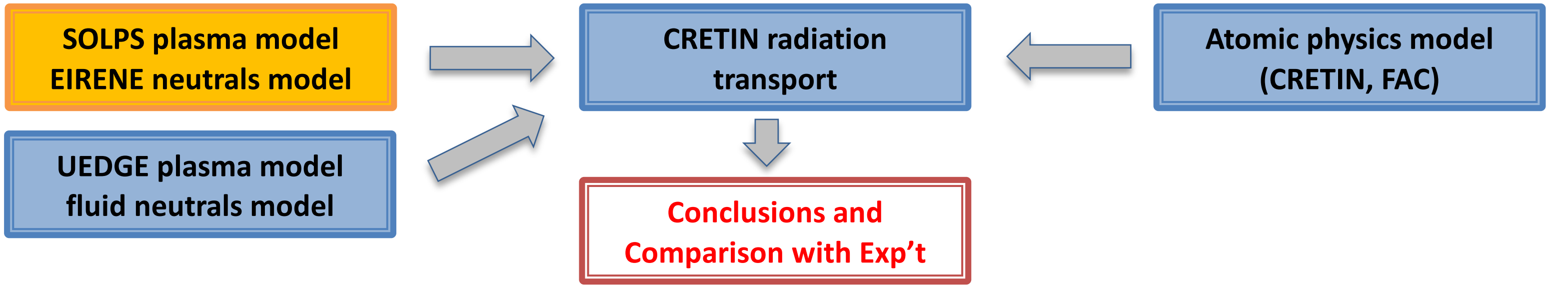
*References:

- Krasheninnikov, S. I. & Pigarov, A. Yu. NF Suppl. 3, 387–394.
- Post D.E. 1995 JNM 220 143
- Reiter D., Wiesen S. and Born M. 2003 JNM 313 845
- Kotov V. et. al 2006 CPP 46 635
- A. Kukushkin et. al. 2005 NF 45, 608–616
- H.A. Scott et al. JNM 266-269 (1999) 1247
- A.S. Wan et al. JNM 220-222 (1995) 1102
- A.A. Pshenov et al. NF 59 (2019) 106025

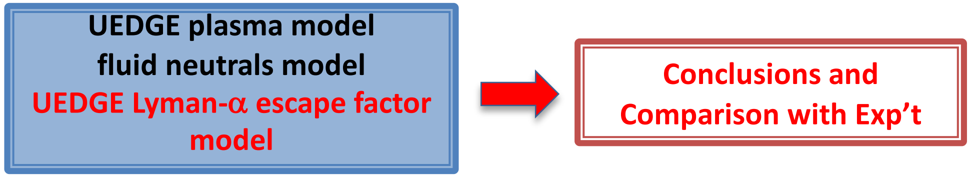
- Modeling shows *lower* upstream n_e (p_e) threshold for highly radiative (detached) regimes in Super-X and snowflake divertor configurations cf. standard divertor
  - Super-X divertor – D. Moulton, EPS 2017
  - Snowflake divertor – A. Khrabryi, IAEA FEC Poster 771
  - Can radiation transport potentially change the modeling conclusions for advance divertors?

This modeling effort aims at understanding the role of radiation transport in advanced divertor performance in MAST-U

- Method 1: Plasma from SOLPS-EIRENE and UEDGE, CRETIN radiation transport



- Method 2: Plasma from UEDGE, UEDGE Ly_{α} escape factor model

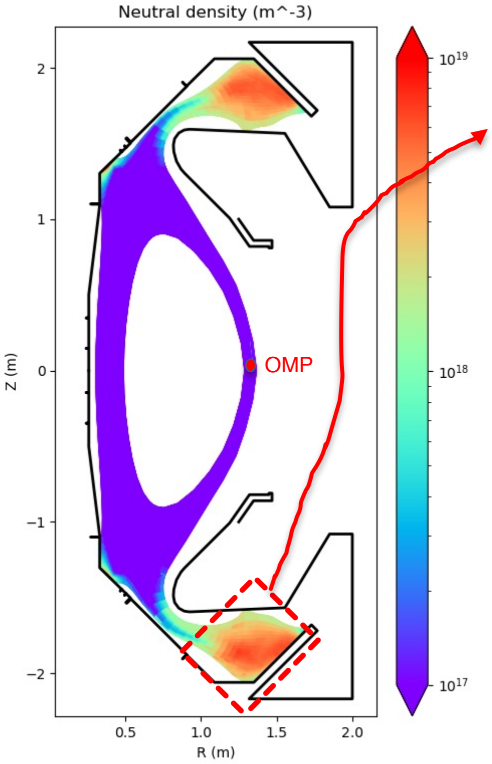


Super-X divertor plasma model from SOLPS is used as input to radiation transport and collisional-radiative code CRETIN

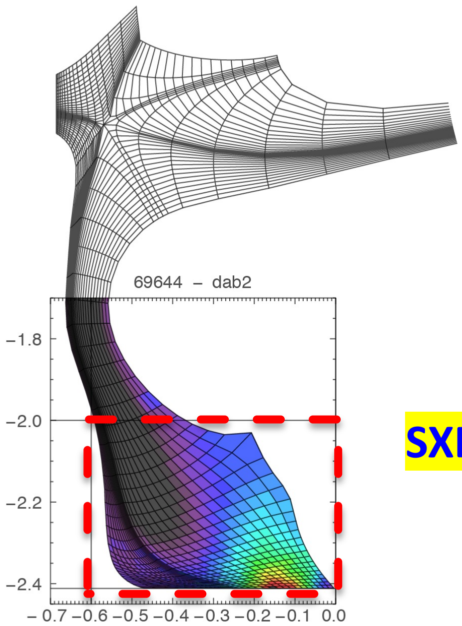
- SOLPS-ITER v5.0 : Braginskii multi-fluid plasma transport model
- EIRENE: Monte-Carlo neutral transport model for D atoms and D_2 molecules
- Super-X divertor, conventional divertor configurations
  - Super-X divertor: P. Valanju, PoP 16 (2009) 056110
- Case SXD1H from **D. Moulton, EPS 2017**
  - Grid 148 x 38
  - H-mode kinetic profiles (SXD1_PEX_nbiP1_pumpP1_Hmode)
  - 2.5 MW input power (50% electrons, 50% ions)
  - Transport coefficients $D_{e,i}$, $\chi_{e,i}$ with radial variation
  - Full carbon impurity model (7 fluids C^{0+}-C^{6+})
  - R=1.0 on divertor plates and wall
  - AMJUEL H.4.2.1.5 hydrogen ion. and recombination rates
  - Density scans n_e^{core}= (1-8) x 10^{19} m^{-3}, n_e^{sep}= (0.2-3.5) x 10^{19} m^{-3}

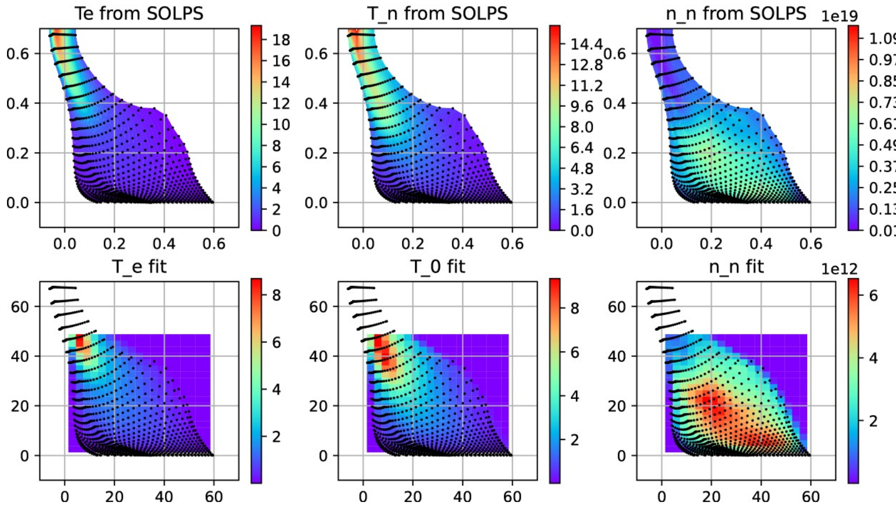
- CRETIN (H.A. Scott, JQSRT 71 (2001) 689
  - Implicit NLTE population solver
    - The populations respond to the radiation through the effects on transition rates
  - Separate treatments of continuum, line and spectral radiation fields
    - Absorption and emission coefficients for bb, bf, and ff transitions
  - Line shape calculations include Doppler broadening, Stark effect, and Zeeman splitting
  - The calculations are self-consistent w.r.t. the line radiation, ionization balance and excited populations
  - Discrete ordinates method (short characteristics)
  - The continuum radiation is treated with formal transfer
  - Angular scattering off electrons is included (isotropic approximation in 2D)
  - The line transfer enforces consistency between populations and line strengths through a complete linearization procedure
  - Complete frequency redistribution
- Internal “hydrogenic” deuterium atom model in CRETIN
  - Z=1, A= 2.0141
  - Two iso-sequences (neutral, ion)
  - 15+1 levels, 120 LS sublevels (L<14)
  - 1224 photoexcitation transitions
  - 15 photoionization transitions
  - 105 collisional excitation transitions (Johnson)
  - 15 collisional ionization transitions (Johnson)

Data from Super-X divertor SOLPS model is interpolated for CRETIN radiation transport calculations



- Coordinate system rotated 45°

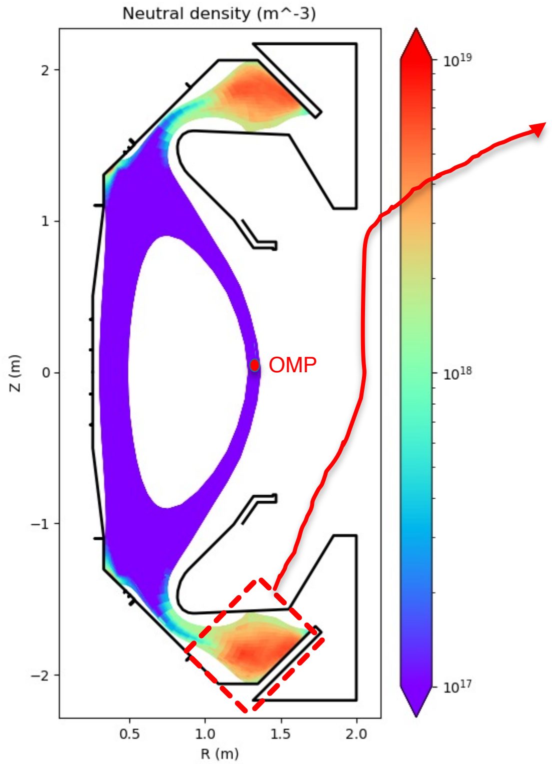


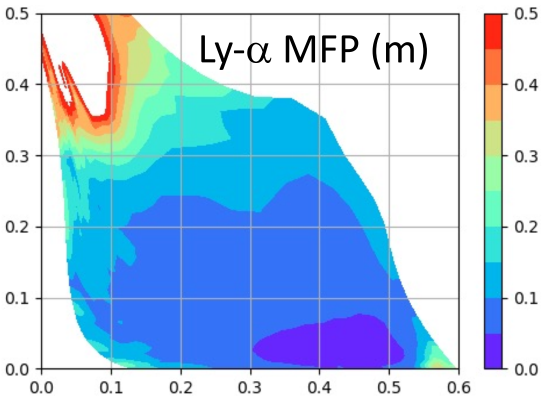


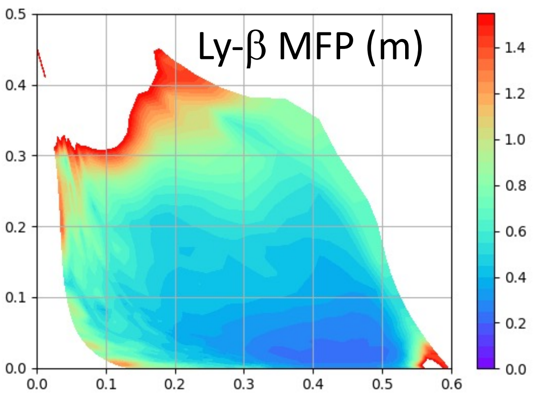
SXD1H

- 2D distributions T_e, T_d, n_d, B_{tor} from SOLPS
- 2D mesh 20x20 for CRETIN

Super-X divertor SOLPS model shows that Lyman opacity is expected at high neutral density in radiative (detached) regime







- Opacity $\tau = L_{div} / mfp \sim L\, n_a$

SXD1H

- Photon mean free path (e.g., Lyman series)
  - MFP = $(5.4\text{x}10^{-9}\, \lambda\, f_{ij}(\mu/T_0)^{1/2} n_a)^{-1}$ (cm) = $1.3\text{x}10^{13}\, T^{1/2} n_a^{-1} f_{1j}^{-1}$ (cm)
  - Oscillator strengths : $f_{12} = 0.4162$, $f_{13} = 0.079$, $f_{14} = 0.029$

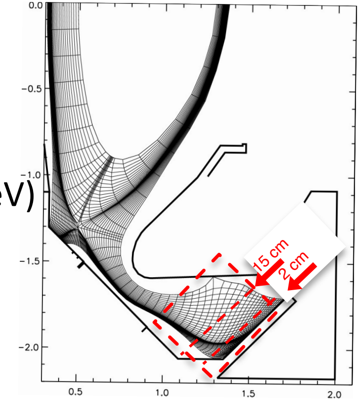
CRETIN optical depths show modest Ly-α trapping when divertor approaches radiative (detached) regime

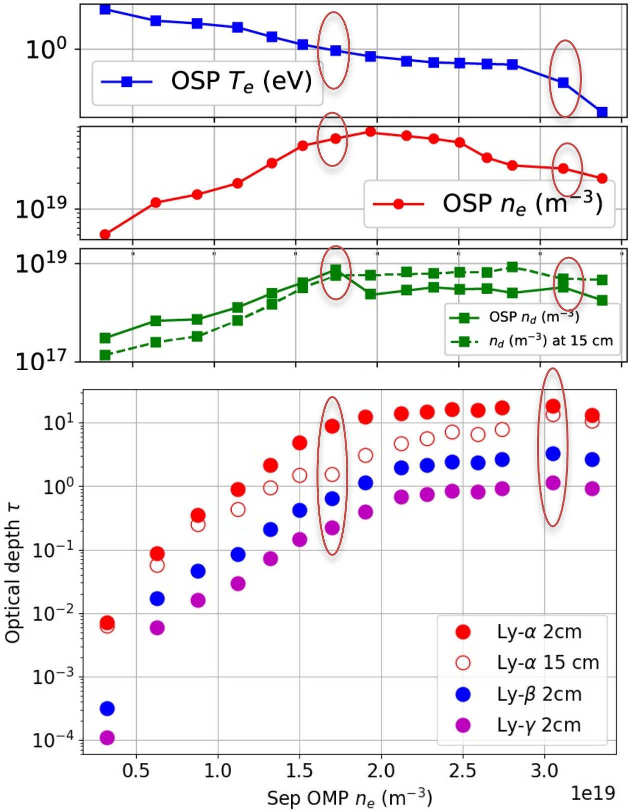
- As OMP density increased, divertor approaches radiative (detached) regime (SOLPS)
- CRETIN optical depths for Ly-α, Ly-β, and Ly-γ increase
- CRETIN optical depths
  - *h*=2 cm – just above divertor target
  - *h*=15 cm – through divertor leg as VUV spectrometer line of sight

SXD1H

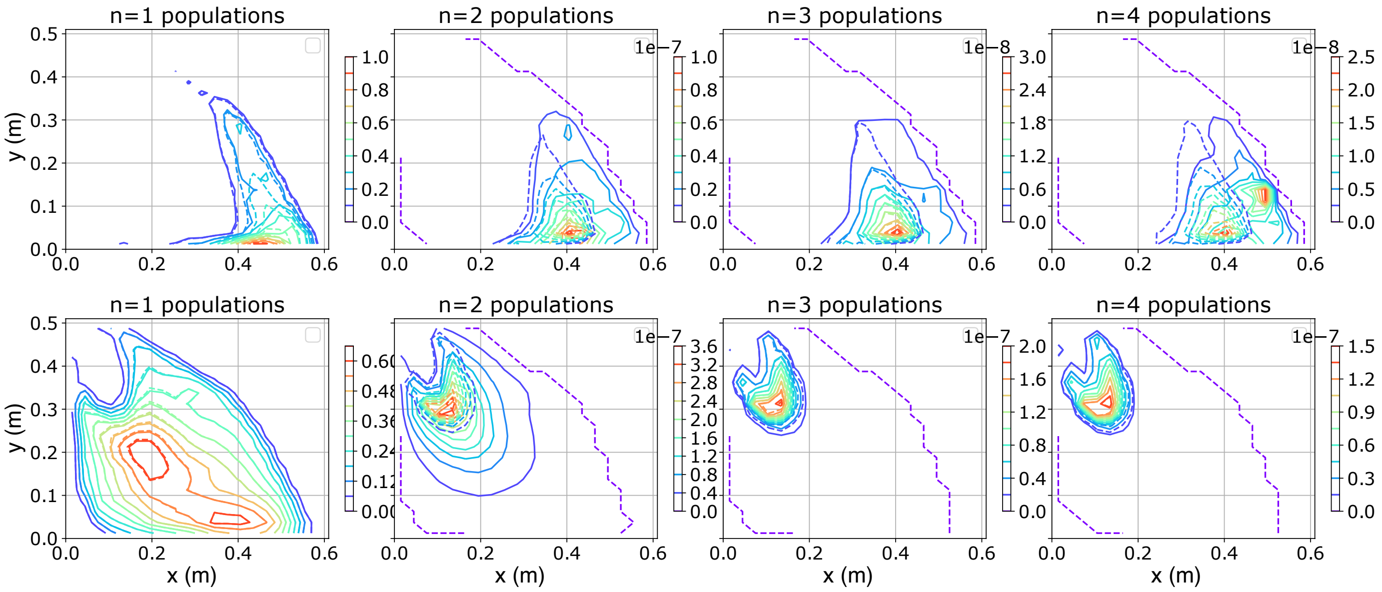
$$\tau_\nu = \int_0^L \kappa_\nu \, \rho \, dx$$

- Circled points represent high Lyman opacity cases for Super-X divertor
  - Point 1 – outer SP transition to detachment (T_e ~1 eV)
  - Point 2 – outer SP detachment (T_e ~1 eV)
- These conditions will be analyzed in detail





Lyman series radiation transport weakly affects hydrogen *n=2-4* level populations

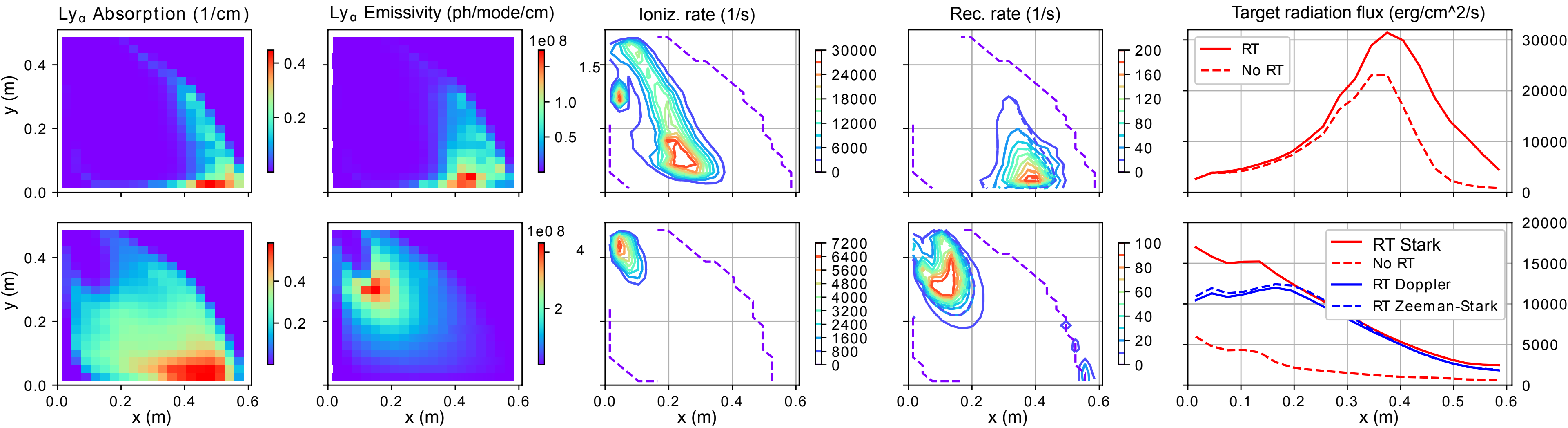


Top row: transition to detachment, $n_{e,\ OMP\ sep}$=1.7 x 10^{19} m^{-3}
Bottom row: detachment, $n_{e,\ OMP\ sep}$=3 x 10^{19} m^{-3}

- Comparing D atom population distributions (in units of 10^{19} m^{-3}) with (__) and without (---) radiation transport
- Populations of *n=1* weakly affected
- Population of *n=2,3,4* broader distributed due to radiation transport

SXD1H

Deuterium ionization and ion recombination rate changes due to radiation transport appear to be small

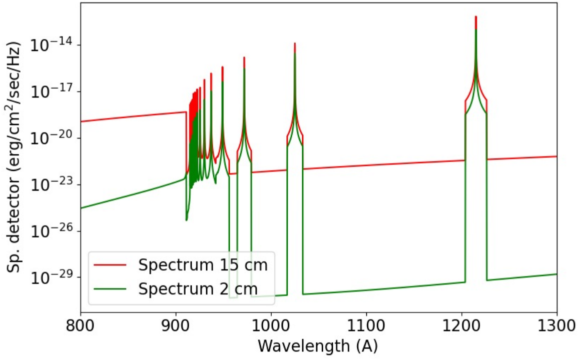


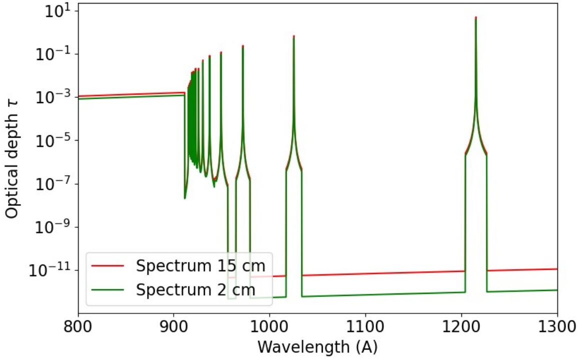
- Radiation transport included (__) and without (---) radiation transport
- Top row: transition to detachment, $n_{e,\ OMP\ sep}$=1.7 x 10^{19} m^{-3} , Bottom row: detachment, $n_{e,\ OMP\ sep}$=3 x 10^{19} m^{-3}

SXD1H

Divertor radiation transport is mostly due to Lyman line transfer whereas continuum radiation transport is negligible

- Strong Lyman series emission at divertor plasma parameters esp. hign-n at low T_e
- Absorption due to Lyman-α line (optical depths 10^{-3}-20)
- Emission and absorption due to free-free and bound-free transitions negligible





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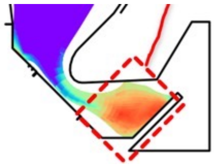
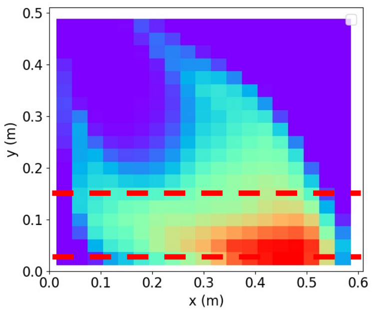
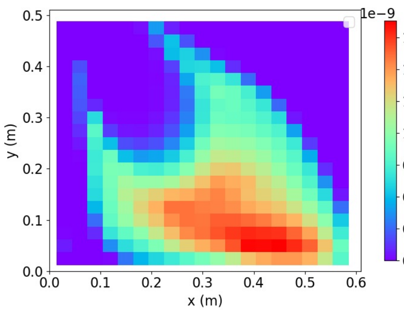


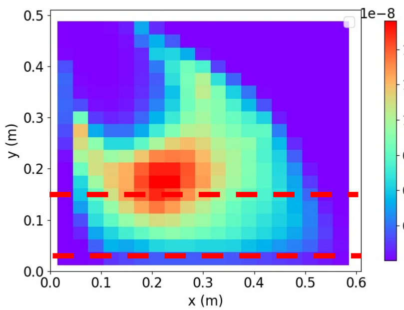
Ly-α (center) abs. coeff.



Continuum abs. coeff.

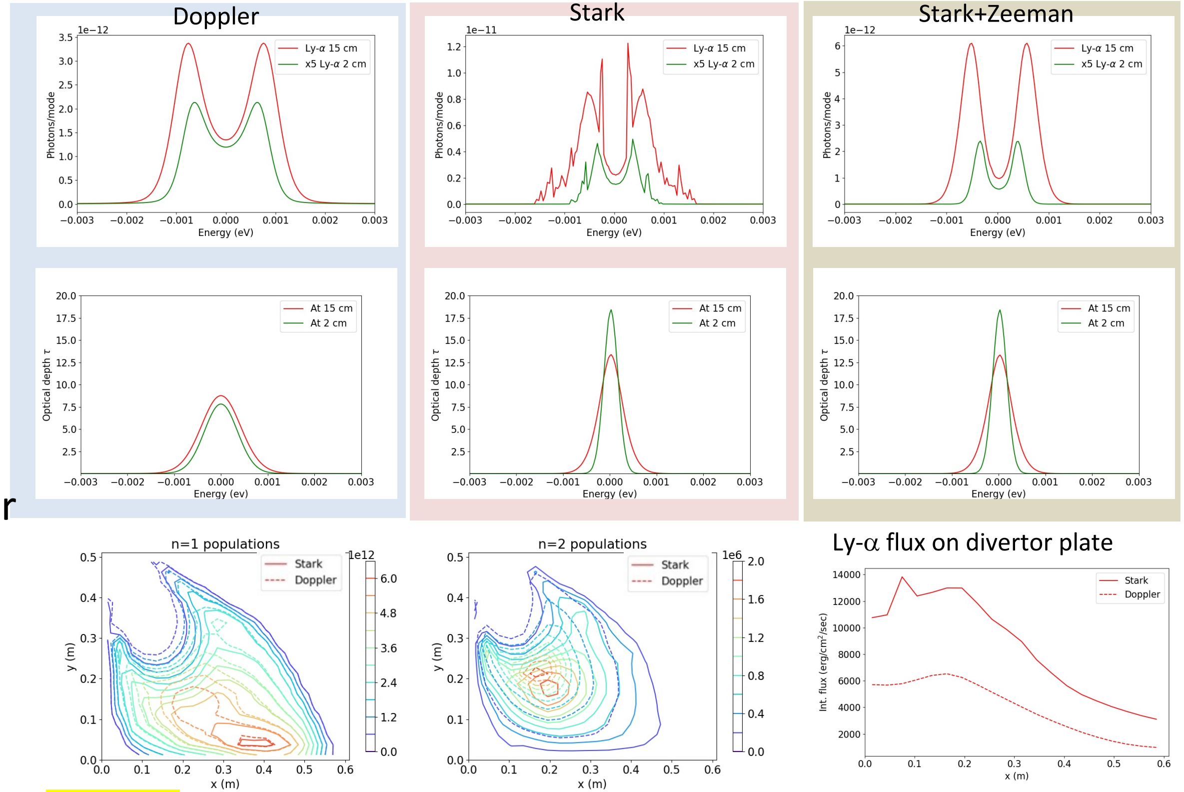


Ly-α emission coeff.



Choice of line shape model in CRETIN affects radiation transport calculations

- All transfer calculations used line Stark broadening (TOTAL code)
  - Complete redistribution
- Tested calculations with Doppler, Stark broadenings and Zeeman splitting
  - Super-X toroidal field 0.3-0.4 T
  - Doppler width 10-80 x 10^{-5} eV
  - Stark width 85 x 10^{-5} eV
  - Zeeman splitting 4-7 x 10^{-5} eV
- Optical depths within ~2 for Doppler and Stark line models
- Populations and divertor fluxes also within x2
- Ly-α line dip due to self-absorption

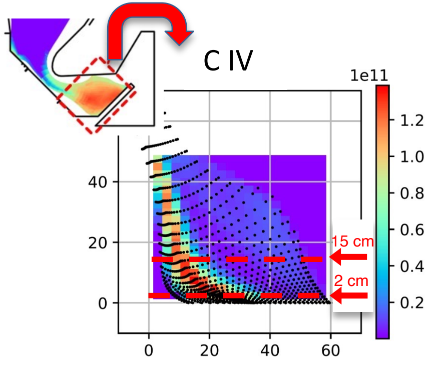


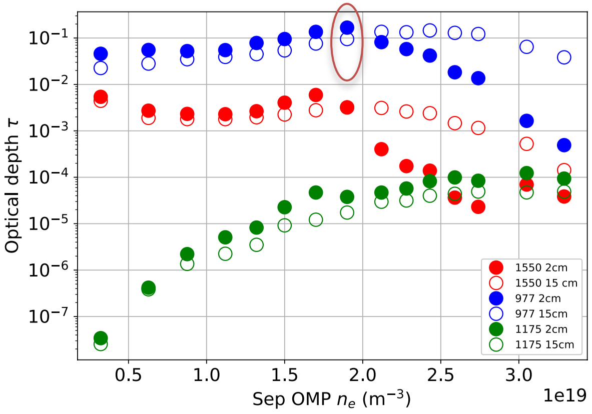
SXD1H

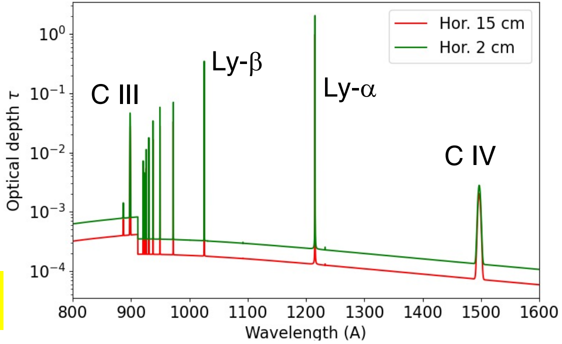
CRETIN carbon opacities are small - carbon line radiation (hence radiated power) weakly affected

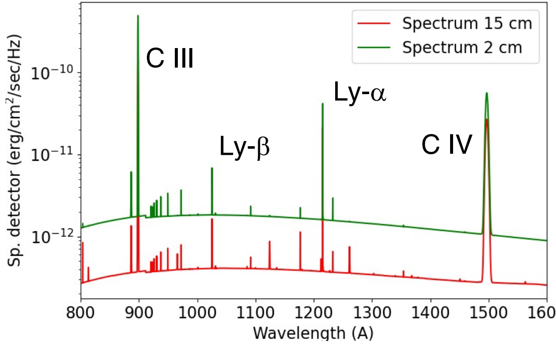
- Opacity of carbon lines considered for DIII-D divertor
  - R. Isler, Phys. Plasmas 4, 355 (1997)
- Plasma and carbon density distributions taken from SOLPS (D. Moulton, EPS 2017)
- Carbon atomic structure and rates from FAC
  - 7 iso-sequences, up to *n*=25 each, 2057 levels
- In divertor with graphite PFCs, most radiated power is due to 3 carbon lines
  - C III: $2s^2$-2s2p, λ=977 A (FAC: 898 A, f= 0.7837)
  - C III: 2s2p-$2p^2$, λ=1175 A (FAC: 1268 A, f= 0.3074)
  - C IV: 2s-2p, λ=1550 A (FAC: 1497 A, f= 0.2877)
- The carbon line opacities are small
  - Carbon opacities show different dynamics in the divertor than Lyman opacities
  - Carbon line optical depths are order(s) of magnitude lower than Ly-α

SXD1H



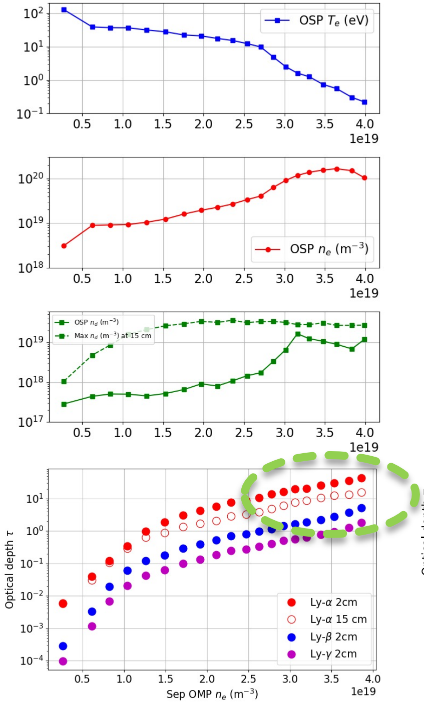




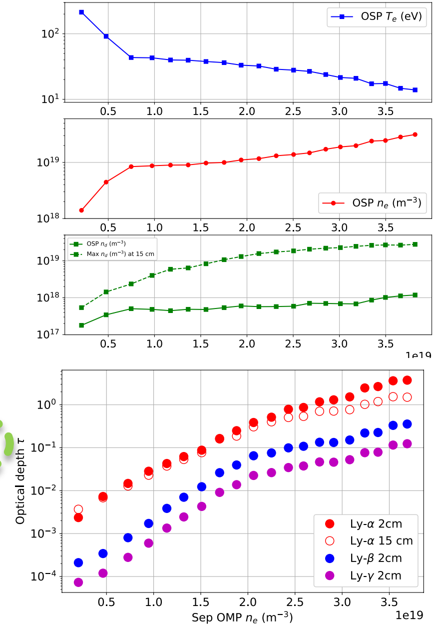


When MAST-U is upgraded to higher NBI power (5 MW), higher deuterium opacities are predicted in H-mode SXD without cryo-pumping, and optically thin plasmas with cryo-pumping enabled

- SOLPS-EIRENE case **SXD15H** from **D. Moulton, EPS 2017**
  - H-mode kinetic profiles (SXD1_PEX nbiP2_pumpP1_Hmode)
  - 5 MW input power (50% electrons, 50% ions), NO cryopumping
  - Density scans n_e^{core}= (1-20) x 10^{19} m^{-3}, n_e^{sep}= (0.2-3.7) x 10^{19} m^{-3}
- SOLPS-EIRENE case **SXD2H** from **D. Moulton, EPS 2017**
  - H-mode kinetic profiles (SXD1_PEX nbiP2_pumpP2_Hmode)
  - 5 MW input power (50% electrons, 50% ions), cryopumping
  - Density scans n_e^{core}= (1-20) x 10^{19} m^{-3}, n_e^{sep}= (0.2-3.7) x 10^{19} m^{-3}
- SXD leg conditions approach highly radiative detached regime (~ 1 eV) in SXD15H, but not in SXD2H
- In comparison with SXD1H (lower NBI power and no cryopumping)
  - In SXD15H, deuterium atomic densities at target and in the leg are higher, in SXD2H lower
  - In SXD15H, CRETIN optical depths for Ly-α, Ly-β, and Ly-γ are higher – subject of future work
  - In SXD2H, CRETIN optical depths for Ly-α, Ly-β, and Ly-γ are lower and the case is not interesting from radiation transport perspective
- Deuterium radiation trapping is stronger, the plasma is optically thick to Lyman radiation in SXD15H



SXD15H



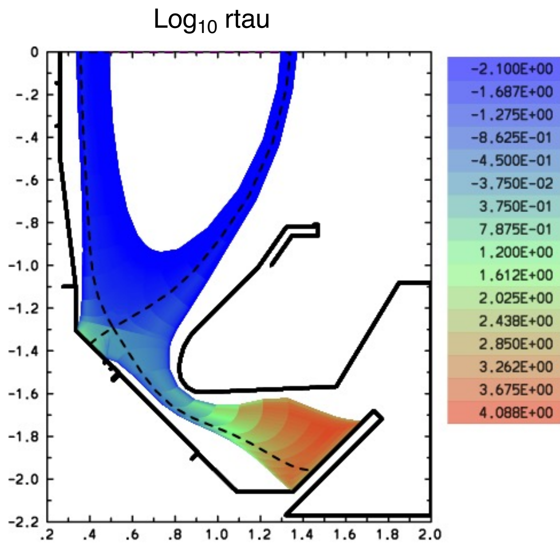
SXD2H

UEDGE model of Super-X divertor with Ly-α trapping enables direct evaluation of radiation transport effects on divertor radiative and detached regimes

- UEDGE – 2D multifluid Braginskii transport code
  - Escape-factor model for Ly-α radiation transport
  - Based on normalized Ly-α optical depth
  - Local corrections to ionization and recombination rates based on CRETIN tables (H. A. Scott and M. L. Adams, CPP 44, 51 (2004))

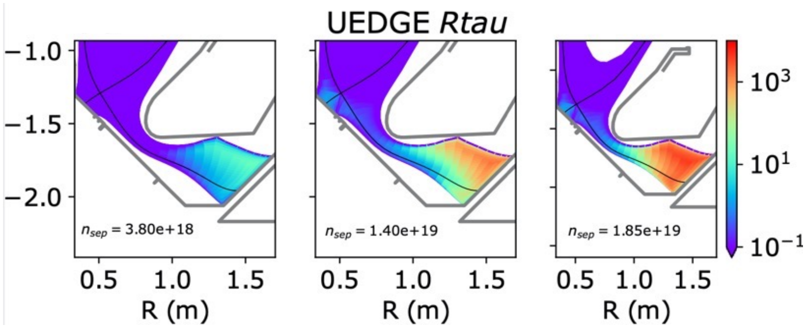
$$rtau(R,Z) = C \int_{(R,Z)}^{Bdry} n_g dr$$

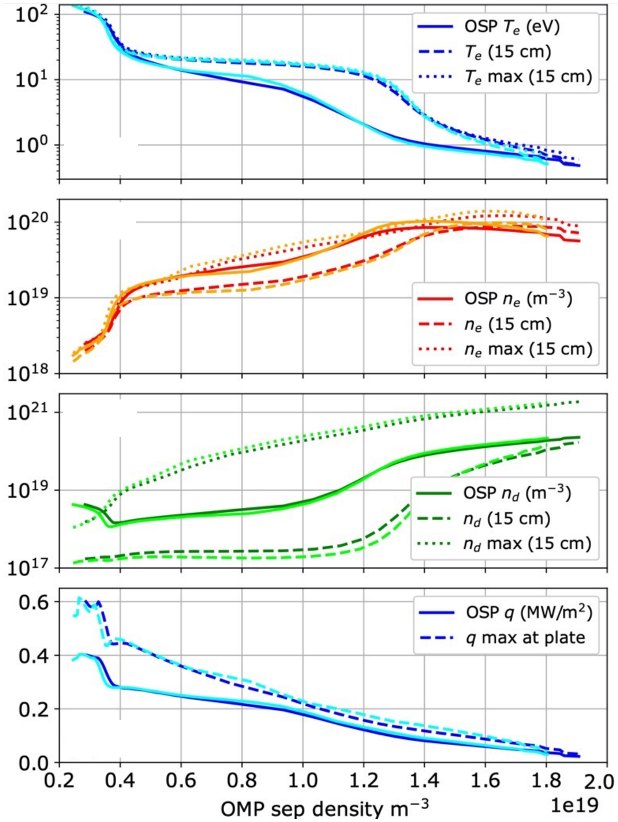
- UEDGE model of Super-X divertor with Ly-α escape factor treatment
  - Input power 2.5 MW
  - SOLPS-like transport coefficients
  - Recycling R=1, wall albedo a=0.
  - Fluid deuterium neutrals, all carbon charge states
  - Density scan from n_e^{core} = 2x10^{19} m^{-3} to 10^{20} m^{-3}



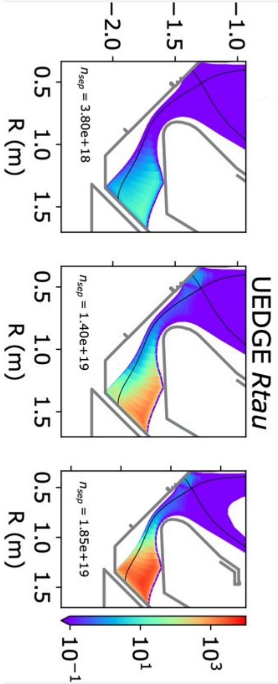
UEDGE with Ly$_\alpha$ trapping shows little impact on plasma parameters due to radiation transport

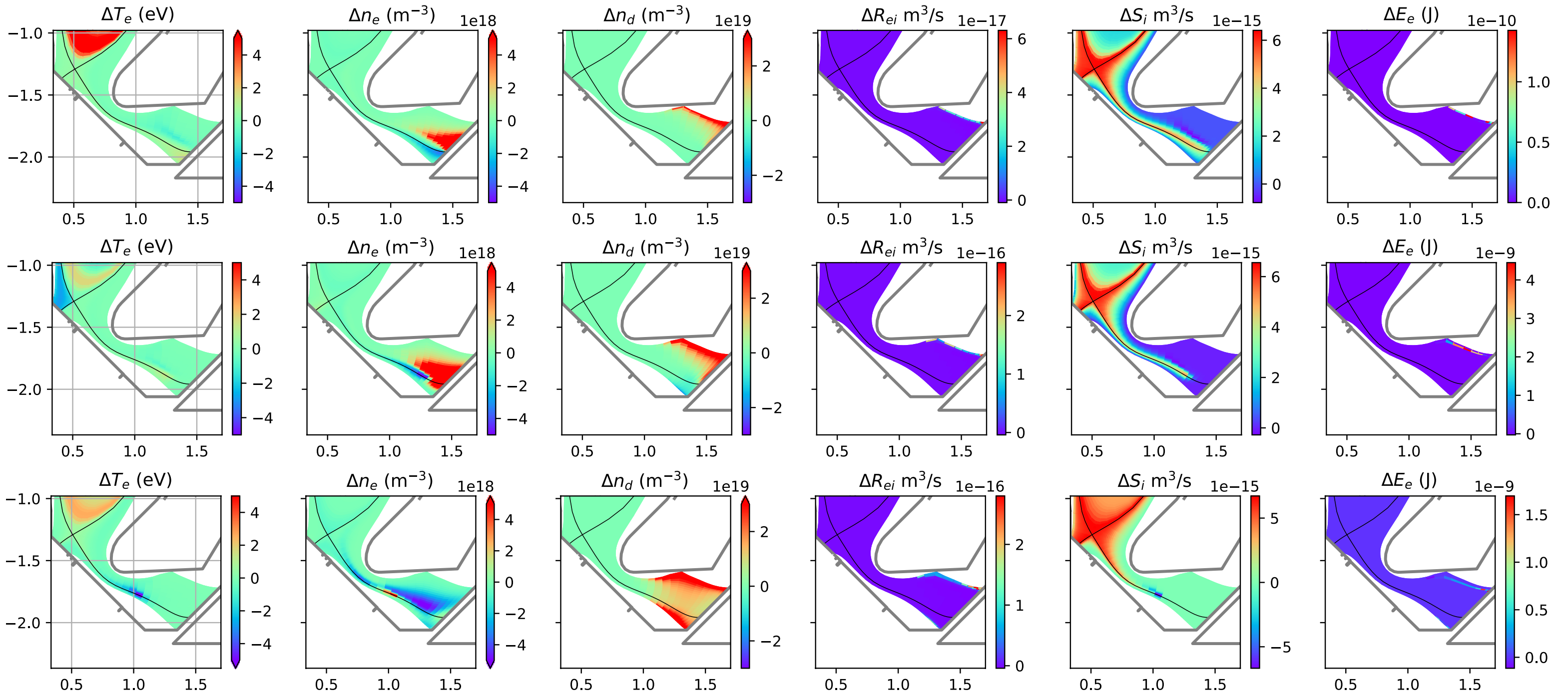
- Shown outer divertor T_e, n_e, n_d and target heat flux at SP and 15 cm above target
- Little impact on radiated power and ion momentum
- Transition to outer SP detachment and detachment are not affected
- Ly$_\alpha$ optical depths show significant change as divertor transitions from attached to detached outer SP





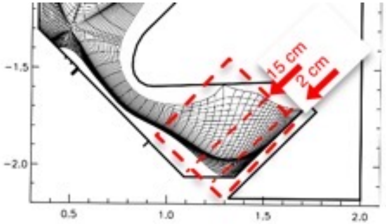
Insignificant changes in outer SXD conditions and ionization-recombination rates as outer SP detaches

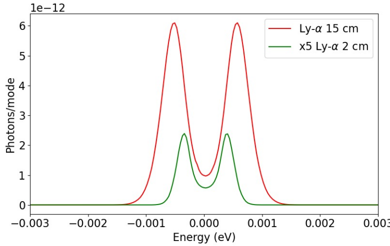


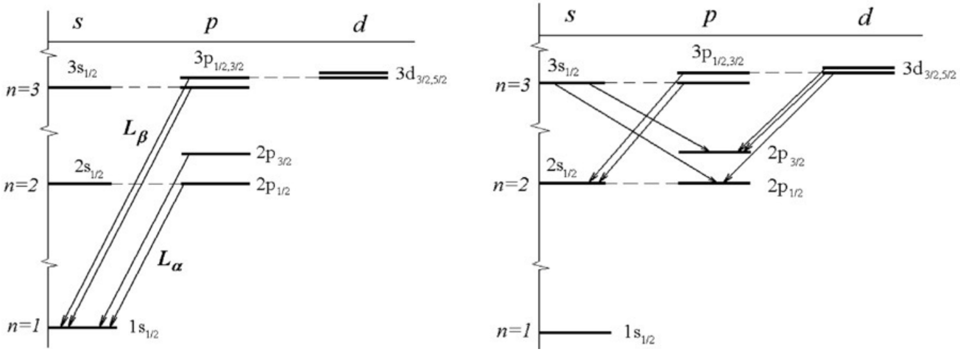


Predicted (modest) Ly_α opacity may be possible to diagnose in experiment

- Possible direct measurements (e.g., D. Reiter JNM 313 845 (2003))
  - modifications of line ratios of the Balmer series w.r.t CRM
  - modification of line ratios Ly-β over Balmer-α with common upper level
  - Modifications of doublet components with different oscillator strengths (trapped differently)
  - modification of line shapes of individual lines

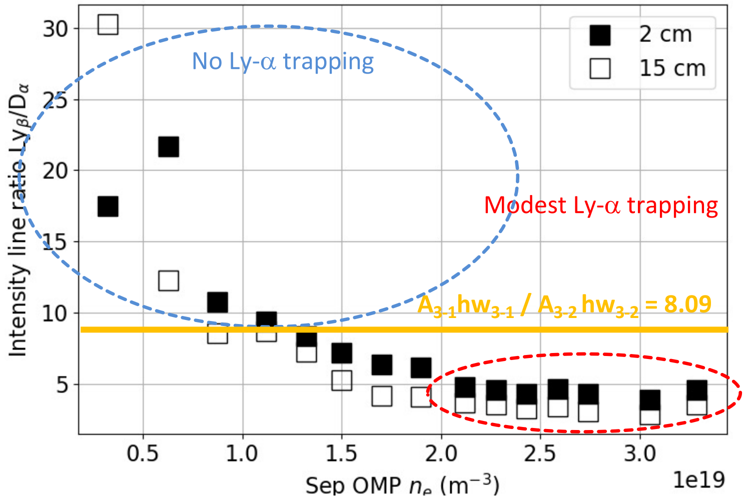






Lyman-α and -β

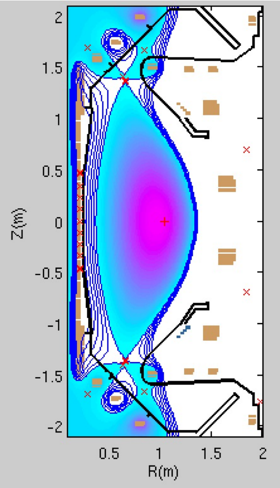
Balmer-α n=3->2



Snowflake divertor experiments are planned in MAST-U

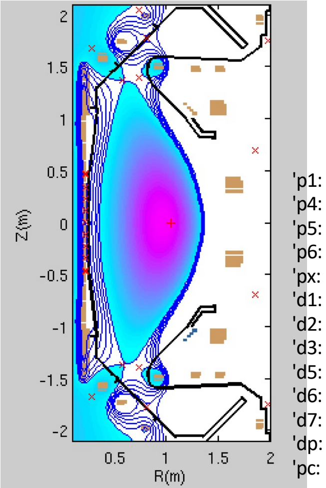
- FIESTA code used to develop snowflake divertor configurations
  - FIESTA free-boundary Grad-Shafranov equilibrium solver
  - The initially developed MAST-U snowflakes used different assumptions and coils
  - Here, same three-coil algorithm as in NSTX and DIII-D experiments

Exact snowflake



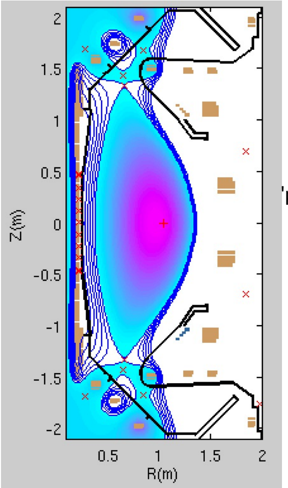
'p1: -15000.00'
'p4: -11151.88'
'p5: -6451.88'
'p6: -0.00'
'px: 3500.00'
'd1: 3400.00'
'd2: -6000.00'
'd3: 5100.00'
'd5: -1650.00'
'd6: -480.00'
'd7: 1005.00'
'dp: 2800.00'
'pc: 12000.00'

Snowflake-minus



'p1: -15000.00'
'p4: -11151.88'
'p5: -6451.88'
'p6: -0.00’
'px: 3000.00'
'd1: 3600.00'
'd2: -5300.00'
'd3: 1000.00'
'd5: -1650.00'
'd6: -480.00'
'd7: 1005.00’
'dp: 3400.00’
'pc: 12000.00'

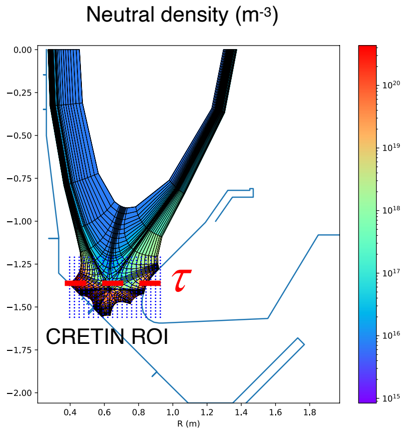
Snowflake-plus

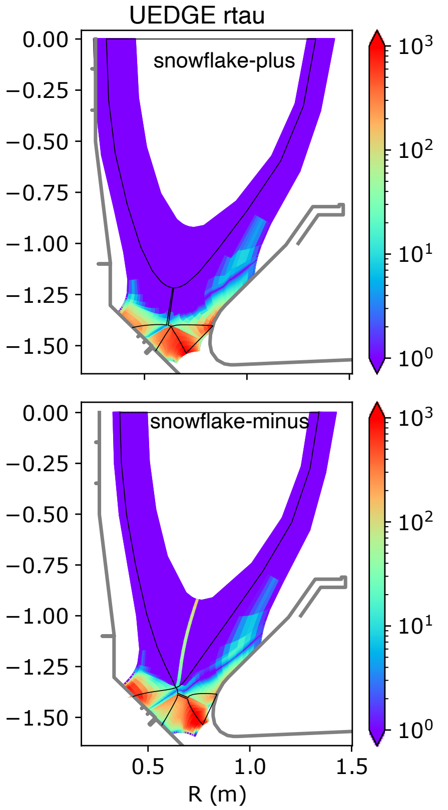


'p1: -15000.00'
'p4: -11151.88'
'p5: -6451.88'
'p6: -0.00'
'px: 3500.00'
'd1: 3500.00'
'd2: -5700.00'
'd3: 4700.00'
'd5: -1650.00'
'd6: -480.00'
'd7: 1005.00'
'dp: 2900.00'
'pc: 12000.00'

Snowflake divertor configurations in MAST-U show small Ly_{α} optical depths suggesting SF divertor plasma are optically thin

- Snowflake (SF) divertor configuration
  - — D. D. Ryutov, PoP 14, 064502 (2007)
- Geometry, transport and detachment in SF divertors in MAST-U – A. I. Khrabryi, Poster IAEA FEC 771
- Neutral density highest in SF-plus and SF-minus with smallest inter-null distance and lowest transport (D=0) due to SF plasma mixing

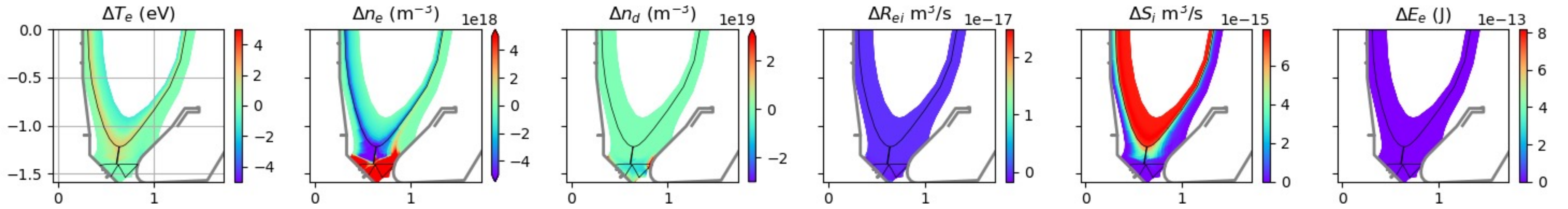




- SF divertor models with Ly-α trapping show little impact of radiation transport on plasma
  - — With detached strike points, the plasma, neutral and radiation fields highly non-uniform
  - — Ly_{α} photon MFP several cm in strike point regions
  - — CRETIN model shows weak Ly_{α} line center trapping
    - Optical depth between divertor throat sides (targets) $\tau \leq 2$
  - — Opacity shows mostly in the additional SF divertor legs

$$rtau(R,Z) = C \int_{(R,Z)}^{Bdry} n_g dr$$

Snowflake divertor configurations in MAST-U are not impacted by Lyman radiation transport



- SF divertor models with Ly_{α} trapping show little impact of radiation transport on plasma
  - UEDGE model with Ly_{α} escape factor shows small local SP changes, little impact on plasma
  - Shown is SF-plus divertor with d_{xx}=2.5 cm, at n_{sep}=5.83 x 10^{19} m^{-3} and strongest SF divertor mixing (D=490)
  - Insignificant differences between the cases with and without Ly_{α} trapping in electron temperature, density, neutral density, ionization and recombination rates, and electron energy losses per ionization