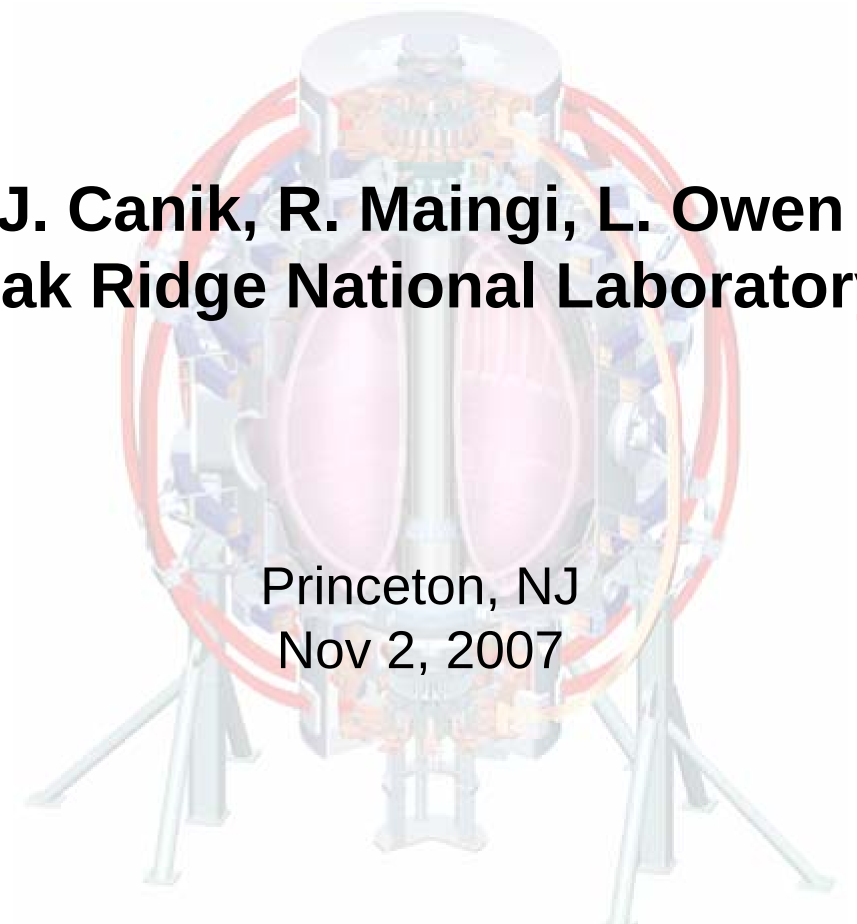
2-D Divertor Design Calculations for the NHTX



J. Canik, R. Maingi, L. Owen
Oak Ridge National Laboratory

Princeton, NJ
Nov 2, 2007

Progress in predictions of divertor plasma characteristics in NHTX

- Introduction to NHTX
- Code description
- Detailed calculations for single configuration
  - Power scan from 10-50 MW at neped ~ 1.5e20
  - Density scan from 7.5e19 - 3e20 at Pheat=30 MW
  - Recycling scan from 0.9-0.99
  - Impurity radiation scans for carbon, neon, argon
- Calculations for three other configurations
- Discussion and conclusions

The development of advanced fusion reactors will require the integration of key areas of fusion science

- Four key requirements are well known:
  1. High thermal confinement, well confined α's
  2. High plasma beta
  3. Steady state operation
  4. **Solution for *reactor-level* high-heat-flux plasma-boundary interface**

- The integration of advanced-reactor-level high-heat-flux handling with high confinement, high β, and steady-state operation has not been demonstrated
  - and apparently will not be demonstrated by planned long-pulse devices

- **NHTX mission:**

  "To study the integration of high-confinement, high-beta, long-pulse non-inductive plasma operation with a fusion-relevant high-power plasma-boundary interface."

NHTX can lead the field in the integration necessary for successful CTF/FDF & Demo

	R (m)	a (m)	P (MW)	P/R (MW/m)	P/S (MW/m^2)	Pulse (s)	I_p (MA)	Species	Comments
JT-60SA	3.01	1.14	41	14	0.21	100	3.0	D	JA-EU Collaboration
KSTAR	1.80	0.50	29	16	0.52	300	2.0	H (D)	Upgrade Capability
LHD	3.90	0.60	10	3	0.11	10,000	–	H	Upgrade capability
SST-1	1.10	0.20	3	3	0.23	1000	0.2	H (D)	Initial heating
W7-X	5.50	0.53	10	2	0.09	1800	–	H	30MW for 10sec
NHTX	**1.00**	**0.55**	**50**	**50***	**1.13**	**1000**	**3.5**	**D (DT)**	**Initial heating**
ITER	6.20	2.00	150	24	0.21	400-3000	15.0	DT	Not for divertor testing
Component Test Facility Designs									
CTF (A=1.5)	1.20	0.80	58	48	0.64	weeks	12.3	DT	2 MW/m^2 neutron flux
FDF (A=3.5)	2.49	0.71	108	43	1.61	weeks	7.0	DT	2 MW/m^2 neutron flux
Demonstration Power Plant Designs									
ARIES-RS	5.52	1.38	514	93	1.23	months	11.3	DT	US Advanced Tokamak
ARIES-AT	5.20	1.30	387	74	0.85	months	12.8	DT	US Advanced Technology
ARIES-ST	3.20	2.00	624	195	0.99	months	29.0	DT	US Spherical Torus
ARIES-CS	7.75	1.70	471	61	0.91	months	3.2	DT	US Compact Stellarator
ITER-like	6.20	2.00	600	97	0.84	months	15.0	DT	ITER @ higher power, Q
EU A	9.55	3.18	1246	130	0.74	months	30.0	DT	EU "modest extrapolation"
EU B	8.60	2.87	990	115	0.73	months	28.0	DT	EU
EU C	7.50	2.50	794	106	0.71	months	20.1	DT	EU
EU D	6.10	2.03	577	95	0.78	months	14.1	DT	EU Advanced
SlimCS	5.50	2.12	650	118	0.90	months	16.7	DT	JA
CREST	7.30	2.15	692	95	0.73	months	12.0	DT	JA

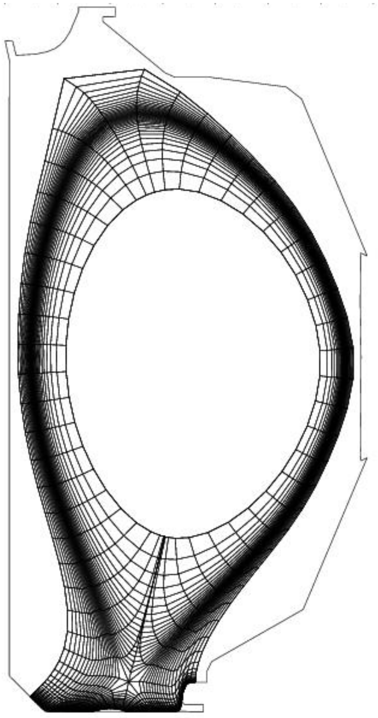
* Flux compression, low R_X/R, SND, additional power allow higher heat flux.

NHTX Heating and Current Drive

- Neutral beams: 32 MW, 120 kV D_0 NBI, steerable off axis
- 18 MW RF – type to be determined
- Results from NSTX, C-MOD, DIII-D will be critical to selection of RF system(s)
  - EBWCD: High efficiency, remote coupling.
  - Inside-launch 120 GHz 2nd harmonic ECCD: lower efficiency, more complex access.
  - LHCD: High efficiency, intimate coupling.
- 2MA bootstrap current at operating point
- For confidence in 3.5 MA steady-state operation, desirable to be able to drive ~ 1.5 MA with beams + RF (R_0 = 1m)

SOLPS is used to calculate SOL plasma properties

- SOLPS: Scrape Off Layer Plasma Simulation
  - 2D plasma fluid code (B2.5)
    - Plasma transport through SOL to targets
  - Monte Carlo neutrals code (Eirene)
    - Takes wall fluxes, returns neutral sources to B2
  - Two are coupled via
    - Atomic processes (ionization, recombination)
    - Plasma-wall process (recycling, sputtering)



- Used to model the edge of tokamak plasmas
  - Core parameters are an input to the code
  - Here we're interested in n, T, heat/particle fluxes at targets

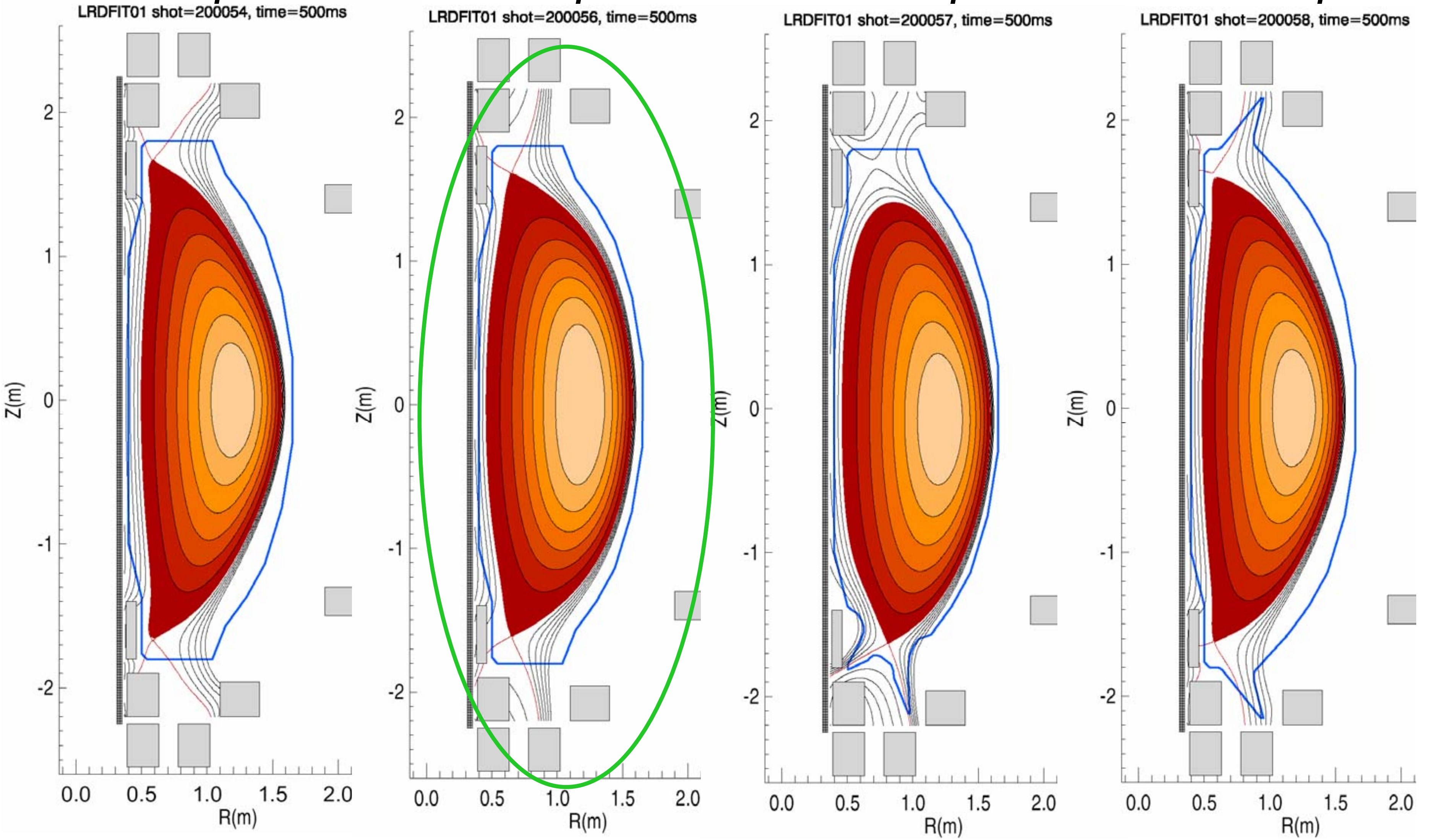
Assumptions used in NHTX modeling

- Pure deuterium plasmas
  - Transport of impurities not included
  - Radiation added using constant impurity concentration
- Transport
  - Classical in parallel direction
  - Anomalous transport coefficients perpendicular to B

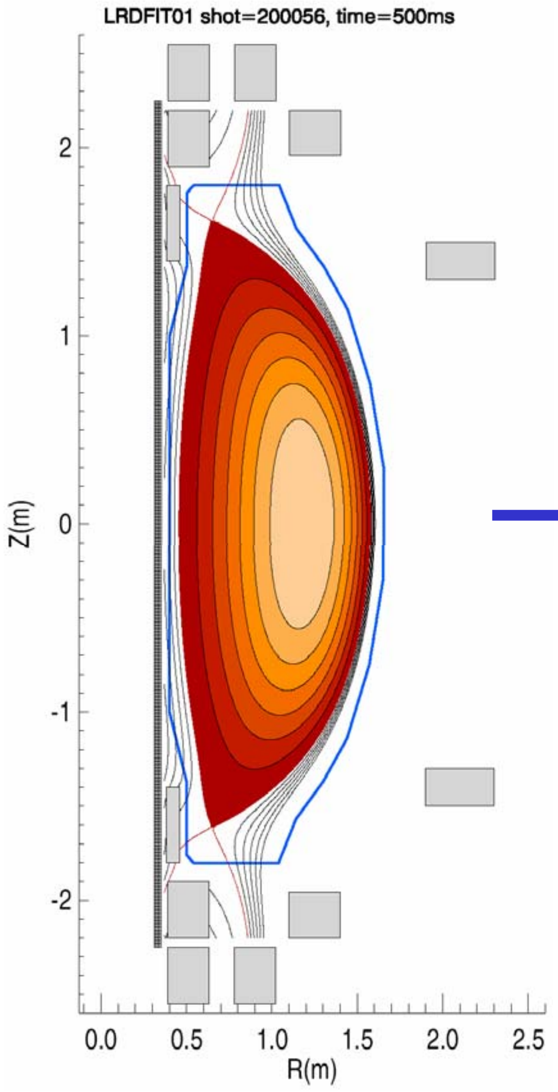
    $\Rightarrow$ NHTX: D, χ = 0.4, 1.6 m^2/s
- Boundary conditions used
  - Core
    - Input power fixed to values between 10 and 50 MW
    - Density fixed between 7.5×10^{19} and 3.0×10^{20} m^{-3}
  - Targets
    - Recycling coefficients set to 0.90-0.99 (1 elsewhere)
    - No sputtering included at this point

2-D SOL and divertor calculations completed for four different configurations

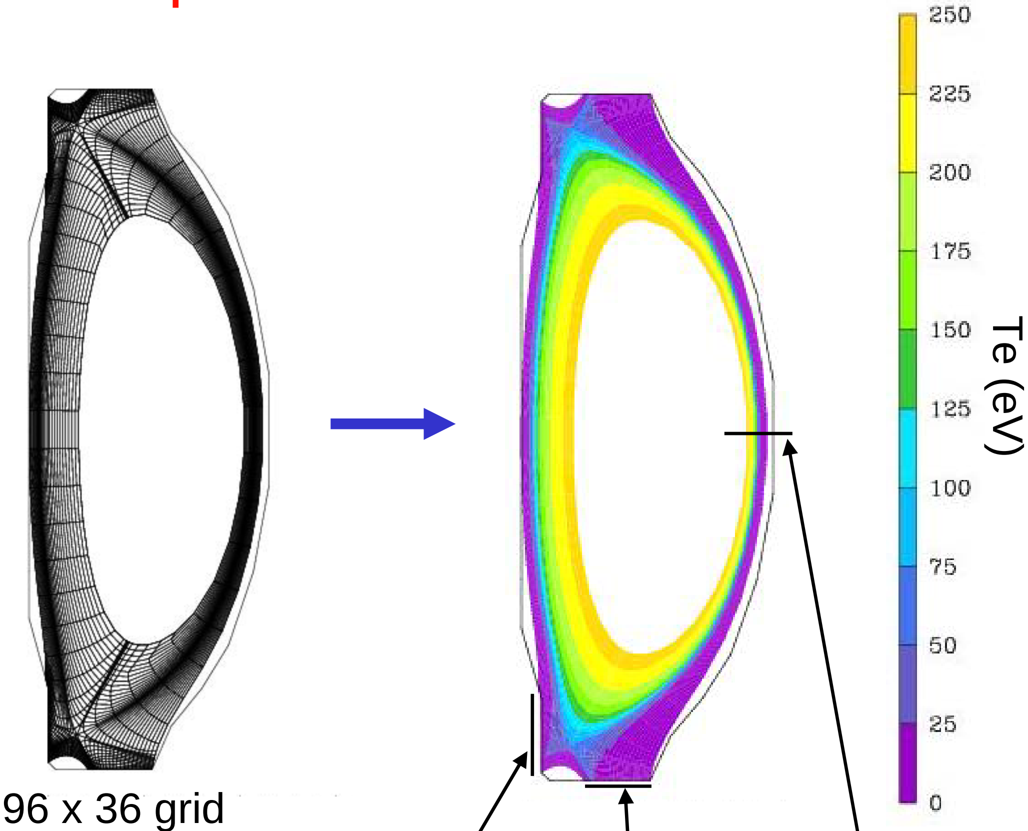
DN f_{exp} ~ 21 **DN f_{exp} ~ 10** **LSN f_{exp} ~ 5** **DN slot f_{exp} ~ 25**



Comparison of Equilibrium to Computational Grid



2D quantities calculated…



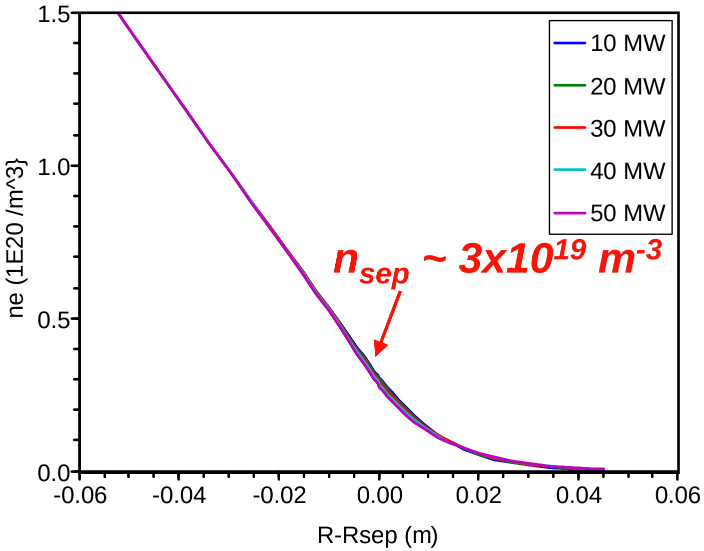
96 x 36 grid

1D quantities plotted along left and right targets, midplane

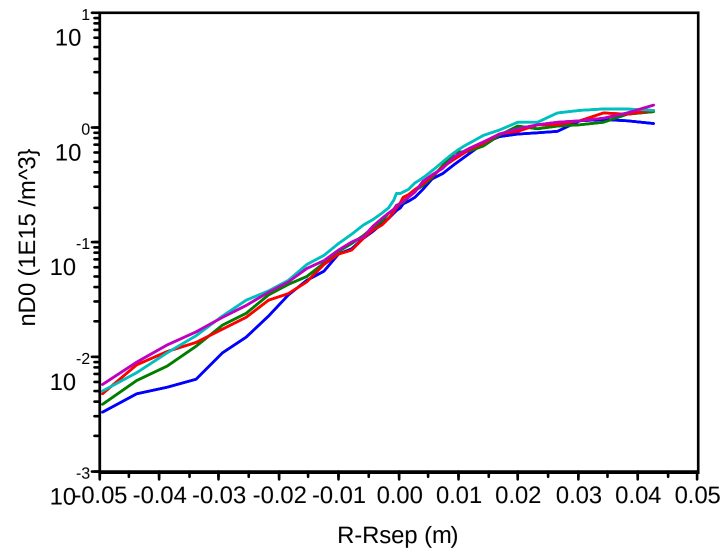
Midplane profiles at fixed core density, P = 10 – 50 MW

NSTX

Midplane Electron Density



Midplane Atomic Density

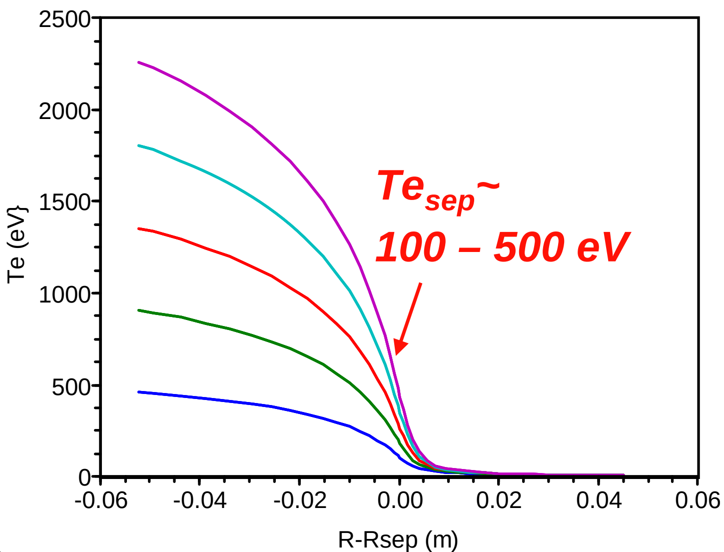


g200056

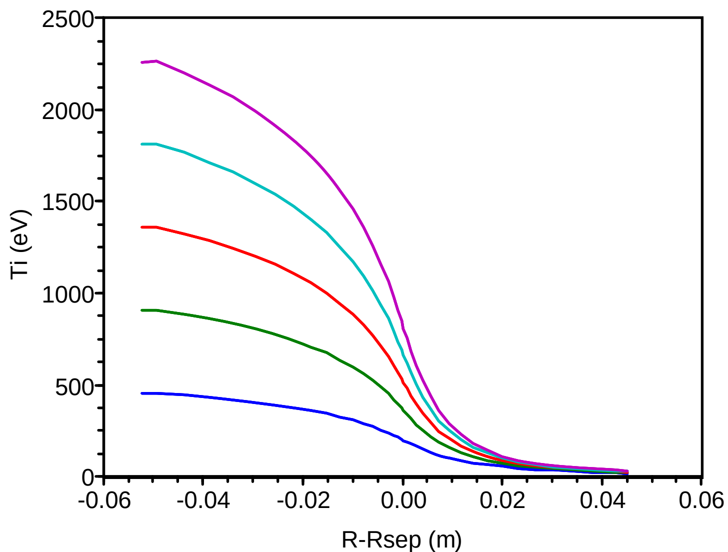
n_{core} = 1.5e20

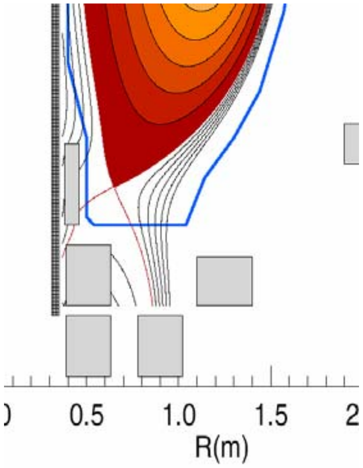
R = 0.95

Midplane Electron Temperature



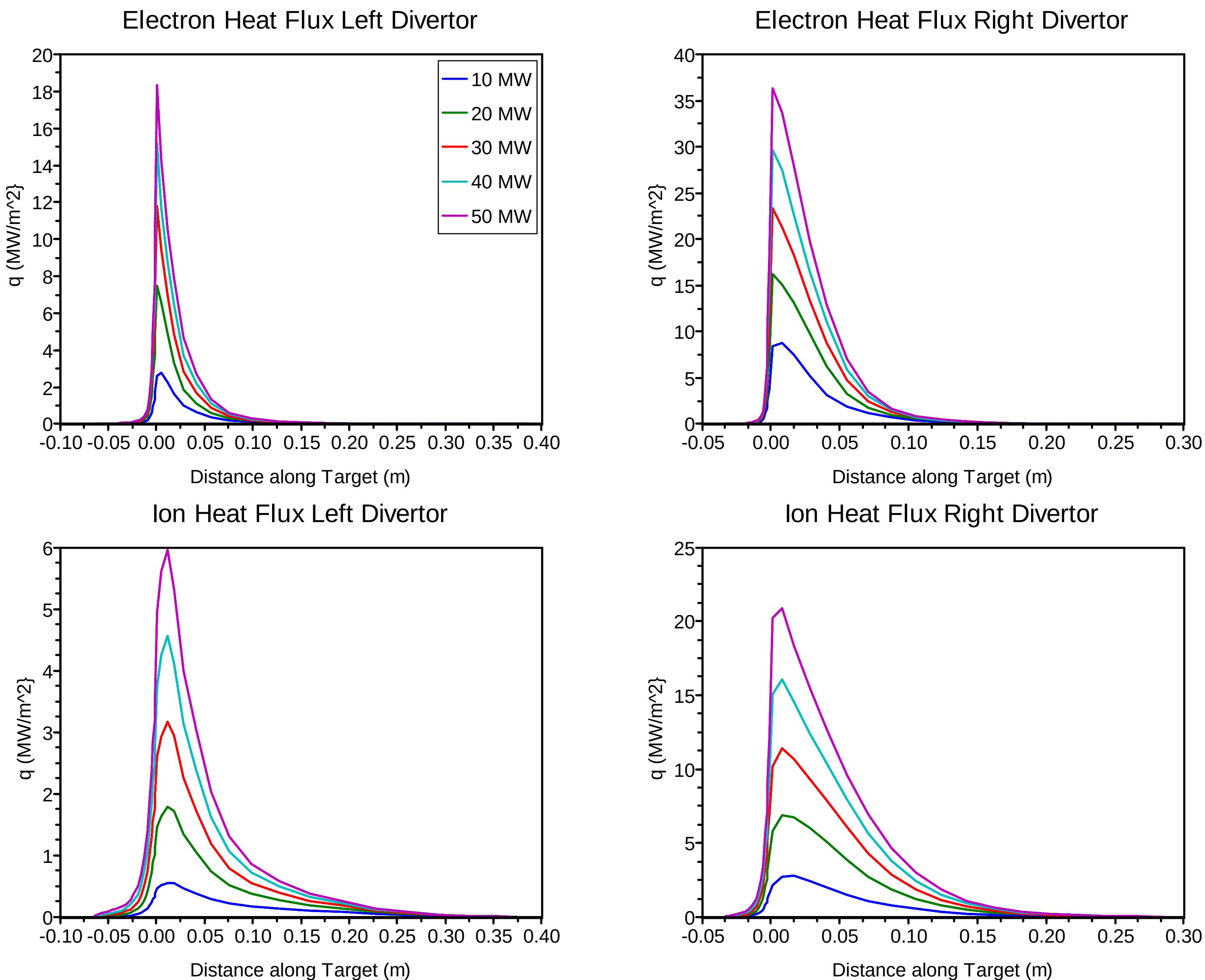
Midplane Ion Temperature





ornl
Oak Ridge National Laboratory

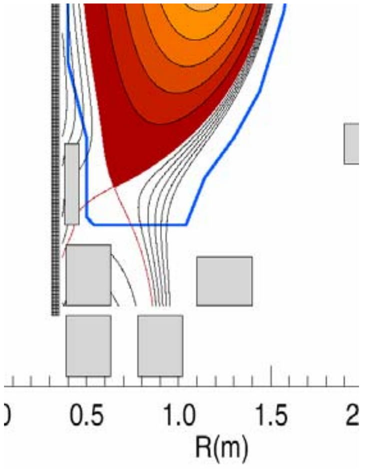
Ion/electron heat fluxes are larger at outboard divertor leg



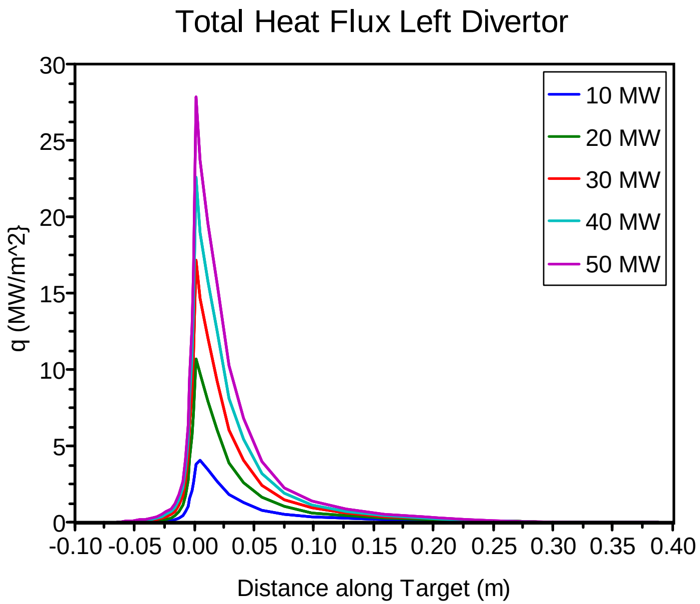
g200056

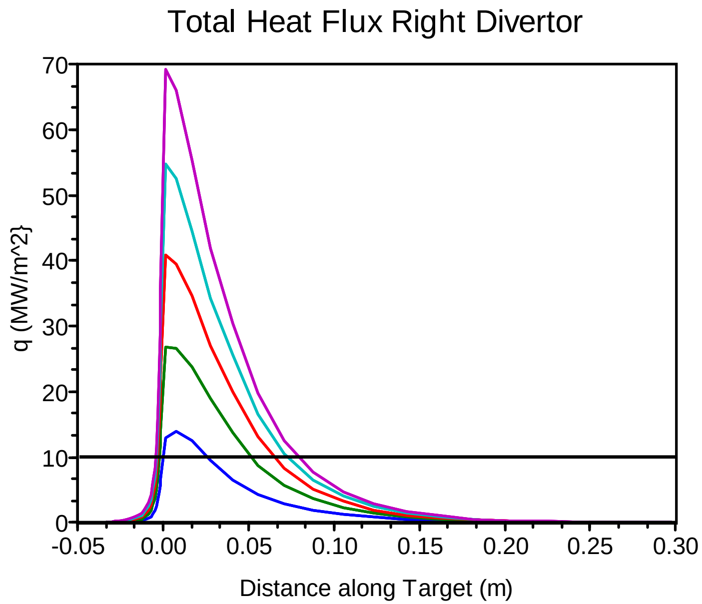
n_{core} = 1.5e20

R = 0.95



Total heat flux is up 70 MW/m^2 at outer target

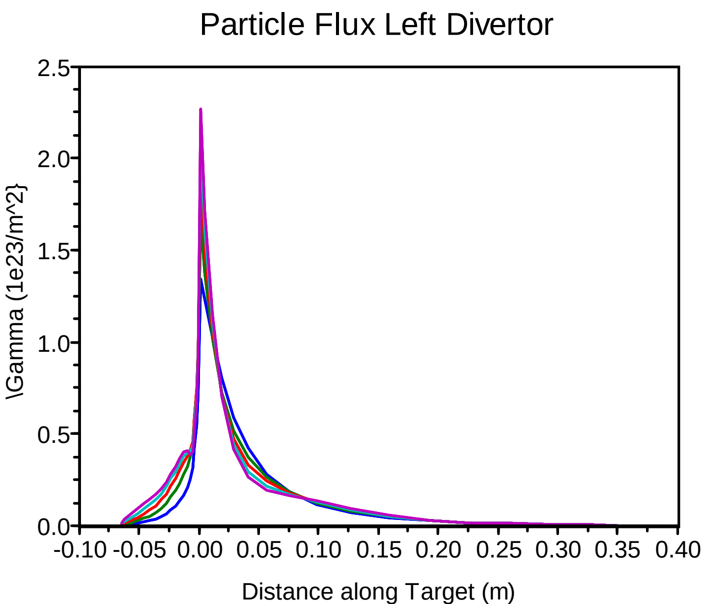


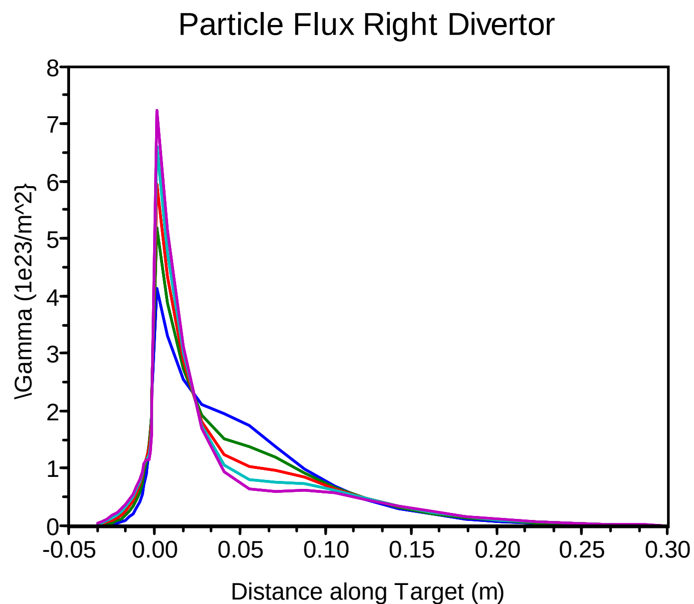


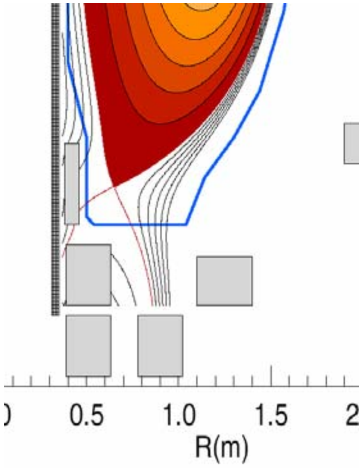
g200056

n_{core} = 1.5e20

R = 0.95



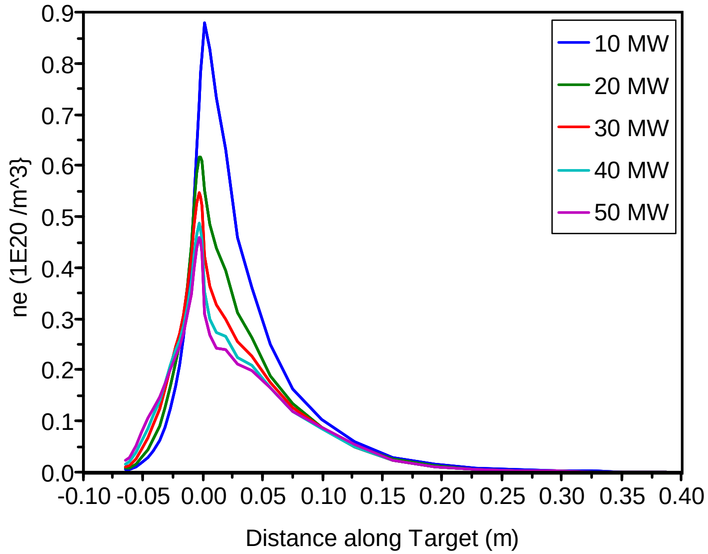




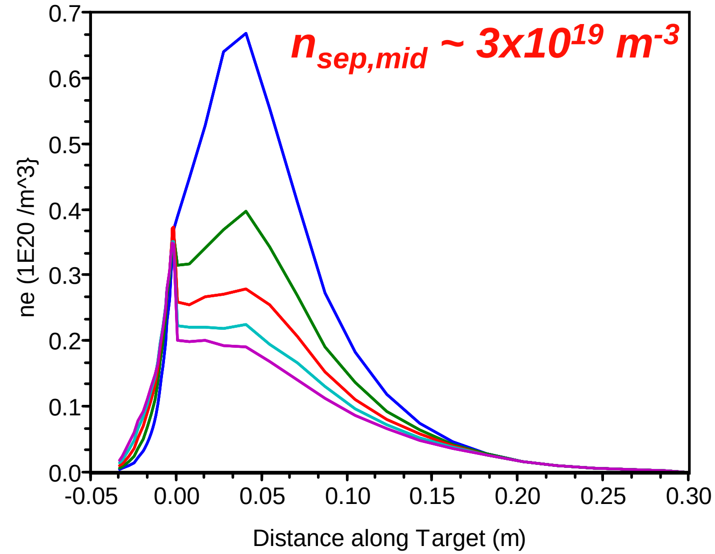
SOL plasma is sheath-limited near separatrix: T, n ~ midplane values

NSTX

Electron Density Left Divertor



Electron Density Right Divertor

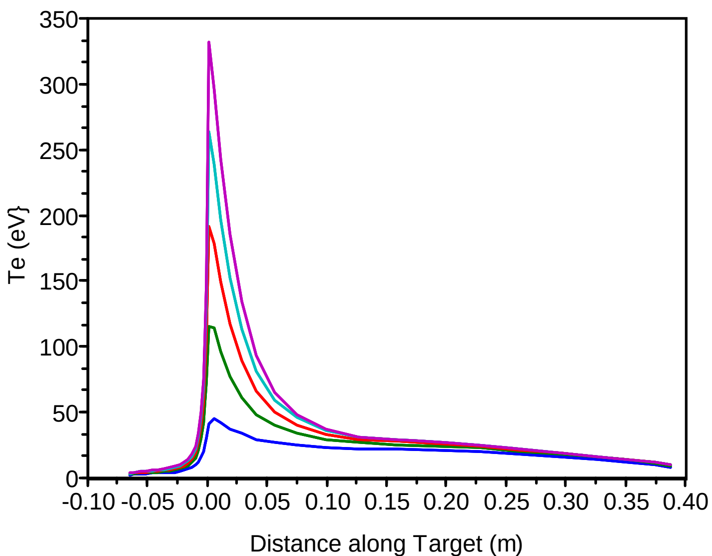


g200056

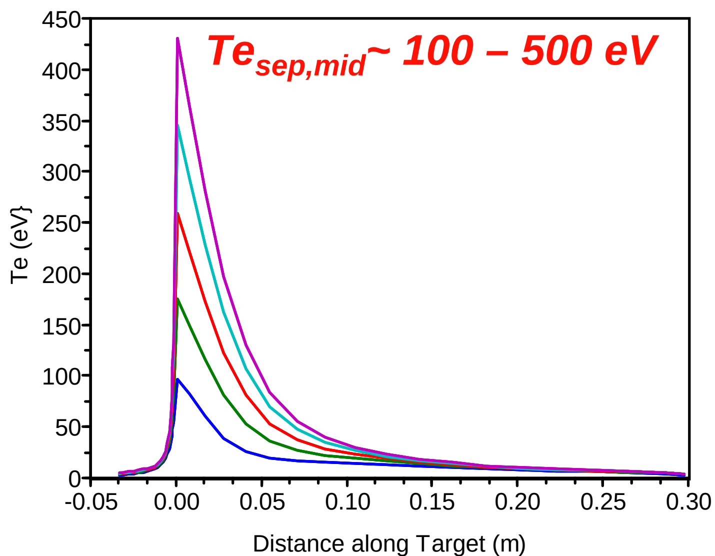
n_{core} = 1.5e20

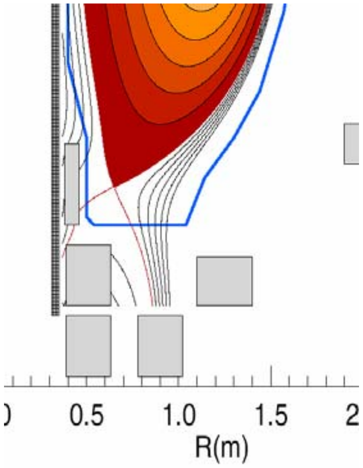
R = 0.95

Electron Temperature Left Divertor



Electron Temperature Right Divertor



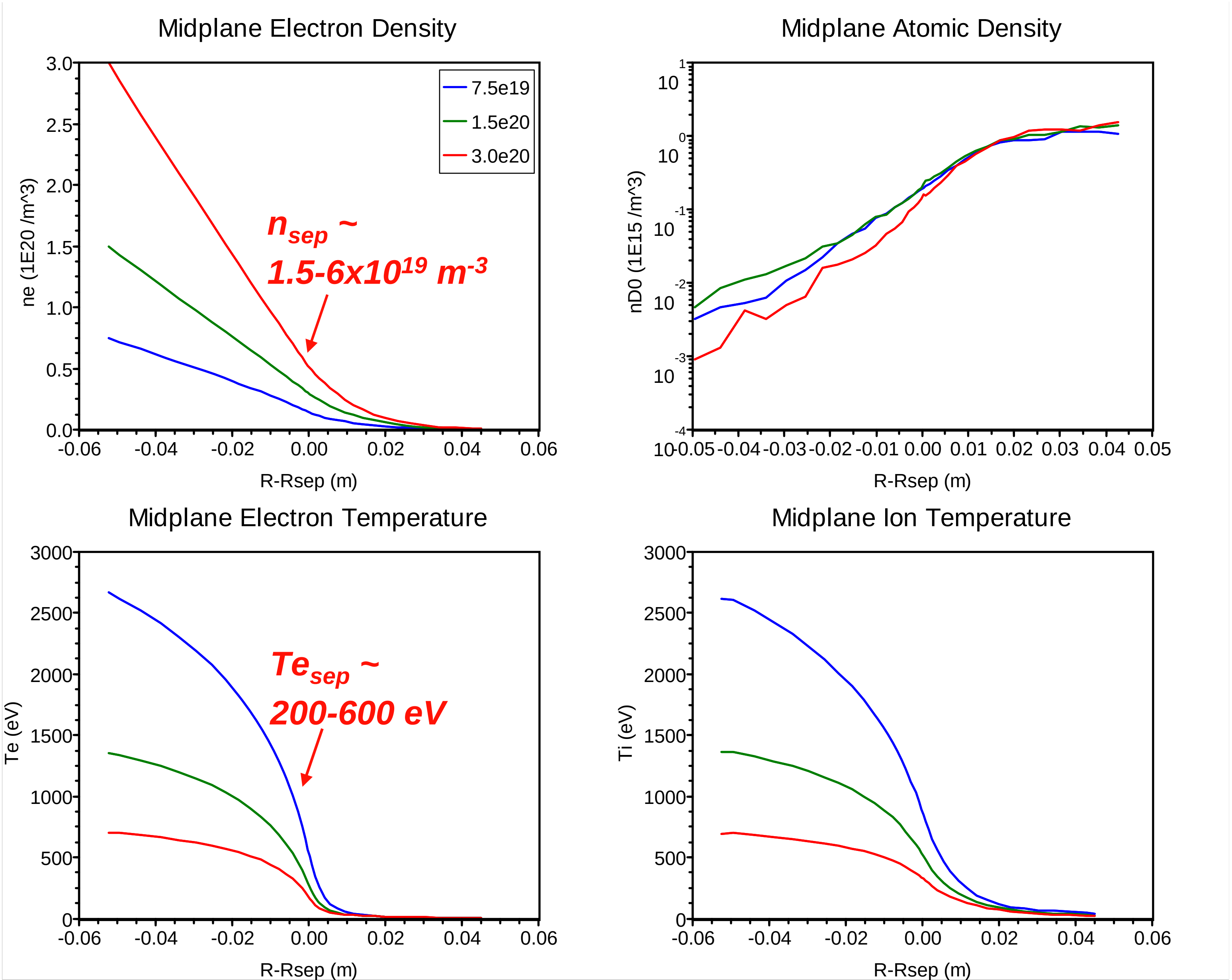


ornl

Outline

- Introduction to NHTX
- Code description
- Detailed calculations for single configuration
  - Power scan from 10-50 MW at neped ~ 1.5e20
  - **Density scan from 7.5e19 - 3e20 at Pheat=30 MW**
  - Recycling scan from 0.9-0.99
  - Impurity radiation scans for carbon, neon, argon
- Calculations for three other configurations
- Discussion and conclusions

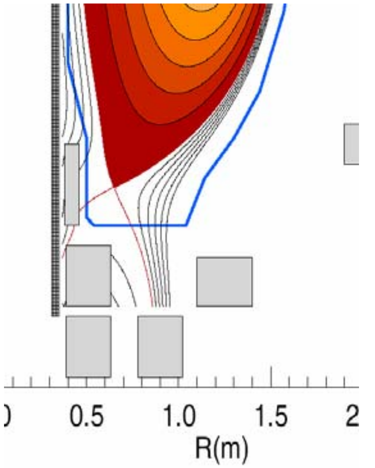
Midplane profiles at fixed power (30MW), n_{core} = 0.75-3.0e20



g200056

P = 30MW

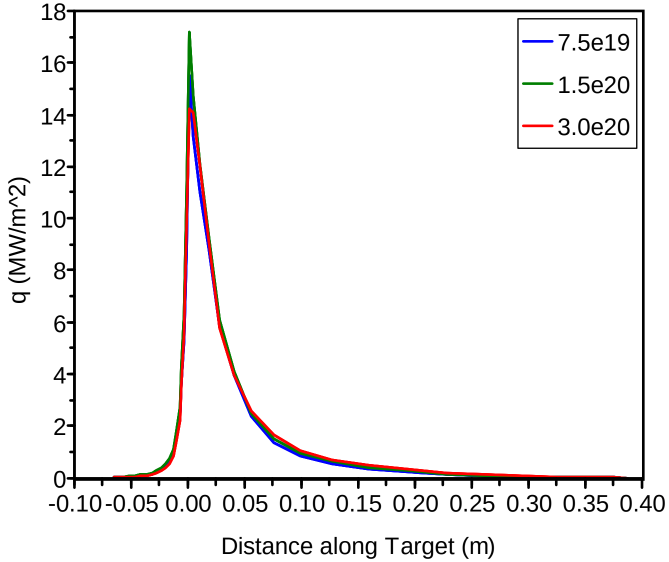
R = 0.95



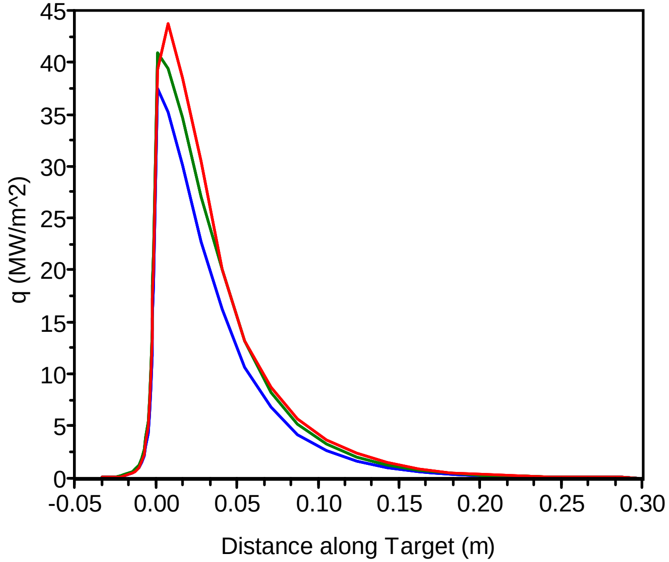
Peak heat flux is fairly insensitive to separatrix density

NSTX

Total Heat Flux Left Divertor



Total Heat Flux Right Divertor

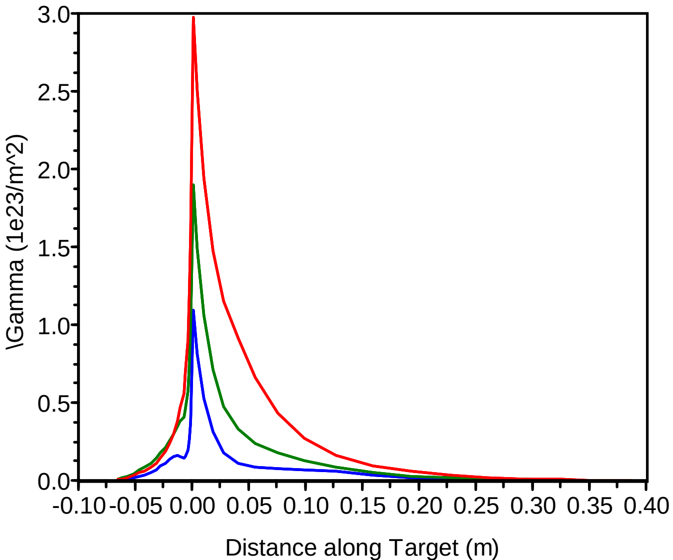


g200056

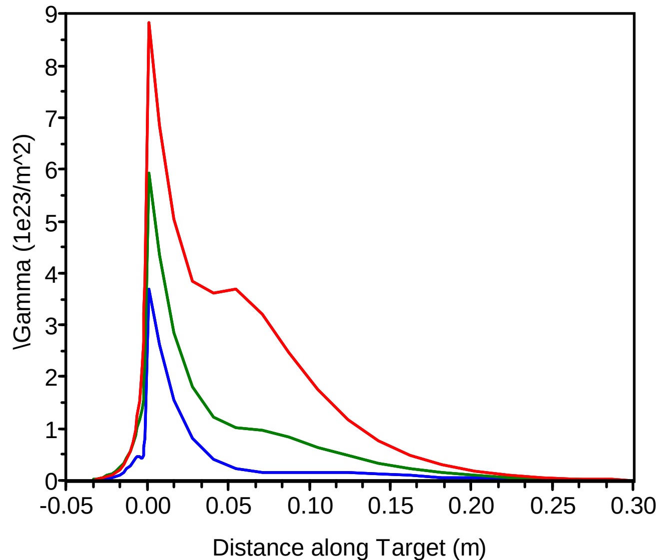
P = 30MW

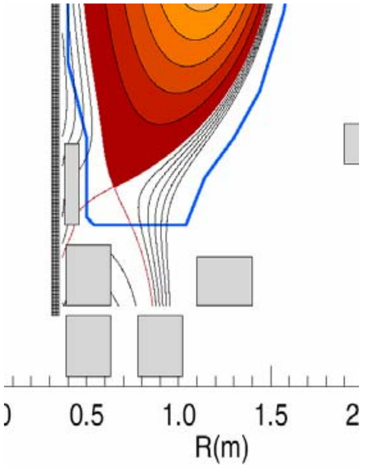
R = 0.95

Particle Flux Left Divertor

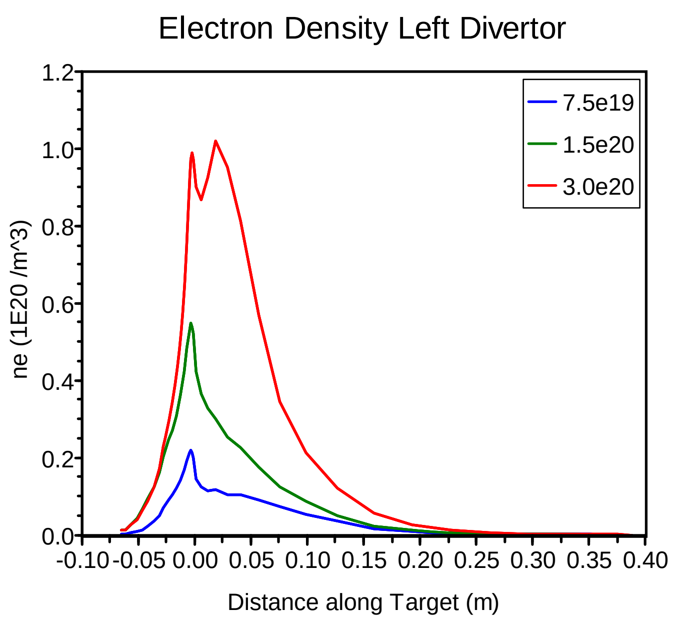


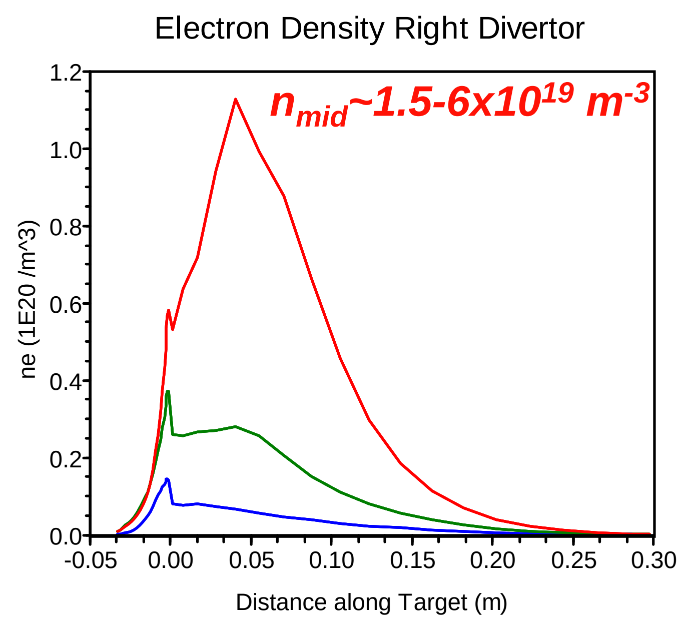
Particle Flux Right Divertor





Divertor plasma remains sheath-limited near separatrix

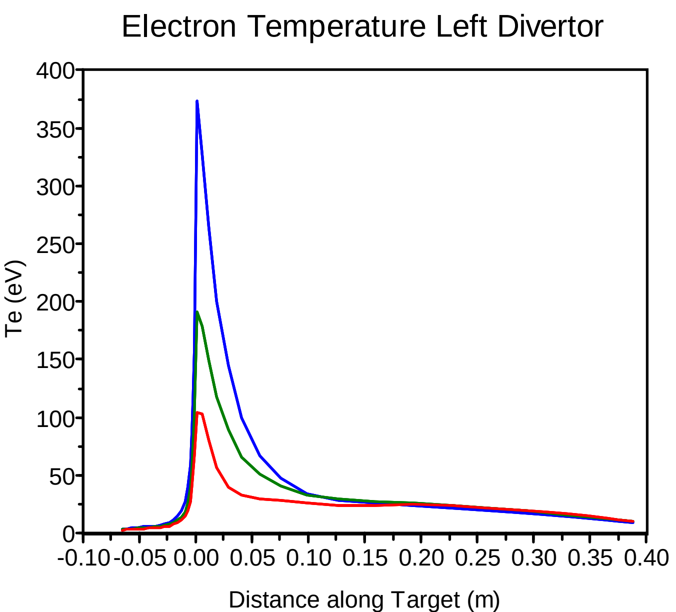


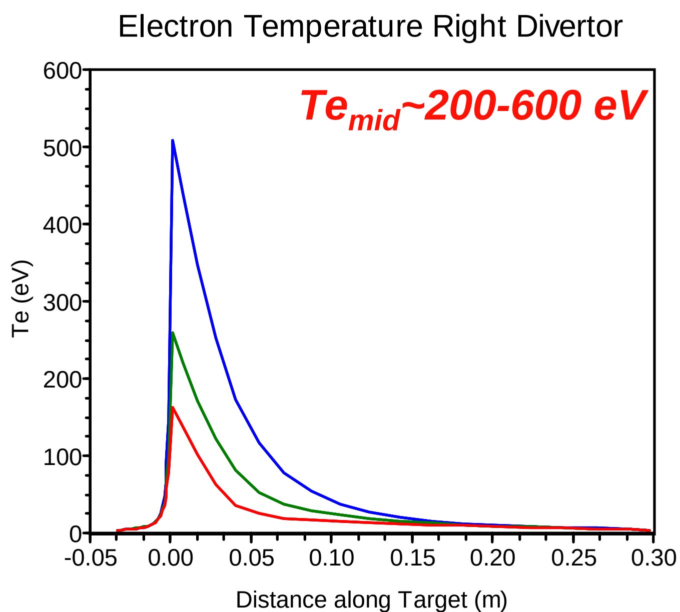


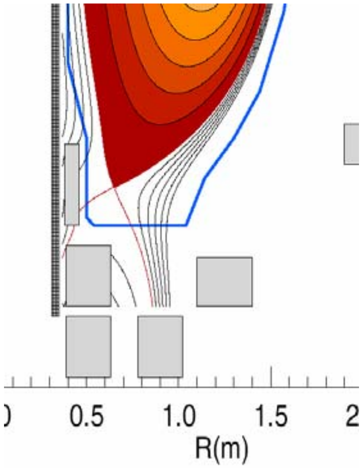
g200056

P = 30MW

R = 0.95

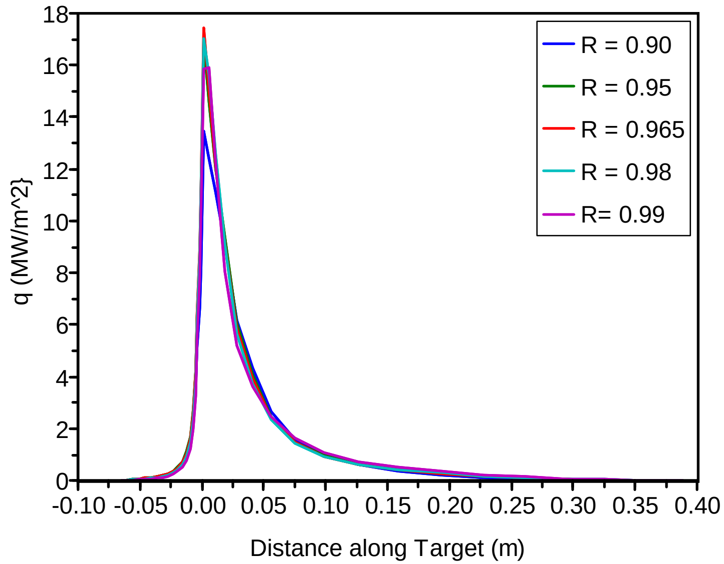




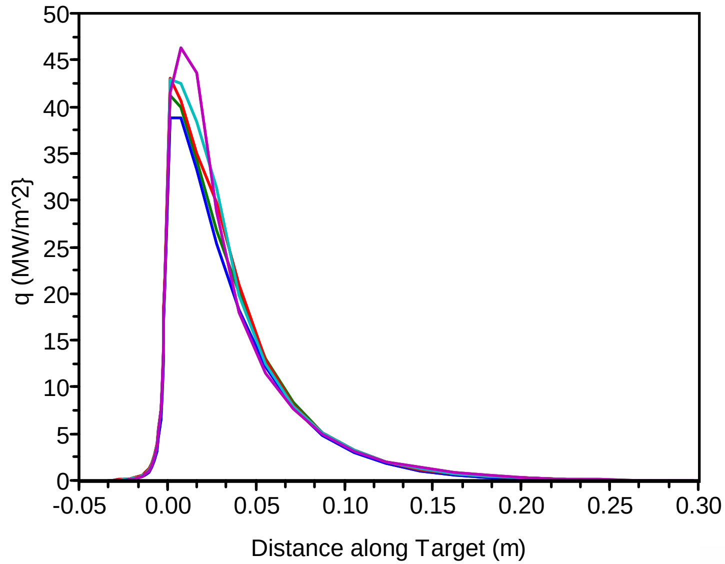


Recycling scan: away from separatrix, divertor moves towards high-recycling regime

Total Heat Flux Left Divertor



Total Heat Flux Right Divertor

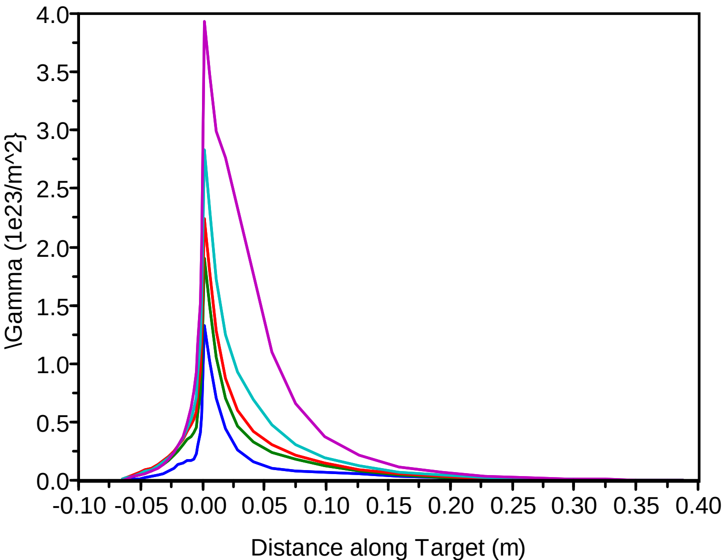


g200056

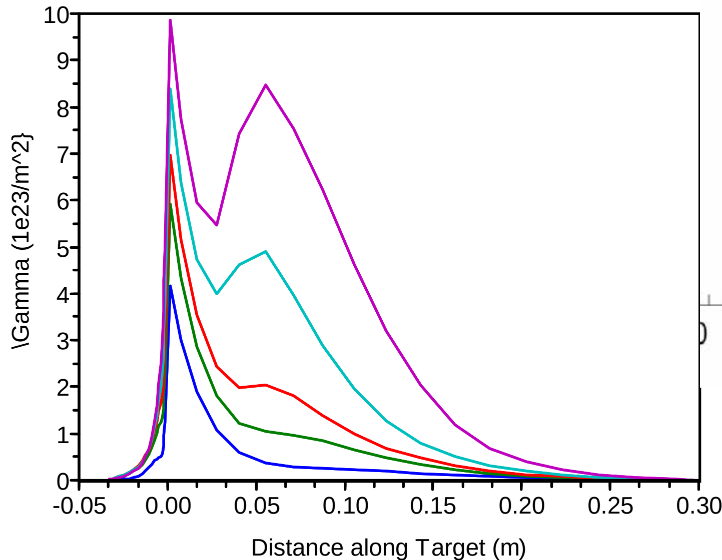
P = 30MW

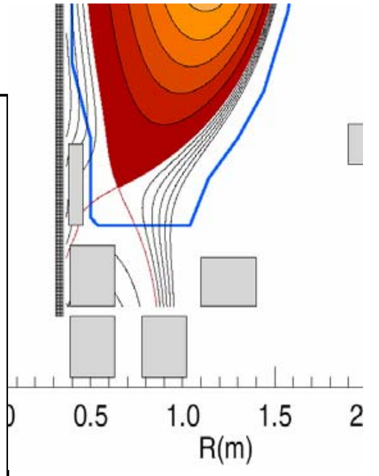
n_{core}= 1.5e20

Particle Flux Left Divertor

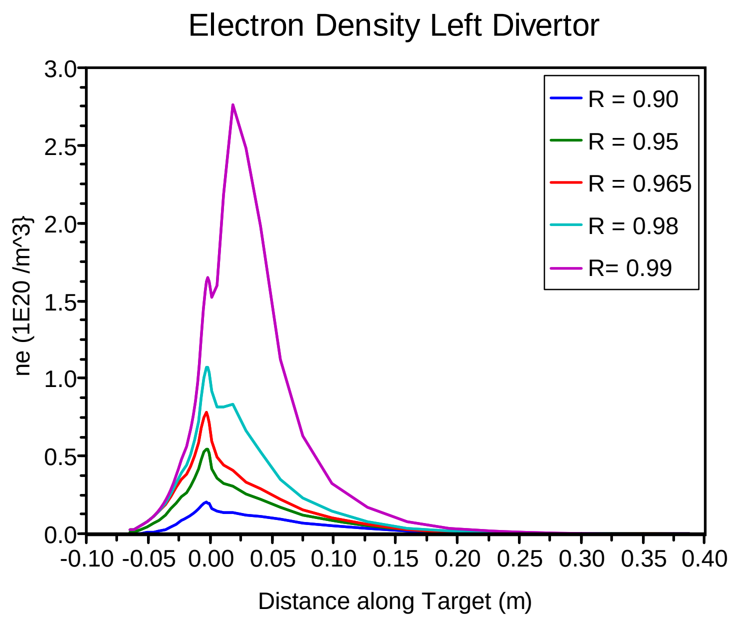


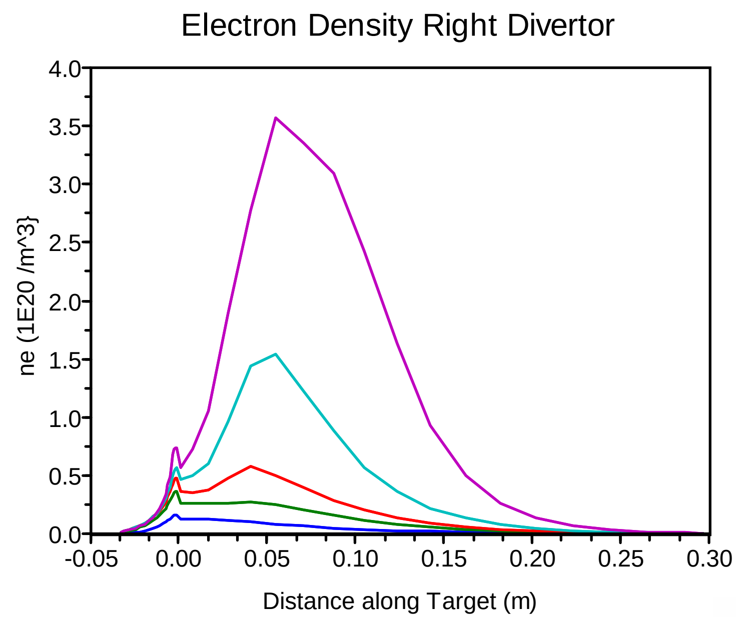
Particle Flux Right Divertor





Recycling scan: away from separatrix, divertor moves towards high-recycling regime

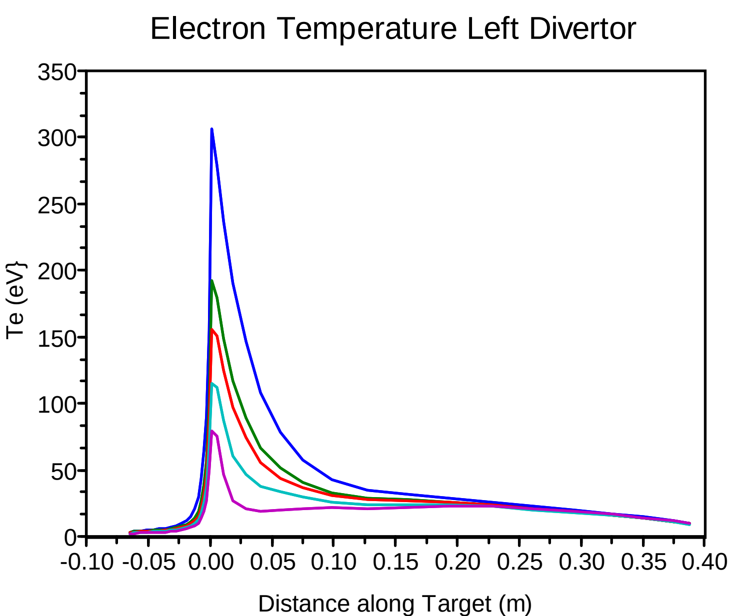


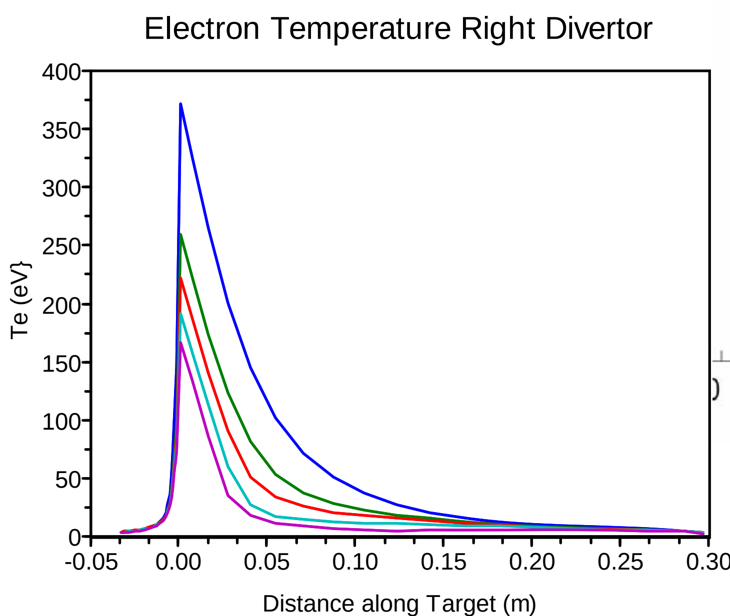


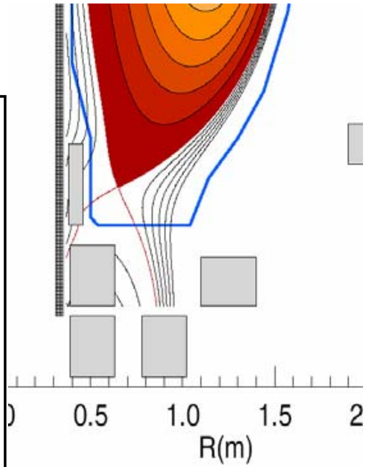
g200056

P = 30MW

n_{core}= 1.5e20



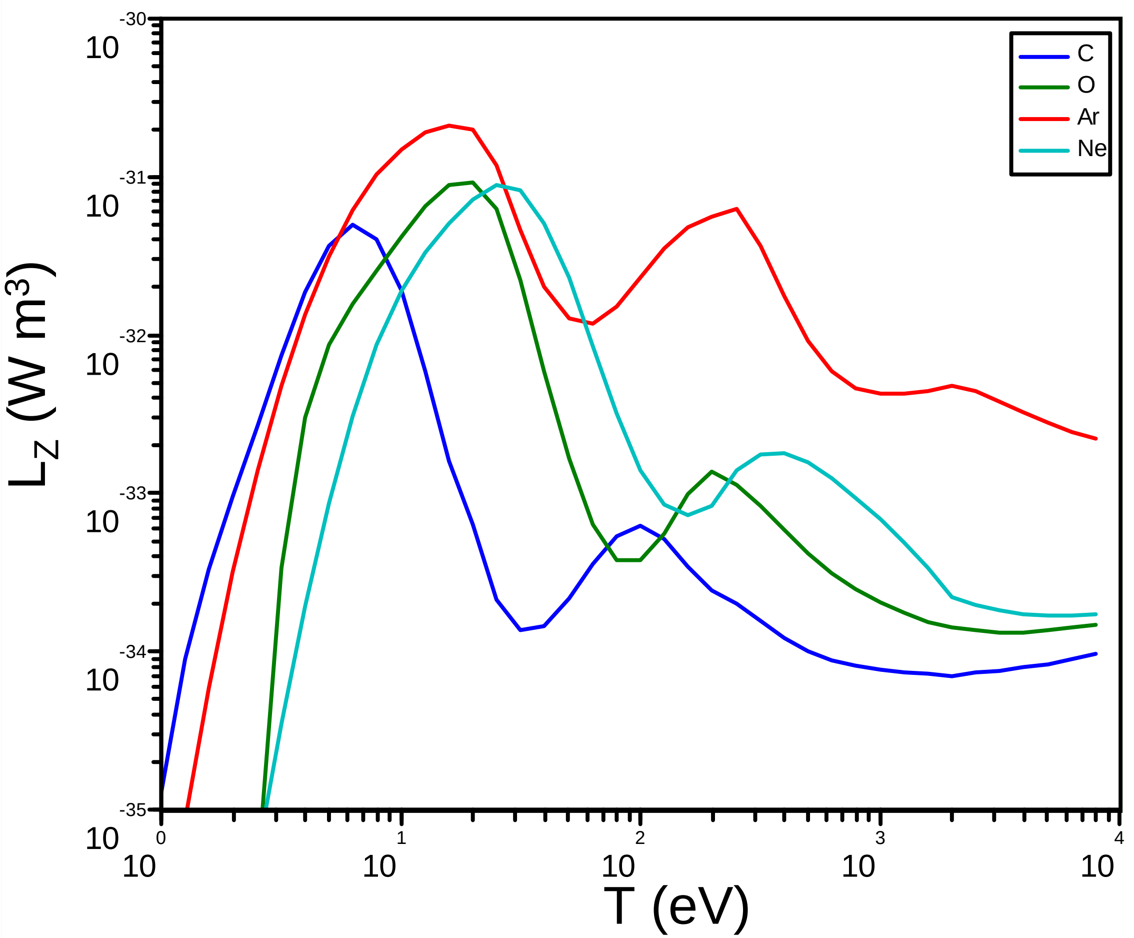




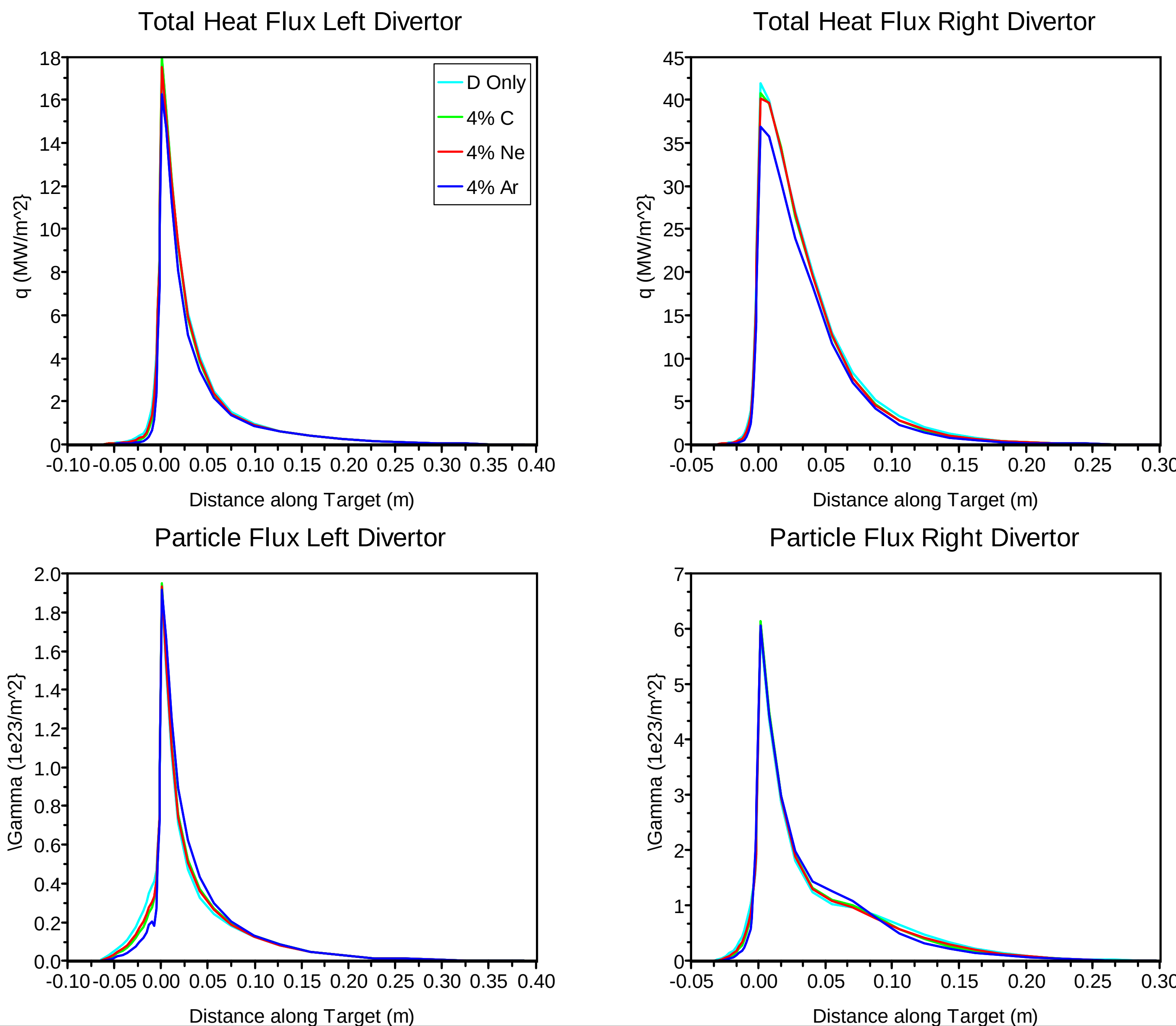
Artificial Impurity Radiation Model

Choose an impurity and a concentration f: $n_Z = f*n_e$

Add to SOLPS radiated power density: $L_Z n_e * n_Z$



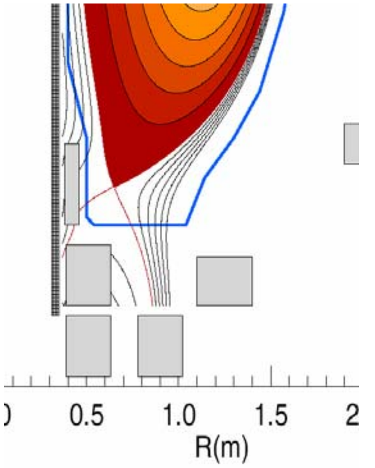
Adding impurities: SOL radiation is limited at these Te



P^{rad}_{C} = 1 MW

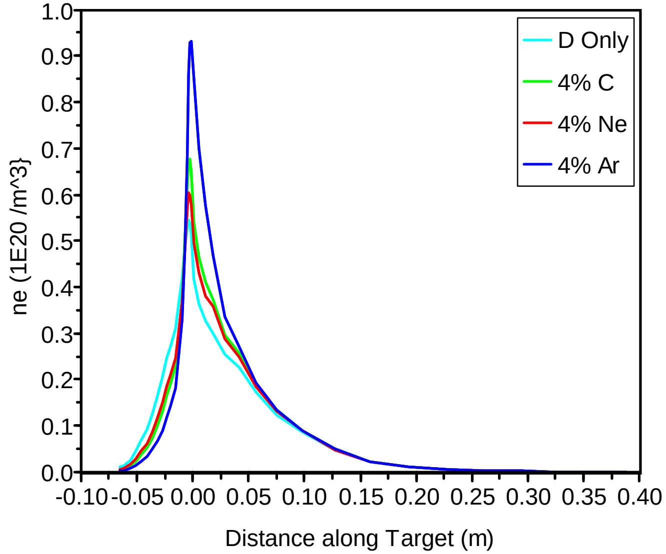
P^{rad}_{Ne} = 1 MW

P^{rad}_{Ar} = 4 MW

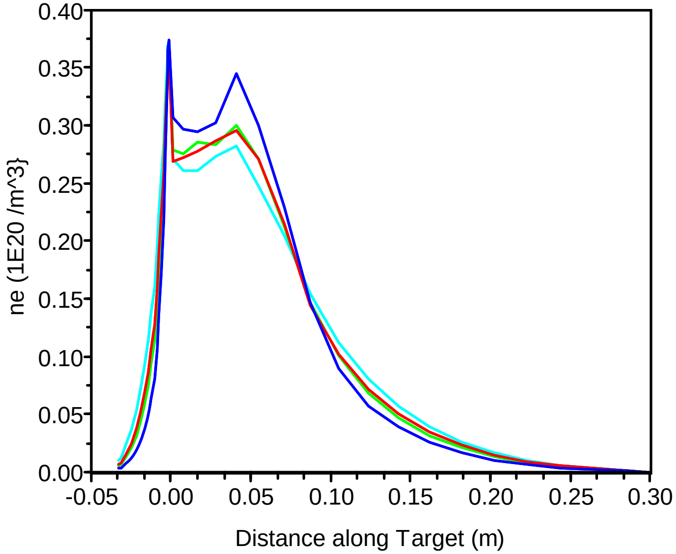


Adding impurities shows SOL radiation is limited at these Te

Electron Density Left Divertor



Electron Density Right Divertor

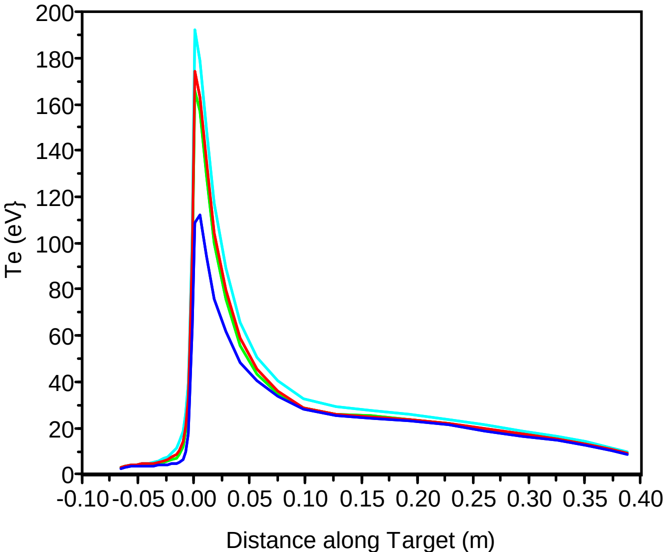


P^{rad}_{C} = 1 MW

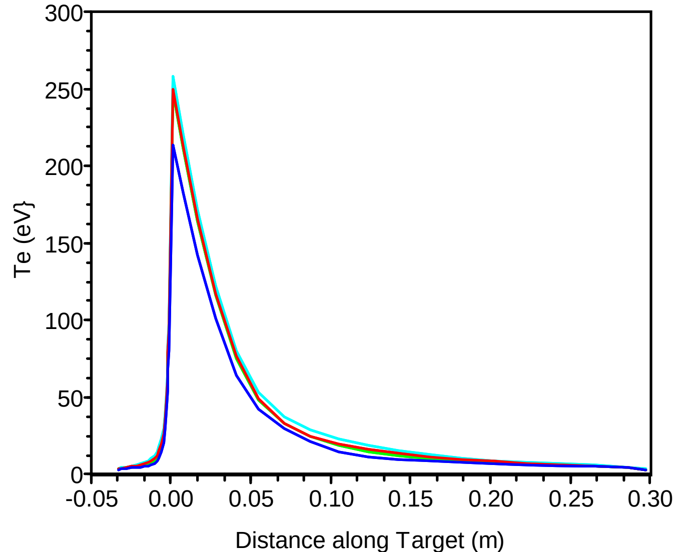
P^{rad}_{Ne} = 1 MW

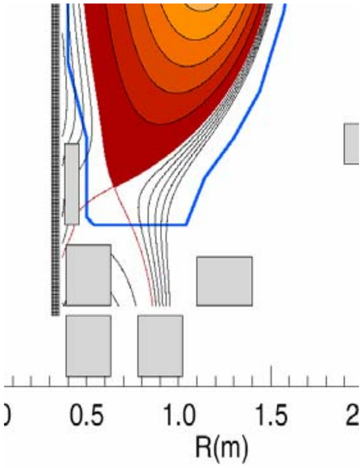
P^{rad}_{Ar} = 4 MW

Electron Temperature Left Divertor



Electron Temperature Right Divertor

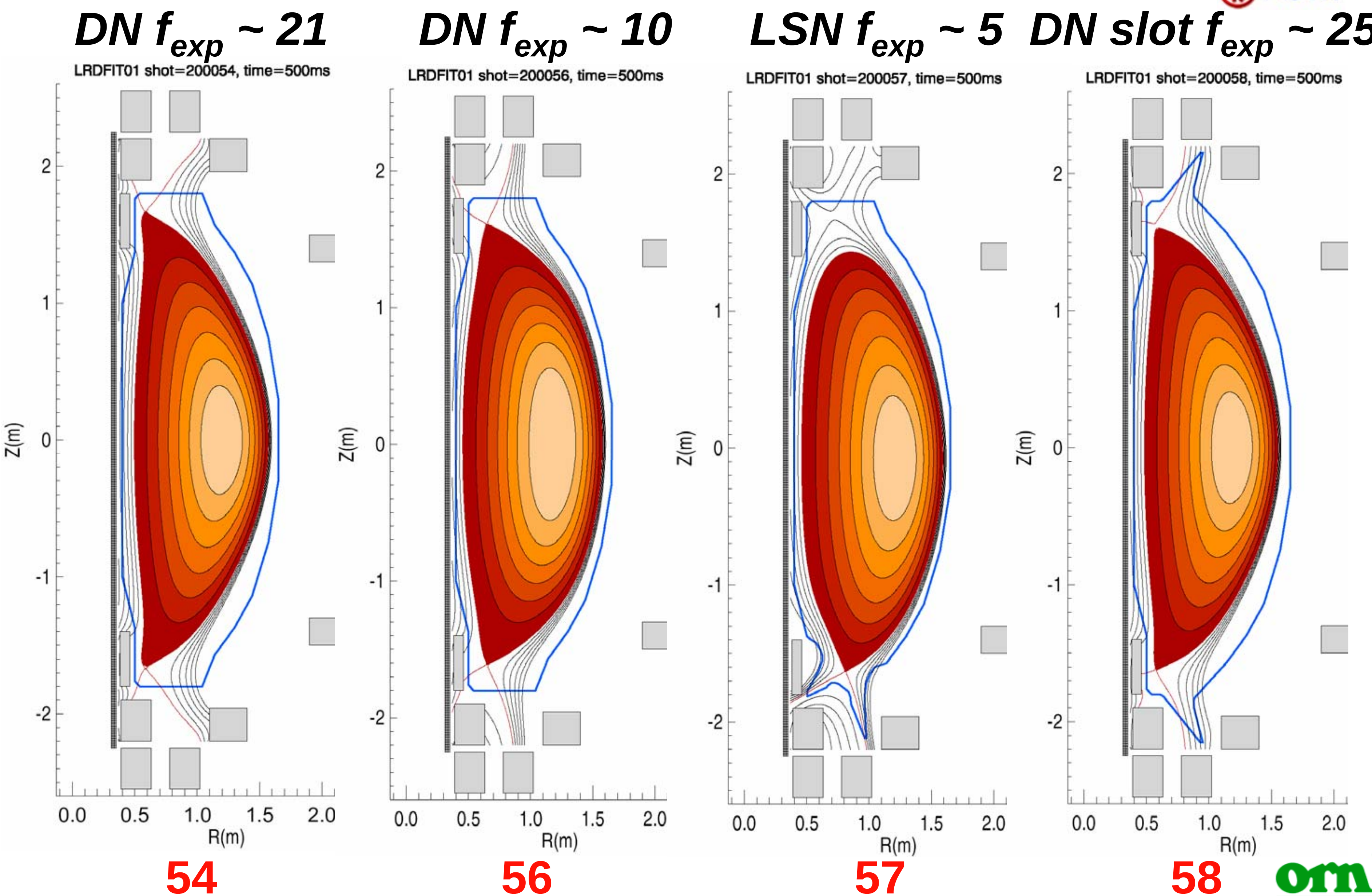




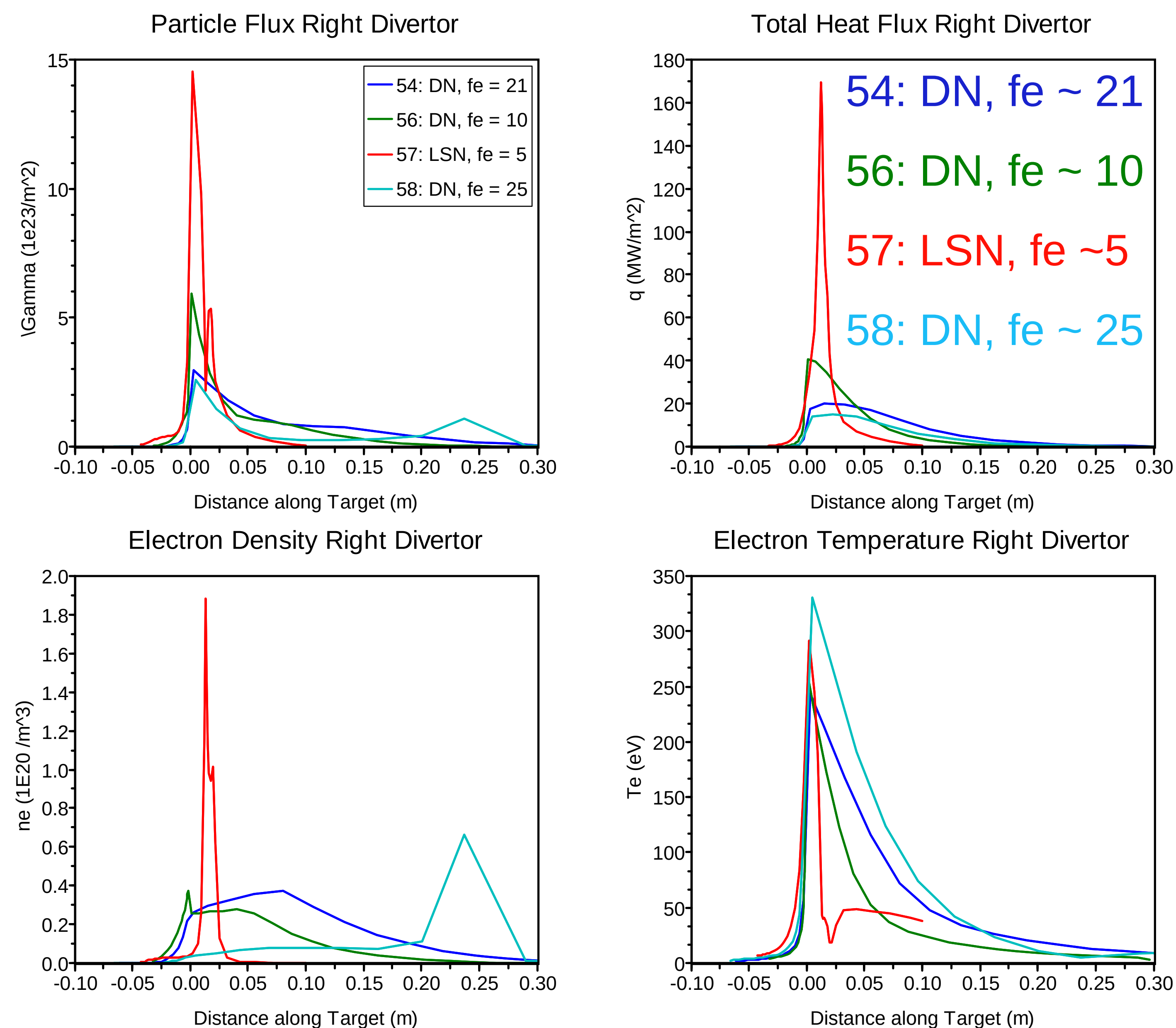
Outline

- Introduction to NHTX
- Code description
- Detailed calculations for single configuration
  - Power scan from 10-50 MW at neped ~ 1.5e20
  - Density scan from 7.5e19 - 3e20 at Pheat=30 MW
  - Recycling scan from 0.9-0.99
  - Impurity radiation scans for carbon, neon, argon
- **Calculations for three other configurations**
- Discussion and conclusions

2-D SOL and divertor calculations completed for four different configurations



Variations in geometry strongly affect heat flux, divertor parameters



P = 30MW

n_{core} = 1.5e20

R = 0.95

Discussion and Conclusions

- Transport is sheath limited near separatrix in both inner and outer divertor legs
  - Peak heat flux increases roughly linearly with input power
  - Heat flux is nearly independent of density, recycling coefficient
  - High electron temperature makes radiative solution difficult
    - Needs more work – self consistent impurity production/transport, etc.
  - SOL approaching conduction limit away from separatrix
    - In outer leg at higher density/recycling coefficient
    - At inner leg with low input power

- Configuration scan shows effects of flux expansion and number of divertors
  - Heat flux profiles broader with high FE
  - LSN, low FE case has very high peak heat flux

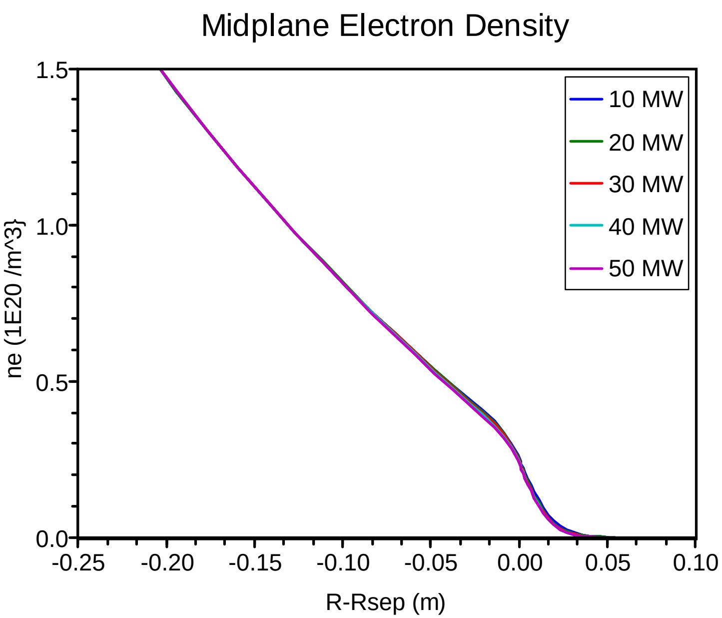
Discussion and Conclusions

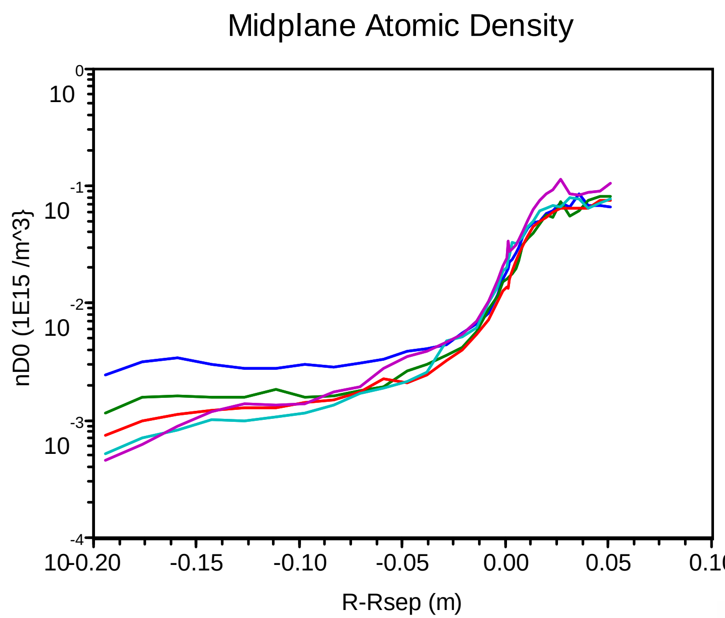
- NHTX allows a wide operational range of heat fluxes for PFC evaluation
  - Can be varied by a factor of ~ 10
  - Heat flux can be very high – well above 10 MW/m^2

- Results illustrate the challenge of high heat flux boundary
  - Initial modeling shows unacceptably high target temperature, little control over heat flux
  - Target geometry optimization, more sophisticated use of radiators (impurity mixes, low-power startup), etc. will be necessary to bring boundary under control

Backup

Inner midplane profiles at fixed core density, P = 10 – 50 MW

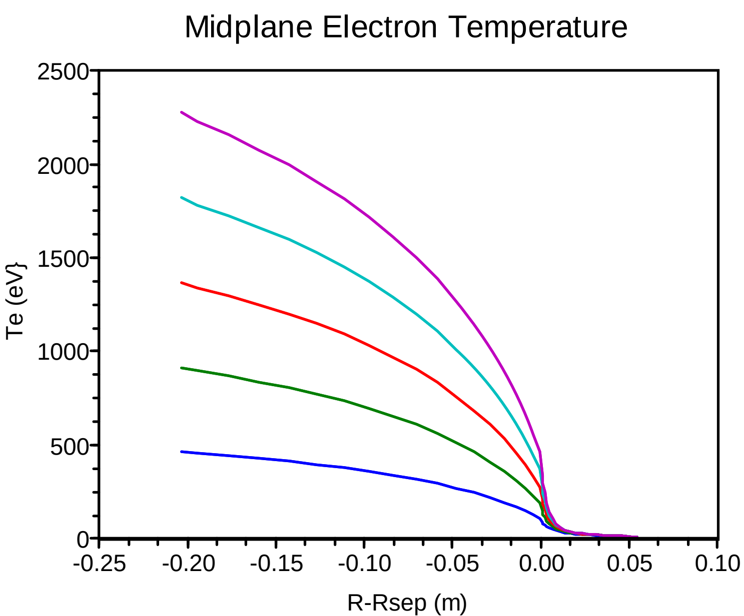


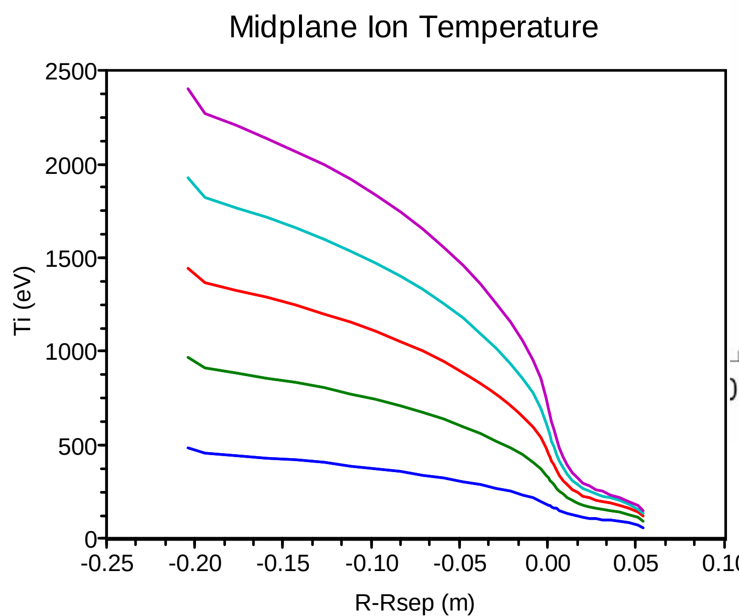


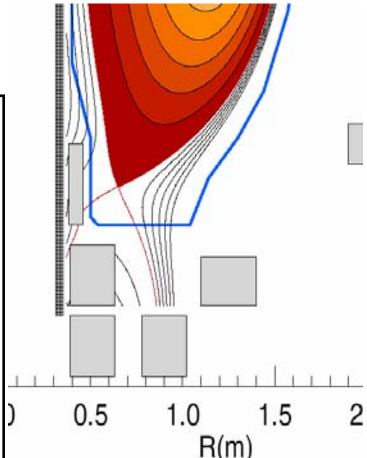
g20056

n_{core} = 1.5e20

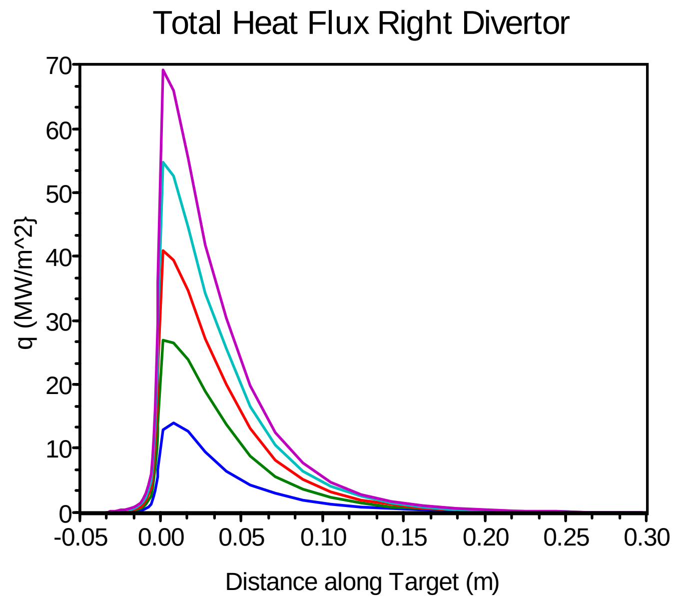
R = 0.95

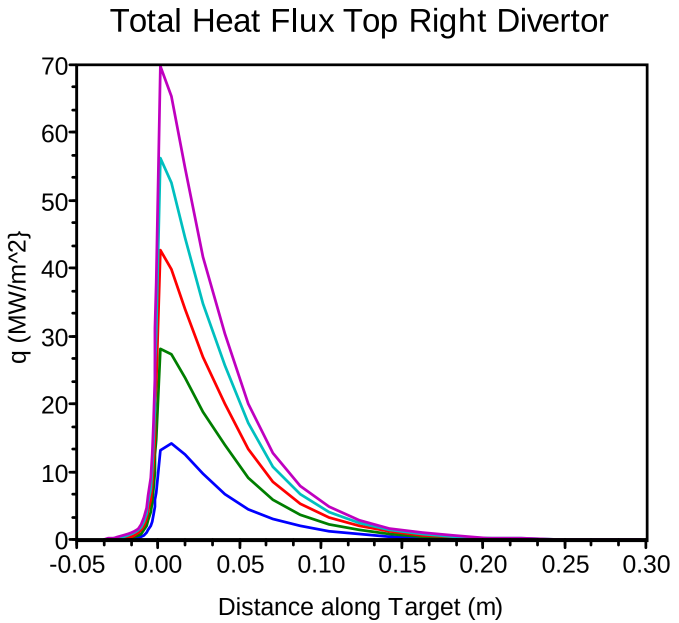


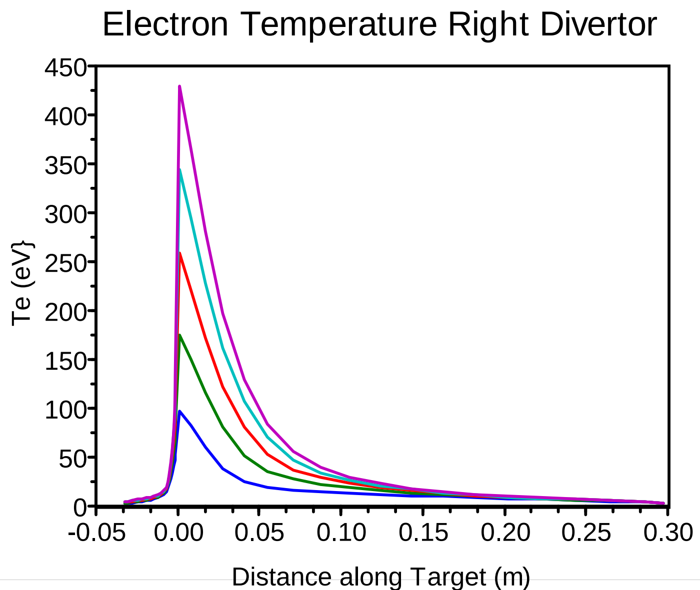


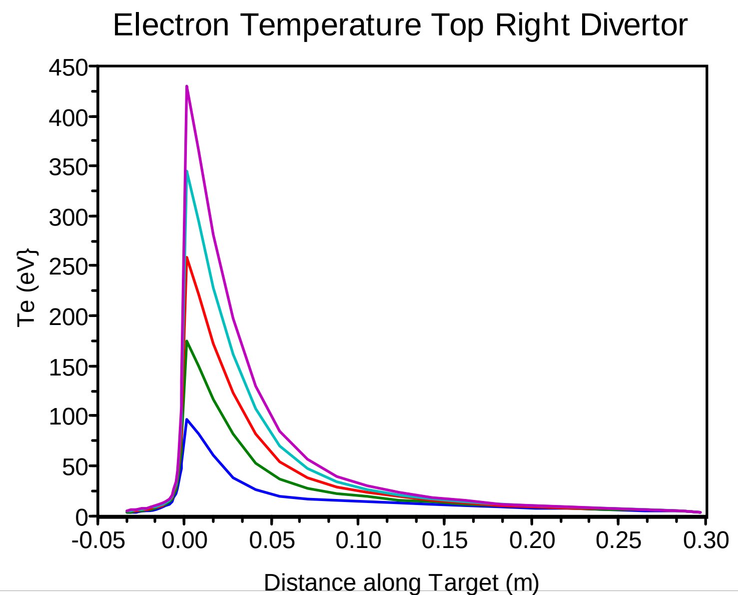


Basic predictions of power scan - upper divertor

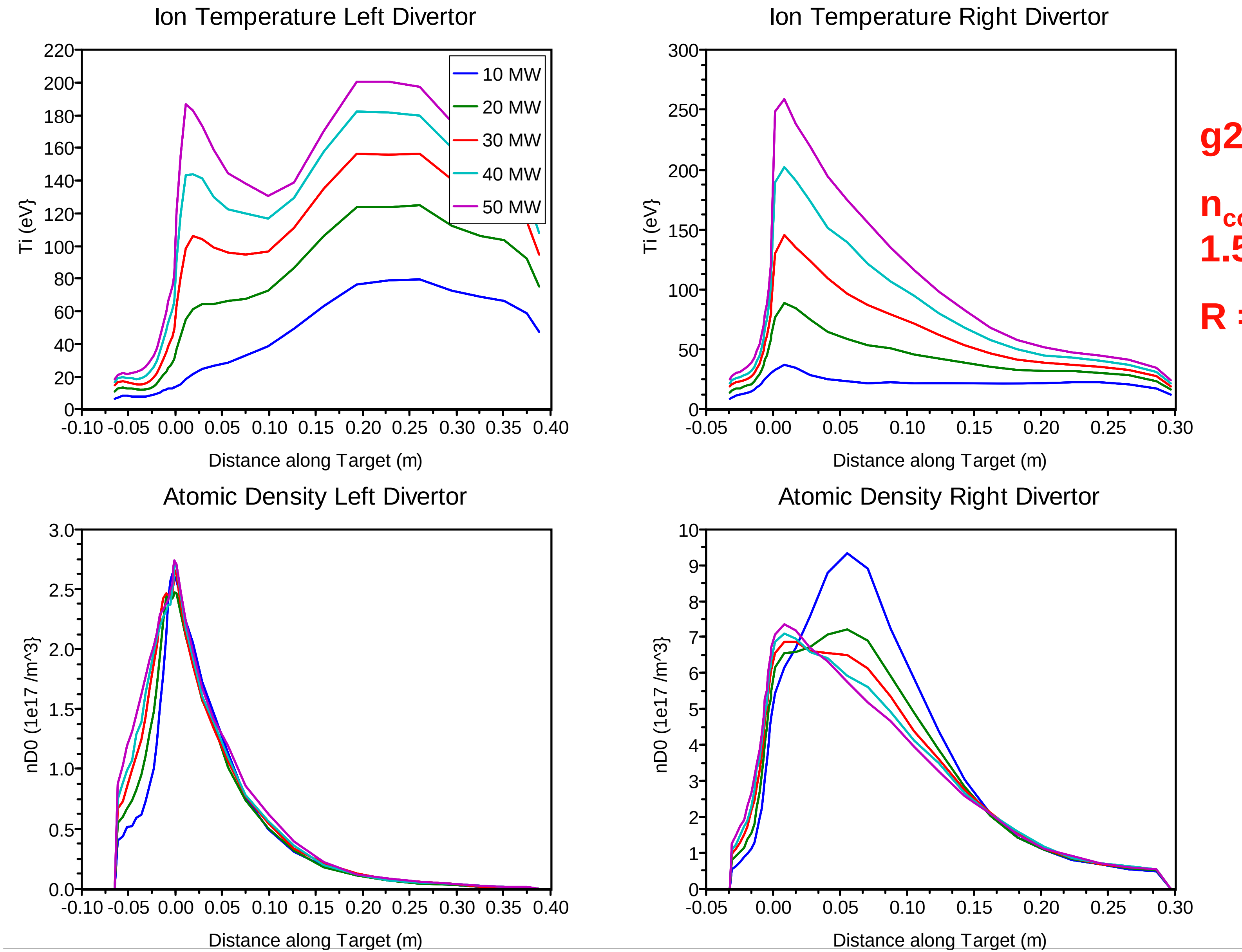








Basic predictions of power scan – ion temperature and atomic density

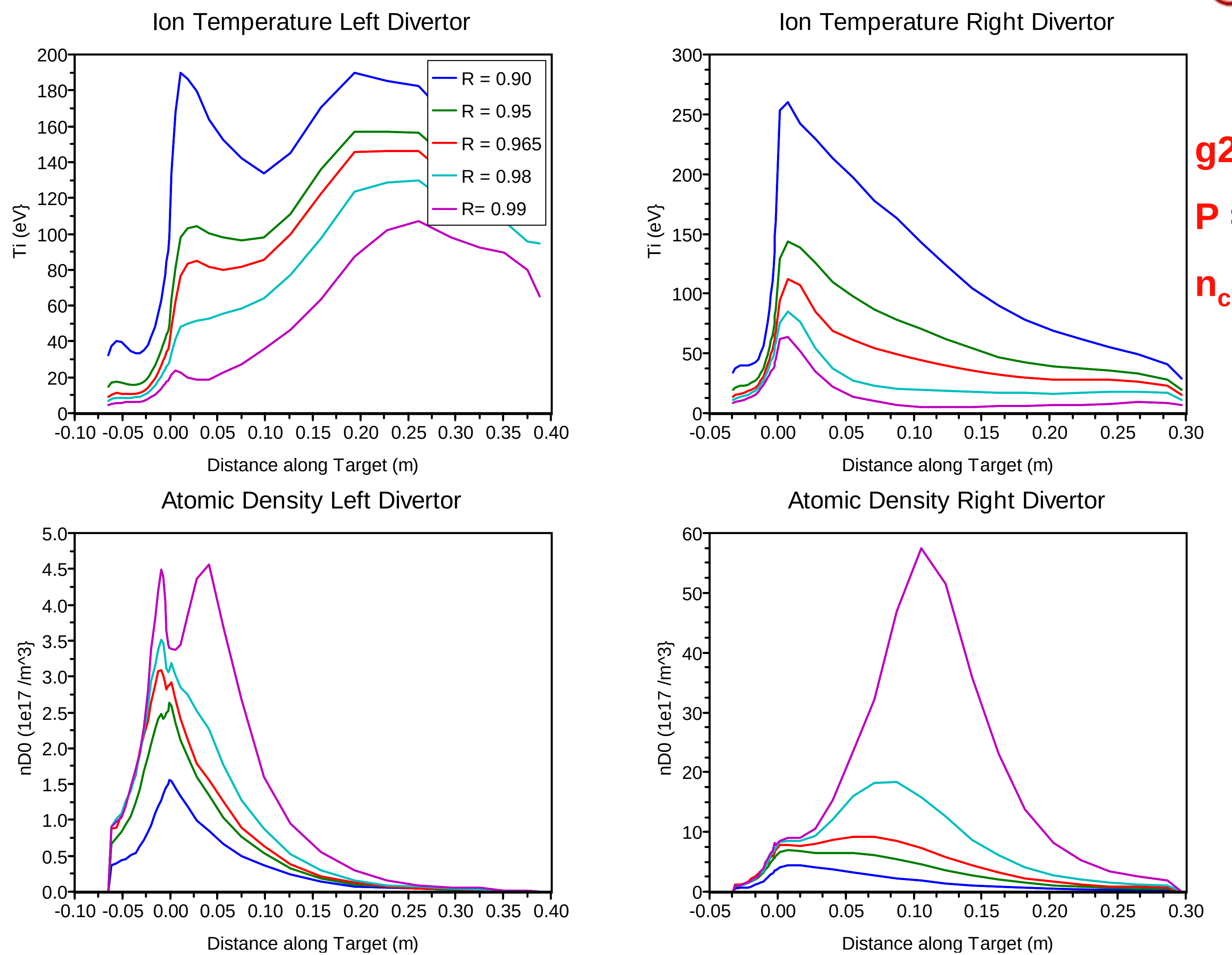


g20056

n_{core} = 1.5e20

R = 0.95

Basic predictions of recycling scan - divertor

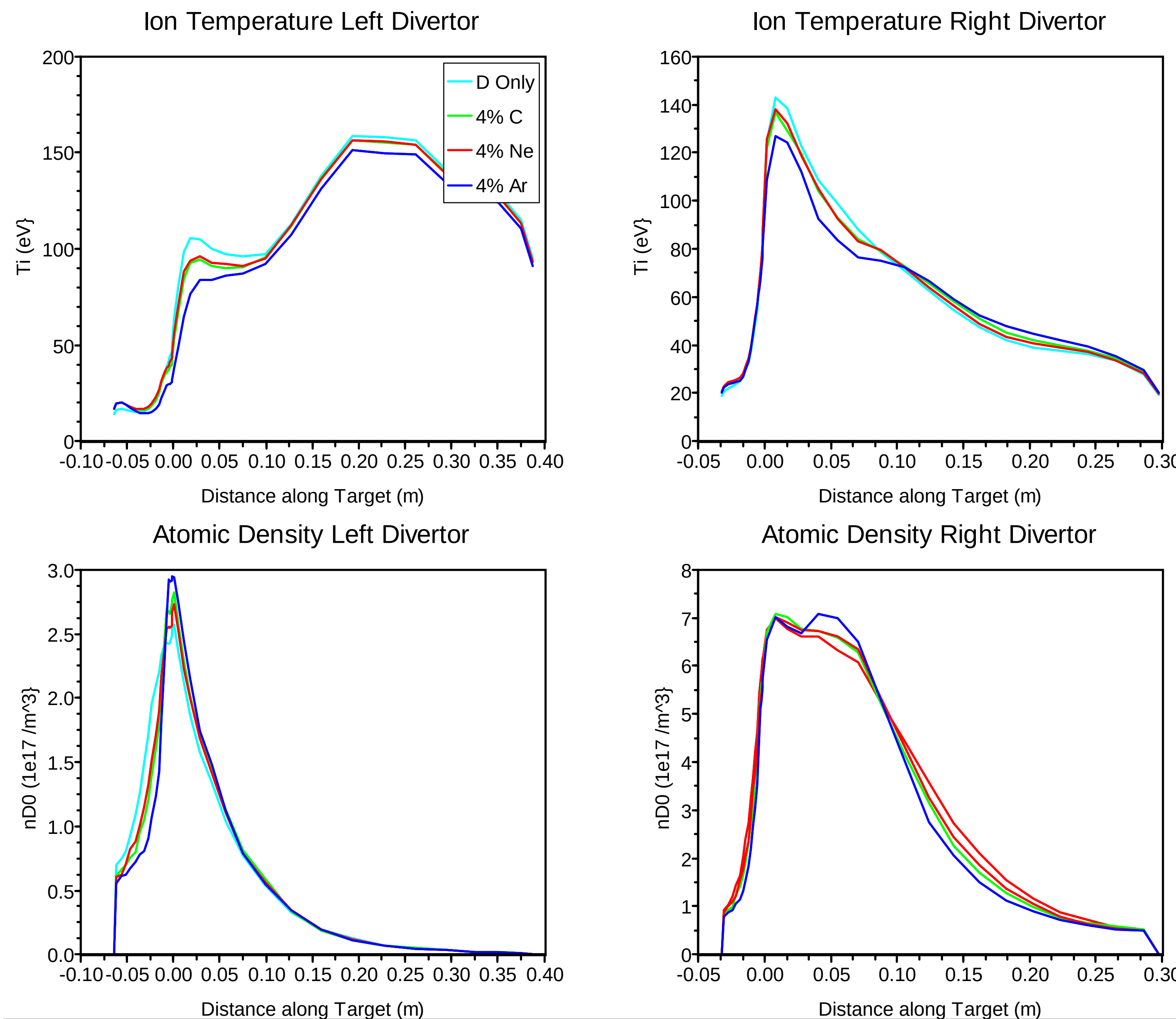


g20056

P = 30MW

n_{core}= 1.5e20

Adding impurities shows SOL radiation is limited at these Te

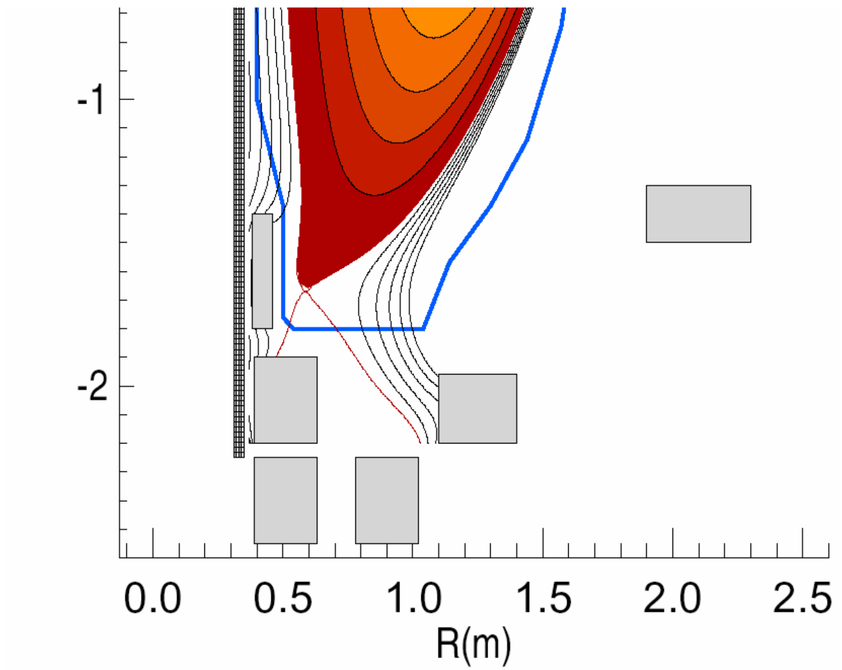


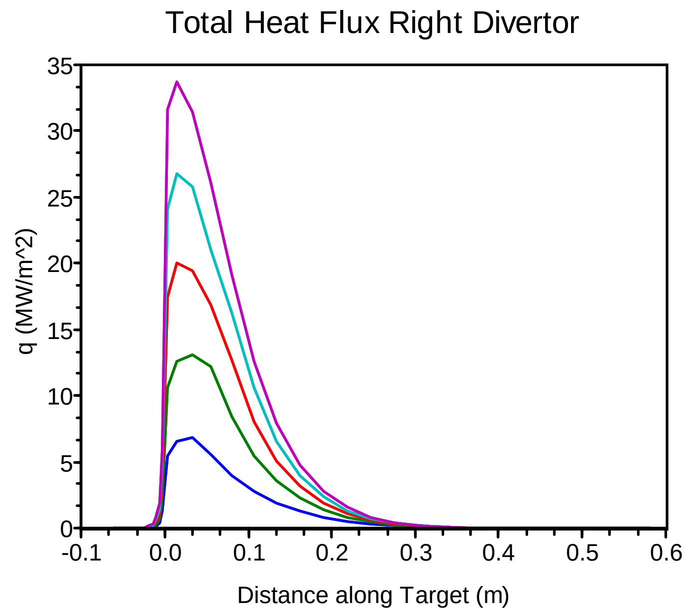
P_C = 1 MW

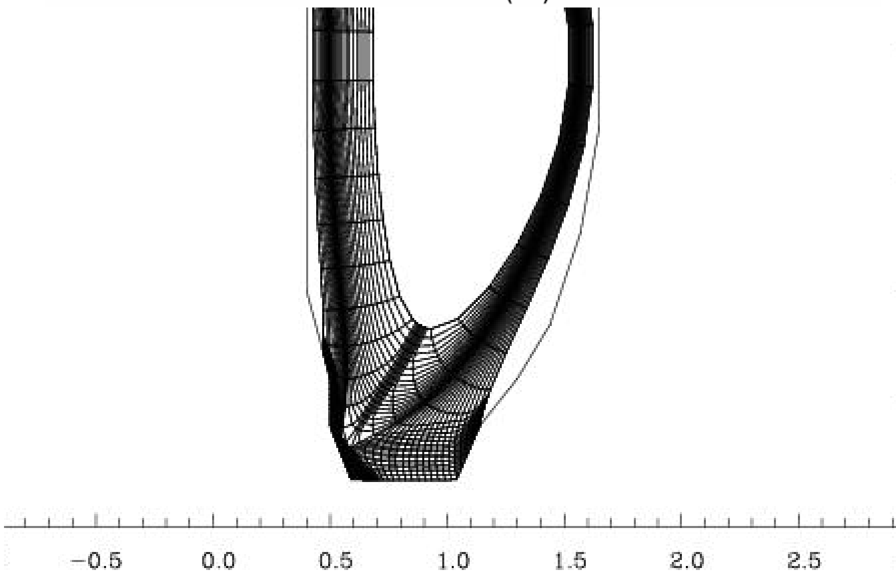
P_{Ne} = 1 MW

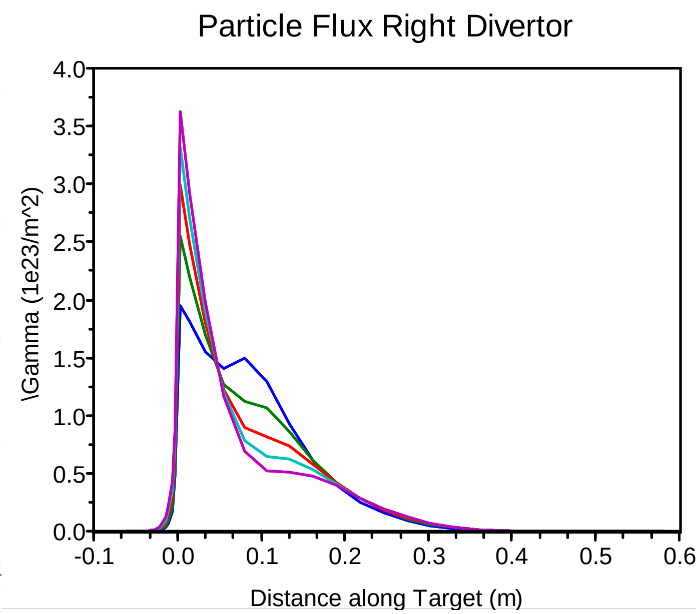
P_{Ar} = 4 MW

200054 Basic predictions of power scan - divertor

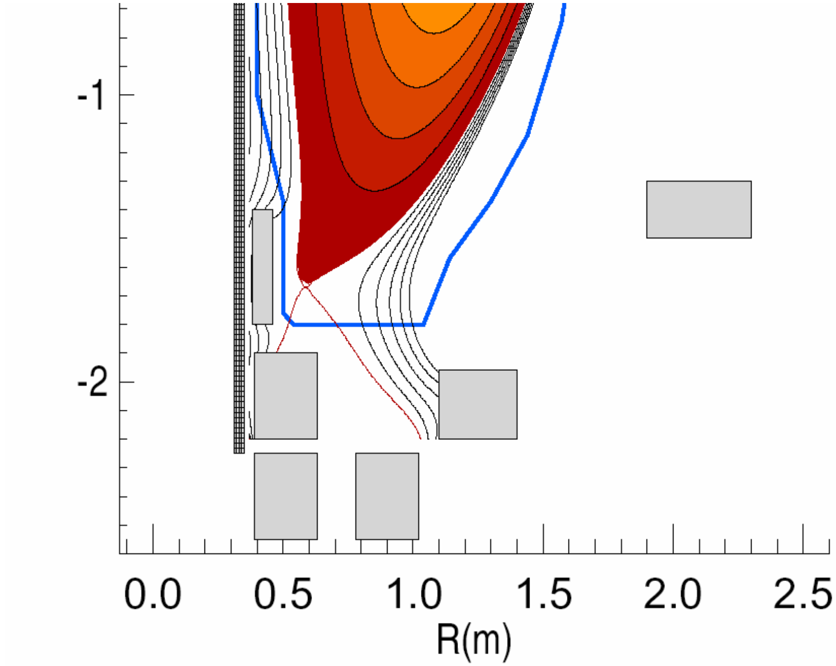


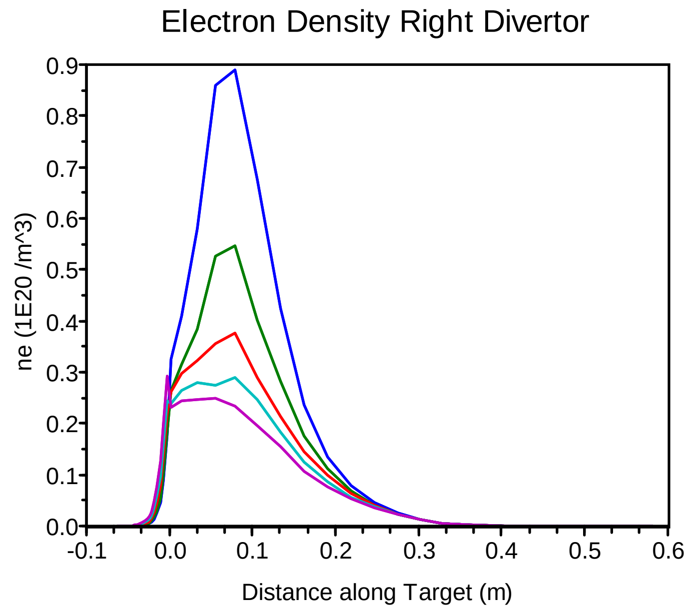


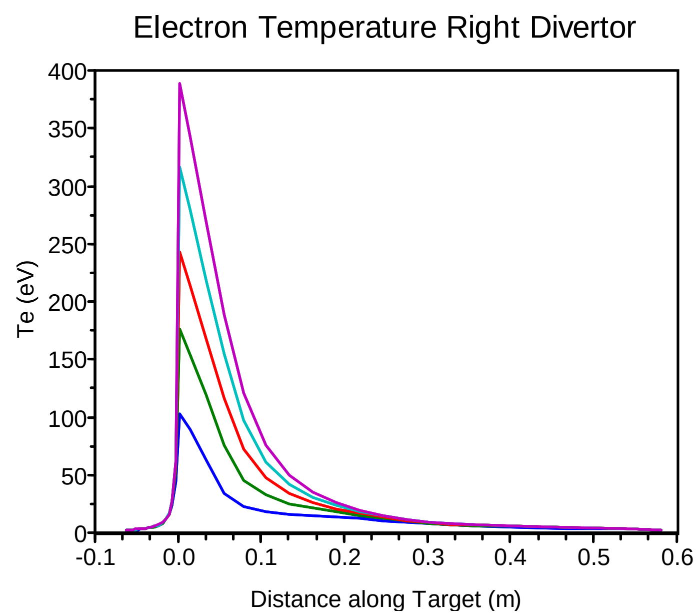


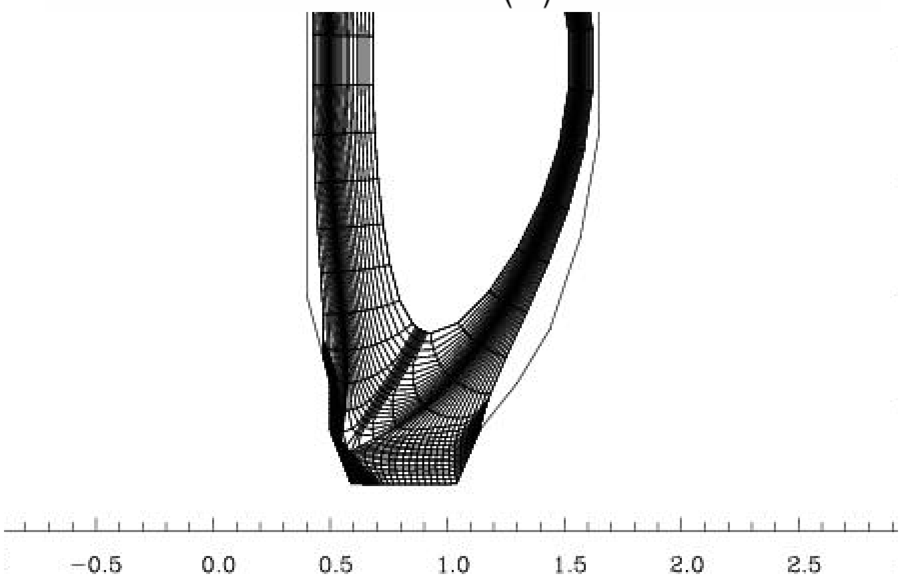


200054 Basic predictions of power scan - divertor

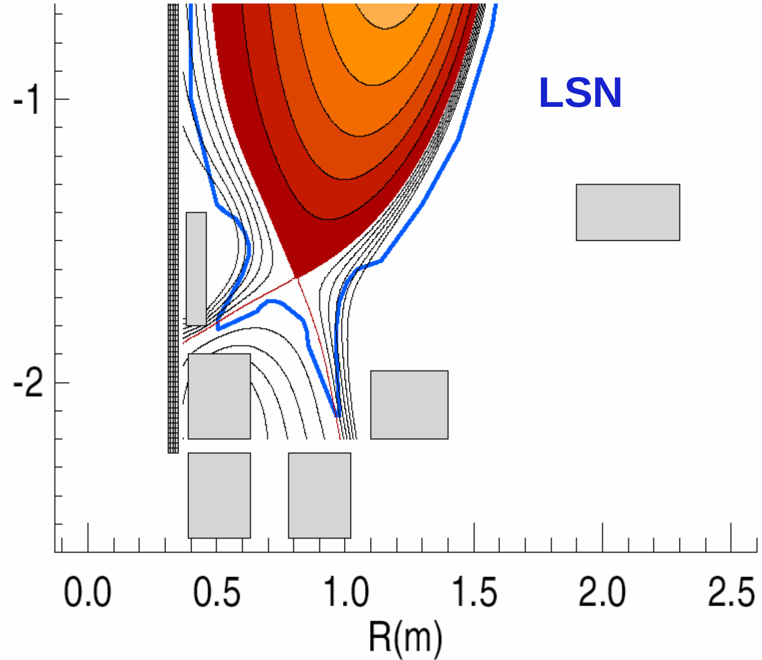


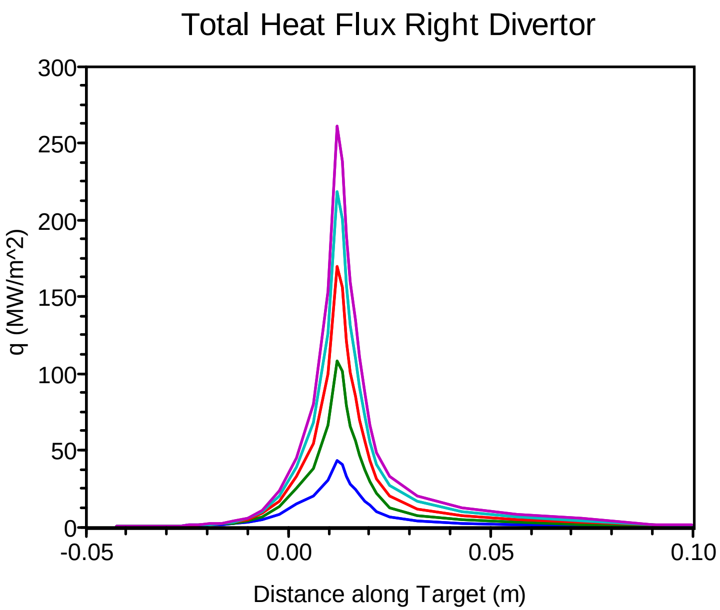


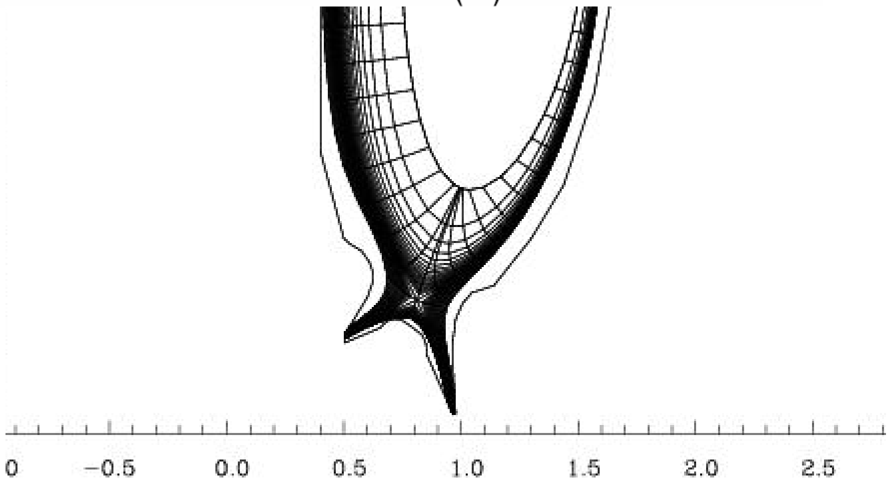


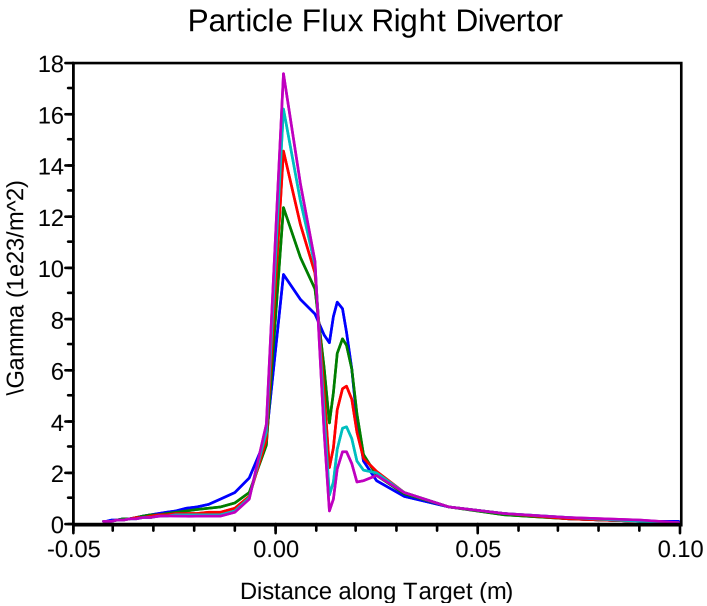


200057 Basic predictions of power scan - divertor

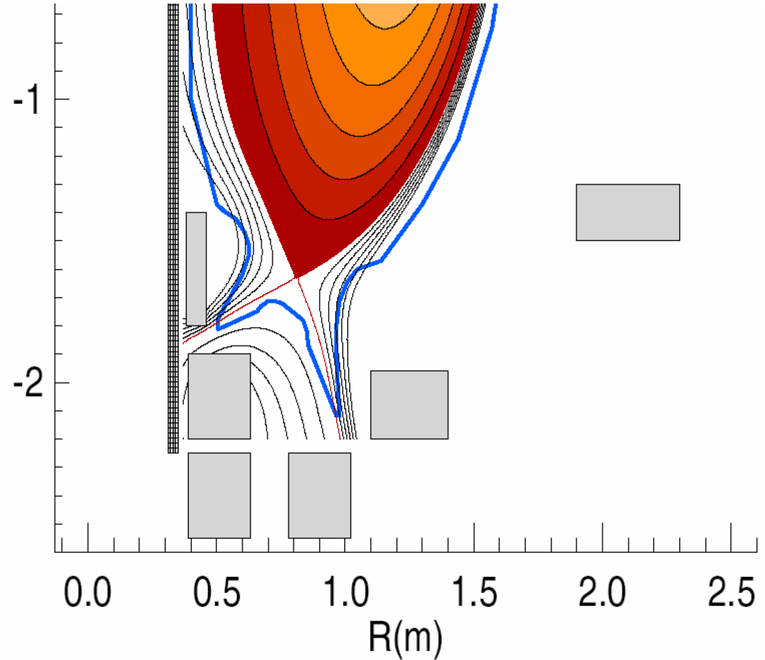


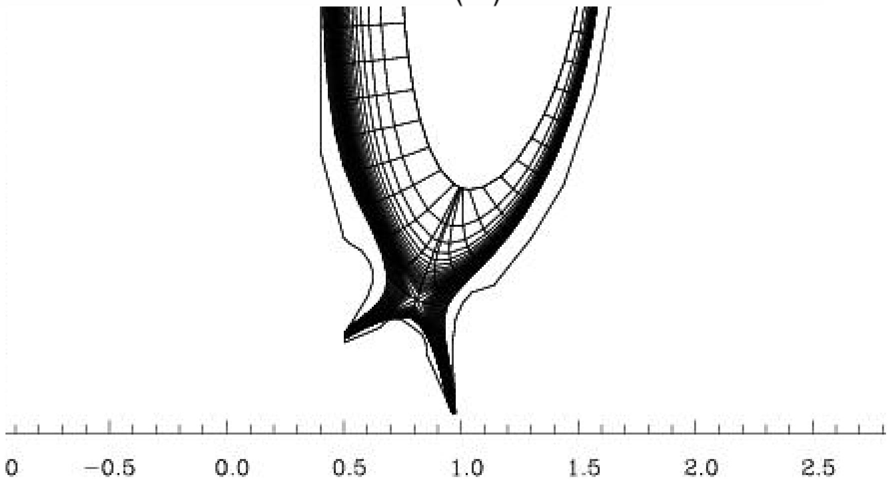


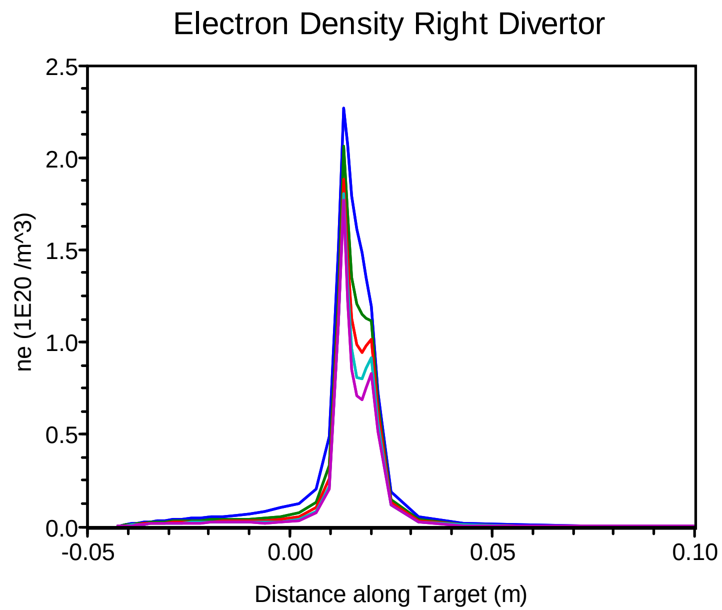


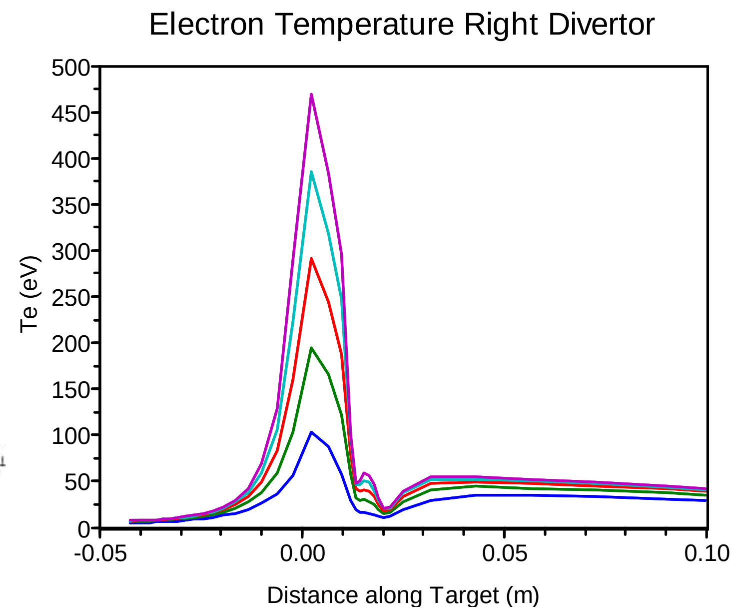


200057 Basic predictions of power scan - divertor

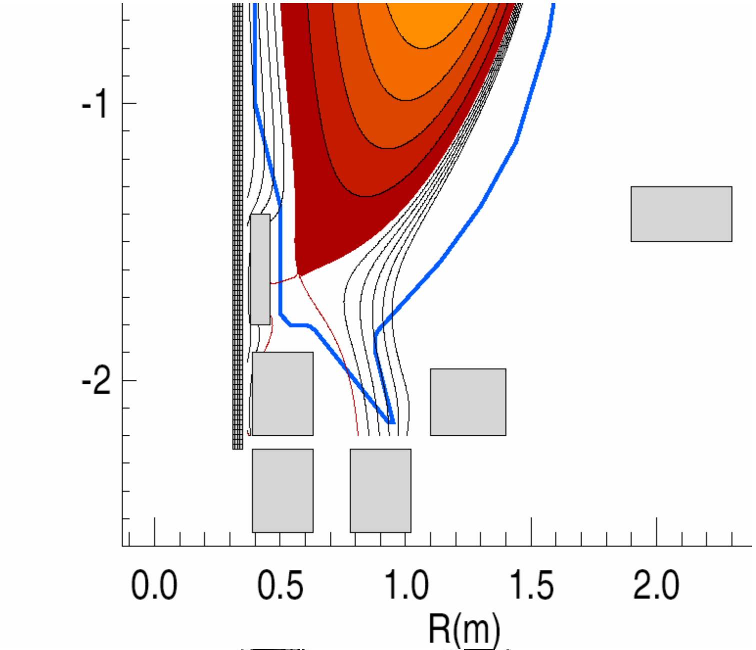


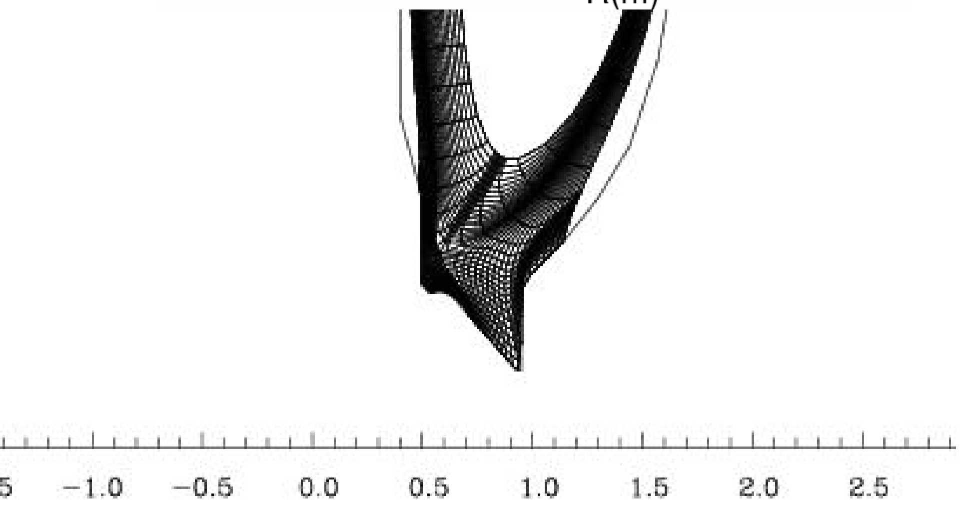


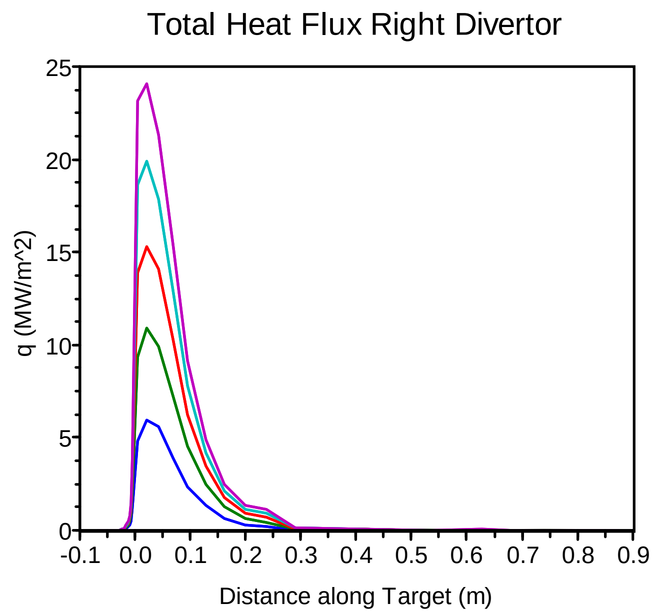


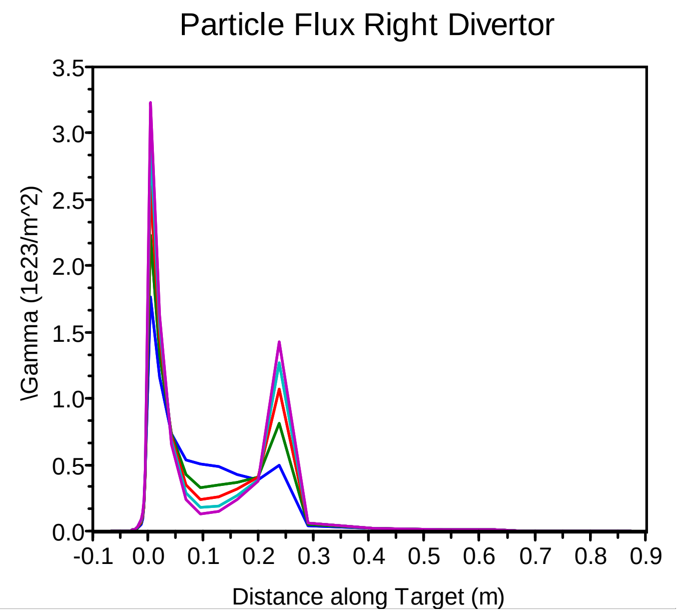


200058 Basic predictions of power scan - divertor





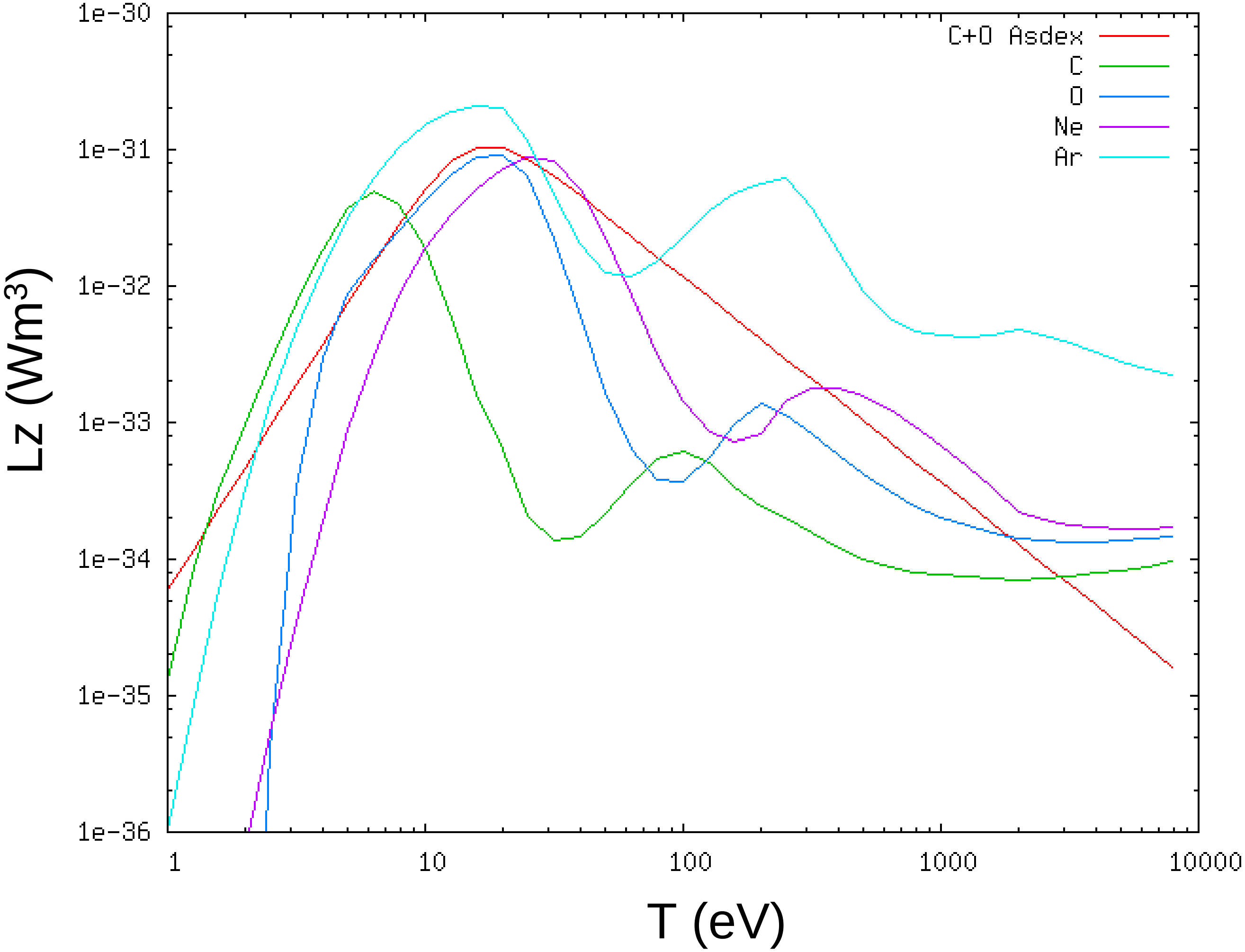




Artificial Radiation Model

Fixed impurity concentration f: $n_Z = f*ne$

Radiated power is $L_Z ne*n_Z$



200058 Basic predictions of power scan - divertor