U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

UEDGE modeling of snowflake divertors in NSTX-U

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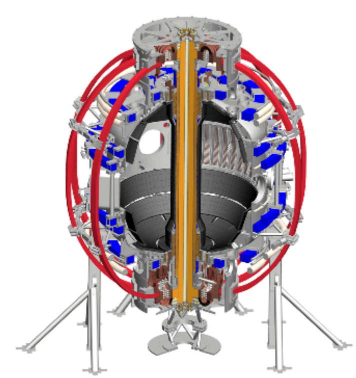
PPPL



LLNL-POST-707405

Abstract

New UEDGE code capabilities have been developed for simulations of snowflake (SF) divertors (SF-plus/SF-minus) with NSTX-U simulated equilibria. A robust grid generator for SF magnetic configurations including nonorthogonal plate geometries has been developed. UEDGE convergence is achieved on SF grids with a secondary X-point. Different SF-minus and SF-plus geometries are compared with each other permitting various physics studies such as investigating the effects of leg lengths or plate geometries using different impurity and transport models. The results include: (i) Leg lengths of a SF-minus affect the distribution of the parallel velocity, core performance (temperature) and detachment for a fixed fraction impurity model. (ii) Heat flux at the additional strike point in a SF-minus geometry is observed without enhancing the transport. (iii) Radiation front moves further away from divertor plates for shorter legs. Post-processing analyses are performed via a UEDGE module under OMFIT.

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Highlights & Conclusions

- Development of **Gingred**, a new universal grid generator: (main collaboration with **M.V. Umansky**)

Universal 2D indices maps & grids for snowflakes (w/ & w/o plate geometry constraints)

- First time of snowflakes simulations with UEDGE:

Effects of SF-minus & SF-plus on detachment & core
Effects of leg lengths w/ SF-minus & impurity fixed fraction
Effects of Pcore w/ SF-minus & charge state resolved

- Perspectives on Gingred/UEDGE:

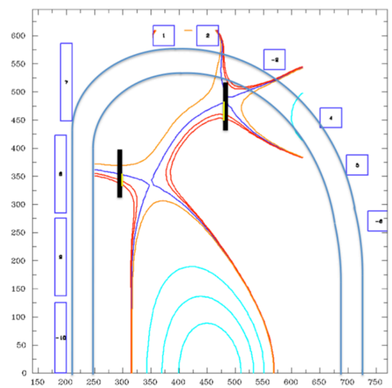
Reach the attachment with Pcore, ncore, D, χ
Observe the effects of plate geometries and other impurities
Gingred grids for FRC (PPPL), ARC (MIT), etc.

1 - Motivation of Advanced Divertors

Soukhanovskii, Edge Coordinating Committee Fall 2014 Technical Meeting

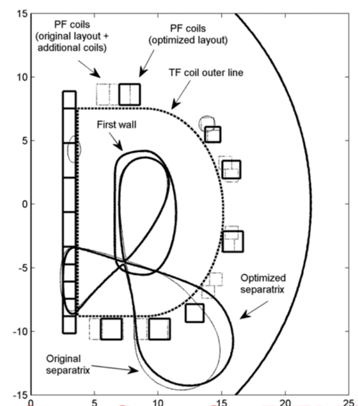
Goals:
Long life divertor components, cost efficiency, real time control, advanced confinement

Many pre-DEMO and DEMO designs include snowflake and Super-X configurations



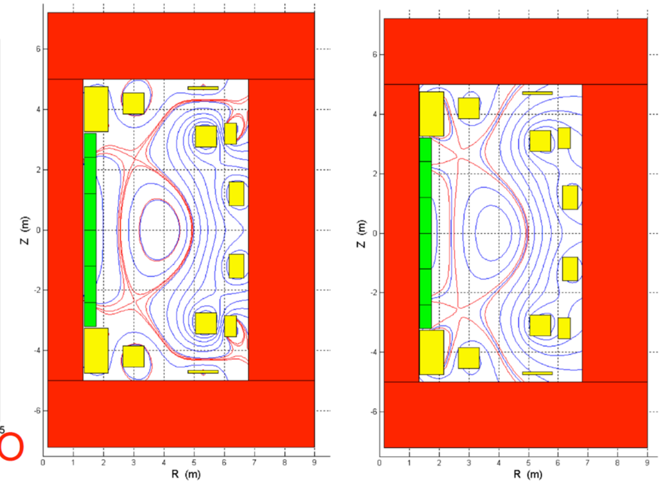
Super-X for Aries Slim CS

M. Kotschenreuther et. al, ARIES Workshop 2010



Snowflake for DEMO

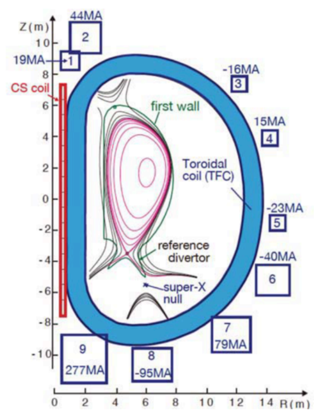
R Albanese et. al, PPCF, 56 (2014) 035008

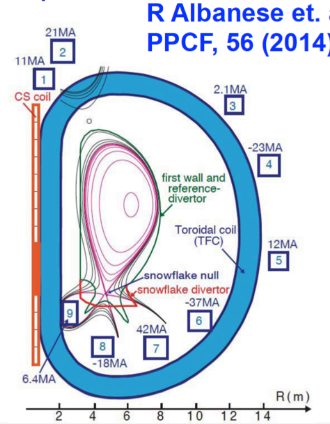


China Fusion Experimental Reactor

Y. Wan, SOFE 2013

Z. Luo et.al, IEEE TRANSACTIONS ON PLASMA SCIENCE, V42, 2014, 1021





Super-X and Snowflake for DEMO

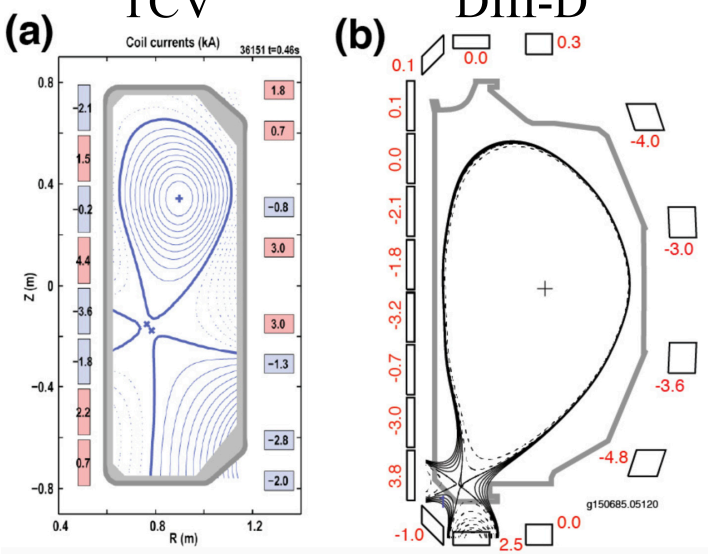
N. Asakura et.al, Trans. Fus. Sci. Tech. 63, 2013, 70.

1 - Radiative snowflake could be the best solution

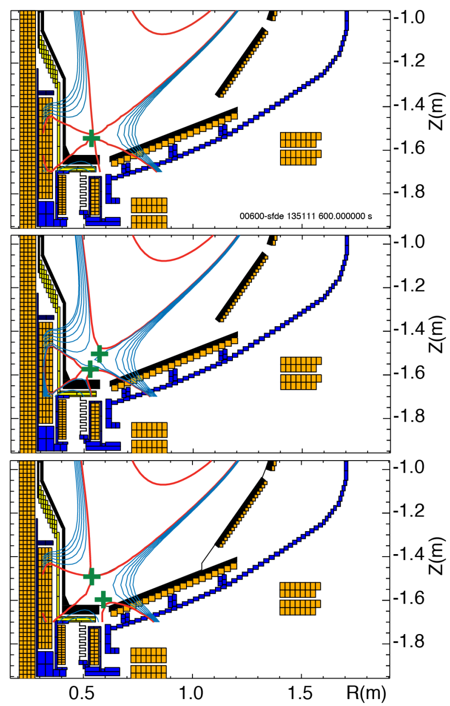
Ryutov & Soukhanovskii, PoP **22** (2015) 110901

- Experimental observation in TCV, DIII-D & NSTX of the peak heat flux reduction in presence of radiative snowflakes
- Could be the best solution for material protection during ELMs
- All future devices will have to manage the heat flux: ST-FNSF, ARC (MIT), ITER, DEMO…
- NSTX-U parameters: P_{NBI} up to 10MW

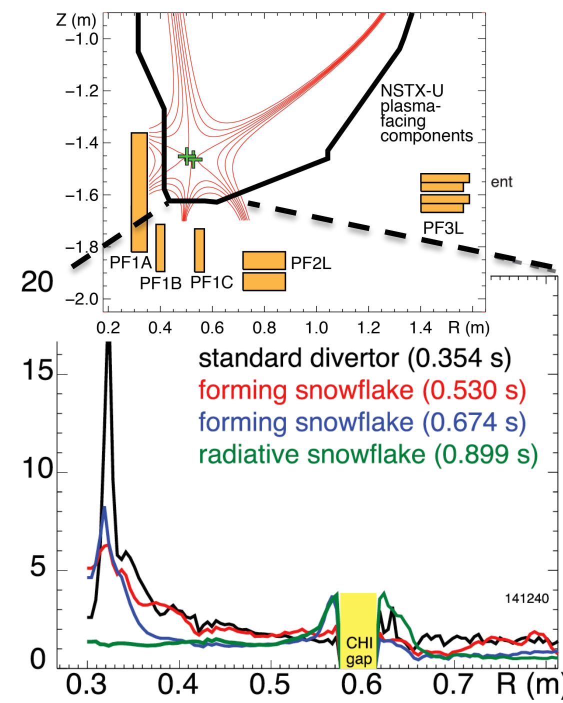
TCV DIII-D



NSTX-U



NSTX-U

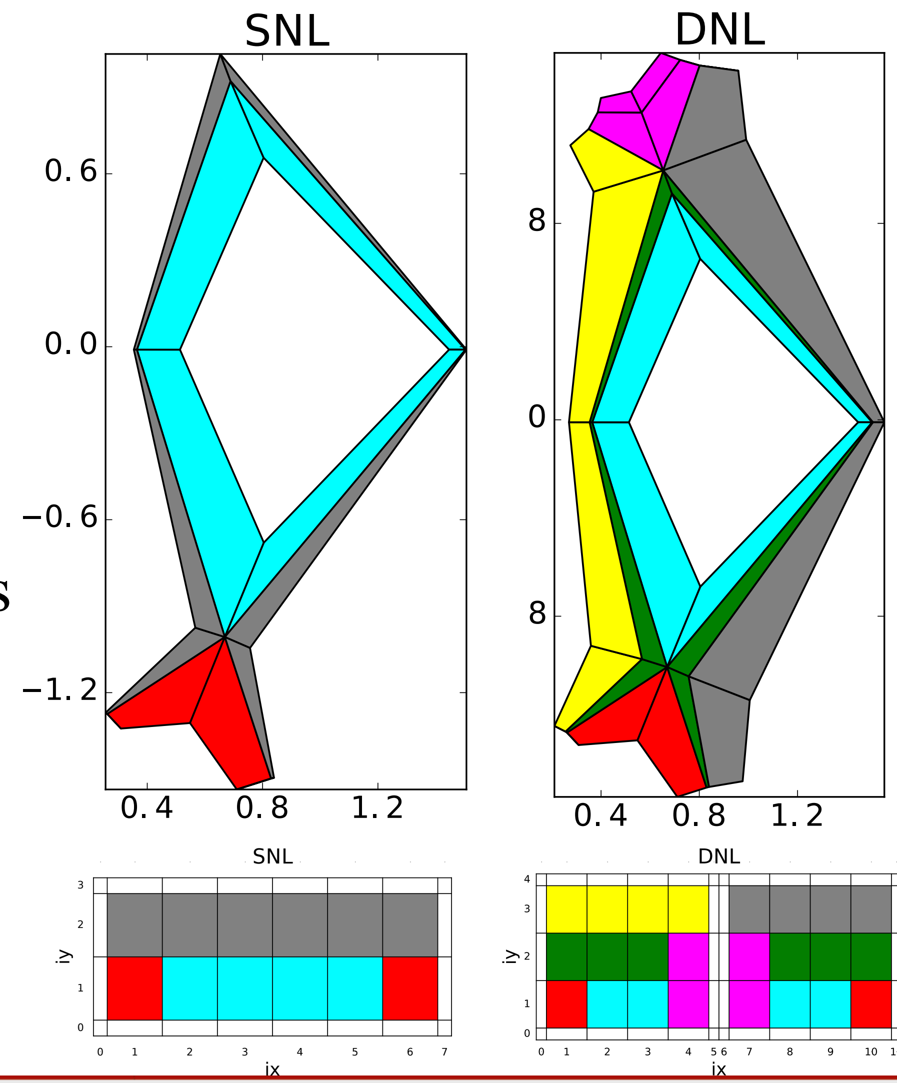


2 – Development of a new universal grid generator: Gingred

Gingred, a universal grid generator for arbitrary magnetic geometry (IDL code for now)
- uses reliable built-in IDL routines such as root finding & a biquadratic interpolation of magnetic flux
- interactive debugging capability
- user interface, manual refinement
- generic grid via 2D maps of indices
- nonorthogonal legs constraints from arbitrary plate geometry
- standard light procedure to import new grids in UEDGE

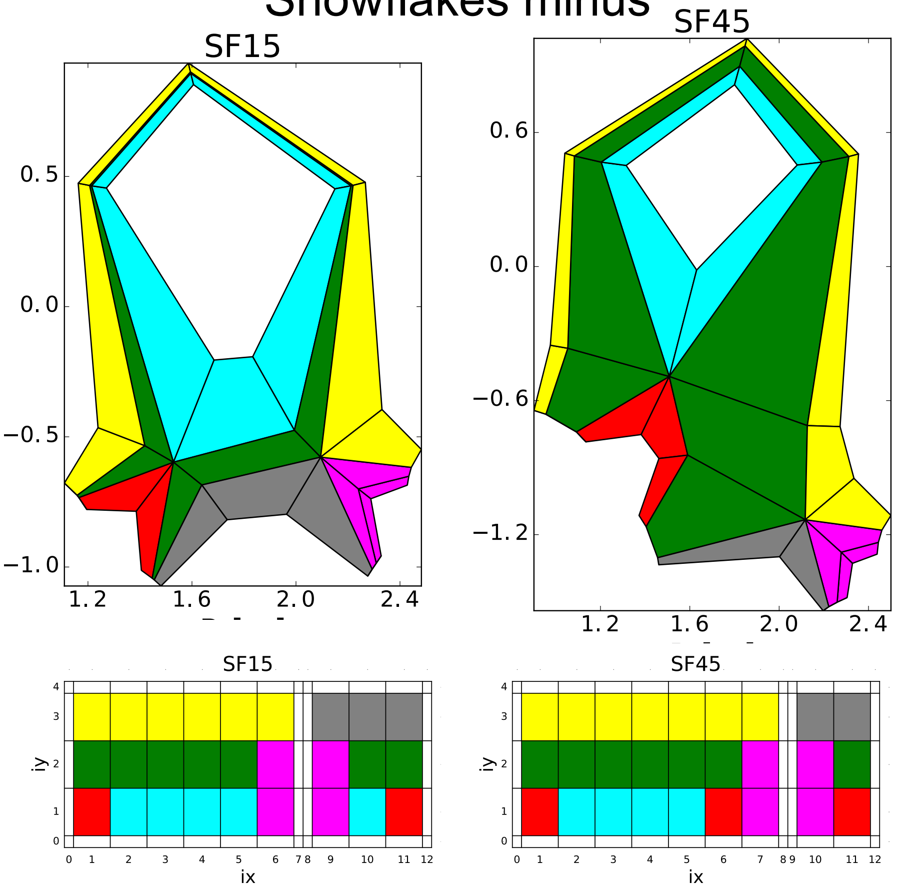
Special thanks to M.E. Rensink & T.D. Rognlien

Initial grids and indices maps

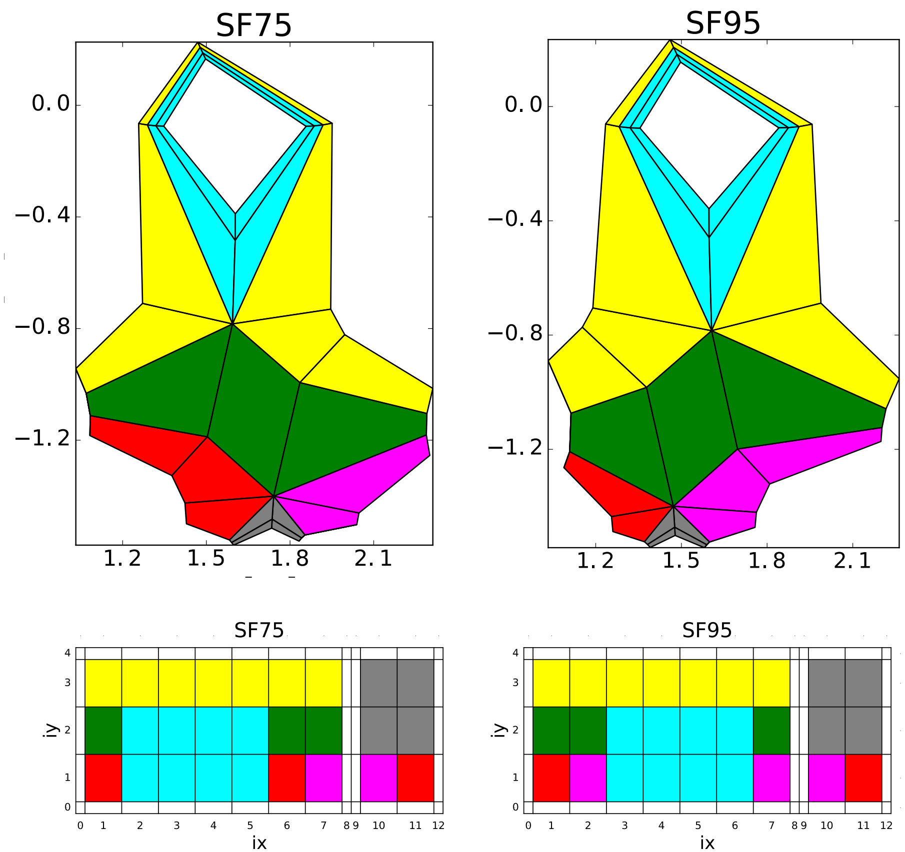


2 – Main snowflakes grids

Snowflakes minus



Snowflakes plus



Perspectives:

- Generalization to an arbitrary number of X-points: FRC (0 X-points, already done), cloverleaf (3), lower-SF + upper X-point, lower-SF + upper-SF, etc.
- Improvements: non mid-cells splits, Python version (for OMFIT)

2 – Main command lines of Gingred

Detailed manual is under progress. It contains explanations and examples of using the following IDL commands [many options are not detailed]:

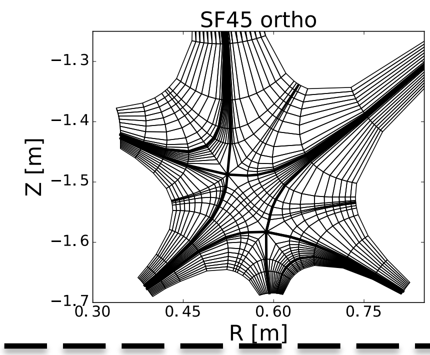
- `read_efit`
  to import a magnetic equilibrium from a standard geqdsk file
- `gingred, /m, conf="SF75"`
  to specify boundaries and X-point(s)
- `gridcells_all, g0, conf="SF75"`
  to create initial grids (see previous slides)
- `show_grid, g0`
  to plot the grid
- `doubler`, `doublep`, `refgridr` and `refgridp`
  functions to refine the grid
- `plates_add, g0, gpout=g1`
  to add nonorthogonal legs with plate geometry constraints
- `grid_export, g1`
  to create the grid file gridue

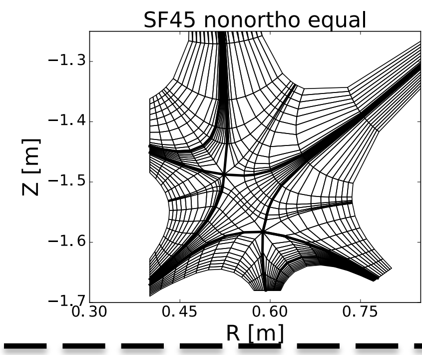
Each step is straightforward for new users with the visualization (plots)

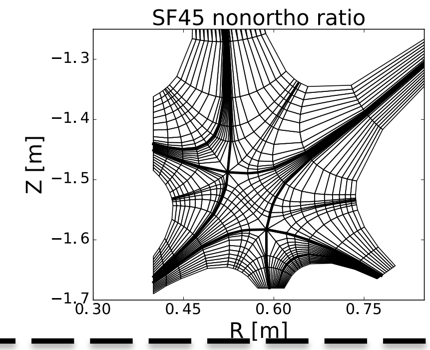
2 – Examples of snowflakes grids

Orthogonal legs | Nonorthogonal legs with plates constraints

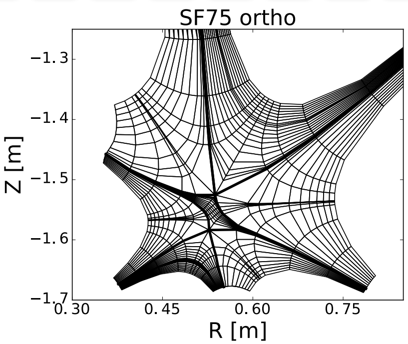
Snowflake minus

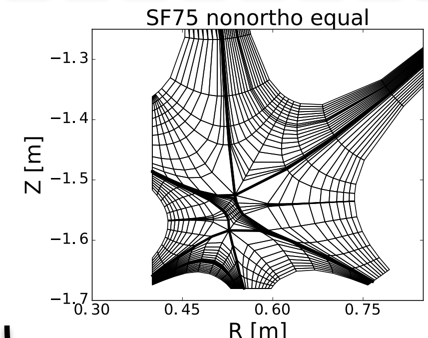


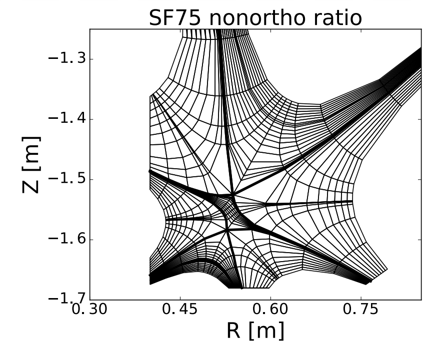




Snowflake plus







2 available options (for now): "equal" or "ratio" distribution of cell poloidal lengths

O. Izacard & **M.V. Umansky**, (2016) *Gingred, a universal grid generator for arbitrary magnetic geometry* (manuscript to be submitted soon in *Comm. Comput. Phys.*)

3 – Overview of UEDGE challenges

Main new solutions/techniques for UEDGE simulations:

- **Gingred** resolves the fact that the internal UEDGE grid generator is not ready for SF grids

- **Standardization**: All post-analysis scripts (BASIS) are now implemented in the UEDGE module of OMFIT framework (Python):
  Notebook, particle & power balance, radiation, heat flux, etc.

- Used standard procedures to **converge** UEDGE (a few exceptions):
  isbcwdt=1, Dirichlet boundaries, ftol=1e-8, etc.

- All snowflake grids generated by **Gingred** and **imported** in UEDGE without using the internal UEDGE grid generator

3 – Parameters used in our simulations

Species: Deuterium ions + neutrals, Carbon impurities + neutrals

Impurity model: Fixed fraction (afracs=5%) vs Charge state model (fhaasz=1)

Particle diffusion D = 0.5 m^2/s, Heat conduction kye = kyi = 1.5 m^2/s

Radial and poloidal constants

Boundary conditions:

ncore=2e19 m^{-3} (or 2.5e19 m^{-3}), pcoree=pcorei=2 MW (or 3.75 MW)

recycm=-0.5 (parallel velocity)

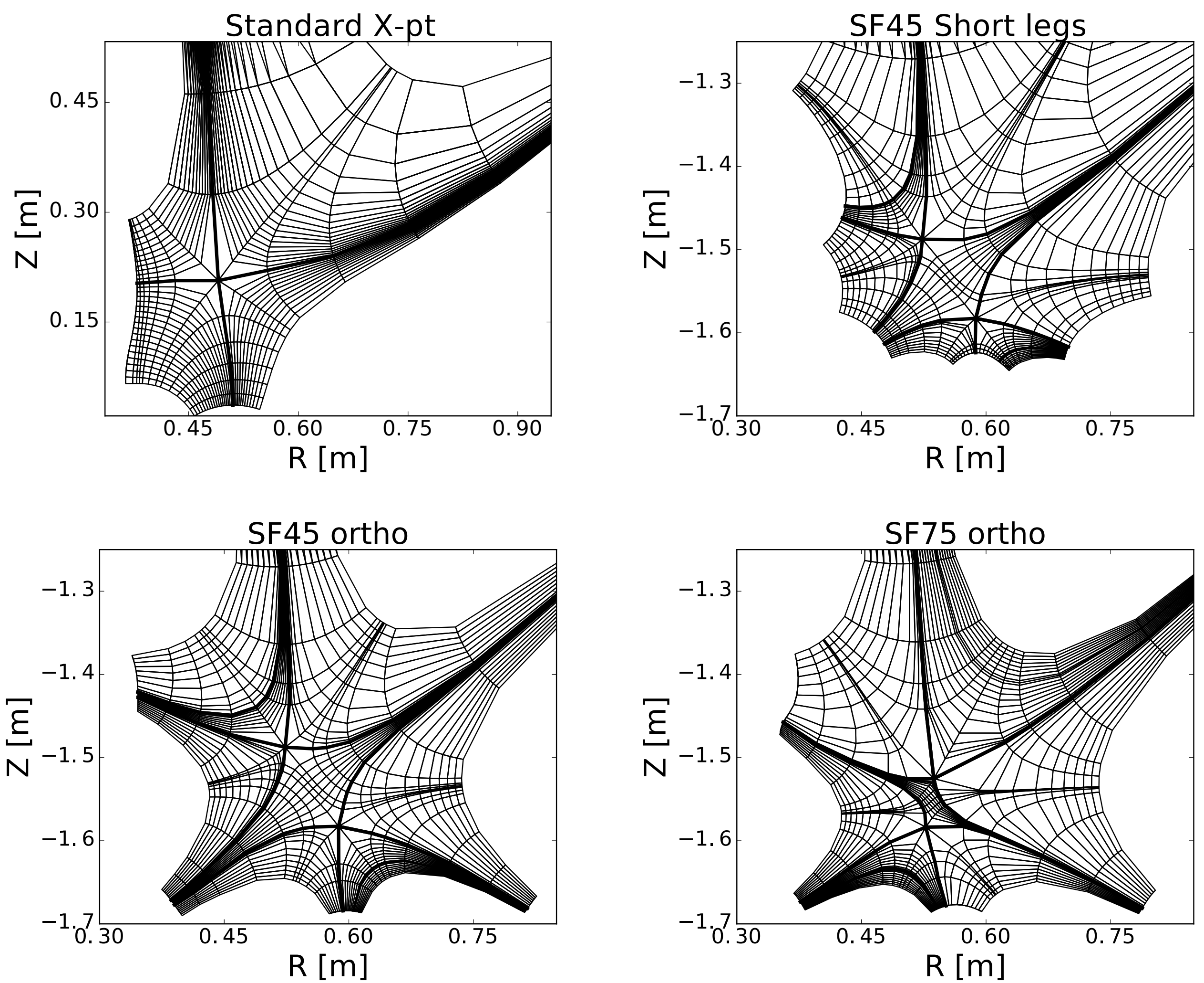
high recycling: plates recycp=0.99-1, wall recycw=1

Dirichlet boundaries

no gas puffing (except SF75)

3 – Comparison geometries

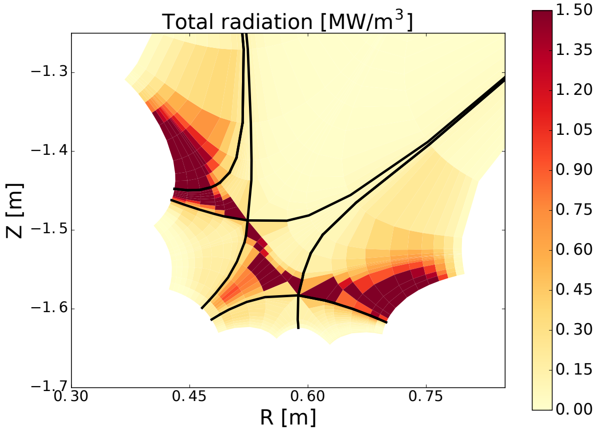
Need comparison of:
 - Parallel connection length
 - Flux expansion
for Standard X-pt, SF-minus (SF45) short legs, SF45 long legs and SF-plus (SF75)



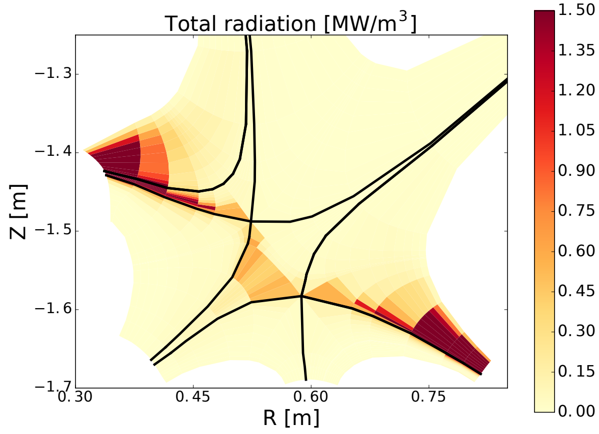
3 – Total radiation for different snowflakes

With Fixed fraction C

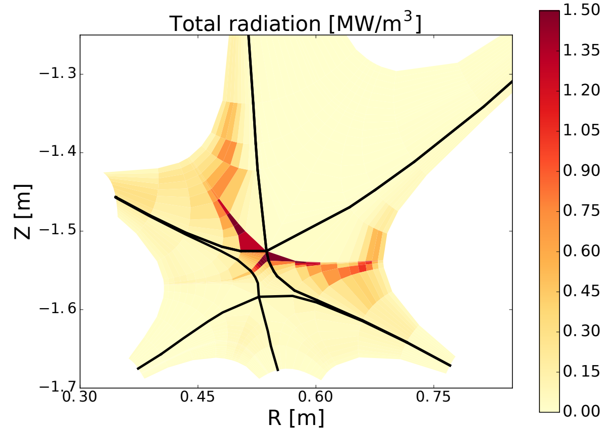
SF45



SF45



SF75



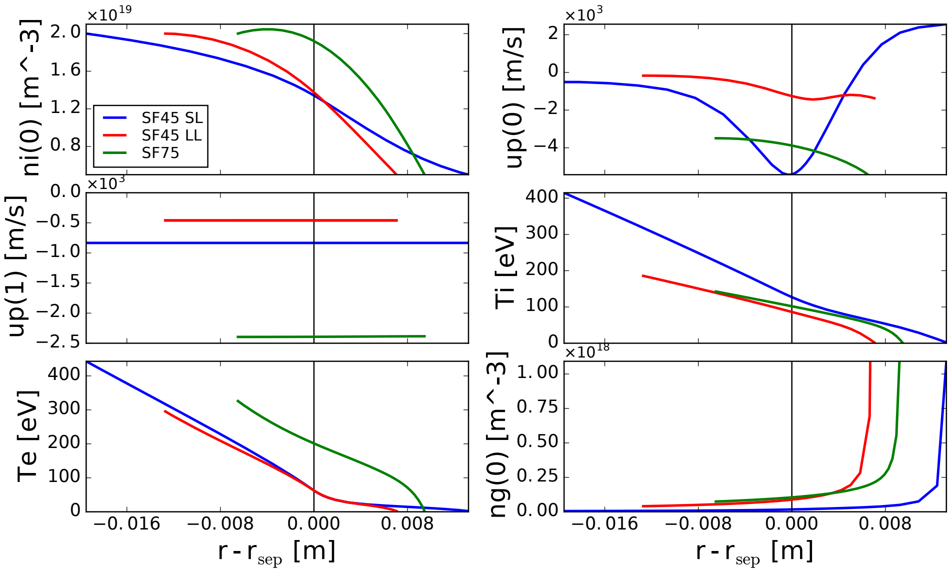
Gas injection explains the strong detachment

- Short legs shows higher total radiation between 2 X-pts than longer legs
- SF-plus is more likely to detach divertor plates
- SF-plus seems to better protect divertor plates due to position of radiation front!!!

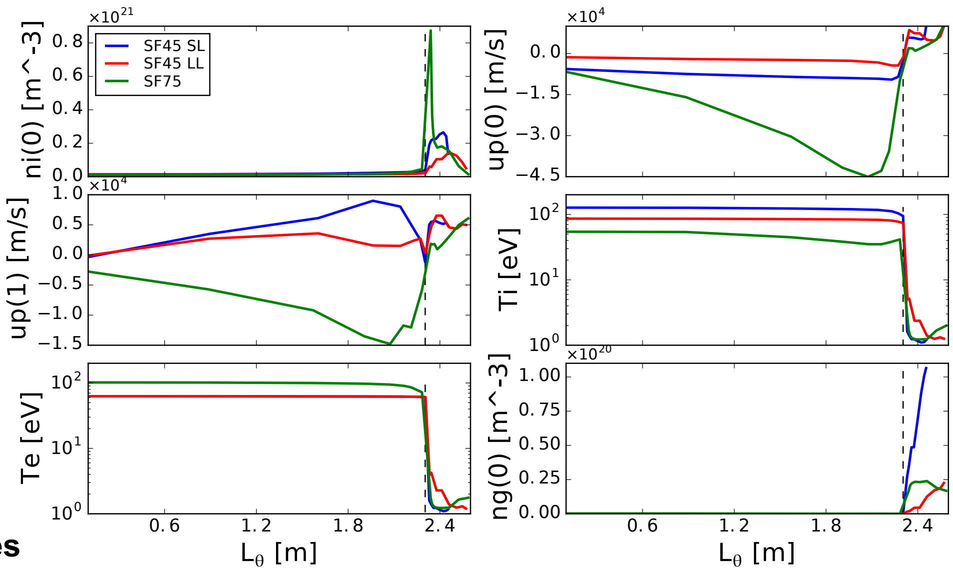
Need to increase core density and particle & temperature diffusions

3 – Effects of different SFs on OMP/θ profiles w/ fixed fraction C

OMP profiles

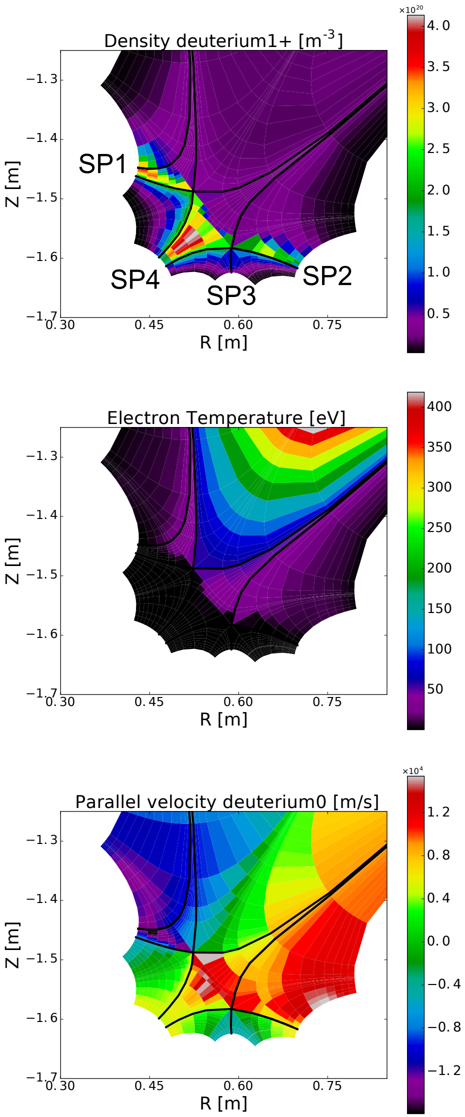


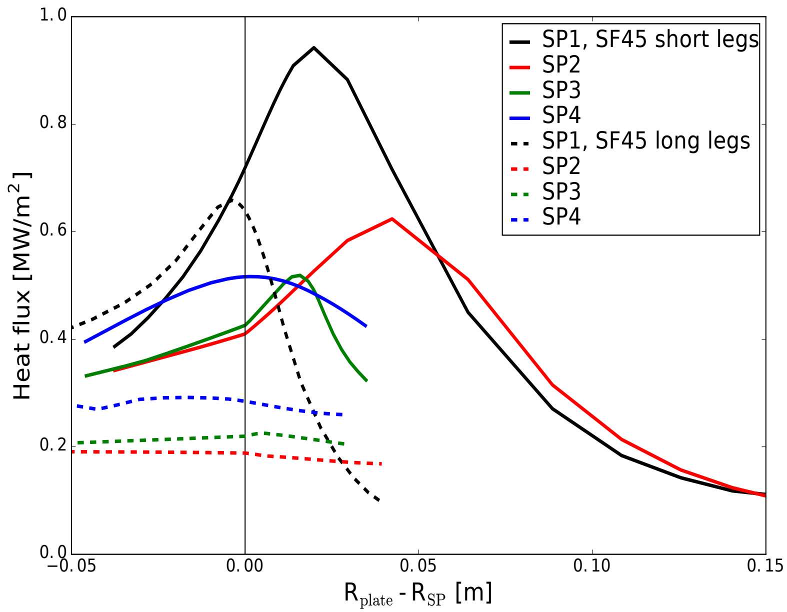
- Long legs in SF-minus seems to enhance the detachment
- SF-plus seems to offer better core performances but may result in stronger instabilities due to steeper gradients

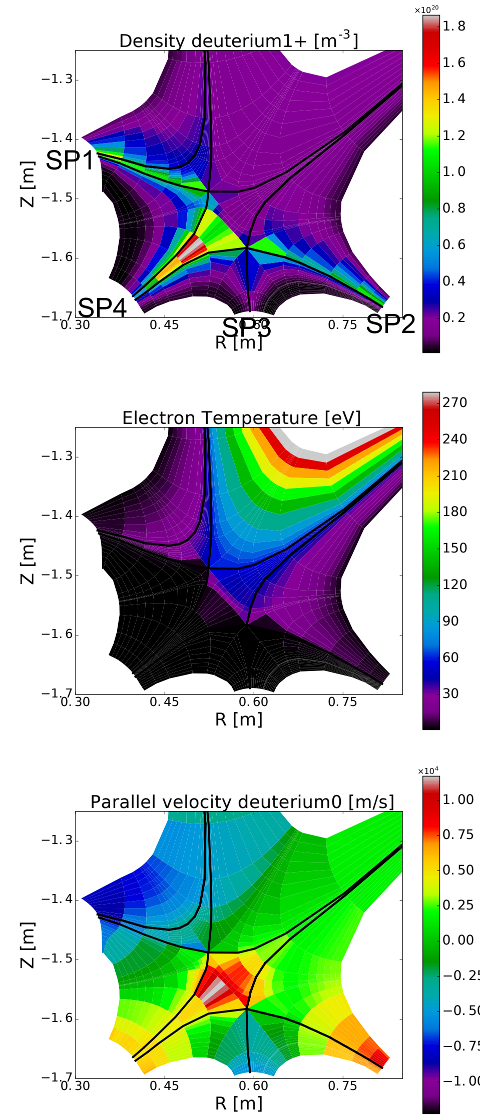


Poloidal profiles

3 – Leg length effects on heat flux for SF-minus w/ fixed fraction C







- LONG LEGS seems to protect more the divertor plates.

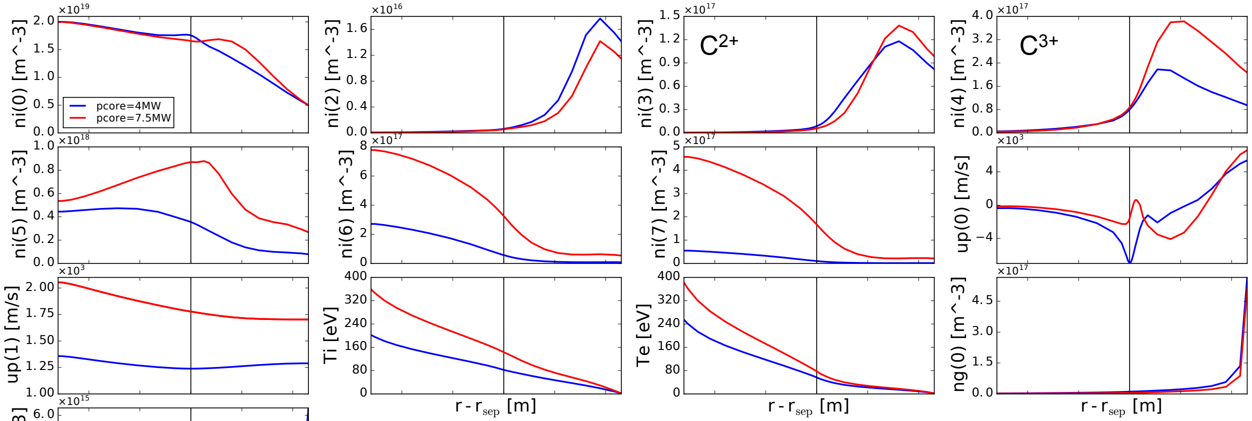
- Connection length dominates flux expansion in this case.

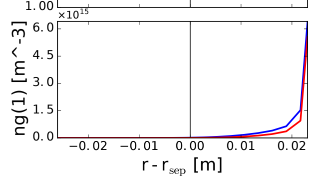
3 – Charge State Resolved (CSR): Pcore 4MW➔7.5MW effects on SF-minus

OMP and poloidal profiles help to diagnose the detachment trends:

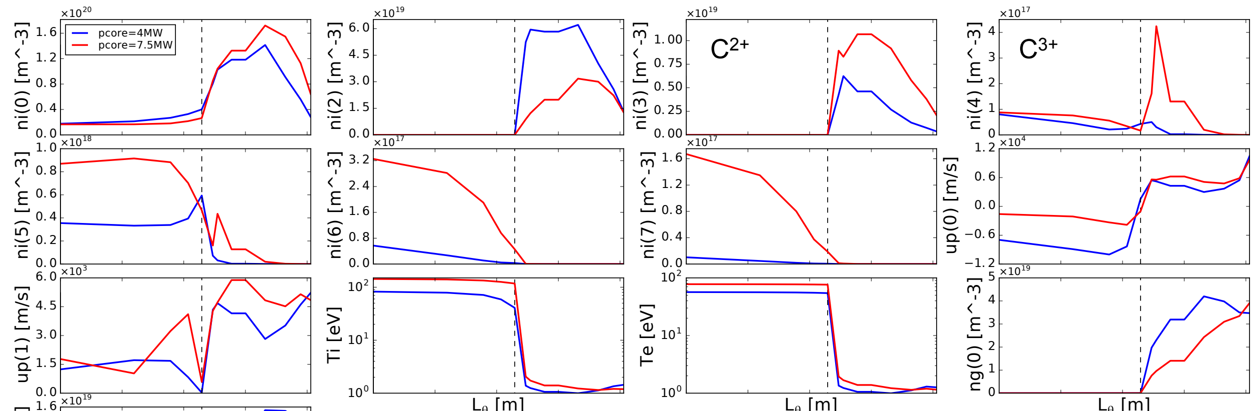
- $n_{Ck+}(k>2)$ increases w/ p_{core}
- n_{D+} peak moves away from separatrix => shift of peak heat flux w/ short legs?
- $v_{//,D+}$ shear significantly modified
- neutral densities significantly reduced below X-pt => inverse for ions above X-pt

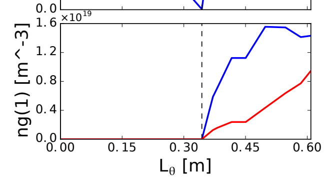
Need to move away detachment front from X-pt (poloidal)





OMP



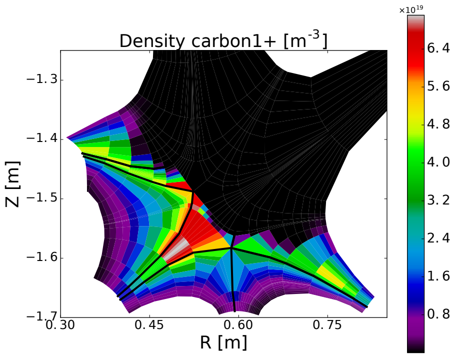


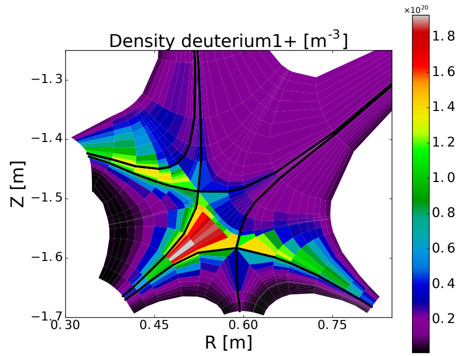
Poloidal profiles

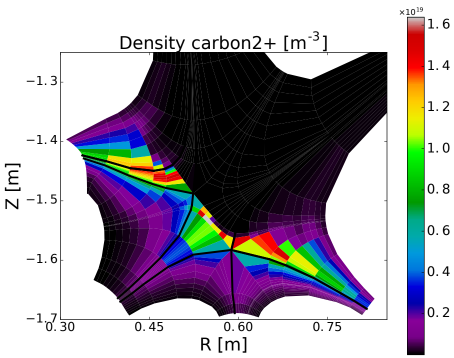
dashed line correspond to X-pt position, L_θ = distace w.r.t. OMP

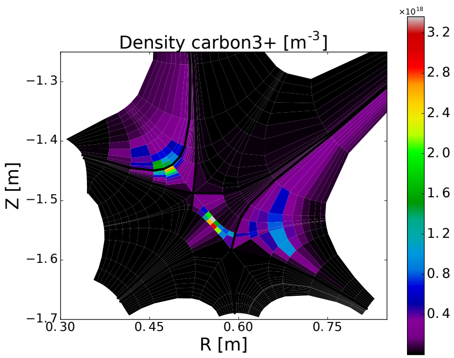
3 – CSR: Pcore 4MW➔7.5MW effects on radiation & detachment

4MW

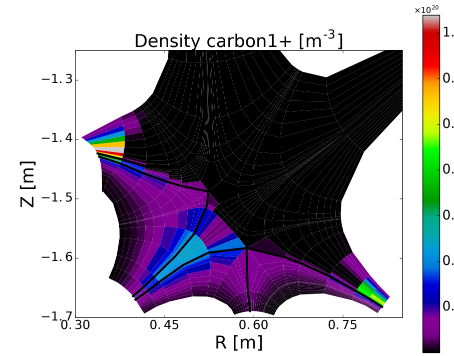


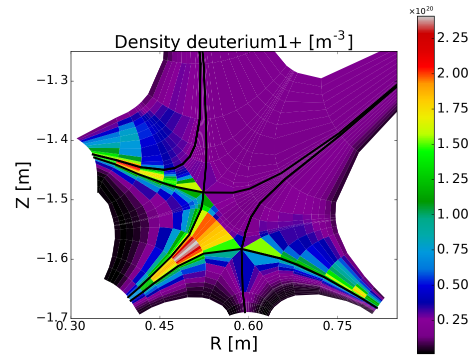


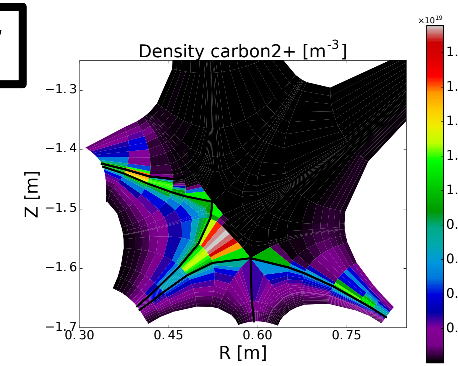


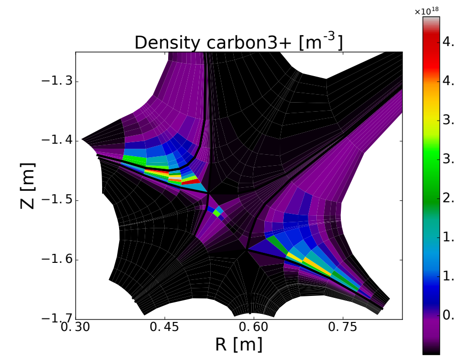


7.5MW



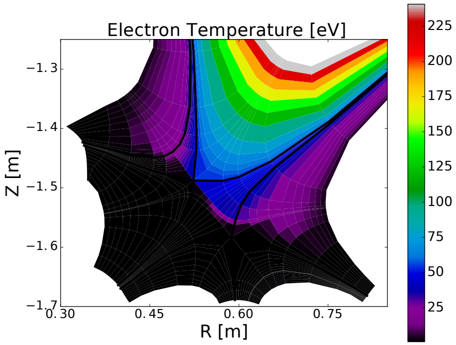


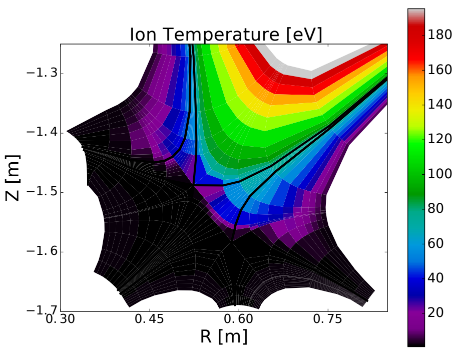


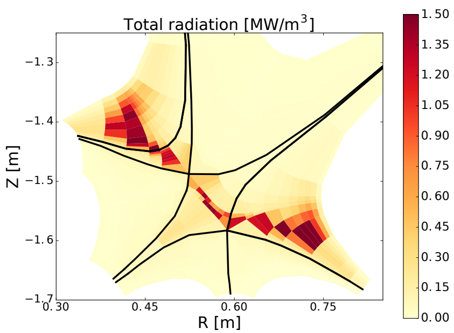


- **Carbon3+ density increases in front of divertor plate**
- **Pcore could let us play with heat load repartition on different plates**

3 – CSR: Pcore 4MW➔7.5MW effects on radiation & detachment

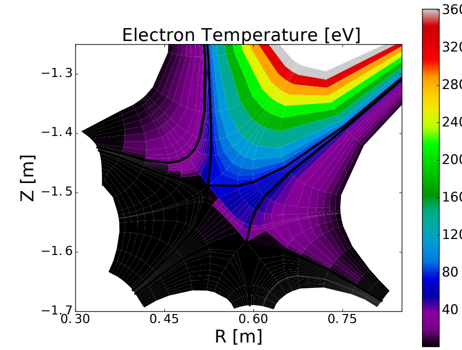


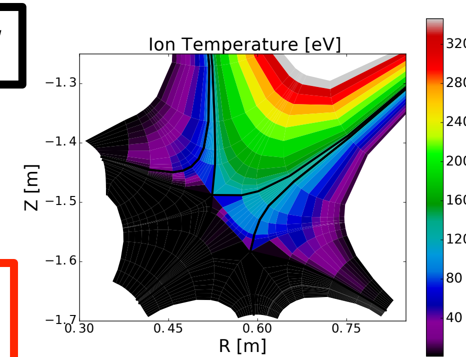


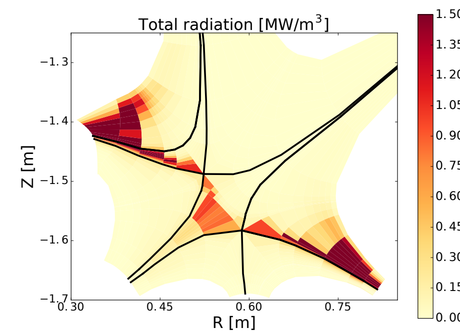


4MW

7.5MW







- Radiation and detachment front start to move toward divertor plate

Need to increase core density and particle & temperature diffusions

4 - Discussion

Results of our UEDGE simulations:

• It seems there is a competition between the radiation in the snowflake region and the radiation in front of the divertor plates:

- radiation enhancement between the 2 X-pts when short legs
- radiation enhancement in front of divertor plates when long legs

• Front of detachment moves toward snowflake by increasing input power

• Peak heat flux in a SF-minus is reduced with longer legs

• Full impurity model shows stronger radiation with a SF-plus in front of divertor plates w.r.t. the fixed fraction model. The total radiation power is under-evaluated by the fixed fraction model.

4 - Perspectives

- **Snowflakes simulations in UEDGE:**
  - NSTX-U snowflakes (with 2 X-points) are performed with full C impurity model. Need to validate UEDGE simulations against DIII-D snowflakes experiments. Can we find the best divertor configuration? (open/close inclinations, distance, etc.)
  - Snowflake transport modification by churning mode
  - Radiative snowflake divertor with impurities (CD_4, N_2, Ne, Ar)
- **Standardization of UEDGE via OMFIT:**

  Continue development of UEDGE module in OMFIT framework and standard convergence procedure for daily experiments (single/double null)
- **Explanation of required transport coefficient profiles to match profiles between UEDGE simulations and experimental data:**

  Interpreted non-Maxwellian INMDF [**Izacard**, PoP (2016)] explains the exact kinetic origin of transport coefficients for the first time [**Izacard**, JPP (2016) Submitted]. See my poster **YP10.70**
- **Include self-consistent kinetic effects (INMDF fluid) in UEDGE:**

  Need to replace not-self-consistent transport coefficients with next generation of self-consistent fluid codes