IFERC-CSC Workshop on JFRS-1 (18 May 2021 Online)

Study of multiple impurity seeding effect by integrated divertor code SONIC

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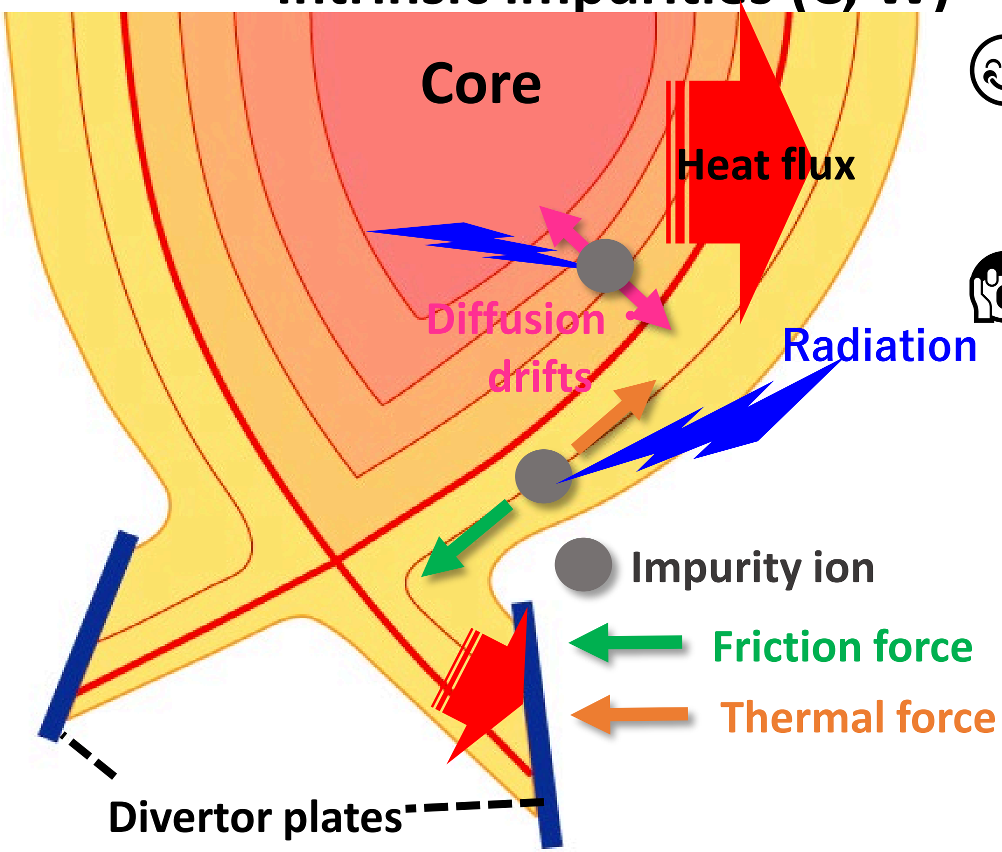
Impurities: Key player for ITER and DEMO

Impurities lower plasma temperature by radiation cooling

Example: **Extrinsic impurities (Ne, Ar, etc.)**
Intrinsic impurities (C, W)



😊 Impurity in **Div./SOL/Edge**

- **Reduces divetor heat load** (radiation)

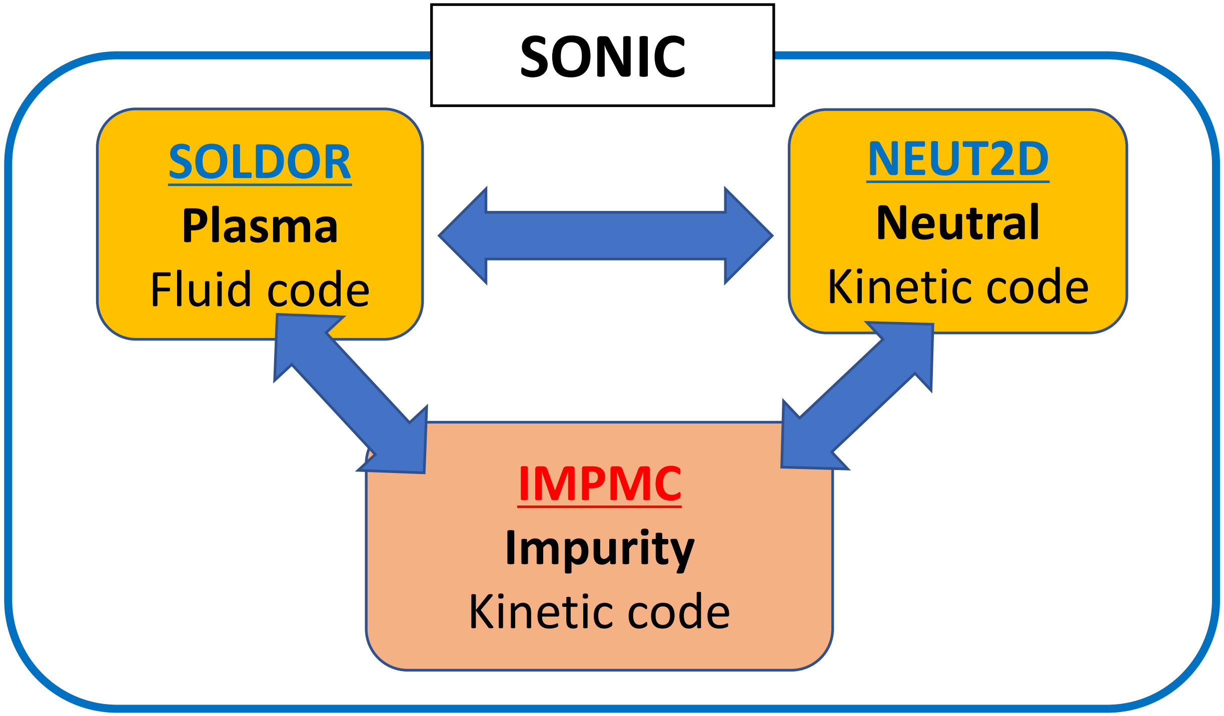
😱 Impurity in **core**

- **Harmful to core performance** (dilution/radiation)

BOTH low divertor heat load and high core performance are required in future devices

To obtain understandings of impurity transport processes & to establish a method to control impurity transport are necessary

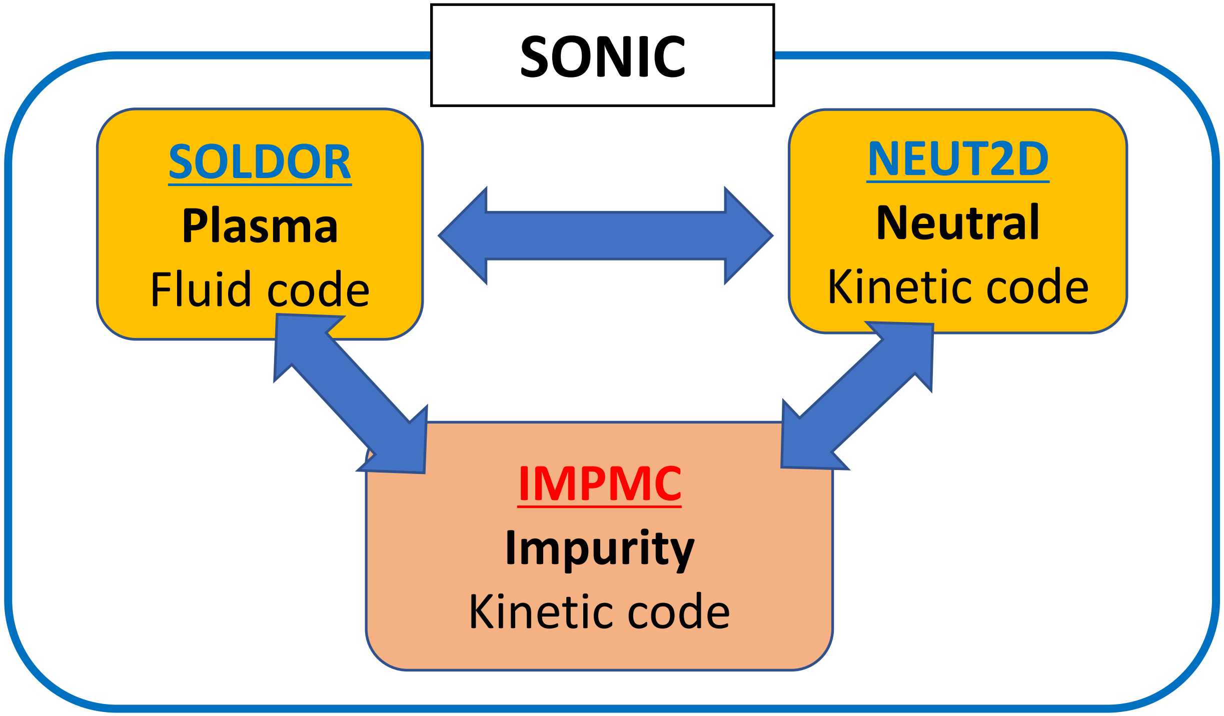
SOL/Div impurity transport study by means of integrated divertor code SONIC



- Self-consistently computes transport processes of plasma, neutral and impurity
- Computes impurity transport **kinetically** by IMPMC code

1. Study of mixed-impurity (Ar+Ne) seeding
2. Improved kinetic modelling of thermal force
3. Benchmarking activity against SOLPS-ITER

SOL/Div impurity transport study by means of integrated divertor code SONIC



SONIC

SOLDOR
Plasma
Fluid code

NEUT2D
Neutral
Kinetic code

IMPMC
Impurity
Kinetic code

- Self-consistently computes transport processes of plasma, neutral and impurity
- Computes impurity transport **kinetically** by IMPMC code

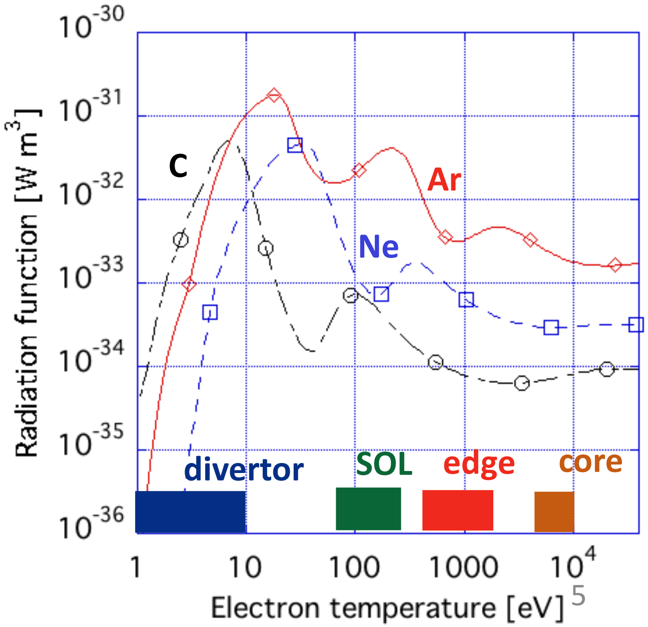
1. **Study of mixed-impurity (Ar+Ne) seeding**
2. **Improved kinetic modelling of thermal force**
3. **Benchmarking activity against SOLPS-ITER**

One of the possible seeding strategies is mixed-impurity seeding

To establish control method of impurity transport in the SOL/divertor is necessary

Ar-only: 😊 radiative in Div./SOL/Edge
😱 high charge/ radiative in core

Ne-only: 😊 radiative in Div.
😱 larger seeding rate than Ar required
-> dilution in core



Mixed impurity seeding (Ar + Ne) experiment in JT-60U

Better core plasma performance than Ar-only [Asakura NF 2009]

-> Different radiation characteristics of each species

Is it possible to control impurity transport?

Ar + Ne mixed impurity seeding simulation in JT-60SA is performed by SONIC

Calculation parameters of JT-60SA steady-state high-β operation

Input parameters

P_{out} = 23 MW

Γ_{ion} = 2.8 x10^{21} s^{-1} (from NBI),

$\Gamma_{\mathrm{puff}}^{\mathrm{osol}}$ = 4.25 x 10^{21} s^{-1}

S_{pump}= 50 m^3/s,

D = 0.3 m^2/s, $\chi_i = \chi_e = 1.0\ \mathrm{m}^2/\mathrm{s}$

Seeding impurity

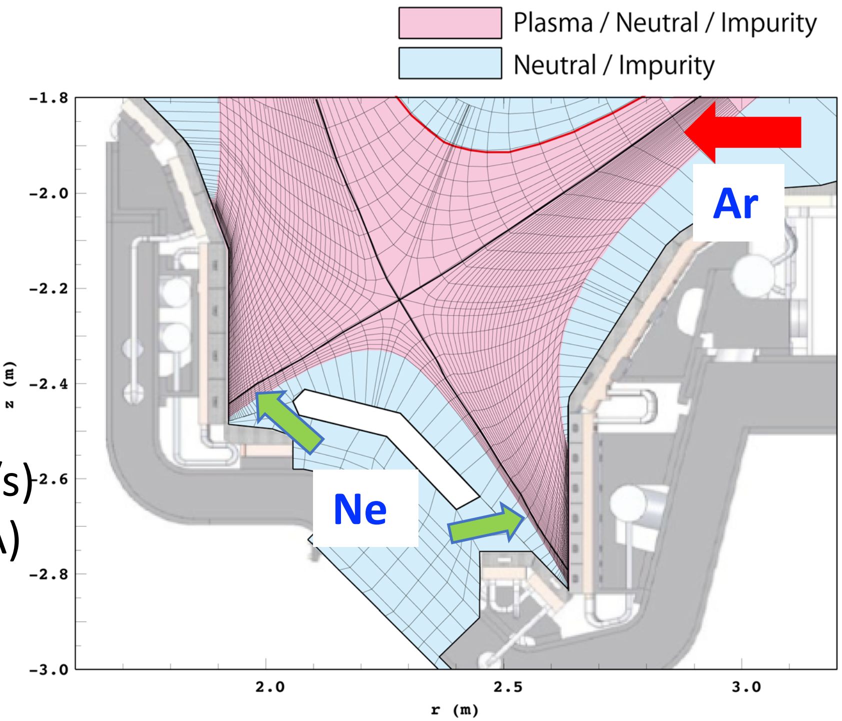
Case A: Ar (0.2 Pa m^3/s)

Case B: Ar (0.2 Pa m^3/s) + Ne (0.02 Pa m^3/s)

(Additional Ne seeding into Case A)

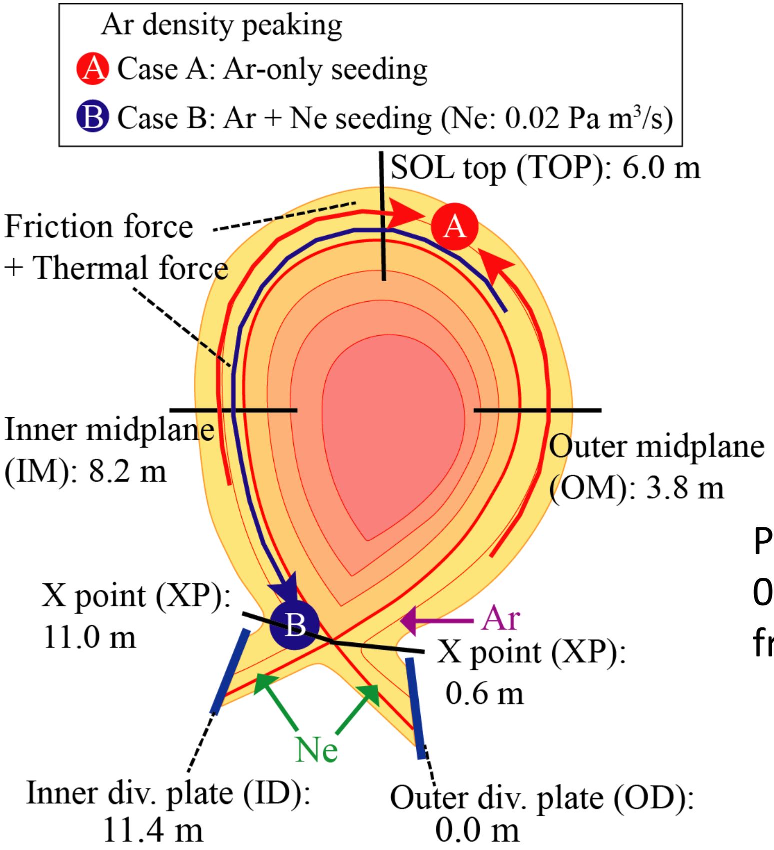
+ intrinsic C impurities (wall material)

Computational grid for JT-60SA

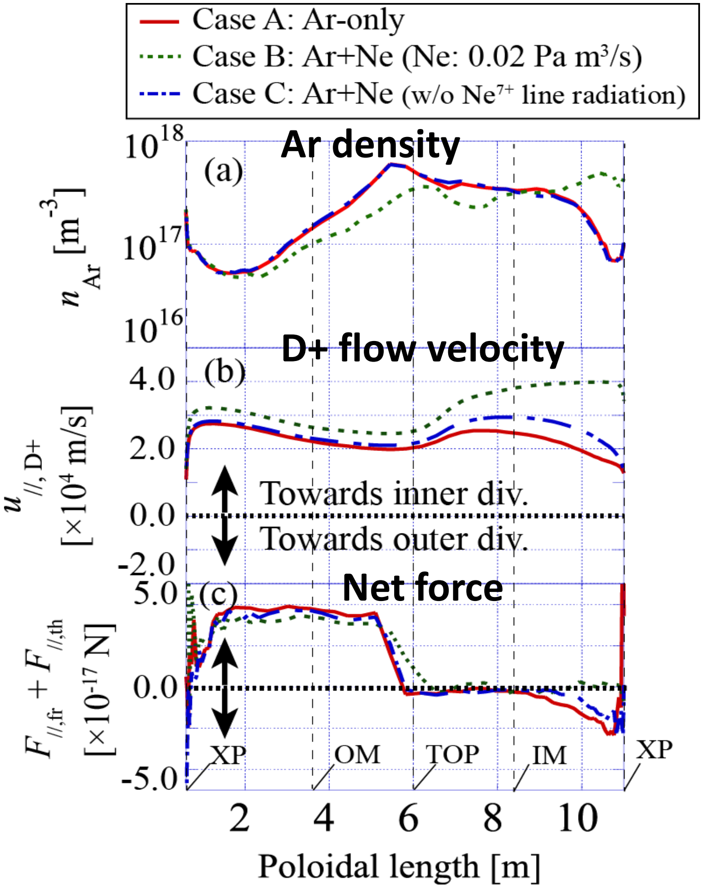


C generation: Chemical sputtering, C self sputtering, Physical sputtering by D, Ar, Ne

Additional Ne seeding into Ar-seeded plasma results in low Ar density at SOL top



Plot along flux tube 0.8 mm outside from sep. at OM



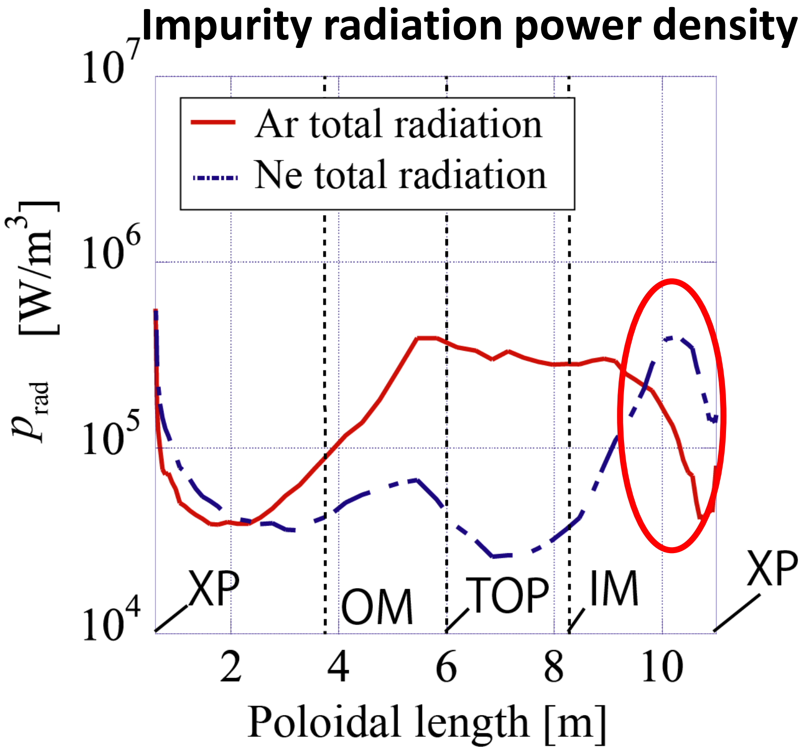
Case A: high Ar density in SOL top by thermal force

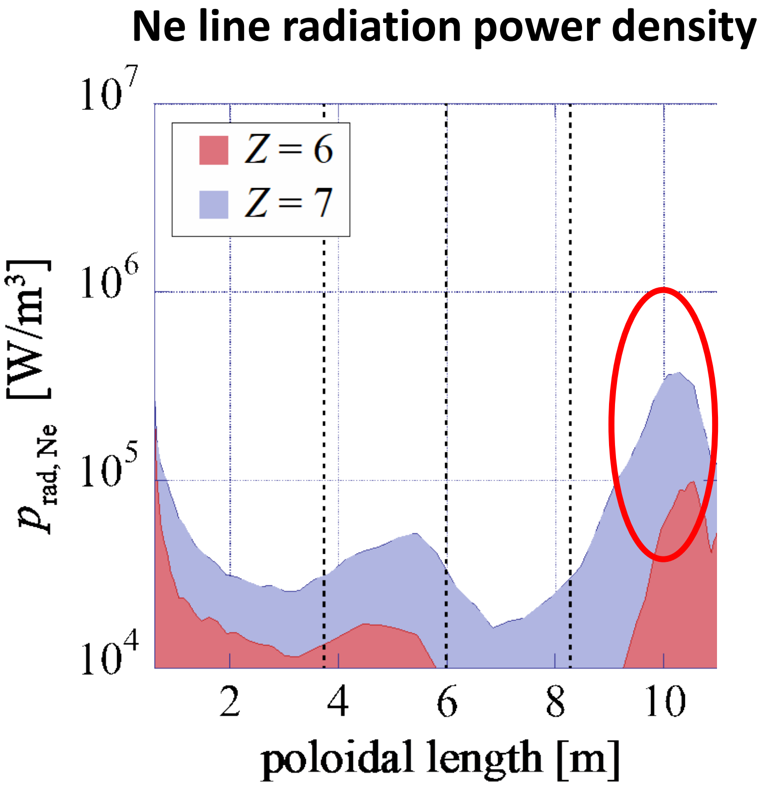
-> main source of Ar ions into core

Case B: low Ar density in SOL top by friction force enhanced by high D$^+$ parallel flow towards inner divertor region

Impurity transport control in SOL could be possible by mixed-impurity seeding

Ne^{7+} has a key role for low Ar density in top of SOL





High Ne radiation power in HFS side near X-point (mainly line radiation of Ne^{7+})

Additional calculation without line radiation of Ne^{7+}

- High D^+ flow cannot be seen: Ne^{7+} has a key role for low Ar density in top of SOL

Importance of Ne^{7+} line radiation is consistent with spectroscopic/bolometric observation in JT-60U Ar+Ne seeding experiment.

Analysis of transient state by time-dependent version of SONIC is ongoing

1. **Study of mixed-impurity (Ar+Ne) seeding**
2. **Improved kinetic modelling of thermal force**
3. **Benchmarking activity against SOLPS-ITER**

Improved modelling of thermal force is necessary for DEMO SOL plasma prediction

Parallel impurity transport process

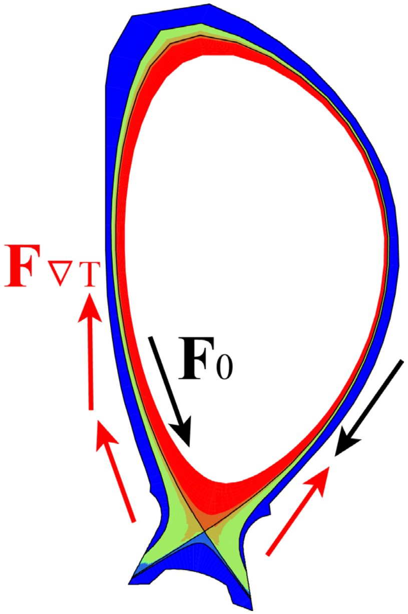
Friction F_0 + Thermal force $F_{\nabla T}$

$$\mathbf{F}_0 \propto m_z \nu_{zi} \mathbf{u}$$

$$\mathbf{F}_{\nabla T} \propto \nabla T \propto -\mathbf{q}$$

Collisionality dependence NOT included in conventional thermal force model

- only assumes high-collisional plasma

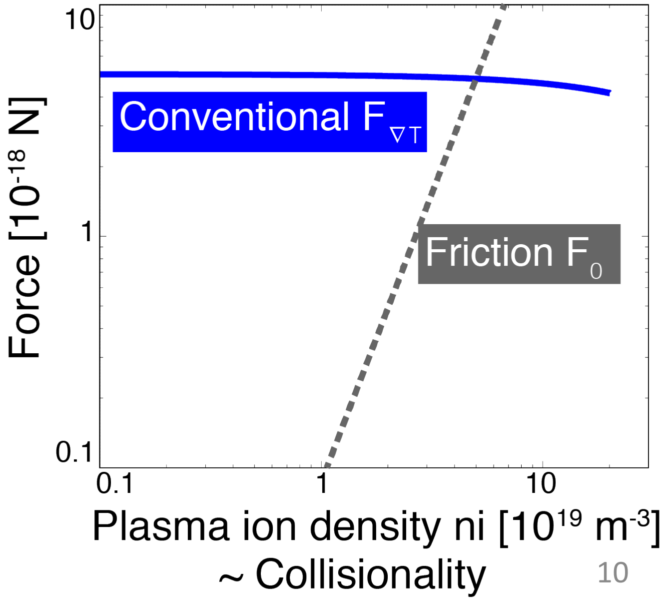


DEMO:

high temperature and low density in SOL

-> lower collisional plasma condition

To improve $F_{\nabla T}$ model to cover lower collisional plasma condition for DEMO SOL prediction is needed



Development of collisionality-dependent thermal force model

$$\mathbf{F}_{\nabla T} \propto \nabla T \propto -\mathbf{q}$$

Two thermal force models based on heat flux models

[W. Fundamenski PPCF 2005]

(1)Free-Streaming Energy type model (FSE)

(2)Generalized Moment equation model (GM)

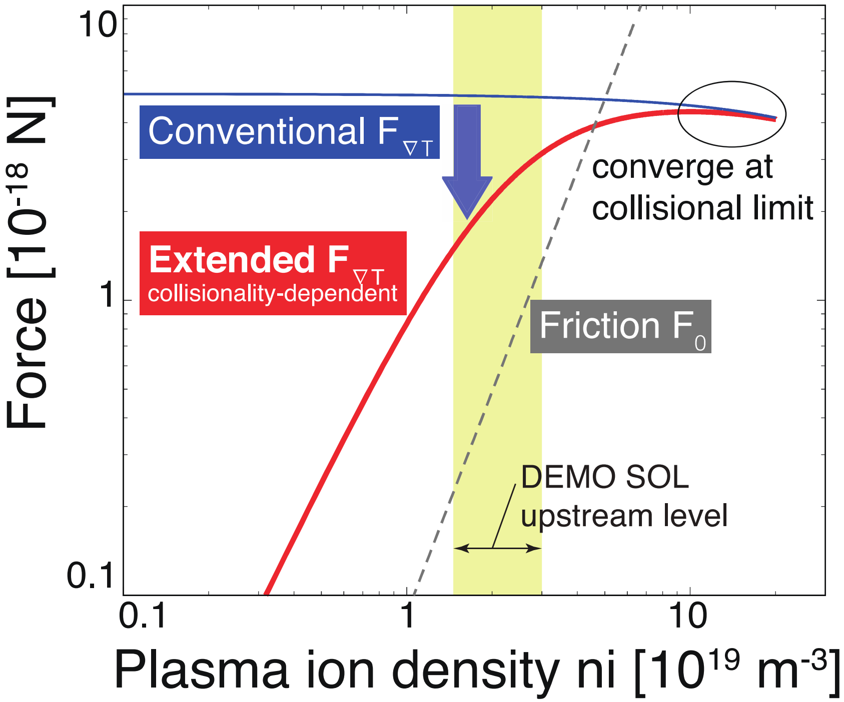
Different **collisionality dependence**
with **parameter l^{MFP}/L**

FSE ➔ temperature $L_{\nabla Ti} := T_i/\nabla T_i$; GM ➔ flow $L_{\nabla ui} := u_i/\nabla u_i$

Heat flux model	Coll. dependence	Heat conduction in low coll. plasma $\lambda/L \sim 1$
FSE q^{FSE}	$\propto \left(1 + \frac{3.9}{\alpha}\frac{\lambda_{ii}^{MFP}}{L_{\nabla_\parallel T_i}}\right)^{-1}$	**Reduce** if $\|\nabla T\|$ large
GM q^{GM}	$\propto \left(1 + 5.88\sqrt{\frac{m_i}{2T_i}}u_i\frac{\lambda_{ii}^{MFP}}{L_{\nabla_\parallel u_i}}\right)^{-1}$	**Reduce** if $\nabla u>0$ **Enhance** if $\nabla u<0$

New extended thermal force models

	Heat flux	Coll. dependence	In low coll. plasma λ/L ~1
$F_{\nabla T}^{FSE}$	**FSE**	$\propto \left(1+\frac{3.9}{\alpha}\frac{\lambda_{ii}^{\mathrm{MFP}}}{L_{\nabla_{\parallel} T_i}}\right)^{-1}$	**Reduce** if |∇T| large
$F_{\nabla T}^{GM}$	**GM**	$\propto \left(1+5.88\sqrt{\frac{m_i}{2T_i}}u_i\frac{\lambda_{ii}^{\mathrm{MFP}}}{L_{\nabla_{\parallel} u_i}}\right)^{-1}$	**Reduce** if ∇u>0 **Enhance** if ∇u<0



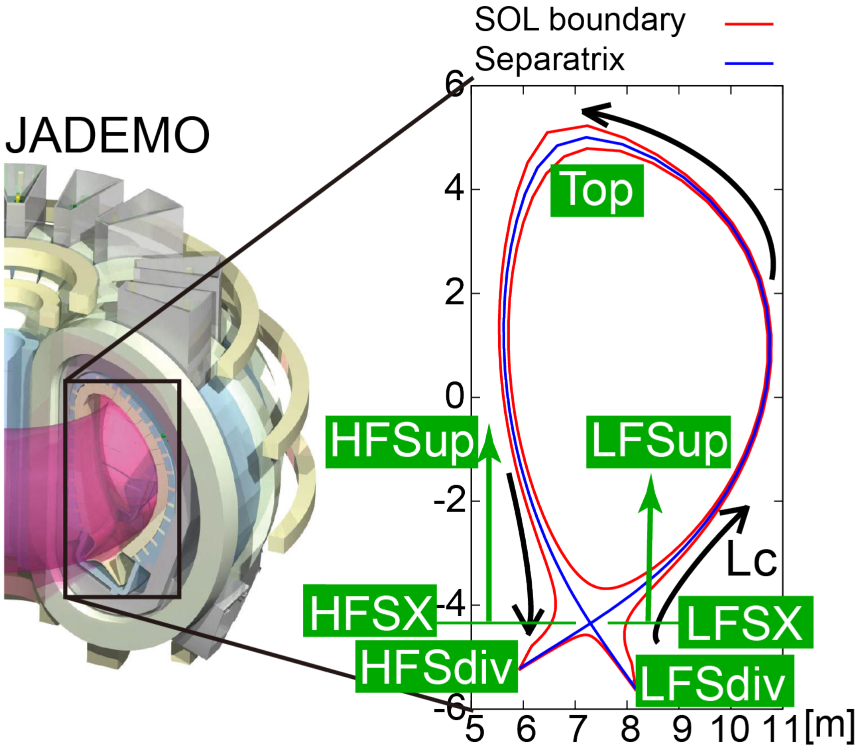
New thermal force expected to be weaker than conventional model in DEMO SOL relevant condition

Implement into SONIC

Applied to predictive simulation of JA-DEMO

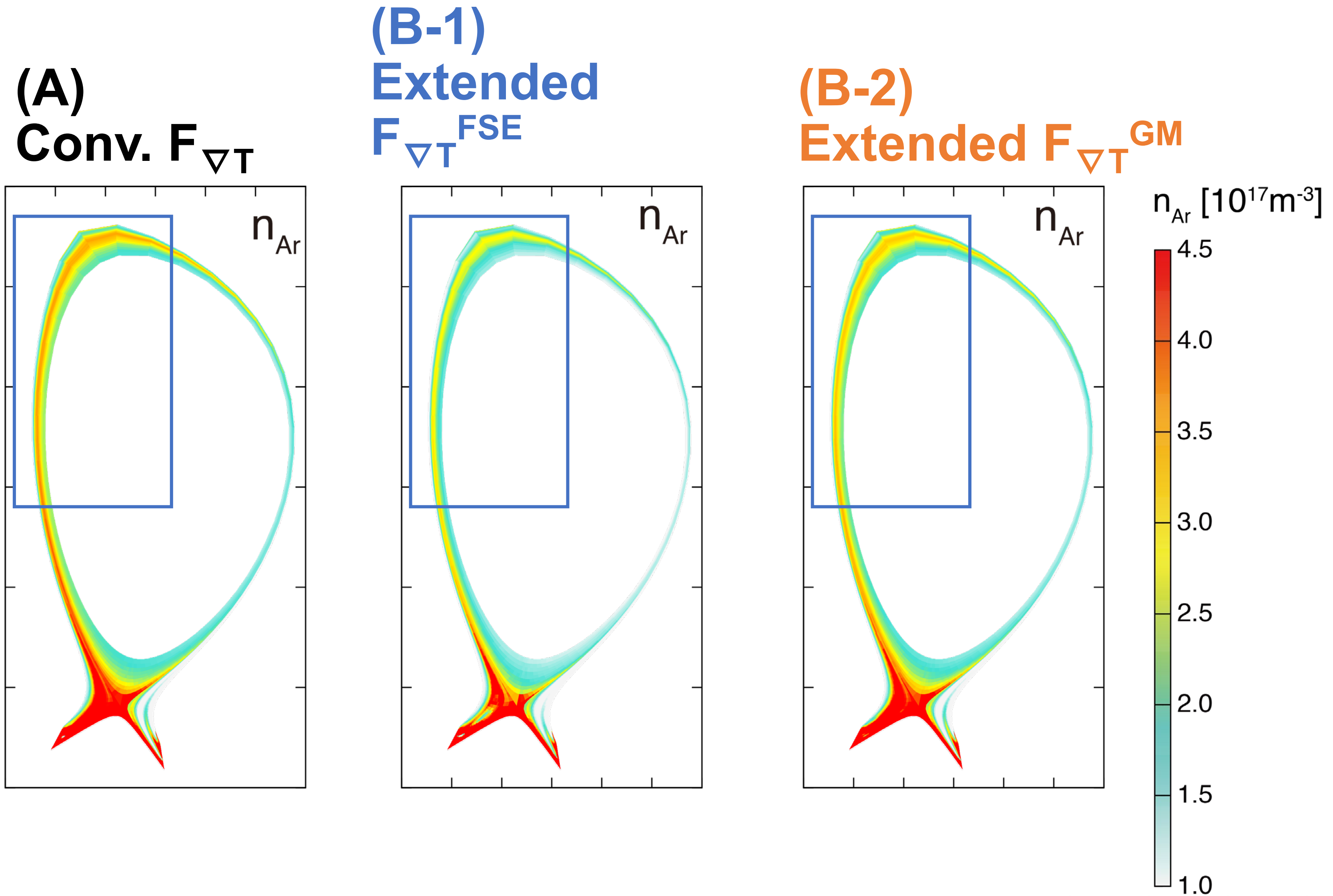
Calculation conditions of JA-DEMO

- **Seeded Ar** is simulated in **JA DEMO SOL** by SONIC
- **(A) Conventional $F_{\nabla T}$**
  (B-1) Extended $F_{\nabla T}$ w. **FSE heat flux (α=1.5)**
  (B-2) Extended $F_{\nabla T}$ w. **GM heat flux**
- Representative poloidal positions & Length along separatrix **Lc**
  Positive direction : LFS → HFS



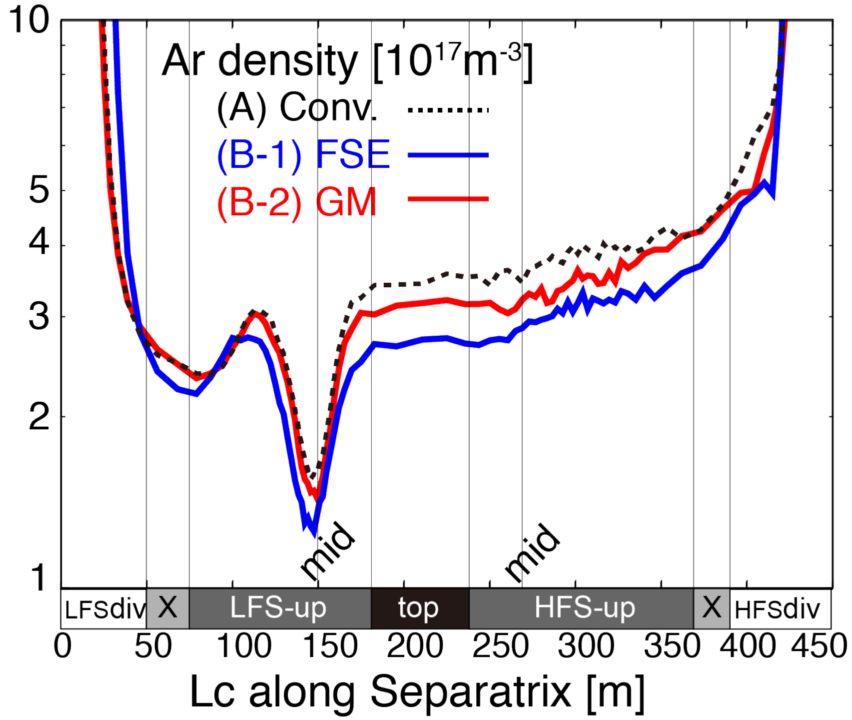
JA DEMO parameters	
Fusion Power P_{fus}	~1.5GW
Major rasius R_p	8.5m
Minor radius a_p	2.4m
Geo. Center B_T	5.9T
Plasma current	12.3MA
Vol. av. Density (SOL density)	$6.6\times10^{19}m^{-3}$ ($2\times10^{19}m^{-3}$)
SOL ion temp. Ti	700eV
Prad at SOLdiv	~ 200MW

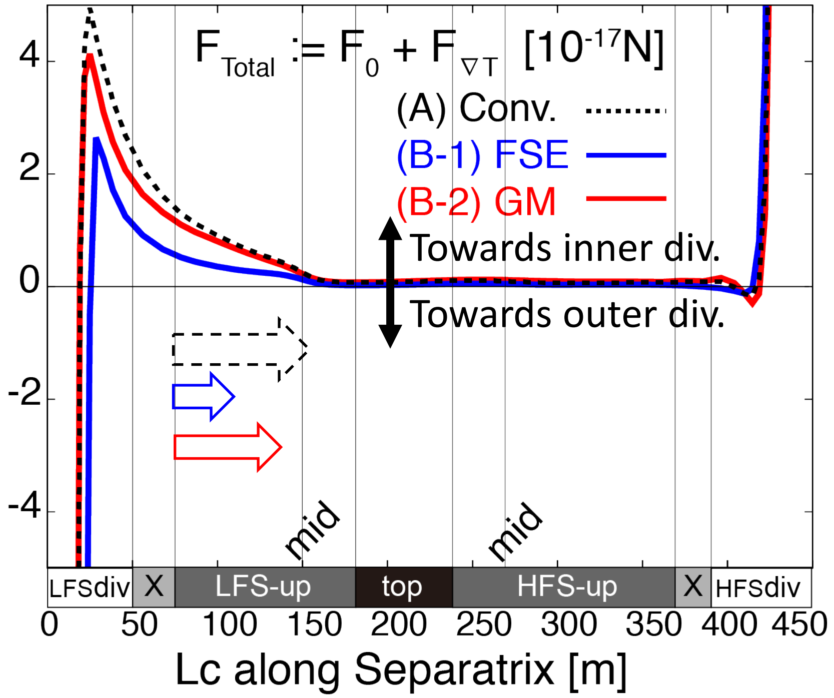
Lower Ar density in SOL is obtained in new models



Impurity transport simulations with extended $F_{\nabla T}$ in (B-1) & (B-2) result in low Ar density in SOL upstream

Weaker $F_{\nabla T}$ and resultant low Ar density in LFS-upstream and outer divertor plasmas





Introduction of extended $F_{\nabla T}$ reduced n_{Ar} at SOL HFS-upstream in present DEMO due to weaker $\mathbf{F}_{\nabla T}$ in LFS-upstream and outer divertor region

Results demonstrate importance of collisionality dependence in thermal force model in SOL plasma of DEMO

1. **Study of mixed-impurity (Ar+Ne) seeding**
2. **Improved kinetic modelling of thermal force**
3. **Benchmarking activity against SOLPS-ITER**

Benchmarking activity between SONIC and SOLPS-ITER under collaboration between JA, EU and IO

Aim: Validate/improve transport modelling of both codes

Step 1: D-only reference case in JT-60SA
Step 2: D-only case with intrinsic C impurities
Step 3: Extrinsic Ar-seeded case

- ✓ Development of mesh converter of SOLPS fluid mesh to SOLDOR mesh
- ✓ Installation of IMAS onto JFRS-1 for systematic comparison
- ✓ Development of IMAS interface for SONIC

Summary

1. Study of mixed-impurity (Ar+Ne) seeding

Numerical simulations of SONIC shows that Impurity transport control in SOL could be possible by mixed-impurity seeding

Ar-only seeding: high Ar density in SOL top (due to thermal force)
Ar+Ne seeding: low Ar density in SOL top (due to friction force)

- Friction force is enhanced by high D+ parallel flow towards inner divertor region by Ne radiation (Key: Ne^{7+} line radiation)

2. Improved kinetic modelling of thermal force

Results demonstrate importance of collisionality dependence in thermal force model in SOL plasma of DEMO

- Two models (FSE/GM) of collisionality-dependent thermal force have been developed
- Introduction of extended $F_{\nabla T}$ reduced n_{Ar} at SOL HFS-upstream in present DEMO due to weaker $\mathbf{F}_{\nabla T}$ in LFS-upstream and outer divertor region

3. Benchmarking activity against SOLPS-ITER

Benchmarking activity between SONIC and SOLPS-ITER is ongoing under collaboration between JA, EU and IO