US-Japan Workshop on Integrated Modeling
September 21-23, 2004, Princeton

Divertor Simulations with Comprehensive Fluid + Monte-Carlo Code (SONIC) and with PIC + Monte-Carlo Code (PARASOL)

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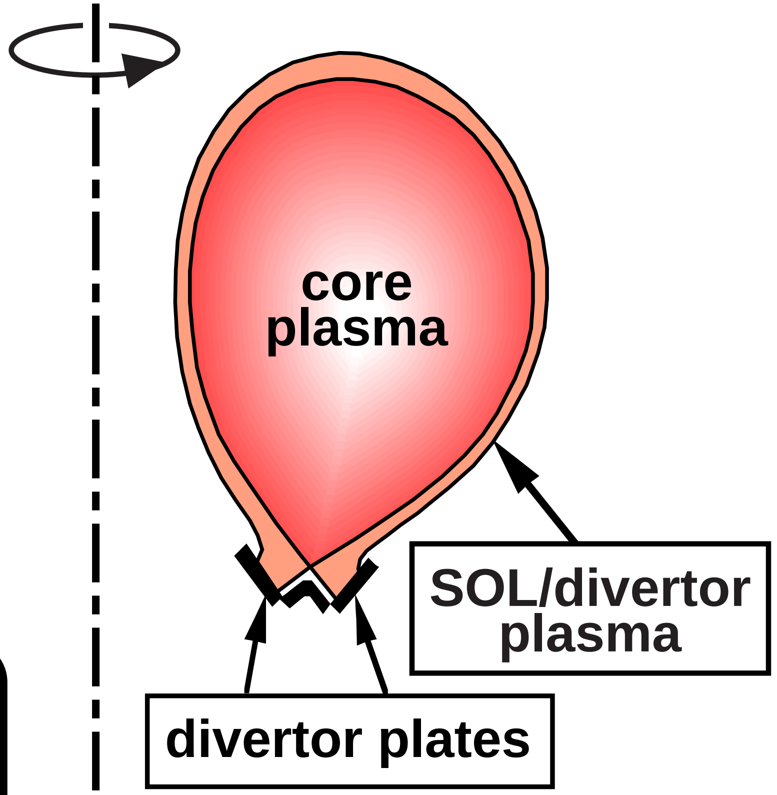
1. Introduction

Power and Particle Control by SOL/Divertor Plasmas

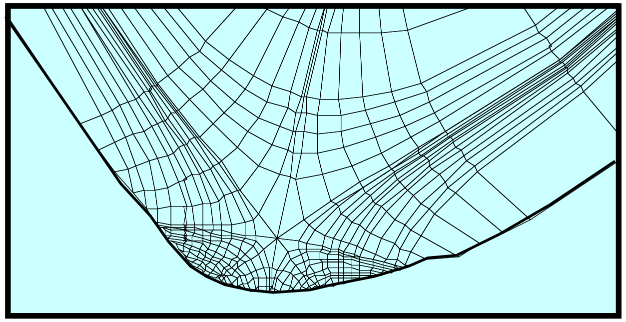
Since the SOL/divertor plasmas attach walls directly, plasma particles and heat escape to the walls mainly along magnetic field lines.

Utilizing this nature, we expect divertor functions for the **heat removal**, **ash exhaust**, and **impurity shielding** in fusion reactors, such as ITER.

Experimental analyses and prediction studies for divertor functions have been performed by using comprehensive simulation codes.



Complexity of Divertor Simulation Requires Various Types of Codes and Their Integration

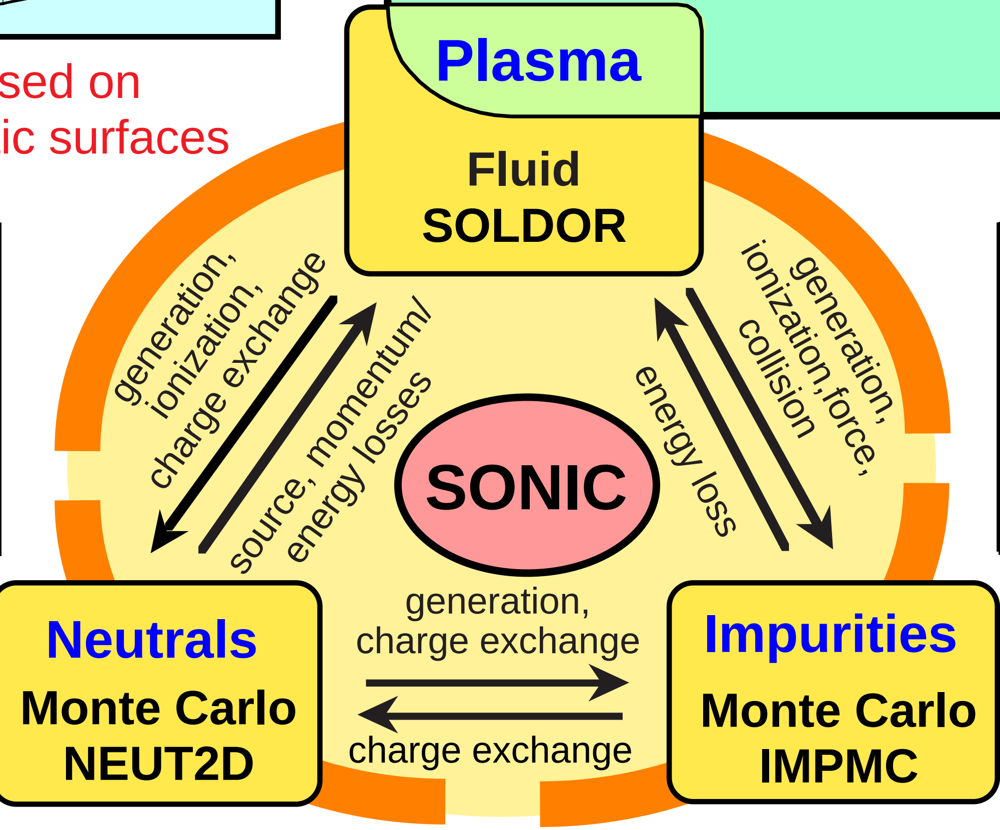


- Motions based on the magnetic surfaces

PIC + Monte Carlo

PARASOL

- Kinetic effect
- Collision
- Sheath, Drift, Transport etc.



Plasma

Fluid
SOLDOR

SONIC

generation, ionization, charge exchange

source, momentum/ energy losses

generation, ionization, force, collision

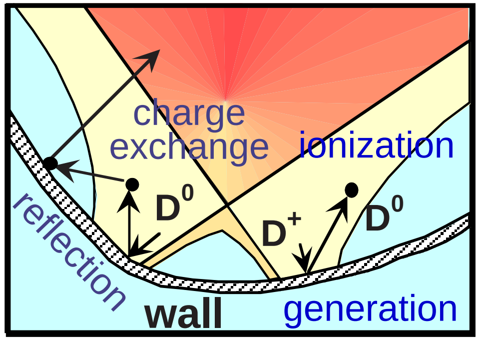
energy loss

Neutrals
Monte Carlo
NEUT2D

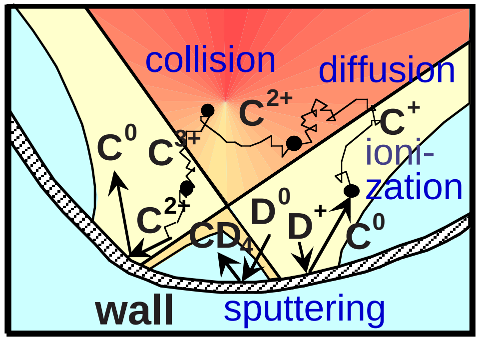
generation, charge exchange

charge exchange

Impurities
Monte Carlo
IMPMC



- Straight motion
- Strong dependence on the wall structure



- Straight motion
- Motions based on the magnetic surfaces

2. Fluid + Monte Carlo Code (SONIC)

SOLDOR the Plasma Fluid Code

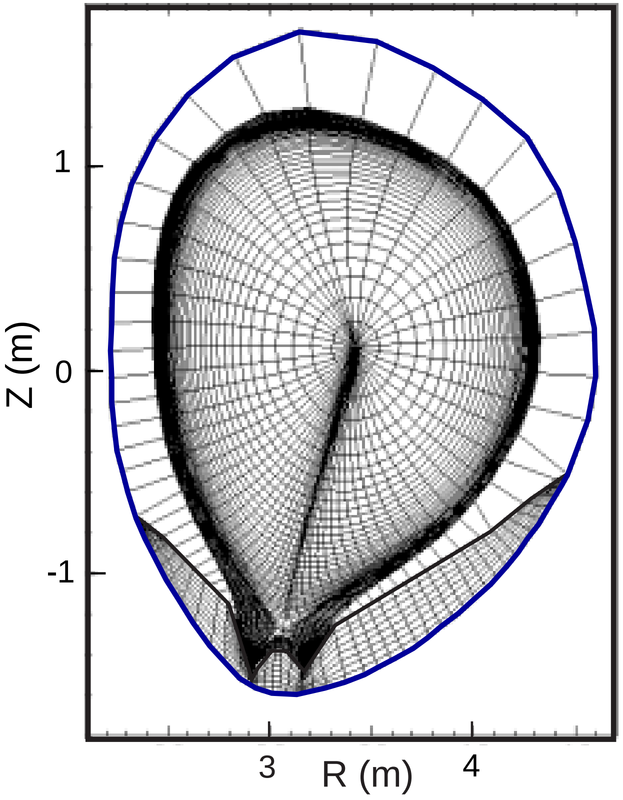
Plasma fluid equations

n, V, T_e, T_i, (ϕ, ...)

Numerical method

- Finite volume method for complex geometry
  Mesh accumlation near the divertor plate
- Full implicit time difference method
- Newton-Raphson method
  to solve nonlinear equations
- Approximate factorization method
  to solve 2D equations
- Total variation diminishing scheme
  for convective terms

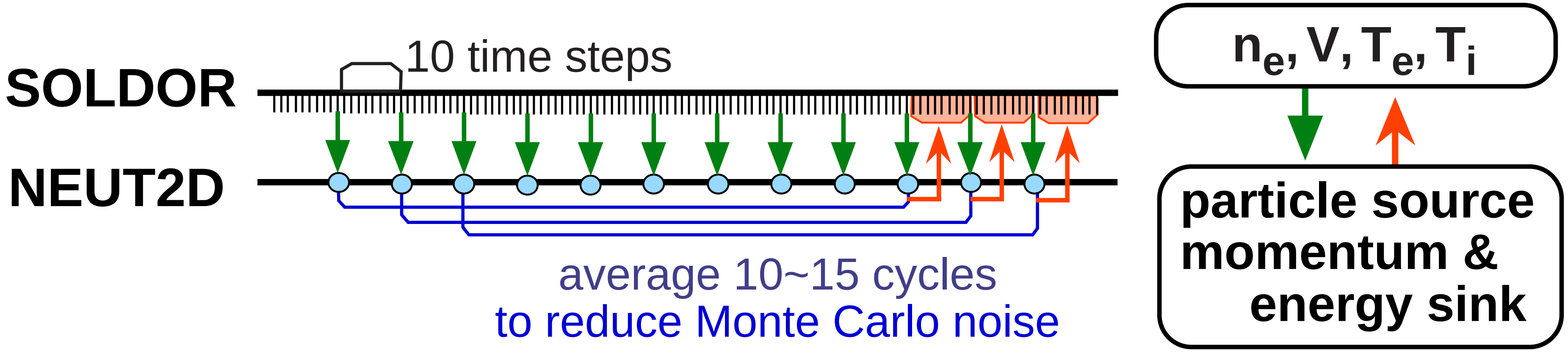
K. Shimizu et al., J. Nucl Mater. **313-316** (2003) 1277.



JT-60U plasma
W-shaped divertor

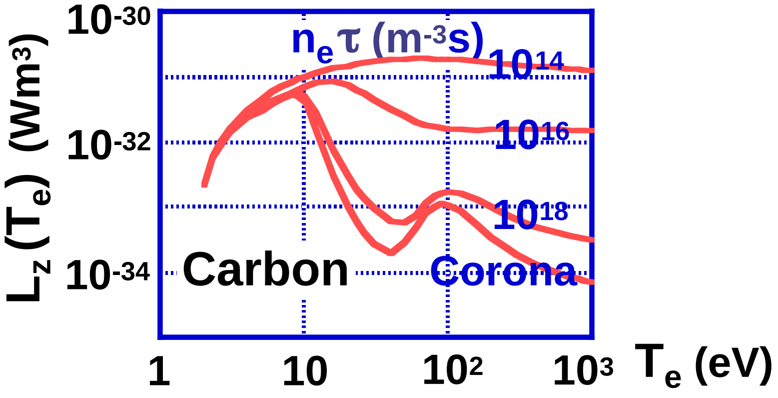
$N_\psi = 35$, $N_\chi = 120$
$\Delta\chi$ (near plates) $\approx$ 2 mm

NEUT2D the Neutral Monte Carlo Code

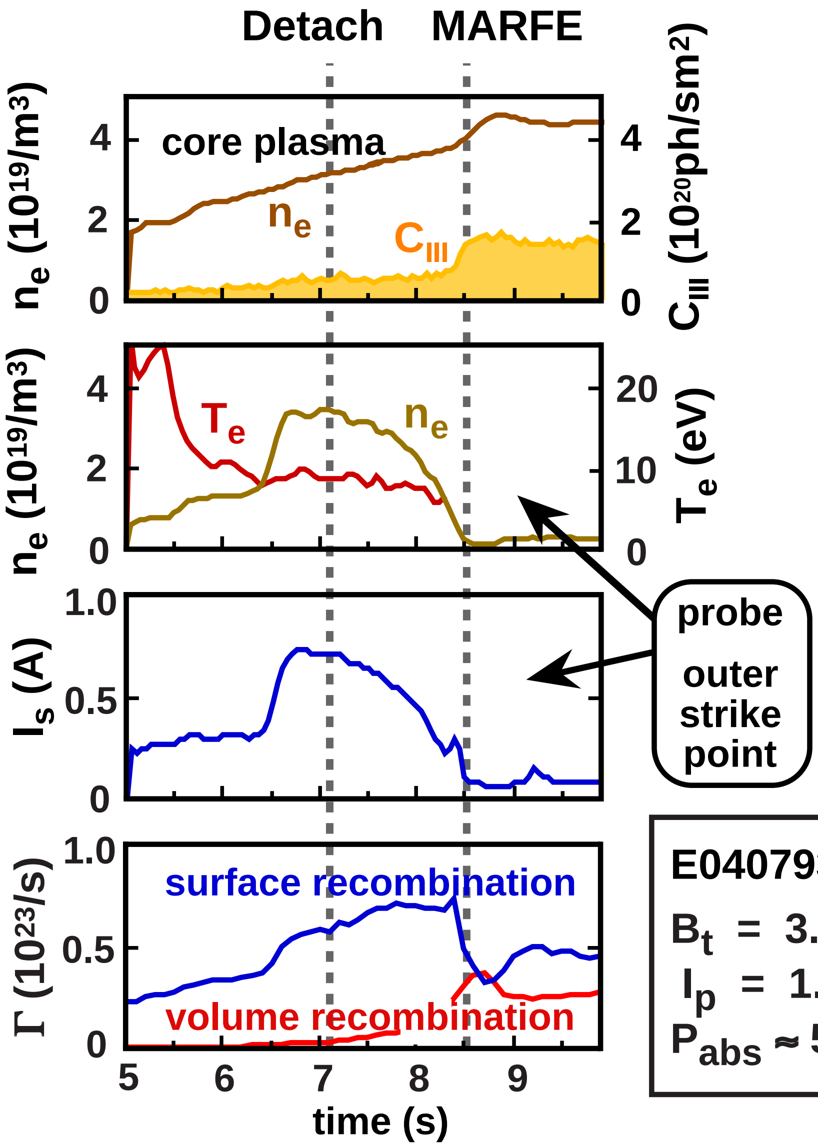


tracing 5000 test particles from divertor plates until steady state in one cycle of NEUT2D (whole region inside vessel, parallel computing)

Impurity Monte Carlo Code (IMPMC) is not combined in the present simulations. Simple radiation model is applied.



X-point MARFE in JT-60U



E040793

B_t = 3.5 T

I_p = 1.5 MA

P_{abs} ≈ 5.2 MW

SONIC simulation parameters

$\Gamma_{sep} = 0.2 \times 10^{22} s^{-1}$

$n_{e\text{-}edge} = 1.5 \times 10^{19} m^{-3}$

$Q_{sep} = 2$ MW

$N_{gas\text{-}puff} = 0.8 \times 10^{22} s^{-1}$

$S_{pump} = 15\ m^3/s$

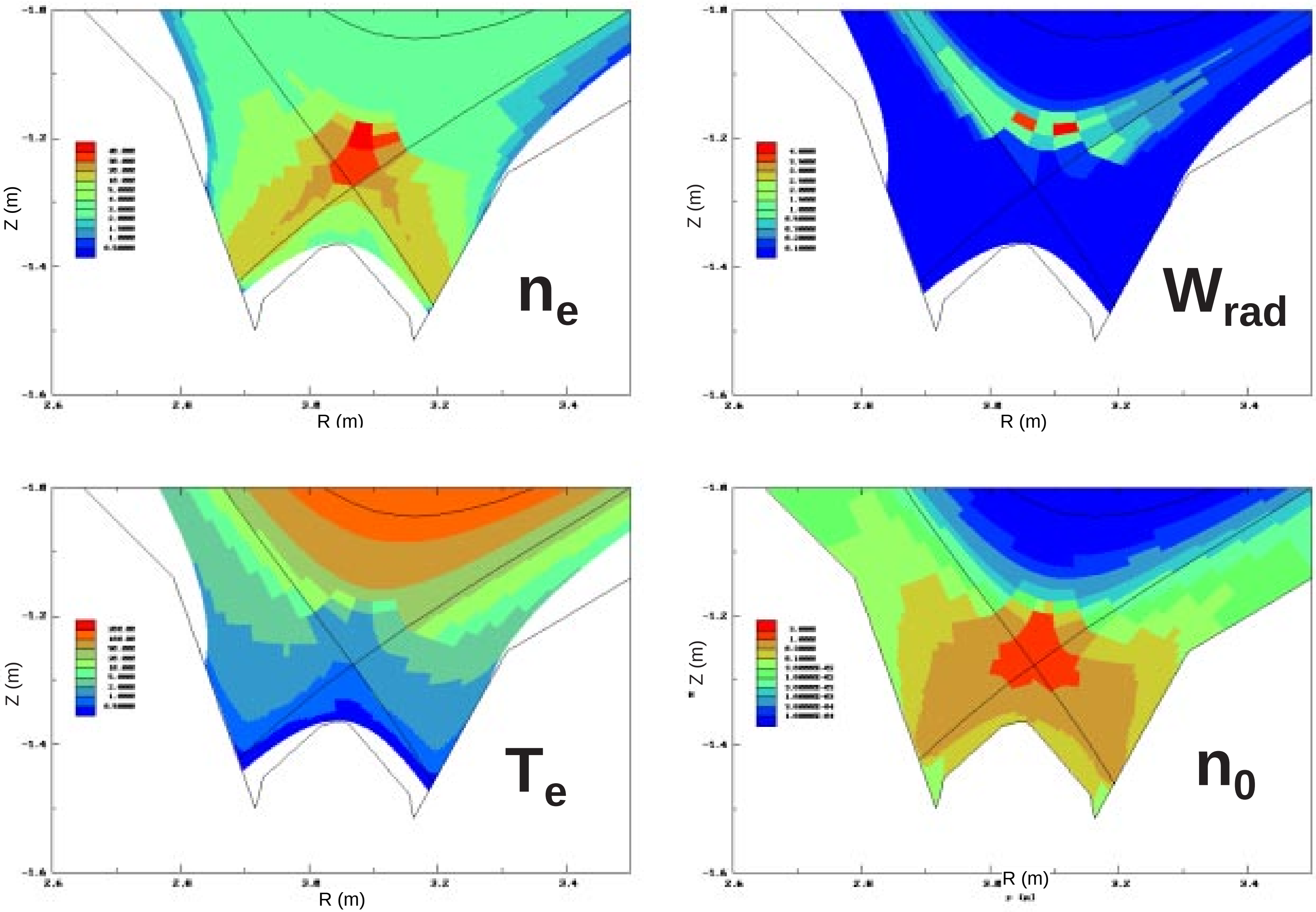
$\chi_e = \chi_i = 1\ m^2/s$

$D = 0.3\ m^2/s$

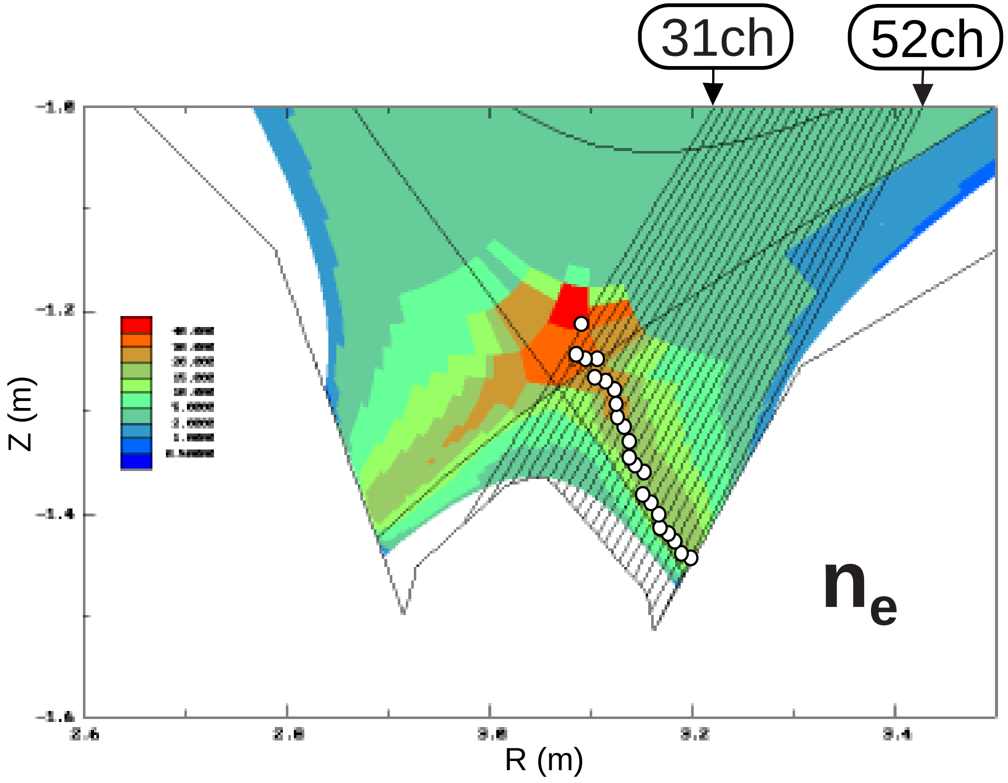
$n_C/n_e = 1\ \%$

$n_e \tau_{recycle} = 10^{16} m^{-3}s$

Simulation Realizes X-point MARFE with High n_e and Low T_e



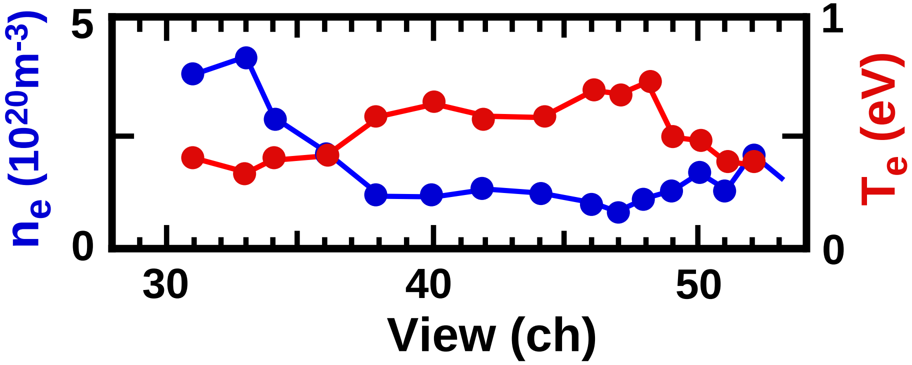
Simulation results agree fairly well with experiment



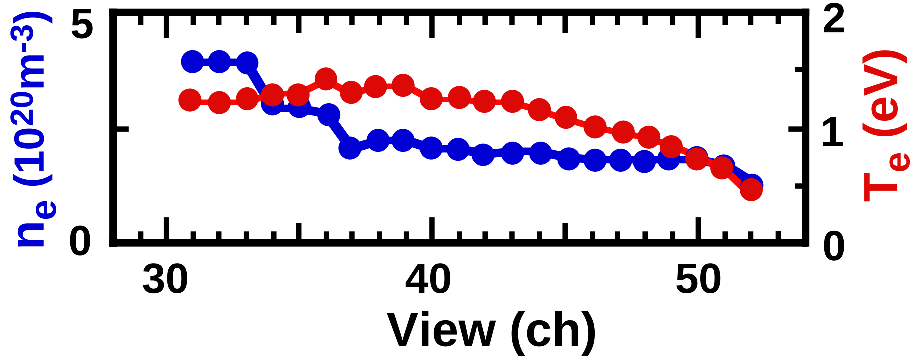
○ maximum recombination point along a line of sight

Experiment

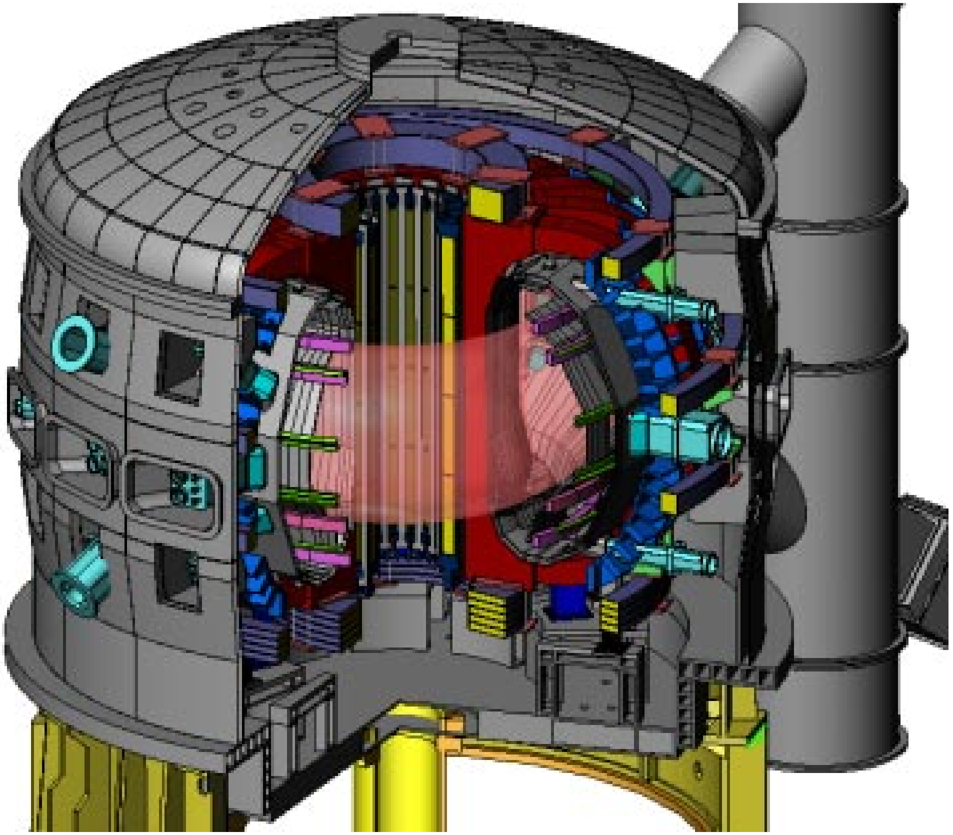
measured from line emissions of H* generated by recombination



Simulation



Divertor Design of NCTF (National Centralized Tokamak Facility)



R = 2.8 - 3.1 m

A = 2.6 - 3.3

B_t = 2.8 - 3.8 T

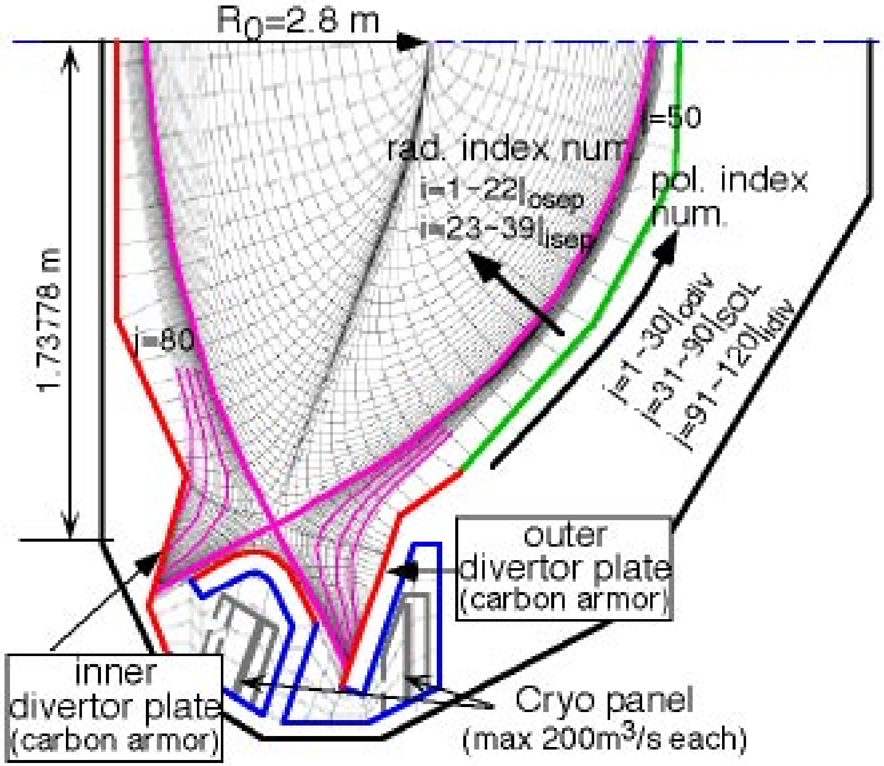
I_p = 4 - 5.5 MA

P_{in} = 44 MW (10 s)

15 MW (100 s)

under optimization

S. Ishida, the JT-60 Team, and the JFT-2M Group, Phys. Plasmas **11** (2004) 2532.



SONIC simulation parameters

I_p = 4 MA, B_t = 3.7 T

A = 3.3, κ = 1.9, δ = 0.3

$\Gamma_{sep} = 1.0 \times 10^{22} s^{-1}$

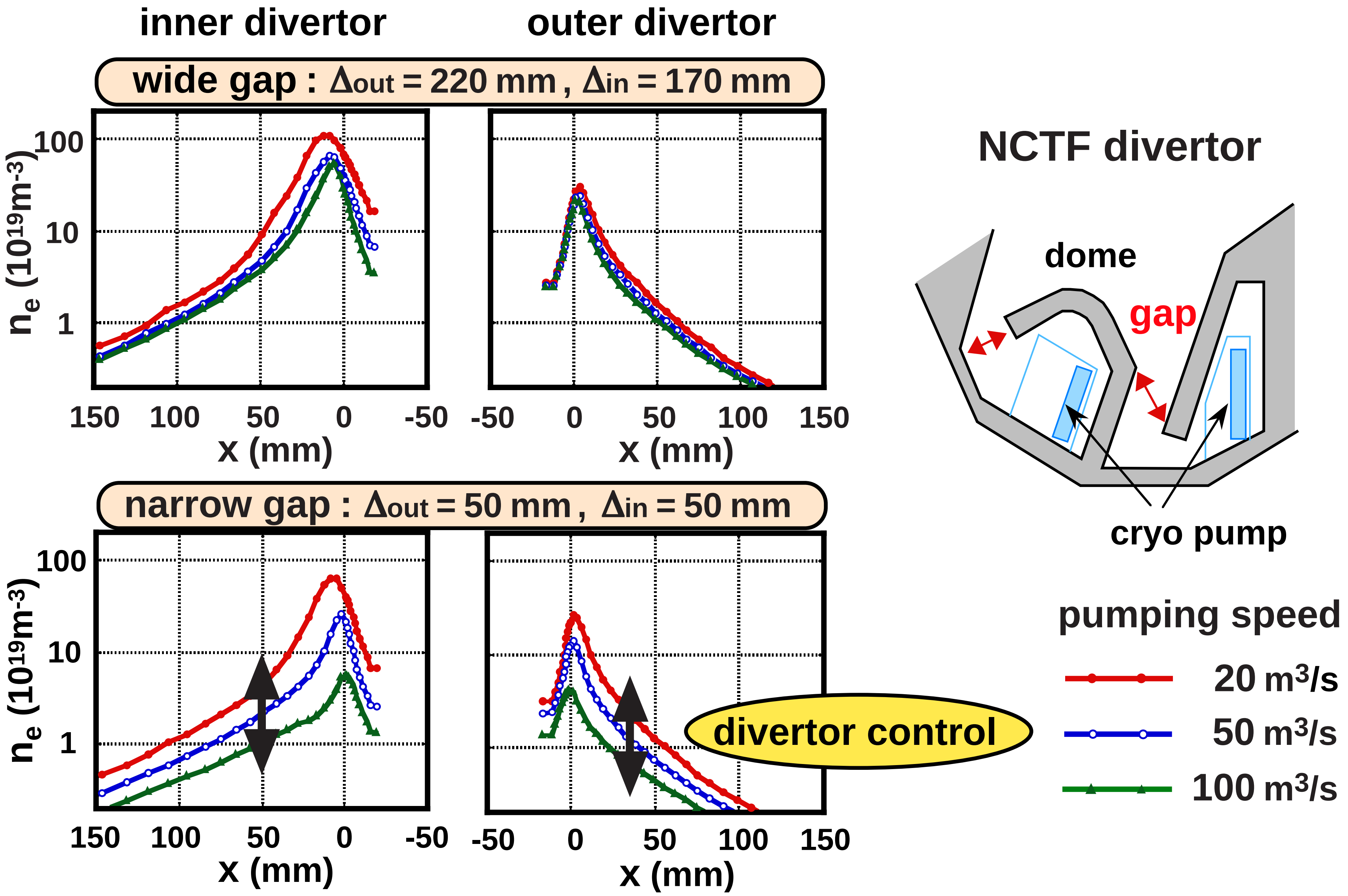
Q_{sep} = 12 MW

S_{pump} = 10~100 m^3/s

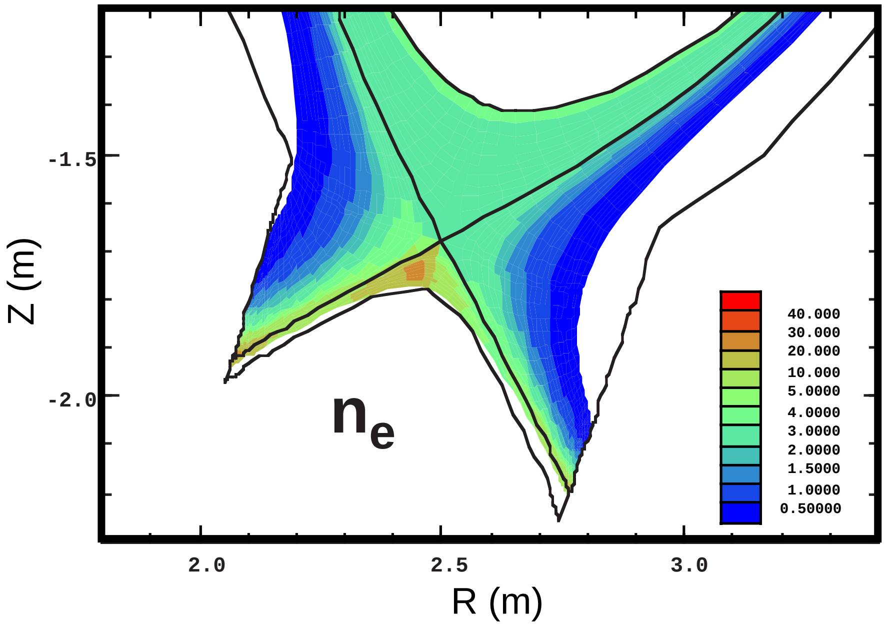
$\chi_e = \chi_i = 1\ m^2/s$

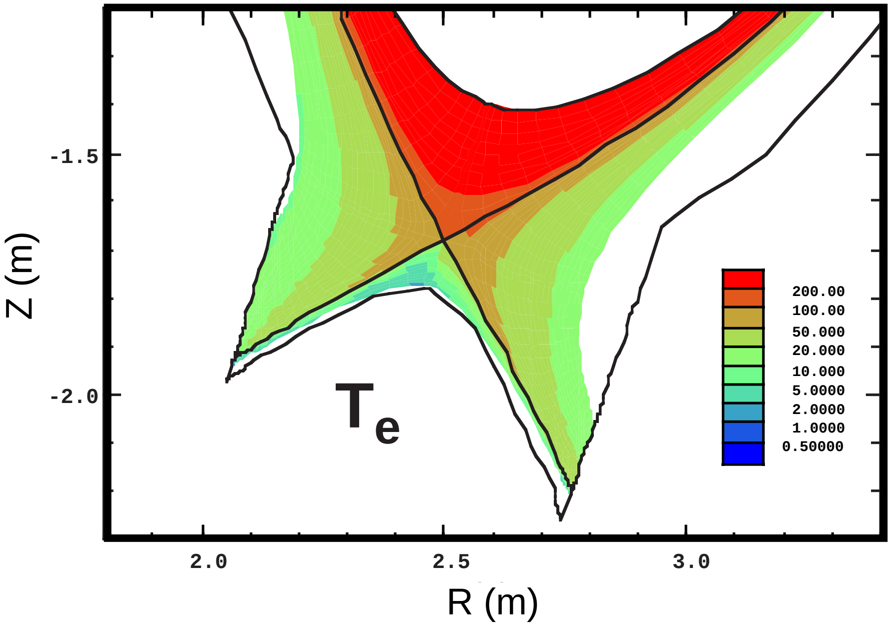
D = 0.3 m^2/s

Narrow gap enhances pumping capability

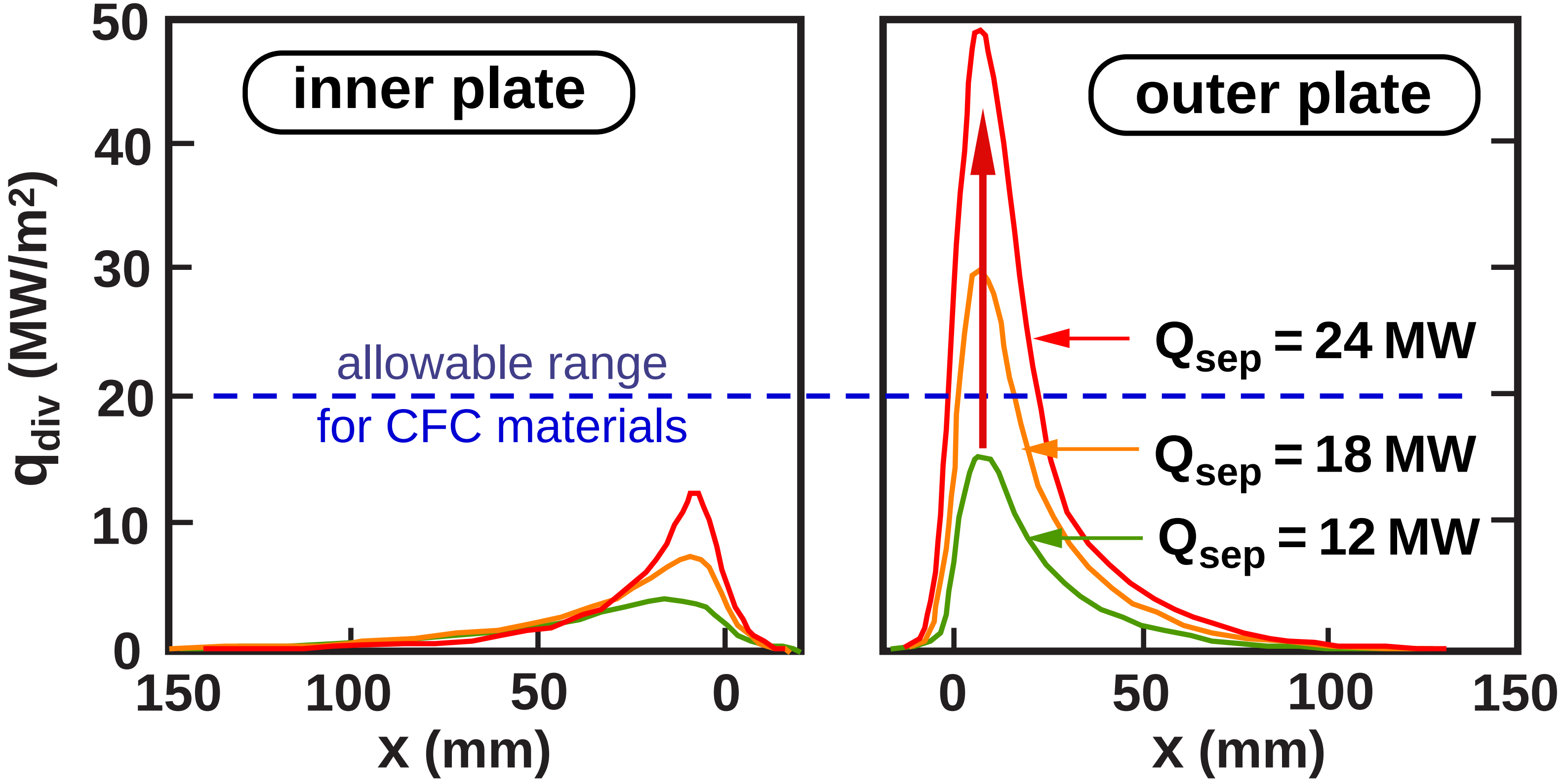


Dense and Cold Divertor Plasma near the Inner Divertor Plate





Heat load on divertor plates becomes high for strong heating operation



Future simulation study of the heat load reduction
for NCTF divertor design
Remote radiation cooling by impurity seeding

3. PIC + Monte Carlo Code (PARASOL)

In the fluid model for SOL/divertor plasmas, various **physics models** are introduced, i.e., boundary conditions at the plasma-wall boundary, heat conductivity etc;

$V_{//} = C_s$ (Bohm condition) $q_{cond} = - \kappa_{//} \nabla_{//} T$

Kinetic approach is required to examine the validity of such physics models.

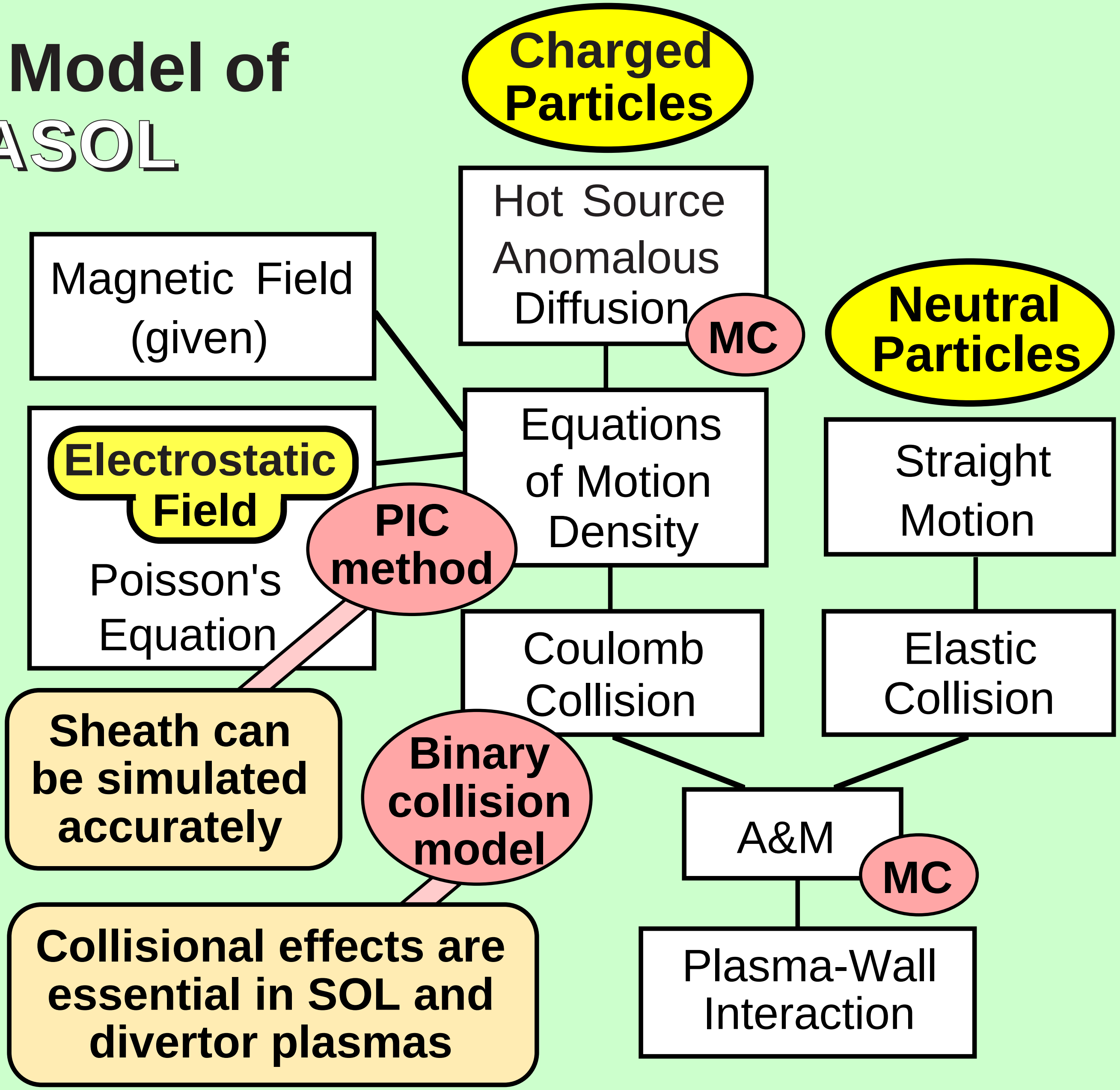
One of the most powerful kinetic models is the **particle simulation**.

An advanced particle simulation code **PARASOL**

PARticle Advanced simulation for SOL and divertor plasmas was developed.

T. Takizuka, "Edge Plasma Modeling Using PARASOL Code",US-Japan workshop on Theory-Based Modeling and Integrated Simulation of Burning Plasmas", 2003, Kyoto.

Physics Model of PARASOL



Charged Particles

Hot Source
Anomalous Diffusion

MC

Magnetic Field
(given)

Electrostatic Field

Poisson's Equation

PIC method

Equations of Motion
Density

Neutral Particles

Straight Motion

Coulomb Collision

Elastic Collision

Sheath can be simulated accurately

Binary collision model

A&M

MC

Collisional effects are essential in SOL and divertor plasmas

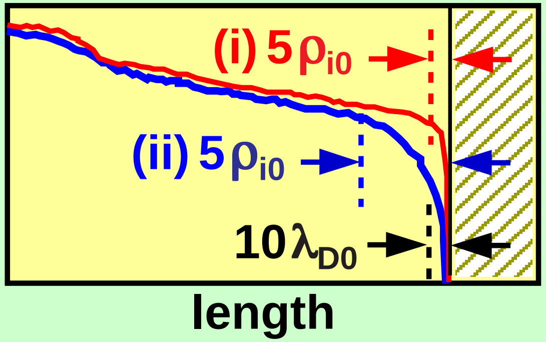
Plasma-Wall Interaction

T. Takizuka, M. Hosokawa, K. Shimizu, Trans. Fusion Tech. **39**, 111 (2001).

Various versions of PARASOL

1D Stationary code

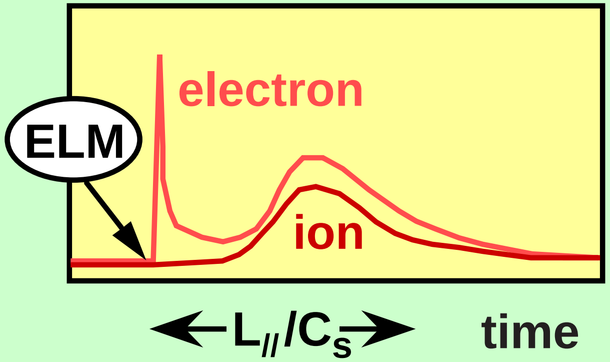
Sheath formation
Parallel transport



1D Dynamic code

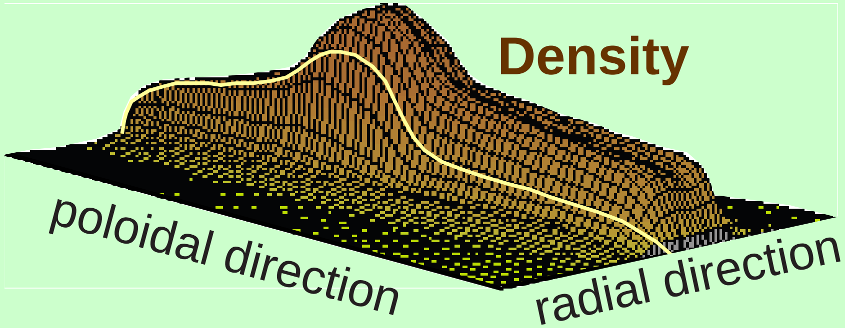
Response to ELM

Heat flux at divertor plate



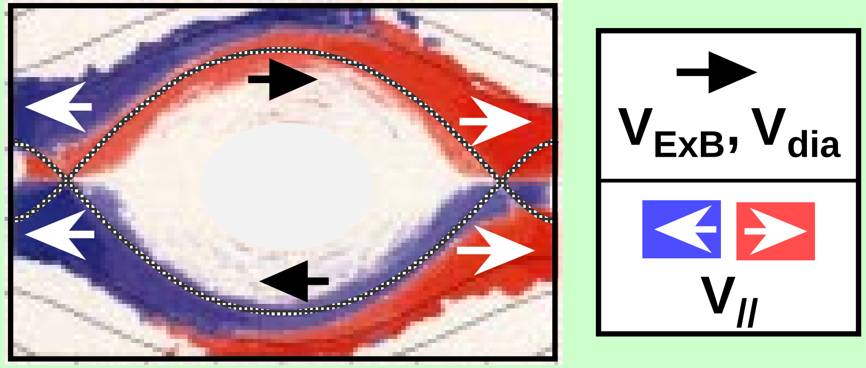
2D Slab code

Divertor asymmetry,
Drift effect

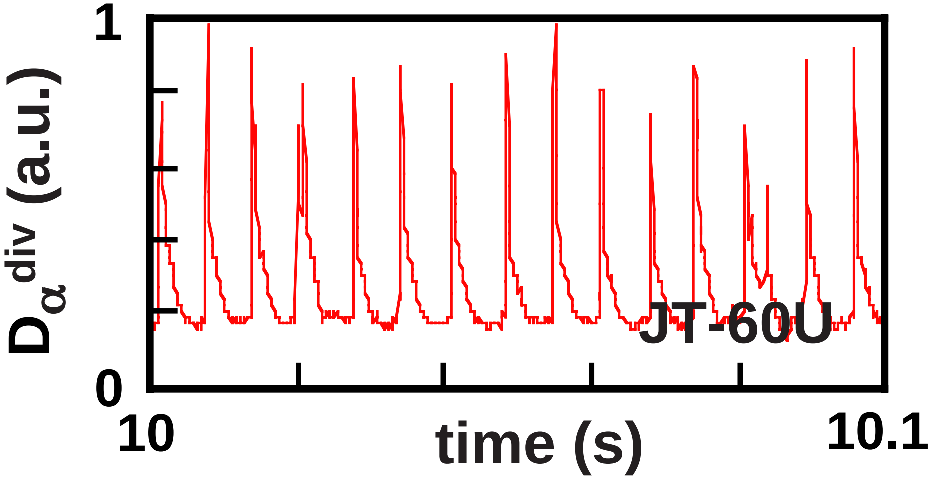


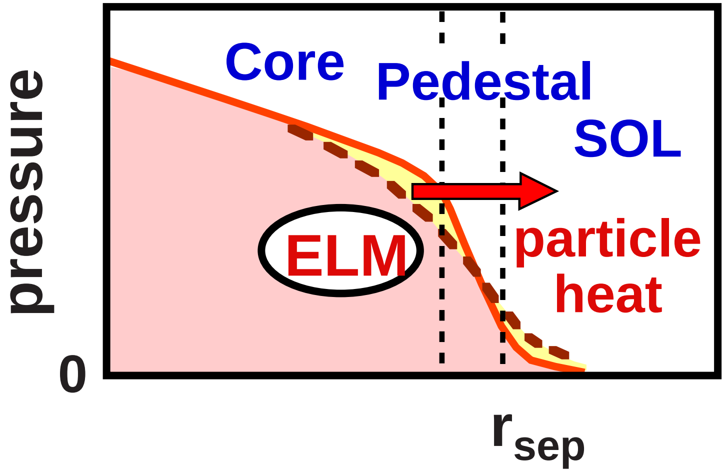
2D Separatrix code

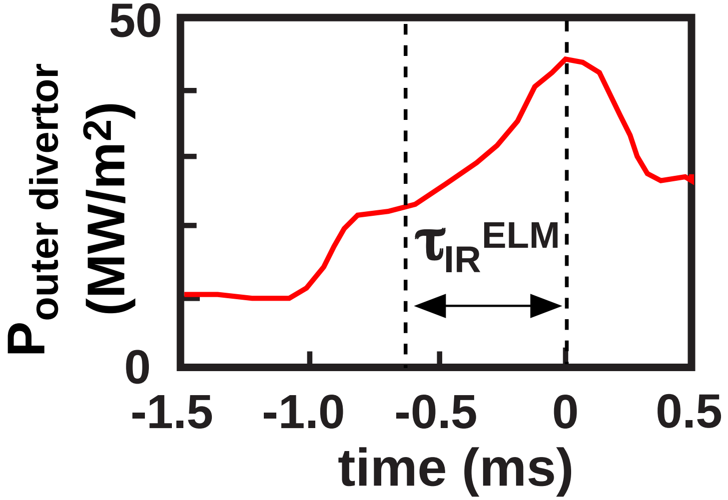
Flow control

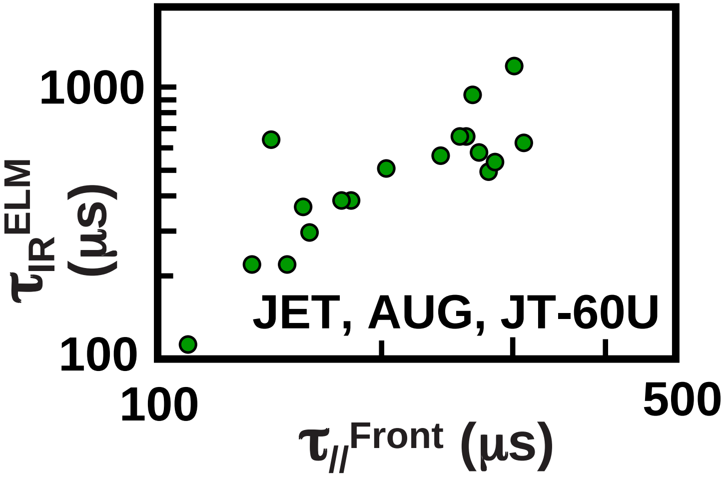


Dynamic Simulation for ELM Energy and Particle Losses to Divertor Plates









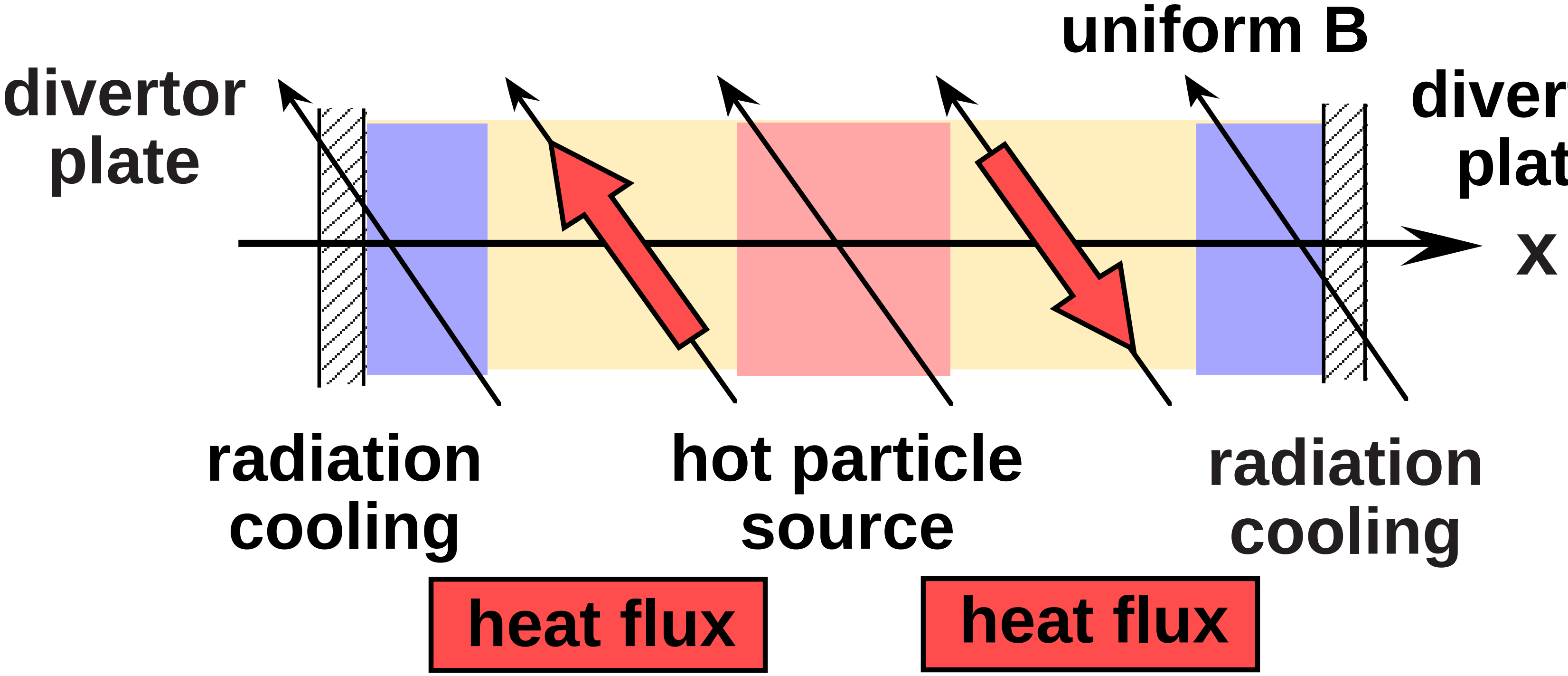
A. Loarte et al., J. Nucl. Mater. **313-316** (2003) 962.

Kinetic effect on the Heat Transport parallel to B

Very large heat transport parallel to B is essential for ELM energy loss through SOL/divertor plasma.

$q_{//} = - \kappa_{//} (dT/dx)$?

PARASOL 1D Simulation



Classical Diffusive Heat Flux

$$q_{cond} = q_{cl}$$

$$q_{cl} = -\,\kappa_{e//}\, dT_e/ds$$
$$\propto\ T_e^{5/2}\, T_{e//}\, (1 - g^{7/2}) / \nu_{d0}\, L_{ab}$$

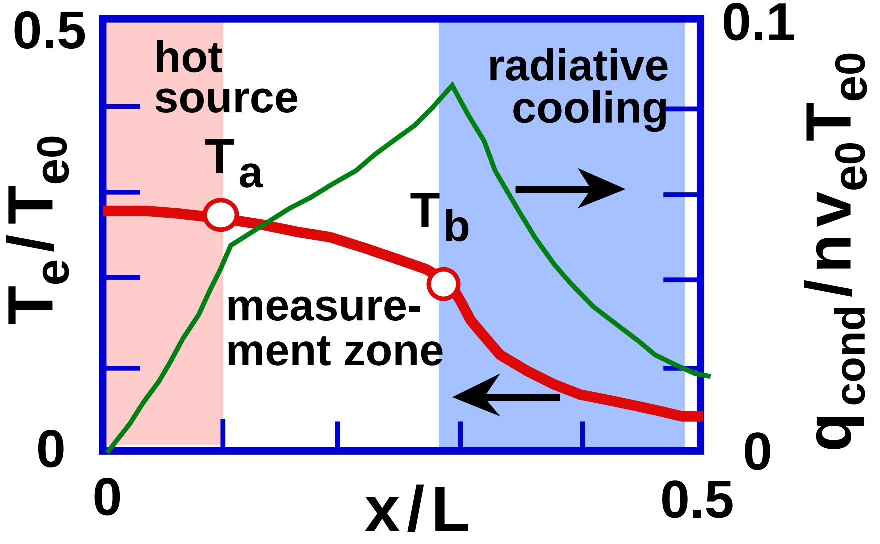
($g = T_b/T_a$,
L_{ab} = measurement-zone length // **B**)

Limited Heat Flux for $l_{mfp} \geq L_{ab}$

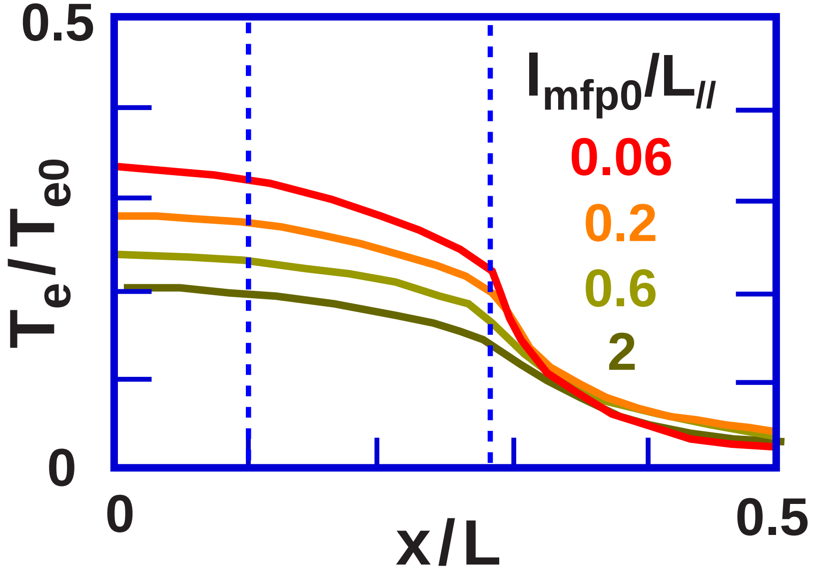
$$q_{lim} = \alpha_q\, n\, T_e\, (T_{e//}/m_e)^{1/2}$$

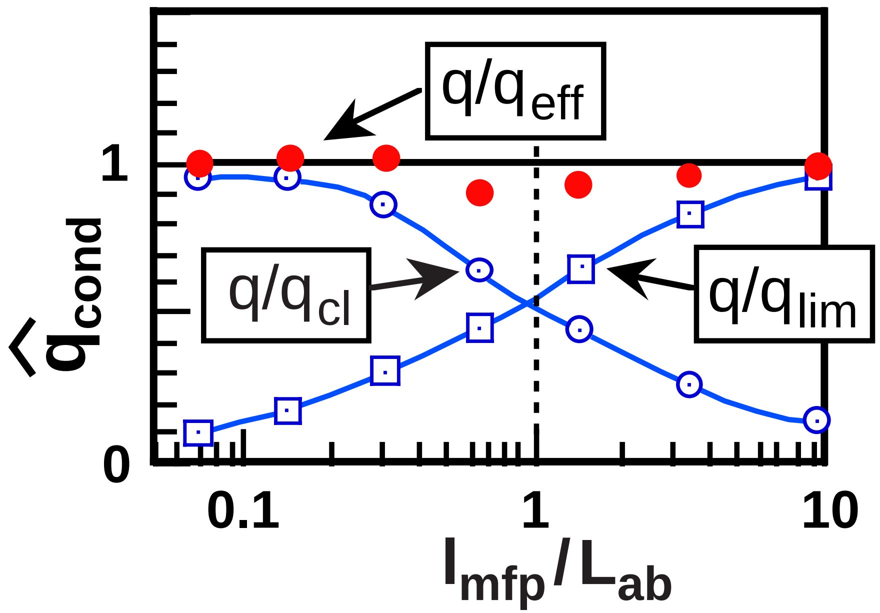
$$l_{mfp} = (T_{e//}/m_e)^{1/2}\, (3T_e/T_{e0})^{3/2} / \nu_{d0}$$

PARASOL Simulation



Numerical Experiments → Measurement → Analysis → Physics Understanding





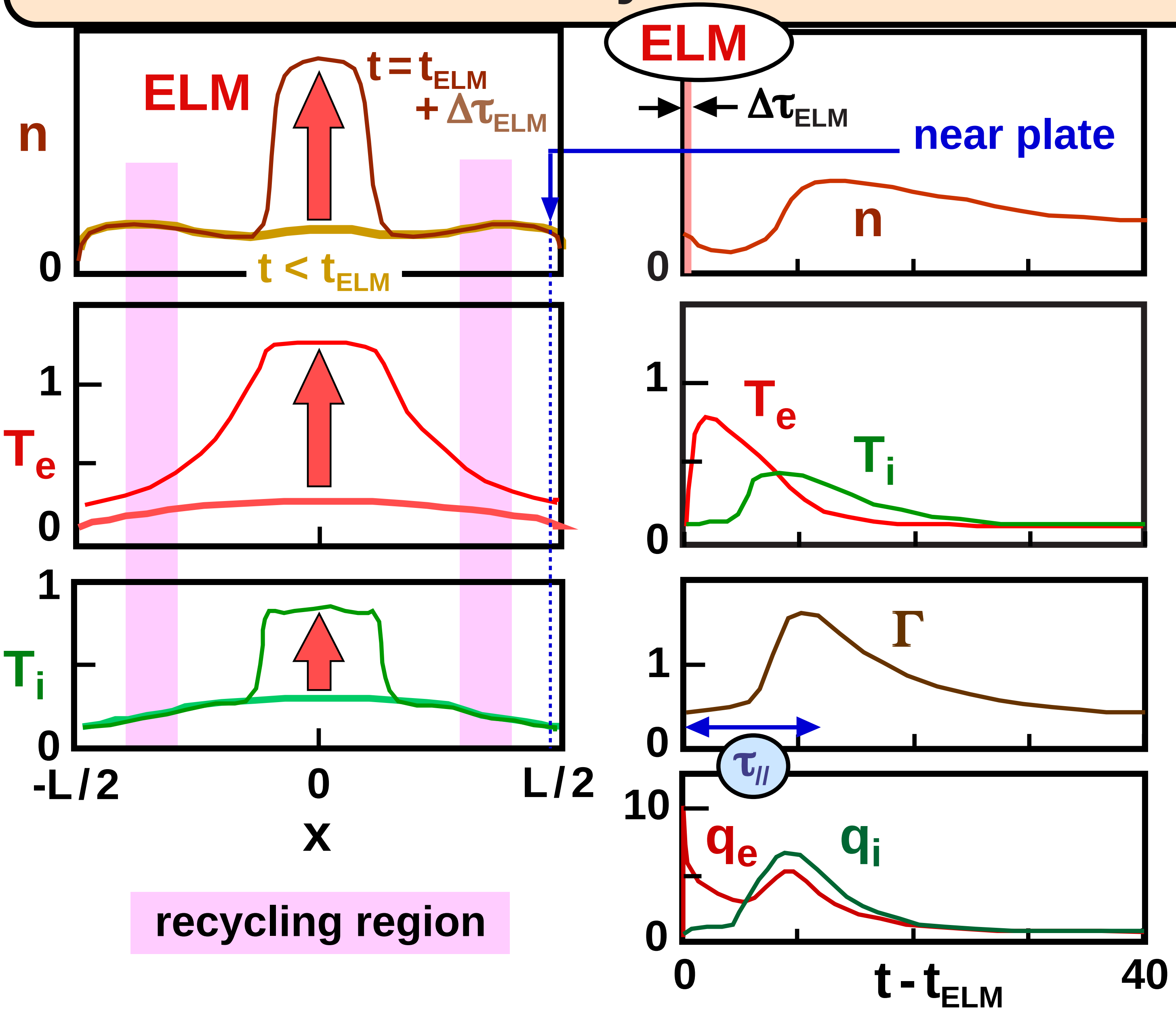
$$q_{lim} = \alpha_q n T_e (T_{e//}/m_e)^{1/2}$$

$\alpha_q = 3/4$

$$1/q_{eff}^{k} = 1/q_{cl}^{k} + 1/q_{lim}^{k}$$

$k = 4/3$

1-Dimensional Dynamic Simulation for ELM



$B_x/B = 0.2$

$t_{nor} = L_{//}/v_{e0}$

$\Delta\tau_{ELM} = 0.5$

$m_i/m_e = 1800$

$C_s = 0.033\, v_{e0}$

$(T_e = T_i = 1)$

$\tau_{//} = (0.4 L_{//})/C_s$

$= 12$

$\Gamma_{rec}/\Gamma_{plate} = 0.5$

$l_{mfp0}/L_{//} = 0.06$

SOL/Divertor Plasma Responce for ELM

Simulation Results by PARASOL 1D-Dy

PARticle Advanced Simulation for SOL and divertor plasmas

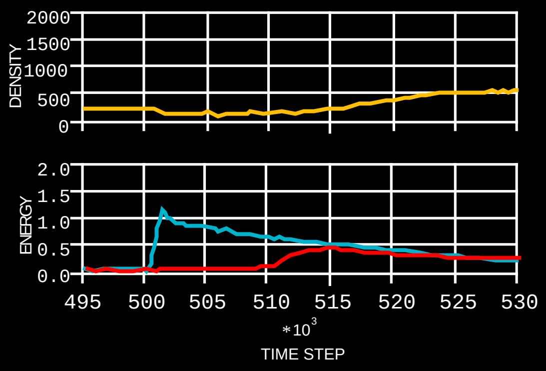
INDEX

	KTPR2	RATE1 / RMFPL			
		0.5 / 3.0	0.5 / 0.3	0.9 / 0.3	0.5 - 0.9 / 0.3
Density, Energy	500	a1l.mpeg	b1l.mpeg	c1l.mpeg	d1l.mpeg
	100	a1m.mpeg	b1m.mpeg	c1m.mpeg	d1m.mpeg
Density, Potential	100	a2m.mpeg	b2m.mpeg	c2m.mpeg	d2m.mpeg
Density, Velocity	100	a3m.mpeg	b3m.mpeg	c3m.mpeg	d3m.mpeg
Ion Energy, Energy Flow	100	a4m.mpeg	b4m.mpeg	c4m.mpeg	d4m.mpeg
Electron Energy, Energy Flow	100	a5m.mpeg	b5m.mpeg	c5m.mpeg	d5m.mpeg

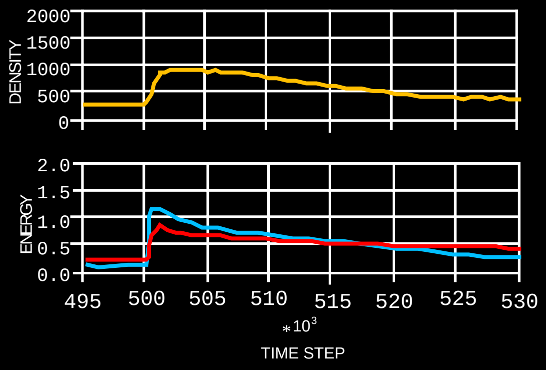
BACK TO INDEX

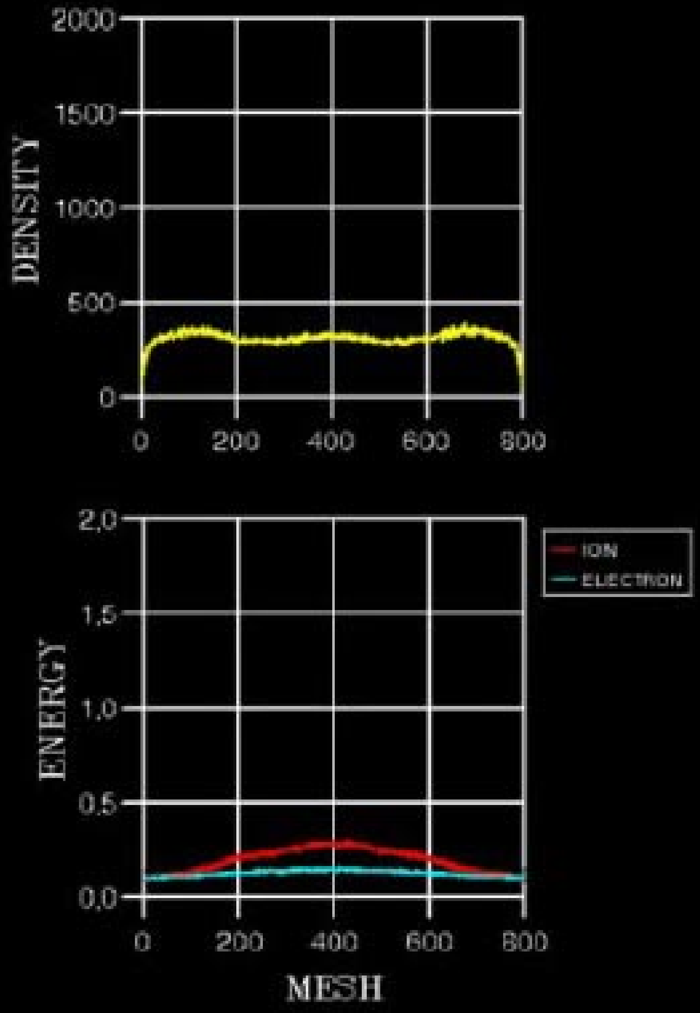
DENSITY, ENERGY
RATE1 = 0.5
RMFPL = 3.0
KTPR2 = 100
PROBE CENTER = 15 (MESH)
PROBE DIVERTOR = 315 (MESH)

DIVERTOR

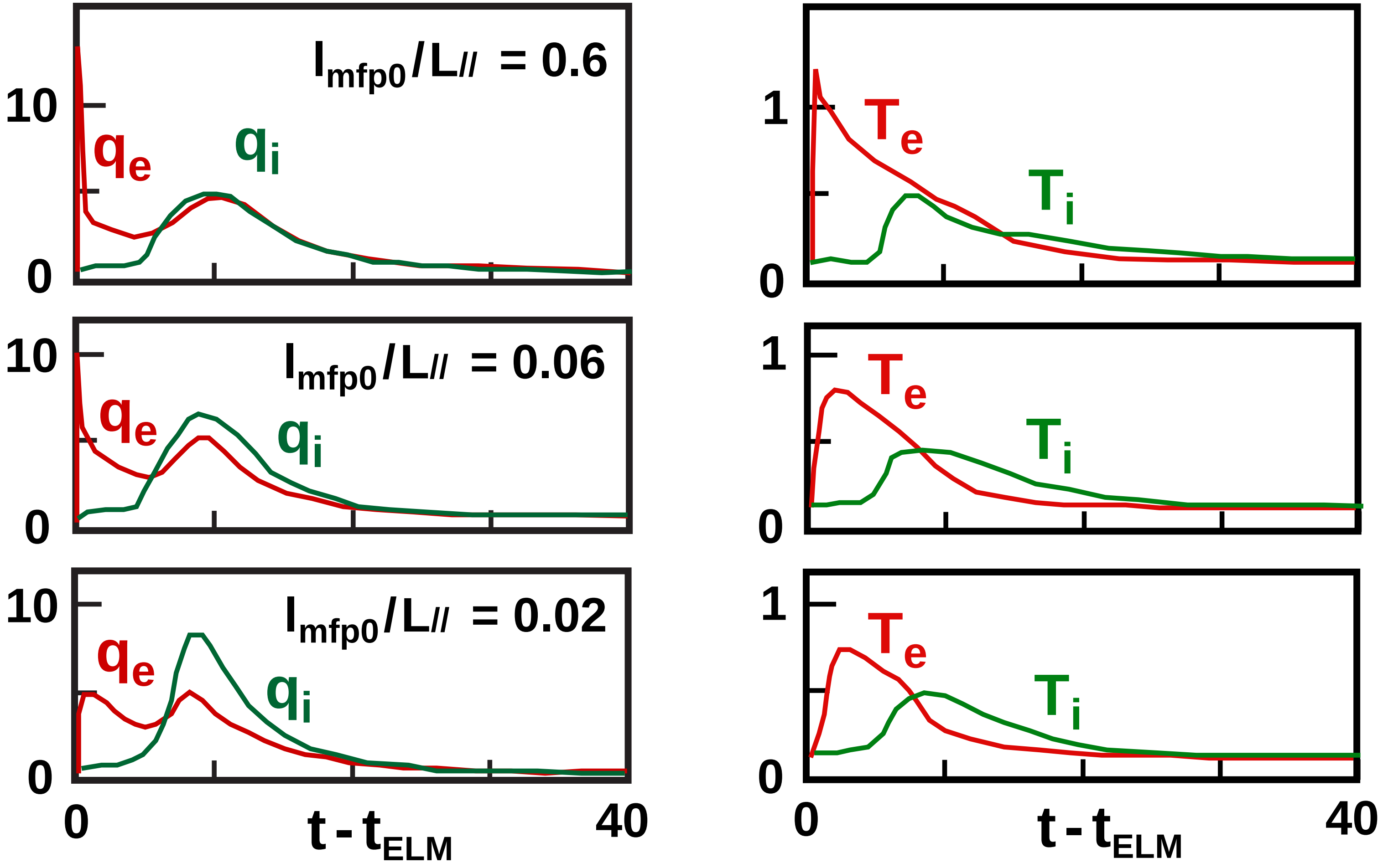


CENTER





ELM heat fluxes depend on collisionality



Analysis of simulation results is in progress.
2D PARASOL simulation for ELM is started.

Summary

- Complexity of divertor simulation requires various types of codes and their integration.

- Fluid + Monte Carlo code (SONIC) simulation realizes the x-point MARFE. Results agree fairly well with JT-60U experiment.

  SONIC simulation for NCTF divertor design shows the importance of configuration for particle control.

- PIC + Monte Carlo code (PARASOL) simulation can establish the basis of physics model for comprehensive divertor simulations.

  PARASOL simulation clarifies the physics of ELM energy and particle losses to divertor plates.