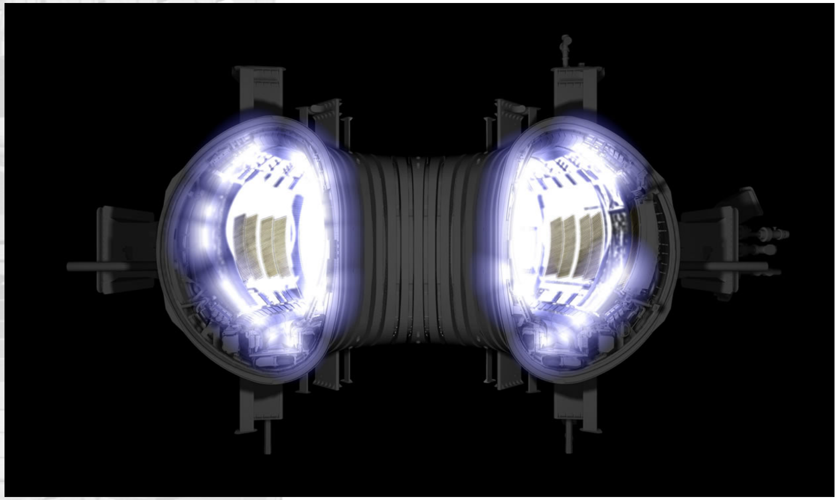
Magnetic fusion plasmas and impurity transport



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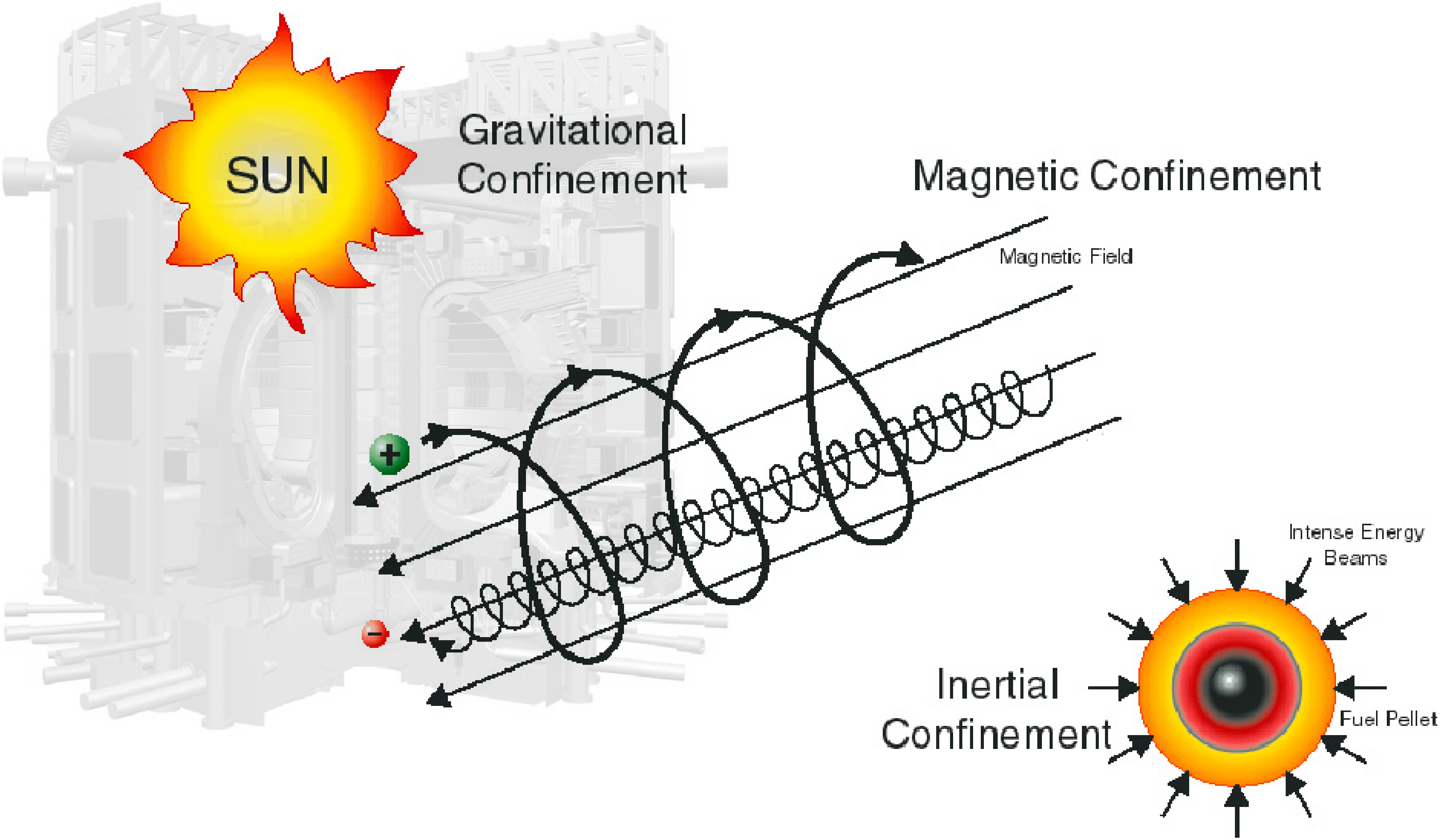
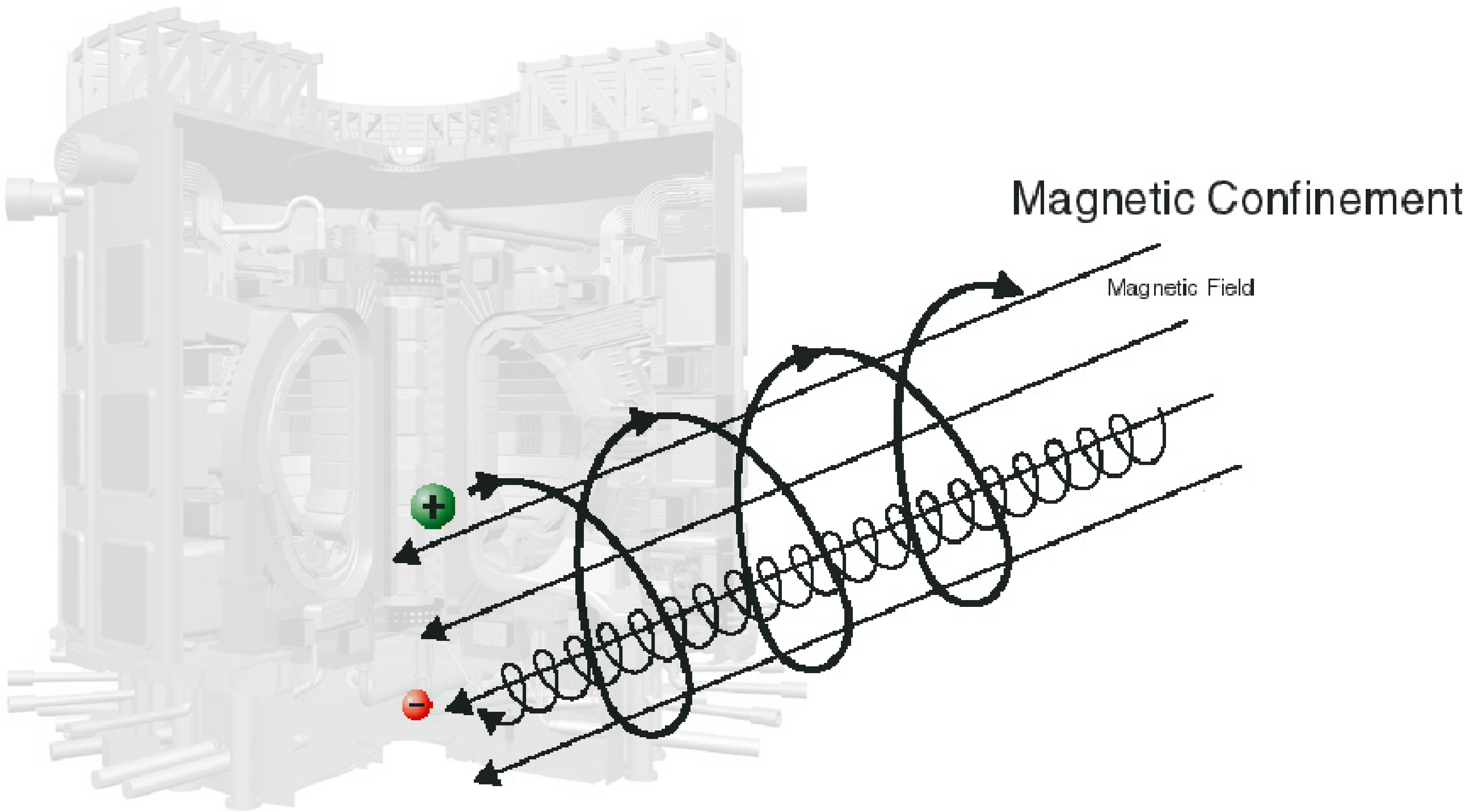
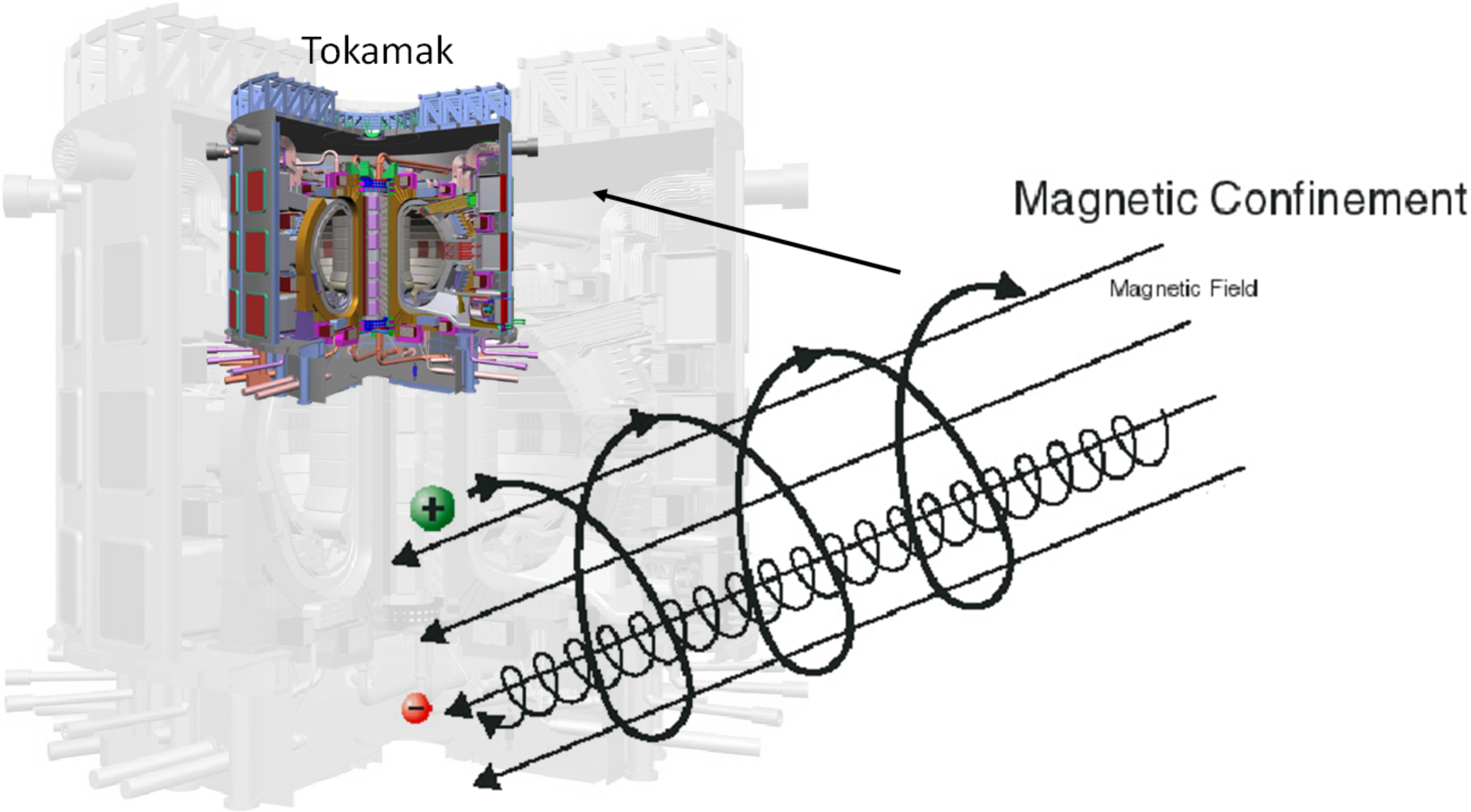
Fusion plasma confinement



Fusion plasma confinement



Fusion plasma confinement



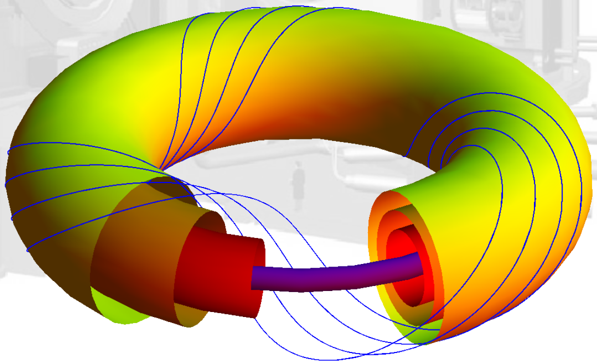
Magnetic fusion plasmas

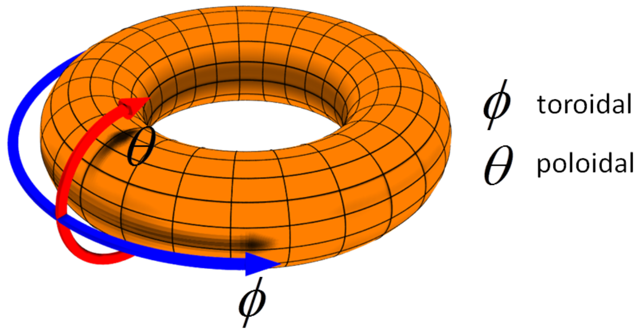
- Temperature $T \sim 100\,000\,000$ K $(\approx 10$ keV$)$.
- Particle density $n \sim 10^{20}$ m^{-3}.
- Magnetic field strength $B \sim 2 - 6$ T.
- Typically consists of electrons, fuel ions (deuterium, tritium), fusion ash (helium ions) and impurities (heavier ions).
- To achieve a self-sustained burning plasma the ignition criterion must be fulfilled $n\tau_E T > 2.6 \cdot 10^{21}$keVm^{-3}s $\Rightarrow$ the energy confinement time τ_E should be long enough.

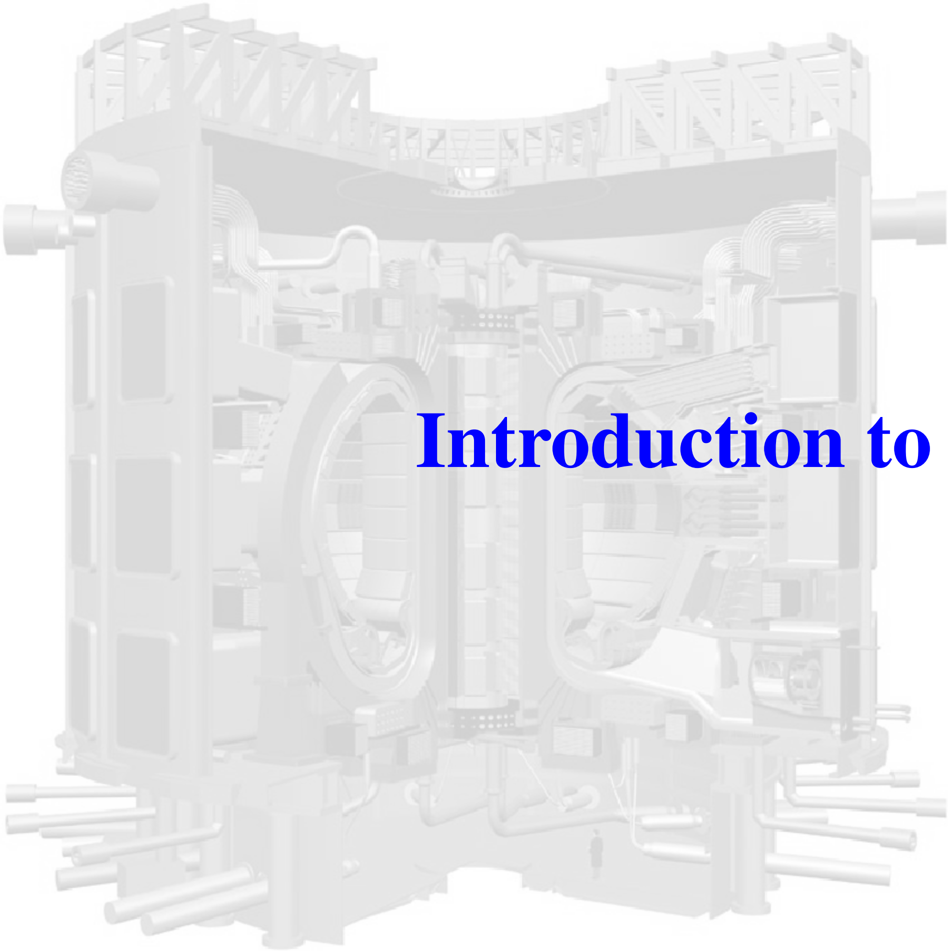
Magnetic fusion plasmas

Geometry

- Toroidal shape, only topology with non-vanishing continuous tangent vector field.
- Magnetic field lines twisted to cancel out particle drifts.
- Field lines trace out *flux surfaces*.



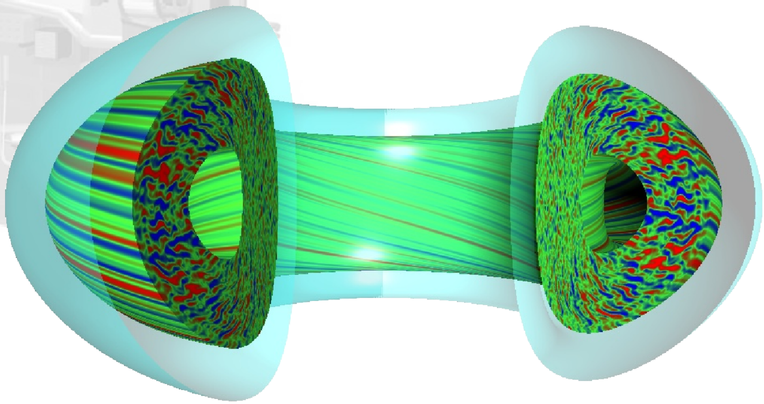




Introduction to turbulent transport

Turbulent transport

- To maximize energy confinement time τ_E, the radial transport should be minimized.
- Collisional transport theory describes an irreducible minimum of the diffusional transport in toroidal fusion plasmas.
- Usually overshadowed by higher losses due to fine-scale turbulent fluctuations, so-called *microinstabilities*.
- Understanding the resulting "anomalous" transport requires sophisticated kinetic models and non-linear, multi-dimensional numerical simulations.



Electron density fluctuations calculated by GYRO

Kinetic transport models

- Particle species represented by the six-dimensional phase space distribution $f\left(\mathbf{r},\mathbf{v},t\right)$.

- Described by the Fokker-Planck kinetic equation

$$\frac{\partial f}{\partial t}+\mathbf{v}\cdot\nabla_r f+\frac{q}{m}\left[\mathbf{E}\left(\mathbf{r},t\right)+\mathbf{v}\times\mathbf{B}\left(\mathbf{r},t\right)\right]\cdot\nabla_v f=C\left(f\right),$$

  where the RHS is the collision operator.

- From the distribution function the flux surface average of the radial particle and energy fluxes are found:

$$\langle\mathbf{\Gamma}\cdot\nabla r\rangle=\left\langle\int d^3v\, f\,\mathbf{v}\cdot\nabla r\right\rangle$$

$$\langle\mathbf{Q}\cdot\nabla r\rangle=\left\langle\int d^3v\,\frac{mv^2}{2}\,f\,\mathbf{v}\cdot\nabla r\right\rangle$$

Gyrokinetic description

- For investigating microinstabilities and turbulent fluxes.
- Distribution function split into perturbed $\hat{f}$ and equilibrium f parts

$$\left[\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla_r + \frac{q}{m}\left(\mathbf{E} + \hat{\mathbf{E}} + \mathbf{v} \times \left(\mathbf{B} + \hat{\mathbf{B}}\right)\right) \cdot \nabla_v\right]\left(f + \hat{f}\right) = C\left(f + \hat{f}\right),$$

  where

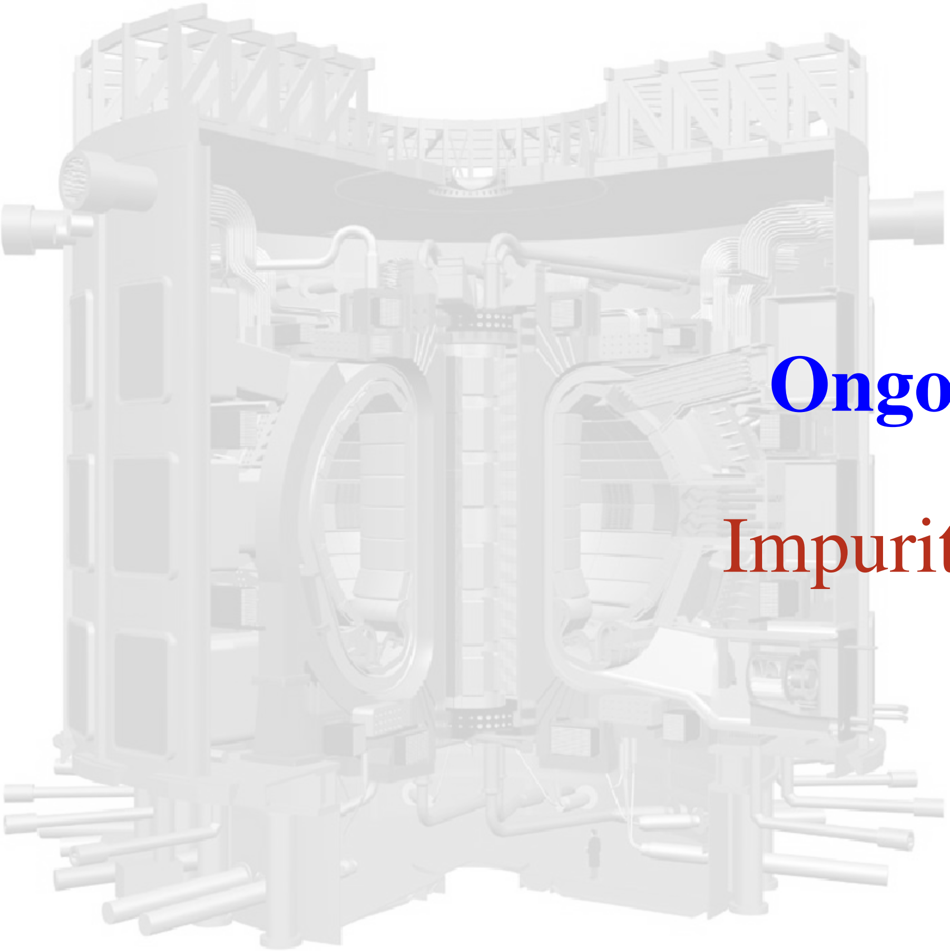
$$\frac{\hat{f}}{f} \sim \delta = \rho / L \ll 1$$

  + additional orderings.

- Expand quantities in δ, $\hat{f} = \hat{f}_1 + \hat{f}_2 + \ldots$, and average over gyro-motion to obtain the gyrokinetic equation.
- Lowest order equilibrium distribution usually a Maxwellian.

Microinstabilities

- Perturbed fields assumed to be $\propto \exp\left(i\,\mathbf{k}\cdot\mathbf{r}\right)\exp\left(-i\omega t\right)$
- Use quasineutrality to obtain a dispersion relation and find mode eigenvalues $\omega = \omega_r + i\gamma$.
- Drift waves, destabilized by ion/electron magnetic drifts, $\mathbf{v}_{\nabla B}$ and $\mathbf{v}_{\kappa}$. Ion Temperature Gradient mode and Trapped Electron mode
  - electrostatic,
  - driven by $\nabla_{\perp} p$,
  - low frequency $\ll \omega_{ci}$.
- Heavy numerical task to simulate microinstabilities. We use the widely recognized GYRO code developed at General Atomics, USA.



Ongoing work

Impurity transport

Impurities

- Produced by the fusion reaction
  $\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} + 17.6\ \mathrm{MeV}$.

- From wall materials.
  Typical impurity ions: Be^{+4}, C^{+6}, Ar^{+18}, Ni^{+28}, Mo^{+32} and W^{+40}.

- Leads to radiation losses and plasma dilution ($\Rightarrow$ decrease in τ_E), especially high-Z impurities in the core are detrimental.
  Radiation losses $\propto Z^2$.

- But can be beneficial at the edge by distributing the plasma heat over larger areas to protect the surrounding walls.

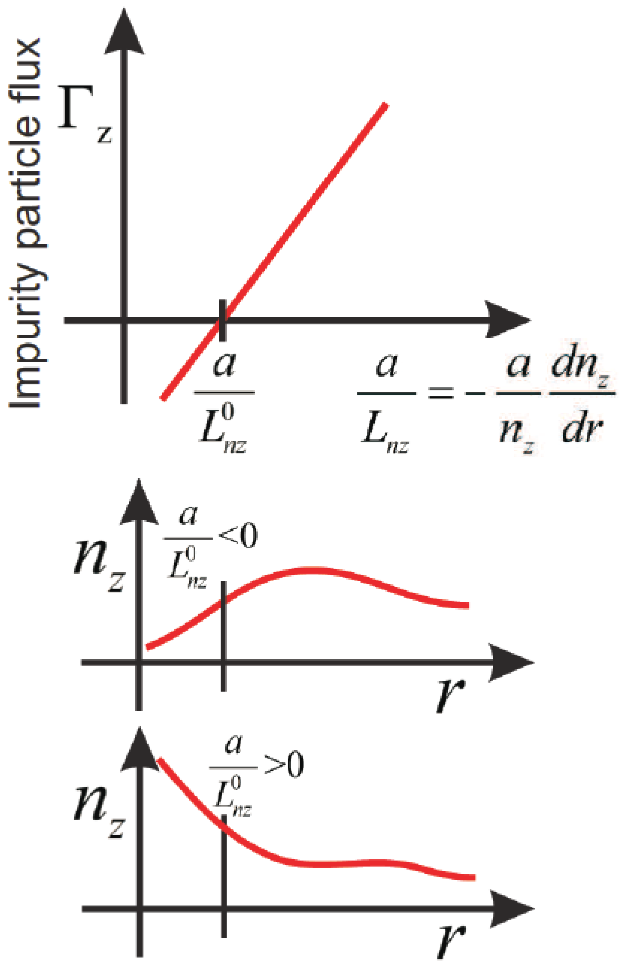
We want to transport impurities out of the core to the edge region.

$\Downarrow$

Need to understand impurity transport.

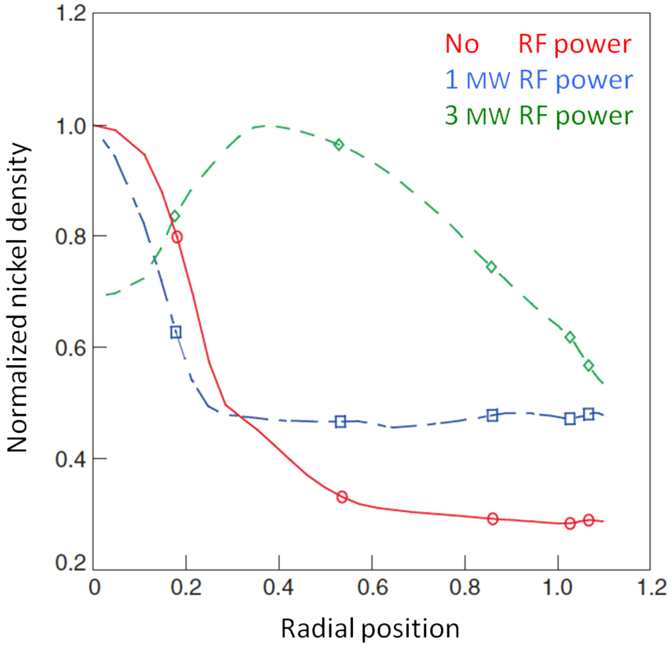
Impurity transport

- The peaking factor a/L^0_{nz} is the zero-flux density gradient. Calculated from $\mathbf{\Gamma}_z = 0$.
- Typically density profiles are peaked, i.e. positive peaking factor.
- A negative impurity peaking factor would indicate a configuration with no core accumulation.



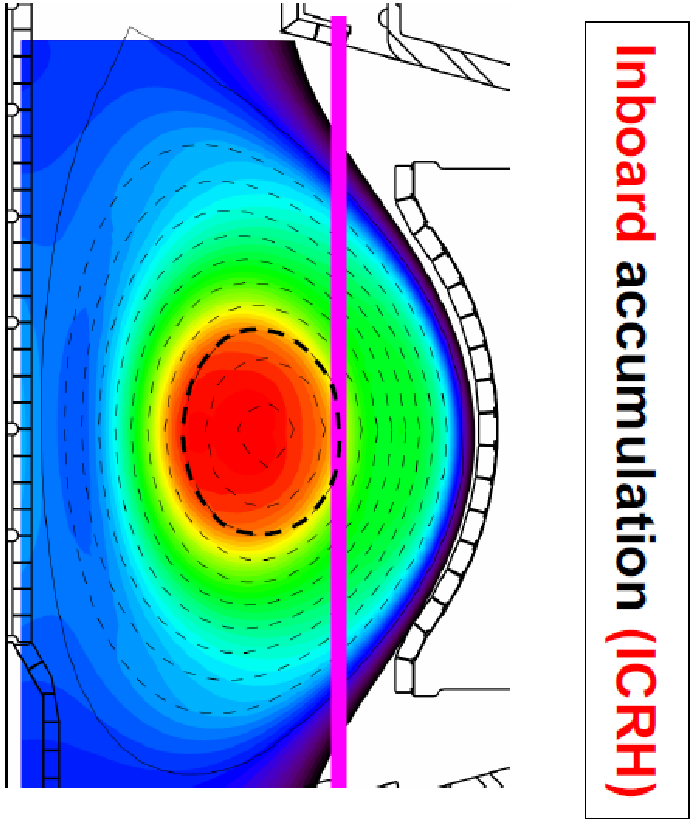
Impact of radiofrequency heating

- Plasma heating using radiofrequency waves has shown to decrease the concentration of high-Z impurities in the core.
- A beneficial side-effect.
- Theoretical understanding of the effect not clear.



Impact of radiofrequency heating

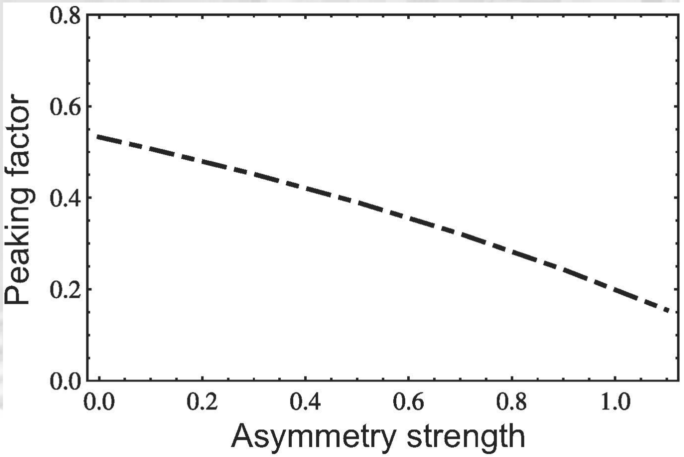
- Normally impurities are evenly distributed over a flux surface.
- RF heating yields an inboard accumulation of impurities, i.e. poloidal asymmetry.
- Affects the radial transport.

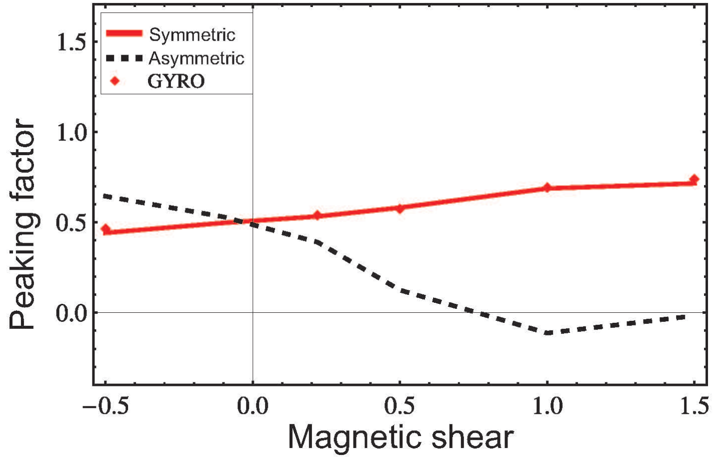


M.L. Reinke et al., Alcator C-Mod experiments, PPCF, 2012

Effects of poloidal asymmetries on radial transport

- Assume high-Z trace impurity, $Zn_z/n_e \ll 1$.
  Turbulence almost unaffected by presence of trace impurities.
- Use GYRO to find most unstable mode.
- Incorporate poloidal asymmetries into the linear gyrokinetic model and calculate the peaking factor.





We can obtain a negative peaking factor, i.e. outward transport of impurities!

Conclusions & outlook

- Poloidal asymmetries seem to affect the radial impurity transport.
- Experimentalists are starting to plan for dedicated experiments.
- Developers are starting to implement poloidal asymmetries in gyrokinetic codes.

Publications

- T. Fülöp and S. Moradi, *Phys. Plasmas*, **18** 030703 (2011).
- S. Moradi, T. Fülöp, A. Mollén, and I. Pusztai, *Plasma Phys. Control. Fusion* **53**, 115008 (2011).
- A. Mollén, I. Pusztai, T. Fülöp, Ye. O. Kazakov, S. Moradi, *Phys. Plasmas* **19**, 052307 (2012).