Plasma Flow Characteristics and Enhanced Confinement Regimes in Stellarators

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BACKGROUND

Stellarators, due to their three-dimensional magnetic field structure, provide a qualitatively different coupling between plasma flows, momentum sources, radial electric fields, and neoclassical transport than is the case for toroidally-symmetric devices. In tokamaks and STs, sheared radial electric fields can be driven by parallel momentum input, enhanced fast ion loss, or internally generated by mechanisms such as the Reynolds stress. For stellarators, the same mechanisms apply, but in addition neoclassical transport requires a finite electric field to achieve ambipolarity; also static magnetic islands can induce flow shear. The viscous flow damping characteristics of stellarators differ from those of tokamaks due to the different variation of |B| along a field line; the flow damping characteristics depend on the type of quasi-symmetry, i.e., quasi-helical (HSX), quasi-poloidal (QPS), or quasi-toroidal (NCSX). The connection between electric fields and flows depends on the flow damping mechanism. For example, for exact symmetry the radial electric field is $(B_{toroidal}/B_{poloidal})^2$ higher in a poloidally symmetric system than in a toroidally symmetric system for the same $v_{||}$.

Recent developments in stellarator neoclassical theory allow improved quantitative evaluations of these effects. Stellarators provide important sources of data on enhanced confinement regimes that augment and extend the physics that can be addressed in tokamaks and STs. On the fundamental level, ion and electron neoclassical transport is modified by E x B drifts affecting guiding center orbits. For anomalous transport, sheared poloidal flows should be more effective than sheared toroidal flows in shredding turbulent eddies. Some unique aspects of enhanced confinement in existing experiments include: the HDH mode in W7-AS, which provides improved confinement and expels impurities; simultaneous formation of ion and electron temperature gradient barriers in CHS; influence of stationary magnetic islands on sheared electric fields and barrier formation (TJ-II); and measurements of the electric field with two HIBPs (CHS).

- QPS/NCSX/HSX have been strongly optimized
  - so that neoclassical losses << anomalous losses
  - remaining transport-related differences are in the parallel momentum transport properties
- Recently, a theoretical framework has been developed that allows quantitative, self-consistent assessment of the parallel and perpendicular transport in 3-D systems
  - H. Sugama and S. Nishimura, Physics of Plasmas, 9 (November, 2002) 4637
  - extends DKES transport coefficients (based on pitch-angle scattering operator) for momentum-conservation and ion-electron frictional coupling effects
  - provides particle/energy fluxes, viscosity tensor, flows, and bootstrap current
- Calculation of flow velocity profiles for stellarators is motivated by
  - relevance to turbulence suppression/enhanced confinement regimes
  - comparison with impurity line measurements
  - impurity accumulation/shielding studies
- More accurate collisional bootstrap current prediction and ambipolar electric field estimation

Radial fluxes, bootstrap current, and parallel, poloidal, toroidal flow velocities are obtained via the parallel force balance relation

Radial particle flows required for ambipolar condition ➡ self-consistent energy fluxes and bootstrap currents

$$\begin{bmatrix}\Gamma_e\\ q_e/T_e\\ \Gamma_i\\ q_i/T_i\\ J_{BS}^E\end{bmatrix} = -\begin{bmatrix} L_{11}^{ee} & L_{12}^{ee} & L_{11}^{ei} & L_{12}^{ei} & L_{1E}^{e}\\ L_{21}^{ee} & L_{22}^{ee} & L_{21}^{ei} & L_{22}^{ei} & L_{2E}^{e}\\ L_{11}^{ie} & L_{12}^{ie} & L_{11}^{ii} & L_{12}^{ii} & L_{1E}^{i}\\ L_{21}^{ie} & L_{22}^{ie} & L_{21}^{ii} & L_{22}^{ii} & L_{2E}^{i}\\ L_{E1}^{e} & L_{E2}^{e} & L_{E1}^{i} & L_{E2}^{i} & L_{EE}\end{bmatrix}\begin{bmatrix}X_{e1}\\ X_{e2}\\ X_{i1}\\ X_{i2}\\ X_E\end{bmatrix}$$

where $X_{a1} \equiv -\frac{1}{n_a}\frac{\partial p_a}{\partial s} - e_a\frac{\partial \Phi}{\partial s}$, $X_{a2} \equiv -\frac{\partial T_a}{\partial s}$, $X_E = \langle BE_{||}\rangle / \langle B^2\rangle^{1/2}$

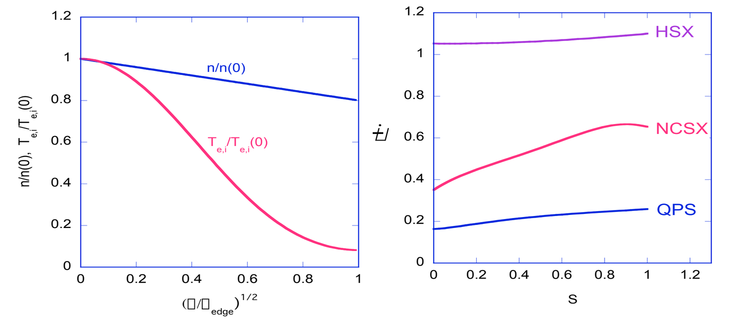
Parallel mass and energy flows:

$$\begin{bmatrix}\langle Bu_{||i}\rangle\\ \frac{2}{5p_i}\langle Bq_{||i}\rangle\end{bmatrix} = \frac{1}{\langle B^2\rangle}\begin{bmatrix}M_{i1} & M_{i2}\\ M_{i2} & M_{i3}\end{bmatrix}\begin{bmatrix}l_{11}^{ii} & -l_{12}^{ii}\\ -l_{12}^{ii} & l_{22}^{ii}\end{bmatrix}^{-1}\begin{bmatrix}N_{i1} & N_{i2}\\ N_{i2} & N_{i3}\end{bmatrix}\begin{bmatrix}X_{i1}\\ X_{i2}\end{bmatrix}$$

Poloidal and toroidal (contravariant) flow velocities:

$$\begin{bmatrix}\langle u_i^{\theta}\rangle/\Phi'\\ \langle u_i^{\zeta}\rangle/\Phi'\end{bmatrix} = \frac{4\pi^2}{V'}\begin{bmatrix}B_{\zeta}/(\ldots\langle B^2\rangle) & \ldots\\ B_{\theta}/(\ldots\langle B^2\rangle) & \ldots\end{bmatrix}\begin{bmatrix}\langle Bu_{||i}\rangle/\langle B^2\rangle\\ X_{i1}\end{bmatrix}$$

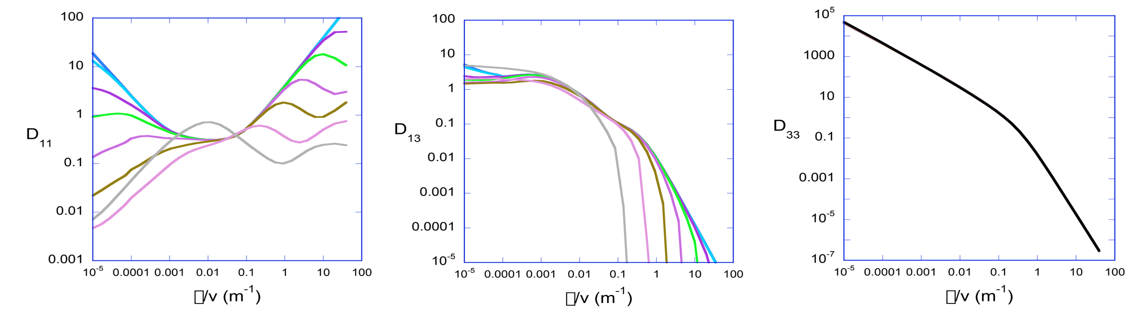
Profiles and parameters



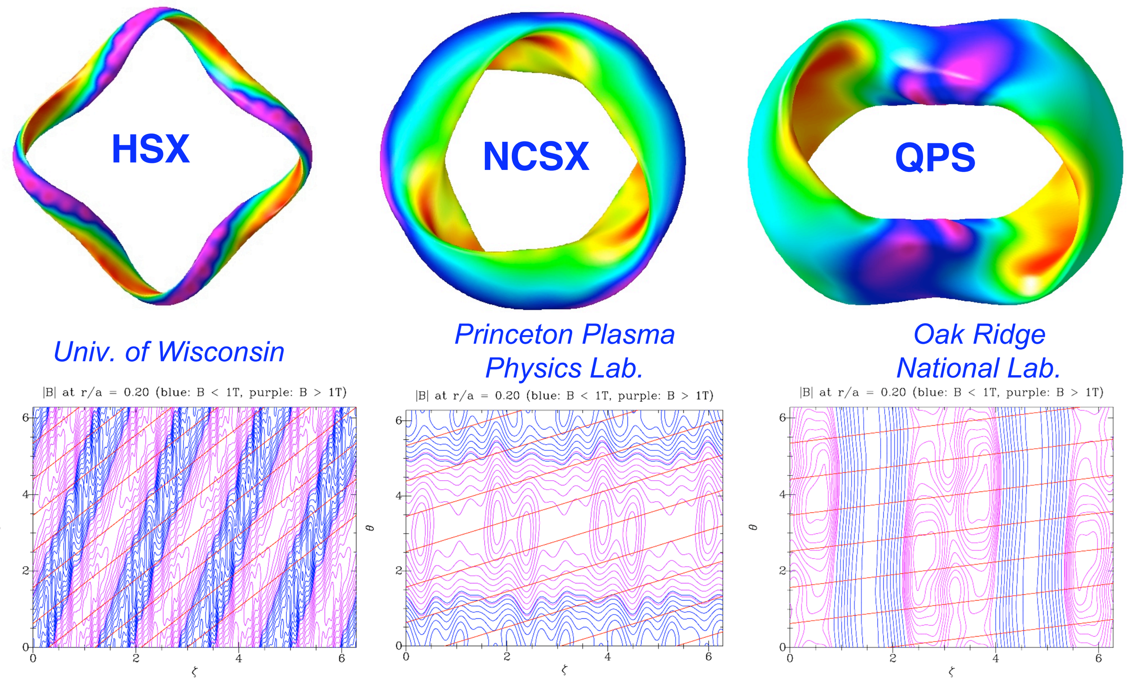
ECH Regime:
$n(0) = 2 \times 10^{19}$ m^{-3}
$T_e(0) = 2.1$ keV
$T_i(0) = 0.2$ keV

ICH Regime:
$n(0) = 8.3 \times 10^{19}$ m^{-3}
$T_e(0) = 0.53$ keV
$T_i(0) = 0.38$ keV

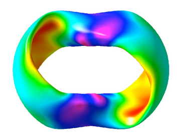
Typical DKES monoenergetic transport coefficients



- Quasi-symmetric stellarators based on the 3 unique forms of quasi-symmetry either operating or planned in the U.S. program
  - HSX: quasi-helical symmetry |B| ~ |B|(m□ □ n□)
  - NCSX: quasi-toroidal symmetry |B| ~ |B|(□)
  - QPS: quasi-poloidal symmetry |B| ~ |B|(□)



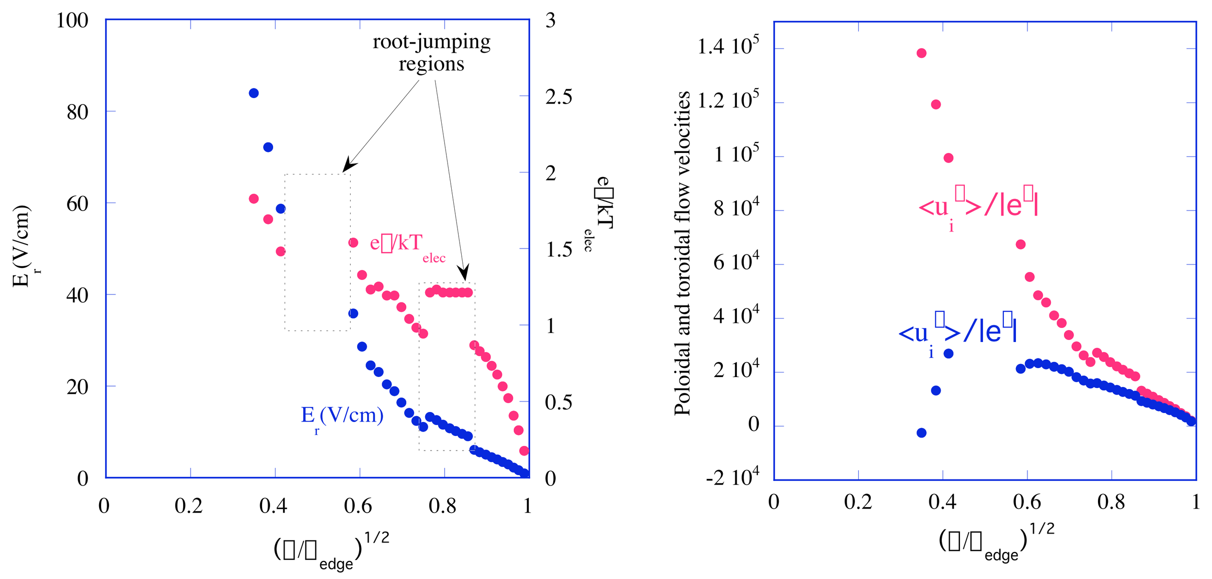
QPS - ECH regime



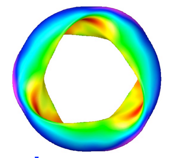
electric field and flow velocities

Toroidal flow suppressed - poloidal flow dominates

$n(0) = 2 \times 10^{19}$ m^{-3}, $T_e(0) = 2.1$ keV, $T_i(0) = 0.2$ keV



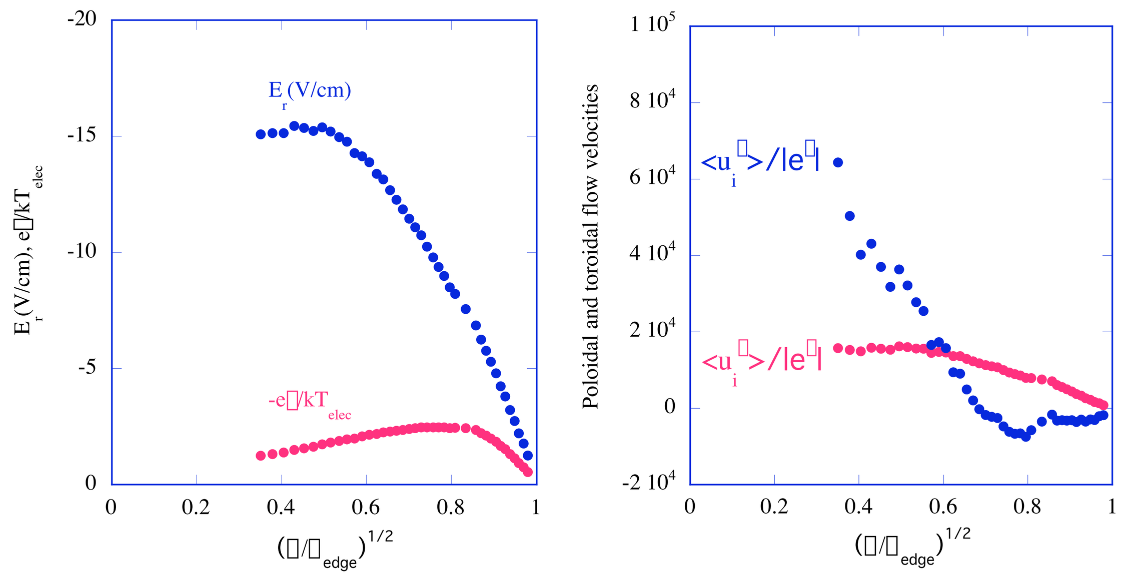
NCSX



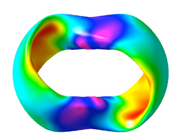
electric field and flow velocities

Toroidal flow dominant in center, poloidal flow at edge

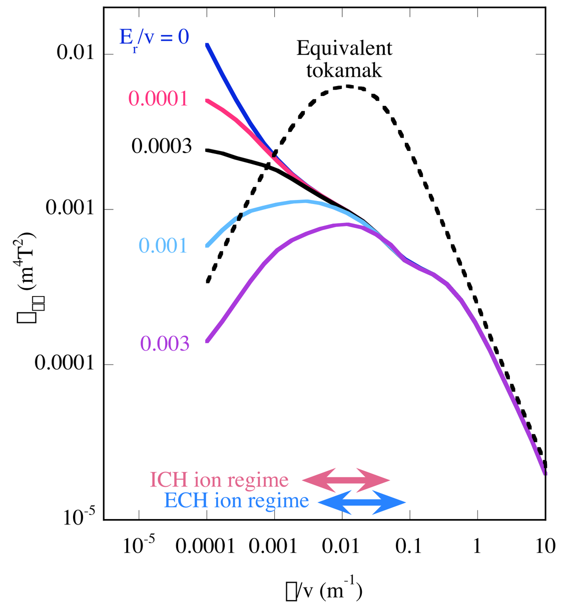
$n(0) = 8.3 \times 10^{19}$ m^{-3}, $T_e(0) = 0.53$ keV, $T_i(0) = 0.38$ keV



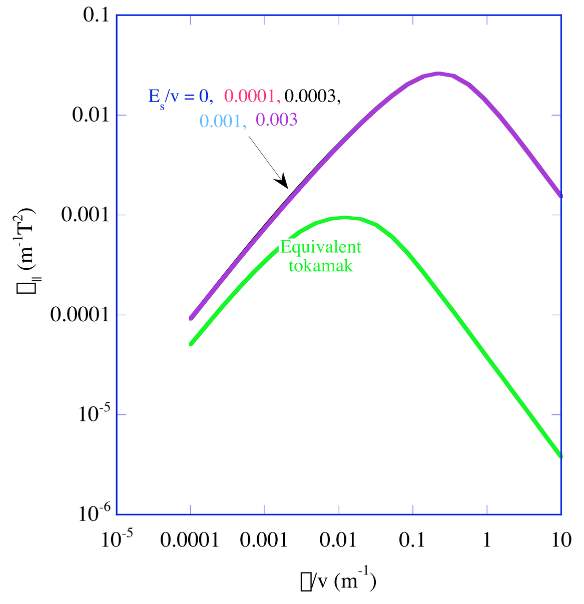
QPS - viscosities show strongly reduced poloidal flow damping from an equivalent axisymmetric device



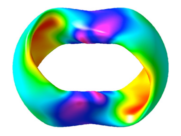
poloidal - 10 x less than tokamak



parallel



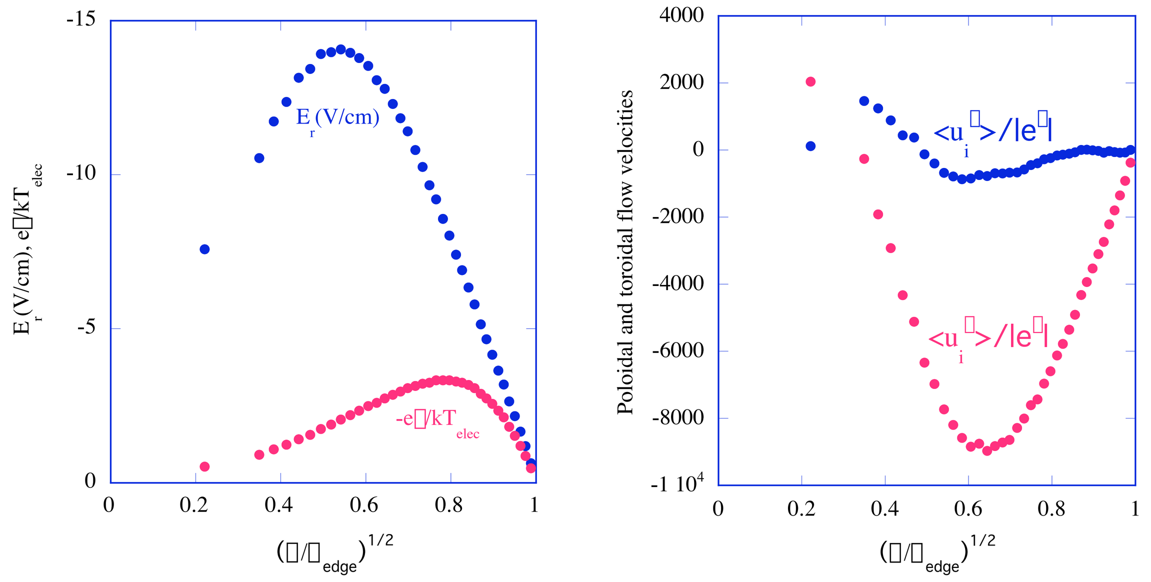
QPS - ICH regime



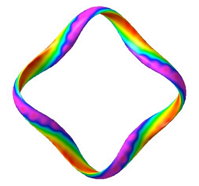
electric field and flow velocities

Toroidal flow suppressed - poloidal flow dominates

$n(0) = 8.3 \times 10^{19}$ m^{-3}, $T_e(0) = 0.53$ keV, $T_i(0) = 0.38$ keV

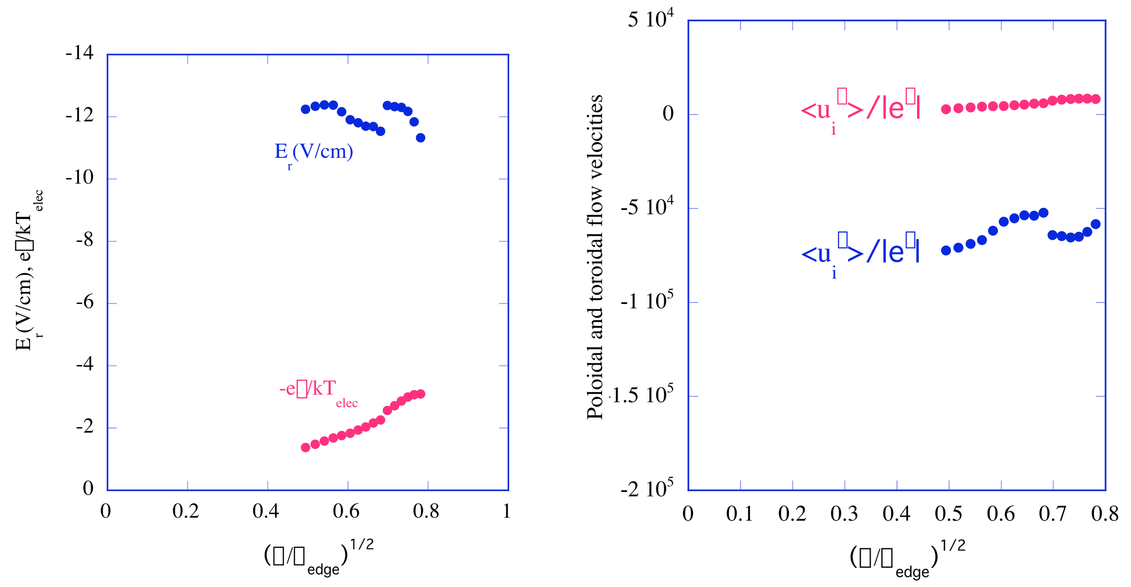


HSX



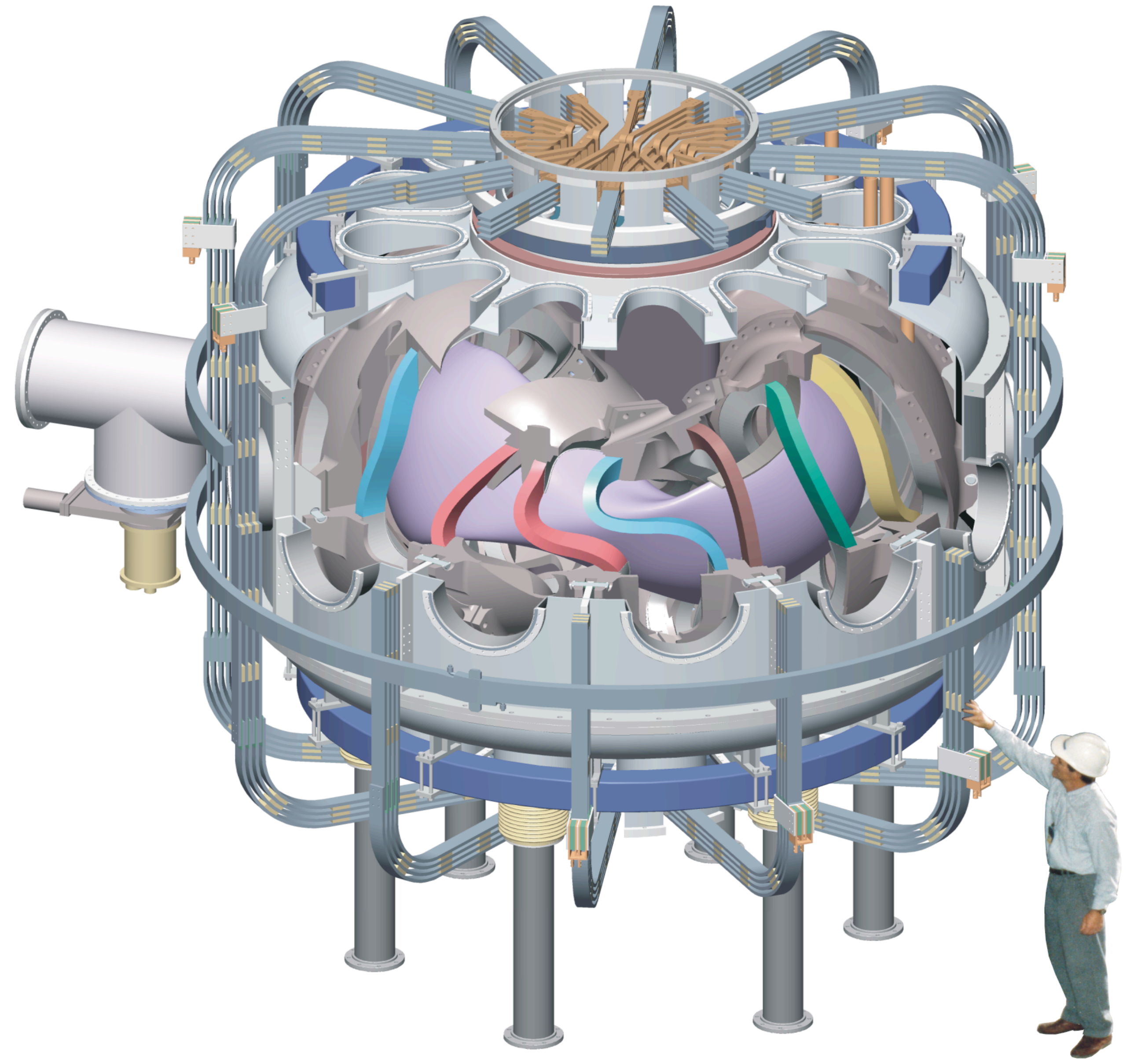
electric field and flow velocities (radial scan incomplete at this point)

Flow follows helical |B| contours - mostly toroidal



QPS Can Study the Effects of Quasi-Poloidal Symmetry on Anomalous Transport Suppression

- Enhanced confinement regimes attributed to electric field shear
  - shredding of turbulent eddies
- This can be driven by a variety of sources
  - self-amplified background plasma flows
  - flows driven by external sources (biased plates, RF)
  - turbulence, pressure gradient drive
- QPS contributes to better understanding through
  - damping in the poloidal (symmetry) direction is weak in QPS, allowing self-generated and externally-driven poloidal flows
  - reduction of anomalous transport by poloidal flow shear and electric fields
  - sheared poloidal flows could be more effective than sheared toroidal flows
  - is there anomalous poloidal flow damping?



QPS Parameters

$\langle R_{pl}\rangle = 0.95$–$1$ m, $\langle a_{pl}\rangle = 0.3$–$0.4$ m, $V_{pl} = 2$–3 m^3,

$I_{plasma} < 50$ kA, $B_{mod} = 1$ T (1.5 s), $B_T = \pm 0.15$ T

$P_{heating} = 1$–2 MW ECH/EBW + 2–3.5 MW ICRF

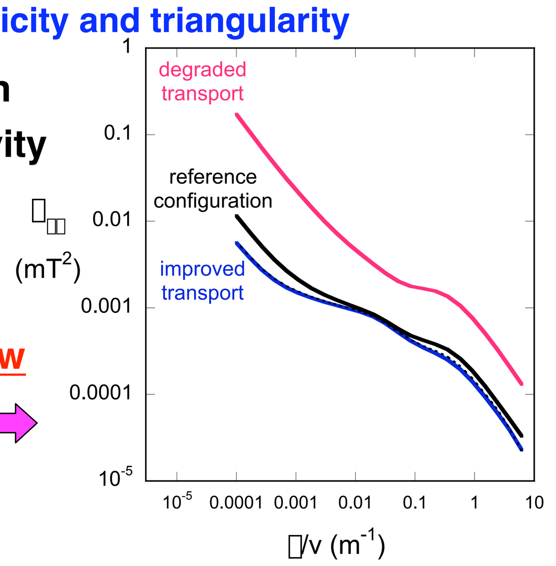
Quasi-Poloidal Symmetry

Most experiments rely on toroidal symmetry
- tokamaks, spherical torus, RFPs, NCSX

QPS is the only experiment that relies on poloidal symmetry
- has a closer connection to toroidally linked mirrors

It will explore a new physics regime using quasi-poloidal symmetry at very low aspect ratio
- very low damping for poloidal flows: improved confinement
- reduced neoclassical transport, bootstrap current,
- sensitivity to □, second stability threshold

- Main focus of the QPS program is use of quasi-poloidal geometry to explore toroidal physics issues at low *R/a*
  - flux surface robustness at *R/a* > 2.5 and sensitivity to □ with strong toroidal/helical coupling
  - *reduction* of neoclassical and anomalous transport
  - *variation* of effective ripple, trapped particle fraction, stellarator or tokamak shear, quasi-poloidal symmetry, poloidal viscosity and poloidal flow shear, ambipolar electric field & internal transport barriers, bootstrap vs. Ohmic current, magnetic island size,
  - magnetic beach ICRF and EBW heating
- A secondary component is study of □ limits and the character of MHD instabilities
- Benchmarking and improvement of 3-D theory
- 9 independent coil currents in QPS allow varying
  - rotational transform (1/*q*); stellarator or tokamak shear
  - helical axis excursion; magnetic field ripple
  - toroidal mirror ratio; helical vs. toroidal field components
  - plasma aspect ratio; ellipticity and triangularity
- This allows large variation in
  - neoclassical heat diffusivity (factor ~25)
  - quasi-poloidal symmetry (factor ~10)
  - poloidal viscosity and flow damping (factor 5-10)
  - □ limits (factor ~3)



- QPS shows strong dominance of poloidal flows
  - Expected efficiency for turbulence suppression due to
    - extended nature of turbulent eddies along field lines (poloidal flow shear more effective than toroidal flow)
    - weak coupling to toroidal flow generation (momentum source is not expended on driving toroidal flows)
- Future developments
  - Continued refinement of transport coefficient calculation and connection formulas
  - Parallelization of DKES over electric field parameter
    - Speed up turn-around on different configurations
  - Multi-ion species
    - Impurity flow velocities
    - Impurity accumulation studies
  - Neutral flow damping
  - Study multiple electric field roots and their stability
  - Bootstrap current evaluation/benchmark
  - External flow drive (bias electrodes, RF flow drive, beams)