The New York Times.

"All the News That's Fit to Print"

LATE CITY EDITION

Section 1

MAYOR GIVES DEWEY ANSWER TO MOVING ON SALES TAX RISE

Million a Year Flee Mexico Only to Find Peonage Here

Illegal Migration Across 1,600-Mile Border by Seasonal Slave Labor Depresses Latin and U. S. Levels Alike

GAMBLER TESTIFIES TO LONG SUSPICION OF GARDEN'S GAMES

PERON ANNOUNCES NEW WAY TO MAKE ATOM YIELD POWER

Washington and MacArthur Clash Anew on Truce Offer

Officials Say They Did Not Know of His Plan and Would Not Have Approved It—State and Defense Aides Confer

M'ARTHUR ORDERS PARALLEL CROSSING IF NECESSITY ARISES

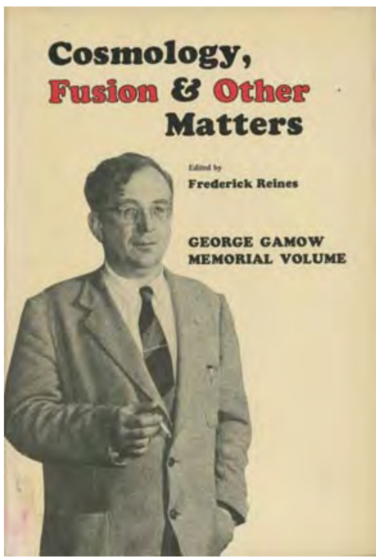
PEIPING SILENT ON TRUCE

TESTS HELD SUCCESSFUL

March 25, 1951

"Peron Announces New Way to Make Atom Yield Power"

President Juan Peron announced today that Argentina had found a way to produce atomic energy … According to the President, Argentine experiments … had been able to produce thermonuclear reactions identical to those through which the sun releases atomic energy.



March 27, 1951

George Gamow: "There will be no way to keep the gases within a given volume. The melting of the walls will permit the immediate expansion of the hot gases and the temperature will inevitably fall."

New York Times, March 27, 1951:

"The Argentine claim would require the achievement of at least three miracles – the production of temperatures of at least millions of degrees, the maintenance of the temperature for longer than a millionth of a second and the development of materials that would not evaporate long before such a temperature could be attained."

February 3, 2016: Chancellor Angela Merkel initiates first hydrogen discharge in the Wendelstein 7-X stellarator

"With a temperature of 80 million degrees and a lifetime of a quarter of a second, the device's first hydrogen plasma has completely lived up to our expectations"

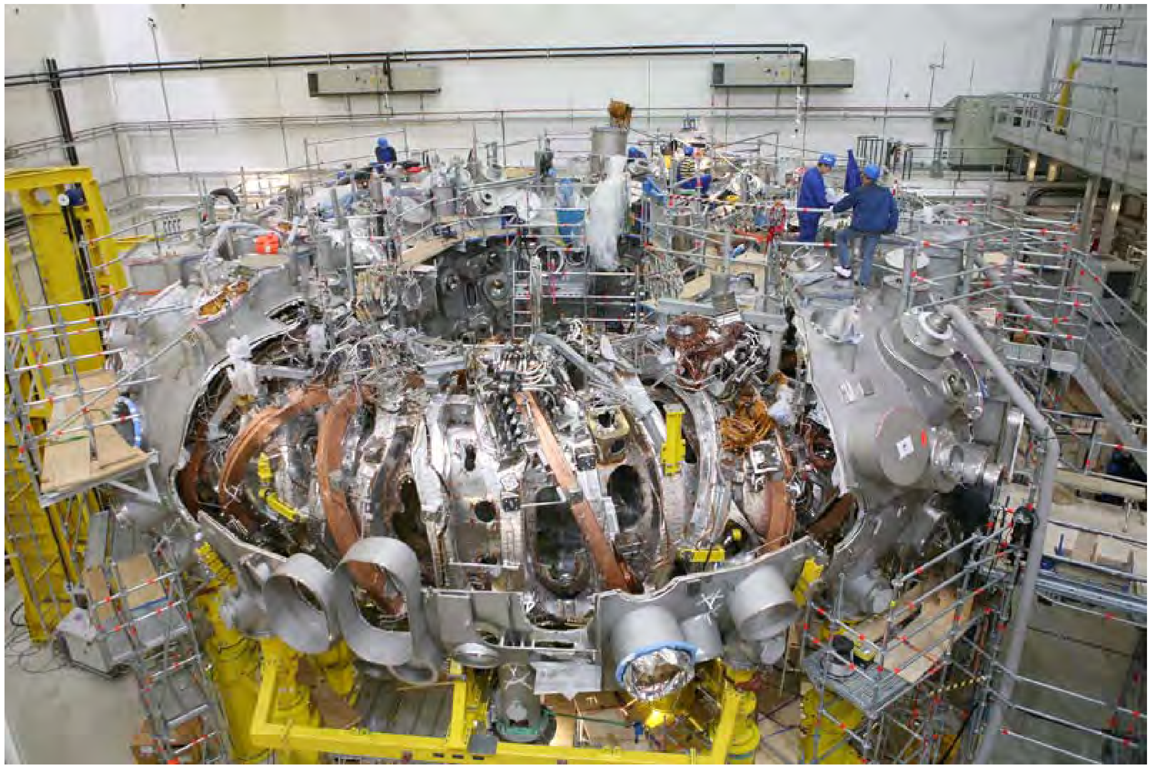
--- Dr. Hans-Stephan Bosch

It’s been a long climb from the first stellarator…

In response to Peron announcement in 1951 Lyman Spitzer Jr. first thought of the stellarator concept while skiing in Aspen

His first stellarator, the Model ‘A’, began operation in 1953

To the achievements of today



Wendelstein 7-X before closure of the cryostat

How did we get here and where are we going?

The Role of Theory and Computation in Advancement of the Stellarator Concept

-an experimentalist's perspective

Presented by D.T. Anderson, University of Wisconsin-Madison

2016 Sherwood Theory Conference, Madison, WI

Topical Flow

Theory and computation have driven tremendous progress in stellarator research

- Lack of symmetry provided obstacles to both equilibrium and transport in 3D
- Neoclassical transport was a catastrophe in the long-mean-free-path regime
- Focus on historically how theory and computation lead to a resolution of the neoclassical transport problem, with <u>many</u> possible solutions

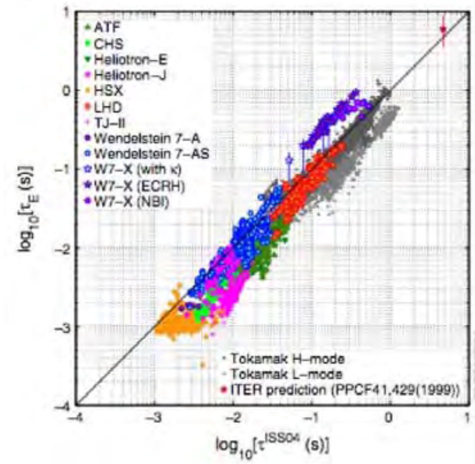
    As exemplified by omnigeneous (W7-X) and quasisymmetric (HSX) configurations
- These solutions opened the door for the stellarator to advance towards a reactor

...but significant challenges remain where input is essential

- Confinement of energetic particles
- Open issues in MHD
- Impurity transport and edge/divertor structure
- Reduction of turbulent transport through optimization

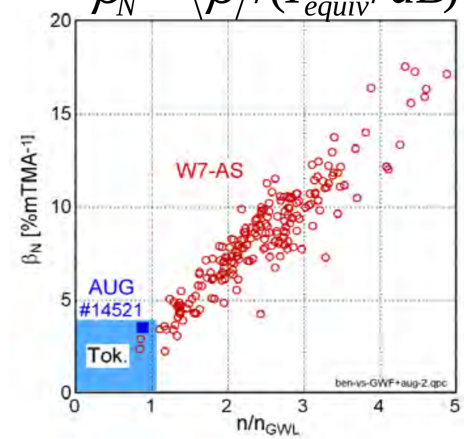
Stellarator research has remained active, despite successes within the tokamak program

- **Confining magnetic fields are externally imposed**
  - -Inherently steady state
  - -No current drive needed
- **Confinement similar to tokamaks**



- **Can operate with no disruptions or virulent MHD**
- **Flexibility and robustness in operations**
  - -Density limit not set by Greenwald value
  - -Profile resiliency has not been observed to date; can we avoid pedestals (?)
  - -ELM-free operational modes
  - -Complicated magnetic control not required
- **Possibility for ignited operation**

$$\beta_N \equiv \langle\beta\rangle/(I_{equiv}/aB)$$

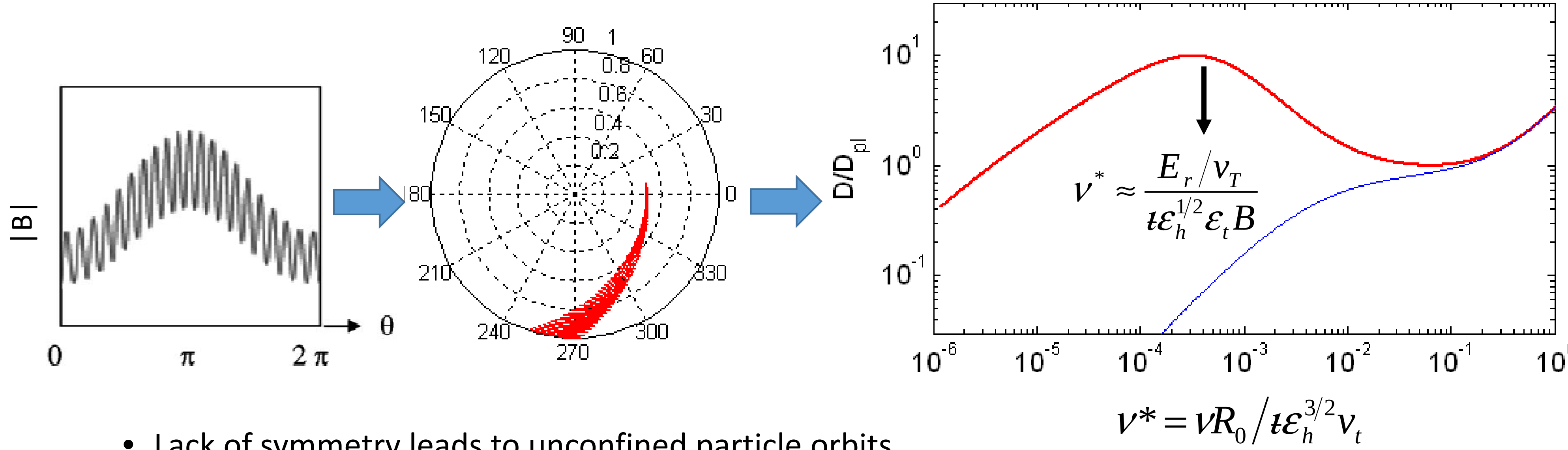


Stellarators faced challenges inherent with their required 3D structure

- **Unacceptable low collisionality transport; both thermal and energetic particles**
- **Existence of 3D equilibrium; stability limits**
- **Complex geometry**
  - -Difficult coil fabrication
  - -Mixed edge magnetic structure
  - -Sufficient plasma/coil spacing and wetted area for divertors
- **Vastly increased parameter space defining 3D shape and magnetic field spectrum**
  - -Typically 20 or more shape coefficients (vs ~5 in axisymmetric systems)
  - -How to select?

Modern stellarator design REQUIRES optimization
Need guidance from theory and computation

Conventional stellarator: asymmetric ripple leads to high transport at low collisionality



- Lack of symmetry leads to unconfined particle orbits
  - Particles trapped in helical ripple have net radial drift
- Heat flux scales as up to $T^{7/2}$, depending on collisionality
- Electric fields mitigate scaling
  - Much more effective for ions (E_r/v_t higher)
  - "Typical" situation: ions are in ν, $\nu^{1/2}$ regime; electrons in $1/\nu$
  - Does not affect α-particle losses

Modern stellarator design only possible through advances in computational ability

-based on fundamentals established from analytic theory

Codes:

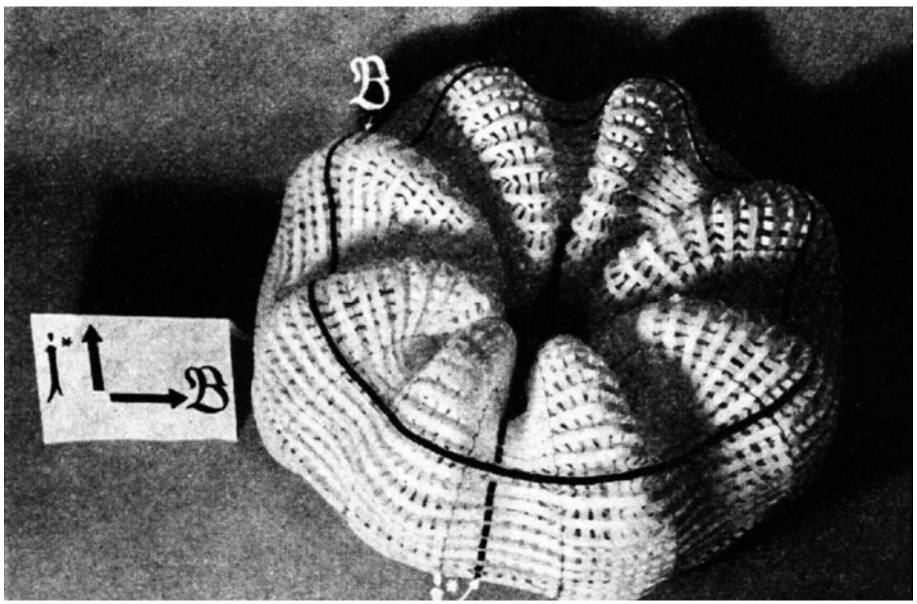
- Equilibrium and stability: BETA, VMEC, PIES, HINT, SIESTA, SPEC, NIMROD, CAS3D, M3D, COBRA, STELLGAP, AE3D, +++
- Transport: GSRAKE, SFINCS, NEO, BOOTSJ, Monte Carlo techniques: DKES, PENTA, GNET, FORTEC3D, EUTERPE,+++
- Coil design: NESCOIL, COILOPT, CAD/CAM, NASTRAN,
- Edge/Divertor structure: EMC3-EIRENE
- Configuration optimization: JUN, STELLOPT, ROSE, +++
- Simulations (gyrokinetics): GENE, GS2, GTC, GYRO, +++

Compute power:

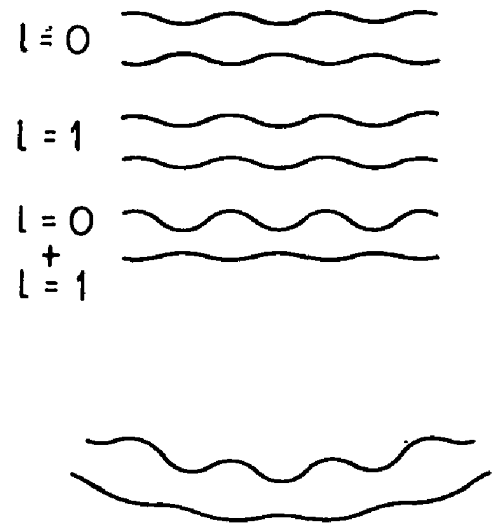
- Cray-2 of 1990 (2 giga-FLOPS) => EDISON of today (NERSC; 2 peta-FLOPS)
- Many codes can now run on workstations, PC’s and laptops!

Enhanced ripple on inboard side motivated to improve equilibrium (surprise: confinement too!)

Meyer & Schmidt 1958 paper model



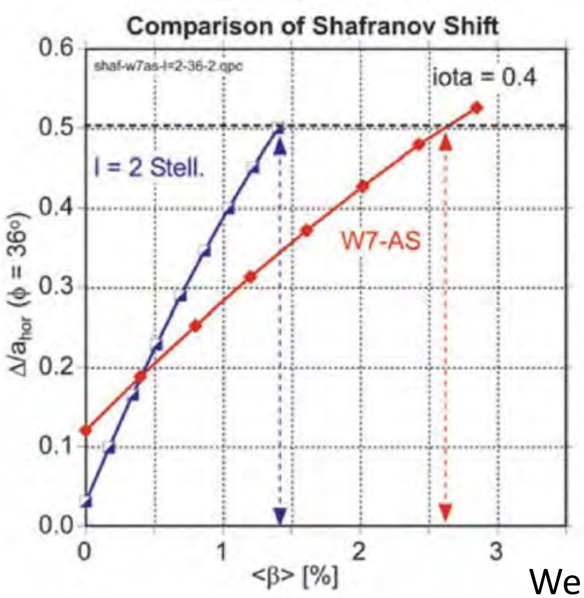
Combination of l = 0 and l = 1 corrugation along with toroidal field was basis of Scyllac theta pinch at Los Alamos in 1970s



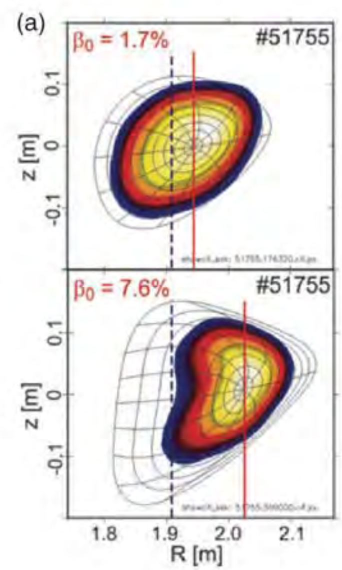
W7-AS (1988-2002) was first partially optimized stellarator

- Goal was to lower toroidal curvature to decrease Pfirsch-Schlüter current
  - Decrease Shafranov shift
  - Improves passing particle confinement, but not trapped particles

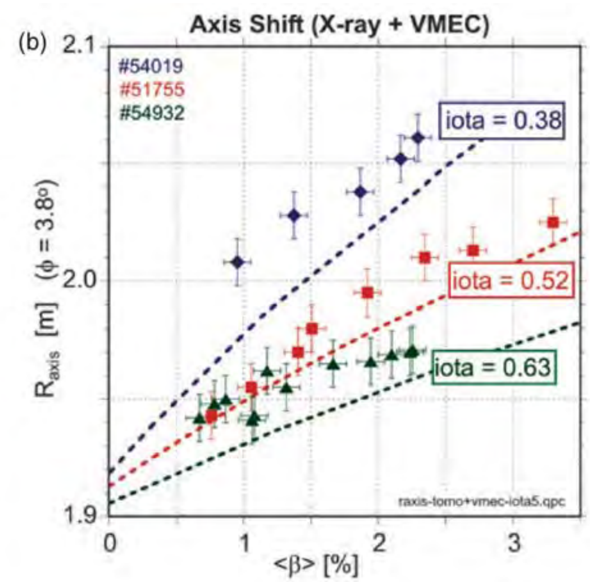
Factor of 2 reduction in axis shift compared to l = 2 stellarator according to VMEC equilibrium code



Tomographic reconstruction of x-ray emissivity compared to free boundary VMEC maps magnetic axis location



Experimental magnetic axis location versus <β> compared to VMEC for 3 values of iota.



Weller PPCF 2003

Mynick (1982) developed fundamental concept of quasi-omnigenous configuration

Modulate helical ripple with so-called ‘sigma optimization’:

$$B = B_0[1 - \varepsilon_t cos\theta - \varepsilon_h \cos(m\theta - n\varphi)(1 - \sigma cos\theta)]$$

yields bounce-averaged equations of motion

$$\overline{\dot{r}} = v_{B0} sin\theta[\varepsilon_t - \sigma\varepsilon_h \overline{\cos(m\theta - n\varphi)}]$$

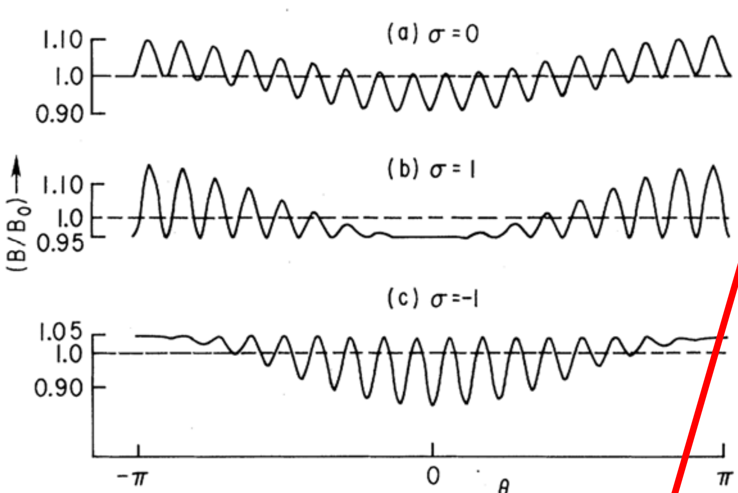
Cancel drift due to toroidal curvature with modulation of the helical ripple

Cancellation occurs only for a particular class of particles, such as deeply trapped ➔ quasi-omnigenous

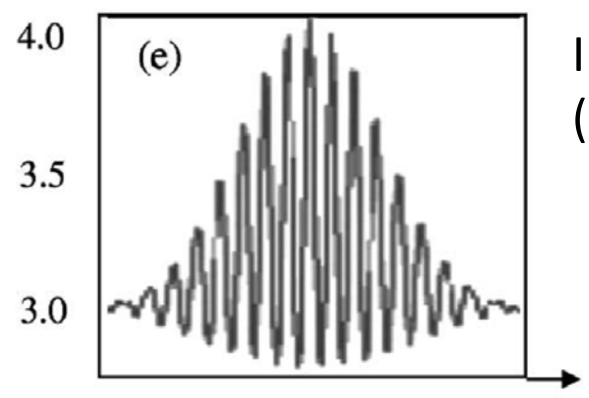
Isodynamic B=B(ψ), magnetic field structure proposed by Palumbo (1968); Relaxation are omnigenous J=J(ψ) structures (Hall and McNamara 1975): tokamaks and straight stellarators are examples of omnigeneity

$$J = \oint m v_{||} dl$$

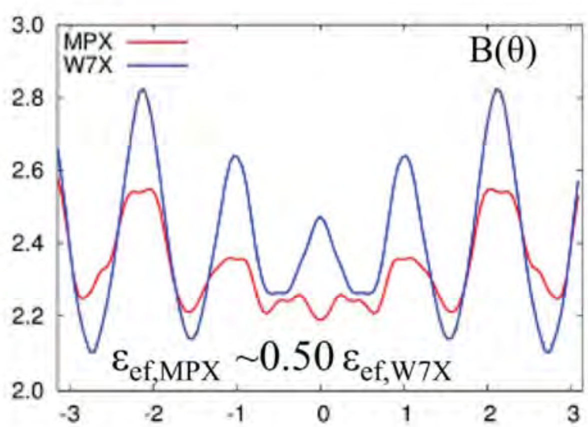
Quasi-omnigenous configurations include W7-X and inward shifted stellarators



Mynick σ = +1 configuration has larger ripple on the inside of torus (similar to M&S)



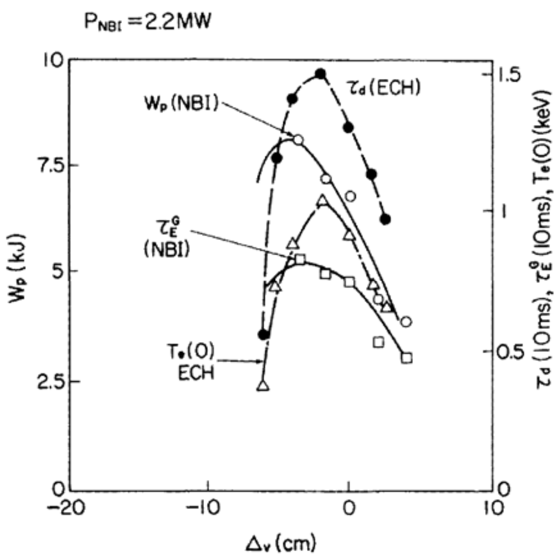
Inward shifted LHD (magnetic hill)



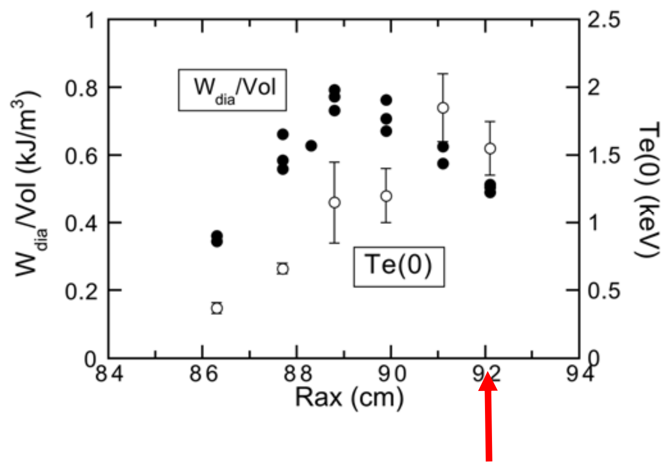
Wendelstein 7-X (magnetic well)

Mynick PRL (1982)
Mynick PoP (2006)
Mynick PPCF (2014)

Confinement improvement demonstrated with inward shift



Heliotron E: Stored energy, $T_e(0)$ and τ_E improves with inward axis shift (Wakatani PPCF 1996)



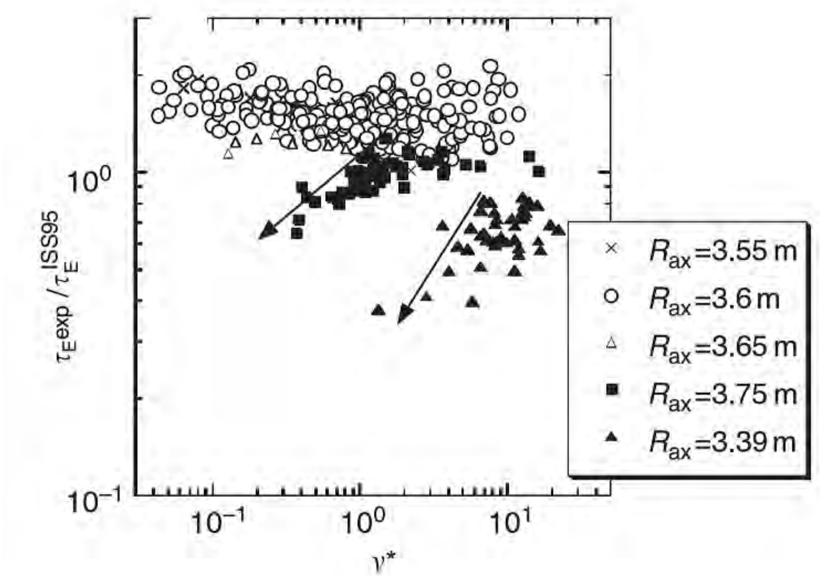
CHS: Stored energy improves with inward axis shift (Okamura NF 1999)

We will soon see results from W7-X!

LHD:

- τ_E improves with inward shift, degrades with outward shift.
- Confinement improvement persists even at high collisionality
- Turbulent transport improves?

(Komori PPCF 2003)



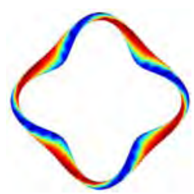
Big step forward: Theory introduces quasisymmetry as a transport optimization approach

- The guiding center equations of motion in Boozer coordinates (1980) depended only upon |B|: $B = \sum_{n,m} b_{nm}(\psi)\cos(n\phi - m\theta)$
- Boozer further showed (1983) that if a system had a symmetry in flux coordinates, orbits and transport are isomorphic to those of any other symmetric system!
  - A system with symmetry in |**B**|, but not necessarily **B**, is referred to as "quasisymmetric"
  - True even though the configurations may appear <u>wildly</u> different in 3D physical space

True symmetry ⊂ quasisymmetry ⊂ omnigeneous

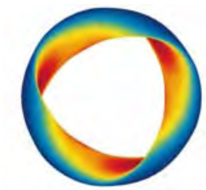
- 3D quasisymmetric plasma shapes were discovered computationally:

Quasi-helically symmetric
Nuhrenberg and Zille (1988)
(Figure below of HSX)



$B=B_o[1-\varepsilon_h\cos(n\phi-m\theta)]$

Quasi-axisymmetric
Nuhrenberg, Lotz, Gori (1994)
Garabedian (1996)



$B=B_o[1-\varepsilon_t\cos(m\theta)]$

- The *effective* transform , ι_{eff}= n-mι can be significantly larger than the actual transform
- Throughout neoclassical transport
  q -> $1/\iota_{eff}$
- Quasisymmetric systems have low flow damping in the direction of symmetry
- Distinction from omnigeneous systems

High effective transform reduces Pfirsch-Schlüter and bootstrap current in QH vs QA

Pfirsch-Schlüter current:

$$J_{PS} = \frac{1}{B_0}\frac{dp}{d\psi}\sum_{n,m}\frac{nI+mg}{n-m\iota}\delta_{nm}\cos(n\phi - m\theta)$$

- reduced in magnitude
- helical in HSX due to lack of toroidal curvature
- dipole currents are opposite of tokamak where field in HSX is tokamak-like (grad B drift is opposite).

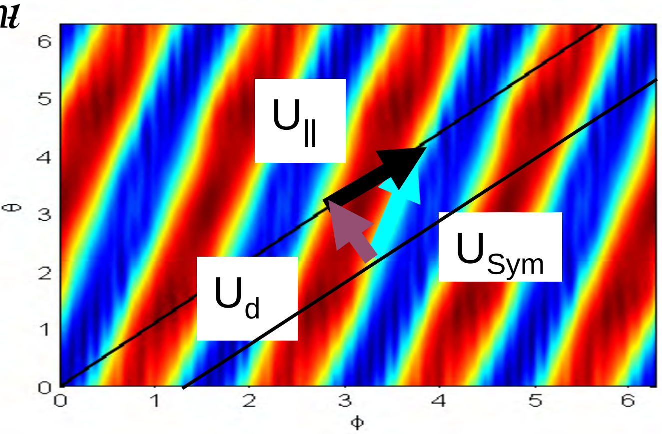
Bootstrap current:

$$J_B \sim 1.46\sqrt{b_{nm}}\,\frac{m}{n-m\iota}\,\frac{g}{B_0}[gradients]$$

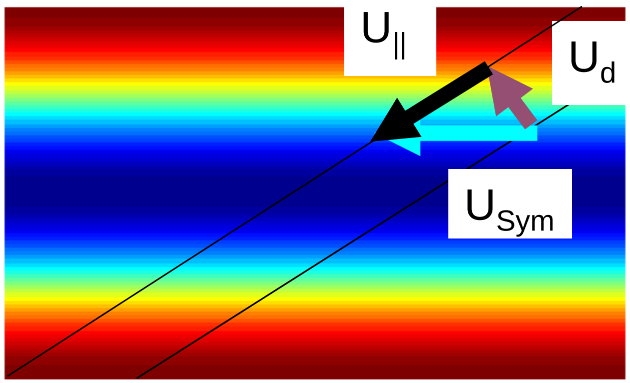
- reduced in magnitude
- opposite direction to tokamak
- reduces transform but confinement improves due to factor $n-m\iota$

Boozer, '82 '92

HSX or QH



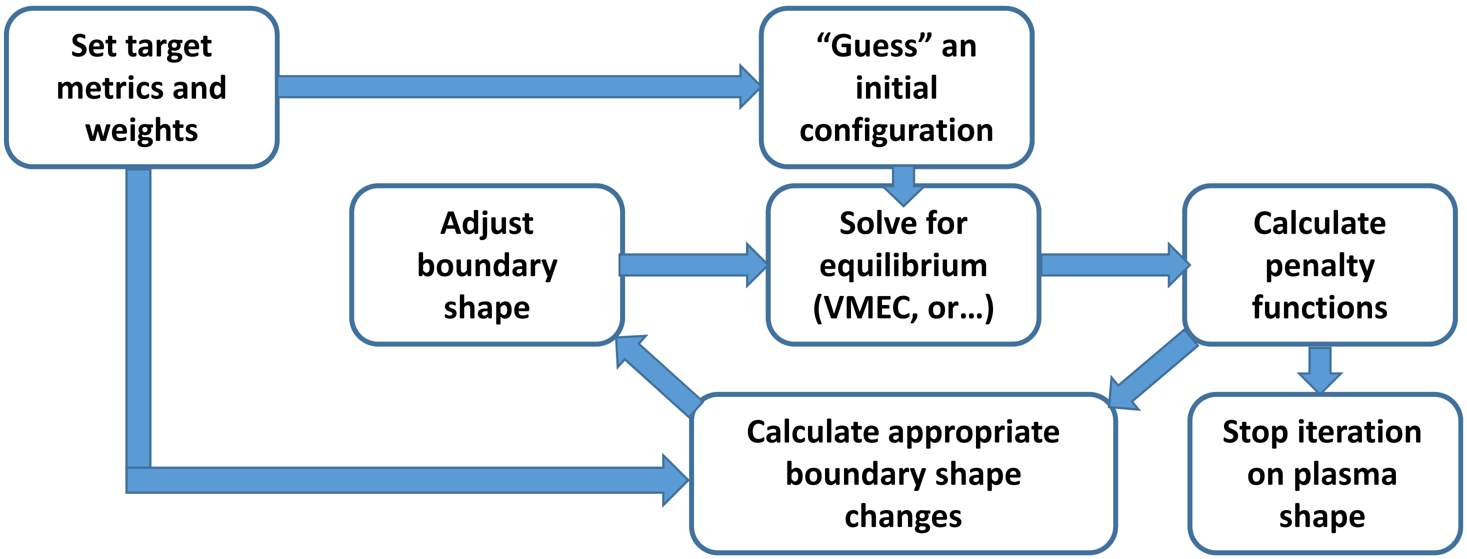
Tokamak or QA



Generating physical solutions has historically been a two step process

Find the magnetic (plasma) configuration

- Equilibrium properties of a magnetic configuration are determined by the outer boundary and the current and pressure profiles.
- High performance computing and rapid configuration analysis have made possible optimization over the large shaping parameter space

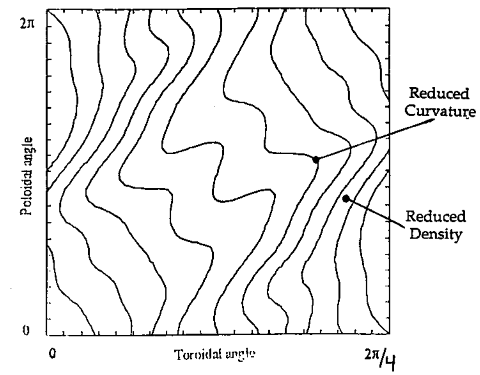


The optimization is only as good as the metrics, penalty calculations, and minimization routines

Generating physical solutions has historically been a two step process

Find the coils to produce the plasma configuration

- NESCOIL (Merkel NF 1987) solved the Neumann boundary value problem so that the normal component of **B** was minimized (~0) on the plasma boundary
- Again, an optimization loop was used to target a 'best' shape for the external current lines (coils) given target parameters and weights, e.g.
  - Smallest j_{max}/j_{min} [coils not too 'crowded']
  - Minimum radius of curvature of the coils [not too 'kinky']
  - Minimum distance between the coils and the plasma [room for a vacuum vessel +++?]
- Significant advances in intervening years (driven by NCSX)
  - COILOPT (Strickler FST 2002)
  - COILOPT++ (Breslau EPR 2013 [unpublished])
  - STELLOPT (original-Spong NF 2001); Modified to account for some engineering into plasma design.
  - Can we make 'simpler' coils (discussion in Boozer J. Plasma Phys. (2015))



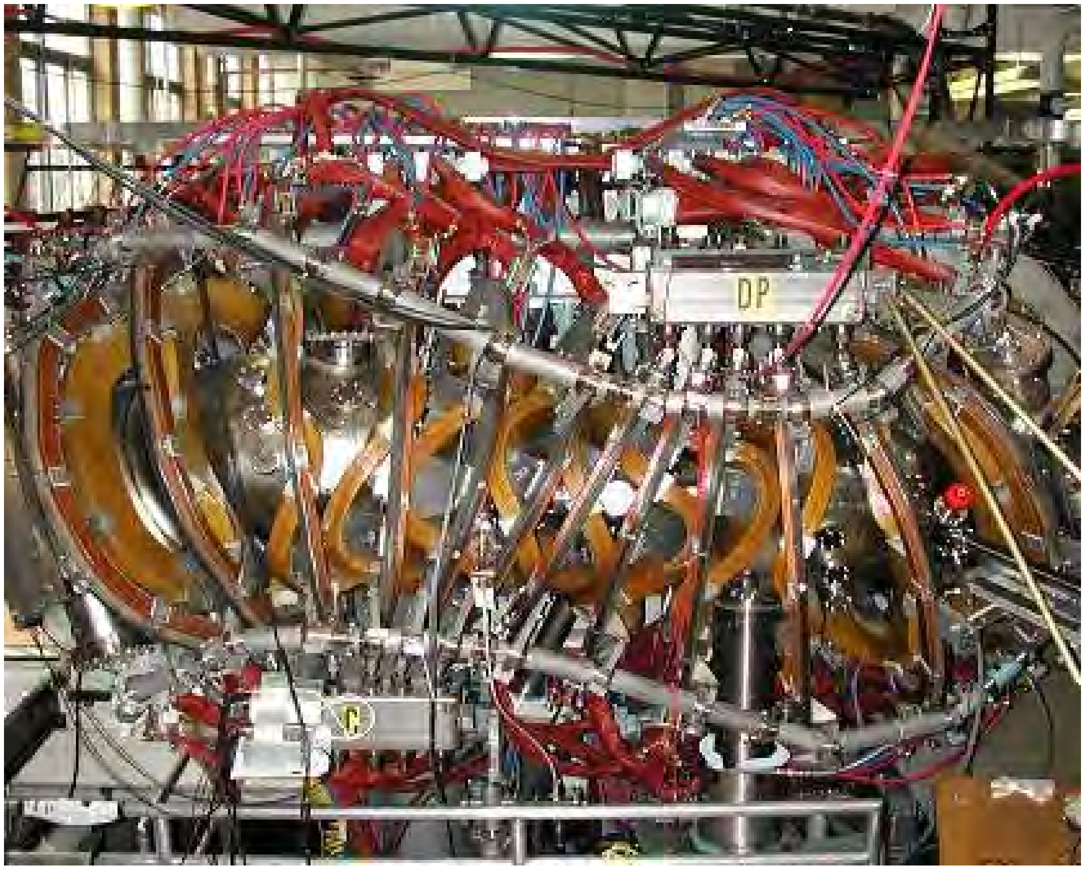
NESCOIL output for HSX design

See Landreman poster P1.020

Moving forward need further integration between plasma and coil design

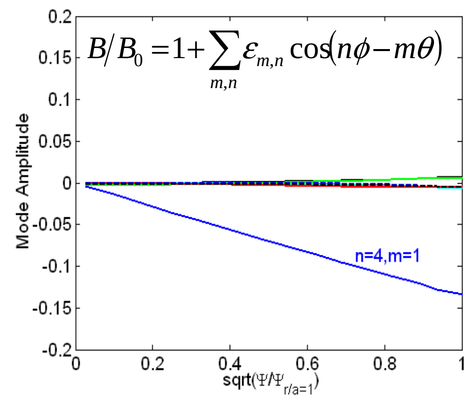
Metrics critical

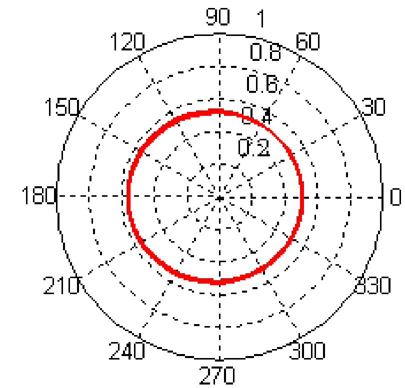
HSX: Only experimental test of quasisymmetry to date



R=1.2 m, <a$_p$> ~.12m, B=1.0T, ECH ≤200 kW
$n_{e0} \leq 1 \times 10^{13}$, $T_{e0} \leq 2.5$ keV

QHS Magnetic Spectrum





Optimization targets:

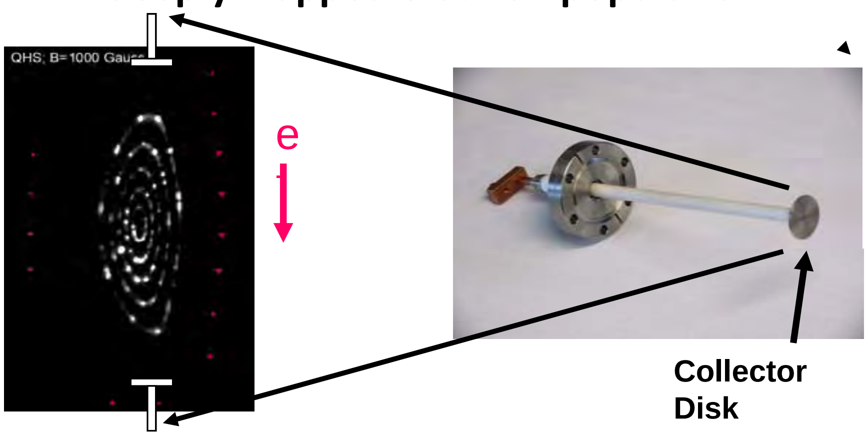
Minimum off-diagonal spectral components
Marginal magnetic well
Transform avoiding low order resonances

Attained optimization confirmed:

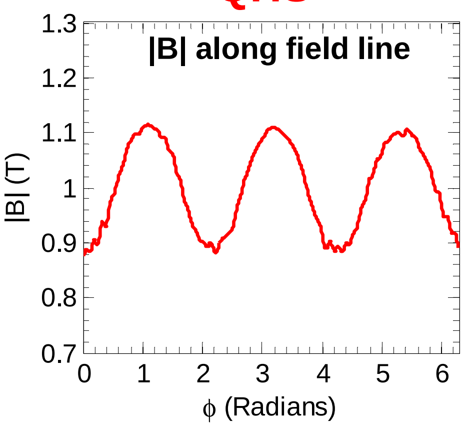
Mapping of spectral components
Measurement of reduced plasma currents
Reduction of flow damping and neoclassical transport

Good trapped particle confinement with QHS

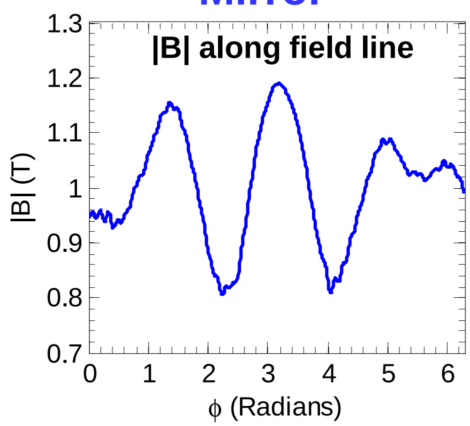
2nd harmonic ECRH used to create energetic deeply-trapped electron population



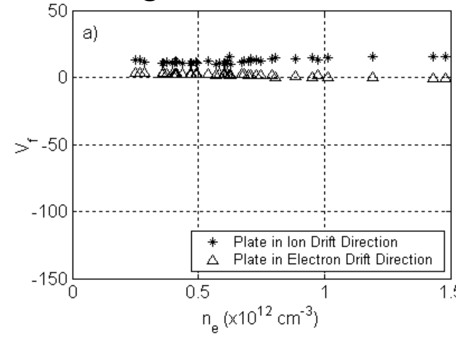
QHS



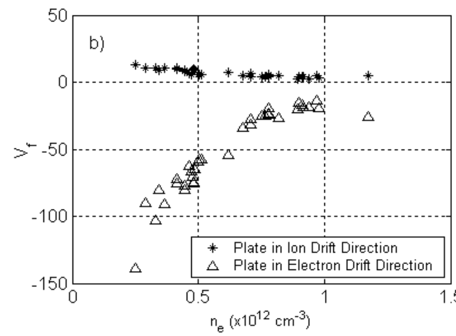
Mirror



Floating Potential vs Density



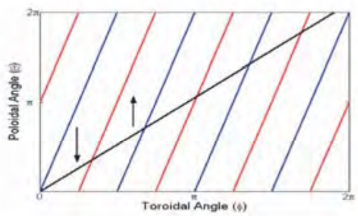
QHS



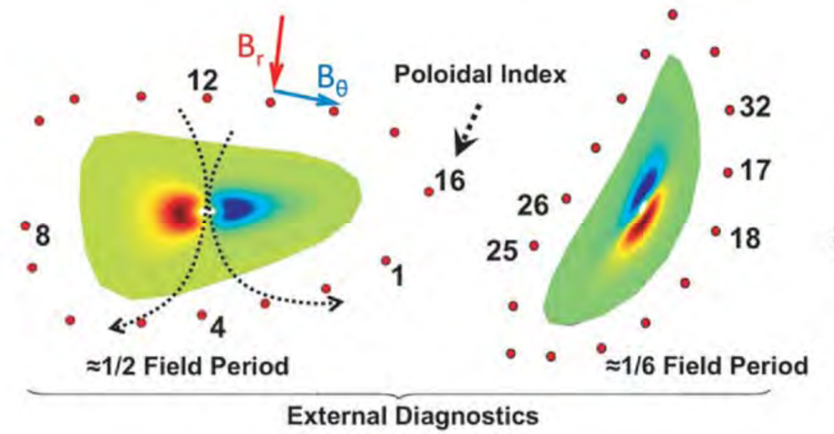
Mirror

- **Collector disk in direction of electron ∇B drift shows large negative potential when quasisymmetry broken.**
- **Larger HXR flux in QHS configuration also observed.**

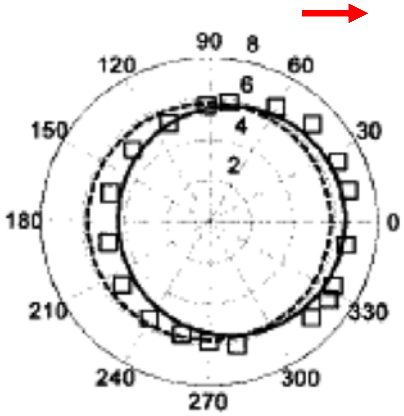
Passing particle orbits and helical Pfirsch-Schlüter current indicates lack of toroidal curvature in HSX



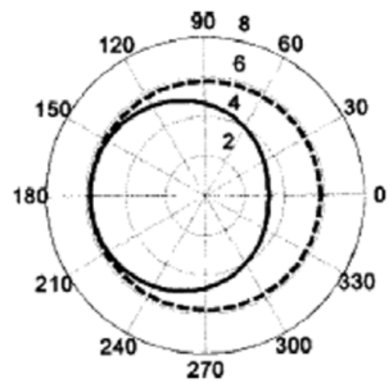
Mapping of electron beam to Boozer coordinates shows small shift (due to N – mɫ) and opposite direction shift (due to $B \times \nabla B$) compared to tokamak



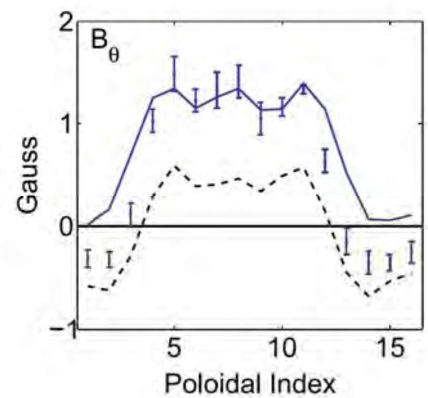
Relative shift

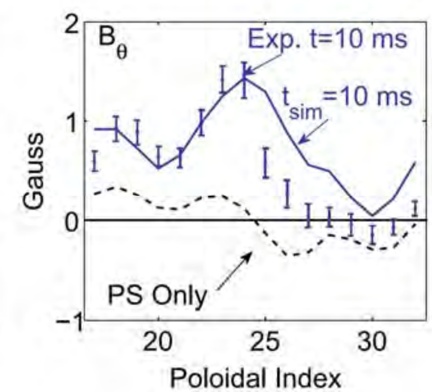


HSX



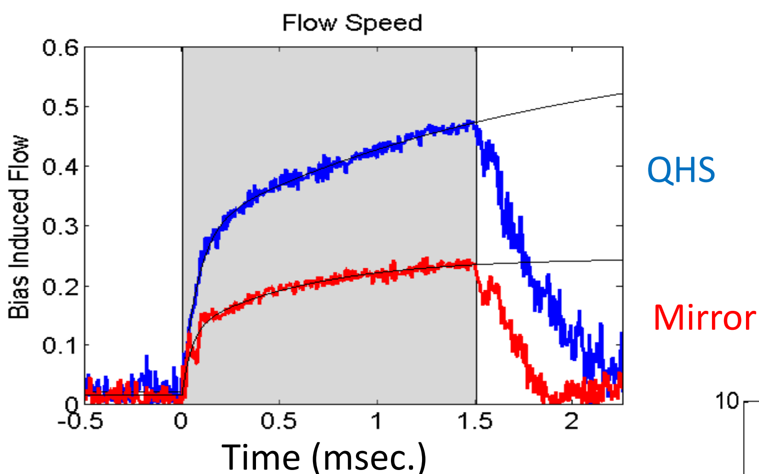
Tokamak



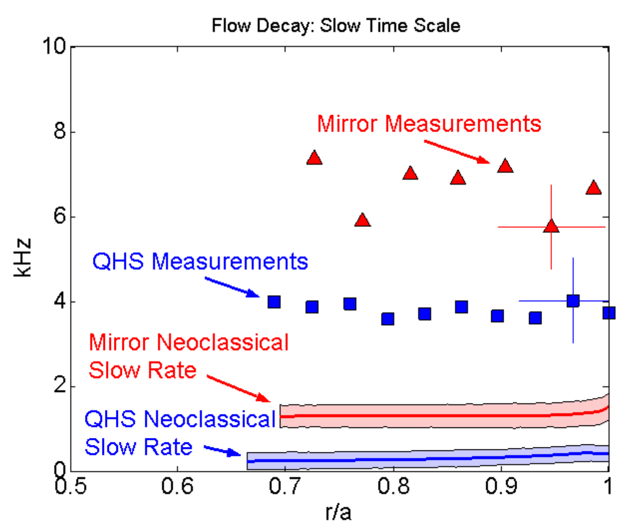


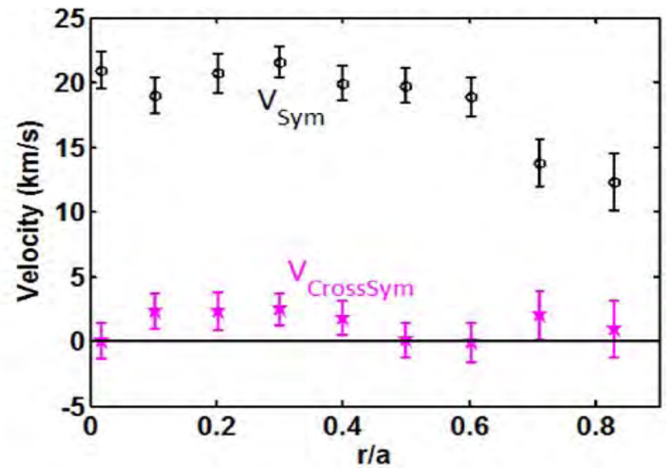
Larger Plasma Flow and Smaller Damping with Quasisymmetry

Plasma Edge: Electrode Induced Flow, measured with probes, is larger with quasisymmetry



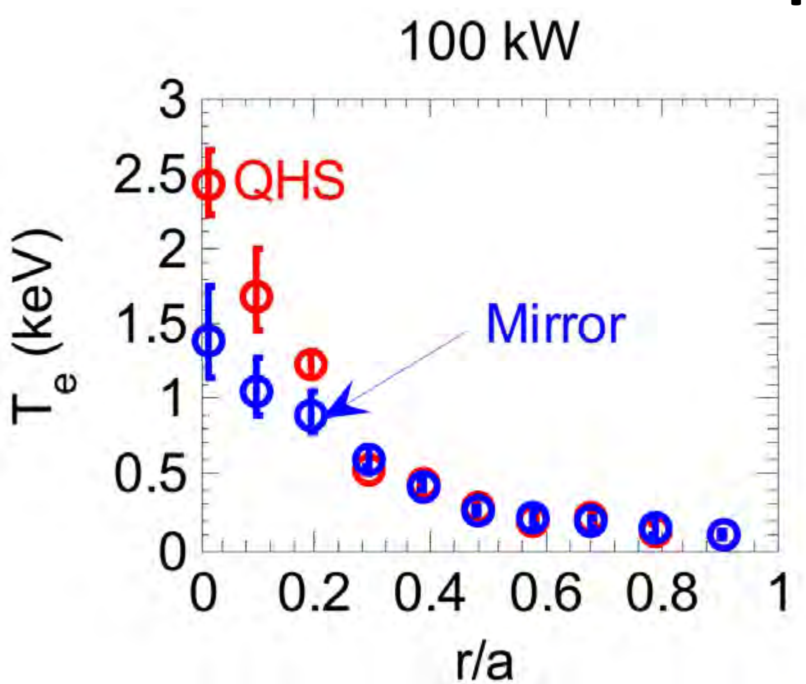
Plasma Edge: Flow decay is slower in QHS than Mirror, but faster than neoclassical





Charge Exchange Recombination Spectroscopy shows large intrinsic plasma flow in direction of symmetry

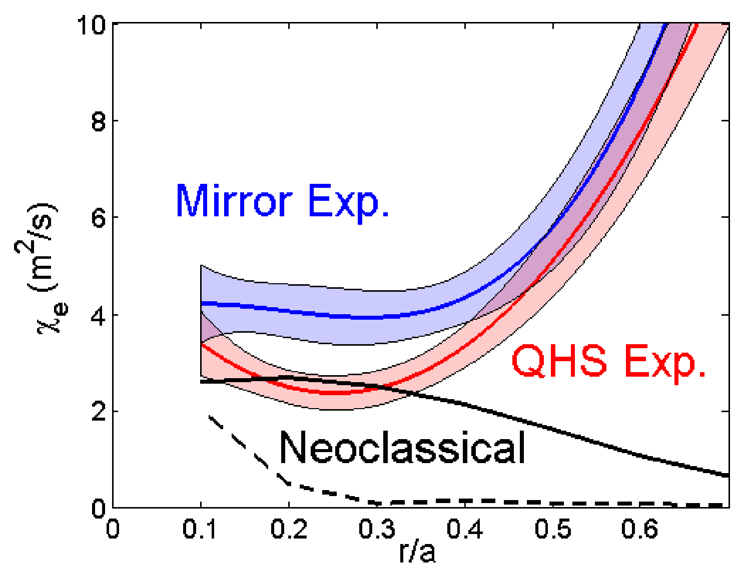
Electron thermal diffusivity is reduced in core with quasisymmetry



$T_e(0)$ drops by 1 keV with degradation of quasisymmetry (mirror configuration)

B = 1.0 T

- QHS has lower core χ_e
  - At r/a ~ 0.25, χ_e is 2.5 m^2/s in QHS, 4 m^2/s in Mirror
  - Difference is comparable to neoclassical reduction (~2 m^2/s)

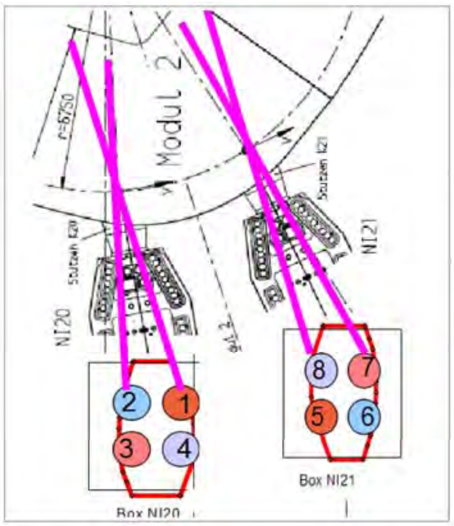


B = 0.5 T

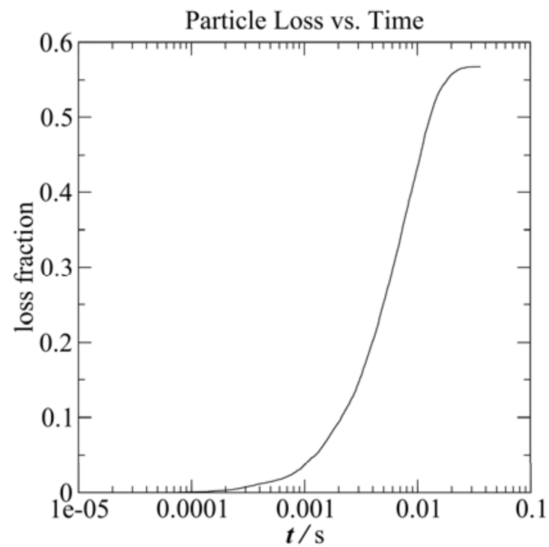
Solutions seem to be in hand for neoclassical transport

- Significant challenges and opportunities remain where guidance from theory and computation are essential
  - Confinement of energetic particles
  - Open issues in MHD
  - Impurity transport
  - Effective divertor
  - Reduction of turbulent transport

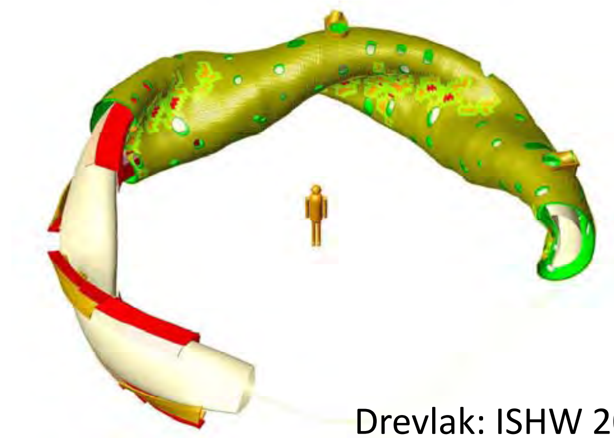
Energetic ion confinement could be a problem on W7-X



Steep injection angle due to cryostat leads to large population of deeply trapped ions



Large fraction of particles are born off axis where confinement is sub-optimal



Drevlak: ISHW 2013
NF 2014

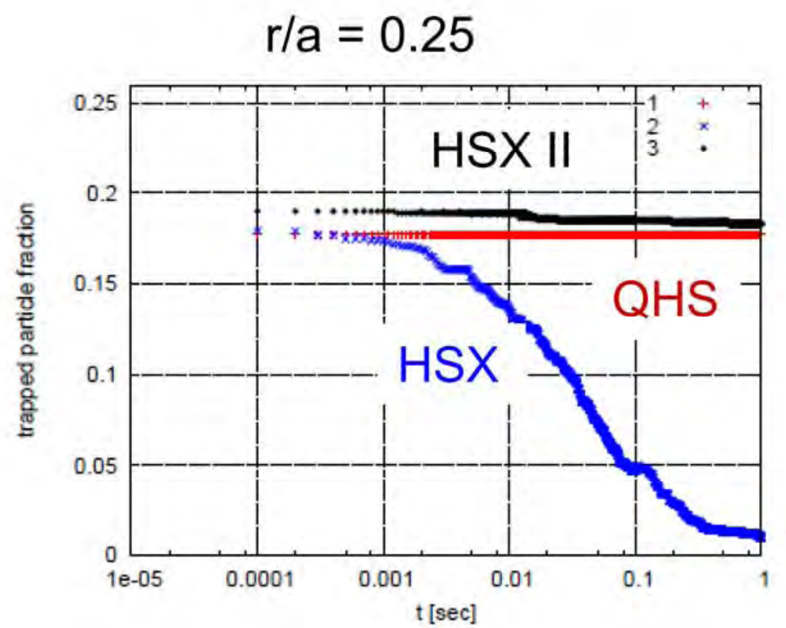
Excessive NBI losses may damage vessel, divertor, baffles

- Possible solution is to use only beam lines that inject at shallower angle to B

"Primary goal of demonstrating fast particle confinement is at risk"

Alpha particle confinement in HSX reactor is degraded compared to original QHS design

- All configurations scaled to 5T, a = 1.6 m
- QHS is ideal equilibrium by Nuhrenberg & Zille (1988)
- HSX is represented by actual finite coils that are very close to plasma
  - n = 48, m = 0 term due to number of modular coils accounts for alpha particle losses
- HSX II is HSX with twice the # of coils, reduces alpha losses back near original QHS
- Coils need to be further away from plasma in a reactor to provide room for blanket and shield
  - Reduces modular ripple but can increase toroidal extent of modular coils



Need for theory and computation to design simpler coils that improve alpha particle confinement

Improvements in energetic ion confinement are needed

- Optimization for thermal particle confinement does not guarantee energetic particle confinement.

- Small magnetic ripples in an otherwise optimized geometry can lead to large alpha particle losses
  - ARIES-CS reactor design found that scaling NCSX quasiaxisymmetric stellarator to a reactor led to alpha particle losses ~ 30%
  - Addition of a symmetry-breaking mirror term reduced losses to 5%

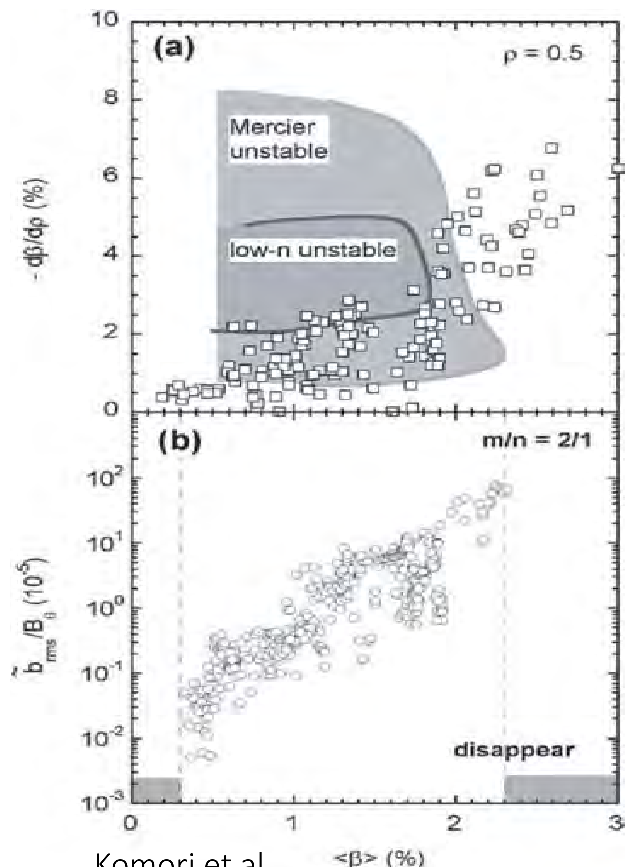
- Energetic particle instabilities can lead to additional energetic ion loss
  - Stellarators can have tokamak-like Alfvén gaps plus additional modes due to 3-D
  - Higher density operation is favorable for stabilization
  - Important opportunity to include 3-D shaping to reduce or control instabilities

How does MHD set limits in stellarators?

- In conventional low-current stellarators, beta is not limited by a disruptive response to MHD instabilities
- Stellarators have exceeded linear ideal MHD stability limits without disruptions
- When pressure-driven MHD limits are exceeded, weak confinement degradation usually observed; no discharge termination

In present day stellarators hard beta limit not set by pressure-driven MHD instabilities.

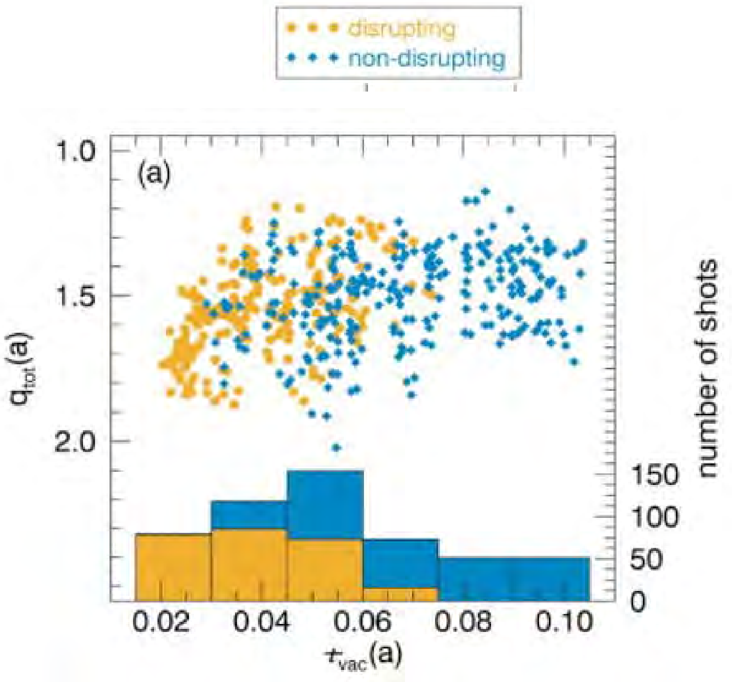
How should we factor these limits into optimization?



Komori et al, PPCF 2003

How do 3D fields control current driven disruptions?

- In quasi-symmetric configurations there is a bootstrap current which provides a free energy source for MHD instabilities
- The externally generated stellarator fields provide confinement even in the event of a current quench
- Experiments on W7-A showed suppression of disruptions with external transform; **how much is enough?**
- The Compact Toroidal Hybrid (CTH) at Auburn University is a tokamak/stellarator hybrid with a key element of its mission to address this issue



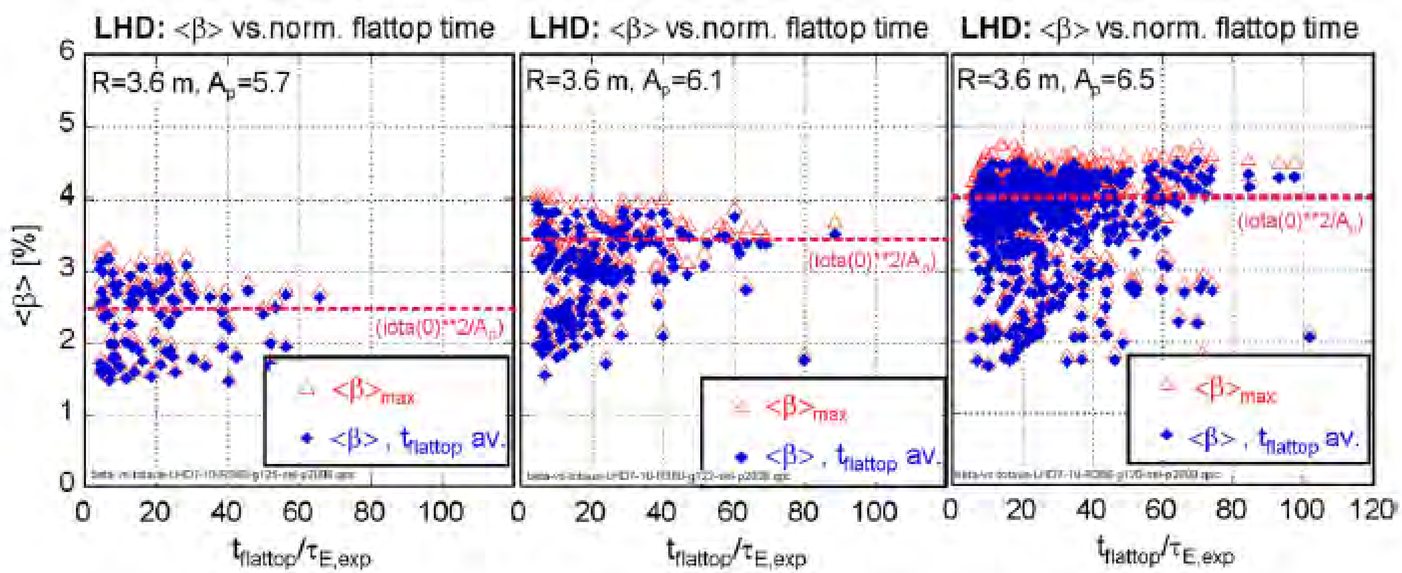
Pandya et al, PoP '15

Need guidance from extended MHD community on proper metrics for disruption avoidance

NIMROD applied to sawtoothing in CTH: Robards poster P1.010

Equilibrium limits in 3D also not clear

- Beta-limit in stellarators also constrained by MHD equilibrium considerations
- Conventional equilibrium underestimates β-limit in high-shear LHD plasmas
  - Large Shafranov shift deforms flux surfaces, generates islands & stochasticity via Pfirsch-Schluter current induced resonant fields
  - Experiment exceeds these limits



Weller et al, NF '09

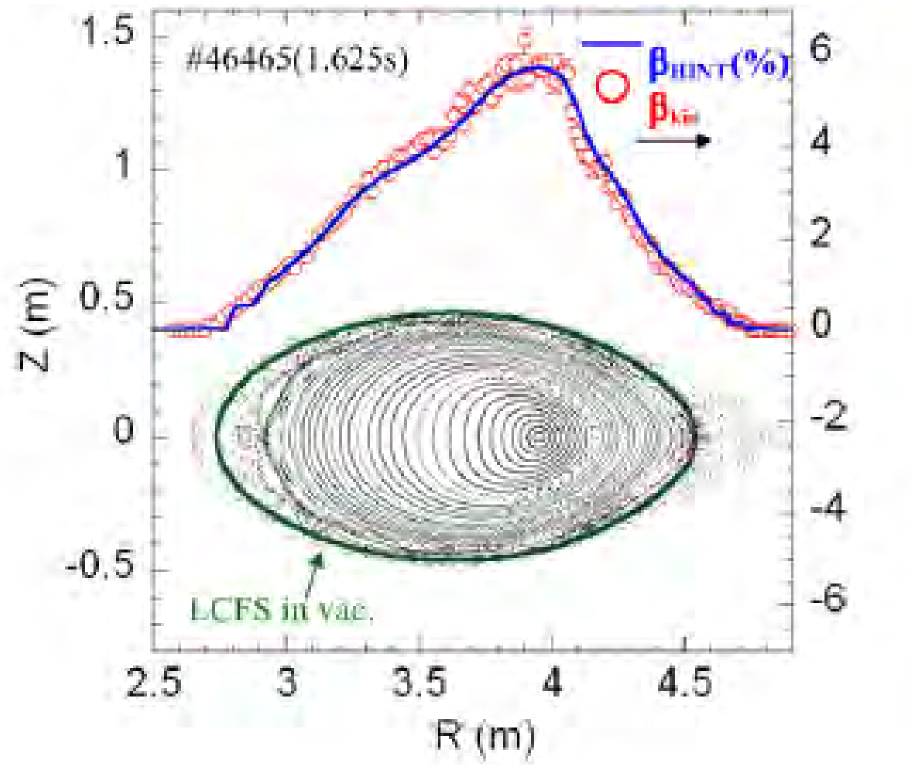
Equilibrium limits may need a more closer examination

See poster P1.025 by Weitzner for equilibrium discussion

3D MHD equilibrium appear to be more robust that 3D equilibrium tools predict

- Observed edge pressure gradients are sustained in theoretically predicted (HINT, PIES) stochastic regions
  - Inconsistent with ideal MHD
  - Edge magnetic field properties are complex
  - Role of long connection lengths vs ideal surfaces
  - Finite beta “healing”
- While 3D equilibrium may not rigorously exist (Grad, Weitzner), experiment suggests very good approximations.
- Can extended MHD explain observations?

Bechtel poster on High β extended MHD P1.031



Watanabe et al PPCF ‘07

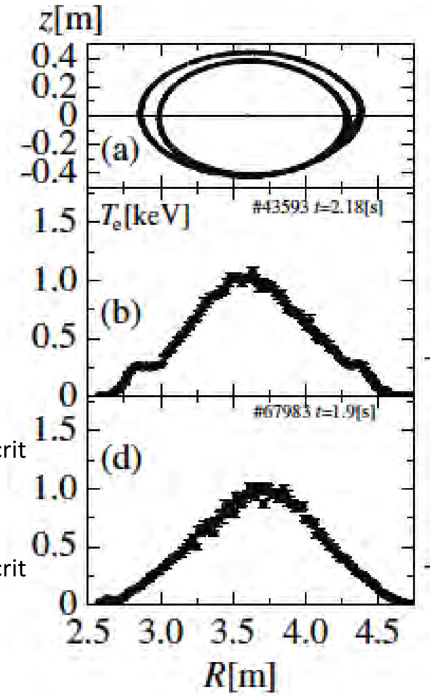
Spontaneous healing of magnetic islands observed in LHD

- Healing of large vacuum islands observed in LHD at critical β

Large island in vacuum island disappears at $\beta > \beta_{crit}$

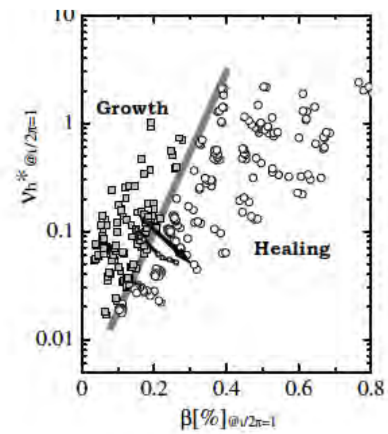
$\beta < \beta_{crit}$

$\beta > \beta_{crit}$

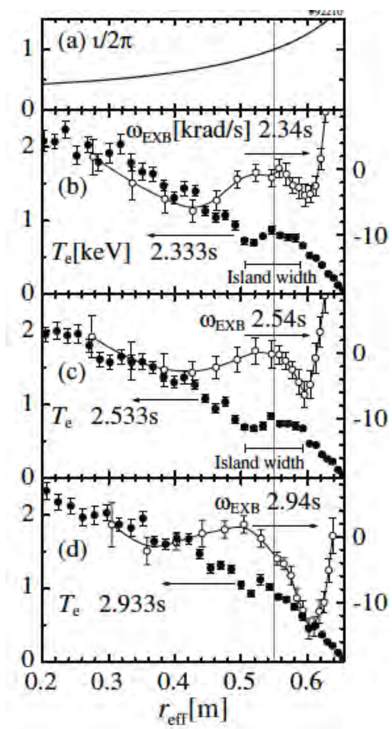


Narushima et al NF '11

β_{crit} depends upon ν^*



Plasma flows can induce shielding currents that heal islands --- (Hegna, NF, '11)



3D MHD needs closer examination; metrics for optimization

"The fate of the stellarator line will critically depend on the **impurity** transport characteristics."

Neoclassical transport is the problem:

Wagner Phys. Plasmas 2005

$$\Gamma^\alpha = -\mathcal{D}_1^\alpha n^\alpha \left(\frac{1}{n^\alpha}\frac{\mathrm{d}n^\alpha}{\mathrm{d}r} - \frac{q^\alpha E_r}{T^\alpha} + \left(\frac{\mathcal{D}_2^\alpha}{\mathcal{D}_1^\alpha} - \frac{3}{2}\right)\frac{1}{T^\alpha}\frac{\mathrm{d}T^\alpha}{\mathrm{d}r}\right)$$

where

$$\mathcal{D}_j^\alpha = \frac{2}{\sqrt{\pi}}\int_0^\infty \mathrm{d}X\, D(X)\, e^{-X}\, X^{j-1/2}$$

$$X = \kappa^\alpha / T^\alpha$$

and D is the monoenergetic diffusion coefficient

Solving for E_r in the ion root by setting $\Gamma_i = 0$ and writing equation for impurity flux yields:

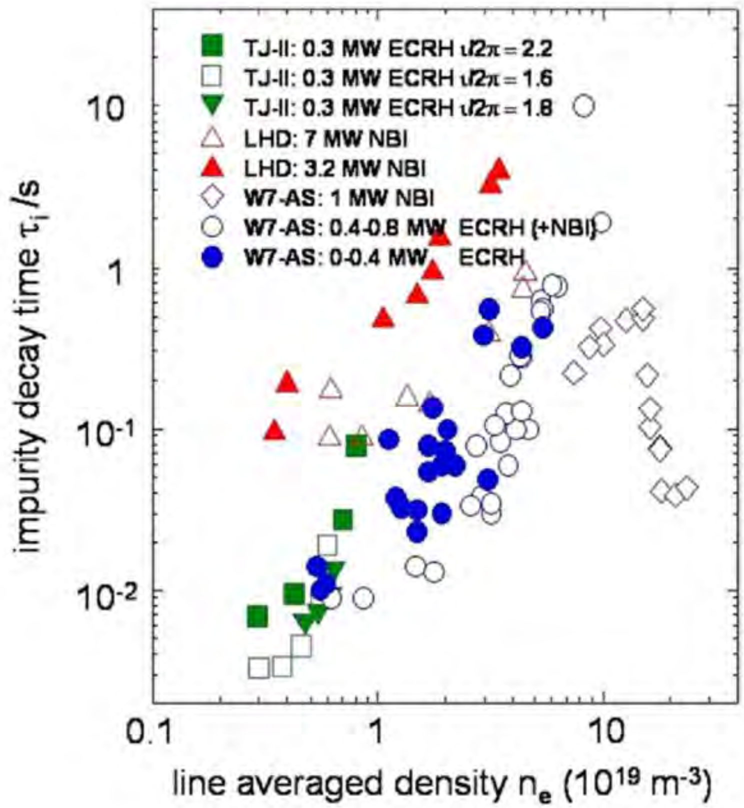
$$\Gamma^I = -\mathcal{D}_1^I n^I \left(\frac{1}{n^I}\frac{\mathrm{d}n^I}{\mathrm{d}r} + \left(\frac{\mathcal{D}_2^I}{\mathcal{D}_1^I} - \frac{3}{2}\right)\frac{1}{T^i}\frac{\mathrm{d}T^i}{\mathrm{d}r} - \frac{q^I}{q^i}\left\{\frac{1}{n^i}\frac{\mathrm{d}n^i}{\mathrm{d}r} + \left(\frac{\mathcal{D}_2^i}{\mathcal{D}_1^i} - \frac{3}{2}\right)\frac{1}{T^i}\frac{\mathrm{d}T^i}{\mathrm{d}r}\right\}\right)$$

Impurity flux depends on n,T of bulk ions:

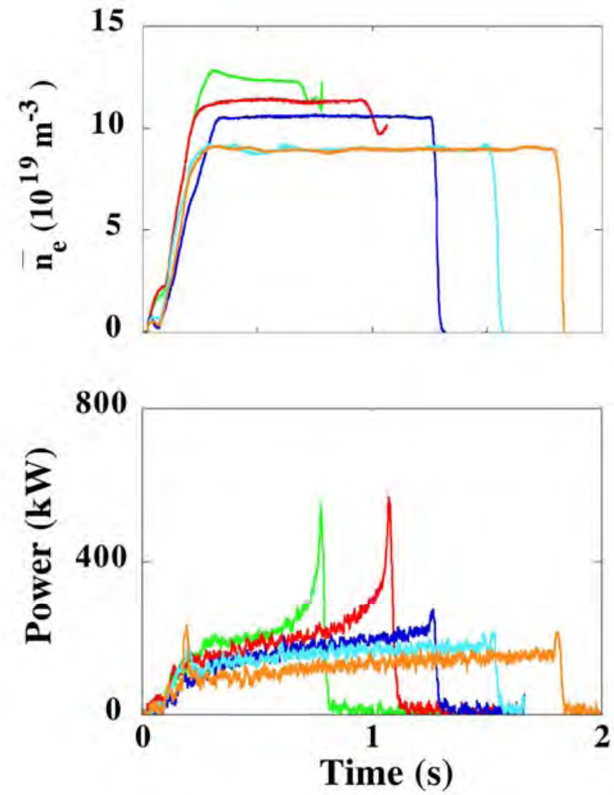
- $dn_i/dr < 0$ ➔ impurity accumulation
- For peaked T_i profile, only $\left({}^{D_2^i}/_{D_1^i} - 3/2\right) < 0$ gives impurity expulsion

No impurity expulsion for low collisionality plasma as in tokamak.
For ion root ($E_r < 0$) there is only impurity accumulation!

Impurity confinement increases with density and limits long pulse operation



Burhenn NF 2009

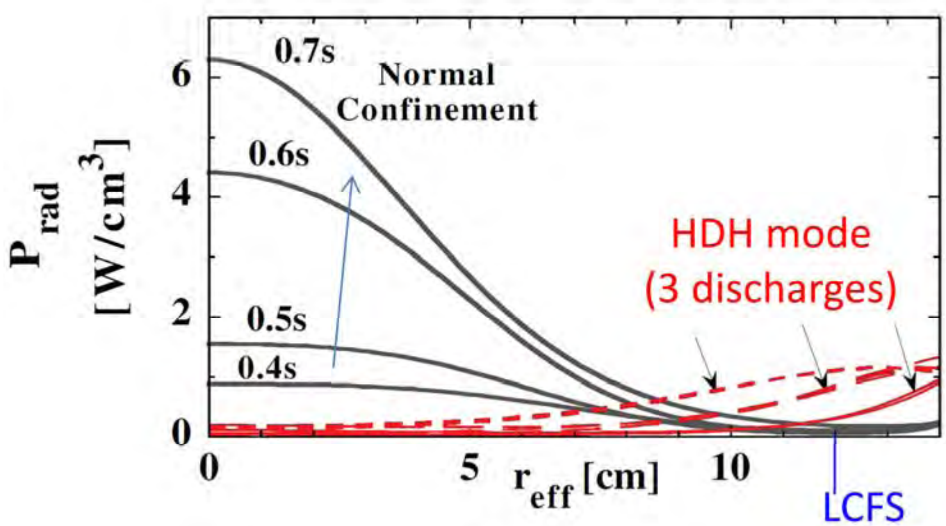


Giannone PPCF 2000

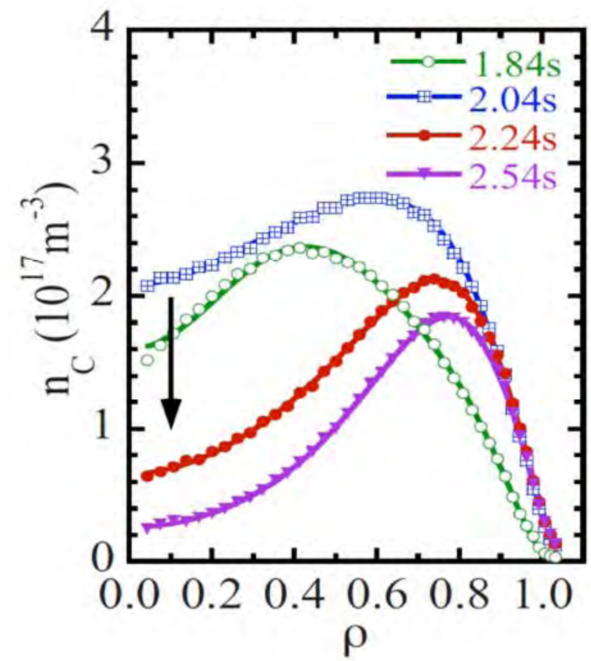
Possible solutions to impurity problem

- Electron root (Er > 0) observed to expel impurities, but not reactor relevant

- HDH mode in W7-AS expelled impurities for n_e > 1-2 x 10^{20} cm^{-3}

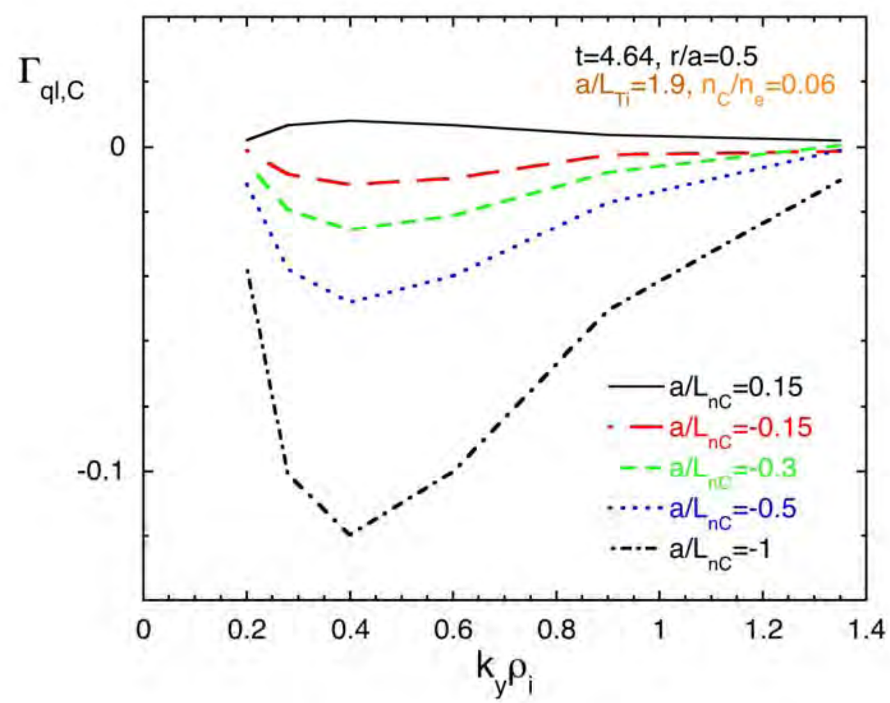


- Carbon hole in LHD with high T_i gradient even with E_r < 0



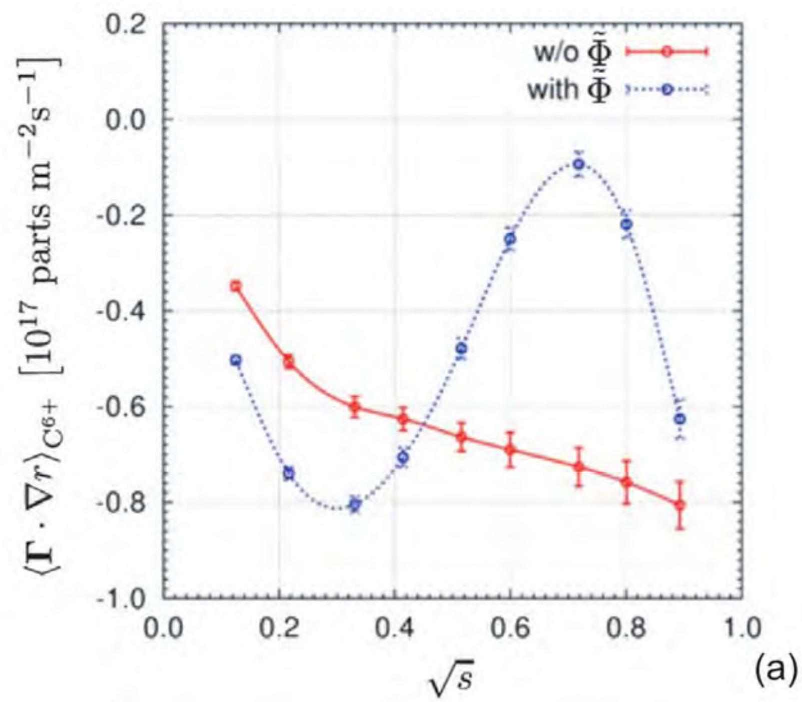
Carbon hole in LHD is still not well understood

First 3D gyrokinetic simulation with impurity species shows inward flux, contrary to experiment



Mikkelsen PoP 2014

Including potential variation on magnetic surface ϕ_1 can modify flux, but not enough to explain carbon hole



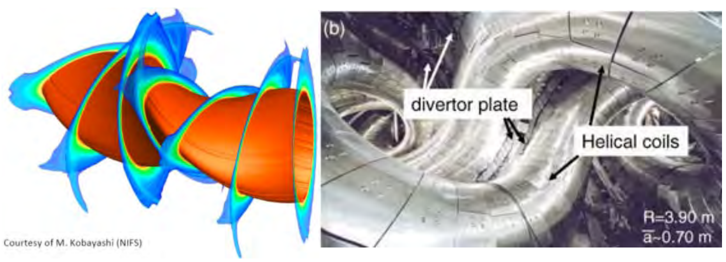
Garcia-Regana 2013

3D makes stellarator divertors different from tokamaks

- Edge has mixed topology with islands (or ‘remnants’) and stochastic regions
- Large variations in connection lengths
- Structure is strongly coupled to particular magnetic geometry

LHD has a continuous helical divertor

-robust; flux emerges between the helical coils



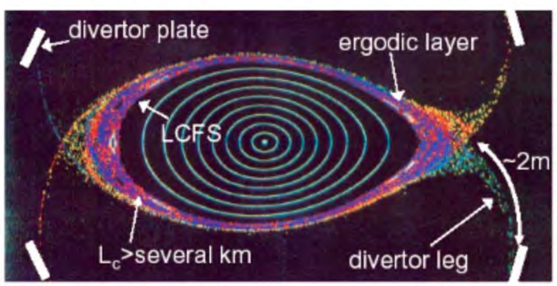
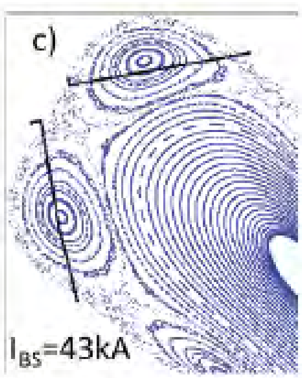


Fig. 2 Field and divertor geometry of the helical divertor in LHD.

W7-X employs an island divertor

-need edge resonance to create islands

-plates intersect islands

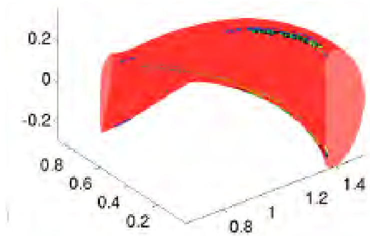


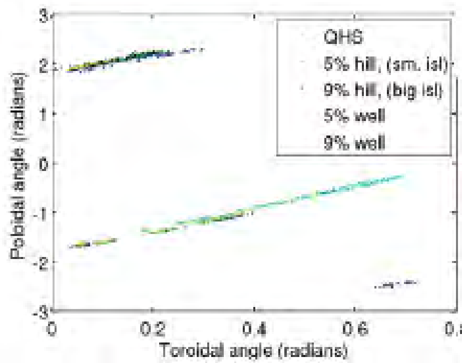
See poster P2.039 by Effenberg

Non-resonant plasma boundary (HSX)

-strikepoints determined by main shaping

-location appears less sensitive to edge transform

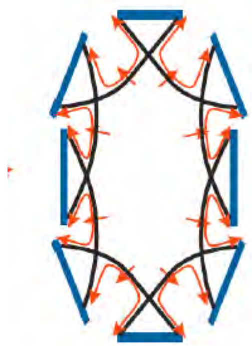


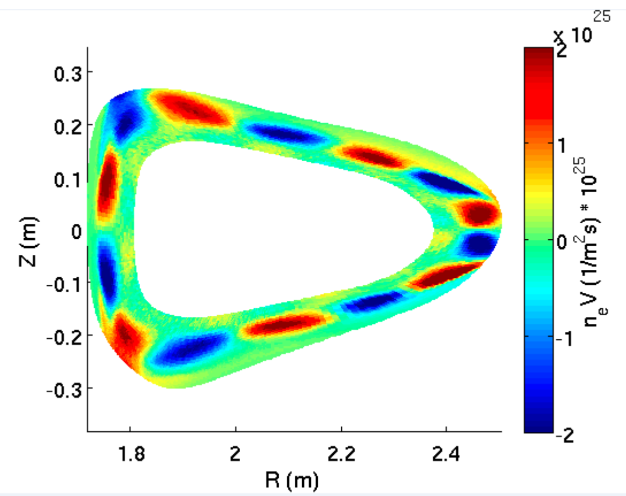


See poster P2.026 by Bader

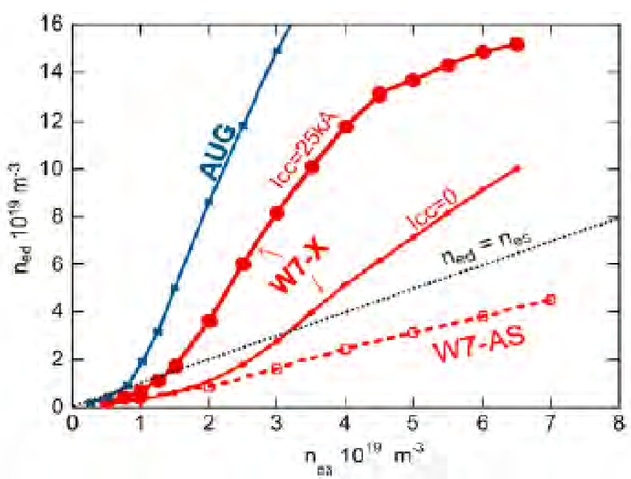
3D structure gives rise to new physical phenomena

- Primary computational tool is EMC3-EIRENE code (Feng 2004)
- High recycling regimes have not (yet) been observed in stellarators
  - Parallel momentum loss can occur due to viscosity from counter streaming flows around island chains
- Stable detached plasmas have been observed in LHD with introduction of a n/m=1/1 island in stochastic region

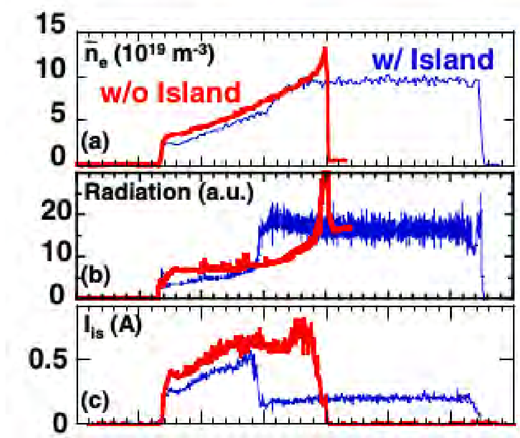




EMC3-EIRENE predicted flows in the HSX edge region (Bader NF 2013)



EMC3-EIRENE predicts high recycling regime in W7-X (Feng PPCF 2011)

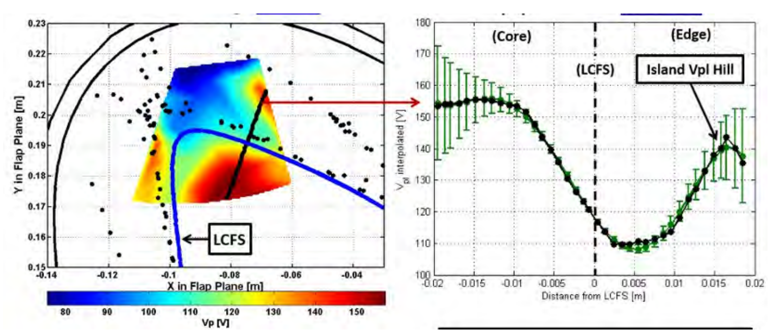


LHD detached plasmas (Kobayashi PoP 2010)

A robust divertor solution is needed for stellarators

- There are some potential advantages to 3D divertors!
  - Naturally occurring; may not need additional coils
  - Longer connection length; more competition between parallel and perpendicular transport; bigger λ_q?
  - Possible to operate without ELM's?; higher density more compatible with divertor operation
  - Possibly get stable detached plasmas at reactor relevant conditions; radiate the power?

- Many challenges and needs
  - What are the requirements in the edge structure for good divertor performance?
  - A better understanding of detachment and stability
  - Flexibility to optimize for divertor, BUT must be integrated with core confinement
  - Avoid requirement for active control
  - Need to get sufficient space between separatrix and coils
  - What are the appropriate metrics for optimization codes?
  - There exist major modeling gaps with respect to 2D

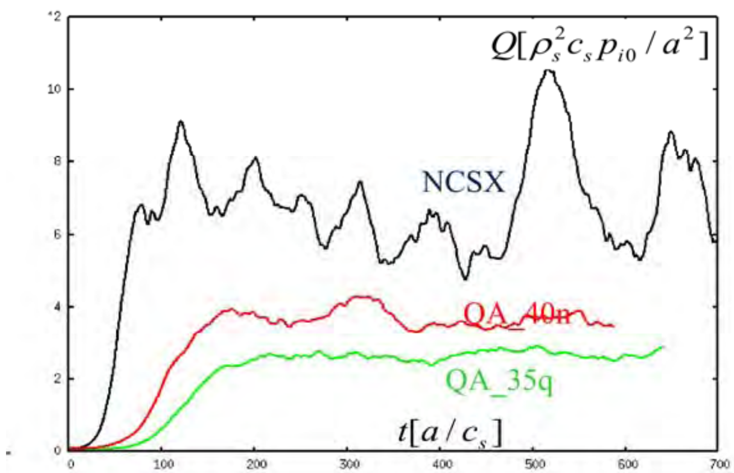


Edge electric fields and drifts may need to be included

Integration of stellarator divertor design with core confinement is crucial to advancement to the next generation

Reduction of turbulent transport is a new frontier for stellarators

- Reduced electron transport in HSX shows that optimization has been very successful for neoclassical transport (problems still with energetic ions).
- With 3D gyrokinetic codes and STELLOPT optimization code – and advances in computational ability! --- 3D shaping now being used to reduce turbulent transport.
- Not practical to bundle nonlinear turbulence calculation with STELLOPT ➔ Use proxy functions or linear growth rates, then check nonlinear calculation (Mynick).



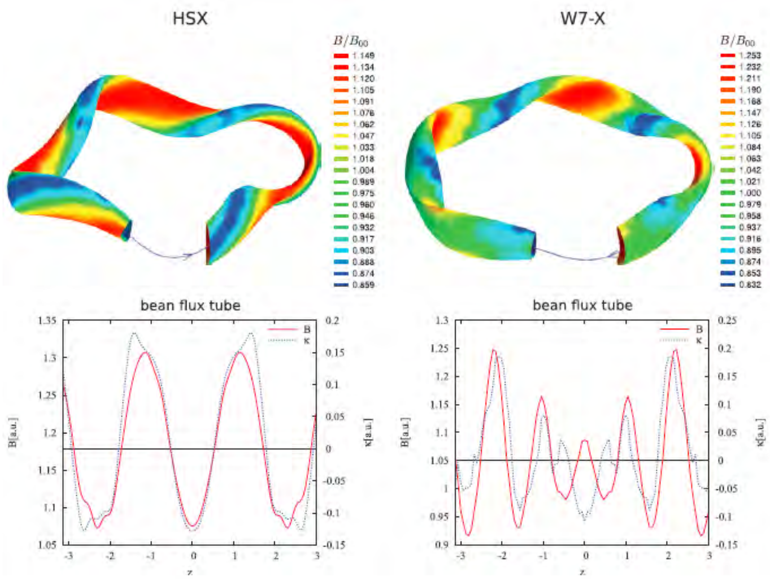
Optimization for ITG in NCSX shows factors of 2 – 3 improvement in nonlinear heat flux

- QA_40n also has reduced neoclassical

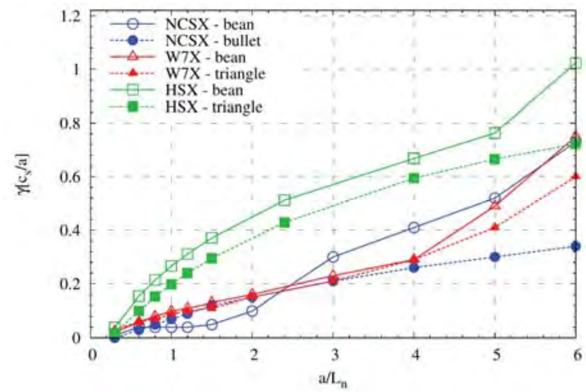
(Mynick PRL 2010)

See Poster P2.033 Lazerson, "The QUASAR experiment as a facility to test ITG turbulence"

Growth rates are only part of the story



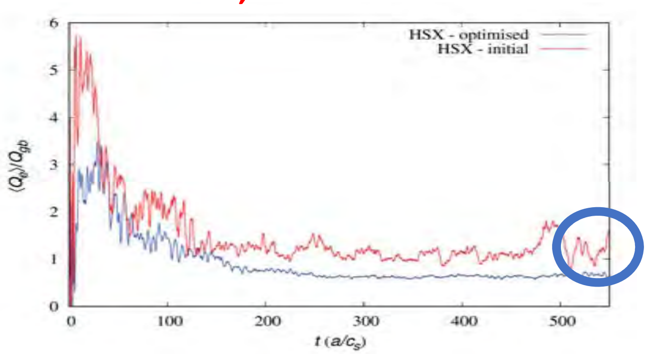
- In HSX virtual complete overlap of trapping region and bad curvature
- W7-X has small trapped particle populations in bad curvature regions



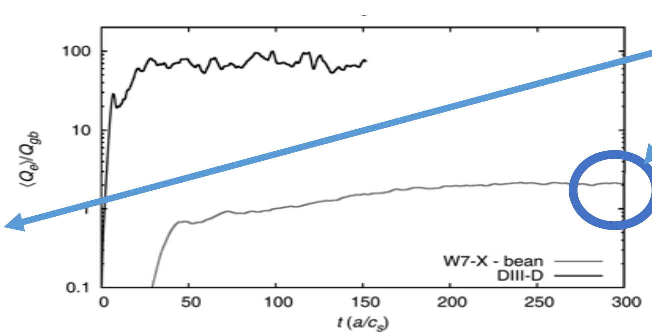
HSX has higher linear growth rates

From Proll et al PPCF **58** (2015) 014006

BUT, normalized heat flux for HSX and W7X are comparable!



Proll PPCF 2014

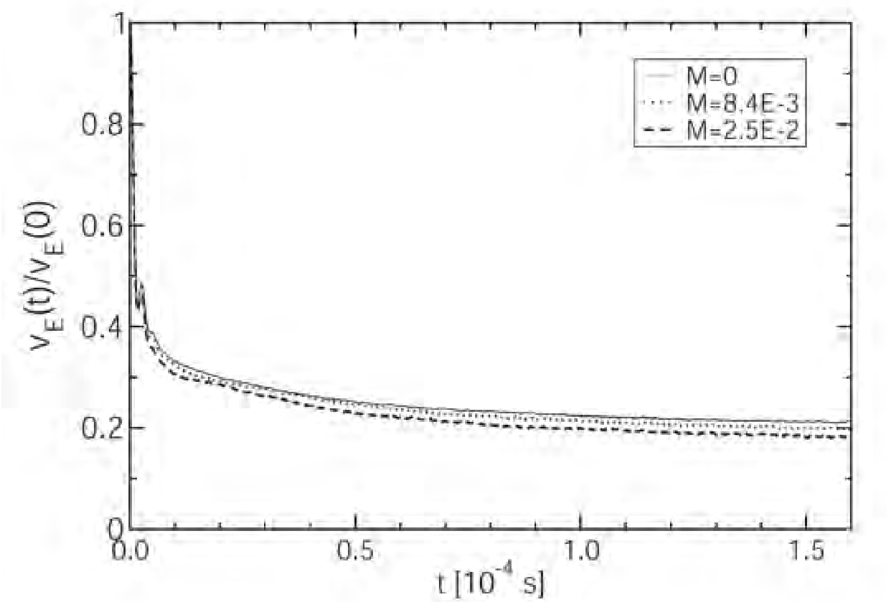


Helander NF 2015

$\langle Q_e/Q_{gb} \rangle \sim 1$

Need for reliable proxies for heat flux saturation levels

- Residual zonal flow in HSX is higher than in W7-X or LHD (Kleiber CPP 2010)
- Quasisymmetry naturally leads to lower flow damping



- Do zonal flows play a role in the non-linear heat flux saturation?

How can we sensibly include reduction of turbulent transport into optimization codes?

Nonlinear GENE calculation for TEM heat flux in HSX in good agreement with experimental measurements

See Invited talk Faber: “Nonlinear coherent structures from linearly stable modes in stellarator TEM turbulence”

See Invited talk Terry: “Large Scale Sinks in Saturatiion Scalings of ITG Turbulence”

Concluding Remarks

- Stellarators have achieved significant parameters

  B > 5%; T_i, T_e > 10 keV; n_{emax} ~ 1 x 10^{15} cm^{-3}, Discharge lengths ~ 1 hour; τ_E ~ 1/3 s
- W7-X has begun operation!
- Quasi-symmetry and quasi-omnigeneity provide low ν transport solutions
- Experiments have shown a rich field needing attention from theorists and modelers:
  - Why are b-limits so soft?
  - Importance of flows.
  - What sets the current and density limits in ‘high’ current stellarators?
  - Can we use the complexity in the stellarator edge to our advantage?
  - What sets stability on 3D detached divertors?
  - What determines impurity transport?

The Next Stellarator Step Requires Further Optimization

- Turbulent transport can be optimized
- Improvements in energetic ion confinement
- Development of a robust, workable divertor solution
- Conditions needed for core impurity expulsion.
- Can we simplify coil design while maintaining necessary physics properties of the magnetic field?

How do we prioritize/trade-off conflicting directions?

- Need useful metrics to incorporate into optimization codes.
- Many analysis codes exist (gyrokinetics, extended MHD, neoclassical transport, energetic particle modes, divertor modeling); all need validation
- Need guidance from theorists in extending into relevant areas

There is a tremendous opportunity for continued advancement in the stellarator

It is a scientifically rich field full of challenging problems

Major need is active committed people to carry this forward!