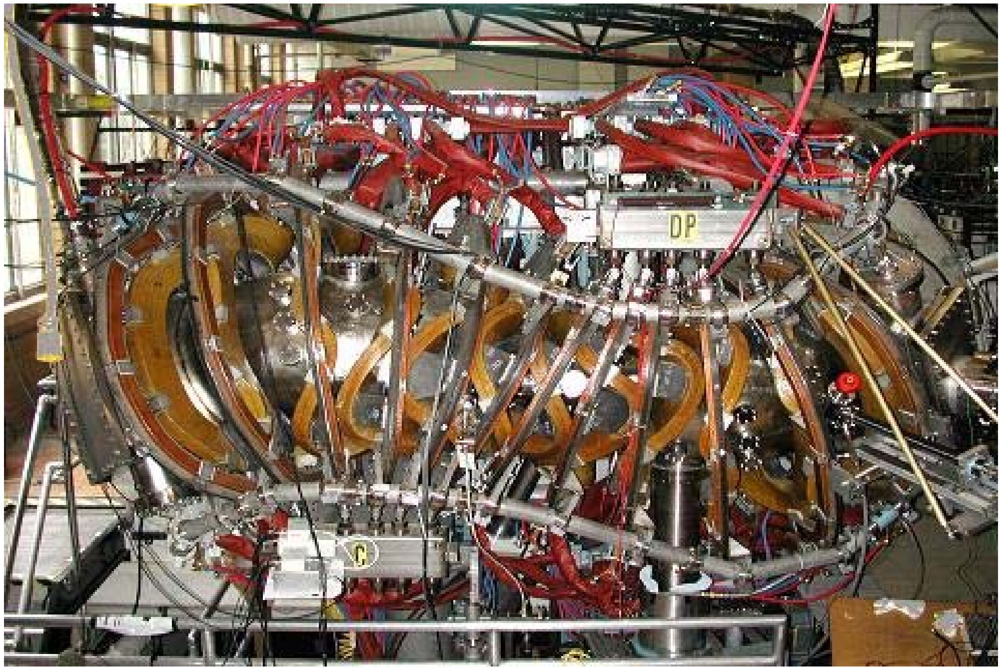
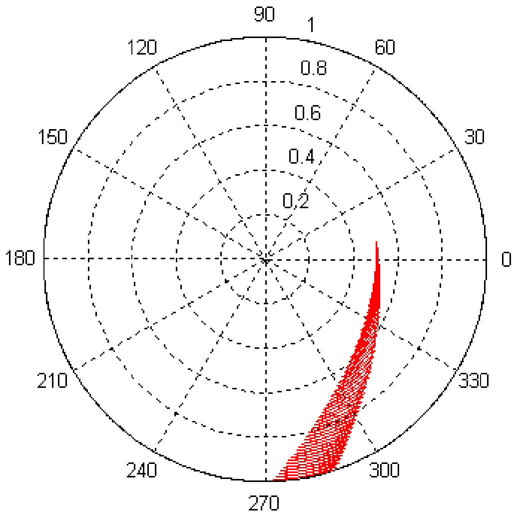
Energetic Particle Experiments on HSX



Does quasisymmetry fix the energetic particle loss problem?



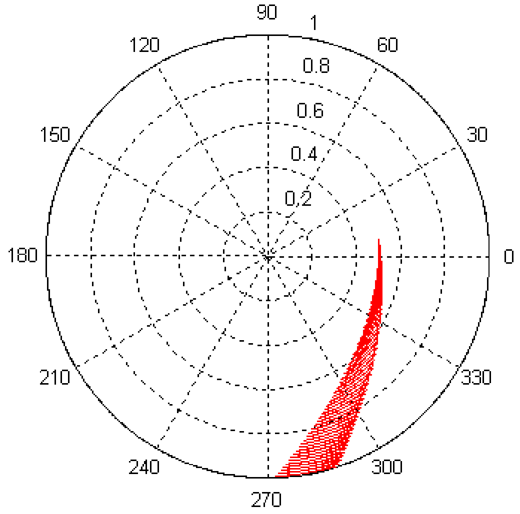
D.T. Anderson for the HSX Group
US-Japan Stellarator Workshop
Auburn AL February 25-27, 2019

Structure

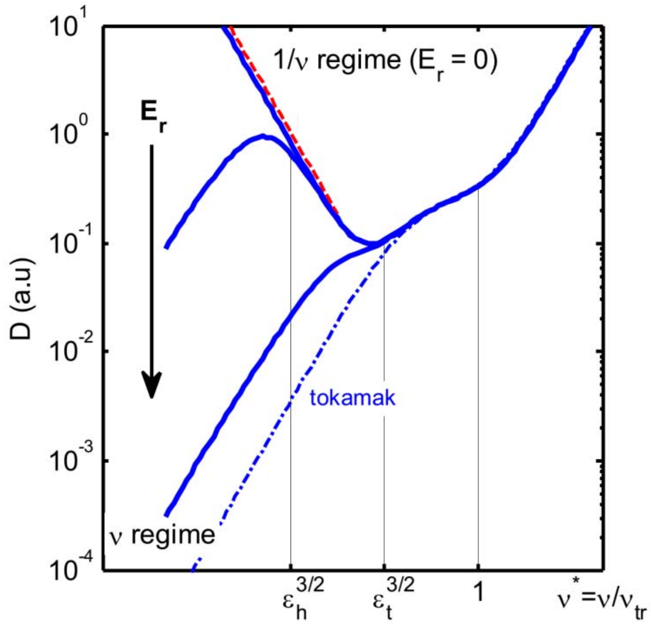
- Good thermal confinement does not insure good energetic particle confinement
- Methods focusing on the energetic particles can be successful
- HSX would like to test these metrics by use of a neutral beam to introduce energetic test particles
- Coil design and finite-build are equally important as the ideal plasma design to containing energetic particles
- Concluding Remarks

Diffusion in notorious ‘*1/ν*’ regime ~ $T^{7/2}$

Collisionless Orbit



+ Collisions



$$D \sim \frac{(\Delta x)^2}{\Delta\tau} \sim \varepsilon_h^{1/2}\frac{\left(V_D\tau_{eff}\right)^2}{\tau_{eff}} = \varepsilon_h^{1/2}\frac{{V_D}^2}{\nu_{eff}} = \varepsilon_h^{3/2}\frac{{V_D}^2}{\nu} = \varepsilon_h^{3/2}\frac{T^2}{T^{-3/2}} = \underbrace{\varepsilon_h^{3/2}}\,T^{7/2}$$

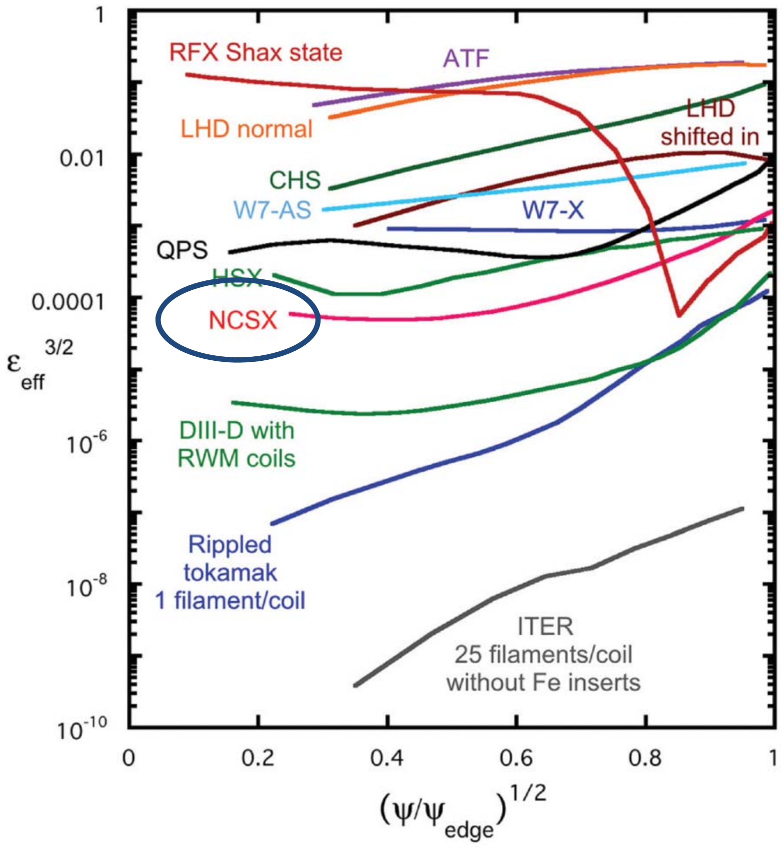
$$\boxed{\chi \sim T^{9/2}}$$

For multiple symmetry breaking terms, replace by effective ripple ε_{eff}

- Effective ripple is incorporated into optimization codes.
- Is it the right metric for energetic particles? (no..)

Symmetry-breaking characterized by ε_{eff}

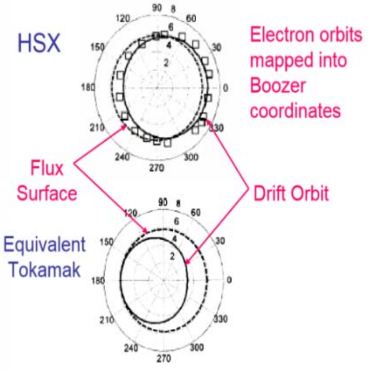
- Convenient method to compare neoclassical transport for 3D systems
- Transport in optimized stellarators factors of 10 – 100 lower than classical stellarators in this regime
- National Compact Stellarator Experiment would have had lowest effective ripple of any stellarator
- Tokamaks with 3D perturbations still orders of magnitude below stellarators

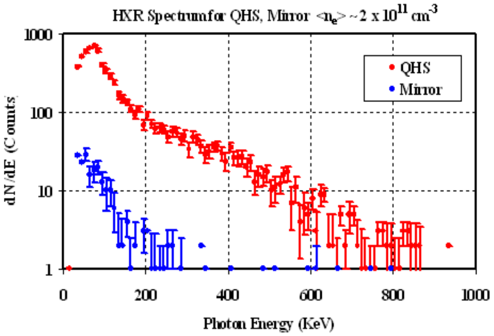


Spong, PoP 2015

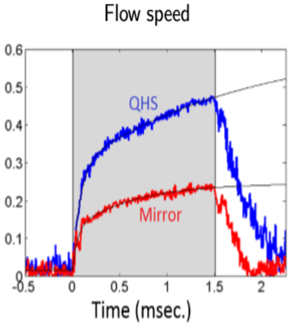
HSX Showed Benefits of QHS for thermal plasma

- Experimentally confirmed achieved QHS structure
  J.N.Talmadge et al., Phys. Plasmas 12, 5165 (2001)
- Significant improvement of deeply-trapped particles
  D.T. Anderson et al., Fusion Science and Technology 50 (2): 171-176 (2006)
- Reduced parallel current magnitudes
  J. C. Schmitt et al., Phys. Plasmas 21 092518 (2014).
  J. C. Schmitt et al., Nucl. Fusion 53 082001 (2013).
- Reduction in momentum, particle, and heat transport





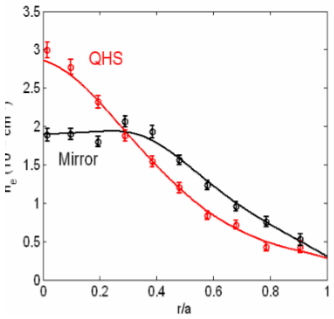
Momentum



Larger flows in QHS with equivalent torque

→ Lower parallel viscous damping

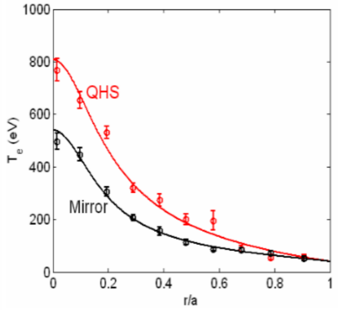
Particle



Peaked density profiles in QHS

→ Reduced thermodiffusion

Heat



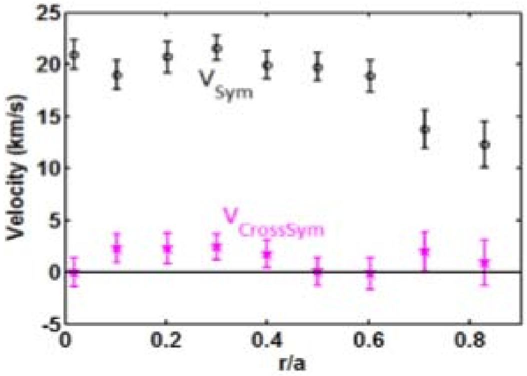
Higher T_e in QHS with same absorbed power

→ Lower χ_e

S.P. Gerhardt et al., Phys. Rev. Letters 94 (2005) 015002

J.M. Canik et al., Phys. Rev. Letters 98 (2007) 085002

Carbon ion flows measured with CHERS flow in the direction of symmetry for QHS



A. Briesemeister et al., Plasma Physics and Controlled Fusion, 55, 014002 (2013)

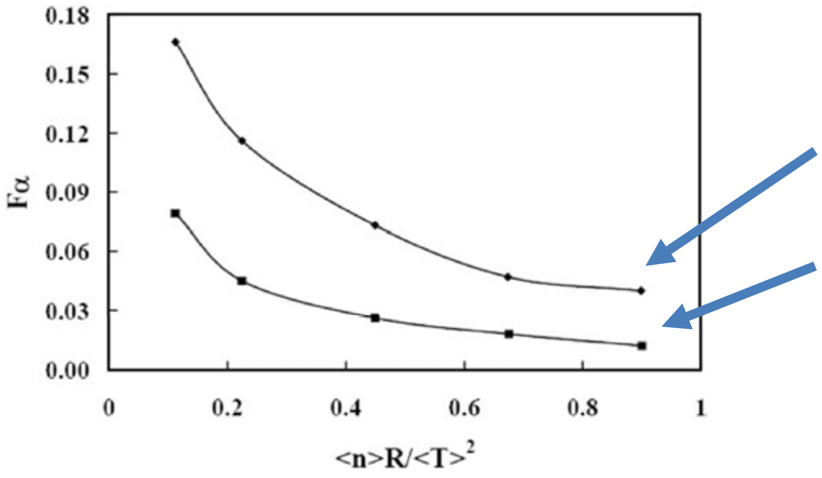
Large α losses in scaled ARIES-CS even with a low ε_{eff}

- National Compact Stellarator Experiment (NCSX): minimize $n \neq 0$ terms in $|B|$ spectrum

- Scaled to a reactor, **27% of alpha energy is lost**! (Mynick PoP 2006)

- For ARIES-CS reactor study, ORBIT3D + STELLOPT minimized F_{LOSS}
  - New configuration with mirror term: $n = 1$, $m = 0$; reduced quasi-axisymmetry

- Alpha losses < 10% (Ku & Garabedian FST 2006) and < 5% at higher density (Ku FST 2007)



Alpha losses reduced to below:
5% for R = 7 m reactor,

3% for R = 10 m (Ku FST 2008)

It should be noted these were all based on plasma target, not coils!

Takeaway from NCSX/ARIES-CS

- One can never achieve perfect quasisymmetry, but HOW you break it is very important

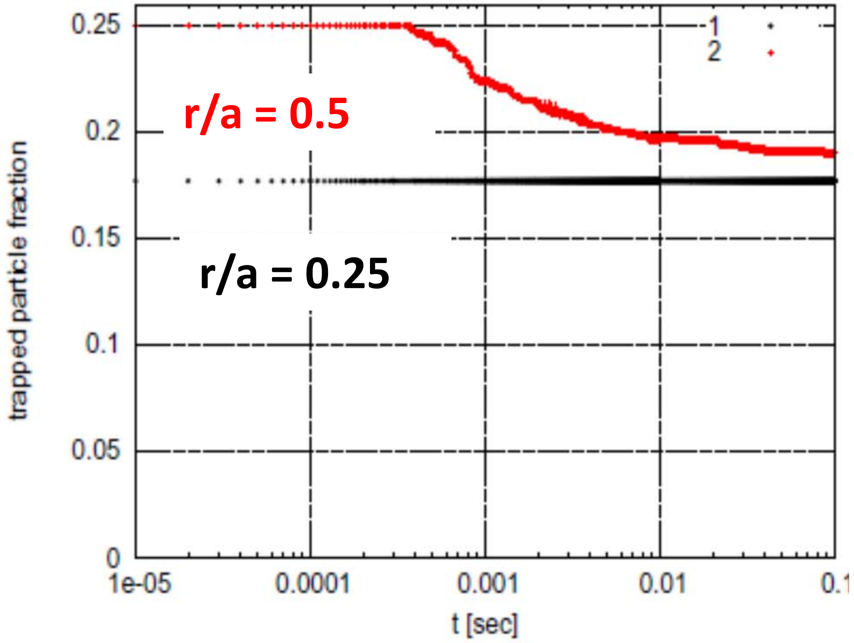
- If your symmetry-breaking components lead to $B \times \nabla B$ in the flux surface rather than across, you win! [That's what the mirror term does to improve alpha confinement, Mynick 2006]

- Approximate quasisymmetry is worthy goal BUT
  - ➢ Thermal transport only needs to be reduced to turbulent levels
  - ➢ Electric field helps thermal transport ($1/\nu$ is for $E_r = 0$)
  - ➢ More important to confine alpha particles

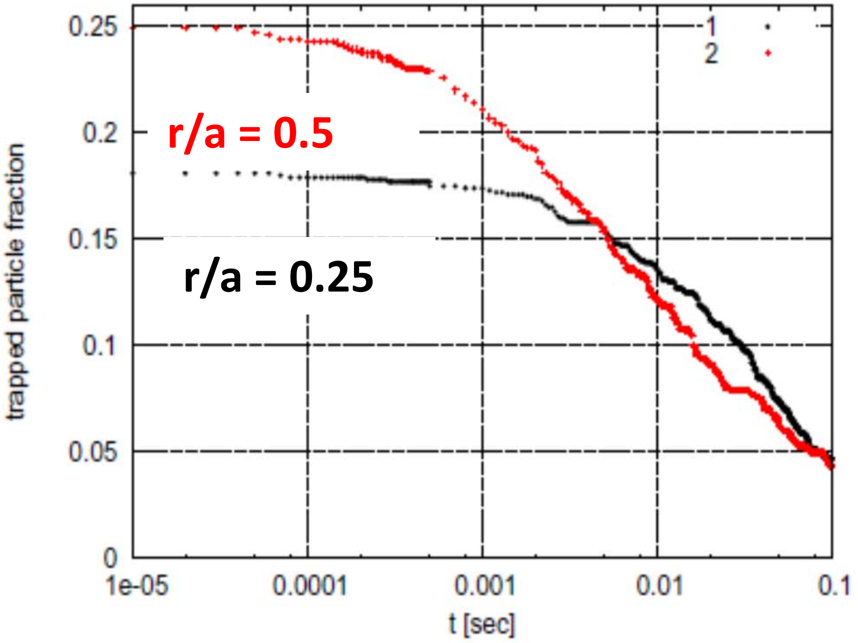
Low effective ripple does not seem to equate to adequate alpha particle confinement

In Ideal Case of QHS Energetic Particles are Confined Inside r/a=0.25; at r/a=0.5 not so good!

QHS



HSX



- Collisionless trapped alpha particles for original QHS & HSX
    - QHS is the original Nührenberg & Zille (1988)
    - Scaled to 5T, a = 1.6 m
- HSX described by finite coils ➔ 13% lost @ r/a ~ 0.25
    - QHS is an idealized VMEC equilibrium ➔ no loss!

Nemov PoP 2014

Methods to Improve Energetic Particle Confinement

- Historically, ε_{eff} , the effective ripple
  - metric for neoclassical transport; focuses on deeply-trapped particles
  - seen this is suspect in present form
- Improve the quasisymmetry in configurations
  - Perfect quasisymmetry confines all particles
  - Cannot be achieved!
  - How good is good enough?
- Possible strategy is to try and match J contours to flux surface by minimizing $\partial J/\partial\theta_0$ and maximizing $\partial J/\partial\psi$

Drift in $\nabla\psi$

Poloidal drift

Nemov Target Functions Characterize Energetic Particle Confinement

- Analogue to effective ripple which targets confinement in $1/\nu$ regime
- Evaluated with field-line following code or 3D equilibrium w/ islands
- Trapped particle motion evaluated for every magnetic ripple

bounce-averaged drift velocity across magnetic surface

poloidal drift velocity

γ_c: angle between J contours and magnetic surface

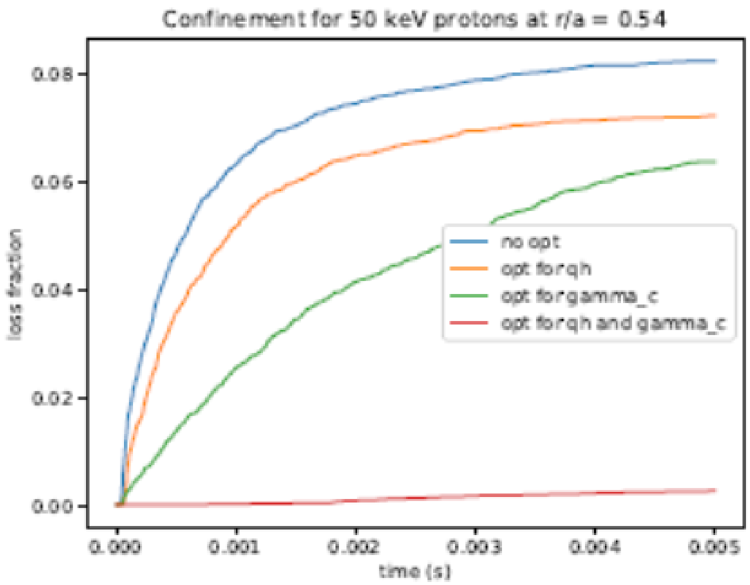
  - For $|\gamma_c| = 1.0$, trapped particle quickly lost

- Average over pitch angle and flux surface → $\Gamma_v \;\; \Gamma_p \;\; \Gamma_c$

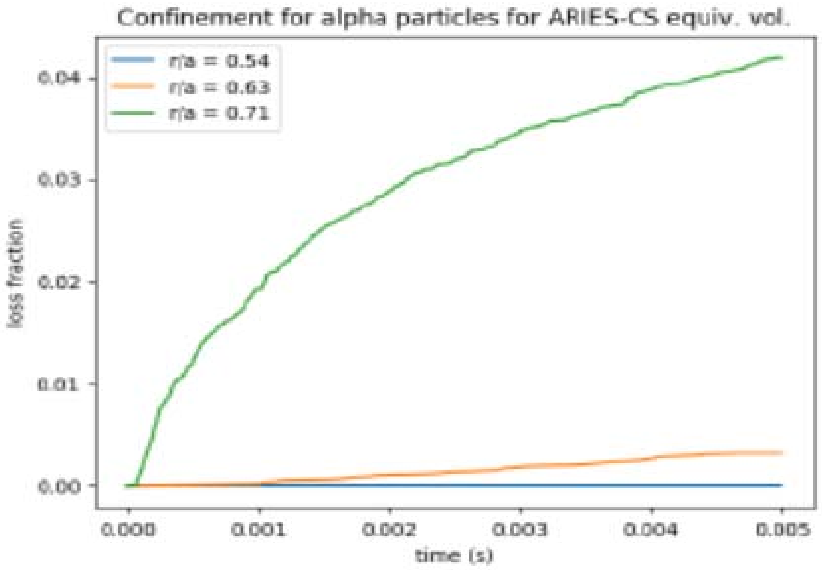
Nemov et al., PoP 2005; 2008

Nemov Metrics in the ROSE Optimizer Gives Configuration with Good EP Confinement

Plots/calculations courtesy A. Bader



Good confinement of 50 keV protons with B=2T R=2m in QHS optimized for both symmetry and gamma_c



Good confinement of alphas in configuration scaled to volume/field of AIRES-CS

No losses inside ½ radius!

Can HSX Test the Effectiveness of the Nemov Metrics?

Goal: We would like to look at the confinement of energetic particles as the magnetic configuration is changed and relate that to the degree of quasisymmetry and the metrics for fast particle confinement

Method:

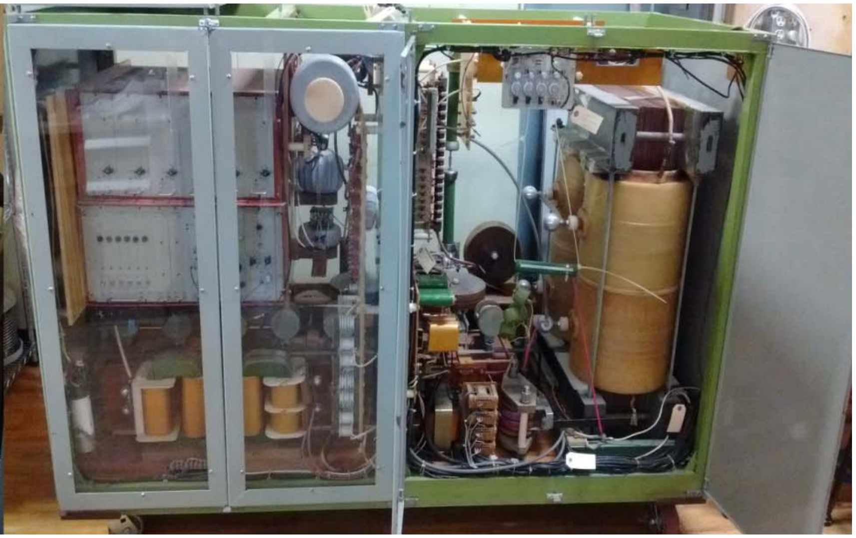
Use an optimizer (ROSE) to search for configurations within HSX (different combinations of auxiliary coil currents) which have significant variations in the energetic particle metrics

Utilize a 'low' energy neutral beam as a source of fast particles. Infer confinement by monitoring neutron production rate for a deuterium beam injected into a deuterium plasma (ala CHS and MST)

A Deuterium Capable Beam is Available

The beam used for this experiment on MST is available for use on HSX

Beam Head and Neutralizer

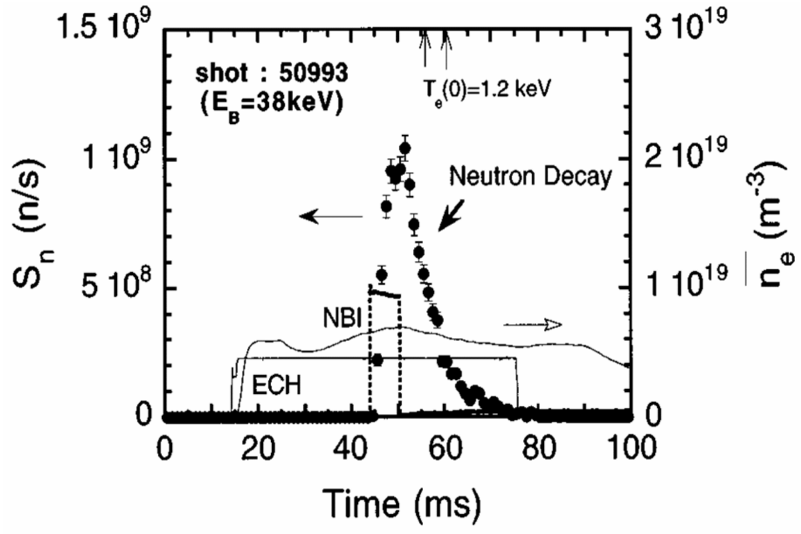


High Voltage Power Supply Rack

Acceleration Voltage	20 kV
Emitted Current	40 A (0.8 MW)
Estimated Current into Plasma	25 A (0.5 MW)
Gaussian Beam Diameter / Divergence	5.4 cm / 1.2 degs.
Pulse Time	1.2 msec
Injection Angle	90 – 72 degs.
Length along Beam Axis into Plasma	31 – 38 cm

A Similar Experiment on CHS gives Confidence in Success

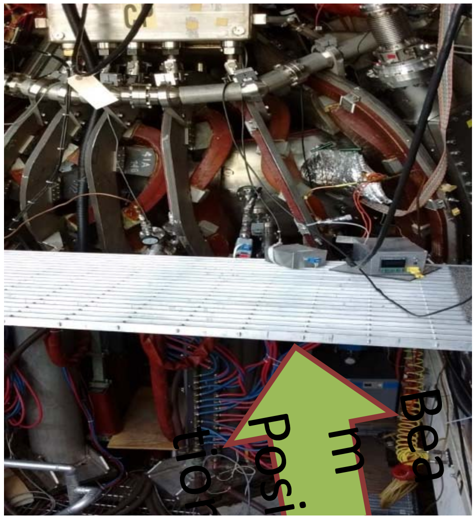
- The beam on CHS was 38 keV which has a higher fusion cross-section than the 20 keV beam planned for HSX
- The lower reactivity is compensated by using a full deuterium beam on HSX (vs one with 1% doping of a hydrogen beam on CHS)
- Neutron detectors will be borrowed from MST for initial experiments and for beam testing.
- The beam should be operational on a test stand within about one year.

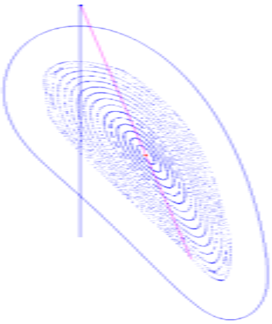


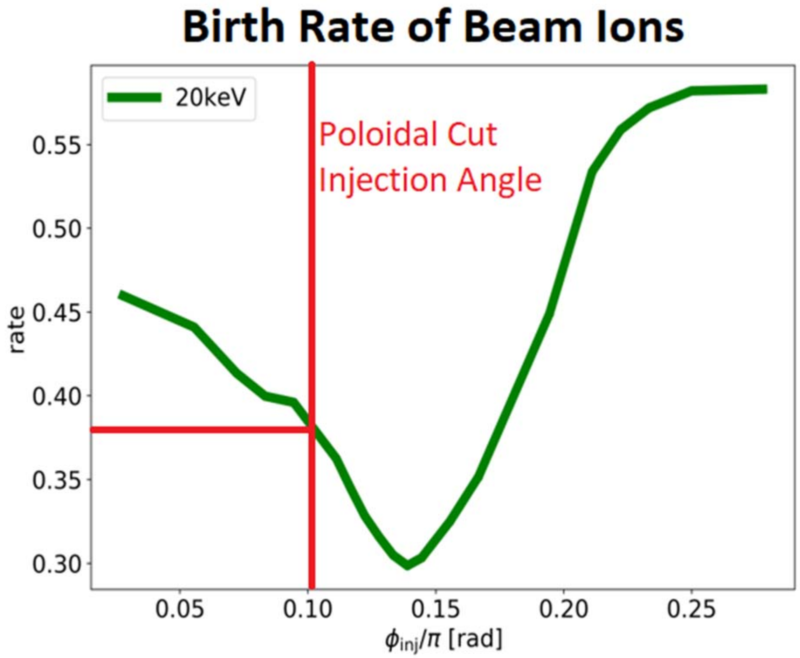
Neutron production rates as observed in CHS under nearly identical conditions as proposed here for HSX. Figure from M. Isobe et al., Rev. Sci. Instrum. 68 532 (1997).

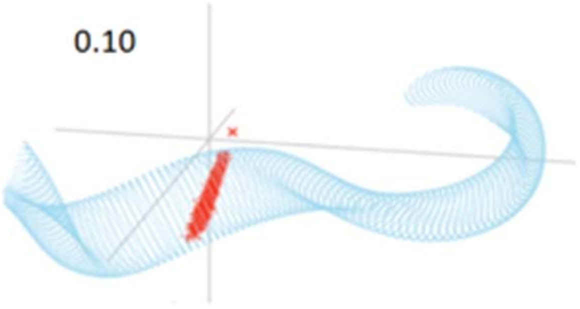
The Geometry at HSX Presents Challenges

- Tangential injection is not possible due to coil interferences



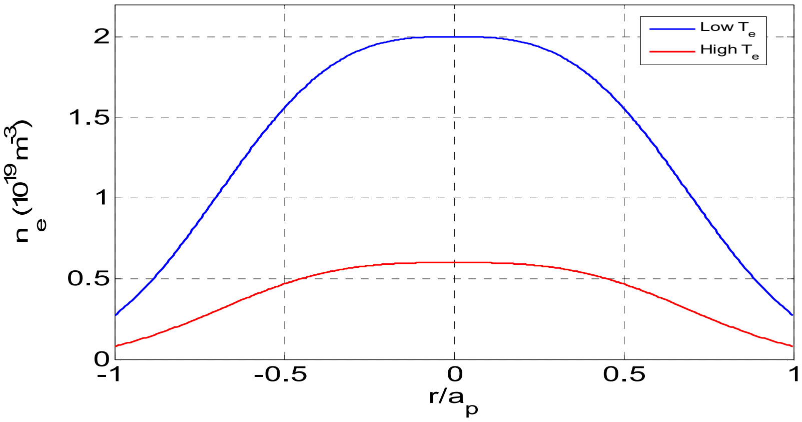


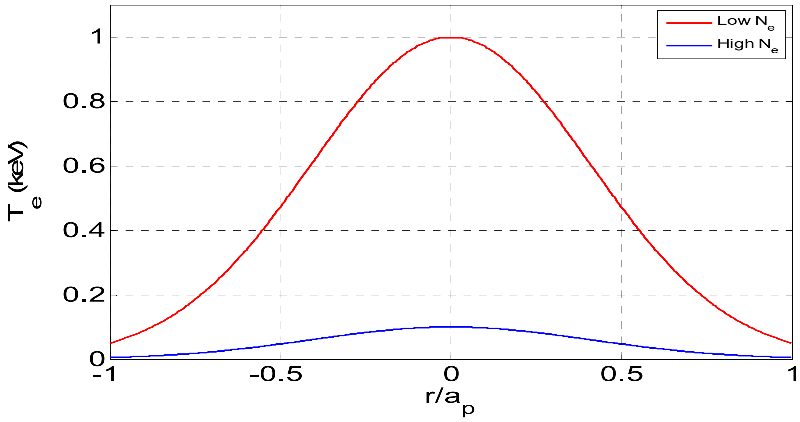




Calculations by S. Murakami at Kyoto University show that we can get ~38% ionization of the beam with attainable plasma targets and injection geometry

The Target Plasma Density Needs to Be as High as Possible



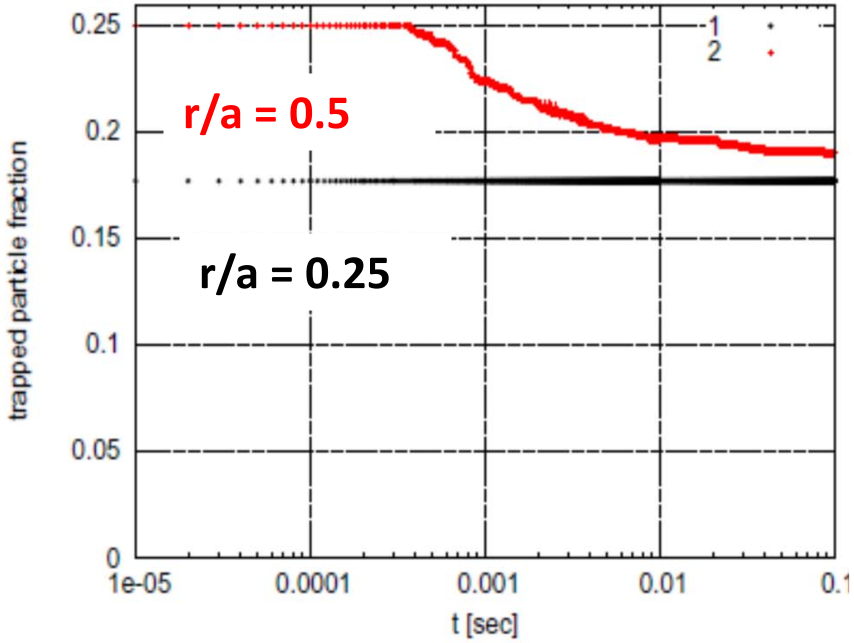


- Our 28 GHz source has a cutoff at 1 x 10^{19} m^{-3}
- Short path length requires us to use overdense (cold) plasma
- Electron temperatures are still ~100eV; electron impact ionization is only weakly dependent on T in this range (n much more important)
- The HFREYA birth calculations used the higher density profiles
- The plan is to use GNET (Murakami/Kyoto) to model fast ion confinement and neutron production

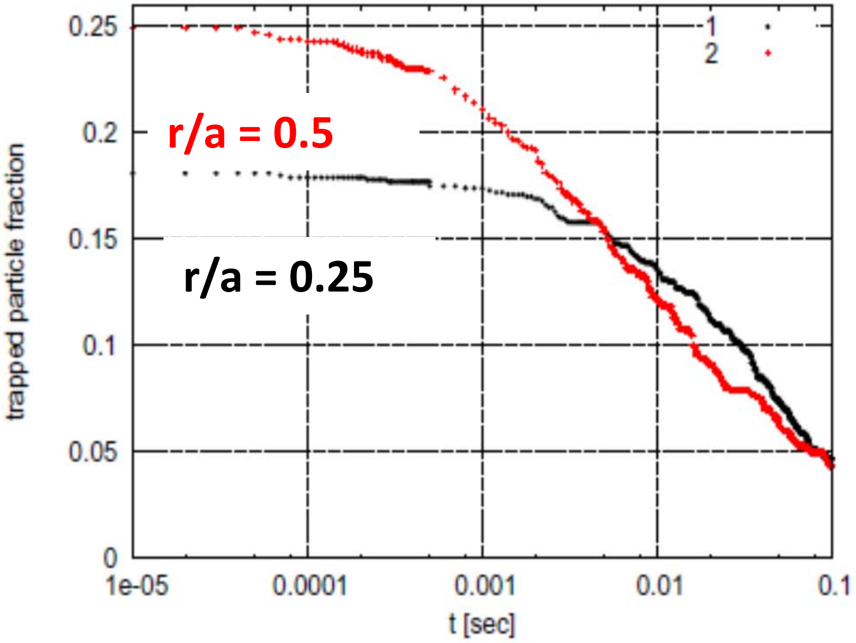
This will give us a diagnostic to look at the effects of configurational changes on confinement of energetic ions produced by the beam

Alpha Particle Confinement in HSX Reactor is Degraded Compared to Original QHS Concept

QHS



HSX



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  - QHS is the original Nührenberg & Zille (1988)
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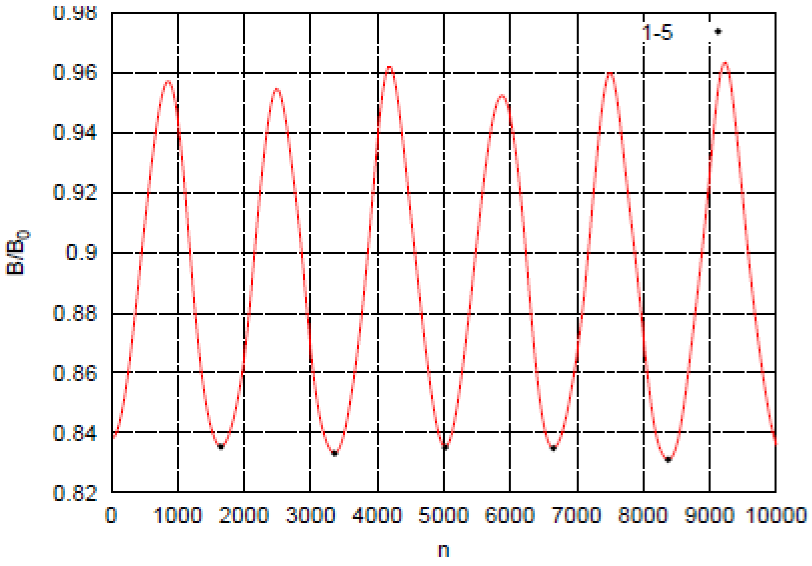
- **HSX described by finite coils ➔ 13% lost @ r/a ~ 0.25**
  - QHS is an idealized VMEC equilibrium ➔ no loss!

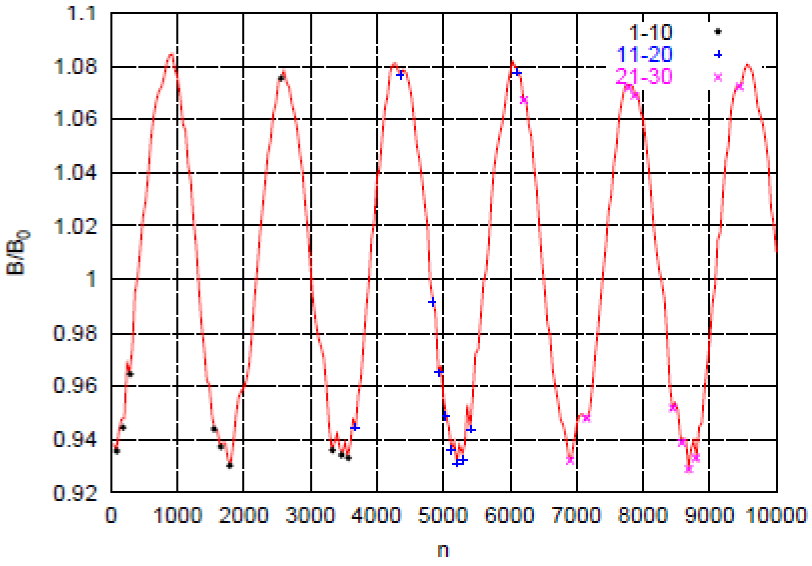
Nemov PoP 2014

48 modular coils in HSX add additional ripple

QHS



HSX

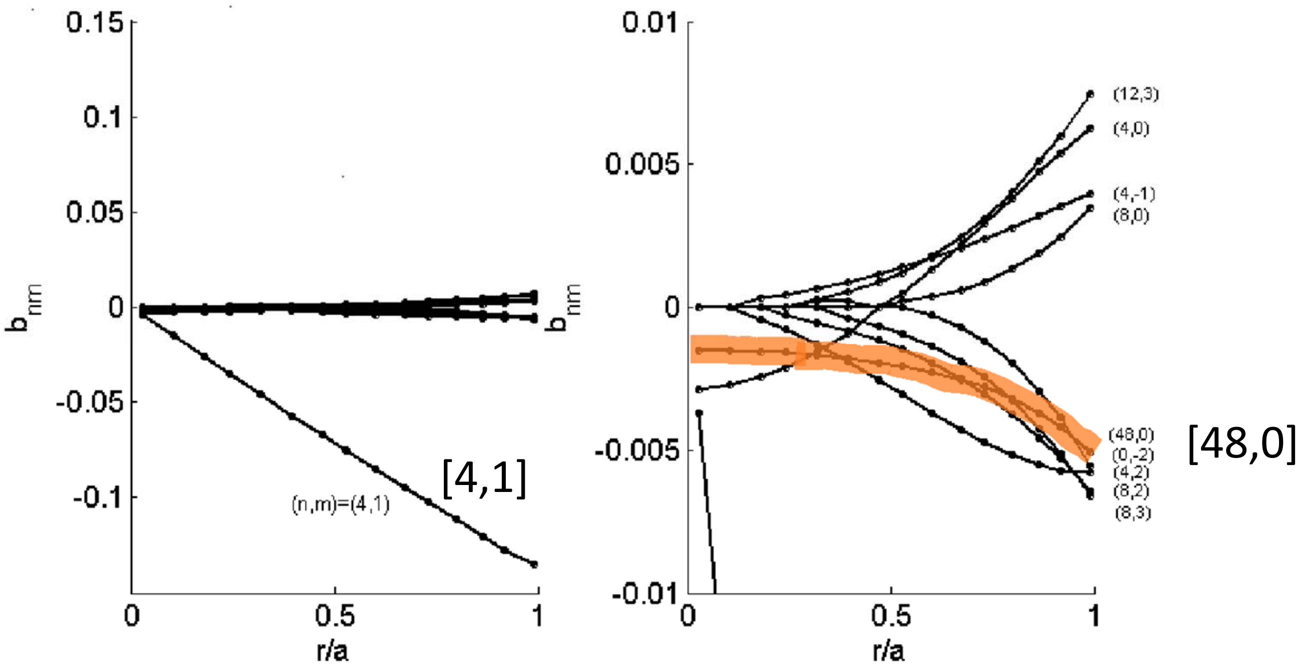


- |B| along field line at r/a = 0.5
- Finite coils produce additional local minima in |B|

Magnetic Field Spectrum Shows Large [48,0] Term in Core

$\frac{B}{B_0} = \sum_{n,m} b_{nm} \cos(n\phi_B - m\theta_B)$ where ϕ_B = toroidal angle in Boozer space

θ_B = poloidal angle

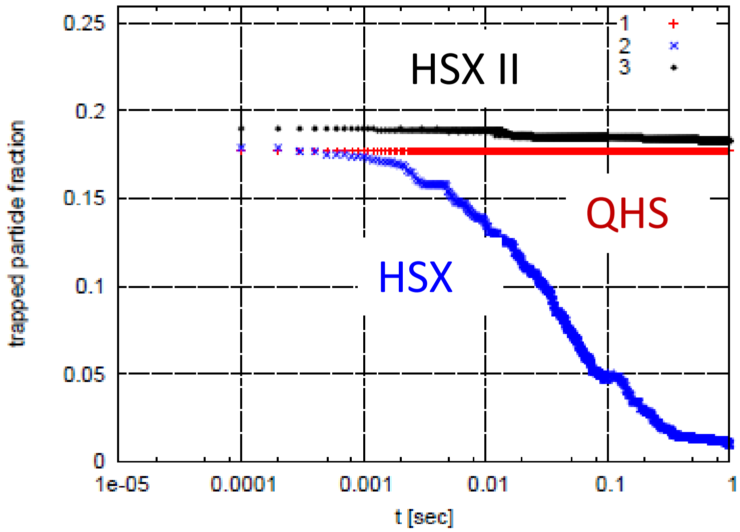


- Largest term is helical [4,1] term
  - ➢ toroidal curvature [0,1] doesn’t show up on this scale

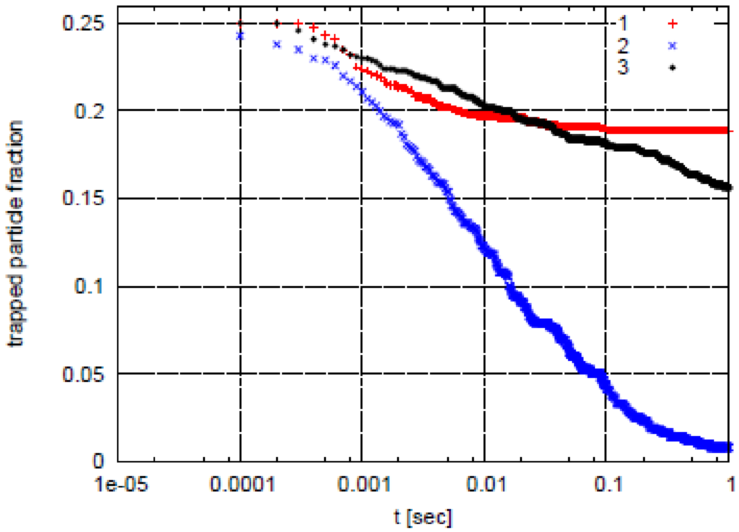
- Modular coil ripple [48,0] remains finite even down to magnetic axis

HSX II and Original QHS have Similar Alpha Particle Confinement

r/a = 0.25



r/a = 0.5



Alphas lost by t = 0.1 s

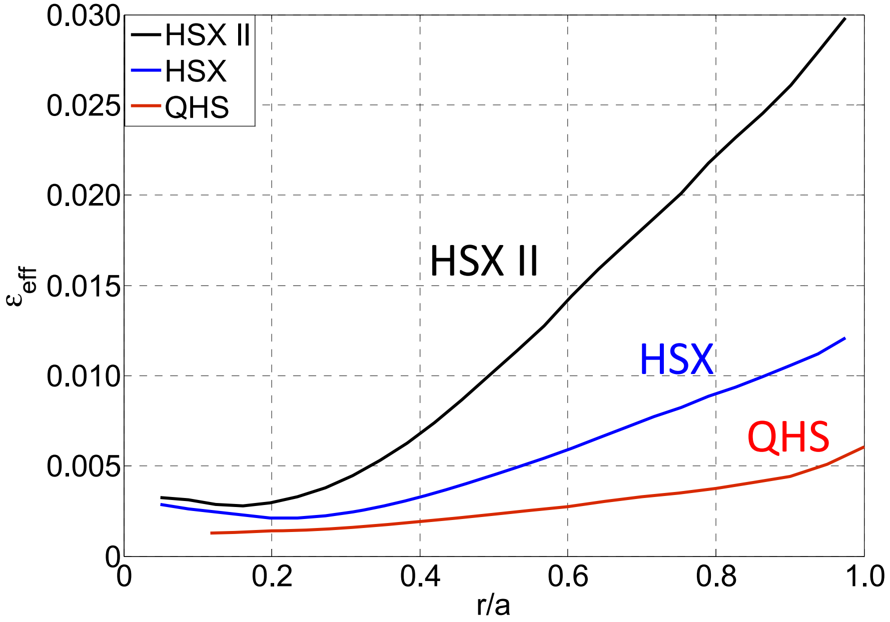
QHS	0%	ideal
HSX	13%	48 coils
HSX II	0.5%	96 coils

QHS	6%	ideal
HSX	20%	48 coils
HSX II	7%	96 coils

- Simply getting rid of the modular coil ripple, without optimization, dramatically improved alpha particle confinement ➔ is there a better way than more coils?

HSX II has Higher ε_{eff} Compared to HSX

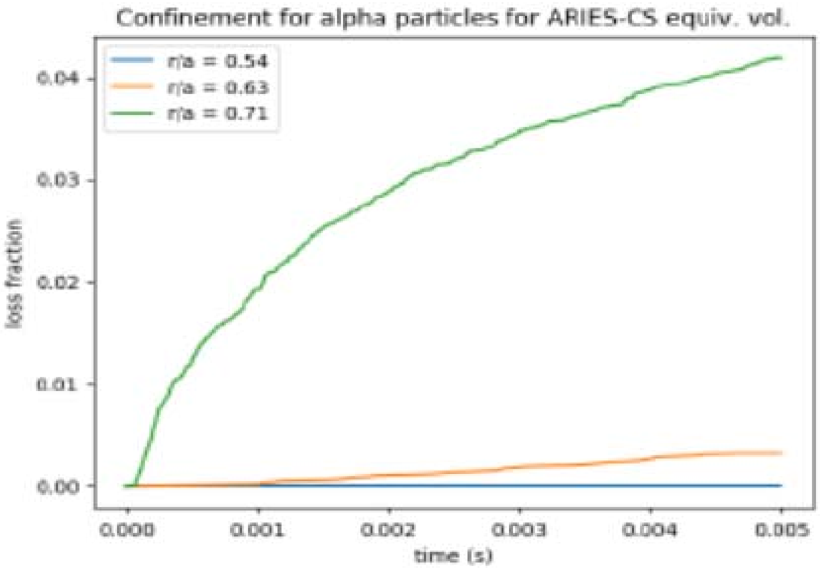
Effective Ripple



- Effective ripple – indicative of thermal transport in $1/\nu$ regime --- is higher with 96 coils than for 48, even though alpha confinement is significantly improved.

- $\mathcal{E}_{eff}$ is not an adequate figure of merit for energetic particles

Alpha Loss Can Be Reduced By Several Methods



Bader has shown very low loss configurations when you optimize for both QHS and the Nemov metric
~zero within ½ radius!

Many efforts underway with FOCUS to move coils farther from the plasma to drop discrete coil ripple

Open question: Can we use ferritic elements as done in tokamaks to reduce this harmful ripple component.

If HSX can be successful in introducing and measuring energetic ion confinement use of ferritic elements could be an exciting area of investigation in the future

Concluding Remarks

- Energetic particle confinement is an open issue in stellarators
- It may be the defining issue for stellarators moving into fusion plasmas
- Optimized neoclassical confinement does not insure good energetic particle confinement
- Methods are developed which permit improvement of the ideal plasma magnetic structure
- Coils to generate this structure can introduce significant changes to the energetic particle confinement, BOTH in filamentary and ESPECIALLY in the finite-build cases.

Concluding Remarks

- HSX is developing a program to experimentally investigate energetic ion loss as a function of magnetic structure
- Potentially investigate whether ferritic inserts can reduce coil ripple and fast particle loss
- Continue efforts to define a next-step stellarator for the US Program

Side note: The W7-X group has donated a 500 kW 70GHz gyrotron to HSX for use in our program. This will greatly extend the capabilities of HSX into ongoing investigations. Specifically:

- B upgraded to 1.25 T
- Attainable density up to 3 x 1019 m-3
- 4-8 times increase in absorbed power
- Pulse length up to 0.5 seconds
- Increased ion temperatures