Stability (CAS3D) and Energetic Particle Confinement

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Outline

* Stability Calculations with CAS3D

    - Fixed Boundary
    - Free Boundary
    - Vertical Instability

* Particle Confinement

    - Magnetic Geometries
    - Thermal Ion Transport
    - Neutral Beam Ion Transport
    - Alpha Particle Transport

* Conclusions and Future Work

I. CAS3D Stability Calculations

A. Fixed Boundary Calculations

- Calculations of stability of low and high n modes
  for 2 field period case
  benchmarked against TERPSICHORE in detail.

- Structure of eigenfunctions,
  trends in eigenvalues with beta
  and beta stabilization of most unstable mode
  in good agreement

- Work presented at Sherwood, ICC meetings this
  spring.

B. CAS3d Free Boundary Stability Calculations

* Test case for external kink stability point of ARIES
    - Compared to PESTII and TERPSICHORE
        (wall at 2a from plasma center)
        revealed bug in CAS3D.

* CAS3D always predicted instability,
    while PESTII and TERPSICHORE
    - Found stability around 2% beta
    - Good agreement between those codes.

* Neuhrenberg has fixed the bug
    - Has given us corrected subroutines

* CAS3D run in Germany
    - Gives good agreement with PEST II for the
        Aries test case at 2.1% beta.
    - Eigenfunctions and beta stabilization plots have been faxed to us indicating that the code does give agreement with PEST for ARIES kink stability.

* We will verify
    - New code agrees with PEST calculations of stability for Aries
    - No change in the earlier fixed boundary cases

* This work should be complete by APS
    - Routine kink stability calculations with TERPSICHORE can be verified with CAS3D.

C. CAS3D Vertical Instability Calculations

* This same version of CAS3D can be used for vertical instability calculations.

* C. Neuhrenberg has told Monticello she will work along with us to do the calculations for NCSX.

* First, a benchmark test case will be used with TSC that shows stabilization of a vertical instability

- This should be work in progress by APS.
  - The code can then be used to check vertical stability of promising designs.

Summary - Stability Calculations with CAS3D

* Fixed boundary benchmarks with TERPSICHORE in good agreement for 2 field period 20% NCSX case

* Free boundary kink mode stability comparisons with PESTII and TERPSICHORE for ARIES case

    - Found bug in CAS3D, fixed at IPP

    - Still need to verify that our version agrees with PESTII and TERPSICHORE for ARIES kink stability

    - and that the fixed boundary cases remain in good agreement

* Vertical stability calculations
    - Will begin with benchmarking against TSC case
    - Once kink stability agreement is verified for the new CAS3D

Energetic Particle Confinement

* Simulate thermal ion transport in QAS for deuterium ions at 7 keV and evaluate diffusion coefficients.

* Simulate and follow the particles in QAS

  - Neutral beam confinement in PBX-M size

  - Alpha particle confinement in reactor size

Are the Ions Collisionless?

$$\nu_* = \nu/\omega_b$$

	Thermal ions	Neutral Beam	Alpha Particles
qas2_20	0.03		
qas2_40	0.03		
qas4_40	0.07	0.002	
qas3b	0.12	0.002	
tok0	0.05		
qas_00	0.05		
qas2_20 reactor			0.000018

* Ratio of the collision frequency to the bounce frequency is small for all ions in these plasmas.

* Banana regime transport expected.

Energetic Particle Confinement
- Particle Following Simulation Method

* STELL Code developed by R.B White at PPPL, from the tokamak `ORBIT' code

  - Follows orbits of monoenergetic ions in a stellarator

  - Individual particles (256-1000) move in the magnetic field, possibly leaving plasma.

* Calculate diffusion rate of particles and total particle and energy loss

* Collision Model
  - The collision frequency has radial dependence

$$\nu = \nu_0(1 - \psi/\psi_a)$$

  - E = 7KeV, $N_{eo} = 3x10^{13}/cm^3$, T_{eo}=3.5keV, Zeff=2.5, ν = 324/sec, no slowing down

* STELL reads $\{B_{mn}\}$ from VMEC equilibrium code

$$B = \sum_{m,n} B_{mn}\cos[m\theta + nN_p\varphi]$$

  - Used 50 largest harmonics

  - VMEC code was used to simulate magnetic geometry and flux surfaces (Ku,Monticello,Hirshman)

  - VMEC solves equilibrium equation $P = j \times B$

Magnetic Geometries

* Stellarator with two field periods,
  20% external transform - qas2_20

* Stellarator with two field periods,
  40% external transform - qas2_40

* Stellarator with three field period - qas3b

* Stellarator with four field period - qas4_40

* Tokamak case equivalent to qas2_20 - qas_00
  - The equivalent tokamak has same n=0 Bmn, defining the boundary, total plasma current, toroidal flux and pressure profile.

  - Only difference is the flux coordinate dependence of the n=0 Bmns due to the difference in equilibrium.

* High aspect ratio analytic tokamak - tok0

* Reactor size version of qas2_20 - qas2reactor

Thermal Ion Transport

* 1000(4000) particles are simulated
  for 400(40) transit times

* 50 largest (over entire plasma) $\{B_{mn}\}$ used

* pitch angle scattering collision frequency = 324/sec

* Evaluate $D \quad \Delta r^2/2t$

Code plots

$$f(t) = 1/(2N_k) \sum_k (\sqrt{\psi_t}-\sqrt{\psi_{0t}})^2 \quad a^2/\psi_a$$

where

$a = r_w$ - Rmaj = midplane average radius

define $D_* = \delta f/\delta t$

then

$$D = (\langle a\rangle/a)^2 \; D_*$$

scale by stellarator averaged minor radius

Thermal Ion Diffusion Results
400 transit times, 1000 particles

	fractional loss	D(cm^2/sec)
qas2_20	3%	7000
qas2_40	23%	--
qas3b	32%	--
qas4_40	11%	--
qas_00 (equiv tok)	2%	8000
tok0	65%	--

More Accurate Thermal Ion Diffusion Results
40 transit times, 4000 particles

	fractional loss	D (cm^2/sec)
qas2_20	0.03%	7800
qas2_40	1.3%	14400
qas3b	0.5%	7200
qas4_40	4%	12400
qas_00 (equiv tokamak)	0%	--
tok0	22%	--

* qas2_20, qas3b and equiv. tok. qas_00 ~ same D

* qas2_40, qas4_40 D higher by roughly a factor 2

* Simulation times must be short, small total losses. Higher loss rates give erroneous estimates for D as lost particles are held fixed at the plasma edge

Conclusion- Thermal Ion Losses

* For qas2_20 : benchmarked code with H. Mynick:
  - GC3 found D = 7426 cm^2/s and
    STELL found D = 7000 cm^2/s

* Confinement improved by high φ_{edge} (toroidal flux), distance to wall (Δr_w)

* Larger external iota correlates with higher loss fraction, and higher diffusion coefficient as well as smaller $\Delta r_{w.}$ (qas2_40, qas4_40)

* Low diffusion coefficient can be linked to high loss fraction of thermal ions if Δr_w is small.

* Qas2_20 and comparable tokamak qas_00 have similar loss fractions and D.

* φ_{edge}, Δr_w for tok0 are smaller than qas_00, so that tok0 confines particles less well.

* Future work:

- Obtain edge poloidal flux and $<\Delta r_w>_\varphi$ for these cases

- Compare to equivalent tokamak with qas2_20 q(r)

- Compare D's with other Mynick GC3 cases

Neutral Beam Ion Energy (Particle) Loss during τ_{sl} for QAS2_20

$\nu / \nu_{\varepsilon} = 1$

	with pitchangle scattering	$\nu_{pa} = 0$	Bz = 28kG
rtan = 130cm	21 (39)%	0.4 (0.4)%	6 (11)%
rtan = 34cm	72 (88)%	4 (4)	
rtan = -34cm	88 (96)%	53 (57)	
rtan = -130cm	47 (70)%	0.4 (0.4)	

* QAS_00 has 9 (18)%

* Effect of collisions doubles loss rate for perpendicular injection

* Best confinement for parallel, coinjection, low Zeff

* Doubling toroidal field from 14kG to 28 kG greatly reduces loss

* ν = 17/sec, ν_{ε}= 17/sec, τ_{sl} = 0.06 sec for Ne = $3 \times 10^{13}/cm^3$, Zeff=2.5, E = 50kev, NRL formulary

* $\nu_{pa} = \nu / 2$

* Losses x2 higher than equivalent tokamak losses are found for rtan = 130cm

Neutral Beam Ion Loss during τ_{sl} for QAS2_20

$$\nu / \nu_{\varepsilon} = 1/2$$

	with pitchangle scattering	no collisions
rtan = 130cm	10%	0%
rtan = 34cm	48%	2
rtan = -34cm	73%	29
rtan = -130cm	35%	2

* 40kev beam ions

* Effect of collisions more than doubles loss rate for perpendicular injection

* Best confinement for parallel, coinjection, low Zeff

* These collision rates correspond to PBX-M best shot,

  with Ne(0) = 4×10^{13}, Zeff =2.7, E= 40kev
  - Expect lower losses than for $\nu / \nu_{\varepsilon} = 1$

* ν = 34/sec, ν_{ε}= 66/sec, τ_{sl} = 0.015sec
  - $\nu_{pa} = \nu / 2$, so $\nu_{pa}/\nu_{\varepsilon} = 1/4$

Neutral Beam Ion Loss during τ_{sl} for Stellarator Designs of PBX-M Size

$\nu / \nu_\varepsilon = 1$

Percentage Energy (Particle) Loss

qas2_20	21 (39)%
qas2_40	35 (62)%
qas3b	19 (38)%
qas4_40	28 (52)%
qas_00	9 (18)%

* All simulations for tangency radius = 130cm, parallel coinjection.

* Find lowest beam ion losses in qas2_20 and qas3b,
  - Similar to best thermal ion loss rates

* Collision frequencies were 17/sec for both ν and ν_ε
  - Based on 50KeV beams, $3 \times 10^{13}/cm^3$ density, Zeff 2.5.

* For $\nu / \nu_\varepsilon = 1$
  Loss is double that of equivalent tokamak

* Losses from ripple wells and scattering into bad orbits

Alpha Particle Simulations

* Based on QAS2_20 scaled to reactor size

* R_maj = 4.53 m, B = 79 kG, $N\alpha=(1-(r/a)^2)^9$,
  $\langle N_e \rangle=2.3\times10^{14}/cm^3$, $N_{eo} = 4.7\times10^{14}/cm^3$,
  Te=25keV, <a>=2.2m, Zeff=2
  ν_{pa}/ν_ε =.07, ν =1.03/sec, ν_ε= 7.6/sec, τ_ε=0.13sec

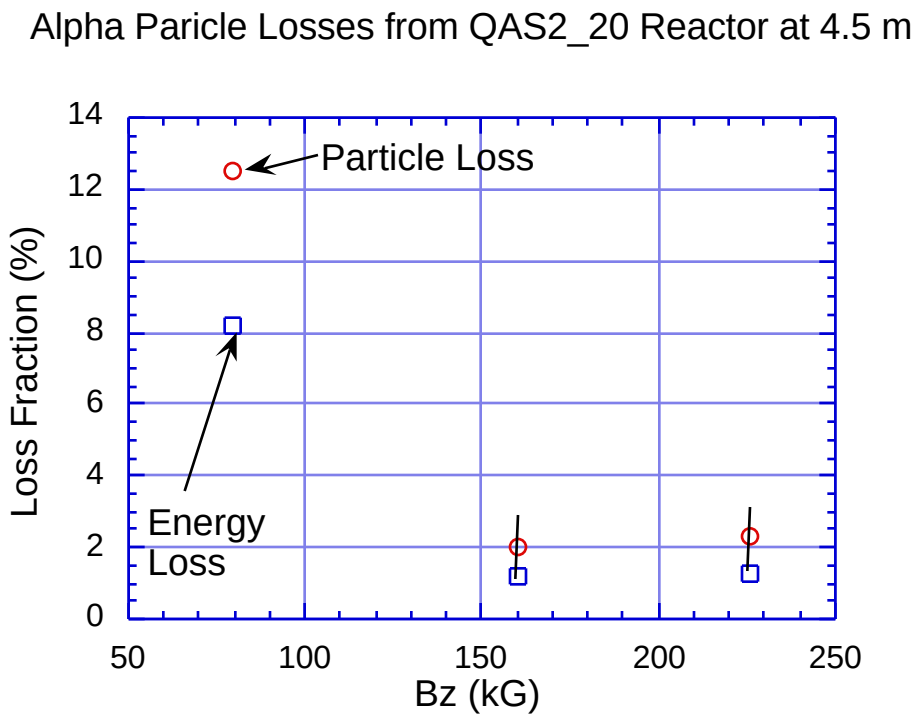
* Excellent confinement without pitch angle scattering:
  0.8% +/- 0.4% alpha particles lost in τ_ε

*** But collisions (pitch angle scattering) lead to 8 (12.5)% alpha energy (particle) loss in τ_ε**

* Simulations of alpha loss in a comparable tokamak reactor, without TF ripple
  - showed no alpha loss arising from pitch angle scattering over one slowing down time.

* The stellarator alpha losses may be due primarily to ripple wells,
  - not to low edge poloidal flux (trapped ions being ~30%)

* Increasing B to 160kG leads to
  1 (2)% alpha energy (particle) loss in τ_ε



5% alpha heating loss at 90 kG =BT

Conclusions- Energetic Particle Confinement

* STELL code

- Enhanced by thermal diffusion coefficient diagnostics.

  - Benchmarked for thermal ions against Mynick GC3 code for qas2_20

  - Several magnetic geometries investigated

  - Thermal ion diffusion coefficient of qas2_20 and qas3b are similar to equivalent tokamak

* NCSX neutral beam ion simulations based on PBX-M best shot

  - 40 Kev, qas2_20, R_maj = 1.45 m, B = 14 kG

  - Parallel co-injection and low Z_eff are required for the lowest particle and power loss

* Neutral beam ion loss is lowest for qas2_20 and qas3b,

  - Still too high
  2-3x losses of a comparable tokamak

* **Reduction of alpha loss (8% in qas2_20 reactor)**
  through reduced ripple wells :high priority

* Plans for future work - see talk by M. Zarnstorff tomorrow