Helical RFP's –Analysis Using Stellarator Tools

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ReNew Workshop; Theme V
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NESCOIL: P. Merkel, M. Drevlak, Greifswald

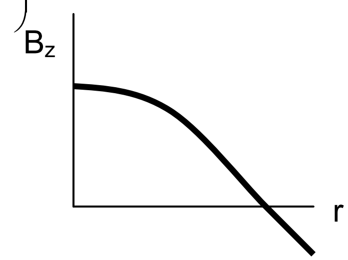
Helical RFP - good properties - sustainment?

- In axisymmetry, a reversal in B_ϕ cannot be maintained by a V_t

eg. Cylinder, force-free $\mu_0 \boldsymbol{J} = k\boldsymbol{B}$, current profile $k(r,t)$

determined by Ohm's law along **B:** $k(r,t) = \dfrac{\mu_0}{\eta B^2}\left(\dfrac{V_p}{2\pi r}B_\theta + \dfrac{V_t}{2\pi R}B_z\right)$

$dB_z/dr = -kB_\theta \;\Rightarrow\; k \neq 0$ where B_z passes through zero



- A poloidal loop voltage works, but only transiently
- A toroidal loop voltage V_t plus a helical magnetic field can work, as understood by Ohkawa (1980).
- SHA configurations observed to have good transport properties
- Numerical tools developed for stellarators useful for helical RFP's

VMEC as a tool for exploring helical RFP's

- Input profiles are EITHER

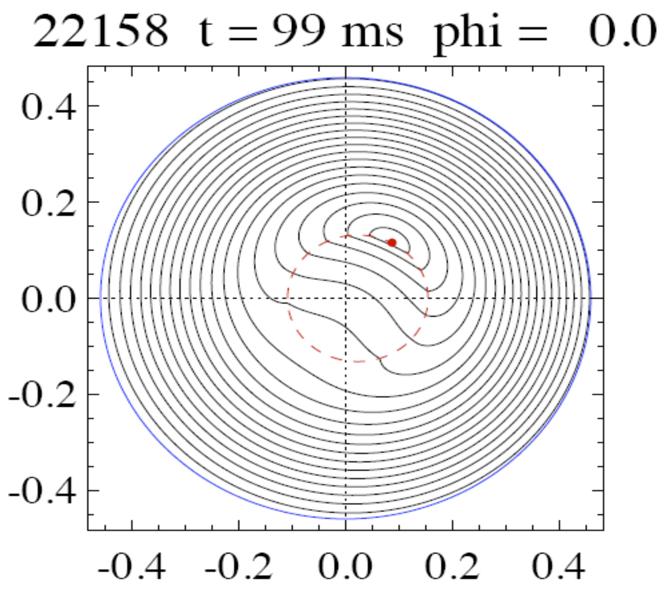
  p(s) and ι(s) (iota = 1/q) OR

  p(s) and k_0(s) where $k_0 = \langle J \cdot B \rangle / \langle B \cdot B \rangle |_{p=0} = I'$ AND

  outer boundary shape if running "fixed boundary", or external fields from coils if running "free boundary"

- Also need initial guess (typically crude) for ψ (R,ϕ,Z)
- Radial variable, s, is normalized toroidal flux ⇒ field reversal with standard version impossible, however fix is simple (Hirshman)
- Output is ψ (R,ϕ,Z) and k(s) OR ψ (R,ϕ,Z) and ι(s)
- VMEC assumes "good" flux surfaces, so must generate singular currents to shield out any islands that may be present

VMEC – applied to model of RFX SHA x



⇐ RFX SHA x reconstruction

From "Helical equilibria for SHAx states", Emilio Martines, 3 Feb 2009

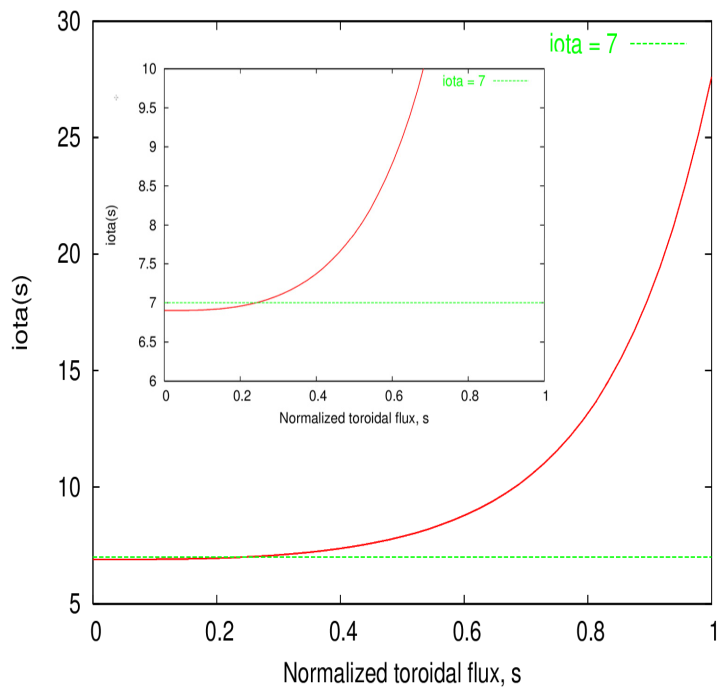
~12 cm helical shift of mag. axis

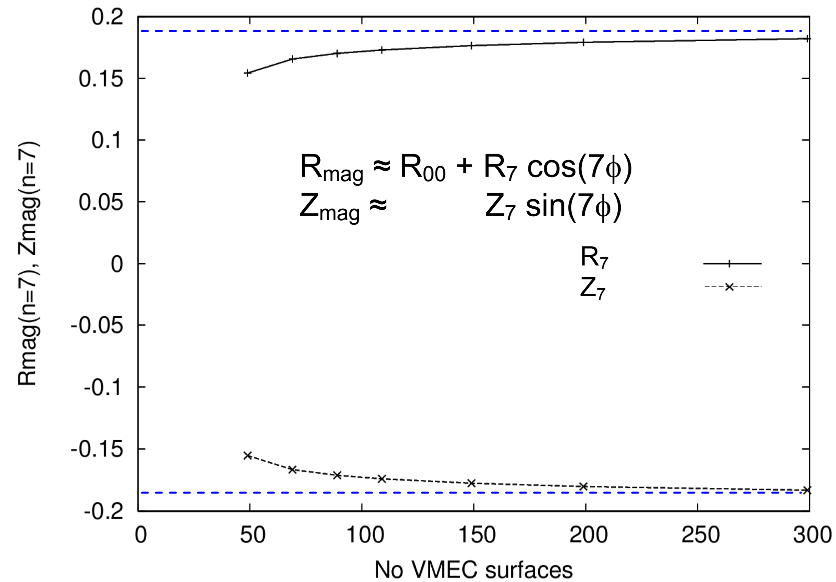
Can VMEC produce such a state assuming fixed, axisymmetric outer boundary? YES

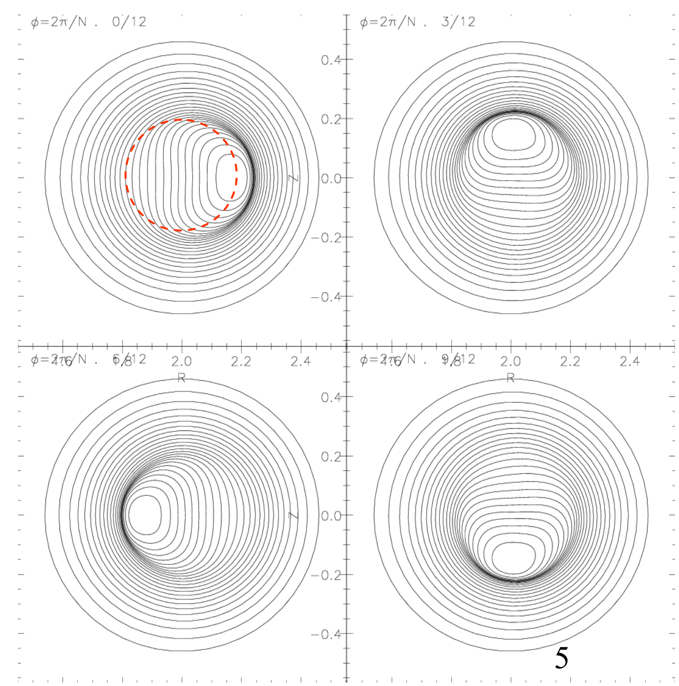
$R = R_0 + a \cos(\theta)$, $Z = a \sin(\theta)$
$R_0 = 2.00$m, $a = 0.46$m

Assume monotonic $\iota(s)$ with rational ι=7 at $r/a \approx 0.5$ ($s = 0.24$); $p(s)$ linear in s

VMEC input ι and convergence of mag axis







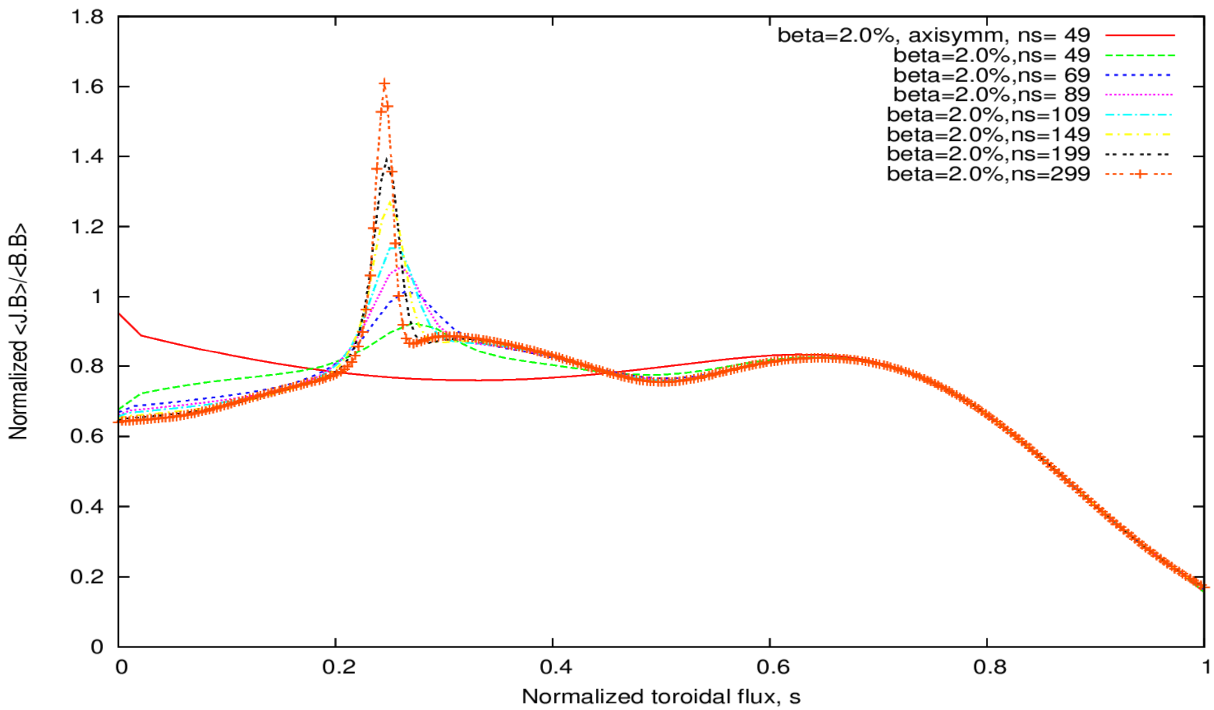
For given profiles, and β = 2%, convergence to helical axis with shift ~18cm

Final state robust to numerics

Axis shift depends on β and ι'

VMEC equilibrium k(s) profile

- essentially axisymmetric in outer region s>0.7 !!

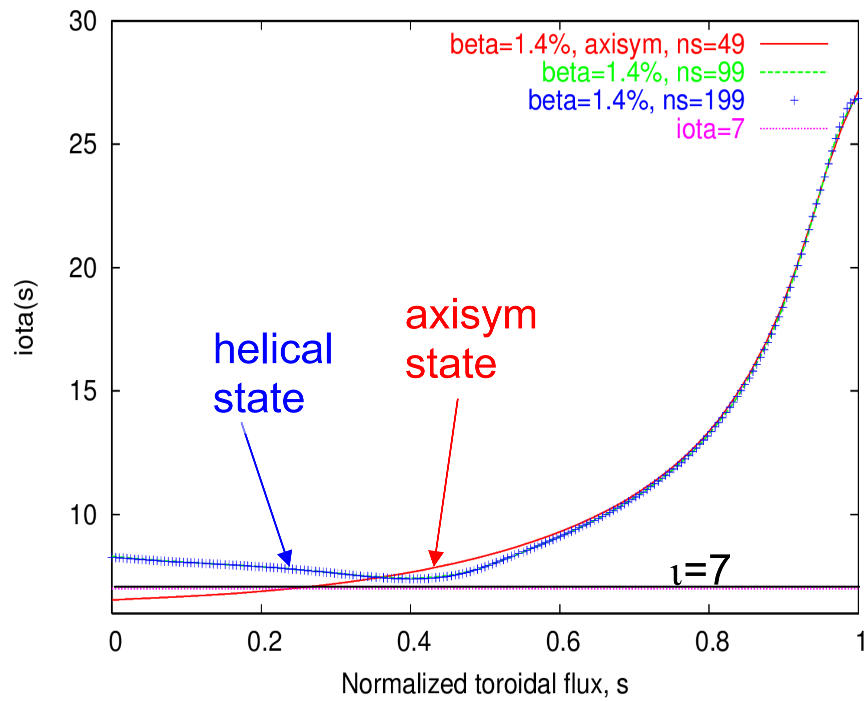


- Recall - axisymmetric systems are not compatible with a toroidal loop voltage supporting the plasma current $\Rightarrow$ edge region problematic
- So consider allowing the whole plasma current to be helical, rather than trying to maintain the plasma boundary axisymmetric?

Similar story if supply initial k(s) profile

- Choose $k_0(s)$ to approx “fit” the k(s) output from previous case, but interpolating through peak at rational surface

- Adjust I_p so that ι=7 at s ≈ 0.24 for axisym equilibrium, as before.



•3D helical states are formed, as before

•Now iota profile is modified by VMEC to AVOID passing through ι=7

•Again, little change (in $\iota(s)$) from axisym profile for s > 0.7 (r/a > 0.84)

Use of helical fields to allow a long-pulse RFP

Phys Plas. 16, 022507 (2009) – current issue (Feb)

- Impose helical wobble of magnetic axis by applying external helical field, providing transform for reducing the required k
- The helical field that reduces the required k is non-resonant, so good magnetic surfaces can be maintained

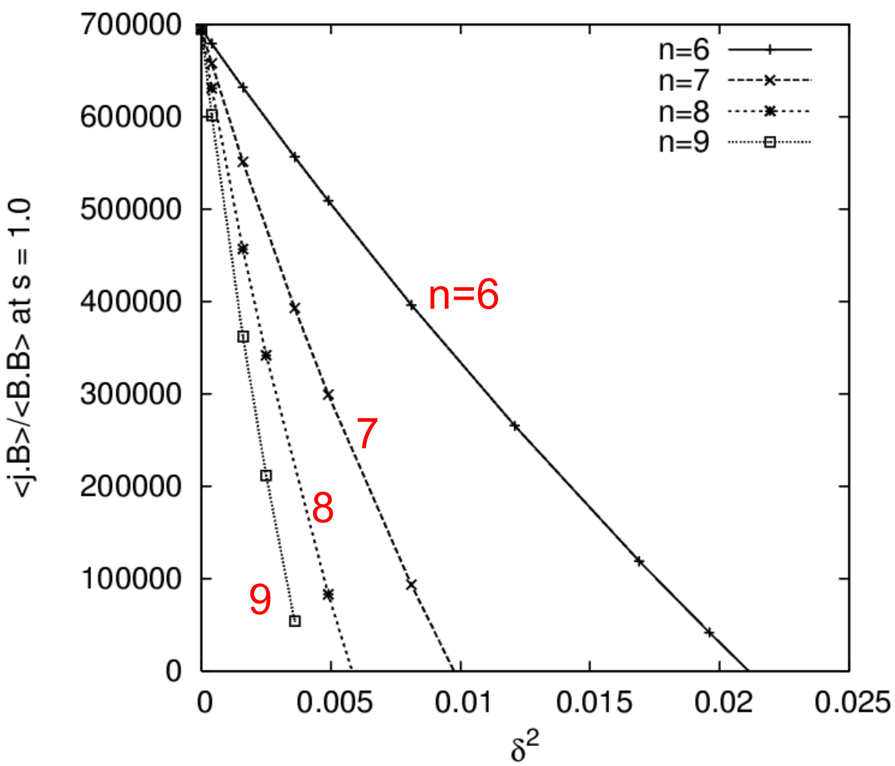
Assume fixed outer boundary shape with helical wobble of periodicity n

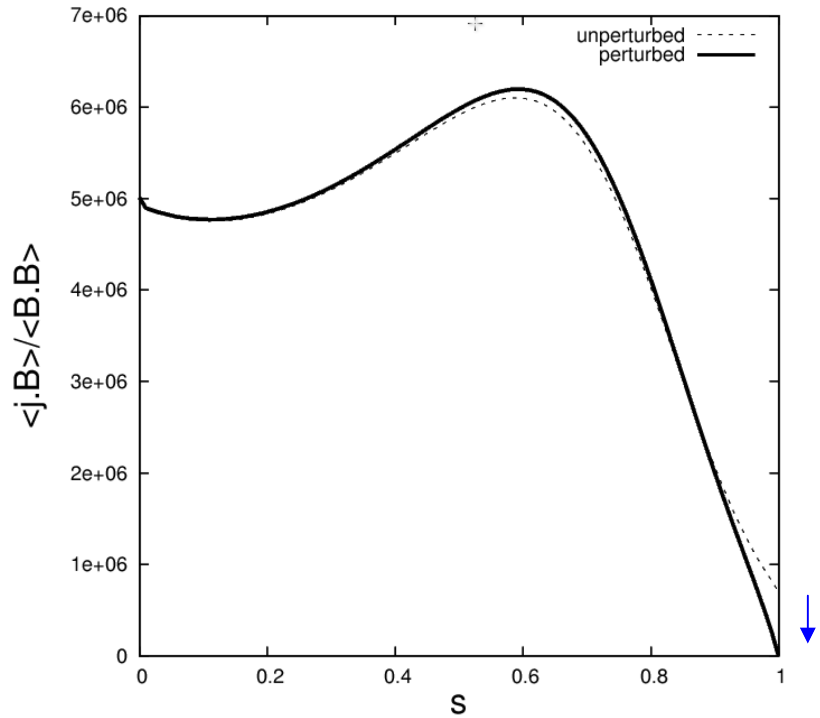
$$R(\theta,\phi) = R_{00} + a\cos\theta + \delta\cos n\phi, \quad Z(\theta,\phi) = a\sin\theta + \delta\sin n\phi;$$ R_{00} = 2.00m, a = 0.46m

- Vary helical boundary wobble amplitude, δ, until

$$k = \mu_0 \frac{<J\cdot B>}{<B\cdot B>} = \frac{\mu_0}{\eta B^2}\frac{V_t}{2\pi R}B_\phi = 0$$ at plasma edge, consistent with a current that can be maintained by a spatially constant V_t

VMEC Results – Required Helical Wobble





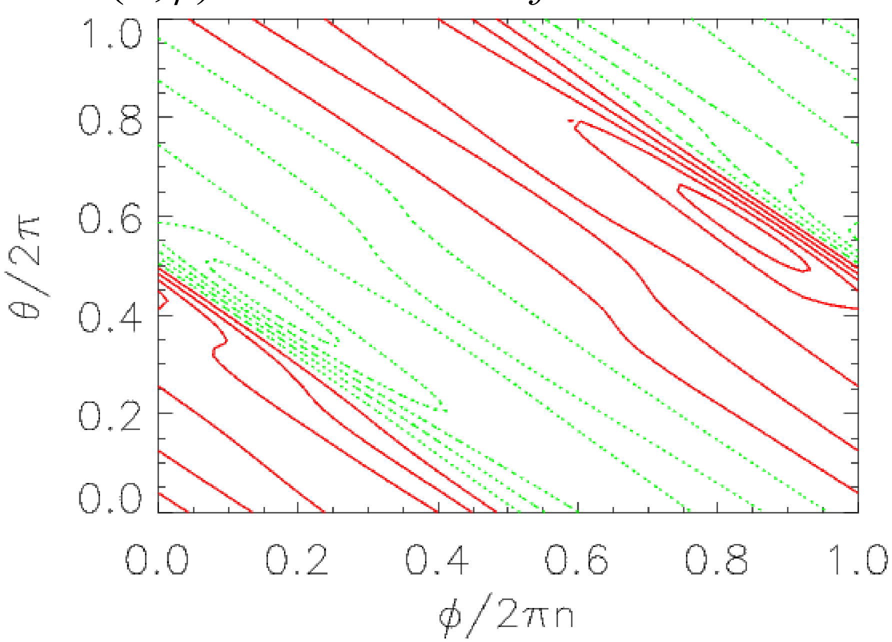
- Parallel current k(s) reduced at plasma edge as helical wobble is increased
- Approx scaling $\Delta k(1) = n^4 \delta^2$

To determine the helical field coils must provide, use stellarator design tool NESCOIL (P. Merkel et al, Greifswald)

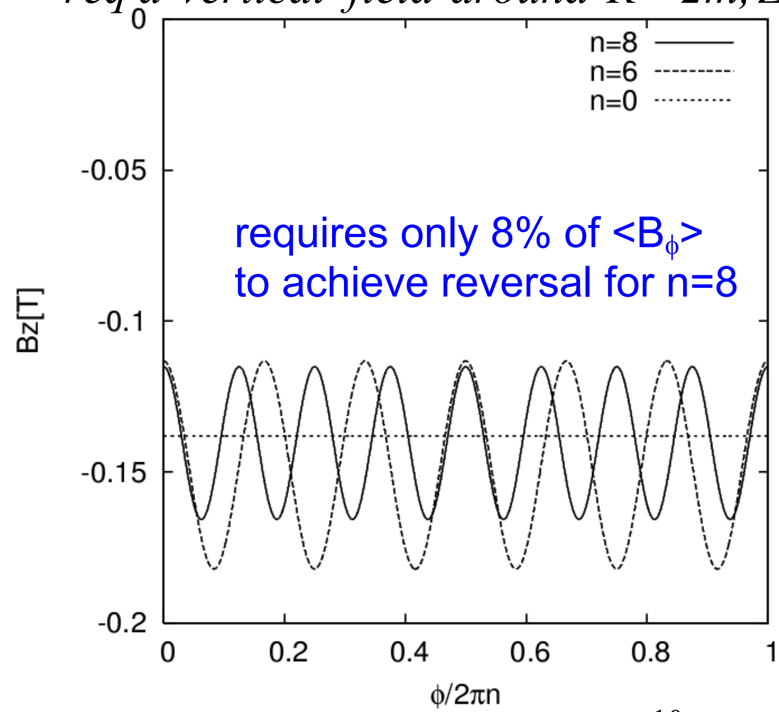
NESCOIL results- Required Vertical Field from saddle coils on RFX

- NESCOIL determines the current distribution on a chosen coil surface s.t. the B_n from this distribution matches B_n from the plasma at the plasma boundary. $\boldsymbol{j} = \delta(r - r_c)\nabla r \times \nabla \kappa(\theta,\phi)$

$\kappa(\theta,\phi)$ *over* $1/8$ *torus for* $n = 8$ *wobble*



req'd vertical field around $R = 2m, Z = 0m$



RFX experiments

- RFX saddle coils can produce 0.04T of (n=8,m=1) helical field
- Experimental exploration of whether a toroidal loop voltage can maintain quiescent plasmas is within the RFX capability
- Preliminary experiments have commenced (March 2009), more are planned

Conclusions

- Stellarator tools can contribute to analysis of SH states in RFP's and model potentially useful experiments
- Only a weak helical field is required to make k(r) zero at the edge so a spatially constant loop voltage can maintain an RFP
- RFX has already (this month) performed preliminary experiments applying m=1,n=7 fields (so far, after q reversal) and will continue.
- The external field can (future) be chosen to ensure good neoclassical confinement (quasi-axisymmetry)
- The external helical + axisymmetric shaping fields can be optimized for MHD stability
- STELLOPT can be used as an optimization tool for RFP's