Alpha particle confinement in the European DEMO

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September 1st, 2015
Motivation

In the refinement of the European DEMO design
- integrate knowledge from existing machines (JT60-SA, etc.) + ITER
- take into account wide range of tokamak related phenomena
- compromise/trade-offs but also opportunity for optimisation

Fusion alpha particles
- assess/verify confinement in current coil design
- special focus on magnetic ripple created by the 18 TF coils
- application of modelling capabilities:
  - Coil.Sphell (vacuum fields, Biot-Savart) [Cooper et al., 2004]
  - VMEC (3D MHD equilibrium) [Hirshman and Whitson, 1983]
  - VENUS–LEVIS (orbit solver, Monte-Carlo code) [Pfefferlé et al., 2014]
Motivation

Modelling approach and work flow

description of TF and PF coils (current filaments)

Coil.Sphell (Biot-Savart) → 3D vacuum fields

VMEC (free-boundary MHD) → background profiles $n(s), T(s), j_\phi(s)$

VENUS-LEVIS (orbit-code) → saturated alpha particle distribution, losses, etc.

code input files intermediate result final result

D.Pfefferlé (CRPP-PPPL) DEMO alphas, 14th IAEA September 1st, 2015
Outline

1. Coils, plasma and ripple: two contrasting models to represent 3D stationary fields
   - Vacuum ripple field + 2D plasma model
   - 3D ideal MHD equilibrium model

2. Dynamics of ripple perturbed orbits
   - Ripple well trapping and separatrix crossing
   - Stochastic diffusion of bounce tips

3. Fusion alpha confinement
   - Slowing-down simulations
   - Lost particles, loss rates
Single-null diverted plasma:
\[ R_0 = 9.25 \text{m}, \; a = 2.9 \text{m}, \; B_0 = 6 \text{T}, \]
\[ I_p = 19.6 \text{MA}, \; V = 2145 \text{m}^3, \; \beta = 2.2\% \]
Coil-Sphell calculation of 3D vacuum field and ripple

\[ \delta B_{\phi} \approx \delta (R, Z) \cos(N\phi)B_{\phi} \]

[Yushmanov, 1990; McClements, 2005]

\[ \delta(R, Z) \sim J_N(\alpha R) \cosh(\alpha Z) \propto (\alpha R)^N \]
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Magnetic ripple from TF coils

- permanent/fixed source of non-axisymmetric fields
- can be reduced using ferritic inserts (FI)
- no large magnetic islands nor stochasticity when added to 2D plasma (response neglected):
  minimal detachment of field-lines from flux-surfaces (high-n mode, small resonances at rational $q$, low shear)

\[
\rho_{tor} = \sqrt{\Phi_N}
\]

Poincaré plot of field-lines at $18\phi/2\pi = 0.57$
Input profiles in VMEC

- SOF profiles $j_{tor}$, $n_e$, $n_i$, $T_e$, $T_i$, $P = \sum n_j T_j$ (ions: $50\%$D, $50\%$T)
  1. at 19.6MA with $q_{edge} = 3.2$
  2. at 16.6MA with $q_{edge} = 4.9$
3D MHD equilibrium with free-boundary VMEC

- 3D MHD plasma response with nested flux-surfaces: no islands nor stochasticity
- fine-tuning of PF coil currents, sensitive results to changes in current profile (q-profile)

ripple included in 3D geometry, deformations of LCFS < 1 cm

enhanced displacement

$200 \times (R_{3D} - R_{2D})$
3D MHD ripple from VMEC is similar to vacuum field

- high-n and non-resonant perturbation ⇒ identical ripple field as vacuum model
  (unlike previous work on RMPs [Pfefferlé et al., 2015])

\[
B_{3D} - B_{2D} \text{ at } (R,Z)=(11.5,0)
\]

\[
\frac{\delta B}{B} \%
\]

\[
\frac{\delta B}{\delta B_{\phi} \delta B_{R} \delta B_{Z}}
\]
Effect of ripple on energetic ion orbits (collisionlessly)

- **Axisymmetry** ⇒ GC motion is integrable by virtue of $E$, $\mu$ and $P_\phi$ being CoM ⇒ drift-surfaces
- **Magnetic ripple spoils conservation of** $P_\phi$
  - passing not important as long as no magnetic islands nor stochasticity
  - trapped significant effect on bounce tips (stochastisation)

\[\text{axisymmetric}\]
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Dynamics of ripple perturbed orbits

Ripple wells and separatrix crossing in DEMO

**modulus of \(|B|\) along field-line**

- **2D**
- **2D+vac**
- **ripple**

Criterion for existence of local wells:
\[ \delta > \left| \frac{\partial_\theta B}{B N q} \right| \approx \varepsilon \left| \sin \theta_b \right| / N q \]

- particles with \(v_\parallel < \sqrt{\delta}\) can become trapped
- \(\nabla B\)-drift leads to rapid vertical motion (downward)
- de-trapping, separatrix crossing
  - [Yushmanov, 1990; Cary et al., 1988]
- geometry, elongation, tear-drop shape and up-down asymmetry helps
- collisions \(\Rightarrow\) enhanced diffusive transport (superbanana)
  - [Yushmanov, 1983; Mynick, 1986]
DEM0 ripple well domain such that 
\[ \delta > \delta_w = \left| \frac{\partial \theta B}{BNq} \right| \]

numerical evaluation (VENUS-LEVIS) of bounce tip displacement
Resonant/stochastic motion of bounce tips in DEMO (low)

precession/bounce resonances
Resonant/stochastic motion of bounce tips in DEMO (low)

- approximate criterion of stochastic threshold [Goldston et al., 1981]
  \[ \delta > \delta_{GWB} = \left( \frac{\epsilon}{N \pi q} \right)^{3/2} \frac{1}{\rho_L q'} \]

  but \( \delta_{GWB} \) too low [White et al., 1996]

- resonances are bound by KAM layers \( \Rightarrow \) limited vertical motion

- collisions \( \Rightarrow \) resonance regime [Yushmanov, 1983]

- difficult to evaluate, depends on geometry and orbit effects \( \Rightarrow \) accurate orbit solver
Fusion alpha confinement

Slowing-down simulations

- Initial distribution of 3.5MeV $^4_2$He, isotropic in $\nu/\nu$,
  \[ R(\mathbf{x}) = n_D n_T <\sigma v>_M \quad [\text{Bosch and Hale, 1992}] \]
- Non-canonical guiding-centre equations [Littlejohn, 1983]
- Slowing-down and pitch MC operators [Boozer and Kuo-Petravic, 1981]

Graph showing fusion alpha density

$$P_\alpha [\text{MW/m}^3]$$

$$\rho_{\text{tor}} = \sqrt{\Phi_N}$$

$$Z [\text{m}]$$

$$R [\text{m}]$$
Confined versus lost fusion alphas

- prompt and ripple loss regions are far away from core fusion power ⇒ good confinement
- ripple causes losses at specific toroidal locations

lost particles at LCFS in 2D+vac ripple model

19.6MA plasma

fusion density and birth regions of

lost particles
Phenomenology of losses

- Quantitative match between 2D+vacuum and 3D ripple models
- Losses are enhanced by ripple, order of magnitude larger (resonance/stochastic regime)
- Losses peak at energy range 100 – 200 KeV (superbanana regime), pitch-angle scattering increases well trapping ⇒ Helium ash removal
**Lost particle velocity-space**

- **axisymmetric case**
  - Lost population in axisymmetric case consists of barely trapped particles.
- **3D equilibrium**
  - Ripple significantly enhances deeply-trapped particles losses \( (v_\parallel \sim 0, \text{ superbanana transport}) \)
Disagreement between ripple models of toroidal position of losses through LCFS

- field-lines have different nature
- 2D+vac separation from flux-surfaces
- equilibrium 3D deformation of nested field-lines
- behaviour outside plasma up to wall?
Conclusions

- numerical simulation and theoretical considerations indicate that fusion alpha confinement in the European DEMO is **good**
- ripple does enhance losses via known diffusive and non-diffusive mechanisms, **superbanana** transport being dominant
- stochastic ripple diffusion is **difficult to predict**, but **threshold is higher** than expected

Coils, plasma and ripple

- \( \delta_{max} \propto 0.76^N \) implies that increasing \( N = 18 \rightarrow 20 \) will not make a **significant difference** (having \( N \) odd would reduce resonances)
- re-positioning of wall or adding ferritic inserts should be considered instead
- unlike RMPs, **minimal difference** between 2D+vacuum and 3D plasma response model \( \Rightarrow \) **reliability** of analytic calculations and scaling laws
Conclusions (2)

Numerical results
- integrated modelling exercise: realistic vacuum fields, consistent MHD equilibrium and accurate fusion alpha orbits
- benchmarks against ASCOT are underway (2D+vacuum model)

Limitations and questions for future work
- losses evaluated at LCFS, re-entry orbits neglected, not exact wall loads (toroidal position) ⇒ extension in progress
- results sensitive to input profiles, plasma shape and position relative to ripple field (control and scenario problem)
- NBI fast ions may have wider radial distribution
- toroidal flow is neglected (no radial electric field)
- cyclotron resonance with ripple not considered: in principle negligible effect (mostly passing-particles), full-orbit simulations envisaged
Thank you for your attention

Questions?
Comparison between 19MA and 16MA case \((q_{edge})\)

Same density, temperature, pressure and current profiles / varying total plasma current and PF coils.

- orbit width \(\Delta \propto \varepsilon^{1/2} v/\Omega_\theta \sim q\rho L \varepsilon^{-1/2}\)
  \(\Rightarrow\) more prompt losses in 16MA case
- lower ratio between ripple and 2D losses


H. Mynick, Nuclear Fusion 26, 491 (1986).
Bibliography II


