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VERTICAL STABILITY REQUIREMENTS FOR ARIES-I REACTOR

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ABSTRACT: The vertical stability of the ARIES-I reactor design is analyzed with the NOVA-W, PSTAB, and TSC codes. A growth rate of $\sim 5.7 \times 10^{-1}$ is predicted for a vacuum vessel positioned behind the scrapeoff, first wall, and blanket (0.7 in inboard and 0.9 in outboard thickness) and acting as a passive stabilizer. A reactive power of $\sim 2 \text{ MW}$ would be required for active feedback coils located outside of the TF coils $\sim 3 \text{ m}$ beyond the plasma in the equatorial plane) to correct a 50-mm vertical displacement of the magnetic axis. A multipolar expansion technique used in the TSC analysis is also used to examine options that minimize stored energy.

I. INTRODUCTION

The ARIES-I tokamak reactor design¹ minimizes the cost of electricity (COE) by minimizing the plasma current and the associated current-drive cost. The resulting low beta ($\beta \sim 0.02$) device² is characterized by a large safety factor ($q_{95} \sim 4$), moderate-to-high aspect ratio ($A \geq 4.5$), high field (2.4 T at the toroidal-field (TF) coils), and separatrix high elongation ($\kappa_r = 1.8$). The large A and κ make vertical stability an important issue for ARIES-I; related issues that must be addressed by the ARIES-I conceptual design are outlined below. A toroidally continuous conducting shell is required to retard the growth of an externally excited vertical instability that range from an Alfvén time scale $\tau_A \sim \mu\text{s}$ without a shell to a time scale on the order of the electrical LR time constant of the shell, $\tau_{L/R}$. The passive stabilization provided by this shell must be augmented by an active feedback system that provides vertical stability for times $\gtrsim \tau_{L/R}$. A rigid-plasma model (PSTAB)³ and linear (NOVA-W)⁴ and non-linear (TSC)⁵ deformable plasma models are used to estimate the location and size of the passive stabilizer. Time-dependent TSC simulations are used to determine the current, voltage, location and size of the feedback coils.

The placement of the ARIES-I poloidal field (PF) coils external to the TF coils permits the use of a multipolar expansion technique^{6,7} to describe accurately the PF coil fields used in TSC computations. Limiting the multipolar expansion to hexapole and lower moments minimizes the number of dependent variables required to describe the plasma shape. Using the multipolar expansion technique to examine plasma equilibria parametrically for a range of κ and triangularity, δ , values resulted in a prescription for minimizing the PF coil stored energy, W_{PF} , that is used in the ARIES-I systems code.

II. MULTIPOLAR APPROACH

The TSC code was modified so that the poloidal flux produced by a PF coil set could be determined either by specifying the PF-coil locations and currents or by specifying the amplitudes of the even and odd moments in the multipolar expansion series⁸ that is truncated beyond the even decapole. In addition, TSC was modified to perform the inverse operation of decomposing the poloidal flux produced by a PF-coil set into the multipolar components of the same truncated series. The TSC code was then used to analyze parametrically the equilibrium of an $A = 4.5$ and $\kappa_r = 2.13$ interim design point. Because the PF coils are relatively far from the plasma, the multipolar expansion could be limited to hexapole and lower moments, thereby reducing the number of variables. The plasma current, toroidal field, profile factors, major and minor radii, and the nullapole and dipole moments were held fixed at the interim design values, which differ somewhat from those reported in Ref. 2. The ratio of the hexapole to quadrupole amplitudes was selected as the dependent variable. The absolute magnitudes of these

amplitudes were determined as the minimum amplitudes that produced a separatrix with the specified minor radius. This algorithm, subsequently, generates a set of plasma equilibria that are produced with a minimum PF-coil current $\sum |I_{PF}|$ and a minimum W_{PF} . Because plasma elongation and triangularity are produced primarily by the quadrupole and hexapole moments, respectively, this algorithm yields the δ that minimizes W_{PF} for a given κ , as is shown in Fig. 1. Plasmas below the δ - κ correlation of Fig. 1 would not have a separatrix, and those above the correlation would either have a smaller minor radius (smaller A) or require higher multipolar moments and larger W_{PF} to maintain the same minor radius. This analysis also produced a correlation between W_{PF} and κ that indicates W_{PF} increase as κ decreased (δ increased). This W_{PF} - κ correlation did not have a significant impact on determining the final design values² of κ and δ , however.

Fig. 1. The correlation between plasma triangularity and elongation, that minimizes the PF coil stored energy for $A = 4.5$ (solid) and $A = 6$ (dash).

To pursue further the issue of minimizing W_{PF} , a code FLXCON was developed to determine the locations and currents of a PF-coil set that would reproduce the flux pattern of a given set of multipolar moments. The FLXCON code moves the coils along a specified surface while minimizing an object function defined as the sum of a term measuring the relative error with which the coils reproduce the flux of the given set of multipolar moments on a test surface representative of the plasma surface and a term measuring W_{PF} . To illustrate the use of FLXCON, an HEQ generated equilibrium⁹ for $A = 4.5$ ($R_0 = 6.12 \text{ m}$ and $a = 1.36 \text{ m}$) and $\kappa_r = 1.71$ was modeled with TSC using the same set of 12 PF coils with 6 current groups; the HEQ and TSC results are given for comparison in Table I. The small differences in R_0 , a , and κ_r between the HEQ and TSC results are directly attributable to numerical inaccuracy in both codes. The multipolar decomposition of the PF-coil flux was used to generate three sets of six PF coils and six current groups labeled DEC, OCT, and HEX in Table I to denote the maximum multipolar moment used. As the higher moments are eliminated $\sum |I_{PF}|$ decreases as expected, but W_{PF} is lower only for the HEX case. The plasma shape, however, drifts from the base shape because the higher moments were used inefficiently to suppress κ and provide additional triangularity. A more efficient

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method to generate the same plasma shape would require less quadrupole and more hexapole, and will be used in the future.

TABLE I
Equilibria Comparison with Different Multipolar Moments

	HEQ ^(a)	BASE ^(b)	DEC ^(b)	OCT ^(b)	HEX ^(b)
Major Radius, R_T (m)	6.12	6.12	6.12	6.13	6.13
Minor Radius, a (m)	1.36	1.35	1.35	1.34	1.34
Magnetic Axis, R_T (m)	6.33	6.355	6.358	6.358	6.34
Elongation					
κ_x	1.75	1.73	1.68	1.70	1.84
κ_{95}	1.58	1.59	1.55	1.56	1.67
Triangularity					
δ_x	0.74	0.77	0.75	0.68	0.46
δ_{95}	0.48	0.50	0.49	0.47	0.36
Separatrix Coordinates (m)					
R_s	5.11	5.12	5.14	5.25	5.51
z_s	2.38	2.39	2.31	2.32	2.53
Beta					
Total, β (%)	1.84	1.86	1.94	1.98	1.86
Poloidal, β_p	1.85	1.77	1.78	1.78	1.74
Plasma Volume (m^3)	347.348	337.329	343		
Safety Factor					
$q(0)$	1.59	1.59	1.54	1.50	1.58
$q(a)$	7.84	7.02	6.46	6.19	6.52
Current, $\sum I_{PF} $ (MA)	142.142	114.111	82		
Stored Energy, W_{PF} (GJ)	7.57	7.57	7.78	8.10	6.80

(a) PF-coil flux determined by coils.

(b) PF-coil flux determined by truncated multipolar-expansion series

III. PASSIVE STABILIZATION

Without passive stabilization the plasma will move vertically on an Alfvén time scale ($\leq 10 \mu s$). The placement of passive conductors around the plasma will slow this vertical motion sufficiently to allow an active feedback systems operate on a longer time scale ($\geq 100 ms$) to control the vertical position of the plasma with a reasonable expenditure of reactive power ($\leq 10 MW$). To simplify the ARIES-I design the only passive conductor is the vacuum vessel. The radial location of the vacuum vessel is then determined from compliance with a passive stability constraint in conjunction with other assembly and maintenance requirements.⁹ Passive stability performance is measured by the stability parameter $f \approx 1 + \tau_v / \tau_{I, H}$, where $\tau_v = \gamma^{-1}$ is the vertical instability time constant and γ is the growth rate. A design constraint of $f \geq 1.3$ is adopted to ensure that a sufficient stability margin exists above the $\gamma = \infty$ limit under all plasma conditions.

A preliminary analysis of the maximum allowable distance permitted between the plasma and the vacuum vessel for passive stability was performed with the PSTAB code. The PSTAB formulation assumes the plasma is a massless, rigid body simulated by an array of filamentary current elements. The equations describing a small vertical displacement in the presence of an array of resistive filamental conductors simulating the passive stabilizer are linearized and solved as an eigenvalue problem.¹

The notation used to describe the location of the passive stabilizer relative to the plasma is shown in Fig. 2. The plasma surface is assumed to be given by $z = a \kappa \sin \theta$ and $R = R_T + a \cos(\theta + A \sin \theta)$, where $R_T = 6 m$ is the major radius, $a = 1 m$ is the minor radius, $\kappa = 2$, and $A = 0.5$, and the angle θ varies from 0 to 2π . The passive stabilizer is placed on a surface parallel to the plasma surface. The poloidal coverage, p/a , and the normalized radial location, c/a , of a passive outboard stabilizer were varied for $A = 0.5$; results are shown in Fig. 3. Relatively small passive stabilizers ($p/a \sim 0.2$) meet the stability constraint, but these conductors must be located close to the plasma ($c/a \sim 1.1$). Such small values of c/a would have an adverse effect on tritium breeding and problems related to neutron damage and activation are expected. Placement of the passive stabilizer behind the 0.9 m-thick outboard blanket, first wall, and scrapeoff with full coverage on the outboard side does not provide sufficient stabilization (i.e., $f < 1.3$). Vertical stability and physics considerations drove the design

Fig. 2. The geometry of the plasma and the passive stabilizer (shell).

to $A = 4.5$, which turns out to be the minimum cost design,⁷ with a passive stabilizer positioned behind both 0.7-m-thick inboard and the 0.9-m-thick outboard blanket, first wall, and scrapeoff. In order to find a vertically stable design at $A = 4.5$, the elongation was varied with the passive-stabilizer geometry shown in Fig. 4; results are shown in Fig. 5. This analysis indicates that $\kappa_x \leq 1.83$ is required for a stabilizer located behind the inboard and outboard blankets.

Fig. 3. The stability parameter f versus poloidal coverage (p/a) of an outboard stabilizer for various radial locations (c/a) (Fig. 2).

Fig. 4. The geometry of the plasma and the passive stabilizer (vacuum vessel) for $A = 4.5$ and $\kappa_x = 1.74$. A similar geometry was used for the other cases in the κ parametric study. The coil locations used in the active-feedback analysis are also indicated

Fig. 5. Dependence of the stability parameter on elongation for $A = 4.5$ and stabilizer geometry shown in Fig. 4.

The accuracy of the PSTAB results was then checked by benchmarking the $\kappa_x = 1.74$ case against the TSC and NOVA-W codes. The TSC code performs time-dependent simulations of free-boundary, axisymmetric plasmas and the associated external circuits and, consequently, is more costly to use than either PSTAB or NOVA-W. A two-dimensional transport model is used in TSC to describe a plasma interacting with external conductors that obey circuit equations with active feedback amplifiers included. The plasma force balance in TSC is modified by scaling up the plasma mass and viscosity to maintain the plasma in force balance, while alleviating the time scale disparity between wave and diffusion phenomena. This parameter scaling does not affect plasma bulk motion that is stable on the ideal MHD time scale (μs), but does affect the growth rate of a vertical instability. To calculate τ_v , TSC is set up with the plasma and passive stabilizer geometry shown in Fig. 4. The PF coils are represented with a multipolar series truncated with the even decapole. The simulations begin with a radial magnetic field applied for $1 \mu s$ to produce an initial ~ 3 mm vertical displacement of the plasma. The plasma simulation is then continued until the equilibrium effects of the initial perturbation are damped out and the vertical instability asymptotically

relaxes to a linear growth rate, as reported by inboard and outboard pickup coils. Corroboration of the value of τ_v predicted from the pickup coils was obtained by fitting the vertical displacement of the magnetic axis, z_M , with the functional form $z_M(t) = z_0 e^{t/\tau_v}$. This τ_v calculation was then made for four values of plasma mass and denoted as solid squares in Fig. 6. A quadratic polynomial was fit to the three results with the largest mass enhancement factor and then extrapolated to a unity mass enhancement factor to determine the mass independent value of τ_v reported in Table II. This extrapolation is accurate as is demonstrated by the passage of the polynomial fit through the smallest mass-enhancement-factor result displayed in Fig. 6.

Fig. 6. Dependence of the vertical-stability time constant, τ_v , on plasma mass enhancement factor as calculated with TSC for $A = 4.5$, $\kappa_x = 1.74$, and the stabilizer geometry shown in Fig. 4.

This calculation was repeated with the NOVA-W code, which code is an extension of the non-variational ideal MHD code NOVA¹⁰ that allows for resistive walls and feedback circuits in the vacuum region. A Green's function is used to express perturbed poloidal flux in the vacuum region in terms of the perturbation amplitude on the plasma boundary. A thin-wall approximation is used to calculate the time derivative of the poloidal flux at the wall where a discontinuity exists flux gradient.⁴ The NOVA-W result is given in Table II. Agreement between NOVA-W and TSC is good at 3 % for τ_v and 1 % for f , but agreement between PSTAB and TSC is 24 % for τ_v and 21 % for f . The differences between PSTAB and TSC result in part from rigid-versus-deformable plasma effects and from differences in the calculation of the stabilizer inductances. Also, a 20 % difference was obtained in the PSTAB and TSC calculations of τ_L/R with a vertically asymmetric current distribution in the stabilizer.

TABLE II. Benchmark of the vertical-stability time constant, τ_v , and stability parameter, f , as calculated by PSTAB¹, NOVA W⁴, and TSC⁵ for the configuration shown in Fig. 4.

Code	τ_v (ms)	f
PSTAB	217	1.88
TSC	175	1.56
NOVA W	169	1.54

IV. ACTIVE FEEDBACK

The active feedback power requirements were determined from TSC simulations of the $A = 4.5$ and $\kappa_x = 1.74$ case used in the passive stability benchmark described in the previous section. A simulation begins with the vertical coordinates of the plasma magnetic axis, z_M , maintained in the equatorial plane for $0.1 \mu s$. The feedback coils are preprogrammed to initiate a 50 mm vertical displacement of z_M at $0.1 \mu s$ into the simulation and to maintain that position once attained. As the plasma mass does not affect the

voltage or current of the feedback coils, a large mass enhancement factor (FFAC = 8,000) was used for computational expediency. Simulation results for the Feedback Coil A shown in Fig. 4 are given in Fig. 7. A gain for driving the feedback-coil current was selected to yield a common value of $G \sim -2.6$ for the dimensionless gain defined as the ratio of the response flux difference produced by the feedback coils to the flux difference produced by the plasma in the pickup coils. The dimensionless gain must be in the range of -1 to -10 to ensure stability and practicality of the feedback system (yet to be designed). A value of $G \sim -2.6$ rapidly moves the plasma to a 50-mm displacement with only a ~ 10 -mm overshoot. The gain for driving the feedback-coil voltage is set at a low value of 1 mV/A to ensure a smooth voltage response. A pickup-coil location approximately equal to Feedback Coil B in Fig. 4 was used for Feedback Coils A and C. For Feedback Coil B a pickup-coil location corresponding approximately to the location of Feedback Coil A was used to obtain a clear resolution of the flux difference produced by the plasma.

The maximum reactive power occurs at the maximum vertical displacement of x_M and scales with x_M^2 . The reactive power requirements for the three feedback-coil locations of Fig. 4 are shown in Fig. 8 for a common 50-mm displacement of x_M . The feedback coils were simulated with a 0.1×0.1 -m cross section of room-temperature, copper alloy with a conductor filling fraction of 0.7. Feedback Coil C is preferable over the other two coil locations. This coil is positioned just outside of the TF-coil and represents the easiest coil to maintain. The $\sim 2 \text{ MVA}$ reactive power required to drive this coil is well within the 26 MJ of recirculating power set aside for miscellaneous plant needs.² Furthermore a 50-mm displacement could not be tolerated by the divertor and represents a maximum design constraint.

Fig. 7. The vertical position of the magnetic axis, x_M , and the feedback coil current and voltage versus time as calculated with TSC for $A = 4.5$, $\kappa_F = 1.74$, the stabilizer geometry shown in Fig. 4, and Feedback Coil A in Fig. 4.

Fig. 8. The vertical position of the magnetic axis, x_M , and the feedback-coil current and voltage versus time as calculated with TSC for $A = 4.5$, $\kappa_F = 1.74$, the stabilizer geometry shown in Fig. 4, and Feedback Coil A in Fig. 4.

V. CONCLUSIONS

A prescription for choosing a plasma shape that minimizes the stored energy in the PF coils. A benchmark of the PS1AB, NOVA-W, and TSC codes indicated that passive-stability analysis produced by the less-expensive found to provide suitable passive stabilization if positioned between the blanket (0.7 inboard and 0.9 m outboard thickness) and shield. The final ARIES-I equilibrium configuration⁸ has the same A as, but larger a ($\sim 1.45 \text{ m}$) and κ_F (~ 1.3) than the larger a for constant blanket, first-wall, and scrapeoff thickness will improve passive stability (i.e., raise f). However, the larger κ will exacerbate the passive-stability problem. Further analysis of the new design point is required to resolve fully the passive stability of ARIES-I. An active-feedback power of $\sim 2 \text{ MVA}$ was required to suppress a 50-mm displacement of the magnetic axis with coils positioned outside of the TF coils.

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