Design and Fabrication of a DC Feeder System of New TF Magnet Power Supply for Accelerator-Based In-Situ Materials Surveillance in Alcator C-Mod

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Design, Analysis and Fabrication of a New Magnet Power Supply System for Accelerator-Based In-Situ Materials Surveillance in Alcator C-Mod


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Advanced Plasma Material Interaction (PMI) science requires in-situ time and space-resolved measurements over a large area of Plasma Facing Component (PFC) surfaces to study fuel retention & recovery, erosion & redeposition, material mixing, etc. A novel PFC diagnostic technique Accelerator-based In-situ Materials Surveillance (AIMS) has been developed for Alcator C-Mod. At present, the AIMS diagnostic covers a relatively small 35 cm poloidal section of the inner wall PFCs at single toroidal angle; an upgrade is now underway for the toroidal and poloidal C-Mod magnet power supplies that will enable nearly full poloidal (about 124 cm) and 40 degree toroidal PFC coverage.

This paper will introduce the design, analysis and fabrication of the new magnet power supply system for this upgrade. It will cover three areas. First, the design of the busbar system and its support structures will be presented. The power supply includes power supply, bidirectional crowbar and varistor protection assemblies, and a high current bus switch. The busbar is required to carry 15 kA current for long pulse operation of up to 25 minutes. A fault condition with 400 kA for 1 second is possible. More difficult is that the layout of the busbar should not conflict with the existing magnet systems or their support structures in the densely populated power room. New support structures also need to fit. Secondly, multi-physics analyses involved in the design will be presented. Electro-magnetic analysis is required to evaluate the spreading load of the two current-carrying busbars while Joule heating analysis is needed to evaluate the temperature rise in the material. Structural analysis is necessary to guarantee that the support structures will stand the spreading load plus weight of the busbars. All analyses will be done using finite element analysis (FEA) software COMSOL, which has been successfully used in previous analyses for C-Mod. Traditional analytical calculations will also be included to validate the FEA results. Finally, the fabrication of the whole system will be described.

I. INTRODUCTION

In the tokamak Alcator C-Mod, AIMS provides advances in surface diagnostic capabilities of Plasma Facing Components (PFC). AIMS measures the effects of plasma material interactions with unprecedented temporal (a few seconds, after each shot) and spatial resolution (2 cm). Measurements are made in-situ, without vacuum break, over a large poloidal/toroidal range, and are non-destructive to material. AIMS can directly measure erosion/deposition, retention of hydrogen isotopes, migration and mixing of plasma facing materials. $^{1,2}$

The measurement range of current AIMS is 35 cm along poloidal direction at a specific toroidal angle. Ideally, it can scan up to 40 degrees toroidally and full poloidal coverage (about 124 cm) at any toroidal angle.

New magnet power supplies will dramatically improve the spatial coverage of measurements. In this paper, the technical requirements, busbar layout, and design of support structure are presented in Section II, and related multi-physics analyses are presented in Section III. Section IV summarizes the work with a brief statement on the fabrication of the power supply system.

II. DESIGN OF THE POWER SUPPLY SYSTEM

The upgrade of the power supply system includes poloidal field upgrade, RF amplifier and Toroidal Field (TF) upgrade. This paper focuses on the TF power supply upgrade. An existing power supply will be re-purposed for the poloidal field supply upgrade. The following lists the technical requirements for the TF upgrade design:

- Fault level: 400 kA for 1 second
- Continuous current rating ($I_{total}$): +/- 15 kA
- Voltage rating ($V_{total}$): +/- 50 V
- Busbar ambient temperature: 25 °C
- Max. permissible busbar operating temperature: 65 °C
- Permissible busbar final temperature at the end of the fault: 200 °C
- Max. duration of continuous current: 25 min.

Fig. 1 shows the preferred upgraded AIMS TF power supply operation.

![Supply current and voltage graphs](image)

The busbars are placed parallel to each other about 343 mm apart. Including the connection between busbar and power supply, there are total 16 joints.

As there are some existing busbars, only partial bushbars needed to be added. The two-way length of the new bushbars is about 22.7 m and that of the existing ones is about 13.4 m, which yields a total length of about 36.1 m. Maximum mounting height is 3.7 m and weight of the new bushbars is 711 kg. When existing and new busbars are considered, the overall weight is 1,131 kg.

### II.B. Busbar Support Structure

As shown in Fig. 2, the existing support structure for the existing busbars will be used. New support structures for the new busbar need to be added.

In the new support structure, legs and lower pads are Unistrut stainless steel 304. The balance is G10 (fiberglass epoxy laminate insulating sheet) with thickness 12.7 mm).

![Busbar support structure](image)

### II.C. Power Supply and Related Components

The new power supply is connected to one end of the new busbar. Existing TF busbars to Alcator C-Mod tokamak are connected to the other end of the new busbar. The power supply system includes the power supply itself, varistor protection assembly, and others.

#### II.C.1. The Power Supply Itself

A six pulse 4-quadrant dual lockout converter power supply is used. Estimated dimensions of the power supply cabinet (length x width x height) are 3.1 x 1.4 x 2.8 m.

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*Fig. 2. Layout of busbars and their support structures.*

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**Equation 1:**

\[
\theta_i = \frac{k}{100} \left( \frac{I_{sc}}{A} \right)^2 \cdot \left( 1 + \alpha_{20} \theta \right) \cdot t
\]

where \( \theta_i \) is temperature rise (45 °C), \( k = 1.166 \) for aluminum, \( I_{sc} \) is symmetrical fault current r.m.s. (400 kA), \( A \) is cross-sectional area of the conductor (mm^2), \( \alpha_{20} \) is temperature coefficient of resistance at 20 °C, which is 0.00363 for aluminum alloys; \( \theta \) is operating temperature of the conductor at which the fault occurs (65 °C), and \( t \) is duration of fault (s). Based on Eq.1, the minimum area is 7.973 x 10^-3 m^2. The busbar with 304.8 x 38.1 mm was selected, and its cross-sectional area of 1.16 x 10^-2 m^2 meets the requirement.
II.C.2. Varistor Protection Assembly

The Varistor Protection Assembly (VPS) connects across the supply output bus, providing fast passive protection against bus overvoltage. It is located on the power supply side of high current switch, and backs up the power supply auto-crowbar system. The clamping voltage is 1,500 V, and insulation is rated at 5 kV for 1 min.

The first design step is to check the current rating of each disc to decide how many discs are needed. The current rating for each disc is 250 A, so the current rating for each unit (6 discs) is 1.5 kA. As the total current is 15 kA, at least 10 units are needed. To keep a design margin, 15 units are selected. Each disc sees 167 A, less than the 250 A/disc rating.

Secondly, the energy rating of each disc must be checked. The energy rating for each disc is 75 kJ. For our application, the total current is 15 kA, inductance \( L_1 = 0.007 \) H, so the total energy can be calculated as follows.

\[
E = \frac{1}{2} \times L_1 \times I_{\text{total}}^2 = 787.5(kJ)
\]

As there are 90 discs, the energy for each disc is 8.75 kJ, which is less than the 75 kJ/disc rating.

II.C.3. Other Power Supply Components

Other requirements for the TF upgrade include an automatic, self-powered, bidirectional crowbar circuit, and a high current double-pole pneumatically-actuated switch (18 kA/pole) to connect the TF power supply to the TF bus during AIMS operation. New controls must coordinate operation with existing C-Mod systems.

III. ANALYSES RELATED TO THE POWER SUPPLY SYSTEM

After the preliminary layout of the busbars and corresponding support structures was done, relevant analyses were performed to either confirm the design is feasible or make suggestions on the modification of the relevant parts. The analyses are presented in the following order.

- Joule heating of the busbar
- Electromagnetic analysis of the busbar
- Structural analysis of busbar support structures
- Resistive heating of one varistor disc
- Electromagnetic analysis of one varistor disc

III.A. Joule Heating of the Busbar

A FEA model of the new busbar is created. The current running through the busbar is 15 kA for 25 minutes. Initial temperature is 25 °C. The material properties of the aluminum alloy are listed in TABLE I.\(^7\)

As shown in Fig. 4, maximum temperature after 25 min. is 61.5°C, which is below the permissible level (65 °C).

Joule heating analysis has also been performed for a fault condition (400 kA for 1 second), the maximum temperature is 75 °C, which is below the allowable (200 °C).

<table>
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<tr>
<td>Density, kg/m(^3)</td>
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<tr>
<td>Electrical conductivity, S/m</td>
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<tr>
<td>Heat capacity, J/(kg*K)</td>
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<tr>
<td>Thermal conductivity, W/(m*K)</td>
<td>167</td>
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<tr>
<td>Melting point (°C)</td>
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<tr>
<td>Yield strength at 100°C, MPa</td>
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Fig. 4. Temperature distribution in busbar. Continuous operation, current 15 kA for 25 minutes.
III.B. Electromagnetic Analysis of the Busbar

When two busbars are placed parallel to each other with current of opposite direction, there will be a load trying to push the two parallel busbars apart called the spreading load.

A 2D FEA model is created to estimate this spreading load and resulting stress. The length out of the 2D plane is the length of new busbar (one way direction) 11.35 m.

The calculated spreading load is about 1,338 N. The von Mises stress in busbar is shown in Fig. 5. The deformation is exaggerated (scaled by 5 x 10^5) to show the tendency to push the two parallel busbars apart. The stress in the busbar is about 11.9 kPA, which is well below the allowable 170 MPa (two thirds of the yield strength of the material).

As the electromagnetic stress is much less (order of 10^4 Pa rather than 10^6 Pa), it can be ignored.

![Fig. 5. von Mises stress in busbar from electromagnetic analysis of the busbar. For viewing purposes, the deformation is exaggerated by scale 5 x 10^5.](image)

III.C. Structural Analysis of the Busbar Support Structure

The weight of the new busbars is estimated by the following equation where density $\rho$ is 2700 $\frac{kg}{m^3}$, total length $l$ is 22.7 m, width $w$ is 304.8 mm and thickness $t$ is 38.1 mm. Thus, the total weight is 711.0 kg.

$$W_g = \rho \times l \times w \times t = 711.0 (kg)$$ (3)

The weight needs to be carried by the support structure. Material properties of G10 are density 1800 $\frac{kg}{m^3}$, Young’s modulus 18.6 GPa and Poisson’s ratio 0.15. Maximum stress in the structure is benign, as shown in Fig. 6, which is within the allowable (Aluminum alloy 170 MPa, G10 175 MPa, stainless steel 304 143 MPa).

![Fig. 6. Stress in busbar supports.](image)

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![Fig. 6. Stress in busbar supports.](image)

III.D. Resistive Heating Analysis of One Varistor Disc

Initial temperature is 25 $^\circ$C, so the temperature rise for one disc is 12 $^\circ$C with input energy of 8.75 kJ. Regarding cooling, free air convection is applied and the convection coefficient is $15 \frac{W}{m^2 K}$. It takes about 1.5-2 hours to cool down to the initial temperature from peak temperature. Both temperature and cooling time are in agreement with vendor information.

To confirm the FEA simulation, an analytical calculation of the temperature rise is also done.

The mass of one disc can be calculated as follows

$$m = \frac{\pi}{4} \times (D^2 - d^2) \times L \times \rho = 0.85 (kg)$$ (4)

The heat gain calculation is based on the following equation where $q$ is the energy gained (J), $C_p$ is the specific heat ($\frac{J}{kg \cdot K}$), $m$ is the mass (kg), and $\Delta T$ is the change in temperature ($^\circ$C).

$$\Delta T = \frac{q}{C_p \cdot m} = \frac{8.75 \times 10^3}{840 \times 0.85} = 12.3 (^\circ C)$$ (5)

In reality, part of the energy is stored in the components other than the silicon carbide disc. The disc temperature change is smaller than the number estimated here since the calculation is conservative.
Calculated thermal stress is based on this equation:\textsuperscript{10}

$$\sigma = E \times (\alpha \times \Delta T \times L) = 0.40\text{(MPa)} \quad (6)$$

where $\sigma$ is the thermal stress due to thermal expansion (Pa), $E$ is the Young’s modulus (410 GPa), $\alpha$ is the strain (no unit), $\Delta T$ is the change in temperature (12.3 $^\circ$C), $L$ is the strain, and $\alpha$ is the coefficient of thermal expansion ($4 \times 10^{-6} \frac{m}{m \cdot ^\circ C}$). $\Delta T$ is the change in temperature (12.3 $^\circ$C) and $L$ is disc thickness (0.02 m). The disc is fixed as shown in Fig. 7.

This stress is along the axial direction. Similarly, in the radial direction, since the outer diameter is 0.152 m and the radius is 0.076 m, the stress is 1.52 MPa. The stress is based on temperature from Eq. 5 (12.3 $^\circ$C). If the temperature used is lower, the max. stress is even smaller.

**III.E. Electromagnetic Analysis of One Varistor Disc**

The current flow path for one varistor unit is analyzed and shown in Fig. 7. Furthermore, stress analysis due to the electromagnetic force is simulated, and maximum stress in each disc is 112 MPa, which is within the allowable (207 MPa for SiC).

![Current flow path in each varistor unit. The terminals are rotated and projected to paper.](image)

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**IV. CONCLUSIONS**

A new magnet power supply system is proposed for purpose of enlarging the spatial measurement range of Accelerator-based In-situ Material Surveillance in Alcator C-Mod from 35 cm to 124 cm poloidally and to 40 degree toroidally. Busbars, corresponding support structure, power supply footprint, and varistor protection assembly are designed. Multi-physics analyses indicate the design meets all requirements. All component drawings have been completed and the system is ready for fabrication. Final installation of the system will be initiated when the power supply is procured and in place.

**ACKNOWLEDGMENTS**

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