1X-980923-CLN-01

TO: DISTRIBUTION
FROM: C NEUMEYER
SUBJECT: CENTER STACK CASING/OUTER VV ELECTRICAL CONNECTIONS

References:

[1] NSTX-CALC-33-01, " CS Ohmic Heating"

INTRODUCTION

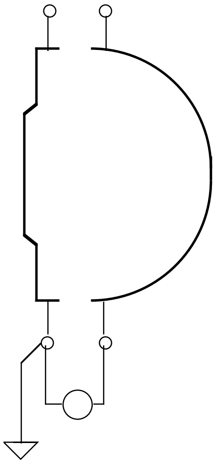
Capability for electrical connections to/between the center stack casing and outer vacuum vessel is required as follows:

1) Connection to CHI power supply circuit for CHI operations, along with ground reference
2) Jumpering between CS casing and outer VV during non-CHI operations
    a. to establish common voltage (jumpers across upper or lower ceramic insulator), and provide ground reference
    b. to simulate continuous vacuum vessel (jumpers across upper and lower ceramic insulators), and provide ground reference
3) Connection to external power supply for bakeout ohmic heating, along with ground reference.

The GRD requires the aforementioned connections to be provided at four toroidally symmetric locations.

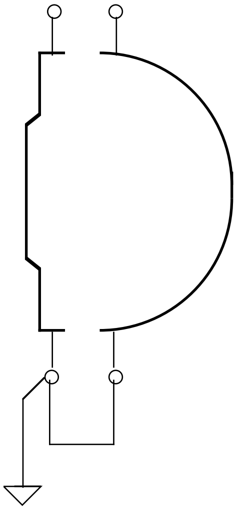
1) Connection to CHI power supply circuit for CHI operations

CHI power supply system can provide voltage up to 2kV to drive 50kA peak current into the plasma.



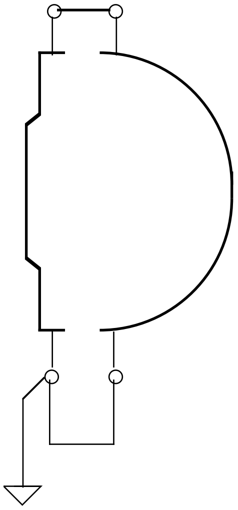
With 4 parallel connections, current per strap is 50/4 = 12.5kA. Sustainment mode calls for injection of 20kA-5 seconds once every 300 seconds ($\int I^2t = 2 \times 10^9$ amp^2-sec). Corresponding rms current is 20*sqrt(5/300)= 2.6kA. With four parallel connections rms current per connection is 650 amps.

2.a) Jumpering between CS casing and outer to establish common voltage and ground reference



CS casing and outer VV jumpered and connected to ground. One of the ceramic insulators is jumpered, the other is open. Current through jumper and to ground is minimal. There is no complete path for poloidal currents.

2.b) Jumpering between CS casing and outer VV during non-CHI operations to simulate continuous vacuum vessel and provide ground reference

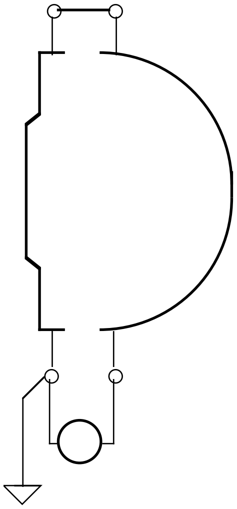


CS casing and outer VV jumpered together across both ceramic insulators and connected to ground. A complete path is available for poloidal currents. Two poloidal current sources are identified herein: mutual coupling with TF coils, and halo currents driven by the plasma.

According to [1] the poloidal resistance of the vacuum vessel, including the CS casing, is approximately 800$\mu\Omega$. If the vacuum vessel was perfectly coupled to the TF then the peak poloidal loop voltage would be 1000volts/36 turns = 27.8 volts/turn. The maximum possible poloidal current flow would then be 27.8volts/800$\mu\Omega$ = 34.7kA. Assuming that there are four jumpers, the maximum current per jumper due to TF ramping would be 34.7/4 = 8.7kA.

Per the GRD the poloidal halo current can amount to 10% of I_p with toroidal peaking factor of 2. This amounts to 0.1*1e6/4*2 = 50kA per jumper. It is clear that the halo current case will produce the largest current magnitude.

4) *Connection to external power supply for bakeout ohmic heating, along with ground reference*



Per [1] a current of up to 2.6kA shall be driven by a DC power supply through the center stack casing and returned through jumpers across the opposite ceramic insulator. Current per jumper in this condition is 2.6kA/4 = 650 amps, continuous.

During bakeout the flanges of the center stack casing to which the jumpers must connect are heated by Dowtherm fluid to 350C.

SUMMARY OF REQUIREMENTS

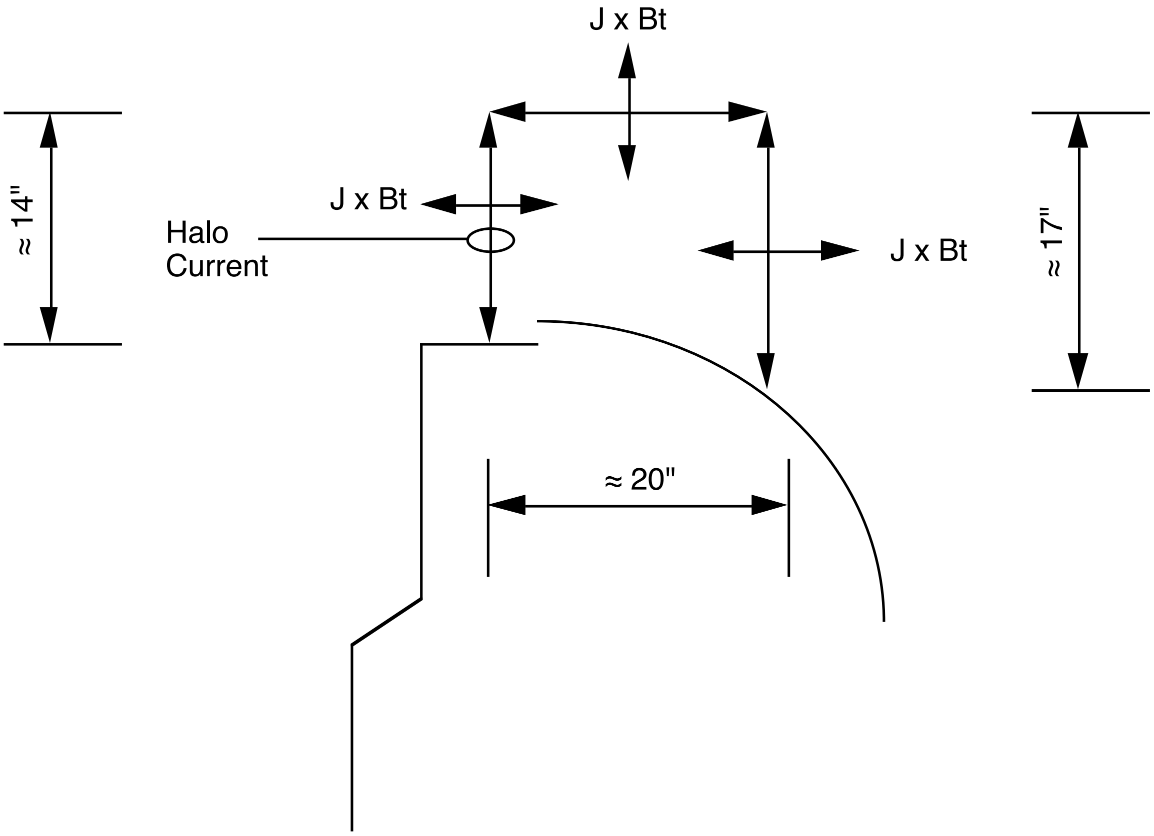
Electrical connections must provide for CHI and bakeout power supply connection, as well as jumpered modes. Current carrying requirements, per each of four connections, are as follows:

Peak current	50kA
Max. $\int I^2 t$	2×10^9 amp^2-sec
Min. rep period	300 sec
Max. I_{rms}	650 amp
Prospective short circuit current	120kA (due to 2 parallel power supply sections)

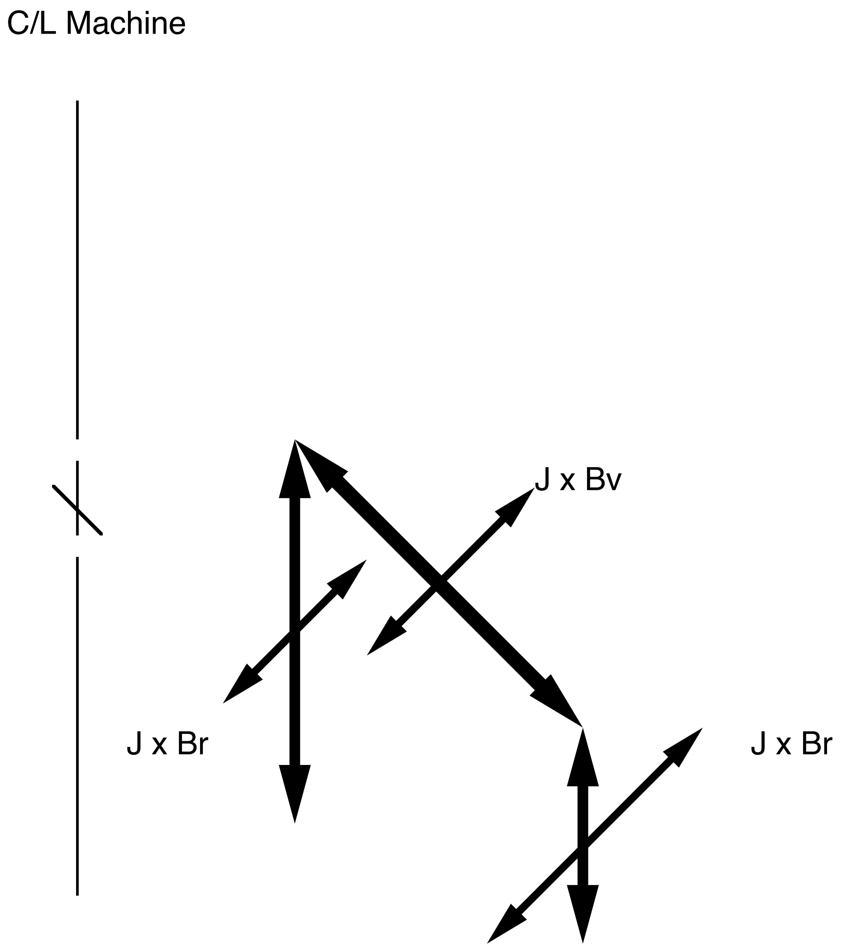
Physical configuration is such that connection must run approximately 14" vertical downward from flange, 20" radial, and then 17" vertical back to outer vacuum vessel to provide path for jumper. Corresponding forces due to the halo current (50kA) are derived in the following spreadsheet. Background poloidal field values are based on field plots with worst case currents in OH, PF1b, and PF2 coils.

	CSC-Jumper	Jumper	Jumper-VV	
Ip	1.00E+06	1.00E+06	1.00E+06	Amp
k	0.10	0.10	0.10	
peaking	2.00	2.00	2.00	
#segment	4.00	4.00	4.00	
Ipoloidal	50000.00	50000.00	50000.00	Amp
R1	0.384	0.384	0.892	m
Z1	1.654	2.010	2.010	m
R2	0.384	0.892	0.892	m
Z2	2.010	2.010	1.578	m
Theta	90.000	0.000	-90.000	degrees
Ravg	0.384	0.638	0.892	m
Forces Due to Bt...				
R0	0.854	0.854	0.854	m
Bt(R0)	0.600	0.600	0.600	T
Bt(Ravg)	1.334	0.803	0.574	T
L poloidal	0.356	0.508	0.432	m
Fnormal/segment	23714.38	20394.03	12399.72	N
	5330.99	4584.58	2787.46	lbs
Fradial/segment	-5330.99	0.00	2787.46	lbs
Fvertical/segment	0.00	4584.58	0.00	lbs
Forces Due to Bp...				
Br	0.56	0.44	0.33	T
Bv	0.78	0.78	0.78	T
Ftoroidal/segment due to Br	27800.00	0.00	-16400.00	N
	6249.44	0.00	-3686.72	lbs
Ftoroidal/segment due to Bv	0.00	22100.00	0.00	N
	0.00	4968.08	0.00	lbs

Orientation of forces due to interaction with toroidal field is indicated in the following figure. As indicated, it is prudent to assume that the currents, fields, and forces, could occur in either direction.



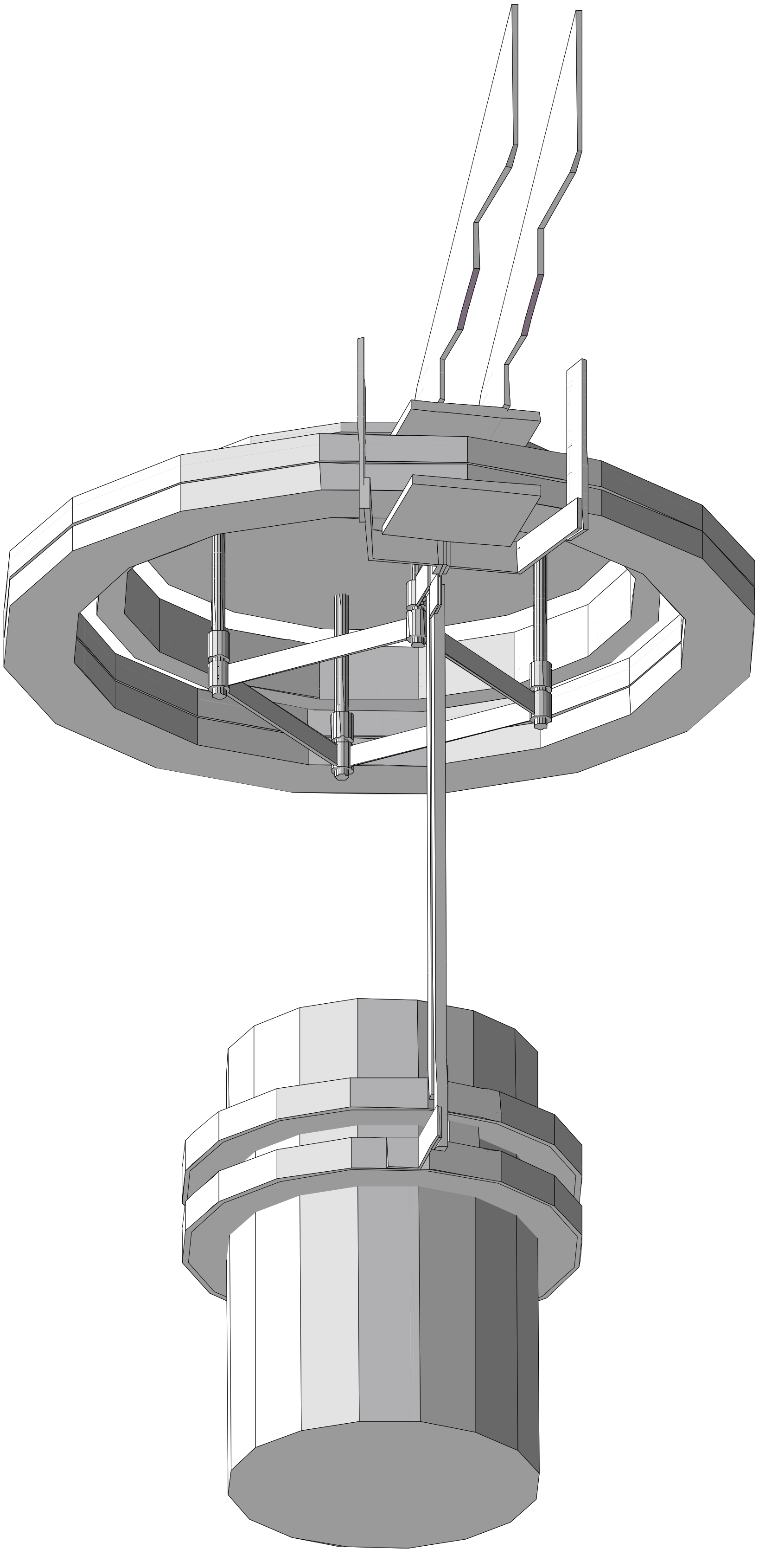
Isometric view of toroidal force due to interaction with the vertical and radial poloidal fields is shown in the following figure. Again, it is safe to assume that the forces could be imposed in either direction.

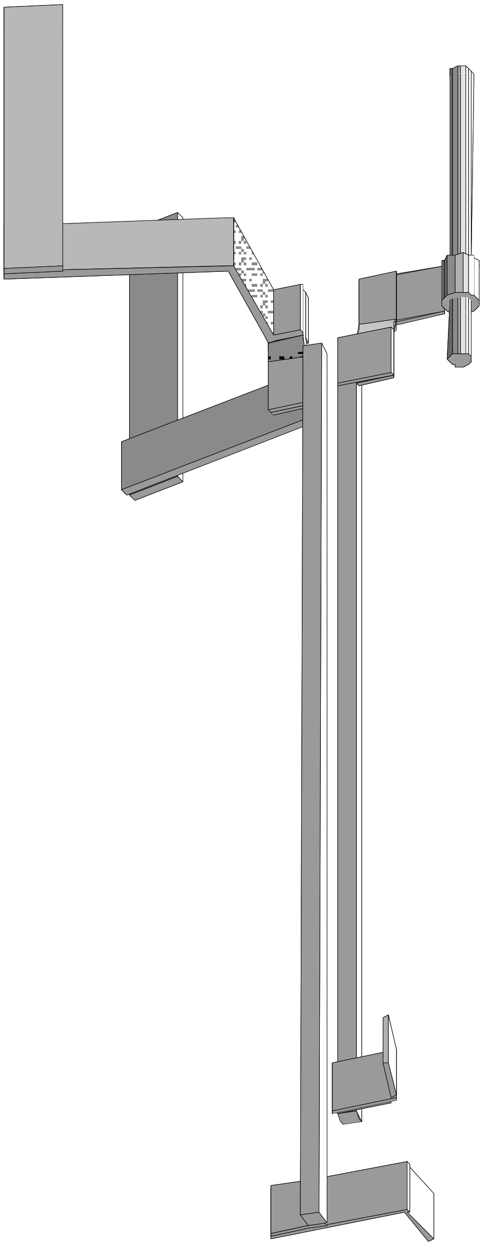


In addition to the above requirements, it is noted that the connection scheme must accommodate power supply voltage up to 2kV and must attach to flange at 350C.

DESIGN OF CONNECTIONS

3D model of proposed scheme is shown in the following figures. One of the four connection points is depicted.





Connection to center stack casing flange is accomplished using four 1-1/4″ diameter copper rods, approximately 16″ in length, which are screwed into flange. Connection to rod is accomplished using bronze straight tee "tubing to flat bar tap" standard bus bar connector such as Square D part TTF-1230-1 (catalog sheet attached). This is designed to connect a 1-1/4″ tube (or rod) to a 3″ wide bus bar.

A similar part (TTF-1220-1) can be used to connect 1/4″ thick stainless steel straps from rod to rod to provide structural rigidity.

Connection to the outer vacuum vessel is accomplished using copper straps which are attached to the domes in the region adjacent to the ribs. The attachment could consist of a stainless steel tabs or pads, welded on to the vessel, with bolt holes or studs to provide for attachment to the copper straps.

Connection between the center stack casing and the outer vacuum vessel is accomplished via bolting a 3″ wide by 1/4″ thick straight copper shorting jumper connecting from the tube-to-bar tap across to the copper angle pieces, where it is sandwiched in between.

Feeds from the CHI or bakeout power supply are accomplished by connecting vertical riser bus bars, 1″ x 1″ square, 1/4″ water cooling hole, spaced 1″ apart, with copper flags brazed on at each end. These bus bars are uninsulated. Jumper straps connect these flags to the center stack casing and outer vacuum vessel when the shorting jumper is removed. These feeds are joined together electrically and connected to the incoming power source via copper bus bar rings mounted on insulators to the pedestal assembly. Although shown toroidally continuous in the figures given herein, there would be a toroidal break to avoid closed toroidal loops.

JUSTIFICATION OF THE DESIGN

Copper rods, rather than stainless steel rods, are used in order to keep the resistance down. If the rods were constructed of stainless steel, then the resistance of each rod would be of order 400 $\mu\Omega$, and the equivalent of 4 in parallel, 2 in series ≈ 200 $\mu\Omega$ net in the poloidal loop. This is to be compared [1] to the effective poloidal resistance of the center stack casing @ 720 $\mu\Omega$ and outer vacuum vessel @ 80 $\mu\Omega$.

If the rods are constructed of copper then their resistance will be negligible compared to the center stack casing and outer vacuum vessel.

The stainless steel rods would easier to implement (stronger, lower thermal conductivity, and could be tack welded after insertion to prevent turning), but they would likely cause the halo current behavior to deviate considerably from that which would result from a continuous vacuum vessel, due to the extra impedance they present, especially to localized currents.

The 1/4″ x 2″ stainless steel straps which bridge between the four rods serve to provide structural rigidity. It is noted that, if it were not for the toroidal asymmetry of the halo current, the net force on the four rods would be zero. So, by tying the rods together, they need only react the asymmetric component of the force.

The 1/2″ thick x 3″ wide copper straps which connect to the outer vacuum vessel provide a lower impedance, symmetric connection to the vessel at eight locations above and below the midplane. Their orientation is such that their section modulus presents the maximum resistance to bending in the direction of the maximum applied forces.

The shorting jumpers provide a direct, low impedance path across the ceramic insulator assemblies. In case further study indicates that they cannot be readily accessed in the suggested location, they can be implemented at the bottom end of the vertical riser bus bars if necessary. In this case an extra impedance is introduced in the loop.

The vertical riser bus bars, 1″ x 1″ with 1/4″ diameter cooling passage, can carry the required 650 amps continuous, even without water cooling. The purpose of the water cooling is, mainly, to remove the heat flowing down the 1-1/4″ diameter copper rods attached to the center stack casing flange, which can be at 350C during bakeout. This scheme, which holds the temperature of the bars well below 100C, permits the use of G-10 clamps to react the short circuit force due to the prospective 100kA fault current which could flow in the (+) and (-) conductors. If the water cooling is lost during bakeout, there is a concern that the heat from the center stack casing could raise the temperature of the vertical riser bars well above 100C. However, the fact that they are uninsulated means that there will be significant heat lost to the ambient air in case of loss of water flow, so as to minimize the temperature rise in case of such an occurrence.

Thermal electrical design of the vertical riser bus bars is given in the following spreadsheet. This includes, in addition to the conductor I^2R losses, 500 watt additional power input due to a gradient of 350-10 = 340 C across the 16″ long, 1-1/4″ diameter copper rod.

Cond resistivity @ 20C	1.73E-06	Ω-cm
Cond res temp coeff	0.00393	1/degC
Cond heat capacity	0.386	J/gm-degC
Cond density	8.89	gm/cc
Ambient Temperature	35	deg C
Max Current	5000.0	amp
Max ∫i^2dt	6.45E+02	A^2-s
Min ESW	5.000	sec
Min Repetition Period	300.0	sec
Max RMS Current	645.5	amp
Bus length per pole	6	feet
Inlet temperature	35	deg C
Max temperature	80	deg C
Conductor width	1	in
Conductor height	1	in
Cooling hole dia	0.25	in
Corner radius	0.0625	in
# Conductors	1	
Cond CSA	0.9	sq in
	6.1	sq cm
Res @ 20C per pole	5.17E-05	Ω
Res @ 25C per inch	7.32E-07	Ω/inch
Water flow/conductor	2	GPM
Water flow velocity	13.1	feet/sec
	398.4	cm/sec
#Series Water Paths	2	
ΔP	16.5	psi
Heat Capacity	7.67E+03	J/degC
Heat Capacity per inch	1.07E+02	J/degC/in
Thermal Res of Coolant	1.89E-03	deg C/watt
Film Res Cond to Coolant	6.22E-04	deg C/watt
Total Res Cond to Coolant	2.51E-03	deg C/watt
Thermal tau	19.3	sec
Res @ Tmax per pole	5.78E-05	Ω
Voltage Drop @ Imax (both poles)	0.6	volt
Conductor I^2R Loss per pole	24.1	watt
Total Conductor Loss	48.2	watt
Additional Heat Input	500.0	watt
Total Heat Input	548.2	watt
Tmax @ Irms	36.4	deg C
Tmax @ Irms + ΔT @ Imax @ ESW min	38.0	deg C

Electromechanical design aspects of the vertical riser bus bars is given in the following spreadsheet. This indicates the need for a G-10 support clamp every 8″ or so.

Separation	1	in
CL-CL Bus Spacing s	2	in
width a	1	in
height b	1	in
a/b ratio	1	
(s-a)/(a+b)	0.5	
k factor	0.983333	
Operating Current	5000.0	amp
Operating Force	6.6375	#/foot
Short Circuit Current	120000	amp
Short Circuit Force	3823.2	#/foot
	318.6	#/in
Support Spacing	8	in
Support Force	2548.8	#
#Bolts	2	
Bolt Load	1274.4	#
Moment of Inertia	0.083333	in^4
Section Modulus	0.166667	in^3
Elasticity	1.60E+07	
Force/length	318.6	#/in
Bending Moment	2548.8	in-lb
Stress	15292.8	psi
Deflection	0.012744	in

OPEN ISSUES

Detailed layout study needs to be performed to insure that there are no interferences, and that access is available to parts as needed. Specific items which need to be confirmed are:

1) Will the vertical riser bars pass through the radial TF flex connection region without interference?

2) Can the shorting jumper be accessed after all parts are assembled? If not, then the shorting needs to be accomplished at the bottom of the vertical riser bus bars in the area of the rings mounted to the pedestal.

Detailing is needed in terms of:

1) Means of connection to outer vacuum vessel

2) Method of support, particularly of straps which connect to outer vacuum vessel.

3) G-10 clamps associated with vertical riser bus bars

4) Actual dimensions and drawings of required parts and associated hardware

Further analysis is needed to:

1) Confirm mechanical integrity of the scheme, given the loads.

2) Temperature of parts in case of loss of cooling water during bakeout.

Finally, Physics has indicted a desire to measure the currents flowing in the jumpers when the center stack casing is shorted to the outer vacuum vessel. If the rods connecting to the center stack casing flange were constructed of stainless steel, they might have served well as current viewing resistors. However, with copper rods the resistance is probably too low for this purpose (e.g. at 50kA there would be a 275 mV drop across 10" of the rod length). Therefore it is recommended that Rogowski coils be used for this purpose, at exact locations TBD.

INITIAL CONFIGURATION

For first plasma, it is recommended that configuration 2.a) described above be in place, namely that in which the center stack casing and outer vacuum vessel are jumpered together at the bottom of the machine and grounded, with no jumper in place on top. In this case there will not be a path for poloidal current flow. So, if the tight schedule dictates, the jumper can consist of cables connecting from the connectors on the copper rods to the connection pads on the outer vacuum vessel. The bus bar is not required.

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