Radial Cooling of a Spherical Torus (ST) Toroidal Field (TF) Centerpost*

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Abstract—**It is best for fusion to operate STs at the highest feasible toroidal field. This may not be obvious since dissipated electrical power increases as the square of magnetic field strength. However, fusion power density increases even faster. For example, increasing TF by 10% increases electrical losses by 21% but it also may increase fusion power by 46.4%.**

The main impediment blocking increased toroidal field is centerpost heat removal. Heat deposited by resistive heating and by radiation from the fusioning plasma is removed by coolant flowing through holes cut in the centerpost. Conventional designs have used axial flow within spaced, vertically oriented holes, and they have optimized flow speed, temperature rise, and cooling hole size. However, with all flow paths having the same length, the conductor volume removed is just the product of centerpost height by total flow area.

Radial flow cooling is a radically different scheme promising a factor of almost two improvement over axial flow designs in the volume of conductor removed for cooling. Its performance advantage stems from its shorter average flow path length while retaining the same total flow cross sectional areas for inflow, outflow, and internal flows. This is accomplished by cooling the upper centerpost from the top and cooling the lower centerpost from the bottom, with no coolant crossing the horizontal midplane.

For a single-turn TF, high pressure coolant is supplied both from the top and from the bottom to a central manifold located radially in the middle of the centerpost conductor. Coolant flows outward through many small diameter radially oriented cooling holes in the centerpost conductor into a low pressure annular manifold surrounding the centerpost. The external membrane surrounding the low pressure manifold includes sealed penetrations for the centerpost electrical connections and mechanical supports.

Radial cooling optimization includes tapering of the manifold cross sections over their axial length in conjunction with varying the density and size of the radial cooling holes so that coolant flow speed is spatially constant and local cooling matches local heating.

Radial cooling may simplify single-turn TF centerpost fabrication since it eliminates the need for long, narrow cooling holes as required for the axial schemes.

I. INTRODUCTION

Radial cooling is a radically different alternative to the axial cooling designs usually pursued for the toroidal field (TF) centerposts of low aspect ratio tokamaks. Radial cooling's performance advantage stems from its removal of less conductor material for coolant flow ducts. This is due to the fact that the average length of flow ducts in radial cooling is shorter than flow ducts in conventional axially cooled designs which extend the full height of the centerpost.

Radial cooling's performance advantages are that it reduces electrical losses dissipated in the centerpost for constant toroidal field and coolant flows, and that it increases the achievable cooling power so that a higher toroidal field becomes feasible. It may also simplify centerpost construction, reducing its manufacturing costs.

Fig.1 illustrates the radial cooling scheme. In radial cooling of a centerpost, the coolant fluid, e.g.,water, flows between pressurized inner and outer manifold volumes through many spaced radially directed cooling holes in the electrical conductor. Coolant fluid is separately supplied to the inner manifold from external supply pipes connecting both at the centerpost's top and bottom. Outer manifold coolant also exits from both the centerpost's top and bottom to external return pipes. Thus, coolant fluid parcels follow U-shaped paths through the centerpost.

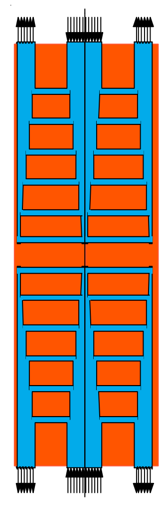

Figure 1: Radial Cooling scheme

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Thus, coolant fluid entering from a coolant supply pipe flows vertically within the inner manifold from either centerpost end toward its waist, then turns and flows radially outward through one of the many small diameter cooling holes, then turns again and flows vertically within the outer manifold back to the same end of the centerpost whence it came, then finally exits to a coolant return pipe. The amount of coolant flow that turns at a junction from a vertical manifold to flow through a radial hole is determined by the flow-pressure properties of the entire hydraulic ladder network, whose dimensions must be carefully designed.

With these U-shaped paths, coolant fluid never vertically crosses the horizontal midplane. At any vertical location, the vertical mass flow rate in the inner manifold is matched by the oppositely directed vertical mass flow rate in the outer manifold. However, because of the radial flows between the manifolds through the centerpost conductor, the total vertical flows in the manifolds vary with vertical location. They are maximized at the centerpost's ends but at any other location they are reduced by the cumulative radial flow between that location and the nearest end, thus reaching zero at the centerpost's horizontal midplane. The manifolds are therefore designed to be tapered in their horizontal cross-sections so that the coolant traveling vertically in them can proceed at a uniform speed. Thus, the conductor material which must be removed to form the manifolds varies from a maximum at the centerpost's top and bottom to zero at the centerpost's waist. Additional conductor is removed for the radially oriented holes, but since the radial holes are short this volume is small.

Fig.2 illustrates the conventional axial cooling scheme which has been used in all ST centerpost designs. If duct cross sections are also spatially constant, the coolant flow speed only varies due to fluid density dependence on spatially changing temperature and pressure. Coolant fluid flows in one direction through each of many spaced axial (i.e., vertical) holes which comprise flow ducts in the TF centerpost conductor. There are no internal flow network junctions. All flow path ducts extend the full height of the centerpost. The mass flow rate within each duct is spatially constant.

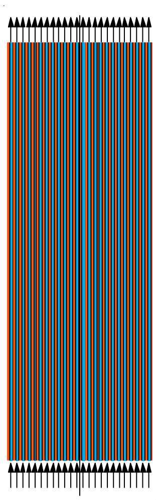

Figure 2: Axial Cooling scheme

II. WHAT SHOULD BE MAXIMIZED

The goal for ST reactors is to produce as much steady DT fusion power as feasible within a compact and relatively inexpensive device. Total DT fusion power varies as follows;

$$P_{fusion} = V_{plasma} \frac{\overline{n^2}}{4} \langle \sigma v \rangle (17.6\,\text{MeV}) \tag{1}$$

where V_{plasma} is the plasma volume, n is the plasma density, and $\langle\sigma v\rangle$ is the velocity averaged fusion cross section. Within the 10 to 20 keV plasma temperature range appropriate for magnetic confinement fusion, $\langle\sigma v\rangle$ varies approximately in proportion to the plasma temperature squared, i.e.,

$$\langle \sigma v \rangle \approx 1.1 \times 10^{-24}\,\text{m}^3\text{s}^{-1} \left(\frac{T}{1\,\text{keV}} \right)^2 \tag{2}$$

Since the plasma pressure is the product of plasma density, n, and temperature, T, fusion power density scales as the square of plasma pressure, at fusion relevant temperatures.

$$P_{fusion} = V_{plasma} c \overline{n^2 T^2} = V_{plasma} c_1 \left(\overline{p} \right)^2 \tag{3}$$

However, magnetically confined plasmas become unstable if their pressure becomes too high for the confining magnetic field. This is best quantified by normalizing plasma pressure to the magnetic field pressure,

$$\beta \equiv \frac{\left(\overline{p} \right)}{p_{magnetic}} \quad \text{where} \quad p_{magnetic} = \frac{B^2}{2\mu_0} \tag{4}$$

where μ_0 is the permeability of free space. All magnetic confinement schemes have maximum stable plasma beta values, all fractions smaller than one. Combining (3) with (4),

$$\begin{aligned} P_{fusion} &= V_{plasma} c_1 \left(\overline{p} \right)^2 = \\ &= V_{plasma} c_2 \left(\beta B^2 \right)^2 = V_{plasma} c_2 \beta^2 B^4 \end{aligned} \tag{5}$$

Thus, fusion power density scales with the square of β times the fourth power of magnetic field strength, B.

Low aspect ratio tokamaks of the ST type show promise primarily because their maximum stable plasma β values are an order of magnitude larger than for higher aspect ratio tokamaks. A second reason is that they are more compact and thus may be less expensive.

On the other hand, ST reactor designs have challenges. The toroidal field B within the plasma is reduced by the low aspect ratio to a smaller fraction of the maximum toroidal field strength than is the case for higher aspect ratio tokamaks. Most importantly, there is not enough space surrounding an ST centerpost for adequate radiation shielding unless the ST is excessively large. In compact ST DT reactor designs lacking such shielding, the centerpost will be bombarded with a high flux of 14 MeV neutrons from the DT fusion reactions.

Conventional electrical insulation systems are incompatible with this unshielded high neutron flux and must be avoided. Superconducting magnet systems cannot be used to generate the ST's toroidal field, not only because of the need to avoid conventional insulation but also the near impossibility of maintaining magnet temperatures close to absolute zero while the magnet is absorbing a large amount of nuclear heating.

Therefore, TF centerpost designs for future ST DT reactors employ normal copper near ambient temperature as their conductor, and to avoid insulation, they must use single turn designs operating at very high dc current and low voltage. The high currents imply developing a new TF electrical power supply technology to unconventionally provide tens of millions of dc amperes steadily at only a few volts. It is not clear whether the best power supply solution should use rotating homopolar generators or ac voltage stepdown transformers followed by thousands of parallel diode rectifiers with their forward voltage losses, or some other scheme. What is clear, this new TF power supply will need to be located as close as possible to the ST to avoid electrical power transmission losses. Another challenge caused by the high unshielded neutron flux in the centerpost region is that plasma startup will require developing new techniqueswithout any OH solenoid. Yet another challenge is that an ST reactor's centerpost will need to be periodically replaced due to accumulated neutron damage. With all of the difficulties, it is important to preserve the advantage conferred by higher β. This is why B should be optimized.

It is useful to compare the toroidal magnetic field scaling of the fusion power produced to the centerpost electrical dissipation losses. TF centerpost losses are large and vary proportionally to the square of magnetic field while fusion power varies in proportion to the fourth power of magnetic field. Thus, the ratio of fusion power to resistive losses improves rapidly as the magnetic field is increased.

III. AXIAL FLOW CALCULATIONS

Toroidal magnetic field requires a centerpost current,

$$I = \frac{2\pi RB}{\mu_0} \tag{6}$$

which causes electrical heating of the centerpost.

$$P_{elec} = \frac{\eta L^2}{V_{centerpost}(1-x)} I^2 \tag{7}$$

Here, B is the magnetic field strength, μ_0 is the permeability of free space, I is the centerpost current, η is the electrical resistivity of the centerpost conductor material, L is the length of the flow passages which in this axial flow design are all as long as the centerpost is tall, $V_{centerpost}$ is the volume of the centerpost, and x is the fraction of the centerpost volume removed for cooling channels. There is also radiation heating of the centerpost, P_{rad}.

The cooling power is the rate at which thermal energy is removed. It is the product of density and specific heat of the coolant with the coolant's temperature rise, speed, and the total duct's cross sectional area.

$$P_{cooling} = \frac{\rho C_p (T_H - T_C) v V_{centerpost}}{L} x \tag{8}$$

These are combined by requiring the cooling power to balance the total heating power.

$$P_{elec} + P_{rad} = P_{cooling} \tag{9}$$

or

$$\frac{\eta L^2}{V_{centerpost}(1-x)} I^2 + P_{rad} = \frac{\rho C_p (T_H - T_C) v V_{centerpost}}{L} x \tag{10}$$

Solve for current, I, then find the x value which maximizes it. The result is:

$$x = 0.5 + \frac{P_{rad}}{2V_{centerpost}} * \frac{L}{\rho C_p (T_H - T_C) v} \tag{11}$$

Alternatively, define a function proportional to fusion power divided by centerpost losses, i.e.

$$Q_{ENG} = \frac{I^4}{P_{elec}} \tag{12}$$

using the above relations, then it is elementary to show that its maximum is reached at the following condition:

$$x = 0.33 + \frac{2P_{rad}}{3V_{centerpost}} * \frac{L}{\rho C_p (T_H - T_C) v} \tag{13}$$

Thus in axial cooling, the highest possible toroidal magnetic field without radiation heating results if half of the centerpost volume is replaced with coolant flow channels. Also, the highest possible Q_{ENG} results (again, without radiation heating) if one third of the centerpost conductor were replaced by cooling channels. Even more conductor material should be replaced by coolant channels if there is also significant radiation heating.

Of course, this analysis entirely neglects the temperature dependence of resistivity. It has been included in more detailed analyses[1] and it modifies these results to some extent. In addition to varying x such analyses need to vary the diameters of flowpaths and their spacings, determine the film heat transfer coefficient using, e.g., the Dittus-Boelter correlation, and also approximate average heat conduction temperature gradients within the conductor material. For each of these there is an approximate algebraic formula, thus making such investigations straight forward.

IV. SIMPLIFIED RADIAL COOLING MANIFOLD DESIGN CALCULATIONS

Radial cooling designs require the manifolds to be shaped and the density of radial holes selected to match expected spatial profiles of heat deposition. In the present section these design calculations are approached in a simplified way. The cylindrical coordinate system with independent variables (r,θ, z) is used for description. Only the upper half, z>0, is considered since z<0 has mirror symmetry An allowable spatial envelope volume is identified within which the centerpost conductor, cooling manifolds and radial holes must fit. It's outer boundary is an axisymmetric surface specifed by stating its radius, $R_{MAX}(z)$ as a function of vertical position, z. An inner axisymmtric limiting surface, $R_{MAX}(z)$, is also defined but can be specified as zero .

It is assumed that $R_{MAX}(z)$, $R_{MIN}(z)$ and any other functions of *z* are piecewise continuous and differentiable. For the radial cooling scheme the z>0 cooling water is conveyed axially inward (in the -*z* direction) through an inner high pressure manifold and axially outward (in the +z direction) through an outer low pressure manifold. At any elevation, *z*, the cross-sectional manifold areas within the local constant-elevation cutting plane may be referred to as $A_{inner}(z)$ and $A_{outer}(z)$. The centerpost electrical conductor is in the annular region between the inner and outer manifolds, defined as $R_{Cu-\min}(z) < r < R_{Cu-\max}(z)$ where $R_{Cu-\min}(z)$ and $R_{Cu-\max}(z)$ are respectively the inner and outer edges of the centerpost's conductor region.

Since the inner and outer manifolds are annular, the radial and areal quantities are interrelated as follows:

$$A_{inner}(z) = \pi\left(\left(R_{Cu-\min}(z)\right)^2 - \left(R_{MIN}(z)\right)^2\right) \tag{14}$$

$$A_{outer}(z) = \pi\left(\left(R_{MAX}(z)\right)^2 - \left(R_{Cu-\max}(z)\right)^2\right) \tag{15}$$

The interest here is in configurations in which the water speed is everywhere constant. A consequence is that the inner and outer manifolds have identical area profiles, i.e.,

$$A_{outer}(z) \equiv A_{inner}(z) \text{ for all } z \tag{16}$$

or equivalently

$$\left(R_{Cu-\max}(z)\right)^2 + \left(R_{Cu-\min}(z)\right)^2 \equiv \left(R_{MAX}(z)\right)^2 + \left(R_{MIN}(z)\right)^2 \tag{17}$$

Another consequence of constant speed is that the total *radial* flowpath cross section between any two elevations must match the change in manifold area between those same two elevations. However, to state this mathematically it is necessary to first define another function quantifying the cross-sectional area of radially oriented flowpaths through the conductor between the two manifolds. It is envisioned that there will be a great number of radial flow paths, all of very small circular cross section, each created by drilling radially through the conductor between outer and inner manifold regions. The function, $A_{radial}(z)$ is hereby defined as the total cumulative cross-sectional area summed over all radial holes located between the horizontal midplane and the horizontal plane through positive elevation *z*. For the flow speed to be the same constant value in the radial holes that it is in the manifolds, it is necessary that their cross-sectional areas must be equal. The mathematical statement is then as follows:

$$A_{inner}(z) = A_{radial}(z) \tag{18}$$

It is hereby assumed that the function $A_{radial}(z)$ becomes smooth and differentiable. Differemtiatmg (18),

$$\frac{d}{dz}\left(A_{radial}(z)\right) = \frac{d}{dz}\left(A_{inner}(z)\right) = \frac{d}{dz}\left(A_{outer}(z)\right) \tag{19}$$

This can be restated in terms of the manifold radii as follows:

$$\begin{aligned}\frac{d}{dz}\left(A_{radial}(z)\right) &= \pi\frac{d}{dz}\left(\left(R_{Cu-\min}(z)\right)^2 - \left(R_{MIN}(z)\right)^2\right) = \\ &= \pi\frac{d}{dz}\left(\left(R_{MAX}(z)\right)^2 - \left(R_{Cu-\max}(z)\right)^2\right)\end{aligned} \tag{20}$$

Then

$$\begin{aligned}\frac{d}{dz}\left(A_{radial}(z)\right) &= 2\pi R_{Cu-\min}(z)\frac{d}{dz}\left(R_{Cu-\min}(z)\right) \\ &- 2\pi R_{MIN}(z)\frac{d}{dz}\left(R_{MIN}(z)\right)\end{aligned} \tag{21}$$

and

$$\begin{aligned}\frac{d}{dz}\left(A_{radial}(z)\right) &= 2\pi R_{MAX}(z)\frac{d}{dz}\left(R_{MAX}(z)\right) \\ &- 2\pi R_{Cu-\max}(z)\frac{d}{dz}\left(R_{Cu-\max}(z)\right)\end{aligned} \tag{22}$$

The simple physics invoked will require that at any elevation, *z*, the local radial coolant flow will convect away the local heating produced by ohmic electrical dissipation in the conductor, in an exact balance. Nuclear heating of the centerpost is neglected but clearly could be included. The heat removed from the centerpost is modeled simply as the product of coolant flow speed, coolant density, coolant specific heat, coolant passage cross-sectional area, and an assumed constant coolant temperaure rise, ΔT. Actual centerpost temperature is ignored in this initial look. Thus, the lineal density (per unit elevation) of heat removed is modeled as follows:

$$\frac{dP_{removed}}{dz} = v\rho c_p \Delta T \frac{dA_{radial}}{dz} \tag{23}$$

For the ohmic heating dissipation produced, it is assumed herein that the current redistributes itself immediaely arround the radial holes so that at every elevation, z, it is perfectly uniform across the effective cross section there. The local dissipation produced is modeled as follows:

$$\frac{dP_{dissipated}}{dz} = \frac{\eta I^2}{A_{current-effective}(z)} \quad (24)$$

where I is the total centerpost current, where η is the centerpost conductor's electrical resistivity, and where $A_{current-effective}(z)$ is the effective cross-section for current flow at elevation z. This effective cross section for current flow is less than the total annular conductor cross section, $\pi\left((R_{Cu-\max}(z))^2 - (R_{Cu-\min}(z))^2\right)$, by an amount modeling the missing conductor materiaal removed for the drilled-out radial cooling passage holes. Note that each drilled-out hole has a cylindrical volume in which the cylinder's radially-oriented height is $(R_{Cu-\max}(z) - R_{Cu-\min}(z))$. Note that the total cross section of all the drilled-out cylinders between elevations z and $z+dz$ is $\left(\frac{dA_{radial}(z)}{dz}\right)dz$. The missing conductor volume in the annular disk between elevations z and $z+dz$ is therefore their product, i.e., $(R_{Cu-\max}(z) - R_{Cu-\min}(z))\left(\frac{dA_{radial}(z)}{dz}\right)dz$.

Dividing this missing volume by the disk thickness, dz, yields the ***effective missing area*** for centerpost current flow, $(R_{Cu-\max}(z) - R_{Cu-\min}(z))\left(\frac{dA_{radial}(z)}{dz}\right)$.

Thus, the effective cross-sectional area for current flow at elevation z is taken to be as follows

$$\begin{aligned} A_{current-effective}(z) &= \pi\left((R_{Cu-\max}(z))^2 - (R_{Cu-\min}(z))^2\right) \\ &- (R_{Cu-\max}(z) - R_{Cu-\min}(z))\left(\frac{dA_{radial}(z)}{dz}\right) \end{aligned} \quad (26)$$

Thus, the heating and cooling balance is written as follows:

$$\frac{dP_{removed}}{dz} = \frac{dP_{dissipated}}{dz} \quad (27)$$

or equivalently

$$v\rho c_p \Delta T \frac{dA_{radial}}{dz} = \frac{\eta I^2}{\left(\begin{aligned}&\pi\left((R_{Cu-\max}(z))^2 - (R_{Cu-\min}(z))^2\right) \\ &- (R_{Cu-\max}(z) - R_{Cu-\min}(z))\left(\frac{dA_{radial}(z)}{dz}\right)\end{aligned}\right)} \quad (28)$$

To proceed further, it was decided to retain $A_{inner}(z)$ and eliminate other functions which can be calculated from it.

After substituting several identities and algebraically rearranging on obtains the following equation. This form emphasizes the fact that it is a quadratic equation in the derivative variable $\left(\frac{dA_{inner}(z)}{dz}\right)$, in which all other parameters are either specified in advance or involve the unknown function, $A_{inner}(z)$.

$$\begin{aligned} &\left(\sqrt{(R_{MAX}(z))^2 - \frac{A_{inner}(z)}{\pi}} - \sqrt{(R_{MIN}(z))^2 + \frac{A_{inner}(z)}{\pi}}\right)\left(\frac{dA_{inner}(z)}{dz}\right)^2 \\ &-\left(\pi\left((R_{MAX}(z))^2 - (R_{MIN}(z))^2\right) - 2A_{inner}(z)\right)\left(\frac{dA_{inner}(z)}{dz}\right) \\ &+\left(\frac{\eta I^2}{v\rho c_p \Delta T}\right) \\ &= 0 \end{aligned} \quad (29)$$

Eq.(29) is a standard quadratic equation form, $ax^2 + bx + c = 0$, where

$$\begin{aligned} x &\equiv \left(\frac{dA_{inner}(z)}{dz}\right) \\ a &\equiv \left(\sqrt{(R_{MAX}(z))^2 - \frac{A_{inner}(z)}{\pi}} - \sqrt{(R_{MIN}(z))^2 + \frac{A_{inner}(z)}{\pi}}\right) \quad (30) \\ b &\equiv -\left(\pi\left((R_{MAX}(z))^2 - (R_{MIN}(z))^2\right) - 2A_{inner}(z)\right) \\ c &\equiv \left(\frac{\eta I^2}{v\rho c_p \Delta T}\right) \end{aligned} \quad (25)$$

The roots are of course:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad 31)$$

and the actual solution for the derivative ot duct area is one of them. One notes that in the limit of small electrical current and thus small heating density, the c parameter approaches zero, a remains positive, b remains negative, and x should approach zero to signify that inner and outer manifold areas remain nearly constant over nearby elevations while the density of radial holes there is near-zero. This criterion excludes the root that does not approach zero as c approaches zero, leaving the root which does as the true solution, i.e. :

$$x = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \quad (32)$$

Substituting the actual a, b, c, x terms leads to an involved, complicated multiterm expression.covering an entire page, but it can be simplified by reintroducing the radii of duct boundaries from (14) and (15). The result is as follows:

$$\left(\frac{dA_{inner}(z)}{dz}\right)=\frac{\pi}{2}\left(R_{Cu-\max}(z)+R_{Cu-\min}(z)\right)-\sqrt{\left(\frac{\pi}{2}\left(R_{Cu-\max}(z)+R_{Cu-\min}(z)\right)\right)^{2}-\frac{\left(\frac{\eta I^{2}}{\nu\rho c_{p}\Delta T}\right)}{\left(R_{Cu-\max}(z)-R_{Cu-\min}(z)\right)}} \qquad (33)$$

A code was written to numerically solve (33) in conjunction with (14) and (15), thus automatically generating manifold designs and the density profiles for radial hole patterns.

V. APPLICATION TO FNSF

Fig. 3 illustrates a centerpost profile that is being considered for possible 1,6 meter major radius FNSF designs. Although it has not been envisioned as using radial cooling, that was the focus of a limited preliminary investigation.

The computed shape was entered into the code and the code used to scan through a grid of combinations of toroidal field at R=1.6 m and water flow speed in the coolant channels, generating a different manifold and radial holes system for each combination. The resulting centerpost electric power dissipations levels (MW) and centerpost cooling water flow rates (m^3/s) are shown respectiveely as contour plots. in Figs. (4) and (5), plotted against internal water flow speed and magnetic field..

Fig.6 shows the shape of optimized manifolds in the upper half of the centerpost for the 3 Tesla case with internal water flow speed 3 m/s, and Fig.(7) shows the same manifold shapes with an expanded horizontal scale. This operating condition requires 250 MW of centerpost electrical power and it requires about 1.3 m^3/s of cooling water, supplied at 12C and returned aat 60C, to remove all centerpost heat. (No nuclear heat sources were included.)

It is noteworthy that each of the plotted contours stops before reaching the left side of these graphs. That occurs because it is not possible to operate there at high magnetic field with low water flow rates and restricted temperature rises. That impossibility is manifest by the solution of the quadratic (29) acquiring imaginary component

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[1] A. Lumsdaine, J. Tipton, M. Peng, "Thermal fluid multiphysics optimizationof spherical tokamak centerpost", Fusion Engineering and Design 87 (2012) 1190-1194

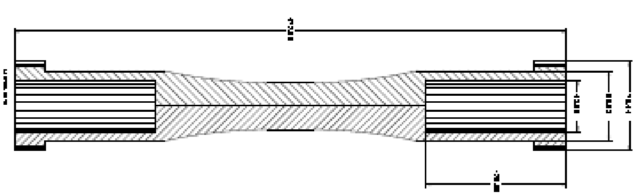

Figure 3: A Proposed Centerpost Layout for FNSF

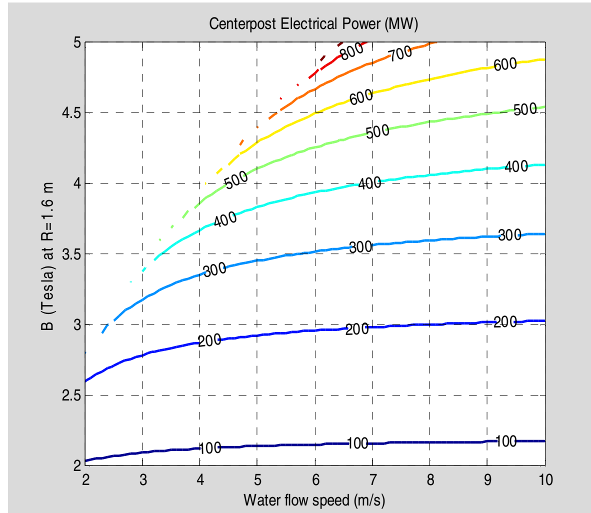

Figure 4: Radially Cooled Fig.3 Centepost: Power vsWater flow and TF

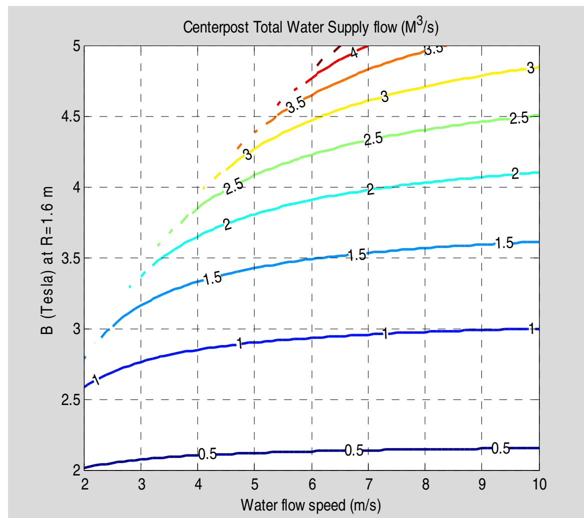

Figure 5: Radially Cooled Fig.3 Centepost: WaterFlow vs Waterspeed &TF

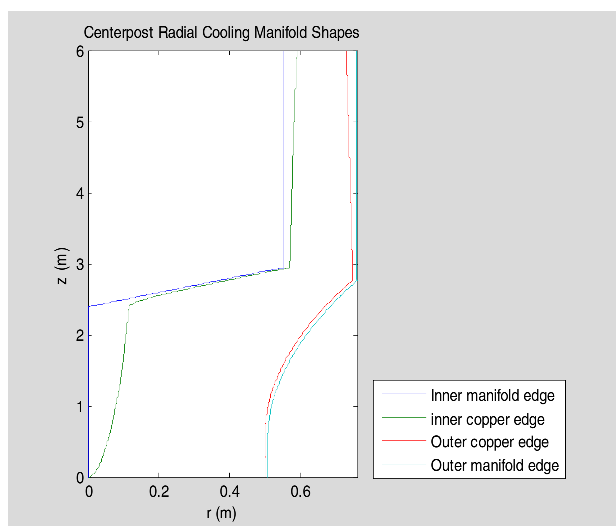

Figure 6: Radial Cooling Manifolds for Fig.3, Water speed 3 m/s, B=3 Ts