SIZING OF THE THERMAL AND ELECTRICAL SYSTEMS FOR AN FED BUNDLE DIVERTOR DESIGN WITH MgO INSULATION

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ABSTRACT

The high-order dependence of toroidal ripple from a bundle divertor on the magnet shield thickness increases the desirability of a magnet technology with minimal shielding requirements. A jacketed conductor with MgO powder insulation has been used successfully in highly irradiated environments. Its properties and limitations are described. A thermal and electrical sizing code has been developed for magnet design with this technology. Two design examples for ETF and FED missions show reduced recirculating power from previously reported designs.

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Because of the very high-order dependence of hot-ion ripple losses in a tokamak plasma, such as the Engineering Test Facility (ETF) or the Fusion Engineering Device (FED), on the magnetic moment of a bundle divertor coil system, it is interesting to investigate magnet technologies which require the least amount of shielding against neutrons and gamma rays. Previous studies [1,2] have indicated that, for both superconducting and normal conductor magnets with organic insulation, the most limiting factor is insulation life. Therefore, a good direction to look is at ceramic insulations, such as MgO powder. Ceramics have higher radiation resistance than organic insulations on general principles, because of their absence of easily broken chemical bonds. However, interest in ceramic insulations in general and MgO powder in particular is best justified by the superior operating performance of MgO powder insulated coils in high gamma irradiation and high-heat environments.

(1) History

MgO powder insulation is used in commercial stove elements, thermocouples for nuclear reactors and as a magnet insulation for accelerator magnets in a high gamma flux environment. Approximately 40 such magnets have been built by A. Harvey's group at the Los Alamos Scientific Laboratory (LASL) and 20 for accelerators operated by SIN (Suisse Institut Nucleaire) in Switzerland. There have been no failures related to insulation degradation in the several dozen magnets using ceramic powder insulation in a high gamma irradiation environment. The world's record irradiation is not known, but is believed to be greater than 10^{10} rads in one of the SIN magnets. Some of the magnets at LASL have logged over 30,000 hours of failure-free dc operation.

The operational experience of organic insulations in radiation environments is difficult to obtain. Failure reports appear infrequently in the open literature [3]. Few magnets have failed because of radiation damage to the insulation. Most accelerators never achieve their original design specification radiation dosages. Insulations are routinely inspected at laboratories such as Stanford and Brookhaven and are replaced when significant discoloration or delamination of the insulation is observed. According to D.Hay[4], at the Stanford Linear Accelerator (SLAC), magnets with Al_2O_3-filled epoxy glass insulation are routinely replaced after irradiations of 10^9 rads because of observed depolymerization. Therefore, magnets subjected to successful preventive maintenance can not test the hypothesis that thin insulations will continue to function successfully at irradiations well beyond the threshold to visible damage. The most spectacular unreported magnet failure, which was unambiguously due to radiation damage, is the failure of the DESY ring magnets in West Germany at radiation doses of about 10^8 rads. These magnets used aliphatic amine cured epoxies with mica and glass fillers. Dozens of magnets failed at radiation levels of 10^8 rads. It is believed that the failure mechanism was bubble rupture, bubbles being prevented from diffusing out of the insulation by the mica fillers. The most encouraging example of nonfailure that I have identified that of the NINA bending magnets in Darsbury, England (near Liverpool). R. Sheldon at Princeton [5] believes that these insulations have been irradiated to greater than 10^{10} rads with no magnet failures. The insulations are S-glass filled imide epoxies, cured with NMA. They are relatively thin, thus avoiding trapped gas formation.

While no spectacularly high magnet irradiations have been reported for MgO insulation, the insulation of the neutron flux detectors in the Canadian Pickrell reactors is known to have been irradiated to 10^{14} rads in the first three full power years [6]. No insulation failures occured. When the detectors were removed from service, the insulation resistance had changed from 10^9 Ω to 10^8 Ω at 100 V. This contrasts with the order of magnitude reduction in the resistivity of G-10 after an irradiation of 10^{10} rads reported by Coltman [7]. Brechna [8] reported a decrease in the unirradiated resistivity of wet-wound epoxy DER 332 of 5 orders of magnitude at an irradiation of 10^{10} rads and of 10 orders of magnitude at an irradiation of 10^{13} rads. Therefore, the electrical properties of MgO insulation appear to be far more stable under irradiation than those of organic insulations.

The difference in the operating experience of inorganic vs. organic insulation magnets is one argument in favor of using the MgO insulation in highly irradiated environments in ETF. The other, and probably more powerful argument, is the lack of clearly identified integrated failure mechanisms for ceramic powder insulation, as will be explained below. In order of applicability, relevant environments include (1) the bundle divertor magnets, (2) toroidal ripple compensation coils, attached to a shield or vacuum vessel flange, (3) internal poloidal divertor coils or (4) the main TF coils if very high beta is established by the current experimental program.

(2) Design Code Description

The ceramic insulation technology has several limitations, which have been modeled in a thermal-electrical systems sizing code, entitled BUNDLE LCOIL. There are also several variations of this code in use at MIT which include models of L-shaped coils, such as have been recommended for use in bundle divertors, circular coils, internally-cooled conductors and externally-cooled conductors. Our worked example in section three will be a bundle divertor with L-shaped coils with internally-cooled conductors, since this appears to be the most attractive fusion application of the ceramic insulation technology. The limitations on how lightly shielded the magnet can be include (1) instantaneous nuclear heating, (2) copper transmutations, (3) copper lattice displacements, (4) neutron-induced leakage current in the MgO insulation, (5) electrolysis of the ceramic break in the external coolant line, (6) electrolysis of the MgO insulation by neutron-enhanced migration of ceramic impurities, (7) erosion of the copper by radiolyzed water derivatives, (8) swelling of the insulation and (9) embrittlement of the copper. These limitations will be discussed below.

Instantaneous neutron and gamma heating appears to be the single most limiting factor for coils built with the MgO insulation technology, even at very high duty factors and availabilities. Typical heating rates have been calculated by Engholm [9] and are modeled in BUNDLE LCOIL by the correlation

$$Q''' = 18.8\, P_{wall} \exp(-a\; Thick_{shield}) \qquad (1)$$

where P_w is the wall-loading in (W/m^2) and a, the attenuation coefficient, is 13 m^{-1} for tungsten with titanium hydride and 11 m^{-1} for stainless steel and borated water. Notice that the Joule heating of a conductor with a current density in copper of 3 kA/cm^2 is 15 W/cc. If the nuclear and gamma heating is to held to about one-tenth of that amount, then approximately 30 cm of stainless steel/borated H_2O shield, 24 cm of tungsten/titanium hydride shield or, possibly, 16 cm of tungsten/titanium hydride shield plus a 10 cm thick steel coil case would be required.

Copper is transmuted by neutrons to unstable isotopes of copper, which decay into nearly equal amounts of zinc and nickel. Each atom of zinc or nickel can be thought of as the equivalent of three or four lattice displacements in their effect on the copper resistivity. The code BUNDLE LCOIL uses the following uses the following relations:

$$Atom\ density_{Cu} = .75\ 10^{22}\ (cc^{-1}) \tag{1}$$

$$Transmutation\ density = \frac{Fluence}{efold\ distance} \tag{2}$$

where the e-folding distance of transmutations in copper is taken to equal 10 cm.

$$Appm = \frac{10^6\ Transmutation\ density}{Atomic\ density} \tag{3}$$

where appm is the atomic parts per million of transmutations.

A single fusion 14 Mev fusion neutron can be expected to cause 1200 lattice displacements in copper. A typical fission spectrum would cause about 400 displacements per neutron. At room temperature, about 85 % of those displacements would be almost immediately annealed out. There is also a saturation limit of about .1 % defects that can be supported in copper at room temperature. Both the annealing and the saturation limits improve at elevated temperatures. However, I don't have design data over a range of temperatures and will use the conservative room temperature values. Therefore, each fusion neutron entering the magnet is assumed to cause (400(1-.85)=60) sixty lattice displacements, until a level of .001 dpa is reached. Each transmutation is taken to be 3.5 times worse than each lattice displacement in its effect on additional resistivity.

$$\Delta\rho_{lattice} = \frac{dpa}{.001}\ .4\ x\ 10^{-8}\ (\Omega - m) \tag{3}$$

for dpa $<$ .001 and

$$\Delta\rho_{lattice} = .4\ x\ 10^{-8}\ (\Omega - m) \tag{4}$$

for dpa $>$ .001. The resistivity due to transmutations is

$$\Delta\rho_{transmut} = 3.5\ appm \frac{.0148\ 10^{-8}}{300}\ (\Omega - m) \tag{5}$$

The temperature dependent resistivity of copper is taken to equal

$$\rho_{temp} = (1.48 + .00754\, T_{av})\, x\, 10^{-8}\, (\Omega - m) \qquad (6)$$

The neutron induced leakage current in the MgO insulation is based on Clinard's irradiation experiments with Al_2O_3. Since there are, as yet, no data on neutron-induced free carriers in MgO, we have to assume that the behavior of alumina is typical of ceramics. As will be seen, this assumption has a significant effect on the magnet and electrical circuit design and requires more careful analysis and, hopefully, further experiment. Clinard found that the electrical conductivity of Al_2O_3 is almost linear with irradiation over a fairly broad range of irradiation intensities [10]. Clinard's data is fitted with the correlation

$$\sigma_{rad} = 5.6\; 10^{-6} \left(\frac{Grays}{6.6}\right)^{.65} \qquad (7)$$

where Grays is the instantaneous irradiation in Grays/second. Scaling from the LASL Reverse Theta Pinch Reactor (RTPR) ceramic first-wall design, the following conversion is used:

$$Grays = .05\, P_w \qquad (8)$$

where P_w is the magnet wall-loading in W/m^2.

In order to predict the temperature rise in the MgO and, thus, the possibility of electrical breakdown due to thermal runaway, the following correlation was developed from the MgO thermal conductivity reported in Kingery,Bowen and Uhlmann[11].

$$T_{norm} = \frac{T_{max,Cu}}{100} \qquad (8)$$

$$K_{MgO} = -.7728 + \frac{84.835}{T_{norm}} - \frac{62.96}{T^2_{norm}} + \frac{16.23}{T^3_{norm}} \qquad (9)$$

Weeks [12] discovered that MgO crystals in a dc electrical field could suffer destruction through electrolyis at elevated fields. Dielectric breakdown was observed at fields as low as 10-100 V/mm after 5 to 150 hours of heating at 1200 K. Subsequent, unpublished tests on Al_2O_3 showed superior performance, with no evidence of electrolyis at temperatures in the range of 800-1000 C. While there is reason to believe that neutron and gamma irradiation will enhance ion migration at the lower temperatures typical of magnets, I have assumed that electrolysis will not be a failure mechanism. However, this should be confirmed by experiment.

At high water velocities, very high purity water is required in order to prevent rapid erosion of a copper channel. A certain number of residual impurites, as well as gamma-hydrolyzed oxygen, may attack an internally cooled conductor, such as the jacketed conductors manufactured by Pyrotenax. The total absorption mass attenuation coefficient ($\frac{\mu}{\rho}$) of water is .03 cm^2/g over a broad range of photon energies. If all of the photon absorption energy went into chemical bond breaking, a worst-case 100 W/cm^2 channel wall flux would cause an absorption rate of 3 W/cc or, at a weighted average of about 1 ev per molecular dissociation, 7.5 x 10^{19} ions/cc per second. Recombination may not be negligible, but recombination products will include a significant fraction of corrosive free radicals and hydrogen peroxide; erosion is desired to be low. Therefore, if convection were the dominant ion removal mechanism, a 10 m/s water flow velocity through a 10 m hydraulic path would leave a residual ion population of 7.5 x 10^{19} ions/cc, which is equal to the the number of hydrogen ions in an acid with a pH of 2.6. Although this calculation is extraordinarily crude, even if the population of corrosive radiolysis products due to gamma irradiation is 1,000 times lower, there is a strong prima facie case that there should be an erosion-resistant cladding between the water and the copper.

Radiolysis products also attack the ceramic break needed between the cooling channels of internally-cooled conductors and the grounded plumbing system. It is standard practice at the LAMPF facility [3] to provide a 6 mm sacrificial electrode in the ceramic tubing end. However, one insulator has failed after a few years at LAMPF because of electrolytic corrosion.

An interesting idea for a cladding-coolant combination might be to use stainless-steel or a hafnium alloy, which are good neutron absorbers in the epithermal range and borated H_2O, which is a good absorber of thermal neutrons and a good moderator over a wide range. It might be possible to reduce neutron absorption in the copper and insulation by a nontrivial factor (1.5-2) by this use of "internal shielding", while simultaneously solving lifetime limitations due to water erosion. (The relatively obscure hafnium alloys are very similar in their mechanical and thermal properties to the widely-used zirconium alloys. They are not used in nuclear reactors, largely because they are neutron absorbers.) A candidate reference conductor is shown in Figure 1.

According to F. Clinard [13], MgO swells about 1 % at magnet temperatures, at relatively low doses

($10^{20} - 10^{21}$ n/cm^2), but then saturates. The dominant failure mechanism in bulk ceramics is cracking along grain boundaries, which don't exist in the fine MgO powder. Of course, most of the stress "relief" comes from the fact that the powder may only have a 95-97 % packing factor. It should be noticed that the 10^{12} rad limitation on ceramic insulation, which one sees frequently quoted in fusion literature [2], must be referring to cracking in bulk ceramics due to swelling. This failure mechanism probably doesn't exist for the ceramic powder technology. In fact, no lifetime limiting mechanism has been clearly identified for this insulation.

According to T.H. Blewitt [14], neutron embrittlement of the copper should not be a factor. Up to a fluence of 10^{20} n/cm^2, there should be no significant loss of ductility in copper or any other metal with face-centered-cubic crystals. Blewitt irradiated pure copper crystals to an irradiation of 10^{22} n/cm^2 on the HIFR reactor at room temperature and measured no significant change in the yield strength from the unirradiated case. Therefore, copper embrittlement has been ignored.

(3) ETF/FED Design Examples

A recent ETF bundle divertor magnetic design was developed by T.F. Yang [15]. Dimensions, except for currents, are shown in Figure 2. Each L-shaped coil near the main plasma required 6.72 MAT, while each coil far from the main plasma required 4.8 MAT. If a 10 cm thick coil case and 20 cm of tungsten-titanium hydride shielding are used, then a cross-section of at least 54 cm x 74 cm should be available for each conductor, or an overall current density in the near conductors of 1.89 kA/cm^2 and 1.2 kA/cm^2 in the far conductors.

Significant parameters of the electrical and thermal system were reported at the ETF Interim Design Review [15]. The reported power in the near coils of 48 MW per coil was undesirable, but there was very little design freedom to improve the situation, with current day conductor technology, which is limited at best to about 60 % overall packing factor in the conductor. However, A. Harvey's group at LASL is currently collaborating with Pyrotenax to develop a conductor with an overall current density of 75 %. The new technology would involve larger conductors and preformed ceramic rings, instead of tamped in powder. They also hope to eliminate the failure mechanisms of copper erosion and ceramic break corrosion by using external steel or nickel-alloy conductors, without breaks. I have used the goal of 75 % packing factor as an input in a model of an internally-cooled conductor in order to find an ETF example with desirably low recirculating power.

One solution with a number of desirable features is shown in Tables I and II. The recirculating power in each of the front coils is down to 28.2 MW. The maximum temperature in the copper is only 55 C, keeping the copper resistivity low and considerably lower than allowable temperatures. Even with 30 paralleled leads to reduce the electric field in the insulation and the leakage current losses, the MgO loss/unit length is still 1,160 W/m, comparable to the 5,120 W/m lost in the copper. This necessitates a 134 kA bus for each of the front coils. The water velocity is 10 m/s and the head drop for each single turn hydraulic circuit is 12 atmospheres.

Currently, the ETF design center is considering a Fusion Energy Device (FED), which would have a reduced mission from that of the original ETF, such as a plasma Q = 5, and which would also, hopefully, have significant economies compared with the original ETF mission. A key feature of the FED is the reduction of the overall integrated duty factor to .02, from the ETF duty factor of .5. This allows both lower current and lower shielding in a bundle divertor coil. A possible FED bundle divertor design was generated by reducing the shielding by 10 cm, and keeping the original major machine and bundle divertor dimensions, while reducing all magnetic fields to reflect the reduced mission. This leads to a bundle divertor front coil requirement of 5.05 MAT, with an overall conductor current density of 1.03 kA/cm^2, as shown in Figure 2. The candidate conductor for the front coils is shown in Figure 1.

The parameters of a candidate FED bundle divertor design are shown in Tables III and IV. All limitations have now been greatly relaxed. The power requirement of each front coil is only 10.9 MW, while the entire bundle divertor system requires slightly over 30 MW. The water velocity has been reduced to 5 m/s, significantly reducing any vibration problems that might arise at the higher water velocity. The number of terminal pairs has been held at 30, which reduces the loss/length due to leakage currents to 246 W/m, despite the decreased shielding, while the nuclear heating/unit length has risen to 1,287 W/m. The dc terminal voltage is now only 67 V, greatly reducing the possibility of insulation electrolysis or electrical breakdown, even in a highly irradiated environment.

If the insulation thickness is reduced and the heat flux from the insulation is held constant by placing more conductors in parallel, the electrical bus current must increase. In the reference design, with 7.6 kA conductors and 30 parallel turns per coil, two 105 kA busses are required for the near coils and two 60 kA busses for the far coils, if the conductors are connected $\pm$ to ground. If standard copper bus is designed for a total voltage drop of 10 V and costs \$50/kA-m (9), then the bus losses would equal 4.5 MW and cost \$4.5 M for a 200 m run, forward and return. Large rectifiers have been purchased to drive the toroidal field coils of

ORMAK, Alcator C and TFTR at a specific cost of only \$4/kW, including transformers and switchgear. If this is still possible, then the rectifiers and rectifier-transformers would cost \$2.0 M. For the reference design, both the buswork and the rectifier costs will be functions of current only, so doubling the number of parallel turns will nearly double the cost of the electrical circuits. While not clearly desirable, there is some flexibility in this trade-off, if recirculating power is to be reduced further.

While an optimization code could certainly be written for the total electrical energy, the trade-offs are such that judgment on design limitations and inherent inaccuracies in modeling overwhelm the prospect of there being any reality to the computer-predicted gains in system performance. The two candidate systems were selected by the personal judgment of the author, after inspecting 36 possible designs for each system.

The technology of jacketed, MgO-insulated coils presents the safest way of doing magnet design at high irradiations. A disadvantage of the current technology is that it has a moderately low overall packing density. This could hopefully be remedied by a development program to work with larger billets for the same insulation filling gap or with lower filling gaps. In order to be attractive, more benefit can be imagined from coil topology optimization, relaxation of physics constraints or changes in overall reactor dimensions than from conductor size optimization.

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Table I

ELECTRICAL PARAMETERS OF ETF BUNDLE DIVERTOR

Joule heating	27.7 MW
Total electric power consumption	28.2 MW
Turns per coil	750 turns
Terminal pairs	30 pairs
Terminal voltage, dc	144 V
Conductor current	8,955 A
Copper resistivity	2.32 x 10**-8 (Ohm-m)
Overall current density	1.89 kA/cm**2
Bus current	134 kA

Table II

THERMAL PARAMETERS ETF BUNDLE DIVERTOR

Conductor height	2.0 cm
Coolant channel height	6.0 mm
Water inlet temperature	20 C
Water outlet temperature	51 C
Inlet-outlet head loss	12 atmospheres
Water velocity	10 m/s
Ideal pump power	.3 MW
Heat flux	21.8 W/cm**2
Maximum temperature in the copper	55 C
Joule loss/unit length	5120 W/m
MgO loss/unit length	1160 W/m
Nuclear heating/unit length	117 W/m

Table III

ELECTRICAL PARAMETERS OF FED BUNDLE DIVERTOR

Joule heating	10.86 MW
Total electric power consumption	10.94 MW
Turns per coil	662 turns
Terminal pairs	30 pairs
Terminal voltage, dc	67 V
Conductor current	7,625 A
Copper resistivity	2.23 x 10**-8 (Ohm-m)
Radiation induced resistivity	4.1 x 10**-9 (Ohm-m)
Overall current density	1.03 kA/cm**2
Bus current	114 kA

Table IV

THERMAL PARAMETERS OF FED BUNDLE DIVERTOR

Conductor height	2.5 cm
Coolant channel height	7.5 mm
Water inlet temperature	20 C
Water outlet temperature	43.4 C
Inlet-outlet head loss	2.7 atmospheres
Water velocity	5 m/s
Ideal pump power	.05 MW
Heat flux	11.9 W/cm**2
Maximum temperature in the copper	45.9 C
Joule loss/unit length	2,278 W/m
MgO loss/unit length	246 W/m
Nuclear heating/unit length	1,287 W/m

Appendix : Program Listing of BUNDLE LCOIL

```
c BUNDLE EXTKUL is an open-loop version of BUNDLE LCOIL, which analyzes
c   rather than sizing a magnet conductor for a highly-irradiated magnet,
c   using the technology developed by Pyrotenax of Canada, Ltd, for
c   accelerators.  The conductor consists of an externally-cooled, squared-off
c   conductor, with MgO powder insulation, in a water-tight sheath.  This
c   first program asssumes that the development effort at the LAMPF facility
c   at LASL will succeed in its goal of producing a conductor with 75 %
c   overall packing factor.
 implicit real(i-n,I-N)
 integer n,ma,mh,mwthick,mv,NR,NW
2000 format(v)
      NR=5
      NW=6
      kCu=350.
      kmon=21.8
      Tin=20
      Deltat=10
c     kCu is the thermal conductivity of copper (W/m-K)
c     kmon is the thermal conductivity of monel (W/m-K)
c     Tin is the inlet temperature of the cooling water (C)
c     Deltat is the wall drop (C).  The above input is just a first
c     guess
      Tavguess=100.
      Tmaxguess=150
c       h is the height of  conductor copper, flat-to-flat (m)
c       a is the height of conductor cooling channel, flat-to-flat (m)
c       Tavguess is the first guess at the copper average temperature (C)
c       Tmaxguess is the first guess at the copper maximum temperature (C)
      Ampturns=6.72e6
      Vleg=1.2
      Hlegtor=1.2
      Hlegrad=1.2
      Npairs=30.
c       Ampturns is the total number of ampere-turns in one magnet (A-T)
c       Vleg is the height of the vertical leg of an L-coil (m)
c       Hlegtor is the length of a horizontal leg in toroidal direction (m)
c       Hlegrad is the length of a horizontal leg in radial direction (m)
c       Npairs is the number of pairs of leads paralleled at the bus ()
      Pwall=2.4*10.**6
      Jcond=1.89*10.**7
c       Pwall is the neutron wall-loading of the reactor (W/m**2)
c       Jcond is the current density over the entire conductor (A/m**2)
      duty=.89
      avail=.5
      years=5
c       duty is the single-cycle duty factor ()
c       avail is the integrated plant availability ()
c       years is the desired lifetime of the magnet (yr)
      Shthick=.3
      Npar=4
c       shield is the shield material ()
c       Shthick is the shield thickness (m)
c       Npar is the number of parallel conductors in one lead ()
      RhoH2O=1000.
      CpH2O=4178
      CondH2O=.61
c       RhoH2O is the density of water (kg/m**3)
c       CpH2O is the specific heat of water (J/kg-C)
c       CondH2O is the thermal conductivity of water (W/m-C)
      do 3004 mh=1,3
```

```
      h=.005+mh*.005
      do 3003 ma=1,3
      aoverh=.1+.05*ma
      do 3002 mwthick=1,2
      wthickoverh=.025+.05*(mwthick-1.)
      do 3001 mv=1,2
      v=5.*mv
c       a is the height of the water-cooling channel (m)
      a=h*aoverh
c       wthick is the wall thickness of the cooling channel (m)
      wthick=wthickoverh*h
      Tmax=Tmaxguess
      Tav=Tavguess
      do 3000 n=1,4
c     shield is the shield material.  0 means a tungsten and
c     titanium hydride shield.  1 is a stainless steel and borated
c     water shield
 shield=1
       if (shield .eq. 0) Atten=13
          if (shield .eq. 1) Atten=11
c       Fluence is the neutron fluence at the surface of the
c         coil (n/cm**2)
       Fluence=.44e16*Pwall*duty*avail*years*exp(-Atten*Shthick)
c       Atomdens is the atomic density of copper (atoms/cc)
       Atomdens=6.023e23*8/64
c       efoldcu is the e-folding distance of neutron capture in copper (cm)
       efoldcu=10.
c       Transmudens is the density of transmuted atoms in copper (atoms/cc)
       Transmudens=Fluence/efoldcu
c       appm is the atomic parts per million of transmuted atoms ()
       appm=Transmudens*1.e6/Atomdens
c        Nucheat is the volumetric nuclear and gamma heating (W/m**3)
       Nucheat=18.8*Pwall*exp(-Atten*Shthick)
c         Rhocu is the thermal resistivity of copper (m-K/W)
       Rhocu=1/kCu
c         Rhomon is the thermal resisitivity of monel (m-K/W)
       Rhomon=1/kmon
c       Acu is the cross-section area of copper in the conductor (m**2)
       Acu=h**2*Npar
c       Tjack is the jacket thickness (m)
       Tjack=h/(16*1.63)
c       Hjack is the flat-to-flat height of the jacket  (m)
c         This is somewhat arbitrary, based on known goals of LASL program
c         to achieve overall packing factor of .75.
       Hjack=h*1.8/1.63
c       Tins is the insulation thickness (m)
       Tins=(Hjack-h-Tjack)/2.
c       Ajack is the area of the copper, in sulation and jacket (m**2)
       Ajack=Hjack*Hjack*Npar
c         Acond is the total conductor area including cooling channels (m**2)
      Acond=Npar*(h+2*Tins+2*Tjack)*(h+2*Tins+2*Tjack+2*wthick+a)
c       Qnuc is the dissipation per unit length due to nuclear heating (W/m)
       Qnuc=Nucheat*Ajack
c        Pacfac is the overall packing factor (copper/conductor)
       Pacfac=Acu/Acond
c       Jcu is the maximum current density in the copper itself (A/m**2)
       Jcu=Jcond/Pacfac
c       Icond is the conductor current    (A)
       Icond=Jcond*Acond
c       Jjack is overall current density in conductor and jacket (A/m**2)
       Jjack=Icond/Ajack
```

```
c       Lturn is the length of a single turn (m)
       Lturn=2.*(Vleg+Hlegtor+Hlegrad)
c       Nturns is the number of turns required ()
       Nturns=Ampturns/Icond
c       Minbend is the maximum permissible bending radius (m)
       Minbend=12.*Hjack
c       dpn is the expected displacements per neutron after annealing
       dpn=60
c       dpa is the expected lattice displacements per atom
       dpa=dpn*appm*1.e-6
c       Rholattice is the electrical resistivity of the copper (Ohm-m)
c       due to lattice displacements.
      if ( dpa .lt. .001 ) go to 17004
      go to 17005
17004       continue
       Rholattice=(dpa/.001)*.4*10.**(-8)
      go to 17006
17005       continue
       Rholattice=.4*10.**(-8)
17006     continue
c       Badtrans is the badness ratio of additional resistivity () due to a
c       single transmutation over that due to a single lattice displacement
       Badtrans=3.5
c       Rhotransmu is the electrical resistivity of the copper due to
c  transmutations of the copper into zinc and nickel   (Ohm-m)
       Rhotransmu=Badtrans*appm*(.0148*10.**(-8))/300.
      print,"appm,Badtrans",appm,Badtrans
      print,"Rhotransmu",Rhotransmu
c       Rhotemp is the electrical resistivity of copper as a function of
c       temperature. (Ohm-m)
       Rhotemp=(1.48 + .00754 * Tav)*1.e-8
      print,"Tav",Tav
      print,"Rhotemp",Rhotemp
c       Rhocu is the total electrical resistivity of the copper (Ohm-m)
       Rhocu=Rhotemp + Rholattice + Rhotransmu
      print,"Rhocu",Rhocu
c       Qprime is the dissipation per unit length (W/m)
       Qprime=Rhocu*Jcu**2*Acu
      print,"Qprime",Qprime
c       Jsquarerho is the power/volume dissipated in the conductor (W/m**3)
       Jsquarerho=Rhocu*Jcu**2
c       Tdiffcu is the difference between the copper hot-spot and cold-spot
c       temperatures (C)
       Tdiffcu=(Jsquarerho+Nucheat)*h/(2*Npar*kCu)
c       Turndiss is the power dissipated per single turn (W)
       Turndiss=Lturn*Acu*Jsquarerho+Lturn*Acond*Nucheat
c       Turndisse is the electrical power dissipated per turn
       Turndisse=Lturn*Acu*Jsquarerho
c         Qcu is the heat flux into the coolant tubes (W/m**2)
       Qcu=Acu*Jsquarerho/(Npar*Hjack)
c       Coildiss is the power dissipated per coil (W)
       Coildiss=Turndiss*Nturns
c       Coildisse is the electric power dissipated per coil (W)
       Coildisse=Turndisse*Nturns
c       Acondtotal is the area required by all the turns of the coil (m)
       Acondtotal=Nturns*Acond
c         Nchannel is the number of cooling channels in a conductor ()
       Nchannel=Npar*Hjack/(a+2*wthick)
c       Qh is the heat flux into the water-cooling channel (W/m**2)
       Qh=Turndiss/(Lturn*4*a*Nchannel)
c       Pw is the wetted perimeter (m)
```

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      Pw=4*a*Nchannel
c       Achan is the area of the coolant channel (m**2)
      Achan=a**2*Nchannel
c       Dh is the hydraulic diameter (m)
      Dh=4*Achan/Pw
c       Visc is the viscosity of water as a function of temperature (kg/s-m)
      Visc=(Tin+20.)**.9*(Tin/400 + 1.)
           Visc=95./Visc
           Visc=Visc/3600
c     Gm is the mass flow rate/unit area
      Gm=RhoH2O*v
c       Re is the Reynold's number
      Re=Gm*Dh/Visc
c       Pr is the Prandtl number
      Pr=Visc*CpH2O/CondH2O
      do 3006 m=1,5
c       HGiar is the heat-transfer coefficient, according to the
c       Dittus-Boelter correlation as modified by Giarratano
      HGiar=.259*(CondH2O/Dh)*Re**.8*Pr**.4*(Tin/(Tin+Deltat))**.716
c       Deltat is the wall drop (C)
      Deltat=Qh/HGiar
3006  continue
c       Deltiojoule is difference between outlet and inlet temperature (C)
c       due to Joule heating.
      Deltiojoule=Turndisse/(v*RhoH2O*Achan*CpH2O)
c         Deltionuc is the difference between outlet and inlet temperature (C)
c         due to nuclear heating.
      Deltionuc=Lturn*Acond*Nucheat/(v*RhoH2O*Achan*CpH2O)
c       Npairs is the number of terminal pairs per coil ()
c       Vrterm is the resistive terminal voltage at the coil
      Vrterm=Coildisse/(Icond*Npairs)
c       Vterm is the total terminal voltage at the coil
      Vterm=Vrterm*1.4
c       Efield is the dc electric field across the insulation.
      Efield=Vterm/Tins
c       KMgO is the thermal conductivity of MgO. (W/m-K)
c       Thermophysical properties of MgO from Kingery,Bowen and Uhlmann,
c       Introduction to Ceramics, Wiley-Interscience, 1976
c       Correlation by Schultz.
      Tnorm=Tmax/100.
         KMgO=-.7728+84.835/Tnorm-62.696/Tnorm**2+16.23/Tnorm**3
c       RhoMgO is the thermal resisitivity of MgO. (m-K/W)
      RhoMgo=1/KMgO
c       RTPRconv is the conversion factor (Gray/s/W/m**2)
c         scaling from the RTPR design
c       for a ceramic facing combine neutron and gamma radiation
c       from W/m**2 to Gray/s
      RTPRconv=.05
c       Magrad is the maximum radiation absorption in the magnet insulation
c       in Gray/s
      Magrad=RTPRconv*Pwall
c       Sigrad is the electrical conductivity of the insulator due to
c       irradiation.  Data taken from Clinard's contribution to the
c       LASL 1979 Special Purpose Materials Annual Progress Report
      Sigrad=5*10.**-6*(Magrad/6.6)**.66
c       Emgo is the electric field in the MgO
      Emgo=Vrterm/Tins
c       Jmgo is the current density in the MgO
      Jmgo=Emgo*Sigrad
c       Powmgo is the power density in the MgO due to leakage currents
      Powmgo=Jmgo**2/Sigrad
```

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c        Qmgo is the heat flux in the insulation
       Qmgo= Powmgo*Tins
c        Deltatmgo is the temperature rise in the MgO
       Deltatmgo=(Powmgo+Nucheat)*Tins**2/(2*KMgO)
c             Powlmgo is the power dissipation per unit length in the MgO (W/m)
       Powlmgo=4*Tins*Hjack*Powmgo
c             Deltiomgo is inlet-outlet temperature drop in the water (C)
c             due to leakage current in the MgO
       Deltiomgo=Powlmgo*Lturn/(v*RhoH2O*Achan*CpH2O)
c             Qmon is the heat flux generated in the monel (W/m**2)
       Qmon=Nucheat*wthick
c             Qinmon is the heat flux entering the monel (W/m**2)
       Qinmon=2*Qmgo+Qcu
c             Deltatmon is the temperature drop in the monel coolant wall (C)
               Deltatmon=Qinmon*wthick/kmon+Qmon*wthick/(2*kmon)
c        Deltiotot is the inlet-outlet temperature drop in the water (C)
c          due to combined Joule heating, nuclear heating and leakage current
       Deltiotot=Deltiojoule+Deltionuc+Deltiomgo
c        f is the friction factor.()
c This expression is good for clean steel pipe, if Re < 10.**5
       f=0.04/(Re**0.16)
c        fKoo is the friction factor.  Good for Re > 2000 in smooth tube
       fKoo=.0014 + .125/(Re**.32)
c        Delpl is the pressure drop per unit length
       Delpl=2*fKoo*RhoH2O*v**2/Dh
c        Powpl is the ideal pump power per unit length
       Powpl=v*Achan*Delpl
c        Pdelt is the pressure drop per hydraulic channel
       Pdelt=Delpl*Lturn
c        Deltmu is the temperature rise due to isenthalpic expansion.
c        Mu is the Joule-Thomson coefficient -dT/dP at constant enthalpy.
       Mu=CondH2O/(RhoH2O*CpH2O)
            Deltmu=Pdelt*Mu
c   Deltio is the difference between inlet and outlet water
c     temperature (C)
       Deltio=Deltiotot+Deltmu
c        Tout is the outlet temperature of the water
       Tout=Tin+Deltio
c        Tmax is the copper hot spot temperature (C) with the specified water
          write(NW,2000)Deltatmon
          Tmax=Tout+Tdiffcu+Deltat+Deltatmgo+Deltatmon
c         Tav is the average temperature in the copper (C)
       Tav=Tmax-Tdiffcu/2.
3000  continue
c        SigmapH2O is the stress in the jacket due to the water pressure (Pa)
       SigmapH2O=Pdelt*a/(h-a)
c        Pumpower is the pump power per coil
       Pumpower=Powpl*Lturn*Nturns
c        Elecpump is the electrical power need for the pump motors
       Elecpump=1.5*Pumpower
         Totalpower=Elecpump+Coildisse
 print,"****************************************"
 print,"h,Tins,Tjack",h,Tins,Tjack
 print,"wthick,a",wthick,a
 print,"v",v
 print," "
 print," "
 print,"Electric power dissipation (MW)",Coildisse*1.e-6
 print," Total power (MW)",Totalpower*1.e-6
 print," "
 print,"Tmax",Tmax
```

```
 print,"Tav",Tav
 print,"Tout",Tout
 print,"Deltio",Deltio
 print,"Deltiojoule,Deltionuc,Deltiomgo",Deltiojoule,Deltionuc,Deltiomgo
 print,"Deltmu",Deltmu
 print,"Tdiffcu",Tdiffcu
 print,"Deltatmgo",Deltatmgo
 print,"Deltatmon",Deltatmon
3001  continue
3002  continue
3003  continue
3004  continue
      end
```

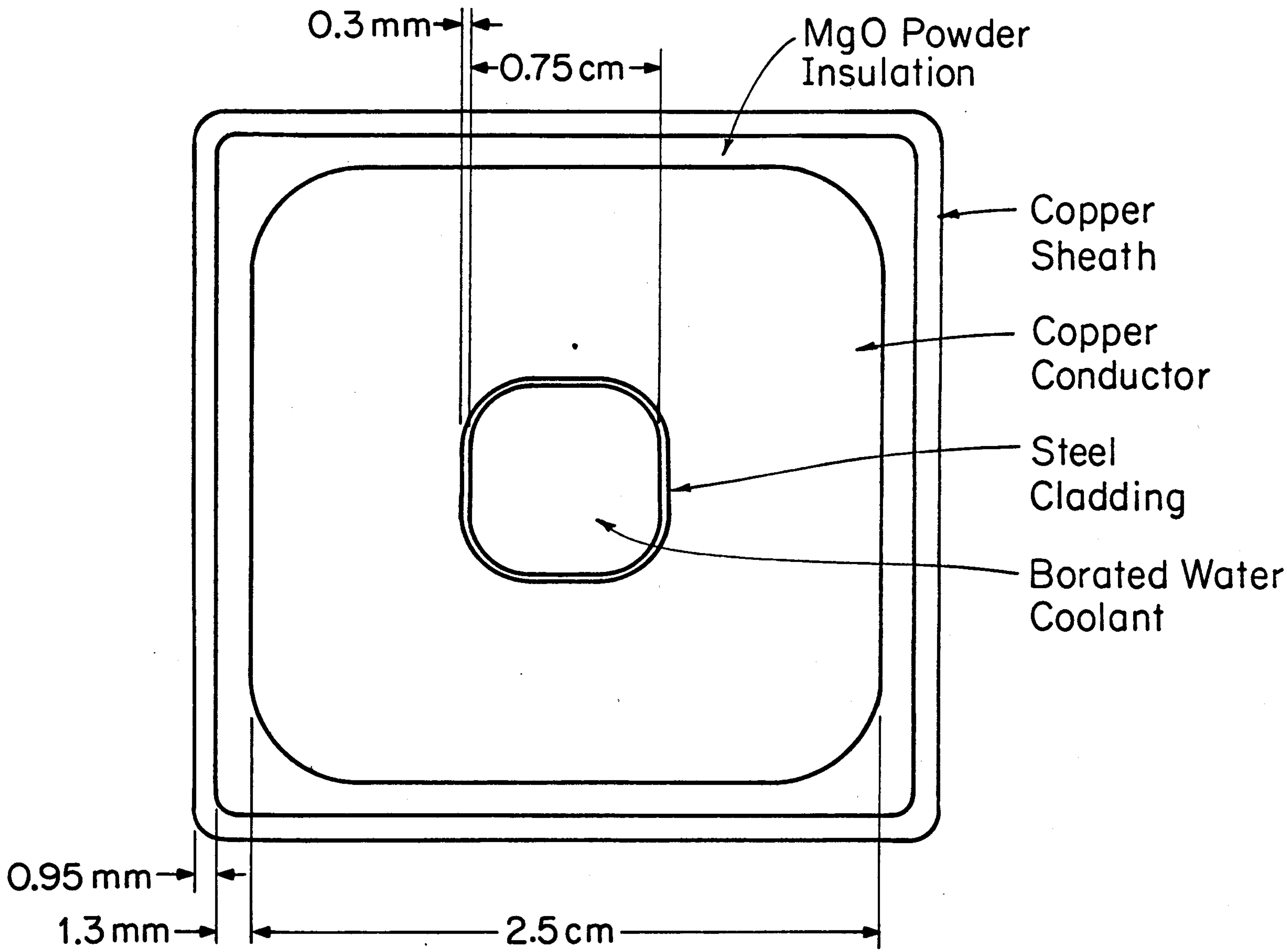

Figure 1
Conceptual Conductor Design for an ETF Bundle Diverter Coil

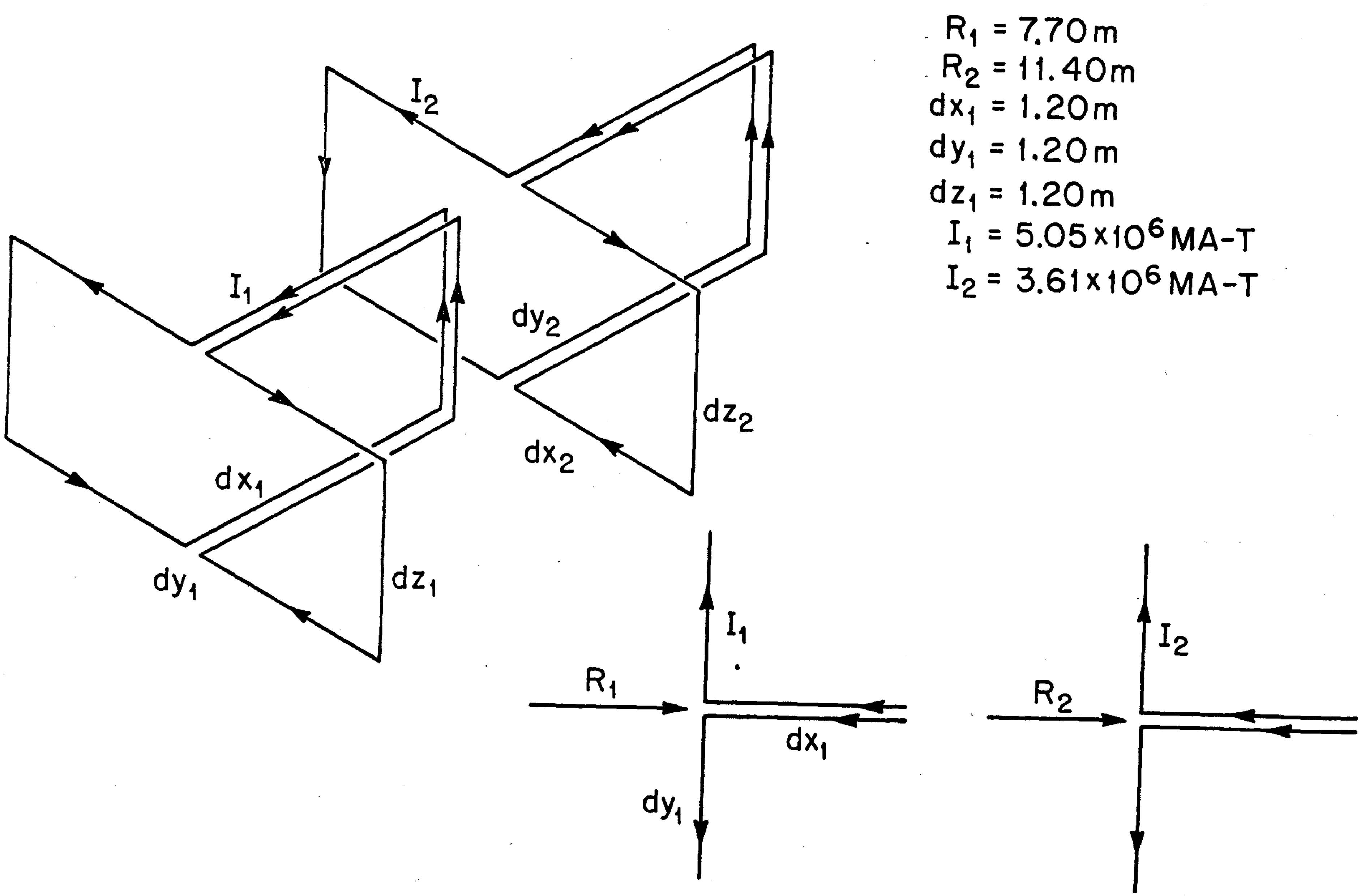

Figure 2
ETF Bundle Divertor Example Design by T. F. Yang