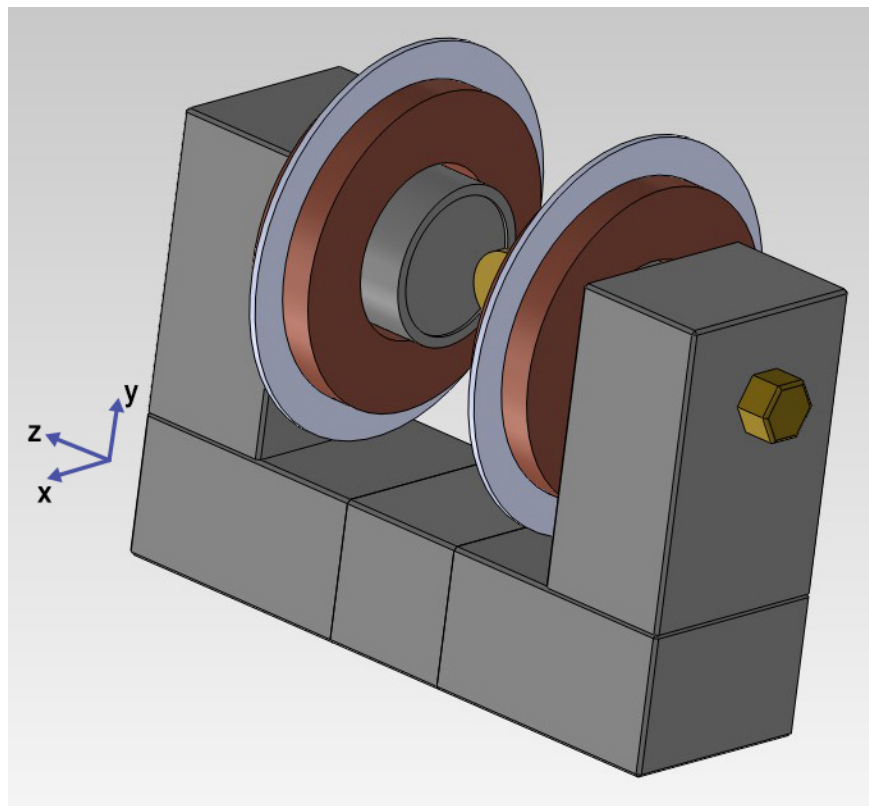


## 2 Technical Quotation

### 2.1 Technical Approach

The National Institute of Standards and Technology (NIST) has a requirement to add to its Small Angle Neutron Scattering (SANS) instruments, the unique capability to detect changes in the magnetic microstructure of materials subjected to an oscillatory magnetic field. This capability requires a custom designed electromagnet and associated power supply and control system. This system will be utilized in the NIST Center for Neutron Research (NCNR) in Gaithersburg, MD.



**Figure 1: 3470HFAC dipole electromagnet showing the magnetic circuit and the SANS sample volume.**

GMW Associates is proposing to design a Model 3470HFAC dipole electromagnet with high frequency AC operation for the SANS application. The magnetic circuit elements are illustrated in Figure 1 which also indicates the volume in which the SANS sample is contained (20mm in diameter and 3mm thick). The pole gap adjustment is to be achieved by removing the pole,

inserting a pole spacer and replacing the pole. The vertical white fins are ceramic discs which assist in transporting the heat generated within the body of the coil to the exterior.

### 2.1.1 Coil Specifications

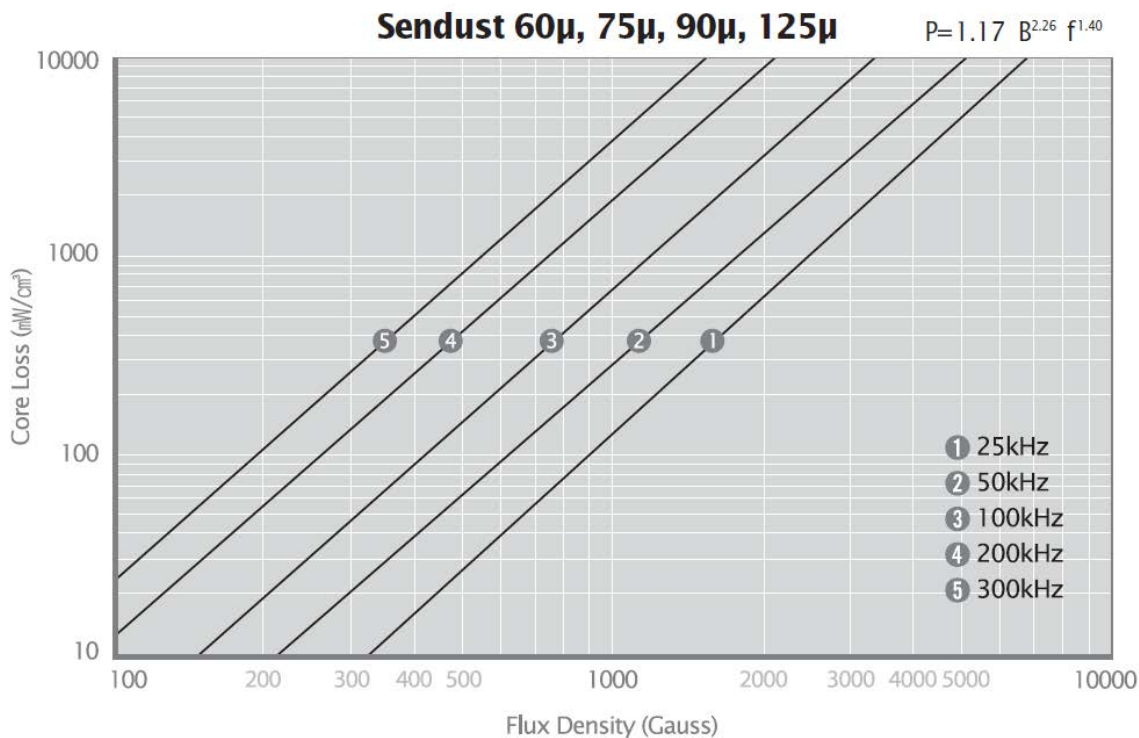
The coil is fabricated from Litz conductor which is available in rectangular braided ribbon comprising many strands of 36AWG insulated wire ( $\varnothing$  0.127mm). Each coil is wound as a double pancake coil with electrical terminations located on the outer diameter of the coil. In order to achieve the desired coil inductance using a standard product each coil is wound using three-in-hand winding of 11.43mm x 0.97mm, 288 strand Litz wire (0.450" x 0.038"). This produces a 14 turn coil with 7 turns per layer. A ceramic disc is located on the median plane of the coil and serves to electrically insulate the layers of the coil while assisting in extracting heat from the interior of the coil. The coil is to be vacuum impregnated with epoxy in order to immobilise the conductor and to assist with the distribution of heat. The coil will be mounted to the vertical post of the yoke so that the pole can be independently removed for pole gap adjustment.

**Table 1: Coil parameters for each coil. The coil is wound as a double layer pancake with 14 turns per coil.**

| Coil Parameter | Value | Unit       |
|----------------|-------|------------|
| Inner diameter | 49    | mm         |
| Outer diameter | 89    | mm         |
| Depth          | 26    | mm         |
| Inductance     | 136.9 | $\mu$ H    |
| Resistance     | 4.78  | m $\Omega$ |

### 2.1.2 Yoke and Pole Specifications

The yoke and pole are fabricated from soft magnetic powdered metal (PM) core material. More specifically the material is Sendust which is a widely used material for inductor cores and chokes; it is an alloy of Fe, Si and Al. The material is selected for its low core loss, its machinability into complex forms and its availability in standard block sizes up to 140x60x40mm. This core material is not sintered and represents a high saturation field ( $B_{sat}=1.0$  T) and low permeability ( $\mu=60$ ). These magnetic properties have been incorporated into a finite element analysis and the suitability of the material for the present application has been confirmed.



**Figure 2: Volumetric core loss is indicated here showing the frequency and field power law dependencies. For the core heating calculations performed these power laws are assumed to extend down to 10 and 20 kHz.**

### 2.1.3 Magnet Excitation and Field Performance

The magnet is to be energised using 7548 power amplifiers from AE Techron. The 7548 amplifiers can be configured in series or parallel with up to four amplifiers operating as a single system. The coils may be connected in series or individually excited. This allows for several operating configurations depending on how the coils and amplifiers are connected. One key advantage of this approach is to provide an initial configuration for assessment and then to add amplifiers later as greater performance is required.

Figure 3 illustrates the peak magnetic fields achievable as a function of frequency when the coils are connected in series. The amplifiers are connected in series providing higher peak voltage as more amplifiers are added. The effective peak voltage of the amplifier bank is indicated for each configuration. The dashed line illustrates a peak field of  $50\text{mT}_{\text{RMS}}$  ( $70\text{mT}$  peak).

Figure 4 illustrates the magnetic field performance when the coils are individually excited; symmetrical excitation is assumed so that each coil has the same number of amplifiers. Note that the peak voltage is limited to 680V so that electrical insulation does not require a complex solution.

Figure 5 illustrates the performance when the amplifiers are connected in parallel providing higher peak currents. This configuration is useful at the lower frequency range as the available voltages are lower. Operation at higher currents will result in greater coil heating and it is not known if this mode of operation will be able to achieve continuous operation.

One final mode of operation is achieved with resonant coupling of the supply to the magnet. If the magnet is connected in parallel with a carefully chosen capacitor to tune the circuit to a particular frequency then considerably higher currents may be achieved for a given amplifier bank. In this mode of operation the width of the resonant band will define the useful frequency range of operation. A selection of frequency bands may be achieved by varying the resonant capacitor.

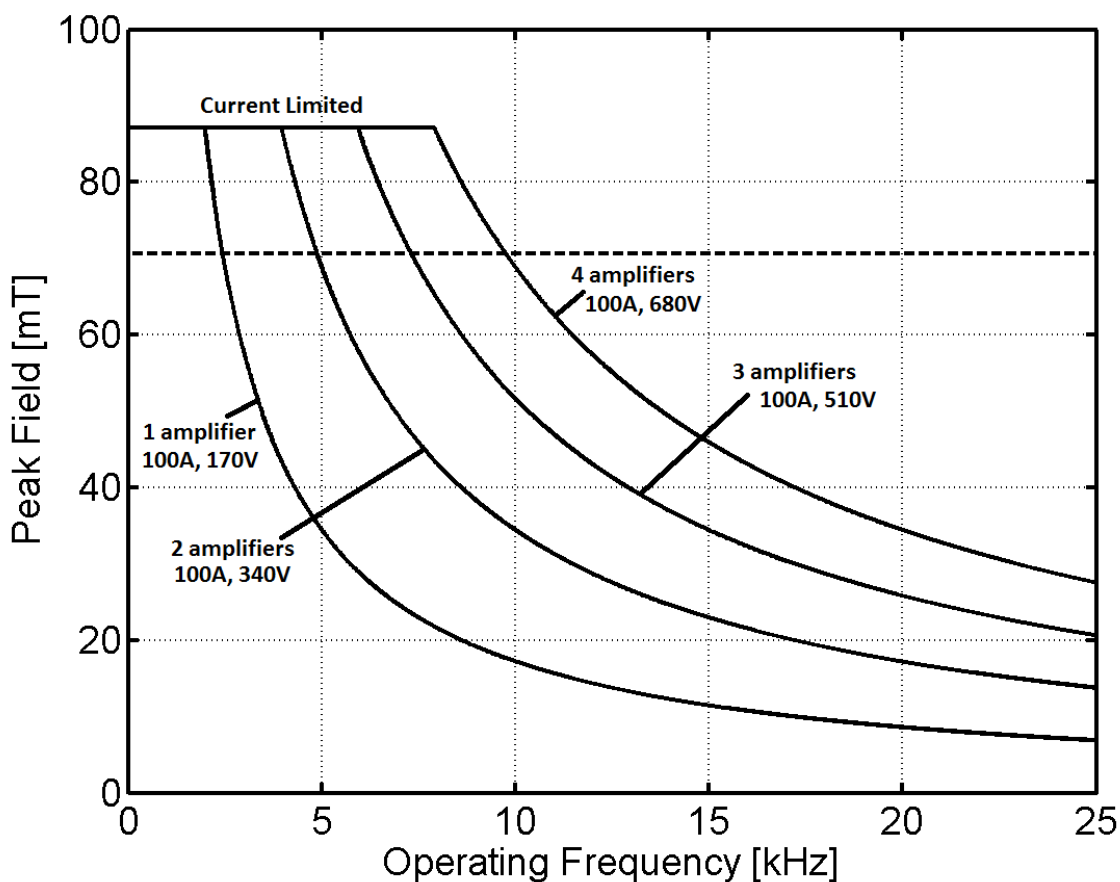


Figure 3: Field performance as a function of frequency for one through four amplifiers with a pole gap of 35mm. Coils are connected in series. The dashed line represents 70mT or 50mT<sub>RMS</sub>. Amplifiers are connected in series.

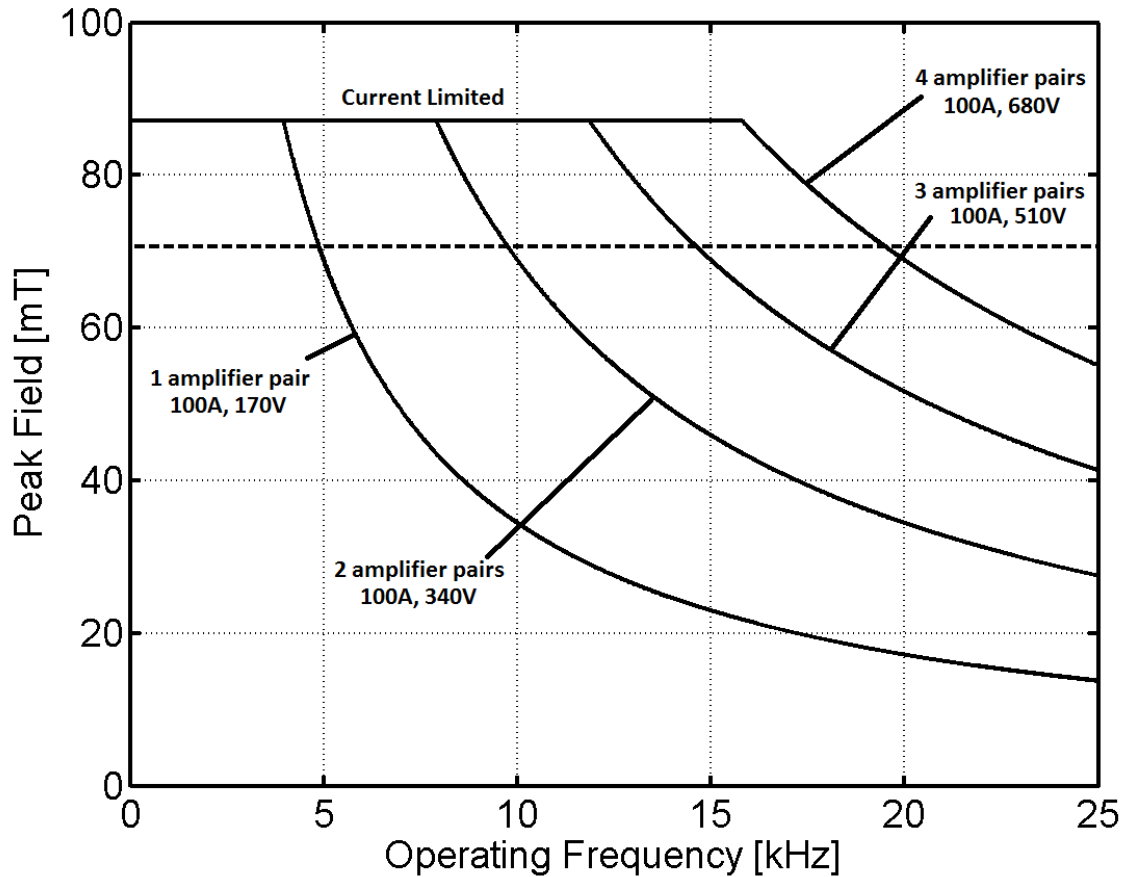


Figure 4: Field performance as a function of frequency for one pair through four pair of amplifiers (two amplifiers through eight amplifiers) with a pole gap of 35mm. Coils are individually excited. The dashed line represents 70mT or 50mT<sub>RMS</sub>. Amplifiers are connected in series.

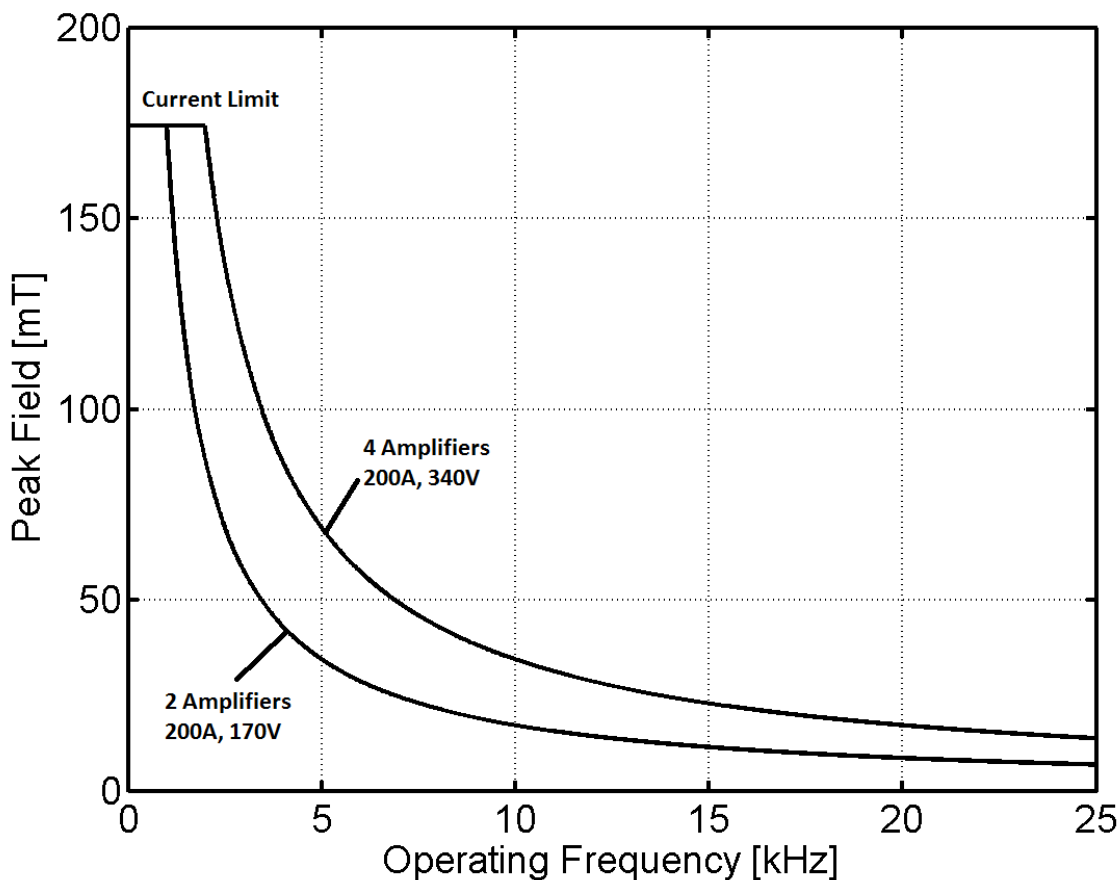


Figure 5: Illustration of series/parallel configuration of amplifiers to create a 200A peak supply. This configuration is useful where higher fields are required at lower frequencies.

### 2.1.4 Field Uniformity

The field uniformity is illustrated in Figures 6 and 7. The field perpendicular to the beam direction is the Bx field. This is shown horizontally across the sample, Figure 6, and vertically across the sample, Figure 7. The Rose shim illustrated in Figure 1 may be further optimized to improve field uniformity.

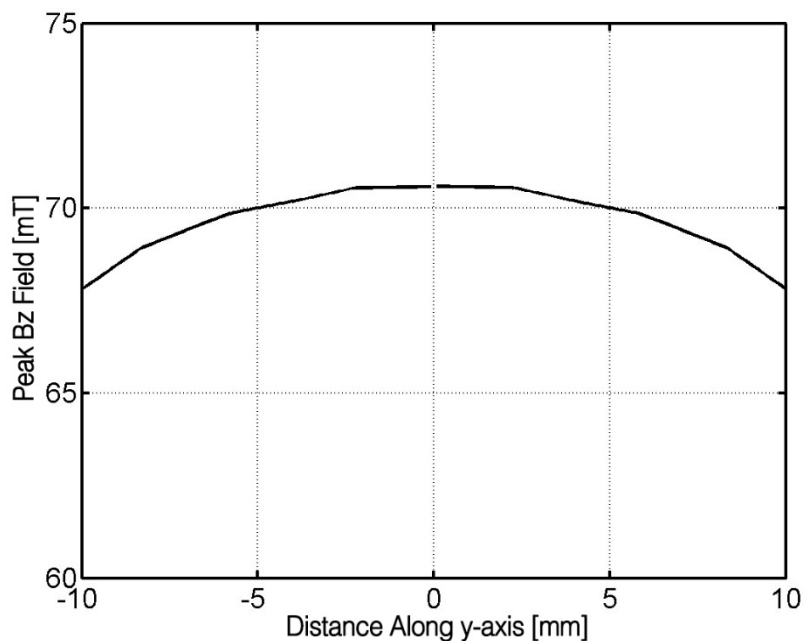


Figure 6: Peak Bz field along the y-axis (transverse to the field) at full excitation.



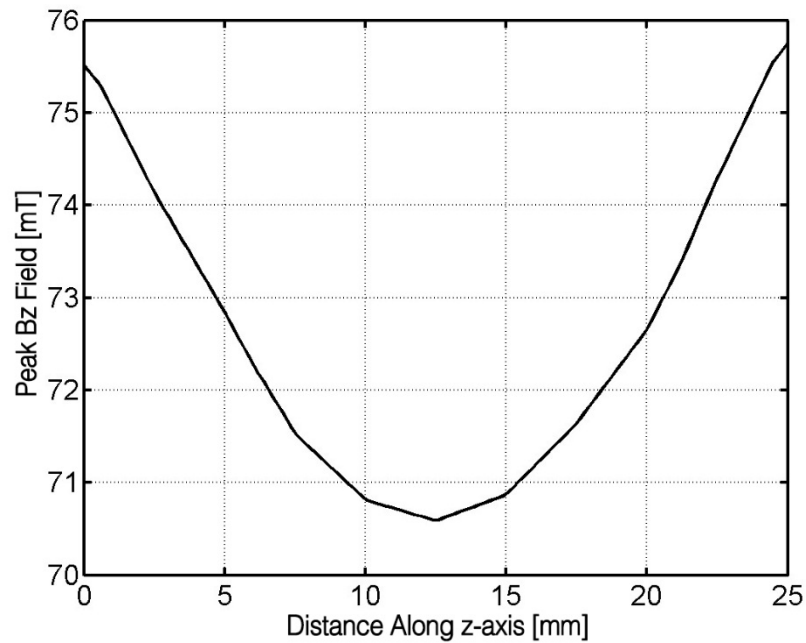
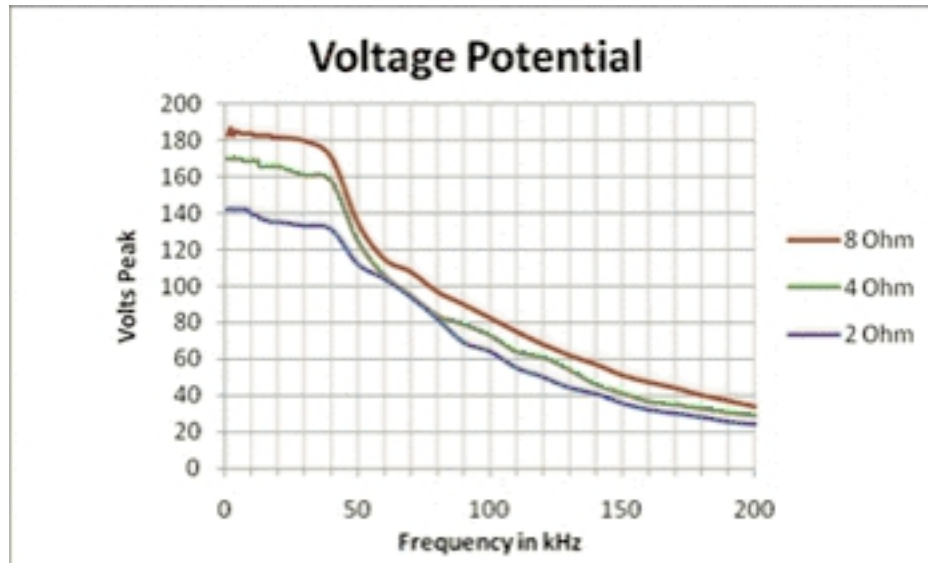


Figure 7: Peak Bz field along the z-axis (along the field) at full excitation

### 2.1.5 Power Supply Specifications

The 7548 power amplifier offers up to 100 Ap power, DC - 100 kHz bandwidth, controlled current or controlled voltage modes of Operation, in a compact 5U size. The 7548 works best with loads of  $2\Omega$  or more. For greater voltage (up to 750Vp) or current, units can be combined in series or parallel.



**Figure 8: The peak voltage depends on frequency and load. This figure reports the published data from AE Techron for the 7548 amplifier.**

For the calculations performed here the peak voltage of 170V is used. This represents the impedance of a single coil at 5kHz. The 7548 Specification sheet is in Appendix A.

### 2.1.6 Computer Control and Monitor

It is envisaged that the System Control be provided by standard GMW components with some software changes. The basis is the 5972 Magnet Control (Item 7 of the Quotations) which includes a National Instrument DAQ, NI USB-6251, with USB interface. This is a 20MS/s DAQ that is used for analog programming of the Power Amplifier (or Amplifiers), monitoring the current and voltage from the Amplifier, monitoring Magnet temperatures and monitoring the Field Transducer (Item 8). It may be that there is a more appropriate DAQ, eg a much higher sample rate 12 bit DAQ. This will be evaluated in the Design of the 3470HFAC System (Item 1 of the Quotations). The control Computer is Item 11 of the Quotations and the application software is Item 12. The software, LVMCTRL, is Item 12 of the Quotation and will be provided as a runtime version. The LabView Source Code will be provided to enable NIST to modify or integrate the software if desired. This Code require LabView 2010 or later which is not included in this Quotation. See Appendices B and C.

Item 8 is a Senis Field Transducer with a very thin Field Sensor and cable which can be mounted in a "Probe Cap" on one Pole. The active area of the Field Sensor is on the Pole axis and the total thickness of the mounting is <1mm. That is, for a 35mm Pole gap the clear gap is reduced to about 34mm by the Field Probe. The frequency response of the selected Transducer is 50kHz (-3dB) which we believe will be adequate. This will be further evaluated in Item 1, Design of the 3470HFAC System. See Appendix D.

A 19" Electronic Rack is included in the Quotations as Item 13. In Q17421 and Q17422 the Rack is bench height with 20U of available mounting height. In Q17423 with four Power Amplifiers (Item 5) the rack is of full height with 40U of available mounting height.

### 2.1.7 Thermal Specifications

The magnet has been designed using Litz wire conductor and very low core loss material in order to minimize the heat load. However, some heating will occur and estimates of size and location of these heat sources are provided in Table 3. The dominant cooling method for this magnet is intended to be natural convection from the surface and the available surface areas proximate to each heat source are tabulated in Table 4 along with estimates of the natural and forced convective cooling available.

Table 2: Summary of calculated sources of heat.

| Losses (real power)   | @81A <sub>P</sub> | @81A <sub>P</sub> |          |
|-----------------------|-------------------|-------------------|----------|
|                       | 10kHz             | 20kHz             |          |
| Coils – resistive     | 31.4              | 31.4              | W        |
| Coils – eddy currents | 4.7               | 18.8              | W        |
| Yoke Body             | 4.7               | 12.4              | W        |
| Pole                  | 17.7              | 46.7              | W        |
| <b>Total</b>          | <b>58.5</b>       | <b>109.3</b>      | <b>W</b> |

Table 4: Exposed surface areas and anticipated cooling capacities.

| Surface areas | Surface Area               | Natural Convection | Forced Convection |
|---------------|----------------------------|--------------------|-------------------|
| Coils         | 335 cm <sup>2</sup>        | 52 W               | 156 W             |
| Cooling fins  | 132 cm <sup>2</sup>        | 21 W               | 63 W              |
| Yoke Body     | 750 cm <sup>2</sup>        | 116 W              | 348 W             |
| Pole          | 127 cm <sup>2</sup>        | 20 W               | 60 W              |
| <b>Total</b>  | <b>1344 cm<sup>2</sup></b> | <b>209 W</b>       | <b>627 W</b>      |

For the yoke body the available surface area is sufficient for natural convection to cool the magnet. However, at higher frequency operation the available cooling to the pole and the coils requires forced convection. The inner surface of the coils and the outer surface of the poles are not in contact. This is required for pole gap adjustment. A thin cylindrical air gap is therefore formed between these, and is available to form a cooling channel through which air can be blown in order to extract the excess heat. The width of this air gap may be made sufficiently narrow and air forced through at sufficient velocity to achieve highly turbulent flow (Reynolds number > 2000) and therefore extract heat with the greatest efficiency.

In order to provide a thermally conductive path from the interior of the coil to the outside air a cooling plate is incorporated into the coil between the winding layers. This cooling plate is fabricated from ceramic ( $\text{Al}_2\text{O}_3$ ) which is electrically insulating but has a high thermal conductivity (25 W/m.K)