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N. Tsoupas

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A Skew Quadrupole for the AGS to minimize the Polarization losses of the Polarized Beams*

N. Tsoupas†, V. Badea, S. Belavia, H. Huang, D. Lehn, R. Lynch, G. Mahler, I. Marneris, J. Sandberg, V. Schoefer, J. Tuozzolo

Brookhaven National Laboratory, Collider-Accelerator Department, Upton, LI, NY 11973, USA

Abstract

The partial helices installed in the Alternating Gradient Synchrotron (AGS) [1] eliminate both, the imperfection and the vertical intrinsic spin resonances thus yielding a 70% polarized proton beam with rigidity 79.4 [Tm] with 2x10^{11} protons/bunch at the end of the AGS acceleration cycle.
The initial beam polarization at the exit of the 200 MeV Linac is measured to be 80%. The 10% loss of the polarization at the end of the AGS acceleration cycle is due to the horizontal spin resonances which are caused by the betatron oscillations of the beam in the presence of the partial helices. To reduce the effect of these horizontal spin resonances on the beam polarization, the "jump Quads method" is applied in the AGS [2] which eliminates, almost all, the horizontal spin resonances and increases the final polarization of the proton beam to the value of 70%. A study [3] shows that these horizontal spin resonances can be totally eliminated by introducing into the AGS ring, skew quadrupoles which linearly couple the beam motions to excite new horizontal spin resonances which minimize the horizontal-spin-resonances caused by the partial-helices.

These skew quadrupoles are excited during the time the polarized beam crosses these horizontal spin resonances. The time interval of the spin-resonance-crossing is of the order of a milliisecond and this requires that the material of the skew quadrupoles is made of ferrite or of laminated iron to minimizes the eddy currents in the conductive parts of the skew quadrupoles.

In this technical note we provide results from the electromagnetic design [4] of the Skew Quadrupole. This study includes the calculation of the magnetic multipoles of the quadrupole and the Ohmic losses in the coils and all the conductive parts of the quadrupoles including the 0.025" thick lamina-

*Work supported by the US Department of Energy

†tsoupas@bnl.gov

tions of the quadrupole. This study presents also results of the pesence of the beam pipe on the magnetic field at the region of the circulating beam. The information provided in this technical note should be sufficient for the reader to reproduce a 3D model of the skew quadrupole and introduce it in the OPERA computer code [4] to obtain the results presented in this paper. This quadrupole will be used in the AGS ring as a skew quadrupole and will be refered in this paper as either skew quadrupole of simply quadrupole.

Keywords: Iron laminated quadrupole magnet

1. Introduction

As part of the EIC project [5] a Research and Development (R&D) effort is under way to increase the polarization of the polarized beams accelerated in the EIC complex with the goal to maximize the polarization value of the polarized proton beam to a value larger than 70% at the final EIC proton energy of 275 GeV.

At the present time the AGS synchrotron is equipped with two partial helices [1] which totally eliminate both the imperfection and the vertical intrinsic spin resonances which occur during the acceleration of polarized protons to a final beam rigidity of 79.4 [Tm] with 2x10^{11} protons/bunch yielding a 65% final polarization of the proton beam.

Although the two partial helices eliminate the imperfection and the vertical intrinsic vertical spin resonances, they fall short in eliminating the horizontal spin resonances. These horizontal spin resonances occur through the interaction of the beam's betatron oscillations with the magnetic field of the partial helices.

To overcome the horizontal spin resonances the method of “jump Quads” [2] is currently being used and the polarization of the beam increases to 70%.

To further increase the polarization of the extracted beam from the AGS, by totally eliminating the horizontal spin resonances, two methods were proposed; The method of using four partial helices in AGS [6] and the method of using skew quadrupoles in the AGS ring [3].

Although theoretical studies show that either method totaly eliminates the horizontal spin resonances the skew quadrupoles method [3] was chosen.

The skew quafrupole method is based on the linear coupling introduced by the skew quadrupoles which can excites horizontal spin resonances that can-

cel the ones caused by the partial helices.
The skew quadrupoles are being used and placed at specific locations on the available space along the straight sections of the AGS. A perspective view of the skew quadrupole is shown in Fig. 1.
In this technical note a brief description of the mechanical design of the skew quadrupole is given, and some of the results from the electromagnetic study of the quadrupole are presented. Namely the magnetic multipoles at a radius R=2 cm, the Ohmic losses including those losses caused by the eddy currents in the coil-conductors and the conducting parts of the quadrupole like the iron laminations.
The electromagnetic study utilizes the 3D-AC-steady state electromagnetic module of the OPERA computer code [4]. In addition the 3D transient electromagnetic module of the OPERA computer code is used to reproduce with better accuracy the magnetic field and the Ohmic losses during the actual operation of the skew quadrupoles. Results from both studies, the AC-steady-state and the transient study are presented.

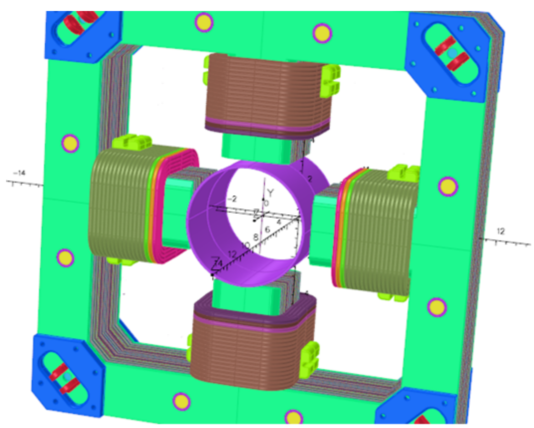

Figure 1: A perspective view of the skew quadrupole. A 3D drawing in "igs" format is imported to the OPERA code which performs the electromagnetic calculations. The green objects are 1/4" thick plates made of magnetic iron to retain the 0.025" thick laminations withing the plates. The little green objects on the outer surfaces of the coils are conducting masses made of aluminum to abduct the heat generated by the coils. This heat abducted by the aluminum masses is removed by water running inside copper tubing which is thermally epoxy-bonded to the aluminum cooling blocks. The copper tuping is not shown in this drawing.

2. Mechanical Considerations of the Skew-Quadrupole

As mentioned earlier the skew quadrupoles will be positioned in available spaces within the straight sections of the AGS ring.
Such spaces are rather short because all the straight sections are occupied by other devices like tune-quadrupoles chromaticity-sextupoles, or other devices which leave only a limited space for the skew quadrupoles.
Fig. 2 is a picture of the available space of 17.5 cm in length for the placement of the skew quadrupole. On the left side of the picture in Fig. 2 are the coils (grey objects), and the iron yoke (green object) of the AGS main magnet and on the right side of the picture is one of the chromaticity sextupoles of the AGS. The space between the AGS main magnet and the sextupole is for the placement of the skew quadrupole.
The drawing in Fig. 3 on the left is a projection of the skew quadrupole on a plane normal the beam direction, and the drawing on the right is a projection of the quadrupoles on a horizontal plane. A 3D drawing of the quadrupole is shown in Fig. 1. The following is a list of items of some of the geometrical constrains that have been applied in the design of the skew quadrupole.

- the length of the quadrupole including the coils, along the beam direction, should occupy a length no greater than 16.51 cm
- the iron core of the quadrupole magnet is of laminated steel of 0.025” thick to reduce the eddy currents.
- the 0.25” thick end-plates showing in green in Fig. 1 are to hold the laminations together.
- the coils should be as far as possible from the center of the quadrupole to reduce the ohmic losses on the coils due to the eddy currents.
- the aperture of the quadrupole should be adequate for the quadrupole to be placed over the beam pipe of the AGS.
- Each of the 17 turns of the conductor is separated in four isolated conductors inside the coil to reduce the eddy currents and minimize

the Ohmic losses due to eddy currents. Each set of the four conductors are electrically connected at the entrance and exit of the coil[1].

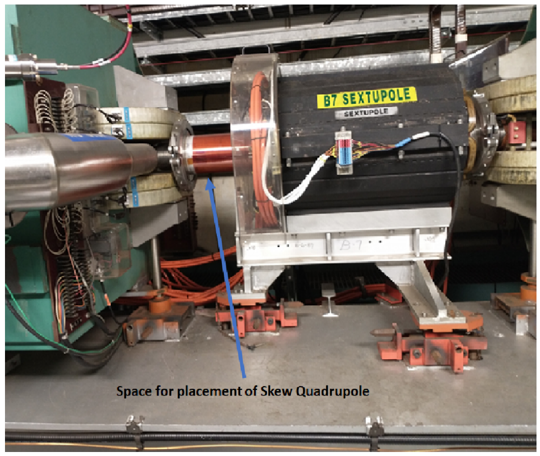

Figure 2: A picture of the B7 straight section of the AGS. The Skew Quadrupole will be placed in the available straight section between the AGS main magnet (green object on the left) and the chromaticity sextupole on the right.

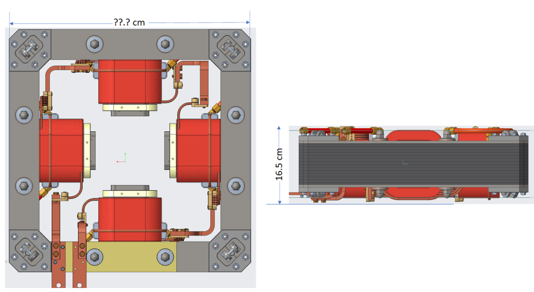

Figure 3: Two 2D drawings of the skew quadrupole. The drawing on the left is a projection on a plane normal to the beam direction, and the one on the right is a projection on a plane which includes the beam direction.

Table 1 shows some dimensions of the skew quadrupole including some information on the coils.

[1]A technical note on this quadrupole will report more details on the mechanical design of this skew quadrupole.

Table 1: Table Some dimensions of the skew quadrupole

Ap-Radius	Length	Width	Vacuum pipe wall	Coil-turns	Cond/turn
[cm]	[cm]	[cm]	[mm]		
8.5	16.5	35	3	17	4

3. Electrical connections and shape of the current pulse to excite the Skew-Quadrupole

Each of the skew quadrupoles will be exited during the time the beam crosses an horizontal spin resonances. Such time corresponds to the beam momentum which satisfies the condition $G\gamma = Q_x + n$ where Q_x is the horizontal tune and n is an integer.
Each quadrupole will be powered by its own power supply and will generate a pulse of a given amplitude for each crossing over a spin resonance during the AGS acceleration cycle.
The red trace shown in Fig. 4 is a schematic shape of a current pulse which will be generated as the beam crosses each horizontal spin resonance. The amplitude of the current pulse will vary depending on the strength of the horizontal spin resonance the beam crosses.
Fig 5 is a typical plot of the current pulses of an individual skew-quadrupole during the acceleration cycle. Note that the current pulses have varied amplitude and are either positive or negative in value.
The four coils of each skew quadrupole are connected in series and the two conductor leads at the bottom of the picture are connected to a bipolar power supply. The drawing on the left in Fig 6 shows the wire connection of the four coils. The "cooling pipes" on this drawing are made of copper material and abduct the heat from the cooling aluminum blocks which are in conduct with each of the coils. The aluminum masses which abduct the heat from the coils are electrically insulated from the conductors of the coils. The drawing on the right is a cross section of the coil which shows that each turn of the coil consists of four electrical isolated conductors which are electrically connected at the entrance and exit of each coil. This splitting of each turn into four conductors and their electrical isolation of these four conductors inside the coil reduces the eddy currents which results in the reduction of the Ohmic losses generated by the coil. The copper masses which abduct the heat from the Ohmic losses of the coils are also shown on the left drawing of Fig 6.

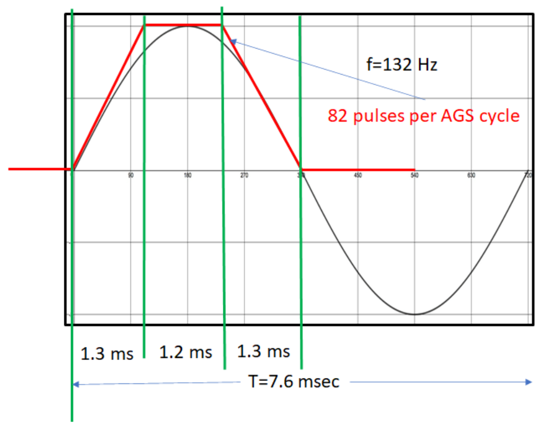

Figure 4: The red trace represent a typical current pulse which excites the quadrupoles at the time interval the beam crosses an horizontal spin resonance. The amplitude of these pulses varies depending the strength of the horizontal spin resonance to cancel.

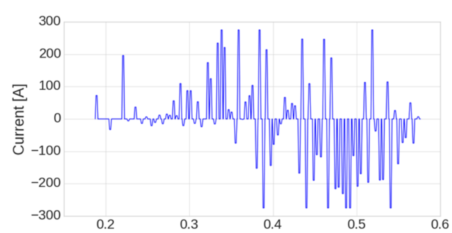

Figure 5: A typical set of current pulses which excite an individual skew quadrupole during an AGS cycle. The amplitude of each current pulse which excites the skew quadrupole is different for each horizontal spin resonance.

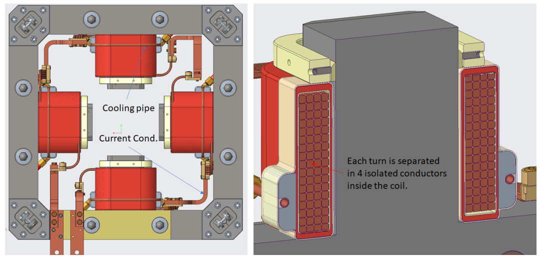

Figure 6: The left picture shows the conductors which are used for the electrical connection of the coils. The pipes which carry the cooling water of the "cooling copper" blocks are also shown. The left picture shows the quadrupole cut in half with a plane normal to the longitudinal axis of the quadrupole. This picture shows the 17 turns of the coil. Each turn consists of four electrically isolated conductors 0.23 cmx0.23 cm in cross section each. The four conductors of each turn are electrically connected only at the entrance and exit of each of the four coils of the quadrupole but they are electrically isolated inside each coil.

4. Modeling the Skew-Quadrupole for the Electromagnetic Calculations

Only 3D electromagnetic calculations were performed on the skew quadrupole by the use of the OPERA computer code. Due to the relatively low B-field in the magnetic material all the calculations were performed with a constant permeability μ=4000 for all the magnetic material involved in the calculations. The reason of using constant permeability is due to the very large number of nodes used in the OPERA code calculations to describe the quadrupole model that otherwise would require weeks of calculations instead of three to four days required when the quadrupole is modeled with constant permeability. The 2D calculations were excluded for two reasons, first, the length of the magnet was short compared to the aperture-radius of the quadrupole, therefore no constant gradient values were generated within the quadrupole, and second the normalized beam emittance of 15π[mm.mrad] makes a beam size, even at injection beam energies into the AGS, much smaller as compared to the aperture (R=8.05 cm) of the quadrupole therefore all the multipoles, higher than the quadrupole multipole, at the beam radius are not significant and there was no reason to shape the pole faces of the quadrupole to minimize the 12-pole multipole which is the first allowed multipole. The maximum integrated quadrupole field required to be generated by the quadrupole is 0.2 [T]. Given that the iron length of the quadrupoles is 11.45 cm and the radius of the quadrupole's aperture is 8.05 cm the maximum a pole tip magnetic field of the quadrupole should be $\sim$0.14

[T]. Although such a pole tip magnetic field is low enough for the quadrupole to be constructed by ferrite material which saturates at 0.3 [T] the decision was made for the quadrupole to be fabricated with 0.025" thick iron laminations. The iron laminations allow for stronger gradient in the quadrupole due to higher saturation of $\sim$1.7 T in the iron, the eddy currents generated in the laminations result in Ohmic losses which are part of the study in this paper. The results from this study provides information on the effect of the eddy currents, generated in all conductive parts of the quadrupole, on the main quadrupole field and also on the ohmic losses on the conductive materials of the quadrupole. The skin depth δ of the electromagnetic field in magnetic iron at the frequency of 135 Hz is given by the formulae

$$\delta = 503\left(\frac{1}{f\sigma\mu_r}\right)^{1/2} \tag{1}$$

In the equation above the skin depth δ is in [m] the frequency f in Hz the conductivity σ is in $(\Omega\mathrm{m})^{-1}$ and μ_r is the relative permeability of the iron. Fig 7 is a plot of the skin depth vs frequency for various materials.

From this plot one can estimate that the skin depth in magnetic iron like "Si-Fe" for the frequency of 135 Hz is 0.17 mm. The lamination thickness used in the quadrupole is 0.63 mm which is not much larger as compared to the the skin depth of 0.17 mm. In the OPERA model of the quadrupole each 0.063 cm thick lamination is electrically isolated from the neighboring one, in additions to make the calculations more accurate each 0.63 mm thick lamination is split into two 0.63/2 mm=0.315 mm thick entities and the distance between two neighboring nodes in the OPERA model was set to "quadratic" thus further increasing the accuracy of the calculations.

In such a thin lamination if the magnetic field is parallel to the large surface of the lamination the eddy currents which will be created in the lamination, will partially cancel each other inside the lamination. However for a short quadrupole the direction of the magnetic field is not parallel to the laminations but there is a component of the B-field which is normal to the laminations. This component of the field generates additional eddy currents inside the laminations which do not cancel each other. To explain graphically the above sentences related to eddy currents cancelation or non cancelation we refer to Fig 8. The figure on the left shows the magnetic field direction parallel to the lamination. The change of the magnetic field generates eddy currents in and out of the page. If the width of the lamination is comparable to the skin depth there will be some cancelation of the eddy currents.

However if the direction of the magnetic field is not parallel to the lamination like in the left figure of Fig. 8 the change of the B_x component of the field will generate eddy currents which will not cancel each other because the dimension "L" of the lamination is long compared to the skin depth.

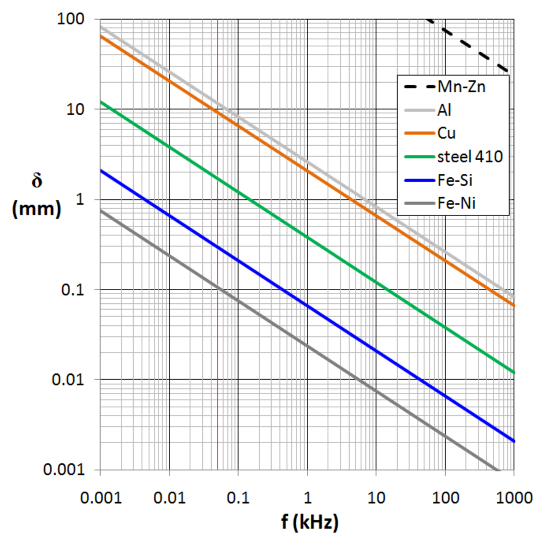

Figure 7: A plot of the skin depth of the electromagnetic wave versus frequency in various materias embedded in such EM waves. The skin depth in the material used for this quadrupole at f=135 Hz is ∼0.17 mm.

5. Purpose of the Electromagnetic calculations on the Skew-Quadrupole

Given that the quadrupole will operate in a transient mode as shown by the red trace in Fig. 4, the purpose of the electromagnetic field study is to obtain results to determine the following physical quantities during the operation of the quadrupole.

- The integrated quadrupole field as a function of time
- The Ohmic losses in the coils
- The Ohmic losses in the 0.025" thick laminations
- The Ohmic losses in the 0.25" thick end plates
- The integrated field multipoles at the radius of the beam

- The effect of the eddy currents generated in the material of the vacuum pipe on the magnetic field at the region of the circulating beam

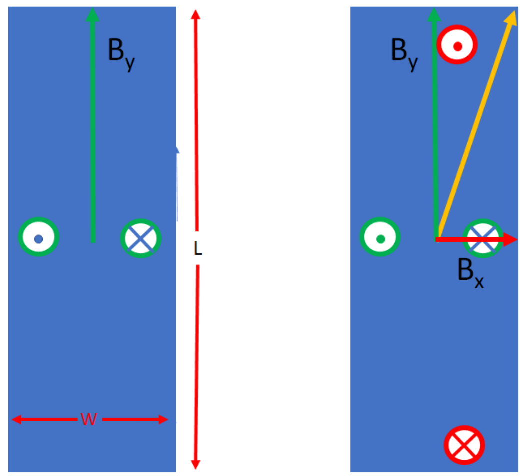

Figure 8: The B_y field on the left figure is parallel to the surface of the lamination. The change of the B_y field will generate eddy currents which will partially cancel each other if the width of the lamination is comparable to the skin depth. In the right picture the B-field is not parallel to the surface of the lamination and the change in time of the B_x component of the B-field which is normal to the surface of the lamination will generate eddy currents (red circles) which will not cancel each other if the dimention "L" of the lamination is much larger than the skin depth.

The opera computer code has the capability to determine all the quantities in the list above. There are two modules in the OPERA computer code which can be used; namely the AC steady state module and the transient module. The frequency of the sinusoidal AC steady state current which is close to a single transient pulse (red trace) shown in figure Fig. 4 is f=135 Hz. The results from the AC steady state solution are very conservative and correspond to almost 40 times of the Ohmic losses as compared to the actual operation of the skew quadrupoles which is a set of pulses, over an AGS cycle, of varying amplitude shown in Fig. 5. Before we proceed with the results from the OPERA solutions a brief explanation, on modeling the iron laminations in the OPERA code is provided below.
The drawing on the right of Fig. 9 is a projection of the skew quadrupole on a plane normal to the laminations of the quadrupole. The left side of Fig. 9 is a schematic diagram of only three of the 160 iron laminations. Each

iron lamination is 0.025" thick and is electrically isolated by an infinitely thin layer (OPERA's feature) from the adjacent lamination. In addition, as part of the OPERA model-design, each laminations is split in the middle thus each laminations is made of two laminations of 0.0125" thick electrically connected. The distance between two adjacent nodes has been set to 0.05" "quadratic" which in effect reduces the node-distance and increases the accuracy of the calculations. Although the "layering" feature of the OPERA model could have been used to split each lamination into thinner ones, it was decided to simply split each 0.025" thick lamination in two. The "Geometric layering" feature of the OPERA is being used for the 0.25" thick "holding plates" (green material in Fig. 1) where two thin layers of 0.025 cm thick at either of the large surfaces of the plates are being used. Table 2 displays some properties of the materials the quadrupole is made of which are relevant in the OPERA model calculations. Other nonconductive and nonmagnetic material which are used in the structure of the magnet are not significantly contributing to magnetic field distribution of the magnet at these frequencies of 135 Hz.

5.1. Results from the AC Steady State Calculations at f=135 Hz

The AC steady state calculations were performed by using the frequency of 135 Hz because it is the best frequency which fits the transient pulse as shown in Fig. 4. It is the sinusoidal black trace which better fits one of the single transient pulses which excites the skew quadrupole at the time the beam crosses the horizontal spin resonances.
The OPERA model was made in IGS format which was imported into the OPERA code. Fig. 10 is a perspective view of the $1/8^{th}$ size 3D model used in the OPERA computer code.
The plot of the B_x field at a phase angle of 90^o and R=1 cm from the axis of the quadrupole is shown in Fig. 11. From this plot the integrated quadrupole field $\int_{-\infty}^{+\infty} B_Q\, dz$ of the skew quadrupole is calculated to be 0.215 T when the quadrupole is excited at a current of 185 A. This integrated field is slightly larger than the required maximum field of 0.19 [T]. From this plot of the B_x field vs z distance, it appears that there is no "uniform quadrupole field" along the length of the quadrupole because the small L/R ratio of the quadrupole.
From the Fourier analysis of the radial B_r field calculated at a radius of 4 cm it is concluded that the 12^{th} pole component of the field which is the first alowed multipole of the quadrupole is less than 0.003% of the quadrupole

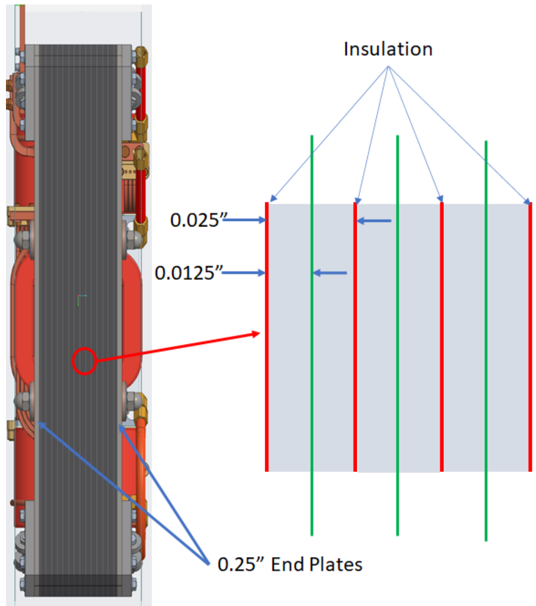

Figure 9: A schematic diagram showing the boundaries (red lines) of the 0.025" thick laminations. The insulation (red line) is of zero thickness. Each 0.025" thick lamination is electrically isolated from the next and is made of two entities electrically connected, 0.0125" thick each, in the model. The green line shows schematically the separation of each lamination in two 0.0125" thick laminations.

field. This justifies the reason that the pole faces of the quadrupole were not mechanically shaped to minimize the 12-pole component of the field.

In addition to the quadrupole field and its quality generated by the quadrupole, another important physical quantity from the operation of the skew quadrupole is the power dissipation in the conductive parts of the quadrupole like, laminations, end-holding plates, and the main coils. These quantities appear inTable 3.

Although these quantities of average power dissipation during the AC steady state operation may appear excessive, especially for a non-water-cooled conductor coil, in the actual operation of the quadrupole these quantities are very small because the duty cycle of the actual operation of the skew quadrupole in AGS is $1/40^{th}$ of the duty cycle of the steady state operation at 135 Hz.

To speed up the calculations and check for any errors the initial OPERA model of the quadrupole used a coarse mesh. As the grid size of the mesh in the various parts of the model was decreasing so the average power dissipation in the coils, the holding plates, and the laminations. At a grid size

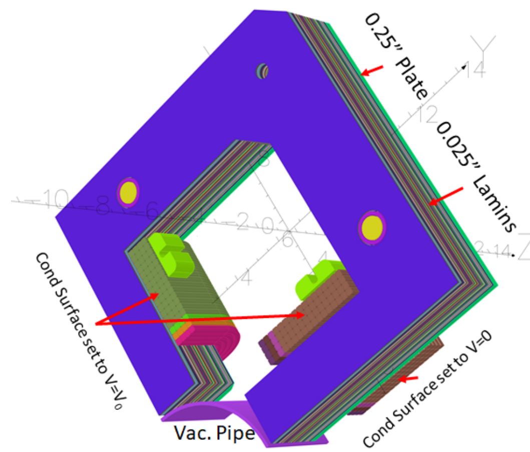

Figure 10: A perspective view of $1/8^{th}$ model of the quadrupole's 3D model used in the OPERA computer calculations. The z=0 symmetry plane cuts the 17x4 conductors of each coil and exposes 17x4 conductor-surfaces of each coil as shown in the figure. These conductor surfaces were assigned the voltage $V=V_0$ Volts. The other conductor surfaces which were exposed from the cut by the symmetry planes y=0 and x=0 were set to V=0 Volts.

of 0.4" and below in the coil, the power dissipation in the coil remained constand, the same was also for the power dissipation in the holding plates for grid sizes 0.06" and 0.05". But this was not the case for the grid size in the laminations where the power dissipation was still projected to decrease for grid size below the value of 0.05". However it was not possible to decrease the grid size in the laminations at a lower value than 0.05" because the model could not be meshed in either the 128 RAM PC or the 128 RAM UNIX computer.
In an attempt to provide a more accurate value for the power dissipation in the laminations the OPERA quadrupole model run for various grid sizes in the laminations ranging from 0.4" to 0.05" and a plot of power dissipation vs grid size in the laminations was made and the data points were fitted by a polynomial to obtain the power dissipation for very small grid size. Unfortunately this method did not work because it was yielding a " negative power dissipation" at the limit of grid size aproaching to zero.
A communication with the OPERA consultants will soon start to explore the reason why the model cannot be meshed with the grid size smaller than 0.05".

The average power in each of the 80 laminations lamination when the

Table 2: Material properties used in the OPERA model of the quadrupole

Material	conducrivity	Thickness	μ
	$[\Omega\mathrm{m}]^{-1}$	[cm]	
Laminations	1x10^7	0.0635	4000
Iron Plates	1.0x10^7	0.635	4000
Coil-Conductor	5.89x10^7	0.519x0.519	1.0
Vac-Pipe	1.0x10^7	0.3	1.0

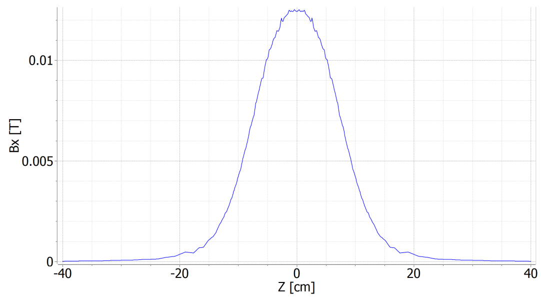

Figure 11: The B_x field at R=1 cm of the skew Quadrupole at 90^o phase. The integrated quadrupole at this phase of 90^o is 0.22 [T]. From this plot it appears that the ratio L/R of this quadrupole is too small to provide a uniform quadrupole field along the length of the quadrupole.

quadrupole is running in an AC steady state with frequency of 135 Hz is plotted in Fig. 12 which plots the average power dissipation in each 0.025" thick lamination. The power dissipation on the other 80 laminations downstream, is a mirror image of the Fig. 12. It is worth noticing that the power dessipation in each lamination increases with the distance from the center of the magnet. This increase in the power is due to the eddy currents which are created by the time varying B-field component which is normal to the surface of the lamination as shown in Fig. 8. The power dissipation in the Coils the lamination and the holding-plates also appears in Table 3. Given that the

Table 3: Results from the 3D AC steady state calculations

			Average Power		
I_{max}	$L_{(Induct.)}$	$\int B_Q$dz	Coil	Lam	Plate
$[A]$	[mH]	[T]	[W]	[W]	[W]
185	0.64	0.21	725	285	115

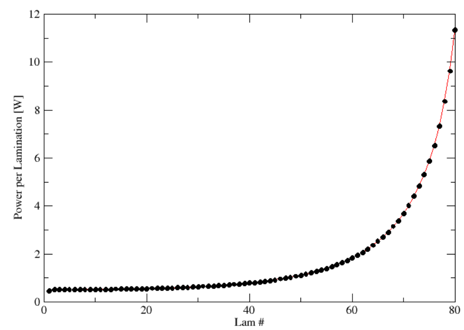

Figure 12: The average power dissipation in each of the 80 laminations of the quadrupole, when the quadrupole runs in an AC mode steady state at a frequency of 135 Hz. The power dissipation in each of the other 80 laminations is a mirro image of this plot.

duty cycle of quadrupole under normal operation is $\sim 1/40^{th}$ of that during the AC steady state operation of the quadrupole at f=135 Hz and I_{max}=185 A. The power dissipation is small enough and the heat can be abducted by the method mentioned earlier in this paper.

5.2. The effect of the eddy currents in the vacuum pipe on the field of the circulating beam region

The vacumm pipe of the circulating beam has been included in the OPERA model and the effect of the eddy currents generared in the vacuum pipe on the B-field of the circulating beam region was calculated. This effect on the B-field and some of the results from these calculations are presented in this section.
Fig. 13 shows $1/8^{th}$ of the magnets's model with the vacum pipe which has been segmented into four sections, each 4 cm long, along the length of the quadrupole as shown in Fig. 13 to allow the calulation of the power loss due to the eddy currents in each 4 cm long section of the pipe instead of the whole 2X16 cm length of the pipe.

Table 4 tabulates some of the geometrical and physical properties of the vacuum chamber and the power loss in vacuum pipe due to the eddy currents. To obtain a better information on the power loss in the vacuum pipe, the pipe was segmented in 4 cm length of 8 segments in total (four sections upstream and four sections downstream). The power loss in the four upstream

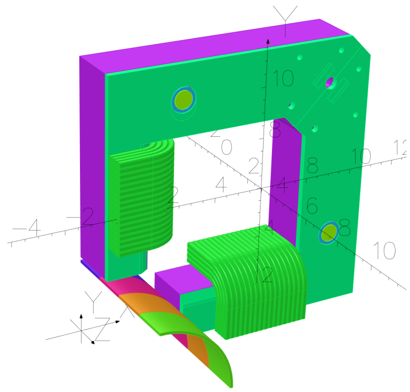

Figure 13: Some geometrical and physical properties (first three culums) of the vacuum pipe. The average power dissipation in each of the four 4 cm in length rings of the vacuum pipe appears in the last four columns.

Table 4: Goemetric and material properties of Vacuum pipe

			Average Power dissipation per section			
R_{inner}	$Wall_{thick}$	σ	Sec1	Sec2	Sec3	Sec4
$[cm]$	[cm]	[Siem/m]	[W]	[W]	[W]	[W]
7.46	0.26	7.4×10^6	596	448	148	32

segments, starting from the segment at the center of the magnet appears in the last four columns of Table 4. This power dissipation corrsponds to a steady state operation of the quadrupole at a frequency f=135 Hz.
It is noticable as expected that the power dissipation in the vacuum pipe is reduced with the distance from the center of the magnet. The heat generated from this Ohmic power loss will partly be abducted by the cooler part of the pipe upstream and downstream of the magnet. Regarding the effect of the eddy currents on the B-field of the main field region Fig. 14 plots the B-field at a radius R=1cm, starting from the center of the magnet up to a distance 30 cm from the center. The integrated field difference between the two plots, one with conducting pipe made of inconel material the other without pipe, is 7.4%. Thus the eddy currents generated in the 2.6 mm thick vacuum pipe reduces the integrated quadrupole strength by 7.4% and changes the phase between Voltage and Current by 20^o.
Although it appears that the Ohmic losses on the vacumm pipe due to the eddy-currents are very large close to 2.45 kW as calculated based on the stady state operation of the magnet at a frequency of 135 Hz the actual

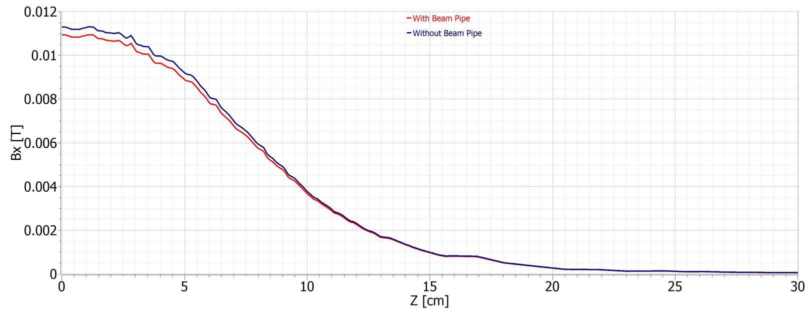

Figure 14: Plots of the B-field at R=1 cm from the reference orbit of the quadrupole for two cases. One without a vacuum pipe and the other with a 2.6 mm vacuum pipe made of inconel.

power dicipation is less than 100 W. In addition this power can be abducted by the cooler part of the vacuum chamber upstream and downstream of the quadrupole.

To complete the discussion of this section we refer the reader to Fig. 15 which shows the counrour plots of the eddy currents on part of the vacuum pipe on the left picture. The right picture shows the direction of the current density of the eddy currents on the area enclosed by the little circle. -

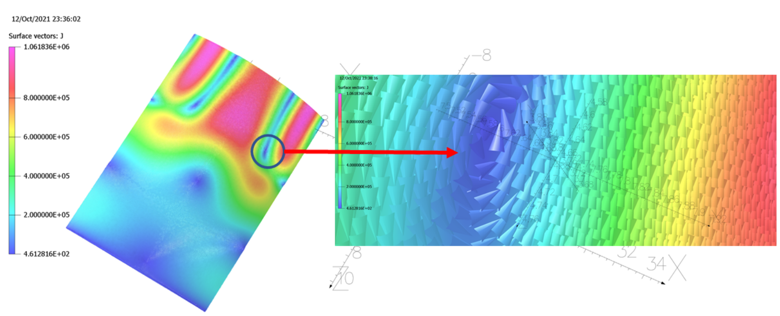

Figure 15: Countor plot of the density of the Eddy current in the pipe at particular time during the AC cycle. Only one eighth of the pipe is shown. The part of the pipe which is inside the quarupole shows the highest current density. The right picture is a magnification of the part of the pipe enclosed by the circle and shows with arrows the dirrection of the currents.

6. Conclusions

A skew quadrupole has been designed to operate in a transient mode during the AGS cycle. The magnetic core of the quadrupole was made of iron laminations of 0.025" thick which are held by two iron plates 0.25" thick.
The Ohmic losses during the actuall operation of the quadrupole are low enough for the coil to be air cooled with only a copper mass in conduct with the coil as a preventive mean for the coil to abduct any heat which might harm the operation of the quadrupole. The strength of the 12-pole multipole which is the first allowed multipole of the quadrupole is calculated to be negligible.
The eddy currents generated in the 3.6 mm thick inconel vacuum pipe cause a 7.4% reduction of the integrated quadrupole field. The Ohomic losses in the vacuum pipe generate less than 100 W of heat during the operation of the quadrupole. This heat can be abducted by the rest of the pipe which has lower temperature.

7. References

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