Effect of Power Frequency and Skin Effect on Current Carrying Rods, Pipes and Channel

AC Magnetics Simulation

QuickField 6.6 Field Simulation Software

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May 25, 2022

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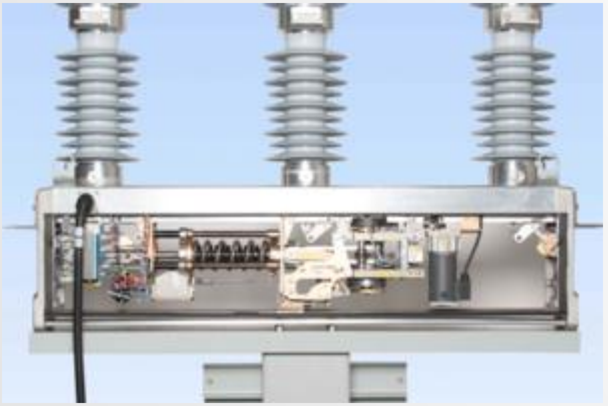
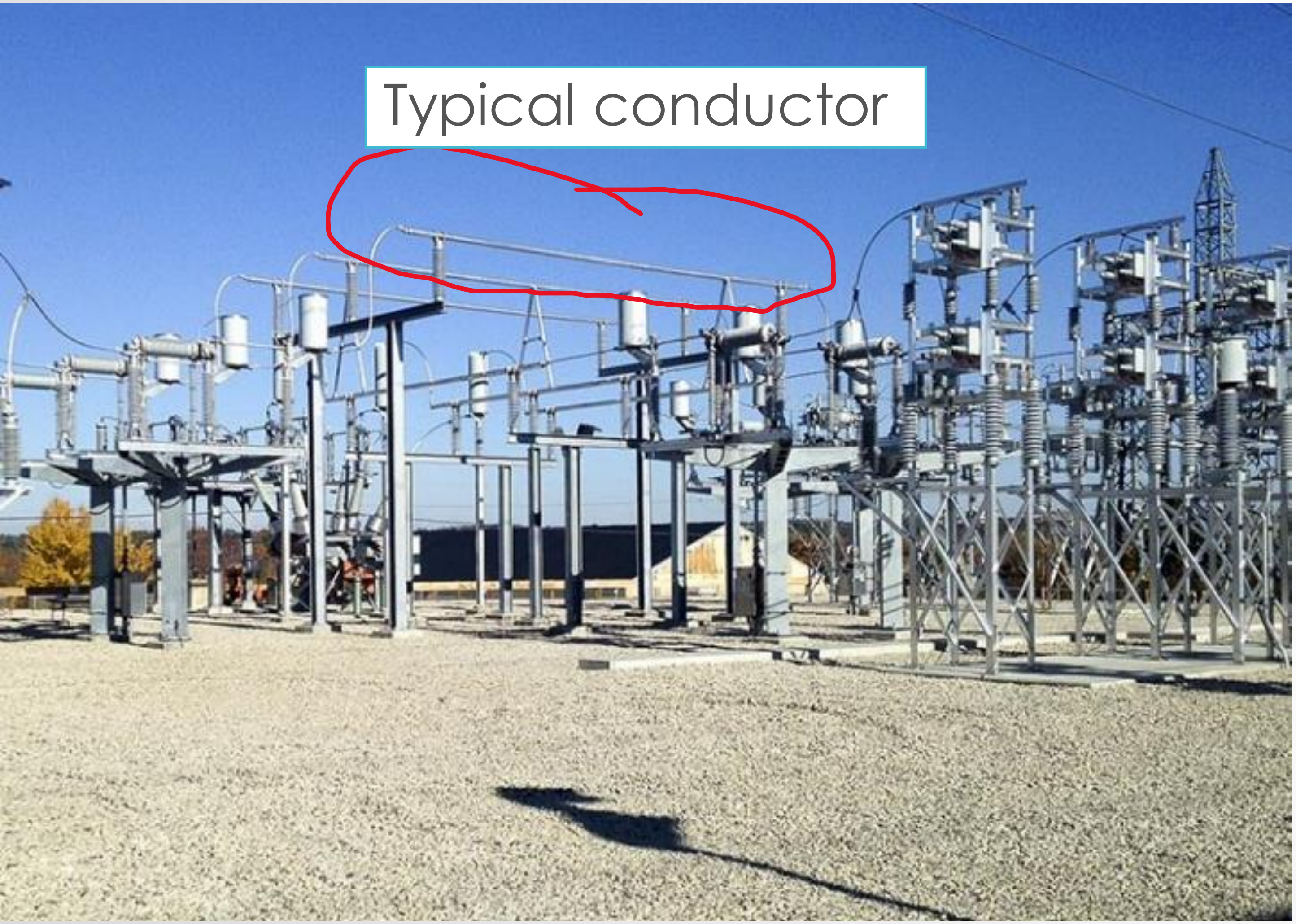
Neil A. McCord P.E., Consulting Engineer and Designer for Low, Medium and High Voltage Switchgear



Over 34 years of experience designing circuit breakers, switches and other switchgear devices.

Over 28 years on the IEEE PES Switchgear Committee.

High Voltage Substation Conductors



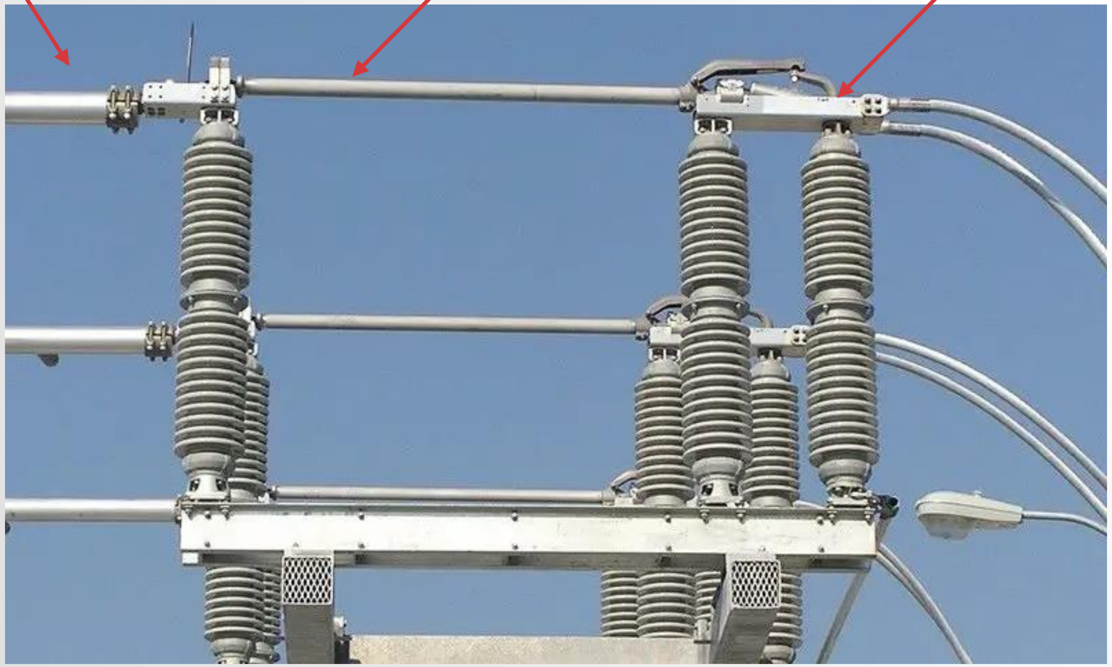
- High voltage substations are a key component in the transmission of electrical power from power generation to commercial and residential use.
- Generally, these conductors are made of aluminum pipe

High Voltage Substation Air Disconnect Switch

Substation Bus Conductor

Switch Blade

Jaw and Hinge conduct current in a channel



- These conductors are made of aluminum either 6061-T6 or 6063-T6

Model Skin Effect in Different Shaped Conductors

- We will start by modeling a round bar and examining the electrical properties
- Then we will model a pipe with the same OD and current
- A flat bar will be modeled
- Last, we will model a channel with the same weight per foot of the pipe and examining the electrical properties and current distribution
- We will then contrast the effect of the shapes

Overall:

It is the intent of this presentation to focus on the properties of the Block and Edge labels, post processing and understanding the meaning of the results.

For a good reference on the physics of the Skin Effect please see QuickField proximity webinar by Dieter Stotz:

https://quickfield.com/seminar/seminar_proximity.htm

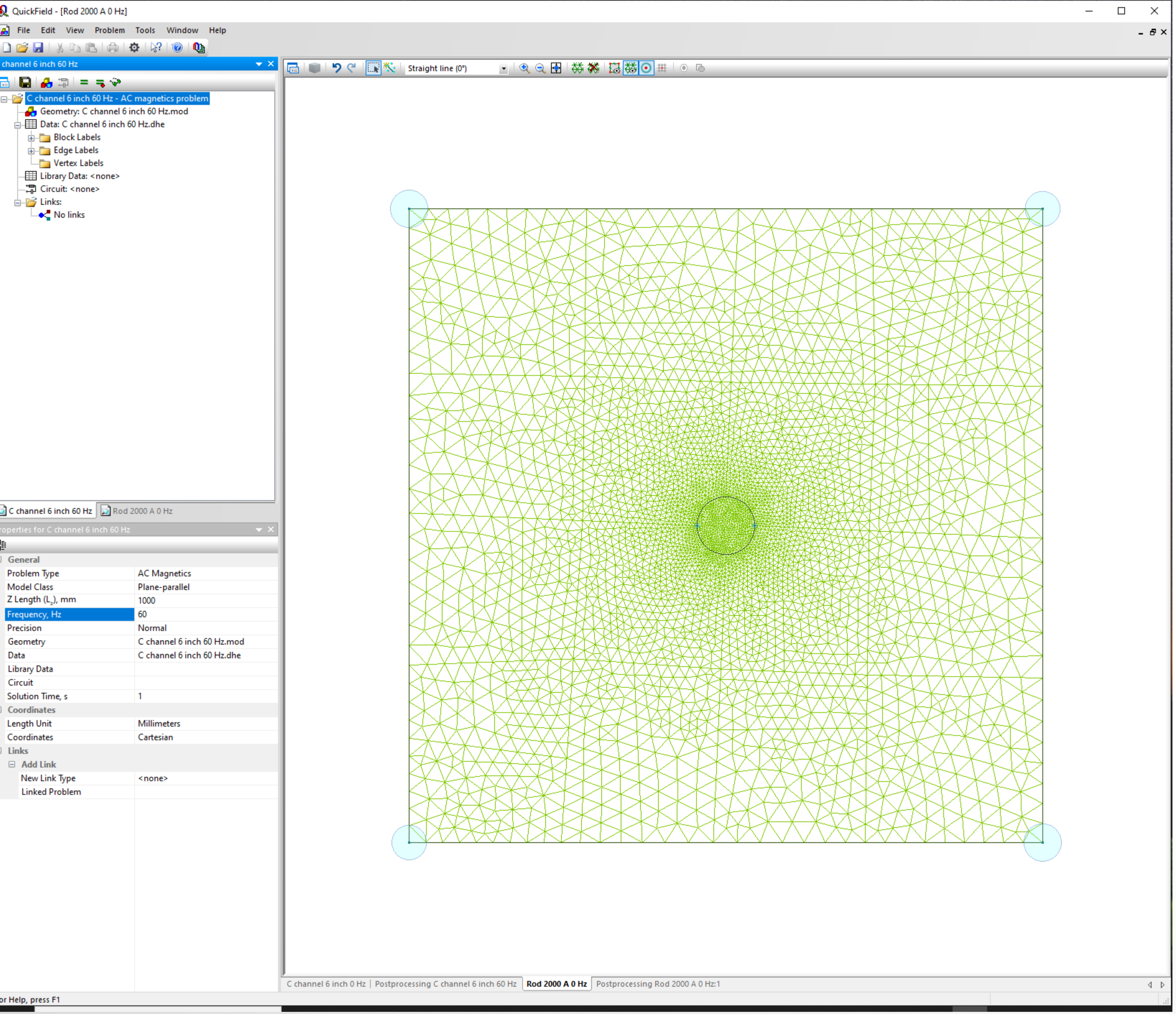
FOR THIS ANALYSIS WE WILL USE:

Given: AC Magnetics Analysis

- Current of 2000 A for all simulations.
- Frequency 0 Hz and 60 Hz
- Quick field requires a depth with the AC-Magnetic Plane Parallel models. For consistency they all have a Z length of 1000 mm.
- Aluminum 6063-T6, IACS 52%, Conductivity 3.01E7 S/m, relative permeability 1

Shapes to model:

- 2 5/8” solid round aluminum bar
- 2.5” Schedule 80 Pipe, 2.875” OD (73 mm), 2.323” ID (59 mm)
- Bar 6” Width, 0.5” Thick
- Channel 6” Width, 2.5” Depth, 0.29"Web, 0.17 Flange, 0.3 Fillet



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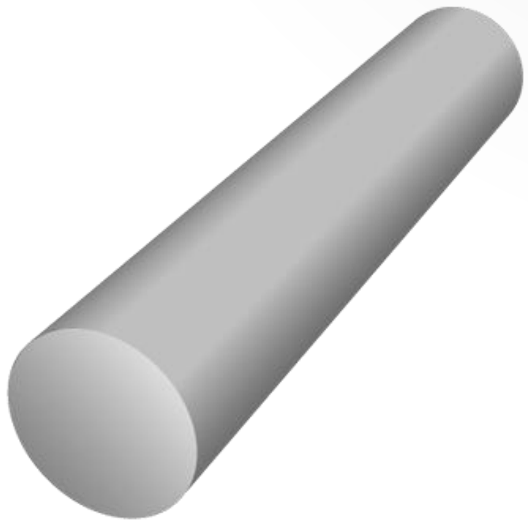
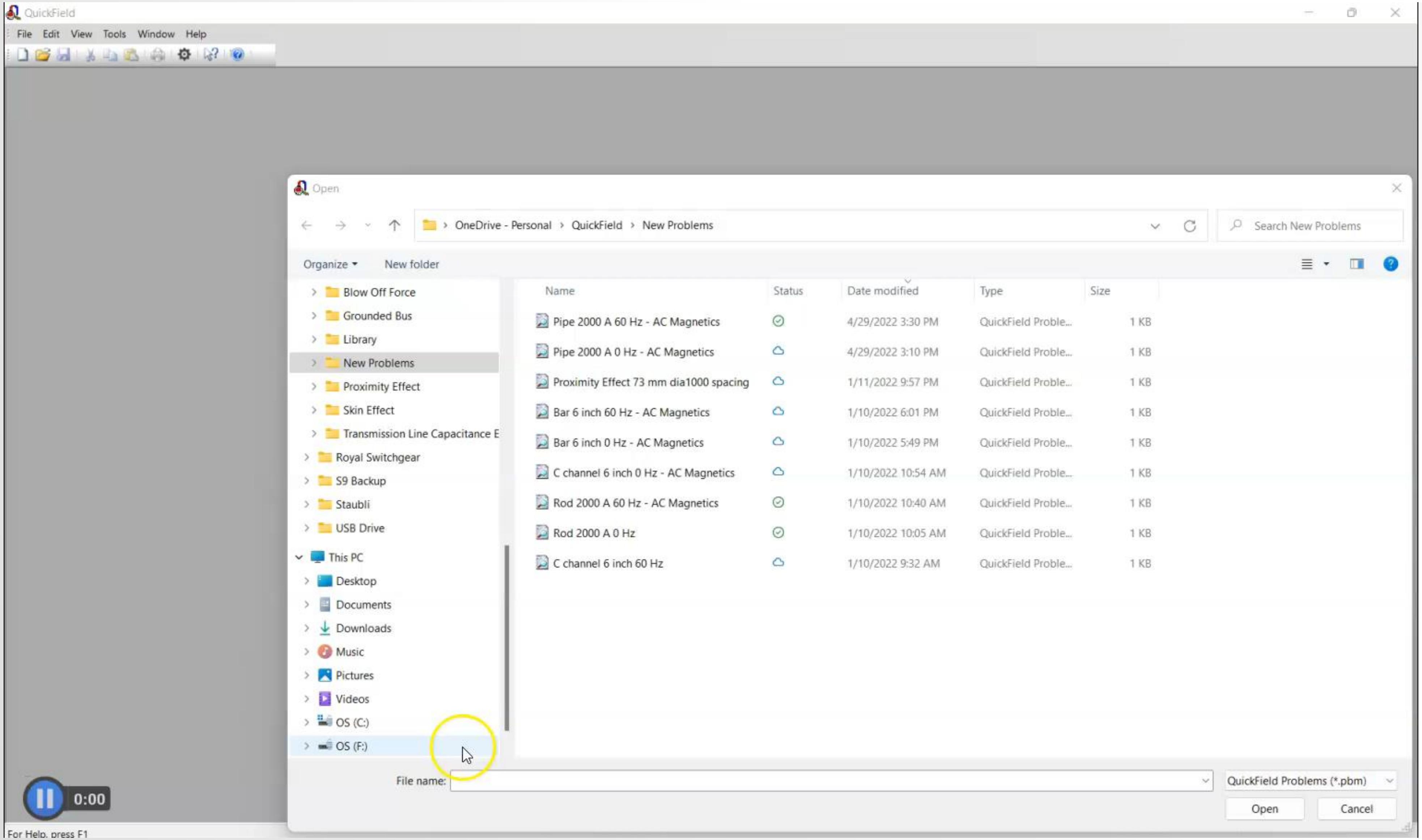
This is the geometry model of a solid rod with a complete and refined mesh.
2 5/8” solid round bar



This video shows how the model was created.



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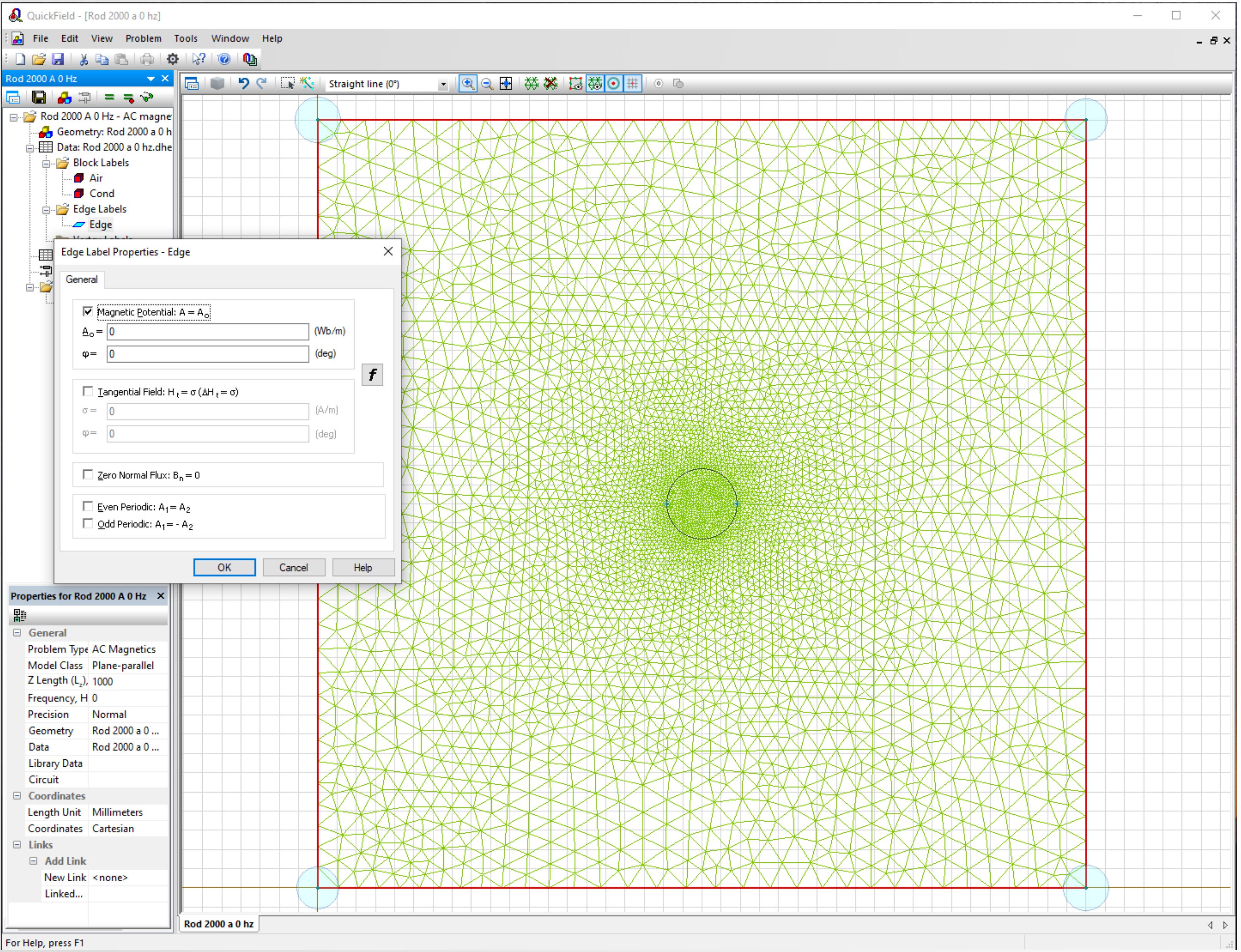
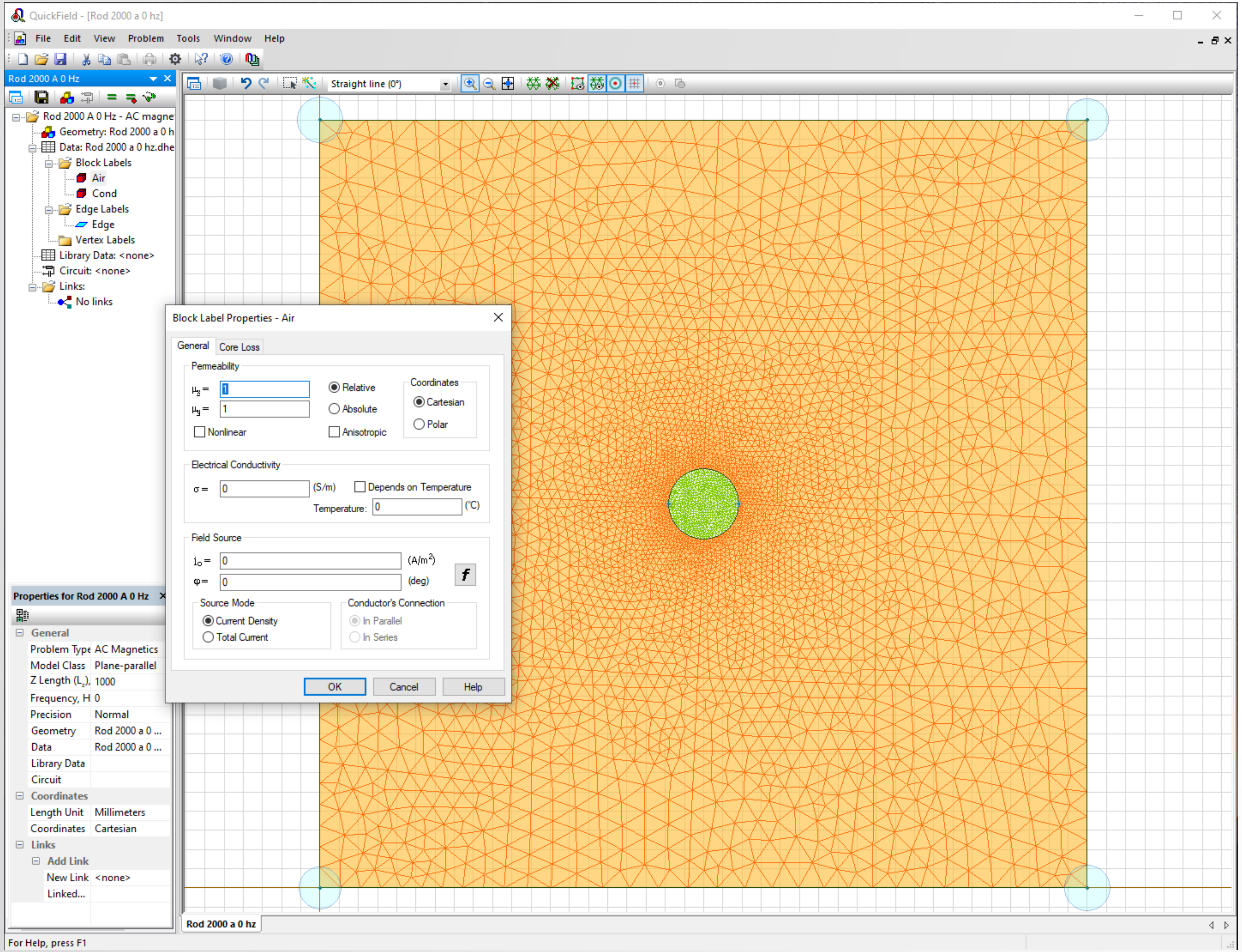


Boundary condition for the outer edge “red line” of the model

Magnetic Potential A_o=0



Block Label Properties for Air highlighted in orange.

Relative Permeability

Air μ=1.00000037
Aluminum μ=1.000022

In electromagnetism, permeability is the measure of magnetization that a material obtains in response to an applied magnetic field. Permeability is typically represented by the (italicized) Greek letter μ.

Wikipedia: Permeability (Electromagnetism)

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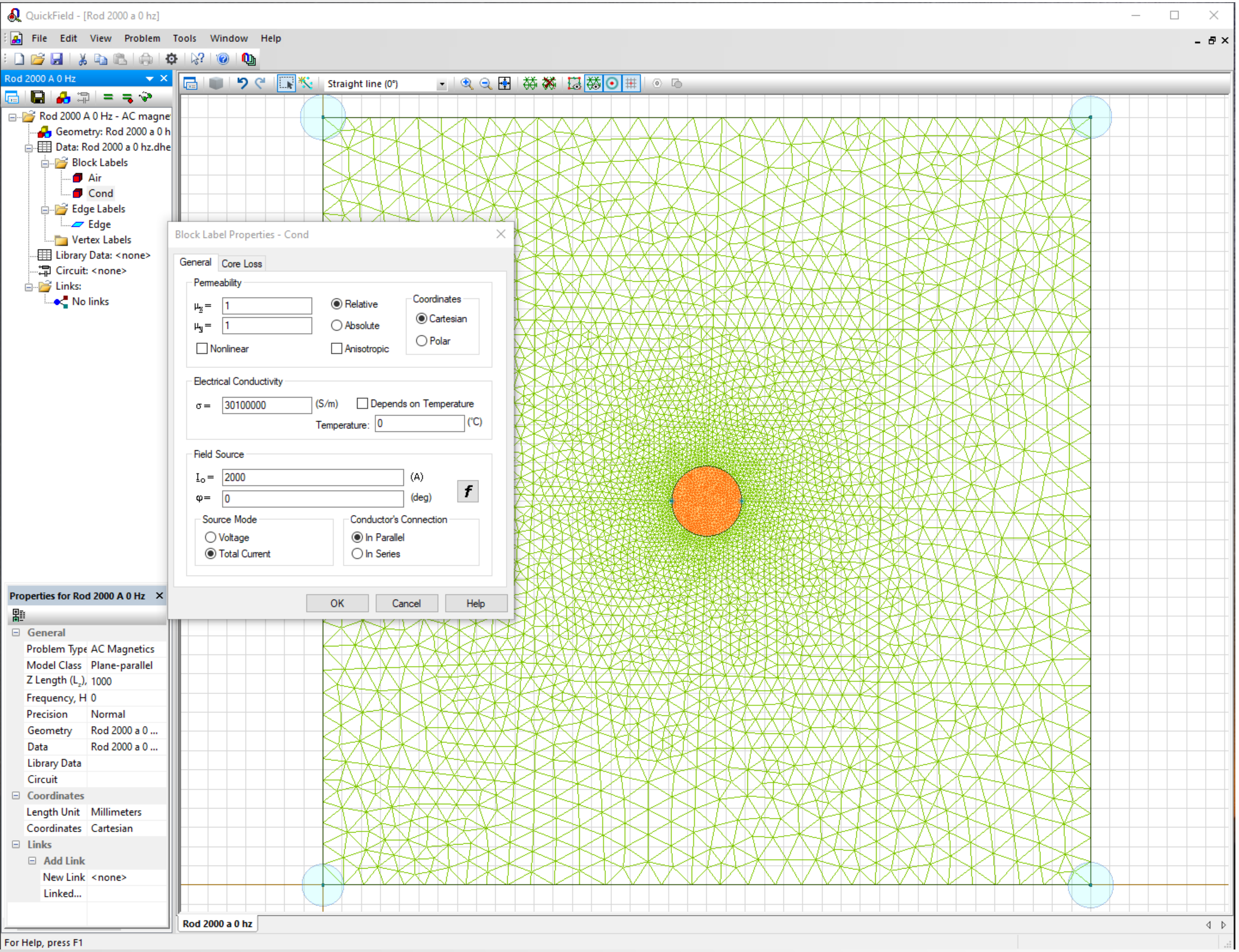

Block Label Properties for the region labeled Cond. This represents the current carrying conductor.

- σ=30,100,000 S/m for 6063-T6 Aluminum
- I_o=2000A

Electrical conductivity or specific conductance is the reciprocal of electrical resistivity. It represents a material's ability to conduct electric current. It is commonly signified by the Greek letter σ (sigma), but κ (kappa) (especially in electrical engineering) and γ (gamma) are sometimes used. The SI unit of electrical conductivity is siemens per meter (S/m).

Wikipedia: Electrical resistivity and conductivity

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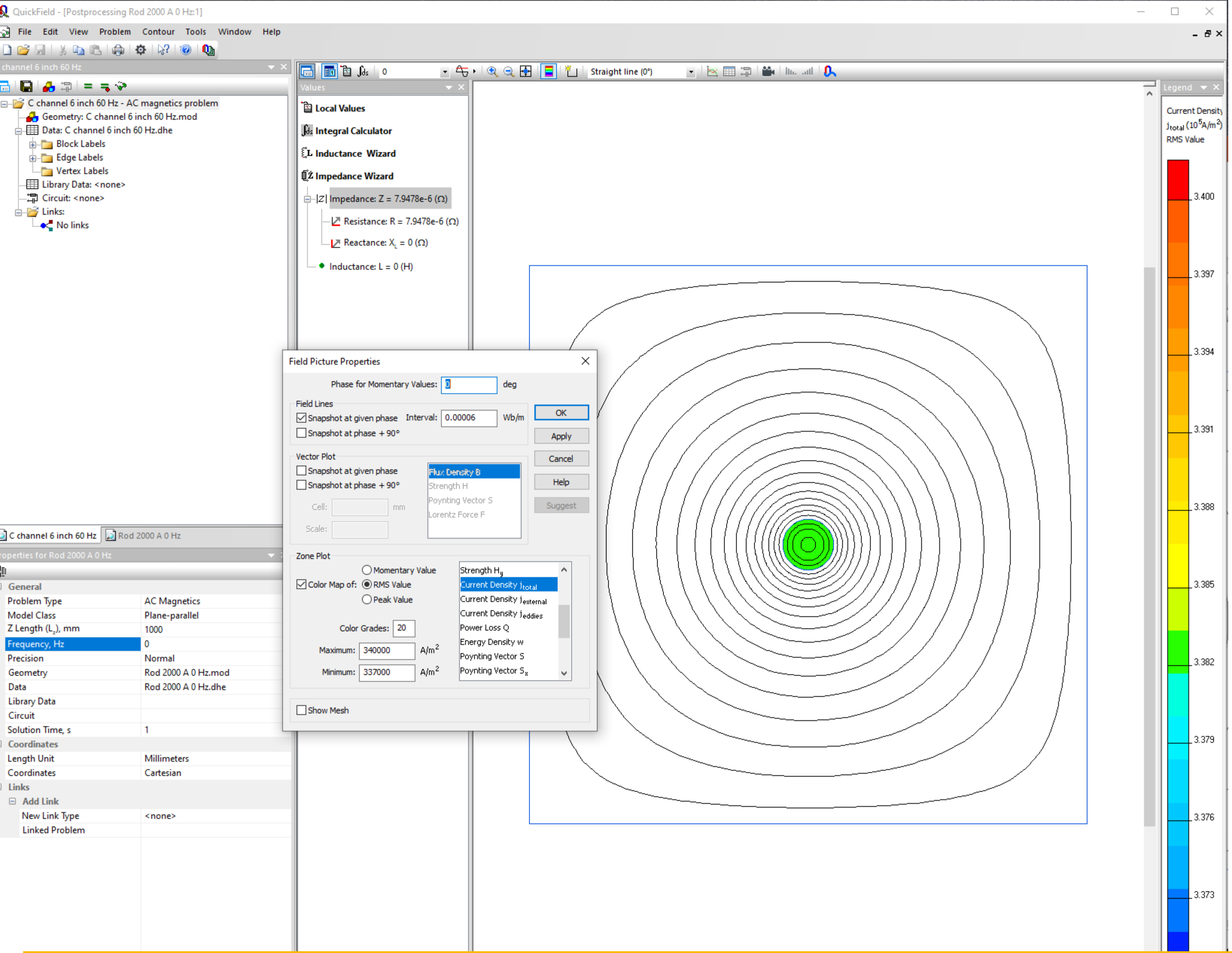
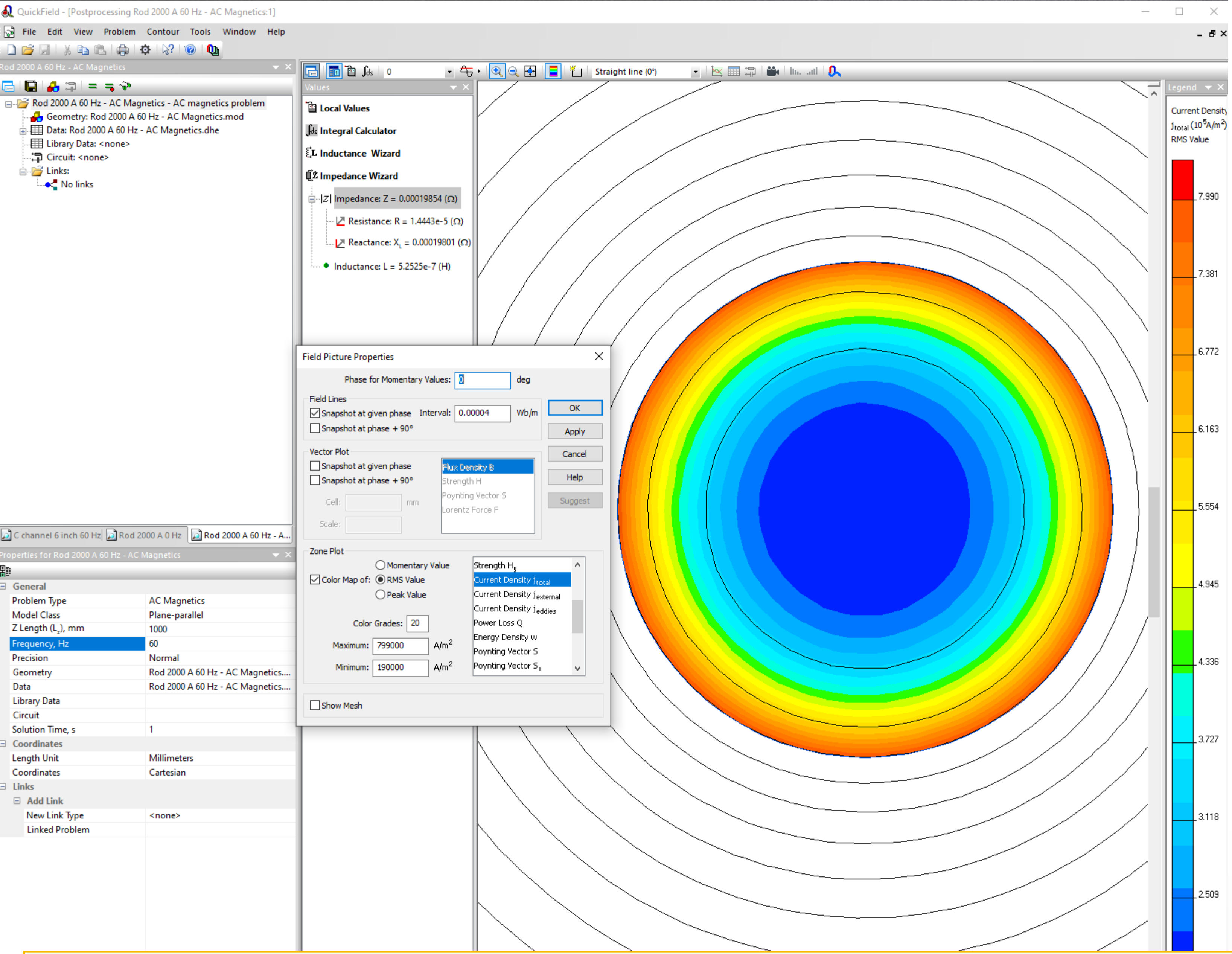


This analysis was performed at 0 Hz. This is DC without any AC frequencies

QuickField calculates the following values:

- Resistance 7.95e-6 Ω
- Impedance 7.95e-6 Ω
- Current Density 3.38e5 A/m^2 (218 A/in^2)
- Power Loss Q 3.8e3 W/m^3

Notice that at 0 Hz the Resistance and Impedance match and the current is evenly distributed.

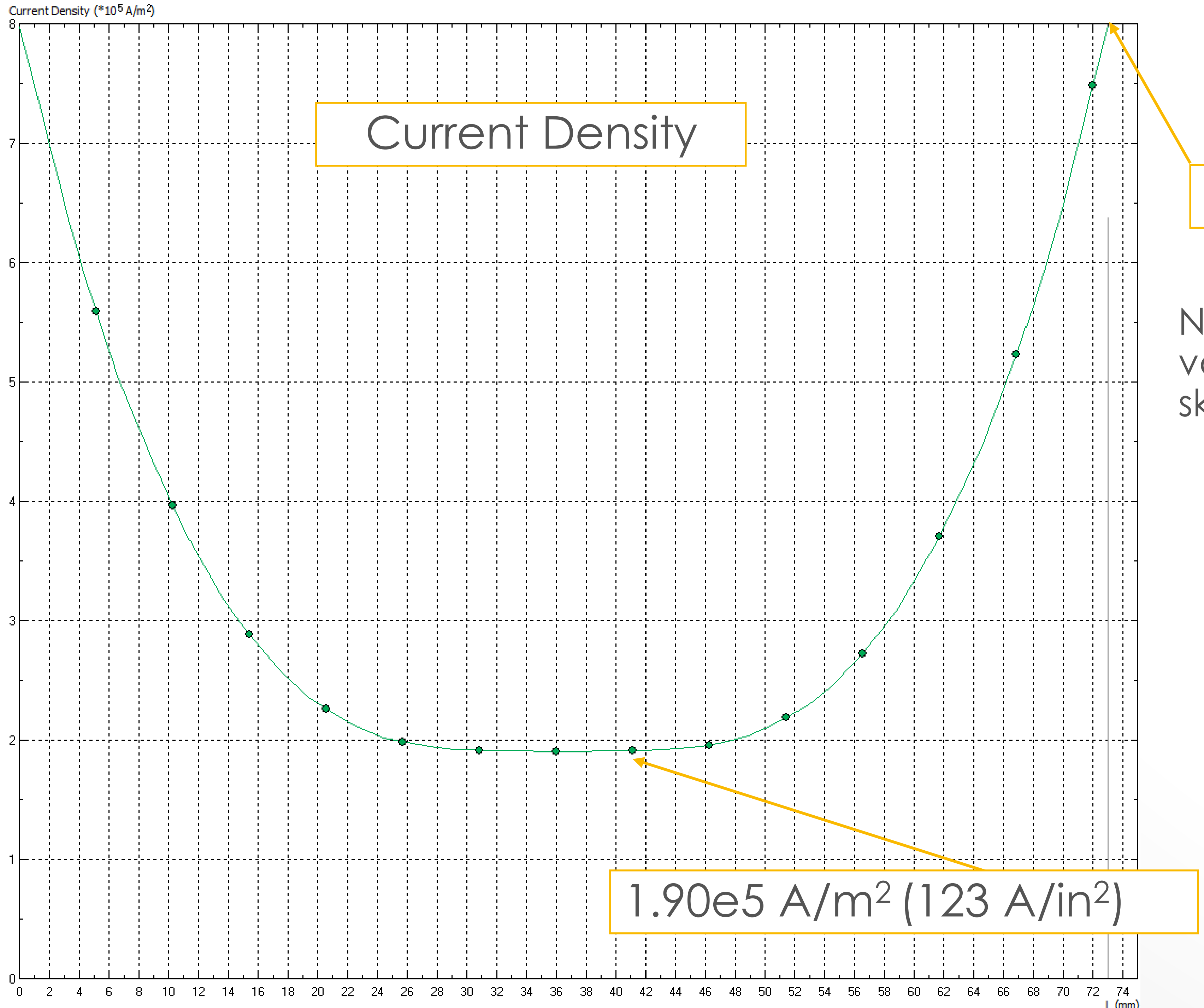


This analysis was performed at 60 Hz. This is the standard AC frequency in the United States.

QuickField calculates the following values:

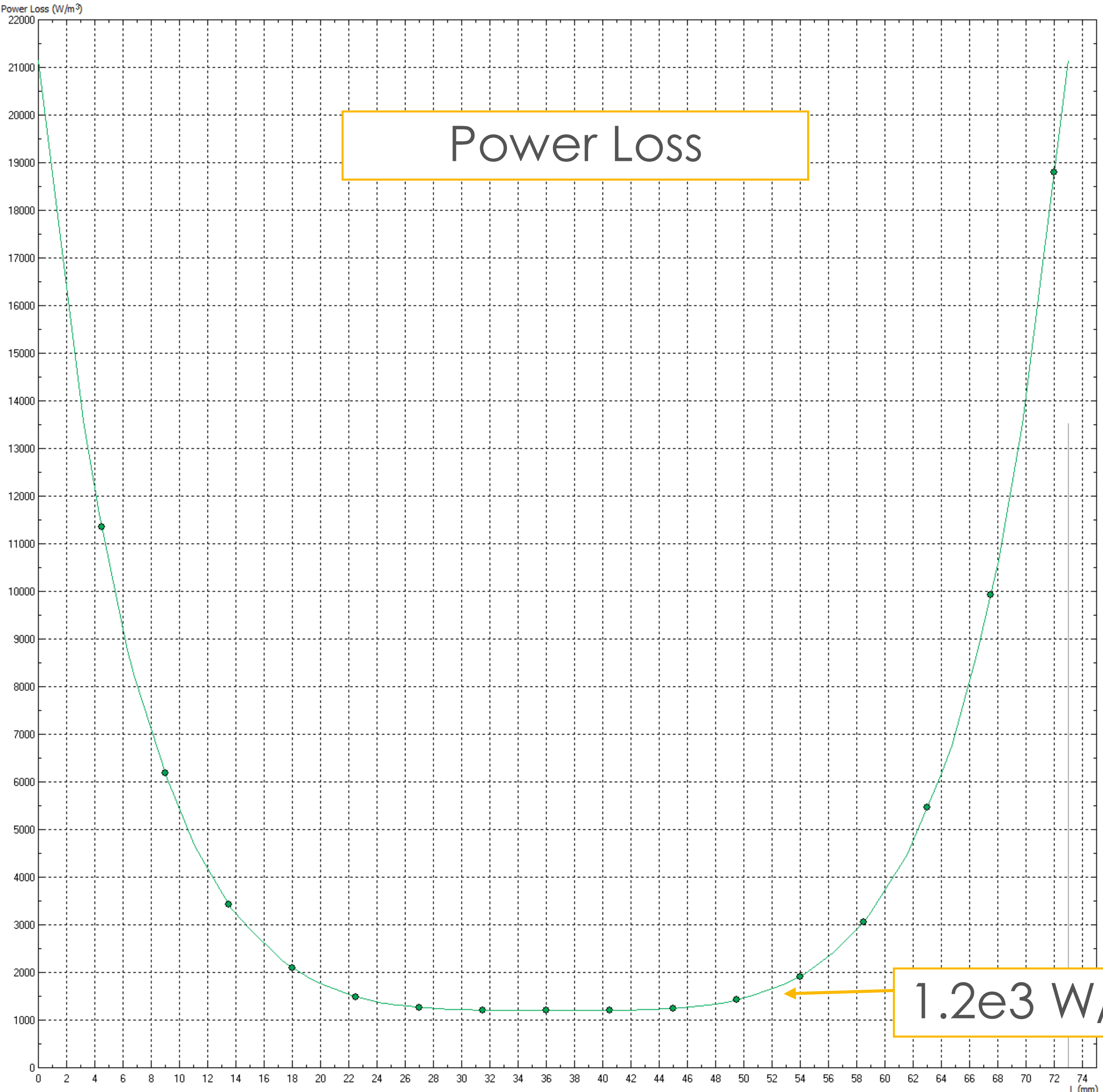
- Resistance 1.44e-5 Ω
- Impedance 1.99e-4 Ω
- Current Density 8.00e5 A/m^2 (515 A/in^2)
- Current Density 1.90e5 A/m^2 (123 A/in^2)
- Power Loss Q 2.12e4 W/m^3
- Power Loss Q 1.2e3 W/m^3
- Energy Density w 21.7 J/m^3

Notice that at 60 Hz the Resistance and Impedance do not match and the current is distributed on the outside of the rod due to the skin effect.



8.00e5 A/m² (515 A/in²)

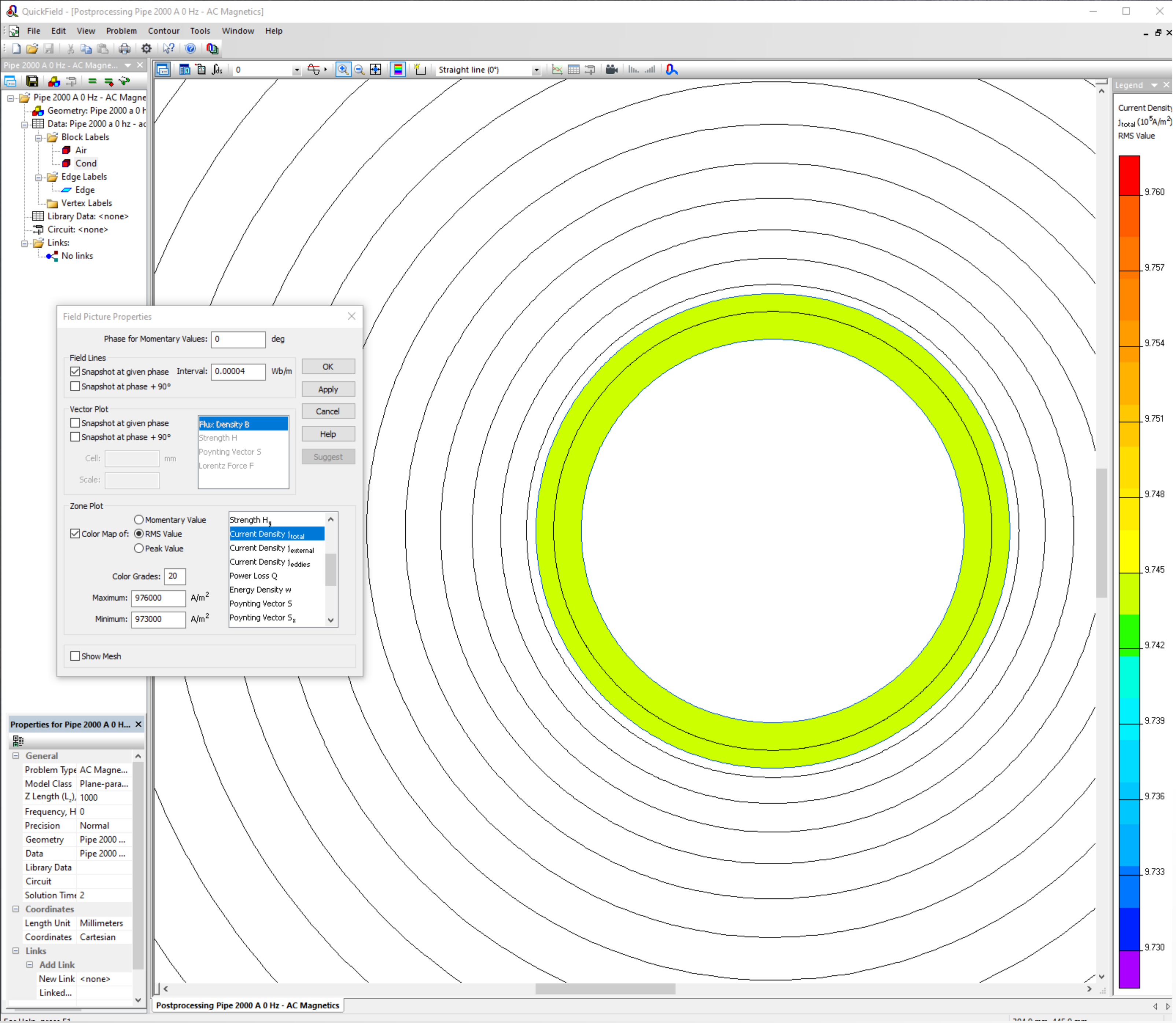
Notice how the current density varies across the rod due to the skin effect.



2.12e4 W/m³

1.2e3 W/m³

Notice how the Power Loss varies across the rod due to the skin effect.



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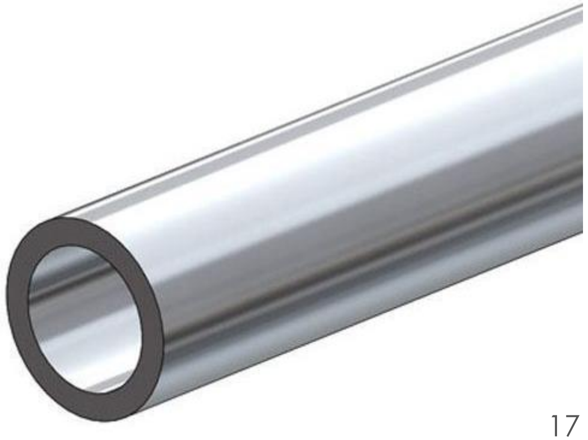
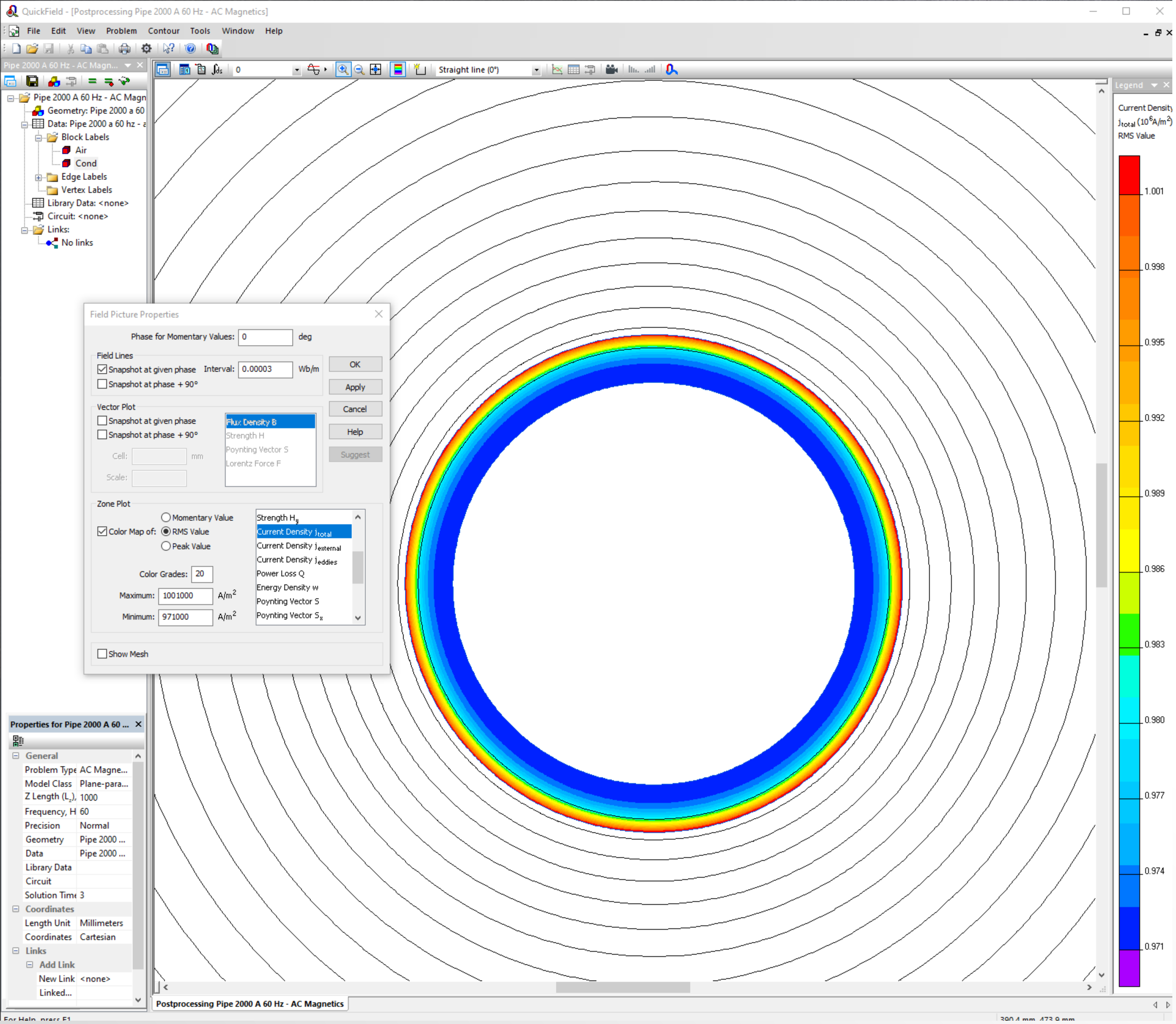
2.5" Schedule 80 Pipe

This analysis was performed at 0 Hz. This is DC without any AC frequencies.

QuickField calculates the following values:

- Resistance 2.29e-5 Ω
- Impedance 2.29e-5 Ω
- Current Density 9.76e5 A/m^2 (903 A/in^2)
- Power Loss Q 31700 W/m^3





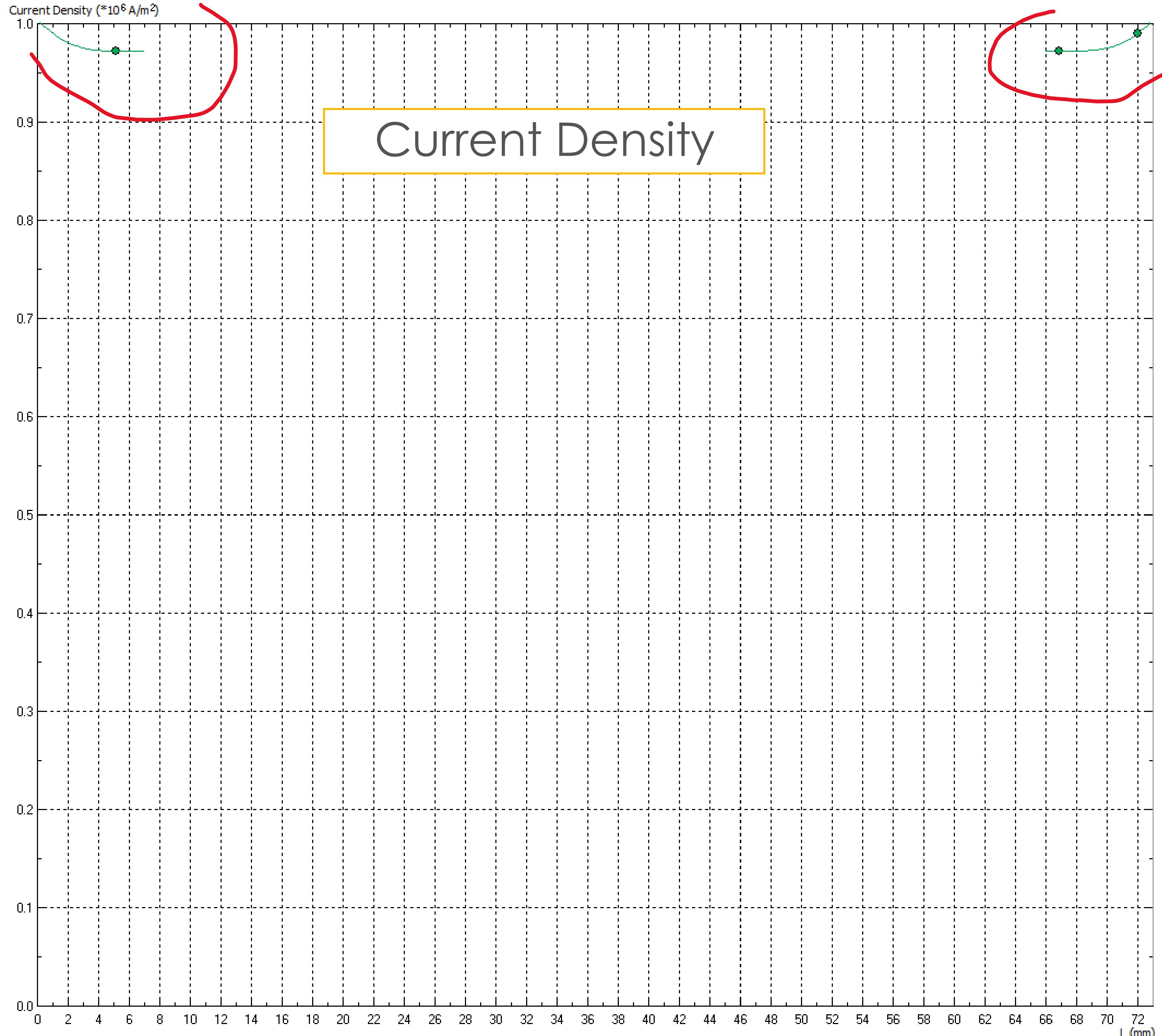
2.5" Schedule 80 Pipe

This analysis was performed at 60 Hz.

QuickField calculates the following values:

- Resistance 2.3112e-5 Ω
- Impedance 1.92e-4 Ω
- Current Density 1.00e6 A/m^2 (646 A/in^2)
- Current Density 9.71e5 A/m^2 (626 A/in^2)
- Power Loss Q 3.4e4 W/m^3
- Power Loss Q 3.1e3 W/m^3
- Energy Density w 23.7 J/m^3

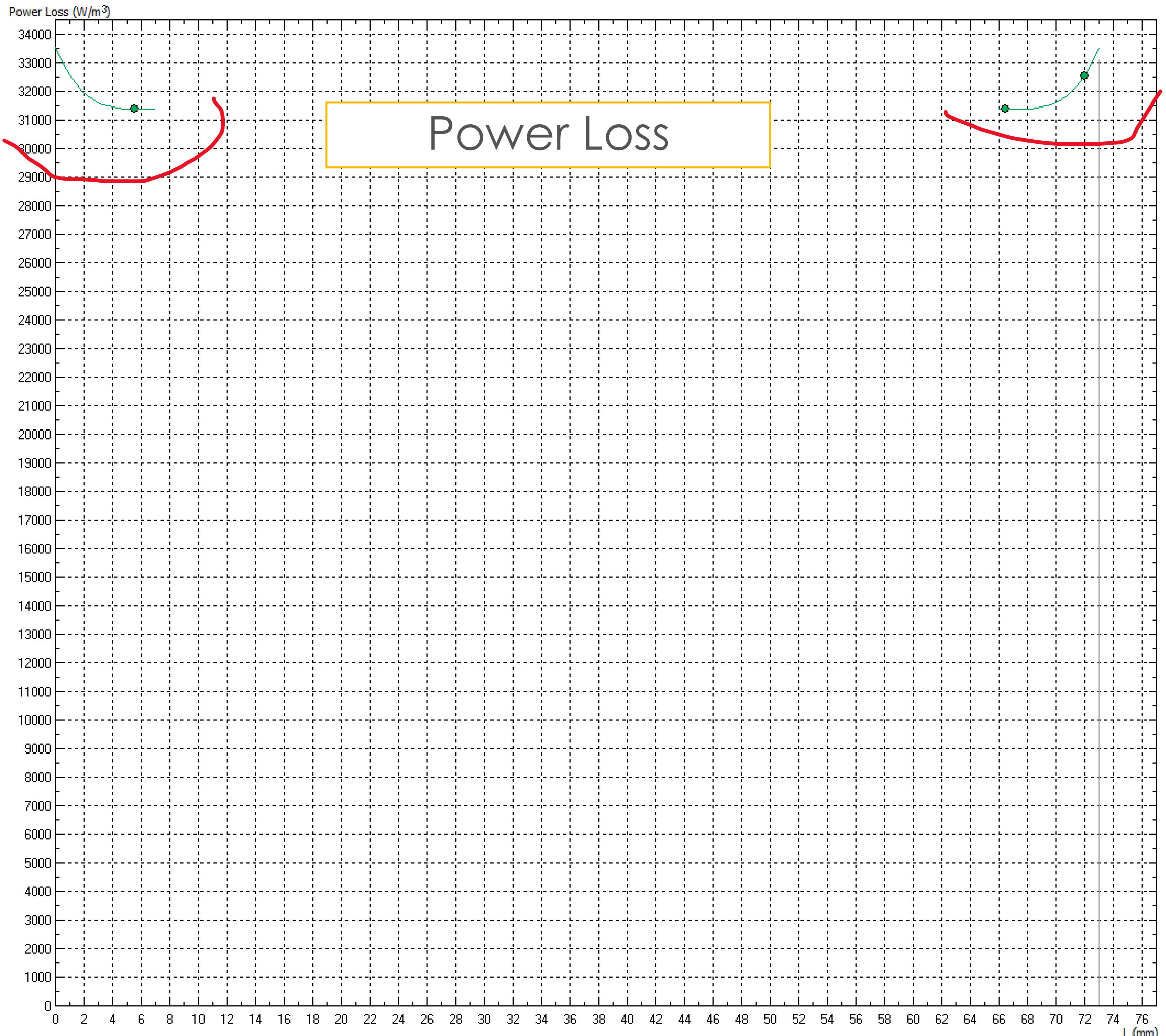
Current Density



KEC Precision

QuickField calculates the following values:

- Resistance 2.3112e-5 Ω
- Impedance 1.92e-4 Ω
- Current Density 1.00e6 A/m^2 (646 A/in^2)
- Current Density 9.71e5 A/m^2 (626 A/in^2)
- Power Loss Q 3.4e4 W/m^3
- Power Loss Q 3.1e3 W/m^3
- Energy Density w 23.7 J/m^3



QuickField calculates the following values:

- Resistance 2.3112e-5 Ω
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- Current Density 9.71e5 A/m^2 (626 A/in^2)
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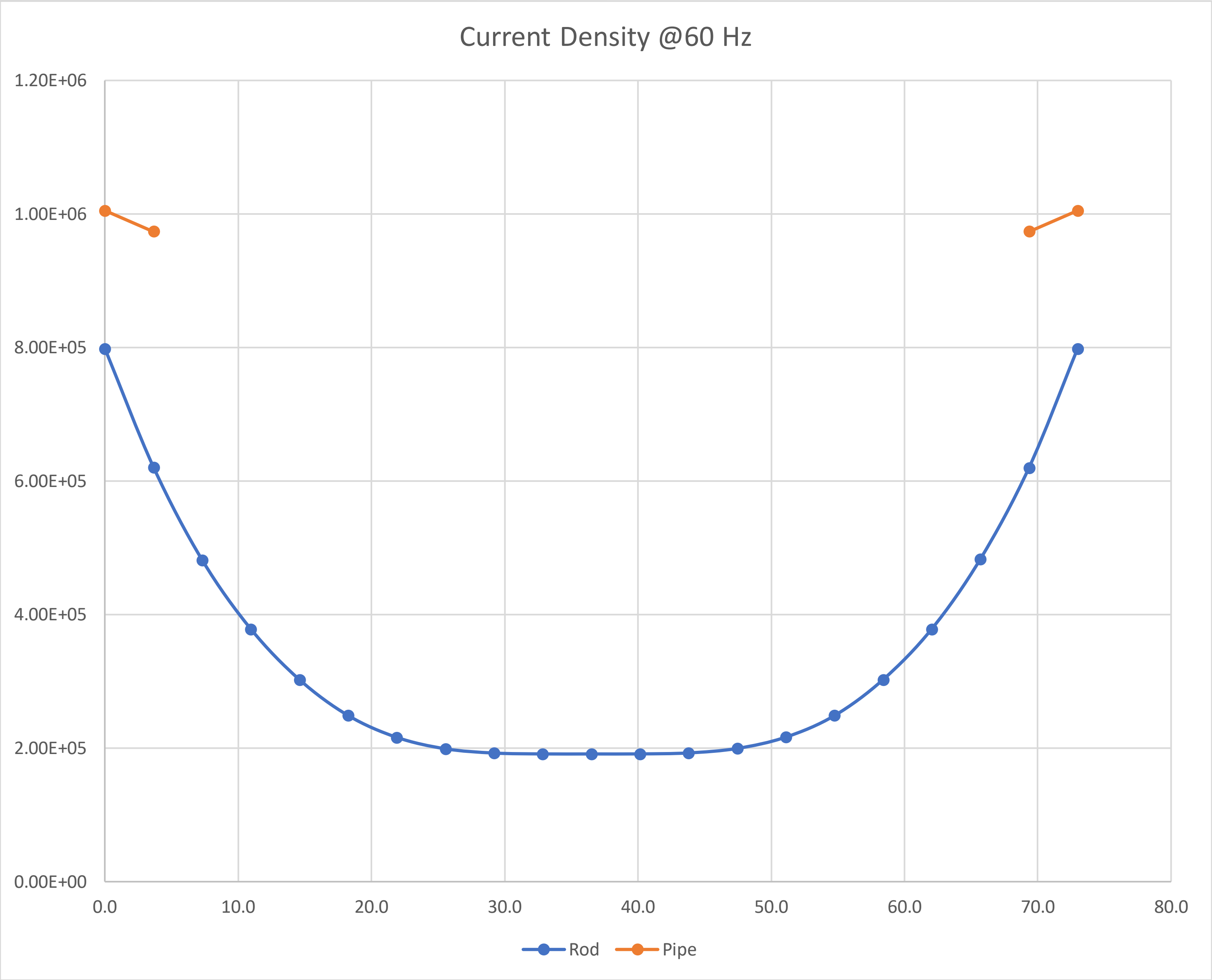

This slide shows the current density of the Rod vs Pipe at 60 Hz

The previous Excel graph was made by copying the table from the postprocessor from QuickField directly into Excel

Please note that all of the data is in one table.

L (mm)	x (mm)	y (mm)	Nx	Ny	jtotal (A/m2)	jexternal (A/m2)	jeddies (A/m2)	Q (W/m3)	V (V)	B (T)	Bx (T)	By (T)	Bn (T)	Bt (T)	H (A/m)	Hx (A/m)	Hy (A/m)	Hn (A/m)	Ht (A/m)	S (W/m2)	Sx (W/m2)	Sy (W/m2)	w (J/m3)	F (N/m3)	Fx (N/m3)	Fy (N/m3)	A (Wb/m)	s (S/m)	m	T (°C)
0.0	364	400	0	-1	7.98E+05	8.45E+06	7.92E+06	2.11E+04	2.81E-01	7.31E-03	2.36E-05	0.0073	0.0073	2.36E-05	5817	19	5817	5817	18.79	115.49	115.49	-0.46	21.26	4368	4368	-17.2325	6.98E-04	3.01E+07	1	-273.15
3.6	367	400	0	-1	6.20E+05	8.45E+06	8.20E+06	1.28E+04	2.81E-01	5.98E-03	5.18E-05	0.0060	0.0060	5.18E-05	4757	41	4757	4757	41.25	77.18	77.17	0.85	14.22	2919	2919	32.0844	7.22E-04	3.01E+07	1	-273.15
7.3	371	400	0	-1	4.81E+05	8.45E+06	8.39E+06	7.69E+03	2.81E-01	4.69E-03	2.46E-05	0.0047	0.0047	2.46E-05	3735	20	3735	3735	19.60	47.72	47.72	-0.31	8.77	1805	1805	-11.668	7.40E-04	3.01E+07	1	-273.15
11.0	374	400	0	-1	3.78E+05	8.45E+06	8.53E+06	4.74E+03	2.81E-01	3.68E-03	9.67E-06	0.0037	0.0037	9.67E-06	2925	8	2925	2925	7.70	30.14	30.14	-0.01	5.37	1140	1140	-0.47884	7.51E-04	3.01E+07	1	-273.15
14.6	378	400	0	-1	3.02E+05	8.45E+06	8.60E+06	3.03E+03	2.81E-01	2.89E-03	4.60E-05	0.0029	0.0029	4.60E-05	2301	37	2301	2301	36.59	19.64	19.64	-0.37	3.33	743	743	-13.8293	7.58E-04	3.01E+07	1	-273.15
18.3	382	400	0	-1	2.48E+05	8.45E+06	8.64E+06	2.05E+03	2.81E-01	2.28E-03	1.87E-05	0.0023	0.0023	1.87E-05	1814	15	1814	1814	14.85	13.42	13.42	-0.12	2.07	508	508	-4.53601	7.61E-04	3.01E+07	1	-273.15
21.9	385	400	0	-1	2.15E+05	8.45E+06	8.65E+06	1.54E+03	2.81E-01	1.78E-03	9.17E-06	0.0018	0.0018	9.17E-06	1420	7	1420	1420	7.30	9.64	9.63	-0.05	1.27	364	364	-1.89785	0.000762	3.01E+07	1	-273.15
25.6	389	400	0	-1	1.98E+05	8.45E+06	8.65E+06	1.31E+03	2.81E-01	1.33E-03	3.77E-06	0.0013	0.0013	3.77E-06	1061	3	1061	1061	3.00	6.88	6.88	0.00	0.71	260	260	0.074222	7.62E-04	3.01E+07	1	-273.15
29.2	393	400	0	-1	1.92E+05	8.45E+06	8.64E+06	1.22E+03	2.81E-01	8.77E-04	1.34E-05	0.0009	0.0009	1.34E-05	698	11	698	698	10.68	4.44	4.44	0.06	0.31	168	168	2.37554	7.62E-04	3.01E+07	1	-273.15
32.9	396	400	0	-1	1.91E+05	8.45E+06	8.63E+06	1.21E+03	2.81E-01	4.65E-04	1.68E-05	0.0005	0.0005	1.68E-05	370	13	370	370	13.33	2.34	2.34	-0.08	0.09	89	89	-3.1929	7.61E-04	3.01E+07	1	-273.15
36.5	400	400	0	-1	1.91E+05	8.45E+06	8.63E+06	1.21E+03	2.81E-01	1.71E-05	6.70E-06	0.0000	0.0000	6.70E-06	14	5	13	13	5.33	0.09	-0.08	-0.03	0.00	3	-3	-1.26063	7.61E-04	3.01E+07	1	-273.15
40.2	404	400	0	-1	1.91E+05	8.45E+06	8.63E+06	1.21E+03	2.81E-01	4.50E-04	1.86E-05	0.0004	0.0004	1.86E-05	358	15	357	357	14.77	2.27	-2.26	0.09	0.08	86	-86	3.53853	7.61E-04	3.01E+07	1	-273.15
43.8	407	400	0	-1	1.92E+05	8.45E+06	8.64E+06	1.23E+03	2.81E-01	8.72E-04	2.73E-05	0.0009	0.0009	2.73E-05	694	22	694	694	21.75	4.42	-4.42	0.14	0.30	167	-167	5.24534	0.000762	3.01E+07	1	-273.15
47.5	411	400	0	-1	1.99E+05	8.45E+06	8.65E+06	1.31E+03	2.81E-01	1.30E-03	2.61E-05	0.0013	0.0013	2.61E-05	1037	21	1037	1037	20.73	6.74	-6.74	0.14	0.68	255	-255	5.1797	7.62E-04	3.01E+07	1	-273.15
51.1	415	400	0	-1	2.16E+05	8.45E+06	8.65E+06	1.55E+03	2.81E-01	1.79E-03	1.07E-05	0.0018	0.0018	1.07E-05	1424	9	1424	1424	8.53	9.72	-9.71	-0.06	1.27	367	-367	-2.30911	7.62E-04	3.01E+07	1	-273.15
54.8	418	400	0	-1	2.48E+05	8.45E+06	8.64E+06	2.04E+03	2.81E-01	2.33E-03	7.79E-06	0.0023	0.0023	7.79E-06	1857	6	1857	1857	6.20	13.87	-13.87	-0.04	2.17	524	-524	-1.3452	0.000761	3.01E+07	1	-273.15
58.4	422	400	0	-1	3.02E+05	8.45E+06	8.60E+06	3.03E+03	2.81E-01	2.92E-03	1.14E-05	0.0029	0.0029	1.14E-05	2325	9	2325	2325	9.08	19.92	-19.92	0.09	3.40	753	-753	3.42378	7.58E-04	3.01E+07	1	-273.15
62.1	426	400	0	-1	3.78E+05	8.45E+06	8.53E+06	4.74E+03	2.81E-01	3.67E-03	1.14E-05	0.0037	0.0037	1.14E-05	2922	9	2922	2922	9.05	29.98	-29.98	-0.10	5.36	1134	-1134	-3.76079	7.51E-04	3.01E+07	1	-273.15
65.7	429	400	0	-1	4.82E+05	8.45E+06	8.39E+06	7.73E+03	2.81E-01	4.67E-03	3.92E-05	0.0047	0.0047	3.92E-05	3720	31	3720	3720	31.21	47.73	-47.73	-0.50	8.70	1806	-1805	-18.8876	7.40E-04	3.01E+07	1	-273.15
69.4	433	400	0	-1	6.19E+05	8.45E+06	8.20E+06	1.27E+04	2.81E-01	6.09E-03	1.24E-04	0.0061	0.0061	1.24E-04	4849	99	4848	4848	98.62	79.98	-79.95	2.02	14.78	3025	-3024	76.5306	7.22E-04	3.01E+07	1	-273.15
73.0	437	400	0	-1	7.98E+05	8.45E+06	7.92E+06	2.11E+04	2.81E-01	7.20E-03	2.46E-05	0.0072	0.0072	2.46E-05	5732	20	5732	5732	19.60	111.33	-111.33	0.51	20.65	4211	-4211	19.3684	6.98E-04	3.01E+07	1	-273.15

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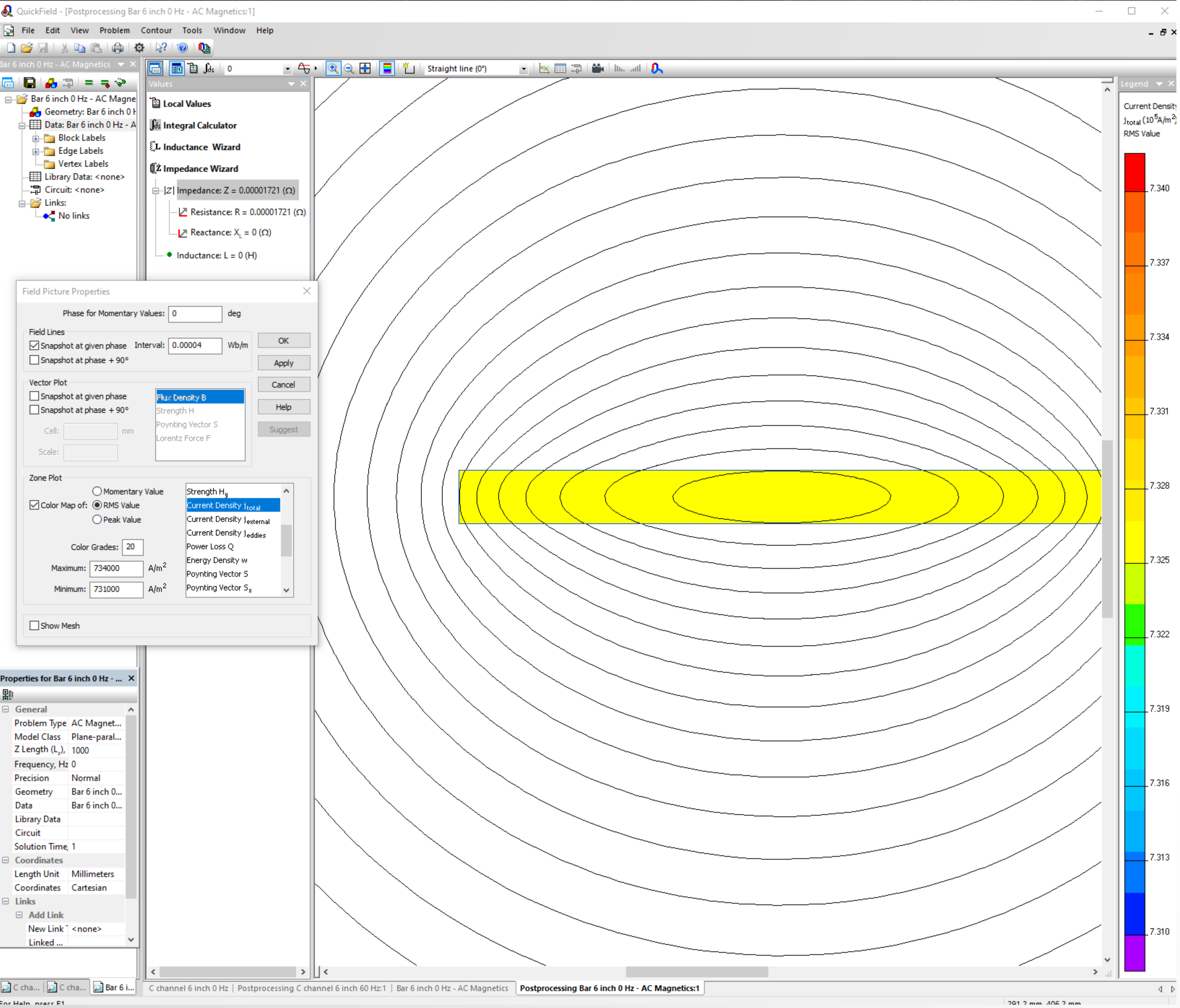
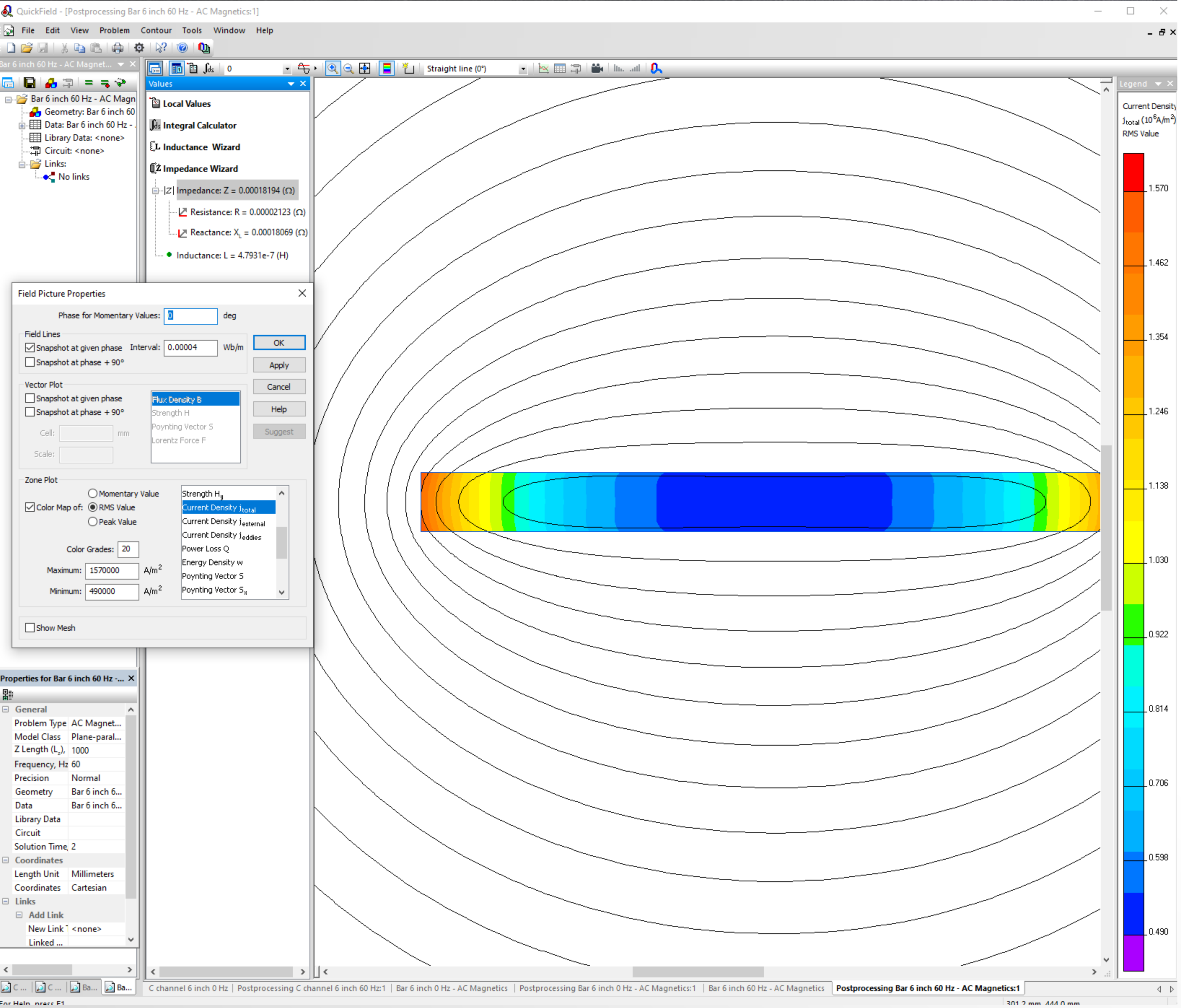


Aluminum bar 6" x ½"

This analysis was performed at 0 Hz. This is DC without any AC frequencies

QuickField calculates the following values:

- Resistance 1.72e-5 Ω
- Impedance 1.72e-5 Ω
- Impedance 7.95e-6 Ω
- Current Density 7.33e5 A/m^2 (473 A/in^2)
- Power Loss Q 1.8e4 W/m^3

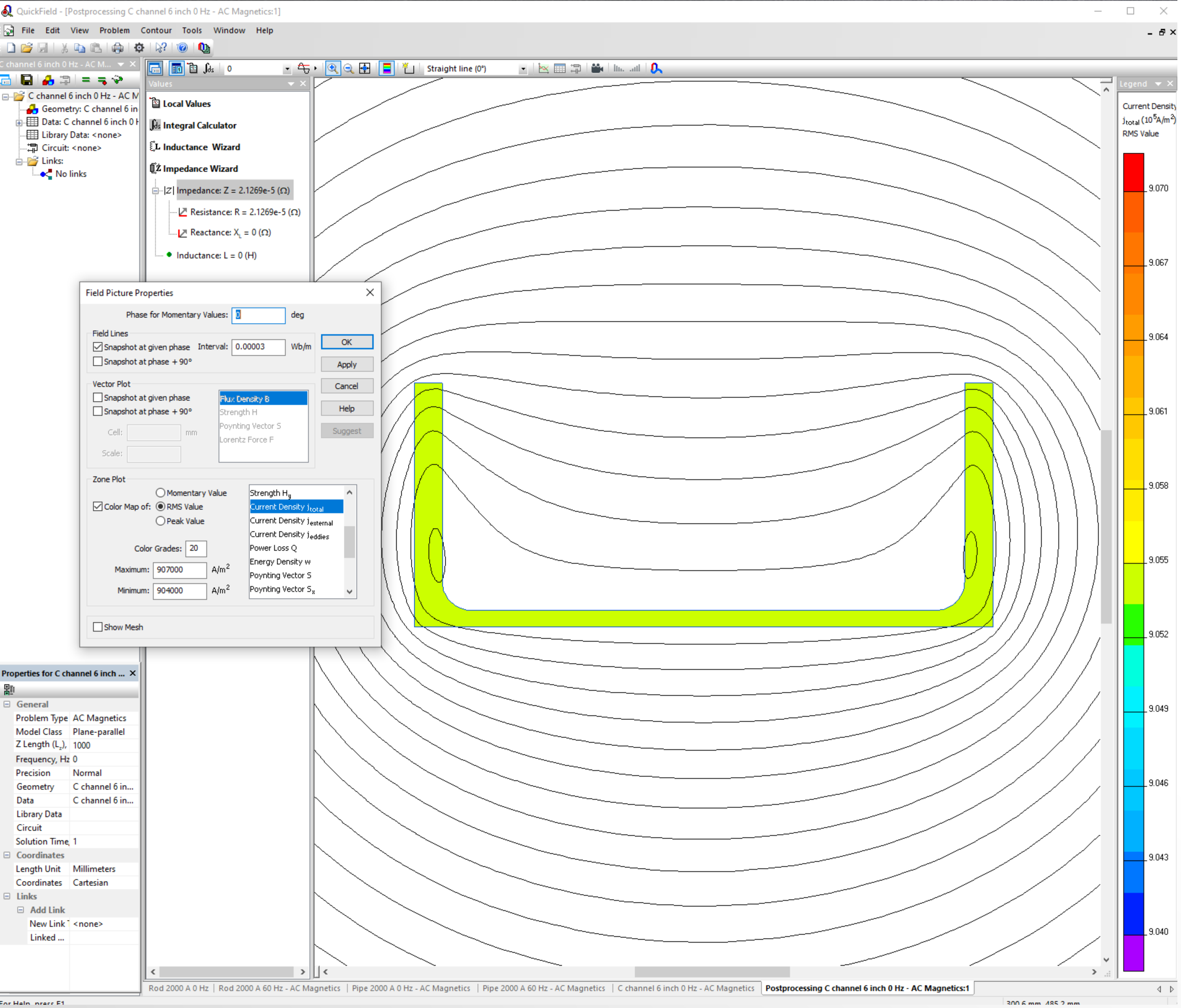


Aluminum bar 6" x ½"

This analysis was performed at 60 Hz AC

QuickField calculates the following values:

- Resistance 2.12e-5 Ω
- Impedance 1.82e-4 Ω
- Current Density 1.57e6 A/m^2 (1013 A/in^2)
- Current Density 4.90e5 A/m^2 (316 A/in^2)
- Power Loss Q 8.17e4 W/m^3
- Power Loss Q 8.00e3 W/m^3



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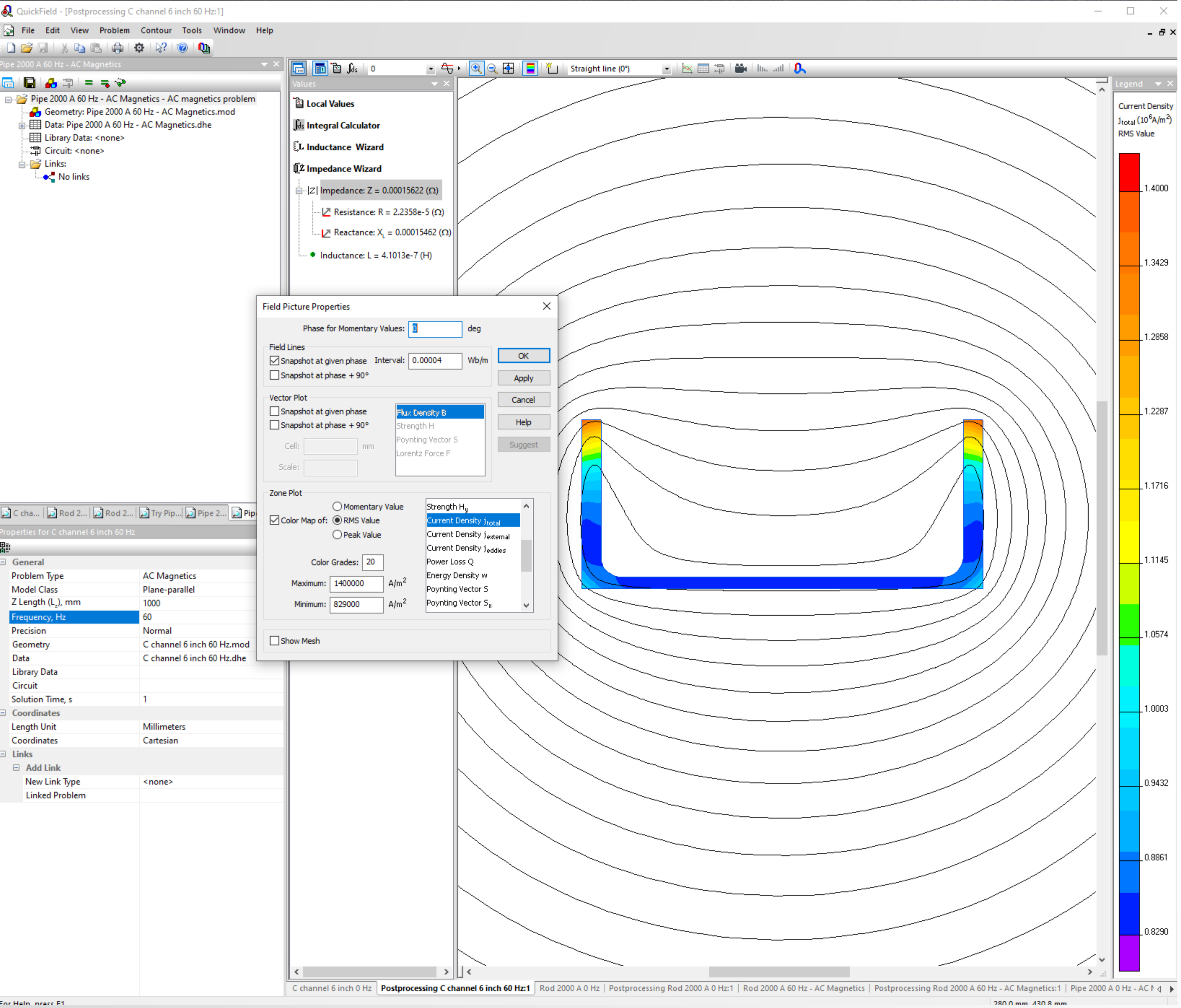
Aluminum Channel 6” w x 2.5” d

This analysis was performed at 0 Hz. This is DC without any AC frequencies

QuickField calculates the following values:

- Resistance 2.13e-5 Ω
- Impedance 2.13e-5 Ω
- Current Density 9.07e5 A/m² (585 A/in²)
- Power Loss Q 2.73e4 W/m³



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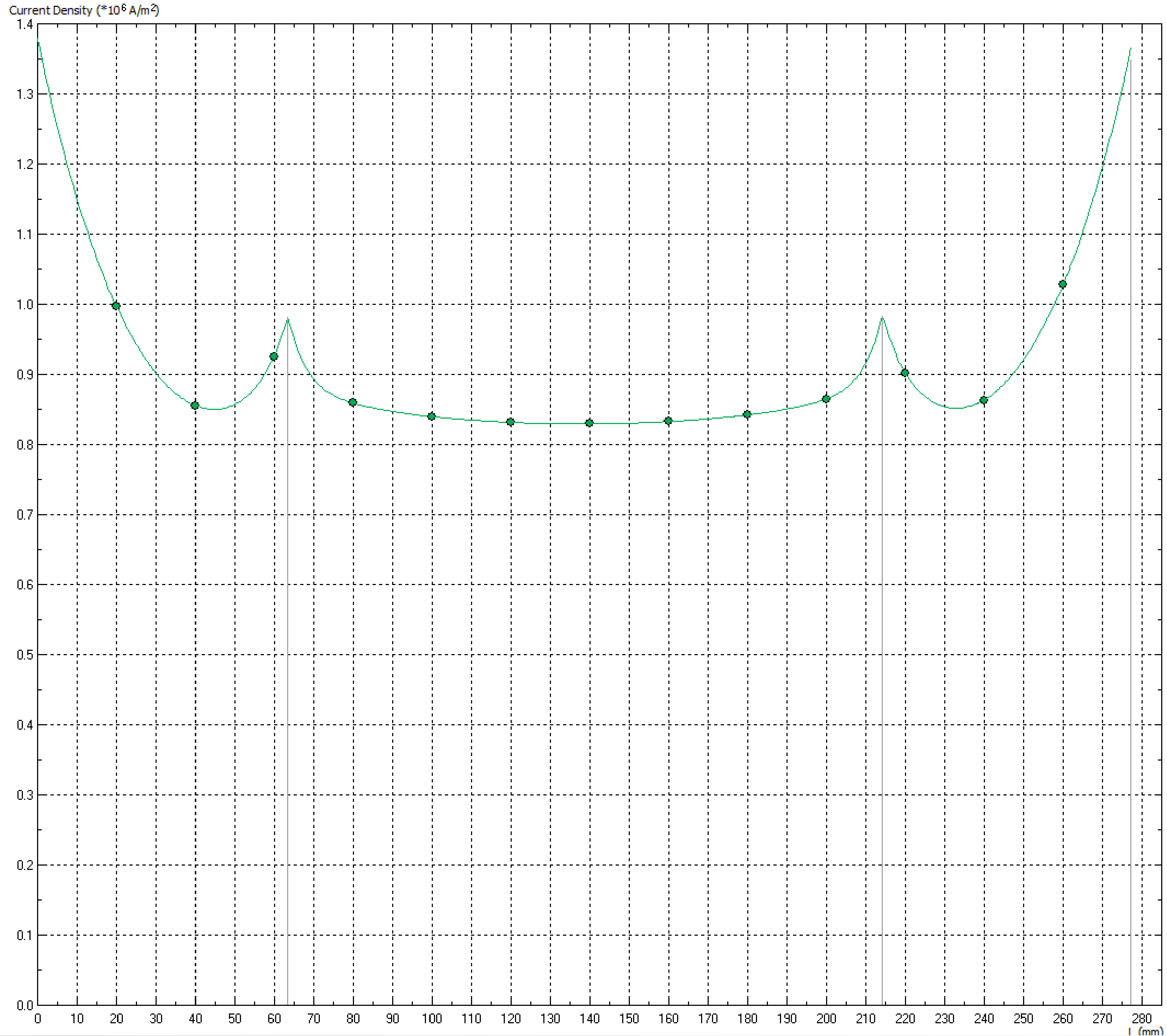
Aluminum Channel 6" w x 2.5" d

This analysis was performed at 60 Hz AC

QuickField calculates the following values:

- Resistance 2.24e-5 Ω
- Impedance 1.56e-4 Ω
- Current Density 1.4e6 A/m^2 (903 A/in^2)
- Current Density 8.29e5 A/m^2 (535 A/in^2)
- Power Loss Q 6.48e4 W/m^3
- Power Loss Q 2.28e4 W/m^3



Aluminum Channel 6" w x 2.5" d

Notice the current distribution along the outer edge of the channel. (note: this is actually just below the surface.

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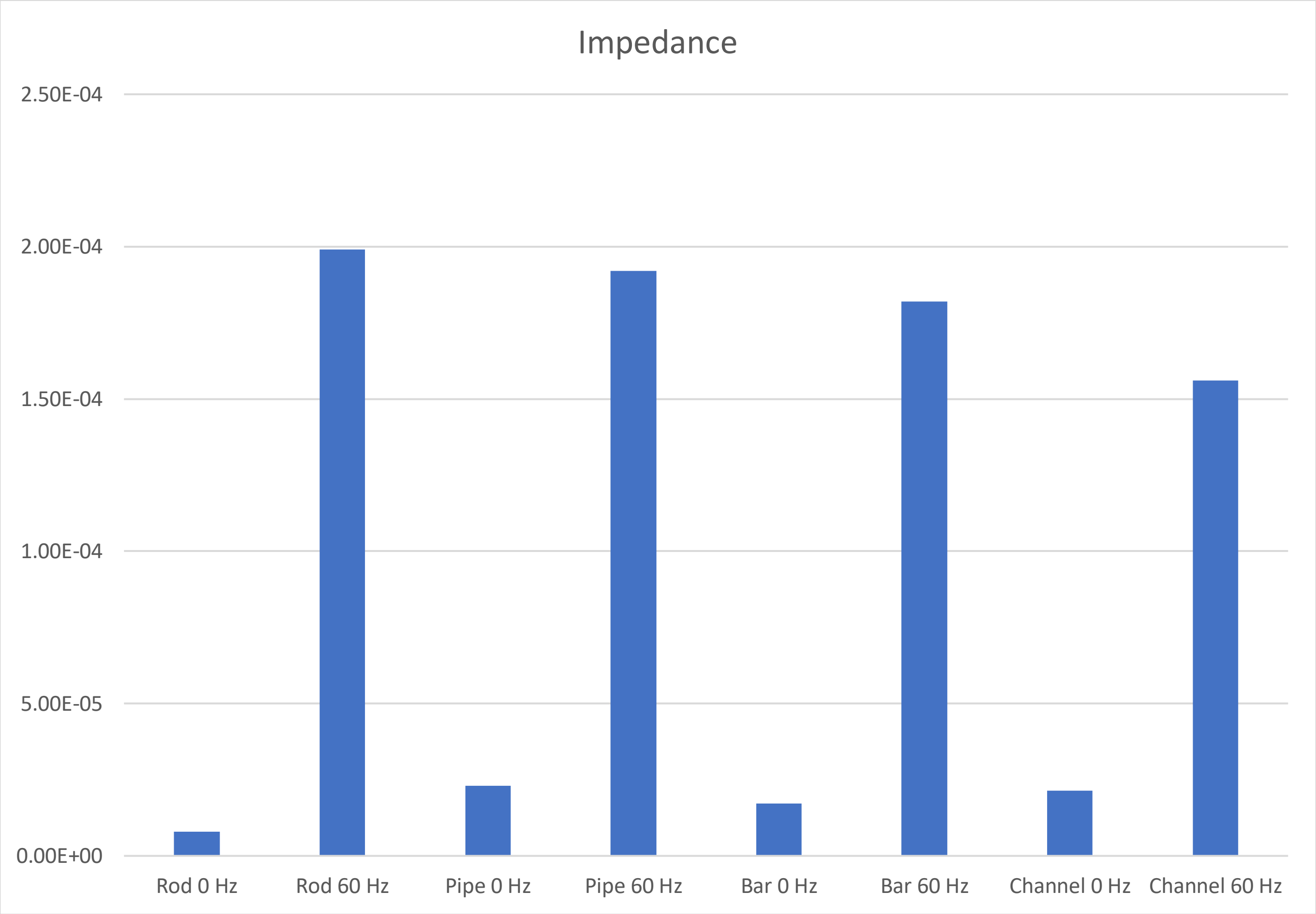


This slide shows the impedance of the various configurations

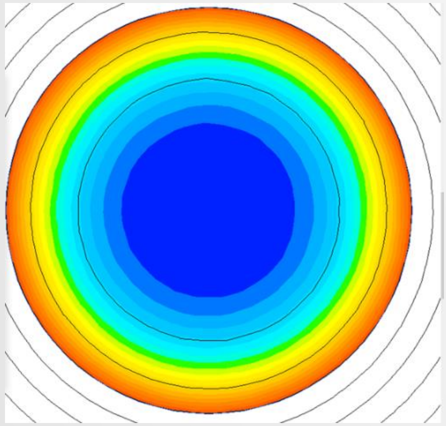
Hz	Impedance Ω	
0	Rod	7.95E-06
60	Rod	1.99E-04
0	Pipe	2.29E-05
60	Pipe	1.92E-04
0	Bar	1.72E-05
60	Bar	1.82E-04
0	Channel	2.13E-05
60	Channel	1.56E-04

Resistance = Impedance at 0 Hz. From this you can see how the impedance increases at 60 Hz.

Let us look at what this means in the real world…

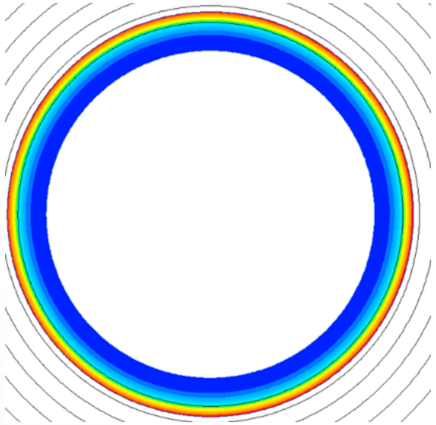
Contrasting the 2 5/8" Round Bar vs 2 ½ Sch 80 pipe with AC current at 60 Hz

AC current at 60 Hz



- Resistance 1.44e-5 Ω
- Impedance 1.99e-4 Ω
- Conductance (5025 mho)
- Weight per foot 6.37
- Cross-sectional Area 6.49 in^2

AC current at 60 Hz



- Resistance 2.3112e-5 Ω
- Impedance 1.92e-4 Ω
- Conductance (5208 mho)
- Weight per foot 2.69
- Cross-sectional area 2.25 in^2

Taking the Conductance and the weight per foot into account you can calculate that the pipe carries the same current as the round bar with only 44% of the weight.

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If you have any questions or would like my help with any issues, please feel free to contact me

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