MultiPhysics Simulation of Direct Double Helix Magnets for Charged Particle Applications

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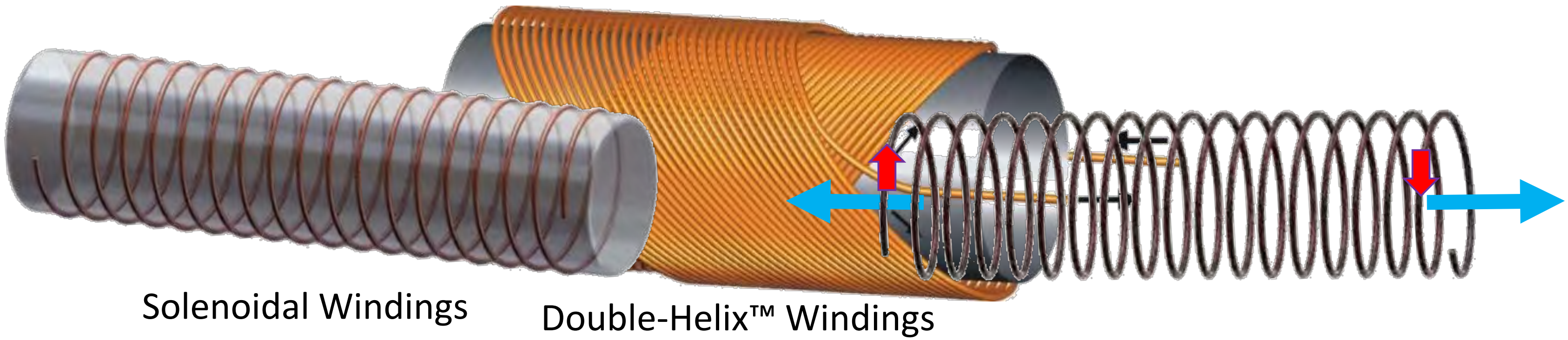
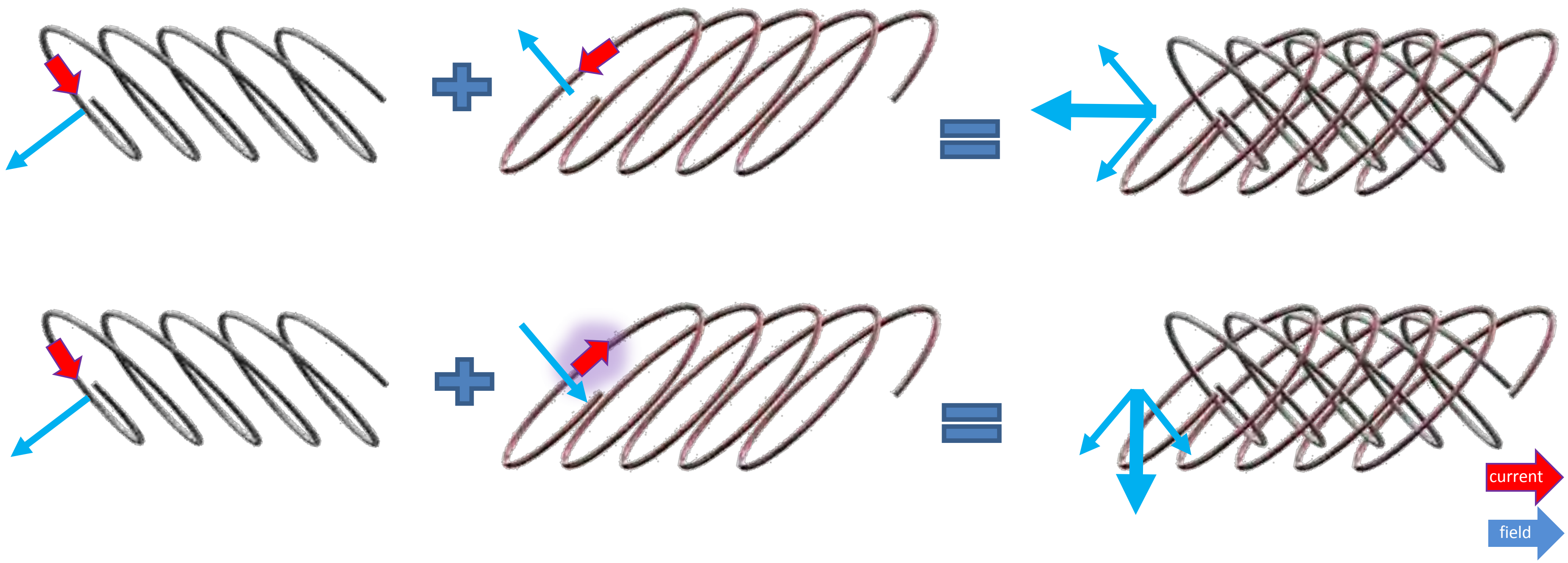
Outline

- Double Helix Windings
- Direct Double Helix
- Geometry in COMSOL
- Current distribution
- “Perfect” field
- Thermal analysis
- Application example
- Conclusion

How Double-Helix™ Works



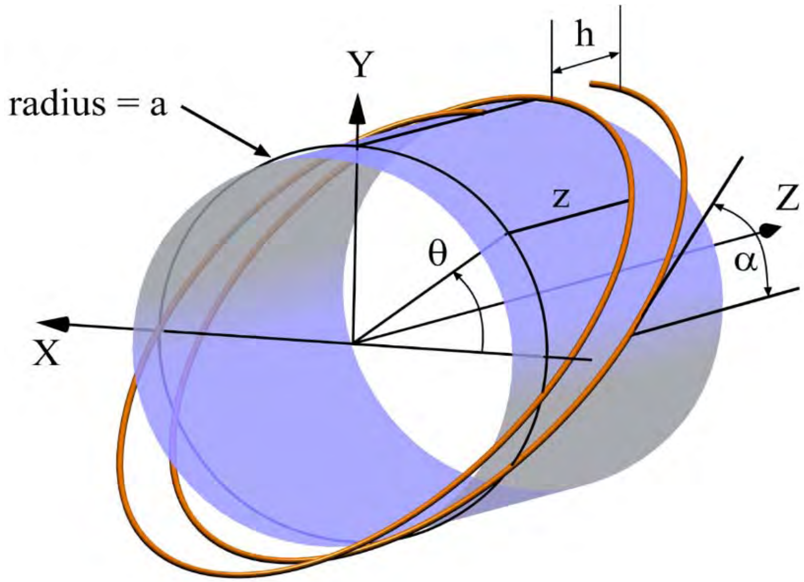


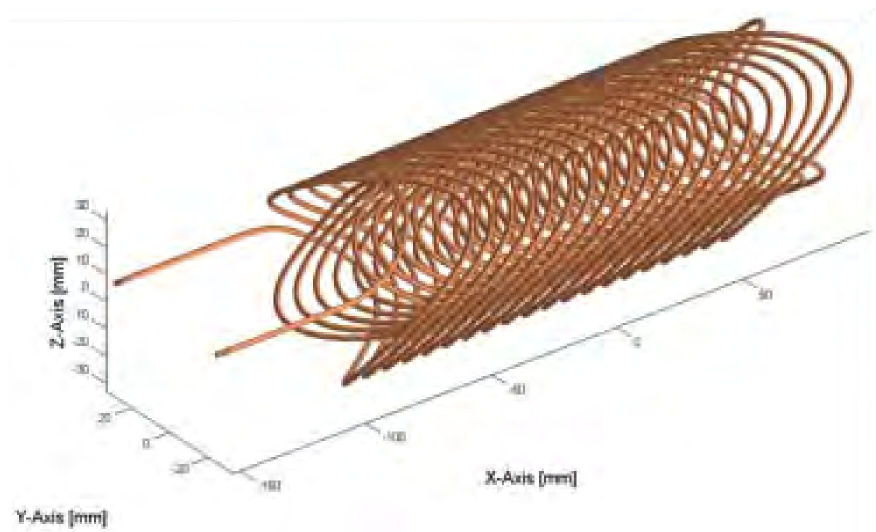
Double Helix Winding in Equations

$$X(\theta) = a\cos(\theta)$$

$$Y(\theta) = a\sin(\theta)$$

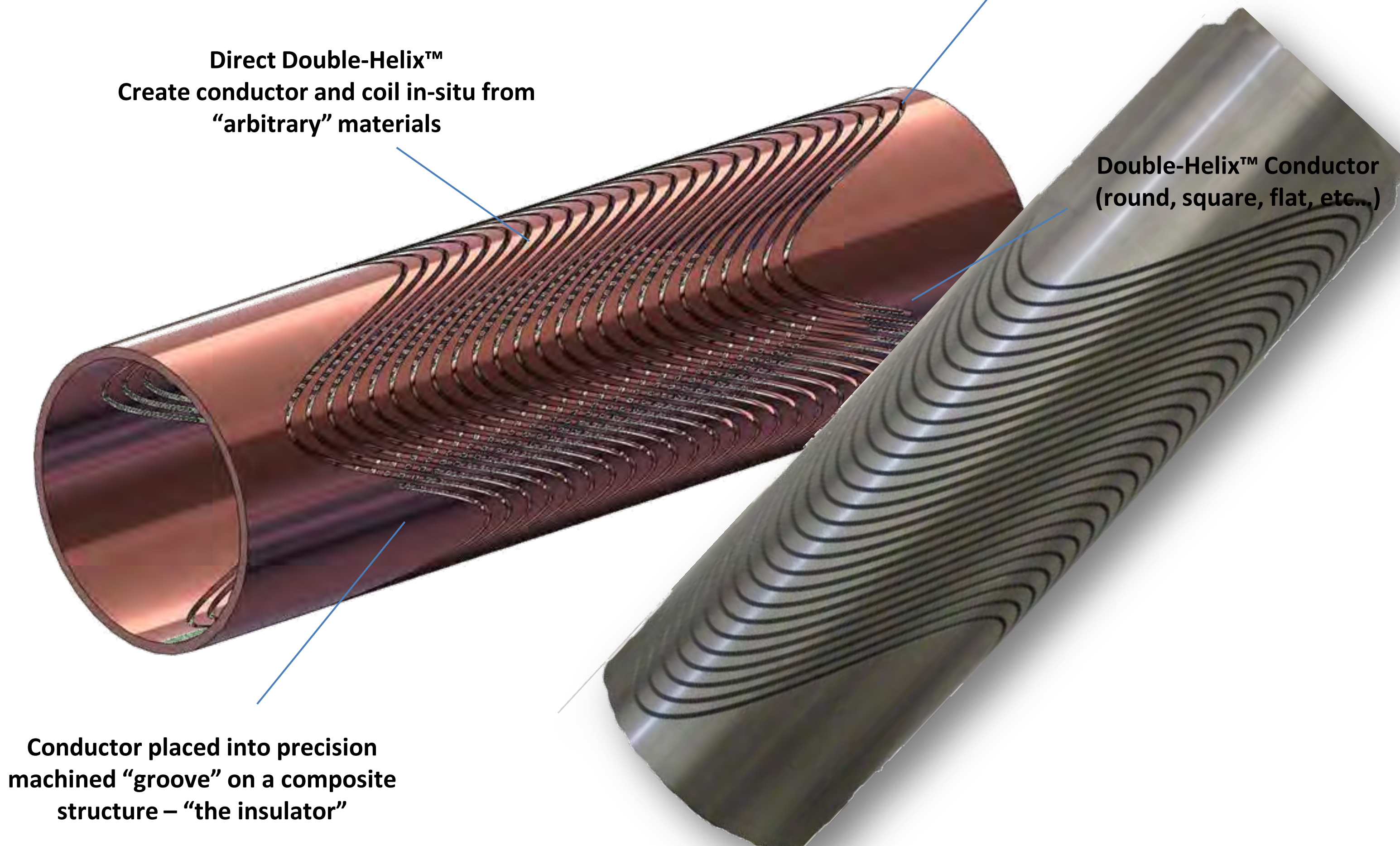
$$Z(\theta) = \frac{h}{2\pi}\theta + \frac{a}{\tan(\alpha)}\sin(n\theta + \varphi)$$





AML Direct Double-Helix™ Technology

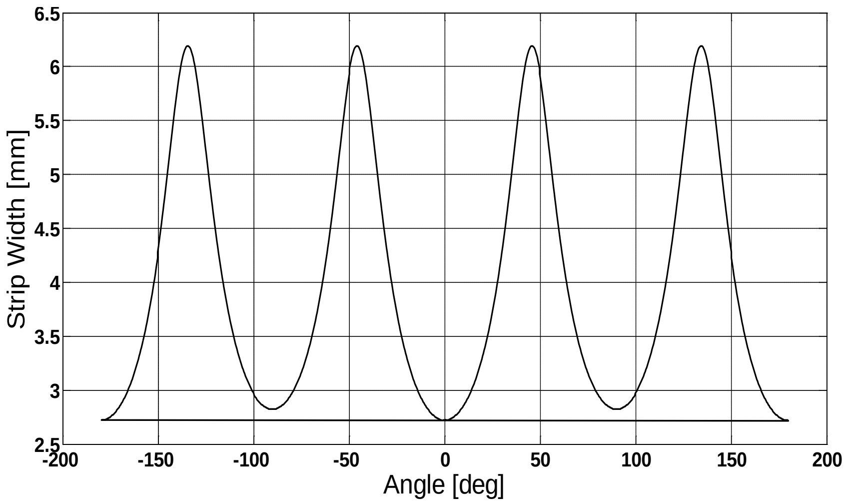
- Double-Helix™ (DH)
- Direct Double-Helix™ (DDH)
  - The “*Inverse of Double-Helix™*”



AML's Double-Helix™ Technology

- ***Direct*** **Double-Helix™ (DDH)**
  - Enables coil, conductor and winding to be created "directly"….

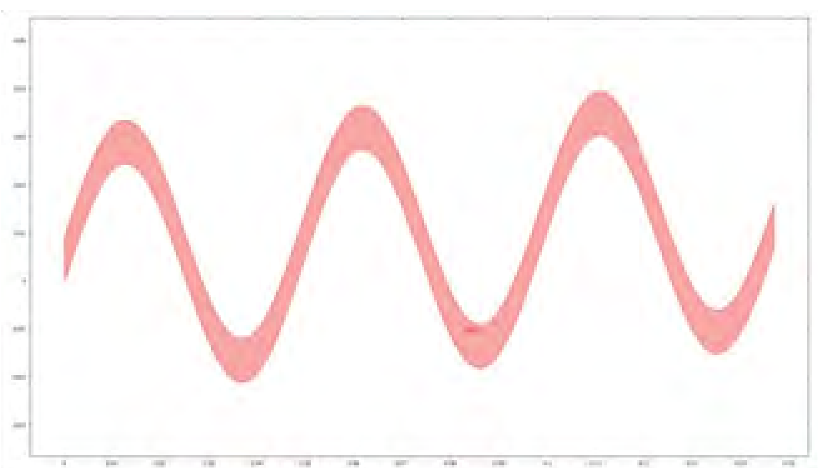
    …and in one automated process
  - Variable cross section of the conducting path drives the resistance down
  - Layer surface directly exposed to coolant provides very effective cooling

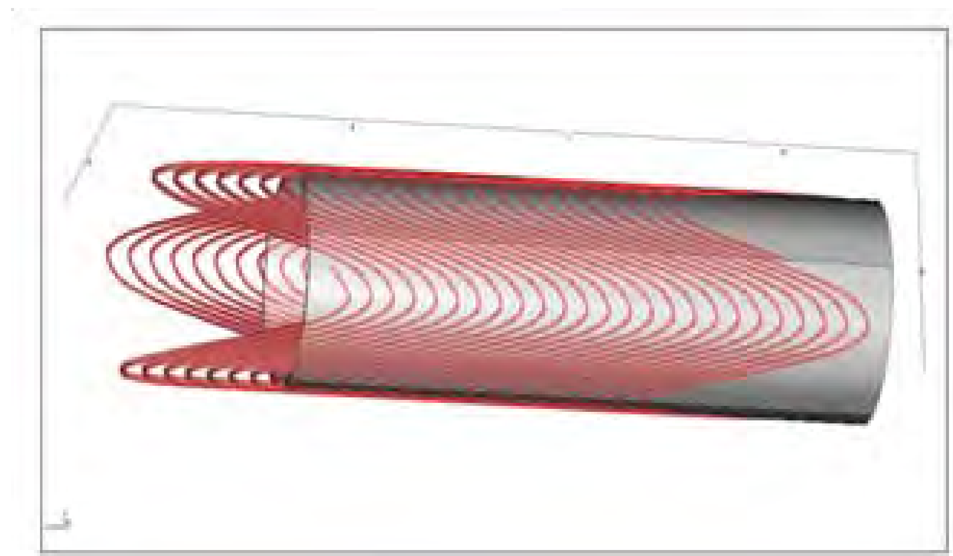


Variation in conductor width as a function of azimuth angle for a single turn of a DDH coil

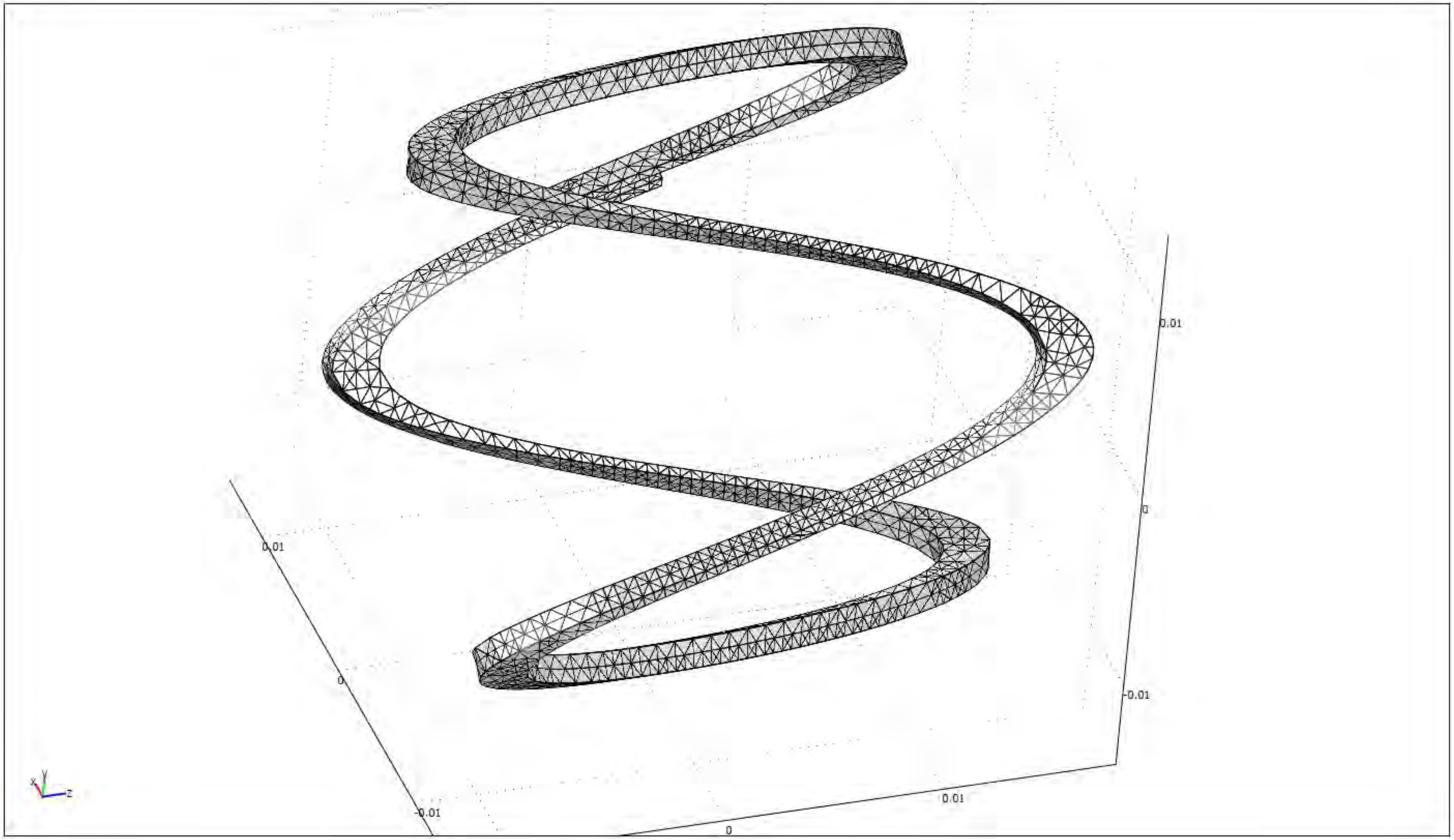
Building the Geometry

- 2D "unrolled"
  - Create vector of X, Y coordinates
  - Use "geomspline" to create curve
  - Use "geomcoerce" to build solid object
- 3D
  - Create vector of X, Y and Z coordinates
  - Use "simplesweep3" to create tool path
  - Subtract to cylinder to build solid object





Mesh



~ 5,500 elements and 12,500 degrees of freedom

Current Density Distribution

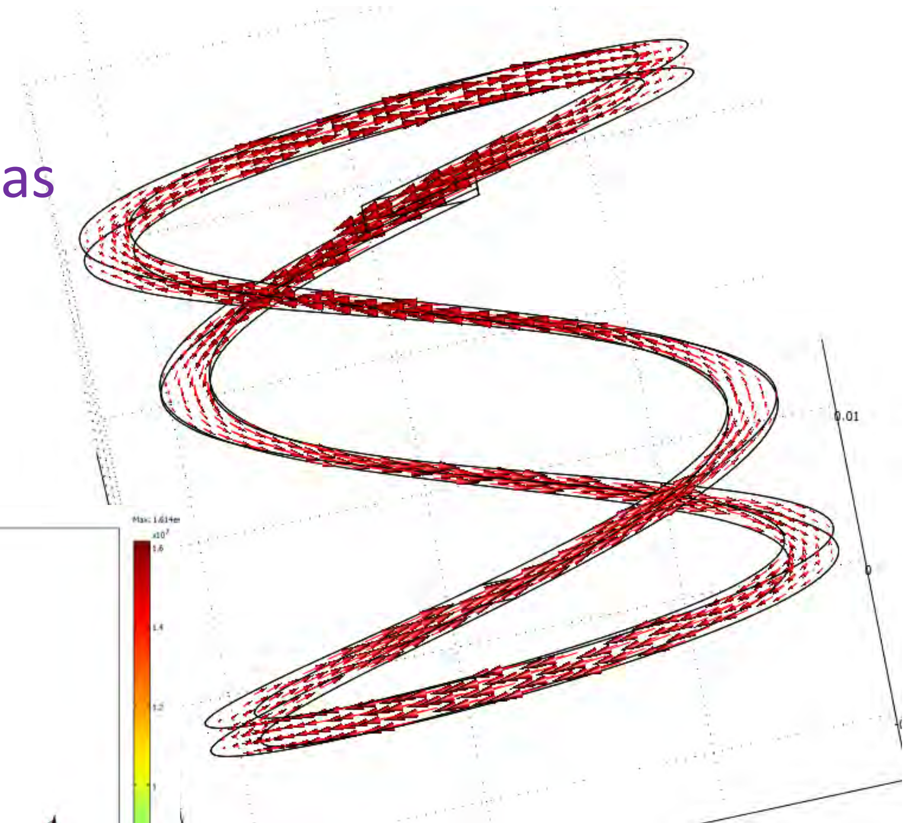
- Non-uniform current density:

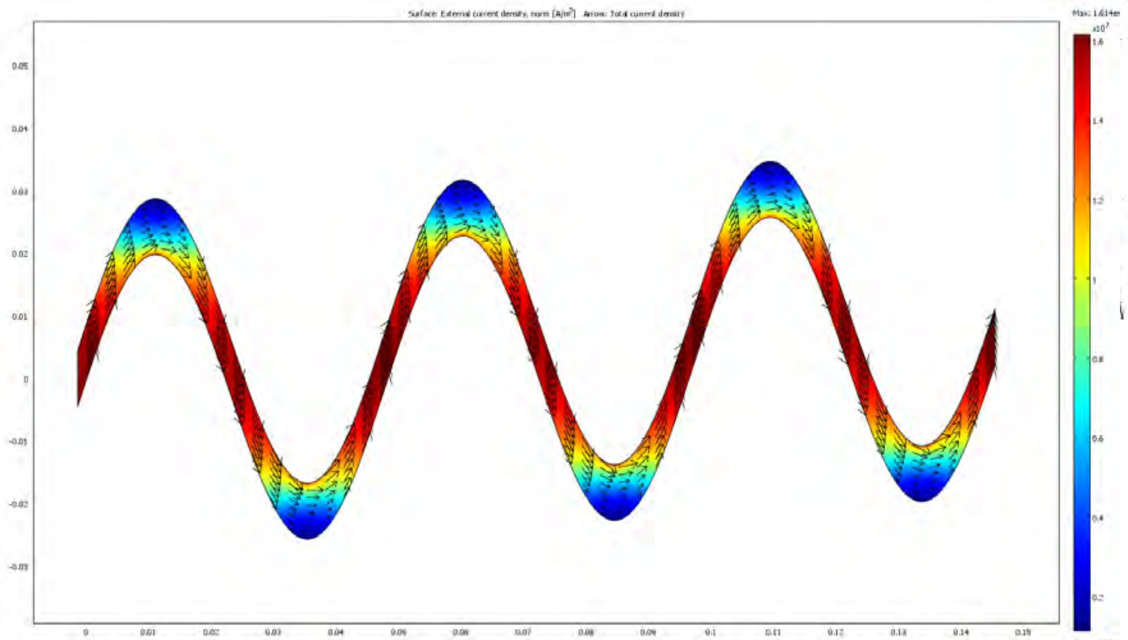
⇒ Lower current density in wider areas

⇒ Lower Joule heating

⇒ Higher current allowed

⇒ Higher field

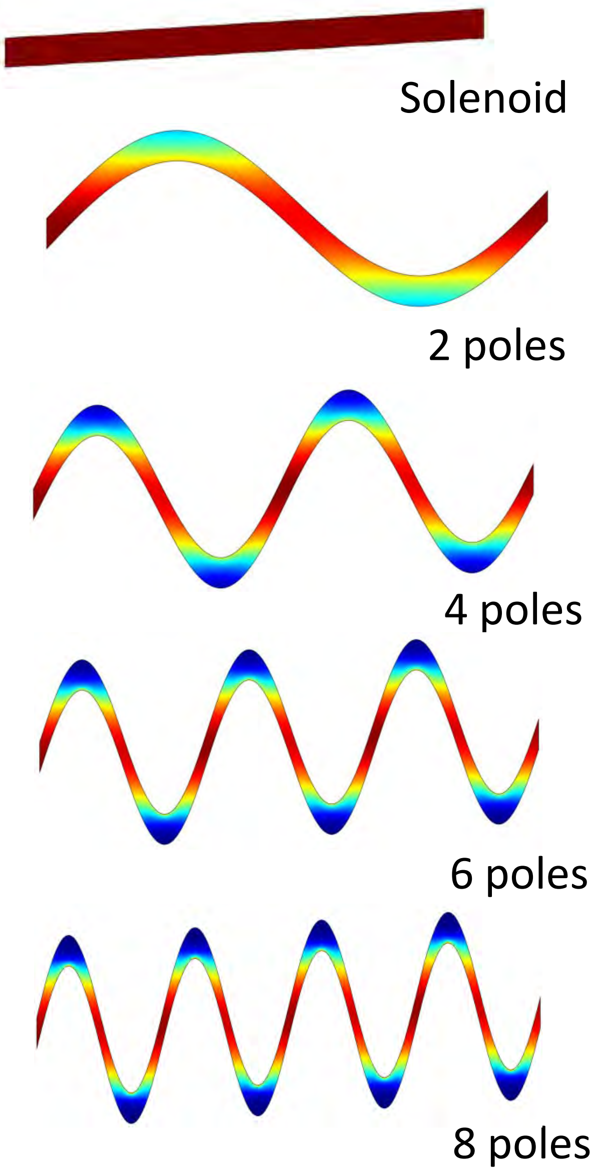


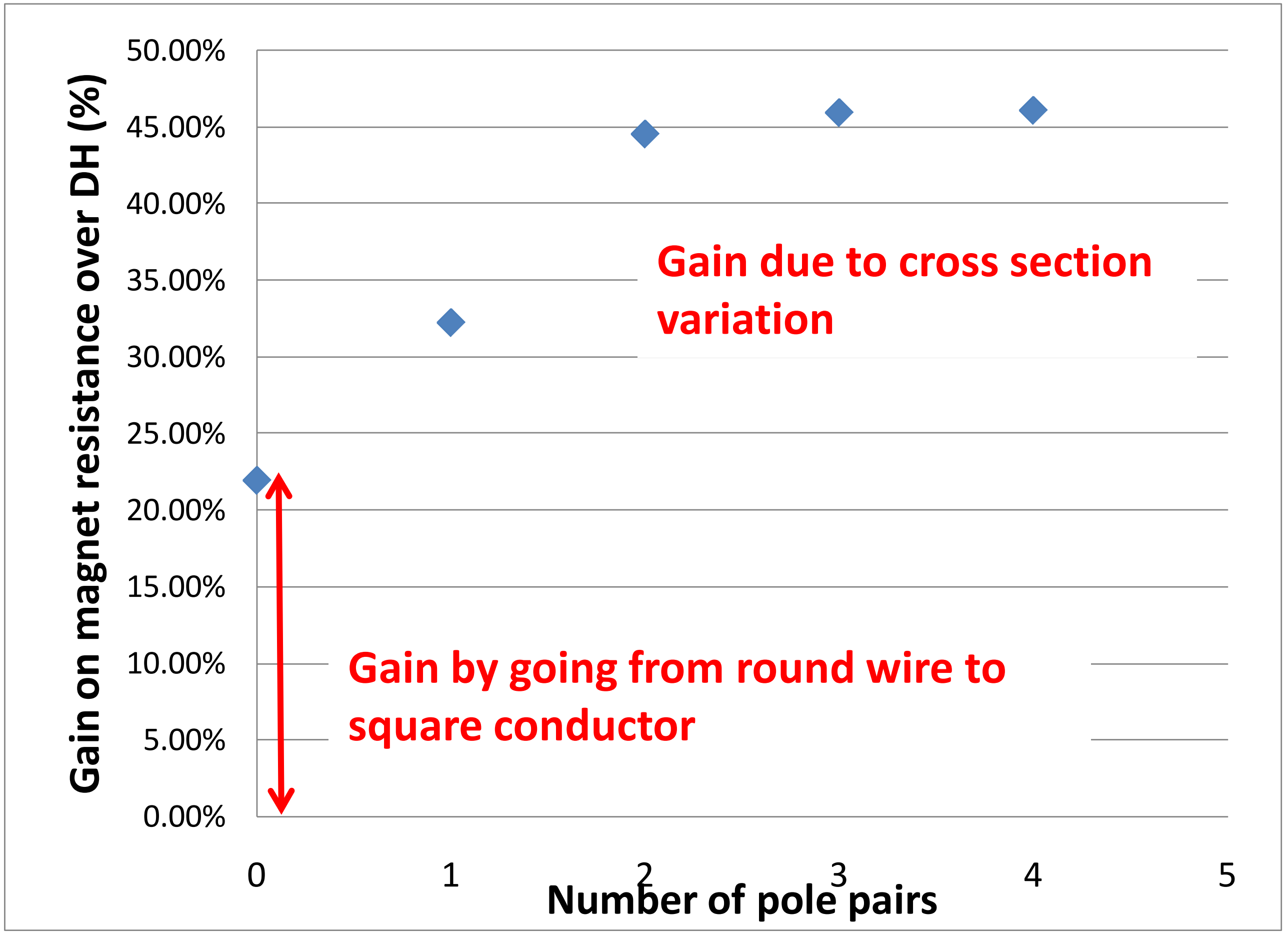


- Magnet resistance is reduced

Effect on Magnet Resistance

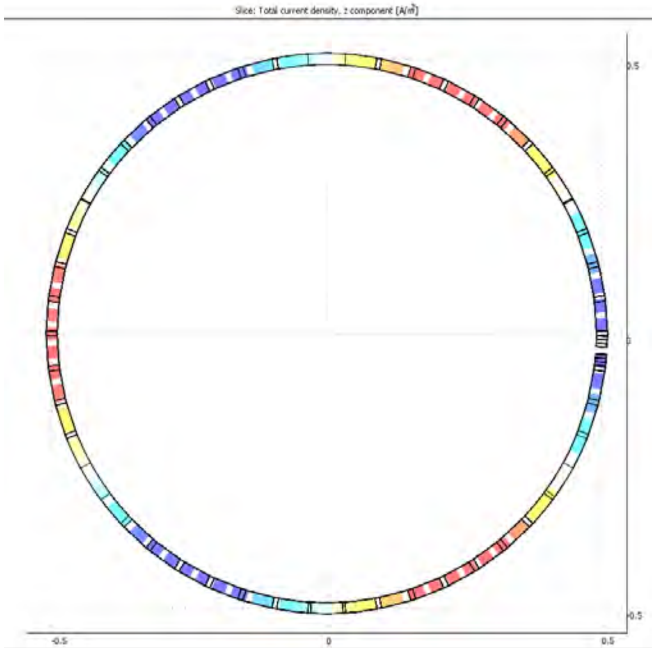
Due to conductor cross-section variation, DDH resistance is lower than that of DH for the same magnet design.

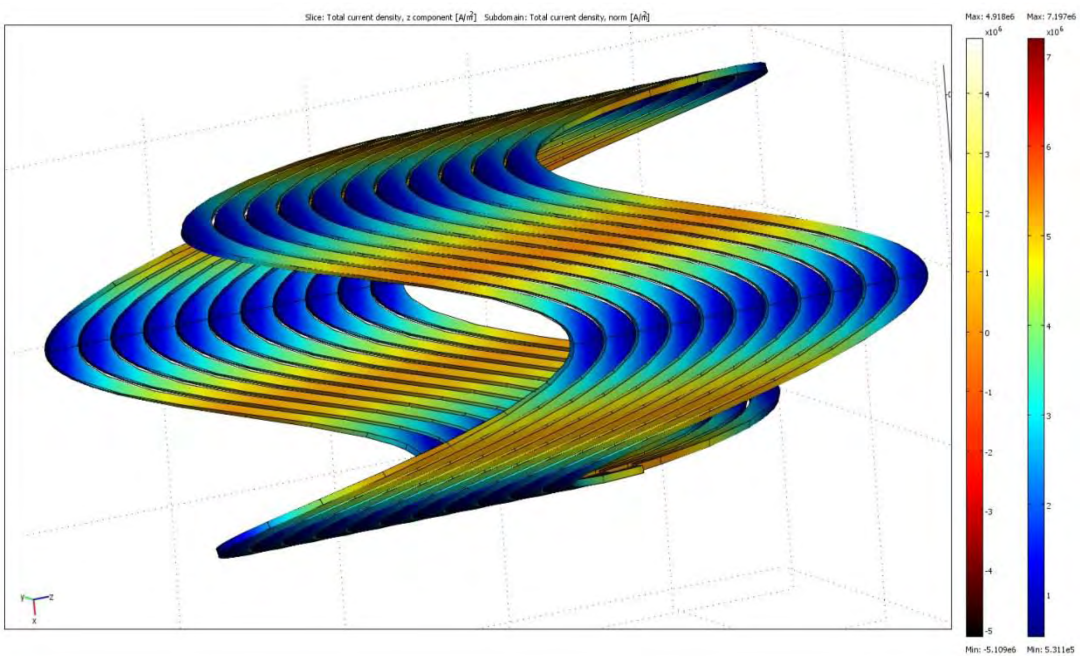




Sinusoidal Current Density Distribution

- Axial component of current density exhibits sinusoidal distribution
- Radial component of two layers compensate for axial field





- Ideal current source for low harmonics field distribution

“Perfect” Field

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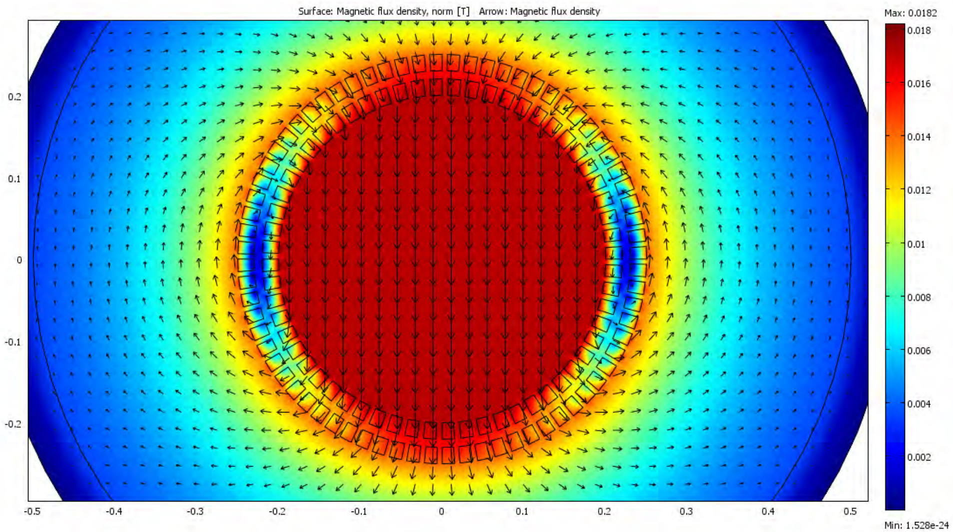
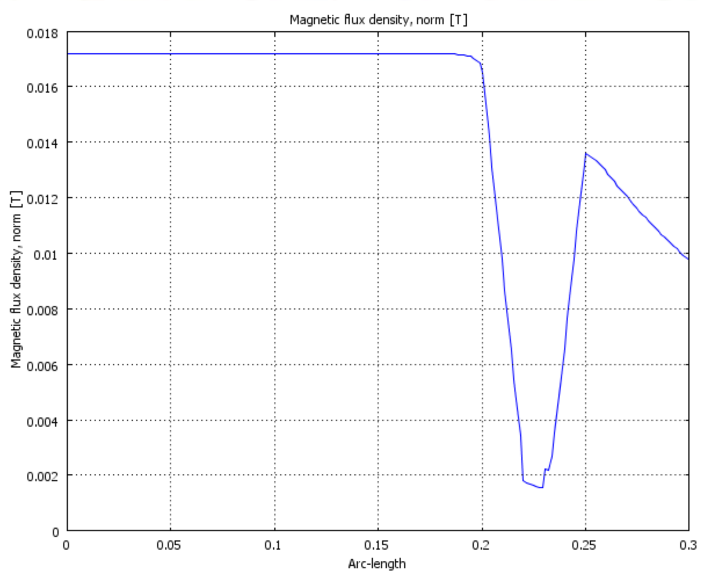
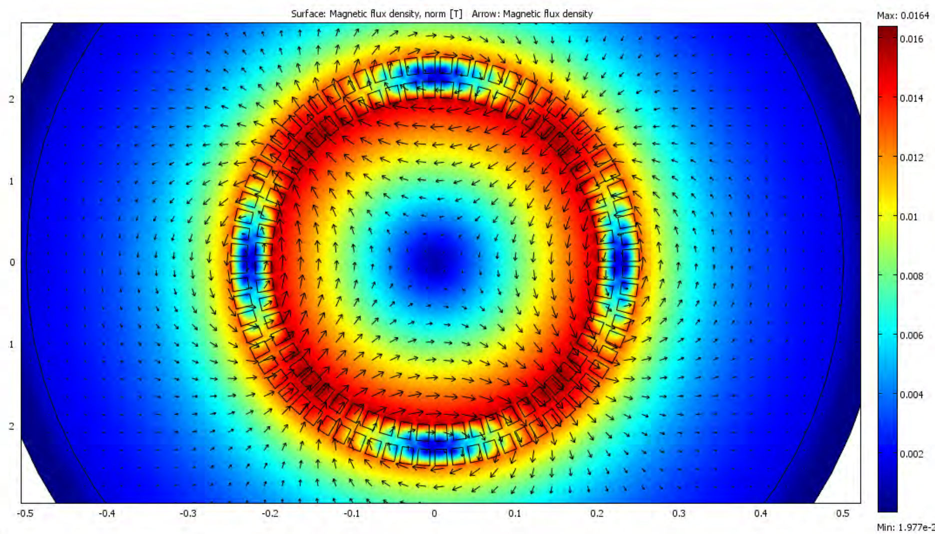
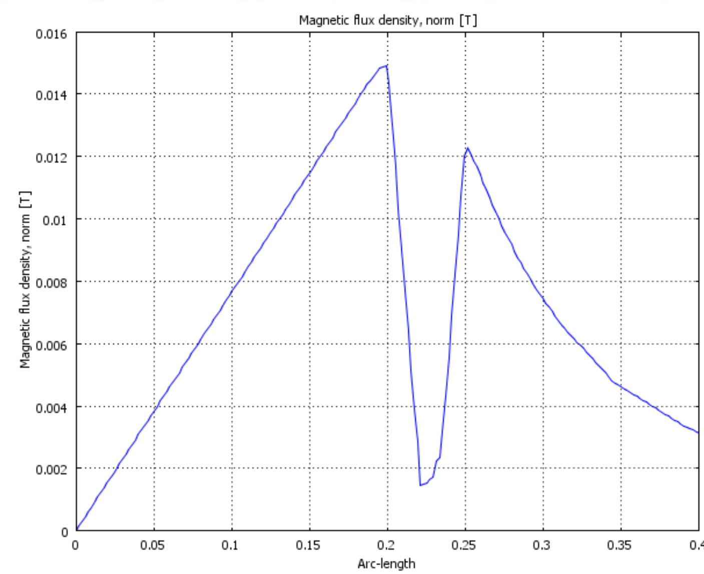
Dipole





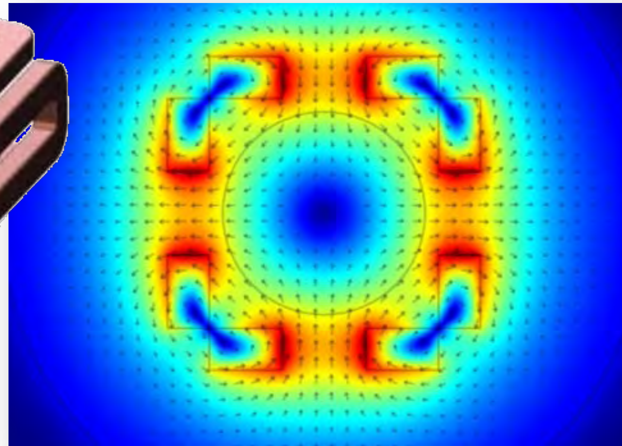
Quadrupole





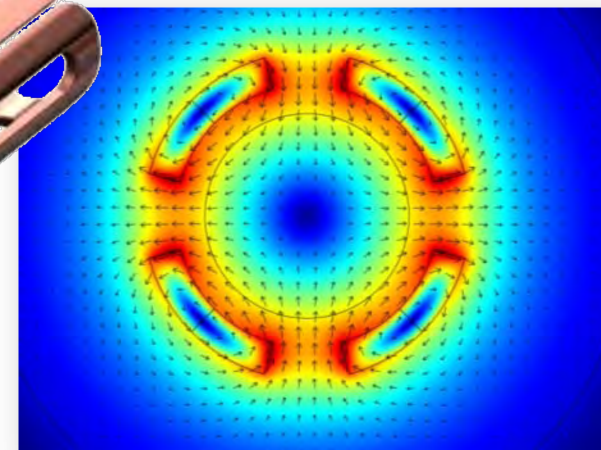
Conventional vs. Direct Double-Helix™

Racetrack Coils



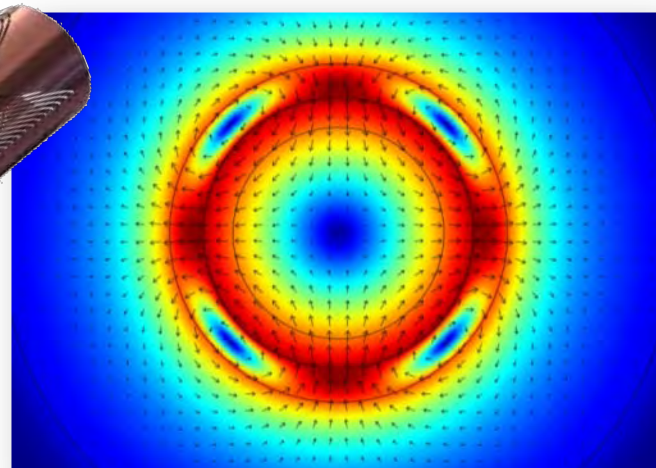
Large distortions, high harmonics content

Saddle Coils



Some harmonics due to non-sinusoidal current distribution

Double-Helix™ Coils



- *Sinusoidal Field Distribution*
- *No Space Harmonics*
- *Multipole Coil with one continuous winding*

Conventional vs. Direct Double-Helix™

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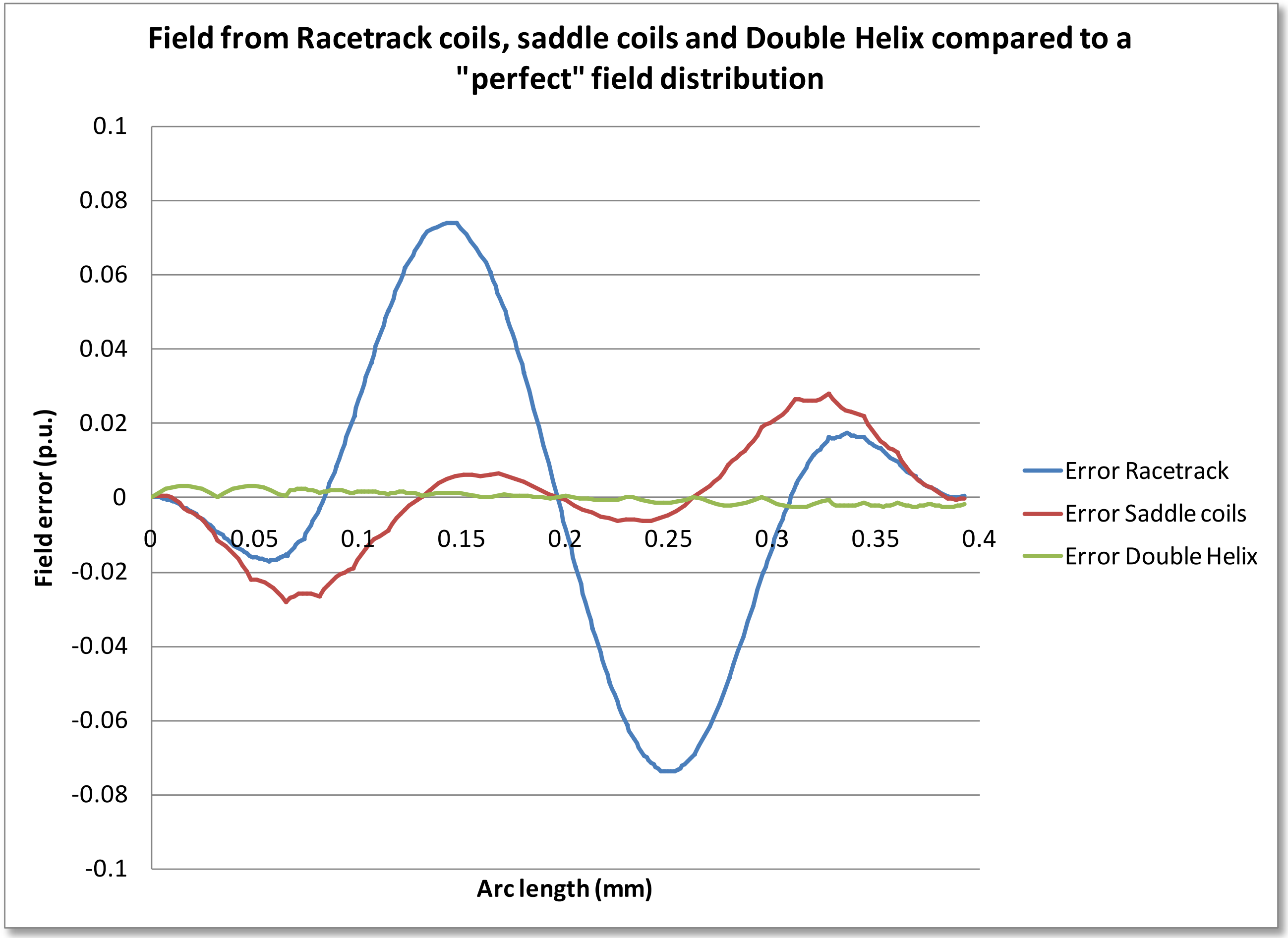
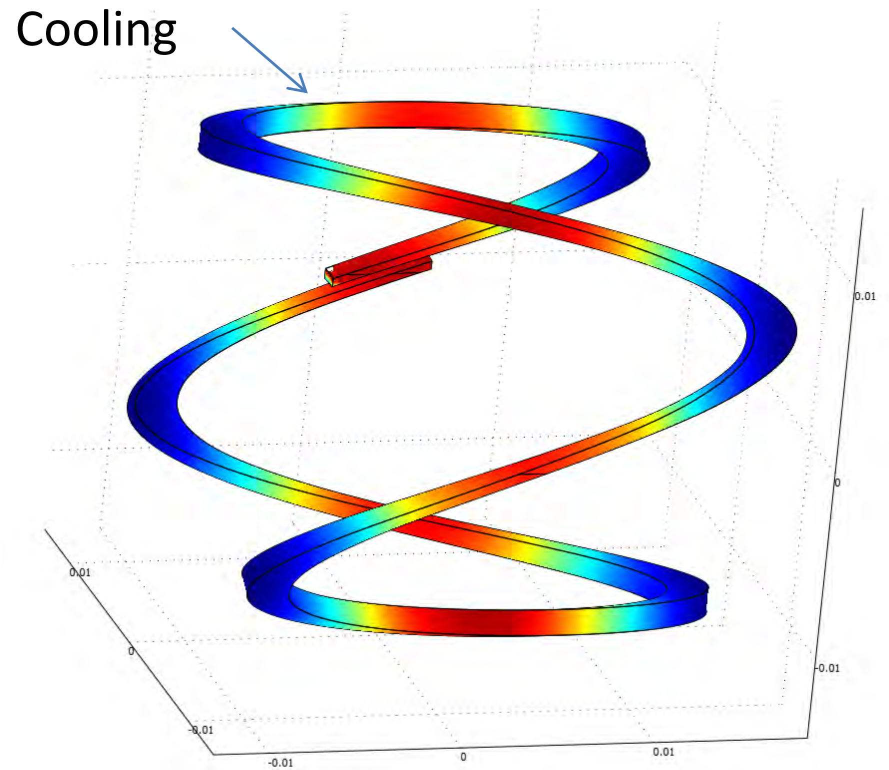
- Double-Helix™ windings are able to generate a perfectly sinusoidal field distribution

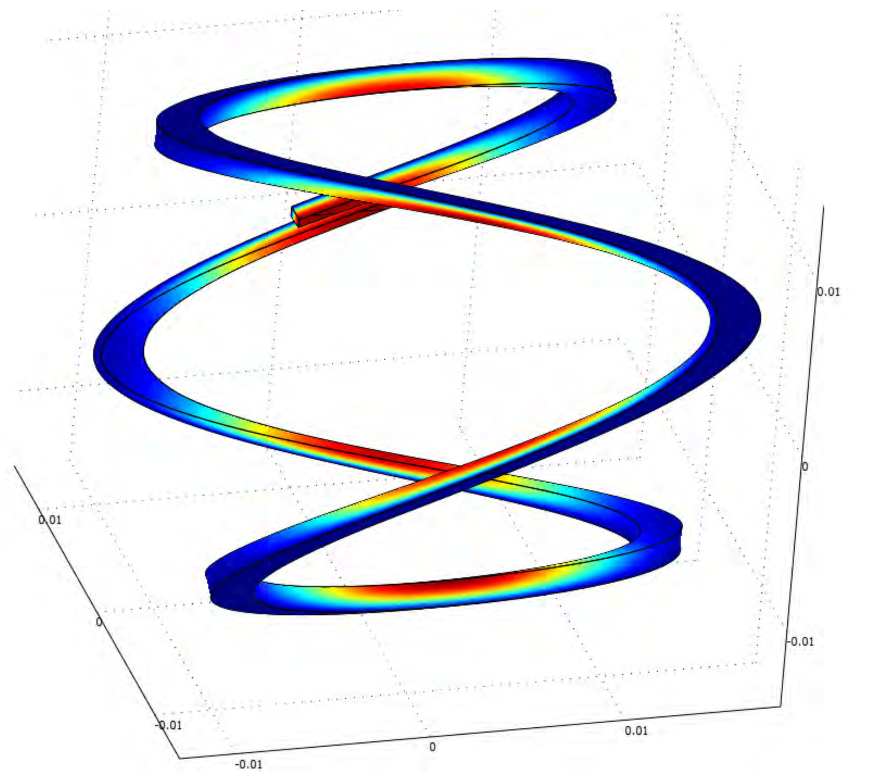


- Resistive heating from current density
- Water cooling on top surface

Cooling



Resistive heating distribution

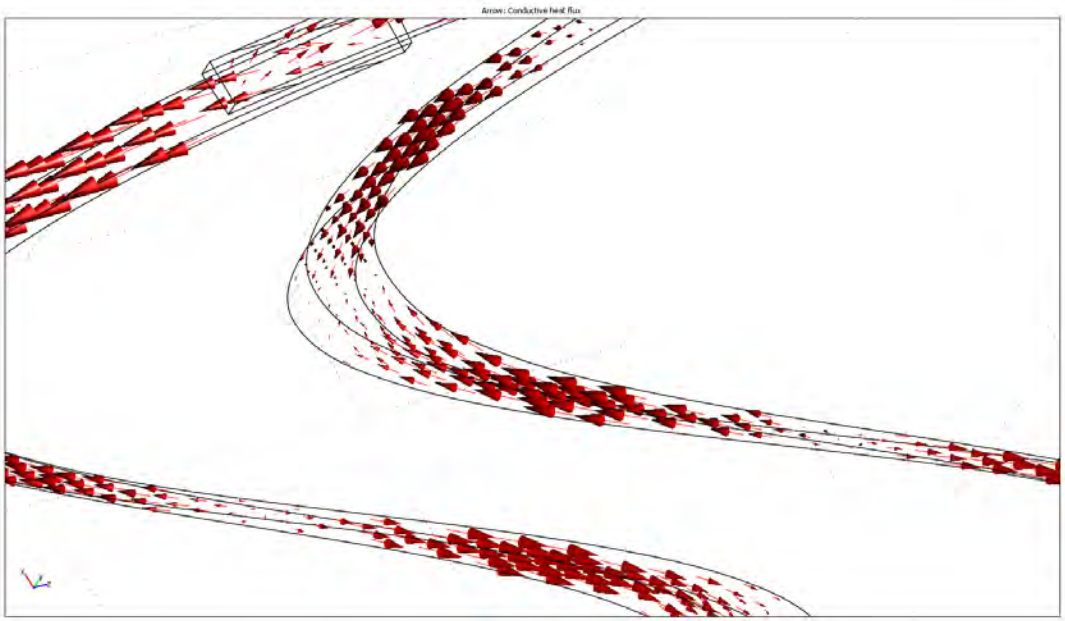


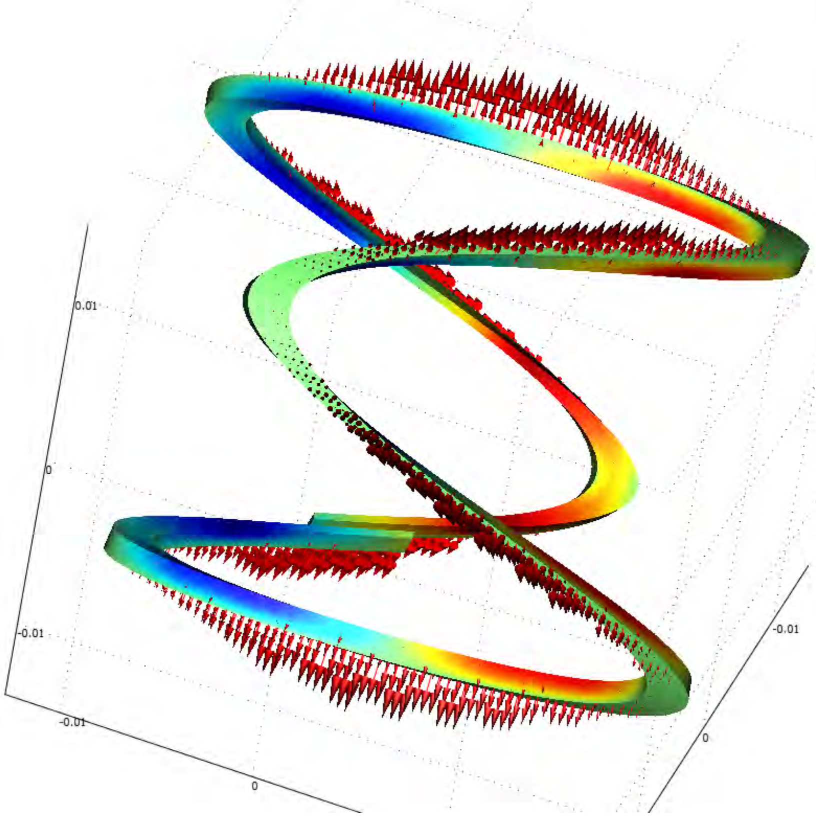
Temperature distribution with good heat transfer on top surface

Heat Flux

- Large cooling surface
- No insulation required
- Improved heat transfer

Heat transfer from the narrow sections to the wider sections





Heat flux in one turn of a quadrupole

- Wider sections act as heat sinks
- Heat transfers from narrow sections to wider sections

Application Example

- Magnetic optics for charged particle applications
  - Dipole steering magnets
  - Quadrupole focusing magnets

I_{nom} (A)	P (W)	Jc Peak (A/mm^2)	T_{Inlet} (C)	T_{Peak} (C)	Field (Gauss)
5.5	73	39	35	39.6	83
7.0	120	49	35	42.7	105
8.5	181	60	35	46.3	128
10	251	70	35	51	150
11	309	78	35	55	165
13	369	92	10	44	195

Operational parameters of vertical steering dipole

I_{nom} (A)	P (W)	Jc Peak (A/mm^2)	T_{Inlet} (C)	T_{Peak} (C)	Field (Gauss)
20	174	38	35	41.1	308
25.0	268	48	35	44.4	385
30	387	58	35	47.8	463
35	515	67	35	52.2	540
40	692	77	35	57.5	617
45	792	86	35	57	694
55	578	106	10	62.5	848
60.0	714	115	10	77.8	925

Operational parameters of horizontal steering dipole

Conclusion

- DDH technology enables more compact magnets to be built with “perfect” field distribution
- DDH intrinsically exhibits lower resistance and allows for very good heat removal
- Unprecedented current densities have been achieved
- COMSOL MultiPhysics allows for better understanding of the physics of DDH magnets and drives further improvements