Novel Accelerator Magnets Compatible with High Energy Deposition

Muon Collider Physics Workshop
FNAL --- November 12, 2009

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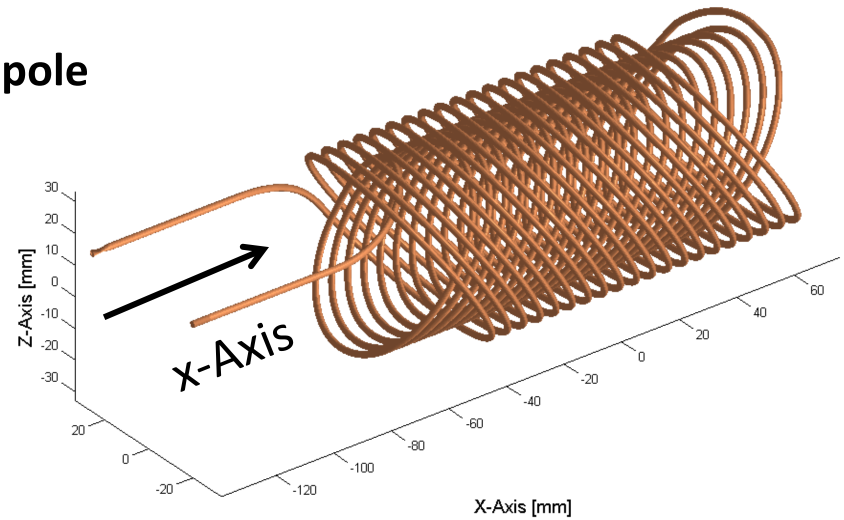
DOUBLE-HELIX™ (DH) COIL CONFIGURATIONS

Dipole

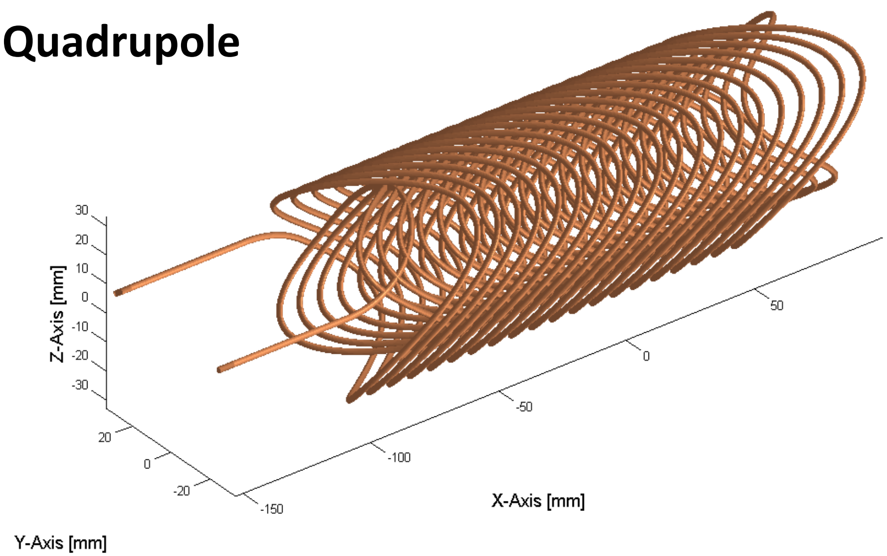


$$X(\theta) = \frac{h}{2\pi}\theta + \sum_{n} A_n \sin\left(n\theta + \varphi_n\right)$$

$$Y(\theta) = R * \cos\left(\theta\right)$$

$$Z(\theta) = R * \sin(\theta)$$

Quadrupole



Transverse magnetic fields:

Generated by "modulated" solenoid winding patterns

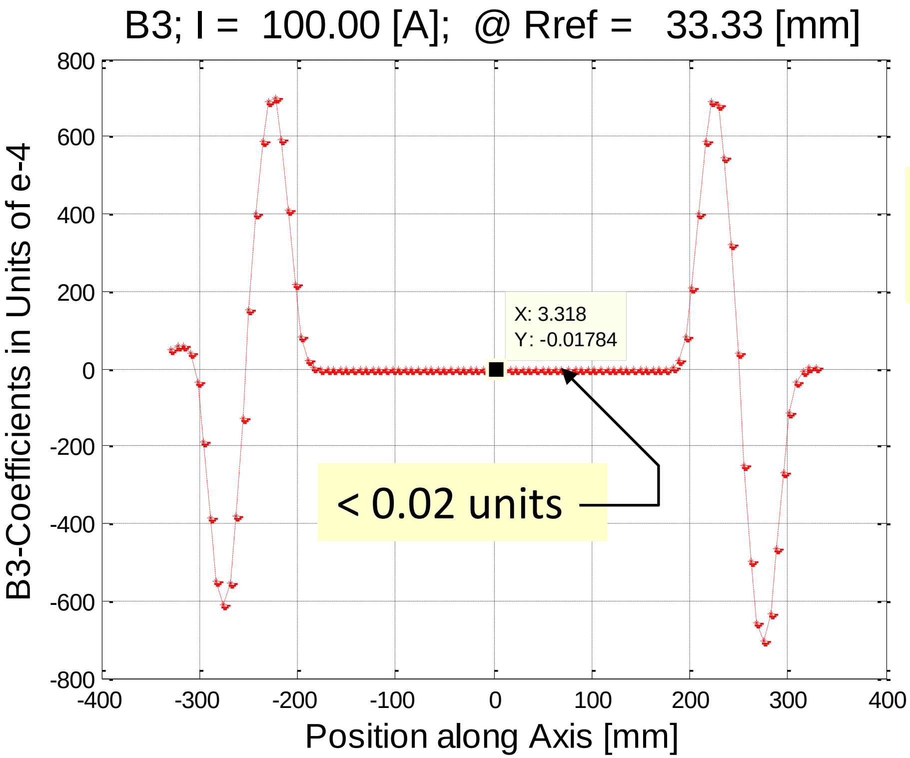
Unique Properties of DH Coil Configurations

- Pure multipole fields without field shaping spacers
  - Small systematic field errors
- Precise conductor placement in machined support grooves
  - Small random field errors
- Accommodates different conductor forms
  - Wire, cable, tape, mini CICC
- Bent coils with pure multipole order
  - Multipole fields introduced by bend can be compensated
- Combined Function Magnets
  - Almost any combination of MP fields possible

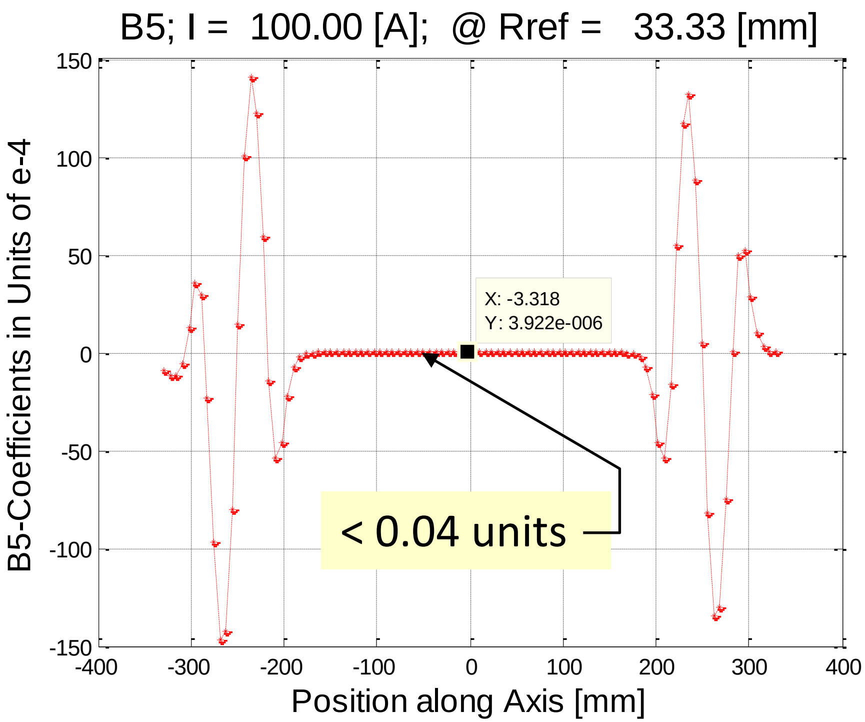
Properties of DH Coil Configurations

- Placement of conductor in V-shaped grooves
  - Enables adhesive free coils
  - Highly efficient cooling similar to CICC
- Mechanical robust solenoid-like winding configuration
  - Excellent quench performance
- Intrinsically large bending radii
  - Facilitating use of brittle conductors (Nb_3Sn, HTS)
- High electrical breakdown strength
  - High reliability
- No magnet specific tooling required
  - Cost-effective manufacturing process
  - One of a kind magnets with little or no cost penalty

Field Uniformity in DH Coils

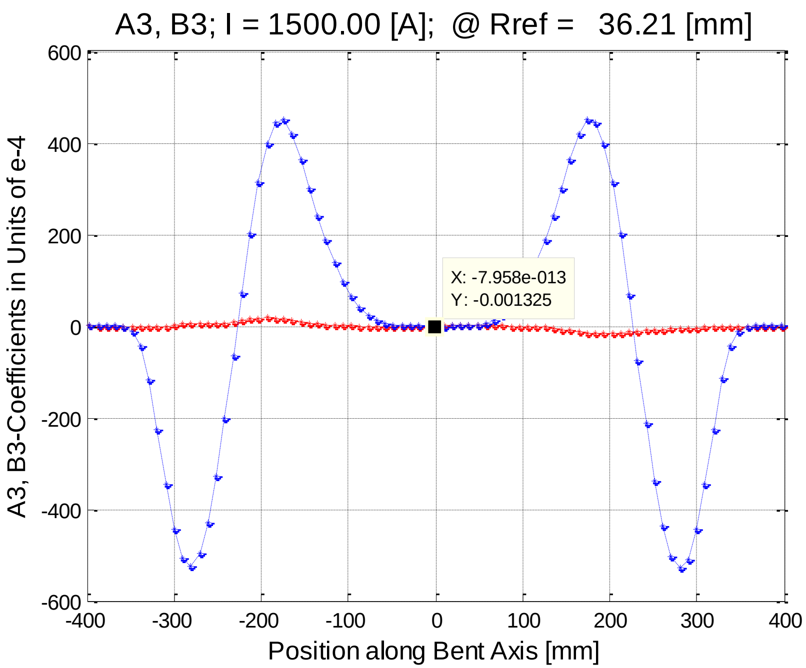


Higher order MP fields highly suppressed Without any optimization

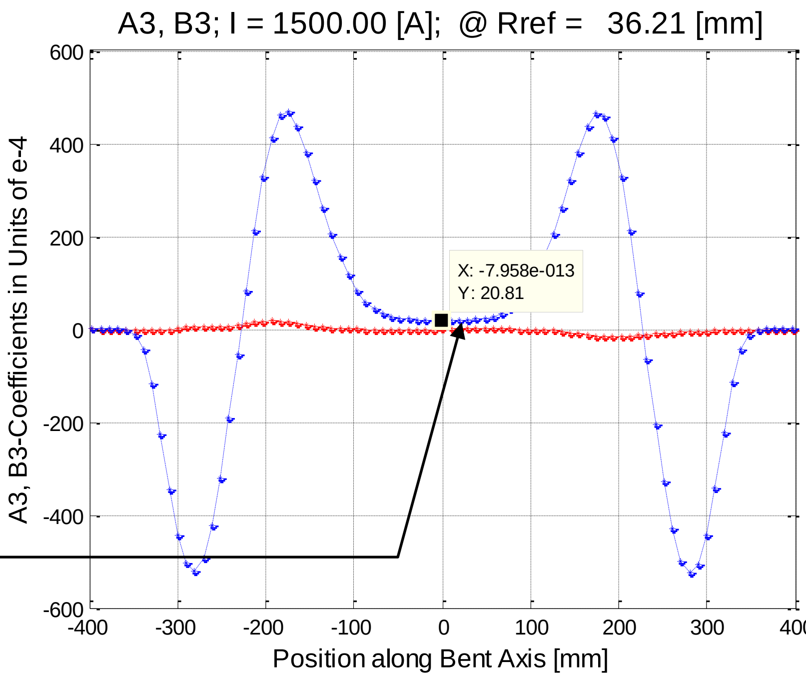


Integrated MP fields over coil ends Automatically ≈ zero

Field Uniformity in Bent DH Coils



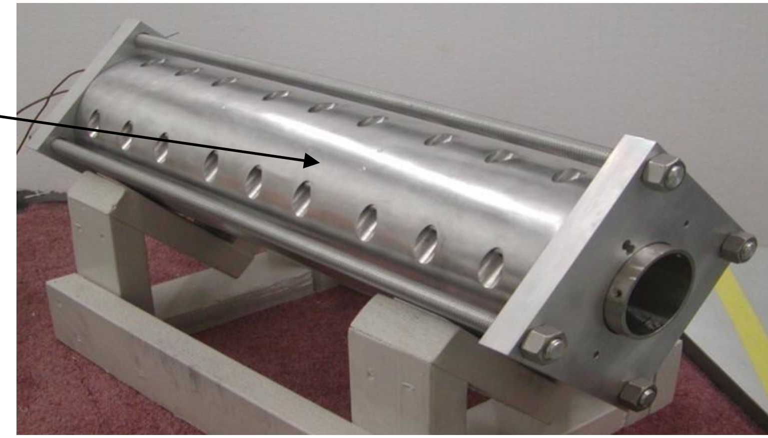
MP fields calculated along bent axis



Sextupole of 20.8 units introduced to compensate for iron yoke effect

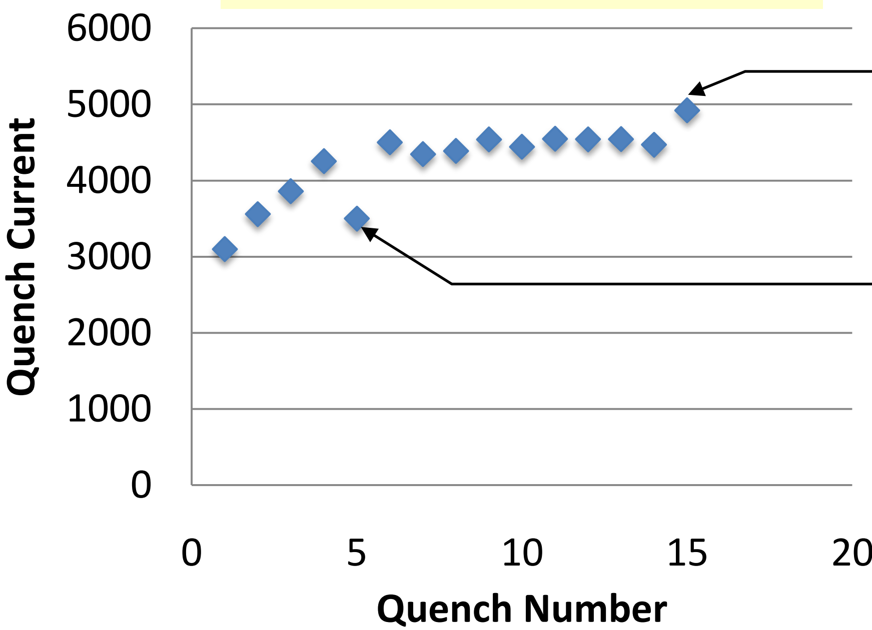
Quench Performance of DH Coils

Test coil to qualify coil cross-section of bent dipole



Nominal Field without yoke 3.5 Tesla
With yoke 4.5 Tesla

Quench Performance



Decreased temperature to verify that coil is limited by conductor performance

Low helium level in cryostat

Manufacturing of Bent Coil

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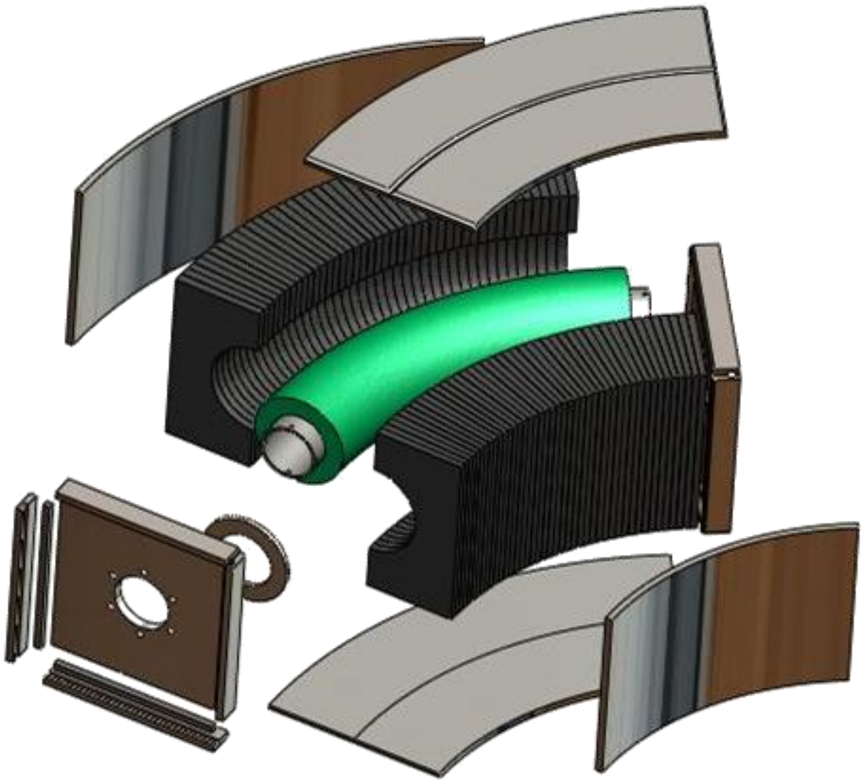
Manufacturing of Bent Coil



Iron Yoke Assembly

DH Technology Accommodates Many Conductor Forms

- Standard wire
  - No insulation required
- Round mini cable
  - 6-aound-1, 15-strands --- fully transposed
- Square mini cable
  - Increase engineering current density
- HTS tape conductor
  - YBCO, MgB2
- Cable-in-Conduit Conductor
  - Mini CICC (see Presentation by S. Pourrahimi)`
  - Nb_3Sn conductor for wind-and-react
  - HTS conductor for applications requiring high temperature margin

Losses versus Frequency in AC Operation

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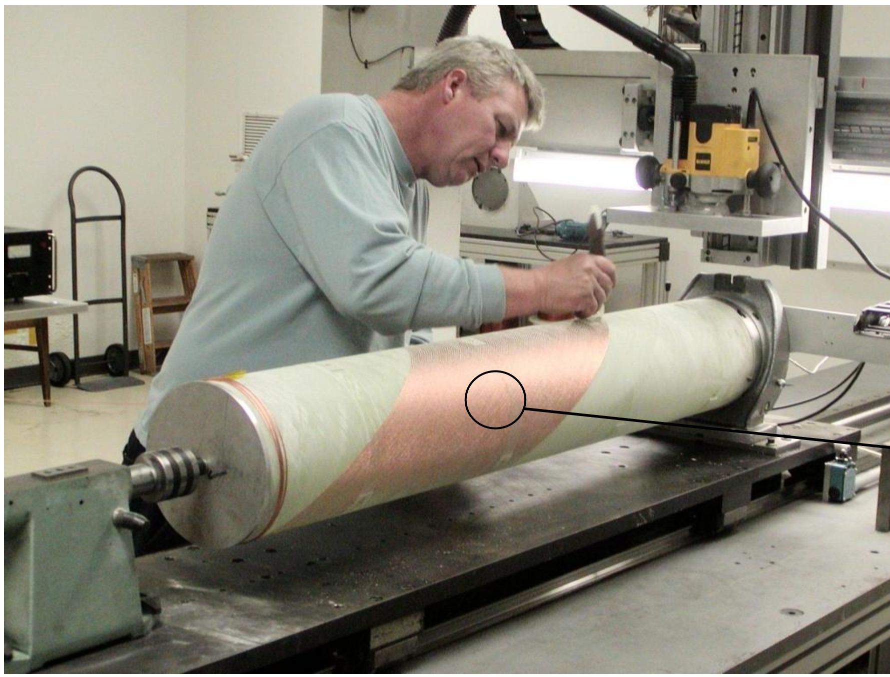
Parameter	Unit	Value
SC Current Density	A/mm^2	1000
Cu to Non-Cu Ratio	--	0.33
Strand Diameter	mm	0.18
Filament Diameter	µm	1.00
Twist Pitch	mm	5.0
Eff. Matrix Resistivity	Ohm*m	1.0E-08
Number of Strands		18

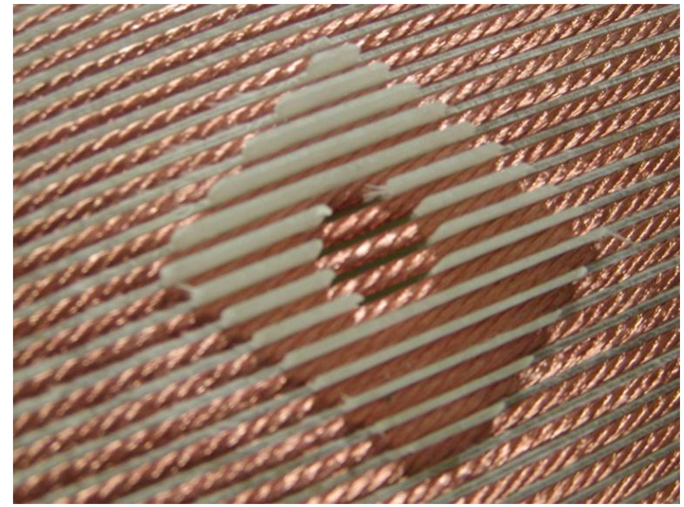
	Frequency	
	10 Hz	60 Hz
Magnetization Losses [W]	3.90	23.3
Eddy Current Losses [W]	0.36	13.0
Coupling Losses [W]	28.60	1030
TOTAL Losses [W]	**32.86**	**1066.3**

- ❑ **Coupling losses, due to matrix resistivity are dominant**
- ❑ **Using a miniature CICC in a DH configuration enables operation at 10 Hz and above**

Adhesive-Free Coils --- Intrinsic CICC

2 kG dipole magnets, AC excitation ≤ 1kHz,
Field uniformity $< 1\times10^{-3}$

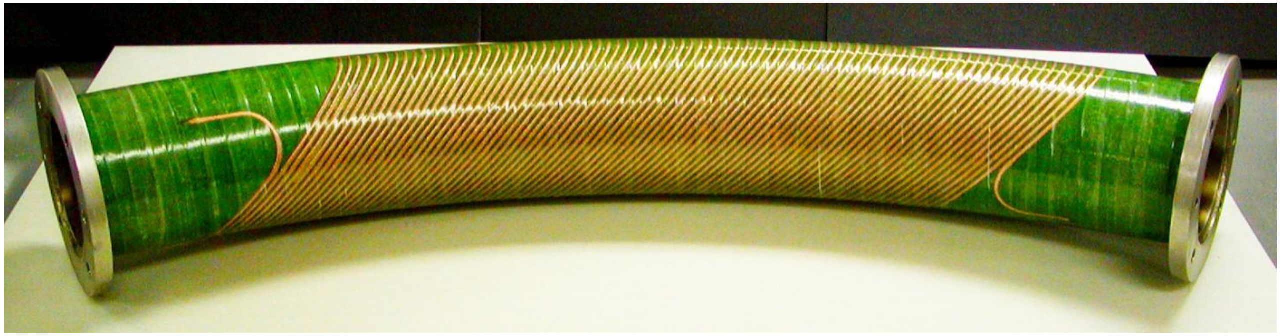




Highly cooling efficiency by direct contact of LN2 with conductors

HTS conductors in V-shaped grooves would offer unprecedented quench energy margin

Bent – Combined Function Magnets

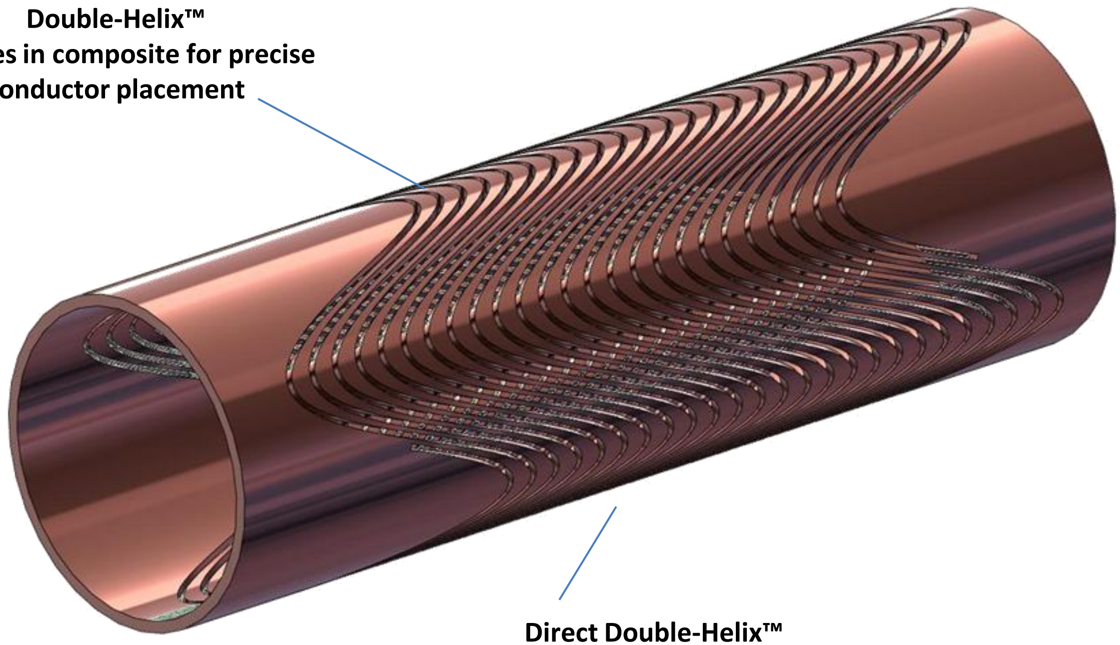


Bent dipole magnet with compensated quadrupole

Combined function magnet – quadrupole with superimposed dipole

Direct Double-Helix™ Technology

- **Resistive magnets with unprecedented current density**
  - **Current densities well above 100 A/mm^2 possible approaching performance of SC**
  - **Great potential for new nano materials**



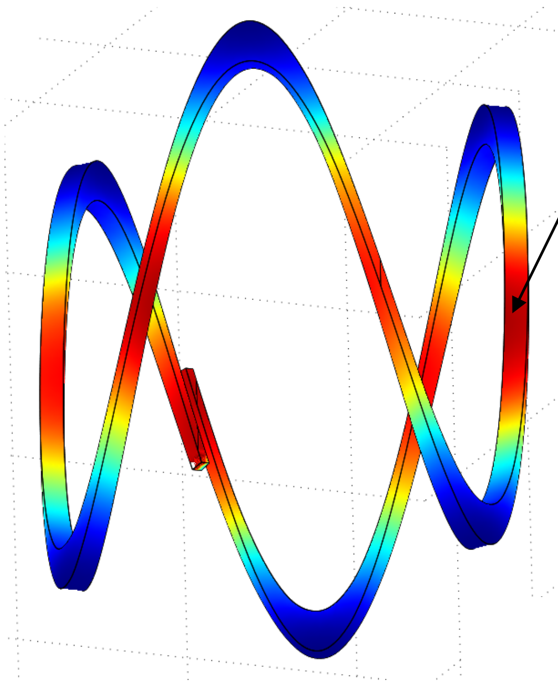
Key Features of DDH Technology

- Field generating current path machined out of conductive cylinders
- Complete control over conductor cross section along its path
- Constraints caused by wire manufacturing eliminated
- Very high cooling efficiency with insignificant thermal gradients
- Current densities in excess of 100 A/mm^2 in DC operation of normal conductors achieved
- High field uniformity due to Double-Helix™ winding configuration
- Magnets with arbitrary multipole order and combined function
- Highly cost-effective since no magnet-specific tooling is needed
- Unprecedented miniaturization of coils feasible
- High radiation hardness based on metals and ceramic materials

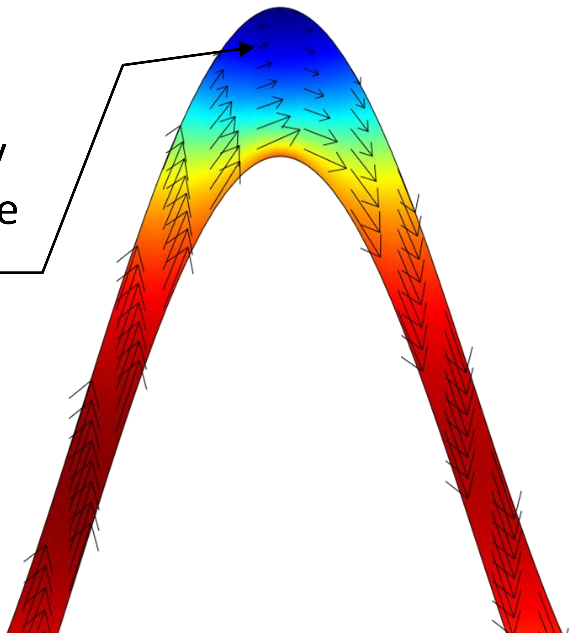
Horizontal and vertical Steering Magnet

0.1 Tesla (operates in 9Tesla background field)
Beam aperture: 20 mm
Magnet OD: 40 mm

Temperature and Current Density Distribution in DDH Windings



High current density
Conduct heat to large
X-section area



Temperature Distribution along 1 turn

Current density distribution

Summary

- ✓ ***Double-Helix and Direct-Double-Helix Technology enables unprecedented performance in respect to energy deposition.***
- ✓ ***The technology accommodates advanced conductors that offer large energy margins due to AC losses and energy deposition.***
- ✓ ***CIC conductors --well qualified in fusion magnets -- become available for accelerator magnets.***
- ✓ ***The DH and DDH technology offers small systematic field errors without complex field forming spacers.***
- ✓ ***The unique manufacturing process of DH and DDH coils enables cost effective manufacturing and rapid prototyping.***