
衆瞽探象之圖

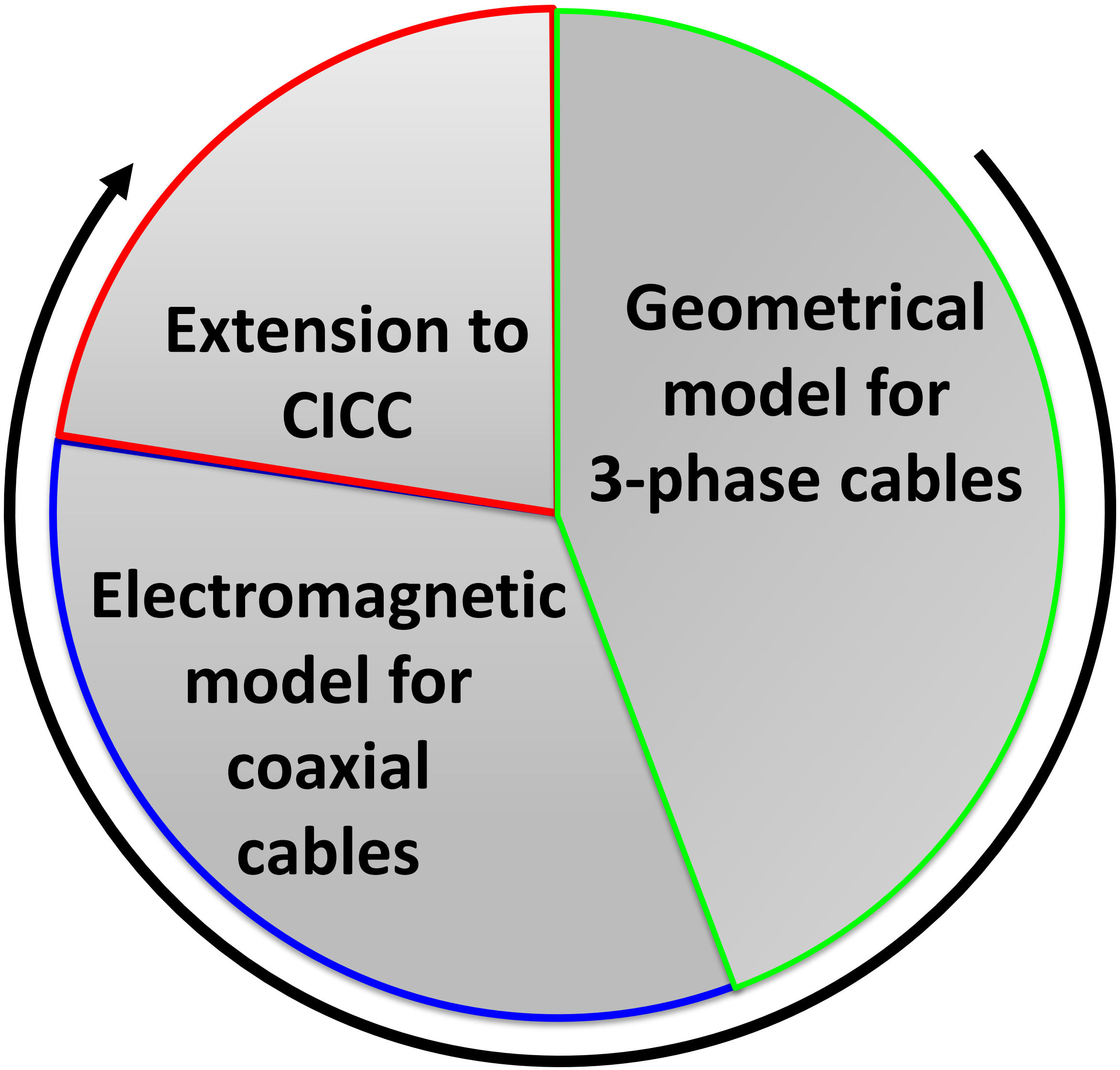
# An approximate electromagnetic model for superconducting helically wound cables and cable-in-conduit conductors

**V. Zermeno, F. Grilli**

**Karlsruhe Institute of Technology**

victor.zermeno@kit.edu

# Content


Extension to CICC
Geometrical model for 3-phase cables
Electromagnetic model for coaxial cables

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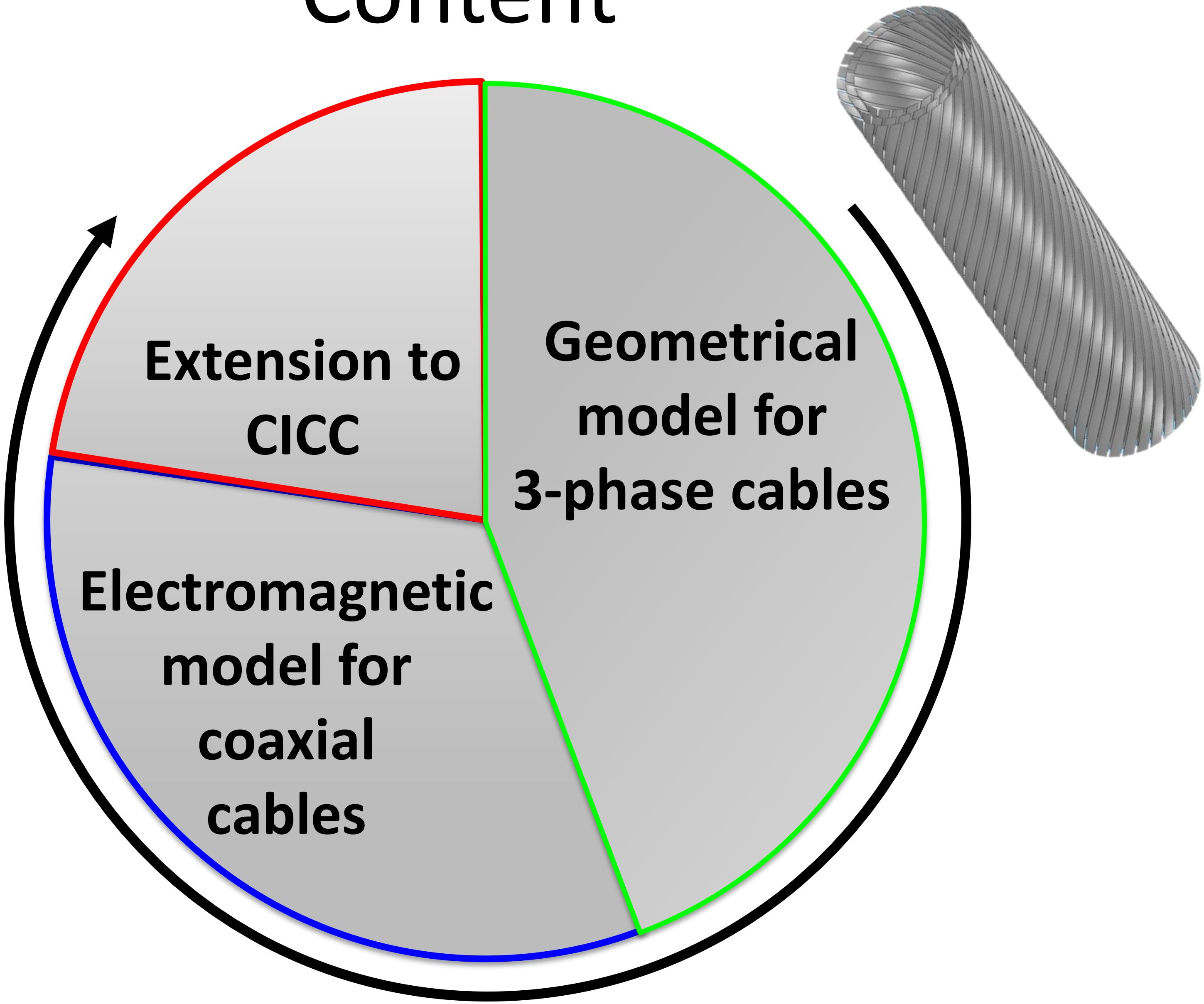
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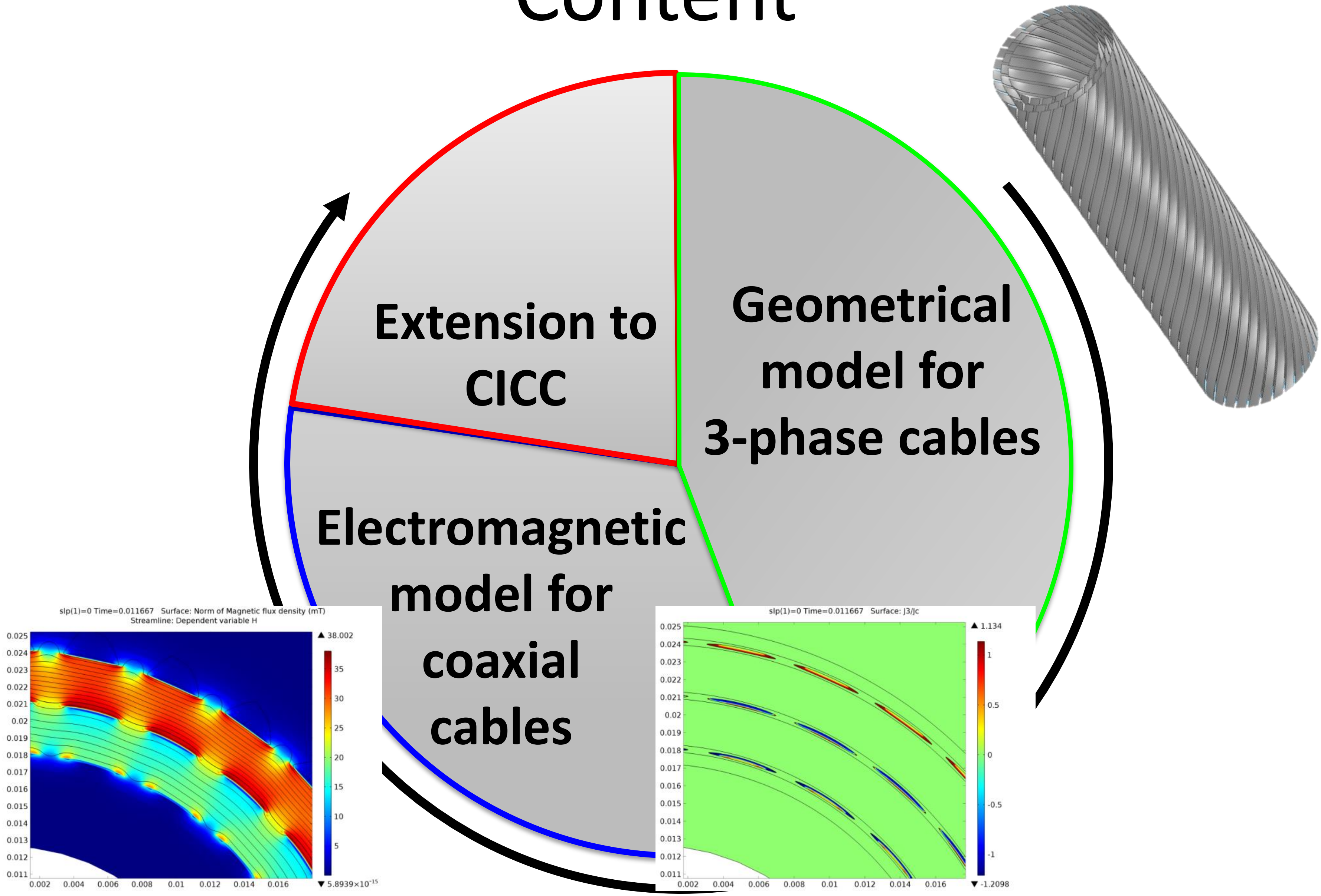

Extension to CICC
Geometrical model for 3-phase cables
Electromagnetic model for coaxial cables
slp(1)=0 Time=0.011667 Surface: Norm of Magnetic flux density (mT) Streamline: Dependent variable H
slp(1)=0 Time=0.011667 Surface: J3/Jc

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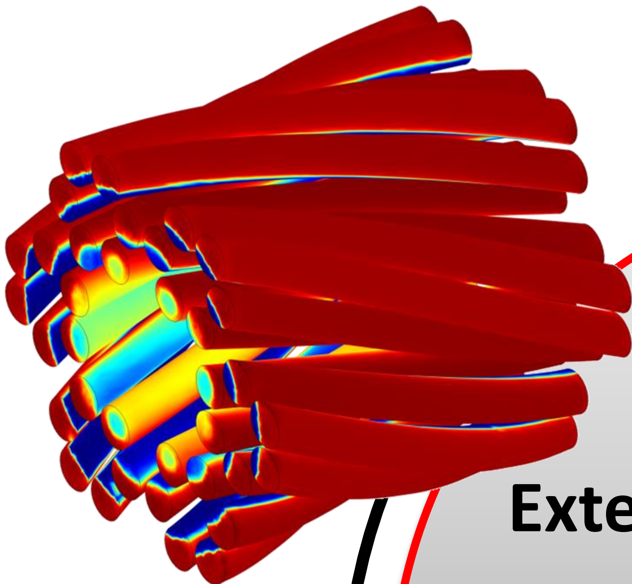
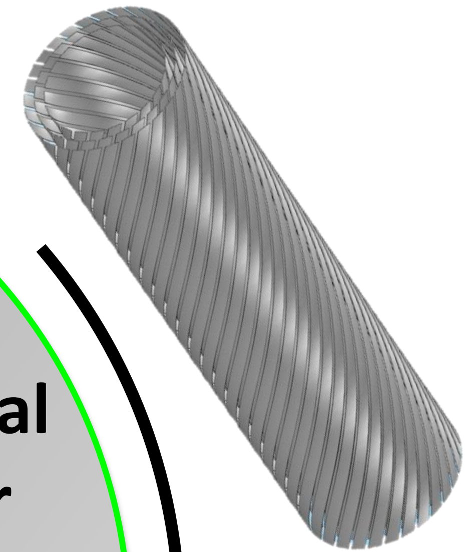
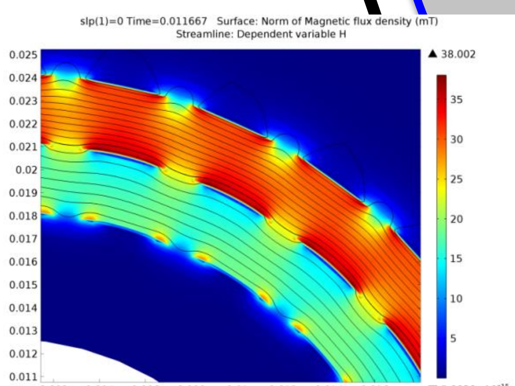


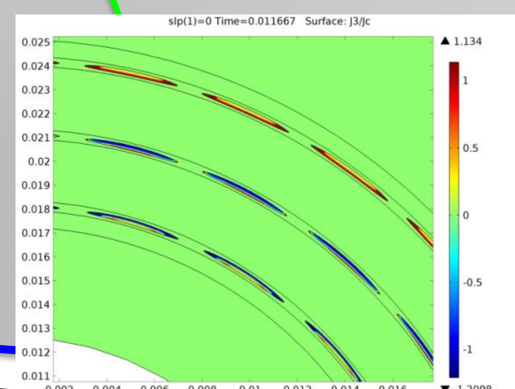


**Extension to CICC**

**Geometrical model for 3-phase cables**

**Electromagnetic model for coaxial cables**



# The modeler’s dilemma

Real vs. Possible
Feasible
Practical


# What is a model?

# Exact Solution


# Analytic Approximation

# Exact Solution


# Numeric Approximation 1

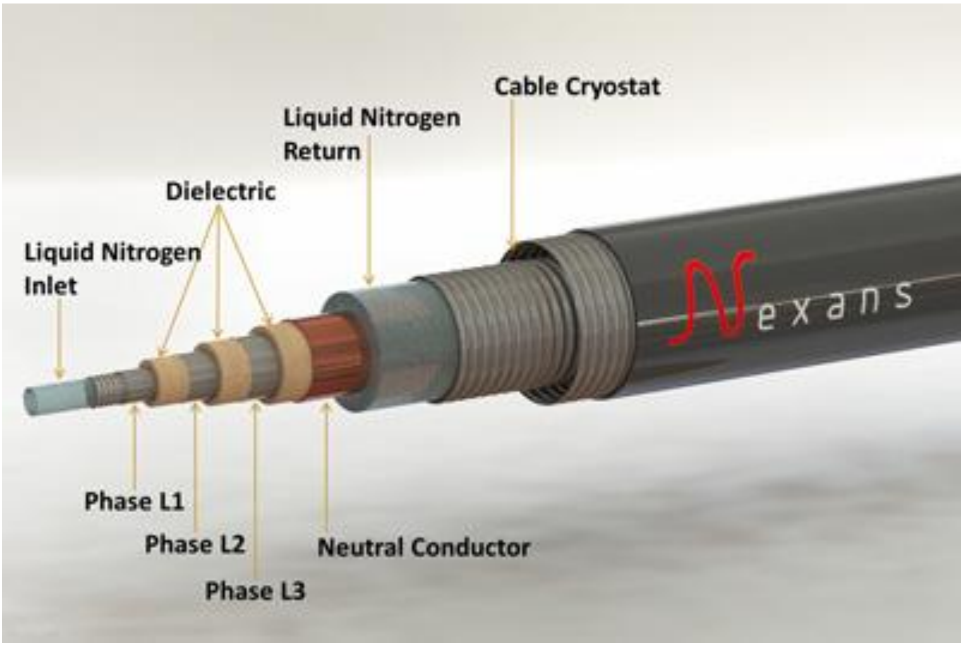
# Exact Solution


# Numeric Approximation 2

# Exact Solution


# Numeric Approximation 3

# Ampacity project

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| Phase | # of tapes | radius | Pitch angle |
|---|---|---|---|
| A | 22 | 36.1 mm | 17.44° |
| B | 26 | 42.1 mm | 17.44° |
| C | 30 | 48.2 mm | 17.44° |

# How to model a 3-phase helically wound cable?

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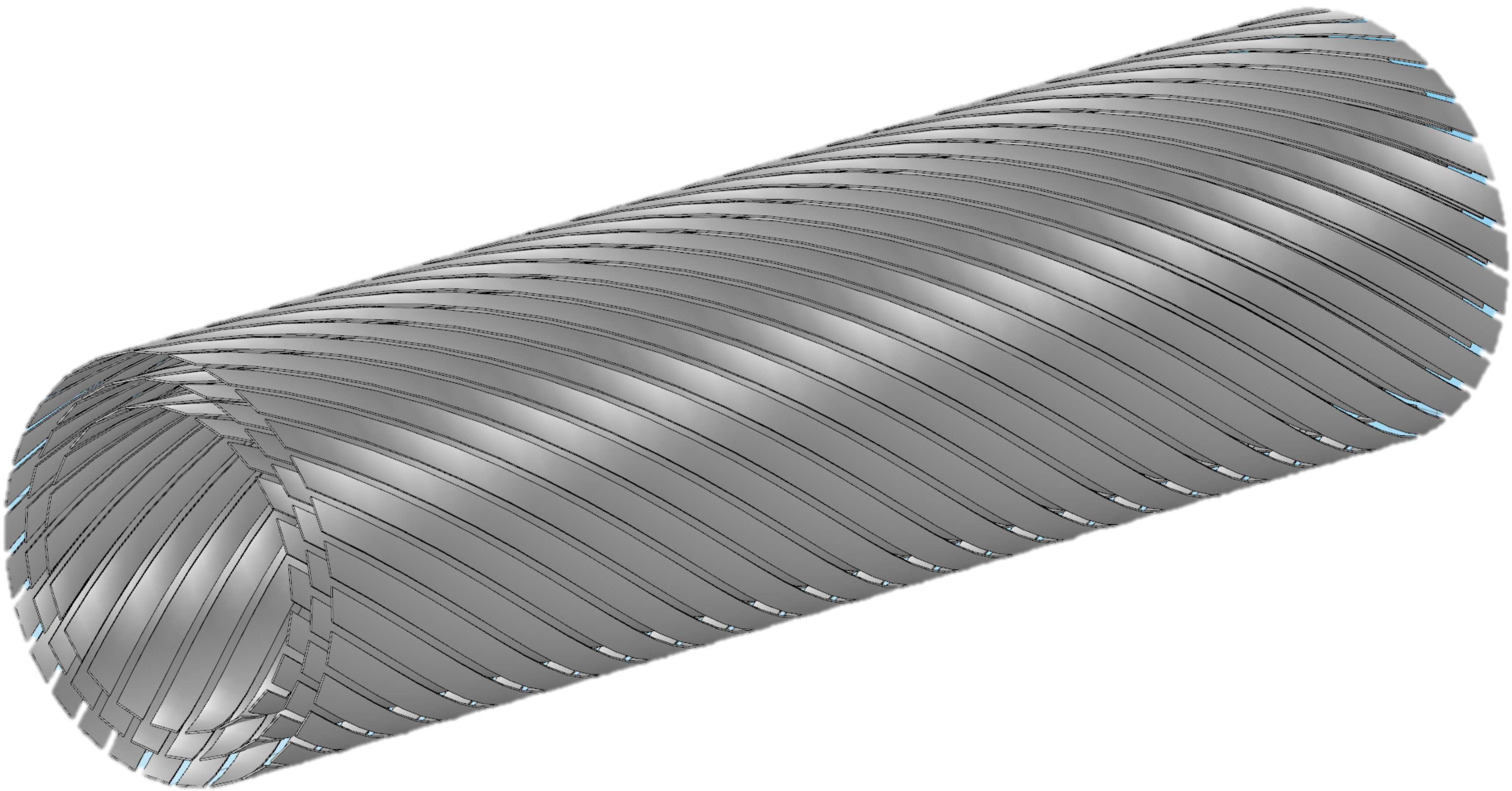
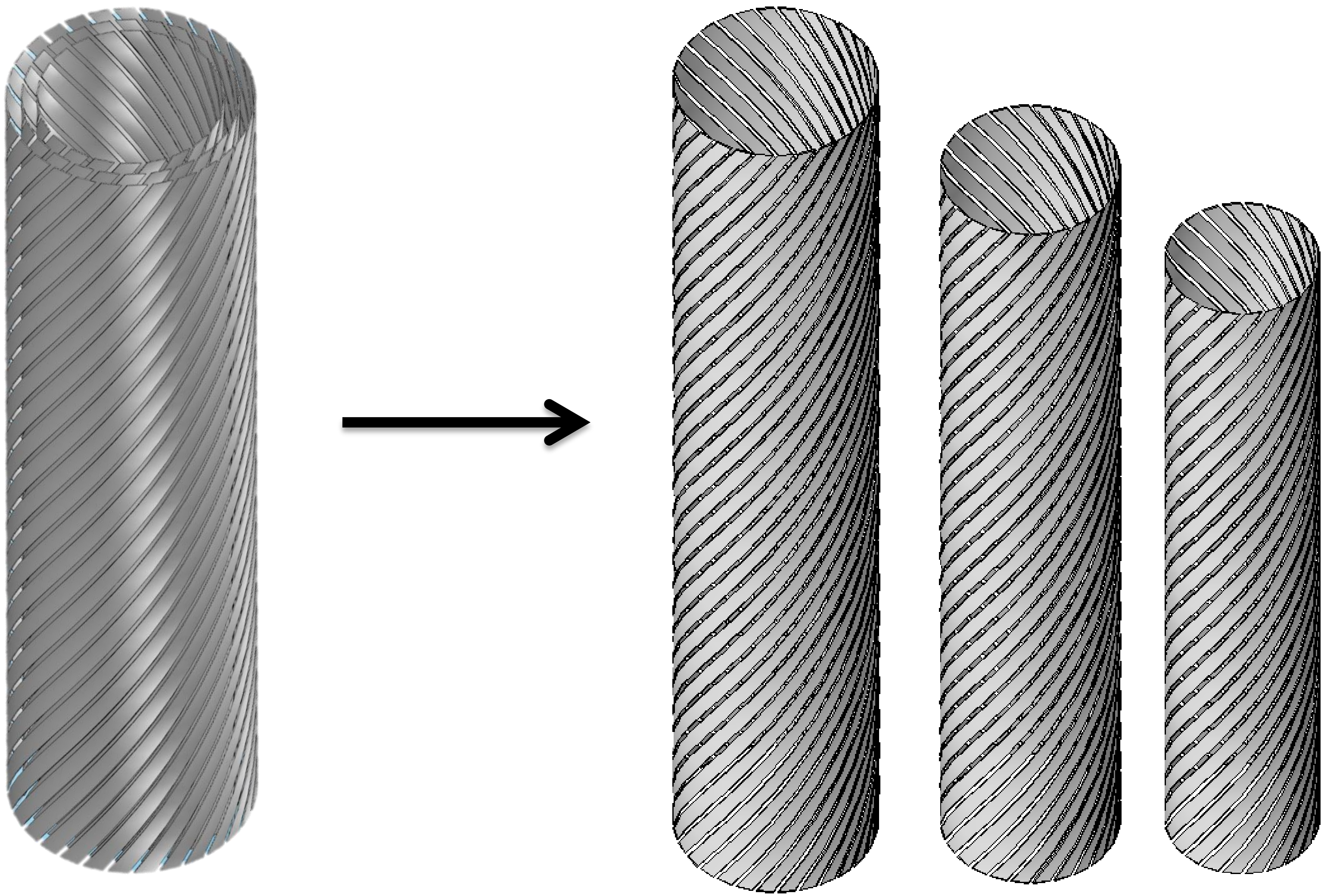
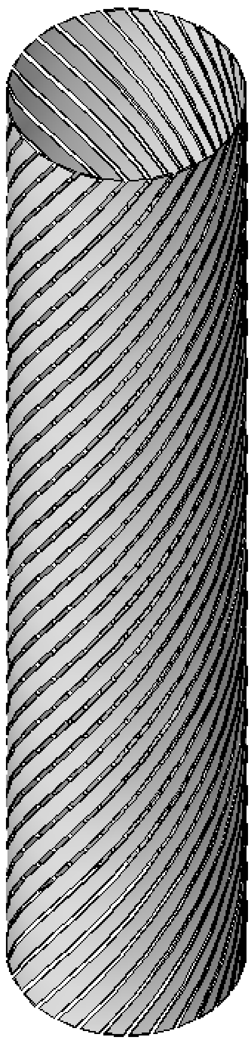


# Original model design dissected

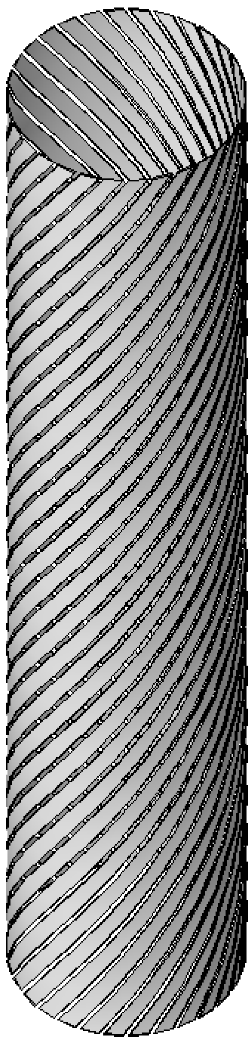


1 pitch length of each phase

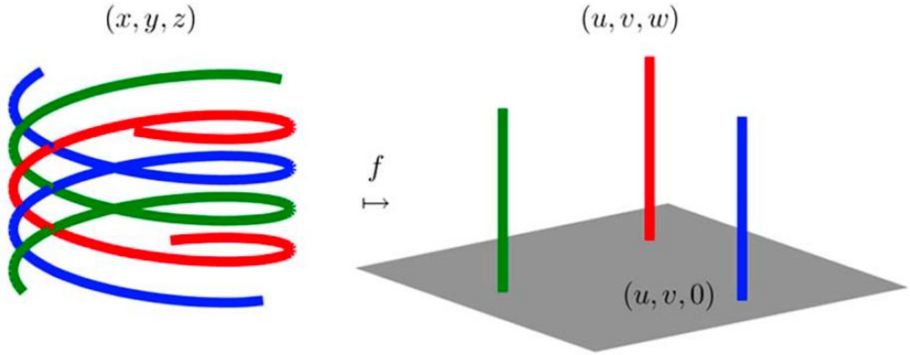
# 1 phase

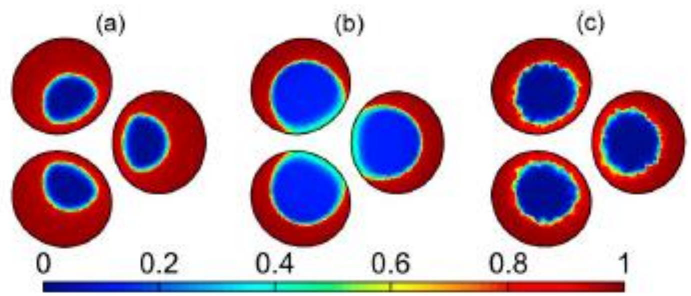


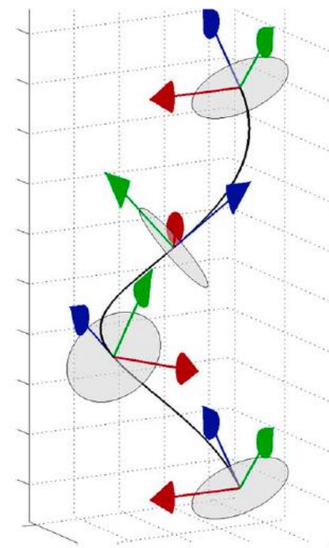
# 1 phase



Geometry can be modelled in 2D using helical coordinates

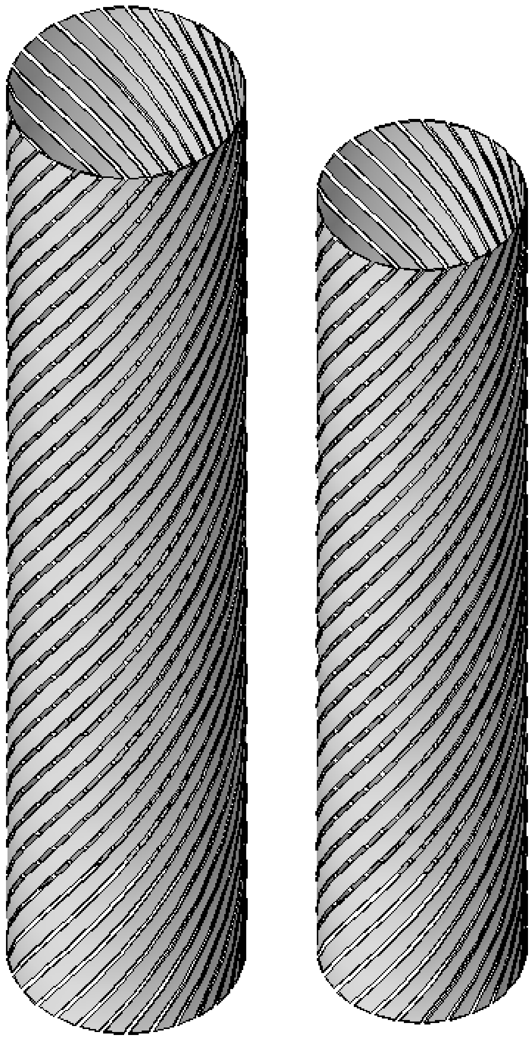


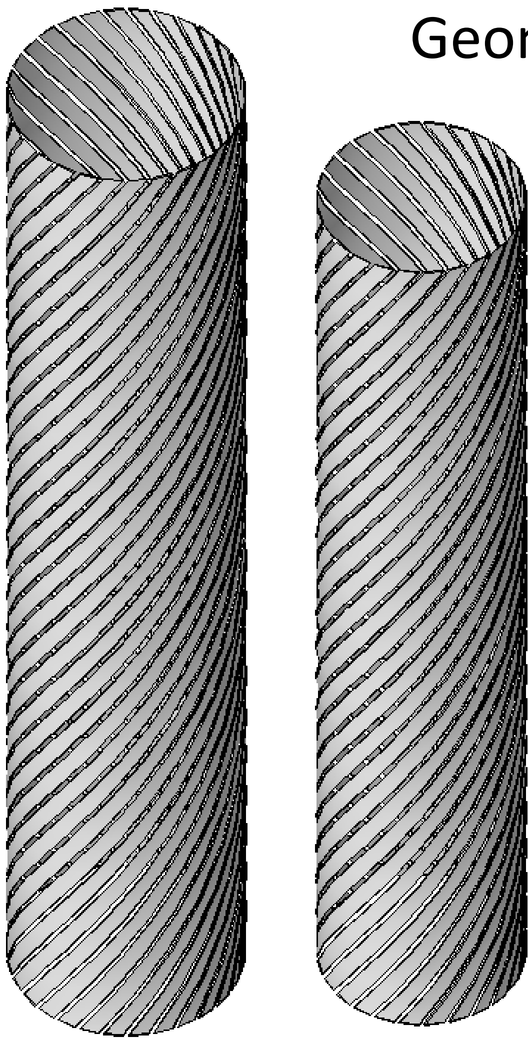
Stenvall, A. et al. IEEE TAS 23 -3 2013

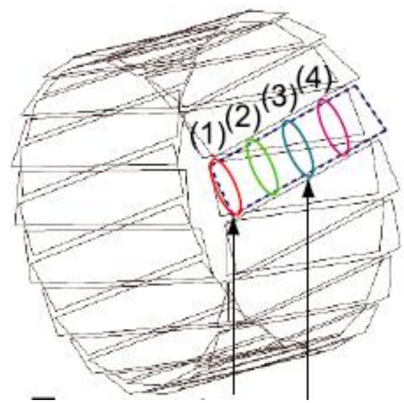
# 2 phases

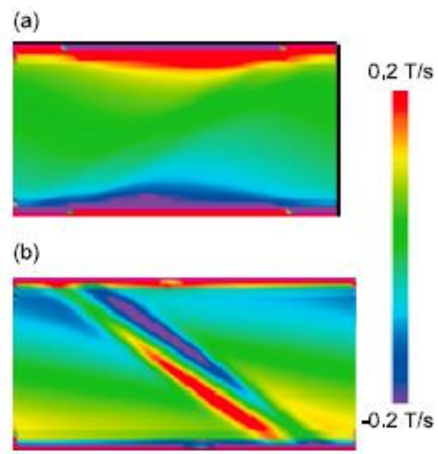


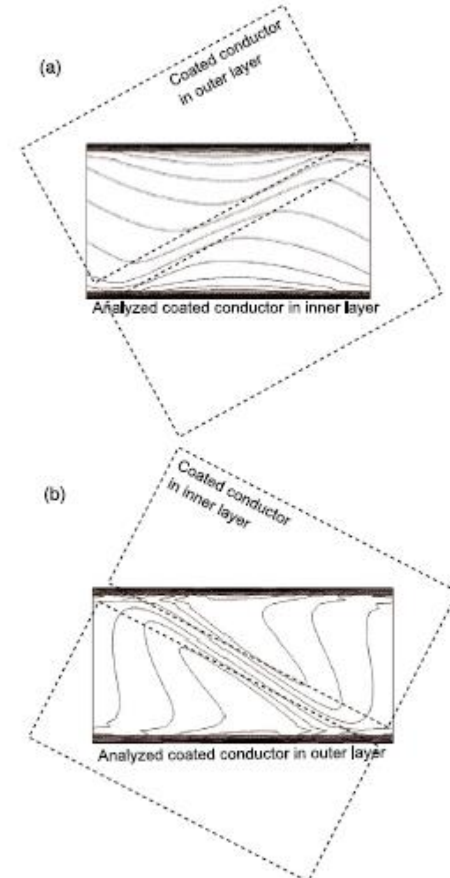
# 2 phases

Geometry must be modelled in a small 3D section



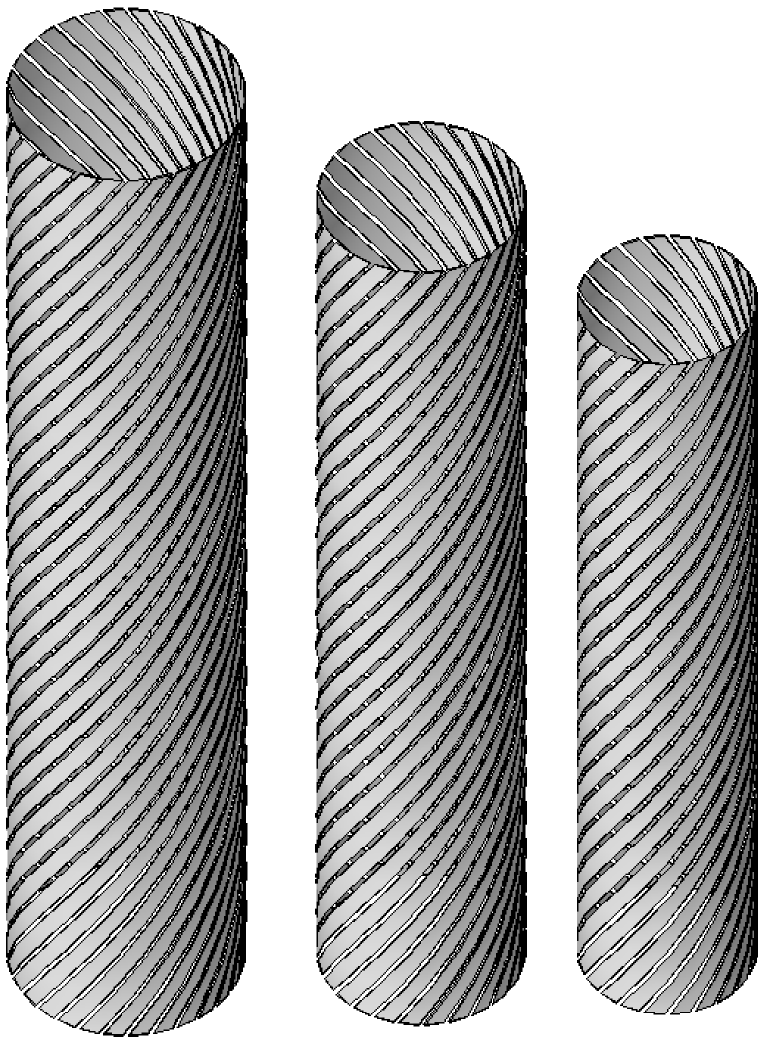


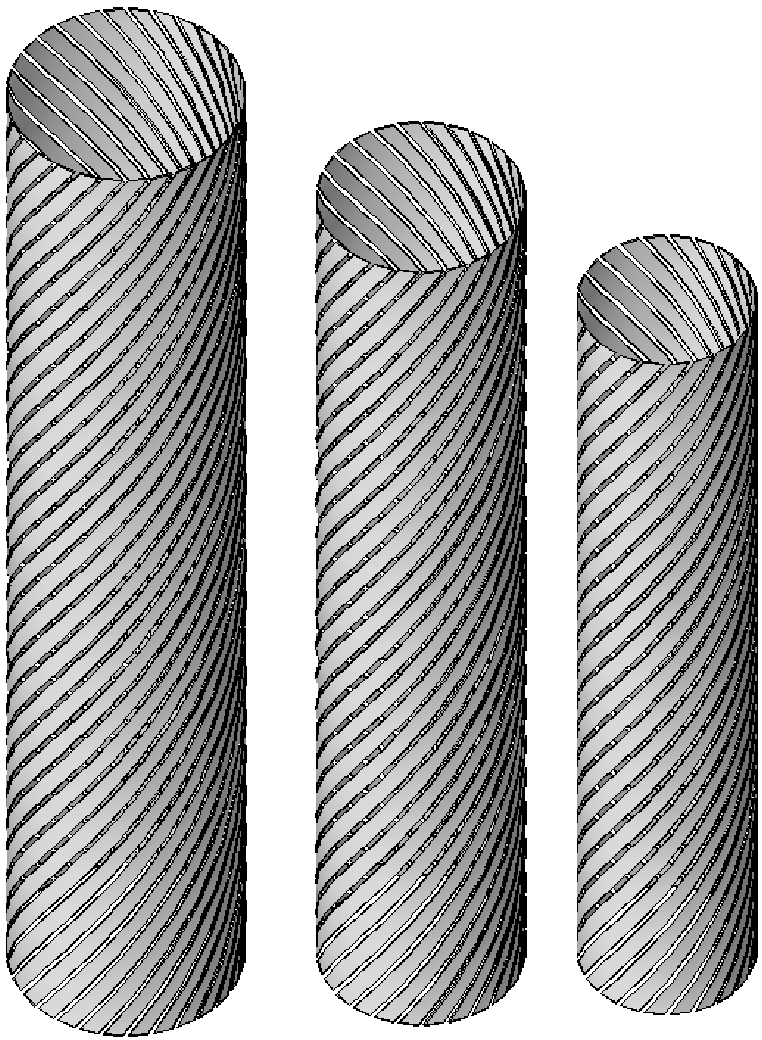

K Takeuchi *et al* Supercond. Sci. Technol. **24** (2011) 085014

# 3 phases



Geometry must be modelled in a large 3D section

# 3 phases



Geometry must be modelled in a large 3D section?

# Model size

- With constant pitch angle (17.44 deg), there are different pitch lengths for each phase:
  - Phase 1 -> **361**.013100007 mm
  - Phase 2 -> **421**.015277294 mm
  - Phase 3 -> **482**.017490868 mm

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  - Phase 1 -> **361**.013100007 mm
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  - Phase 3 -> **482**.017490868 mm

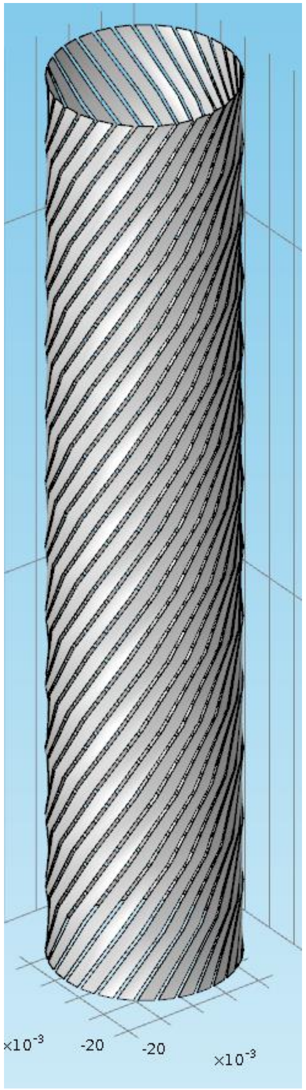
- Lmc(361,421,482)=73254842… so, the spatial period is >73km ☹

# Model size

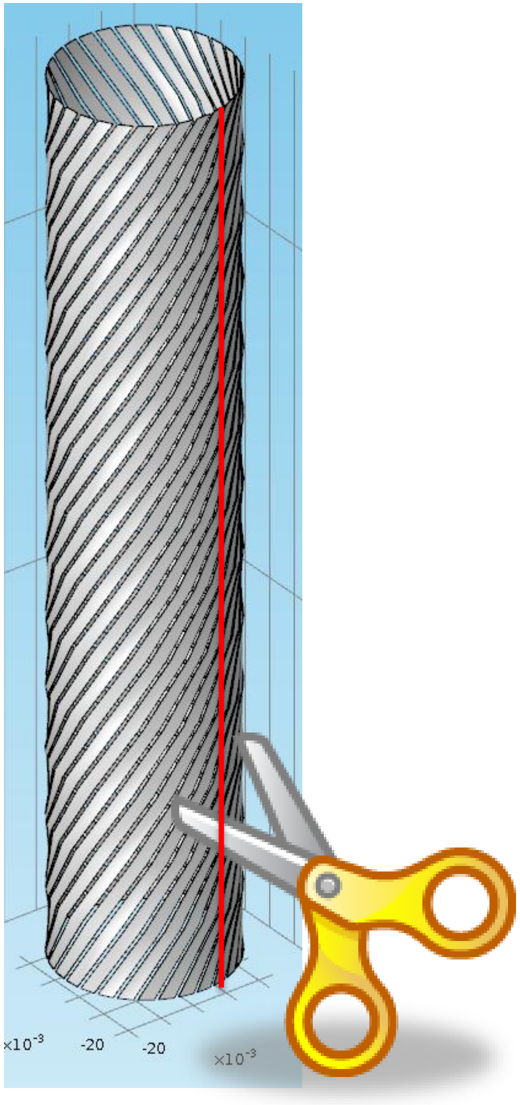
- With constant pitch angle (17.44 deg), there are different pitch lengths for each phase:
  - Phase 1 -> **361**.013100007 mm
  - Phase 2 -> **421**.015277294 mm
  - Phase 3 -> **482**.017490868 mm

- Assume the tolerance is on our side and approximate the actual layout with something similar ☺.

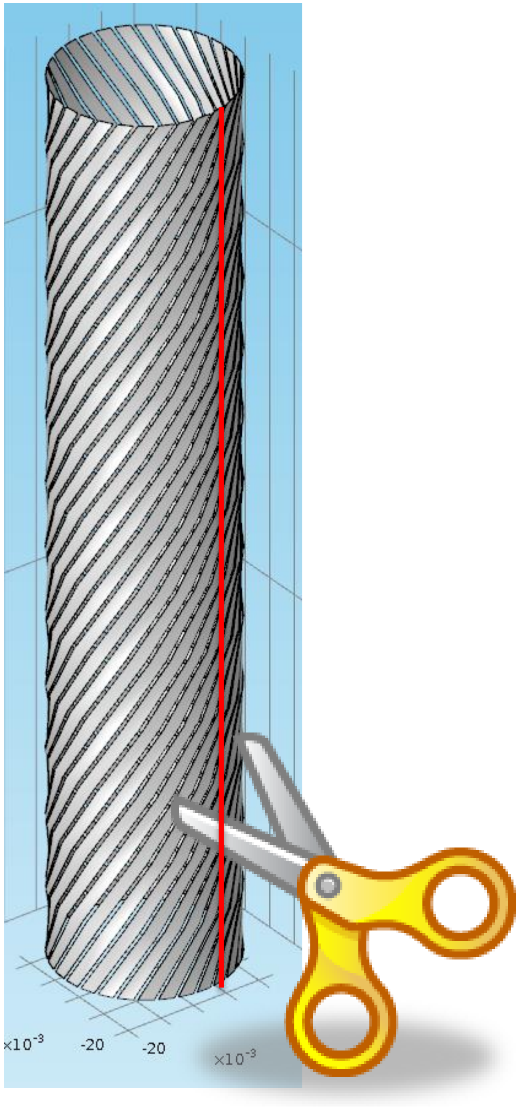
# 1-phase layout

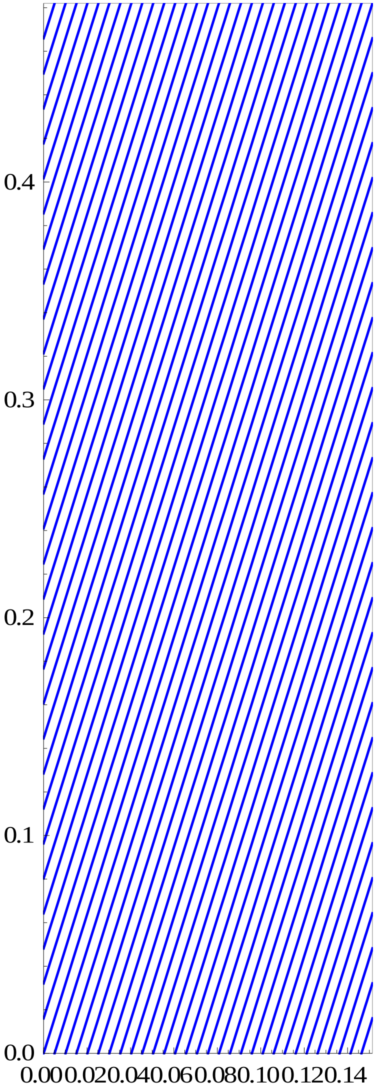


# 1-phase layout

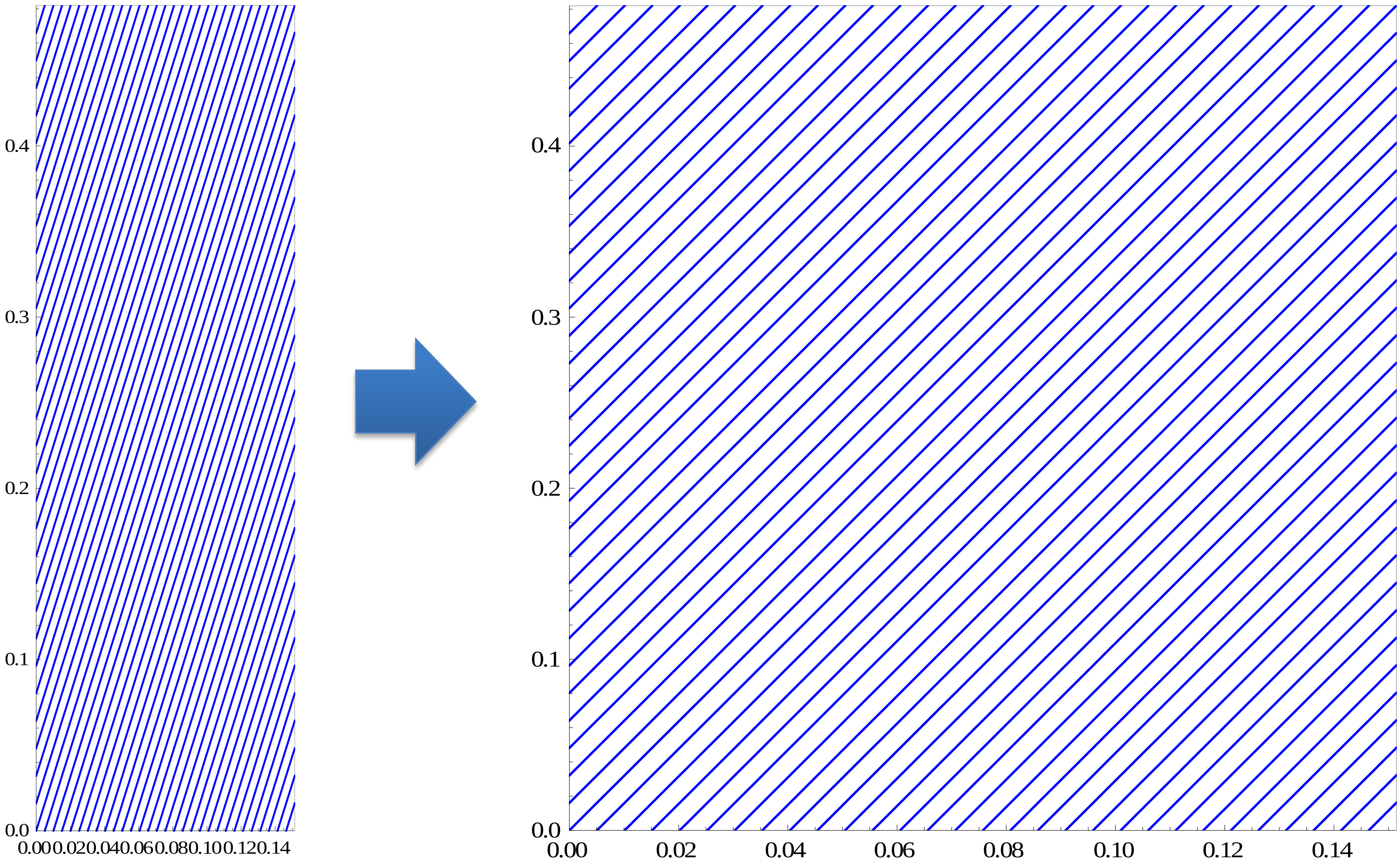


# 1-phase layout

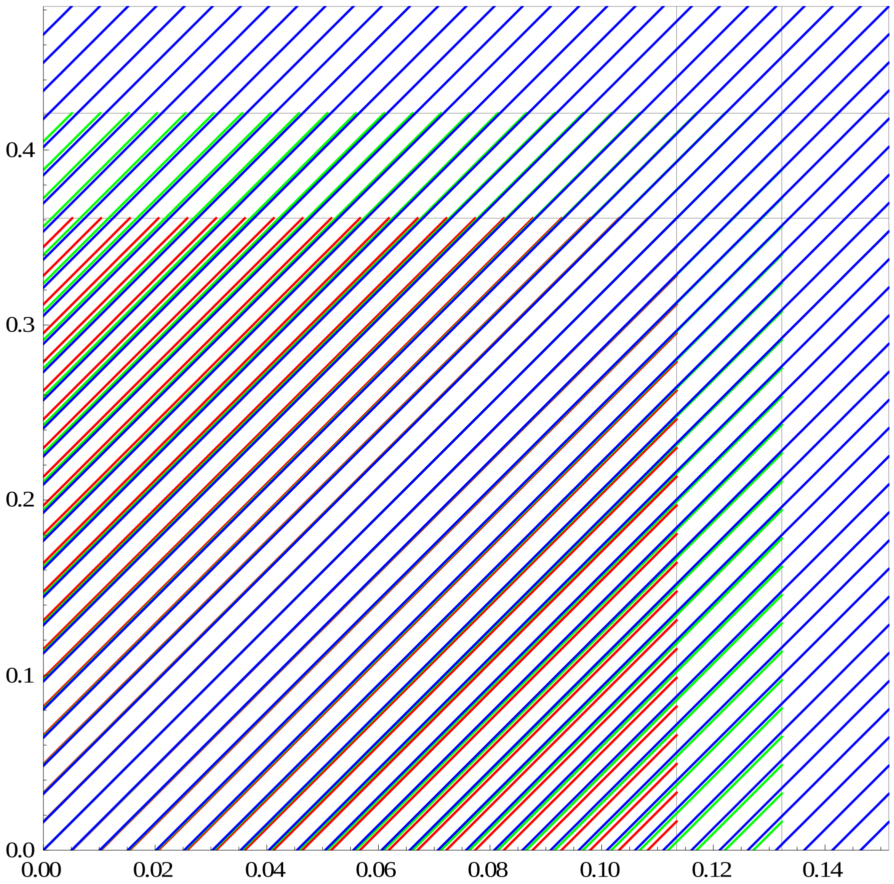


# 1-phase layout

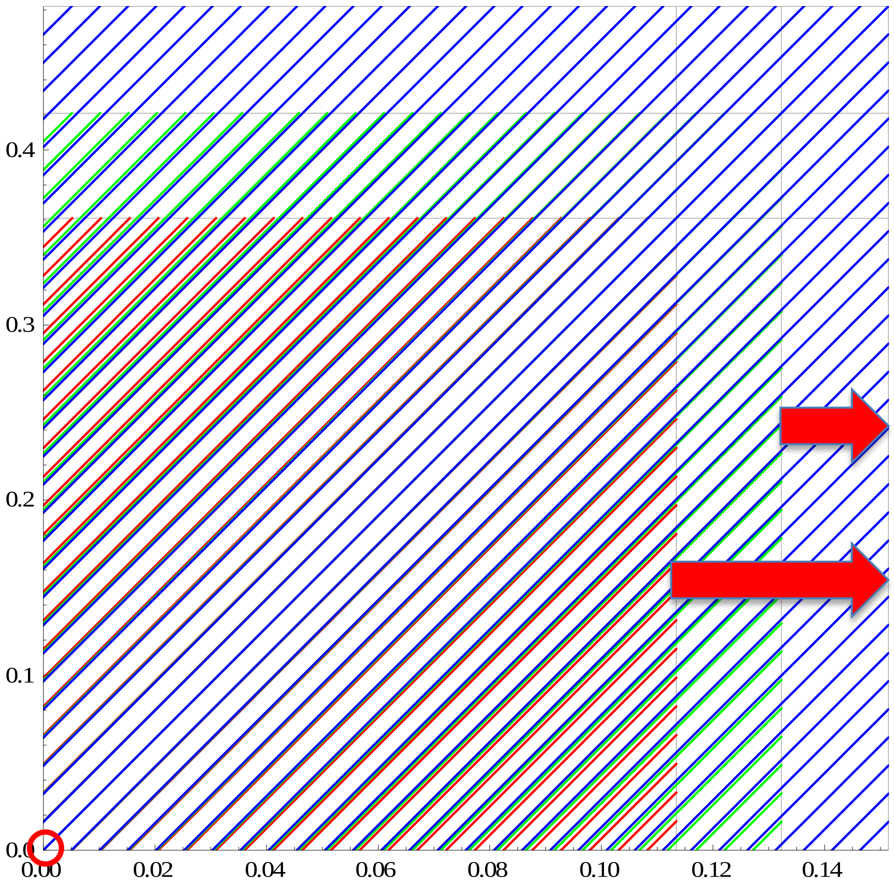


# 3-phase layout

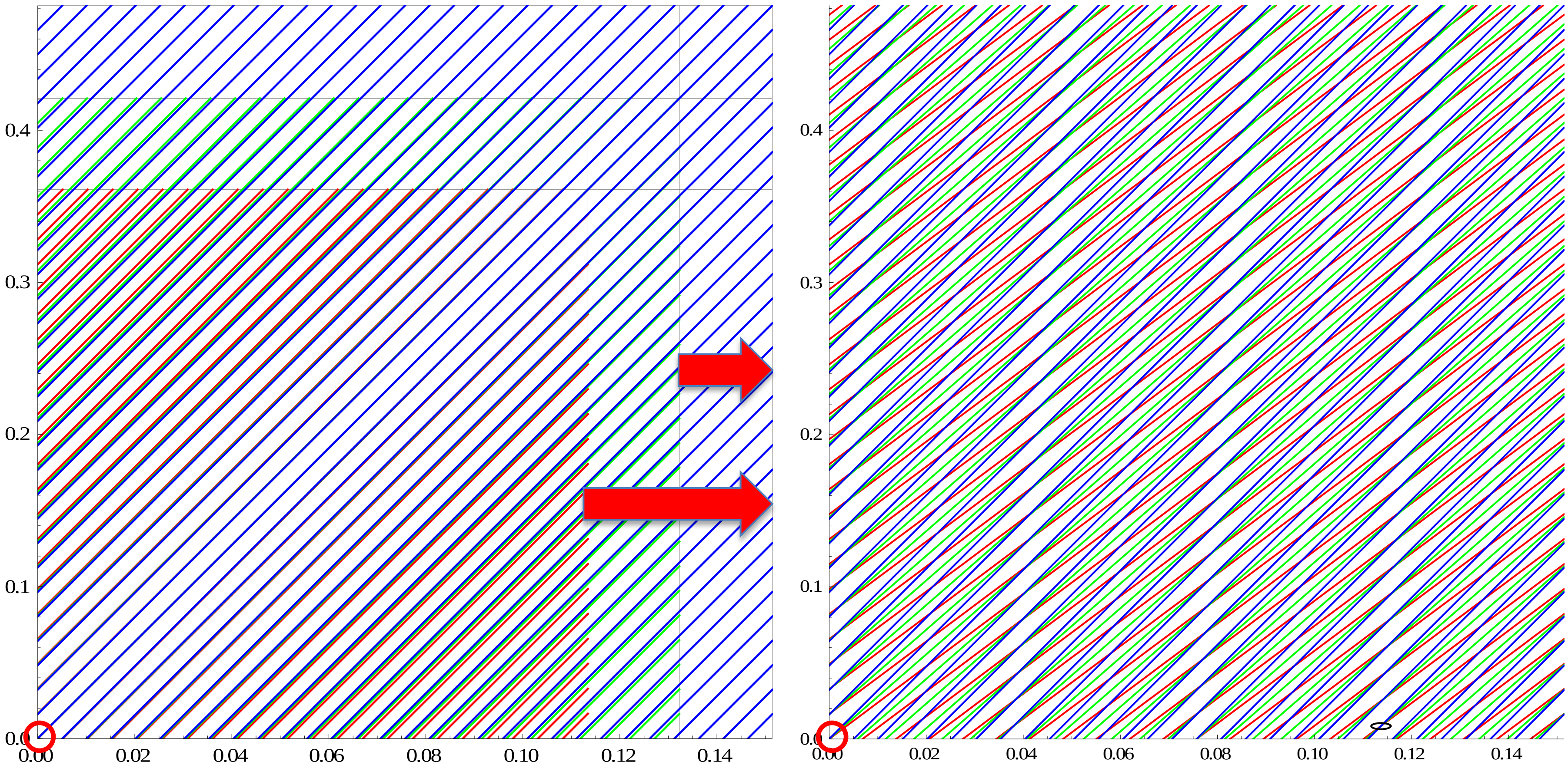


# 3-phase layout

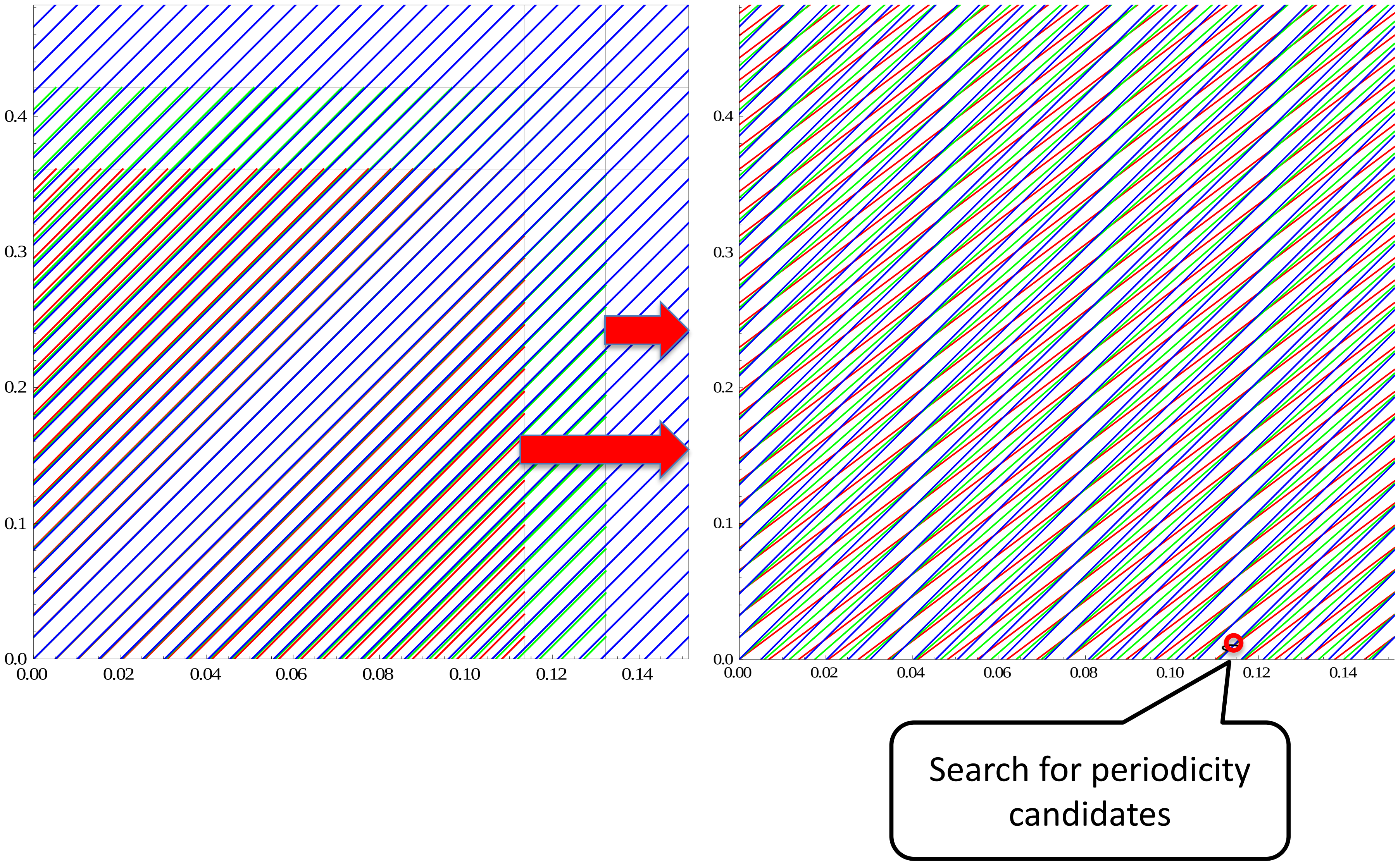
# 3-phase layout projected



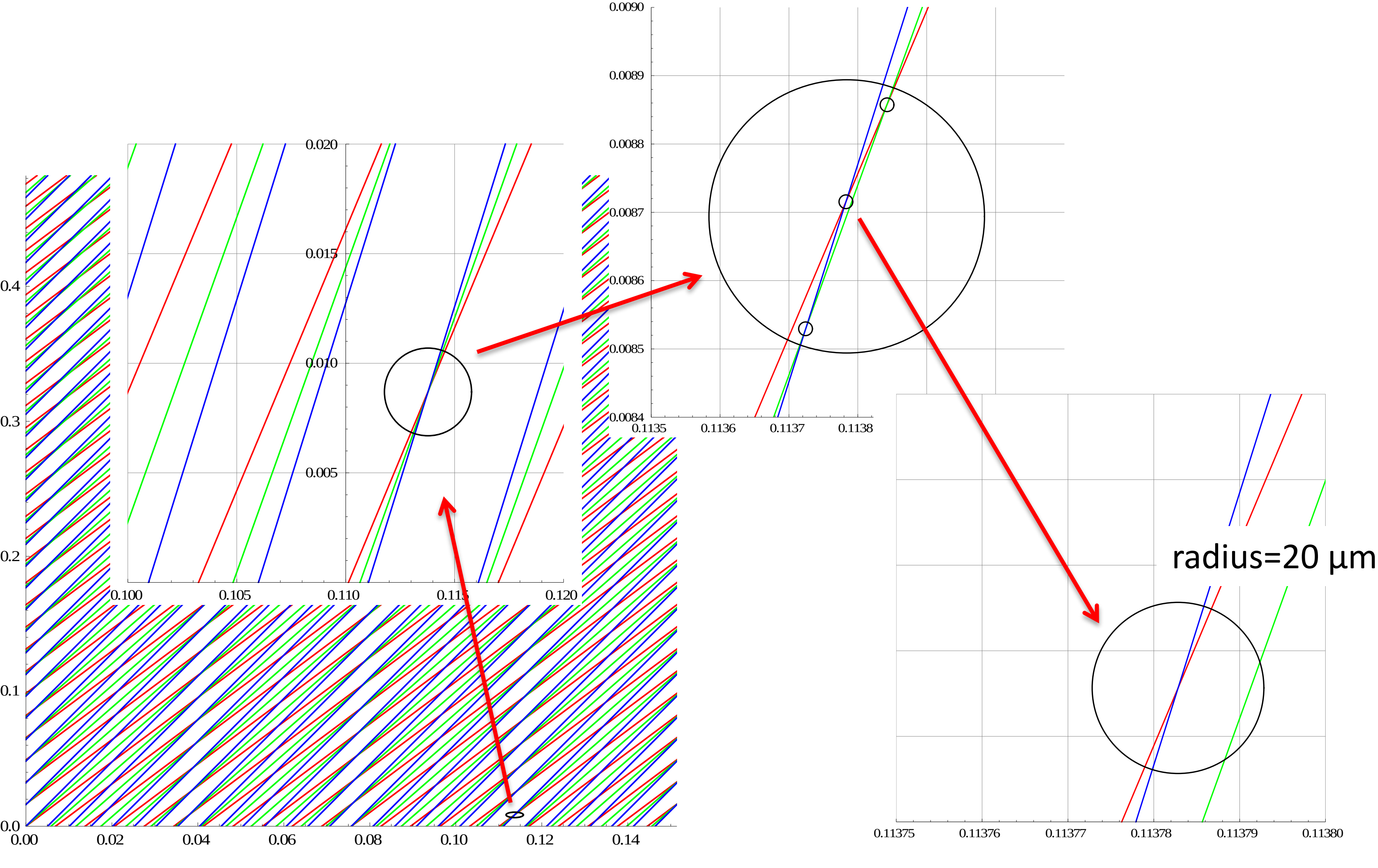
# 3-phase layout projected



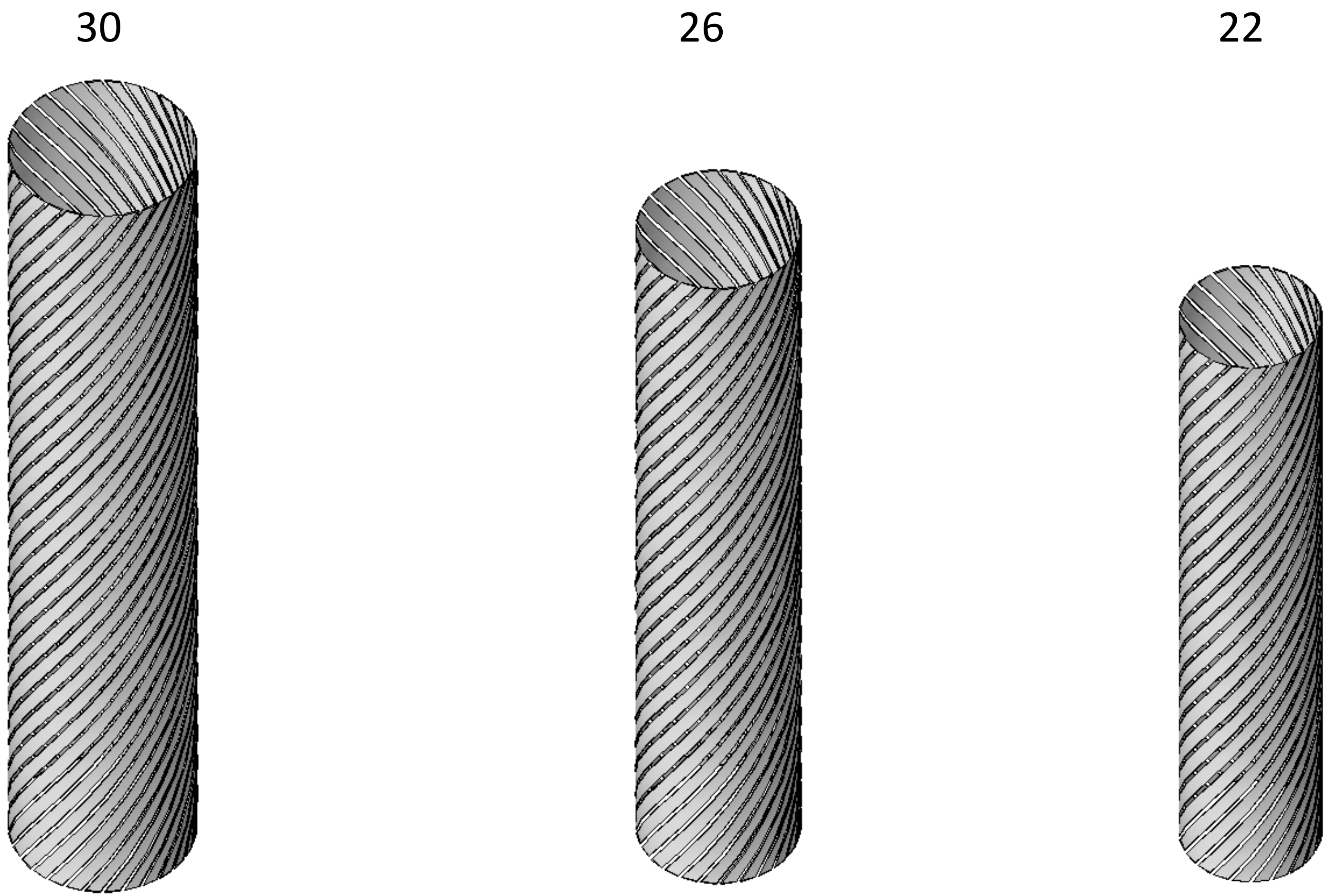
# 3-phase layout projected



# Search for periodicity candidates

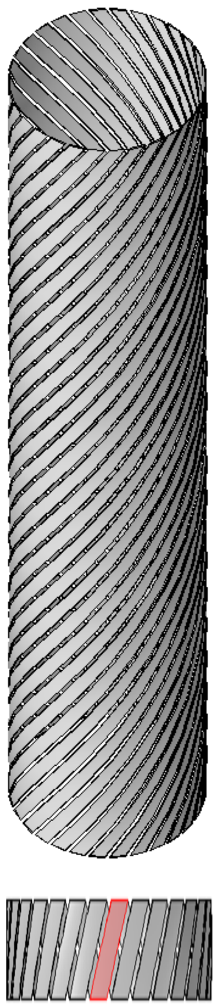


# Find minimum period per phase



# Find minimum period per phase

30



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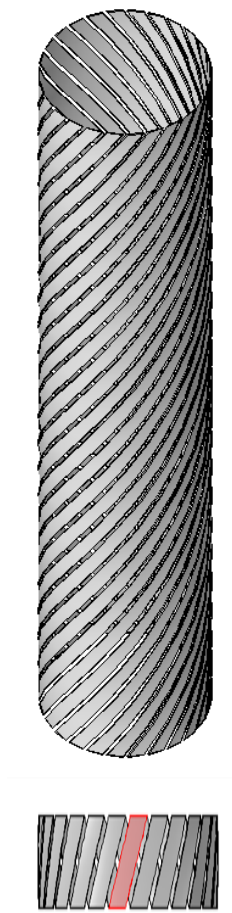

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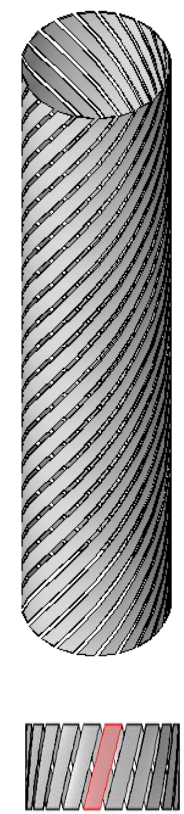

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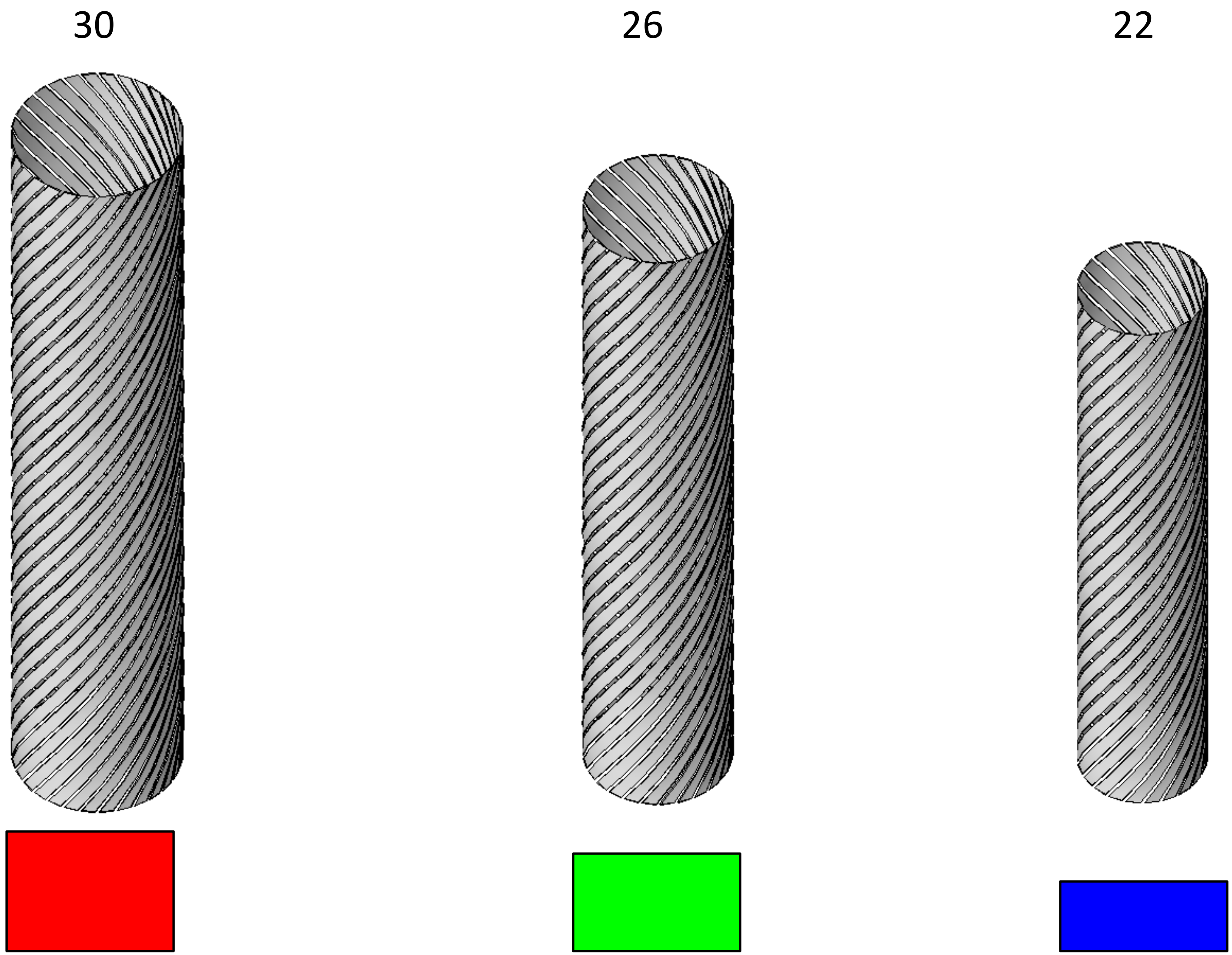
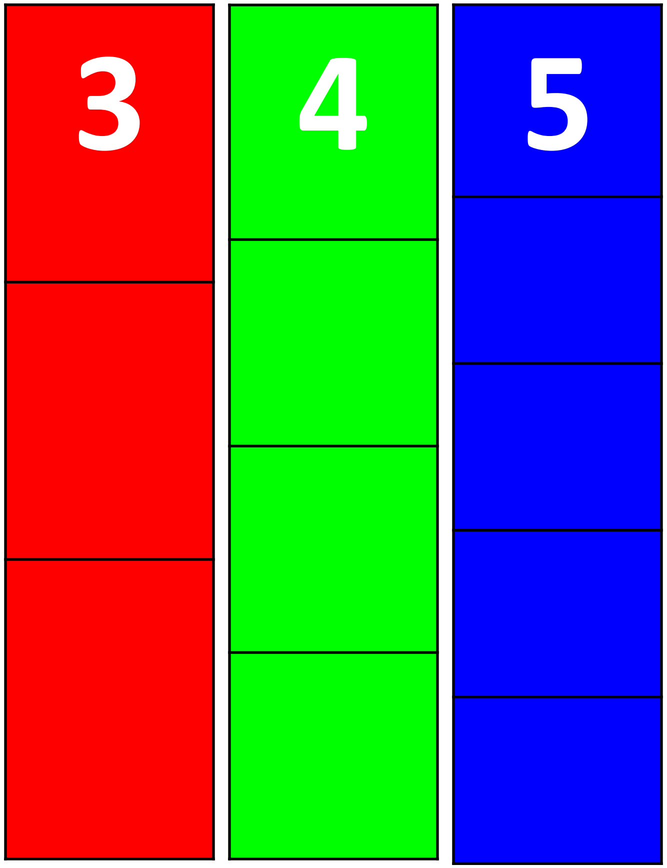


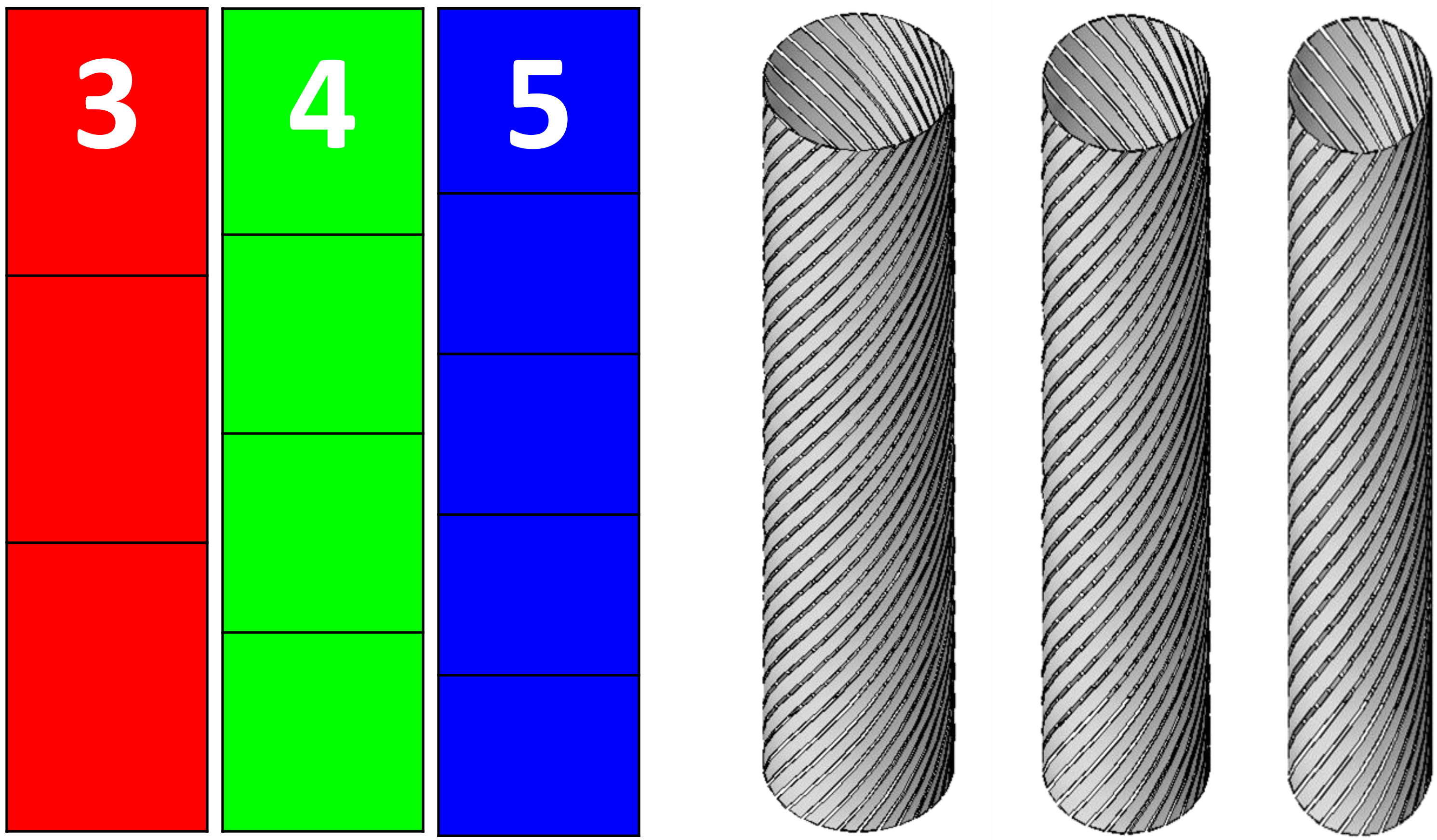
# Search for candidate geometries

Use integer combinations of the minimum periods per phase



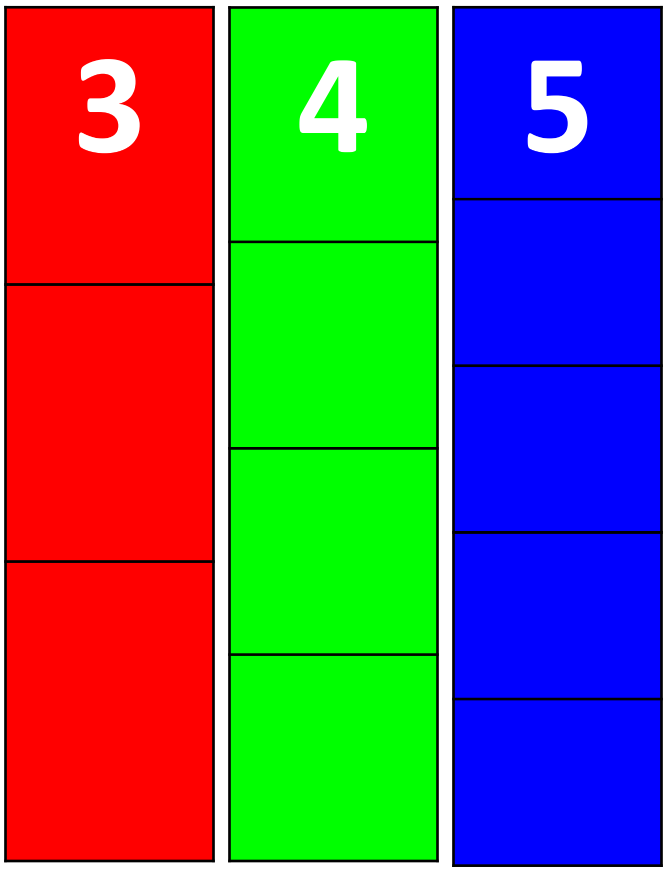
# Search for candidate geometries

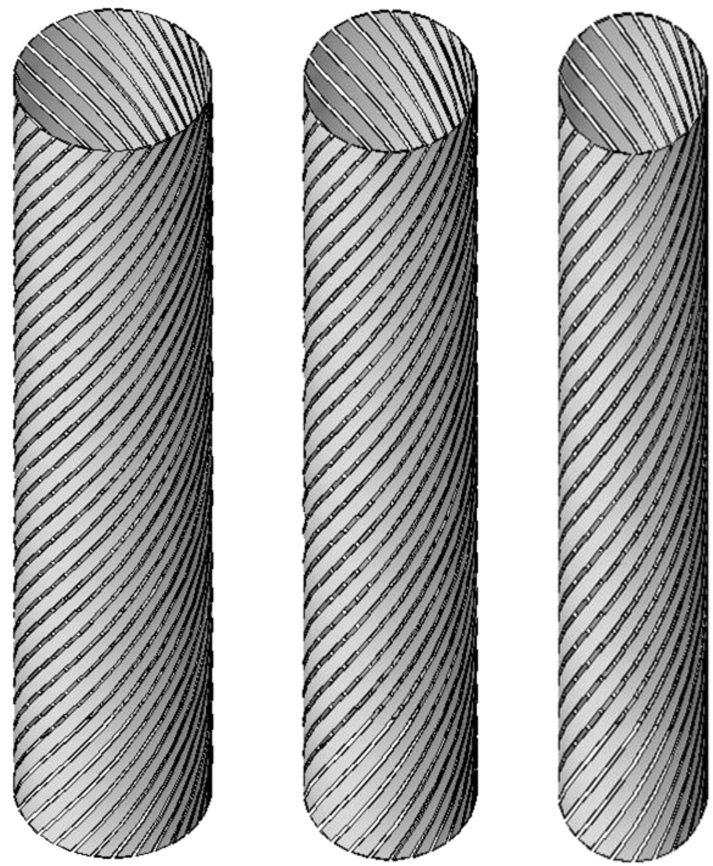
Use integer combinations of the minimum periods per phase



# Search for candidate geometries

Use integer combinations of the minimum periods per phase



And test for the corresponding pitch angles

16° 17.44° 18°

# Approximate pitch length of the cable

Designs under 0.66 m

| Dispersion[deg] | Max error(%) in pitch angle | αa[deg] | αb[deg] | αc[deg] | qa | qb | qc | Pitch length[m] | # of slices |
|---|---|---|---|---|---|---|---|---|---|
| 0.195927 | 1.12343 | 17.2441 | 17.44 | 17.3128 | 39 | 40 | 40 | 0.647716 | 120 |
| 0.206592 | 1.18459 | 17.2334 | 17.44 | 17.3128 | 38 | 39 | 39 | 0.631523 | 117 |
| 0.21782 | 1.24897 | 17.2222 | 17.44 | 17.3128 | 37 | 38 | 38 | 0.61533 | 114 |
| 0.219066 | 1.25611 | 17.6591 | 17.44 | 17.3128 | 1 | 1 | 1 | 0.0161929 | 3 |
| 0.229657 | 1.31684 | 17.2103 | 17.44 | 17.3128 | 36 | 37 | 37 | 0.599137 | 111 |
| 0.242153 | 1.38849 | 17.1978 | 17.44 | 17.3128 | 35 | 36 | 36 | 0.582944 | 108 |
| 0.255365 | 1.46425 | 17.1846 | 17.44 | 17.3128 | 34 | 35 | 35 | 0.566751 | 105 |
| 0.269356 | 1.54447 | 17.1706 | 17.44 | 17.3128 | 33 | 34 | 34 | 0.550558 | 102 |
| 0.284197 | 1.62957 | 17.1558 | 17.44 | 17.3128 | 32 | 33 | 33 | 0.534366 | 99 |
| 0.289227 | 1.65841 | 17.2334 | 17.44 | 17.7292 | 38 | 39 | 40 | 0.631523 | 120 |
| 0.289227 | 1.65841 | 17.6591 | 17.44 | 17.7292 | 39 | 39 | 40 | 0.631523 | 120 |
| 0.299969 | 1.72 | 17.14 | 17.44 | 17.3128 | 31 | 32 | 32 | 0.518173 | 96 |
| 0.30016 | 1.7211 | 17.2222 | 17.44 | 17.7402 | 37 | 38 | 39 | 0.61533 | 117 |
| 0.30016 | 1.7211 | 17.6591 | 17.44 | 17.7402 | 38 | 38 | 39 | 0.61533 | 117 |
| 0.311683 | 1.78717 | 17.2103 | 17.44 | 17.7517 | 36 | 37 | 38 | 0.599137 | 114 |
| 0.311683 | 1.78717 | 17.6591 | 17.44 | 17.7517 | 37 | 37 | 38 | 0.599137 | 114 |
| 0.316761 | 1.81629 | 17.1232 | 17.44 | 17.3128 | 30 | 31 | 31 | 0.50198 | 93 |
| 0.323844 | 1.8569 | 17.1978 | 17.44 | 17.7638 | 35 | 36 | 37 | 0.582944 | 111 |
| 0.323844 | 1.8569 | 17.6591 | 17.44 | 17.7638 | 36 | 36 | 37 | 0.582944 | 111 |
| 0.334675 | 1.91901 | 17.1053 | 17.44 | 17.3128 | 29 | 30 | 30 | 0.485787 | 90 |
| 0.336698 | 1.93061 | 17.1846 | 17.44 | 17.7767 | 34 | 35 | 36 | 0.566751 | 108 |
| 0.336698 | 1.93061 | 17.6591 | 17.44 | 17.7767 | 35 | 35 | 36 | 0.566751 | 108 |
| 0.350306 | 2.00863 | 17.1706 | 17.44 | 17.7903 | 33 | 34 | 35 | 0.550558 | 105 |
| 0.350306 | 2.00863 | 17.6591 | 17.44 | 17.7903 | 34 | 34 | 35 | 0.550558 | 105 |

# Approximate pitch length of the cable

Designs under 0.66 m

| Dispersion[deg] | Max error(%) in pitch angle | αa[deg] | αb[deg] | αc[deg] | qa | qb | qc | Pitch length[m] | # of slices |
|---|---|---|---|---|---|---|---|---|---|
| 0.195927 | 1.12343 | 17.2441 | 17.44 | 17.3128 | 39 | 40 | 40 | 0.647716 | 120 |
| 0.206592 | 1.18459 | 17.2334 | 17.44 | 17.3128 | 38 | 39 | 39 | 0.631523 | 117 |
| 0.21782 | 1.24897 | 17.2222 | 17.44 | 17.3128 | 37 | 38 | 38 | 0.61533 | 114 |
| 0.219066 | 1.25611 | 17.6591 | 17.44 | 17.3128 | 1 | 1 | 1 | 0.0161929 | 3 |
| 0.229657 | 1.31684 | 17.2103 | 17.44 | 17.3128 | 36 | 37 | 37 | 0.599137 | 111 |
| 0.242153 | 1.38849 | 17.1978 | 17.44 | 17.3128 | 35 | 36 | 36 | 0.582944 | 108 |
| 0.255365 | 1.46425 | 17.1846 | 17.44 | 17.3128 | 34 | 35 | 35 | 0.566751 | 105 |
| 0.269356 | 1.54447 | 17.1706 | 17.44 | 17.3128 | 33 | 34 | 34 | 0.550558 | 102 |
| 0.284197 | 1.62957 | 17.1558 | 17.44 | 17.3128 | 32 | 33 | 33 | 0.534366 | 99 |
| 0.289227 | 1.65841 | 17.2334 | 17.44 | 17.7292 | 38 | 39 | 40 | 0.631523 | 120 |
| 0.289227 | 1.65841 | 17.6591 | 17.44 | 17.7292 | 39 | 39 | 40 | 0.631523 | 120 |
| 0.299969 | 1.72 | 17.14 | 17.44 | 17.3128 | 31 | 32 | 32 | 0.518173 | 96 |
| 0.30016 | 1.7211 | 17.2222 | 17.44 | 17.7402 | 37 | 38 | 39 | 0.61533 | 117 |
| 0.30016 | 1.7211 | 17.6591 | 17.44 | 17.7402 | 38 | 38 | 39 | 0.61533 | 117 |
| 0.311683 | 1.78717 | 17.2103 | 17.44 | 17.7517 | 36 | 37 | 38 | 0.599137 | 114 |
| 0.311683 | 1.78717 | 17.6591 | 17.44 | 17.7517 | 37 | 37 | 38 | 0.599137 | 114 |
| 0.316761 | 1.81629 | 17.1232 | 17.44 | 17.3128 | 30 | 31 | 31 | 0.50198 | 93 |
| 0.323844 | 1.8569 | 17.1978 | 17.44 | 17.7638 | 35 | 36 | 37 | 0.582944 | 111 |
| 0.323844 | 1.8569 | 17.6591 | 17.44 | 17.7638 | 36 | 36 | 37 | 0.582944 | 111 |
| 0.334675 | 1.91901 | 17.1053 | 17.44 | 17.3128 | 29 | 30 | 30 | 0.485787 | 90 |
| 0.336698 | 1.93061 | 17.1846 | 17.44 | 17.7767 | 34 | 35 | 36 | 0.566751 | 108 |
| 0.336698 | 1.93061 | 17.6591 | 17.44 | 17.7767 | 35 | 35 | 36 | 0.566751 | 108 |
| 0.350306 | 2.00863 | 17.1706 | 17.44 | 17.7903 | 33 | 34 | 35 | 0.550558 | 105 |
| 0.350306 | 2.00863 | 17.6591 | 17.44 | 17.7903 | 34 | 34 | 35 | 0.550558 | 105 |

# Approximate pitch length of the cable

Designs under 0.66 m

| Dispersion[deg] | Max error(%) in pitch angle | αa[deg] | αb[deg] | αc[deg] | qa | qb | qc | Pitch length[m] | # of slices |
|---|---|---|---|---|---|---|---|---|---|
| 0.195927 | 1.12343 | 17.2441 | 17.44 | 17.3128 | 39 | 40 | 40 | 0.647716 | 120 |
| 0.206592 | 1.18459 | 17.2334 | 17.44 | 17.3128 | 38 | 39 | 39 | 0.631523 | 117 |
| 0.21782 | 1.24897 | 17.2222 | 17.44 | 17.3128 | 37 | 38 | 38 | 0.61533 | 114 |
| 0.219066 | 1.25611 | 17.6591 | 17.44 | 17.3128 | 1 | 1 | 1 | 0.0161929 | 3 |
| 0.229657 | 1.31684 | 17.2103 | 17.44 | 17.3128 | 36 | 37 | 37 | 0.599137 | 111 |
| 0.242153 | 1.38849 | 17.1978 | 17.44 | 17.3128 | 35 | 36 | 36 | 0.582944 | 108 |
| 0.255365 | 1.46425 | 17.1846 | 17.44 | 17.3128 | 34 | 35 | 35 | 0.566751 | 105 |
| 0.269356 | 1.54447 | 17.1706 | 17.44 | 17.3128 | 33 | 34 | 34 | 0.550558 | 102 |
| 0.284197 | 1.62957 | 17.1558 | 17.44 | 17.3128 | 32 | 33 | 33 | 0.534366 | 99 |
| 0.289227 | 1.65841 | 17.2334 | 17.44 | 17.7292 | 38 | 39 | 40 | 0.631523 | 120 |
| 0.289227 | 1.65841 | 17.6591 | 17.44 | 17.7292 | 39 | 39 | 40 | 0.631523 | 120 |
| 0.299969 | 1.72 | 17.14 | 17.44 | 17.3128 | 31 | 32 | 32 | 0.518173 | 96 |
| 0.30016 | 1.7211 | 17.2222 | 17.44 | 17.7402 | 37 | 38 | 39 | 0.61533 | 117 |
| 0.30016 | 1.7211 | 17.6591 | 17.44 | 17.7402 | 38 | 38 | 39 | 0.61533 | 117 |
| 0.311683 | 1.78717 | 17.2103 | 17.44 | 17.7517 | 36 | 37 | 38 | 0.599137 | 114 |
| 0.311683 | 1.78717 | 17.6591 | 17.44 | 17.7517 | 37 | 37 | 38 | 0.599137 | 114 |
| 0.316761 | 1.81629 | 17.1232 | 17.44 | 17.3128 | 30 | 31 | 31 | 0.50198 | 93 |
| 0.323844 | 1.8569 | 17.1978 | 17.44 | 17.7638 | 35 | 36 | 37 | 0.582944 | 111 |
| 0.323844 | 1.8569 | 17.6591 | 17.44 | 17.7638 | 36 | 36 | 37 | 0.582944 | 111 |
| 0.334675 | 1.91901 | 17.1053 | 17.44 | 17.3128 | 29 | 30 | 30 | 0.485787 | 90 |
| 0.336698 | 1.93061 | 17.1846 | 17.44 | 17.7767 | 34 | 35 | 36 | 0.566751 | 108 |
| 0.336698 | 1.93061 | 17.6591 | 17.44 | 17.7767 | 35 | 35 | 36 | 0.566751 | 108 |
| 0.350306 | 2.00863 | 17.1706 | 17.44 | 17.7903 | 33 | 34 | 35 | 0.550558 | 105 |
| 0.350306 | 2.00863 | 17.6591 | 17.44 | 17.7903 | 34 | 34 | 35 | 0.550558 | 105 |

# Approximate pitch length of the cable

Designs under 0.66 m

| Dispersion[deg] | Max error(%) in pitch angle | αa[deg] | αb[deg] | αc[deg] | qa | qb | qc | Pitch length[m] | # of slices |
|---|---|---|---|---|---|---|---|---|---|
| 0.195927 | 1.12343 | 17.2441 | 17.44 | 17.3128 | 39 | 40 | 40 | 0.647716 | 120 |
| 0.206592 | 1.18459 | 17.2334 | 17.44 | 17.3128 | 38 | 39 | 39 | 0.631523 | 117 |
| 0.21782 | 1.24897 | 17.2222 | 17.44 | 17.3128 | 37 | 38 | 38 | 0.61533 | 114 |
| 0.219066 | 1.25611 | 17.6591 | 17.44 | 17.3128 | 1 | 1 | 1 | 0.0161929 | 3 |
| 0.229657 | 1.31684 | 17.2103 | 17.44 | 17.3128 | 36 | 37 | 37 | 0.599137 | 111 |
| 0.242153 | 1.38849 | 17.1978 | 17.44 | 17.3128 | 35 | 36 | 36 | 0.582944 | 108 |
| 0.255365 | 1.46425 | 17.1846 | 17.44 | 17.3128 | 34 | 35 | 35 | 0.566751 | 105 |
| 0.269356 | 1.54447 | 17.1706 | 17.44 | 17.3128 | 33 | 34 | 34 | 0.550558 | 102 |
| 0.284197 | 1.62957 | 17.1558 | 17.44 | 17.3128 | 32 | 33 | 33 | 0.534366 | 99 |
| 0.289227 | 1.65841 | 17.2334 | 17.44 | 17.7292 | 38 | 39 | 40 | 0.631523 | 120 |
| 0.289227 | 1.65841 | 17.6591 | 17.44 | 17.7292 | 39 | 39 | 40 | 0.631523 | 120 |
| 0.299969 | 1.72 | 17.14 | 17.44 | 17.3128 | 31 | 32 | 32 | 0.518173 | 96 |
| 0.30016 | 1.7211 | 17.2222 | 17.44 | 17.7402 | 37 | 38 | 39 | 0.61533 | 117 |
| 0.30016 | 1.7211 | 17.6591 | 17.44 | 17.7402 | 38 | 38 | 39 | 0.61533 | 117 |
| 0.311683 | 1.78717 | 17.2103 | 17.44 | 17.7517 | 36 | 37 | 38 | 0.599137 | 114 |
| 0.311683 | 1.78717 | 17.6591 | 17.44 | 17.7517 | 37 | 37 | 38 | 0.599137 | 114 |
| 0.316761 | 1.81629 | 17.1232 | 17.44 | 17.3128 | 30 | 31 | 31 | 0.50198 | 93 |
| 0.323844 | 1.8569 | 17.1978 | 17.44 | 17.7638 | 35 | 36 | 37 | 0.582944 | 111 |
| 0.323844 | 1.8569 | 17.6591 | 17.44 | 17.7638 | 36 | 36 | 37 | 0.582944 | 111 |
| 0.334675 | 1.91901 | 17.1053 | 17.44 | 17.3128 | 29 | 30 | 30 | 0.485787 | 90 |
| 0.336698 | 1.93061 | 17.1846 | 17.44 | 17.7767 | 34 | 35 | 36 | 0.566751 | 108 |
| 0.336698 | 1.93061 | 17.6591 | 17.44 | 17.7767 | 35 | 35 | 36 | 0.566751 | 108 |
| 0.350306 | 2.00863 | 17.1706 | 17.44 | 17.7903 | 33 | 34 | 35 | 0.550558 | 105 |
| 0.350306 | 2.00863 | 17.6591 | 17.44 | 17.7903 | 34 | 34 | 35 | 0.550558 | 105 |

# Approximate pitch length of the cable

Designs under 0.66 m

| Dispersion[deg] | Max error(%) in pitch angle | αa[deg] | αb[deg] | αc[deg] | qa | qb | qc | Pitch length[m] | # of slices |
|---|---|---|---|---|---|---|---|---|---|
| 0.195927 | 1.12343 | 17.2441 | 17.44 | 17.3128 | 39 | 40 | 40 | 0.647716 | 120 |
| 0.206592 | 1.18459 | 17.2334 | 17.44 | 17.3128 | 38 | 39 | 39 | 0.631523 | 117 |
| 0.21782 | 1.24897 | 17.2222 | 17.44 | 17.3128 | 37 | 38 | 38 | 0.61533 | 114 |
| 0.219066 | 1.25611 | 17.6591 | 17.44 | 17.3128 | 1 | 1 | 1 | 0.0161929 | 3 |
| 0.229657 | 1.31684 | 17.2103 | 17.44 | 17.3128 | 36 | 37 | 37 | 0.599137 | 111 |
| 0.242153 | 1.38849 | 17.1978 | 17.44 | 17.3128 | 35 | 36 | 36 | 0.582944 | 108 |
| 0.255365 | 1.46425 | 17.1846 | 17.44 | 17.3128 | 34 | 35 | 35 | 0.566751 | 105 |
| 0.269356 | 1.54447 | 17.1706 | 17.44 | 17.3128 | 33 | 34 | 34 | 0.550558 | 102 |
| 0.284197 | 1.62957 | 17.1558 | 17.44 | 17.3128 | 32 | 33 | 33 | 0.534366 | 99 |
| 0.289227 | 1.65841 | 17.2334 | 17.44 | 17.7292 | 38 | 39 | 40 | 0.631523 | 120 |
| 0.289227 | 1.65841 | 17.6591 | 17.44 | 17.7292 | 39 | 39 | 40 | 0.631523 | 120 |
| 0.299969 | 1.72 | 17.14 | 17.44 | 17.3128 | 31 | 32 | 32 | 0.518173 | 96 |
| 0.30016 | 1.7211 | 17.2222 | 17.44 | 17.7402 | 37 | 38 | 39 | 0.61533 | 117 |
| 0.30016 | 1.7211 | 17.6591 | 17.44 | 17.7402 | 38 | 38 | 39 | 0.61533 | 117 |
| 0.311683 | 1.78717 | 17.2103 | 17.44 | 17.7517 | 36 | 37 | 38 | 0.599137 | 114 |
| 0.311683 | 1.78717 | 17.6591 | 17.44 | 17.7517 | 37 | 37 | 38 | 0.599137 | 114 |
| 0.316761 | 1.81629 | 17.1232 | 17.44 | 17.3128 | 30 | 31 | 31 | 0.50198 | 93 |
| 0.323844 | 1.8569 | 17.1978 | 17.44 | 17.7638 | 35 | 36 | 37 | 0.582944 | 111 |
| 0.323844 | 1.8569 | 17.6591 | 17.44 | 17.7638 | 36 | 36 | 37 | 0.582944 | 111 |
| 0.334675 | 1.91901 | 17.1053 | 17.44 | 17.3128 | 29 | 30 | 30 | 0.485787 | 90 |
| 0.336698 | 1.93061 | 17.1846 | 17.44 | 17.7767 | 34 | 35 | 36 | 0.566751 | 108 |
| 0.336698 | 1.93061 | 17.6591 | 17.44 | 17.7767 | 35 | 35 | 36 | 0.566751 | 108 |
| 0.350306 | 2.00863 | 17.1706 | 17.44 | 17.7903 | 33 | 34 | 35 | 0.550558 | 105 |
| 0.350306 | 2.00863 | 17.6591 | 17.44 | 17.7903 | 34 | 34 | 35 | 0.550558 | 105 |

# Approximate pitch length of the cable

Designs under 0.66 m

| Dispersion[deg] | Max error(%) in pitch angle | αa[deg] | αb[deg] | αc[deg] | qa | qb | qc | Pitch length[m] | # of slices |
|---|---|---|---|---|---|---|---|---|---|
| 0.195927 | 1.12343 | 17.2441 | 17.44 | 17.3128 | 39 | 40 | 40 | 0.647716 | 120 |
| 0.206592 | 1.18459 | 17.2334 | 17.44 | 17.3128 | 38 | 39 | 39 | 0.631523 | 117 |
| 0.21782 | 1.24897 | 17.2222 | 17.44 | 17.3128 | 37 | 38 | 38 | 0.61533 | 114 |
| 0.219066 | 1.25611 | 17.6591 | 17.44 | 17.3128 | 1 | 1 | 1 | 0.0161929 | 3 |
| 0.229657 | 1.31684 | 17.2103 | 17.44 | 17.3128 | 36 | 37 | 37 | 0.599137 | 111 |
| 0.242153 | 1.38849 | 17.1978 | 17.44 | 17.3128 | 35 | 36 | 36 | 0.582944 | 108 |
| 0.255365 | 1.46425 | 17.1846 | 17.44 | 17.3128 | 34 | 35 | 35 | 0.566751 | 105 |
| 0.269356 | 1.54447 | 17.1706 | 17.44 | 17.3128 | 33 | 34 | 34 | 0.550558 | 102 |
| 0.284197 | 1.62957 | 17.1558 | 17.44 | 17.3128 | 32 | 33 | 33 | 0.534366 | 99 |
| 0.289227 | 1.65841 | 17.2334 | 17.44 | 17.7292 | 38 | 39 | 40 | 0.631523 | 120 |
| 0.289227 | 1.65841 | 17.6591 | 17.44 | 17.7292 | 39 | 39 | 40 | 0.631523 | 120 |
| 0.299969 | 1.72 | 17.14 | 17.44 | 17.3128 | 31 | 32 | 32 | 0.518173 | 96 |
| 0.30016 | 1.7211 | 17.2222 | 17.44 | 17.7402 | 37 | 38 | 39 | 0.61533 | 117 |
| 0.30016 | 1.7211 | 17.6591 | 17.44 | 17.7402 | 38 | 38 | 39 | 0.61533 | 117 |
| 0.311683 | 1.78717 | 17.2103 | 17.44 | 17.7517 | 36 | 37 | 38 | 0.599137 | 114 |
| 0.311683 | 1.78717 | 17.6591 | 17.44 | 17.7517 | 37 | 37 | 38 | 0.599137 | 114 |
| 0.316761 | 1.81629 | 17.1232 | 17.44 | 17.3128 | 30 | 31 | 31 | 0.50198 | 93 |
| 0.323844 | 1.8569 | 17.1978 | 17.44 | 17.7638 | 35 | 36 | 37 | 0.582944 | 111 |
| 0.323844 | 1.8569 | 17.6591 | 17.44 | 17.7638 | 36 | 36 | 37 | 0.582944 | 111 |
| 0.334675 | 1.91901 | 17.1053 | 17.44 | 17.3128 | 29 | 30 | 30 | 0.485787 | 90 |
| 0.336698 | 1.93061 | 17.1846 | 17.44 | 17.7767 | 34 | 35 | 36 | 0.566751 | 108 |
| 0.336698 | 1.93061 | 17.6591 | 17.44 | 17.7767 | 35 | 35 | 36 | 0.566751 | 108 |
| 0.350306 | 2.00863 | 17.1706 | 17.44 | 17.7903 | 33 | 34 | 35 | 0.550558 | 105 |
| 0.350306 | 2.00863 | 17.6591 | 17.44 | 17.7903 | 34 | 34 | 35 | 0.550558 | 105 |

# Approximate pitch length of the cable

Designs under 0.66 m

| Dispersion[deg] | Max error(%) in pitch angle | αa[deg] | αb[deg] | αc[deg] | qa | qb | qc | Pitch length[m] | ♯ of slices |
|---|---|---|---|---|---|---|---|---|---|
| 0.195927 | 1.12343 | 17.2441 | 17.44 | 17.3128 | 39 | 40 | 40 | 0.647716 | 120 |
| 0.206592 | 1.18459 | 17.2334 | 17.44 | 17.3128 | 38 | 39 | 39 | 0.631523 | 117 |
| 0.21782 | 1.24897 | 17.2222 | 17.44 | 17.3128 | 37 | 38 | 38 | 0.61533 | 114 |
| 0.219066 | 1.25611 | 17.6591 | 17.44 | 17.3128 | 1 | 1 | 1 | 0.0161929 | 3 |
| 0.229657 | 1.31684 | 17.2103 | 17.44 | 17.3128 | 36 | 37 | 37 | 0.599137 | 111 |
| [illegible] | [illegible] | 17.1978 | 17.44 | 17.3128 | 35 | 36 | 36 | 0.582944 | 108 |
| [illegible] | [illegible] | 17.1846 | 17.44 | 17.3128 | 34 | 35 | 35 | 0.566751 | 105 |
| [illegible] | [illegible] | 17.1706 | 17.44 | 17.3128 | 33 | 34 | 34 | 0.550558 | 102 |
| [illegible] | [illegible] | 17.1558 | 17.44 | 17.3128 | 32 | 33 | 33 | 0.534366 | 99 |
| [illegible] | [illegible] | 17.2334 | 17.44 | 17.7292 | 38 | 39 | 40 | 0.631523 | 120 |
| [illegible] | [illegible] | 17.6591 | 17.44 | 17.7292 | 39 | 39 | 40 | 0.631523 | 120 |
| [illegible] | [illegible] | 17.14 | 17.44 | 17.3128 | 31 | 32 | 32 | 0.518173 | 96 |
| [illegible] | [illegible] | 17.2222 | 17.44 | 17.7402 | 37 | 38 | 39 | 0.61533 | 117 |
| [illegible] | [illegible] | 17.6591 | 17.44 | 17.7402 | 38 | 38 | 39 | 0.61533 | 117 |
| [illegible] | [illegible] | 17.2103 | 17.44 | 17.7517 | 36 | 37 | 38 | 0.599137 | 114 |
| [illegible] | [illegible] | 17.6591 | 17.44 | 17.7517 | 37 | 37 | 38 | 0.599137 | 114 |
| [illegible] | [illegible] | 17.1232 | 17.44 | 17.3128 | 30 | 31 | 31 | 0.50198 | 93 |
| [illegible] | [illegible] | 17.1978 | 17.44 | 17.7638 | 35 | 36 | 37 | 0.582944 | 111 |
| [illegible] | [illegible] | 17.6591 | 17.44 | 17.7638 | 36 | 36 | 37 | 0.582944 | 111 |
| [illegible] | [illegible] | 17.1053 | 17.44 | 17.3128 | 29 | 30 | 30 | 0.485787 | 90 |
| [illegible] | [illegible] | 17.1846 | 17.44 | 17.7767 | 34 | 35 | 36 | 0.566751 | 108 |
| [illegible] | [illegible] | 17.6591 | 17.44 | 17.7767 | 35 | 35 | 36 | 0.566751 | 108 |
| [illegible] | [illegible] | 17.1706 | 17.44 | 17.7903 | 33 | 34 | 35 | 0.550558 | 105 |
| 0.350306 | 2.00863 | 17.6591 | 17.44 | 17.7903 | 34 | 34 | 35 | 0.550558 | 105 |

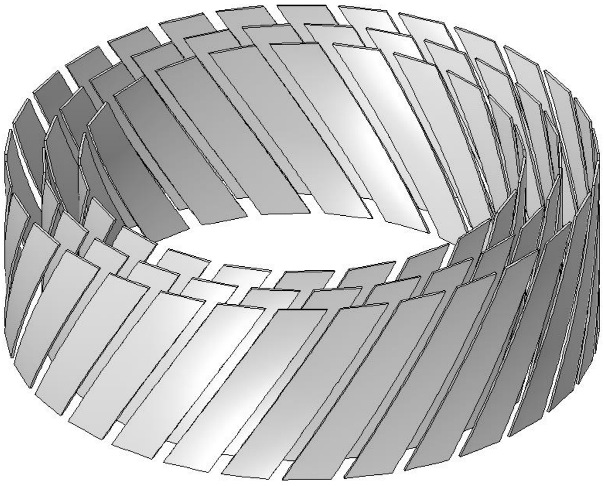
# Approximate pitch length of the cable

Designs under ~~0.65 m~~

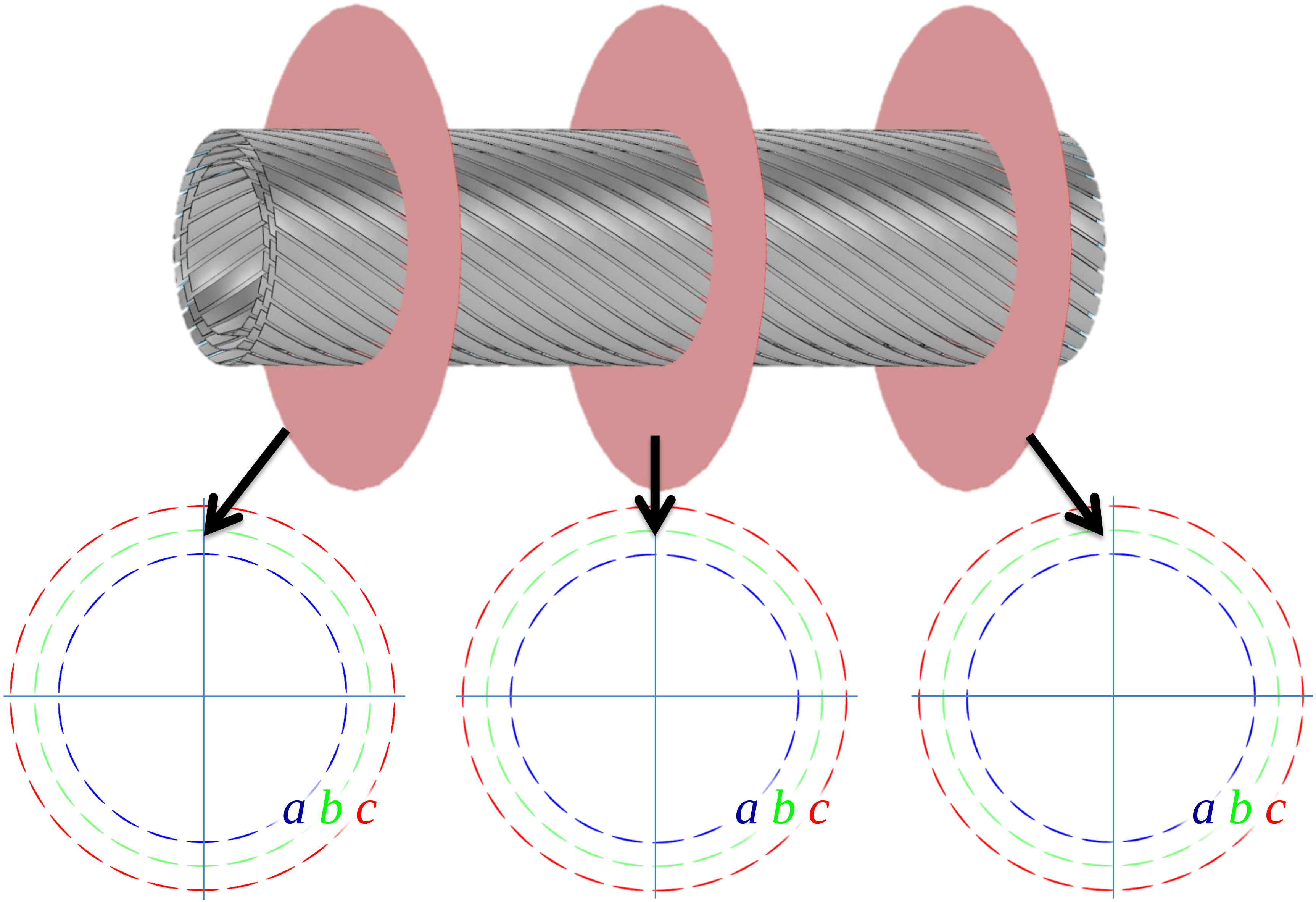
| Dispersion[deg] | Max error(%) in pitch angle | αa[deg] | αb[deg] | αc[deg] | qa | qb | qc | Pitch length[m] | # of slices |
|---|---|---|---|---|---|---|---|---|---|
| 0.195927 | 1.12343 | 17.2441 | 17.44 | 17.3128 | 39 | 40 | 40 | 0.647716 | 120 |
| 0.206592 | 1.18459 | 17.2334 | 17.44 | 17.3128 | 38 | 39 | 39 | 0.631523 | 117 |
| 0.21782 | 1.24897 | 17.2222 | 17.44 | 17.3128 | 37 | 38 | 38 | 0.61533 | 114 |
| 0.219066 | 1.25611 | 17.6591 | 17.44 | 17.3128 | 1 | 1 | 1 | 0.0161929 | 3 |
| 0.229657 | 1.31684 | 17.2103 | 17.44 | 17.3128 | 36 | 37 | 37 | 0.599137 | 111 |
| [illegible] | [illegible] | 17.1978 | 17.44 | 17.3128 | 35 | 36 | 36 | 0.582944 | 108 |
| [illegible] | [illegible] | 17.1846 | 17.44 | 17.3128 | 34 | 35 | 35 | 0.566751 | 105 |
| [illegible] | [illegible] | 17.1706 | 17.44 | 17.3128 | 33 | 34 | 34 | 0.550558 | 102 |
| [illegible] | [illegible] | 17.1558 | 17.44 | 17.3128 | 32 | 33 | 33 | 0.534366 | 99 |
| [illegible] | [illegible] | 17.2334 | 17.44 | 17.7292 | 38 | 39 | 40 | 0.631523 | 120 |
| [illegible] | [illegible] | 17.6591 | 17.44 | 17.7292 | 39 | 39 | 40 | 0.631523 | 120 |
| [illegible] | [illegible] | 17.14 | 17.44 | 17.3128 | 31 | 32 | 32 | 0.518173 | 96 |
| [illegible] | [illegible] | 17.2222 | 17.44 | 17.7402 | 37 | 38 | 39 | 0.61533 | 117 |
| [illegible] | [illegible] | 17.6591 | 17.44 | 17.7402 | 38 | 38 | 39 | 0.61533 | 117 |
| [illegible] | [illegible] | 17.2103 | 17.44 | 17.7517 | 36 | 37 | 38 | 0.599137 | 114 |
| [illegible] | [illegible] | 17.6591 | 17.44 | 17.7517 | 37 | 37 | 38 | 0.599137 | 114 |
| [illegible] | [illegible] | 17.1232 | 17.44 | 17.3128 | 30 | 31 | 31 | 0.50198 | 93 |
| [illegible] | [illegible] | 17.1978 | 17.44 | 17.7638 | 35 | 36 | 37 | 0.582944 | 111 |
| [illegible] | [illegible] | 17.6591 | 17.44 | 17.7638 | 36 | 36 | 37 | 0.582944 | 111 |
| [illegible] | [illegible] | 17.1053 | 17.44 | 17.3128 | 29 | 30 | 30 | 0.485787 | 90 |
| [illegible] | [illegible] | 17.1846 | 17.44 | 17.7767 | 34 | 35 | 36 | 0.566751 | 108 |
| [illegible] | [illegible] | 17.6591 | 17.44 | 17.7767 | 35 | 35 | 36 | 0.566751 | 108 |
| [illegible] | [illegible] | 17.1706 | 17.44 | 17.7903 | 33 | 34 | 35 | 0.550558 | 105 |
| 0.350306 | 2.00863 | 17.6591 | 17.44 | 17.7903 | 34 | 34 | 35 | 0.550558 | 105 |

# Approximate pitch length of the cable

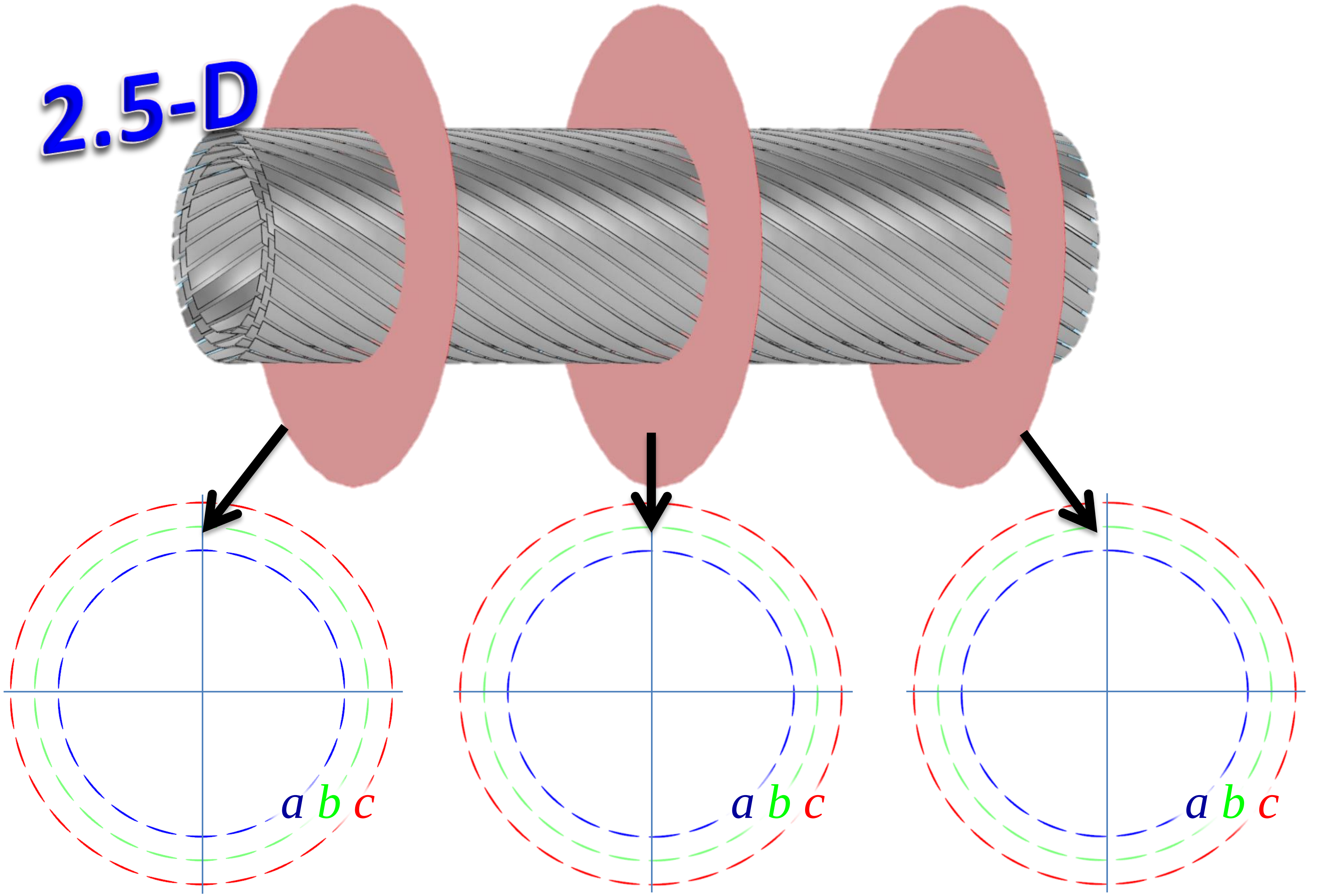
- Using an approximate pitch length of 16.193 mm for each phase:
  - Phase 1 -> 17.659 deg (0.219 deg error)
  - Phase 2 -> 17.44 deg (0 deg error)
  - Phase 3 -> 17.313 deg (0.127 deg error)



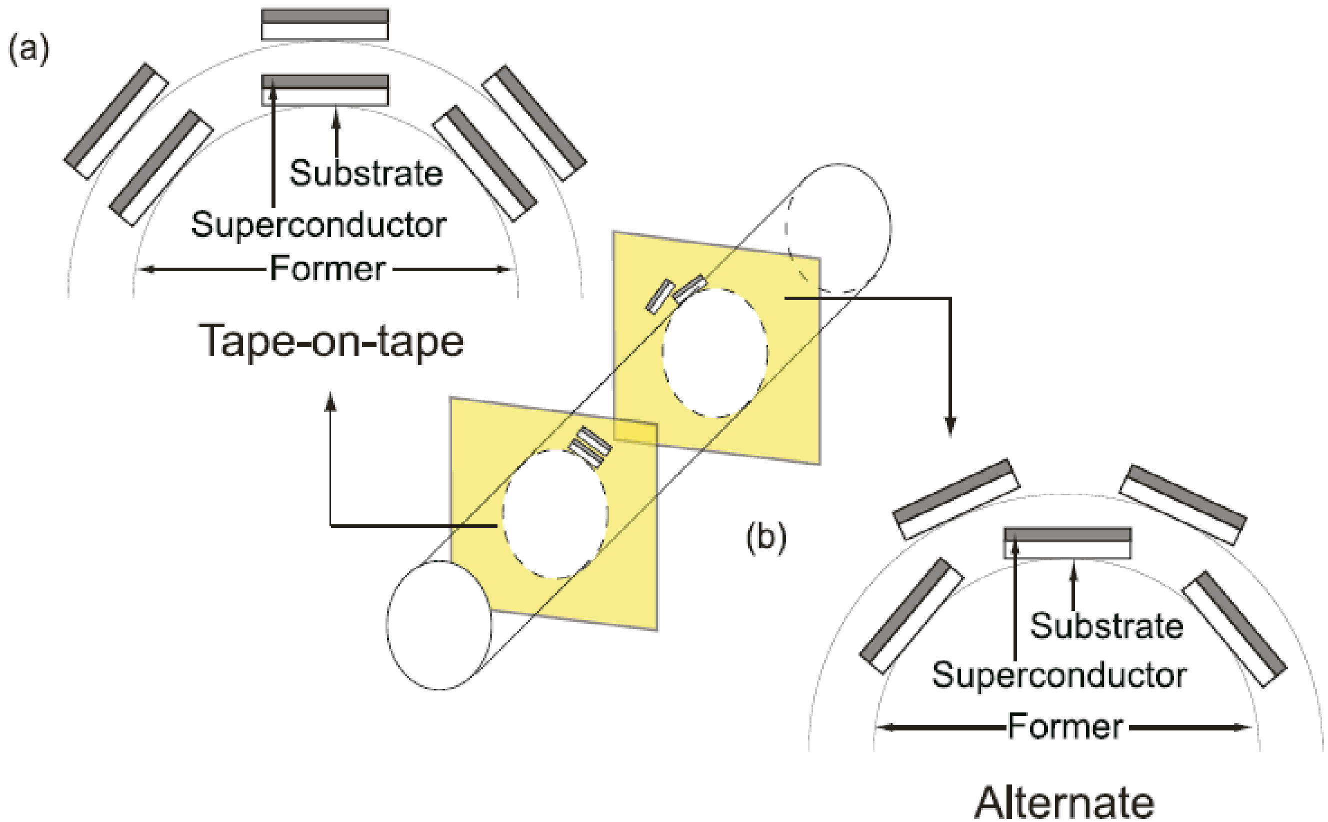
# Model of cable by several 2D slices



# Model of cable by several 2D slices



# Model of cable by two 2-D slices

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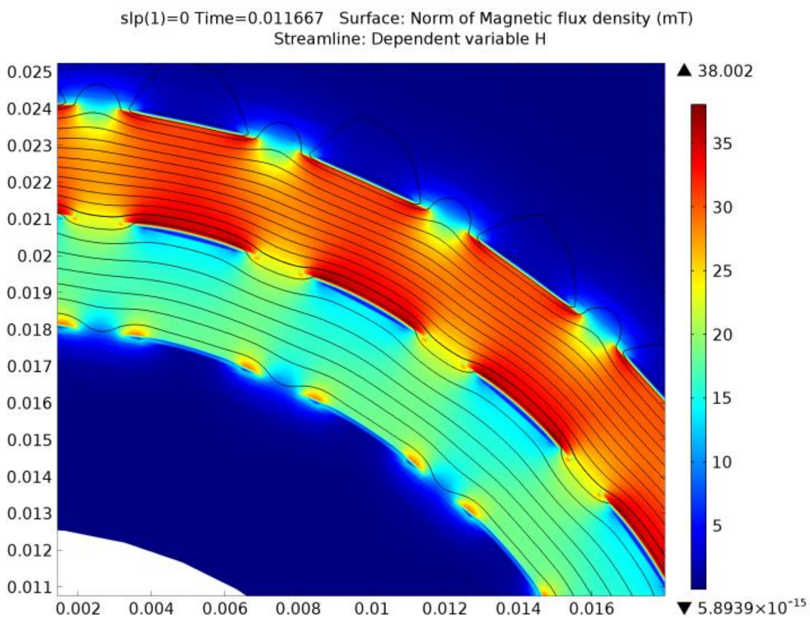
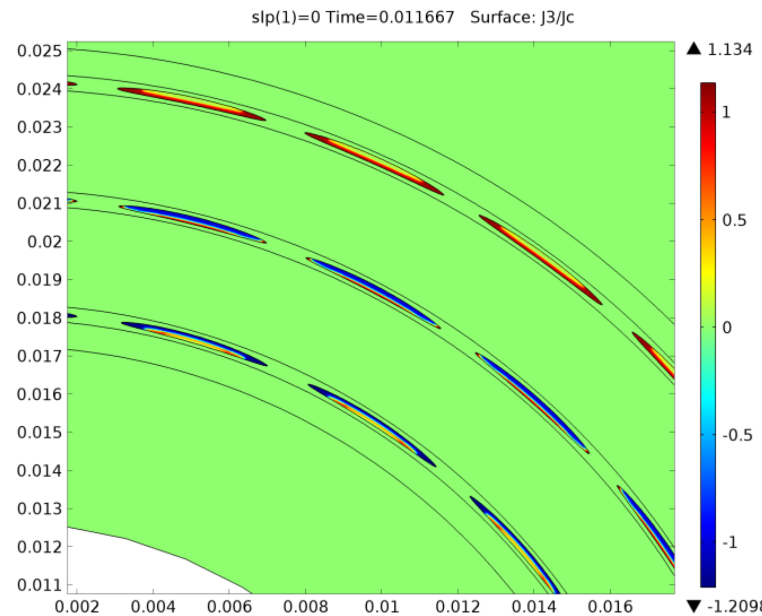
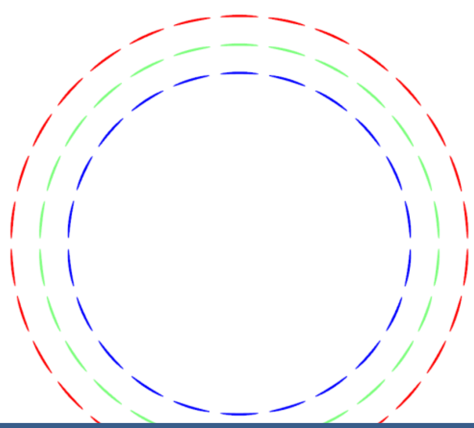
# Model of cable by subsequent 2D slices

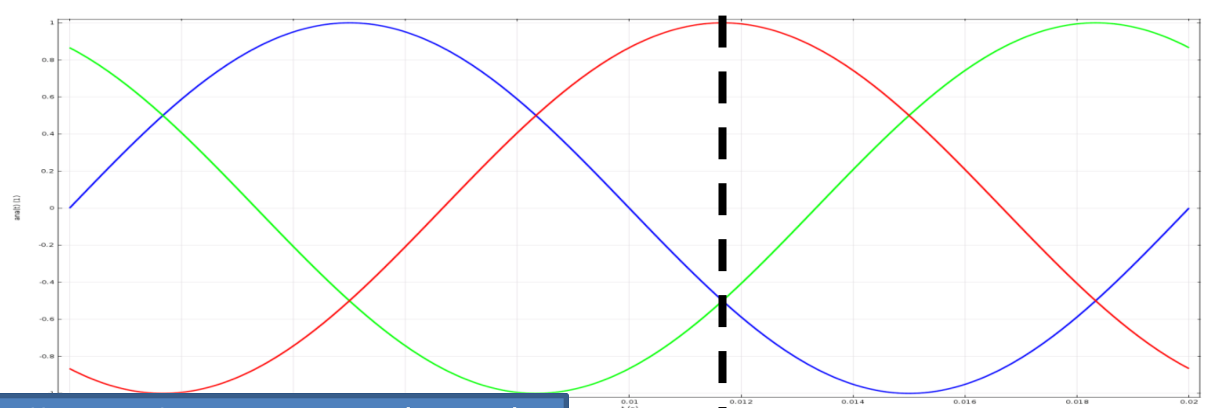
- Takes into account the different relative position of tapes along length (as a result of the pitch)
- Good results expected for low pitch angles
- Neglects axial field
- Manageable computing time (per slice)

# Magnetic flux density and Normalized current density



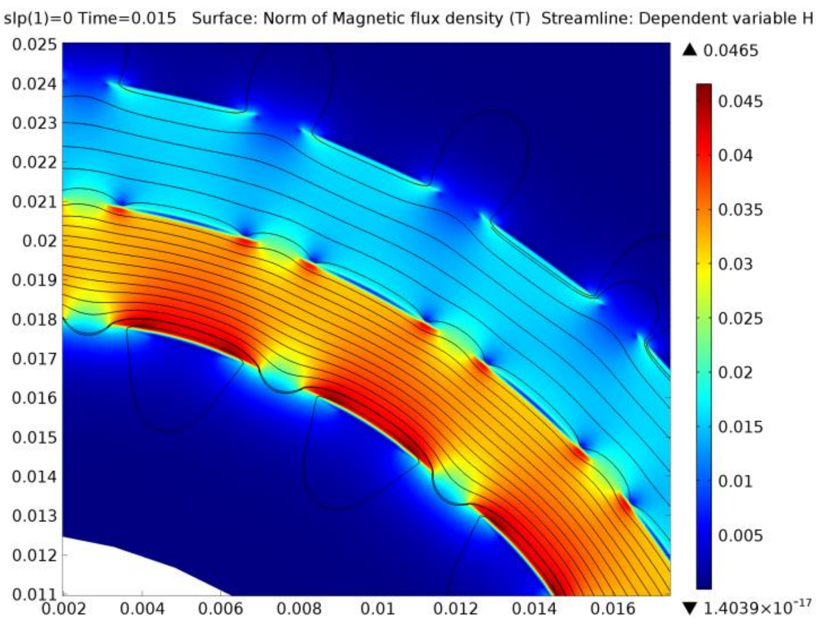



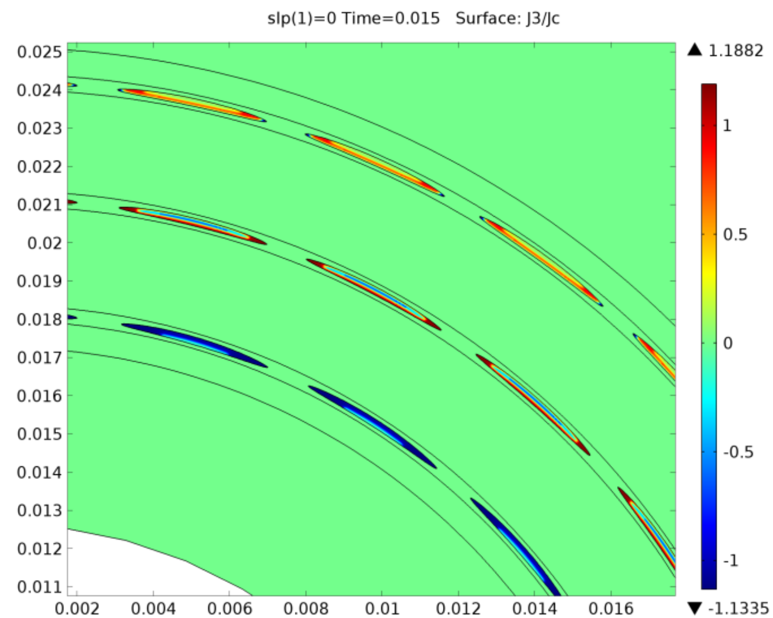



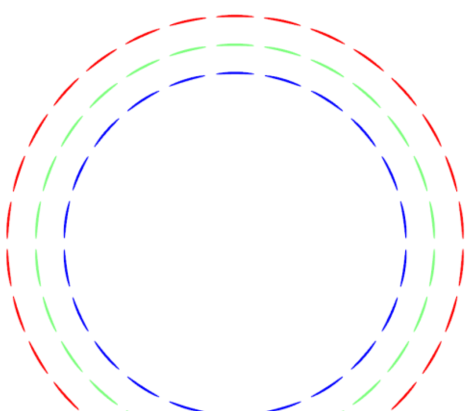


Using H-formulation, Brambilla et al. SUST 20-1 (2007)

# Magnetic flux density and Normalized current density

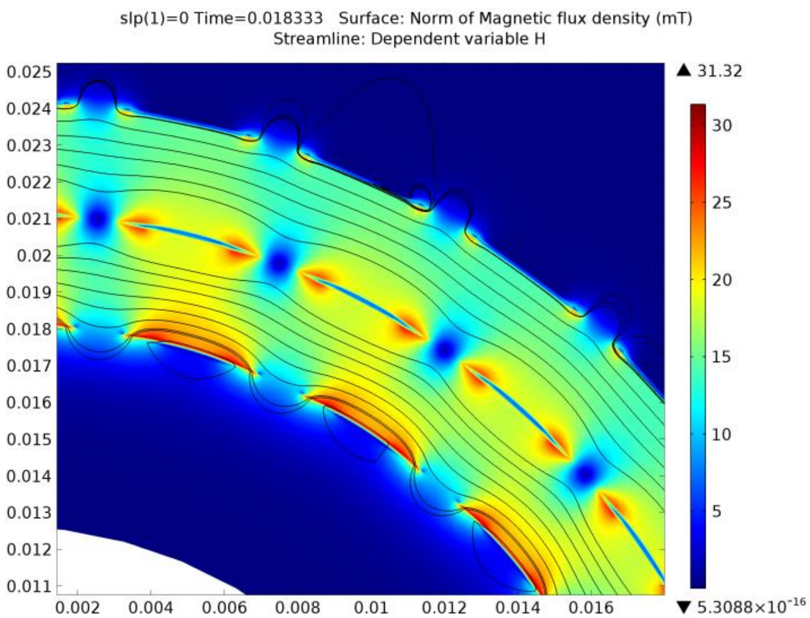


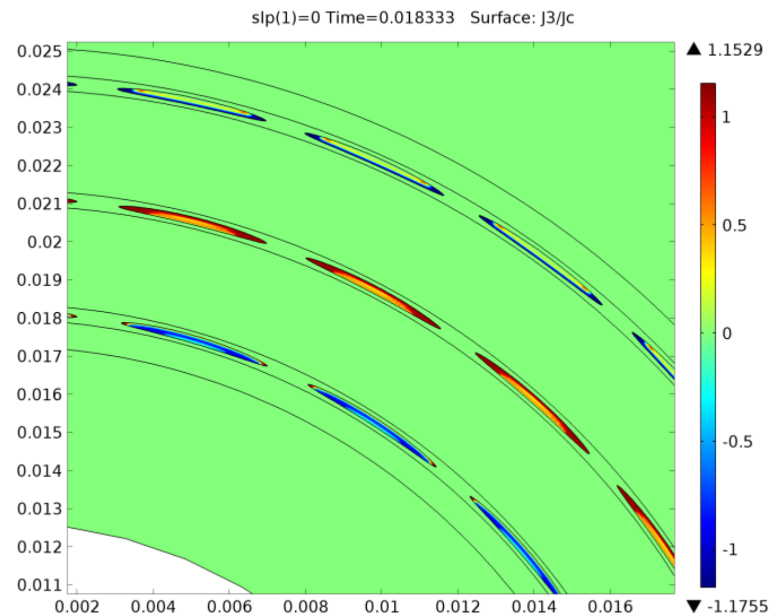



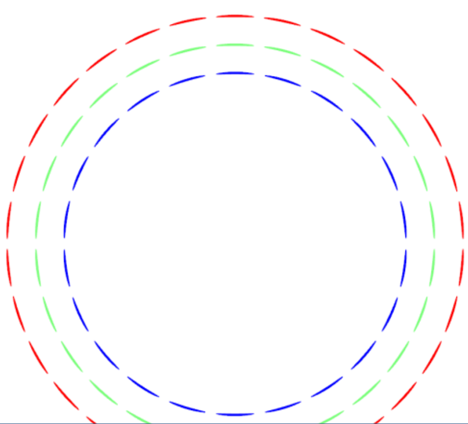



Using H-formulation, Brambilla et al. SUST 20-1 (2007)

# Magnetic flux density and Normalized current density



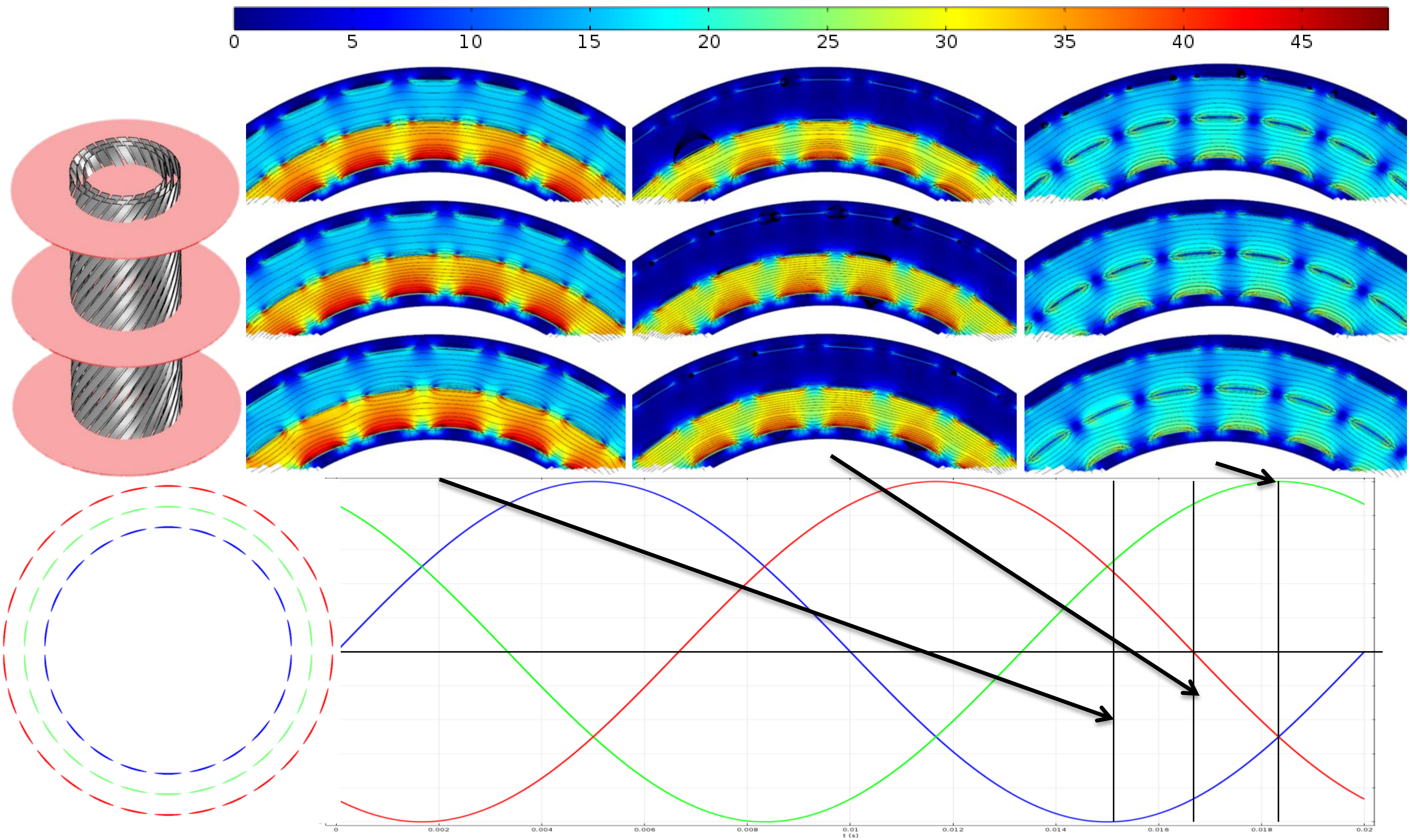



Using H-formulation, Brambilla et al. SUST 20-1 (2007)

# Magnetic field profile in different slices

Surface: |B| (mT)    Streamlines: (B1,B2)



# Assessing the need for several slices

- Magnetic field is almost azimuthal in the inter-phase region:
  - For several time steps and several slice positions

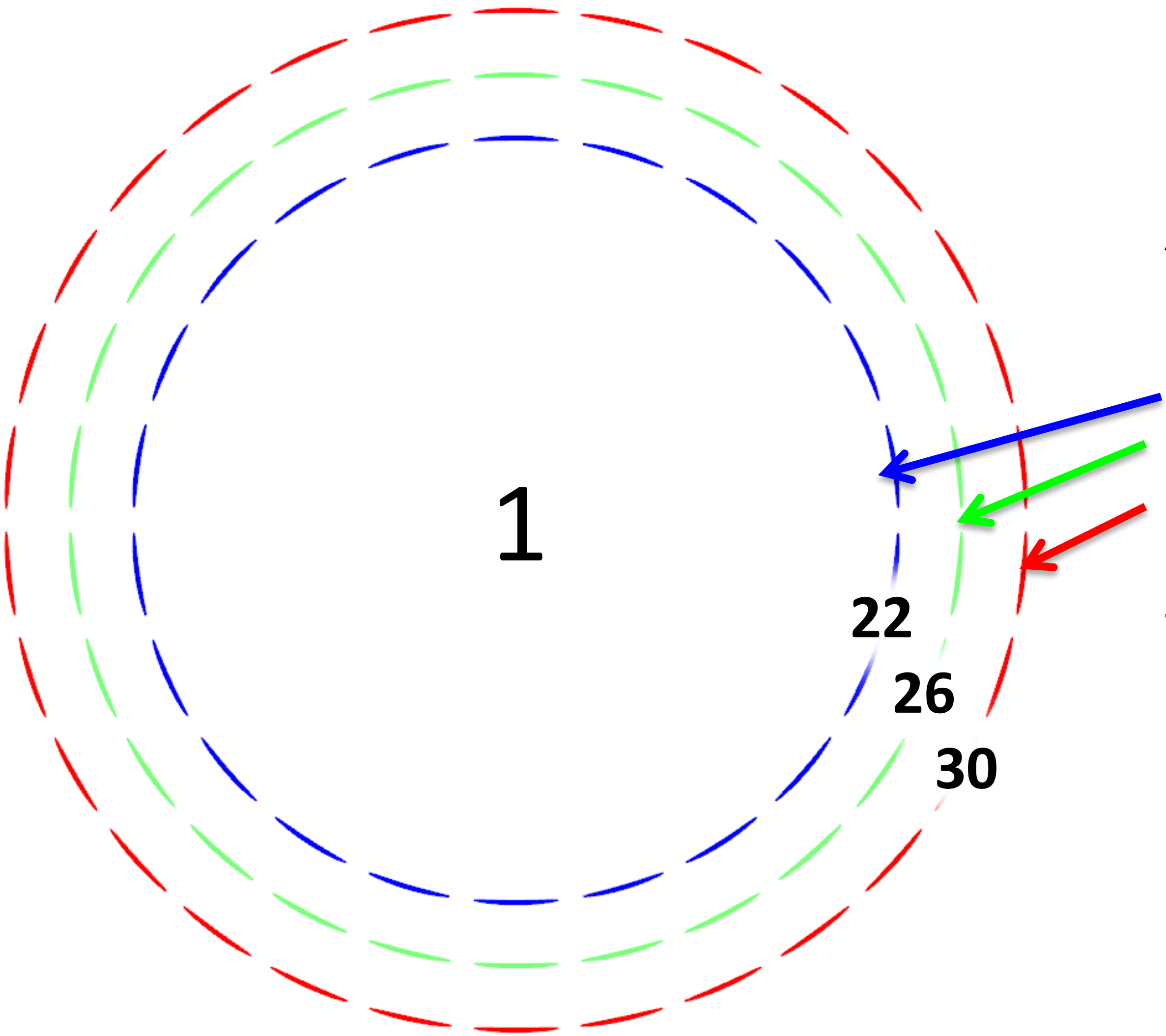
# Assessing the need for several slices

- Magnetic field is almost azimuthal in the inter-phase region:
  - For several time steps and several slice positions
- Computed AC losses using several slices (3-5) provided estimates with less than 0.5% variation.

# Assessing the need for several slices

- Magnetic field is almost azimuthal in the inter-phase region:
  - For several time steps and several slice positions
- Computed AC losses using several slices (3-5) provided estimates with less than 0.5% variation.
- One slice can provide accurate estimates.
  - Fast time to solution.

# Original design: 1



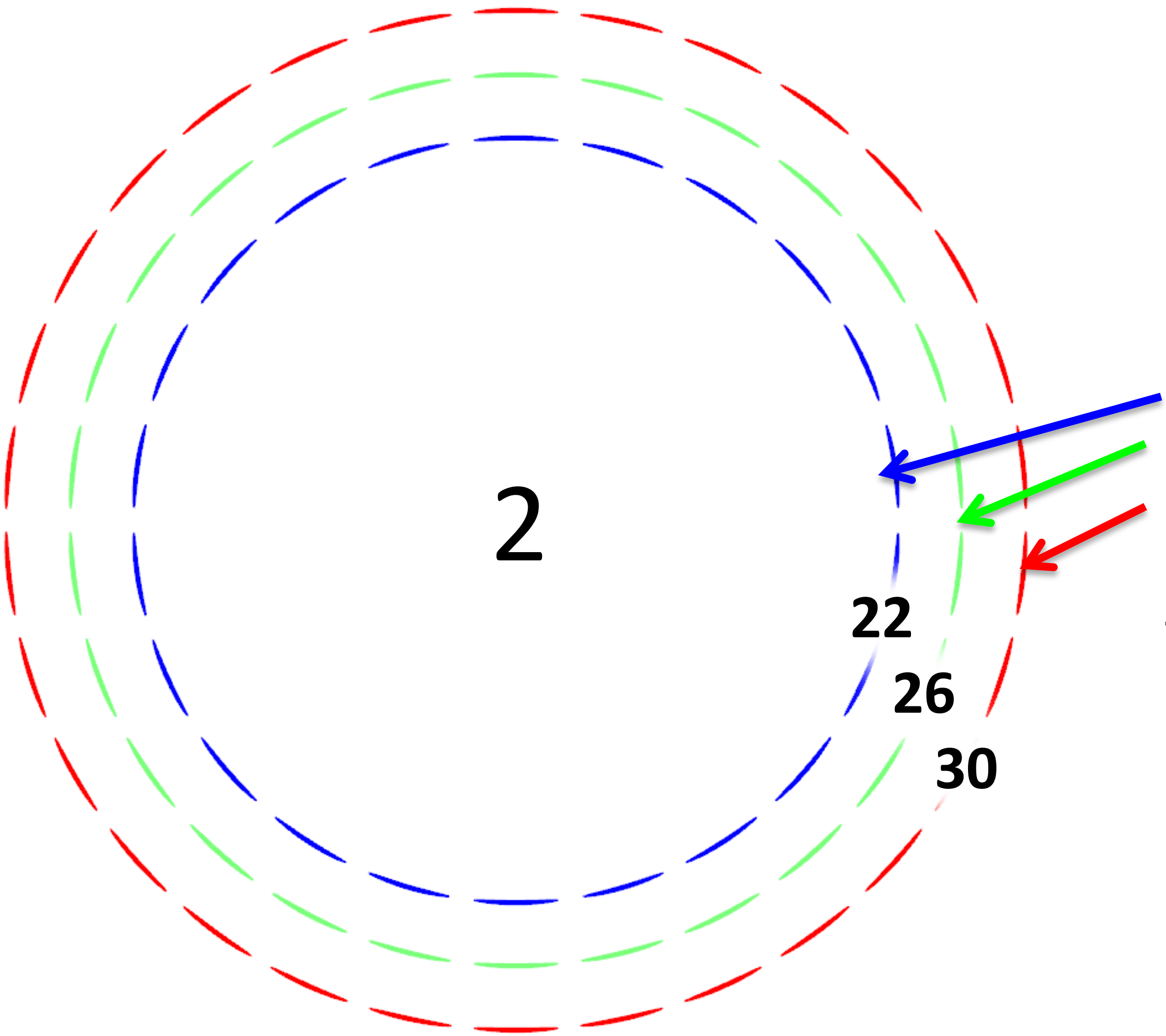

If the Ic of all tapes is assumed to be equal  to 170 A, then the corresponding Ic per phase is:

22 X 170 A = 3740 A
26 X 170 A = 4420 A
30 X 170 A = 5100 A

Total Ic        13260 A

Cable’s Ic is limited by the capacity of phase “a”.

# Optional design: 2



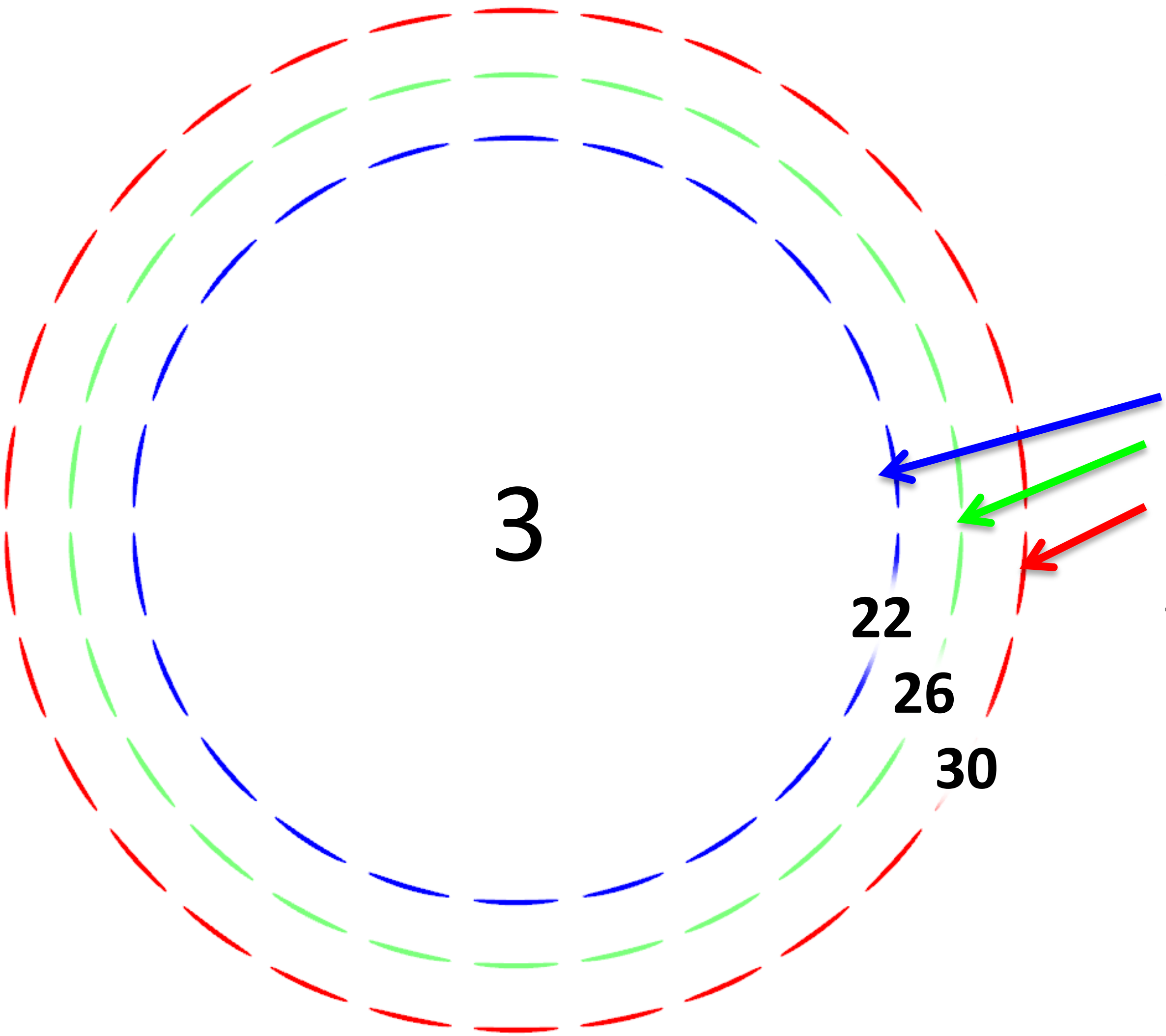

If the Ic of each phase is assumed to be equal to that of phase "a" of the original design, then the Ic per phase is:

22 X 170 A = 3740 A
26 X 143.85 A = 3740 A
30 X 124.67 A = 3740 A

Total Ic 11220 A

15% less Ic than original design (cheaper design)

# Optional design: 3

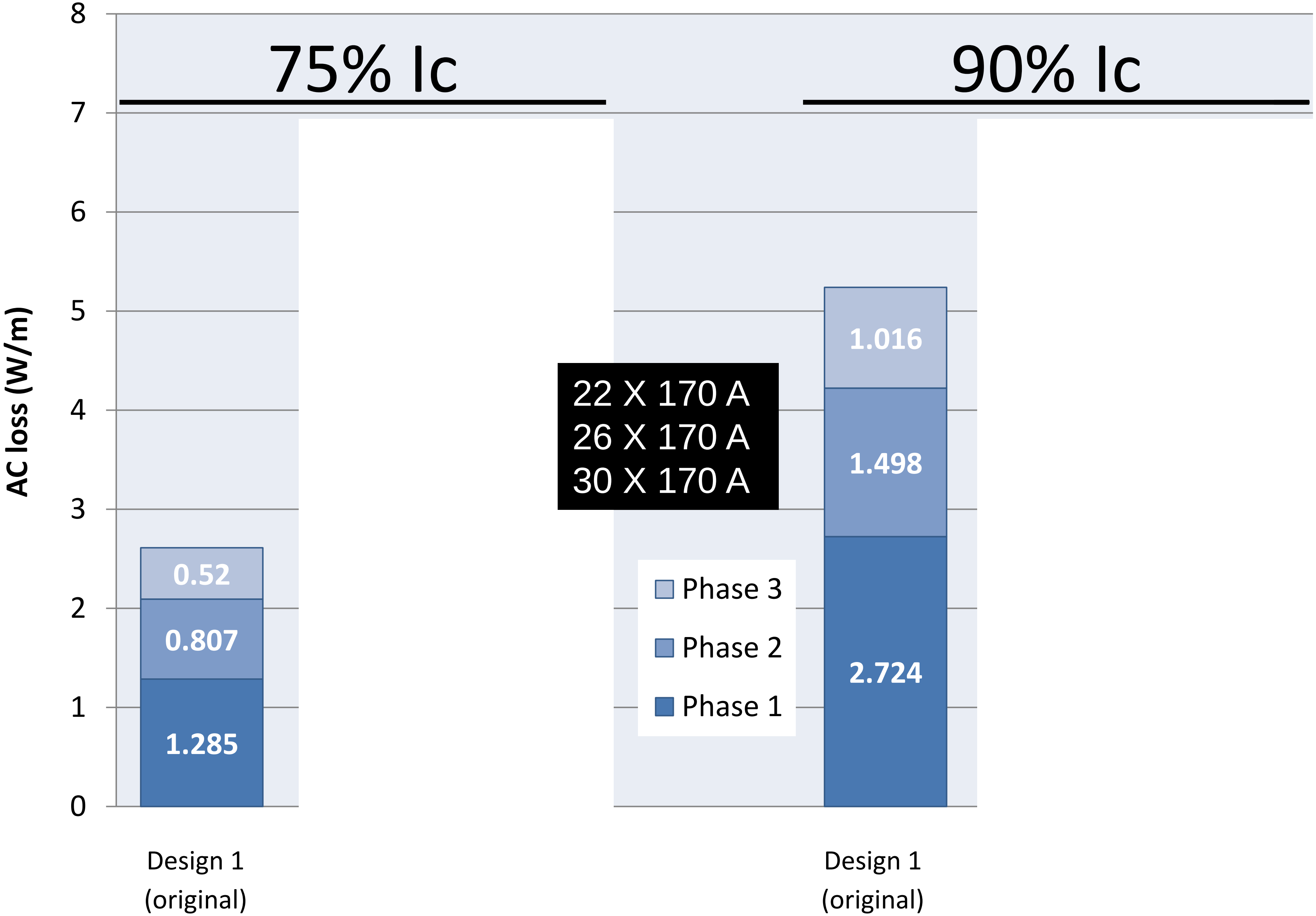



If the Ic of each phase is assumed to be equal to that of phase "b" of the original design, then the Ic per phase is:

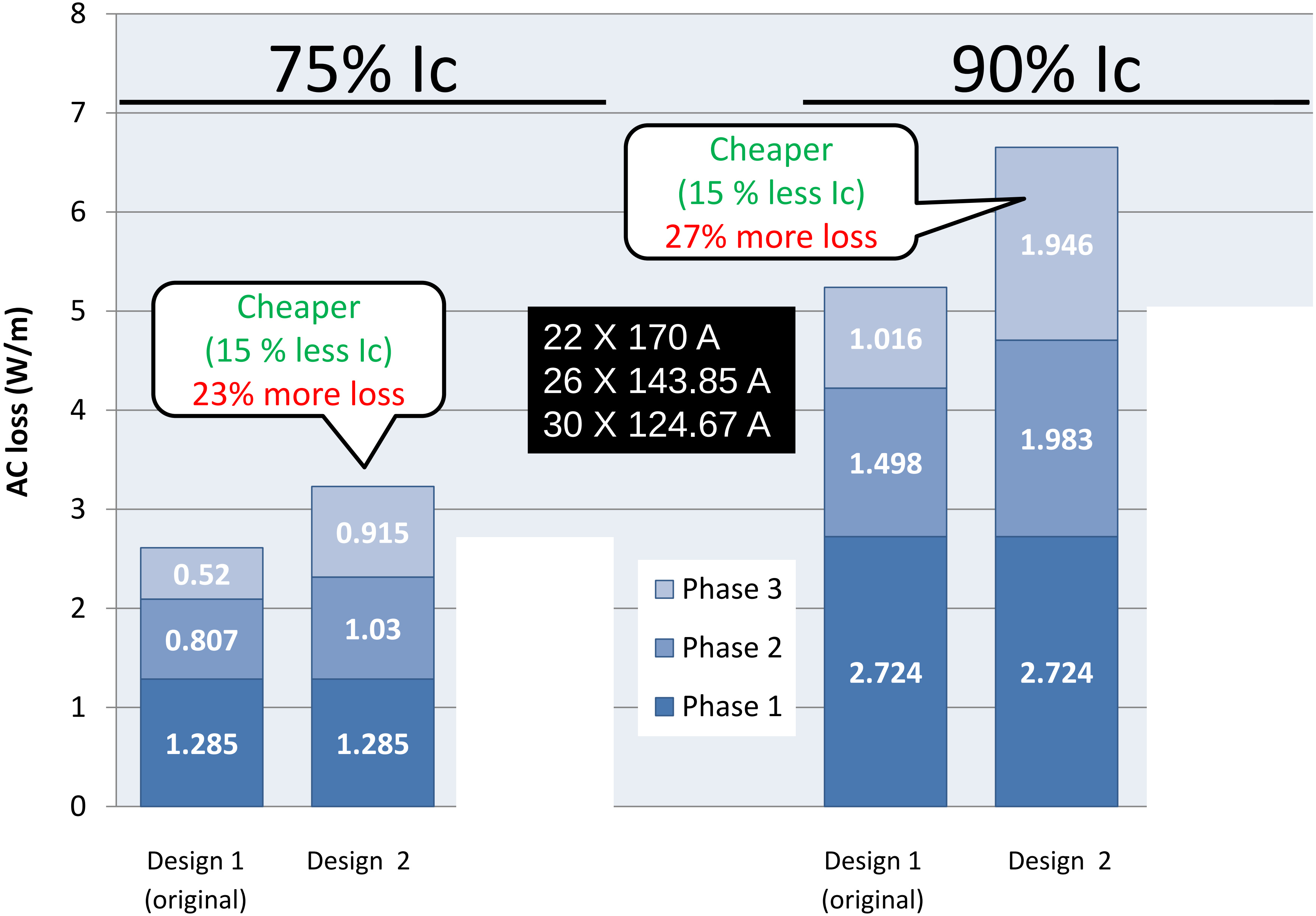
| | |
|---|---|
| 22 X 201 A = | 4420 A |
| 26 X 170 A = | 4420 A |
| 30 X 147.3 A = | 4420 A |
| Total Ic | 13260 A |

Same Ic as original design (similar price design)

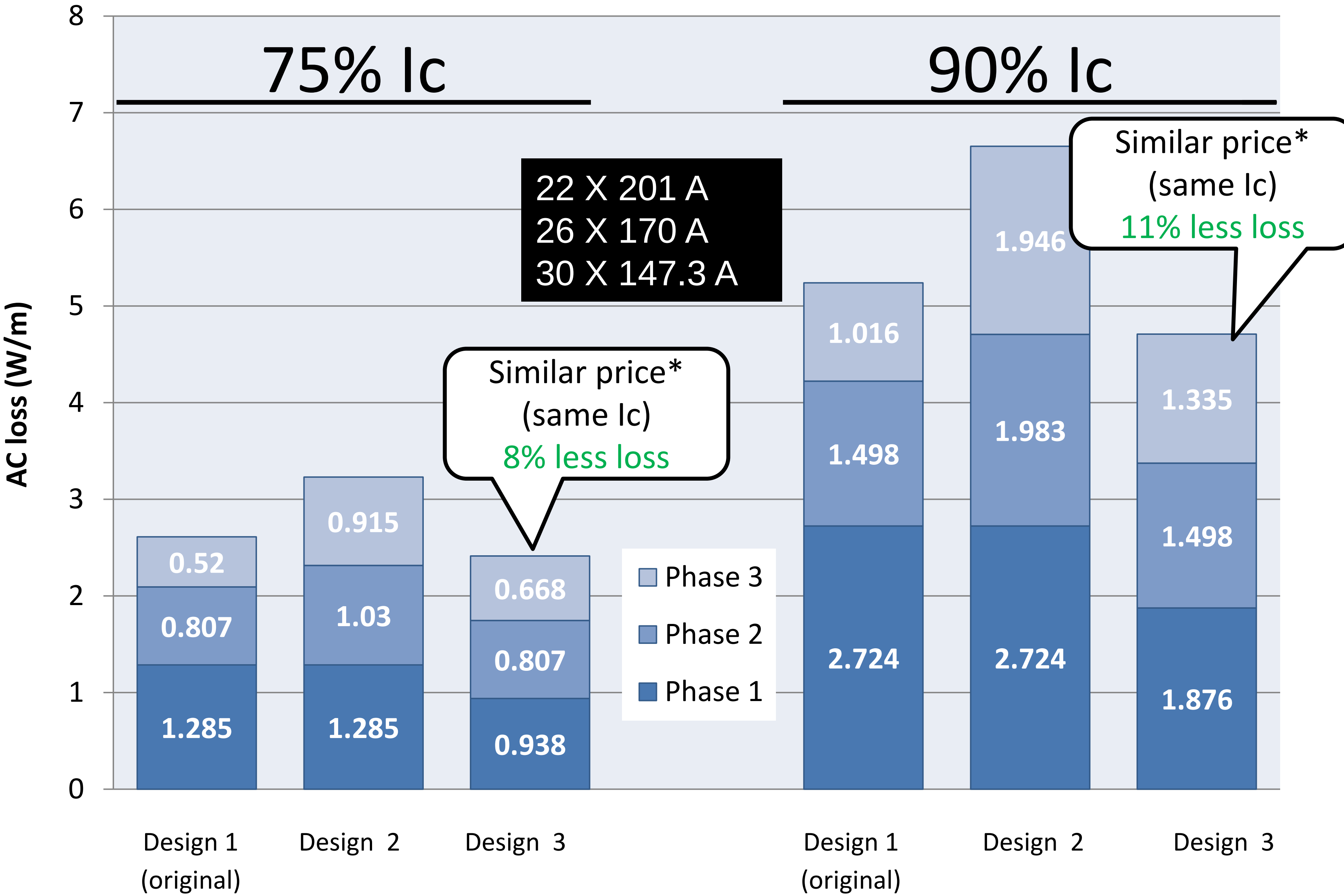
# AC loss in original design



# AC loss comparison for other designs



# AC loss comparison for other designs



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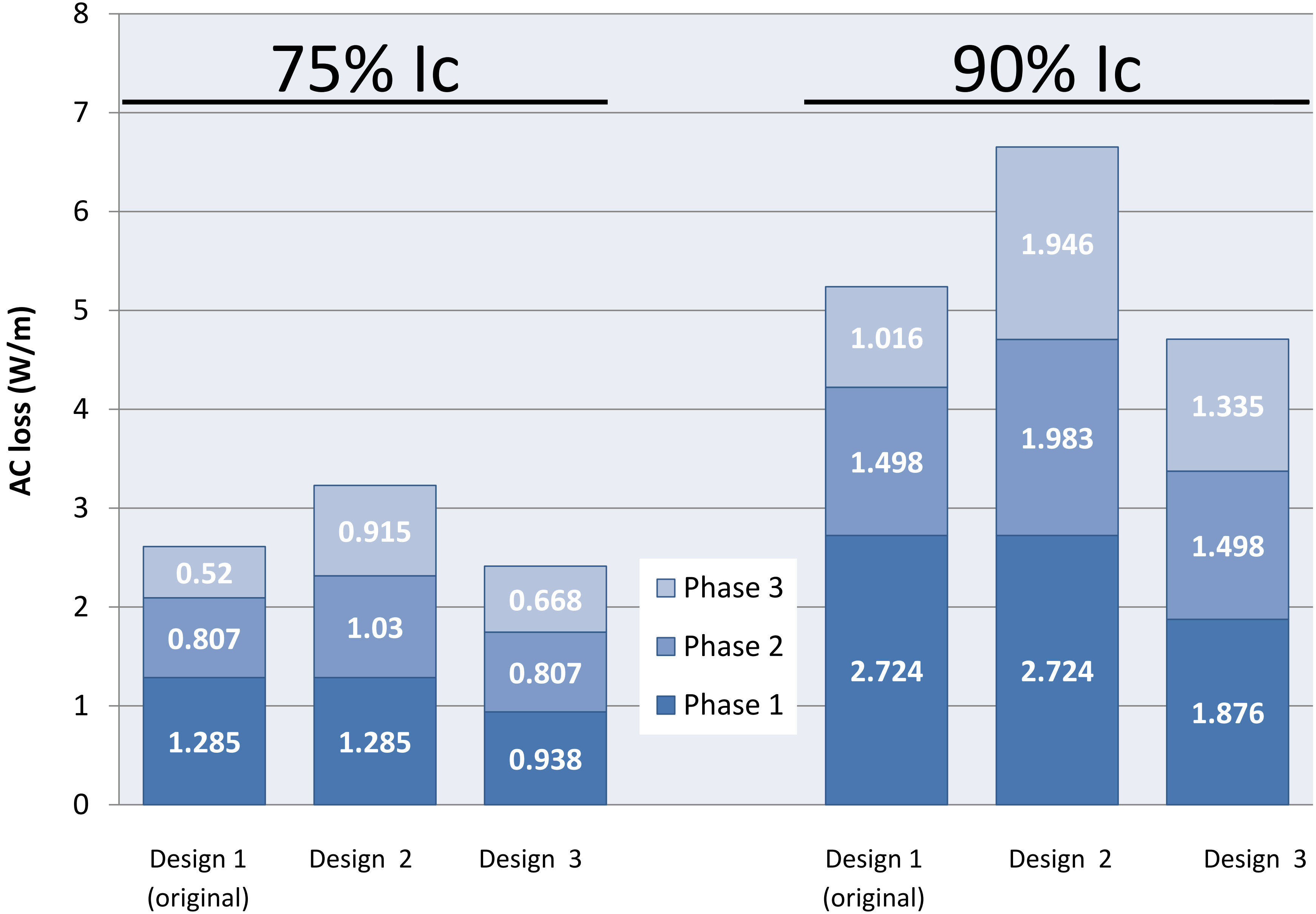
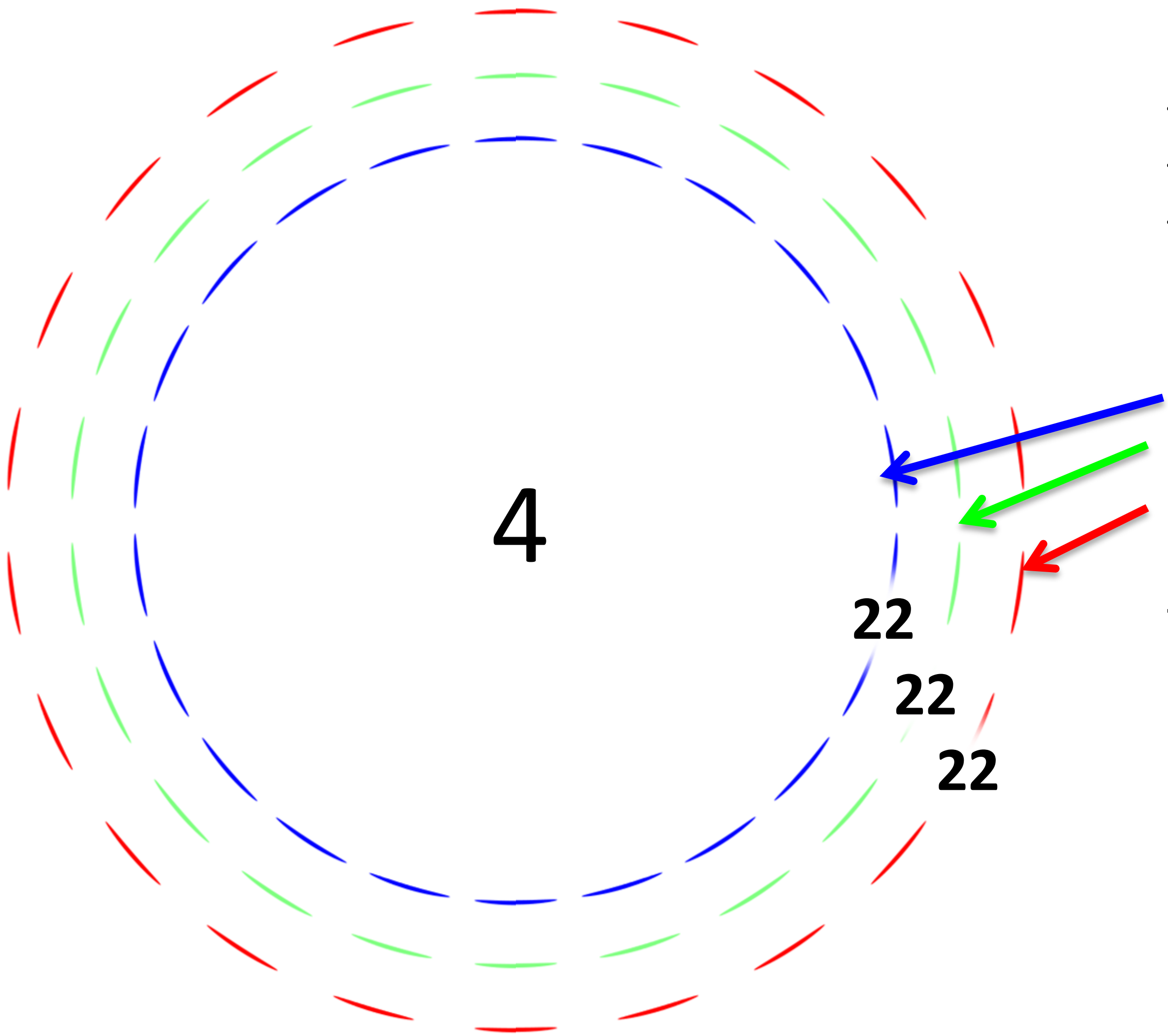


# Optional design:4



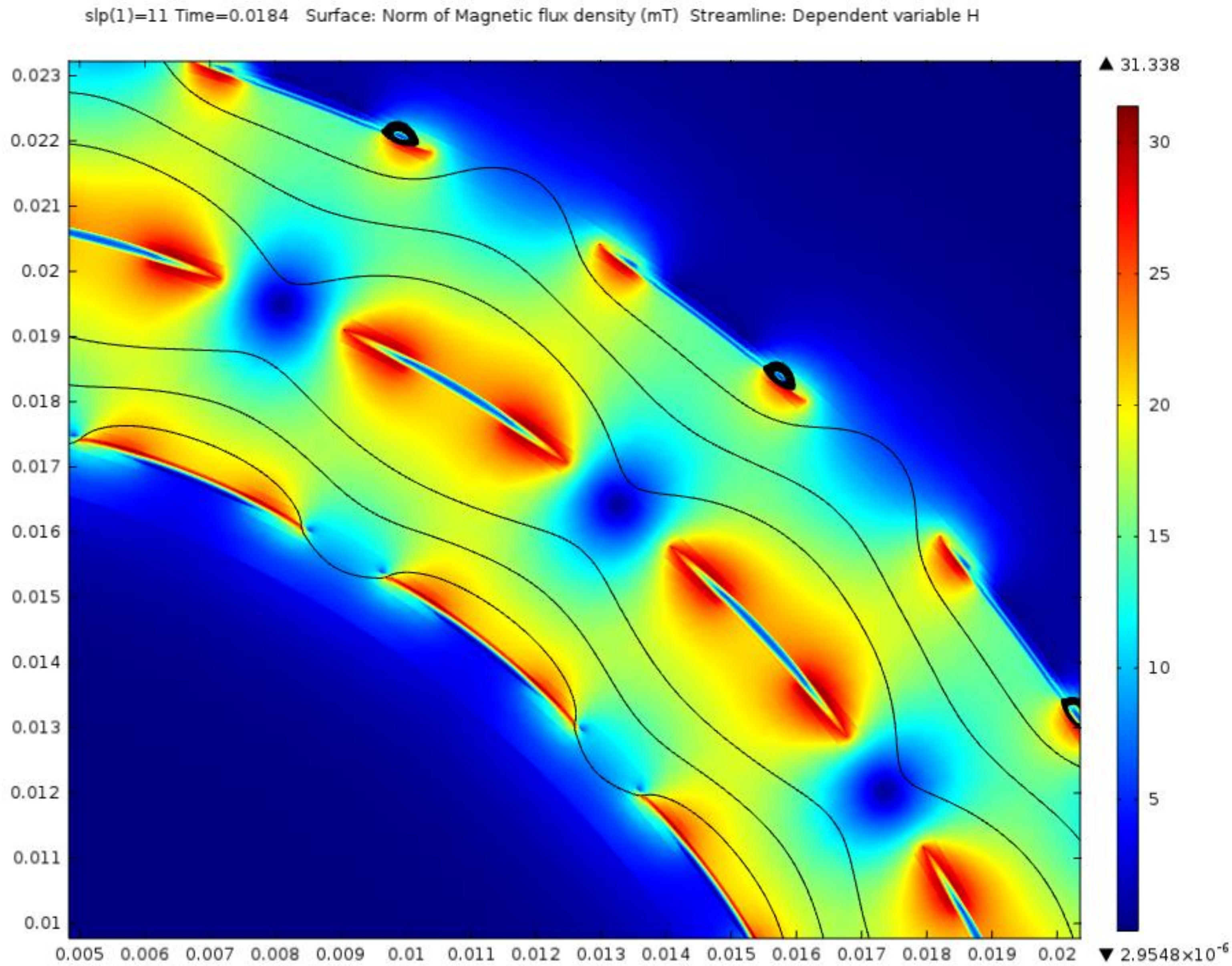

If the Ic of all tapes is assumed to be equal to 170 A and 22 tapes are used in each phase, then the corresponding Ic per phase is:

22 X 170 A = 3740 A
22 X 170 A = 3740 A
22 X 170 A = 3740 A

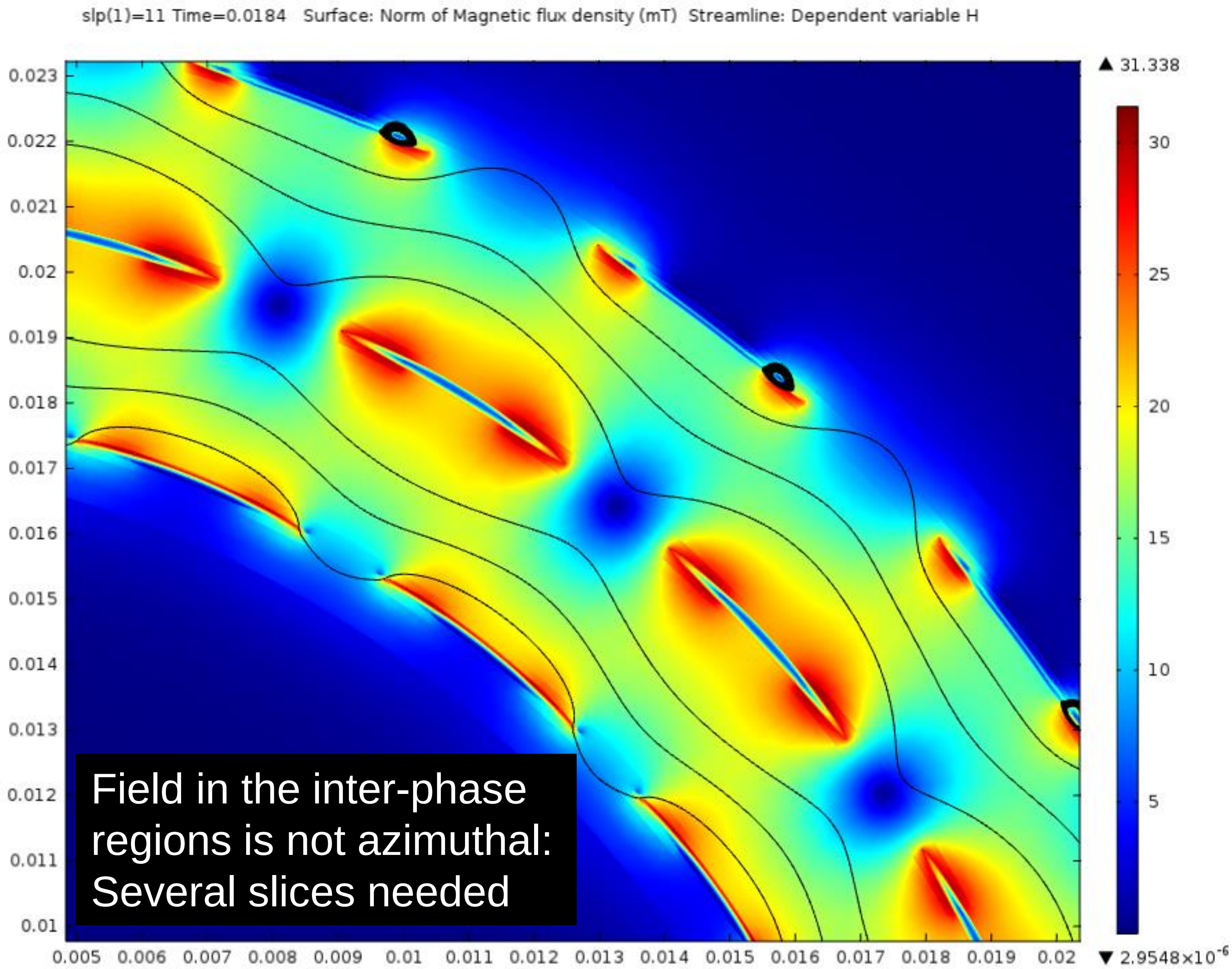
Total Ic 11220 A

15% less Ic than original design (cheaper design)

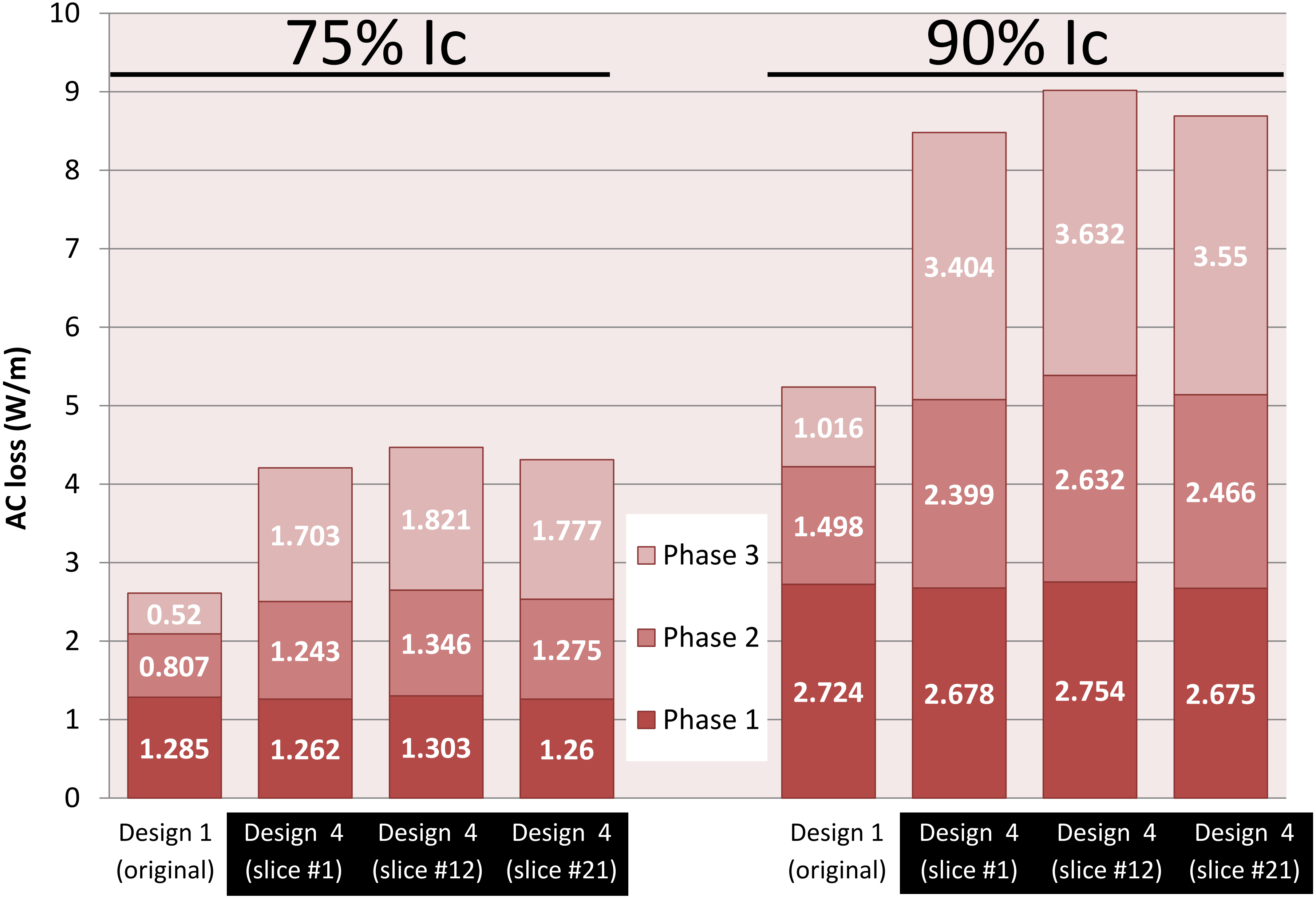
# Original design:4



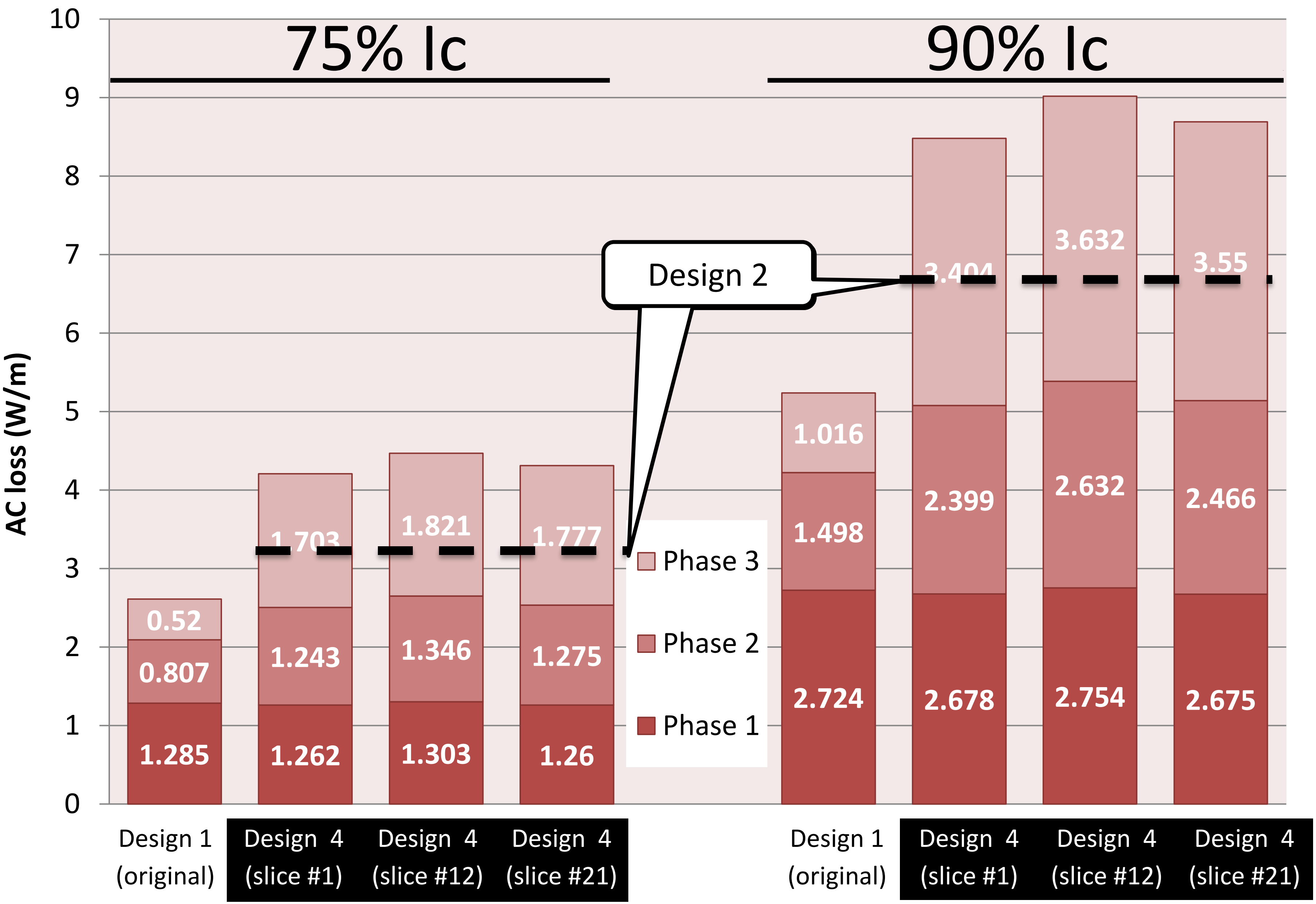
# Original design:4



# Cable with 22 tapes per phase

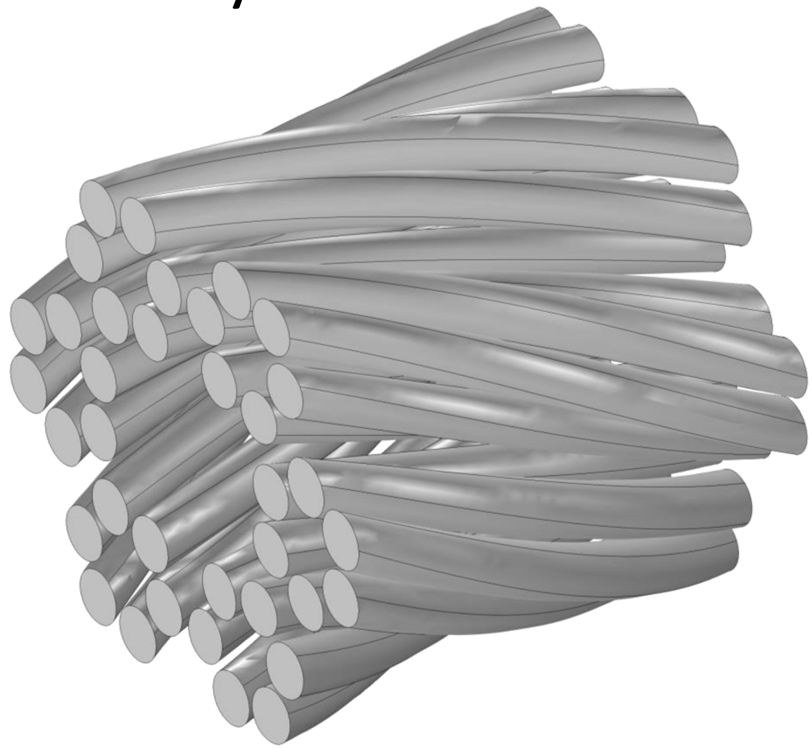


# Cable with 22 tapes per phase

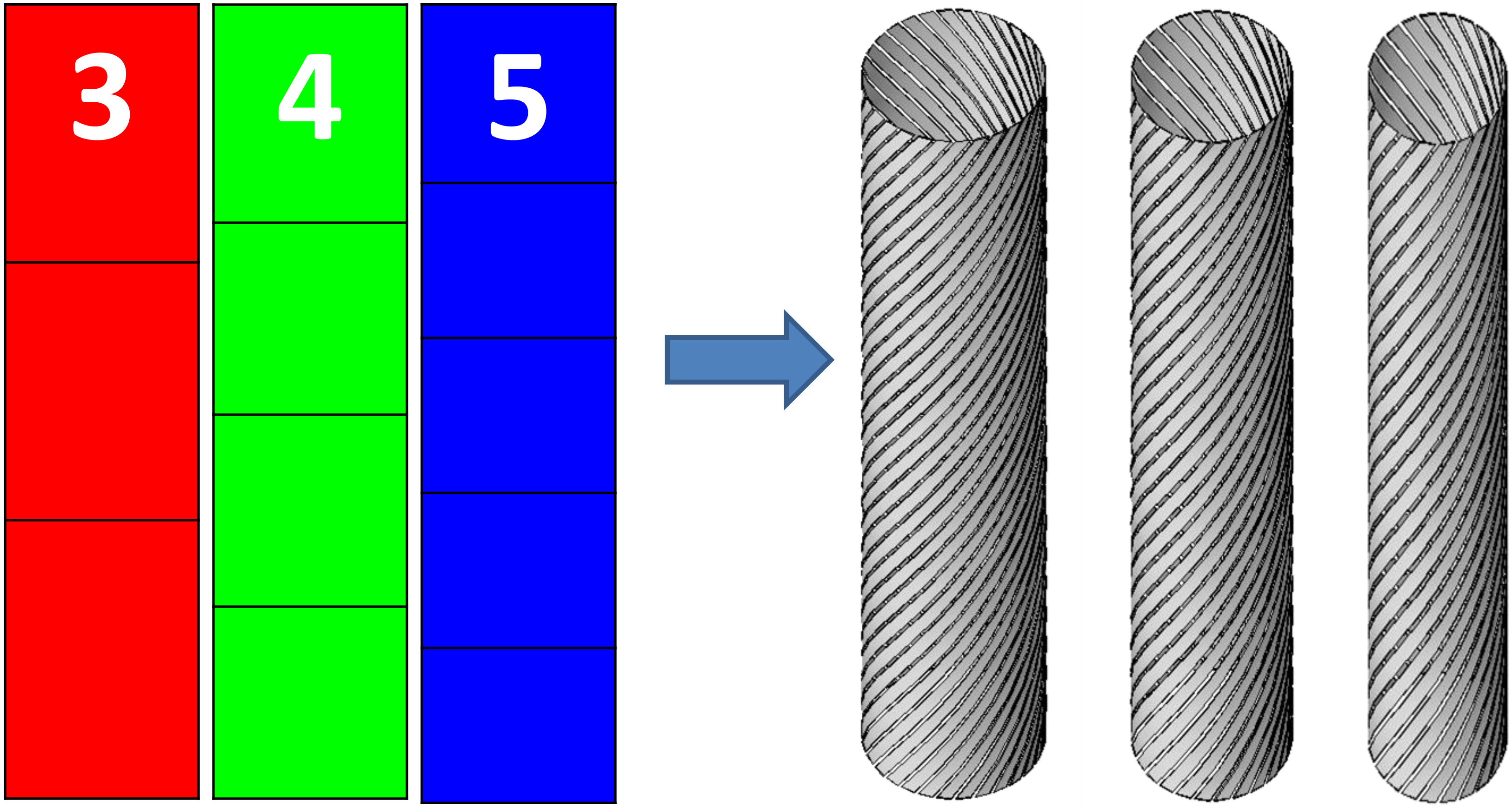


# How about CICC?

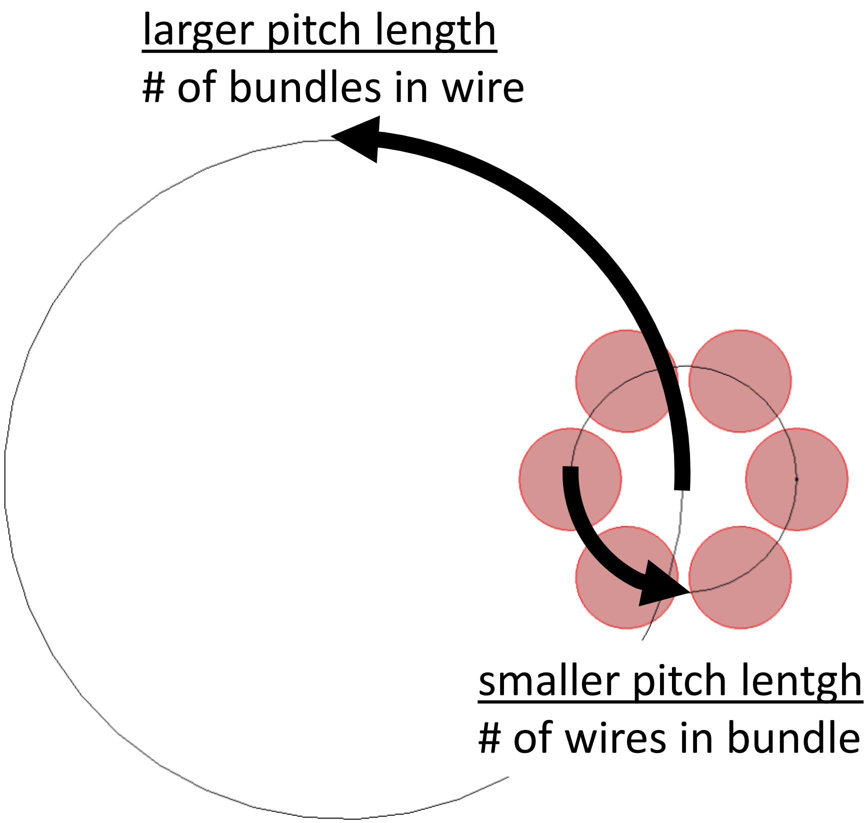
- Similar strategy can be followed:
  - Pitch length now relates to wires and filaments rather than to layers.

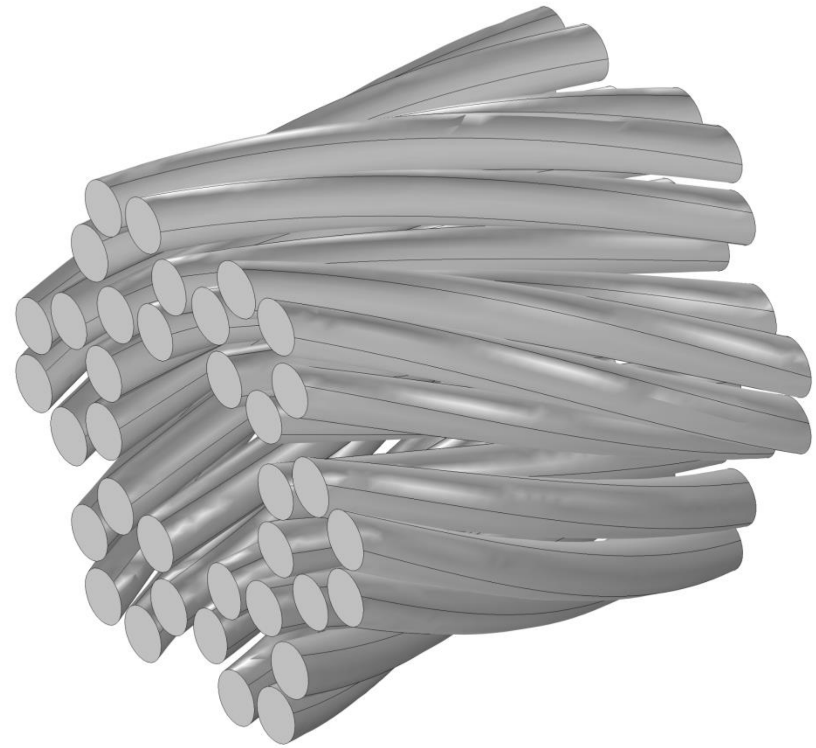


# In helically wound cables:

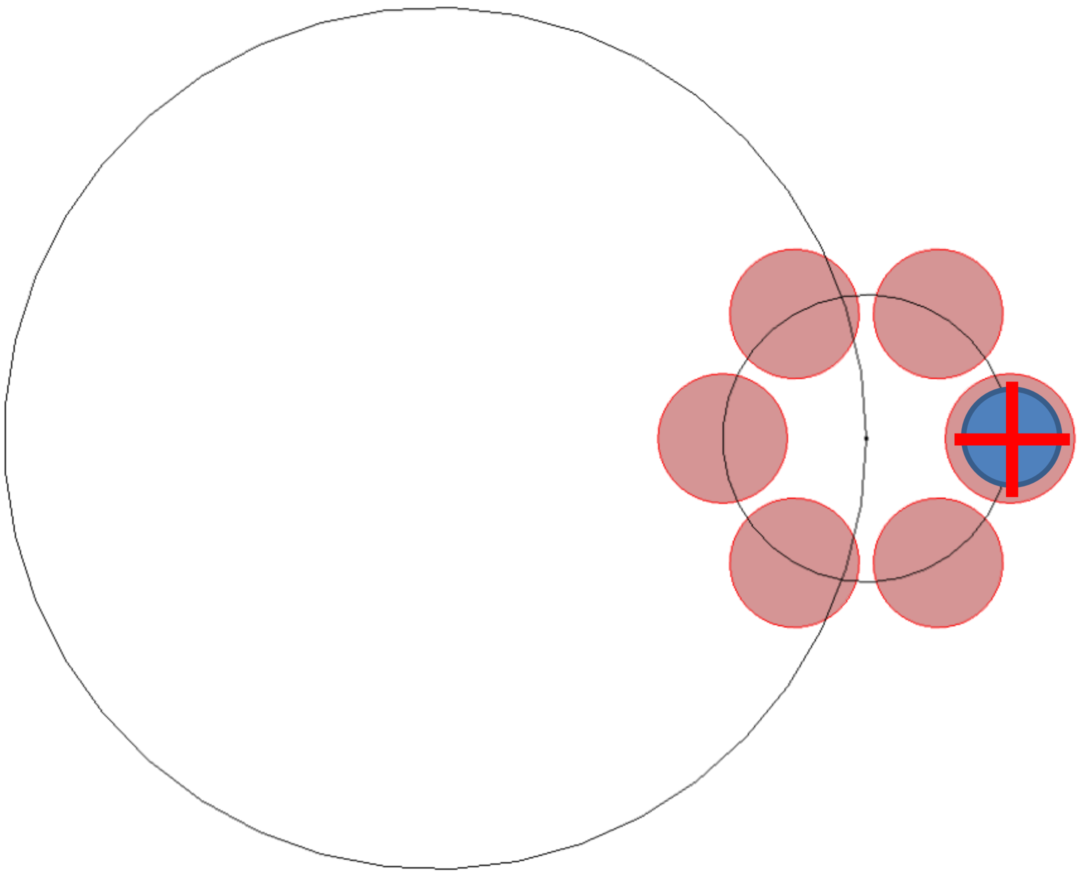


# In CICC:

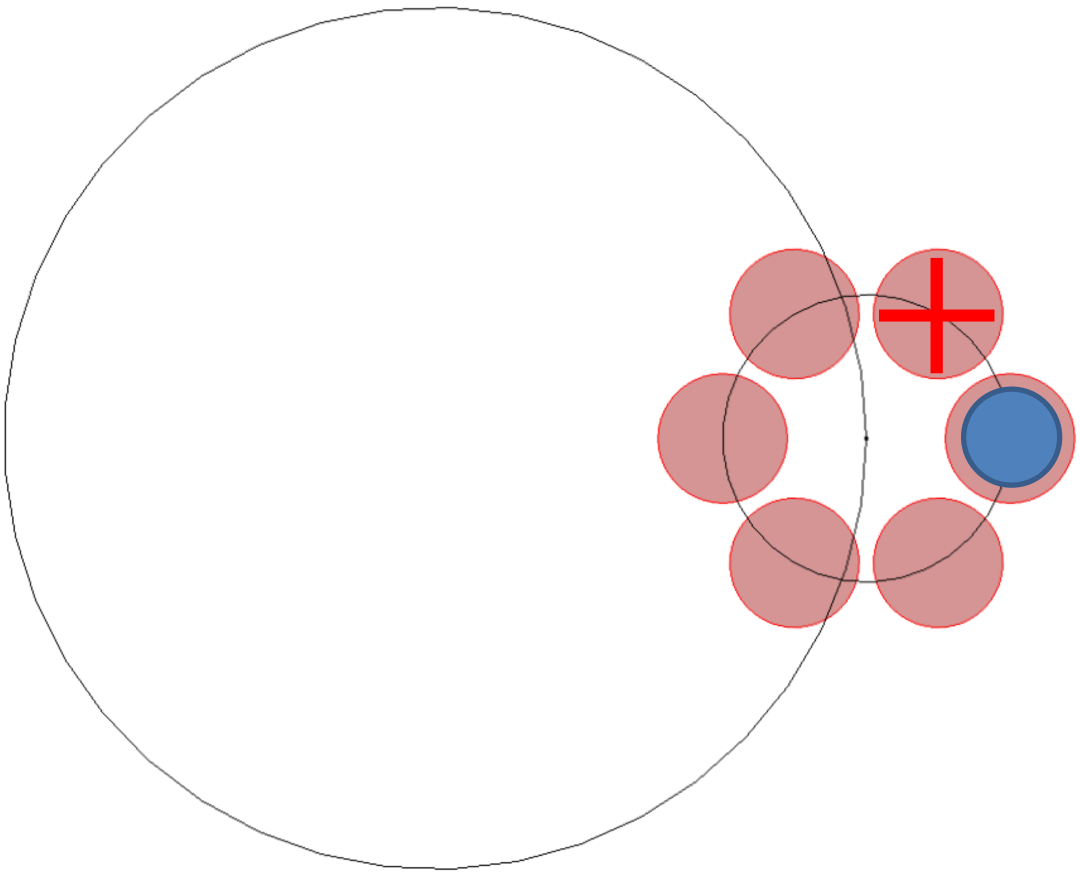

larger pitch length
# of bundles in wire
smaller pitch lentgh
# of wires in bundle



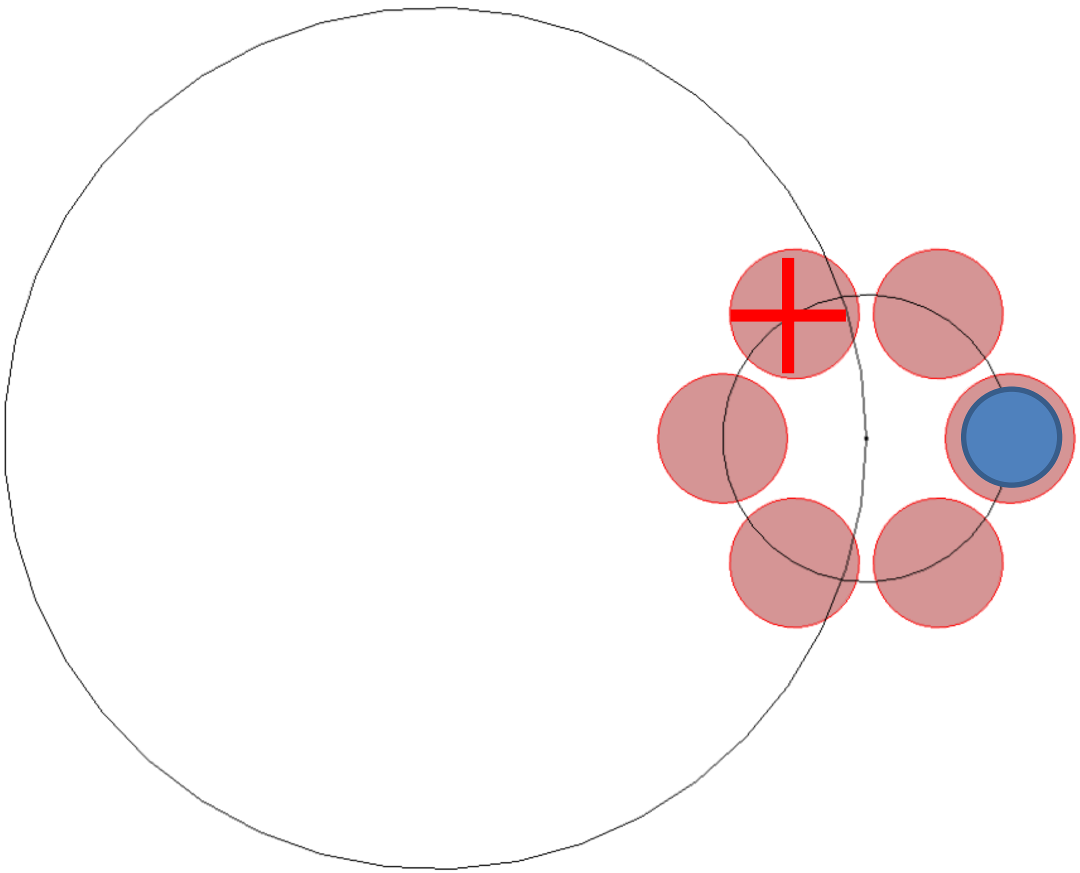
# In CICC:



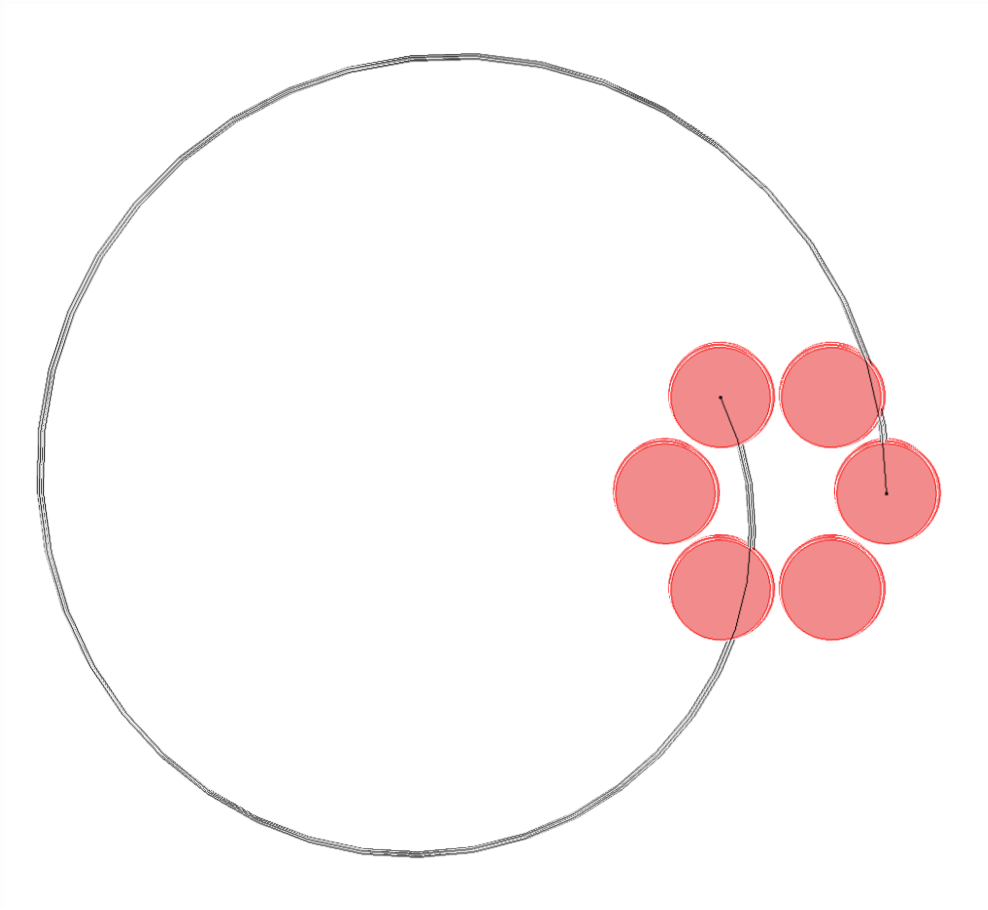
# In CICC:

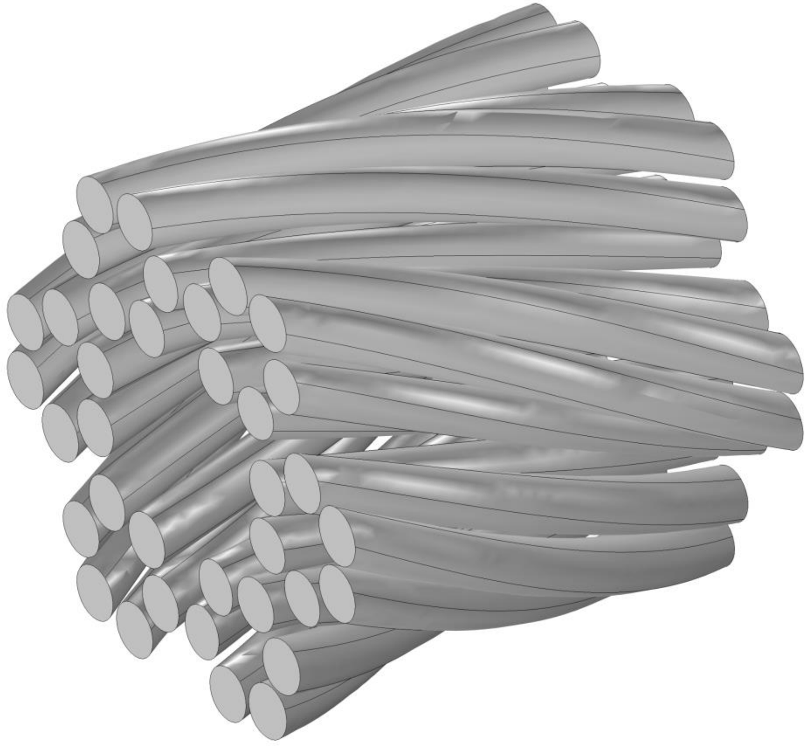


# In CICC:



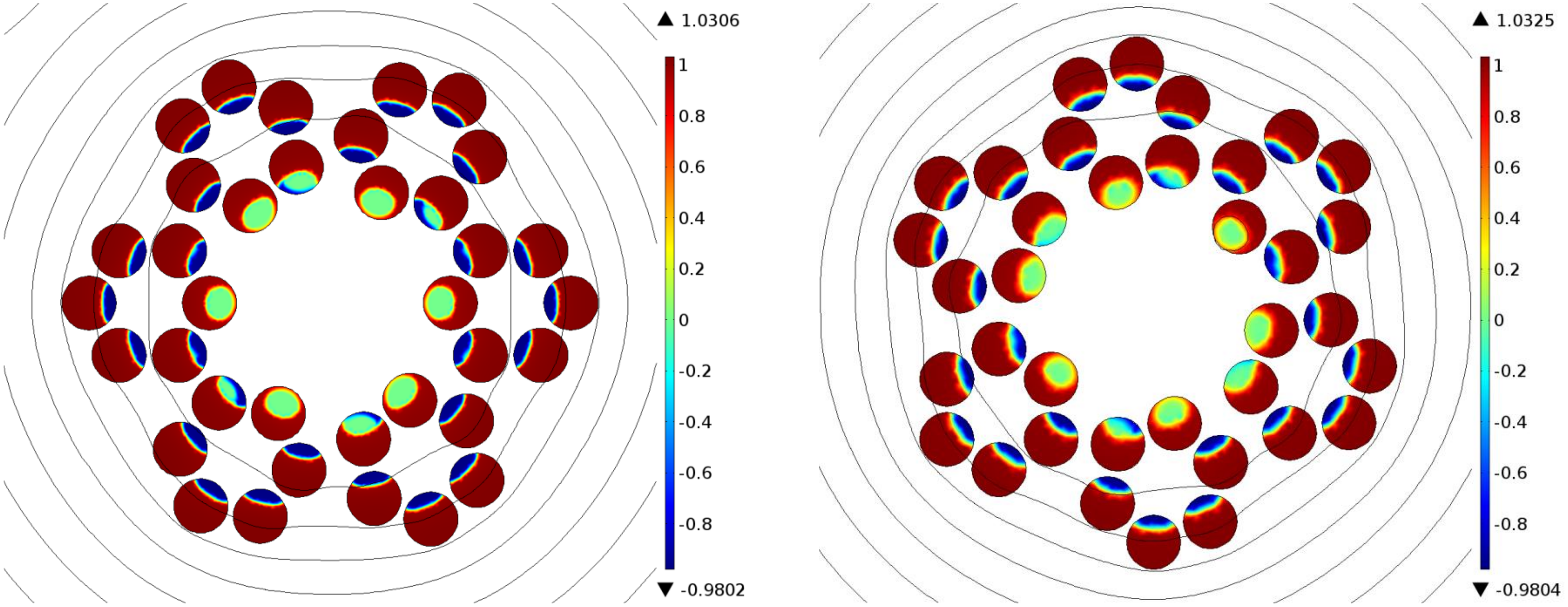
# Test design





# Test design (2.5-D)

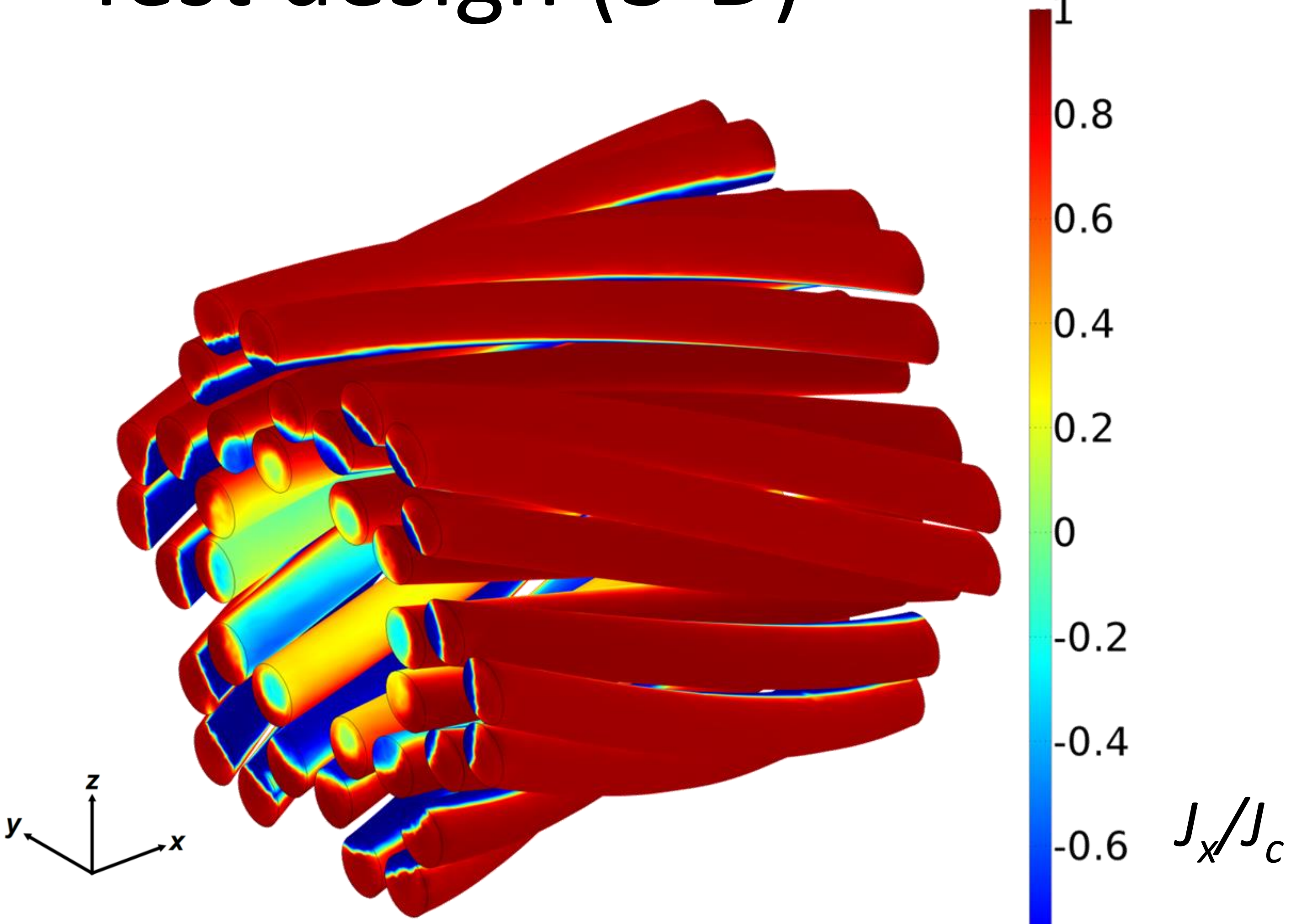
Surface: |J/Jc| Streamlines: (B1,B2)




Use of several slices provided similar AC loss calculation (~1% difference)

Using H-formulation, Brambilla et al. SUST 20-1 (2007)

# Test design (3-D)




Using CSM: Campbell, A. SUST 22-3 (2009)
(DOI: 10.1088/0953-2048/22/3/034005)

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- A 3-D model based in the CSM was implemented