Lightweight Superconducting Magnet Technology for Medical Applications

Shlomo Caspi*

NAPAC16

October, 2016

Many thanks to L. Brouwer, D. Robin, D. Arbelaez, A. Sessler, W. Wan, S. Prestemon, R. Hafalia and A.Hodgkinson

Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, U. S. A.

Outline

- **Light and Heavy magnets**
- Basic Concept:
  - **Straight CCT magnet**
- Extended Concept:
  - **Curved CCT magnet**

Courtesy of Young-Kee Kim

Motivation and Challenges for a Final Bending Superconducting Gantry Magnet

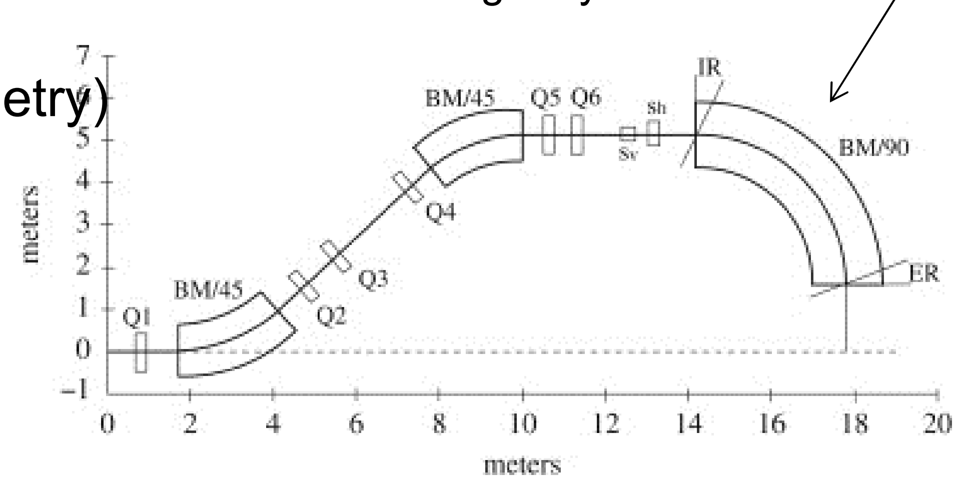
<u>Motivation</u>

The final 90^{o} dipole drives the size, weight, and cost of the gantry

<u>Challenge</u>

- Bend beam by 90^{o} (curved geometry)
    - **Windings**
    - **Field quality**
- Large aperture
    - **Structure**
- Rapid field change (up to 1 T/s)
    - **Protection**
    - **Cryogenic**
- Combined function fields

final bend in Pavlovic gantry*



*M. Pavlovic, et al, Nucl. Inst. and Meth A 545 (2005) 412-426

Selected Rotating gantries

Type	Institute	Super-conducting	Field (T)	Rigidity (T-m)	Bend weight (t)	Bend Radius (m)
Carbon	HIT[1]/DE	No	**1.81**	6.64	**90**	3.67
	CIRT[2]/JP	Yes	**2.37**	6.6	**~30**	2.8
Proton	PSI-2[3]/CH	**No**	**1.53**	3.6	**46**	1.5
	LBNL-PSI-Varian[4] US-CH-DE	**Yes**	**2.3**	~3.2	**~1.5**	0.9
LHC	CERN	Yes/1.9k	**8.3/10**	-	**31**	linear

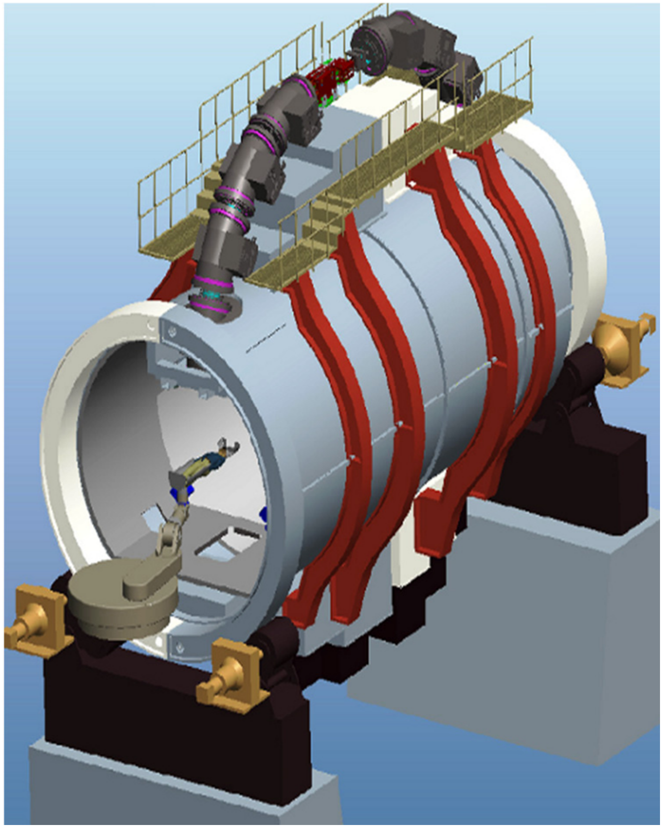
The radius and weight of a final superconducting magnet bend for protons ~1m , ~ 2ton

1 Heidelberg Ion Beam Therapy Center, https://idw-online.de/de/news504069
2 Y. Iwata *et al*., "Beam commissioning of a superconducting rotating-gantry for carbon-ion radiotherapy," Nucl. Instrum. Methods Phys. Res. A, vol. 834, pp. 71–80, 2016.
3 Gabard, M. Negrazus, V. Vrankovic and D. George, "Magnetic Measurements and Commissioning of the Fast Ramped 90 Bending Magnet in the PROSCAN Gantry 2 Project at PSI," in *IEEE Transactions on Applied Superconductivity*, vol. 20, no. 3, pp. 794-797, June 2010
4 W. Wan *et al*.,"Alternating-gradient canted cosine theta superconducting magnets for future compact proton gantries," Physical Review Special Topics - Accelerators and Beams, vol. 18, no. 10, p. 103501, 2015.

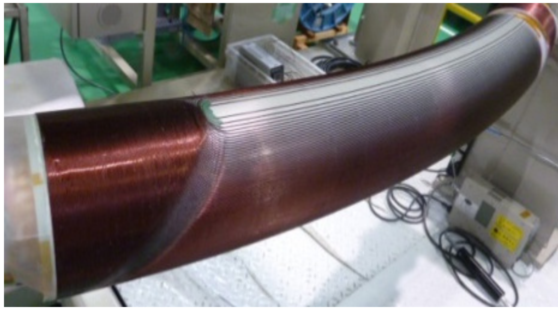
Rotating gantries

Heidelberg Ion Beam Therapy Center

CIRT superconducting carbon-ion gantry, JAPAN



Curved magnet



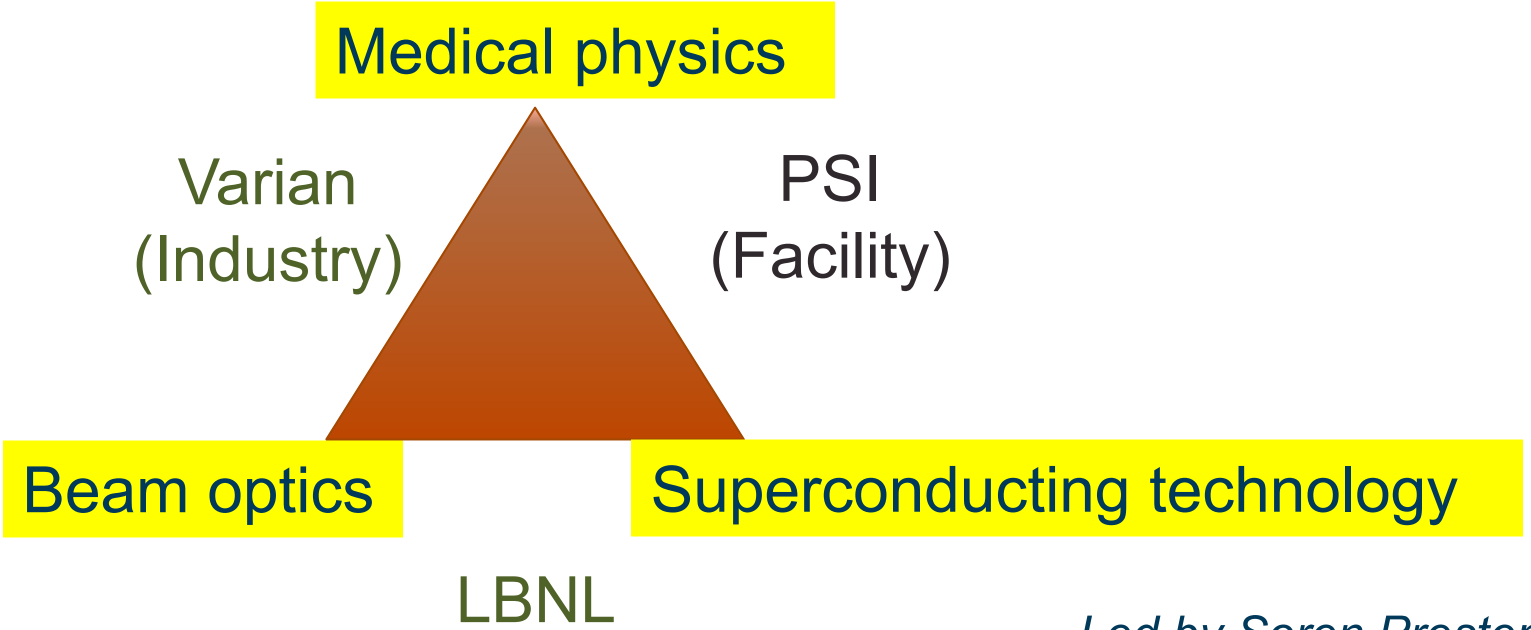
PSI 2 PROSCAN Proton

Collaboration LBNL-PSI-Varian

A DOE Proposal awarded in September FY15

<u>Major challenge and goal:</u>

An *achromatic superconducting magnet* that is light weight and allows rapid 3D scanning with *minimal field ramping.*

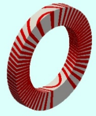


Led by Soren Prestemon

The Canted-Cosine-Theta (CCT) magnet

The CCT is a paradigm shift in the design of SC magnets

- Maintains **winding** position to handle **field quality**
- Combines coil and structure to intercept **Lorentz forces**
- Potential of reducing magnet **cost**

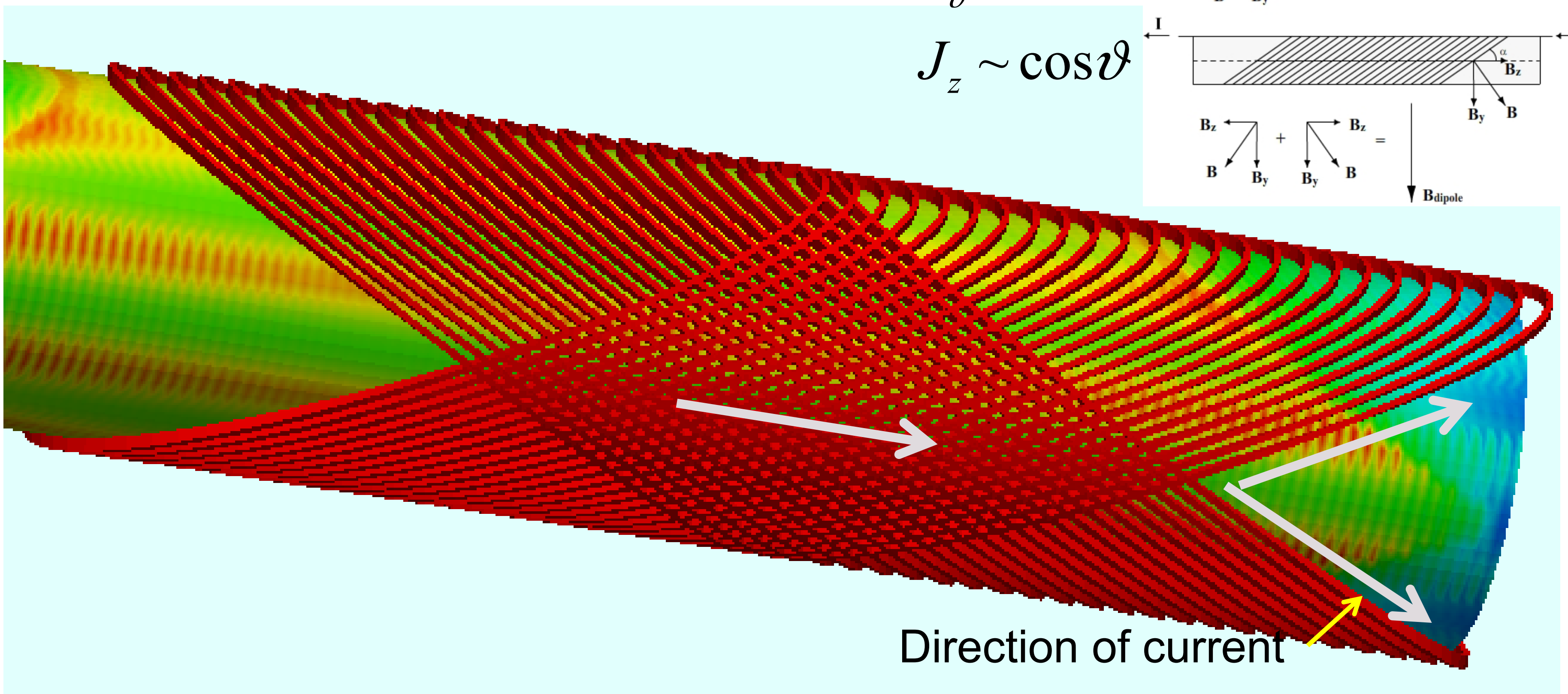


The Canted-Cosine-Theta (CCT) Magnet

Two superimposed coils, oppositely skewed, achieve a pure cosine-theta field and eliminate axial field.

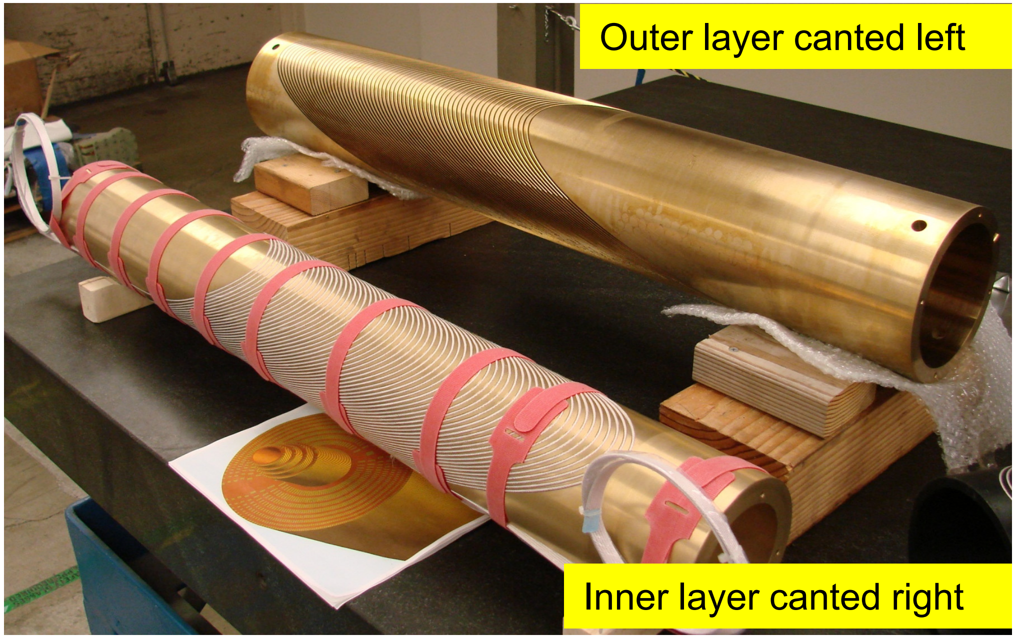
$$J_\vartheta \sim const$$

$$J_z \sim \cos\vartheta$$



D.I. Meyer and R. Flasck "A new configuration for a dipole magnet for use in high energy physics application", Nucl. Instr. and Methods 80, pp. 339-341, 1970.

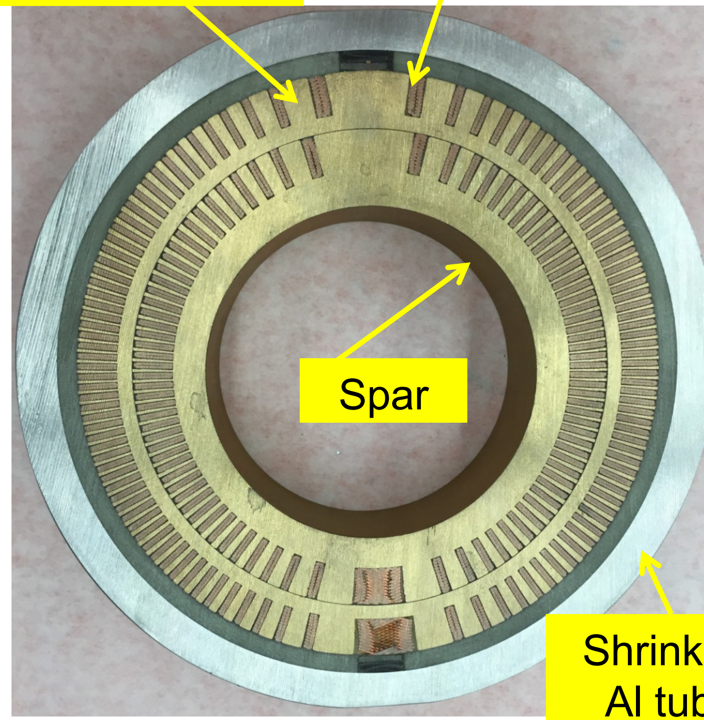
Combining conductor and structure



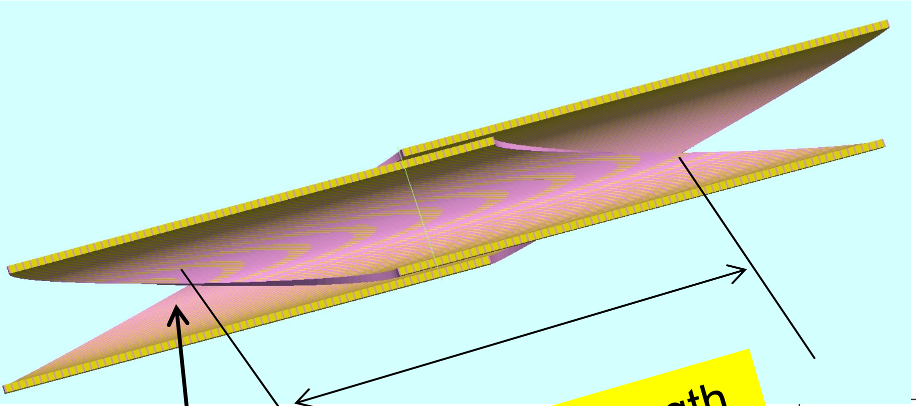
Past tests

Dipole	Cond.	Field (T)
CCT1	**NbTi**	**2.4**
CCT2	**NbTi**	**4.6**
CCT3	**Nb_3Sn**	**7.4**

Spar intercepts Lorentz forces

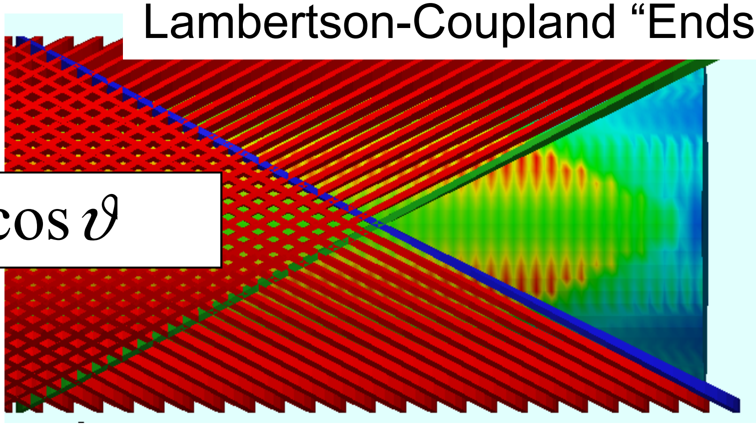


Magnetic length and “Ends” harmonics

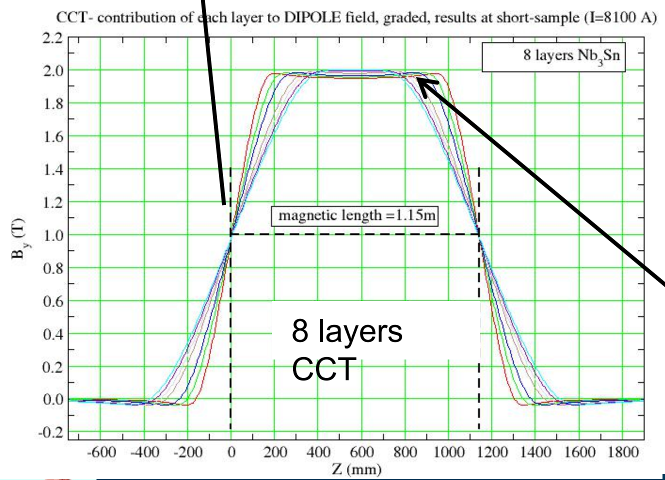


magnetic length

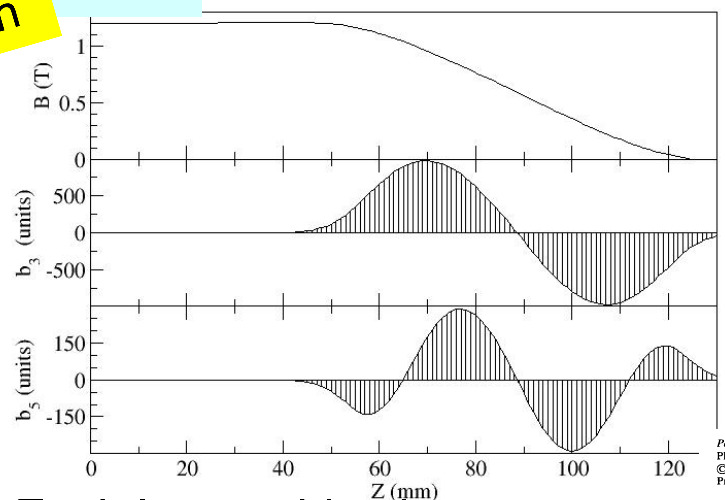
Lambertson-Coupland “Ends



$$J_z \sim \cos\vartheta$$



8 layers CCT



Dipole field

Sextupole integrates to zero

Decapole integrates to zero

Each layer adds the same dipole field

Particle Accelerators, 1987, Vol. 22, pp. 1–14
Photocopying permitted by license only

CONFIGURATION OF COIL ENDS FOR MULTIPOLE MAGNETS†

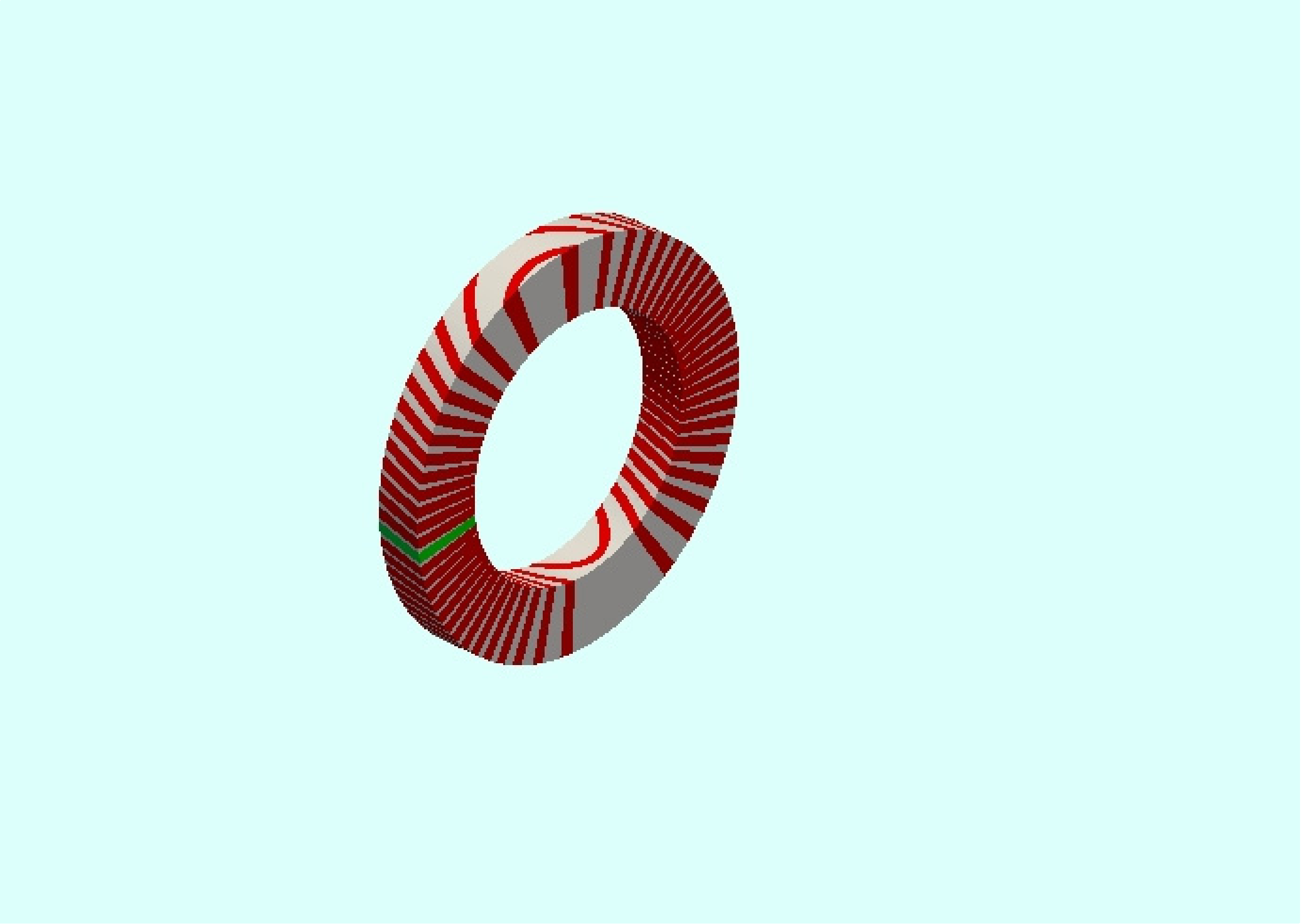
L. JACKSON LASLETT, S. CASPI, and M. HELM
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720

(Received October 15, 1986)

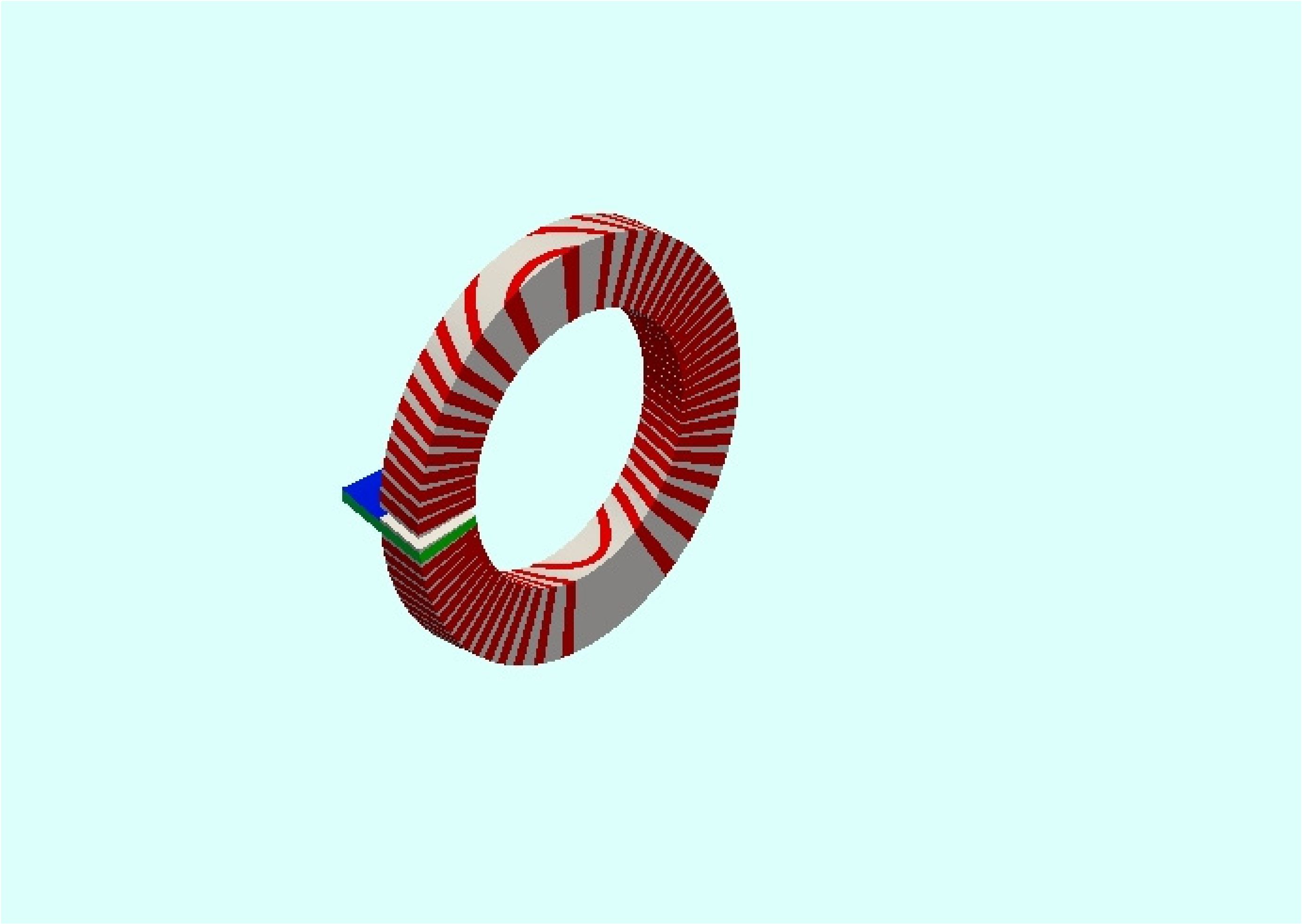
Symmetry - lamination

Symmetry - lamination

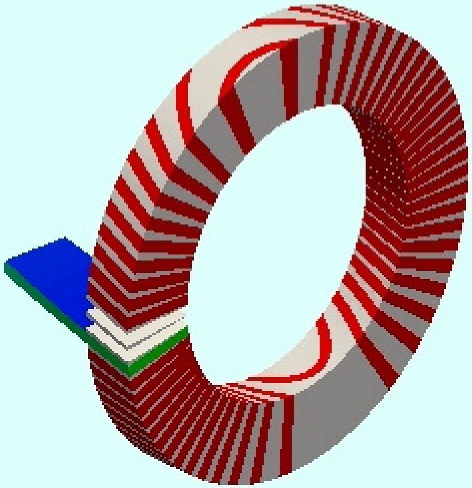
Symmetry - lamination



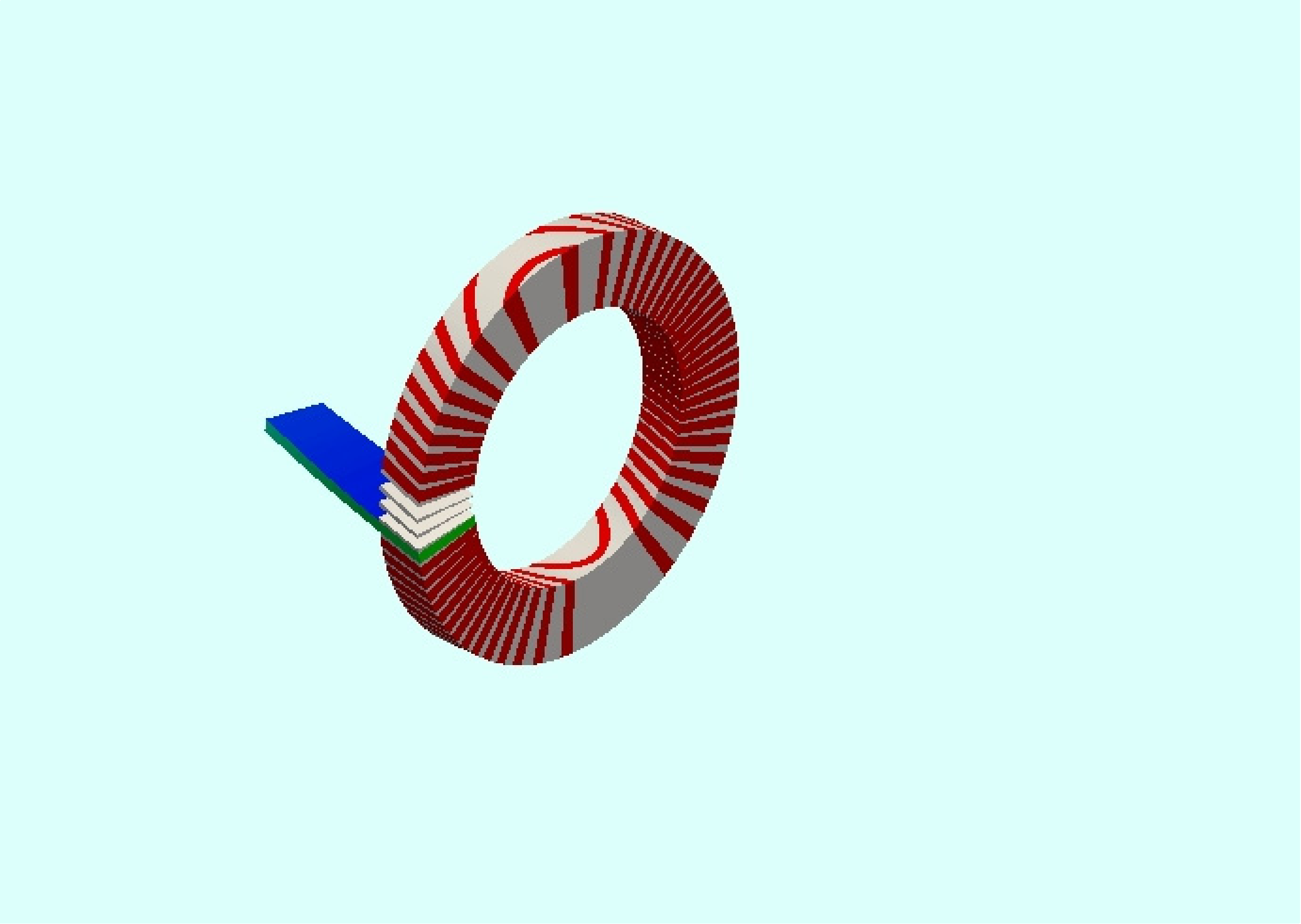
Symmetry - lamination



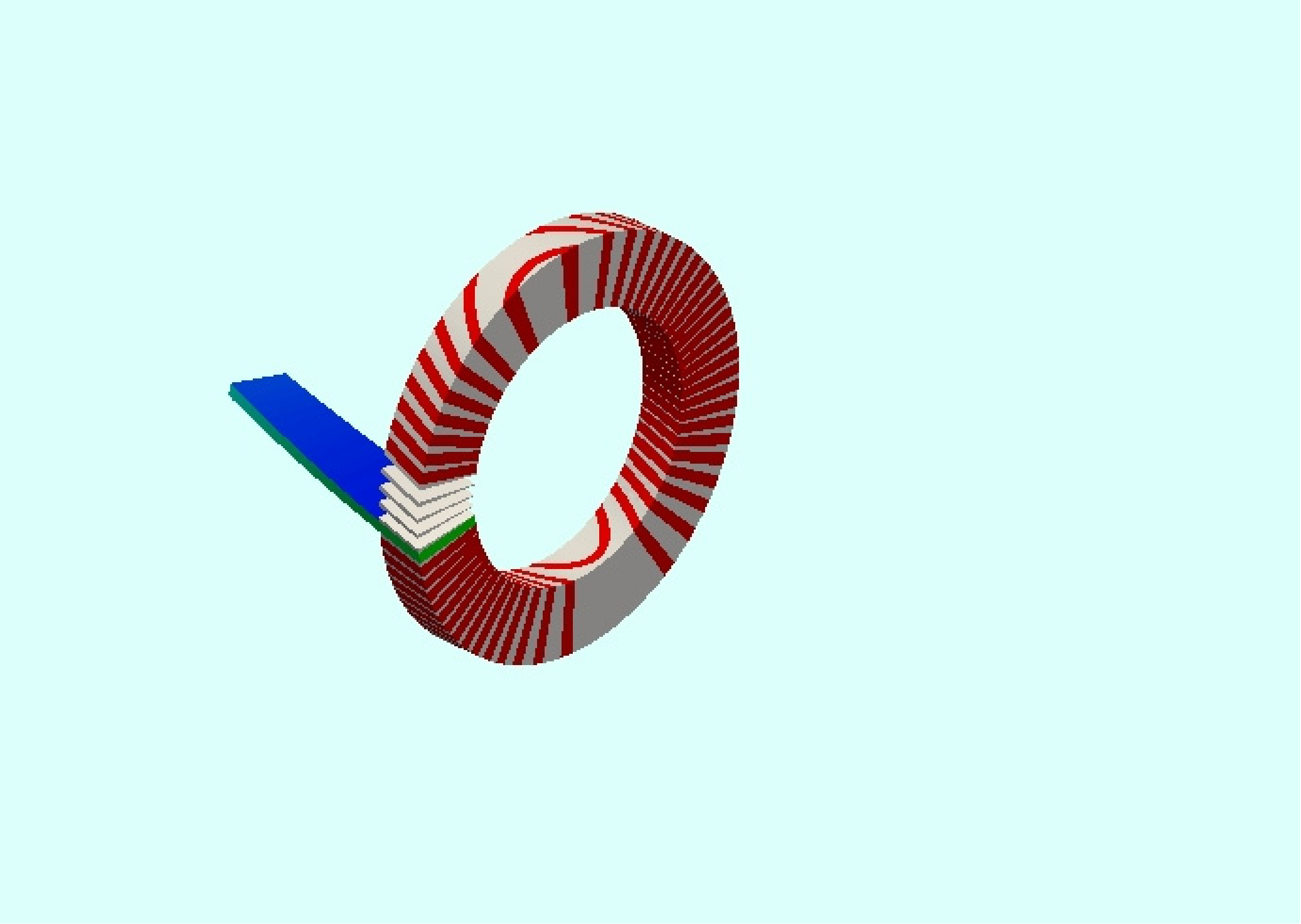
Symmetry - lamination



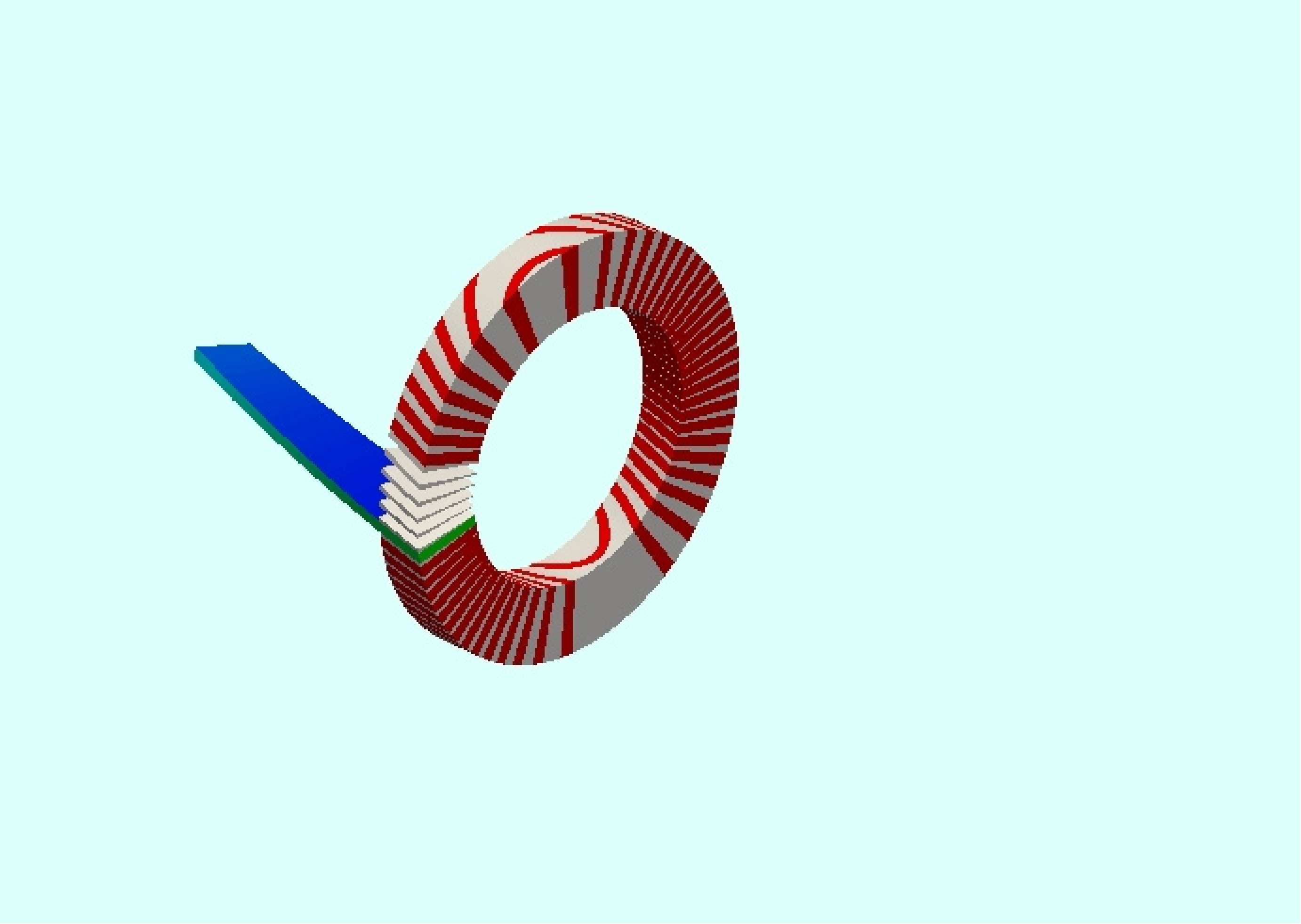
Symmetry - lamination



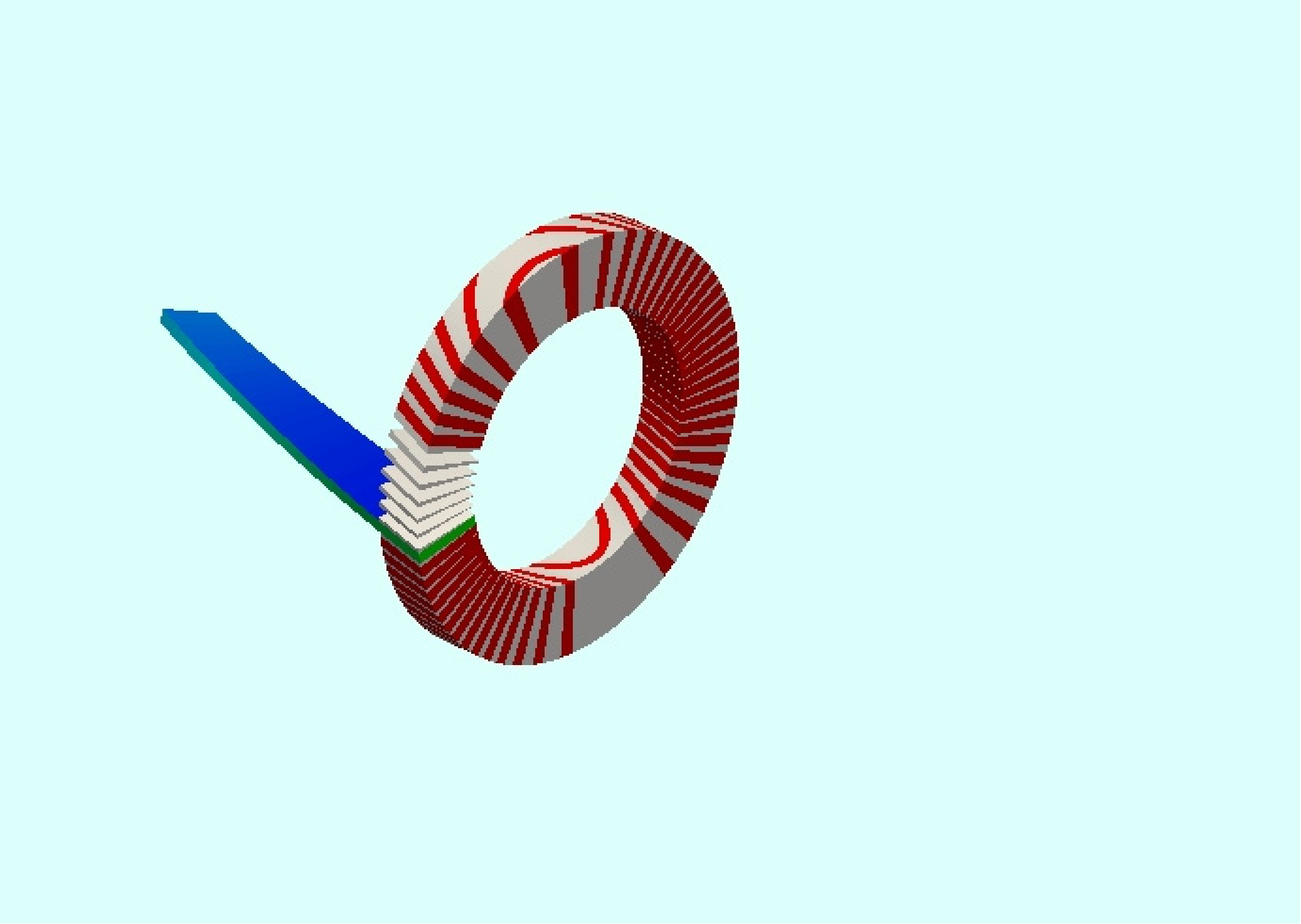
Symmetry - lamination



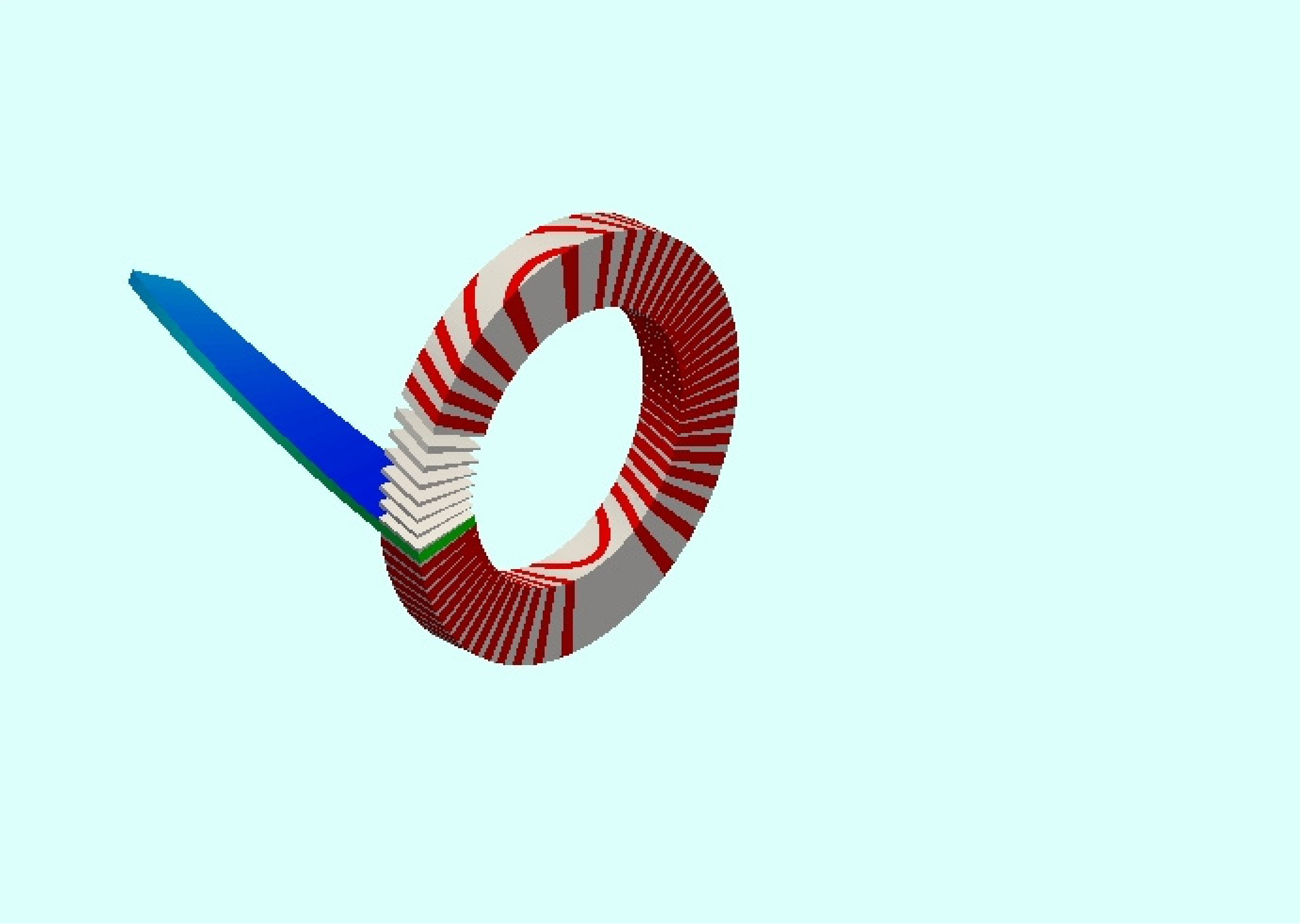
Symmetry - lamination



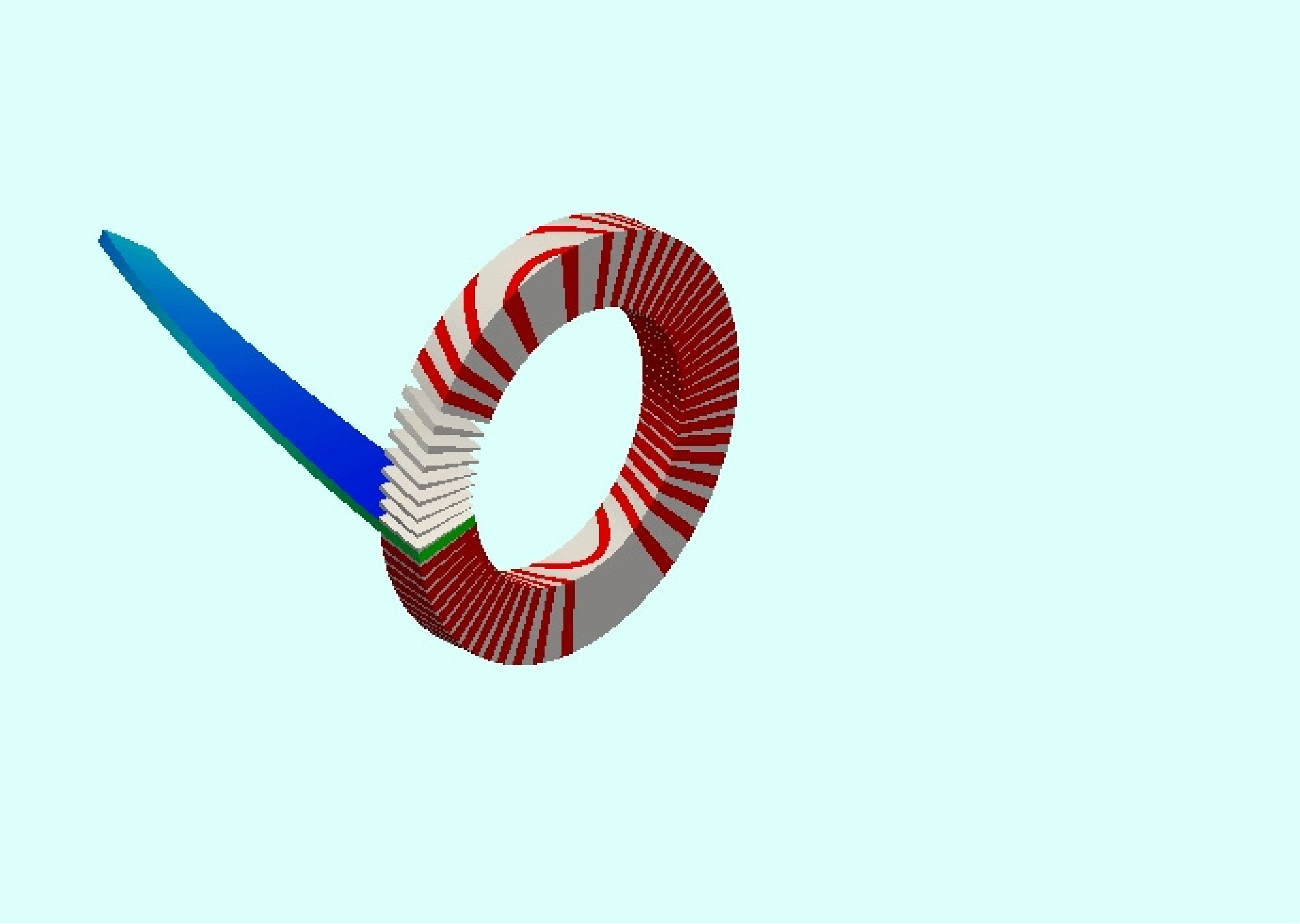
Symmetry - lamination



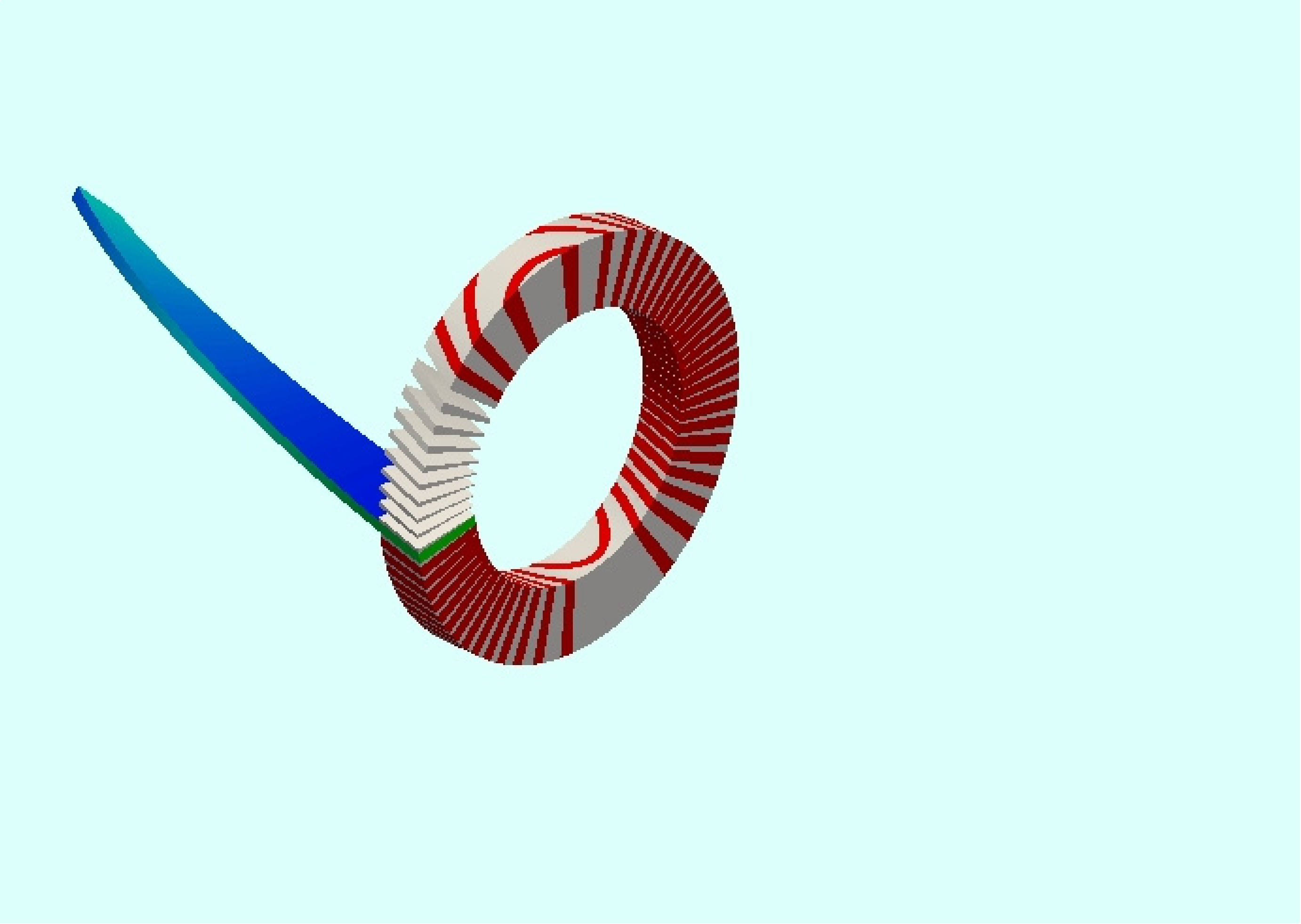
Symmetry - lamination



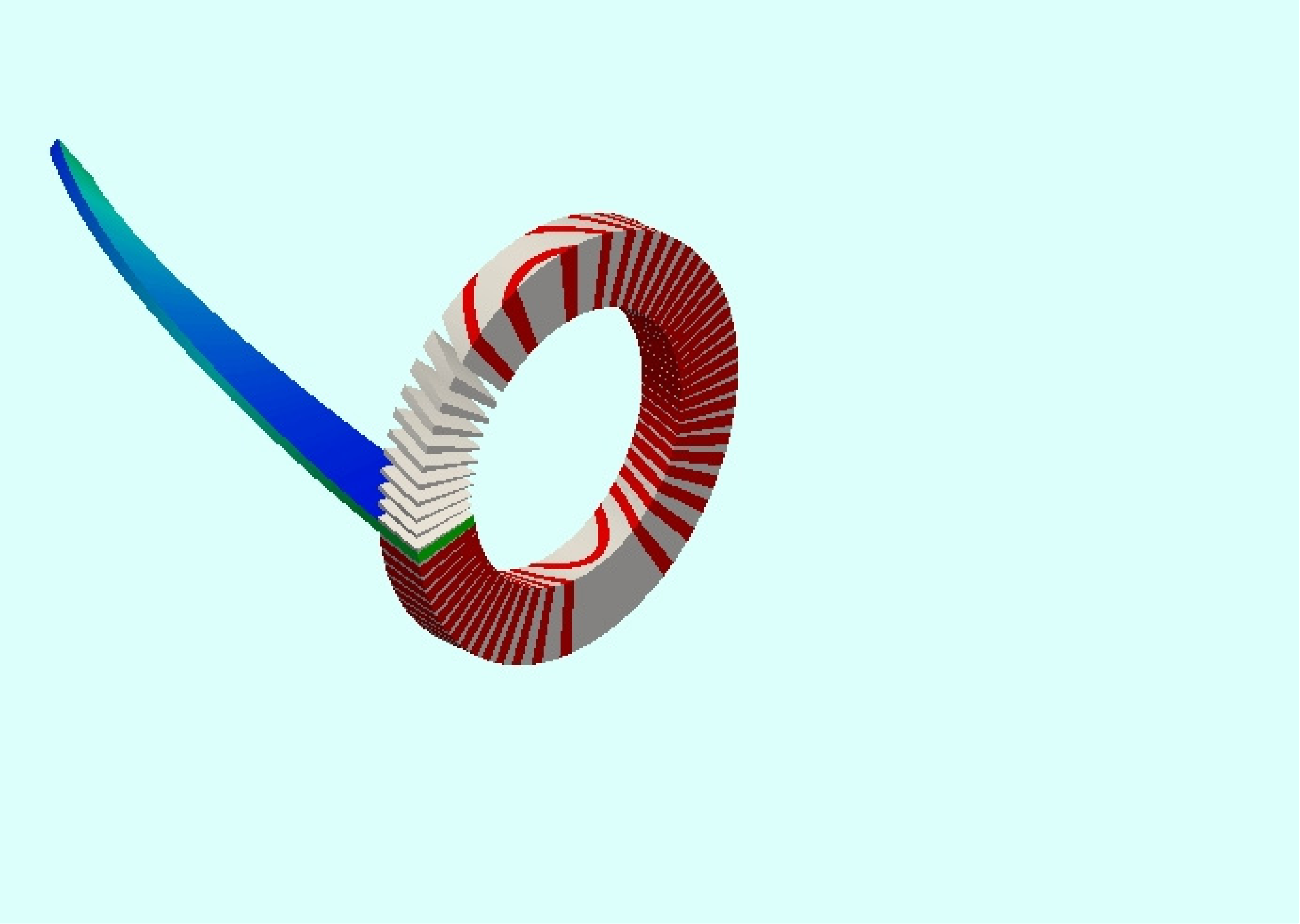
Symmetry - lamination



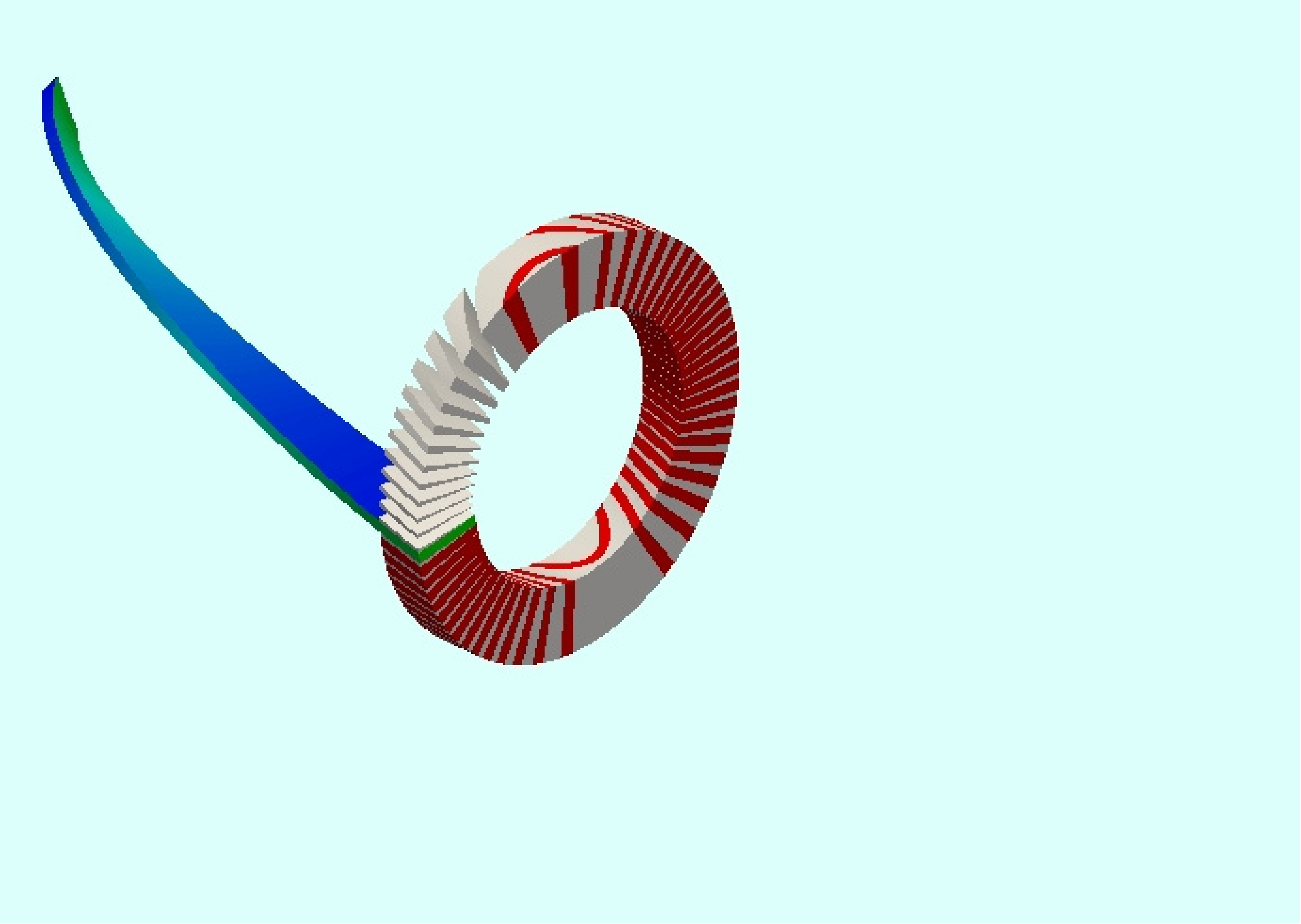
Symmetry - lamination



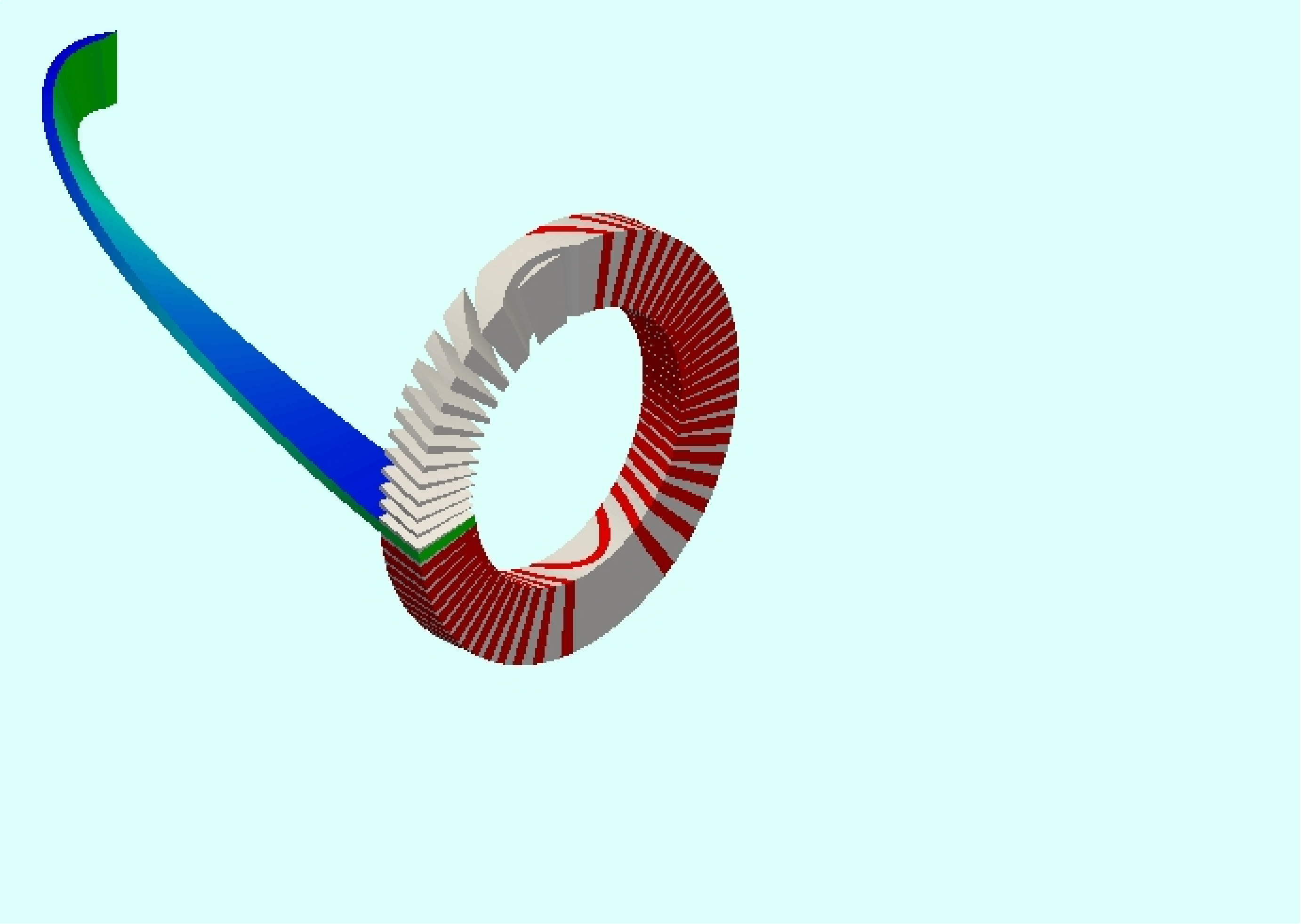
Symmetry - lamination



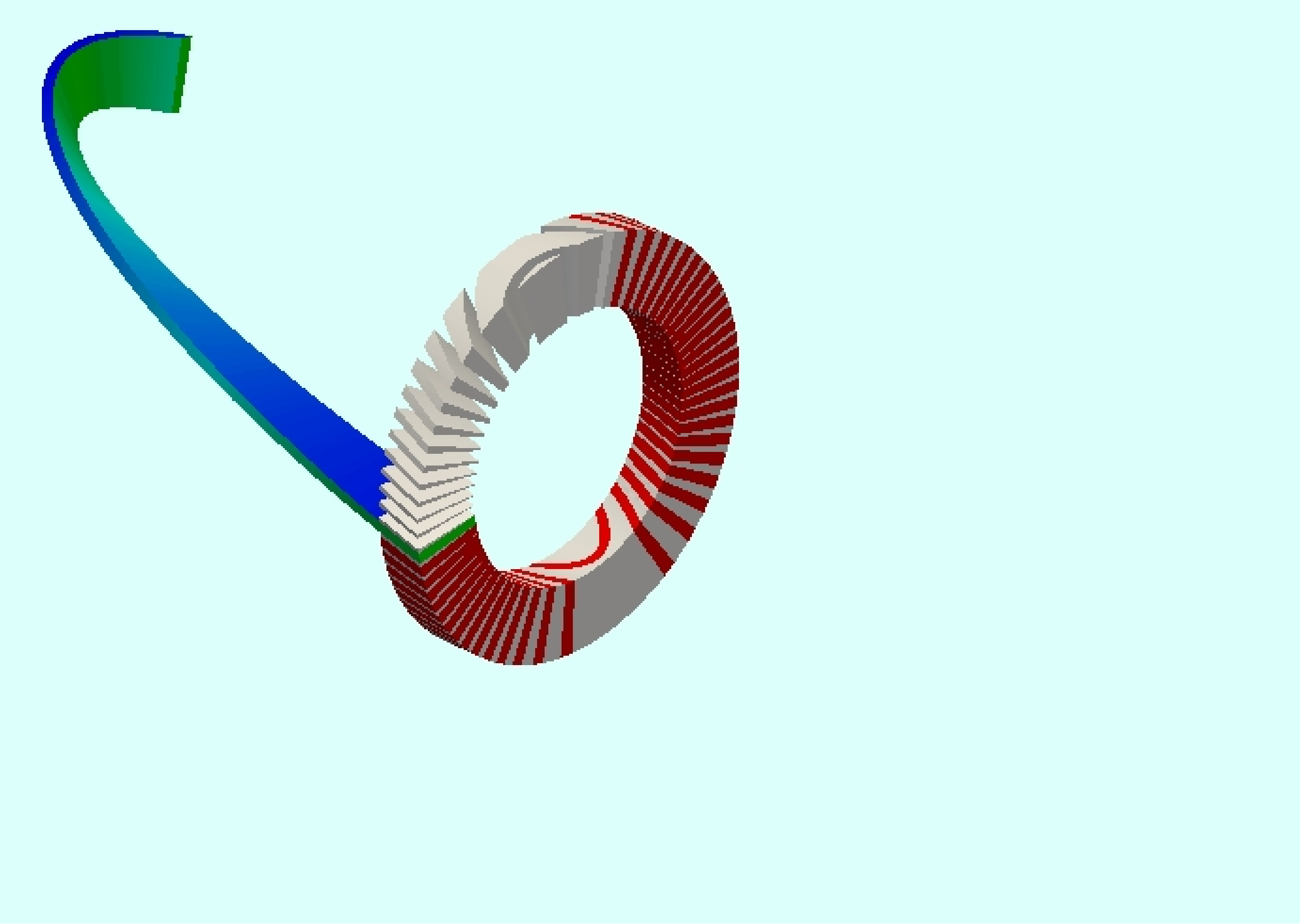
Symmetry - lamination



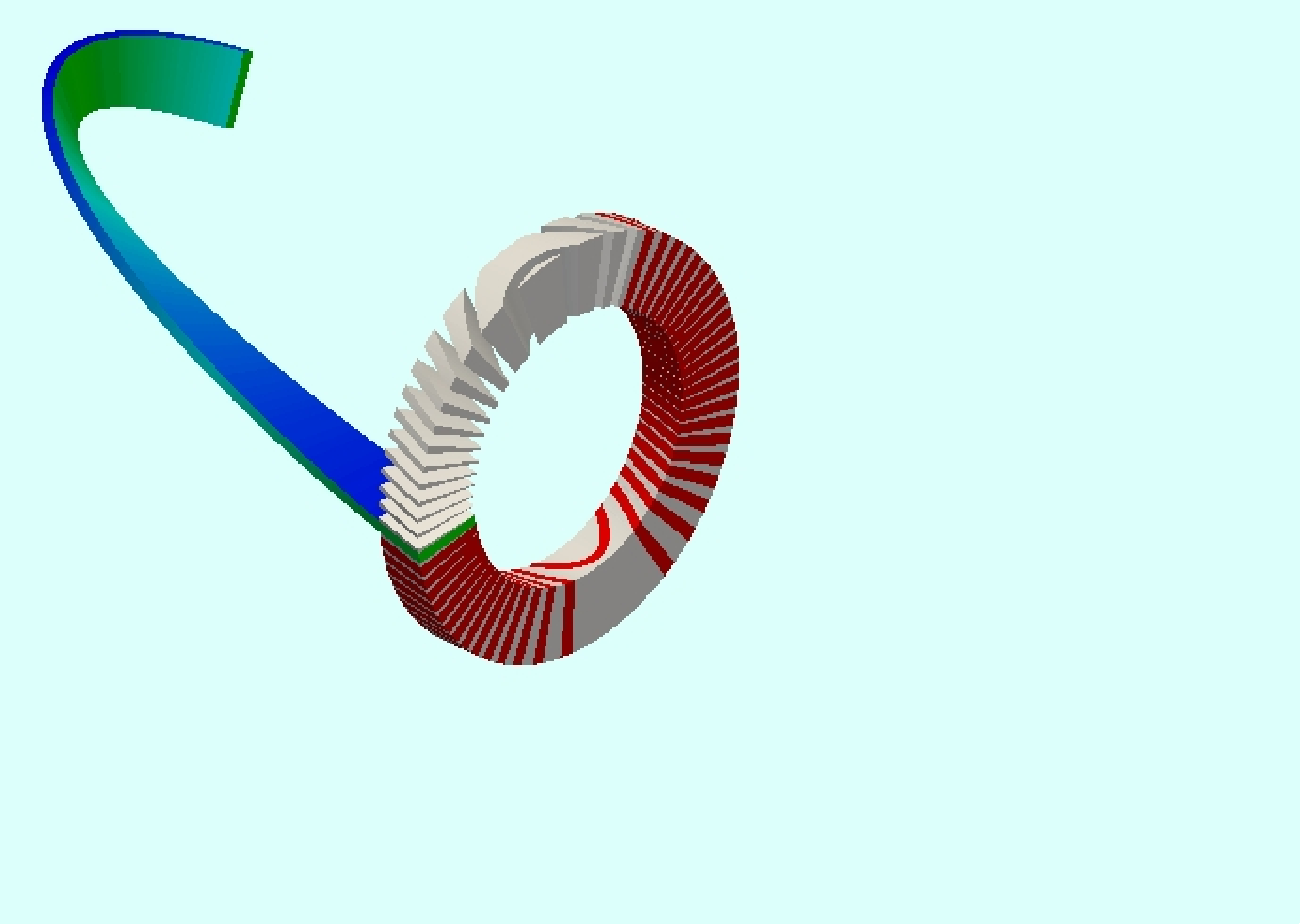
Symmetry - lamination



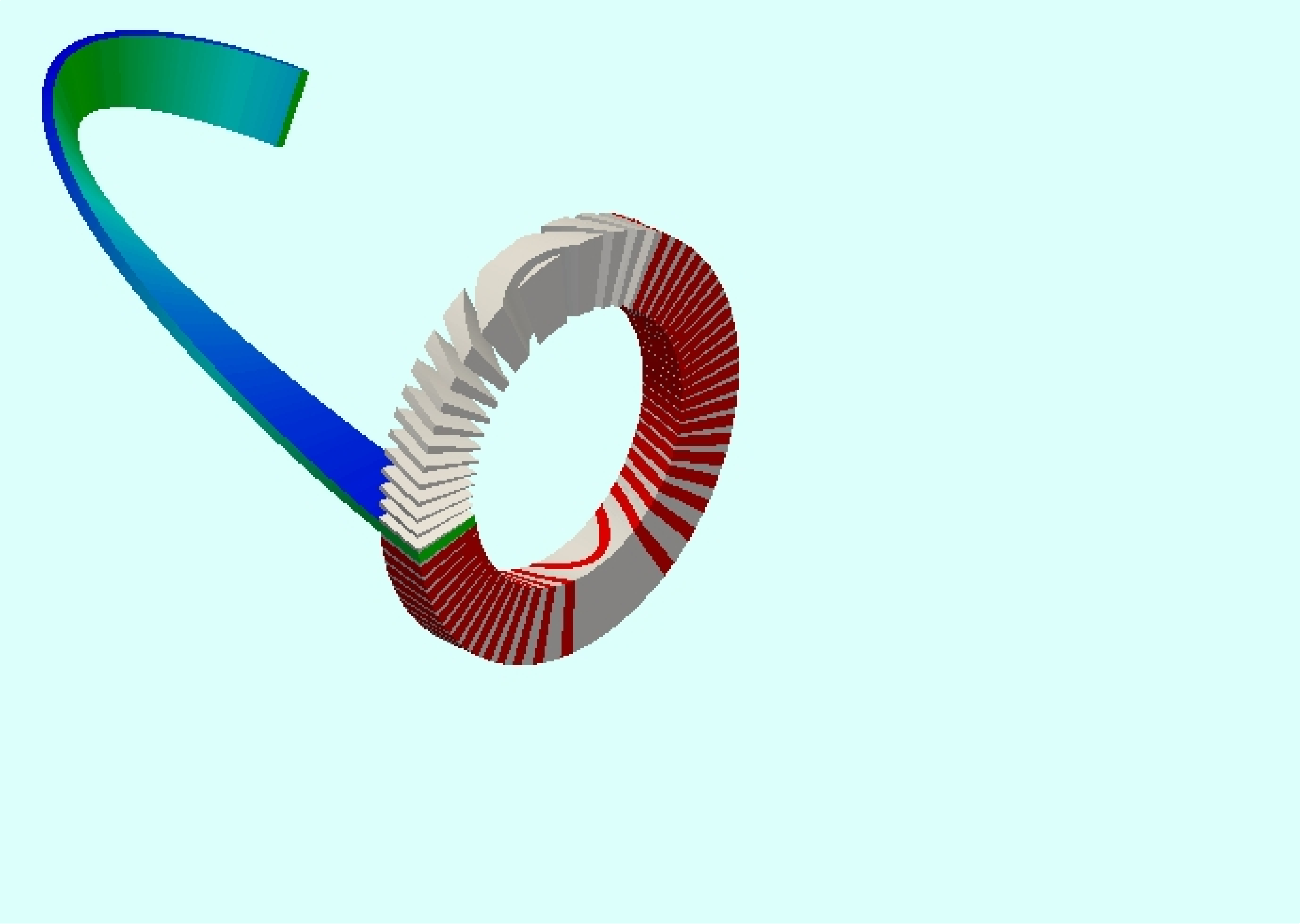
Symmetry - lamination



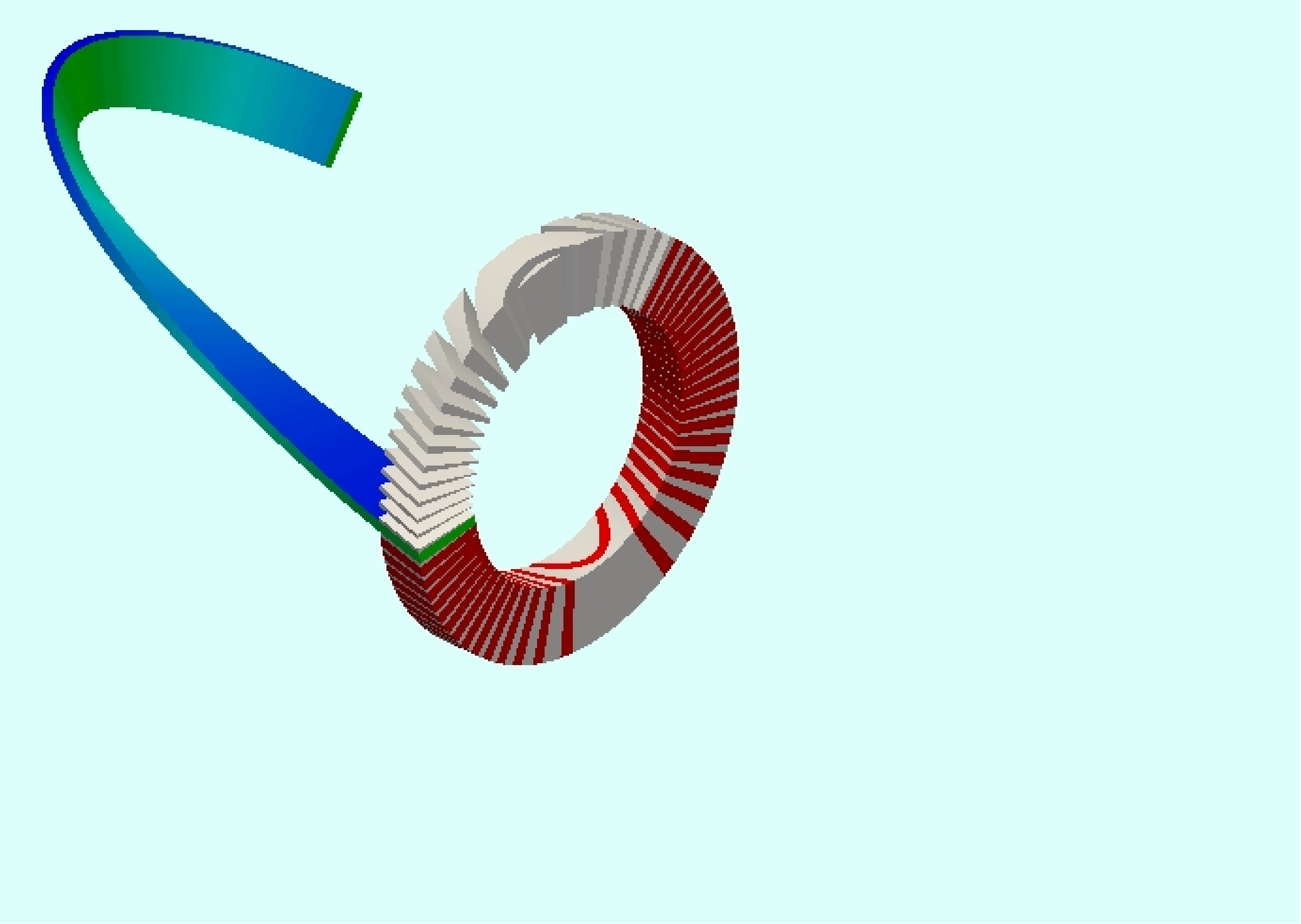
Symmetry - lamination



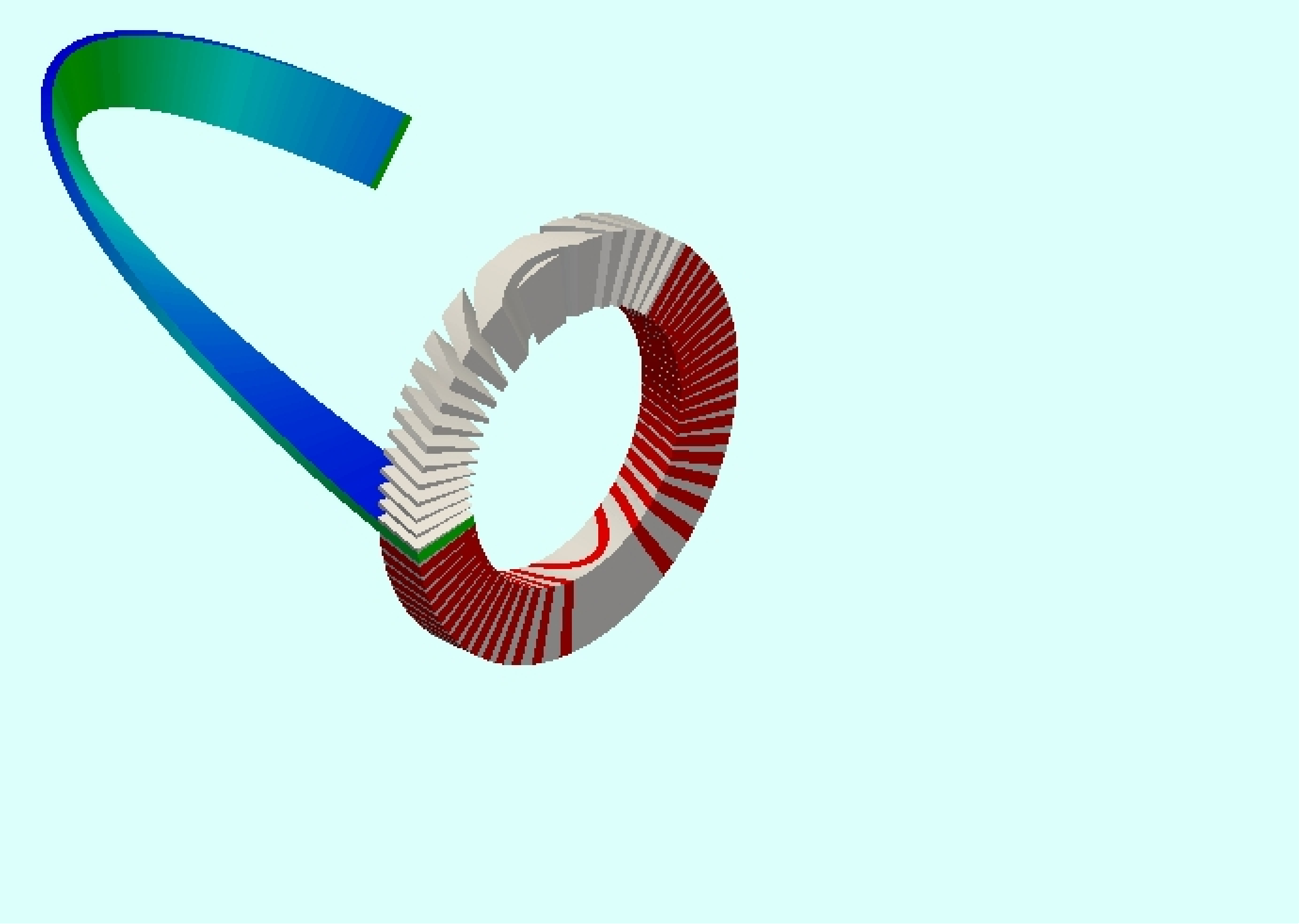
Symmetry - lamination



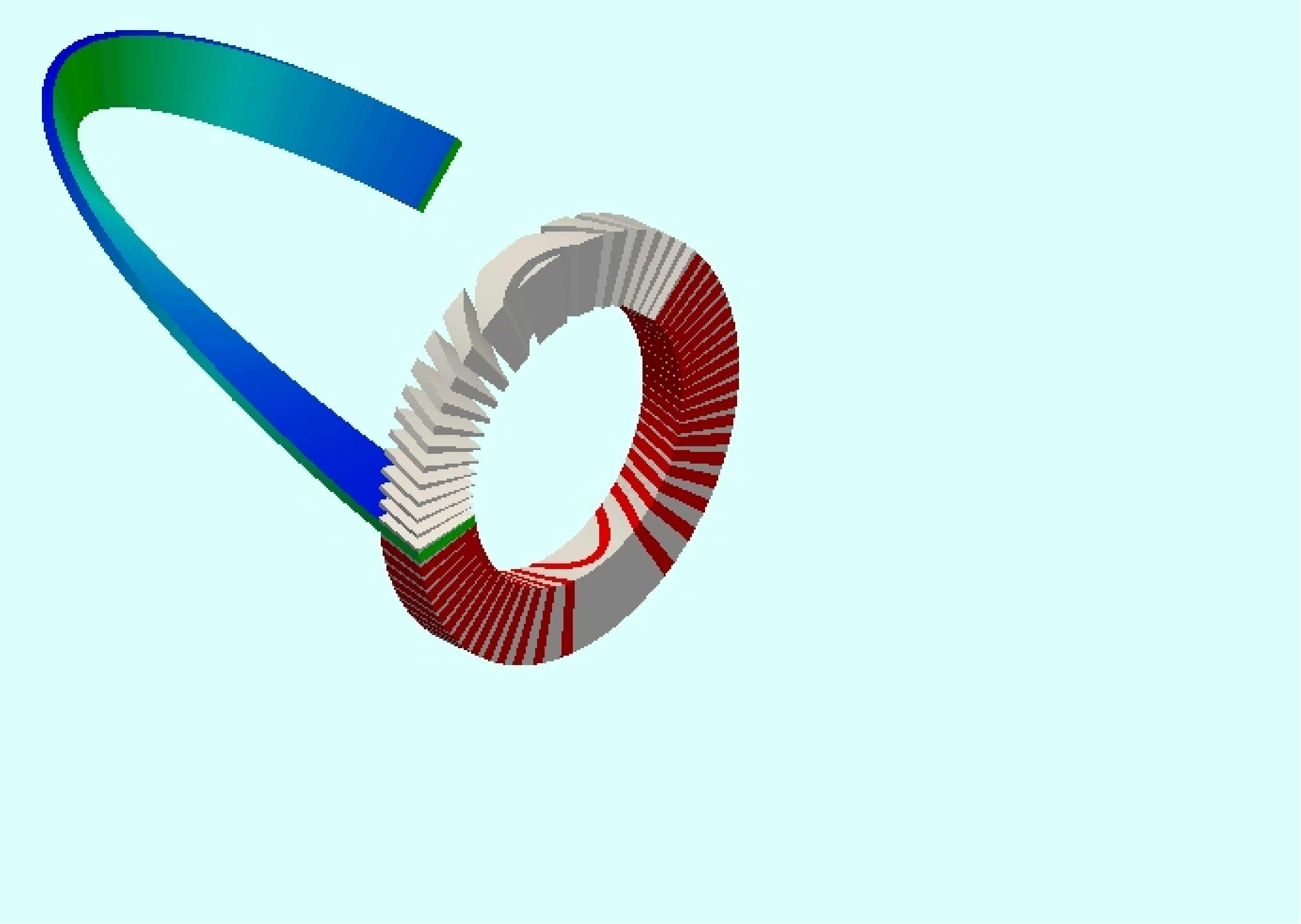
Symmetry - lamination



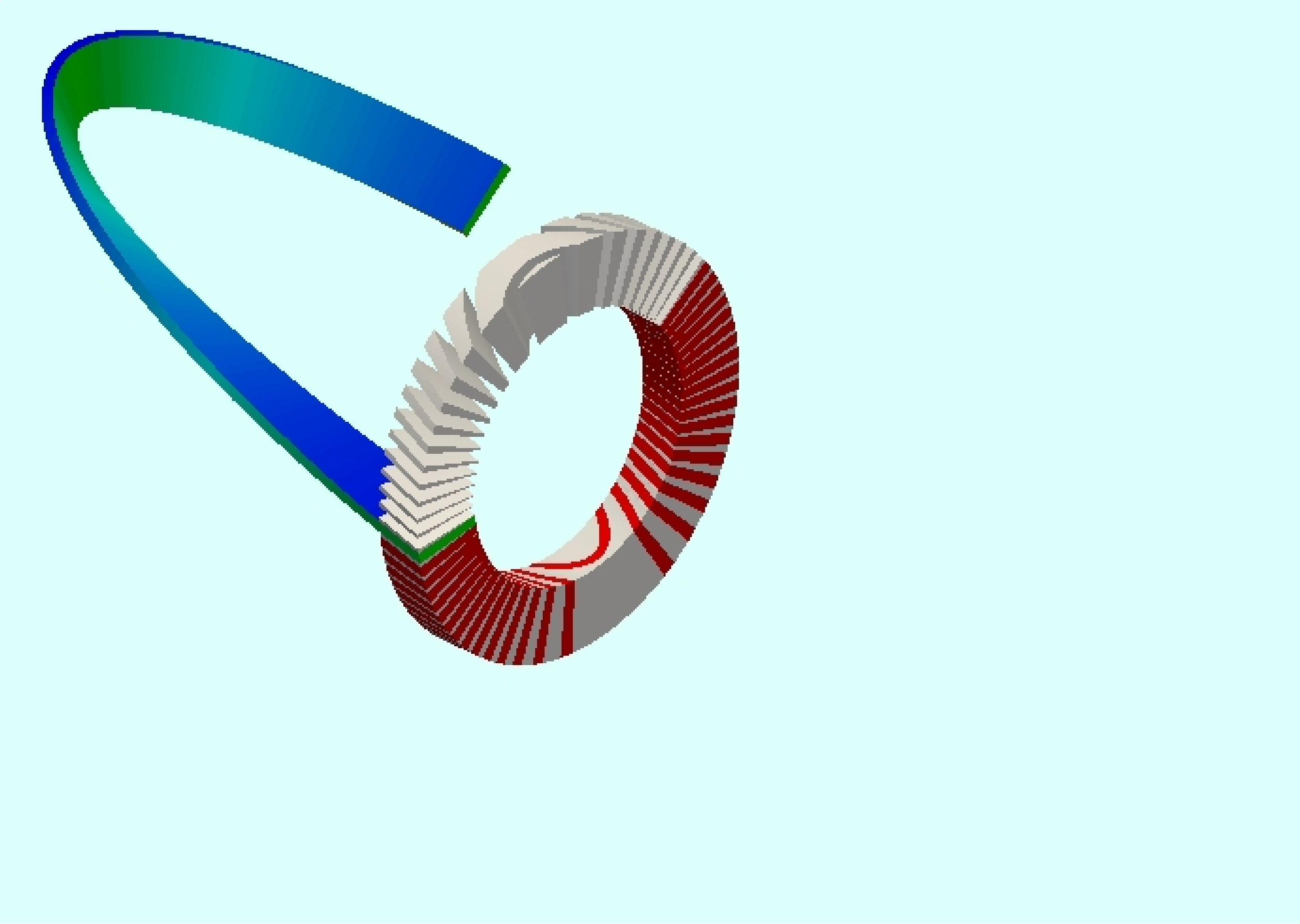
Symmetry - lamination



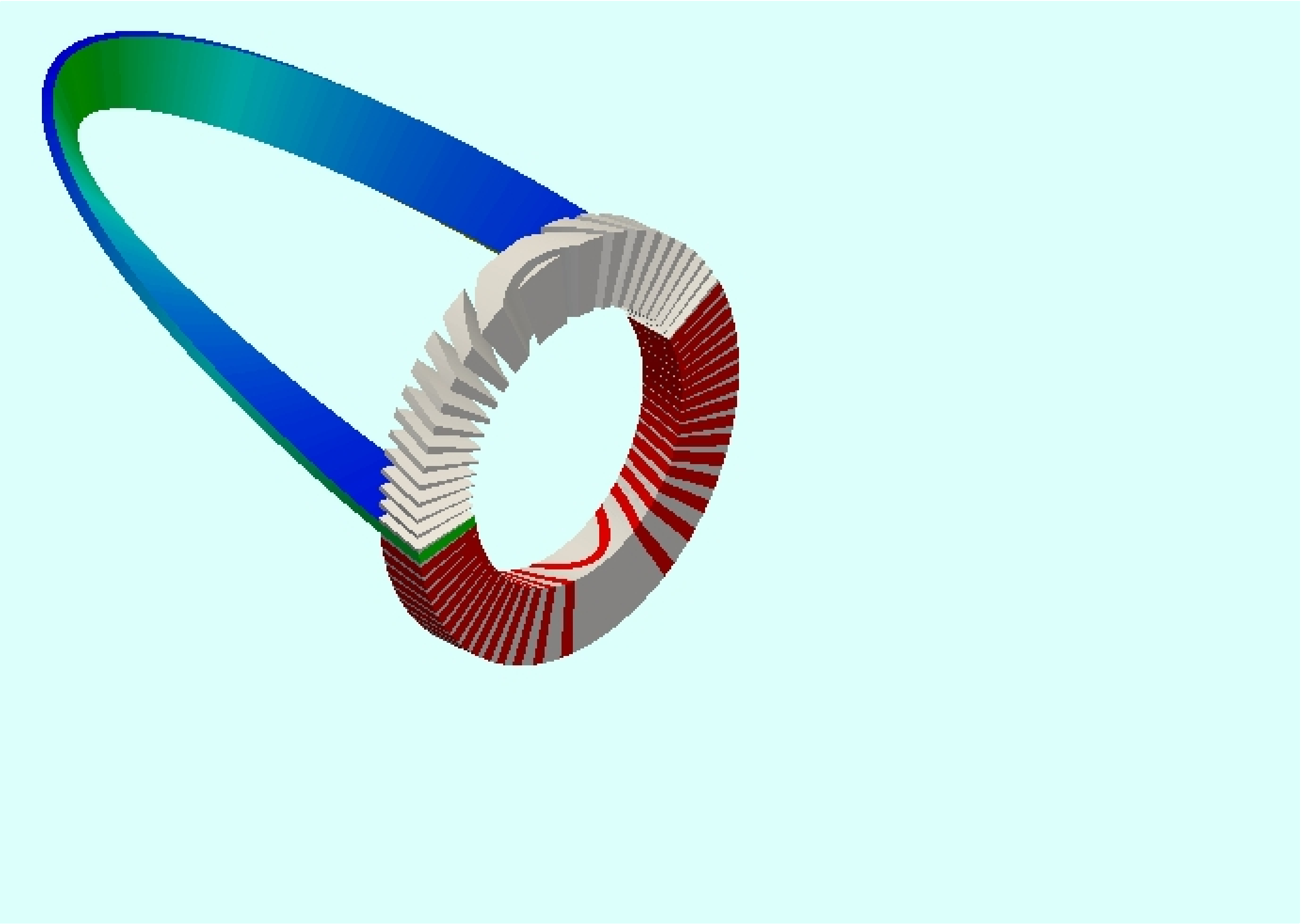
Symmetry - lamination



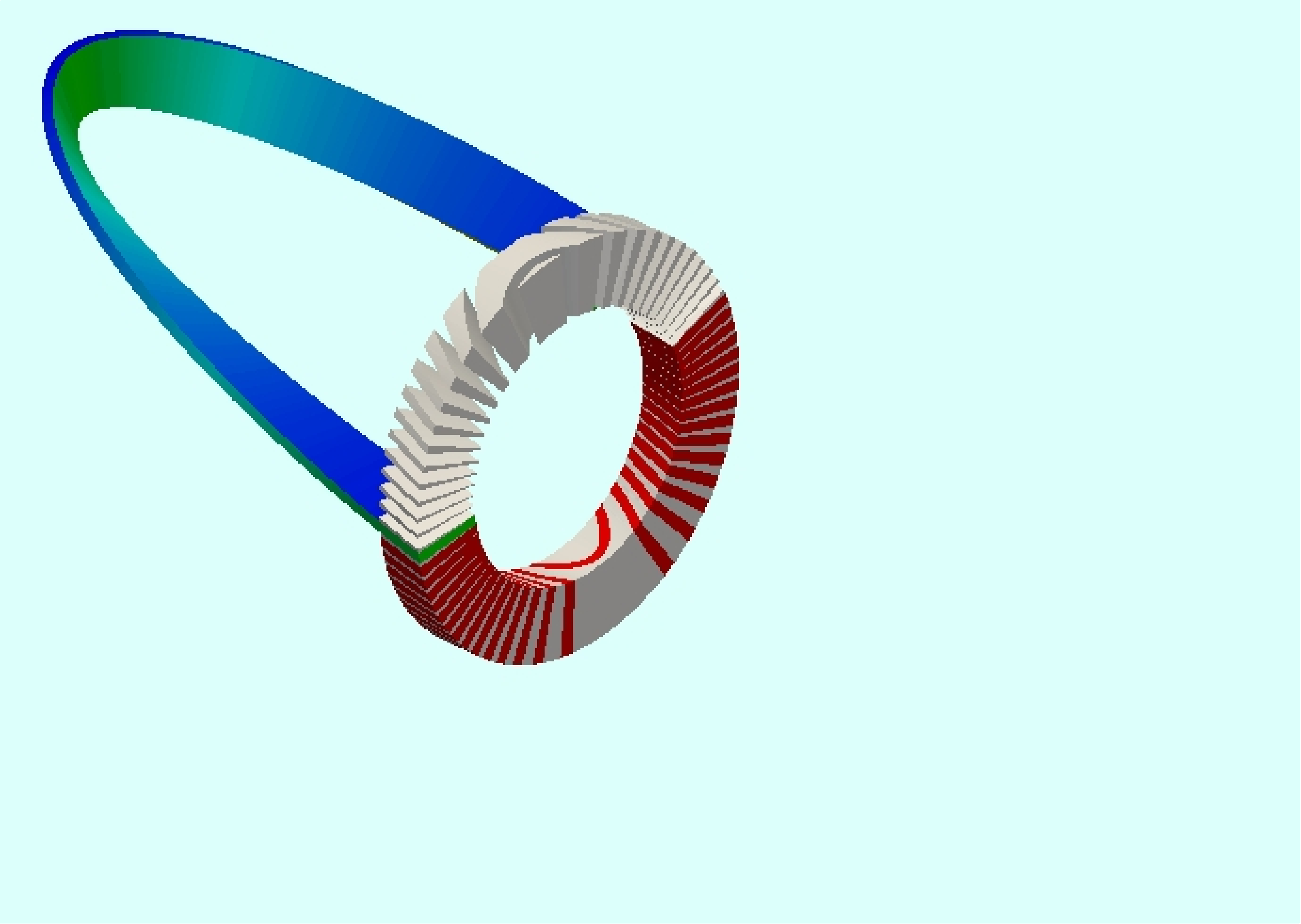
Symmetry - lamination



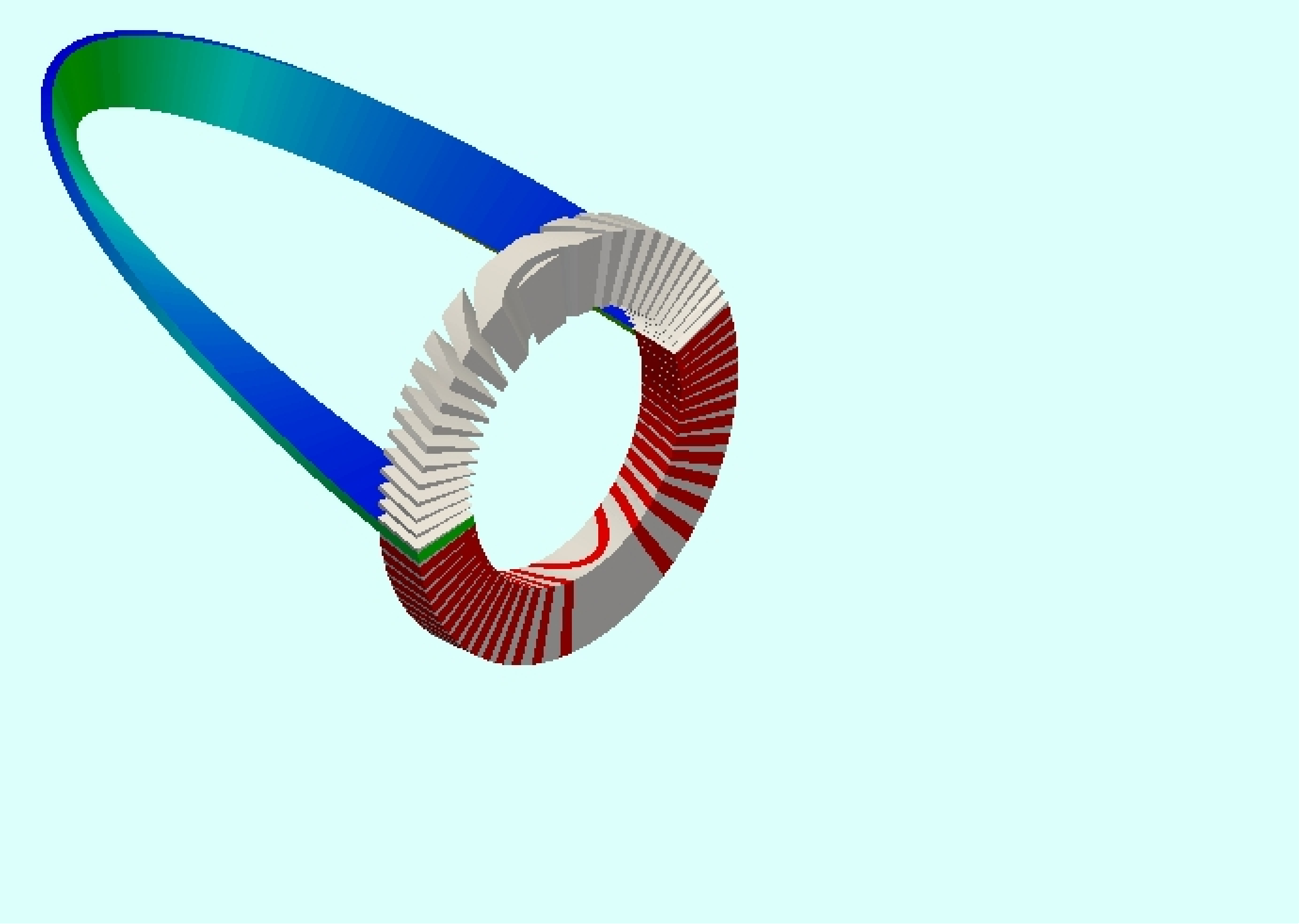
Symmetry - lamination



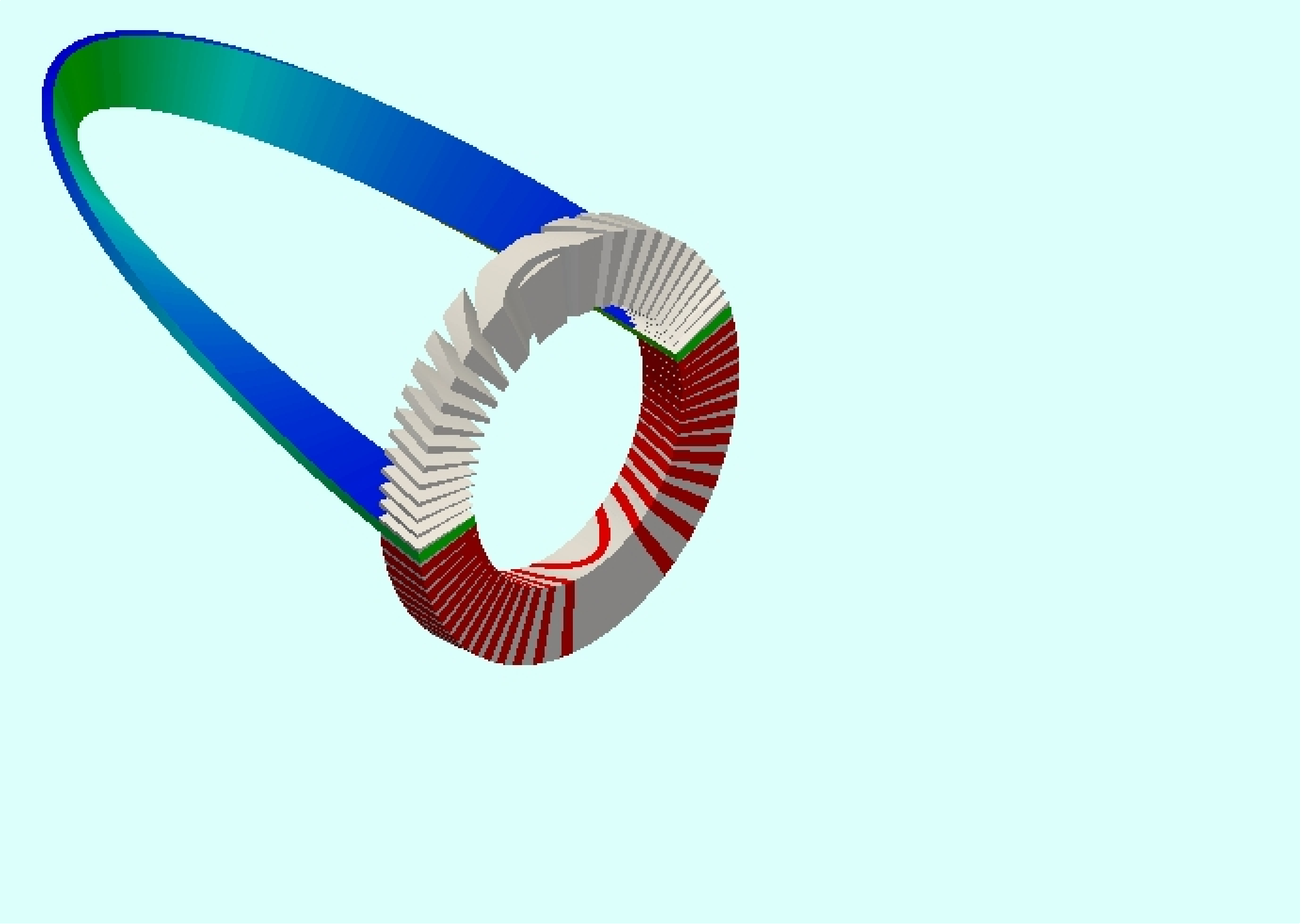
Symmetry - lamination



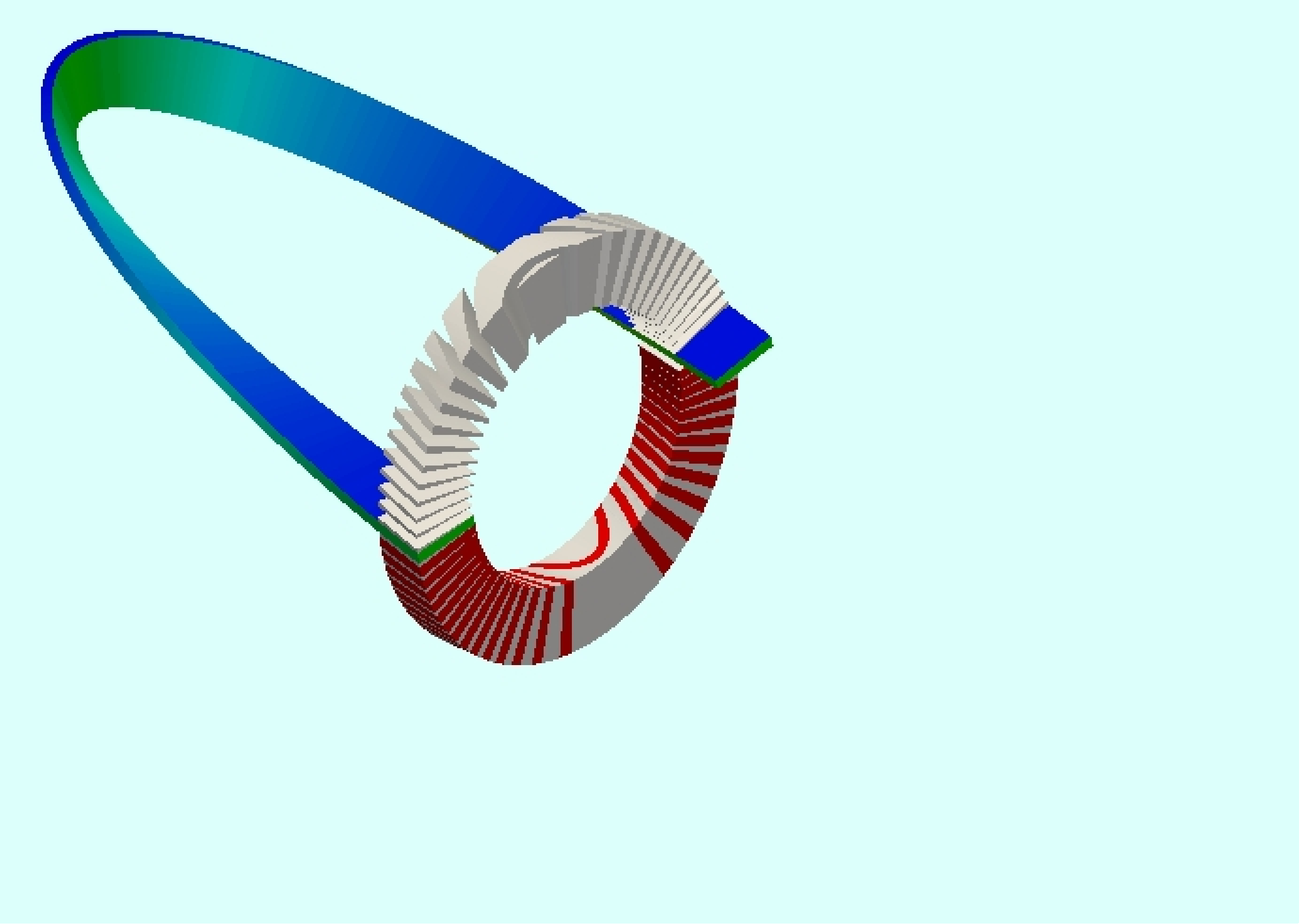
Symmetry - lamination



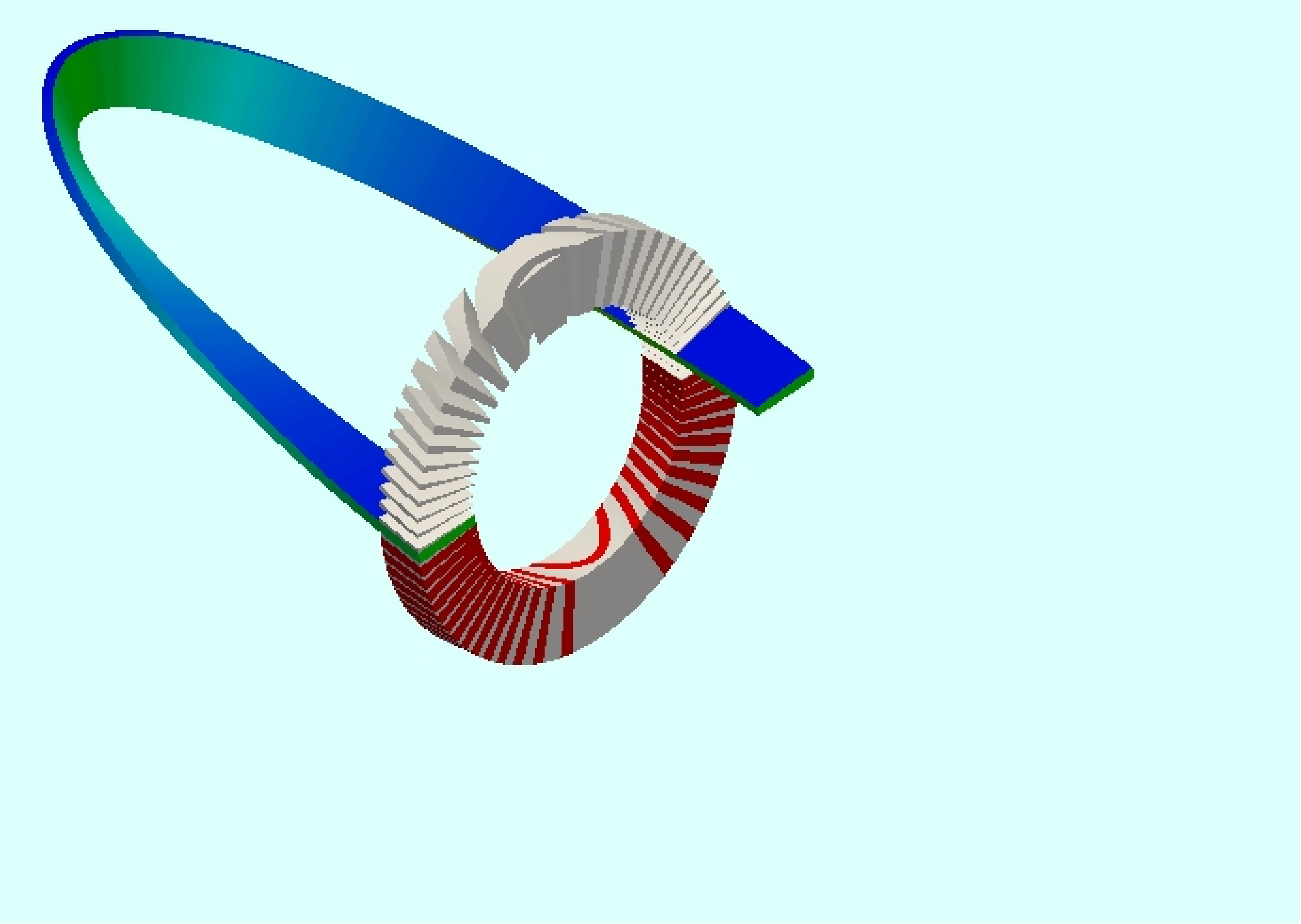
Symmetry - lamination



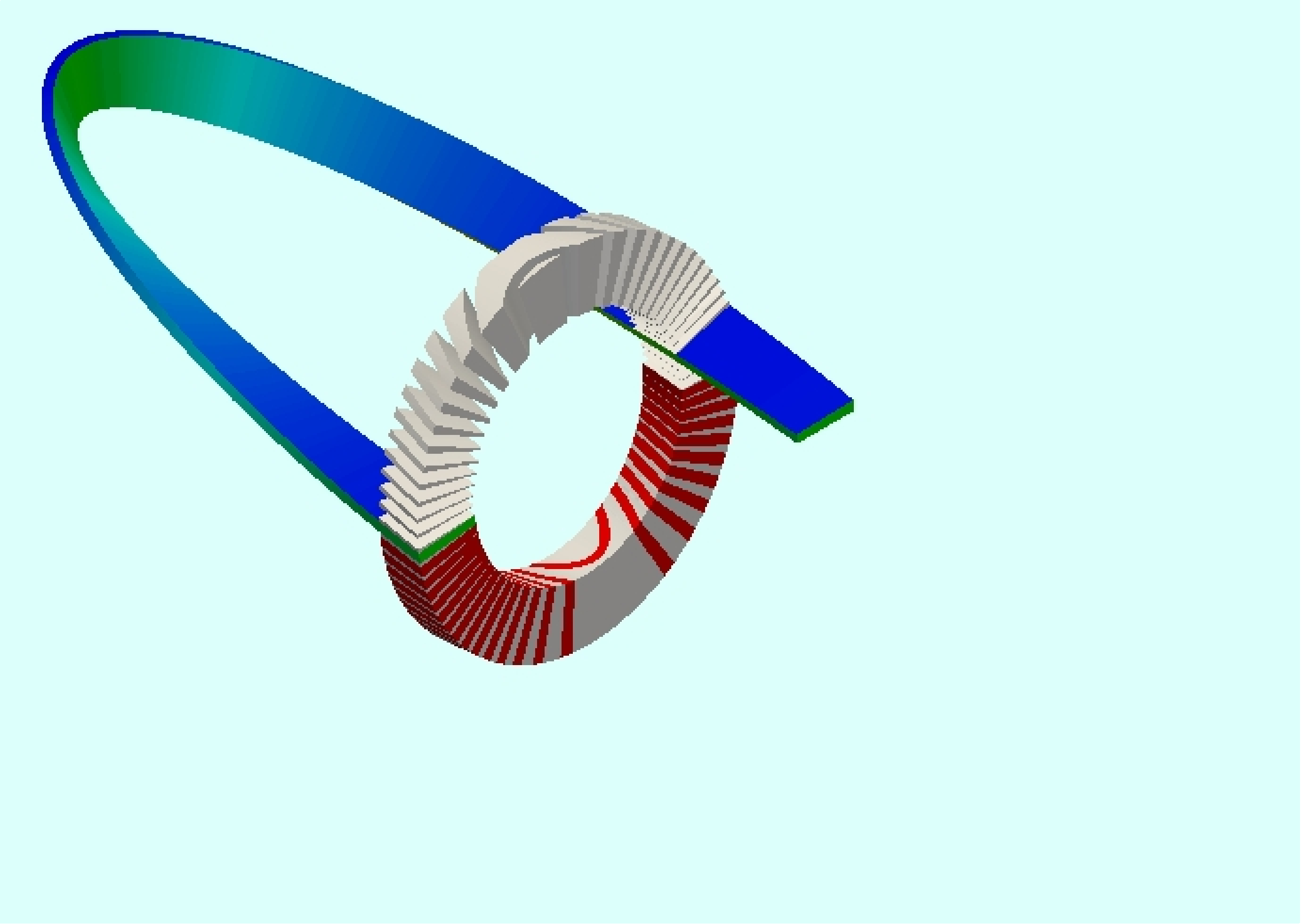
Symmetry - lamination



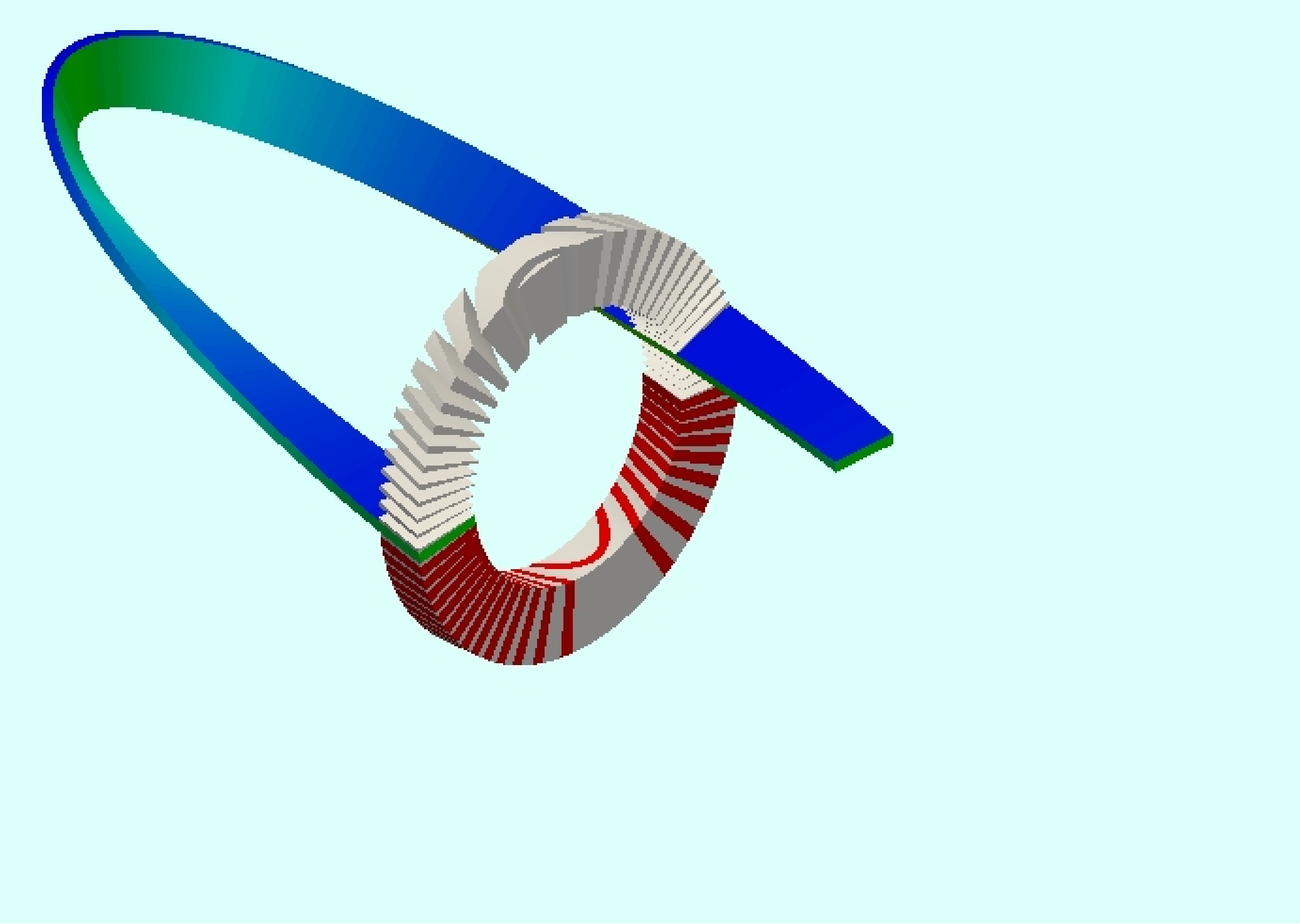
Symmetry - lamination



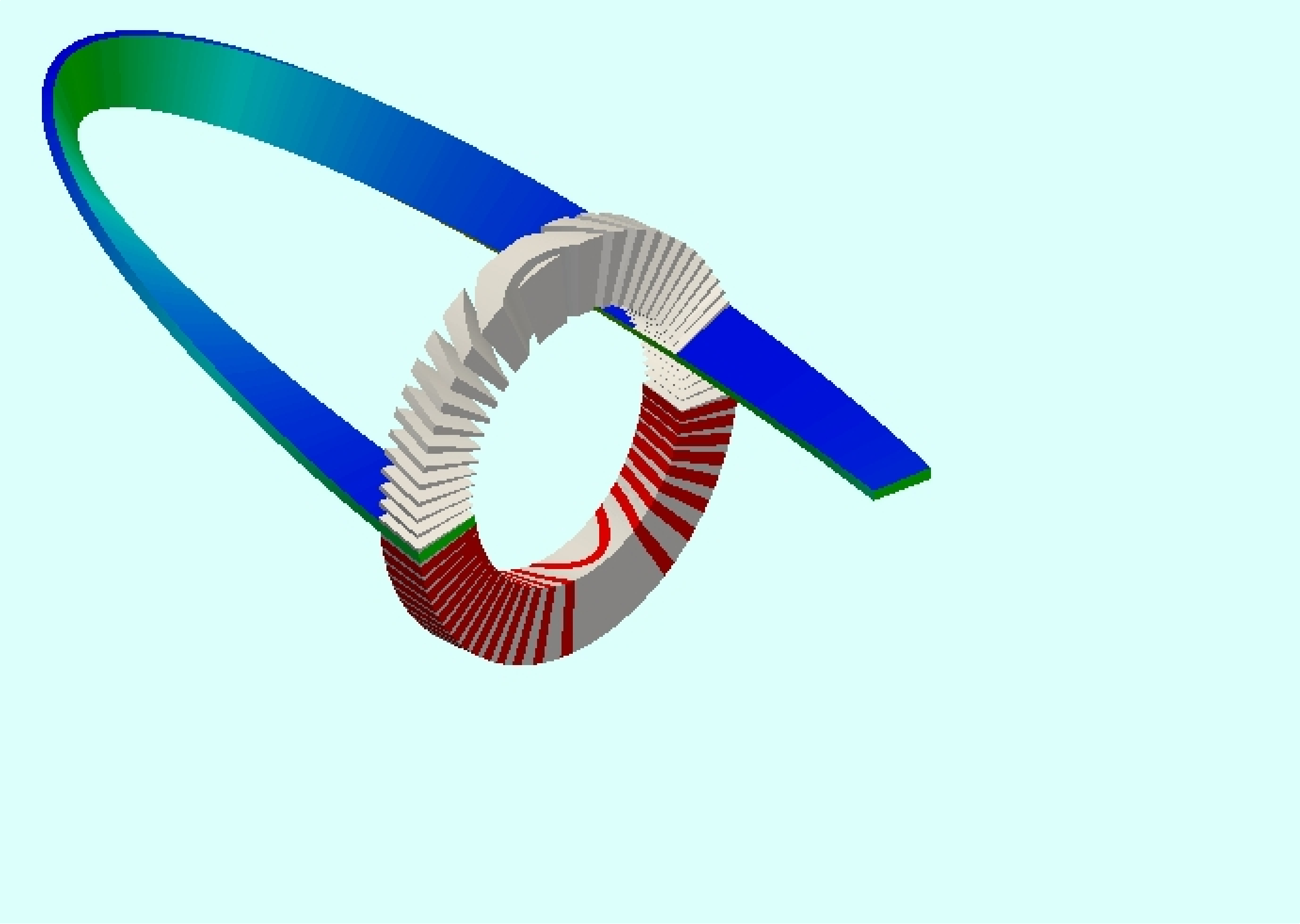
Symmetry - lamination



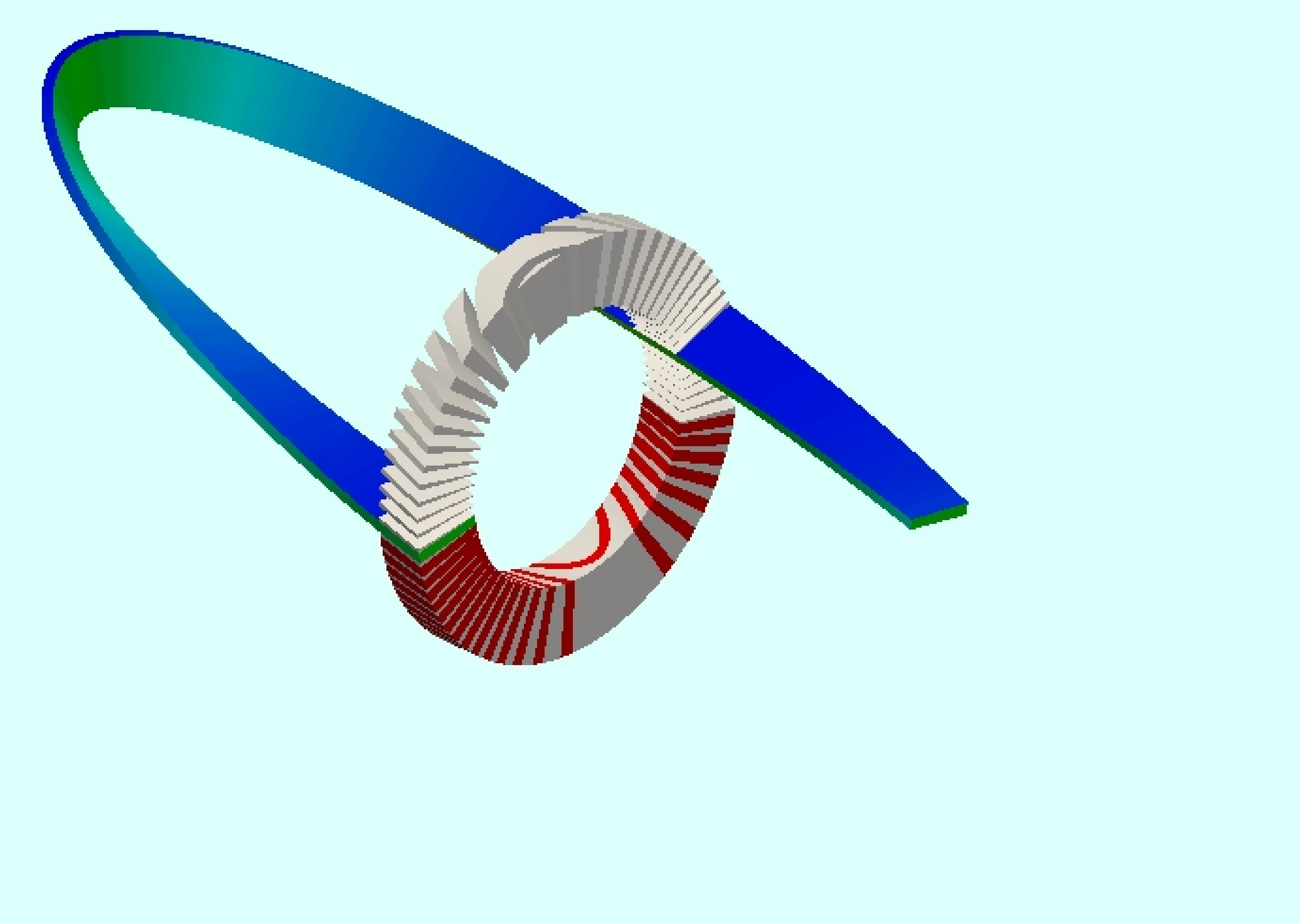
Symmetry - lamination



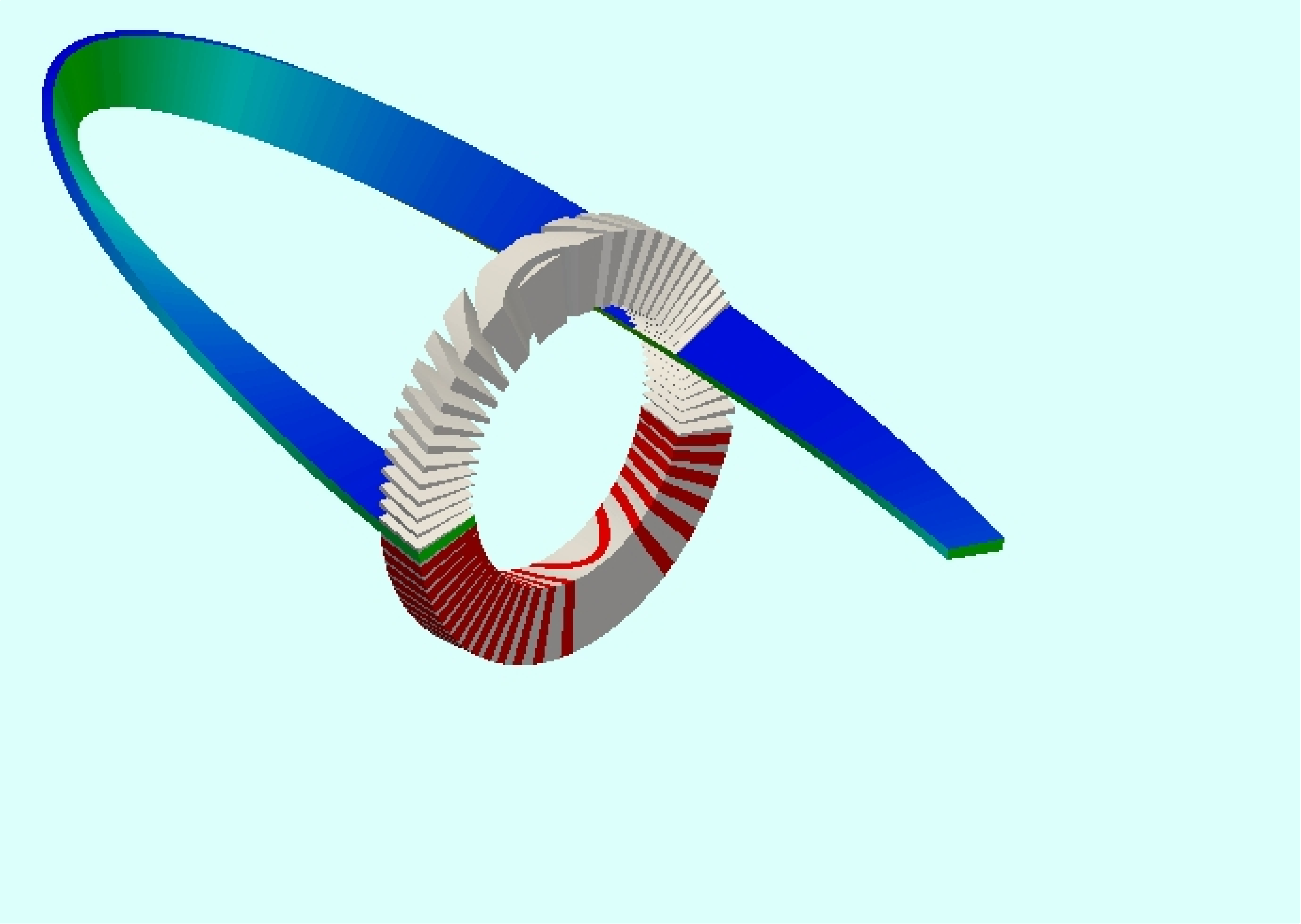
Symmetry - lamination



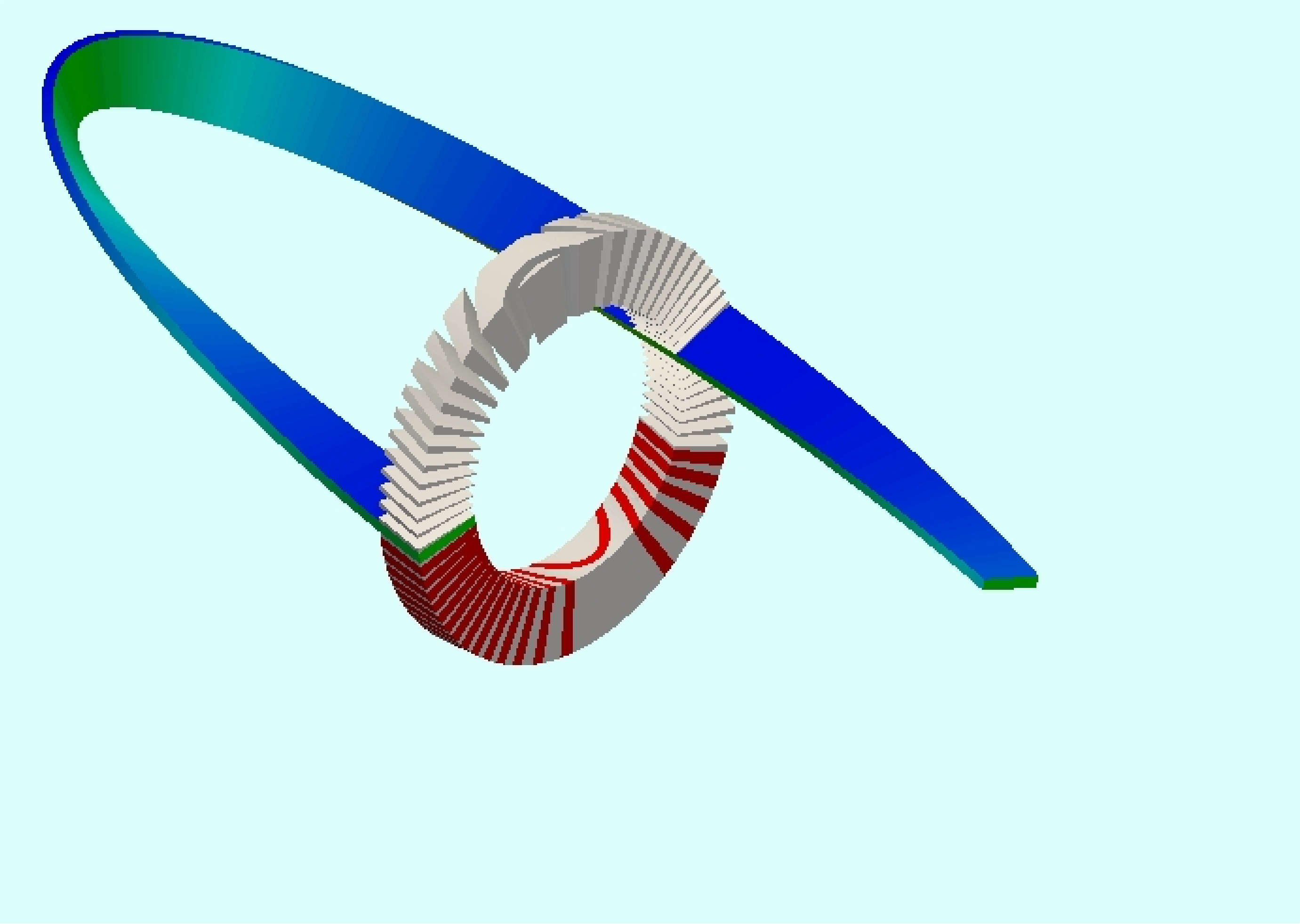
Symmetry - lamination



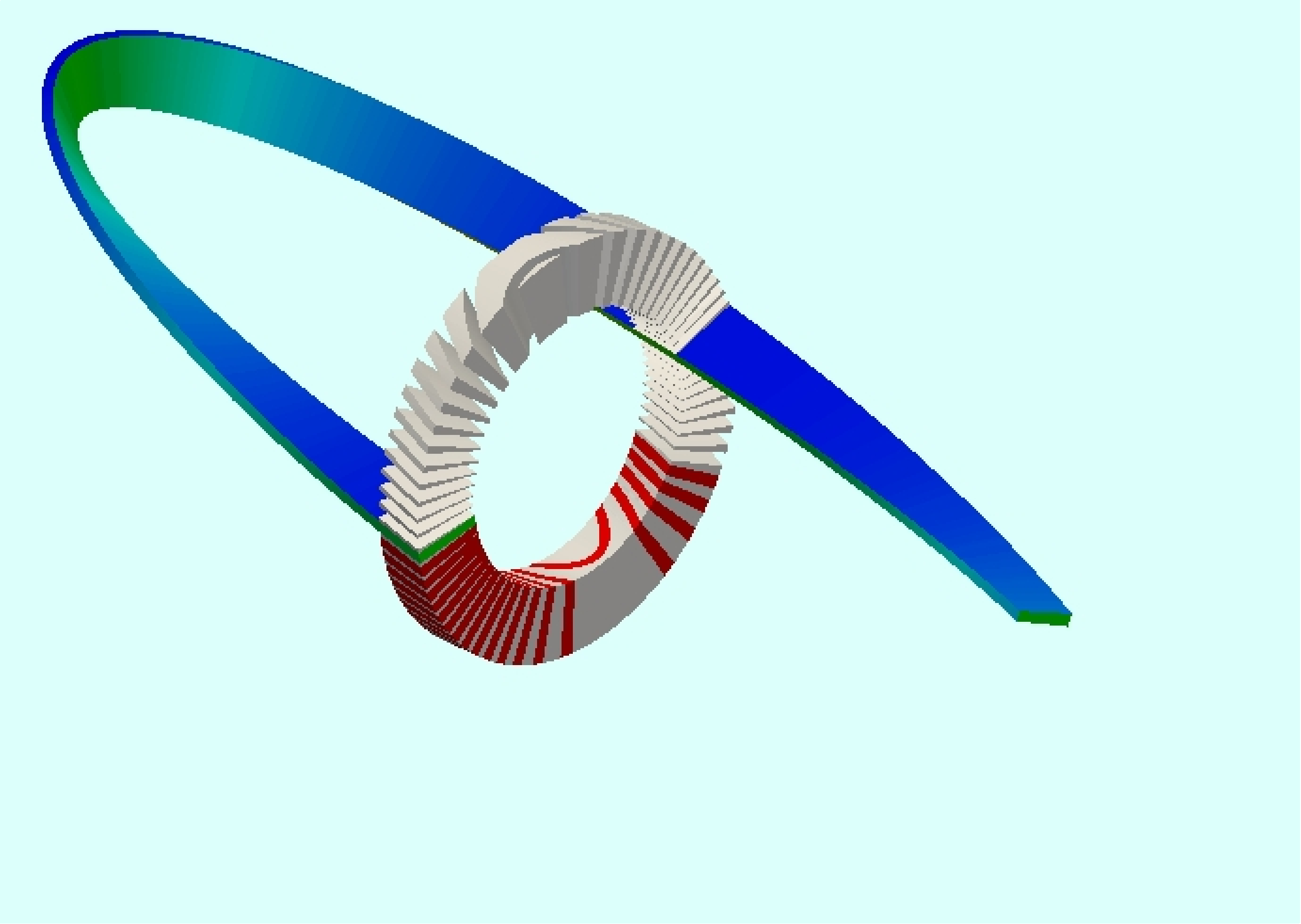
Symmetry - lamination



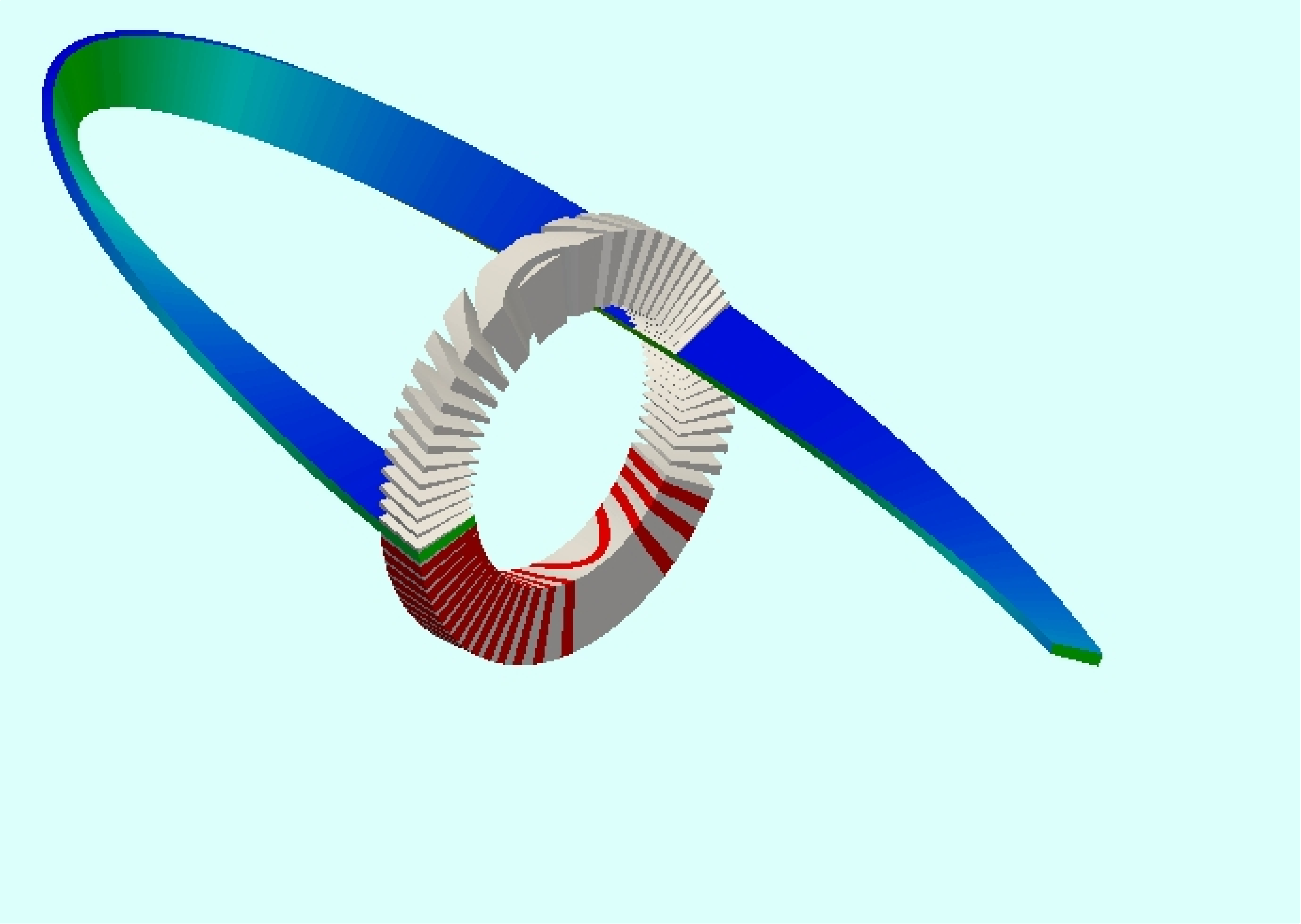
Symmetry - lamination



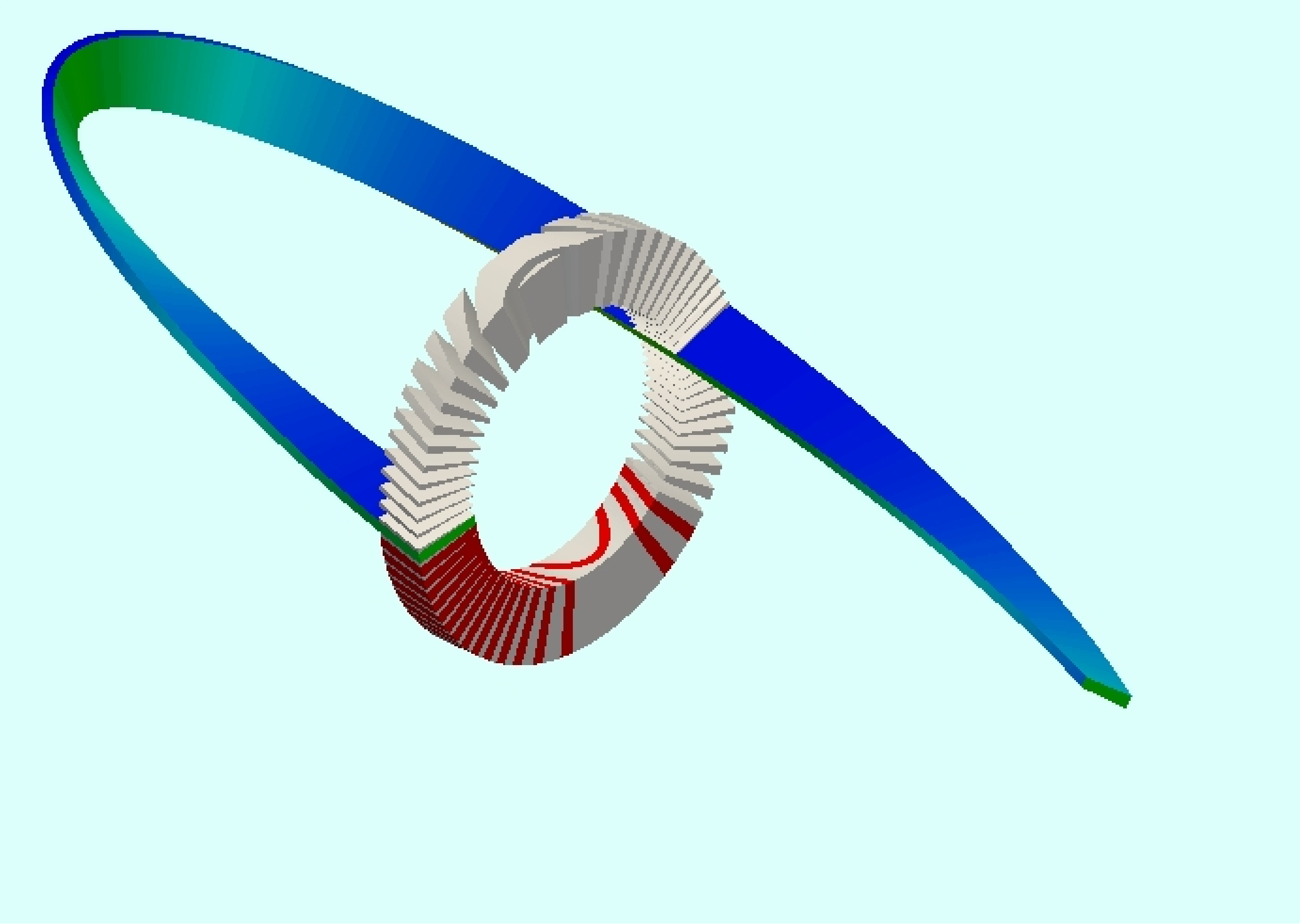
Symmetry - lamination



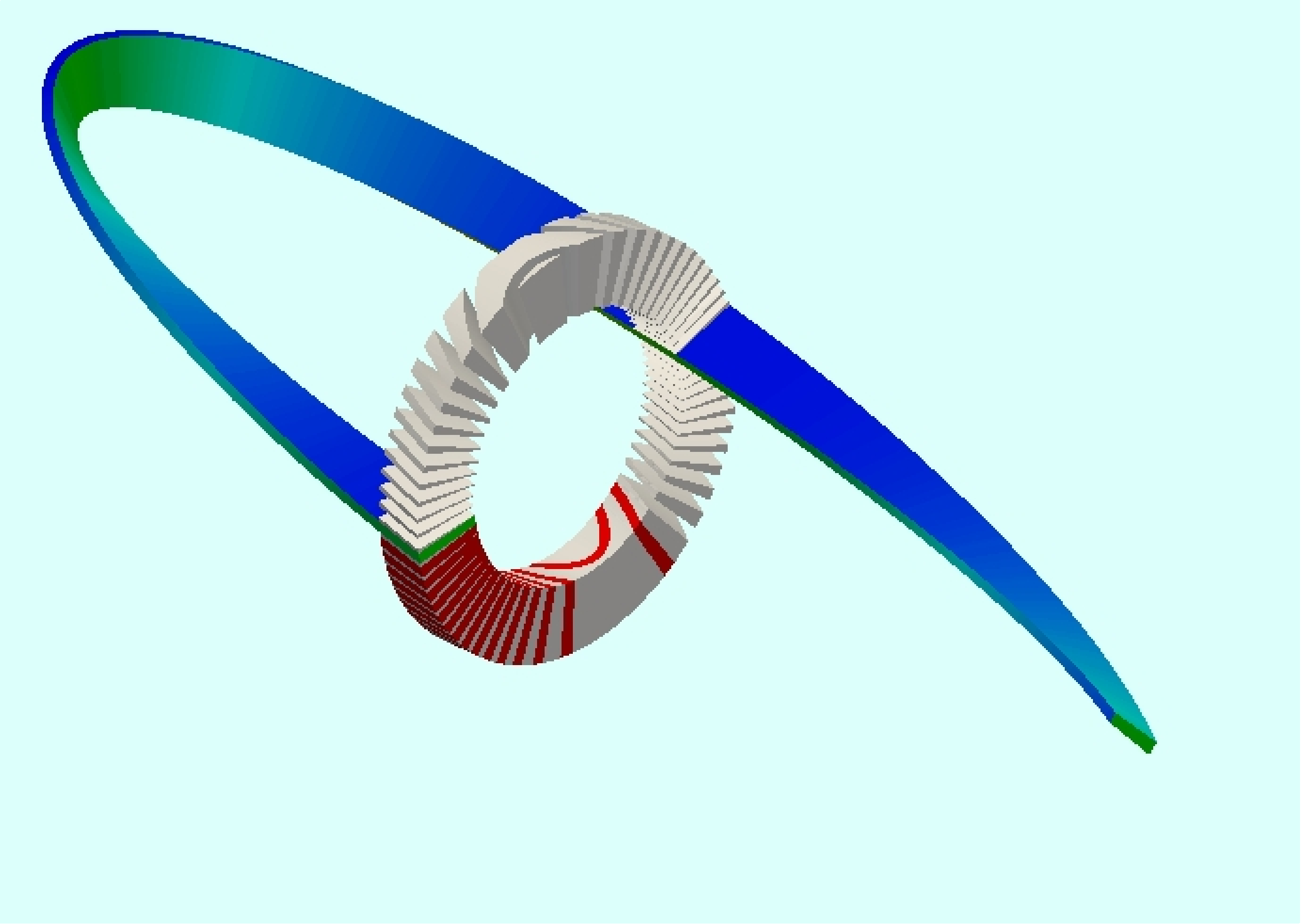
Symmetry - lamination



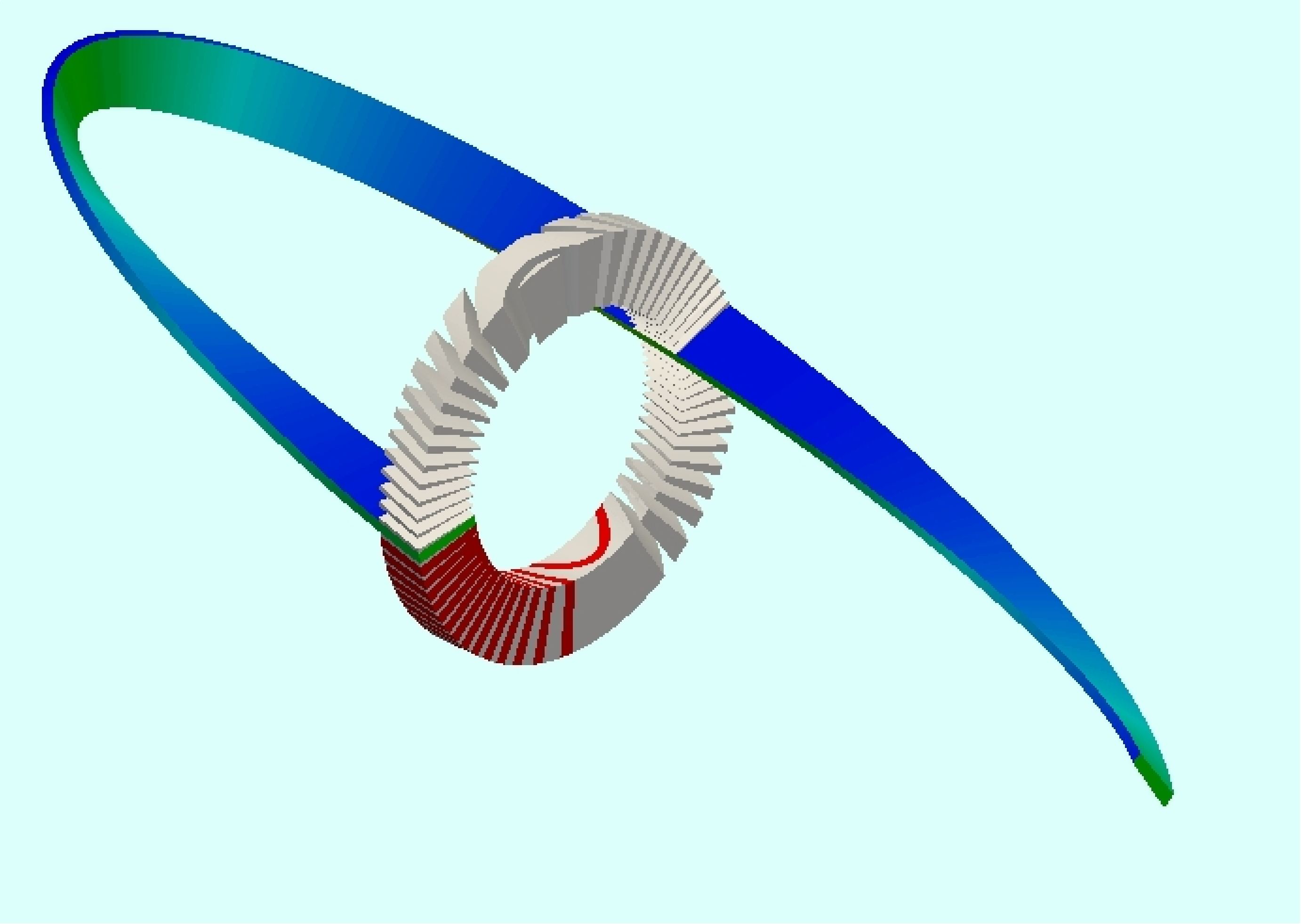
Symmetry - lamination



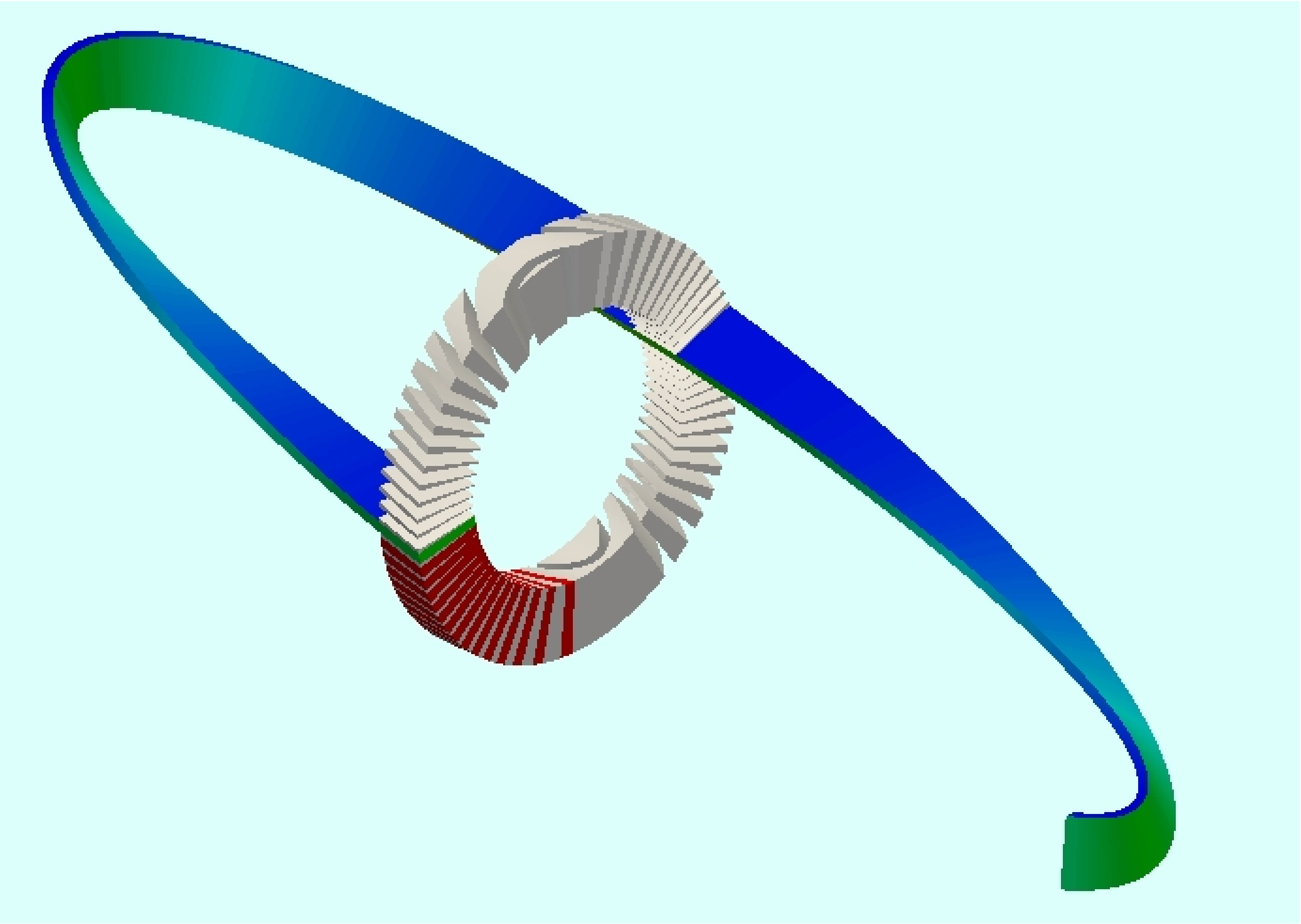
Symmetry - lamination



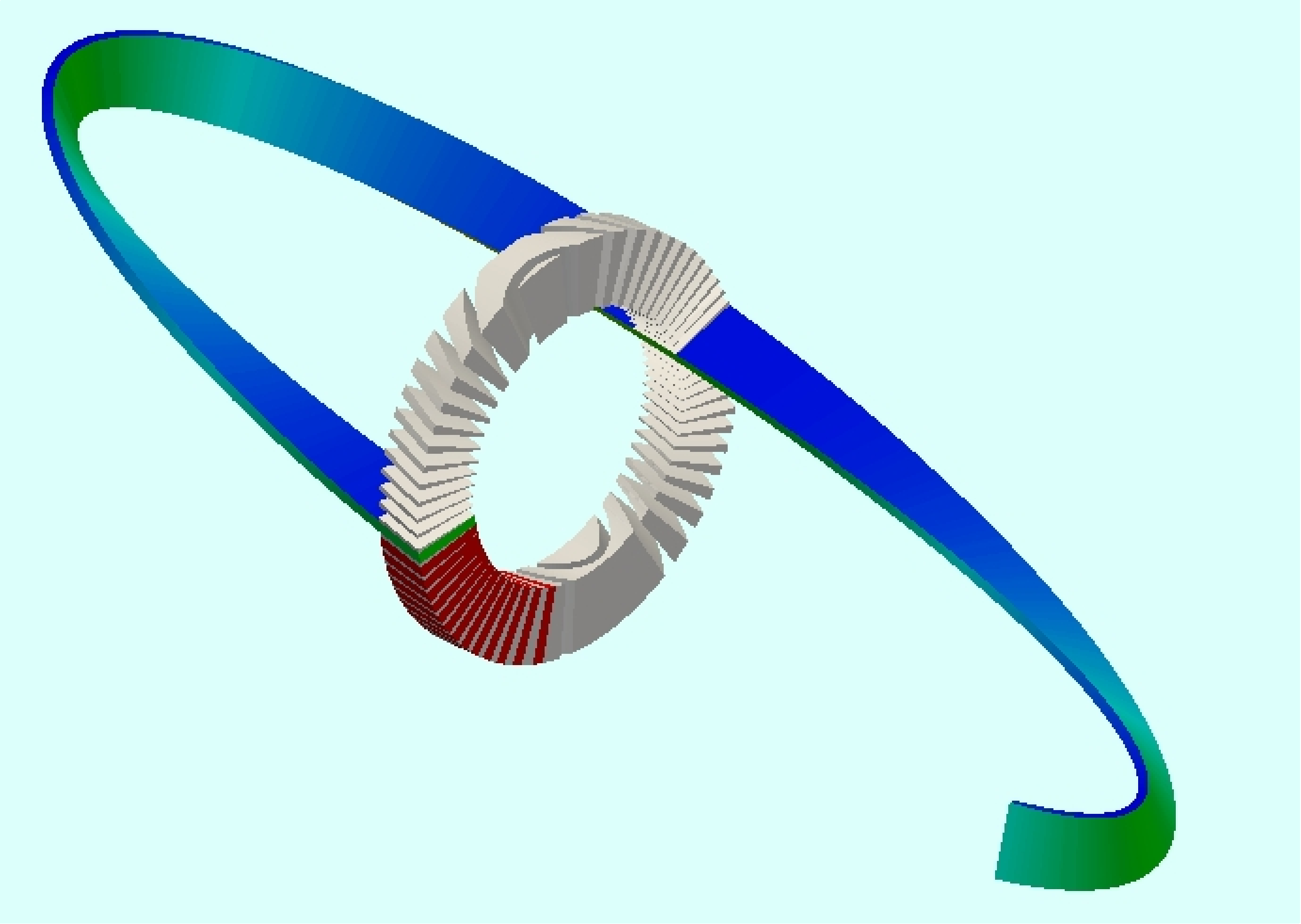
Symmetry - lamination



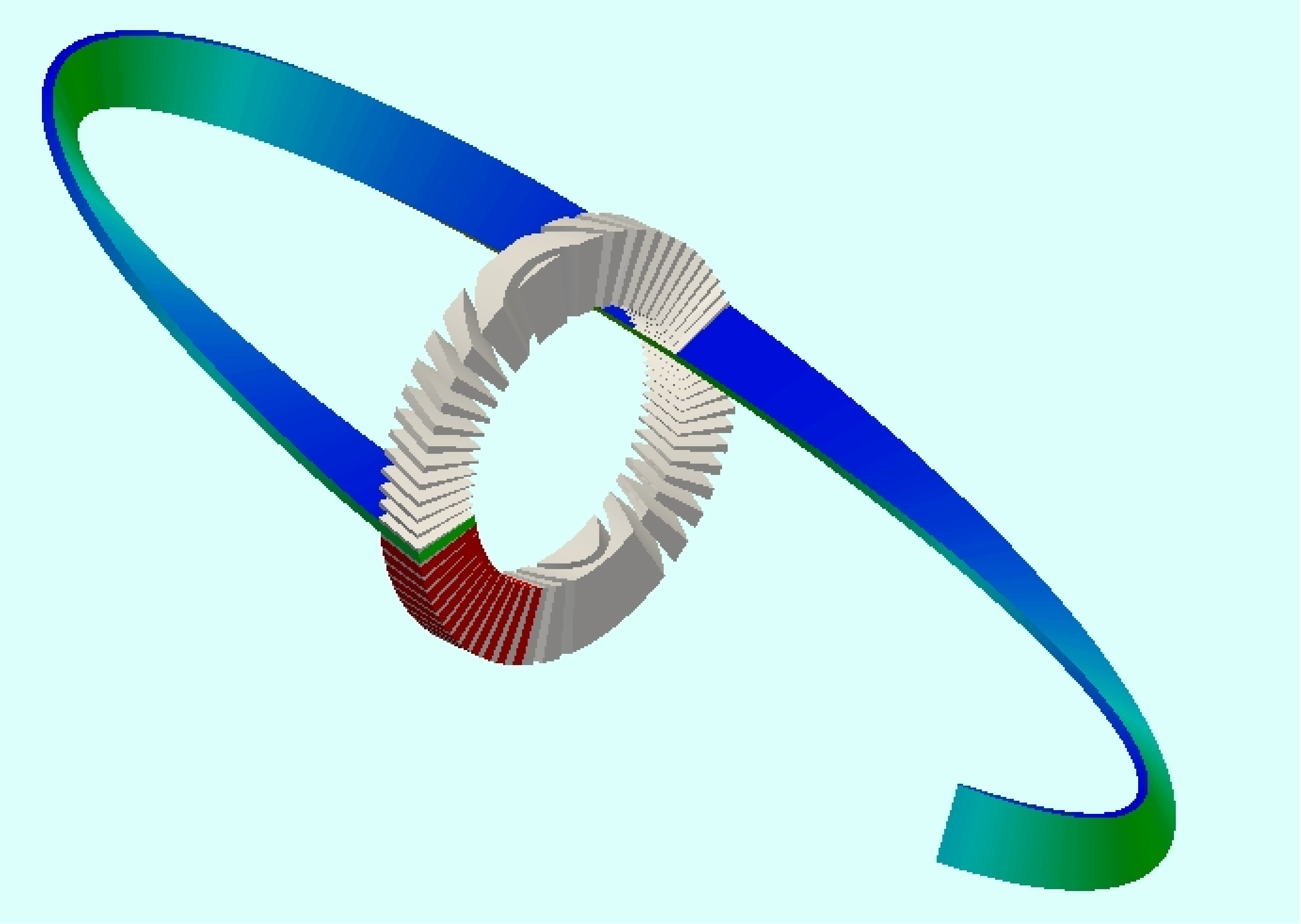
Symmetry - lamination



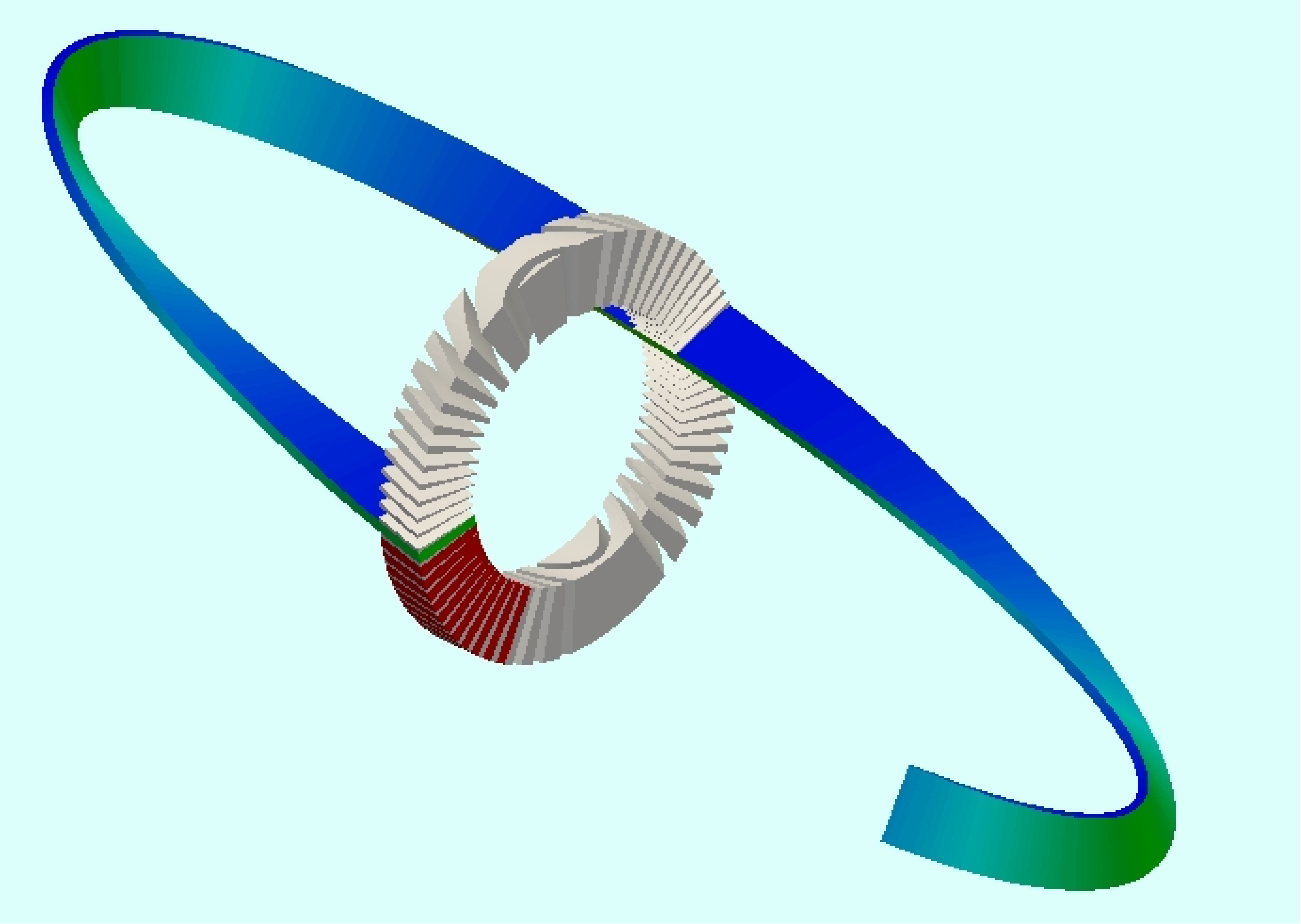
Symmetry - lamination



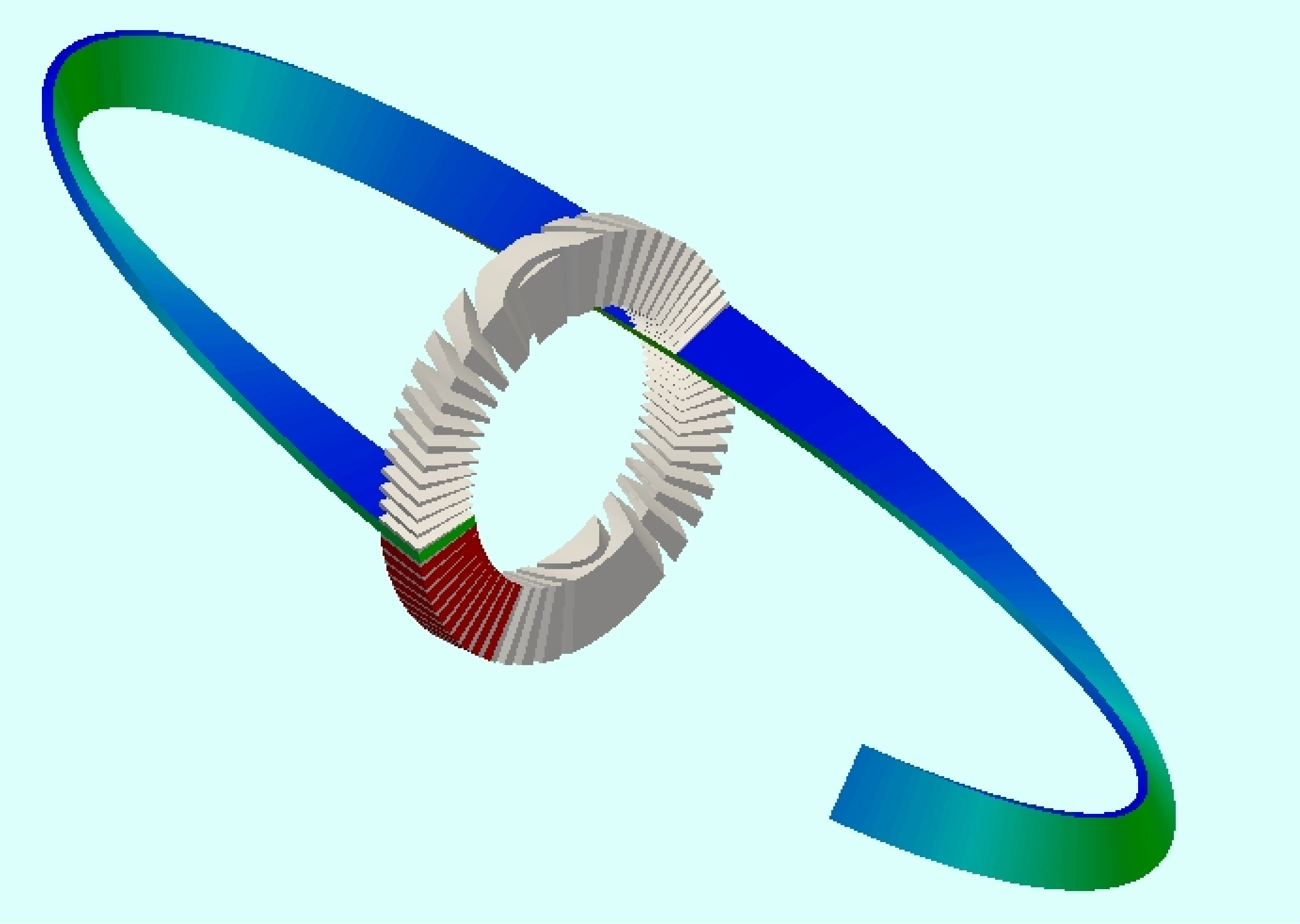
Symmetry - lamination



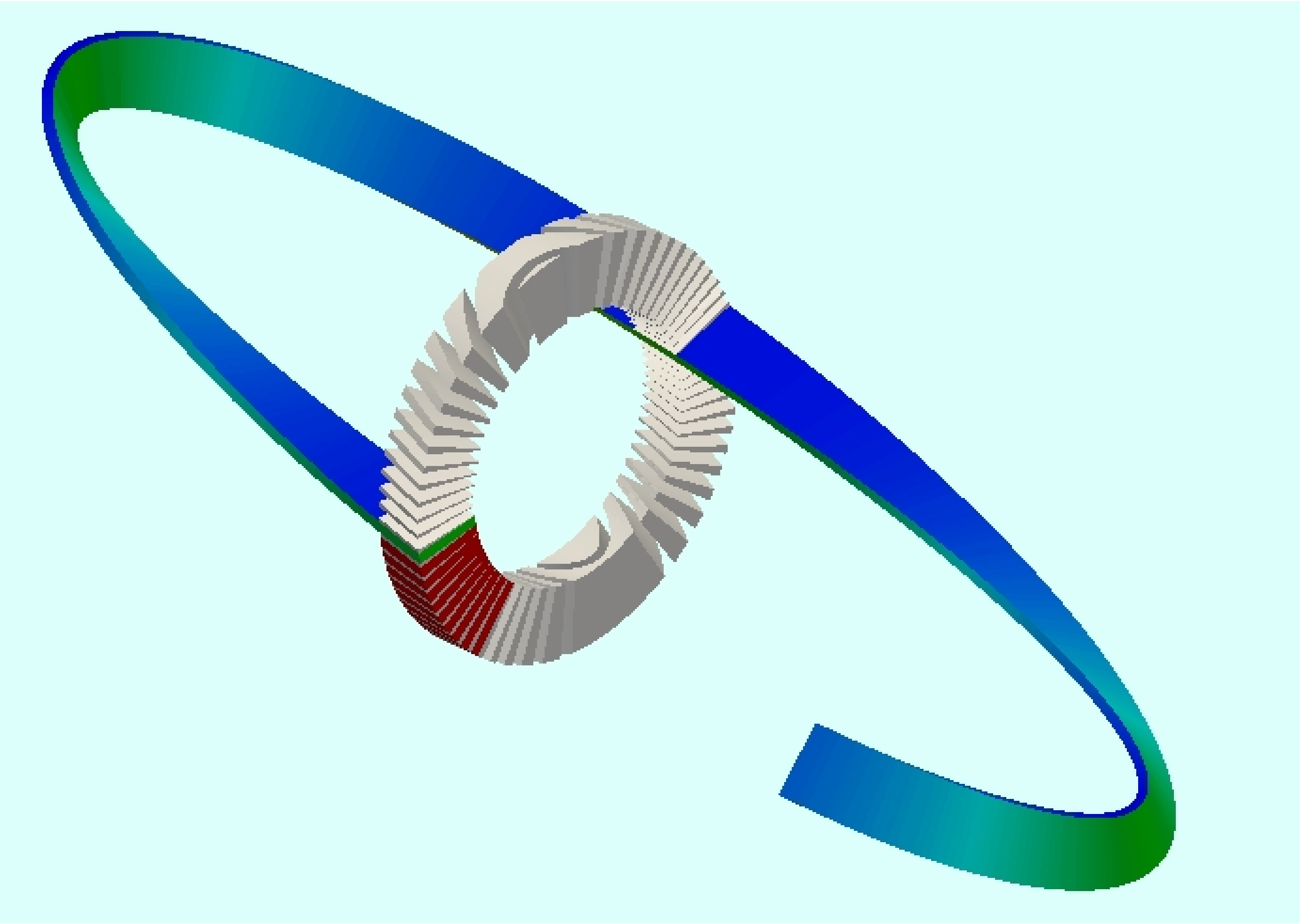
Symmetry - lamination



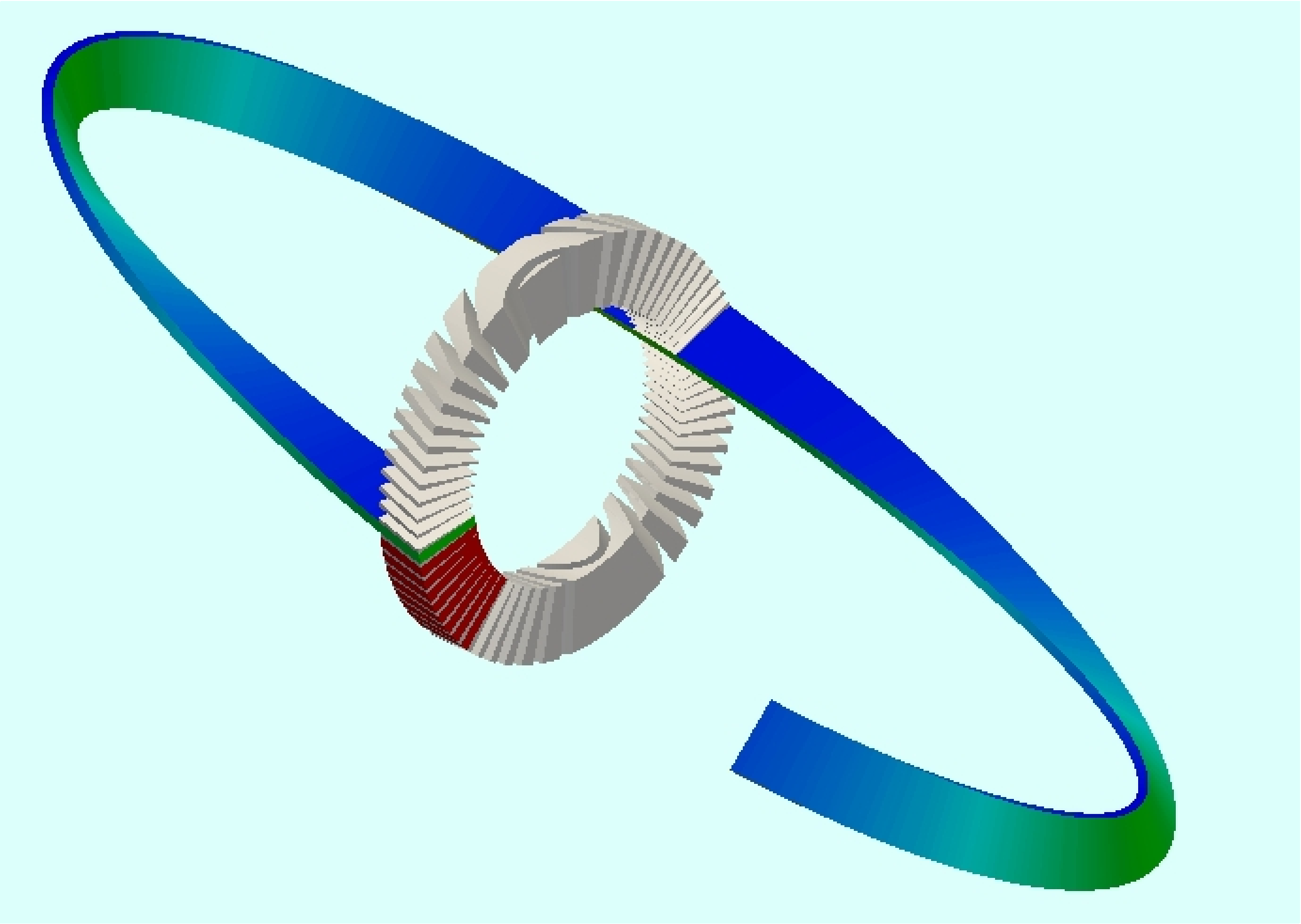
Symmetry - lamination



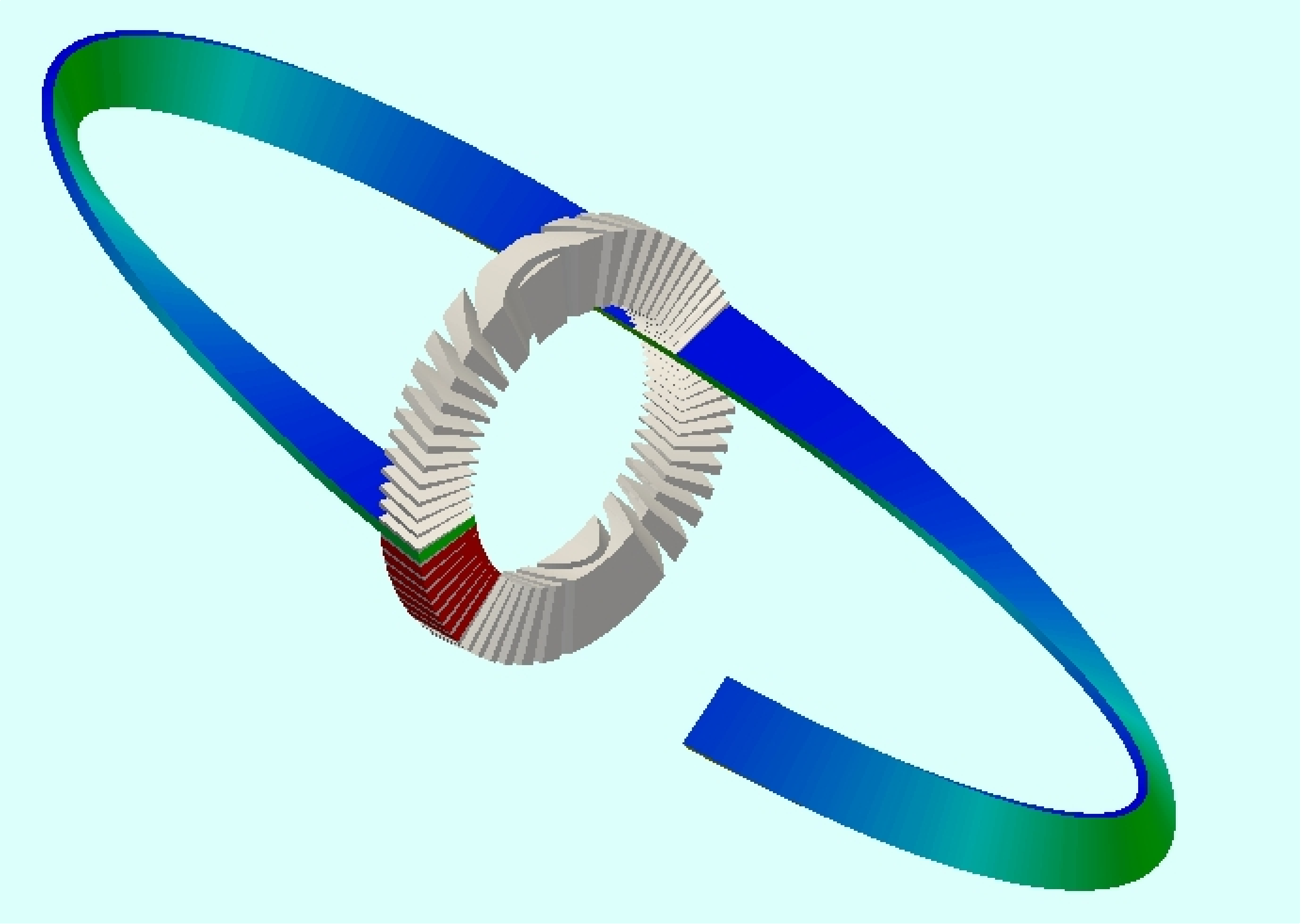
Symmetry - lamination



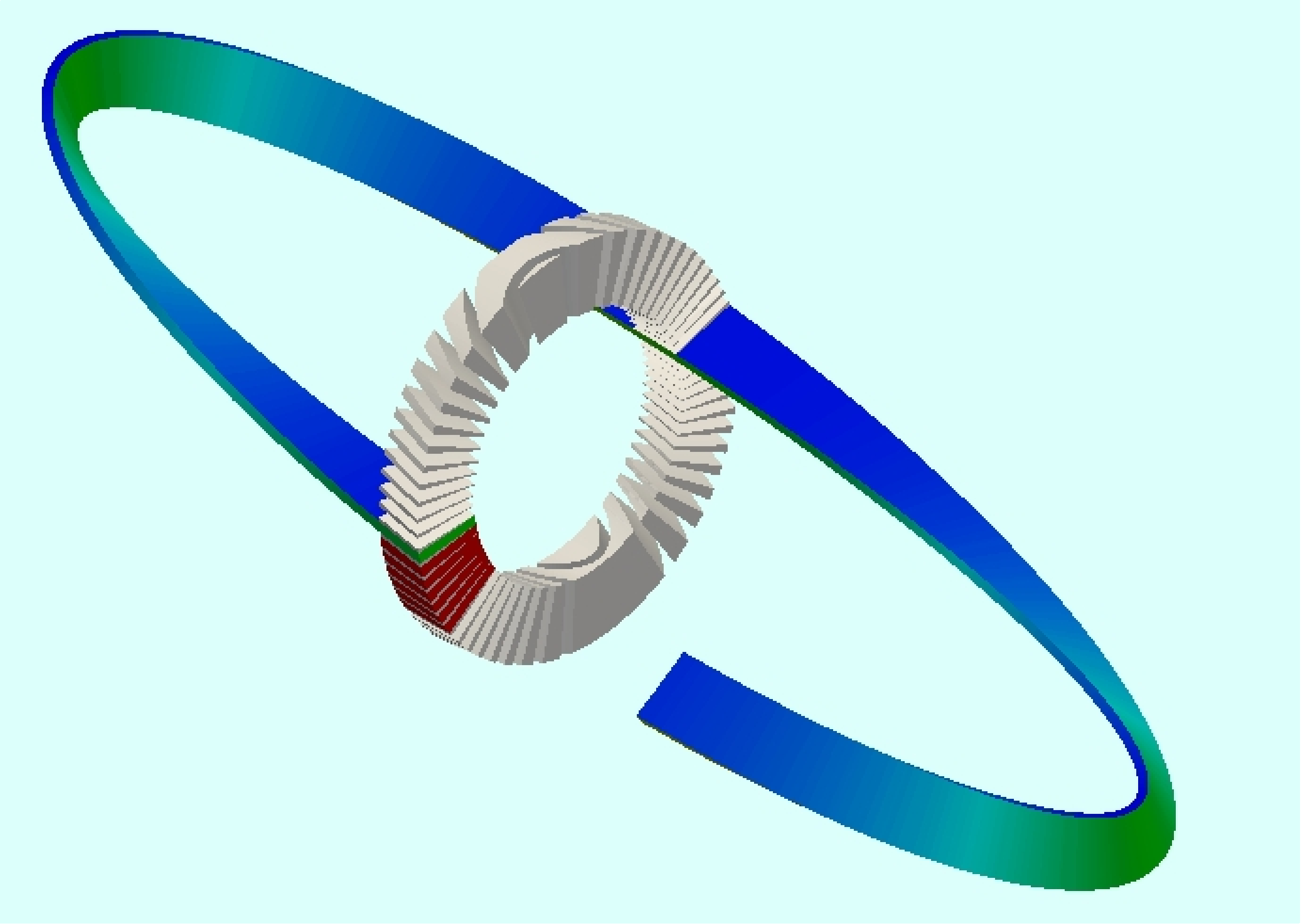
Symmetry - lamination



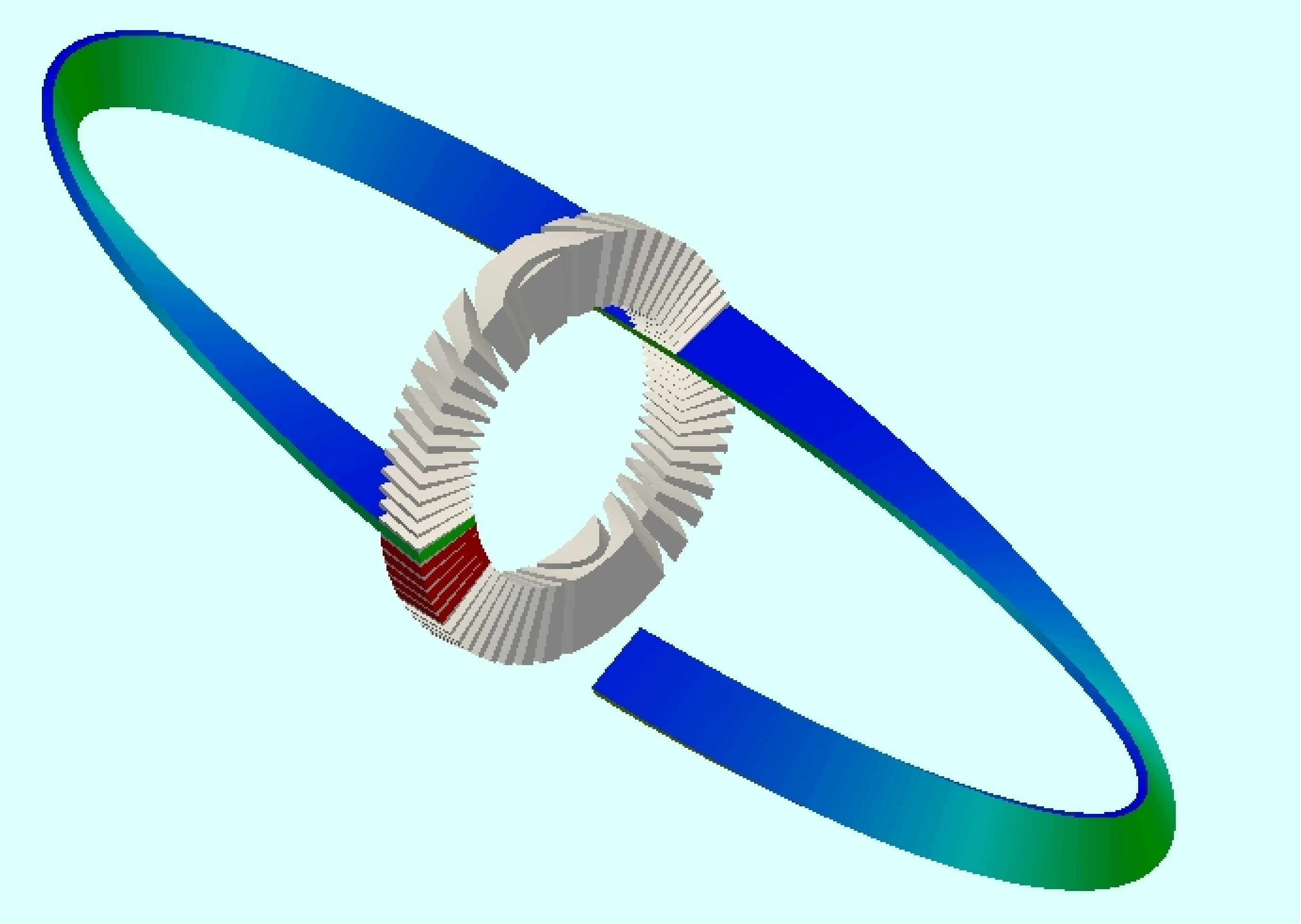
Symmetry - lamination



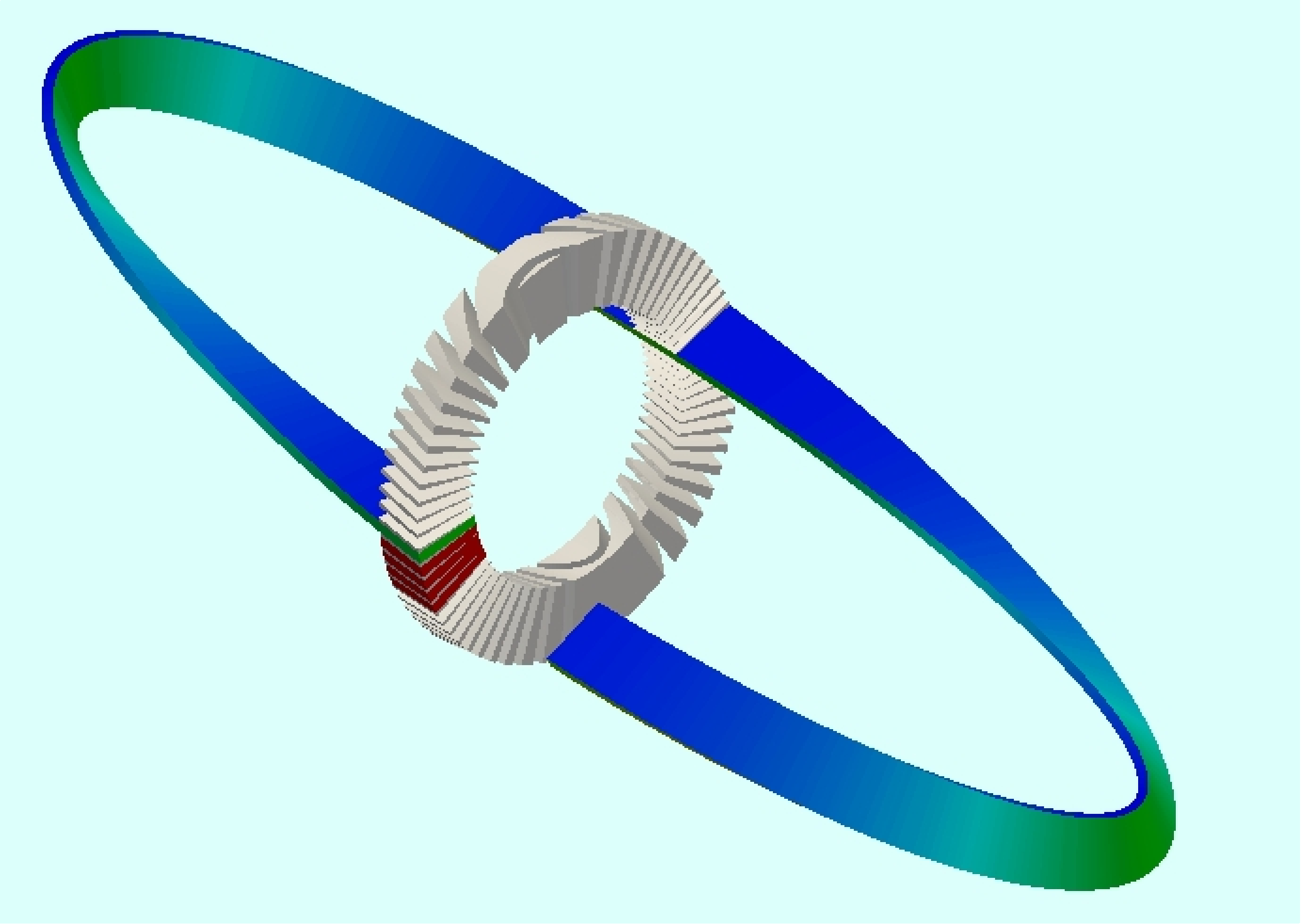
Symmetry - lamination



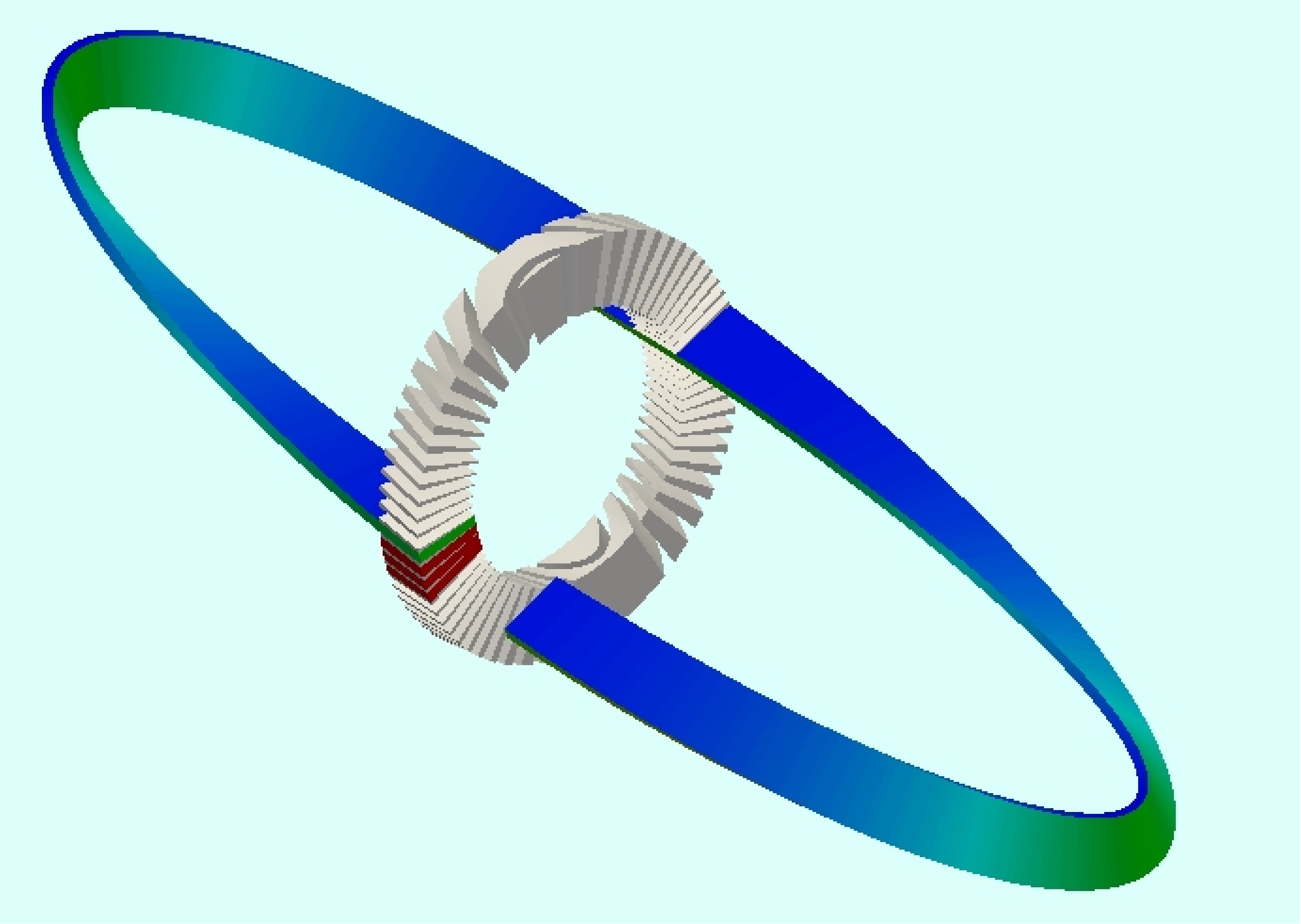
Symmetry - lamination



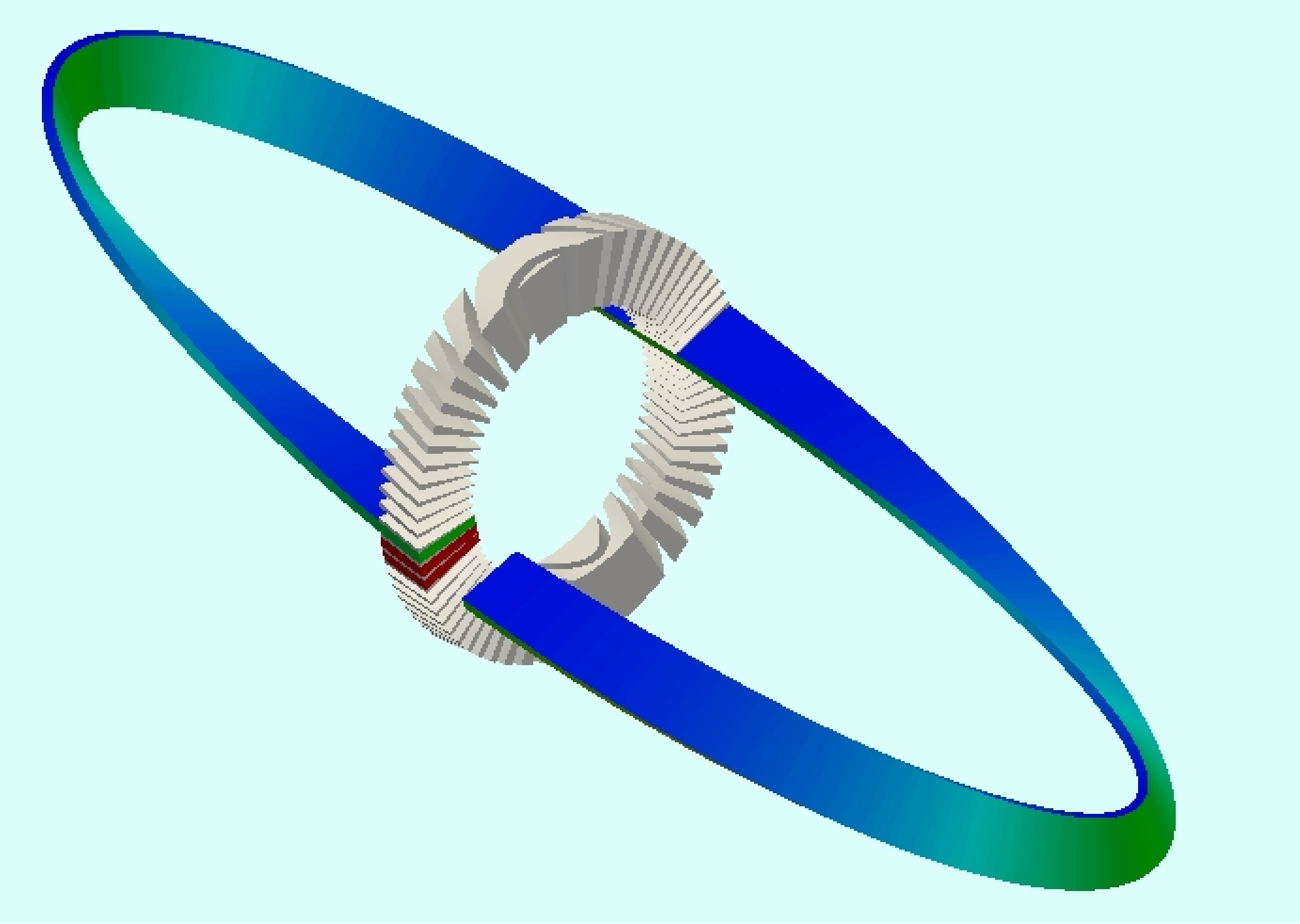
Symmetry - lamination



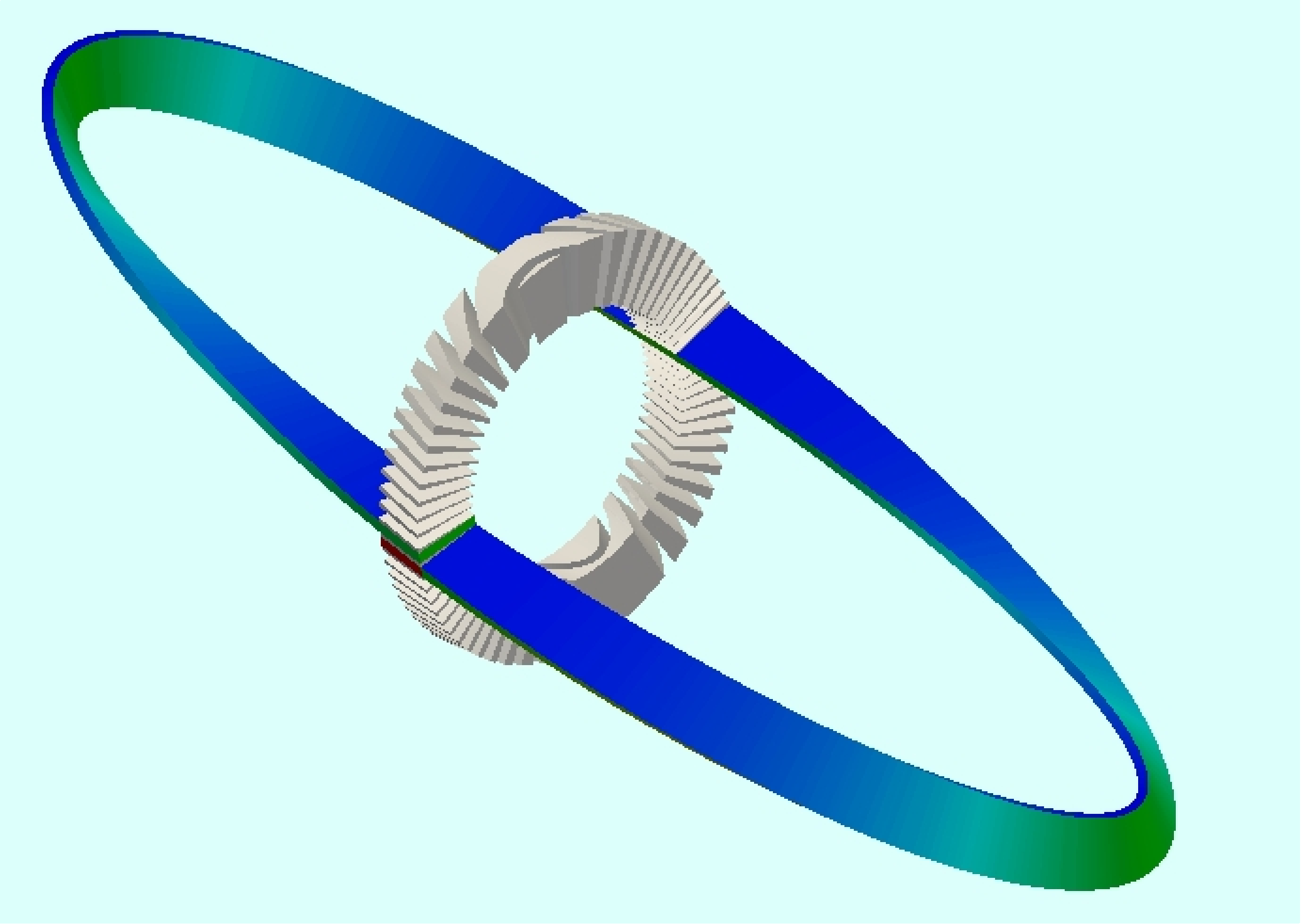
Symmetry - lamination



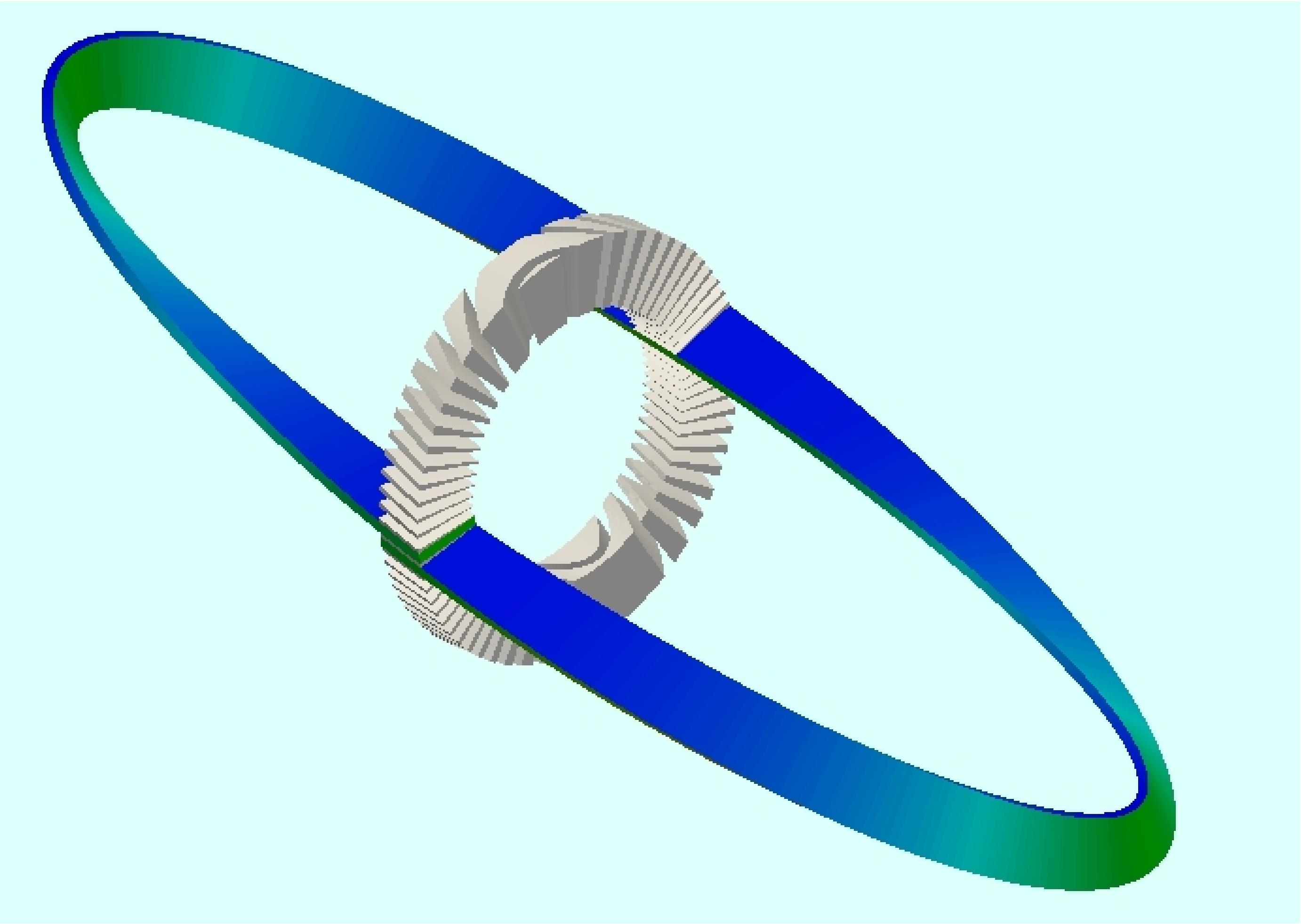
Symmetry - lamination



Symmetry - lamination



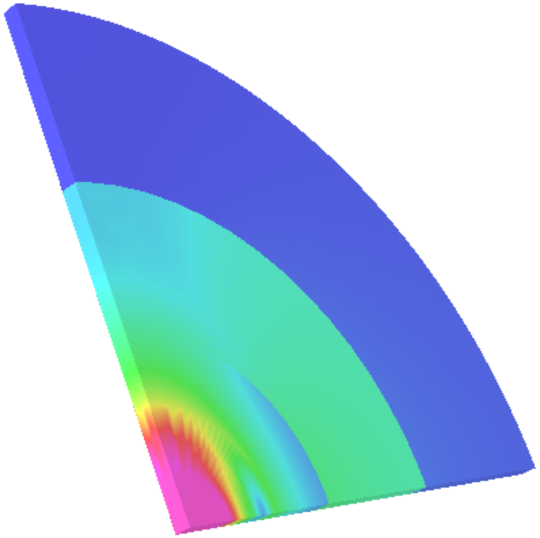
Symmetry - lamination



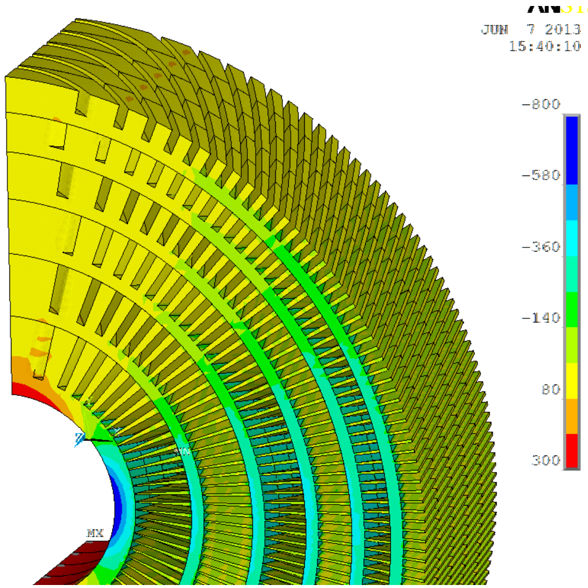
Lamination

Impact:

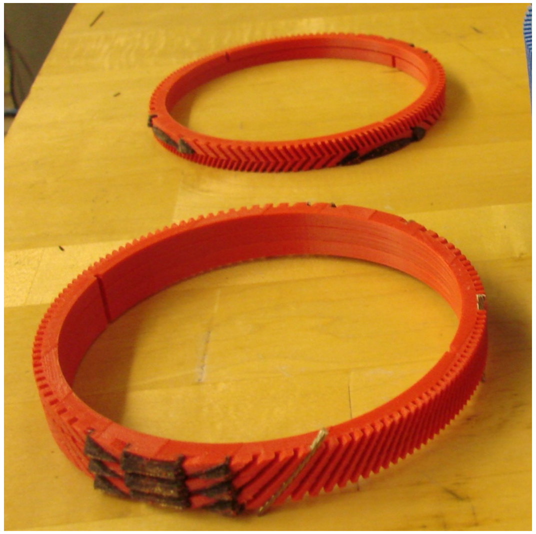
- **Design**
- **Construction**
- **Computation**



Magnetics
TOSCA



Structural ANSYS



Modeling using RP

Extension to a Curved Magnet

Similar advantages to a straight CCT

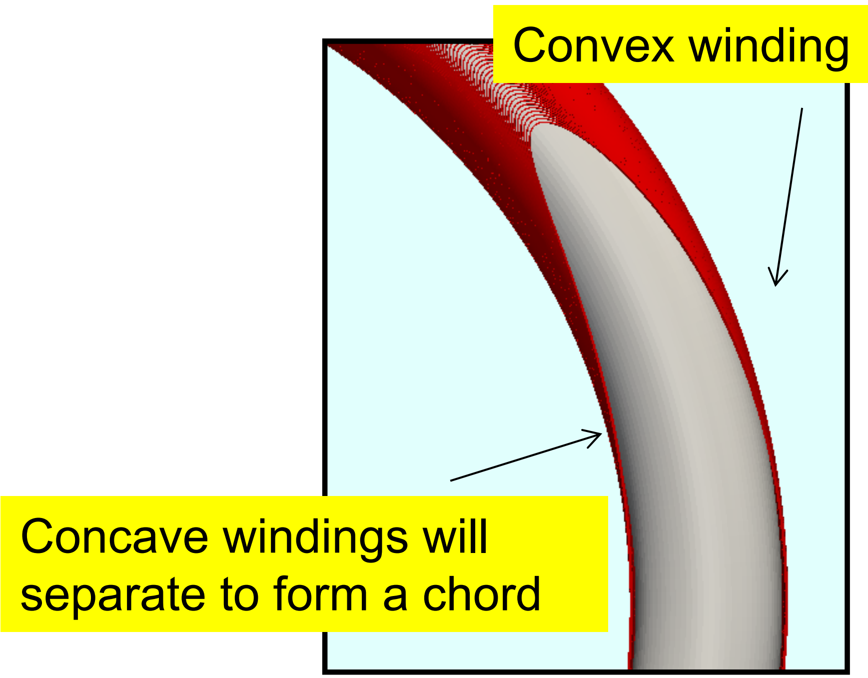
plus

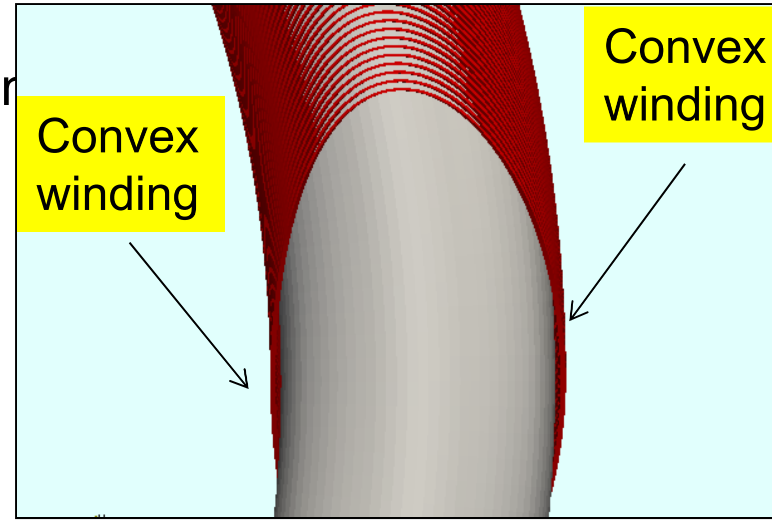
- Maintain winding on both sides of a curved magnet
- Defines relation between coil winding and beam position

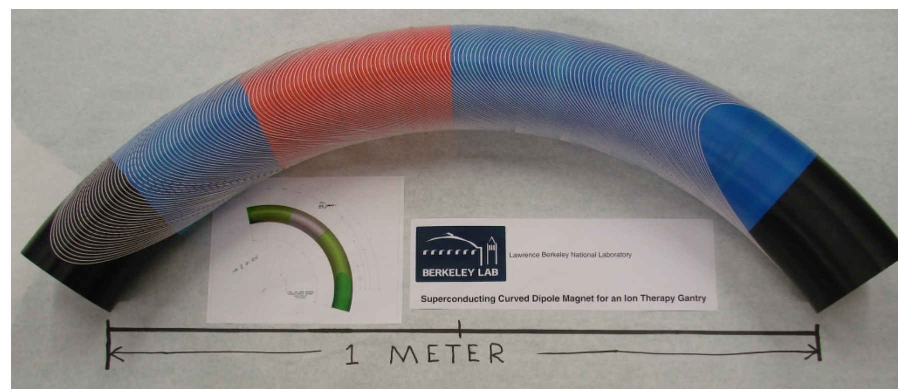
Maintaining Windings-Mandrel Contact

Curved Windings

- Limiting the winding tilt angle maintai
- No need for special winding tooling



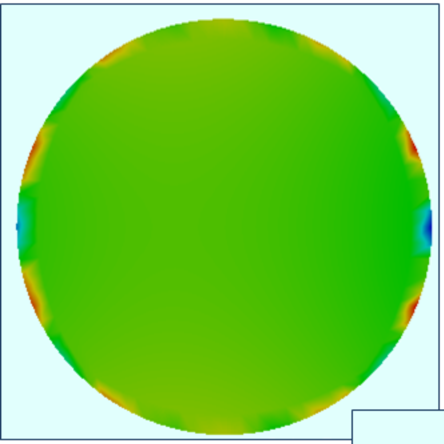


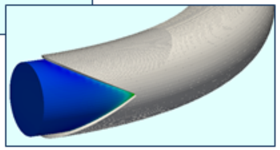


S. Caspi, et al. *A superconducting magnet mandrel with minimum symmetry laminations for proton therapy*, Nucl. Instrum. Meth.in Physics Research A 719, 2013

"Pure " 2D" Multipoles in Curved Geometry

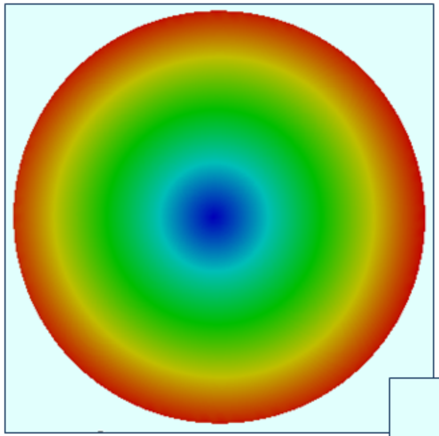
Dipole

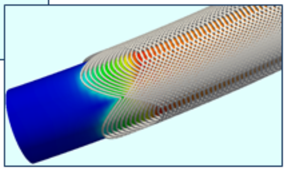




Uniform dipole field

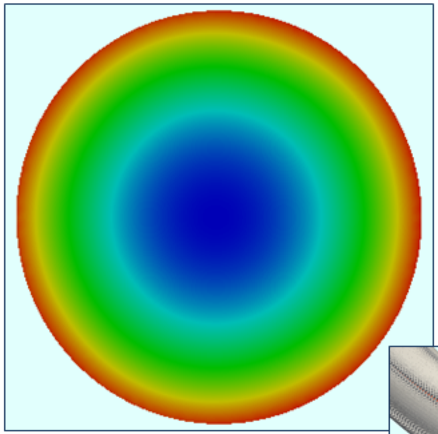
Quadrupole

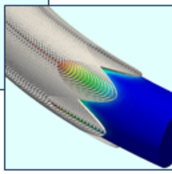




Uniform quadrupole field

Sextupole



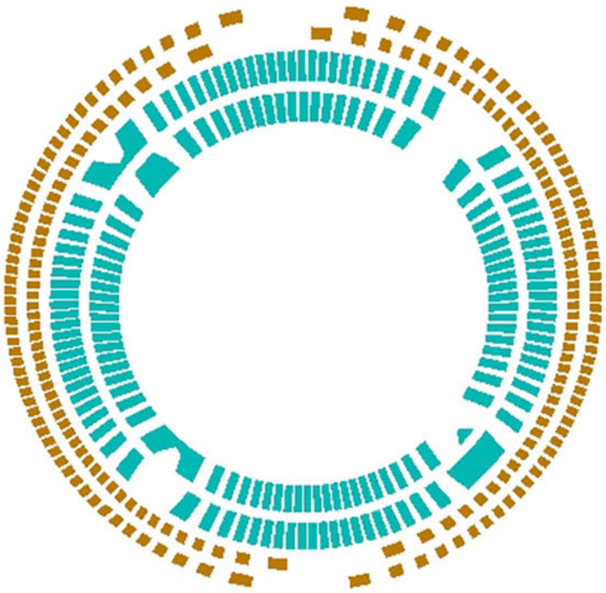


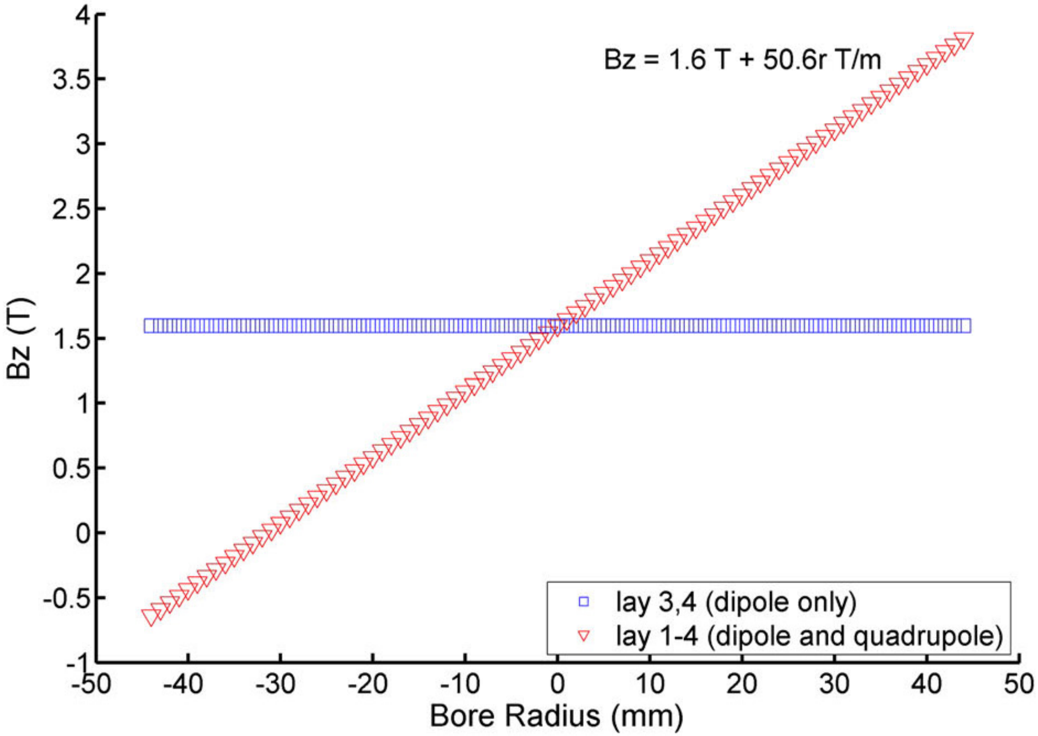
Uniform sextupole field

$$\phi = \theta / n + a_0 \sin\theta + a_1 \sin 2\theta + a_2 \sin 3\theta$$

Windings follow a path that negates harmonics that rise from the magnet curvature

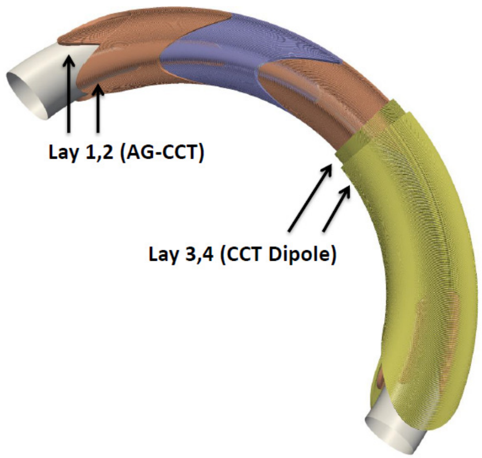
Concept of LBNL-PSI-Variant Final Bend

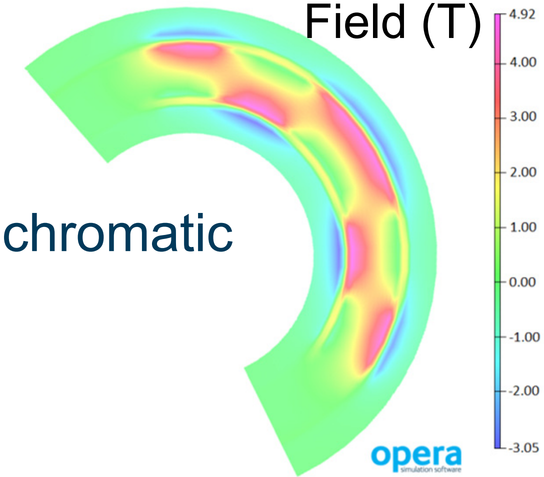




Dipole windings (outer two layers) and quadrupole windings (inner two layers)
W. Wan, L. Brouwer, S. Caspi, S. Prestemon, A. Gerbershagen, J.M. Schippers, and D. Robin, "Alternating-gradient canted cosine theta superconducting magnets for future compact proton gantries" Phys. Rev Accel. Beams, vol 18, 103501, 2015

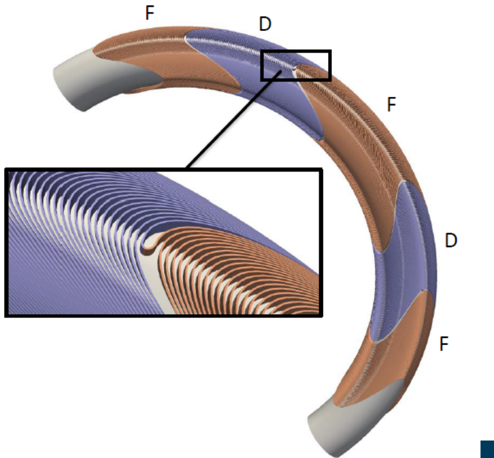
LBNL-PSI-Variant



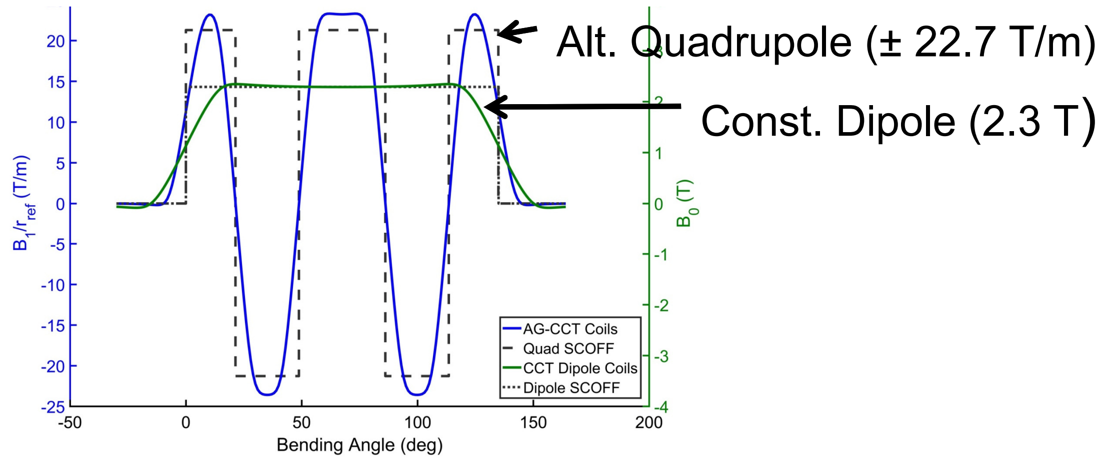


Locally achromatic

AG-CCT continuous alternating quadrupole coil (5 sections: FDFDF)



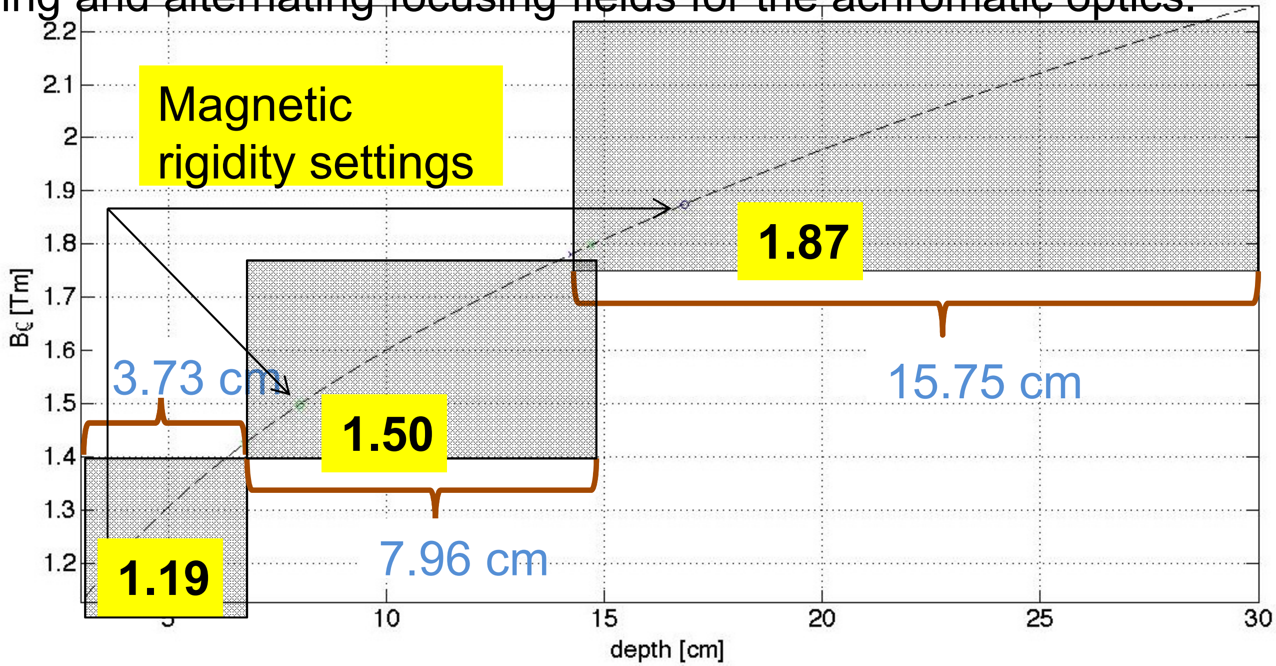
Coil field compared with desired integral multipoles



Design of an Achromatic Superconducting Magnet for a Proton Therapy Gantry

Recent studies have shown **strong, alternating focusing magnets can be used to greatly increase the energy acceptance of hadron therapy gantries**. The Canted-Cosine-Theta concept is extended to a curved magnet system generating the desired bending and alternating focusing fields for the achromatic optics.

Depth versus Momentum: Example 1% versus **25%** momentum range



L. Brouwer, S. Caspi, R. Hafalia, A. Hodgkinson, S. Prestemon, D. Robin, and W. Wan "Design of an Achromatic Superconducting Magnet for a Proton Therapy Gantry" paper 2LPO2H-07 to be published in *IEEE Transactions on Applied Superconductivity*, ASC September 2016.

Beam Meets Magnets for a Curved Gantry Dipole

1. Initial gantry optics study leads to magnet specifications
   - **optics code uses standard definition for sector bend fields/fringe**
   - specification of dipole, gradient, sextupole (local 2D multipoles)

2. Optimization/design of a multilayer CCT
   - **Generate the winding path based on the local multipole specification**

3. Particle tracking through the CCT coil design
   - Biot-Savart fields from coils used at **each tracking iteration**
     - **contains all field irregularities: end effects, radial spacing between coils, etc.**
   - re**adjustment of windings** or optics design are DA based with particle tracking, through the coils using the program software COSY .

A Four Layer Magnet Design

Specifications, NbTi Conductor

Bending Radius 900 mm
Bore Radius 105 mm
Magnetic Bend 135 deg
Momentum Acceptance (p/p) 20 %
Constant Dipole 2.3 T
Alternating Quadrupole 22.7 T/m
Stored Energy 0.86 MJ

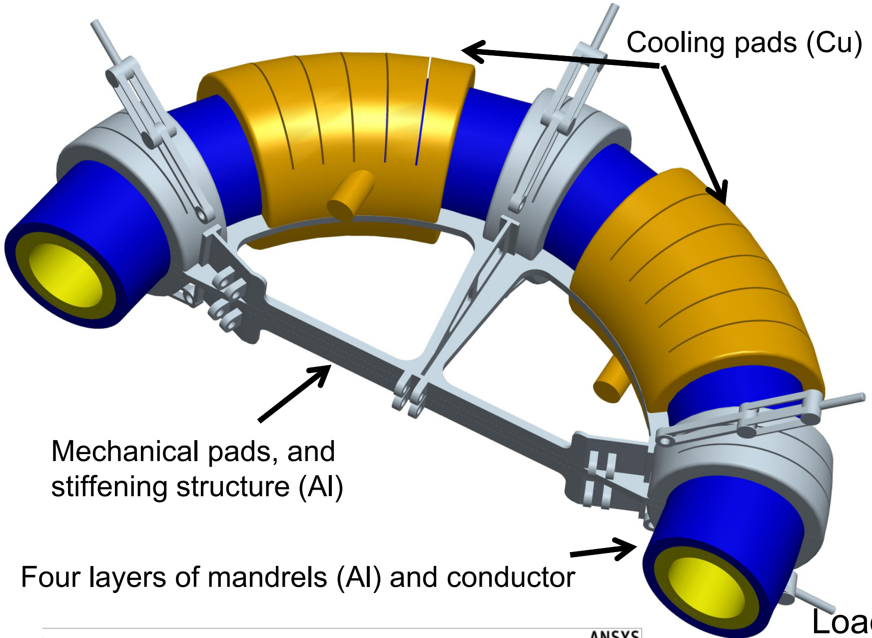
Bare Dimensions	1.6 x 1.6 mm
Insulated Dimensions	1.7 x 1.7 mm
Insulation	Formvar
Cu:SC	2.8:1
Filament Diameter	20 μm
Ic (5 T, 4.2 K)	1570 A

Short Sample: current and temperature

Individual power supplies
5.2 T peak field at the conductor
30% current and 1.25 K temperature margin

Lay	Type	I/Wire	Wires	B_{cond}	I_c Mar.	Temp. Mar.
1	AG-CCT	763 A	8	5.2 T	29%	1.25 K
2	AG-CCT	763 A	8	5.2 T	29%	1.25 K
3	CCT dipole	922 A	6	4.7 T	29%	1.25 K
4	CCT dipole	922 A	6	3.8 T	45%	1.70 K

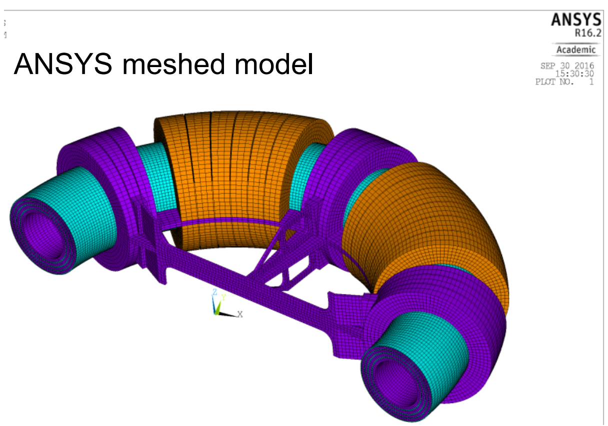
Weight-Displacements-Stress



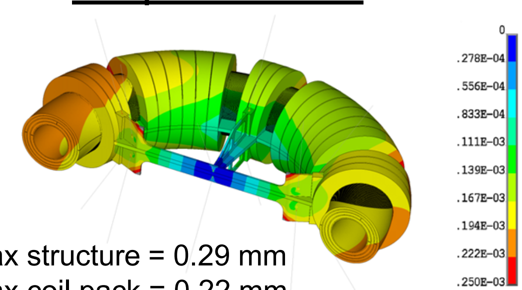
Conductor length, dipole & quad (km)	14.9
Conductor/Epoxy weight (kg)	358
Al Mandrels weight (kg)	323
Total dipole & quad (kg)	681
Al+Cu External support structure (kg)	550
Cold mass total (kg)	**1231**
Weight (t/m)	**0.6**

Load steps: (1) pre-tension (2) cooldown to 4.2 K, (3) Lorentz forces

ANSYS meshed model

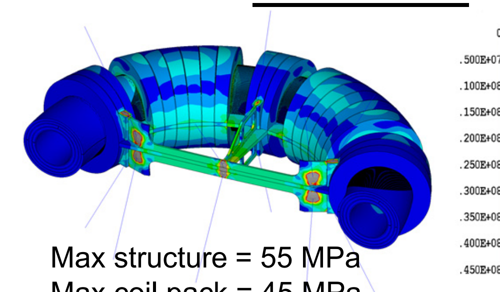


Displacement



Max structure = 0.29 mm
Max coil pack = 0.22 mm

von Mises



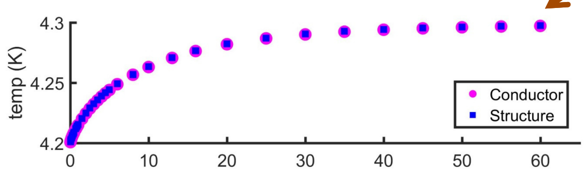
Max structure = 55 MPa
Max coil pack = 45 MPa

Thermal Analysis

<u>For a Dipole Ramp Rate of **0.02 T/s**</u>

mandrel eddy loss vs. **lamination angle 6 deg.**

peak conductor and structure are similar

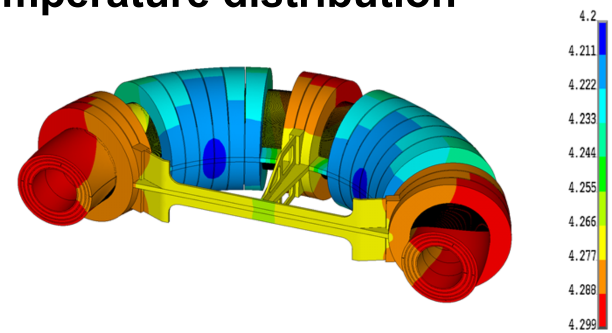


Peak Temp (K)	4.63
Min. Margin (K)	1.17
Peak Power (W)	6.3
Int. Pow./Duty (W)	2.11

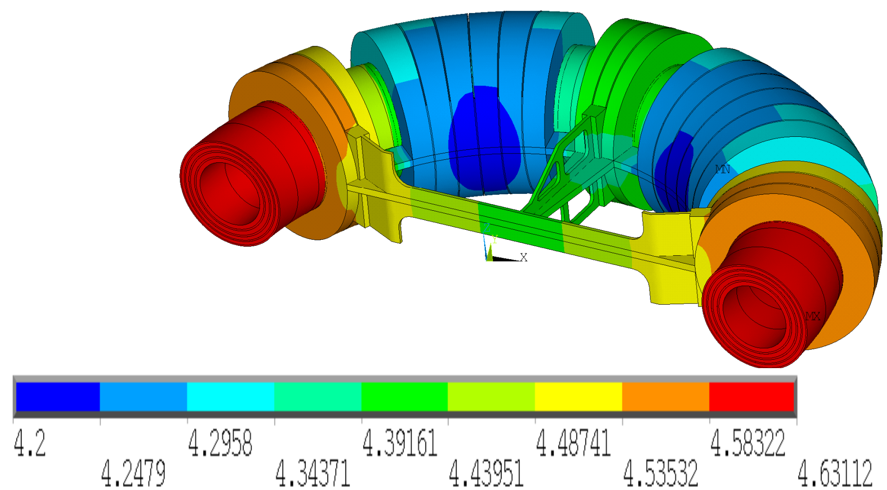
Eddy currents	Hysteresis (dominate at low rates)	Inter-filament-coupling (dominate at high rates)	Stabilizer	total
0.31	1.08	0.408	0.313	2.11 W

baseline conductor at peak temperature

steady state temperature distribution



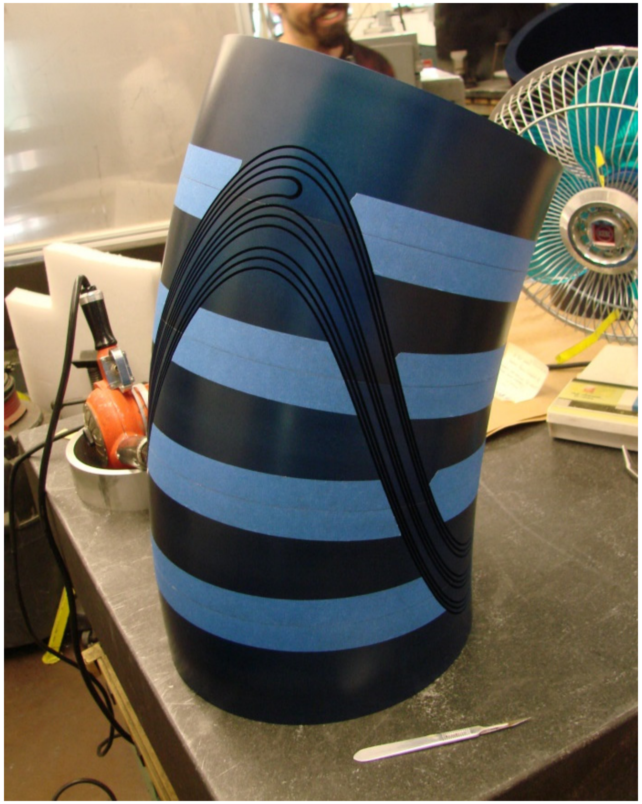
eddy current and AC loss loads applied



Assembly of laminations using a thermal dovetail

The practice coil -- inner two quadrupole layers

- 5 sections reduced to a 30 degrees sector
- bore radius, conductor channel depth, and bend radius are the same



SUMMARY

- A Superconducting final bend magnet for gantries weighs only a few tons
- Iron is excluded to reduce magnet weight
- AG-CCT high momentum acceptance benefits the optics, reduces ramp rates
- The CCT provides a way of winding curved multipole magnets
- A way of handling field quality and reduce Lorentz stress on the conductor
- Integrates beams and magnet to track all field irregularity during the design phase

see Lucas Brouwer dissertation for many details:
http://escholarship.org/uc/item/8jp4g75g

[1] W. Wan, L. Brouwer, S. Caspi, S. Prestemon, D. Robin, A. Gerbershagen, and J. M. Schippers, “Alternating-gradient canted cosine theta superconducting magnets for future compact proton gantries,” Physical Review Special Topics - Accelerators and Beams, vol. 18, no. 10, p.103501, 2015.
[2] “Workshop on Ion Beam Therapy Summary Report,” 2013. [Online]. Available: http://science.energy.gov//media/hep/pdf/ accelerator-rd stewardship/Workshop on Ion Beam Therapy Report Final R1.pdf
[3] J. Alonso and T. Antaya, “Superconductivity in medicine,” Rev. Accl. Sci. Tech., vol. 5, pp. 227–263, 2012.
[4] Y. Iwata, K. Noda, T. Shirai, T. Murakami, and T. Furukawa, “Design of a superconducting rotating gantry for heavy-ion therapy,” Physical Review Special Topics - Accelerators and Beams, vol. 15, no. 4, p. 044701, 2012.
[5] Y. Iwata, K. Noda, T. Shirai, T. Furukawa, and T. Murakami, “Development of Curved Combined-Function Superconducting Magnets for a Heavy-Ion Rotating-Gantry,” IEEE Trans. Appl. Supercond., vol. 23, no. 3, p. 4400505, 2014.
[6] V. Derenchuk, “The ProNova SC360 Gantry, Modern Hadron Therapy Gantry Developments, Cockcroft Institute, January, 2014.”
[7] Y. Iwata, T. Fujimoto, S. Matsuba, T. Fujita, S. Sato, T. Furukawa, Y. Hara, K. Mizushima, Y. Saraya, R. Tansho, N. Saotome, T. Shirai, and K. Noda, “Beam commissioning of a superconducting rotating-gantry for carbon-ion radiotherapy,” Nucl. Instrum. Methods Phys. Res. A, vol. 834, pp. 71–80, 2016.
[8] C. Priano, P. Fabbricatore, S. Farinon, R. Musenich, M. Perrella, and S. Squarcia, “A Superconducting Magnet for a Beam Delivery System for Carbon Ion Cancer Therapy,” IEEE Trans. Appl. Supercond., vol. 12, no. 1, pp. 988–992, 2002.
[9] D. Trbojevic, R. Gupta, E. Keil, B. Parker, and A. Sessler, “Superconducting Non-scaling FFAG Gantry for Carbon/Proton Cancer Therapy,” in Proceedings of IPAC2007, 2007, p. THPMS092.
[10] A. Gerbershagen, D. Meer, J. Schippers, and M. Seidel, “A novel beam optics concept in a particle therapy gantry utilizing the advantages of superconducting magnets,” Z. Med. Phys., p. 10664, 2015.
[11] C. Calzolaio, S. Sanfilippo, M. Calvin, A. Gerbershagen, M. Negrazus, J. Schippers, and M. Seidel, “Preliminary Magnetic Design of a Superconducting Dipole for Future Compact Scanning Gantries for Proton Therapy,” IEEE Trans. Appl. Supercond., vol. 26, no. 3, p. 4401005, 2016.
[12] D. Meyer and R. Flasck, “A new configuration for a dipole magnet for use in high energy physics applications,” Nucl. Instr. Meth. Phys. Res. A, vol. 80, no. 2, pp. 339–341, 1970.
[13] C. Goodzeit, M. Ball, and R. Meinke, “The Double-Helix Dipole – a Novel Approach to Accelerator Magnet Design,” IEEE Trans. Appl. Supercond., vol. 13, no. 2, pp. 1365–1378, 2003.
[14] S. Caspi, F. Borgnolutti, L. Brouwer, D. Cheng, D. R. Dietderich, H. Felice, A. Godeke, R. Hafalia, M. Martchevskii, S. Prestemon, E. Rochepault, C. Swenson, and X. Wang, “The Canted-Cosine-Theta Magnet (CCT) - a Concept for High Field Accelerator Magnets,” IEEE Trans. Appl. Supercond., vol. 24, no. 3, p. 4001804, 2014.

[15] D. Robin, D. Arbelaez, S. Caspi, C. Sun, A. Sessler, W. Wan, and M. Yoon, “Superconducting toroidal combined-function magnet for a compact ion beam cancer therapy gantry,” Nucl. Instr. Meth. Phys. Res. A, vol. 659, no. 1, pp. 484–493, 2011.
[16] S. Caspi, D. Arbelaez, H. Felice, R. Hafalia, D. Robin, C. Sun, W. Wan, and M. Yoon, “Conceptual Design of a 260 mm Bore 5 T Superconducting Curved Dipole Magnet for a Carbon Beam Therapy Gantry,” IEEE Trans. Appl. Supercond., vol. 22, no. 3, p. 4401204, 2012.
[17] S. Caspi, D. Arbelaez, L. Brouwer, D. Dietderich, H. Felice, R. Hafalia, S. Prestemon, D. Robin, C. Sun, and W. Wan, “A superconducting magnet mandrel with minimum symmetry laminations for proton therapy,” Nucl. Instr. Meth. Phys. Res. A, vol. 719, pp. 44–49, 2013.
[18] M. Berz and K. Makino, Michigan State University Technical Report, no. MSUHEP-060803, 2006.
[19] A. V. Gavrilin, M. D. Bird, V. E. Keilin, and A. V. Dudarev, “New concepts in transverse field magnet design,” IEEE Trans. Appl. Supercond., vol. 13, no. 2, pp. 1213–1216, 2003.
[20] H. Witte, T. Yokoi, S. Sheehy, and K. Peach, “The Advantages and Challenges of Helical Coils for Small Accelerators - A Case Study,” IEEE Trans. Appl. Supercond., vol. 22, no. 2, p. 4100110, 2012.
[21] S. Farinon and P. Fabbricatore, “Refined modeling of superconducting double helical coils using finite element analyses,” Supercond. Sci. Technol., vol. 25, no. 6, p. 065006, 2012.
[22] C. Goodzeit, R. Meinke, and M. Ball, “Combined function magnets using double-helix coils,” in Proceedings of IPAC2007, 2007, pp. 560– 562.
[23] L. Brouwer, D. Arbelaez, S. Caspi, H. Felice, S. Prestemon, and E. Rochepault, “Structural Design and Analysis of Canted-Cosine-Theta Dipoles,” IEEE Trans. Appl. Supercond., vol. 24, no. 3, p. 4001506, 2014.
[24] K. Chow and G. Millos, “Measurements of Modulus of Elasticity and Thermal Contraction of Impregnated Niobium-Tim and Niobium- Titanium Composites,” IEEE Trans. Appl. Supercond., vol. 9, no. 2, pp. 213–215, 1999.
[25] M. Wilson, Superconducting Magnets. Oxford University Press, 1983.
[26] B. Turck, F. Lefevre, M. Polak, and L. Krempasky, “Coupling losses in rectangular multifilamentary superconducting composite,” Cryogenics, vol. 22, no. 9, pp. 441–450, 1982.
[27] L.J.Laslett, S.Caspi and M. Helm, Conguration of coil ends for multipole magnets, Particle Accelerators Vol. 22, pp. 1-14, 1987.
[28] S. Caspi, M. Helm and L.J. Laslett, The use of harmonics in 3D magnetic fields IEEE Trans. On Magnetics, Vol. 30 pp. 2419-2422, July 1994.
[29] A. Devred, et al., Overview and status of the next European dipole joint research activity, Supercond. Sci. Technol. 19, pp 67-83, 2006.
[30] S. Caspi, D.R. Dietderich, P. Ferracin, N.R. Finney, M.J. Fuery, S.A. Gourlay, and A.R. Hafalia, Design, Fabrication, and Test of a Superconducting Dipole Magnet Based on Tilted Solenoids, IEEE Trans. Appl. Supercond, Vol. 17, part 2, pp. 2266-2269, 2007.