# Magnetic Design Studies of the Sextupole

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Prototype Lattice Magnet Design Review

January 28, 2008

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# Overview

## Considerations in the Development of Sextupole Design

**Iron poles should clear the beam tube:**

- A major consideration in the development of the design
- Beam tube was shaved but had still left with sufficient material
- Aperture was increased from 66 mm to 68 mm

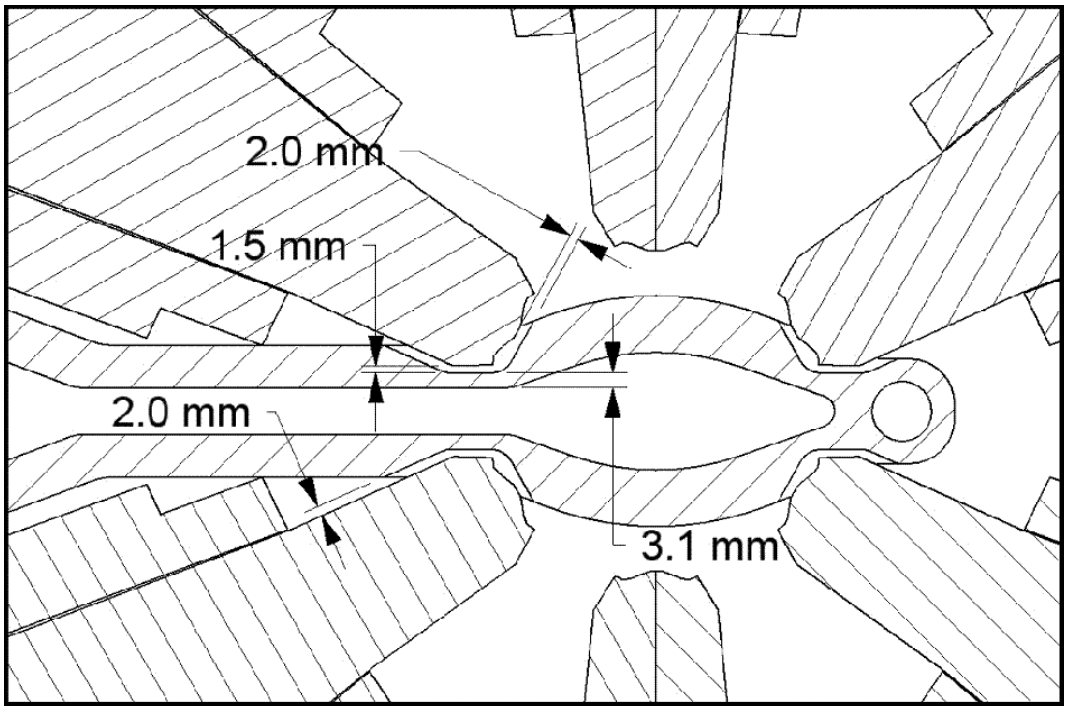
**Obtain the desired field quality:**

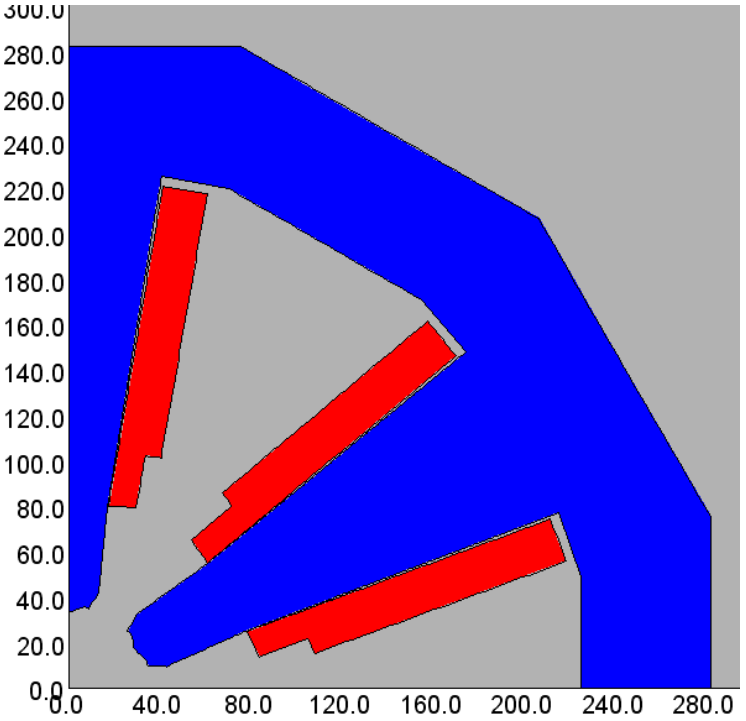
- All harmonics should be less than 5 unit (22 mm reference radius)
- Wide sextupole breaks basic symmetry and creates certain harmonics (semi-allowed) that are not allowed in sextupole
- A new technique has been developed for reducing these semi-allowed harmonics

**Strategy for obtaining field quality in machine magnets:**

- Chamfers will be optimized after initial measurements

# 68 mm Aperture Sextupole (Current Aperture)

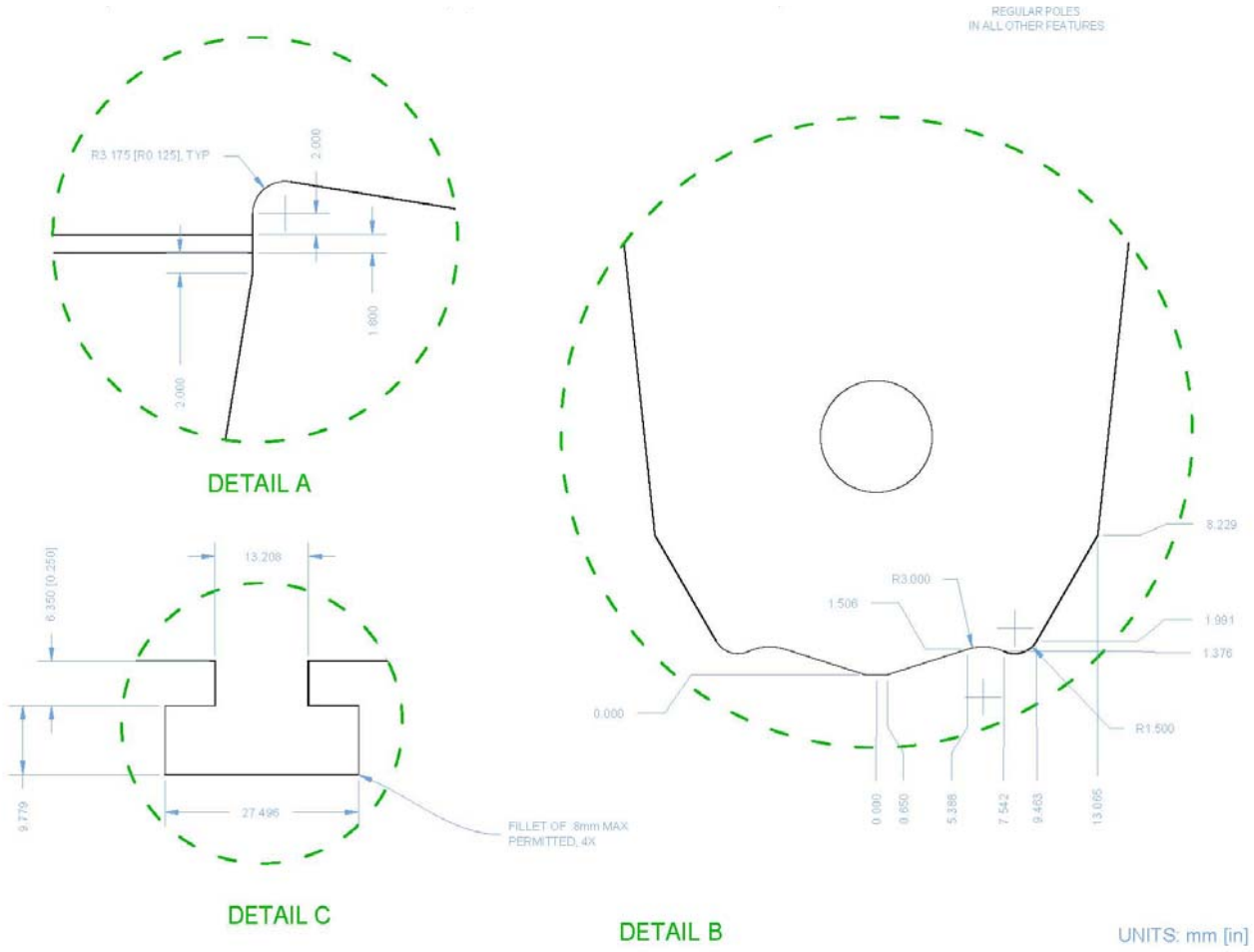



## To allow enough material for beam tube

- Sextupole aperture was increased from 66 mm to 68 mm
- Pole shape was re-optimized within the confine of overall geometric constraints

# Details of Pole Piece

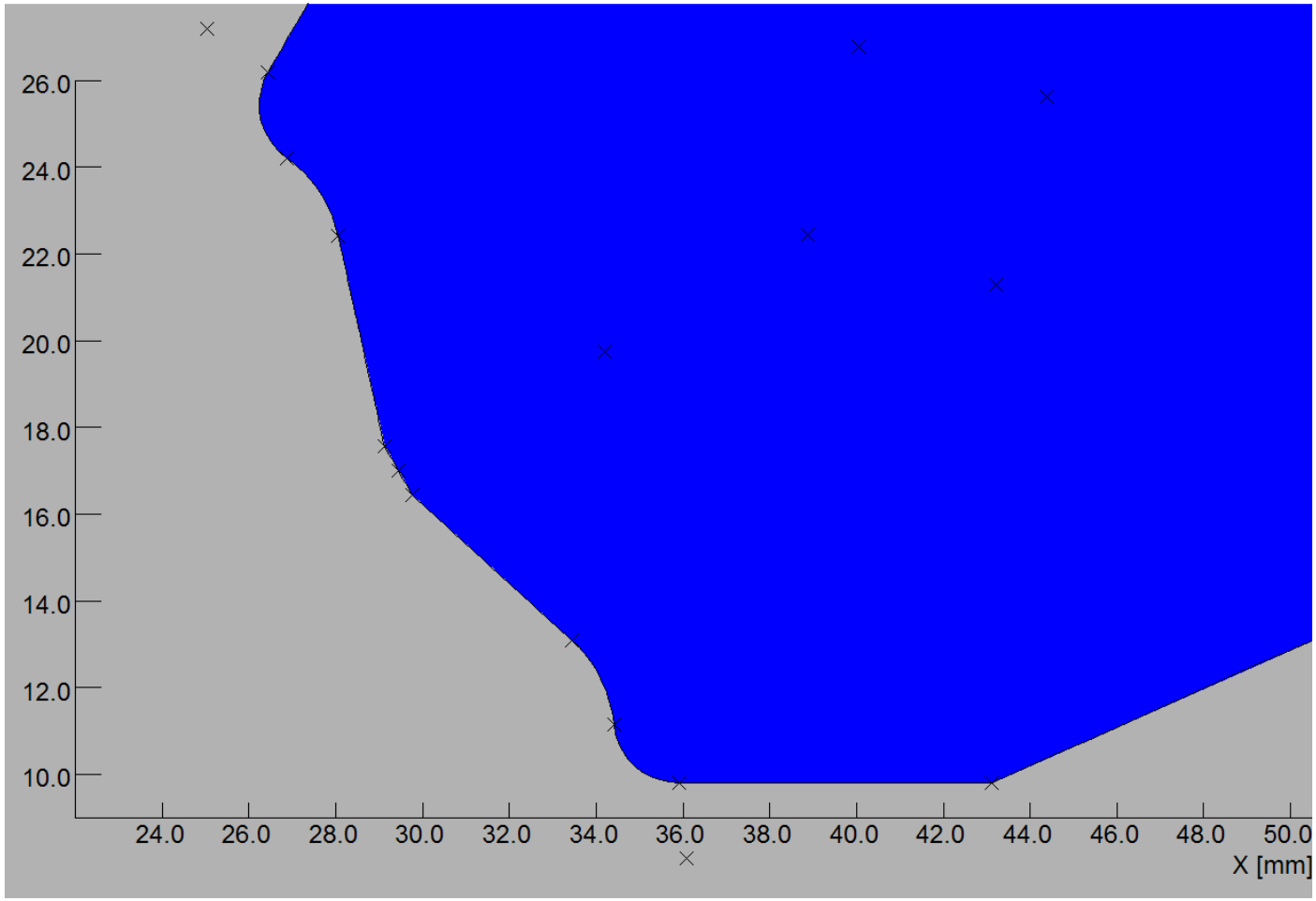



**Pole piece may appear to have sharp corners (illusion due to long piece), but in reality it does not.**

**Laminations can be reasonably cut.**

**Radii are 3 mm and 1.5 mm.**

# Magnetic Optimization of Pole Profile

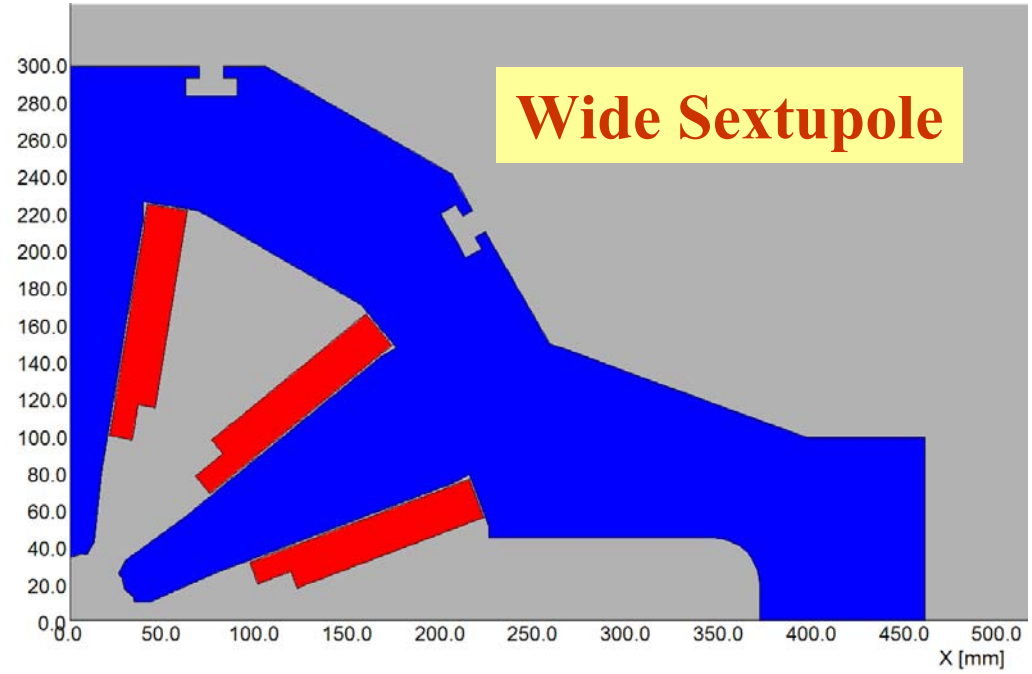



**Six points (position) and two radii were used in optimizing pole profile to obtain low allowed harmonic while satisfying geometric constraints.**

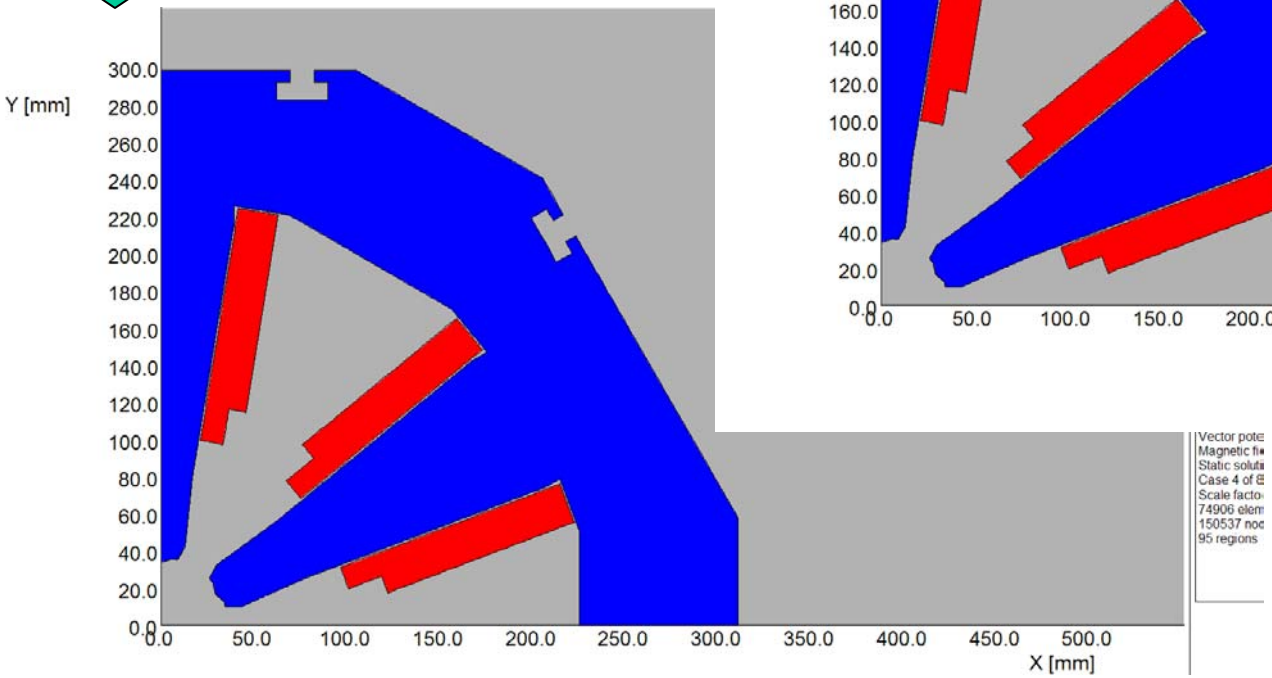
**All allowed harmonics are ~1.5 unit or less. Earlier design had $b_{15}$ of ~13 unit. Initially required value of all harmonics 5 units or less.**

# Sextupoles for NSLS2

**NSLS2 requires two type of cross-sections: Standard and wide**




**Wide Sextupole**




**Standard Sextupole**

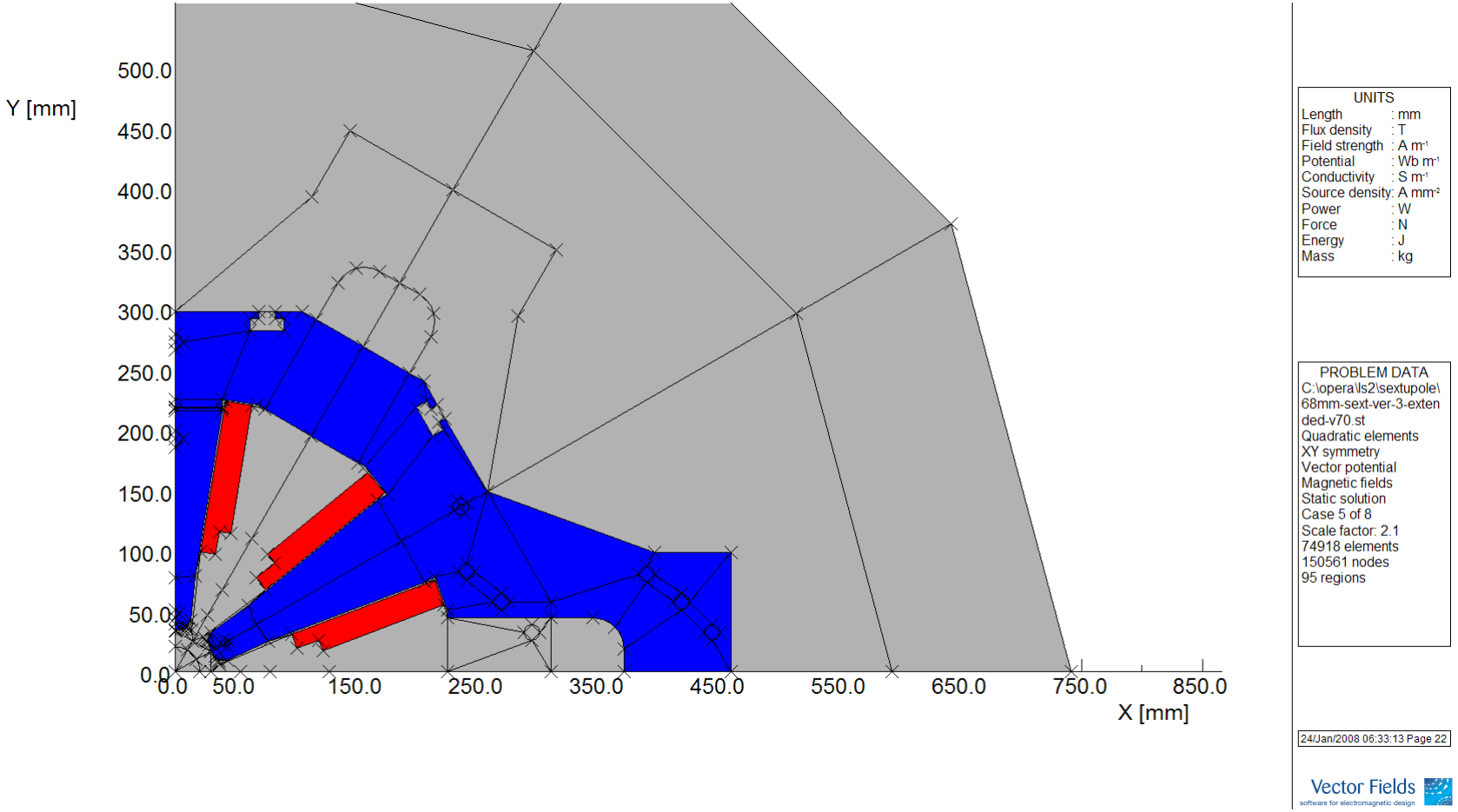
# Magnet Models to Increase Computational Accuracy

We want to obtain as good results as possible for

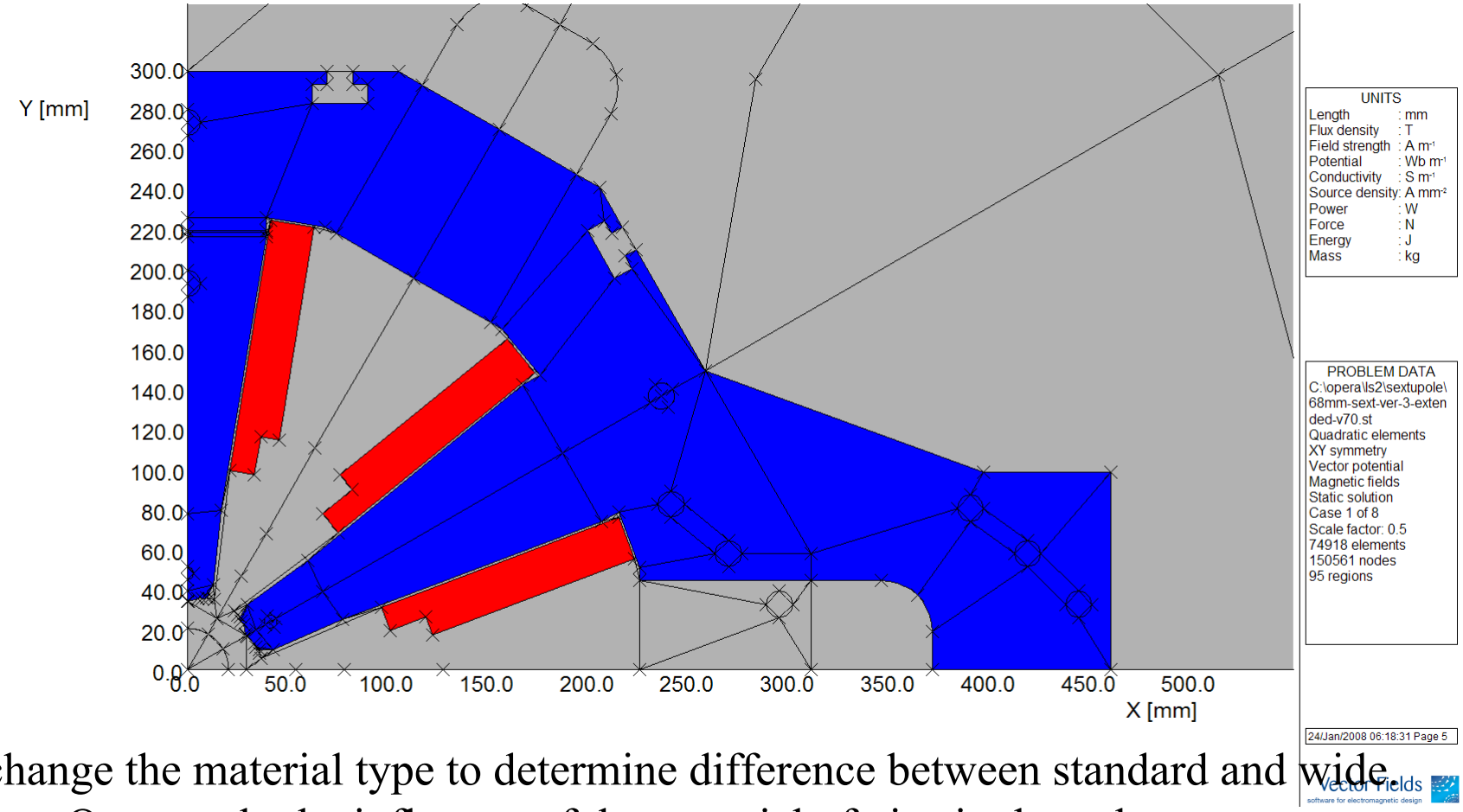
- Non-allowed (or semi-allowed) harmonics due to break in symmetry in wide sextupole
- Influence of pins to align laminations
- Increase general accuracy

**With these guideline, a special model/mesh is created.**

# Symmetric Model (as much as possible) for Better Accuracy



# Common Model for Standard and Wide Sextupole Magnets to Minimize Computational Errors in Harmonics

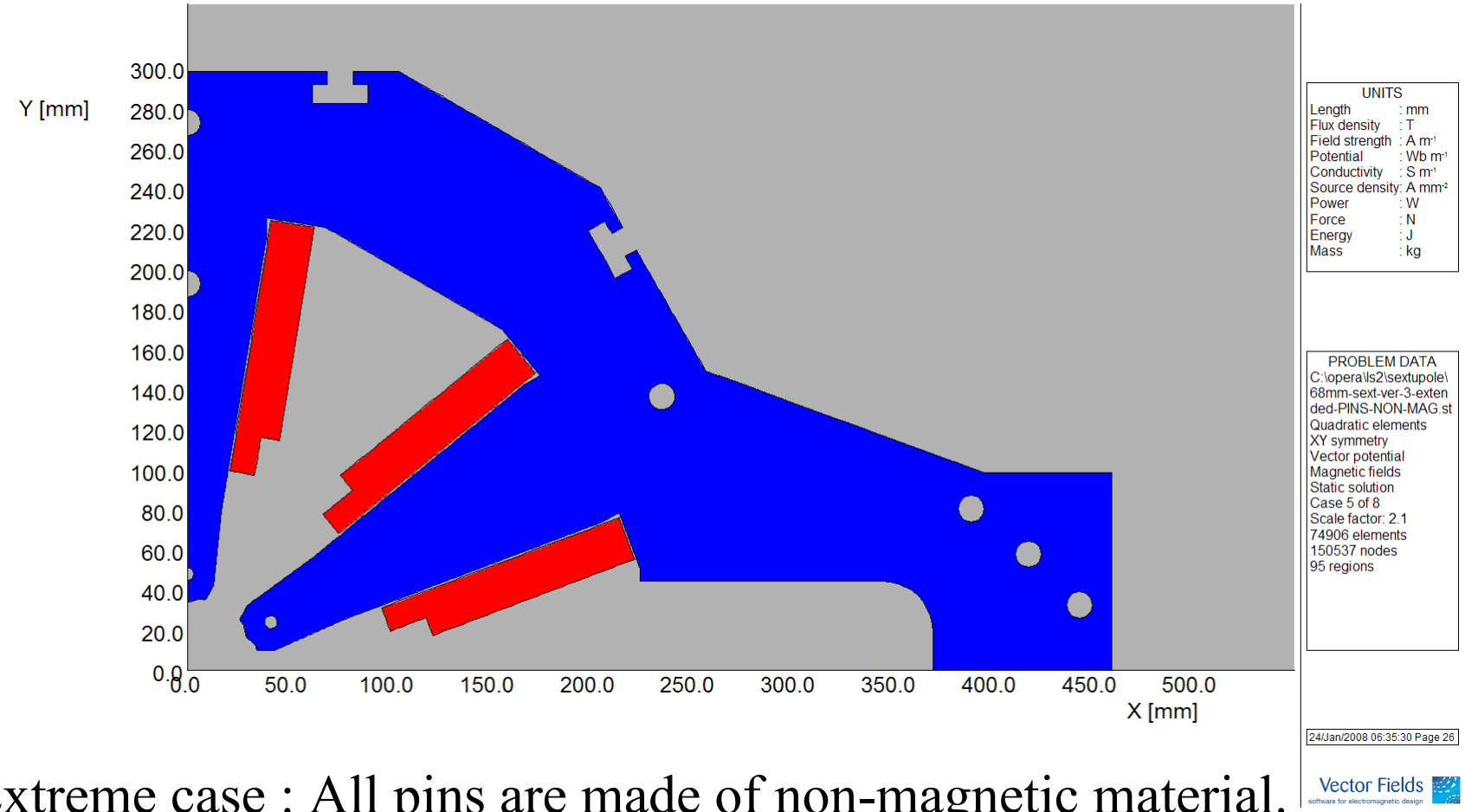



Just change the material type to determine difference between standard and wide.

Or to study the influence of the material of pins in the yoke.

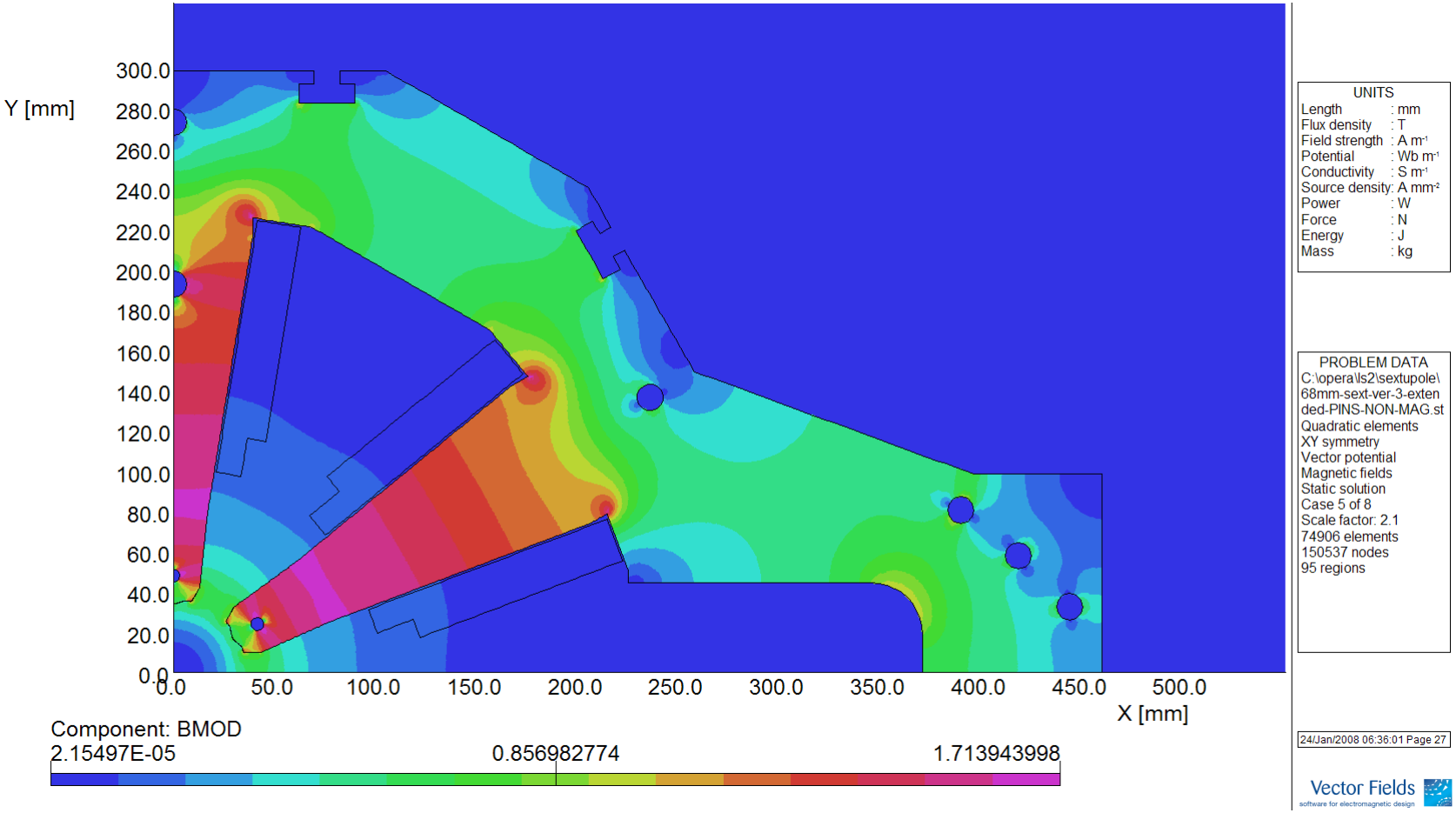
- **This technique minimizes computational errors due to change in mesh.**

# Influence of Alignment Pins




Extreme case : All pins are made of non-magnetic material.
Even this did not change harmonics significatly.

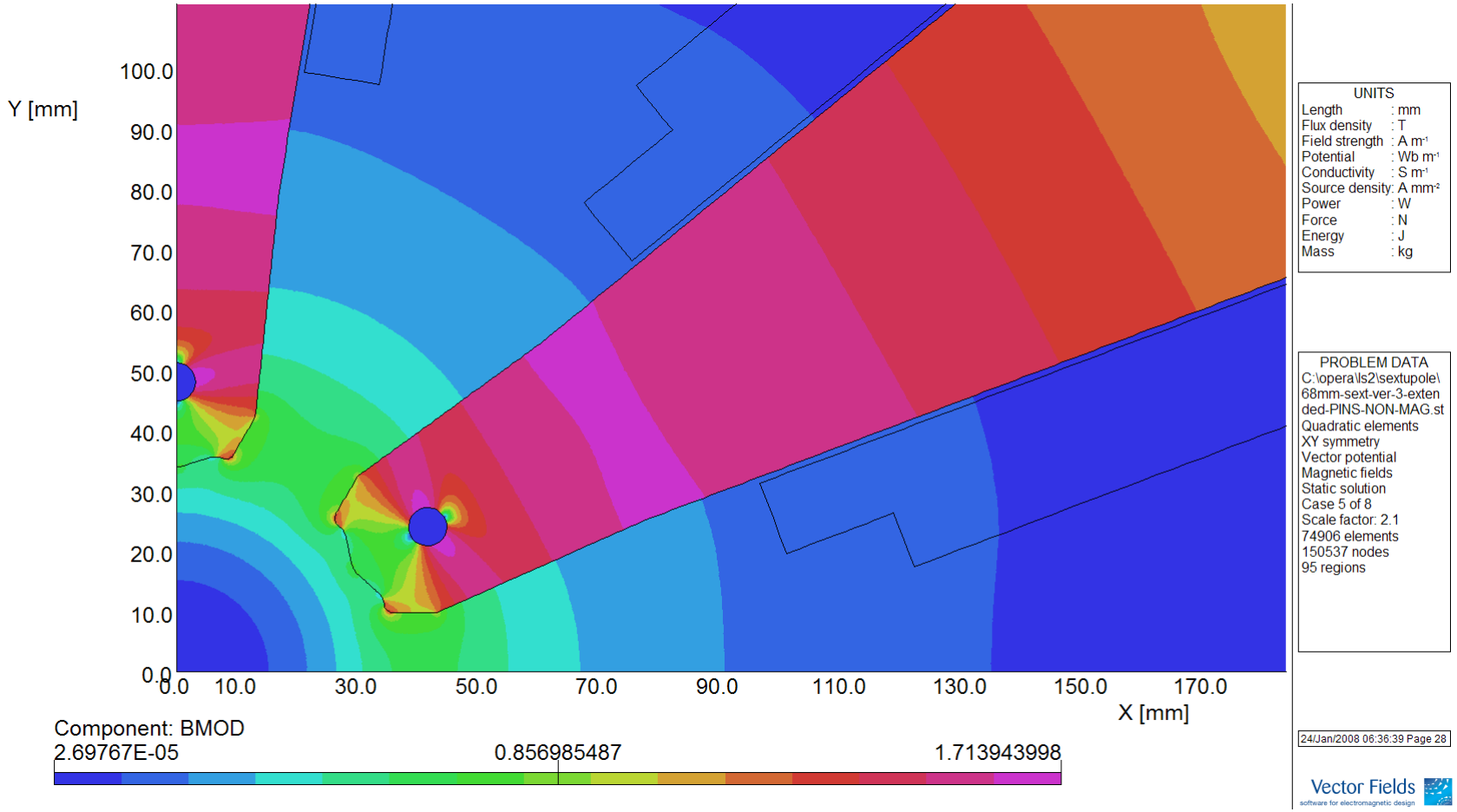
# Influence of the Material/Tight Fitting of of Pins (extreme case – non-magnetic) - 1




Maximum saturation (field) does not go up … and in pole region..

# Influence of the Material/Tight Fitting of of Pins (extreme case – non-magnetic) - 2

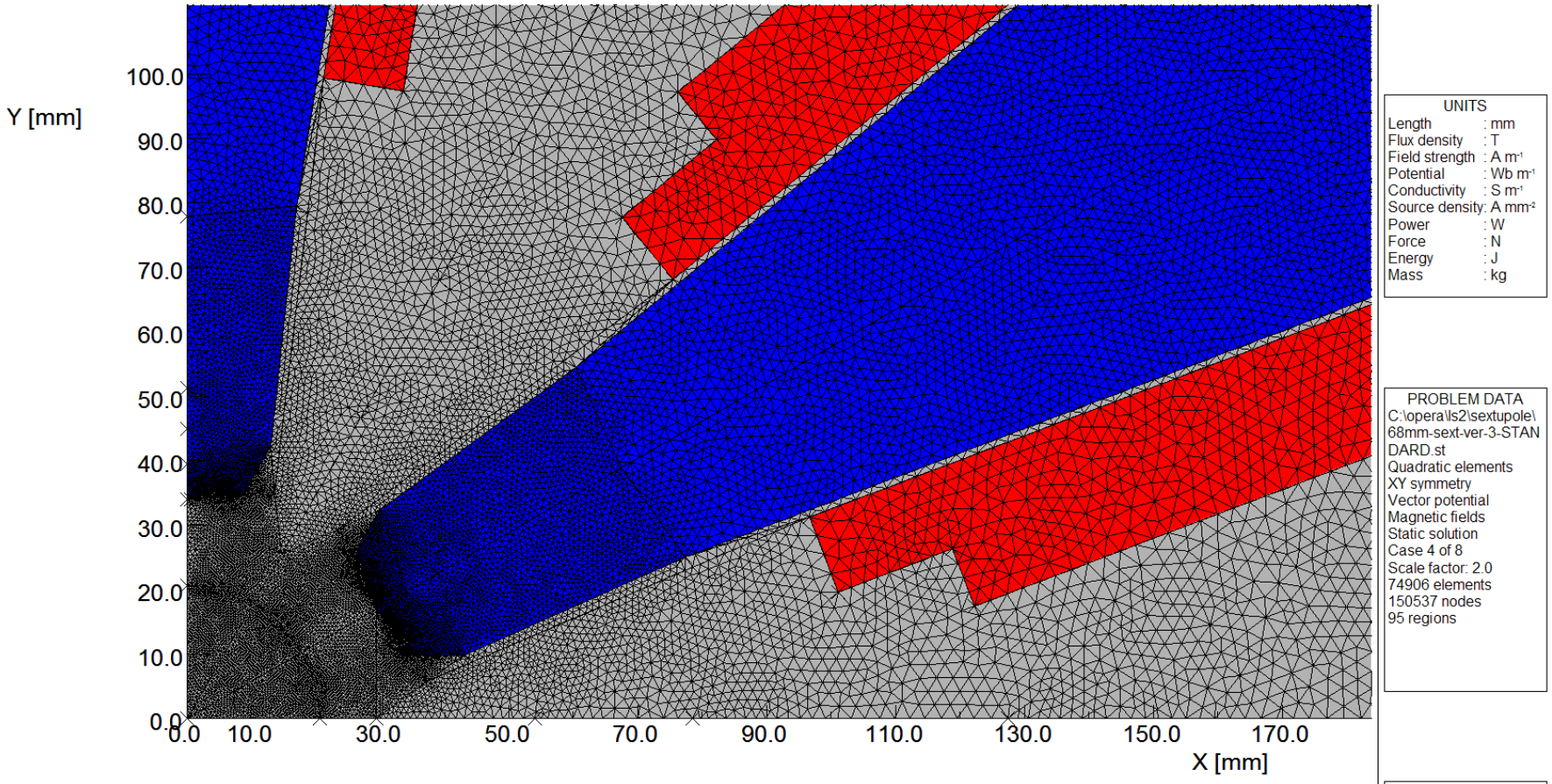
Maximum saturation (field) does not go up; and in pole region



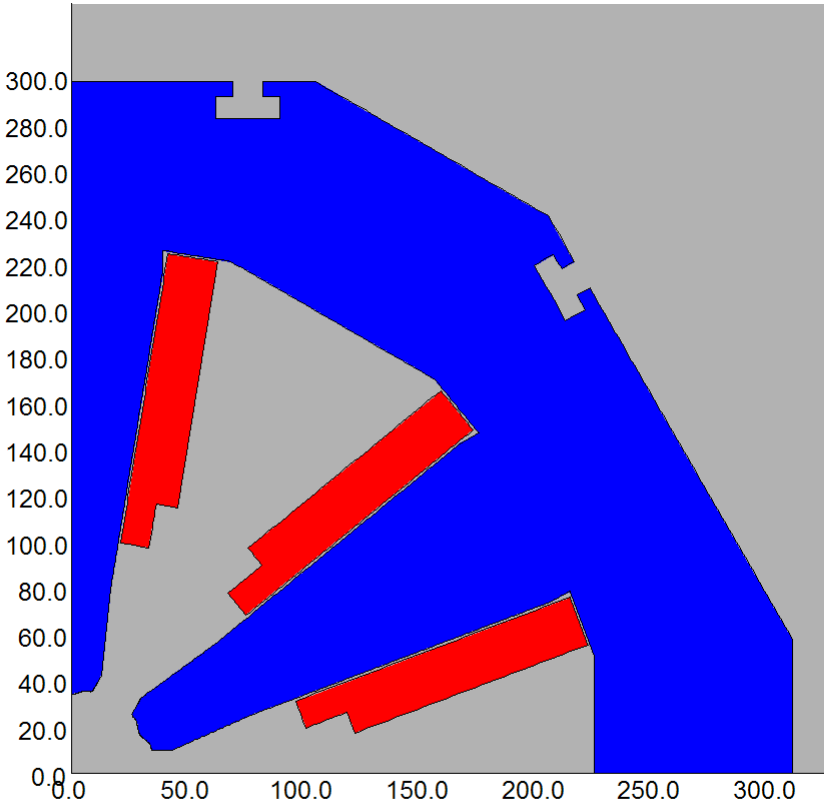

**it makes pole saturate more uniformly**

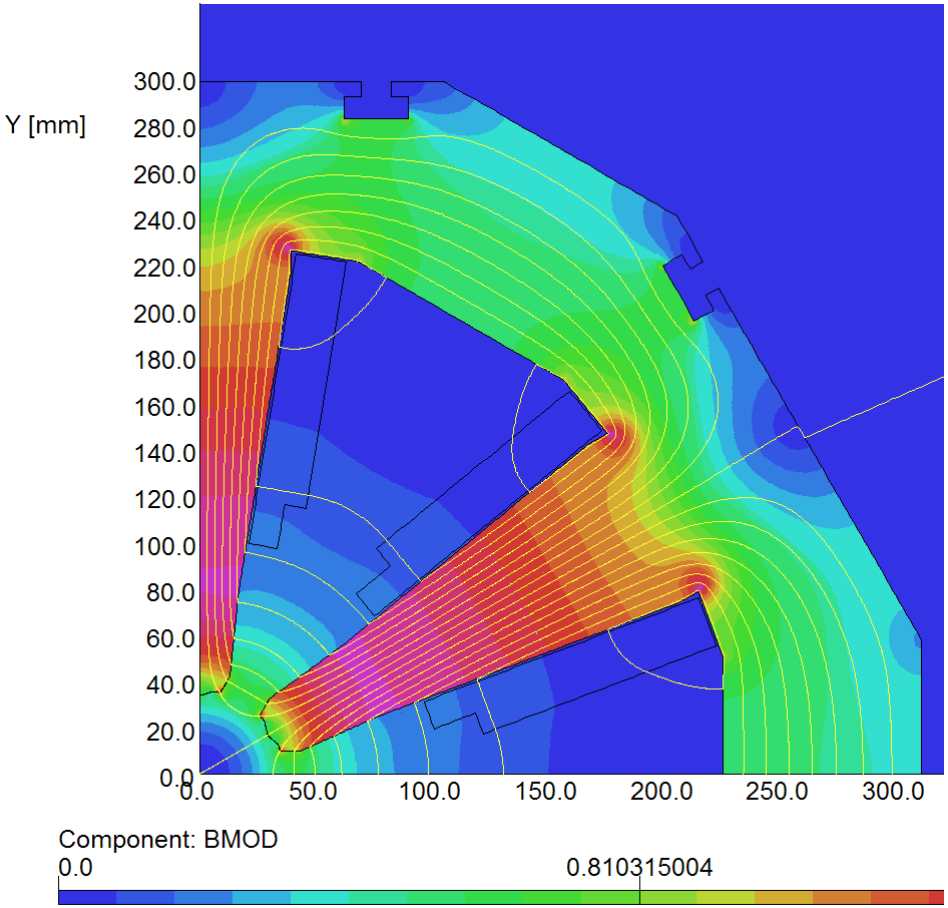
# Mesh for Increasing Accuracy of Calculations

**Quadratic elements are used in sextupole and quadrupole models.**
**Mesh density is higher in critical regions.**



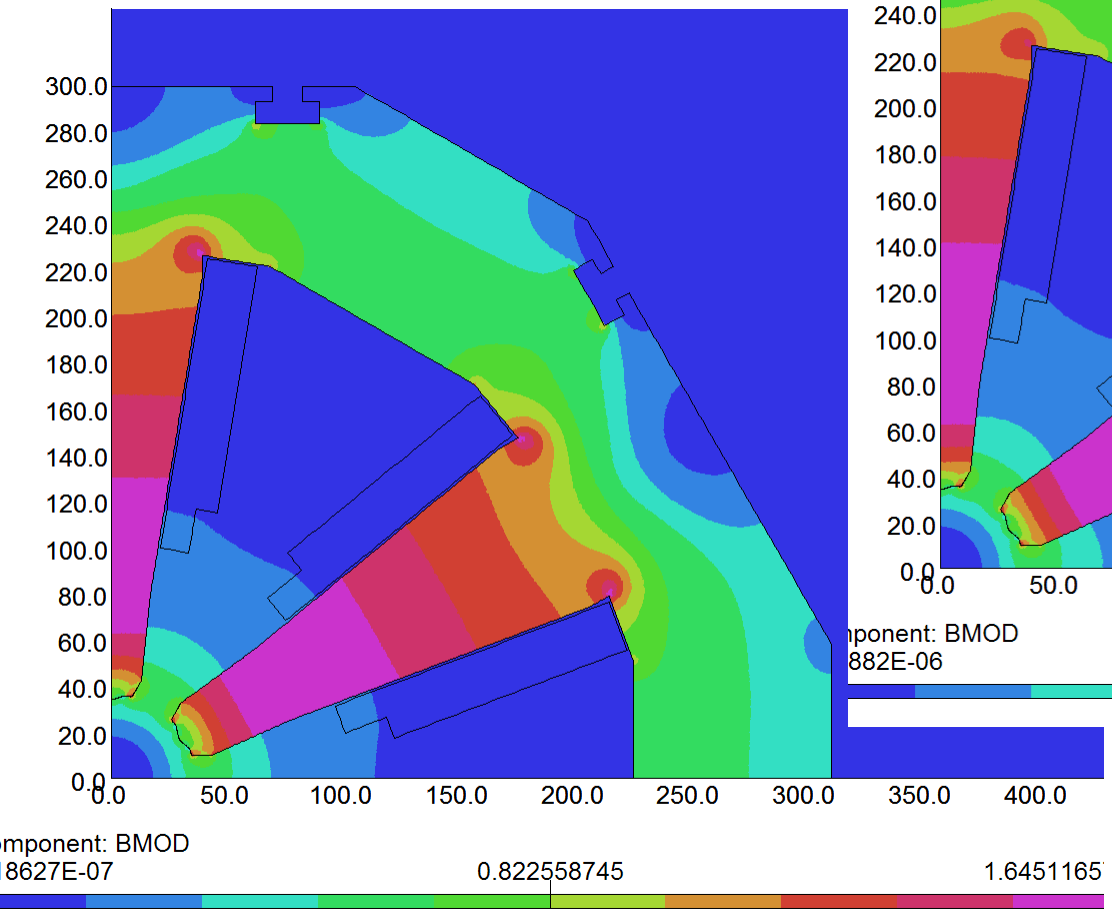
# 68 mm Standard Aperture Sextupole



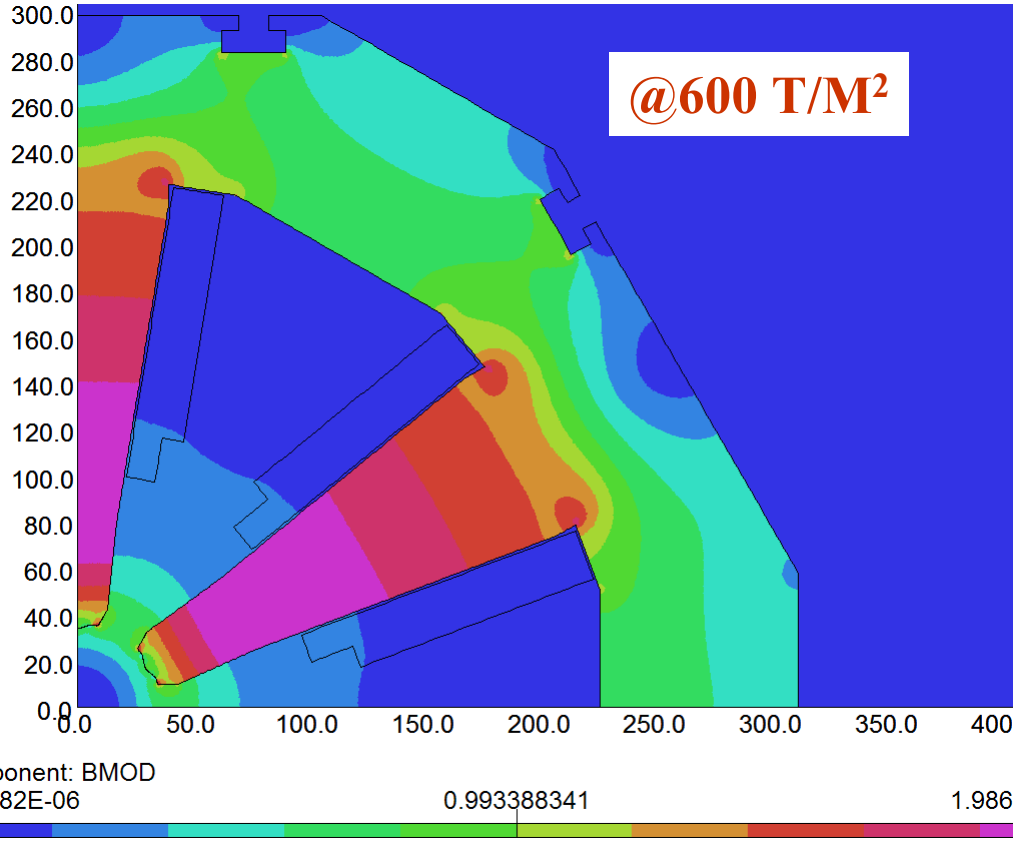



# Magnitude of the Field in Yoke

@475 T/M²




@600 T/M²



# Harmonics in Standard Sextupole

Harmonics at 22 mm reference radius in NSLS2 68 mm aperture sextupole - standard aperture

File: 68mm-sext-ver-3-standard

| Case# | Scale | Fundamental | Sext (T/m^2) | T.F. | d(TF),% | 1 | 3 | 5 | 7 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.5 | 0.0578 | 115.7 | 231.3 | 0 | 2.52 | 10000 | 0.316 | 0.023 | 0.497 |
| 2 | 1 | 0.1158 | 231.6 | 231.6 | 0 | 2.37 | 10000 | 0.297 | 0.022 | 0.504 |
| 3 | 1.5 | 0.1734 | 346.7 | 231.2 | 0 | 2.21 | 10000 | 0.277 | 0.020 | 0.481 |
| 4 | 2 | 0.2279 | 455.7 | 227.9 | 1 | 3.14 | 10000 | 0.391 | 0.029 | 0.476 |
| 5 | 2.1 | 0.2375 | 475.0 | 226.2 | 2 | 3.35 | 10000 | 0.418 | 0.031 | 0.473 |
| 6 | 2.5 | 0.2672 | 534.5 | 213.8 | 8 | 3.26 | 10000 | 0.406 | 0.031 | 0.451 |
| 7 | 3 | 0.2882 | 576.5 | 192.2 | 17 | 2.46 | 10000 | 0.306 | 0.023 | 0.416 |
| 8 | 3.5 | 0.2999 | 599.7 | 171.4 | 26 | 2.07 | 10000 | 0.258 | 0.019 | 0.387 |

| Case# | Scale | Fundamental | Sext (T/m^ | 11 | 13 | 15 | 17 | 19 | 21 | 23 | 25 | 27 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.5 | 0.0578 | 115.7 | -0.003 | 0.000 | -1.425 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |
| 2 | 1 | 0.1158 | 231.6 | -0.003 | 0.000 | -1.426 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |
| 3 | 1.5 | 0.1734 | 346.7 | -0.003 | 0.000 | -1.424 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |
| 4 | 2 | 0.2279 | 455.7 | -0.004 | 0.000 | -1.424 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |
| 5 | 2.1 | 0.2375 | 475.0 | -0.004 | 0.000 | -1.424 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |
| 6 | 2.5 | 0.2672 | 534.5 | -0.004 | 0.000 | -1.423 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |
| 7 | 3 | 0.2882 | 576.5 | -0.003 | 0.000 | -1.421 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |
| 8 | 3.5 | 0.2999 | 599.7 | -0.003 | 0.000 | -1.420 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |

**Values of non-allowed harmonics in black indicates the modeling errors.**

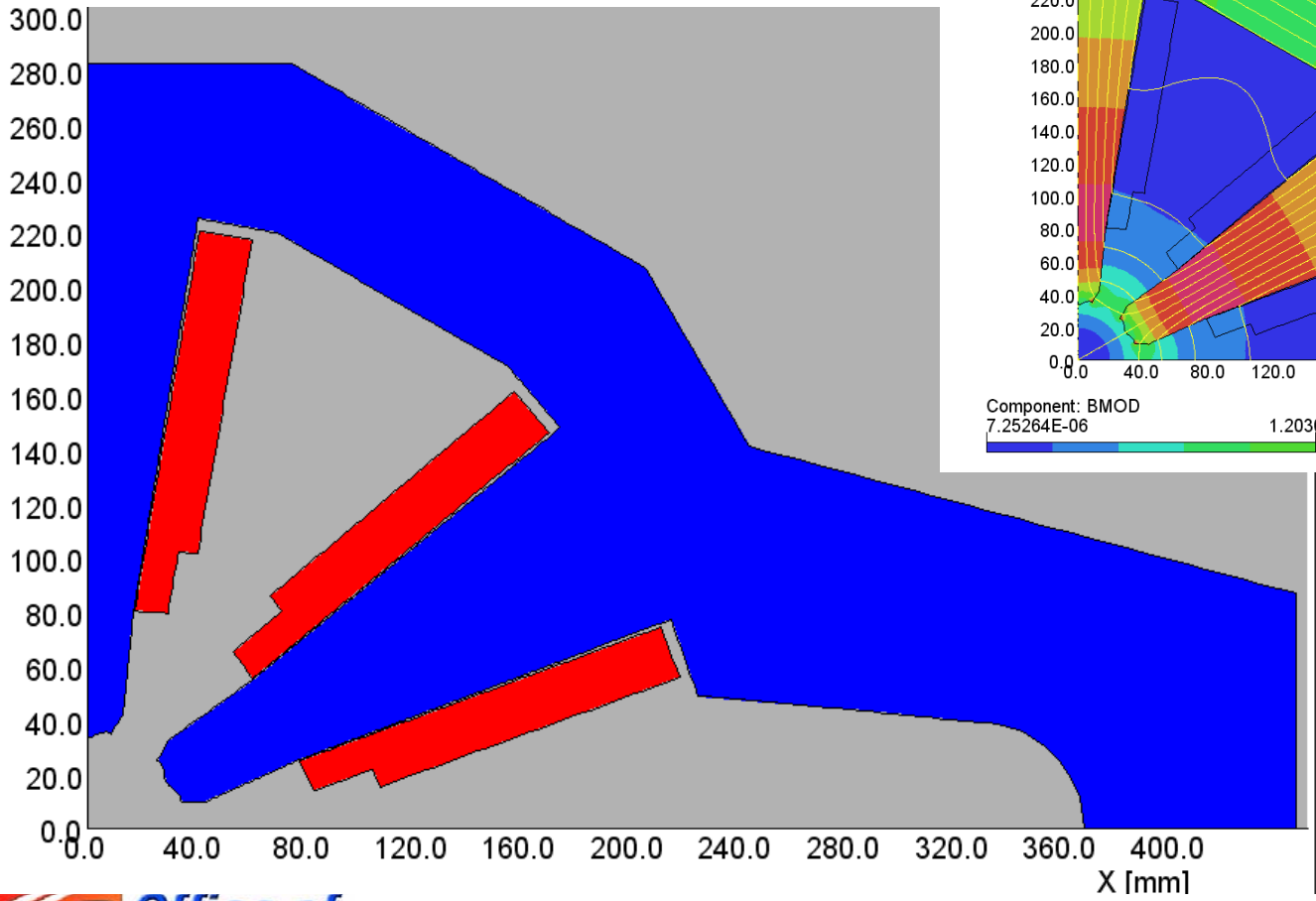
In many terms harmonics are not reliable to the third decimal places.

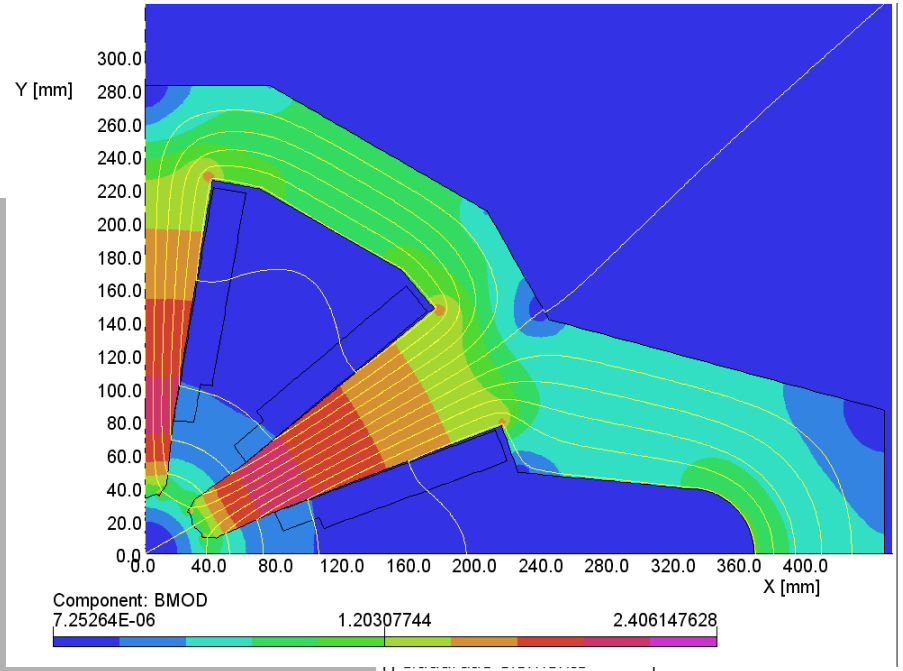
**Note: Small allowed harmonics (<5 units)**

# 68 mm Wide Aperture Sextupole

**Remember:**

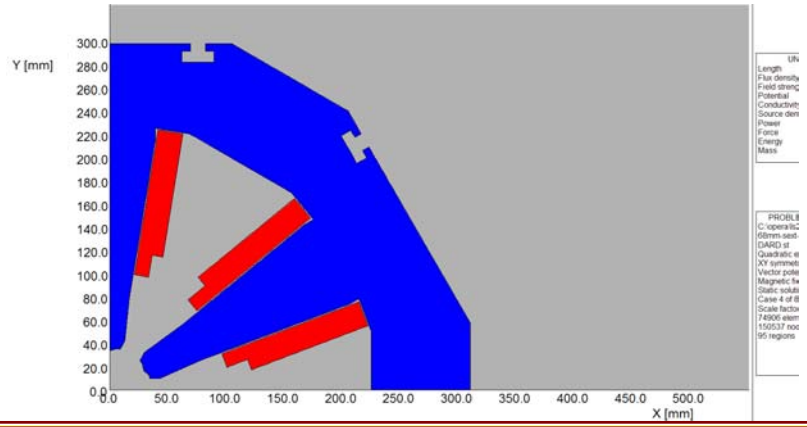
**Mesh is the same as in standard sextupole, only the material properties changed.**

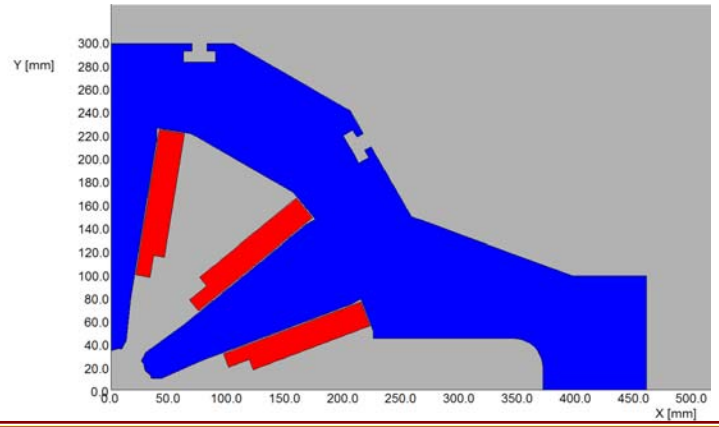



XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 7
Scale factor = 1.0
52477 elements
105536 nodes
53 regions

# Harmonics Due to EXTRA CUTOUT in Wide Sextupole




**Basic sextupole symmetry is broken. Expect harmonics that are not allowed in sextupole. Material property changed between the two models and differences are taken**

| Scale | Sext (T/m^2) | db1 | db3 | db5 | db7 | db9 | db11 | db13 |
|---|---|---|---|---|---|---|---|---|
| 0.5 | 115.5 | -43.6 | -15.9 | -5.4 | -0.42 | 0.00 | 0.05 | 0.01 |
| 1 | 231.2 | -39.3 | -14.3 | -4.9 | -0.38 | 0.00 | 0.05 | 0.01 |
| 1.5 | 346.3 | -36.6 | -13.3 | -4.5 | -0.36 | 0.00 | 0.04 | 0.01 |
| 2 | 455.2 | -32.9 | -10.9 | -4.1 | -0.32 | 0.00 | 0.04 | 0.01 |
| 2.1 | 474.5 | -32.2 | -10.2 | -4.0 | -0.31 | 0.00 | 0.04 | 0.01 |
| 2.5 | 534.1 | -27.5 | -6.4 | -3.4 | -0.27 | 0.00 | 0.03 | 0.00 |
| 3 | 576.3 | -21.0 | -3.3 | -2.6 | -0.21 | 0.00 | 0.03 | 0.00 |
| 3.5 | 599.6 | -17.3 | -2.1 | -2.1 | -0.17 | 0.00 | 0.02 | 0.00 |

**Calculation to such a reliability is possible only because of the same mesh in two cases**

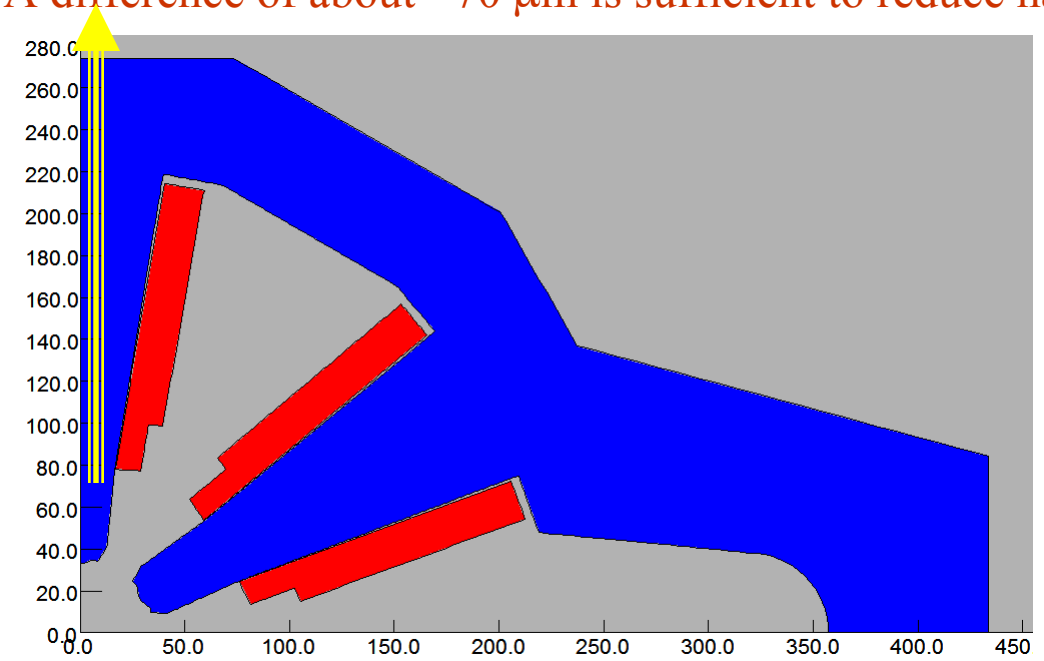
# A Technique for Reducing Semi-allowed Harmonics

These "semi-allowed" sextupole harmonics (b1, b5, b7, etc.) are created in because removing the iron at horizontal plane breaks the ideal six fold symmetry.

**Suggested Fix :**

Compensate this asymmetry by another deliberate asymmetry – by moving the poles at vertical plane away from the center.

A difference of about ~70 μm is sufficient to reduce harmonics well below acceptable errors.




Values at ~350 T/m$^2$
(2/3 of the design field)

| N | bn(new) | bn(old) |
|---|---|---|
| 1 | -8.1 | -37.6 |
| 3 | 9,979 | 10,000 |
| 5 | 0.0 | -4.5 |
| 7 | -0.25 | -0.36 |
| 9 | 0.27 | 0.48 |

# Harmonics in Wide Sextupole

File: 68mm-sext-ver-3-extended-v70

| Case# | Scale | Fundamental | Sext (T/m^2) | T.F. | d(TF),% | b1 | b3 | b5 | b7 | b9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.5 | 0.0576 | 115.2 | 230.5 | 0 | -12.5 | 10000 | -0.52 | -0.29 | 0.28 |
| 2 | 1 | 0.1154 | 230.7 | 230.7 | 0 | -8.4 | 10000 | 0.00 | -0.25 | 0.29 |
| 3 | 1.5 | 0.1728 | 345.6 | 230.4 | 0 | -5.9 | 10000 | 0.30 | -0.23 | 0.27 |
| 4 | 2 | 0.2272 | 454.3 | 227.2 | 2 | -1.6 | 10000 | 0.83 | -0.19 | 0.26 |
| 5 | 2.1 | 0.2368 | 473.6 | 225.5 | 3 | -0.9 | 10000 | 0.92 | -0.18 | 0.26 |
| 6 | 2.5 | 0.2666 | 533.2 | 213.3 | 8 | 2.4 | 10000 | 1.33 | -0.15 | 0.24 |
| 7 | 3 | 0.2877 | 575.4 | 191.8 | 17 | 6.6 | 10000 | 1.85 | -0.11 | 0.20 |
| 8 | 3.5 | 0.2994 | 598.7 | 171.1 | 26 | 9.0 | 10000 | 2.15 | -0.09 | 0.17 |

| Case# | Scale | Sext (T/m^2) | b11 | b13 | b15 | b17 | b19 | b21 | b23 | b25 | b27 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.5 | 115.2 | 0.17 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |
| 2 | 1 | 230.7 | 0.17 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |
| 3 | 1.5 | 345.6 | 0.17 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |
| 4 | 2 | 454.3 | 0.16 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |
| 5 | 2.1 | 473.6 | 0.16 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |
| 6 | 2.5 | 533.2 | 0.16 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |
| 7 | 3 | 575.4 | 0.15 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |
| 8 | 3.5 | 598.7 | 0.15 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |

**Not corrected for meshing errors.**

# Here are all the details

## Standard symmetric sextupole

Harmonics at 22 mm reference radius in NSLS2 68 mm aperture sextupole - standard aperture
File: 68mm-sext-ver-3-standard

| Case# | Scale | Fundamental | Sext (T/m^2) | T.F. | d(TF),% | 1 | 3 | 5 | 7 | 9 | 11 | 13 | 15 | 17 | 19 | 21 | 23 | 25 | 27 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.5 | 0.0578 | 115.7 | 231.3 | 0 | 2.52 | 10000 | 0.316 | 0.023 | 0.497 | -0.003 | 0.000 | -1.425 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |
| 2 | 1 | 0.1158 | 231.6 | 231.6 | 0 | 2.37 | 10000 | 0.297 | 0.022 | 0.504 | -0.003 | 0.000 | -1.426 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |
| 3 | 1.5 | 0.1734 | 346.7 | 231.2 | 0 | 2.21 | 10000 | 0.277 | 0.020 | 0.481 | -0.003 | 0.000 | -1.424 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |
| 4 | 2 | 0.2279 | 455.7 | 227.9 | 1 | 3.14 | 10000 | 0.391 | 0.029 | 0.476 | -0.004 | 0.000 | -1.424 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |
| 5 | 2.1 | 0.2375 | 475.0 | 226.2 | 2 | 3.35 | 10000 | 0.418 | 0.031 | 0.473 | -0.004 | 0.000 | -1.424 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |
| 6 | 2.5 | 0.2672 | 534.5 | 213.8 | 8 | 3.26 | 10000 | 0.406 | 0.031 | 0.451 | -0.004 | 0.000 | -1.423 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |
| 7 | 3 | 0.2882 | 576.5 | 192.2 | 17 | 2.46 | 10000 | 0.306 | 0.023 | 0.416 | -0.003 | 0.000 | -1.421 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |
| 8 | 3.5 | 0.2999 | 599.7 | 171.4 | 26 | 2.07 | 10000 | 0.258 | 0.019 | 0.387 | -0.003 | 0.000 | -1.420 | 0.000 | 0.000 | -0.294 | 0.001 | 0.000 | 0.022 |

## Wide sextupole with no pole adjustment

Harmonics at 22 mm reference radius in NSLS2 68 mm aperture sextupole, extended
File: 68mm-sext-ver-3-extended

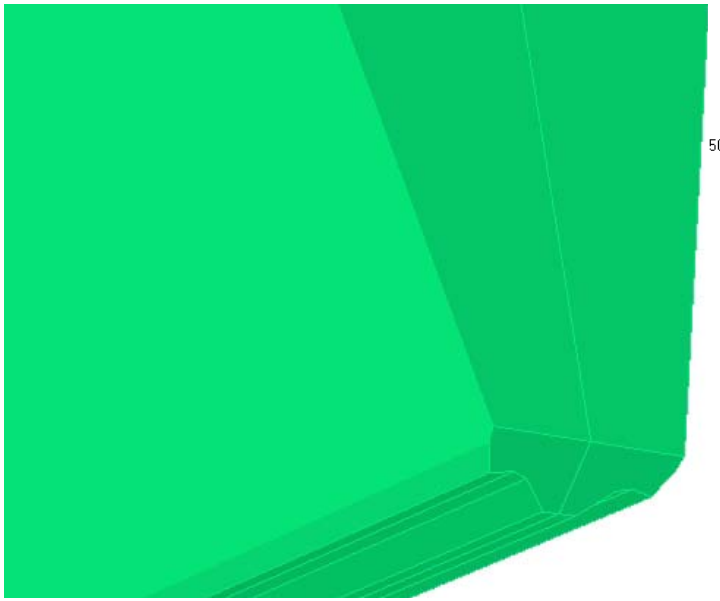
| Case# | Scale | Fundamental | Sext (T/m^2) | T.F. | d(TF),% | b1 | b3 | b5 | b7 | b9 | b11 | b13 | b15 | b17 | b19 | b21 | b23 | b25 | b27 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.5 | 0.0577 | 115.5 | 230.9 | 0 | -41.1 | 10000 | -5.08 | -0.40 | 0.50 | 0.05 | 0.01 | -1.43 | 0.00 | 0.00 | -0.29 | 0.00 | 0.00 | 0.02 |
| 2 | 1 | 0.1156 | 231.2 | 231.2 | 0 | -36.9 | 10000 | -4.56 | -0.36 | 0.50 | 0.04 | 0.01 | -1.43 | 0.00 | 0.00 | -0.29 | 0.00 | 0.00 | 0.02 |
| 3 | 1.5 | 0.1731 | 346.3 | 230.9 | 0 | -34.4 | 10000 | -4.26 | -0.34 | 0.48 | 0.04 | 0.01 | -1.42 | 0.00 | 0.00 | -0.29 | 0.00 | 0.00 | 0.02 |
| 4 | 2 | 0.2276 | 455.2 | 227.6 | 1 | -29.7 | 10000 | -3.67 | -0.29 | 0.48 | 0.04 | 0.01 | -1.42 | 0.00 | 0.00 | -0.29 | 0.00 | 0.00 | 0.02 |
| 5 | 2.1 | 0.2373 | 474.5 | 226.0 | 2 | -28.8 | 10000 | -3.56 | -0.28 | 0.47 | 0.03 | 0.01 | -1.42 | 0.00 | 0.00 | -0.29 | 0.00 | 0.00 | 0.02 |
| 6 | 2.5 | 0.2671 | 534.1 | 213.6 | 7 | -24.2 | 10000 | -2.99 | -0.24 | 0.45 | 0.03 | 0.00 | -1.42 | 0.00 | 0.00 | -0.29 | 0.00 | 0.00 | 0.02 |
| 7 | 3 | 0.2881 | 576.3 | 192.1 | 17 | -18.5 | 10000 | -2.28 | -0.18 | 0.42 | 0.02 | 0.00 | -1.42 | 0.00 | 0.00 | -0.29 | 0.00 | 0.00 | 0.02 |
| 8 | 3.5 | 0.2998 | 599.6 | 171.3 | 26 | -15.2 | 10000 | -1.86 | -0.15 | 0.39 | 0.02 | 0.00 | -1.42 | 0.00 | 0.00 | -0.29 | 0.00 | 0.00 | 0.02 |

## Wide sextupole with 70 micron vertical adjustment in pole (moved up by adjusting shims)

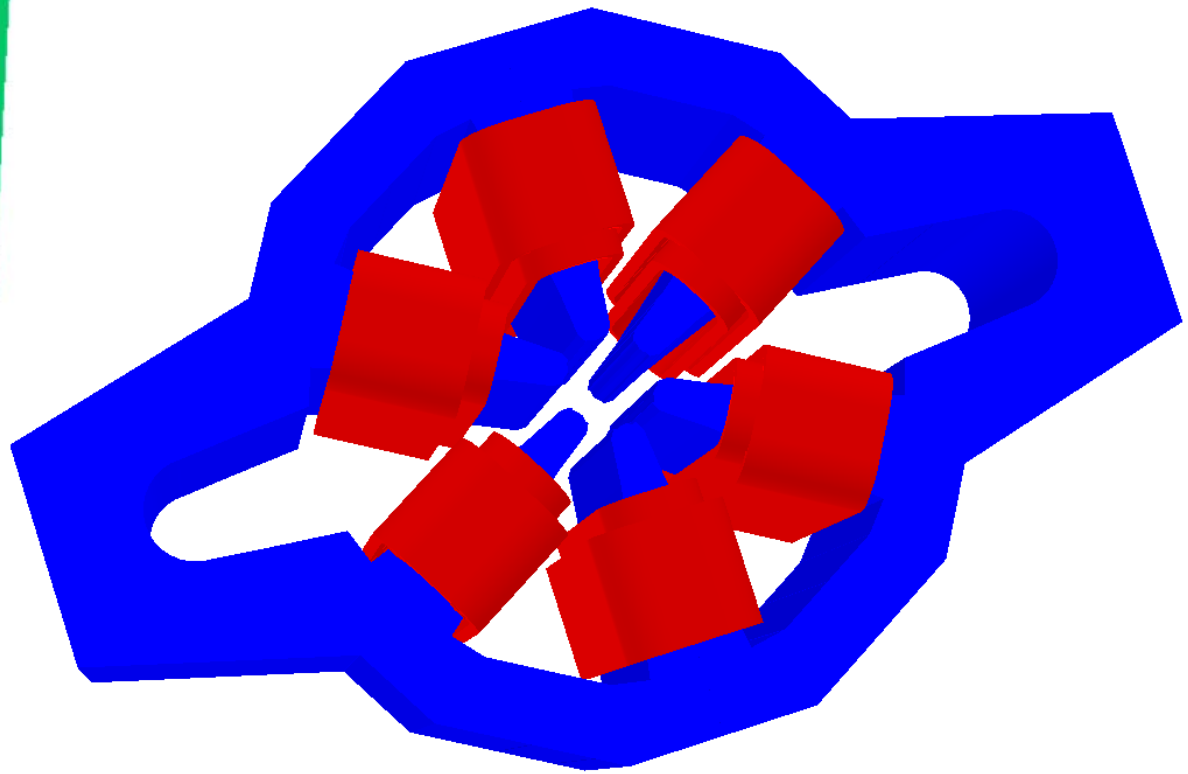
Harmonics at 22 mm reference radius in NSLS2 68 mm aperture sextupole, extended with 70 micron vertical pole offset
File: 68mm-sext-ver-3-extended-v70

| Case# | Scale | Fundamental | Sext (T/m^2) | T.F. | d(TF),% | b1 | b3 | b5 | b7 | b9 | b11 | b13 | b15 | b17 | b19 | b21 | b23 | b25 | b27 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.5 | 0.0576 | 115.2 | 230.5 | 0 | -12.5 | 10000 | -0.52 | -0.29 | 0.28 | 0.17 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |
| 2 | 1 | 0.1154 | 230.7 | 230.7 | 0 | -8.4 | 10000 | 0.00 | -0.25 | 0.29 | 0.17 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |
| 3 | 1.5 | 0.1728 | 345.6 | 230.4 | 0 | -5.9 | 10000 | 0.30 | -0.23 | 0.27 | 0.17 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |
| 4 | 2 | 0.2272 | 454.3 | 227.2 | 1 | -1.6 | 10000 | 0.83 | -0.19 | 0.26 | 0.16 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |
| 5 | 2.1 | 0.2368 | 473.6 | 225.5 | 2 | -0.9 | 10000 | 0.92 | -0.18 | 0.26 | 0.16 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |
| 6 | 2.5 | 0.2666 | 533.2 | 213.3 | 7 | 2.4 | 10000 | 1.33 | -0.15 | 0.24 | 0.16 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |
| 7 | 3 | 0.2877 | 575.4 | 191.8 | 17 | 6.6 | 10000 | 1.85 | -0.11 | 0.20 | 0.15 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |
| 8 | 3.5 | 0.2994 | 598.7 | 171.1 | 26 | 9.0 | 10000 | 2.15 | -0.09 | 0.17 | 0.15 | -0.05 | -1.42 | 0.01 | -0.01 | -0.29 | 0.00 | 0.00 | 0.02 |

# 3-d Modelling of the Sextupole




**Ends will be chamfered to minimize measured integral harmonics.**



**Note: Flat coils save space in the end.**

# SUMMARY

- Sextupole design is sufficiently developed to go in production.
- Pole shape has been optimized to significantly reduce field errors and comfortably meet the field quality requirements.
- The design meets mechanical requirements in terms of leaving enough material on beam tube.
- A design technique has been developed and implemented to reduce semi-allowed harmonics in wide sextupole.