# QW Magnet Design and Analysis  Results (V03)

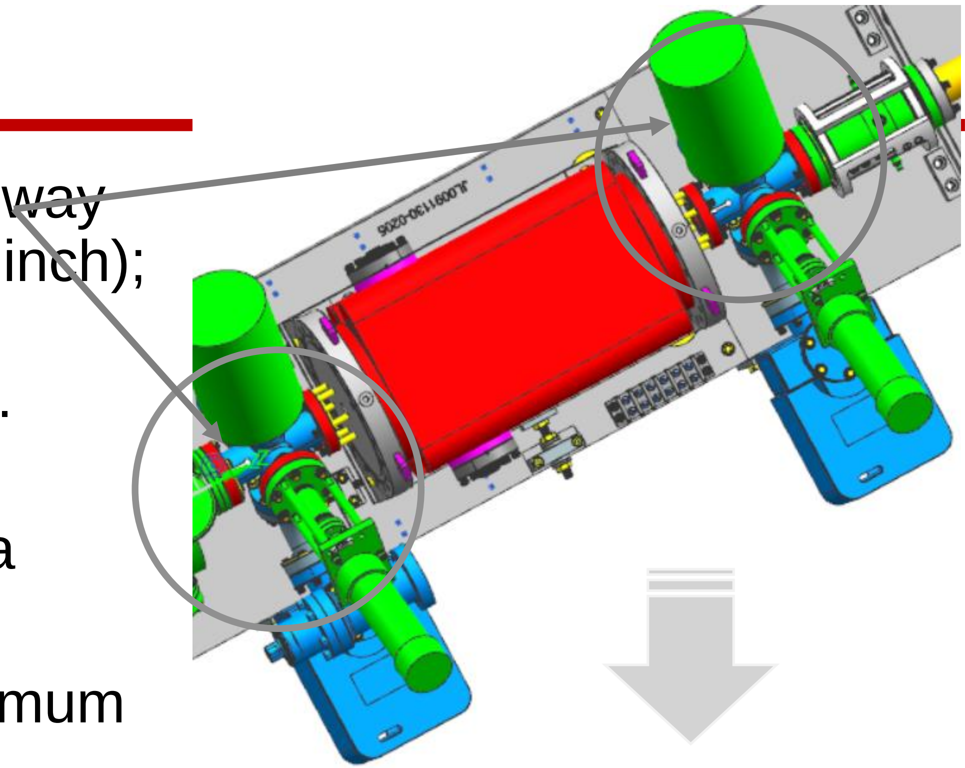
S-L. Lalitha

September 12, 2020

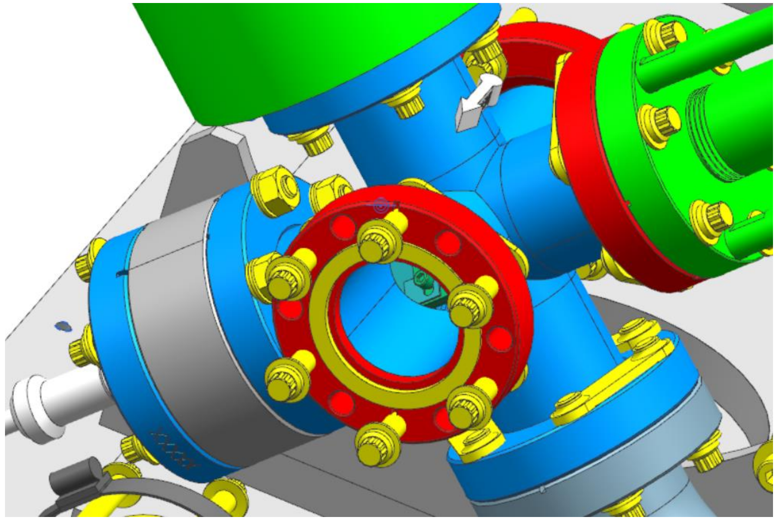
# Contents

- Design and Performance Requirements
- Design Considerations
  - Coil
  - Coil support structure
  - Conductor selection
  - Conductor layout in the coils
  - Support clamps for the magnet assembly into the vacuum cross fitting
- Magnetic Results
  - Field distribution
  - Multipole field components
  - Integrated quadrupole field gradient, quadrupole field homogeneity in good field region
  - Inductance, Stored energy
  - Coil resistance at RT
- Power supply requirement
- Summary and Recommendations

# Design and Performance Requirements

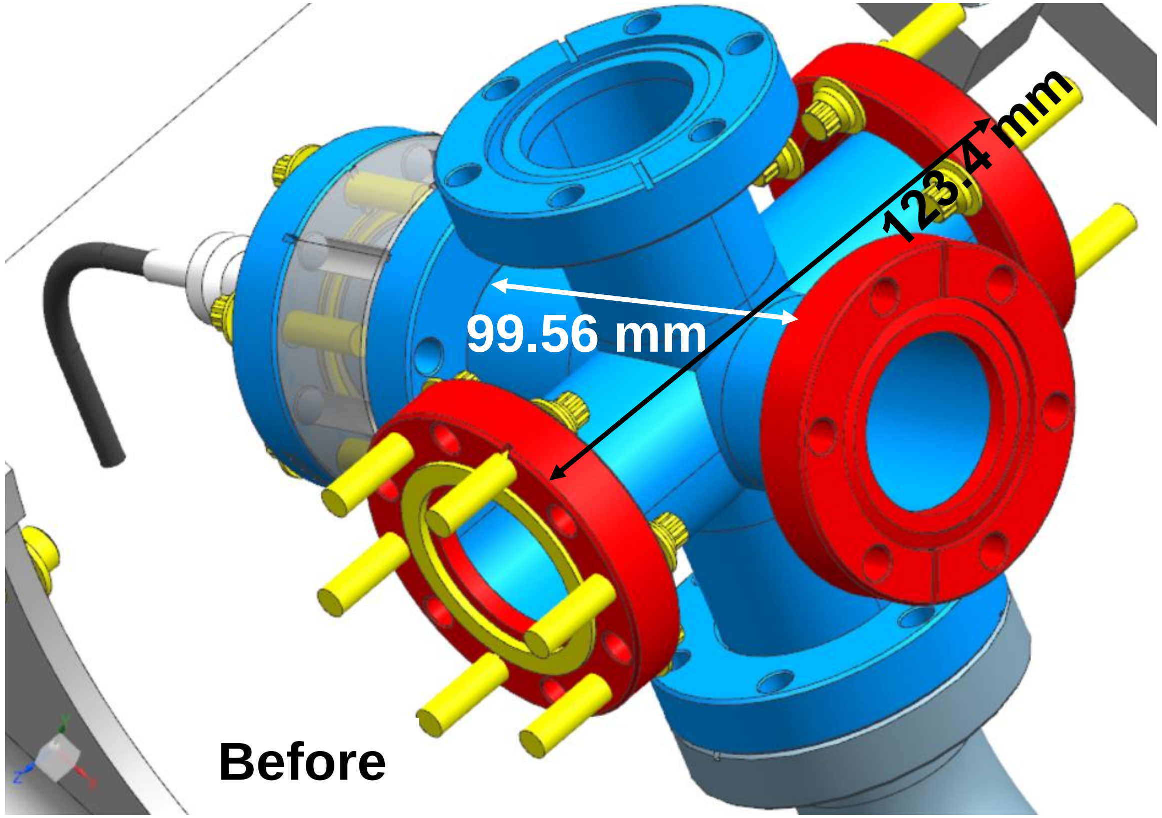


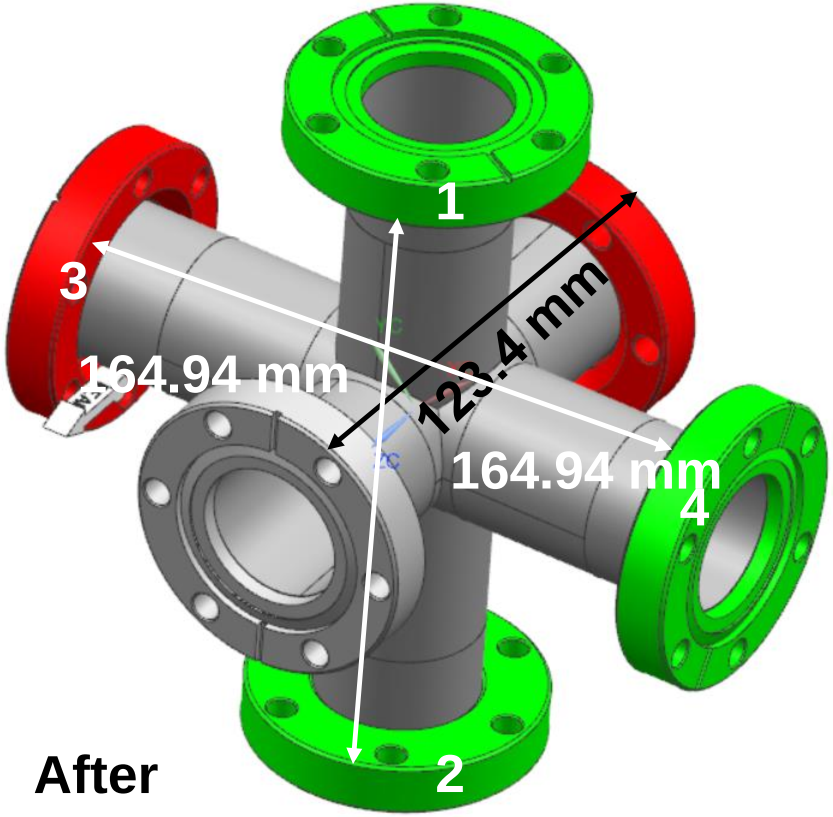
- The QW quadrupole coils should be able to fit over a six way vacuum cross CF flange fitting (pipe OD- 38.1 mm (1.5 inch); flange OD 69.85 mm (2.75 inch)).
  - The assembly is rotated 45° from horizontal axis (X-axis) .
- The components used in the coil winding and magnet assembly should be able to withstand heat treatment at a max. of 200 °C for 72 h.
- The quadrupole magnet should be able to deliver a maximum integrated field gradient of 0.01 T (100 Gauss)
- Radius of the GFR ($R_{ref}$): 7.5 mm
- Field homogeneity requirements-None for the design
  - Estimate from the EM design analysis.
- Fringe field requirements: none



# Space Available for QW Magnet Assembly

- Design changes (since QW design (V02) meeting Aug 31, 2020 )
- Extended the pipe length radially (from 99.56 mm to164.94 mm)+ added tapped-bored flanges (1-4).
- No change made to (A) the cross length length-wise and (B) upstream and downstream CF flange configuration or hardware (bolts and spring washers).

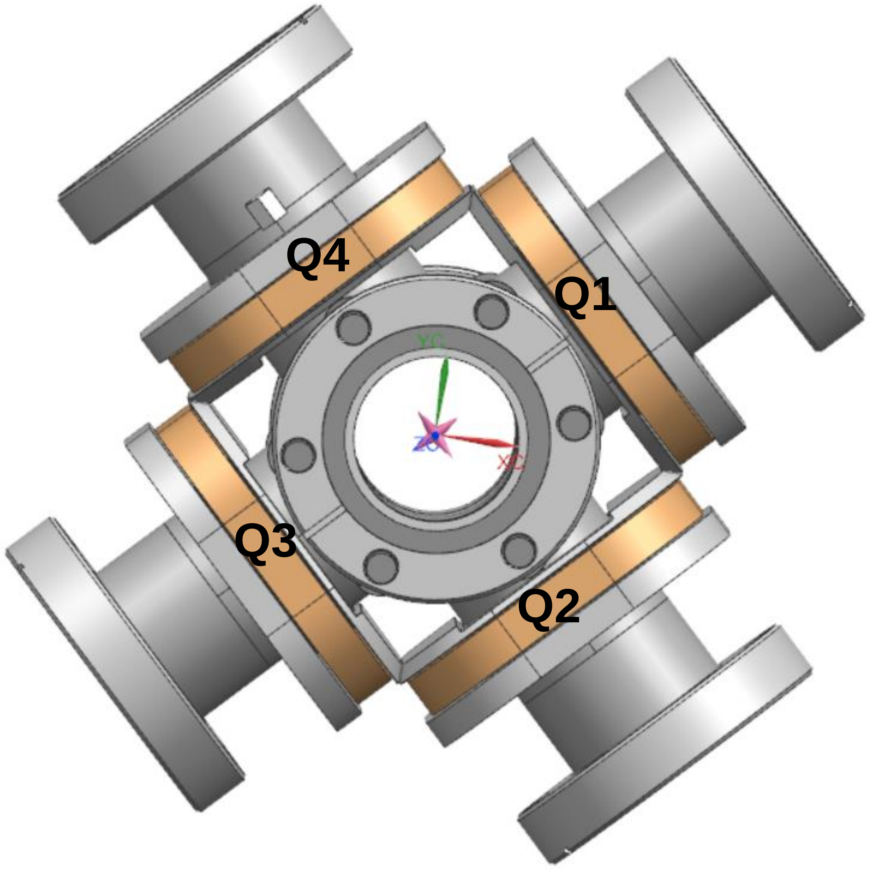


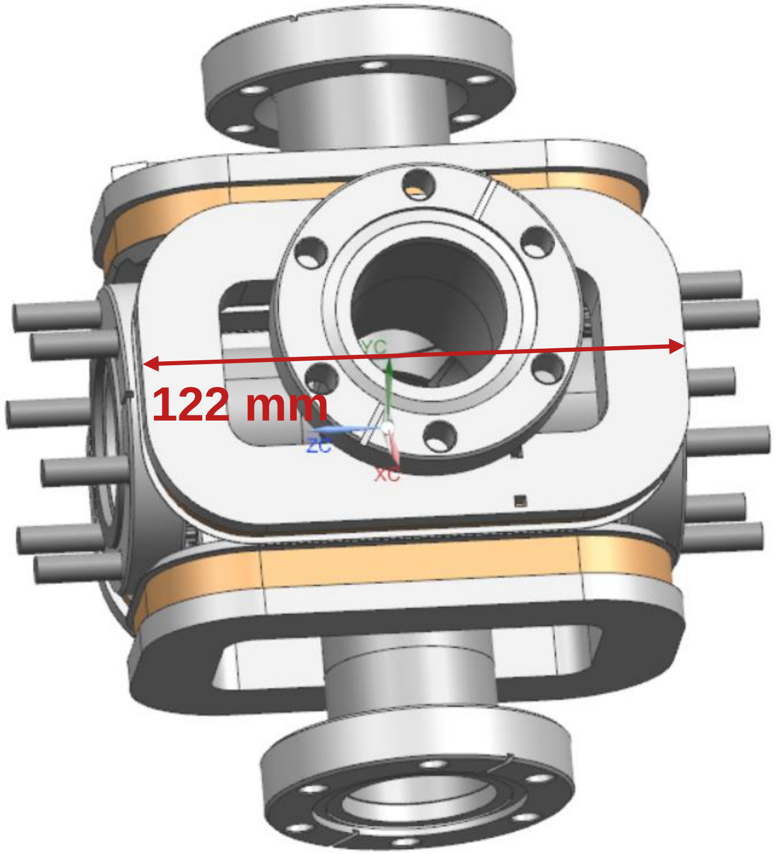



# Design Considerations: QW Coil Layout on the Vacuum Cross Fitting

- Racetrack coils (Q1, Q2, Q3, Q4) arranged in quadrupole geometry.
  - 76 mm gap between the opposite coils.
- The coil bobbin is made out of stainless steel.

**QW Magnet ( new design)**



# Design Considerations: Conductor Selection

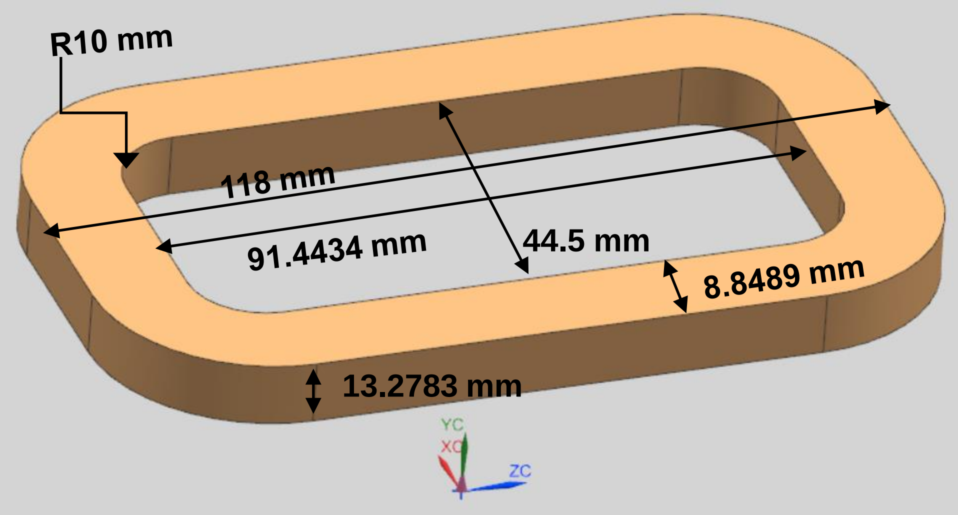
- Kapton insulated 12 AWG square conductor with round corner. (potential supplier- MWS Wire Industries, CA)

| Magnet wire parameters (Max. dimensions) | Unit | Value |
|---|---|---|
| Shape | | Square with round corner |
| Copper grade | | C101 or C102 |
| Bare conductor size (equivalent AWG) | | 12 |
| Bare conductor dimensions: width = thickness | mm | 2.0777 |
| Corner radius | mm | 0.508 |
| Radial thickness of the Kapton insulation | mm | 0.0635 |
| Insulated conductor dimensions: width = thickness | mm | 2.2047 |

# Design Considerations: Coils

- Flat coils ("easy to wind" geometry. Simplifies the tooling for the coil winding and the requirements for the support structure for magnet assembly)
- Wet wound with AREMCO 526 N epoxy.

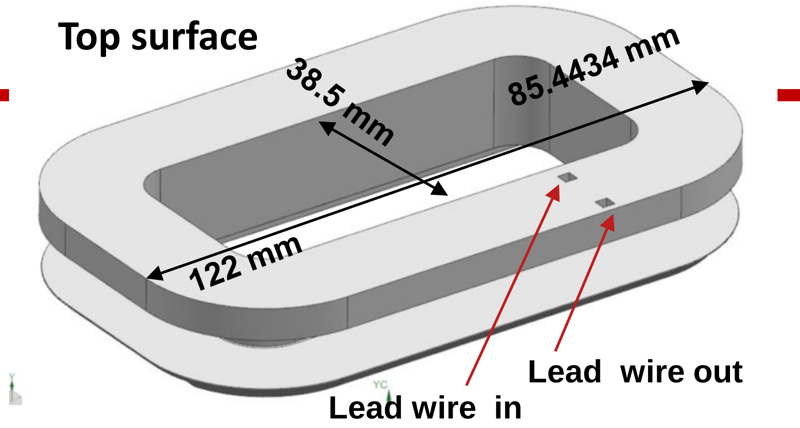
| QW coil parameters (Assumption: Coil wound on a PTFE bobbin) (estimated using the max. dimensions of the conductor) | Unit | Value |
|---|---|---|
| Distance between the opposite coils in the quadrupole assembly | mm | 76 |
| Radial thickness of the epoxy between the turns (assumed) | mm | 0.01 |
| Inner gap-<br>radial (X direction), longitudinal (Z direction) | mm | 44.5,<br>91.4434 |
| Radial thickness of the winding (X direction) | mm | 8.8489 |
| Height of the winding (Y direction) | mm | 13.2783 |
| Straight length,<br>Overall length of the coil | mm | 71.4434,<br>118 |
| Inner corner radius | mm | 10 |
| Total turn count (Number of layers, Number of turns per layer) | | 24 (6,4) |
| Estimated length of conductor per coil (5% extra for unknowns) (+1m for each lead wire) | m | ~ 8.9 |
| Req. length of conductor per magnet (four coils+ lead wires) | m | ~35.6 |

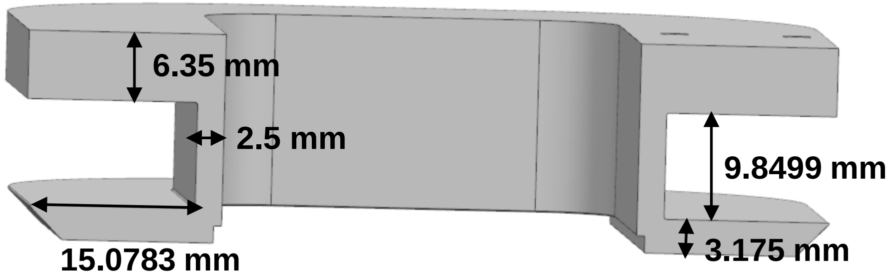


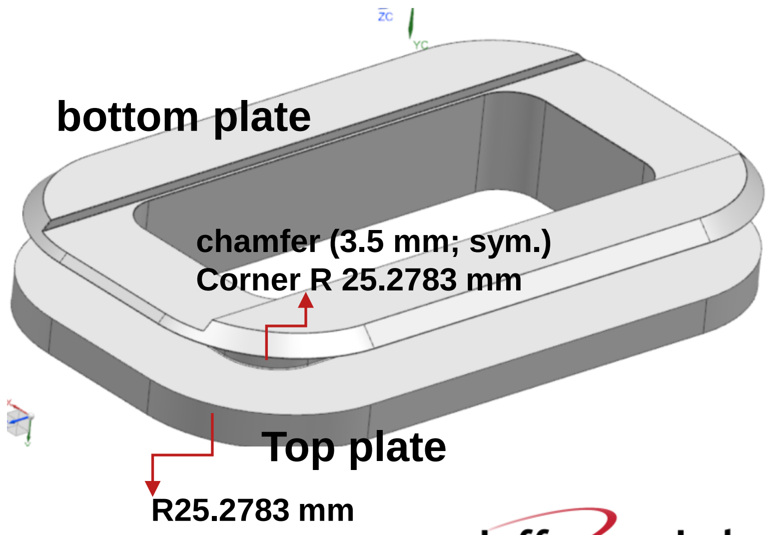
# Design Considerations: Coil Former

- Made out of single piece of material; Material: SS(304 grade)
  - Bottom plate is shaped to fit the coil pack in the quadrupole geometry with 76 mm gap between the opposite coils.
  - The lead wires route through the top plate of the coil former.
  - Kapton insulation between the coil and bobbin.

| Coil Former dimensions | Unit | Value |
|---|---|---|
| Inner gap-<br>radial (X direction), longitudinal (Z direction) | mm | 38.5,<br>85.4434 |
| Corner radius of the inside surface of the core | mm | 7 |
| Thickness of the core | mm | 2.5 |
| Thickness of the bottom plate, top plate | mm | 3.175, 6.35 |
| Overall length | mm | 122 |
| Overall height | mm | 19.3749 |
| Radial thickness of Kapton around the core<br>(two layers of 0.25 mm thick film) | mm | 0.50 |
| Thickness of pre-cut Kapton spacer between coil and top and bottom plates of the bobbin | mm | 0.50 |

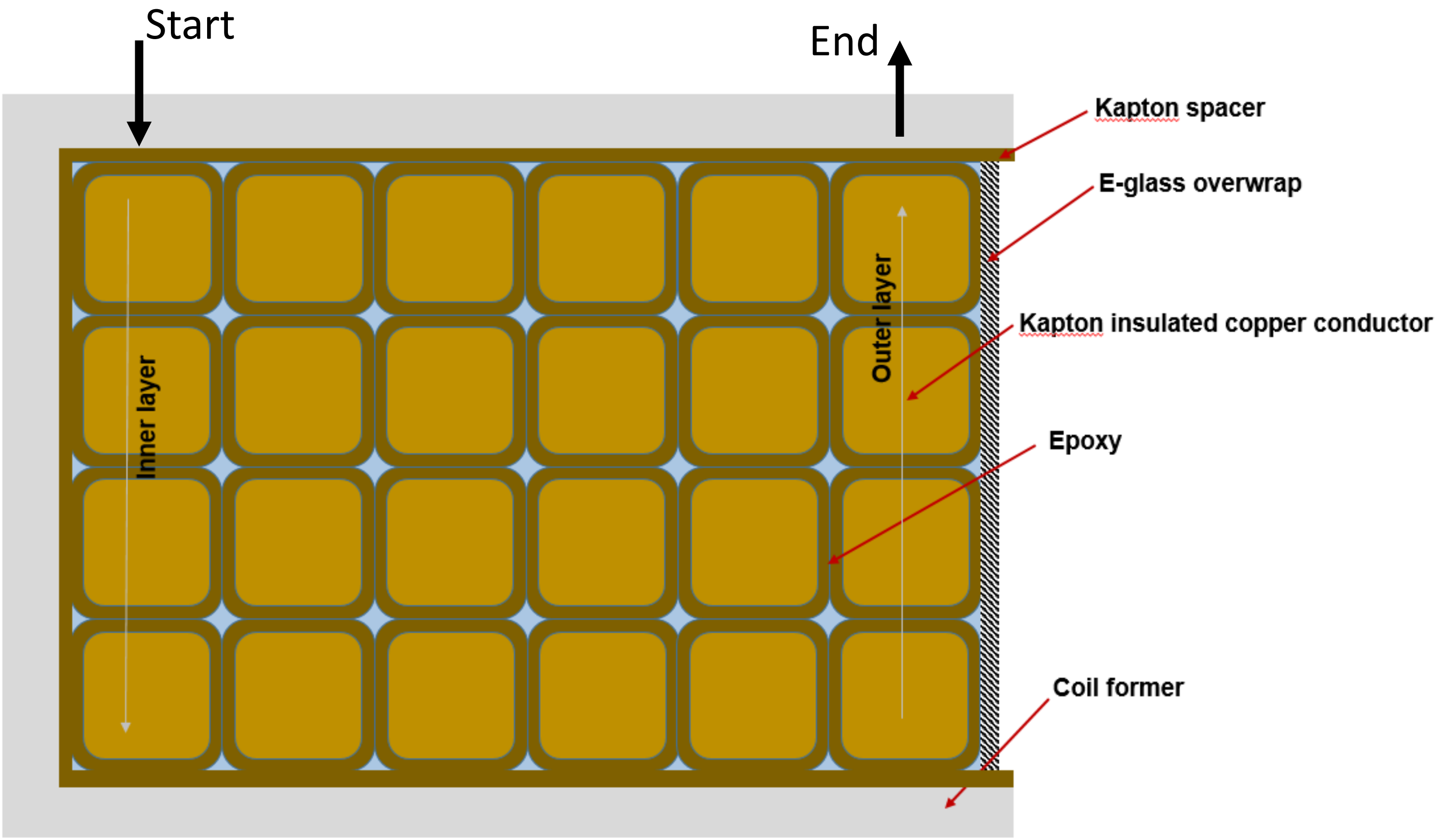


# Conductor Layout in the Coil

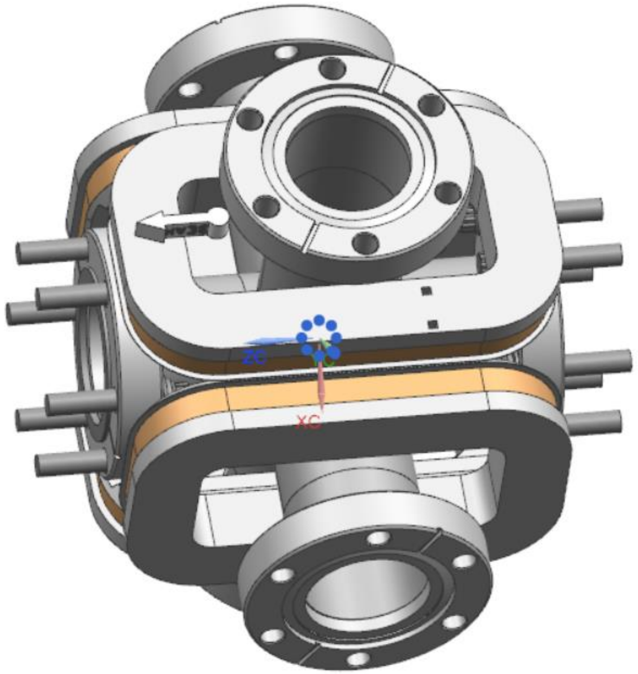
- The coil wound directly on the SS former.
- Uses single piece length of the copper conductor.
- Wet wound with AREMCO 526 N Epoxy. (assumption: 0.01 mm thick epoxy filling between the coil turns)
- The coil winding tight against the bottom plate of the former.
- Filler could be used, as needed, in the gap between the top surface of the coil and former plate.
- Additionally 2 layers of 0.1 mm thick E-glass wrapped under tension on the outer surface of the finished coil and painted with the same epoxy.



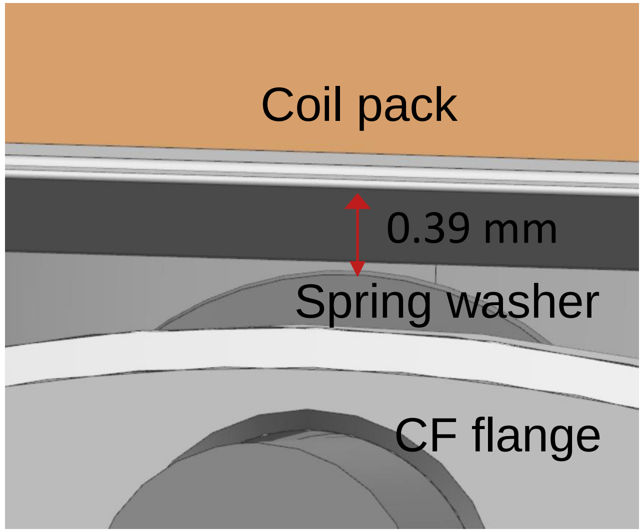

**Conductor layout in the QW coil**

Note: flat coils, "easy to wind" geometry and tooling requirements;
Considering the overall space constraints, the coil manufacturing process should strictly adhere to the suggested layout of the conductor and overall dimensional specification of the coils

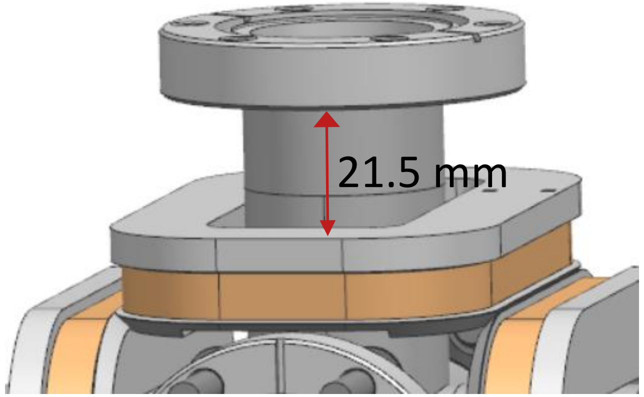
# Design Considerations: Coil Assembly on the Vacuum Cross Fitting



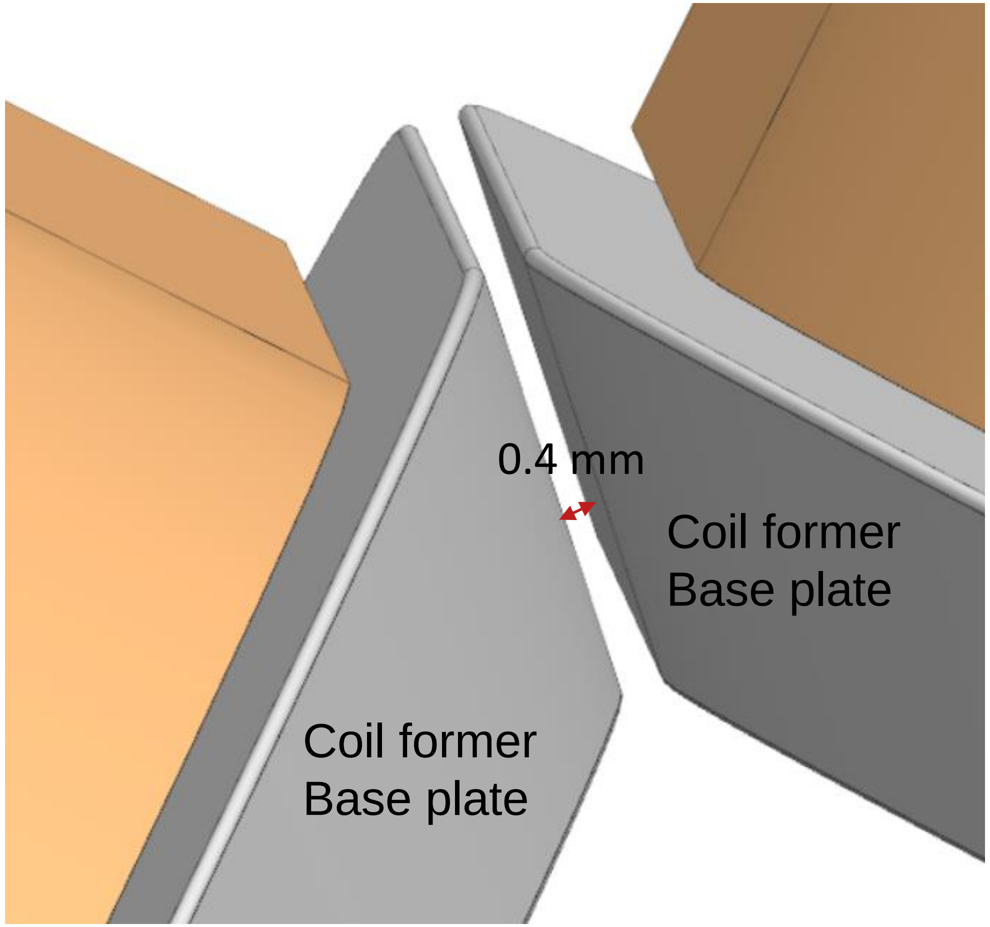

Flexibility to move or rotate the coil pack  during the assembly stage.




Sufficient clearance between the CF flange hardware and the coil pack

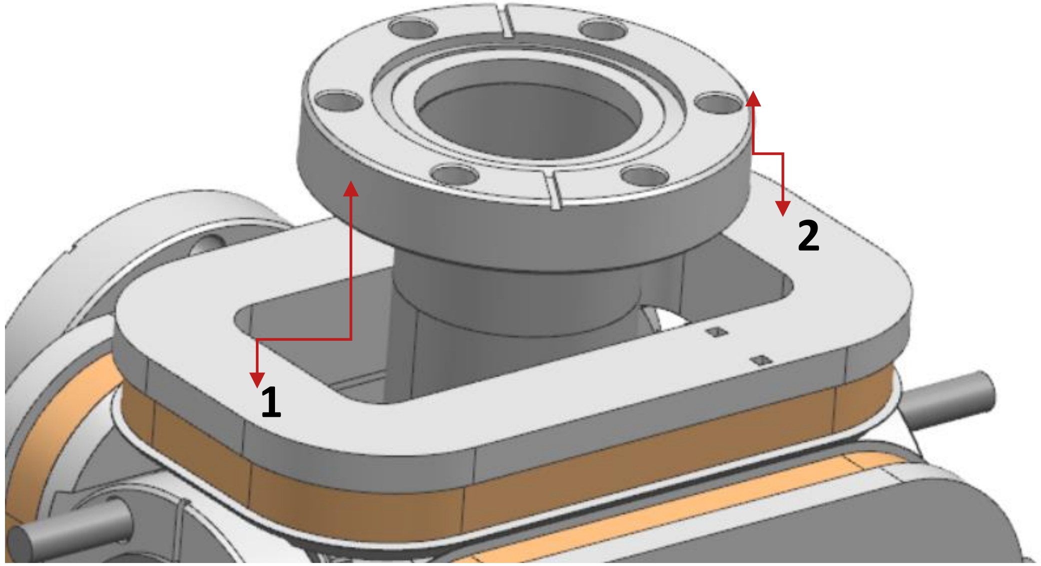



~21.5 mm clearance between the CF flange and coil (in radial direction)

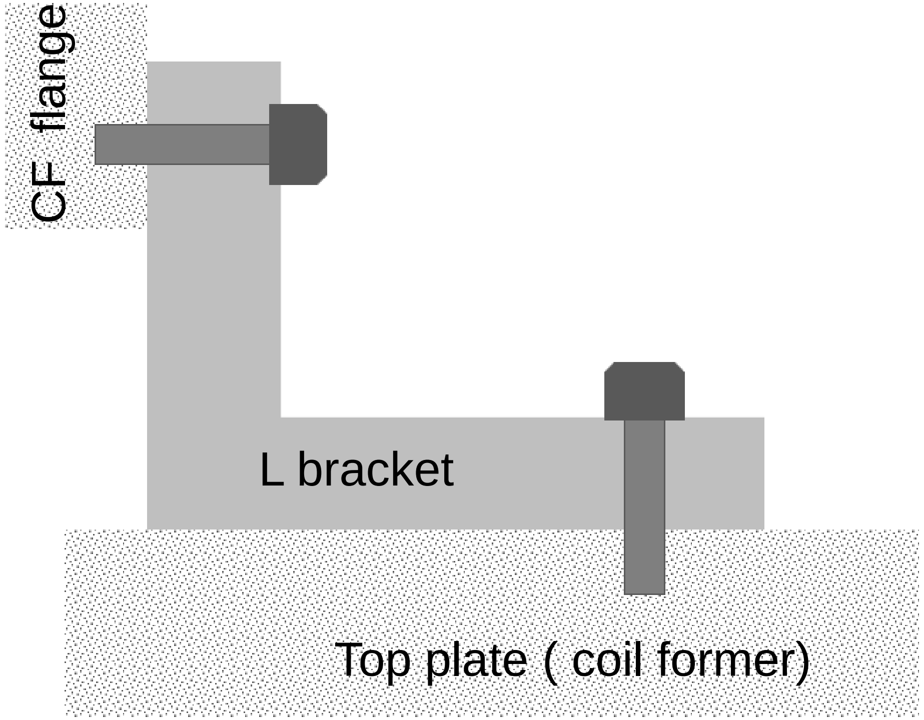



~0.4 mm clearance radially between the base structures of the coil former

# Design Considerations: Magnet Support Structure



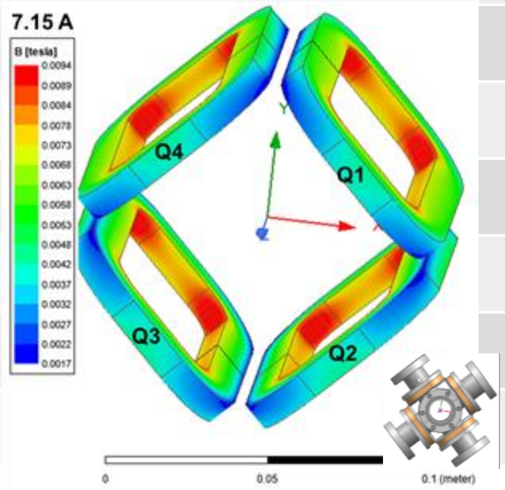

- L bracket or angled pipe bracket (SS) From top plate of the coil former at locations 1 and 2 as shown

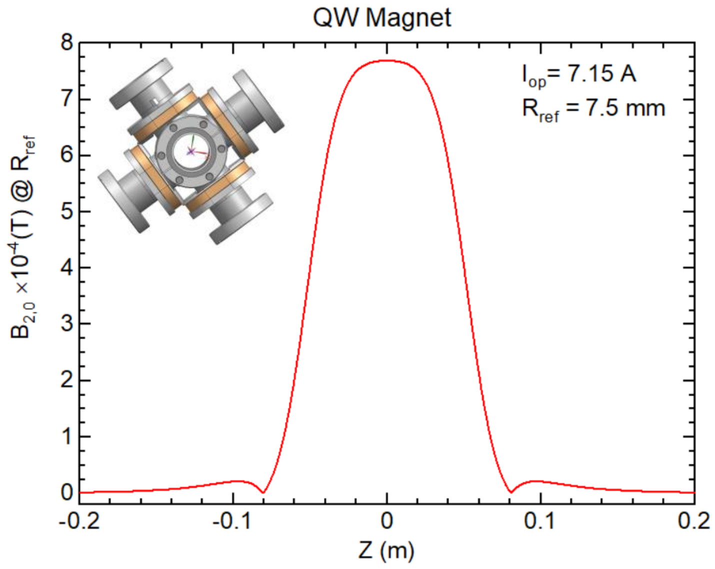


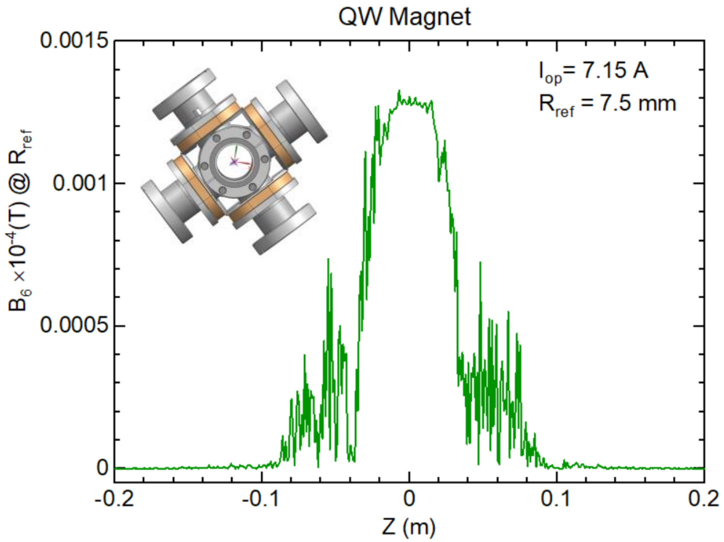
# Magnetic Performance Parameters (@ Max. Operating Conditions)

- EM design fulfills the performance requirements and provides sufficient operating margin (~12.5 %).
- 10 A power supply is required.

| Parameter | Unit | Value |
|---|---|---|
| Operating current | A | 7.15 |
| Operating current density in the copper conductor | A/mm$^2$ | 1.75 |
| Integrated quadrupole (n=2) field strength at $R_{ref}$ (Requirement: 0.01 T integrated field gradient corresponds to $7.5\times10^{-5}$ T.m int. field strength) | T.m | $7.502\times10^{-5}$ |
| Integrated quadrupole field uniformity at $R_{ref}$ (only the 12 pole (n=6) component present) | % | 99.99 |
| Effective magnetic length at $R_{ref}$ | m | 0.975 |
| Max. field strength of the coil | mT | 9.38 |
| Inductance of each coil | µH | 71.12 |
| Magnetic Stored Energy | mJ | 8.71 |
| Resistance of the coil at 20 °C | mΩ | 37.18 |
| Cumulative force on each coil pack | mN | 9.38 |



# Summary and Recommendation

Tech note will be prepared later

- The new QW magnet design fulfills the performance requirements.
  - Need to energize the coils at 7.15 A to achieve a maximum of 0.01T integrated quadrupole field gradient.
  - 10 A power supply is required.
  - Provides additional 12.5% performance margin.
  - Integrated quadrupole field homogeneity better than 99.99%.
  - Structural evaluation- in progress
  - No room to include field clamp to minimize the fringe field interaction between the QW magnet and the neighboring (Haimson) steering magnet
    - The magnet to magnet interaction will be quantified.
    - We can add a stand-alone shield between these magnets if needed.
  - Limit the max. operating current to 8.3 A (recommendation).
  - Keep the bake temp to 180° C (recommendation)
    - To prevent the local hotspot exceeding 200 ° C .