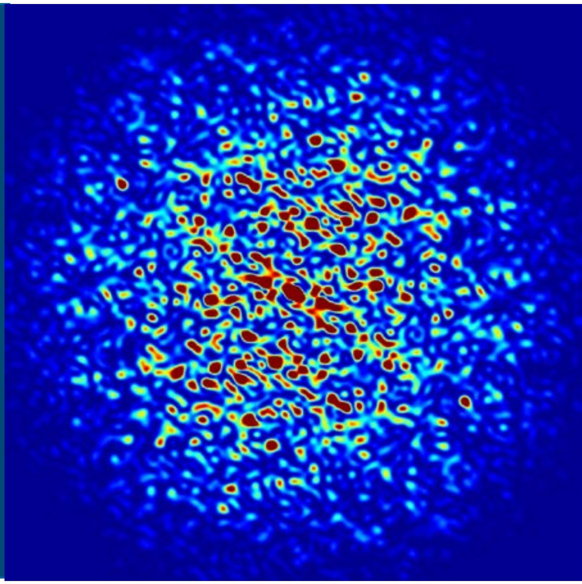
Status of magnetic measurements for the Advanced Photon Source Upgrade*



Animesh Jain, Charles Doose, Scott Izzo, Mathew Virgo, Robert Soliday
Argonne National Laboratory

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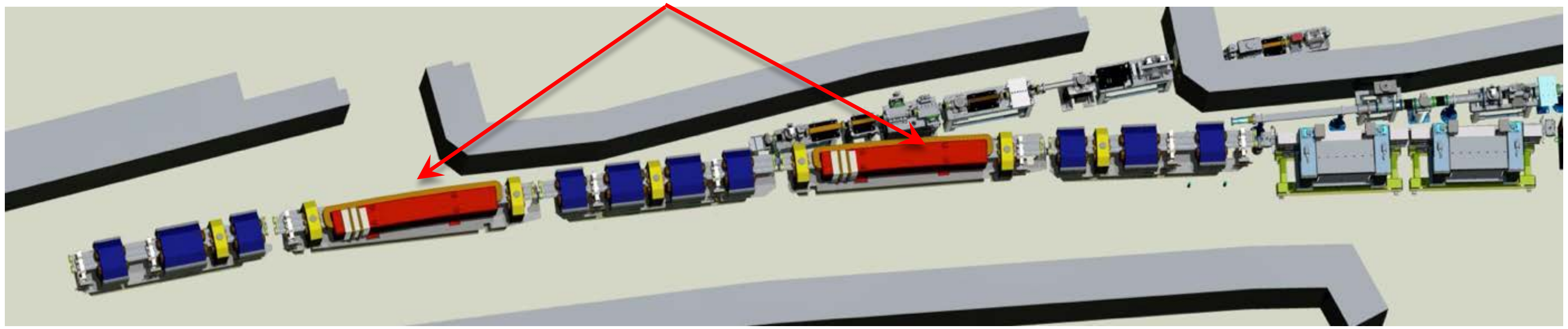
Introduction

- It is planned to upgrade the Advanced Photon Source (APS) currently operating at Argonne National Laboratory to provide much brighter beams of X-rays (the APS-U project).
- As part of this upgrade, the entire storage ring will be replaced with a new storage ring based on a 42 pm Multi-bend Achromat (MBA) lattice.
- The new storage ring will contain over 1300 new magnets, which will have to be measured and aligned in an assembly of magnets.
- A "Critical Decision 3" review was held last week and we anticipate moving into full production phase very soon. However, a large fraction of the required magnets are already under production under a previous "CD-3b" authority.
- A new magnetic measurement laboratory is just setup for the measurements and fiducialization of the storage ring magnets.
- Status of magnetic measurements for APS-U is presented in this talk.

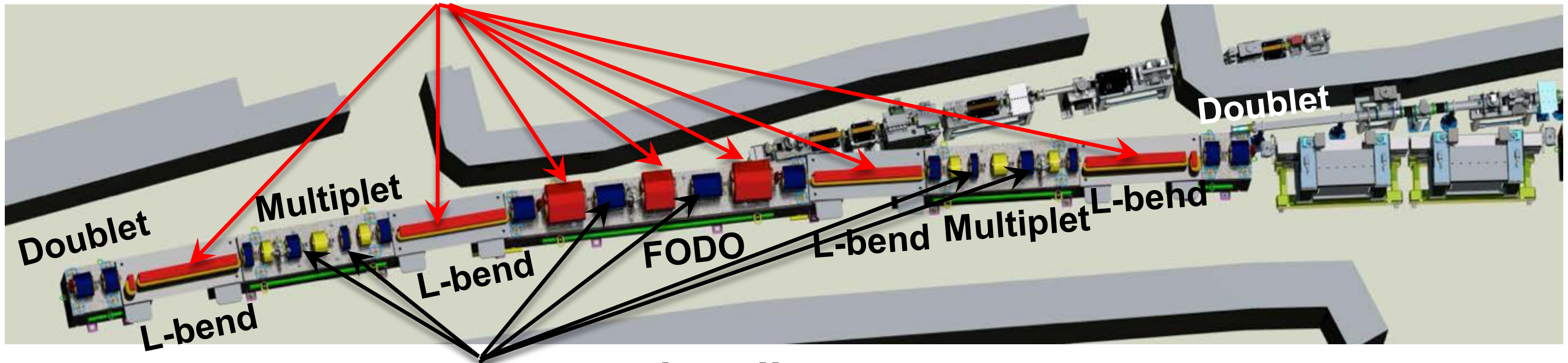
Advanced Photon Source Upgrade (APS-U)

2 bending magnets (Double Bend Achromat)



Present Lattice

7 "forward" bending magnets



6 "reverse" bending magnets

Upgrade Lattice

4 longitudinal gradient dipoles (L-bends; Dipole field only)
3 transverse gradient dipoles (**Q-bends**; dipole + quadrupole fields)
6 reverse bending magnets (**R-bends**; dipole + quadrupole fields)
13 bends total (Multi-bend Achromat)

Status of magnet procurements (as of June 14, 2019)

Magnet Type	Quantity Ordered	Quantity Received
8-pole fast correctors	162	0
Q1	82	82
Q2	81	67
Q3	83	0
Q4	82	1
Q5	82	1
Q6	82	0
S1/S3	164	0
S2	82	1
M1	82	0
M3	82	0
Total	**1064**	**152**

Magnets remaining to be ordered

Magnet Type	Quantity to be Ordered
Q7	82
Q8	82
M2	82
M4	41
Total remaining	**287**

All magnet designs are completed.

Waiting for funding authority to place orders (expected very soon)

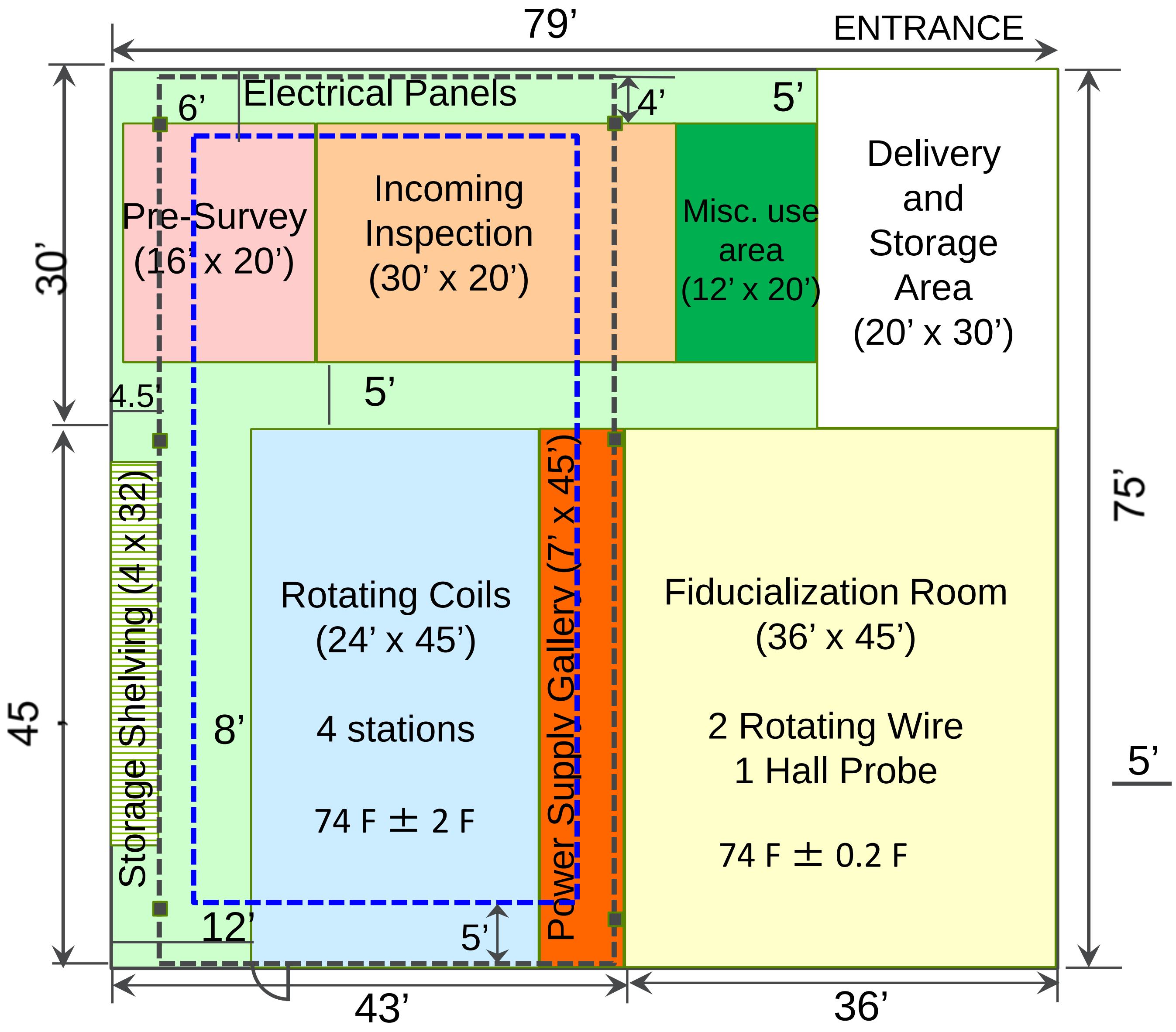
~79% of all magnets are already ordered

We have over 150 magnets in house that are waiting to be measured.

New magnetic measurement laboratory for APS-U

- The existing space used for measurements during R&D phase is not big enough to accommodate the needs of the full APS-U production.
- We need space for up to 4 rotating coil benches, two fiducialization benches, and one Hall probe bench, in addition to space for incoming mechanical and electrical inspections, pre-survey of dipoles, and storage of some magnets to match the throughput of approximately one week.
- A portion of an existing building at Argonne was identified as a suitable candidate around January 2018, but the space was being used for other purposes at that time.
- The space was vacated, existing unwanted structure was demolished, and the space was re-built according to the needs of the measurement laboratory.
- We received final occupancy of the new space in April 2019.

General plan of the new measurement laboratory



Construction is completed, and the space was handed over for setting up the laboratory in April 2019.

Magnet measurement lab: Incoming inspection area

Incoming inspection area

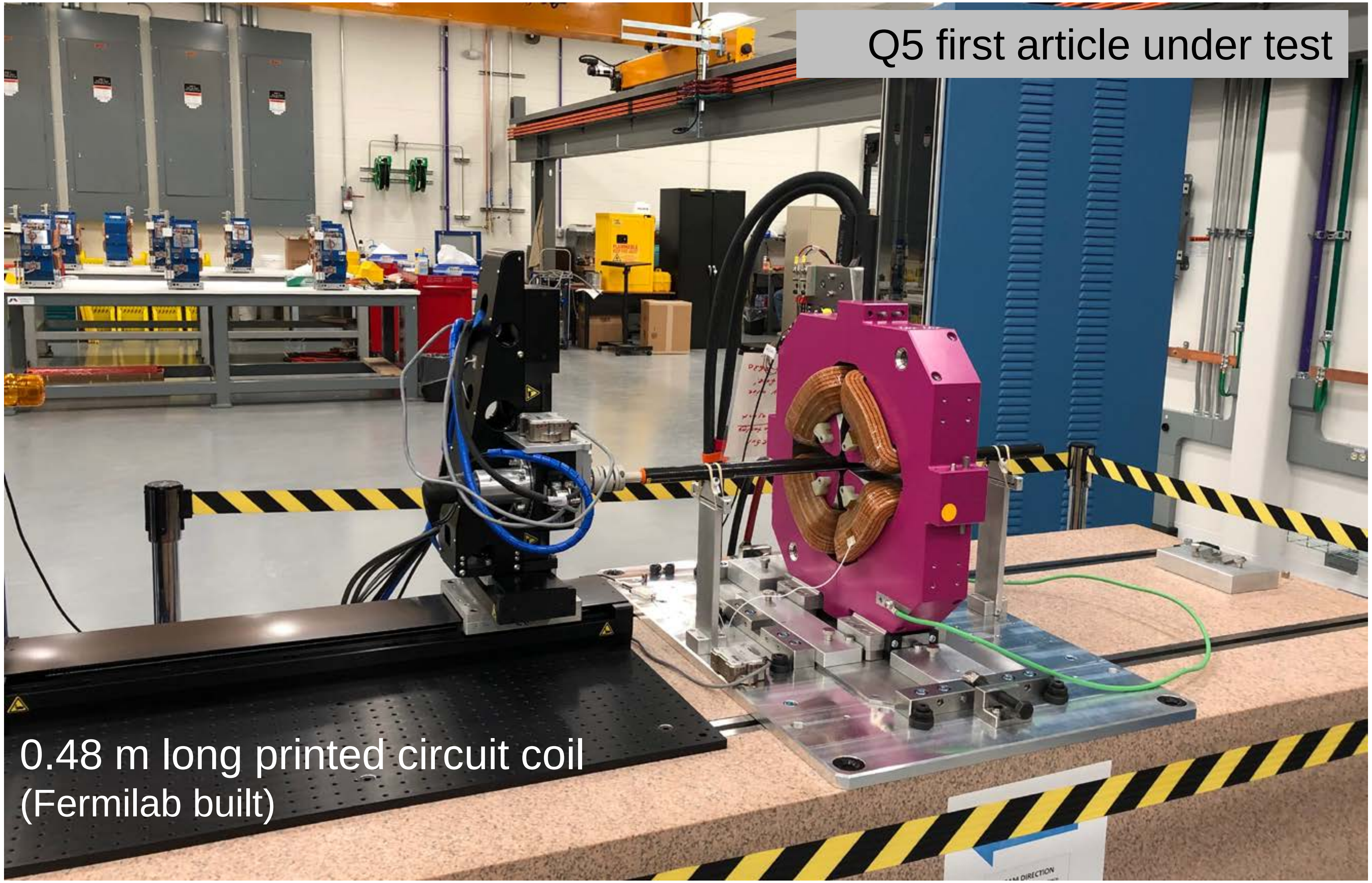
Photo credit: Mark Jaski

All magnets received so far have been mechanically inspected.

The magnet manufacturers are responsible for meeting only the mechanical requirements, and not field quality, since all magnet designs are by Argonne, and the magnets are built as a "build-to-print" contract.

However, in the end, field quality is important and magnetic measurements are essential.

Magnet measurement lab: First rotating coil bench



This bench is now fully assembled and operational.

0.48 m long rotating coil

Routine measurements have started as of June 17, 2019

Magnet measurement lab: Fiducialization room

"Short" Rotating Wire Fiducialization Bench

Environment: ±0.1 C

The bench is now fully assembled and operational. However, the data acquisition software is still not equipped to automatically find the magnetic center of all types of magnets, including the combined function Q-bends.

Measurements are possible with manual intervention.

A second bench for longer magnets will have a similar design.

Simple measurements with rotating coils

Magnet Type	Length (m)	Quantity	Bend Angle (mr)	Comments
Q1	0.250	82	--	Quadrupole
Q2, Q3, Q6	0.225	246	--	Quadrupoles
Q4*	0.244	82	-1.7069	Sagitta = 0.046 mm
Q5*	0.150	82	-1.1575	Sagitta = 0.016 mm
Q7	0.424	82	--	Quadrupole
Q8*	0.646	82	-5.3586	Sagitta = 0.392 mm
S1, S3	0.229	164	--	Sextupole
S2	0.260	82	--	Sextupole
8-pole Fast Correctors	0.160	162	--	Normal and skew dipole; skew quad
Total		**1064**	**(~79% of all magnets)**	

* Sagitta is small and simple integral measurements are sufficient.

Two rotating coil lengths (0.48 m and 1.0 m) will cover all of these magnets.

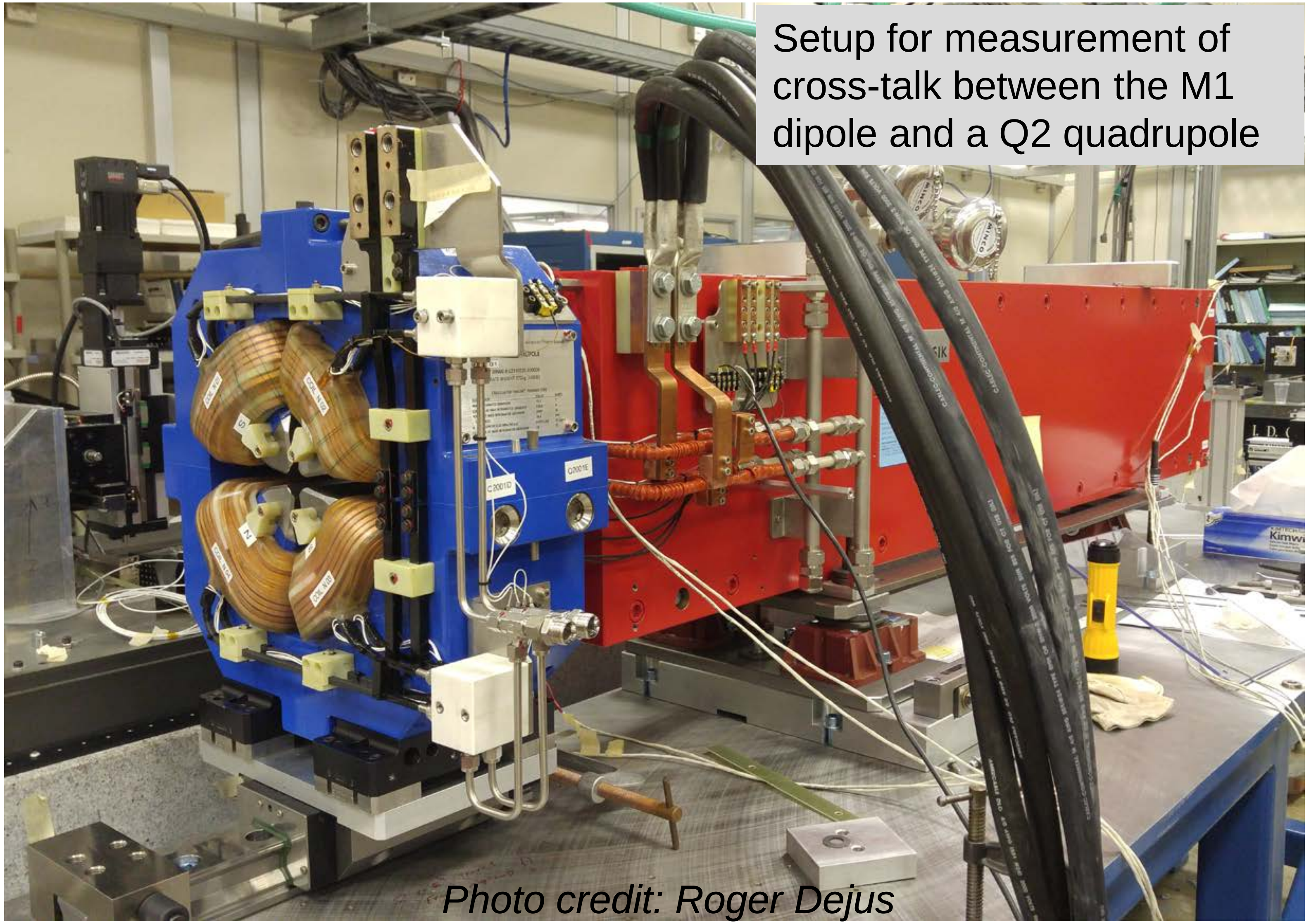
– Two benches with 0.48 m long coils, and one bench with 1.0 m long coil

Simple measurements with Hall probes

Magnet Type	Length (m)	Quantity	Total Bend Angle (mr)	Comments
M1	2.225	82	28.5716	5-segment L-bend B_{max}/B_{min} ~ 4.6
M2	1.985	82	23.2944	5-segment L-bend B_{max}/B_{min} ~ 2
Total		164	(~12% of all magnets)	

- These magnets are built straight, but the beam is curved with a curvature changing with axial position, as the field changes.
- These magnets will be mapped on a rectangular grid at the magnet midplane.
- The Hall maps will be used to:
  - Ensure that the field integral on a nominal beam path is within tolerance (< ±0.1% magnet-to-magnet variation), and adjust the end shields if necessary.
  - Determine the optimal installation of the magnet to preserve the vertex point and minimize beam excursion from the magnet centerline.

Hall probe mapping of a R&D M1 L-bend dipole



Setup for measurement of cross-talk between the M1 dipole and a Q2 quadrupole

Photo credit: Roger Dejus

The bench used for R&D measurements will be needed for insertion device measurements.

A new Hall probe mapping bench is being designed and will be fabricated in-house.

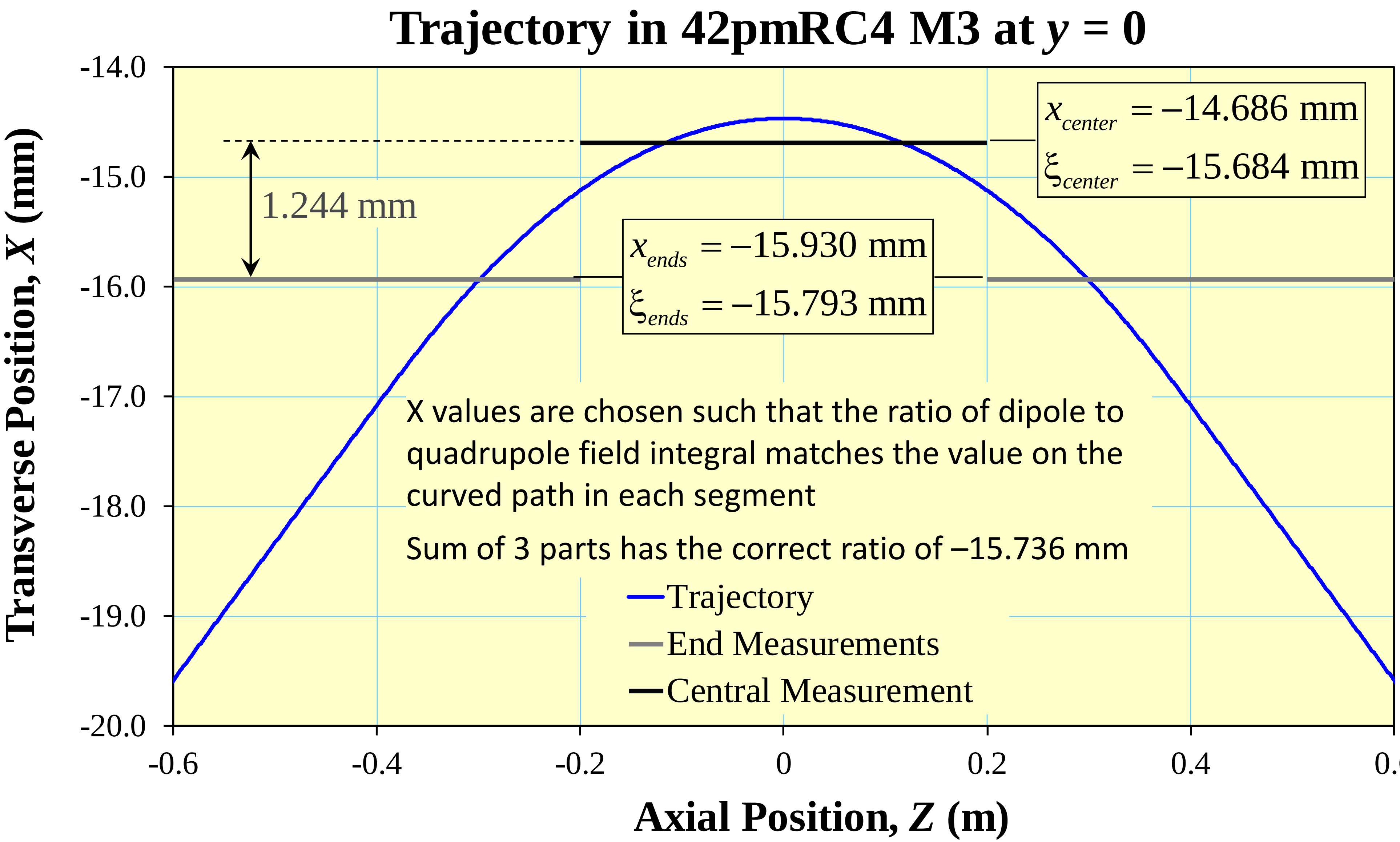
New bench is expected to be available in early 2020.

Most challenging magnet types

Magnet Type	Length (m)	Quantity	Total Bend Angle (mr)	Comments
M3	0.820	82	25.0793	Sagitta = 2.405 mm
M4	0.700	41	19.6350	Sagitta = 1.584 mm
Total*		123	(~9% of all magnets)	

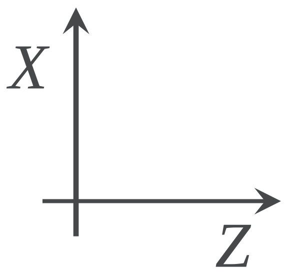
- These magnets have strong dipole and quadrupole components.
- Magnet yokes are built straight, but are fitted with curved pole tips.
- Hall maps are inconvenient to measure (no access from the side).
- Also need to locate the “magnetic center” precisely enough for aligning to other magnets in the same FODO assembly to 0.030 mm.
- Need to devise new measurement methods that can be easily applied in a production environment (best to adapt well known techniques).
- A scheme has been developed to measure field quality using a straight rotating coil, and magnetic center using straight wires. **(See talk at IMMW20)**

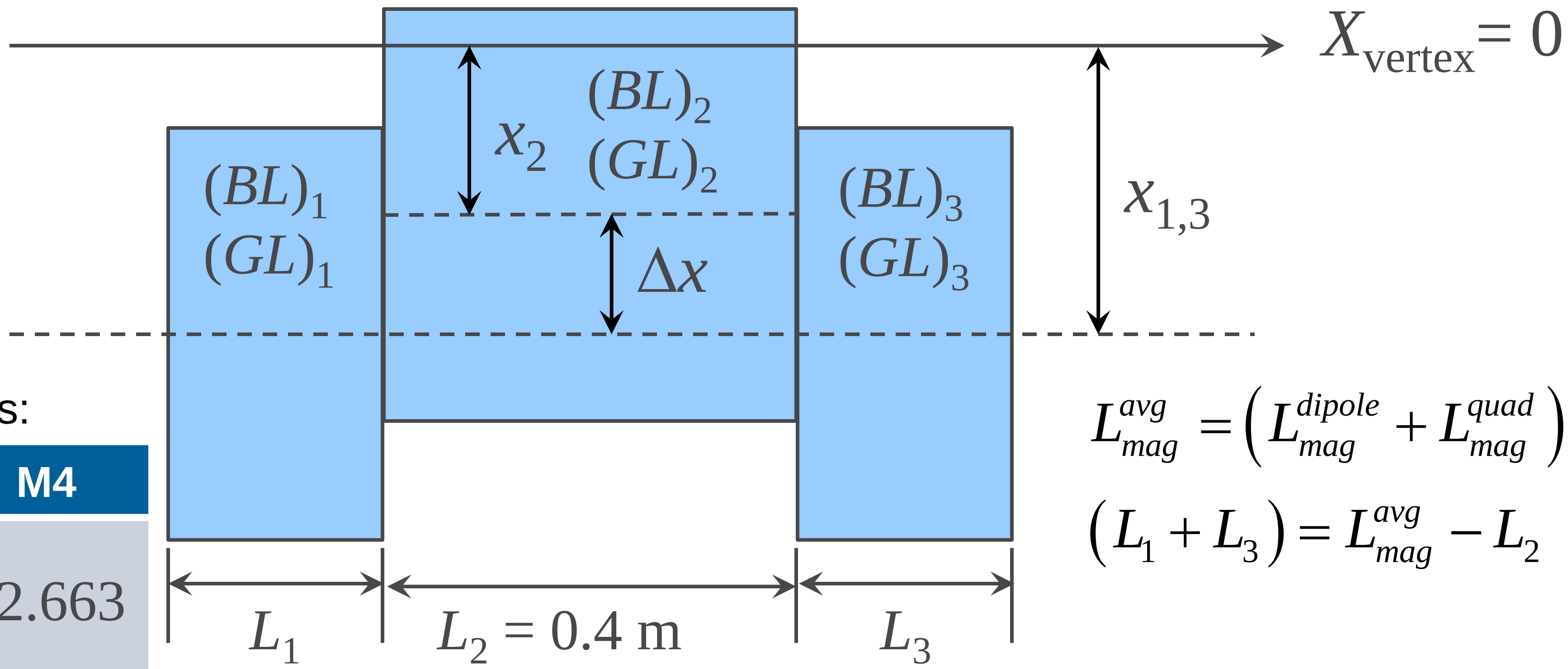
3-part measurement in M3 magnet



$$\xi = \left(\frac{BL}{GL}\right)$$

3-part representation of the M3 and M4 magnets





$$L_{mag}^{avg} = \left(L_{mag}^{dipole} + L_{mag}^{quad}\right)/2$$

$$\left(L_1 + L_3\right) = L_{mag}^{avg} - L_2$$

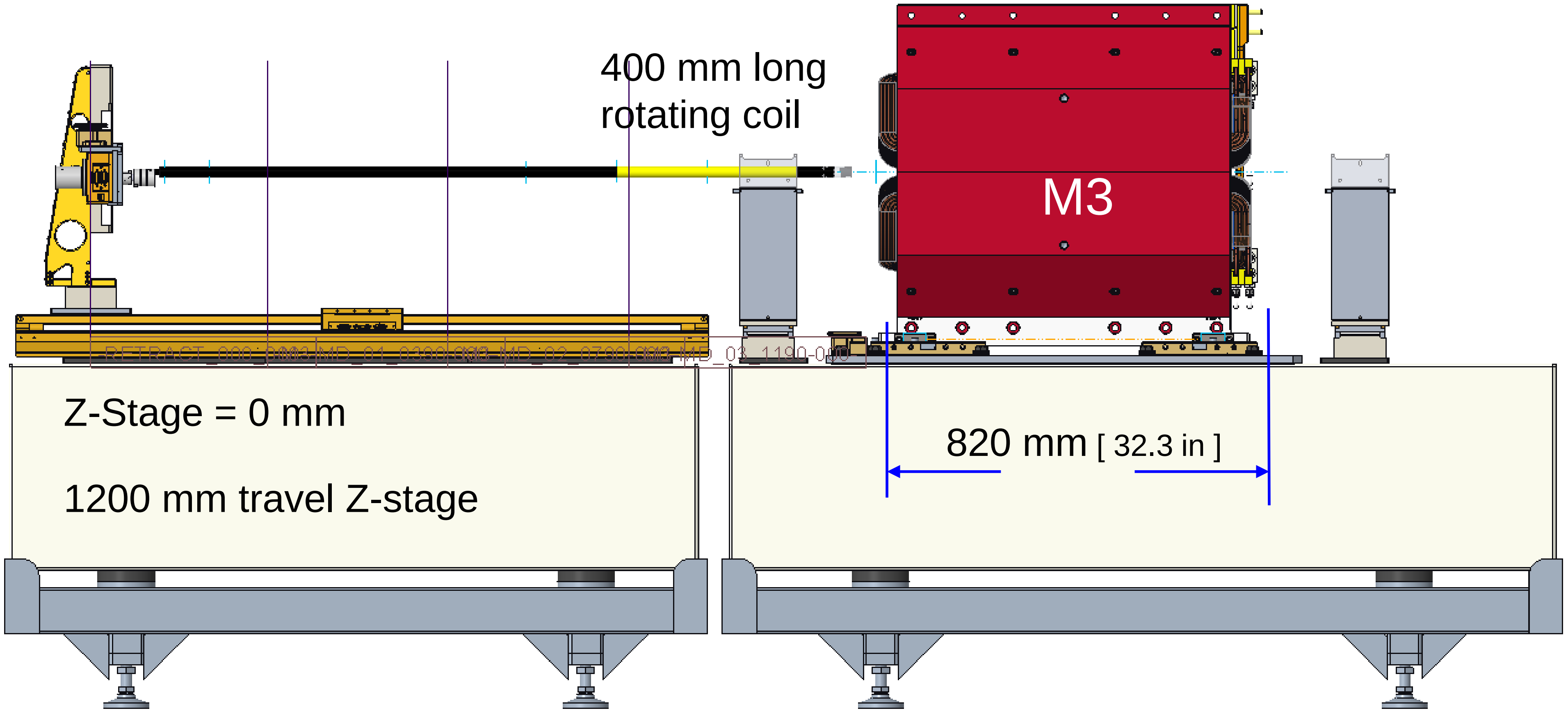
From Opera-3D analysis:

Quantity	M3	M4
$x_{1,3}$ (mm)	–3.868	–2.663
x_2 (mm)	–2.624	–1.787
L_1=L_3 (m)	0.1814	0.1206
Δx (mm)	1.244	0.876

$$L_1 = \left(\frac{1}{2}\right)\left[\frac{(BL)_1}{(BL)_1 + (BL)_3} + \frac{(GL)_1}{(GL)_1 + (GL)_3}\right]\left(L_{mag}^{avg} - L_2\right)$$

$$L_3 = \left(\frac{1}{2}\right)\left[\frac{(BL)_3}{(BL)_1 + (BL)_3} + \frac{(GL)_3}{(GL)_1 + (GL)_3}\right]\left(L_{mag}^{avg} - L_2\right)$$

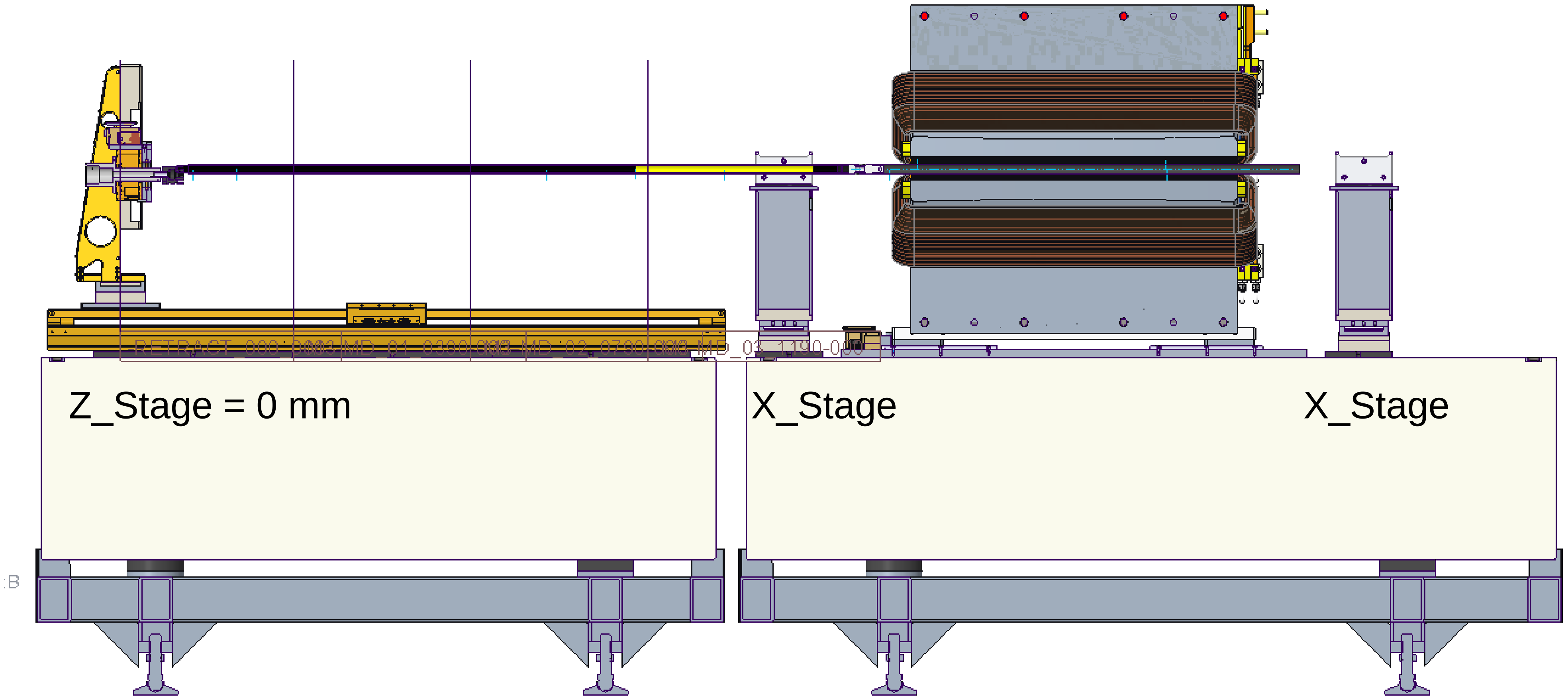
M3-M4 Q-bend rotating coil system design



A similar concept is used for the Q7-Q8 rotating coil system

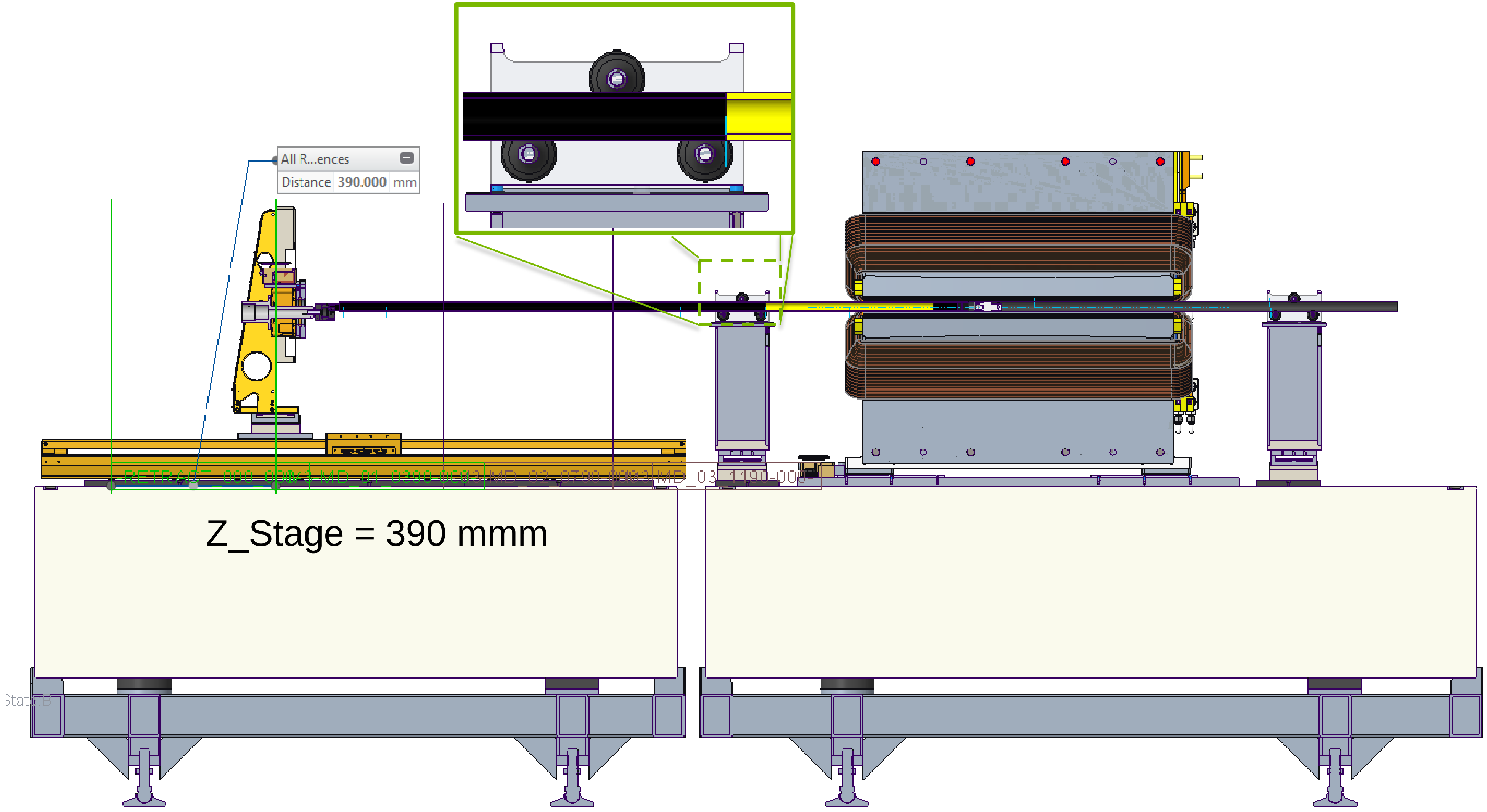
M3-M4 rotating coil system: with coil extension attached

Q2



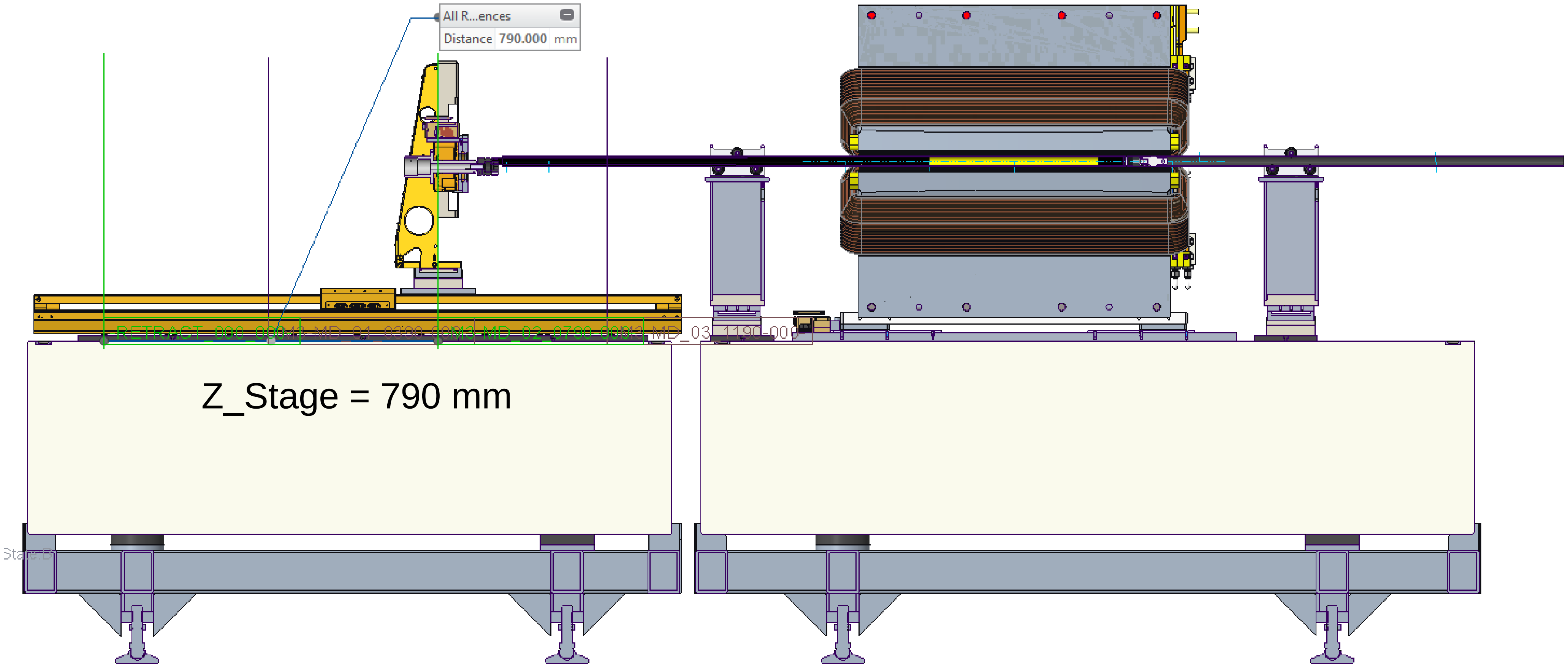
Granite block is segmented to keep the weights of individual pieces within the crane capacity (5 tons)

M3-M4 rotating coil system: 1st measurement position



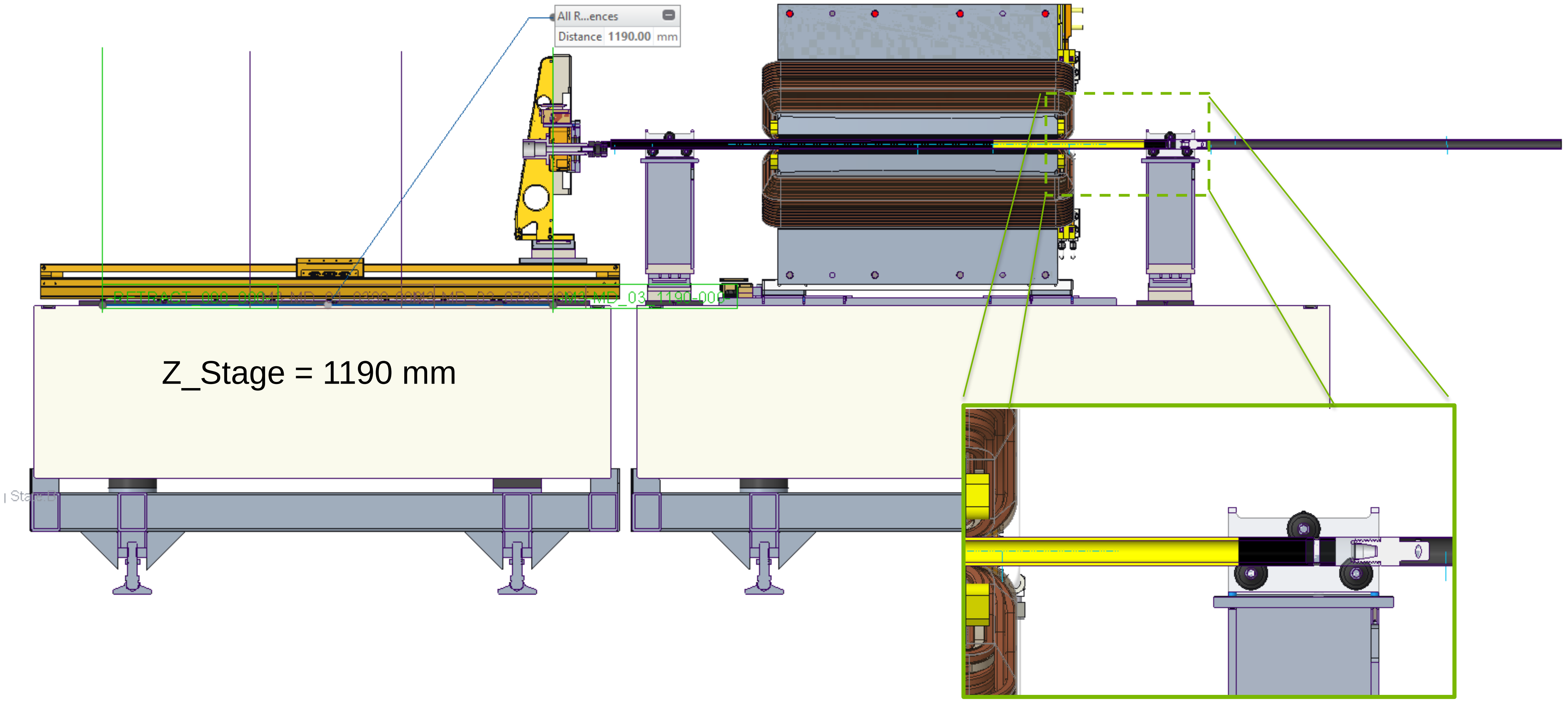
Rotating coil is secured at both ends in all measurement positions

M3-M4 rotating coil system: 2nd measurement position

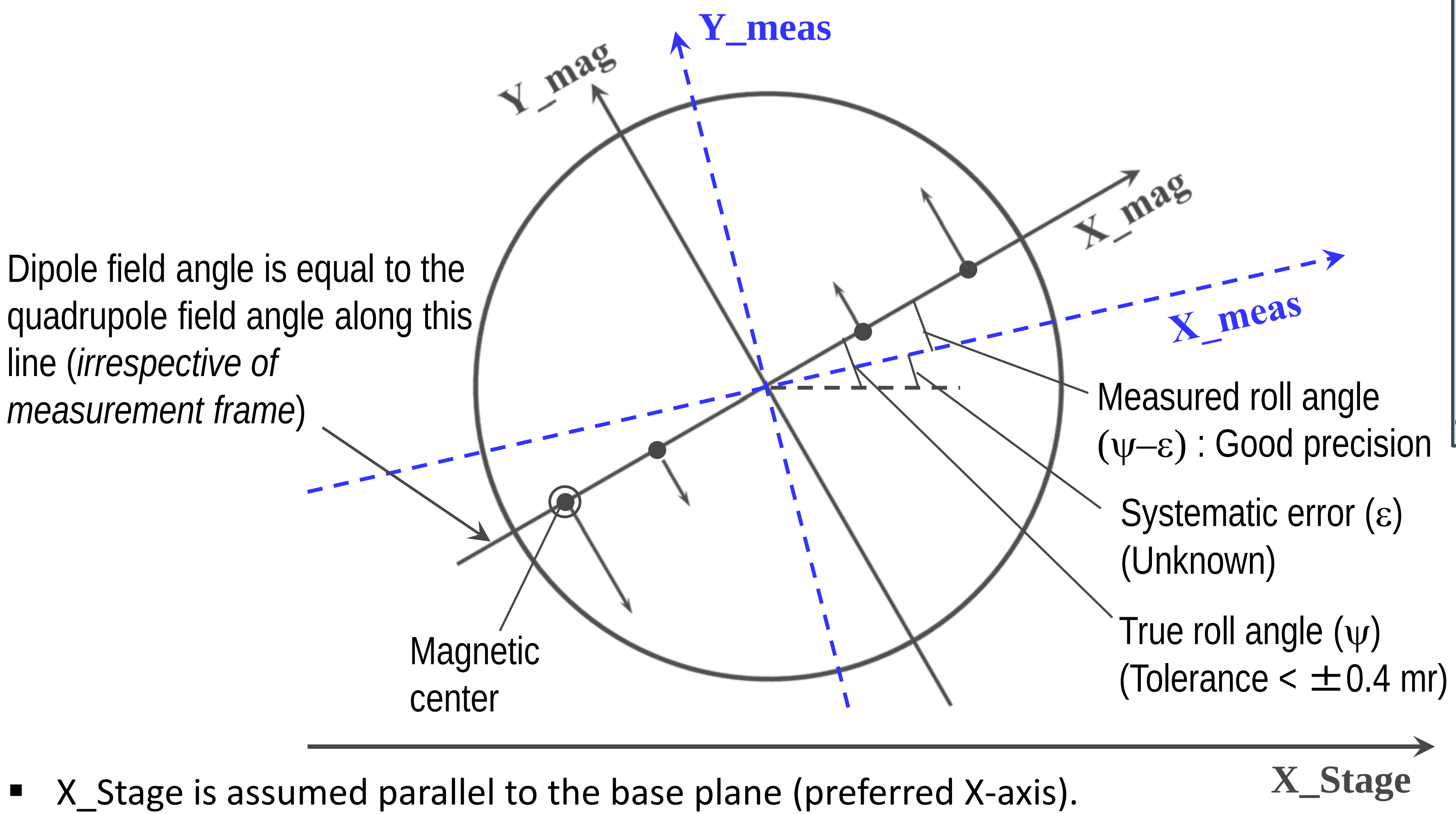


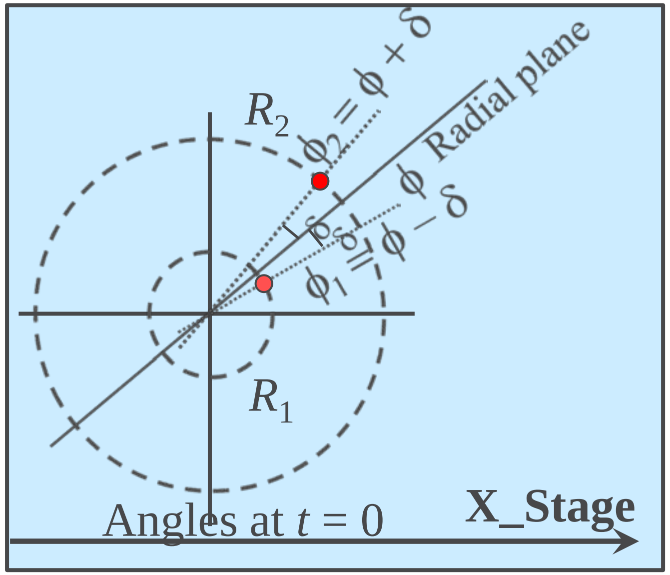
The coil is moved in X as a function of Z-position, to approximate the curved beam path

M3-M4 rotating coil system: 3rd measurement position



Fiducialization: Q-bend with arbitrary roll angle relative to base





A complete calibration of the rotating wire geometry is essential to measure both the dipole and quadrupole components with a consistent calibration for both field amplitude and phase.

A calibration procedure is developed.

- X_Stage is assumed parallel to the base plane (preferred X-axis).
- Y_Stage is only *approximately* orthogonal to X_Stage (within ~a few mr).
- Quadrupole field angle is relatively insensitive to X-Y position (small higher order terms).
- Dipole strength and field angle depend strongly on the X-Y position.

Measurement systems design/fabrication summary

System	Status	Magnet Types	Number of Magnets	AVAIL date (expected)
RC1	Ready to be assembled	Q1, Q3, Q4, Q5, Q6	405	12-Jul-2019
RC2	Available	Q2, S1/S3, S2, FC	486	14-Jun-2019
RW1	Available, but with software limitations	Q1, Q2, Q4, Q5, S1/S3, S2	567	21-Jun-2019
RW2	Design will be similar to RW1	Q3, Q6, Q7, Q8, M3, M4	446	16-Oct-2019
RC3	Printed circuit coil to be built by Fermilab; basic design is completed, final drawings are to be made.	M3, M4	122	06-Feb-2020
RC4	Printed circuit coil to be built by Fermilab; basic design is completed, final drawings are to be made.	Q7, Q8	162	24-Apr-2020
HP1	Design yet to be started	M1, M2	162	24-Jan-2020

Summary

- The upgrade of APS at Argonne will require measurements of 1351 magnets for the new storage ring.
- A new magnet measurement laboratory is built to handle the high volume of magnetic measurements. All measurements must be completed by the end of September 2022.
- The first rotating coil and the first rotating wire benches are just operational. A total of seven benches are planned (four rotating coil, two rotating wire, and one Hall probe).
- Approximately 90% of the magnets can be measured using well established rotating coil and Hall probe techniques. The remaining ~10% are the Q-bends M3 and M4, which require special treatment.
- Schemes are developed to adapt rotating coil and wire based techniques to curved combined function magnets M3 and M4, as described in more detail at IMMW20.
- All magnets will be fiducialized, but quick alignment in a module assembly is expected to be achieved using reference surfaces on the magnets and support plates. Alignment will be checked using laser trackers and fiducialization data. Any out of alignment magnets will be shimmed if necessary.
- There are ~150 magnets in hand waiting to be measured. We expect to clear this backlog by the end of calendar year 2019 to be ready to receive the next batch of production magnets.