# MAX IV 3 GeV ring magnets

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# Outline

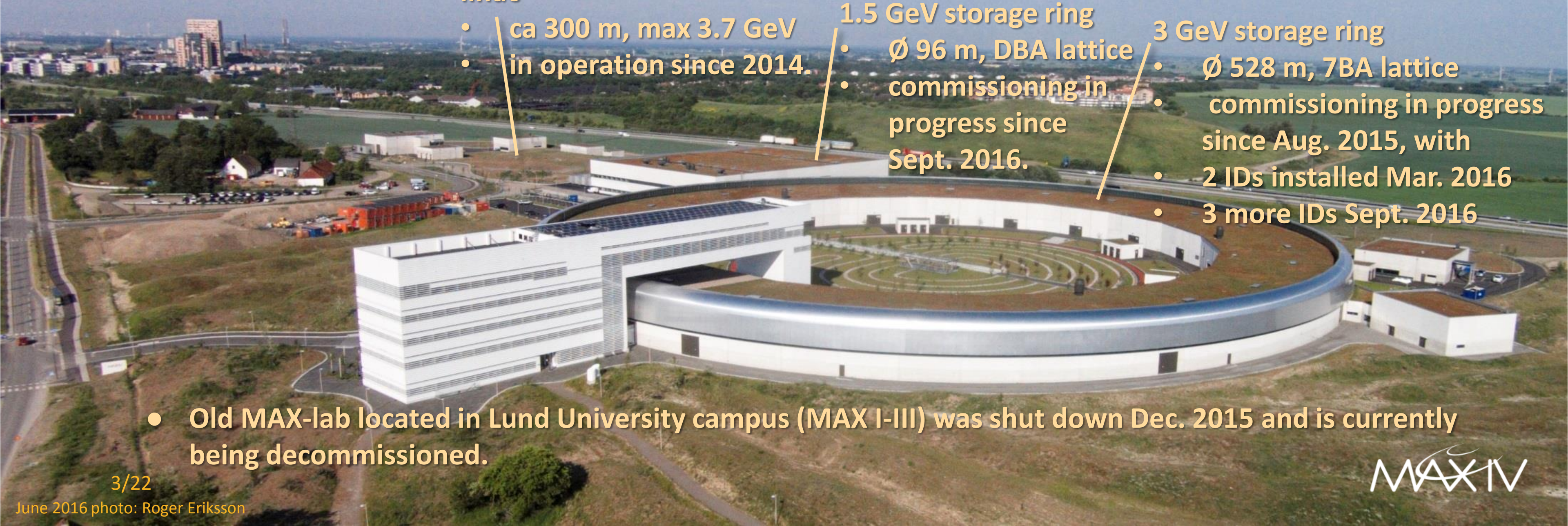
- introduction
  - the MAX IV Laboratory
  - 3 GeV ring magnet concept
- specification, manufacturing and results
- installation



MAX IV

# The MAX IV Laboratory

- Located in Lund, Sweden.
- Facility dedicated to synchrotron radiation research. National Laboratory, hosted by Lund University, with ca 200 employees.



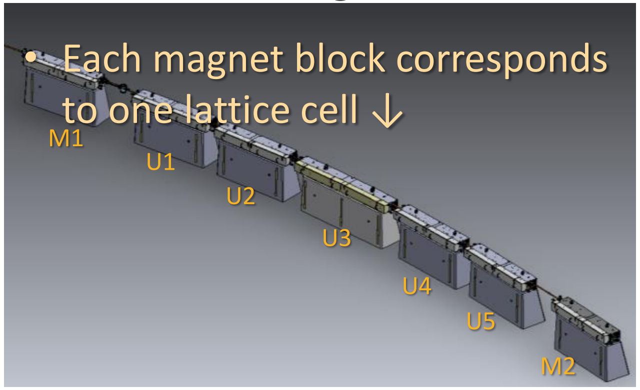

- Old MAX-lab located in Lund University campus (MAX I-III) was shut down Dec. 2015 and is currently being decommissioned.

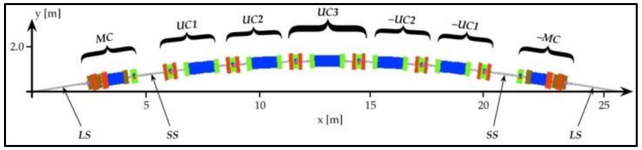


June 2016 photo: Roger Eriksson

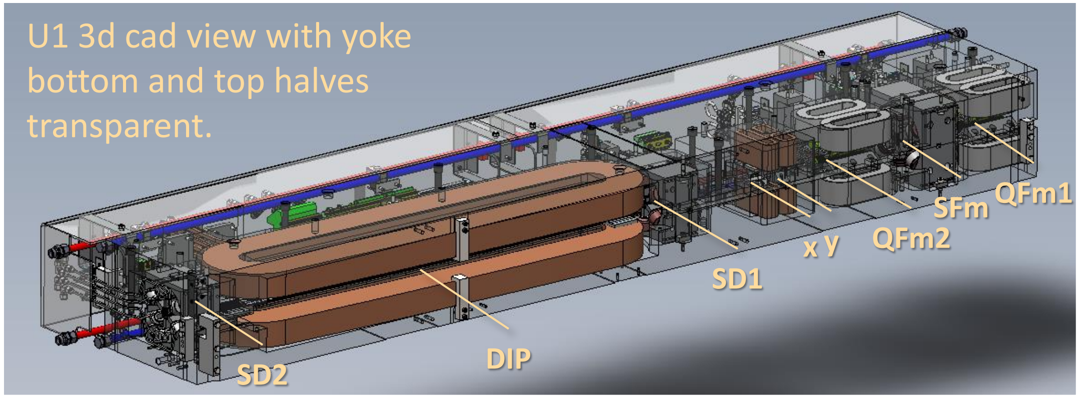
# the MAX IV 3 GeV ring magnets – key aspects:

- Relatively small magnet aperture of Ø 25 mm.
- Magnet block concept → integrated unit containing several consecutive magnet elements.
- Each magnet block corresponds to one lattice cell ↓

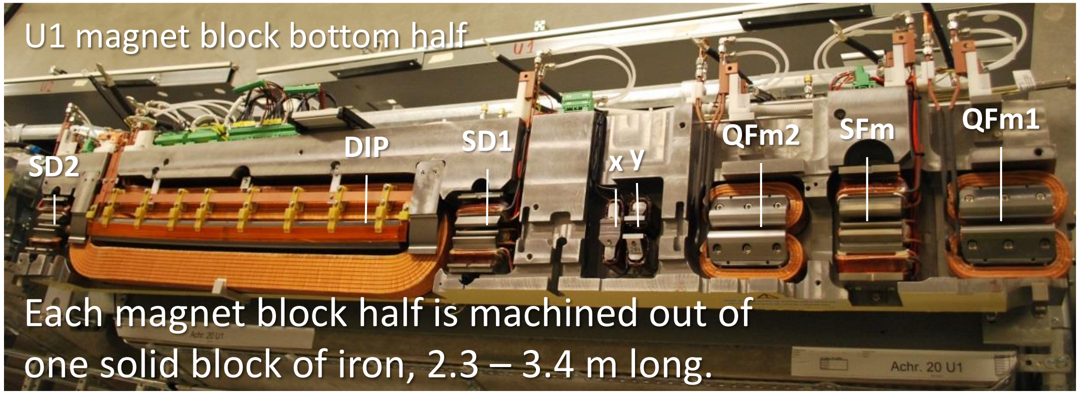



- 20 achromats x 7 cells = 140 magnet blocks, containing 1320 magnet elements.

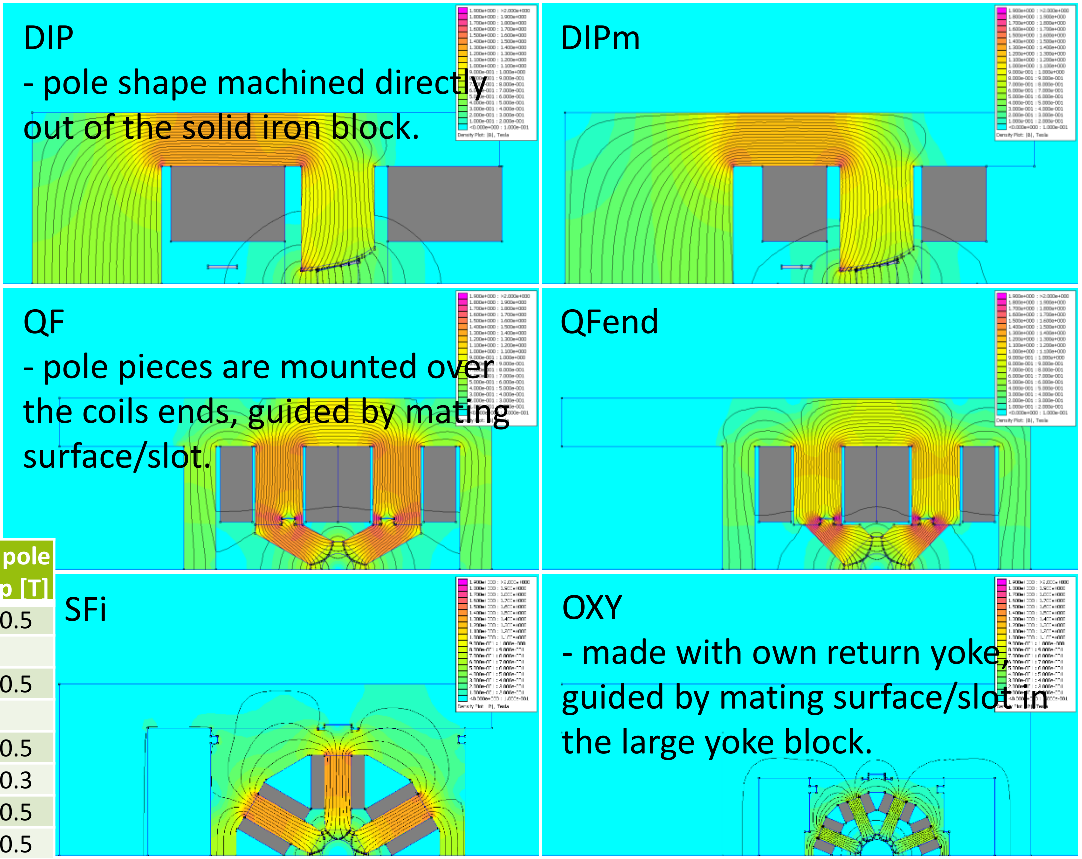






# 3 GeV ring magnet types

- Example production version magnet cross sections →
- List of magnet types ↓ with lengths and field strengths according to design lattice[1]



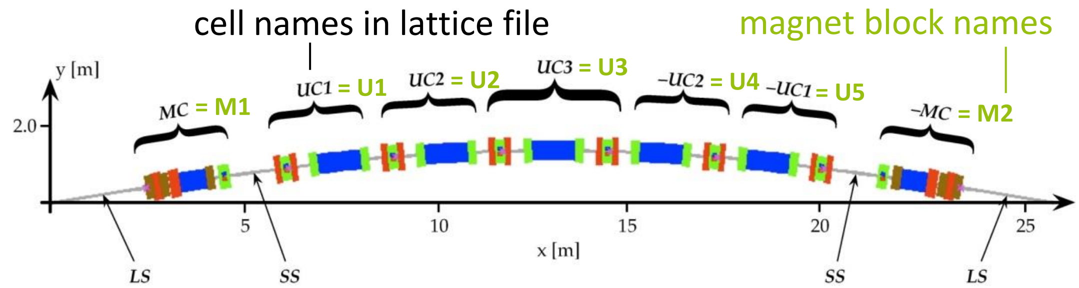

| magnet | No [pcs] | block | l [m] | $r_{pole}$ [mm] | B [T] | B' [T/m] | B''/2 [T/m$^2$] | B'''/6 [T/m$^3$] | B pole tip [T] |
|---|---|---|---|---|---|---|---|---|---|
| DIP [2] | 100 | U1-5 | ~1.22 | 14 | -0.53 | 8.66 | | | 0.5 |
| pfs | | | | | | ±4 % | | | |
| DIPm [2] | 40 | M1,2 | ~0.75 | 14 | -0.53 | 8.71 | | | 0.5 |
| Pfs | | | | | | ±4 % | | | |
| QFend | 40 | M1,2 | 0.25 | 12.5 | | -36.57 | | | 0.5 |
| QDend | 40 | M1,2 | 0.25 | 12.5 | | 25.06 | | | 0.3 |
| QFm | 80 | U1,5 | 0.15 | 12.5 | | -37.77 | | | 0.5 |
| QF | 160 | U2-4 | 0.15 | 12.5 | | -40.34 | | | 0.5 |
| SDend | 40 | M1,2 | 0.1 | 12.5 | | | 1701 | | 0.3 |
| SFm | 40 | U1,5 | 0.1 | 12.5 | | | -1701 | | 0.3 |
| SD | 200 | U1-5 | 0.1 | 12.5 | | | 1167 | | 0.2 |
| SFo | 40 | U2,4 | 0.1 | 12.5 | | | -1742 | | 0.3 |
| SFi | 40 | U3 | 0.1 | 12.5 | | | -2076 | | 0.3 |
| OXX | 38[3] | M1,2 | 0.1 | 12.5 | | | | 33000 | 0.1 |
| OXY | 38[3] | M1,2 | 0.1 | 12.5 | | | | -65459 | 0.1 |
| OYY | 40 | M1,2 | 0.1 | 18 | | | | 28429 | 0.1 |
| corr x | 200 | all | | 12.5 | ±0.25 mrad | | | | 0.1 |
| corr y | 178[4] | all | | 12.5 | ±0.25 mrad | | | | 0.1 |
| total = | 1320 | | | | | | | | |

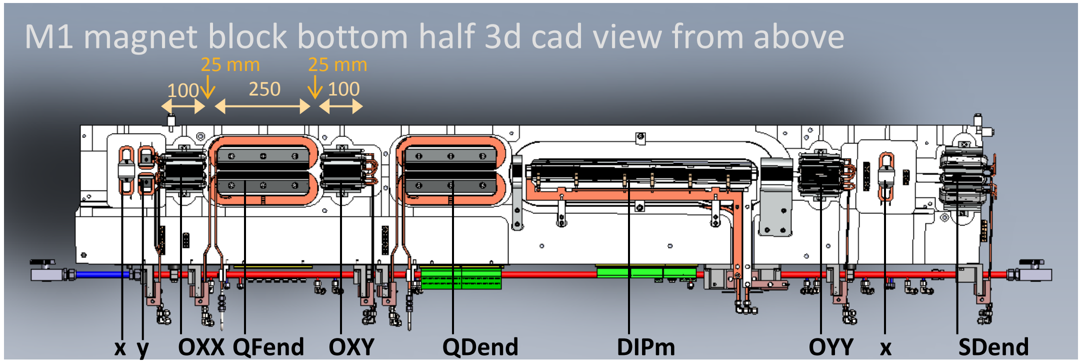
[1] lattice version = MAX-lab Internal Note 20121107
[2] DIP and DIPm are defined in the lattice as 12 longitudinal slices. Above lengths are sum of slices, fields are central slice.
[3] +2 OXX and 2 OXY in achromat 01 (injection) w. pole radius 18 mm.
[4] +2 vertical correctors in achromat 01 with pole gap = 2*18.5 mm.

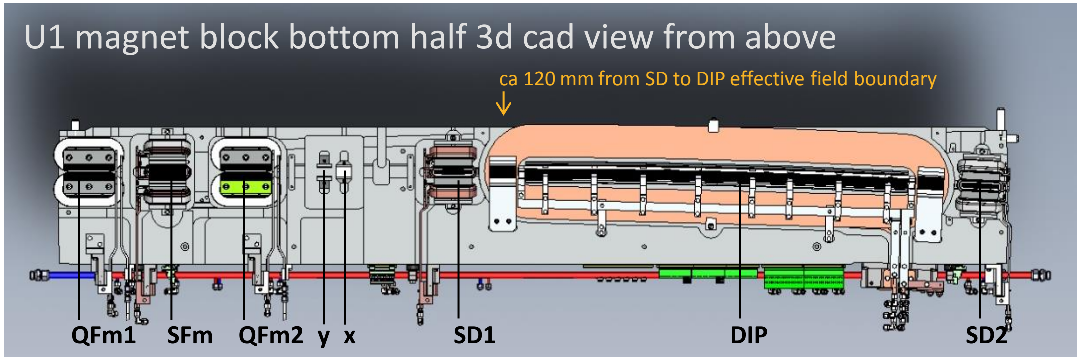
- Compared to new MBA lattice storage rings that are being designed/built now, MAX IV magnets have relatively modest focusing strengths (strongest quad -40 T/m).
  - Therefore, DIP and DIPm are gradient dipoles rather than offset quads, and no magnet has tapered poles, all coils are straight race track-shaped.
- Note that there are, on purpose, no built in position adjustment between the different parts.
  - So, alignment and field quality depends entirely on the machining tolerances of the big yoke blocks and pole/yoke pieces.

# the different magnet block types

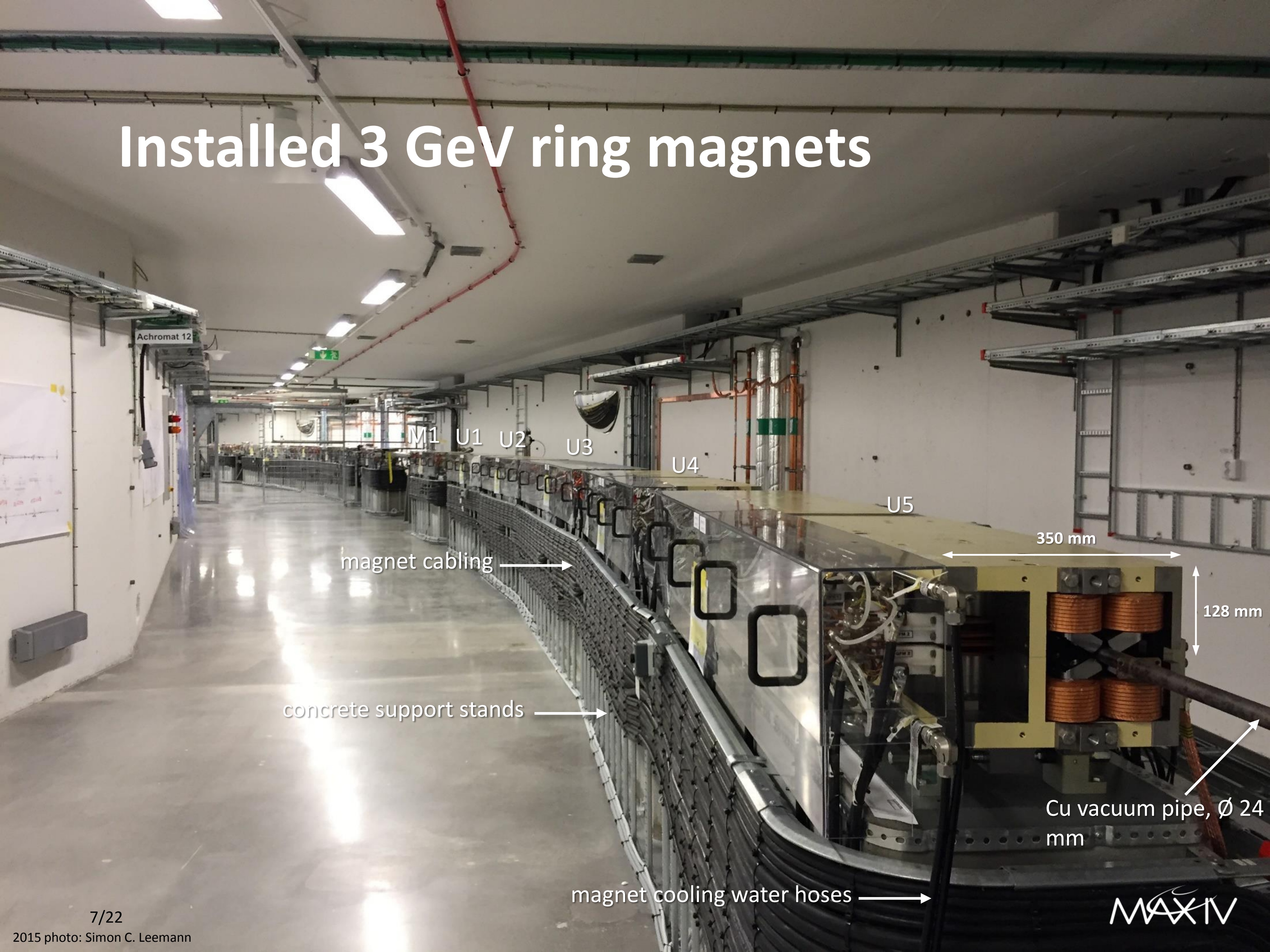
- Lattice sketch of achromat →
- M1 (matching cell) and U1 (unit cell) magnet blocks ↘
- M1 and M2 are mirror identical.
- U1, U2, U4 and U5 are identical/mirror identical.
- U3 layout is like other U, but symmetric around the dipole.
- Closest distance between consecutive magnet elements = 1 pole gap, in M1/M2 ↗
- Distance between DIP and adjacent elements ≈ 5 pole gaps →



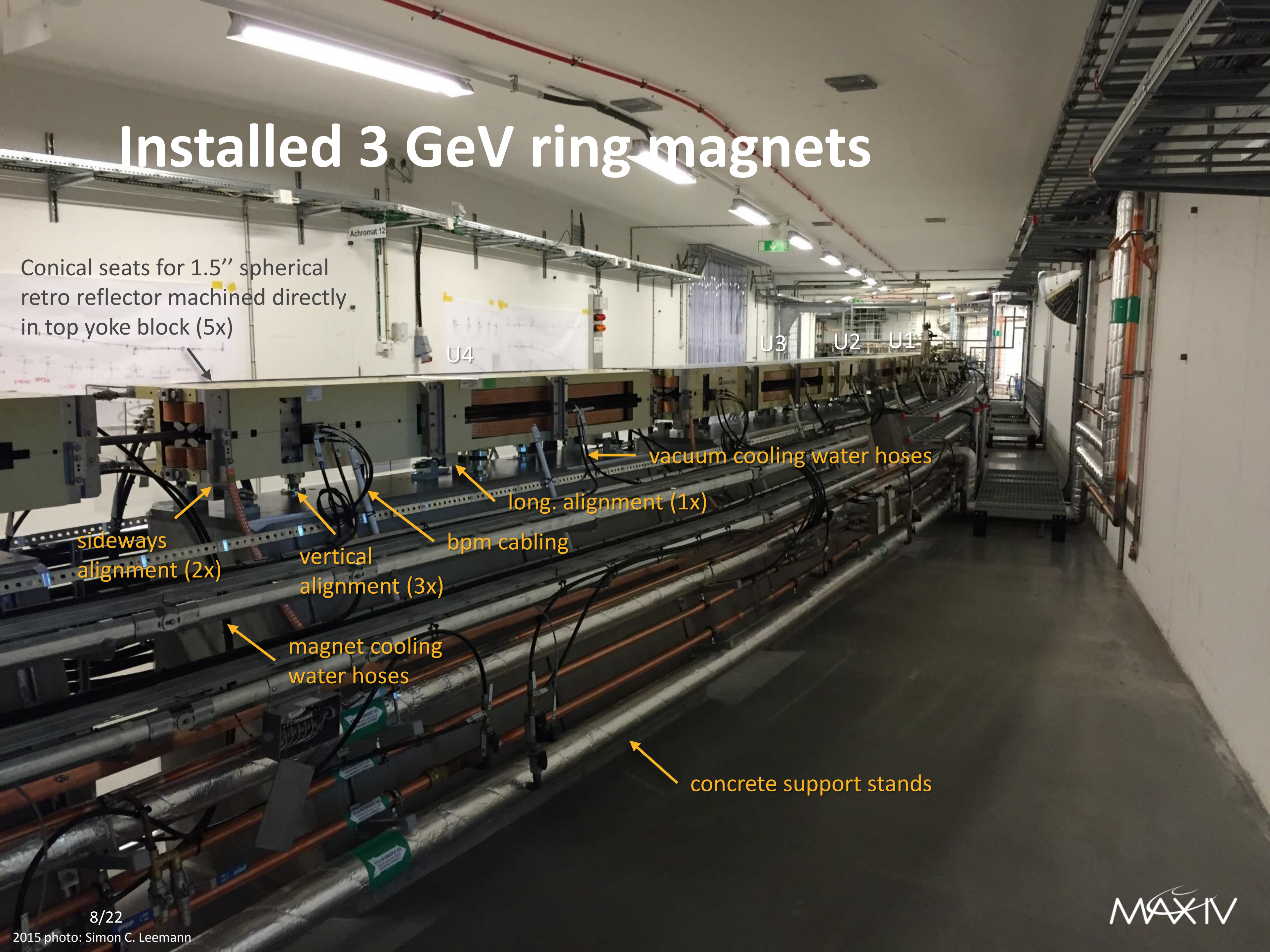
# Installed 3 GeV ring magnets





2015 photo: Simon C. Leemann

# Installed 3 GeV ring magnets




2015 photo: Simon C. Leemann

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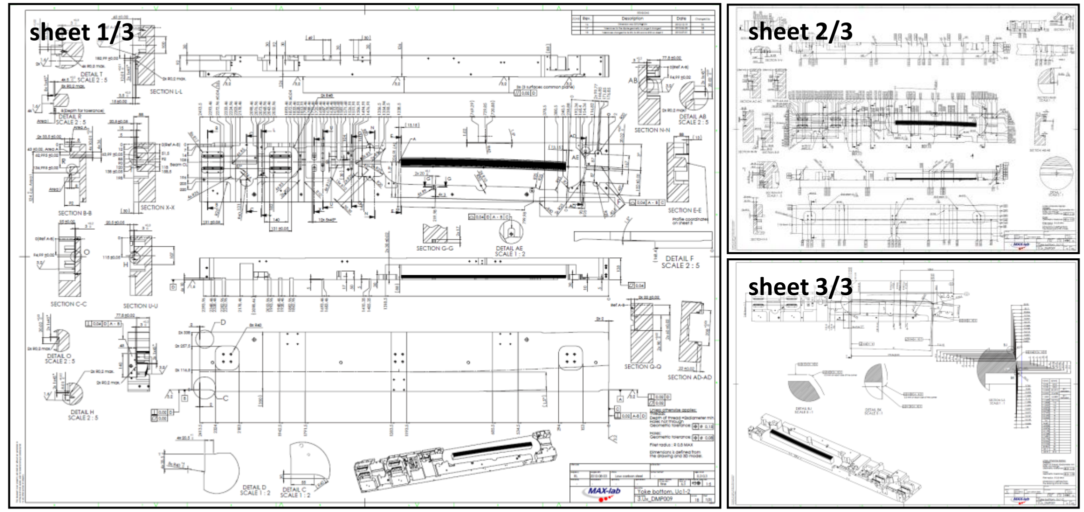
# specification and procurement

- Production sourced as build to print-contracts for fully assembled and tested magnet blocks, with MAX-lab providing technical specifications and full sets of manufacturing drawings.
- Suppliers responsible for mechanical tolerances, ±20 µm for the yoke bottom and top blocks (2.3-3.4 m long), and for performing field measurements according to MAX-lab spec.
- MAX-lab responsible for magnetic field properties!
- Contracts signed Sept 2011:
  - Danfysik A/S, Taastrup, Denmark: M1, M2 and U3 = 60 magnet block units.
  - Scanditronix Magnet AB, Vislanda, Sweden: U1, U2, U4 and U5 = 80 magnet block units.

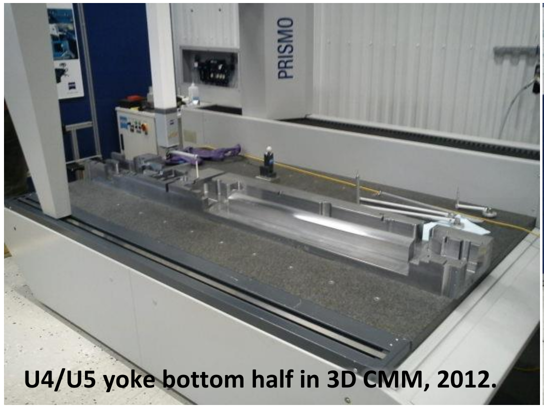
- Example part drawing, U1/U2 yoke bottom:



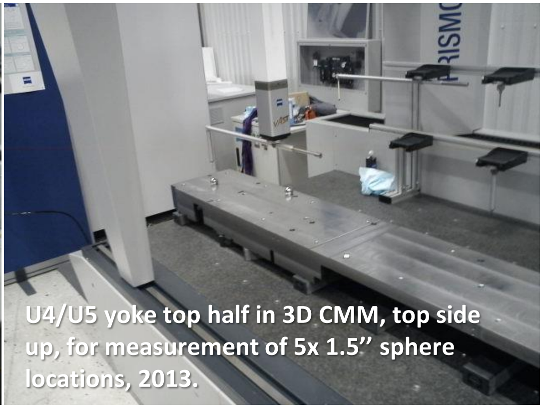

- Drawing defines midplane and two outer corners of the block as reference planes,
- and defines tolerances, relative to these reference planes, for function critical surfaces:
  - vertical mating surfaces location = ±0.02 mm
  - sideways guiding slots location= ±0.02 mm
  - midplane flatness = 0.04 mm
  - dipole surface shape = 0.04 mm (ie ±0.02 mm)
- Specification states: “*minor and few deviations up to 0.03mm may be accepted after discussion with MAX-lab.*” – recognizing that these tolerances are very challenging!
- Specification states: “*All dimensions with tolerances smaller than 0.1mm must be measured and recorded.*” – implying 3D Coordinate Machine Measurement for every single yoke part, and defining their measurement reports as a key part of the supplier’s documentation in this project.

# yoke bottom/top blocks machining results

- The two magnet suppliers subcontracted machining of the large yoke bottom/top halves to three different CNC machining companies.
- Raw yoke blocks (Armco pure iron grade 4) were purchased by MAX-lab and free issued to magnet suppliers.
- Machining method = conventional 3 axis CNC-milling.
- As per specification, every yoke half measured in 3D CMM
  - example photos ↗
- outcome = RMS results within or just at ±0.02 mm tolerance.
  - full series (280 pcs) statistics →
  - similar results for three machining subcontractors →



U4/U5 yoke bottom half in 3D CMM, 2012.


U4/U5 yoke top half in 3D CMM, top side up, for measurement of 5x 1.5" sphere locations, 2013.

Summary of yoke bottom/top block mechanical measurement results, per block type and category, for the full production series of 280 yoke blocks.

| yoke block type | surface category | min. [mm] | max. [mm] | RMS [mm] |
|---|---|---|---|---|
| M1/M2, [80 pcs] | vertical | -0.030 | 0.037 | 0.012 |
| | sideways | -0.030 | 0.031 | 0.009 |
| | midplane | 0.011 | 0.039 | 0.021 |
| | dipole [1] | 0.011 | 0.033 | 0.018 |
| U1/U2 [80 pcs] | vertical | -0.031 | 0.029 | 0.009 |
| | sideways | -0.024 | 0.047 | 0.016 |
| | midplane | 0.019 | 0.040 | 0.032 |
| | dipole [1] | 0.010 | 0.037 | 0.022 |
| U3 [40 pcs] | vertical | -0.032 | 0.038 | 0.013 |
| | sideways | -0.023 | 0.024 | 0.010 |
| | midplane | 0.014 | 0.037 | 0.028 |
| | dipole [1] | 0.016 | 0.026 | 0.020 |
| U4/U5 [80 pcs] | vertical | -0.028 | 0.024 | 0.009 |
| | sideways | -0.030 | 0.038 | 0.013 |
| | midplane | 0.012 | 0.040 | 0.026 |
| | dipole [1] | 0.005 | 0.029 | 0.018 |

[1] value stated here is "surface shape"/2 = the amplitude of the largest deviation on the pole surface.

## other yoke parts

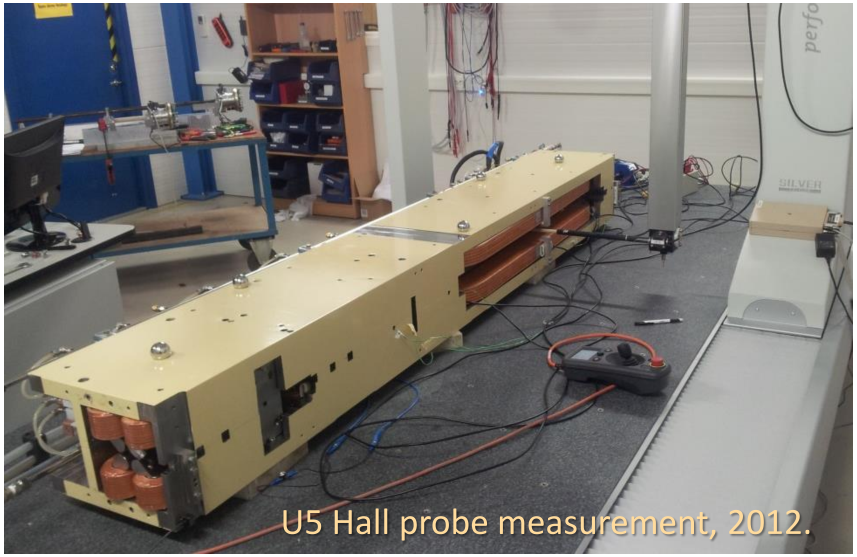
- quad poles and 6pole/8pole yoke halves have surface shape tolerance 0.02 or 0.04 mm (ie ±0.01 or ±0.02 mm) relative to mating surfaces.
- Material purchased by suppliers, to same spec. as the large yoke blocks.
- machining method = EDM
- All parts (2240 pcs) verified by 3D CMM.
- Note that all parts are measured separately – assembled magnets field quality and alignment depends on tolerance chain!



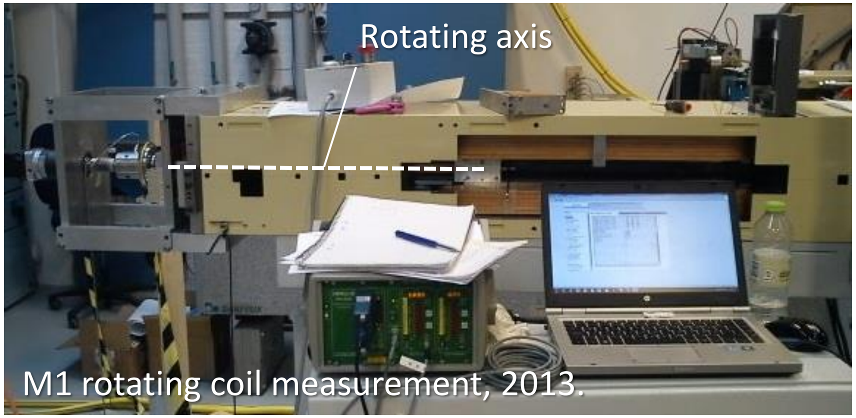
MAX IV

# field measurements

- Suppliers performed field measurements of all magnets – 1320 elements in 140 magnet blocks.
- The technical specification listed what field measurement data should be provided for each magnet element, given some basic instructions and performance requirements, with the suppliers responsible for solving how to perform.
- No field measurements were done at MAX-lab.
- Briefly stated, the measurements to be provided,
  - Hall probe,
    - Dipole field map at nominal current.
    - Dipole field map at nom I. + pole face strips at max I.
    - Quadrupoles transverse lines at nom I.
  - Rotating coil,
    - Quadrupoles, sextupoles, octupoles and correctors at nom I.
    - Sextupole and octupole trim coils at max I. for each connection mode.
  - Extended with more current levels and repeatability tests for a few magnet blocks of each type.


U5 Hall probe measurement, 2012.

- Both suppliers chose to procure both new Hall mapping benches and rotating coil systems.
- For rotating coil access, both suppliers chose the solution of several longitudinally spaced measurement coils in a common rotating shaft.

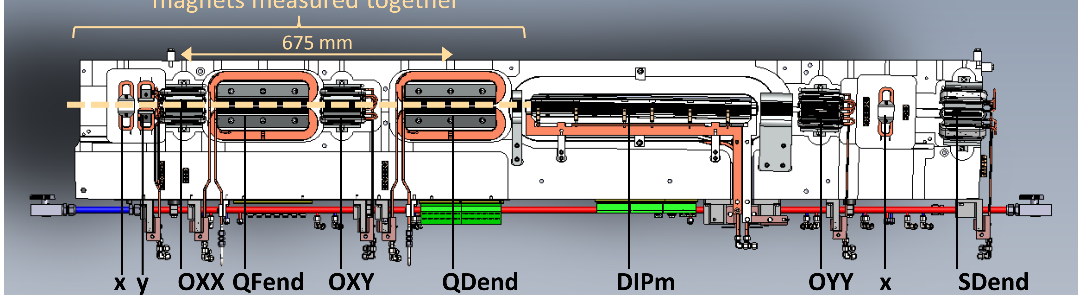


M1 rotating coil measurement, 2013.

## field measurement results - alignment

- From specification, the project did not include any verification of alignment of magnet centers within magnet blocks,
  - no stretched wire measurement
  - no hard requirement on rotating coil position
- However, with the chosen rotating coil measurement method, we could see relative alignment among consecutive elements!
- Outcome = RMS alignment < 10 µm
  - full series statistics ↗
- We interpret these results as confirming that magnetic centers agree with mechanical centers!
- We interpret these results as that we are within the MAX IV DDR alignment requirement of 25 µm RMS with 2σ cut-off!

M1 magnet block bottom half 3d cad view from above




**Summary of rotating coil meas. results, relative alignment between consecutive magnet elements, for the full production series of 140 [1] magnet blocks.**

| m. block type | elements | length [mm] | eval. [pcs] | relative alignment | min [µm] | max [µm] | RMS [µm] |
|---|---|---|---|---|---|---|---|
| M1,2 | 4 | 675 | 39/40 [1] | dx | -10 | 12 | 3 |
| | | | | dy | -27 | 20 | 9 |
| U1,2,4,5 | 3 | 400 | 79/80 [1] | dx | -16 | 12 | 4 |
| | | | | dy | -24 | 30 | 6 |
| U3 | 4 | 928 | 20/20 | dx | -10 | 13 | 5 |
| | | | | dy | -41 (-21) | 29 (19) | 18 (8) |

[1] Excluding 2 magnet blocks for which relative alignment analysis is invalid due to corrective action on a magnet element after the original rotating coil meas, followed by re-meas of only that element.

**For U1,2,4,5, only 3 consec. elements analyzed since rotating shaft had extra bearing in the middle to counteract sag.**

**dy values include the influence of rotating shaft sag under own weight**

**U3 values in ( ) compensated for calculated shaft sag.**

## comparing to mechanical tolerances?

- the rotating coil measured relative dx,dy are lower than 3D mechanical measured sideways,vertical deviations...
- ... looking at the 3D CMM data, this is due to that the mechanical deviations are typically correlated along the length of the yoke bottom/top blocks!



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# field measurement results - spread in strength

- Integrated strength of all magnet elements known from Hall map or rotating coil.
  - full series statistics →
- Series measured min/max spread roughly agrees with ±0.025 mm error on pole radius 12.5 mm, which would be,
  - ±0.2 % for dipole
  - ±0.4 % for quadrupole
  - ±0.6 % for sextupole
  - ±0.8 % for octupole
- Ie, we see no clear indication of additional spread in strength caused by material properties, etc.
- Magnets are series connected per achromat or around the whole ring
  - Beam sees spread in strength of individuals.
  - Magnets are designed with possibility to passively adjust individual strengths with shunt resistors.
  - But so far, this has not been used!

**Spread in strength at nom. I, per magnet element type for the full production series of 140 magnet blocks.**

| magnet element | No [pcs] | in magnet blocks | specified int. field | measured avg. int. field | min. [%] | max. [%] | RMS [%] |
|---|---|---|---|---|---|---|---|
| DIP $B_0$ | 80 | U1,2,4,5 | -0.524 Tm | -0.522 Tm | -0.15 | 0.17 | 0.07 |
| DIP $B_0$ | 20 | U3 | -0.524 Tm | -0.523 Tm | -0.41 | 0.19 | 0.16 |
| DIPm $B_0$ | 40 | M1,2 | -0.262 Tm | -0.263 Tm | -0.13 | 0.14 | 0.06 |
| DIP B’ | 80 | U1,2,4,5 | 8.538 T | 8.529 T | -0.27 | 0.23 | 0.11 |
| DIP B’ | 20 | U3 | 8.538 T | 8.529 T | -0.46 | 0.23 | 0.15 |
| DIPm B’ | 40 | M1,2 | 4.211 T | 4.244 T | -0.18 | 0.20 | 0.09 |
| QDend | 40 | M1,2 | 6.265 T | 6.032 T [3] | -0.45 | 0.48 | 0.19 |
| QF | 80 | U2,4 | -6.050 T | -6.117 T | -0.38 | 0.32 | 0.16 |
| QF | 80 | U3 | -6.050 T | -6.250 T | -0.41 | 0.43 | 0.25 |
| QFend | 40 | M1,2 | -9.143 T | -8.209 T [3] | -0.38 | 0.35 | 0.14 |
| QFm | 80 | U1,5 | -5.666 T | -5.918 T | -0.36 | 0.33 | 0.15 |
| SD | 160 | U1,2,4,5 | 116.7 T/m | 126.8 T/m | -0.57 | 0.79 | 0.25 |
| SD | 40 | U3 | 116.7 T/m | 130.0 T/m | -0.37 | 0.25 | 0.16 |
| SDend | 40 | M1,2 | 170.1 T/m | 182.1 T/m | -0.46 | 0.39 | 0.17 |
| SFi | 40 | U3 | -207.6 T/m | -211.7 T/m | -0.38 | 0.77 | 0.21 |
| SFm | 40 | U1,5 | -170.1 T/m | -180.0 T/m | -0.50 | 0.68 | 0.27 |
| SFo | 40 | U2,4 | -174.2 T/m | -187.1 T/m | -0.41 | 0.54 | 0.21 |
| OXX | 38 [1] | M1,2 | 3300 $T/m^2$ | 3231 $T/m^2$ | -0.57 | 0.58 | 0.29 |
| OXY | 38 [1] | M1,2 | -6546 $T/m^2$ | -6497 $T/m^2$ | -0.24 | 0.93 | 0.27 |
| OYY | 40 | M1,2 | 2843 $T/m^2$ | 2793 $T/m^2$ | -0.33 | 0.38 | 0.15 |
| corr x | 200 | all | ±0.25 mrad | 3.8 Tmm | | | |
| corr y | 178 [2] | all | ±0.25 mrad | -3.7 Tmm | | | |

[1] Excluding 2 + 2 larger aperture OXX and OXY in achromat 01 (injection).
[2] Excluding 2 larger aperture vertical correctors in achromat 01 (injection).
[3] QDend and QFend low strength caused by pole manufacturing drawing error, which was accpeted, instead increasing current. For QF/QFm on the other hand, the pole design was updated (cf. slide 5).

- Measured strength as function of current of all individuals has been uploaded as calibration to the 3 GeV ring control system.
  - Extra measurements to cross calibrate between the two suppliers’ data exists.
  - But so far, this has not been implemented, we are using the data from the suppliers at face value!

# field measurement results – field quality

- DIP and DIPm are gradient dipoles – main performance requirement is correct B’/B ratio,
  - Full series Hall map results →
  - The 0.2-0.3 % gradient difference to nominal is well within the adjustment range of the pole face strips.
  - Higher order field terms not large enough to be of any concern.
- For quads/6poles/8poles, we express field purity in terms of harmonic content,
  - Example full series result for one magnet type, U2/U4 QF →
  - Summarized results for all magnet types →→
  - The min/max generally agree with worst case displacements of the individual poles within the mechanical tolerances, given the pole radius of 12.5 mm.

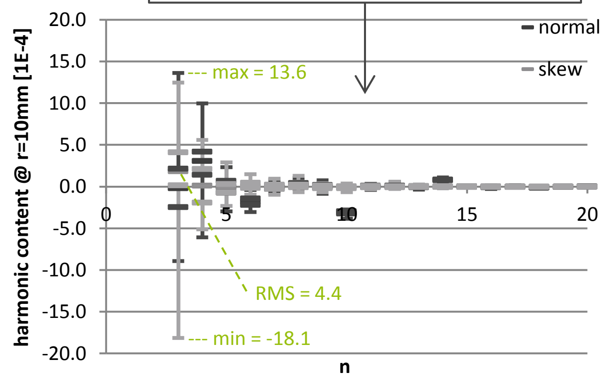
**Hall probe field map results, per magnet type , integrated strength B and B’ series average at nominal current, integrated B’ difference to nominal series spread, and higher order content and residual at nom. current.**

| magnet | No [pcs] | block | int B avg [Tm] | int B’ avg [T] | int B’ diff. to nom. avg [%] | min [%] | max [%] | rms [%] | int B’’/2 min–max [T/m²] | int B’’’/3 min–max [T/m³] | int residual p2p max [T] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| DIP | 80 | U1,2,4,5 | -0.522 | 8.529 | 0.20 | -0.07 | 0.43 | 0.11 | 0.4 – 1.9 | -15 – 102 | 0.00013 |
| DIP | 20 | U3 | -0.523 | 8.529 | 0.22 | -0.24 | 0.44 | 0.15 | 2.0 – 3.0 | -9 – 19 | 0.00006 |
| DIPm | 40 | M1,2 | -0.263 | 4.244 | 0.31 | 0.13 | 0.51 | 0.09 | 2.7 – 3.0 | -32 – -6 | 0.00006 |

same values as in previous slide (int B avg, int B’ avg)

scaled to series average int B = nom. bend angle. (int B’ diff. to nom.)

**This distribution is typical in that the error terms directly above the main term are the largest, and that “allowed” terms can be seen ≠ 0.**




**Boxplot of rotating coil meas. data, harmonic content higher order terms, for 80 pcs U2/U4 QF at nom I.**

**Rotating coil results per magnet type, largest higher order term (in 1E-4 of main term at r = 10 mm) series min/max/rms.**

| magnet | No [pcs] | block | harm cont. [1E-4] min | max | RMS |
|---|---|---|---|---|---|
| QFend | 40 | M1,2 | -10.4 | 7.3 | 3.0 |
| QDend | 40 | M1,2 | -9.6 | 8.0 | 3.1 |
| QFm | 80 | U1,5 | -16.0 | 11.0 | 4.2 |
| QF | 80 | U2,4 | -18.1 | 13.6 | 4.4 |
| QF | 80 | U3 | -8.4 | 8.5 | 3.1 |
| SDend | 40 | M1,2 | -17.5 | 17.6 | 6.5 |
| SFm | 40 | U1,5 | -19.6 | 23.9 | 10.9 |
| SD | 160 | U1,2,4,5 | -42.2 | 35.5 | 9.8 |
| SD | 40 | U3 | -19.4 | 18.3 | 6.2 |
| SFo | 40 | U2,4 | -25.4 | 44.5 | 12.3 |
| SFi | 40 | U3 | -17.2 | 8.4 | 5.5 |
| OXX | 38 | M1,2 | -22.4 | 29.4 | 9.3 |
| OXY | 38 | M1,2 | -26.8 | 34.6 | 9.0 |
| OYY | 40 | M1,2 | -13.3 | 14.5 | 4.7 |

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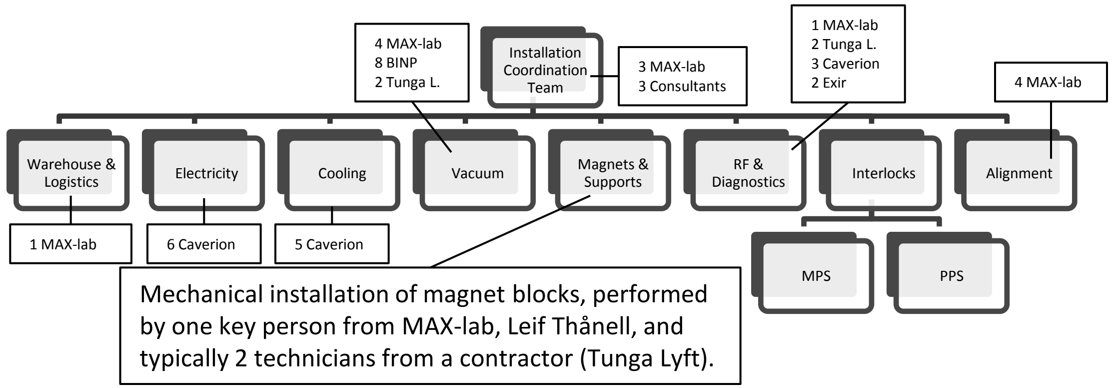
MAX IV

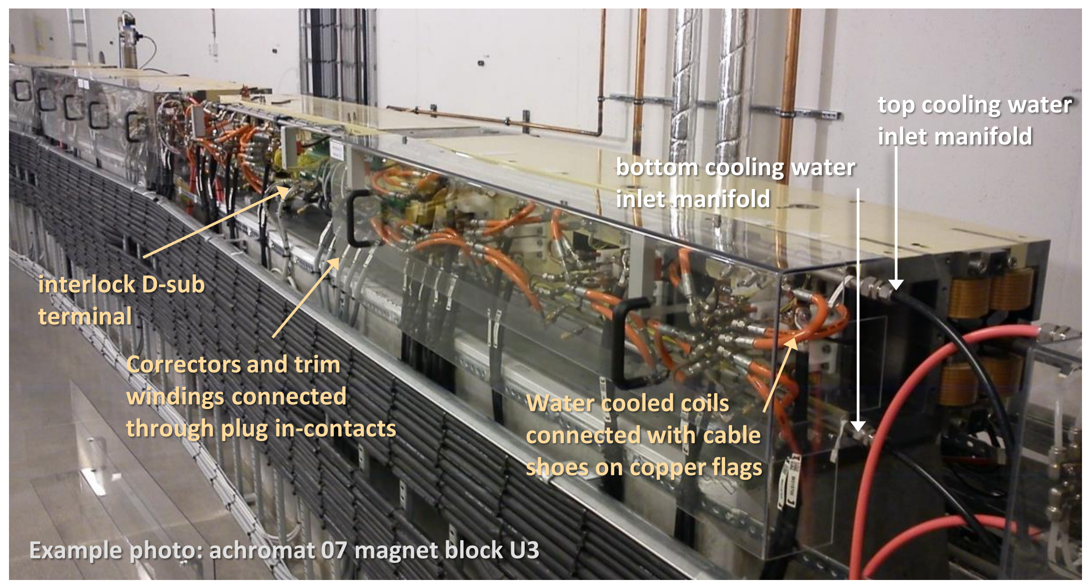
## magnet block installation

- installation sequence summarized,
    - Magnet blocks for one achromat were taken into the tunnel and lifted onto the concrete stands.
    - Alignment with laser tracker.
    - Magnet block top halves removed and placed on pallets.
    - Vacuum chamber installation sequence – whole achromat.
    - Magnet block top halves re-assembled.
    - Cooling water connected.
    - Power and interlock cables connected at magnet.
    - Cables connected at power supply.
    - Alignment re-check.
    - Handover to subsystem tests.
- Magnet subsystem tests,
    1. tests by power supply group
    2. tests by control system group
    3. tests by magnet group

- Background - through fall 2014 to summer 2015, ca 40 FTEs doing the hands on installation work in the 3 GeV ring tunnel
    - consisting of a mixture of contractors and MAX-lab staff ↓

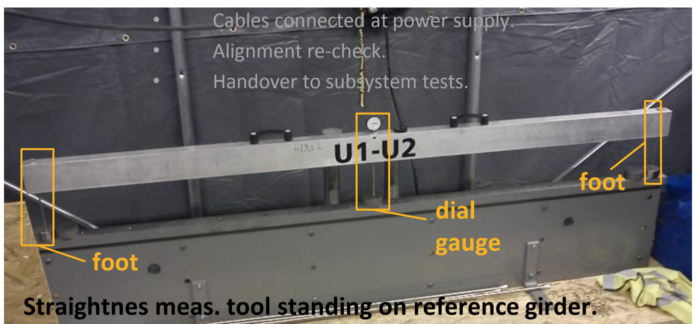



- Electrical and water installation scope on the magnet blocks was just connection of external cables/hoses - cabling and piping within magnet blocks was done by the suppliers.

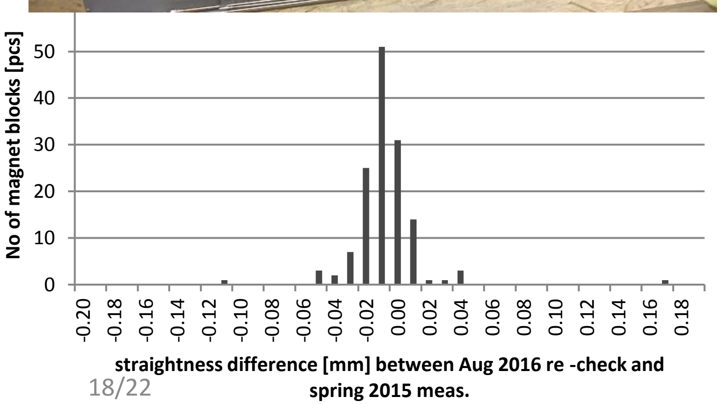


## tests during installation

- Installation sequence summarized,
  - Magnet blocks for one achromat were taken into the tunnel and lifted onto the concrete stands.
  - Alignment with laser tracker.
  - Magnet block top halves removed and placed on pallets.
  - Vacuum chamber installation sequence – whole achromat.
  - Magnet block top halves re-assembled.
  - Cooling water connected.
  - Power and interlock cables connected at magnet.
  - Cables connected at power supply.
  - Alignment re-check.
  - Handover to subsystem tests.



Straightnes meas. tool standing on reference girder.




## - Magnet block straightness

- Mechanical checks at top half re-assembly consist of,
  - Verifying sidewas/longitudinal alignment of top half to bottom half. Top half is guided to bottom half by three external ”guide blocks” at reference corners (no dowel pins in the midplane).
  - Straightness of three points on the midplane...
- ... because the magnet block bottom half by itself is not stiff enough to maintain the midplane flatness tolerance 0.04 mm when standing on three support feet.
- We only began to understand this behaviour in 2012 after the magnet block production had already started.
- Assembly procedure to ensure straightness,
  - consisted of adding extra struts between the bottom half and concrete stand, adjusting the struts to compensate for the sag, then removing the extra struts after top half re-assembly, arriving at a measured straightness within ±0.04 mm (ie flatness 0.04 mm).
  - Meaning that the alignment procedure was unchanged, using three vertical feet and three sideways/longitudinal adjusts only.
  - The midplane is hidden after re-assembling the top half...
  - ...so, we had the suppliers drill three holes spaced along the length of the top half, allowing access to the midplane, and measured ← straightness of these three points mechanically.
- Do the magnet blocks remain straight?
  - ↙ Aug 2016 re-check shows no, not all!
  - Two magnet blocks are outliers, unknown why they have chenged so much. They were re-adjusted within tolerance.
  - But even disregarding these outliers, RMS change is 0.015 mm. One more individual that had changed outside tolerance was re-adjusted.
- Consequence is that magnet block straightness should be re-checked at every long shutdown.



MAX IV

## tests during installation

- Installation sequence summarized,
  - Magnet blocks for one achromat were taken into the tunnel and lifted onto the concrete stands.
  - Alignment with laser tracker.
  - Magnet block top halves removed and placed on pallets.
  - Vacuum chamber installation sequence – whole achromat.
  - Magnet block top halves re-assembled.
  - Cooling water connected.
  - Power and interlock cables connected at magnet.
  - Cables connected at power supply.
  - Alignment re-check.
  - handover to subsystem tests.

### insulation resistance

- Correct insulation resistance value is measured with de-ionized cooling water connected and flowing.
- Insulation resistance is de-ionized water resistivity through hose to manifold + from manifold to distribution pipe. Single cases of manifold touching magnet yoke were fxed to obtain same insulation resistance everywhere.

## - flow and pressure tests

- Total flow/achromat and individual flow/magnet block.
  - These were not sensitive enough to see a single blocked cooling channel within a magnet block – no magnet issues found.
- Pressure proof test, for full achromat.
  - Found a few failed brazings at coil exit leads and a few ruptured water hoses. Repaired in situ as warranty cases by supplier.

## - Insulation tests

- Added for all magnet elements, insulation between terminals and gound, before connecting cables.
  - ⇙ understood behaviour!
  - Poor clearance between pole face strips and dipole ends fixed by gluing epoxy glass lamnite strips in situ – done by supplier for whole series for three magnet block types.
  - One insulation fault between coil body and yoke req. exchange to spare coil. Faulty coil sent back to factory as warranty case.
  - A few blocked cooling water circuits detected through insulation test! – no flow, standing water, means not de-ionized...

## - Insulation tests

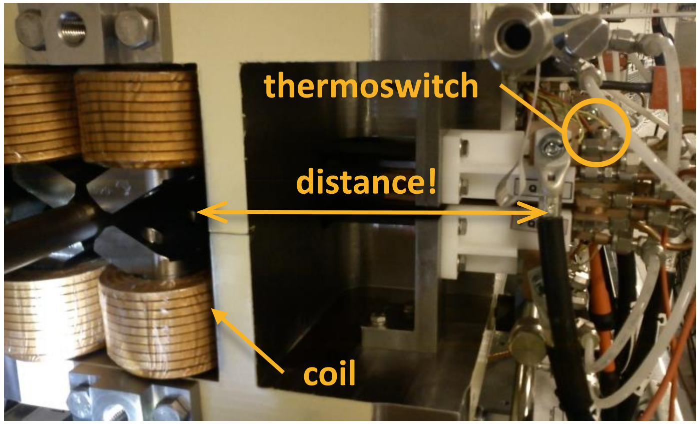
- For full circuit, insulation between cables and ground, at cabinets before connecting to power supply terminals.
  - Variation in measured insulaton resistances among supposedly identical circuits prompted backtracking to disconnect cables at all magnet elements and subsequent individual insulation tests (see above).



MAX IV

## magnet subsystem tests

- Installation sequence summarized,
  - Magnet blocks for one achromat were taken into the tunnel and lifted onto the concrete stands.
  - Alignment with laser tracker.
  - Magnet block top halves removed and placed on pallets.
  - Vacuum chamber installation sequence – whole achromat.
  - Magnet block top halves re-assembled.
  - Cooling water connected.
  - Power and interlock cables connected at magnet.
  - Cables connected at power supply.
  - Alignment re-check.
  - Handover to subsystem tests.
- Magnet subsystem tests,
  1. tests by power supply group
  2. tests by control system group
  3. tests by magnet group




## - PLC tests

- Thermoswitches and limit switches (for plastic covers) are connected to PLCs (ie not directly to ps interlock terminals).
- Tests included hot air gun test of every single thermoswitch.
  - Found several cabling errors within magnet blocks, connected to wrong pins at D-subs – corrected in situ by magnet suppliers.

## - power supply front panel operation

- Up to at most ca 10 % of nominal current.

## - launch/verify ps remote operation

- Includes setting 1 A current.

## - field polarity and coil temperature rise

- Ps remote operated  through synoptic GUI.
- Field polarity checked with Hall probe through access ports in magnet blocks for every single magnet (1320 pcs).
  - Found a few polarity errors from incoming cabling installed at MAX IV.  Most common were x- and y-correctors. No errors within magnet blocks.
- Coil temperature rise at steady state measured by tc and/or voltage over terminals for every water cooled magnet (940 pcs).
  - Found a few blocked cooling channels req. exchange to spare coil.
  - Follow up-investigations demonstrated that thermoswitch ↖ placement in our design is not good enough in case of a totally blocked cooling channel!

# 3 GeV ring commissioning

- Installation and subsystem test outcome resulted in two new installation tasks,
    - adding thermoswitches (improved placement and/or rating) for all dipoles and quads,
    - and adding cooling water filters at distribution pipe inlet for each achromat.
- But, we were able to keep commissioning start date unchanged,
    - with remaining installation tasks done during long shut downs and other short access occations, completed Aug 2016.

- 2015 early commission milestones:

| | |
|---|---|
| Aug 11 | beam in TR3 |
| Aug 25 | first turn |
| | many turns |
| Sep 15 | stored beam 0.1 mA |
| Oct 8 | stacking 4 mA |
| ... | and so on... |

- From the magnet point of view, these milestones were noteworthy in that first turn was achieved without using any correctors (all set to 0 A), and with all other magnets set to lattice nominal current levels calculated from the field measurements made by the suppliers.
- More turns and then stored beam were achieved with correctors manually adjusted but other magnets still at the calculated current levels.
- Conclusion, from the magnet perspective, is that alignment and field measurements accuracy was OK!

# workshop question

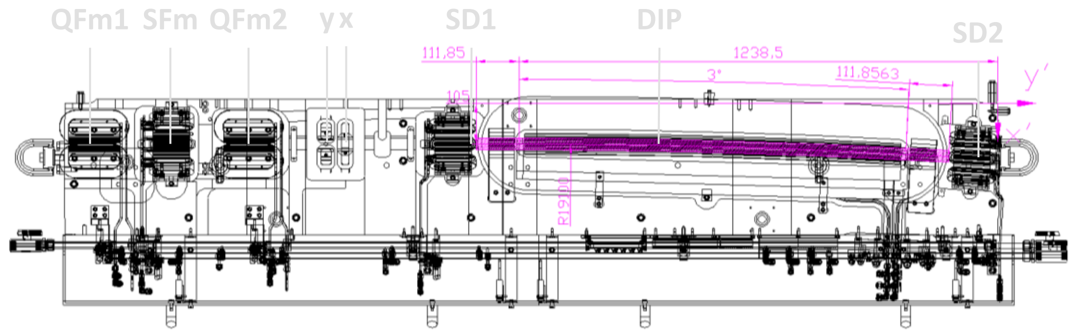
- *”We would like to ask all speakers and especially those of the third day (16 September ) to dedicate one slide on how the industry would help on their particular R&D”*
- Our concept has been to have the magnet suppliers do as much as possible, for example all field measurements.
- The “magnet blocks” are an alignment concept that relies on the accuracy of CNC milling and 3D coordinate measurement machines, techniques which are available at large number of machining subcontractors.
    - As opposed to stretched wire alignment, which is typically only available at a few accelerator labs.
- With only a limited amount of prototyping done by MAX-lab before purchasing the production series, the “R&D” of finding out what mechanical tolerances were actually achievable for these magnet blocks was essentially done by our suppliers.

Thank you for your attention!

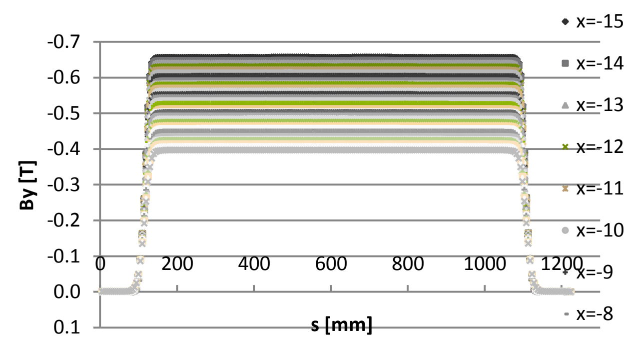
# Extra slides...

# Field map slice evaluation

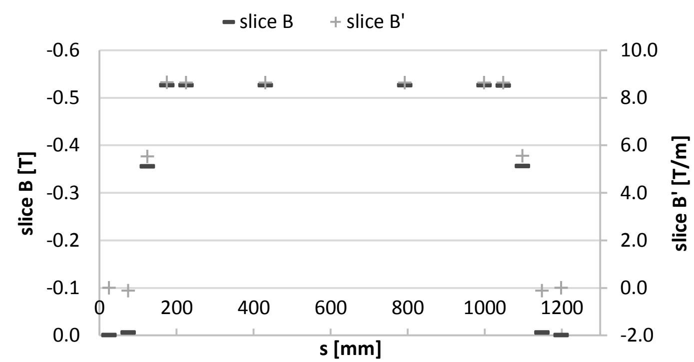
- The dipole Hall probe field maps were presented as an x,s grid of $B_y$ values,
  - over x = ± 15 mm and s = 0 - 1223.78 or 754.24 mm (for DIP or DIPm) with 1x5 mm spacing
  - following a simplified nominal beam trajectory: straight line going into the dipole, constant radius through the dipole, and a straight line going out ↗
- The field maps were analyzed by dividing into 12 longitudinal slices and calculating slice average By(x) = intBy(x,s)ds/slice length, then applying a 3rd order polynomial fit over x = ±11 mm to each slice.
  - Example field map ↗
  - Example slices →



**U1 magnet block 3D cad view from above with DIP field map area sketched purple**



**Example DIP Hall probe field map, By(s) for x = -15, -14, …, +15 mm (total 7688 data points), at nominal current.**



**B and B' slice values calculated from this field map.**