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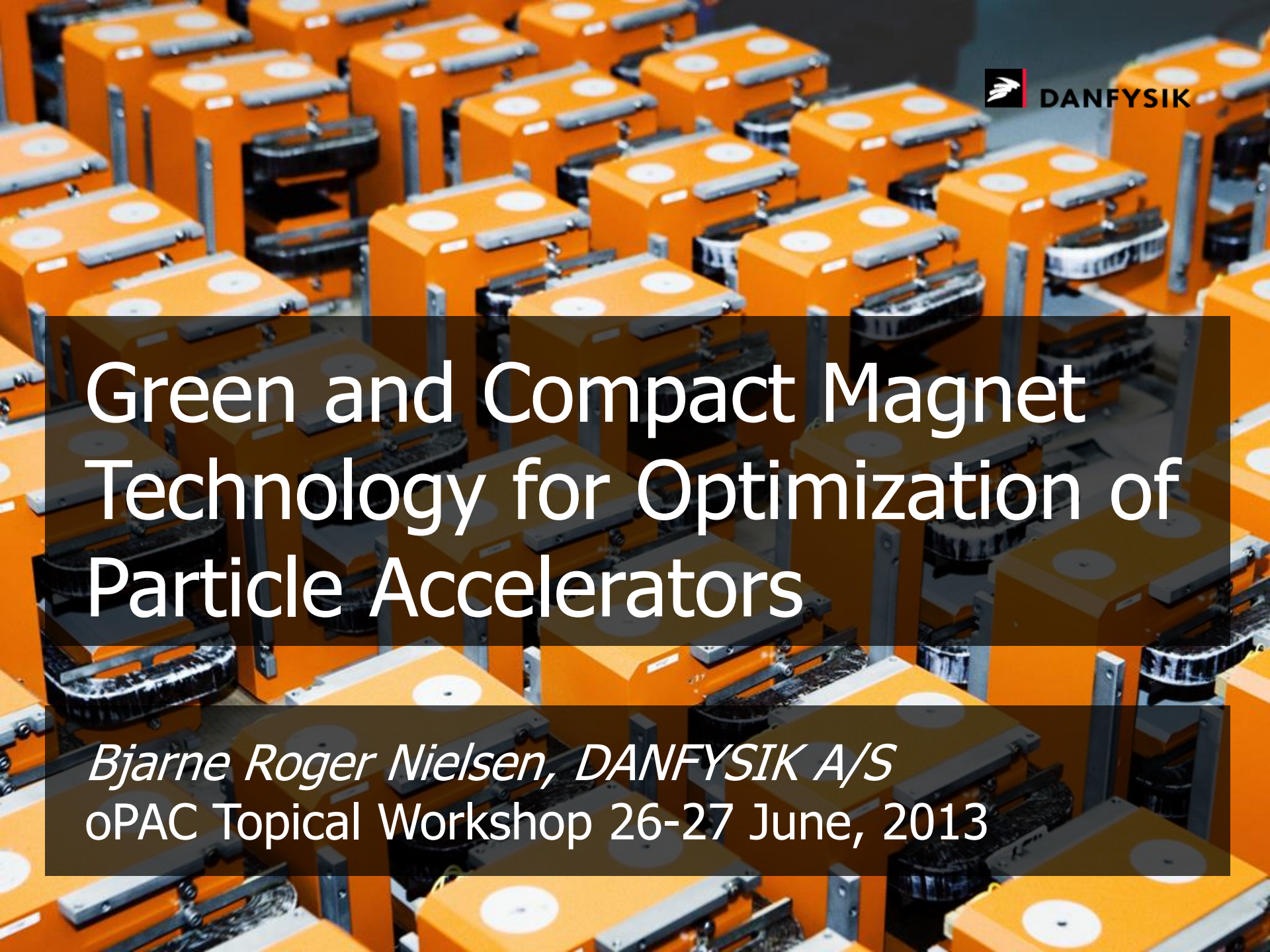
it's all about innovation



Green and Compact Magnet Technology for Optimization of Particle Accelerators

Bjarne Roger Nielsen, DANFYSIK A/S

oPAC Topical Workshop 26-27 June, 2013

Accelerating Technology Business

DANFYSIK

- 1964 - Danfysik A/S was founded by Ejnar Jespersen

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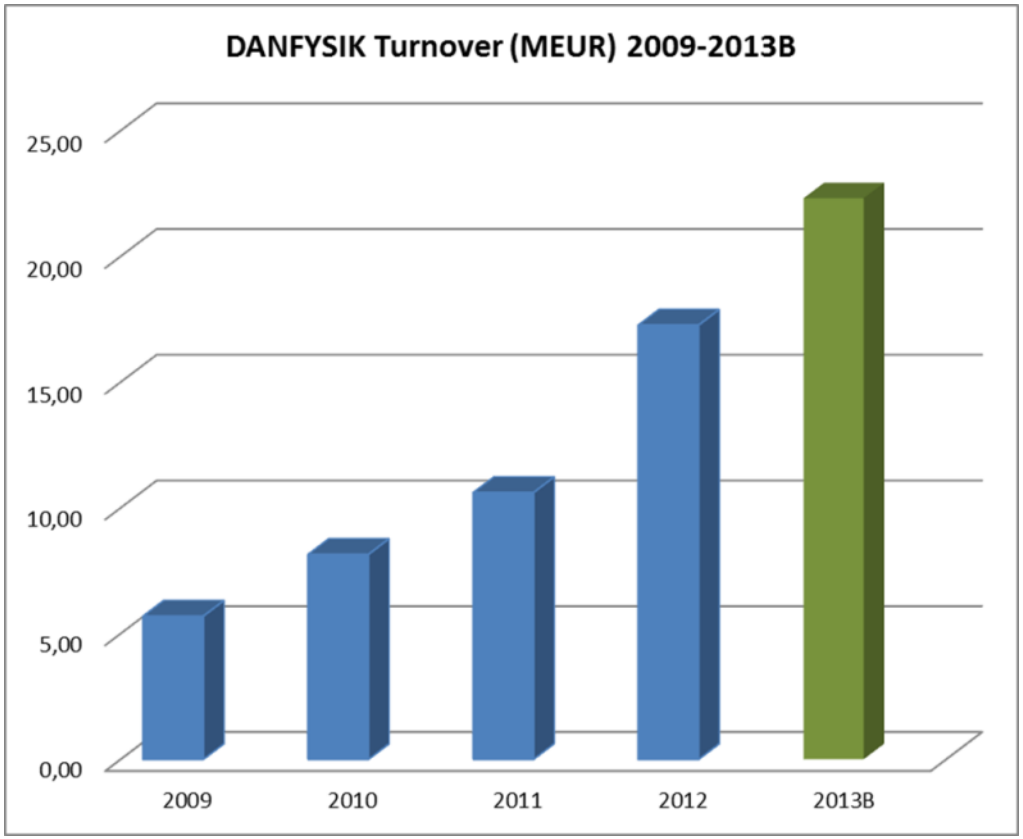
DANFYSIK A/S today

Staff: 120 (45% eng/phys, 45% techs, 10% adm)
Owner: Danish Technological Institute (100%)
Turnover: 22 M€ (2013B)



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Accelerator products, services & systems

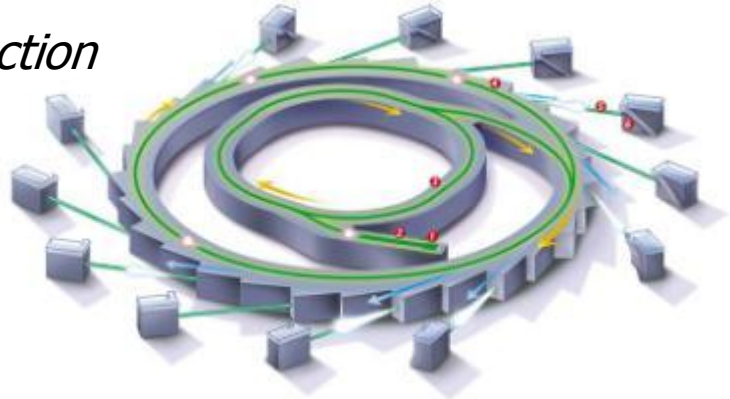
- Magnets (fast & slow), electrostatics + related equipment
- Ultrastable power supplies (fast & slow) + converter technol.
- Insertion devices, undulators and wigglers
- Ion sources and beam diagnostics
- Ion accelerators, ion implanters and isotope separators
- Turn-key systems, electron & ion synchrotrons, microtrons
- Installation, commissioning and after-sales service

DANFYSIK - Accelerator systems

Australian Synchrotron Project

100 MeV Linac, LEBT, 3.0 GeV Synchrotron, HEBT

Lattice:	*Combined function*
Booster circumference:	*130m*
Injection energy:	*100MeV*
Peak energy:	*3.0GeV*
Beam current (multi bunch train):	*5mA*
Cycle rate:	*1Hz*



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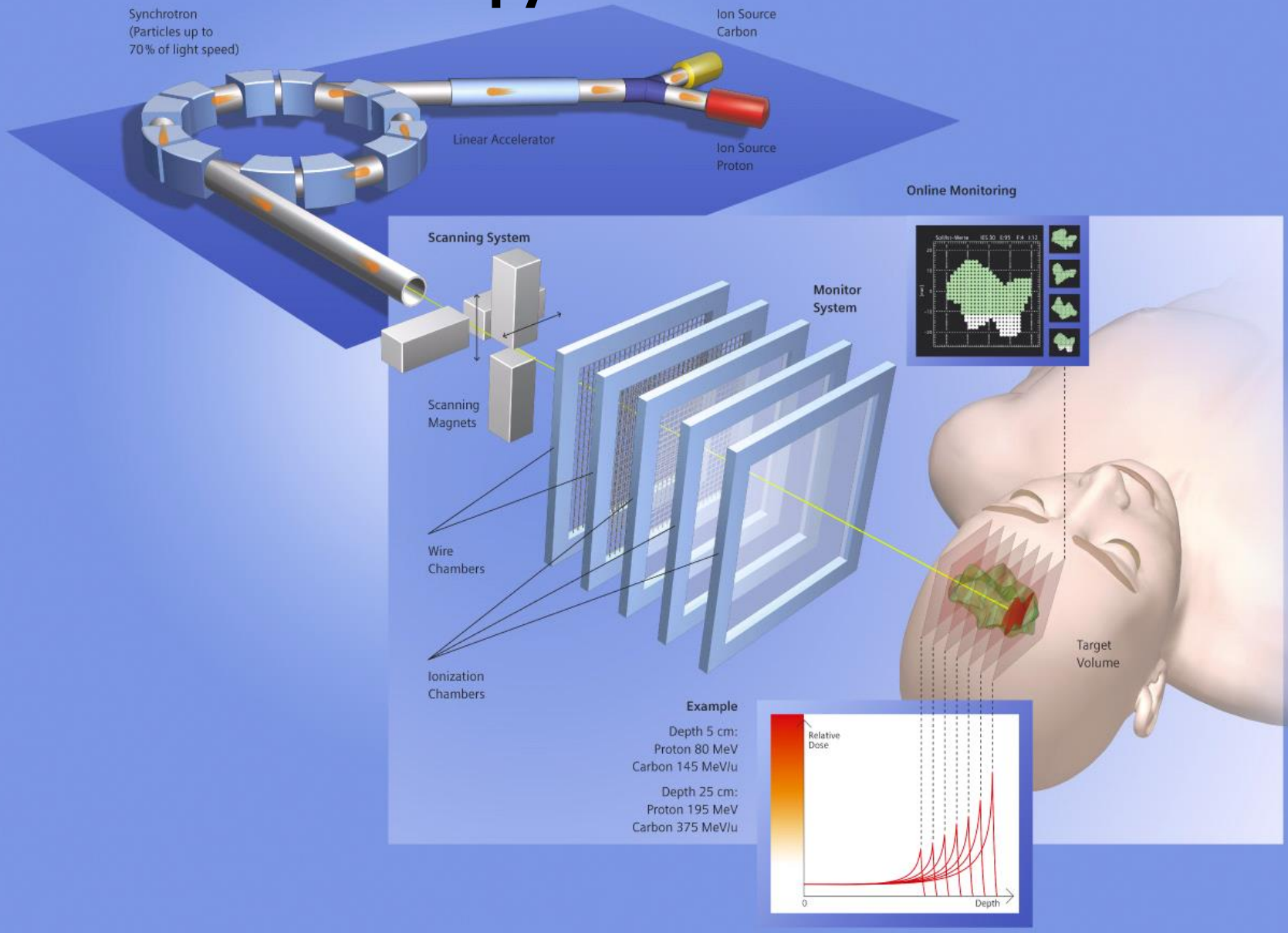
Particle Therapy with Siemens Healthcare



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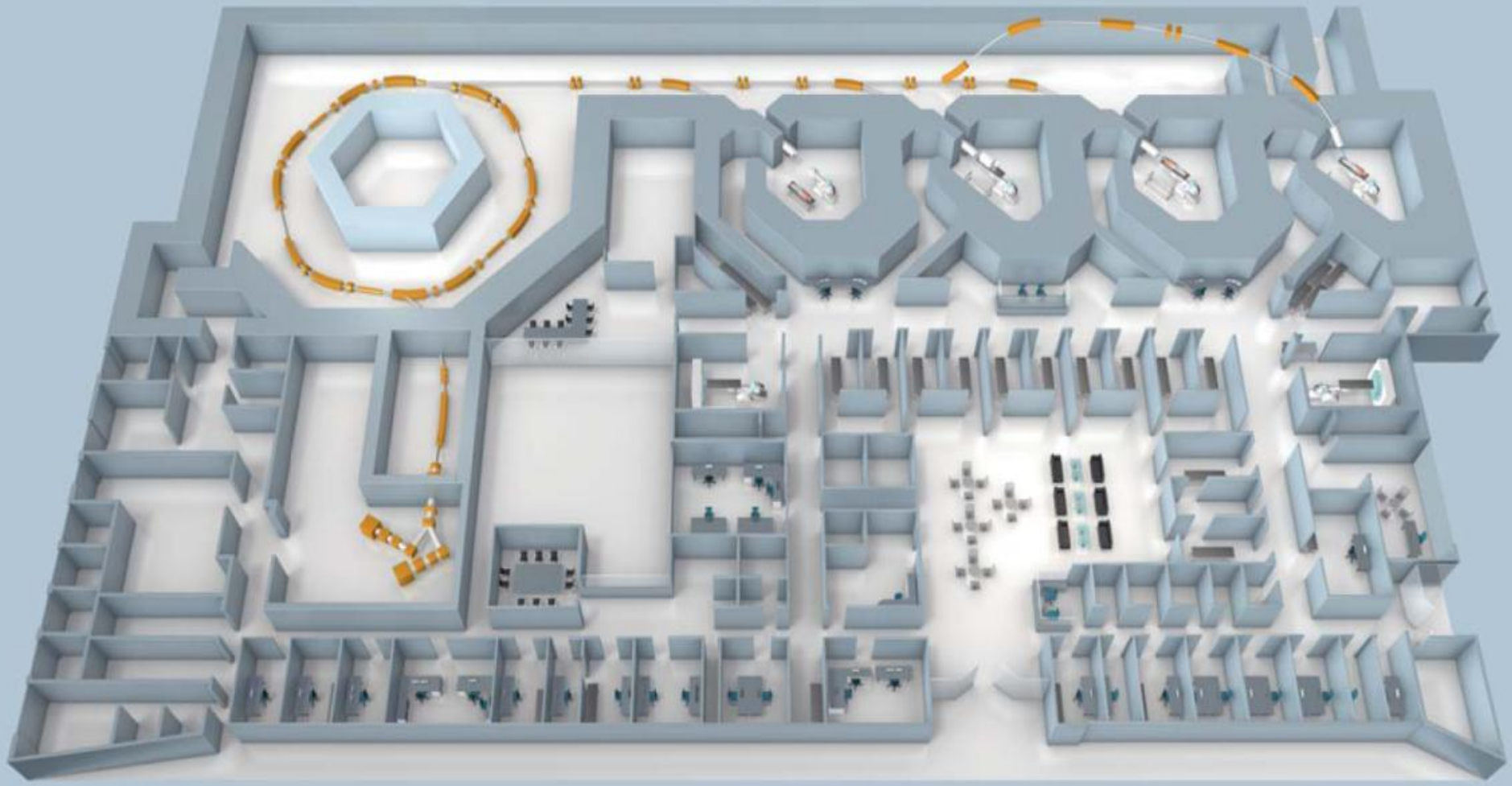
Combined (H^+,C^+,..$^+$) PT facility



Courtesy Siemens AG

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DANFYSIK has a longstanding tradition for collaborating with universities and research laboratories to improve our technology

Technology development in DANFYSIK - based on collaboration

- 1964 – Foundation of Danfysik A/S
- 1964 – First magnet power supplies (AU)
- 1967 – First turnkey ion accelerator system (AU)
- 1974 – First synchrotron magnet system (MPI)
- 1987 – First high current ion implanter (GSI)
- 1995 – First insertion devices for synchrotrons (ESRF)
- 1997 – First turnkey synchrotron (AU + FZK)
- 1999 – First superconducting magnets (CERN)
- 2001 – First synchrotron X-ray beam line (OI)
- 2006 – First particle therapy synchrotron (AU, GSI, SAG)
- 2012 – First compact accelerator magnets (MAXLab)
- 2013 – First Green Magnets (AU, SINTEX, ETH)
- 201? – and more to come……

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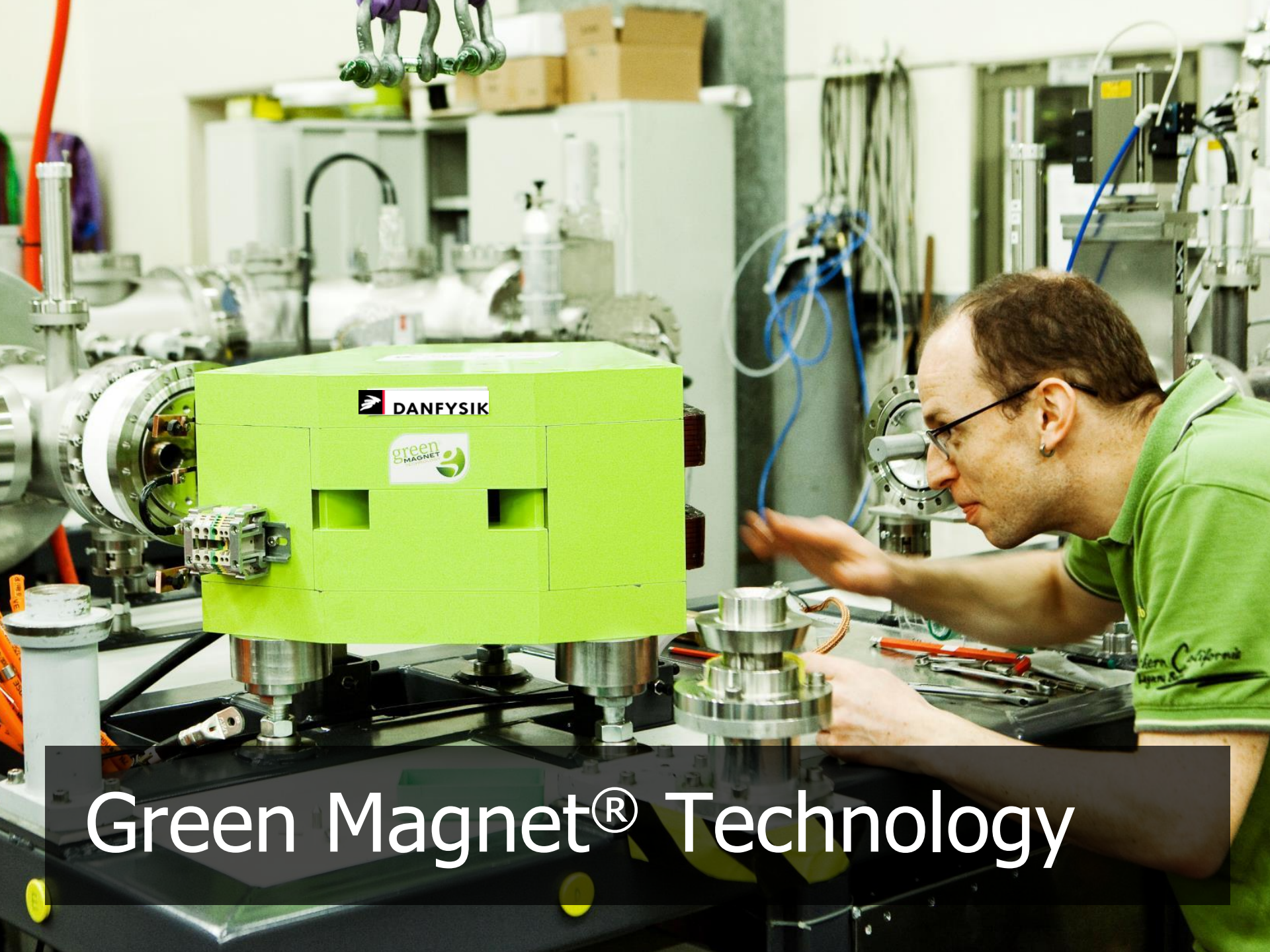

Green Magnet® Technology

Green Magnets

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Accelerator magnets are big consumers of electrical power

- Large magnet power supplies
- Large installed electrical power
- Large installed cooling system
- Infrastructure – cabling, water cooling, air cooling

How can we reduce power consumption in acceleator magnets?

- Optimize (reduce) size of aperture/gap and good field width
- Increase copper amount in coils ($P \propto I/A$)
- Replace room temperature magnets with superconducting
- **Replace electromagnets with permanent magnets**

Green Magnets

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The idea

- Use our 20 years' experience with PM technology for insertion devices
- Replace magnet coils (partly or fully) with permanent magnets
- Make more sustainable accelerator systems
- Less environmental impact
- Reduce cost of ownership

ETH Zürich

Interviews with accelerator experts

- Opportunities
- Barriers
- Investment vs. operating costs

Green Magnets

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The main challenges

- Maximum field strength
- Field variation / flexibility
- Temperature dependence
- Sensitivity to radiation
- Assembly
- Installation

- Up to 1 Tesla
- 40-50% makes sense
- Solved
- Can be handled
- Special tools
- Integrated in design

Green Magnets – Case 1

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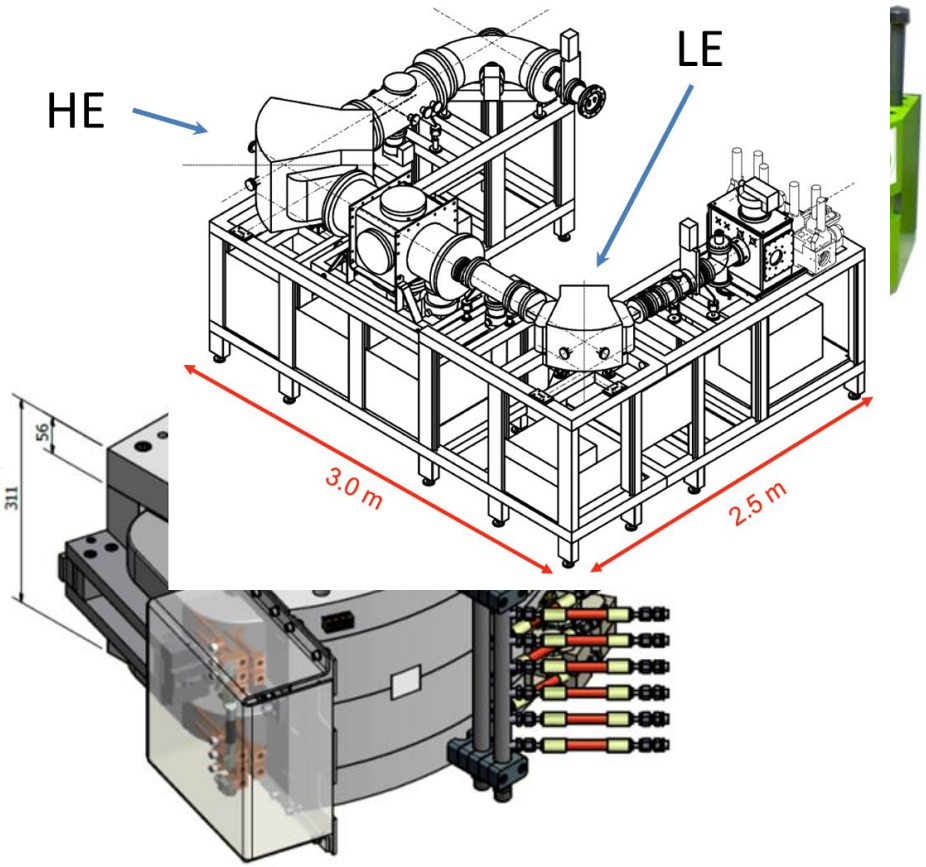
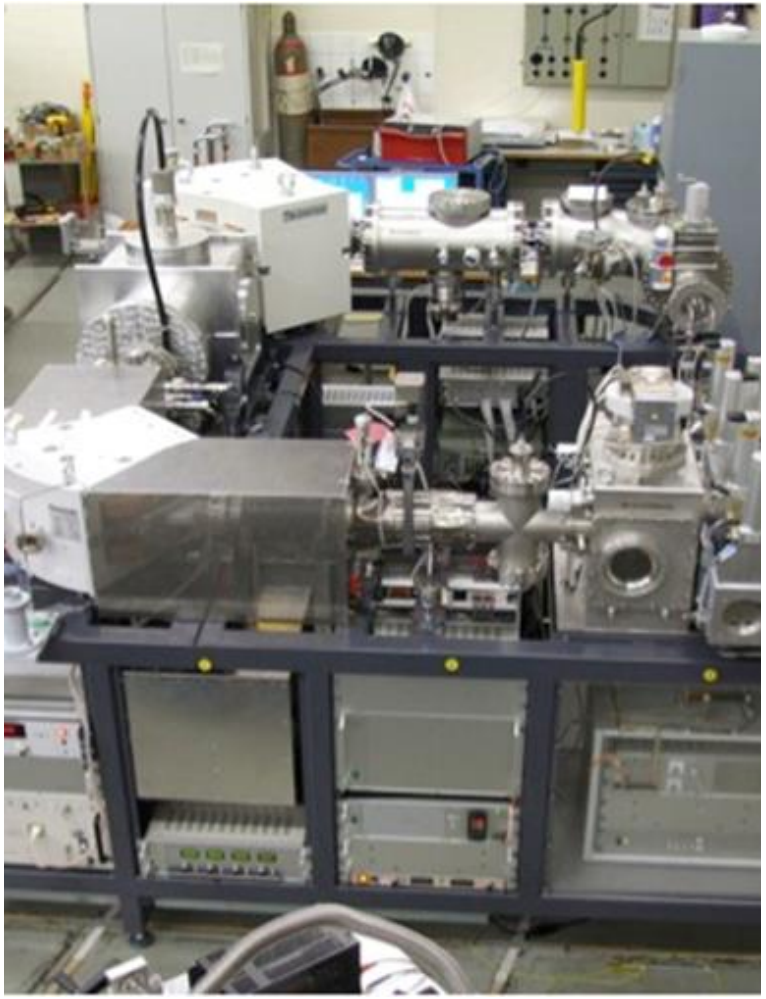
Accelerator Mass Spectrometer
MICADAS for ^{14}C dating at ETH





Permanent 90° bending magnet for AMS.

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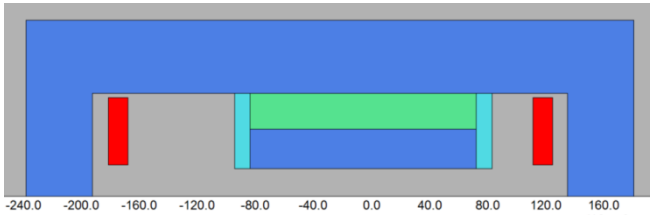
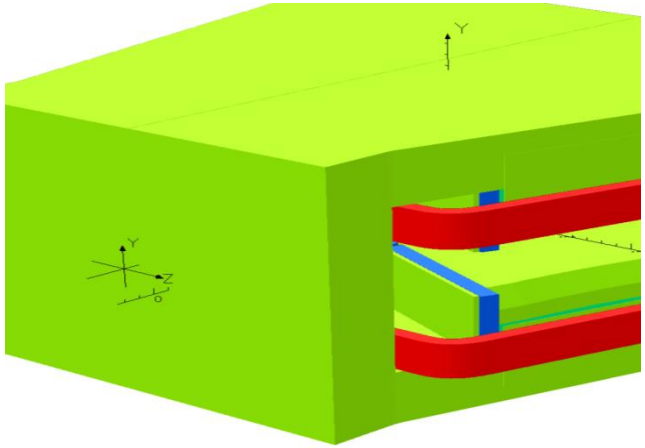
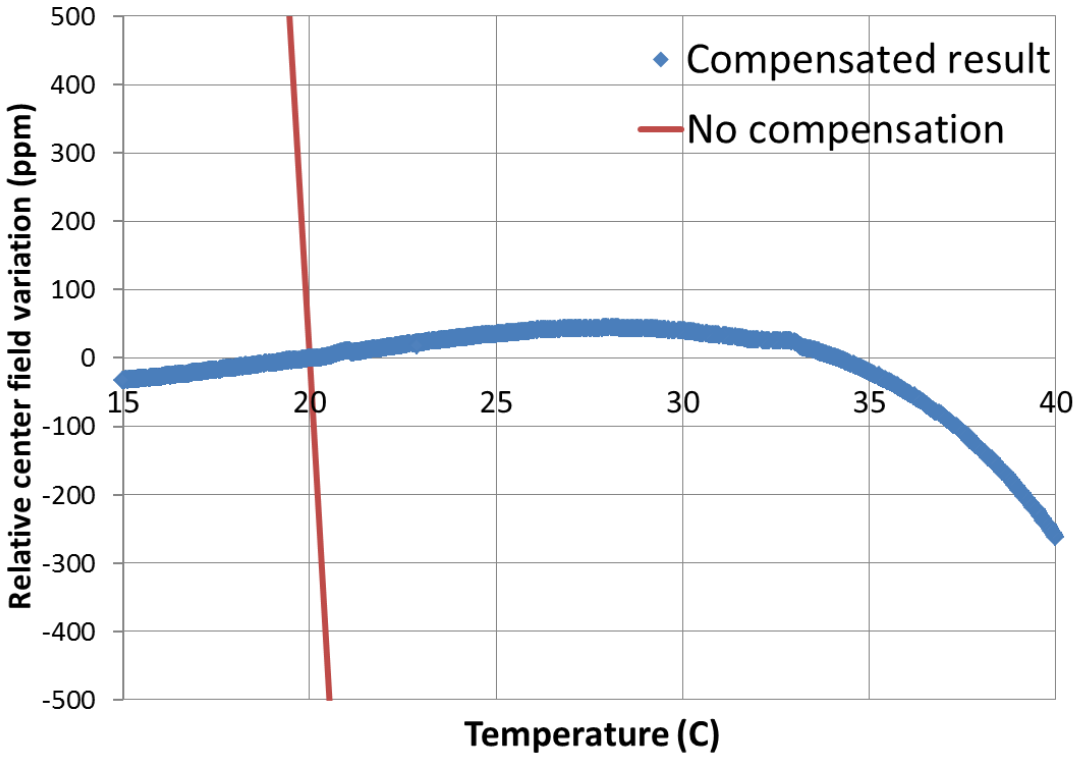




Parameter	Specification	Obtained
Deflection angle	90°	90°
Pole gap	38.5 mm	38.51 mm
Radius of curvature	250 mm	250 mm
Magnetic length	393 mm	394 mm
Center field	0.4267 T	0.42673 T
Operating range	0 - 2 %	0 - 3 %
Field homogeneity	$< 1 \cdot 10^{-3}$	$< 0.8 \cdot 10^{-3}$
Fringe field shim angle	28.52 ± 0.1°	28.45°
Thermal stability, 15-35°C	< 50 ppm/°C	< 20 ppm/°C

Temperature Stability

- Thermal drift of permanent NdFeB magnets is about 1000 ppm/°C
- This can be reduced to 10-50 ppm/°C by passive compensation
- Temperature drift is negligible in a 10°C range around optimum.



”The Green Magnet is running in our MICADAS. We have had no problems tuning the system with the new magnet and operating the system in this configuration since then.

From our measurements, we can conclude that the magnet is performing very nicely, and we can achieve a very similar performance to that of the conventional magnet.”

Hans-Arno Synal, ETH Zürich

Green Magnets – Case 2

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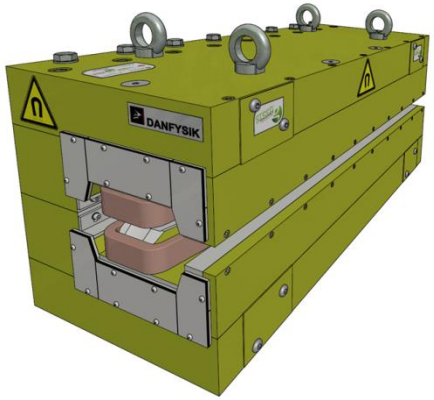
Dipole Bending Magnet

for the ASTRID2 Synchrotron Light Source at Aarhus University, DK



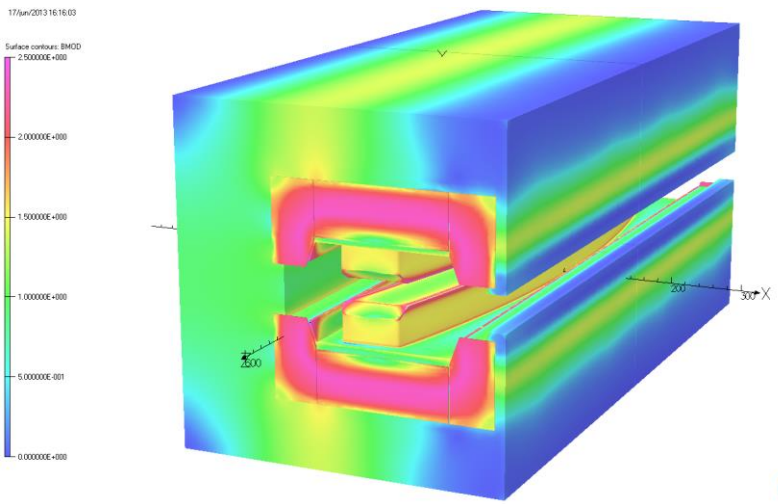
Permanent 30° C-type bending magnet for synchrotron light source.

Air cooled coils for ± 2% field adjustment.

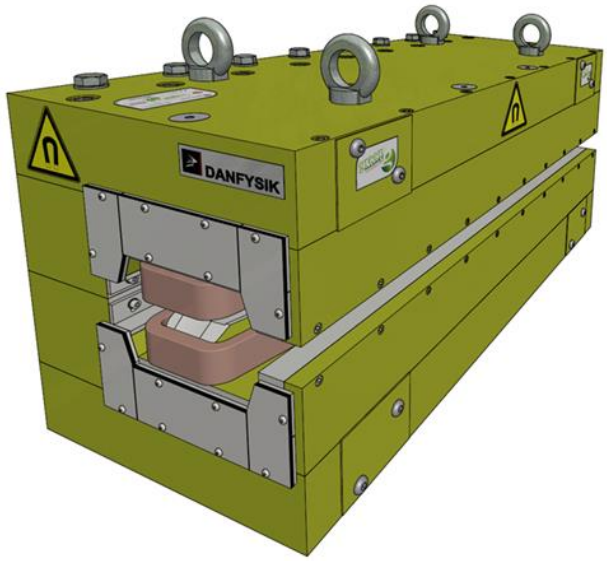
Passive temperature compensation

Magnets protected from beam line of sight

Status: Being assembled



Parameter	Unit	Specifications
Magnet type		Solid C-type
Magnetic length	m	1.00
Deflection angle	°	30.0
Nominal dipole field	Tesla	1.013
Operating range	%	98-102
Radius of curvature	m	1.9099
Aperture (width x gap)	mm^2	45×30
Good field region	mm^2	39×24
Field accuracy		$1 \cdot 10^{-3}$
Field stability	PPM	100 (50 ppm/C)
Edge angle incident/exit	°	15/15 ± 0.5



Green Magnets

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Radiation sensitivity

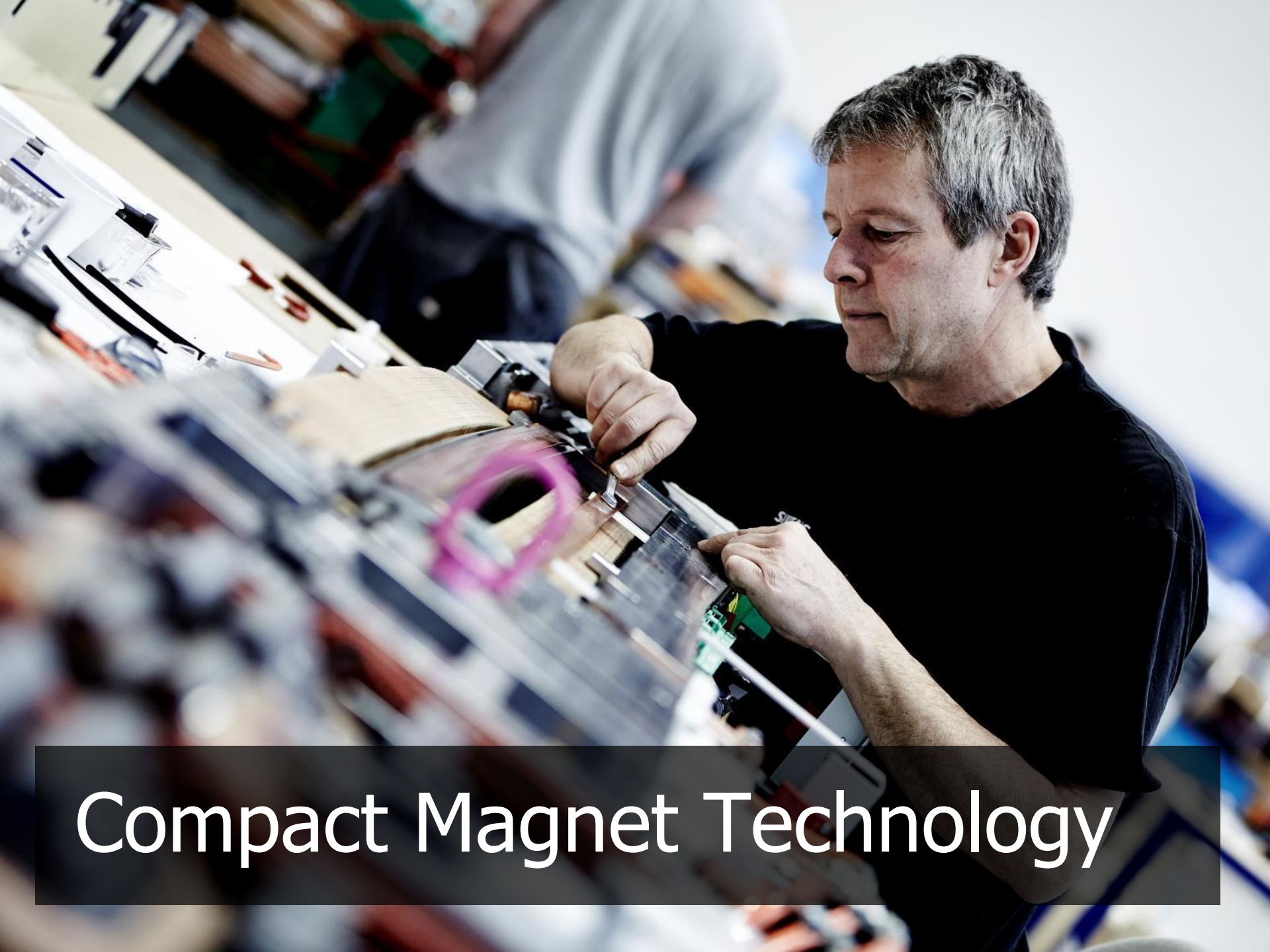
- PM magnets are being tested in a 100 MeV electron beam
- Different materials and grade have different sensitivity
- Results of first tests show that beam induced radiation damage on the NdFeB magnets is not of significant concern for applications such as for example a synchrotron light facility
- Recessed design of PM's location (protected from beam)
- Field homogenizing effect of the iron yoke and poles
- Relatively large volume of permanent magnet material
- Interlock from beam loss monitors

Green Magnets

DANFYSIK

CONCLUSION

- Green Magnets were developed as energy saving alternatives to electrical current excited accelerator magnets.
- The first Green Magnet was built at Danfysik and tested at a carbon dating system at the ETH in Zurich.
- The magnet performed well, was easy to install and we could not observe any difference to the normal AMS operation.
- A 1,0 Tesla dipole is being produced for use at ASTRID2.
- Green Magnet technology is found to be a cost effective, safe and mature technology.


Compact Magnet Technology

Compact Magnet Technology

MAX IV

- Energy 3 GeV
- Circumference 528 m
- Horrizonthal emittance 0.33 nm rad
- 20 x 7-bend achromats

M. Eriksson et al., Proc. IPAC 2011, THPC058

Multiple Function Magnet Systems for MAX IV

Focus for the MAX IV 3 GeV storage ring design:

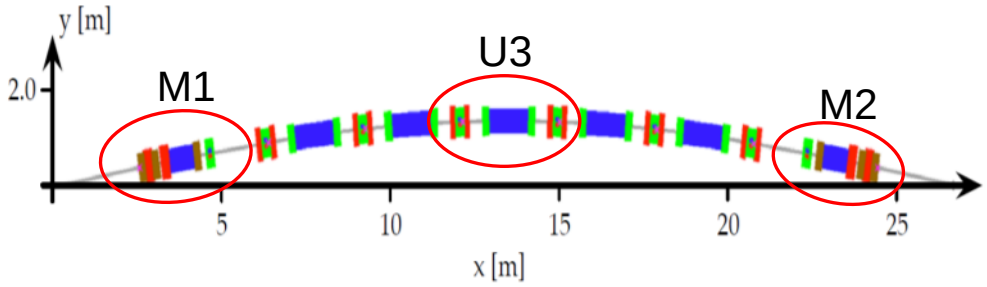
- a very low emittance ring
- a sufficient number of straigth sections
- a relatively low cost

- Very compact magnet systems
- Same principle as used in MAX III

- Low field
- Small aperture

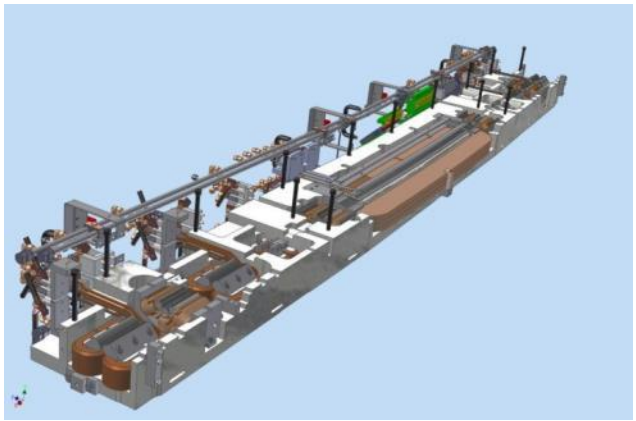
=> Low power consumption

Production of MAX IV magnet girders

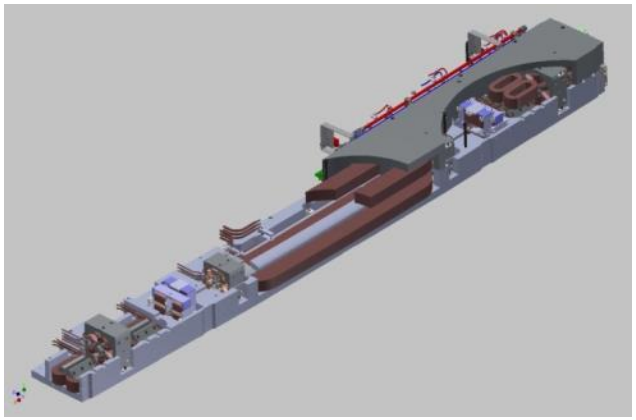


- Danfysik is producing 20 each of M1, M2 and U3 with up to 12 individual magnets
- In total 60 combined function dipoles, 220 steerers, 160 quadrupoles, 120 sextupoles, 120 octupoles
- Total of 680 individual magnets, 2880 individual coils
- Small multipole apertures (25 mm dia.)

M1



U3



Production of MAX IV magnet girders

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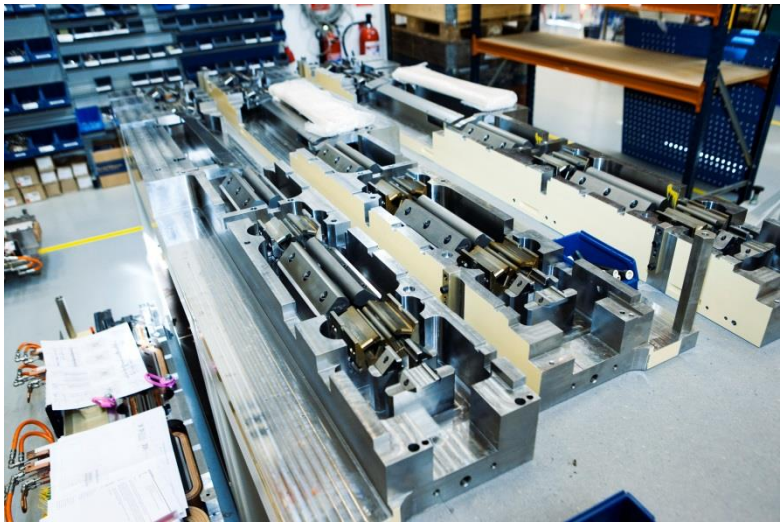
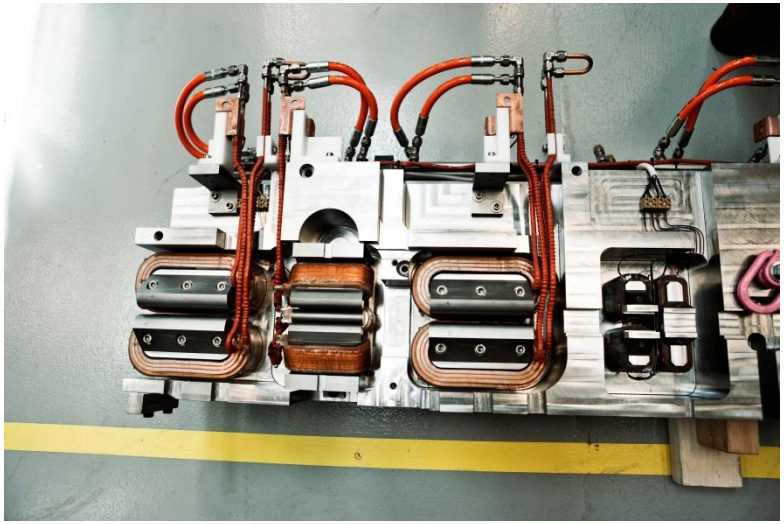
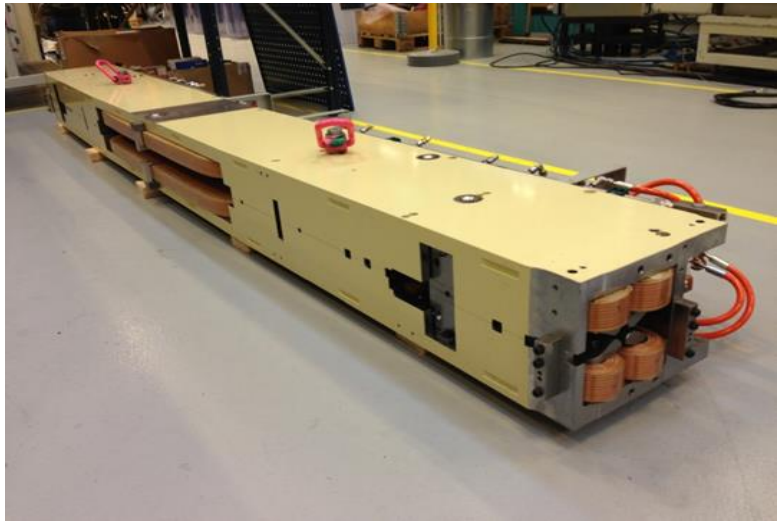
Main challenges:

- Precision machining of large (2.5 – 3.3 m long) soft steel structures to ± 20 µm

- Magnetic test of all individual magnets in the structures





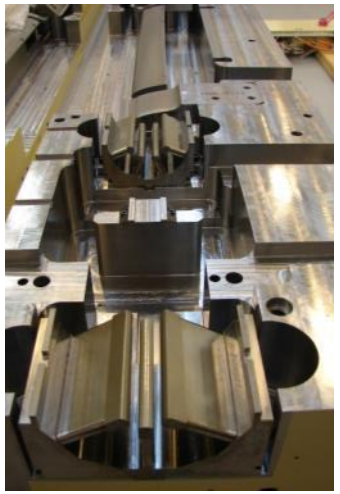


Machining and production

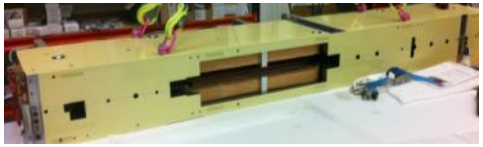
- Challenging tolerances of ±0.02 mm over full length of up to 3.3 m
- Iterative machining refinement process
- First M1, M2 and U3 completed and machining finished for first 10 M1
- 3D measurement campaign ⇒ results are within spec

Main body
Rough machining
Heat treatment
Fine machining
3D measuring
Fine machining
3D re-measuring

Multipole inserts
Rough machining
Heat treatment
Fine machining
Sub-assembling
Wire erosion
3D measuring
Fine machining
3D re-measuring



Assembly



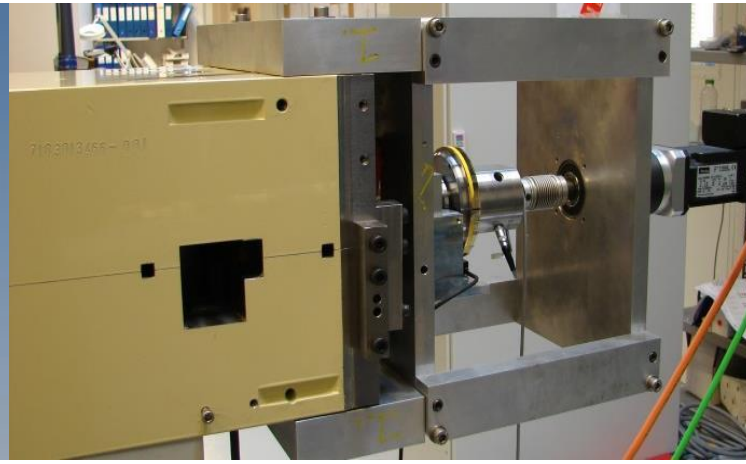
Hall probe mapper setup

- Precision Hall mapper on long granite table
- Laser feedback on longitudinal z-axis and linear encoders on x,y-axes
- Usual probe positioning not possible without line-of-sight though magnet
- Alignment by scanning over magnetic pins at know positions
- Short term position st.dev. < 2 µm, long term drift <10 µm

Scanning dipole from side & quadrupoles through small holes in yoke

Harmonic insertion coil concept

- Coil inserted from girder end with external encoder and motor
- Mechanical coil positioning from girder reference surfaces
- Tangential coil with a 10.7 mm measurement radius
- One short harmonic coil segment for each magnet
- Up to 5 coil segments per support rod
- Calibration of each segment (both phase and gradient)
- Full automation / remote control of test



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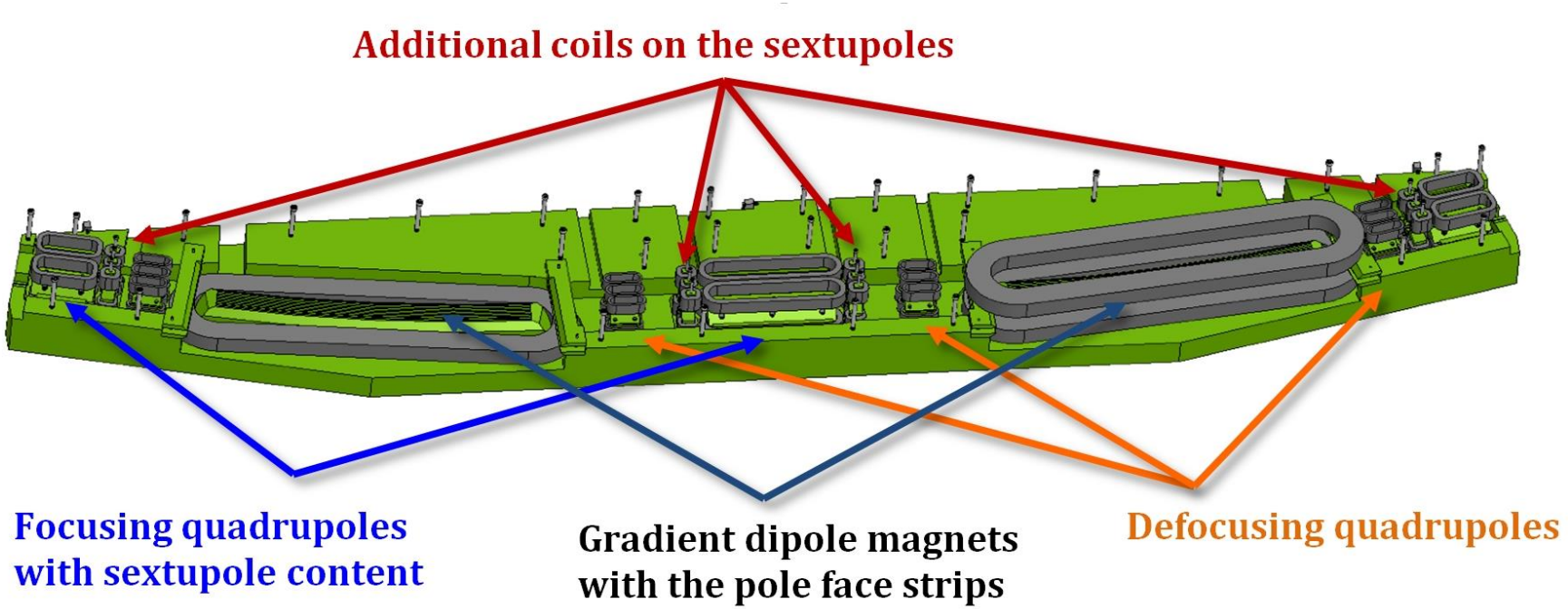
Our next challenge

MAX IV and SOLARIS 1.5 GeV rings

Each 12 off 30° sections – length 4.5 m

Each with 13 individual magnets



Compact Magnets

DANFYSIK

CONCLUSION

- Three pre-series magnet systems for MAX-IV have been completed
- The magnet blocks machined to the required (high) tolerances
- Hall probe field mapping with very good alignment and stability
- Harmonic coils inserted from girder end give high quality results
- The results are in general agreement with MAX-IV calculations
- Series production of 60 magnet systems are progressing well

Acknowledgements

Green Magnets

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B. Anderberg, Amacc

.....et al

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Thank you for your attention