Magnet design, manufacturing and measurements at *Med*Austron

17th International Magnetic Measurement Workshop
La Mola Resort, Barcelona, Spain
September 2011

Th. Zickler on behalf of the MedAustron magnet team

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- Magnets for MedAustron
- Specific magnetic measurements
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  - The synchrotron main dipole
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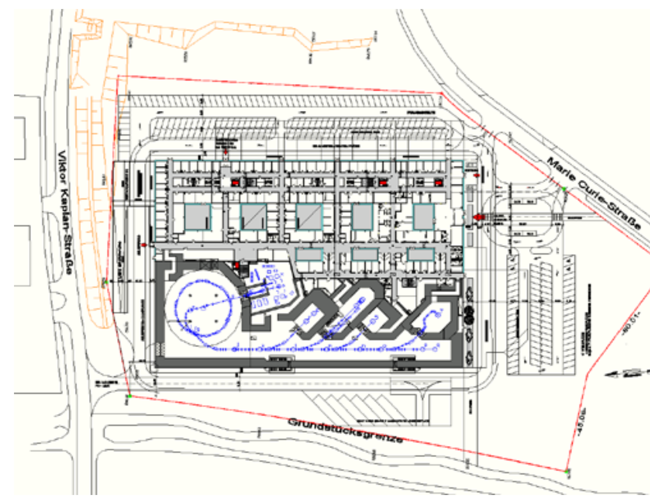
  - The synchrotron quadrupole prototype
- Magnetic Measurement Program
- Summary & conclusions

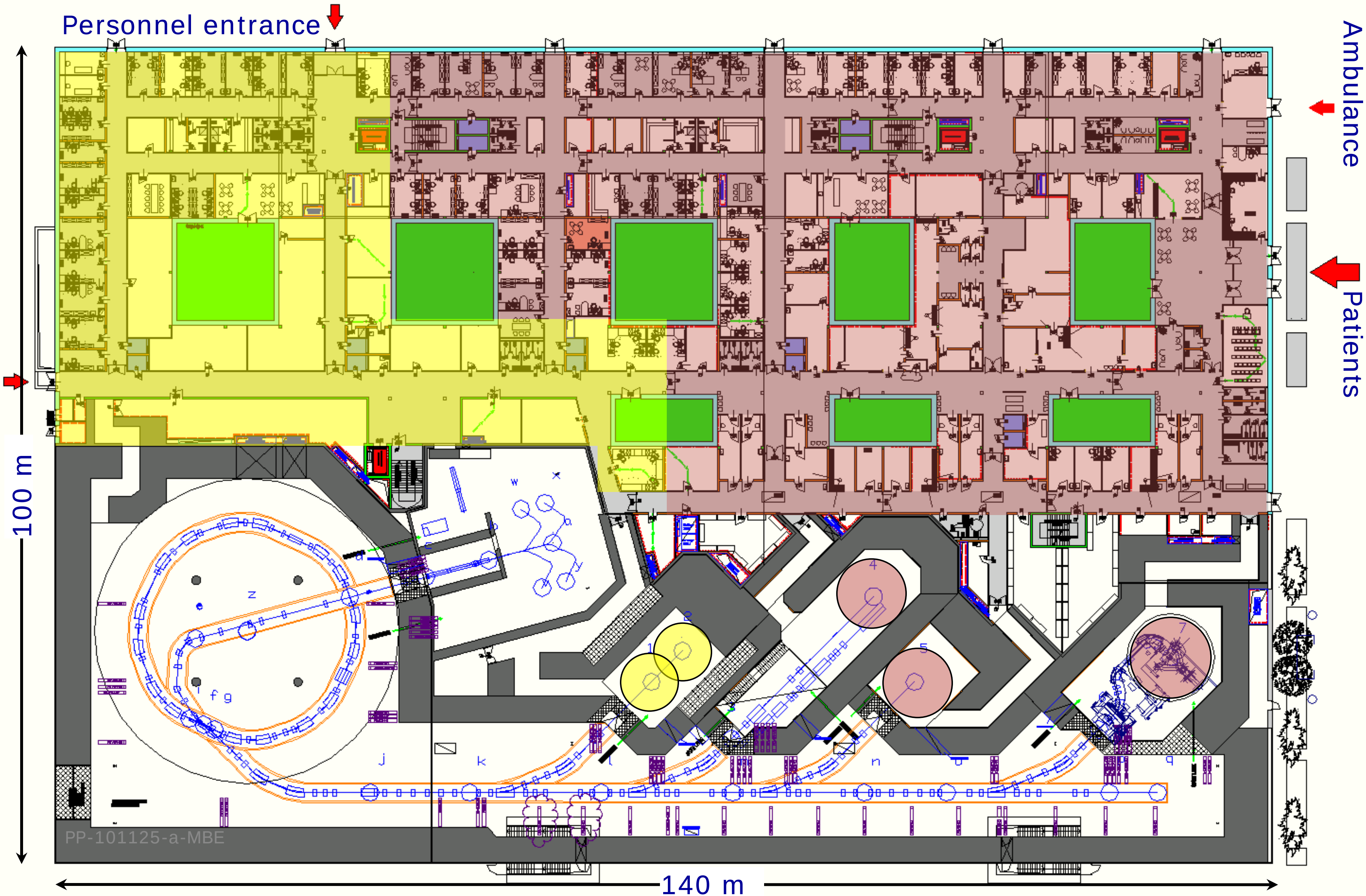
Introduction to MedAustron

- MedAustron is located in Wiener Neustadt (50 km north of Vienna) next to the future site of the new hospital

- Medical Treatment
  - Tumour treatment
  - Clinical research
- Non-clinical Research (NCR)
  - Medical Radiation Physics
  - Radiation biology
  - Experimental physics
- Accelerator operates 24/7

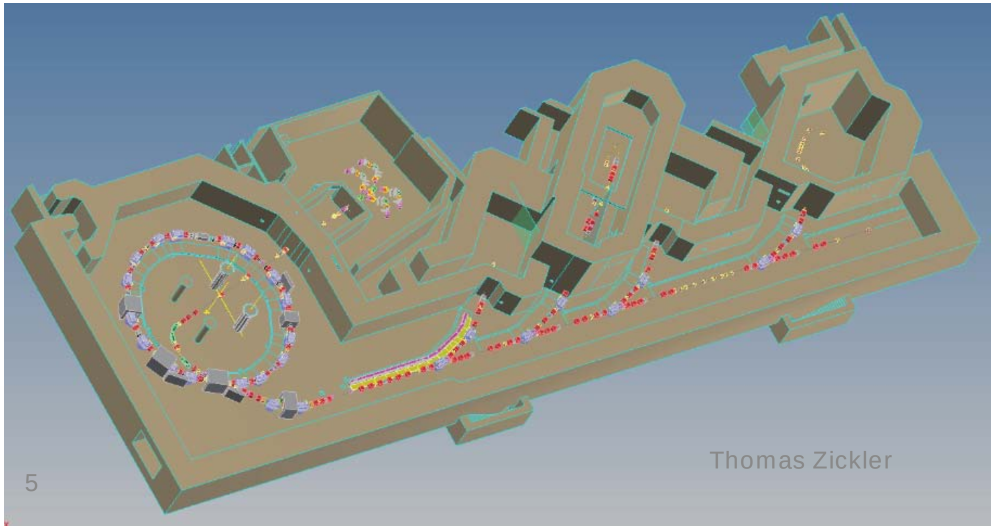


Functional Areas – Main Floor



Accelerator Main Parameters

- Synchrotron based (circumference 76 m)
- Ion species: protons and carbon ions
  - Optionally and at a later stage other ions with q/m>1/3 are possible
- Energy range
  - Proton: 60-250 MeV (medical)
    - Higher proton energy provided for experimental physics: up to 800 MeV
  - Carbon: 120-400 MeV/n
- Intensities (maximum) in irradiation rooms
  - Proton: $1*10^{10}$ /cycle
  - Carbon: $4*10^{8}$ /cycle
- Cycle time > 1 second



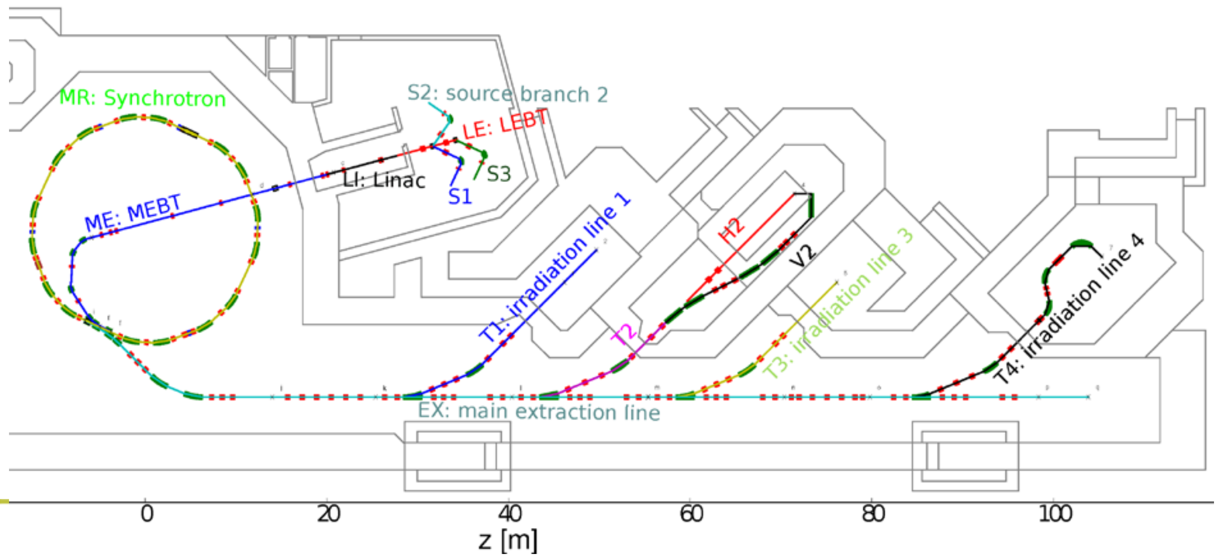
Irradiation rooms

Medical facility:

- IR2
  - Horizontal and vertical beam
  - Protons and carbon ions
- IR3
  - Horizontal beam
  - Protons and carbon ions
- IR4
  - Gantry
  - Protons

Non-clinical research facility:

- IR1
  - Horizontal beam line
  - Protons (up to 800 MeV) and carbon ions



Medical Treatment Capacity

- 24.000 single irradiations (fractions) per year
  - Patient treatment typically requires 20 fractions
  - Patient receives one fraction/day during ~4 weeks
- MedAustron capacity ~1200 patients per year
  - About 100 patients/day
- Optimizing for optimum accelerator occupancy during medical mode
- 3 medical irradiation rooms
  - 2+1 fixed beams and one proton gantry
  - Operation of three irradiation rooms in parallel
  - About 25 minutes per treatment room and patient

Implementation Strategy

Austrian Accelerator Centre is at CERN

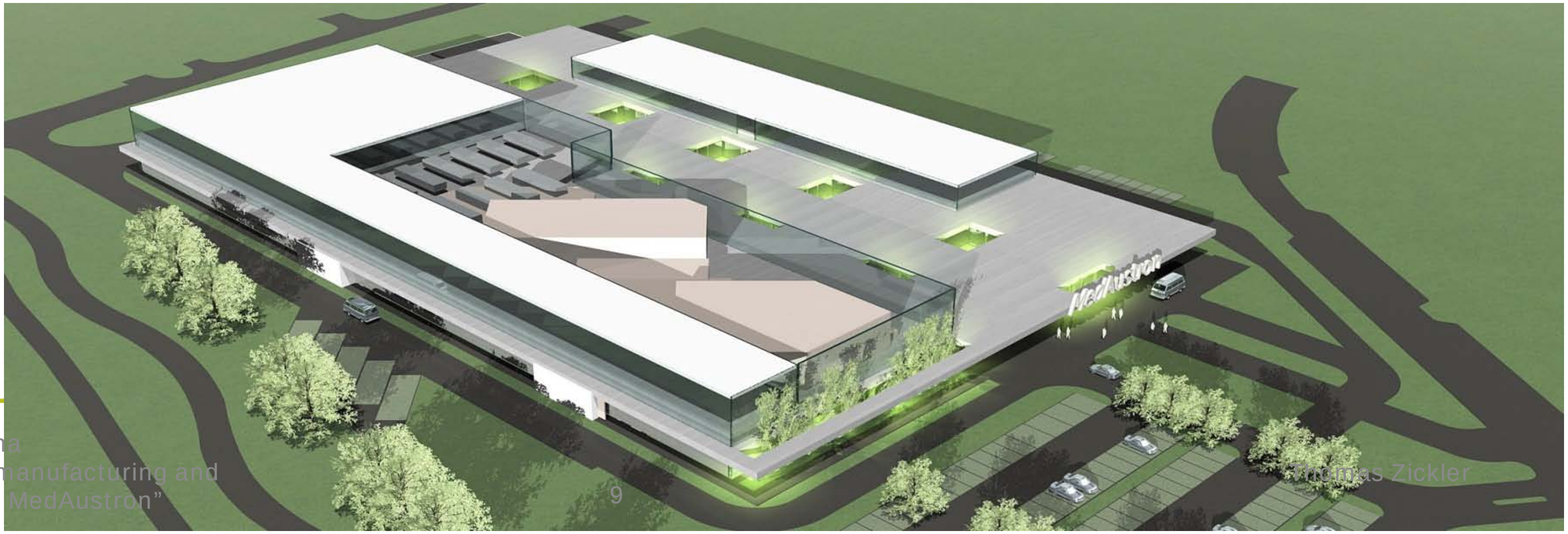
- Austrian local know-how on this sector not available

EBG MedAustron - CERN partnership:

- Build up an EBG MedAustron Accelerator team at CERN
- Currently ~40 MedAustron staff at CERN
- Team integration in the technical groups at CERN to establish know-how transfer
- Design, procurement and installation with the support of CERN experts
- Operation in Wiener Neustadt by the EBG MedAustron team

Project Schedule

- Summer 2008 — Start of project planning and team building
- End 2010 — EIA notification
- February 2011 — Ground breaking and civil engineering start
- September 2012 — Start of accelerator installation (sequential)
- March 2013 — Start of beam commissioning (sequential)
- Mid 2014 — Start of medical commissioning
- 2015 — First patient treatment



Civil engineering

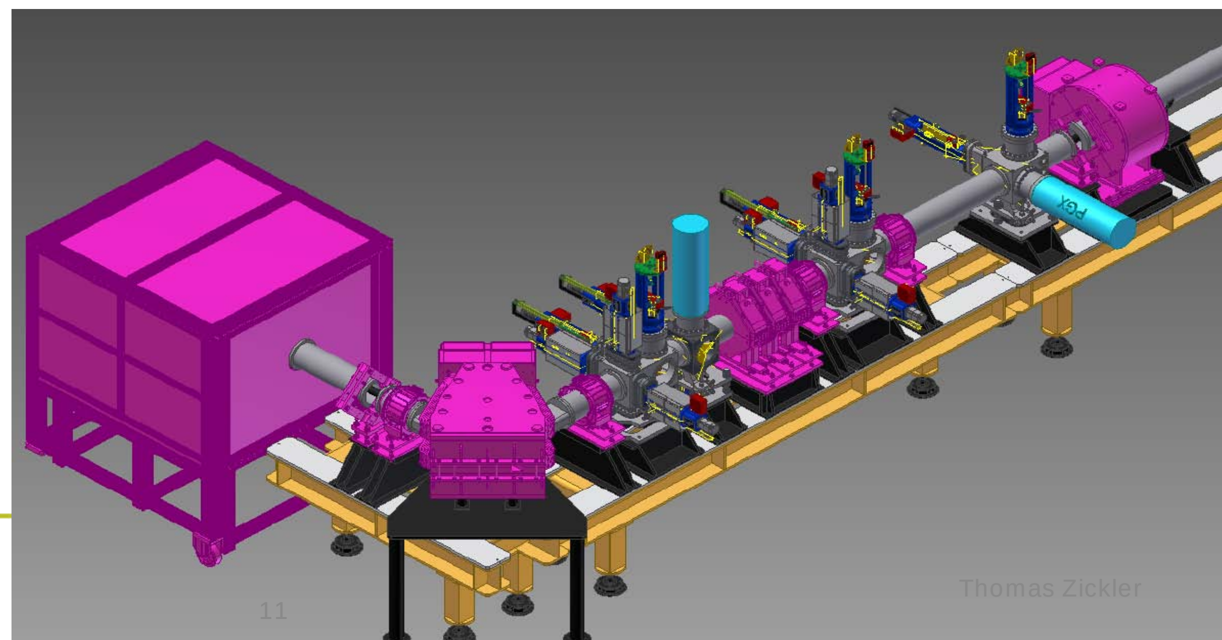
10. September 2011

Status

Contracts concluded

- 3 ECR ion sources & spectrometer lines
- Injector RFQ und IH tanks & RF amplifiers
- Main magnets
- Special magnets
- Power converters

Preparation of injector test stand at CERN started



Magnet Work Package

Scope of the Magnet Work package:

"*Design, engineering, construction, procurement, production follow-up, testing, measurements, installation, commissioning of all 'standard' electro-magnets and magnet components for LEBT, MEBT, Synchrotron, HEBT and treatment rooms*"

- > 285 magnets in total
- 30 different types!
- Size ranges from a few kg to 75 tonnes
- Responsibility for p-Gantry magnets within Magnet WP
- Special magnets (kicker, bumper, septa) not included

IMMW17

ebg MedAustron

List of Magnets

Magnet type	Name	Installation	Number of units
Solenoid	MSO-A	S3, (S4), LE	3
Spectrometer	MBH-A	S1, S2, S3, (S4)	4
LE Steering dipole (H + V)	MCX-A	S1, S2, S3, (S4), LE	17
LE Quadrupole	MQZ-A	S1, S2, S3, (S4), LE	20 (=6 triplets + 1 singlet)
Switching dipole	MBS-A	LE	2 [+ 1]
ME Bending dipole	MBH-B	ME	3 [+ 1]
ME Quadrupole	MQZ-B	ME	10 [+ 1]
ME Steering dipole (H + V)	MCX-B	ME	8 [+ 1]
MR Bending dipole (+T4 bending)	MBH-C, (MBH-D)	MR, PCR, T4	16 + 1 (+2) [+ 1]
MR Quadrupole (+ skew)	MQZ-C, (MQS-C)	MR	12 (+ 1) [+ 2]
MR Sextupole (+ resonance)	MXZ-C, (MXR-C)	MR	5 (+ 1) [+ 1]
MR Steering dipole (H / V)	MCH-C, MCV-C	MR	10 [+ 1] + 8 [+ 1]
MR Betatron Core	MIN-C	MR	1
HE Bending dipole	MBH-E, MBV-E	EX, T1, T2, T3, V2	12 [+ 1]
HE Quadrupole	MQZ-E	EX, T1, T2, T3, T4, H2, V2	78 [+3]
HE Steering dipole (H / V)	MCH-E, MCV-E	EX, T1, T2, T3, H2, V2	17 [+1] + 17 [+ 1]
Vertical bending dipole 90°	MBV-F	V2	1
Scanning dipole (H)	MSH-E	T1, T2, T3, V2	4 [+ 1]
Scanning dipole (V)	MSV-E	T1, T3, T3, V2	4 [+ 1]
Gantry bending dipole 58°	MBR-G	T4	2
Gantry bending dipole 90°	MBR-H	T4	1
Gantry Quadrupole (+ corrector)	MQZ-G (MQC-G)	T4	7 (+ 1) [+ 1]
Gantry Steering dipole (H + V)	MCX-G	T4	> 4 (t.b.c.)
Gantry Sextupole	MXZ-G	T4	2 (t.b.c.)
Gantry scanning dipole (H)	MSH-G	T4	1
Gantry scanning dipole (V)	MSV-G	T4	1

Design, engineering and production

Magnet team at CERN:

- 2 engineers
- 3 physicists
- 2 technical engineers
- 3 technicians

Magnetic design at CERN

- Size of team requires to do design work in series
- Critical or large number types first
- Comprehensive 2D and 3D field computations
- Studies of field quality, transient and hysteresis effects

Manufacturing in industry

- According to detailed technical specifications
- Close collaboration between MedAustron and partners in industry

Design and engineering

Introduction to MedAustron

Magnets for MedAustron

Specific magnetic measurements

The synchrotron main dipole

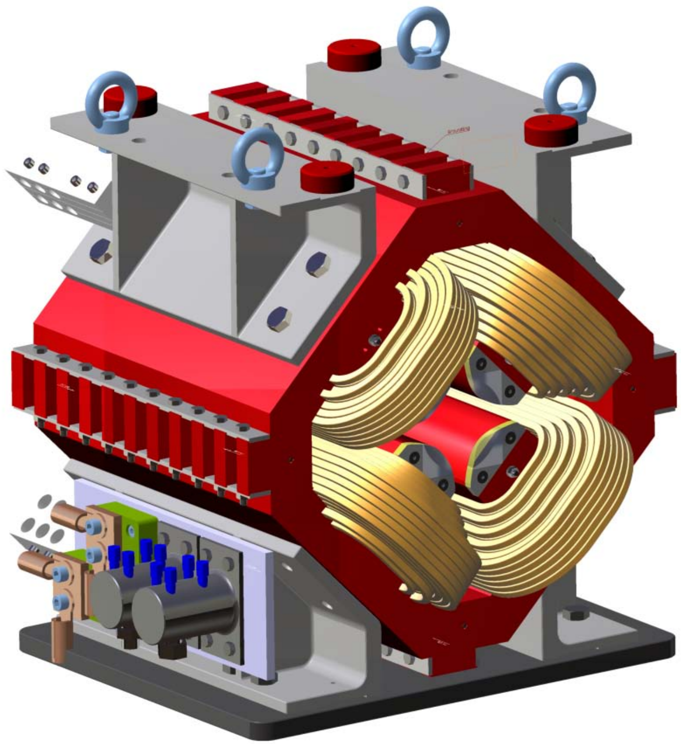
Eddy currents

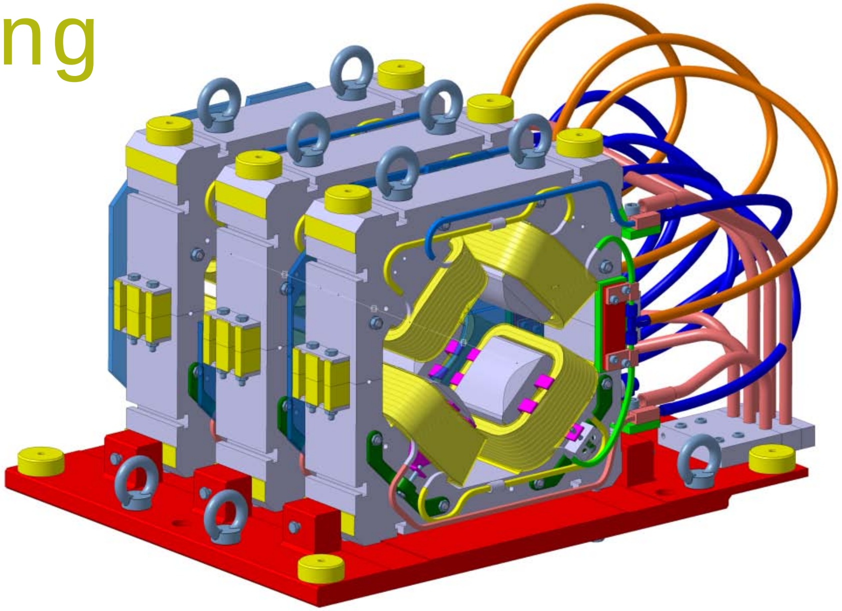
Electrical steel

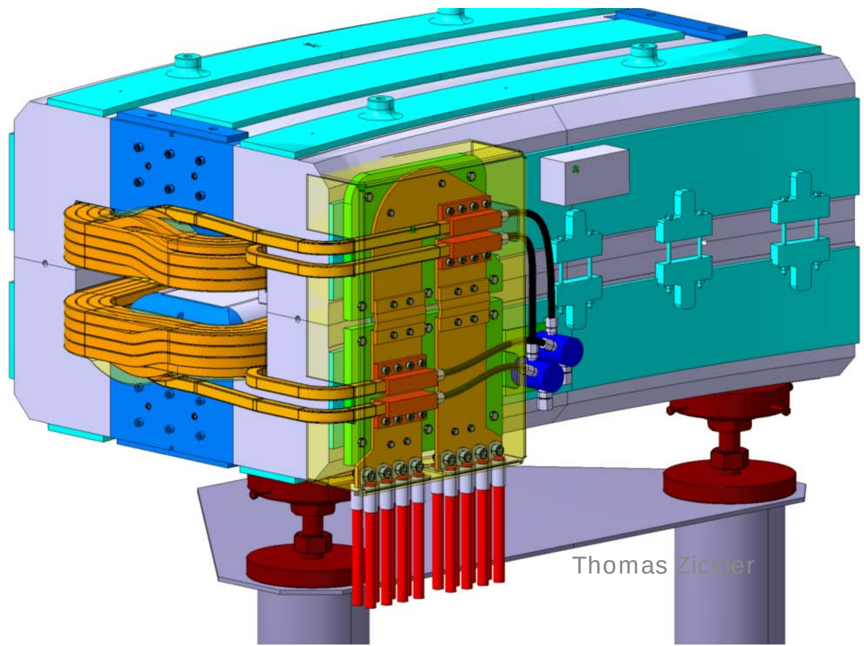
The synchrotron quadrupole

Magnetic measurement program

Summary







Specific magnetic measurements

Magnetic measurements are needed during all phases throughout the entire project, not only for end-control!

Design & engineering

- Characterization of material properties
- Benchmarking finite element models
- Testing of prototypes
- Selection of raw materials
- Testing of manufacturing techniques and processes

Production

- Design validation before series production (pre-series)
- Acceptance tests of raw materials
- Definition of end-shim profile

Post-production

- Special measurements on individual magnets
- Systematic acceptance measurements on series magnets

Operation

- B-train

Example: The Synchrotron Main Dipole

Requirements:

- Operation: 1 Hz
- Field stabilization time after ramp end: 100 ms
- Number of dipole magnets in series: 16
- Operational field levels: 90 mT – 1.5 T
- Field quality: $\pm 2\times10^{-4}$ ($\pm$60 mm × $\pm$30 mm)
- Uniformity of magnetic lengths: 1×10^{-3}

FE-Design using OPERA:

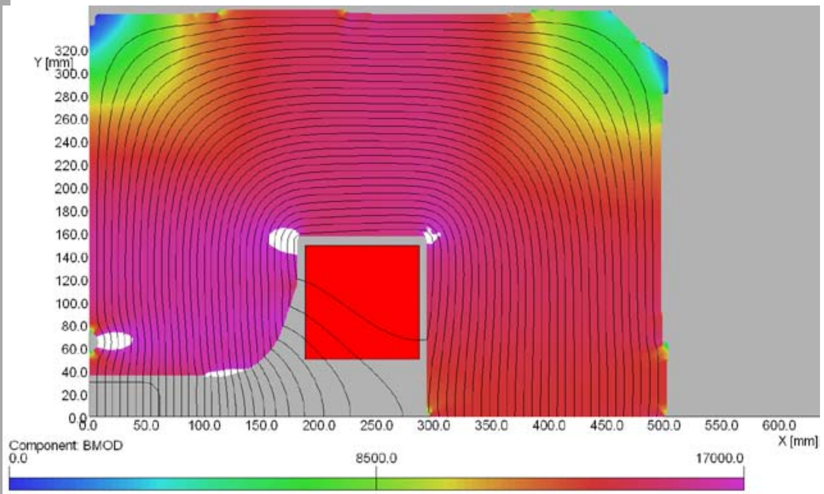
- 2D static (isotropic/anisotropic): pole profile optimization
- 3D static: integrated field quality incl. particle tracking
- 2D & 3D transient: eddy current effects in the tension bars and pole ends
- 2D DEMAG: hysteresis effects and residual fields

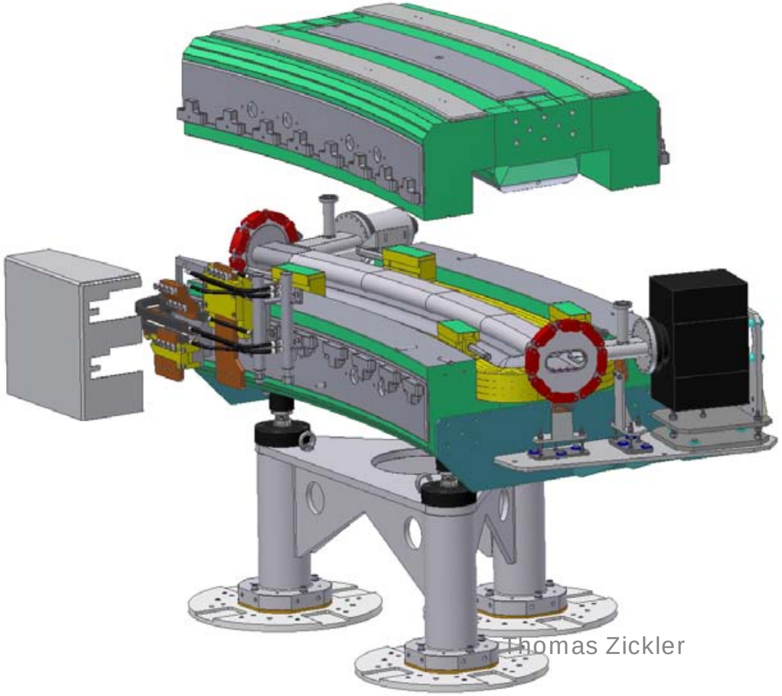
M. Stockner at al: *Design and Optimization of the MedAustron Synchrotron Main Dipoles*, IPAC Proceedings, Spain, 2011

Example: The Synchrotron Main Dipole

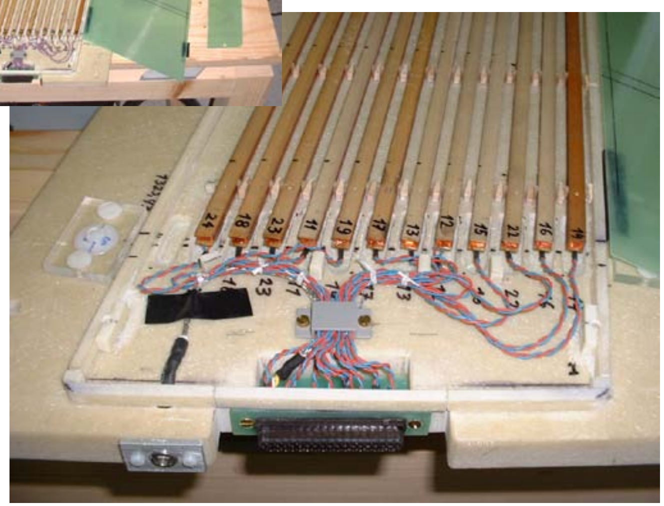
Design features:

- Laminated curved yoke
- Pole profile with shims, central bore and Rogowski roll-off
- Removable end shims with Rogowski profile
- High-quality low-carbon electrical steel supplied by VOEST-Alpine
- Stainless steel tension bars

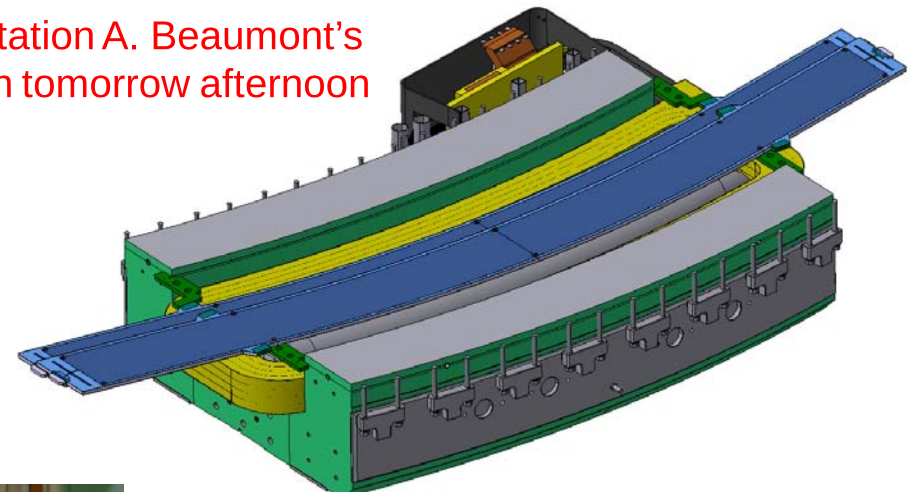


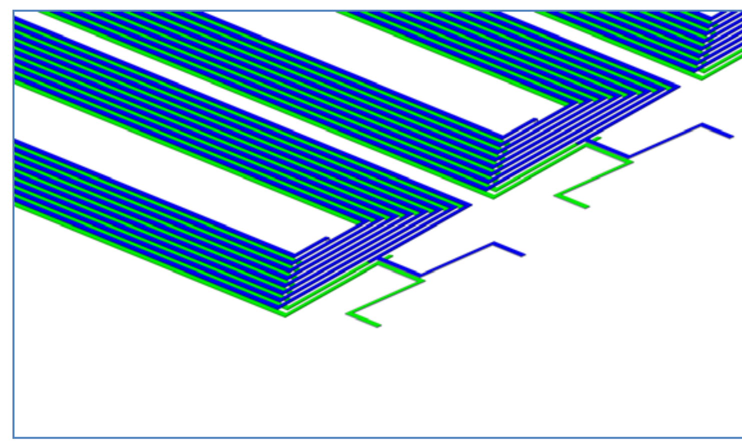


PCB-Fluxmeter development



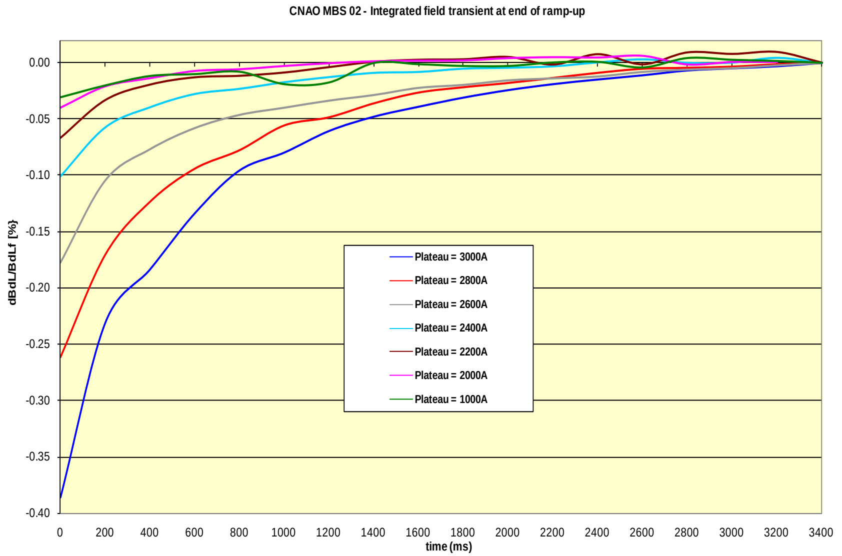
See presentation A. Beaumont's presentation tomorrow afternoon





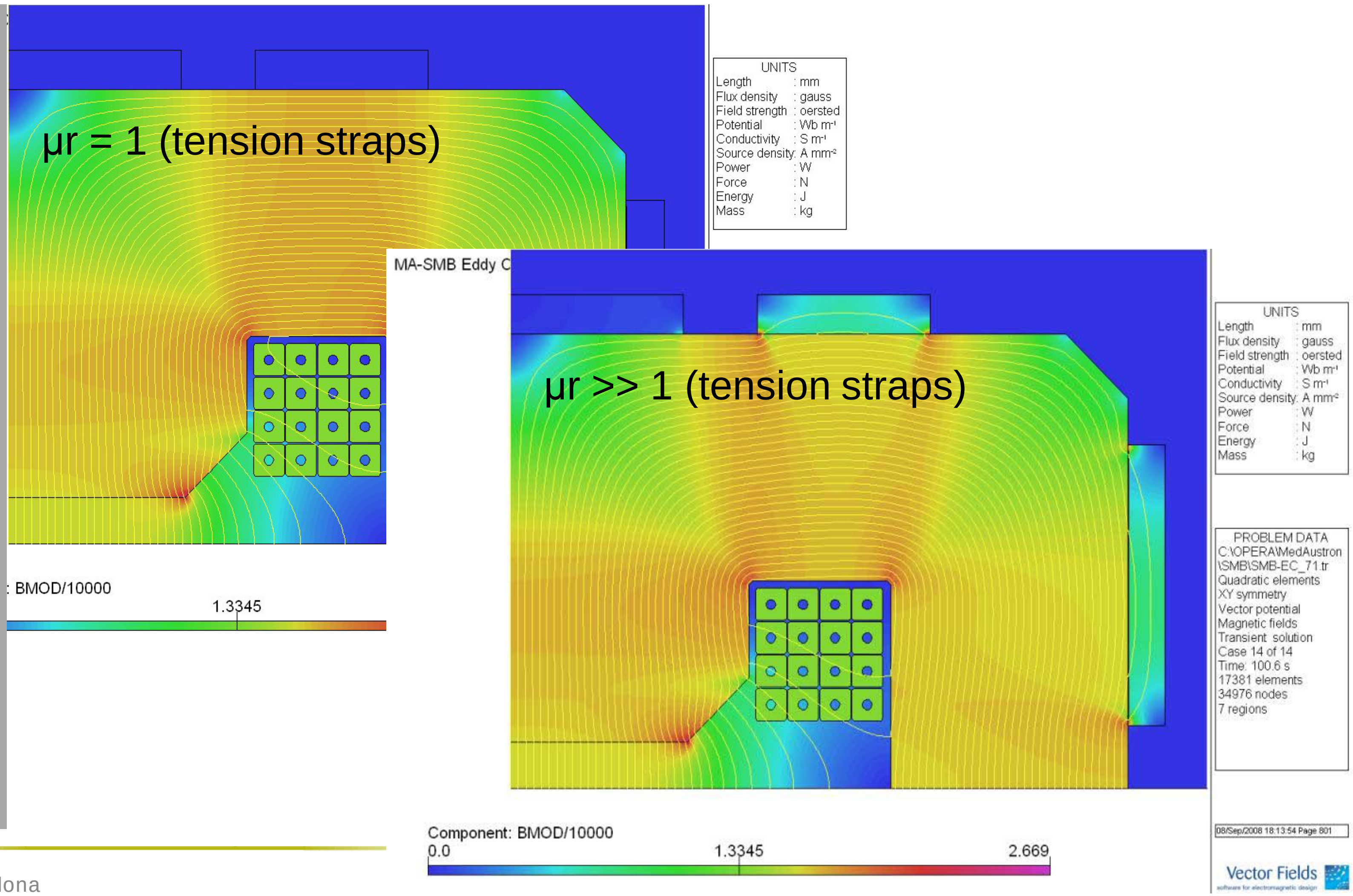
Eddy currents

- Significant magnetic field delay with respect to coil current has been observed in similar magnets
- Time constants up to 600 ms measured
- Field error at ramp end up to 0.41 %
- Weak dependence on dI/dt
- Strong dependence on flat top field level

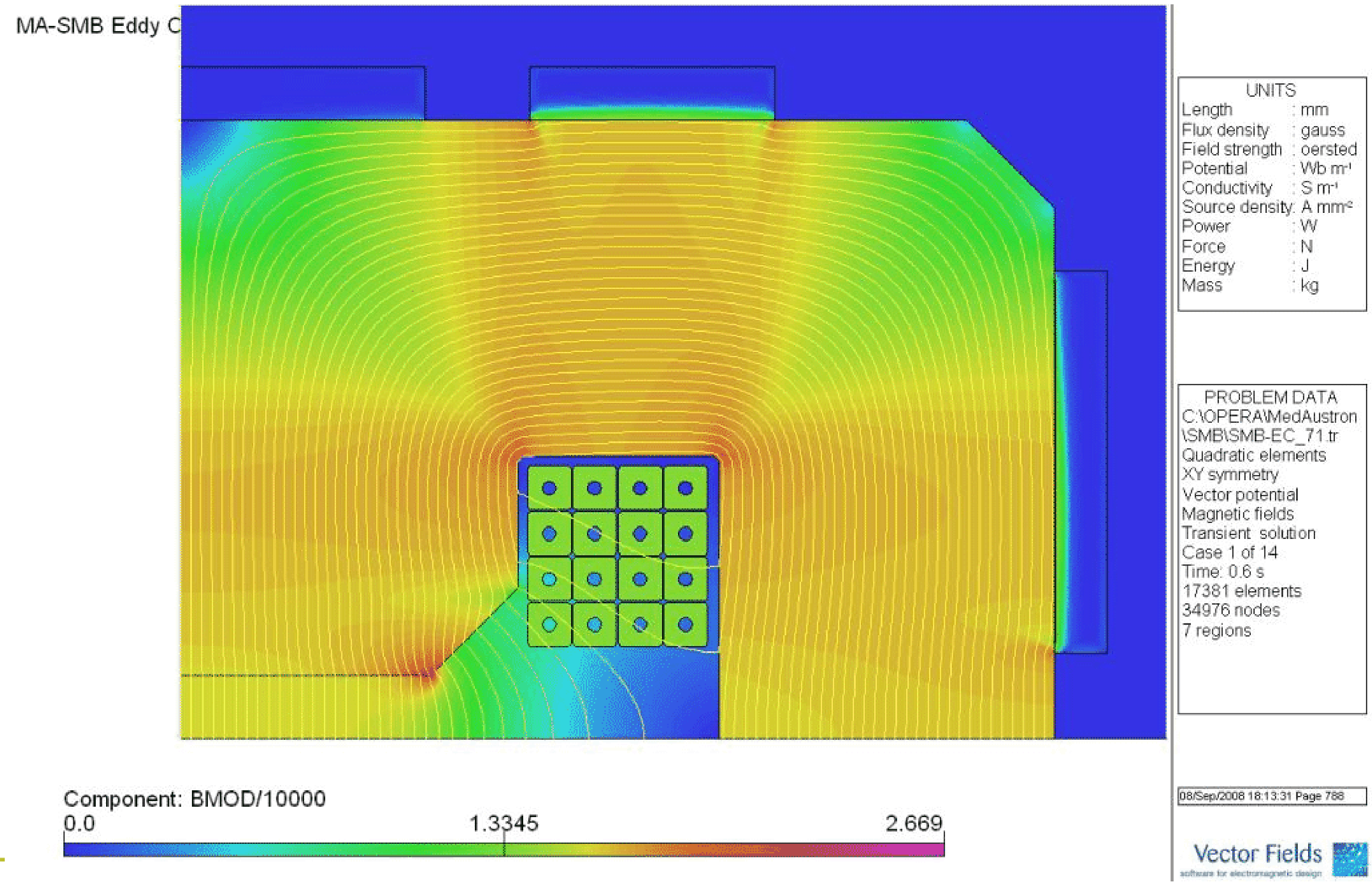


- Several explanations:
  - Poor steel quality ?
  - Poor insulation between laminations ?
  - Eddy currents from longitudinal field components in the magnet ends ?
  - Eddy currents in the non-laminated tension bars?

Eddy currents - static case



Eddy currents



Eddy currents

- Introduction to MedAustron
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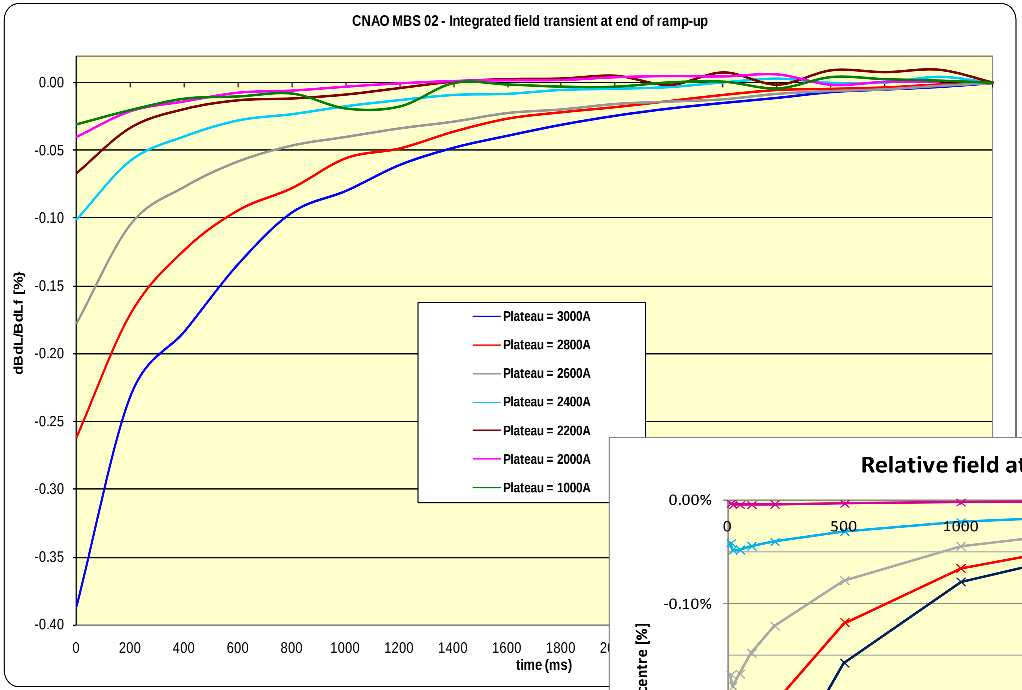
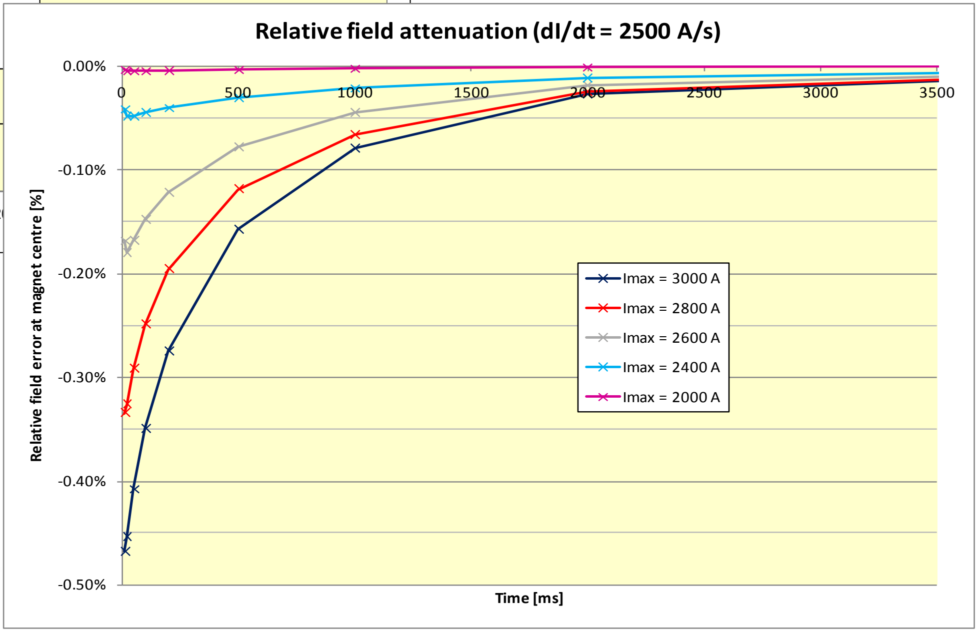
- Specific magnetic measurements
- The synchrotron main dipole
- Eddy currents
- Electrical steel
- The synchrotron quadrupole
- Magnetic measurement program
- Summary



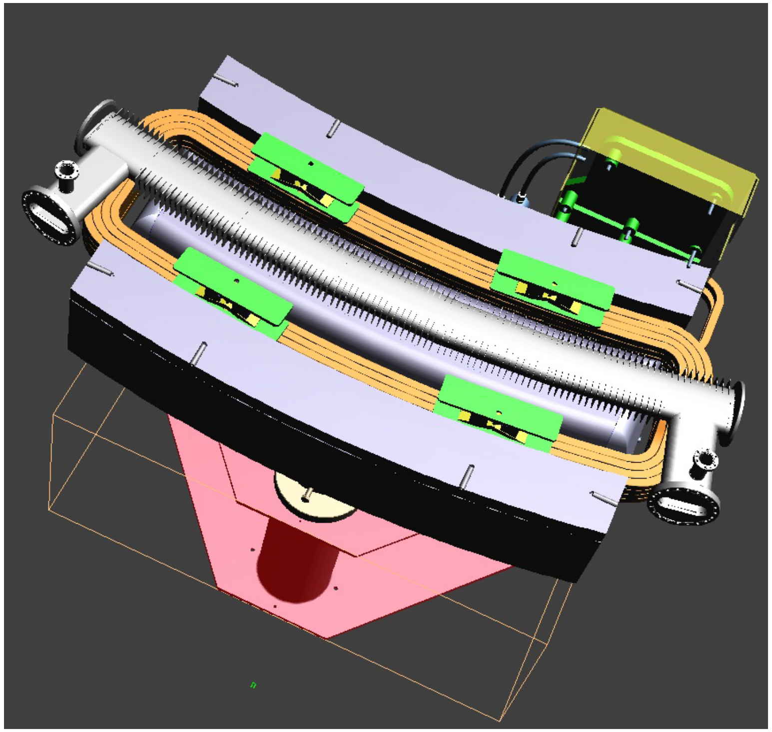
Measured curves
(Courtesy of D. Cornuet, R. Chritin)



Calculated curves

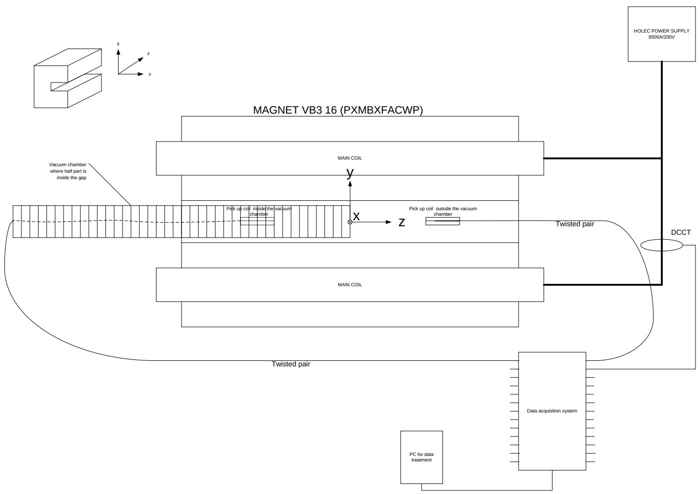
Vacuum chamber

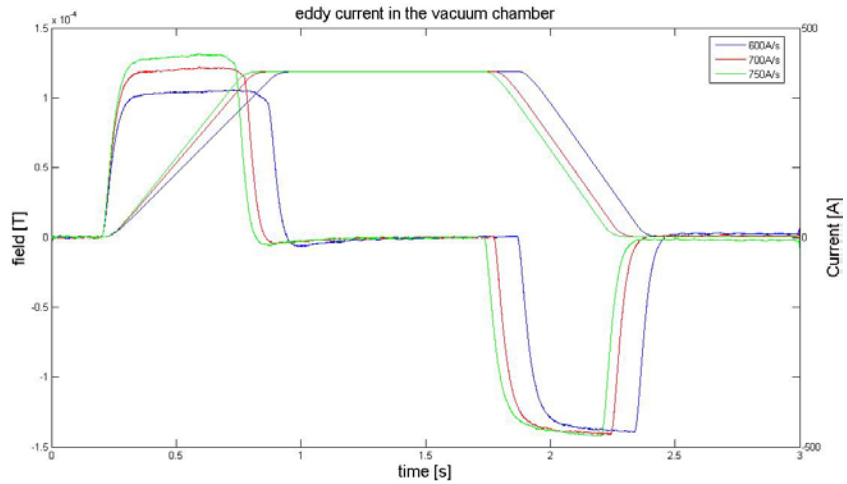
- For cost optimization, a thick vacuum chamber was proposed for the synchrotron main dipoles
- Impact on field quality and dynamic behavior due to:
  - wall thickness
  - material (resistivity)
  - reinforcement ribs
  - brazing
- Calculations showed:
  - Field errors at injection acceptable



Vacuum chamber

- Differential measurement with two search coils





Courtesy of A. Beaumont

- Measured time constant in the vacuum chamber (20 ms) not larger than magnet time constant
- Result: Proposed vacuum chamber design is acceptable

Electrical Steel

➢700 tonnes needed for MedAustron magnets

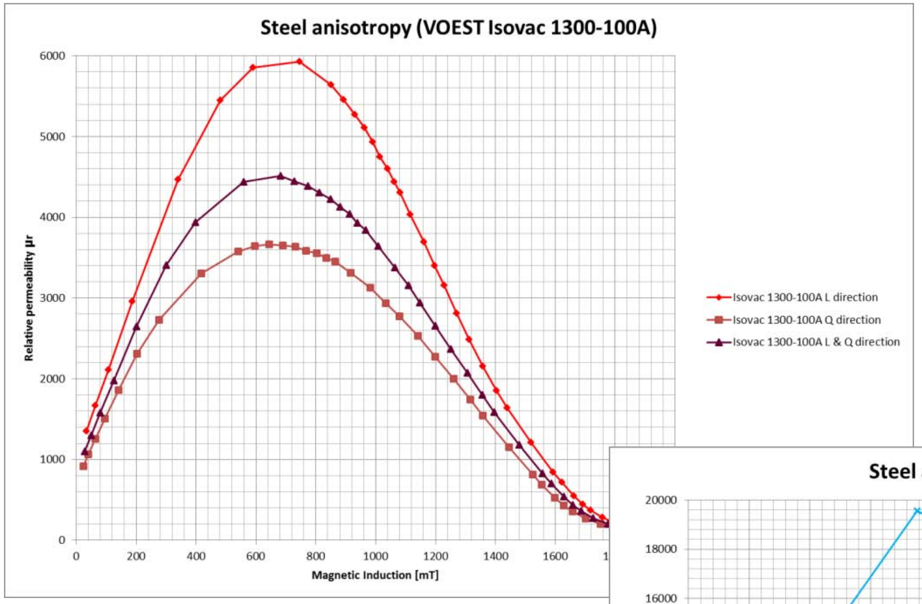
Strategy:

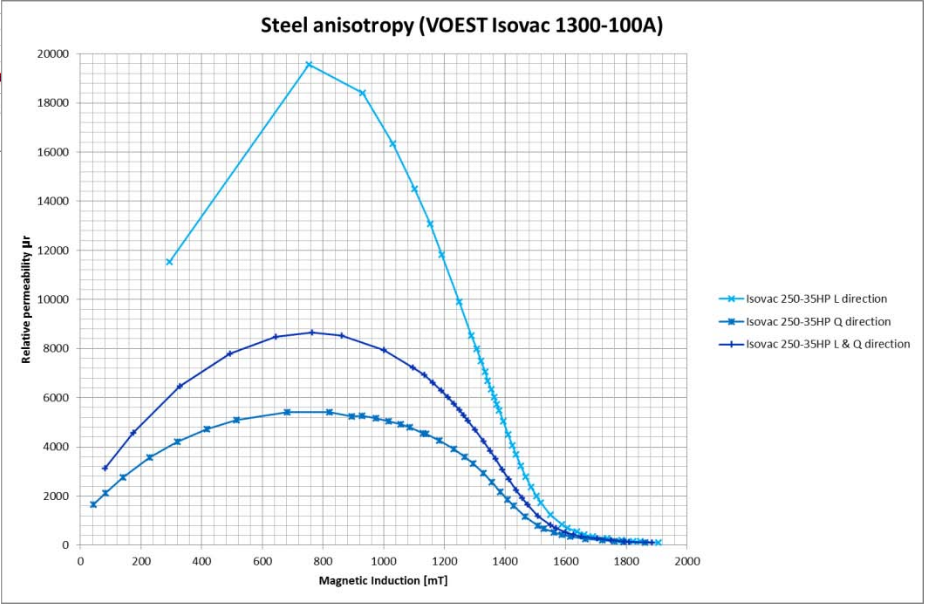
- Common procurement for all magnets and dispatch to magnet manufacturers' upon request
- Reproducible quality, known properties, minimum delays
- For synchrotron magnets: measurement, selection and sorting to assure most homogenous quality
- Contract with VOEST-Alpine

Properties:

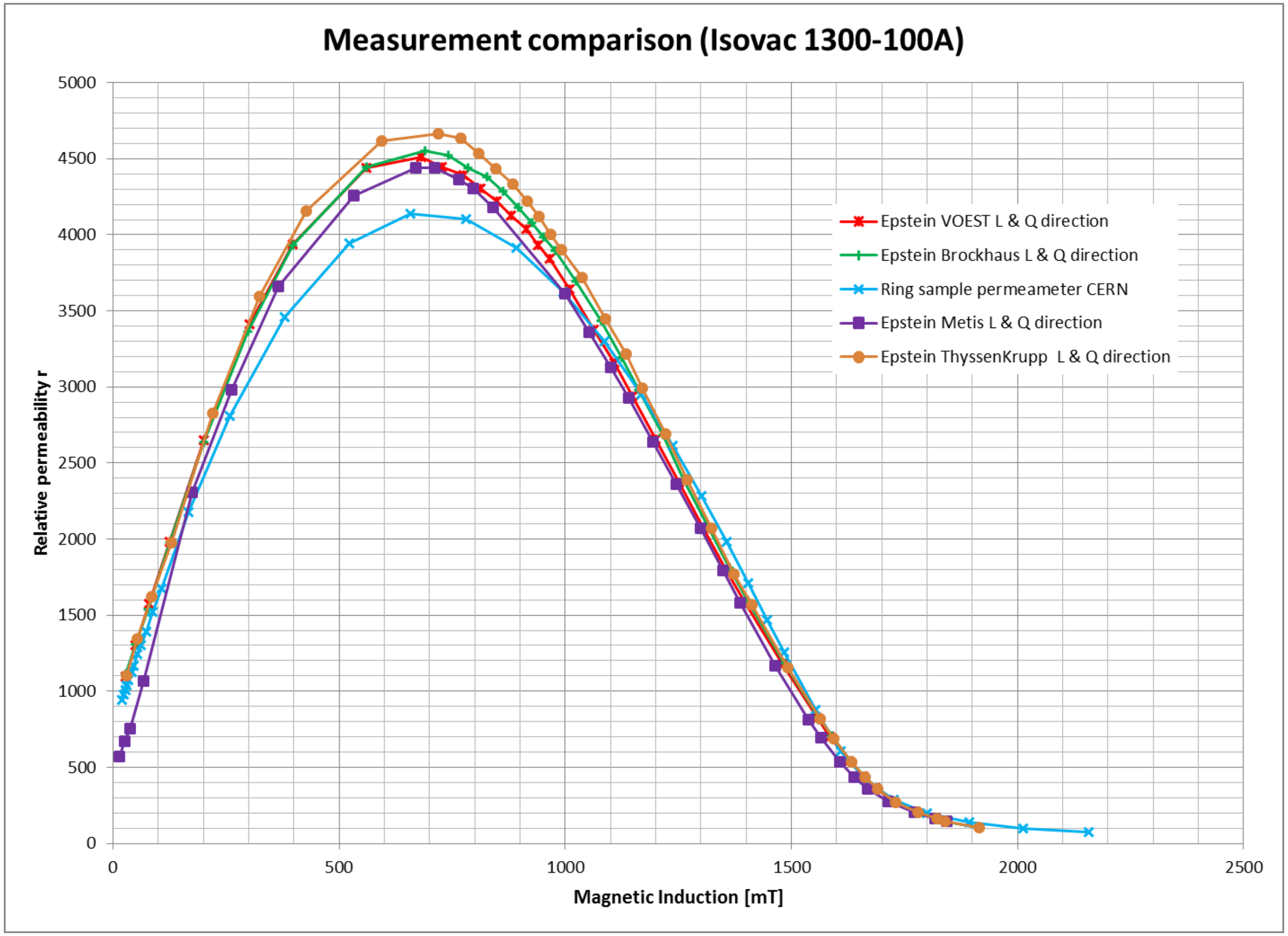
- Cold rolled, non-grain oriented, low-carbon steel
- 1 mm thick steel sheets, grade Isovac 1300-100A
- Two-side epoxy coating for electrical insulation and bonding
- Thickness variation <7 μm perpendicular to the rolling direction
- Permeability variation < 4%, coercivity variation < ±2 A/m

Steel anisotropy: input for FEM

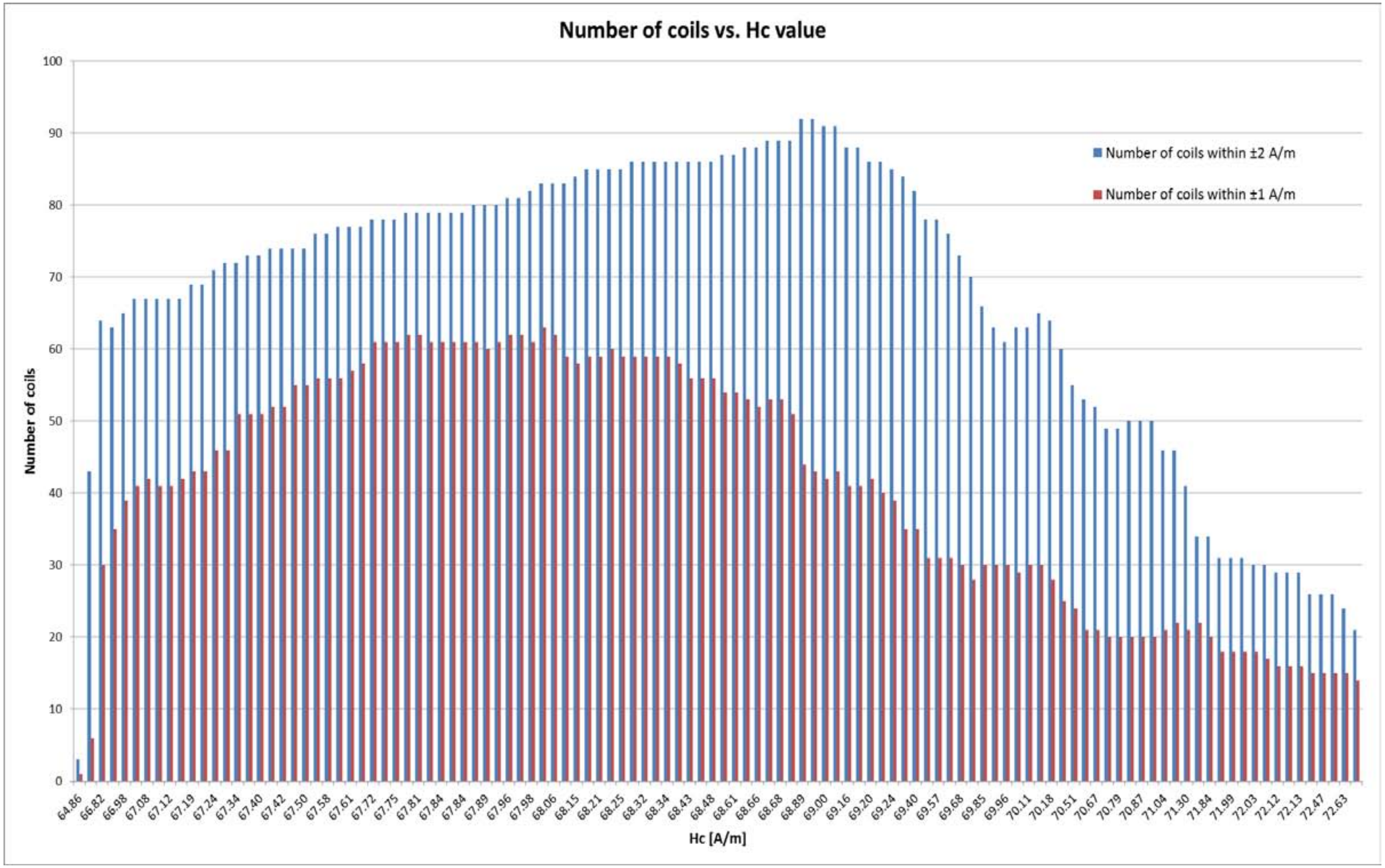




Permeability measurements

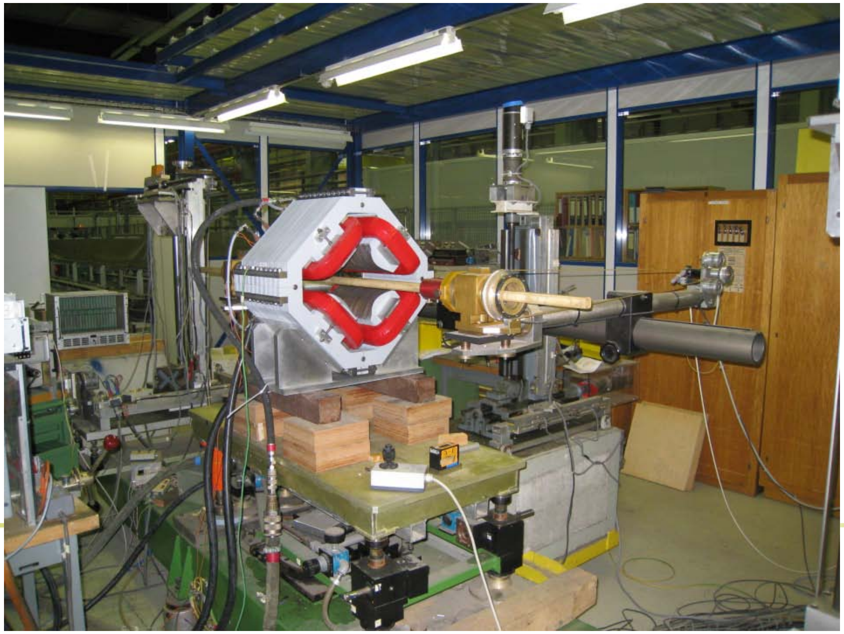


Statistics: selecting materials



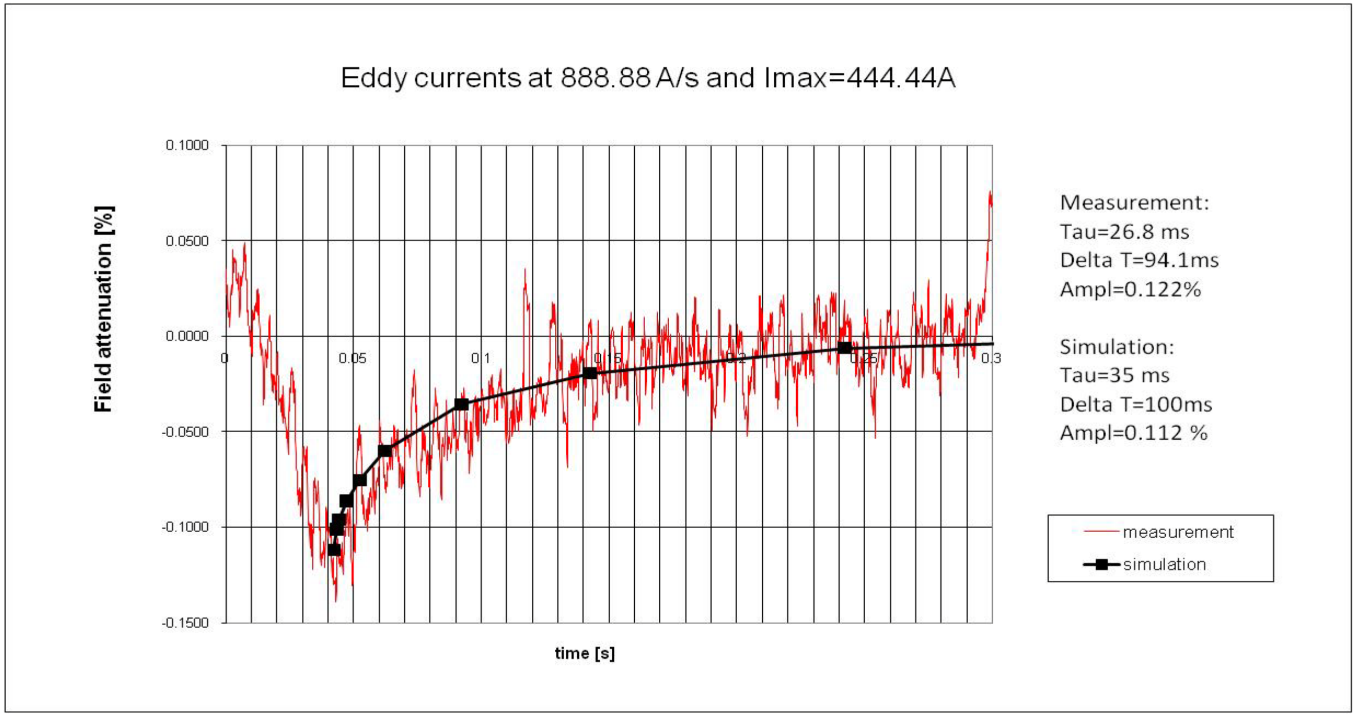
Synchrotron quadrupole

- Field computations revealed that standard steel is not suitable for synchrotron quads and sextupoles:
  - Long time constant
  - Large residual fields
- Different steel grade proposed by VOEST (Isovac 250-35HP)
- Benchmark measurements on prototype



Dynamic field measurements

- Dynamic measurements with static coil to determine eddy current amplitude, stabilization time and time constant



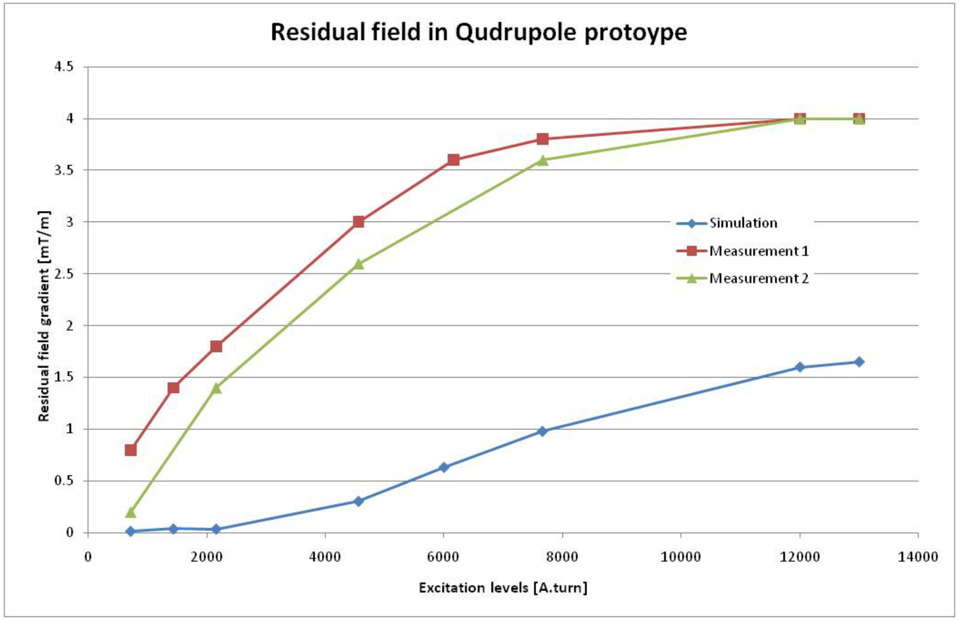
- Result: Stabilization time constant acceptable

Courtesy of A. Beaumont

- Reasonable good correlation with OPERA 3D FE-simulation

Hysteresis measurements

- Rotating coils measurement of the residual gradient as function of the excitation current



- Result: Residual field is acceptable

Courtesy of A. Beaumont

- Poor correlation with OPERA DEMAG-simulation results
- Further efforts needed to improve FE-model

Magnetic measurement program

- NMR/Hall Probes
  - 3D Field map
  - Fringe field
  - Transfer function
  - Hysteresis
  - Local field
  - Time constant
- Rotating coils
  - Field integral
  - Multipole components
  - Transfer function
  - Hysteresis
  - Magnetic axis
  - Roll angle
  - Time constant *
- Short coils
  - Transfer function
  - Hysteresis
  - Local field
- Fluxmeter or search coil
  - Tracking
  - Field integral
  - Transfer function
  - Time constant
- Shimming
  - Adjustment of magnetic length
  - Multipole suppression

Magnetic measurement program

Measurement strategy:

100% of the magnets will be measured

At CERN: prototypes, all pre-series, small series and all series dipoles

At magnet supplier or external company: series magnets (quadrupoles, corrector dipoles, sextupoles) by using rotating coils

Measurements at CERN:

- 40 dipoles and 30 pre-series and small series in 2 years (=25%)
- Special measurements: fringe fields, transients, time constants, residual field, hysteresis, etc ...

The amount of magnets and the complexity of the measurements require a careful planning

Magnetic measurement program

	Magnet type	Number	NMR/Hall Probe						Rotating coil							Short coil			Fluxmeter/Search coil				Shimming	
			Field map	Local field	Fringe field	Transfer function	Time constant	Hysteresis	Field integral	Multipole components	Transfer function	Hysteresis	Magnetic axis	Roll angle	Time constant	Transfer function	Hysteresis	Local field	Tracking	Integrated field	Transfer function	Time constant	Magnetic length	Multipole suppression
Bending magnets	LEBT Spectrometer	4	S	S	P	S																		S
	LEBT Switching	3		S	S				S	S	S	P						P						
	MEBT bending	4		P	P				S	S	S				P									
	Synchrotron bending	20	P	S	P			P								P		P	S	S	S	S	S	S
	HEBT bending	13	P	S	P			P								P		P	S	S	S	S	S	P
	V2 90 degree	1		P	P			P												P	P	P	P	P
	Gantry 90 degree	1		P	P			P												P	P	P	P	P
	Gantry 58 degree	2		P	P			P											S	S	S	P	S	P
Steering magnets	LEBT H+V	12	S	S		S			P	P	P	P			P									
	MEBT H+V	9		S	P				S	S	S	P			P			P						
	Synchrotron H/V	20		S	P				S	S	S	P			P			P						
	HEBT H/V	36		S	P				S	S	S	P			P			P						
	Gantry H+V	4		S	P				S	S	S	P			P			P						
Scanner	Scanner H+V	10	P	S	P				S	S	S	P			S			P						
	Gantry scanner H+V	2	P	S	P				S	S	S	P			S			P						
Magnetic lenses	LEBT quad (triplet)	20							S	S	S		S	S				S						
	LEBT solenoid	3	S	S	S	S																		
	MEBT quad	11							S	S	S	P	S	S				S					P	P
	Synchrotron quad	13							S	S	S	P	S	S	P			S					S	S
	Synchrotron skew quad	2							S	S	S		S	S				S						
	Synchrotron air core quad	1							S	S	S		S	S				S						
	Synchrotron sextupole	7							S	S	S	P	S	S	P			S					P	P
	HEBT quad	81							S	S	S	P	S	S	P			S					P	P
	Gantry quad	9							S	S	S	P	S	S	P			S					P	P

P = Pre-series **S = Series** **CERN** **Industry**

Summary & Conclusions

- MedAustron is progressing well
- 40% of the design work is done
- Magnet production has started and is taking up speed
- Magnetic measurements are important for all project stages from design to operation
  - Reliable measurement results are essential to make correct design choices
- Series measurements at CERN and in industry will start soon
- Lots of interesting work with many technical challenges ahead of us

… to be continued…

Detailed measurement results and more highlights will be presented at the next IMMW… so see you hopefully in 2013!

Thank you for your attention!

Questions ?