Lessons learned in the construction of Wendelstein 7-X

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Outline of the talk

- Introduction
- Organisation of a big project - lessons learned
- Planning aspects - lessons learned
- Fabrication of components - leasons learned
- Integration - lessons learned
- Conclusions

W7-X, from theory to reality

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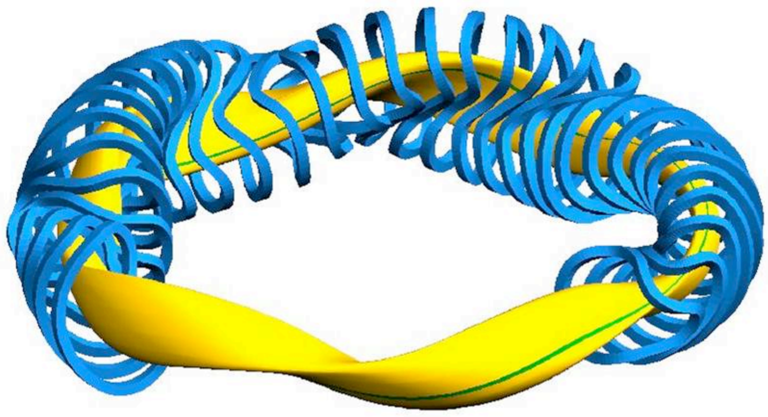
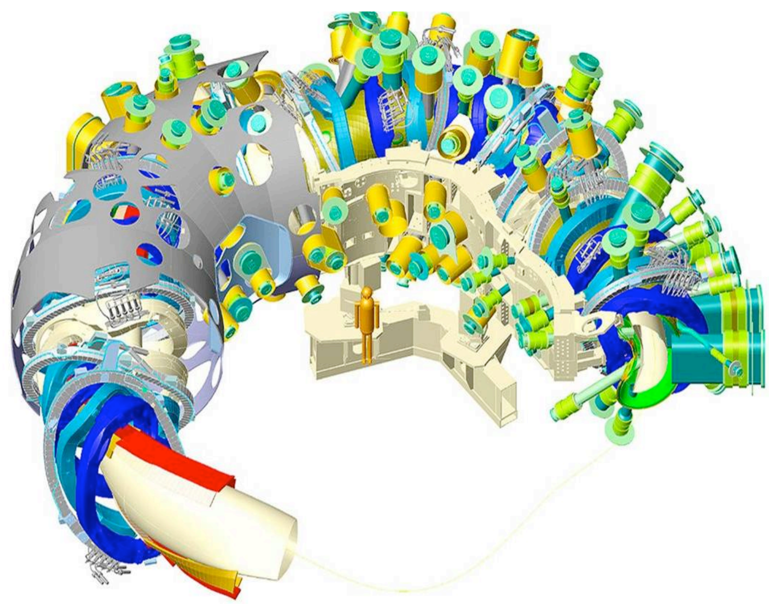


major radius	5,5 m
minor radius	0,53 m
plasma volume	30 m^3
magnetic field	< 3 T
rot. transform	5/6 – 5/4
non-planar coils	50
planar coils	20

heating power	15 – 30 MW
pulse length	30 min
stored energy	600 MJ
device diameter	16 m
device height	4,5 m
device mass	725 t
cold mass	425 t



Major challenges with the W7-X project

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Wendelstein 7-X is

- a first-of-a-kind device
  - numerically optimized, big scientific step
  - many new technologies to be developed
- designed for high-power steady-state operation
  - 30 min plasma operation with 10 MW ECRH
  - superconducting magnet system
  - pressure water cooling of in-vessel components
- a big machine
  - 30 m^3 plasma volume, 750 t total weight
  - large and expensive components
  - demanding tools for fabrication and assembly
- a cryogenic device
  - 425 t total cold mass
  - with high technical complexity
  - extreme quality demands in general

Project history

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time line		planned completion date
1991	EURATOM approval phase 1	1999
1995	EURATOM approval phase 2	2004
1996	official project start	2006
2000	inauguration of new building
2002	insolvency Babcock GmbH (coil manufacturer)
	external audits of the project	2010
2003	first restructuring of the project
2004	device assembly interrupted due to coil repair	2012
	second restructuring of the project
2005	assembly resumed
2006	assembly plan revision	2016
	counter measure package implemented	2014
2007	first magnet module completed
2009	all magnets manufactured and tested
	assembly of four magnet modules in progress
2011	all magnet modules assembled	2014

All magnet modules completed

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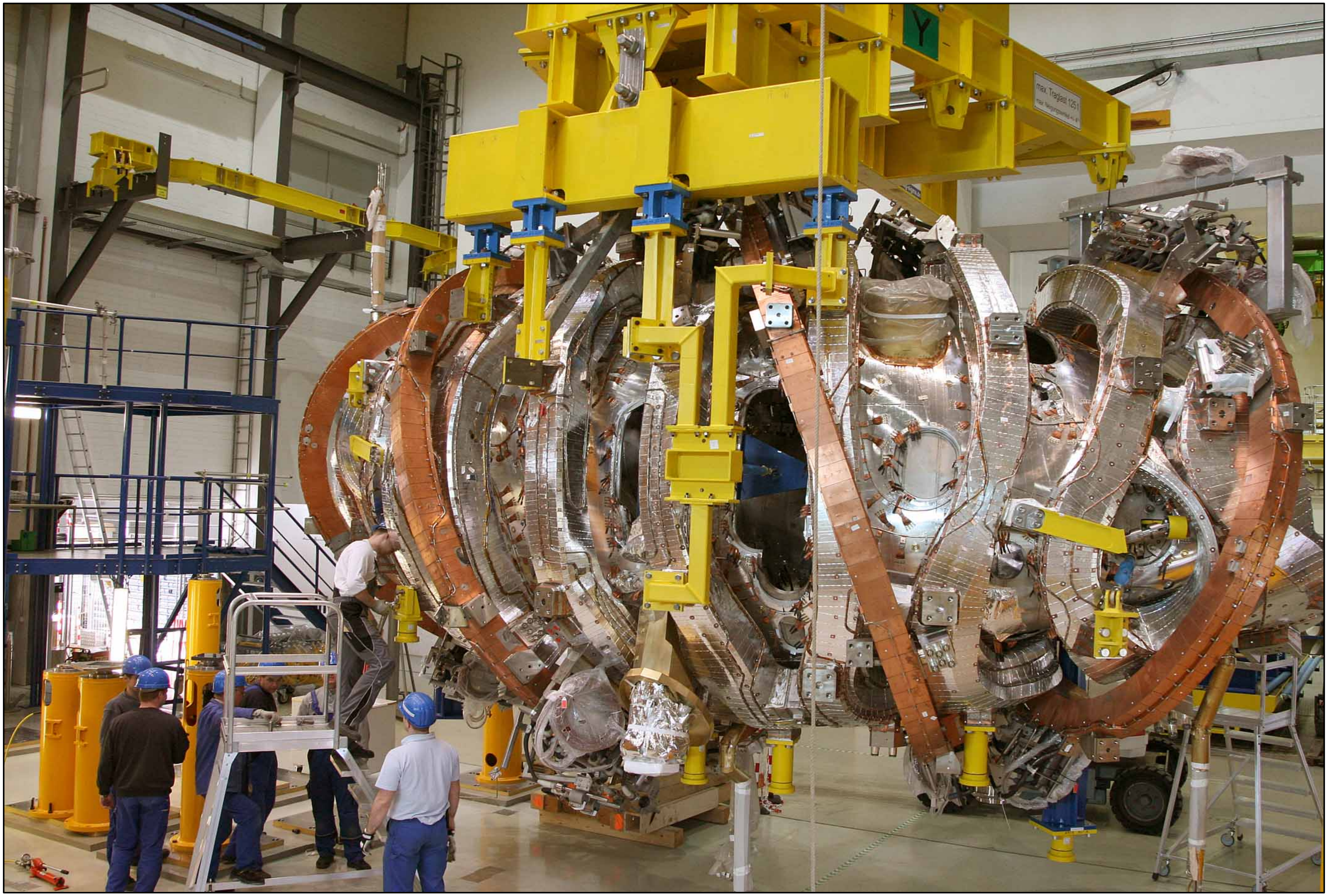

1st magnet module in lower shell of cryostat

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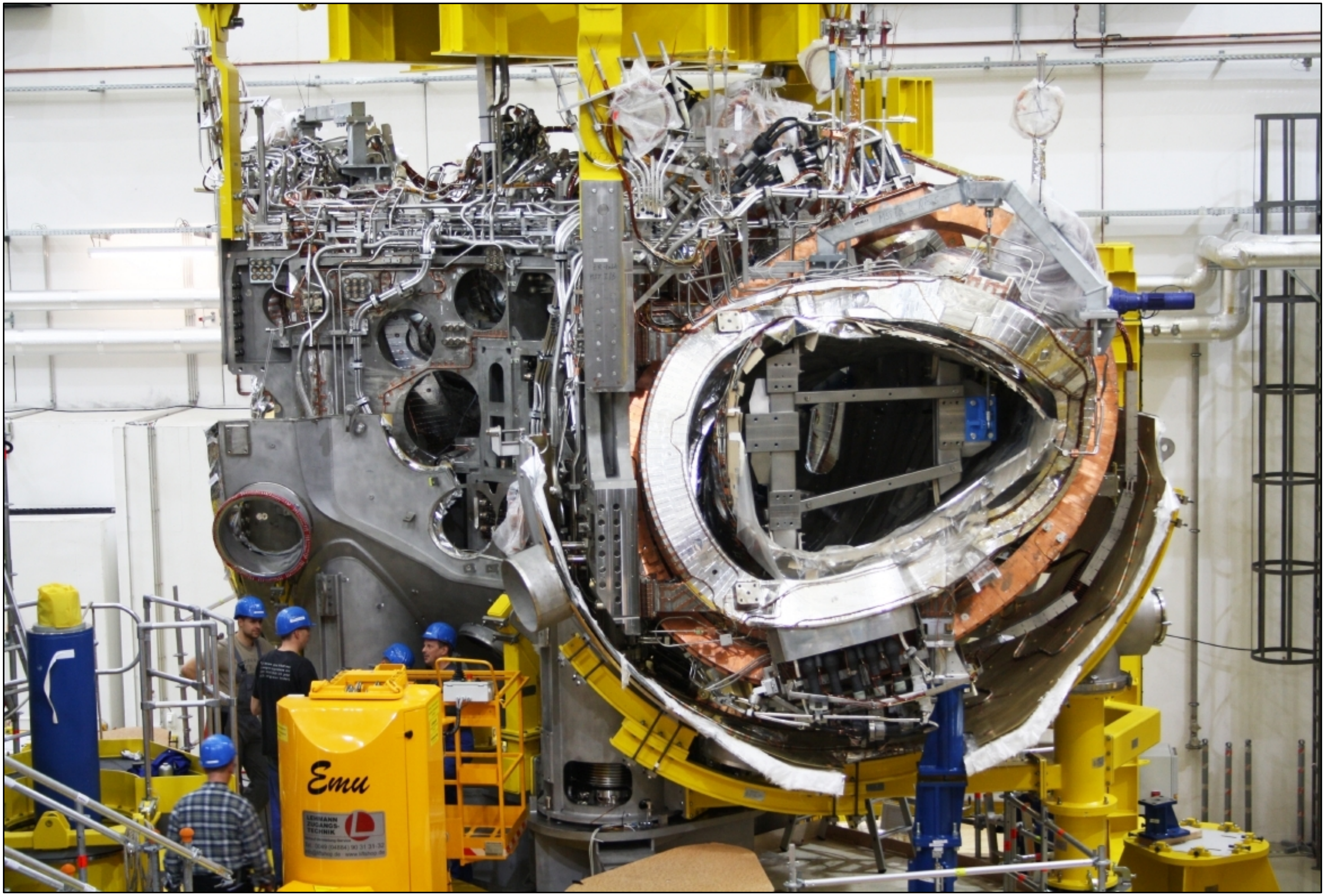

Port assembly in first module, September 2010

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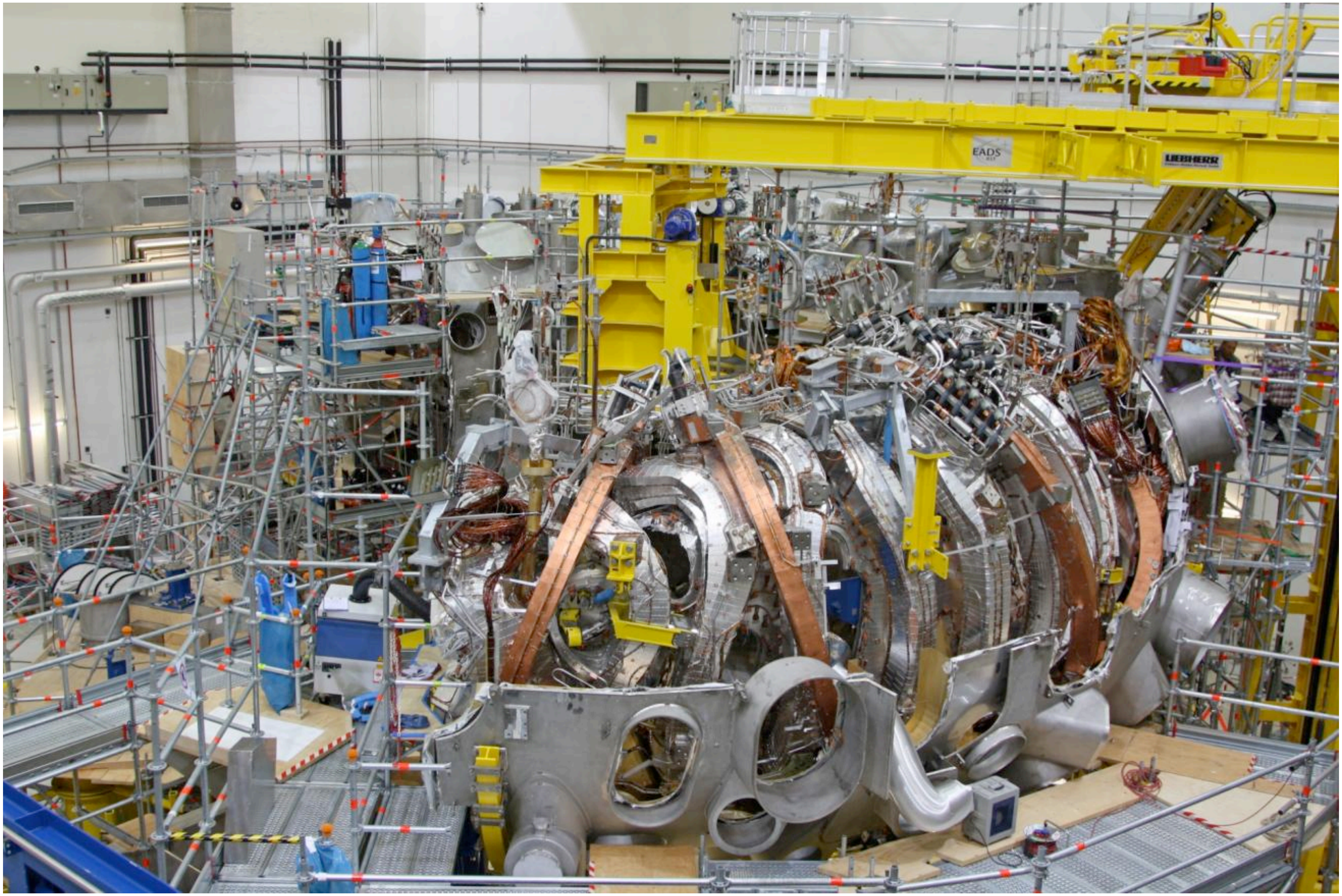
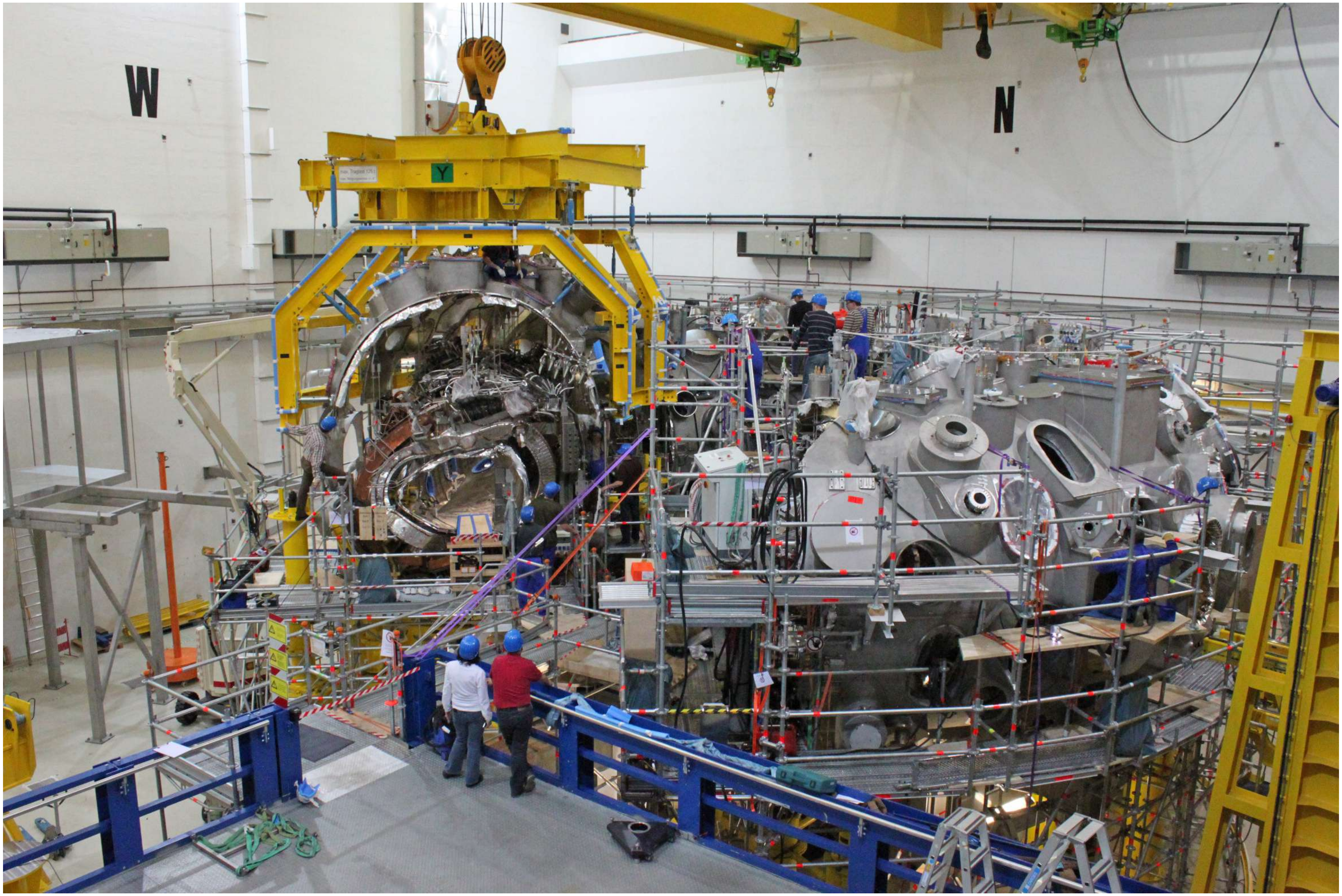


4th module on machine base, April 2011



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Project organisation – lessons learned

Organisation

- clear responsibilities and structures are mandatory
- quick decision making must be secured
- structures are living and should be adapted to the phase of a project

But: often not compatible with the institutional reality

Strong project planning and coordination

- a professional full-time team is required
- this team must have a lead function in the project

But: planning basis is often weak, man power not available

Appropriate infrastructure/tools for the project

- QMS (ISO 9001) which defines/monitors the processes within the project
- (electronic) documentation of documents and CAD-models
- clear boundary conditions should be defined also for the technical level (handbooks, guidelines e.g. for materials, electronic or IT standards)

But: acceptance on the working level (scientists); “additional” effort

Evolution of project structure

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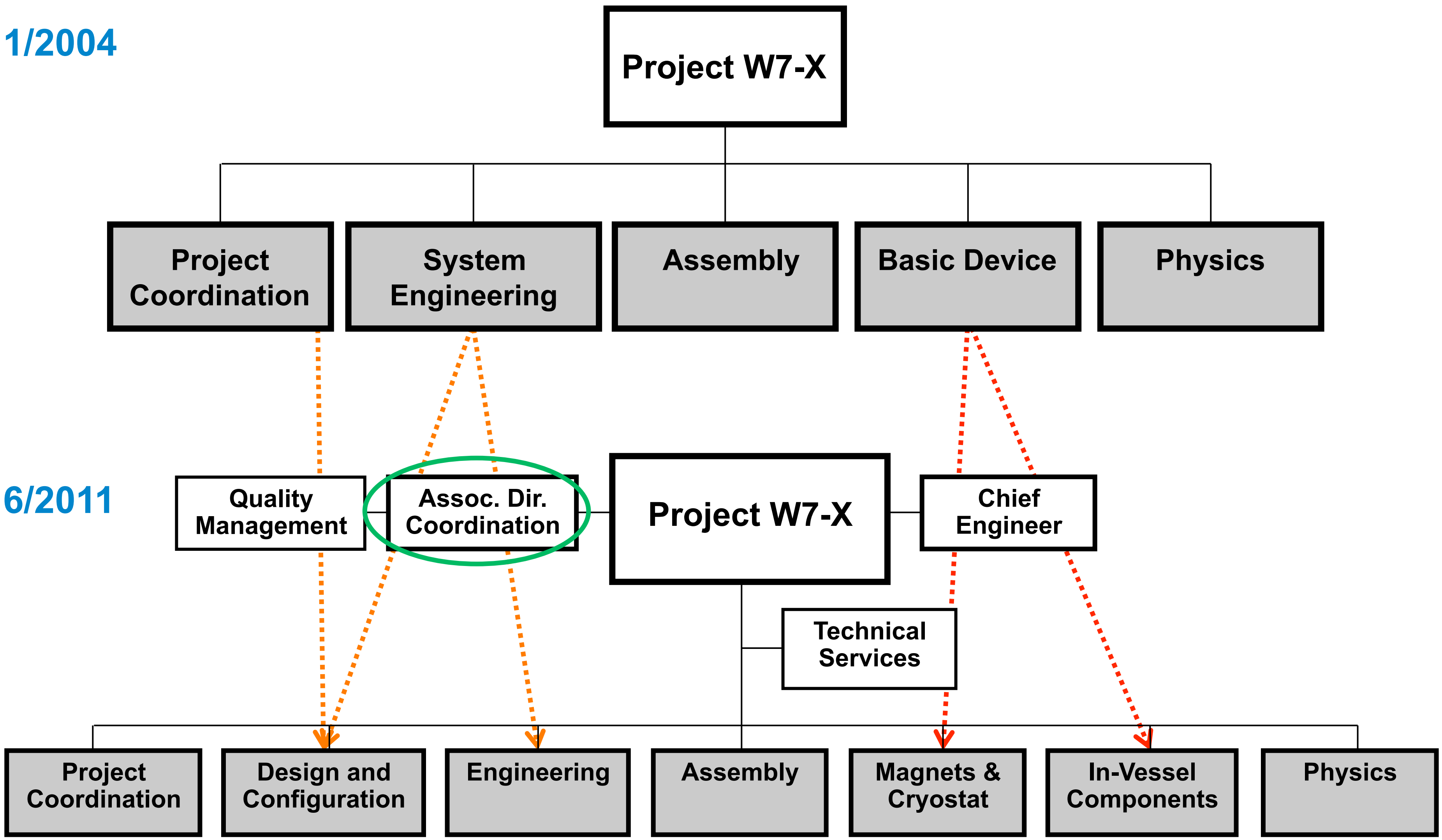

Evolution of project structure

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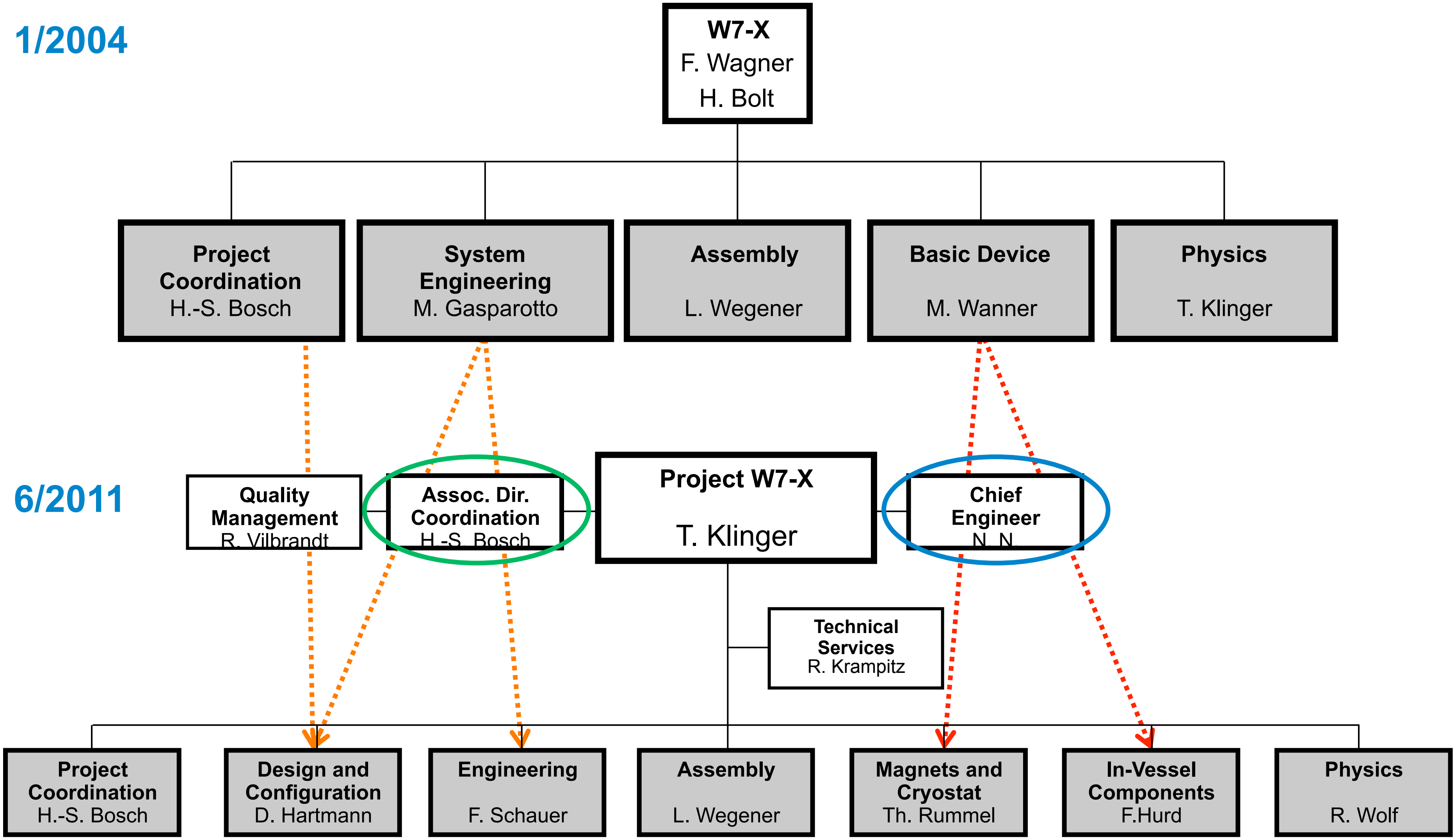


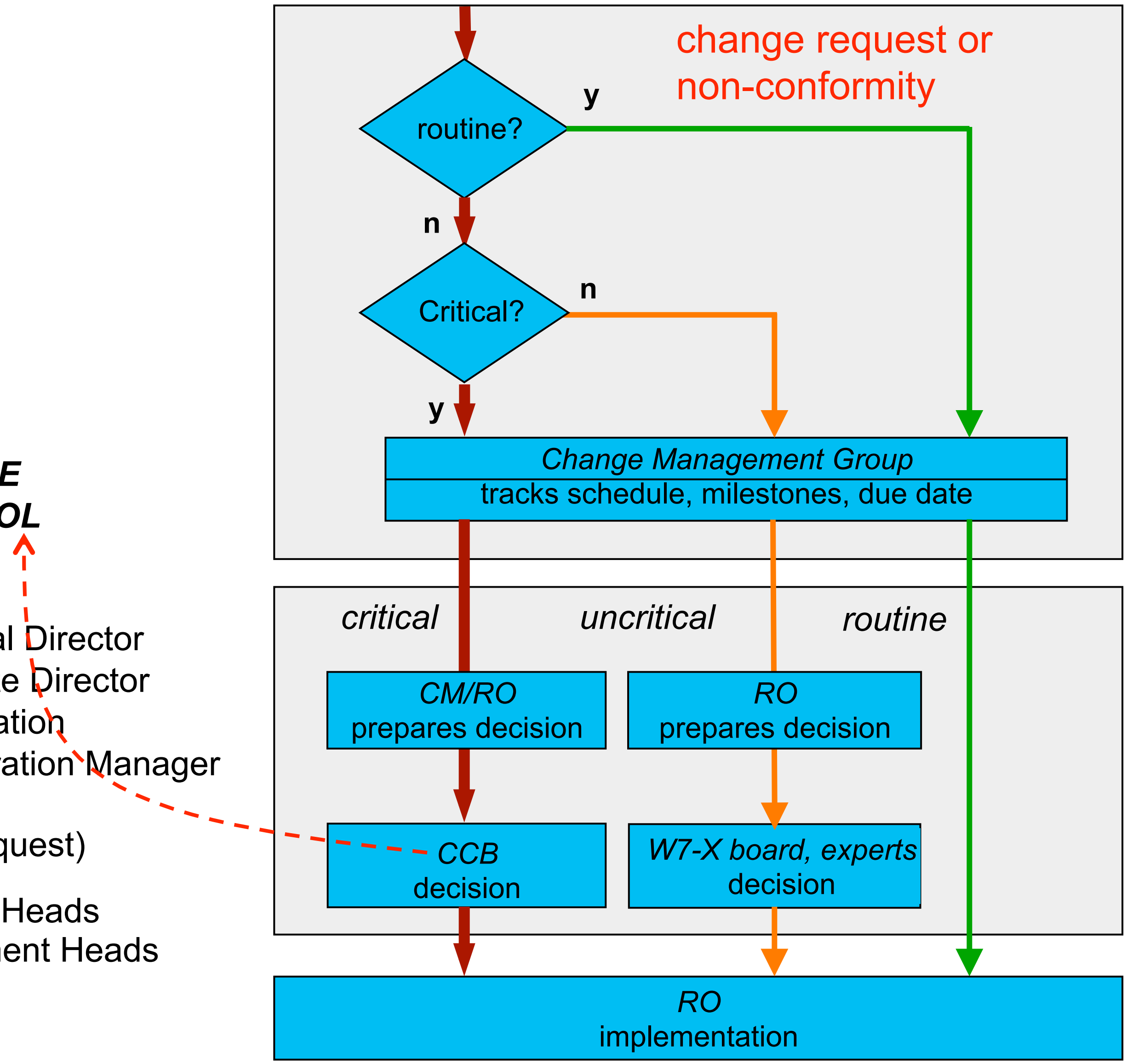
Change Management

CHANGE CONTROL BOARD

Technical Director
Associate Director
Coordination
Configuration Manager

+ (on request)

Division Heads
Department Heads
Experts



ASSESSMENT

Responsible officer (RO)
Configuration Management (CM)

Quality management
Project Control
Documentation

DECISION PROCESS

IMPLEMENTATION

- Introduction
- Organisation of a big project - lessons learned
- **Planning aspects - lessons learned**
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Project plannning – lessons learned

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Realistic planning of time, budget and staff

- typically the estimates are too low ⇒ continuous increases
- cost increases and delays damage the relation to funding agencies and to the public

But: estimates usually are fixed in an early stage: planning not yet detailed enough, little man power

Contingencies are neccessary

- a reasonable contingency avoids permanent revision of the planning
- without contingency, decision-making (work processes) are slowed down

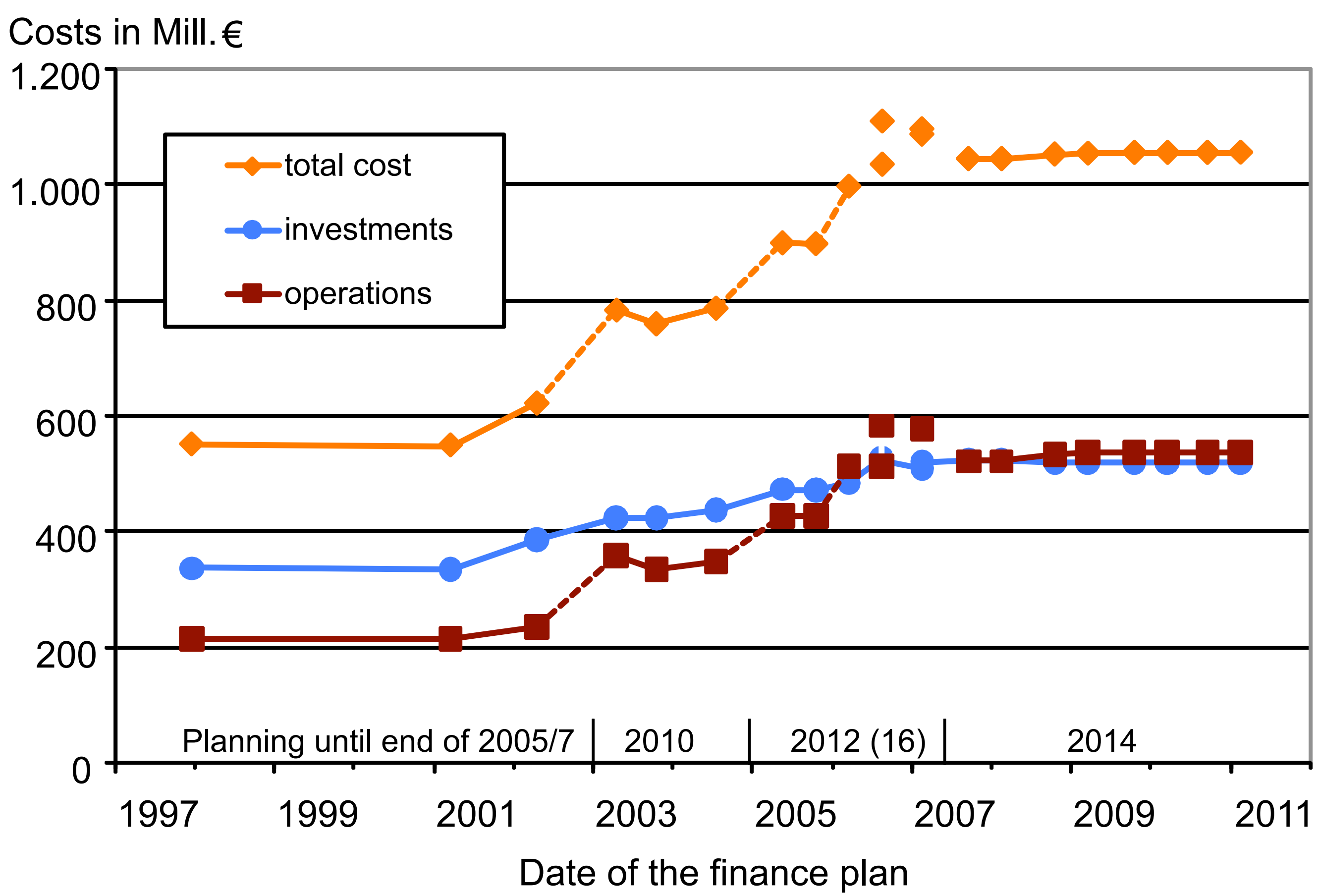
But: in many cases, a contingency is not granted

Appropriate planning and monitoring tools

- standard tools of PM must be available from the beginning (WBS (multi-level), milestone plans, trend analyses)
- detailed planning of work and finances (integrated planning)
- Earned Value Management ⇒ **A. Lorenz, SO4C-4**

But: acceptance on the working level has to be “enforced”

Cost evolution of W7-X



total cost
+ 92 %

operations
+ 150 %

investments
+ 55 %

Project contingency

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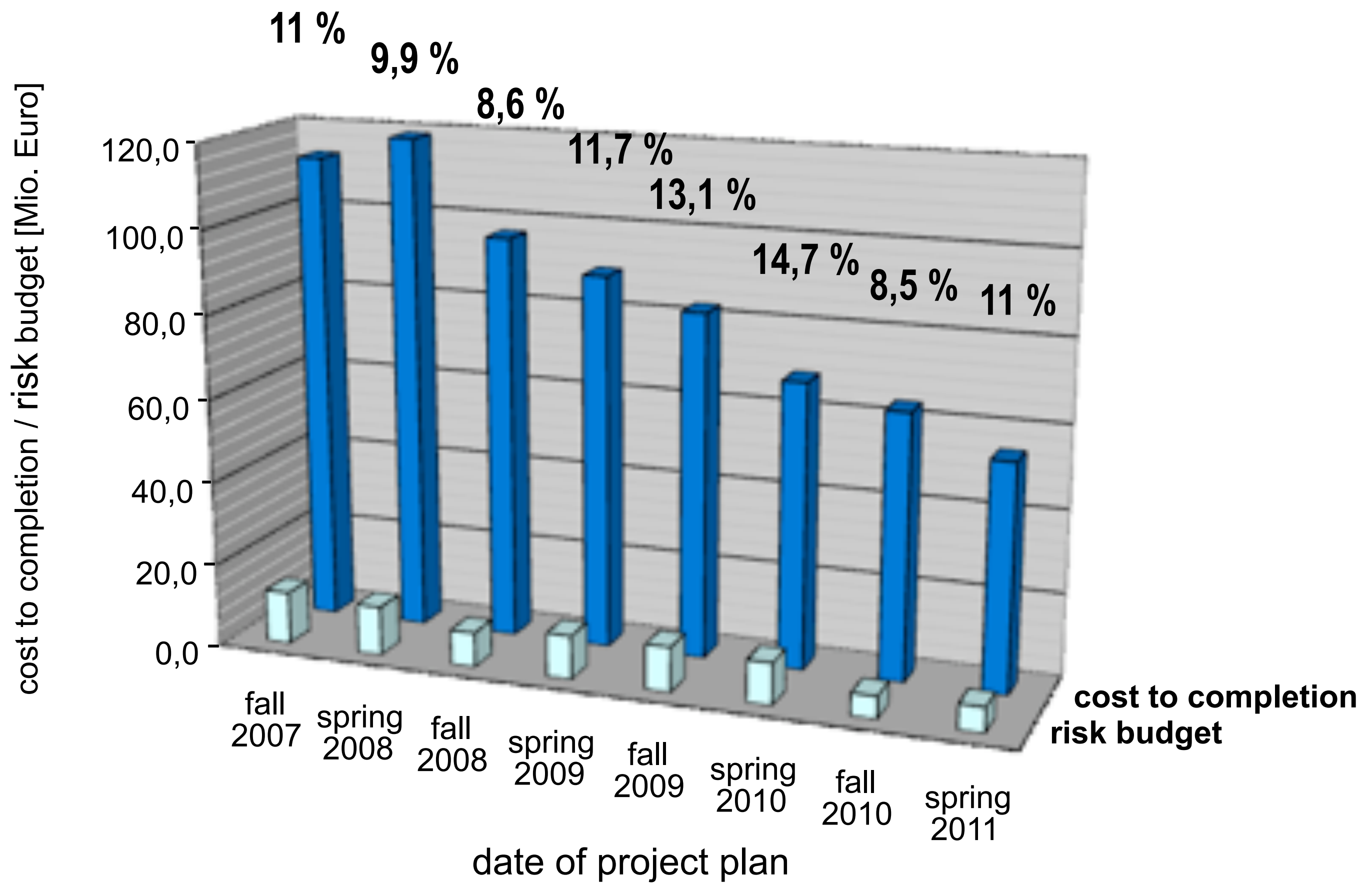

Project Schedule

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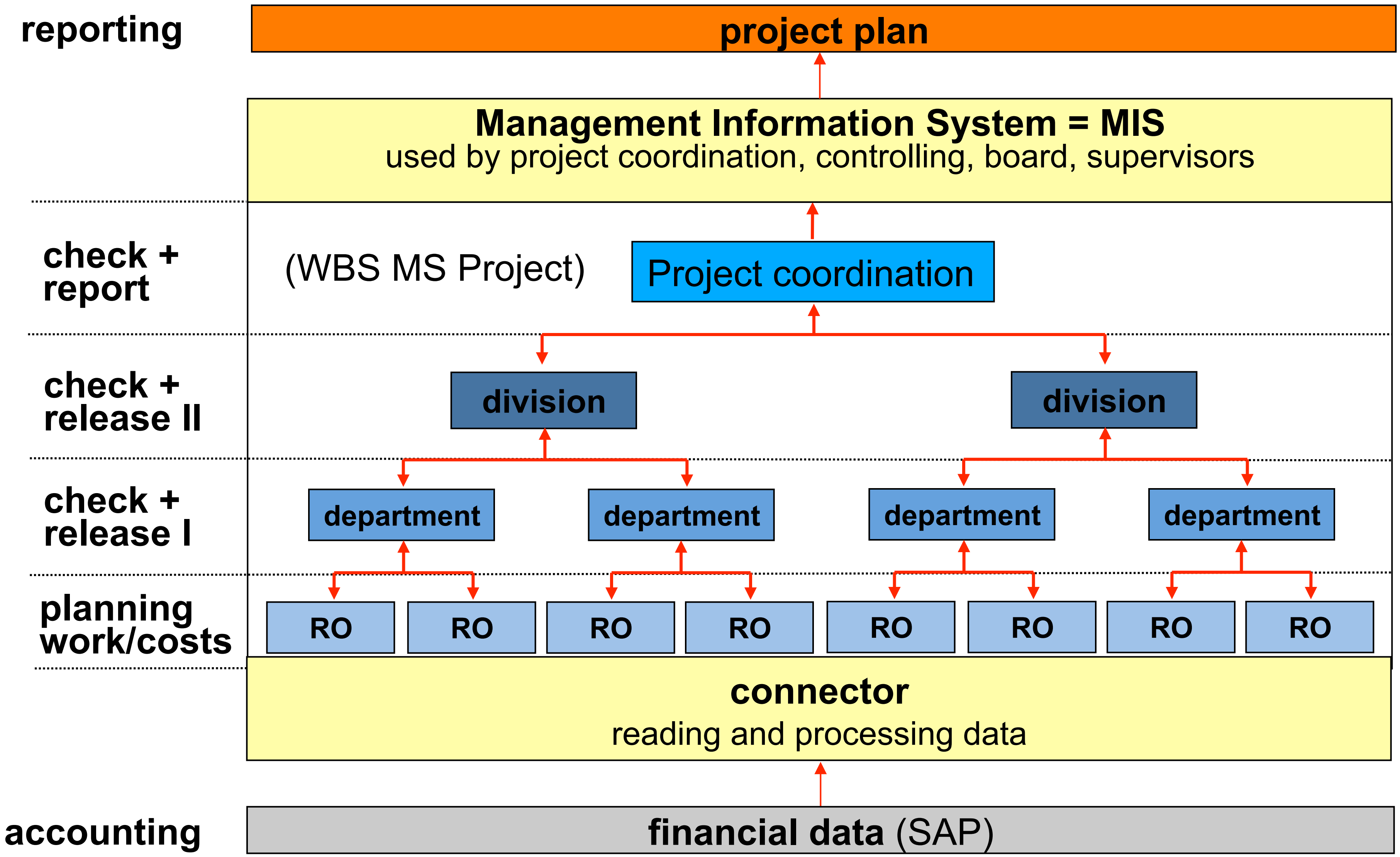
Integrated Planning Tool



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Component fabrication– lessons learned (I)

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Component design

- design has to be completed (and checked) before tendering
- design changes during the manufacturing have to be avoided
- clear specifications have to be provided

But: high time pressure and requirements on the fund flow

Fabrication skills and capacities

- industry should have proven the skills and know-how
- manufacturing capacities have to be secured
- complex consortia can be problematic - clear responsibilities preferred

But: monopoly situation and competition with other fabrication priorities

Component fabrication– lessons learned (II)

Technical risks during development and fabrication

- transfer of risk to industry is extremely expensive
- risks should be minimized by in-house development

But: high work-load in-house ⇔ large, competent team required

Prototypes, tests and quality assurance

- prototypes should be built when possible and affordable
- tests of prototypes and series products is mandatory
- QA also to be performed by the project
- close monitoring of the fabrication by project and by external inspectors

But: see above

Case: superconducting coils

- 50 non-planar coils, 5 types
- 20 planar coils, 2 types
- 243 NbTi strands
- Al cable-in-conduit
- 18.2 kA and 6 kV (non-planar)
- 16 kA and 4 kV (planar)
- 100M€ contract ⇒ consortium

W7-X coils – an European consortium

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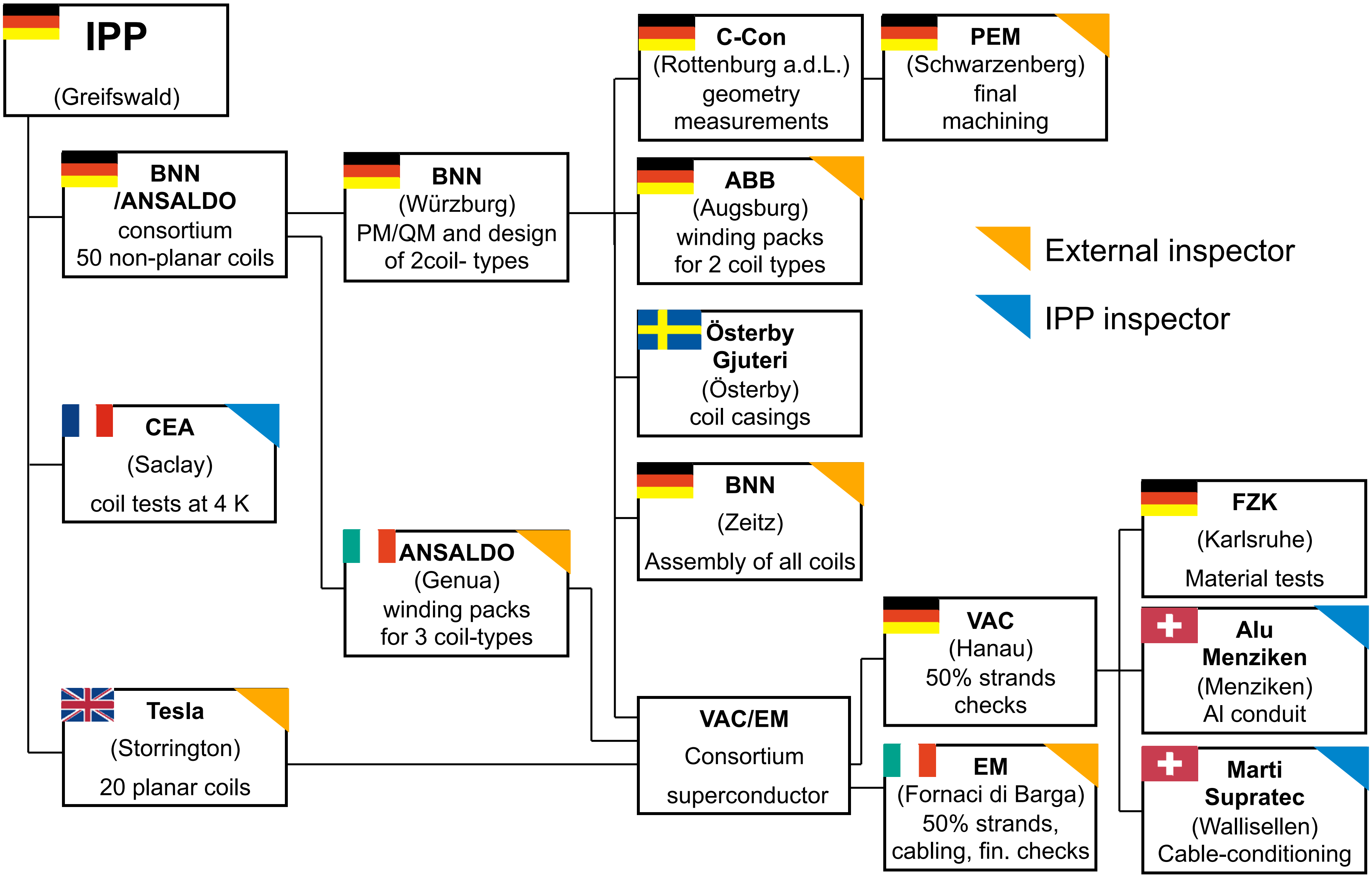

Issues during coil fabrication

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changes

1. **cast steel casing instead of welded coil casing**
2. **reinforcement of coil connection blocks***
3. **reinforcement of planar coil casings***

*** after revised structural calculations done at IPP**

issues

1. **deviations and damages of SC strands**
2. **voids in cast steel coil casings**
3. **geometrical deviations in coil casings**
4. **residuals of Cu-SS soldering flux**
5. **Al and SS welds to be requalified**
6. **quench detection cable damage**
7. **insulation faults in the coil header**
8. **danger of shorts in the coil header**

Coil insulation faults

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insulation tests

- 13 kV in vacuum, RT and 4K
- also under Paschen-conditions
- current monitoring
- camera observation of coil header

complex & risky repair action

- 20 non-planar coils with systematic faults
- deep excavation of header area
- cracks and voids ← charged resin
- repeated Paschen tests
- repeated full cold test

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Management of surprises

- the project must be prepared for surprises
- risk identification and prevention required (mock-ups)
- in case of problems, clear procedures have to be available (CCB)

But: work load and (limited) experience of the staff; complex priorities

Tolerances

- maximum possible tolerance allowables should be foreseen
- fabrication and operation at the limits is costly and time-consuming

But: physics requirements are usually high

Margins

- margins and clearances should be as high as possible
- CAD tools and processes have to be installed (early) to handle geometry problems and space reservations ⇒ **C. Baylard, SO4C-5**

But: additional space is expensive; research facilities are complex and often at the technical limits

Electric and hydraulic connection of the magnets

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- 300 steel pipes and 24 superconducting bus-bars per module
- more than 500 welds and 24 superconducting joints per module
- three-dimensional stellarator geometry

Magnet module from inner side

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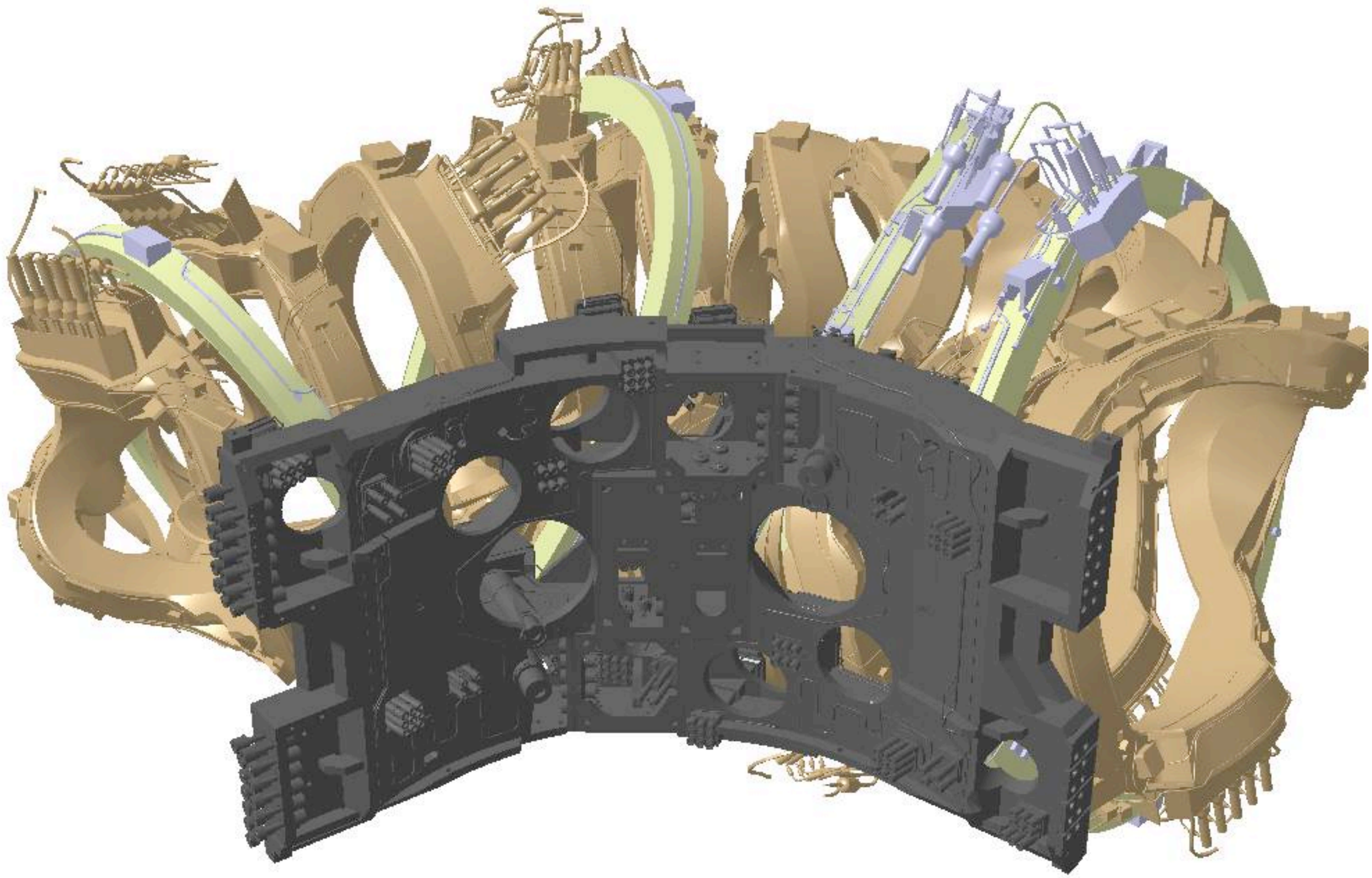
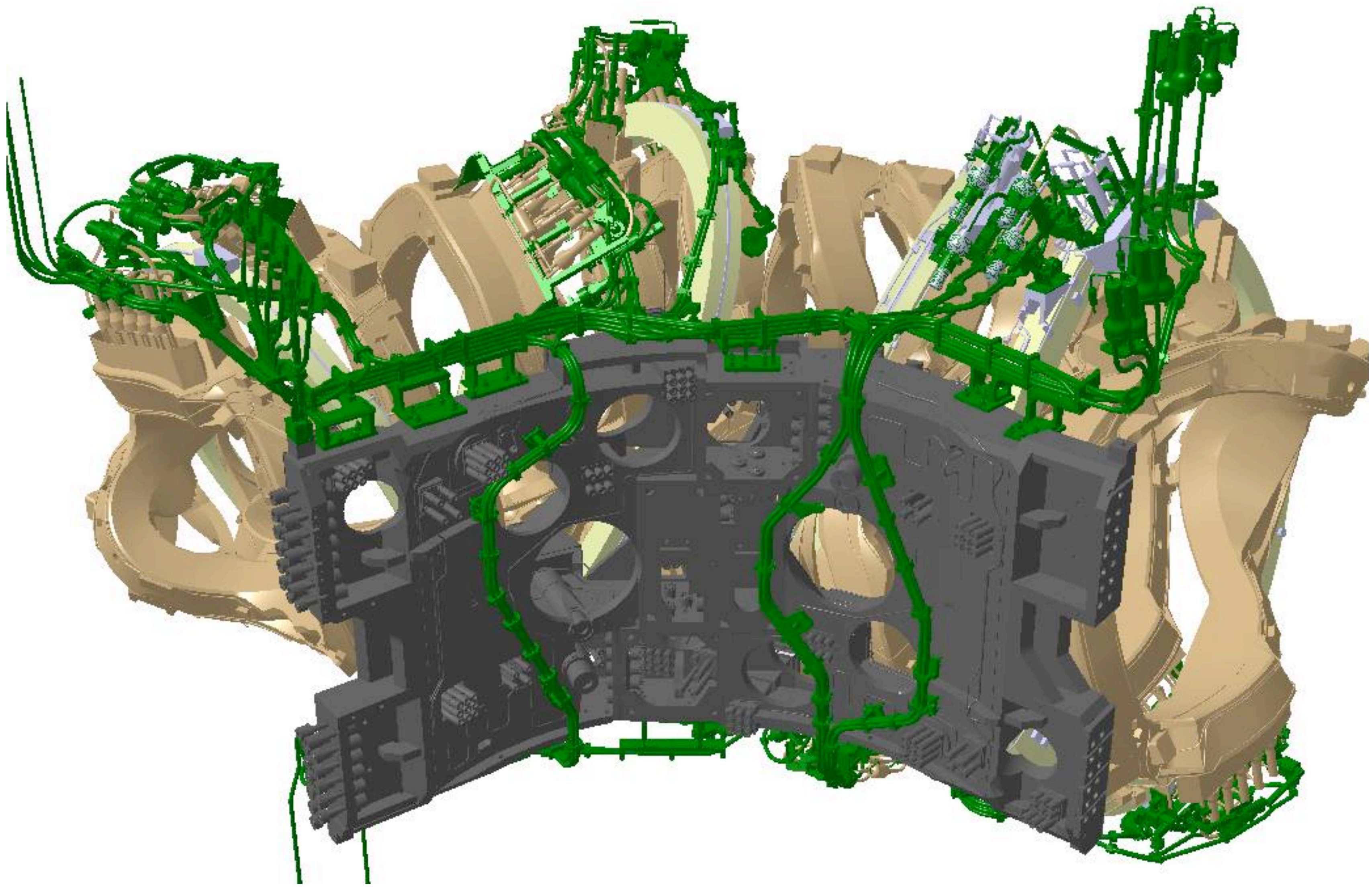


Magnet module with bus-bars



Magnet module, bus-bars and cryo-piping

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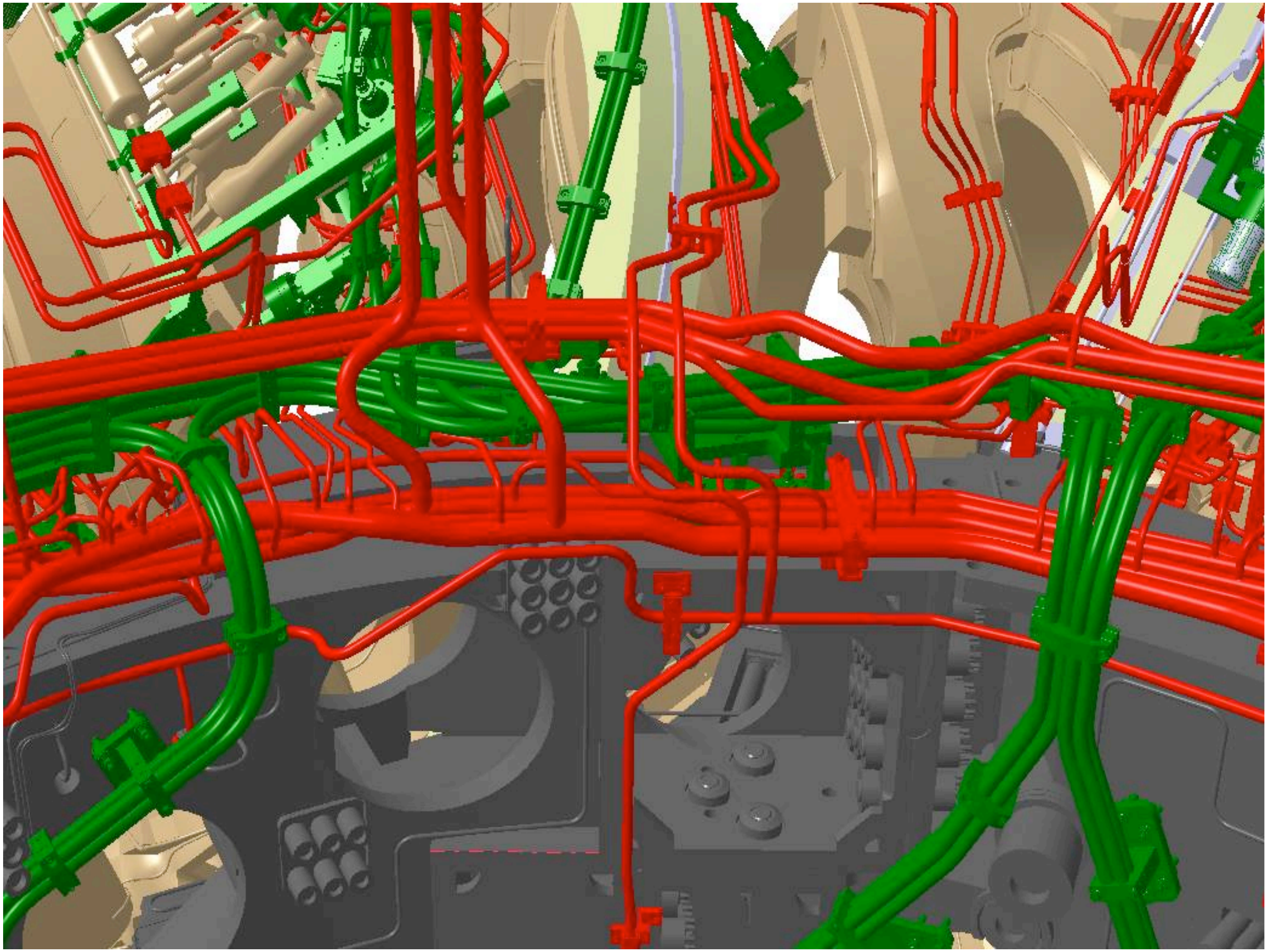

Reality

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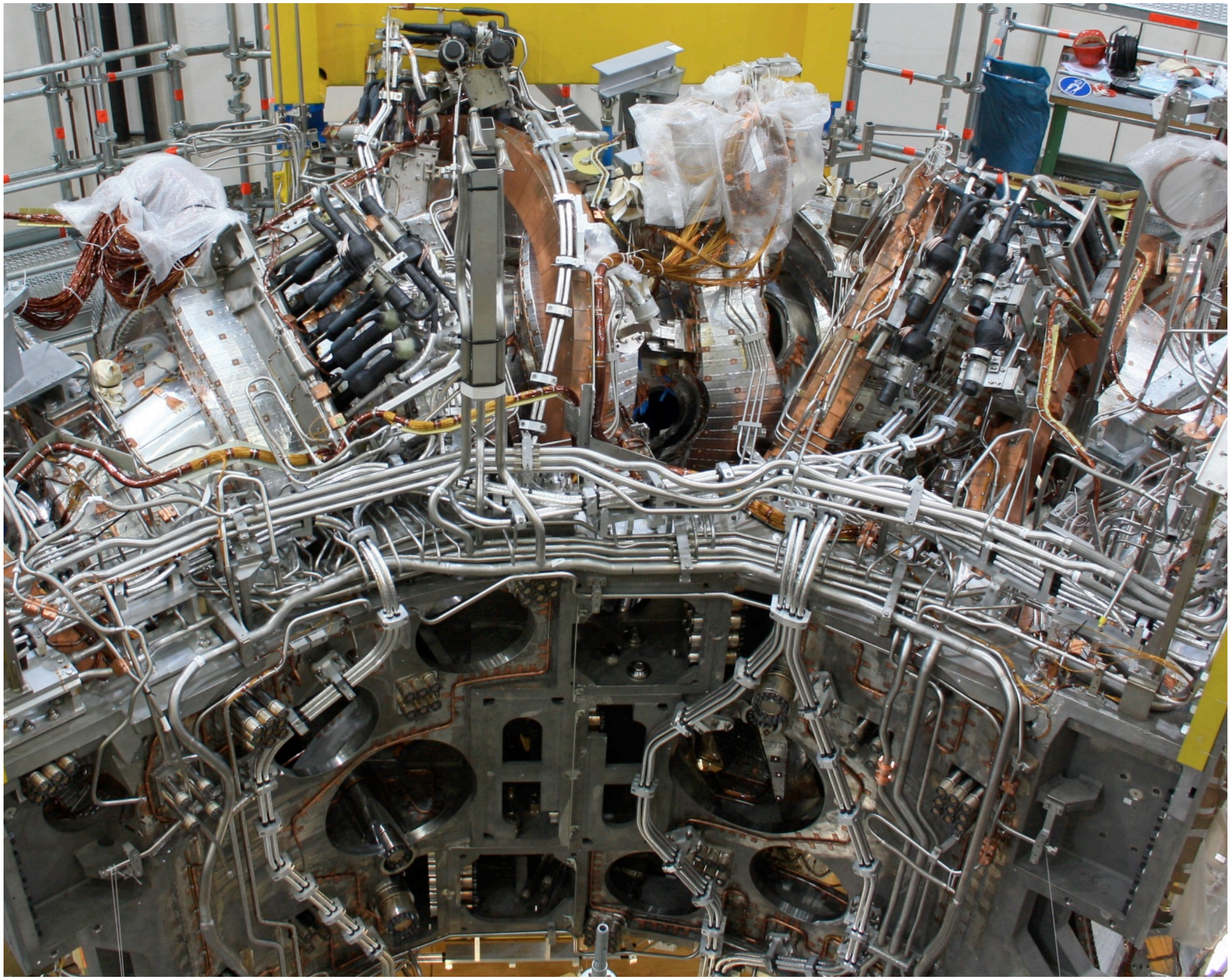

Electric and hydraulic connection of the magnets

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- 300 steel pipes and 24 superconducting bus-bars per module
- more than 500 welds and 24 superconducting joints per module
- three-dimensional stellarator geometry
- motion of magnets for different magnetic configurations up to +/- 15mm
- complex system of clamps and holders, stiff and flexible at the same time
- demanding design & manufacturing, intense metrology, complex change management
- extremely limited available space in the cryostat ⇐ Design decision!

Conclusions

All projects have their individual history and development.

However, the main issues that have led to serious trouble in our project hold for any state-of-the-art fusion and non-fusion projects.

1. A competent project team must be available from the start. Where the know-how is not available, strong external institutional partners must be found and deeply integrated into the project.

2. A lack of reasonable margins, clearances and tolerance levels implies an uncontrolled increase of complexity and frequent changes. This has a strong impact on time, costs and man-power.

3. Major components must be thoroughly tested (prototypes) and qualified prior to tender action. The manufacturing process must be accompanied by an intense QA program. Quality management must be involved in each single step. Trained inspectors must follow up manufacturing in detail.

Conclusions, continued

4. Clear project structures and responsibilities are mandatory. High-level management tools must be implemented and accepted on the working level. Formal procedures and written documents are unavoidable, but must be organized as pragmatic as possible.

5. Development and manufacturing risks should be taken to a large extent by the project. Industry cannot do that or will charge the project to cover unexpected costs, even beyond the contract. The only solution is to solve problems step-by-step with industry.

6. The construction of first-of-a-kind devices requires specialized in-house knowledge and specialized industrial suppliers. Often, a monopoly situation cannot be avoided and must be taken into account in design, planning and management.