Lessons learned
in the construction of Wendelstein 7-X

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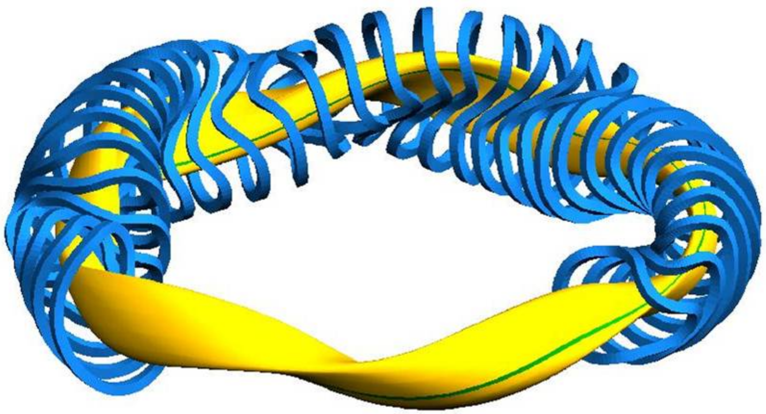
Outline of the talk

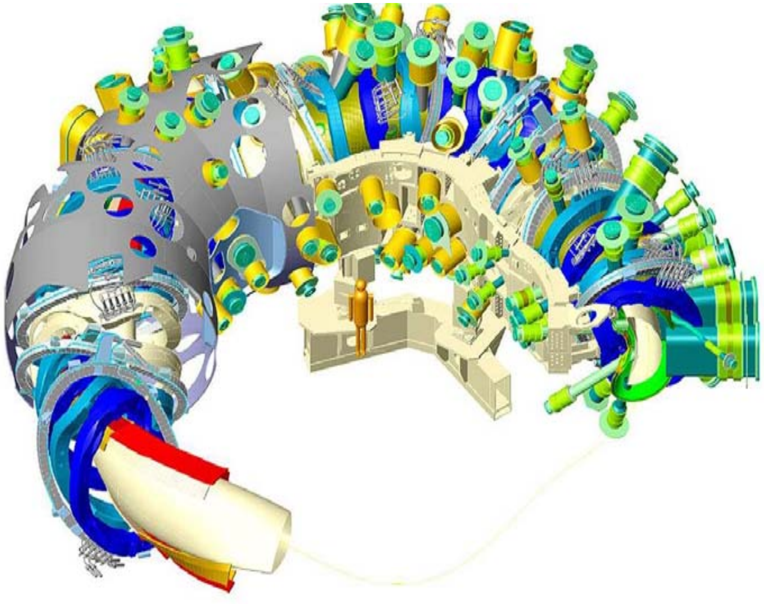
- Introduction
- Organisation of a big project - lessons learned
- Planning aspects - lessons learned
- Fabrication of components - leasons learned
- Integration - lessons learned
- Conclusions

W7-X, from theory to reality



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



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	
	third restructuring of the project	
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

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Project organisation – lessons learned

Organisation

- Clear responsibilities and structures are mandatory
- Structures are living and should be adapted to the phase of a project
- quick decision making must be secured
- Processes have to be reviewed and adapted regularly

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 definedalso 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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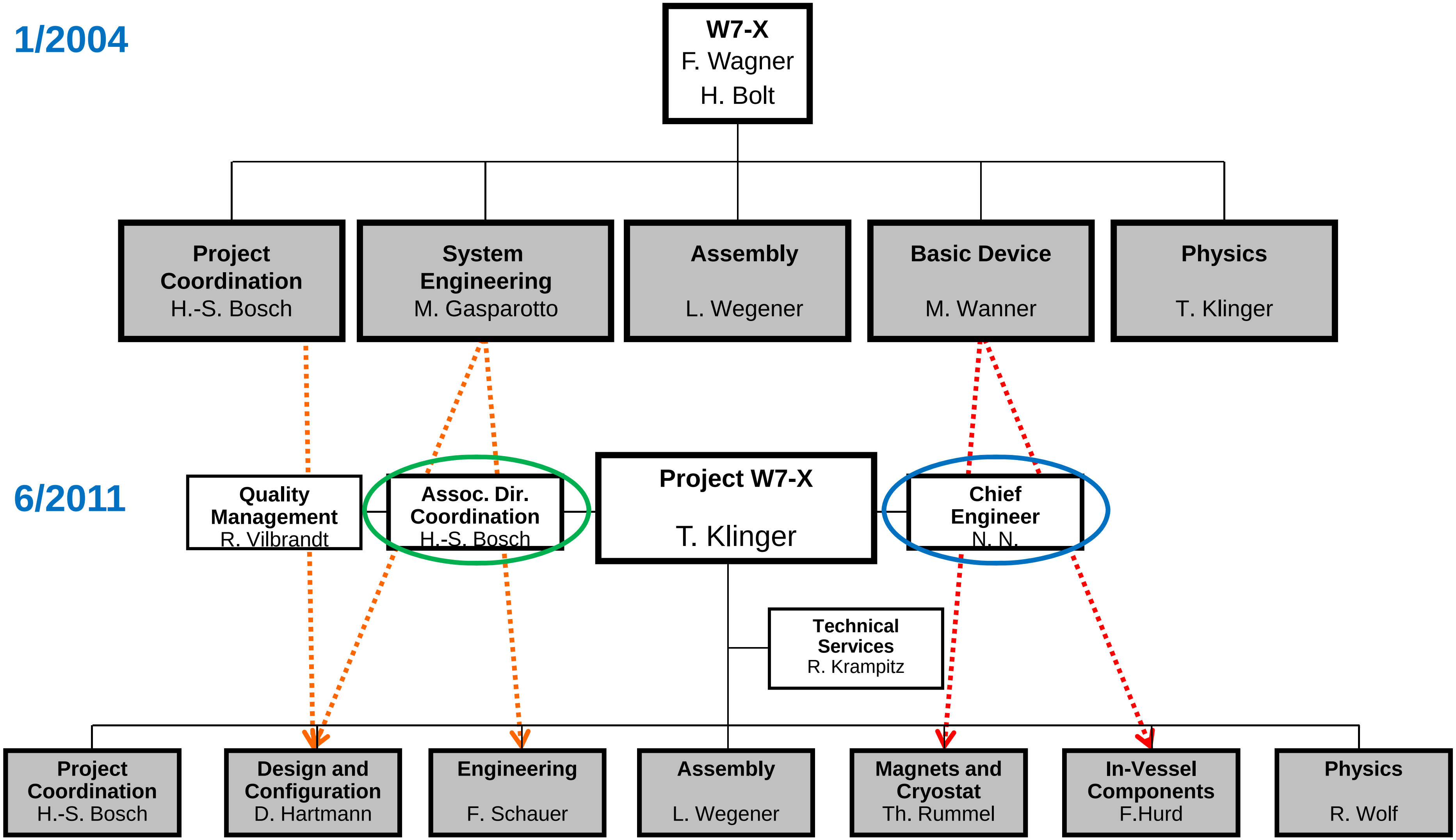

Change Management

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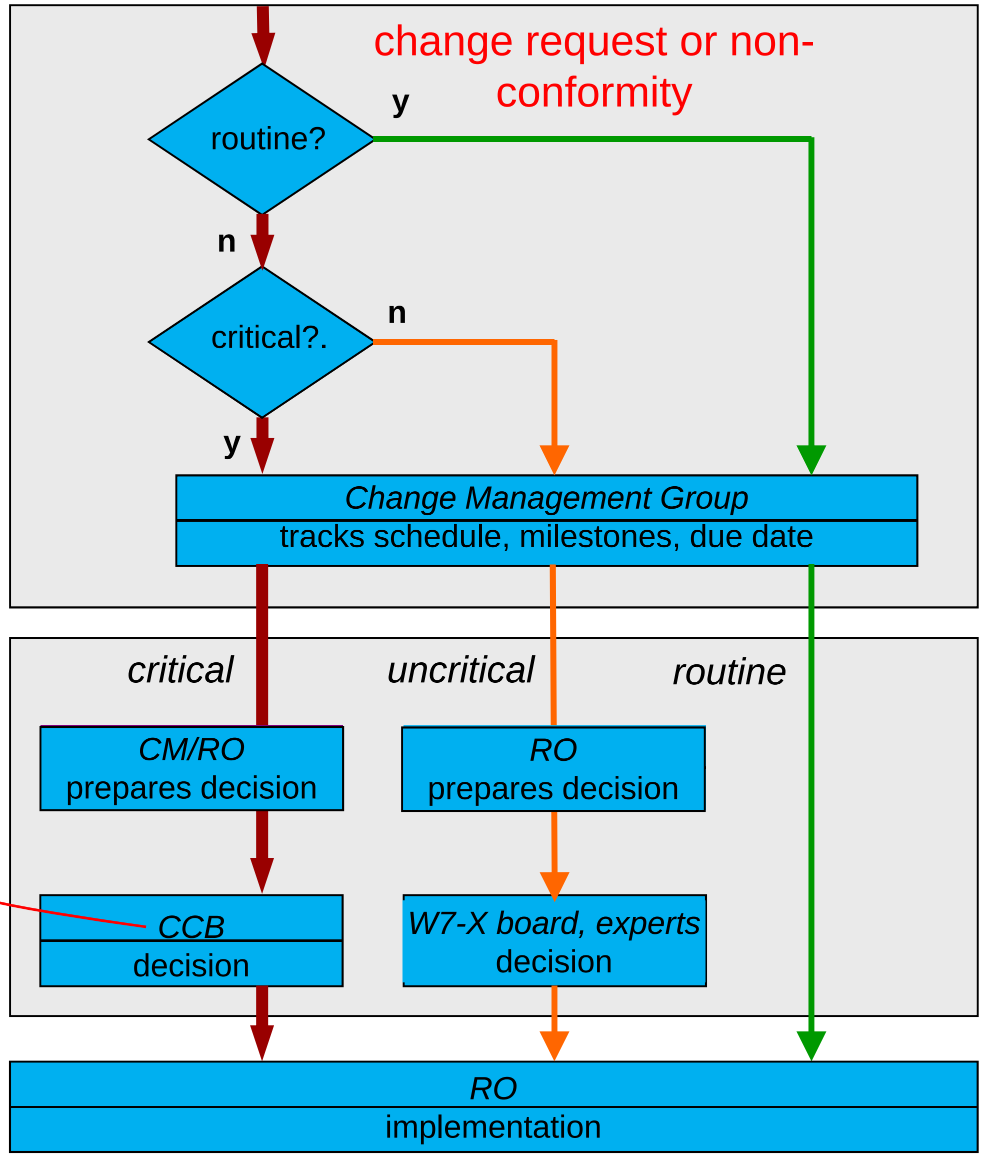

ASSESSMENT

Responsible officer (RO)
Configuration Management (CM)

Quality management
Project Control
Documentation

CHANGE CONTROL BOARD

Technical Director
Associate Director
Coordination
Configuration Manager

+ (on request)

Division Heads
Department Heads
Experts

DECISION PROCESS

IMPLEMENTATION

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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 (PMP, WBS (multi-level), Milestones with trend analyses)
- detailed planning of work and finances (integrated planning)
- Earned Value Management

But: acceptance on the working level has to be enforced

Cost evolution of W7-X

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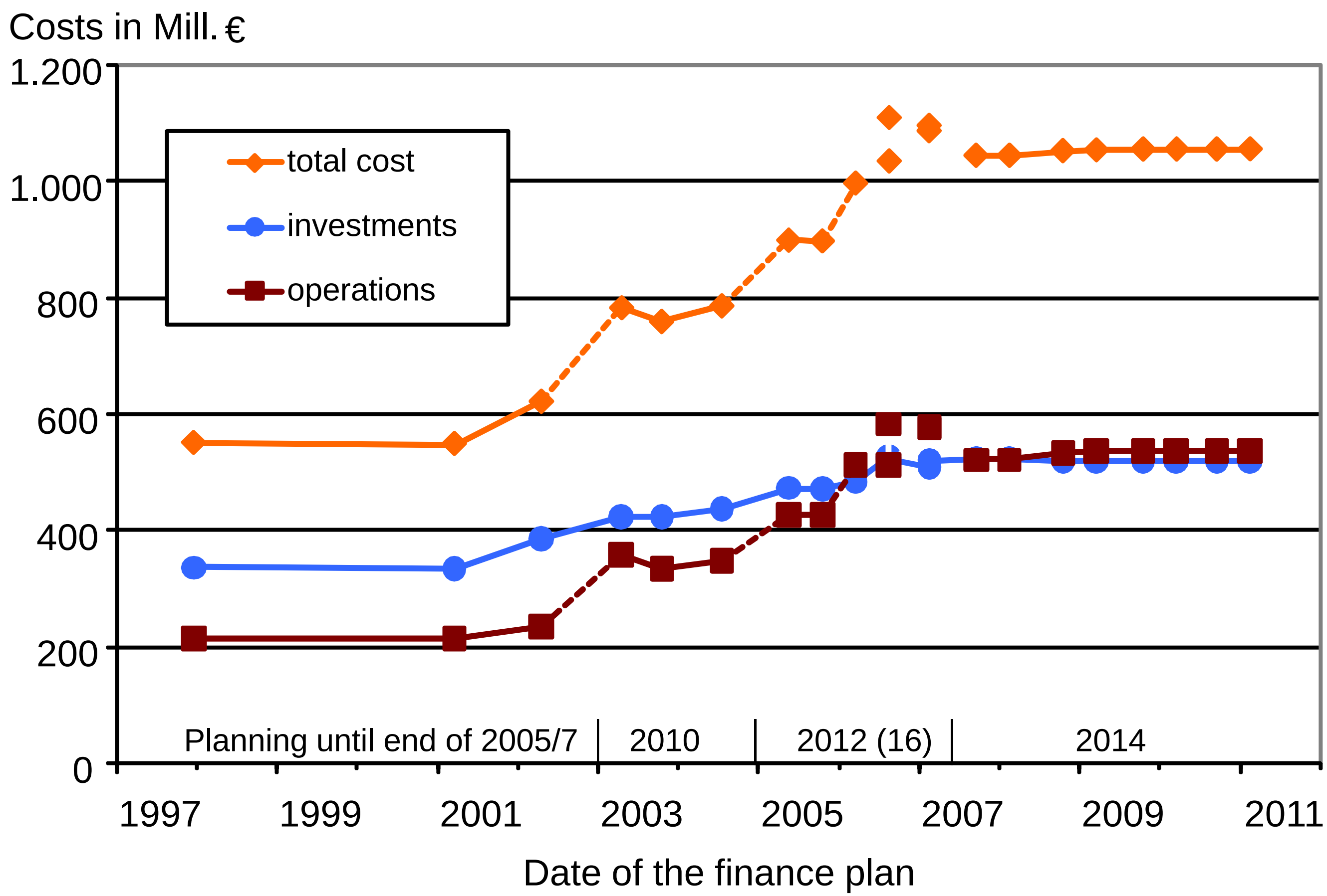
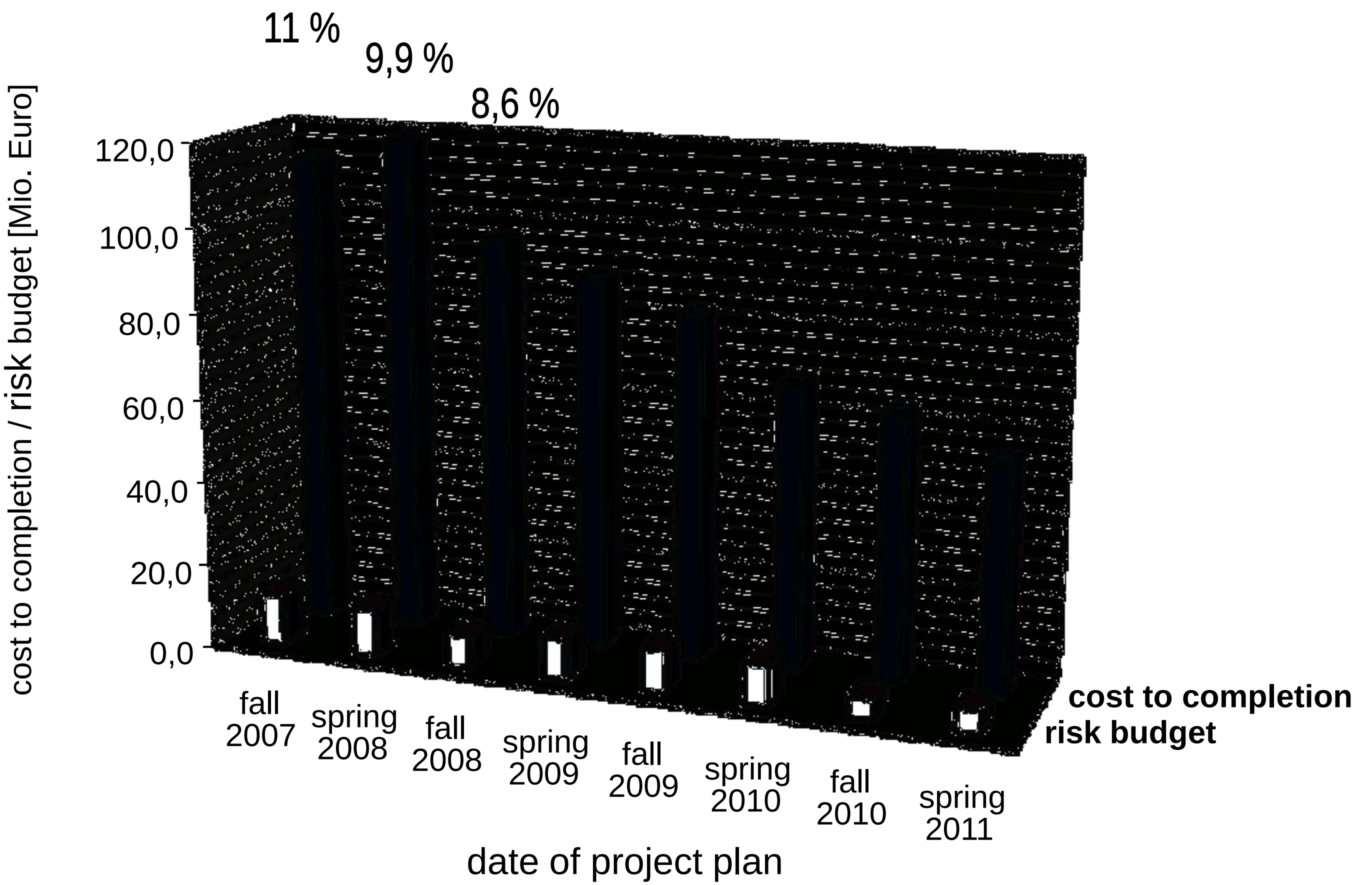


total cost
+ 92 %

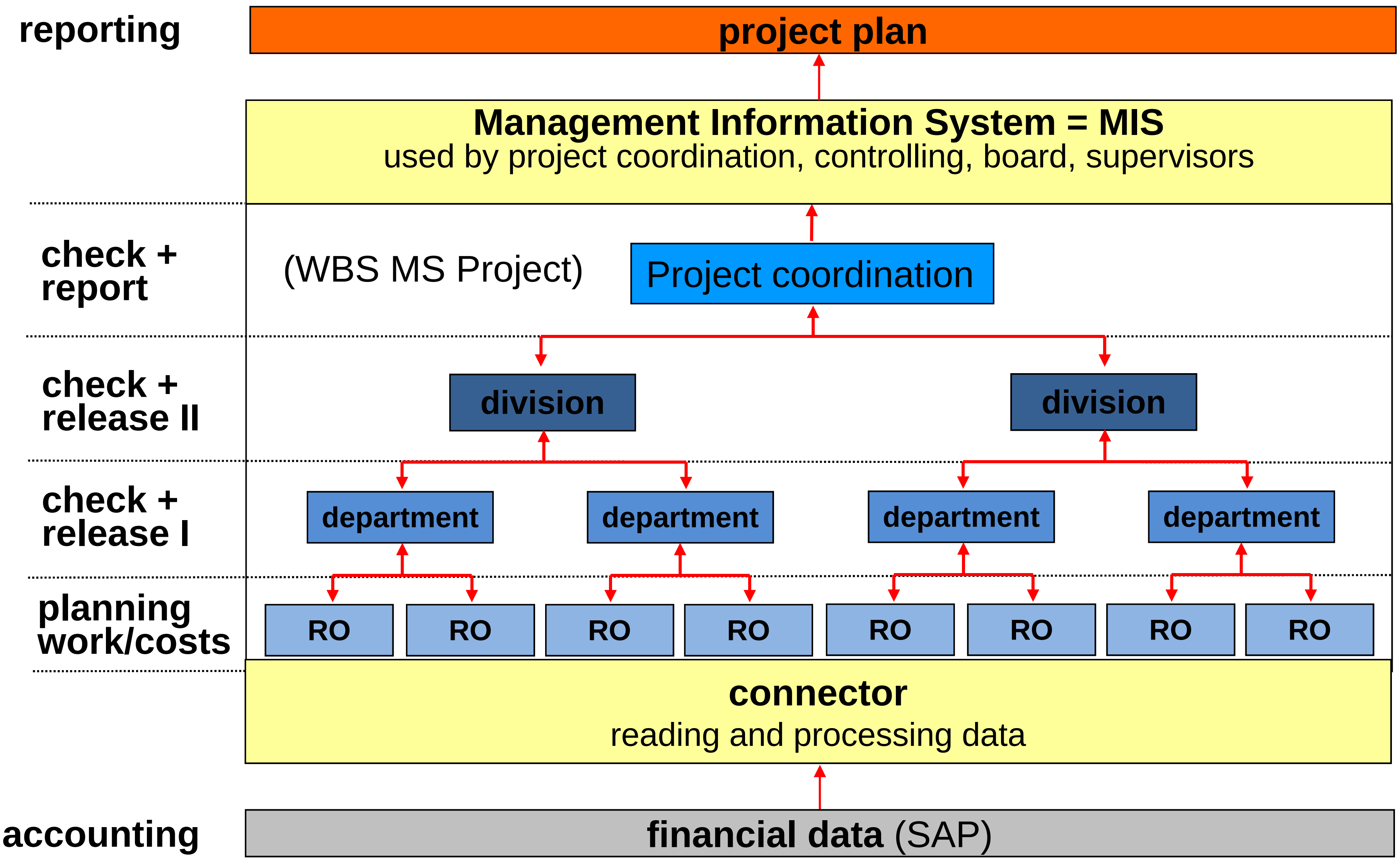
operations
+ 150 %

investments
+ 55 %

Project contingency



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)

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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 to be performed by the project team and by external inspectors

But: see above

W7-X coils – an European consortium

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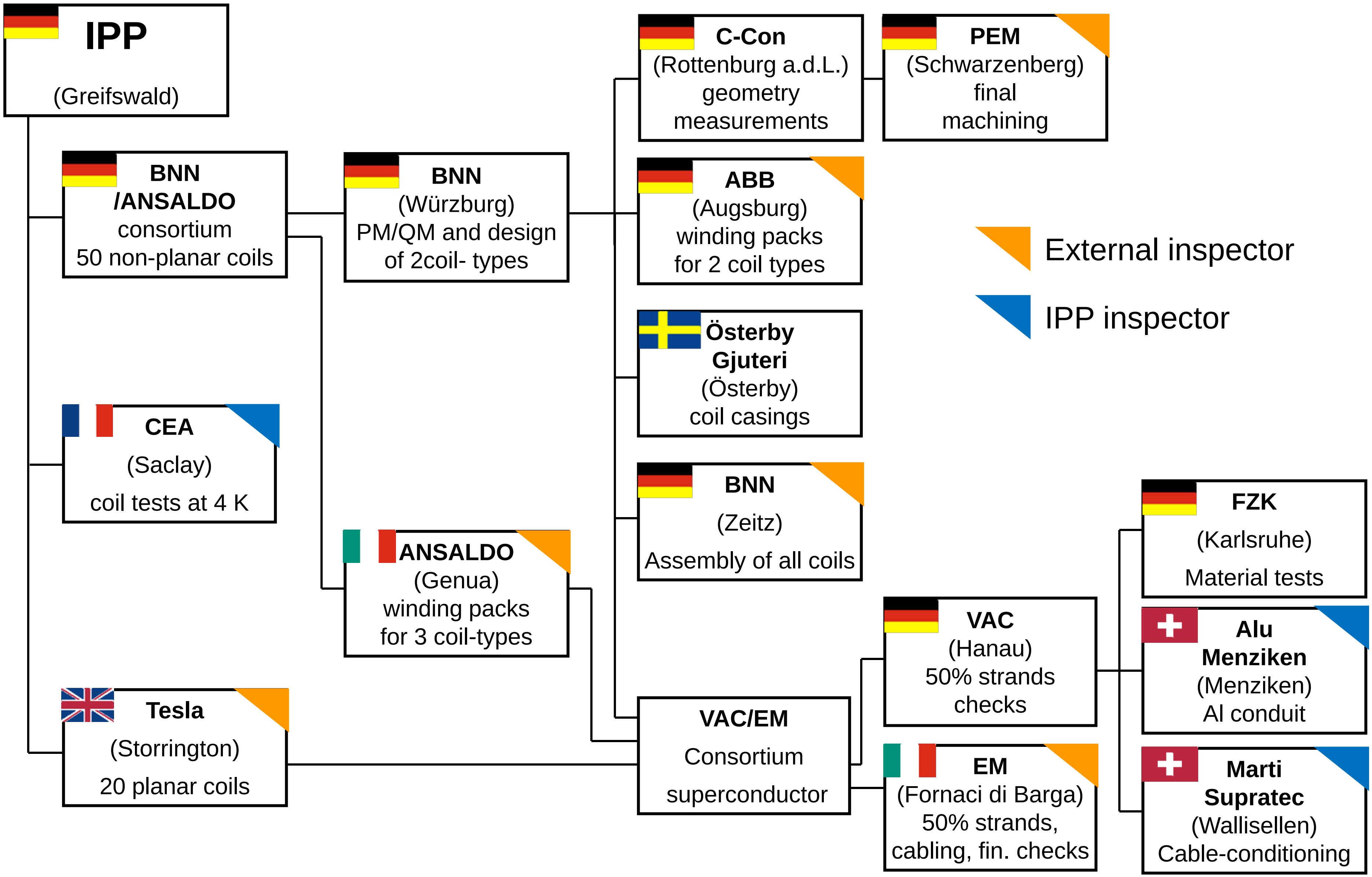

Issues during coil fabrication

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 raisin
- repeated Paschen tests
- repeated full cold test

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Integration– lessons learned

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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 allowable 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
- Fabrication and operation at technical limits is costly and time-consuming

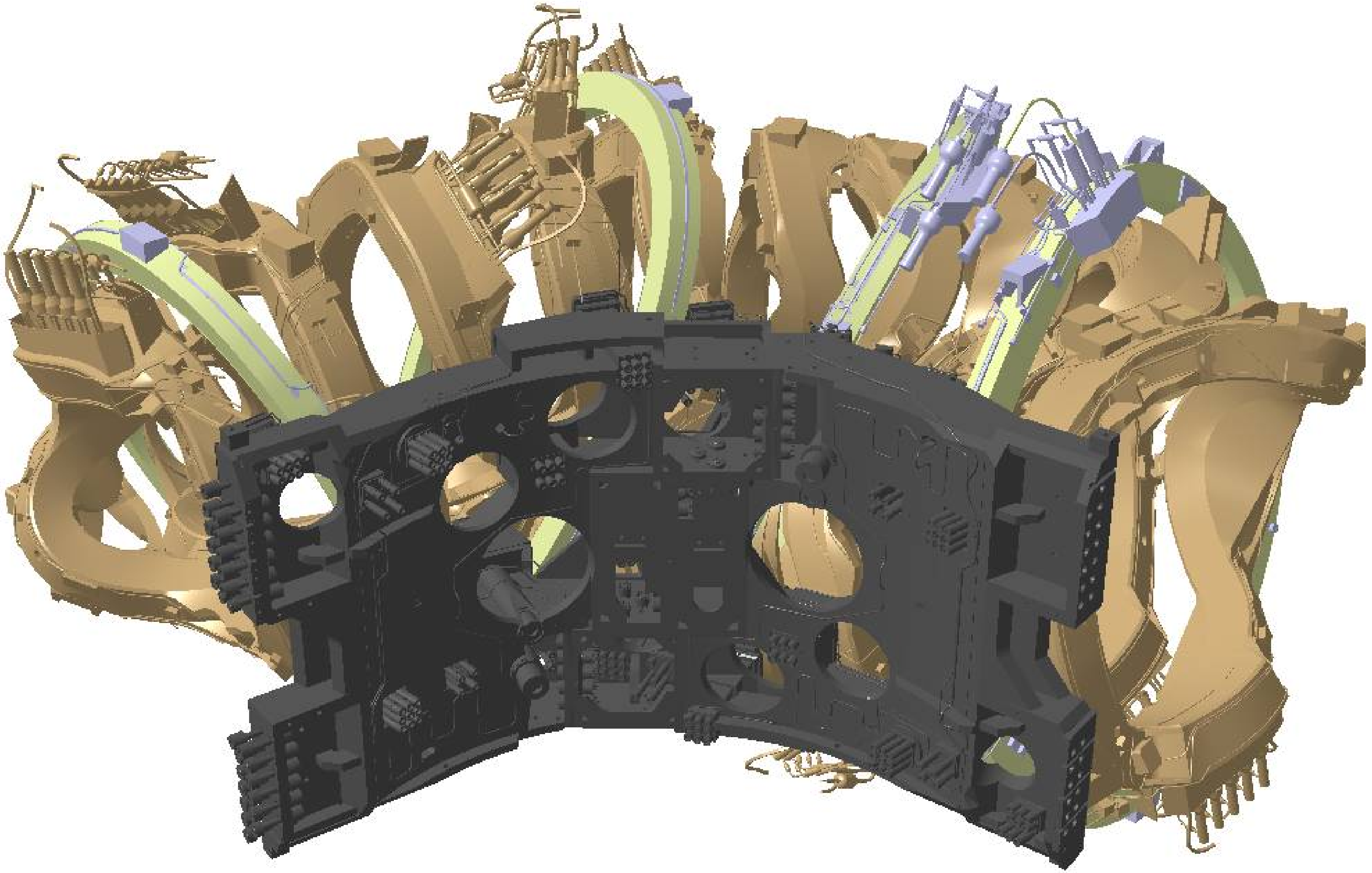
But: Additional space is expensive; research facilities are complex and often at the technical limits

Electric and hydraulic connection of the magnets

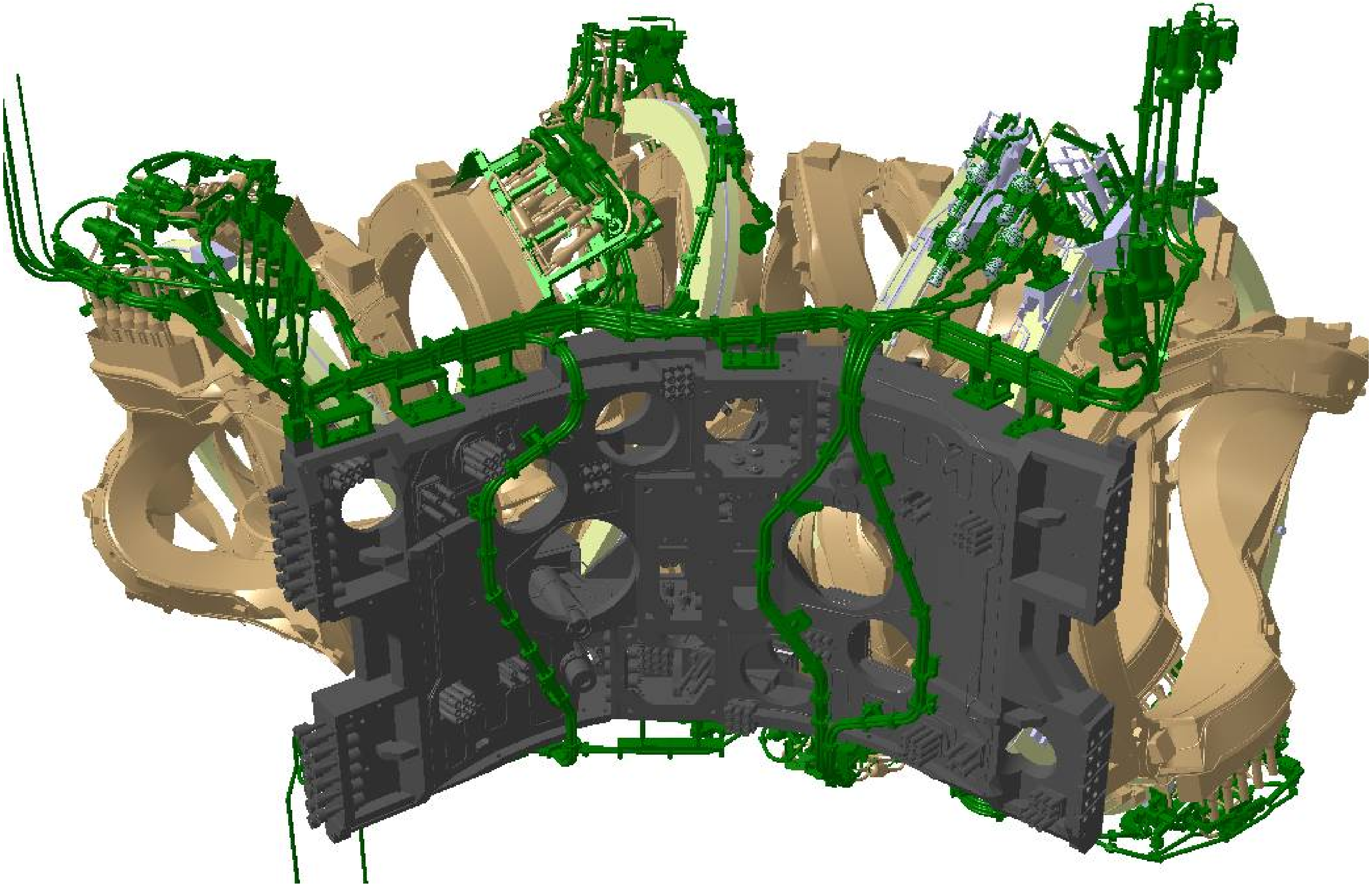
Forschungszentrum Jülich

Institute of Nuclear Physics Krakow

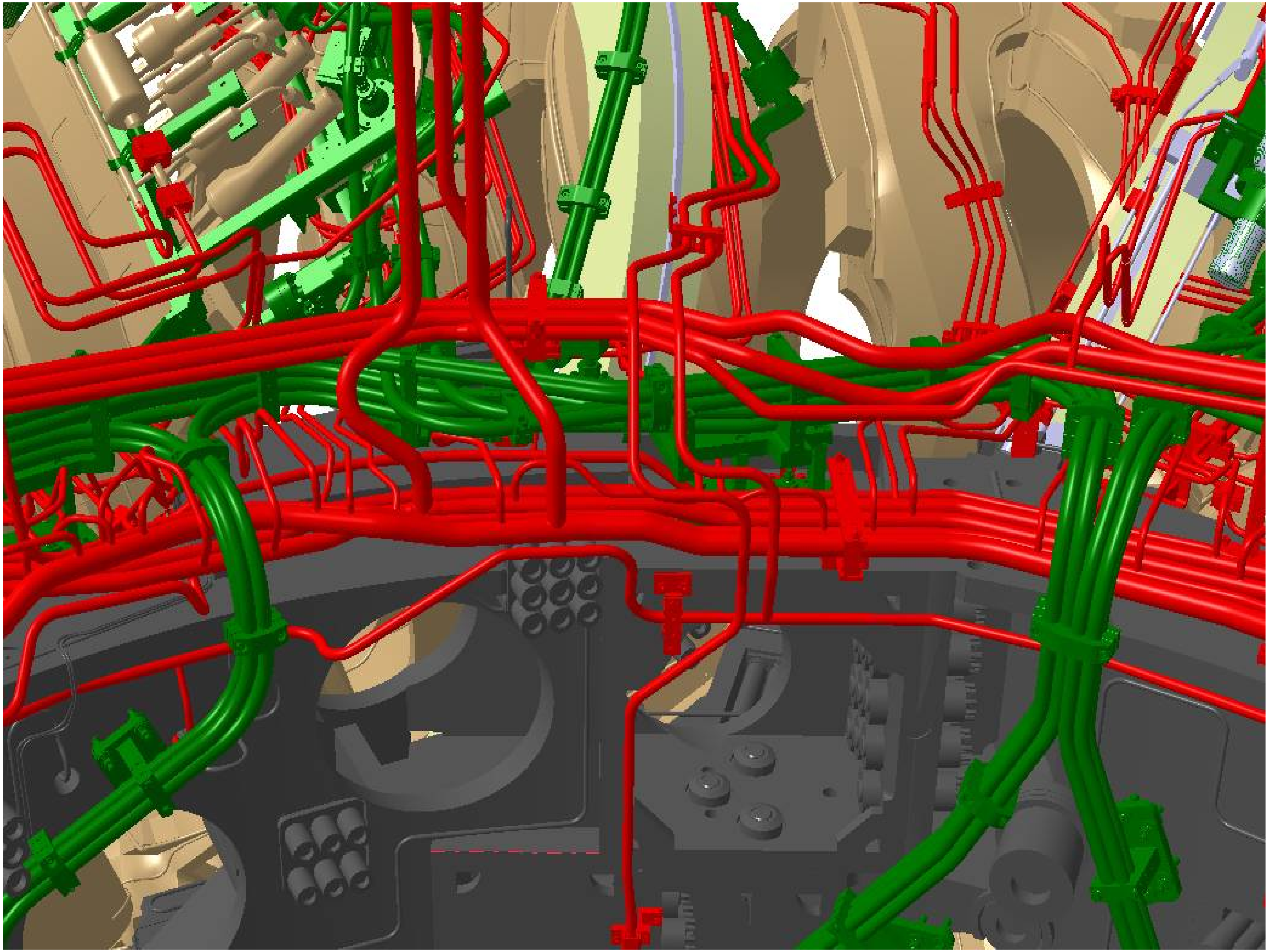
- 300 steel pipes and 24 superconducting bus-bars per module
- more than 500 welds and 24 superconducting joints per module
- three-dimensional stellarator geometry



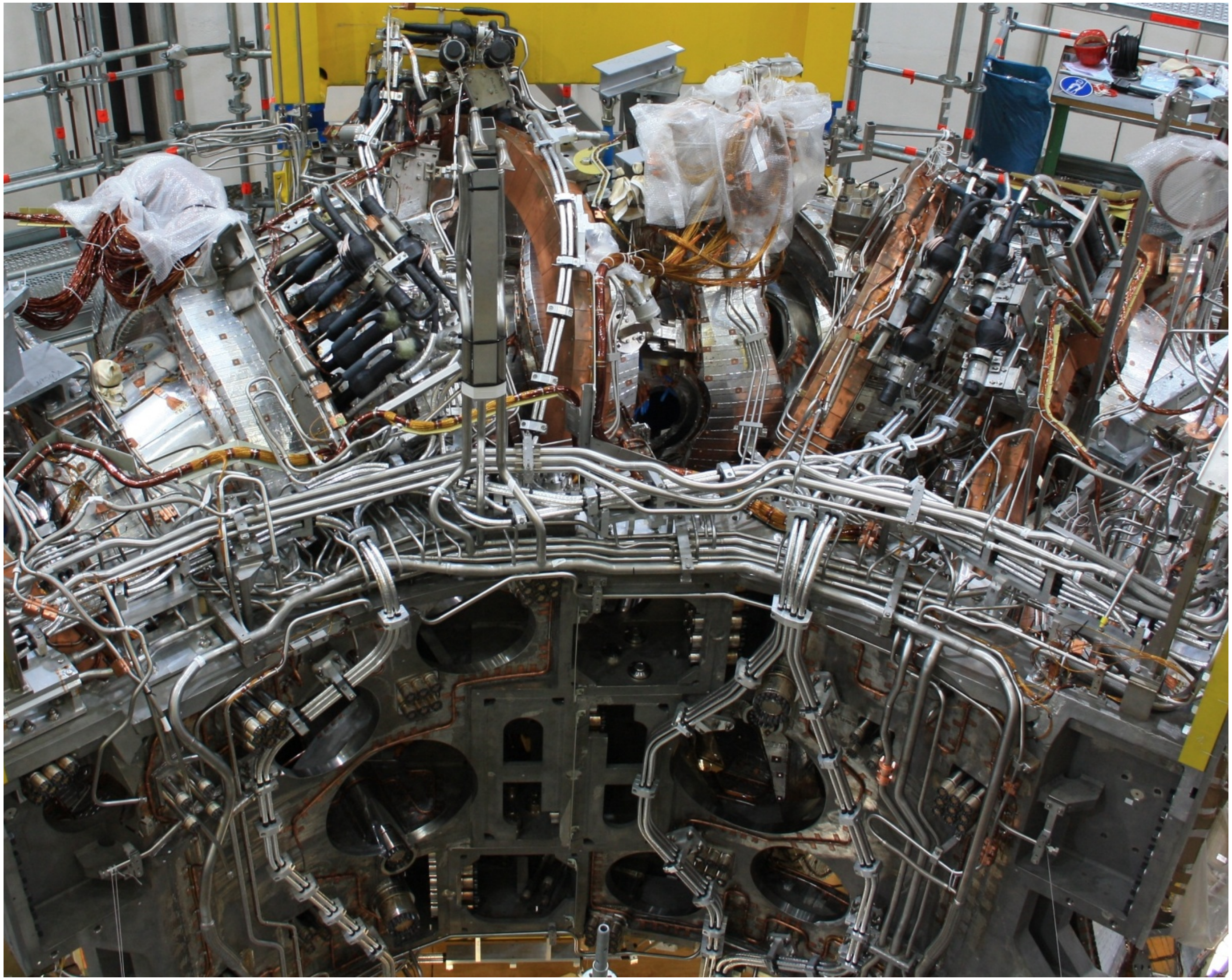
Magnet module with bus-bars



Magnet module, bus-bars and cryo-piping



Reality



Electric and hydraulic connection of the magnets

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Forschungszentrum Jülich

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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
- intense metrology, demanding manufacturing, complex change management
- extremely limited available space in the cryostat ⇐ Design decision!

Conclusions

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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, i.e. prior to design completion, component specification and start of procurement. 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 including a test program on manufacturing samples and mockups. Quality management must be involved in each single step. Trained inspectors must follow up manufacturing in detail.

Conclusions, continued

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4. A project needs a few persons who the device in all details.
   Experience with large construction projects is invaluable.
   Clear project structures and responsibilities are mandatory.

5. The project management must be able to identify risks precisely and timely enough to react with reasonable countermeasures.
   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.

6. 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.

7. 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. Loss of expertise may happen on short time-scale and must be checked.