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für Plasmaphysik

Stellarators difficult to build?

The construction of Wendelstein 7-X

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on behalf of the

enterprise Wendelstein 7-X

Max-Planck-Gesellschaft

Outline of the talk

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I. The project

II. Planning

III. Components

IV. Integration

V. Conclusions

The Wendelstein 7-X Device

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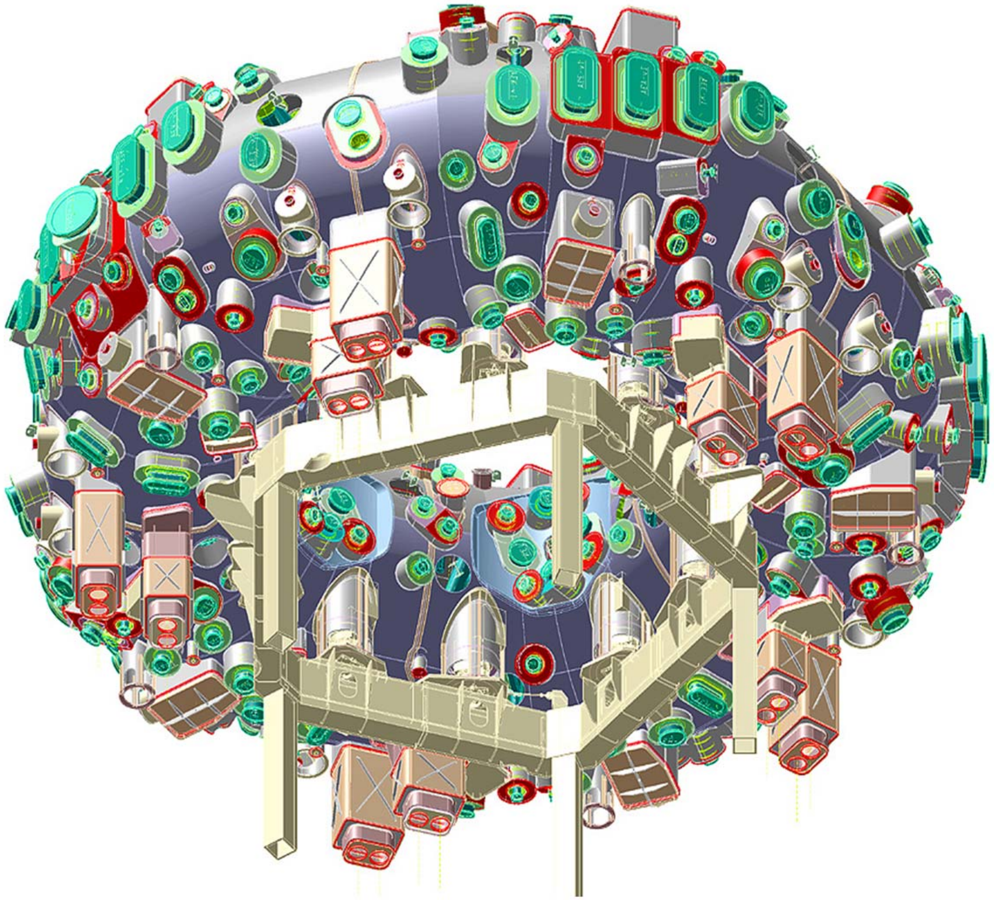
Key Parameters

major radius:	**5.5 m**
minor radius:	**0.53 m**
plasma volume	**30 m^3**
non-planar coils:	**50**
planar coils:	**20**
number of ports:	**253**
rot. transform:	**5/6 - 5/4**
induction on axis:	**< 3T**
stored energy:	**600 MJ**
heating power	**15 - 30 MW**
pulse length:	**30 min**
energy turn around:	**18 GJ**
machine height:	**4.5 m**
machine diameter:	**16 m**
machine mass:	**725 t**
cold mass:	**425 t**



Stellarator optimisation: W7-X

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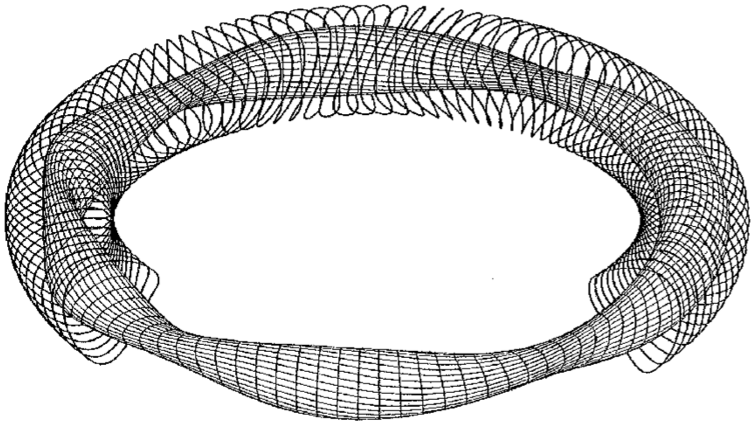
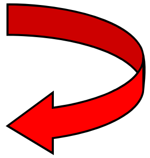
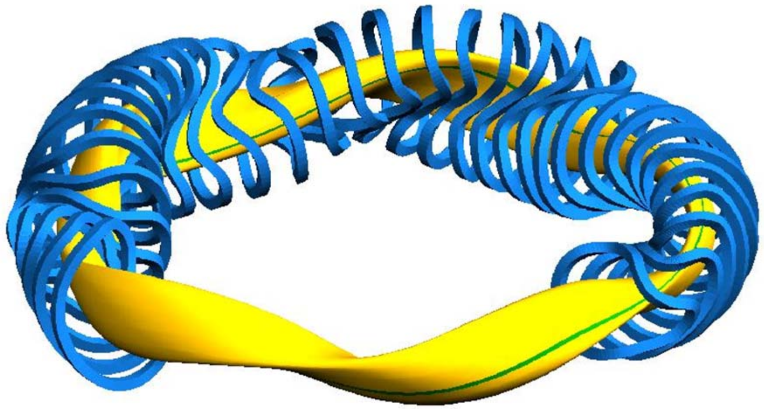
7 optimization criteria

1. feasible modular coils
2. good, nested magnetic surfaces
3. good finite-β equilibria
4. good MHD stability
5. small neoclassical transport
6. small bootstrap current
7. good confinement of fast particles



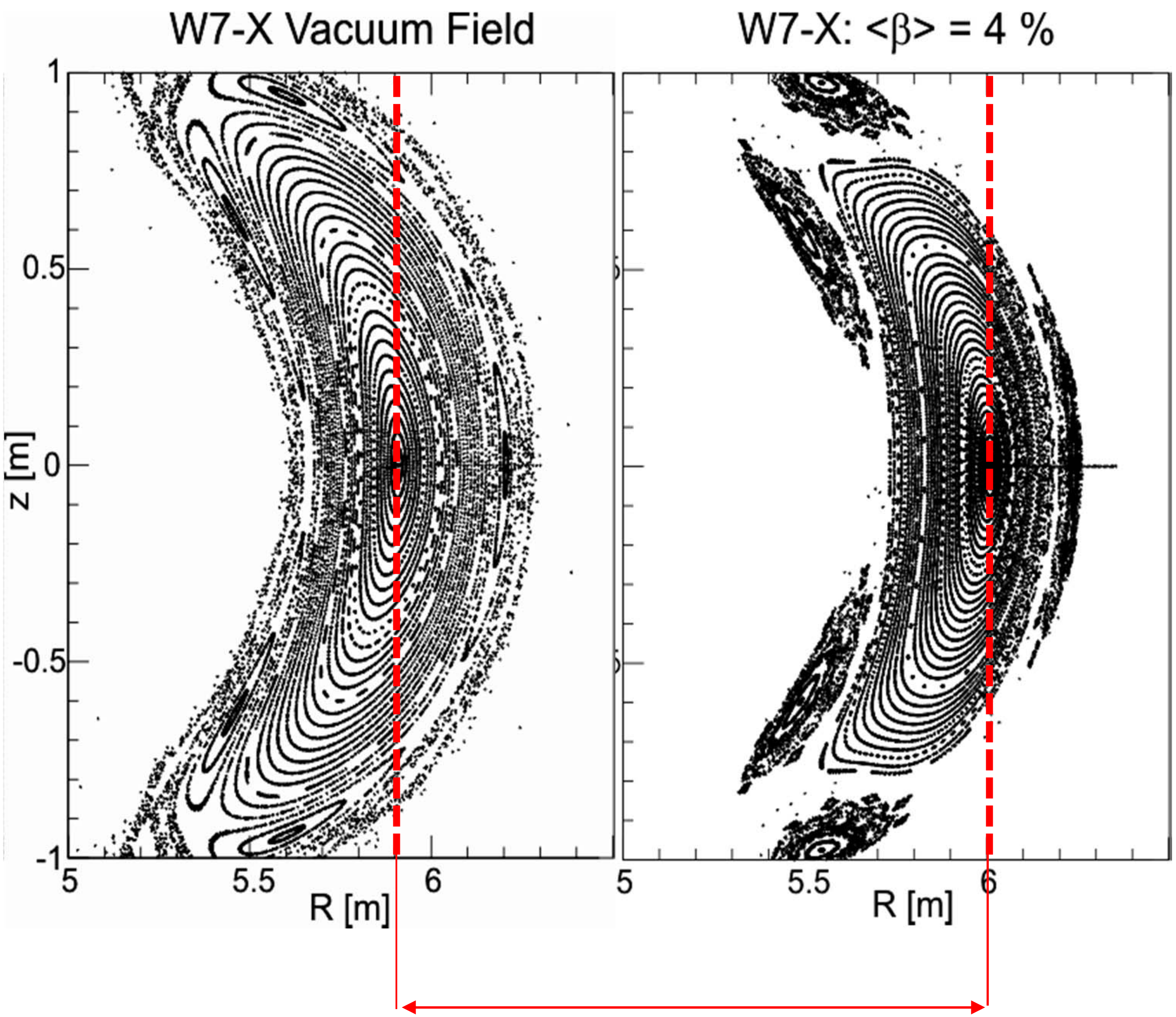




Stellarators

1. no current disruptions
2. better stability
3. steady-state capable
4. optimisation $\rightarrow$ tokamak performance
5. reactor-potential to be proven

ex: good equilibrium properties



Shafarnov shift ~10cm

optimisation for reactor relevant β

↓

- **stiff equilibrium**
- **island location**
- **confined volume**
- **plasma location**

ex: good confinement fast p‘s

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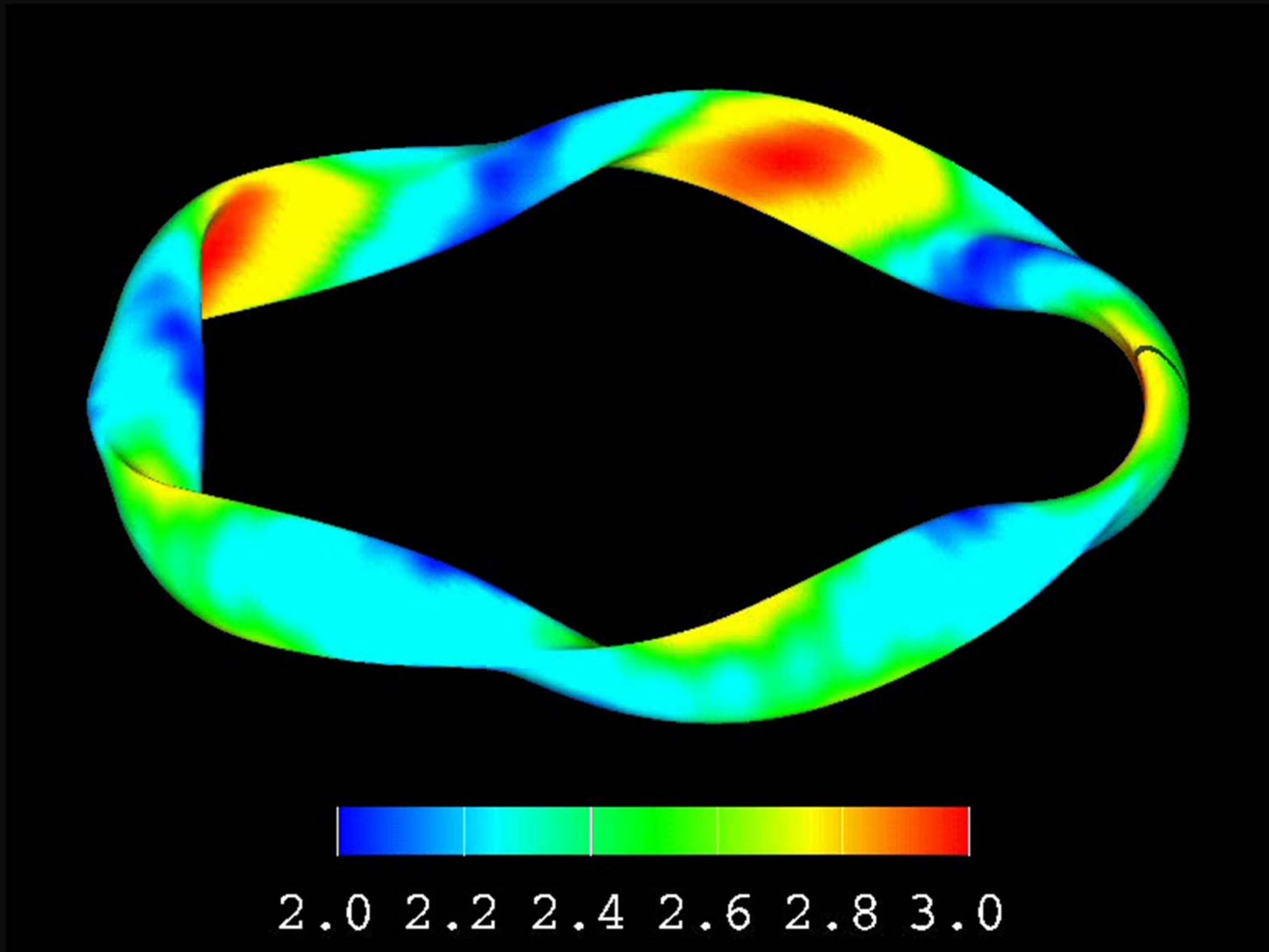

Major construction challenges

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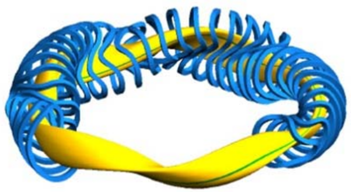
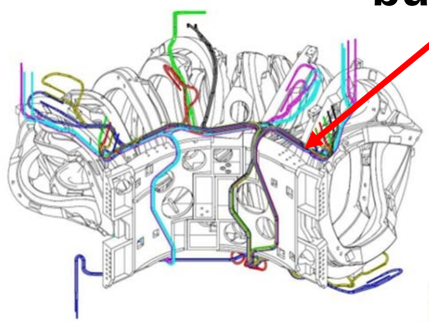
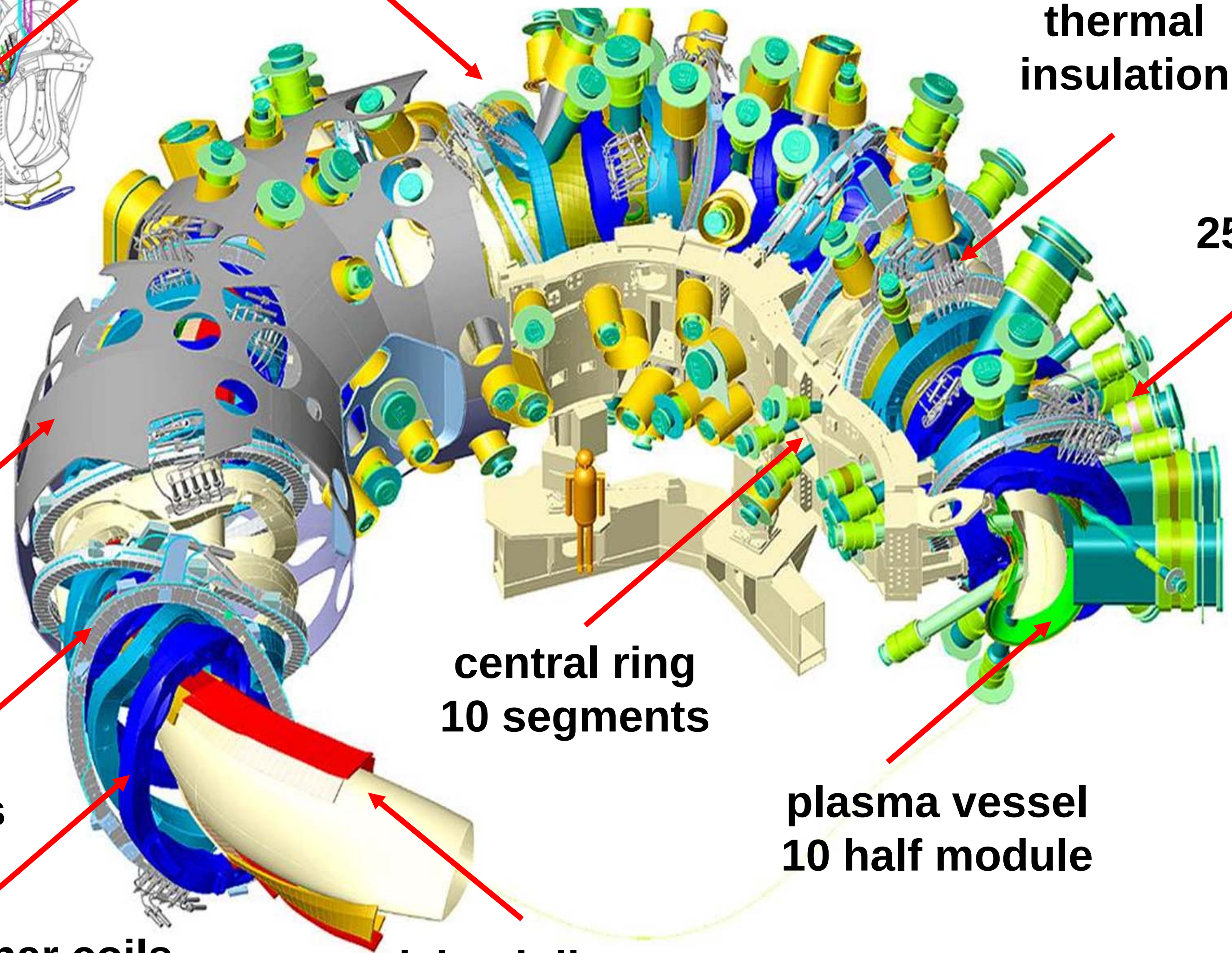
Wendelstein 7-



- **is a first-of-a-kind development**
  - big scientific and technological step
  - many new technologies to develop
  - uncertainties and surprises
- **is a big machine**
  - 30 m^3 plasma volume and 750 t total weight
  - heavy and expensive components
  - demanding tools for manufacture and assembly
- **is a cryogenic device**
  - 425 t total cold mass
  - high technical complexity
  - very high demands on quality in general
- **is designed for high-power steady-state operation**
  - 30 min plasma operation at 10 MW ECRH
  - superconducting magnet system
  - pressure water cooling of in-vessel components

Wendelstein 7-X components





Project History

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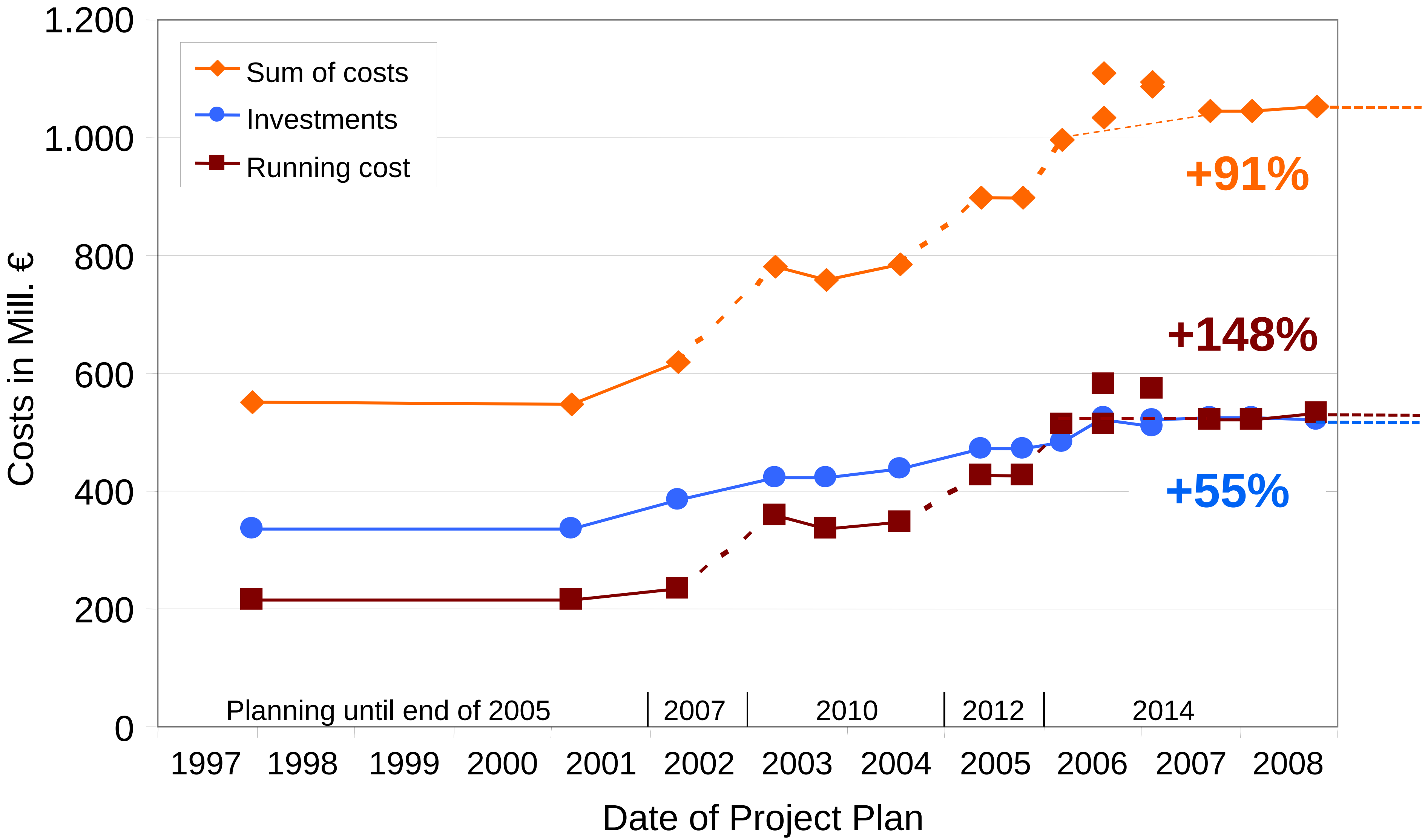
time line		planned completion date
1991	phase 1 EURATOM approval for preferential support	1999
1995	phase 2 EURATOM approval for preferential support	2004
1996	official project start	2006
2000	move into new institute building
2002	insolvency coil manufacturer
	external audits of the project	2010
2003	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	assemply plan revision	2016
	counter measure package implemented	2014
2007	first magnet module completed	2014
2009	all magnets manufactured and tested
	assembly of four magnet modules in progress	2014
2010	all magnets assembled	2014
2011	four out of five modules on machine base	2014

Project Cost Evolution



Status 11/2008

Outline of the talk

Planning Issues

- **Realistic estimates for both time, budget and staffing**
  - ☆ ***typical underestimation is factor of two***
  - ☆ ***damages relationship to the funding agencies and the public***
  - ☆ ***difficulty: only conceptual design and no man power available***
- **Reasonable contingencies**
  - ☆ ***no contingencies mean permanent revision of planning***
  - ☆ ***no contingencies mean slow decision-making***
  - ☆ ***difficulty: contingencies often not granted***
- **Strong planning and coordination office**
  - ☆ ***professional full-time team required***
  - ☆ ***must have a lead function in the project***
  - ☆ ***difficulty: often weak planning basis and lack of man power***
- **Appropriate planning tools**
  - ☆ ***standard tools of project management must be implemented***
  - ☆ ***QM ISO 9001, PLM, CM, WBS + integrated financial planning***
  - ☆ ***difficulty: sometimes poor acceptance on the work level***

Schedule planning and control

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Nr.	Vorgangsname	Anfang	Ende	Dauer	06 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 202
156	Assembly NBI 1. Part	Mo 27.06.11	Sa 07.07.12	52 W	
157	Assembly NBI 2. Part	Mi 30.01.13	Mi 29.01.14	33,31 W	
158	MST 29: Start Commissioning	Mo 19.05.14	Mo 19.05.14	0 W	MST 29

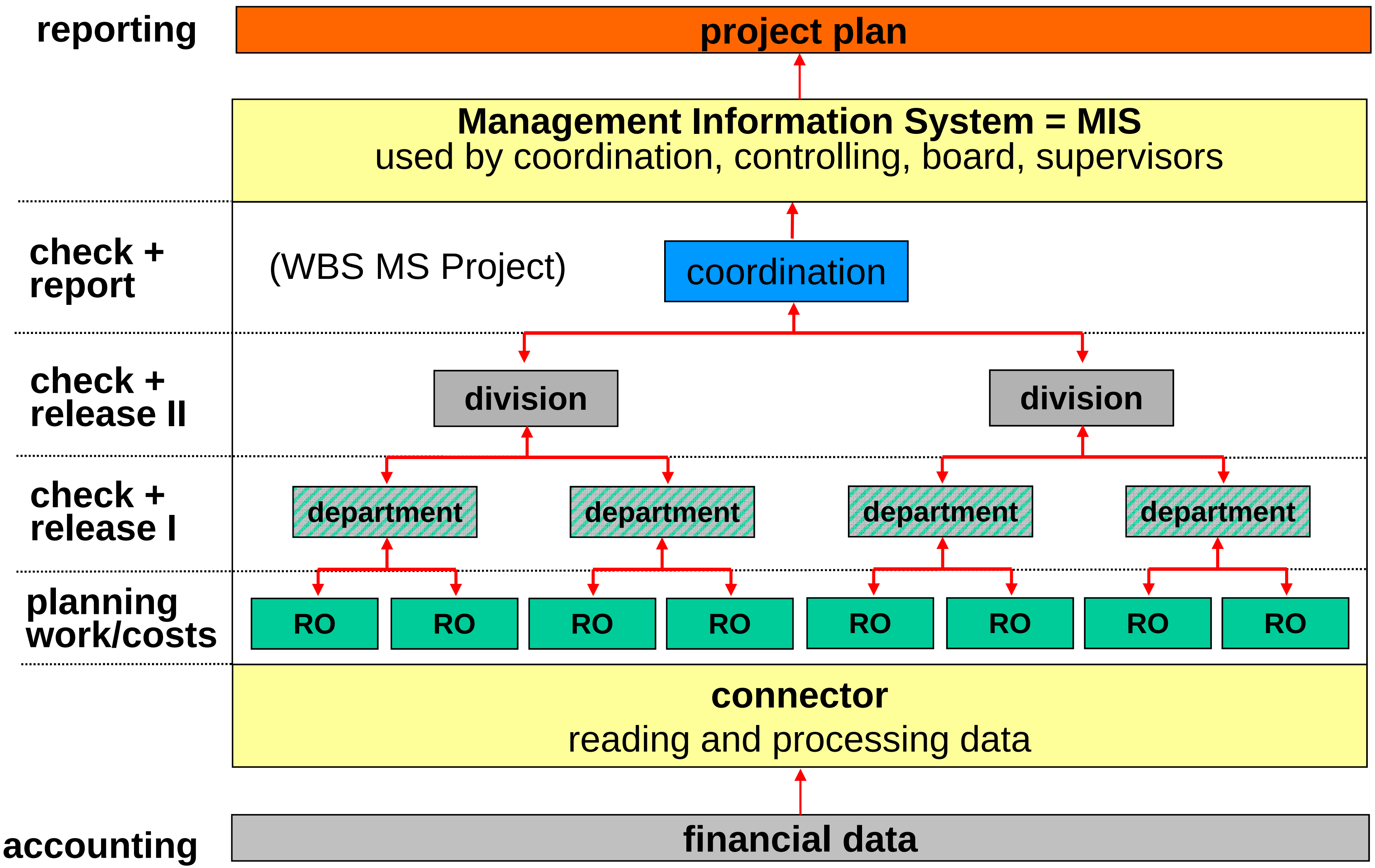
Fundamental revision of planning in 2007

- goal: to stabilized the schedule until completion of the device
- completion date of Wendelstein 7X = mid 2014 – stable since 3.5y
- phased approach to full power steady-state operation
- start with 10s discharges and interially cooled divertor
- 15 months completion shut-down for steady-state divertor

Device assembly plan

- 55 weeks time buffer on critial path allocated in 2007 – 14 weeks left
- 50% of the assembly time still ahead ~ 400.000h
- 29 milestones agreed with funding bodies – 12 passed
- daily tight schedule control by WBS on all work levels

Ex: integrated Planning



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Component issues

- **Component design**
  - ☆ ***design must be complete before specification and tender***
  - ☆ ***avoid design changes after start of manufacturing***
  - ☆ ***difficulty: time pressure and fund flow requirements***
- **Industrial skills and capacities**
  - ☆ ***industry with proven skills, know-how, manufacturing capacities***
  - ☆ ***avoid complex consortia – clear responsibilities instead***
  - ☆ ***difficulty: monopoly situations and other fabrication priorities***
- **Risks in development and manufacturing**
  - ☆ ***transfer of risks to industry is always extremely expensive***
  - ☆ ***risks must be kept as much as possible in house + cooperation***
  - ☆ ***difficulty: high domestic work load = big & competent home team***
- **Tests and quality assurance**
  - ☆ ***quality assurance must be done by the project team + inspectors***
  - ☆ ***tests of prototypes as well as series products are mandatory***
  - ☆ ***difficulty: same as above***

Major Device Components

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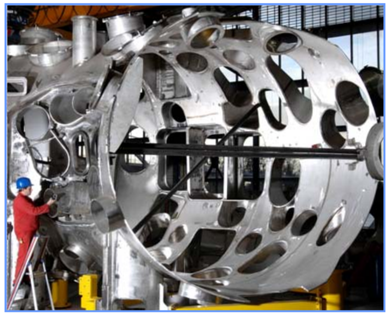
All major components are manfactured, tested, delivered and – most of them – assembled.







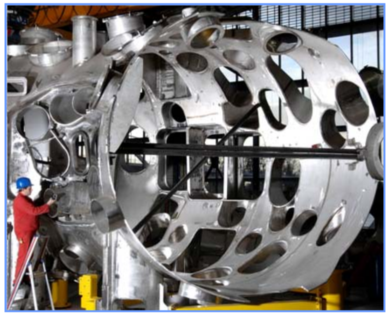
1 machine base	**delivered and assembled**
50 non-planar superconducting coils	**delivered and assembled**
20 planar superconducting coils	**delivered and assembled**
10 central support ring segment	**delivered and assembled**
about 300 support elements	**delivered and assembled**
20 plasma vessel sectors	**delivered and assembled**
10 outer vessel sectors	**delivered and assembly in progress**

Major Device Components

All major components are manfactured, tested, delivered and – most of them – assembled.





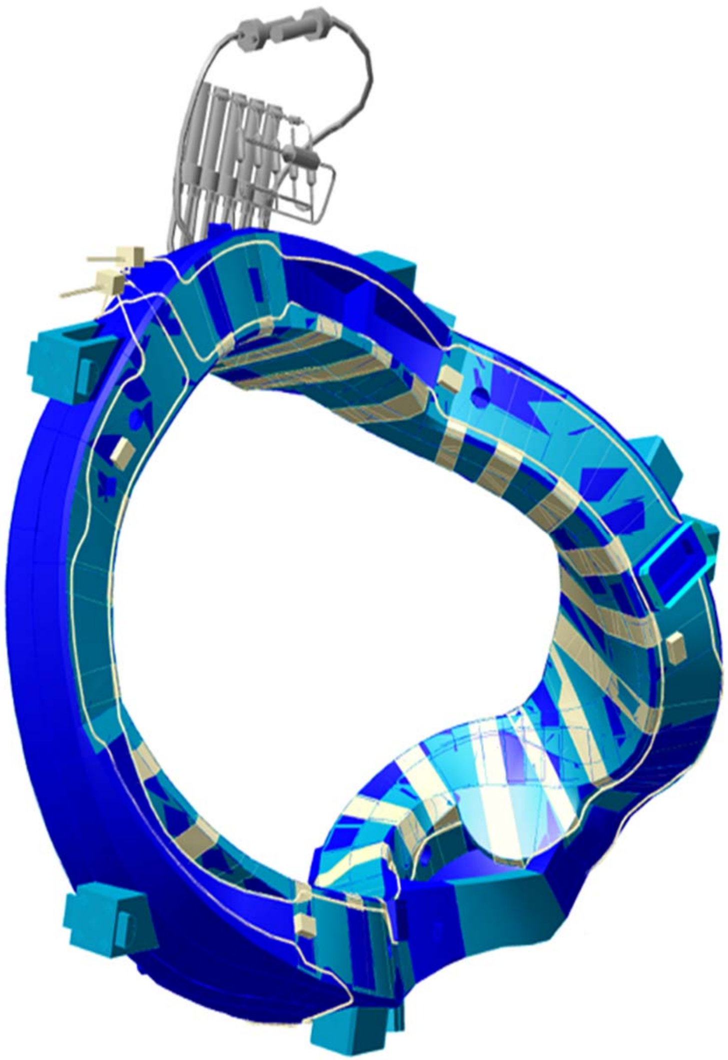


254 ports
about 1700 cryo pipes and supports
15 cryo legs
about 113 bus bars and 400 supports
150 wall panels for plasma vessel
about 1000 thermal insulation elements
14 current leads

delivered and assembly in progress
delivered and assembly in progress
delivered and assembly in progress
delivered and assembly in progress
delivered
delivery and assembly acc to

Case: superconducting coils

drawing of non-planar coil



delivery of first coils in 2004

Superconducting coils

- **50 non-planar and 20 planar coils**
- **243 NbTi strands Al cable in conduit**
- **18.2 resp. 16kA and 6 resp. 4kV**
- **100M€ contract ~ consortia**

cf. Sborchia et al. Applied Superconductivity, Seattle 2006

Coil history

issues

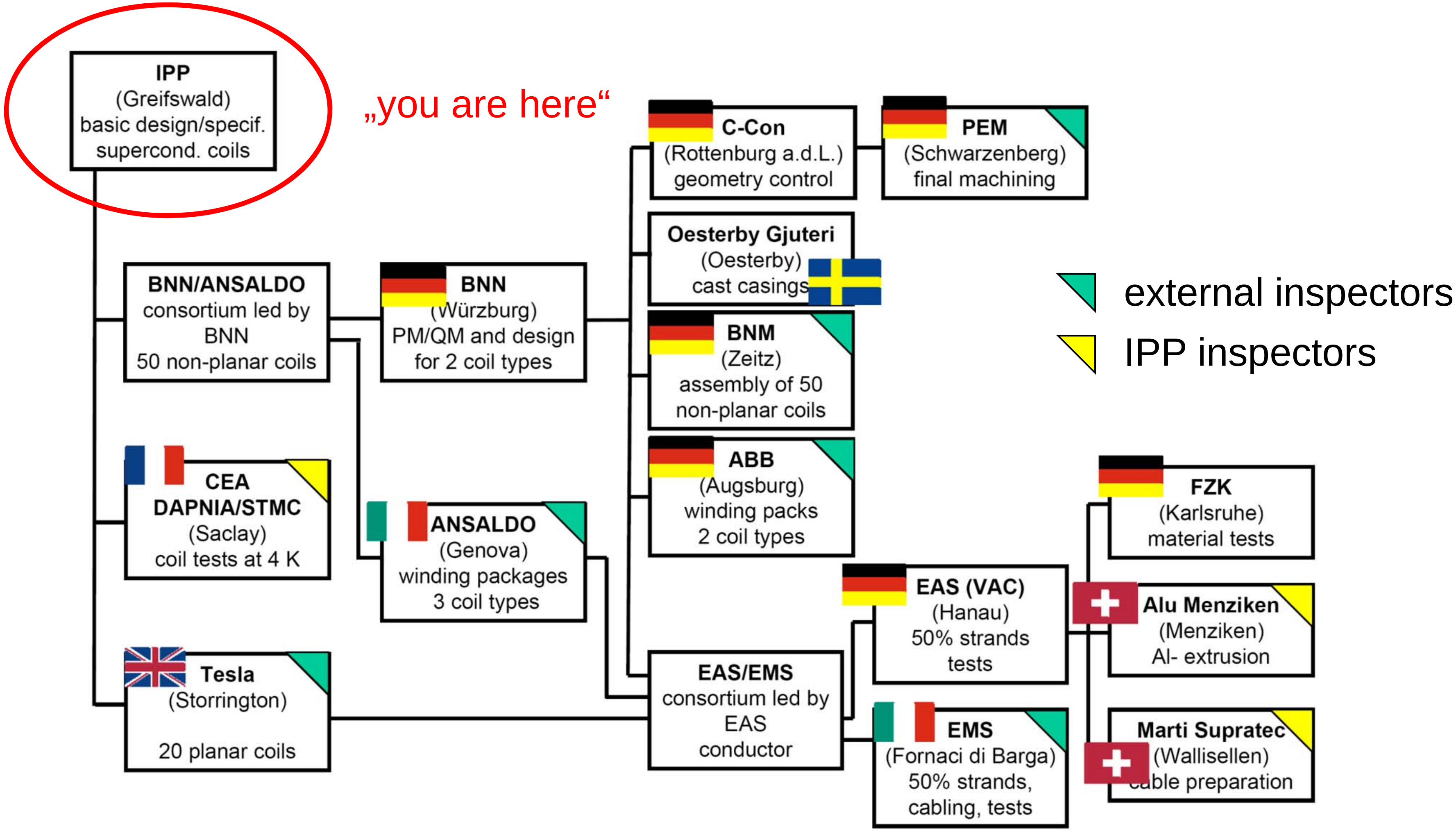
1. **deviations and damages of SC strands**
2. **voids in cast steel coil casings**
3. **geometrical deviations in coil casings**
4. **residuals of Cu-SS soldering flux**
5. **Al and SS welds to be requalified**
6. **quench detection cable damage**
7. ***insulation faults in the coil header***
8. ***danger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

changes

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

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

A European consortium



- **Complex consortium for SC and coil manufacture**
- **R&D and design started in 1993 – contracts placed in 1998**

Manufacturing of the SC coils

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Babcock-Noell/Ansaldo & ABB, Oesterby, Luvata

Coil insulation faults

Insulation test at 4K

- 2.5kV max during fast discharge
- 6kV high voltage proof
- 13kV test vacuum + Paschen min.
- current monitoring
- camera recording of coil header

Complex & risky repair action

- 20 n-p coils with systematic faults
- deep excavation of header area
- cracks and voids ← charged raisin
- repeated Paschen tests
- repeated full cold test

Laborious ~3y coil repair

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Magnet assembly

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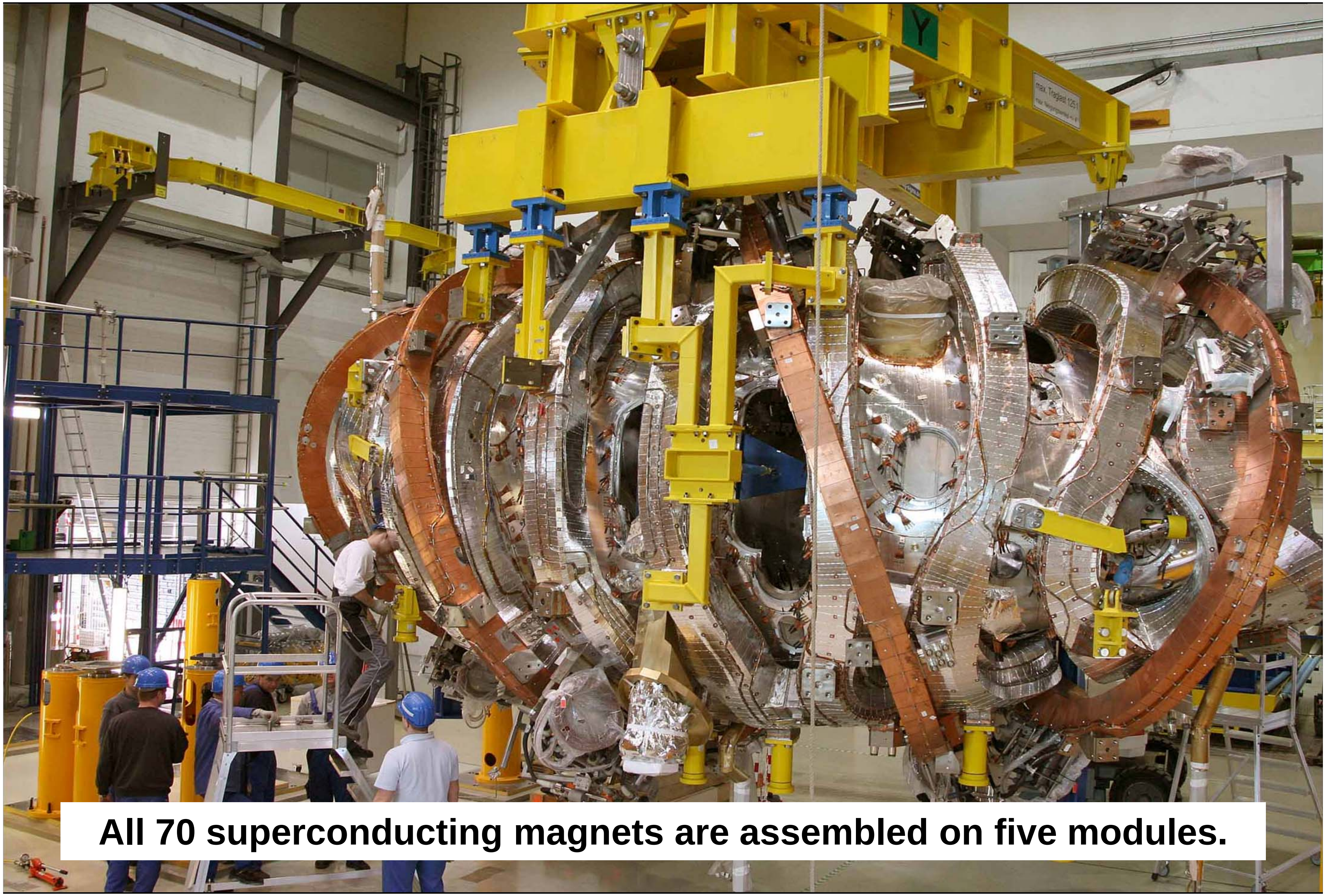

All 70 superconducting magnets are assembled on five modules.

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Magnet module transport

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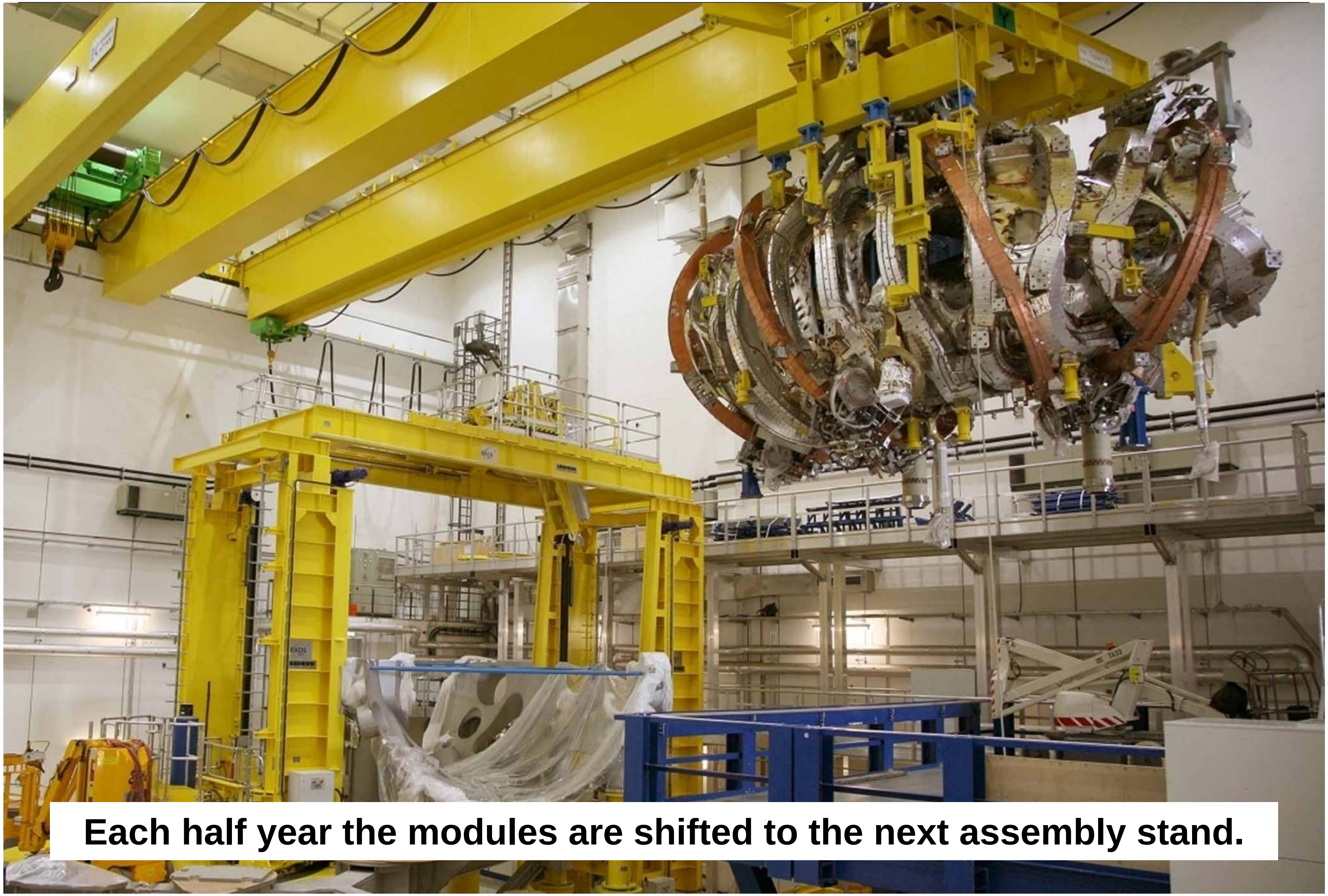
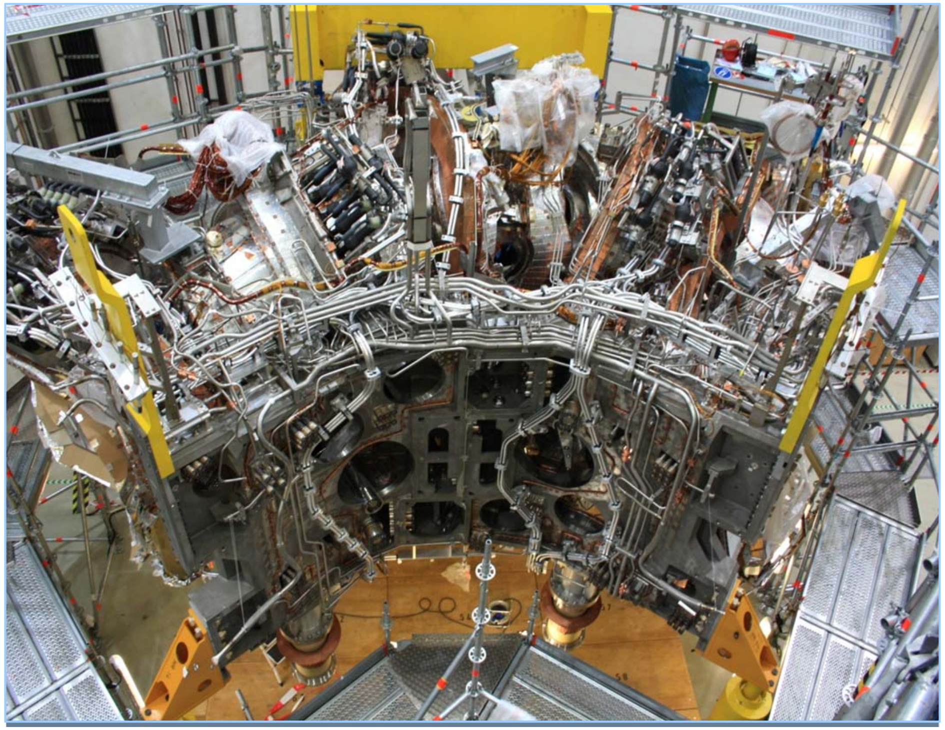


Each half year the modules are shifted to the next assembly stand.

Cryo piping and bus bar design & assembly



– 120 SC bus bars and joints
– 300 low Co steel Helium pipes
– clamps and (semiflexible) holders

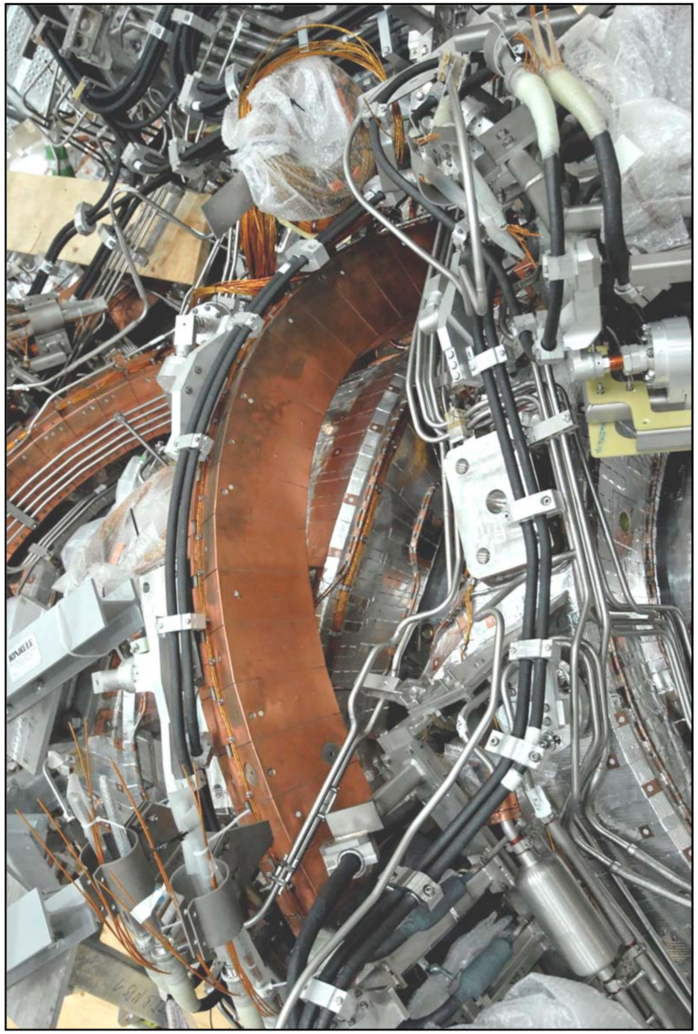
– cryostat design with minimized volume
– extremely tight space conditions
– three-dimensional design
– collision control and mitigation
– pre-manufacturing and assembly

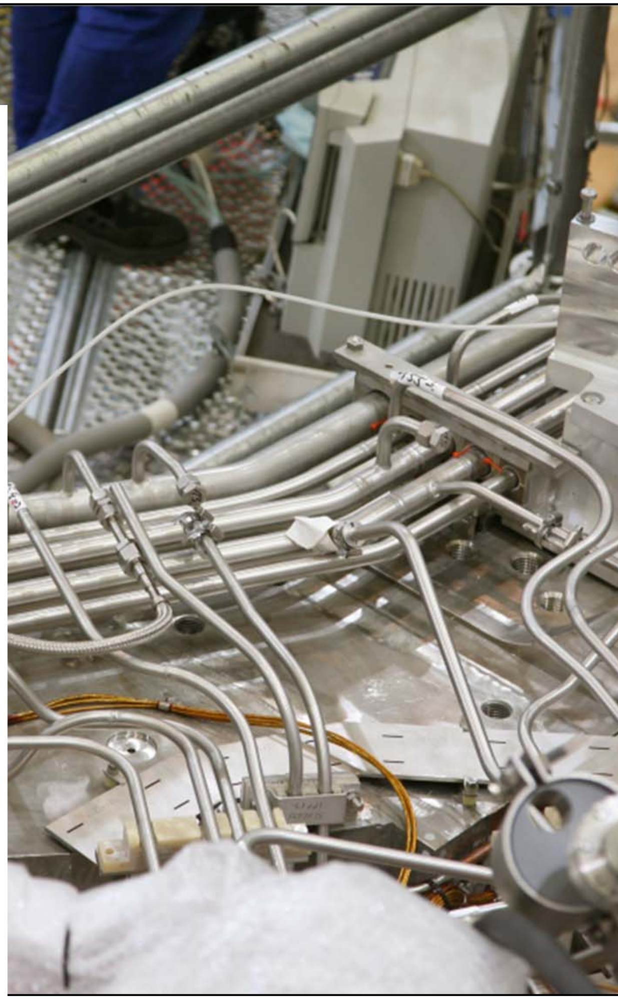
Forschungszentrum Jülich

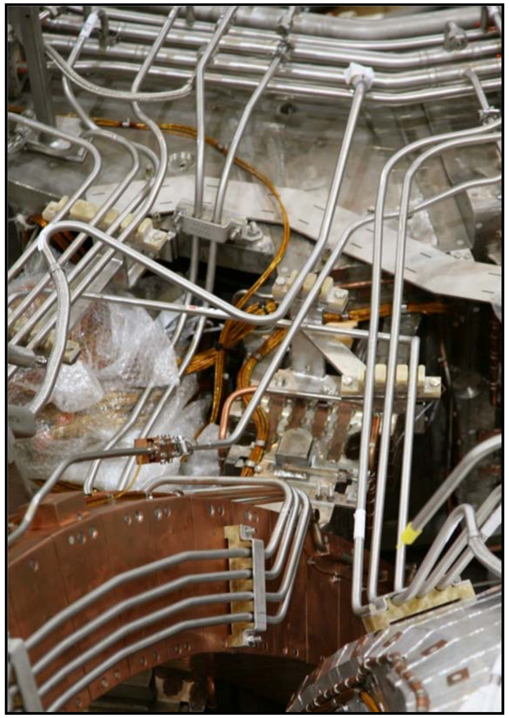
- all bus bars and cryo pipes have been manufactured and delivered
- four out of five modules have both bus bars and cryo pipes assembled

- implementation of systematic change management turned out to be decisive
- risk mitigation by rapid increase of engineering capacity was successful

Helium pipework

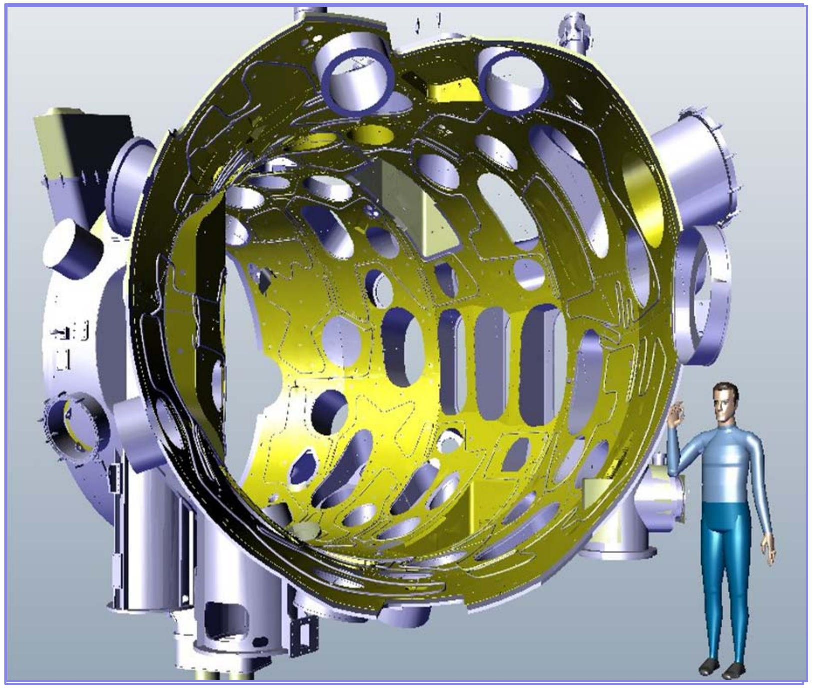


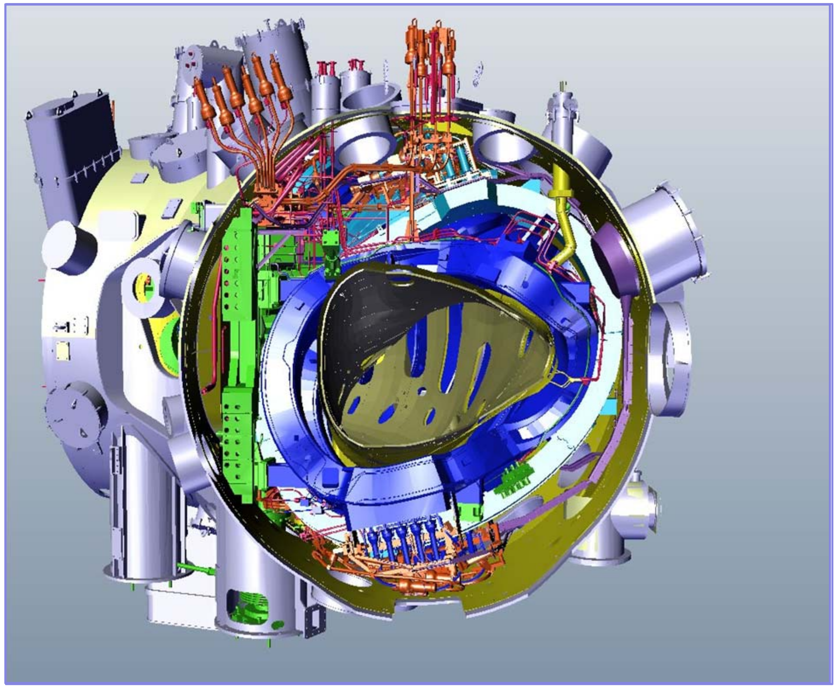




high demands on the quality of 500 orbital welds

Cryostat vessel design & and assembly





- 10 steel half shells
- 500 openings and domes
- deformation by ist own weight
- MLI and LN_2-cooled shields
- very tight tolerance requirements

- magnet module inserted into lower shell
- upper shell inserted on magnet module
- welding of equatorial gap
- removal of stiffeners
- closing the module separation

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The outer vessel

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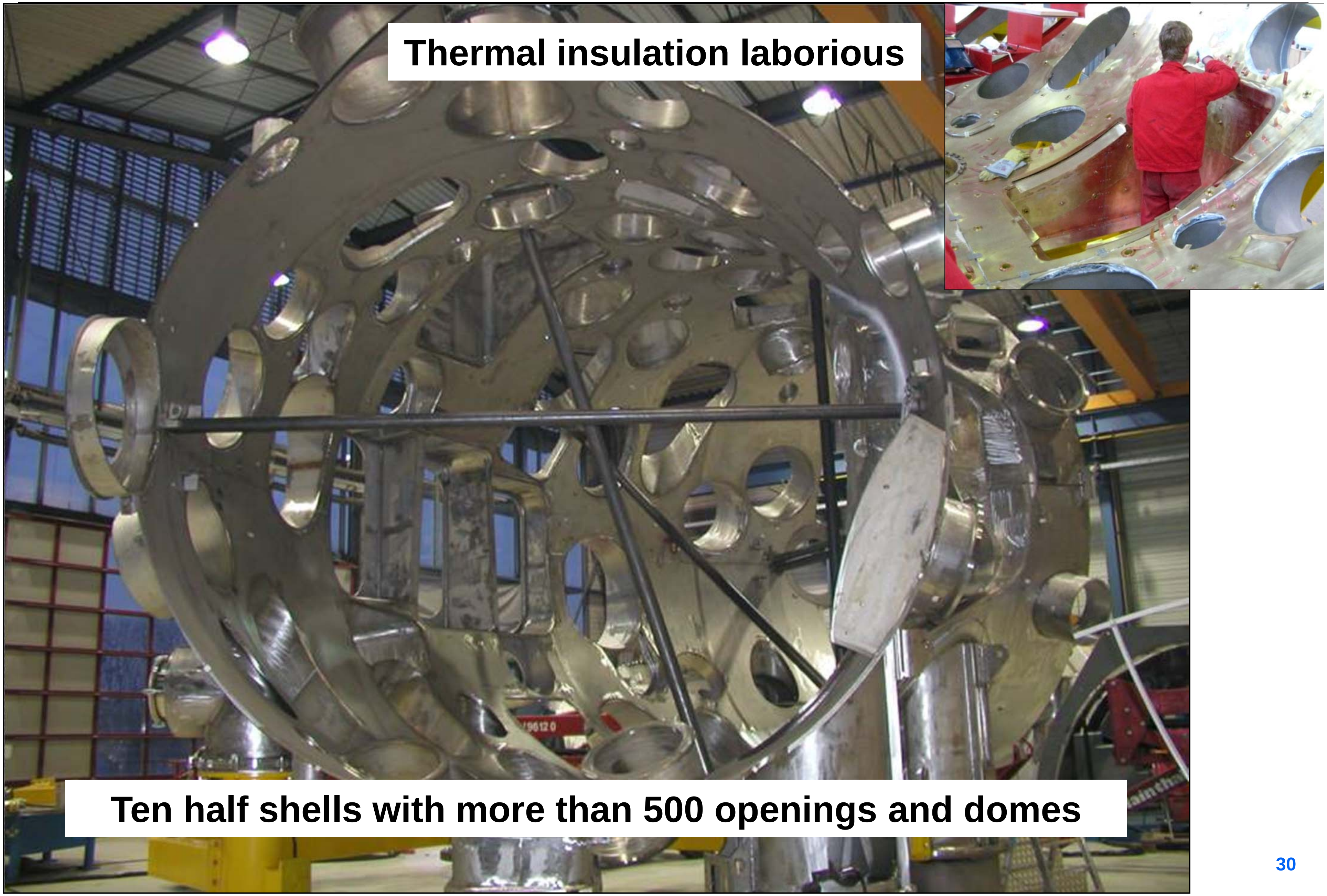

Thermal insulation laborious

Ten half shells with more than 500 openings and domes

Thermal insulation

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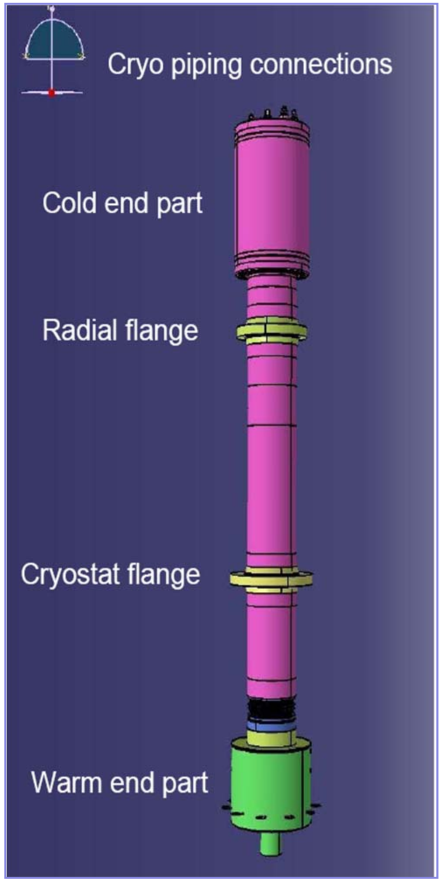
Thermal insulation consisting of MLI and LN2-cooled brass panels.

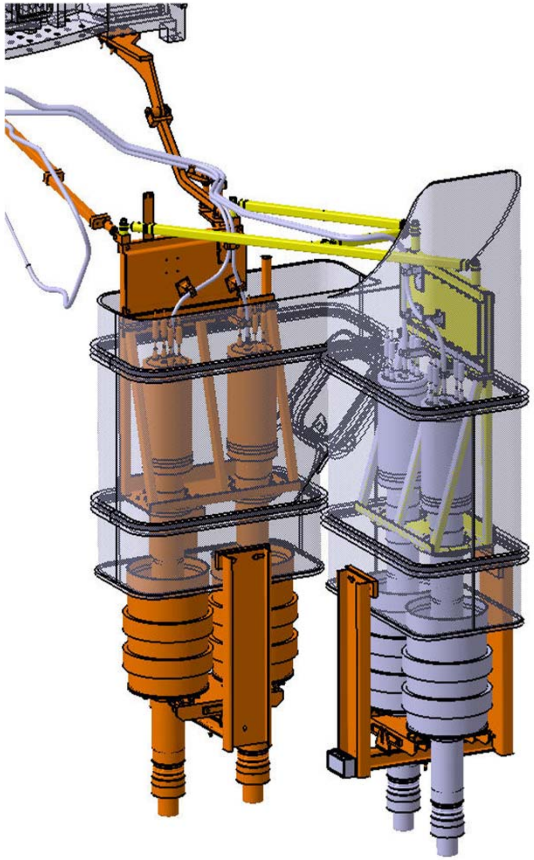
14 current leads

design



manufacturing

assembly



- HTSC based concept
- prototype „upside down“
- test successful

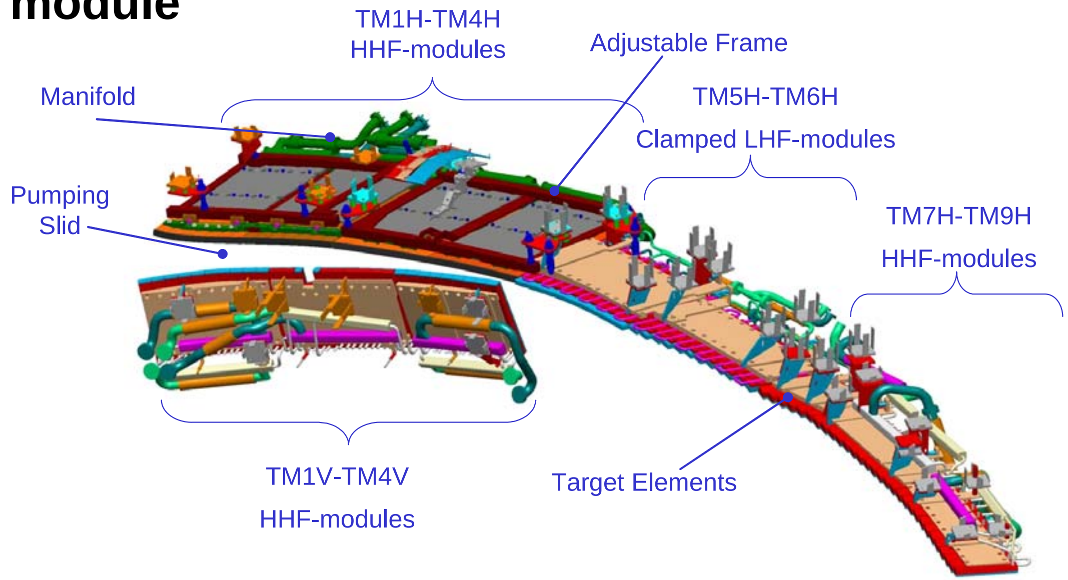
- series manufacturing at KIT
- test cryostat ready
- delivery acc to schedule

- ORNL/PPPL concept
- special tooling
- mock-up tests

In-vessel components

divertor module

water cooling lines



- **260m² total covered surface and about 250.000 parts (4000 major ones)**
- **20m² target elements CFC sealed on cooled CuCrZr**
- **20m² baffle elements graphite clamped on CuCrZr**
- **60m² heat shields graphite bolted on CuCrZr**
- **60m² wall protection steel panels**
- **100m² port liners**
- **everything water-cooled: about 4km in-vessel water pipe lines**
- **cryopumps and sweep coils**

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Manufacturing in-vessel comp‘s

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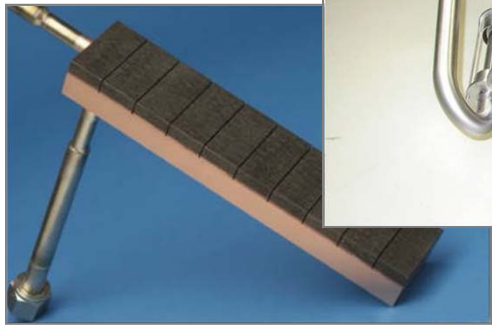
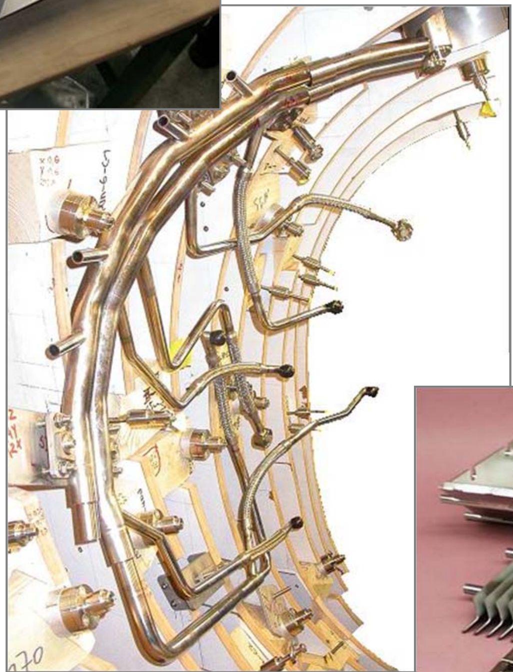
Heat shield (IPP)

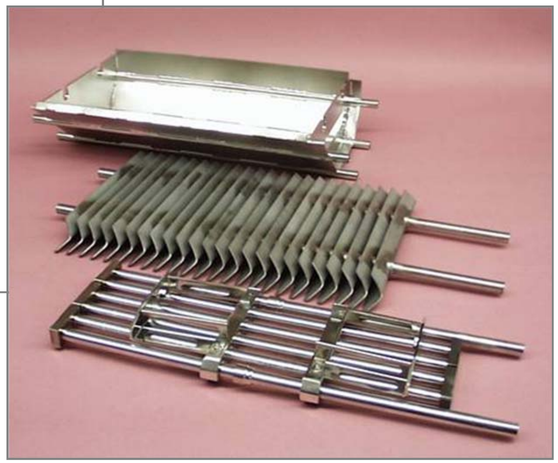
Target modules (Plansee)





Cooling pipes (IPP/Dockweiler)

Wall pannels (MAN DWE)

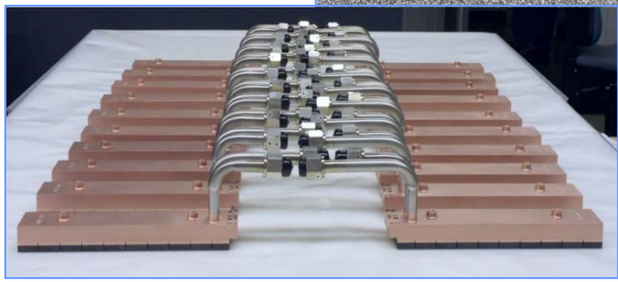


Cryo pumps (IPP)

In-vessel components

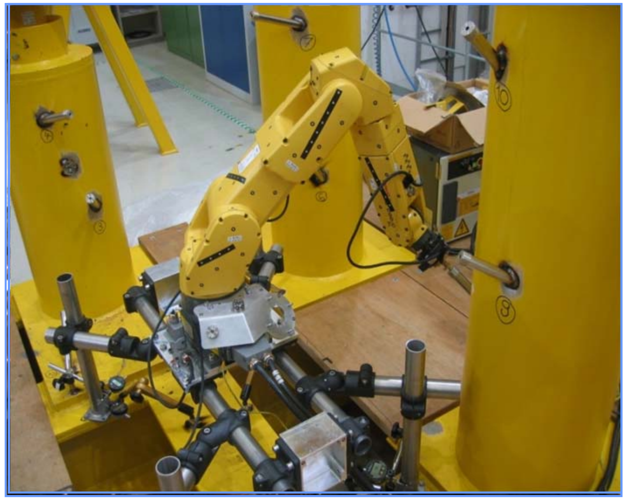
Status

- Plansee contract with significant R&D (TS follow-up)
- CFC HIPed and e-beam welded on CuCrZr
- 46 (out of 890) HHF elements delivered
- test of 20 elements in GLADIS full success
- series manufacturing of first lot released



Assembly preparation

- assembly test program in one magnet module
- precision requirements mostly met
- up to now no show-stopper found
- positioning tools developed
- logistic planning (assembly through 5 man ports)
- re-organisation and increase of personnel resources



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Integration and assembly issues

o Organisation

- ☆ *quick decision making on a daily level must ge guaranteed*
- ☆ *clear responsibilities and structures mandatory – no matrix!*
- ☆ *difficulty: sometimes not in line with political/institutional reality*

o Surprises

- ☆ *one must be prepared for many - mostly unpleasent - surprises*
- ☆ *timely risk identification and mitigation required*
- ☆ *difficulty: peak overload and complex priority setting*

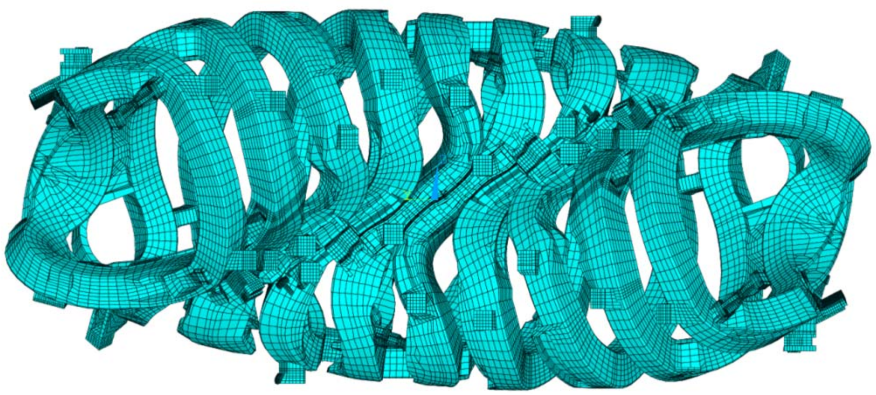
o Tolerances

- ☆ *fight for maximum possible tolerance allowances*
- ☆ *operating at the technical limits is costly and takes time*
- ☆ *difficulty: physics often has high requirements*

o Margins

- ☆ *fight for margins and clearances*
- ☆ *again, operating at the technical limits is costly and takes time*
- ☆ *difficulty: research facilities are complex and in may ways extreme*

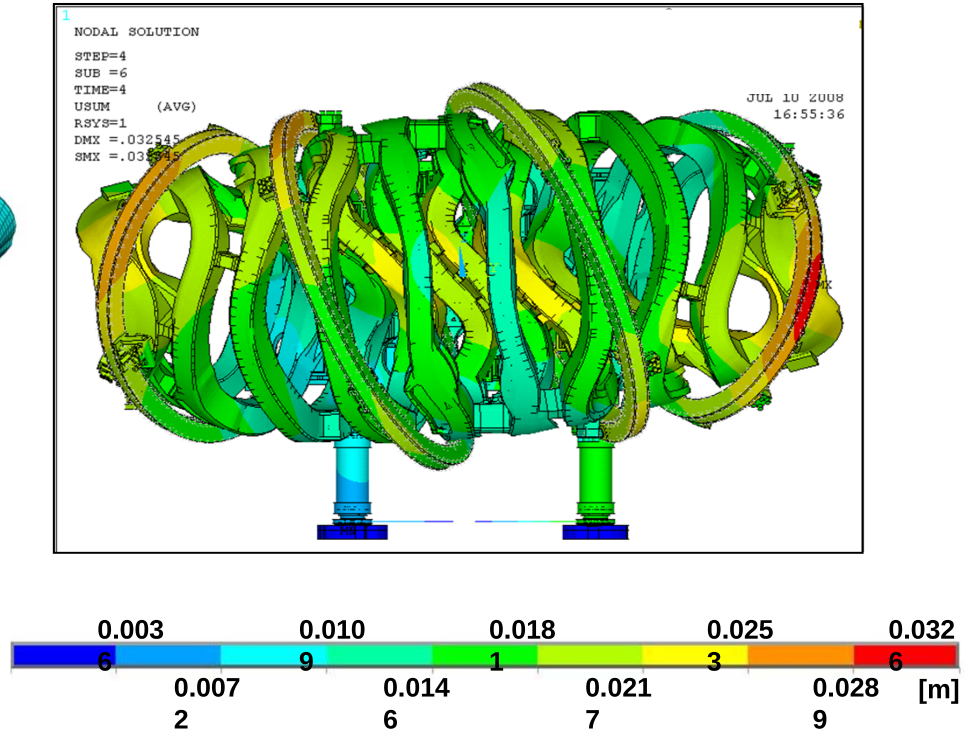
Case: Mechanical structure



Magnet global ANSYS® model

72° = 1/5 of the torus = 1 module

0.85M nodes



- serious overloads a) coil casings

  b) support structure

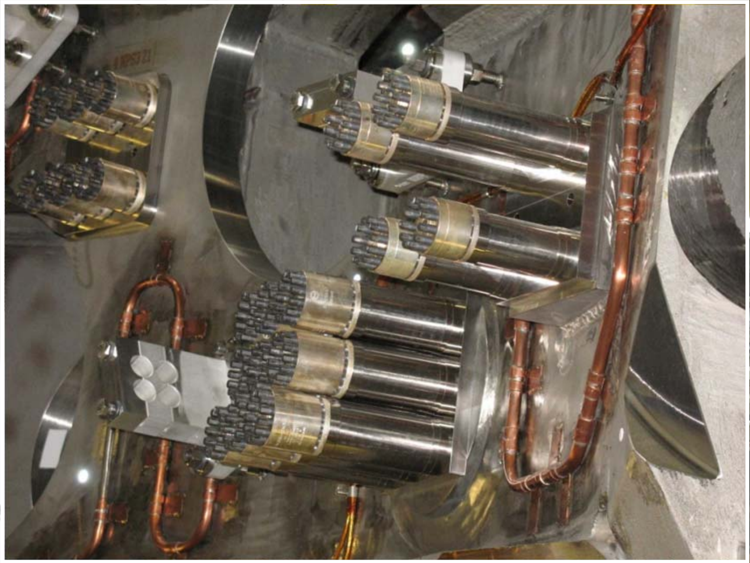
- no reasonable solution for narrow supports

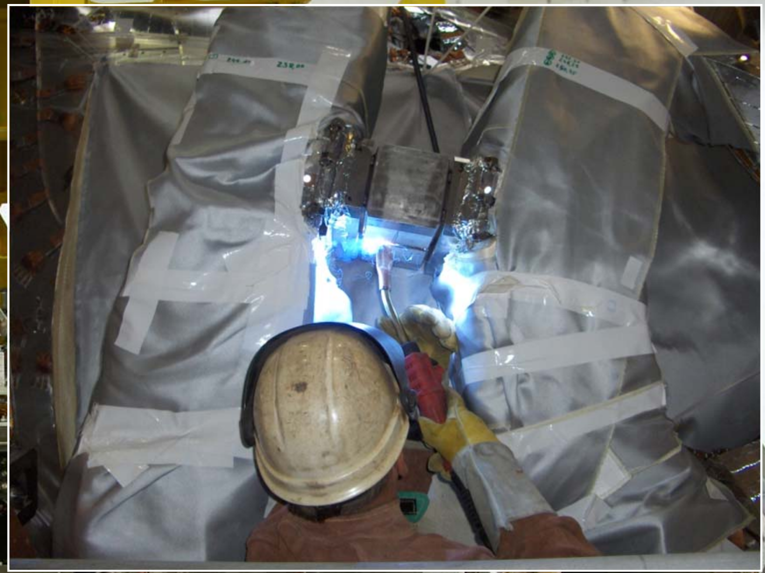
- manufacturing interrupted

- redesign work

- reinforcement measures

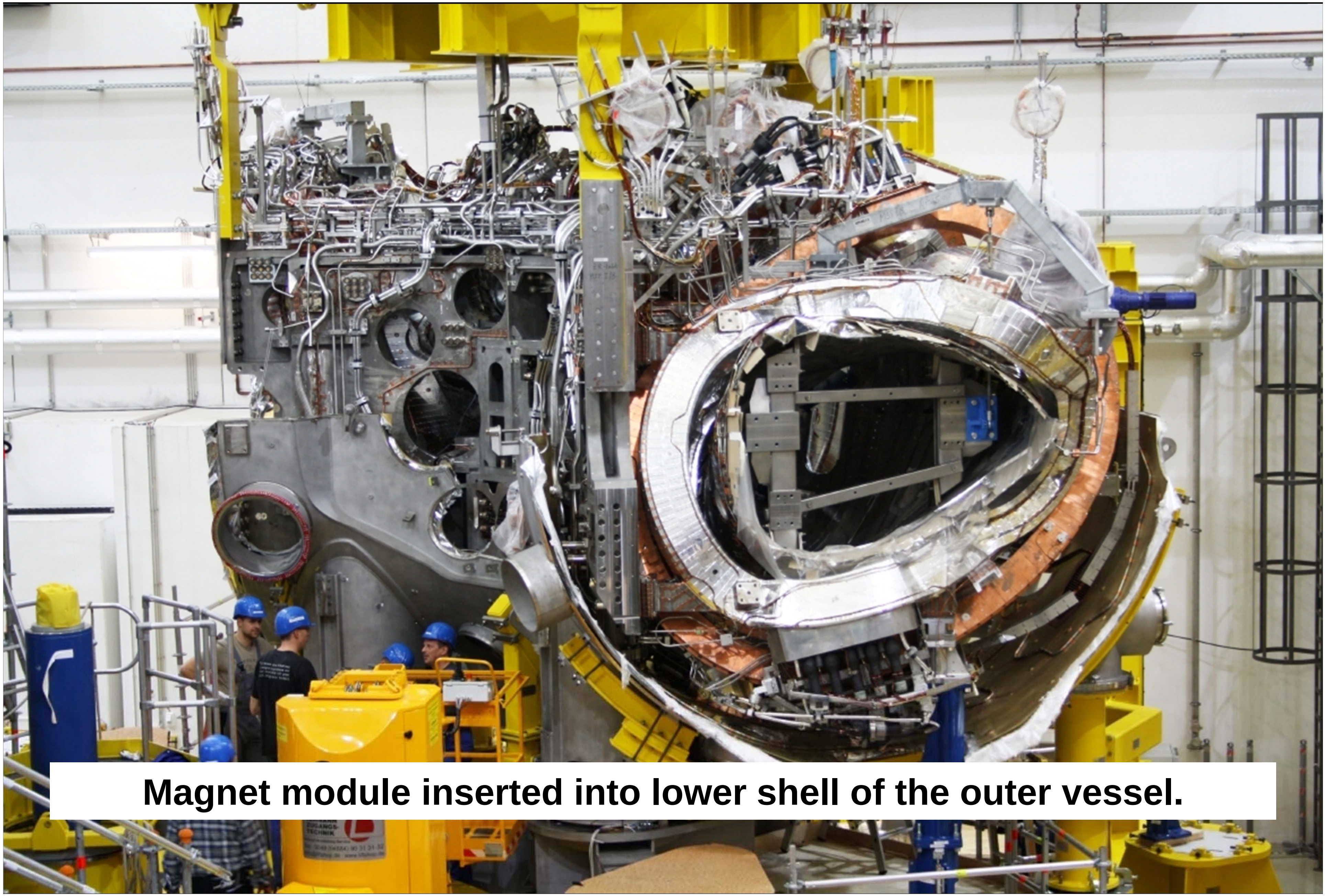
Revision of structural concept





- **Massive increase/modification of welds, ribs, stiffeners**
- **Combination of welded, bolted and sliding contact elements**
  - **reduce stiffness of the magnet system**
  - **Inconel® bolts, Inconel® sleeves, and superbolt® nuts**
  - **sliding Al-bronze elements with MoS_2 coating**
  - **welded steel blocks where unavoidable**

Module assembly



Magnet module inserted into lower shell of the outer vessel.

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Assembly of the bus bar system

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Helium-filled baloons to support the (up to 14m long) bus bars.

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View into the assembly hall

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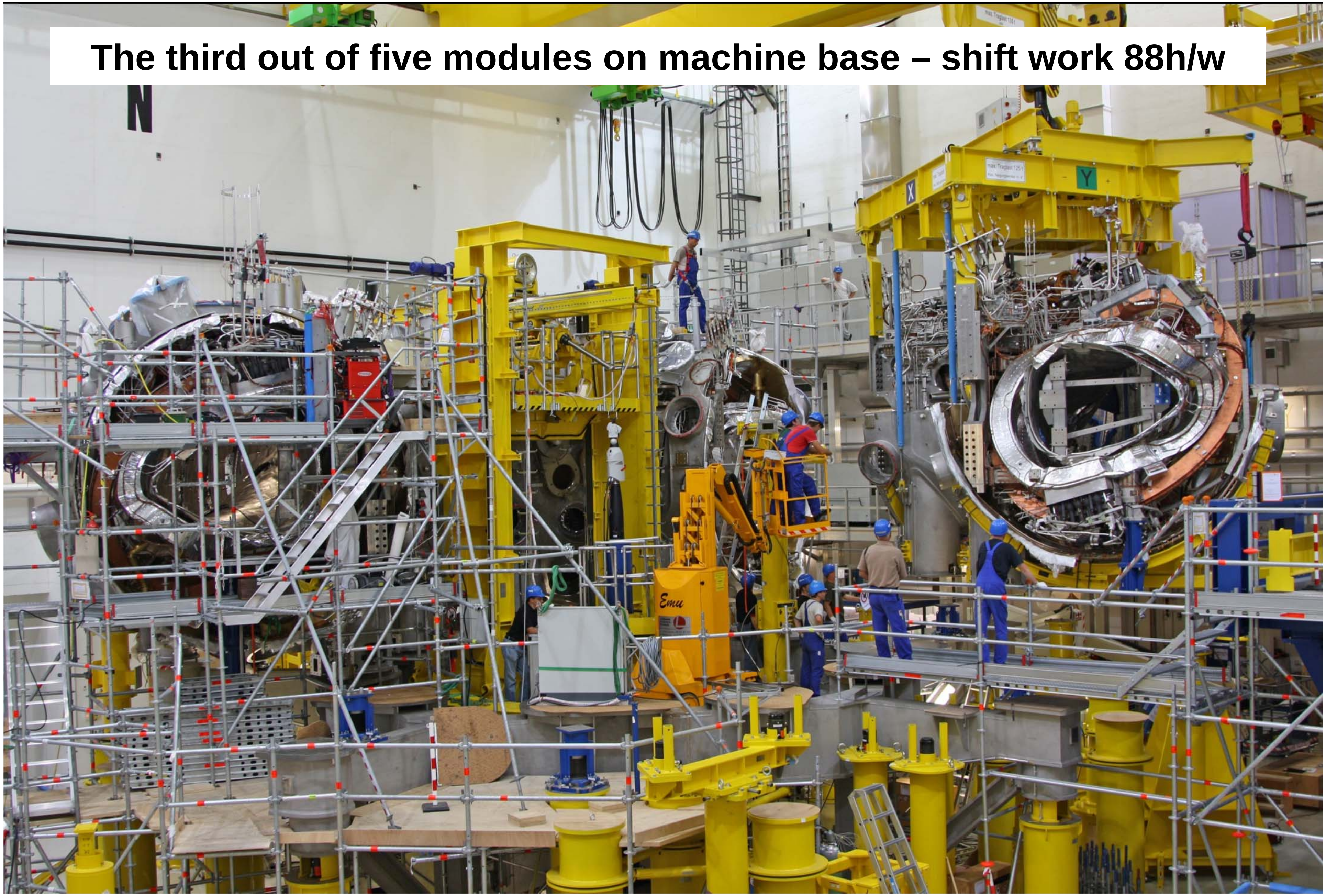
The third out of five modules on machine base – shift work 88h/w



Joining completed modules

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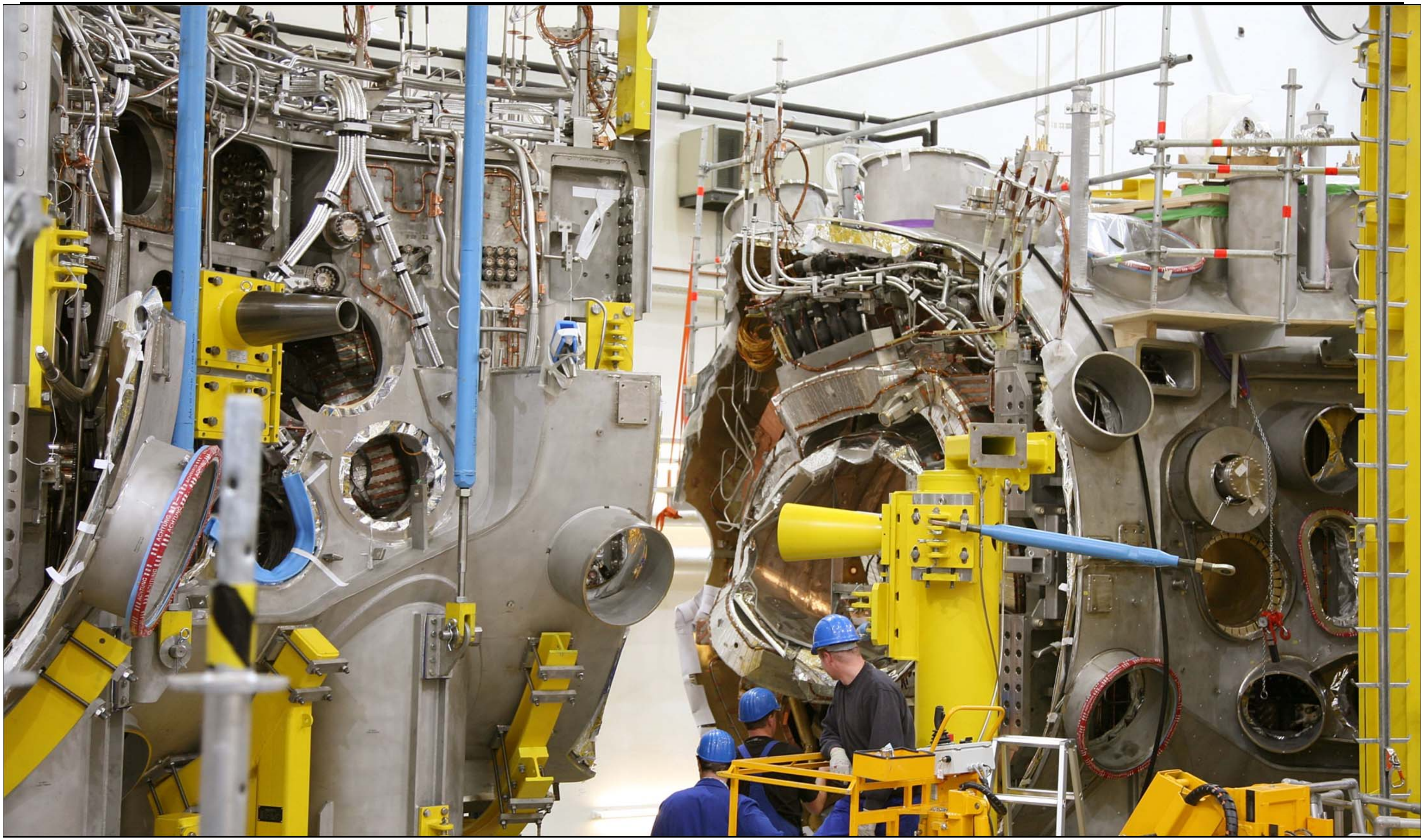
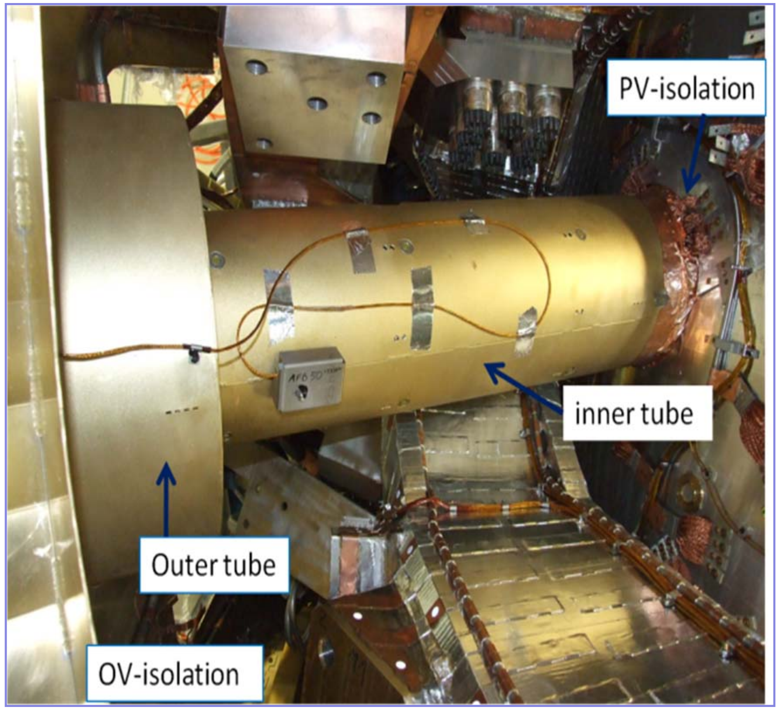
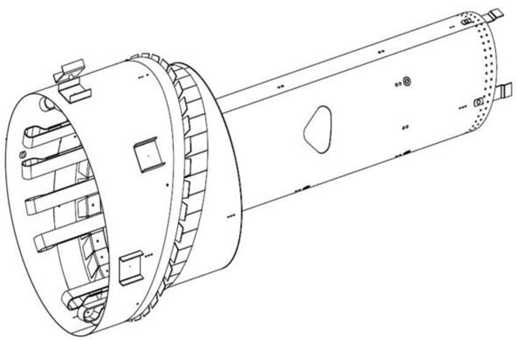


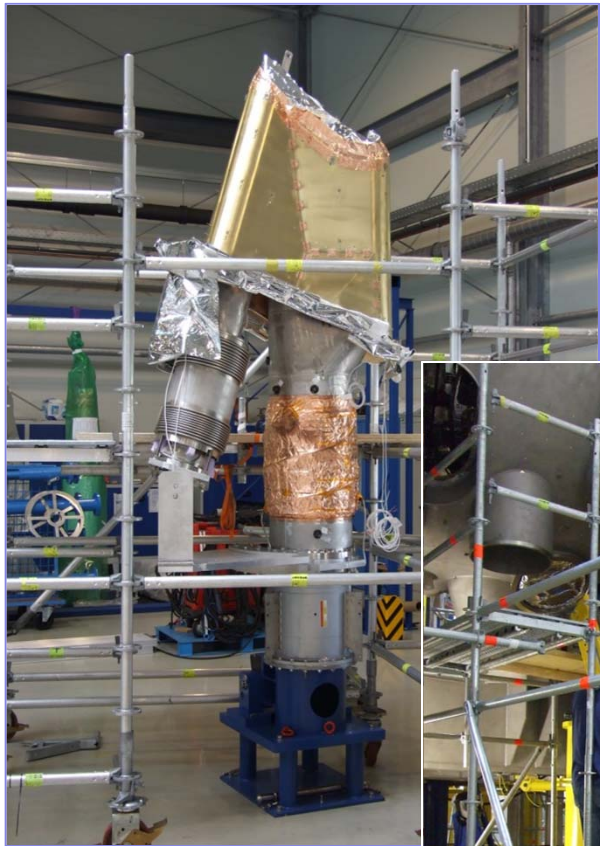
Main task now: assembly of the 253 ports with various geometries

Port assembly



space situation





special ports

port ramp

Port assembly I

Status

Module 5: all ports tack welded and butt welded

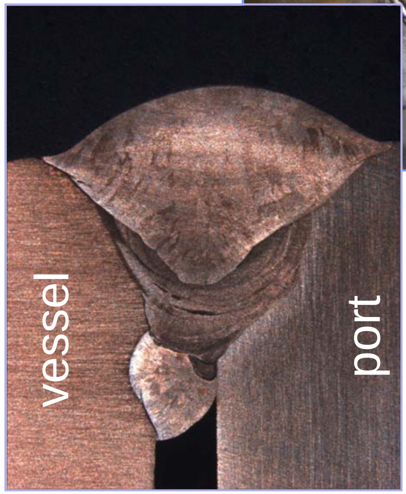
Module 1: all ports tack welded, 20% butt welded

Module 4: first ports tack welded

- dedicated development program
- to achieve the required accuracy
- to keep the process times under control

First experiences

- a few ports out of tolerance
- 10mm instead 3mm deviation at the dome
- almost all can be tolerated
- reason: various – vessel stress plays a role



Port assembly II

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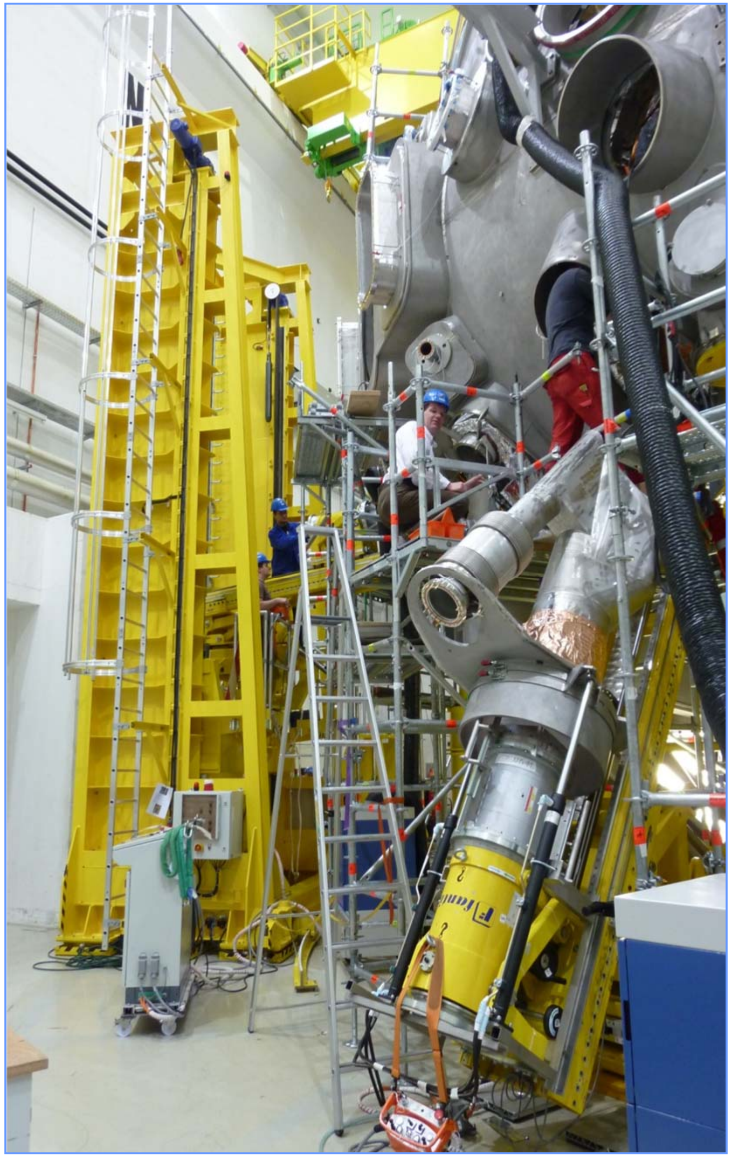
Improvement program

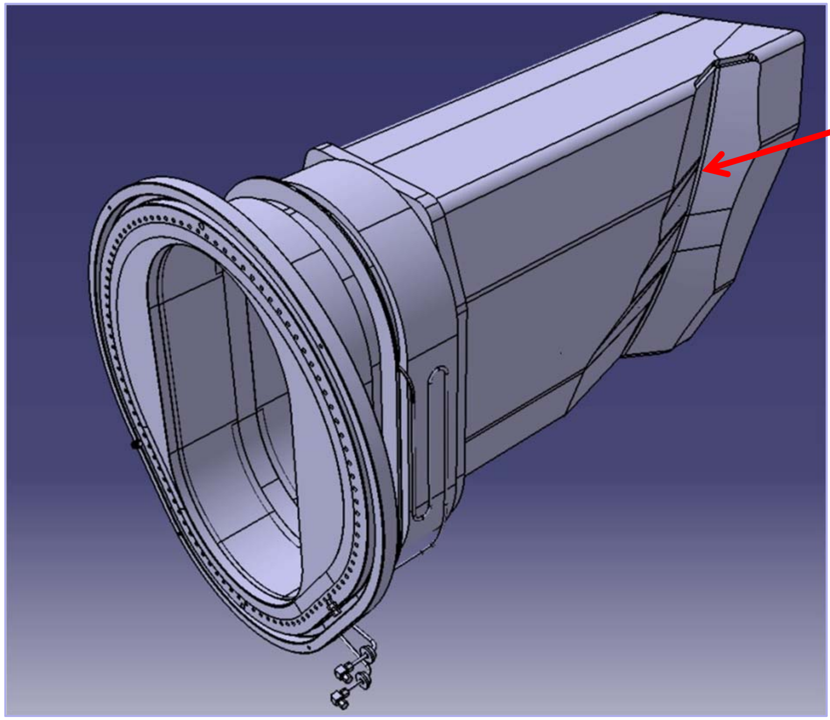
- process time for trial program increased
- 8 trial ports selected
- revised assembly tooling
- full-time laser tracking
- application of full scale welding know-how
- systematic reduction of the tolerance chain in

  1. port positioning
  2. tack welding
  3. butt welding

- result: deviations getting constantly smaller
- moral: even the qualified procedures can fail under the real construction site conditions

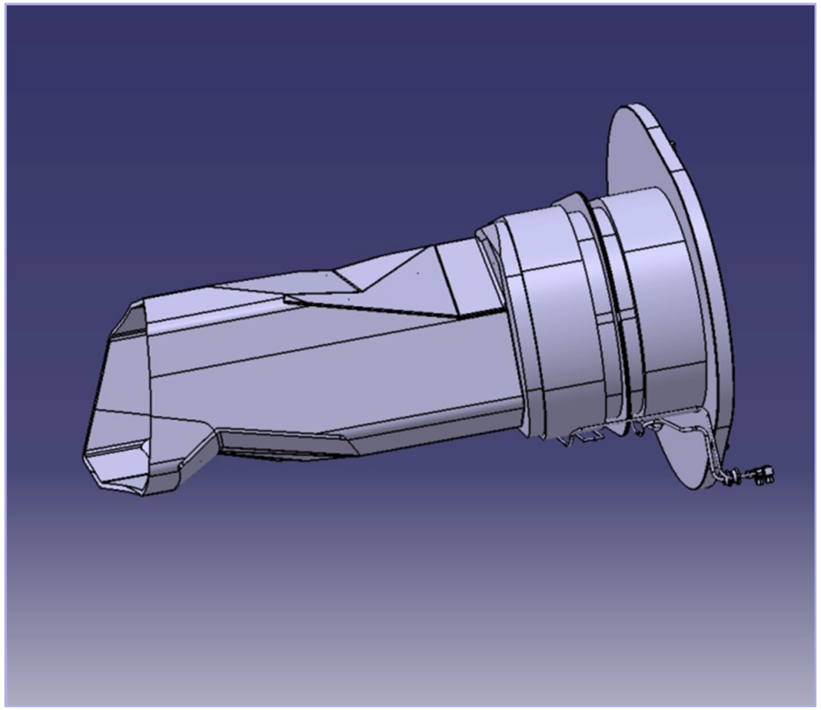


Port assembly III



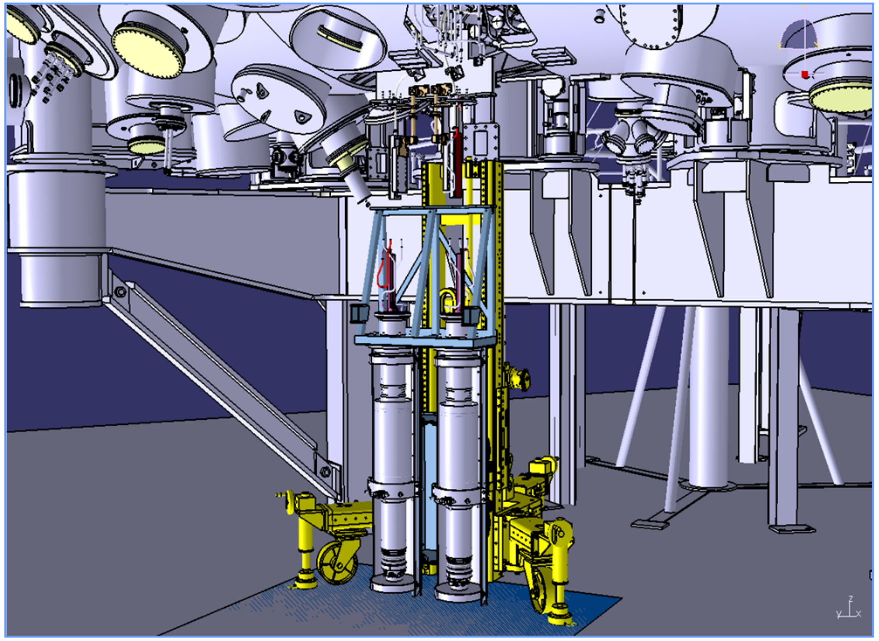
clash with coil

some ports are complex



- NBI port
- maximum space between coils
- split into two parts for assembly

assembly of the current leads



- the current leads are heavy and sensitive
- the space conditions are troublesome
- use of vertical lifting device ~ port ramp
- device can be used as a third port ramp
- dedicated test program on real sized mock-up running
- start of assembly mid 2012

Conclusions I

- stellarators are by nature more complex than tokamaks – no surprise
- one needs the right tools: 3d physics codes
  3d CAD design
  3d FEM
  3d metrology
  3d manufacturing
  3d assembly tools
- the benefit will be most likely much tamer operation incl. steady-state
- goal is to explore the reactor potential of the optimized stellarator
- many possibilities for simplification have been found already now
- to be developed: 3d blanket solutions
  3d remote handling

Conclusions II

- **difficulties in the project were rather generic for big science devices:**

- **challenge to build quickly a strong and competent project team**
- **lack of space and margins causes delays and extra costs**
- **incomplete specifications cause delays and extra costs**
- **necessity to test and qualify everything and every component**
- **necessity to establish both strict and pragmatic procedures**
- **urgent need for early identification of risks – countermeasures!**
- **it is extremely costly and even damaging to shift risks to industry**
- **need for qualified industrial partners with capacity and know-how**
- **technical problems must be solved jointly with industry – inspectors!**
- **monopoly situations often occur and are dangerous**
- **the human factor in the project and outside is important**

Thank you!

Conclusions part I

Stellarators are by nature a more complex than tokamaks. However, the main issues that have led to serious trouble in the project hold for any state-of-the-art fusion and non-fusion projects.

1. **A competent project team must be set up prior to design completion, component specification and start of procurement. Recruitment and head-hunting must be taken extremely serious. Where the know-how is not available, strong external institutional partners must be found and deeply integrated into the project.**
2. **A lack of generous margins, clearances and reasonable tolerance levels implies uncontrolled and uncessary increase of complexity and frequent changes. This has a strong impact on time, money, man-power and potentially sours the relationship to funding bodies.**
3. **Major components must be thoroughly tested and qualified prior to tender action. The manufacturing process must be accompanied by a dedicated in-house test program based on manufacturing samples and mockups. Quality management must be involved in each single step. Trained inspectors must follow up manufacturing in detail.**

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Conclusions part II

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4. **There must be 5-10 persons in the project that know the machine from *a-z*. 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 must be taken to a large extend 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. There the often resulting 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.**