Large structures for experiments and medical applications

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Outlines

Introduction.

Structures in particle detectors, basic requirements.

Design and safety factors, construction, installation.

Integrated design.

Safety factors.

Avoid redundant or over constrained structures.

Load test

Precision. Adjustable parts versus precise parts. Chains of tolerances.

Materials.

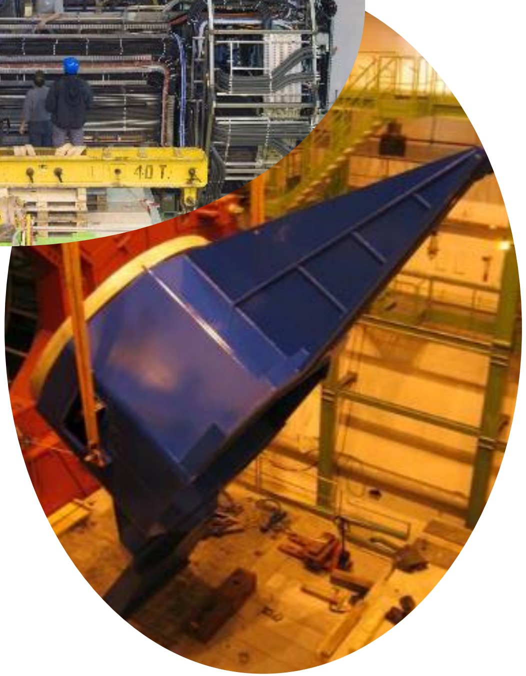
Austenitic stainless steel, aluminium, construction steel.

Welds.

Medical applications.

Gantries.

Conclusions.



Increasing size and complication of the experiments during the years.

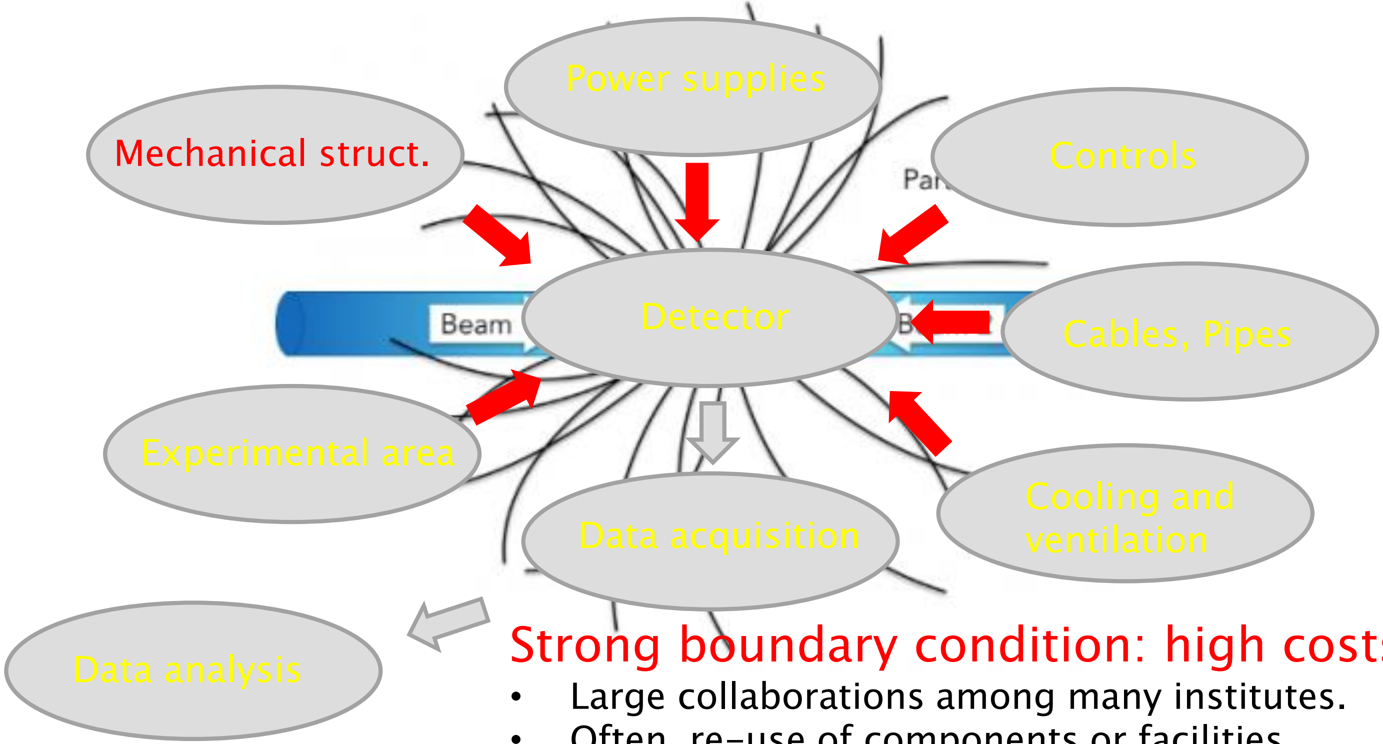
Large, complex support structures.

1964 Brookhaven National Laboratory. CP violation.

Today. ATLAS experiment, CERN.

- The available space is for the detectors.
- Often there is a magnetic field.
- Often radiation environment.
- Installation in large experimental areas with access limitations.
- Evolution of the experiment. New load cases. The lifetime of the structures is longer than a professional life. Documentation!
- Cost versus expectations.

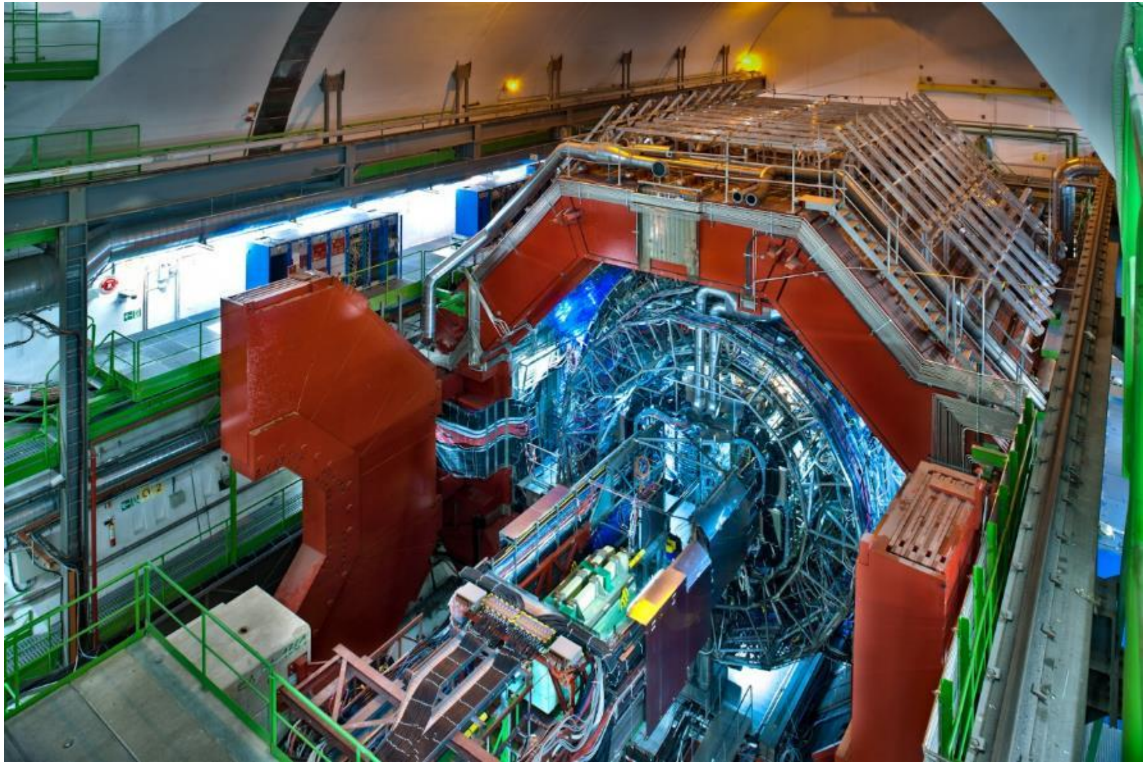
High energy physic experiment



Strong boundary condition: high costs.

- Large collaborations among many institutes.
- Often, re-use of components or facilities.

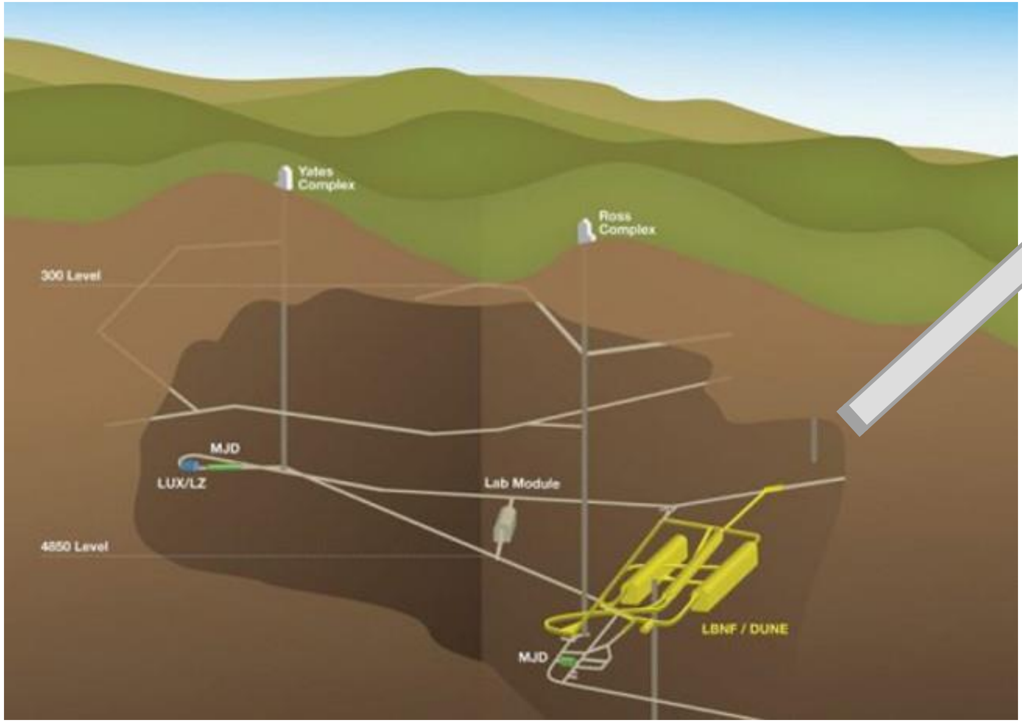
A LHC experiment into a 'second hand' magnet.

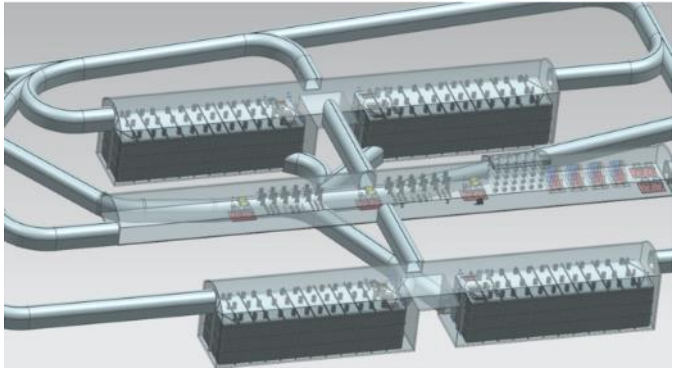


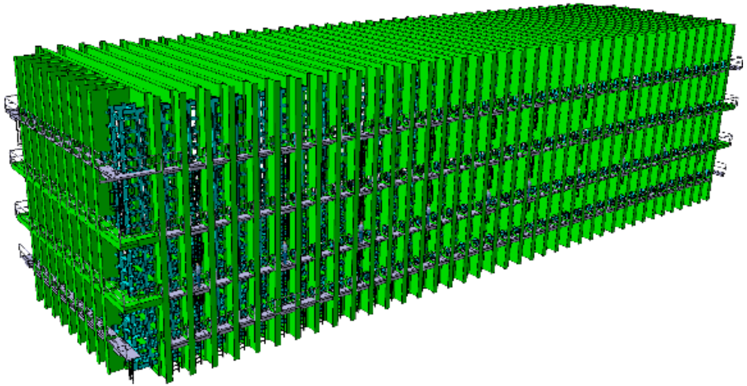
Transfer lines with twisted geometries.

re-used magnets

Dune. A neutrino experiment.
South Dakota old gold mine

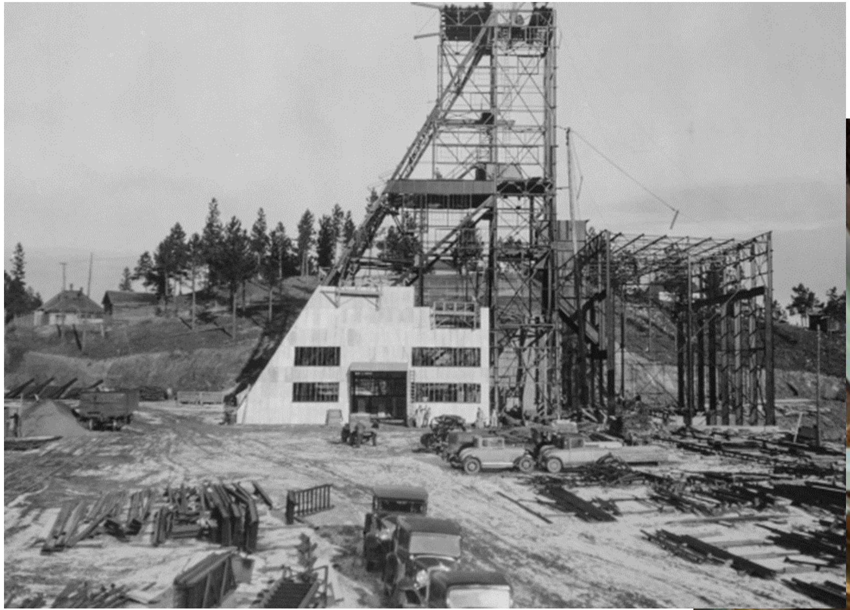






Size equivalent to a 4 floors building ~ 14 m x 16 m x 60 m.
17’000 tonnes of liquid Argon

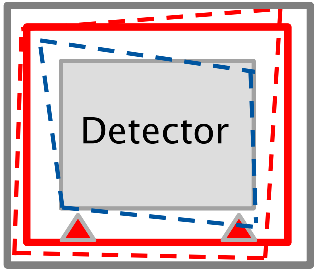
Dune. Ross schaft.



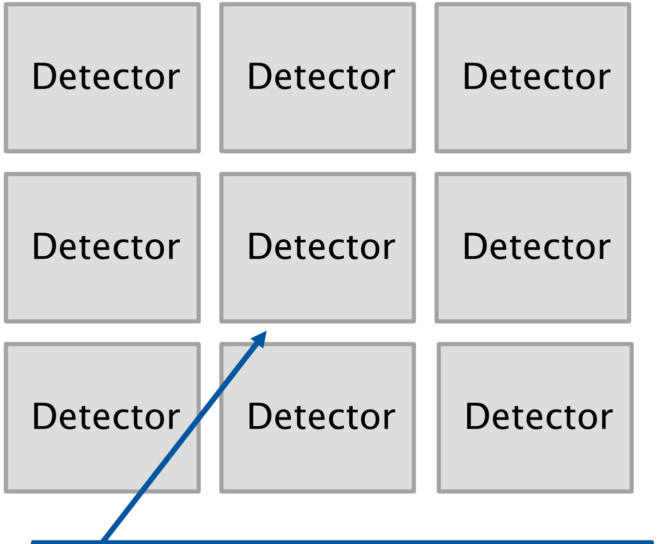
Modular elements
(5 m x 4 m pit).

Minimizing 'dead zones'.

Detector and structure envelope

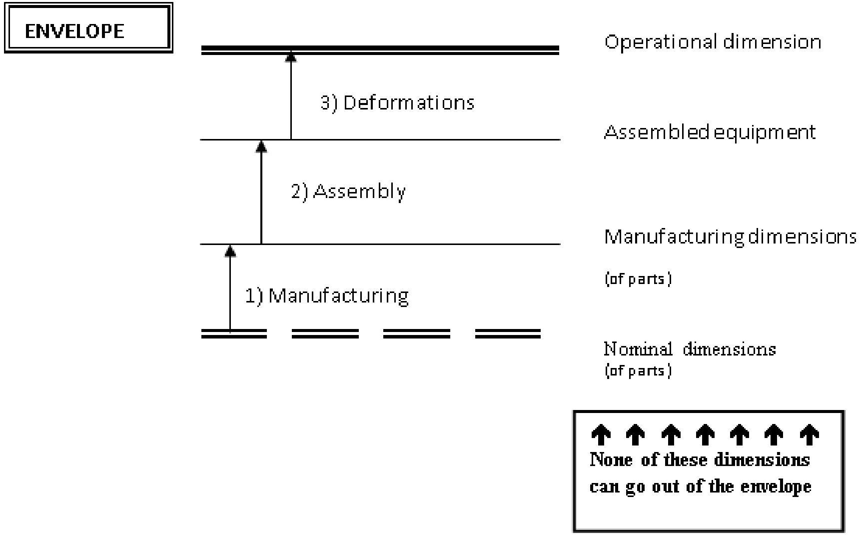


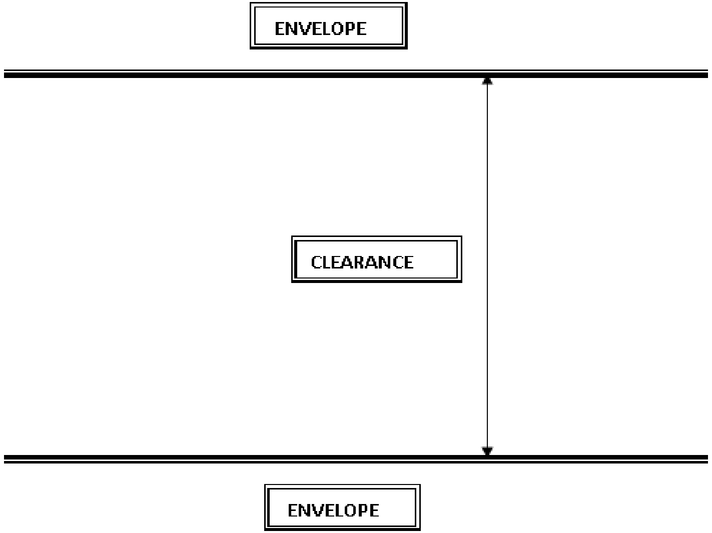
Clearance and support structures are dead zones decreasing the efficiency of a detector.



Small dead zone for supports, services, tolerances, assembly space, deformations.

Definition of Envelope and Clearance





The Envelope is the maximum volume filled by an equipment. This scheme applies in any direction defined in any section of the equipment.

The space between two adjacent envelopes is called Clearance. This is the space necessary for installation, access, alignment, unforeseen loads and fault conditions.

- The definition of the envelopes and clearances is one of the main tasks of the technical coordination in the early design phase of an experiment.

- Assuring the respect of the envelopes by every member of the collaboration is a challenge for the experiment engineer(s) during the whole life of the installations.

- Large structures are heavy. They have millimetric deformations and millimetric tolerances.

- Documentation: CAD models and technical specifications are the reference of the experiment. The memory of old engineers is not always a good and safe solution.

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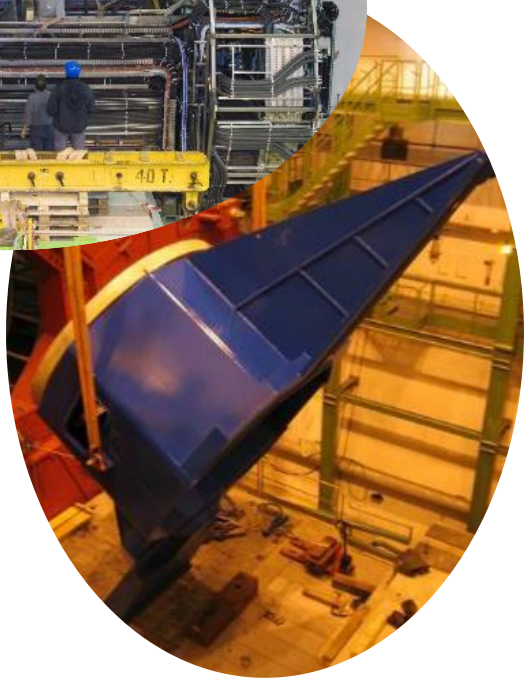


Integrated design

Design of the structure:

- Codes, norms.
- Simplified hand computations – to ‘understand’ the structure.
- FEM simulations – static, dynamic.

Study of the construction and installation sequence:

- Study of the installation transients.
- Design of assembly tools.
- Design of transport and installation tools.

The design and production of a large structure for an experiment requires a ‘system engineering’ approach.

Systems engineering is a discipline that concentrates on the design and application of the whole (system) as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect.

A GUIDE FOR SYSTEM LIFE CYCLE PROCESSES AND ACTIVITIES

Prepared by:
International Council on Systems Engineering (INCOSE)

Design codes – safety factors – easy part

EN Eurocode contents

EN 1990	Eurocode: Basis of structural design
EN 1991	Eurocode 1: Actions on structures
EN 1992	Eurocode 2: Design of concrete structures
EN 1993	Eurocode 3: Design of steel structures
EN 1994	Eurocode 4: Design of composite steel and concrete structures
EN 1995	Eurocode 5: Design of timber structures
EN 1996	Eurocode 6: Design of masonry structures
EN 1997	Eurocode 7: Geotechnical design
EN 1998	Eurocode 8: Design of structures for earthquake resistance
EN 1999	Eurocode 9: Design of aluminium structures

- Static loads (and dynamic) in use.
- Static and dynamic loads during assembly.
- Earthwake resistance.

Each load case is given by the sum of the different loading forces multiplied by their safety factor

The Eurocodes assume that the loads during the life of a structure and the material properties are well known. This is the case for civil engineering in Europe. Consequently, the safety factors in these codes are relatively low.

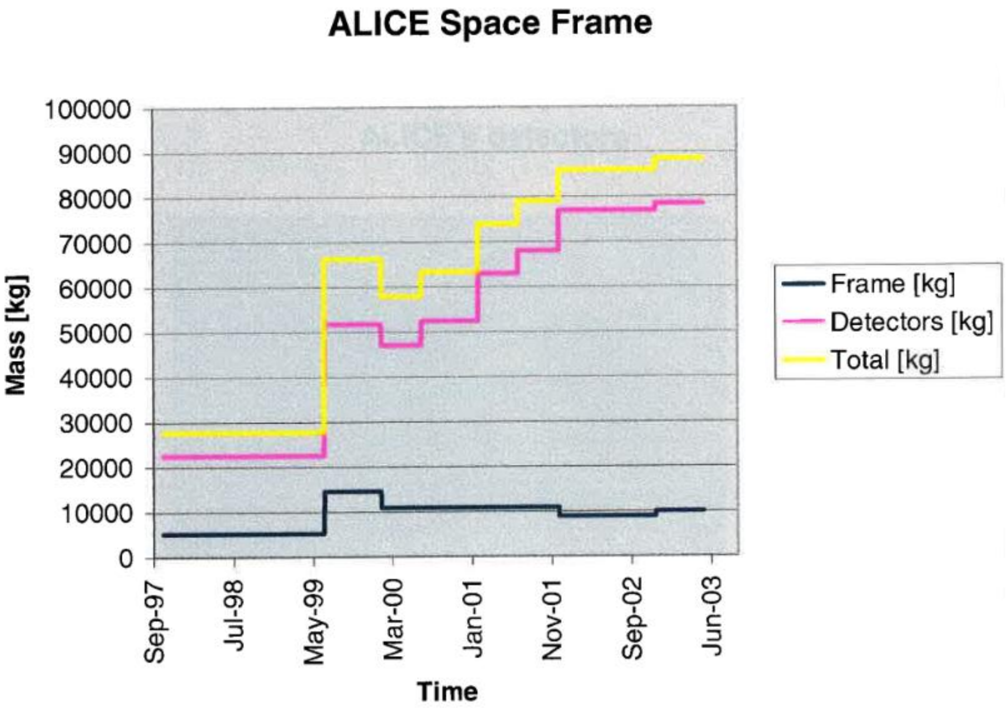
Design codes – safety factors – difficult part

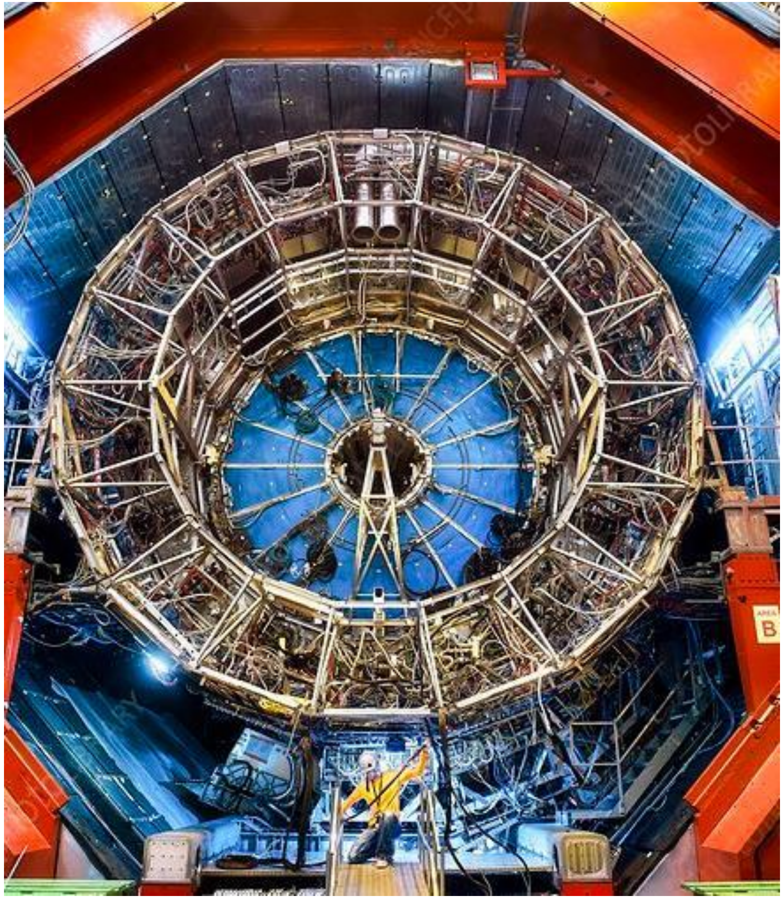
- An experiment has a lifecycle very different from civil engineering structure. Detectors are modified and changed over a period that can reach a couple of decades or more. The support structures are ‘covered’ by services and all the space is filled by active components. Modifications are not always possible.

- In a collaboration some components are delivered late. Not all the institutes get the money they wanted. Not everybody made the right estimation. Detectors (loads) are staged. Stresses in a partially charged structure can be locally higher than in the same structure completely loaded (in particular once the symmetry is lost).

- The weight of the detectors and services are not precisely known and evaluated at the beginning of a collaboration.

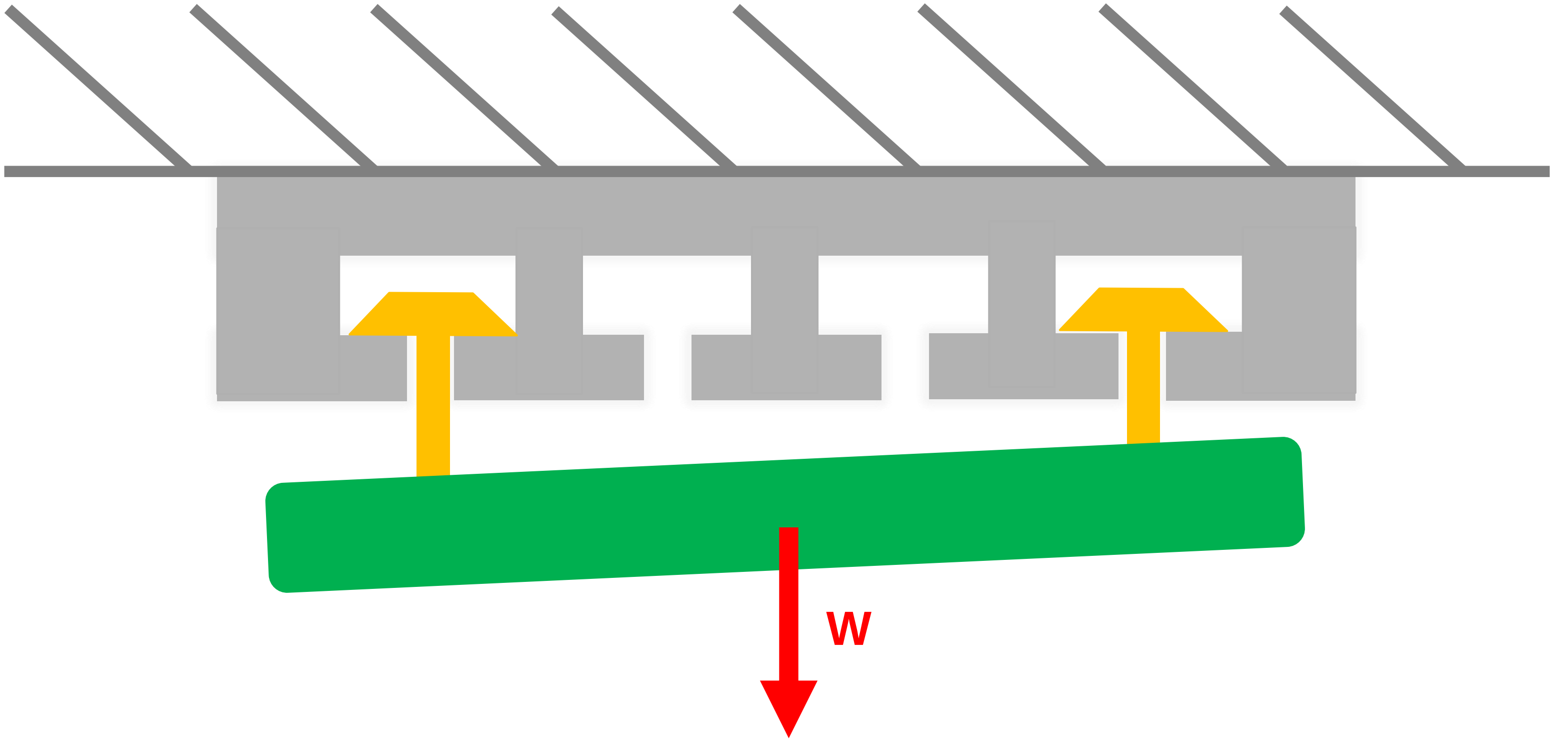
For all these reasons it is better to use the Eurocode in a careful way. I suggest a further ‘extra safety factor’ to be applied to the known loads: 1.5 – 2.0



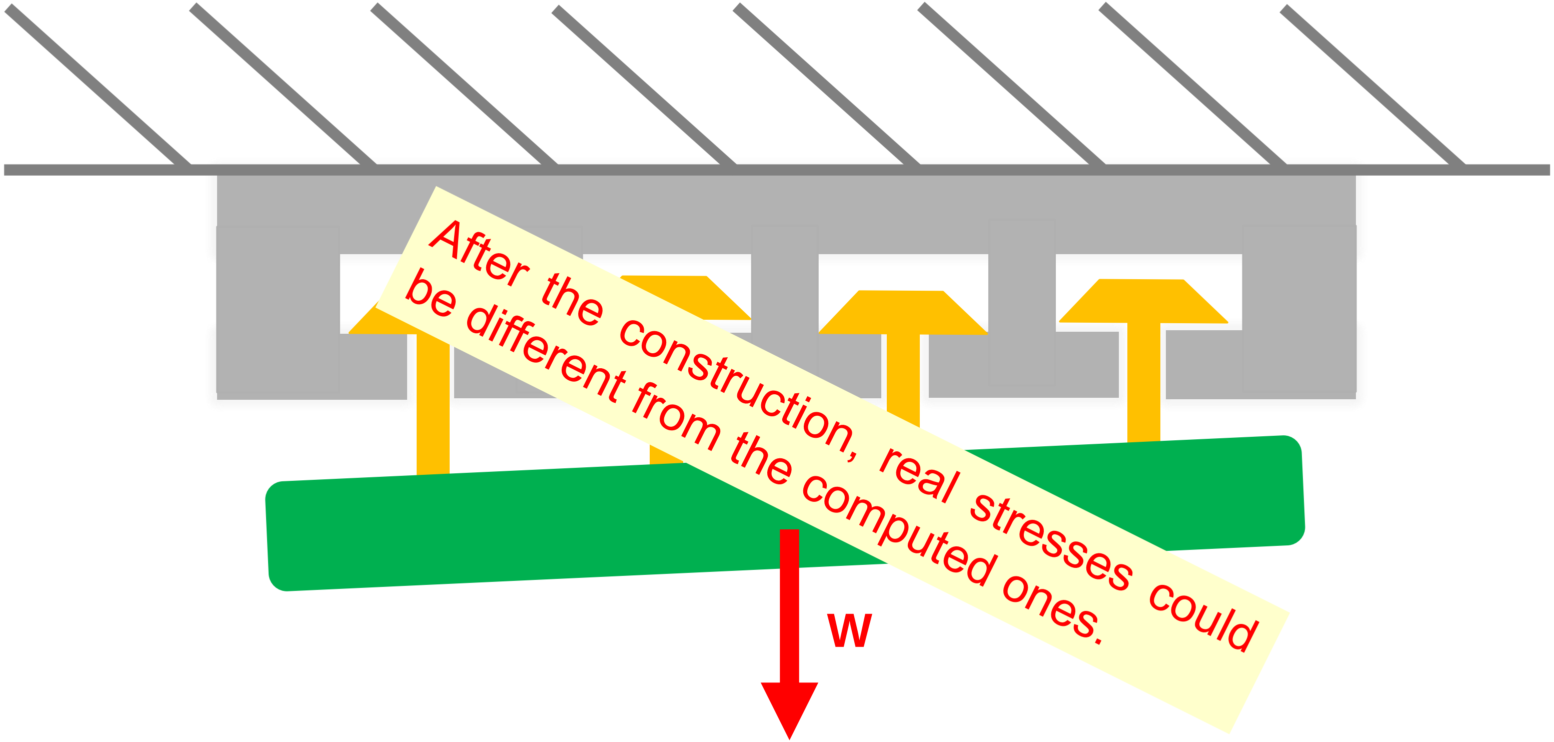


(Weight in June 2003) / (Weight in March 2000) = 1.6
Bare Eurocode coefficients in 2000 would have been too low.

Avoid over constrained structures



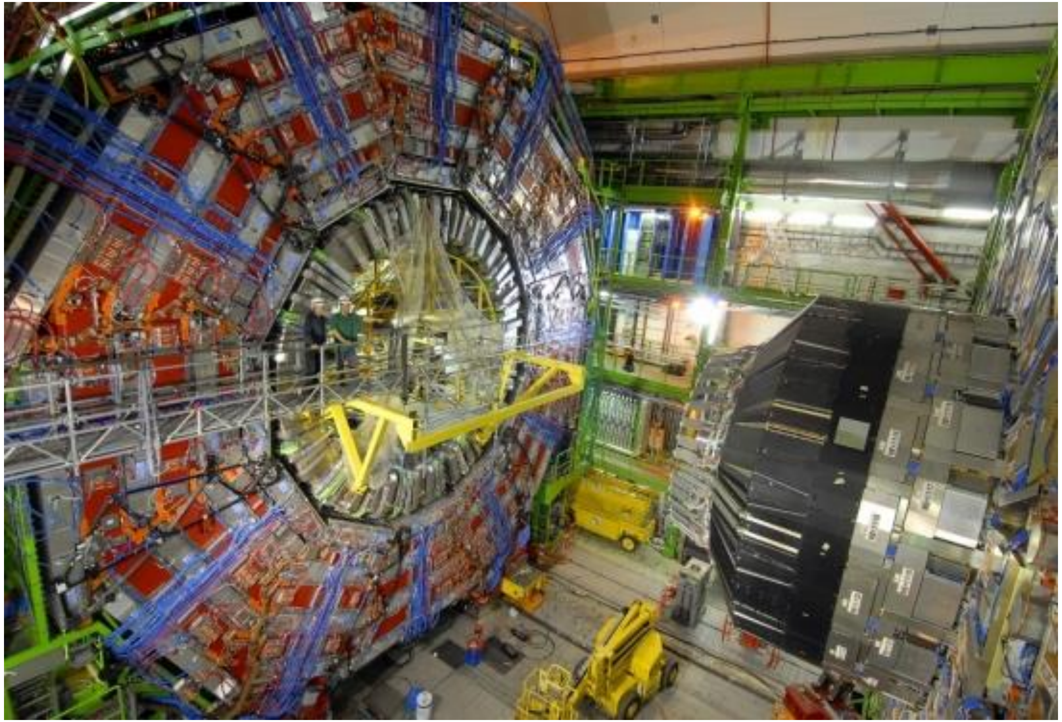
Redundancy of supports does not increase safety. It just increases uncertainty.

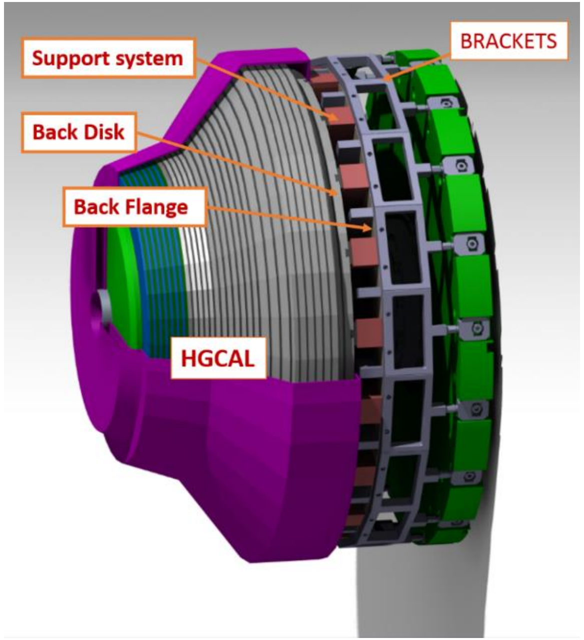


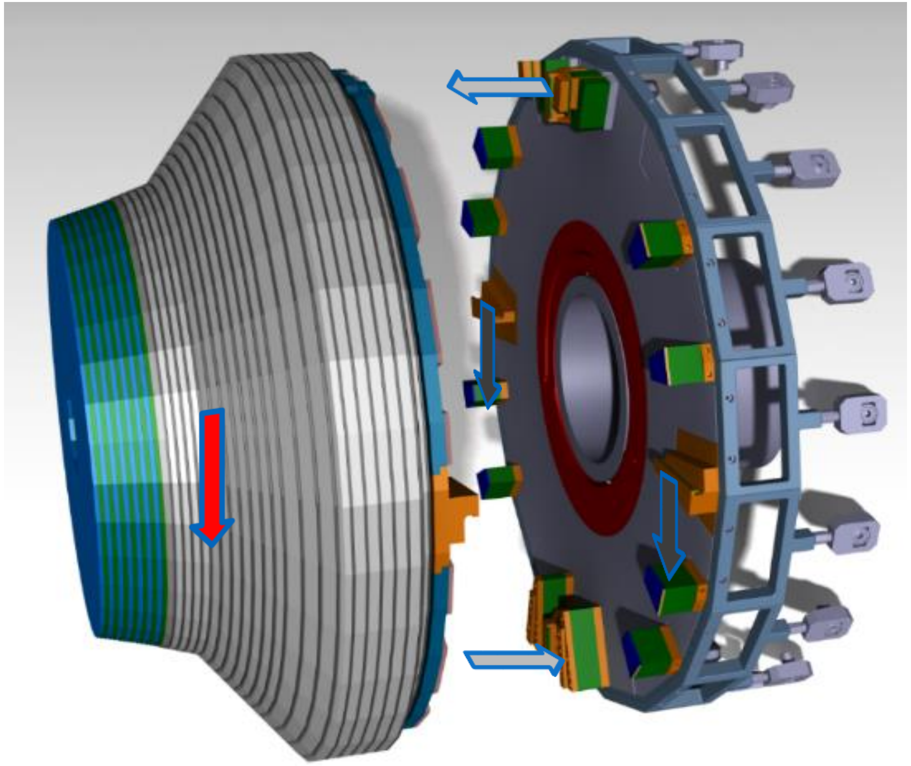
HGCAL for CMS – Upgrade for HL-LHC

Total weight: ~200 tonnes

Sandwich structure made of detector layers and austenitic stainless steel plates.

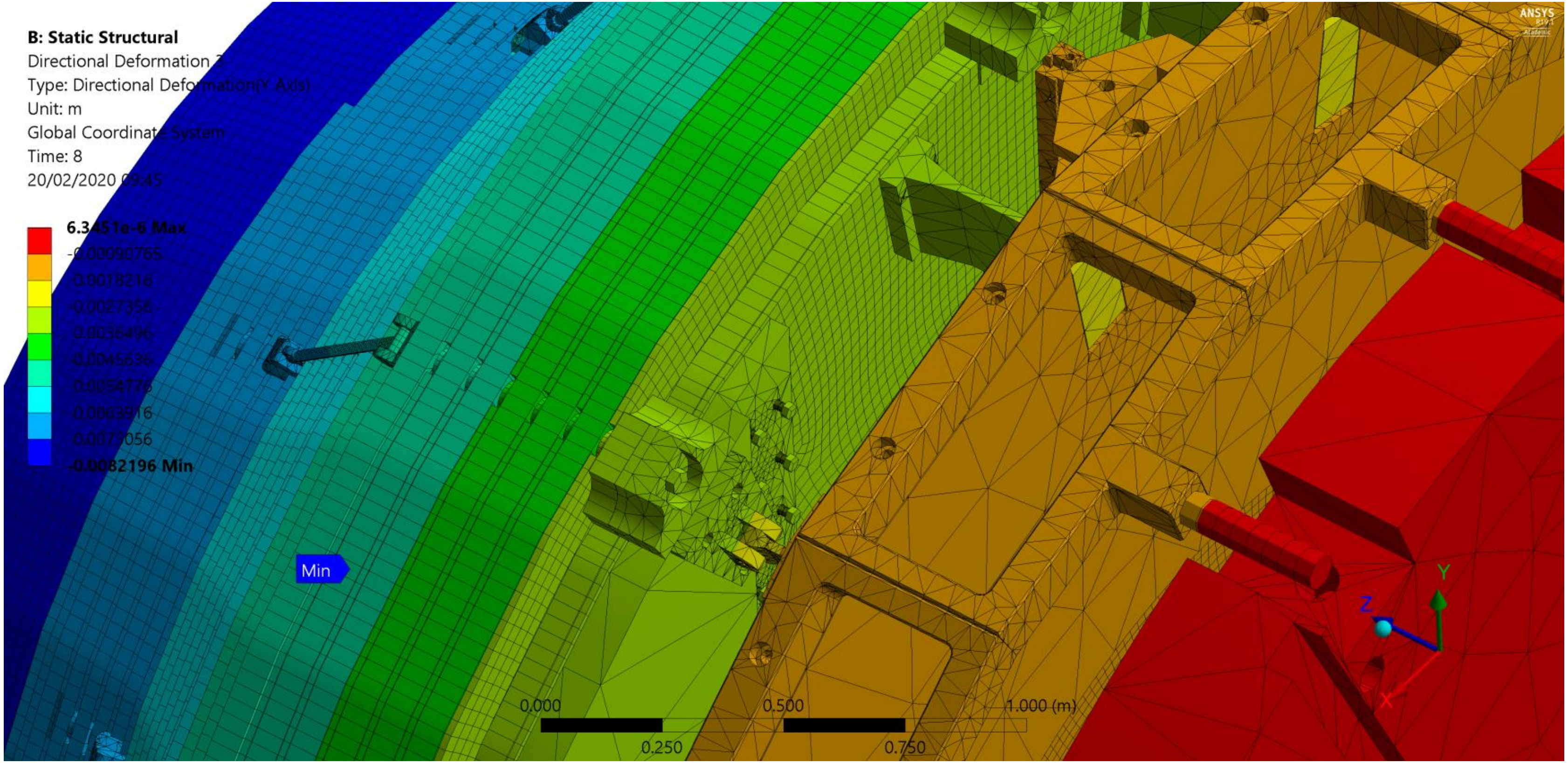






Separate functions

- Two vertical force supports at 3 and 9 o'clock.
- One horizontal traction support at 12 o’clock.
- One horizontal compression support at 6 o’clock.



B: Static Structural
Directional Deformation 3
Type: Directional Deformation(Y Axis)
Unit: m
Global Coordinate System
Time: 8
20/02/2020 09:45
6.3451e-6 Max
-0.00090765
-0.0018216
-0.0027356
-0.0036496
-0.0045636
-0.0054776
-0.0063916
-0.0073056
-0.0082196 Min
Min
0.000
0.250
0.500
0.750
1.000 (m)
ANSYS

Load tests (when possible)

- At the end of the construction and before the final installation it is good practice to use dummy loads and test the structures.

  ✓ Verification of the computations.
  ✓ Verification that the construction respected the technical specifications.

  ✓ Check the linearity of the deformations at increasing loads.
  ✓ Check of the structure at full load.

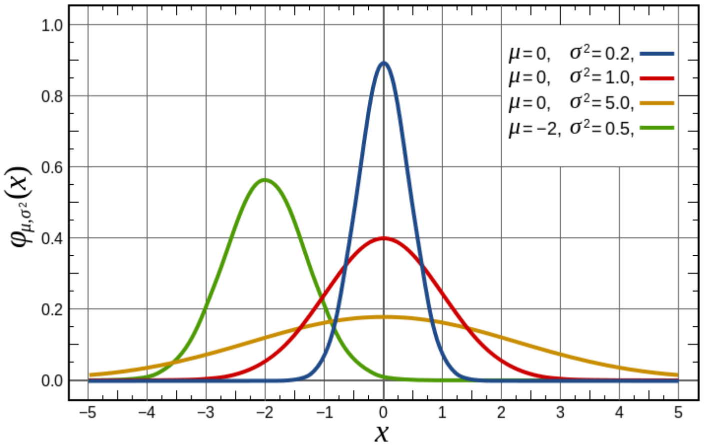
Attention to the boundary conditions and position of the loads. It is not always easy to simulate in a quick and economical way the real configuration of the loads.

The precision required for these measurements should be realistic. Normally half a millimetre, for structures of meters, is enough.

Precision

Chain of tolerances

The resulting size of a mechanical assemblies made of parts with normal distribution dimensions will have a normal distribution.



$$\sigma_{RES}^2 = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \ldots\ldots + \sigma_n^2$$

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

If we pile up N identical pieces with tolerance ± x (gaussian distribution)
Resulting tolerance R = ± x $\sqrt{N}$

If I want a tolerance of ± 1 mm for a structure made of 1000 pieces, I need a tolerance ± 0.03 mm for any piece (tolerances of shape and dimension).

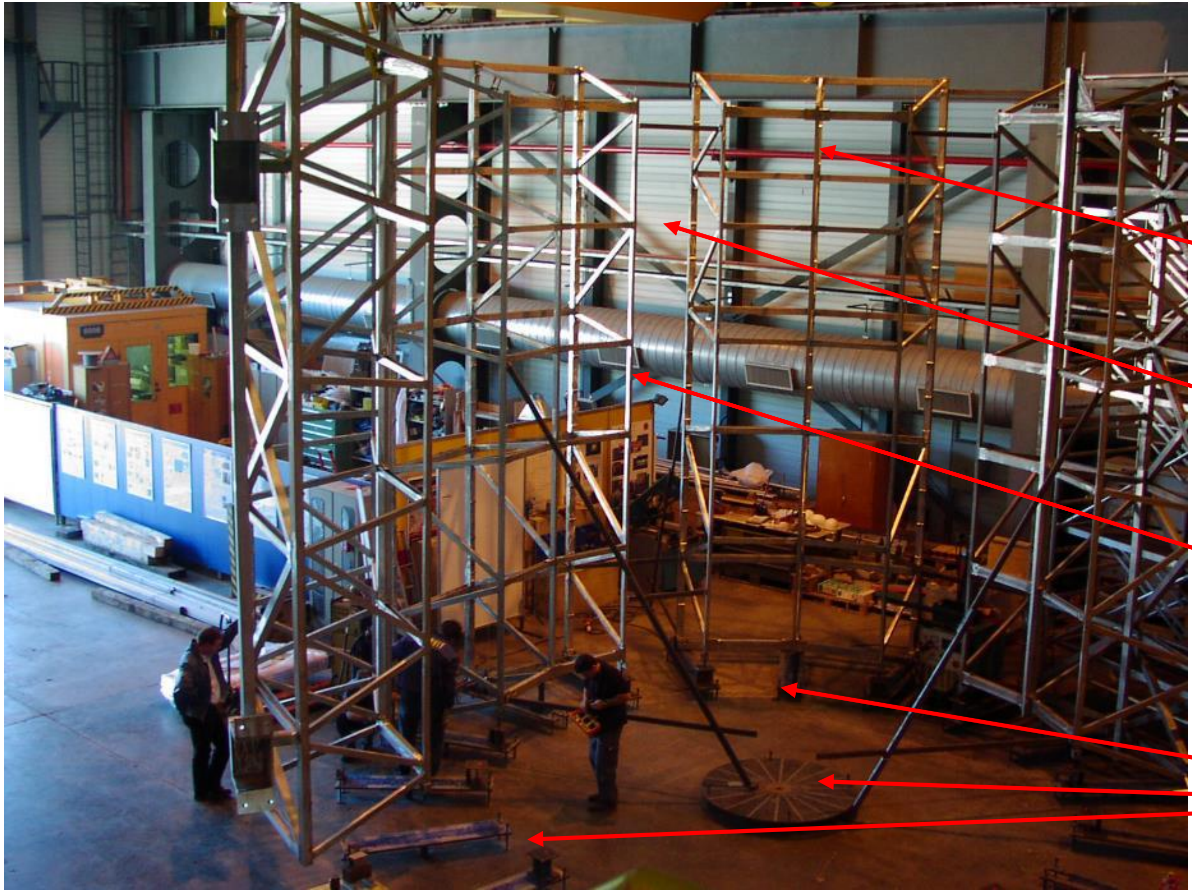
Precision

Instead of increasing the precision (cost) of the parts one should try to foresee adjustable elements: shims, moving plates with screw tuning their relative position, etc..
A wall can be straight even if the bricks are not as precise as watch components.

The construction can made in steps:
Assembly of subcomponents.
Measurement.
Assembly of the rest of the subcomponents with compensation of the dimensions.

Axisymmetric structures will be more precise if assembled with the axis in vertical position. But then it will be necessary to rotate a very heavy and large element.

Vertical assembly of an axisymmetric element



Subcomponent.

Missing beams. Measure and cut to size.

Vertical allignement: weight and wire.

Reference elements.

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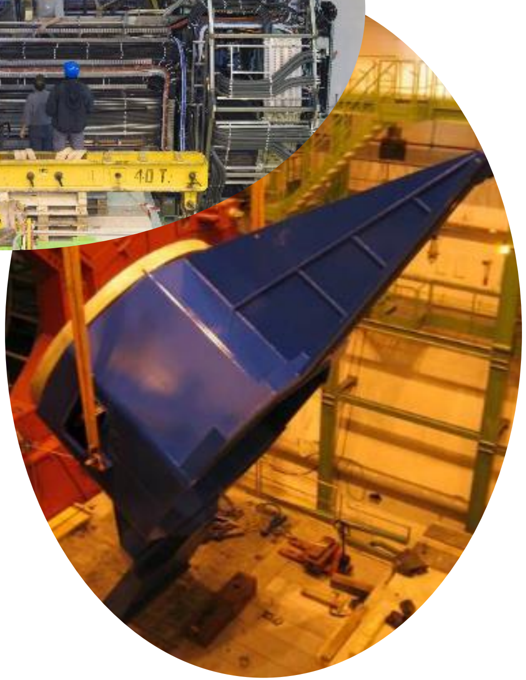
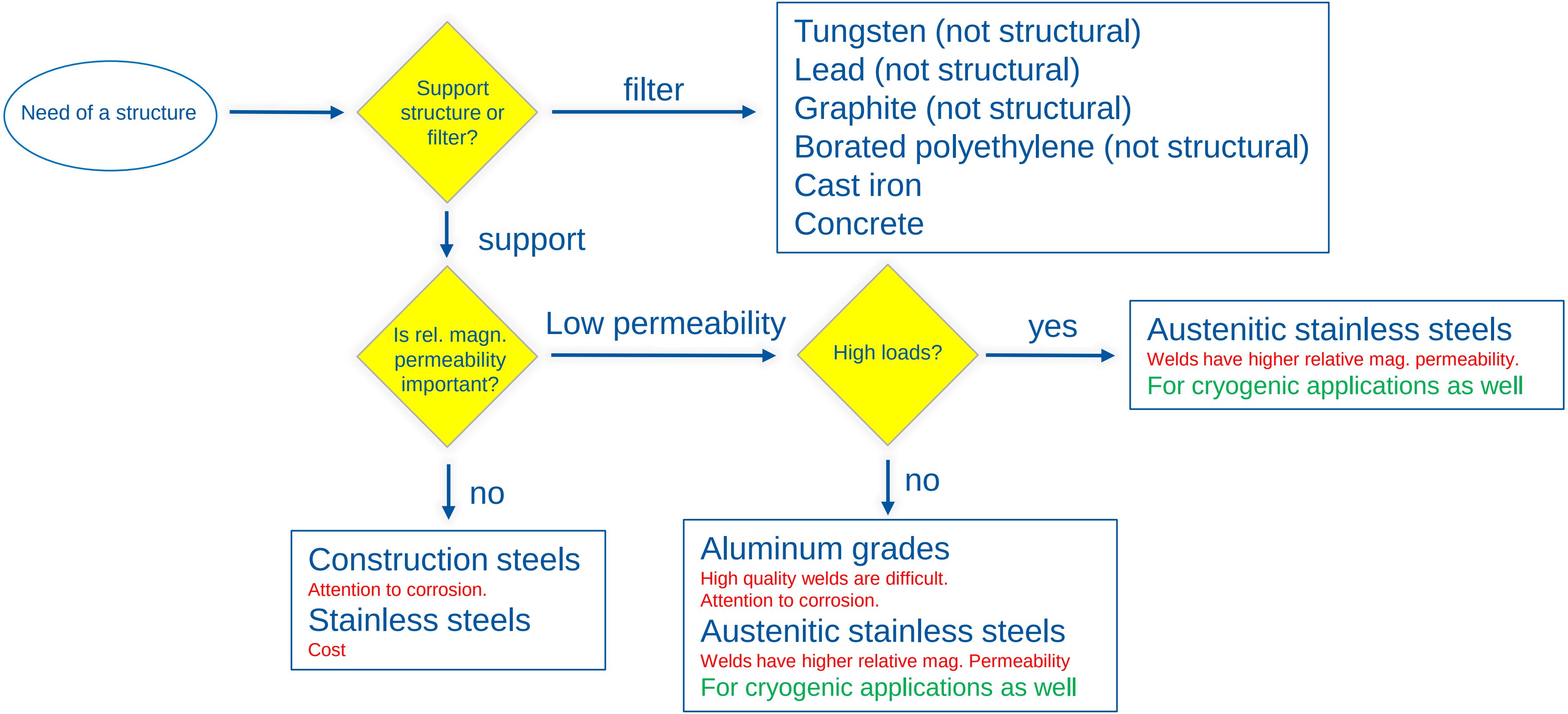
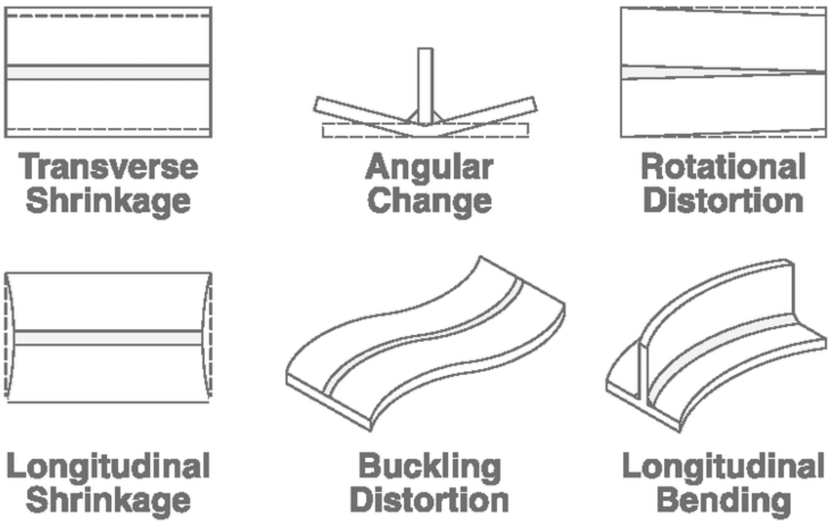


Most common materials used in large structures for experiments



Welds causes millimetric deformations. Sometimes construction tolerances are of the same order of magnitude or (often) smaller.



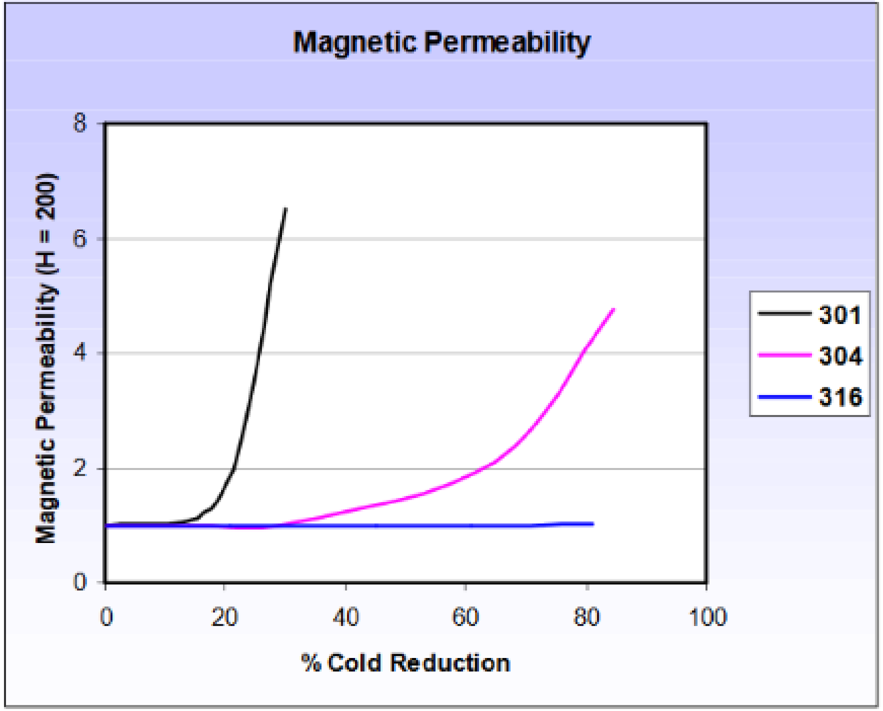
- Measurement of test welds and then modification of the dimensions of the pieces to be welded.
- Compensation using a well-defined sequence of welding (up – down, left – right, etc.). Need of tests.

Relative magnetic permeability of austenitic stainless-steel welds.

The filler metals matching the 300 series austenitic steels, are defined to have a small fraction of delta ferrite phase, typically around 5-15%, to reduce the risk of solidification cracking, which exists for purely austenitic compositions.
As an example the relative magnetic permeability of an AISI 304LN base material can be 1.05 or less while it increases to 1.4 – 1.8 in the weld.

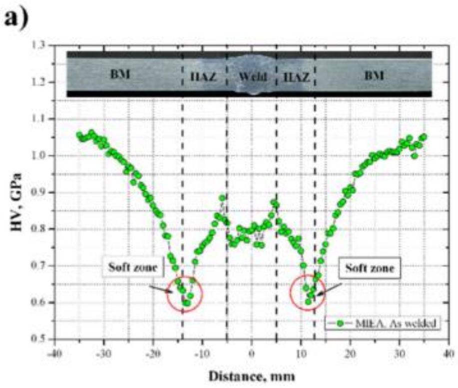
Welds are a small part of the structure. Some welds are close to the sensitive elements of the detectors, others more far away. The effect of slightly magnetic parts has to be evaluated case by case.

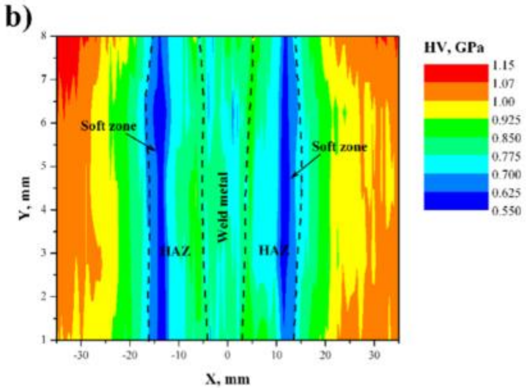
Effect of cold work on magnetic permeability of austenitic stainless steels

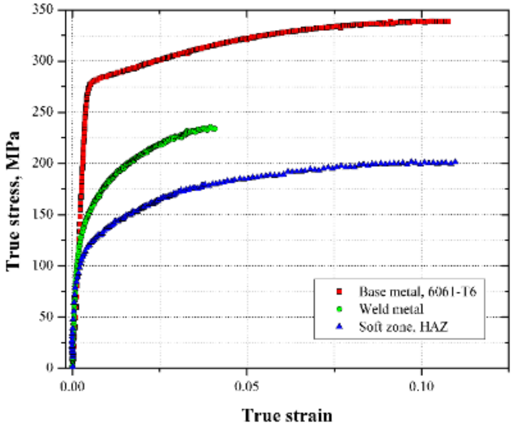


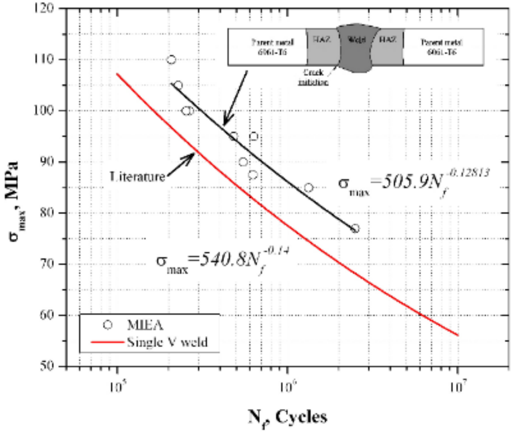
Forming and machining can change the magnetic permeability of low alloyed steels.

Strength of aluminum welds.







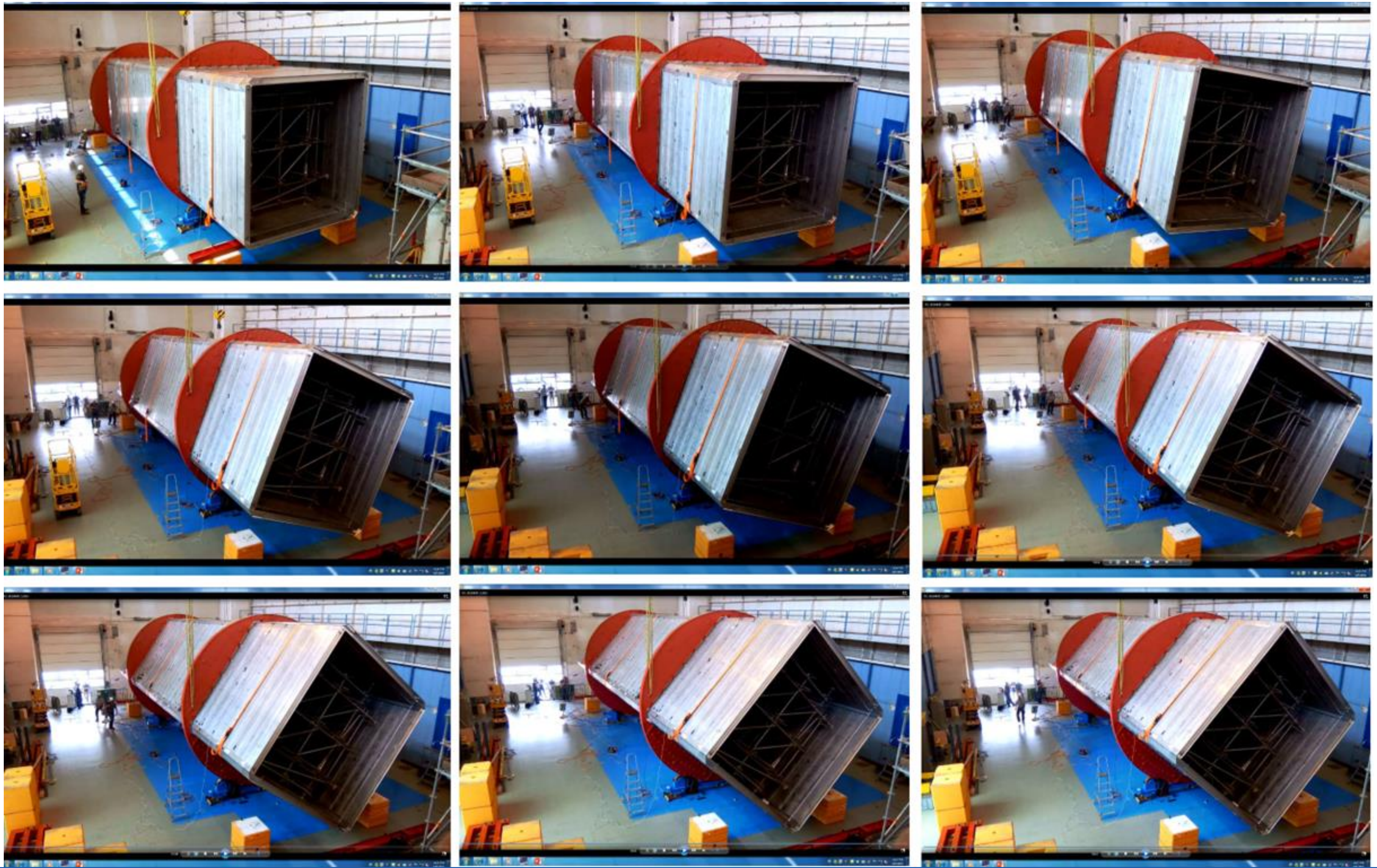


Mechanical Behavior of Precipitation Hardened Aluminum Alloys Welds

R.R. Ambriz and D. Jaramillo

https://www.intechopen.com/books/light-metal-alloys-applications/mechanical-behavior-of-precipitation-hardened-aluminum-alloys-welds

Use of inserts to avoid welds in the stress concentration zone. AW 6082 T4



Icarus cryostat
(neutrino experiment)

Aluminum high quality welds must be executed horizontally.

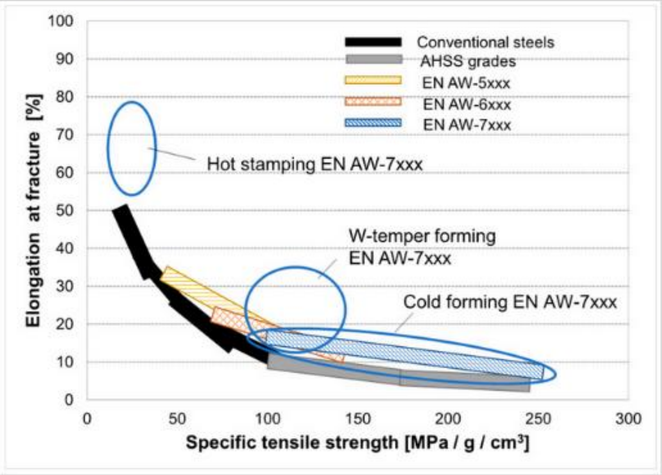
The structure had to be turned many times.

AW 6060 T4

High strength aluminum grades have low elongation.

They are brittle!

Figure 1. Specific tensile strength plotted against elongation at fracture for different aluminium wrought (EN AW) alloy series, conventional steels, and advanced high-strength steels (AHSS). Own illustration based on [3,4].



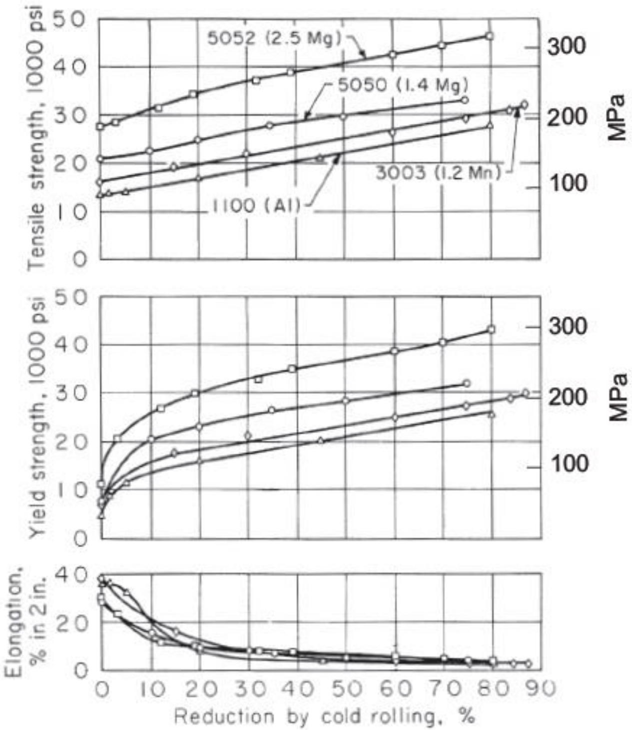
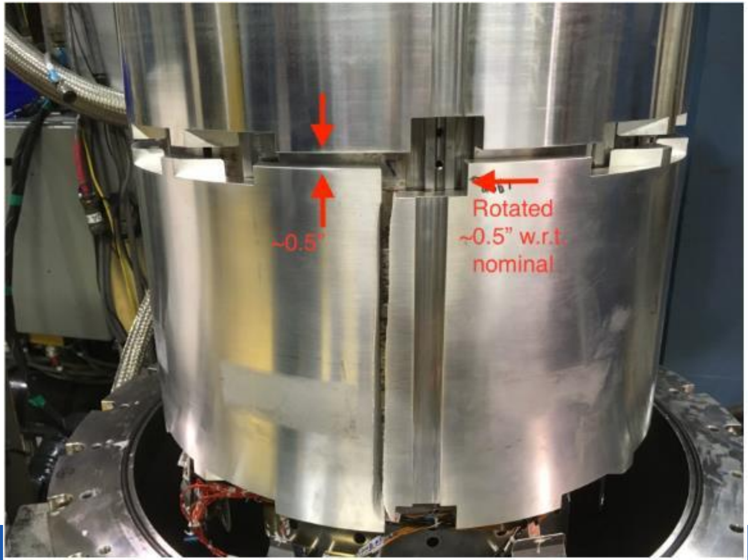
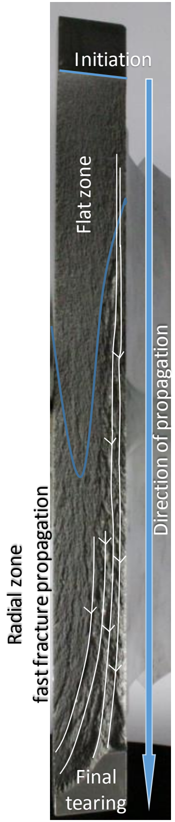
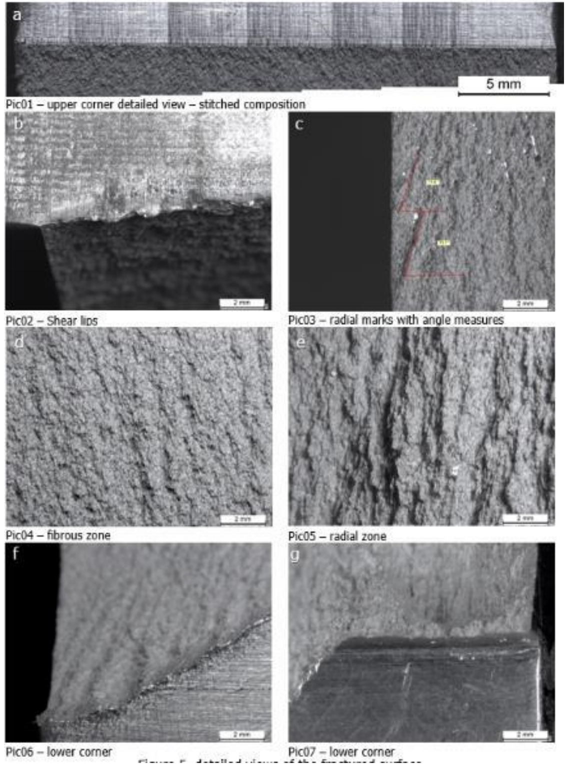


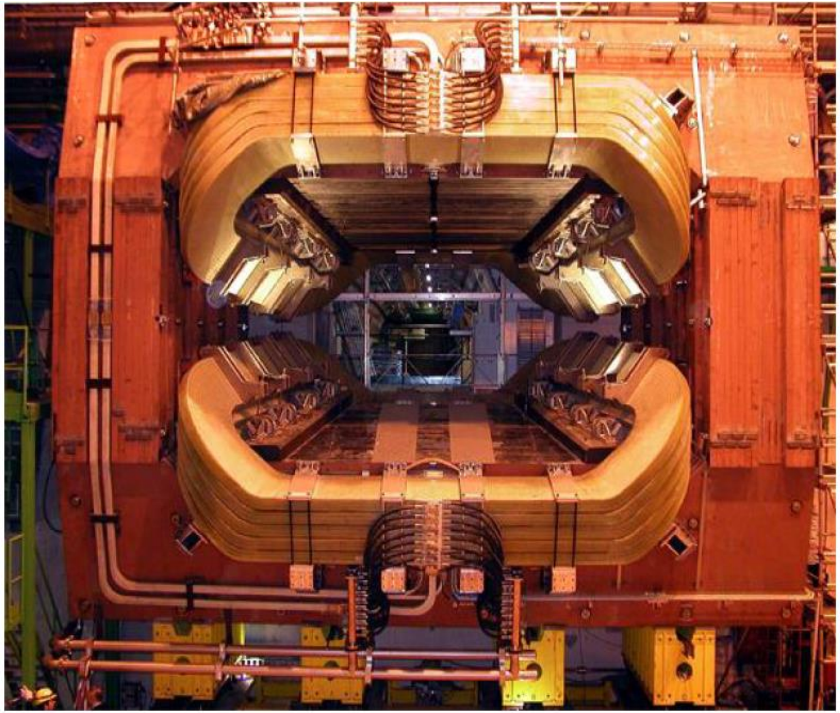
Fig. 5 Work-hardening curves for wrought non-heat-treatable aluminum alloys. Source: Ref 1

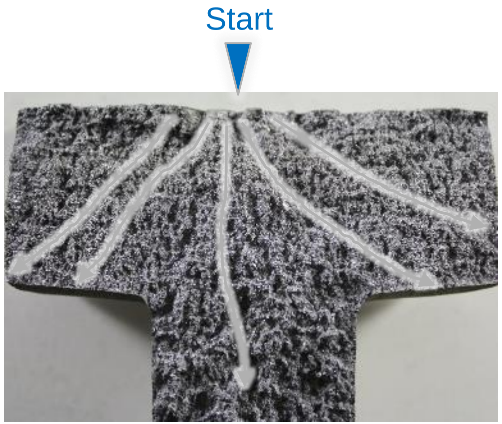
EN AW-7075-T652











EN AC-42100 T6
(AlSi7Mg0.3)
Cast aluminium

Typical properties of some commonly used alloys – laminated plates

	$Rp_{0.2}$ [Mpa]	Rm [Mpa]	A %	HB	Density ρ [kg/m³]	E [GPa]	Weld.	Relative mag. permeability Plate Weld	Cost [CHF/kg]	
AW 6060 T4	60	120	16	45	2700	~70	Yes	1	6	Standard applications
AW 6082 T4	110	205	14	65	2700	~70	Yes	1	7	High strength, low A%.
AW 6082 T5	230	270	8	80	2700	~70	Yes	1	7	High strength, low A%.
AW 2024 T6	345	427	5	125	2700	~70	Bad	1	15	Space applications, low A%.
AISI 304	215	505	70	123	8000	~200	Good	1.2* 2.5*	3	Standard applications
AISI 304 L	210	564	58	140	8000	~200	Good	1.1* 2.0*	4	Standard applications
AISI 316 LN	280	580	40	200	8000	~200	Good	1.005 1.4*	35	UHV, high strength. Availability?
S235JRG2	200	400	22	120	7900	~210	Good	High	2	Standard applications, magnetic, oxidation.

* Order of magnitude values

$E_{ass} = 2.86\ E_{all}$

$\rho_{ass} = 2.96\ \rho_{all}$

Same cross section beam loaded with same forces $\varepsilon_{all} \sim 3\ \varepsilon_{ass}$

To have the same deformations $I_{all} \sim 3\ I_{ass}$, $A_{all} > A_{ass}$

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- **Medical applications.**
  - Gantries.
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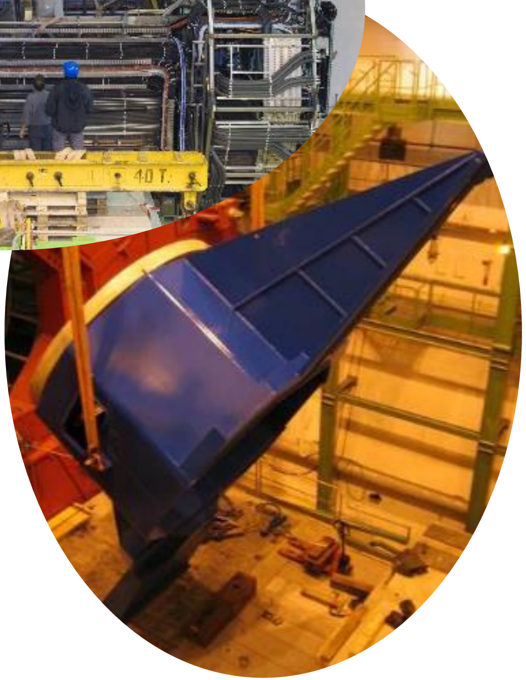
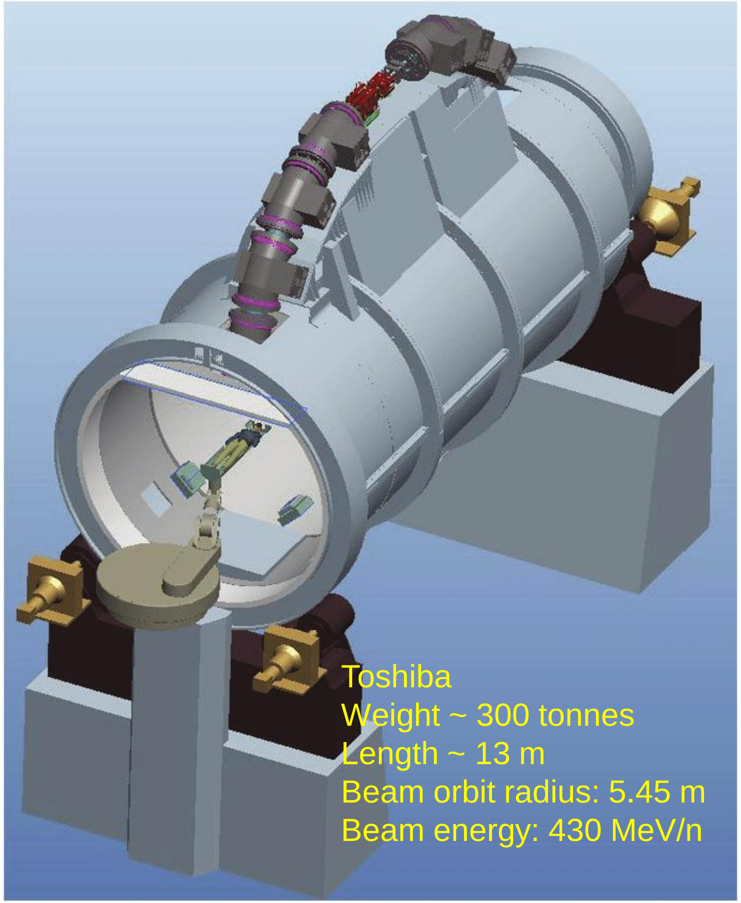
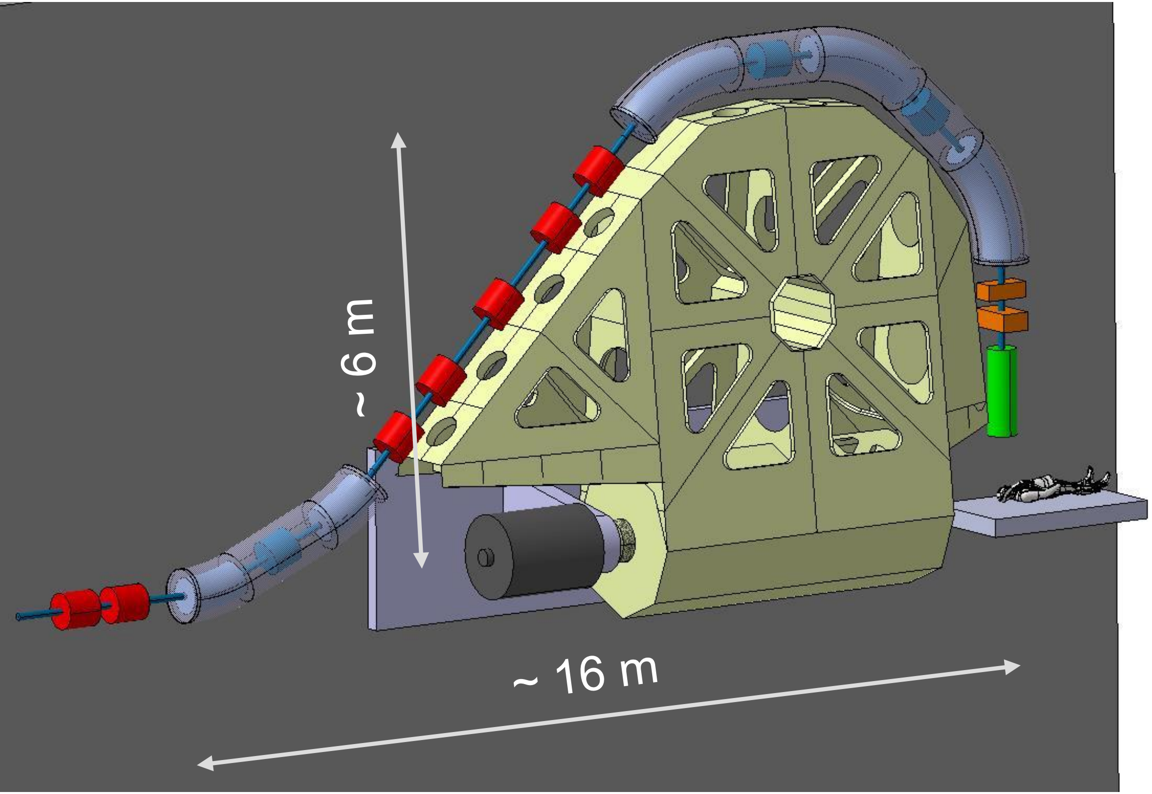




NIRS, superconducting rotating Gantry, 600 tonnes, Heidelberg, operating since November 2012.



- Superconducting ‘bent’ dipoles.
- Electric motor or hydraulic pistons.
- No counterweight.
- Optimized austenitic stainless-steel structure. High rigidity (misalignment of the magnets <0.5 mm).

Weight of magnets	~9 ton
Weight of structure	~18 ton
Total	~ 27 ton

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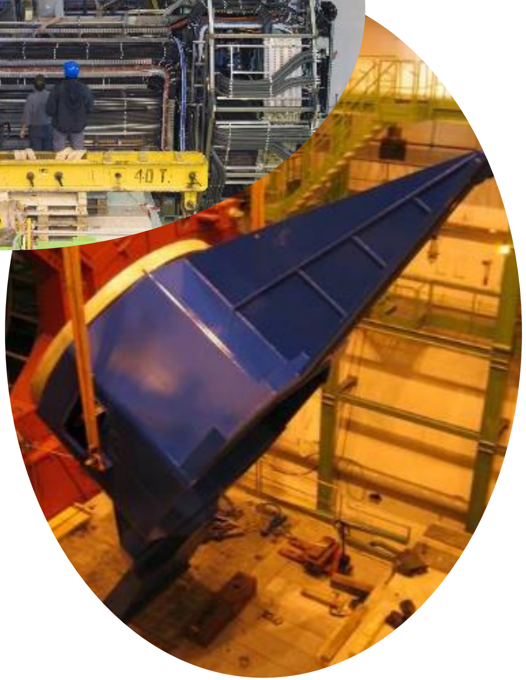

- An experiment represents the integration of many high technology components in a highly optimized volume. Large structures constitute the structural backbone of these systems.

- Accurate design and construction allow the possibility of combining high precision, rigidity and minimum space occupancy.

- These structures are quite unusual, but they are designed and manufactured following the international norms and standards currently applied for all industrial applications.

- Over constrained structures should be avoided.
- High resistance, low elongation materials are dangerous in case all the loading conditions are not perfectly known.
- Attention to the safety factors. Norms are good but do not cover the incertitude of a living experiment.
- Documentation is an investment. It pays back.
- The perfect detector in a bad structure will not work correctly!

Thank you for your attention!

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Spare slides

Cost of a structure

- Computations, drawings and specifications (in average 15% of the total)
- raw materials
- machining of parts
- welds (including qualification of welders and processes)
- control of the welds
- measurements (quality control)
- load test
- transport and installation
- Fabrication and transport tools
- documentation ‘as built’.