Highlights for EP-DT from CERN Accelerator School

Abstract:
The CERN Accelerator School (CAS) took place during two weeks in June of 2024 at NIKHEF in the Netherlands. Due to a long-standing demand, it focussed this time on Mechanical- and Materials Engineering for Particle Accelerators and Detectors. The presentations and much of the hands-on activities were organised by EN-MME. It covered basic mechanical engineering subjects and topics relevant to our niche-world of high energy physics, but also things beyond HEP.

https://indico.cern.ch/event/1326947/

Viren Bhanot
Pierre Rose

Introduction

CERN Accelerator School

- 2-week retreat specialising on detector and accelerator related topics
- CERN works in a niche area
- Knowledge is hard-won
- …and lost easily (cf. Nuclear Reactors)
- CAS ⇒ attempt to keep knowledge in-house

EP

So what was it was like?

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EP

OK, but what was it *really* like?

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This talk (disclaimers)

- Impossible to cover 10 days of material in < 10 days
- Impossible for one person to know everything
- Instead, representative sample via what *we* found interesting
- We took 3-4 topics each
  - Something directly applicable
  - Something interesting for broadening the horizon
  - Something outside of CERN

Outline

Basic Mechanical Engineering

Design
Mechanics and Structures 1 and 2
Engineering Materials
Steels 1
Non-Ferrous Materials
Steels 2
Design for Additive Manufacturing
Plastics and Composite Materials
Computational Tools 1 and 2
Fabrication Summary

Fabrication
Additive Manufacturing
Welding 1
Vacuum Brazing
Welding 2
Surface Treatments and Coatings
Forming

Testing
Physical Properties and Testing
NDT
Mechanical Testing
Mechanical Measurements
Introduction to Metrology
Measurement Uncertainty
Alignment and Metrology

Detectors & Accelerators

Standards and Safety
Intro to Design for Accelerators
Technology Highlights of High Energy
Accelerator Projects
Colliders
Beam Instrumentation
Beam Intercepting Devices
Cryostats and Cryomodules
Digital Twins for Accelerators and Detectors
Vacuum Systems for Accelerators
Undulators

Hands-On
Design
Materials and NDT
Mechanical Measurements
Metrology
Fabrication

Magnets
NC Magnets
SC Magnets

RF
RF Applications
RF Power and Couplers
Detector Magnets and Structures

Beyond HEP

Mechanics of Golf
Einstein Telescope
VDL
Differ
IBS
Sioux
Large Structures for Fusion Technology
Sustainable and Affordable Design

CAS on Mechanical Engineering:
https://indico.cern.ch/event/1326947/

“Mini-CAS” on Mech. Engg. (video lectures):
https://indico.cern.ch/event/958382/

https://indico.cern.ch/event/1463155/

Talk #1

Politecnico di Torino

Introduction to Mechanics and Structures II

Prof. Martina Scapin
martina.scapin@polito.it

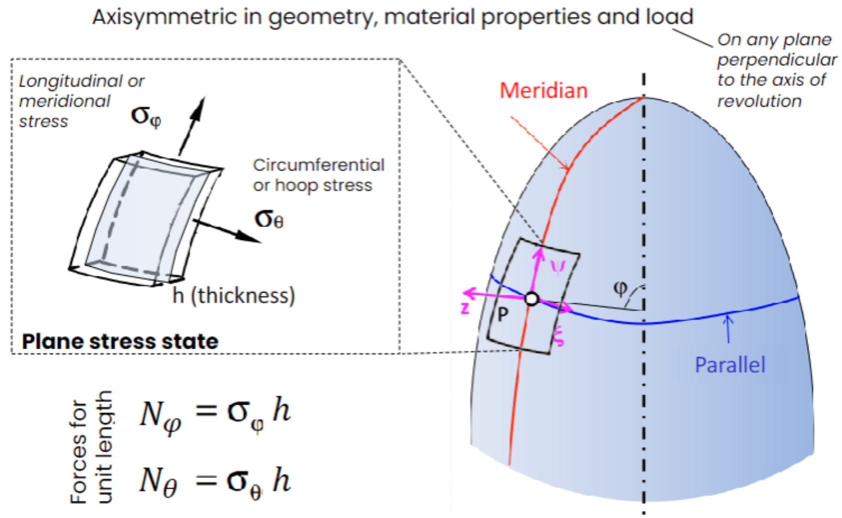
Pressure vessels: theory

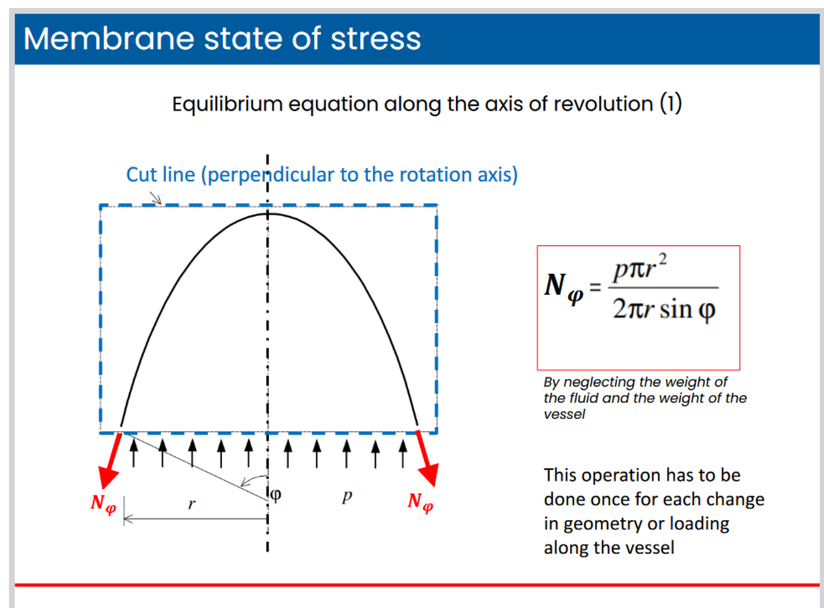
Pressure vessel: EN 13455

https://indico.cern.ch/event/1326947/contributions/5926449/attachments/2868724/5023745/Scapin_II.pdf

Designing Pressure Vessels

- Pressure Vessels: Vessels that hold pressure
- EN 13445 Part 3
  - 900-page bible on pressure vessel design
  - There are 9 other parts
- Thin-walled vessels
  - Rm/t > 10
- Membrane state of stress
  - Bending and twisting moments small enough to neglect
  - Radial stress assumed zero (pressure is small compared to the two other principal stresses)
  - Meridional and hoop stresses considered
- Design by Formula
  - Limited, neglects many real-world factors
  - But with reasonable safety factors: useful
  - Can save analysis time

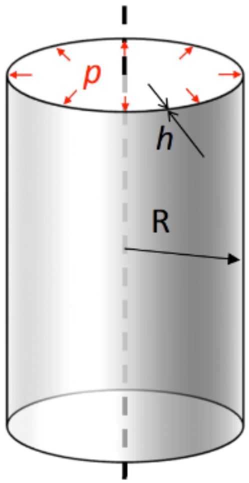


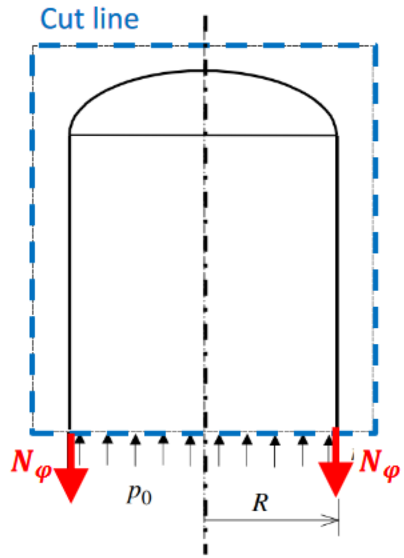


Designing Pressure Vessels

Example: cylinder

INTERNAL PRESSURE





$$N_\varphi = \frac{p \cdot R}{2}$$

$$\sigma_\varphi = \frac{N_\varphi}{h} = \frac{p \cdot R}{2h}$$

$$N_\theta = p \cdot R$$

$$\sigma_\theta = \frac{N_\theta}{h} = \frac{p \cdot R}{h}$$

$$r_\theta = r = R$$

$$r_\varphi \to \infty$$

$$\varphi = \frac{\pi}{2}$$

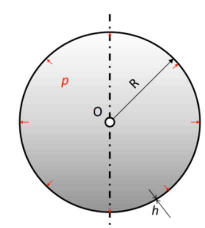
Tresca criterion

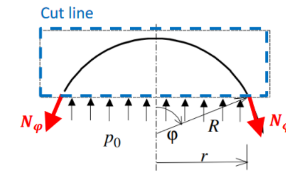
$$h_{\min} = \frac{N_\theta}{\sigma_{\text{adm}}} = \frac{pR}{\sigma_{\text{adm}}}$$

Material limit divided by a safe coefficient

Example: sphere

INTERNAL PRESSURE





$$N_\theta = N_\varphi = \frac{p \cdot R}{2}$$

$$\sigma_\theta = \sigma_\varphi = \frac{p \cdot R}{2h}$$

$$r_\theta = r_\varphi = R$$

Tresca criterion

Half respect to cylinder!

$$h_{\min} = \frac{N_\theta}{\sigma_{\text{adm}}} = \frac{pR}{2\sigma_{\text{adm}}}$$

The Demo Accumulator

450 L pressure vessel to hold 100 bar CO_2 (tested to 143 bar)

outokumpu

INSPECTION CERTIFICATE 3.1
DIN EN 10204 3.1

Requirements, Anforderungen, Exigences
EN 10088-4:2009
AD 2000 W2, W10 & EN 10028-7:2016
ASTM A240/A240M
ASME SA-240/SA-240M II A ED. 2017

Our Order No. / Unser Auftrag Nr. / Notre commande n°: 300508307
Your order: OFERT...

Product, Erzeugnisform, Produit: SHEET , STAINLESS STEEL
Mark of Manufacturer / Zeichen des Lieferwerkes / Signe de producteur: outokum...

Grade, Werkstoff, Nuance: 1.4404 1.4401 TYPE 316L
Tolerances, Toleranzen, Tolérances: EN ISO 9445-2

Marking, Kennzeichnung, Marquage: 1.4404 2B
Marks, Versandzeichen, Marques

Line / Reihe / Ligne	Item / Position / Poste	Charge-test No. / Schmelze-Probe Nr. / Coulée n°	Size, Abmessungen, Dimensions	Quantity / Stückzahl / Nombre
1	6	88346 7	6,0 X 1000 X 2000 MM	13

Chemical composition, Chemische Zusammensetzung, Composition chimiques

Charge no. / Schmelze Nr. / Coulée n°	C %	Si %	Mn %	P %	S %	Cr %	Ni %	MO %
88346	0,020	0,47	0,87	0,037	0,001	17,2	10,1	2,03

Mechanical properties, Mechanische Eigenschaften, Caracteristiques mecaniques

Line / Reihe / Ligne	Sample ID / Proben ID / Echantillon	Rp0.2 MPa	Rp1.0 MPa	Rm MPa	A5 %	A50 %	%	Hardness / Härte, Duraté HBW
1	01	310	353	582	54	54		183
	02	314	359	588	53	53		184

Design Calculations

Proj 2800

20... Rev... Cern CO2 400... (20...

...oom temperature.
...esign temperature.
... at design temperature.
...t design temperature.
...n 100,000 hours at design tempera...
... creep in 100,000 hours hours at d...

Nominal stress at ...

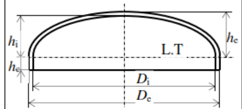
...mal Conditions f_1

Excluding bolting	M4, M5, M6)	MIN ($R^t_{p0,2}$ / 1,5 ; R_m / 2,4)
	Stainless steel (M3 A≥30%)	($R^t_{p1,0}$ / 1,5) ∨ MIN ($R^t_{p1,0}$ / 1,2 ; R^t_m / 3)
	Copper alloy	R^t_m / 4
	Aluminum Alloy	MIN ($R^t_{p0,2}$ / 1,5 ; R_m / 2,4)
	Nickel alloy	MIN ($R^t_{p0,2}$ / 1,5 ; R_m / 2,4)
	Titanium and Zirconium	R^t_m / 3
Bolting	Steel (M2,M4,M5,M6)	MIN ($R^t_{p0,2}$ / 3 ; R_m / 5)
	Stainless steel (M3)	R^t_m / 5
Cast materials		0,7...

A. Silva Matos, Metalomecânica, SA Sever do Vouga Portugal	**Design Calculations** Proj 2800	2021-01-12 Revision : 1 Cern CO2 400 lit 100 bar-R1.emvd (2021-01-12)

Element(s) of geometry under internal pressure
Elliptical Head (30.10) under internal pressure

CODAP 2015 Revision 07/18 Div.2



e_n = nominal thickness	z = Weld joint efficiency
f = Allowable stress	T = Temperature
e = minimum required thickness	σ = circular stress
P = internal pressure	P_{max} = Max. allowable pressure
R = equivalent inside radius	P_h = Hydrostatic pressure
D_i = Internal Diameter	c = corrosion + tolerance
D_e = External Diameter = 610 mm	K = Axis ratio = $D_i/2h_i$ = 1,9
h_e = outside height = 170 mm	$Tol_{\%}$ = tolerance for pipes
$e_{n,min} = (e+c)/Tol_{\%}$ shall be ≤ e_n	$e_u = (e_n \times Tol_{\%}) - c$ shall be ≥ e

X2CrNiMo17-12-2	Plate		Schedule : /	NPS : /
e_n = 20,000 mm		$Tol_{\%}$ = /	PWHT : No	Radiography : Full
Seamless	Cor. = 0 mm	Tol. = 0 mm		

C3.1.4

Conditions of applicability :
$1.7 \le K \le 2.2$ $D_e \ge 12.5e$ Analysis thickness $e_u \ge 0.001 D_e$

Equivalent knuckle radius : $r = D_i\,[0.5/K - 0.08]$ Equivalent crown radius : $R = D_i\,[0.44\,K + 0.02]$

$e_s = PR/(2fz - 0.5P)$

$e_y = \beta\,\beta_k\,(0.75R + 0.2D_i)P/f$ β Table C3.1.5.1c

$e_b = 0.0433\,(0.75R + 0.2D_i)\,(D_i/r)^{0.55}\,(P/f)^{0.667}$ β_k C3.1.9

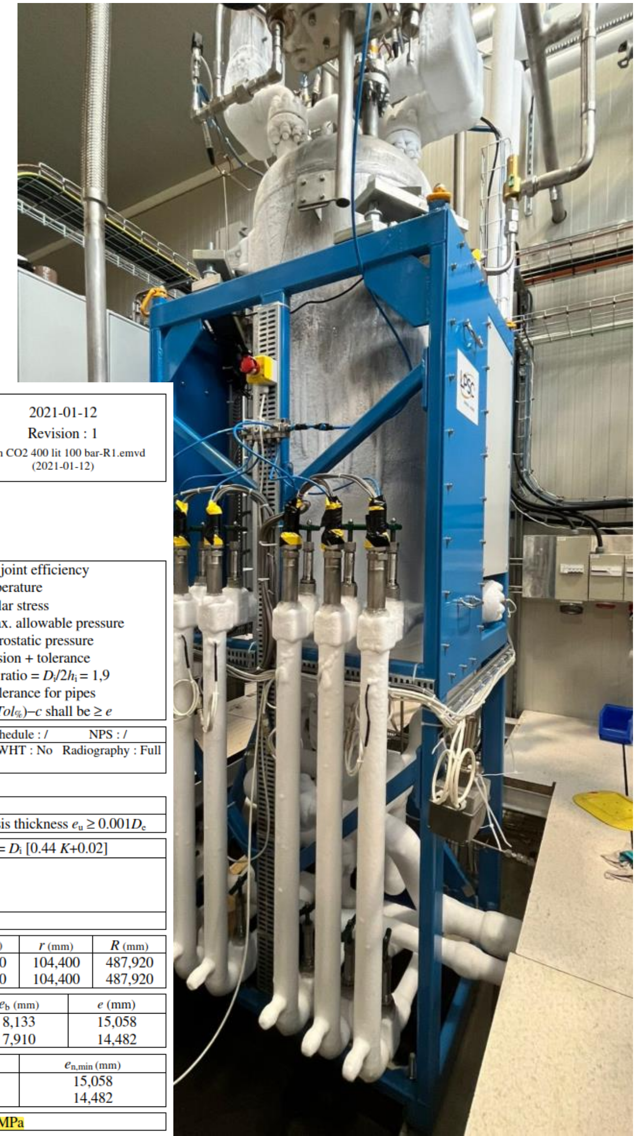
required thickness : $e = \max[e_s, e_y, e_b]$

		P (MPa)	P_h (MPa)	T (°C)	f (MPa)	z	D_i (mm)	r (mm)	R (mm)
Operation	N	10,0191	0,0191	40	165,78	1	570,000	104,400	487,920
Vertical test	X	14,3175	0,0175	20	247	1	570,000	104,400	487,920

		β	β_k	e_s (mm)	e_y (mm)	e_b (mm)	e (mm)
Operation	N	0,5191	1	14,970	15,058	8,133	15,058
Vertical test	X	0,5206	1	14,349	14,482	7,910	14,482

		e_u (mm)	σ (MPa)	P_{max} (MPa)	$e_{n,min}$ (mm)
Operation	N	20,000	147,78	11,24	15,058
Vertical test	X	20,000	211,18	16,75	14,482

MAWP (40 °C, Corroded) = 11,24 MPa MAWP (20 °C, new) = 11,75 MPa



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EP

Talk #2

Cryostats and Cryomodules

Vittorio Parma

CERN – SY/RF Group

CERN Accelerator School on Mechanical and Material Engineering,

Sint-Michielsgestel (Netherlands), 7 June 2024

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https://indico.cern.ch/event/1326947/contributions/5926549/attachments/2872546/5029784/Cryostats%20and%20Cryomodules.pdf

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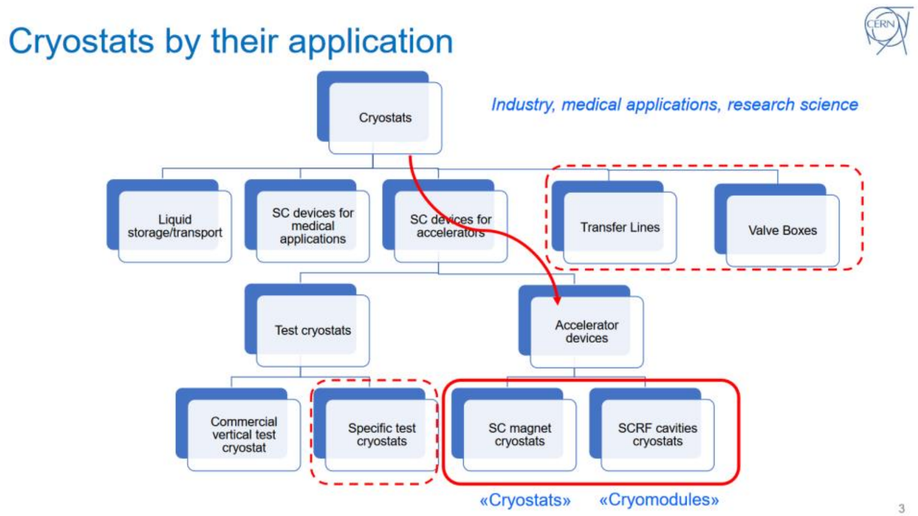
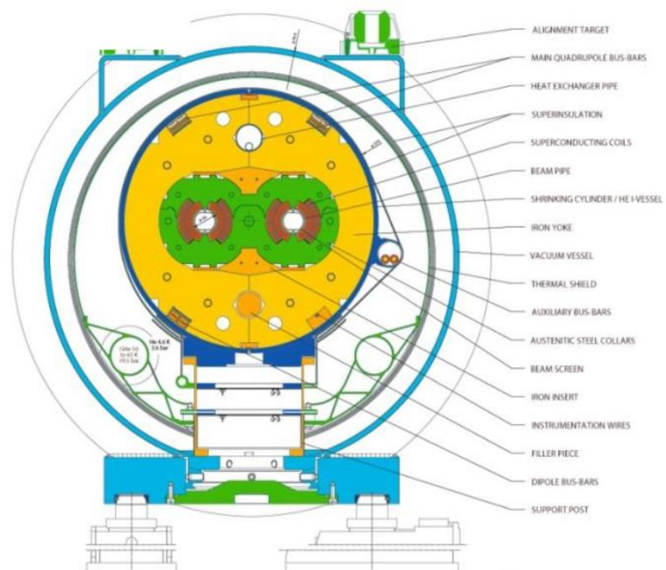
Cryostats and Cryomodules

- Cryostat: A thing that keeps objects inside it cold
- Talk: Cryostats for **superconducting** devices only



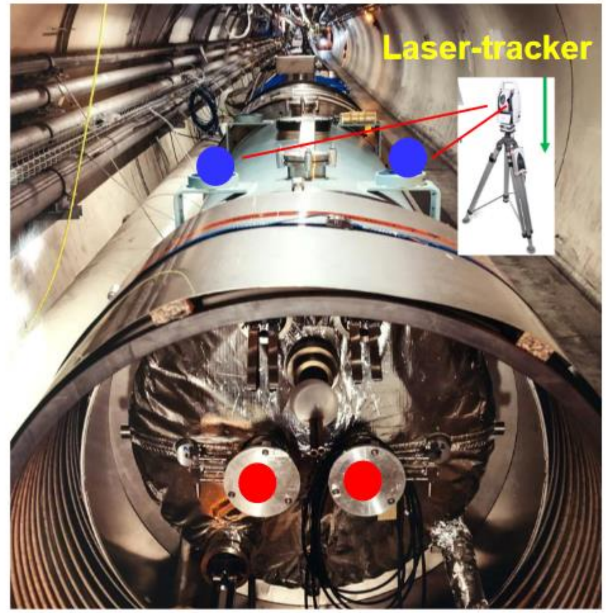
basic components

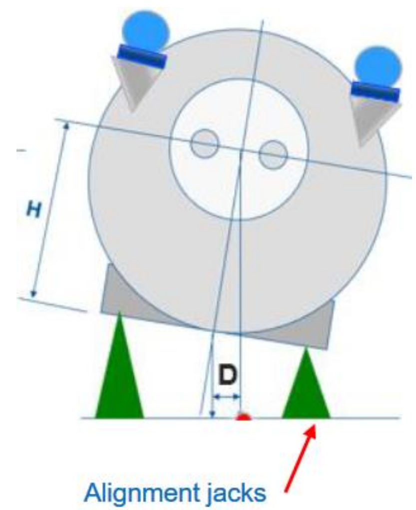
- Helium tank (for SC device, ph.separator, etc.):
  - ✓ austenitic st.steels (Fe-Cr-Ni): 304L(1.4307), 316L(1.4404), 316LN
  - ✓ titanium alloys (Grade 7, Grade-5 (Ti-6Al-4V)) in SRF
- Internal (cold) supporting system
  - ✓ Composites (e.g. GFRE, CFRP, ULTEM)
  - ✓ St.steel, titanium alloys (tie rods)
- Thermal shielding/MLI:
  - ✓ aluminum alloys (series 5xxx, 6xxx, 7xxx)
  - ✓ Copper (Cu OF, Cu OFE)
- Vacuum vessel:
  - ✓ Low carbon steels (e.g. DIN GS-21 Mn5)
  - ✓ st.steels (304L)
- Cryogenic piping and expansion joints (bellows):
  - ✓ st.steel (304L)
  - ✓ Cu (HX tubes)
- Current leads (for SC magnets)
  - ✓ Cu, HTS, st.steel, elect. insulating (Kapton), thermal insulating (G10),etc.
- RF Couplers/HOM (for SRF):
  - ✓ St.steel Cu plated, Nb, ceramics, etc.
- Magnetic shielding (for SRF, as needed)
  - ✓ μ-metal, Cryoperm®, etc.



Cryostats and Cryomodules

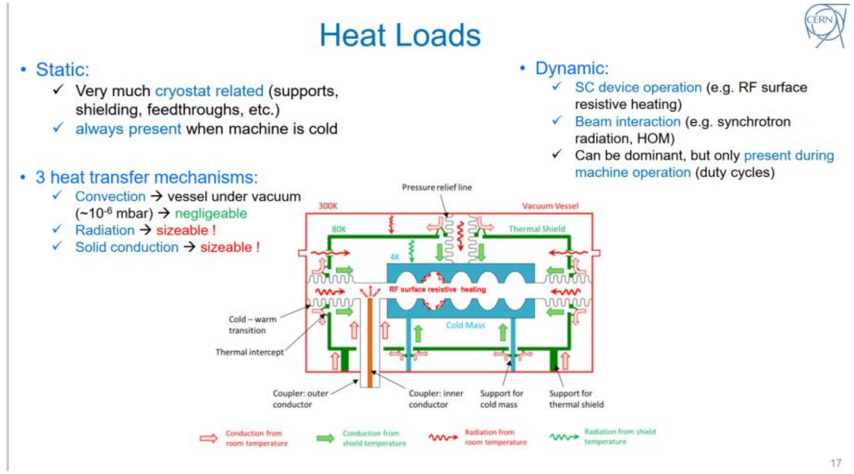
- Main function of Cryostats: position an SC device and enable its operation
- Reproducible positioning is the toughest requirement for a cryostat
  - Survey teams can only measure fiducials on vessel and not the SC device *inside* the vessel
  - They consider cryostats/sc devices as rigid bodies
- Typical machining IT grade: 8-10
- Typical close fits: H7/G6



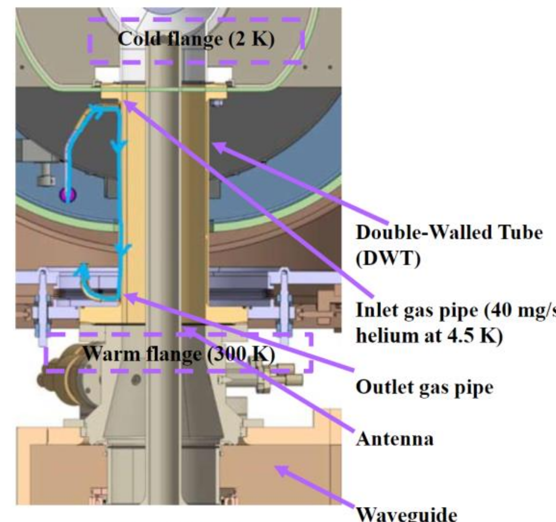


Cryostats and Cryomodules

- Convection is negligible but:
  - Conduction
  - Radiation
- Solved by (respectively)
  - Heat intercepts, and
  - MLI
- Helium latent heat at 4.2K: 20 kJ/kg
  - Water: 2260 kJ/kg at 100°C
  - CO_2: 283 kJ/kg at -20°C
  - He liquid density: 125 kg/m3
- With Helium, they care about **holding time** a lot.
  - He can become vapour extremely quickly.



- Vapour/forced flow cooled RF couplers external conductors



SPL RF Coupler

Effectiveness:
- Reduced static heat conduction
- Partial intercepting of RF resistive heating
- Regulation flexibility (stand by, RF power on)

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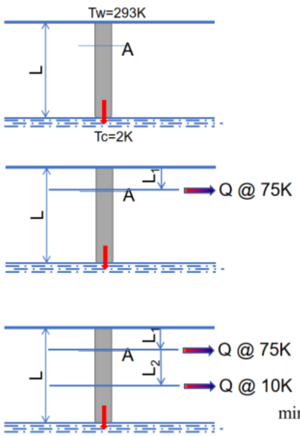
Cryostats and Cryomodules

Heat intercepts (heat sinking) at intermediate temperatures



- simple solid conduction

$$\dot{Q} = \frac{A}{L}\int_{Tc}^{Tw} k(T)dT$$

- 1 heat intercept at optimal distance

$$\min\{f(L_1) = C1\cdot\frac{A}{L_1}\int_{Tw}^{80K} k(T)dT + C2\cdot\frac{A}{L-L_1}\int_{80K}^{Tc} k(T)dT\}$$

→ L_1

- 2 heat intercepts at optimal distance

$$\min\{f(L_1,L_2) = C1\,\frac{A}{L_1}\int_{Tw}^{80K} k(T)dT + C2\,\frac{A}{L_2-L_1}\int_{80K}^{8K} k(T)dT + C3\,\frac{A}{L-L_2}\int_{8K}^{Tc} k(T)dT\}$$

C1, C2, C3, COP at relevant T

→ L_1, L_2

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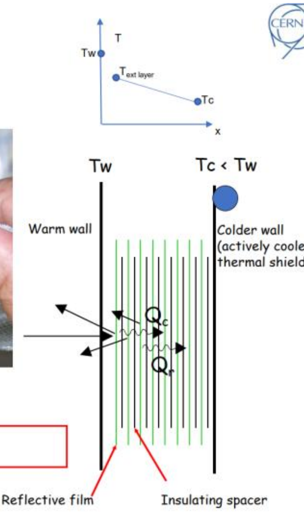
N shields → Multi Layer Insulation (MLI)

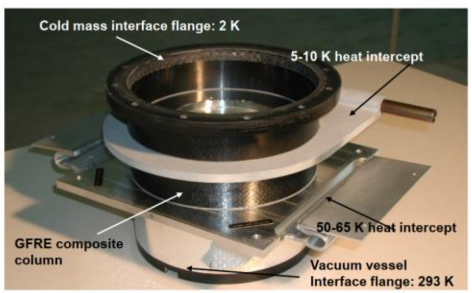
Insulating mechanism:

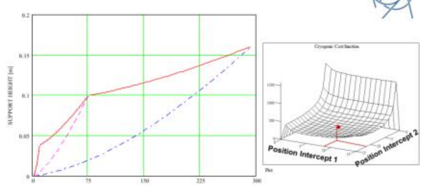
- Multi-layer to enhance radiation protection:
  - N+1 radiation shielding
- Low emissivity of aluminium layer
- Minimal thermal conduction between reflective layers → interposing of isolating layers (e.g polyester net):
- Enhanced performance at low T → use actively cooled shield:
  - Lower emissivity of reflective material layers at low T
  - Extract heat at higher thermal shield T → thermodynamic efficiency



→Actively cooled (50-80 K range) thermal shield with MLI is a must in all cryostats

LHC supports





Two intercepts, 5K & 75K
One intercept, 75K
No intercepts

Minimizing using efficiency factors:
C_1 = 16 w/w @ 75 K
C_2 = 210 w/w @ 5 K
C_3 = 990 w/w @ 1.9 K

	$Q_{1.8K}$ [W]	Q_{5K} [W]	Q_{75K} [W]	$Q_{elec.}$ [W]
1	2.79	-	-	2790
2	0.541	-	6.44	638
3	0.047	0.42	7.1	252

Heat loads comparison for GFRE with & without heat intercepts

- >10 tons vertical compression load
- **4-mm thickness**, glass-fiber epoxy
- Manufactured by **Resin Transfer Moulding (RTM):**
  - Suited to a large-scale industrial production (4'700 units)
  - High reproducibility in thermo-mechanical properties

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- 293 K to 50 K thermal shield with 30 MLI layers: ~1 W/m2
- 50 K to 2 K magnet with 10 MLI layers: ~ 50 mW/m2

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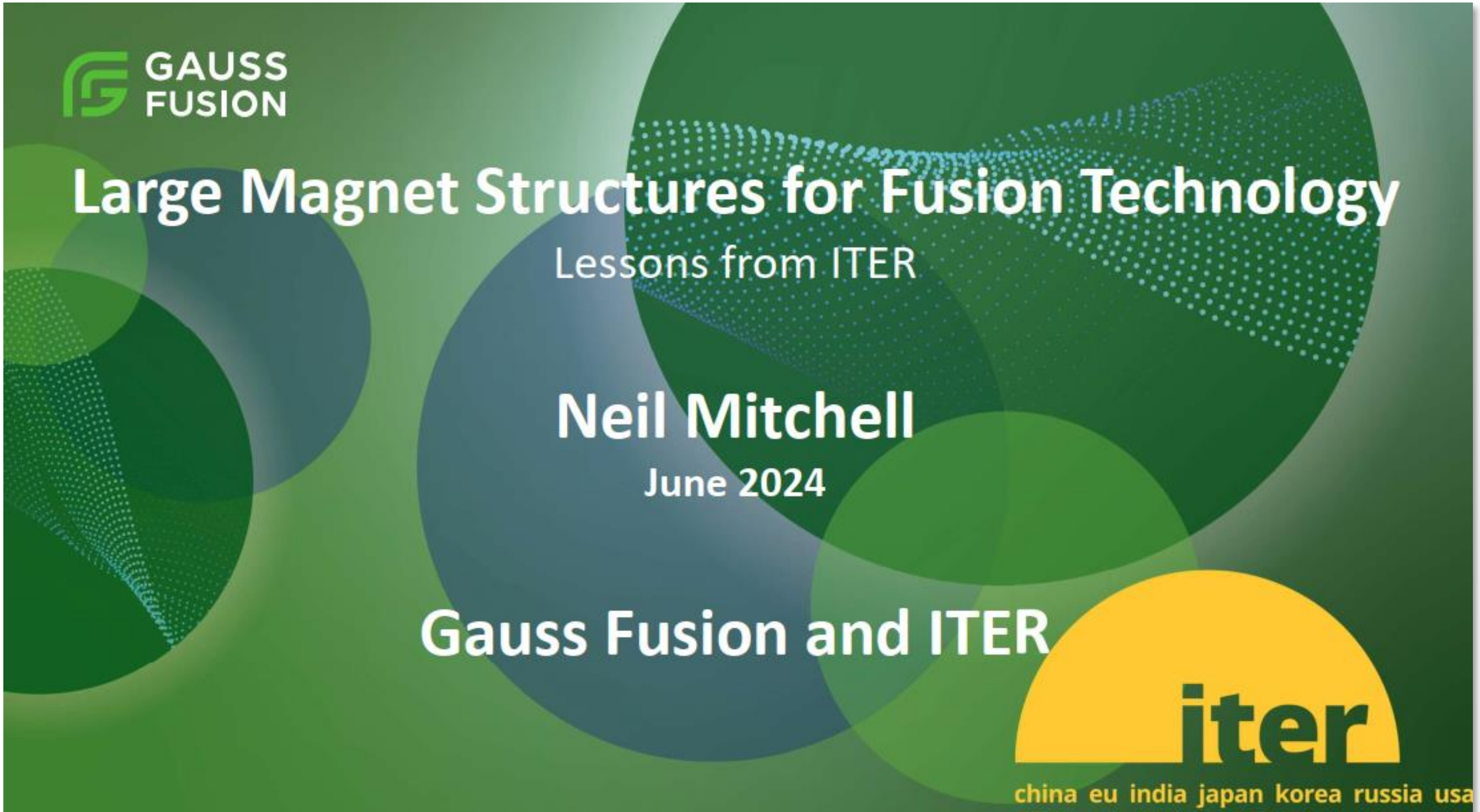
Large magnet structures for fusion (ITER)



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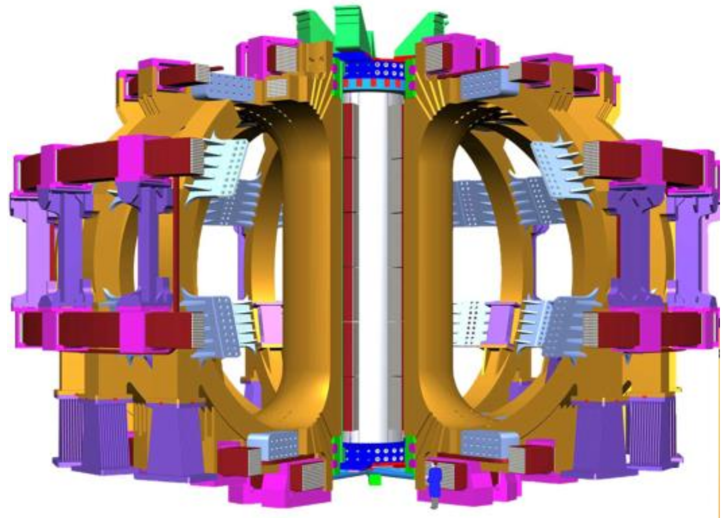
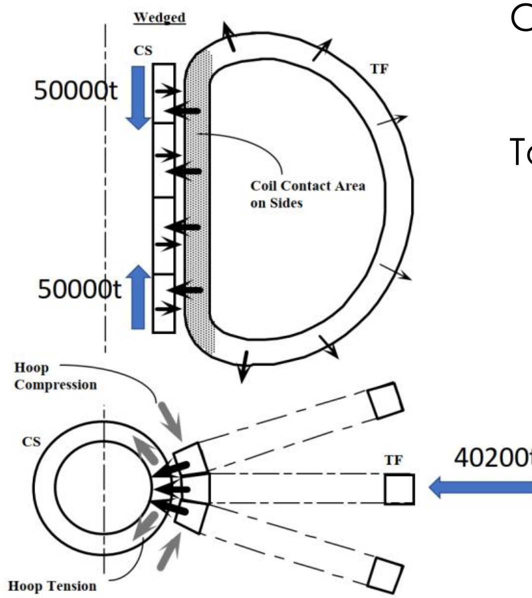
Large magnet structures for fusion (ITER)

- Talk by Neil Mitchell
  - Developing large steel structures
  - Developing large composite structures (*not covered here*)
  - Litany of mistakes (but actually learning from them)
- ITER
  - Toroidal Field coil (steel)
  - Central Solenoid coil (composites)
- Huge forces and movements
  - 40200 T in-plane force on each TF coil
  - 20 mm out-of-plane movement during magnet pulses
  - Cooldown shrinkage of 30 mm





Central solenoid
13 m high
1,000 tons 18
Toroidal field coils
17 m high
360 tons each

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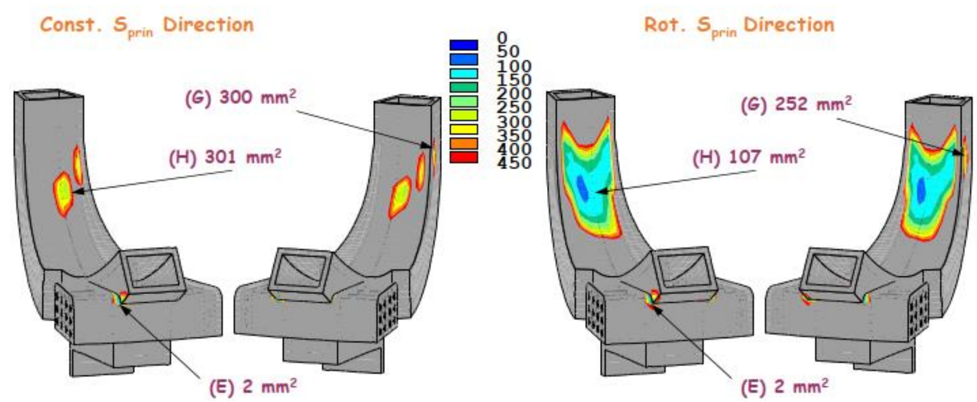
ITER Design Criteria

- Design criteria "chosen to match application, not copied"
- For magnetic metallic structure, ITER worked for *eleven years* just to come up with its own design criteria
  - Nothing existed for load-bearing magnets
  - Much more emphasis on Linear Elastic Fracture Mechanics
  - At 4K (-269.15°C), fatigue crack growth and fast fracture matter more than plastic yielding
  - Residual stresses matter a lot in cryogenic structures
- Making a large, complicated load-bearing, cryogenic magnetic structure?
  - Performance is not defined by "materials properties" datasheet.
  - Instead, can you control imperfections? Locate them? Repair them? **Tolerate** them?
- ITER criteria allows tolerating defects in welding
  - As long as they don't lead to fast fracture
  - 'permitted initial defects'
  - Calibrated blocks with artificial defects
  - ASME also adopted FFS section

ITER Design Criteria



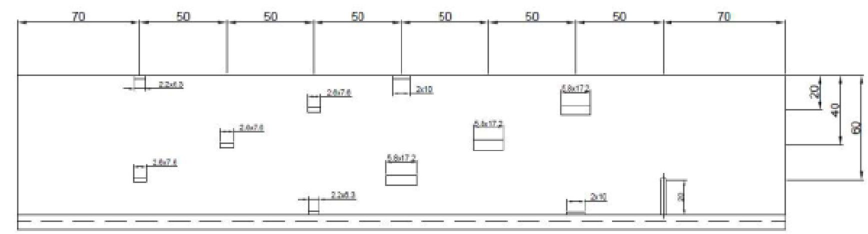
- Example of Fatigue Assessment according LEFM: carried out to provide max initial allowable subsurface defect to sustain 60,000 cycles (safety factor of 2 on cycles).
- Assumptions made about residual stresses in base metal and welds.
- NDT inspection has to be **calibrated** to detect defects at least as small as this

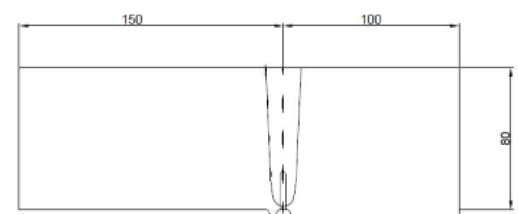
Defect Detection: Calibration Blocks

7 validation/ qualification coupons manufactured with thicknesses ranging from 80 mm -120 mm.

- Test pieces include all the postulated defects in all the chamfer geometries.
- Volumetric defects have been represented by semi-spherical bottom holes.
- Surface-breaking notches have been machined by EDM.
- Sub-surface and embedded planar reflectors have been buried after electrical discharge machining.

Example of validation test piece





Toroidal mechanical scanner

ITER Material Selection

- Started in 1988
- “Success claimed in laboratory scale research but universal failure on industrial scale.”
- “Problems of production of highly composition specific alloys underestimated”
- “Issues such as welding, forging, corrosion neglected”
- “By 2008 only JJ1 remains (TF coil nose) at C1 level and steel properties at same level as obtainable industrially in 1980s”
- Exotic materials (incoloy 908) for conductor jackets for Nb3Sn
  - Incorrect cost assessment because they overestimated the need to have uniform metal contraction from 600°C to -269.15°C
  - Issues because Corrosion was ignored

Bulk Production: Forging, Casting

1996-2000 Various forged sub-sections of the ITER TF coil case, showing the complexity of the forged forms. Top: seamless TF case, bottom, seamless radial plate for TFMC

Trials on TF Structures: curved hollow section of coil case. Ultimately too complex but the know-how obtained by the company (Kind) was used to produce almost all the forgings for the TF coil cases and VV under contracts with EU, KO and JA

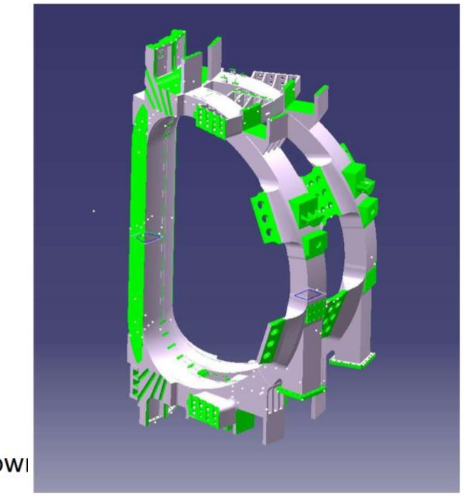
Trial Casting of Components: rejected because of poor properties (low modulus, low strength) and defects (voids) impossible to repair

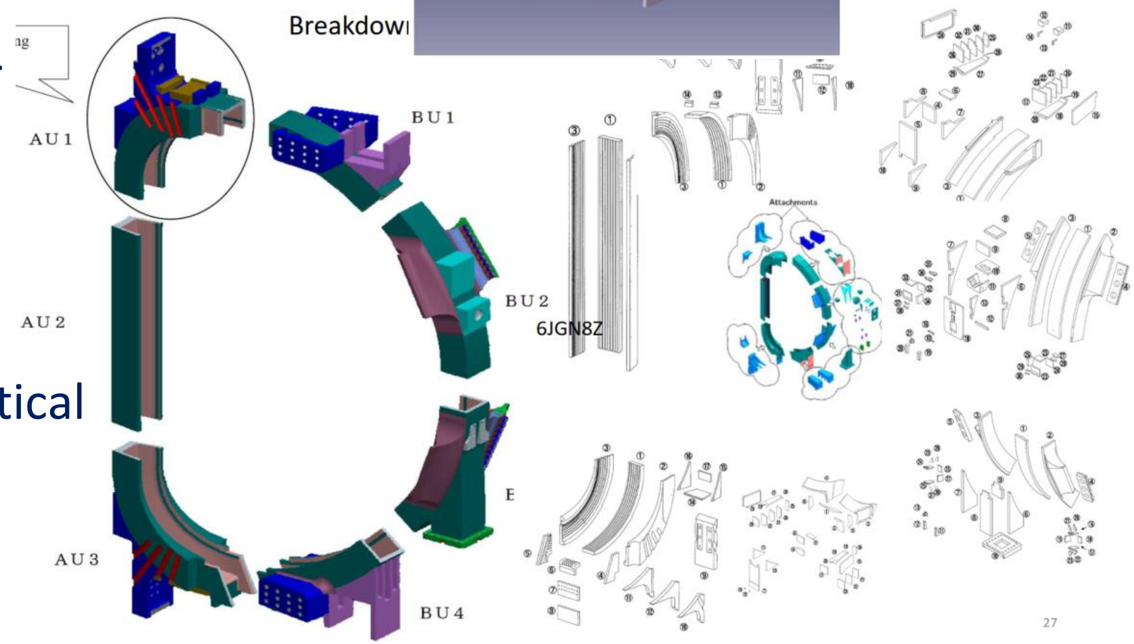
Corrosion 1

Typical SAGBO cracking in Incoloy 908, in CS Model Coil jacket sections (K. Hamada and JAERI)

ITER Tolerances

- “Impossible to build and fit everything in ITER magnets to < 1 mm tolerances.”
- Dimensional errors have an impact because after assembly, load paths must match design intentions.
  - Account for field errors
- Many examples of ‘over-metal’ for removal in final machining to compensate for distortion/welds
  - Expensive, large machines
  - Temperature controlled environment
- “Build up” of large structures is critical
- Large number of extra flanges and supplementary welds ⇒ “poor”





ITER conclusions

Conclusions or Message from the Course

I. Large Steel Structures under High and Complex Stress Systems

High performance materials with small user base and weak supply chains are worse than high quality production with existing high strength steels. Too many unexpected features remain to be discovered

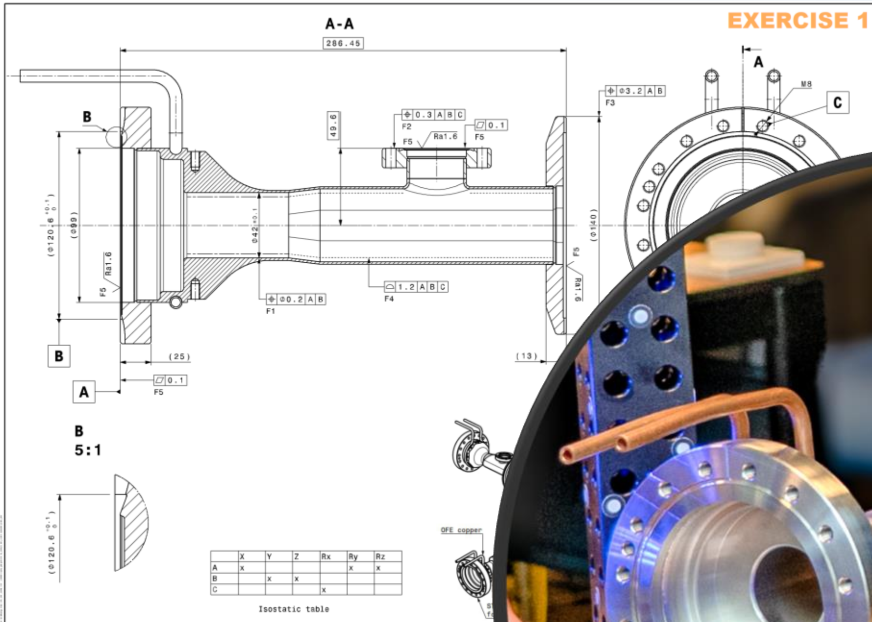
Key to performance is living with imperfections (finding, repairing efficiently and designing for

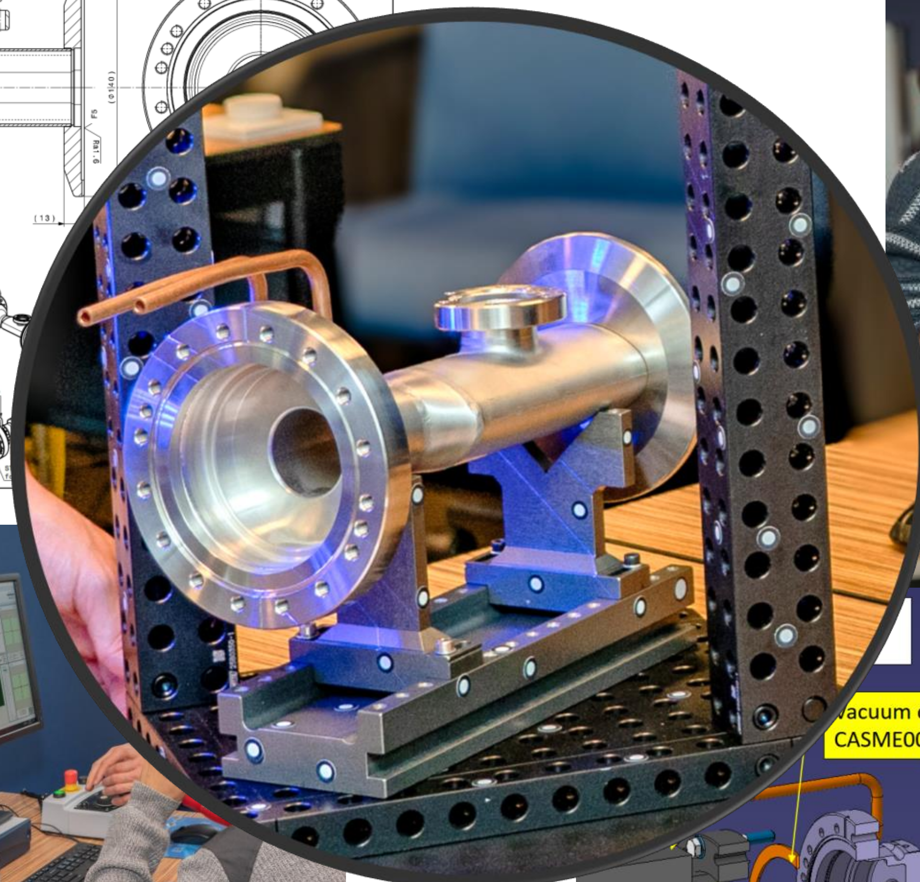
Effective exploitation was limited by weak manufacturing design. Complex structures are not just a question of welding technology but also practicalities like access and machinability after weld distortion (and machining to recover distortion requires extra thickness)

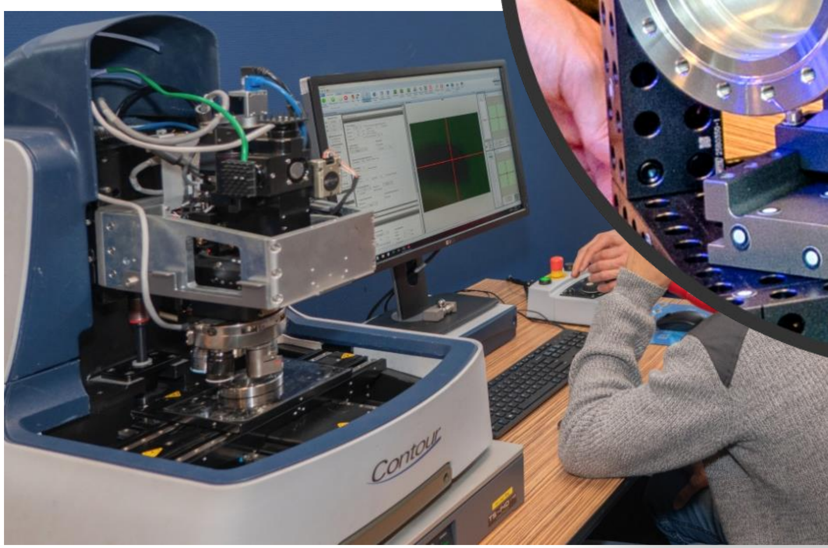
Tight tolerances being achieved by multiple machining steps and over-metal….makes complex manufacturing, expensive. Again, better manufacturing design needed (and not new materials)

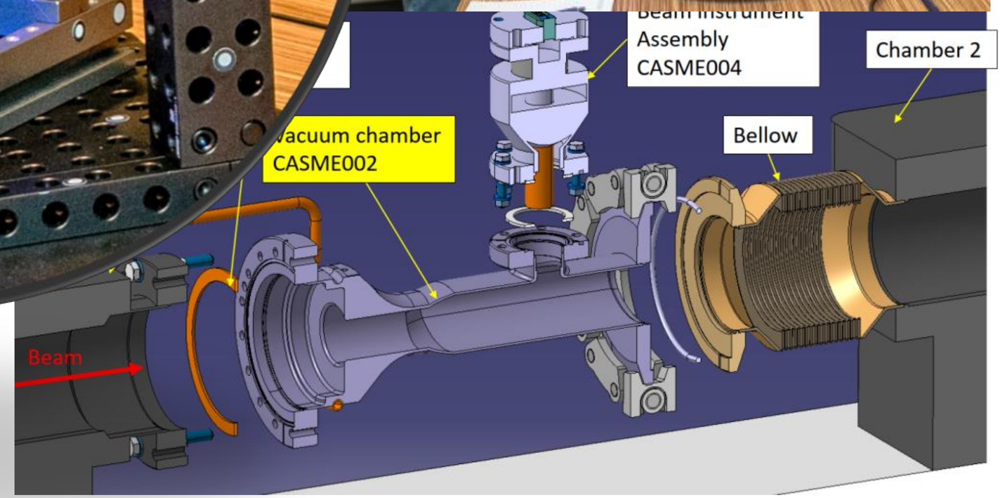
65

Hands On









https://indico.cern.ch/event/1463155/

Talk #1

Slides presented per Anite (EN-MME):
https://indico.cern.ch/event/1326947/contributions/5926527/

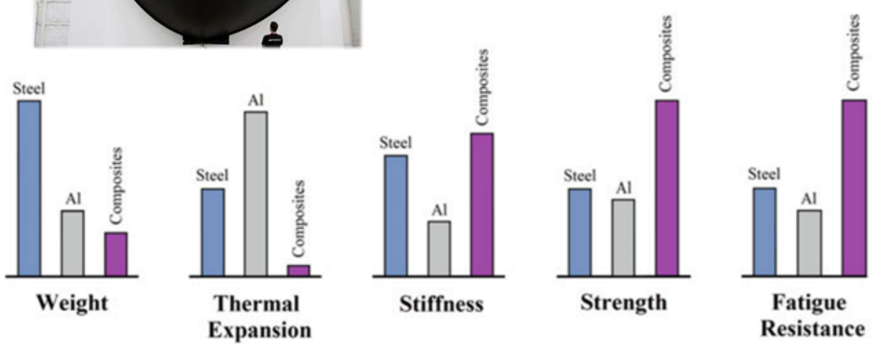
Some slides from Francois Boyer (EP-DT)

Composite Materials

This relatively new family of materials marked a significant advancement in civil construction, energy or aeronautics…meeting the growing need for **stronger yet lighter materials**

Why are they so interesting?

- Possible to achieve combinations of properties not attainable with metals, ceramics or polymers alone
- Design of materials with optimized properties
- Developed in parallel with high stiffness and strength fibres
- Can be produced by various processing techniques
- Large part size possible



Comparison between conventional materials and composite materials.

What are composites?

Composed of at least two phases: the **matrix**, which is continuous and surrounds the **dispersed phase**

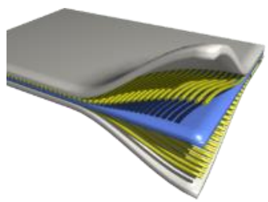
The **properties of composites** are a function of the properties of the constituent phases, their relative amounts, and the geometry of the dispersed phase (shape and size of the particles, distribution, and orientation)

Classification according to the matrix and to the **reinforcement geometry**

MATRIX

- *Provides* cohesion between fibers
- *Transfer of effort between plies*
- Environment stability
- Temperature stability

+



REINFORCEMENT

- *Provides* the mechanical properties
- Stiffness

Organic matrix: divided in 3 categories
- *Elastomer*: formed by long chains
- *Thermoplastics:* could be melted by heating and hardened by cooling
- *Thermosetting*: widely used in the industry (phenolic, epoxy, polyimide …)

Ceramic matrix: used for high temperature applications (Alumina, SiC, carbon, concrete …)

Metallic matrix (Alu, Zinc, Mg …): less used, but used ☺

Mineral matrix (geopolymer): polymer based on silica or alumina

Inorganic fibers:
- *Carbon:* Fibers widely used in high technology
- *Glass*: A, E, S obtained from silica and some additives
- *Ceramic*: for mechanical application in high temperatures
- *Metallic*: very good electrical and thermal properties (Bore, steel)

Organic fibers:
Polymer: Aramide, polyester …
Natural: Hemp, flax …

Polymer-Matrix Composites

Polymeric Matrix Composites (**PMCs**) consist in a plastic matrix with fibers as reinforcement and are the most widely used to manufacture composites.

Two types of matrix:

- **Thermoplastics** → low flow (difficult to infiltrate), expensive but good mechanical properties at high temperature (i. e. Polyetheretherketone-PEEK, Polyphenylene Sulphide-PPS and polyetherimide-PEI)
  - Film stacking, thermoforming, injection moulding…
- **Thermosets (resins)** → low viscosity before curing, cheap, resistant to chemical attack but brittle, very low fracture toughness and limited properties at high temperature (i. e. unsaturated polyester resins, epoxy resins and polyimides)
  - Produced by hand layup and spray techniques, filament winding, pultrusion, autoclave-based methods (“**prepreg**”)…

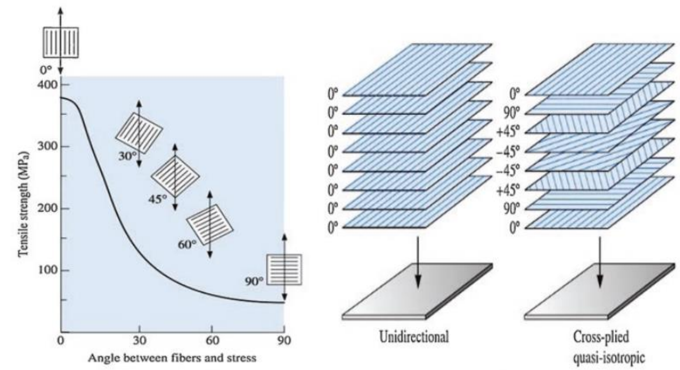
Most typical fibers are Glass Fiber–Reinforced Polymer (**GFRP**), Carbon Fiber–Reinforced Polymer (**CFRP**) and Aramid Fiber–Reinforced Polymer Composites

Composites – Fiber Layout

1D: Is the easiest fibre arrangement in a **unidirectional lamina** also called **ply** or **layer**

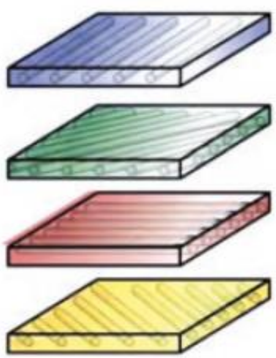
2D fabrics: Multidirectional laminates (built by stacking unidirectional lamina with different orientations and can provide quasi-isotropic properties)**,** woven fabrics, knit, braided, nonwovens (from a set of disordered fibres)

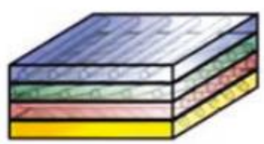
3D fabrics (woven fabrics, non-crimp fabrics, stitching)



Effect of fibre orientation on the tensile strength of E-glass fibre-reinforced epoxy composites.

Post-lay-up processing techniques include autoclave moulding, pressure-bag moulding, and vacuum-bag moulding to reduce the porosity



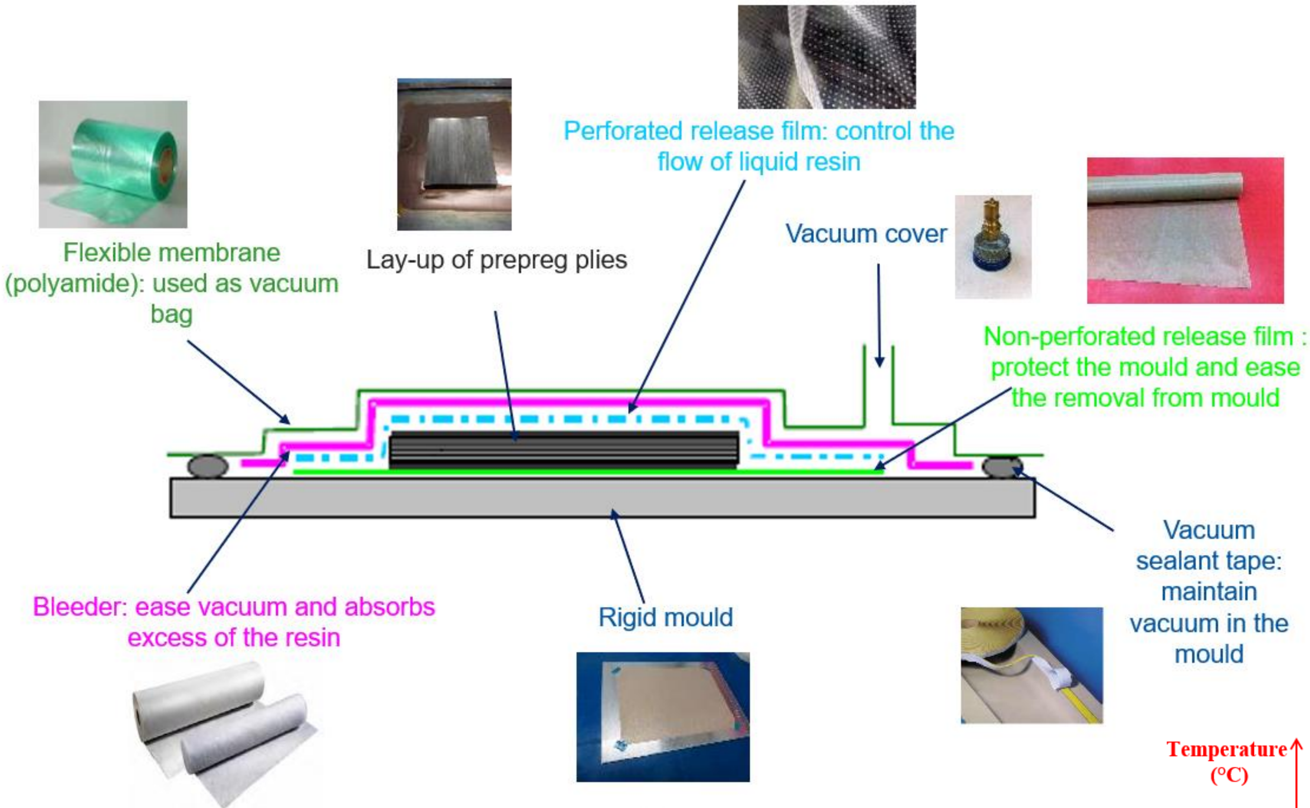


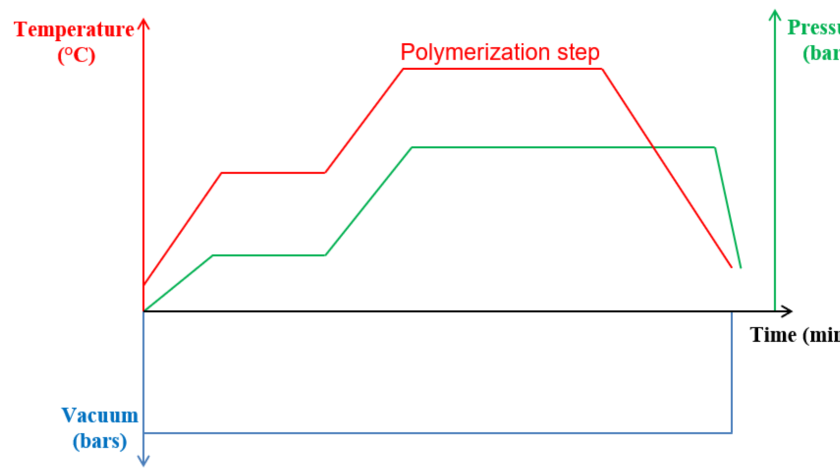
The laminate structures can be manufactured from continuous fibres plies.

A large autoclave that is used to make the wings of Boeing 787

EP

Composites – Vacuum curing





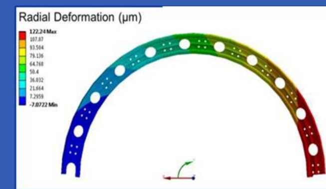
EP-DT product

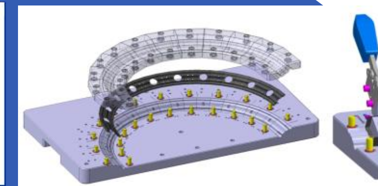
What? CFRP Composite (Carbon Fiber Reinforced Polymer)

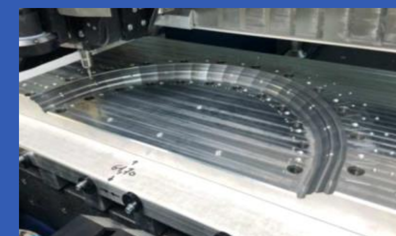
Where? ATLAS Inner Tracker (ITk) structural components

Why? The tracker needs to record particle paths with very high precision, yet be lightweight, to disturb the particles as little as possible
→ Very thin, robust and accurate carbon fiber profiles are needed

For small series production an important invest on the development phase the mechanical simulation is key to validate the configuration of the laminates arranged so that the maximum service stress lies in the direction that has the highest strength







Design and simulation

- *Definition of the material properties*
- *Definition of the stacking sequence*
- *Verify the compatibility with the detector envelope*

Prototype production

- *Cutting of the carbon plies*
- *Lamination of the carbon plies*
- *Polymerization in autoclave*
- *Demoulding of the part*

Tooling and mould

- *Conception of the different parts*
- *CNC machining*

Main design and manufacturing steps of structural ring from CFRP composite "pre-preg" raw material. Courtesy of F. Boyer Composite Laboratory at CERN

EP-DT/EN-MME Study

EP

What? Cooling adaptors machined from Metal Matrix Composites Aluminium-CF (Al-CF) with chopped fibres oriented in XY plane (anisotropic structure)

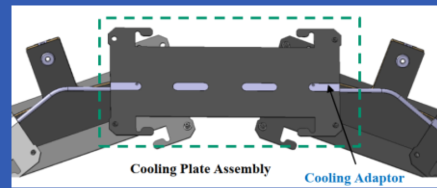
Where? Outer tracker of the CMS detector with silicon sensors at -30C during operation

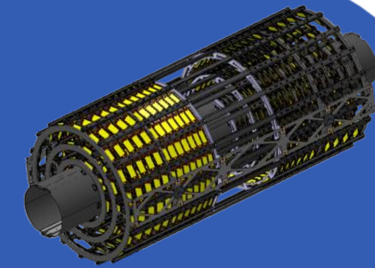
Why? Thermal expansion coefficient should match that of silicon to avoid deformations during cooling cycles, dimensional stability over time (few µm) and non-magnetic

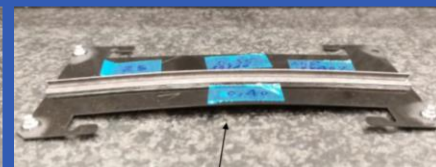
Case of study: Material from two different providers A (Casted Al-CF) vs. B (Sintered Al-CF). Format from "B" (rectangular blocks) is more suitable for the application but important dimensional variations were observed with time.

SEM and EDS pointed out that the degradation is induced by active galvanic corrosion phenomenon happening between the carbon fibre and aluminium matrix.

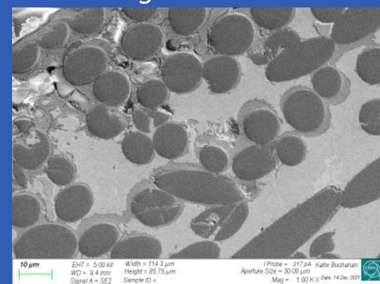
This may be related to the more open structure due to the fabrication route of powder metallurgy

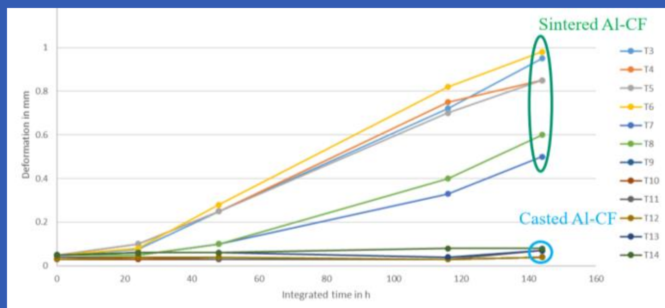


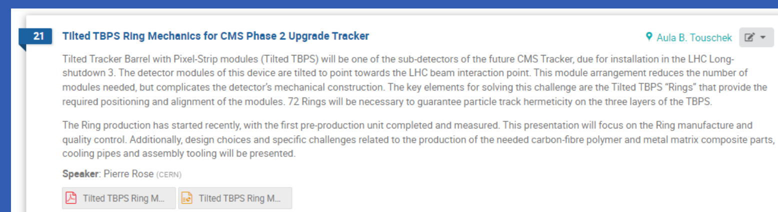




SEM images after wet testing confirmed galvanic corrosion signs at the matrix-CF interface on sintered samples.







21 **Tilted TBPS Ring Mechanics for CMS Phase 2 Upgrade Tracker**

Aula B. Touschek

Tilted Tracker Barrel with Pixel-Strip modules (Tilted TBPS) will be one of the sub-detectors of the future CMS Tracker, due for installation in the LHC Long-shutdown 3. The detector modules of this device are tilted to point towards the LHC beam interaction point. This module arrangement reduces the number of modules needed, but complicates the detector's mechanical construction. The key elements for solving this challenge are the Tilted TBPS "Rings" that provide the required positioning and alignment of the modules. 72 Rings will be necessary to guarantee particle track hermeticity on the three layers of the TBPS.

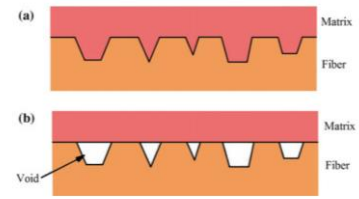
The Ring production has started recently, with the first pre-production unit completed and measured. This presentation will focus on the Ring manufacture and quality control. Additionally, design choices and specific challenges related to the production of the needed carbon-fibre polymer and metal matrix composite parts, cooling pipes and assembly tooling will be presented.

Speaker: Pierre Rose (CERN)

Tilted TBPS Ring M... Tilted TBPS Ring M...

Presentation during Forum on Tracking Detector Mechanics 2022 : link

Fiber-Reinforced Composites



a) Good mechanical bond and b) lack of wettability can make a liquid polymer or metal unable to penetrate the asperities on the fiber surface, leading to interfacial voids [17]

The **mechanical characteristics** of a fiber-reinforced composite depend not only on the properties of the fiber, but also on the degree to which an applied load is transmitted to the fibers by the matrix phase → **Matrix-fiber interface**

The **interface area is very large** in composites (100000 m^2/m^3) and is more important if the fiber radius decreases (i. e. nanotubes reinforcement). We need an **optimized bonding that improves the toughness** of the component

- **Wettability** → Ability of the liquid to spread on a solid surface (infiltration!)
    - Important effect of surface roughness (intimate contact), and coupling agents are frequently used to improve the wettability between the components
- **Bonding** → Mechanical bonding (interlocking or mechanical gripping when the matrix contracts), physical bonding (van der Waals forces…), chemical bonding (dissolution bonding, and reaction bonding). Interlock effect between rough surfaces

Interface mechanical behaviour is characterized by shear stress (// to the interface), normal strength and interface fracture energy: Flexural test, bending test, interlaminar shear strength (ILSS), fibers push-in/push out test, pull-out test, instrumented indentation test…

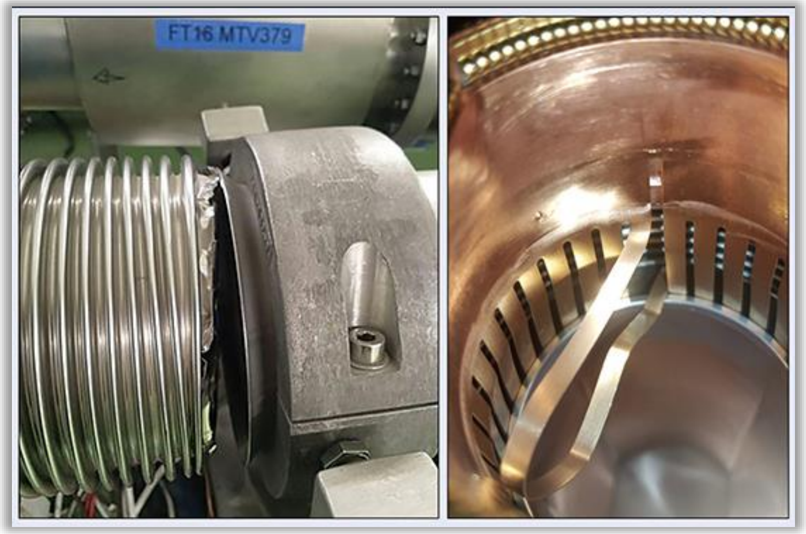
Talk #2

Slides presented per Marc Timmins (EN-MME):
https://indico.cern.ch/event/1326947/contributions/5926464/

Design

What is a robust and reliable design ?

Damaged LHC dipole interconnexion



Bellow and RF finger failure

LHC jacks ripped from the ground

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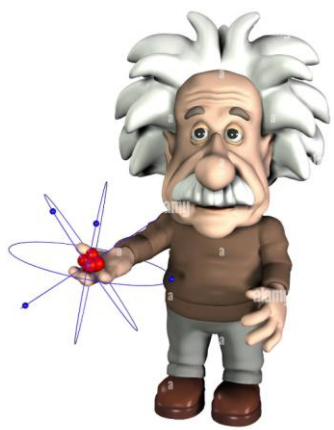
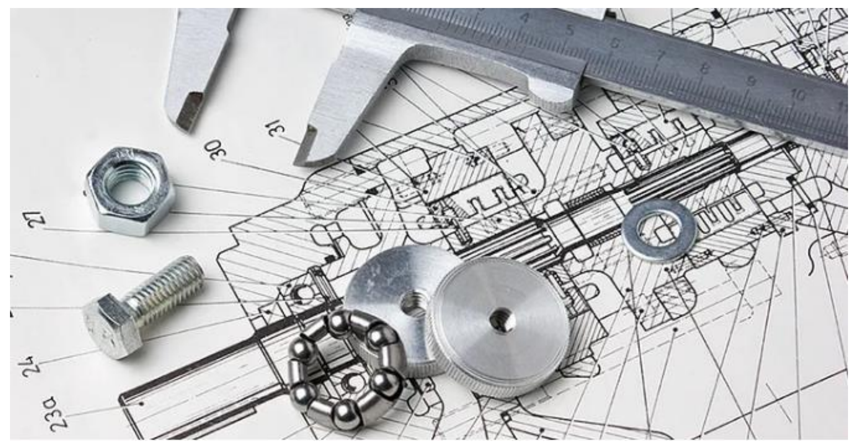
Design

- Get a good understanding of the functional requirements.
- Translate them it into mechanical engineering specifications which are reachable and measurable. Not so easy ! (dimensional tolerances, material specifications, assembly technics, etc…)



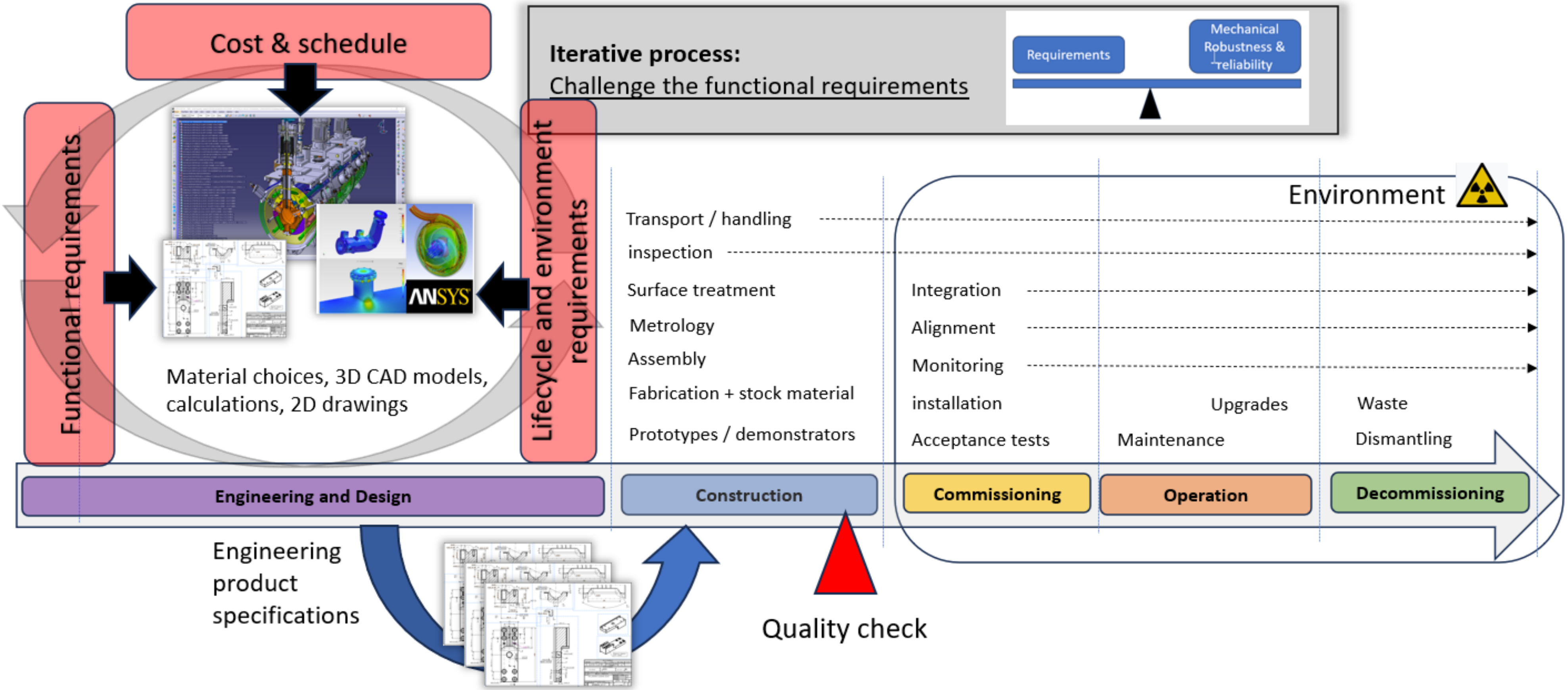
Functional requirement



Mechanical specifications

Design

Identification of the product lifecycle and environmental requirements



Design

Goal: Produce an exhaustive set of 3D models and 2D specification drawings for production.

Keep in mind that the contractual specification for fabrication of a piece of equipment is the **2D drawings** !! This is often overlooked, assuming the 3D model is sufficient.

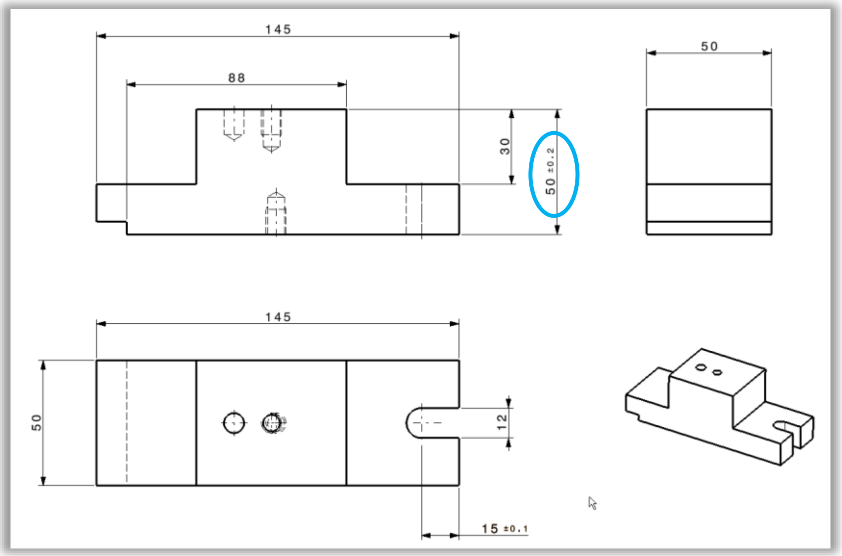
2D drawings carry the exhaustive set of engineering specifications fulfilling the functional requirements.

material specifications, thermal treatments, coatings, tolerances, welding specifications, and so on…

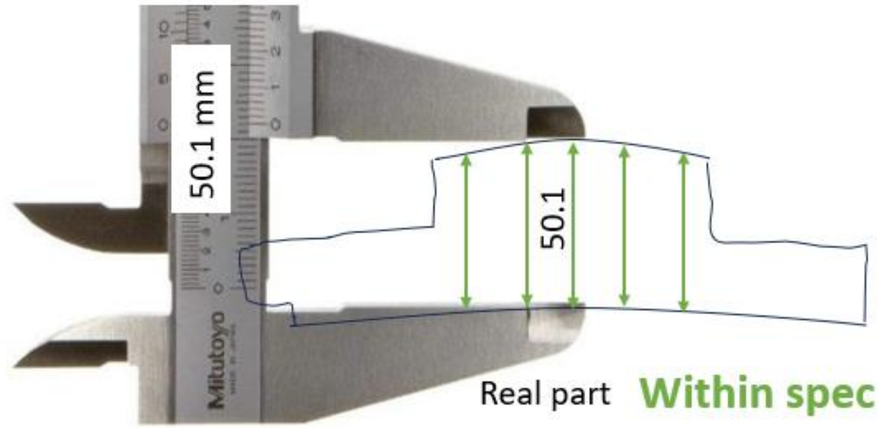
A well defined 2D drawing contributes to making a robust and reliable design.

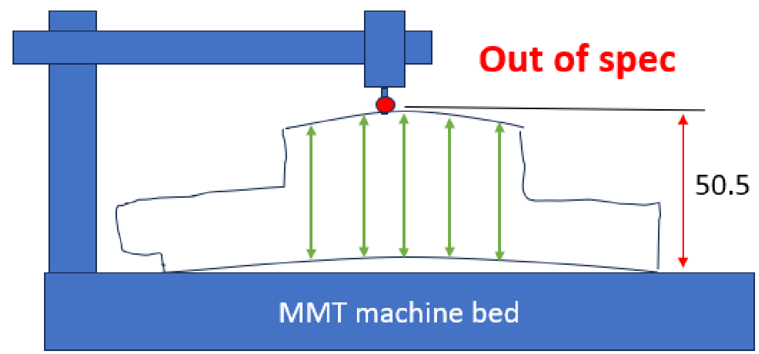
Design

Traditional dimensioning using linear dimensions are not precise enough to express a need in a clear way



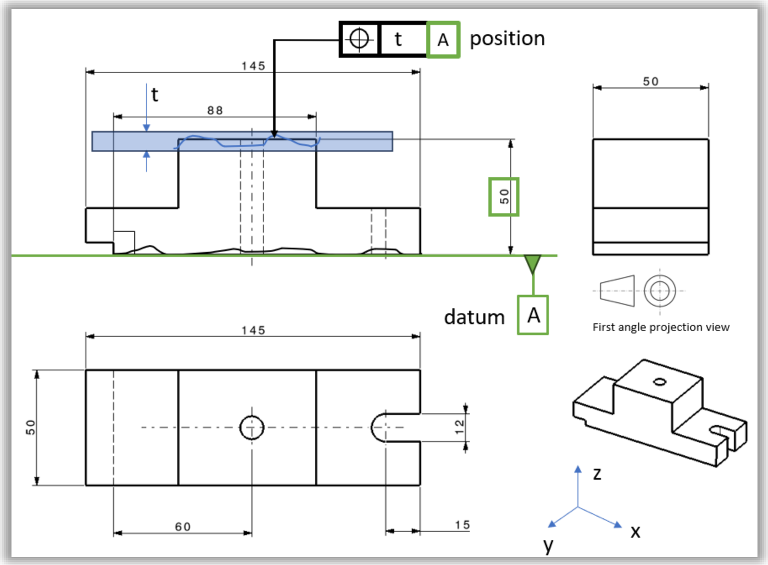
Drawing spec

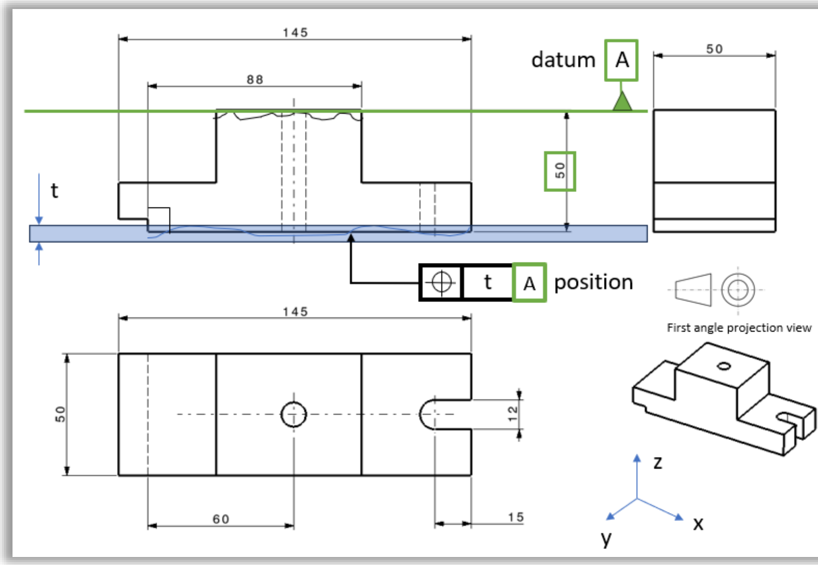




Does it respect your need ?

Design





t = tolerance zone
Ex: ±0.2 (t=0.4)

How do we choose the correct surface for setting our datums ?

Answer in Marc’s presentation ☺

Understanding basics rules of GD&T and ISO GPS framework

Geometric Dimensioning and Tolerancing — Geometrical Product Specification

access to ISO GPS booklet :

https://cetiso.fr/livret-iso-gps/

Livret cotation ISO-GPS

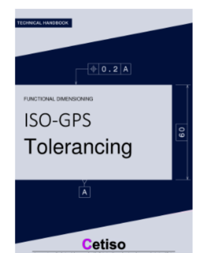
Handbook ISO-GPS Dimensioning

Le nouveau livret est disponible en version 1.12 du 14/05/2024.
– Modifications mineures suite à vos retours.
– Version anglaise

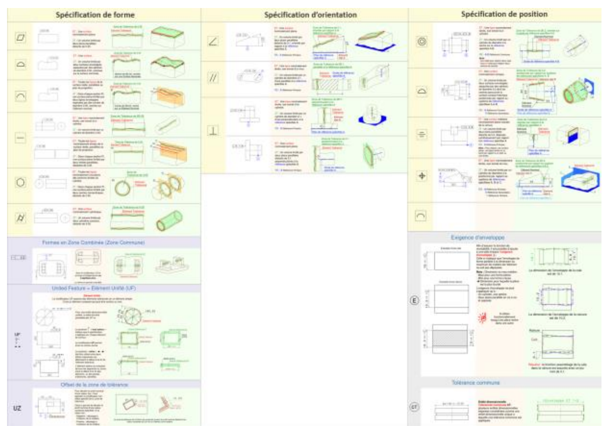
Ce livret est une synthèse des meilleures pratiques en cotation ISO.
Il a été créé pour être mis à disposition gratuitement auprès de tous les utilisateurs de la cotation ISO.
Nous assurons son évolution et sa diffusion gratuitement.
Pour être exploité dans les meilleures conditions, il est préférable d'avoir suivi les formations Cetiso.

Téléchargement

Version Française



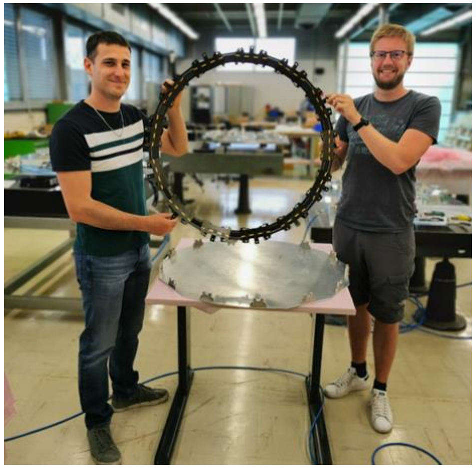
English version

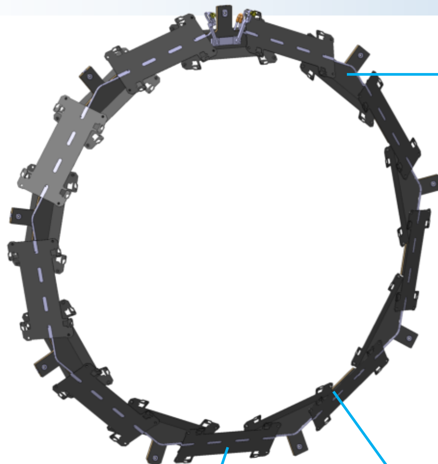


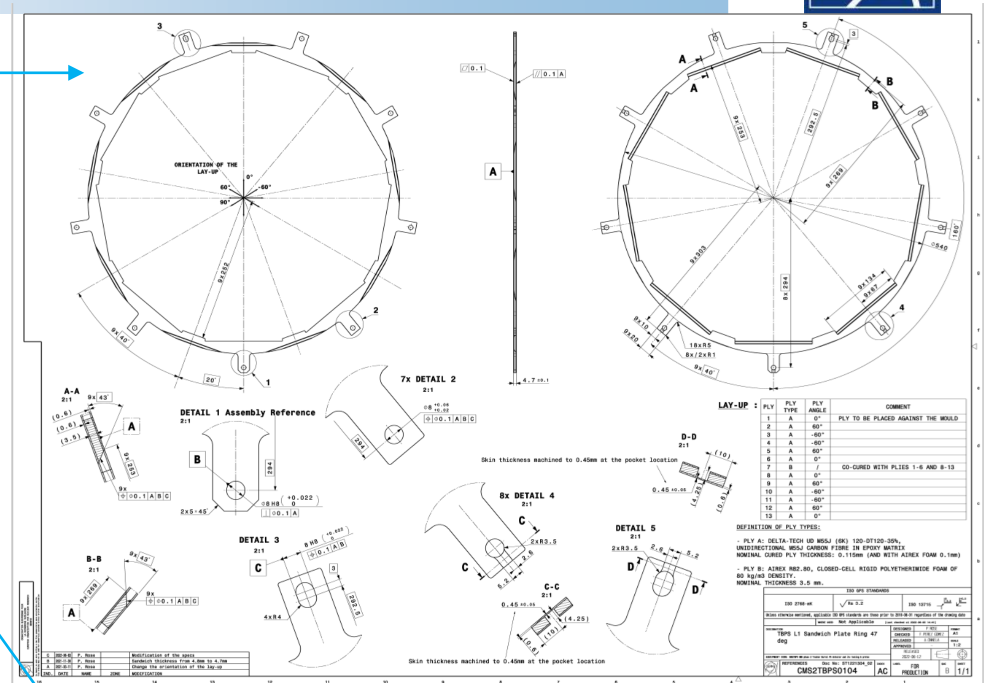
ISO GPS Symbol definitions

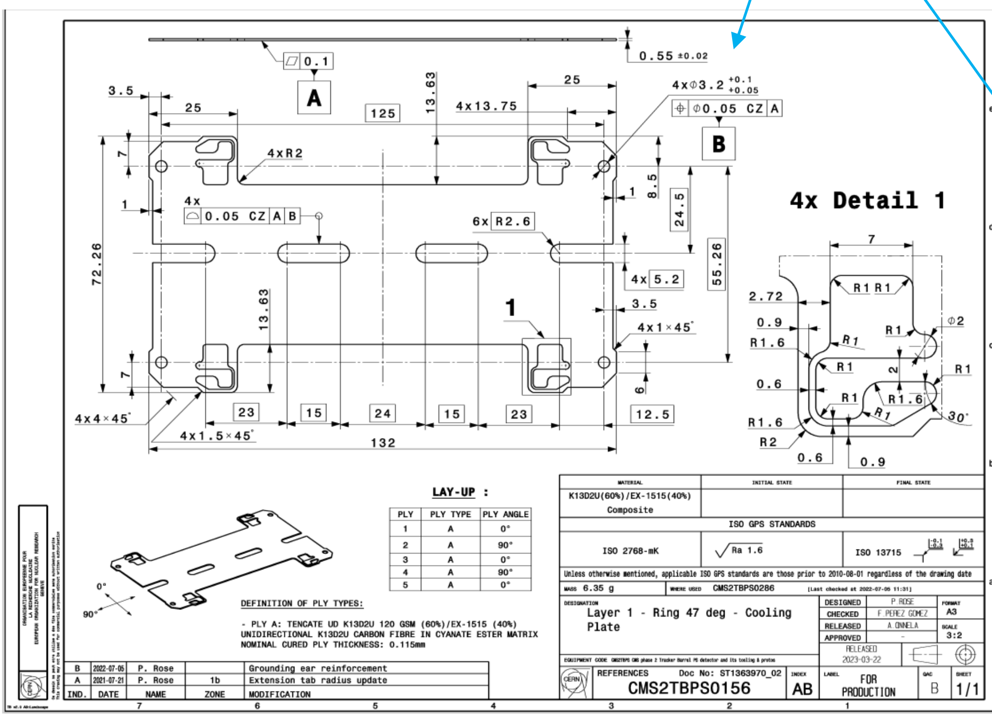
EP

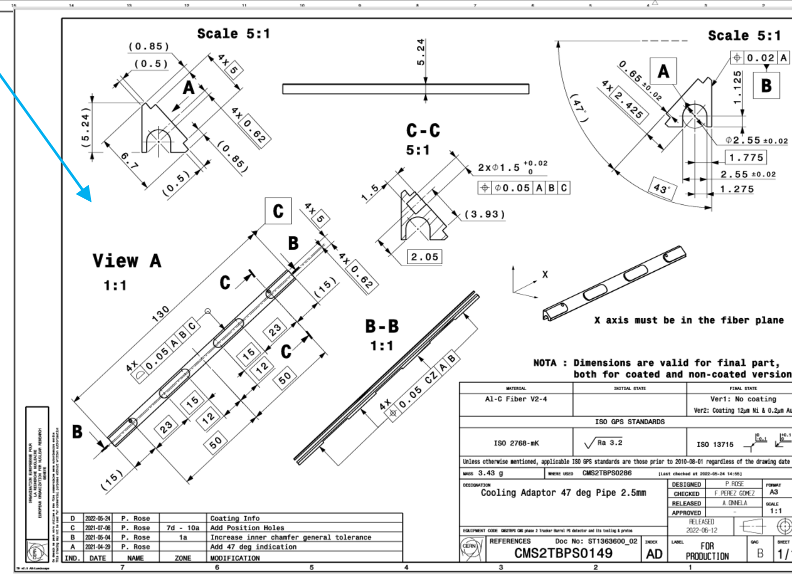
Drawings for CMS TBPS Ring









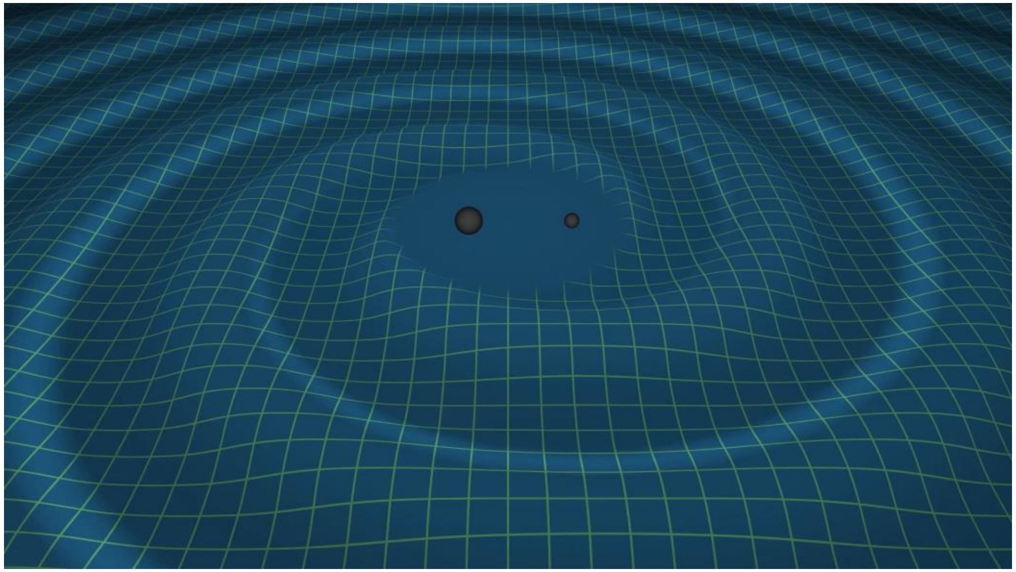


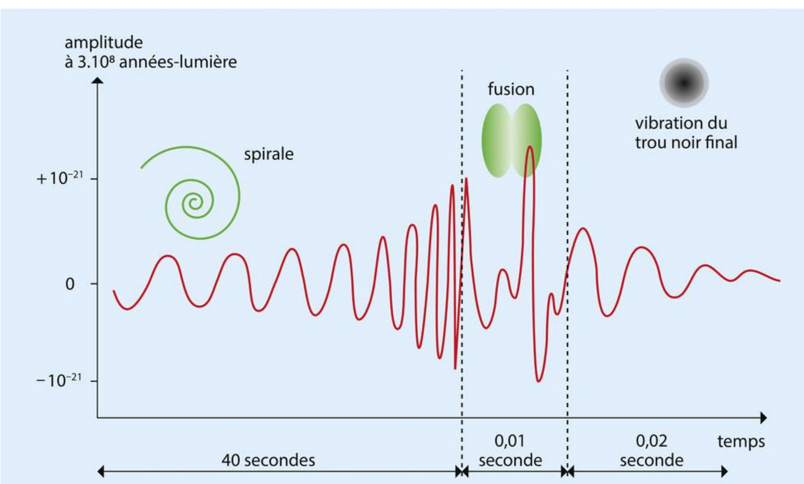
https://indico.cern.ch/event/1463155/

Talk #3

Slides presented per Patrick Werneke (Nikhef & ETO):
https://indico.cern.ch/event/1326947/contributions/5987565/

Einstein Telescope





According to numerical simulations, the coalescence of two black holes generates gravitational waves (red curve) characteristic of the different phases of the motion. Firstly, as the black holes approach each other in a spiral, the gravitational waves emitted have an increasingly large amplitude. When the two black holes merge, in a fraction of a second, they reach their maximum amplitude. The final black hole evacuates its irregularities and rapidly stops emitting gravitational waves.

Einstein Telescope

Einstein Telescope (ET) or Einstein Observatory, is a proposed third-generation ground-based gravitational wave detector, currently under study by some institutions in the European Union. It will be able to test Einstein's general theory of relativity in strong field conditions and realize precision gravitational wave astronomy.

The ET is a design study project supported by the European Commission under the Framework Programme 7 (FP7). It concerns the study and the conceptual design for a new research infrastructure in the emergent field of gravitational-wave astronomy.

Gravitational waves: ripples in the universe
Our universe vibrates daily when black holes or neutron stars orbit or collide somewhere in the universe. Albert Einstein predicted back in 1916 that distances stretch and contract almost immeasurably when such a gravitational wave passes by. In 2015, the US detector LIGO managed to measure that phenomenon for the first time.

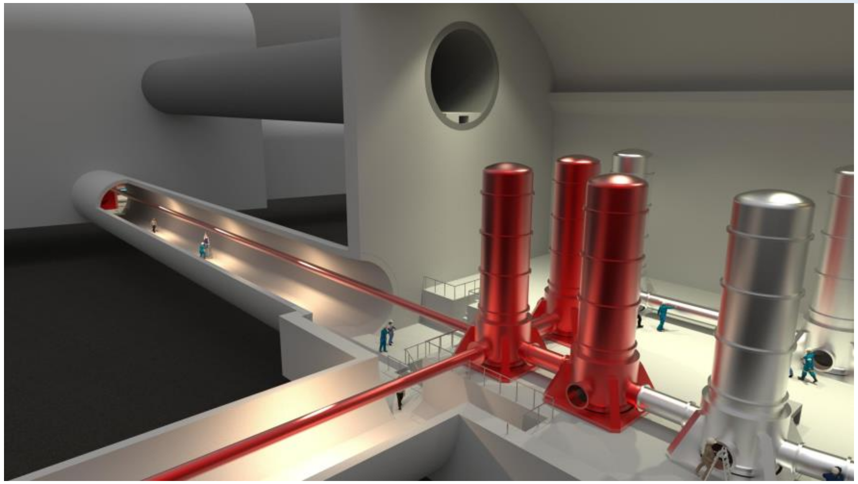
With the Einstein Telescope, researchers will look for instance at the birth process of black holes, the structure of neutron stars, and the nature of the universe immediately after the Big Bang. They also want to test the predictions of Einstein's theory of relativity as never before. This will give us new insights into our universe. This makes the observatory of great significance for international physics and astronomy.

Einstein Telescope

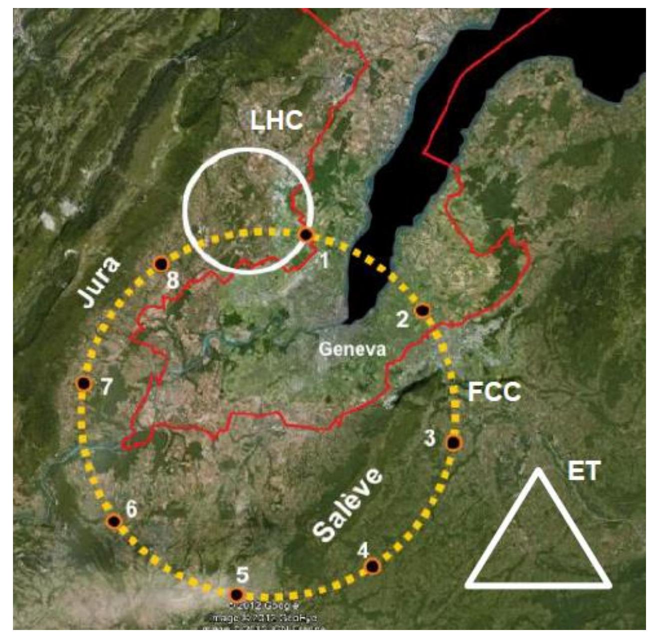
Underground observatory
The three 10-kilometer tunnels of the Einstein Telescope will be sited 250 to 300 meters underground in order to make undisturbed measurements of gravitational waves. Above ground, hardly anything will be visible of the observatory.

EP

ET and CERN



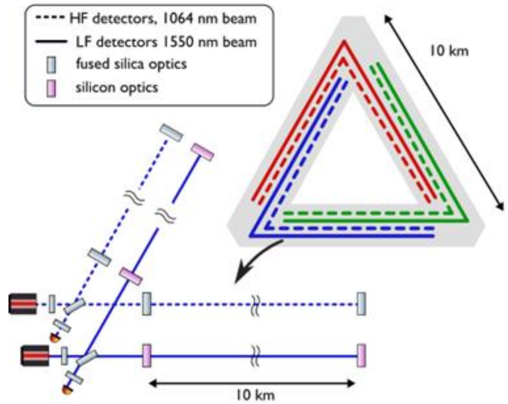
Interesting is the CERN role in the development of the Einstein Telescope.
There are several similarities between ET and CERN projects:

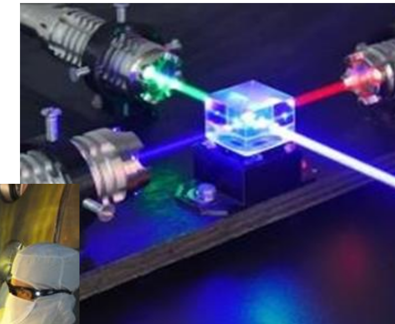


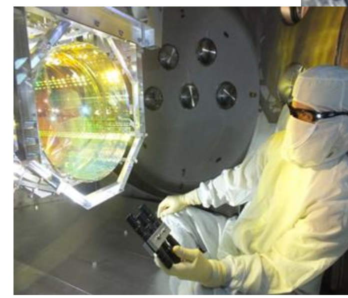
- Underground civil infrastructure
- Large ultra-high vacuum infrastructure
- Cryogenics
- Materials
- Controls
- Managing a large and complex scientific project
- Strong scientific interest from particle physicists

EP

ET Questions







How is CERN contributing to ET design ?

- Large research infrastructure with very quiet vacuum systems where noise, vibrations and electromagnetic can contaminate the measurements

How does the ET detect GW?

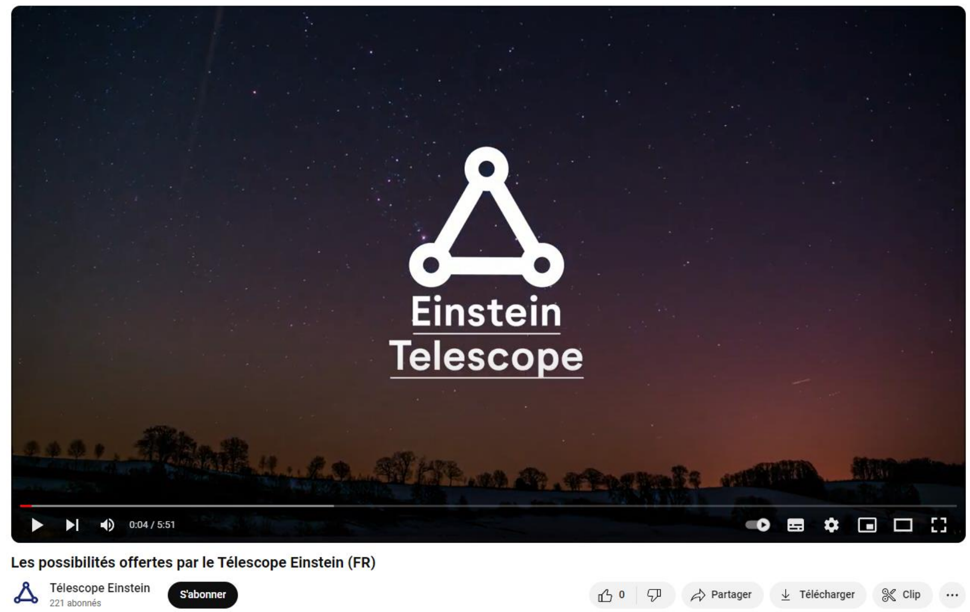
- The Einstein Telescope measures gravitational waves by constantly monitoring the length of its three 10 km detector corridors with sensitive lasers and vibration-free suspended lasers (6 interferometers). If that length changes in a specific pattern, it is the signal of a passing gravity wave.

What GW can tell us about the Universe?

- Gravitational Wave is a ripple of the curvature of the space-time generate by a collision
- The collision generates a wave at the speed of light that cannot be stopped by obstacles, this is a message from the Universe because we can see things that happened millions or billions of years ago

EP

ET Questions



Video Link

Video Link

Conclusions

- CERN Accelerator School was great.
- Takeaways
  - Tackling a wide variety of topics
  - Stepping outside your bubble
  - Knowing whom to call!
- CAS: well organized
  - For e.g.: more lectures in the beginning, lower intensity stuff later
- EN-MME did an outstanding job
- Next step: Thermal CAS? ;)
  - Cryogenics
  - HVAC
  - CFD @ CERN
  - Advanced controls (MPC etc.)
  - Dynamic simulations
  - Virtual commissioning
  - CO2 (the ever-faithful)
  - C3F8 and C6F14 (the also-rans)
  - Krypton (the future)
  - Thermal safety aspects