Characterization of Low-Carbon Steel for High-Field Accelerator Magnets.

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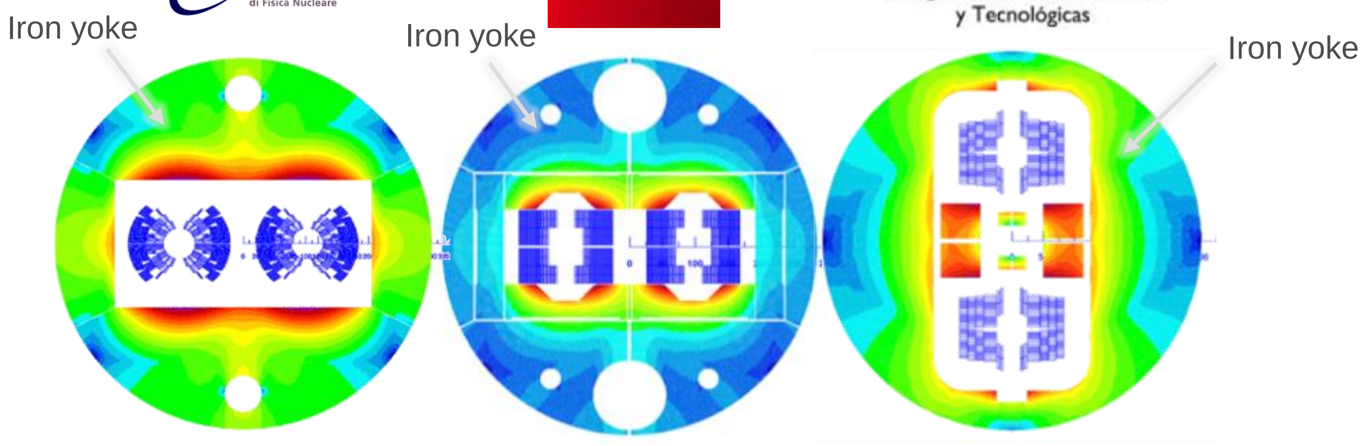
With crucial contributions of: S. Izquierdo Bermudez, S. Sgobba and M. Crouvizier (CERN), K. P. Weiss and N. Bagrets (KIT), C.J. Huang and L. Lai – Feng (TIPC)

Outline

- Introduction and motivation
- Design approach
- Results obtained on ARMCO® at room temperature
- Rationale and motivation of the cryogenic testing
- Results obtained on ARMCO® at cryogenic temperature (4.2 K)
- Discussion and implementation of the results for MQXF (in collaboration with G. Vallone (BNL))
- Conclusions

Introduction and motivation

- 16 T magnet development for FCC
- EuroCirCol designs rely on bladder & key mechanical assembly concepts, where the iron yoke has a key mechanical function.
- This study triggered the need of solid mechanical characterization of the material at room and cryogenic temperature.



Cosine - theta | block – coils | common - coil

Introduction and motivation

- For HL – LHC, with respect to LHC: from MAGNETIL ® to ARMCO ® grade 4
  - Mainly motivated by unavailability of MAGNETIL®, an ‘equivalent’ product was found.
- An invitation to tender (IT – 4009) for the supply of the yokes for the dipoles and quadrupoles of HL – LHC was launched in 2015. The quantity was 1800 tons of 5.8 mm thick sheets.

AK Steel International

ARMCO® PURE IRON HIGH PURITY IRON

GRADE 2

Composition		Max. Analysis %
Carbon	(C)	0.010
Manganese	(Mn)	0.100
Phosphorus	(P)	0.010
Sulfur	(S)	0.008
Nitrogen	(N)	0.006
Copper	(Cu)	0.030
Cobalt	(Co)	0.005
Tin	(Sn)	0.010

GRADE 4

Composition		Max. Analysis %
Carbon	(C)	0.010
Manganese	(Mn)	0.060
Phosphorus	(P)	0.005
Sulfur	(S)	0.003
Nitrogen	(N)	0.005
Copper	(Cu)	0.030
Cobalt	(Co)	0.005
Tin	(Sn)	0.005

The high purity of ARMCO Pure Iron is the primary reason for the following special properties:

- Excellent magnetic properties

Introduction and motivation

Example of material certificate of IT - 4009

thyssenkrupp Steel Europe thyssenkrupp

Werks-Nr. / Works-No. / No. de l'usine A08	Zeugnis-Nr. / Certificate-No. / No de certificat A03	Sendungs-Nr. / Shipment-No. / No d'envoi	Seite-Nr. / Page-No. / Page-No.
4358558	1843063001	47199253	1

thyssenkrupp Steel Europe AG·47161Duisburg A01

A06
AK STEEL INTERNATIONAL B.V.
HOLZMARKT 1
D 50676 KÖLN

BESCHEINIGUNG ÜBER MATERIALPRÜFUNGEN EN 10204
DOCUMENT ON MATERIAL TESTS EN 10204
DOCUMENT DE CONTROL DES MATÉRIAUX EN 10204

A02
INSPECTION CERTIFICATE 3.1

Bestell-Nr. / Order-No. / No de commande: POMD-160149 CERN
A07.1-A07.5

26.10.2017 mm
0203 52 75220
0203 52 75213 A05
abnahme_zeugnisse.grobblech@thyssenkrupp.com

Werkstoff; Quality; Matériau / Lieferbedingungen; Specification; Conditions de livraison B02/B03
ARMCO61 AKDE032-ARMCO-HR PLATES ANNEALED REV.2 04.17
TOL.EBENH. EN10029 KL.S OB EN 10163 KL.B/1
SCHWEFEL MAX.0,03 (3-STELLIG AUSWEISEN)ZEUGNIS IN ENGLISCH WIE 1801975

Kennzeichnung / Marking / Marque: B06 MATERIAL, HEAT-NO., MANUFACTURING/SAMPLE-NO.
Zeichen des Lieferwerks / Supplier'smark / Marque d'usine: A04

ABNAHMEPRUEFSTEMPEL / INSPECTOR'S STAMP / POINCON DU RECEPTIONNAIRE

B01
TYPE OF PRODUCT
HEAVY PLATES, TRIMMED EDGES

LIST OF MATERIAL IDENTS

ITEM	B07 BUNDLE	B07 PLATE-NO.	B07 HEAT-NO.		B08 NUMBER PIECES	B13 WEIGHT Kg
001	B09 x B10 x B11 5,8 x 750,0 x 4000 [mm]					
	A2510704		707901		15	2.060
	A2510904		707901		17	2.340
	A2511702		707901		22	3.030
	A2511704		707901		11	1.510
	A2511902		707901		19	2.717
	A2512001		707901		22	3.147
				*	106	14.804
				**	**106**	**14.804**

TRANSPORT-NO.
TKN-25021

CHEMICAL COMPOSITION OF THE LADLE SAMPLES % C71-C99

B07 HEAT-NO.	C	SI	MN	P	S	AL-G	B-G	CO	CR	CU	MO
707901	,001	,003	,050	,004	,0034	,004	,0003	,002	,017	,006	,001
	N	NB	NI	SN	TI	V	AS	O			
707901	,0035	,001	,016	,002	,000	,001	,001	,010			

C70 HEAT PROCESS OXYGEN STEEL

thyssenkrupp Steel Europe AG
Abnahme – FOLGESEITE –

Werks-Nr. / Works-No. / No. de l'usine A08	Zeugnis-Nr. / Certificate-No. / No de certificat A03	Sendungs-Nr. / Shipment-No. / No d'envoi	Seite-Nr. / Page-No. / Page-No.
4358558	1843063001	47199253	2

MECHANICAL CHARACTERISTICS T E N S I L E T E S T

B07 HEAT-NO.	C00 SAMPLE NO.	C01/02 POS.	B05 STAT.	C10 TYPE	AGED	C03 TEST TEMP °C	C11 R MPa	R Art	C12 Rm MPa	R/Rm %	L0 mm	C13 A %	Z %	Rm*A
707901	*A2510701	0401	0021	0002	0006	+20	217	RE H	281	77	75	53	81	14893
707901	*A2510901	0401	0021	0002	0006	+20	207	RE H	285	73	75	54	79	15390
707901	*A2511701	0401	0021	0002	0006	+20	232	RE H	285	81	75	55	81	15675
707901	*A2511901	0401	0021	0002	0006	+20	208	RE H	286	73	75	47	77	13442
707901	A2512001	0401	0021	0002	0006	+20	227	RE H	289	79	75	51	79	14739

MECHANICAL CHARACTERISTICS H A R D N E S S T E S T

B07 HEAT-NO.	C00 SAMPLE NO.	B05 STAT.	C30 METHOD	C32 AVERAGE	AVERAGE THICKNESS mm
707901	*A2510701	0021	HARDNESSTEST BRINELL	82,0	
707901	*A2510901	0021	HARDNESSTEST BRINELL	82,0	
707901	*A2511701	0021	HARDNESSTEST BRINELL	83,0	
707901	*A2511901	0021	HARDNESSTEST BRINELL	83,0	
707901	A2512001	0021	HARDNESSTEST BRINELL	83,0	

MECHANICAL CHARACTERISTICS G R A I N S I Z E

B07 HEAT-NO.	C00 SAMPLE NO.	1) SAMPLE-TYPE 2)	CLASS-1	WITH	CLASS-2	WITH	CLASS-3
707901	*A2510701	1)					
		2)	4.5		4.5		4.5
707901	*A2510901	1)					
		2)	4.5		4.5		4.5
707901	*A2511701	1)					
		2)	5.0		5.0		5.0
707901	*A2511901	1)					
		2)	4.5		4.5		4.5
707901	A2512001	1)					
		2)	6.0		6.0		6.0

* SAMPLE PLATE NOT INCLUDED IN DELIVERY

L E G E N D S

STAT.
0021 = ANNEALED

AGED
0006 = NOT AGED

POSIT (IST)
0401 = TRANS. TOP S.

TYPE TENSILE TEST
0002 = FLAT TENSILE TEST

S T A T U S P R O D U C T

001 ANNEALED

Z02
ABNAHMEBEAUFTRAGTER DES HERSTELLERS
THE MANUFACTURER'S AUTHORIZED INSPECTION REPRESENTATIVE
LE REPRÉSENTANT AUTORISÉ DU CONTRÔLEUR DU PRODUCTEUR

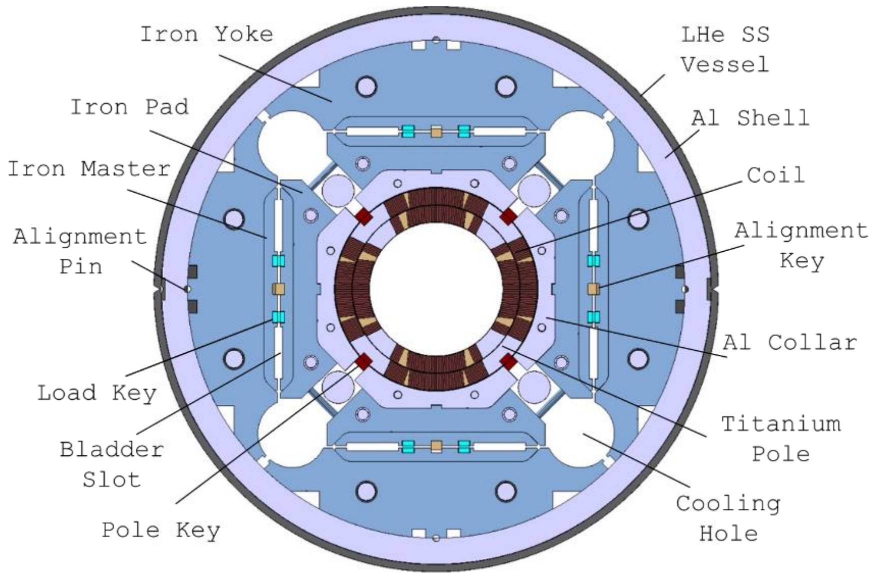
Kern
Z03 Prof. Dr.-Ing. Kern

thyssenkrupp Steel Europe AG
Abnahme

Es wird bestätigt, dass die Lieferung den Vereinbarungen bei der Bestellung entspricht.
We hereby certify that the above mentioned materials have been delivered in accordance with the terms of order.
Z01 Nous attestons que les produits livrés sont conformes aux stipulations de la commande.

Introduction and motivation

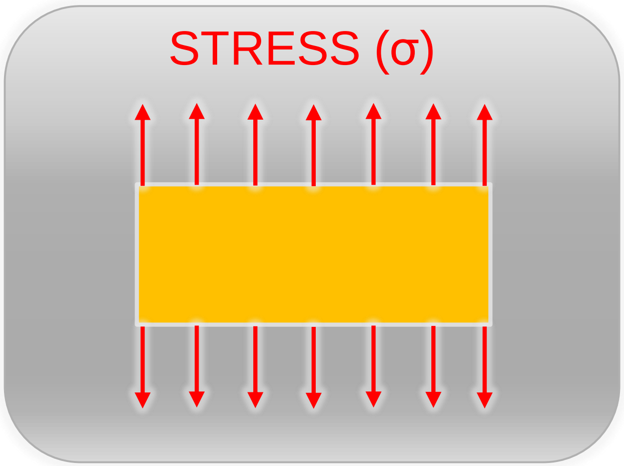
- In order to combine the material and mechanical characterization with a functional magnet design, a detailed assessment and its application on a currently used magnet is proposed: MQXF

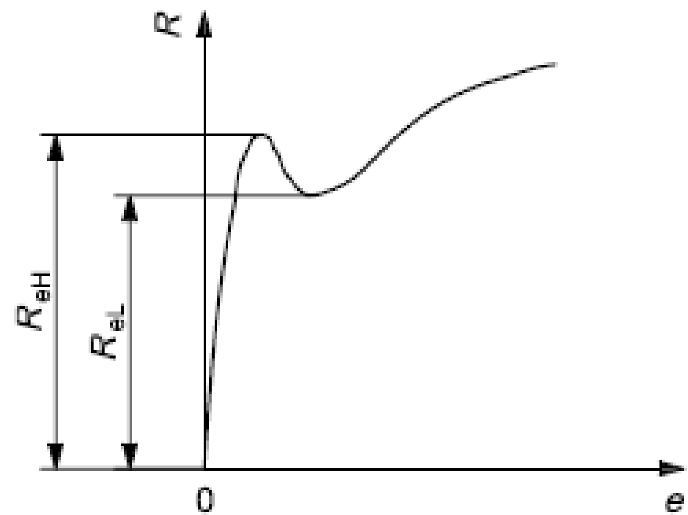


Design approaches: strength of material

MATERIAL RESISTANCE

DRIVING FORCE





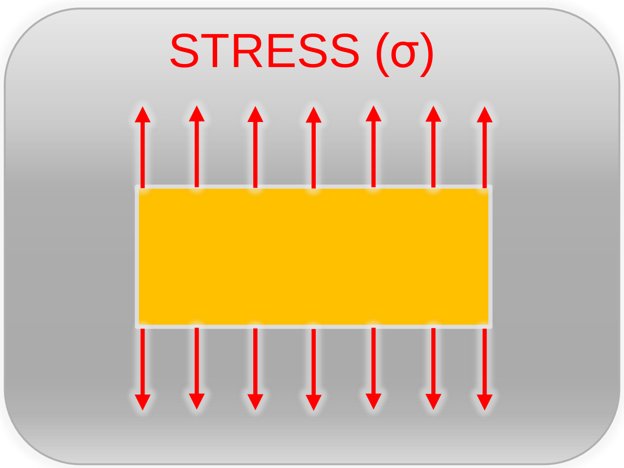
$$S \cdot \sigma < R_{eL}$$

Safety factor

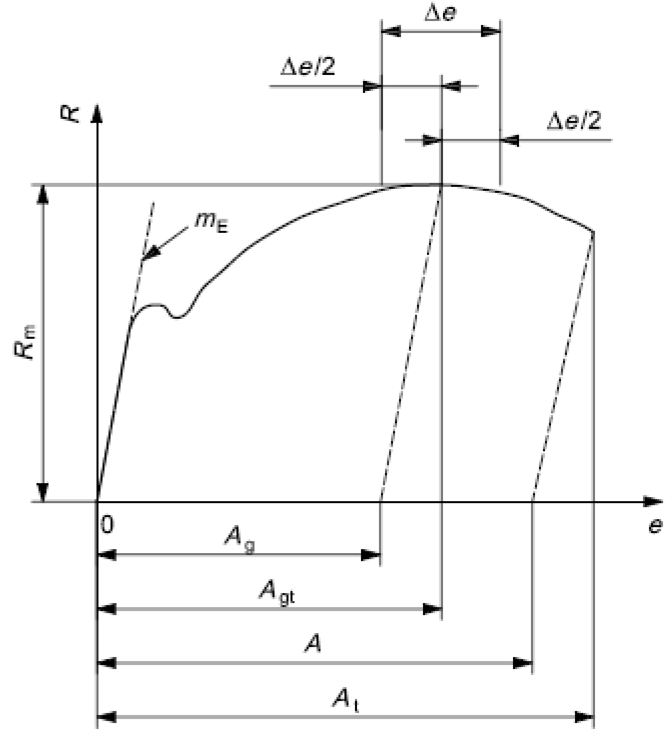
Lower yield strength

Design approaches: strength of material

DRIVING FORCE



MATERIAL RESISTANCE

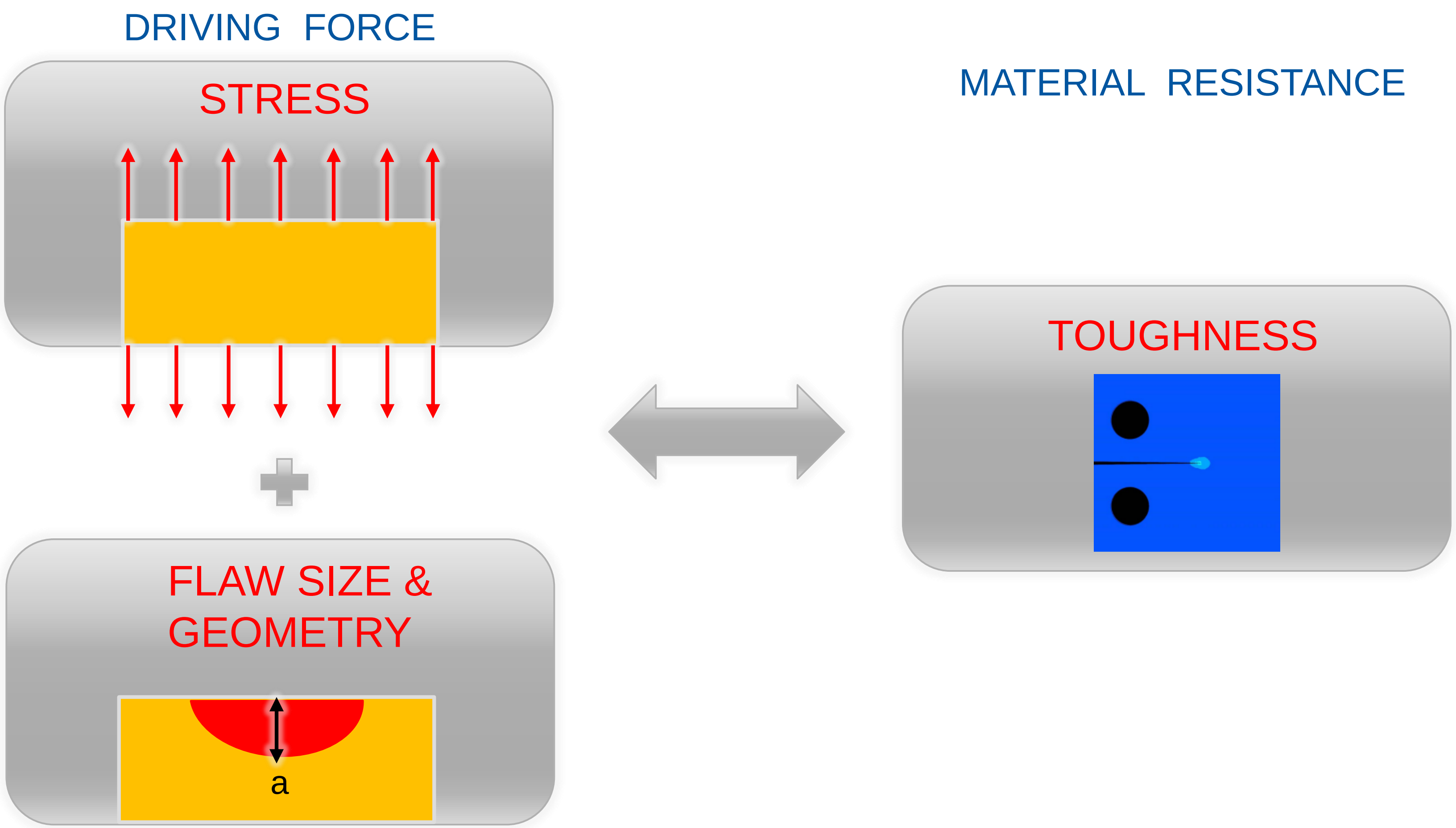


$$S \cdot \sigma < R_m$$

Security factor

Tensile strength

Design approaches: fracture mechanics



$$S \cdot Y \cdot \sigma \cdot \sqrt{\pi \cdot a} < K_{IC}$$

Safety factor — Geometrical factor — Flaw size — Fracture toughness

Test campaign

- 2 families of materials were tested:
  - ARMCO ® as received (after hot rolling). Rolling direction
  - ARMCO ® annealed (980°C during 1 hour).
    - The goal was to compare the properties with the as – received state

The test campaign, carried out in 2016 – 2017, was performed as follows:

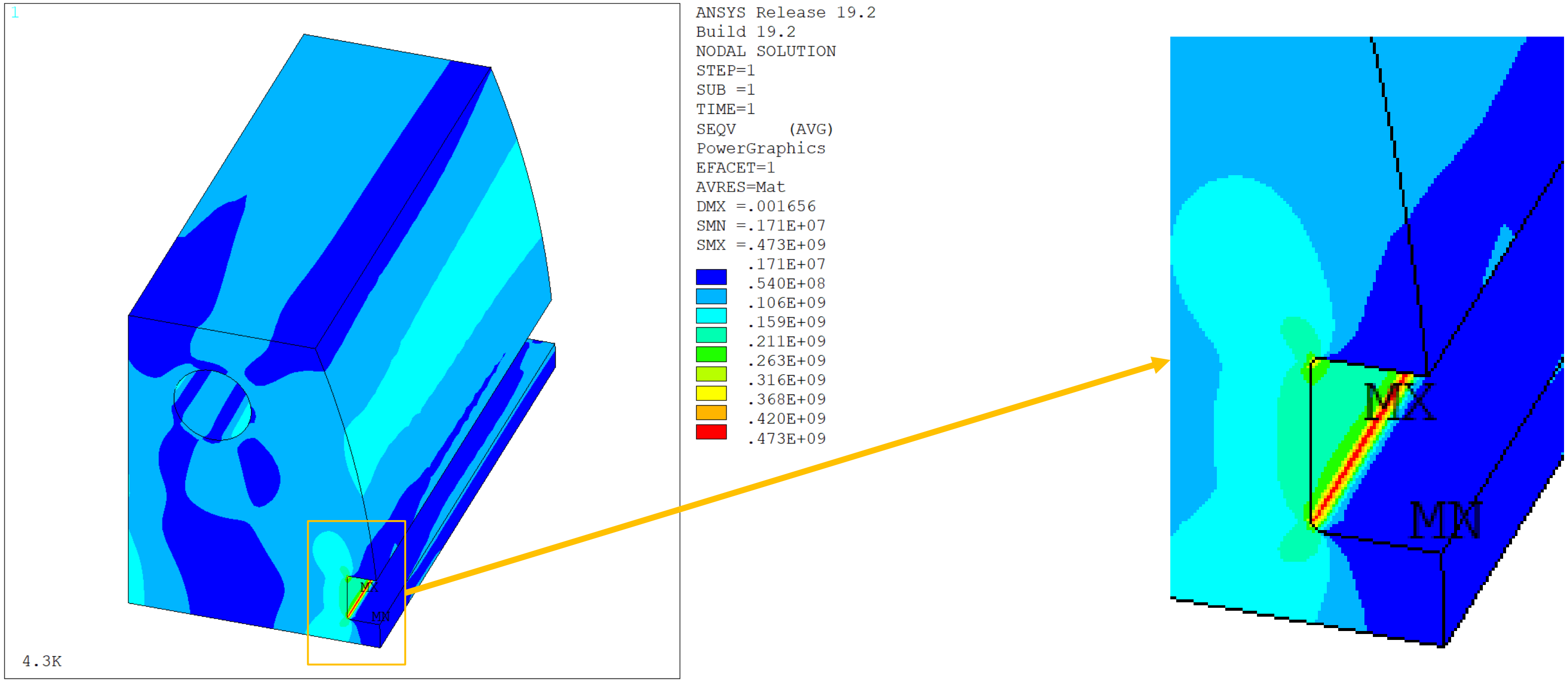
- Uniaxial tensile tests @ RT & 4.2 K → CERN (M. Crouvizier)
- Fatigue testing @ 4.2 K → TIPC (CN)
- Fracture toughness @ 4.2 K → KIT (GE)

Test matrix

Material	Specimens	Test
ARMCO® annealed	6 @ RT and 6 @ 4 K (3 per direction)	Tensile RT & 4 K
	3 rolling direction and 3 longitudinal direction	Fatigue at 4 K
	2 specimens. LT orientation 2 specimens. TL orientation	Fracture toughness at 4 K
ARMCO® As – received	3 @ RT and 3 @ 4 K	Tensile RT & 4 K
	3 specimens	Fatigue at 4 K
	2 specimens. LT orientation	Fracture toughness at 4 K

Rationale and motivation of the cryogenic testing

- In order to asses the static, cyclic and toughness properties at temperature close to operation.
- MQXF **nominally** requires a coil prestress of **120 MPa** on the pole to avoid unloading during powering, and of **140 MPa** to avoid unloading at **ultimate current**.
- The stress distribution in the yoke after cooldown at 145 MPa (more severe) is the following:



Rationale and motivation of the cryogenic testing

- In order to rule out a premature failure during the whole lifespan of the components.
- Cycles tailored for MQXF case.
- Number of cycles: 20000 (EDMS 1171853). Safety factor: 20

6.2 MECHANICAL REQUIREMENTS

6.2.1 MECHANICAL FUNCTIONAL SPECIFICATIONS

6.2.1.1 CONTAINMENT OF LORENTZ FORCES

The insulation system has been chosen also to minimize interconnection deformation under the effect of the repulsive Lorentz forces between thebus bars. The design values are listed in Table VII [11].

	Value
Design load linearly distributed on the bus bar and exercised by the Lorentz forces (12850A)	1.2 kN/m
Distance between bus bar support points external to the interconnection (worst case MB->MQ interconnect with worst support positioning tolerances)	0.6 m
Number of LHC cycles (continuous operation 20 years, 250 days operation/year, 4 ramps/day)	20.000

Table VII. Reference values for mechanical dimensioning of the insulation system in term of Lorentz force restrain

Remark: the foreseen number of cycles is 12.000 [13]. The design value is increased to 20.000 as extra margin.

Design Description Document:

DDD 11
ITER_D_22HV5L v2.2

Magnet

The first fatigue assessment method uses SN curves established by component testing. The curves are preferably measured for the standard +/- (R=-1) cycle with zero mean stress (not R=0 often used at 4K), if not they have to be converted using empirical scaling rules linking fatigue life to yield/ultimate stress such as Goodman or Soderberg. After scaling from the SN +/- curve for mean stress effects, and correcting for multi-axial cyclic stress components, a safety factor is applied either to the cyclic stress, of a factor of 2, or to the number of cycles, of a factor of 20, using whichever gives the most conservative cyclic stress allowable.

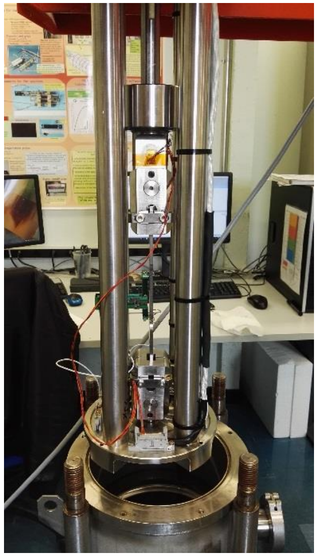
Results: Tensile tests

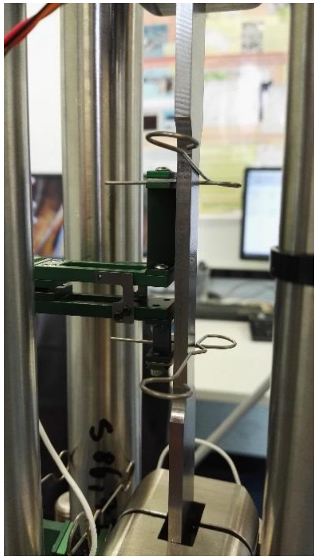
- At RT, we are mostly interested in the R_m (R_m < 280 MPa) as it has a major impact in the fabrication costs. Additionally, R_{eL} > 150 MPa is required to avoid plastic deformation in the yoke during loading at room temperature.

Material	R_{eL} [MPa]	R_m [MPa]	A [%]
ARMCO as received. Rolling direction	229 ± 1	293 ± 2	42 ± 1
ARMCO annealed. Rolling direction	237 ± 3	304 ± 2	41 ± 2
ARMCO annealed. Transverse direction	251 ± 1	301 ± 1	44 ± 2
Reference from material certificates	210 ± 12	286 ± 2	51 ± 3

Sample geometry according to ISO 6892. Thickness: 4 mm

Results: Cryogenic tensile tests





Material	R_m [MPa]	A [%]
ARMCO as received (rolling direction)	1043 ± 4	0.4 ± 0.1
ARMCO annealed (Rolling direction)	972 ± 8	0.2 ± 0.1
ARMCO annealed (Transverse direction)	975 ± 6	0.3 ± 0.1

- Width in the calibrated section reduced from 12.5 mm to 8 mm to guarantee breakdown outside the heads.
- **They all broke in the elastic region** (brittle)
- R_m increases by a factor of ~ 3 @ 4.2 K

Results: Cryogenic fatigue testing

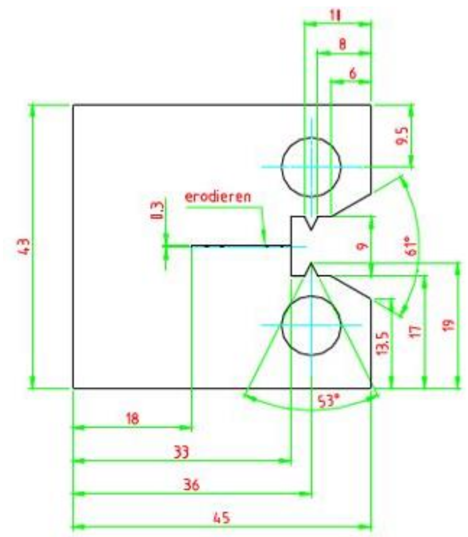
Specimen	Temp. [K]	σ_{max} [MPa]	R ratio	Frequency [Hz]	Survival Cycles
	Fatigue Parameters				
ARMCO as received (rolling direction) x 3	4.2	500	0.1	7	>400,000
ARMCO annealed (Rolling direction) x 3					>400,000
ARMCO annealed (Transverse direction) x 3					>400,000

Frequency below 8 Hz to avoid heating the sample during fatigue testing at 4.2 K

All the samples which were tested survived the designed load cycles for 400 kcycles

Fracture toughness results @ 4.2 K

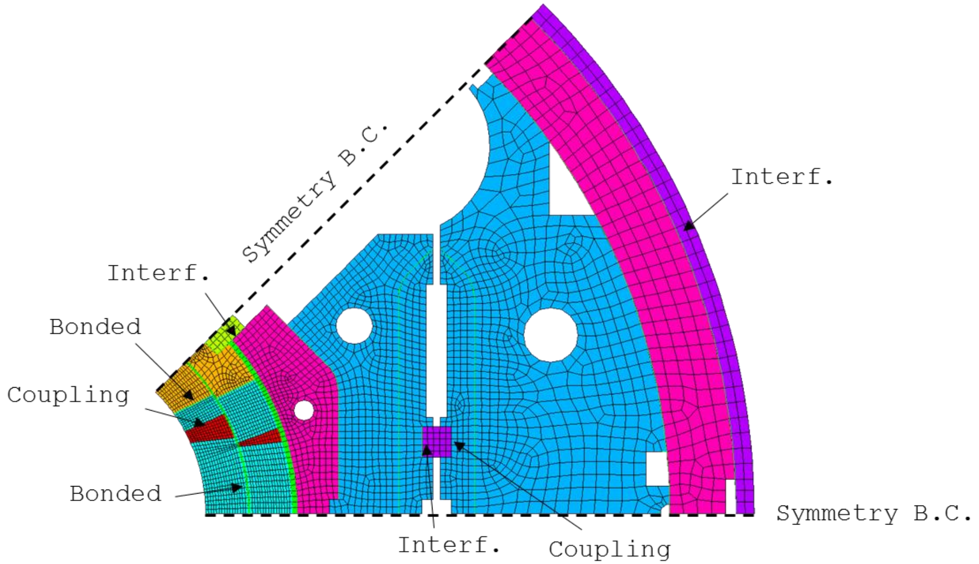
- In order to implement a fracture toughness based design
- Compact tensions specimens (5.8 mm thickness)
- ‘K’ tests for low toughness materials (according to ASTM E399)

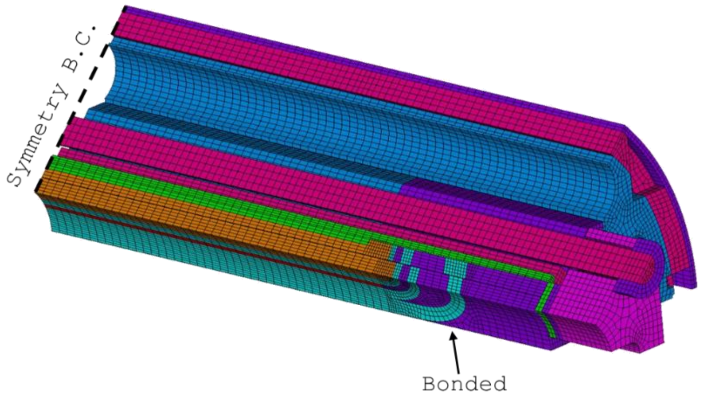


Specimen ID	Material	Fracture toughness (K_{IC}); [MPa√m]	Fracture toughness uncertainty; [MPa√m]
AR–LT-CT1	ARMCO as received	27.98	0.22
AR – LT- CT2	ARMCO as received	26.91	0.22
AN TL-CT1	ARMCO annealed (short side)	24.44	0.16
AN TL-CT2	ARMCO annealed (short side)	25.71	0.52
AN LT-CT1	ARMCO annealed (long side)	25.37	0.21
AN LT-CT1	ARMCO annealed (long side)	28.17	0.53

Application of the results: MQXF

MQXF FE Model

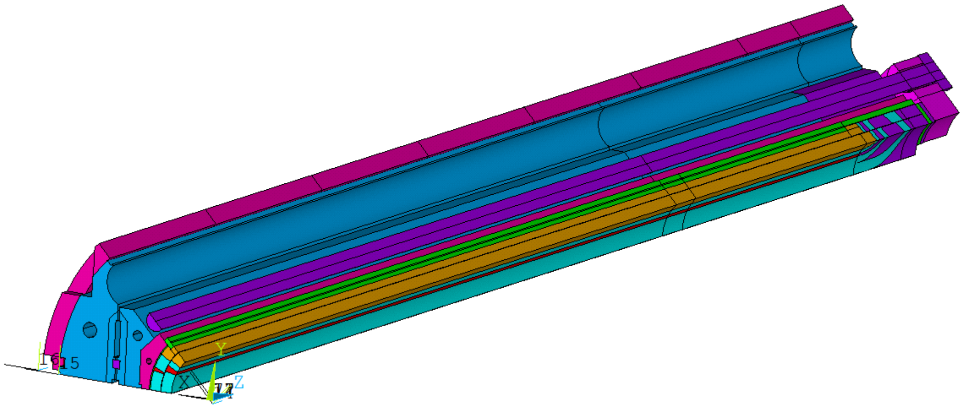


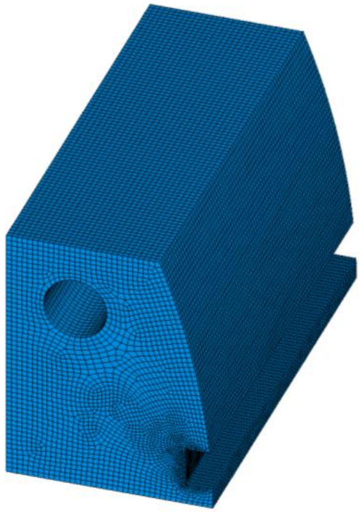


- Standard MQXF FE model
  - 2D and 3D
  - 1 octant, ½ length
- Material properties → linear elastic

Application of the results: MQXF

Submodelling strategy





- Global model from MQXFS and MQXFA
- Stress state is very similar, MQXFS is obviously faster to run
- Detailed model of the end region
- Displacements after cooldown
- Similar stress during powering

Introduction – Failure Assessment Diagram

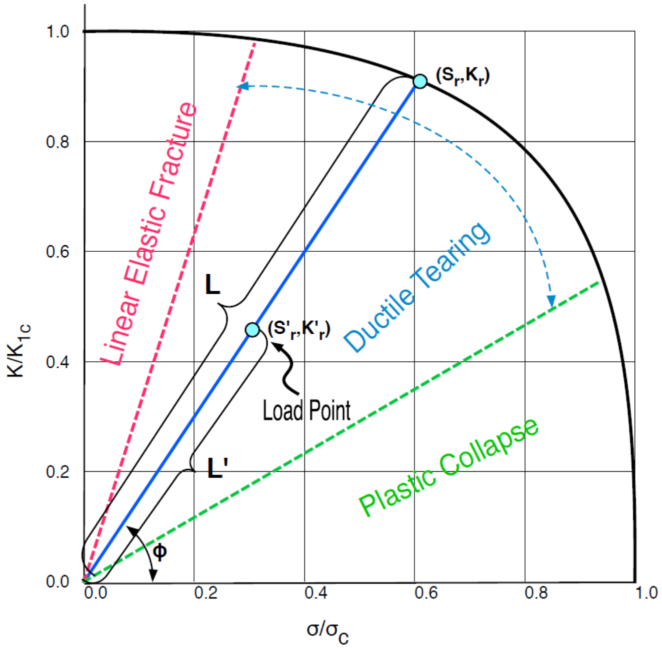
$$Load\ Factor = \sqrt{\frac{(S_r{}^2 + K_r{}^2)}{(S_r'{}^2 + K_r'{}^2)}}$$

$$K_r(S_r) = S_r\left[\frac{8}{\pi^2}\log\left(\sec\left(\frac{\pi}{2}S_r\right)\right)\right]^{-1/2}$$

$$S_r = {}^{\sigma}/_{(\sigma_c)}$$

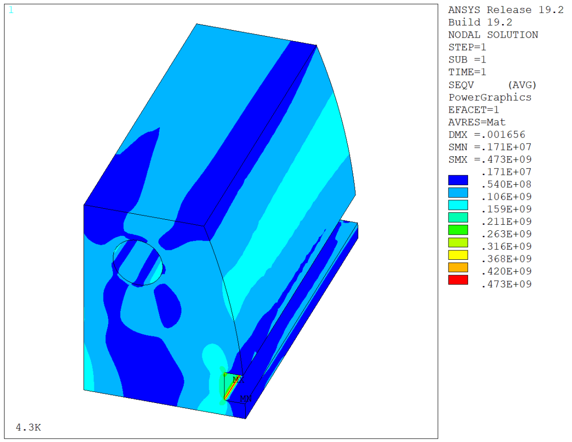
σ_c = 974 MPa

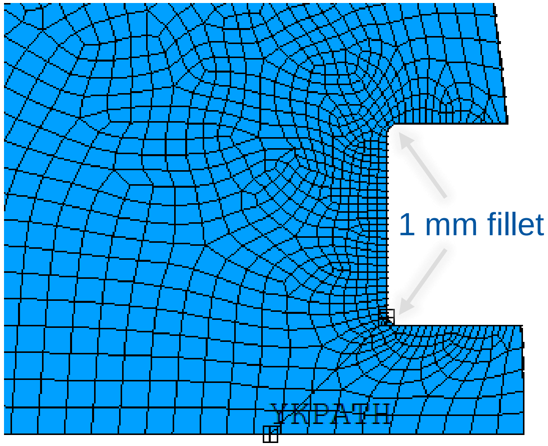
K_{IC} = 26 MPa √m

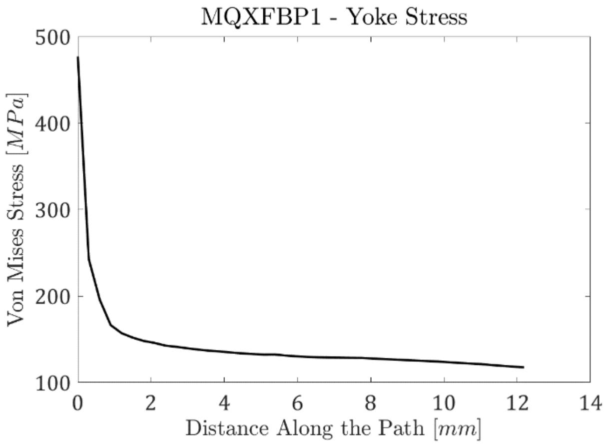


- R6 Failure Assessment Diagram (FAD): R6 PANEL. *R6: Assessment of the integrity of structures containing defects.* Revision 4, as amended. Gloucester: EDF Energy, 2001.
- Load points inside the curve are considered safe
- A load margin (load factor) can be computed projecting the loading point onto the curve

Discussion of the results: application to MQXF

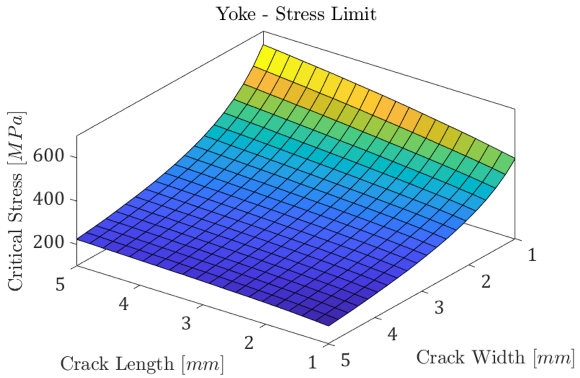


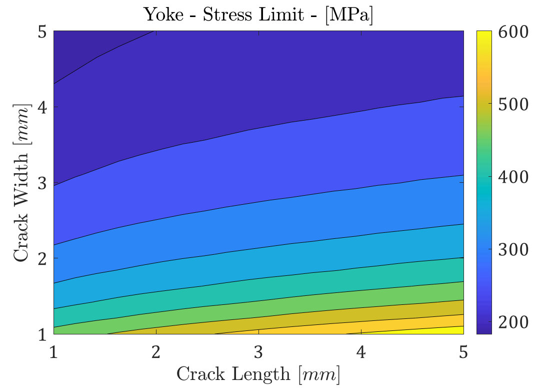


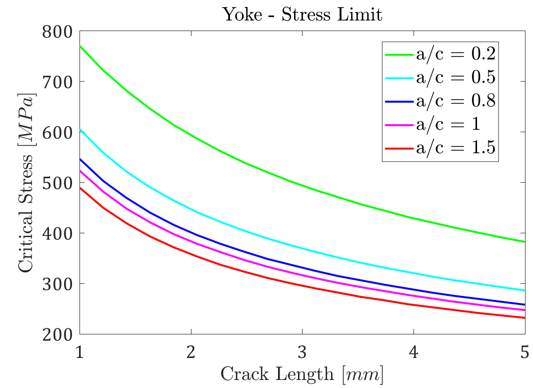


- 1st approach:
  - **Assuming a constant stress** (average peak stress) along the crack path
  - Very conservative
- Refined approach:
  - **Path from the max stress along the min. gradient line**
  - Stress is a function of the applied prestress
  - We refer here after to the stress applied on the pole with the standard assembly parameters

1st approach: stress limit & crack size results for MQXF. Constant stress

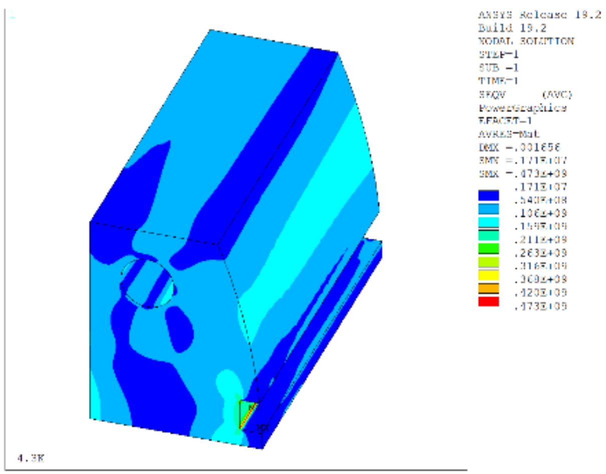




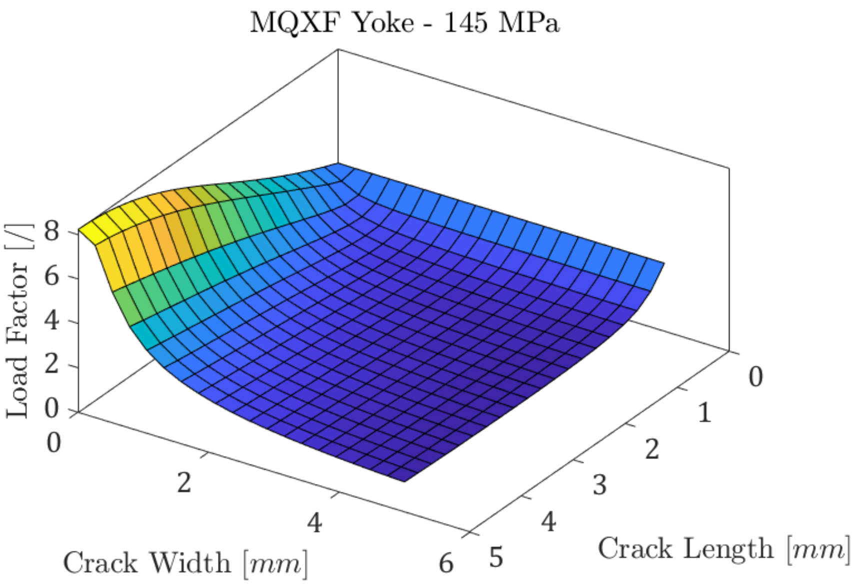


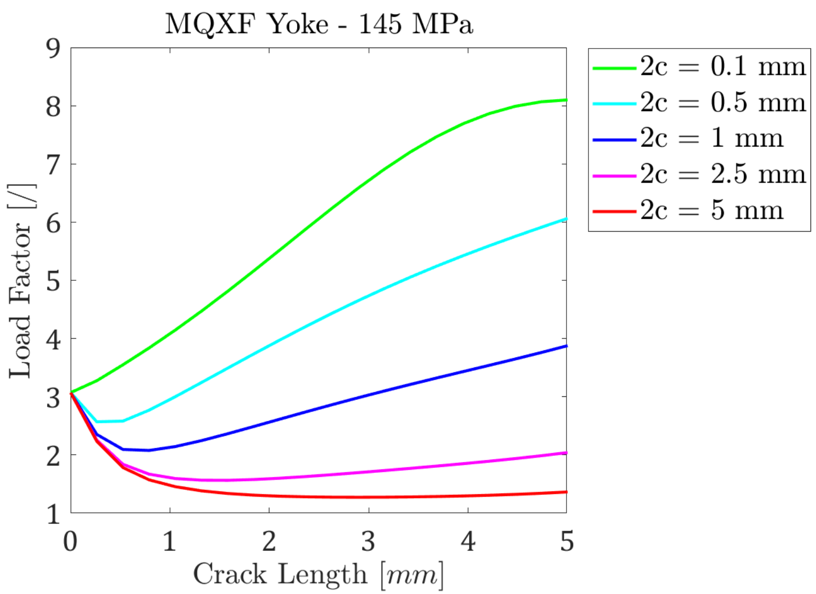
- For the stress profile of MQXF, K_I increases but the stress at the crack tip decreases when increasing crack length.
  - The crack preferentially propagates in width
  - UT detectability: With a UT inspection a flat bottom hole (FBH) of 1.2 mm would be easy to detect, the stress limit could go between 500 MPa and 750 MPa

Stress profile of MQXF



Refined approach: FAD results for MQXF. **Path from the max stress along the min. gradient line**.

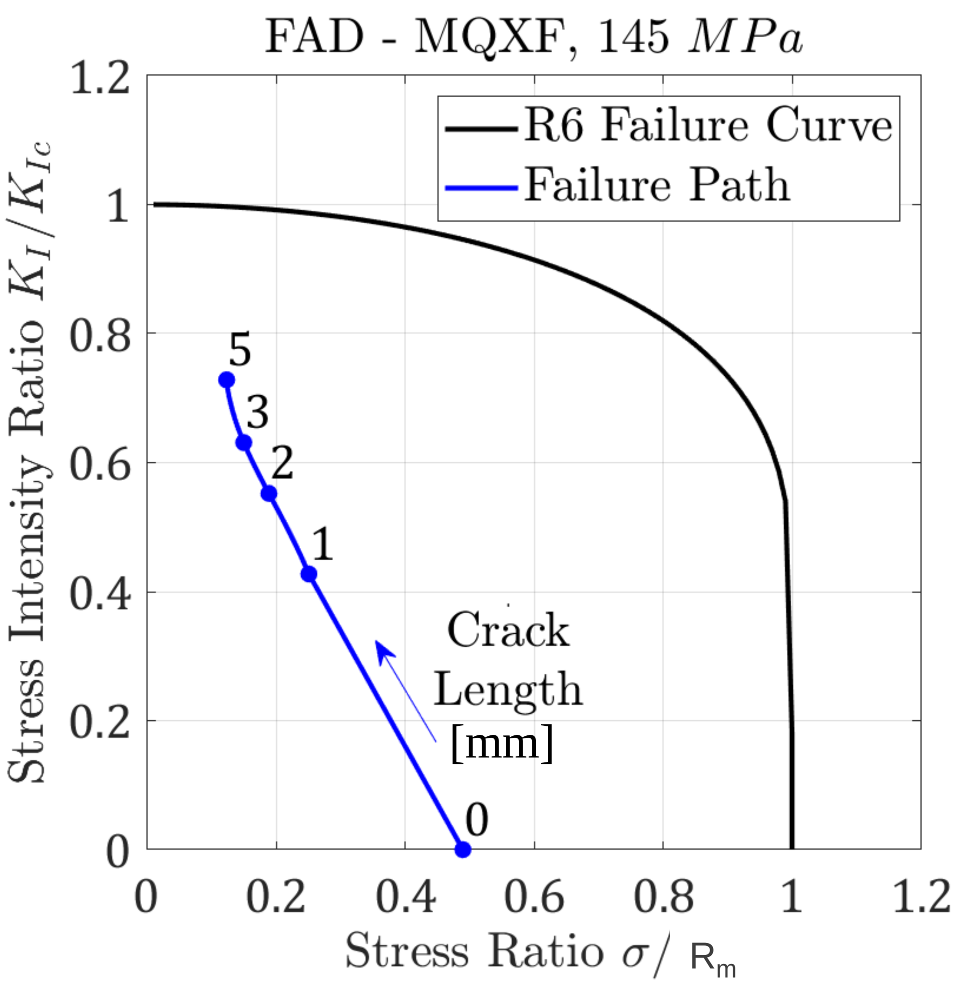




- With a UT inspection a flat bottom hole (FBH) of 1.2 mm would be easy to detect:
  - A minimum load factor of 2

- Load factor increases with crack length: For the stress profile of MQXF, K_I increases but the stress at the crack tip decreases.

Refined approach: FAD results for MQXF



- Position in the FAD with increasing crack length and a = c
- Very comfortably in the safe **region**

Discussion of the results

NDT

- Under the required conditions, it is technically possible to detect defects of 1.2 mm.
- It is typically done for high added value products (e.g. austenitic stainless steel > 10 CHF/Kg for this range of thickness).
- In addition, a surface inspection (visual, Eddy currents, penetrant testing) could be also put in place in order to detect surface cracks.
- Alternatively, a statistical NDT program could be performed for some 'as fine blanked' products at the surface and cross sections

Conclusions

- Yoke lamination with **well-defined yield strength at warm and cold** are required for a **reliable and cost-efficient design**.

- Tensile properties at room and cryogenic temperature (4.2 K) have been assessed for ARMCO ©:
  - **R_{el} = 244 MPa @ RT**. Important value since should be enough to avoid plastic deformation during RT loading.
  - **R_m = 974 MPa @ 4.2 K**, more than 3 times the value at RT. Material breaks in the elastic region (brittle).

- All samples which were tested survived the designed fatigue load cycles (security factor of 20 in the number of cycles).

- Based on the calculation performed with **fracture toughness @ 4.2 K of 26 MPa √m** and a detection limit in principle set to 1.2 mm, a **critical stress of 500 MPa is obtained.** A **refined calculation** shows a rather **high load factor** for different crack sizes.

Conclusions

- The case study of **MQXF** shows that, when a **fracture mechanics' approach to design** is applied a **critical stress can go to rather high values** without jeopardizing the structural integrity of the magnets for small crack sizes.

- With a suitable NDT program, 100% of the volume can be controlled and imperfections of 1.2 mm can be detected, but would increase the production costs.

- **The two – step methodology** shown in this presentation (FAD constant stress along the path + refined method) **can be implemented for any future magnet design**.

- It has been shown here a **successful synergy between core competences of EN/MME** (NDT, material characterization + mechanical testing at cryogenic temperature) **and TE/MSC** (a very specialised application of advanced FEM)

Thanks for your attention. Questions??