„Beispiele für ingenieurtechnische Hochtechnologie am CERN“

Friedrich Haug
CERN, Technology Dep
2014/2/06

Programmteil

14:30 „Beispiele für ingenieurtechnische Hochtechnologie am CERN“
(Friedrich Haug, 20' Vortrag + 10‘ Diskussion)

15:00 Gang zum Kryolab (Gebäude 165/163)

15:10-16:40 Besichtigung Kryotechnik, Supraleitung und Messtechnik
Doktorandenforschung in High-Tech Laboren

- Technologietransfer und Kryotechnik (Geb. 165, Friedrich Haug)
- Supraleitende Kabel Test Facility (Geb. 163 Amalia Ballarino)
- optional: Messtechnik Labor (Geb. 181, Stephan Russenschuck)

Kurze Vorstellung F. Haug

- Studium an FH Ulm und **Univ. Stuttgar**
- **Promotion Univ. Stuttgart**
- 3 Jahre Stipendiat der Europ. Gem. (Forschungszentrum Italien)
- 2 Jahre Postdoc (Los Alamos, USA)

Ich bin Maschinenbau-Ingenieur.
Meine Professoren waren u.a. Groll, Stephan, Wachter, Hahne, Busse, Dolezal (Quack), Höcker, Emendörfer, Lein, Bullinger…

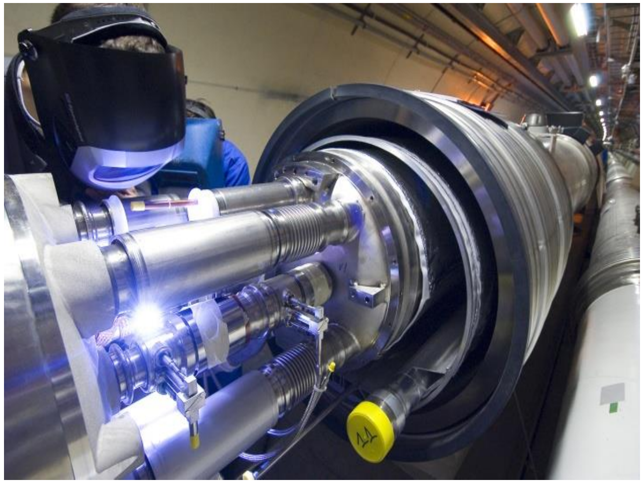
- **<u>Seit 1986 am CERN</u>**
- Mitarbeit Entwicklung supraleitender LHC Magnete. Betrieb kryotechnischer Einrichtungen. Stellvertretender Gruppenleiter. Entwurf und Bau Kryotechnisches System für den <u>ATLAS</u> Detektor.
- Jetzt: in Forschung und Entwicklung, Technologie Transfer
- *Nebenjob: Lehrbeauftragter am KIT*
- *+ HS Heilbronn*

Technologien am CERN

(ein Auszug)

- Detektortechnologie
- Informationstechnik
- **Vakuumtechnik**
- **<u>Kryotechnik</u>**
- Elektronik
- Elektrotechnik
- Gebäude- und Klimatechnik
- **<u>Magnettechnik</u>**
- **<u>Supraleitung</u>**
- Mechanik
- **Materialkunde**
- Hochfrequenztechnik
- Prozesssteuerung
- **Bauingenieurswesen**
- Sicherheit (Strahlenschutz) etc.

Zur Erreichung der gesetzten Ziele in der Teilchenphysik muss CERN oft existierende Technologien bis an ihre Limits vorantreiben oder auf neue Technologien setzen.



CERN ist das führende Teilchenphysiklabor
CERN ist ein High-Tech Zentrum

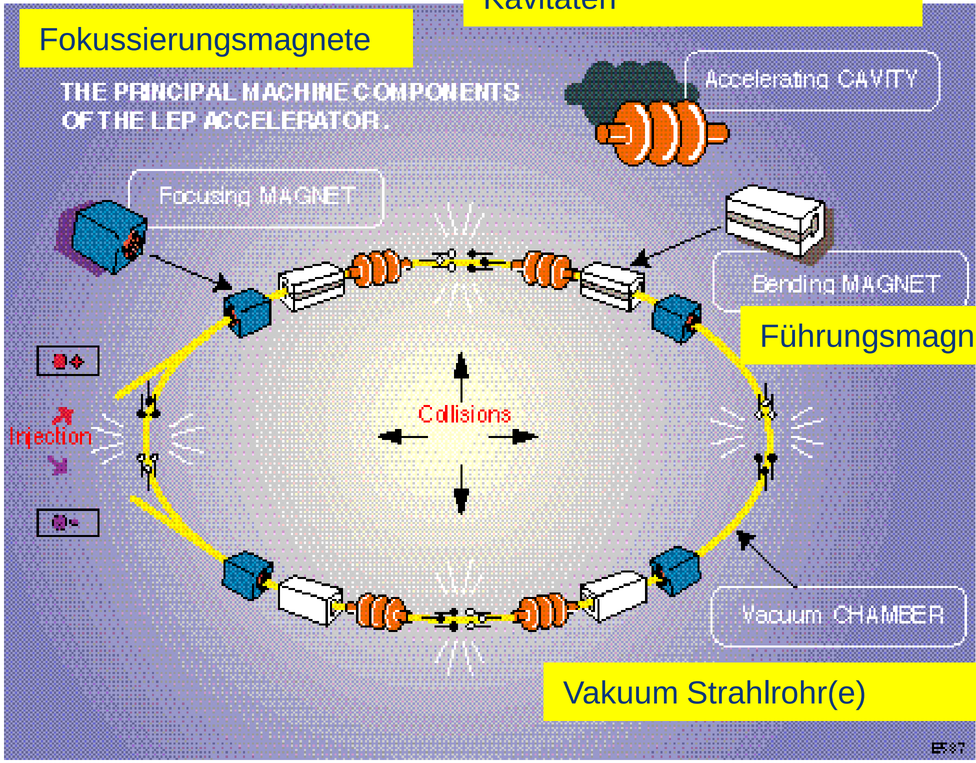
Wir brauchen Physiker, Ingenieure, Techniker als Angestellte als auch als Studenten, Doktoranden, Fellows, Trainees etc.

Beschleuniger und Detektoren

1) Konzentration der Energie in den Teilchen durch Beschleunigung auf quasi Lichtgeschwindigkeit

→

2) Kollision der Teilchen mit Freisetzung der Energie und Umwandlung in Masse (neue Teilchen)



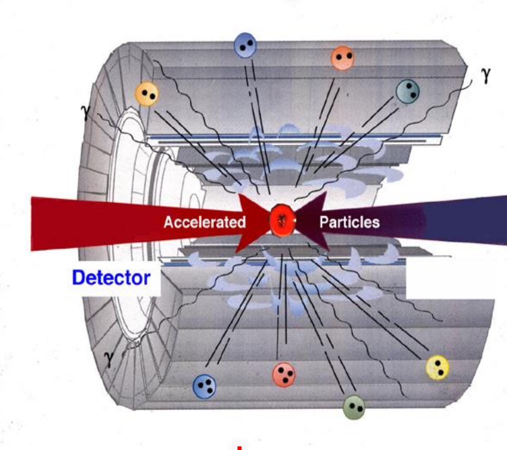
RF Beschleunigungs-Kavitäten

Fokussierungsmagnete

Führungsmagnete

Vakuum Strahlrohr(e)

↓



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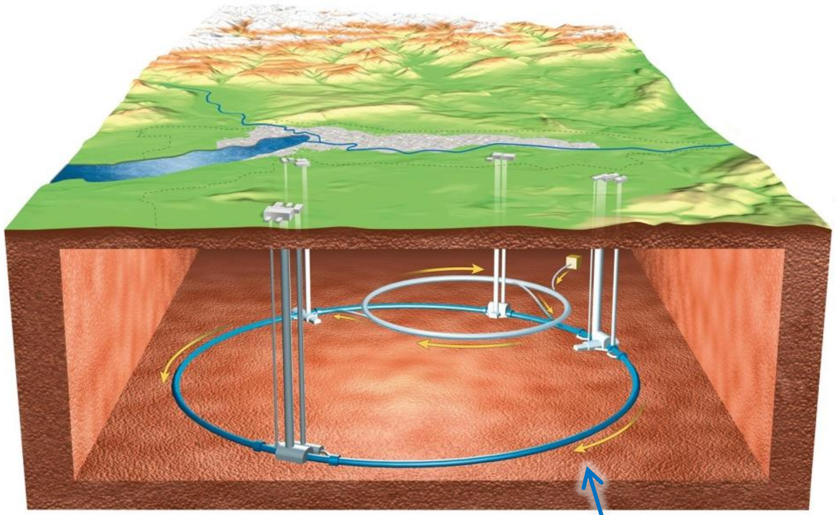
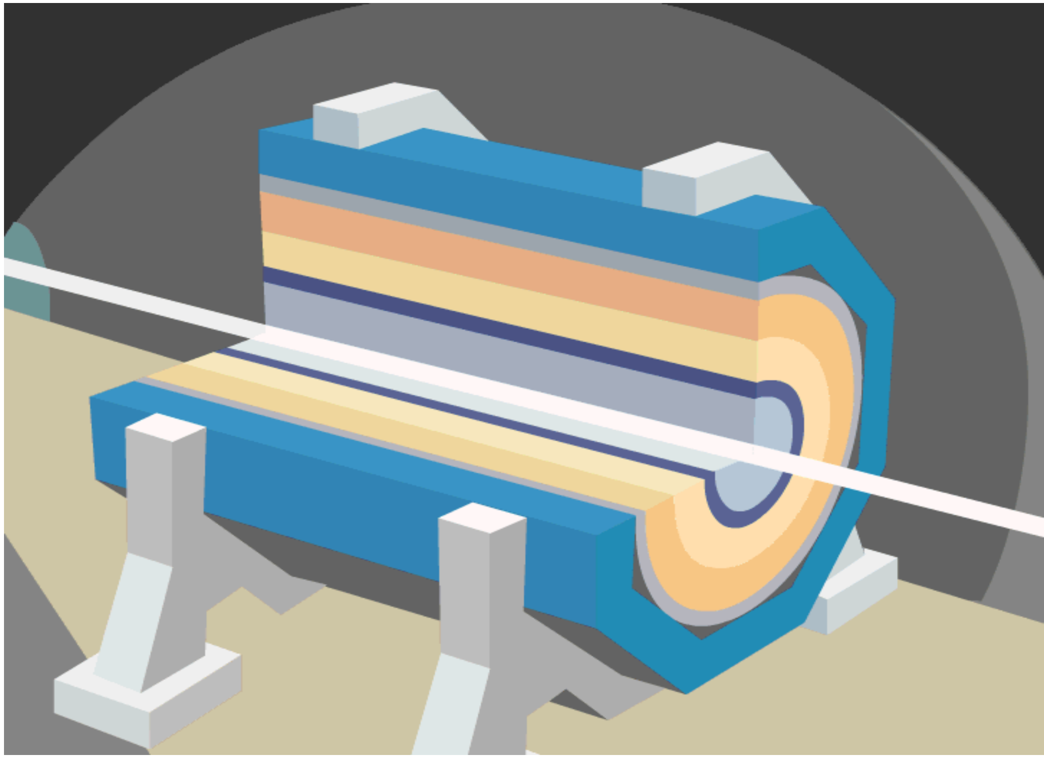
3) Identifizierung der neuen Teilchen durch Detektoren

CERN’s LHC Collider

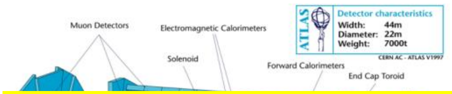


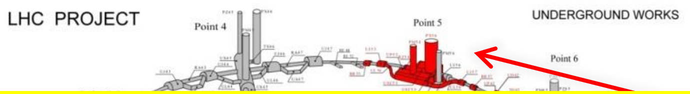
- LHC Beschleuniger im 27 km Umfang Tunnel
- Beschleunigung von Protonen oder Schwerionen, zwei gegenläufige Strahlen
- Kollision der Teilchen in Detektoren

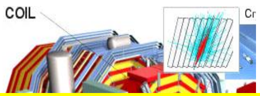
Tunnel 3,8 m Durchmesser



Schlüsseltechnologien am LHC: Supraleitung und Kryotechnik







CMS supraleitender 4 T Magnet mit 6 m Durchm.

Supraleitende Spulen nötig

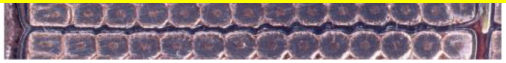
1.) um die erforderlichen sehr grossen Magnetfeldstärken für den LHC Beschleuniger zu erreichen. (Die Endenergie der beschleunigten Teilchen ist direkt proportional zum Dipolmagnetfeld)

2.) zur effektiven Fokussierung der Teilchenstrahlen (Erhöhung der Ereignisrate)

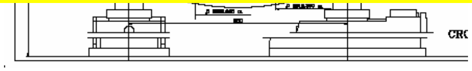
3.) zur Erzeugung grossvolumiger Magnetfeldern in Teilchendetektoren

Supraleitende Beschleunigungskavitäten zur Erzeugung hoher Beschleunigungsspannungen

Kryotechnik im Grossmassstab zur Kühlung der Spulen notwendig zwischen 4.2 K und 1.9 K. Weiterhin kalte Detektoren (ATLAS) mit flüssig Argon (90 K)

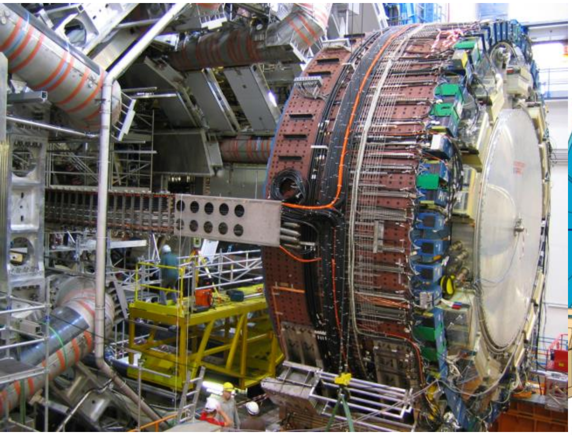


Magnetfeld

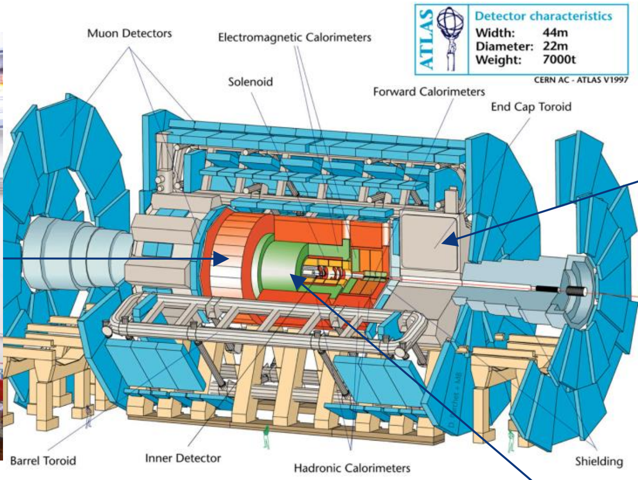


LHC supraleitende Magnete auf 24 km Länge auf 1.9 K gekühlt mit suprafluidem Helium

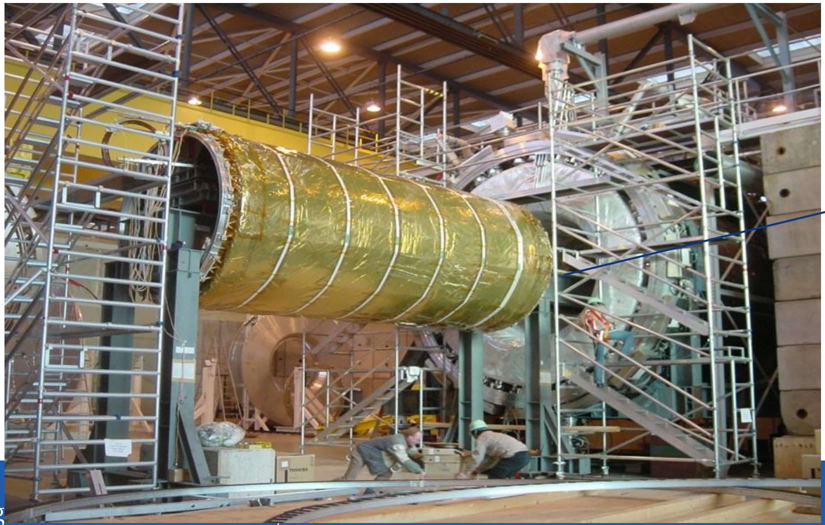
ATLAS SC Magnete und Kryotechnik



End Cap calorimeter
during integration



Central
Solenoid during
integration in
the common
cryostast of the
Liquid Argon
Barrel detector
at hall 180



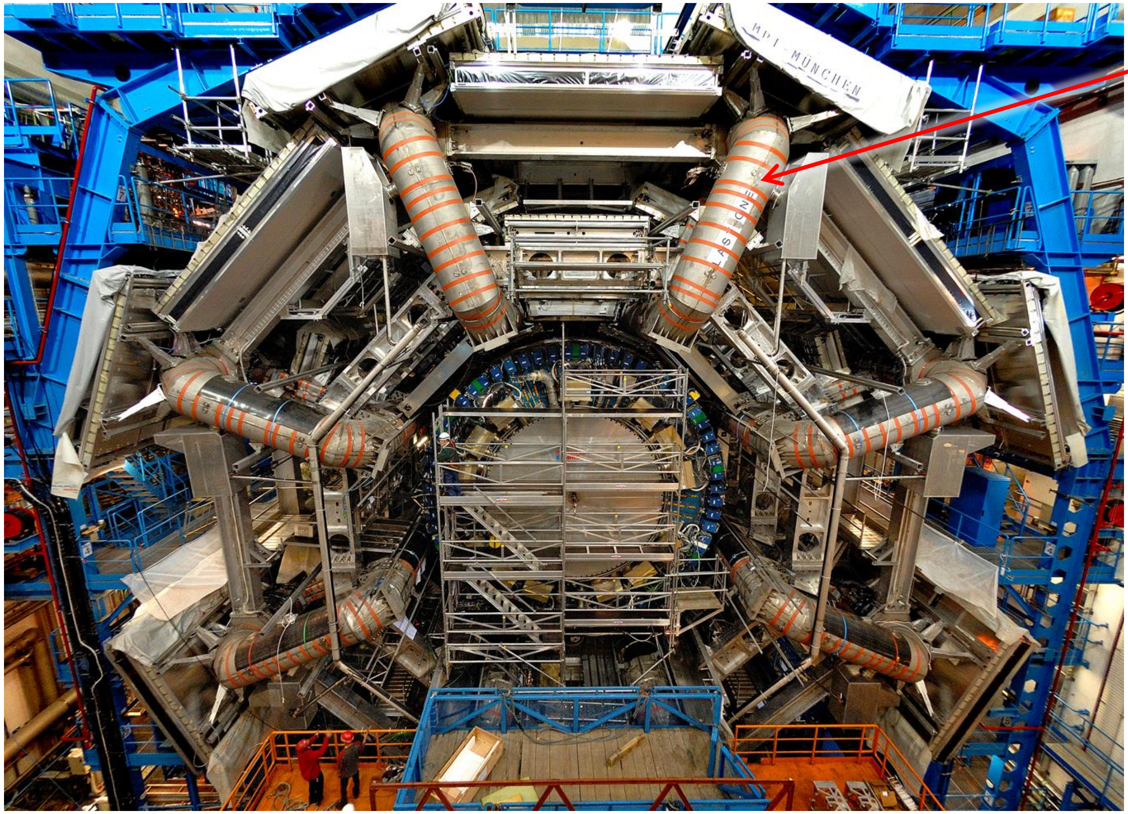
Liquid argon
barrel
calorimeter
cryostat during
lowering in the
pit

ATLAS SC Magnete und Kryotechnik

Barrel Toroid; The **8 coils (4.2 K)** assembled form a barrel with length 25 m and diameter 20 m.

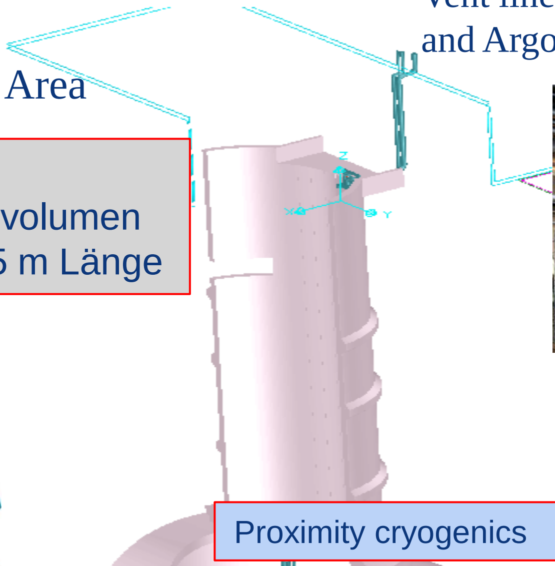
4 Tesla field on conductor, 1 Tesla at Muon chambers

3 Liquid argon calorimeter (90 m3 liquid Argon at **90 K**)



Superconducting Magnets • Barrel Toroid (8 coils) • 2 End Cap Toroids • 1 Solenoid 600 tons cold mass 1.6 GJ stored energy	Helium Cryogenic Systems
Liquid Argon Calorimetry • 1 Barrel Cryostat • 2 End Cap Cryostats 600 tons cold mass 82 m3 liquid Argon	Nitrogen & Argon Cryogenic Systems

ATLAS Kryotechnik

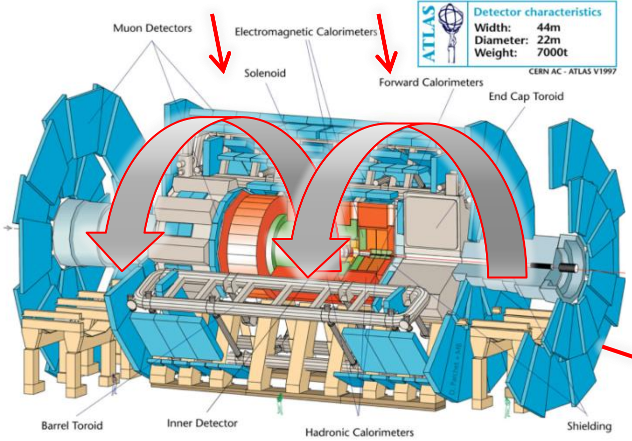


Surface Area

Vent line (Nitrogen
and Argon)

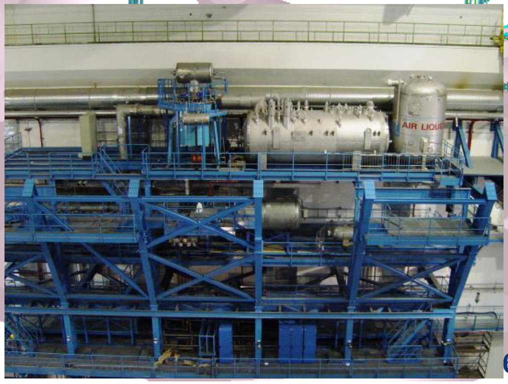
2 x 50 m3 Liquid Nitrogen
Dewars at surface

für die MuonenkammernToroidales Magnetfeld mit > 1Tesla in Zylindervolumen mit 20 m Durchmesser und über 25 m Länge



2 Helium
refrigerators

Proximity cryogenics



Impeller of the 1200 g/s = 10 l/s
centrifugal liquid helium pump

Detector Cavern (-93m)
11,000 l of LHe
15,000 l of LN2
90,000l of LAr

e Cavern with
rs and local

enches in
floor for spilled LAR

LHC Beschleunigermagnete

Zur Führung der Teilchen auf quasi Kreisbahn und zu ihrer Fokusiering:

- auf 24 km Länge sind mehr als 1800 supraleitende Hochfeldmagnete installiert zur Erzeugung des z.Z. höchsten technisch erreichbaren Magnetfelds in Serienmagneten von 7-8 Tesla…
- …sie sind auf 1.9 K gekühlt…
- … mit einer Million Liter flüssigem Helium
- …erzeugt wird die Kälte…

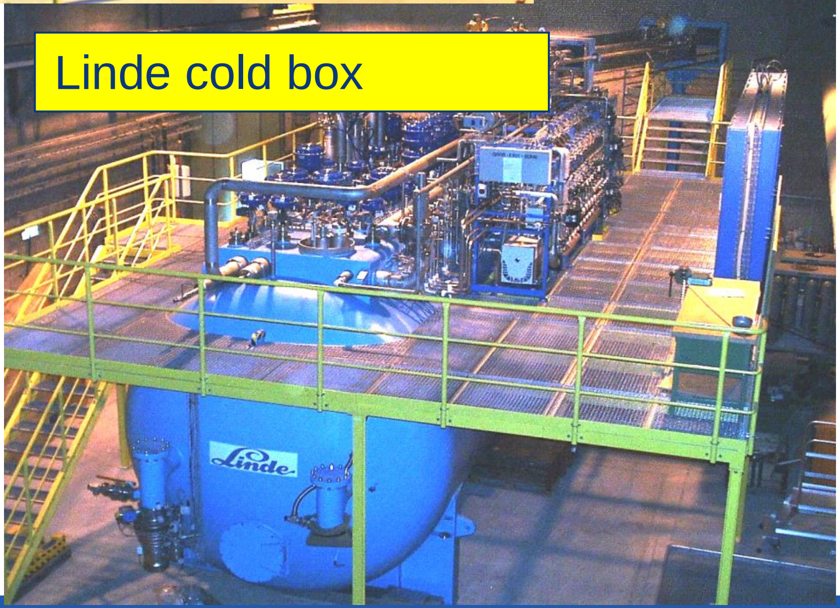
LHC supraleitender Magnet String im unterirdischen Tunnel mit 27 km Umfang

18 kW @ 4.2 K Refrigerator/Verflüssiger

Specific capacity
33 kW @ 50 K to 75 K
23 kW @ 4.6 K to 20 K
41 g/s liquefaction (current leads)
Complex “mixed mode”: both refrigeration + liquefaction

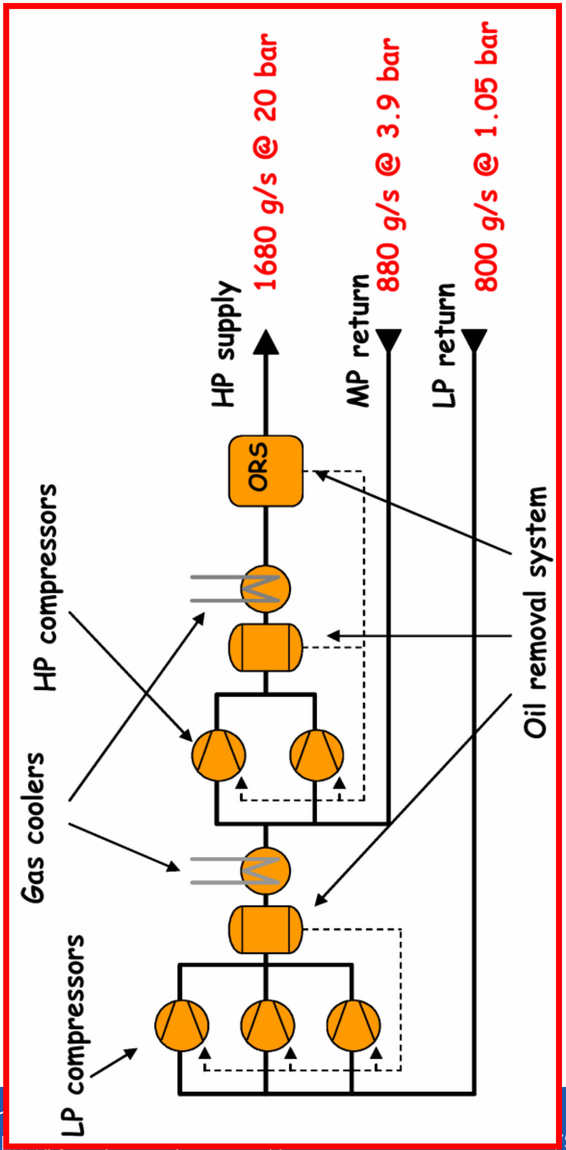
Warm compressor station (4 MW el. input)

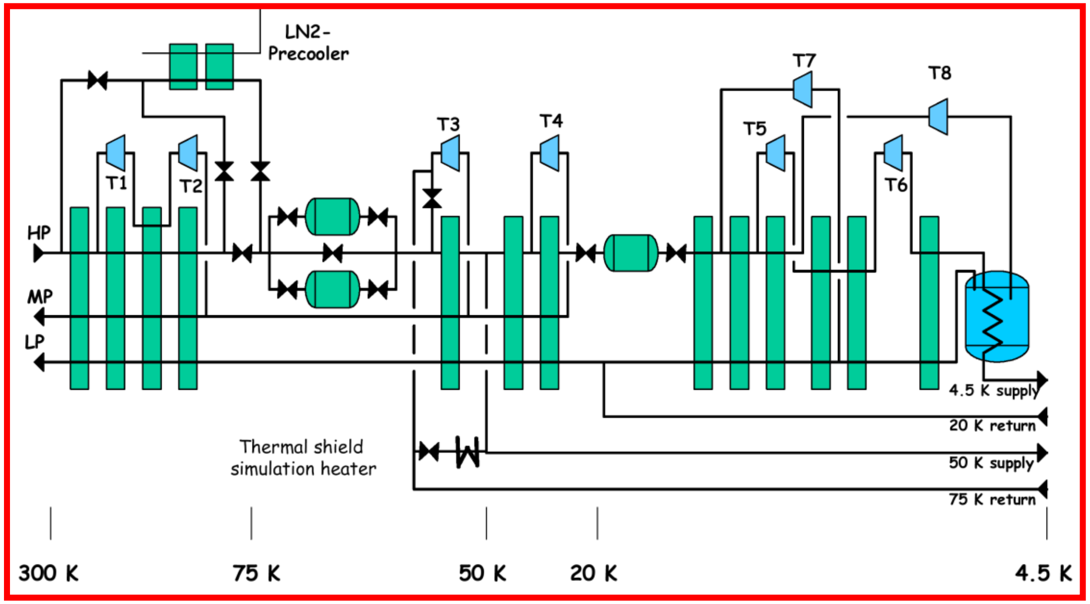
Air Liquide cold box

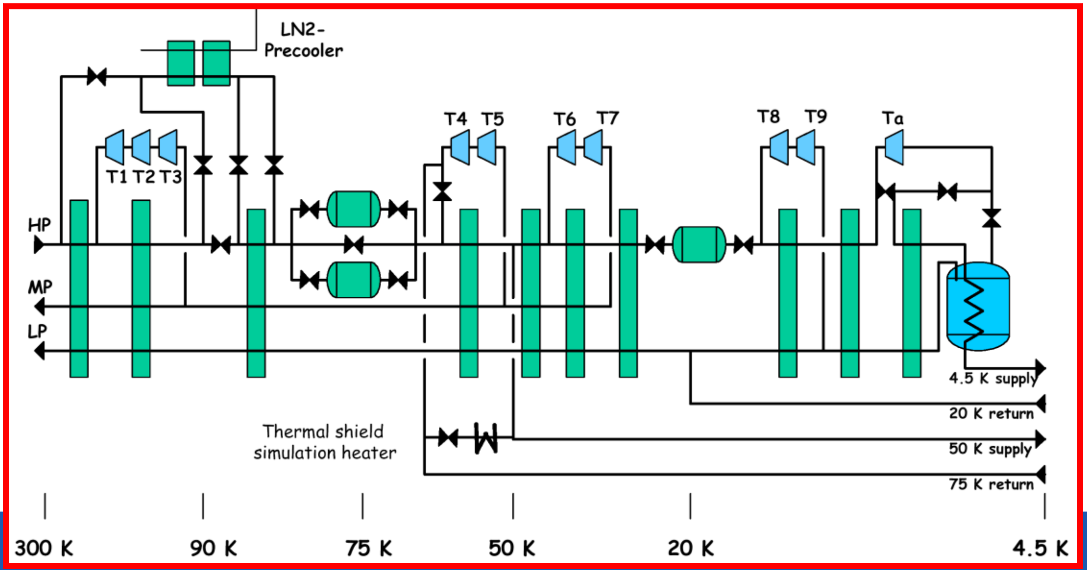


Linde cold box

Process cycle

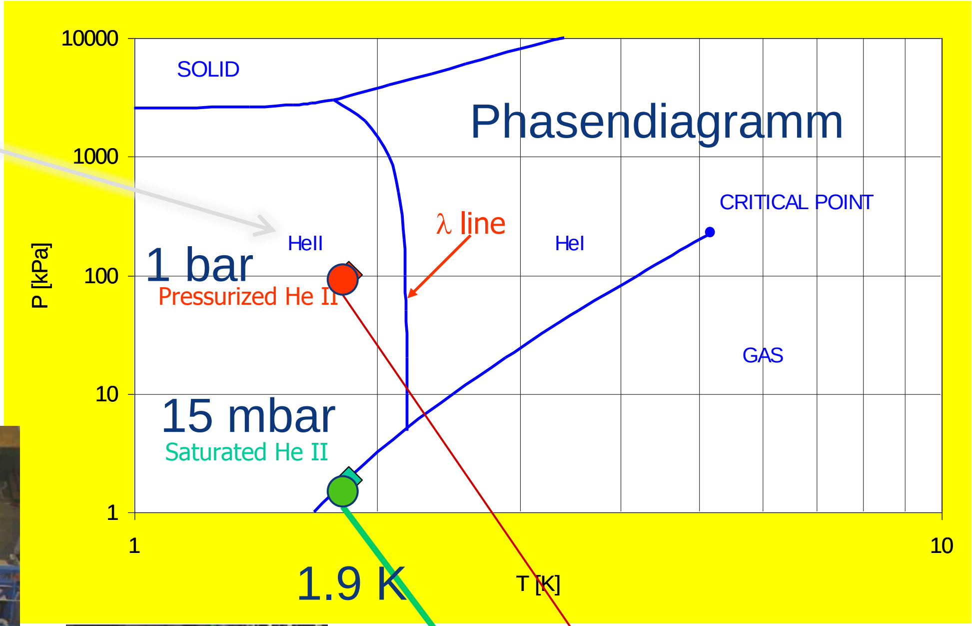






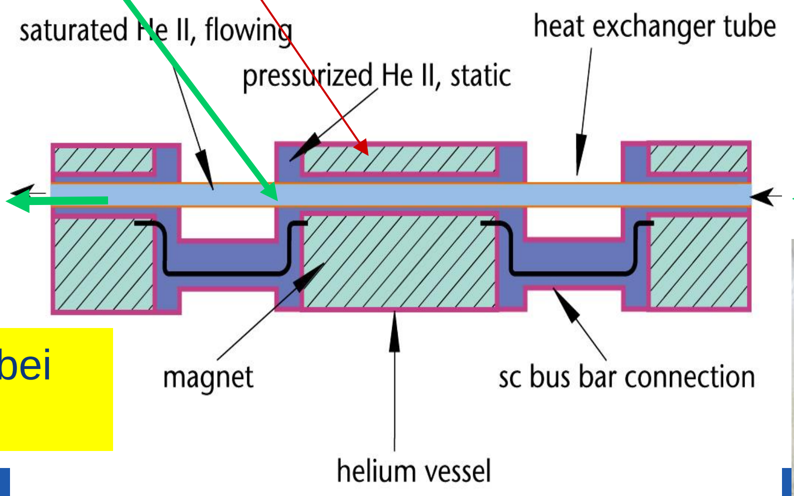
Kühlprinzip

unterkühltes Superfluides Helium



Supraleitender Magnet in statischen Bad mit superfluidem He bei 1bar

Kühlung durch verdampfendes Helium in Wärmetauscherrohr bei 1.8 K (15 mbar). Absolutdruck von 15 mbar wird durch kalte (und warme) «Vakuumpumpen» erzeugt

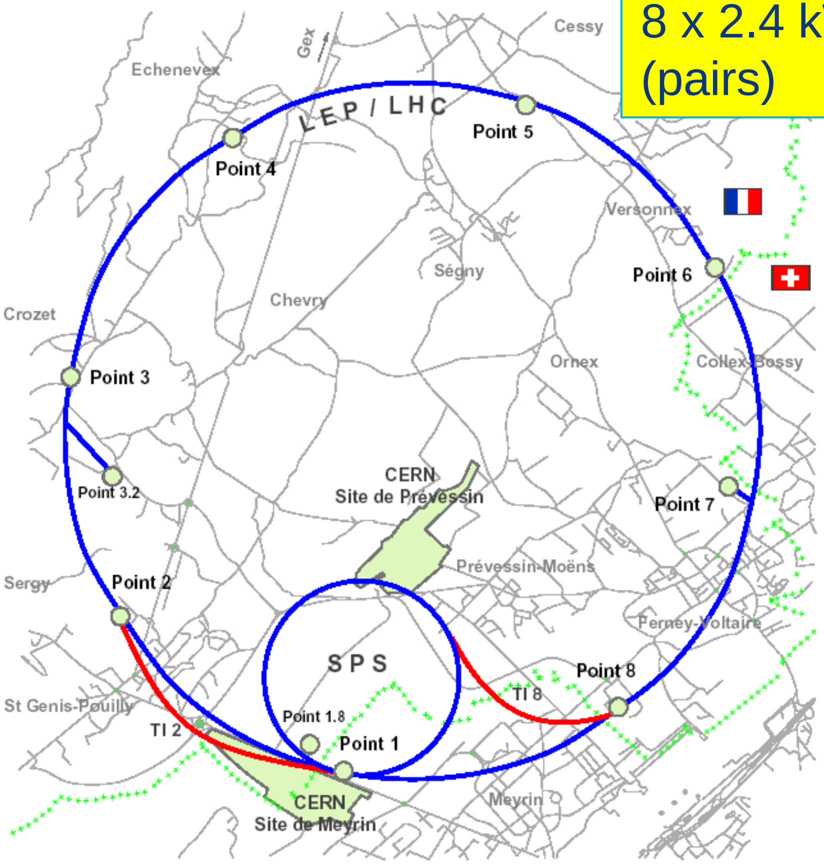


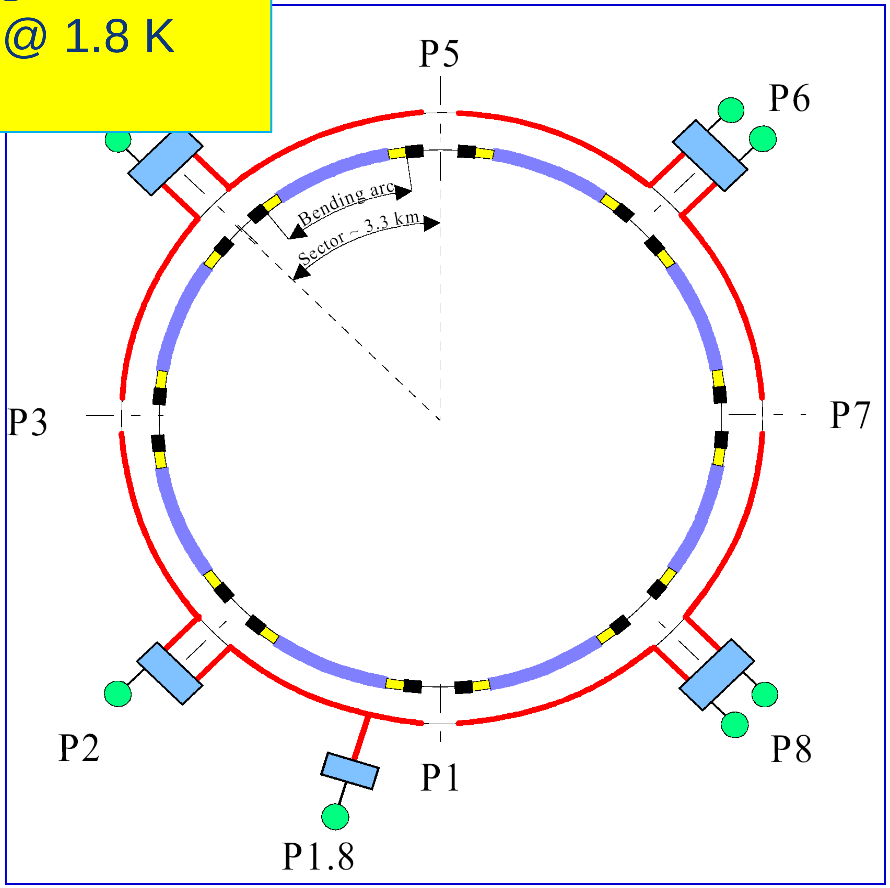
Zufuhr HeII

Abpumpen des verdampfenden He II bei 1.8 K mit Kaltkompressoren

Verteilung der Cryoplants

8 x 18 kW @ 4.2 K
8 x 2.4 kW @ 1.8 K
(pairs)





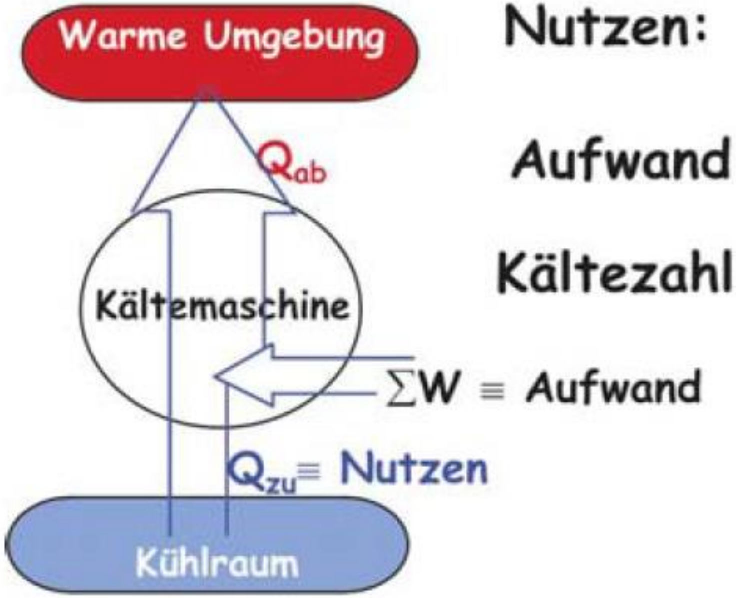
To provide the cooling capacity for the superconducting magnets. One pair of plants or each arc of **3.3 km length**. Electric plug-in power close to 40 MW

Thermodynamik: Kältemaschine

Technische Thermodynamik - Teil 1
Prof. H. Müller-Steinhagen, Dr. W. Heidemann
Institut für Thermodynamik und Wärmetechnik

Universität Stuttgart

Grundlagen:



Nutzen: zugeführte Wärme
(wird Kühlgut entzogen)

Aufwand: Kreisprozessarbeit

Kältezahl:

$$\varepsilon_{KP} = \frac{Q_{zu}}{\sum W} = \frac{q_{zu}}{\sum w} = \frac{q_{zu}}{|q_{ab}| - q_{zu}}$$

$$= \frac{\dot{Q}_{zu}}{\sum P} = \frac{q_{zu}}{\sum w_t} = \frac{q_{zu}}{|q_{ab}| - q_{zu}}$$

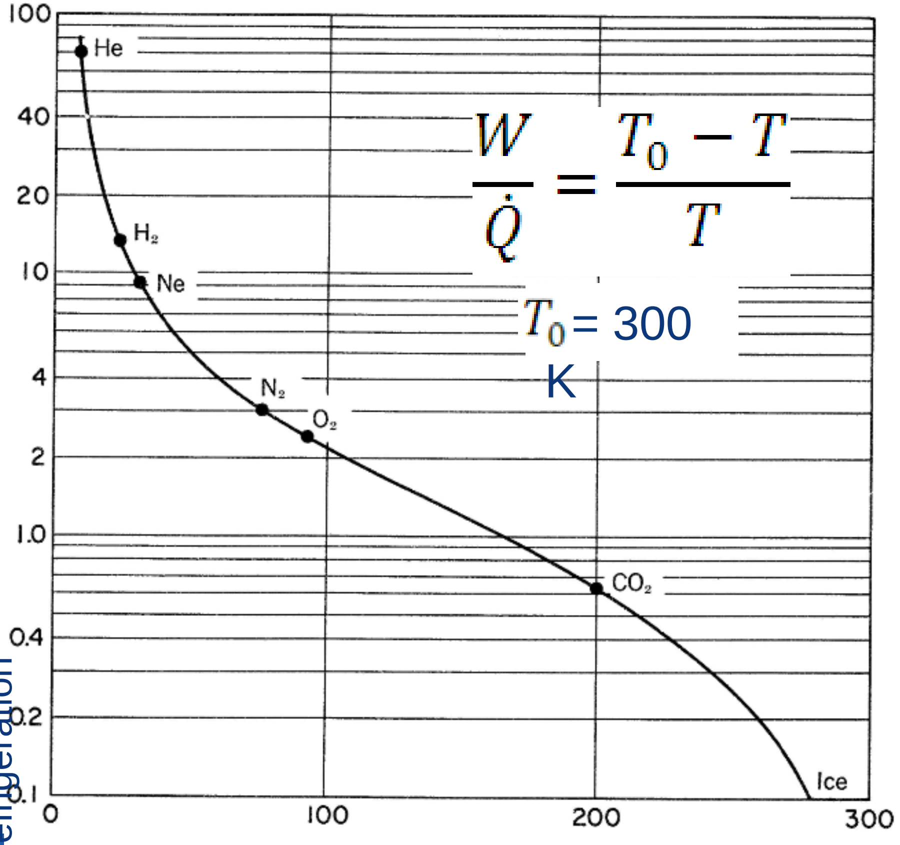
Statt Kältezahl COP verwenden wir in der Kryotechnik oft den Kehrwert 1/COP

Ideal work for refrigeration

Inverse coefficient of performance

$$\boxed{COP_{Inv,ideal} = 1/COP_{ideal} = COP_{ideal}^{-1}}$$

W/W



Units of work to produce one unit of refrigeration

$$\frac{W}{\dot{Q}} = \frac{T_0 - T}{T}$$

T_0 = 300 K

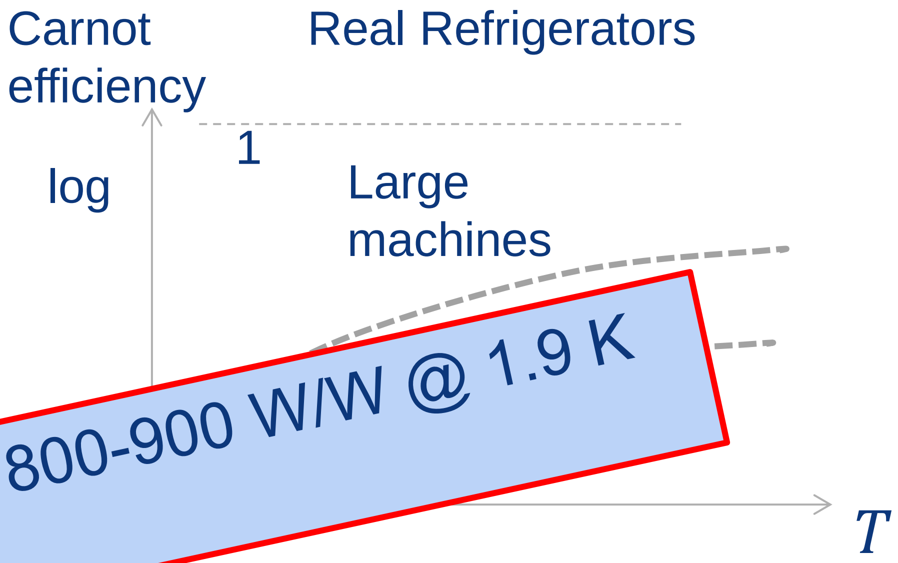
Units of work required to produce one unit (1 W) of refrigeration of an ideal machine. Equation used

$$\frac{W}{\dot{Q}} = \frac{T_0 - T}{T} \quad \frac{[Watts]}{[Watt]}$$

Gas	Normal boiling point [K]	Ideal Work for refrigeration [W/W]
Oxygen (O2)	90.18	2.3
Argon	87.28	2.4
Air	78.80	2.8
Nitrogen (N2)	77.36	2.9
Neon	27.09	10.1
Hydrogen (H2)	20.27	13.8
Helium-4	4.21	70.3

Cooling Power = f(parameters)

Gas	**Normal boiling point [K]**	**Ideal work for refrigeraction [W/W]**
Helium-I	4.21	70.3
Helium-II	2.0	150
Helium-II	1.8	167
Helium-II	1.6	187



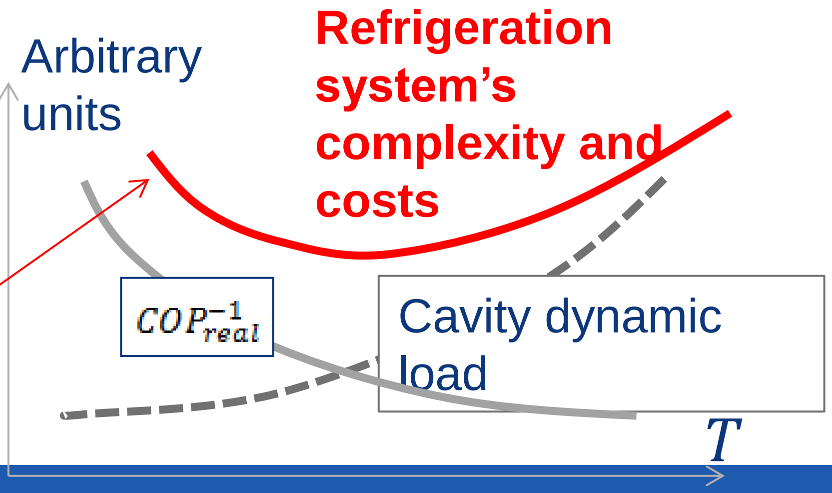
LHC Refrigeratoren ungefähr 800-900 W/W @ 1.9 K (rekordverdächtig…)

But in additi

portionally

$$COP_{real}^{-1} = {COP_{ideal}^{-1}}/{\eta_{Carnot}}$$

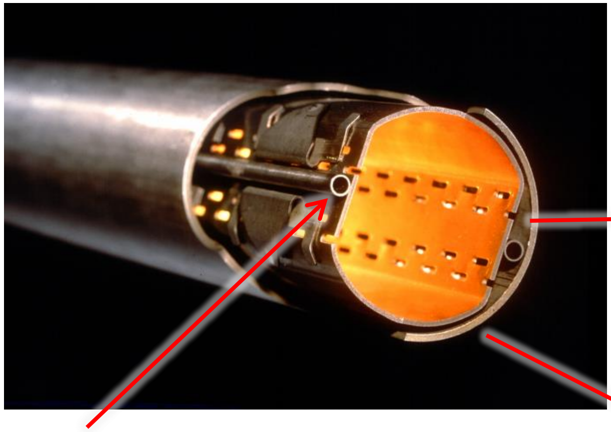
Size, complexity and cost of refrigerators and systems increase unproportianally with decreasing temperatures

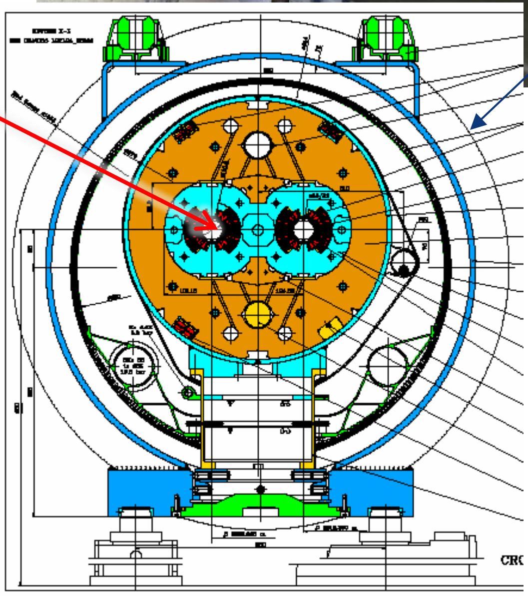


Vakuum am LHC

Um Kollissionen mit residuellen Gasen auf ein Minimum zu reduzieren: Hochvakuum

Vakuumröhren für den Teilchenstrahl



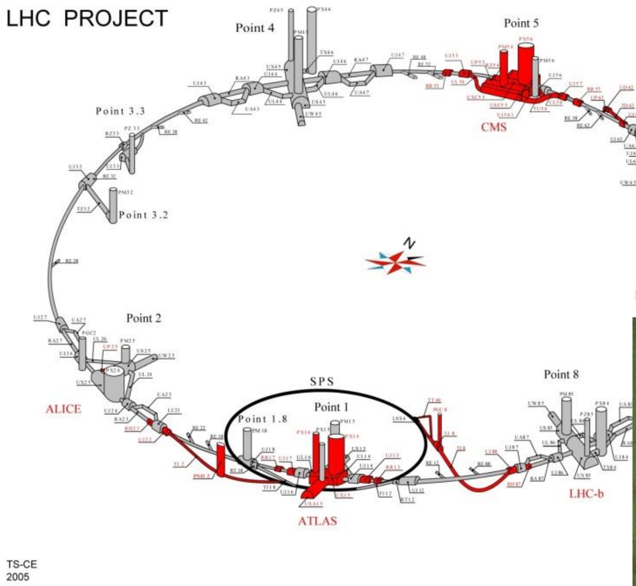


Querschnitt eines supraleitenden Magneten

+Cryopumping von residuellen Gasen (Absorber auf 5-20 K gekühlt:)
+ NEG (Getter-Pumping ausserhalb der sc Magnete)

Vakuum:
1E-12 mbar
1E-10 mbar (mit Teilchenstrahl)

Bauingenieurswesen



- Tunnelbau
- Detektorkavernenbau

ATLAS Kaverne in der Bauphase

Beschleunigertunnel

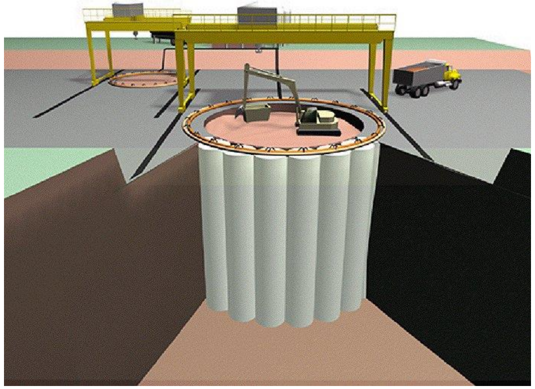
Lastwägelchen

Boden mit Eisenarmierung
für ATLAS Detektor
Fundament

Bauingenieurswesen: CMS

Bei Aushub Schacht grosse Probleme entdeckt

Grundwasser: Unterirdischer Wasser-Abfluss vom Jura zum Genfer See



Lösung: Einfrieren des Erdreichs (Molasse) vor Abbau mit Baumaschinen

Calcium-chloride, brine solution was circulated through a closed pipework system before returning to the refrigeration plant on the surface for re-chilling. The brine was circulated at a temperature of around –25°C in order to achieve an average frozen ground temperature of –10°C. The refrigeration plant used an ammonia-charged compressor system. (I cite John Osborne, civil engineering)

100 m tiefe vertikale Zugangsschächte 12.1m und 20.5m Durchmesser

Visit of the rector of the technical university Dresden at CERN, 6 Feb. 2014

Selected slides by SSg for the presentation of F. Haug

- Mechanical testing at cryogenic temperatures
- X-Ray microtomography

Materialkunde hat grösste Bedeutung für:
Geeignete Auswahl an Materielen (z.b Strukturmaterial)
Entwicklung und Qualifizierung von neuen Materialen
Qualitätskontrolle
Zuverlässigkeit
Sicherheit
am CERN teilweise ungewöhnliche Randbedingungen:
z.B. extreme Temperaturen, ionisierende Strahlung....

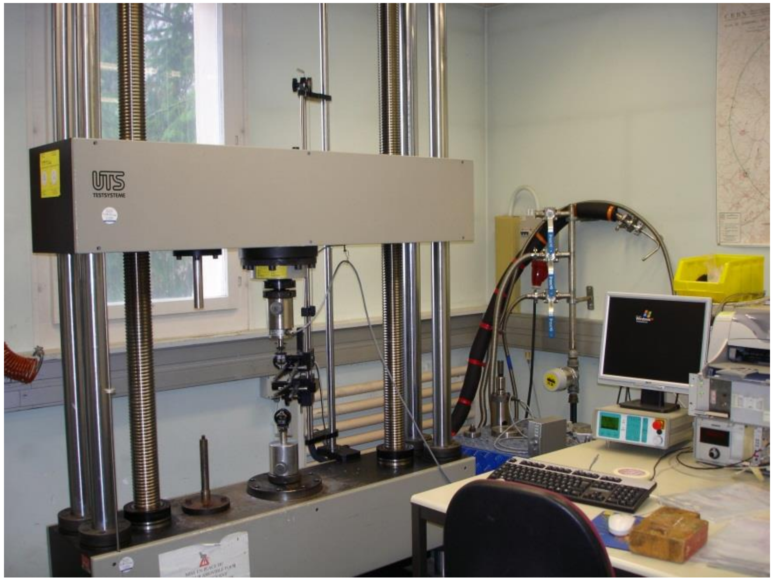
Stefano Sgobba
EN-MME-MM

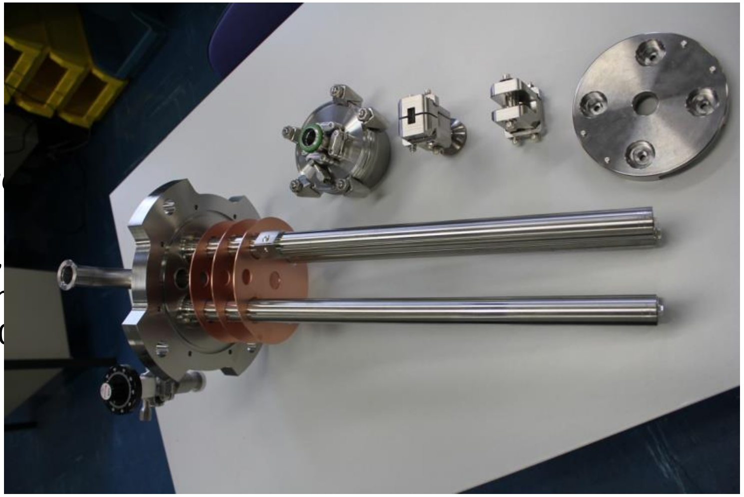
Mechanical testing

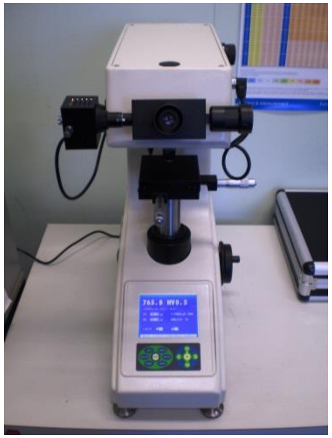
100 kN cryostat for tensile testing and eventually fracture mechanics at 4.2 K in testing and calibration phase

Tensile testing machines

Two column electromechanical universal testing machine *UTS 200*
Load cells 1 kN, 20 kN and 200 kN, stroke 800 mm
Knives and clip-on extensometers
Tensile grips, compression plates, bending tools
System for tests at 77 K and 4.2 K, 25 kN load cell
Single column press *ZPM 1000-500.* Load cell 1 kN, stroke 500 mm





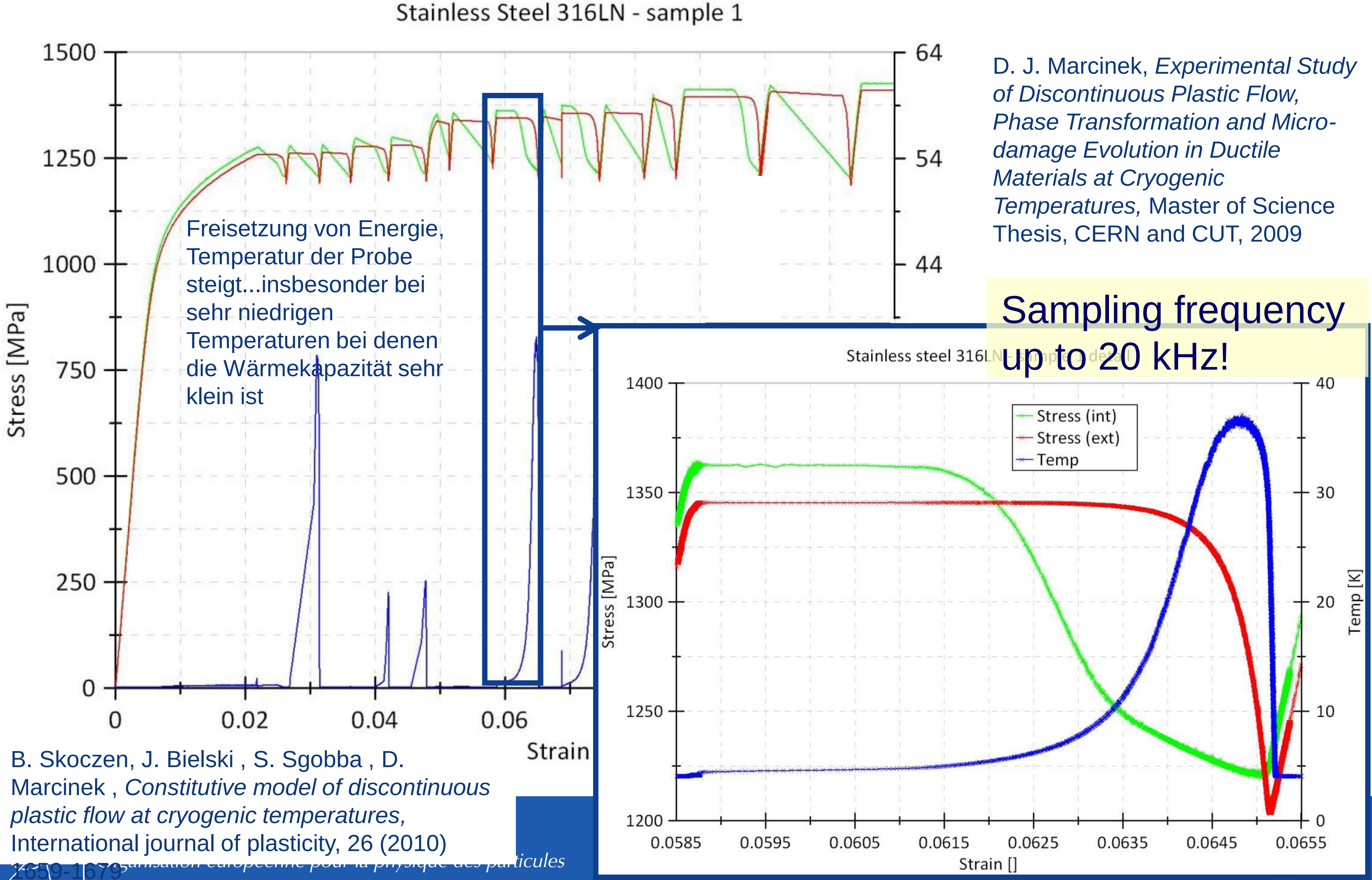


Hardness

Hardness. *Wolpert 2R*
Load 1
Brinell,
Micro hardness autor
Load 1

Capabilities of the equipment

Serrated yielding at low temp. (particularity at 4 K)...Sägeartiges Fliessen



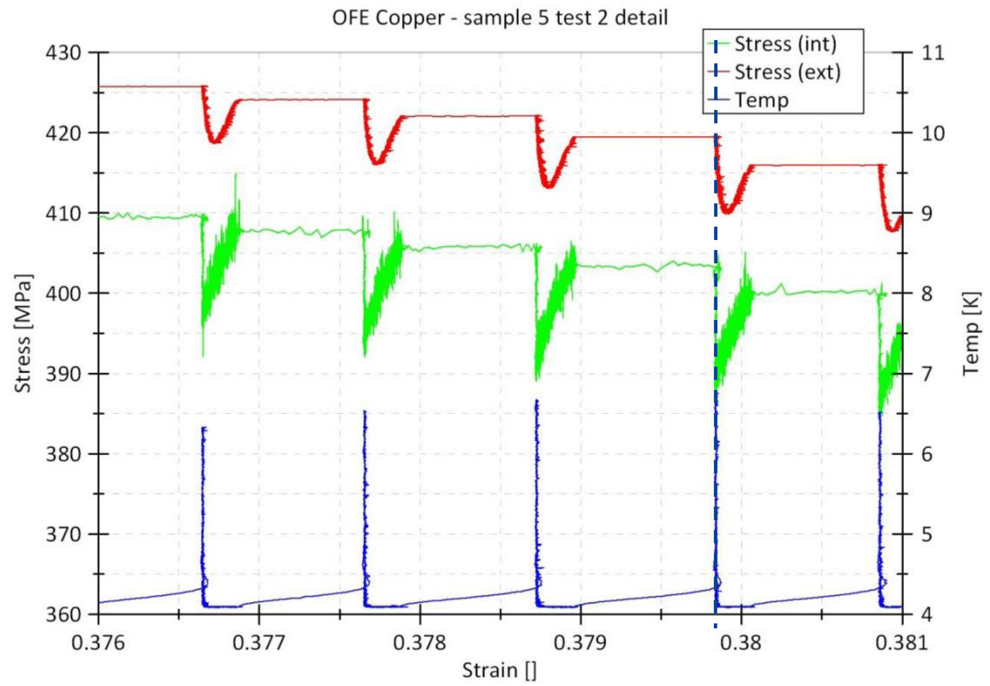
Freisetzung von Energie, Temperatur der Probe steigt...insbesonder bei sehr niedrigen Temperaturen bei denen die Wärmekapazität sehr klein ist

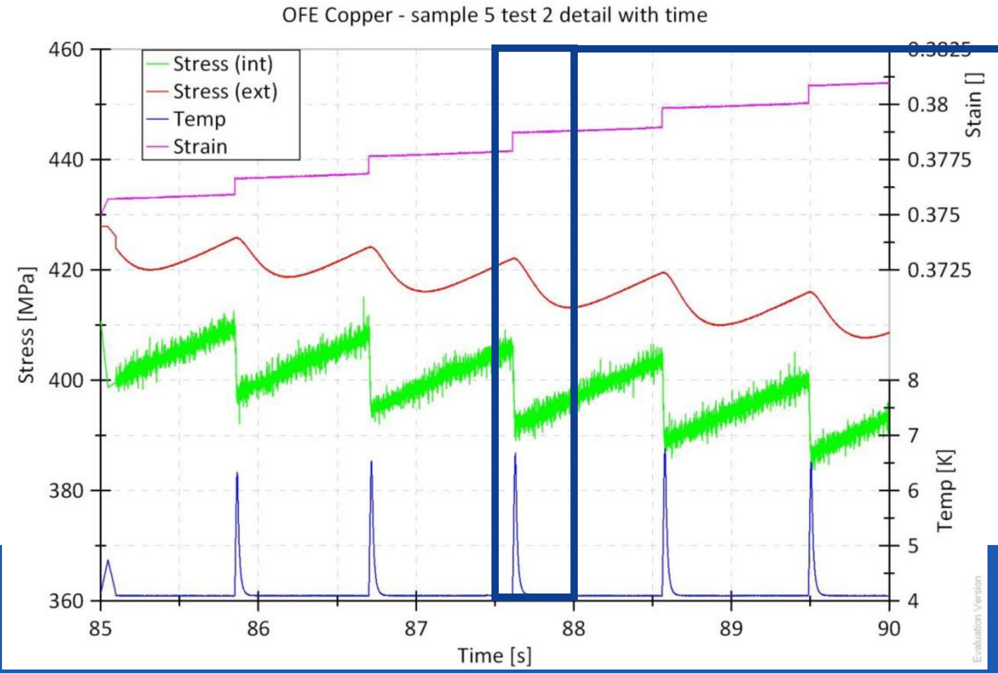
Sampling frequency up to 20 kHz!

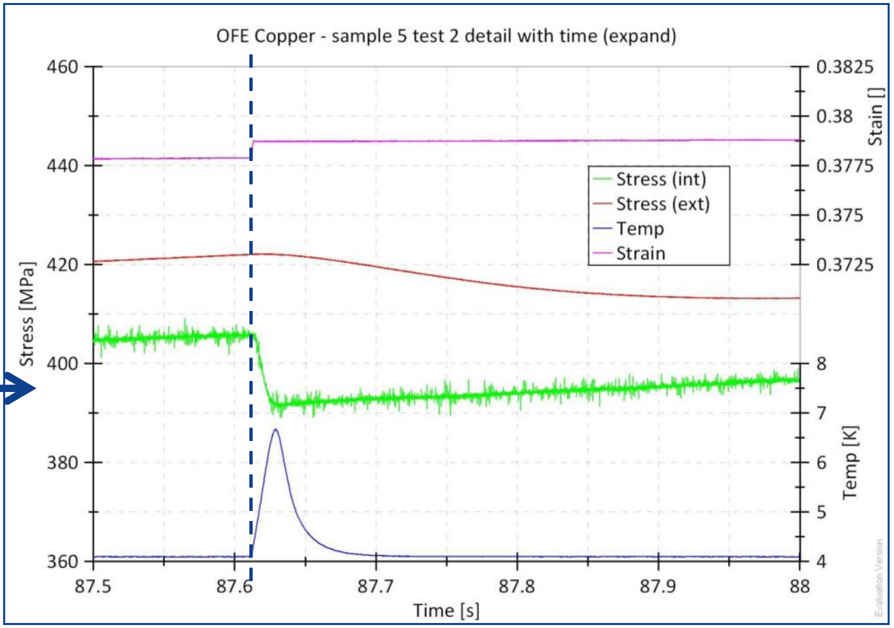
D. J. Marcinek, *Experimental Study of Discontinuous Plastic Flow, Phase Transformation and Micro-damage Evolution in Ductile Materials at Cryogenic Temperatures,* Master of Science Thesis, CERN and CUT, 2009

B. Skoczen, J. Bielski , S. Sgobba , D. Marcinek , *Constitutive model of discontinuous plastic flow at cryogenic temperatures,* International journal of plasticity, 26 (2010) 1659-1679

OFE Cu, serrated yielding recorded during necking (engineering stress-engineering strain plot)

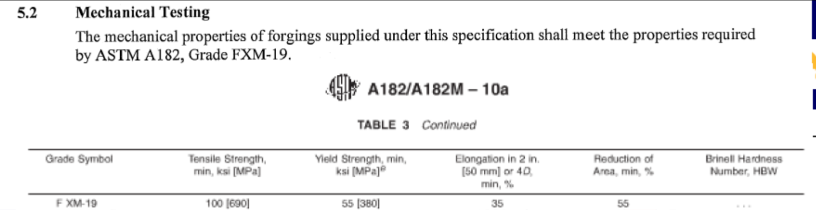






D. J. Marcinek, *Experimental Study of Discontinuous Plastic Flow, Phase Transformation and Micro-damage Evolution in Ductile Materials at Cryogenic Temperatures,* Master of Science Thesis, CERN and CUT, 2009

Mechanical testing at 4.2 K, the present and future



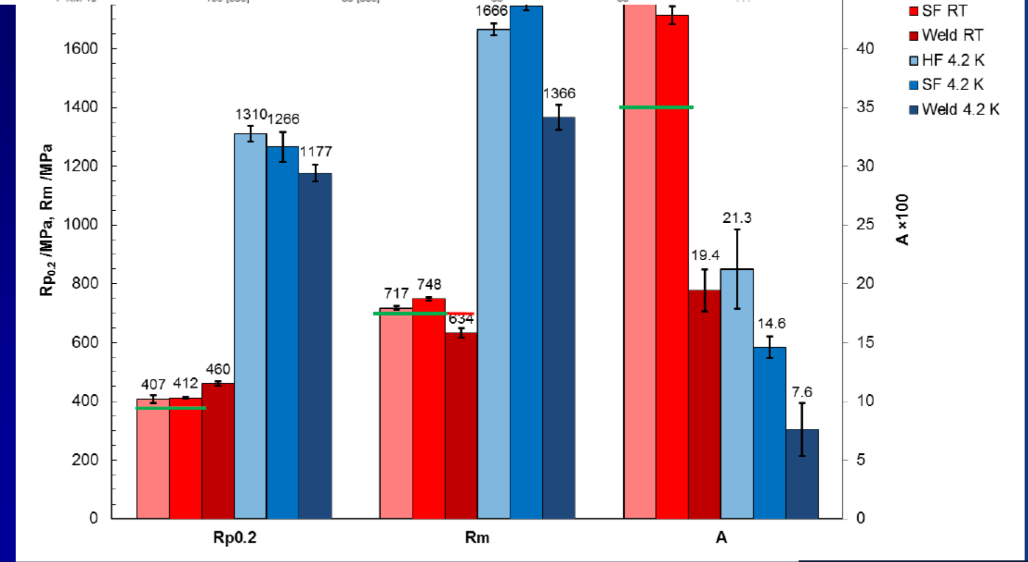
5.2 **Mechanical Testing**

The mechanical properties of forgings supplied under this specification shall meet the properties required by ASTM A182, Grade FXM-19.

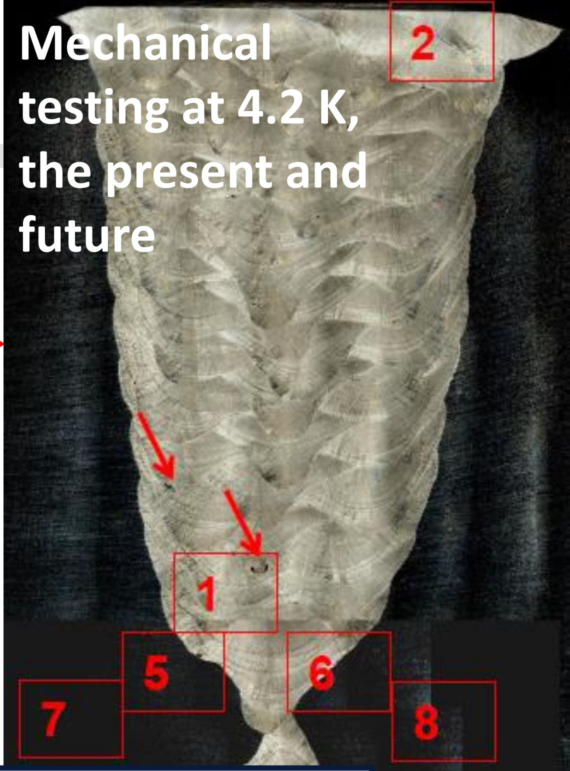
A182/A182M – 10a

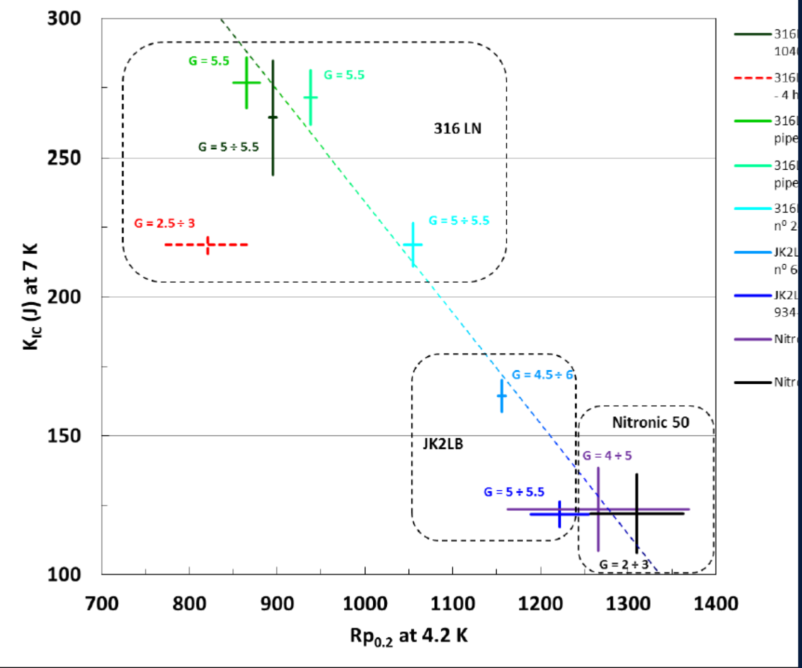
TABLE 3 *Continued*

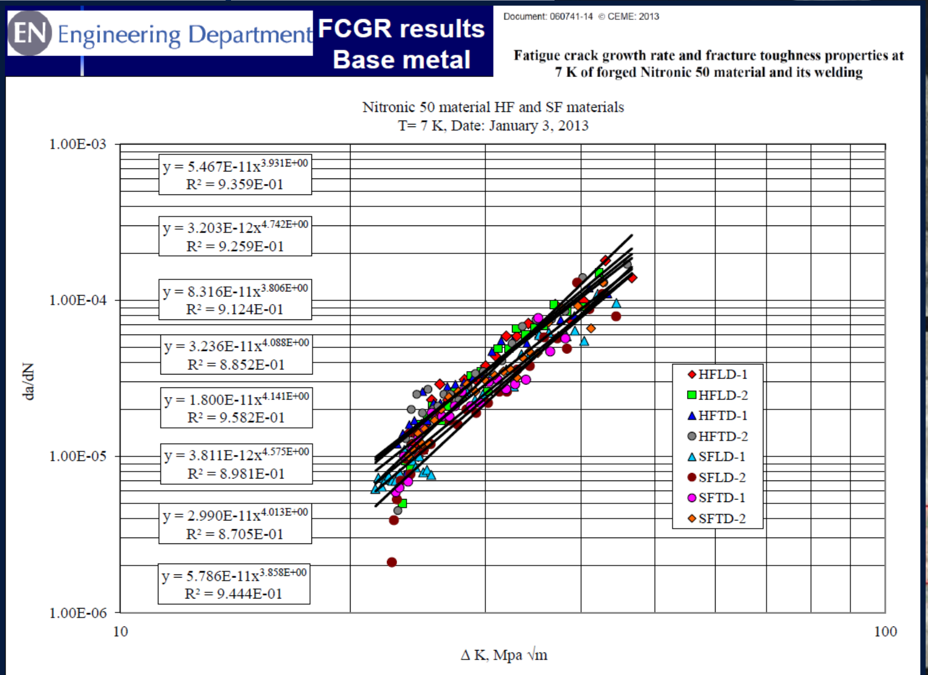
Grade Symbol	Tensile Strength, min, ksi [MPa]	Yield Strength, min, ksi [MPa]^{B}	Elongation in 2 in. [50 mm] or 4*D*, min, %	Reduction of Area, min, %	Brinell Hardness Number, HBW
F XM-19	100 [690]	55 [380]	35	55	. . .



CERN + CEME







EN Engineering Department

FCGR results Base metal

Document: 060741-14 © CEME: 2013

Fatigue crack growth rate and fracture toughness properties at 7 K of forged Nitronic 50 material and its welding

Nitronic 50 material HF and SF materials
T= 7 K, Date: January 3, 2013

$y = 5.467E\text{-}11x^{3.931E+00}$
$R^2 = 9.359E\text{-}01$

$y = 3.203E\text{-}12x^{4.742E+00}$
$R^2 = 9.259E\text{-}01$

$y = 8.316E\text{-}11x^{3.806E+00}$
$R^2 = 9.124E\text{-}01$

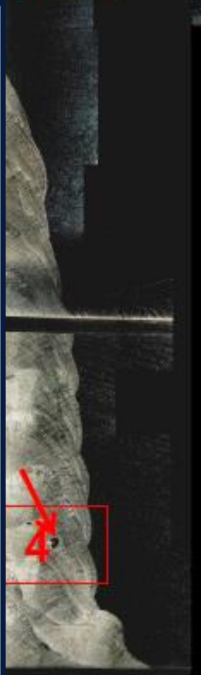
$y = 3.236E\text{-}11x^{4.088E+00}$
$R^2 = 8.852E\text{-}01$

$y = 1.800E\text{-}11x^{4.141E+00}$
$R^2 = 9.582E\text{-}01$

$y = 3.811E\text{-}12x^{4.575E+00}$
$R^2 = 8.981E\text{-}01$

$y = 2.990E\text{-}11x^{4.013E+00}$
$R^2 = 8.705E\text{-}01$

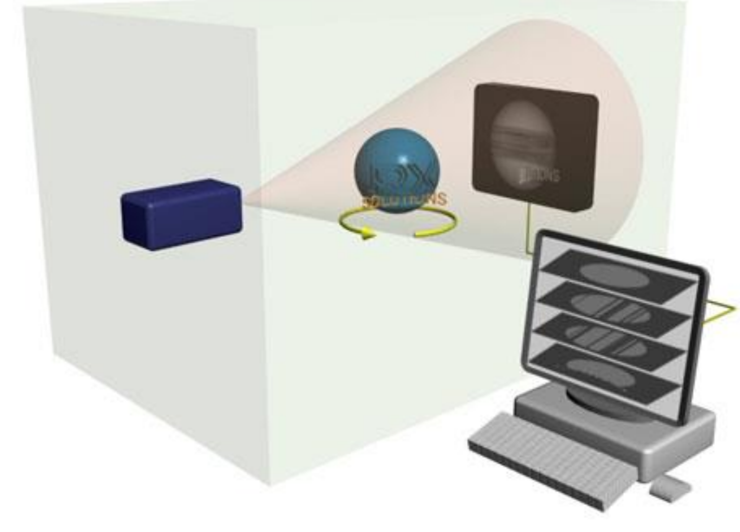
$y = 5.786E\text{-}11x^{3.858E+00}$
$R^2 = 9.444E\text{-}01$



3D microtomography, description of the technique

Courtesy of RX Solutions

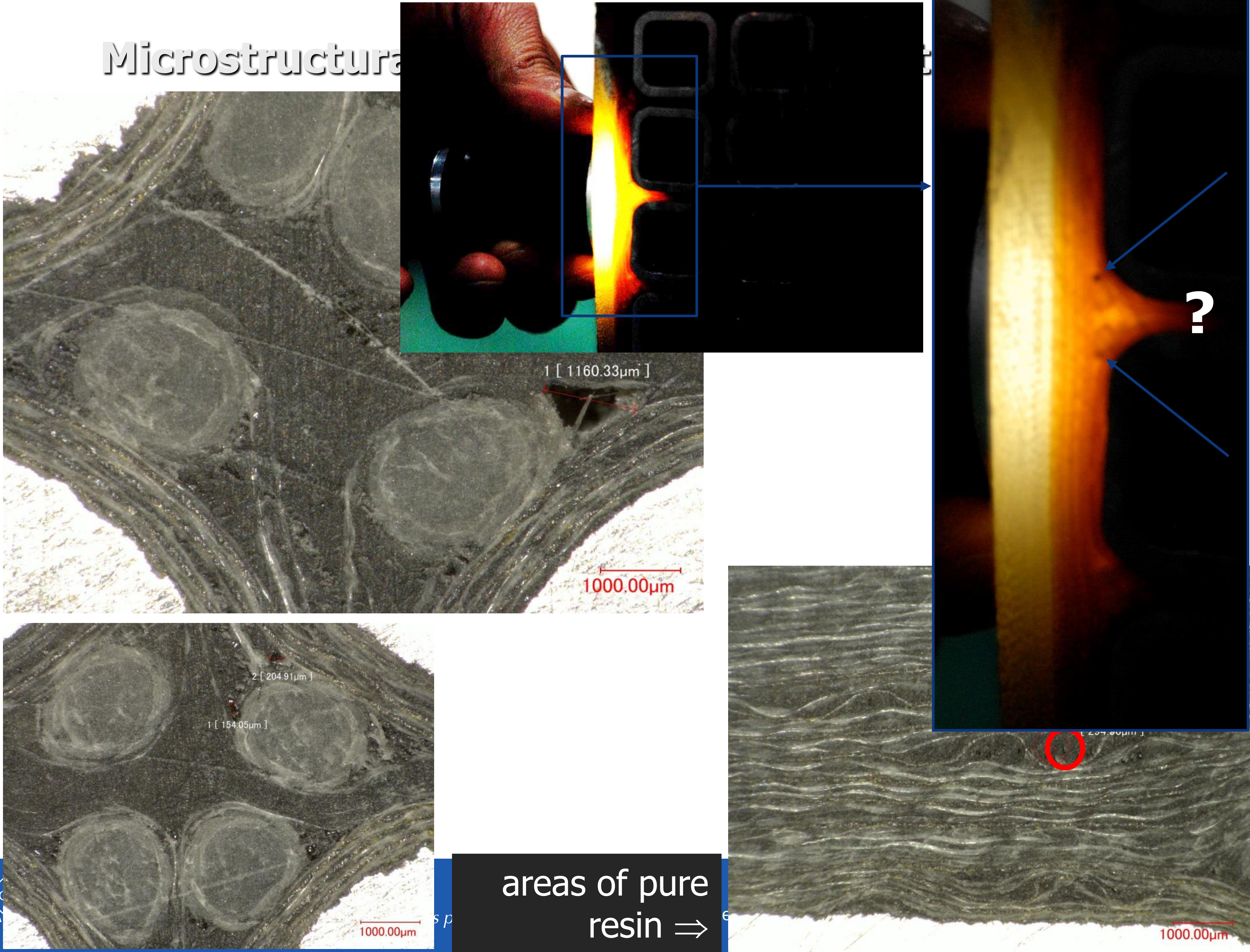
Zerstörungsfreie Prüfung mit enormer Präzision



Sample of the Vacuum Pressure Impregnation (VPI) of ITER correction coils (CCs)

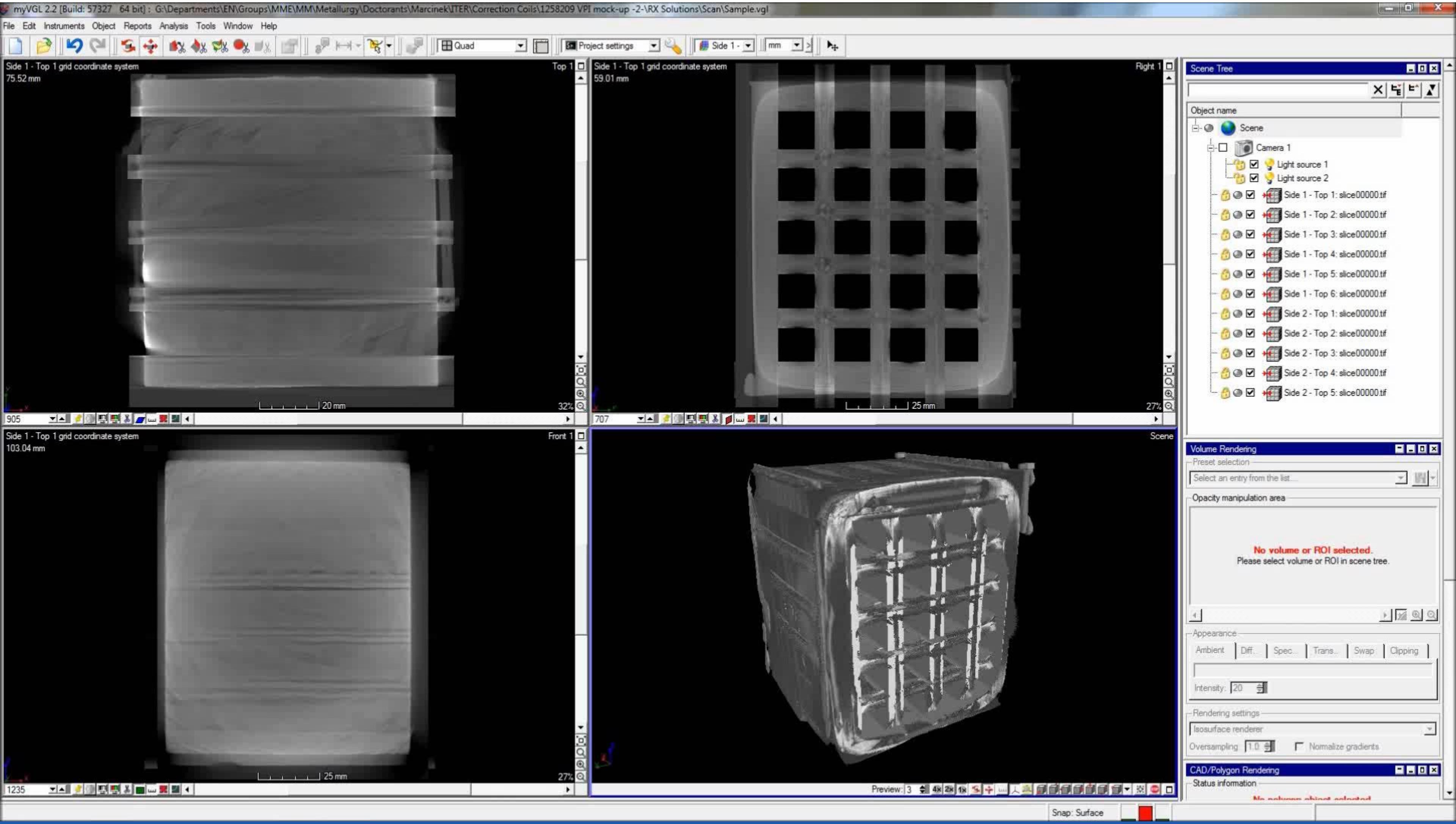
11 separate 360° scans were combined to compile a final single 3D object reconstruction while avoiding shadows due to steel conduits

Microstructura



areas of pure resin ⇒

X-Ray
Computed Tomography (CT)



No volume or ROI selected.
Please select volume or ROI in scene tree.

Intensity: 20

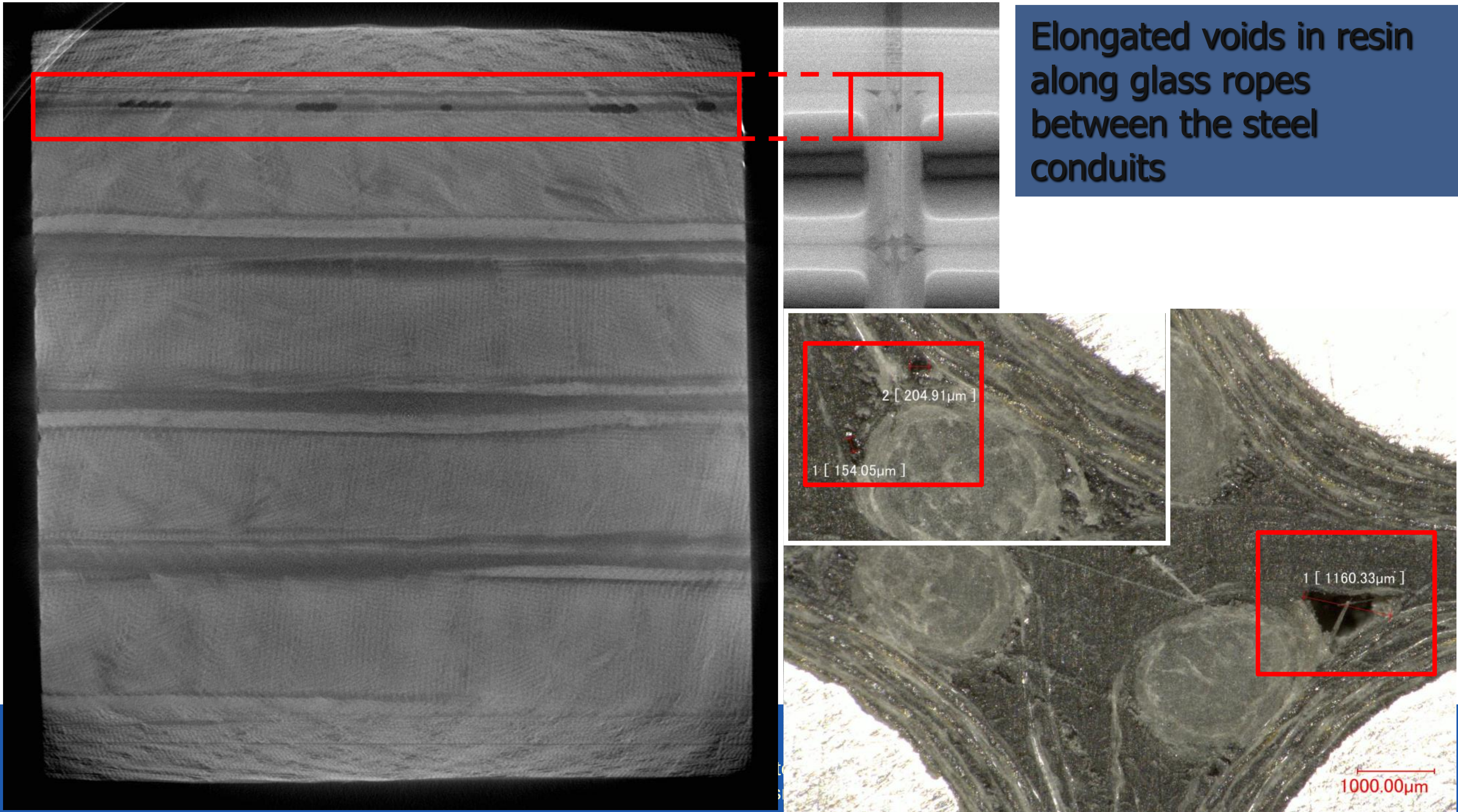
Isosurface renderer

Oversampling: 1.0

☐ Normalize gradients

No polygon object selected

X-Ray
Computed Tomography (CT)

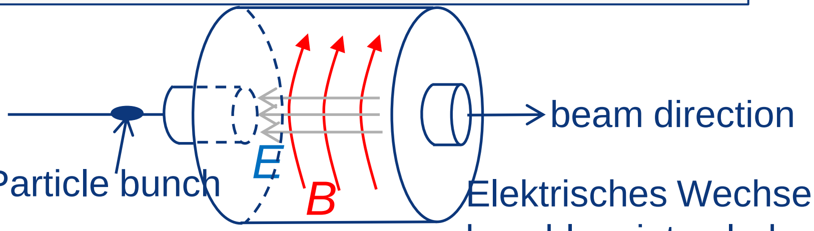


Elongated voids in resin along glass ropes between the steel conduits

Superconducting radiofrequency (SRF) cavities

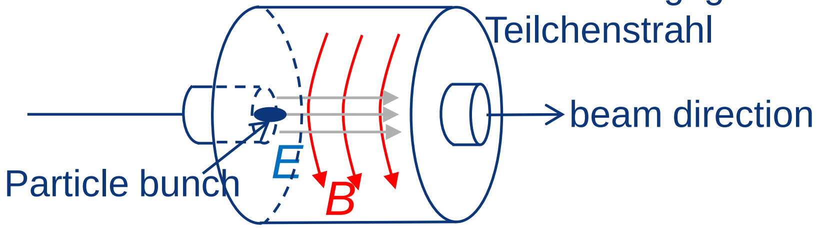
Resonator wird zu elektromagnetischen Eigenschwingungeen angeregt

1. Before the particle bunch enters the cavity the electric field is pointing in opposite direction of the beam axis

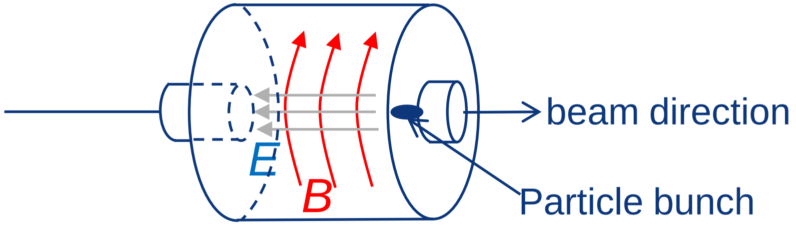


Elektrisches Wechselfeld
beschleunigt geladenen
Teilchenstrahl

2. The particle bunch enters the cavity. The electric field is pointing in the direction of the beam axis → The particle is accelerated



3. The particle bunch leaves the cavity. The field direction has changed again

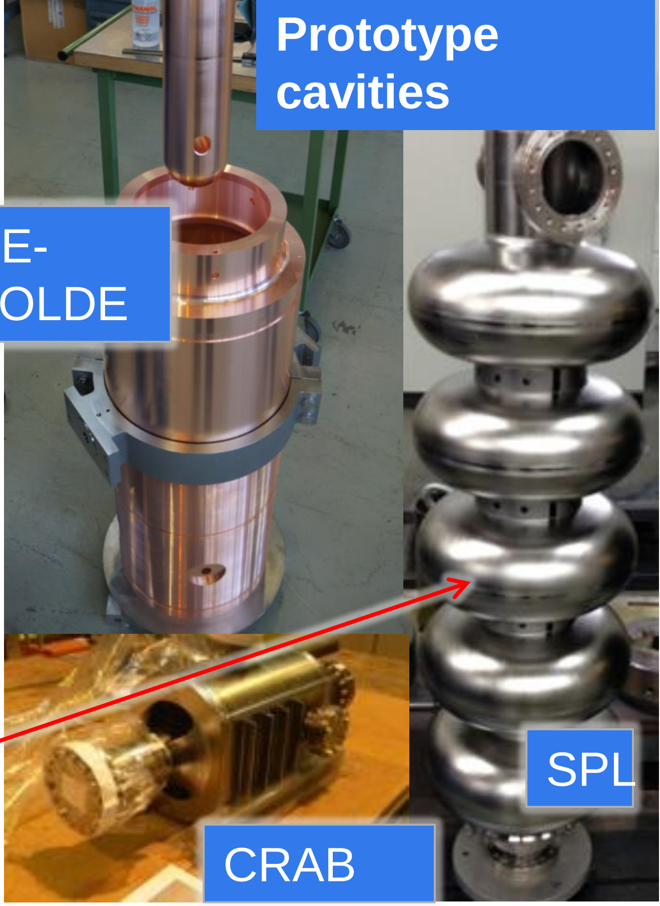


Zusammenstellung T. Junginger

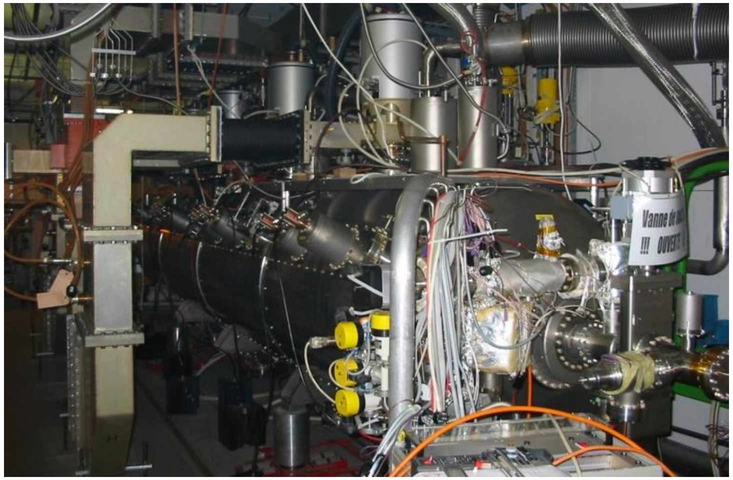
- Cavities are used to accelerate particles by an alternating electric field
- An alternating electric field causes an alternating magnetic field
- The cavity confines the electromagnetic fields by surface shielding currents
- These currents create losses (heating), which can be reduced by using superconducting materials

SRF activities at CERN

- LHC – SRF (Machine + Spares)
- Post accelerator for nuclear research: HIE-ISOLDE
- Deflecting (CRAB) cavities for LHC upgrade
- High Gradient Research (SPL)
- Future projects, e.g. Energy Recovery Linac
- SRF infrastructure upgrade
- R&D – Cryolab



Niob Vollmaterial



LHC: Spare module ready for high power test

S. Aull.
B. Peters
T. Junginger

R&D – Cavities/Cryo

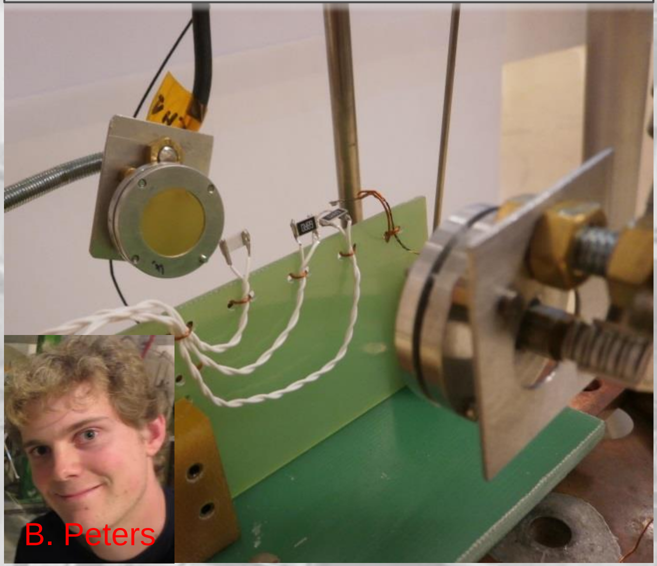
New Coating Technologies: HIPIMS on 1.3 GHz cavities

Collaboration with TE-VSC
S. Calatroni and G. Terenziani

Fundamental SRF studies using the Quadrupole Resonator

PhD Thesis S. Aull (Univ. Siegen)
Supervisor: S. Doebert

Cavity Diagnostic Developments with OSTs



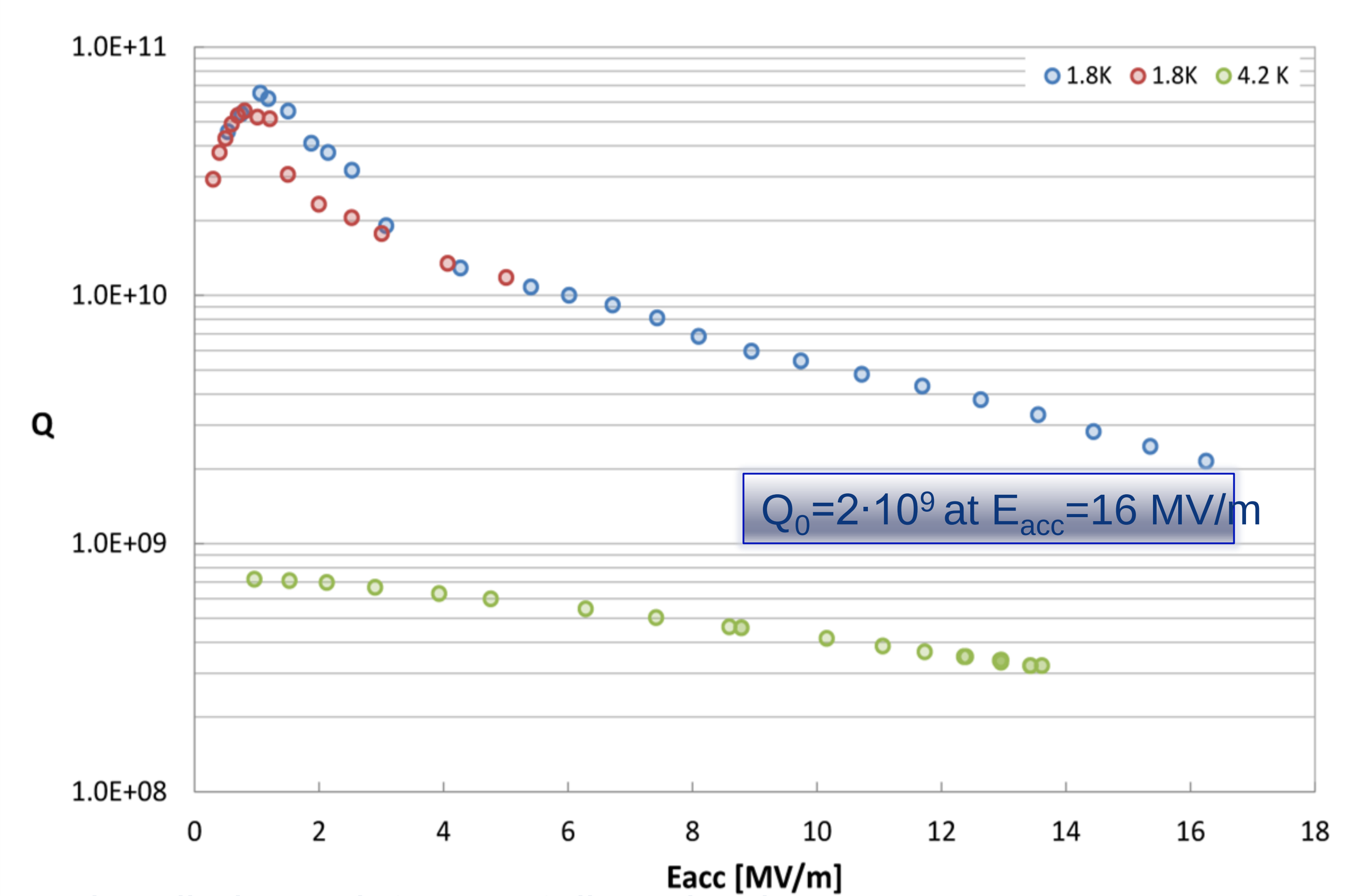
Master Thesis B. Peters (Univ. Karlsruhe) with Co-Supervisor T. Koettig (TE-CRG)

Thanks to the cryolab team for their support in more than 20 cold tests in 2013!

S. Aull.
B. Peters
T. Junginger

R&D – Cavities/Cryo

New Coating Technologies: HIPIMS on 1.3 GHz cavities

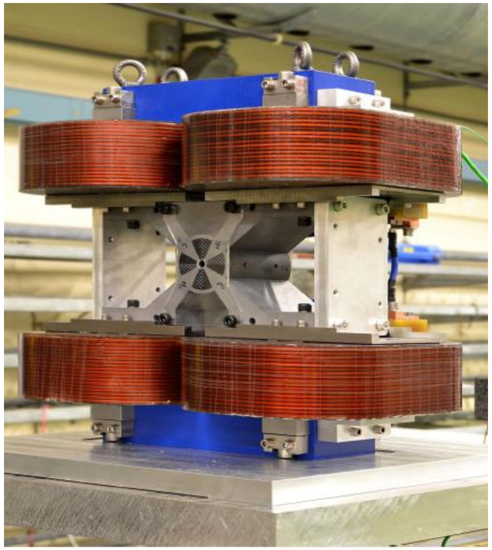


$Q_0 = 2 \cdot 10^9$ at $E_{acc} = 16$ MV/m

Qualität Qo hat direkten Einfluss auf die Höhe der notwendigen Kühlleistung, die so klein wie möglich sein soll

Magnetic Measurement Laboratory

Kollege Russenschuck



Supra-, Kryotechnik-, Messtechnik Labors

Wer	Anstellung	Was
• Daniel Berkowitz	**Gentner Doktorand (KIT**)	Technology Transfer
• Dr. Tobias Junginger	**Fellow, Ex-Gentner (Heidelberg)**	Supraleitende Kavitäten
• Joanna Liberadzka	Tech. Studentin aus Warschau	He3/He4 Mischkühler
• Dr. A. Ballarino	CERN Staff, Sektionschefin	SC Cable test facility
• Chr. Scheuerlein	CERN Staff, Materialwissenschaftler	
• Dr. S. Russenschuck	CERN Staff, Sektionschef	Magnet-Messtechnik
• Oliver Köster	**Gentner Doktorand (TU Darmstadt**)	