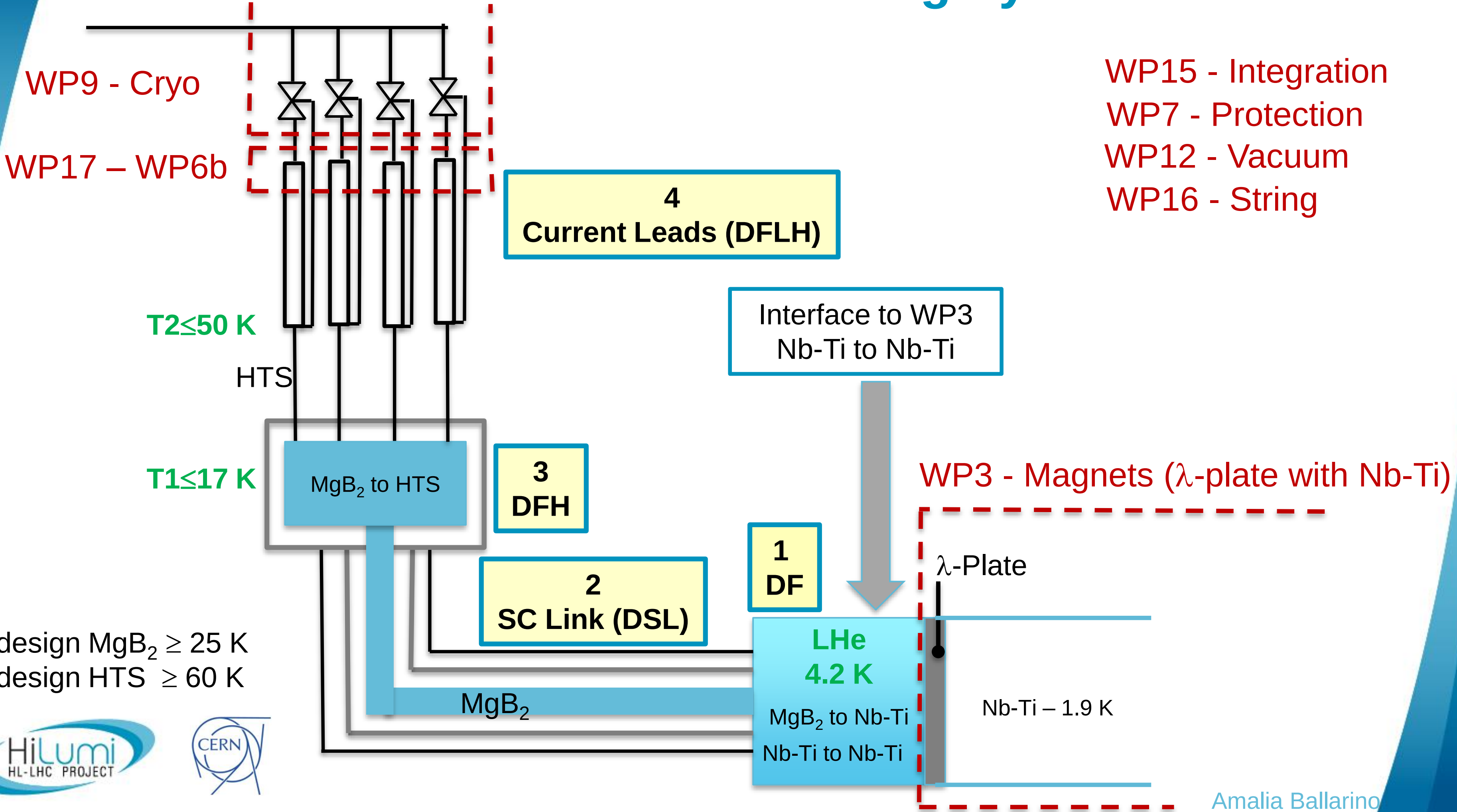
The new Cold Powering for HL-LHC Test results and final layout

Amalia Ballarino for the WP6a

9th HL-LHC Collaboration Meeting - Fermilab - 14-16 October 2019

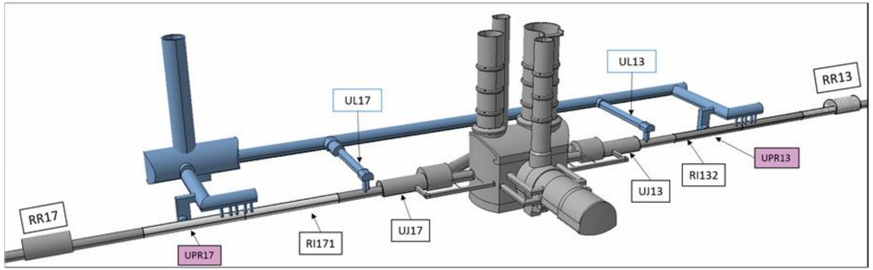
The HL-LHC Cold Powering System

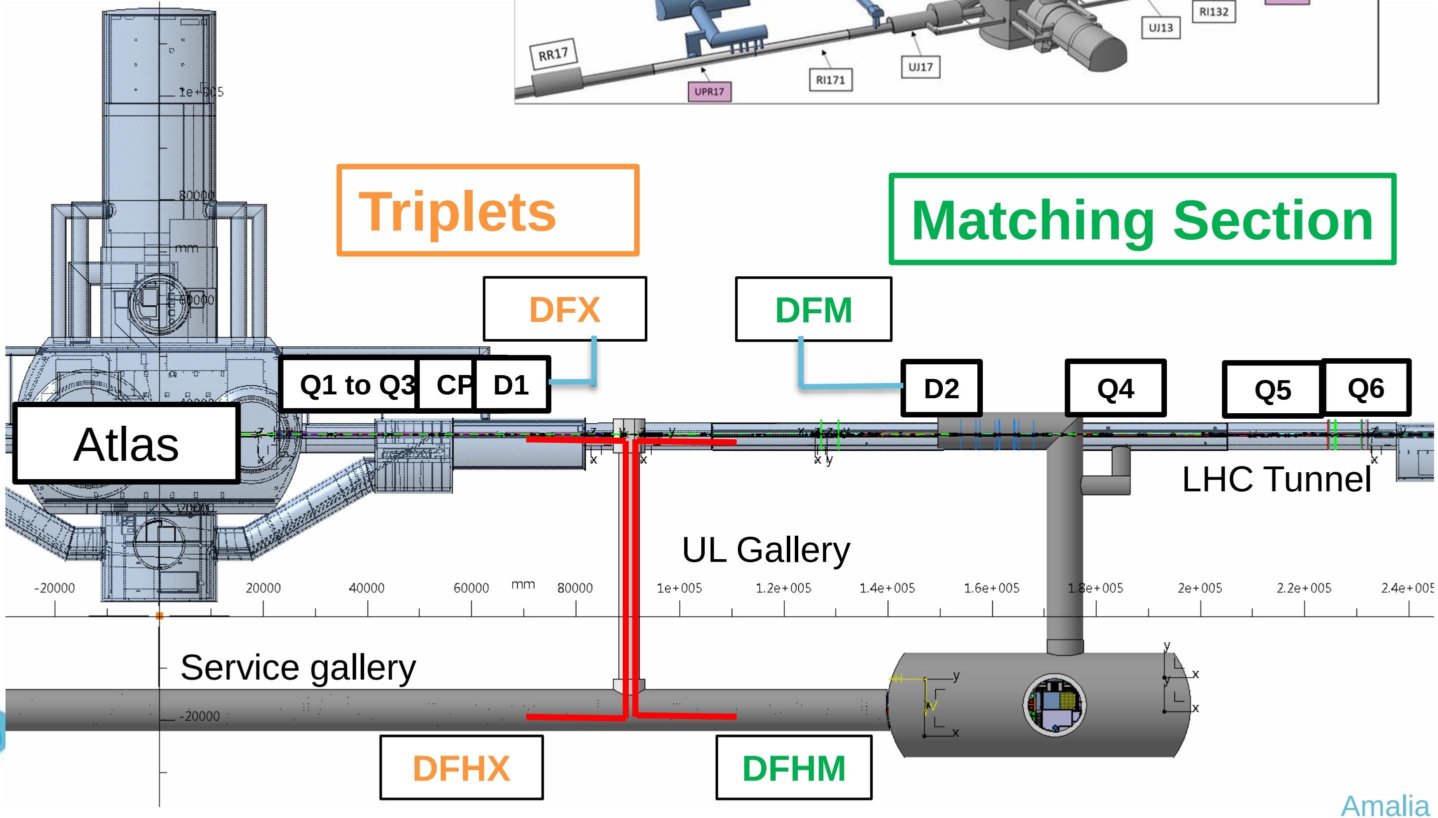


WP15 - Integration
WP7 - Protection
WP12 - Vacuum
WP16 - String

Tdesign $MgB_2 \geq 25$ K
Tdesign HTS ≥ 60 K

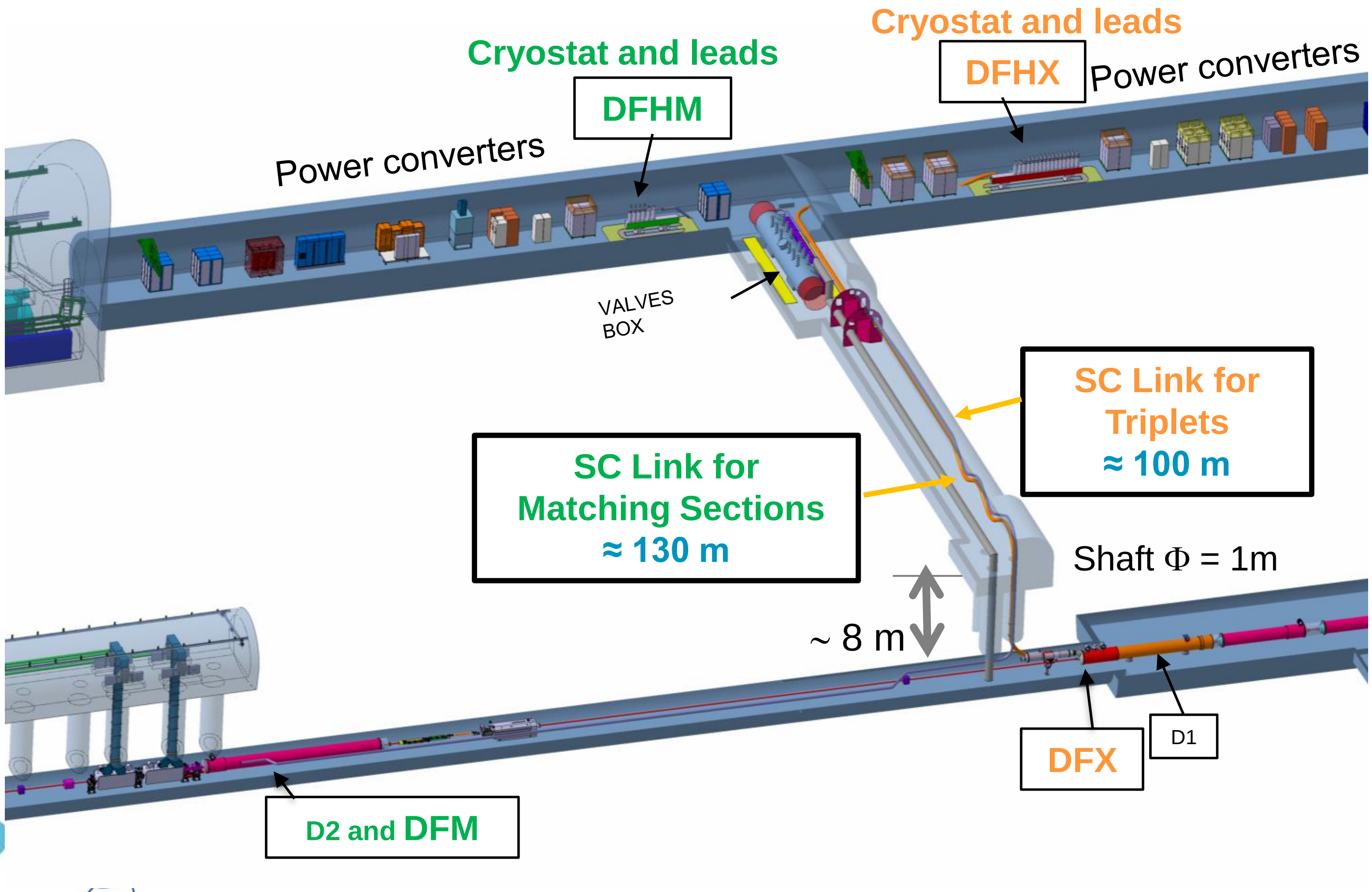
Cold Powering System in LHC underground





Amalia Ballarino

Cold Powering System in LHC underground



Number of components

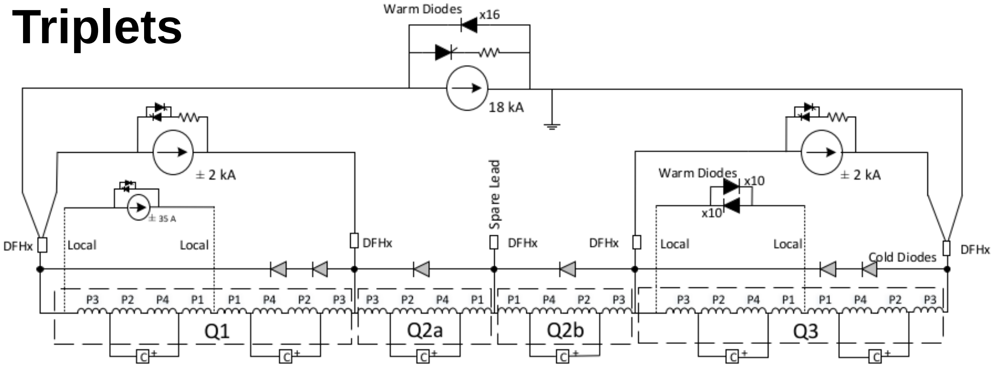
- **Ten SC Links** of two different types (4 for ITs plus 4 for MSs plus one spare per type) for powering the HL-LHC Triplets region and the HL-LHC Matching Sections
- **Ten DFH cryostats** (4 for ITs plus 4 for MSs plus one spare per type)
- **Ten DF cryostats** (4 for ITs plus 4 for MSs plus one spare per type)
- **176 HTS Current leads** (148 for series plus few spares per lead type) for powering the HL-LHC **ITs + 50 HTS Current leads** (40 plus few spares per lead type) for powering the **MSs** (226 units in total)

Two Cold Powering System topologies (One for ITs and one for MSs)
Four Cold Powering Systems per topology

Electrical baseline

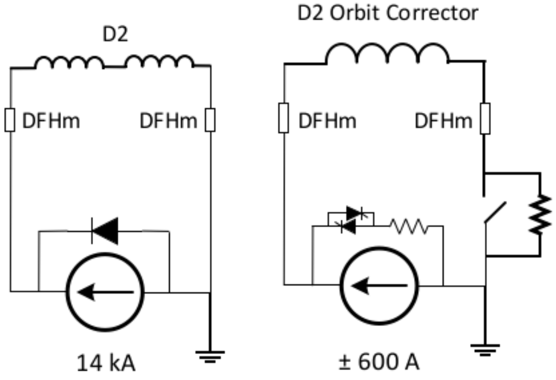
Electrical circuits

Triplets

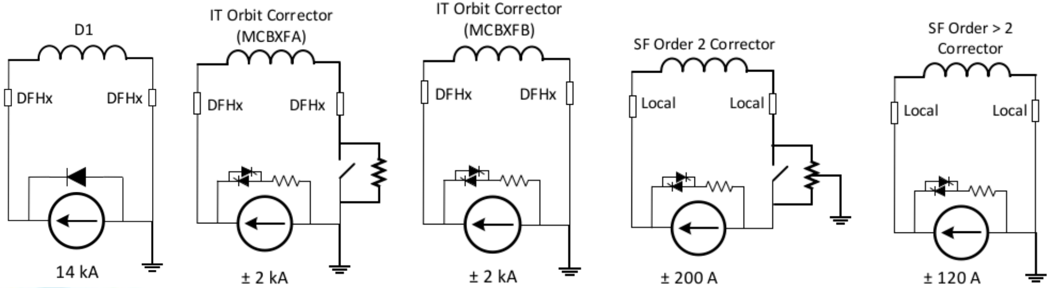


One main 18 kA circuit
Two Trims: 2×2 kA (Q1 and Q3)
k-modulation: 1×0.035 kA (Q1a)

Matching Sections



In addition: D1, Orbit Correctors and Higher Order Correctors individually powered:



D2 and its Correctors individually powered

Design Currents: Baseline for Triplets

	Magnet	Cold Powering			
	I_{ult}(kA)	I_{peak}(kA)	I_{lead} (kA)	I_{cable}(kA)	N_{leads}/N_{cables}
MQXF	17.82	-	18	18	2
Trim Q1	2	2.4	2*	7	1
Q2a/Q2b	Protec.	5.6	2*	7	1
Trim Q3	2	6.8	2*	7	1
MCBXFB	1.73	-	2	2	2+2
MCBXFB	1.59	-	2	2	2+2
MCBXFA	1.73	-	2	2	2
MCBXFA	1.59	-	2	2	2
MQSXF	0.2	-	0.2	0.2	2
MCSXF/MCSSXF	0.12	-	0.12	0.12	2+2
MCOXF/MCOSXF	0.12	-	0.12	0.12	2+2
MCDXF/MCDSXF	0.12	-	0.12	0.12	2+2
MCTXF/MCTSXF	0.12	-	0.12	0.12	2+2
D1	12.96	-	18	18	2

SC Link (MQXF to MCBXFA)

Local Powering (also k-mod within WP3) ECR (MQSXF to MCTXF/MCTSXF)

SC Link (D1)

$|I_{tot}|$ (SC Link) ~ 120 kA

EDMS NO.	REV.	VALIDITY
1821907	2.0	APPROVED

HiLumi HL-LHC PROJECT CERN

Design Currents: Baseline for Matching Sections

D2 and its correctors

	Iult (kA)	Ileads/cables (kA)	N_{leads}	N_{cables}
D2	13367	18	2	2
MCBRD	0.422	0.6	8	8

$|Itot|$(SC Link) ~ 31 kA

Ratings for series units (ITs and MSs): **18 kA**, **2 kA**, **7 kA** and **0.6 kA**

HV Levels - Triplets

EDMS NO.	REV.	VALIDITY
1821907	2.0	APPROVED

Rating (kA)	Worst case voltage to ground during operation (V)	Acceptance tests of components to ground (V)		Insulation test voltage of system to ground (V)		Leakage current per component (µA)	Test duration (s)
		RT	NOC	RT	NOC		
18	900	4600	2300	460	1080	≤10	30
7	900	4600	2300	460	1080	≤10	30
2	540	3160	1580	316	648	≤10	30
0.2	540	3160	1580	316	648	≤10	30
0.12	40	1160	580	220	360	≤10	30
0.035	900	4600	2300	460	1080	≤10	30

RT = Room Temperature (20 ± 5 °C)

NOC = Nominal Operating Conditions. For all WP6s components, it corresponds to GHe at RT and 1.30 ± 0.05 bar

HV Levels – Matching Sections

D2: treated as a 18 kA circuit – conservative

18 kA

Rating (kA)	Worst case voltage to ground during operation (V)	Acceptance tests of components to ground (V)		Insulation test voltage of system to ground (V)		Leakage current per component (µA)	Test duration (s)
		RT	NOC	RT	NOC		
18	900	4600	2300	460	1080	≤10	30

D2

Rating kA	Worst case voltage to ground during operation (V)	Acceptance of components to ground (V)		Insulation voltage of system to ground (V)		Leakage current per component (µA)	Test duration (s)
		RT	**NOC**	**RT**	**NOC**		
D2	525	3100	1550	310	630	≤10	30

D2 correctors: 0.6 kA rating, Worst case to ground = 590 V, Components test: 5.7 kV (RT) - Components test 2.860 kV (NOC)

Protection Strategy

EDMS NO.	REV.	VALIDITY
1821907	**3.0**	**APPROVED**

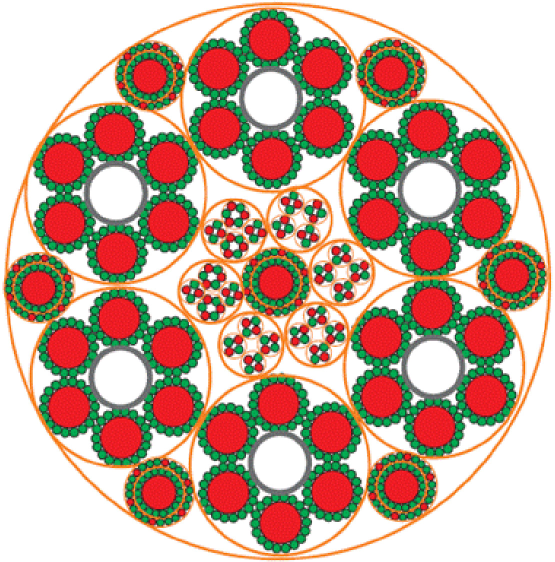
For the 18 kA and 7 kA cables (HTS/MgB_2) and leads, which are part of the inner triplet main circuit, the baseline protection strategy is that if any of them quenches (for the cables) or suffer a thermal run-away (for the leads), the entire quench protection system (quench heaters and CLIQ) of all MQXF magnets is fired. For the 18 kA cables and leads for D1, if any of the cables (HTS/MgB_2)/leads quench/suffer thermal run away, the quench protection system of D1 (quench heaters) is fired. For the other corrector circuits (2 kA, 0.2 kA and 0.12 kA), the corresponding corrector circuit's quench protection system (quench heaters or energy extraction and power converter crowbar) are fired.

Rating (kA)	MIITs ($MA^2 \cdot s$)	dI/dt (kA/s)	τ_n (no quench of magnets) (s)	τ_Q (quench of magnets) (s)	Equivalent time (s)
18 (*)	32	250	130	0.2	0.1
7	5	250	130	0.2	0.12
2 (**)	1	20	20	0.5	-
0.2 (***)	0.02	0.25	21	0.8	-
0.12	0.02	0.22	5	0.8	-

System components

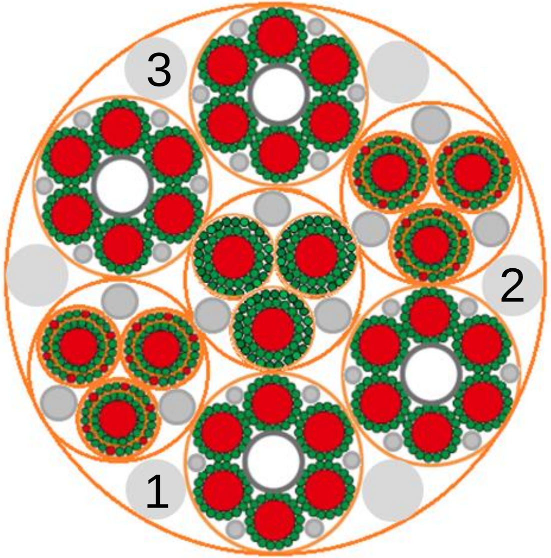
SC MgB_2 Cable Design - Triplets

Layout in 2016



1,2,3 → Instrumentation wires

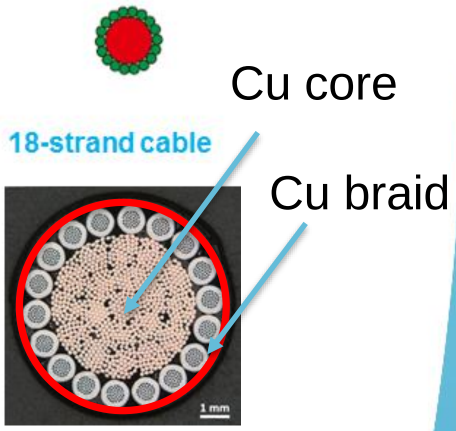
Layout in 2018



Φext ~ 90 mm

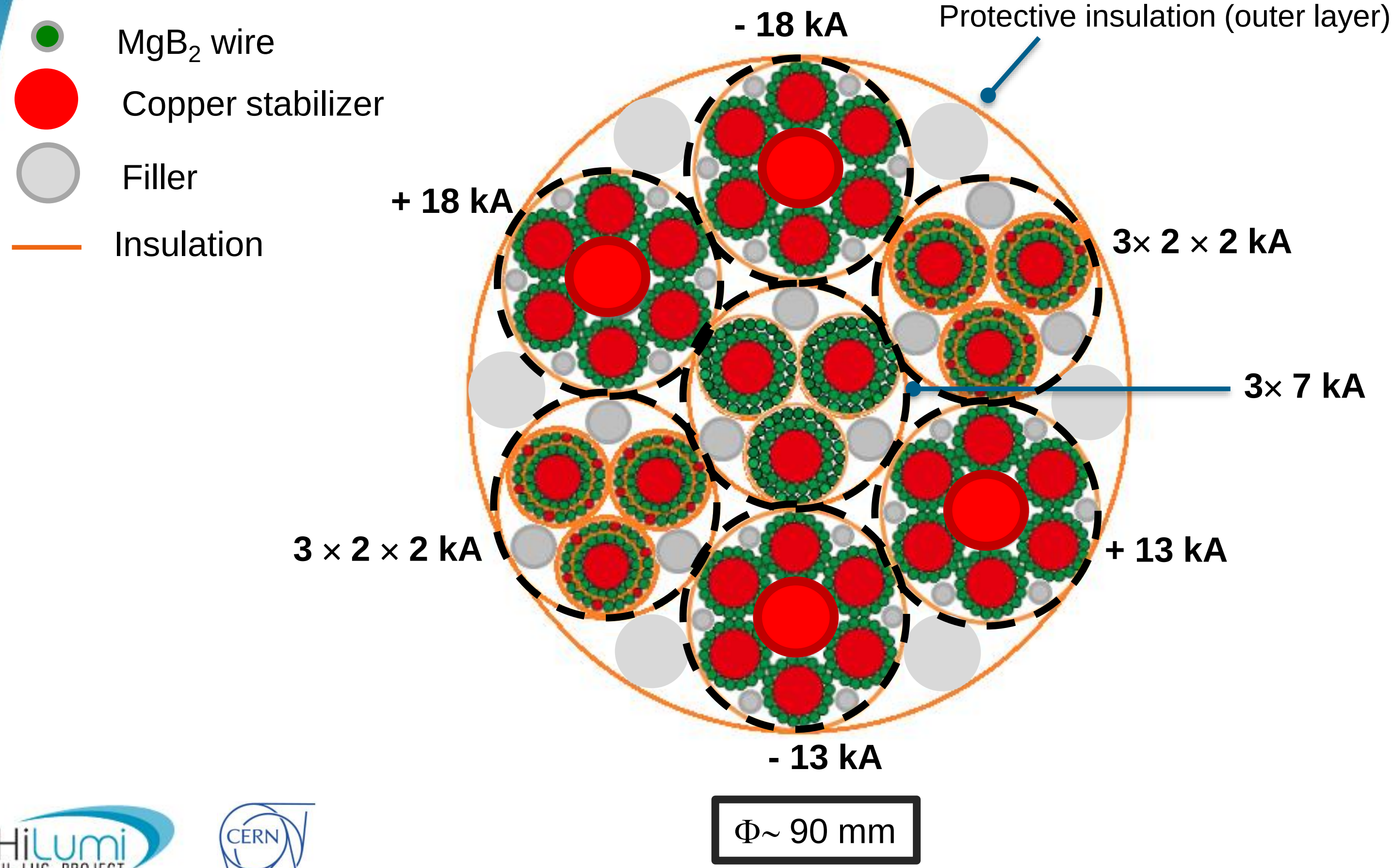
Baseline

Base cable



Φ~7.5 mm

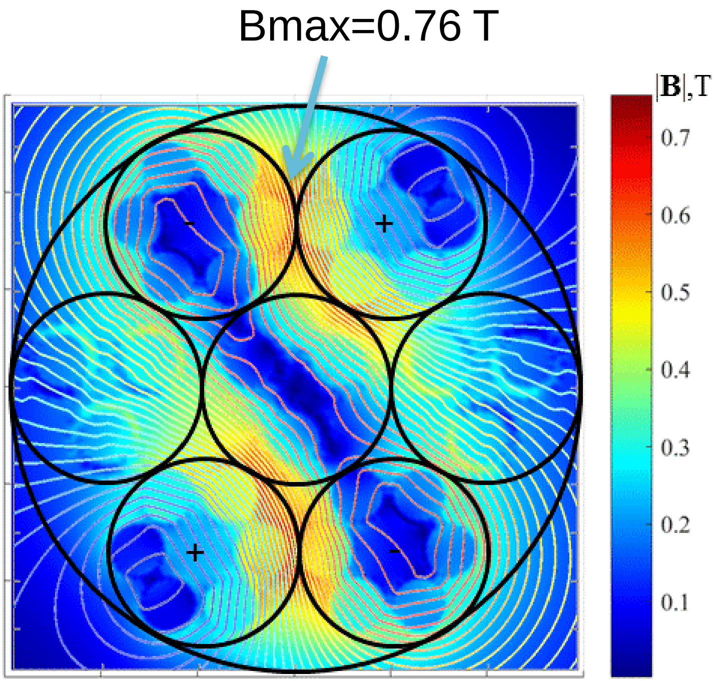
MgB_2 cable design – Triplets

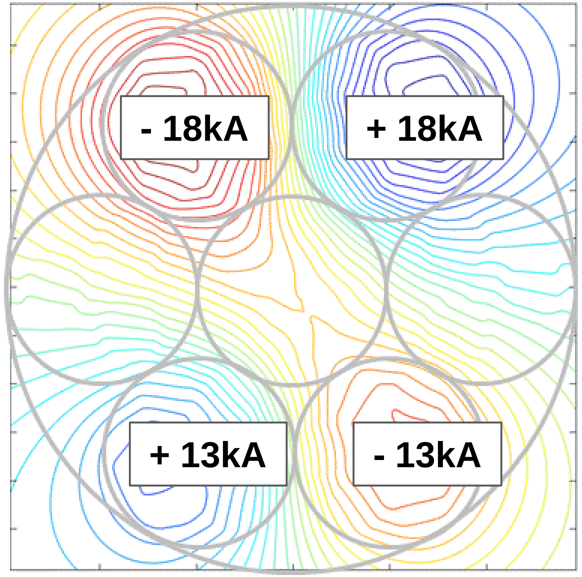


4 × 18 kA
3 × 7 kA
6 × 2 × 3 kA

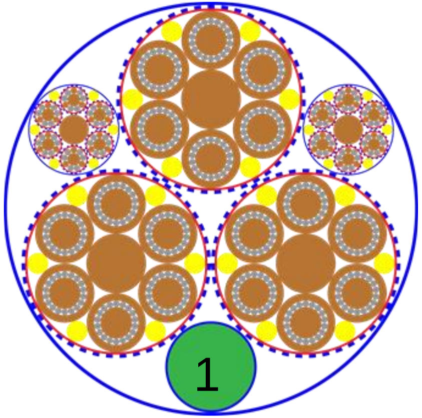
A. Ballarino

MgB_2 cable - Triplets





SC MgB_2 Cable Design – Matching Sections



Φext ~ 60 mm

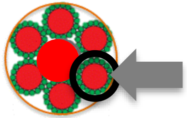
1 → Instrumentation wires

Status of cabling activity

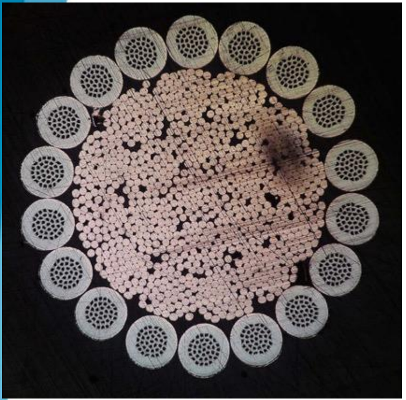
- **Each cable type** assembled and electro-mechanically characterized **at CERN**
- **Cables** (18-strand sub-cable, 18 kA cable, 2 kA coaxial-cable) produced **in industry** (ICAS, cabling at Tratos cavi) via R&D contracts and electro-mechanically characterized at CERN (including HV testing in Ghe)
- Contracts for **full scale prototypes** (80 m long, one copper and one MgB_2, - for ITs and MSs) and for **series production** placed in industry – price enquiry in 2018 followed by adjudication (ICAS) at FC Dec 2018. Completed **first 80 m long copper prototype cable for IT**. Assembly of **80 m long MgB_2 cable for Its is on-going** in industry (delivery to CERN planned by end of October 2019)

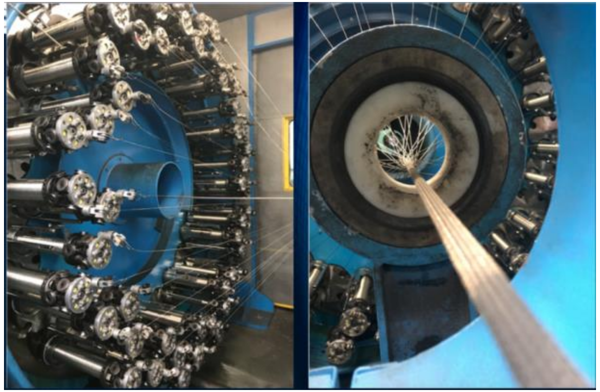
Validation of cabling parameters and materials completed for ITs

Example of qualification at CERN



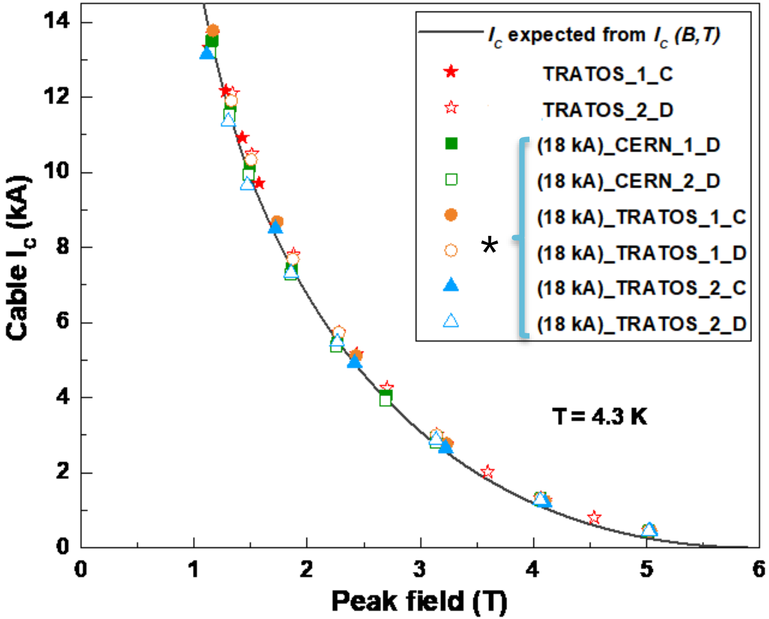
Φ~24 mm





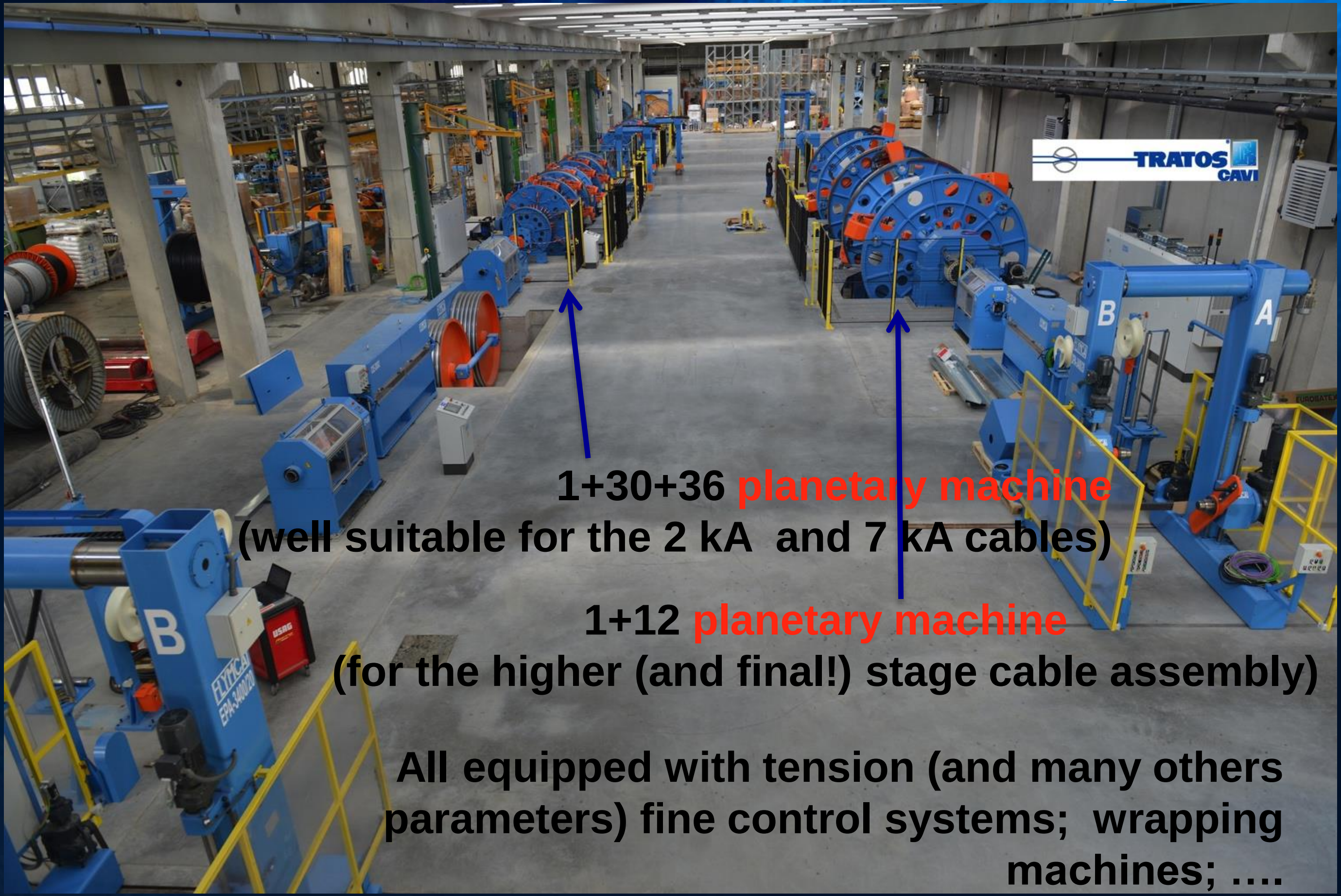
Φcable = 6.5 mm

Measurement of cables (2 m long)

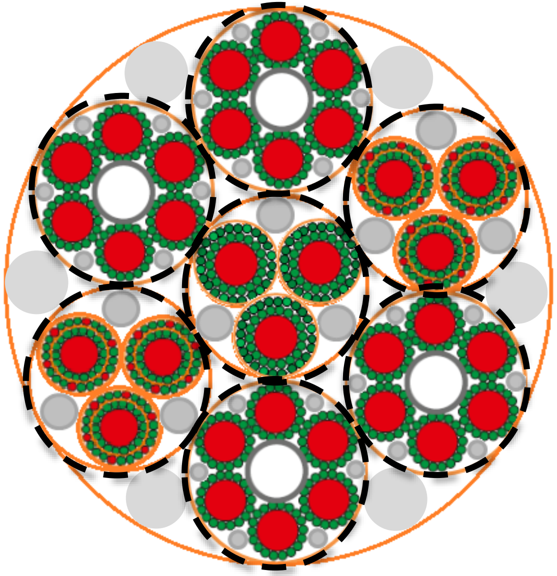


* Extracted from 18 kA cable

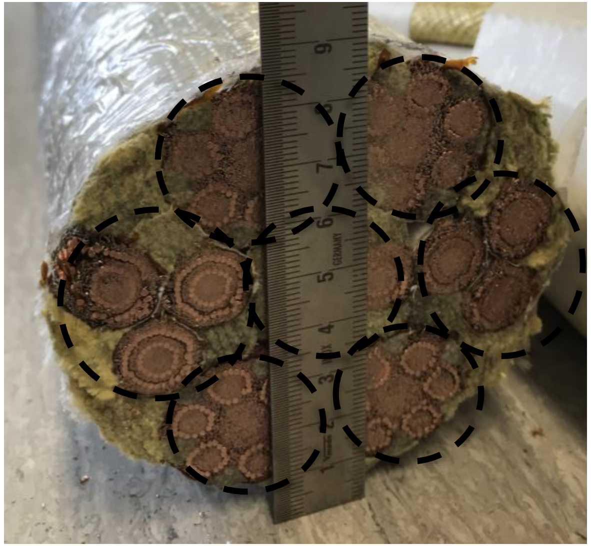
TRATOS installations used for MgB_2 cables



Production in industry of 80 m long dummy-Cu cable for Triplets



Φ~ 90 mm



Insulation tests at the cables' manufacturing site

On-line HV tests: **DC spark testing at 12 kV**

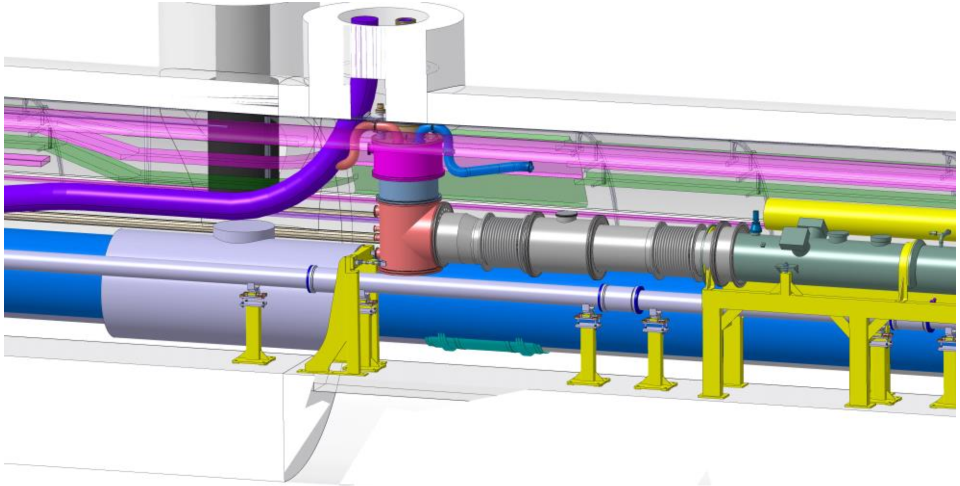
Applied successfully during first 80 m long dummy (copper) cable for Triplets. No faults detected

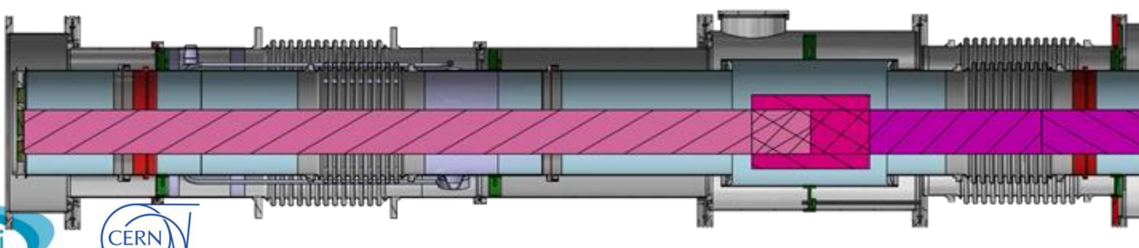
Off-line HV tests: **10 kV** (50 V/s, 120 s). **Ileakage ≤ 10 μA** on final assembly**.** Each cable to ground and between cables. **Applied** successfully during production of first dummy cable for Triplets

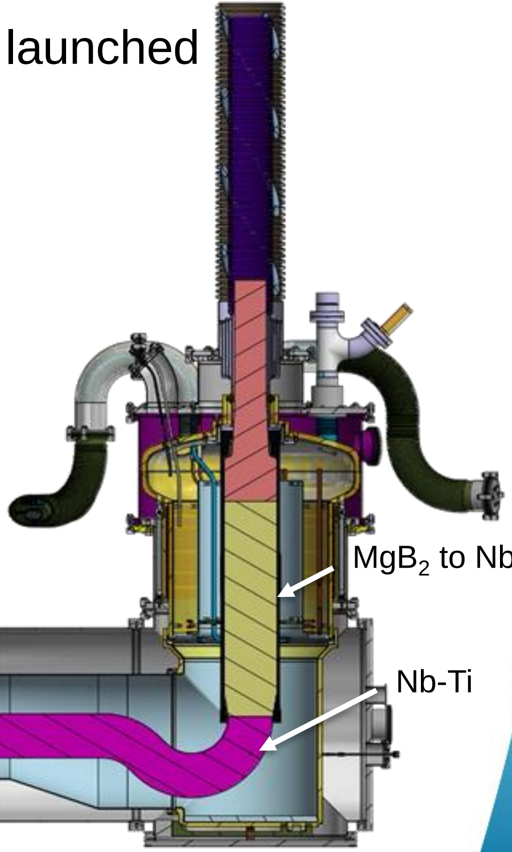
DFX Cryostat – UK1 Collaboration

University of Southampton

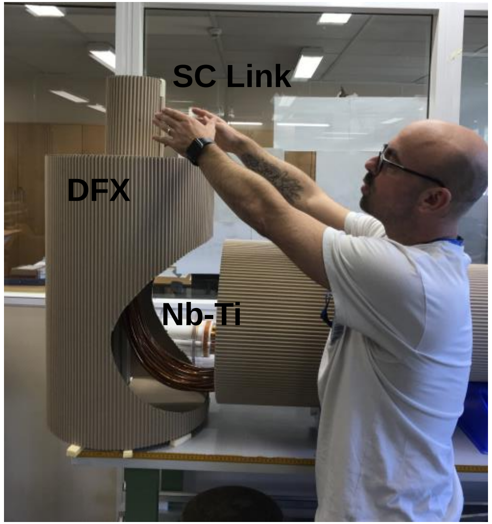
Production of prototype/spare DFX ready to be launched

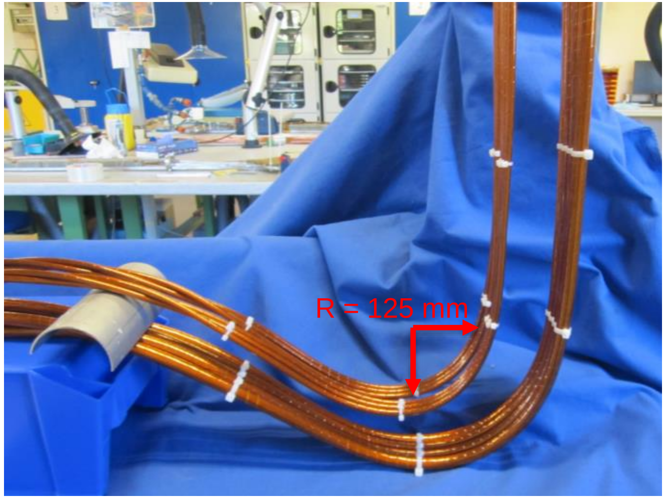






DFX Cryostat – Round LTS bus-bar

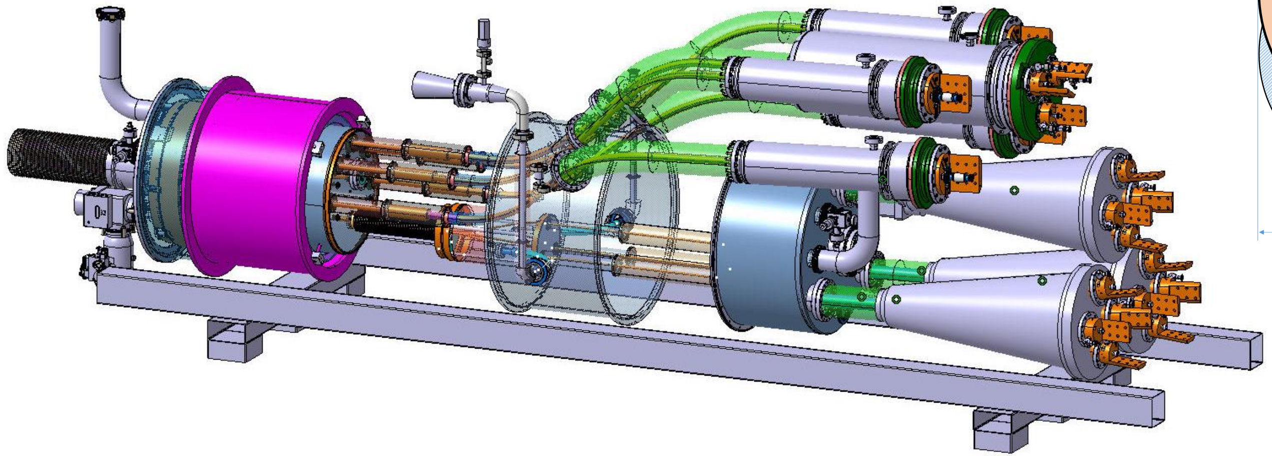


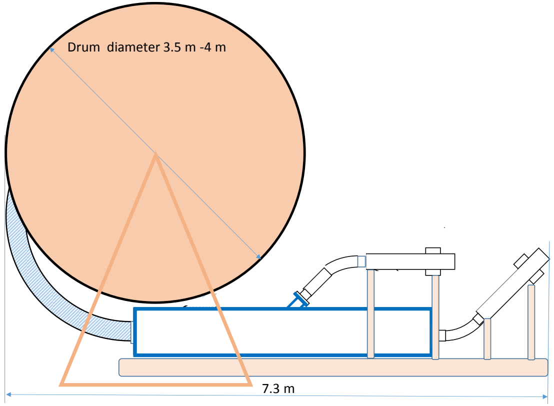


Type of circuit	Current (kA)	Detection time (s)	Equivalent time constant (s)	Quench load from detection (MIITs)	Quench load total (MIITs)	SC cross-section (mm^2)	Cu cross-section (mm^2)	Hot spot temperature (K)
MQXF	18	0.4	0.17	28	157	19	78	**44**
D1	13	0.4	0.35	30	97	19	78	**37**
MCBXFA	1.7	0.4	0.17	0.25	1.4	7.4	19.2	**23**
MCBXFB	1.7	0.4	4	6	7.2	7.4	19.2	**38**

Round Nb-Ti cables developed at CERN

DFHX Cryostat





Total length with current leads ~ 5.8 m

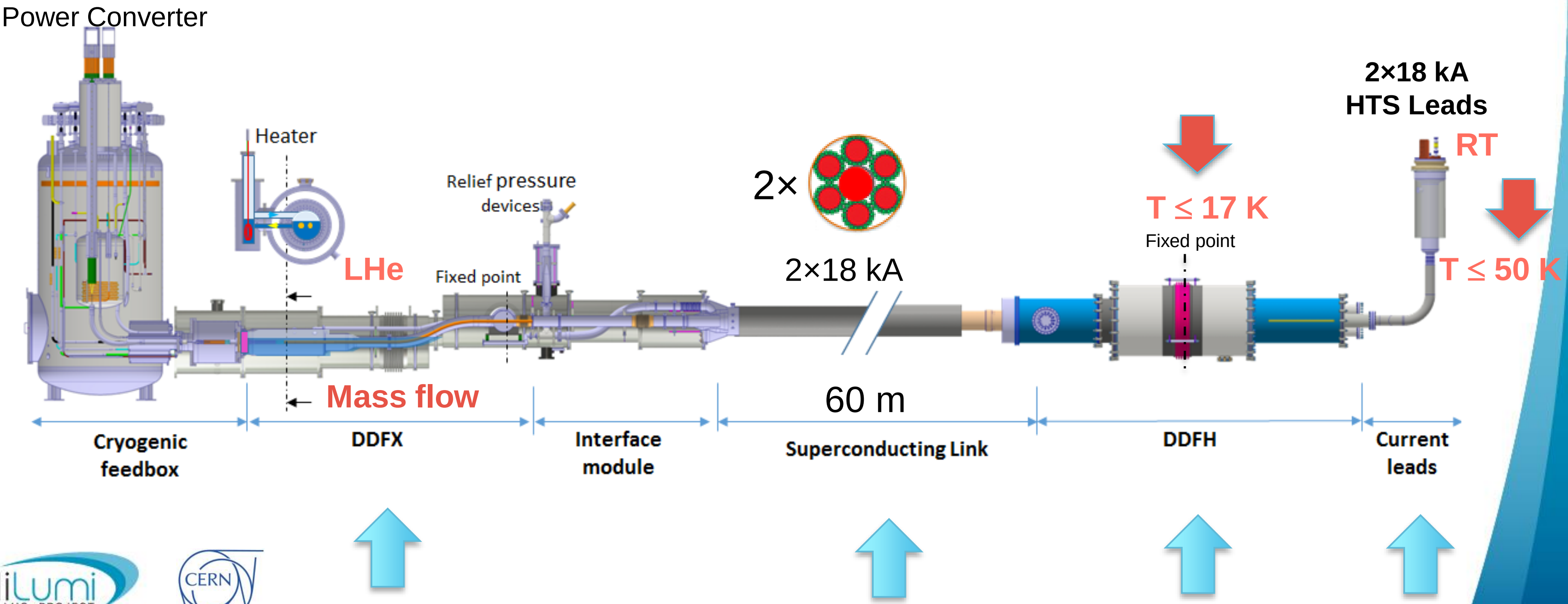
Possibility of assembling and testing the current leads at the surface

Demo 1 - System Demonstration

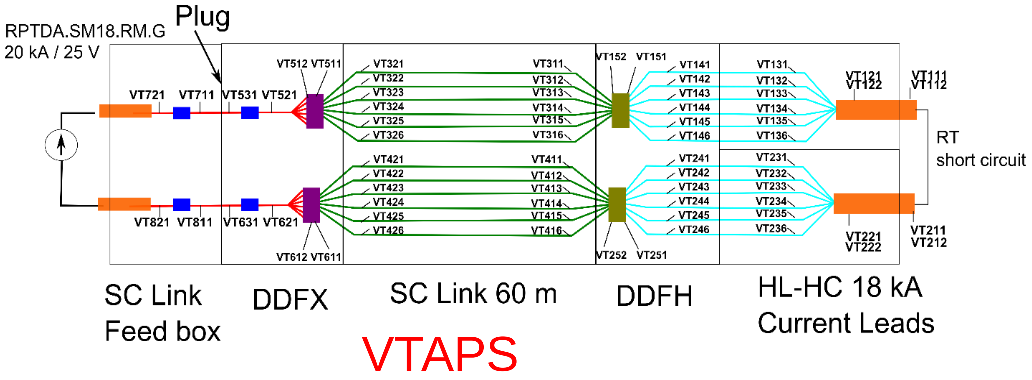
Demo 1

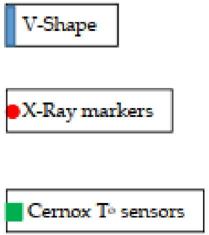
Constructed by WP6a and tested in the SM-18 at different stages.

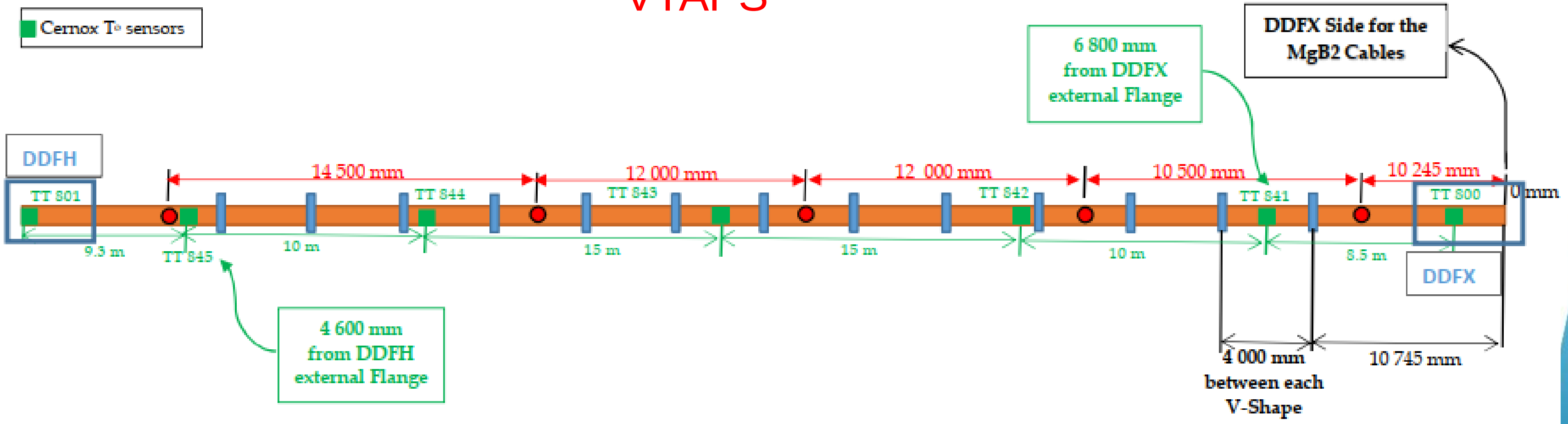
With the last measurement – March 2019 – validation of: **DDFX** Demo, **DDFH** Demo, **SC Link** with **2×60 m MgB_2 cables** made in industry, **2×18 kA HTS** Prototype **Current Leads** made at CERN, **thermal contraction**, **cryogenic control**, **protection of superconducting circuits**, **splices** (MgB_2-HTS, MgB_2-NbTi) in nominal operating conditions (LHe/GHe).



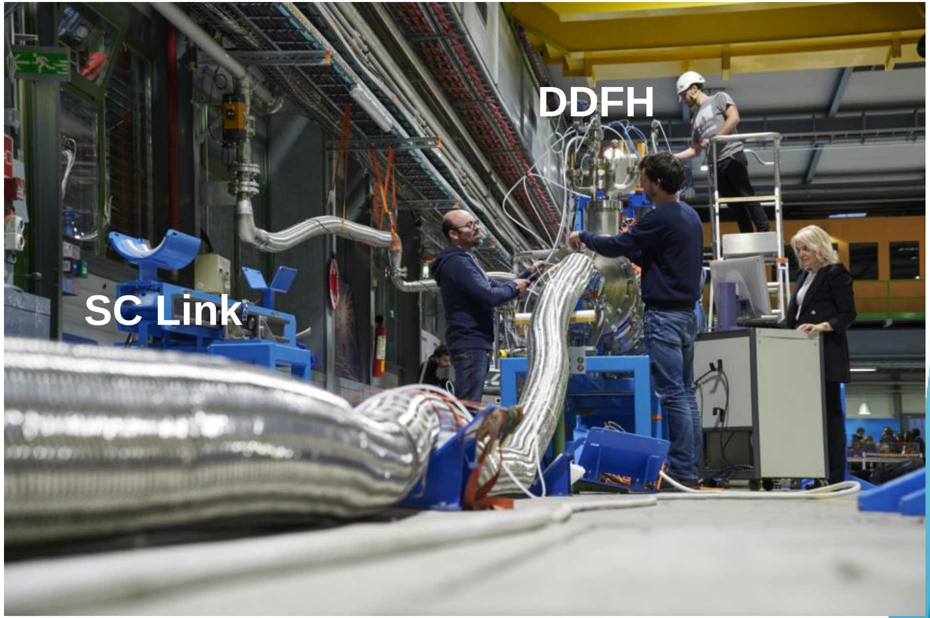
Instrumentation





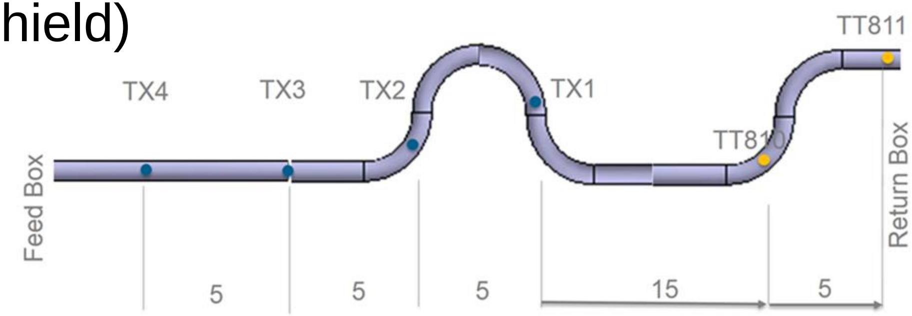


Demo 1 – DDFX, DDFH and SC Link

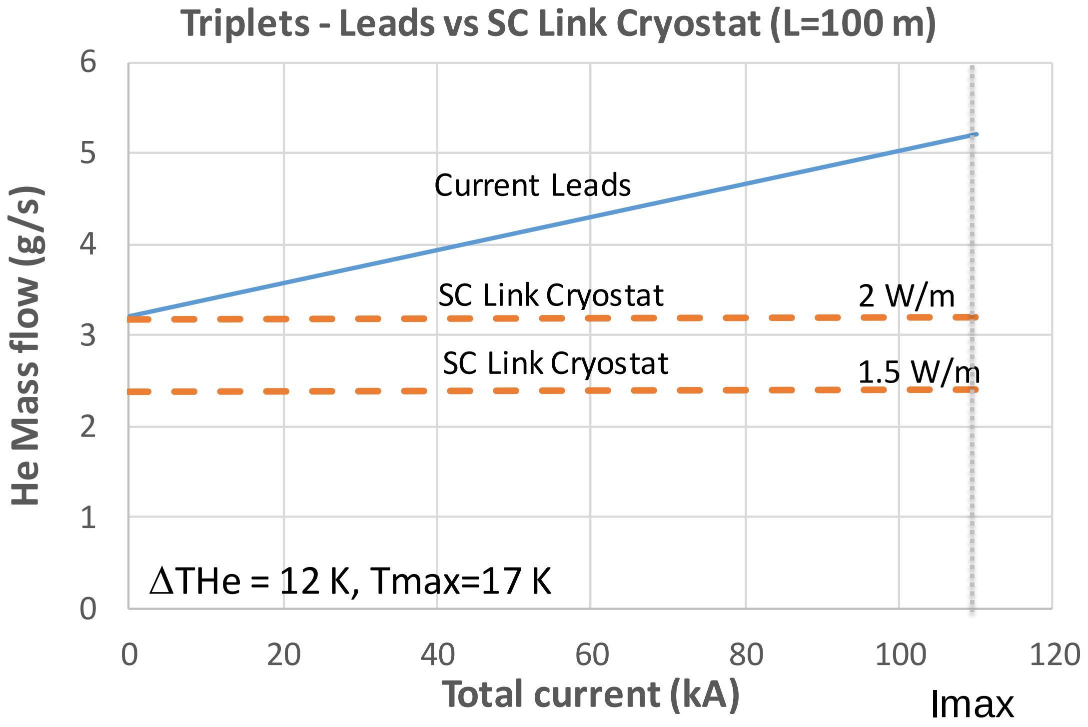


SC Link Cryostat

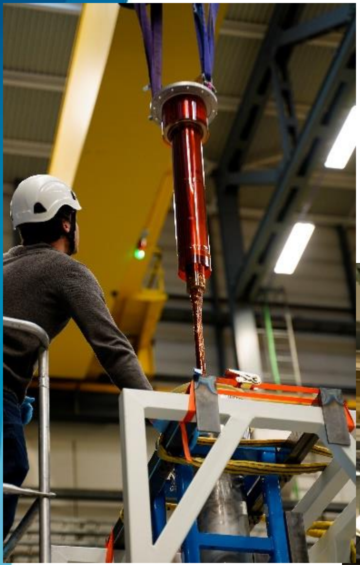
Two-wall configuration (no active shield)
Q ≤ 1.5 W/m
Development done with industry
In-depth qualification at CERN

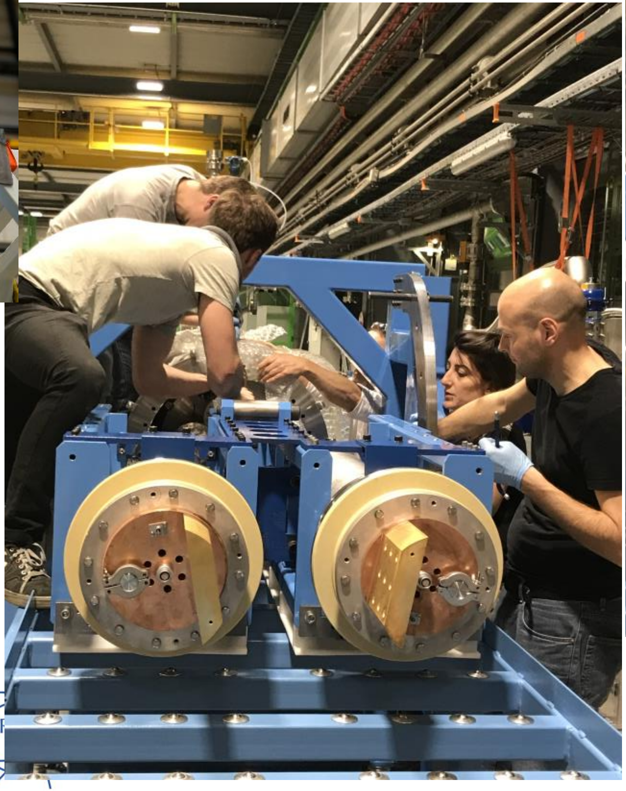


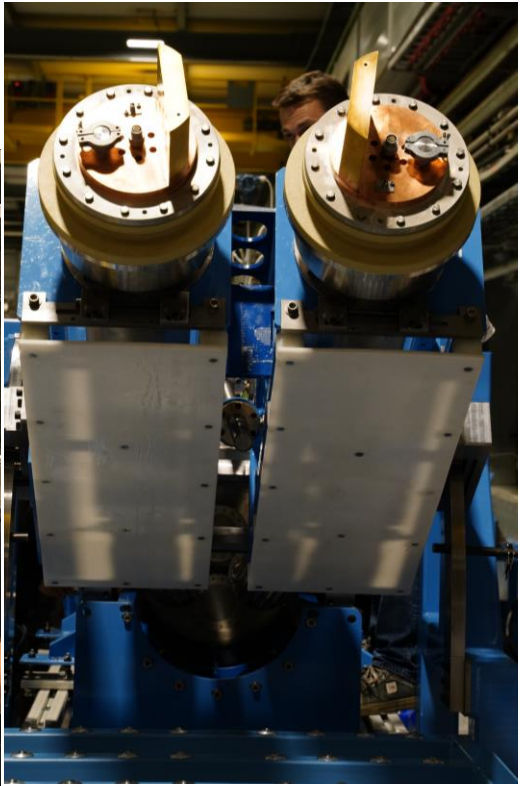
SC Link Cryostat for Triplets



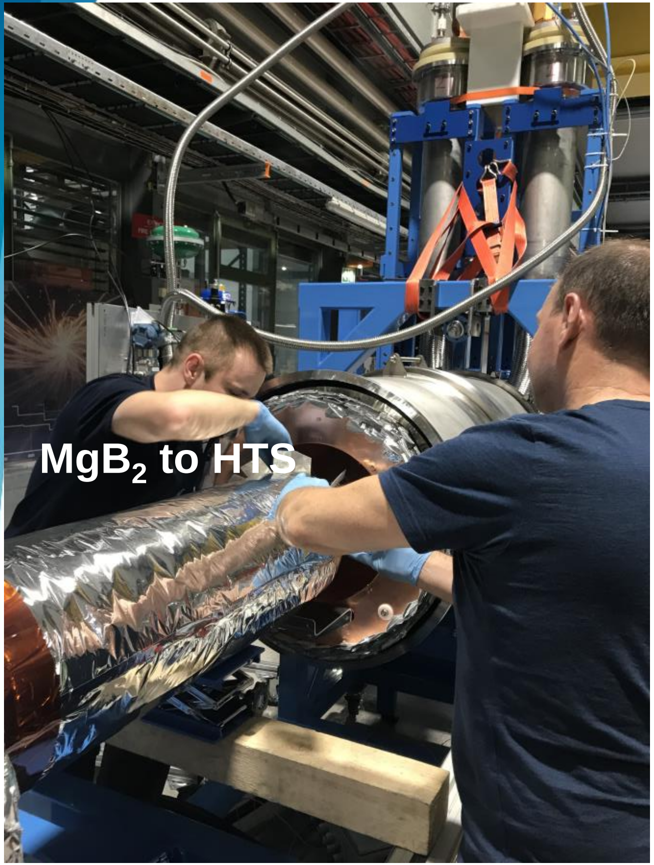
Demo 1 – 18 kA REBCO Current Leads

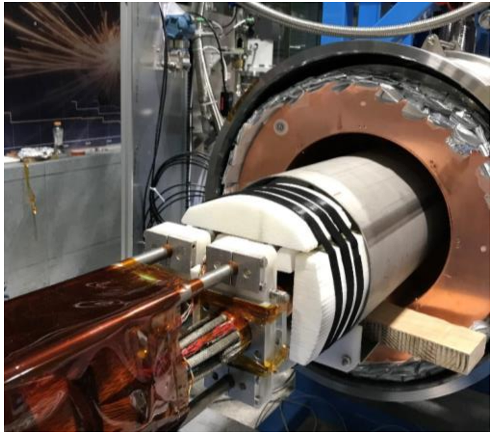




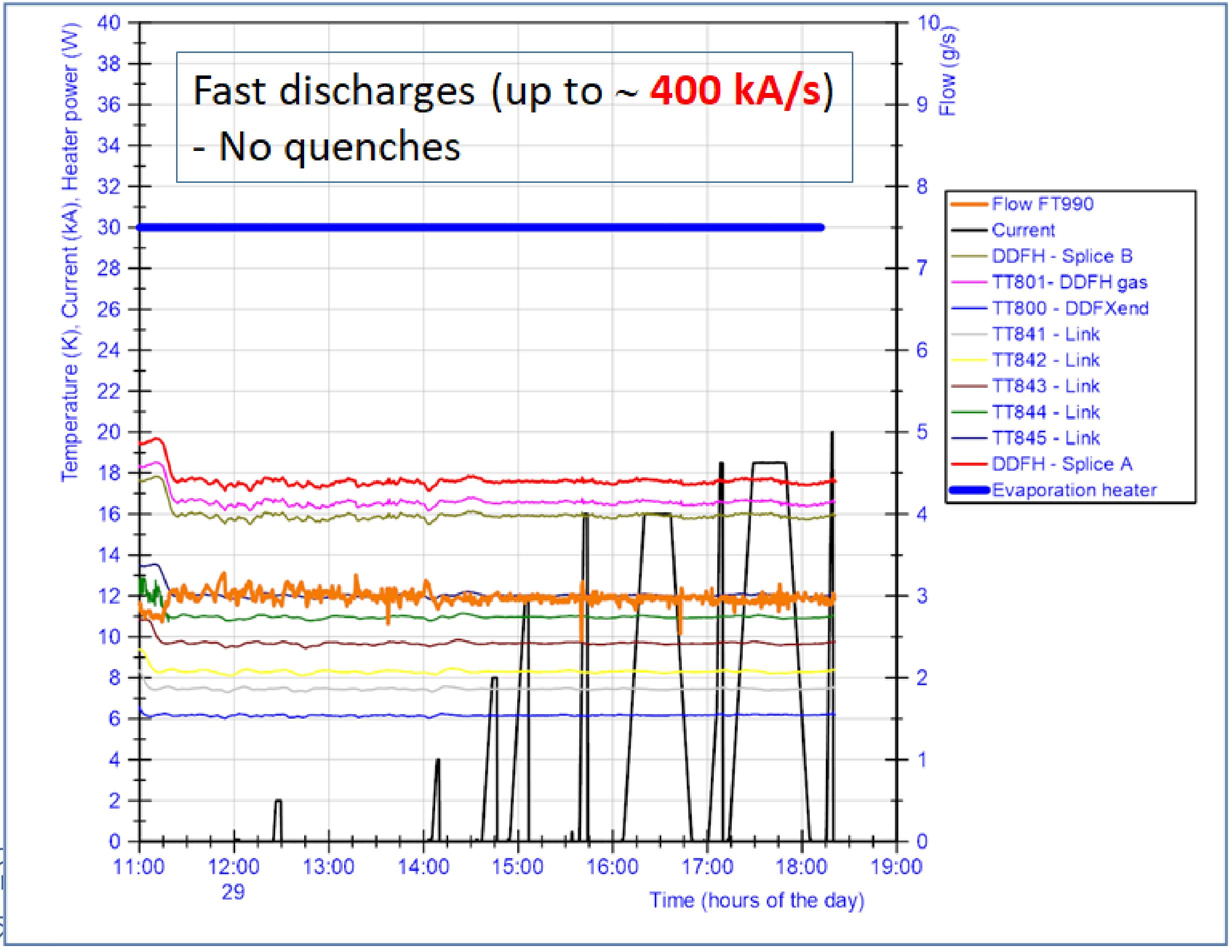


Demo 1 - DDFH and Splices



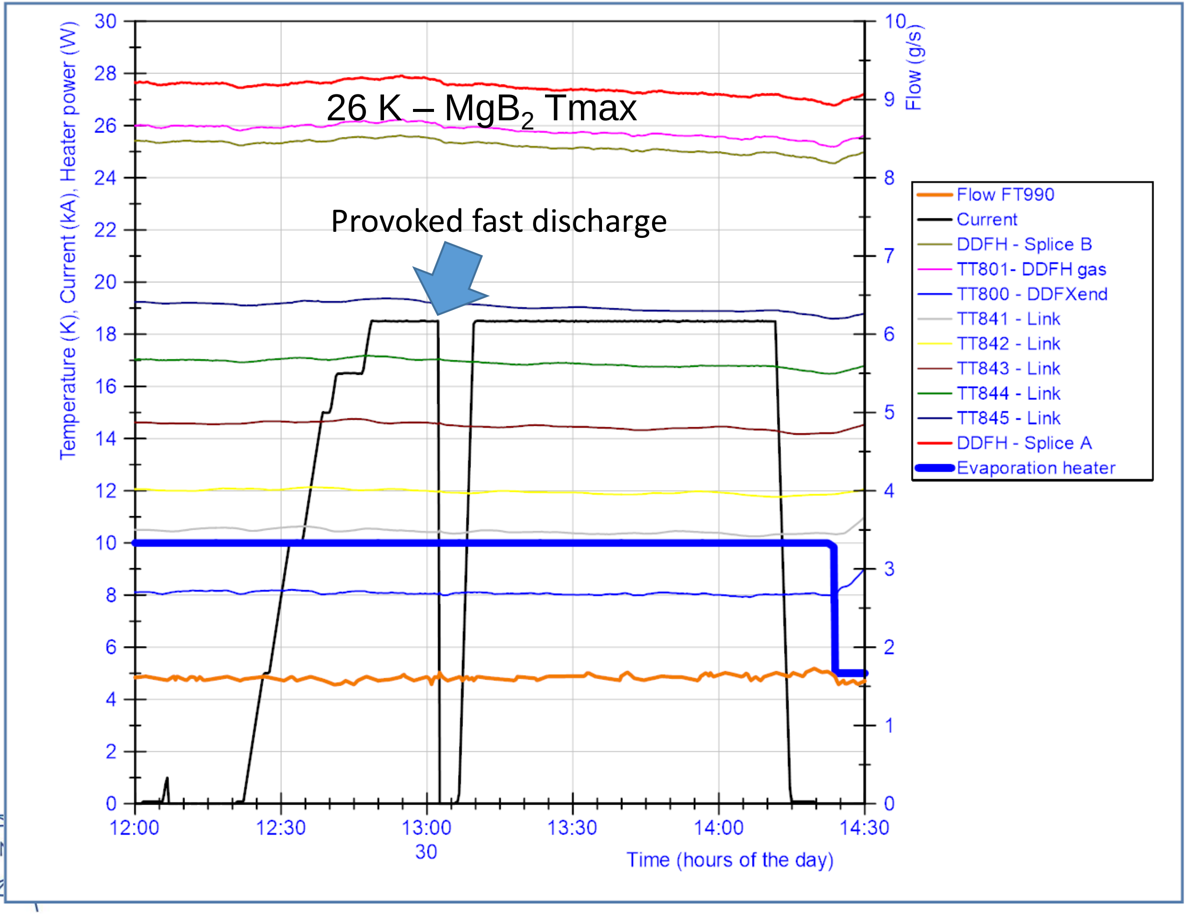


20 kA @ 18 K – No quench

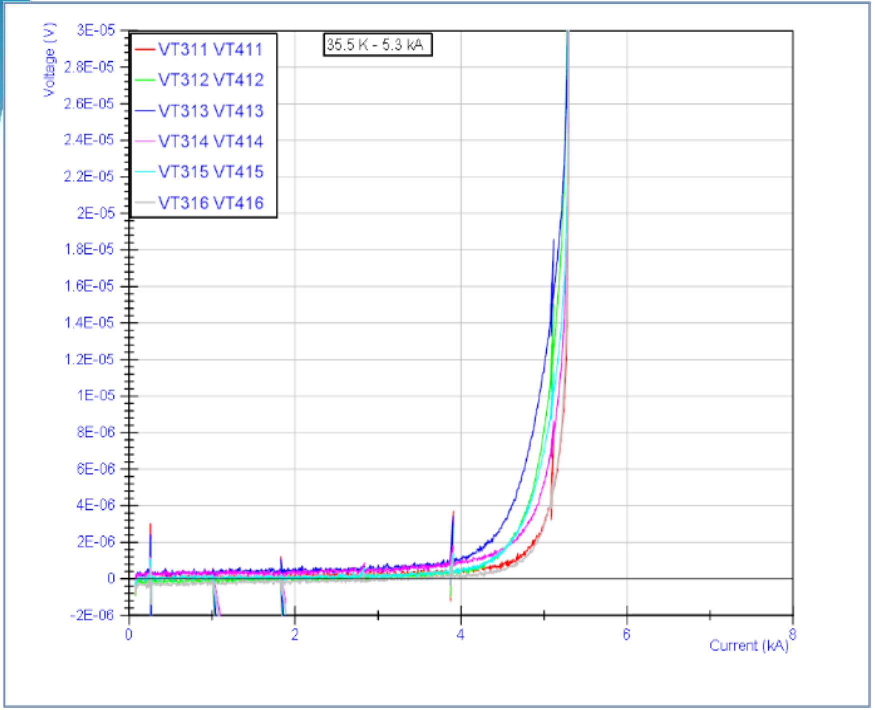


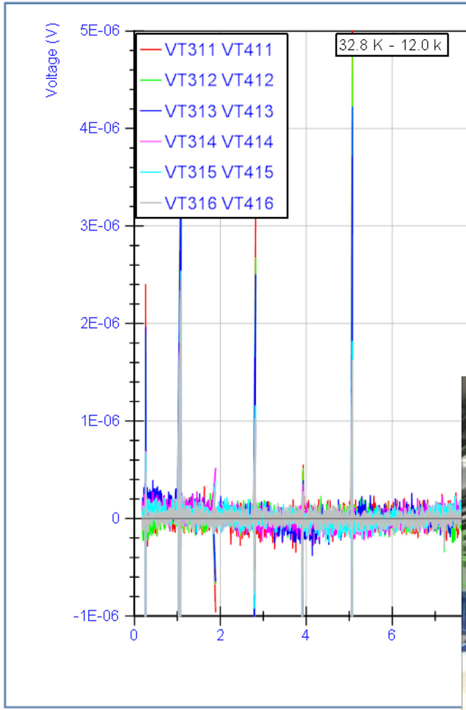
18.5 kA – 1 hour (Tmax ~ 26 K)

T in SC Link

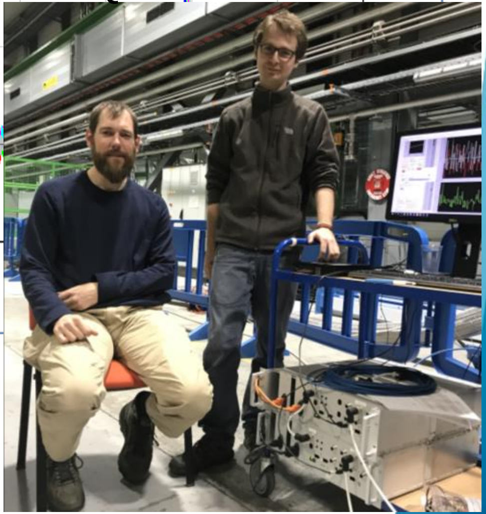


Several quenches – No degradation





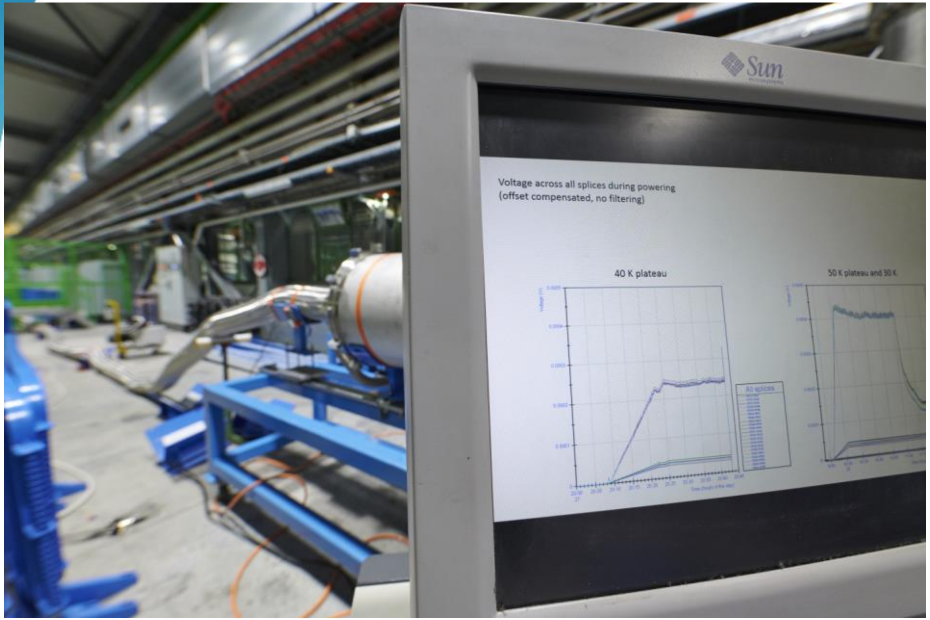
QPS as for LHC

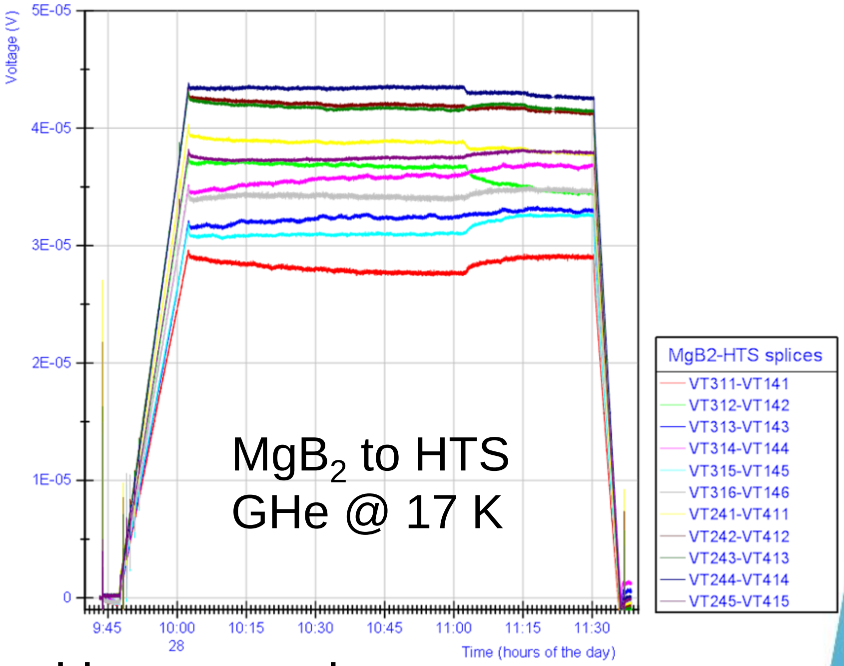


Calculated Tc
31.33 K @ 18 kA
32.3 K @ 12 kA

Demo 1 – Cryogenic/electrical operation

Demo 1 – Splices





Resistance of splices in line with expectations:

MgB_2/NbTi splices:**1 nΩ (0.9 nΩ calculated)**

MgB_2/HTS splices:**1.9 nΩ (1.7 nΩ calculated)**

NbTi/NbTi splices: **0.4-0.7 nΩ (0.6 nΩ calculated)**

Conclusions

- With the WP6a we are developing a completing **new powering technology**

- In the last year, **major progress** has been made on several fronts:
  Demo 1, prototype 18 kA REBCO leads, DFX design, DFH design.
  Two series contracts were adjudicated to industry:
  - 850 km of MgB_2 wire – Columbus. About 100 km of wire delivered;
  - Cabling of MgB_2 wire – ICAS. One prototype Cu cable completed.

- From the electrical point of view, the cold powering systems are designed to meet the circuits' requirements. All electrical functionalities have been defined.

- Next validation test**: Demo 2**. Electrical qualification of **full-scale MgB_2 cable for Triplets**, with simultaneous powering of more than one circuit. The cable is being assembled in industry, and Demo 1 is being upgraded for installation in November 2019

Aknowledgments

The WP6a CERN contributors: P. Cruikshank (deputy), R. Betemps, S. Claudet, I. Falorio, J. Fleiter, A. Gharib, J. Hurte, Y. Leclercq, V. Parma, A. Perin, G. Willering

Y. Yang, W. Bailey – Southampton University

R. Ruber, K. Pepitone, T. Ekelof – Uppsala University

EN MME – P. Moyret, D. Perini, A. Dallocchio, et al.

The MSC group: L. Bottura, A. Devred

The HL-LHC Project office: L. Rossi, O. Bruning, B. Delille, I. Bejar, et al.

The TE Department: M. J. Ijmenez, L. Van Den Boogaard, G. Riddone, et al.

Thank you for your attention !

MgB_2 wire - Specification

Wire diameter	mm	1	± 0.2
Wire ovality	mm	≤ 0.015	
Cu fraction	%	≥ 12	
Cu coating	μm	≥ 30	
Filaments eq. diameter	μm	≤ 60	
Filaments Twist Pitch	mm	≤ 100	± 5
Tensile strain at RT *	%	≥ 0.26	
Bending radius after HT*	mm	≤ 100	
Unit Length	m	≥ 500	
RRR (Cu)	-	> 100	
Ic(25 K, 0.9 T)	A	≥ 186	
Ic(25 K, 0.5 T)	A	≥ 320	
Ic(20 K, 0.5 T)	A	≥ 480	
n-value@ 25 K and 0.9 T	-	> 20	

Cabling of wire after reaction

* Zero Ic degradation