

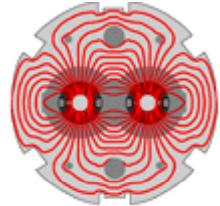
## The Sector 3-4 incident

Ph. Lebrun *on behalf of the*  
Task Force on the Analysis of the 19 September 2008 Incident

LHC Performance Workshop 2009  
Chamonix, 2-6 February 2009



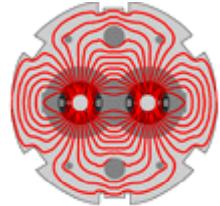
# Contents



- The Task Force on Analysis of the 19 September Incident
- Sector 3-4 before the incident
- The incident: facts and findings
- Recommendations



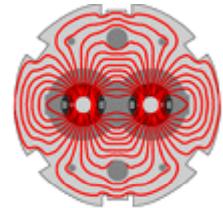
## Mandate of the Task Force



- Establish the sequence of facts, based on experimental measurements before incident, observations after incident and timing
- Analyse and explain the development of events, in relation with design assumptions, manufacturing & test data and risk analyses performed
- Recommend preventive and corrective actions for Sector 3-4 and others



## Contributors to the Task Force

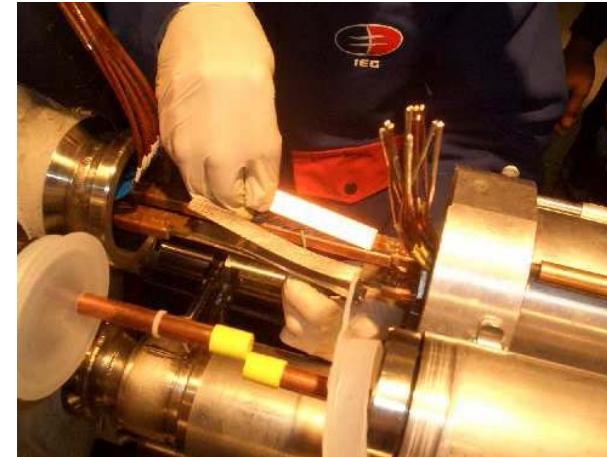
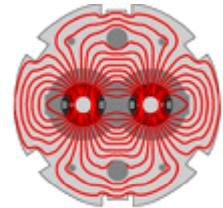


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Knud DAHLERUP-PETERSEN  
Gijs DE RIJK  
Reiner DENZ  
Sandor FEHER  
Paolo FESSIA  
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Jose Miguel JIMENEZ  
Glyn KIRBY  
Mike KORATZINOS  
Sandrine LE NAOUR  
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Rob VAN WEELDEREN  
Raymond VENESS  
Arjan VERWEIJ  
Louis WALCKIERS  
Rob WOLF



## Electrical joints on 12 kA bus bars



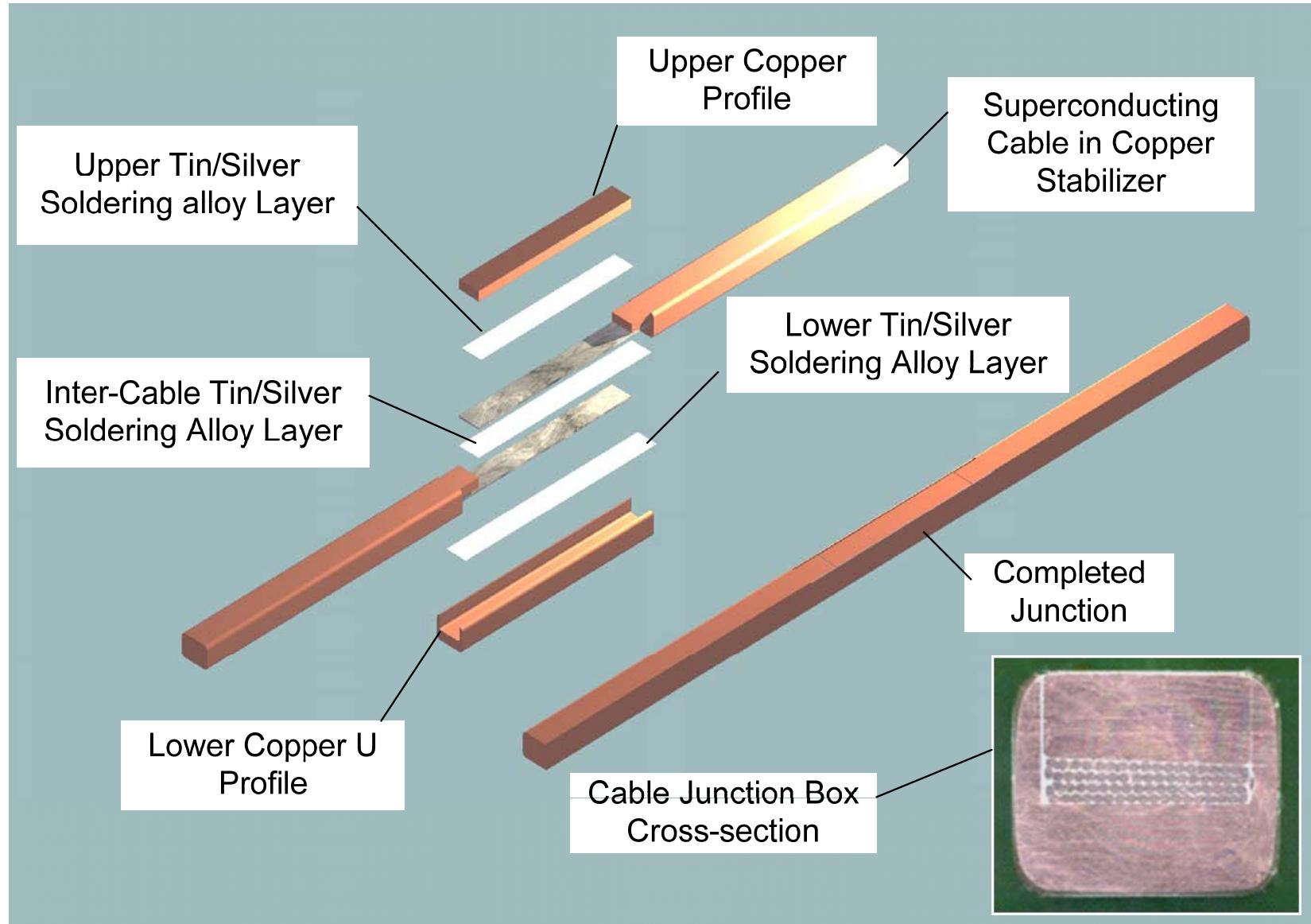
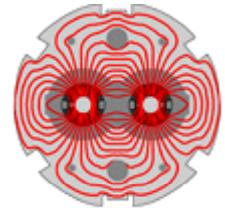
History of interconnections in sector 3-4 (Oct 2006-July 2007) shows no particular cause of defect, but worst working conditions of all machine:

- low temperature and humidity in tunnel
- low productivity of industrial staff (Jan 2007) following contract policy of company

P. Fessia

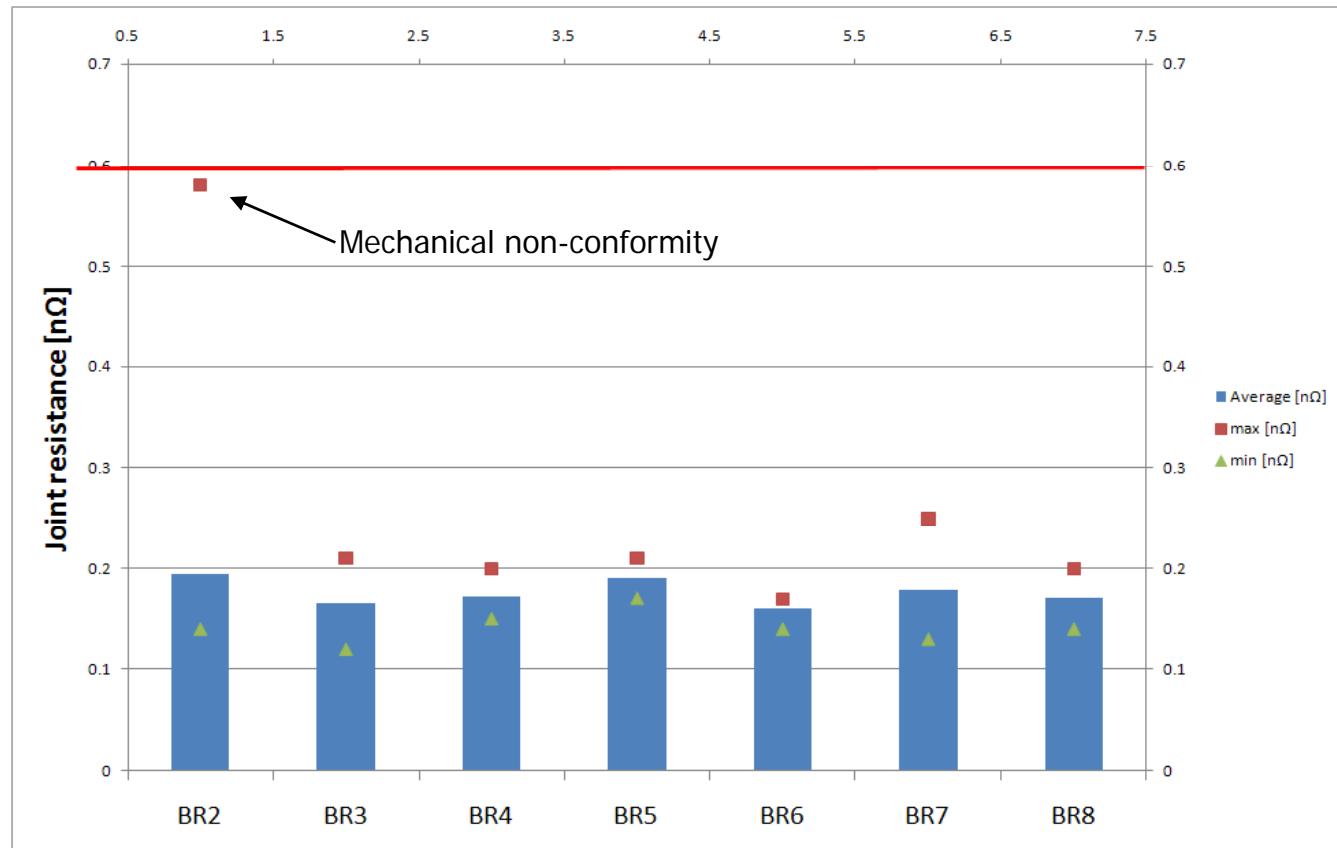
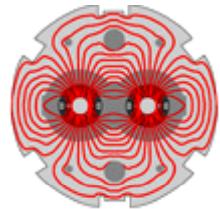


# Electrical joint in 12 kA bus bar





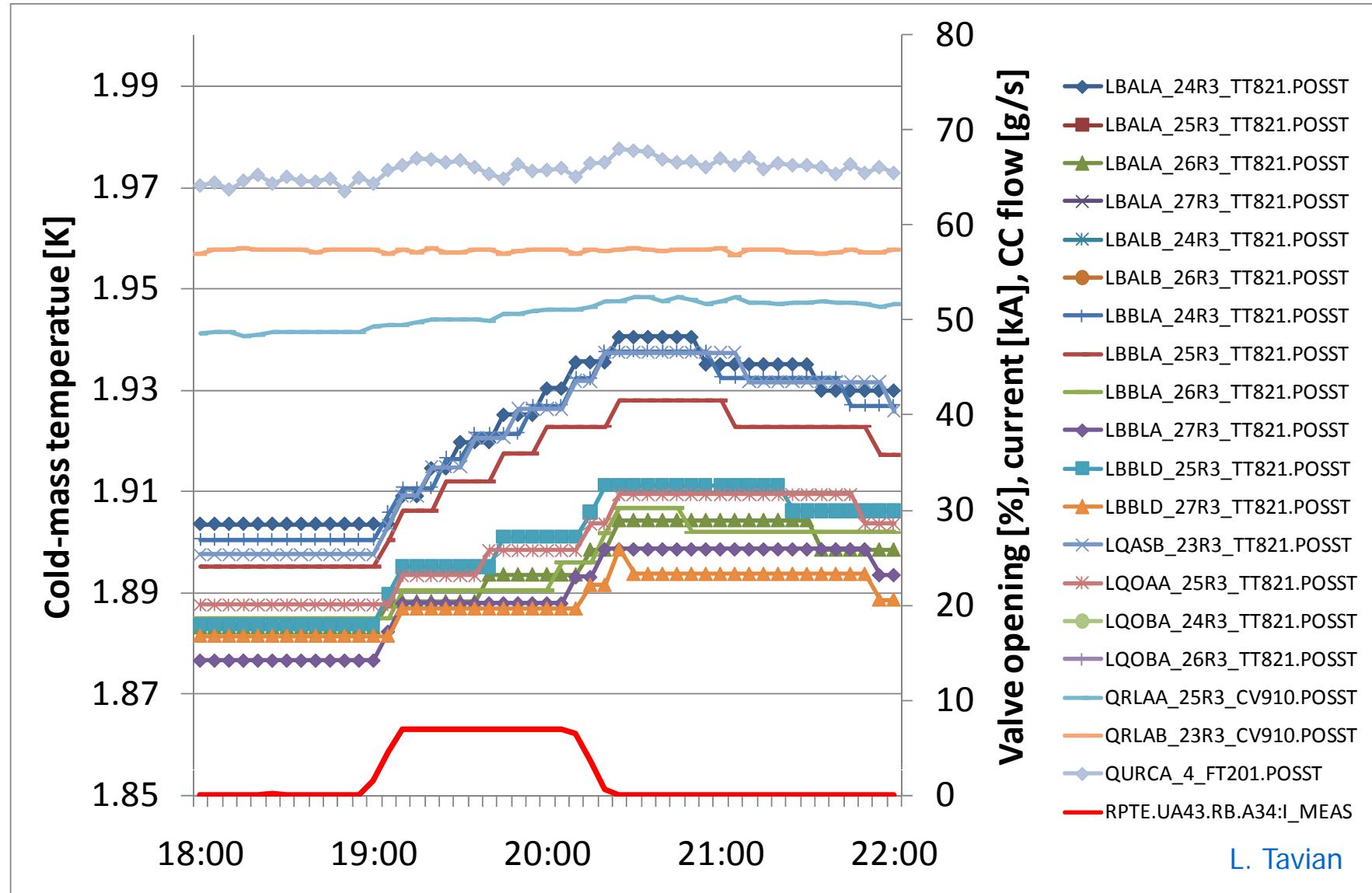
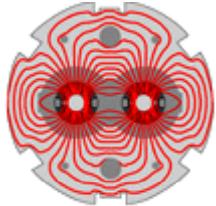
## QA of electrical joints: witness samples



P. Fessia

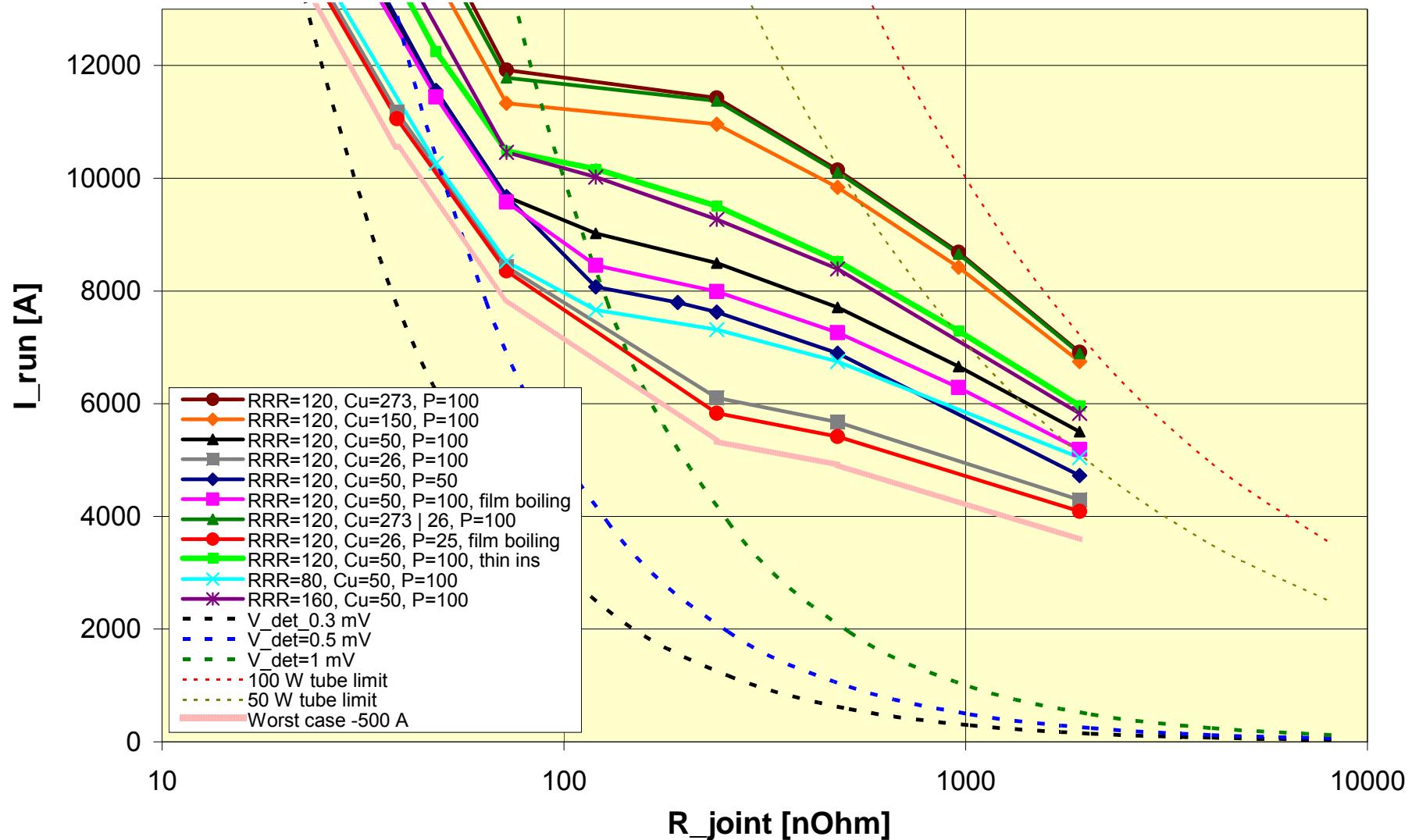
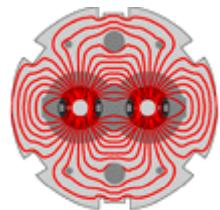


# Temperature drift during 7 kA current flat top (15 Sep 2008)





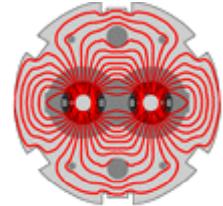
# Simulated thermal runaway threshold of electrical interconnect



A. Verweij

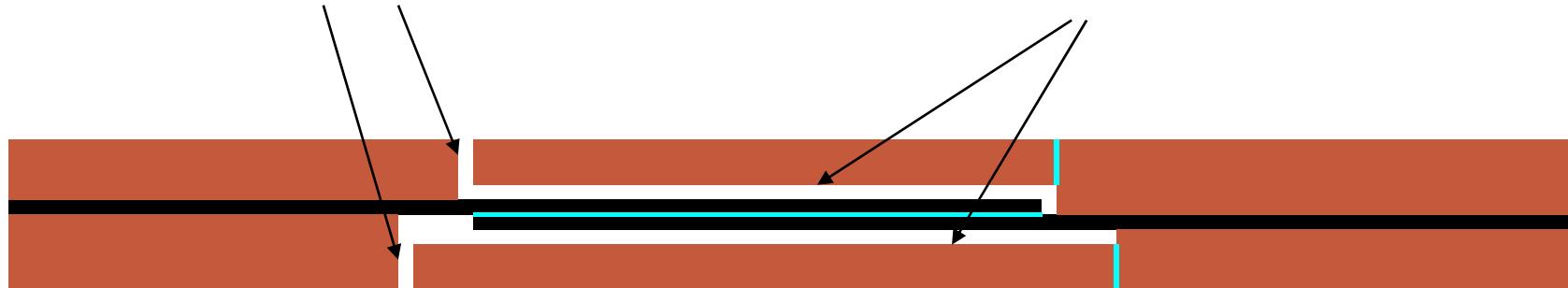


A resistive joint of about  $220 \text{ n}\Omega$  with bad electrical and thermal contacts with the stabilizer



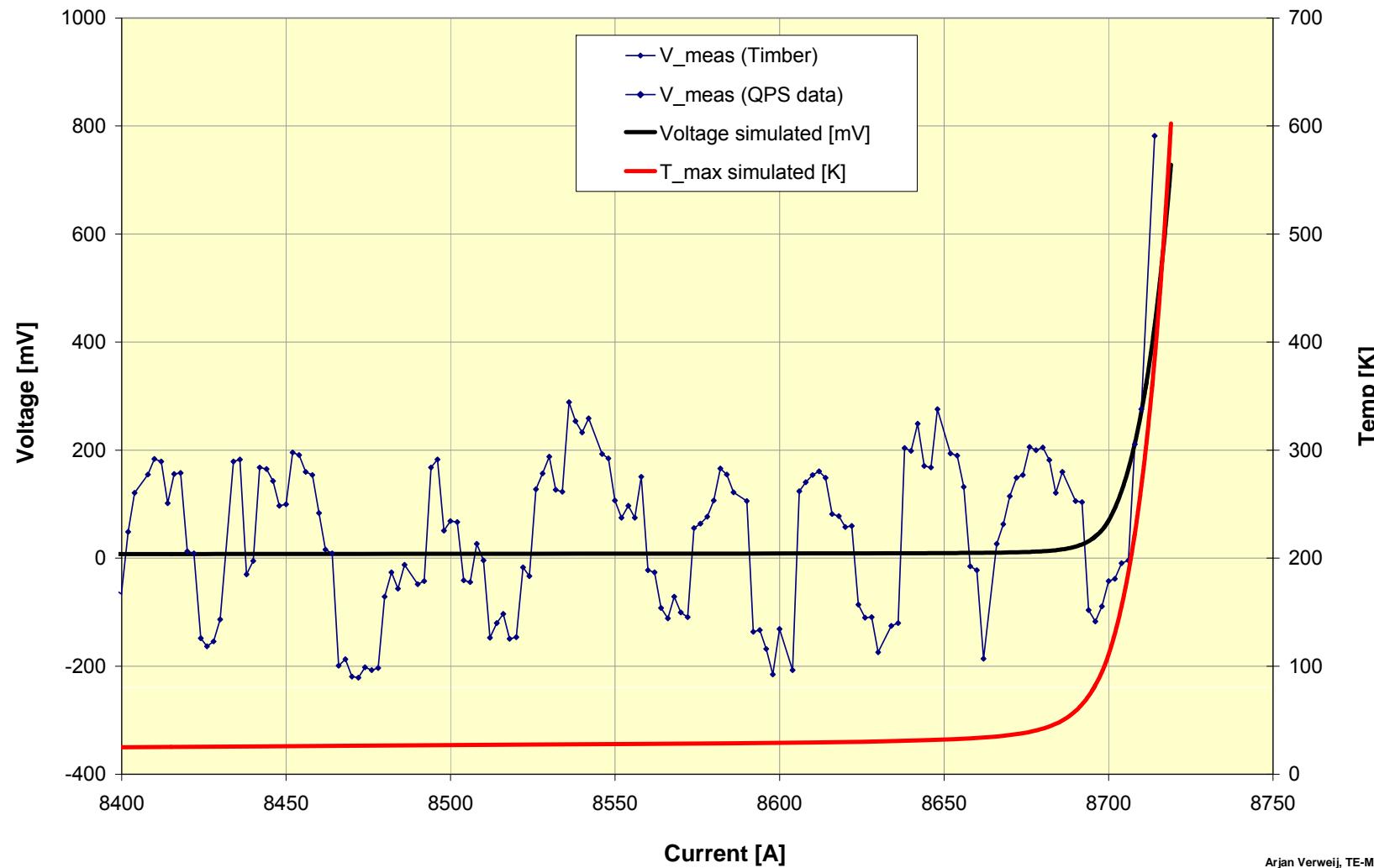
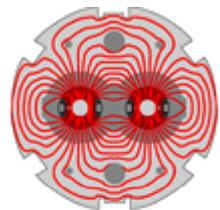
No electrical contact between wedge and U-profile with the bus on at least 1 side of the joint

No bonding at joint with the U-profile and the wedge





# Measured vs simulated incident with 220 nΩ joint and bad contact with U-profile and wedge

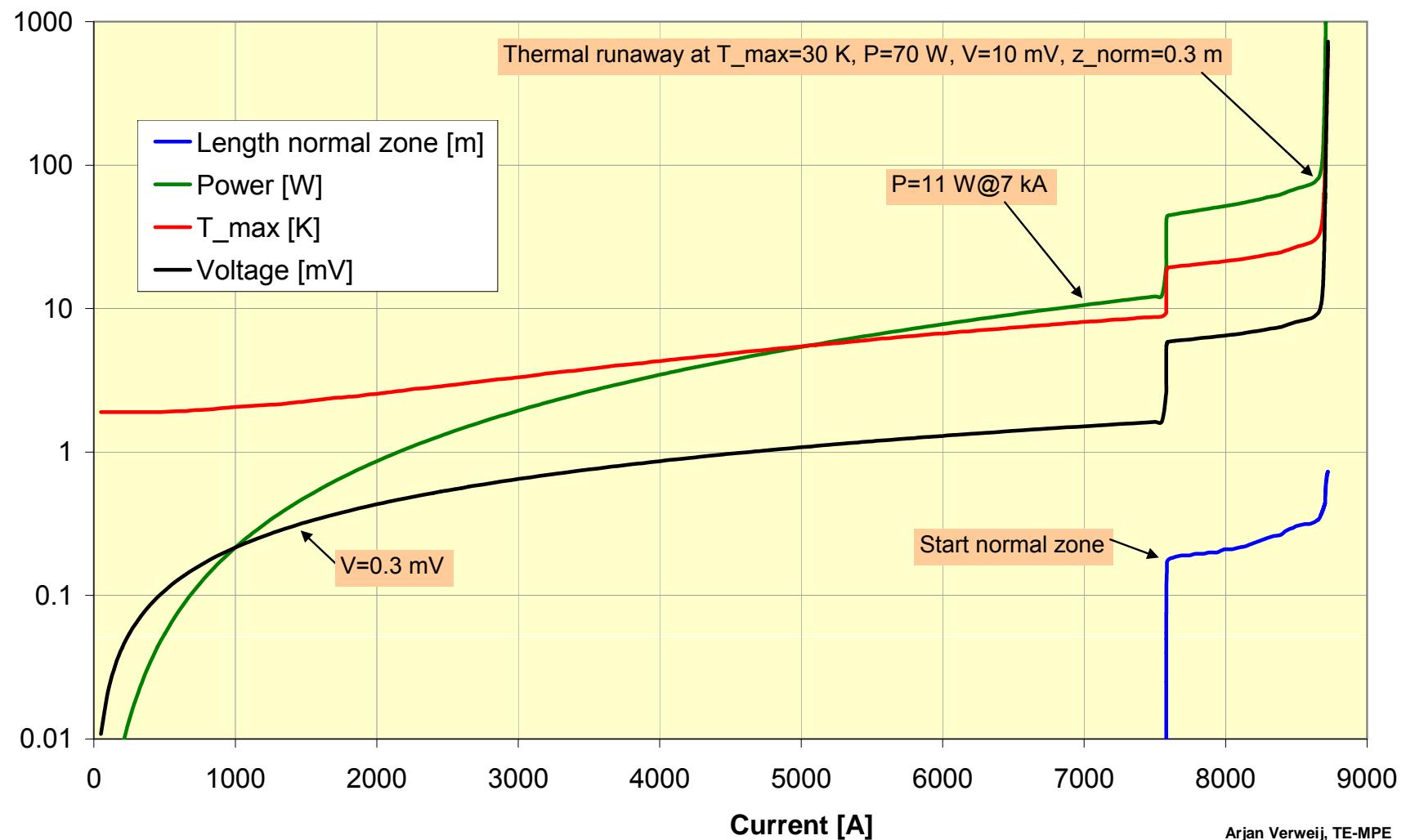
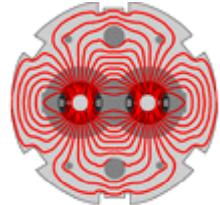


Arjan Verweij, TE-MPE

A. Verweij



# Simulation of incident with 220 n $\Omega$ joint and bad contact with U-profile and wedge

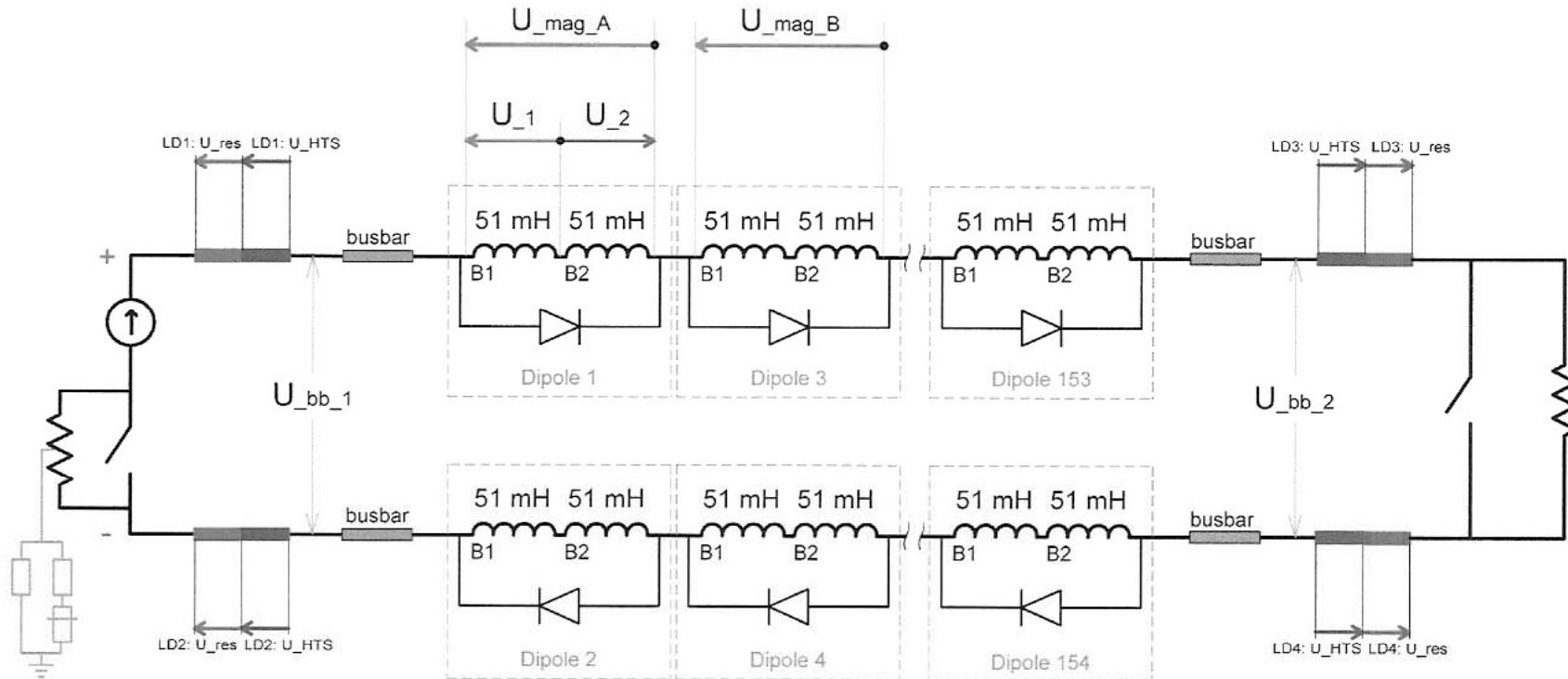
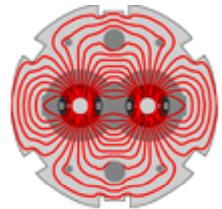


Arjan Verweij, TE-MPE

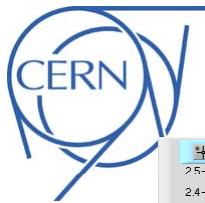
A. Verweij



# Schematic of dipole circuit in sector

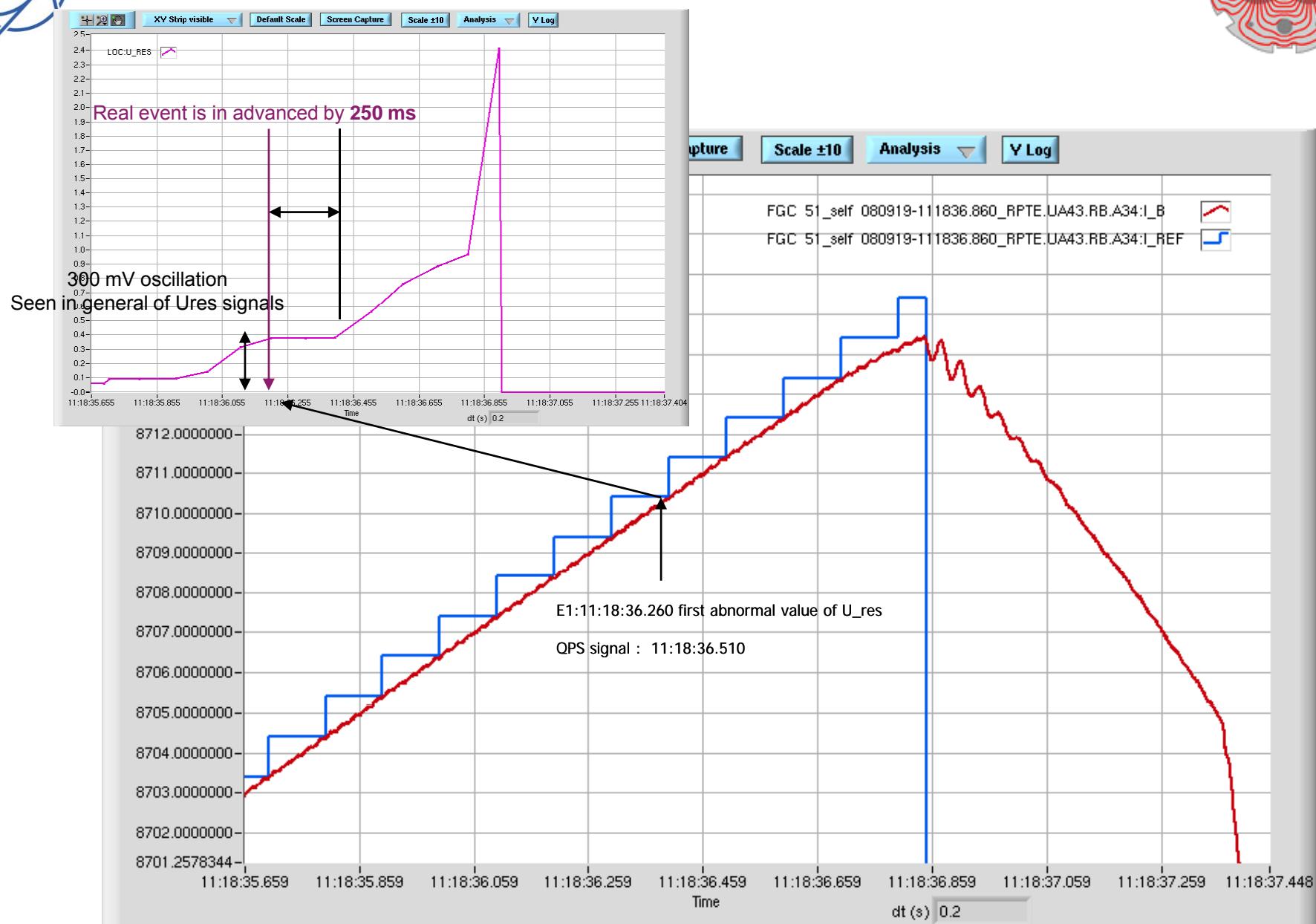
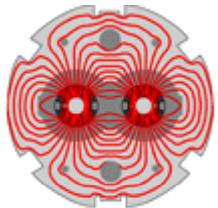


A. Siemko



# Event Nr. 1 @ 11:18:36.260

## Abnormal value of U\_res of bus bar detector

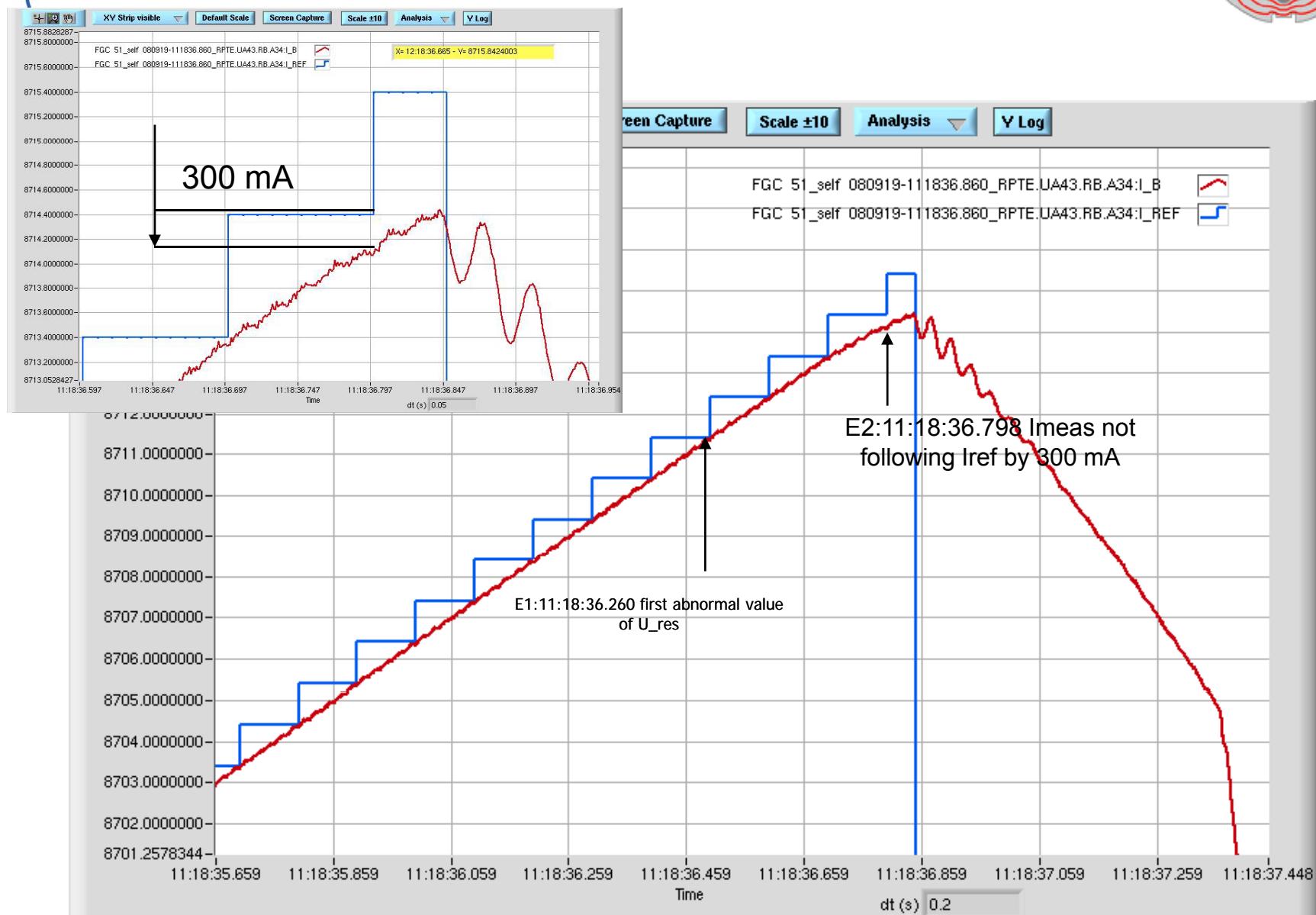
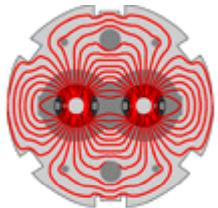


M. Bajko, N. Catalan, G. de Rijk, G. Kirby, S. Le Naour

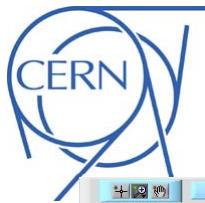


## Event Nr. 2 @ 11:18:36.798

### Imeas not following Iref by 300 mA

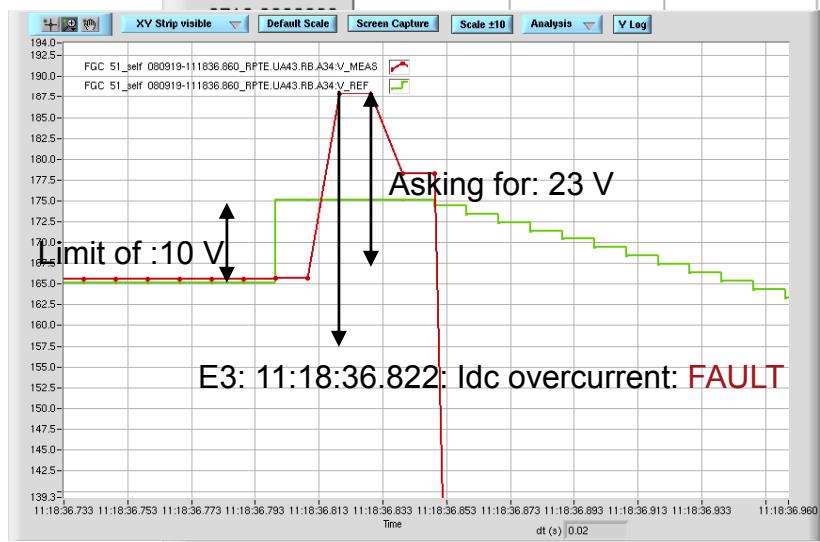
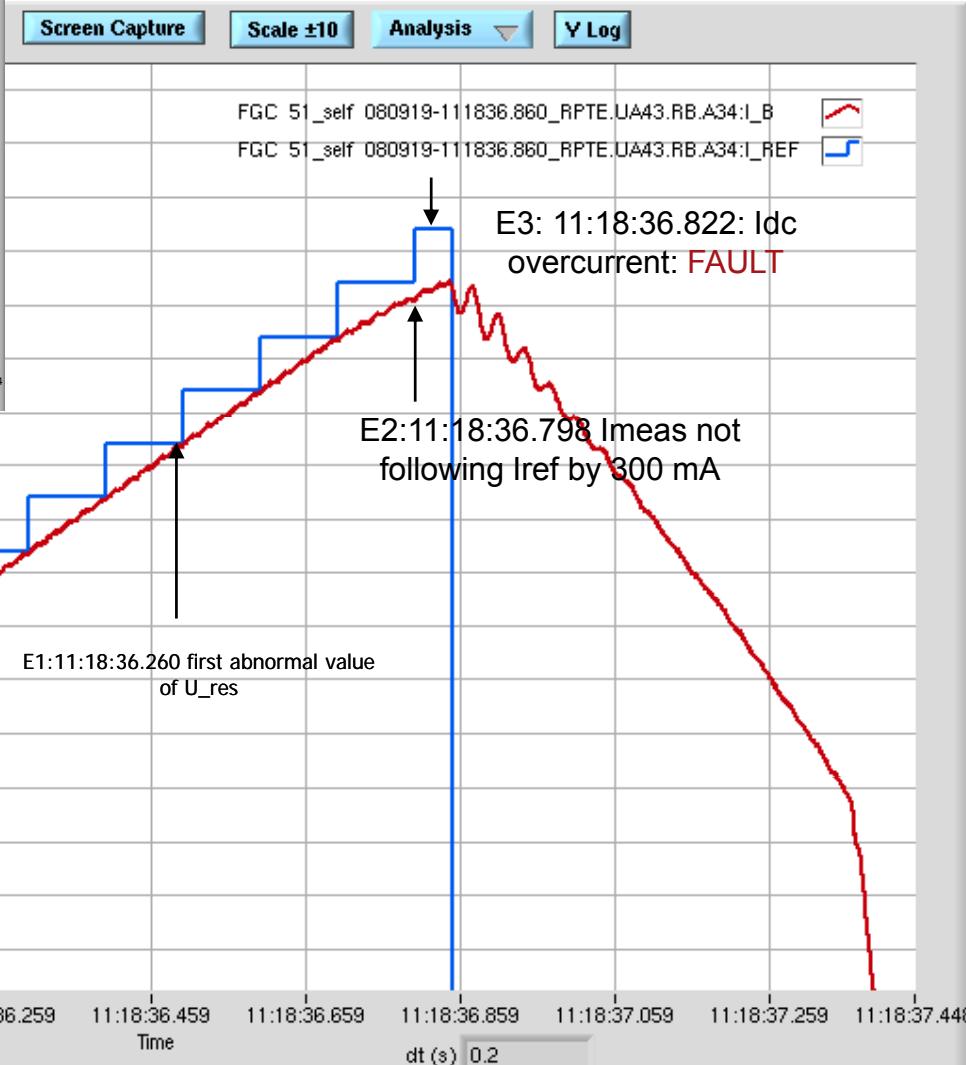
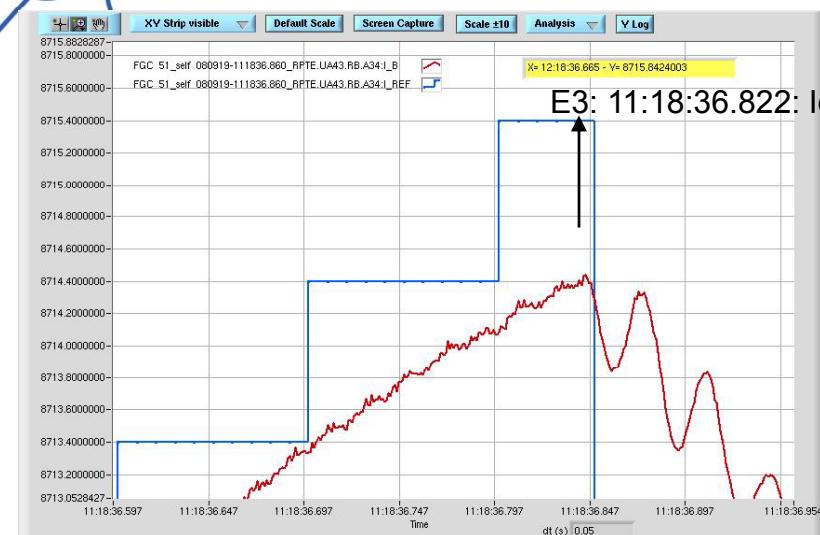
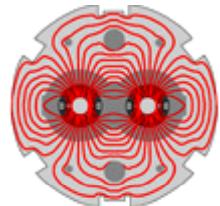


M. Bajko, N. Catalan, G. de Rijk, G. Kirby, S. Le Naour

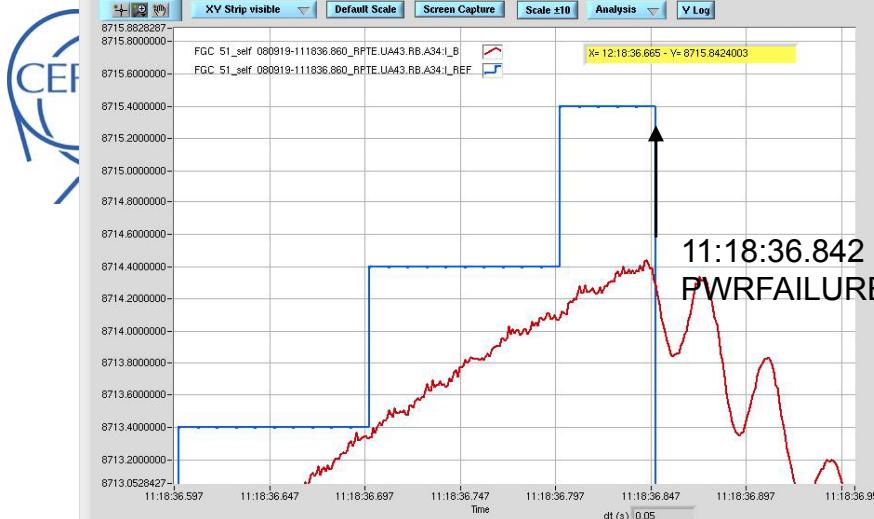


# Event Nr. 3 @ 11:18:36.822

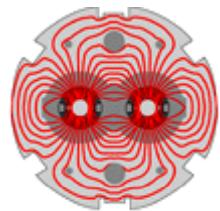
## Idc Current overflow: FAULT



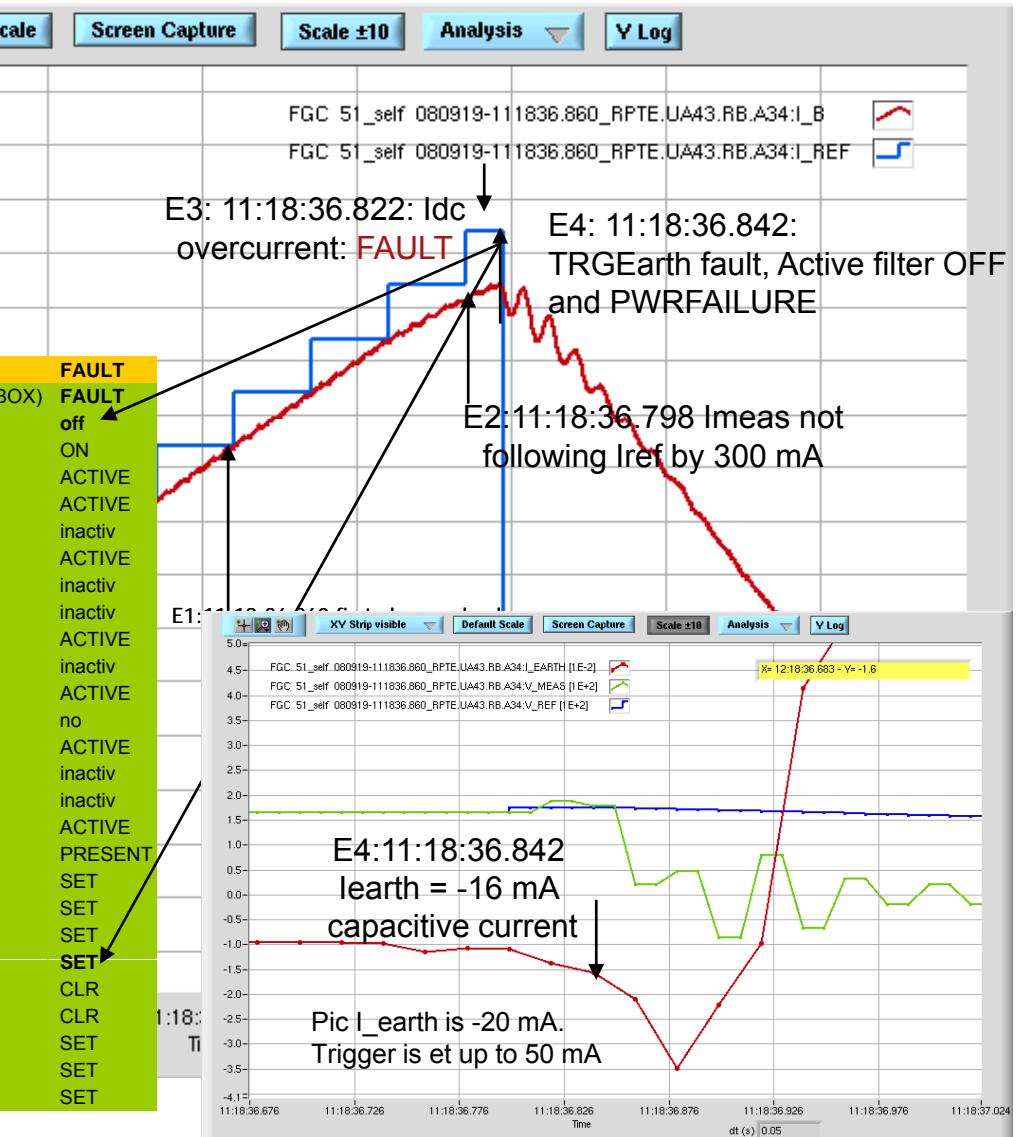
M. Bajko, N. Catalan, G. de Rijk, G. Kirby, S. Le Naour

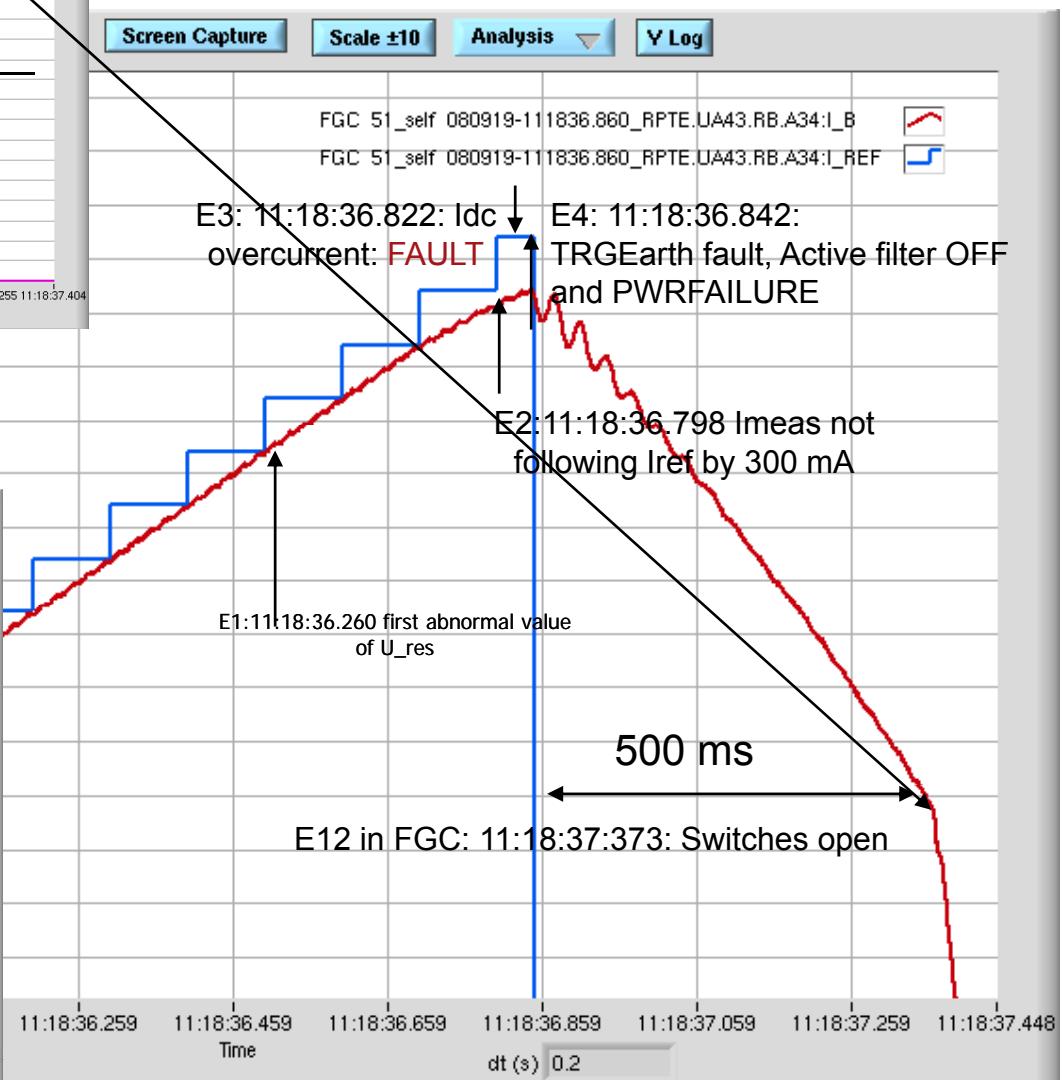
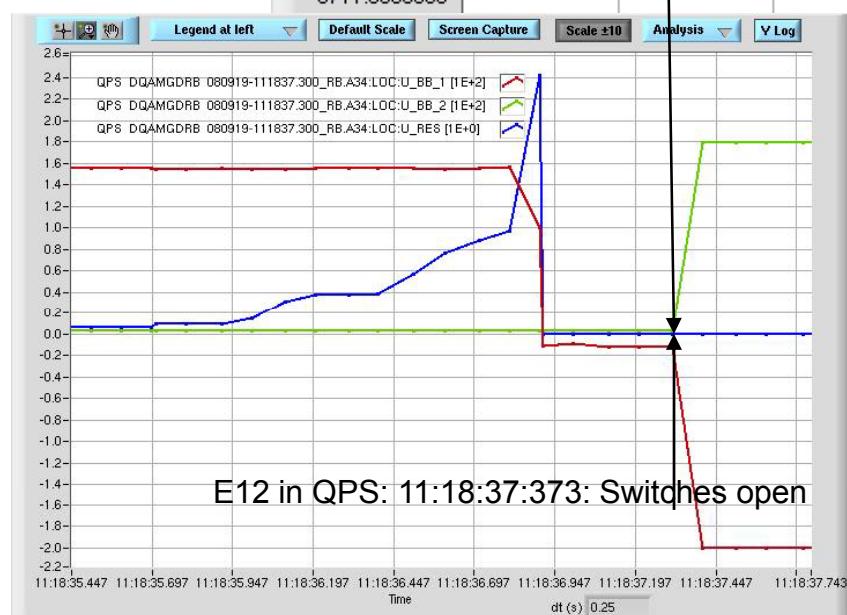


Events Nr. 4-6 @ 11:18:36.842  
TRGEARTH-Fault, Active filter off, PWRFailure

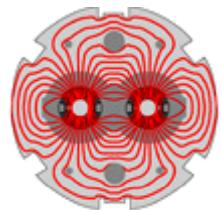


2008-09-19 11:18:36.822	DIM.AF	TRG IDC_OVER_CURRENT	FAULT
2008-09-19 11:18:36.842	DIM.VS	TRG EARTH_FAULT_(FROM_EXTERNAL_BOX)	FAULT
2008-09-19 11:18:36.842	DIM.LOOP	STA ACTIVE_FILTER	off
2008-09-19 11:18:36.842	DIM.LOOP	STA LOOP	ON
2008-09-19 11:18:36.842	DIM.LOOP	STA VLOOP_OK	ACTIVE
2008-09-19 11:18:36.842	DIM.ACT	STA MCB_ON	ACTIVE
2008-09-19 11:18:36.842	DIM.ACT	STA MCB_OFF	inactiv
2008-09-19 11:18:36.842	DIM.ACT	STA MCB_PLUG	ACTIVE
2008-09-19 11:18:36.842	DIM.ACT	STA MCB_UNPLUG	inactiv
2008-09-19 11:18:36.842	DIM.ACT	STA MCB_EARTH	inactiv
2008-09-19 11:18:36.842	DIM.ACT	STA MCB_NOT_EARTH	ACTIVE
2008-09-19 11:18:36.842	DIM.ACT	STA PREMAG_ON	inactiv
2008-09-19 11:18:36.842	DIM.ACT	STA PREMAG_OFF	ACTIVE
2008-09-19 11:18:36.842	DIM.ACT	STA DCCT_ZERO_CURRENT	no
2008-09-19 11:18:36.842	DIM.ACT	STA INSULATION_SWITCH_IN	ACTIVE
2008-09-19 11:18:36.842	DIM.ACT	STA INSULATION_SWITCH_OUT	inactiv
2008-09-19 11:18:36.842	DIM.ACT	STA INSULATION_SWITCH_EARTH	inactiv
2008-09-19 11:18:36.842	DIM.ACT	STA INSULATION_SWITCH_BLOCKED	ACTIVE
2008-09-19 11:18:36.842	DIM.ACT	STA ACTIVE_FILTER	PRESNET
2008-09-19 11:18:36.842	STATE.PC	FLT_STOPPING	SET
2008-09-19 11:18:36.842	VS.STATE	VS_INVALID	SET
2008-09-19 11:18:36.842	DIG.STATUS	VSFAULT	SET
2008-09-19 11:18:36.842	DIG.STATUS	PWRFailure	SET
2008-09-19 11:18:36.842	DIG.STATUS	VSRUN	CLR
2008-09-19 11:18:36.842	DIG.COMMANDS	VSRUN_CMD	CLR
2008-09-19 11:18:36.842	DEVICEFAULTS	VS_FAULT	SET
2008-09-19 11:18:36.842	FGC.ST_UNLATCHED	PWR_FAILURE	SET
2008-09-19 11:18:36.842	FGC.ST_UNLATCHED	POST_MORTEM	SET



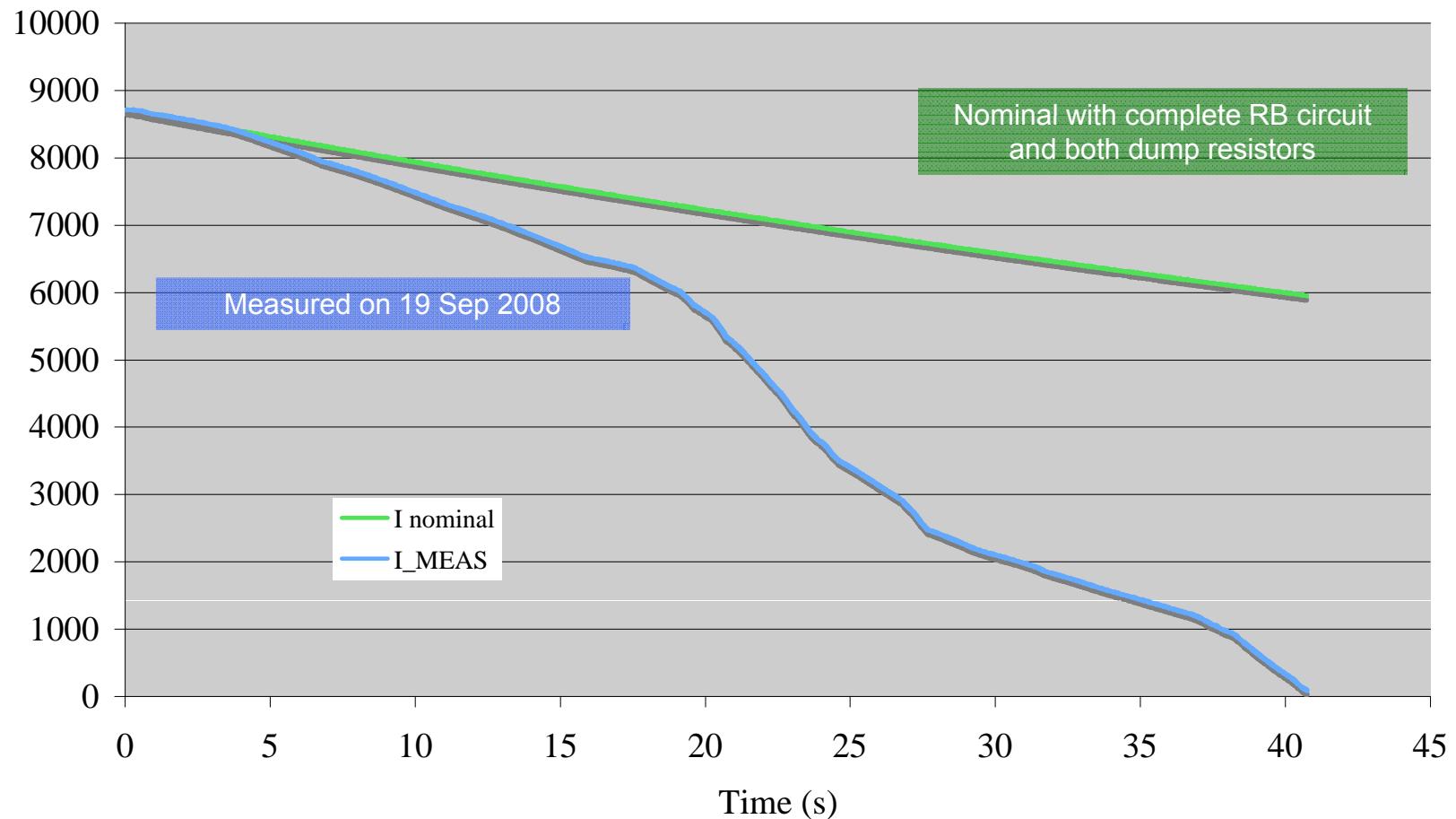
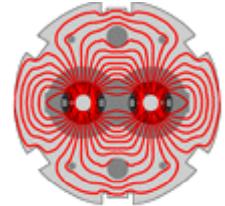


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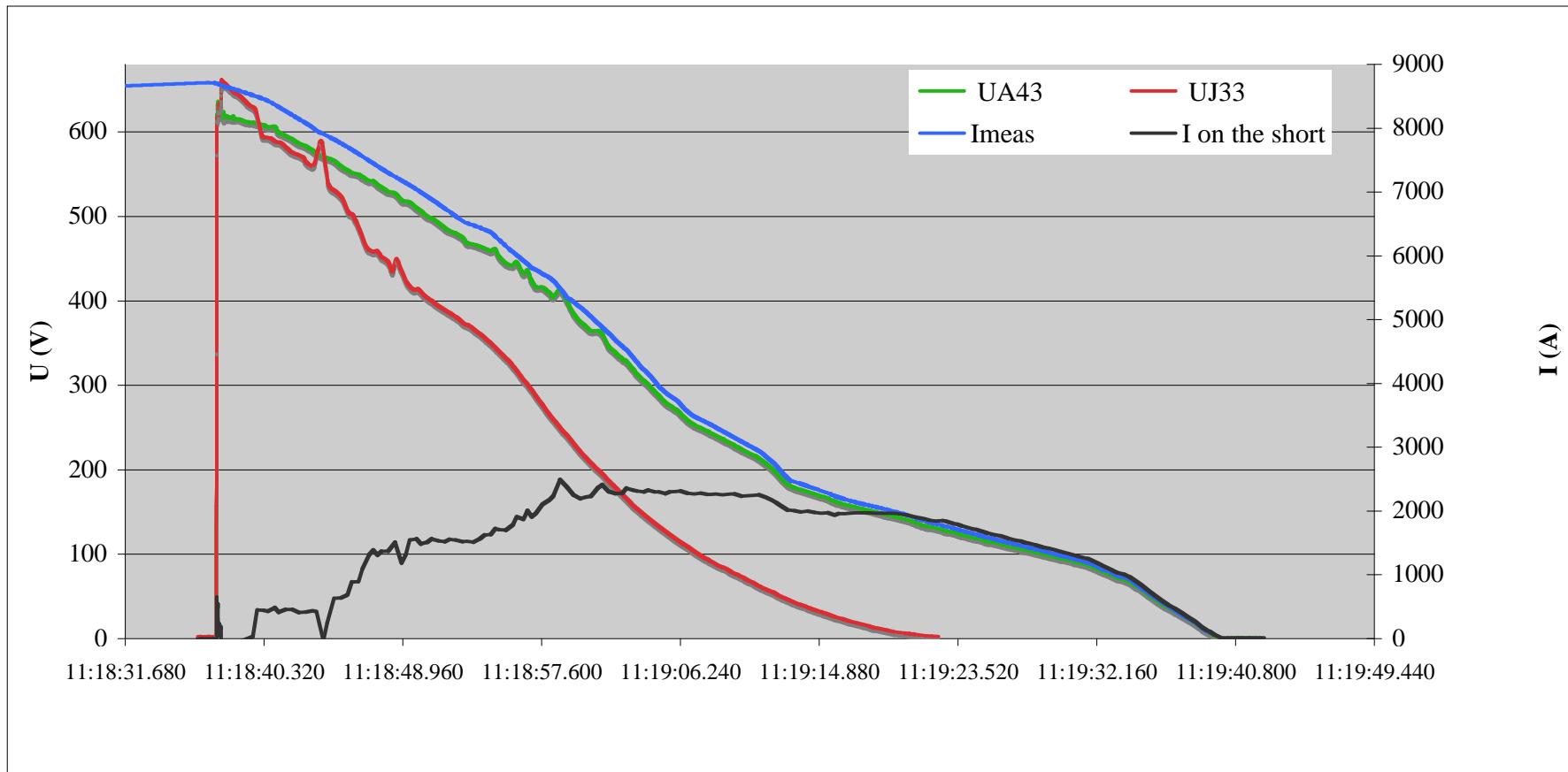
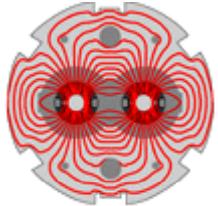


# Current decay in dipole circuit from 8.7 kA



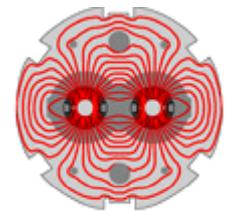
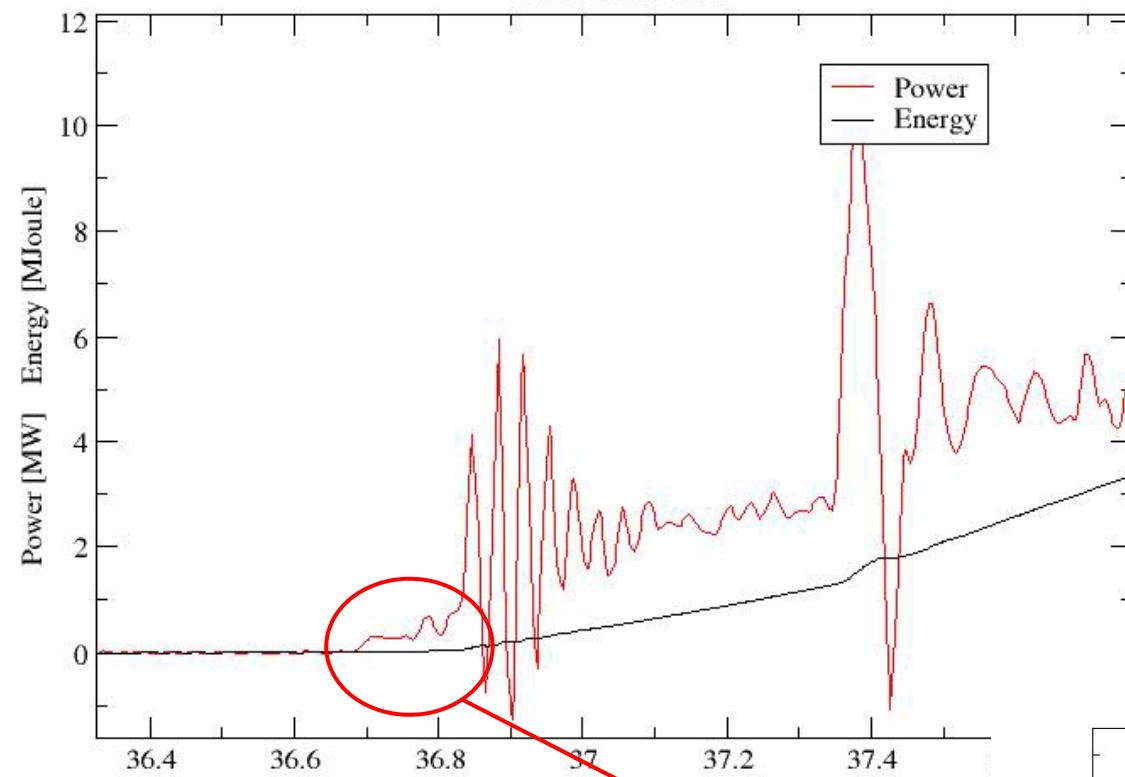


# Decay of current in sub-circuits measured at DCCT & dump resistors on UJ33 and UA43



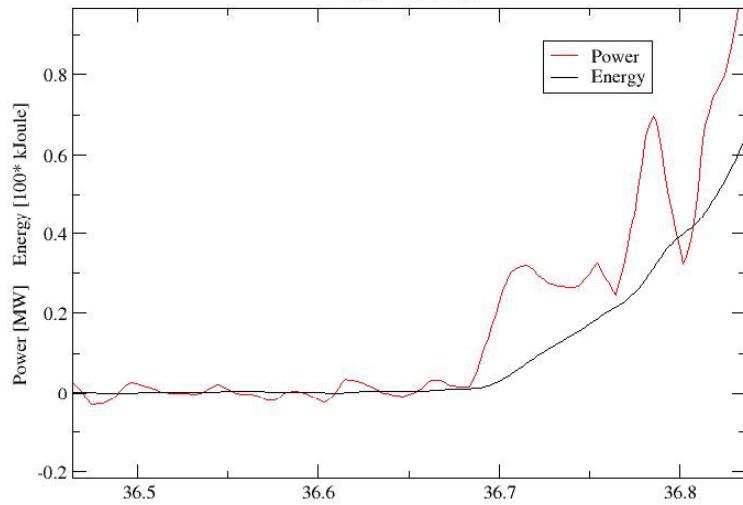
## Estimated Power dissipation by the arc

Based on PC data



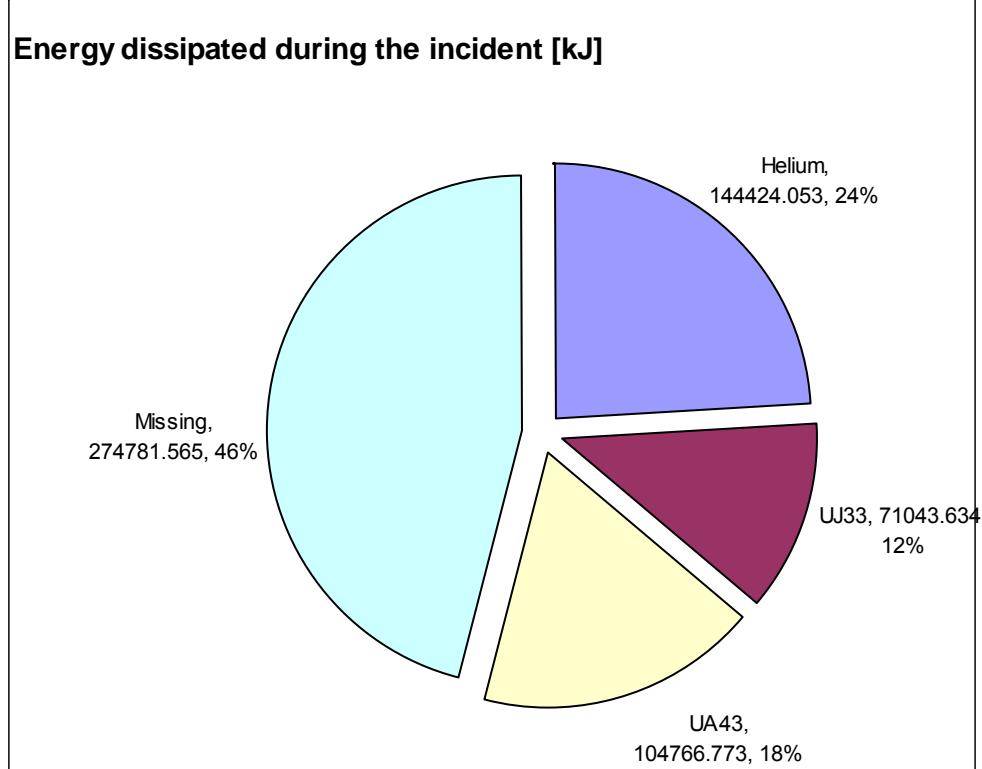
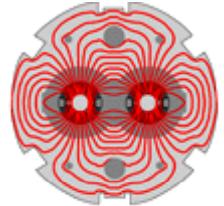
## Estimated Power dissipation by the arc

Based on PC data





# Energy balance in dipole circuit

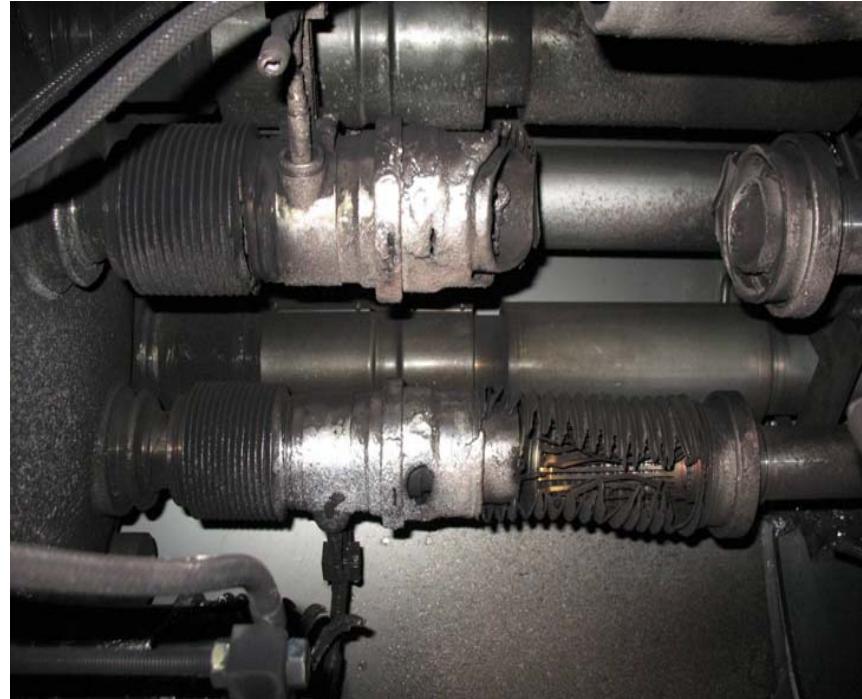
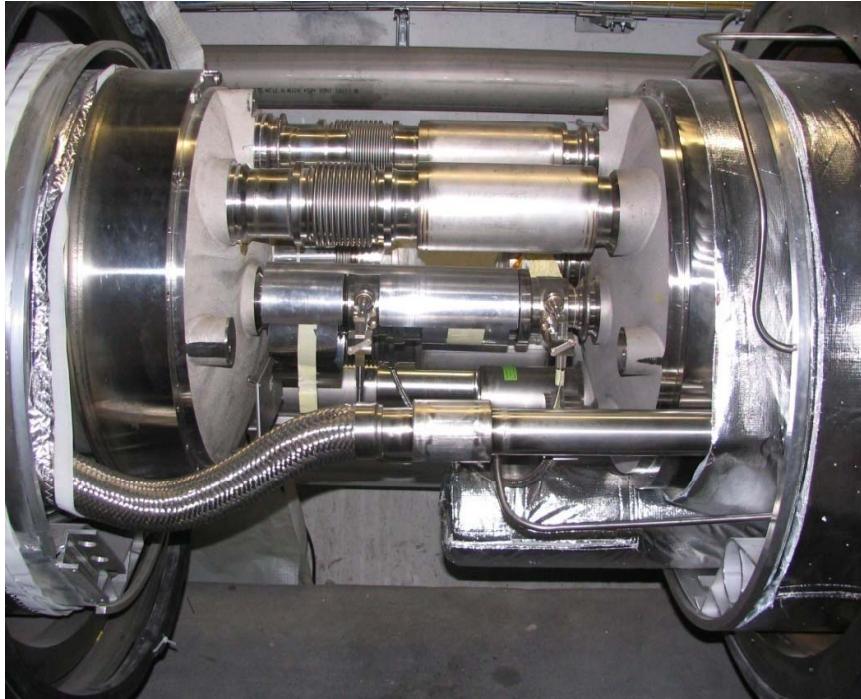
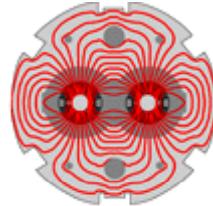


Energy	MJ	%
Stored in the magnets	595.0	100
Dissipated in UJ33	71.0	12
Dissipated in UA43	104.8	18
Dissipated in cold mass	144.4	24
Dissipated in electrical arcs	274.8	46

N. Catalan, S. Le Naour

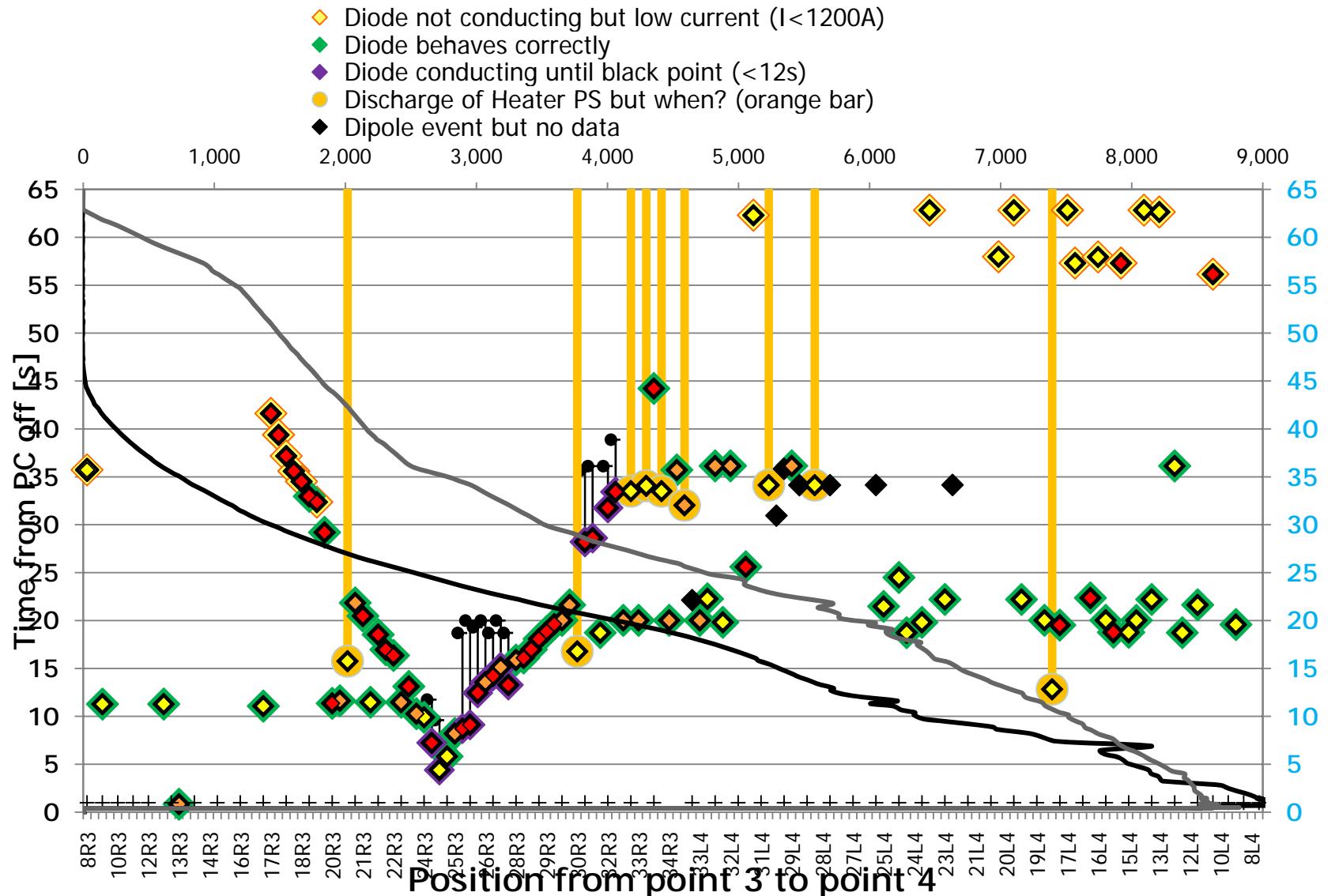
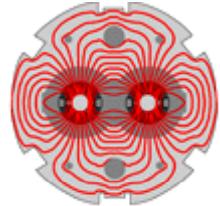


## Electrical arc between two magnets





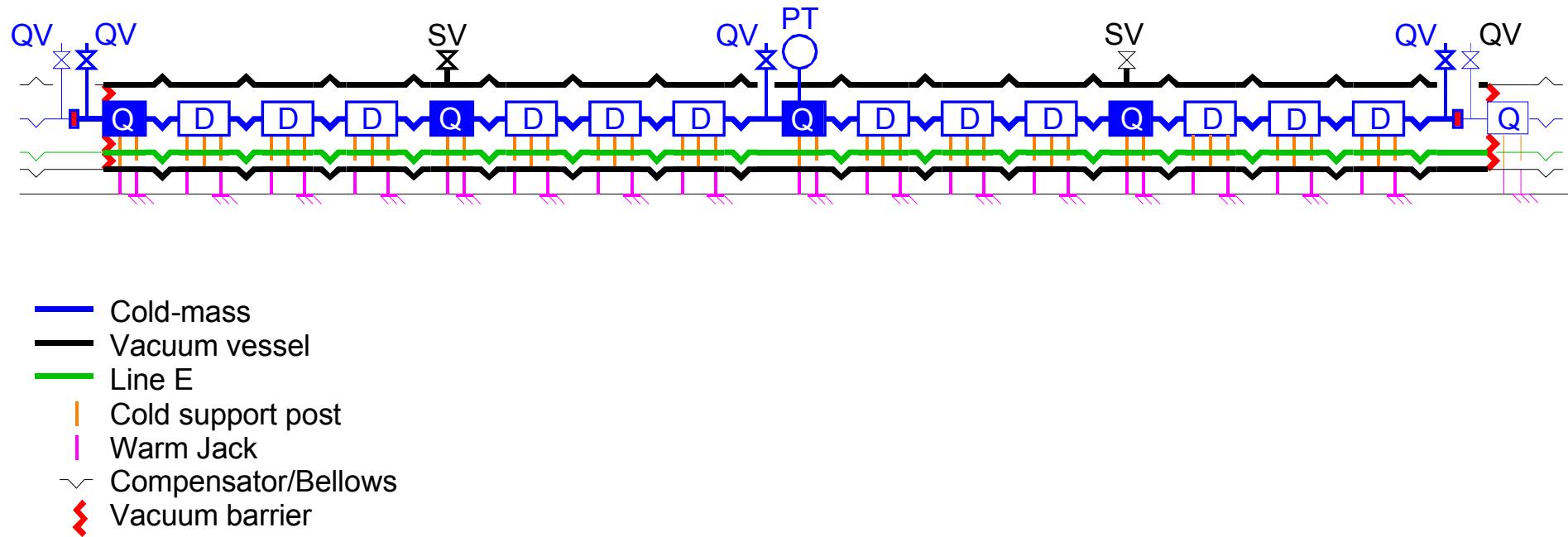
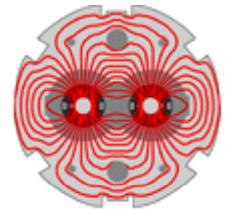
# Long-distance propagation of quenches and quench triggers



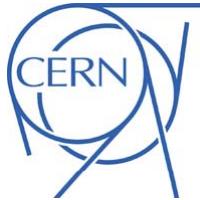
S. Le Naour



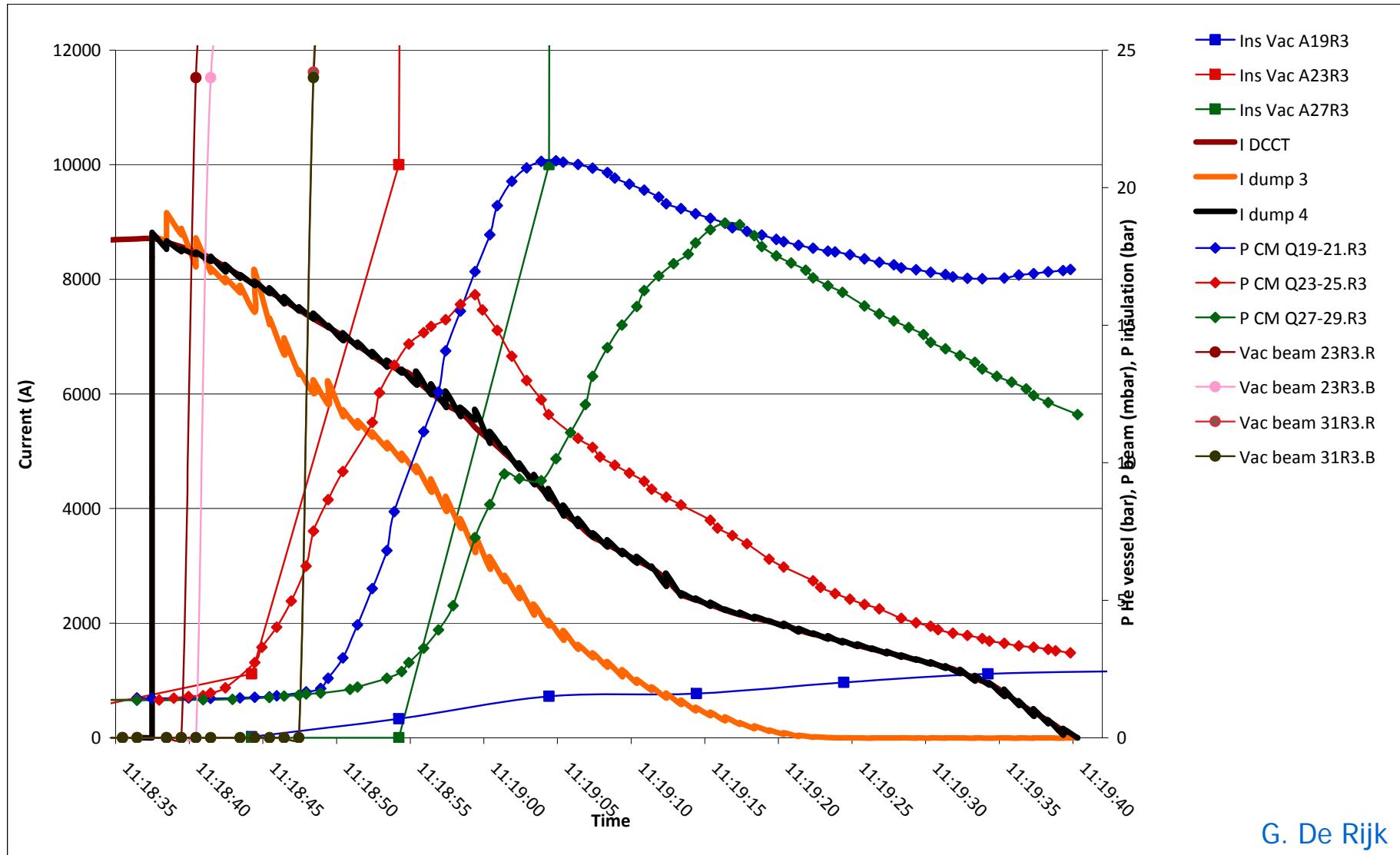
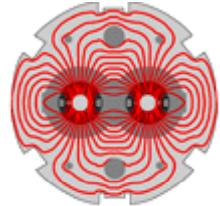
## Simplified scheme of a sub-sector



- Cold-mass
- Vacuum vessel
- Line E
- Cold support post
- Warm Jack
- Compensator/Bellows
- Vacuum barrier



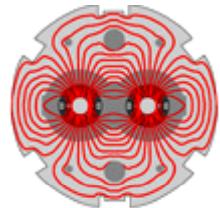
# Development of pressure in helium, insulation vacuum and beam vacuum enclosures



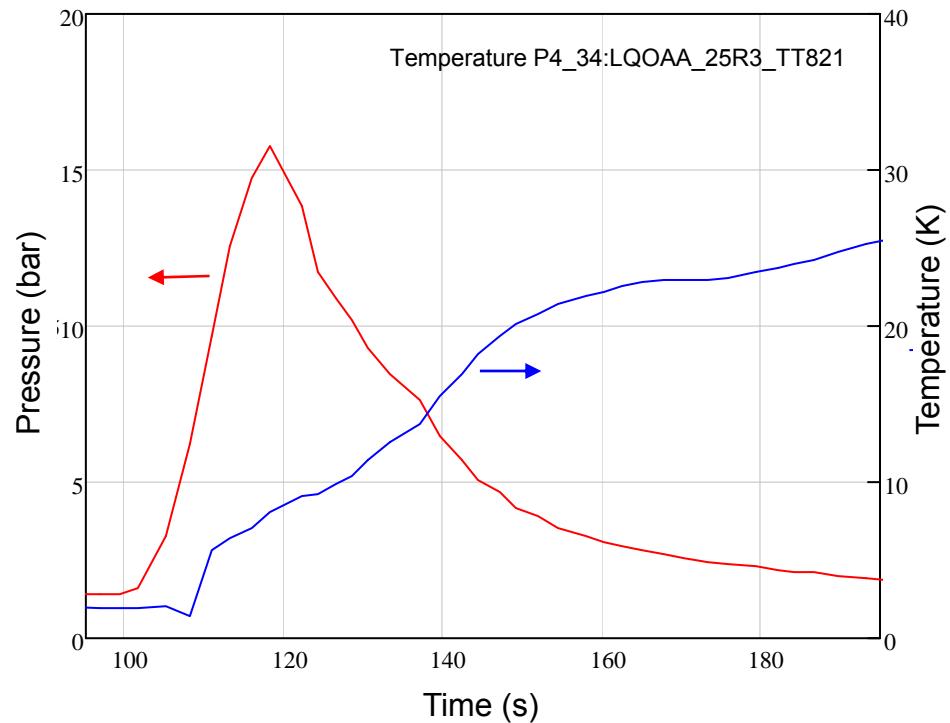
G. De Rijk



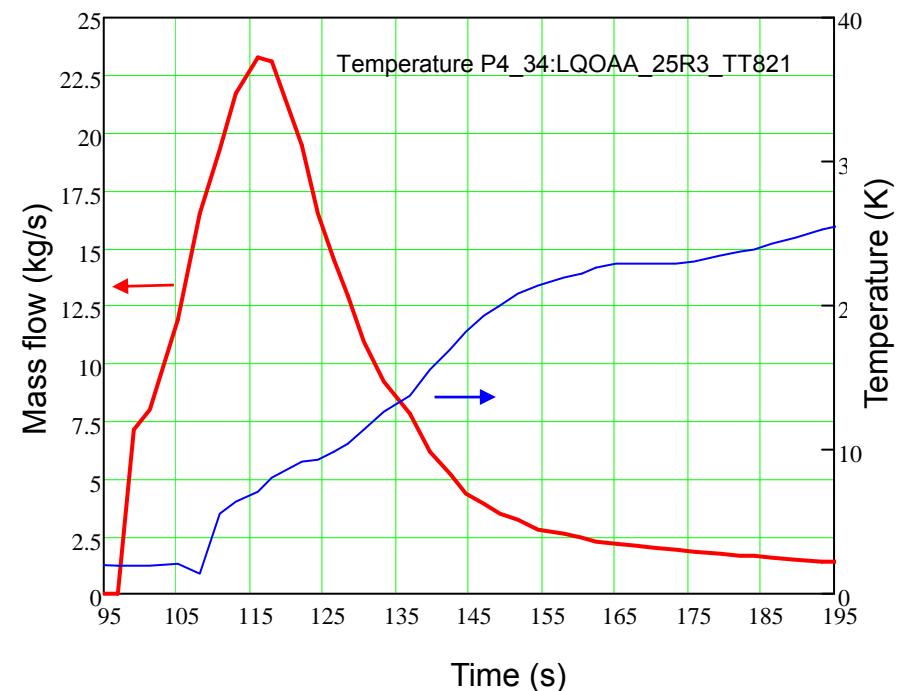
# Estimation of helium discharge from cold mass



Recorded data



Estimated mass flow



## Hypothesis:

Helium temperature given by sensor P4\_34:LQOAA\_25R3\_TT821

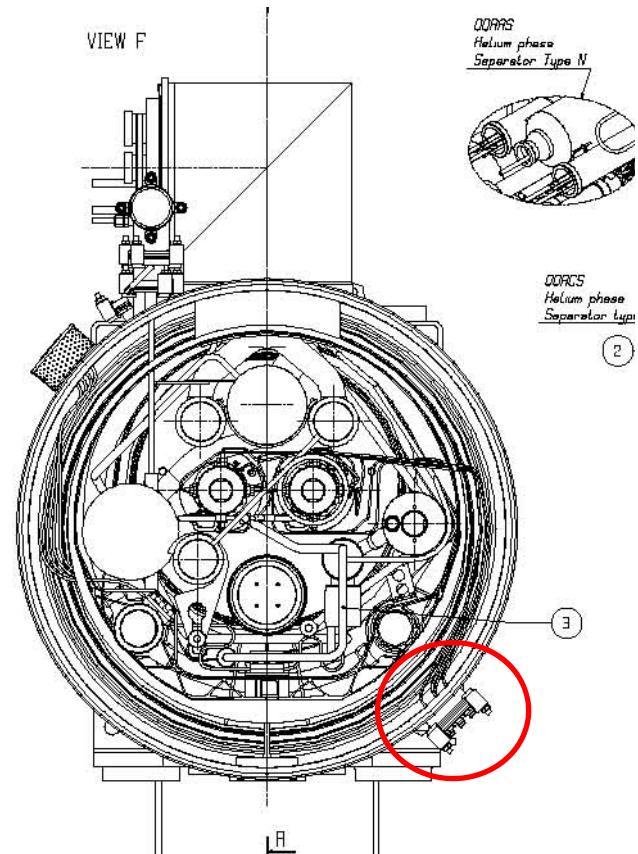
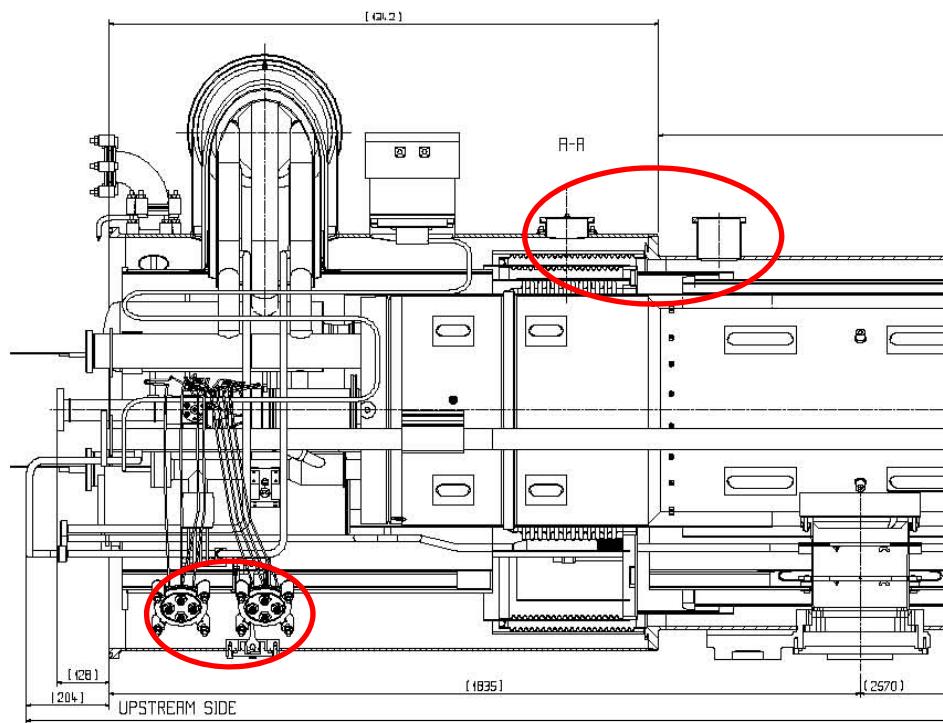
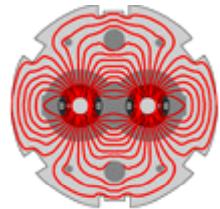
All helium discharged through 1 hole. No plug major failure.

Constant hydraulic diameter 54 mm

Total mass of helium =  $214 \text{ m} \times 0.026 \text{ m}^3/\text{m} \times 147.8 \text{ kg/m}^3 = 822 \text{ kg}$

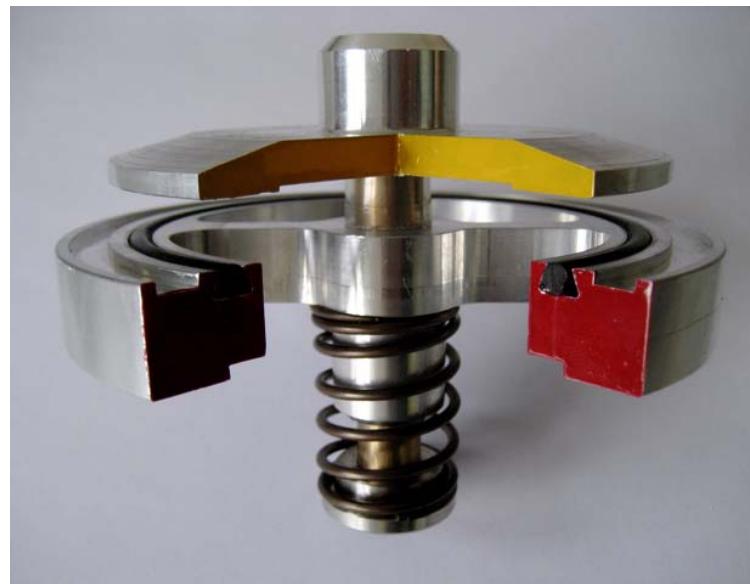
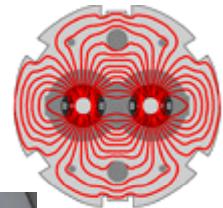


## Existing ports on SSS vacuum enclosure





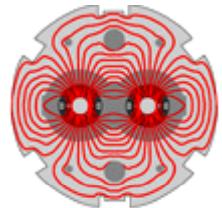
## Relief device on insulation vacuum enclosure



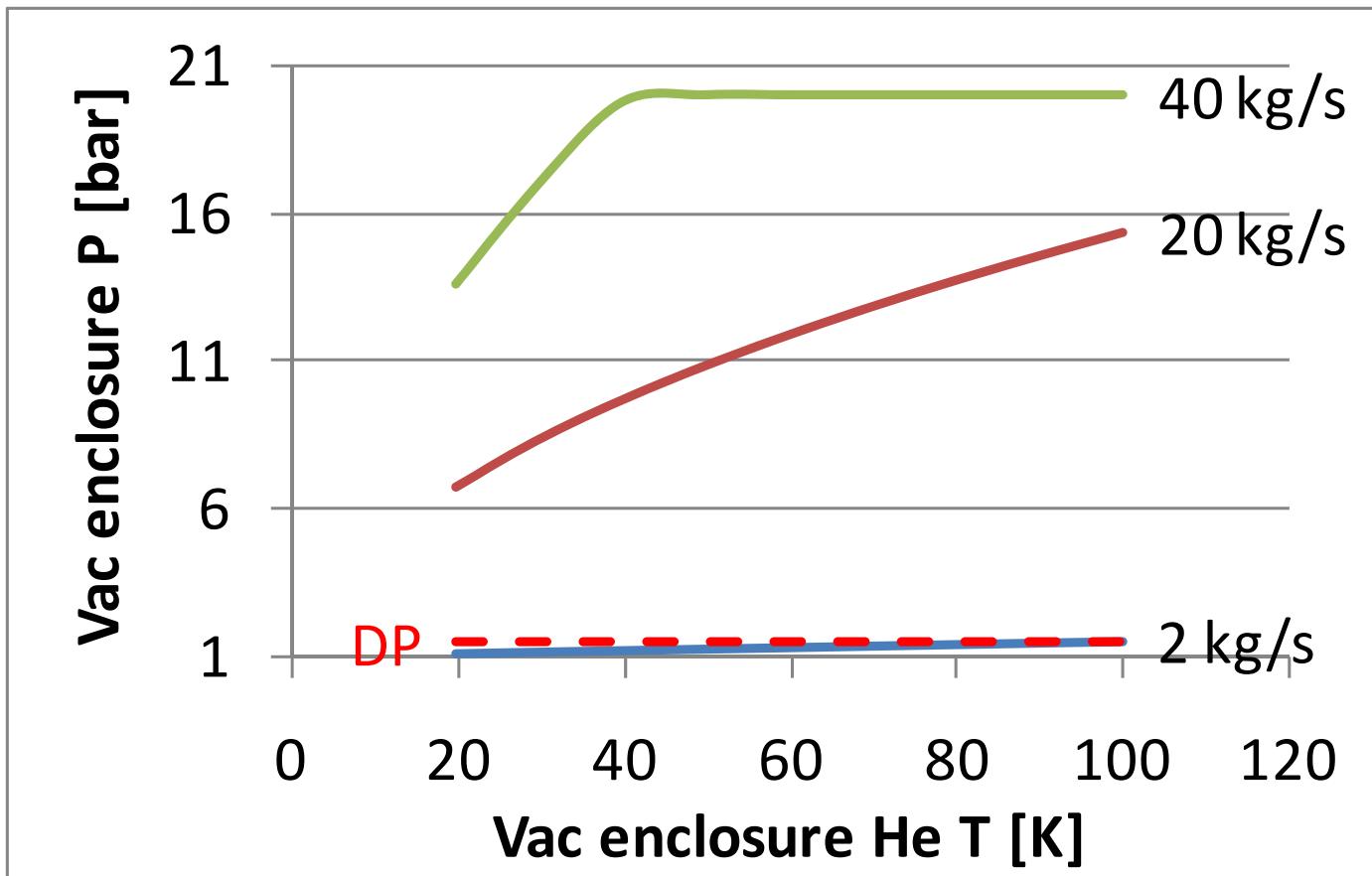
P. Cruikshank



# Flow discharge characteristics of relief devices on insulation vacuum enclosure (per sub-sector)



Present configuration: 2 DN90

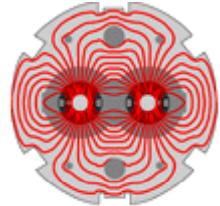


(DP: Design Pressure)

L. Tavian



# Assessment of maximum pressure in insulation vacuum enclosure from deformation of W sleeve



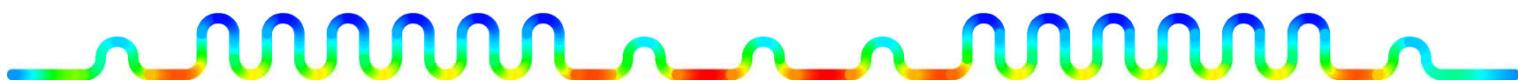
Corrugated sleeve of 1 mm thick AISI 316 L

Yield stress 275 MPa

Nominal diameter 1016 mm

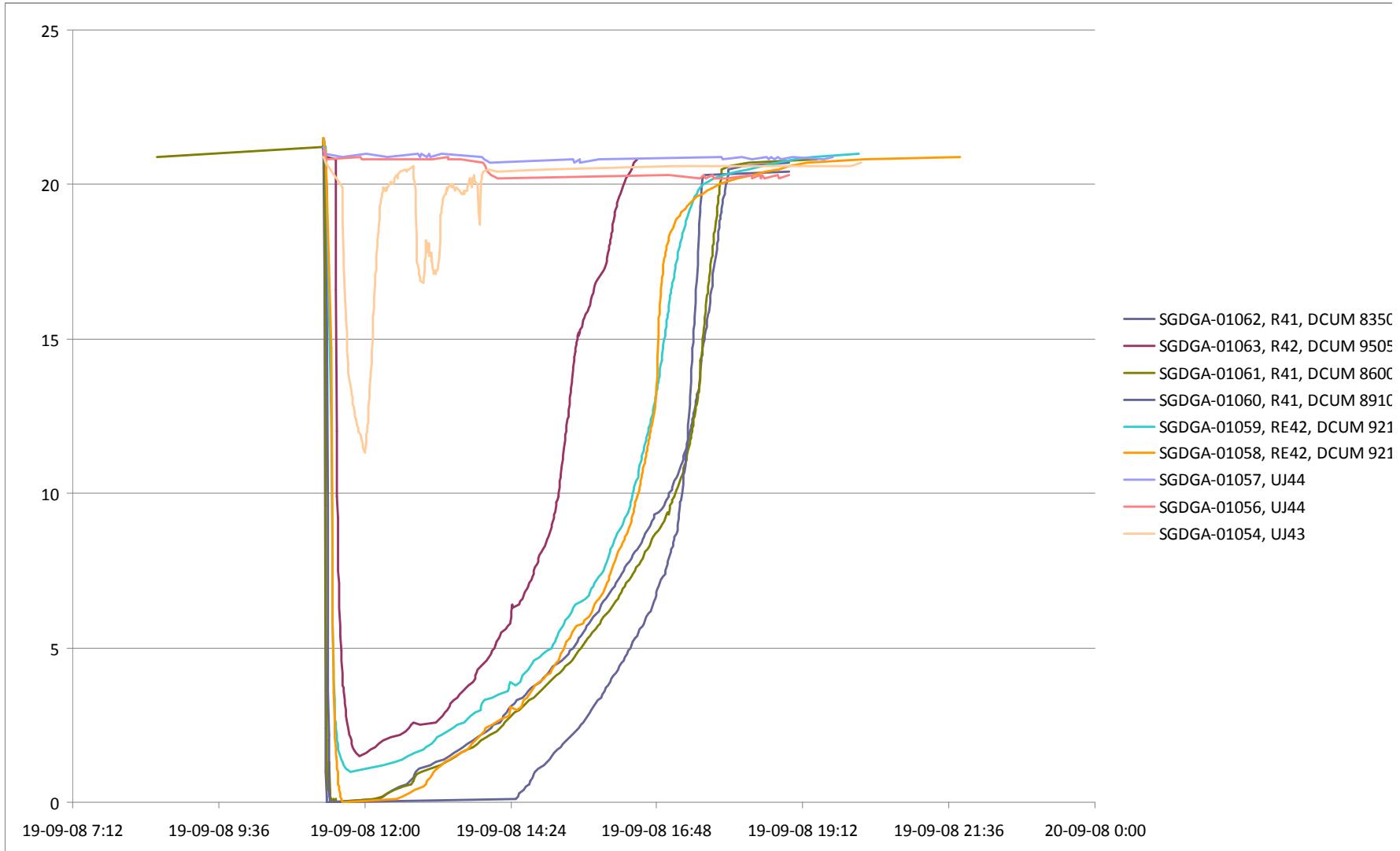
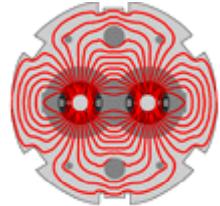
Maximum diameter 1055 mm

FE calculation in large displacement case  
(iterative geometry) gives 7 bar overpressure

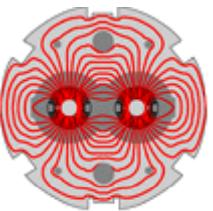
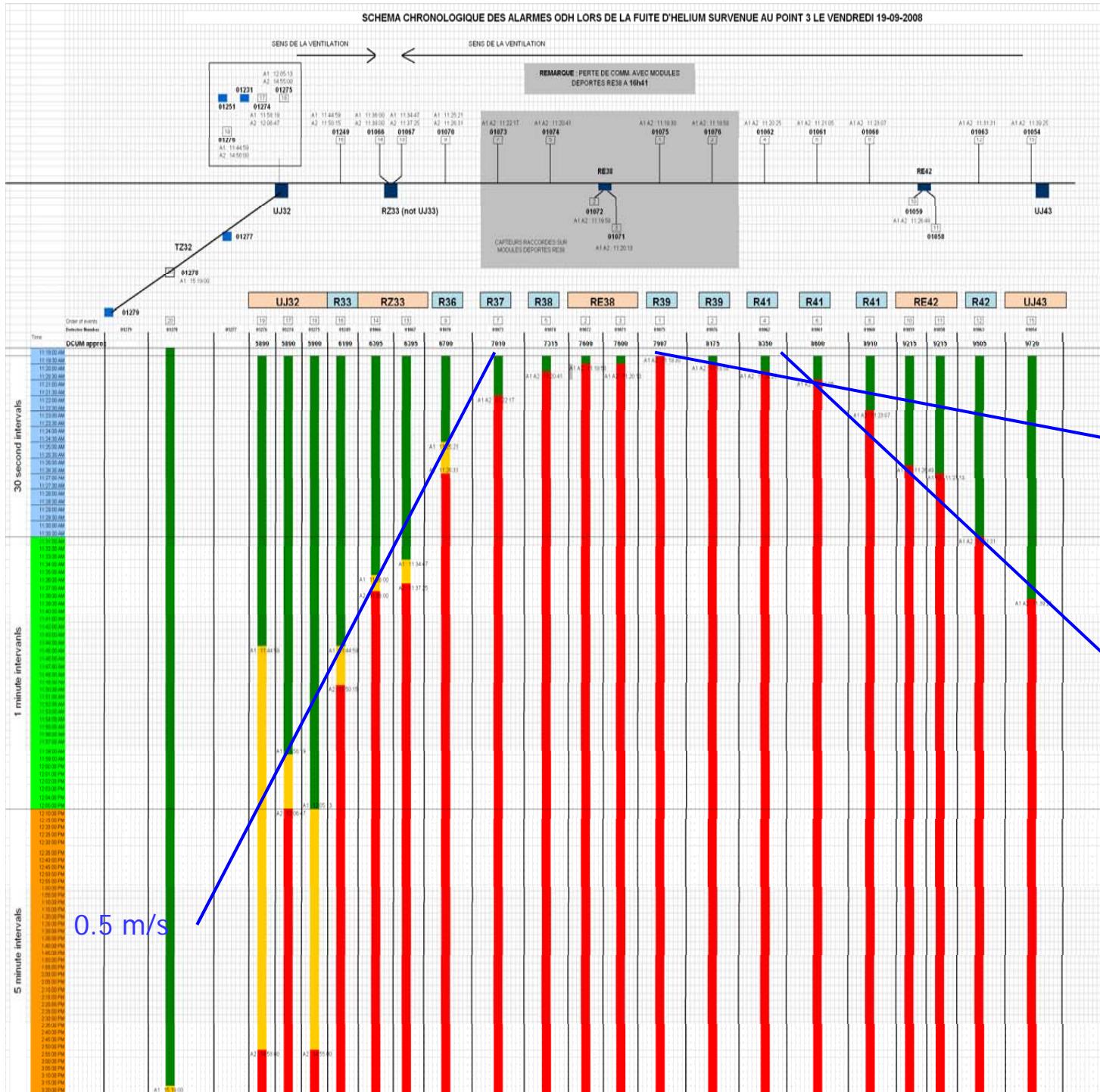
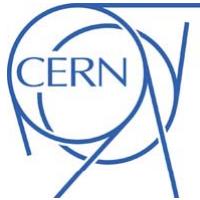




# Oxygen content [%] in tunnel (at ceiling)



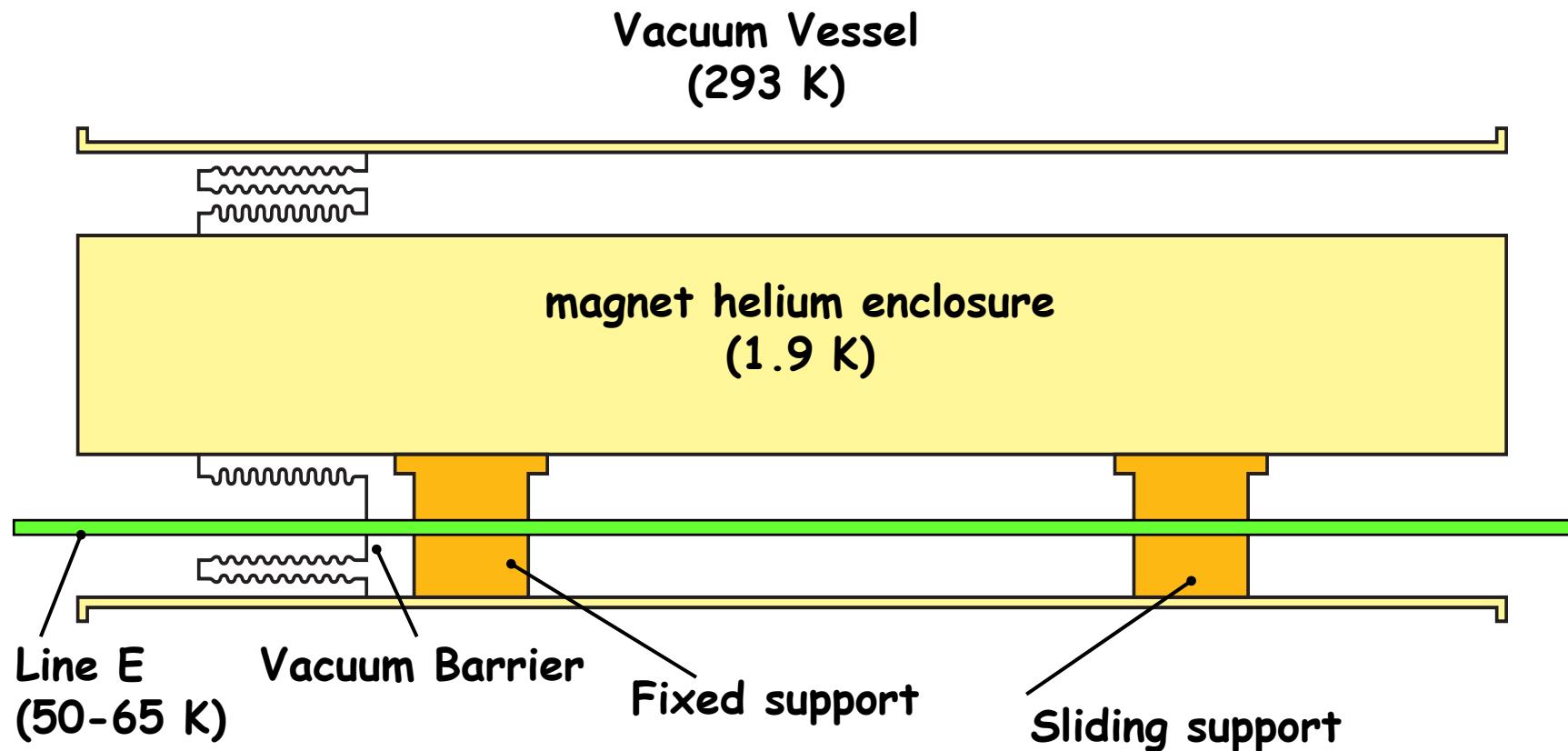
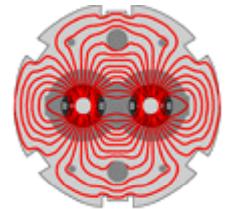
R. Nunes



R. Nunes

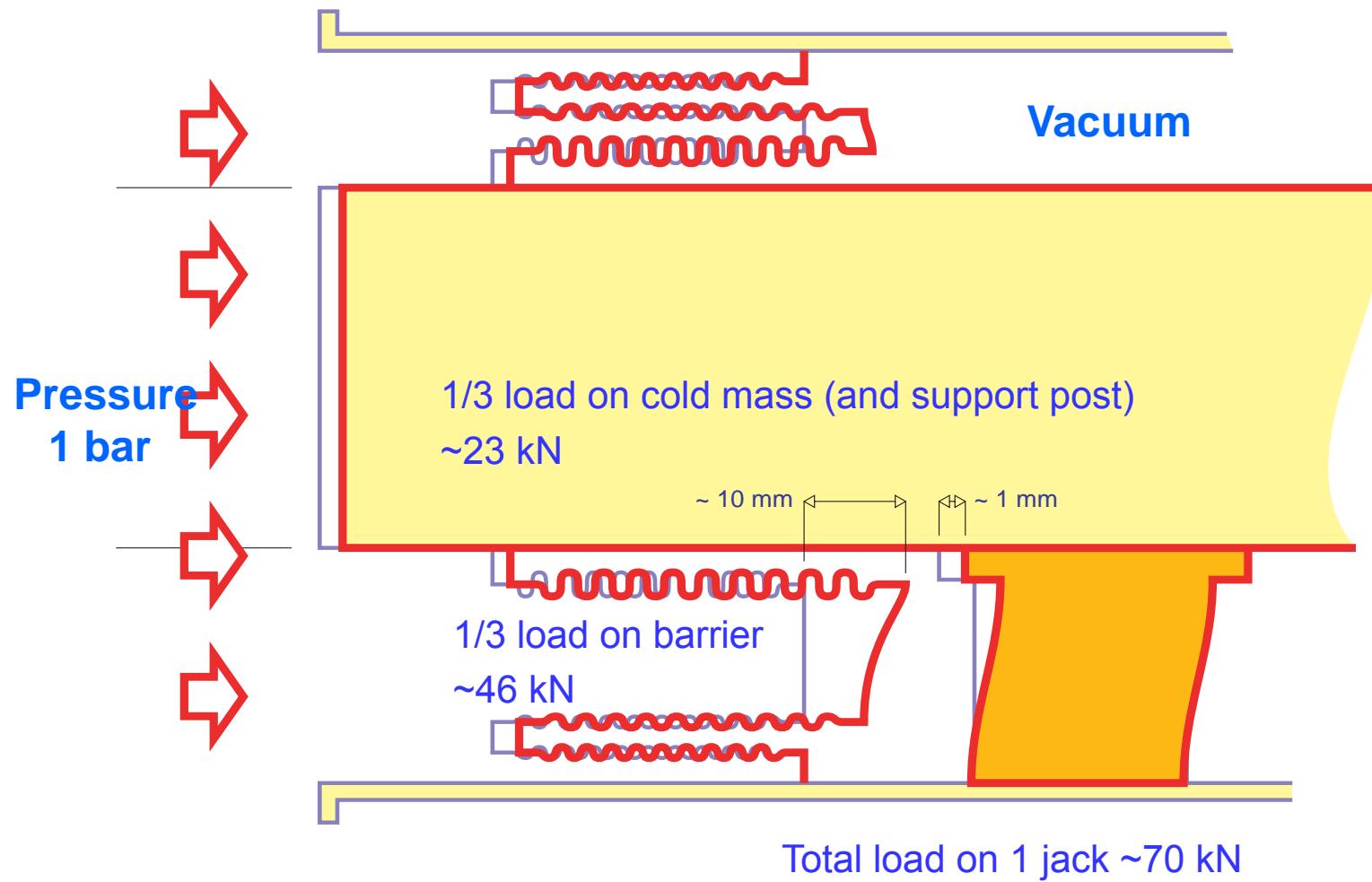
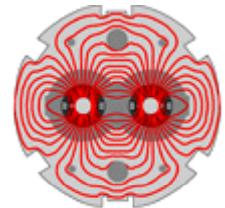


# Simplified scheme of SSS with vacuum barrier



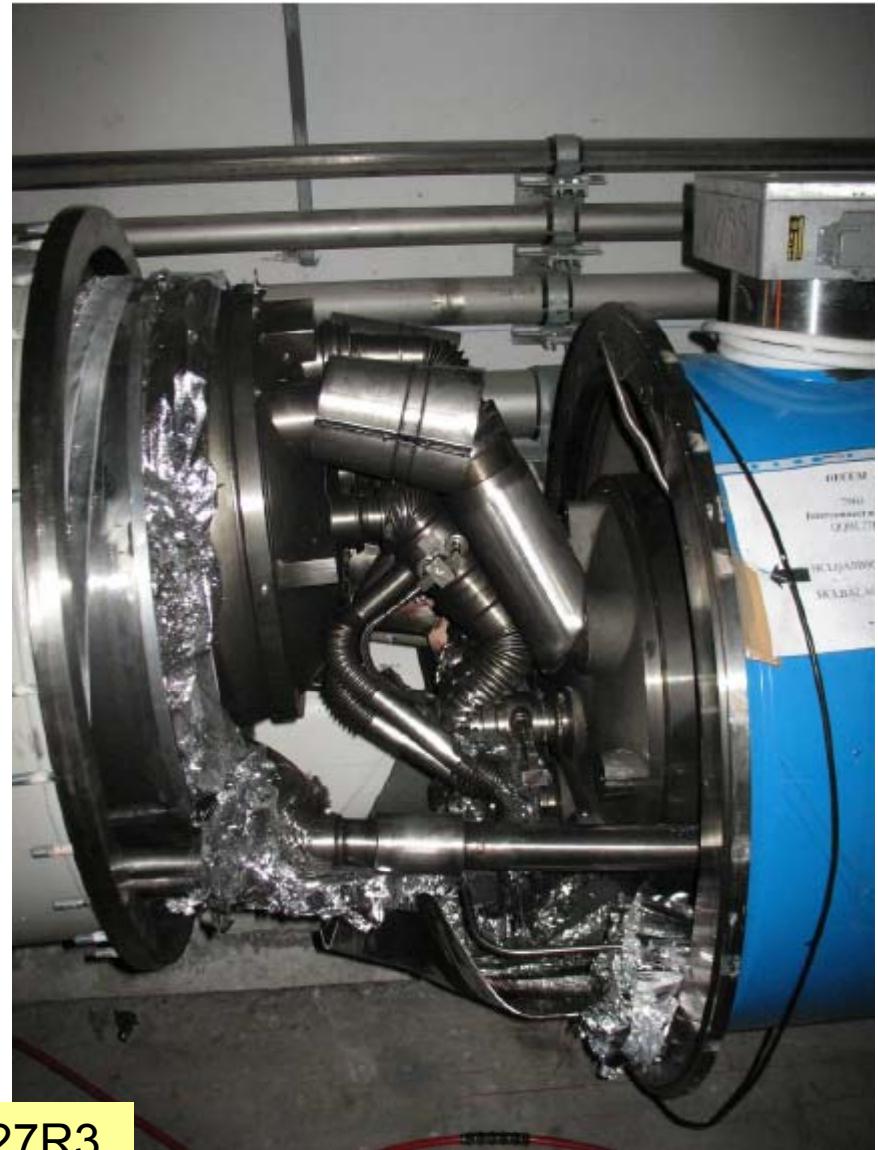
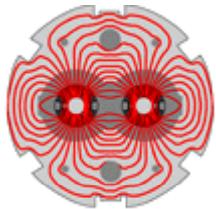


## Pressure forces on SSS vacuum barrier





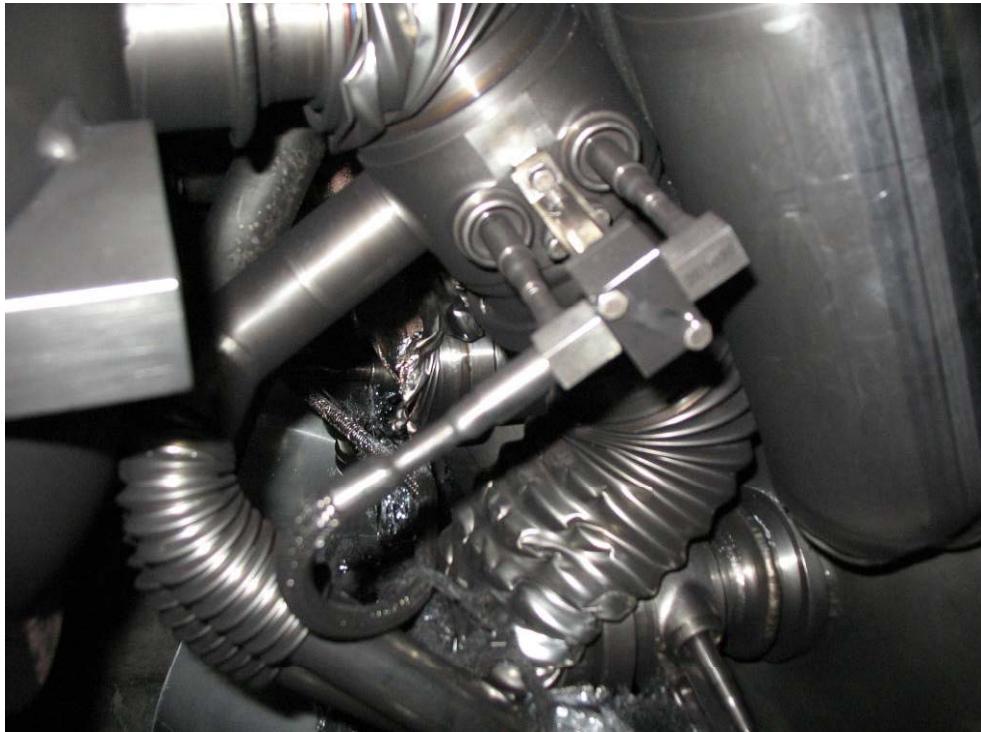
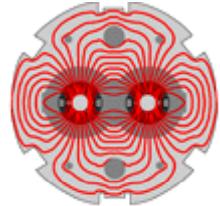
## Collateral damage: magnet displacements



QQBI.27R3



## Collateral damage: magnet displacements



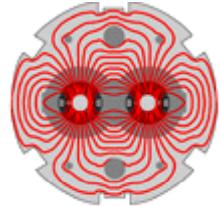
QQBI.27R3  
V2 line



QQBI.27R3  
N line



## Collateral damage: magnet displacements



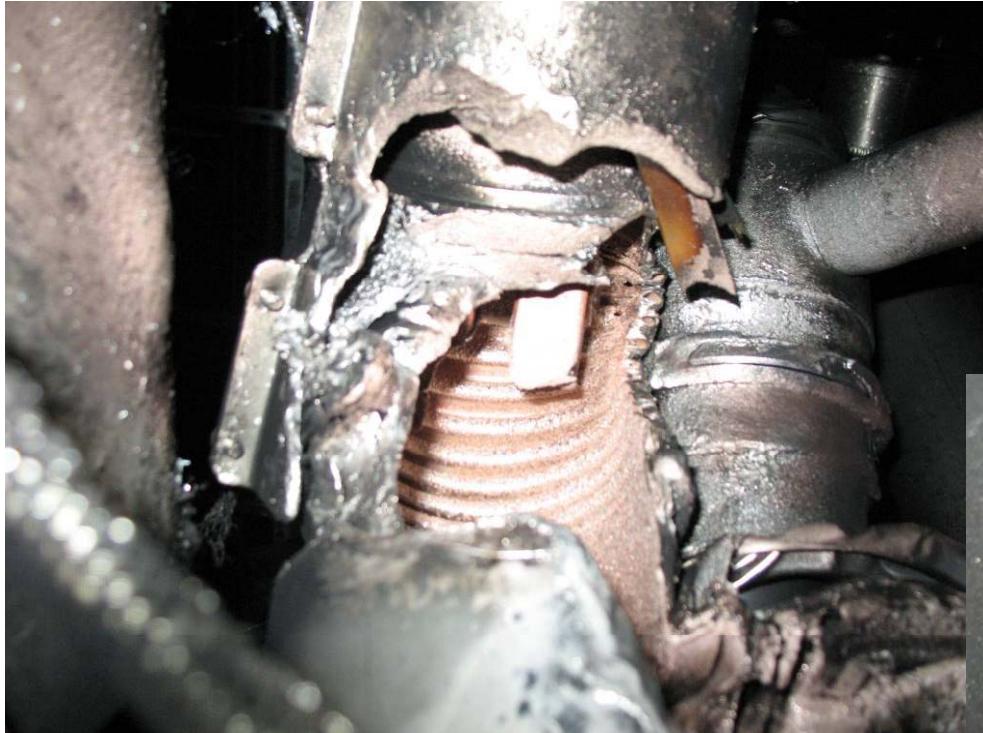
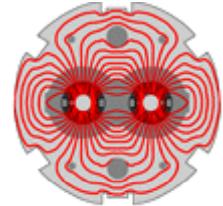
QBBI.B31R3  
Extension by 73 mm



QBQI.27R3  
Bellows torn open



## Collateral damage: secondary arcs



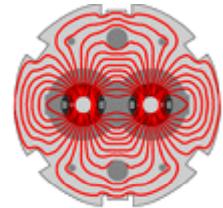
QQBI.27R3 Dipole bus line

QBBI.B31R3 M3 bus line



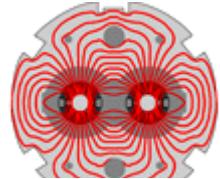


## Collateral damage: ground supports





# Longitudinal displacements in damaged area



## Displacements status in sector 3-4 (From Q17R3 to Q33R3) : P3 side

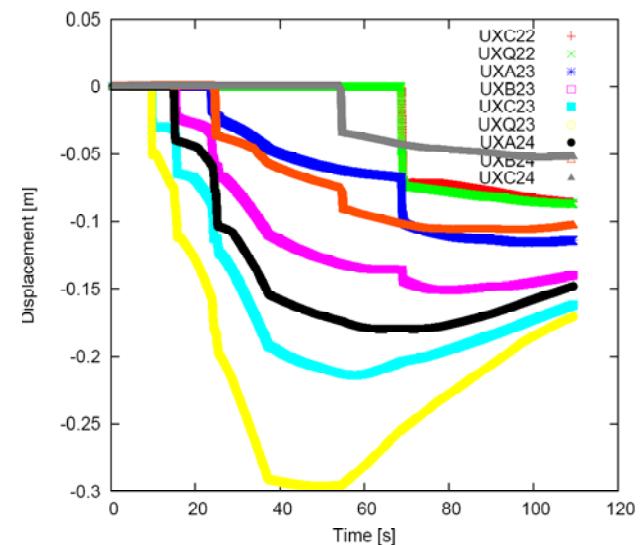
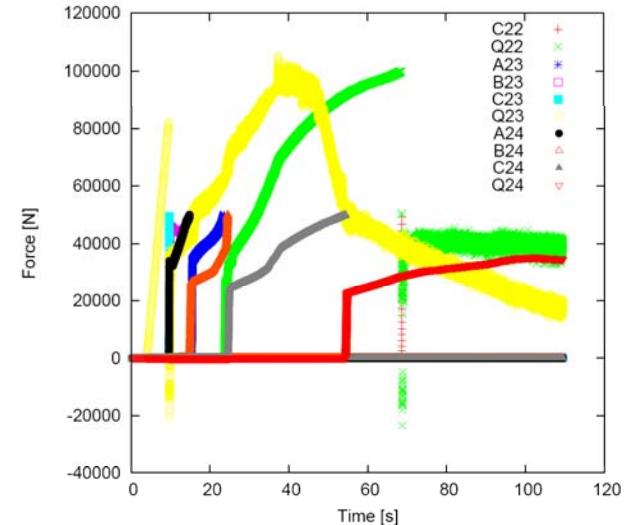
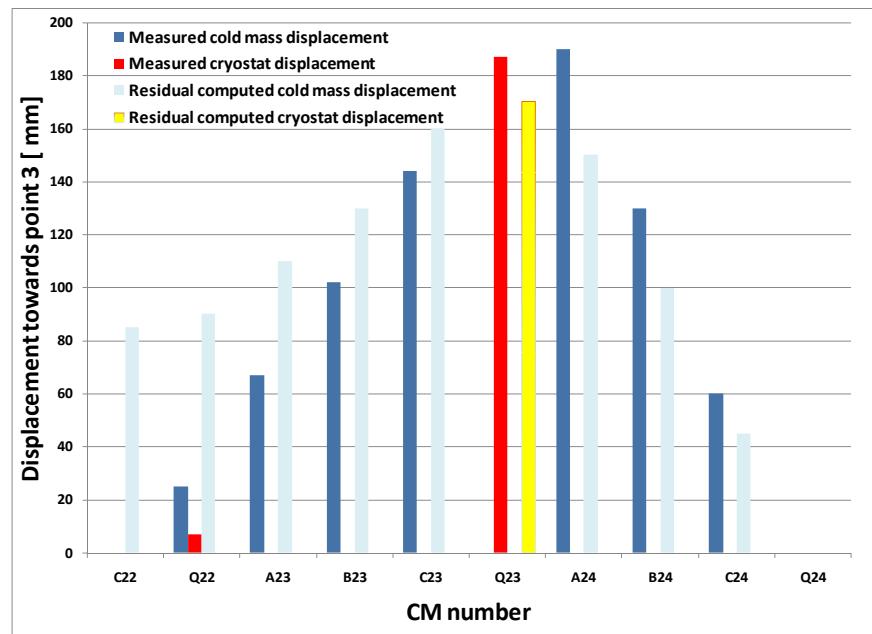
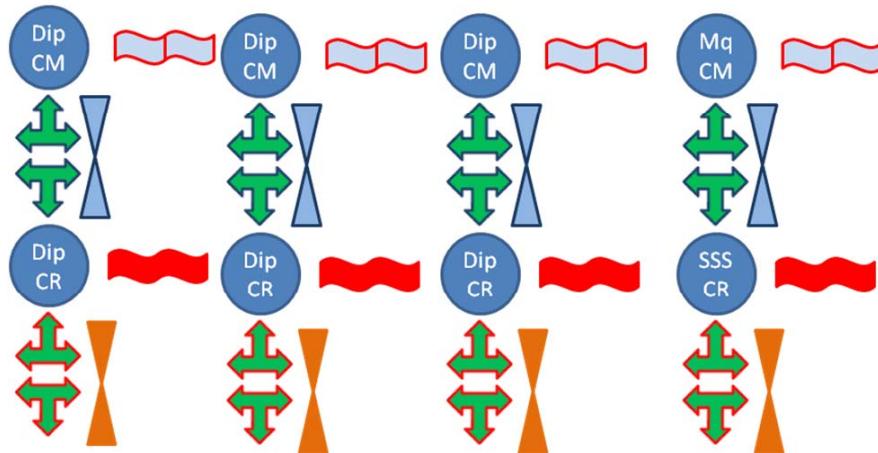
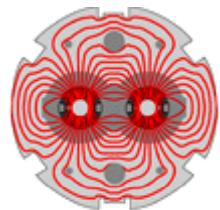
Based on measurements by TS-SU, TS-MME and AT-MCS

	Q17	A18	B18	C18	Q18	A19	B19	C19	Q19	A20	B20	C20	Q20	A21	B21	C21	Q21
Cryostat	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Cold mass	?	?	?	?	?	?	?	?	?	?	<5	<5	<5	<5	<5	<5	<5
	Q21	A22	B22	C22	Q22	A23	B23	C23	Q23	A24	B24	C24	Q24	A25	B25	C25	Q25
Cryostat	<2	<2	<2	<2	-7	<2	<2	<2	-187	<2	<2	<2	<2	<2	<2	<2	<2
Cold mass	<5	<5	<5	<5	-25	-67	-102	-144	<5	-190	-130	-60	<5	<5	<5	<5	<5
	Q25	A26	B26	C26	Q26	A27	B27	C27	Q27	A28	B28	C28	Q28	A29	B29	C29	Q29
Cryostat	<2	<2	<2	<2	<2	<2	<2	<2	474	-4	<2	<2	11	<2	<2	<2	<2
Cold mass	<5	<5	<5	<5	<5	57	114	150?	-45	230	189	144	92?	50	35	<5	<5
	Q29	A30	B30	C30	Q30	A31	B31	C31	Q31	A32	B32	C32	Q32	A33	B33	C33	Q33
Cryostat	<2	<2	<2	<2	<2	<2	<2	<2	188	<2	<2	<2	5	<2	<2	<2	<2
Cold mass	<5	<5	<5	<5	<5	19	77	148	<5	140	105	62	18	<5	<5	<5	?
>0 [mm]		SSS with vacuum barrier Towards P4				Open interconnection Electrical interruptions				Disconnected							
?		Values are in mm				Dipole in short circuit				Electrically damaged IC							
		Not measured yet				Cold mass displacement				Buffer zones							
		Cryostat displacement															

J.Ph. Tock



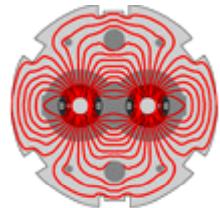
# Lumped dynamic model of cryomagnet string

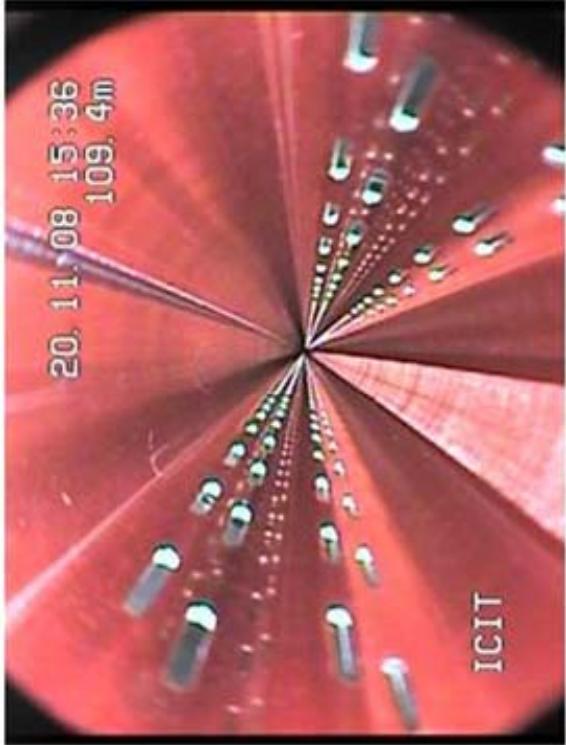
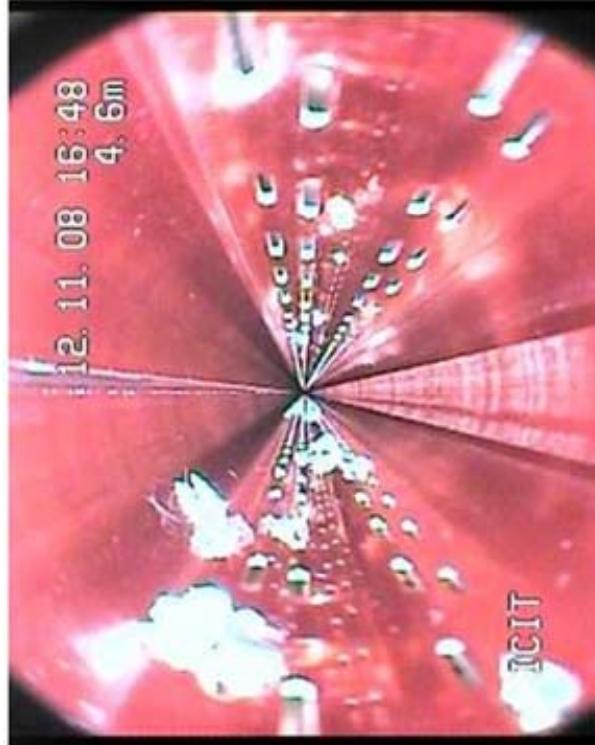
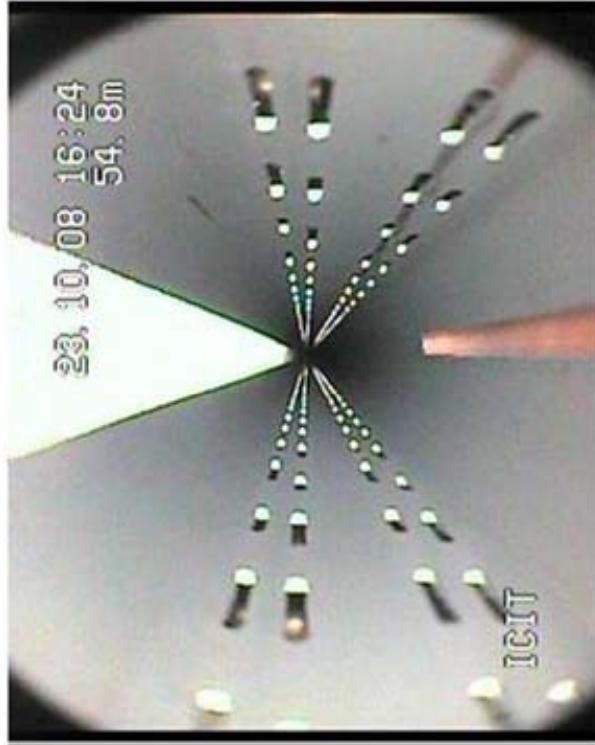


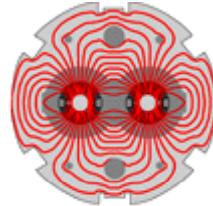
P. Fessia



## Beam vacuum contamination



<p>Beam Screen (BS) : The red color is characteristic of a clean copper surface</p> 	<p>BS with some contamination by super-isolation (MLI multi layer insulation)</p> 	<p>BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.</p> 
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# Beam vacuum contamination

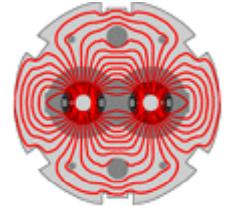
Element	PIM V1	PIM V2	V1 Nested bel.	V2 Nested bel.	BS V1	BS V2	remove CM (VAC)	
DFBA	cut	ok	?	?	Oxydised	Oxydised	no	
Q7R3	cut	ok	?	?	MLI	MLI	no	
A8R3	?	ok	?	?	MLI	MLI	no	
B8R3	?	cut	?	?	DUST	MLI	no	
C8R3	?	cut	?	?	MLI	Metal debris	yes	
A9R3	?	ok	?	?	DUST	ok	no	
B9R3	?	?	?	?	DUST	ok	no	
C9R3	?	?	?	?	DUST	ok	no	
A10R3	?	?	?	?	DUST	ok	no	
B10R3	?	?	?	?	DUST	ok	no	
Q10R3	?	?	?	?	DUST	ok	no	
A11R3	?	?	?	?	DUST	ok	no	
Metal debris removal made in-situ								
B11R3	?	?	?	?	debris coupe	ok	no	
C11R3	?	?	?	?	debris coupe	ok	no	
D11R3	cut	cut	?	?	ok	TACHES	no	
A12R3	?	?	?	?	debris coupe	TACHES	no	
B12R3	?	?	?	?	ok	Oxydised	no	
C12R3	?	?	?	?	ok	ok	no	
Q12R3	cut	cut	ok	ok	ok	ok	no	
A13R3	ok	ok	ok	ok	ok	DUST	no	
B13R3	ok	ok	ok	ok	ok	Oxydised	no	
C13R3	ok	bad	ok	ok	debris coupe	DUST	no	
Q13R3	cut	cut	ok	ok	TACHES	DUST	no	
A14R3	ok	bad	ok	ok	ok	DUST	no	
B14R3	ok	ok	ok	ok	debris coupe	DUST	no	
C14R3	ok	bad	ok	ok	TACHES	DUST	no	
Q14R3	cut	cut	ok	ok	ok	DUST	no	
A15R3	ok	ok	ok	ok	ok	Metal debris	TACHES	no
B15R3	ok	cut	ok	ok	ok	DUST	no	
C15R3	ok	cut	ok	use as is	ok	TACHES	no	
Q15R3	cut	cut	ok	ok	ok	DUST	no	
A16R3	ok	cut	ok	ok	ok	DUST	no	
B16R3	ok	cut	ok	ok	ok	ok	no	
C16R3	ok	cut	ok	ok	ok	TACHES	no	
Q16R3	cut	cut	ok	ok	ok	ok	no	
A17R3	ok	cut	ok	ok	ok	DUST	no	
B17R3	ok	cut	ok	ok	ok	DUST	no	
C17R3	bad	cut	ok	ok	ok	DUST	no	
Q17R3	cut	cut	ok	ok	debris coupe	no		
A18R3	ok	cut	ok	use as is	ok	DUST	no	
B18R3	ok	cut	ok	use as is	ok	DUST	no	
C18R3	ok	cut	ok	use as is	ok	DUST	no	
Q18R3	cut	cut	ok	ok	ok	DUST	no	
A19R3	ok	cut	ok	use as is	ok	DUST	no	
B19R3	ok	cut	ok	use as is	ok	soot	yes	
C19R3	bad	cut	ok	use as is	ok	soot	yes	
Q19R3	cut	cut	ok	ok	ok	soot	yes	
A20R3	ok	cut	ok	use as is	ok	soot	yes	
B20R3	ok	cut	ok	use as is	ok	soot	yes	
C20R3	cut	cut	ok	ok	ok	soot	yes	
Q20R3	cut	cut	ok	use as is	ok	soot	yes	

Element	PIM V1	PIM V2	V1 Nested bel.	V2 Nested bel.	BS V1	BS V2	remove CM (VAC)
A21R3	cut	cut	ok	use as is	ok	soot	yes
B21R3	cut	cut	ok	use as is	ok	soot	yes
C21R3	cut	cut	ok	bad	ok	soot	yes
D21R3	cut	cut	ok	ok	ok	soot	yes
A22R3	cut	cut	ok	bad	ok	soot	yes
B22R3	cut	cut	ok	bad	soot	soot	yes
C22R3	cut	cut	ok	ok	soot	soot	yes
A23R3	cut	cut	ok	bad	soot	soot	yes
B23R3	cut	cut	ok	bad	soot	soot	yes
C23R3	cut	cut	ok	bad	soot	hole	yes
A24R3	cut	cut	ok	ok	soot	soot	yes
B24R3	cut	cut	ok	ok	soot	soot	yes
C24R3	cut	cut	ok	ok	soot	soot	yes
A25R3	cut	cut	ok	ok	soot	soot	yes
B25R3	cut	cut	ok	ok	soot	soot	yes
C25R3	cut	cut	ok	ok	soot	soot	yes
A26R3	cut	cut	ok	ok	soot	soot	yes
B26R3	cut	cut	ok	ok	soot	soot	yes
C26R3	cut	cut	ok	ok	soot	soot	yes
A27R3	cut	cut	ok	ok	soot	soot	yes
B27R3	cut	cut	use as is	ok	soot	soot	yes
C27R3	cut	cut	bad	bad	soot	soot	yes
A28R3	cut	cut	ok	ok	soot	soot	yes
B28R3	cut	cut	ok	ok	soot	soot	yes
C28R3	cut	cut	ok	ok	soot	soot	yes
A29R3	cut	cut	ok	ok	soot	soot	yes
B29R3	cut	cut	ok	ok	soot	soot	yes
C29R3	cut	cut	ok	ok	soot	soot	yes
A30R3	cut	cut	ok	ok	soot	MLI	no
B30R3	cut	cut	ok	ok	soot	MLI	no
C30R3	cut	cut	ok	ok	soot	MLI	no
Q30R3	cut	cut	ok	ok	ok	no	
A31R3	cut	cut	ok	ok	soot	yes	
B31R3	cut	cut	ok	ok	?	?	
C31R3	cut	cut	ok	ok	MLI	no	
Q31R3	cut	cut	use as is	use as is	soot	soot	yes
A32R3	cut	cut	ok	ok	ok	ok	?
B32R3	cut	cut	ok	ok	ok	ok	?
C32R3	cut	cut	ok	ok	ok	ok	?
A33R3	cut	cut	ok	ok	ok	ok	?
B33R3	cut	cut	ok	ok	ok	ok	?
C33R3	cut	cut	ok	ok	ok	ok	?
A34R3	cut	cut	ok	ok	ok	ok	?
B34R3	cut	cut	ok	ok	ok	ok	?
C34R3	cut	cut	ok	ok	ok	ok	?
A35R3	cut	cut	ok	ok	ok	ok	?
B35R3	cut	cut	ok	ok	ok	ok	?
C35R3	cut	cut	ok	ok	ok	ok	?
A36R3	cut	cut	ok	ok	ok	ok	?
B36R3	cut	cut	ok	ok	ok	ok	?
C36R3	cut	cut	ok	ok	ok	ok	?
A37R3	cut	cut	ok	ok	ok	ok	?
B37R3	cut	cut	ok	ok	ok	ok	?
C37R3	cut	cut	ok	ok	ok	ok	?
A38R3	cut	cut	ok	ok	ok	ok	?
B38R3	cut	cut	ok	ok	ok	ok	?
C38R3	cut	cut	ok	ok	ok	ok	?
A39R3	cut	cut	ok	ok	ok	ok	?
B39R3	cut	cut	ok	ok	ok	ok	?
C39R3	cut	cut	ok	ok	ok	ok	?
A40R3	cut	cut	ok	ok	ok	ok	?
B40R3	cut	cut	ok	ok	ok	ok	?
C40R3	cut	cut	ok	ok	ok	ok	?
A41R3	cut	cut	ok	ok	ok	ok	?
B41R3	cut	cut	ok	ok	ok	ok	?
C41R3	cut	cut	ok	ok	ok	ok	?
A42R3	cut	cut	ok	ok	ok	ok	?
B42R3	cut	cut	ok	ok	ok	ok	?
C42R3	cut	cut	ok	ok	ok	ok	?
A43R3	cut	cut	ok	ok	ok	ok	?
B43R3	cut	cut	ok	ok	ok	ok	?
C43R3	cut	cut	ok	ok	ok	ok	?
A44R3	cut	cut	ok	ok	ok	ok	?
B44R3	cut	cut	ok	ok	ok	ok	?
C44R3	cut	cut	ok	ok	ok	ok	?
A45R3	cut	cut	ok	ok	ok	ok	?
B45R3	cut	cut	ok	ok	ok	ok	?
C45R3	cut	cut	ok	ok	ok	ok	?
A46R3	cut	cut	ok	ok	ok	ok	?
B46R3	cut	cut	ok	ok	ok	ok	?
C46R3	cut	cut	ok	ok	ok	ok	?
A47R3	cut	cut	ok	ok	ok	ok	?
B47R3	cut	cut	ok	ok	ok	ok	?
C47R3	cut	cut	ok	ok	ok	ok	?
A48R3	cut	cut	ok	ok	ok	ok	?
B48R3	cut	cut	ok	ok	ok	ok	?
C48R3	cut	cut	ok	ok	ok	ok	?
A49R3	cut	cut	ok	ok	ok	ok	?
B49R3	cut	cut	ok	ok	ok	ok	?
C49R3	cut	cut	ok	ok	ok	ok	?
A50R3	cut	cut	ok	ok	ok	ok	?
B50R3	cut	cut	ok	ok	ok	ok	?
C50R3	cut	cut	ok	ok	ok	ok	?
A51R3	cut	cut	ok	ok	ok	ok	?
B51R3	cut	cut	ok	ok	ok	ok	?
C51R3	cut	cut	ok	ok	ok	ok	?
A52R3	cut	cut	ok	ok	ok	ok	?
B52R3	cut	cut	ok	ok	ok	ok	?
C52R3	cut	cut	ok	ok	ok	ok	?
A53R3	cut	cut	ok	ok	ok	ok	?
B53R3	cut	cut	ok	ok	ok	ok	?
C53R3	cut	cut	ok	ok	ok	ok	?
A54R3	cut	cut	ok	ok	ok	ok	?
B54R3	cut	cut	ok	ok	ok	ok	?
C54R3	cut	cut	ok	ok	ok	ok	?
A55R3	cut	cut	ok	ok	ok	ok	?
B55R3	cut	cut	ok	ok	ok	ok	?
C55R3	cut	cut	ok	ok	ok	ok	?
A56R3	cut	cut	ok	ok	ok	ok	?
B56R3	cut	cut	ok	ok	ok	ok	?
C56R3	cut	cut	ok	ok	ok	ok	?
A57R3	cut	cut	ok	ok	ok	ok	?
B57R3	cut	cut	ok	ok	ok	ok	?
C57R3	cut	cut	ok	ok	ok	ok	?
A58R3	cut	cut	ok	ok	ok	ok	?
B58R3	cut	cut	ok	ok	ok	ok	?
C58R3	cut	cut	ok	ok	ok	ok	?
A59R3	cut	cut	ok	ok	ok	ok	?
B59R3	cut	cut	ok	ok	ok	ok	?
C59R3	cut	cut	ok	ok	ok	ok	?
A60R3	cut	cut	ok	ok	ok	ok	?
B60R3	cut	cut	ok	ok	ok	ok	?
C60R3	cut	cut	ok	ok	ok	ok	?
A61R3	cut	cut	ok	ok	ok	ok	?
B61R3	cut	cut	ok	ok	ok	ok	?
C61R3	cut	cut	ok	ok	ok	ok	?
A62R3	cut	cut	ok	ok	ok	ok	?
B62R3	cut	cut	ok	ok	ok	ok	?
C62R3	cut	cut	ok	ok	ok	ok	?
A63R3	cut	cut	ok	ok	ok	ok	?
B63R3	cut	cut	ok	ok	ok	ok	?
C63R3	cut	cut	ok	ok	ok	ok	?
A64R3	cut	cut	ok	ok	ok	ok	?
B64R3	cut	cut	ok	ok	ok	ok	?
C64R3	cut	cut	ok	ok	ok	ok	?
A65R3	cut	cut	ok	ok	ok	ok	?
B65R3	cut	cut	ok	ok	ok	ok	?
C65R3	cut</td						

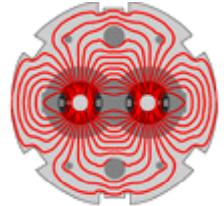


# Recommendations

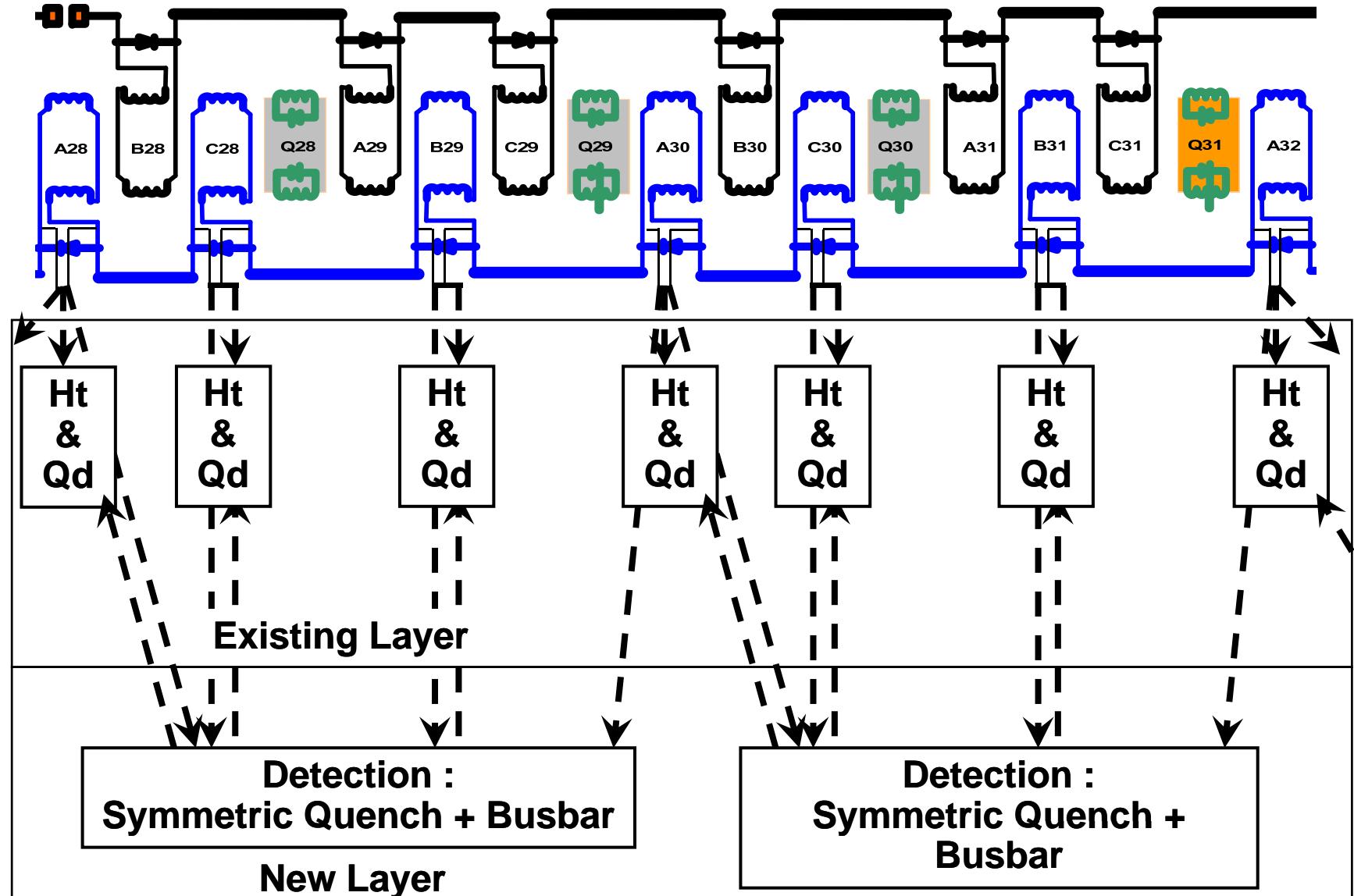
## Prevention of initial fault



- Analyse thoroughly temperature evolution history of cold mass during past power tests to identify « doubtful » cells/subsectors/magnets
  - done in all sectors
- Perform electrical measurements with higher sensitivity ( $< 100 \mu\text{V}$ ) on « doubtful » cells/subsectors powered at limited current
  - done in few locations (15-17R1)
- Track temperature evolution during further power tests, applying normalized ramp/flattop/deramp durations and normalized cryogenic configuration, filtered electrical measurements using quench recorder in « snapshot » mode
  - MB circuits: done on sectors 1-2, 5-6, 6-7, 7-8 and 8-1
  - MQ circuits: done on sectors 5-6, 6-7, 7-8 and 8-1
  - procedure to be established and included in power tests of sectors
- Modify quench detection system to include interconnects and bus bar splices, making use of available voltage taps to generate early warning & interlock signals
  - technical solution defined and implementation launched Dec 2008
- Consider option to measure currents in 13 kA circuits at both ends of sector and detect differentials
- Review possible improvement of mechanical clamping of interconnects and gradually implement whenever possible



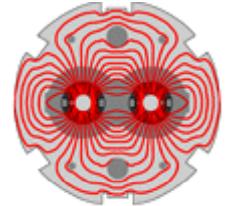
## Additional quench detection system





# Recommendations

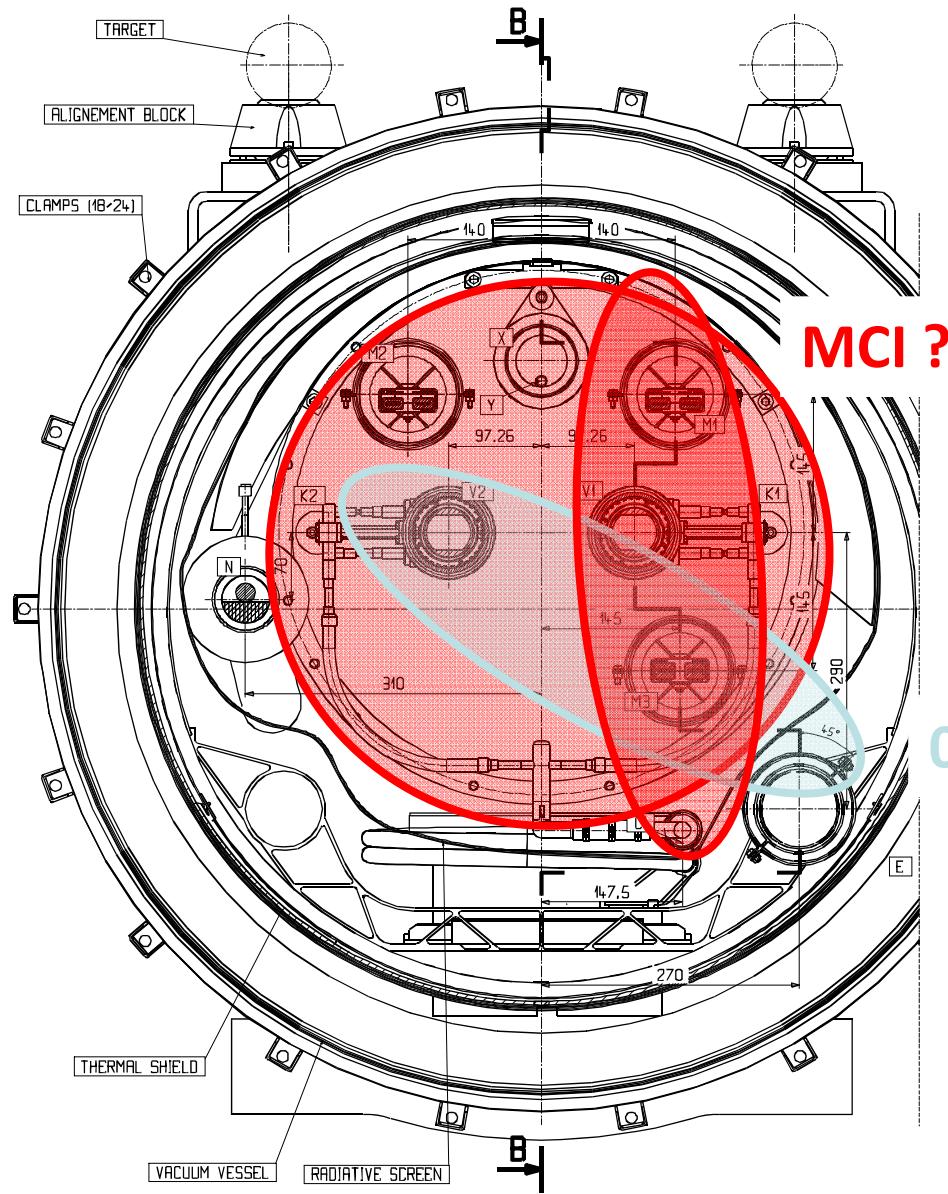
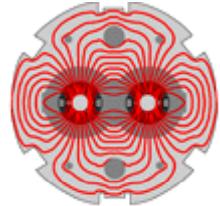
## Mitigation of consequences



- Redefine MCI to cope with collateral effects of helium discharge from cold mass
  - done for electrical arcs
  - to be done for beam-induced damage
- Increase number/size of relief devices on cryostat vacuum vessels for coping with redefined MCI
  - equip SSS with increased-flow, spring-loaded devices on available DN100 and DN63 ports (can be implemented on cold SSS)
  - cut/weld DN 200 ports on cryodipoles and equip with spring-loaded devices (can only be implemented on warm cryodipoles)
  - implement compensatory measures for transitory phase on sectors not yet equipped with DN 200 relief devices
- Review number, size & position of pressure relief devices on beam vacuum system
- Review closure logic of beam vacuum sector valves
- Consider possibility of triggered opening of quench relief valves below set pressure
- Consider general firing of quench heaters pertaining to an electrical circuit as a measure to dissipate energy away from an electrical problem (e.g. arc) occurring in circuit
- Reinforce external anchoring at locations of vacuum barriers
  - will avoid displacement of vacuum vessels, but risk of additional damage to cold supports
- Reexamine personnel underground access rules when powering
  - including neighbouring underground spaces
- Review location of AUG in tunnel and protection from blast
- Review recorded signals, recording frequency and time stamping coherence among different systems



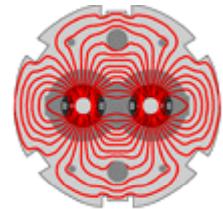
## Revision of MCI due to electrical arc



L. Tavian

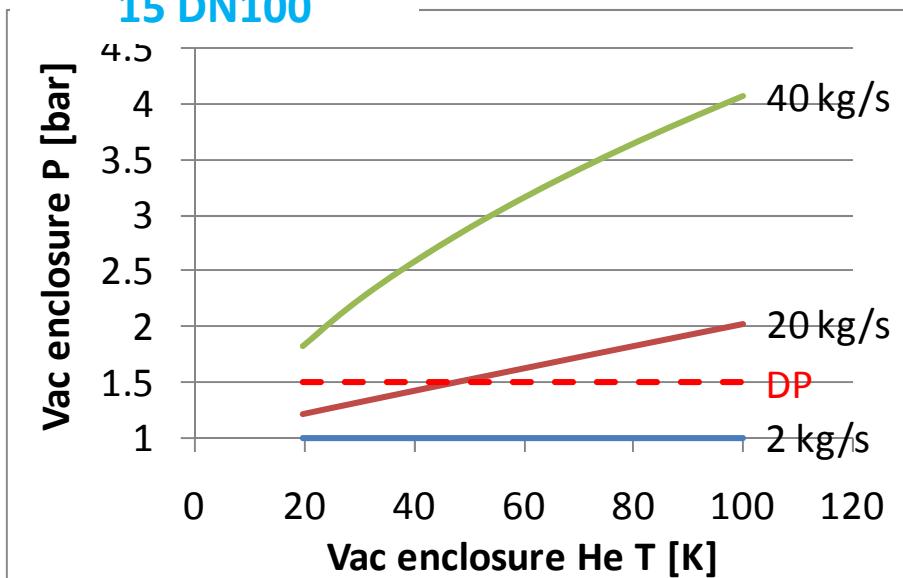


# Flow discharge characteristics of relief devices on insulation vacuum enclosure (per sub-sector)



New configuration  
on cold sectors:

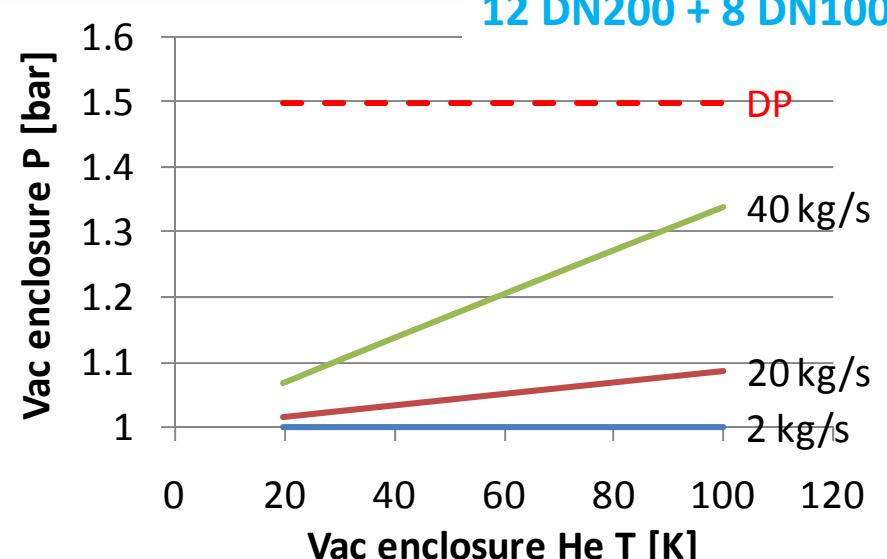
15 DN100



(DP: Design Pressure)

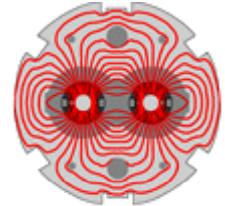
New configuration  
on warm sectors:

12 DN200 + 8 DN100





## Still to be found or understood



- Exact nature of initial fault
  - Primary evidence destroyed
  - Sample tests to reproduce interconnect with  $200 \text{ n}\Omega$  resistance: only omission of soldering can account for such high resistance
  - Inter-aperture splice with  $90 \text{ n}\Omega$  resistance on other magnet examined, confirming likelihood of defect
- Long-distance propagation mechanism of quenches to other magnets in sector
  - Electrical discharge of QPS in helium cloud? negative test!
  - In-rush of warm helium in beam vacuum pipes? simulations inconclusive!
  - Second sound in He II? hydraulic restrictions!
- Comprehensive extent of damage
  - to cold mass of magnets
  - to beam vacuum systems