

# Results of the HL-LHC IT Diode prototype cold test

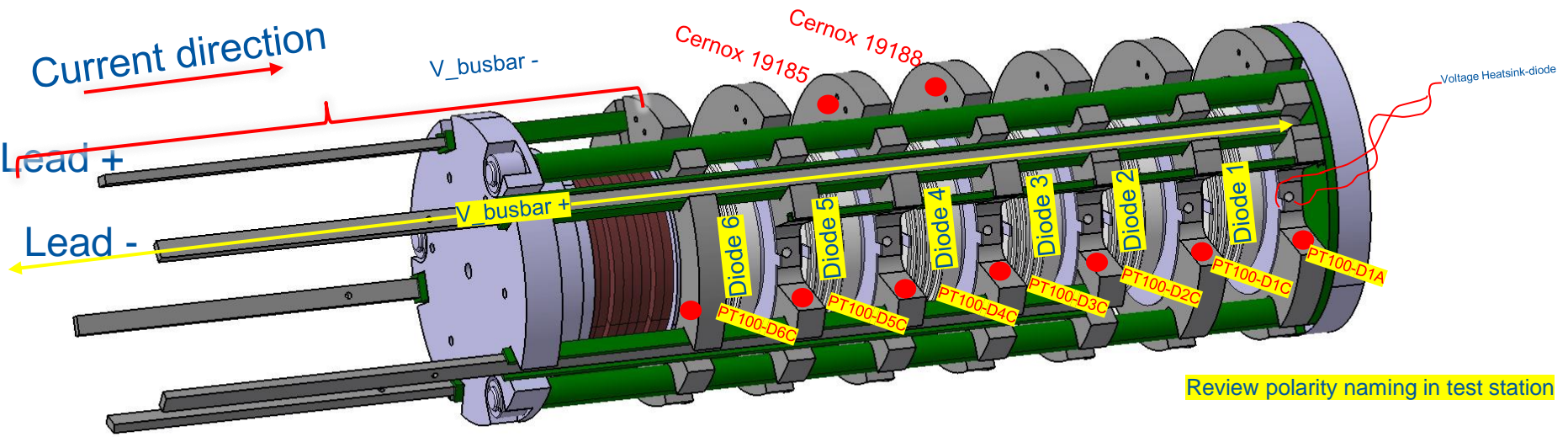
Jerome Feuvrier, Gerard Willering

With thanks to Frederic Daligault, Hugues Thiessen and Giorgio D'Angelo

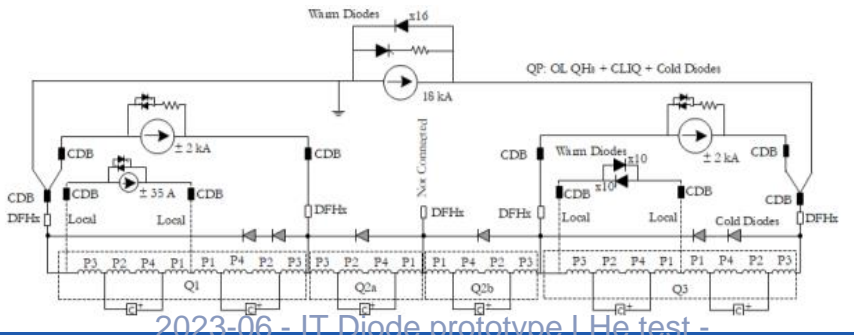
8 June 2023



# HL-LHC IT diode stack



Review polarity naming in test station

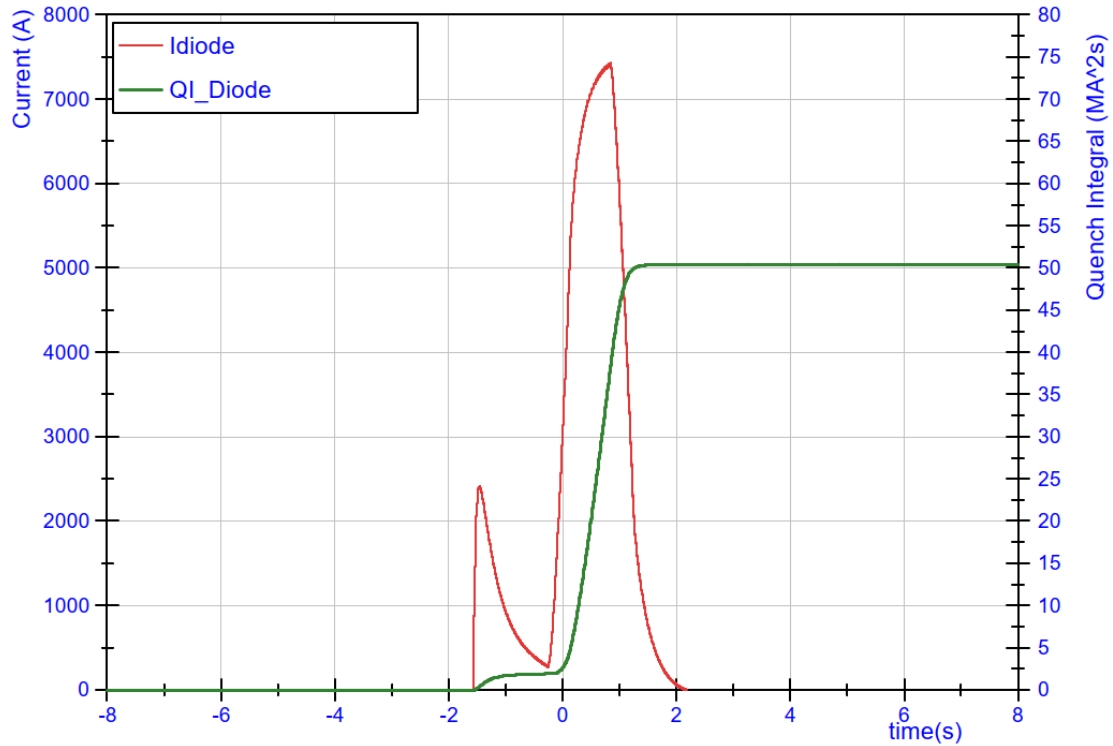


2023-06 - IT Diode prototype LHe test -

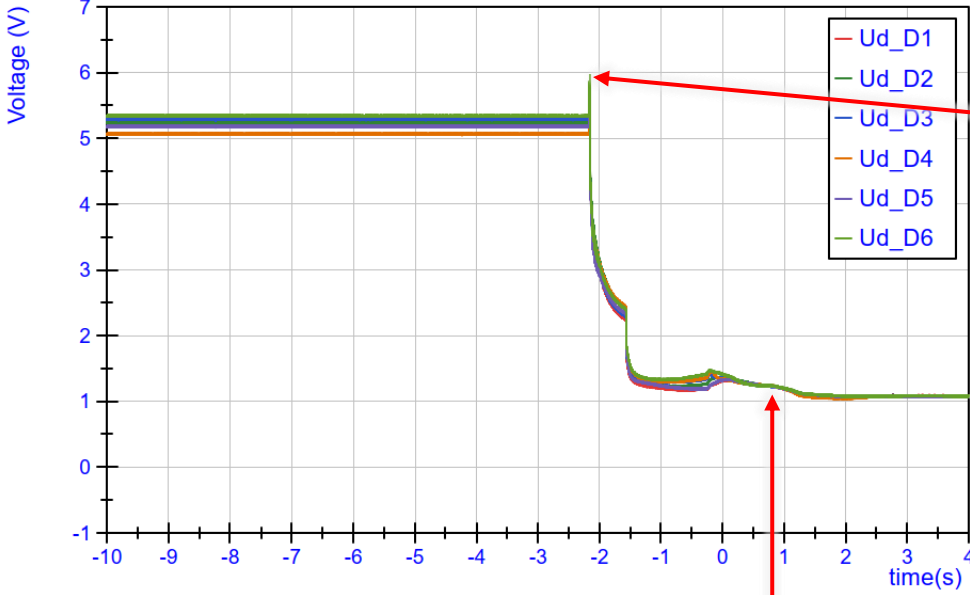
G.Willering, J. Feuvrier



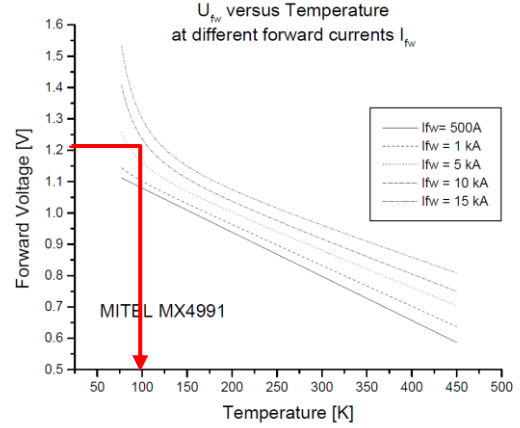
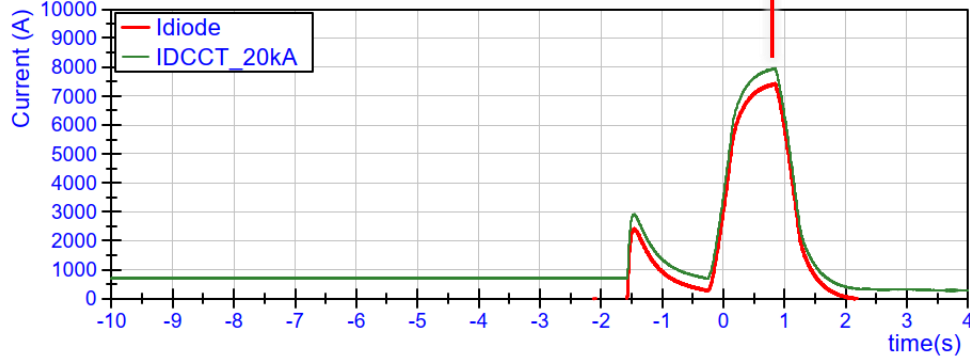
## Example of one standard test run and test analysis

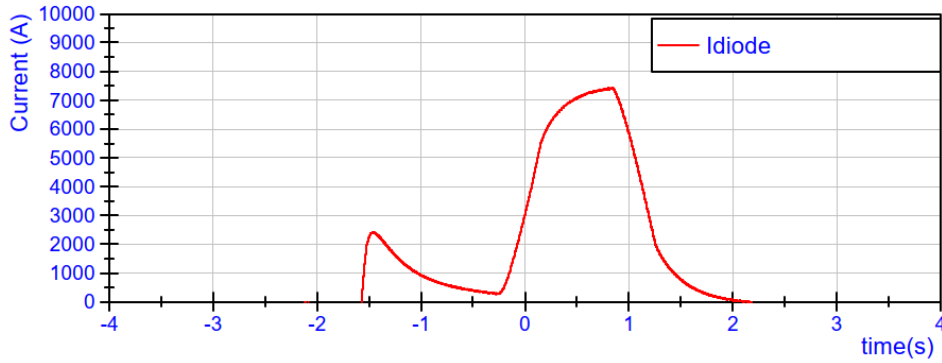


I\_diode\_max = 7427 A  
QI = 50.5 MA<sup>2</sup>s

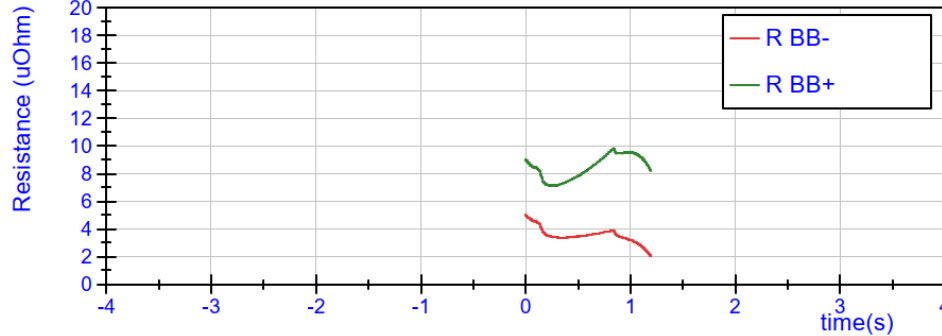
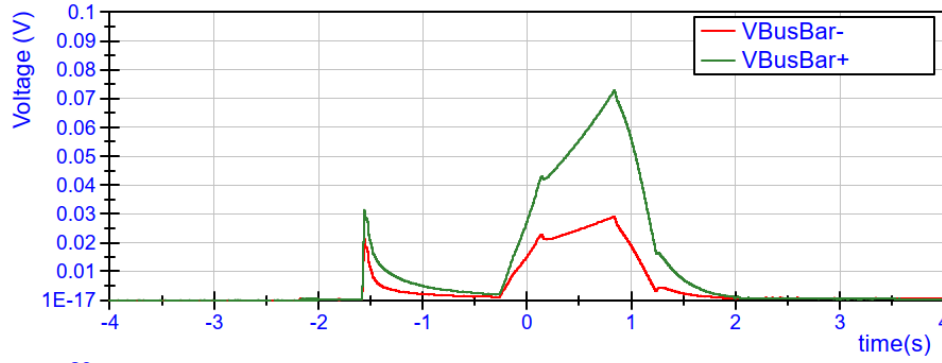


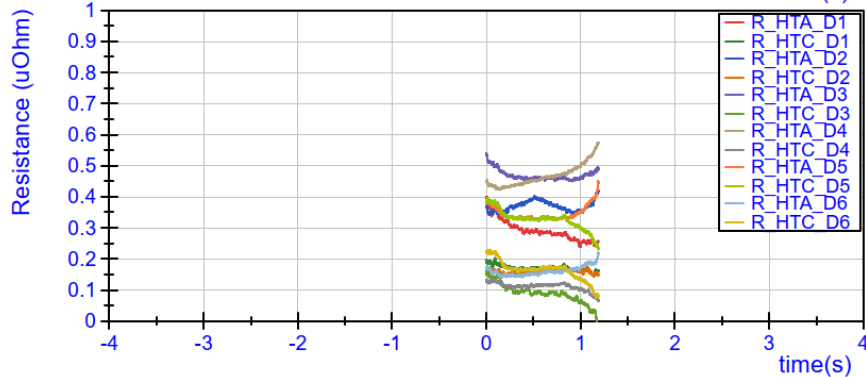
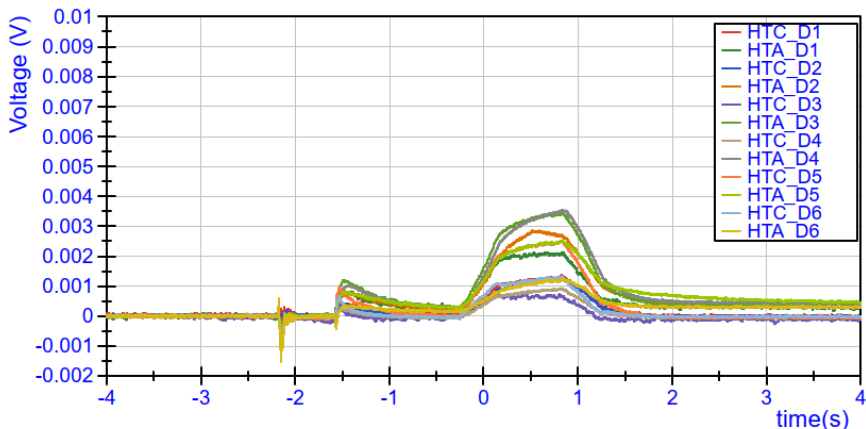
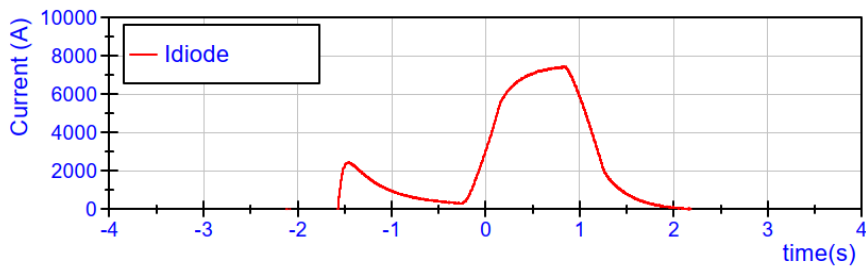
$I_{diode\_max} = 7427 \text{ A}$   
 $Ud\_D1\_max = 5.93 \text{ V}$   
 $Ud\_D2\_max = 5.92 \text{ V}$   
 $Ud\_D3\_max = 5.96 \text{ V}$   
 $Ud\_D4\_max = 5.78 \text{ V}$   
 $Ud\_D5\_max = 5.88 \text{ V}$   
 $Ud\_D6\_max = 5.96 \text{ V}$   
 $Ud\_D1\_at\_I_{max} = 1.22 \text{ V}$   
 $Ud\_D2\_at\_I_{max} = 1.23 \text{ V}$   
 $Ud\_D3\_at\_I_{max} = 1.22 \text{ V}$   
 $Ud\_D4\_at\_I_{max} = 1.24 \text{ V}$   
 $Ud\_D5\_at\_I_{max} = 1.23 \text{ V}$   
 $Ud\_D6\_at\_I_{max} = 1.23 \text{ V}$





I\_diode\_max = 7427 A  
 R BB-\_at\_I\_max = 3.86 uOhm  
 R BB+\_at\_I\_max = 9.76 uOhm





I\_diode\_max = 7427 A

R\_HTA\_D1\_at\_I\_max = 0.29 uOhm  
R\_HTC\_D1\_at\_I\_max = 0.18 uOhm

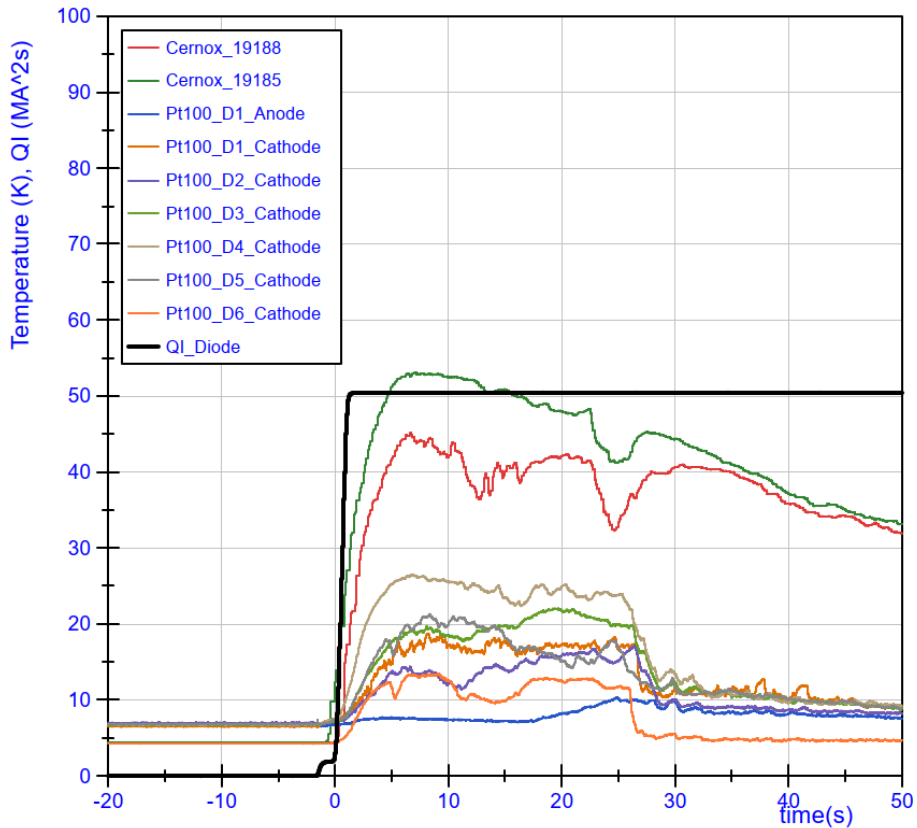
R\_HTA\_D2\_at\_I\_max = 0.36 uOhm  
R\_HTC\_D2\_at\_I\_max = 0.17 uOhm

R\_HTA\_D3\_at\_I\_max = 0.46 uOhm  
R\_HTC\_D3\_at\_I\_max = 0.09 uOhm

R\_HTA\_D4\_at\_I\_max = 0.47 uOhm  
R\_HTC\_D4\_at\_I\_max = 0.12 uOhm

R\_HTA\_D5\_at\_I\_max = 0.33 uOhm  
R\_HTC\_D5\_at\_I\_max = 0.33 uOhm

R\_HTA\_D6\_at\_I\_max = 0.16 uOhm  
R\_HTC\_D6\_at\_I\_max = 0.17 uOhm



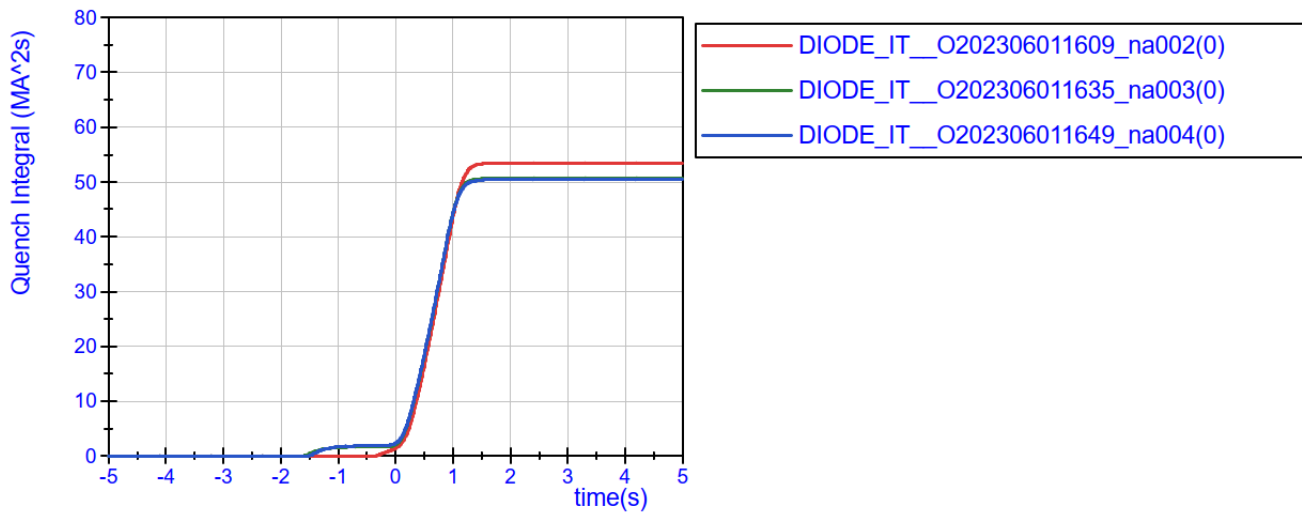
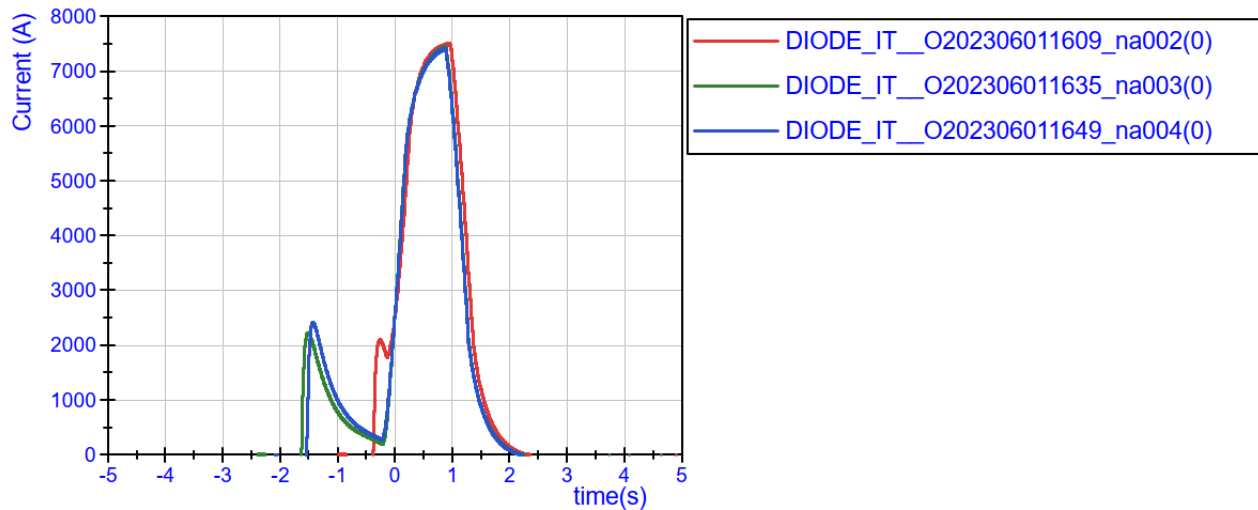
I\_diode\_max = 7427 A  
 QI = 50.5 MA<sup>2</sup>s

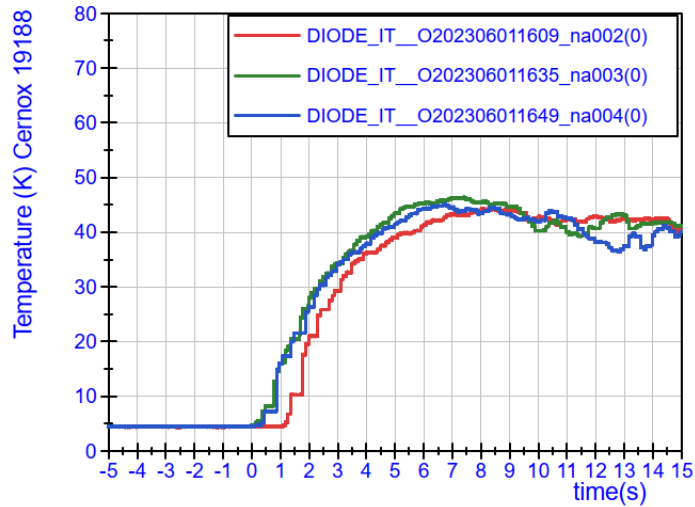
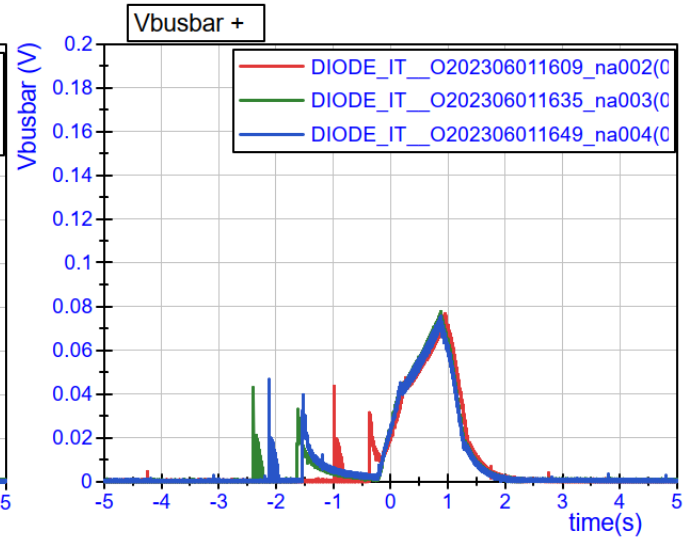
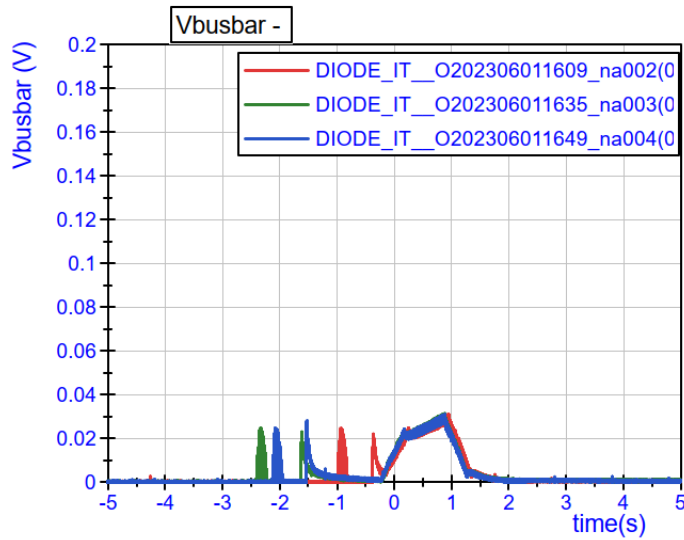
T\_max Cernox\_19188 = 45.1 K  
 T\_max Cernox\_19185 = 53.1 K  
 T\_max PT100\_D1\_Anode = 10.3 K  
 T\_max PT100\_D1\_Cathode = 10.3 K  
 T\_max PT100\_D2\_Cathode = 17.2 K  
 T\_max PT100\_D3\_Cathode = 22.1 K  
 T\_max PT100\_D4\_Cathode = 26.5 K  
 T\_max PT100\_D5\_Cathode = 21.3 K  
 T\_max PT100\_D6\_Cathode = 13.4 K

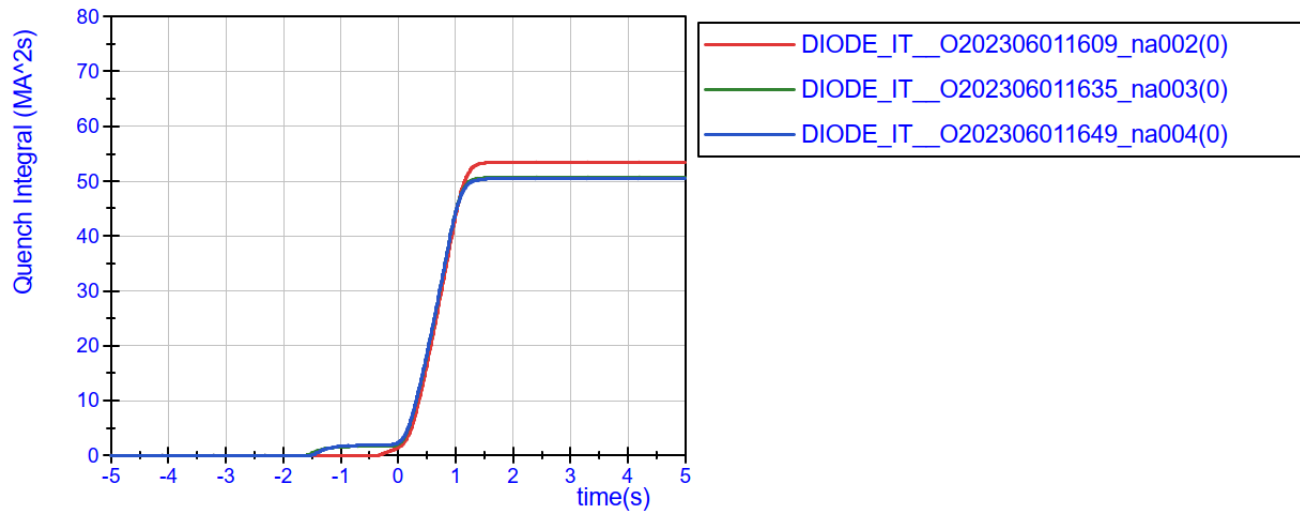
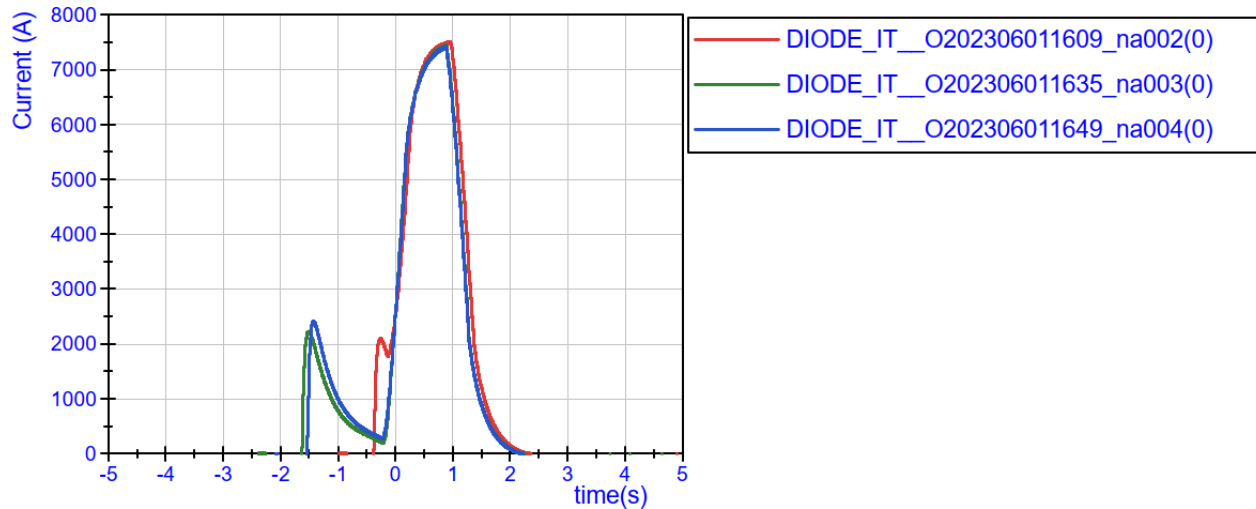
Time\_T\_max Cernox\_19188 = 6.6 s  
 Time\_T\_max Cernox\_19188 = 7 s  
 Time\_T\_max PT100\_D1\_Anode = 24.7 s  
 Time\_T\_max PT100\_D1\_Cathode = 8.2 s  
 Time\_T\_max PT100\_D2\_Cathode = 26.4 s  
 Time\_T\_max PT100\_D3\_Cathode = 19.2 s  
 Time\_T\_max PT100\_D4\_Cathode = 6.7 s  
 Time\_T\_max PT100\_D5\_Cathode = 8.3 s  
 Time\_T\_max PT100\_D6\_Cathode = 6.8 s



## Comparing 3 test runs







## Characteristic values comparing 3 test runs

# Characteristics table - 1

			Trial 1	Trial 2	Trial 3	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Variation
	Maximum current	A	5460	4463	3497	7510	7455	7427								83
Diode 1	Ufw_max	V	5.94	5.94	5.94	5.93	5.91	5.93								0.02
Diode 2	Ufw_max	V	5.9	5.9	5.9	5.89	5.9	5.92								0.03
Diode 3	Ufw_max	V	5.95	5.95	5.95	5.94	5.95	5.96								0.02
Diode 4	Ufw_max	V	5.78	5.79	5.8	5.78	5.78	5.78								0
Diode 5	Ufw_max	V	5.86	5.86	5.87	5.84	5.86	5.88								0.04
Diode 6	Ufw_max	V	5.96	5.97	5.97	5.96	5.94	5.96								0.02
Diode 1	Ufw at I_max	V	1.22	1.23	1.23	1.22	1.23	1.22								0.01
Diode 2	Ufw at I_max	V	1.22	1.23	1.22	1.24	1.24	1.23								0.01
Diode 3	Ufw at I_max	V	1.21	1.21	1.21	1.22	1.22	1.22								0
Diode 4	Ufw at I_max	V	1.21	1.21	1.21	1.24	1.23	1.24								0.01
Diode 5	Ufw at I_max	V	1.22	1.22	1.21	1.23	1.23	1.23								0
Diode 6	Ufw at I_max	V	1.23	1.23	1.23	1.23	1.23	1.23								0
Busbar -	Resistance Busbar - at I_max	uOhm	8.37	7.48	7.36	9.78	10.02	9.76								0.26
Busbar +	Resistance Busbar + at I_max	uOhm	3.86	3.62	3.6	3.86	3.9	3.86								0.04
HTA_D1	R at I_max	uOhm	0.24	0.27	0.27	0.32	0.4	0.29								0.11
HTC_D1	R at I_max	uOhm	0.13	0.11	0.07	0.13	0.17	0.18								0.05
HTA_D2	R at I_max	uOhm	0.38	0.4	0.42	0.45	0.33	0.36								0.12
HTC_D2	R at I_max	uOhm	0.13	0.12	0.12	0.18	0.16	0.17								0.02
HTA_D3	R at I_max	uOhm	0.33	0.34	0.37	0.52	0.5	0.46								0.06
HTC_D3	R at I_max	uOhm	0.09	0.09	0.09	0.12	0.1	0.09								0.03
HTA_D4	R at I_max	uOhm	0.35	0.35	0.39	0.52	0.49	0.47								0.05
HTC_D4	R at I_max	uOhm	0.1	0.09	0.09	0.12	0.12	0.12								0
HTA_D5	R at I_max	uOhm	0.31	0.32	0.34	0.41	0.36	0.33								0.08
HTC_D5	R at I_max	uOhm	0.21	0.23	0.23	0.36	0.35	0.33								0.03
HTA_D6	R at I_max	uOhm	0.15	0.16	0.16	0.13	0.19	0.16								0.06
HTC_D6	R at I_max	uOhm	0.07	0.07	0.07	0.1	0.15	0.17								0.07
	Quench Integral	MA^2s	28.7	20	14	53.5	50.7	50.5								3

# Characteristics table - 2

			Trial 1	Trial 2	Trial 3	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Variation
	Maximum current	A	5460	4463	3497	7510	7455	7427								83
	Quench Integral	MA^2s	28.7	20	14	53.5	50.7	50.5								3
Cernox_19188	Tmax	K	52.2	51.1	50.5	44.3	46.3	45.1								2
Cernox_19185	Tmax	K	56.1	54.4	53.2	52.3	53.8	53.1								1.5
PT100_D1_Anode	Tmax	K	13.7	15.3	14.1	9.2	9.3	10.3								1.1
PT100_D1_Cathode	Tmax	K	13.7	15.3	14.1	9.2	9.3	10.3								1.1
PT100_D2_Cathode	Tmax	K	15.7	23.5	18.6	14.3	15.8	17.2								2.9
PT100_D3_Cathode	Tmax	K	21.5	25.3	20.4	18.4	20.9	22.1								3.7
PT100_D4_Cathode	Tmax	K	20.1	26	22.6	25.5	27.2	26.5								1.7
PT100_D5_Cathode	Tmax	K	18.2	17.4	17.5	19.9	22.5	21.3								2.6
PT100_D6_Cathode	Tmax	K	6.9	7	6.9	12.8	14.4	13.4								1.6
Cernox_19188	time at T_max	s	13	10	9.5	8.3	6.9	6.6								1.7
Cernox_19185	time at T_max	s	6.1	9	9.6	7.5	6.9	7								0.6
PT100_D1_Anode	time at T_max	s	5	3.3	3.7	29.7	24.3	24.7								5.4
PT100_D1_Cathode	time at T_max	s	5	6.2	4.5	9.7	7.2	8.2								2.5
PT100_D2_Cathode	time at T_max	s	4.8	7.1	21.4	26.8	16.3	26.4								10.5
PT100_D3_Cathode	time at T_max	s	5	7.1	21.2	21.2	16.6	19.2								4.6
PT100_D4_Cathode	time at T_max	s	6.3	5.7	16.5	6.5	7.1	6.7								0.6
PT100_D5_Cathode	time at T_max	s	3.6	4.9	3.9	9.4	12.2	8.3								3.9
PT100_D6_Cathode	time at T_max	s	-9.2	-4.3	-10.8	7.6	6.8	6.8								0.8

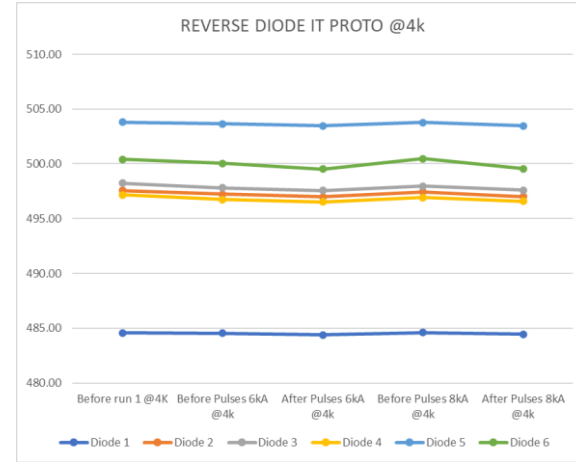


## Reverse voltage measurements



# Diode reverse voltage

REVERSE DIODE IT PROTO	15/02/2023	26/04/2023	2/5/2023	4/5/2023	1/6/2023	2/6/2023	8/6/2023		
	Before tests @300K	Before run 1 @4K	Before Pulses 6kA @4k	After Pulses 6kA @4k	Before Pulses 8kA @4k	After Pulses 8kA @4k	After tests @300K	ST DEV @ 4K	ST DEV @ 300K
Diode 1	601.88	484.57	484.54	484.40	484.61	484.44	601.60	0.09	0.20
Diode 2	616.52	497.56	497.24	496.98	497.45	497.01	616.11	0.26	0.29
Diode 3	618.60	498.25	497.80	497.58	497.98	497.59	618.75	0.28	0.11
Diode 4	617.16	497.18	496.73	496.54	496.94	496.58	617.32	0.27	0.11
Diode 5	625.63	503.82	503.65	503.46	503.79	503.48	625.67	0.17	0.03
Diode 6	622.15	500.41	500.04	499.53	500.47	499.56	621.13	0.45	0.72



## Test requirements



# Requirement vs what we can do in the test station

## MQXF – Dimensioning of the cross-section of the Cold-Diode bus bar

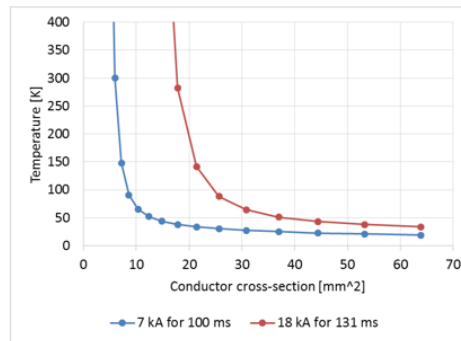
### Assumptions for Cold Diode worst considered case

- Initial temperature: 4 K
- Copper with RRR=100
- 0 magnetic field [no magneto-resistivity]

### Case 1: Worst considered case:

worst-case that can realistically occur.

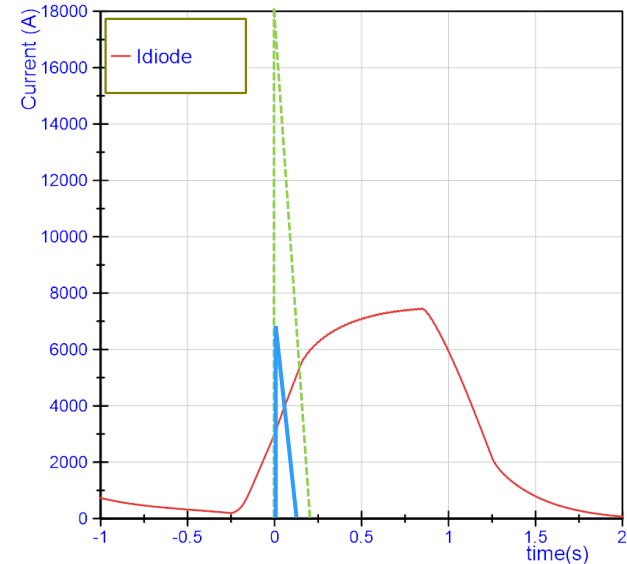
- Peak current: 7 kA
- Thermal load: 4.9 MJt
- Equivalent time, i.e. Thermal load / (Peak current)<sup>2</sup> : 100 ms
- **Recommended Cu cross-section: at least 20 mm<sup>2</sup>**



### Case 2: Diode carrying the full 18 kA during the magnet discharge:

case where the diode needs to carry the full current for the entire magnet discharge time. One cannot see an operational scenario when this could happen, but since the cold diodes are dimensioned for this case, it is considered.

- Peak current: 18 kA
- Thermal load: 42.5 MJt
- Equivalent time, i.e. Thermal load / (Peak current)<sup>2</sup> : 131 ms
- **Recommended Cu cross-section: at least 45 mm<sup>2</sup>**



In red: Test in SM18

In blue: Worst case in HL-LHC

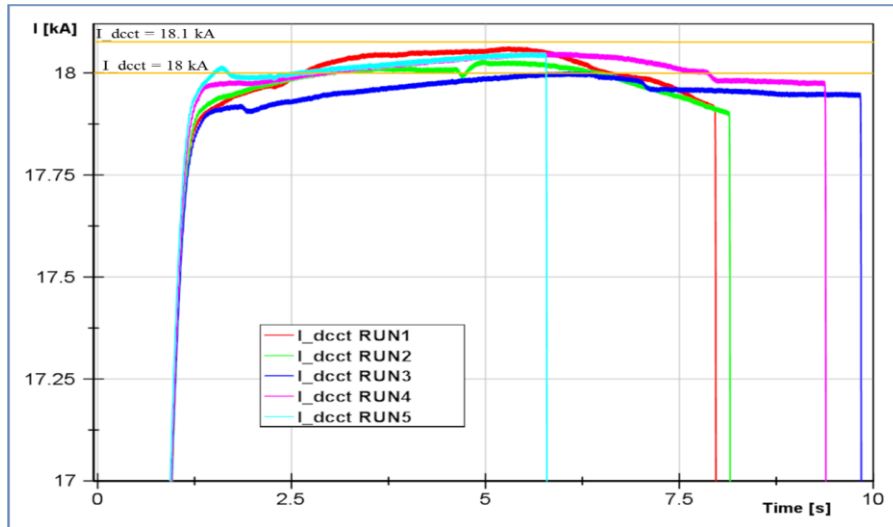
In green dashed: Impossible case.

# Special Diode test at 18 kA, done in 2018

See EDMS 1898621

Type test the diode for 6 to 10 seconds to 18 kA in a standard MB diode stack.

Diode worked well also after the tests.



## Summary

- Test sequence with good repeatability is defined. (this was not easy with the used powering circuit).
- Test done on the IT-Diode-Prototype cover well the worst case scenario foreseen in the HL-LHC
- All tests show repeatable results of the Ufwd, Urev, busbar resistances, temperatures, Diode-HS resistances.
- Time to finalize the test plan and define acceptance criteria.

**Mesure de resistance à reception des diodes****1. Alim Tti Pointe de touche (Multi Keithley 2001)**

	I[A]	HS-A [V]	HS-C [V]
D1	10	4.72E-06	8.30E-06
	20	8.68E-06	1.27E-05
	10	4.65E-06	8.07E-06
	Res[ $\mu\Omega$ ]	<b>0.40</b>	<b>0.45</b>
D2	10	5.78E-06	3.25E-06
	20	1.13E-05	6.20E-06
	10	5.73E-06	3.36E-06
	Res[ $\mu\Omega$ ]	<b>0.55</b>	<b>0.29</b>
D3	10	3.68E-06	1.96E-06
	20	8.94E-06	4.83E-06
	10	4.00E-06	1.91E-06
	Res[ $\mu\Omega$ ]	<b>0.51</b>	<b>0.29</b>
D4	10	4.83E-06	1.79E-06
	20	9.90E-06	4.13E-06
	10	4.95E-06	1.64E-06
	Res[ $\mu\Omega$ ]	<b>0.50</b>	<b>0.24</b>
D5	10	3.11E-06	1.71E-06
	20	6.78E-06	4.05E-06
	10	2.99E-06	1.73E-06
	Res[ $\mu\Omega$ ]	<b>0.37</b>	<b>0.23</b>
D6	10	2.42E-06	6.94E-07
	20	3.44E-06	2.25E-06
	10	1.50E-06	8.62E-07
	Res[ $\mu\Omega$ ]	<b>0.15</b>	<b>0.15</b>





