



Impact of HL-LHC radiation levels on cold diodes and first results from radiation tests

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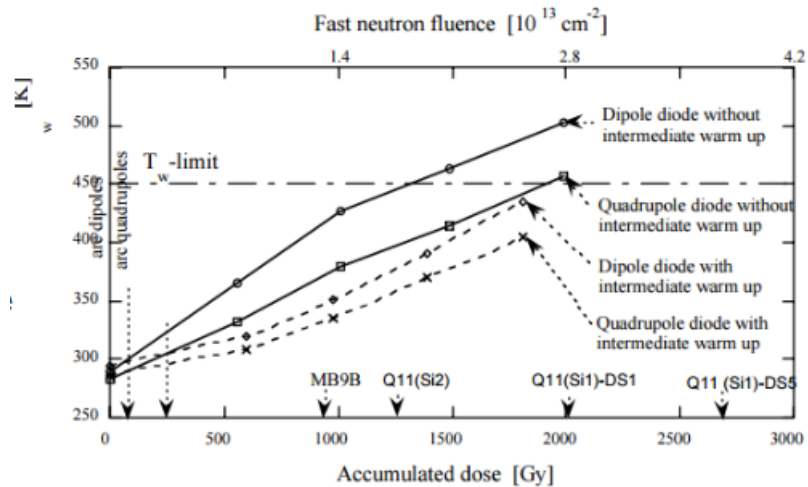
Introduction

- Following **TCC recommendation** (meeting #29, May 2017) to study the **option** of using **cold by-pass diode** to **protect HL-LHC Inner Triplets**, the project started in September 2017.
- Depending on the powering scheme, including constraints for bus bar routing along the cold mass, there are two possibilities:
 - Use **18 kA** cold by pass diode.
 - Use **7 kA** cold diode.
- The estimate radiation level that the cold by-pass diode should withstand is of **30 kGy and $> 10^{14} \text{ n cm}^{-2}$ fluence**, considering 3000 fb-1.
- Start studying the two parallel paths, 18kA and 7kA, based on the experience and know how that we have from the actual LHC diodes produced by Dynex.

LHC Cold diode radiation qualification (2003)



- Specially developed for LHC by-pass diodes manufactured in industry.
- Irradiation tests in TCC2 at liquid nitrogen temperature.
- Installed inside magnet cryostat, relatively close to the beam.
- Effect: wafer temperature increase due to radiation (forward bias increase)
- **Qualified lifetime: 2 kGy and $3 \times 10^{13} \text{ n cm}^{-2}$** (largely sufficient for by-pass diodes at LHC ARC locations; in DS, annual annealing and even replacement was foreseen).



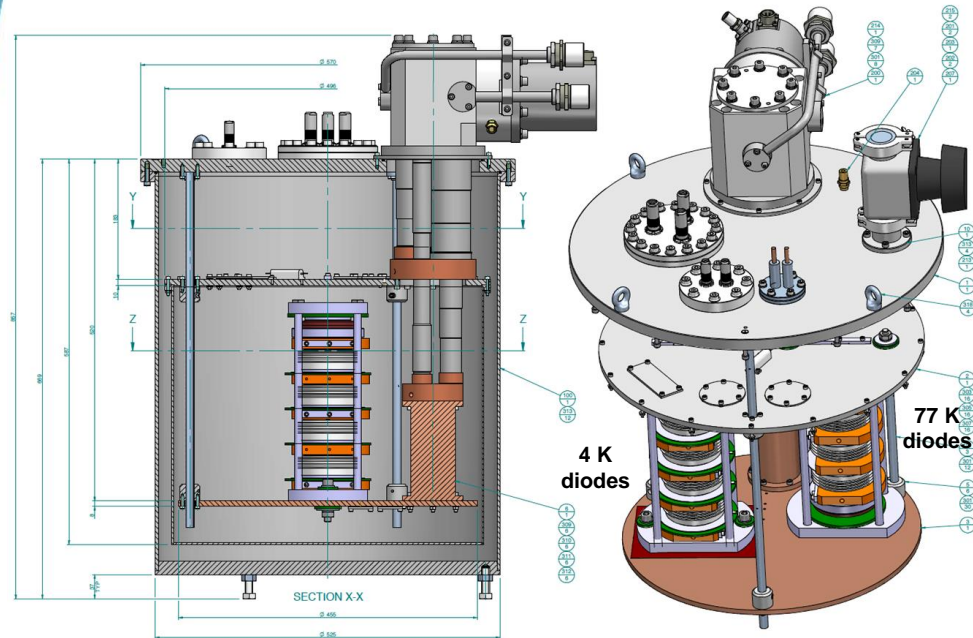
R. Denz, LHC project note 688 (2003).

Cold diodes for HL-LHC triplet circuit

- Re-established the contact with **Dynex** and ensured that they still have the “**know how**” to produce similar diffusion diodes as for the **LHC** (reference).
- Asked Dynex to **specially develop and produce** diffusion by-pass diodes **more radiation tolerant** (thin and very thin base width), in order to **qualify** them in a dedicated radiation area at CERN, in CHARM test facility, **during 2018 RUN**.
- **Comparative** approach for radiation testing: common test campaign to **reproduce the LHC diode radiation test results together with tests of new prototype diodes** in CHARM in 2018. Then to **study their behaviour with the maximum radiation** we could get until end of 2018, as close as possible to HL-LHC requirements.
- **Designed and produced a cryo-cooler based system** in order to qualify the diodes at **77K** and **4K** being exposed to **radiation**.
- **Designed and produced** the entire diodes **test bench** (power and control part) according to the HL-LHC diodes parameters, and **integrate** the system into **CHARM** test facility.
- Perform **specific electrical tests** on the diodes as a function of different parameters (temperature, integrated dose) and monitor their **characteristics**.

Cryo-cooler setup for HL-LHC cold diodes

- 3D model



- Real assembly



Measuring system for HL-LHC cold diodes

- Complete new test bench, built from scratch, for HL-LHC diodes: **18kA**, **40m distance**, radiation environment and capable to:
 - Measure diodes electrical parameters: U_{TO} , U_{FWD} , U_{REV}
 - 77 and 4 K temperatures monitoring
 - Heaters control and regulations
 - Database results



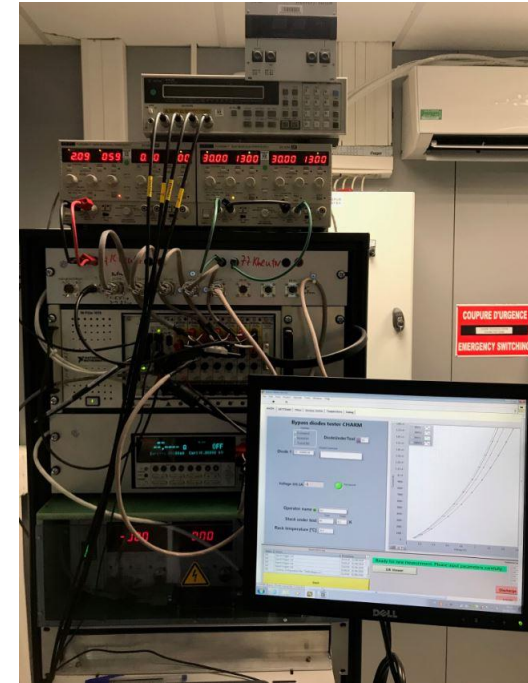
Measuring setup located in control room



Cryo-cooler and diodes in radiation area

Electrical tests and parameters measured on HL-LHC cold diodes

- The **turn-on voltage**, U_{TO} , $I_{to} = f(U_{to})$, at 4.2K and 77.0K is measured by applying a **voltage ramp** with a fast enough rise rate on **each diode individually** and measuring the **voltage drop** over it, e.g. the current flowing through. Voltage ramp rates up to 10 kV/s are possible.
- The **reverse bias voltage** U_{REV} is measured on each diode at 4.2 and 77.0K, up a reverse bias current of 1 mA.
- The **capacitance** measurement is performed using an LCR meter and an excitation voltage amplitude below U_{TO} .
- On the 77 K stack, a **pulse of current** is sent through **4 diodes** connected in series. The **voltage** drop of each diode is **measured individually** at the peak of the current pulse, where $dI/dt=0$. The pulse is generated by the pulse generator, located in the rack located in the control room. We obtain the **full forward characteristics** of the diodes $U_{FWD}(I)$ as a function of the applied current **up to 18 kA**.

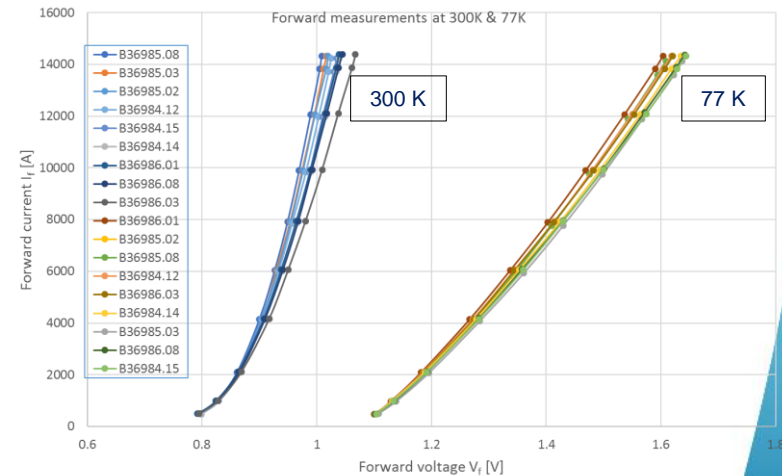


Reference measurements on HL-LHC diodes at 300K and 77 K in MPE diode lab

- “Virgin” measurements were performed on the **3 families** of new diode production, 3 samples of each type: **LHC diodes**, **thin base diodes** (more radiation tolerant) and **very thin base diodes** (even more radiation tolerant).

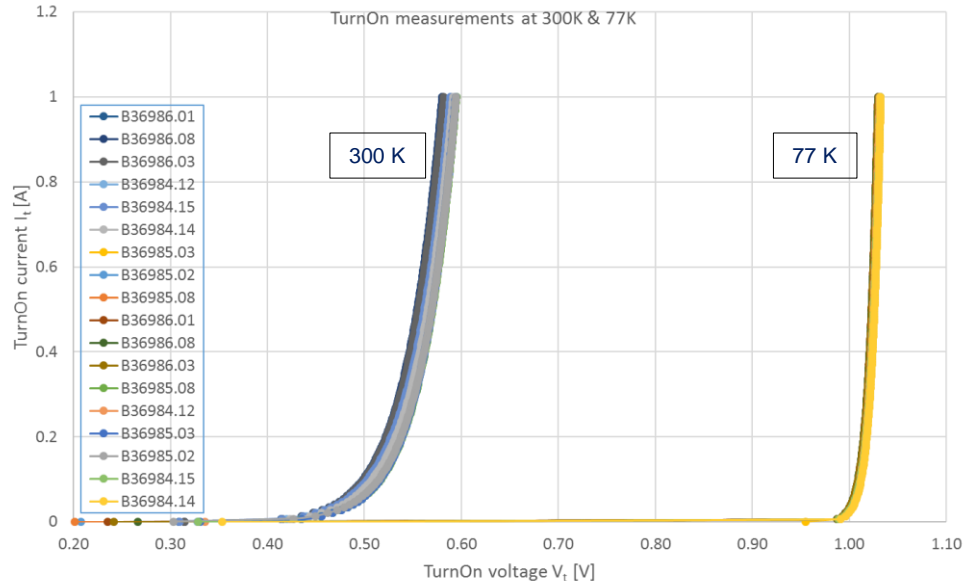


$U_{FWD}(I)$ vs Temp, 3 Diodes types

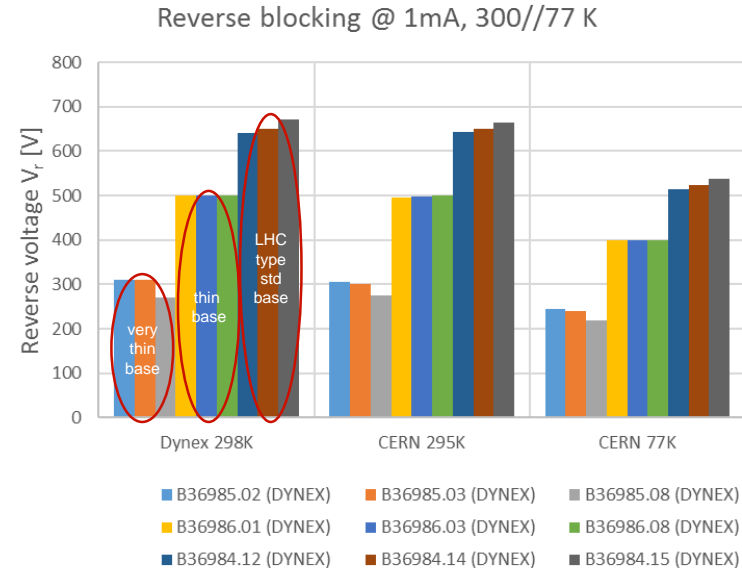


Reference measurements on HL-LHC diodes at 300K and 77 K in MPE diode lab

U_{TO} (I) at 300K and 77K, 3 diodes types



U_{REV} at 300K and 77K, 3 diodes types

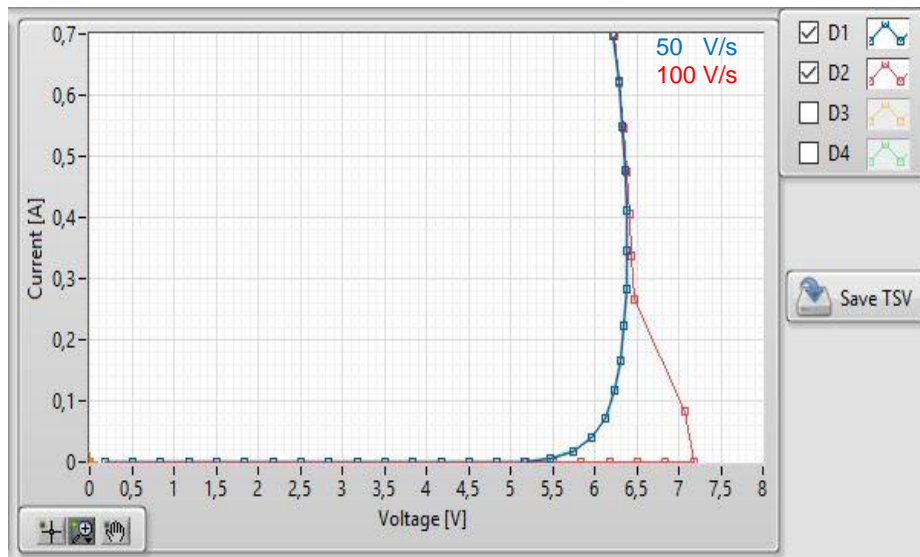
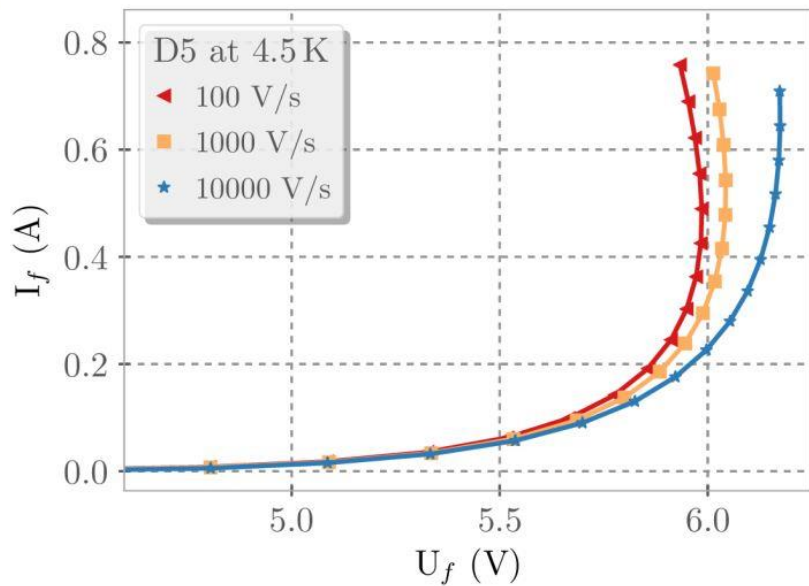


Test conditions and measurement rate for HL-LHC cold diodes in CHARM

- Measure diodes characteristics as **function of temperature** in order to be able to **extrapolate** results for different temperatures.
- Perform **full set of measurements** (U_{TO} , U_{FWD} , U_{REV} and Capacitance) on **77K** and **4K** irradiated diodes, on a **weekly** basis, following a **specific test sequence**, when there is no beam in the target area.
- The average increase in radiation is estimated to be: **500 Gy / week**, total dose of **~10kGy** and total fluence at the end of the 2018 RUN: **$> 10^{14} \text{ n cm}^{-2}$** .

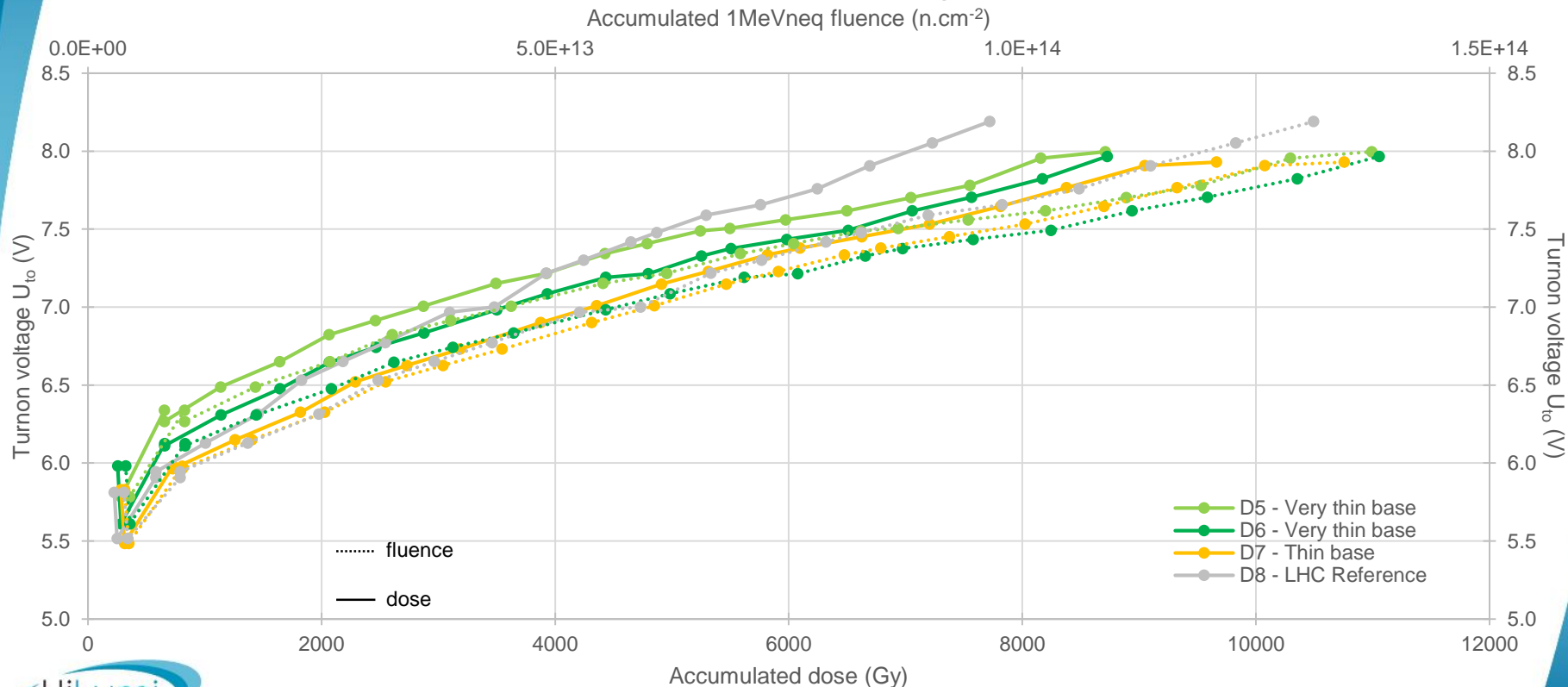
Typical data recorded on a weekly rate basis: U_{to}

- **Turn On** characteristic $I_{to} = f(U_{to})$ of each diode at 4.20K and 77.00K is measured by applying a voltage ramp with proper rise rate on each diode individually and measuring the voltage drop over it, e.g. the current flowing through it.



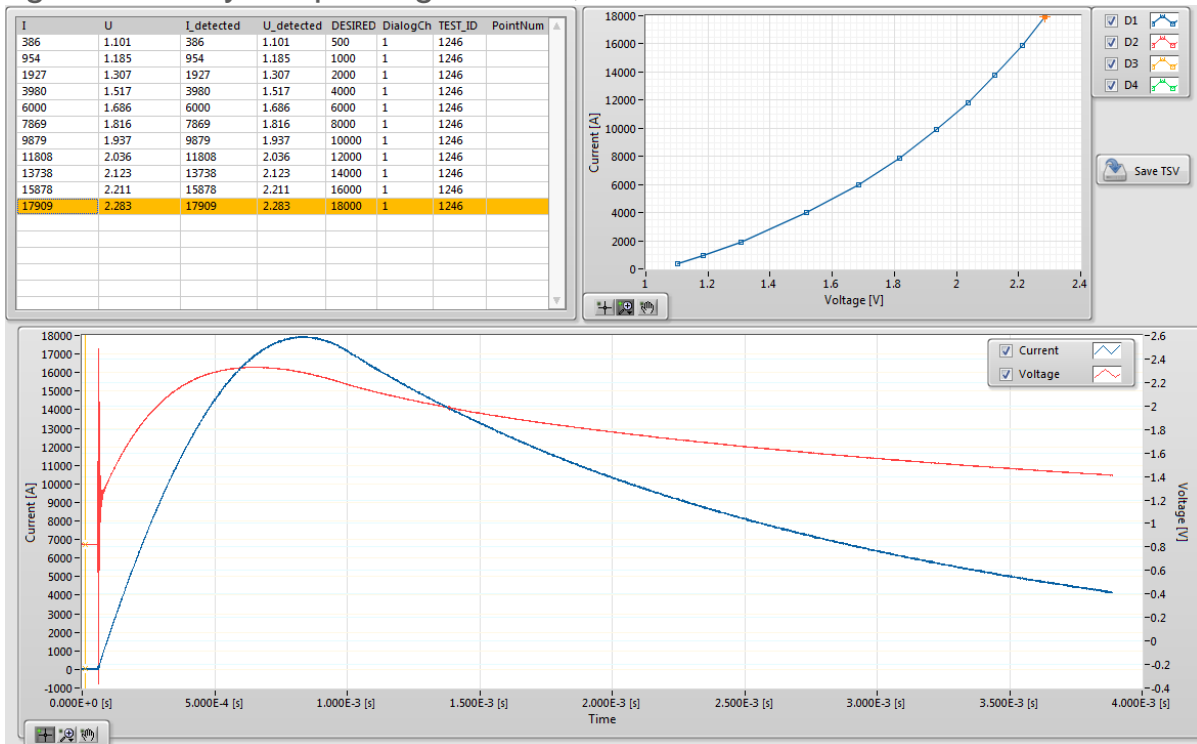
Evolution of U_{to} at 4.20K since the beginning

TurnOn measurements - Maximum voltage value - $T = 4.20K$



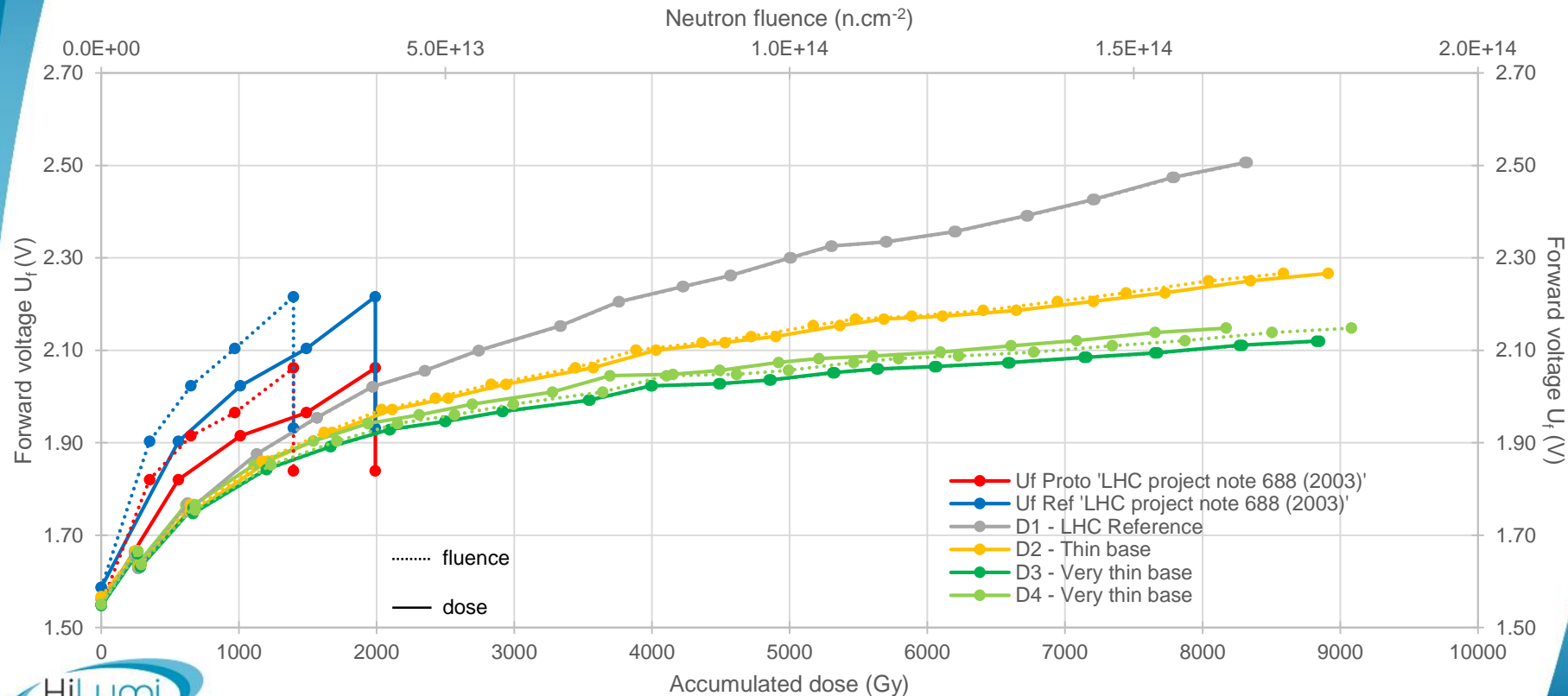
Typical data recorded on a weekly rate basis: U_{FWD}

- To measure the U_{FWD} , a pulse of current is sent through the entire 77K diode stack. The voltage drop on each diode is measured individually at the peak of the current pulse, where $di/dt = 0$. The pulse is generated by the pulse generator, located at the rack in the control room, 40 m away.



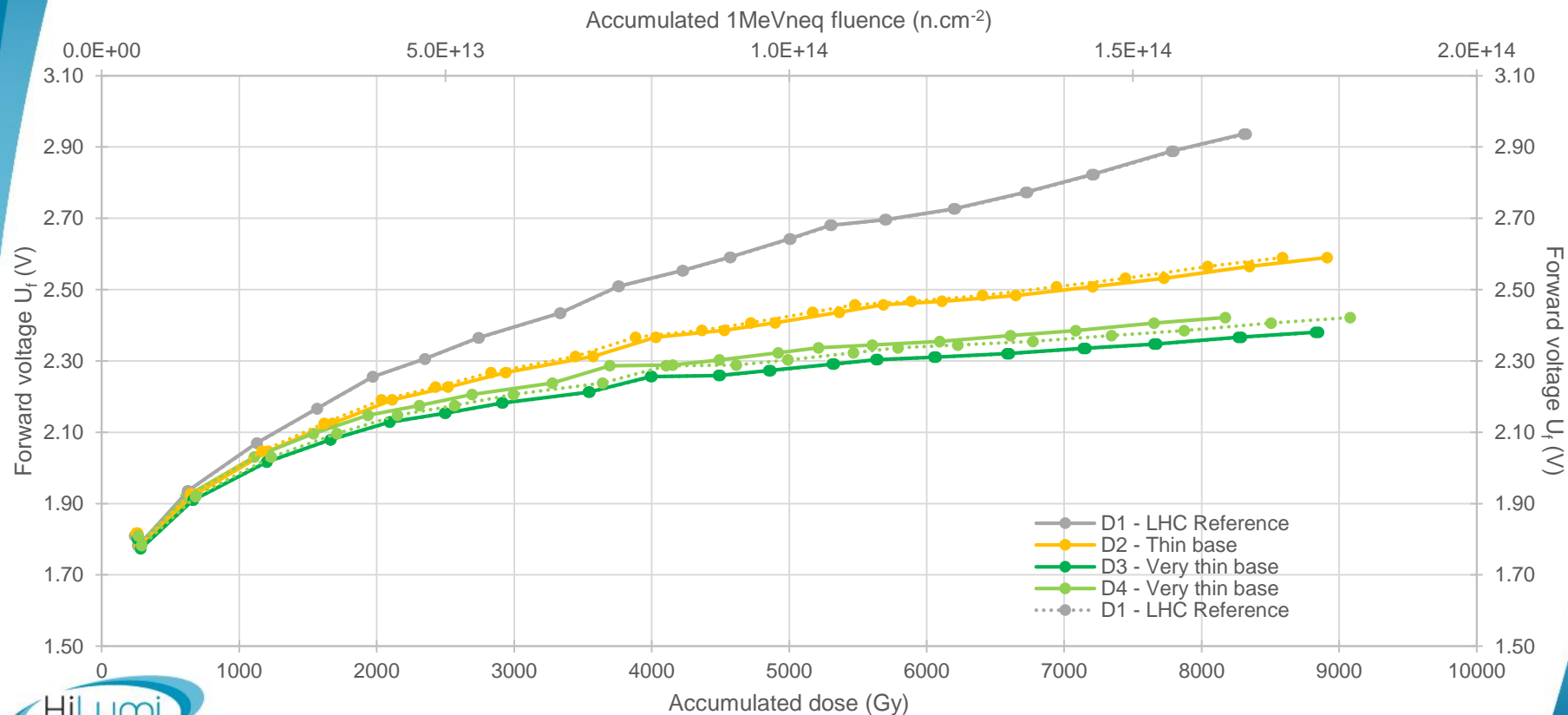
Evolution of U_{FWD} at 12kA since the beginning

Forward measurements - $I = 12\text{kA}$



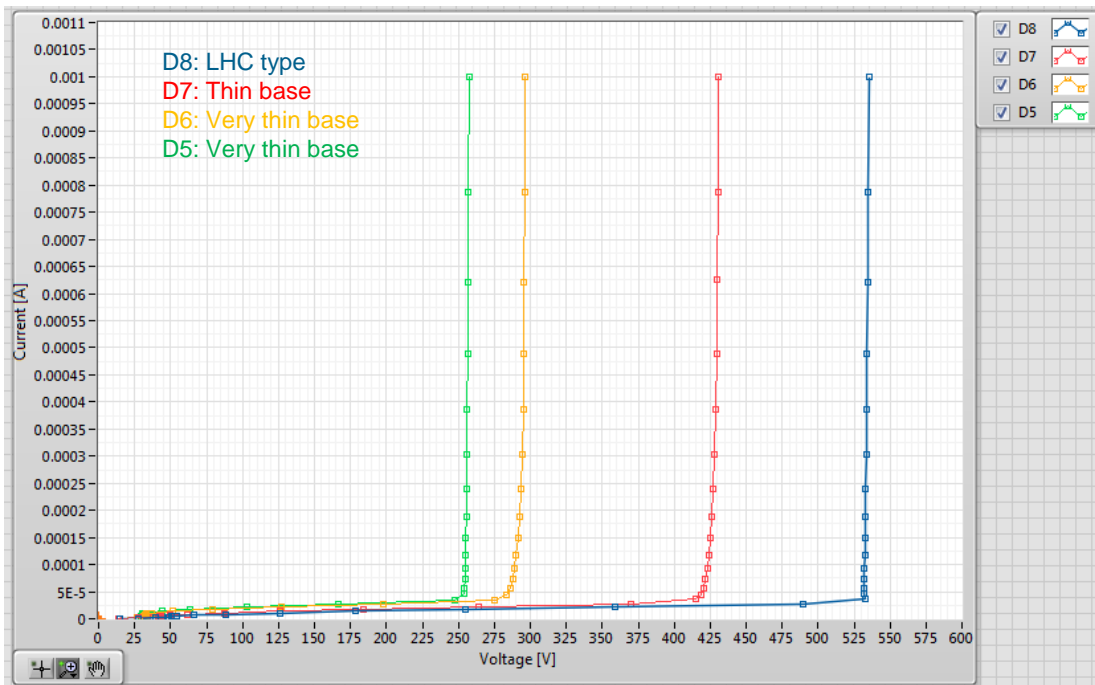
Evolution of U_{FWD} at 18kA since the beginning

Forward measurements - $I = 18\text{kA}$



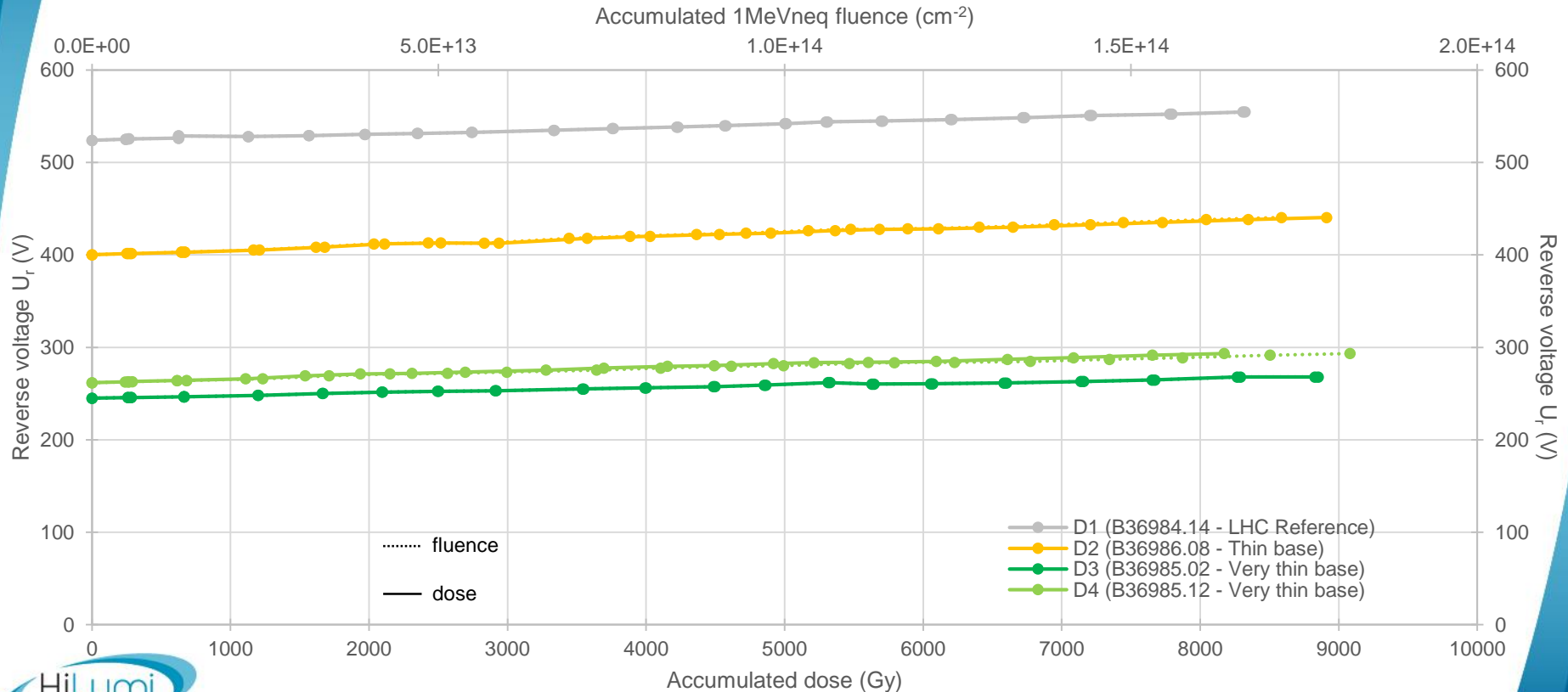
Typical data recorded on a weekly rate basis: U_{REV}

- **Reverse** characteristic $I_r = f(U_r)$ of each diode at 4K and 77K is measured, in each diode separately, up to a maximum reverse bias current of $I_{rmax} = 1$ mA.



Evolution of U_{REV} since the beginning:

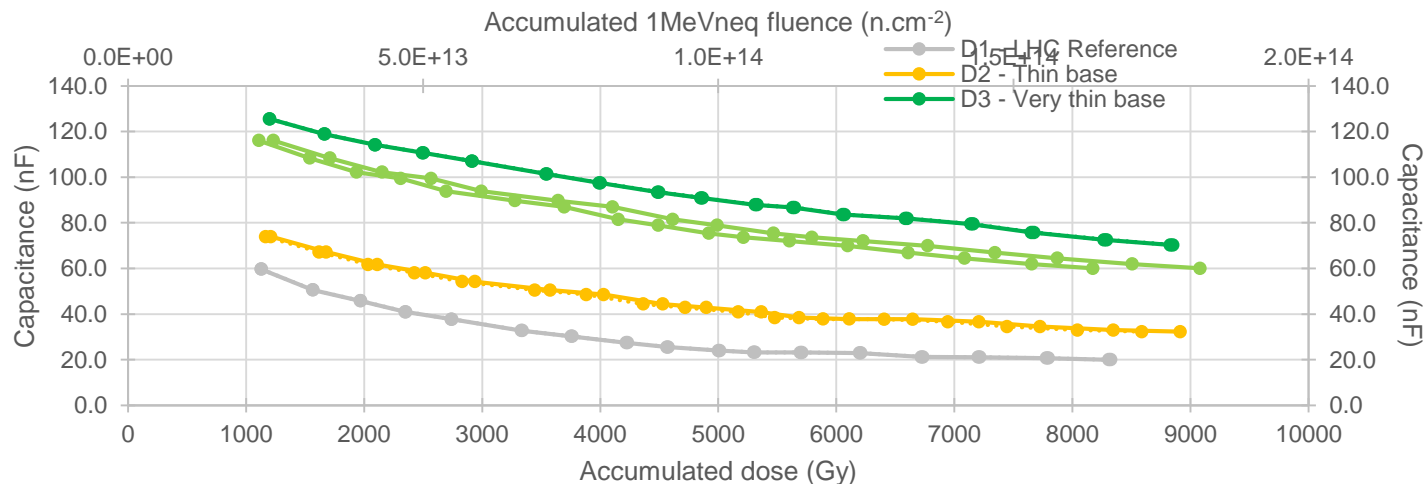
Reverse measurements - $I = 1$ mA - $T = 77$ K ; 4.2 K very similar !



Evolution of the capacitance measurement

- The capacitance measurements at 77K can be used as a marker of the radiation level. The value decreases showing the effect of the radiation on the wafer.

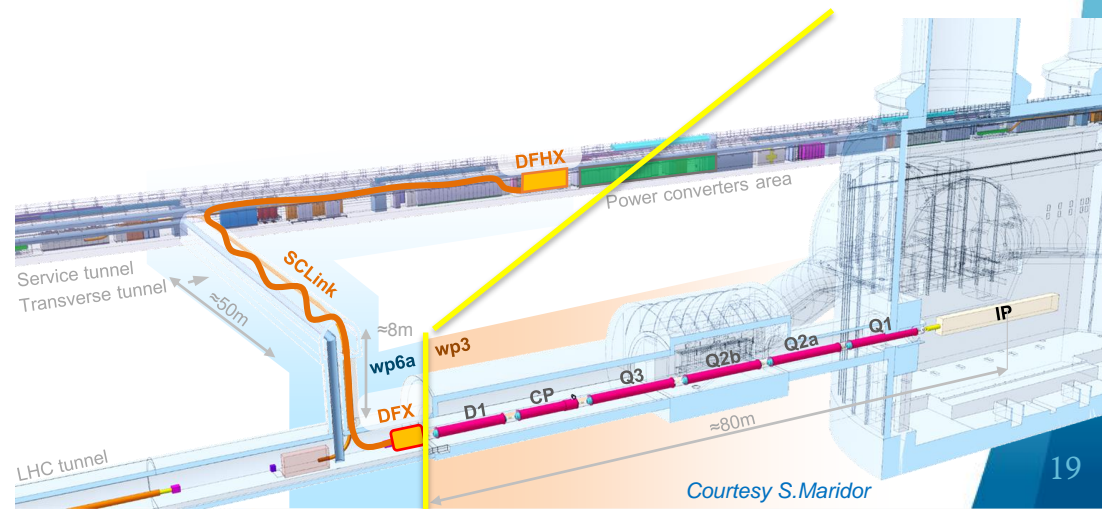
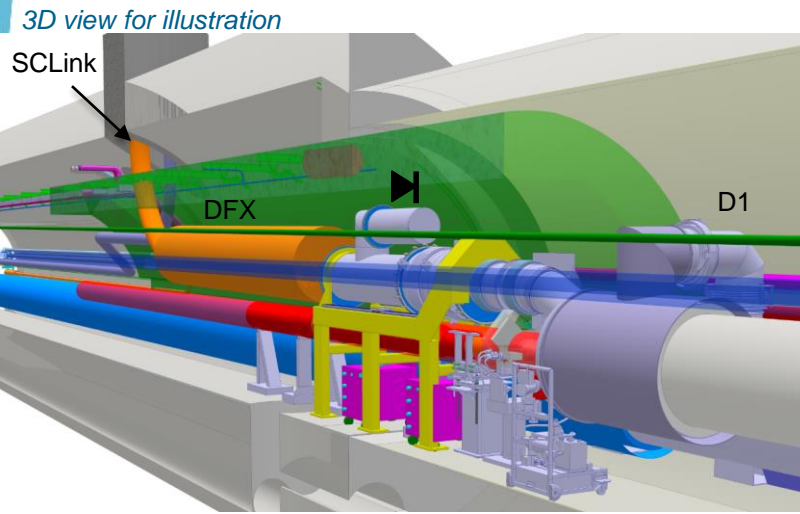
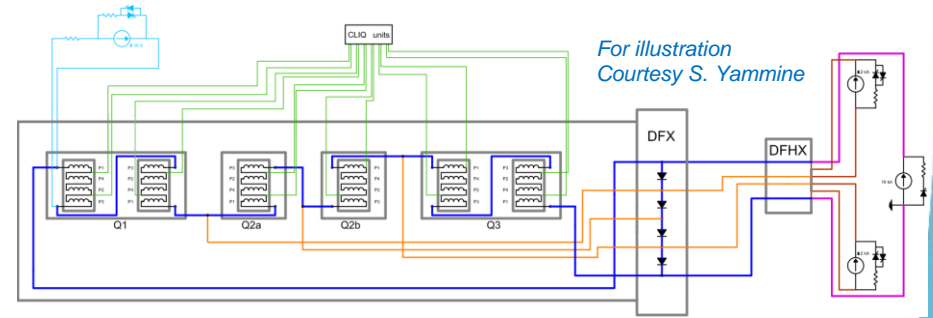
Capacitance measurements - T = 77K



- We plan to study the **annealing effect** at the end of the test campaign this year in order to **extrapolate data for, both LHC and HL-LHC**.

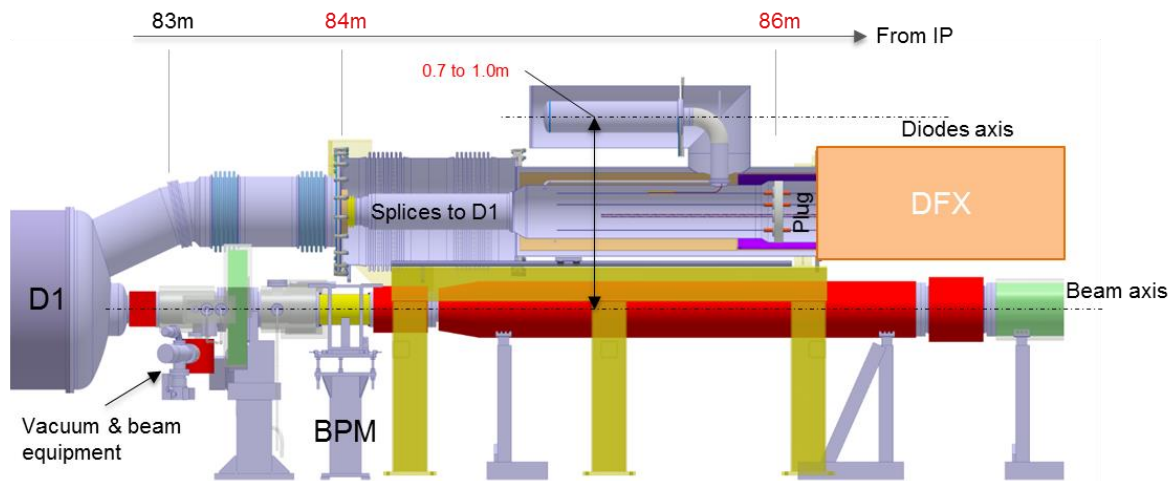
Studies on the integration of the cold diode (Y. Leclercq)

- Integration of cold diodes in triplet magnet electrical circuit
- Best compromise for integration is between Magnets and SCLink
- Between DFX and D1



Update on radiation studies (Rubén García Alía)

Possible inner triplet cold diode HL-LHC location



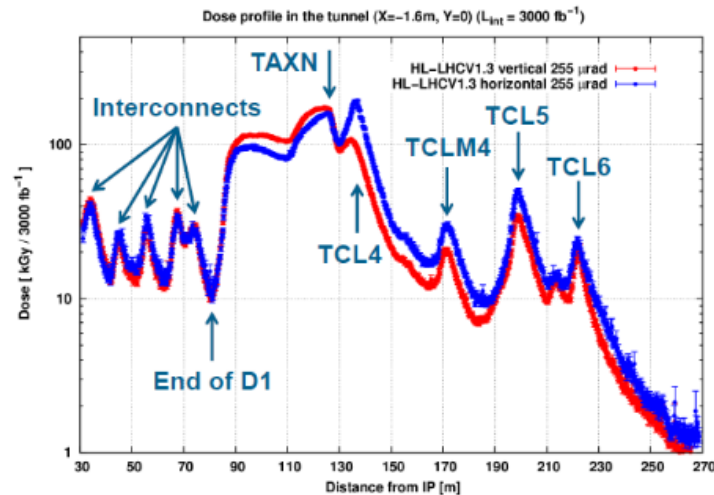
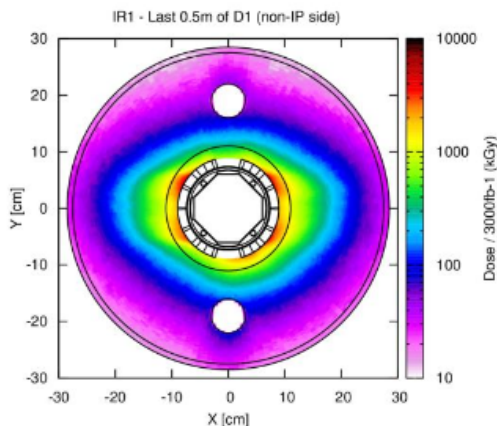
Input from Yann Leclercq (TE-MS),
Further details in parallel session.

- Most up-to-date diode position:
 - ~70 - 100 cm vertically from the beam
 - 85 - 86m from the IP
- Radiation values in this presentation based on slightly different position from previous iteration:
 - **50 - 70 cm vertically**
 - **85m from IP**

Update on radiation studies (Rubén García Alía)

Previous FLUKA results for end of D1 location radiation level evaluation:

- Estimated radiation levels based on “best-case” location near D1
- **$\sim 30 \text{ kGy}/3000 \text{ fb}^{-1}$** for area outside cold mass in last 0.5m of D1
- D1 provides significant dose shielding, values rapidly increase further downstream

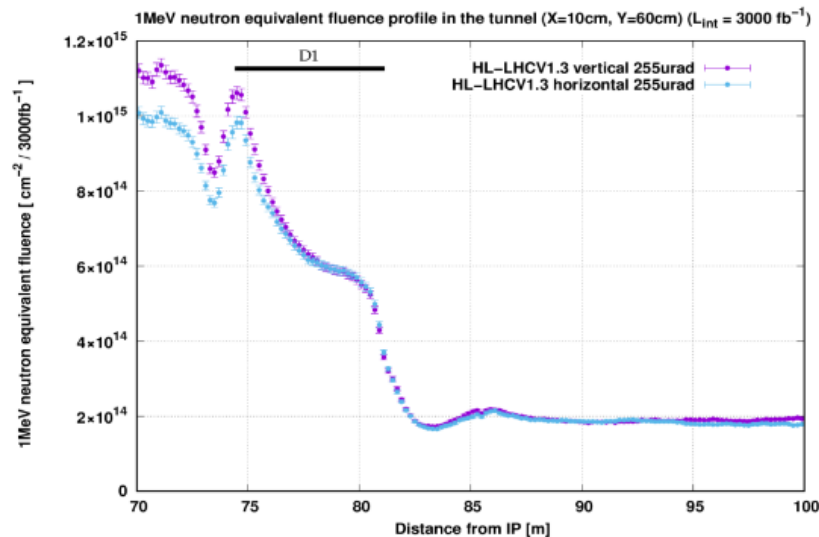
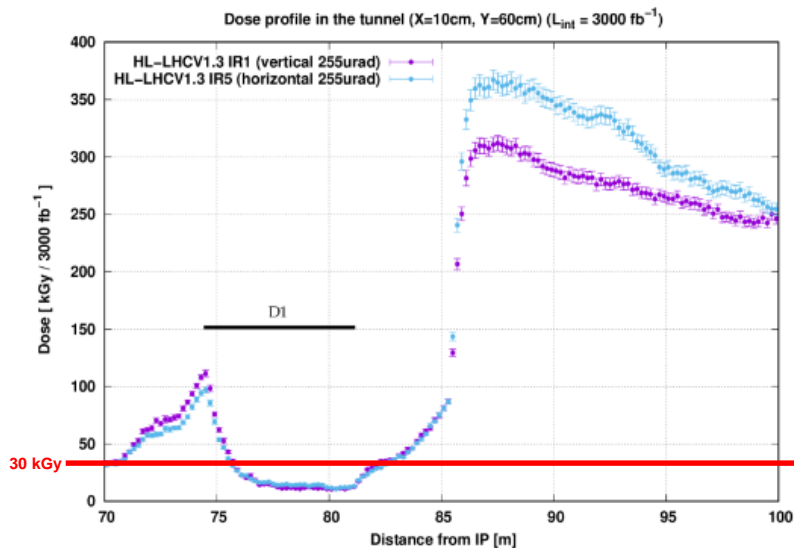


“Update on HL-LHC radiation levels for inner triplet cold by-pass diodes”, R. G. Alia (Nov 2016)

Update on radiation studies (Rubén García Alía)

Radiation levels based on updated diode position

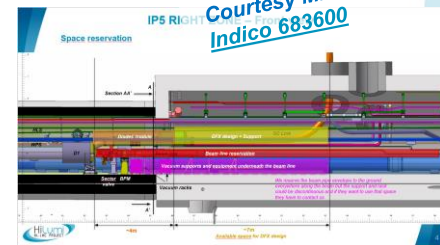
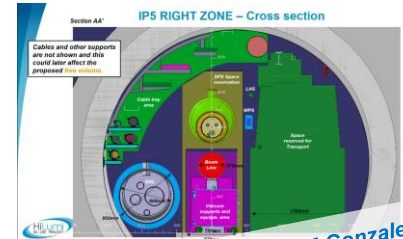
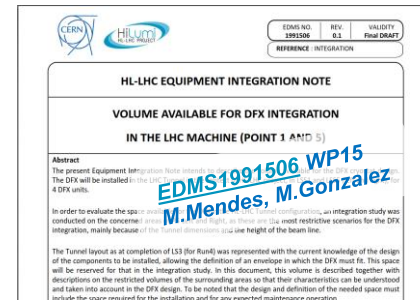
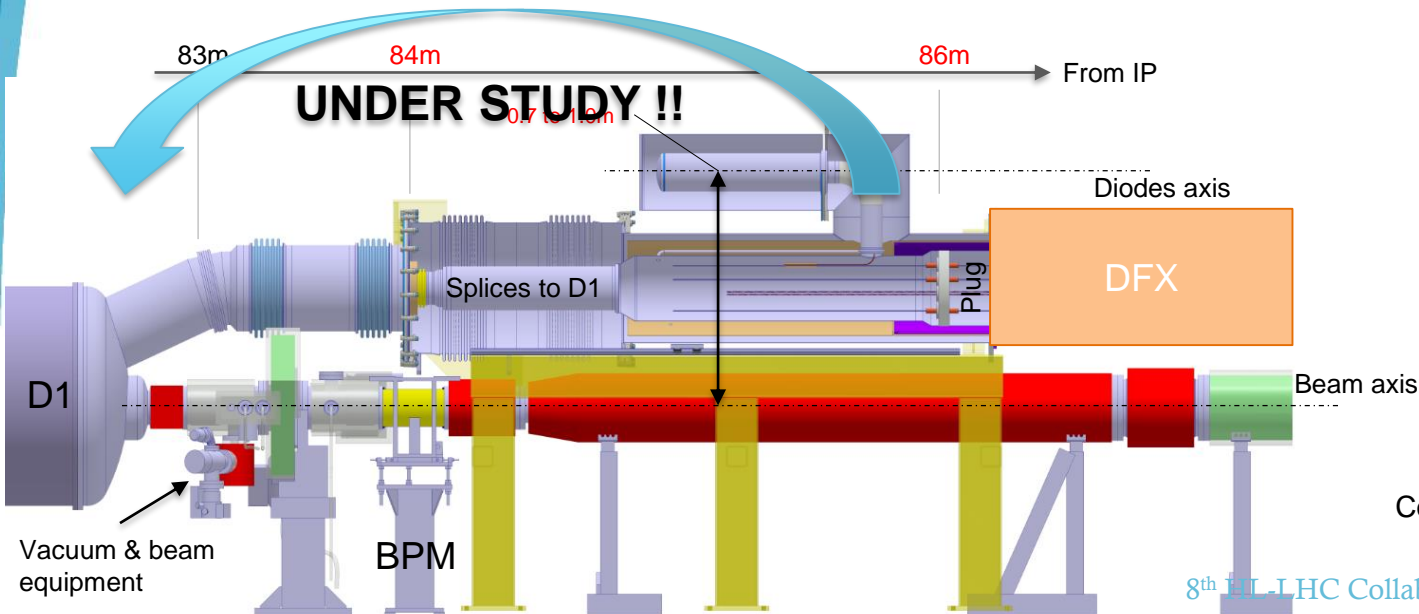
- Scoring region: in air, $0 < x < 20\text{cm}$, $50\text{cm} < y < 70\text{cm}$; HL-LHC optics version 1.3



Simulations by Andrea Tsinganis (EN-STI)

Cold Diodes Module integration

- Integration boundaries extrapolated from EDMS 1991506
- Cold diodes preliminary location:
 - 84-86 m from IP
 - Radially : $\approx 0.7\text{m}$ to 1.0 m from beam axis



Courtesy of Y. Leclercq

Studies on LHC Cold Diodes radiation

- In order to evaluate the **need** of diode replacement in DS sections due to **radiation degradation**, EN/STI team estimate the dose level received by the LHC diodes up to end of 2017, up to LS2 and later for HL-LHC.

Estimated diode dose: today and LS2 projection

- The evaluation of radiation level was based on:
 - For present machine: BLM measurements near diodes scaled with FLUKA for specific diode locations
 - For HL-LHC: FLUKA simulations

BLM	BLM dose (Gy)	dcum (m)	Diode	Total Dose now (Gy)	Ion Dose (Gy)	Total Dose LS2 (Gy)
BLMQI.08R1.B1E30_MQML	41.0	309.3				
BLMBI.09R1.B0T10_MBA-MBB_08R1	54.0	323.6				
BLMQI.11R1.B1E10_MQ	184.1	434.4	MQ11	123	23.5	192
BLMQI.13R1.B1E10_MQ	46.7	542.6				
BLMQI.13L5.B2E10_MQ	36.9	12787.6				
BLMBI.11L1.B0T20_MBA-LEFL_11L1	41.6	26240.1				
BLMQI.09L1.B2E10_MQM	178.5	26318.4	MBB9	119		155
BLMBI.09L1.B0T10_MBB-MBA_08L1	31.3	26335.3				
BLMBI.11L5.B0T20_MBA-LEFL_11L5	154.9	12910.6	MBB11	186	143	437
BLMQI.09L5.B2E10_MQM	195.6	12988.9	MBB9	130		170
BLMQI.08R5.B1E30_MQML	212.7	13638.7	MBA9	142		185
BLMQI.11R5.B1E10_MQ	285.2	13763.9	MQ11	190	25.5	283
BLMQI.10L2.B2I10_MQML	305.5	2950.9	MBB10	204	153	474
BLMQI.12R2.B1I10_MQ	196.3	3821.1	MQ12	131	98	304

Considerations: For quadrupole BLMs: level on diodes 1.5 smaller; for dipole BLMs: level on diode same as BLM + 20% more for Run 1; 2018 luminosities: $50fb^{-1}$ for protons, $1nb^{-1}$ for ions

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Estimated integrated dose and fluence during HL-LHC

Integrated dose and fluence during HL-LHC

Magnet	TID (kGy)	1MeV neq (cm-2)
MBA9	2.11	2.37E+13
MBB9	6.44	7.87E+13
MBB11	2.61	3.39E+13
Q11	5.95	3.80E+13
Q13	1.61	1.29E+13

- Considering **only proton runs, right of IP5**, and normalized to full HL-LHC lifetime of 3000 fb⁻¹

Conclusions

- The study of cold by-pass diodes for the HL-LHC inner triplet in CHARM test facility is proceeding well. Continuous monitoring of the diode characteristics is performed on a weekly basis, until the end of 2018 RUN (Nov. 2018).
 - We expect to get an integrated dose of about **10 kGy** and a total fluence of about **$2 \cdot 10^{14} \text{ n cm}^{-2}$** .
 - The integrated dose will be below HL-LHC requirements, but nevertheless will demonstrate the radiation tolerance of the new diodes minimum till LS4.
 - The **fluence** is dominating damage in the diodes and **$2 \cdot 10^{14} \text{ n cm}^{-2}$** achieved this year is representative for HL-LHC.
- We need to **qualify in future** the same diode type **up to a nominal level** of integrated dose for HL-LHC Inner Triplet of 30 kGy.
- The **position of the cold diodes should be further optimized**, around longitudinal position of **83 m.** from IP.
- The tests in CHARM on LHC standard diodes are showing very satisfactory results indicating no need to replace the LHC diodes in DS radiation hot spots, however the spectrum and uncertainty in dosimetry should be further studied, in particular for ion runs.
- **Two diodes that received the highest dose by LS2** (MBB11.L5 and MBB10.L2, with roughly **500 Gy**) will be removed during the shutdown for further studies.



Special thanks to CHARM test facility team.

Thank you for your attention