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Thurel Yves

With inputs from J. Clar, B. Favre, J. Milovanovitch
CERN, for R2E Annual Meeting - 2021-02-03 @ CERN

Design of a 500 Gy Rad-Tol Converter

Design challenges of R2E-HL-LHC(60;120)A

R2E Annual Meeting

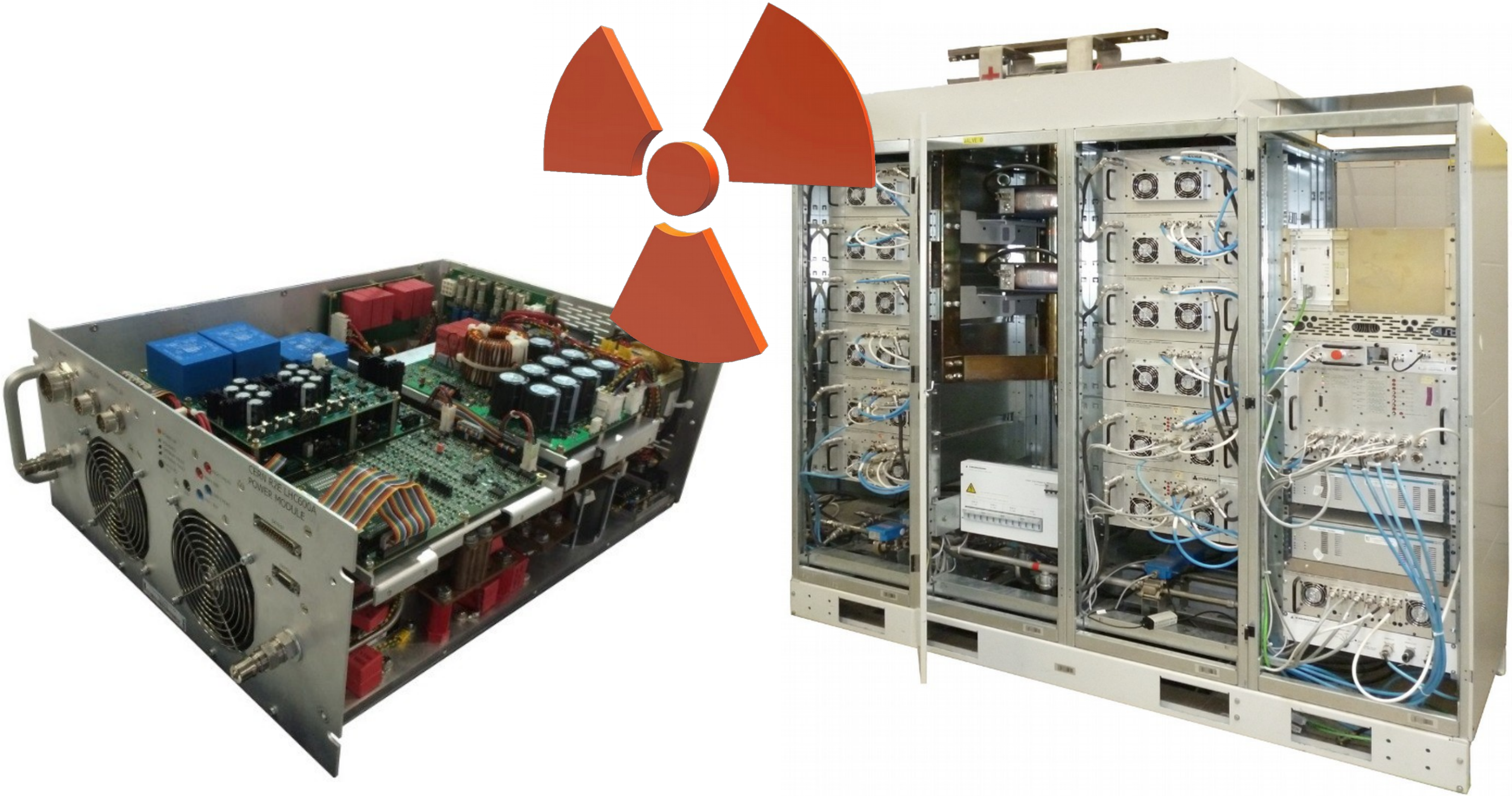
Document source https://edms.cern.ch/document/2475659/
Meeting link (indico) https://indico.cern.ch/event/971222

Introduction

This talk intends to

- Describe the design of a up to 500 Gy power converter in the context of the **current 60/120A re-design of converters**
- Give some hints of our **learnt lessons** from previous design
- Describe some important **design paths** in the coming process

Previous R2E-Converters: installed in LHC @ LS2



Context

From Radiation levels to Converter Project Data, optimizing Design Effort

Context – Radiation Levels in LHC

Radiation levels (HL)

- 600A / kA already renewed
- 60A / 120A highly exposed
  - In the range of [120; 300] Gy
  - 72 units in the tunnel (60A)
  - 92 units in RR1/5 (120A)

Design Target

- 60A / 120A
  - **Set in [400; 500] Gy range** (ELDRS + margin.)

Area	Dose [Gy/year]	1MeV n-eq. [nb/(cm^2.year)]	E>20MeV HE [/(cm^2.year)]
Tunnel R2E-HL-LHC60A-10V 72 units (072 (cell[12;16] Pt1,2,5)	08x 12L/R2: <10 08x 12L(1/5): <10 08x 12R(1/5): <03 48x 14/16-L/R-1/2/5: 1.5	<1E11 3E10	**<1E10** **3E9**
Tunnel LHC60A-08V (678 - 72) units R2E-HL-LHC60A-10V 72 units (550x Cell>17) (120x cell[12;17] Pt3,4,6,7,8)	**0.5**	3E10	**3E9**
RR13/17 R2E-HL-LHC120A-10V 36 units R2E-LHC600A-10V 28 units R2E-LHC6kA-08V 26 units R2E-LHC6kA-08V 04 units ** installed with 5kA DCCT*	level-0: **15** level-1: **25**	level-0: **7E10** level-1: **7E10**	level-0: **1.0E10** level-1: **1.4E10**
RR53/57 R2E-HL-LHC120A-10V 36 units R2E-LHC600A-10V 28 units R2E-LHC6kA-08V 26 units R2E-LHC6kA-08V 04 units ** installed with 5kA DCCT*	level-0: **15** level-1: **25**	level-0: **7E10** level-1: **7E10**	level-0: **1.0E10** level-1: **1.4E10**
RR73/77 R2E-LHC600A-10V 48 units R2E-HL-LHC120A-10V 20 units R2E-HL-LHC600A-10V 02 units	**0.5**	4E9	**2E8**
UL14/16 R2E-HL-LHC120A-10V 16 units R2E-LHC600A-10V 02 units	**0.01** close to US15/17 **0.10** in UL14/16$_{middle}$ **1.00** close to UJ14/16	**2E8** close to US15/17 **1E9** in UL14/16$_{middle}$ **1E10** close to UJ14/16	**2E7** close to US15/17 **1E8** in UL14/16$_{middle}$ **1E9** close to UJ14/16
UA/J(s), TZ76, UJ33, UR15/57 Some local exception in Point 6 "sea level" expected (Th. n. excepted)	**0.01**	[5E6; 2.5E7]	**[1; 5]E6**

Context – (60;120)A Joined Optimized Design

Converter redundancy

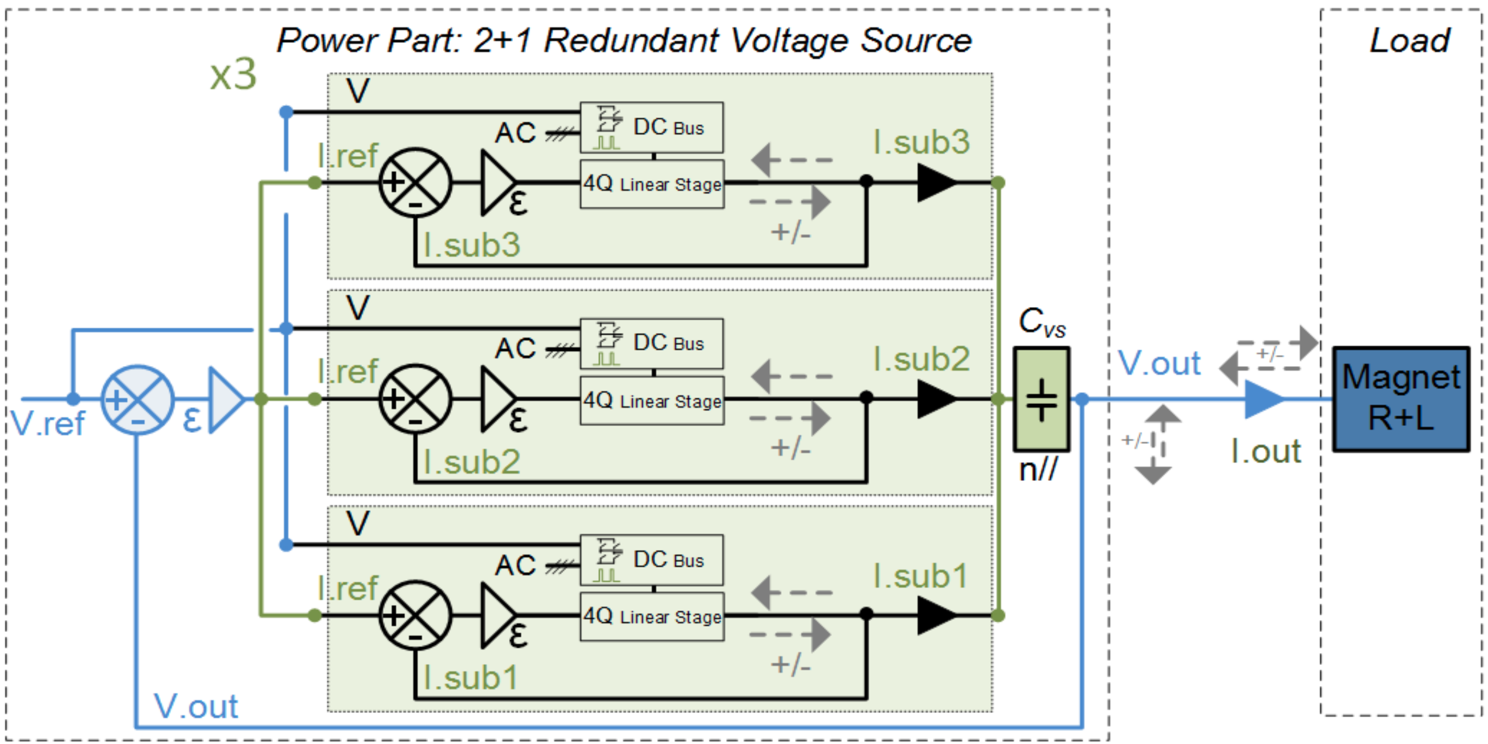
- **Generalization of redundancy concept to new (<120A) R2E versions.**
  - HL-LHC availability target (radiation or not induced impact on operation)
  - **New R2E-HL-LHC60A & R2E-HL-LHC120A will be redundant**

Optimization of Design effort

- **060A converters = 2 x 60A in // (n+1 = 1+1) = 2.0 x installed power**
- **120A converters = 3 x 60A in // (n+1 = 2+1) = 1.5 x installed power**
- **Designing 60A & 120A converters:**
  - **One 60A Power Source only to design which can operate in // for redundancy**

Converter Control Loops

- Inner Current Loop (sharing current load)



Project Data: One Common 60A/120A project

Project Owner & Involved People

- Project owner(s): **Thurel Yves** | project leader
  Benoit Favre | pwr elec. designer
  Jeremie Clar | radiation expert | fellow | 2020-09
  Jeanne Milovanovitch | pwr elec. Designer | fellow | 2020-09

Project Main Purpose

- Provide & manage the delivery of highly reliable & radiation tolerant – redundant – **60A & 120A converters for LHC (R2E) & HL-LHC** (new units), for **LS3**.

Project Main Deliveries

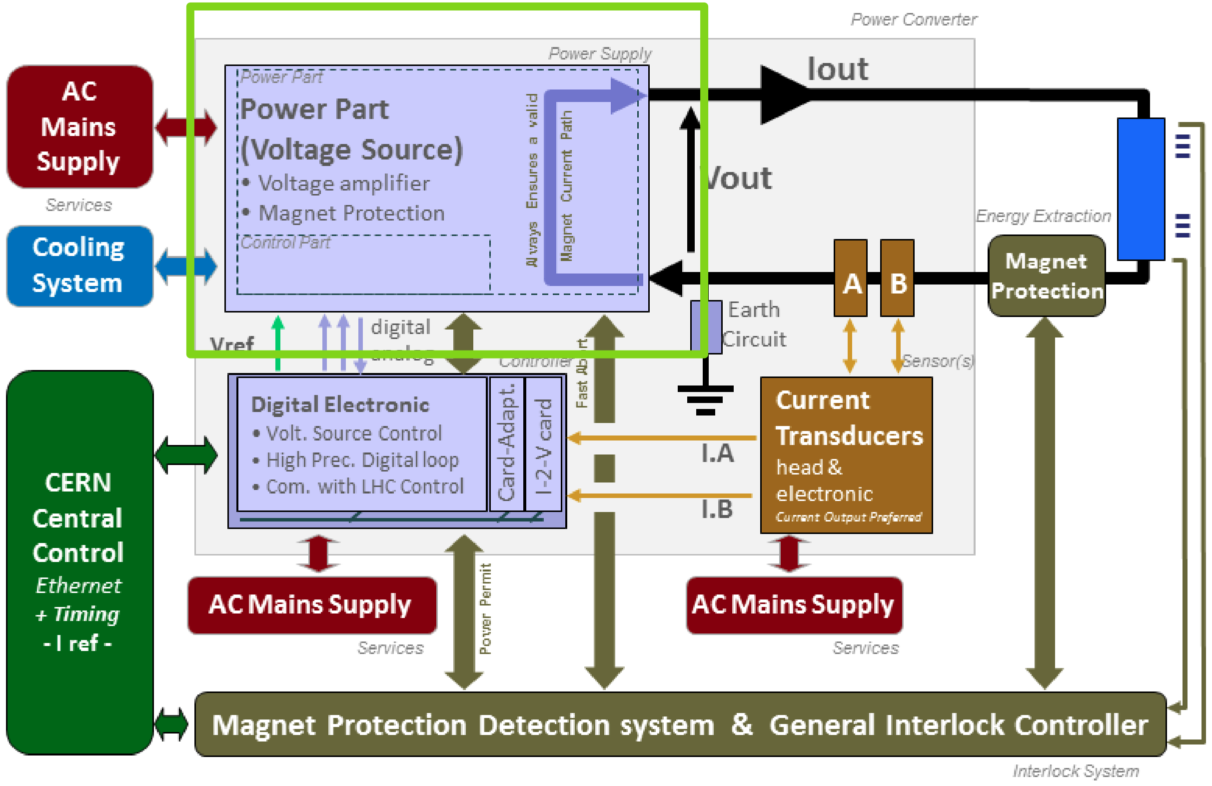
- 144 R2E-HL-LHC60A-10V
- 128 R2E-HL-LHC120A-10V

Lessons learnt from previous designs / projects

With new challenges put in perspective

Context

- A power source can be designed with **standard elementary components,** not requiring high complexity integrated devices (devoted to FGC in R2E-EPC).



Radiation Event Mitigation / Risks

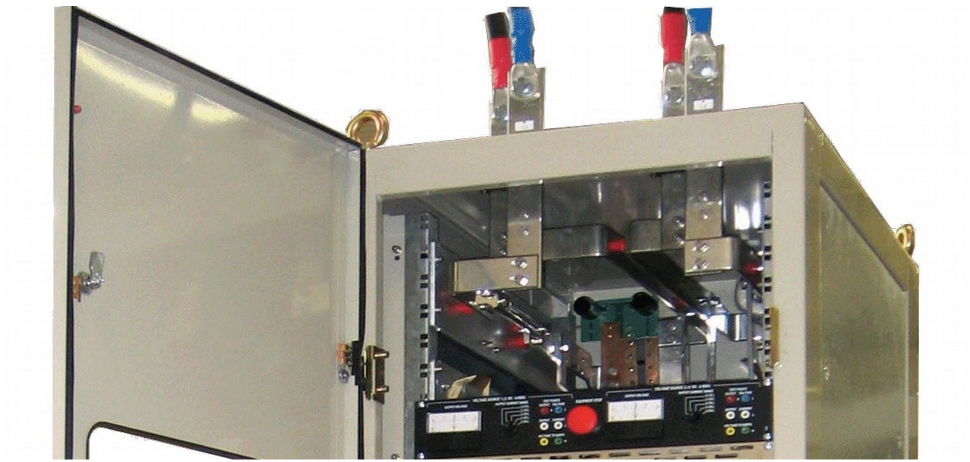
- **Single events** can be very well managed with **gold simple rules**
- **Dose** degradation (TID, DD) must be considered very seriously above **50 Gy**
- **Component** Testing effort versus radiation
  - Should be focusing on critical components (more than verifying known expected behaviour)
    - Single source (PWM), integrated ones (current sensors), very sensitive (optocoupleur)
- **Whole Converter** Testing effort versus radiation
  - Is a key point, and address some failures mechanism difficult to control / predict
  - Gives an opportunity to test many components in one go, in their specific use conditions!
  - Reinforces the trust in design, before installation.

Management of COTS component purchasing process highlight

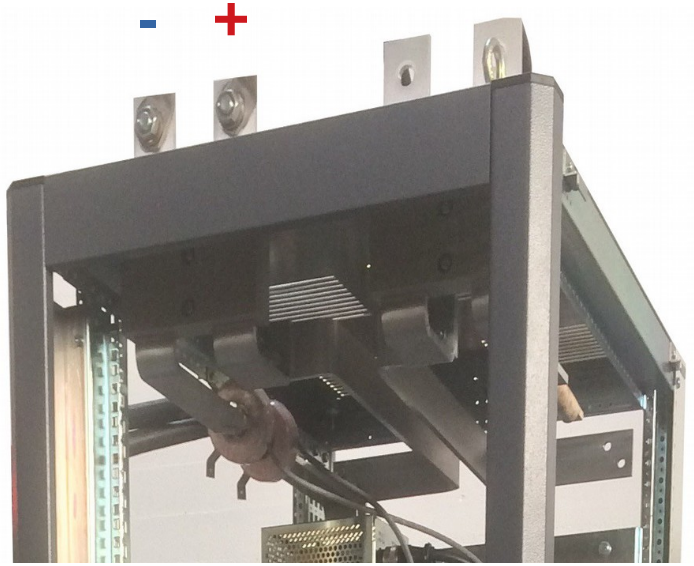
- All semi-conductors purchased by CERN to be sent to external producing companies… was a tough taks, **certainly not justified for most of them.**
- Sensitive COTS must be carefully treated, others addressed in std way.

LS2 R2E new Converters were … “*almost*” like old ones

- “*almost*” already created over-cost + headaches during LS2!



Old design +/- busbars



Busbars Polarity *updated*!

New R2E60/120A converters integration needs even more care attention

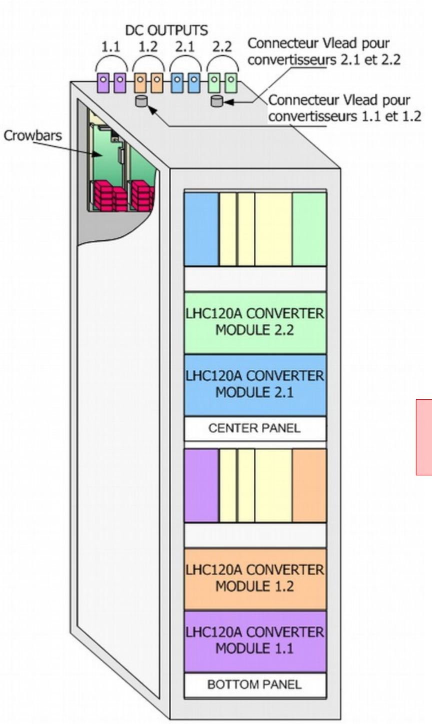
- 60A converters are now (1+1) 60A converter

Need to install **twice** initial power *is **not almost the same***

Lessons learnt from recent R2E project - Integration

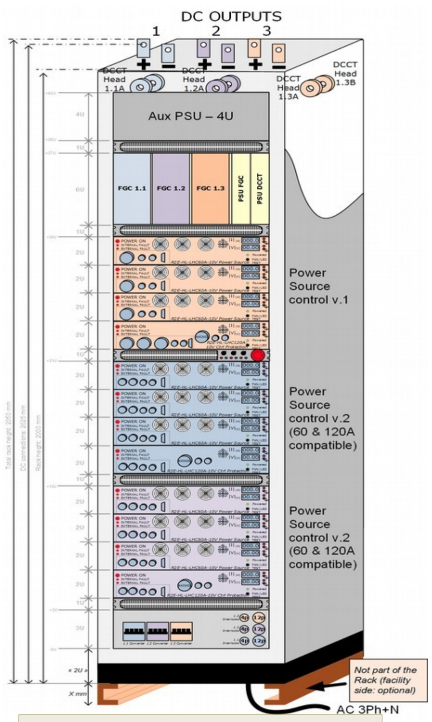
New R2E60/120A converters integration needs even more care attention

- 120A converters comes with **3 converters a rack versus 4 in initial old design.**



Old design
1 rack = 4 cvs

-1

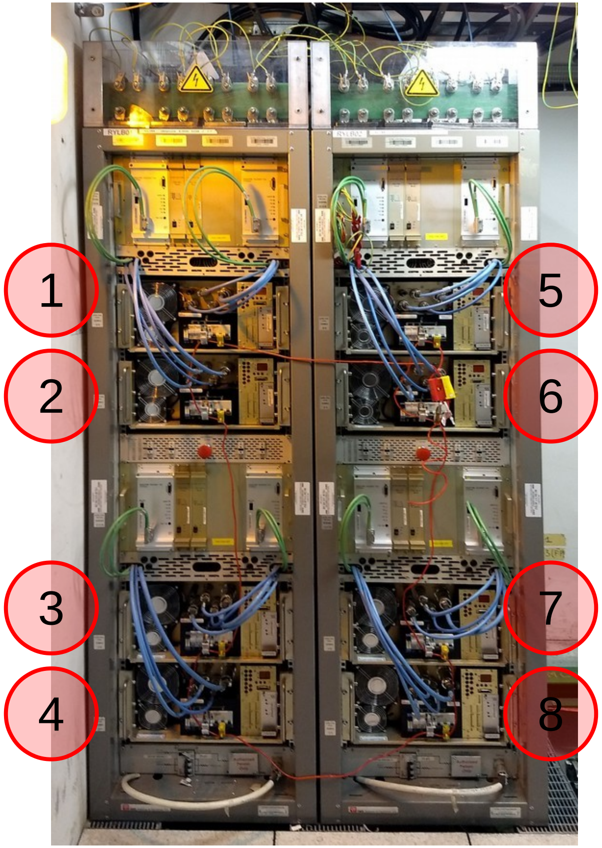


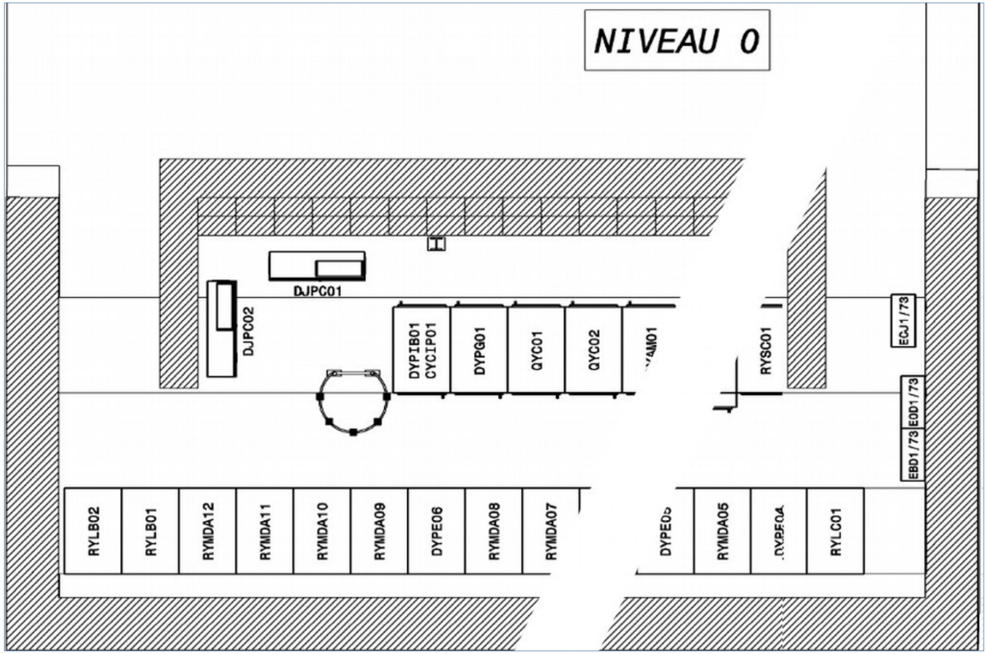
New design
1 rack = 3 cvs

From 4x converters to 3x converters in installed rack *is* ***not almost the same***

New R2E60/120A converters integration needs care attention

- 120A converters comes with **3 converters a rack versus 4 in initial old design.**





Impacting current RR rack layout

Design

Highlighting paths for success

Path-1: Component Selection

A fine selection of all required components is under process

SE Class	TID Class	Type	Reference Datasheet	Manuf.	Case	EDMS	Select List	R2E Lib	R2E Rep^{t}	LTSp. Model
1	1	Power IGBT	IKW15N120BH6, SCT3160KL,	Infineon	TO247					
1	0	Pwr SiC MOSFET	IMW120R140M1H, SCT3160KLGC11	Infineon / Rohm	TO247					
1	0	High Pwr MOSFET *Linear-use-considered*	NA	NA	SOT227					
1	1	Med. Pwr MOSFET	IPD600N25N3-G	Infineon	DPack					
1	1	Low Pwr MOSFET	BSS127, SQ2398ES, FDN86246, ZXMN10A07F	ON, Vishay, Diodes-Inc	SOT23					
0	0	PNP Transistor	BCP53-16	Philips	SOT223					
0	0	NPN Transistor	BCP56-16	Philips	SOT223					
0	0	PNP Transistor	FMMT591	Diodes Inc.	SOT23					
0	0	NPN Transistor	FMMT491TA	Diodes Inc.	SOT23					
0	0	Bridge Rectifier	26MT160	Vishay	D-34A					

Components process

- Sorting candidates
  - Electrical data
  - R2E-reports (if exits)
- Simulation model
  - Standard (0-Gy)
  - R2E (500-Gy)
- Easy access (web)
  - Data summarised for designers / check
  - Sharing our choice for discussion

Path-1: Component Selection

A fine selection of all required components is under process

2	0	● Current Sensors	NA	NA	NA					
2	1	● Phase Sh. PWM	NA	NA	NA					
0	0	● Op. Amplifiers	OPA2134UAG4-TBC, TL052ACD	TI	SO8					
0	0	● Comparators	LM339D	TI	SO8					
0	0	● Volt. Reference	NA	NA	NA					
0	0	● Signal Diodes	BAV70, BAV99, BAW56	Philips	SOT23					
0	0	● Zener Diodes	BZV55	Philips	SOD80C					
0	0	● Med.Pwr Diodes	ES1DHE3_A/H	Vishay	DPack, DO-214AC					
0	0	● Power Diodes	DSS2x111-008A, DSS2x101-015A, MBR2X100A100, DSA240X150NA	Ixys, GeneSiC	SOT227					
0	0	● TVS & Varistors	NA	NA	NA					
0	1	● Opto-Isolators	NA	NA	NA					

Focusing on

- Current sensor
  - Opening the Black-Box with producer company
  - Already done on former R2E projects.
- PWM
  - Converter "Heart"
  - Not many choices (phase shifted techno)

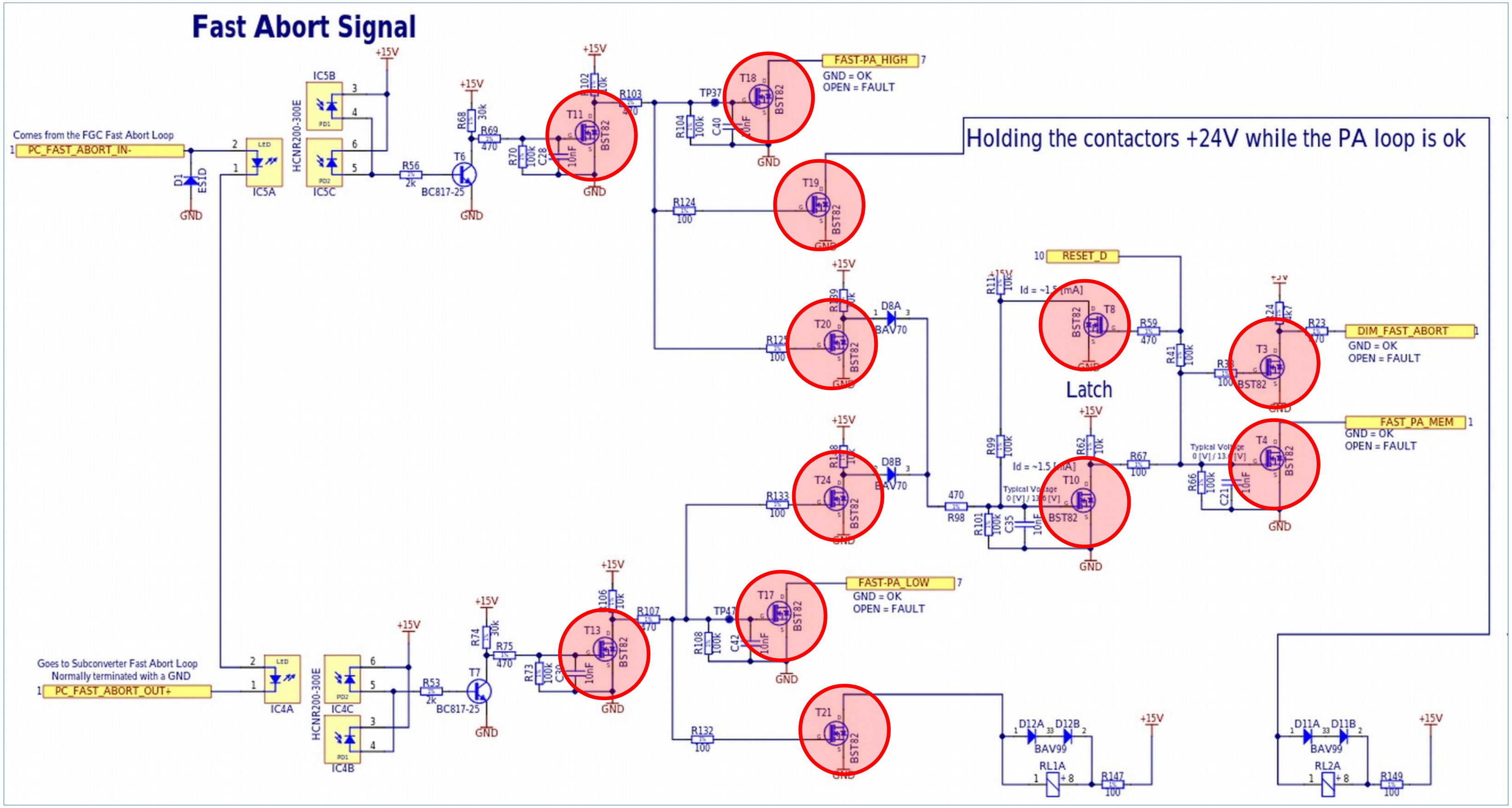
Capitalizing on Known Components

Component Manufacturer If Any	Family Reference If Any	Type	V [Volt]	Ic [A]	Ic peak max [A]	Operating Junction Max T°C [°C]	P [W]	Hfe @ Ic = 150mA	Case	Code	Status	Rating 1=keep 3=drop	Reason for choosing the component or comment	Radiation Testing				
ON Semiconductor	BCP53-16T1G	PNP	80	1	1.5	150	1.3	100	SOT-223	863-BCP53-16T1G	Active	1	Already used in previous design, already tested, good behaviour under radiation.	TRAD	Charm			
ON Semiconductor	BCP56T1G	NPN	80	1	1.5	150	1.3	250	SOT-223	863-BCP56T1G	Active	1	NPN equivalent of BCP53. Already used in R2E design.	PSI				
Nexperia	BC817-25	NPN	45	0.5	1	150	0.35	100	SOT-23	771-BC817-25-T/R	Active	3	Do not use, perfer FMMT491TA instead.	1	2	3	4	5
Diodes inc	FMMT491TA	NPN	60	1	2	150	0.5	100	SOT-23	522-FMMT491TA	Active	1	Use this component over BC817. Plus it can withstand over 400Gy.	1	2	radwg		
Diodes inc	FMMT591TA	PNP	60	1	2	150	0.5	100	SOT-23	522-FMMT591TA	Active	1	PNP equivalent of the component above.	1	2			

But also focusing on new ones (SiC)

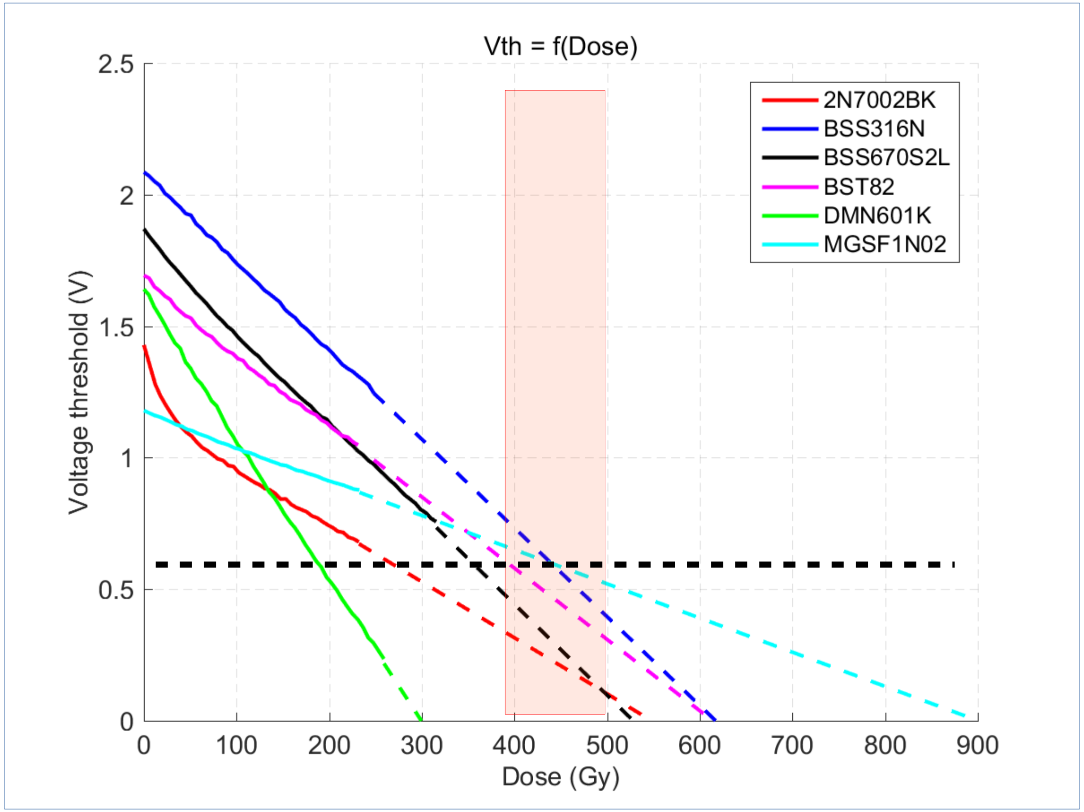
Component Manufacturer If Any	Family Reference If Any	Technology	Topology	Vdss [V]	Min Vgs Threshold [V]	Typ Vgs Threshold [V]	Max Vgs Threshold [V]	Max Pulsed Drain Current [A]	Case	Status	Rating 1=keep 3=drop	Comments	Radiation Testing	Theoretical TID effects on (up to 500 Gy)			Single Event		Displacement damage
														Vgs Threshold	Turn-On Delay	Fall time	Cross section @ Vdss max [p.cm-2]		
Infineon	IMW120R140M1H	SiC	Trench	1200	3.5	4.5	5.7	32	TO-247	Active and preferred	1	Best electrical characteristics regarding this particular application (IGBT replacement)	#N/A						
ST Microelectronics	SCT10N120	SiC	Planar	1200	1.8	3.5	3.5	24	HiP247	Active	2		#N/A						
ST Microelectronics	SCT20N120	SiC	Planar	1200	2	3.5	3.5	45	HiP247	Active	3		#N/A						
ON Semiconductor	NTHL160N120SC1	SiC	Trench	1200	1.8	3.1	4.3	69	TO-247	Active	3		#N/A						
ON Semiconductor	NVHL160N120SC1	SiC	Trench	1200	1.8	3.1	4.3	69	TO-247	Active	3		#N/A						
ROHM	SCT3160KLGC11	SiC	Trench	1200	2.7	#N/A	5.6	42	TO-247	Recommended	1	3rd gen ROHM recommended by Corinna Martinella because of double trench design and similar electrical characteristics as the other selected SiC MOSFET	#N/A						
ROHM	SCT3080KLHR	SiC	Trench	1200	2.7	#N/A	5.6	77	TO-247	Recommended	2		#N/A						
ROHM	SCT3105KLHR	SiC	Trench	1200	2.7	#N/A	5.6	60	TO-247	Recommended	2		#N/A						

Case of Very High Occurrence in the design = Low Power Mosfet



Case of Very High Occurrence in the design = Low Power Mosfet

- VGS threshold starts to be critical above 400 Gy | Robust candidate needed.



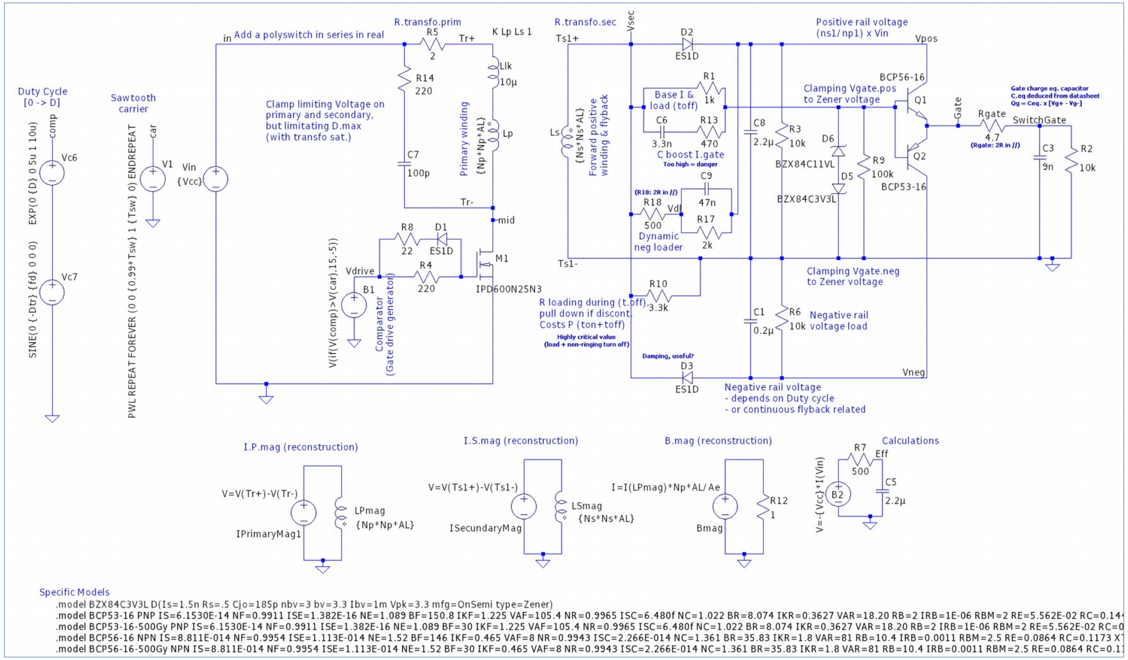
Any Converter Sub-System / Sub-Part is described in detail in web pages

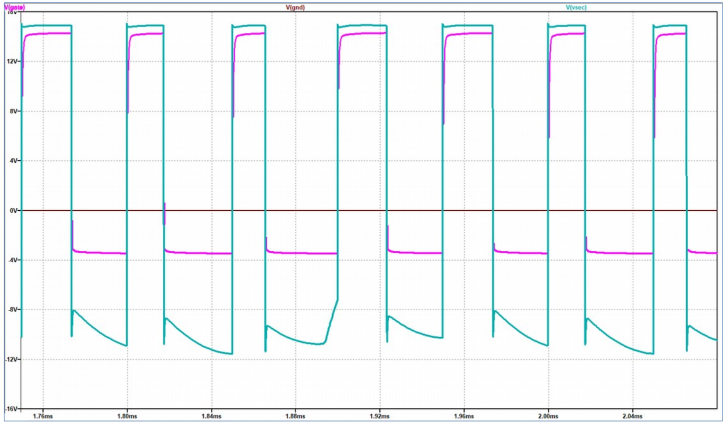
- Any converter part is treated
- Doc = SpreadSheet + Report + LTSPice Model + Presentation
  - Design traceability for future debug
    - Understanding Issues from field
  - Easier Possible Internal Reviews
    - With Electronics Expert

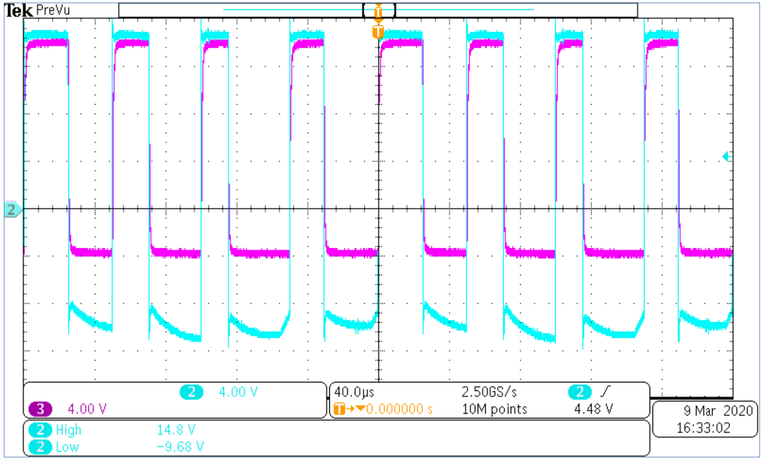
Model/Unit description	Schema overview	EDMS	Link Design	Link Design	Link Pres.	LTSp. Model
High Frequency DC-DC.						
IGBT/MOS Phase Shifted Driver.						
Inverter High Freq. Current (I) Meas.						
Input Power Filter						
Pwr Mod. Aux Power Supplies						
Ctrl & Prot. Aux Power Supplies						
Shared Sources Control						
Power Mosfet Linear Driver						
Current Source (Mosfet-based)						
Earth Leakage Detection System						
Current Leads Monitoring System						

Goal: Very Accurate Simulation

- Systems & components are simulated up to a **quasi-perfect match** vs real board.

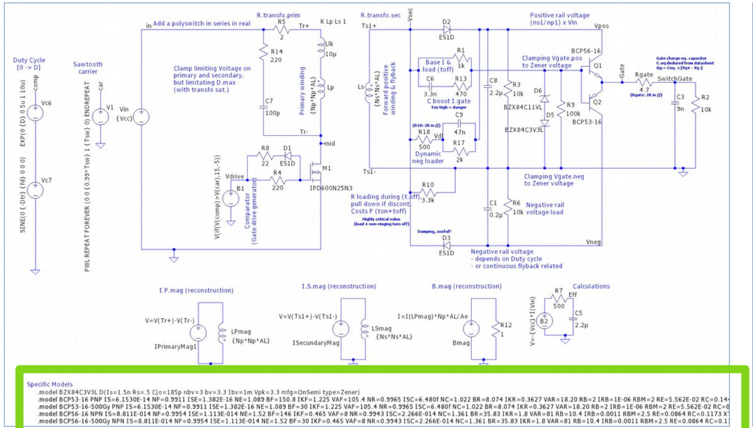






Goal: Very Flexible Simulation – Radiation Effect Included!

- From component fine analyse, a **500 Gy model is injected in simulations**



```
# EDMS document: https://edms.cern.ch/document/2437567/
# One model intends to represent the degradation of the component under irradiation
# revision date:2021-01-25 - VBE degradation added
                2020-11-10 - creation
# 500Gy model:
# > HFE degradation:  125 vs 75        BF = 30 (see EDMS 1583310 - High IC. & EDMS 1171985)
# > VCE sat increase: 170 mV vs 155 mV XX = XX (see EDMS 1583310 - High IC. & EDMS 1171985)
# > VBE degradation:  none             XX = XX (see EDMS 1171985 page 4)

.MODEL BCP53-16 PNP IS=6.1530E-14 NF=0.9911 ISE=1.382E-16 NE=1.089 BF=150.8 IKF=1.225 VAF=1
BR=8.074 IKR=0.3627 VAR=18.20 RB=2 IRB=1E-06 RBM=2 RE=5.562E-02 RC=0.1449 XTB=0 EG=1.11 XTI
TF=8.666E-10 XTF=1.231 VTF=3.008 ITF=0.4581 CJC=5.264E-11 VJC=0.6591 MJC=0.4533 XCJC=0.4401
FC=0.9427 Vceo=80 Icrating=1 MFG=Philips
.MODEL BCP53-16-500Gy PNP IS=6.1530E-14 NF=0.9911 ISE=1.382E-16 NE=1.089 BF=30 IKF=1.225 VA
BR=8.074 IKR=0.3627 VAR=18.20 RB=2 IRB=1E-06 RBM=2 RE=5.562E-02 RC=0.1449 XTB=0 EG=1.11 XTI
TF=8.666E-10 XTF=1.231 VTF=3.008 ITF=0.4581 CJC=5.264E-11 VJC=0.6591 MJC=0.4533 XCJC=0.4401
FC=0.9427 Vceo=80 Icrating=1 MFG=Philips
```

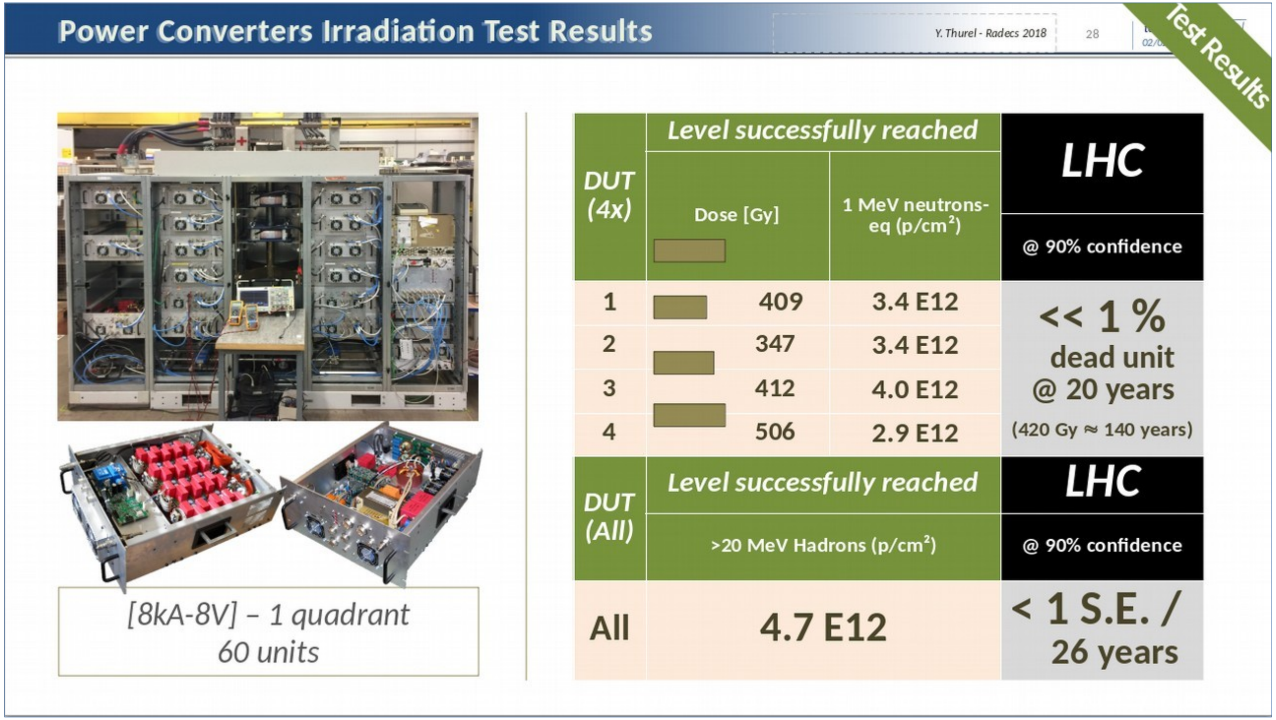
Specific Models

```
.model BZX84C3V3L D(Is=1.5n Rs=.5 Cjo=185p nbv=3 bv=3.3 Ibv=1m Vpk=3.3 mfg=OnSemi type=Zener)
.model BCP53-16 PNP IS=6.1530E-14 NF=0.9911 ISE=1.382E-16 NE=1.089 BF=150.8 IKF=1.225
.model BCP53-16-500Gy PNP IS=6.1530E-14 NF=0.9911 ISE=1.382E-16 NE=1.089 BF=30 IKF=1.225 VA
.model BCP56-16 NPN IS=8.811E-014 NF=0.9954 ISE=1.113E-014 NE=1.52 BF=146 IKF=0.465
.model BCP56-16-500Gy NPN IS=8.811E-014 NF=0.9954 ISE=1.113E-014 NE=1.52 BF=30 IKF=0.465 V
```


ROCK BEATS SCISSORS
SCISSORS BEATS PAPER
PAPER BEATS ROCK
CHARM
NOTHING BEATS a CHARM Test

Nothing beats a full system passing a CHARM test!

- Project already includes up to 10 units for radiation test @ CHARM



DUT (4x)	Level successfully reached: Dose [Gy]	1 MeV neutrons-eq (p/cm²)	LHC @ 90% confidence
1	409	3.4 E12	<< 1 % dead unit @ 20 years (420 Gy ≈ 140 years)
2	347	3.4 E12	
3	412	4.0 E12	
4	506	2.9 E12	

DUT (All)	Level successfully reached: >20 MeV Hadrons (p/cm²)	LHC @ 90% confidence
All	4.7 E12	< 1 S.E. / 26 years

Keeping only One project milestone?

"When Converter is validated vs radiation in CHARM"

Conclusion

Conclusions

Success in R2E design is & stays based on

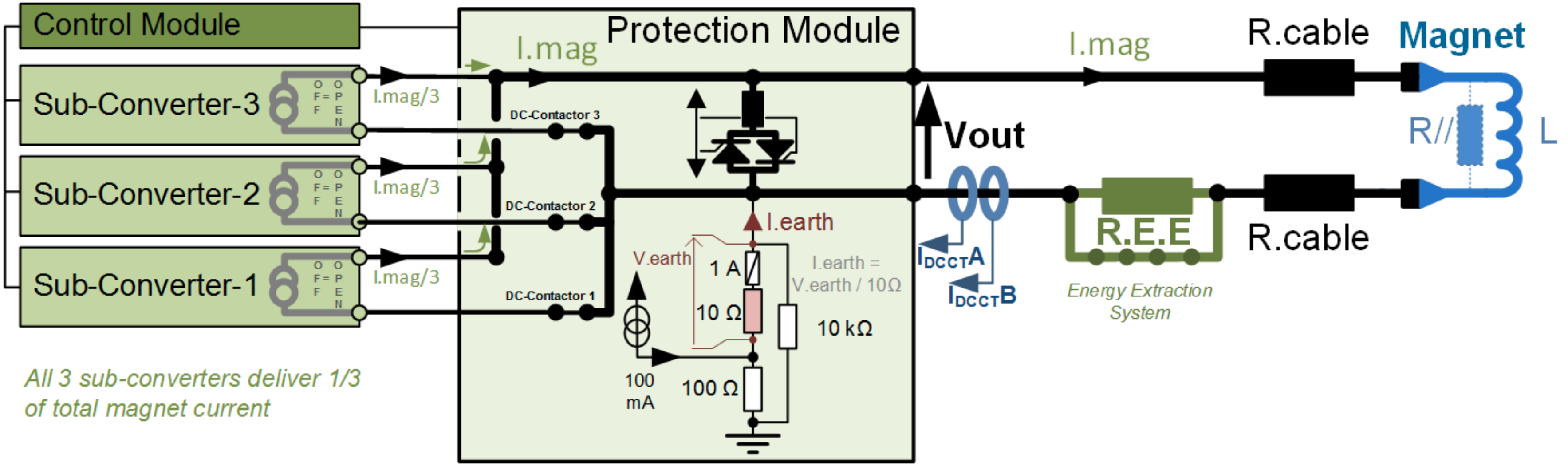
- **Understanding where / what are the threads**
  - Relying on **reliable projections of radiation levels** in the machine
- **Gold design rules**
  - Experience and knowledge at CERN is now very high. Rely on / Share it!
- **Well defined robust & rigid (design & qualification) process**
  - Clear & strong steps are required for a smooth path to success
- **Focusing on / Choosing / Qualifying the right components**
  - Co60, **CHARM**, PSI availability is a key point
- **Testing final systems**
  - Nothing beats a full system having pass **CHARM** test!

www.cern.ch

60A / 120A Block Diagram

Power Modules Arrangement

- Power Modules operating in //
- Still, control & protection module not redundancy
  - Limited to minimum function, requiring high reliable & safe design



Project Deliveries

Reference Unit	Qty[a]	Date	Circuit Use / Name
R2E-HL-LHC60A-10V Op. Pwr Conv. incl. rack	144[B]	LS3	**Tunnel** R2E + rotation **144**:72 units cell12/14/16 Pt1/5/2 +72 units rot. - FGClite
R2E-HL-LHC60A-10V Op. Pwr Conv. incl. rack	004	LS3	**UR15/UR17** **004** : 2x [02 u HL/Q1a] | I. crowbar:4.1kA | FGC3
R2E-HL-LHC120A-10V Op. Pwr Conv. incl. rack	124	LS3	**RR13/RR17** R2E **036** :2x [18 units] -FGClite **RR53/RR57** R2E **036** :2x [18 units] -FGClite **RR73/RR77** R2E **020** :2x [10 units] -FGClite **UL14/UL16** R2E **016** :2x [08 units] -FGClite **USC55/UL557** **016** :2x [08 units] -FGClite