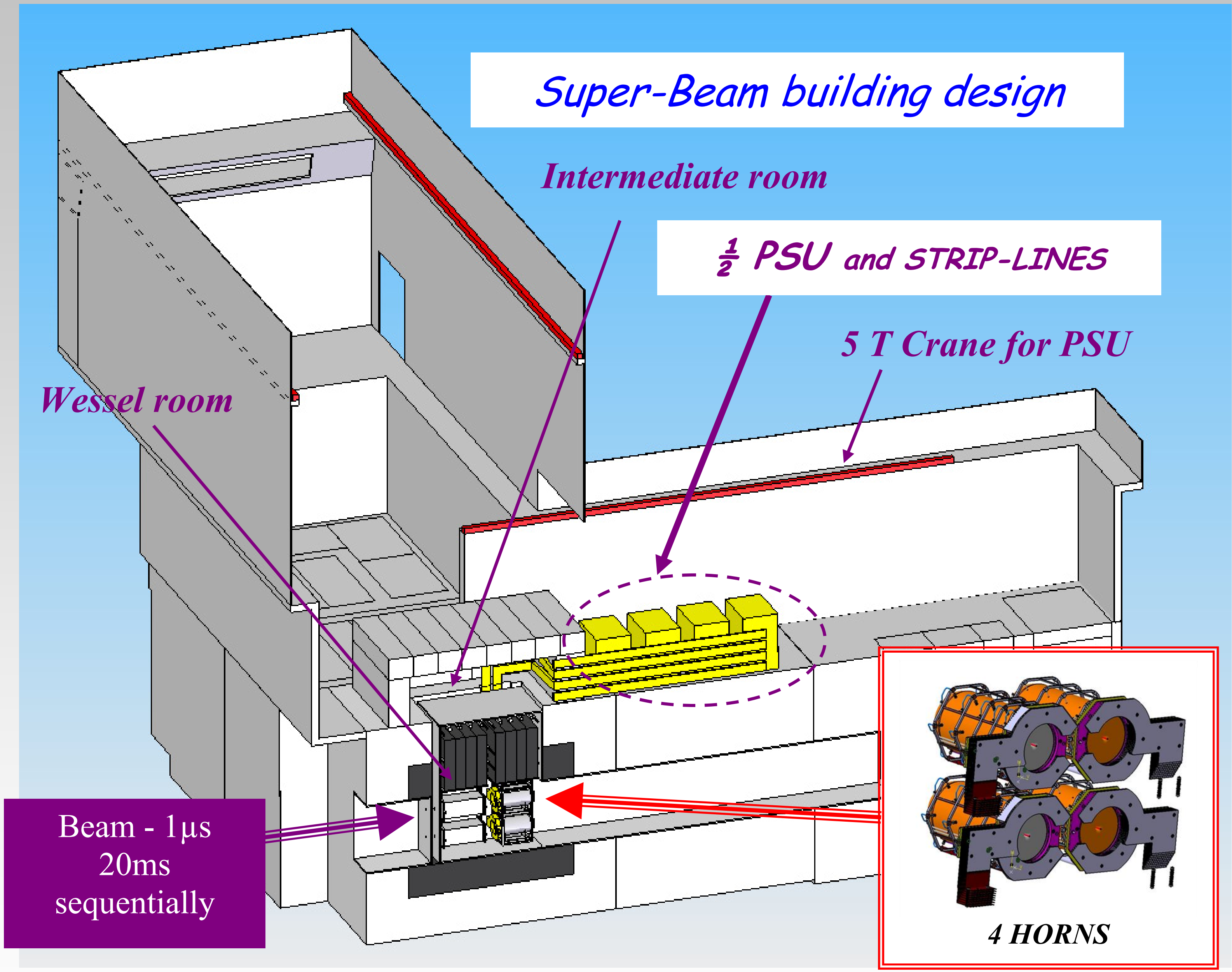
8th NBI workshop, 6-10 November 2012, CERN

4 Horns power supply (PSU) for 50Hz frequency pulsing

Design studies for Super Beam

Pascal POUSSOT

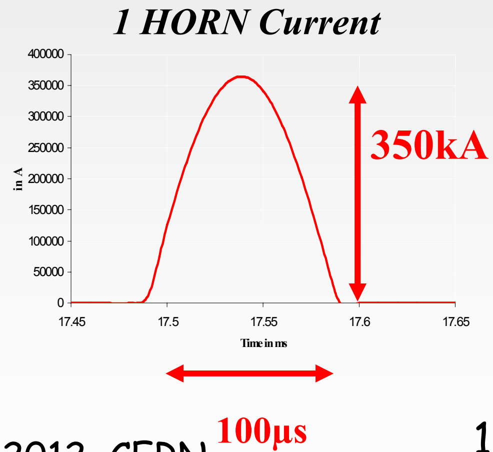


⇨ PSU specifications

- supply 1/2 sinusoid 350kA peak current, 100µs-50Hz

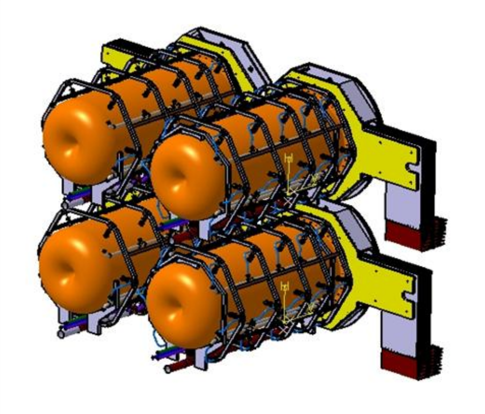
- each horn supply pulsed at 12.5Hz or 16.66Hz

- lifetime 13 billions cycles



- **critical horn electrical characteristics**
  - low values of L & R of horn (short circuit)
  - very high rms current
- **minimize electrical consumption**
  - maximum energy recovery
  - reduce losses in strip-lines
- **modularity approach**
  - allow to test a prototype module

1 Horn electrical characteristics	
L	**0.9µH**
R	**0.235mΩ**
I rms at 12.5Hz	**9kA**
I rms at 16.66 Hz	**10.4kA**

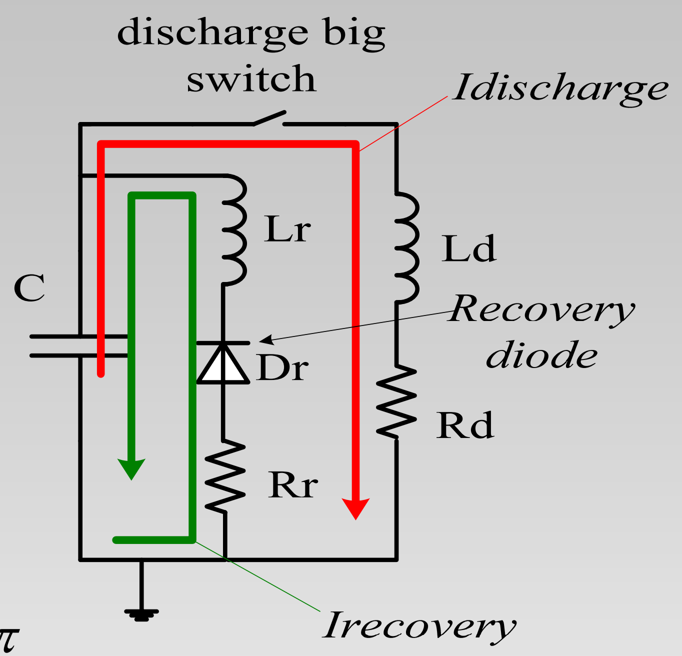


⇨ **maximal operation voltage 20kV**
  - safety and water cooling

⇨ **technological feasibility and costs vs high lifetime**
  - many contacts with manufacturers

- *PSU near the horns (30m maxi)*

⇨ method of discharged capacitor in a damped oscillating Ld, Rd, C circuit

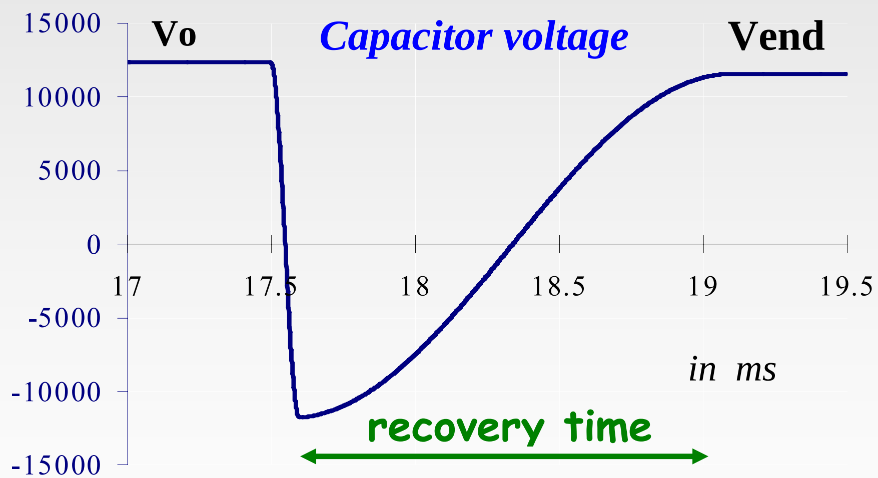


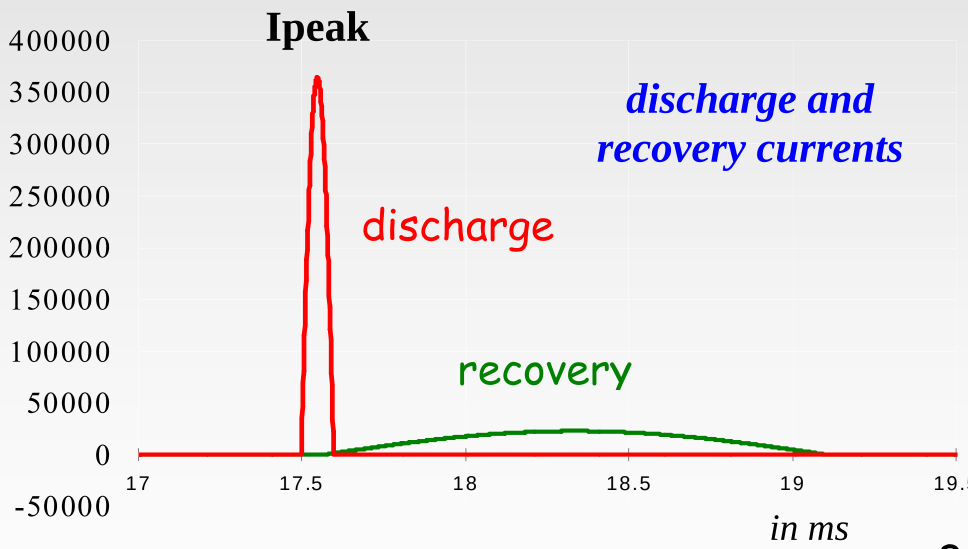
⇨ voltage of capacitors governed by the equation:

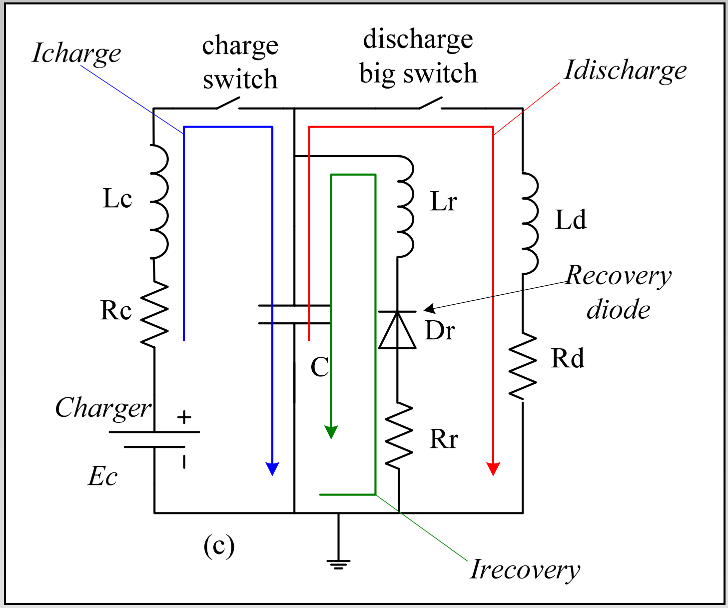
$$\frac{d^2V}{dt^2}+2m\omega\frac{dV}{dt}+\omega^2V=0 \text{ with } \omega=\frac{1}{\sqrt{LC}} \text{ and } m=\frac{R}{2}\sqrt{\frac{C}{L}}$$

☞ peak current I is given by : $I_{peak}=V_o\sqrt{\frac{C}{L}}$

☞ final capacitor voltage: $V_{end}(I=0)=V_o.e^{-(m_d+m_r)\pi}$





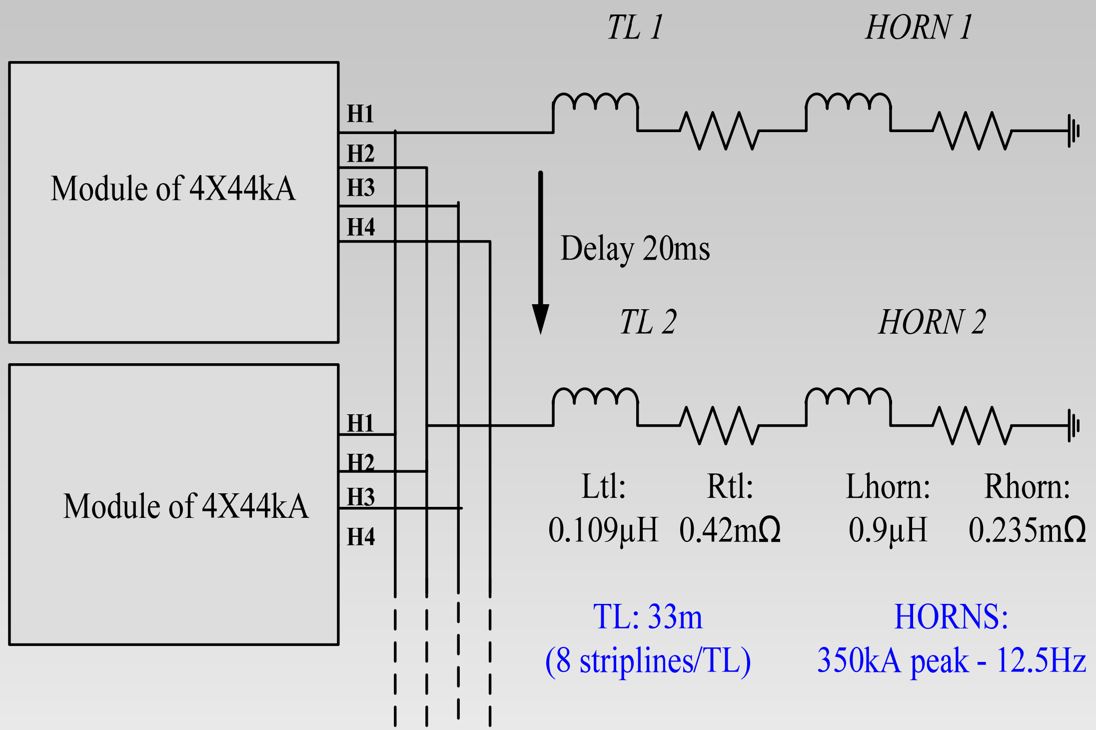


C=1000µF Ec=11kV $\hat{i} = 350\,kA$	**Charge** Lc=25mH Rc=0.475Ω	**Discharge** Ld=1.041µH Rd=0.89mΩ	**Recovery** Lr=0.25mH Rr=5.94mΩ
m	0.0475	0.013	0.005724
ω, rd/s	200	30990	1928
$\frac{di(t=0)}{dt}$, A/µs	0.014	**10846**	43
V_O, V	10616	11293	-10816
V_{end}, V	11293	-10816	10616
$\hat{i}$, A	**68**	**350k**	**21.6k**
I_{RMS},A	**41**(50Hz)	**10.4kA**(16.66Hz)	**4300**(50Hz)

- capacitor charger Ec: +12kV-460kWrms: charge in 18ms at +-0.5%
- very high dI/dt (well higher than best thyristor switches)
- -12kV capacitor voltage during 0.8ms
- strip-lines: reduce length, R and L electrical values, study of thermal cooling and electrical insulation

Challenge for building PSU

☑ modularity approach: find an optimal solution



8 modules connected in parallel

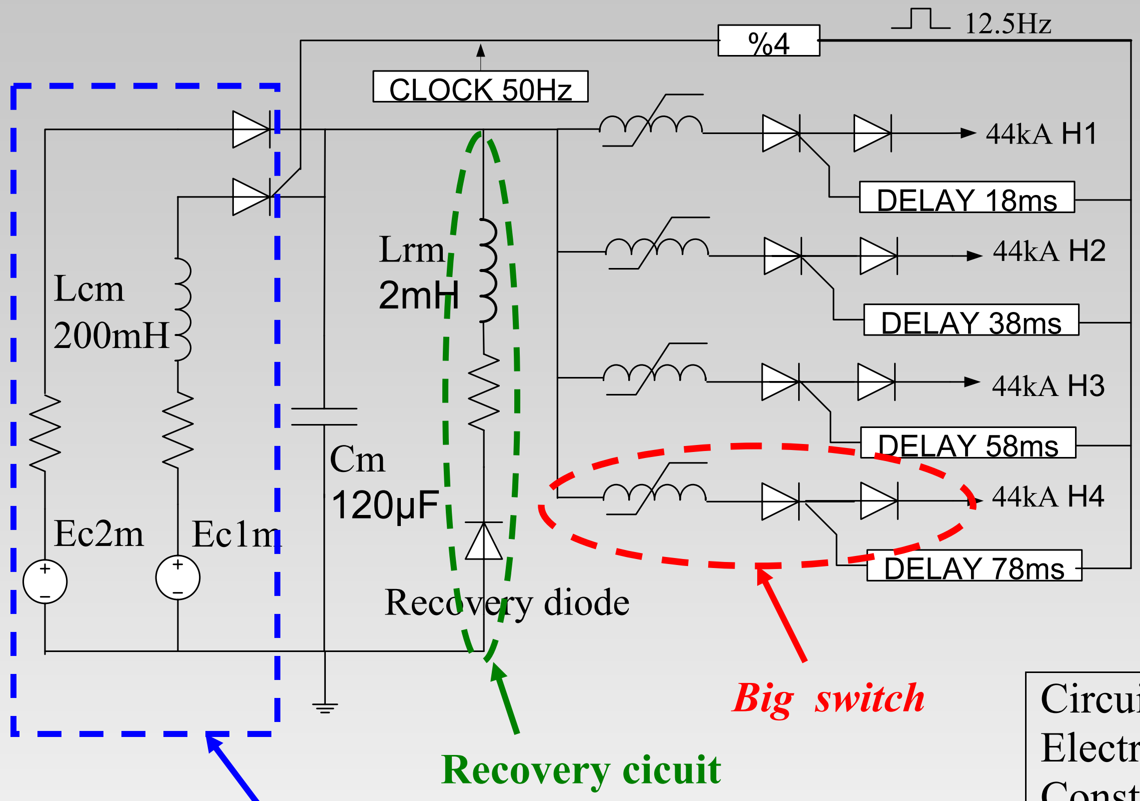
☞ **8 modules of 4X44kA output current connected in parallel**

☞ **module:** charge and recovery at 50Hz, discharge alternatively in the 4 horns every 20ms

☞ **1 transmission line per horn:** based on 8 Al strip-lines (H0.6Xl0.01) spaced by 1cm) and connected in parallel, length reduced to 33meters max.

☐ **4X44kA module: electrical constraints on components to be verified**

4X44kA electrical module



☞ **"big" switch:** very high dI/dt and +-12kV voltages, high reverse currents

☞ **2mH recovery coil:** volume proportional to Ipeak*Irms*Lr and coil saturation (3%), insulation to ground 25kV

☞ **recovery diode:** high -12kV voltage and reverse currents

☞ **hybrid charger:** +12kV-70kWrms

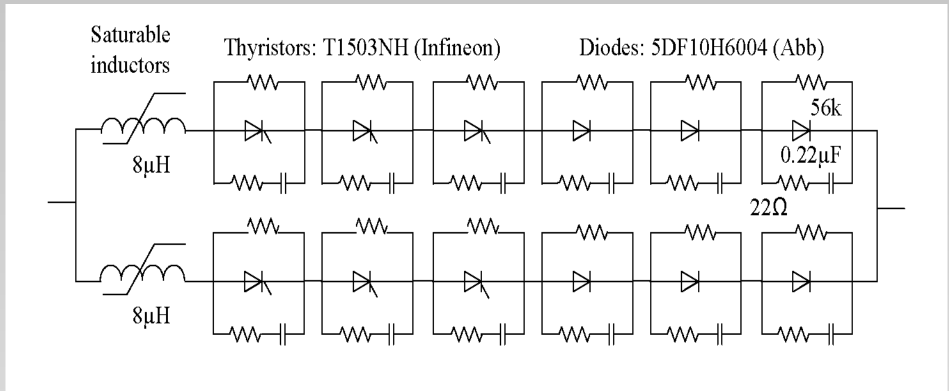
High efficiency of PSU limit current charge to 3%, based on SCR (Ec1) and HF switching (Ec2) technology

4X44kA electrical contraints

Circuits Electrical Constraints	$\frac{dI}{dt}$ A/µs	$\hat{I}$ A	I_{RMS}, A			Q Cb
Ec=+12kV			**50 Hz**	**16.66 Hz**	**12.5 Hz**	
Charge	-	9.56	5.9	-	-	0.09
Recovery	5.88	2864	562	-	-	2.81
Discharge	1461	45.56	2278	1315	1139	2.9

solutions of switch components retained ⇨⇨⇨⇨⇨

Big switch:

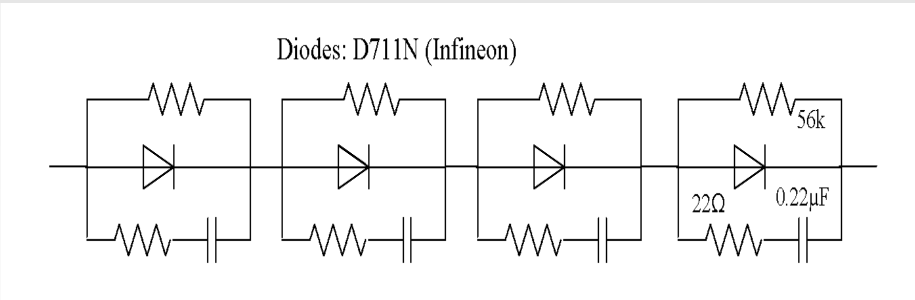


	Thyristor **T1503 Infineon**			Diode **5DF10H6004 ABB**	
	I_{TM} kA	V_{DRM} kV	$\frac{dI}{dt}$ kA/µs	V_{RRM} kV	Q_{RR} mC
Maximal	**40**	**7.5**	**5**	**6**	**6**
Simulations	**22.8**	**4**	**0.75**	**4.5**	**4.1**

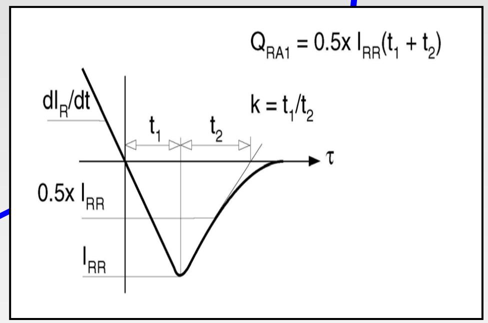
direct voltage

reverse voltage

Recovery diode:



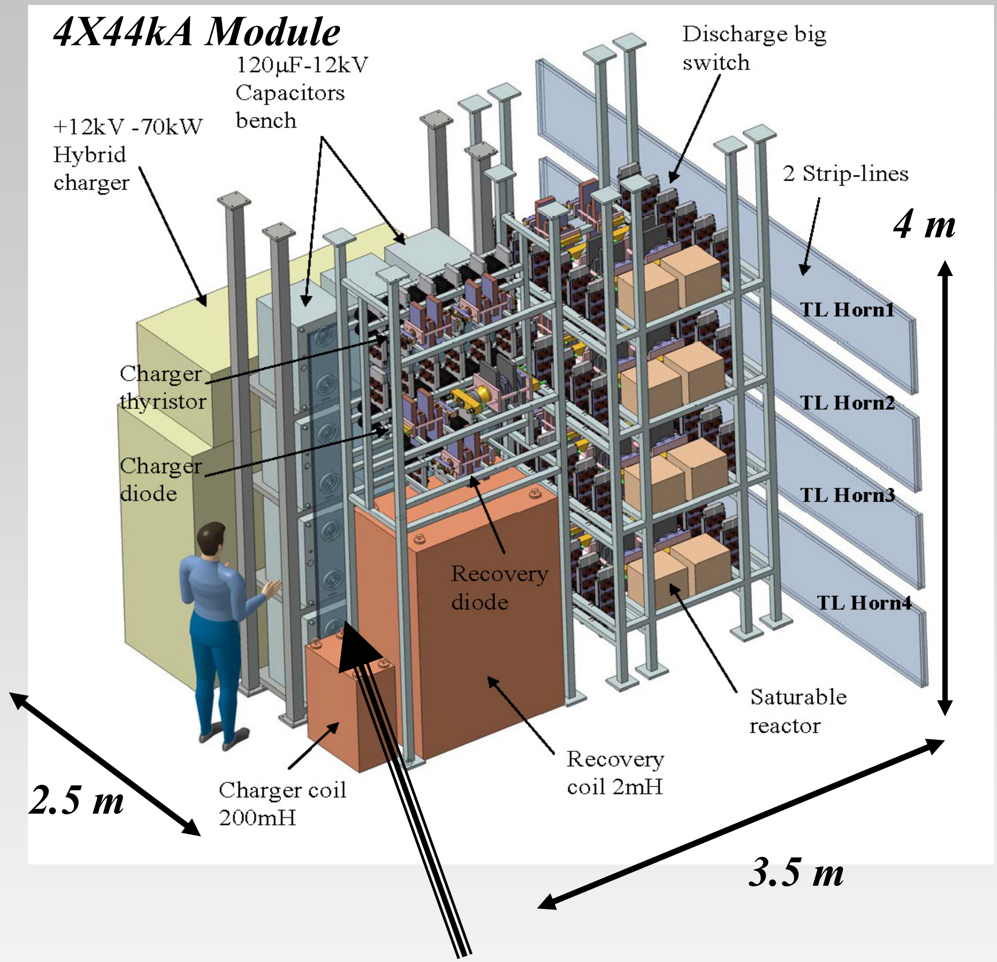
D711N	V_{RRM} kV	Q_{RR} mC
Maximal	**7**	**5.5**
Simulations	**3.5**	**3.2**



Qrr : reverse currents

☞ **lifetime of components : electrical constraints below maximal characteristics (safety margin 50% minimum)**

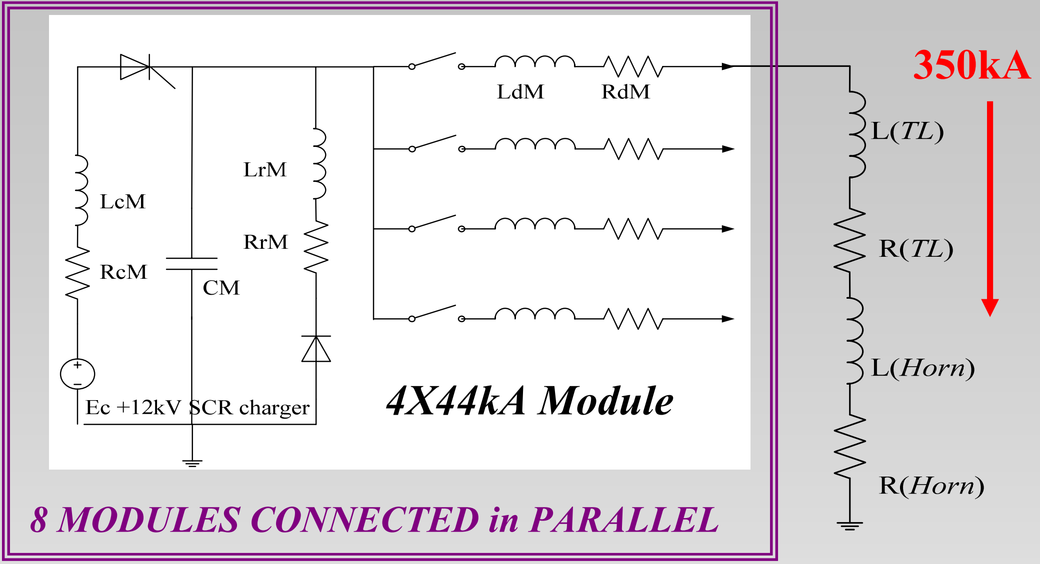
4X44kA module: mechanical & thermal constraints



PSU 4X44kA module	Weight, KG	Thermal dissipation, W	
		Water cooling	*Air Cooling*
4 Big switches	1600	16000	1600
Recovery coil	2200	17000	
Hybrid charger	2400	7100	
Capacitor bench	1700		992
supports...	1000	-	-
TOTAL	**8.9T**	**45kW**	**2.6kW**

- ⇨ total ground area : $8{,}75 m^2$
- ⇨ each set of components is extracted by 5T Crane for maintenance
- ⇨ ground mechanical constraints: $1T/m^2$, $20T/m^2$ at supports
- ⇨ **95% of thermal dissipation extracted by water-cooling**

PSU for 1 Horn: values of Rd & Ld



TOTAL module	LcM 0.2	RcM 3.8	LdM 260	RdM 1.86	LrM 2	RrM 47.48
	H	Ω	nH	mΩ	mH	mΩ
SCR coil	0.2	0.8				
Charger		3				
CM=120µF			**50**	**0.20**		
½ Big Switch	Saturable coil		**120**	**0.2**		
	3 diodes+ 3 thyistors		**300**	**3.12**		
Recovery stage	diode					3.48
	2mH coil				2	44

Low values of discharge circuit

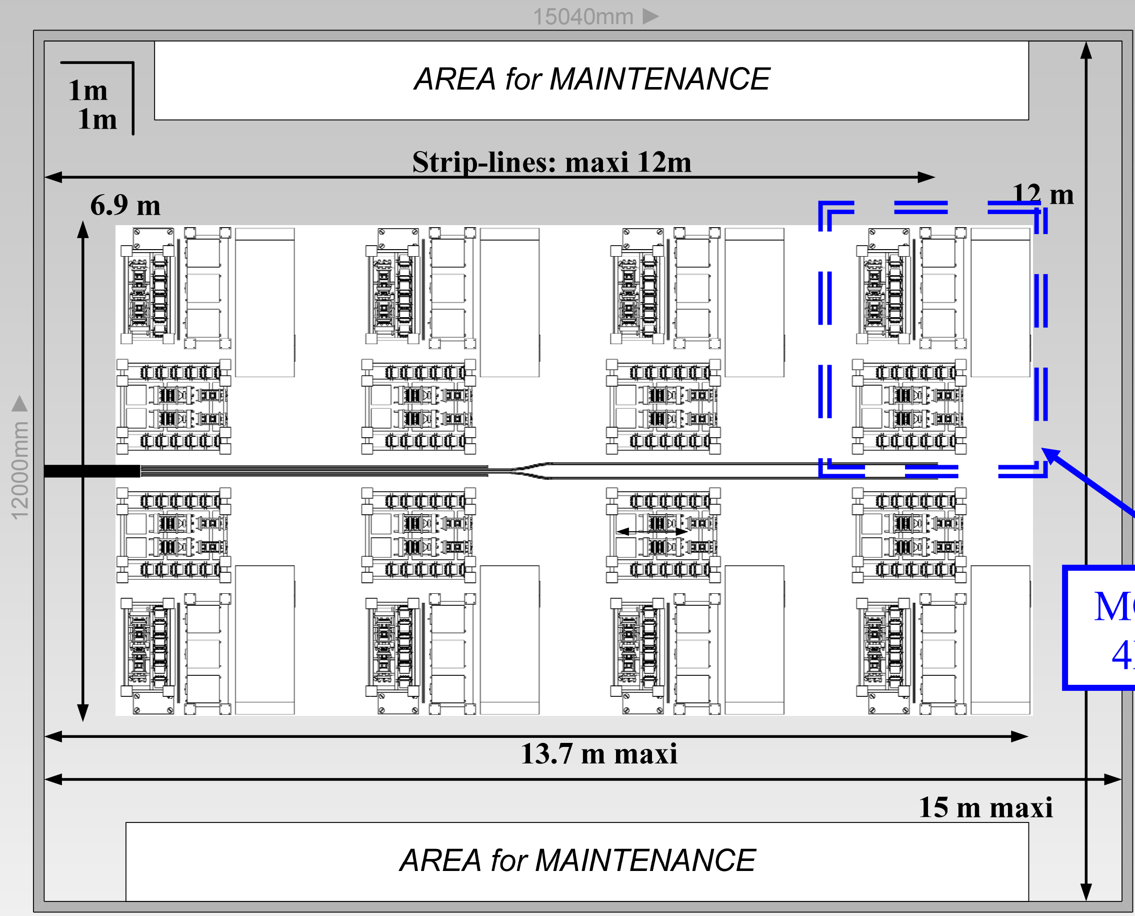
⇨ complete PSU

- Ld = LdM/8 + L(TL) + L(horn)
- Rd = RdM/8 + T(TL) +R(horn)

} <u>low values of total Rd and Ld</u>

PSU for 1 Horn	Ld nH	Rd mΩ
8 outputs of 44kA modules connected in //	32.5	0.235
1 TL (30m)	109	0.42
1 Horn	900	0.235
<u>TOTAL</u>	<u>1041</u>	<u>0.89</u>

PSU 4 Horns: dimensions & thermal constraints



MODULE
4X44kA

⇨ **Strip-line cooling:**

- thermal dissipation : 125W/ml/plate
- air cooling at 5m/s (Tmax=34.5°c)

, by He cooling at 15m/s (Tmax=33.9°c)

⇨ **Rooms air conditioning at 30°c maxi:**

PSU room: P= 117kW Intermediate room: P=40kW

Power dissipation by joule effect		kW	
		Water cooling	*Gas cooling*
PSU room	striplines (L=14m)		1.75X32 =56
	PSU	360	21
Intermediate room	striplines (L=10m)		1.25X32 =40
Wessel room	striplines (L=9.1m)		1.14X32 =36.4
	4 Horns	19X4 =76	
TOTAL	**540kW**	**436kW**	**153kW**

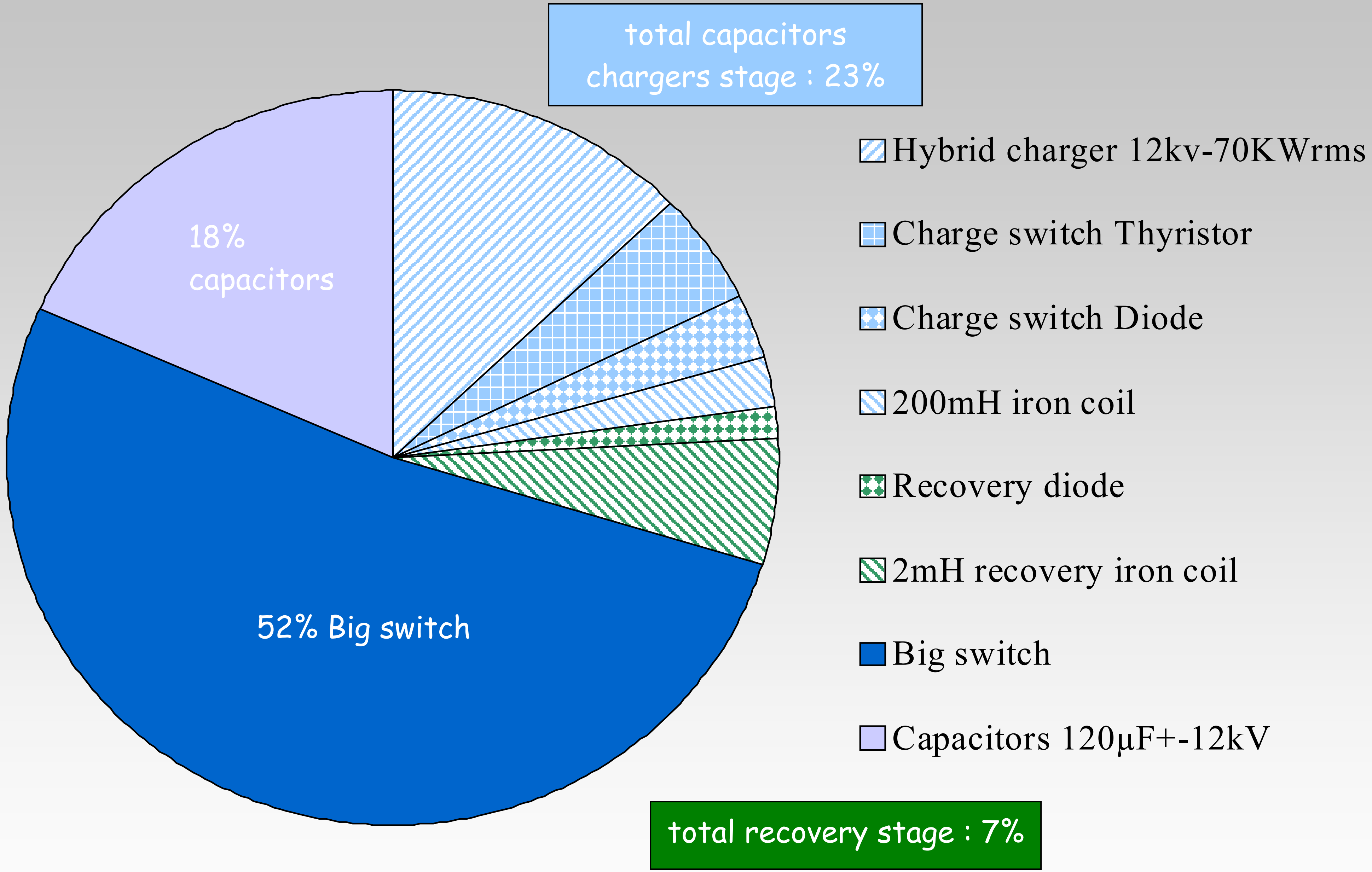
contaminated area	no contaminated area
air cooling	He cooling

⇨ **PSU :**

- **dimensions:** W13.7m X D6.90m X H4m

- **room area:** width 15m X 12m: 180m²

4X44kA MODULE COSTS



Thank you for your attention

[1] E. Baussan & al « Updated Horn Studies » EUROnu WP2 Note 13. http://www.euronu.org.

[2] JM Maugain & al « Study of a horn with integrated target for a neutrino factory », 21 th May 2001

CERN-PS DIVISON

[3] F. Voelker «Note concernant l'étude, en 2001-2003 au CERN, de l'alimentation de la corne NUFACT »

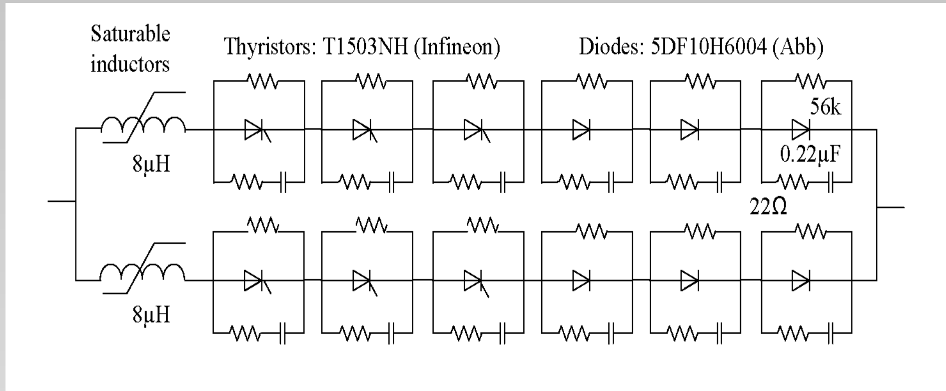
Etude NUFACT, Mars 2011.

[5] Pascal POUSSOT « Skin effect and thermal dissipation in the strip-lines vs. frequency domain » EUROnu WP2 Note 10.14. http://www.euronu.org.

[6] Pascal POUSSOT « Study of 4 horns 350kA peak current, 100μs large & 50Hz electric power supply unit (PSU) with coupled direct devices », EUROnu WP2 Note 15. http://www.euronu.org.

[7] Gérard GAUDIOT « Note sur les amenées de courant », en cours de rédaction, Octobre 2012.

Big switch : 45kA Peak-1297Arms-16.66Hz+-12kV



☞ **saturable inductors:** limit dI/dt in each branch to 150A/µs during start of conduction and blocking steps

☞ **lifetime of components :** constraints below maximal characteristics (safety margin 50%)

electrical contraints on components

	Thyristor **T1503 Infineon**					Diode **5DF10H6004 ABB**				
	I_{TM} kA	I_{TRMS} kA	V_{DRM} kV	$\frac{dI_{cr}}{dt}$ kA/µs	$\frac{dI}{dt}$ kA/µs	I_{FSM} kA	I_{FRMS} kA	V_{RRM} kV	Q_{RR} mC	$\frac{dI_r}{dt}$ A/µs
Maximal	**40**	**3.8**	**7.5**	**0.3**	**5**	**18**	**1.7**	**6**	**6**	**0.3**
Simulations	**22.8**	**0.66**	**4**	**0.15**	**0.75**	**22.8**	**0.66**	**4.5**	**4.1**	**0.15**

☞ **total thermal dissipation of big switch :** 5.3kW@16.66Hz or 4kW@12.5Hz

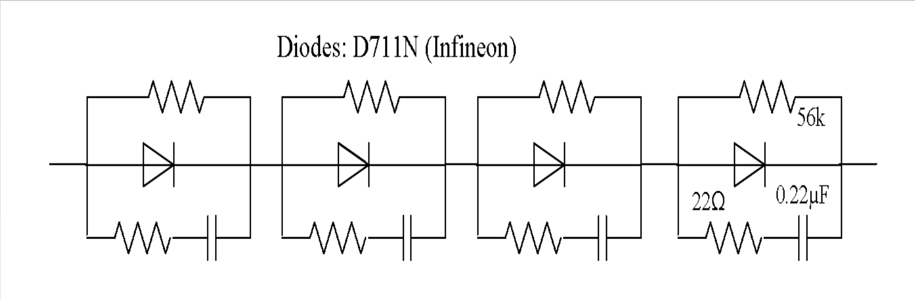
(demineralised water cooling)

6 Thyristors: 1.5kW $(I_{FAV} = F*Q, V_{To}=1.24\text{v}; R_T = 0.44\text{m}\Omega)$: $P_{Thyristors} = 6*(V_{To}.I_{TAV} + R_T.I^2_{TRMS})$

6 Diodes: 3.84kW $(I_{FAV} = F*Q, V_{To\max}=1.5\text{v}; R_D = 0.6\text{m}\Omega)$: $P_{Diodes} = 6*(V_{To\max}.I_{FAV} + R_D.I^2_{FRMS} + V_{RRM}*F*Q_{RR})$

4X44kA MODULE: recovery diode solution

Recovery diode: 2.864 kA Peak-562Arms
50Hz -12kV



☞ **lifetime of diodes :** constraints below maximal characteristics (**safety margin 90%**)

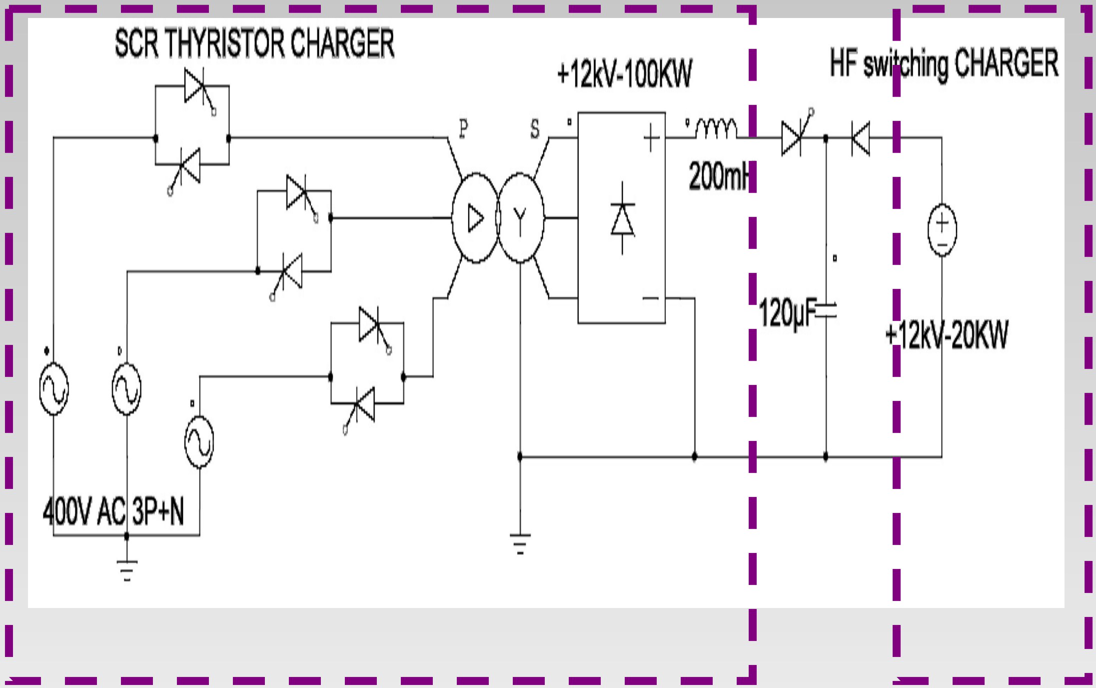
Parameter D711N	V_{RRM} kV	Q_{RR} mC	$\frac{dI_r}{dt}$ A/µs
Maximal	**7**	**5.5**	**10**
Simulations	**3.5**	**3.2**	**5.88**

☞ **total thermal dissipation of diode : 4.7kW@50Hz** (demineralised water-cooling)

Diodes: 4.7kW $(I_{FAV} = F * Q, V_{To\max} = 0.84\text{v}; R_D = 0.87\text{m}\Omega)$: $P_{Diodes} = 4*(V_{To\max}.I_{FAV} + R_D.I_{FRMS}^2 + V_{RRM} * F * Q_{RR})$

Annex2

Principle of hybrid charger: +12kV-5.9Arms-12APeak 50Hz



85% of power is delivered in 16.5ms by SCR thyristors charger, 15% of power in the next 1.5ms by a high frequency (25Khz) switching charger

☞ **advantage of hybrid solution** :

- very high reliability of SCR technology
- fast stabilization of HF switching solution
- very good reactivity to fast 400V variations (typ. +-1% in 40ms)
- reduce EMC and has equivalent cost regardless a 100% HF switching solution
- drive a unique HF module of 20kW maxi
- suggested by 2 manufacturers (an alternative is to place the chargers in serial)

☞ **inconvenients of hybrid solution** :

- need to be tested (R&D)
- peak 400V current higher
- higher volume and weight