LHC status and plans

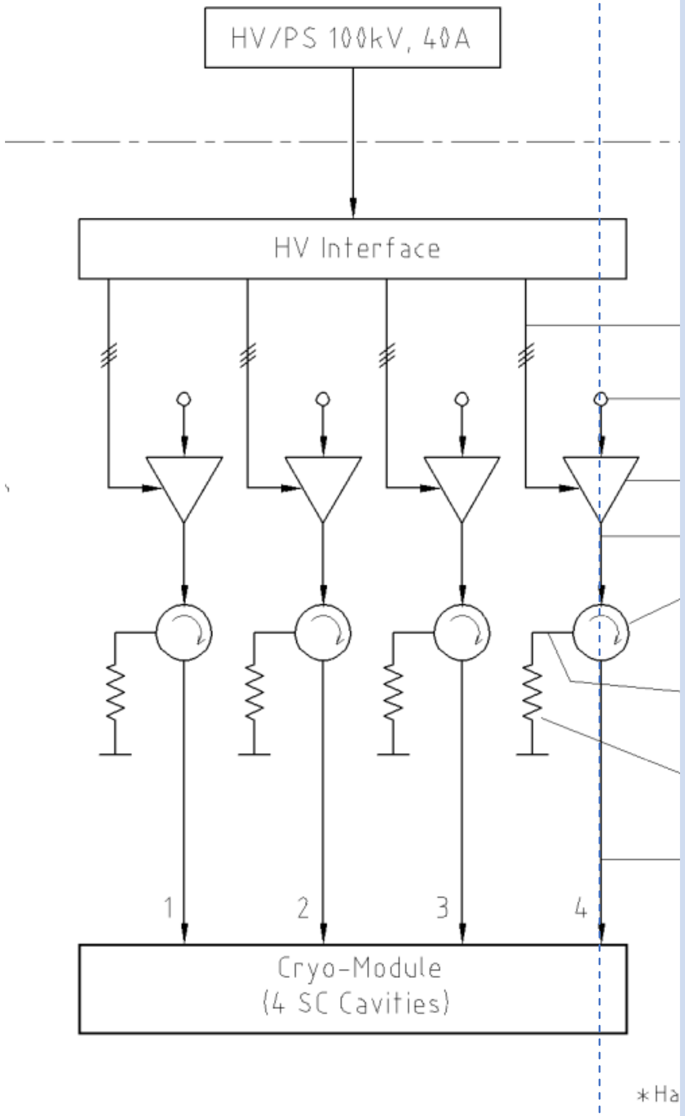
N. Catalan Lasheras

Outline

- Introduction to LHC powering
- Current klystrons status
- LHC RF energy consumption
- New HE klystrons
- HL-LHC expectancies
- Conclusions

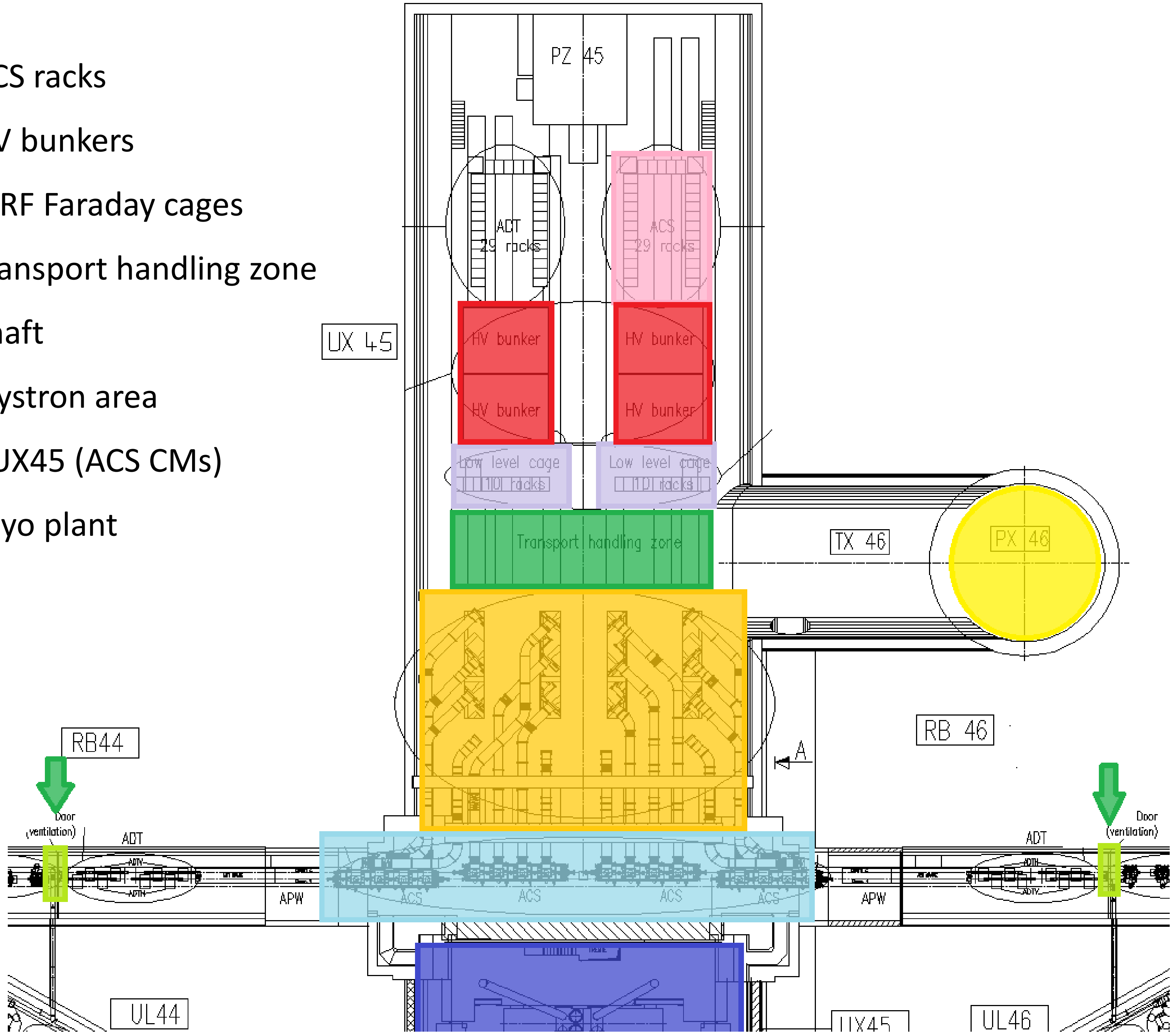
LHC powering scheme

- 4 power converters (SY-EPC)
- 4 Crowbar systems
- 16 MAC10 modulators
- 16 Klystrons (type TH2167)
- RF out max: 300kW/ 400.8MHz
- Working point: 58kV, 8.6A
- DC to RF conversion efficiency: ~60%
- Each klystron feeds a single SC cavity



O. Brunner et all, RF power generation in LHC, PAC2003

- ACS racks
- HV bunkers
- LLRF Faraday cages
- Transport handling zone
- Shaft
- Klystron area
- RUX45 (ACS CMs)
- Cryo plant



HV systems. Status and plans

Crowbar based on thyratrons

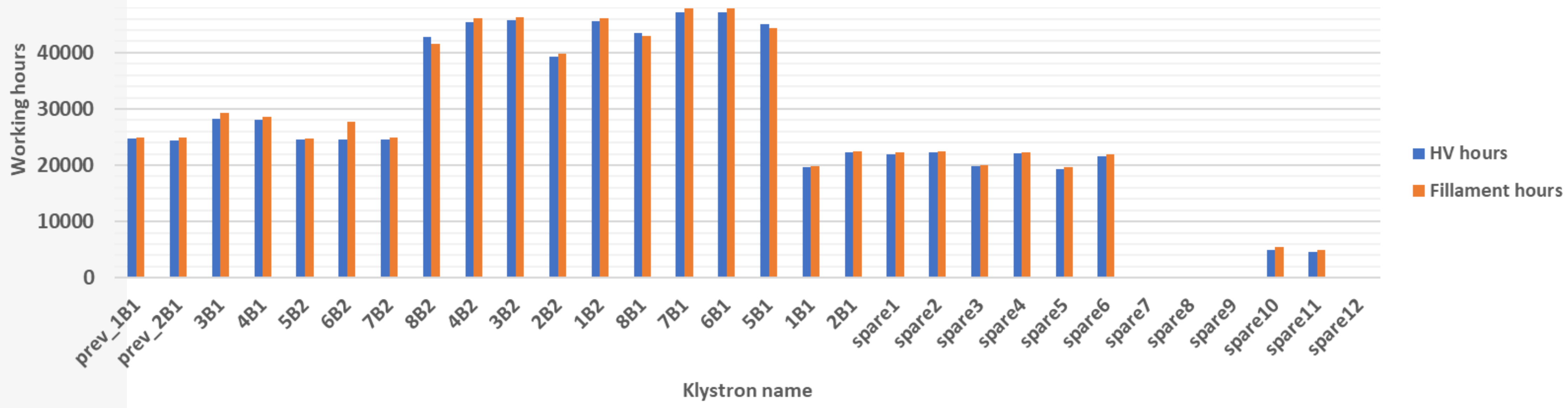
- Replaced by solid state units . Very stable since 10 years
- Study underway to replace PFN line in CLEAR

Tetrode used as HV variable resistance to power the Klystron mode anode

- Tetrode replacement (four per HV bunker, 16 in total)
- Components ageing and old tetrode’s technology is obsolete
- Prototype for new tetrodes is done, SM18 testing this year
- Installation in one of the YETS (t.b.d.)

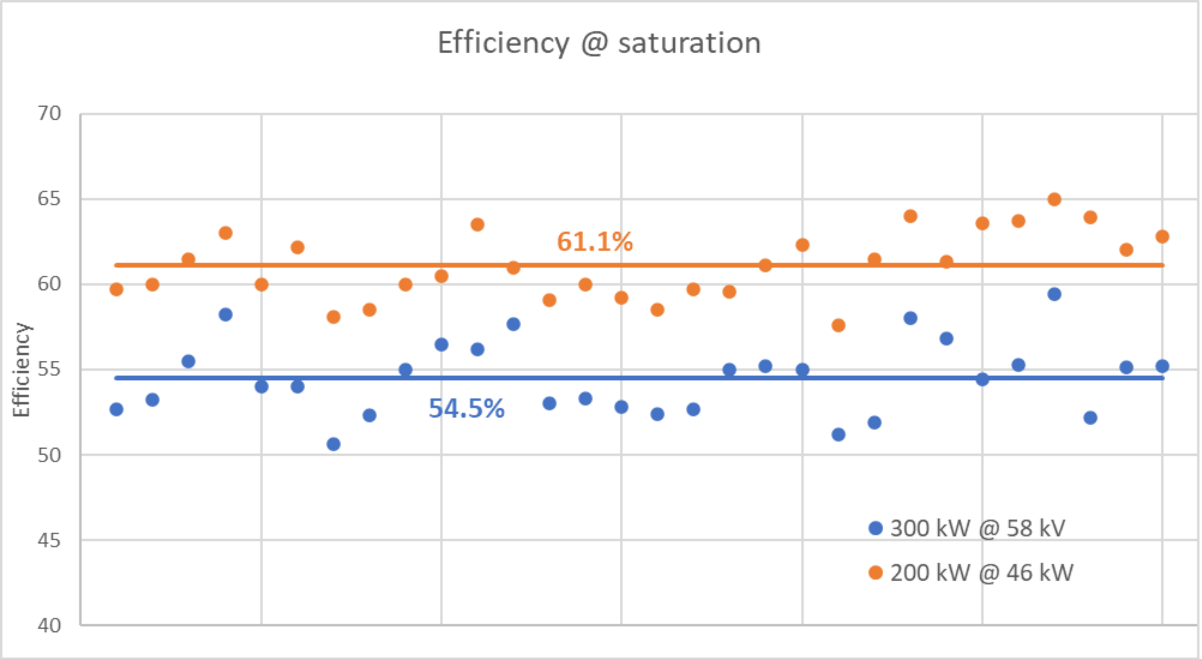
LHC klystrons lifetime

- Main risk of death:
  - Cathode depletion: permanently monitored. No sign of perveance change until now.
  - Ceramic metallisation: leakage current of all ceramics measured periodically. No sign of metallisation observed
- Expected klystron lifetime: 60000hours, still to be seen
- Klystrons exchanged in LS1 to spread running hours and avoid several failures



Klystrons issues

- Collector cooling system improvement
- K22 & K14
  - Some problems detected during high power commissioning → Repeated HV trips, could not hold high voltage
  - Problem not reproduced in the test benches.
- K21
  - Interlock on klystron solenoid during the pilot run → Connection re-soldered
  - Connection opens after klystron test. Heating problem on the coil.



- Average efficiency at nominal conditions > 60%
- Reducing HV to 46 kV yields 200 kW and reduces efficiency to < 55%
- LHC klystron working points @ 50 & 58 kV preserve efficiency

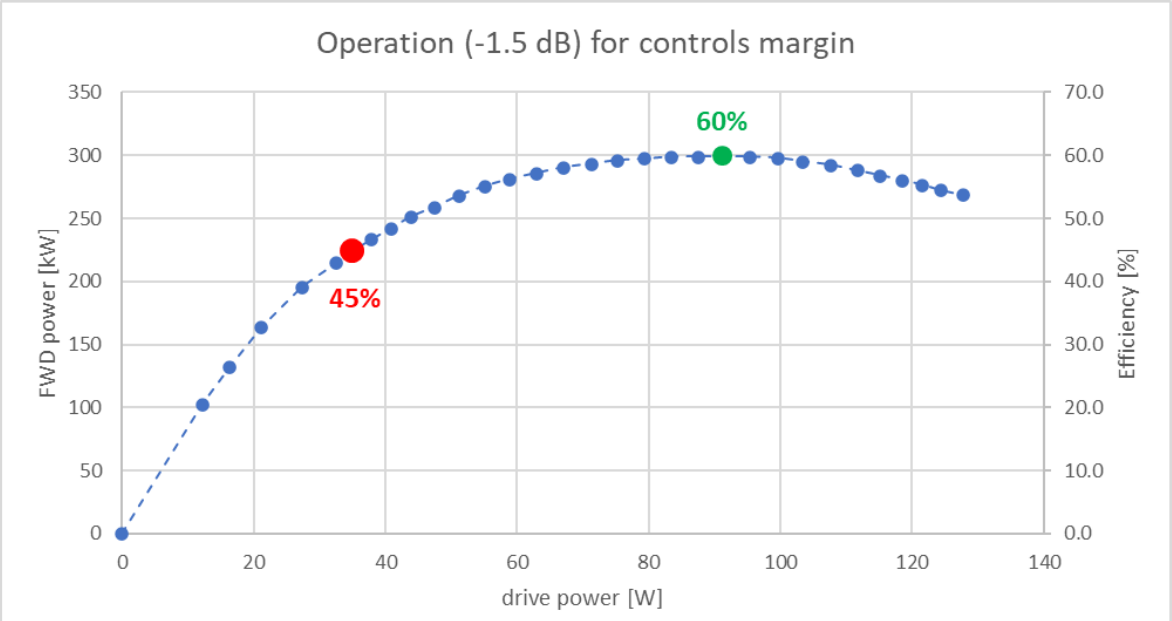
H. Timko, E. Shaposhnikova, K. Turaj, "Estimated LHC RF system performance reach at injection during Run III and beyond", CERN-ACC-NOTE-2019-0005

LHC klystron efficiency

Klystron HV [kV]	Cathode current [A]	DC power [kW]	RF power [kW]	Efficiency [%]
50	7.8	390	230	59
58	8.6	500	300	60

Operational efficiency. Controls margin

- Today’s klystrons are rated for 300 kW CW in saturation. Regular operation for klystrons is typically 1.5 dB below saturation
- Polar loop to linearize the klystron gain
- The trip Level prevents from overdriving the klystron



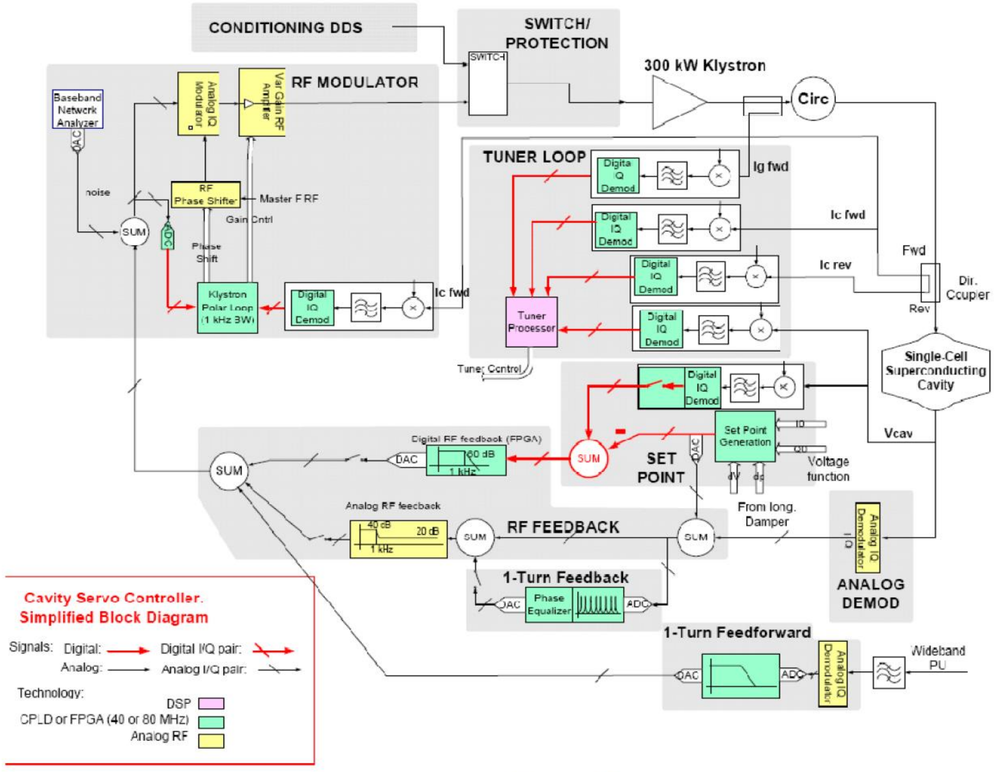


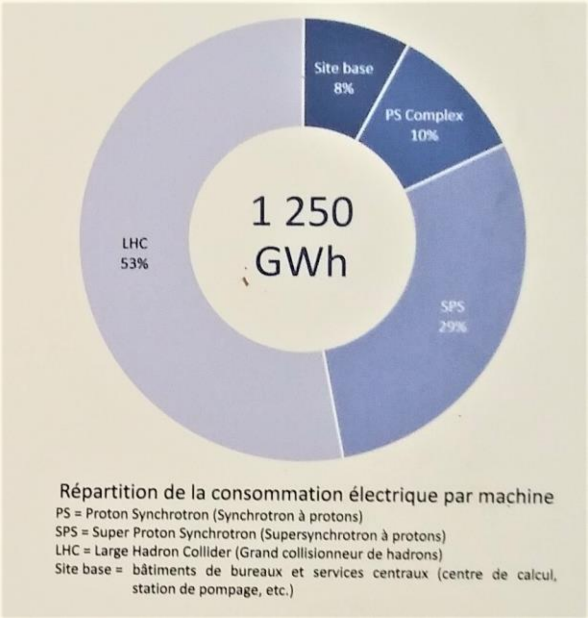
Fig.3: Block diagram of the Cavity Controller

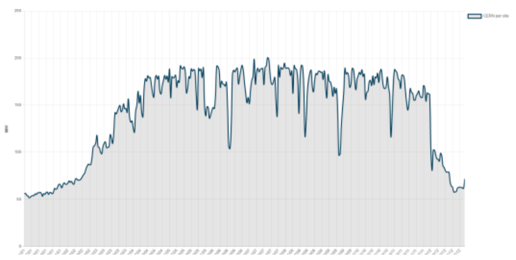
«Hardware and Initial Beam Commissioning of the LHC RF Systems». M.E. Angoletta et al. LHC project report 1172

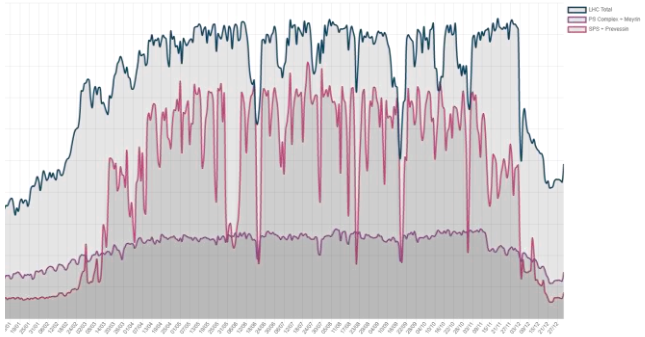
Operational efficiency. LHC cycle

Status	Klystron HV [kV]	Cathode current [A]	DC power [kW]	Drive power [W]	RF power [kW]	Efficiency [%]
STANDBY	10	1.2	12	0	0	0
Injection	58	8.6	499	7.5	120	24
Ramping	50-58	7.73-8.6	387-499	2.3-7.5	45-120	11.6-24
Collision	50	7.73	387	2.3	45	11.6

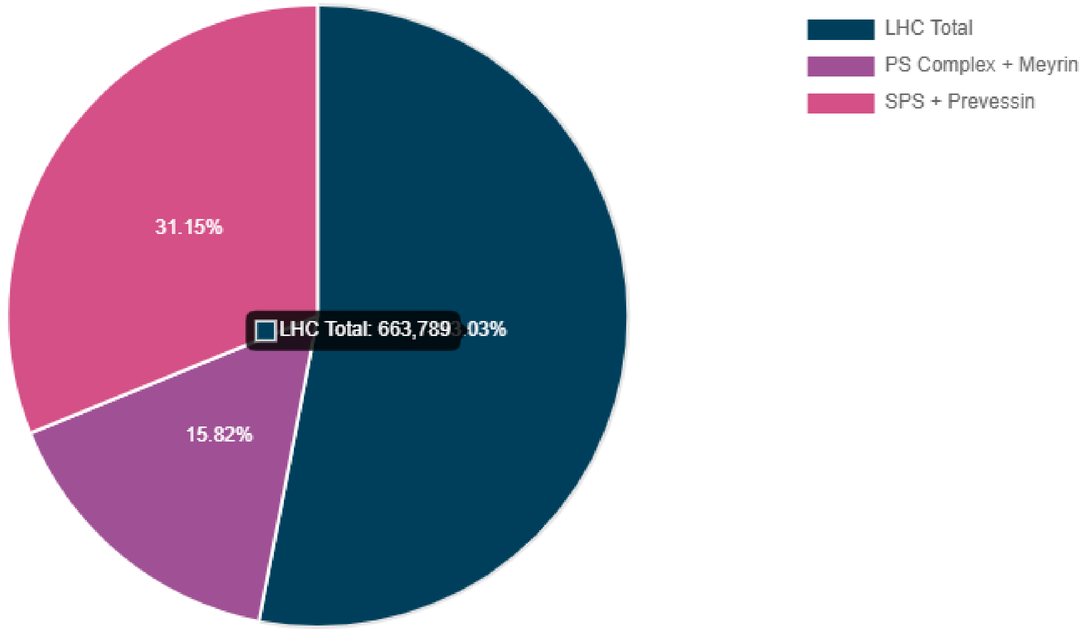
- Most power needed at injection flat top for bunch capture aand avoiding instabilities
- Very little RF power needed at collision. Just cavity losses
- Half-detuned scheme to decrease peak to average voltage ratio
- DC power at collision already reduced by decreasing HV voltage
- Can we do more?

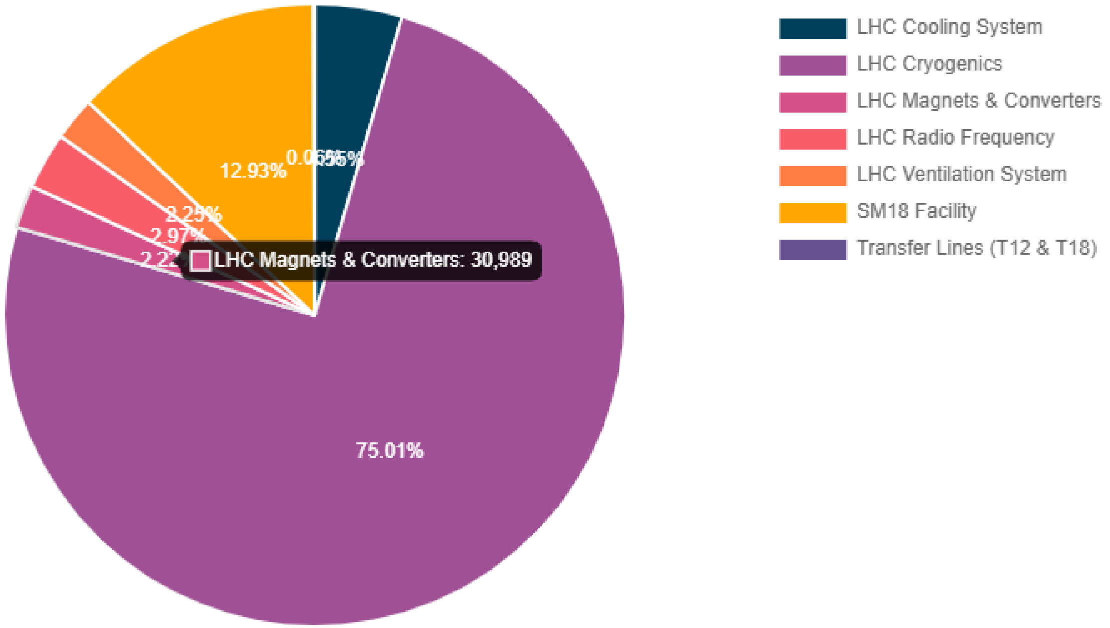


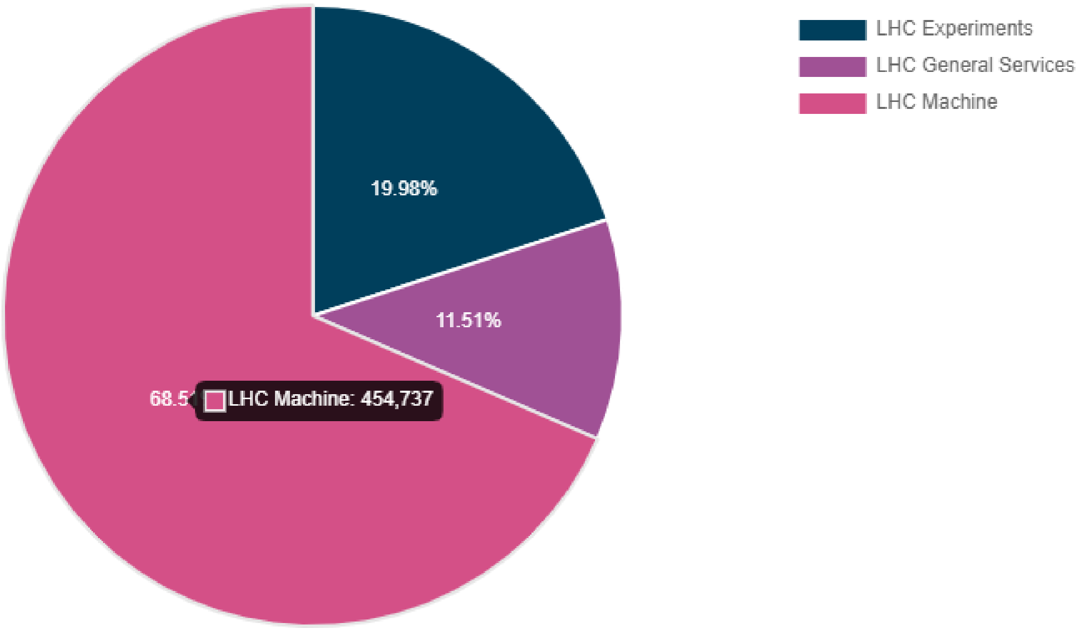


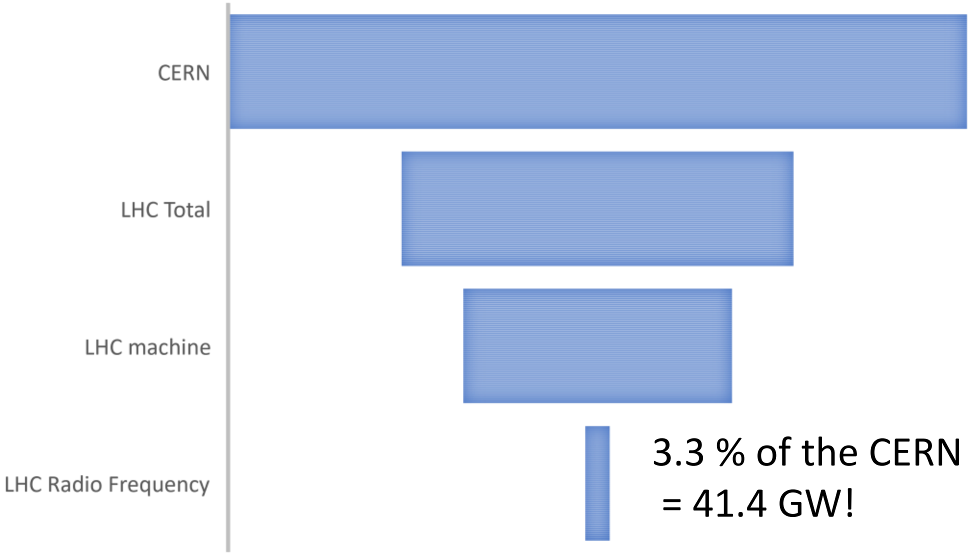


- *The consumption of the LHC represents more than half of the CERN bill*
- *https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.energy_consumption*
- *But how much is the contribution of RF sources?*


LHC Total
PS Complex + Meyrin
SPS + Prevessin
31.15%
15.82%
LHC Total: 663,789

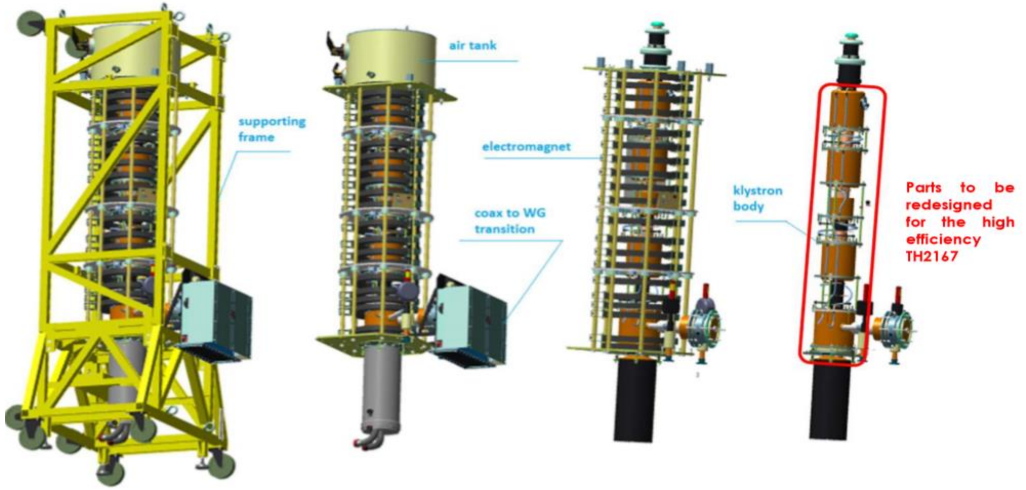

LHC Cooling System
LHC Cryogenics
LHC Magnets & Converters
LHC Radio Frequency
LHC Ventilation System
SM18 Facility
Transfer Lines (T12 & T18)
12.93%
2.25%
2.97%
LHC Magnets & Converters: 30,989
75.01%


LHC Experiments
LHC General Services
LHC Machine
19.98%
11.51%
LHC Machine: 454,737


CERN
LHC Total
LHC machine
LHC Radio Frequency
3.3 % of the CERN
= 41.4 GW!

High efficiency klystron for LHC. IFAST WP11.2

- Design and build an industrial prototype of the LHC klystron reaching 70% efficiency, in collaboration with THALES.
- In order to control the costs, the choice was made to retrofit the existing LHC klystrons, TH2167, with the aim of reusing some components (e.g. solenoid).
- Expected gain in DC to RF conversion efficiency: + 10 - 15 %



Required power for HL-LHC

F. Gerigk @ LHC performance workshop

Scenario			LHC flat bottom			Half-detuning parameters		
Year	Intensity	Small emittance	Voltage	Bunch length	RF peak beam current	Optimum Q_L	Optimum detuning	Minimum klystron forward power
2022	1.4×10^{11} p/b	Yes	4 MV	1.22 ns	1.339 A	16600	-12.07 kHz	84 kW
2022	1.4×10^{11} p/b	No	5 MV	1.28 ns	1.300 A	21360	-9.38 kHz	102 kW
2023-25	1.8×10^{11} p/b	Yes	6 MV	1.22 ns	1.723 A	19350	-10.36 kHz	161 kW
2023-25	1.8×10^{11} p/b	No	7 MV	1.28 ns	1.671 A	23270	-8.61 kHz	183 kW
HL-LHC	2.3×10^{11} p/b	Baseline	7.8 MV	1.24 ns	2.178 A	19890	-10.07 kHz	265 kW

- Compared to 2017 (6 MV), the power at the cavity input needs to increase from 110 kW to 265 kW (x 2.4!) assuming an improved energy matching between SPS and LHC.
- Today's klystrons are rated for 300 kW CW in saturation. **→220 kW** (controls margin).
- Losses from the power transport between klystron and cavity account for 5-10% (wave-guide losses, circulator reflections, ...): **→ 200 kW**
- **Today's LHC RF system cannot provide 265 kW!**

HL-LHC Actions

- Validation of the HE version of TH2167
- Optimisation of the whole HP RF chain needed, goal: 1dB: ~20% in power, ~11% for voltage.
- Improvement of klystron power measurements needed (today in the 20% range, not easy to improve).
- Beam tomography for more precise accelerating voltage measurements. Will be operational for Run3.
- Beam calibration of switch & limit (sets the distance to saturation), already done at every run.
- LLRF & controls optimisation (**not clear today if 1dB is feasible, also needs basically zero reflections from circulator and coupler**).
- Change of circulator settings for injection and flat top (to be studied, motorisation needed).

Conclusions

- The current LHC klystrons are well above 60% efficient
  - No hints of reaching end of life
  - HV systems renovated and very reliable
- Efficiency is given by operational conditions.
  - Operational margin
  - Operating point moves during the accelerator cycle
- Rethinking the powering schemes with efficiency in mind
- Higher efficieny needed for peak power required for HL-LHC

Thanks