# High Efficiency Klystrons for HL-LHC

C. Marrelli, P. A. Arias, O. Brunner, N. Catalan Lasheras, D.S.Guillen, Z. U. Nisa, I. Syratchev (CERN)

J. Cai (UESTC)

A. Baig (STFC)

A. Beunas, K. Haj Khlifa (Thales)

2nd Workshop on Efficient RF Sources
23-25 September, Toledo, Spain

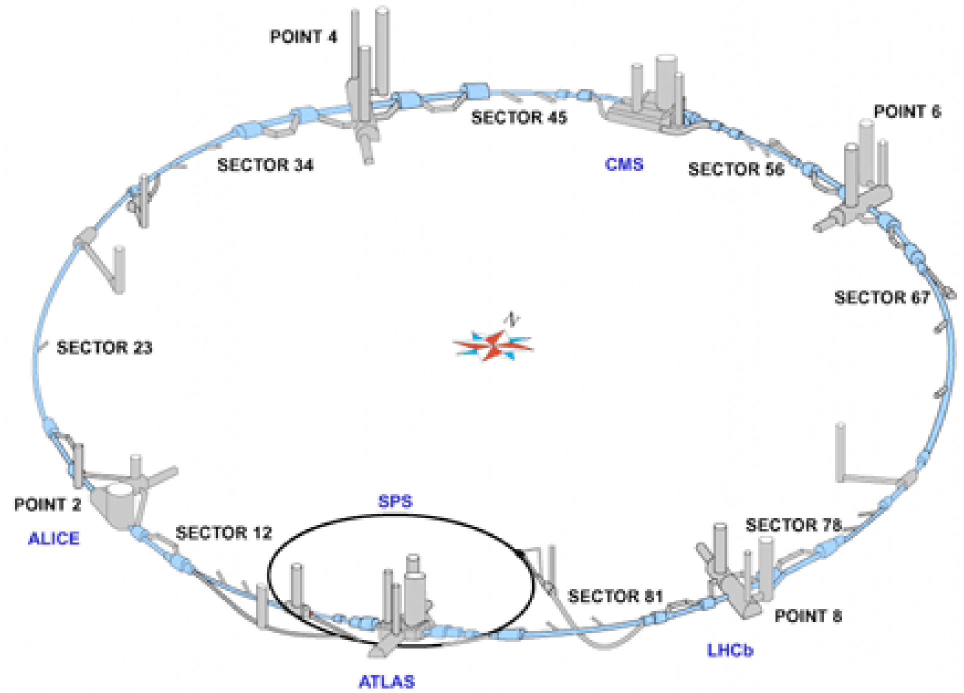
# Outline

- LHC RF system
- HL-LHC requirements
- HE klystrons for HL-LHC
- TH2167HE status and future plans

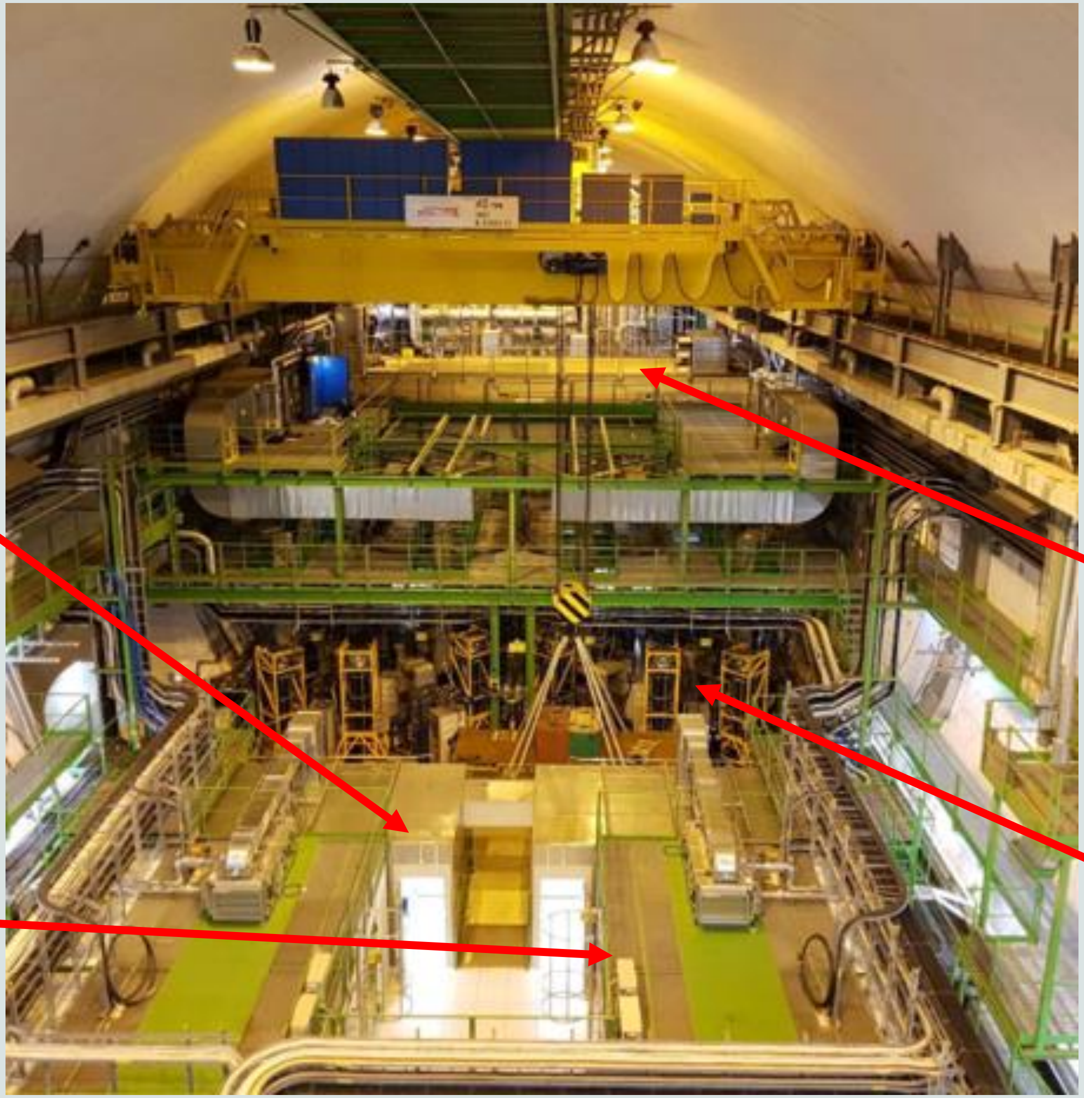
# LHC RF SYSTEMS

16 Superconducting cavities (400.8 MHz, CW) installed in the tunnel in Point4, ≈150 m underground

- 4 Power converters (100 kV, 40 A) from LEP on the surface, one per cryomodule (4 cavities/cryomodule)
  - Power distributed to 4 HV bunkers underground, each equipped with 4 modulators + fast protection system
  - LLRF systems in 2 Faraday cages underground
- 1 LLRF system, 1 klystron / 1 cavity scheme
- Additional beam control equipment located on the surface



# UX45 cavern

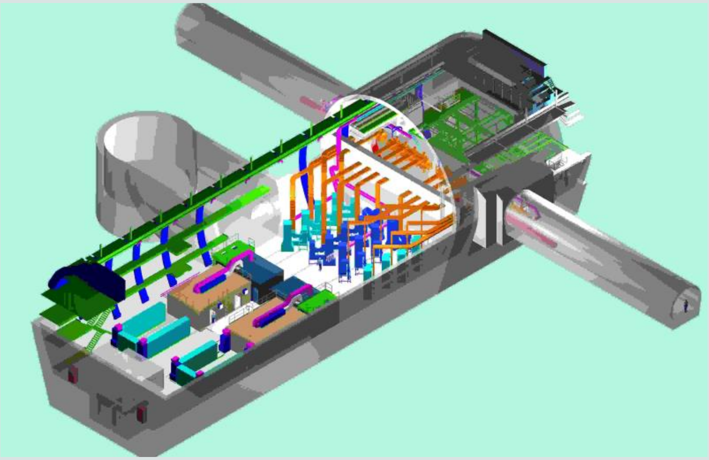


LLRF Faraday Cages

HV Bunkers

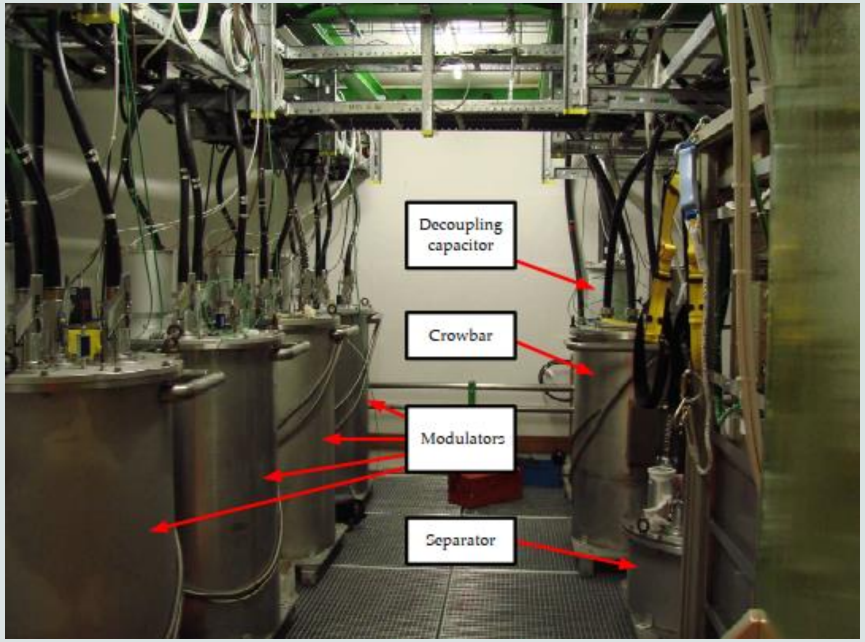
Cavities

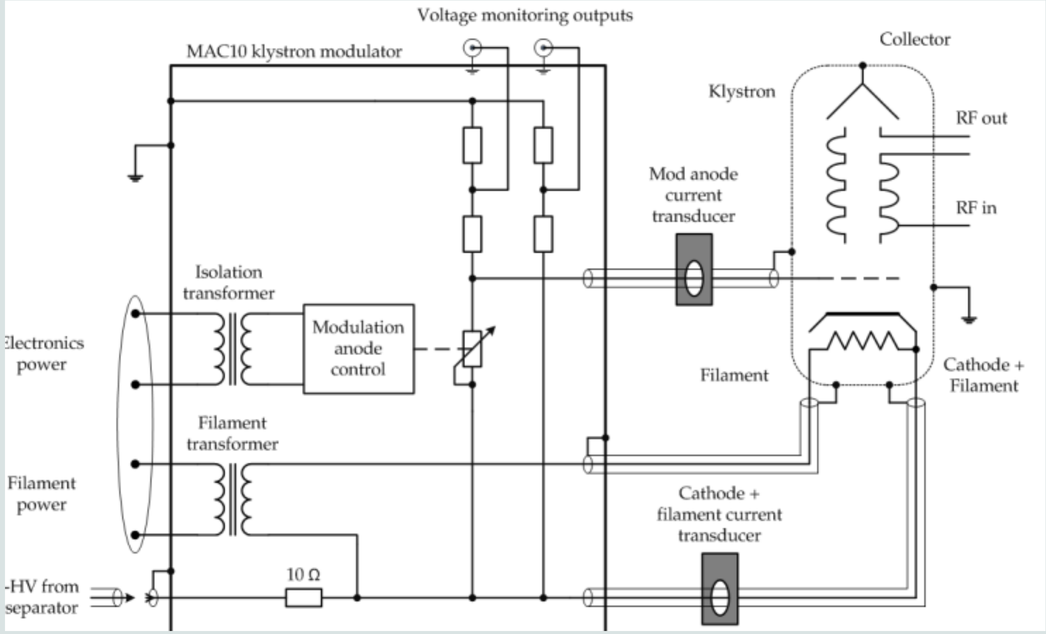
Klystrons + RFDS



# HVPS for LHC klystrons

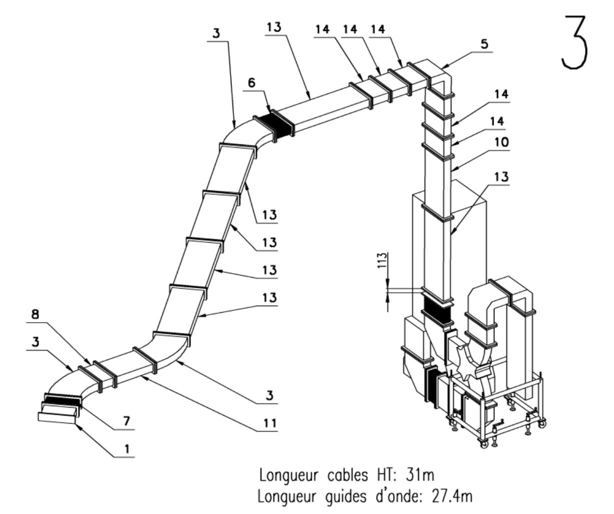
- Power from Power converter distributed to 4 modulators (MAC10) per bunker, providing modulating anode and cathode voltage/current.
- 1 crowbar (Thyristor) and smoothing capacitor in each bunker
- Tetrode TH5186 used to control the anode voltage



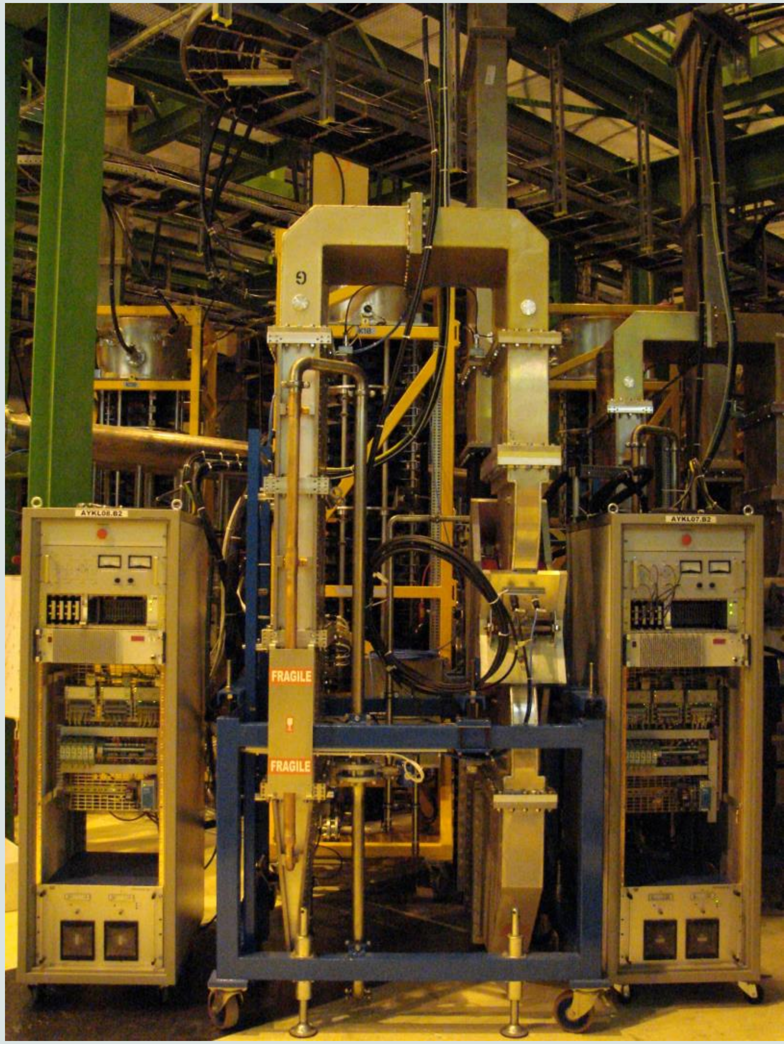


# LHC RF System: RFDS

- All RFDS in WR2300 HH, to individual cavities
- Lines with different lengths (19 to 30 m)
- 1 klystron – 1 circulator + load (ferrite) per cavity
- Circulators and loads rated for 330 kW power
- Circulator equipped with TCU to provide stable match for the klystrons (RL≤28 dB)



Longueur cables HT: 31m
Longueur guides d'onde: 27.4m



# LHC klystrons

- **Thales TH2167**, 400.8 MHz, 300 kW CW
- Vertical orientation, triode gun with air tank on top
- 5 cavities, including 1 second harmonic
- Original specifications included 3 modes of operation: 46, 54, 58 kV (200, 300, 330 kW), only 2 used today (50 kV, 58 kV)
- Output cavity coupled with water cooled loop to coaxial window + T-bar transition to WR2300

| | |
|---|---|
| Power [kW] | 300, 220 |
| Frequency [MHz] | 400.8 |
| Gun microPerveance<br>$P_g \cong \frac{I_b}{V_{MA}^{3/2}}$ | 1.65 |
| Beam microPerveance<br>$P_b = \frac{I_b}{V_k^{3/2}}$ | 0.7 |
| Cathode voltage [kV] | 50, 58 |
| Anode Voltage [kV] | ≤ 35 |
| Beam current [A] | 7.4, 8.5 |
| Efficiency [%] (mode 2) | 60 |
| Gain [dB] | ≥ 37 |
| Bandwidth [MHz] | +/- 1 |
| Group delay [ns] | 130 |

# LHC klystrons: main (past) issues

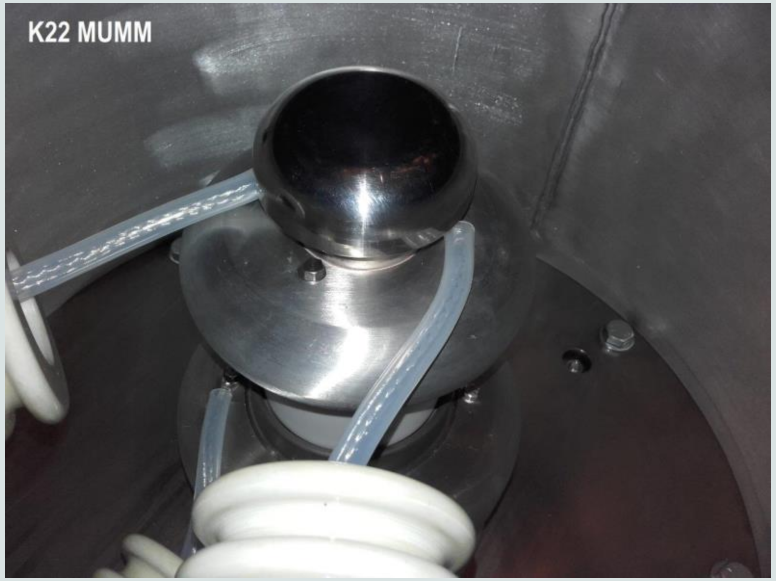
16 klystrons installed in LHC + 13 spares (3 underground) and 1 in SM18 test stand

- Collector issue (before 2010): 1 klystron broken due to vacuum leak after 16000 hours due to collector failure; overheating damages observed on all klystrons

  *Cooling jacket redesigned and replaced (2010-2014)*

  *Operating point changed (from 54 kV, 9 A to 58 kV, 8.5 A)*

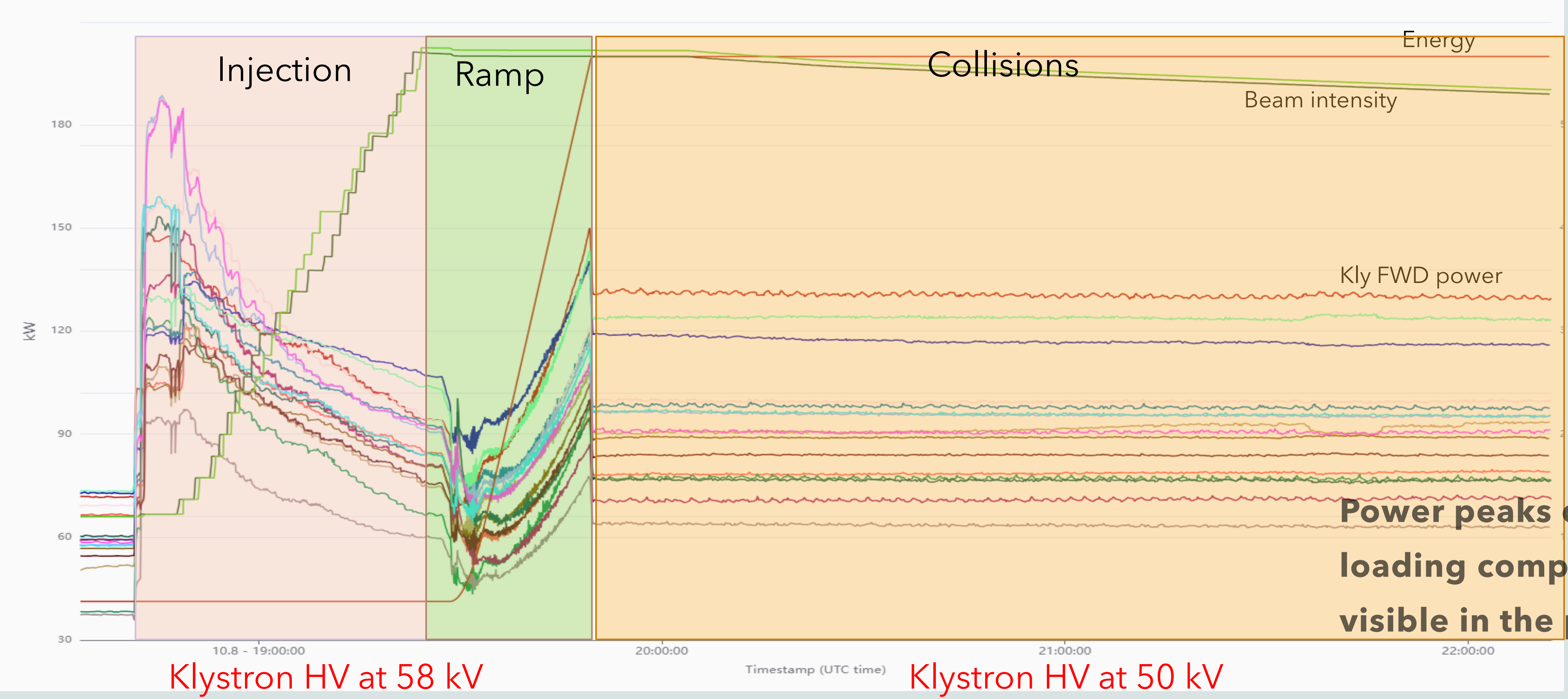
- Multipacting observed on S/N 2 at low output power (60-90 kW) on output coaxial. Corrected with extra cooling.
- "Minor" issues: gun arcing, solenoid connector overheating, shorted filament…



# LHC klystron operation

The LHC “cycle”:

Most power required during injection: klystrons at 58 kV, 8.5 A



**Power peaks due to beam loading compensation not visible in the plot!**

# LHC klystrons: current performances

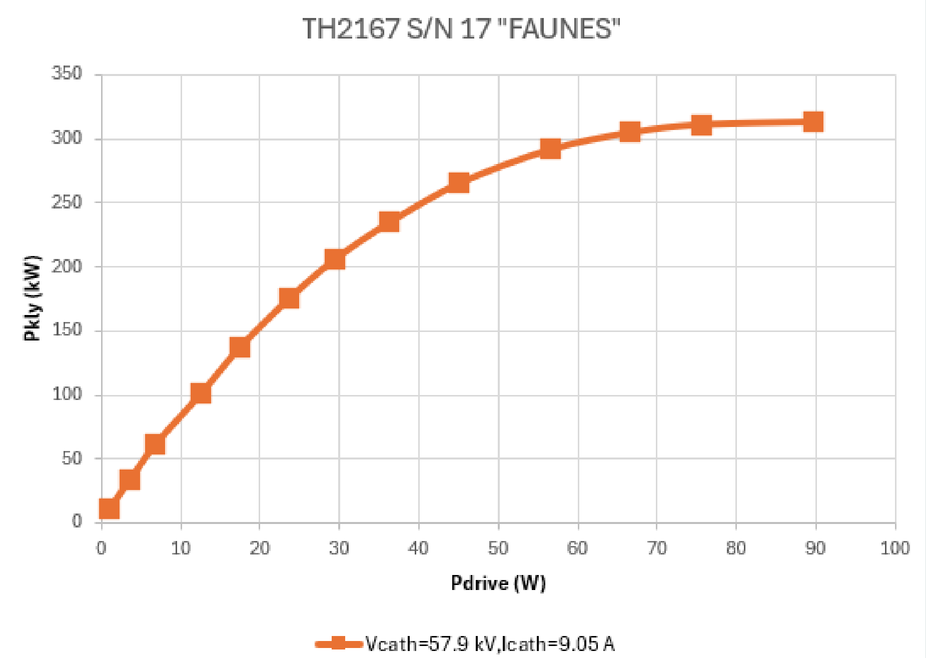
- Klystron efficiency (at saturation) on average around 60%
- Klystron efficiency at operation point…less than 40%

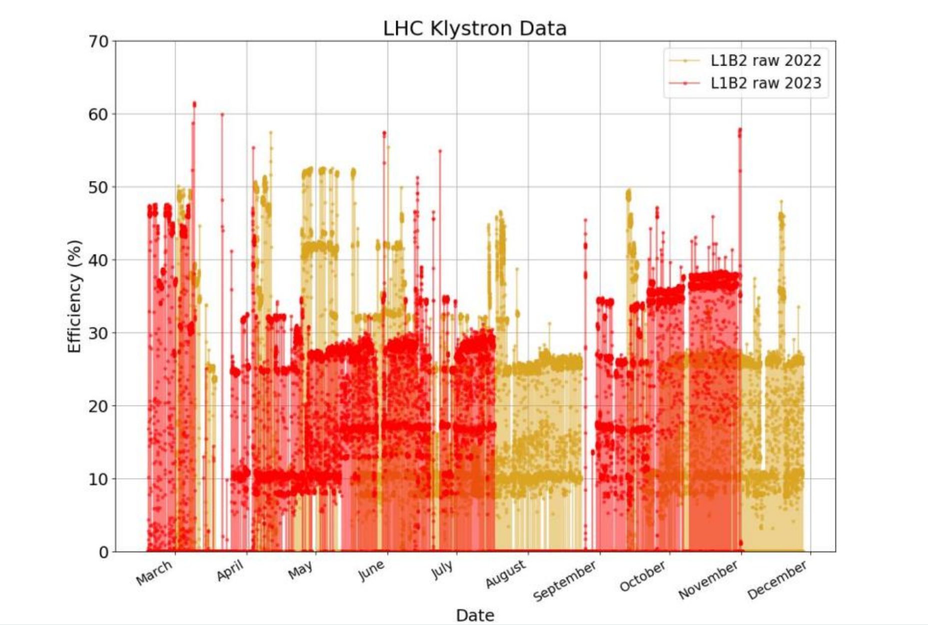
<u>Can we do better (in terms of efficiency?)</u>

…reducing HV helps;

Impact of RFDS and circulator to be further investigated

Running in saturation and regulating with mod-anode???....





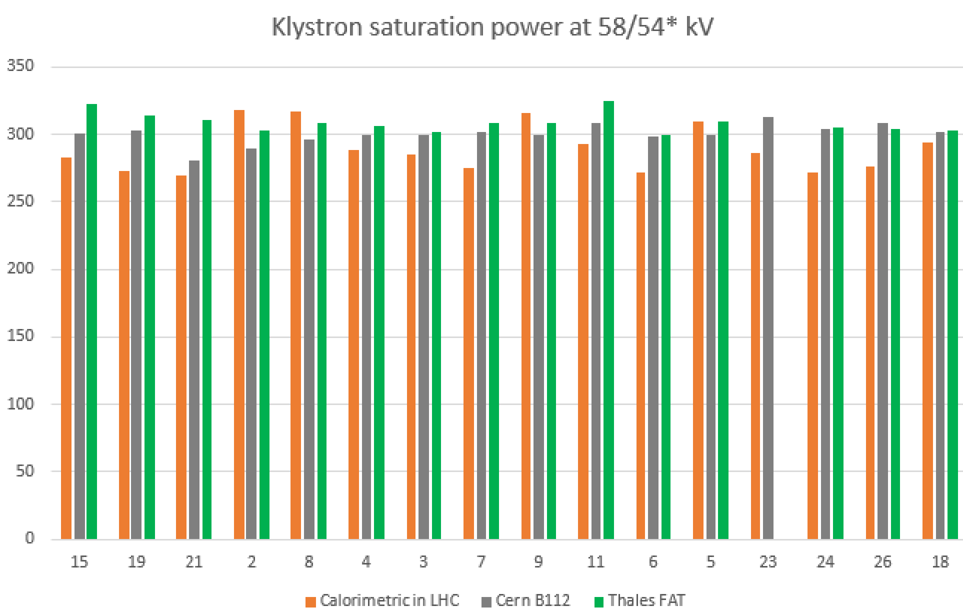
# HL-LHC

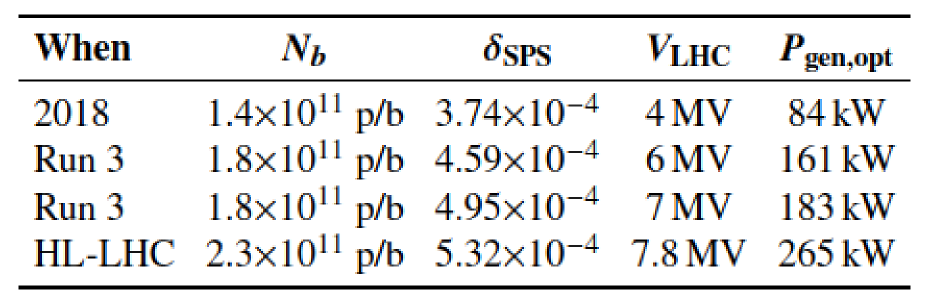
Beam intensity to reach $2.3*10^{11}$ p/b after LS3 (2030)

Capture of higher intensity beams from SPS challenging …many klystrons hit saturation limit during injection (half-detuning scheme);

With present system $2.0*10^{11}$ p/b capture possible with cavity pre-detuning + $Q_L$ / frequency adjustment for individual cavities -> no margin!

For $2.3*10^{11}$ p/b required peak power from the klystrons could reach 340 kW!





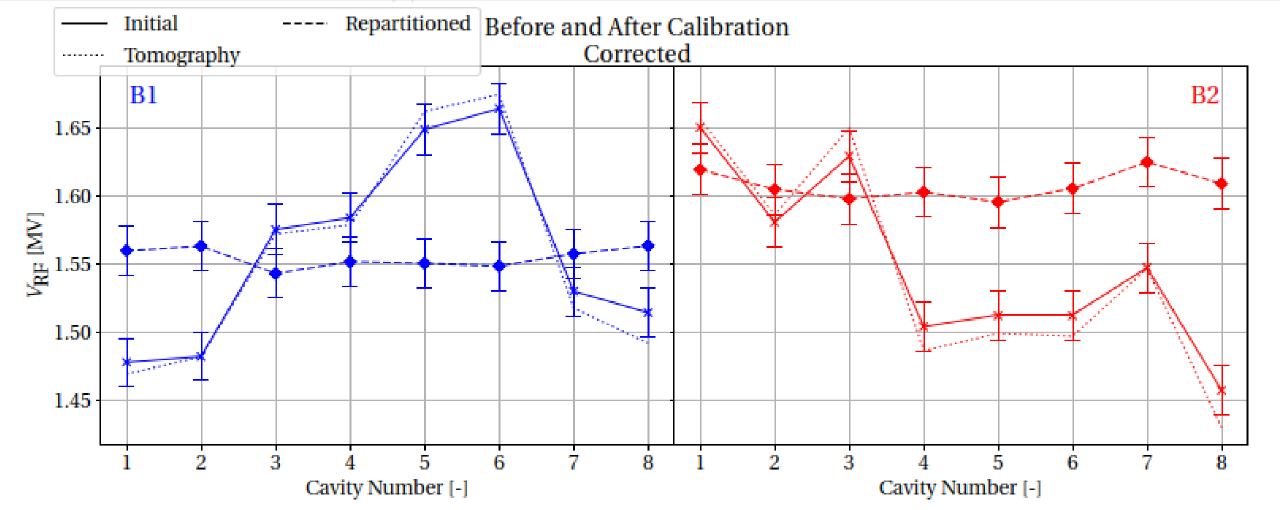
| When | $N_b$ | $\delta_{\text{SPS}}$ | $V_{\text{LHC}}$ | $P_{\text{gen,opt}}$ |
|---|---|---|---|---|
| 2018 | $1.4\times10^{11}$ p/b | $3.74\times10^{-4}$ | 4 MV | 84 kW |
| Run 3 | $1.8\times10^{11}$ p/b | $4.59\times10^{-4}$ | 6 MV | 161 kW |
| Run 3 | $1.8\times10^{11}$ p/b | $4.95\times10^{-4}$ | 7 MV | 183 kW |
| HL-LHC | $2.3\times10^{11}$ p/b | $5.32\times10^{-4}$ | 7.8 MV | 265 kW |

As it is today, LHC RF System is not ready for High-Luminosity

# LHC Power Limitations: ongoing studies

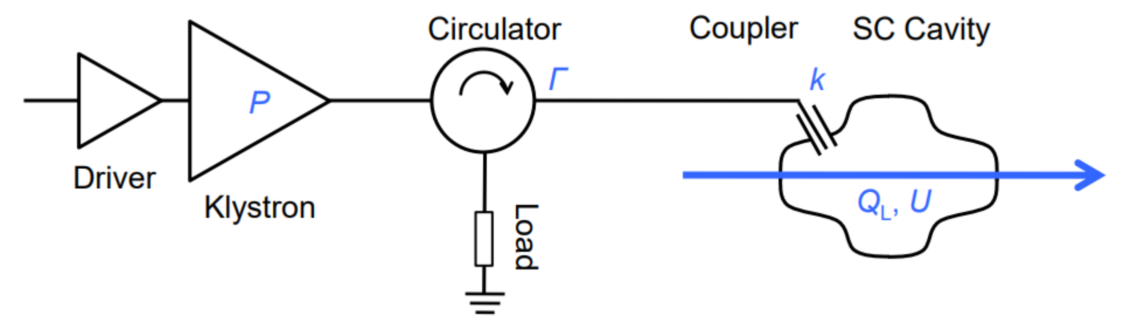
## Power calibration and $Q_L$ measurement campaign

*Cavity voltage -> calibrated with beam, good accuracy (≈3%)*



*Cavity $Q_L$*

- measurement with beam affected by bunch length change during measurement time (10-17 min);
- measurement from voltage decay influenced by Circulator S22 and waveguide match -> **to be checked**



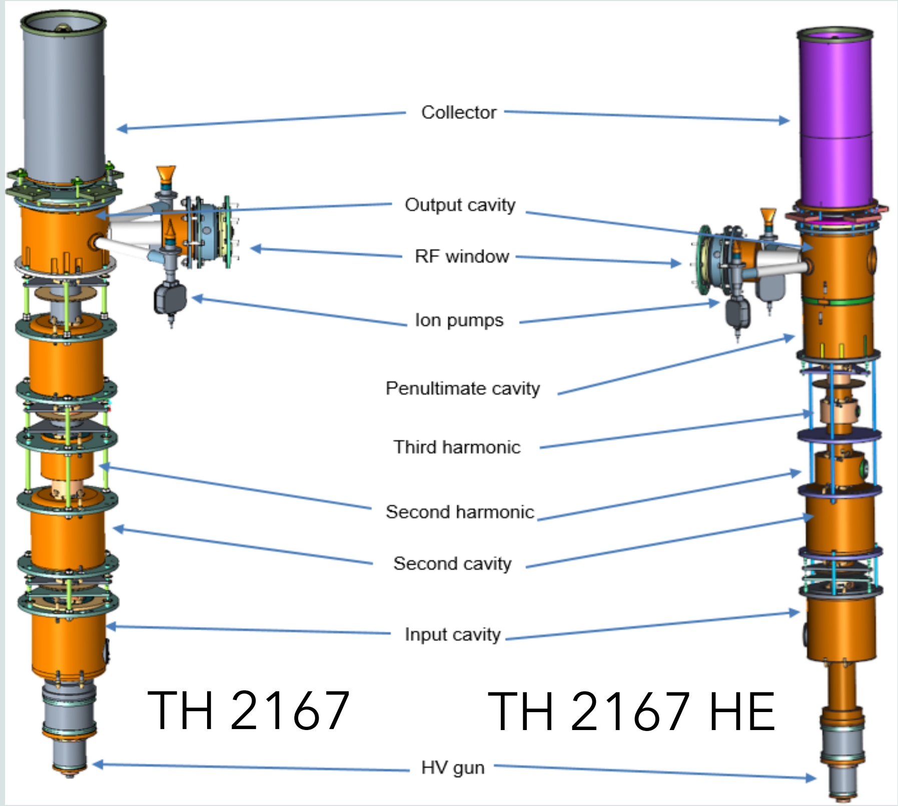
*Cavity FWD and RFL power*

- RF measurements have limited accuracy due to coupler directivity + uncertainty on calibrations -> **to be re-checked**;
- calorimetric measurements available for Klystron FWD power but **needs better measurement of cathode current**

# HE klystrons for CERN

Take advantage of the developments of the High Efficiency Klystron activity at CERN to retrofit the present LHC klystrons to HE version -> 350 kW output power, $\eta_{min}$=67%

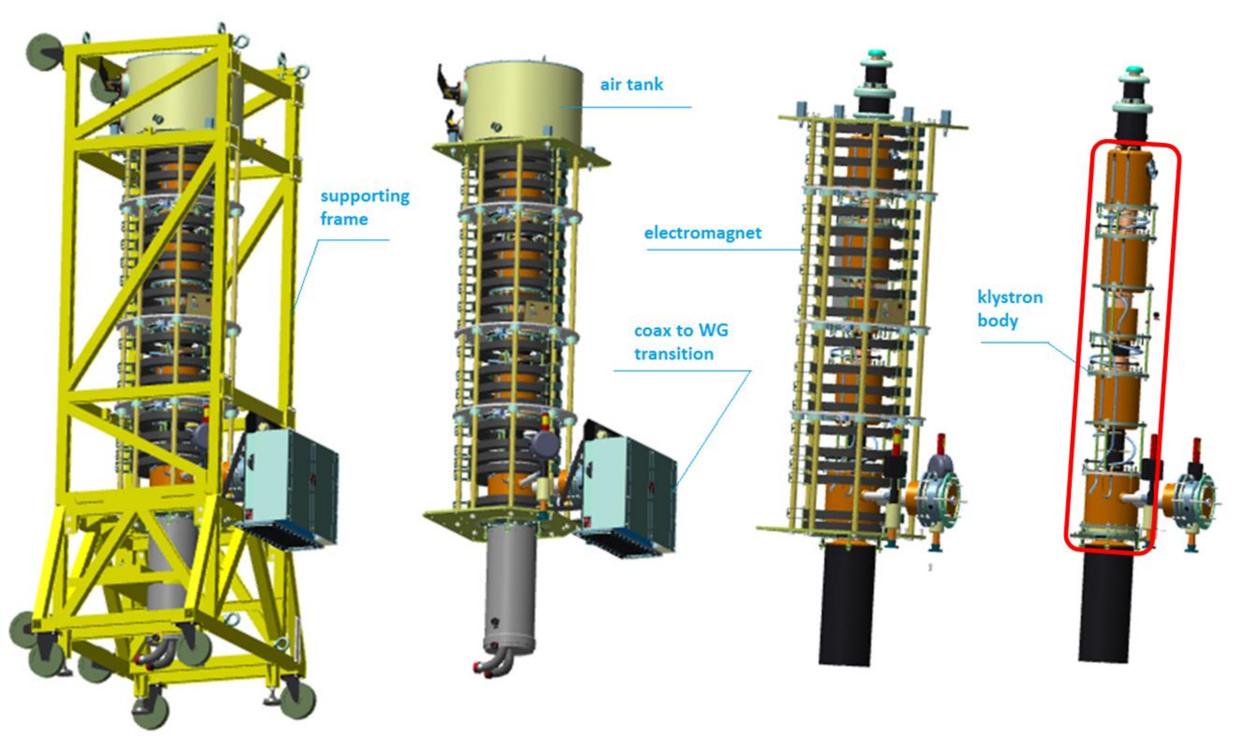
Operating point compatible with present HVPS



Prototype developed in collaboration with Thales in the framework of IFAST WP 11.2

| | **TH2167** | **TH2167HE** |
|---|---|---|
| Power [kW] | **300** | **350** |
| Frequency [MHz] | 400.8 | 400.8 |
| Gun microPerveance $P_g \cong \frac{I_b}{V_{MA}^{3/2}}$ | 1.65 | 1.65 |
| Beam microPerveance $P_b = \frac{I_b}{V_k^{3/2}}$ | 0.7 | 0.7 |
| Cathode voltage [kV] | 58 | 58 |
| Anode Voltage [kV] | ≤ 35 | ≤ 35 |
| Beam current [A] | **8.5** | **9** |
| Efficiency [%] | **60** | **≥ 67** |
| Gain [dB] | ≥ 37 | ≥ 37 |
| Bandwidth [MHz] | +/- 1 | +/- 0.7 |
| Group delay [ns] | 130 | ≤ 250 |

# From TH2167 to TH2167HE



- Same triode gun as the TH2167, compatible with modulator
- Operating point for 350 kW at 58 kV, 9 A
- Same output  circuit as TH2167
- Re-use frame, gun tank, HV connectors, electromagnet and coax to WG transition from existing klystrons.

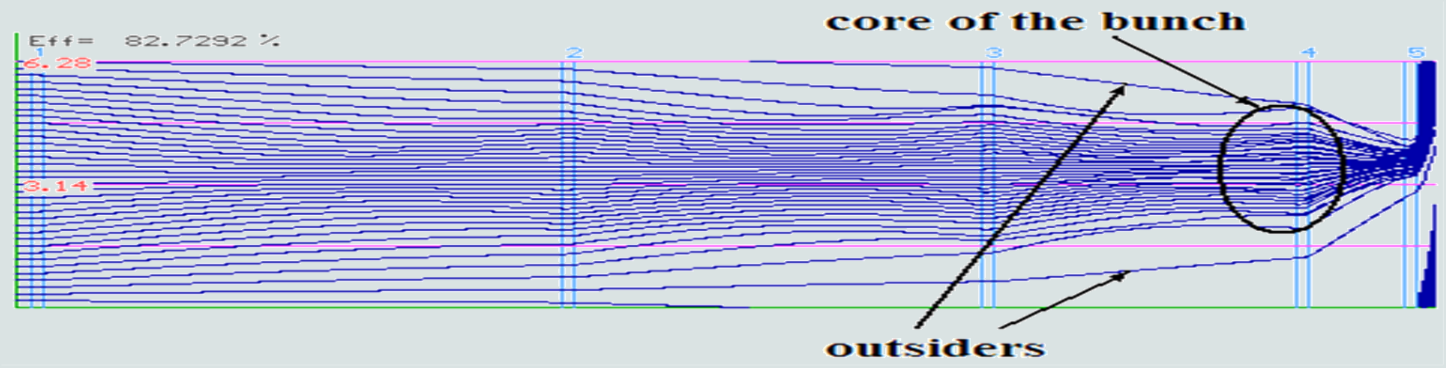
TH2167

TH2167HE

- Solenoid slightly modified (displacement of 3 coils, two power supplies)
- Modified collector/boiler to increase safety margin
- Frame modified to accommodate the new tube
- X-rays shielding modified to meet the new RP standards
- **Replacement of the interaction circuit with new CSM design** from CERN: 6 cavities, including one 2nd and one 3rd harmonic
- Same circuit length

# Bunching methods for High Efficiency

## Bunching techniques for High Efficiency Klystrons

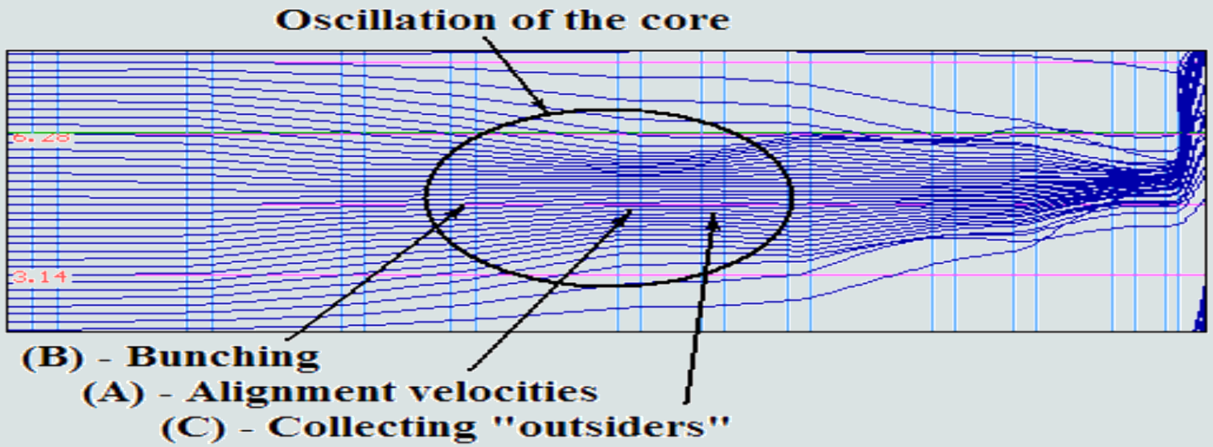


Core Oscillation Method (COM):

- core of the bunch periodically contracts and expands (space charge guided process)
- Outsiders monotonically go to the center of the bunch
- Long interaction length

Bunch Align Collect (BAC) method:

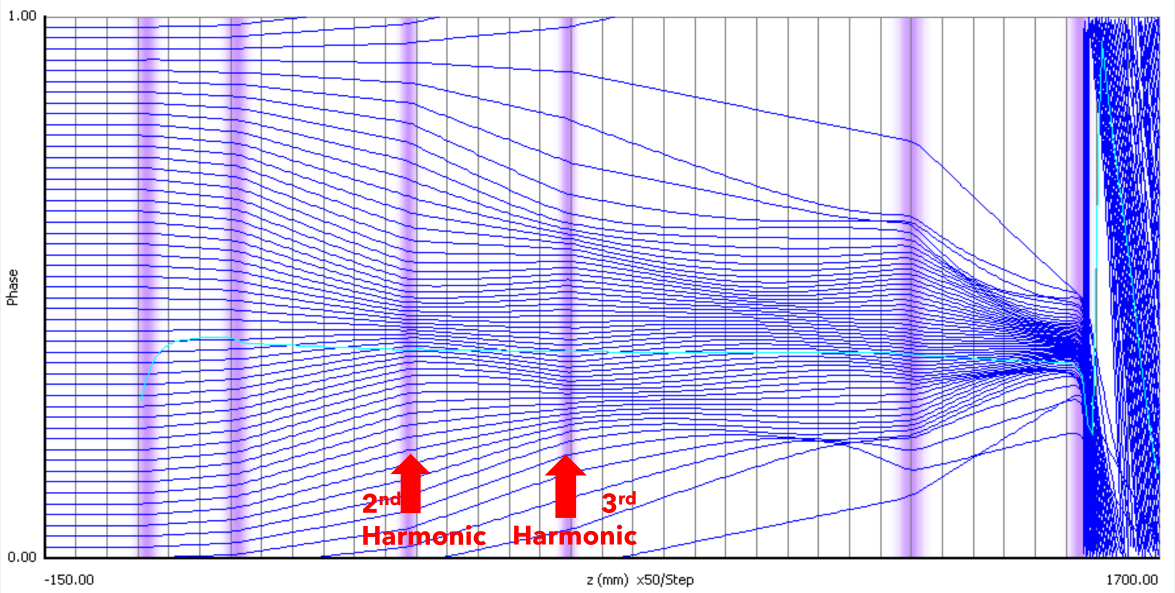
- Tuning of the cavities (inductive+capacitive) creates “artificial” oscillations
- Large number of cavities



# Core Stabilization Method (CSM)

"Harmonic" bunching:

- Harmonic cavities used to introduce non-linear components in the electron transit time from input cavity to output; 2nd harmonic cavities have been used since the 70s (E. L. Lien), but higher harmonics had never been used.
- The harmonic cavities push peripheral particles towards the center of the bunch, while the core forms sub-bunches (depending on the number of harmonics used). **For higher harmonic number the core is stabilized around the center**.
- This process allows to get very good bunch saturation over a short interaction distance.

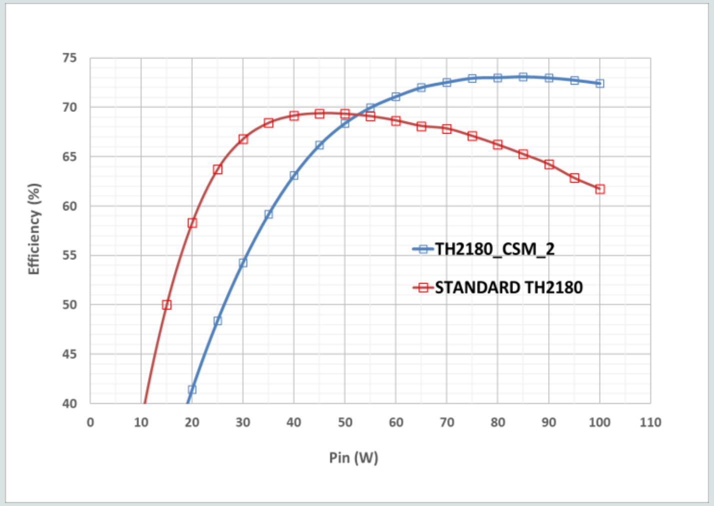


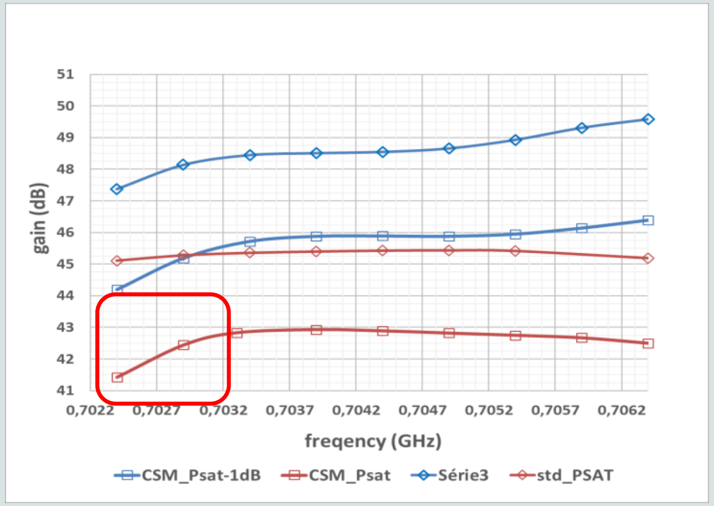
# Previous CSM studies

**Only simulation work!**

HE design for ESS 1.5 MW, 704 MHz klystrons at Thales (compatible with existing modulator).

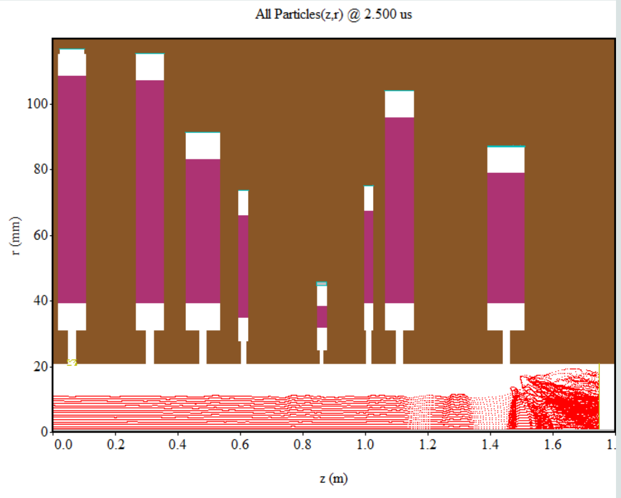
Efficiency (Klys2D): 73%

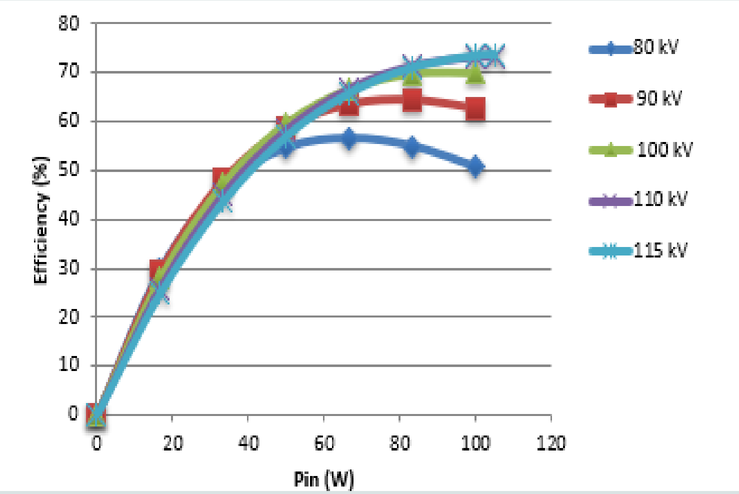




HE design for ESS 1.5 MW, 704 MHz klystrons at ESS (compatible with existing modulator).

Efficiency (KlyC, Magic2D): 73%



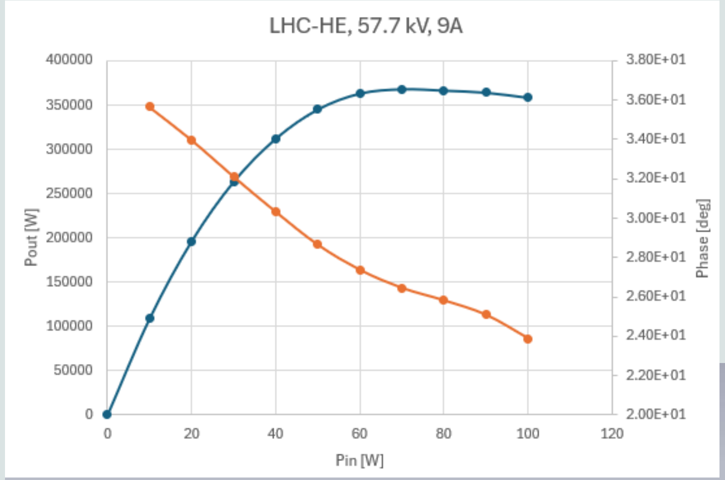


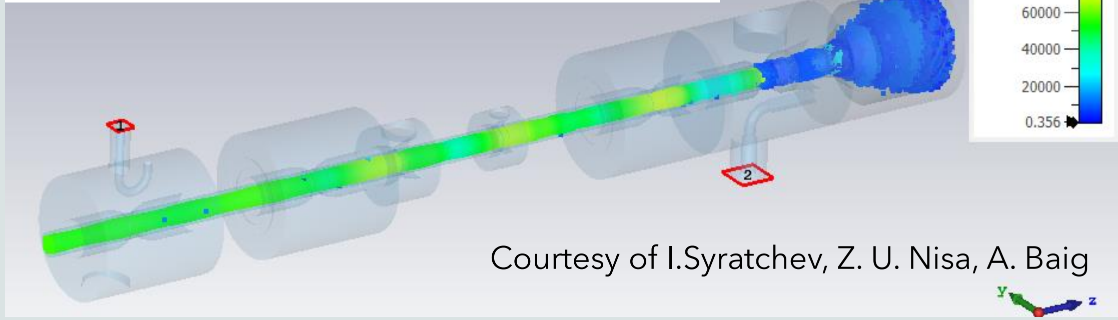
# CSM for LHC

Design at CERN:

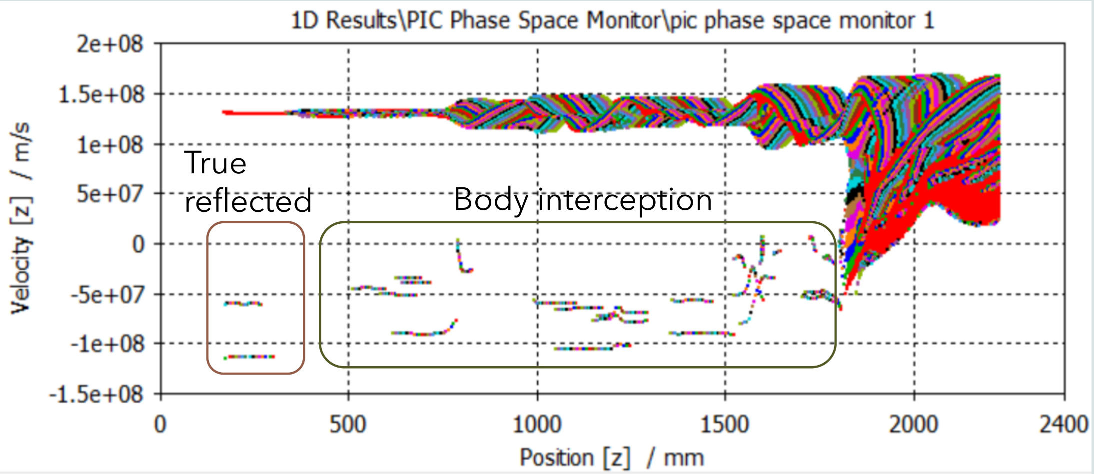
Simulation and optimization done with KlyC, showing 70% efficiency at saturation

- Beam imported in CST TRK to simulate beam transport, focusing (field distribution from 3D B-field simulation) and collector power dissipation
- PIC CST simulations: beam transport under imported B-field, RF interaction with measurement of body losses, intercepted and reflected electrons to cathode, body, collector, in order to calculate balanced efficiency.
- Cavity tuning in PIC done with short bunched beam train
- Predicted efficiency in CST:70%
- Stability and performances checked for different input power levels, frequency, magnetic field
- Option to adjust current on the last two coils to control body dissipation and reflected electrons





Courtesy of I.Syratchev, Z. U. Nisa, A. Baig



# TH-2167 HE

- Manufacturing started in 2022 after validation of CERN design at Thales
- TH2167 S/N 01 “St. Paul” was sent back to Thales after being removed from LHC due to poor vacuum; parts have been re-used for the HE prototype.
- Tube currently under test at Thales
- Simulated efficiency confirmed by tests
- Repeated iterations of measurements and simulations: BW, power and phase transfer curves accurately reproduced by KlyC

More details on manufacturing and factory testing in tomorrow’s presentation by Thales!

# Next Steps

01

FAT at Thales in October 2024

02

Delivery to CERN and installation in the TH2167 test stand

03

Phase 1: test on present test stand to confirm factory performances and compare with TH2167

04

Renovation of the test stand

05

Phase 2: testing on renovated test stand: focus on efficiency measurements and soak test

06

Production of series klystrons and installation during LS3

# References

- A. Mikkelsen, *Digital measurement system for the LHC klystron high voltage modualator*, CERN-THESIS-2014-033.
- *Technical specification for the Supply of 400 MHz, 300 $kW_{CW}$ Klystrons for LHC*, July 2000.
- Thales Electron Tubes and Devices, *TH 2167 CW klystron amplifier Operating Instructions*.
- B.E. Karlsen-Baek et al., *LHC MD 6944: RF Voltage Calibration*, CERN-ACC-NOTE-2024-0008
- H. Timko et al, *Advances on LHC RF Power limitation studies at injection*, HB2023, Geneva, Switzerland.
- V. C. R. Hill, G. Burt, D. Constable, C. Lingwood, C. Marrelli and I. Syratchev, *Particle-in-cell simulation of second and third harmonic cavity klystron*, 2017 Eighteenth International Vacuum Electronics Conference (IVEC), London, UK, 2017, pp. 1-2, doi: 10.1109/IVEC.2017.8289626.
- A. Beunas, *CSM Klystron for LHC*, 1st Workshop on Efficient RF Sources, Chateau de Bossey, 4-6 July 2022.
- C. Marrelli, *High Efficiency klystrons for ESS*, 20th International Vacuum Electronics Conference (IVEC), April 2019.
- N.C. Lasheras et al., *High Efficiency Klystrons from a dream to reality*, IPAC 2024.
- J.C. Cai, I. Syrachev, *KlyC: 1.5D Large Signal Simulation Code for Klystrons*, IEEE Trans. on Plasma Science, vol.47, no.4, pp.1734-1741, April 2019.
- Thales Electron Tubes and Devices , *TH2167HE Design Report*, 2022.
- Z. Un Nisa, A. Baig, I. Syratchev, *TH2167HE klystron analysis in CST*, 2022.

THANK YOU!

This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under Grant Agreement No 101004730