



FUTURE
CIRCULAR
COLLIDER

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POWERING OF RF FOR FCC-EE

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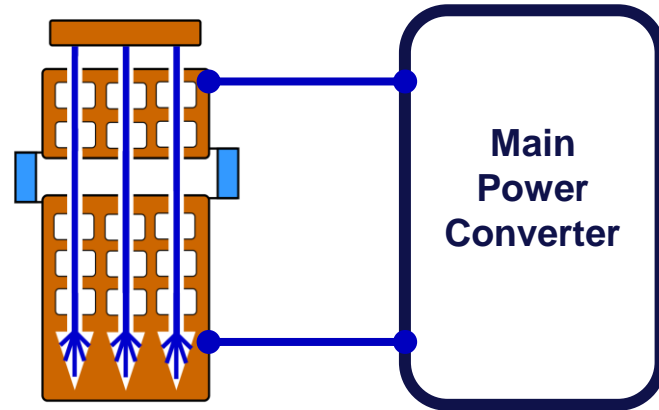
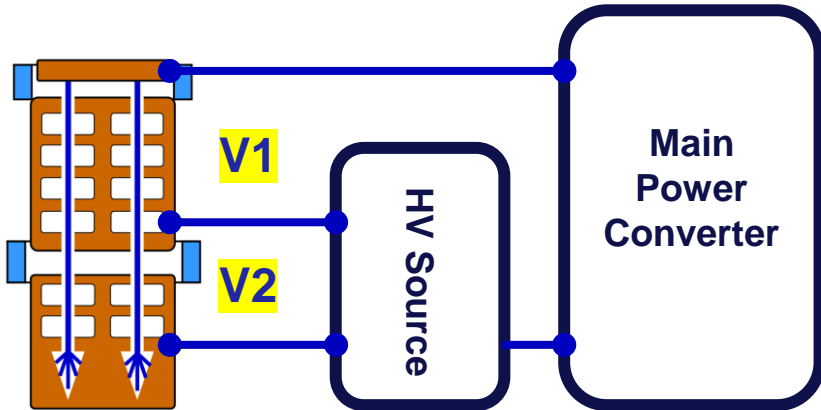
Major update from last year (for both booster & collider)

➤ Previous solution: 2-staged klystron

- 3 powering terminals
- ~ 60 kV
- $V1 = 65 \text{ kV}$; $V2 = 55 \text{ kV}$
- Middle terminal with no current

➤ New baseline: Tristron

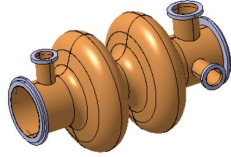
- 2 terminals
- $V \approx 45 - 50 \text{ kV}$



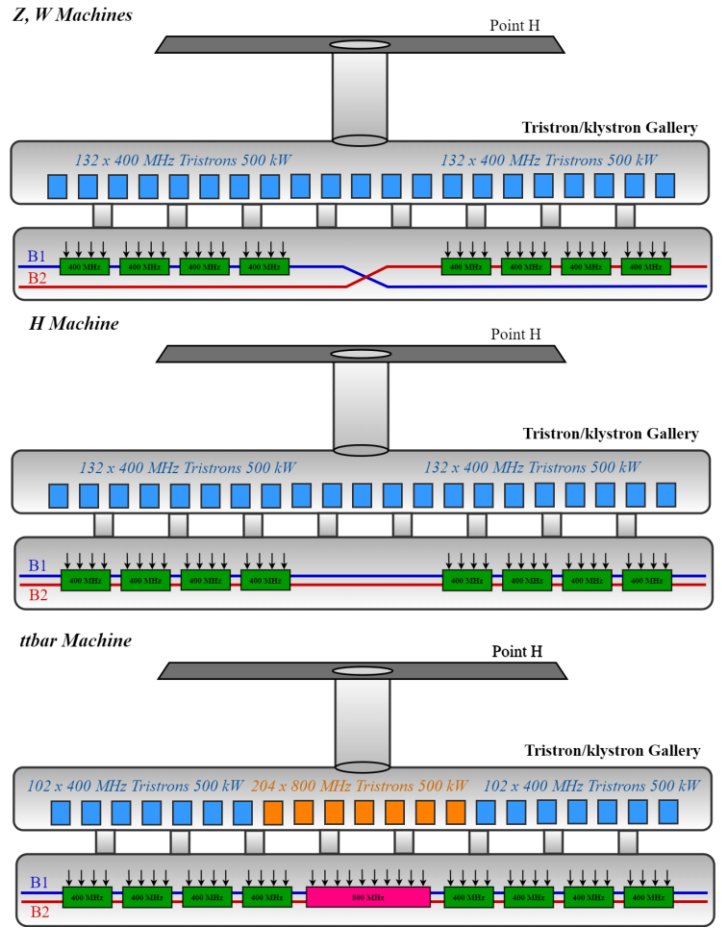
Collider's RF powering

Update on collider powering specs

➤ RF needs



- For Z & W : 2 x 132 cavities
- For ZH : 1 x 264 cavities (no changes for powering)
- Each cavity 380 kW or RF power
 - → 2 x 132 x 380 kW = 100 MW
- For ttbar addition of 408 - 800 MHz cavities & power reduction of the 400 MHz
 - → 2 x 132 x 78 kW + 2 x 204 x 195 kW = 100 MW
- Baseline “RF numbers”
 - 500 kW Tristron’s nominal power (380 kW + overhead)
 - 90 % Tristron efficiency
 - 95 % Waveguides efficiency
 - 3 kW Solenoid consumption
 - 0.1 kW RF driver consumption

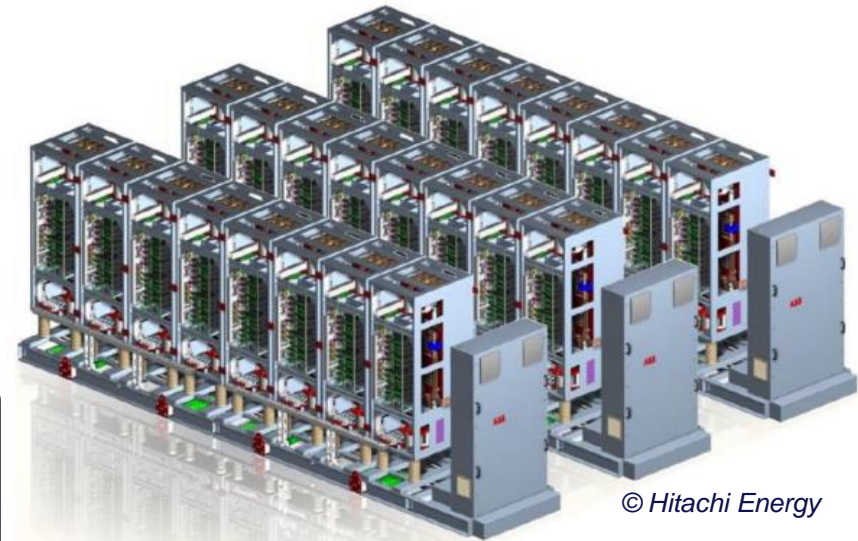


Main RF collider powering strategy

➤ Optimal converter topology: the Modular Multilevel Converter

- Standard in industry for the **50-1000 MW range**
- High voltages easily **achievable** (> 600 kV in HVDC)
- Very good efficiency (> **98.5%**)
- Excellent AC power quality (**no need of filters**)
- Modular → **Very high availability**

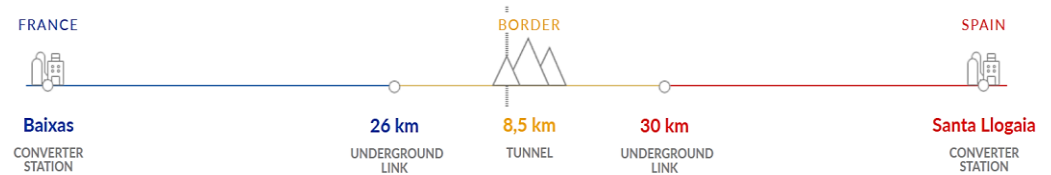
A study contract has been concluded with industry partner to provide a realistic estimation of footprint, CAPEX, and OPEX.



© Hitachi Energy

Visit to an existing MMC

- **INELFE: First on-shore MMC-based HVDC interconnection between France and Spain (2015)**

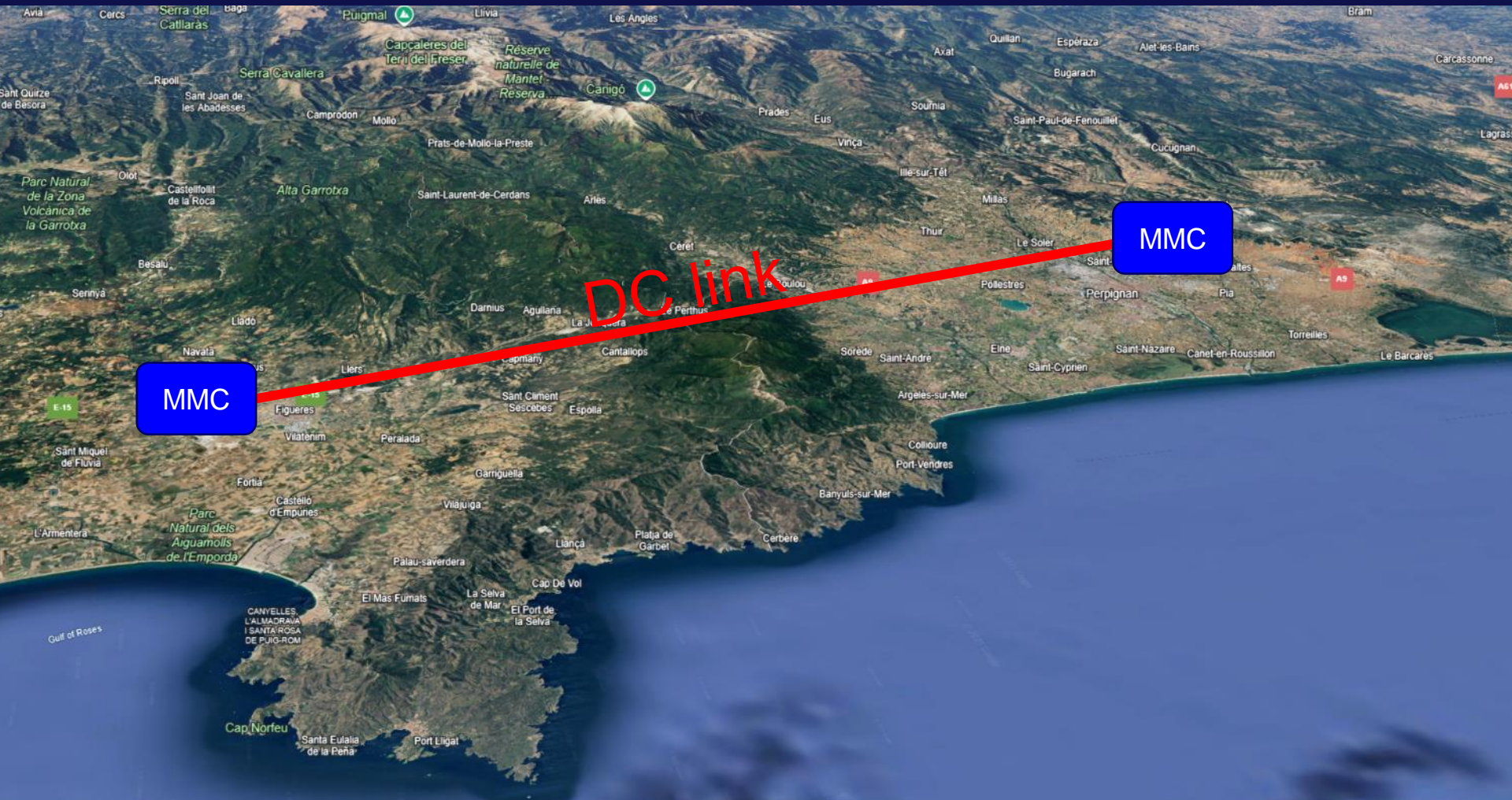


- Operated by Red Eléctrica (Spain) and RTE (France) → **Shared responsibilities**
- Composed of **two 1 GW links** operated independently @ **640 kV DC**
- Context of the visit:
 - MMC is a scalable converter → **Same structure independently of voltage**
 - Basic building block is the submodule → **Operational parameters** (failure rates, losses, maintenance) **can be easily extrapolated to FCC**
 - **Very little information available regarding operation of such converters**



RED
ELÉCTRICA
DE ESPAÑA





DC link

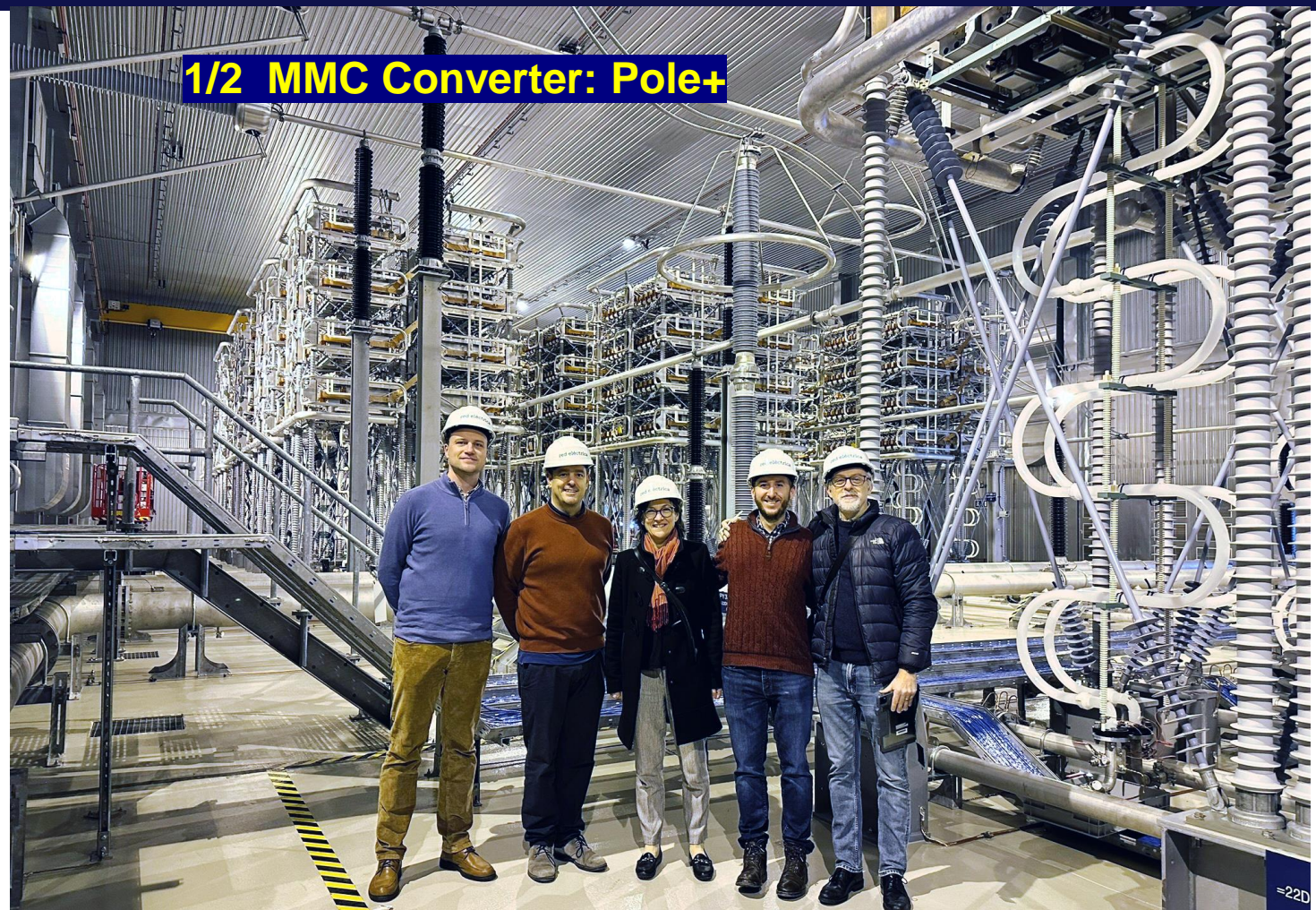
MMC

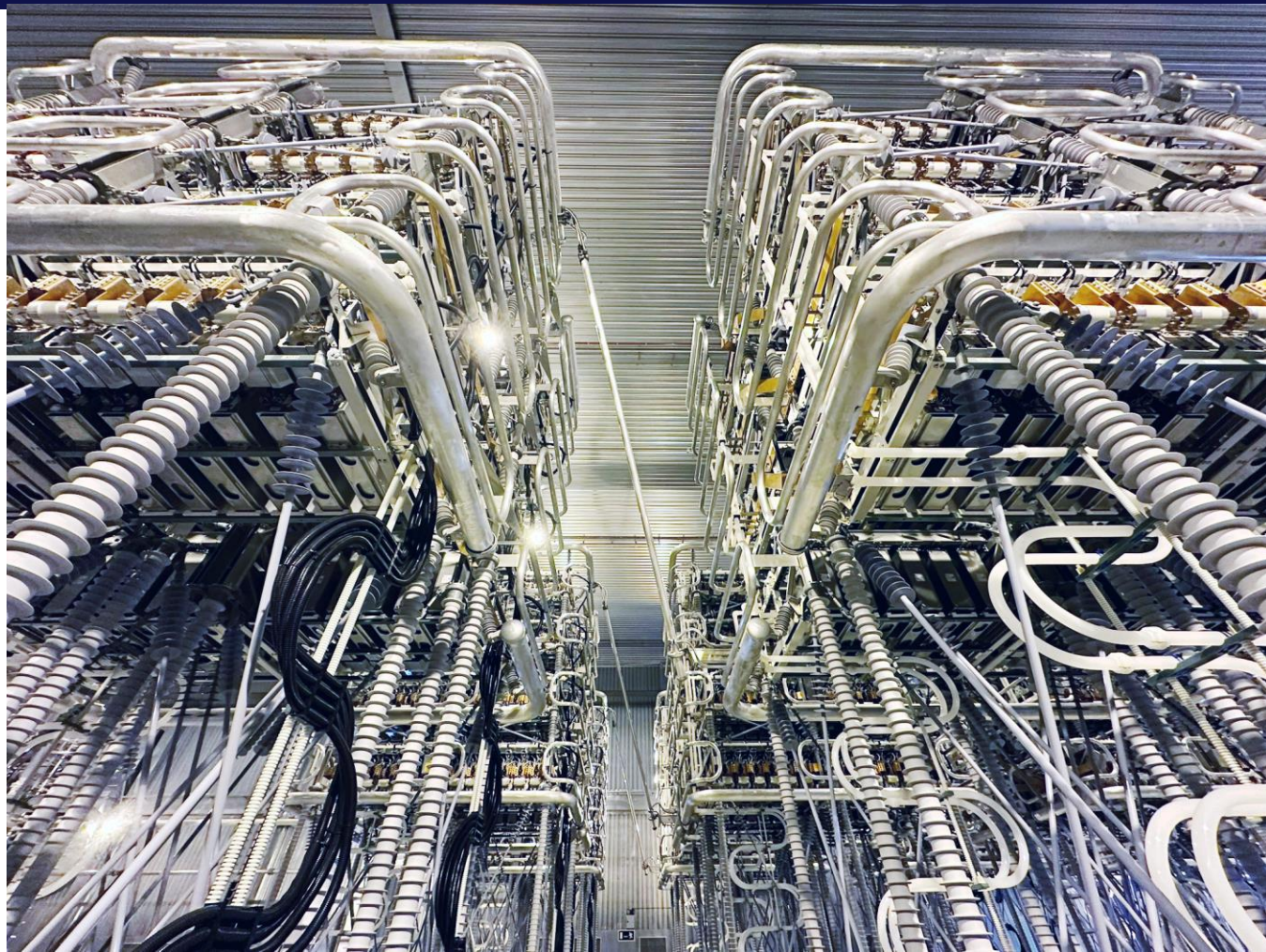
MMC

Visit to an existing MMC



1/2 MMC Converter: Pole+





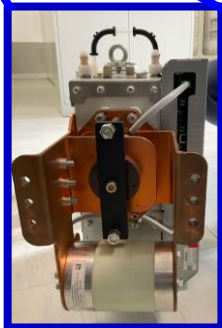
Visit to an existing MMC



2400 Submodules
2400 Capacitors
4800 IGBTs

Still...

Very high availability: ~ 100%
High efficiency: > 98.5 %



Power electronics
valves

Visit to an existing MMC

Valuable lessons learned:

Tendering / Operation

- MMC market currently dominated by few vendors → **little flexibility**
- MMC market is very stressed → Long delivering delays
- Operation of the link does not require human presence during the year

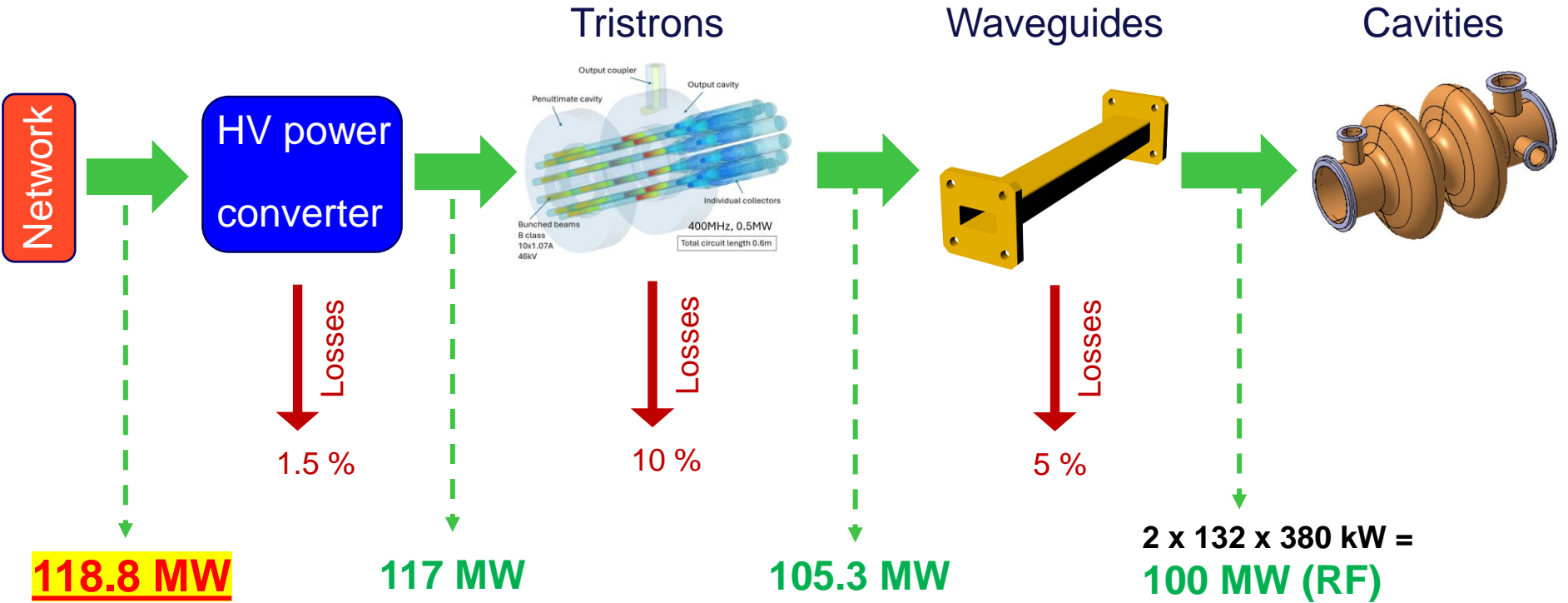
Maintenance

- Maintenance done with manufacturer during warranty
- Nowadays (no warranty), operators are taking care of maintenance
- Usually, it lasts only a few days per year for two links
- **Obsolescence is an issue → high updating cost**



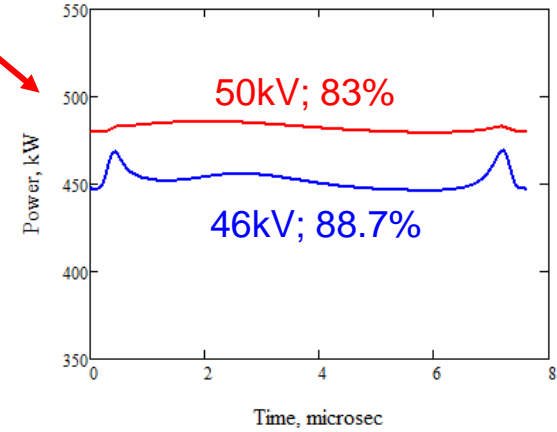
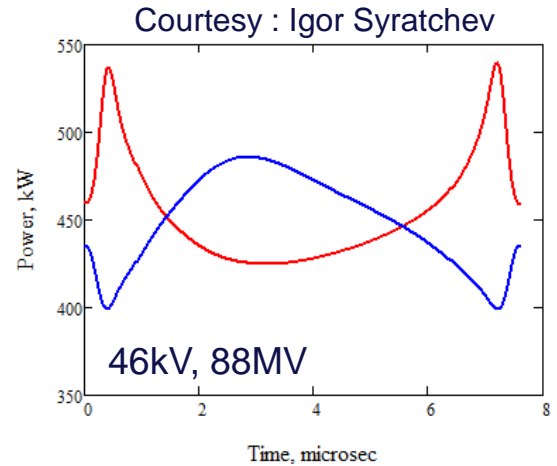
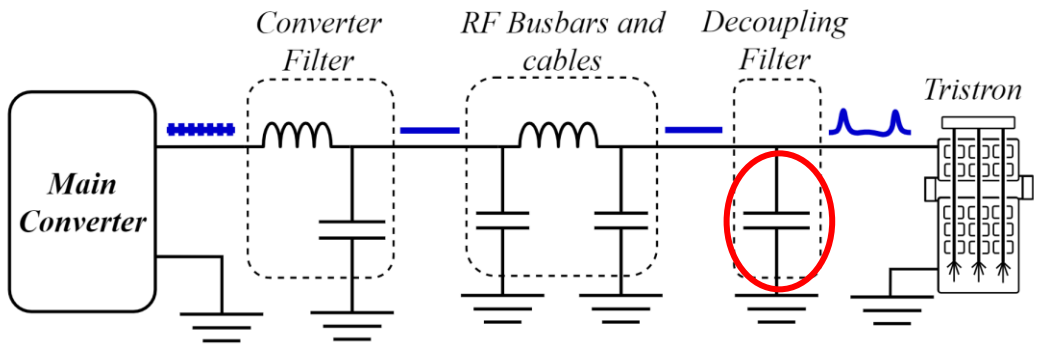
Power consumption – Collider RF

➤ Power consumptions, considering losses in the chain



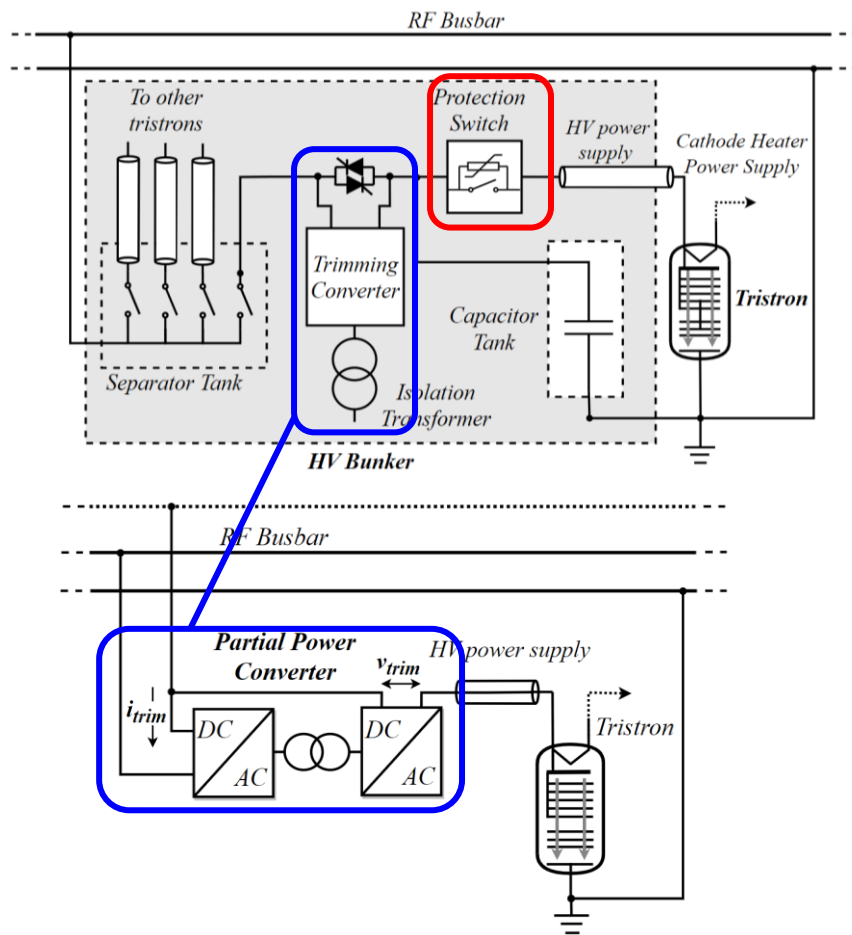
Tristron's auxiliary needs

- **Tristron Characteristics: Transient load**
 - **The LLRF modulates the Tristrons power in time**
 - **Example of power fluctuation (focusing and defocusing cells)** →
 - **Great power fluctuation to be managed!**
 - **When combining 2 Tristrons (powering focusing & defocusing cells), power fluctuation smoothed out**
 - **These power fluctuation (100 kHz – 3 MHz), provoke voltage fluctuation on Tristrons...** →

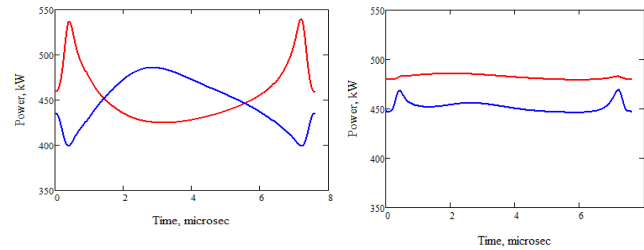


Tristron's auxiliary needs

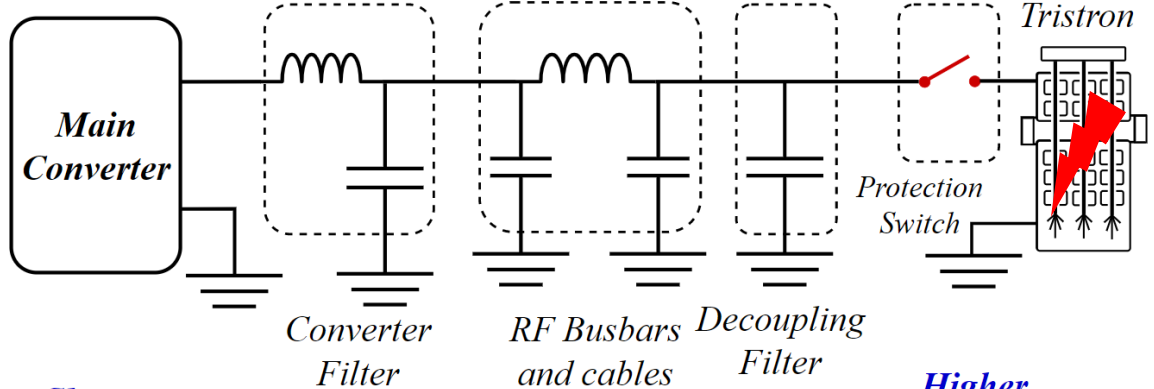
- In case of Tristron failure
 - If one Tristron goes “bang” / arc, need to safely protect it
 - Parallel crowbar not usable in a centralized concept
 - Fast solid-state disconnecter needed to isolate faulty Tristron
- Trimming voltage for each Tristron
 - If tristrons like klystrons, their characteristics may vary from one unit to another
 - Trimming may allow to optimize efficiency!
 - But also help on failure mode (more in a few slides...)



Tristron's auxiliary needs



Fast regulation dynamics → *Smaller filter* ↔ *Smaller filter* → *Lower protection requirements* → *Quality issues*

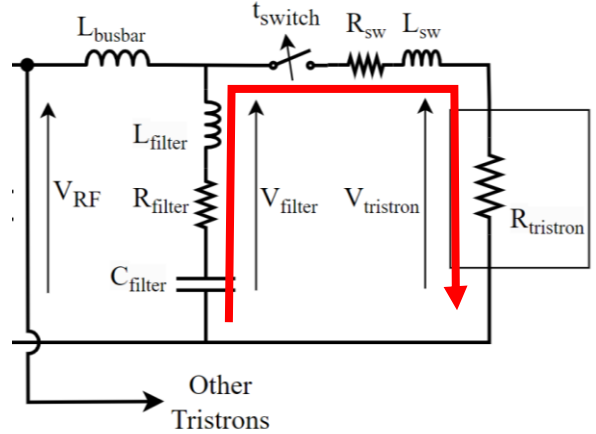


Limited energy deposit in tristron during arc fault (before failure) – typical max energy deposit 5 -20 J

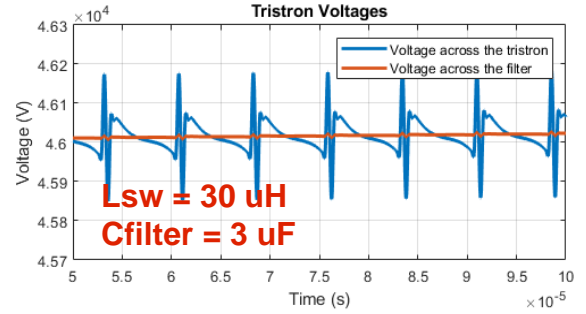
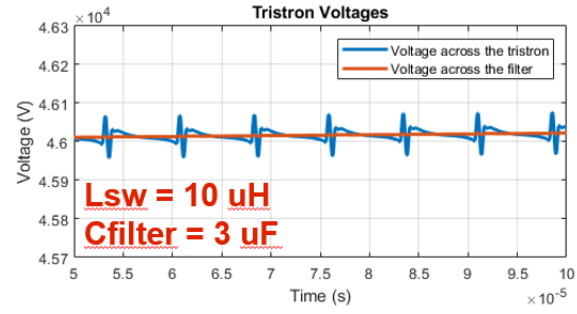
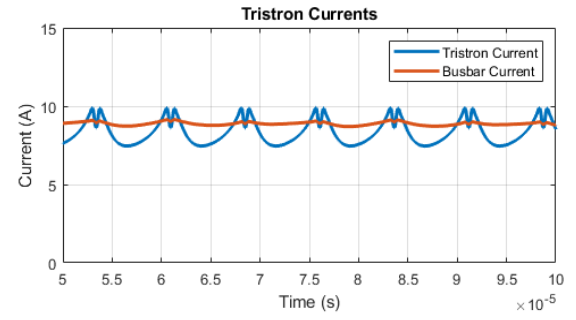
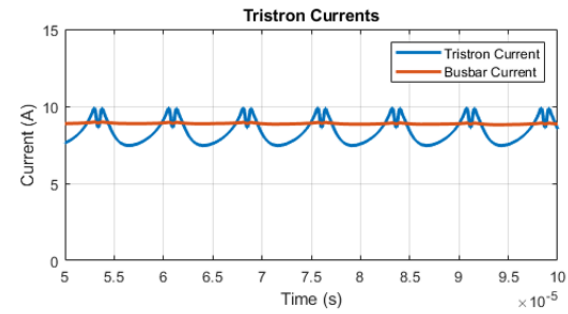
Slow regulation dynamics → *Larger filter* ↔ *Larger filter* → *Higher protection requirements* → **Control & tristron protection issues**

Voltage stability across tristrons: some results

- Need for optimizing C_{filter} value (compromise protection-stability) and minimize stray inductances



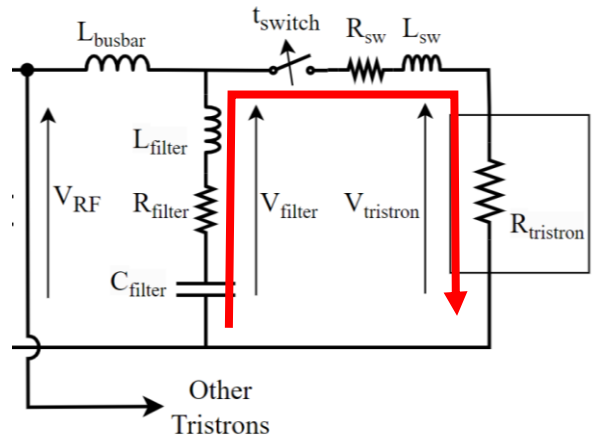
C_{filter} and L_{ws} effects on voltage ripple attenuation:



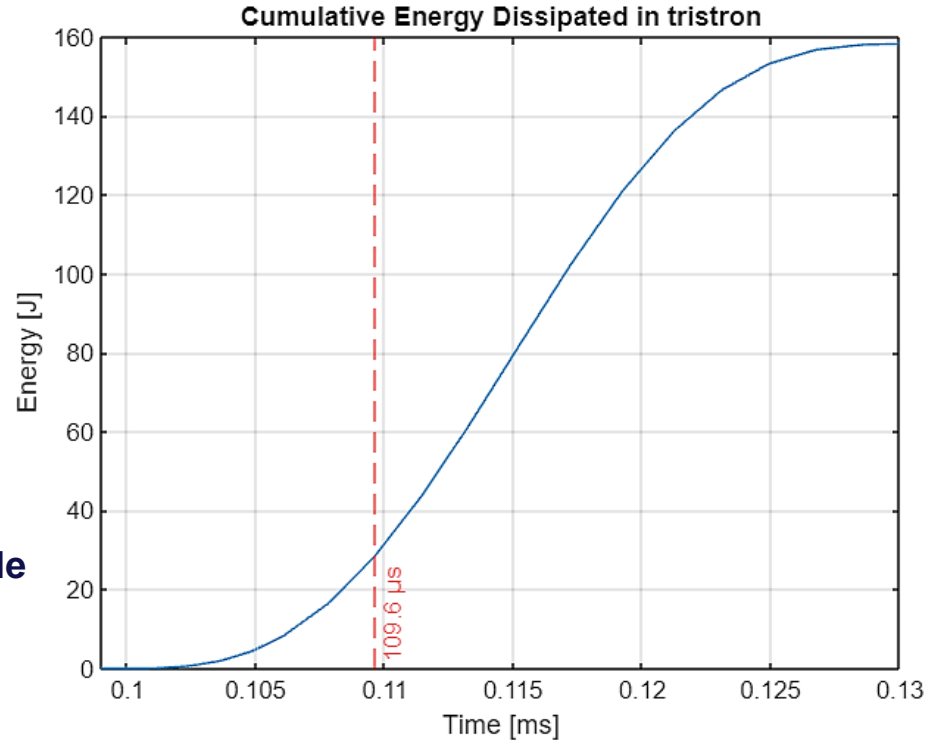
- Important to understand how LLRF control can compensate for residual voltage fluctuations

Tristron protection

- Maximum energy that can be discharged into the tristron is very small → 5 - 20 Joules
- For a certain filter and busbar configuration, maximum disconnection times can be calculated



- For $E_{max} = 25J$ & $L_{sw} = 10 \mu H$, opening time $100 \mu s$ → Challenging but feasible
- Stray inductance can give rise to significant overvoltage during opening

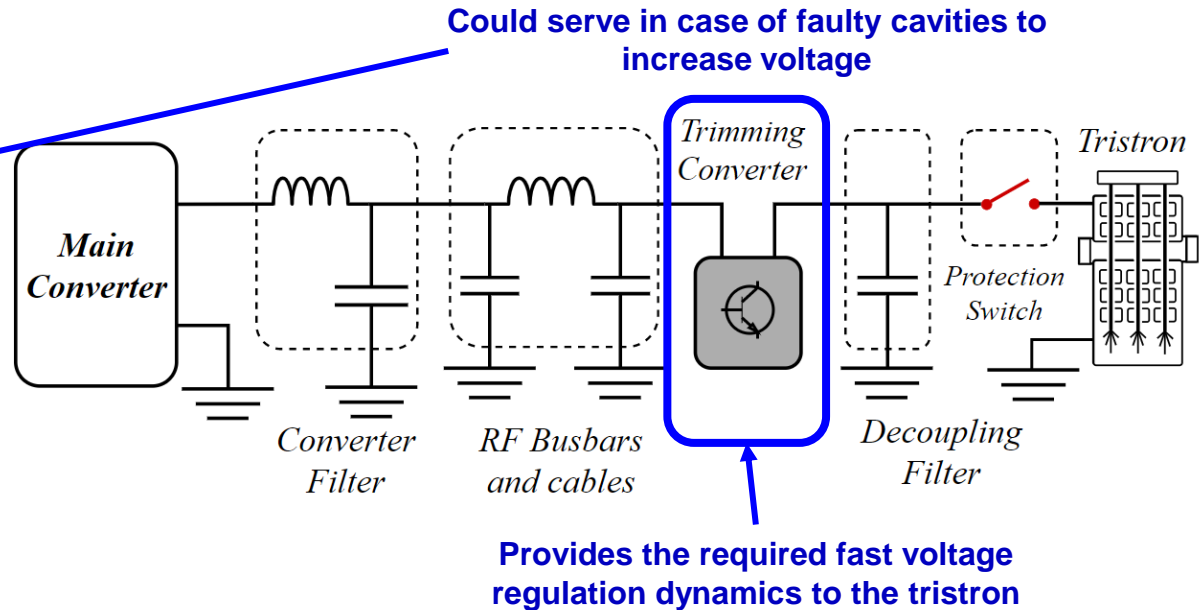
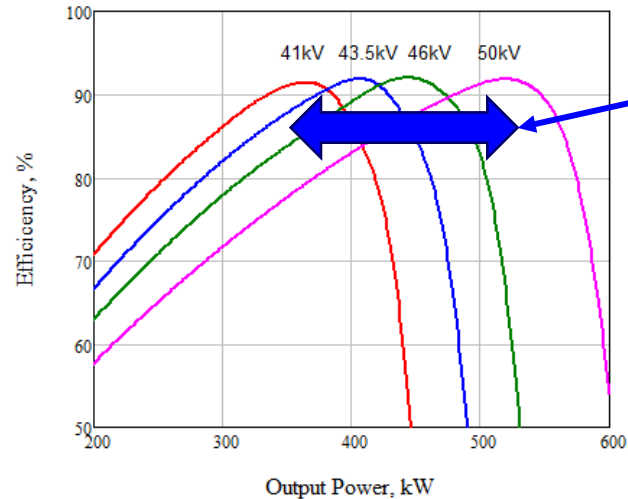


Tristron's auxiliary needs

➤ RF Availability improvement

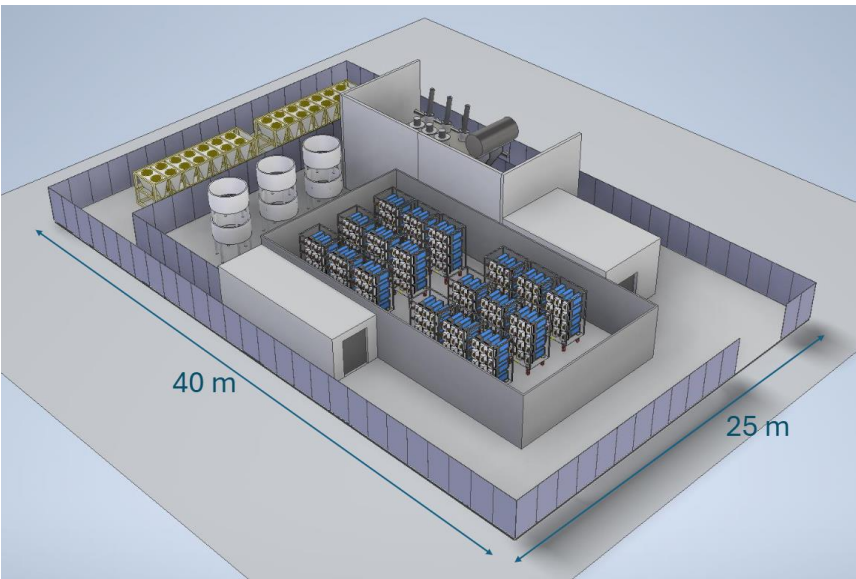
- In case of cavities failure, operation can continue, BUT:
- Voltage needs to be increased by ~ 10% in 200-300μs !

...why voltage increase is necessary?
to guarantee enough efficiency:

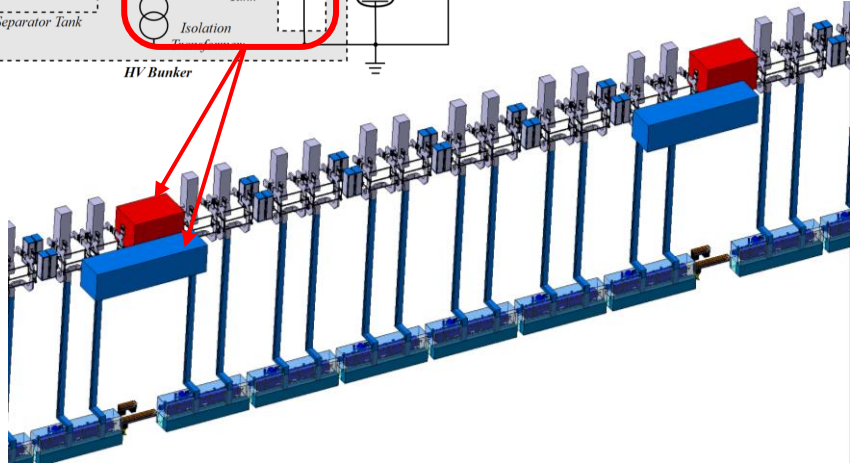
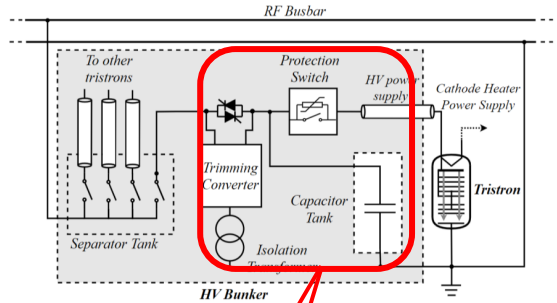


Integration (surface & klystron gallery)

Surface → MMC building



Klystron gallery → Voltage regulators, protections & filtering

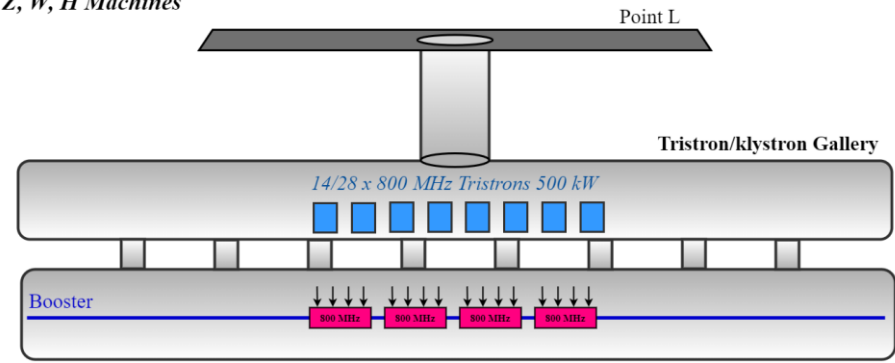


Booster's RF powering

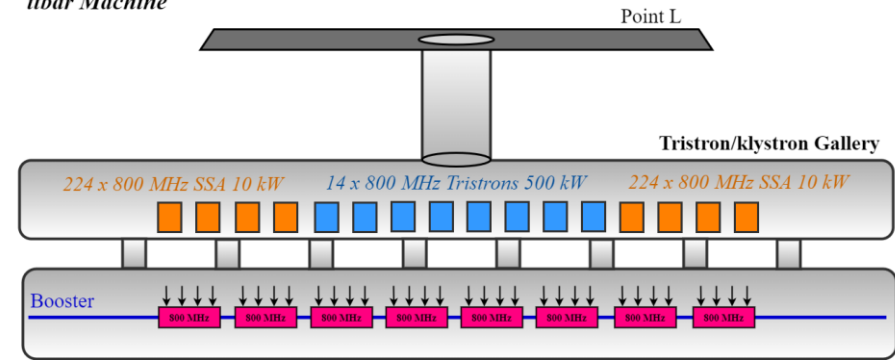
FCC-ee Booster – Update on RF powering

- For Z, W & ZH - Tristrons
 - @ 800 MHz, same characteristics as 400 MHz
 - Same powering concept (centralized) but less power → 7 - 8 MW (electrical)
- For tbar - additional Solid-State Amplifier (SSA) → ~ 8 MW (electrical)

Z, W, H Machines



tbar Machine



Conclusion

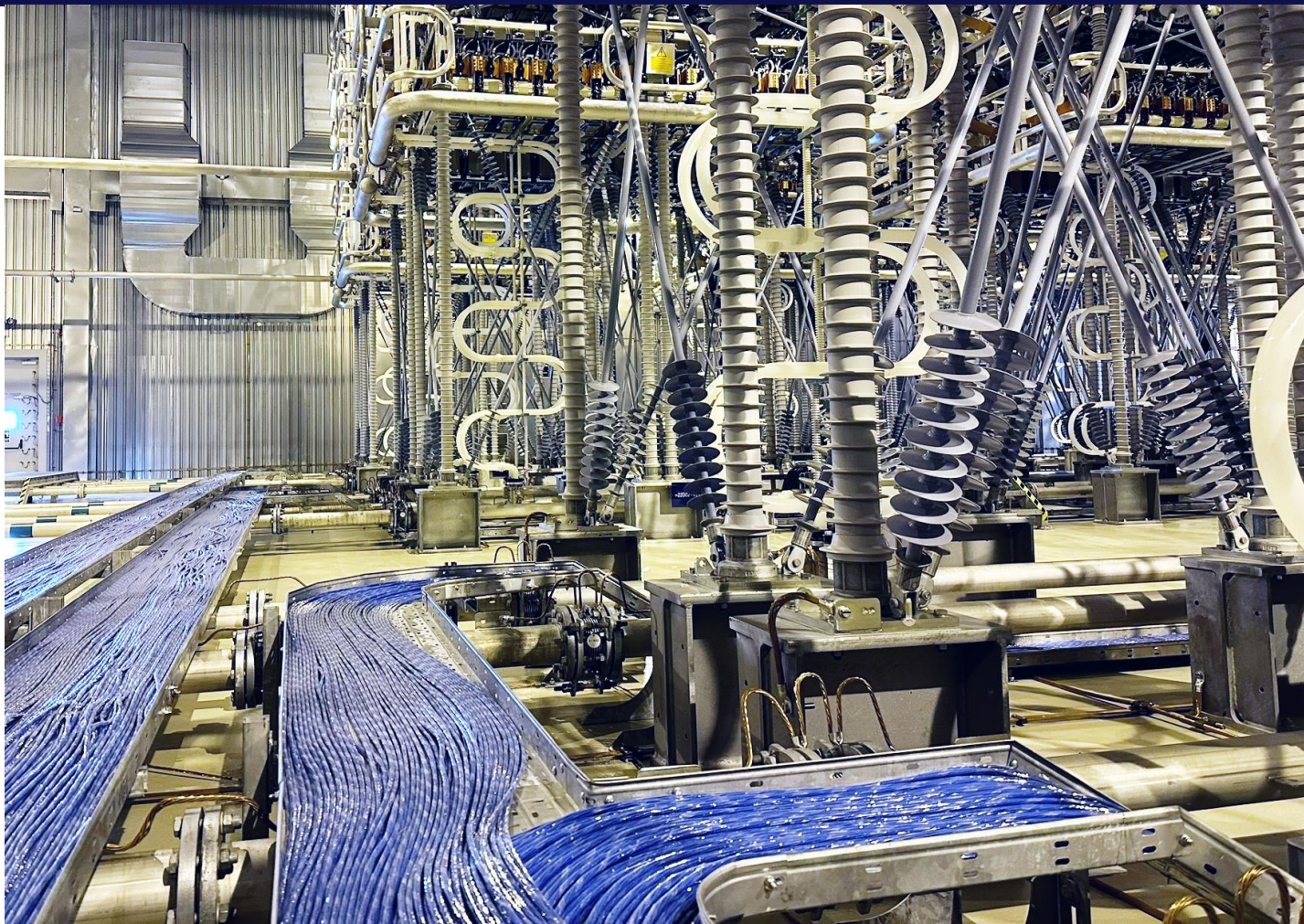
- **Collider RF powering based on available technology**
 - **Very high availability**
 - **Operation, maintenance & ownership philosophy understood & applicable at CERN**
- **Centralized RF powering seems the best in terms of CAPEX & OPEX, alternative decentralized approaches will also be examined**
- **Need to fully prove that a separated focusing/defocusing cavities powering is viable, to ensure good tristron voltage stability & protection**
- **Still lot of R&D needed to:**
 - **Converge on a failure mode powering management**
 - **Probe a reliable tristron protection concept**
 - **Finalize the integration into klystrons/tristrons gallery!**
- **For both Booster & collider RF → need for a fixed baseline in early 2026 to pre-design the powering and provide important inputs for CE integration.**



Thank you
for your attention.

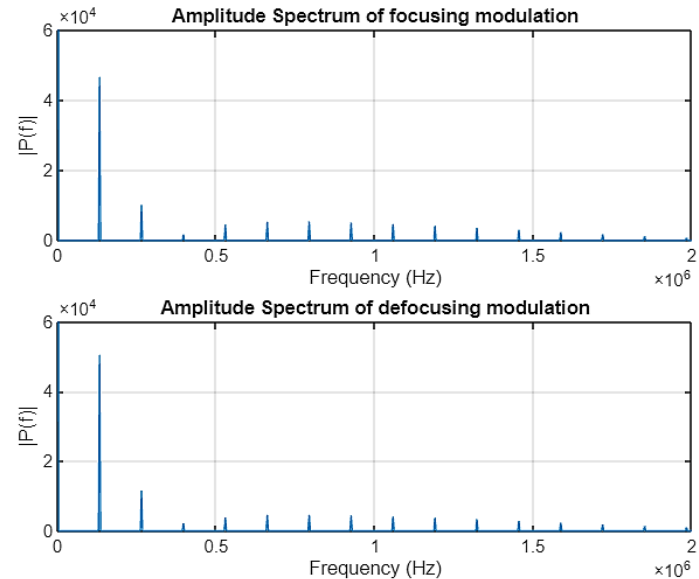
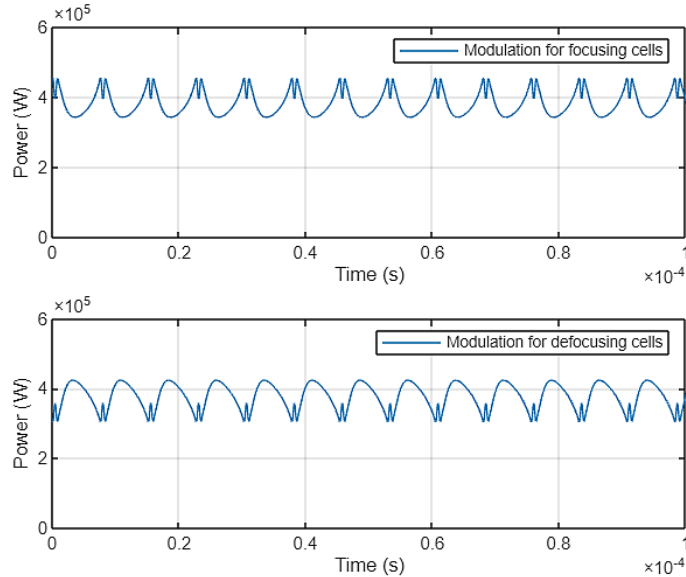


Spare



Voltage stability across the RF busbars

- Tristron input power curves were provided
- We have assumed that modulation is calculated at **constant DC voltage**



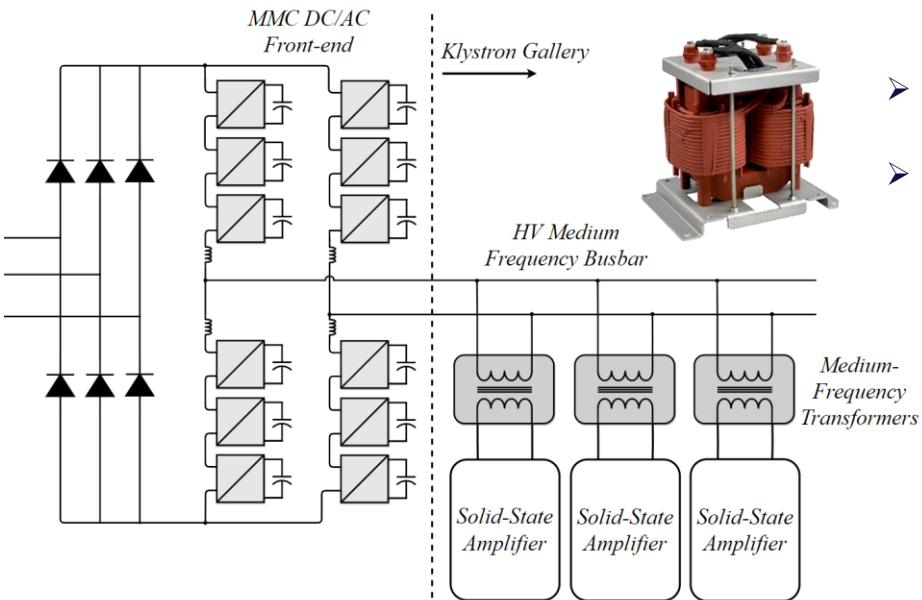
Power fluctuations happen at very high frequencies



First model created to evaluate voltage fluctuations on the tristron

Solid-State Powering in Klystron Gallery

- LV needed in the tunnel as SSA typically supplied via 400V/50Hz
- Several MW needed for the FCC-ee Booster
- Solutions based on Medium Frequency Transformers



- AC to Medium-frequency AC converter placed on the surface
- Power distribution at high voltage and medium frequency
- Medium frequency transformers used to supply the solid-state amplifiers
- Significant reduction of required volumes in the klystron gallery thanks to medium frequency transformers

R&D on Medium frequency transformers starting