FUTURE CIRCULAR COLLIDER

POWERING OF THE FCC-EE RF SYSTEM

M. Colmenero, D.Aguglia, S. Pittet, B. Wicki

CERN
Electrical Power Converter (EPC) Group, Accelerator Systems (SY Dept.)

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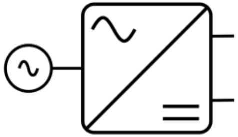
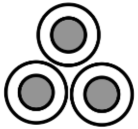
Main Elements of the FCC-ee Powering System

➢ **Goal:** transfer power to the Radiofrequency amplifiers in a **reliable** and **efficient** way

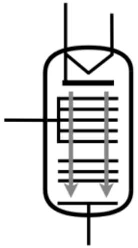
European Electrical Network
- Comply with the grid codes
- Reduce electrical infrastructure on the surface of access point



Power Conversion
- Perform AC to DC power conversion with high efficiency and reliability
- Supply high quality, controlled output voltages to the klystrons.
- Efficiently protect in case of short-circuit



Distribution System
- Bring power from the surface to the klystron gallery



RF Amplifier Control and Protection System
- High voltage switchgear for isolation of klystrons
- Trimming converters for individual klystron control
- Protection devices for fast klystron disconnection in case of fault
- Filament heaters power supply, klystron solenoid power supply

Update on FCC-ee Powering Requirements

➢ Radiofrequency parameters relevant for powering **as presented in FCC Week 2023**

Machine	Z		W		H		ttbar		
	Collid.	Boost.	Collid.	Boost.	Collid.	Boost.	Collid.	Collid.	Boost
RF frequency - type	400-kly	800-kly	400-kly	800-kly	400-kly	800–SS	400–SS	800-kly	800-SS
# of cavities	112	24	264	56	264	108	264	488	600
# of klystrons	112	12	132	14	132	-	-	244	-
# of S.S. modules	-	-	-	-	-	108	264	-	150
Kly. RF power (nom.) [kW]	901	2 x 210	2 x 378	4 x 89	2 x 382	-	-	2 x 163	-
Klystron power [MW]	1	0.5	1	0.5	1	-	-	0.5	-
RF power/SS module [kW]						47	78	-	32
El. power/kly [MW]	1.33	0.671	1.33	0.671	1.33	-	-	0.671	-
El. power/SS module [kW]						96	162	-	92
Waveguides efficiency [%]	95	95	95	95	95	95	95	95	95
Elect. To RF efficiency [%]	80	80	80	80	80	65	65	80	65
RF overheads [%]	11	19	32	40	31	28	28	54	78
Tot. installed [MW]	149	7.91	175	9.4	175	10.4	42.8	164	13.84
Tot. el consumption [MW]	134	0.038*	133	0.38*	134	1.35*	33.4	104	2.8*

Challenging integration due to number of transformers

- **Estimated peak power consumption from the AC mains: 140 MW**
- **Substantial number of Solid-State amplifiers to be installed during the *ttbar* phase**

Update on FCC-ee Powering Requirements

- Peak power consumption remains the same
- Solid-State amplifiers not anymore used in ttbar collider → <u>Simplified Integration</u>

2023

Machine	Z	Z	W	W	H	H	ttbar	ttbar	ttbar
	Collid.	[illegible]	Collid.	Boost.	Collid.	Boost.	Collid.	Collid.	Boost.
RF frequency - type	400-[illegible]	[illegible]	400-kly	800-kly	400-kly	800–SS	400–SS	800-kly	800-SS
# of cavities	1[illegible]	[illegible]	264	56	264	108	264	488	600
# of klystrons	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]4	-
# of S.S. modules	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	150
Kly. RF power (nom.) [kW]	901	2 x 21[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]63	-
Klystron power [MW]	1	0.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-
RF power/SS module [kW]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	32
El. power/kly [MW]	1.33	0.67[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]71	-
El. power/SS module [kW]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	92
Waveguides efficiency [%]	95	95	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	95
Elect. To RF efficiency [%]	80	80	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	65
RF overheads [%]	11	19	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	78
Tot. installed [MW]	149	7.91	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	164	13.84
Tot. el consumption [MW]	134	0.038*	133	0.38*	134	1.35*	33.4	104	2.8*

Need to find compact solutions for easy integration

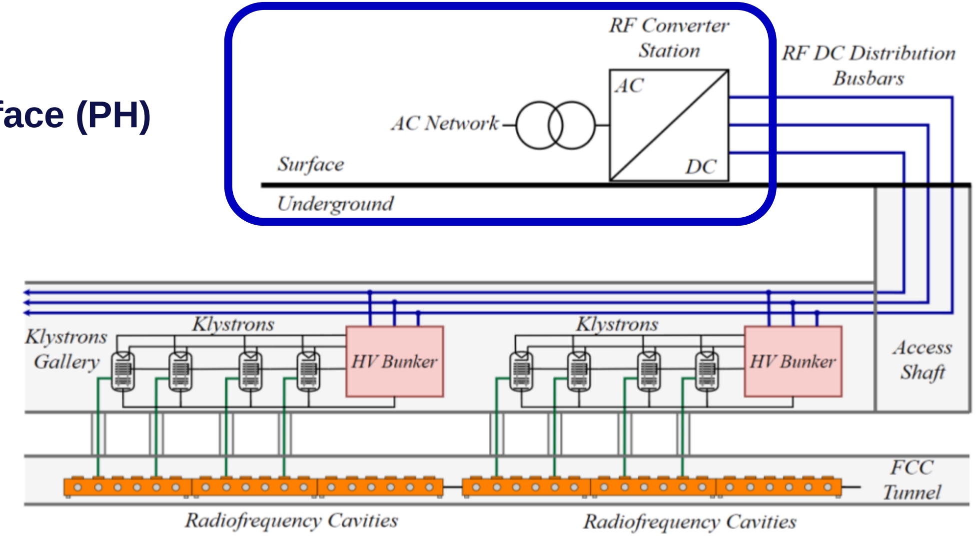
2024

Machine	Z	Z	W	W	H	H	ttbar	ttbar	ttbar	ttbar
	Collid.	Boost.	Collid.	Boost.	Collid.	Boost.	Collid.	Collid.	Boost.	Boost. @Q=1.7
RF frequency - type	400-kly	800-kly	400-kly	800-kly	400-kly	800–kly	400–kly	800-kly	800-SS	
# of cavities	56	8	264	28	264	32	264	488	540	
# of klystrons	112	4	132	14	132	-	33	244	-	
# of S.S. modules	-	-	-	-	-	-	-	-	540	
Kly/SS RF power (nom.) [kW]	894	2 x 110	2 x 377	2 x 144	2 x 378	8x32	2x78	2 x 163	5	20
Klystron power [MW]	1	0.5	1	0.5	1	0.5	1	0.5	-	
RF power/SS module [kW]							-	-	5	20
El. power/kly [MW]	1.18	0.29	1	0.38	1.33	0.34		0.326	-	
El. power/SS module [kW]							162	-	8.1	32.4
Waveguides efficiency [%]	95	95	95	95	95	95	95	95	95	
Elect. To RF efficiency [%]	80	80	80	80	80	65	65	80	65	
Tot. installed [MW]	147	2.65	173	9.2	173	9.2	43.4	160	17.8	
Tot. el consumption [MW]	132	1.16	130	5.32	131	4.71	27	104	4.4	17.5

FCC-ee RF Powering Strategy

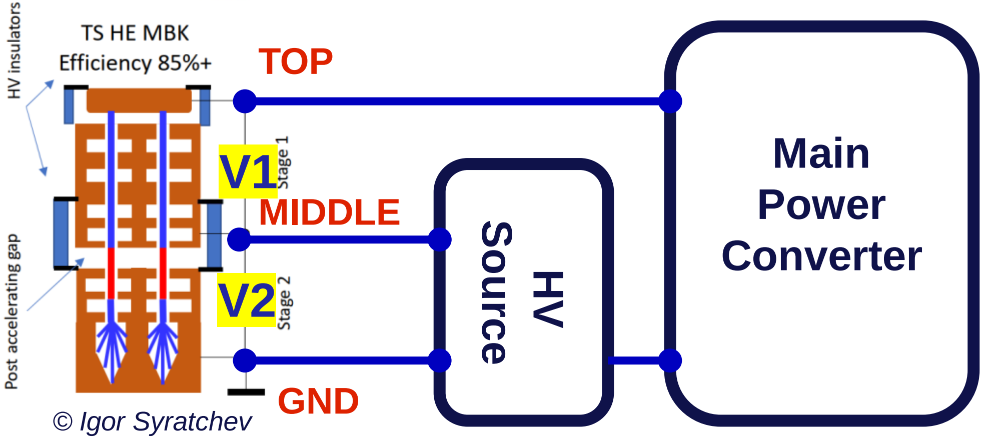
- **Single Power Converter situated on the surface (PH)**
  - 150 MW rated power / 34 kV on AC side
  - Directly supplied from the 400 kV Network
  - **Robust to network perturbations**

- **Single Busbar Scheme:** Klystrons connected in parallel to the same busbar



Requires new protection and control strategies

- **Three-wire distribution scheme → Two-Stage High-Efficiency Klystrons**
  - **Stage 2 (V2) voltage fixed by a low power HV converter (I middle = 0)**
  - **Stage 1 (V1+V2) voltage fixed by the main power converter**



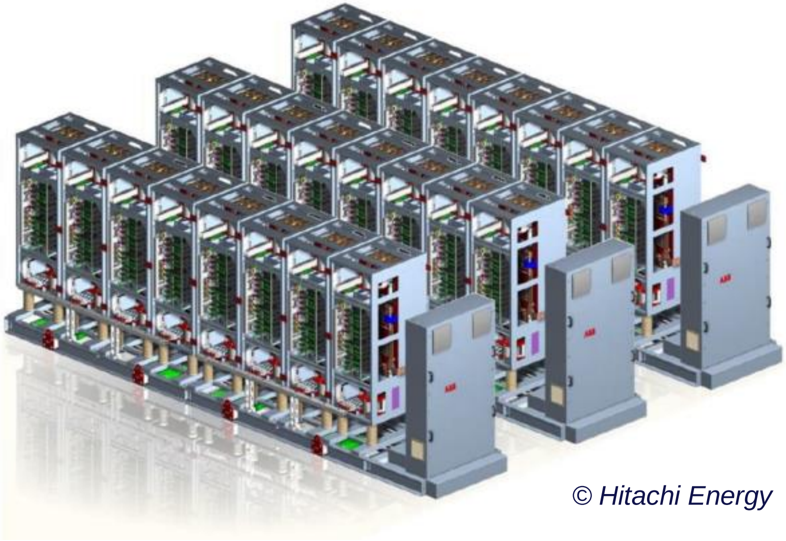
RF Powering based on Modular Multilevel Converters

LHC powering principles not applicable due to space constraints

- Individual klystron powering → **Footprint Constraints**
- Thyristor converters → **Power Quality Constraints**

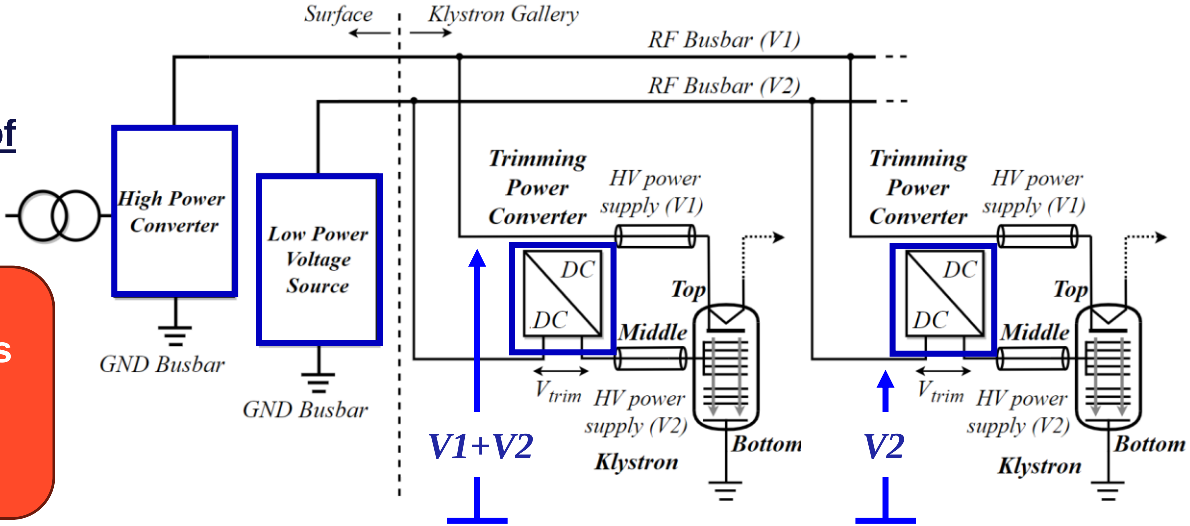
- **Optimal converter topology: the Modular Multilevel Converter**
  - Standard in industry for the **50-1000 MW range**
  - High voltages easily **achievable** (> 600 kV in HVDC)
  - Very good efficiency (**> 98.5%)**
  - Excellent harmonic performance (**no need of filters**)
  - Modular → **Very high reliability**

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



FCC-ee RF Powering Strategy

- Fixing voltage across all klystron **does not allow for compensation of individual RF power deviations**



Optimal efficiency cannot be achieved: differences in perveances cannot be compensated : some klystrons will not operate with optimal efficiency

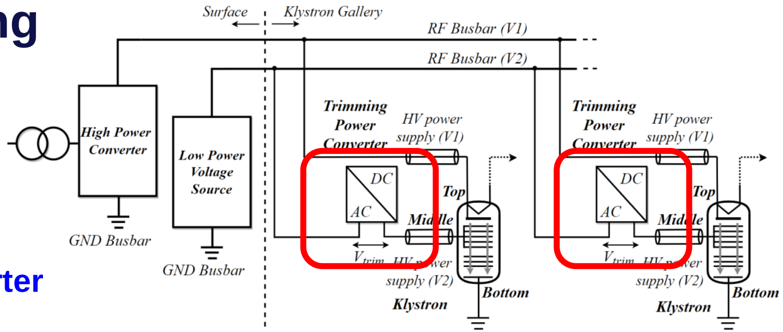
Solution: Act on the ratio between V1 and V2 on each individual klystron

- Allows to set the operation conditions of each individual klystron

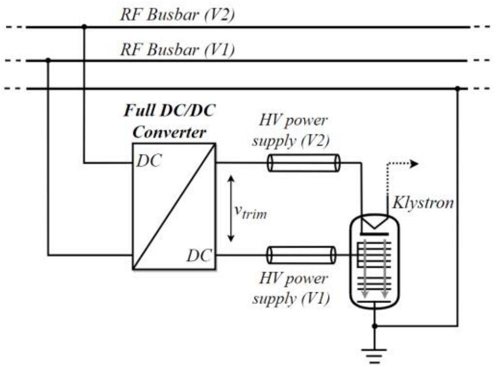
V1/V2 Ratio can be change by adding a power converter to the MIDDLE klystron terminal: klystron trimming converter

FCC-ee RF Powering Strategy: Klystron Trimming

- Optimizing volume and efficiency is critical
- Supplied from the RF busbars to avoid transformers
- Two approaches:

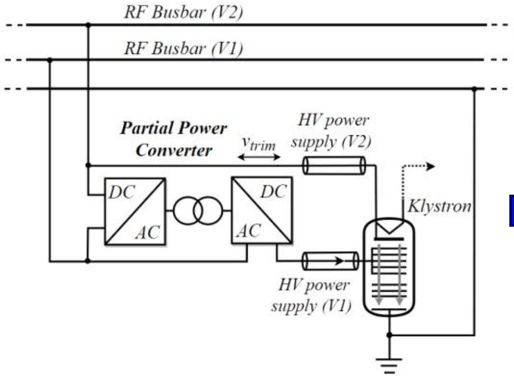


❑ Based on Full DC/DC Converter

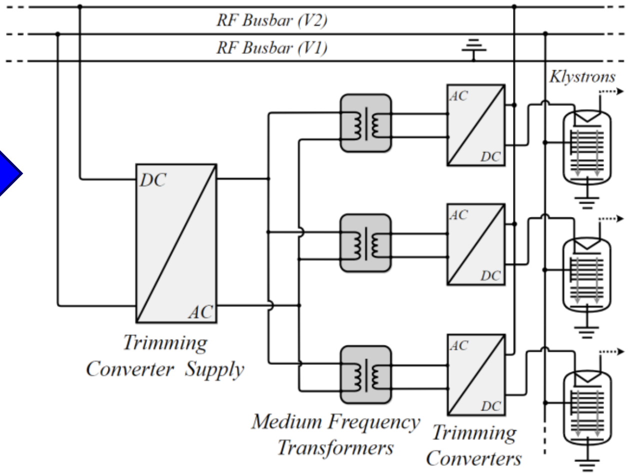


- Full-control of each klystron power through V1-V2 difference
- Can integrate the protection switch
- Bulky converter: **needs to manage the klystron current**

❑ Based on Partial DC/DC Converter



- Cannot integrate the series switch for protection
- **I=0: Reduce volume and size of the converter**



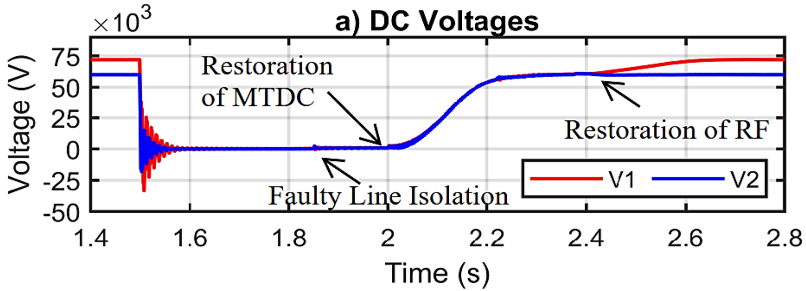
Powering solution based on Medium frequency transformers for reduced volume

RF Powering: Protection

- **Single busbar distribution requires measures to reduce the risk of damage in case of fault**

Short-circuit external to the klystrons

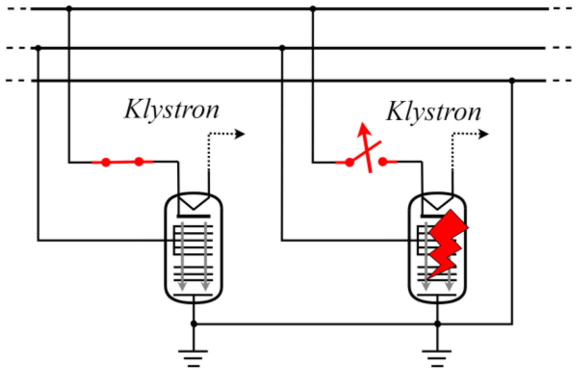
- Protection to be **conducted by the main power converter**
- **Goal: limit the deposition of energy in fault point**
- Investigations on **fault-blocking MMC** ongoing
  - **Fast clearance of the fault drastically reduces the risk of damage on equipment**



Example of a DC short-circuit on one HV bunker with fast RF restoration

Short-circuit internal to the klystrons

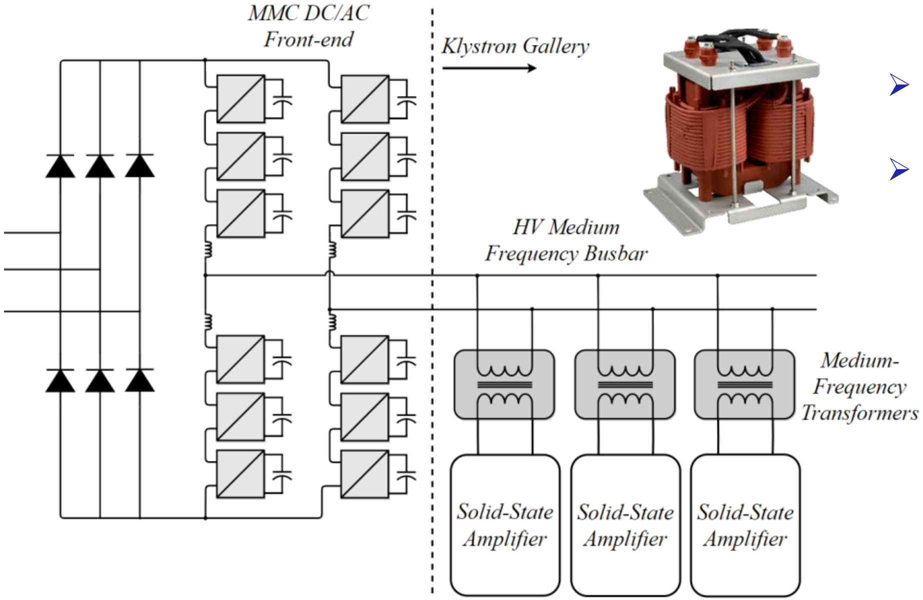
- **Crowbar** protection short-circuits the RF distribution busbar → **Not Feasible**
- **Power Electronics Series Disconnection: fast isolation of** faulty klystron is the preferred option



Very fast operation times required to avoid klystron damage → R&D on solutions based on IGBTs

Solid-State Powering in Klystron Gallery

- LV needed in the tunnel as SS 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

Ongoing R&D on Medium frequency transformers

Update on RF Powering System Integration

Converters on the surface

Converter	Number of Units	Rated Power	Rated Voltage	Dimensions
Main RF Converter	1	150 MW	65 kV	**Building: 35x35x6 m3** **Surface: 45x45 m2**
V2 Voltage Source	1	1 MW	55 kV	Racks: 6x2x3 m3
Solid State Medium Frequency Supply	2	1.5 MW	30 kV	Racks: 6x3x3 m3

- Main power converter hosted in a building approximately the **size of the POPS-B power converter in Meyrin**.
- **Need to add additional surface for the HV switchgear**

To be confirmed once pre-design study with industry is completed (end of 2024)

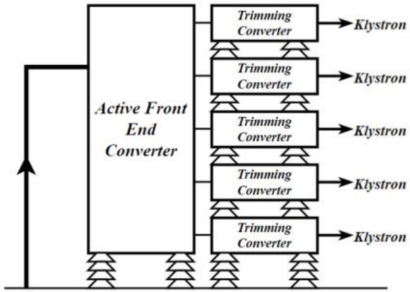
Update on RF Powering System Integration

Equipment in Klystron Gallery

- **Klystron Trimming Power Converters and protection switches**
  - **Option 1:** All trimming converters installed in the HV bunkers
  - **Option 2:** Active Front End in HV bunker and trimming converters next to klystrons
  - **Location of protection elements →** assumed close to klystrons to limit cable discharge
- **Solid-State Medium Frequency Transformers**
  - **Estimated volume:** around 1 m3 / MW → Easy Integration

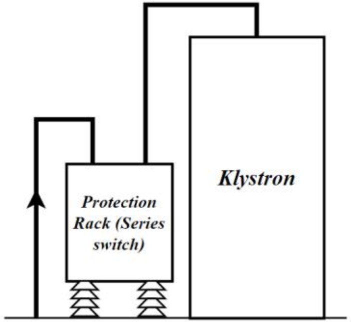
- **Conduct a pre-design of the trimming converter system for accurate volume estimation → <u>Collaboration with Tallin University</u>**
- **<u>More interaction need with RF group for understanding the requirements and integration constraints</u>**

HV Bunker

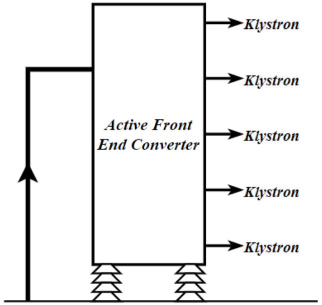


- **Volume: ~ 6 m3**

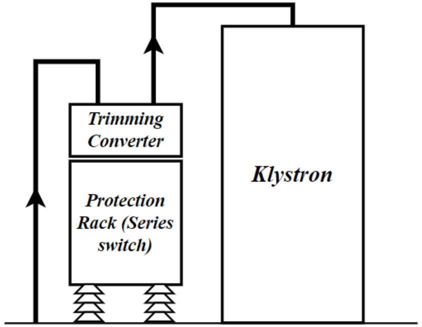
Klystron



- **Volume: ~ 1 m3**



- **Volume: ~ 3 m3**



- **Volume: ~ 1.5 m3**

Conclusions

- ✓ Most probable solution: **centralized MMC converter as main power supply** plus **low power HV source to supply the first stage** of the klystron
- ✓ **Modular Multilevel Converters are the optimum solution** for powering the RF
- ✓ Started a **collaboration with industry** for accurate estimation of footprint, CAPEX and OPEX in view of the feasibility study
- ✓ Single busbar distribution might require **the installation of individual power converters to trim the klystrons**. **Partial power converters allow for reduce size and high efficiency**
- ✓ **Solid State amplifiers to be supplied through medium-frequency transformers**
- ✓ <u>**Collaboration needed with the RF group to define the radiofrequency powering requirements, specially in view of the trimming power converters and control**</u>

Thank you
for your attention.