FUTURE CIRCULAR COLLIDER

POWERING OF RF SYSTEMS – POWER CONVERTERS AND INFRASTRUCTURE

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Outline

FCC-ee RF powering stages (focus on collider)

Powering requirements and solutions

Integration

Conclusion

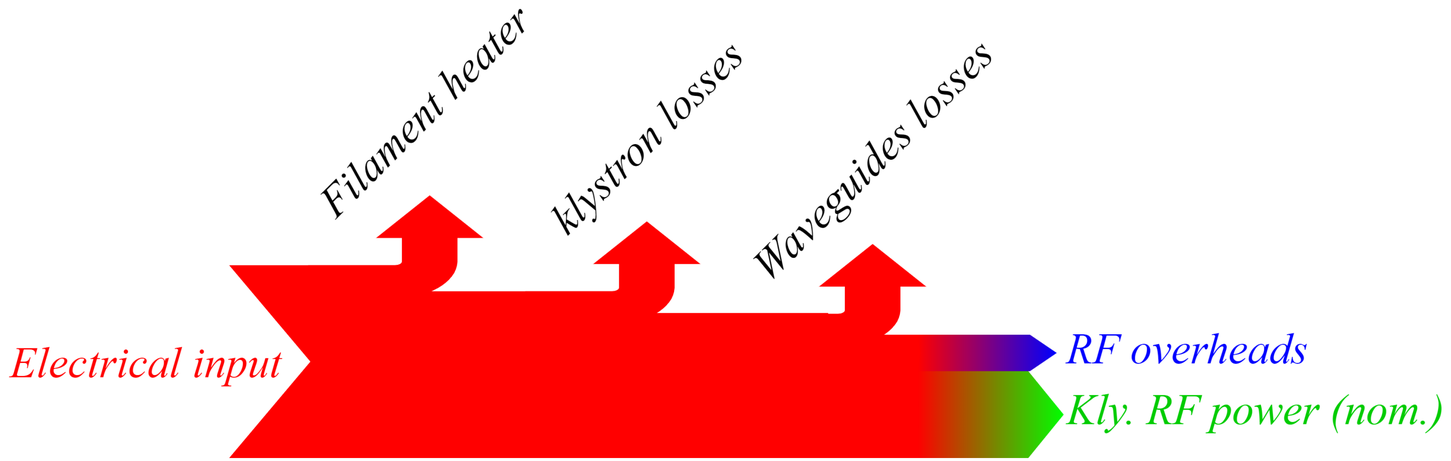
RF stages - Z

Specs for each stage

Machine	Z	
	Collid.	Boost.
RF frequency - type	400-kly	800-kly
# of cavities	112	24
# of klystrons	112	12
# of S.S. modules	-	-
Kly. RF power (nom.) [kW]	901	2 x 210
Klystron power [MW]	1	0.5
RF power/SS module [kW]		
El. power/kly [MW]	1.33	0.671
El. power/SS module [kW]		
Waveguides efficiency [%]	95	95
Elect. To RF efficiency [%]	80	80
RF overheads [%]	11	19
Tot. installed [MW]	149	7.91
Tot. el consumption [MW]	134	0.038*

Filament heater of 10 kW considered

- For collider: both beam lines considered
- Difference between RF nominal power and klystron power defined as “overhead” for RF regulation margin purposes
- Electrical power / klystron includes:



- Installed power: to produce peak power, overhead included → related to CAPEX
- Electrical consumption considers average/nominal regime with no overheads → related to OPEX

RF stages - W

Specs for each stage

Machine	Z		W	
	Collid.	Boost.	Collid.	Boost.
RF frequency - type	400-kly	800-kly	400-kly	800-kly
# of cavities	112	24	264	56
# of klystrons	112	12	132	14
# of S.S. modules	-	-	-	-
Kly. RF power (nom.) [kW]	901	2 x 210	2 x 378	4 x 89
Klystron power [MW]	1	0.5	1	0.5
RF power/SS module [kW]				
El. power/kly [MW]	1.33	0.671	1.33	0.671
El. power/SS module [kW]				
Waveguides efficiency [%]	95	95	95	95
Elect. To RF efficiency [%]	80	80	80	80
RF overheads [%]	11	19	32	40
Tot. installed [MW]	149	7.91	175	9.4
Tot. el consumption [MW]	134	0.038*	133	0.38*

- Changes in the RF infrastructure

BUT

- Slight change in electrical power infrastructure
  → more overheads – installing more power

The 175 MW of installed infrastructure should be done at the Z stage already – very difficult to upgrade from 149 to 175 MW…

* Calculated considering preliminary booster cycles in CDR

RF stages - H

Specs for each stage

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

- No changes for power converters from W to H for collider
- Booster from klystrons to solid state amplifiers

* Calculated considering preliminary booster cycles in CDR

RF stages - ttbar

Specs for each stage

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*

- Big change from H to ttbar – mixture of klystrons and solid state amp. in collider
- Big power overheads

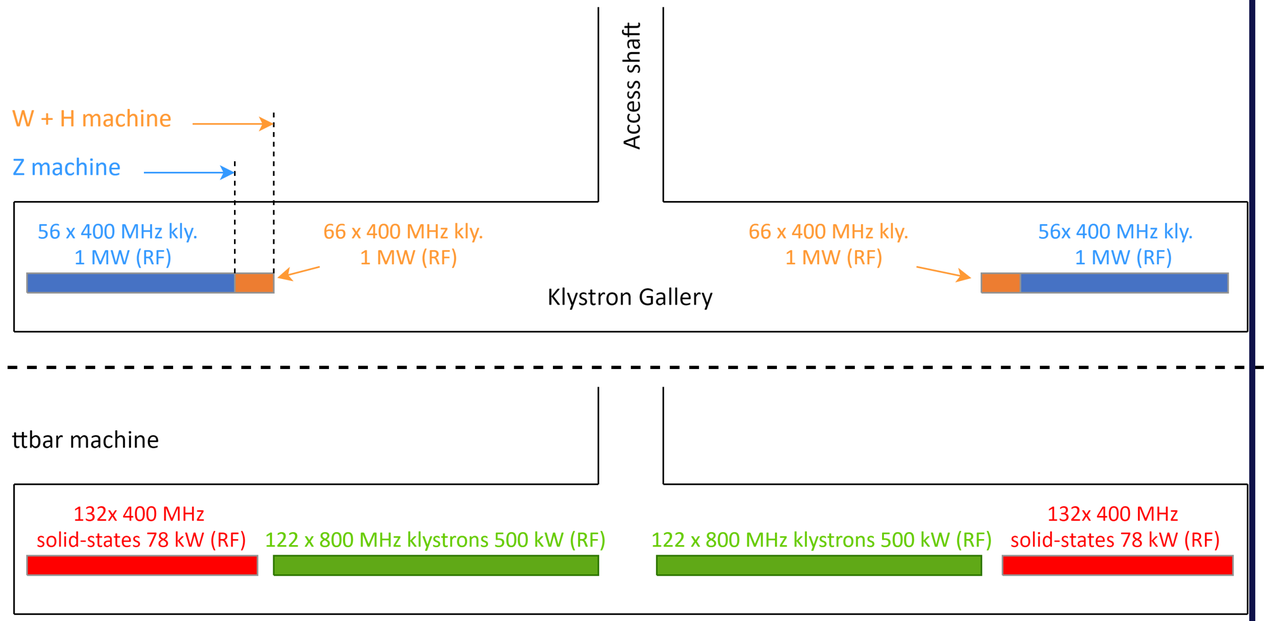
* Calculated considering preliminary booster cycles in CDR

RF stages

Integration aspects & power overheads

- Integration sequencing
- RF power overheads implications
  - power overheads needed for RF regulation purposes
  - Power converter rated at max V & I (dimensioning or installed power)
  - For ttbar converter power overhead 60 %

→ A reduction of this overheads could allow the reuse of many power components – see last slide before conclusion



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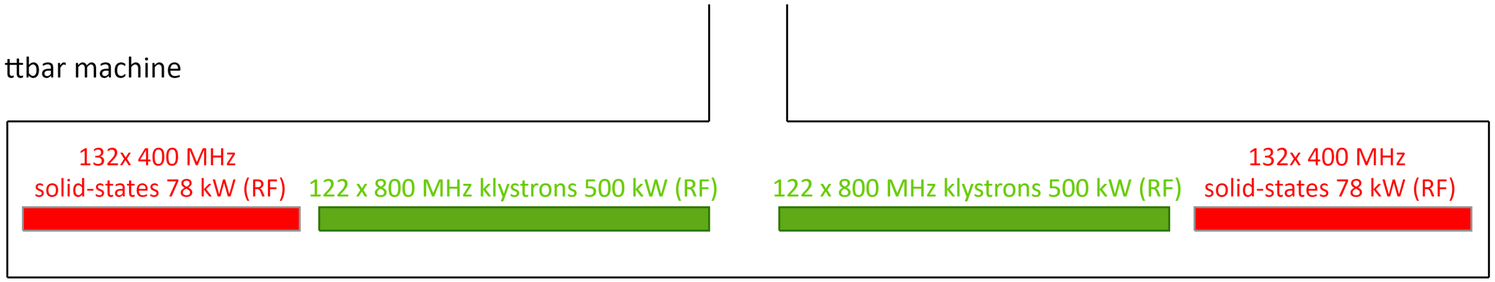
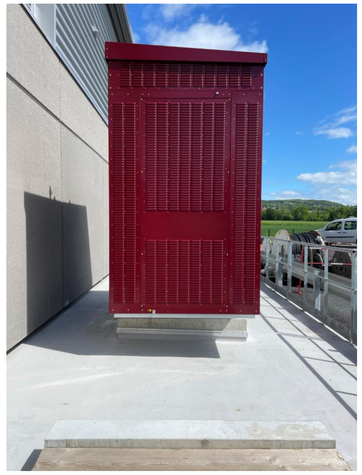
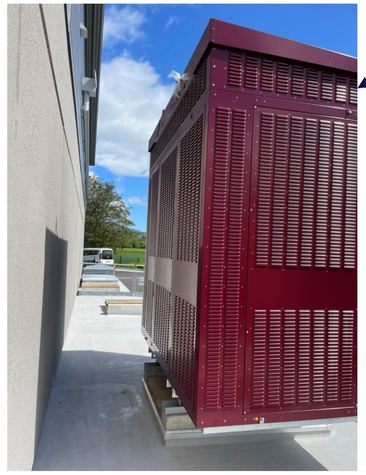
RF stages



Solid-state amplifiers powering

- LV needed in the tunnel as SS typically supplied via 400V/50Hz
- Potential issue in collider form H to ttbar → need to supply 43 MW in the klystron gallery @ LV
- 400 V level need to be produced locally (~1 V/m) → big transformers needed at the level of gallery or end of straight section alcoves
- Using classical 50 Hz transformer very limiting





Example
- 2 MVA transformer (18 kV/400 V)
- Dimensions: 2,5 m x 1,6 m x 3,1 m (height)
- Mass: 6,13 Tons

We would need 22 of them underground…

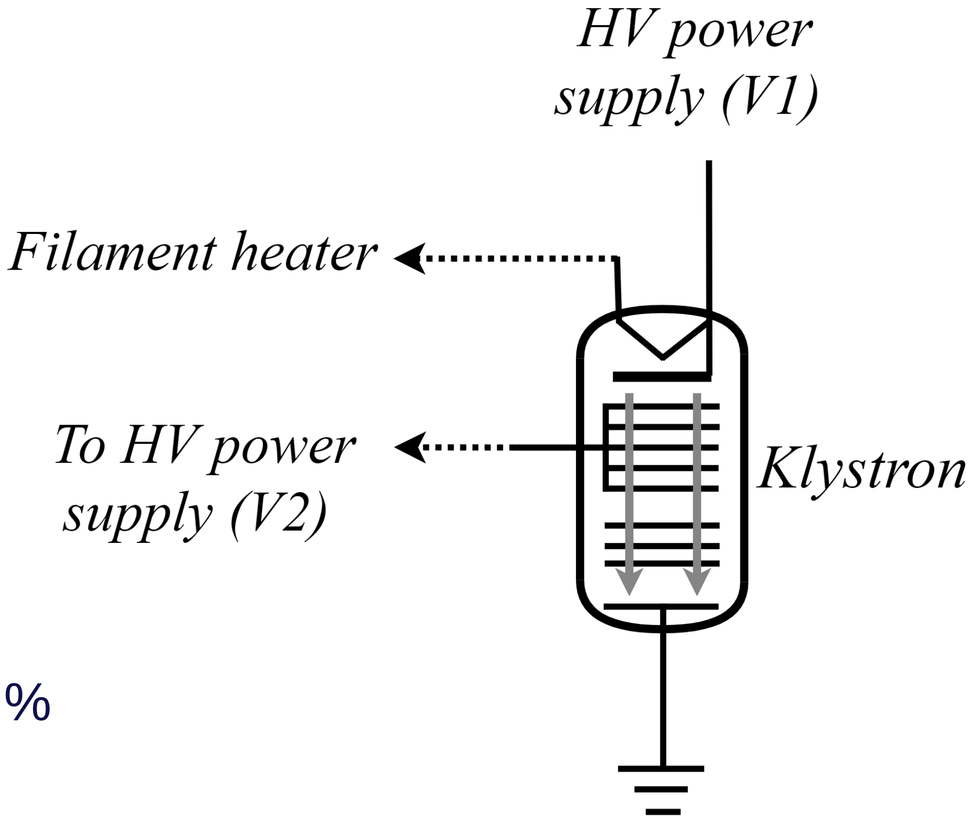
…possible alternative solution presented later on in this presentation…

Powering requirements & solutions

Powering needs of a klystron

- High efficiency klystrons under R&D
- Preliminary specs
  - Efficiency 80%
  - 2 x voltages supply: -72 kV & -60 kV (polarizing)

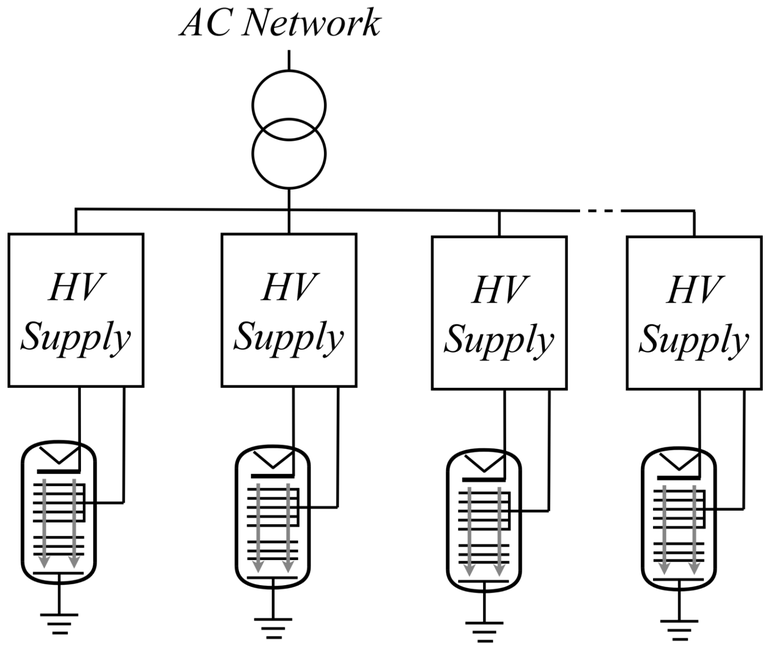
  → max current / klystron: 14 A for 1 MW
  - Filament heater: 10 kW
- Protection
  - Each klystron needs a protection scheme limiting energy deposit during internal arcs (crowbar/disconnector)
- Each klystron need some voltage regulation range (few % - TBD) to fine tune their power at max efficiency



Powering requirements & solutions

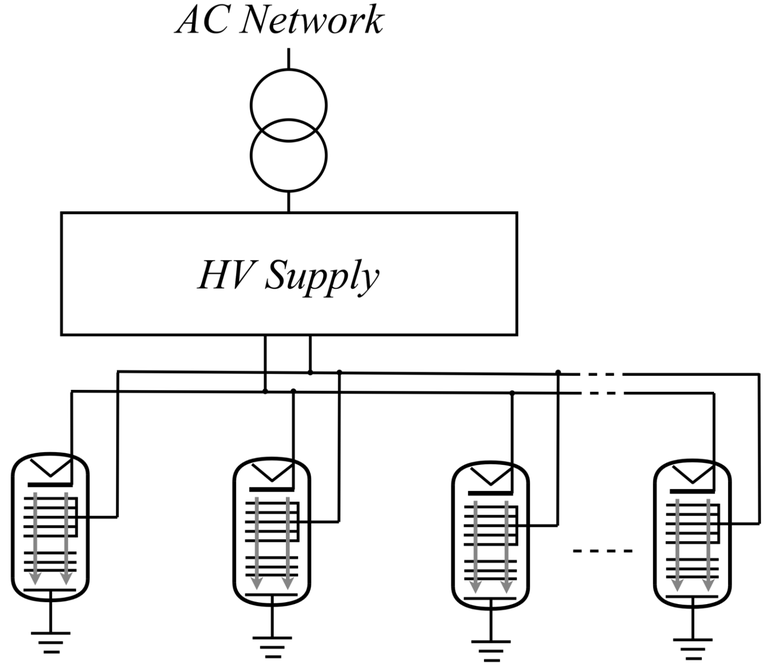
Two extreme powering concepts

- One power converter per klystron



Power converters installed in klystron gallery

- Centralised power converter for all klystrons

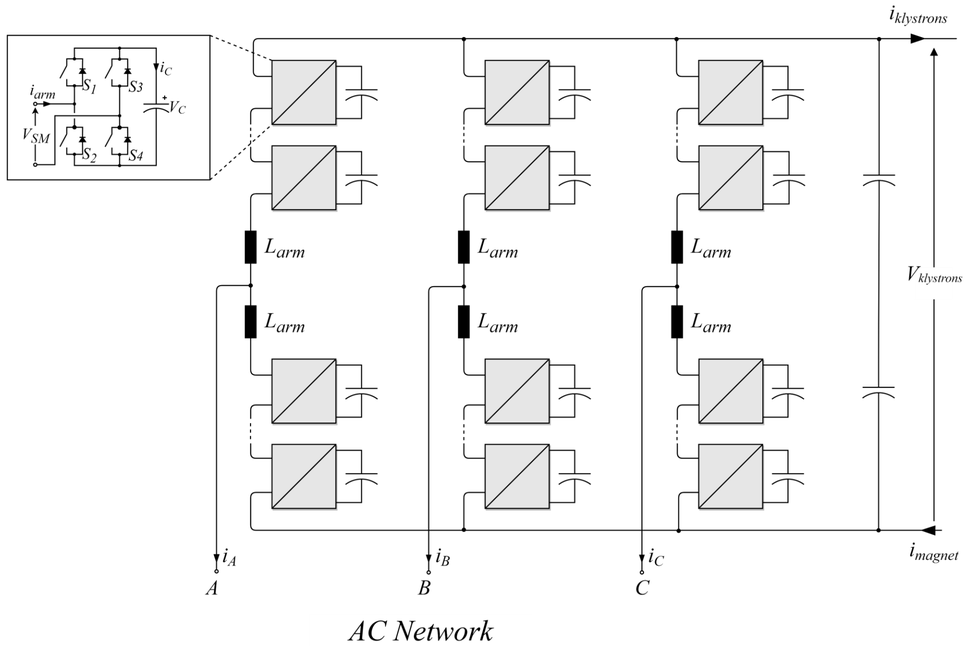


Power converter installed on surface

Powering requirements & solutions

Proposed solution - centralised MMC on surface

- Modular Multilevel Converter (MMC)
- Industrially available now in the 100s of kV & GW range
- Advantages
  - High efficiency: 98 % – 99 %,
  - High availability (redundant modules)
- Special protection techniques needed

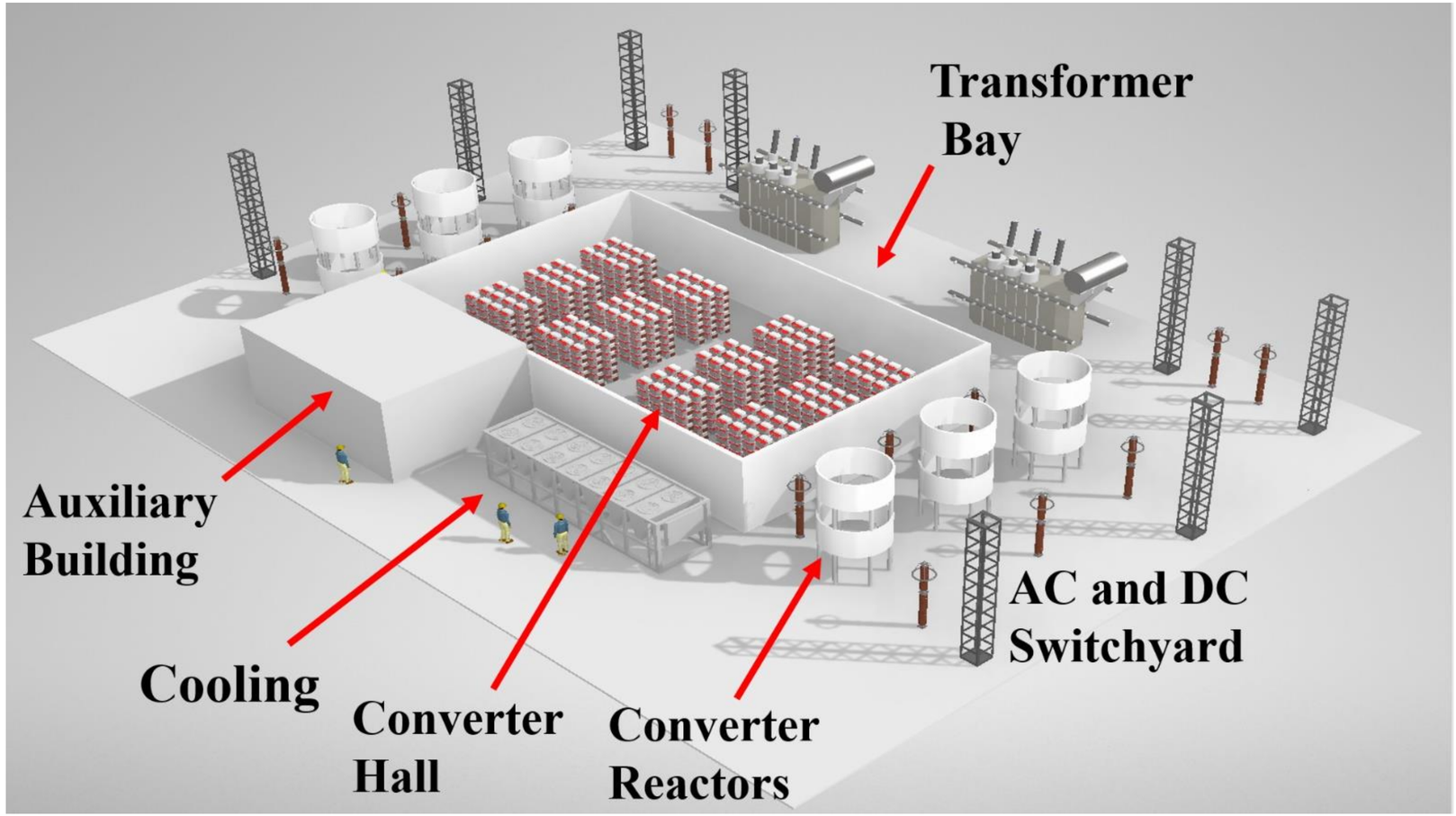


RF powering integration

Proposed solution - centralised MMC on surface

- Needed surface of
  50 m x 30 m = 1500 m^2
- A converter hall/building
- An auxiliary building (e.g. controls)
- Several outdoor equipment:
  - Input transformers
  - Circuit breakers
  - Reactors
  - Cooling
  - Measurements
  - Etc.

Illustration of a draft integration of a ~200 MW MMC

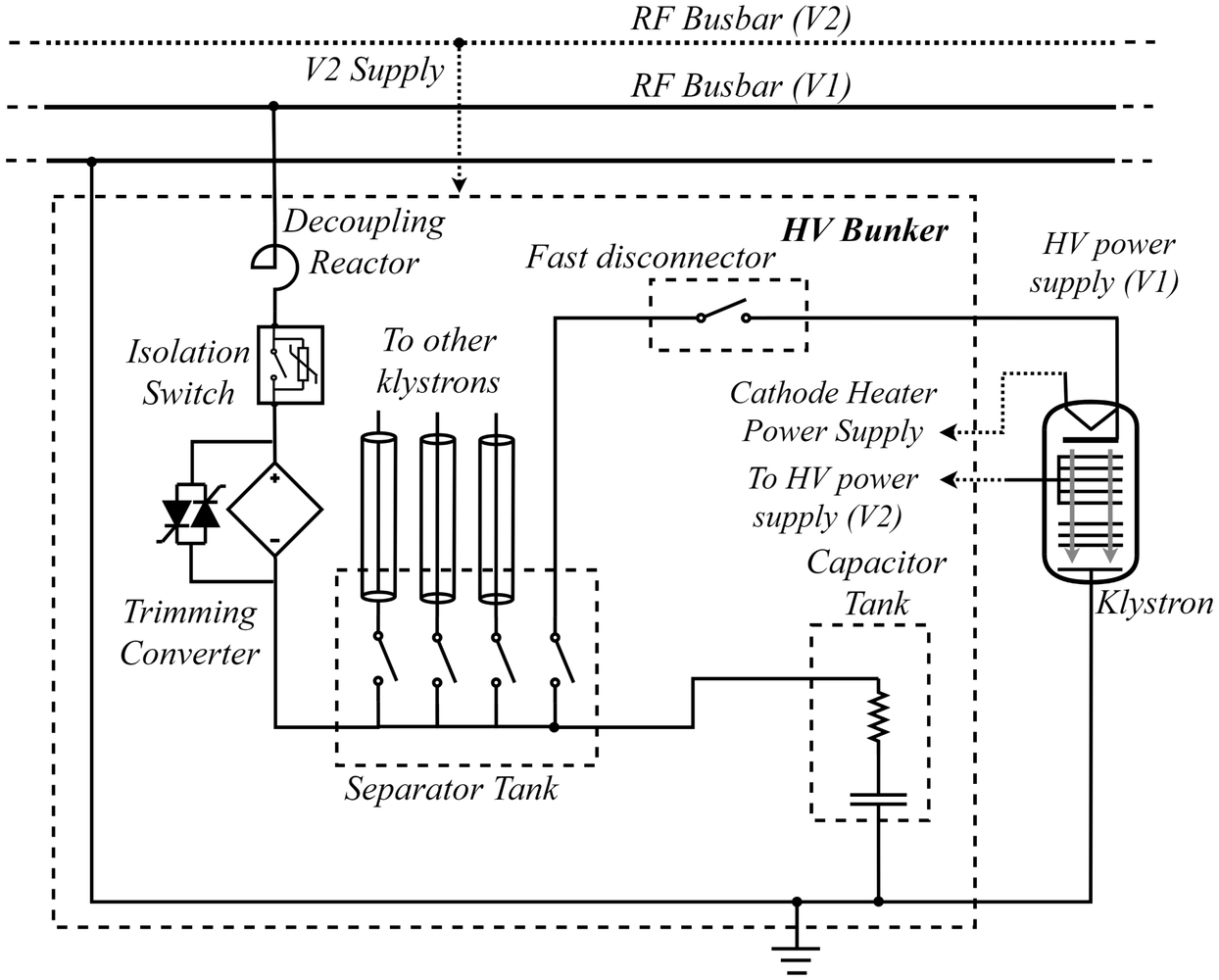


RF powering integration

Proposed solution - centralised MMC – underground equipment

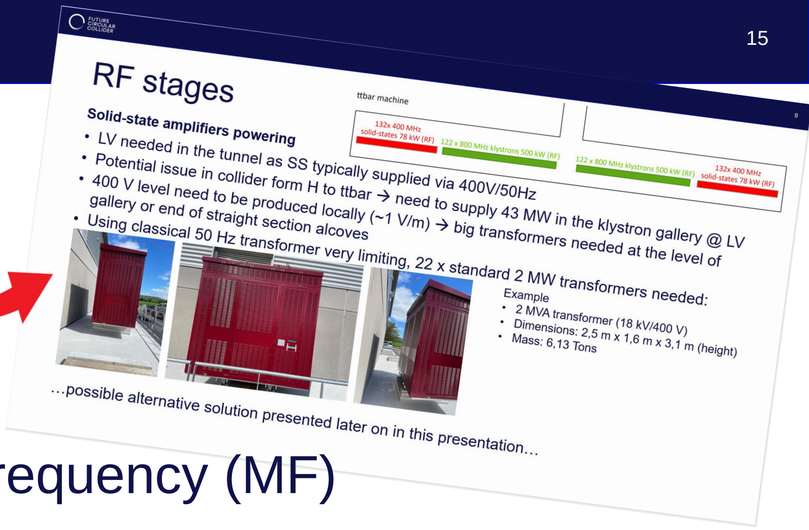
- Equipment in HV bunker (klystron gallery):
  - Capacitor bank
  - Voltage regulator (series connected)
  - Fast disconnector (klystron protection)
  - Decoupling reactor (due to parallel powering of all klystrons)
  - Filament heater power converter
  - Control rack
  - Separator tank (one bunker supplies several klystrons)

Working with RF group to derive a total volume/surface needed in HV bunkers



RF powering integration

Remember this slide?



Proposal for the Solid-State LV powering

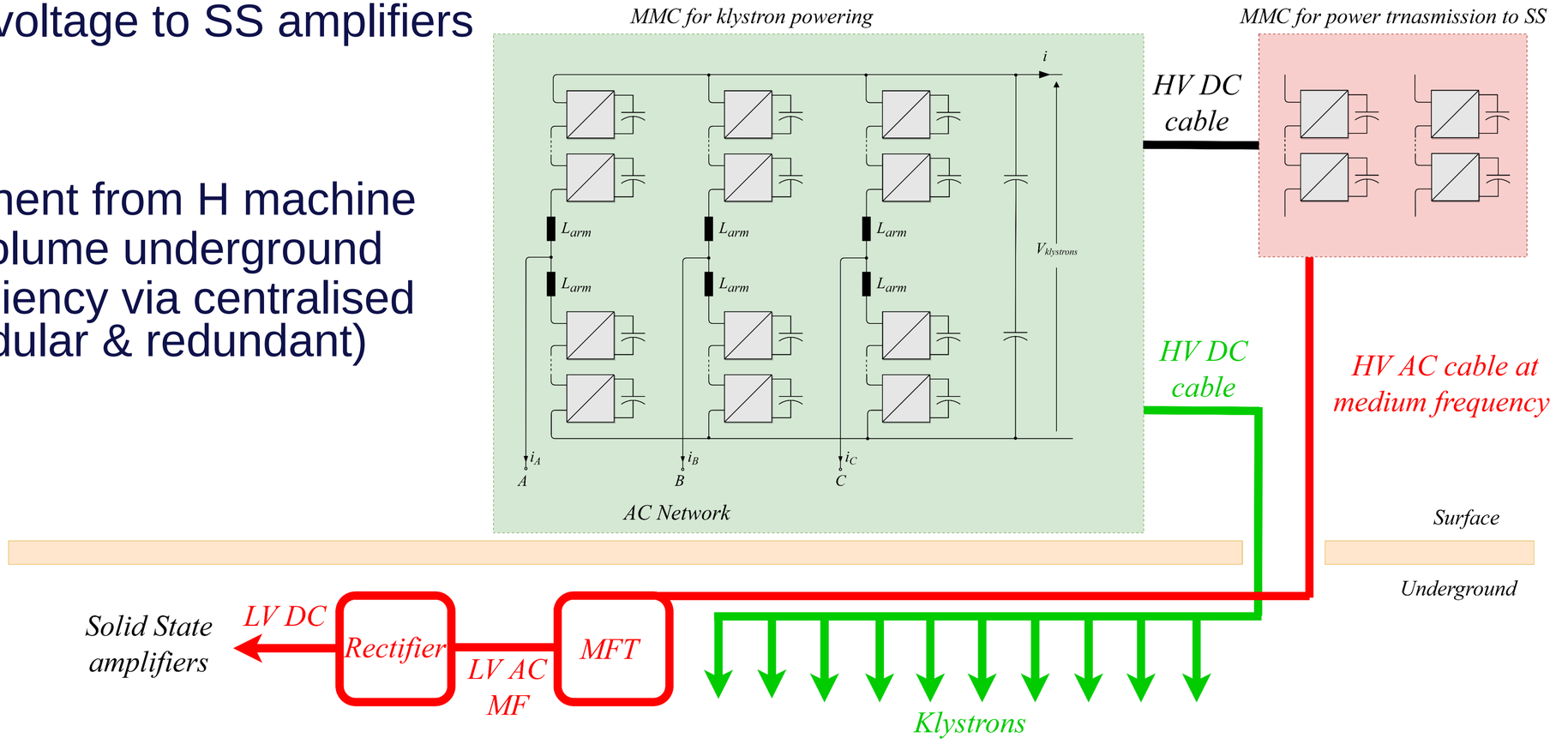
- Re-use MMC modules to create Medium Voltage (MV) / Medium Frequency (MF)
- Have smaller size MF transformers underground
- Directly provide LV DC voltage to SS amplifiers

Advantages

- Reuse of power component from H machine
- Reduced transformer volume underground
- Improve overall SS efficiency via centralised AC/DC conversion (modular & redundant)

Inconvenient

- Slightly more complex



Conclusion

- Most probable solution: centralized power converter to supply all klystrons
- Power converter installed on the surface, need for ~1500 m^2
- Voltage regulators and protection in underground HV bunkers (volume TBD with RF)
- Large RF power overheads for now, need to optimize it to minimize powering CAPEX
- Solid State amp. in collider for ttbar needs a powerful (43 MW) LV distribution
  - ➢ Investigating solutions to minimize impact on CAPEX (civil engineering) via smaller Medium Frequency transformers to be placed underground

Thank you for your attention.

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El. power/kly [MW]	1.33	0.671	1.33	0.671	1.33	-	-	0.671	-
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