Modulator Studies at CERN

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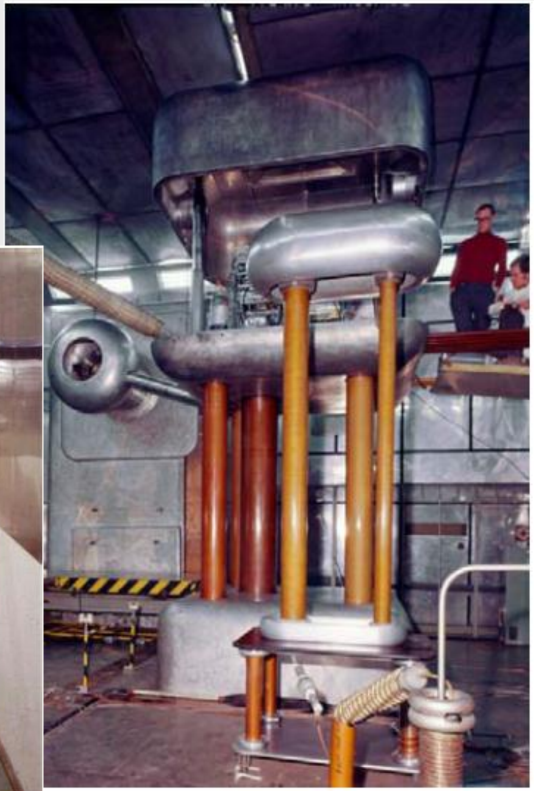
Intro

- Past and present LINACs
- LINAC4
- CLIC
- Modulator Studies for LINACs and CLIC
- Conclusion

Past – LINAC 1 and 2

- LINAC1 and LINAC2
  - Cockcroft-walton generators
  - Used for CERN proton physics until 1993
  - (not recommended for new projects)

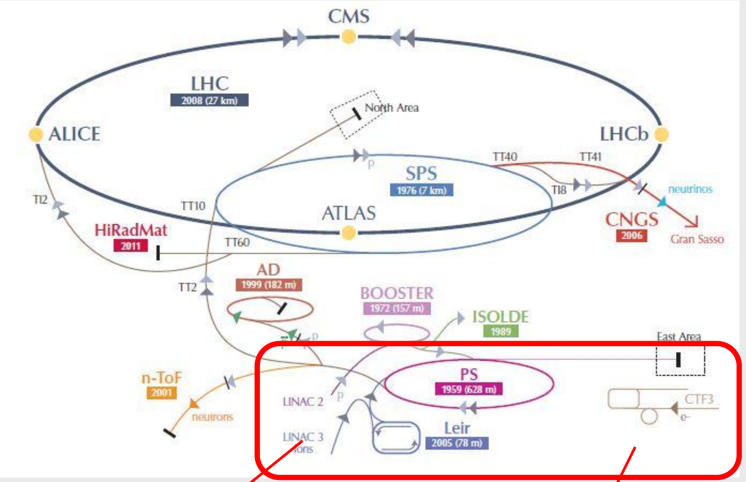


1959: [520kV, 135mA]

1973: [750kV, 150mA]

Present – LINACs 2 and 3, CTF

- Operational pulsed RF power @ CERN
  - LINAC2 (triode)(1976)(x2)
  - LINAC3 (tetrode)(1994)(x2)
  - CTF3 (klystron)(1981)(x11)

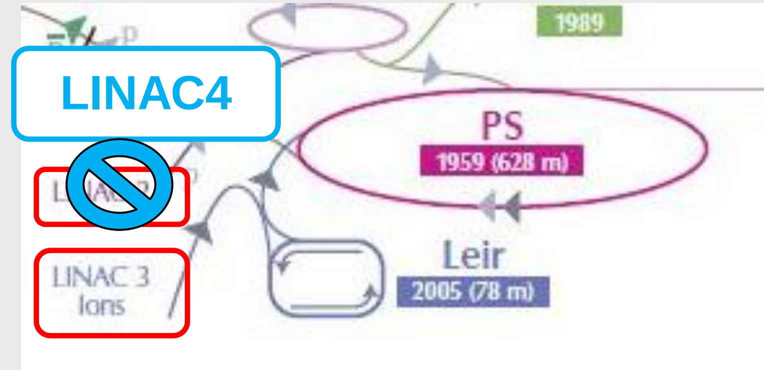


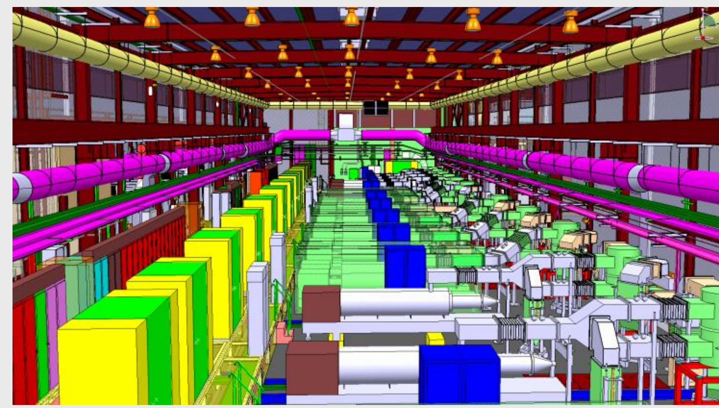
- Also several teststands
  - LINAC4
  - CTF3

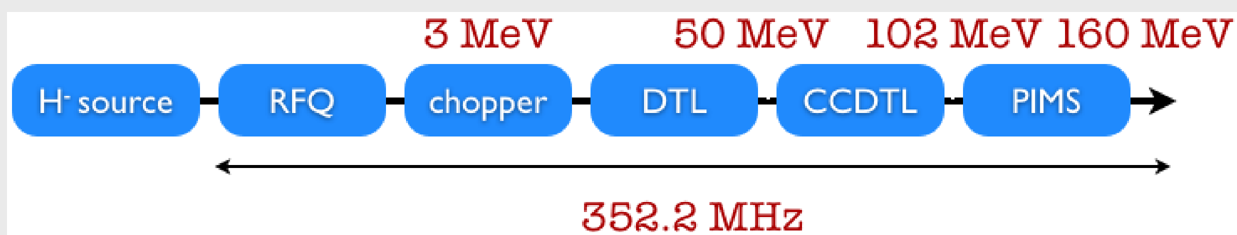
- Pulsed RF power has a modest (but important) presence today

Future - LINAC4

- Due to the age of LINAC2
  - Replace with an H- ‘LINAC4’
  - Higher energy and beam intensity
  - Currently under construction
- 14 klystron modulators
  - 19 klystrons (13 ‘LEP’ klystrons, 6 new klystrons)
  - 25 accelerating cavities

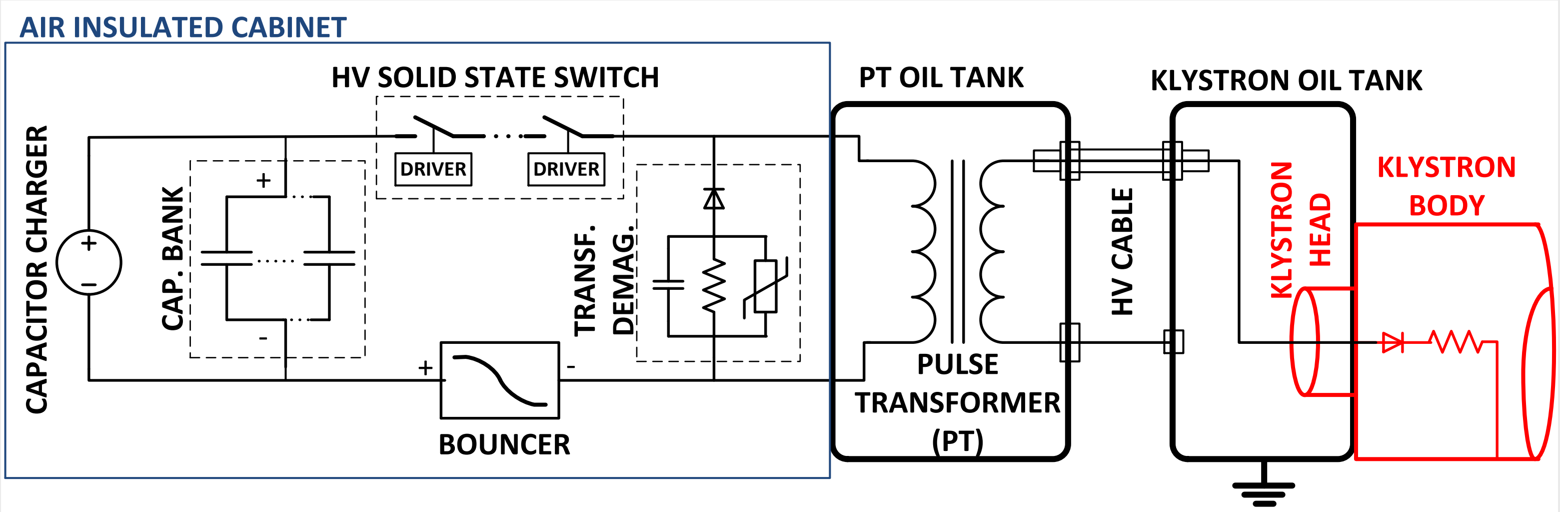






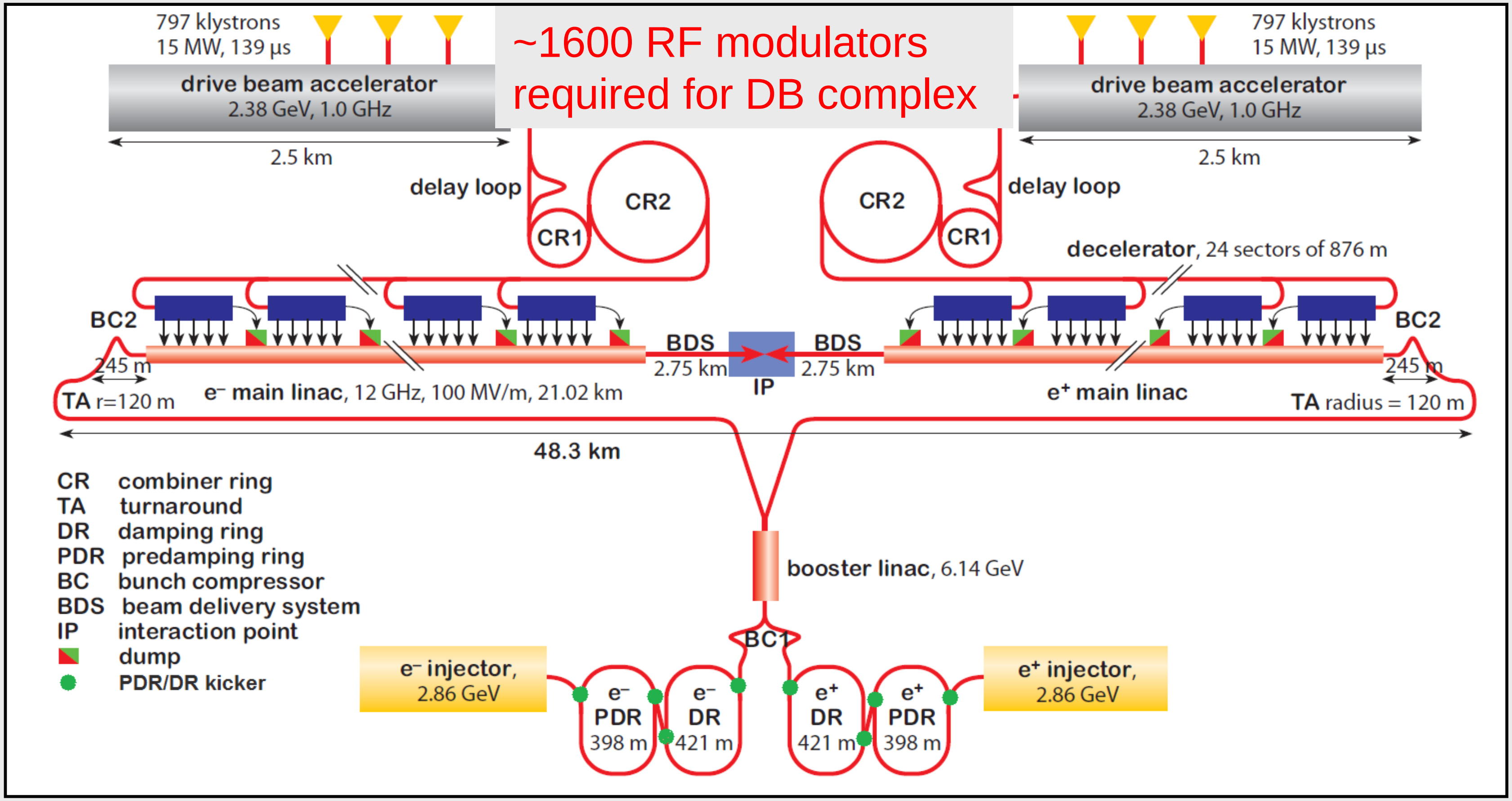
Future - LINAC4

- CERN modulator development for LINAC4
  - Capacitor discharge with LC bouncer droop compensation
  - Classical design used for accelerator applications, eg Fermilab
  - Modest performance requirements
    - Output of [110kV, 50A] at up to 2Hz with 1.8ms pulse
    - Maximum average power of 20kW
    - 1% droop on flat-top, 0.1% reproducibility and precision



Future projects - CLIC

- CLIC : Drive Beam modulators



Future projects - CLIC

- Drive Beam RF requirements

Peak power/klystron	15 MW
Train length after injection	140 μs
Repetition rate	50 Hz
Phase precision	0.05° @ 1 GHz (first 10% of the DB linac) 0.2° @ 1 GHz (next 90% of the DB linac)
Nb of klystrons (DB linac)	2x 797 = 1594

- Leads to demanding modulator requirements
  - pulse reproducibility (<10ppm) and its measurement
  - efficiency and low pulse rise time (>300MW total power in best case)
  - reliability (modular topologies with redundancy and low MTTR)

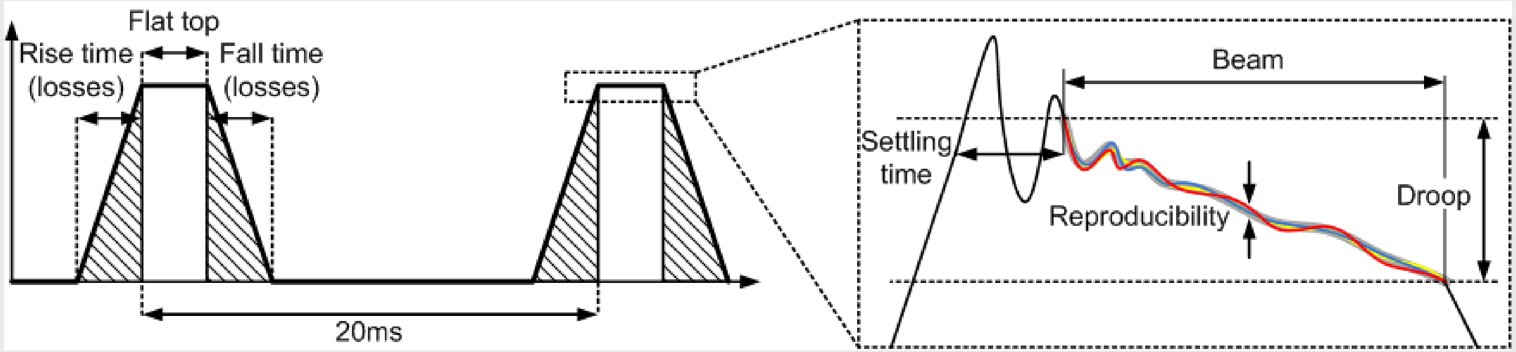
- Modulator R&D studies to demonstrate technical solutions

Future projects - CLIC

- CLIC Drive Beam Modulator specifications

Modulator's output pulse specification			
Nominal pulse voltage	V_{kn}	150	kV
Nominal pulse current	I_{kn}	160	A
Pulse peak power	P_{mod_out}	24	MW
Rise & fall times	t_{rise}, t_{fall}	3	μs
Settling time	t_{set}	5	μs
Flat-top length	t_{flat}	140	μs
Repetition rate	$REPR$	50	Hz
Voltage overshoot	V_{ovs}	1	%

Precisions			
Flat-Top Stability	FTS	0.85	%
Reproducibility (6kHz-4MHz)	PPR	10	ppm
Efficiencies			
Charger electrical efficiency	η_{ch}	96	%
PFS electrical efficiency	η_{pfs}	98	%
Pulse efficiency	η_{pulse}	95	%
Modulator global efficiency	η_{mod_global}	90	%



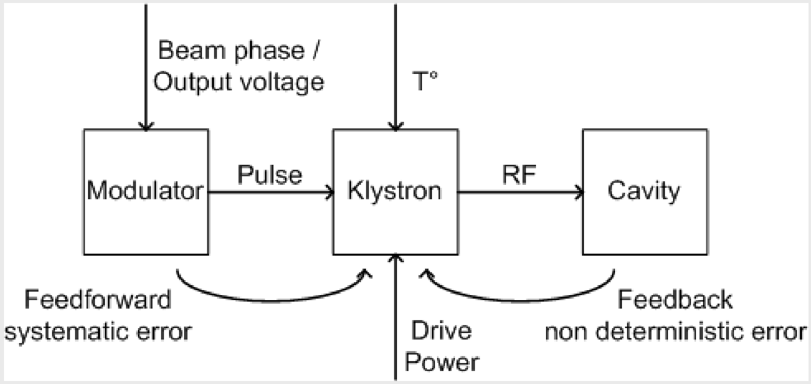
- Average power of 185kW

Future projects - CLIC

- CLIC Drive Beam Modulator studies
  - Due to the challenging specifications, studies are progressing in partnership with several collaborations
    - CERN coordinates the studies
    - External institutes contribute to the modulator technology choices and design
    - CERN develops the test and measurement capabilities
  - Important that CERN obtains rights to use intellectual property for subsequent production
  - Studies will lead to 2 full scale prototypes to be delivered in 2017
    - The prototypes will use different modulator topologies

Modulator studies - Measurement

- How to deliver 10ppm system reproducibility?
  - Today, the requested performance can only be measured in the RF phase or by the beam itself.
- Evaluate the complete system
  - To obtain the desired performance, it is necessary to identify all major sources of non-reproducible behaviour in the RF system ‘from plug to cavity’
  - Stating the obvious
    - Identify potential sources analytically
    - Measure to confirm these effects
    - Correct for these effects
  - The two major ‘complex’ power systems are the modulator and klystron
    - Develop a ‘low frequency’ model of a typical klystron (up to several MHz)?
    - Develop a similar model for the modulator



Modulator studies - Measurement

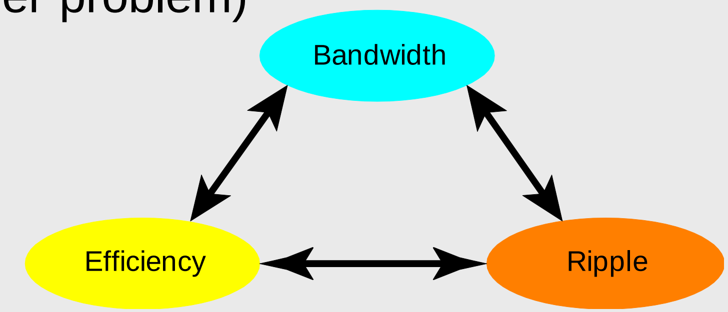
- How to deliver 10ppm modulator reproducibility?
  - Not yet possible to measure performance at the modulator HV output

- Strategy to find a solution
  - Characterise the modulator for a chosen topology, identifying components that contribute to variation in reproducibility
    - Deliver a model that can predict reproducibility, and can highlight main contributors
    - Testbench constructed for first measurements
  - Develop methods to measure performance on pulsed high voltage
    - Studies beginning on techniques that can combine several measurements
  - Develop the measurement acquisition chain (ADC, HV divider)
    - Fast and reproducible ADC characterisation beginning
    - HV divider characterisation (so far only of 'long pulse' systems)
  - Measure the modulator performance and correlate with klystron and RF phase results
    - Once some of the above techniques have been developed, system measurements can start

Power electronics topologies & pulse transformers

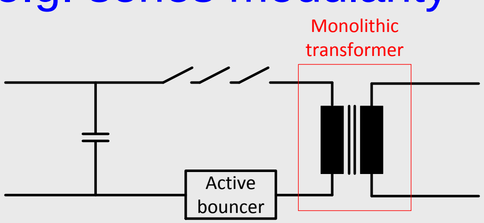
Several topologies under study

- Classical requirements are high bandwidth /efficiency & low ripple (the classical pulsed power problem)

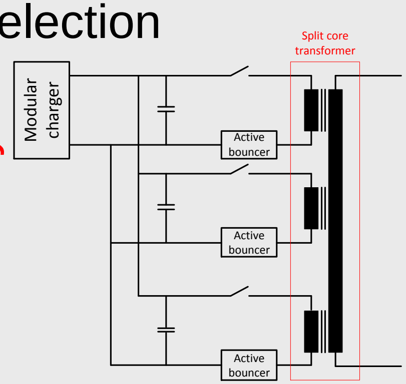


- Availability / reliability / reproducibility have a great impact on topology selection

e.g. series modularity



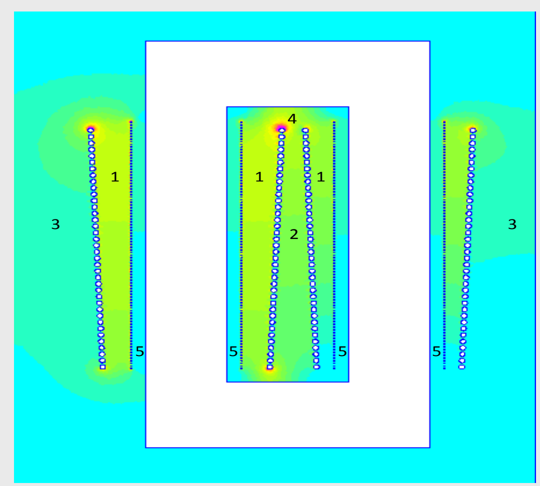
e.g. parallel modularity



Pulse transformers studies

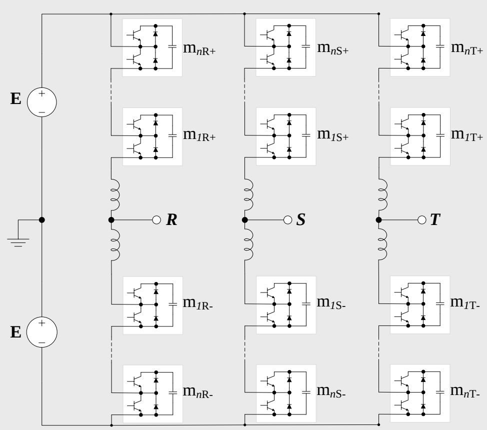
- Effort in very fast rise time pulse transformers design (for topologies where it is required)
- Monolithic and split cores transformers are evaluated

e.g. Monolithic core pulse transformer in FEA



Modulator studies – Charger/grid

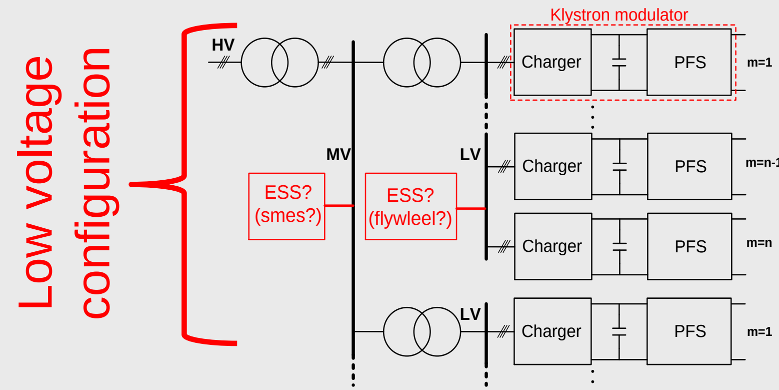
- Optimisation of grid layout and chargers topology
  - Modulator synchronous operation requires ~36GW of pulsed power and ~300MW of average power!
  - Need for chargers with constant power absorption for grid interconnection
  - Cost effective, efficient & modular topologies required!

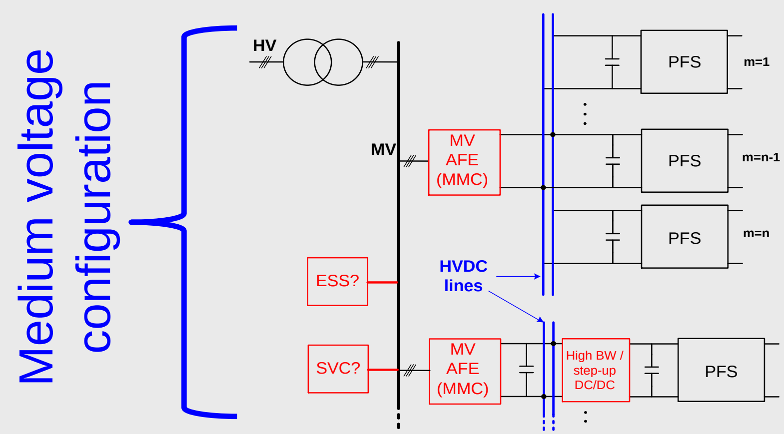


Example of modular topology under study

How to control this converter for constant power absorption & pulsed load?

- Grid layout to be optimised
- Number of modulators per charger?
- HV or LV connection to grid?





Conclusion

- Experience both from CERN and other installations identify the modulator as an important contributor to machine reliability/availability
  - Appropriate topology choice and design effort is necessary for new accelerators

- CERN is reviving competence in the design and specification of pulsed modulators
  - LINAC4 facility will start beam commissioning in 2013
  - CLIC R&D will push specification and measurement boundaries, and explore new technologies

- For applications with challenging specifications, such as required by CLIC, a complete system approach is required including modulator, klystron and low-level control studies

- Interested institutions are welcome to contribute their expertise to the technology challenges