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Status of the Modulator for CLIC MBK

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High Efficiency Klystron Day

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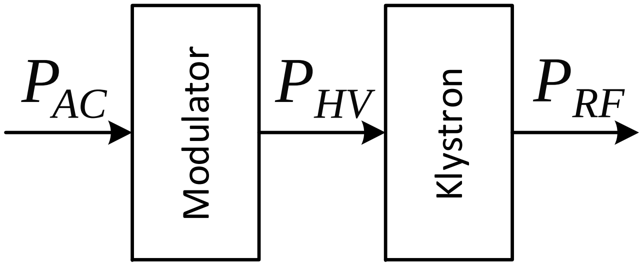
Presentation Outline

- Klystron modulators efficiency definition
  - Classical and “not adapted” formulation
  - A more global efficiency formulation
- Challenges of high dynamical performances
  - The efficiency-bandwidth-precision challenge
- Existing main topologies overview
- Modulator design for CLIC
  - Specifications and challenges
  - A design solution based on monolithic pulse transformer
- R&D Status
- Conclusion

Klystron modulators efficiency definition
Classical and "not adapted" formulation

- In LINACs, power consumption mainly from RF equipment's
- Electrical to RF conversion chain efficiency defined as:



Modulator's Efficiency

$$\eta_{el\_mod} = \frac{P_{HV}}{P_{AC}}$$

Typical : ~ 95%

Klystron's Efficiency

$$\eta_{kly} = \frac{P_{RF}}{P_{HV}}$$

Typical range : ~50%-70%

Then why working on modulator efficiency?

- Reminder:

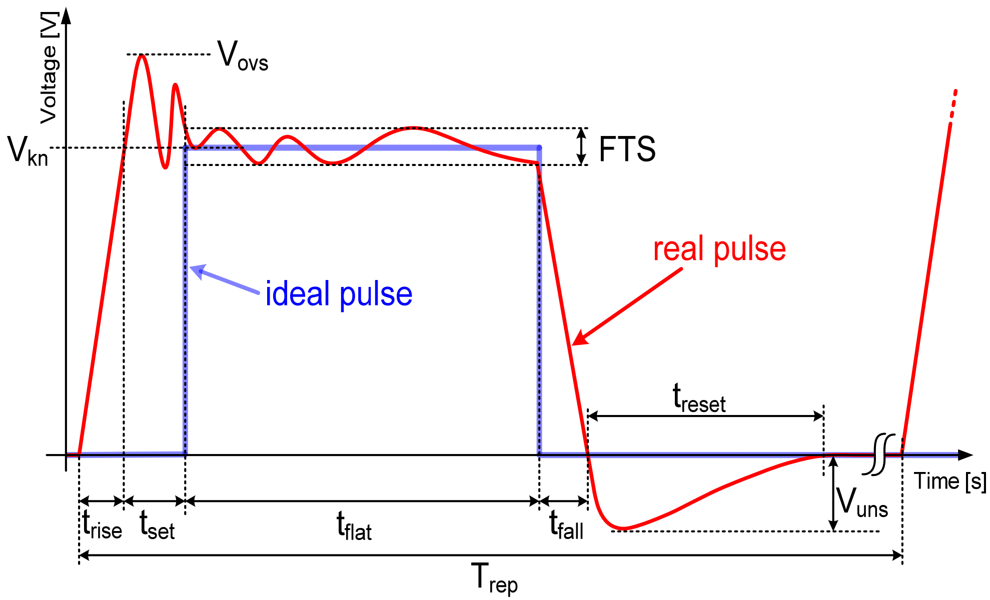
Voltage applied to klystron ≡ Power consumption
…no matter if RF power is produced or not!

A re-definition of the conversion chain efficiency required!

Klystron modulators efficiency definition

A more global efficiency formulation

- Efficiency shall include energy consumption when RF is off (RF filling time neglected)



Pulse efficiency definition

$$\eta_{pulse} = \frac{E_{ideal\_p}}{E_{real\_p}}$$

Global modulator efficiency

$$\eta_{global\_mod} = \eta_{el\_mod} \cdot \eta_{pulse}$$

- Optimal compromise should be found between electrical & pulse efficiency
- Global modulator efficiency should be maximized during optimization design process!

Klystron modulators efficiency definition
A more global efficiency formulation

- High overall efficiency in the electrical to RF conversion chain implies efforts in:
  - Maximizing klystrons efficiency (considerable global effect)
  - Maximizing modulators electrical efficiency (marginal global effect)
  - <u>Maximizing modulators voltage dynamics</u> (considerable global effect)
    - Power electronics topology selection
    - Active and passive components/materials selection (e.g. insulation)
    - Global design optimisation procedures
    - Mechanical integration for maximizing voltage dynamics (shorten HV cables, use klystron tank for pulse transformer, etc.)

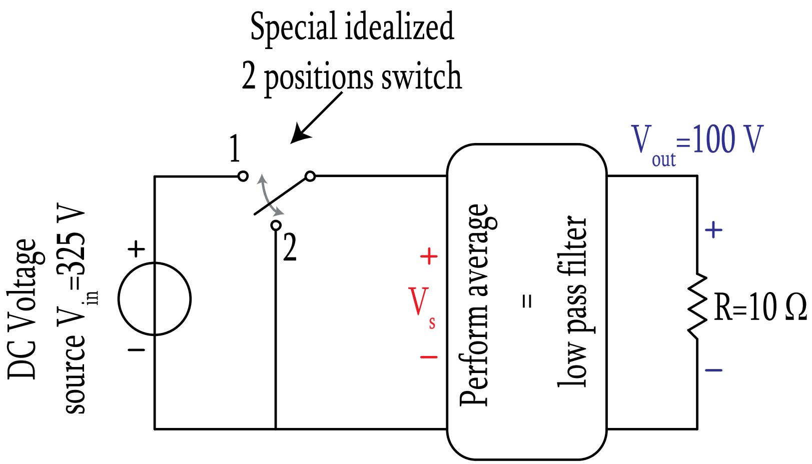
Modulator voltage dynamics impacts overall efficiency, but Klystron cost, size and temperature rise as well!

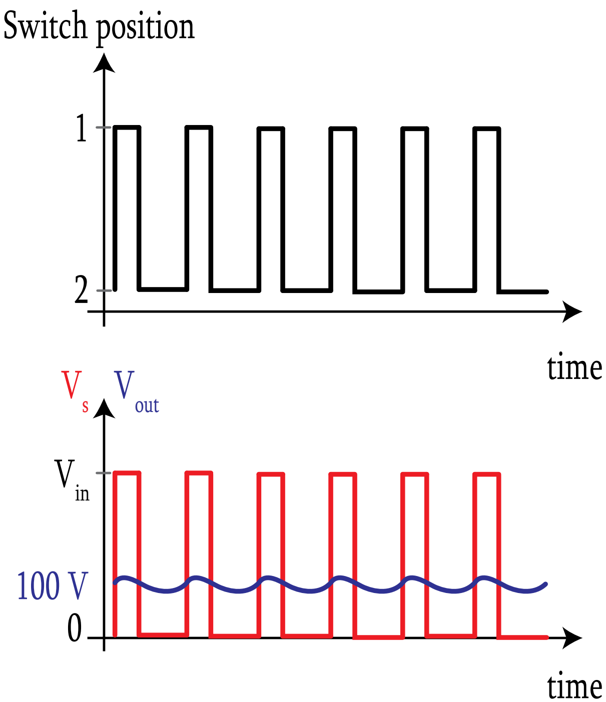
Challenges of high dynamical performances

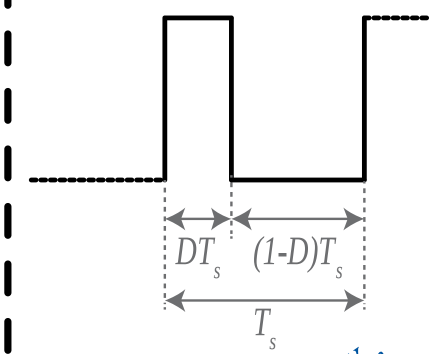
The efficiency-bandwidth-precision challenge

…first: a power electronics refresh

- Modern switching power converters







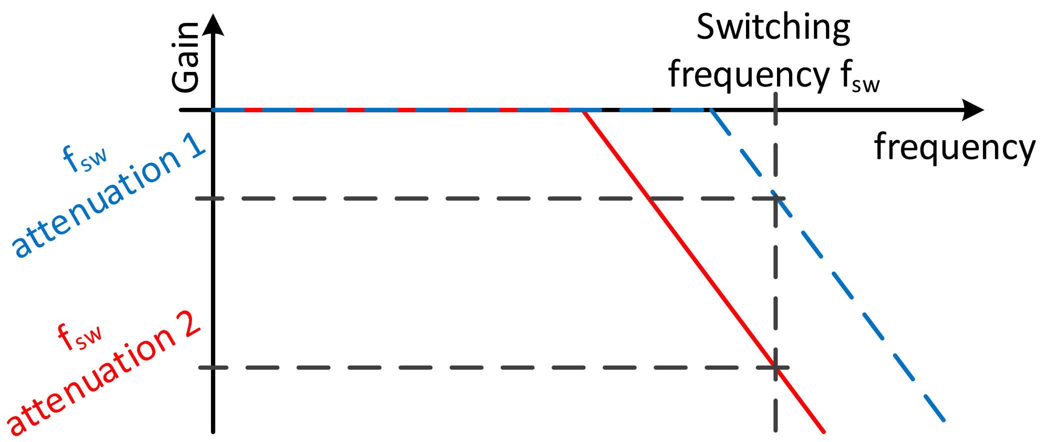
$$V_{out} = \frac{1}{T_s}\int_0^{T_s} V_{in}(t)dt = DV_{in}$$

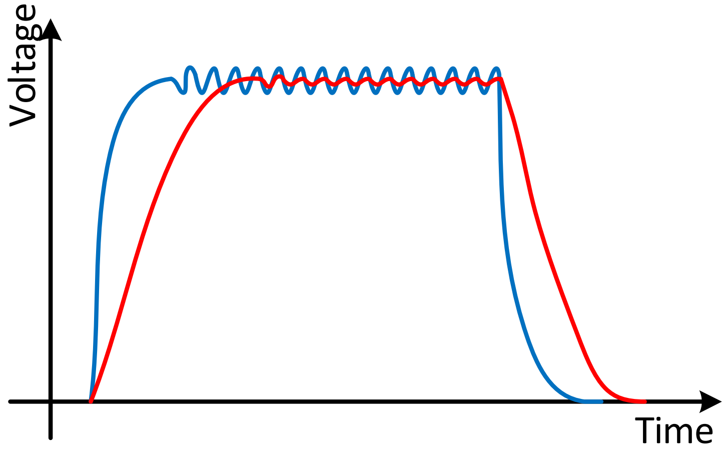
T_s: switching period
$f_s=1/T_s$: switching frequency
D: duty cycle

- Switches in their on or off states only
- Advantages: High Efficiency – smaller size
- Drawbacks: Lower dynamics, residual ripple, EMC issues

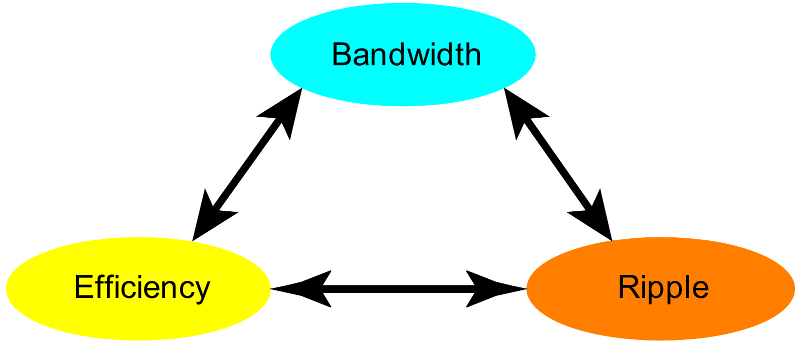
Challenges of high dynamical performances
The efficiency-bandwidth-precision challenge

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

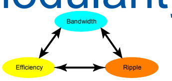




- Higher dynamics ≡ higher ripple (@ const. f_{sw}/losses)
- Ripple and dynamics (precision) increased in efficiency decreased (higher f_{sw} of linear stages)
- A design compromise has always to be found between these performances – for complex problems numerical optimization required

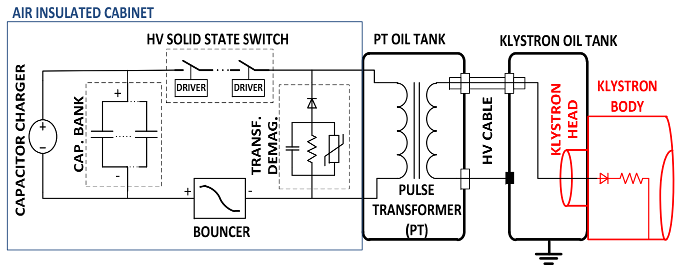


Existing main topologies overview

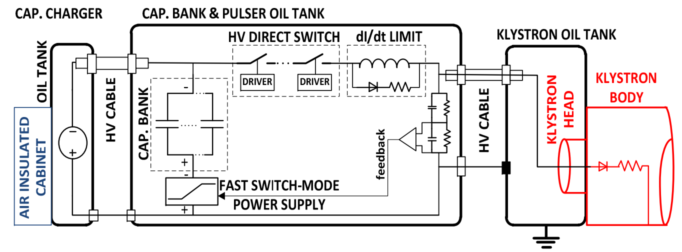
- What factors influence topology selection?
  - Output voltage & current levels
  - Output pulse precision (e.g. repeatability)
  - Reliability (components, insulation system, etc.)
  - Availability and MTTR (e.g. modularity)
  - Global modulator efficiency + 

  - Utility grid specifications (voltage level, power factor, max. power fluctuation, flicker etc.)
  - Cost
- General modulator's topology components
  - Active Front End (AFE – Charger – AC/DC)
  - Energy storage (typically capacitive)
  - Discharging + regulation system
  - Fast HV pulse transformer (optional)
- Topologies classification for flat pulse modulators
  - Transformer based: monolithic, split core, or resonant MF (for "long" flat pulse)
  - Transformer-less: direct switch, or Marx-based

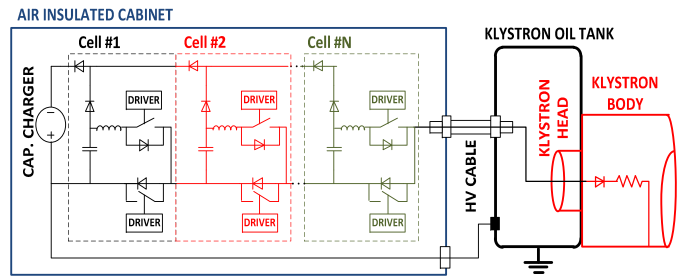
Transformer based (monolithic):



Transformer-less (direct switch):



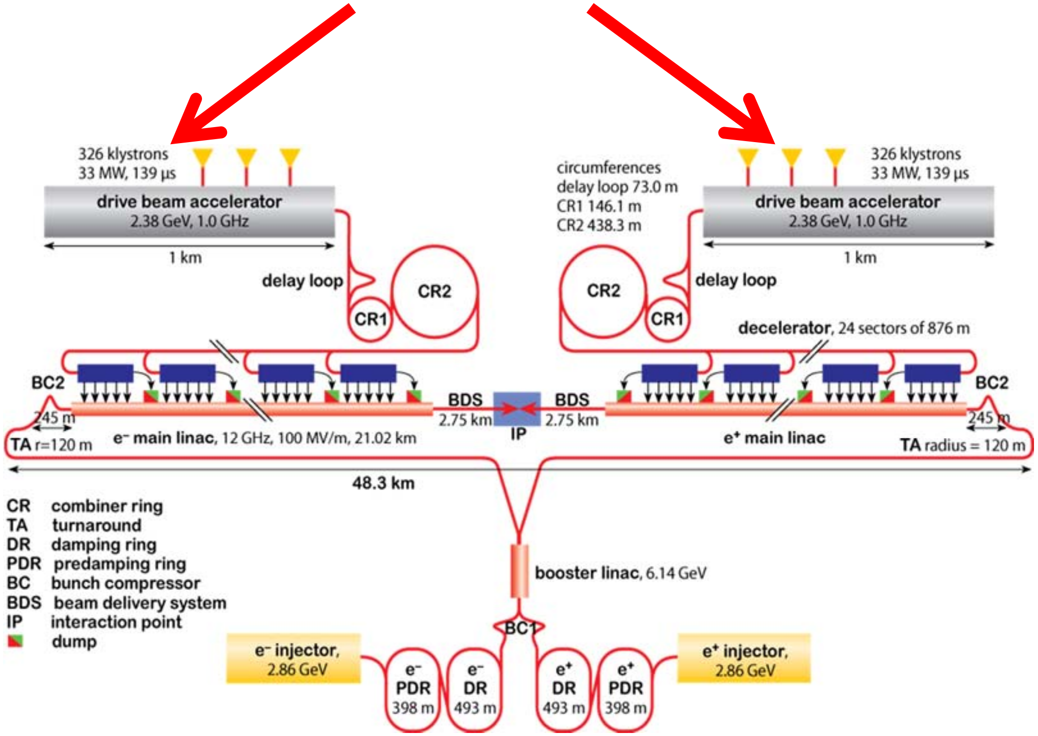
Transformer-less (Marx):



Modulator design for CLIC
Specifications and challenges

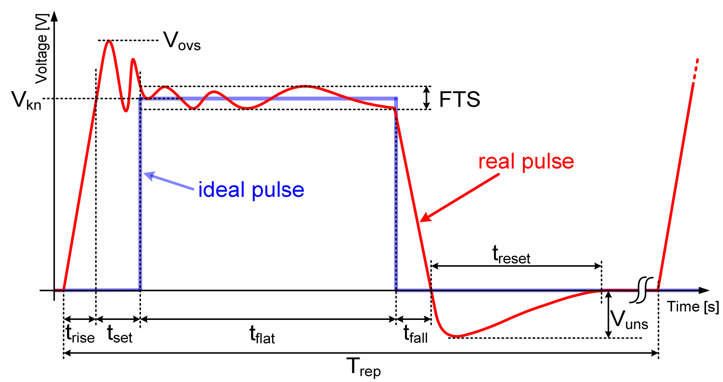
- CLIC klystron modulators for the drive beam

~1300 klystron modulators



~ 300MW average power consumption from grid

Modulator's Specs			
Pulsed voltage	V_{kn}	160-180	kV
Pulsed current	I_{kn}	160	A
Peak power	P_{out}	29	MW
Rise/fall time	$\mathbf{t_{rise}}$	**3**	**µs**
Flat top length	t_{flat}	140	µs
Repetition rate	Rep_r	50	Hz
Flat top stability	FTS	0.85	%
Pulse repeatability	**PPR**	**10-50**	**ppm**



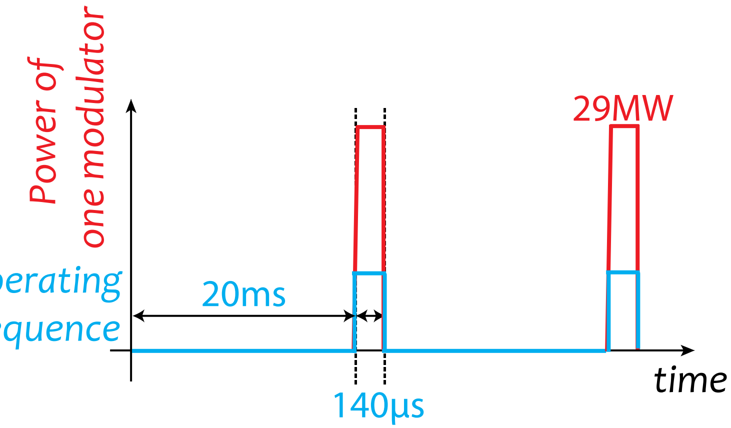
Modulator design for CLIC

Specifications and challenges

- The grid connection challenge – power fluctuation

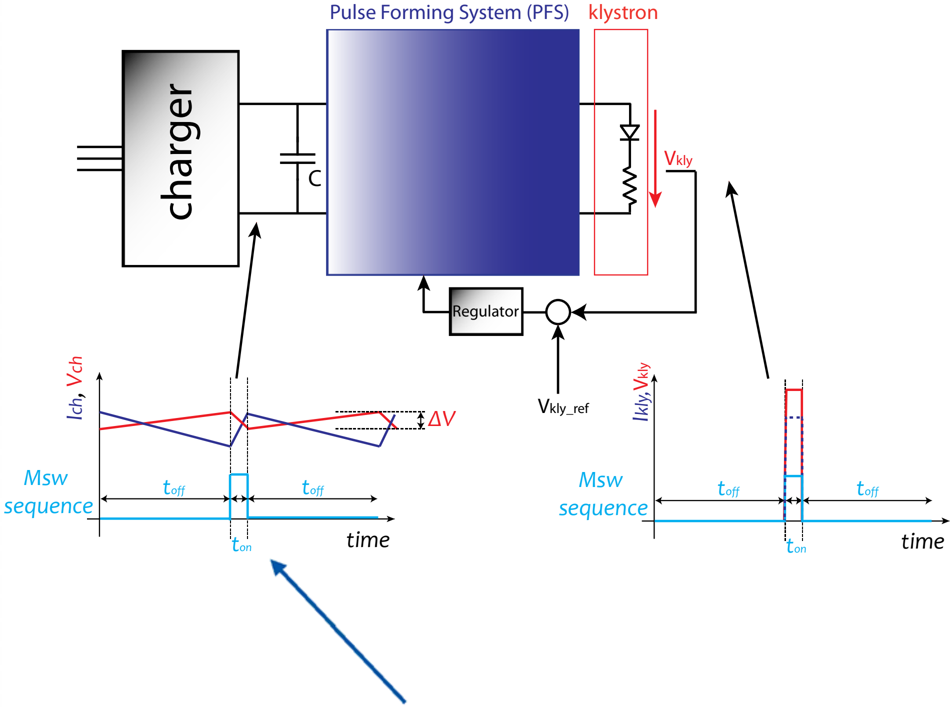
Simultaneous operation of all modulators

➡ 29 MW x 1300 klystrons = **38GW!**



Absorbed AC power must be constant to stabilize distribution voltage!

Even with energy storage, a power fluctuation on the AC side. Active compensation necessary!



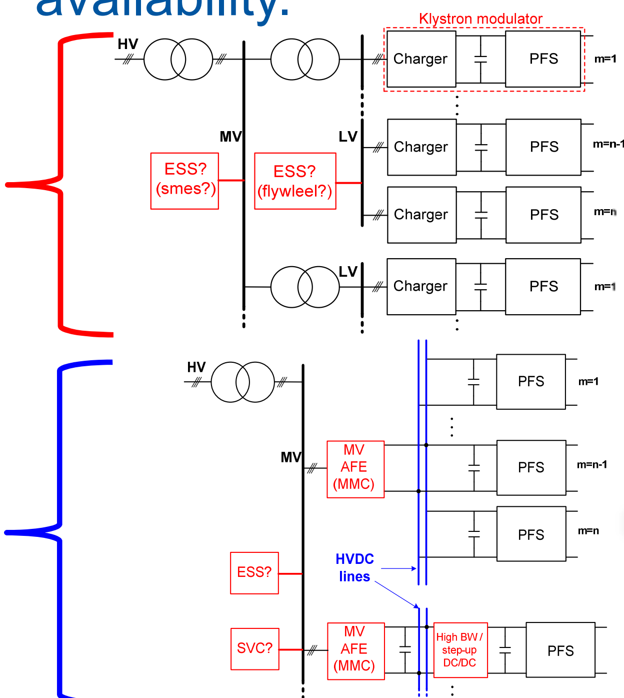
A solution consisting in high dynamics AFE to stabilize power (V*I=const.)

Modulator design for CLIC
Power distribution affects modulator's topology

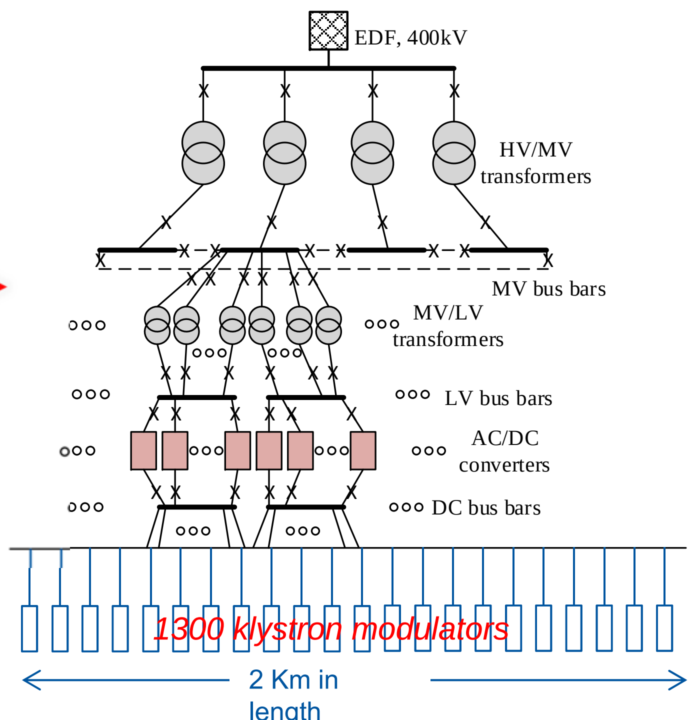
- Grid layout design problem (with Nottingham University)
  - Scope: distribute power efficiently & reliably to all modulator distributed on a 2 km LINAC
  - Method: nonlinear optimization of several grid layout – optimizing efficiency, cost (cables buildings switchgear, etc.) reliability & availability.

Low voltage configuration

High voltage configuration



Most promising Solution

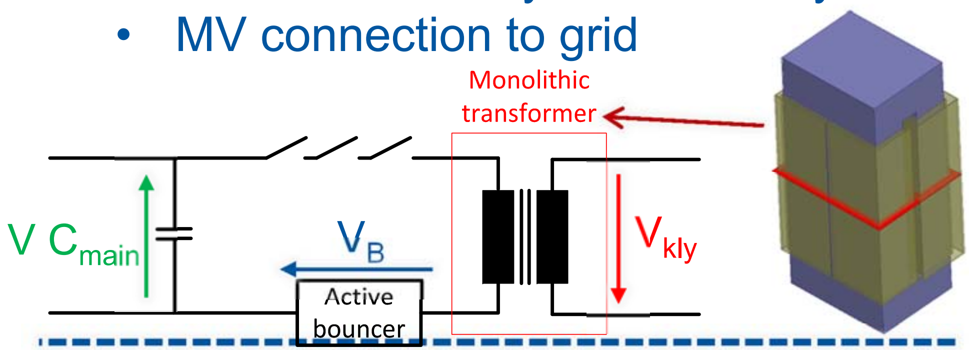


Modulator design for CLIC

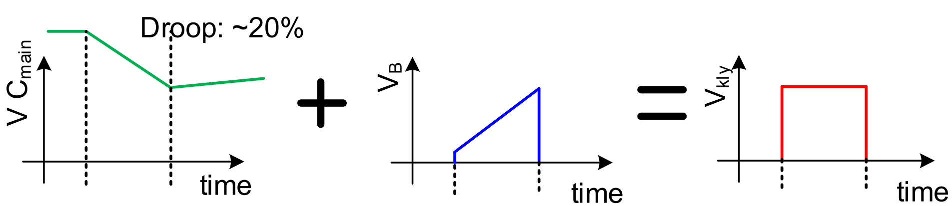
A design solution based on pulse transformer

- Actually two topologies under study

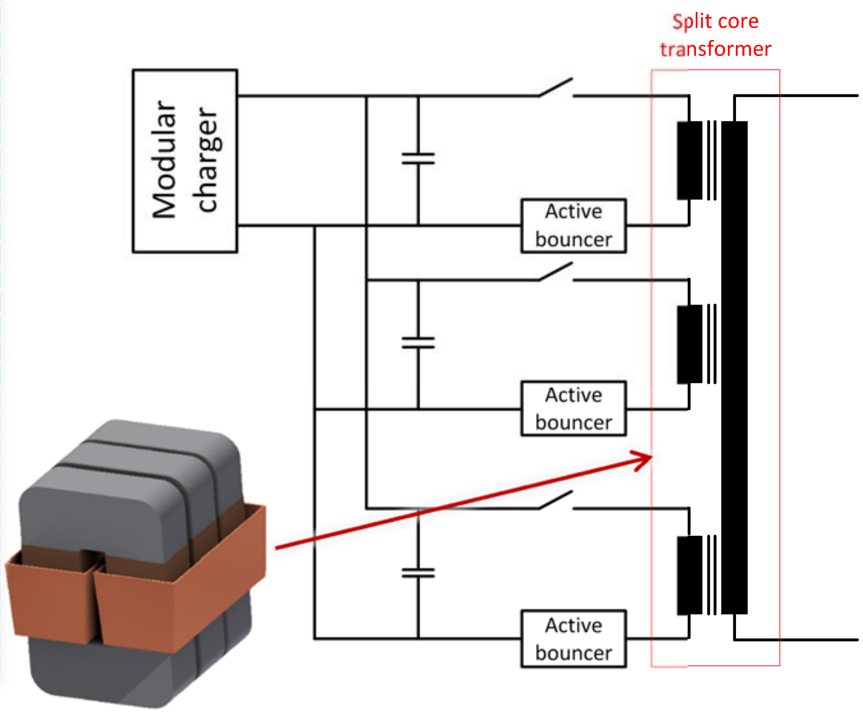
- Monolithic pulse transformer (LAVAL University, Canada)
  - Series modularity / redundancy
  - MV connection to grid



- Active bouncer
  - Compensates capacitor voltage droop
  - Regulates output voltage



- Split-core pulse transformer (ETHZ)
  - Parallel modularity / redundancy
  - LV connection to grid



R&D Status

- Grid layout optimization completed (Nottingham)
- Active Front End (capacitor charger) concept being experimentally validated (Nottingham)
- ETHZ Modulator under construction – sub systems being tested – this year will be at CERN for tests with klystron
- LAVAL University Modulator concept (small scale) being tested – Call for tender for full scale one this year (targeted operation at CERN in 2017)

Conclusion

- Efficiency directly linked to dynamic performances
- Modulators topology choice is a global/complex process, no best topology - optimal solution for each specific application
- Modulator global optimization methodology is mandatory: collaboration of designers from different domains is essential to achieve global efficiency
- Two topologies under study (one in construction) considering CLIC accelerator specificities
- Grid layout drives the input voltage range (thus topology) for the modulators – optimal value 20kV DC
- For power fluctuation control on grid & pulse repeatability, the accelerator operation shall be synchronized with the utility grid's 50Hz

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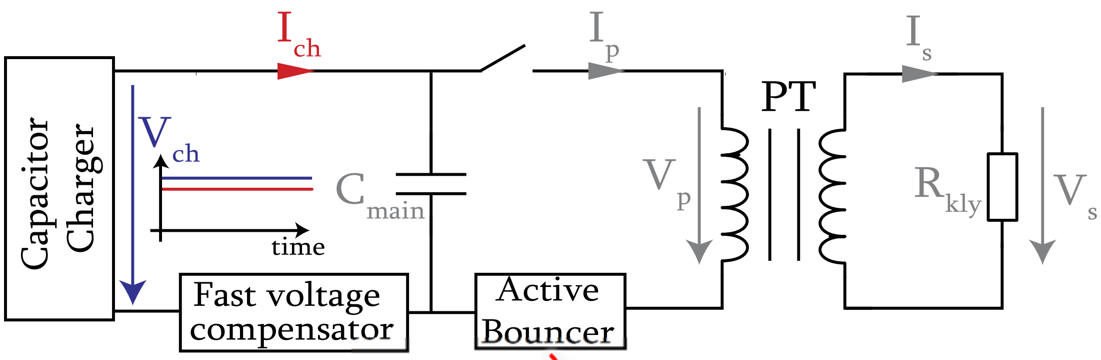
Back-up slides

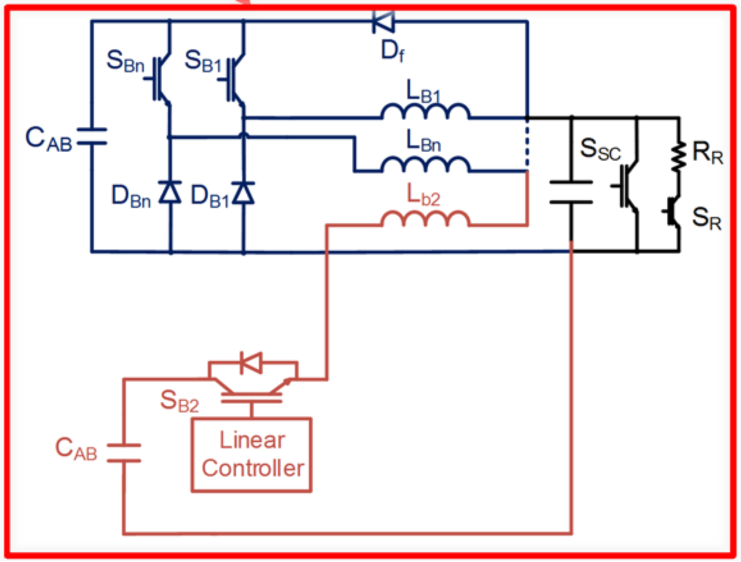
Modulator design for CLIC

A design solution based on monolithic pulse transformer

- Power electronics design



- Fast Voltage Compensator
  - Regulates V_{ch}=Const.
  - Ensures no AC power fluct.
  - Rated at charging current
  - Small & fast converter



- Active bouncer
  - Combines switching & linear stages
  - Switching stage handles majority of current at high efficiency
  - Linear stage efficiency very poor, but fast (global efficiency) – small current handled (small losses overall!)

Nonlinear optimization used to design the whole modulator!

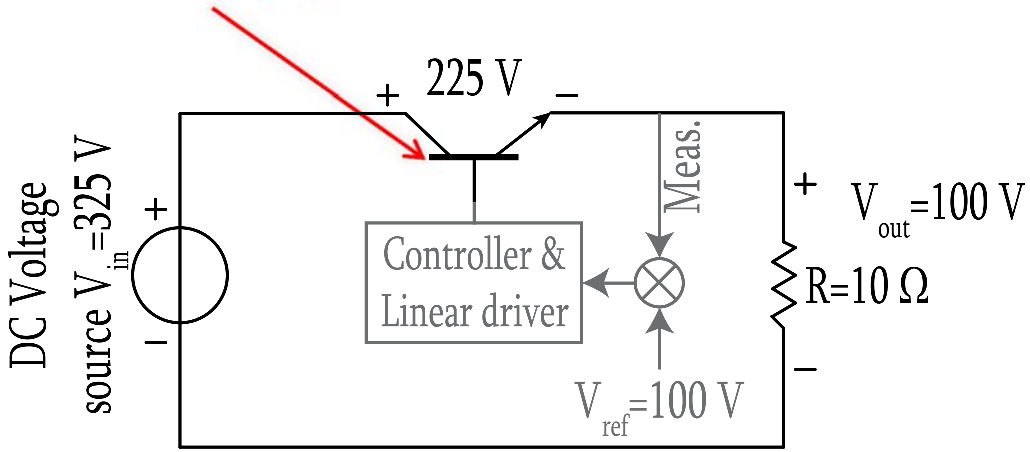
Challenges of high dynamical performances
The efficiency-bandwidth-precision challenge

…first: a power electronics refresh

- ***Old times***: Linear voltage/current regulation

Example: Step-down voltage regulator – 325V in – 100V out – 10A:

Transistor (T) operated in its active/linear region



- Illustrative analysis:

P_{in}=325 V x 10 A=3.25kW

P_{out}=100Vx10A=1kW

P_T=P_{in}-P_{out}=225Vx10A=2.25kW

Efficiency:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{1}{3.25} = 0.3 \longrightarrow \mathbf{30}\%!$$

- Mainly used until 1960s (still used in special applications: audio, high precision, HF amplifiers, …)
- Advantages: High dynamics, no ripple, no EMC issues
- Drawbacks: Low efficiency – size