





High-efficiency and high-voltage klystron modulators

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Presentation Outline

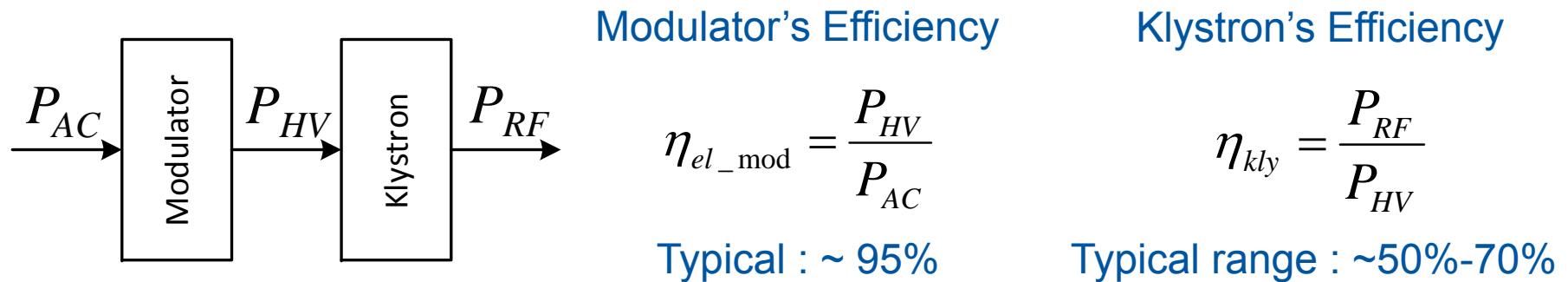
- Klystron modulators efficiency definition
 - Classical and “not adapted” formulation
 - A more global efficiency formulation
- Challenges of high dynamical performances
 - The efficiency-bandwidth-precision challenge
- Topologies overview
- Design example for CLIC
 - Specifications and challenges
 - A design solution based on monolithic pulse transformer
- 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:



Then why working on modulator efficiency?

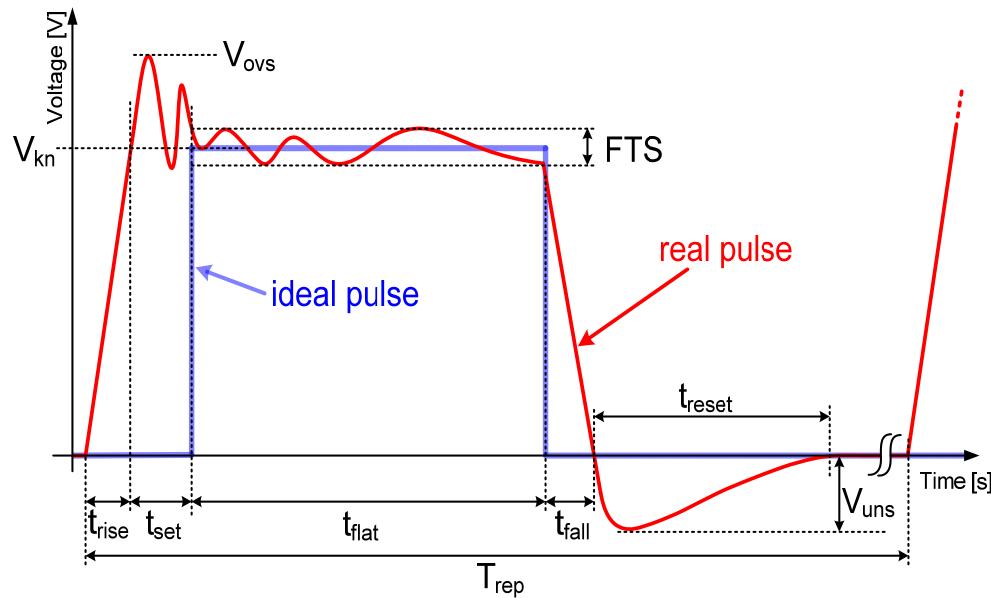
- Reminder:
 - Voltage applied to klystron \equiv Power consumption
...no matter if RF power is produced or not!

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)
 - Maximizing modulators voltage dynamics (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

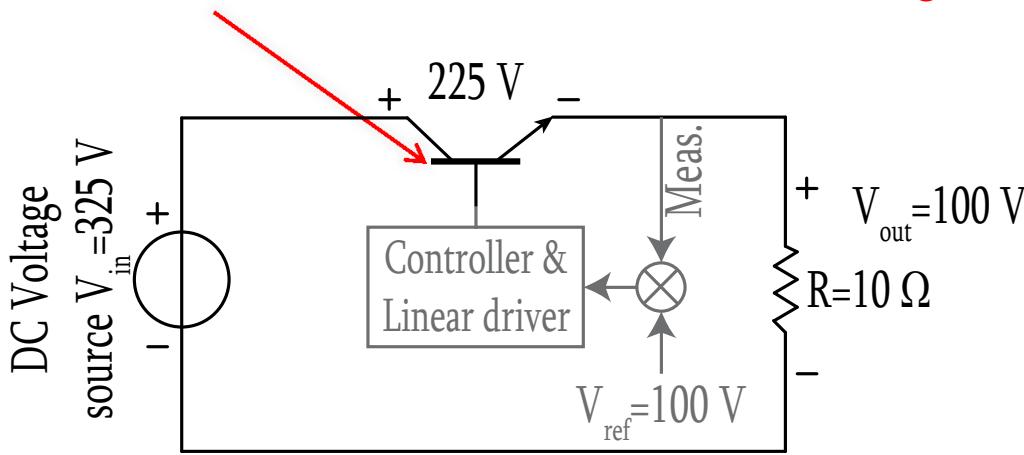
The efficiency-bandwidth-precision challenge

...first: a power electronics refresh

- 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:

$$P_{in} = 325 \text{ V} \times 10 \text{ A} = 3.25 \text{ kW}$$

$$P_{out} = 100 \text{ V} \times 10 \text{ A} = 1 \text{ kW}$$

$$P_T = P_{in} - P_{out} = 225 \text{ V} \times 10 \text{ A} = 2.25 \text{ kW}$$

Efficiency:

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

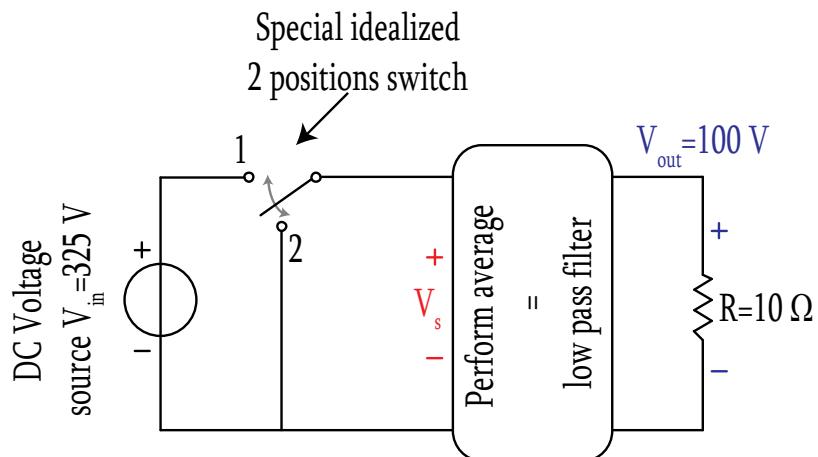
- Mainly used until 1960s (still used in special applications: audio, high precision, HF amplifiers, ...)
- Advantages: High dynamics, no ripple, no EMC issues
- Drawbacks: Low efficiency – size



Challenges of high dynamical performances

The efficiency-bandwidth-precision challenge

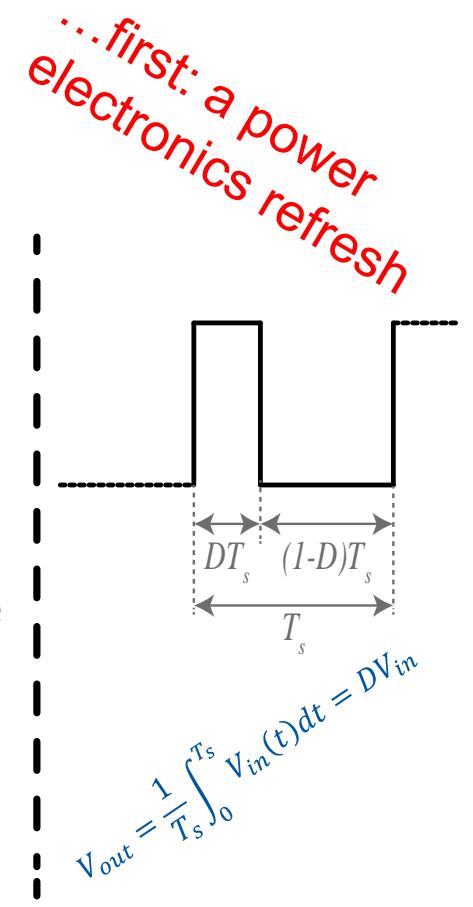
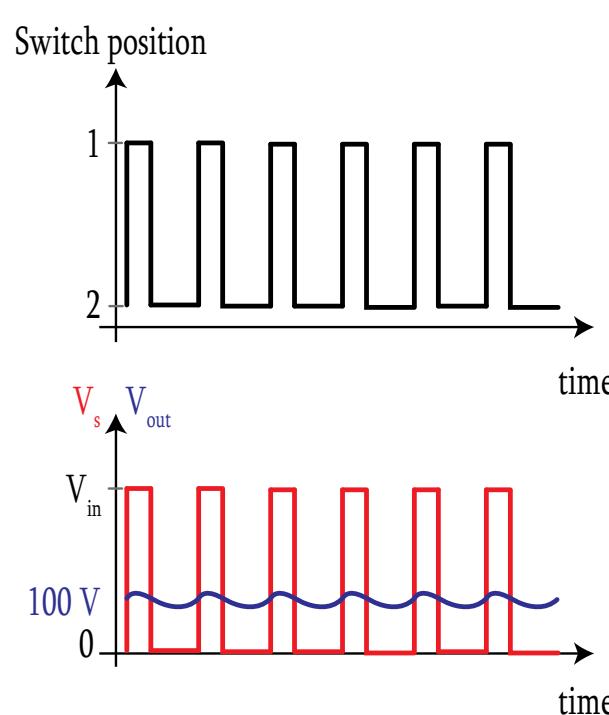
- Modern switching power converters



T_s : switching period

$f_s = 1/T_s$: switching frequency

D : duty cycle



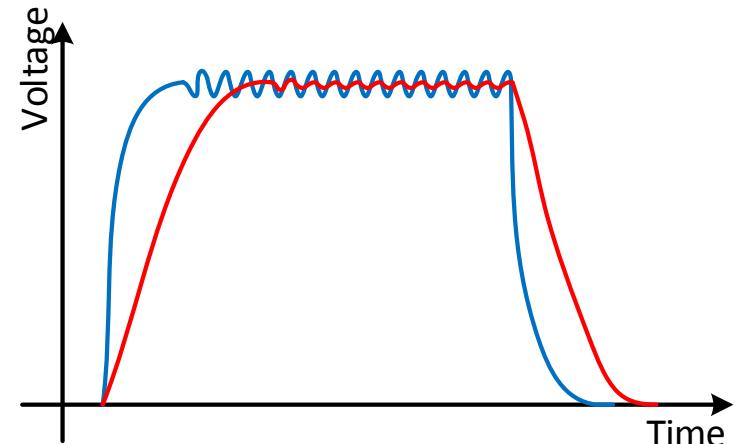
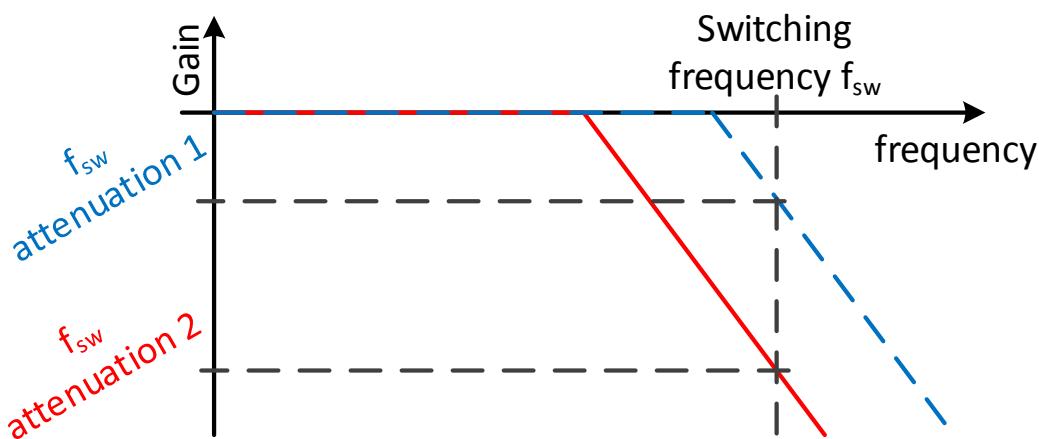
- Switches in their on or off states only
- Advantages: High Efficiency – smaller size
- Drawbacks: Lower dynamics, residual ripple, EMC issues



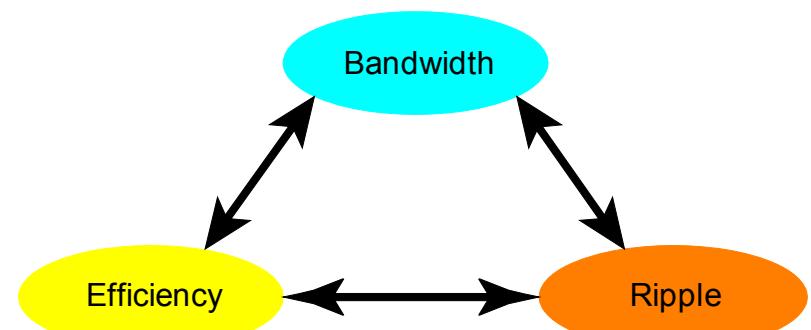
Challenges of high dynamical performances

The efficiency-bandwidth-precision challenge

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



- Higher dynamics \equiv 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

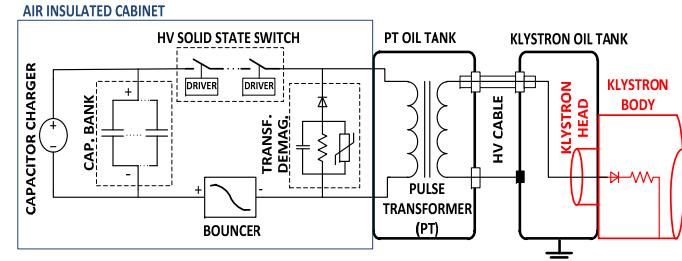


Topologies overview

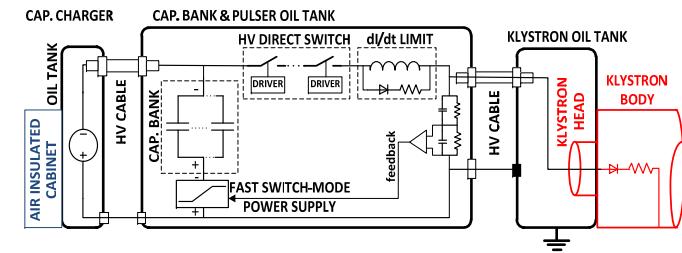
- What factors influence topology selection?
 - Output voltage & current levels
 - Output pulse precision (e.g. repeatability)
 - Reliability (components, insulation system, etc.)
 - Availability and MTTR (e.g. modularity)
 - Global modulator efficiency +

 - Utility grid specifications (voltage level, power factor, max. power fluctuation, 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

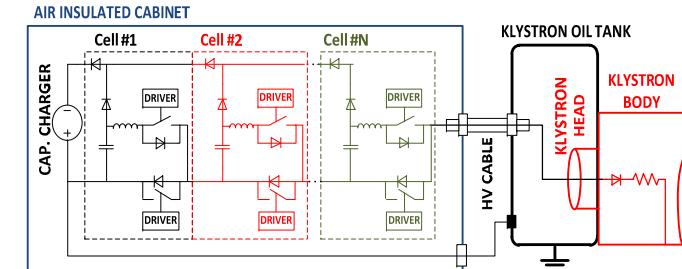
Transformed based (monolithic):



Transformed-less (direct switch):



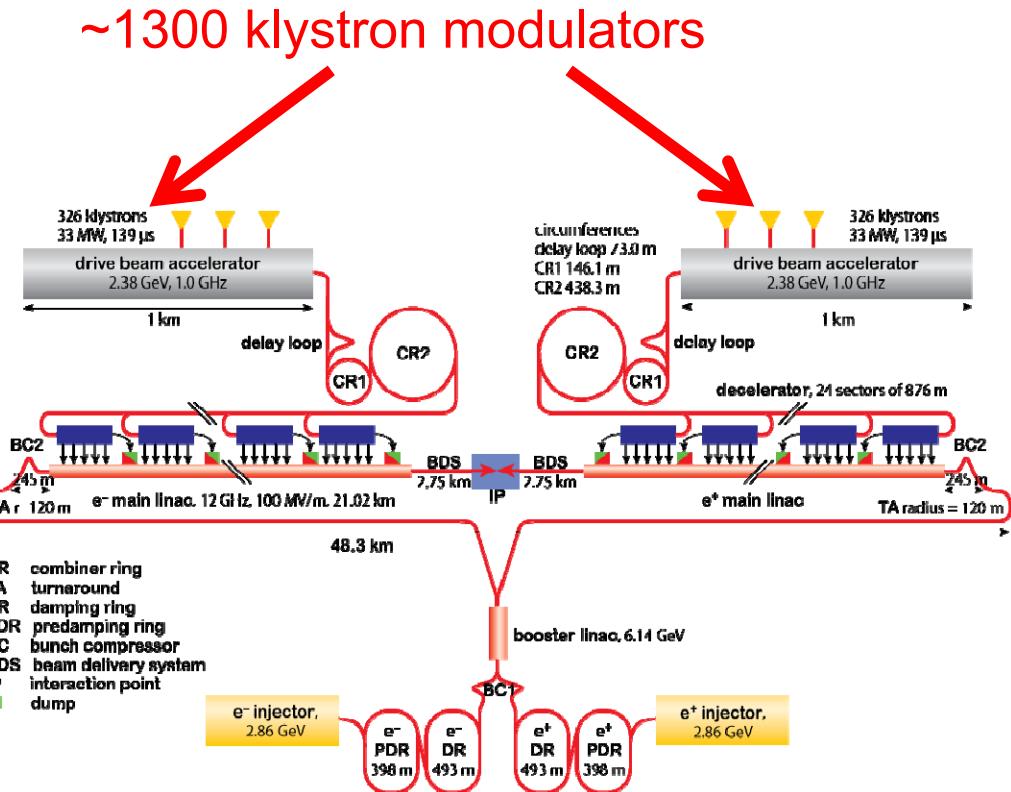
Transformed-less (Marx):



Design example for CLIC

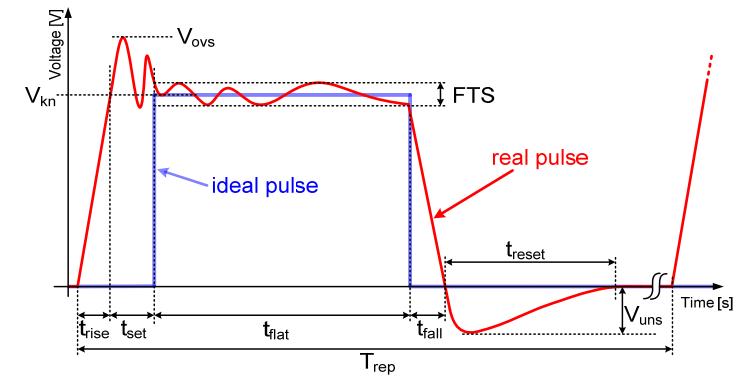
Specifications and challenges

- CLIC klystron modulators for the drive beam



~ 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	t_{rise}	3	μ s
Flat top length	t_{flat}	140	μ s
Repetition rate	Rep_r	50	Hz
Flat top stability	FTS	0.85	%
Pulse repeatability	PPR	10-50	ppm



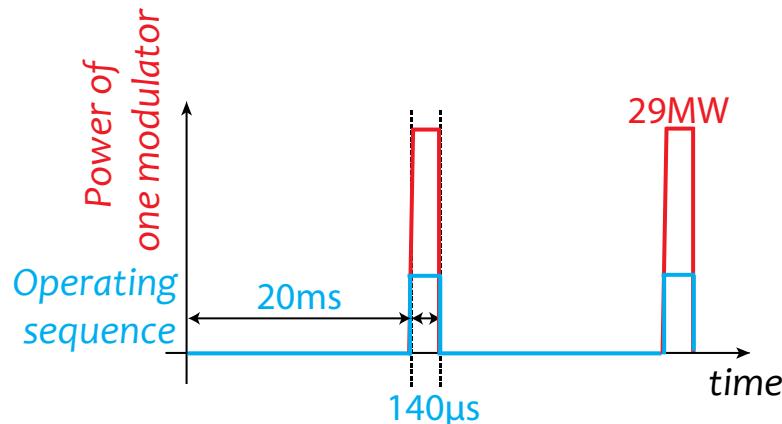
Design example for CLIC

Specifications and challenges

- The grid connection challenge

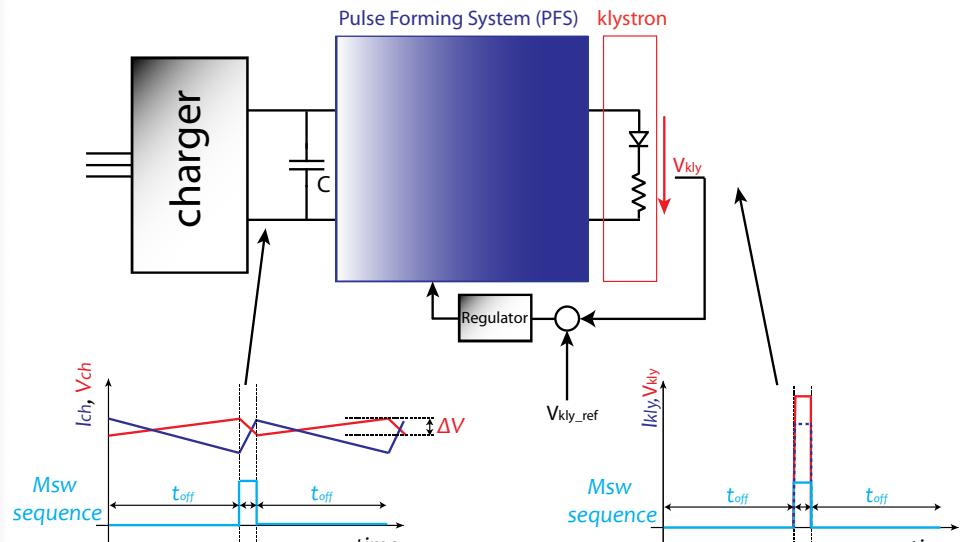
Simultaneous operation of all modulators

→ **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!



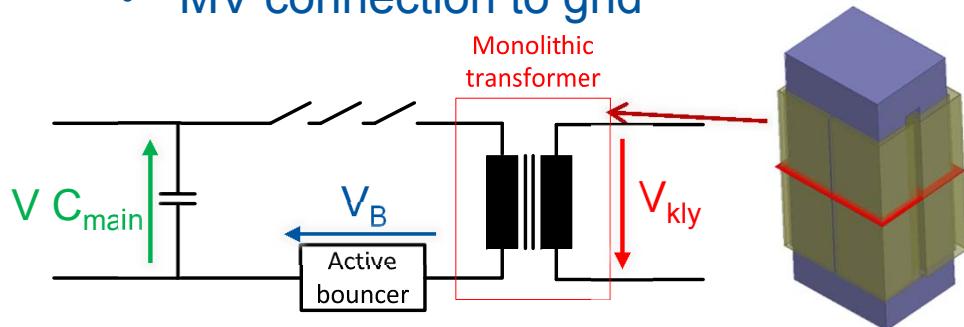
A solution consisting in high dynamics AFE to stabilize power ($V^*I=\text{const.}$)



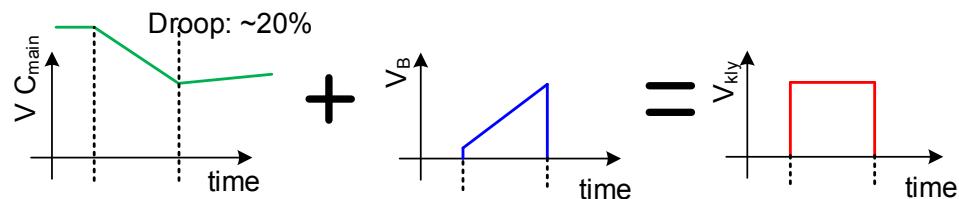
Design example for CLIC

A design solution based on pulse transformer

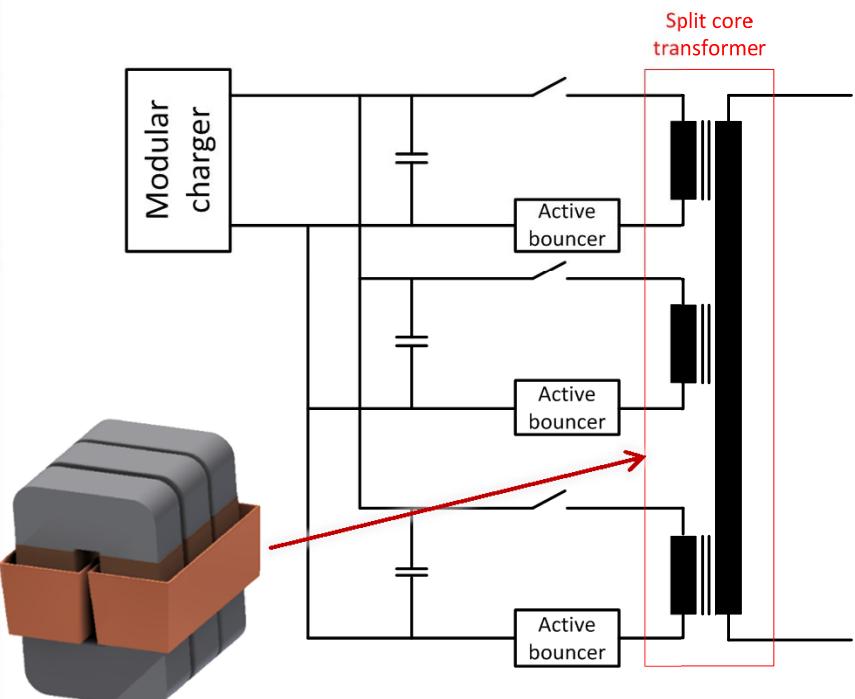
- Actually two topologies under study
- Monolithic pulse transformer
 - Series modularity / redundancy
 - MV connection to grid
- Split-core pulse transformer
 - Parallel modularity / redundancy
 - LV connection to grid



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



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

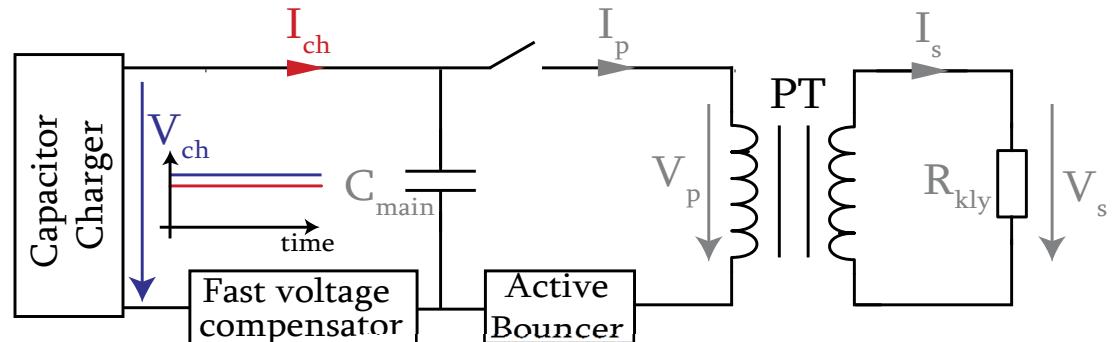


Design example for CLIC

A design solution based on monolithic pulse transformer

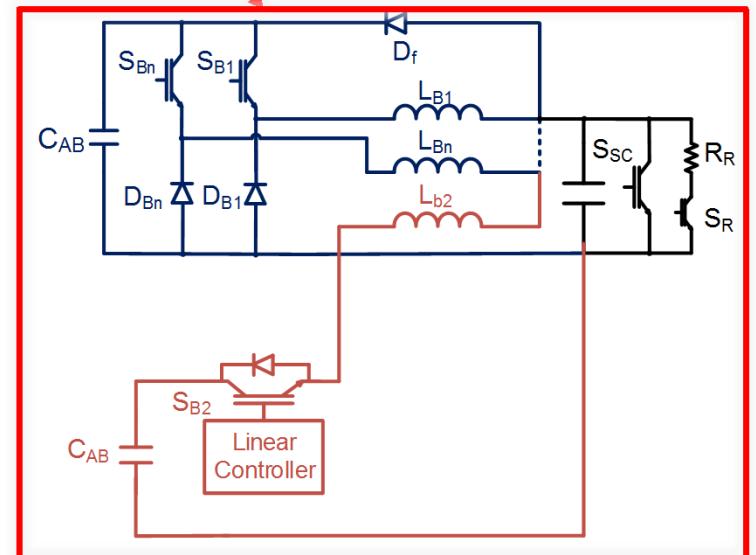
- Power electronics design

- Fast Voltage Compensator
 - Regulates $V_{ch} = \text{Const.}$
 - 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!



Design example for CLIC

A design solution based on monolithic pulse transformer

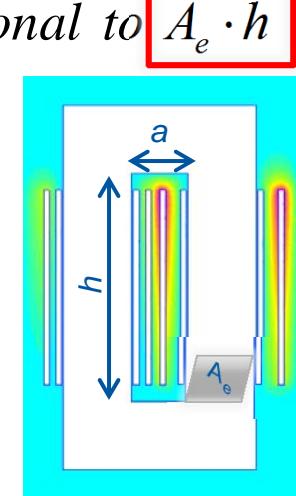
- Pulse transformer design problem
- For fixed magnetic & insulation materials (B_{sat} & E_{max}) Transformer core cross-section A_e & window height h mainly control output pulse rise-time t_{rise} & minimum overshoot OVS for fixed Peak Power P_{out} , Pulsed voltage V_{kn} & Flat top length t_{flat}

unity pulse damping factor ξ leads to $\frac{P_{out} \cdot t_{flat}}{B_{sat} \cdot E_{max}}$ proportional to $A_e \cdot h$

$$t_{rise} \text{ proportional to } \frac{t_{flat}(V_{kn} - V_{1n})}{B_{sat}} \times \frac{1}{\sqrt{A_e}}$$

- Minimum Pulse Transformer window width a imposed by insulation

$$\text{Transformer Core Volume} = A_e \cdot h + 2 \cdot a \cdot A_e$$

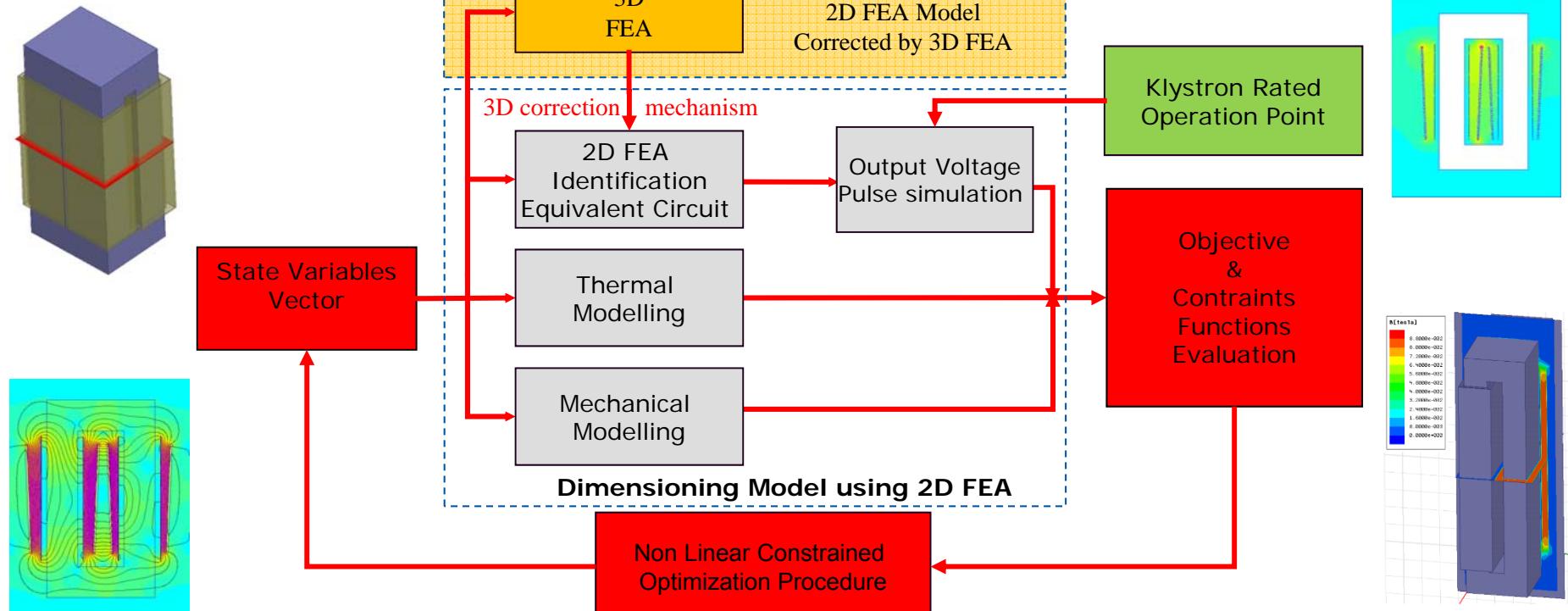


- Transformer size proportional to modulator peak output power & pulse flat-top length
- Transformer volume minimization for pulse rise-time & overshoot imposed by CLIC challenging requirements is the main design objective

Design example for CLIC

A design solution based on monolithic pulse transformer

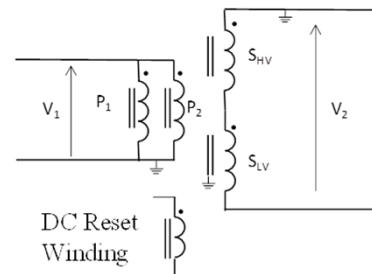
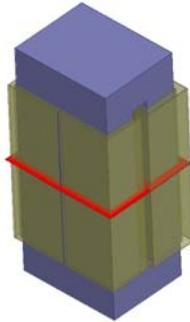
- Transformer CAD environment with global optimization
- Optimal design methodology based on inverse problem approach
- Equivalent circuit capacitances & Inductances directly identified from 2D & 3D FEA simulated tests



Design example for CLIC

A design solution based on monolithic pulse transformer

- Preliminary Design Example

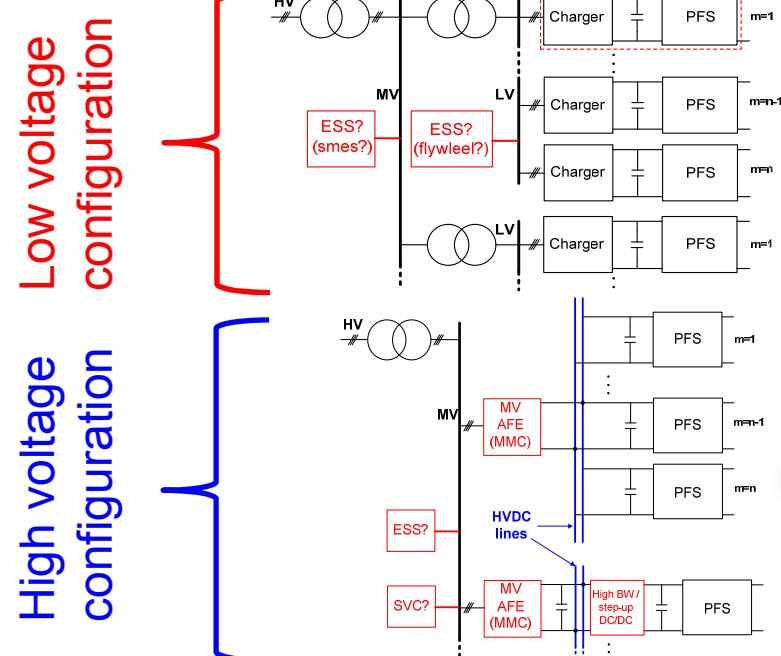


Transformer Characteristics		Transformer Material specifications	
Peak output power P_{out}	29 MW	E_{max} Insulation breakdown field	10 MV/m
Primary rated voltage V_{1n}	15 kV	Insulation relative permittivity	3
Secondary rated voltage V_{2n}	180 kV	Core Relative permeability	4000
Volume	0.069m ³	B_{max} Saturation flux density	1.15 T
Efficiency	> 99%		

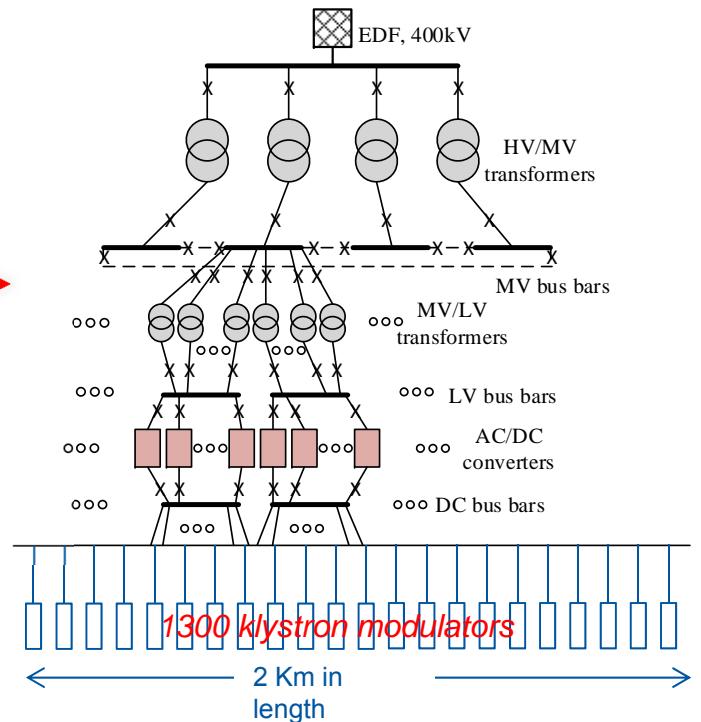
Design example for CLIC

A design solution based on pulse transformer

- The grid layout design problem
 - 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.



Solution
Most promising



Conclusion

- Efficiency is directly linked to dynamic performances
- Less efficient but highly dynamics power electronics solutions sometimes necessary
- Modulators topology choice is a global and complex process, no best topology, but an optimal solution adapted to each specific application
- Modulator global optimization methodology is mandatory: collaboration of designers from different domains is essential to achieve global efficiency



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