Modulators for DB klystrons: requirements and plans for developments

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Klystron parameters

Everything (for the modulator) starts here…

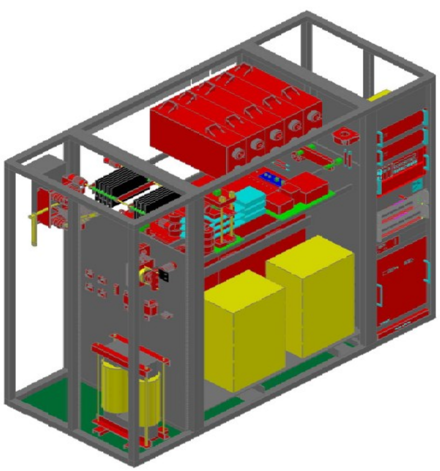
Peak power/klystron	15 MW
Train length after injection	140 μs
Repetition rate	50 Hz
Klystrons efficiency	65% (70% target)
Phase precision	0.05° @ 1 GHz (first 10% of the DB linac) 0.2° @ 1 GHz (next 90% of the DB linac)
Nb of klystrons (DB linac)	2x 819 = 1638

CW and Pulsed Modulators

Why a pulsed modulator?



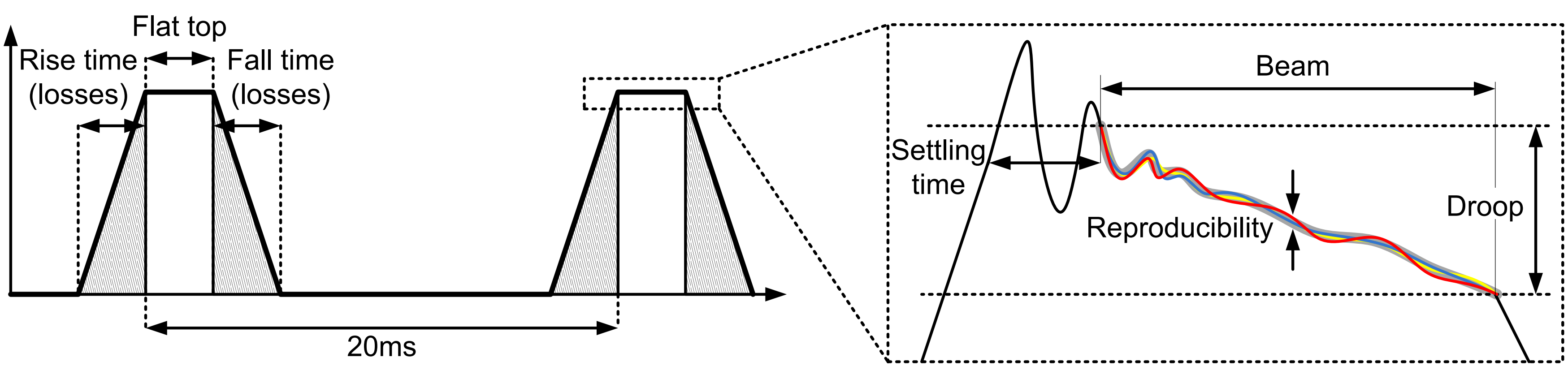

LEP 4MW CW Modulator: ~250 m^3
Average power: 4MW



LINAC4 5MW Pulsed Modulator: ~7 m^3
Average power: 20kW

Pulse parameters

- Rise time: needed to reach the requested voltage.
- Settling time: needed to damp oscillations within the droop window.
- Droop: window in which remaining reproducible oscillations can be cancelled by RF feed-forward.
- Reproducibility: maximum difference allowed between two consecutive pulses.
- Fall time: time for voltage to return to zero.



Specifications overview

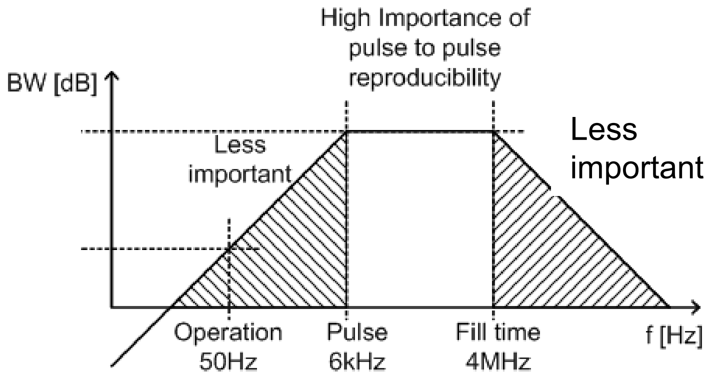
Where	**Type**	**Pulse length**	**frequency**	**Dc voltage**	**Mean power**	**Peak power**	**Droop**	**Precision / reproducibility**
J-Park	HV-thyristor			80kV			10%	
Desy (XFEL)	Pulse transformer	2.3ms	10Hz	120kV	400kW	16.8MW		
SLAC (ILC)	Marx	1.6ms	5Hz	120kV	135kW	16.8MW	1.25%	0.5%
SNS	Resonant	1.6ms	60Hz	140kV	1MW	9.8MW	6%	
KAERI	Resonant	1.5ms	50Hz	105kV	500kW	5.6MW	20%	
DTI	Direct switch	2ms	50Hz	110kV	1MW	9.8MW	5%	
Karlsruhe	SMES	1.7ms	10Hz	130kV	1MW	25MW		0.5%
HP-SPL	*Pulsed*	*1.6ms*	*50Hz*	*110kV*	*210kW*	*2MW*	*1%*	*0.1%*
ESS	*Pulsed*	*2ms*	*20Hz*	*135kV*	*250kW*	*6.2MW*	*3%*	*0.1%*
CERN (LINAC4)	Pulsed	1.8ms	2Hz	100kV	18kW	5MW	1%	0.1%
CLIC	*TBD*	*0.14ms*	*50Hz*	*150kV*	*250kW*	*15MW*	*0.85%*	*0.001%*

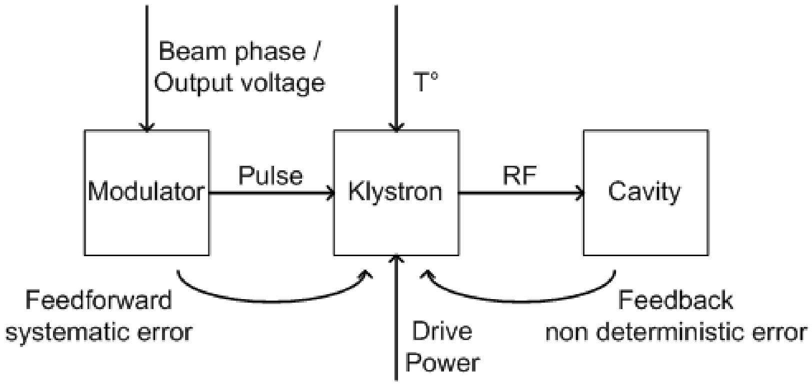
Impact on efficiency

Impact on measurement

CLIC measurement requirements

- RF feed-forward control takes care of modulator harmonics, voltage droop and other systematic errors. 10^{-3} accuracy needed on the voltage at the beginning of the pulse.
- RF feed-back control takes care of low frequencies errors (eg temperature drift, calibration, etc)
- At higher frequencies, precision is less important due to natural machine filtering.
- “by design” 10^{-5} pulse to pulse reproducibility precision required between 6kHz and 4MHz for the first 10% of the DB linac (else $4 \cdot 10^{-5}$).





High precision measurements

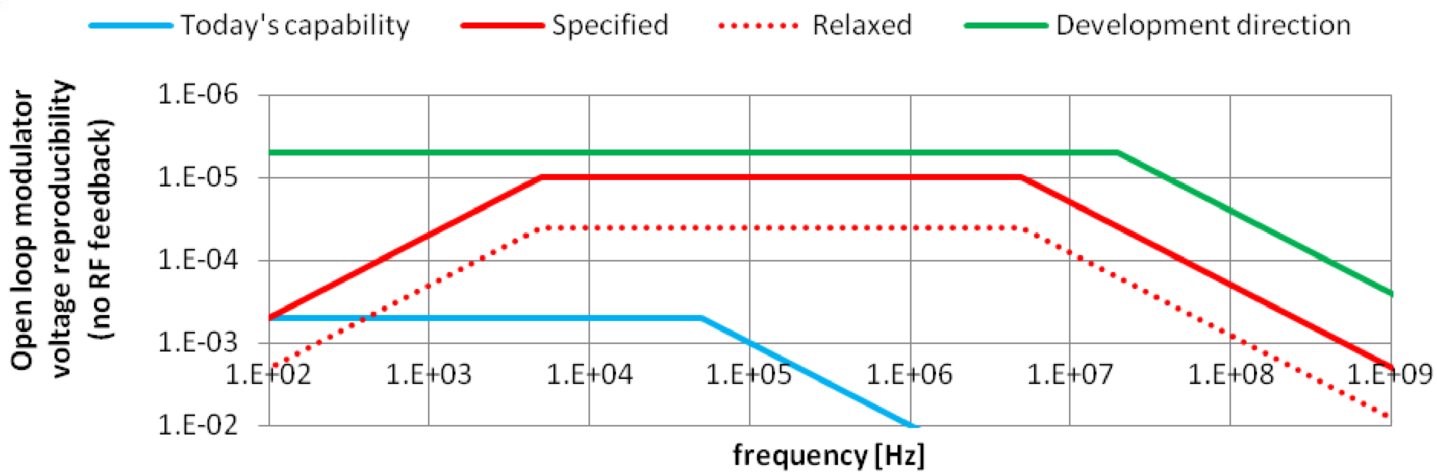
A pulsed high-voltage measurement R&D program for Linac 4 started in 2008.

Today's capability with pulsed 110kV:

- Accuracy: 10^{-3}
- Stability: 10^{-3}
- Reproducibility: $5 \cdot 10^{-4}$
  - $<10^{-5}$ needed
- Bandwidth: 100ksamples/s
  - Up to 10Msamples/s needed

- **R&D effort required on test and measurement capabilities.**

Pulsed HV measurements



If measurement performance does not exceed the red line, performance cannot be demonstrated.

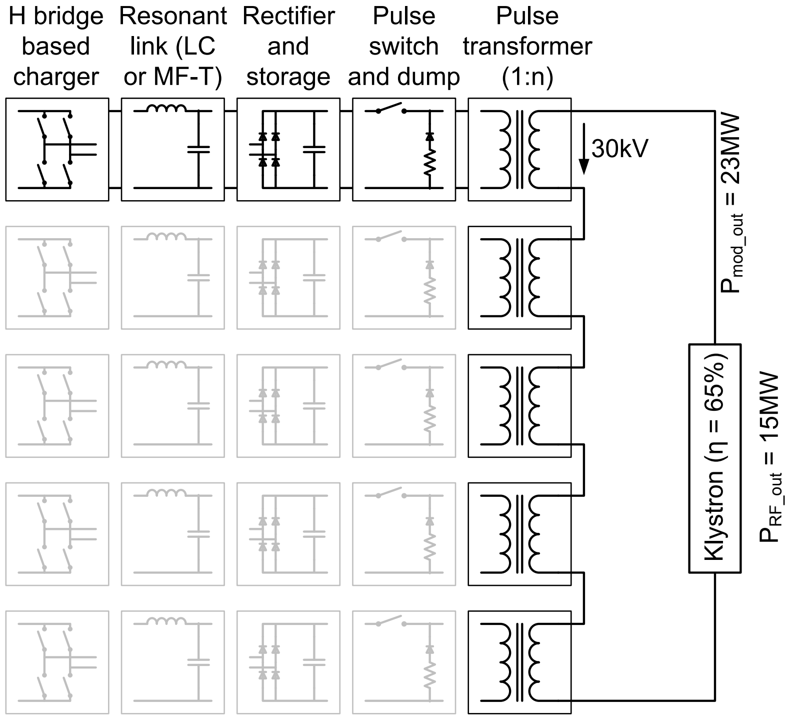
Between the red and green lines, performance can be measured and sorted to meet requirements.

If measurement performance exceeds the green line, feedback on the output voltage may be implemented to fulfill the specification (provided that a 300A/5MHz active voltage compensation can be implemented!)

- **The use of indirect high bandwidth measurement on RF phase to implement a fast in-pulse feedback on the modulator voltage and/or on the klystron RF-input modulation must be studied in parallel.**
- Strongly recommend that phase reproducibility must not rely ONLY on modulator performance.

Modular approach

- Considering the large number of modulators, a modular failure tolerant system is needed to guarantee a reasonable machine availability.



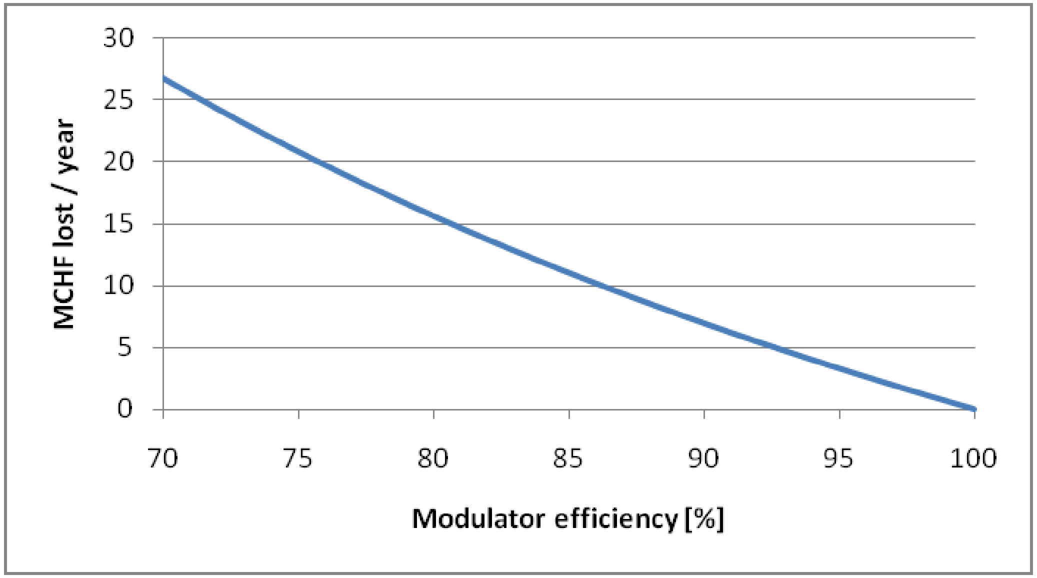
For example:

- Modular approach based on a 'classic' modulator
- Need to design a fast enough pulse transformer

- **R&D of appropriate topologies started in 2011 (1/2 fellow).**
- **External collaborations will also participate.**

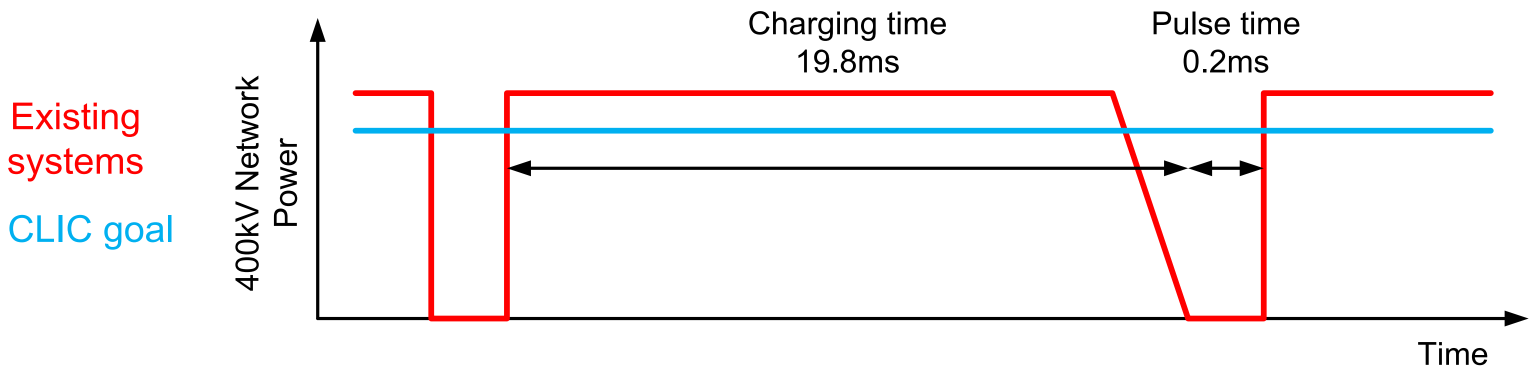
Efficiency

- With more than 250MW of useful electrical power to feed the drive beam injector klystrons, modulator efficiency is a key parameter of CLIC overall consumption.
  - modulator efficiency = useful power provided to the klystron/power consumed from the grid
- Considering 0.051CHF/kWh (2010 price) and 5000 hours of physics / year, several MCHF can be “dissipated” in the modulators depending on the efficiency.



Power from network

- Modulator charging is usually stopped before the output pulse generation.
  - Induces large power transients on the 400kV network and can affect grid stability and quality.
- Studies of methods to assure a constant power load to the grid have begun.



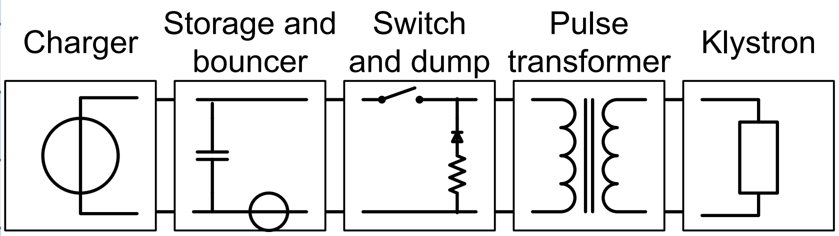
- Other issues will also to be considered (eg how to manage modulator power shutdown, finding optimal charger efficiency, etc).

- **R&D started in 2011 (1 fellow).**

Pulse transformer approach

- Known technology with a charger linking the grid to the capacitor banks, a high voltage switch and a pulse transformer to step-up the voltage.
- Inherent good reproducibility (depending on transformer characteristics).
- The 5µs settling time assumes (not yet proven) that most of the oscillations are reproducible and can be compensated by low level RF.
- Rise and fall time are estimated to be 20µs which are due to the pulse transformer dynamic response. Faster response could be achieved but would lead to a significant increase of pulse transformer volume and cost.

Useful flat-top Energy	22MW*140µs = 3.08kJ
Rise/fall time energy	22MW*20µs*2/3= 0.29kJ
Settling time energy	22MW*5µs = 0.11kJ
Main switch losses	150kV*150A*1µs/3=0.01kJ
Pulse forming system efficiency	0.97
Charger efficiency	0.90
Overall Modulator efficiency	**77%**



- **R&D to be started in 2011 (external collaborations).**

Semiconductor approach

- Alternative technologies where the capacitor bank is directly connected to the klystron through an active switch.
- Removing the pulse transformer significantly reduces the rise time.
  - Technical difficulties to create a reliable switch operating at 150kV
  - SLAC has been developing a solid-state Marx approach for the ILC requirements (1.6ms pulse, 5Hz).
- Topologies using an all semiconductor approach will be evaluated for the CLIC DB modulator requirements.
- The 5µs settling time assumes (not yet proven) that most of the oscillations are reproducible and can be compensated by low level RF.

Useful flat-top Energy	22MW*140µs = 3.08kJ
Rise/fall time energy	22MW*1µs*2/3= 0.01kJ
Set-up time energy	22MW*5µs = 0.11kJ
Main switch losses	150kV*150A*1µs/3=0.01kJ
Pulse forming system efficiency	0.99
Charger efficiency	0.90
Overall Modulator efficiency	**85%**

MARX
Modulator
G.E. Leyh

- **R&D to be started in 2011 (external collaborations).**

R&D external collaborations

- Maximise charger efficiency and power quality
  - **Objective**: better than 90% efficiency with constant power consumption
- Minimise rise, fall and settling time
  - **Objective** for 140us pulse: less than 10us total for rise, fall and setup time
- Maximise operational reliability and availability
  - **Objective**: design for 100% availability assuming interventions every 14 days
- Guarantee exceptional pulse-to-pulse voltage reproducibility
  - **Objective**: 10^{-5} (10ppm) from $pulse_{n-1}$ to $pulse_n$ (RF feedforward gives long term performance)
- Optimise volume
  - **Objective**: mechanical implementation compatible with one system every 3m

Tentative Milestones	Year
Invite proposals and select partners	2011
From submitted studies, select at least one topology for prototyping	2012
Begin construction of full scale prototypes	2014
Deliver up to 3 validated full scale modulator prototypes	2016

R&D Summary

Goal	resources	Risk	Impact on
Measure 150kV reproducibility to 10ppm with high bandwidth	**1 new fellow needed**	**5/5**	**PETS efficiency → luminosity**
150kV modulator topologies with exceptional efficiency, availability and reproducibility	**External collaborations** 0.5 fellow, started in 2011	5/5	Power consumption / cost
Constant power and operational scenarios for the 400kV network	1 fellow, started in 2011	1/5	Network quality

- Test facilities for Drive Beam powering not yet considered.
- High precision measurement validation system to be implemented in collaboration with RF / CTF3.