Long Pulse Modulators

The CERN Accelerator School

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CERN Accelerator School
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HELMHOLTZ GEMEINSCHAFT

DESY

Structure

- Why long pulses?
- Where are long pulse modulators used?
  - Basics
  - RF-Station
  - Klystron
- Modulators
  - Passive components
  - Active components
- Connection to the mains
- EMI aspects
- Next developments

Why long pulses?

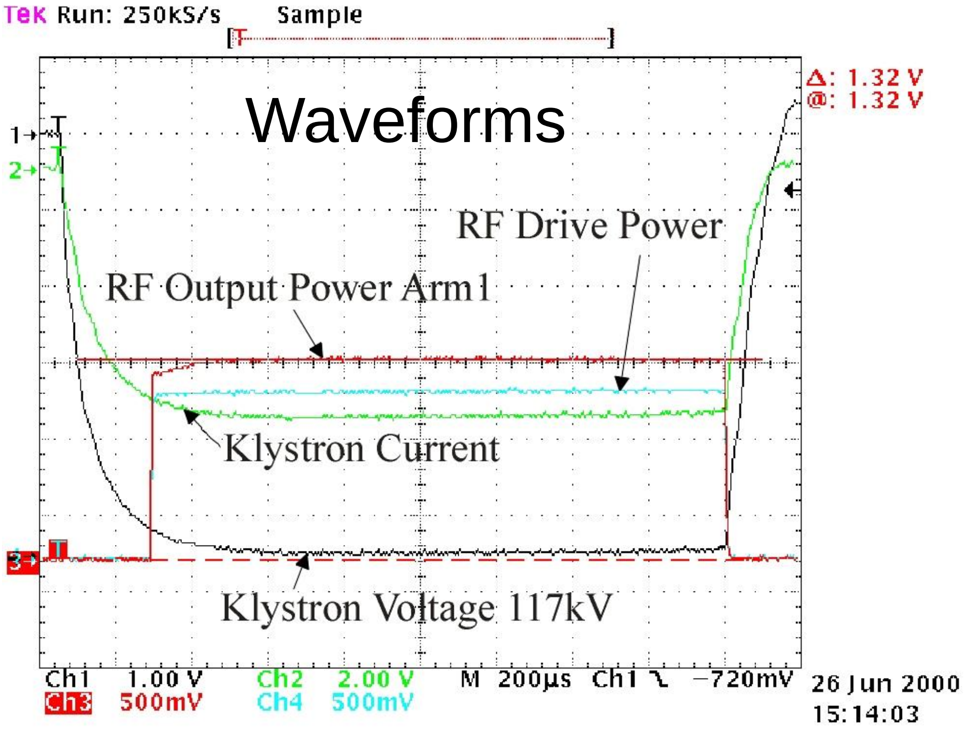
- At DESY the start of investigating long pulse modulators began with the R&D of superconducting cavities in the early 90th at the TESLA Test Facility. (Superconducting linear accelerator facility).

- Since the cavities cannot withstand this this power in CW the machine is pulsed.

- The cryo system is not able to cool this down.

- The pulse duration is determined by:
  - The modulator voltage has a rise time of 200 – 300 µs
  - A superconducting cavity has a loading time of about 500 µs.
  - The bunch train of particles should be around 800 µs.
- The design aim was defined to be 1.7 ms.

The first modulators built by FNAL



First modulator was commissioned in 1994

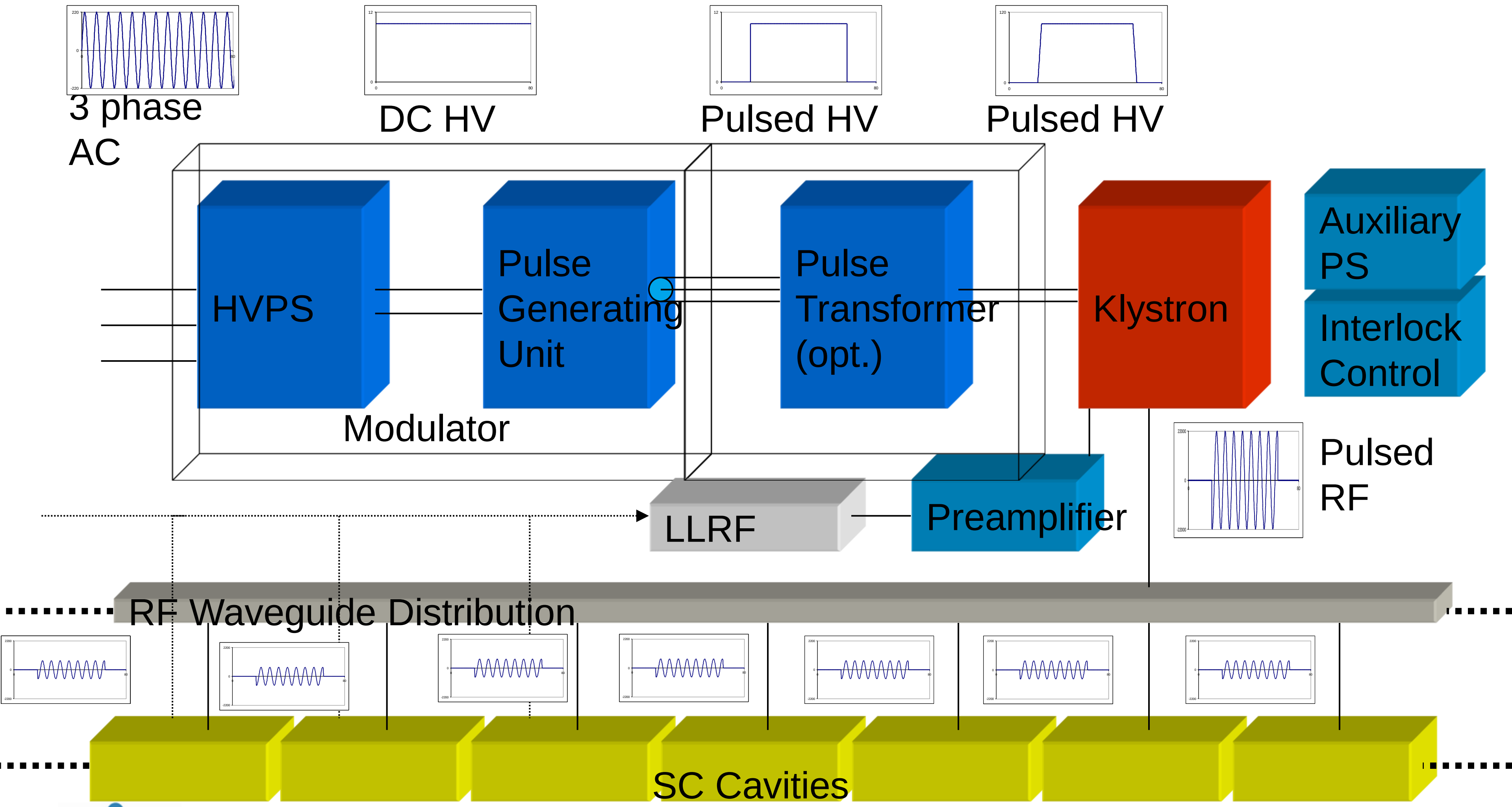
FNAL Modulator at TTF

Basics of modulator

- The units producing the pulsed power are called modulators.
- The modulator takes power from the grid and delivers HV-pulses to the load.
- The modulator is part of an RF-station.
- During the pulse the power is up to several MW
- The average power of a modulator is low in comparison to the pulsed power.
- Pulse width is up to several milliseconds (e.g. XFEL 1.54ms, ESS 3.5ms, SNS 1.35ms).

Where are modulators used?

XFEL RF Station Components

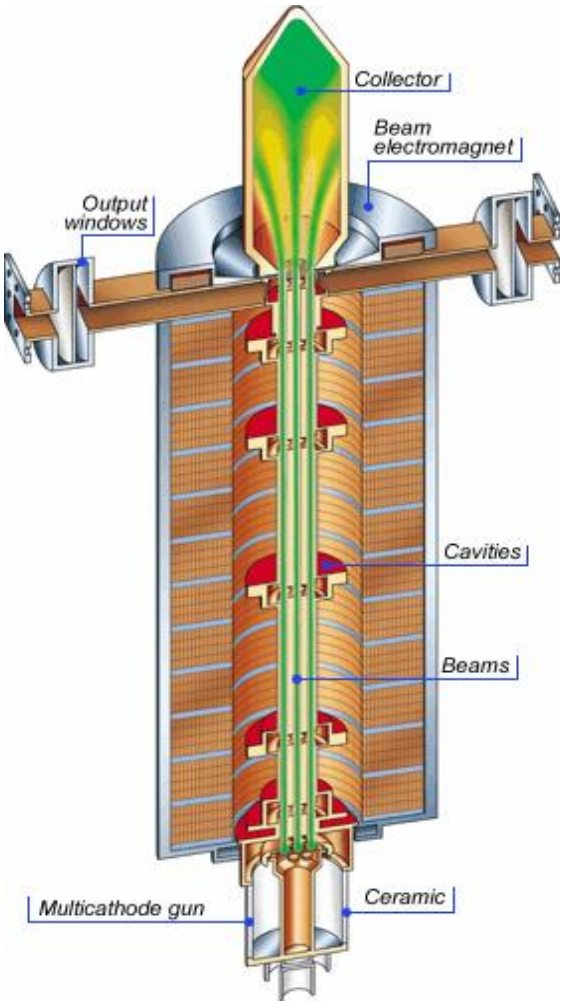


Courtesy Stefan Choroba

Load

- The modulator is part of an RF-Station
- The usual load is a klystron.
- The klystron is a linear-beam vacuum tube. It is used to amplify RF-signals.
- Low RF-power is introduced, high RF-power is taken from the klystron to feed the cavities

Klystron Principle



•The cathode is heated by the heater to ~1000°C.
•The cathode is then charged (pulsed or DC) to several 100kV.
•Electrons are accelerated form the cathode towards the anode at ground, which is isolated from the cathode by the high voltage ceramics.
•The electron beam passes the anode hole and drifts in the drift tube to the collector.
•The beam is focused by a bucking coil and a solenoid.
•By applying RF power to the RF input cavity the beam is velocity modulated.
•On its way to the output cavity the velocity modulation converts to a density modulation. This effect is reinforced by additional buncher and gain cavities.
•The density modulation in the output cavity excites a strong RF oscillation in the output cavity.
•RF power is coupled out via the output waveguides and the windows.
•Vacuum pumps sustain the high vacuum in the klystron envelope.
•The beam is finally dumped in the collector, where it generates X-rays which must be shielded by lead.

Typical data of available klystrons

> Klystron today

Frequency Range:	~350MHz to ~17GHz XFEL 1.3 GHz
Output Power:	CW: up to ~1.3MW Pulsed: up to ~200MW at ~1μs up to ~10MW at ~1ms
Klystron Gun Voltage:	DC: ~100kV Pulsed: ~600kV at ~1μs ~130kV at ~1ms

Electrical behavior of a klystron

- The relation of current to voltage is

$$I = \mu P * U^{3/2}$$

  - The µperveance is a parameter of the klystron gun. This is determined by the geometry and fixed for the klystron, U= klystron voltage, I is the klystron current

- Beam power

$$P_{Beam} = \mu P * U^{5/2}$$

- RF power

$$P_{RF} = \eta P_{Beam}$$

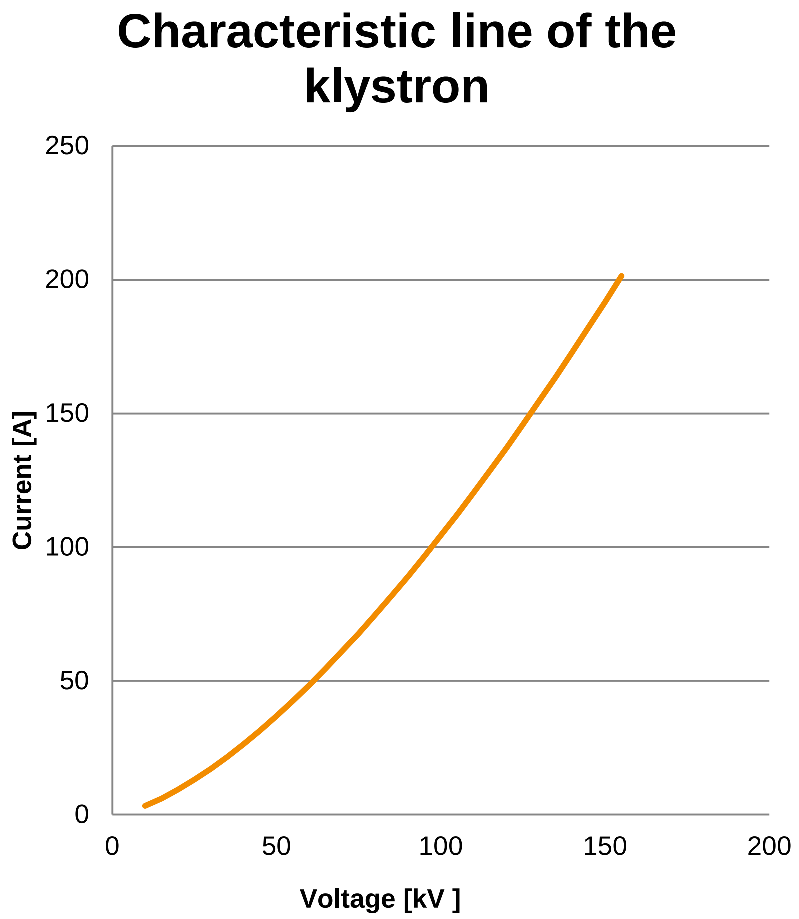
  - η is the efficiency of the klystron

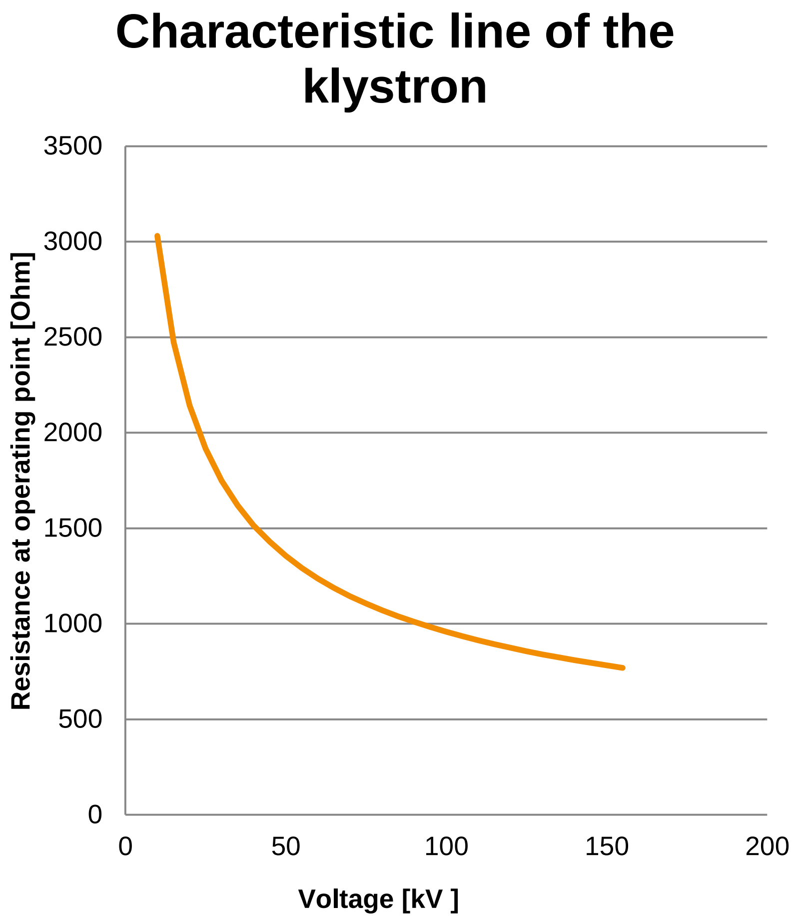
Multi Beam Klystron THALES TH1801 (1)
for further examples the data of this klystron is taken

Electrical data:

Cathode Voltage:	117kV
Beam current:	131A
μPerveance:	3.27
Electrical resistance:	893 Ω @ 117 kV
Max. RF peak power:	10MW
Electrical power:	15.33 MW
RF Pulse duration:	1.5ms (1.7 ms max)
Repetition Rate:	10Hz
Efficiency:	65 %
RF Average Power:	150kW
Average electr. power :	230 kW

Electrical behavior of the klystron



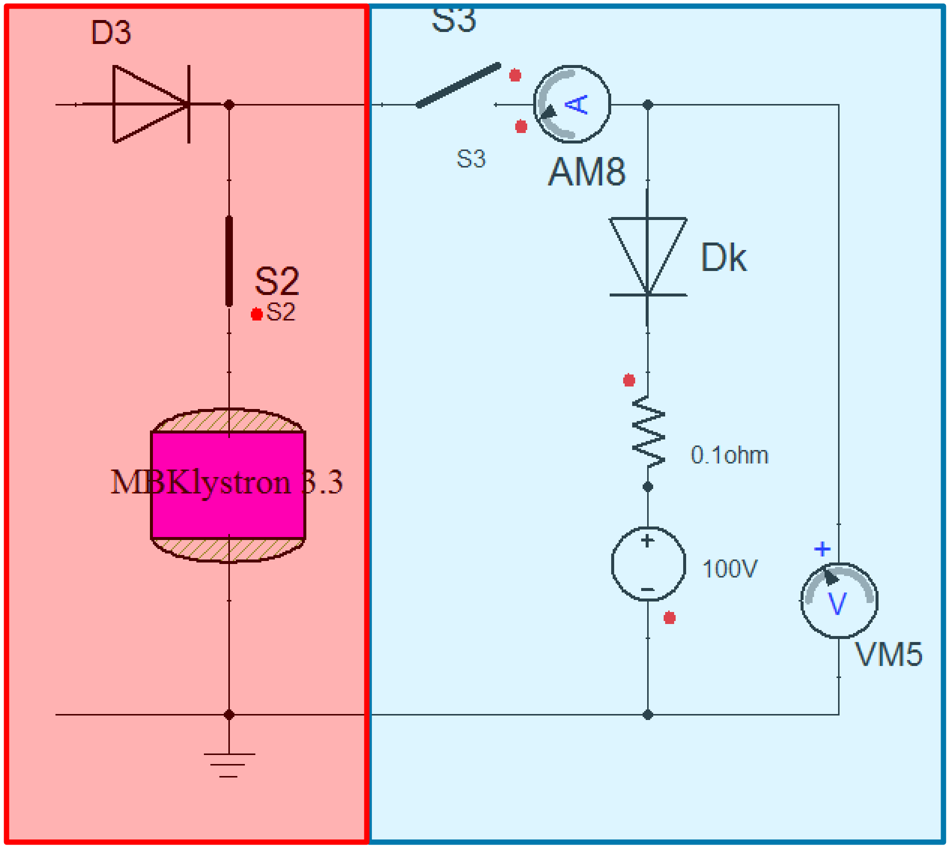


In a simulation this can be simulated as a resistor with a diode in series at the working point, or better as resistor with the characteristic line

Arcing of a klystron

- During operation of a klystron arcs inside occur. In this case the HV collapses to the burning voltage of the arc.
- In case of an arc only 10 – 20 J are allowed to be deposited in the klystron. More energy would damage the surfaces in the klystron.
- The modulator has to protect the klystron.
  - The energy supply has to be interrupted.
  - The energy that is stored in the devices has to be dissipated by the help of extra equipment.
- The model of the arc is a series combination of a voltage source of 100 V and a resistor for the current depending part. This resistor is assumed as 100 mΩ.

Electrical equivalent circuit of the klystron



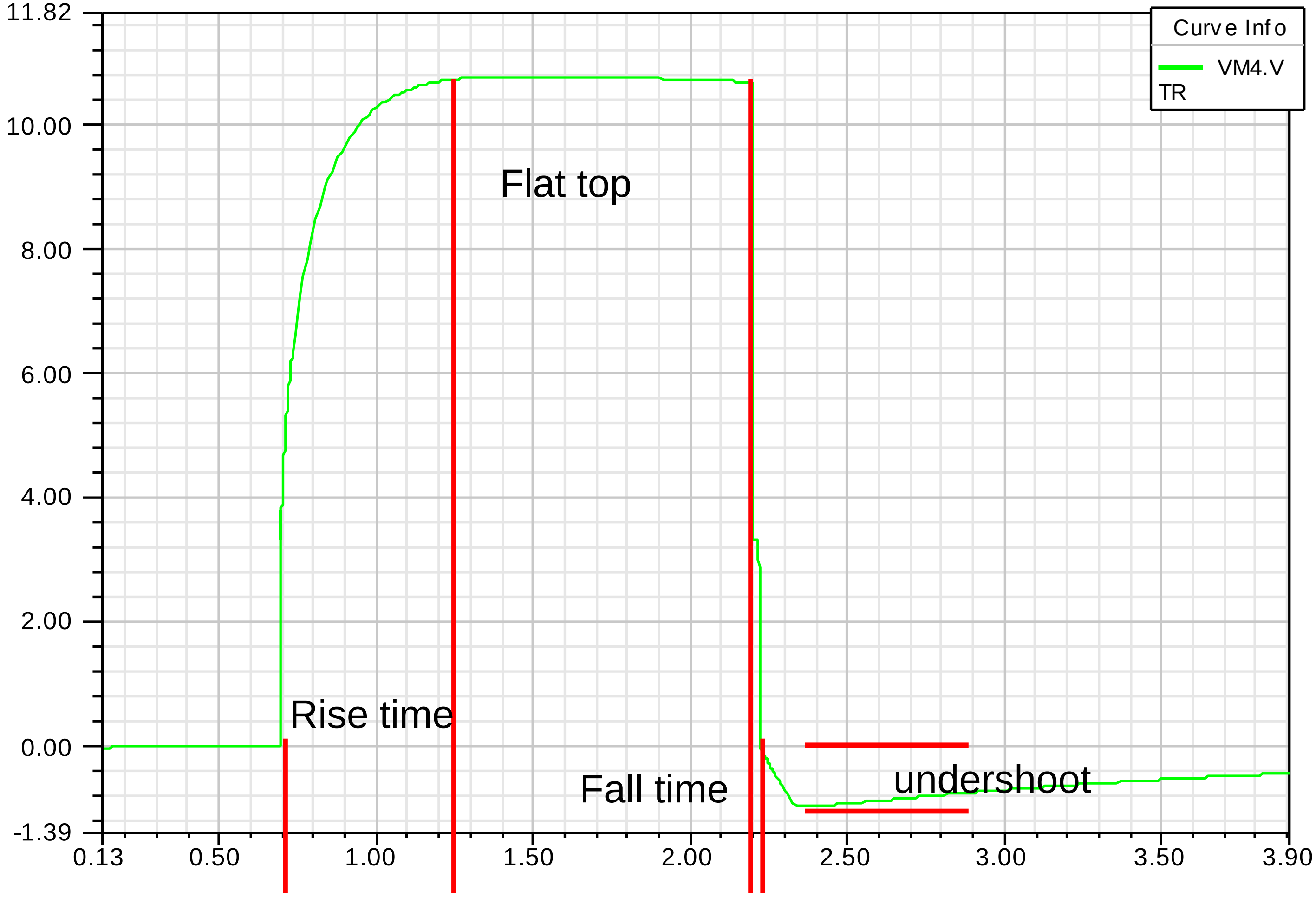
Resistor with characteristic line

Arc simulation

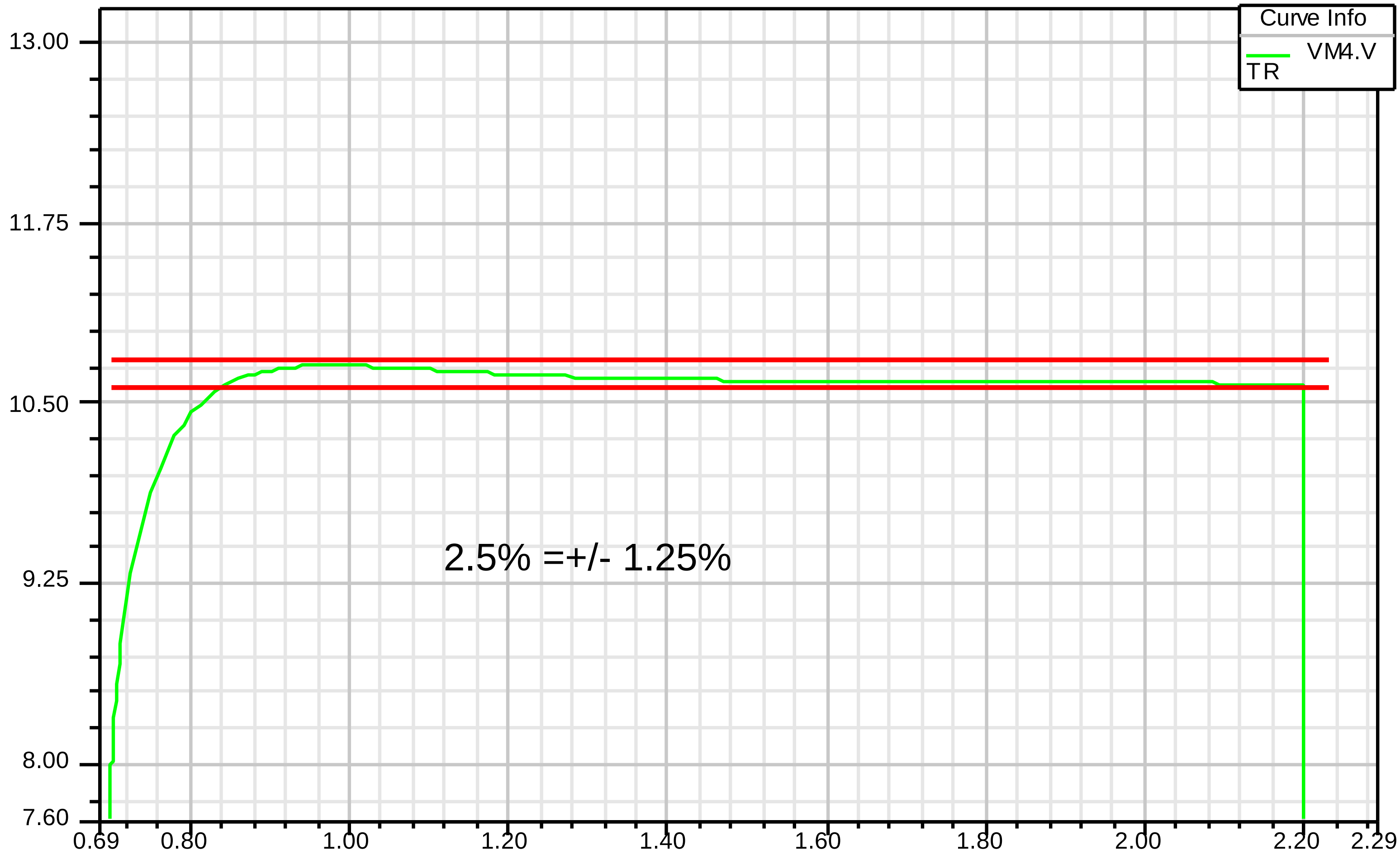
Definition of the pulse

> Rise time	time from the beginning up to the flat top, often it is defined as 10% to 90 or 99%
> Flat top	time when the pulse is at the klystron operation voltage, variations lead to RF-phase shifts that have to be compensated by the LLRF. The flat top is defined as +/- x% of the voltage
> Fall time	Time the modulator voltage needs to go down
> Reverse voltage	undershoot allowed neg. voltage (about 20%)
> Repetition frequency	Frequency of pulse repetition
> Pulse to pulse stability	Repetitive value of the flat top.

Definition

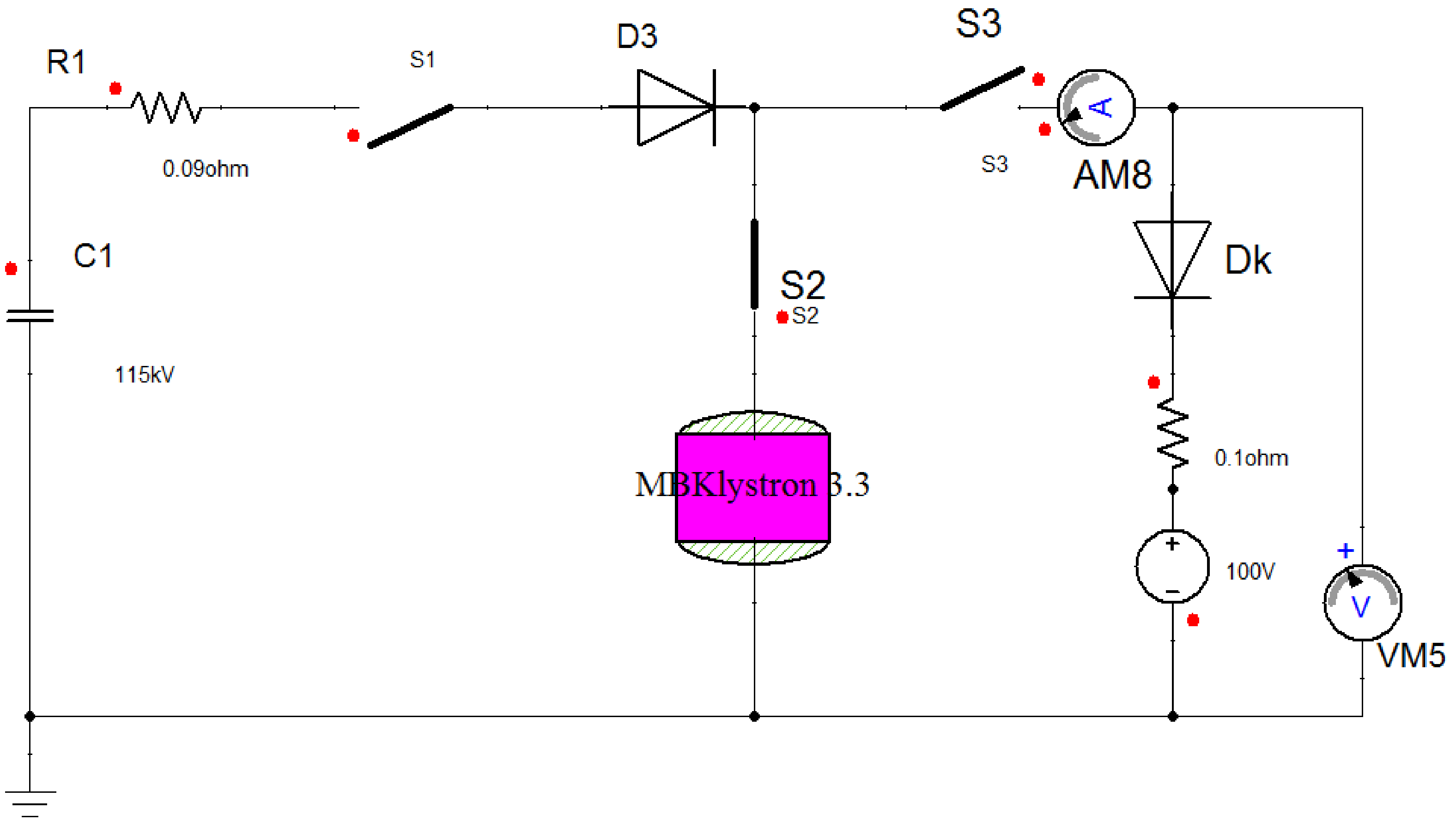

11.82
10.00
8.00
6.00
4.00
2.00
0.00
-1.39
0.13
0.50
1.00
1.50
2.00
2.50
3.00
3.50
3.90
Curve Info
VM4.V
TR
Flat top
Rise time
Fall time
undershoot

Flatness of the pulse



Modulator basics
start with the pulse forming unit

Direct switching



Series switch modulator

Advantage

- Simple design on schematic
- Only few components

Disadvantage

- High voltage at Cap-bank
- Very few suppliers of switches
- Has to operate under oil
- High stored energy

Size of Capacitor

Pulse-Flatness = 0.5 %, exponential decay, XFEL requirements

$$U = U_0 * e^{-\frac{t}{RC}}$$

$$\Delta U = 0.5\% = 0.005$$

$$0.995 = e^{-\frac{t}{RC}}$$

$$\ln(0.995) = -t/RC$$

$$C \ = -t/(R \ln(0.995)$$

With U_0= 115 kV, R= 900 Ω, t=1,7ms

$$C \ = 377 \ \mu F$$

Energies

Pulse energy simplified to rectangular wave form

$$E_{pulse} = U * I * t = \frac{U^2}{R} * t$$

$$E_{pulse} = \frac{115\ kV^2}{900\Omega} * 1{,}7\ ms$$

$$E_{pulse} = 24{,}98\ kJ$$

Stored energy in the capacitor

$$E_{stored} = \frac{1}{2} * C * U^2$$

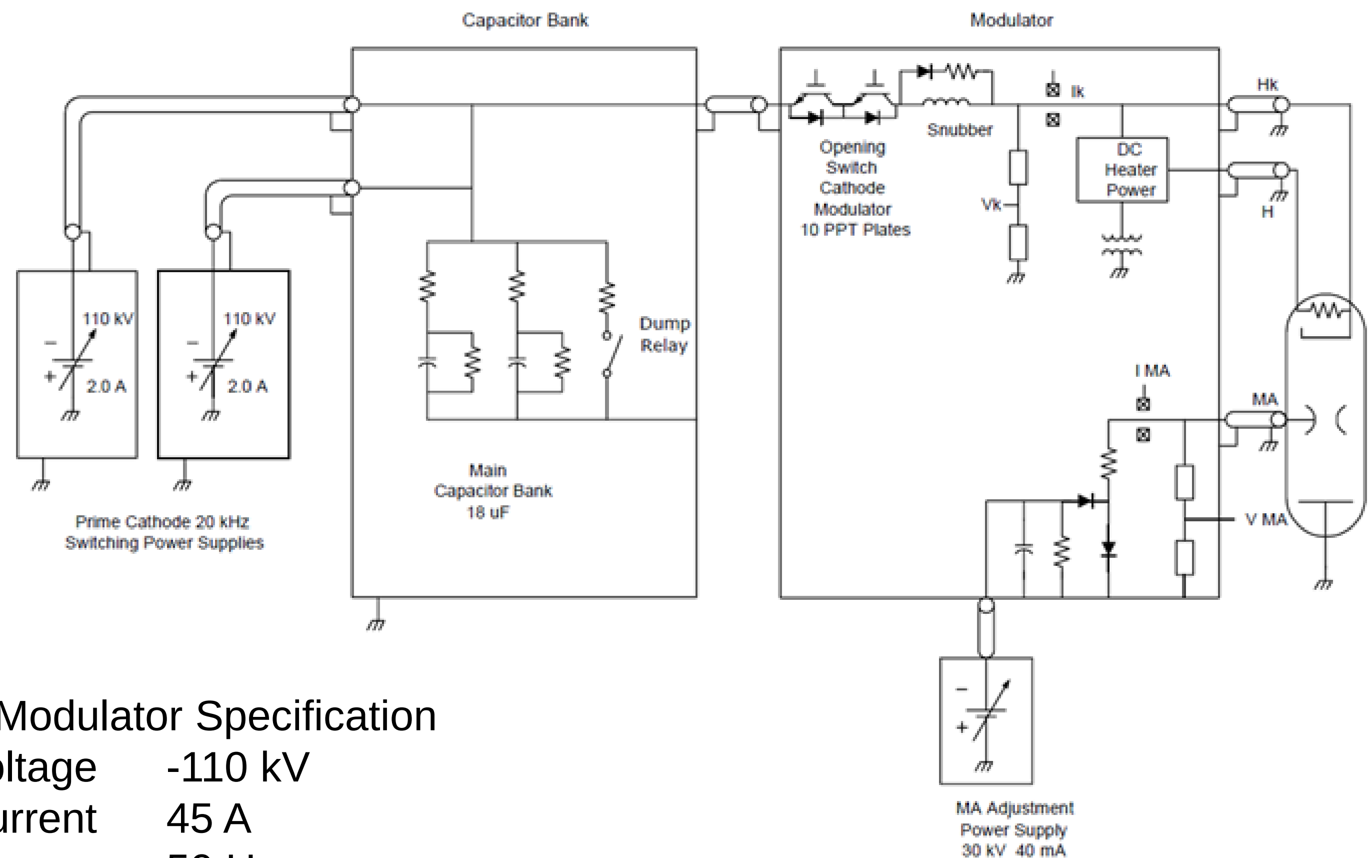
$$E_{stored} = \frac{1}{2} * 377\mu F * 115kV^2$$

$$E_{stored} = 2491{,}8kJ$$

This is nearly 100 times of the required pulse energy.

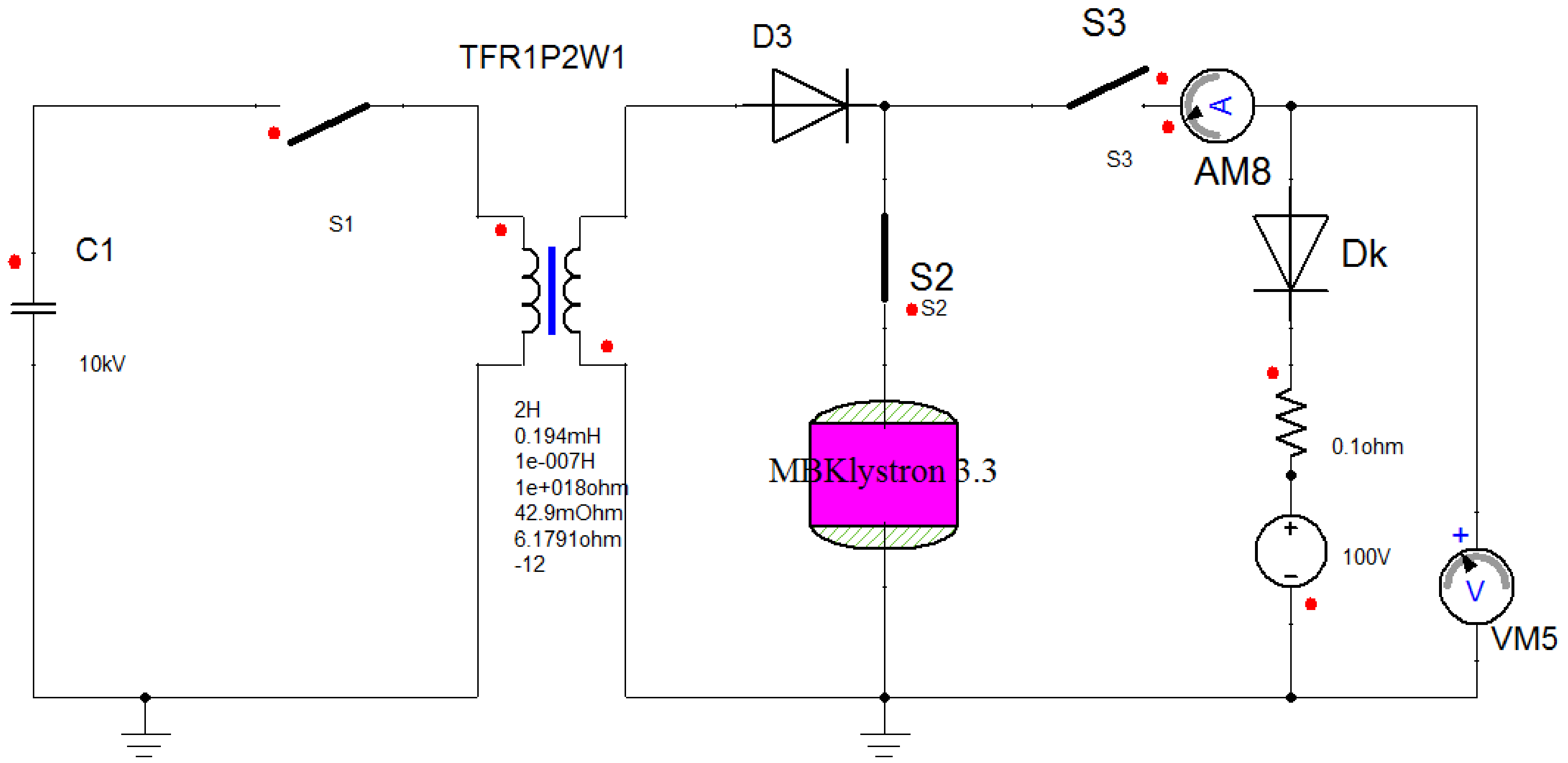
Direct switch realized

e.g. DTI design for ISIS front end test stand



Parameter Modulator Specification
Cathode Voltage -110 kV
Cathode Current 45 A
PRF 50 Hz
Beam Pulse Width 500 µs to 2.0 ms
Droop 5%

Modulator with pulse transformer



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DESY

Series switch modulator with pulse transformer

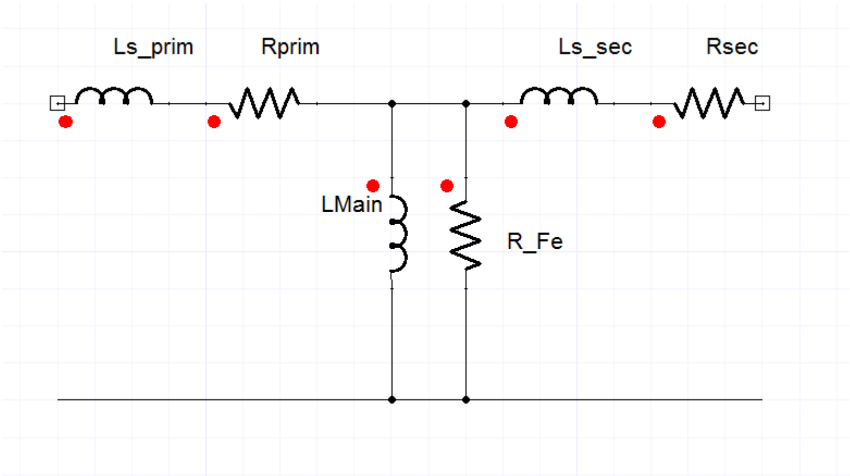
Advantage

- Work on lower voltage level
  - At DESY 10 – 12 kV
- Switch is much easier
- No oil in modulator, but in the transformer tank

Disadvantage

- Additional pulse transformer
- Leakage inductance decreases rise time
- Additional stored energy that has to be dissipated in case of an arc
- **More stored energy**

Equivalent circuit of a pulse transformer



- Transformer introduces additional inductances
- In case of an arc the energy that is stored in the stray inductances and in the main inductances has to be dissipated.
- The Rsec should be taken into account for dissipating the energy in case of an arc

Stored energy in the transformer

> Stray inductance

$$E_{stored\ Ls} = \frac{1}{2} * L * I_{short\ circuit}{}^2$$

Ls XFEL transformer = 200 µH

$$E_{storedLs} = \frac{1}{2} * 200\mu H * 2000A^2$$

$$E_{storedLs} = 400J$$

> Main inductance

$$E_{stored\ LM} = \frac{1}{2} * L * I_{mag.}{}^2$$

Lmain XFEL transformer 5 H

$$I_{Mag} = \frac{U * t}{L}$$

U= 10 kV, t=time of arc 0-1.7ms

$$I_{Magmax} = \frac{10kV * 1.7ms}{5\ H}$$=3.4 A

$$E_{stored\ LM} = \frac{1}{2} * 5H * 3.4A^2 =$$ 28.9 J

Stored energy = 428.9 J

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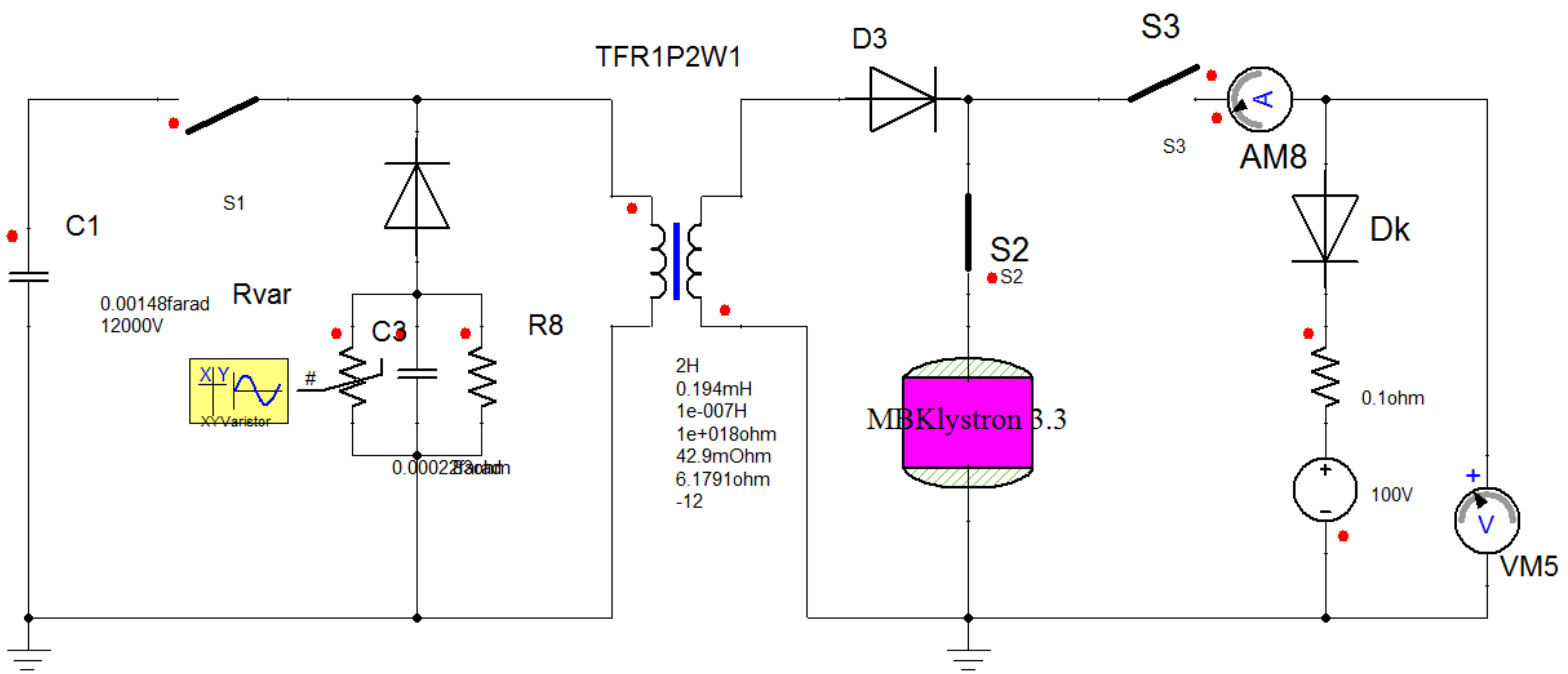
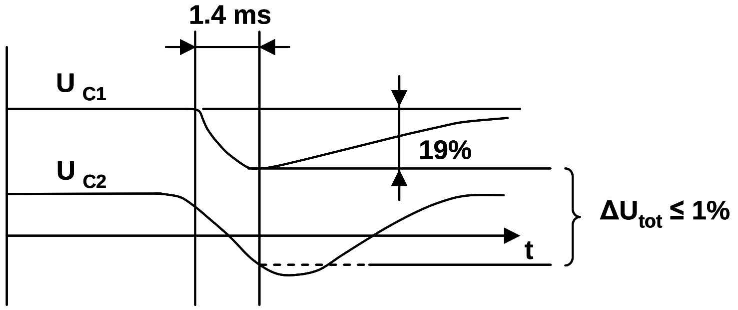
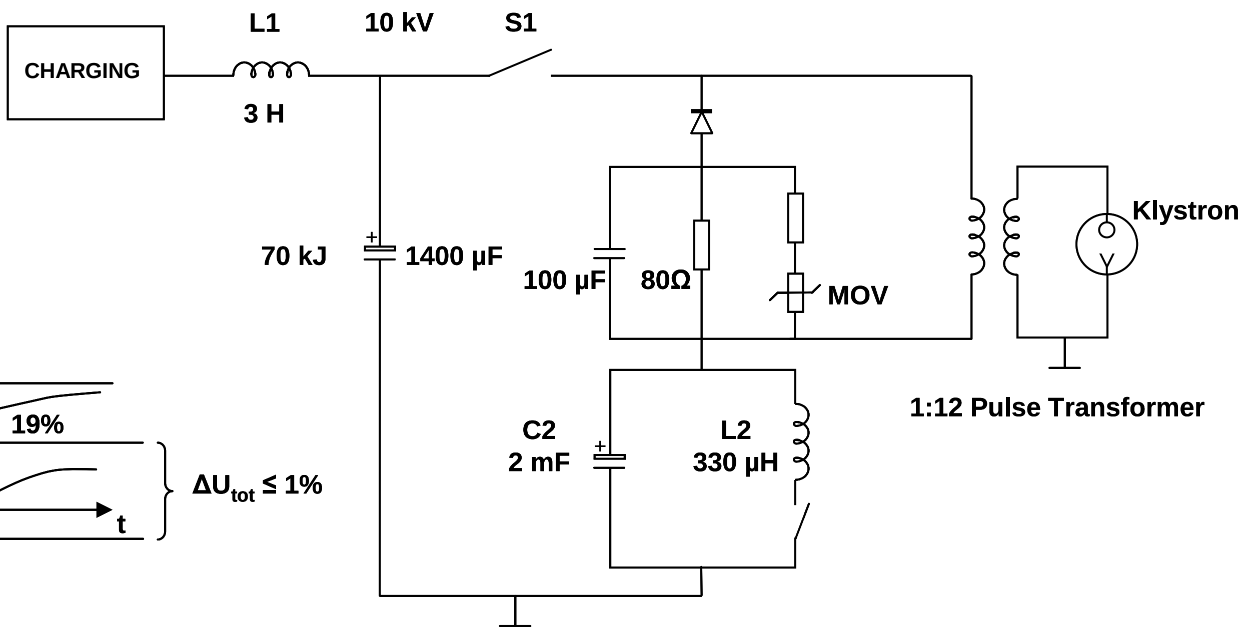
Additional discharge network to dissipate the energy



The energy is stored in a capacitor and dissipated in the parallel resistor

Bouncer Modulator
Bouncer circuit near ground (Fermilab design, later built by PPT)





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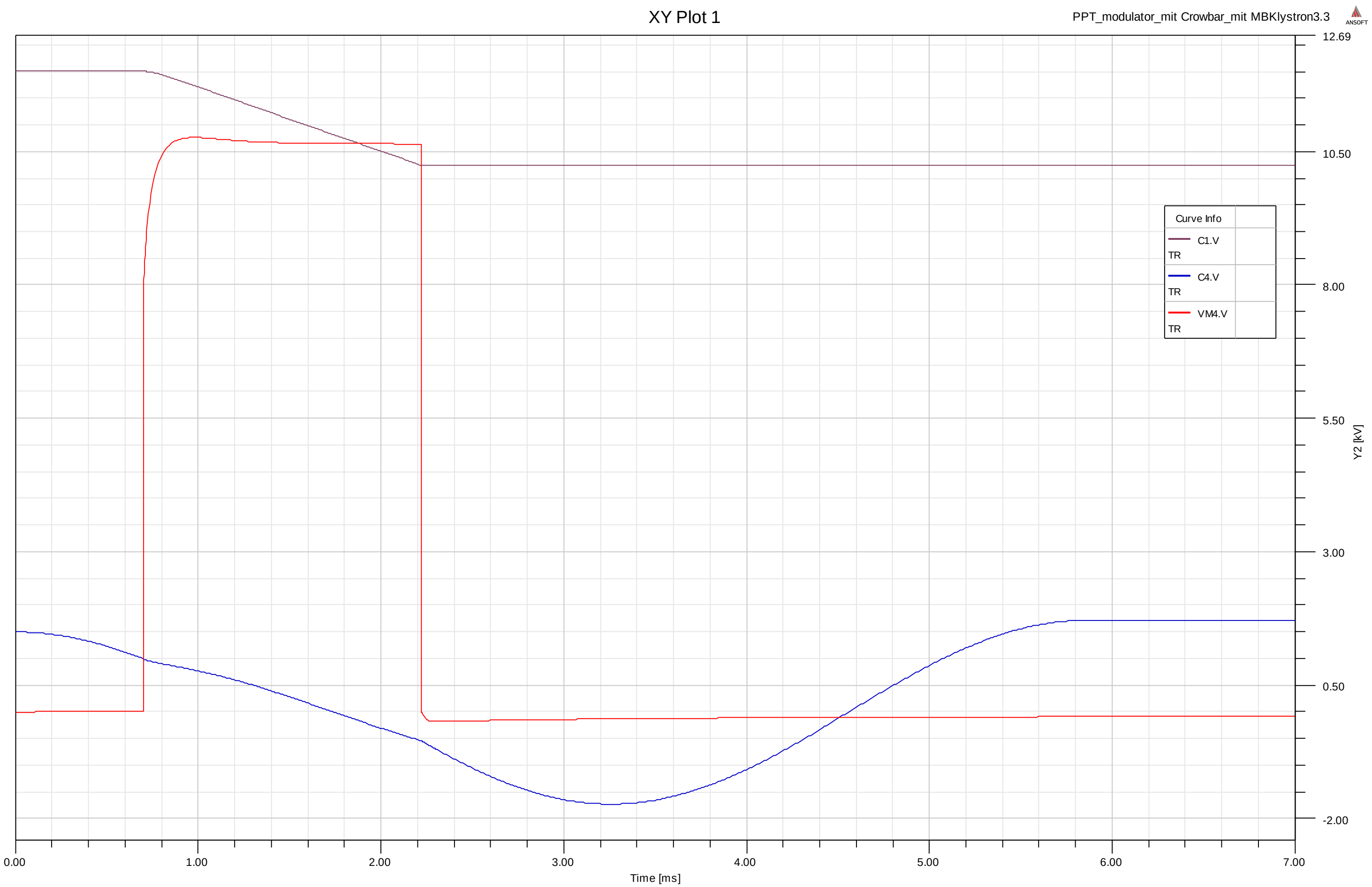
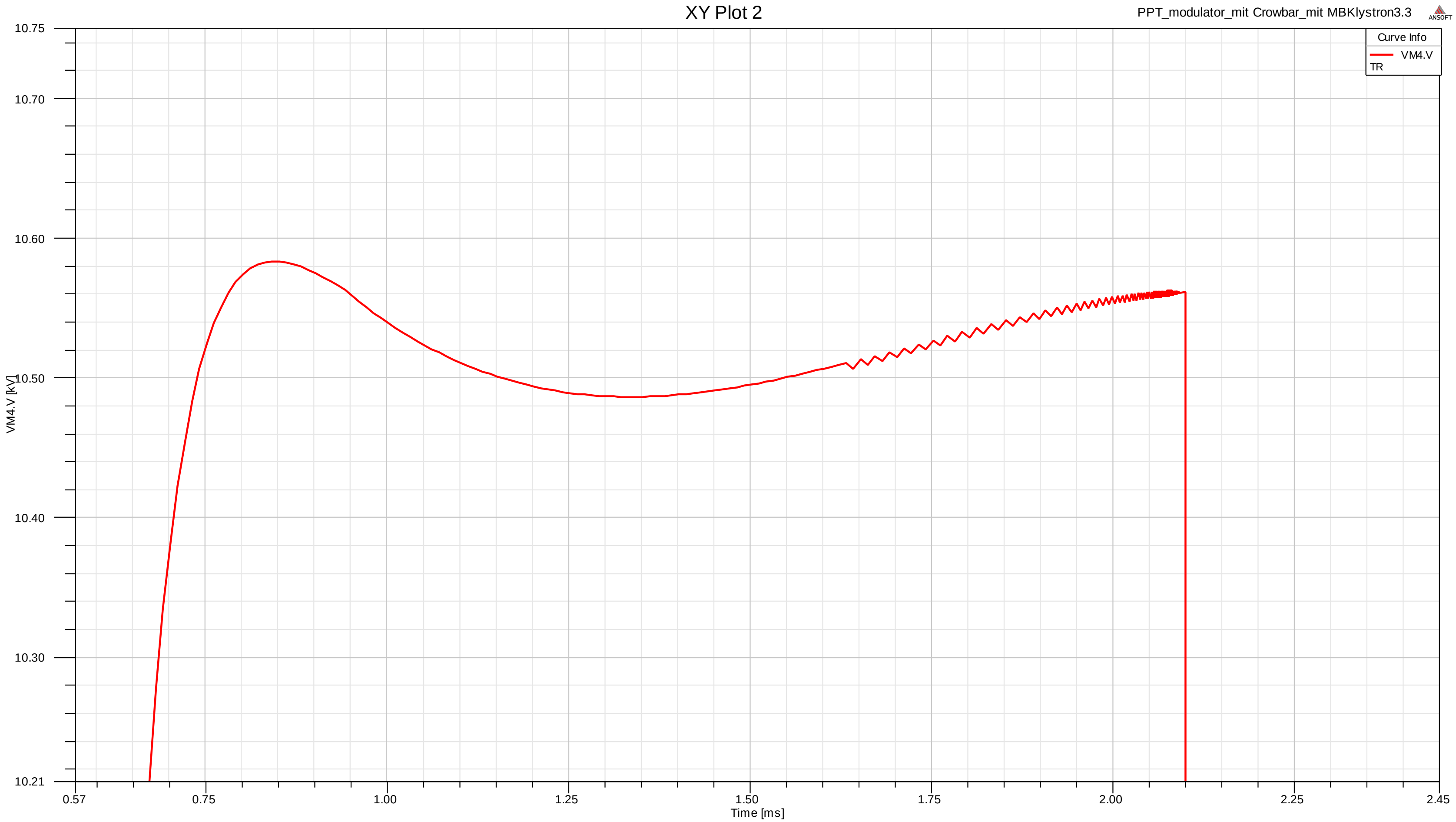
DESY

Voltages of Bouncer modulator

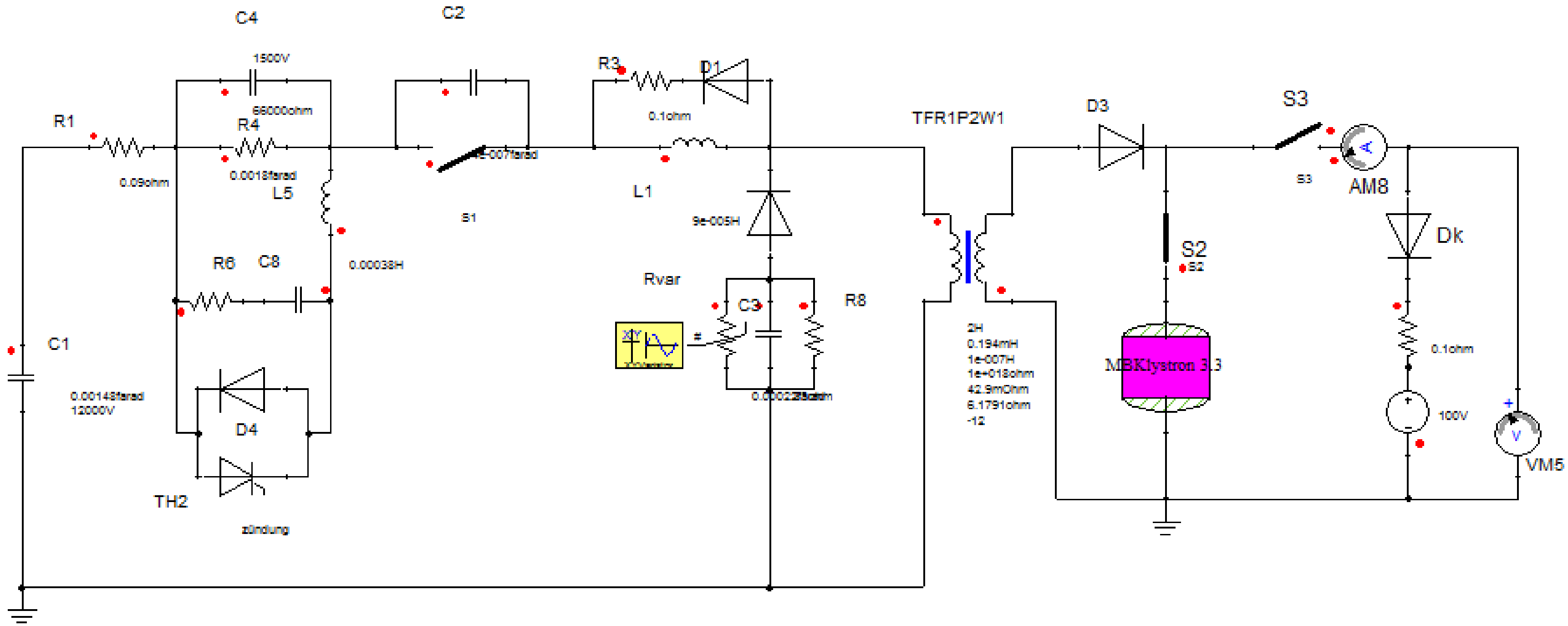


Flat top voltage



Bouncer modulator

Bouncer in the high voltage path (DESY design, built by PPT)



Stored energy in bouncer modulator

Pulse energy simplified to rectangular wave form

$$E_{pulse} = U * I * t = \frac{U^2}{R} * t$$

$$E_{pulse} = \frac{115\ kV^2}{900\Omega} * 1{,}7\ ms$$

$$E_{pulse} = 24{,}98\ kJ$$

Stored energy in the capacitors

Main capacitor

$$E_{stored} = \frac{1}{2} * C_{main} * U^2$$

$$E_{stored} = \frac{1}{2} * 1.4\ mF * 10kV^2$$

$$E_{stored} = 70\ kJ$$

Bouncer

$$E_{stored} = \frac{1}{2} * C_{bouncer} * U^2$$

$$E_{stored} = \frac{1}{2} * 2\ mF * 2kV^2$$

$$E_{stored} = 4\ kJ$$

$E_{stored\ total} = 74$ kJ = 5 * E_pulse

Bouncer modulator with pulse transformer

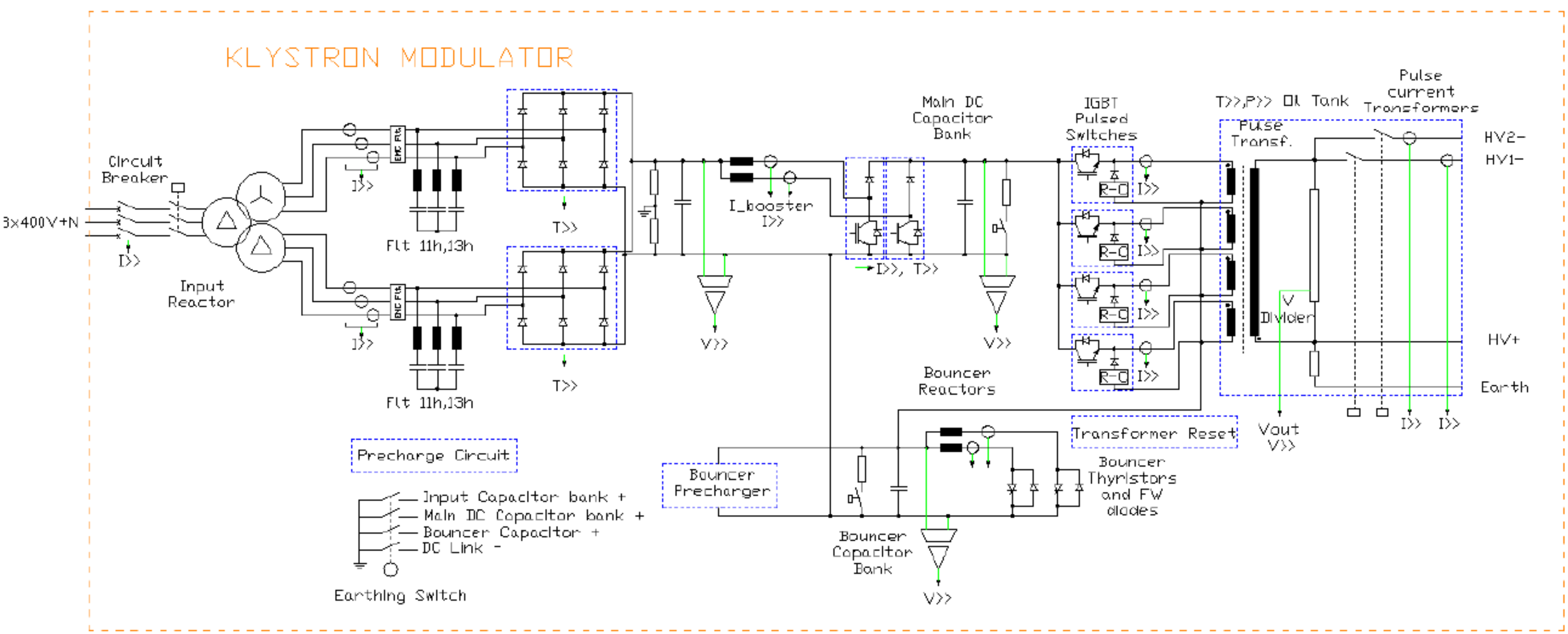
Advantage

- Work on lower voltage level
  - At DESY 10 – 12 kV
- Switch is much easier
- No oil in modulator, but pulse transformer
- **Much lower stored energy**

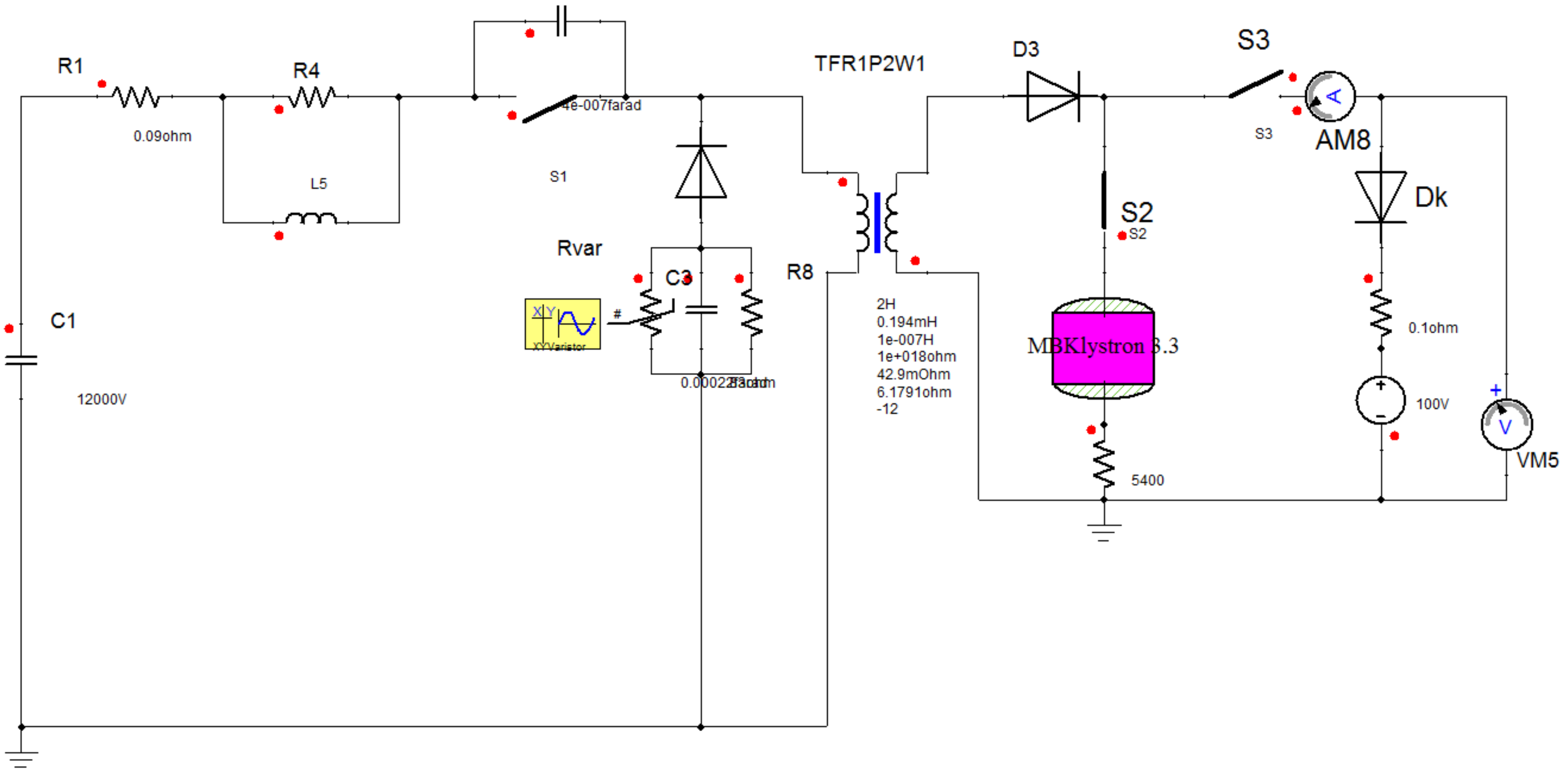
Disadvantage

- Additional pulse transformer
- Leakage inductance decreases rise time
- Additional stored energy that has to be dissipated in case of an arc
- Timing dependent bouncer switching
- High current in the bouncer circuit

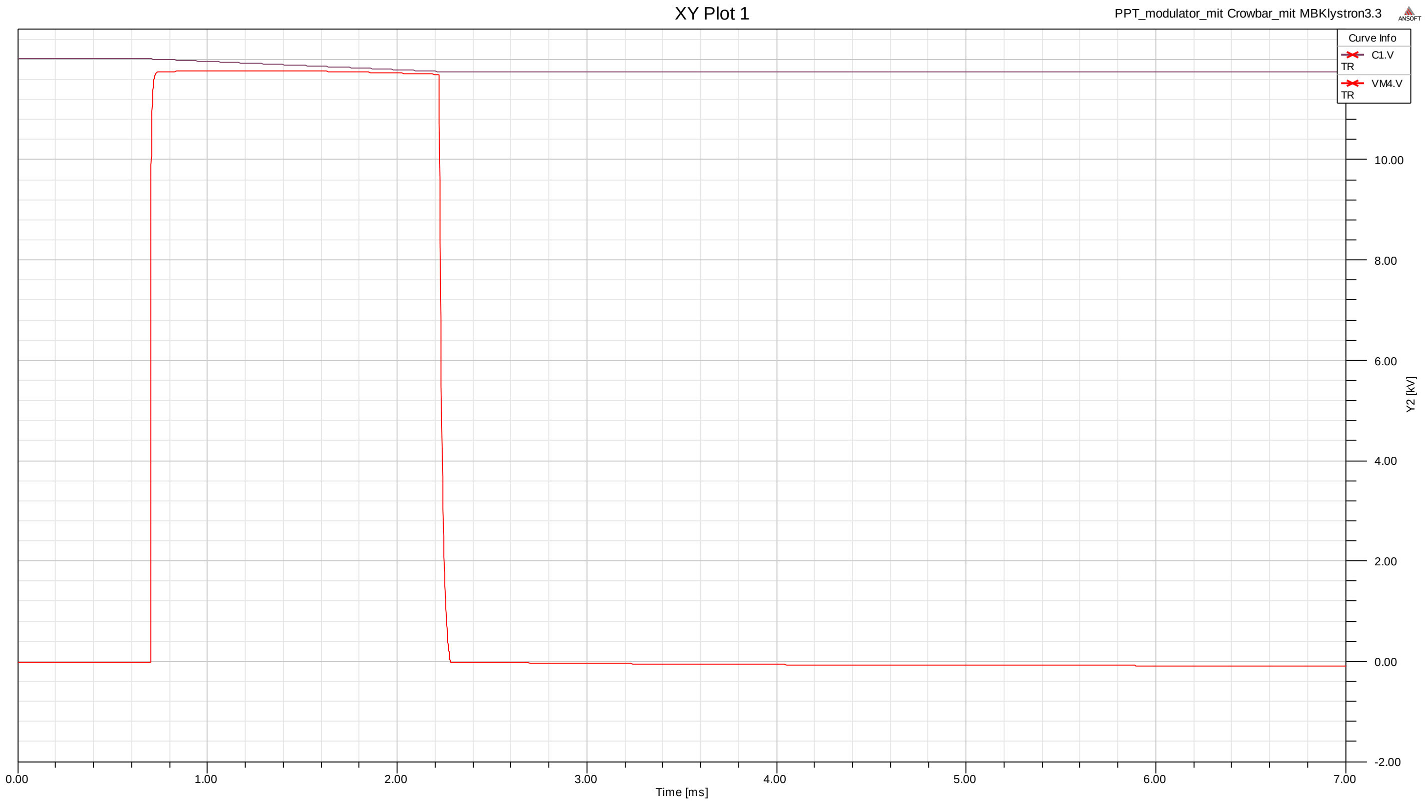
Bouncer modulator with separated primary of the transformer proposed by JEMA



Pulsforming with series RL



Voltage of RL modulator



RL modulator with pulse transformer

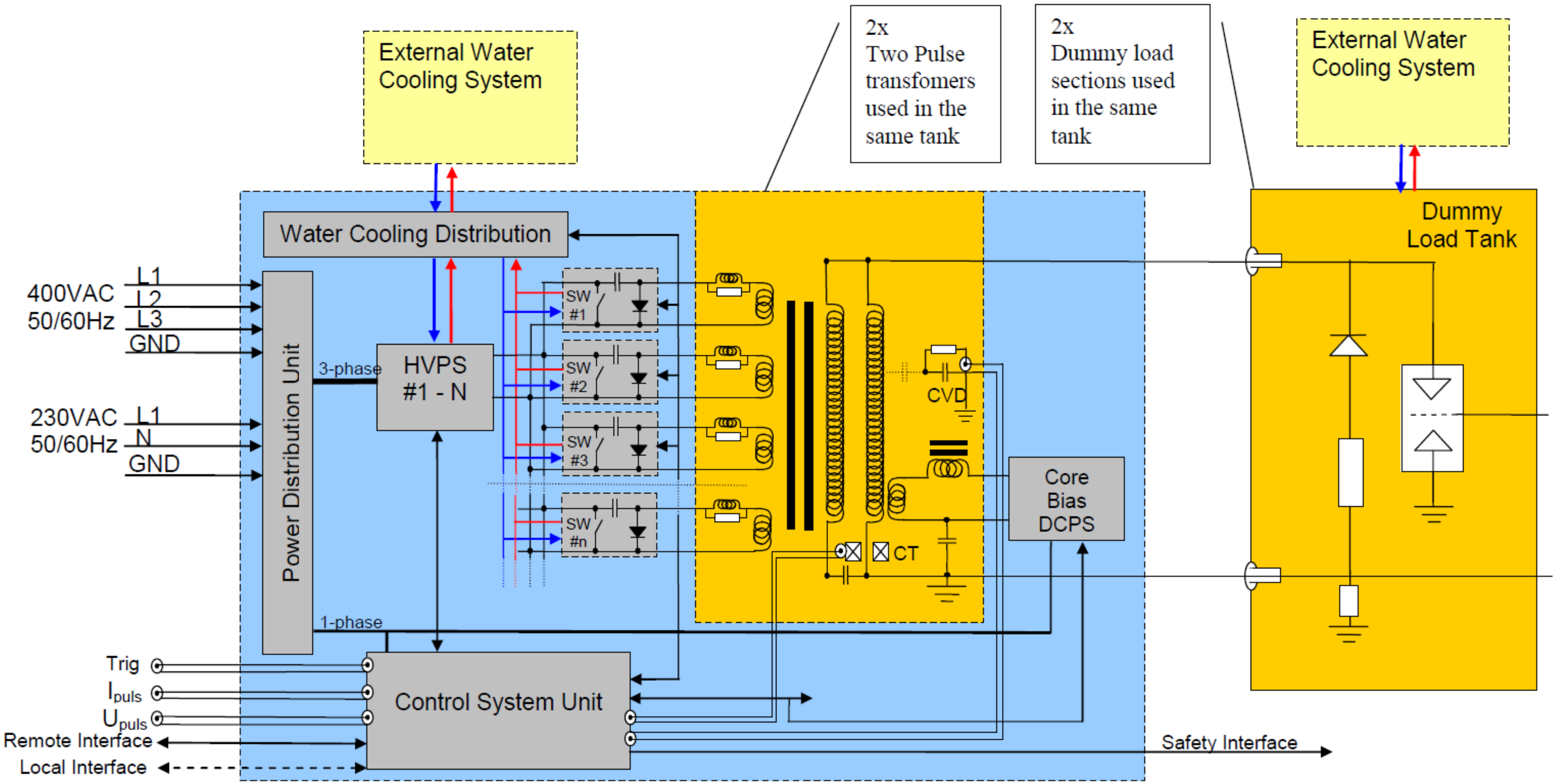
Advantage

- Work on lower voltage level
  - At DESY 10 – 12 kV
- Switch is much easier
- No oil in modulator, but pulse transformer
- Much lower stored energy
- Passive pulse forming

Disadvantage

- Additional pulse transformer
- Leakage inductance decreases rise time
- Additional stored energy that has to be dissipated in case of an arc
- Lower flexibility than bouncer

Pulsforming by series RL
picture Scandinova, RL-Modulator also by PPT

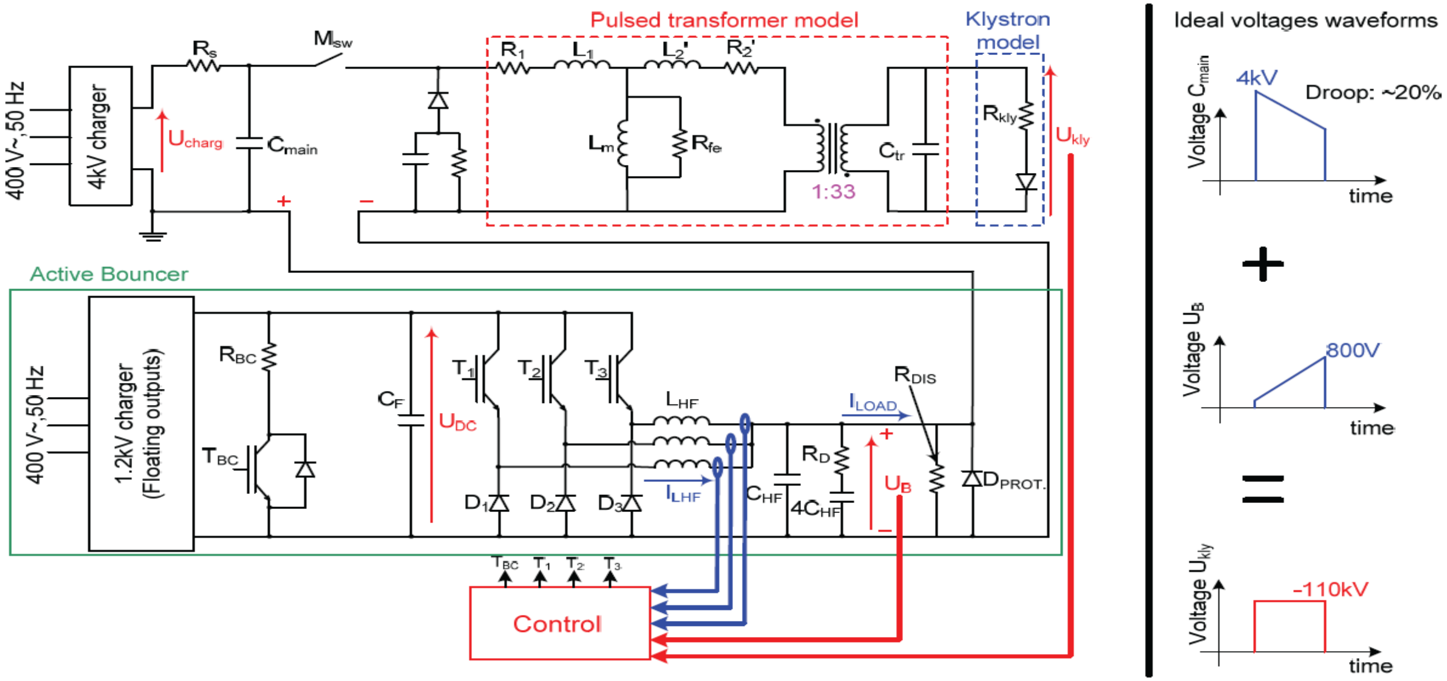


Active voltage correction to replace LC-bouncer

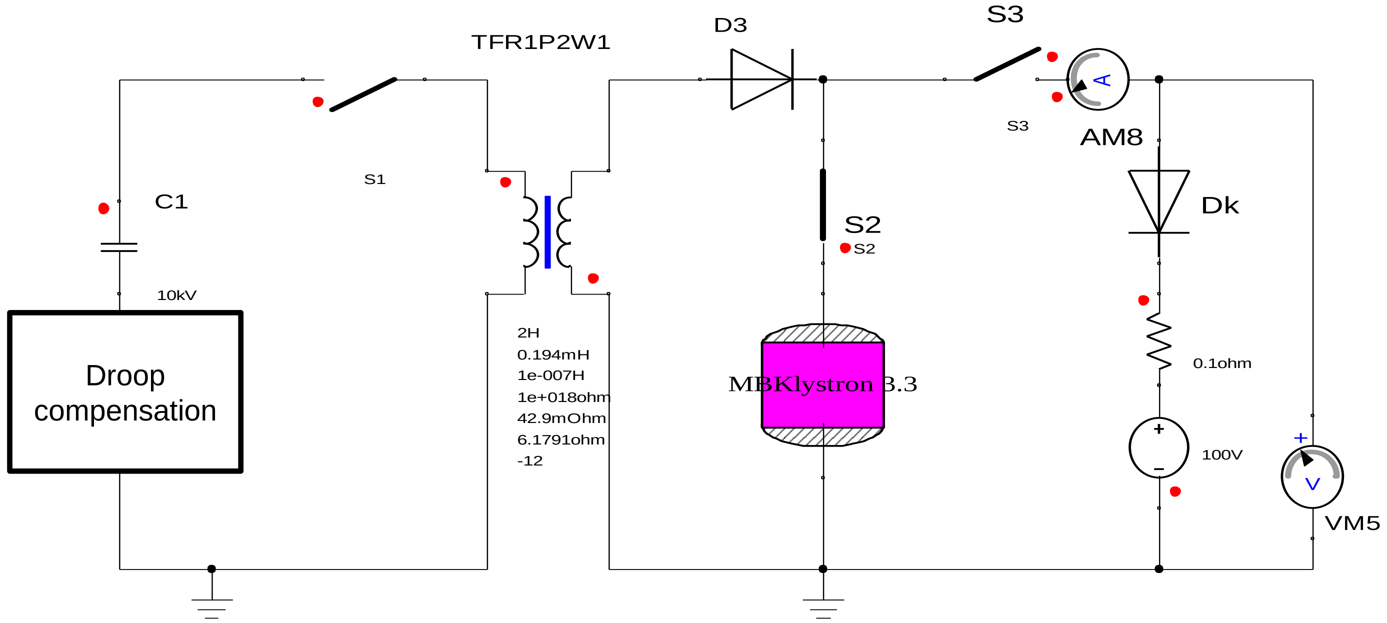
- Instead of using passive components active power supplies can be introduced.
- These have the same function as a bouncer, but have additionally the possibility to adjust during the pulse to achieve better flatness.

Active bouncer converter

Proposed by Davide Aguglia CERN

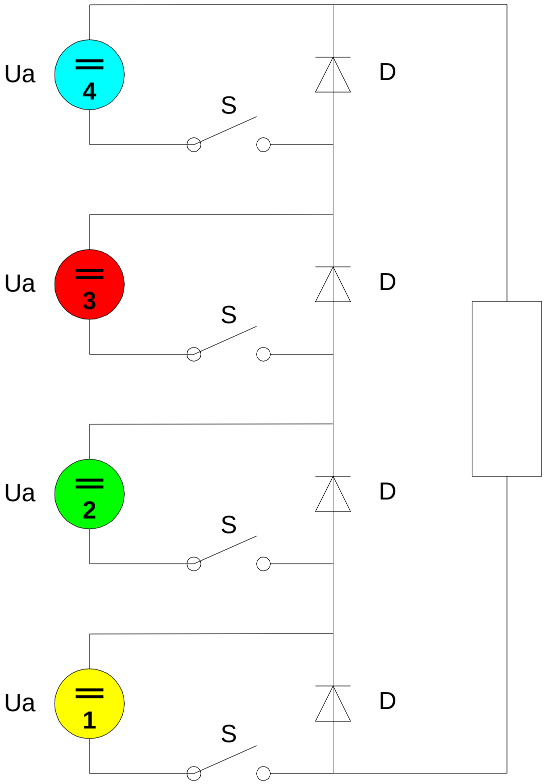


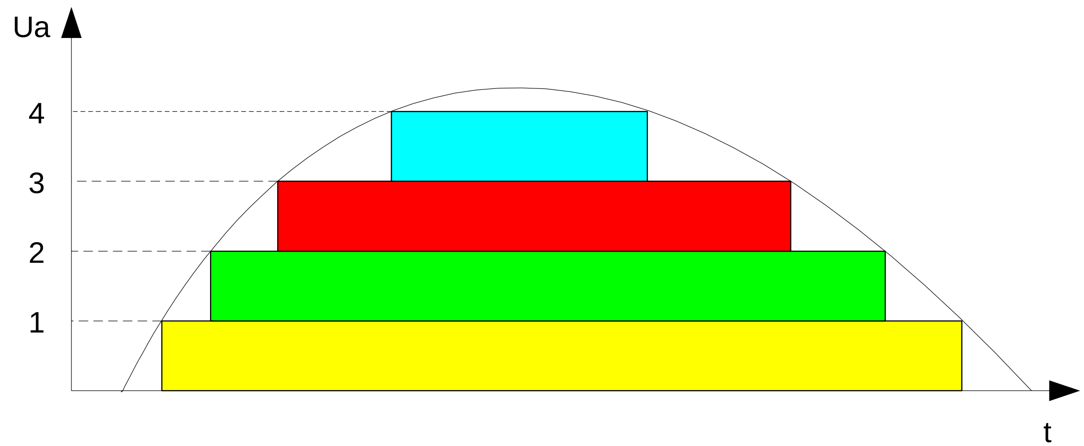
Active bouncer converter
power supply in capacitor branch



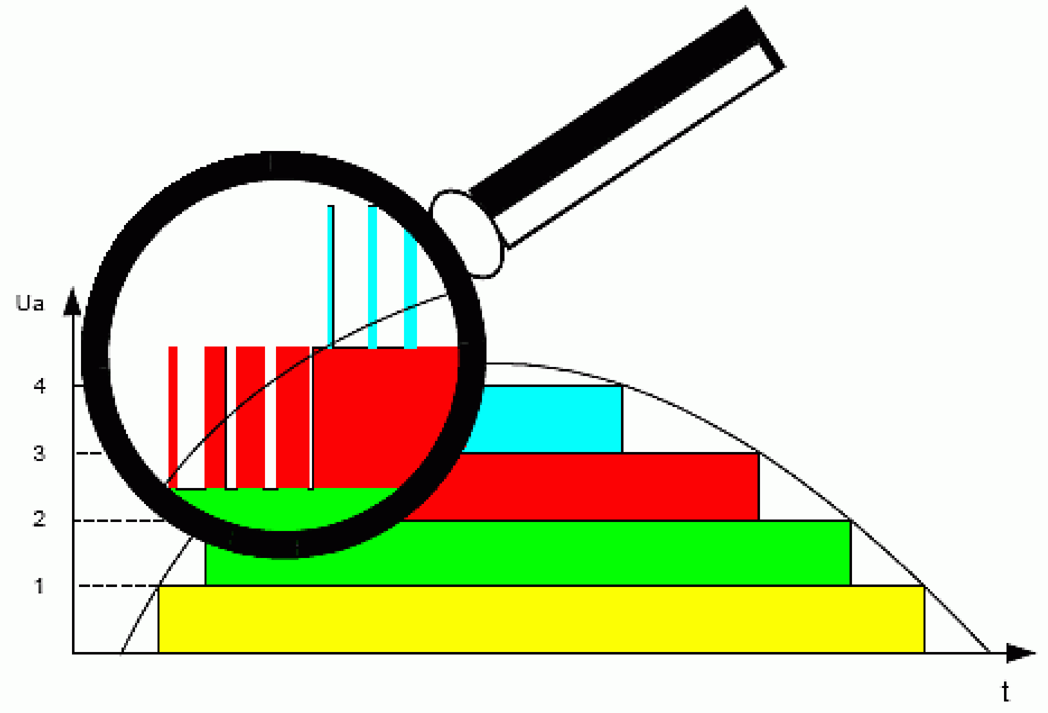
Modulators with active components

Pulse Step Modulator (PSM)
design by Ampegon

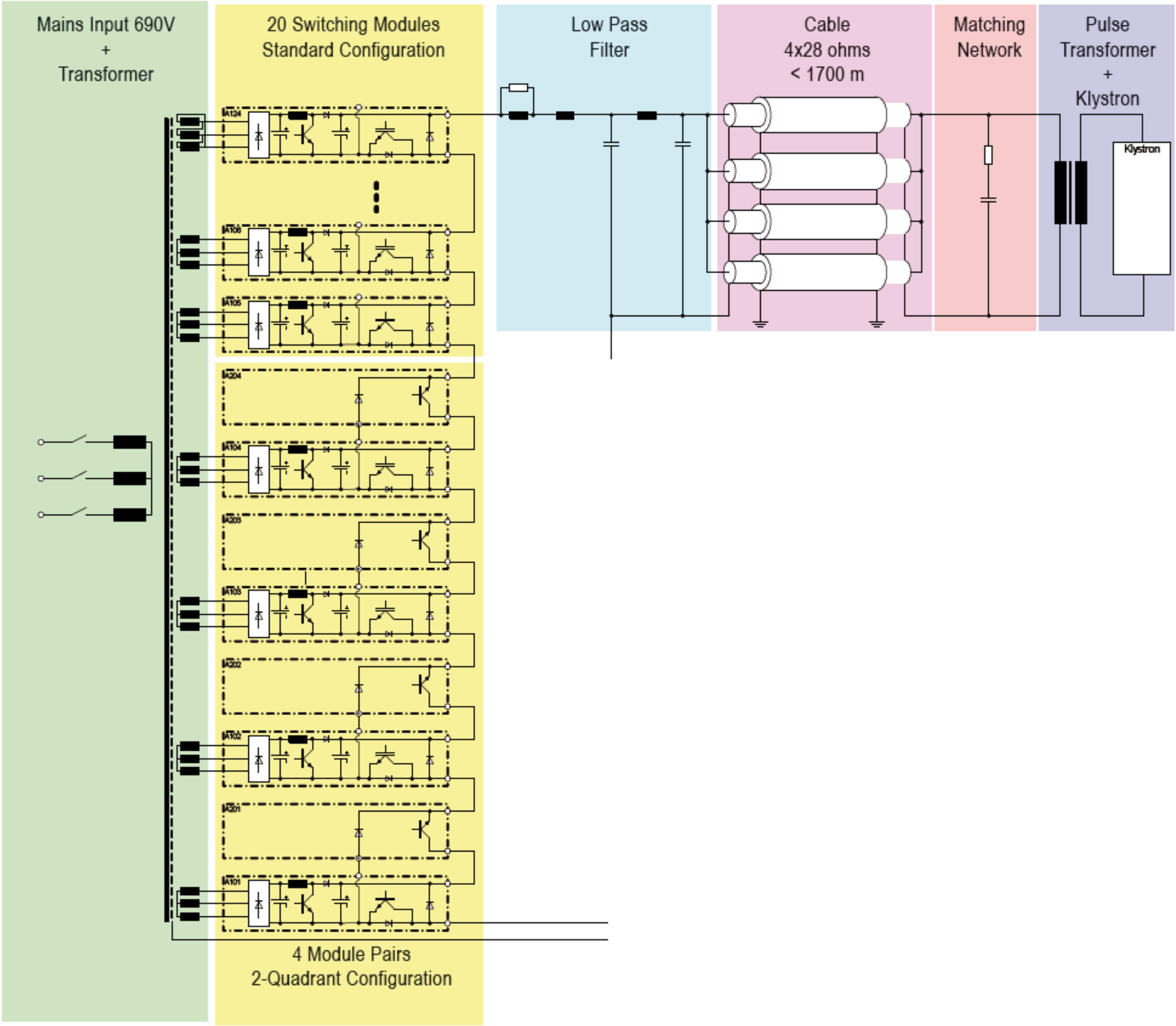




PWM in PSM

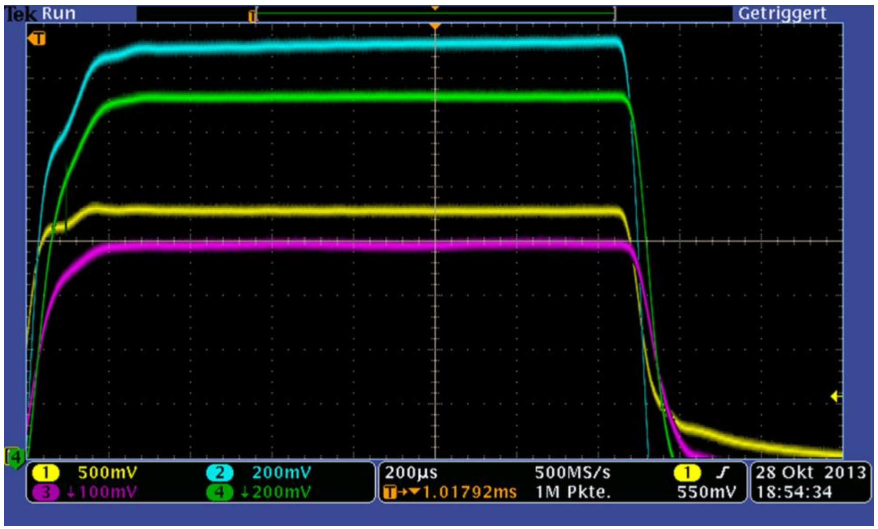


Ampegon modulator for XFEL

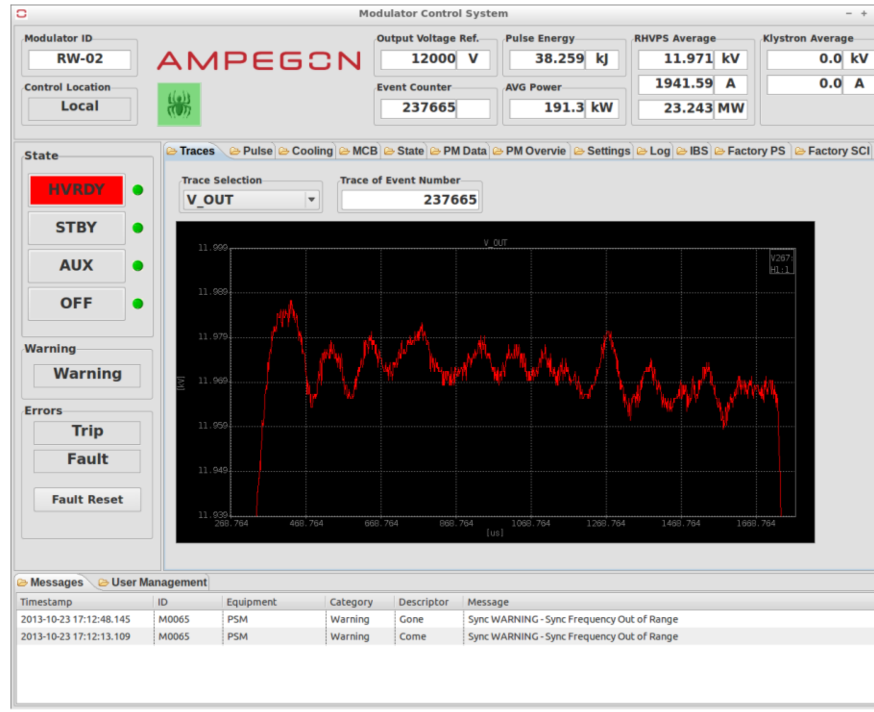


Ampegon modulator for XFEL

> Waveforms of modulator



> Flat top 30 Vpp



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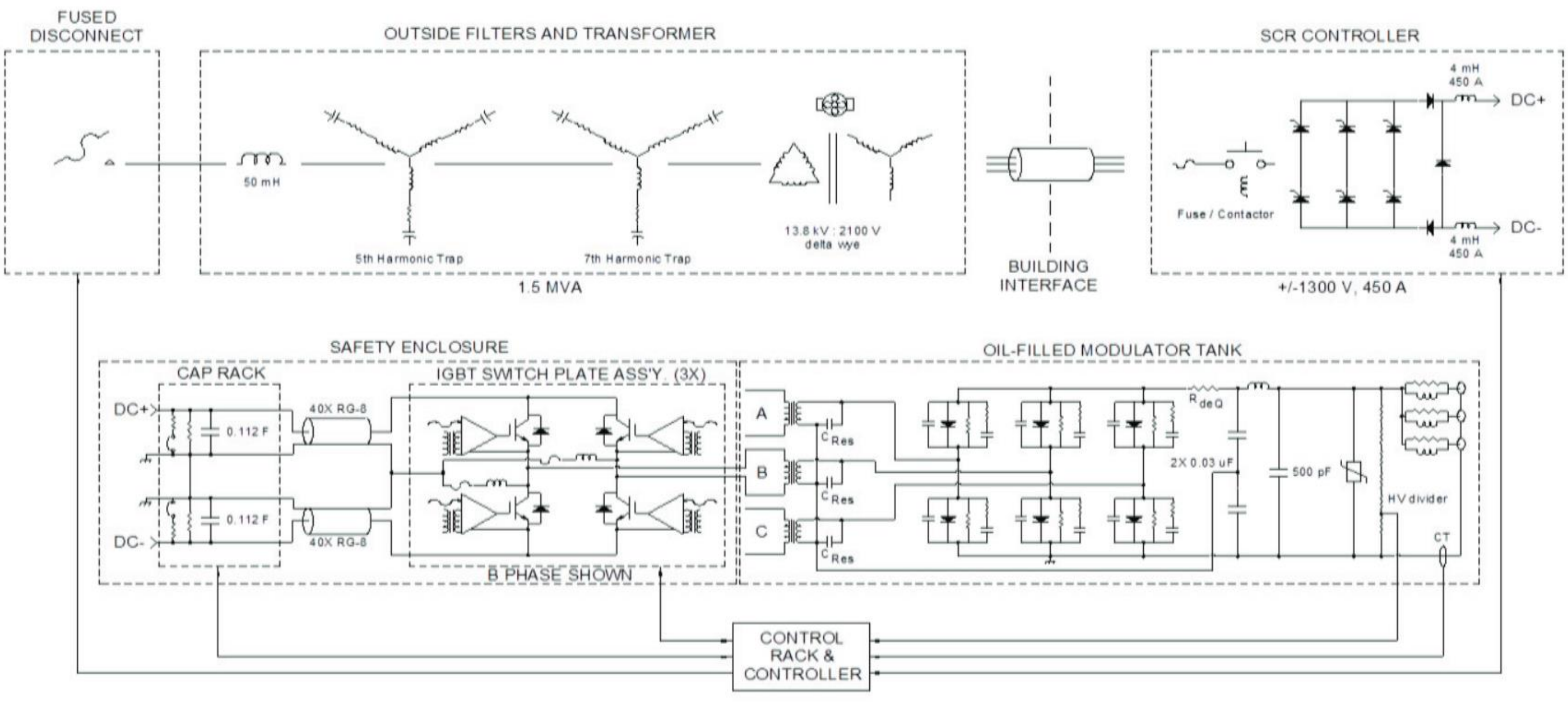
H-bridge Converter/Modulator @ SNS



SNS-Modulator

Provides up to 135 kV, 1.35 ms pulses at 60 Hz to amplify RF to 5 MW

Powers multiple klystrons up to 11 MW peak power

Multi-phase H-bridges driving step-up transformers

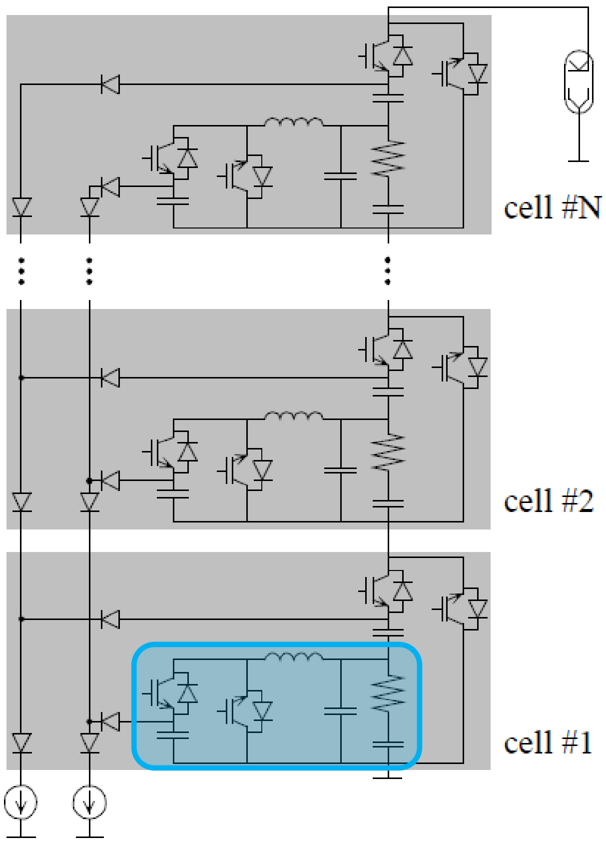
Switching frequency of the IGBTs is 20 kHz

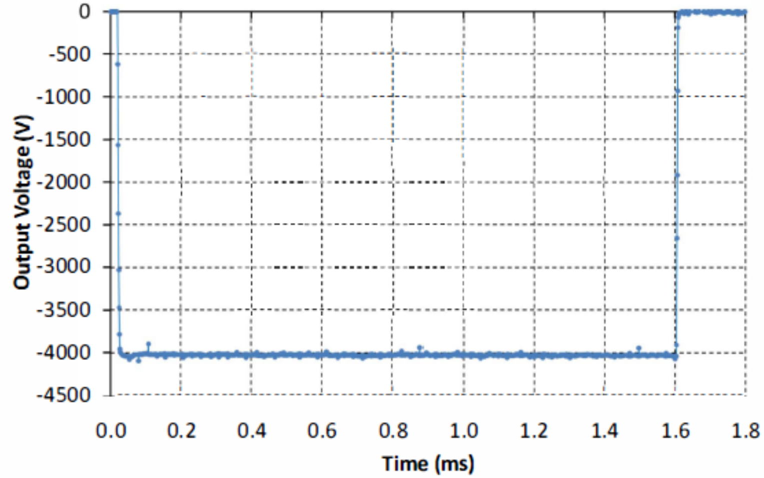
Currently there is up to a 5% pulse droop operating in open-loop, requires feedback loop

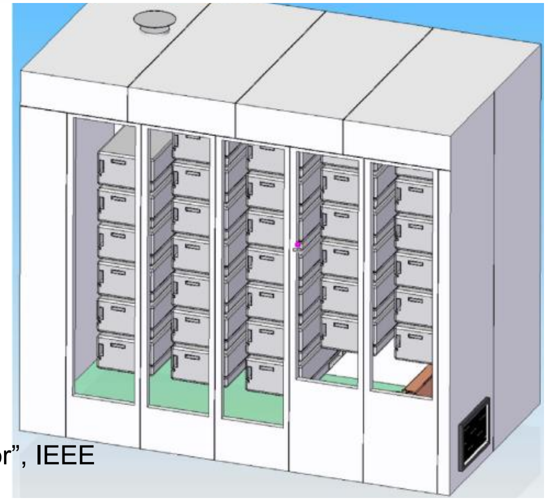
Slide courtesy of D. Anderson

Solid State "Hybrid" Marx Modulator

Modular, redundant variation of traditional Marx
Incorporates "nested" droop correction (buck converter) shown in light blue



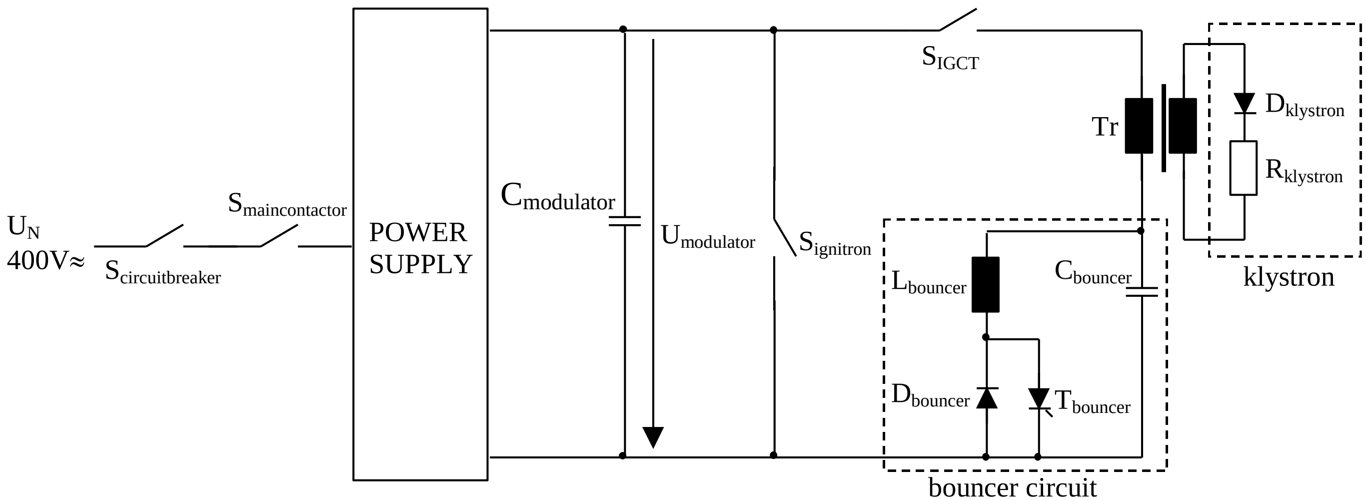


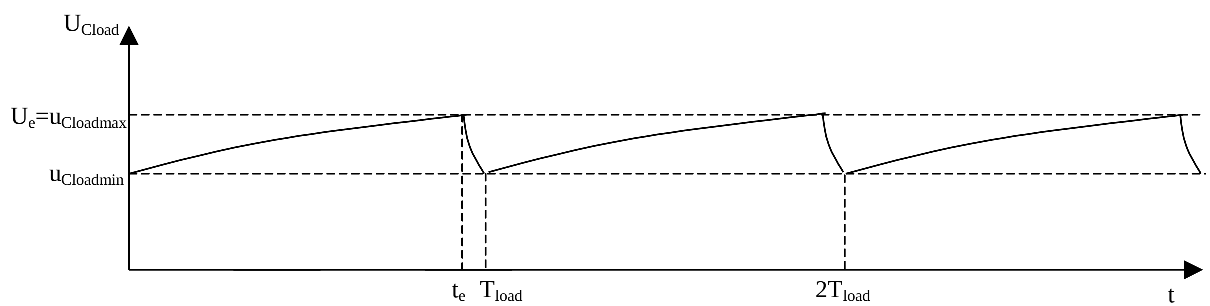


Kemp, et al., "Final Design of the SLAC P2 Marx Klystron Modulator", IEEE PPC, 2011, p. 1582-1589.
Slide courtesy of D. Anderson

Connection to the mains

Bouncer Modulator





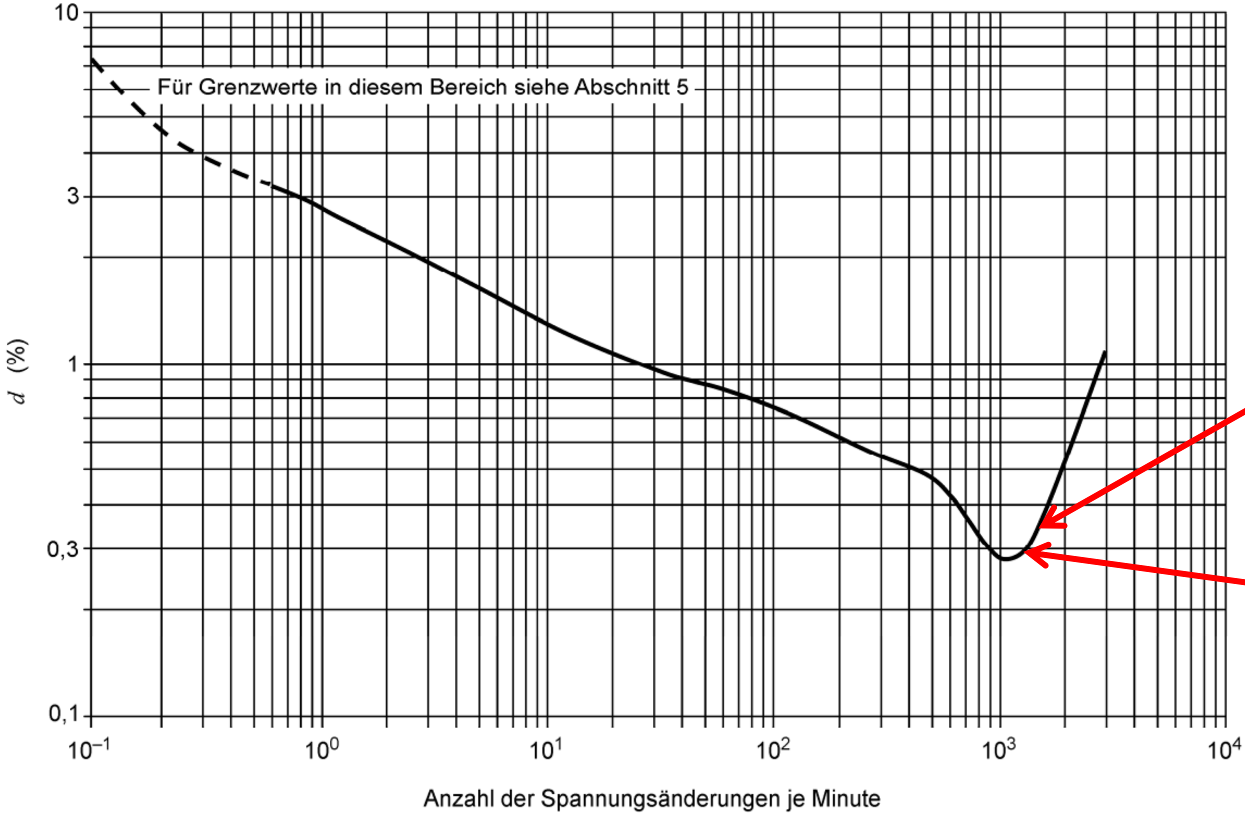
Disturbances to the mains

- The amount of allowed disturbances is defined in the German standard VDE 0838, IEC 38 or the equivalent European standard EN 61000-3-3.
- No energy consumer is allowed to produce more distortions than 3% of the voltage variation of the mains.
- For low frequencies in the visual spectrum this value is even more restricted. The low frequencies are called flicker frequencies. The human eye is very sensitive to changes in light intensities in this frequency domain.
- It is defined as voltage changes per minute.
- This is not to be confused with the frequency since a change is from top to bottom and vice versa

voltage changes / min = 2*frep [1/s]*60 [s/min]

Allowed disturbancies to the grid according to DIN EN 61000-3-3

DIN EN 61000-3-3 (VDE 0838-3):2014-03
EN 61000-3-3:2013



Operation point of
ESS 14 Hz, r = 1680
d ≈ 0.34 %

Operation point of
XFEL 10 Hz, r=1200
d ≈ 0.28 %

Disturbances to the mains

>

$$d = \frac{\Delta S}{S_{sc}} = \frac{\Delta U}{U_n} = 0.28\ \%$$

d= allowed distortion of the voltage

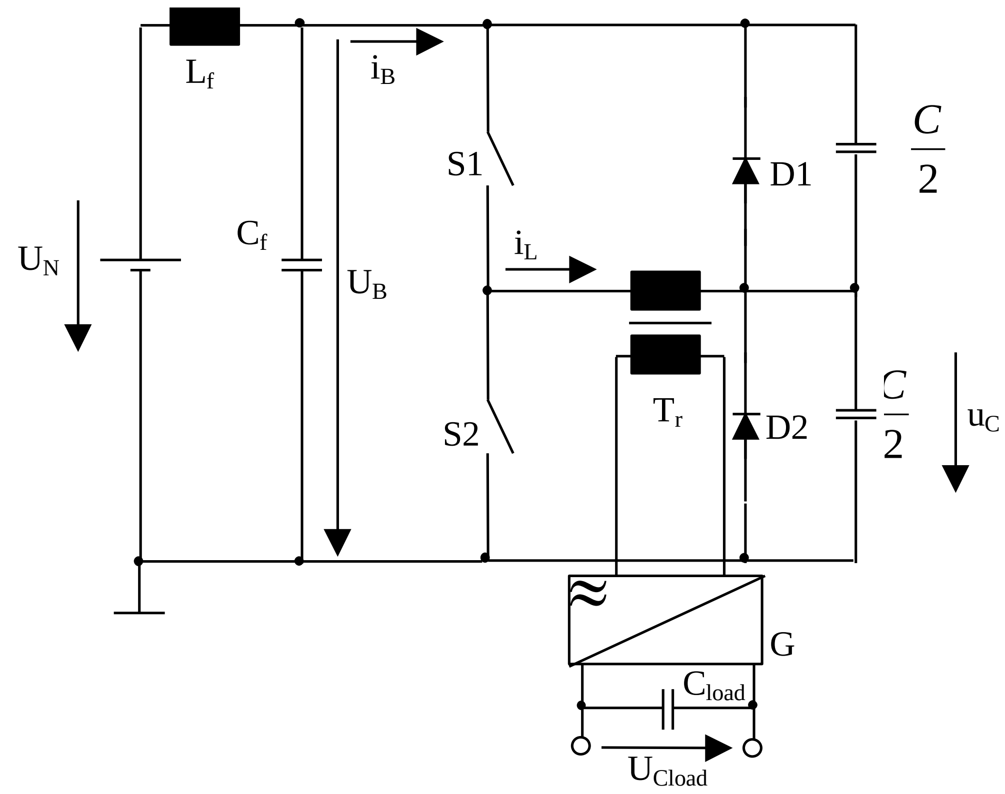
ΔS = variation in apparent power

Ssc = short circuit power

DESY mains and specification

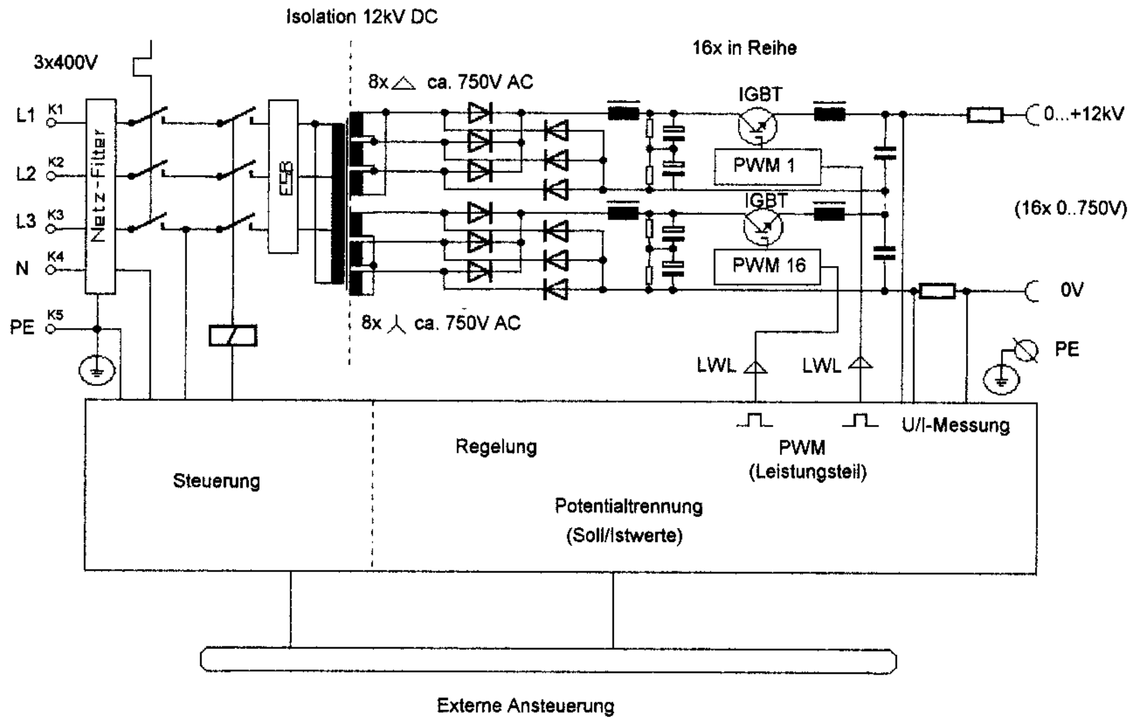
- At DESY the intermediate voltage is 10 kV.
- The short circuit power of the mains station to which the modulators are connected to is 250 MVA.
  - 250 MVA * 0,28%=700 kVA
- The first assumption for the XFEL was that max. 35 modulators could be in operation.
  - Budget of 20 kVA/Modulator
  - This budget was cut by two since other components in the machine are assumed more critical than the human eye
  - 10 kVA per modulator

300 kW-Switched mode supply for constant power
developed by N. Heidbrook



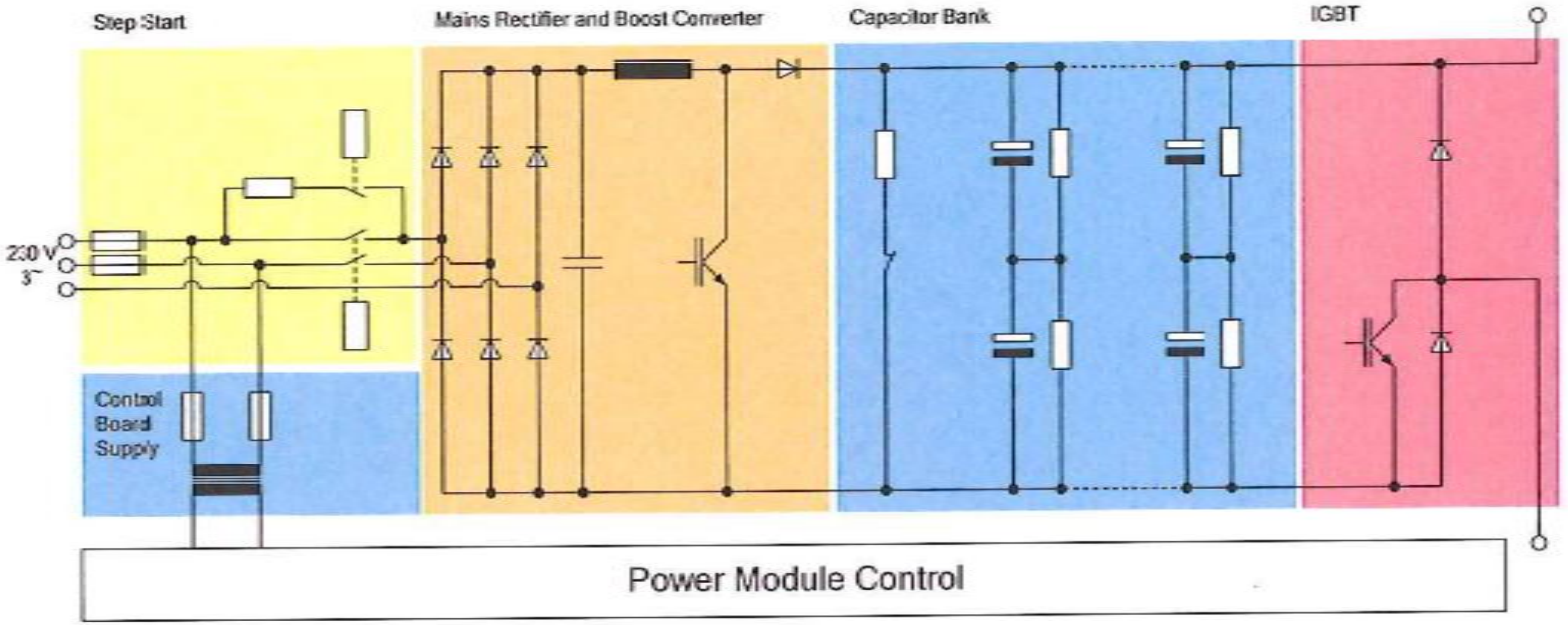
G	Rectifier
i_B	supply current
i_L	primary current of the transformer
u_C	voltage of the resonance capacitor
U_{Cload}	output voltage to the switch of the klystron
i_{Bt1}	current i_B at the time t1
L	primary stray inductivity of the transformer
f	resonance frequency of the resonant circuit of L and C
n	gear ratio of the transformer and rectifier
T	period time of the switching frequency of S1 and S2
C	resonance capacitor
U_B	supply voltage
U_N	line voltage
C_f	filter capacitor
L_f	filter inductance

Series connection of buck converters

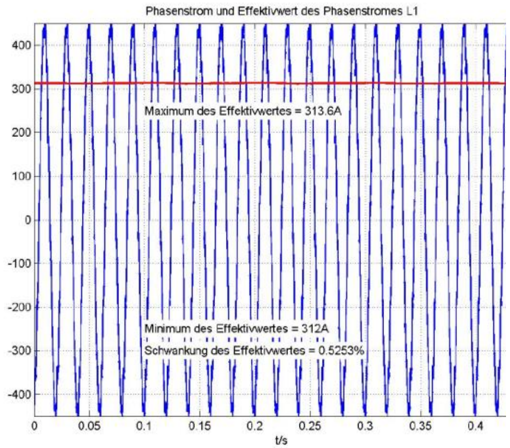


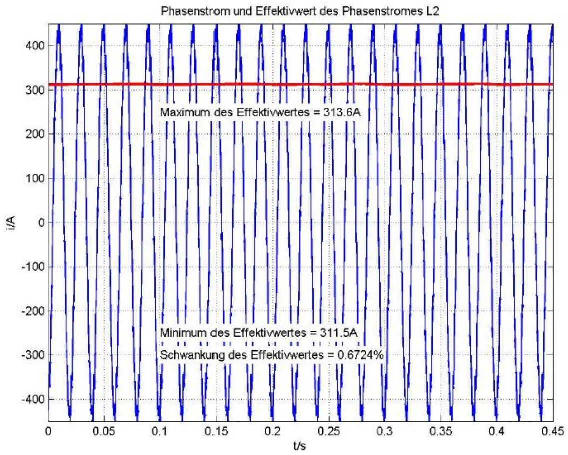
Constant power regulation was done with an analog circuit

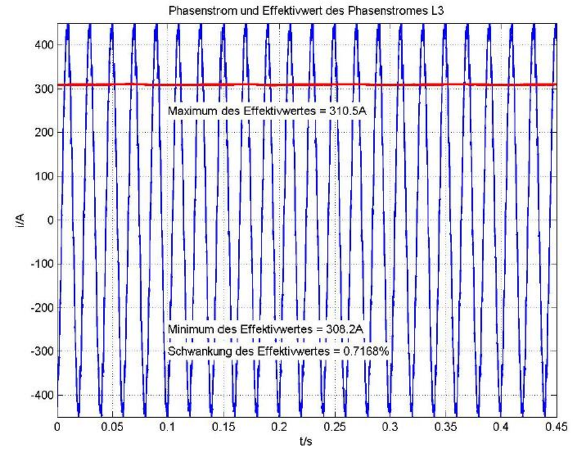
Ampegon Power Module



Variation of the mains current
Ampegon modulator





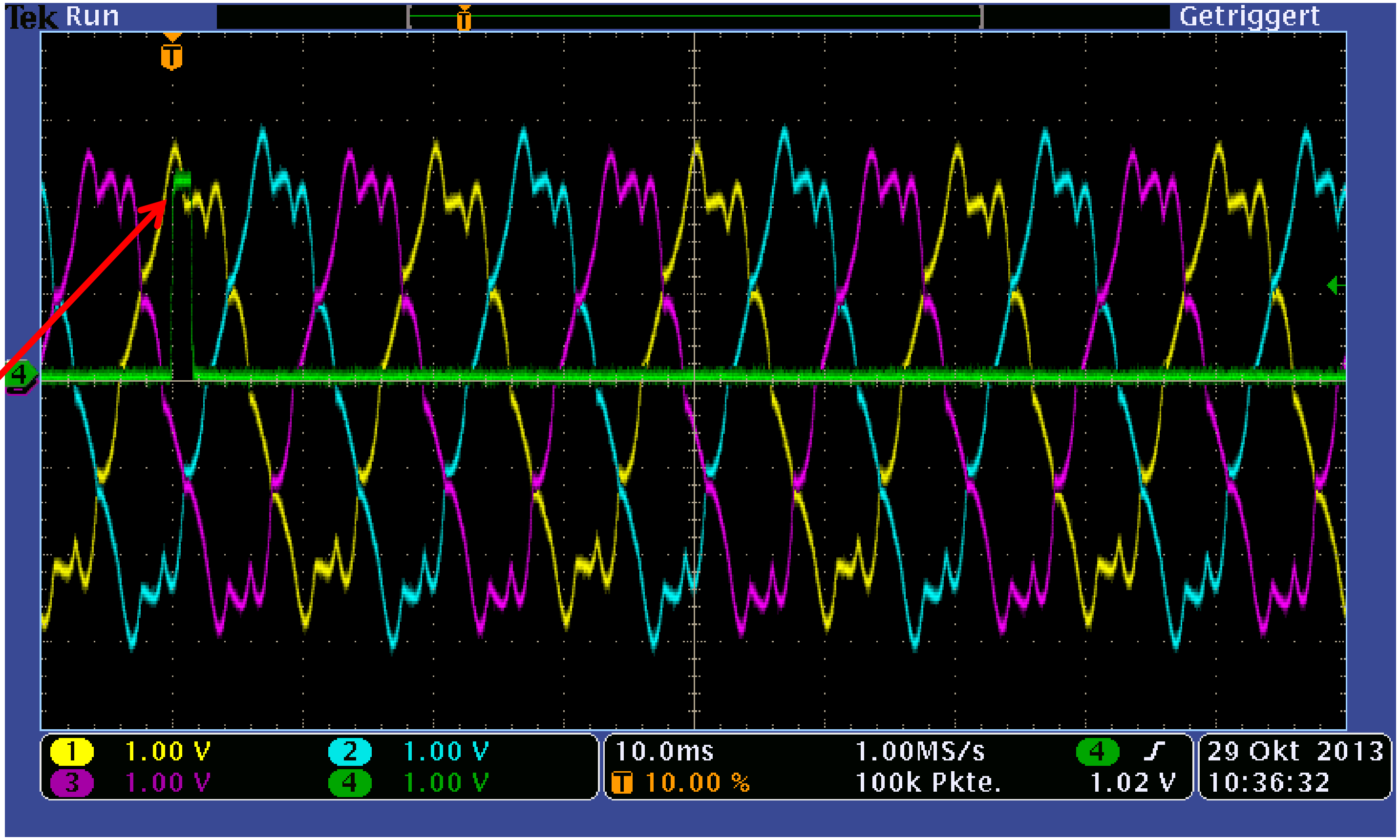


The 10 Hz reprate is suppressed very well. The value of specification would lead to
$\Delta I = \frac{\Delta S}{\sqrt{3} * U} = \frac{10kVA}{\sqrt{3} * 690V} = 8.4\ A$,

Measured result
$\Delta \mathrm{I} = 2.5\ \mathrm{A}\ beeing$ ΔS≈3 kVA

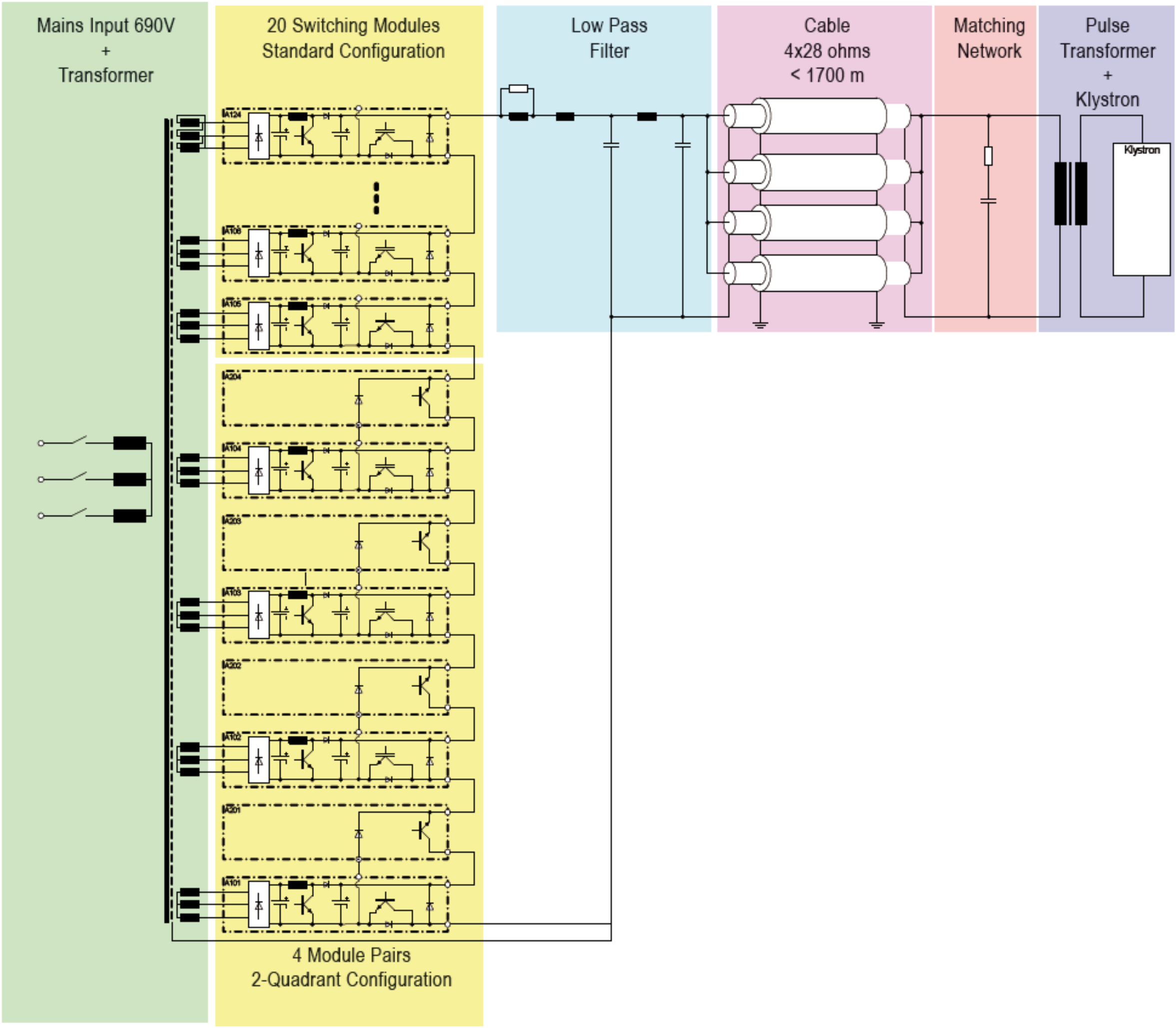
Curve forms taken at commissioning

pulse

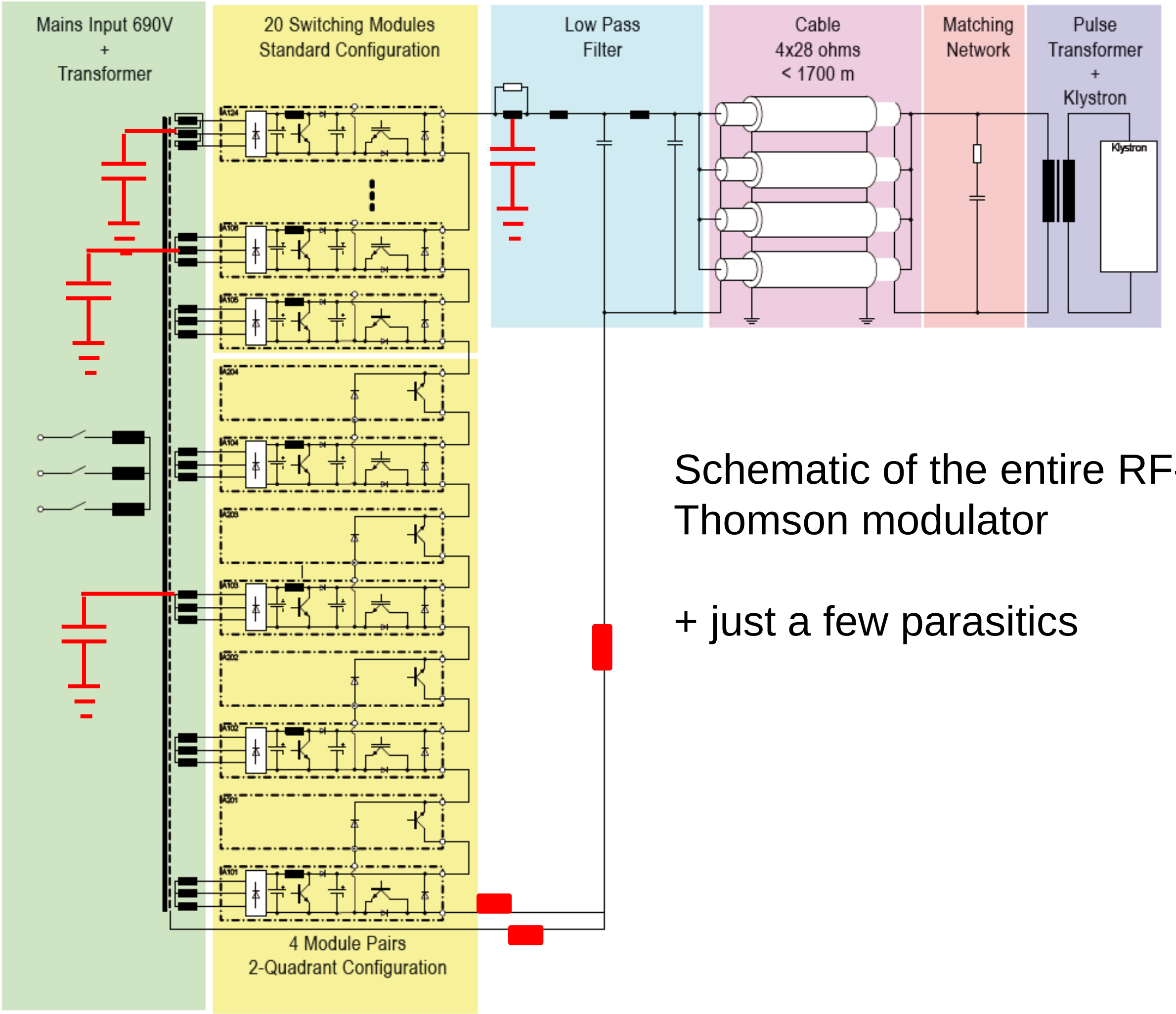


EMI effects

Example for EMI thinking



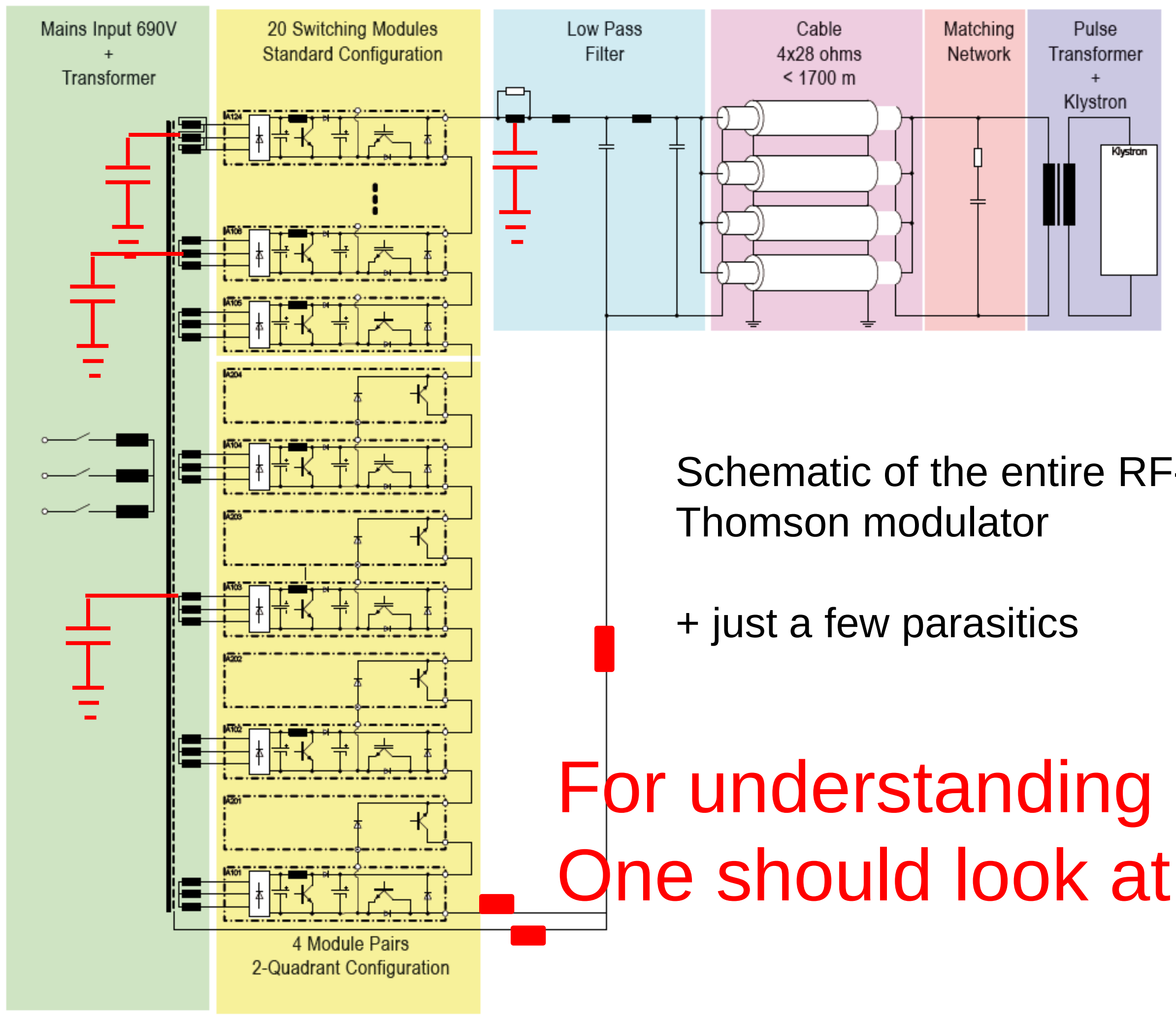
Example for EMI thinking



Schematic of the entire RF-station Thomson modulator

+ just a few parasitics

Example for EMI thinking

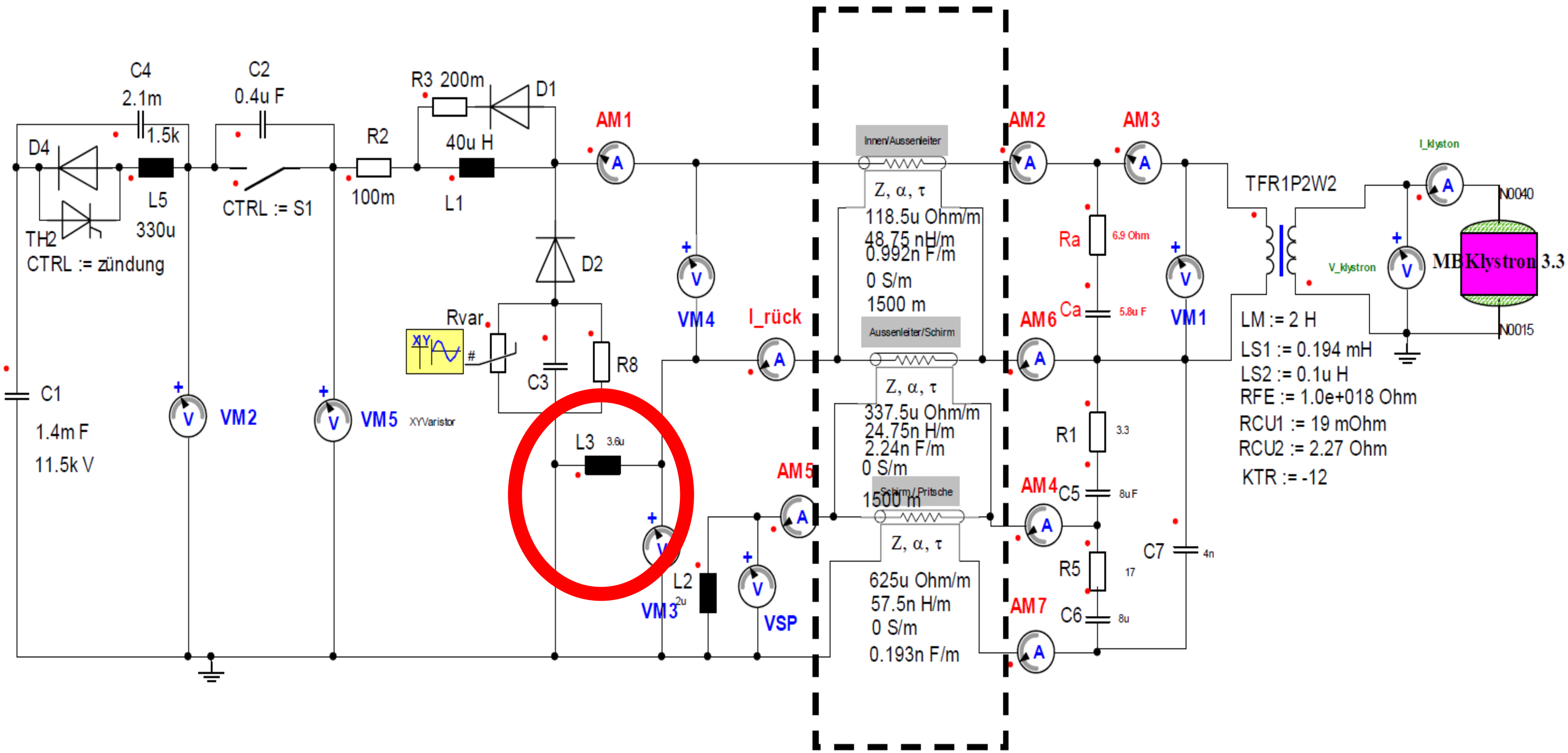


Schematic of the entire RF-station
Thomson modulator

+ just a few parasitics

For understanding EMI
One should look at these

Bouncer Modulator with pulse cables

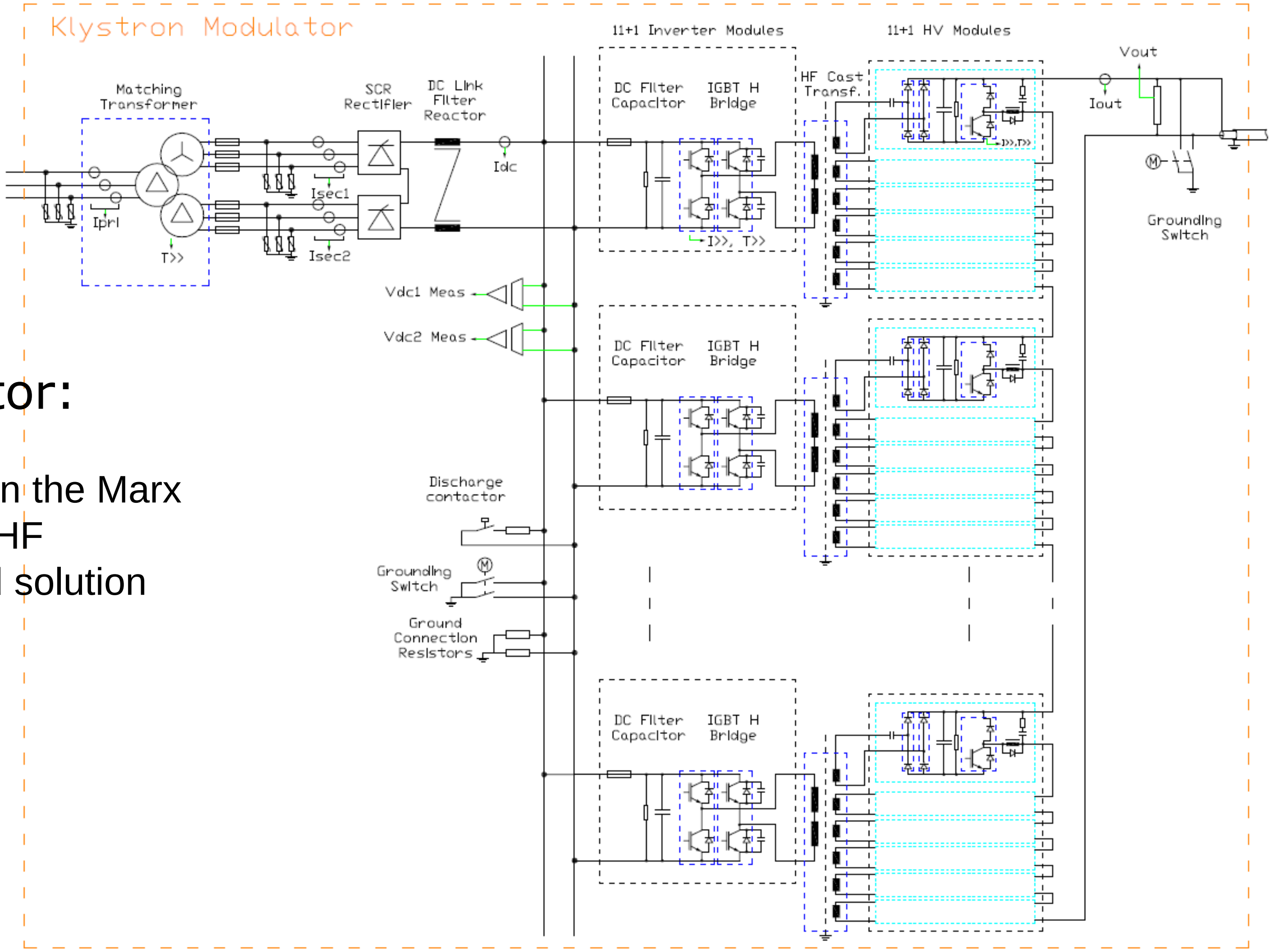


In the inductances the rise time of the current is transformed in voltages.

Near Future

- With the availability of new semiconductor devices new topologies can be chosen.
- Higher switching frequencies are possible.
- The general trend is to lower voltage components
- The large pulse transformer seems to be replaced by smaller HF transformers

Hybrid Inverter Marx System with Custom Potted Transformers

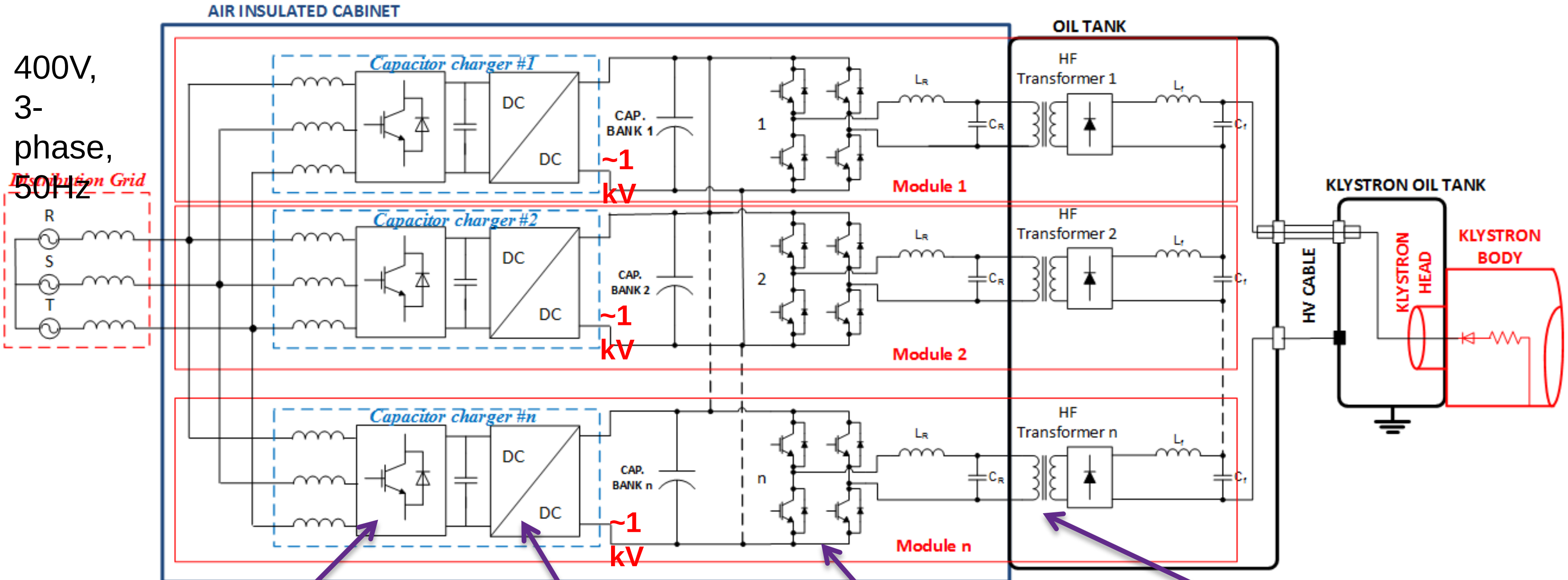


JEMA Modulator:

Topology in between the Marx Modulator and the HF transformers based solution
Switching at 4 kHz

The Stacked Multi-Level (SML) topology

Proposal by Carlos A. Martins ESS



- Sinusoidal current absorption;
- Power factor correction;

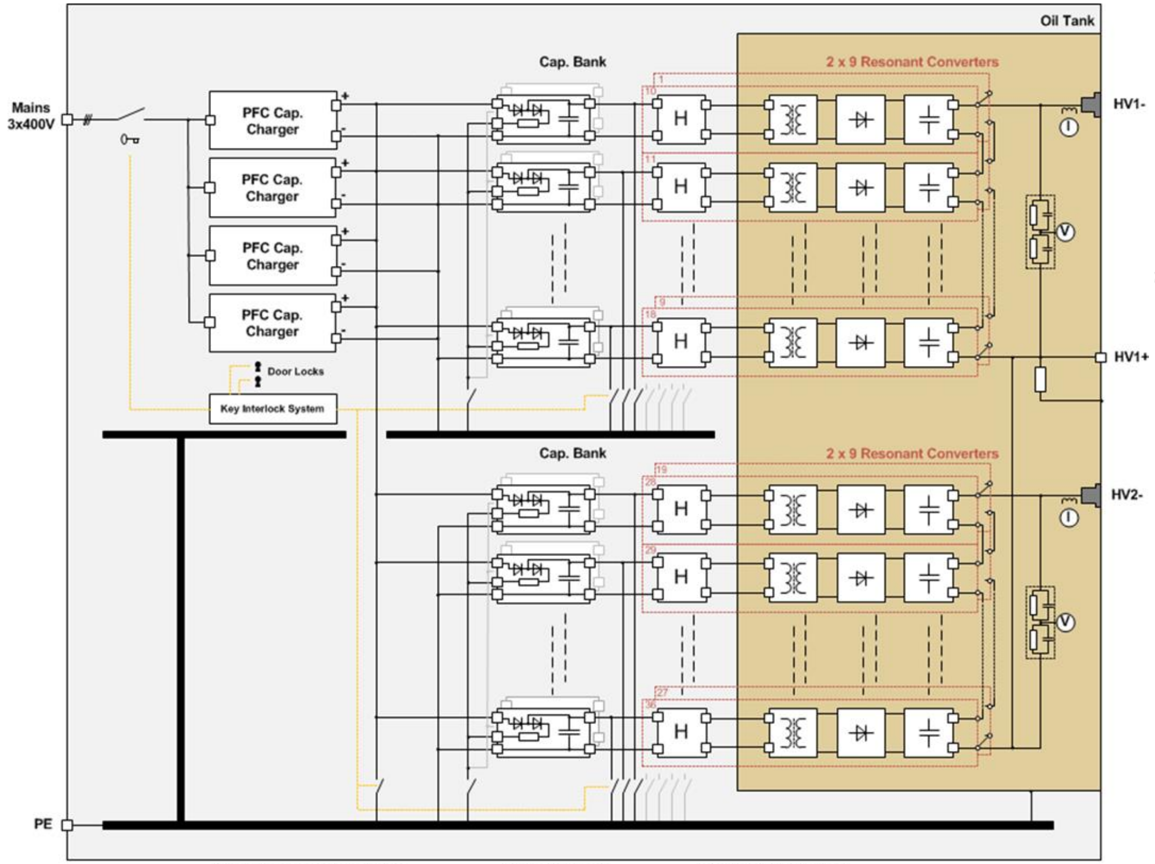
- Precise capacitor charging;
- Regulation of charging power (flicker free);

- Pulse forming;
- Droop compensation;
- Arc protection

- Galvanic isolation;
- Voltage amplification;

Modulator main functions by sub-system

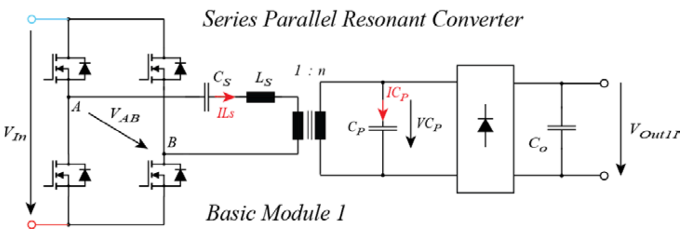
Ampegon proposal for ESS modulator
Switching at 100 kHz

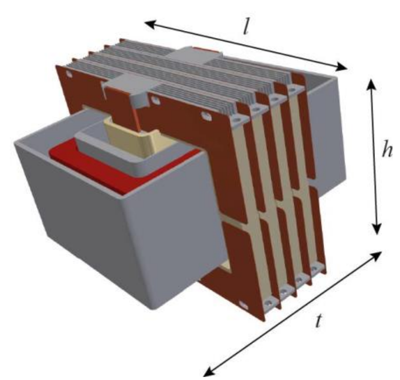


Cap. Charger Power Supply:
- 400V I - Controlled
- 4 x 3-Phase-PFC-Buck-Type-Rectifier (Swiss Rectifier)
- > 96% Efficiency

Capacitor Bank: +Discharging
- 30mF / 400V
- Self Healing
- Metalized PP
- Dry Type

Resonant Converters:
- 15kV / 12.5A per Converter
- Interleaved MOSFET Inverters
- Diode Rectifier
- Ferrite Transformer
- > 95% Efficiency





- l = 280 mm
- t = 264 mm
- h = 212 mm

The CERN Accelerator School

Conclusion

- A lot of interesting R&D was done the last few years and different topologies are available on the market
- There is a lot of development ongoing in the near future which is possible to new and better semiconductors.
- In the near future several large projects will use long pulse modulators:
  - XFEL commissioning
  - European Spallation Source
  - International Linear Collider
  - Project X
  - CLIC

- Power electronic engineers will have a lot of fun.

Thank you for your attention

Questions? !

More values of the modulator

- $I_{rms} = \sqrt{\frac{1}{T}\int_{t0}^{t0+T}(i(t))^2 dt}$

- $I_{rms} = \sqrt{\frac{1}{T} * {I_0}^2 * t}$

- $P_{mod\ out} = \frac{P_{pulse} * t}{T}$

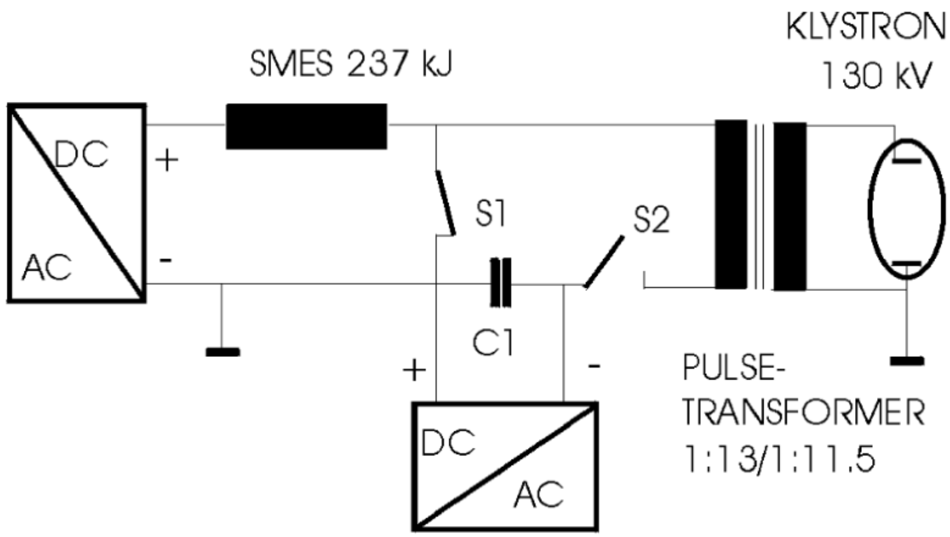
- $P_{mod\ in} = \frac{P_{pulse} * t}{T} * \eta$

Ampegon modulator prototype

Ampegon new output filter with solenoid chokes

PPT Modulator with FuG constant power power supply

25 MW-SMES modulator by Jüngst, KIT



Prototype built but has not been approved for accelerator use