Modulator

Modulator Types (1)

Hard Tube / Series Switch Modulator

Pro:

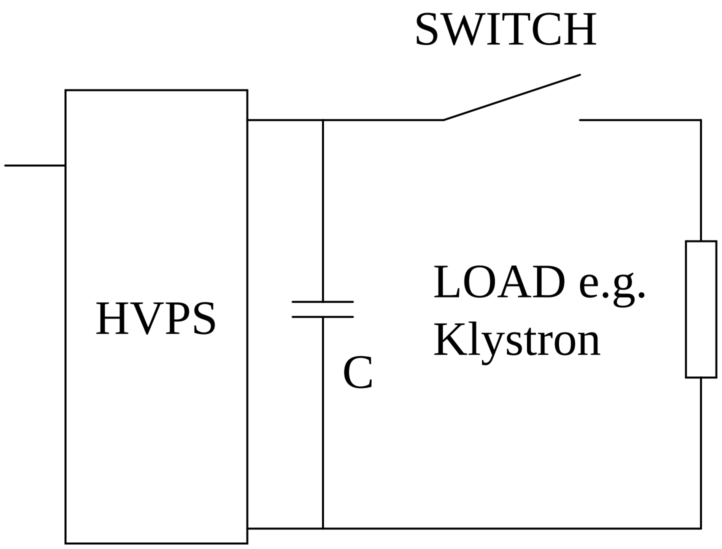
- Very simple circuit diagram

Con:

- Very high DC voltage (~100kV)
- Big capacitor bank

=> high stored energy

- Switch difficult if not impossible
  (high voltage, fast switching time,
  depends on high voltage level)



Some companies have developed semiconductor switches for 150KV/500A

Modulator Types (1b)

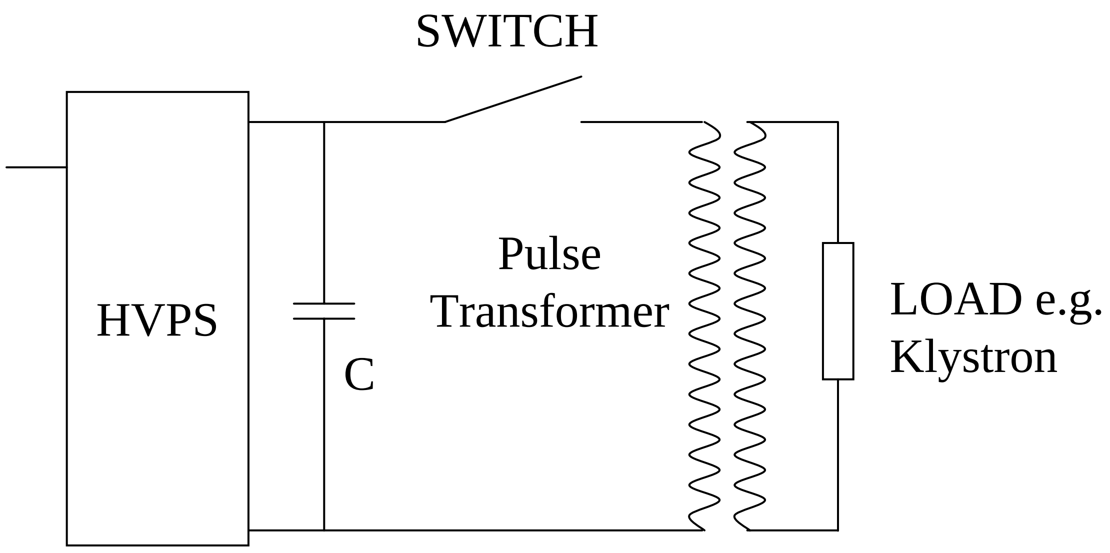
Hard Tube / Series Switch Modulator

- Capacitor have to store for 1% voltage droop 50 times the pulse energy
  example: 1.5ms, 120kV, 140A, 25kJ pulse energy, stored energy 1.26MJ (C= 175mF, U =120kV)

- Switch can be vacuum tube (triode, tetrode) or stack of semiconductors (IGBT, IGCT, GTO, MOSFET)

Modulator Types (2)

Hybrid (Series Switch with Pulse Transformer)



Pro:

- Lower DC Voltage
- Switch easier

Con:

- Higher current
- High stored energy
- Leakage inductance of pulse transformer limits pulse rise time

Modulator Types (3)

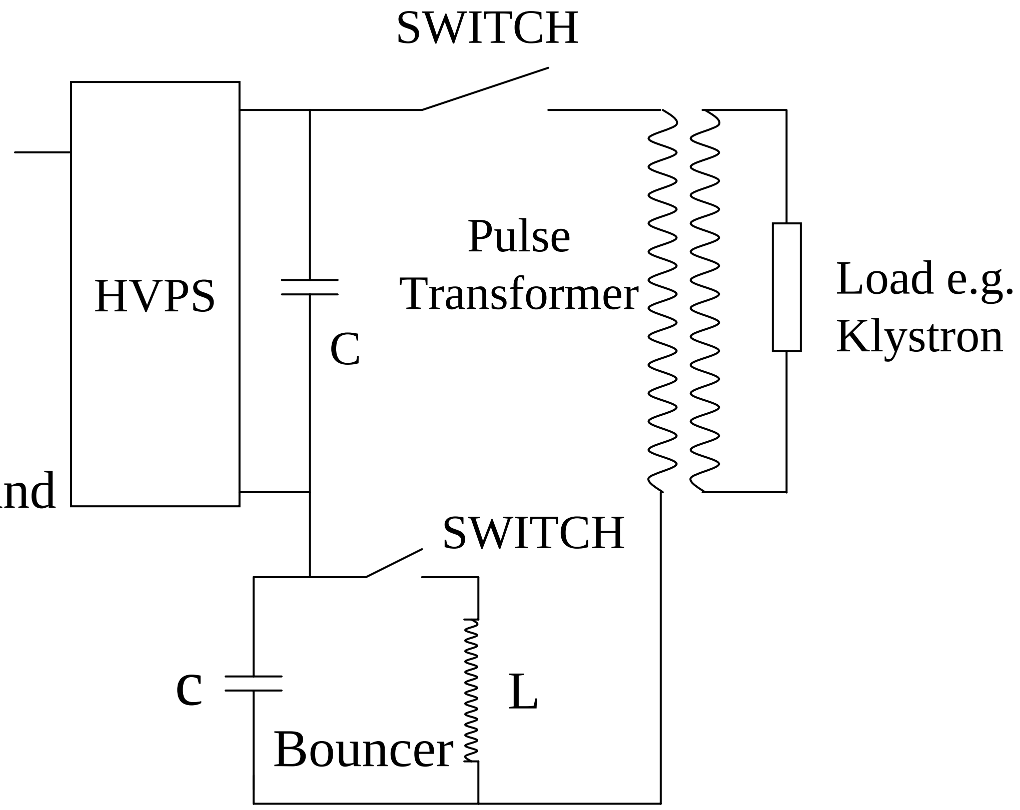
Bouncer Modulator

Pro:

- Lower stored energy

Con:

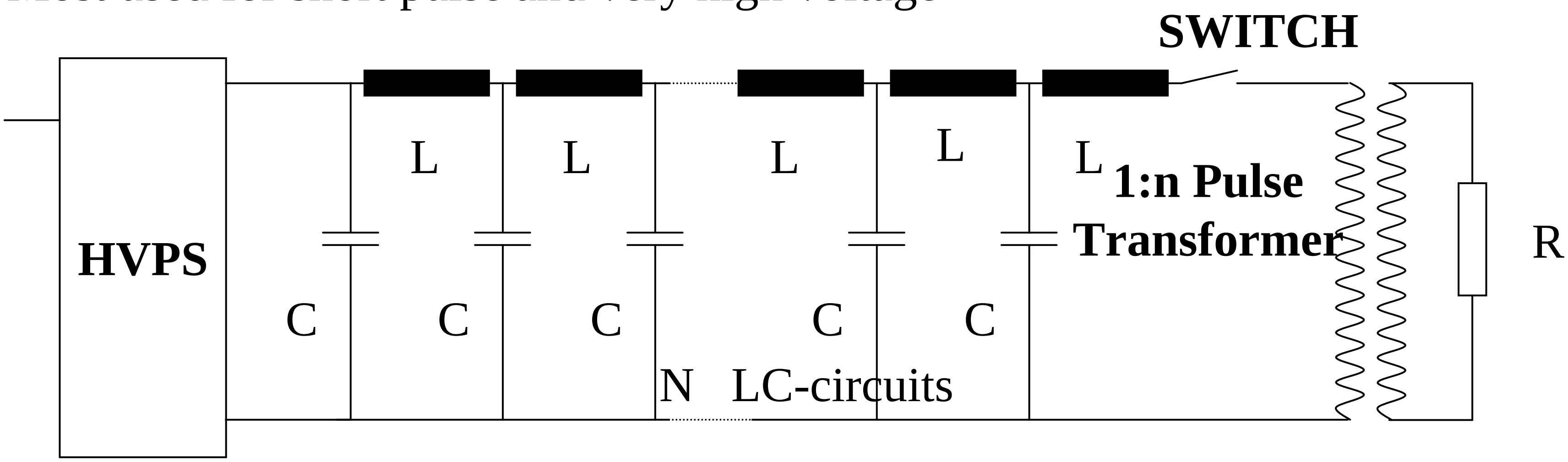
- Additional circuit with big choke and additional cap bank



Modulator Types (4)

PFN (Pulse Forming Network)

Most used for short pulse and very high voltage



Pro:

- Stored energy = Pulse energy
- Only closing switch required

Con:

- Pulse width $T = 2N \times \sqrt{L \times C}$ is not easy to adjust
- Pulse flat top must be tuned
- PFN Impedance $Z = \sqrt{L / C}$ must match load impedance $Z = R / n^2$
- Charging Voltage is 2 x Pulse Voltage

Modulator Types (5)

Series Resonant Converter

Developed at LANL (Bill Reass) for SNS

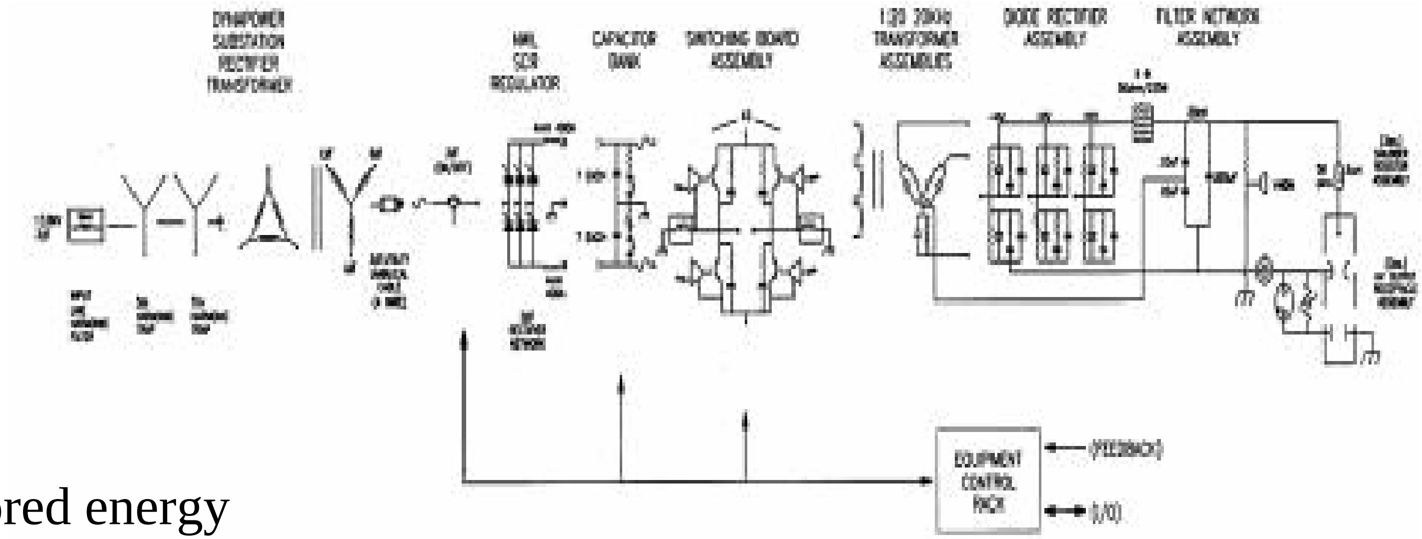


Figure 1 Simplified Block Diagram

Pro:

- Low stored energy
- Small size
- Regulation within pulse possible
- Installed at SNS

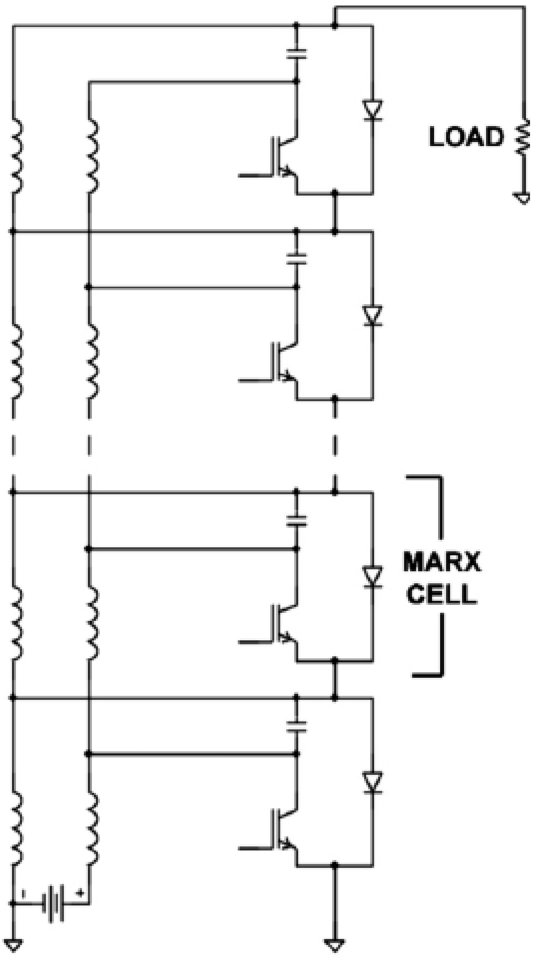
Con:

- New technology (e.g. IGBTs at high switching frequency, nanochrystalline transformer material) needs experience (but see Pro)

Modulator Types (6)

Marx Generator

Developed by Erwin Marx in the 1920s, proposed with modifications to the original design by Leyh, SLAC



Pro:

- Compact
- Potential of cost savings

Con:

- No prototype exits
- Typical use: very high voltage, short pulses, low rep. Rate (single shot), no rectangular waveform

Modulator Types (7)

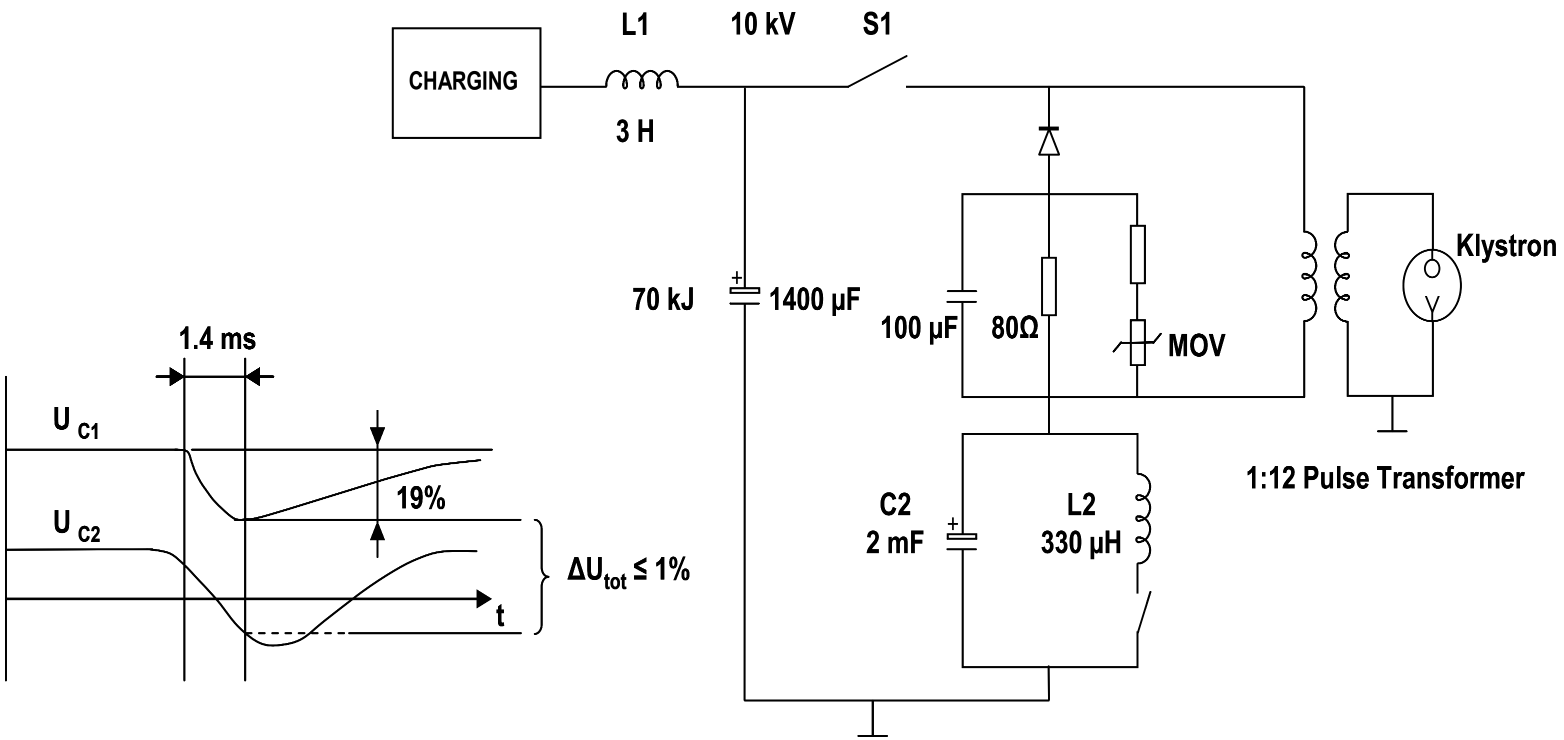
Other

- SMES superconducting magnetic energy storage (FZ Karlsruhe now installed at DESY)
- Induction type modulator
- Blumlein
- Switch mode PS
- Combinations of all already mentioned
- ……

TESLA Modulator Requirements

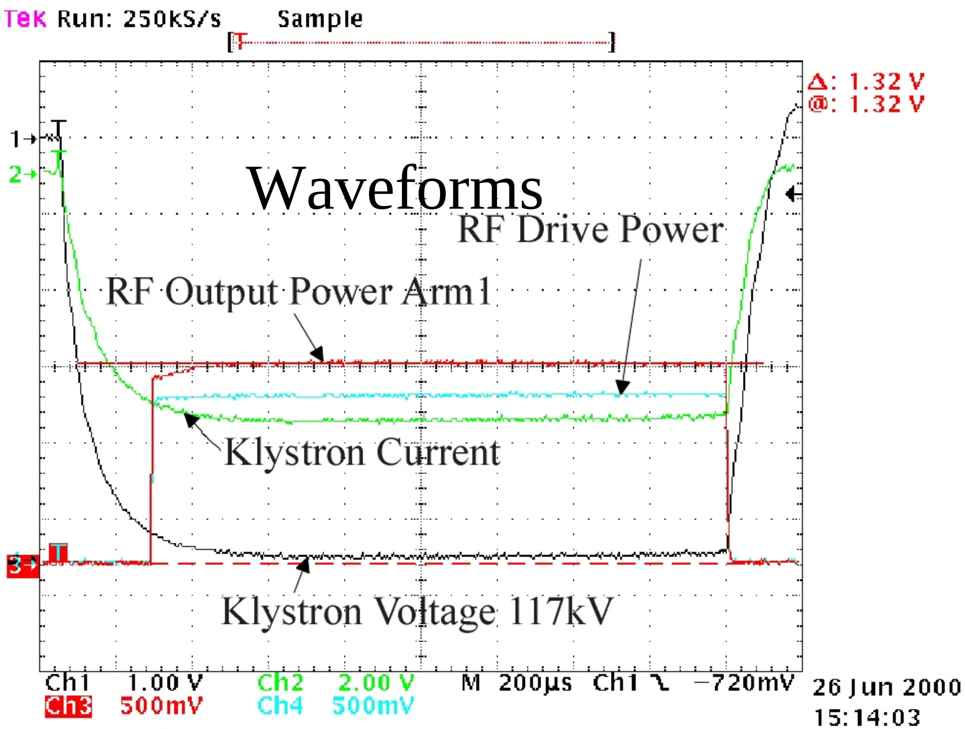
	Typical	**Maximum**
Klystron Gun Voltage:	115kV	130kV
Klystron Gun Current:	130A	150A
High Voltage Pulse Length:	<1.7ms	1.7ms
High Voltage Rise Time (0-99%):	<0.20ms	0.2ms
High Voltage Flat Top (99%-99%):	1.37ms	1.5ms
Pulse Flatness During 1.4ms Flat Top:	<±0.5%	±0.5%
Pulse-to-Pulse Voltage fluctuation:	<±0.5%	±0.5%
Energy Deposit in Klystron in Case of Gun Spark:	<20J	20J
Pulse Repetition Rate	5Hz	10Hz
Transformer-Ratio:	1:12	

Bouncer Modulator Principle



- The linear part of the oscillation of the bouncer circuit is used to compensate the voltage droop caused by the discharge of the main storage capacitor

The FNAL Modulator for TTF



FNAL Modulator at TTF

- 3 modulators have been developed, built and delivered to TTF by FNAL since 1994
- They are continuosly in operation under different operation conditions

Industry made Modulator for TTF (1)

- Industry made subunits (PPT, ABB, FUG, Poynting)
- Constant power power supply for suppression of 10Hz repetition rate disturbances in the mains
- Compact storage capacitor bank with self healing capacitors
- IGCT Stack (ABB); 7 IGCTs in series, 2 are redundant

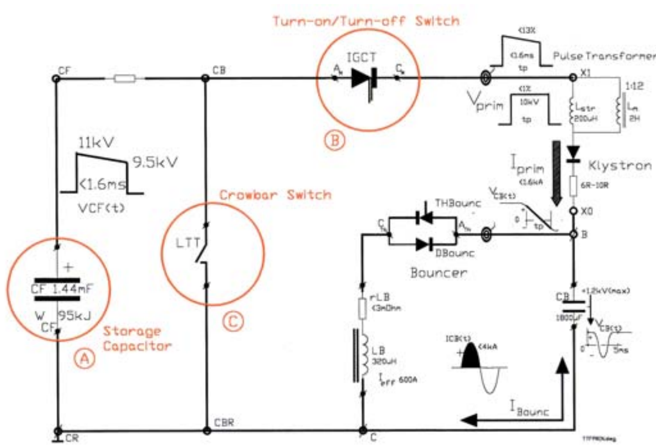
HVPS and Pulse Forming Unit

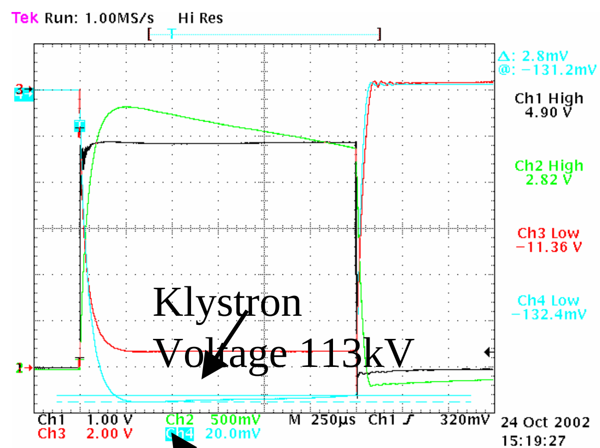
IGCT Stack

Industry made Modulator for TTF (2)

- Low leakage inductance pulse transformer (ABB) L<200mH resulting in shorter HV pulse rise time of <200ms
- Light Triggered Thyristor crowbar avoiding mercury of ignitrons

Pulse Transformer





Klystron Current 132A

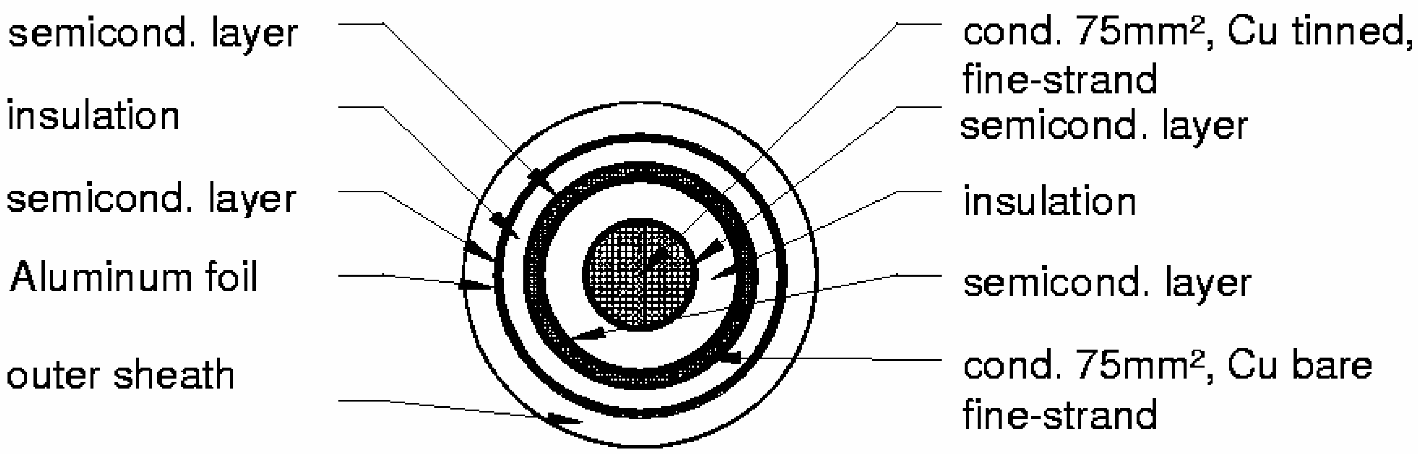
Bouncer Modulator Status

- 10 Modulators have been built, 3 by FNAL and 7 together with industry
- 9 modulators are in operation
- 10 years operation experience exists
- Many vendors for modulator components are available

HV Pulse Cable (1)

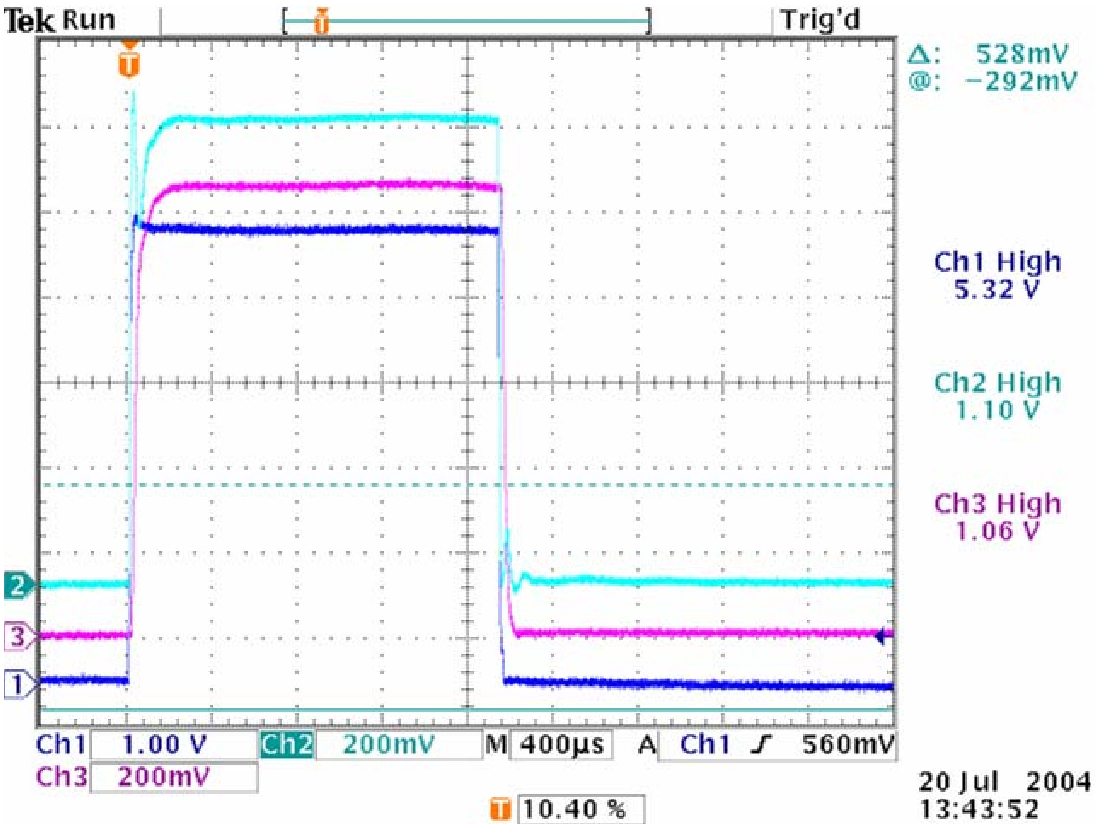
- Transmission of HV pulses (10kV, 1.6kA, 1.57ms, 10Hz from the pulse generating unit (modulator hall) to the pulse transformer (accelerator tunnel) if PGU and PT are separated
- Length ~3km (depends on site and tunnel layout)
- Impedance of 25 Ohms (4 cable in parallel will give 6.25 Ohms in total) to match the klystron impedance
- Triaxial construction (inner conductor at 10kV, middle conductor at 1kV, outer conductor at ground)

HV Pulse Cable (2)



Diameter 30mm
Dielectric material: XLPE

HV Pulse Cable (3)



Primary Current 1.1kA

Klystron Voltage 128kV

Primary Voltage 10.6kV

- Test with 1.5km long cables and a 5MW klystron show the feasibility of pulse transmission
- Remaining problem: EMI needs investigation