



# *Modulator*

## Hard Tube / Series Switch Modulator

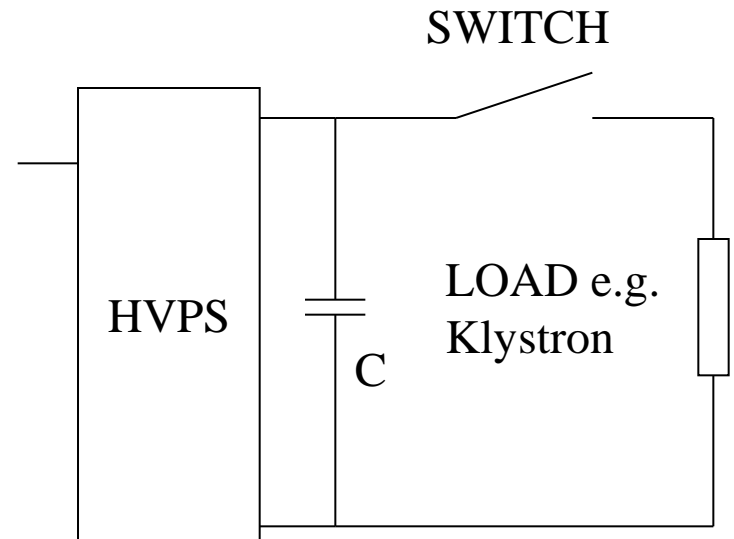
### Pro:

- Very simple circuit diagram

### Con:

- Very high DC voltage ( $\sim 100\text{kV}$ )
- 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  $150\text{KV}/500\text{A}$





## *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)

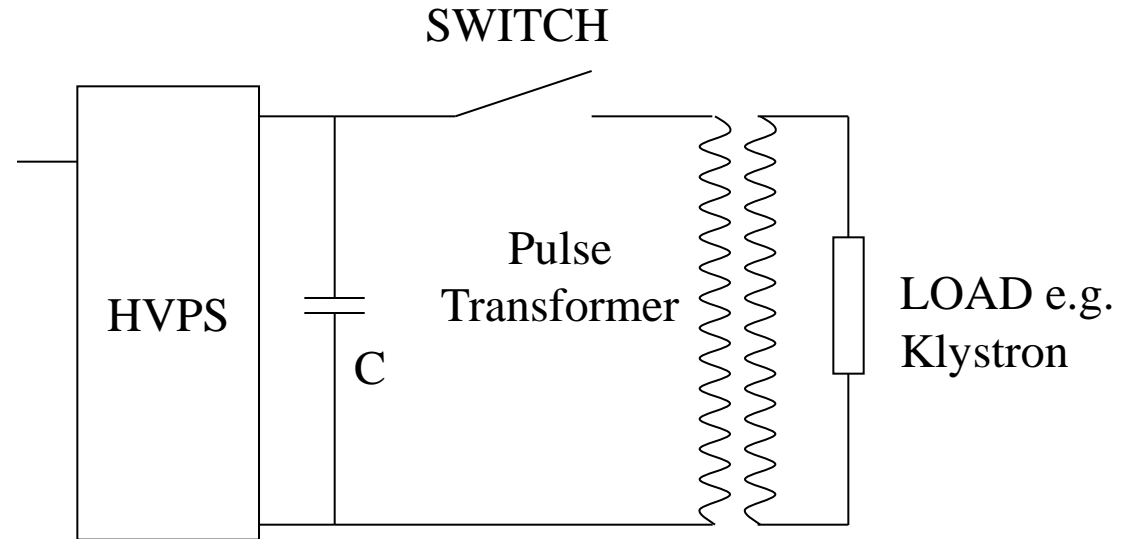
### Hybrid (Series Switch with Pulse Transformer)

#### Pro:

- Lower DC Voltage
- Switch easier

#### Con:

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



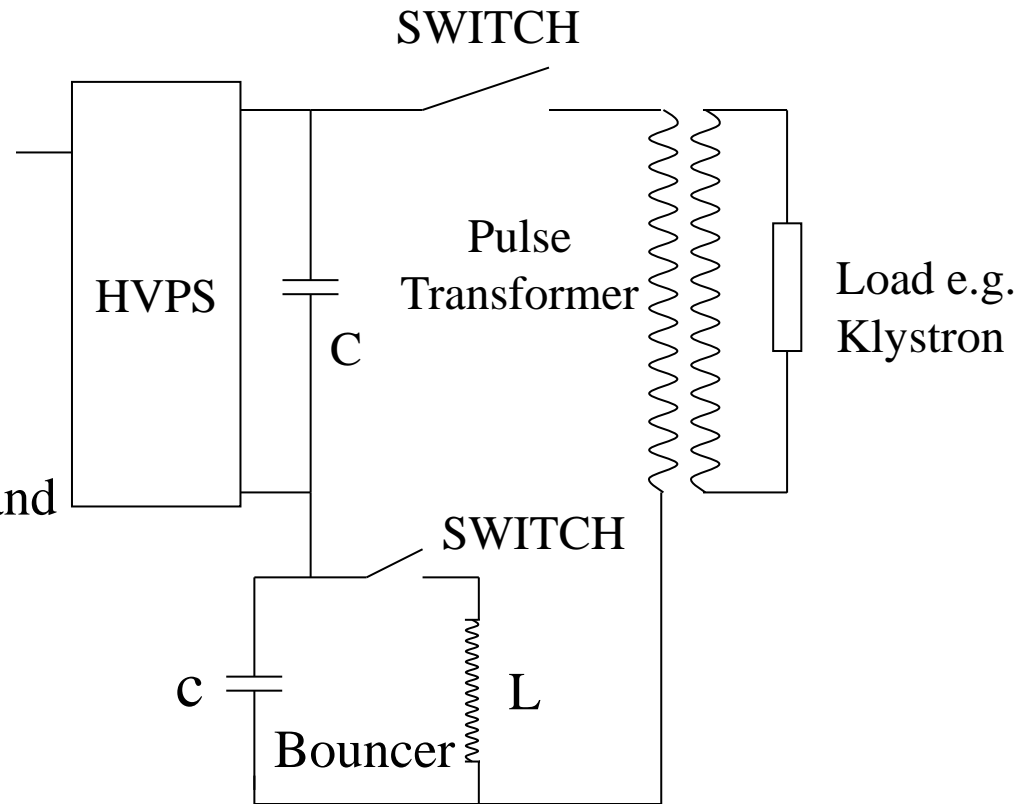
## Bouncer Modulator

### Pro:

- Lower stored energy

### Con:

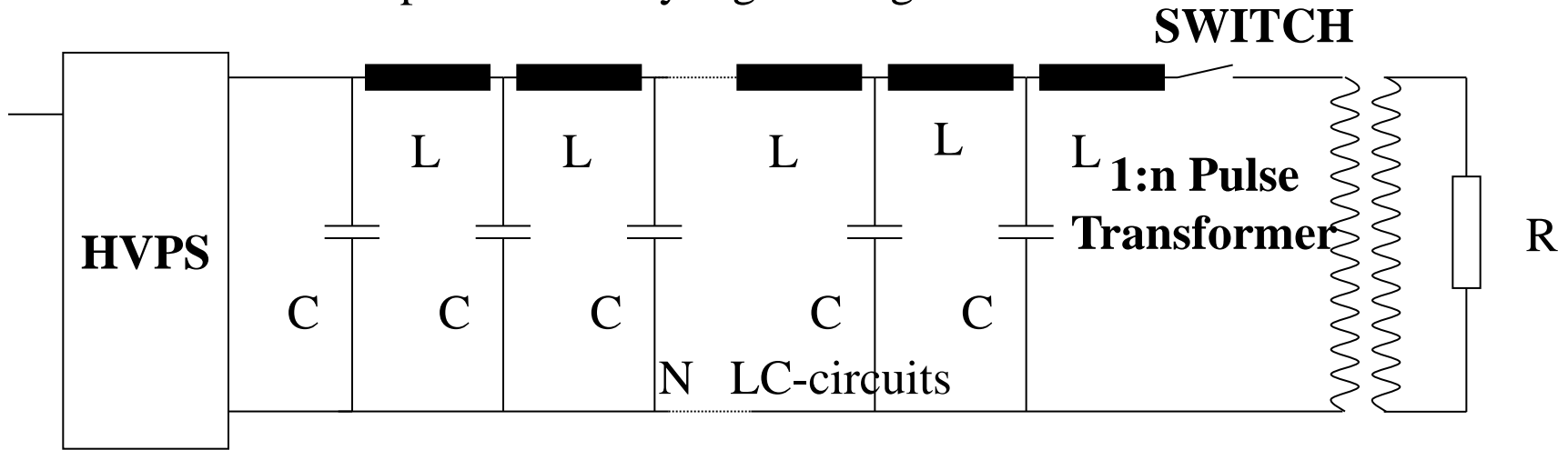
- Additional circuit with big choke and additional cap bank



# 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

## Series Resonant Converter

Developed at LANL (Bill Reass) for SNS

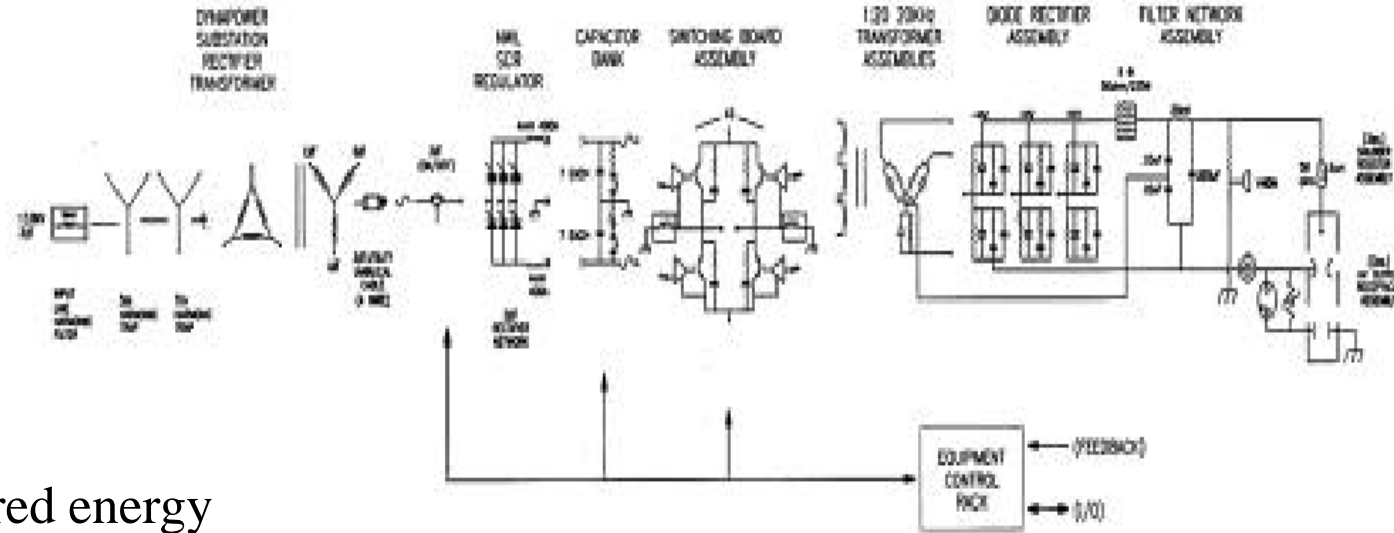


Figure 1 Simplified Block Diagram

### Pro:

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

### Con:

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

## Marx Generator

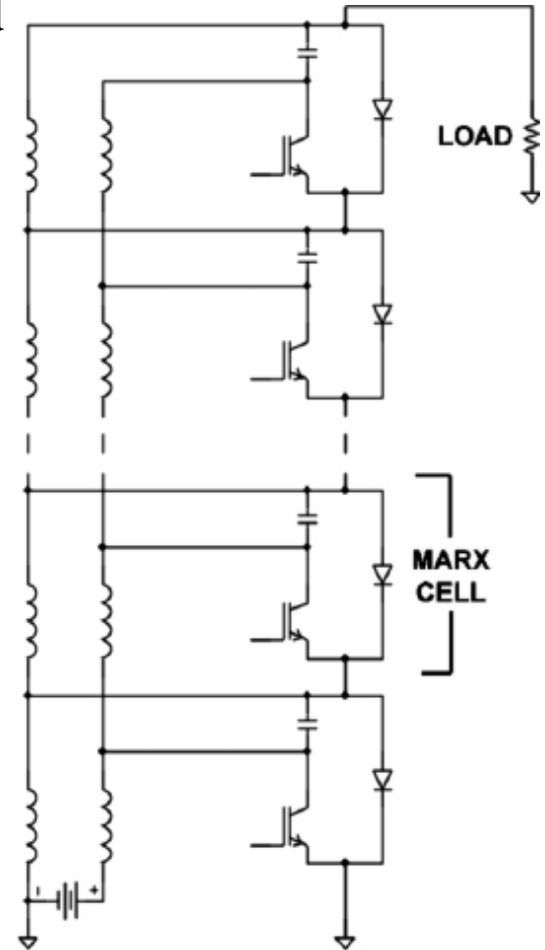
Developed by Erwin Marx in the 1920s, proposed with modifications to the original design by Leyh, SLAC

### Pro:

- Compact
- Potential of cost savings

### Con:

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







## *Modulator Types (7)*

### **Other**

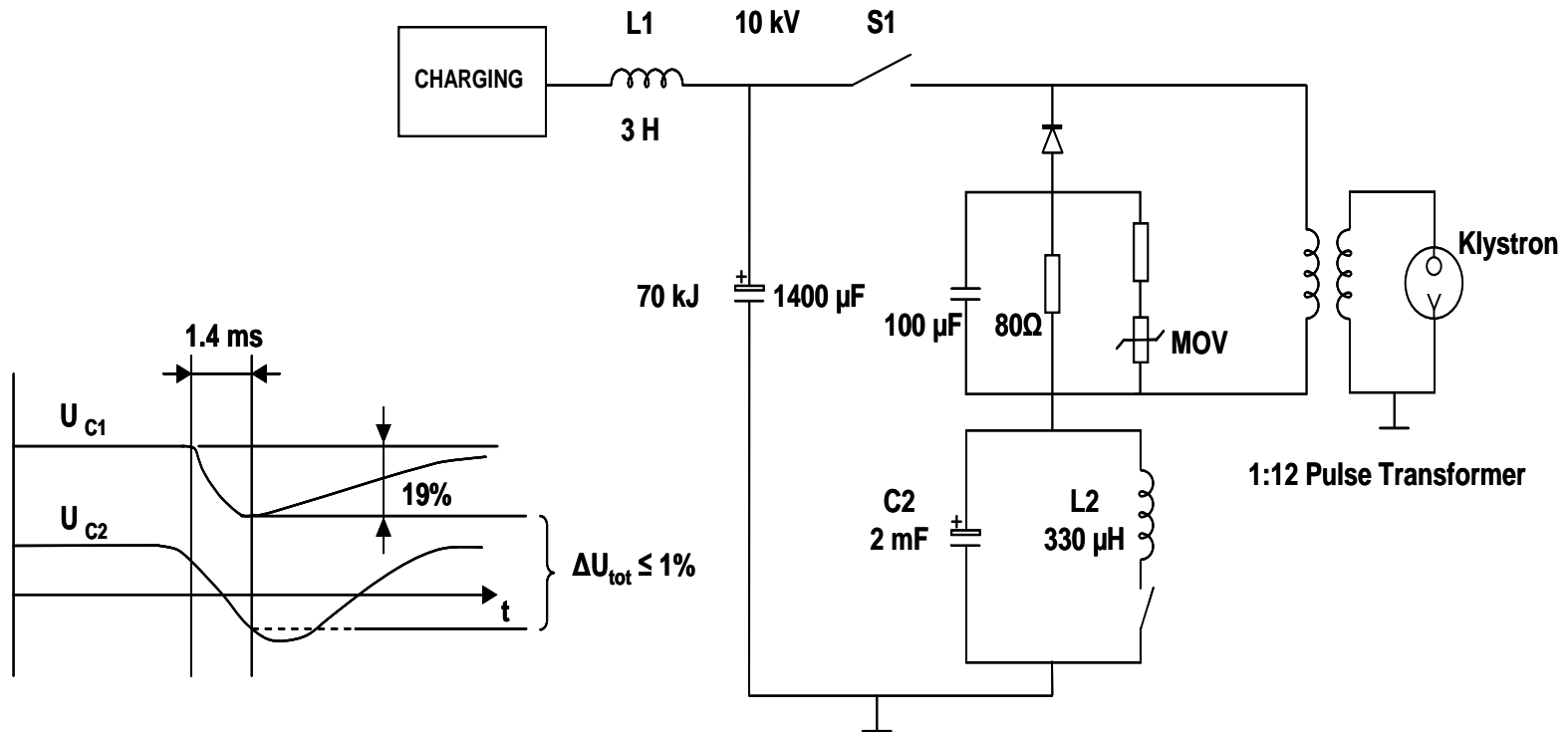
- SMES superconducting magnetic energy storage (FZ Karlsruhe now installed at DESY)
- Induction type modulator
- Blumlein
- Switch mode PS
- Combinations of all already mentioned
- .....



## *TESLA Modulator Requirements*

	<b>Typical</b>	<b>Maximum</b>
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:	< $\pm 0.5\%$	$\pm 0.5\%$
Pulse-to-Pulse Voltage fluctuation:	< $\pm 0.5\%$	$\pm 0.5\%$
Energy Deposit in Klystron in Case of Gun Spark:	<20J	20J
Pulse Repetition Rate	5Hz	10Hz
Transformer-Ratio:	1:12	

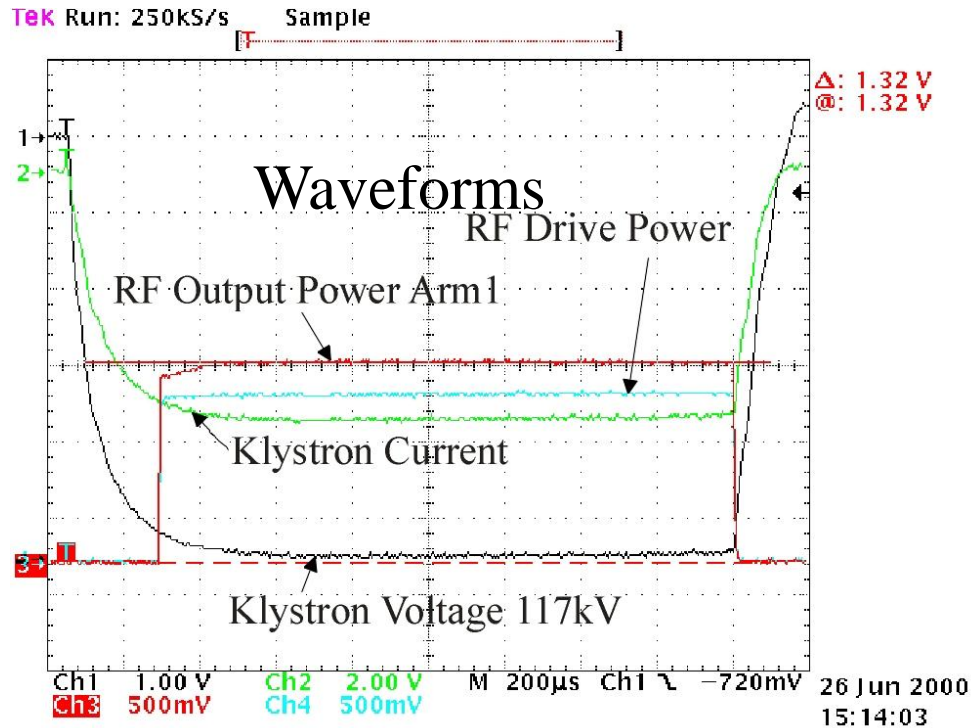
# Bouncer Modulator Principle



- 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**

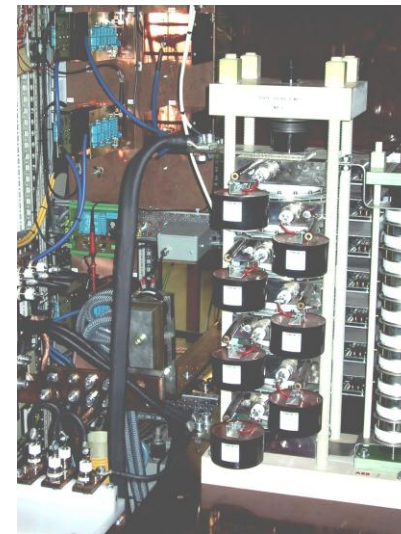
- 3 modulators have been developed, built and delivered to TTF by FNAL since 1994
- They are continuously in operation under different operation conditions



## *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**

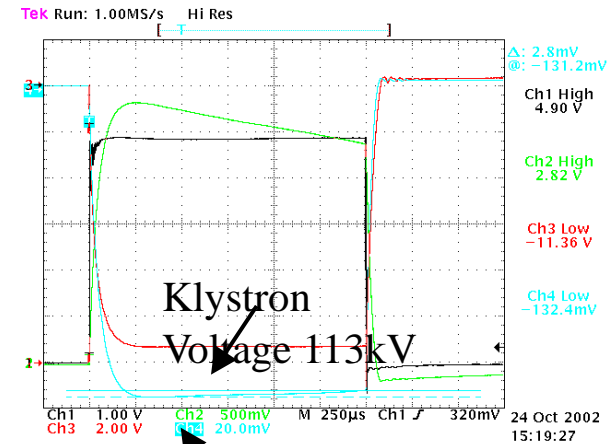
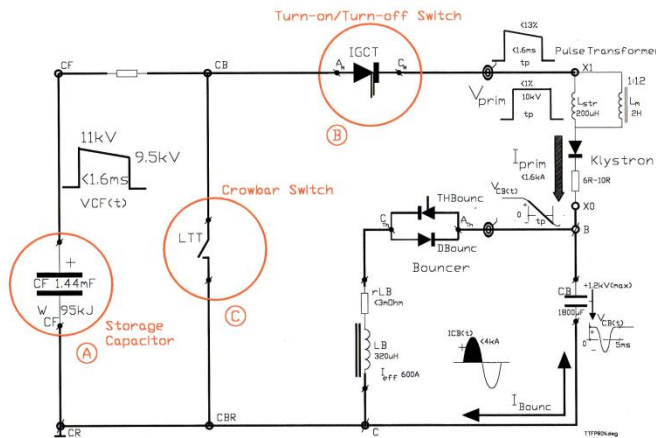


# Industry made Modulator for TTF (2)

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



**Pulse Transformer**





## *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

- Modulators must together with pulse transformer generate HV pulses up to 120kV and 140A, 1.57ms pulse length and 10Hz (30Hz) repetition rate.
- The top of the pulse must be flat within 1% .



- Pulse step modulator has been chosen. It has been successfully tested at the MTF at DESY Zeuthen.

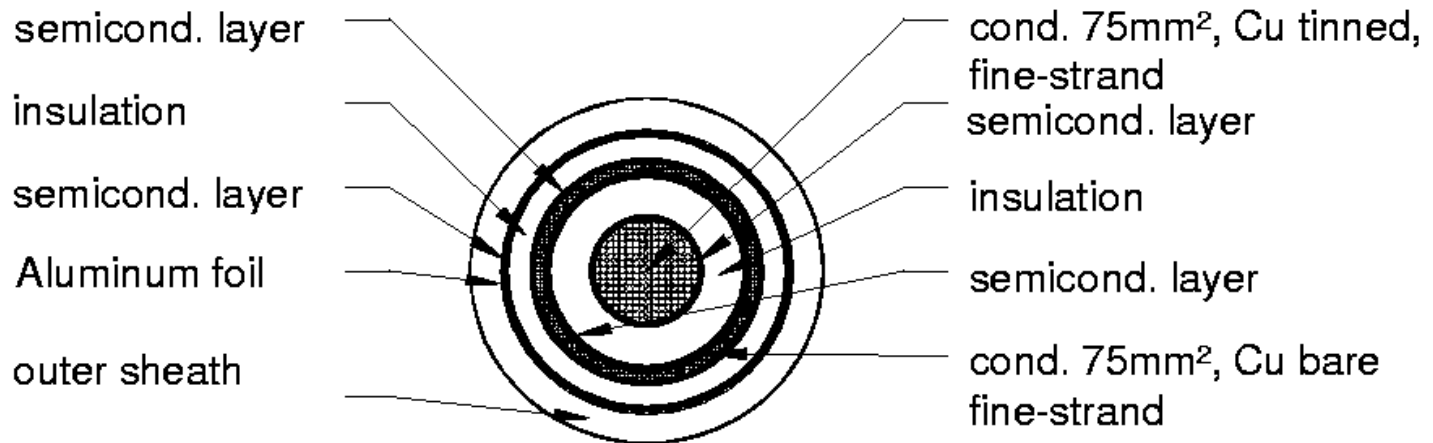




## *HV Pulse Cable (1)*

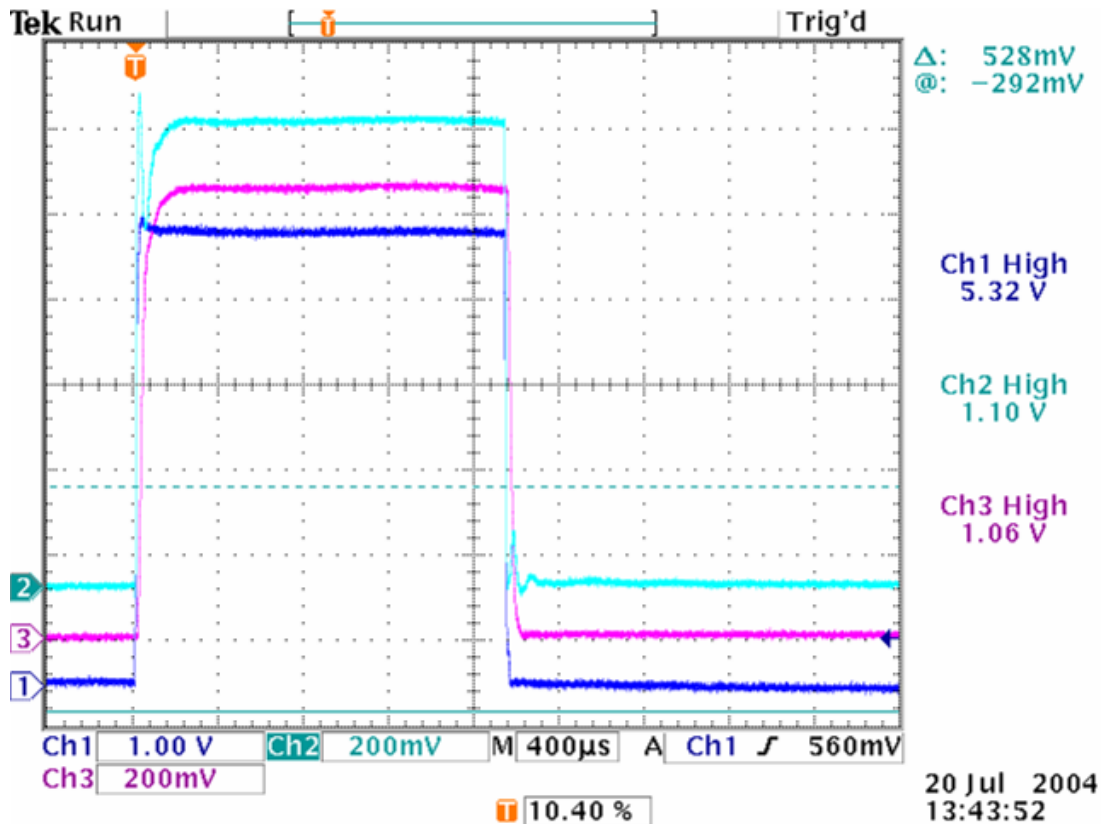
- Transmission of HV pulses (10kV, 1.6kA, 1.57ms, 10Hz from the pulse generating unit (modulator hall) to the pulse transformer (accelerator tunnel) if PGU and PT are separated
- Length ~3km (depends on site and tunnel layout)
- Impedance of 25 Ohms (4 cable in parallel will give 6.25 Ohms in total) 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**



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