University of Cardiff   11th. April 2000
Design of Solid State Pulsers

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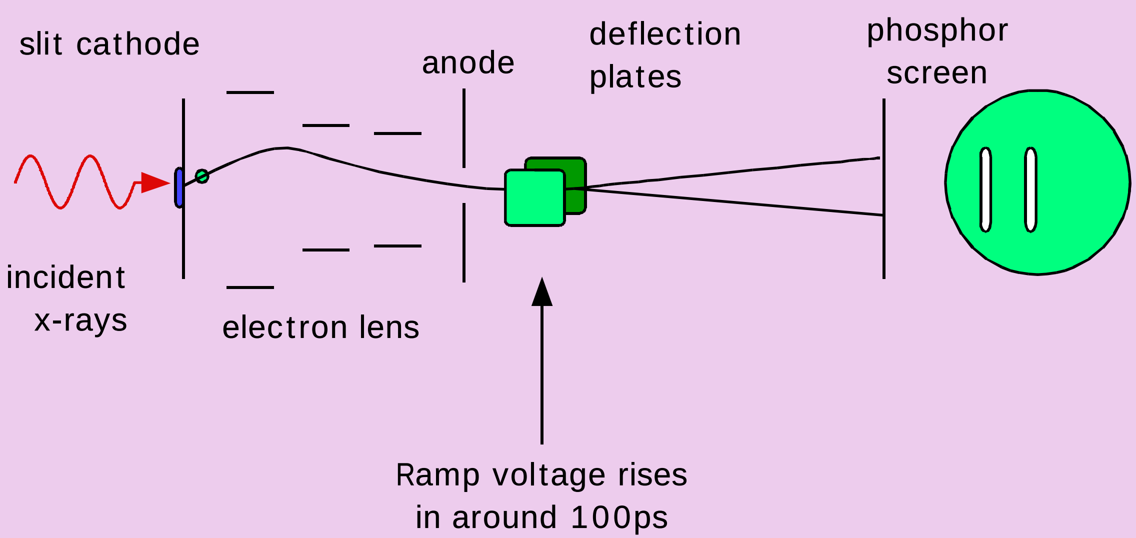
these notes will be posted at
www.kentech.co.uk/tutorials.html

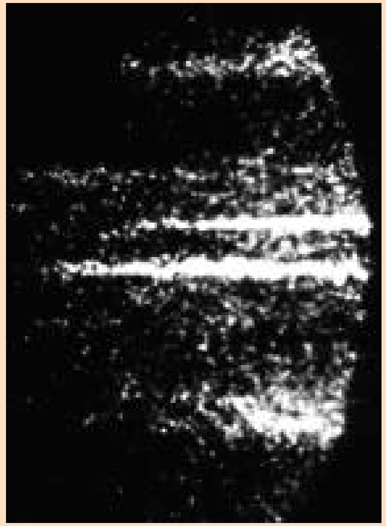
Formerly with Plasma Physics Group at Imperial College
Experience of streak cameras, fast gated cameras, fast high voltage pulsers, etc.
The pulsers are in use all over the world for a range of applications.

Scope of this talk

- Why make Pulse generators. What are they used for?
- General principles.
- Current designs pulsers.

Uses of Pulse Generators

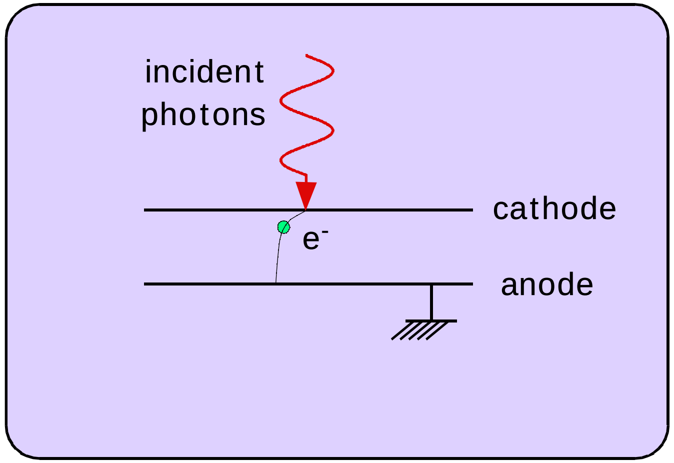


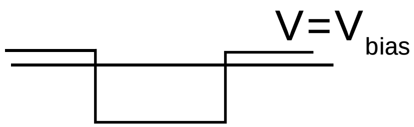


Sweeps of x-ray spectral lines Al Heγ (6.31Å) and Si Lyman α (6.17Å) from a layered target. The sweep calibration gives 3.3ps mm^{-1} at the camera output and a 7ps delay in the onset of Si emission

Streak Camera Ramp Generator

Cathode Gating

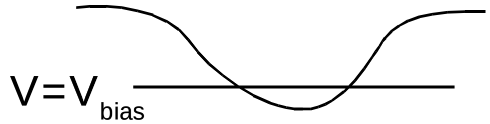




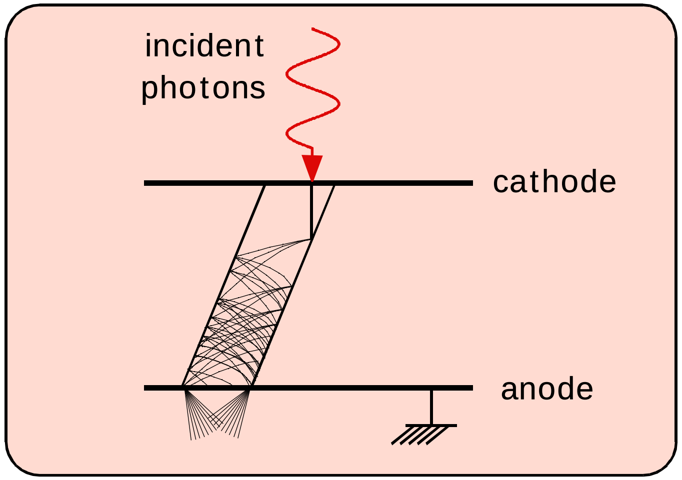
$I=0$ for $V>0$

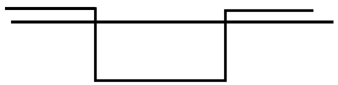
$I= I_{pc}$ for $V<0$

Even relatively slow pulses can give high bandwidth information.



Microchannel Plate Gating



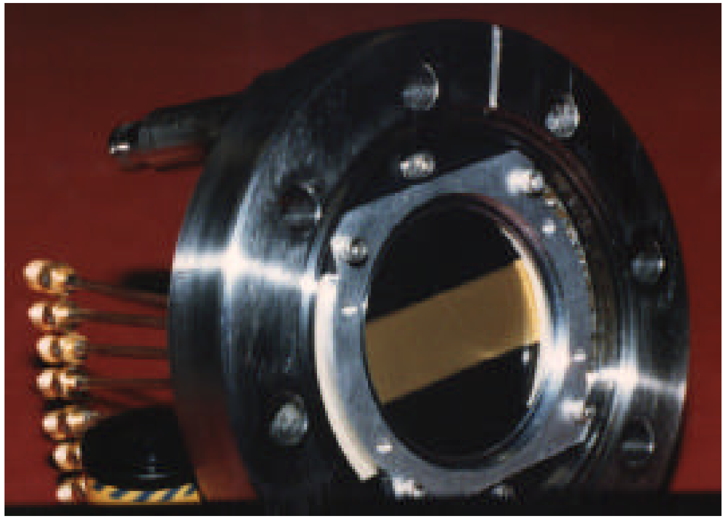


gain α V^n

$n > 1$

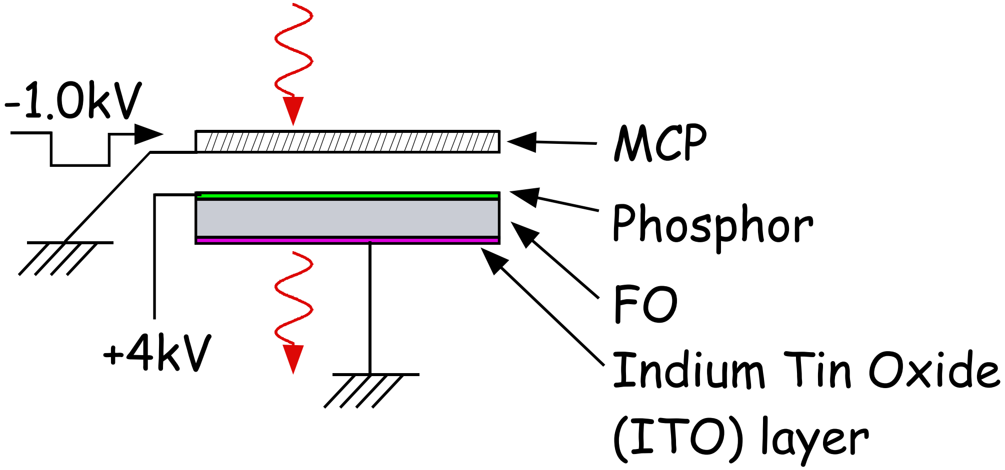
Even relatively slow pulses can give high bandwidth information.

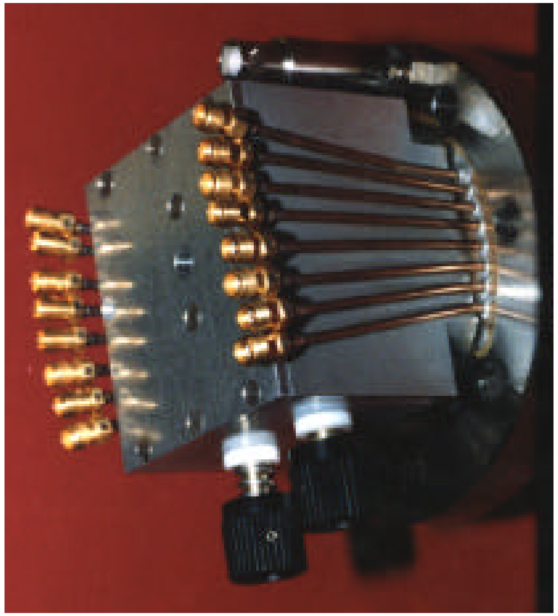
X-ray Gated Imagers



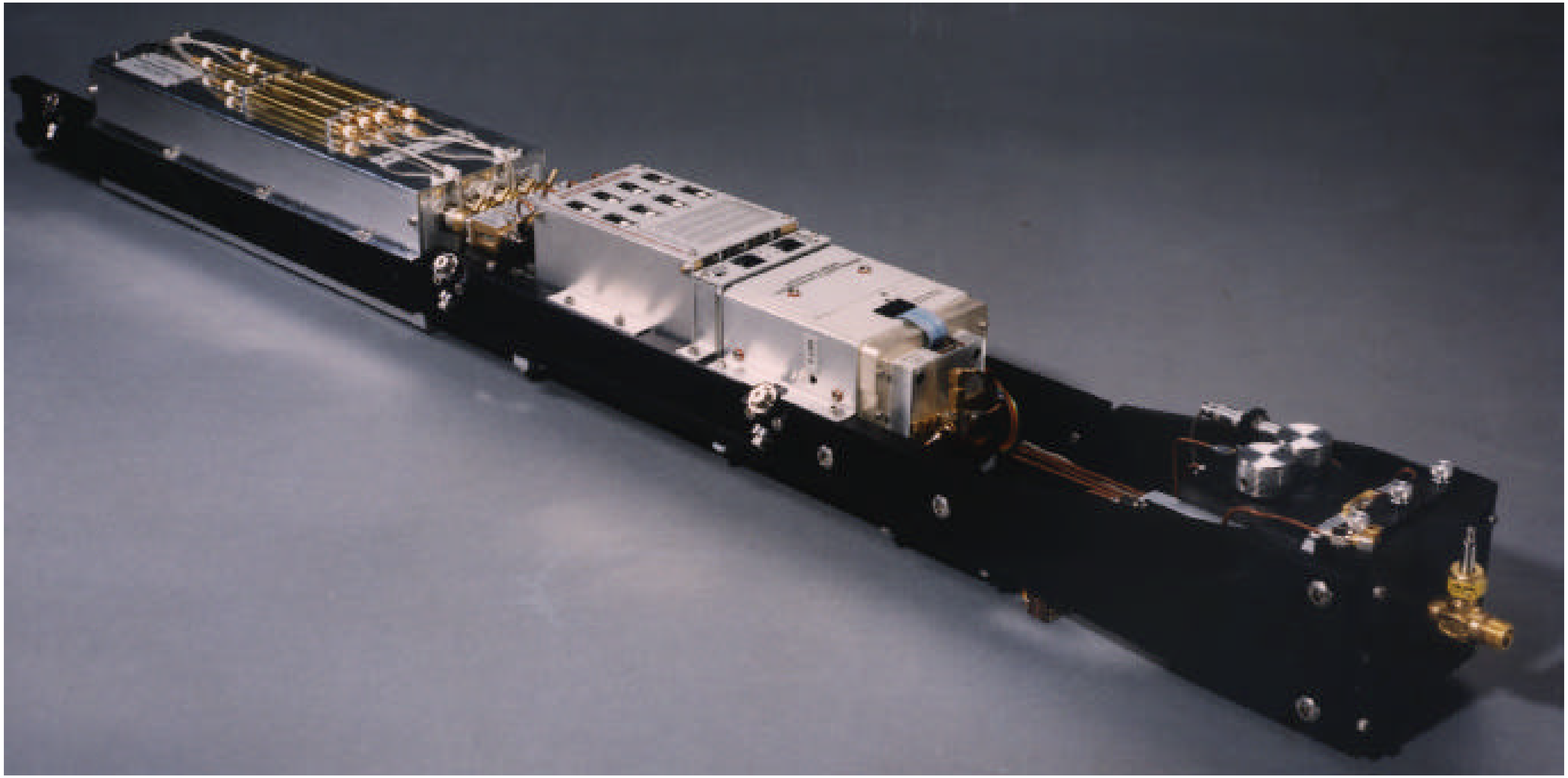
Gate Technique

- Gate the MCP, use stripline geometry.
- Gate voltage around 1kV.
- Devices are not normally sealed.



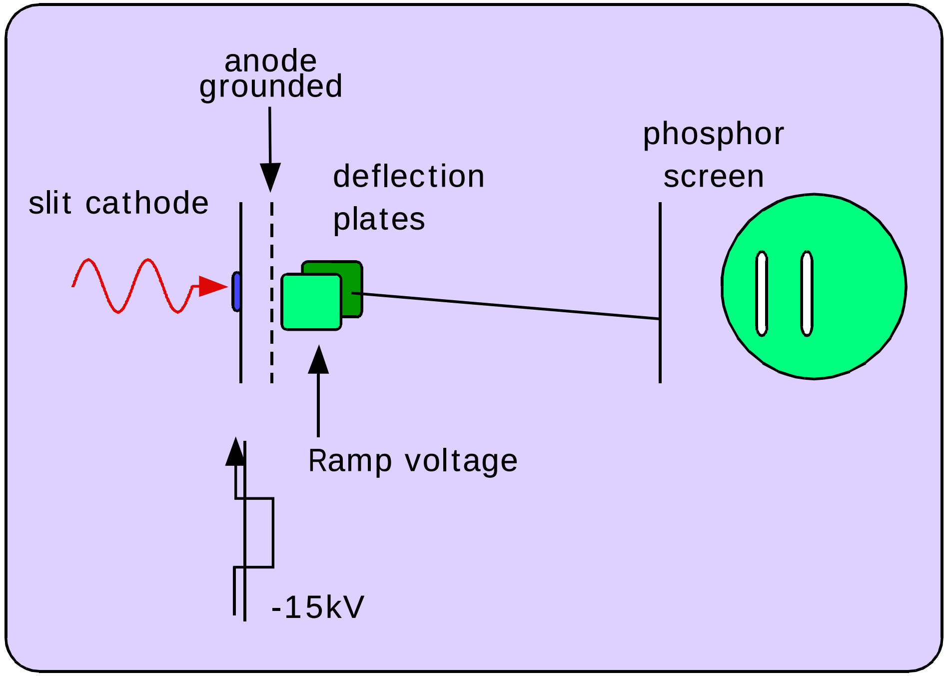


A typical X-ray Gated Stripline Imager

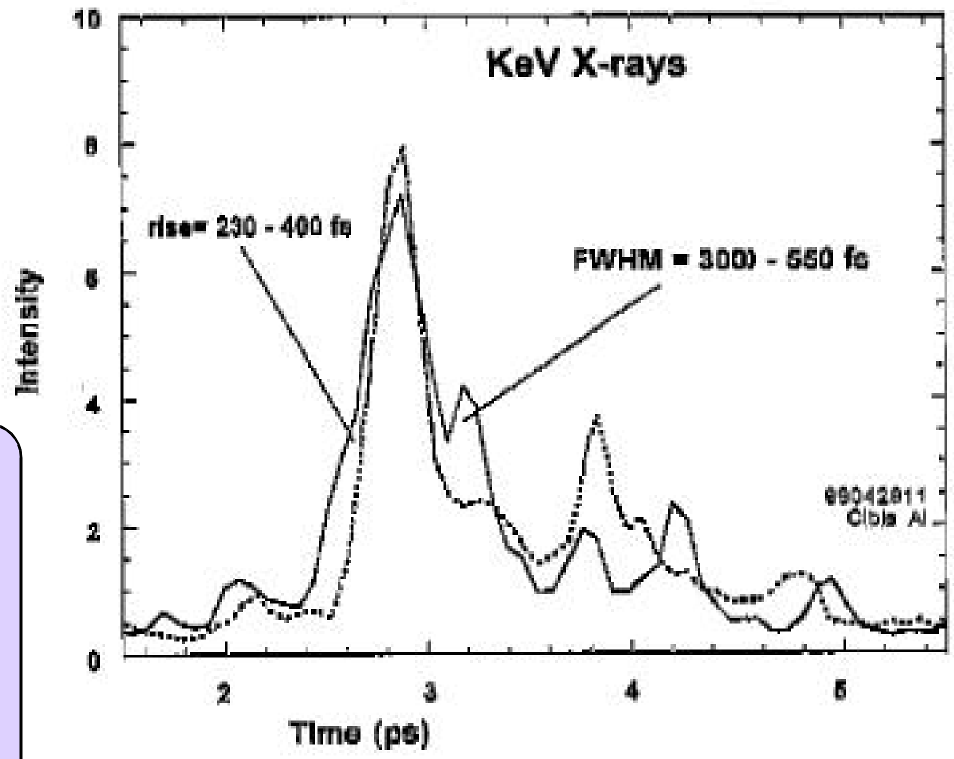


Sub Picosecond Streak Cameras

A proximity focussed X-ray streak camera using a pulsed cathode and extraction grid.



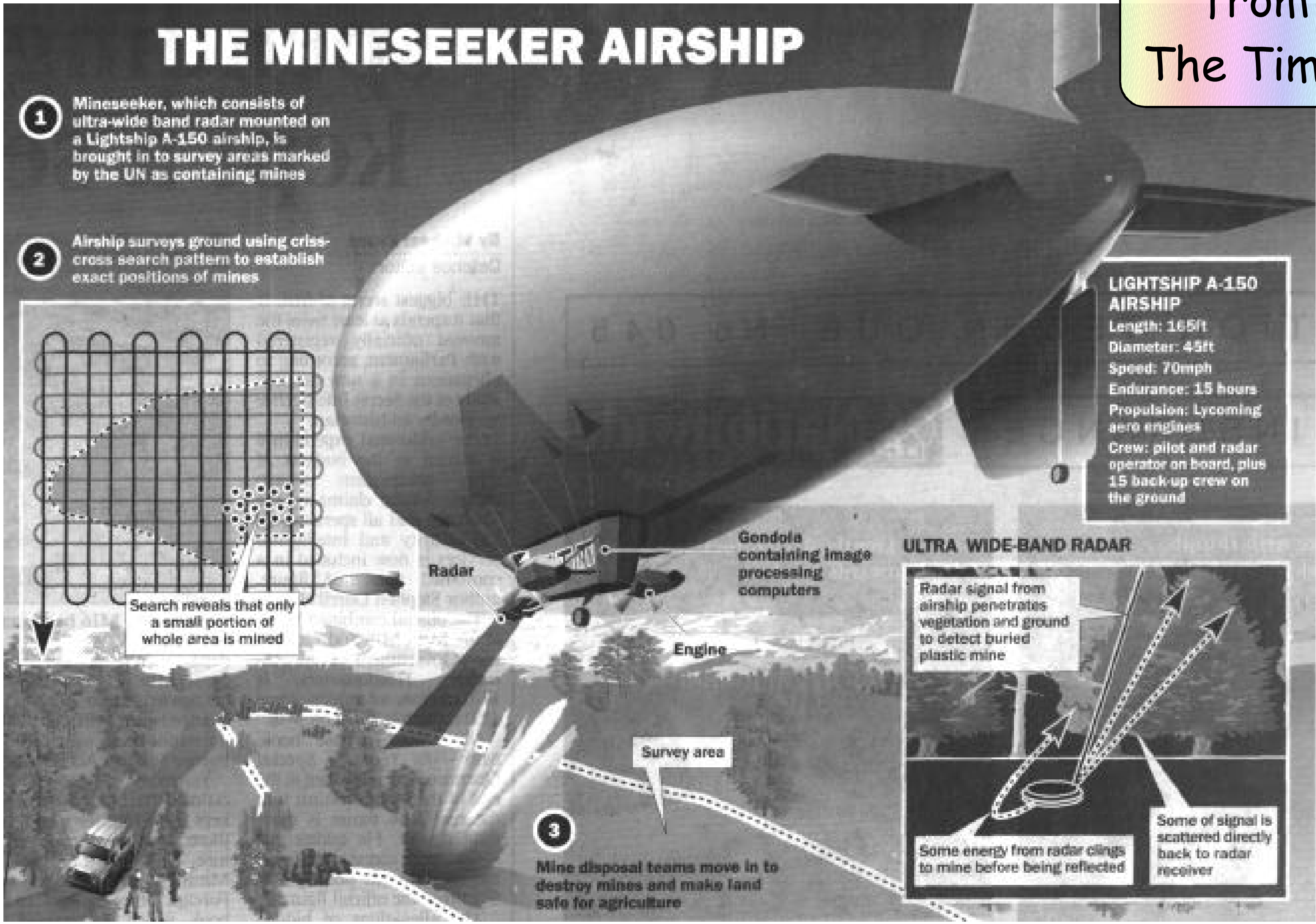
PX1 camera coupled to the Kentech cathode pulser.



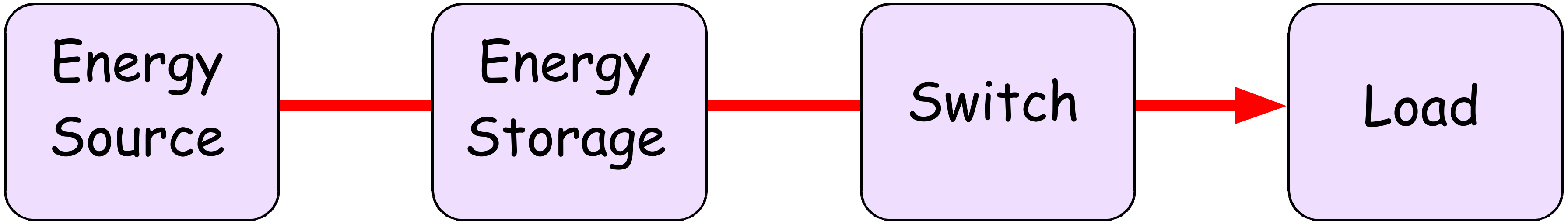
P. Gallant, Z. Jiang, J.C. Kieffer, INRS 18893, April 29

Ultra-wideband Radar

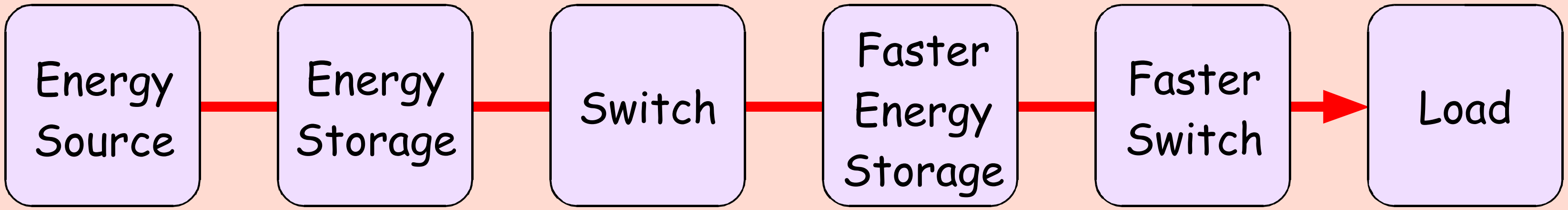
from The Times



Basic Principles



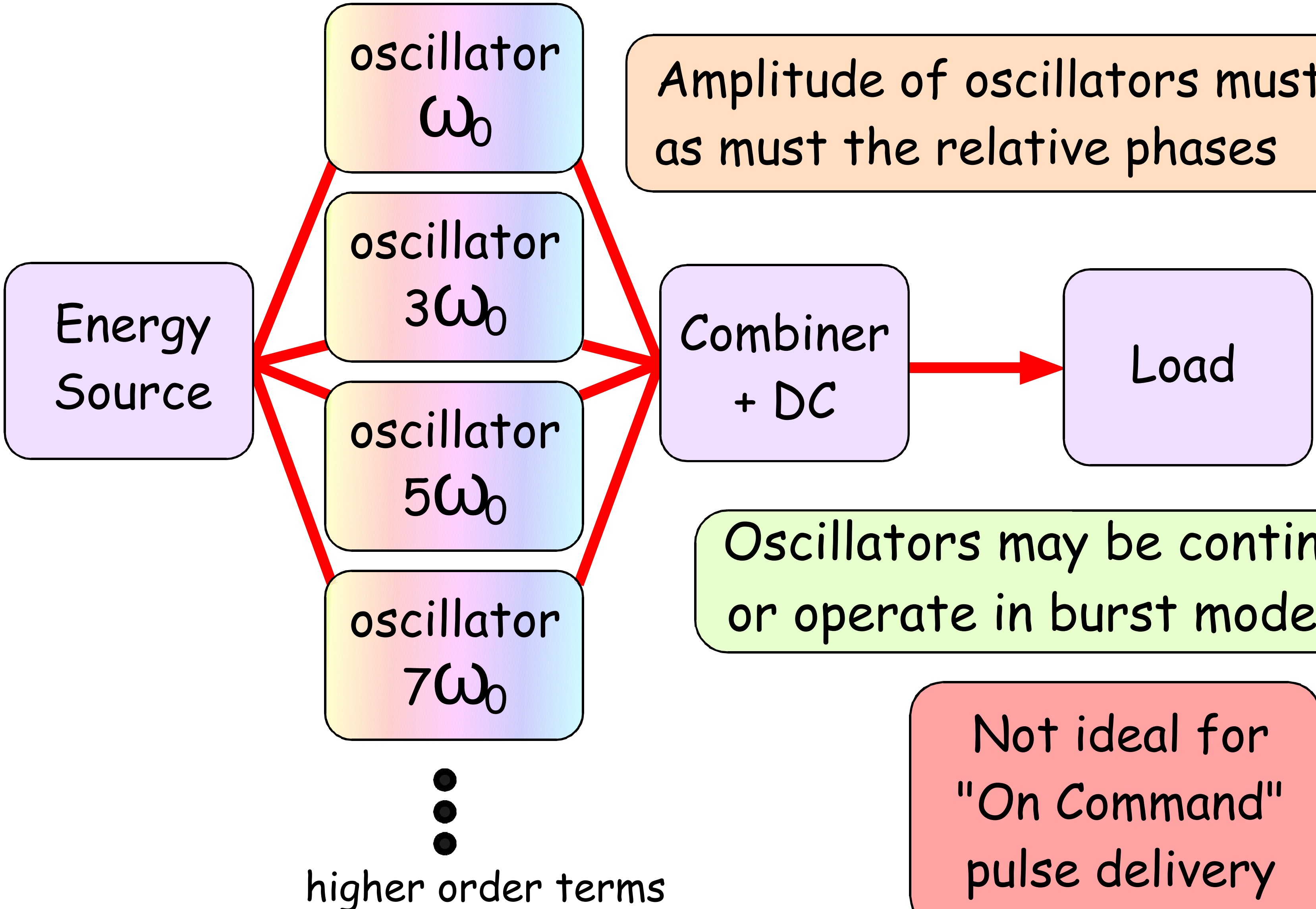
Slightly more complex system



This compresses the stored energy so that it is delivered more quickly, (more power).

This can be extended so that AC power can be turned into 50Hz 1ns spikes.

Alternative Strategy, [Fourier Synthesis]

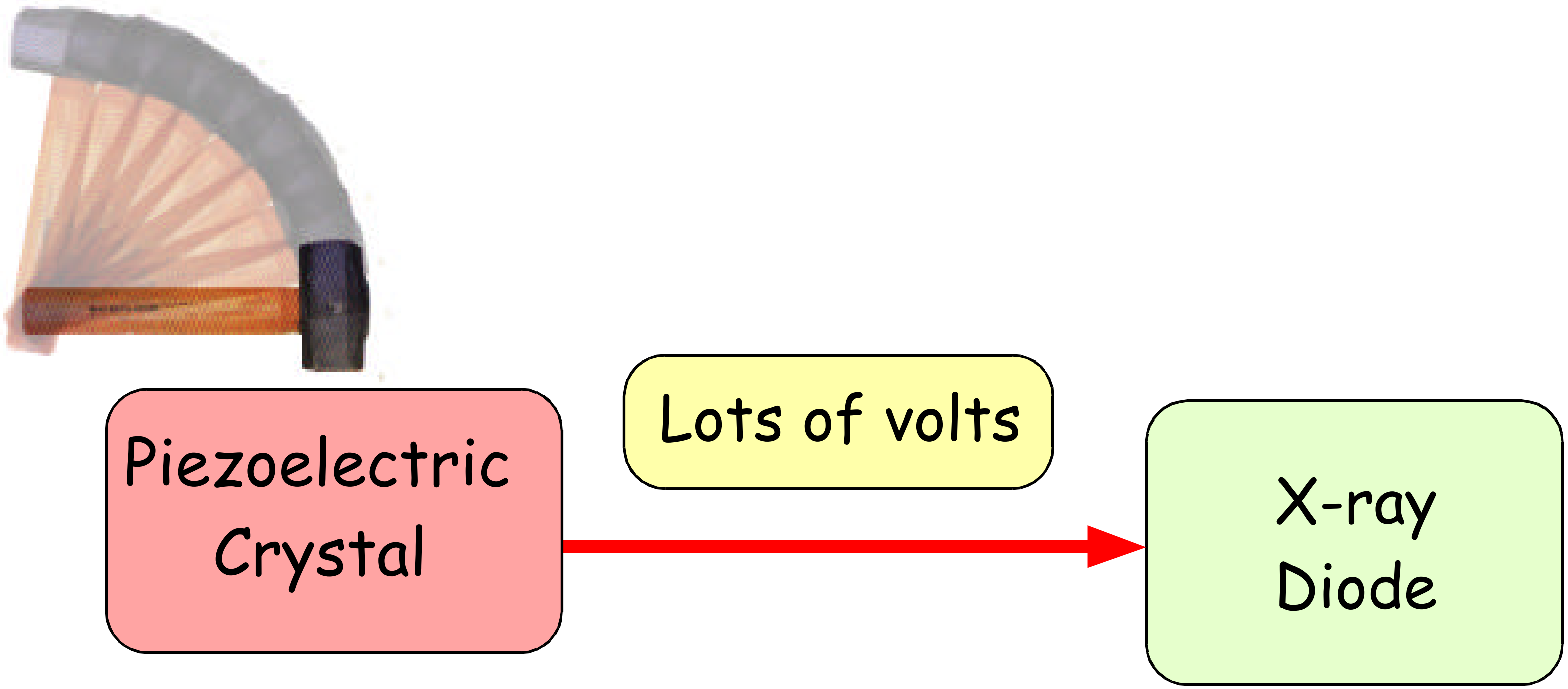


Amplitude of oscillators must be set; as must the relative phases

Oscillators may be continuous or operate in burst mode.

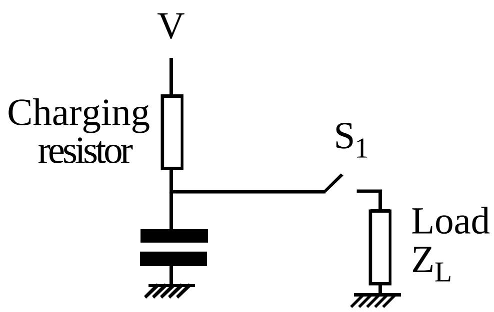
Not ideal for "On Command" pulse delivery

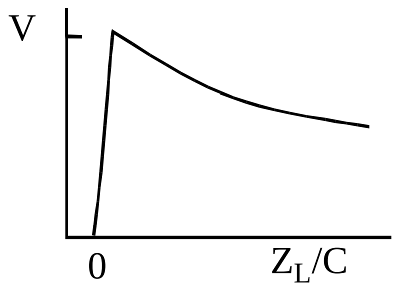
Most pulsers are purely electronic but...



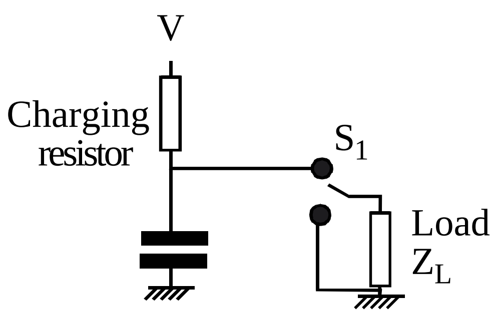
An Introduction into Pulse Forming (1)

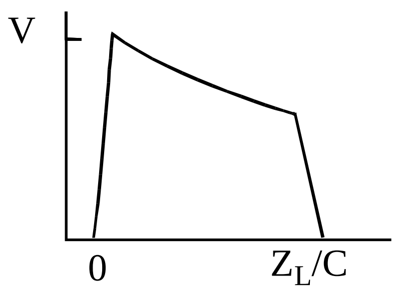
A simple switch and capacitor gives a fast rise followed by an exponential decay.





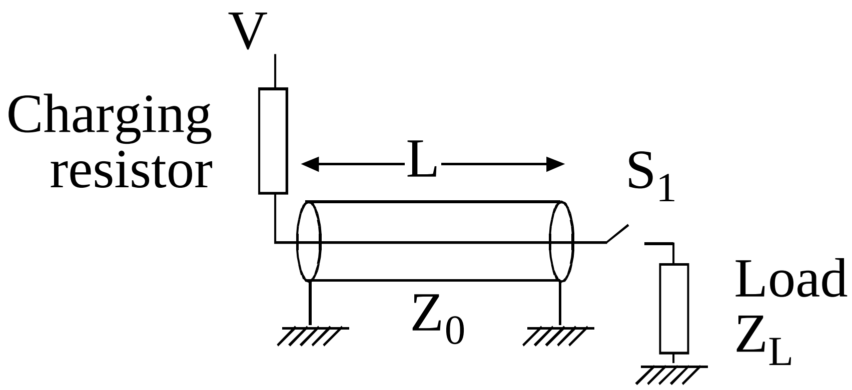
In order to obtain a flat pulse the stored energy is much greater than the pulse energy

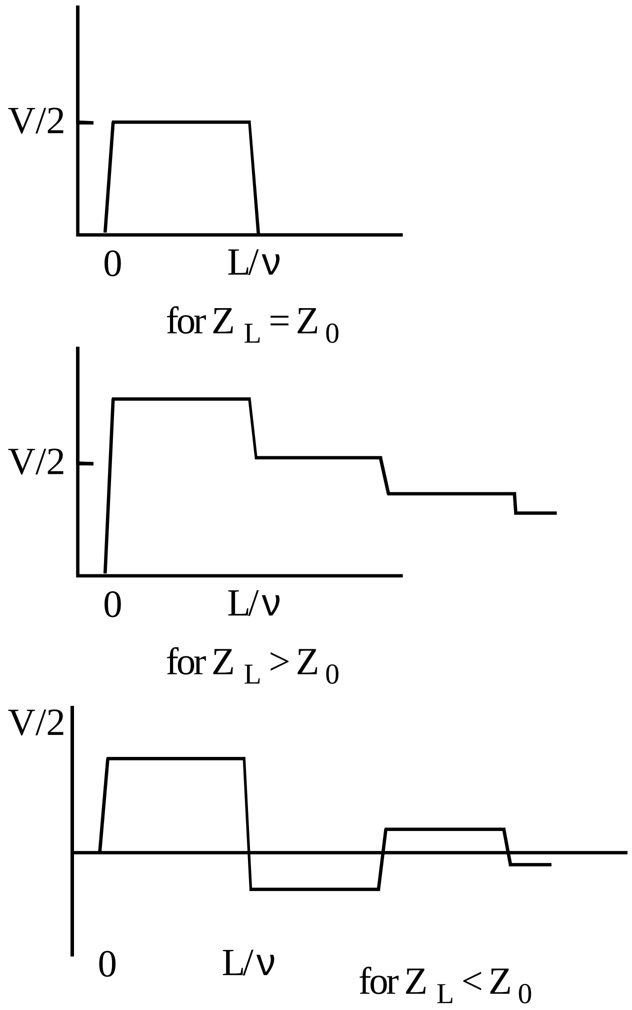




An Introduction into Pulse Forming (2)

By using a transmission line instead of a capacitor all the stored energy is available as a square pulse

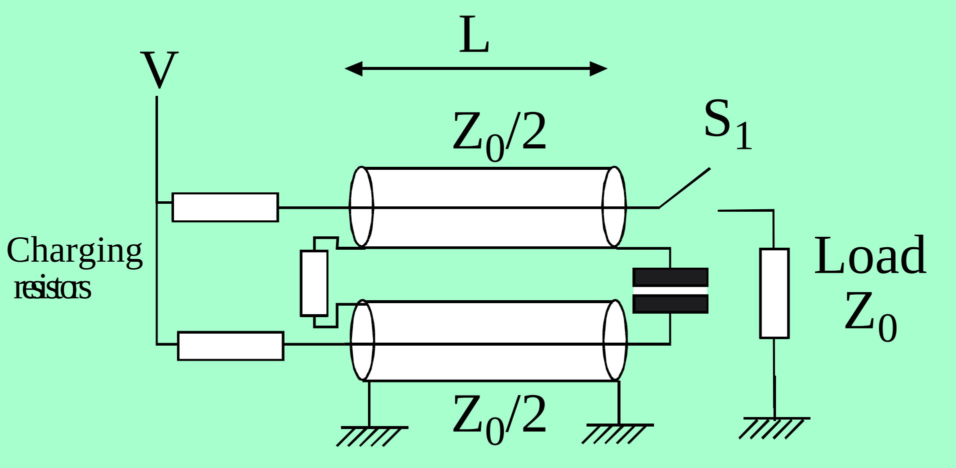




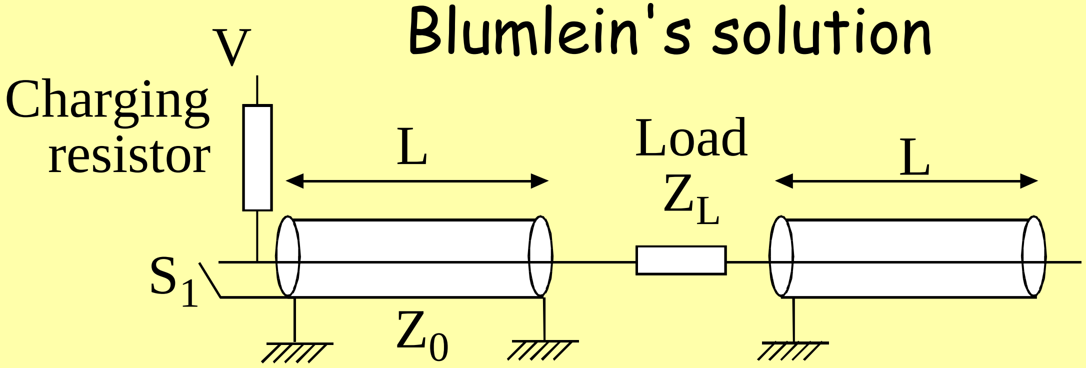
Note that for matched conditions the output voltage is half the charge voltage

An Introduction into Pulse Forming (3)

Solutions for retaining the charge voltage

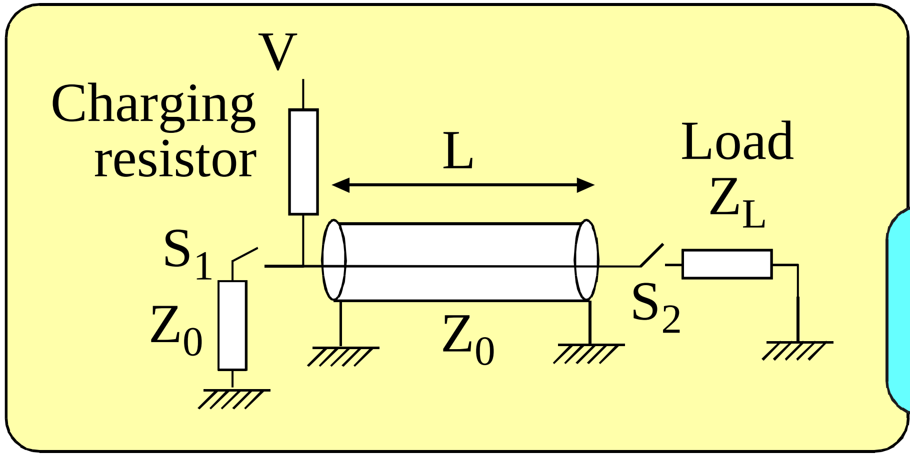


Blumlein's solution

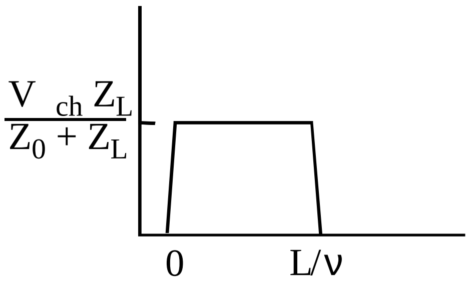


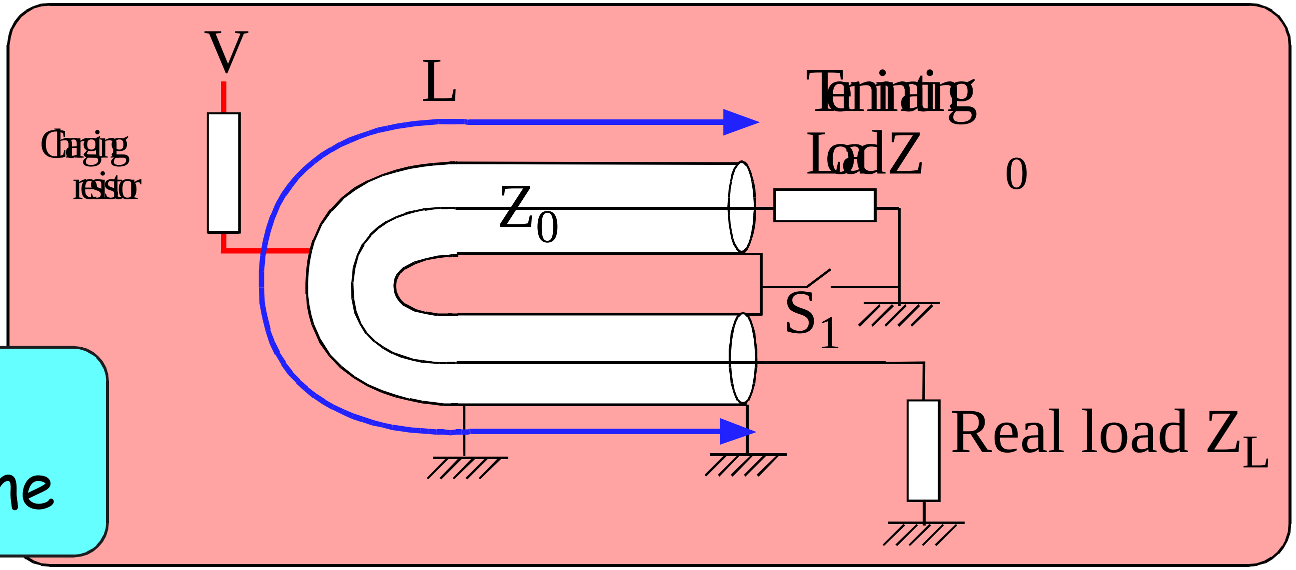
An Introduction into Pulse Forming (4)

Solutions for indeterminate loads



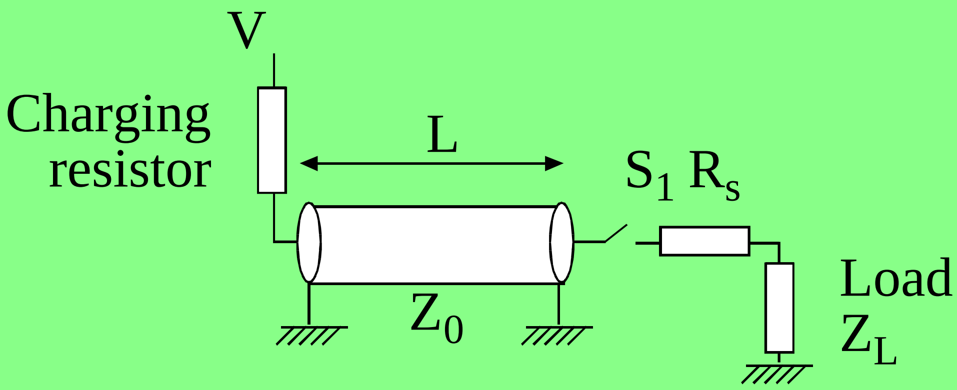
This offers pulse length control as well.





A single switch, self terminated line

Effect of Switch Impedance



The matched condition is now

$$Z_0 = R_s + Z_L$$

Often the load is 50Ω so this means that the charge line impedance should be less than 50Ω

Implications for solid State switches

To obtain a good pulse shape it may be worthwhile manipulating the impedances rather than building a bigger switch

Switch Technologies   Non-Solid State

Mechanical switches

Can be fast (20kV, 20ps), no synchronisation, no method of cascading except with self breaking add ons.

Vacuum switches

Thermionic valves, spark gap

Low lifetime at high power. Spark gaps have jitter, risetime limitation

Gas switches

Krytron, Thyratron, Ignitron, spark gap. Jitter, ageing, risetime limitation. Good for high power applications. Laser triggered gaps can be very good especially if the gas has a suitable adsorption band.

Liquid switches

Spark gap, jitter but can have good lifetime and very high rep. rate if the liquid is flowed. Risetime can be well sub ns

Switch Technologies - Solid State

Solid state switches

Spark gaps are single shot and then replace the material.

Semiconductor Switches Avalanche

Low power but can have very low jitter (~1ps),

Long lifetime > 10^{10} shots

High on resistance in avalanche mode

Can be cascaded in series and parallel for high power.

Large stacks can run at 10kHz. Single devices at 100kHz.

Risetime can be sub 100ps. Limited charge transfer.

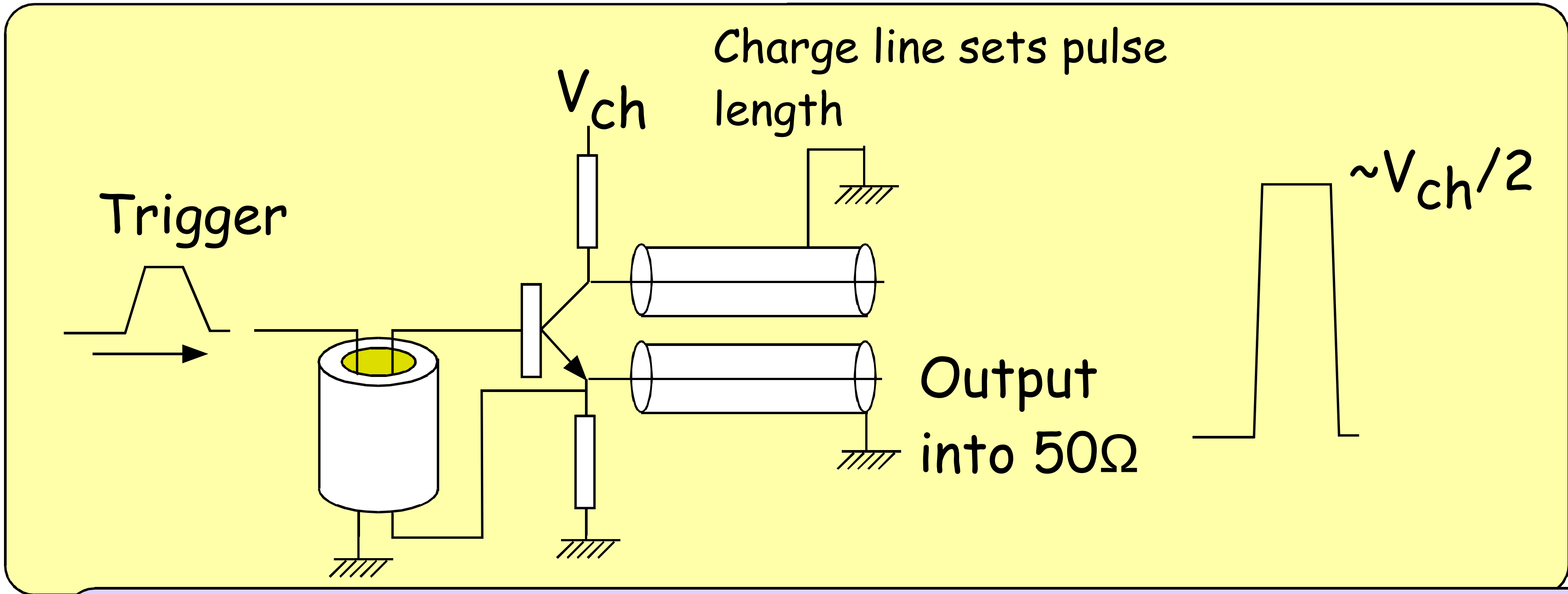
Semiconductor Switches Field Effect transistors

Not as fast as avalanche transistors, ~ 1ns risetime

Can be turned off with care. Will run at many MHz.

cannot switch as much power but can handle large amounts of charge. Low jitter, so can be cascaded, but each device needs to be triggered.

A Simple Avalanche Pulser



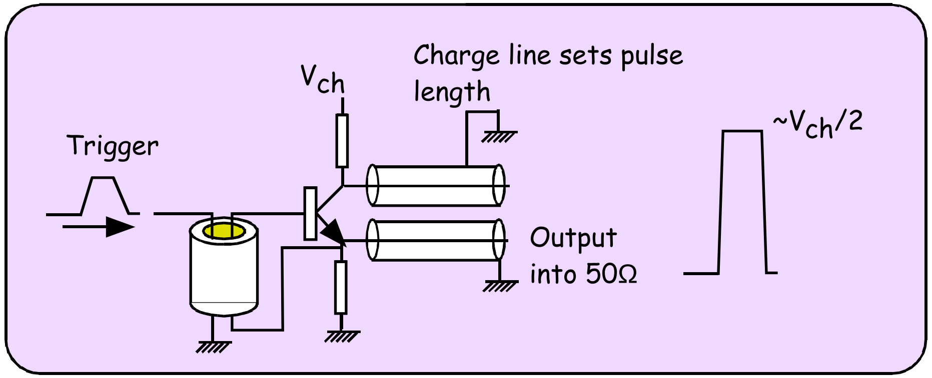
Avalanche devices give ~100 Volts, rise in ~2ns
FET ~1kV, rise in ~2 to 10ns.
FETs go well if the trigger pulse dumps enough charge into the gate to charge it to ~20 volts in a short a time as possible. Use another pulser! (Will it break?), ~100ns pulse from Avalanche, FET as long as the gate is charged.

Alternative High Power Solid State Technologies

SCR,
IGBT,
Break Over Diodes,
Reversely switched dynistors (RSD),
Reversely Controlled Transistors (RCT),
Drift Step Recovery Diodes

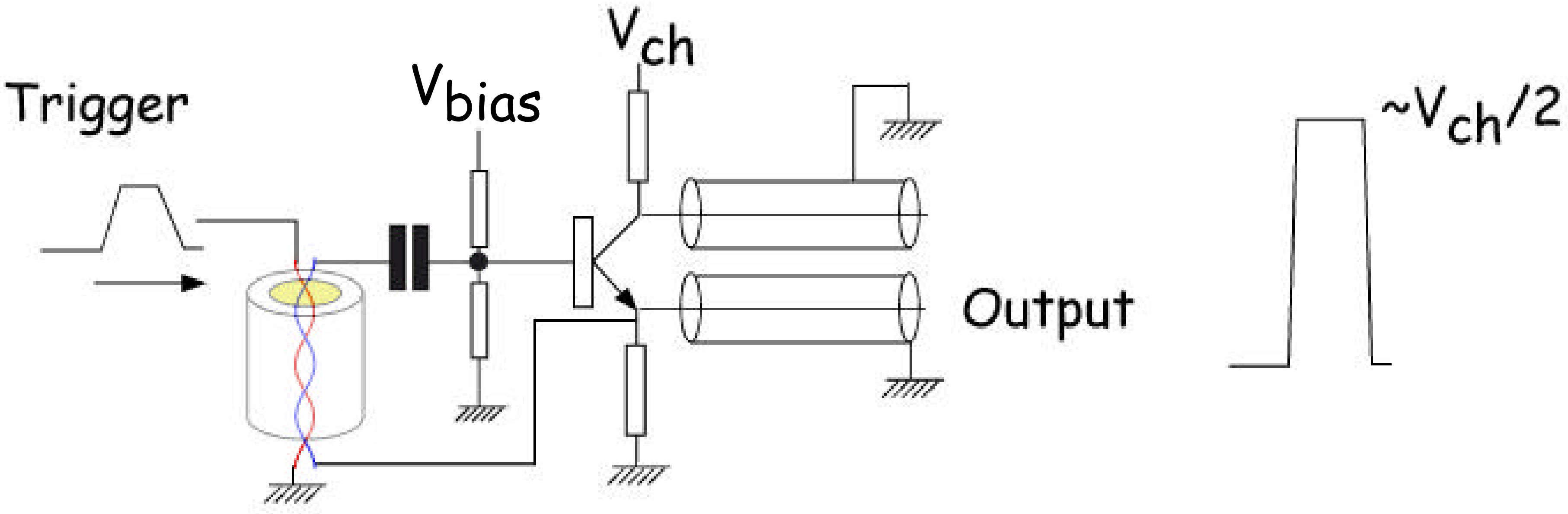
Some are turn off devices. Some have a long charge up time.

Points to note on a trigger device



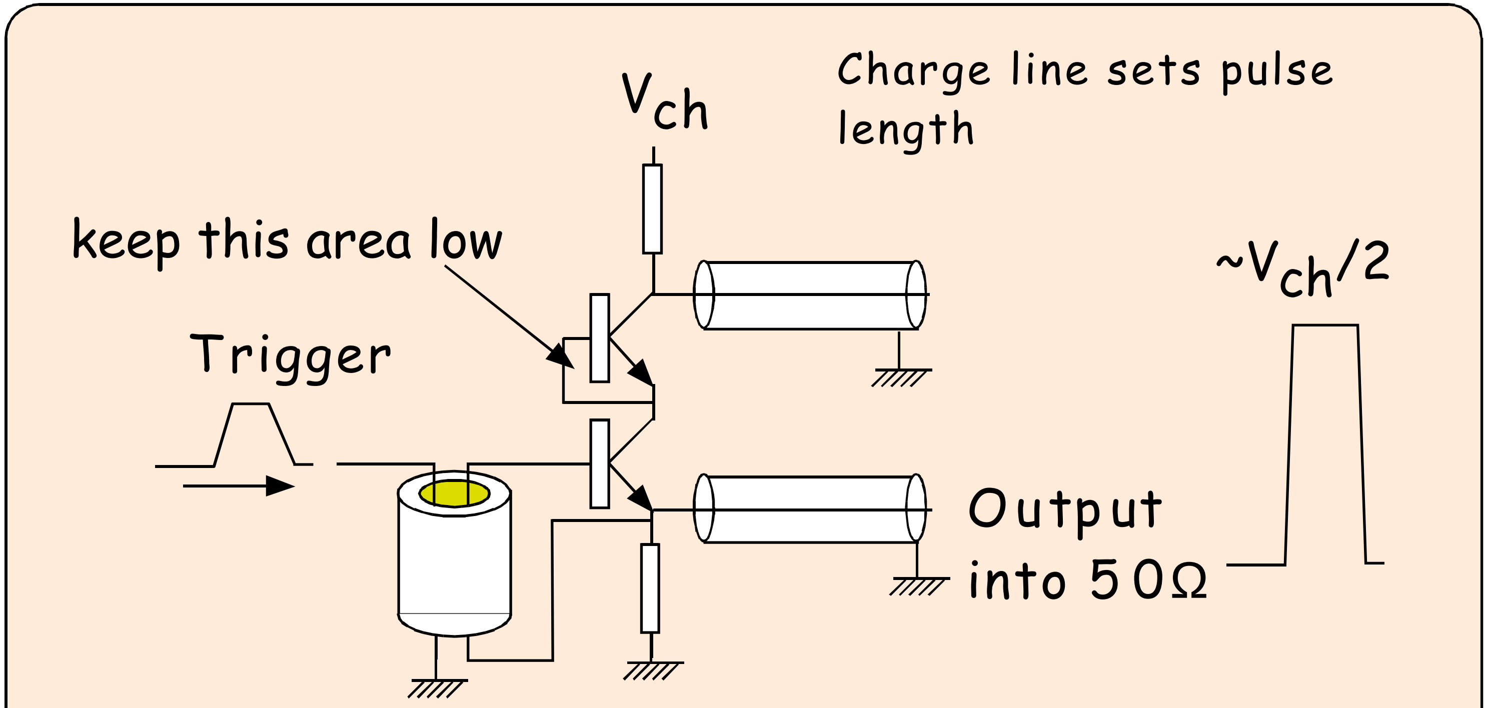
- Avalanche devices are selected bipolar transistors often with a fairly modest bandwidth.
- The collector current continues after the base pulse.
- Trigger pulse injects charge into the base. This must be done quickly to collapse the field in a small region, increase the field elsewhere and initiate avalanche processes. Always limit trigger pulse charge.
- Lots of switched charge destroys the device.
- The collector current should be low when the device turns off.
- ZTX 300 is a very good and hardy example but does need aging.
- ZTX 415 offers more volts but a lot more jitter.

To Increase the Sensitivity



- Use several turns on the transformer, use bifilar windings.
- Bias the base just below DC turn on.
- 100mV can be achieved.

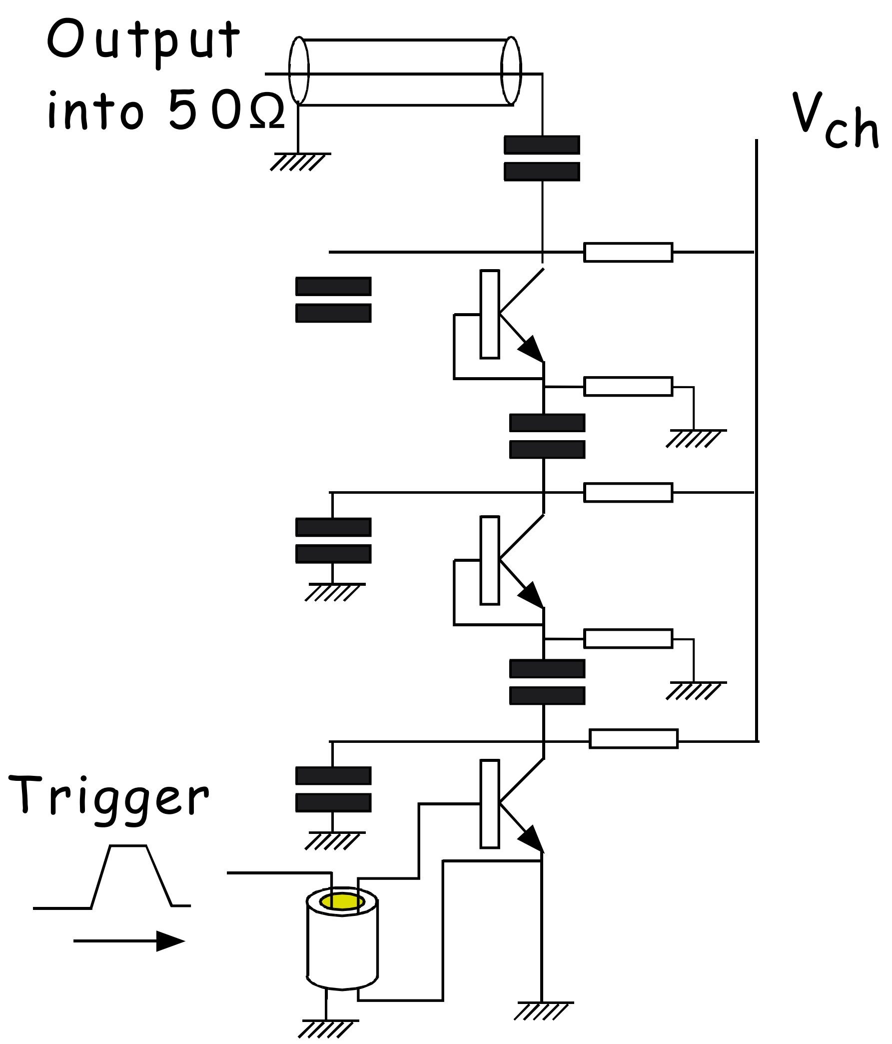
To Increase the Voltage



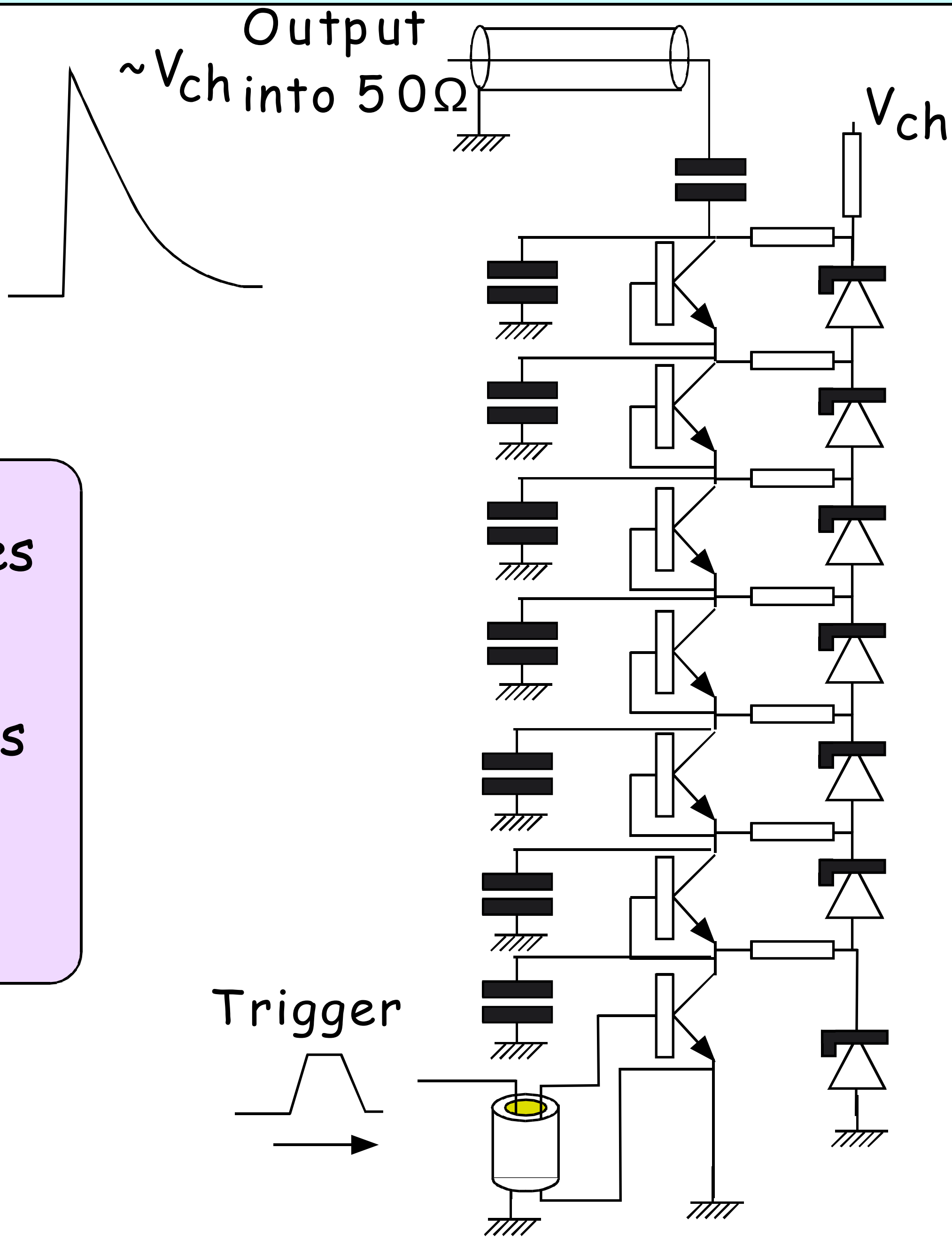
- Add a transistor.
- Short its base to the emitter.
- Doubles the voltage, impedance goes up.

Marx Configuration

This configuration needs a lower charge voltage but the resistance of the series capacitors is a problem.
Most of our pulsers use stacks of 10 transistors arranged in a three stage Marx. This keeps the DC voltage down and corona under control.



To Increase the Voltage More



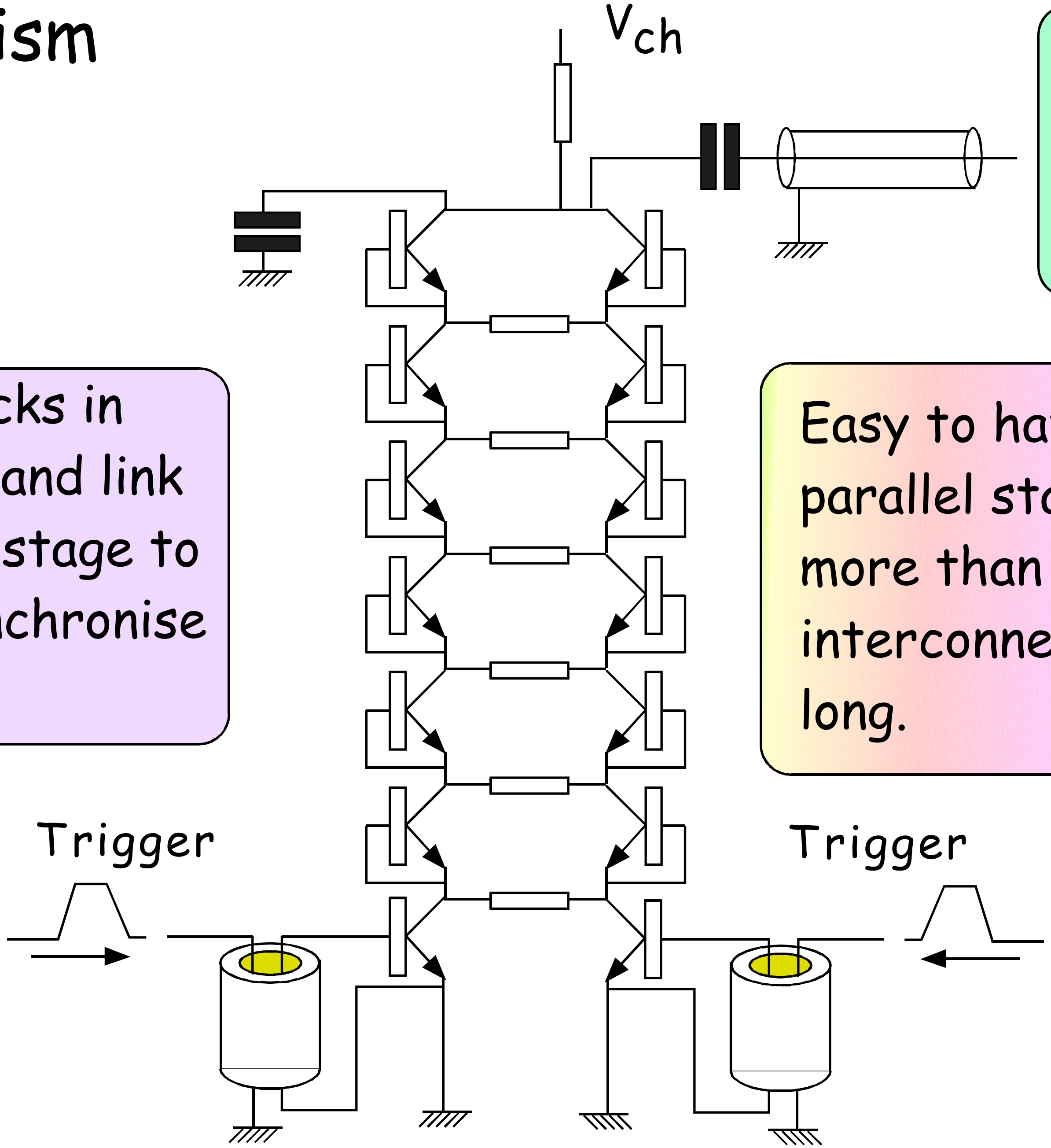
- Up to 20 ZTX300 in series works well
- Up to 30 ZTX415 in series works well
- Losses in devices goes up

Adding devices

- Up to 20 ZTX300 in series works well
- Up to 30 ZTX415 in series works well
- Adding a device puts up the voltage and the current so the loss in each device goes up. Eventually the loss matches the voltage gain and adding devices does not help unless the load impedance also goes up.

Solution is parallelism

Parallelism



Charging elements omitted for clarity

Run stacks in parallel and link at each stage to help synchronise them

Easy to have two parallel stacks but more than two makes interconnections too long.

The Avalanche Process Ionisation Waves.

- Normal model assumes a simple avalanche process like a spark gap.
- As the voltages get higher much faster rise times are seen than this model can explain.
- Grekhov was the first to point this out [Sov. Tech. Phys Lett. 5(8) Aug. 1979, p395] and offer an explanation [p 399]
- Ionisation occurs as a wave through the p-n junction. This is observed in diodes and transistors the former being somewhat faster but exhibiting more jitter and timing differences unless chips are matched.
- Wave propagates through the junction, the voltage is held off by an increasingly thinner layer of material but no significant current flows until the wave reaches the other side of the junction and the insulating layer collapses very quickly.
- In the transistors we use we see pulser rise times of ~90ps and radiation from the pulser > 10GHz. Grekhov has observed transitions in diodes of 30ps.

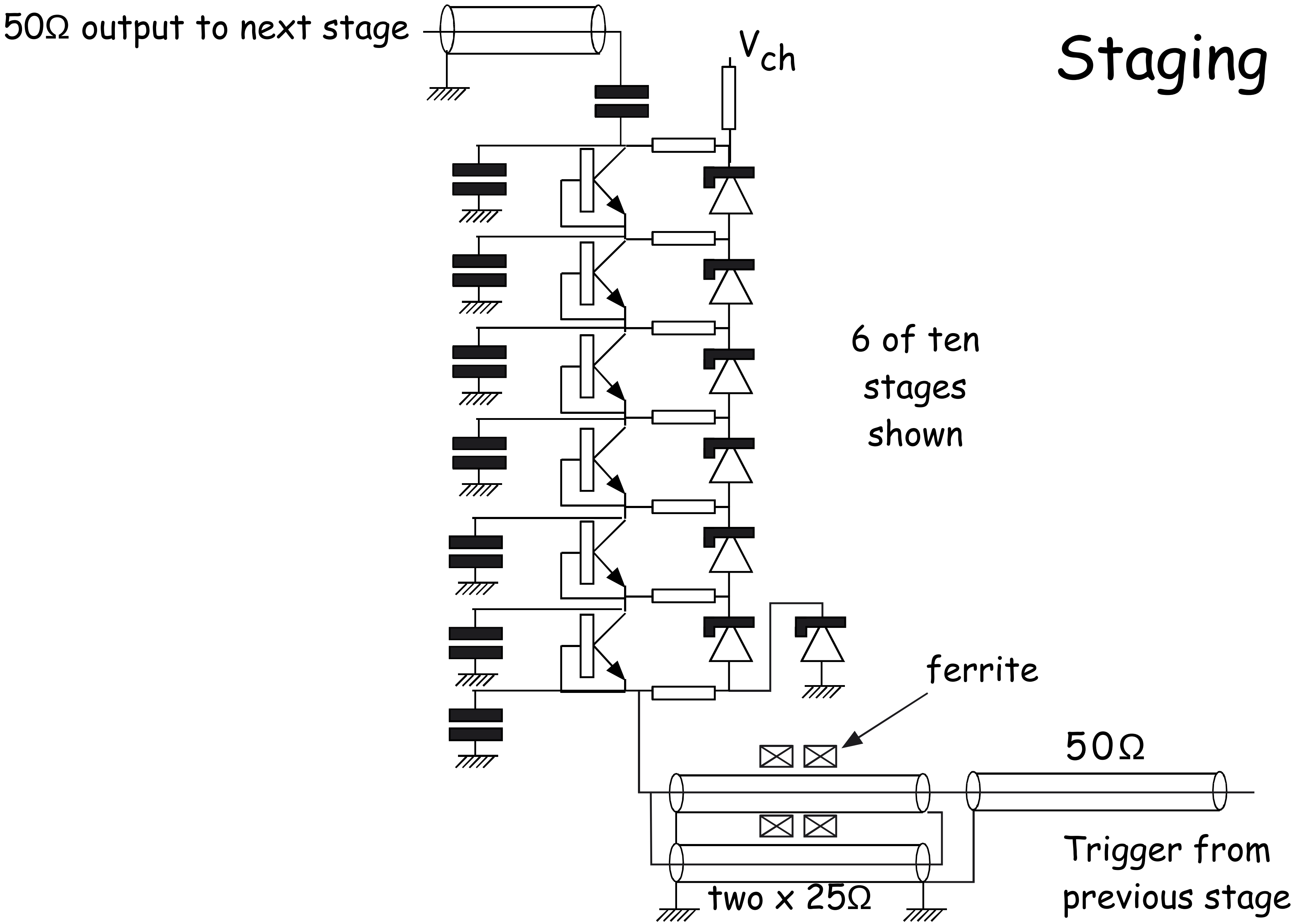
Staging and Mass Series/Parallel Arrays

The route to very high powers

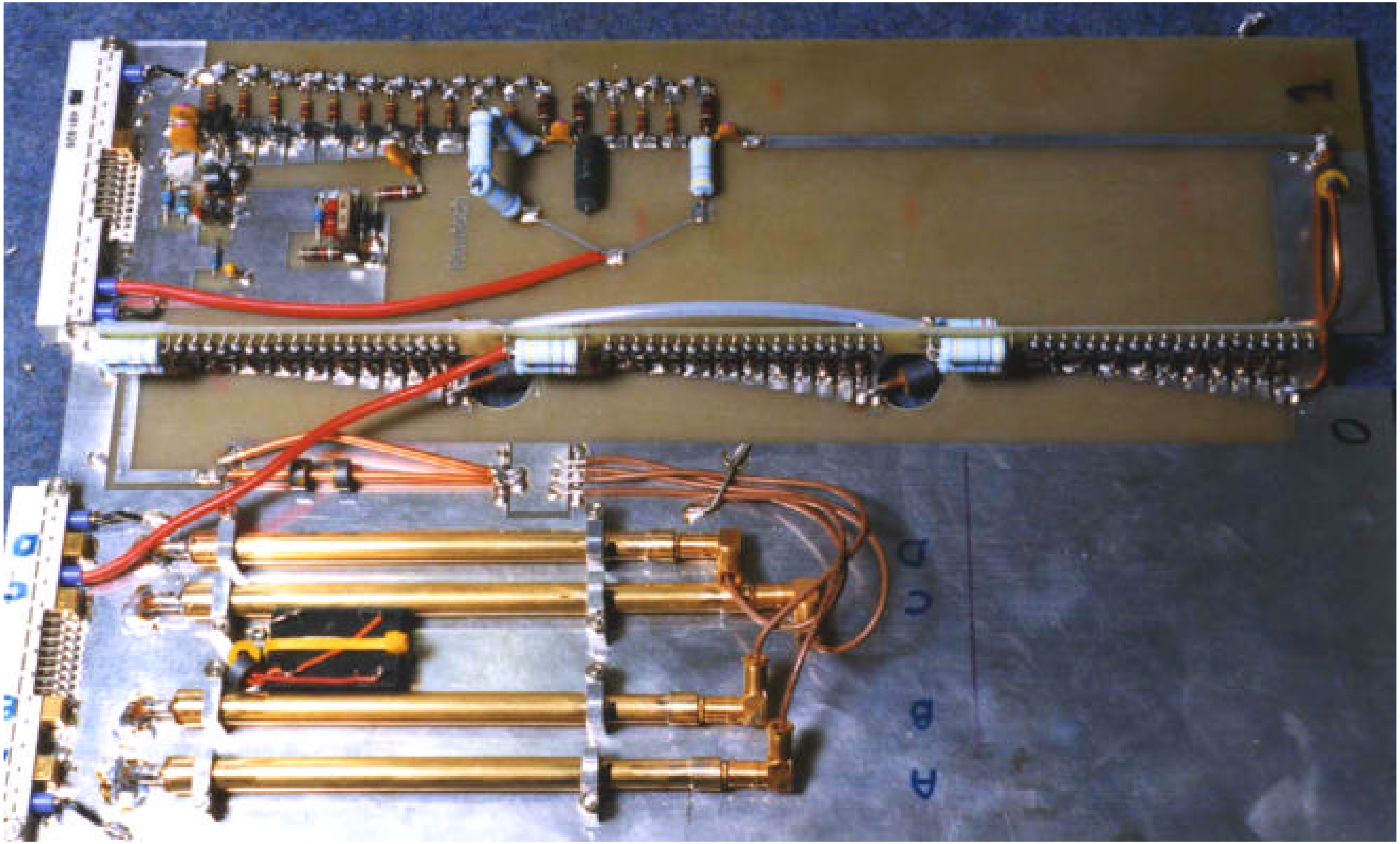
Most of the jitter in a large pulser occurs in the trigger stage with a small contribution from the next few devices in a stack.

Triggering through the base of a device offers the worst rise time, poorest lifetime and it contributes most of the jitter.

Staging

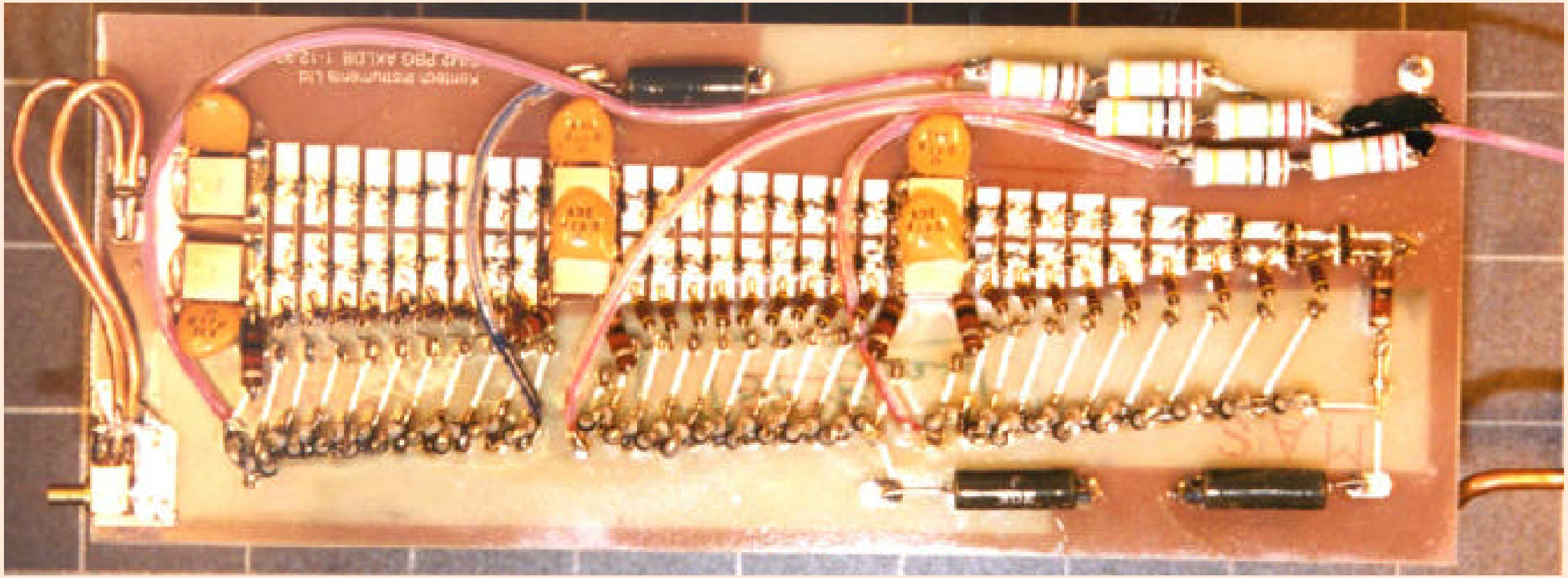

50Ω output to next stage
V_{ch}
6 of ten stages shown
ferrite
50Ω
two x 25Ω
Trigger from previous stage

An example of staging



The Output Card from a Kentech PBG1 pulser

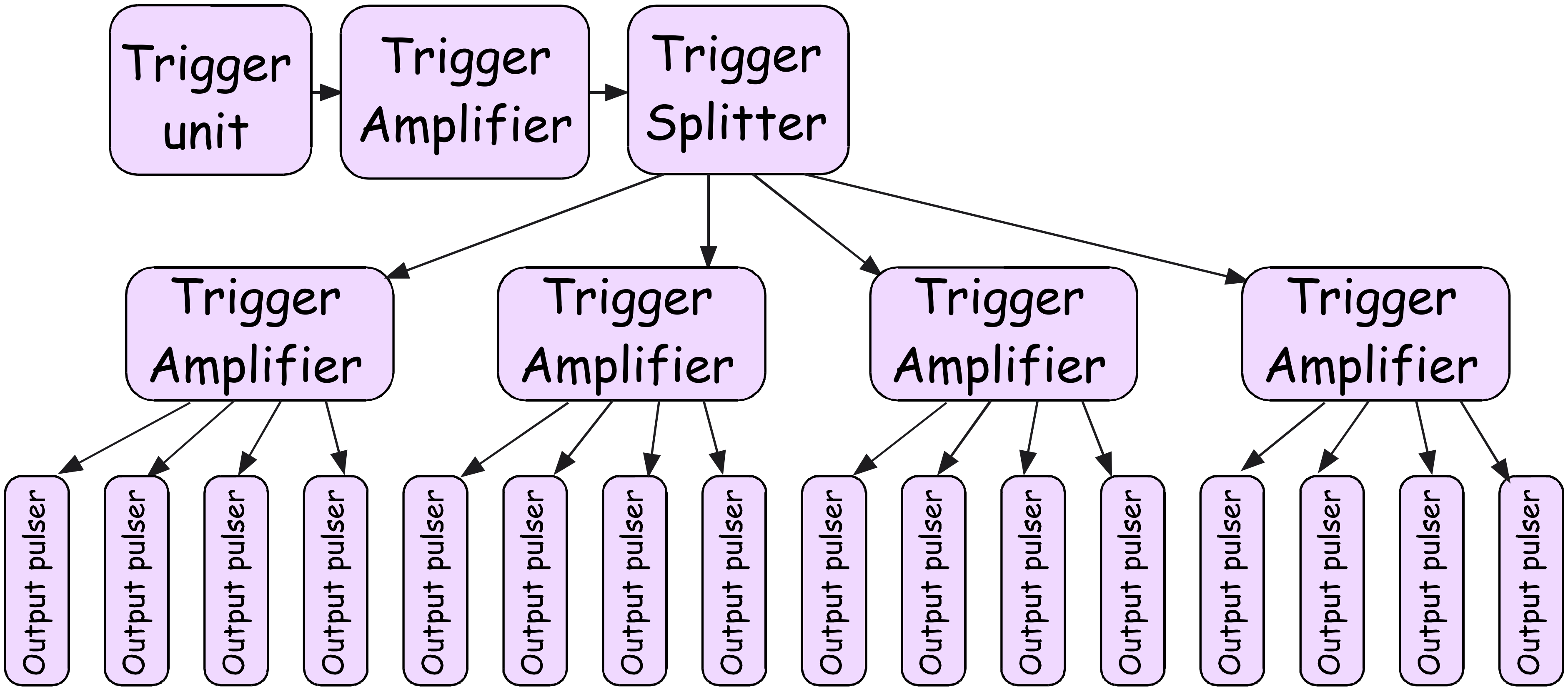
7kV into 50Ω. 2ns slow decay pulse,
100ps risetime, 1kHz possible



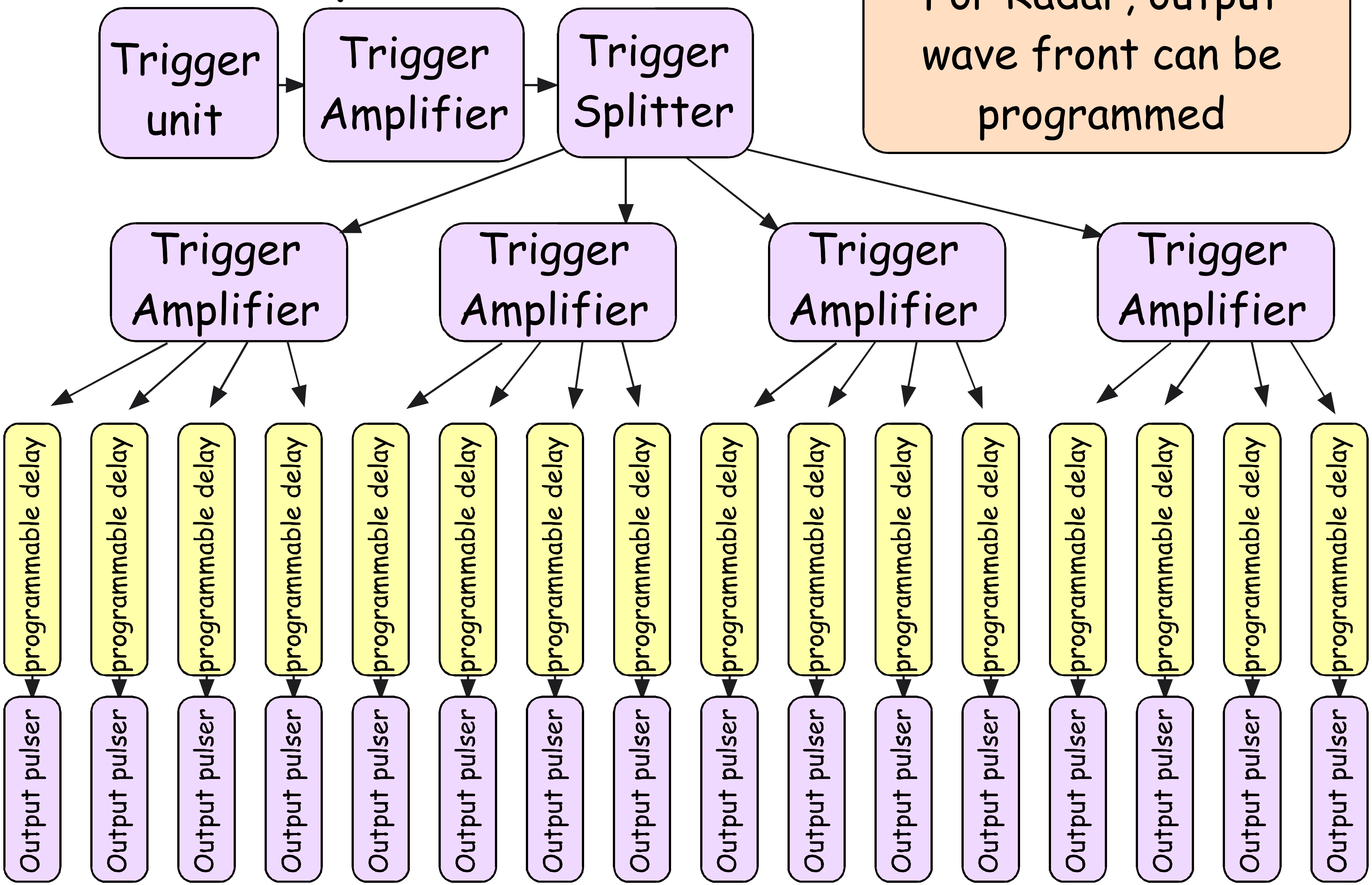
Mass parallelism

With very high trigger voltages

- stage jitter tends to zero and
- stage variation in delay tends to zero.



Phased arrays



For Radar, output wave front can be programmed

Combining Multiple Outputs
Mass Parallelism to Series/Parallel stacks

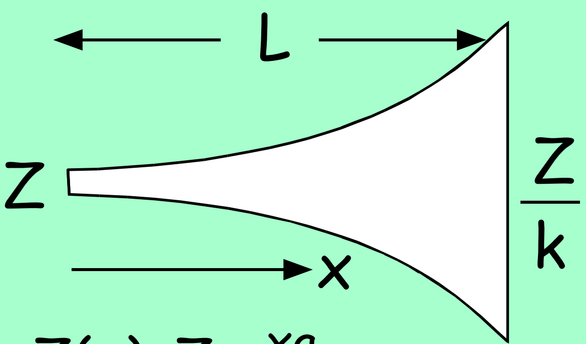
Cable transformers offer large bandwidth and high efficiency

Designs are limited by the range of cable impedances available
10,12,18,25,34,50,75,98,100 Ω
Some of these are not practical at high voltages as only small cable diameters are available.

Exponential line transformers cannot offer high bandwidth without being enormous

Impedance Transformers

Z into Z/k where "k" is any number.

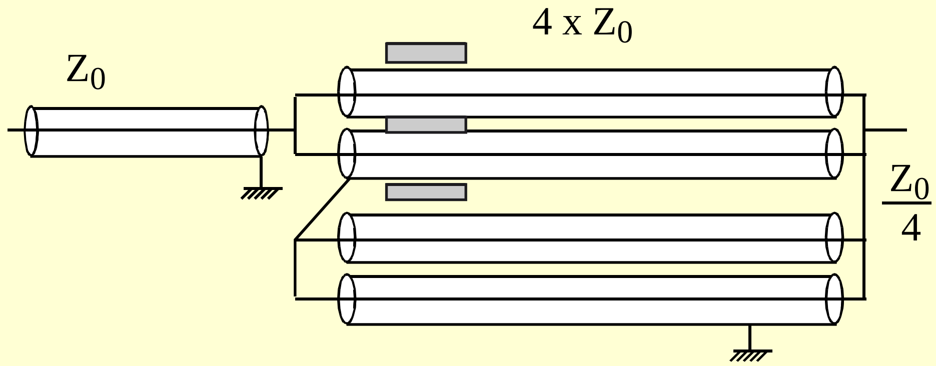


$Z(x)=Ze^{-xa}$

Good for $\tau_r \ll L\varepsilon_r/c$

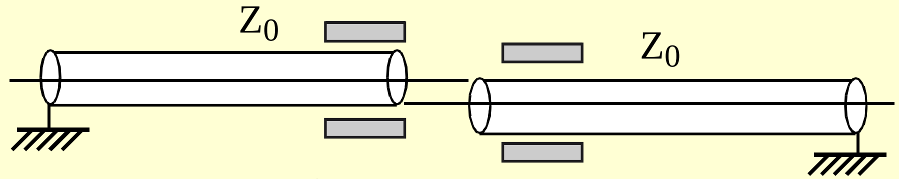
i.e. low frequencies are not transformed

Z into Z/n where "n" is a perfect square.



two in series by two in parallel

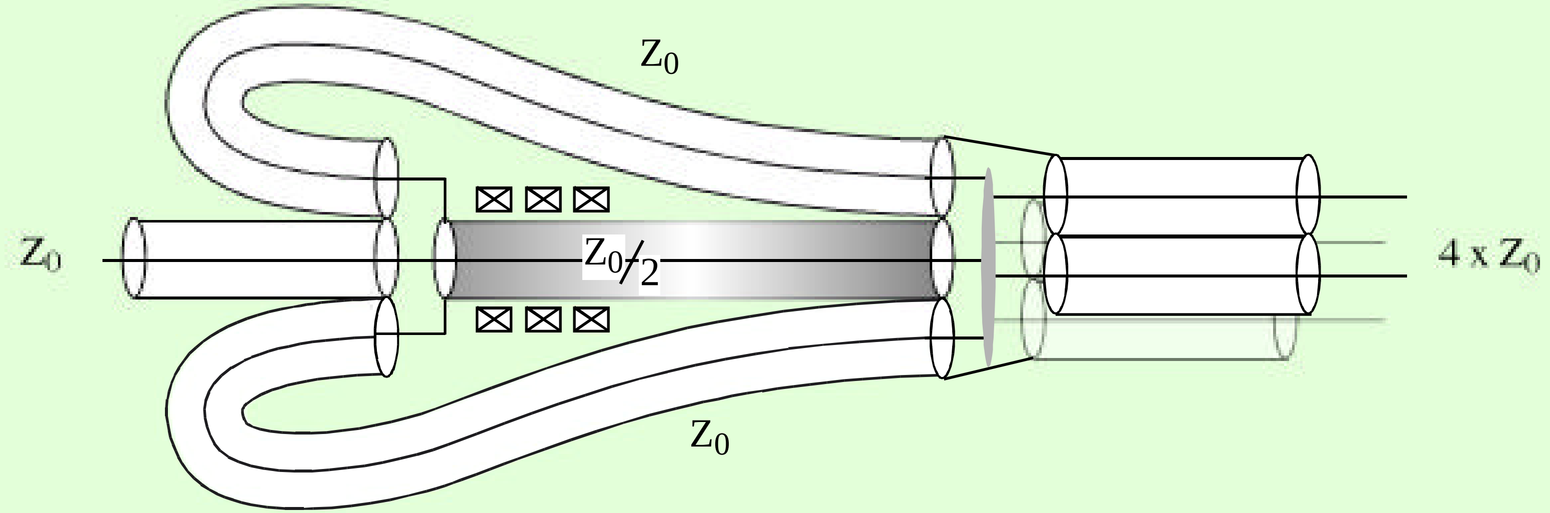
Pulse inverting circuit



ferrite beads

Impedance Transformers

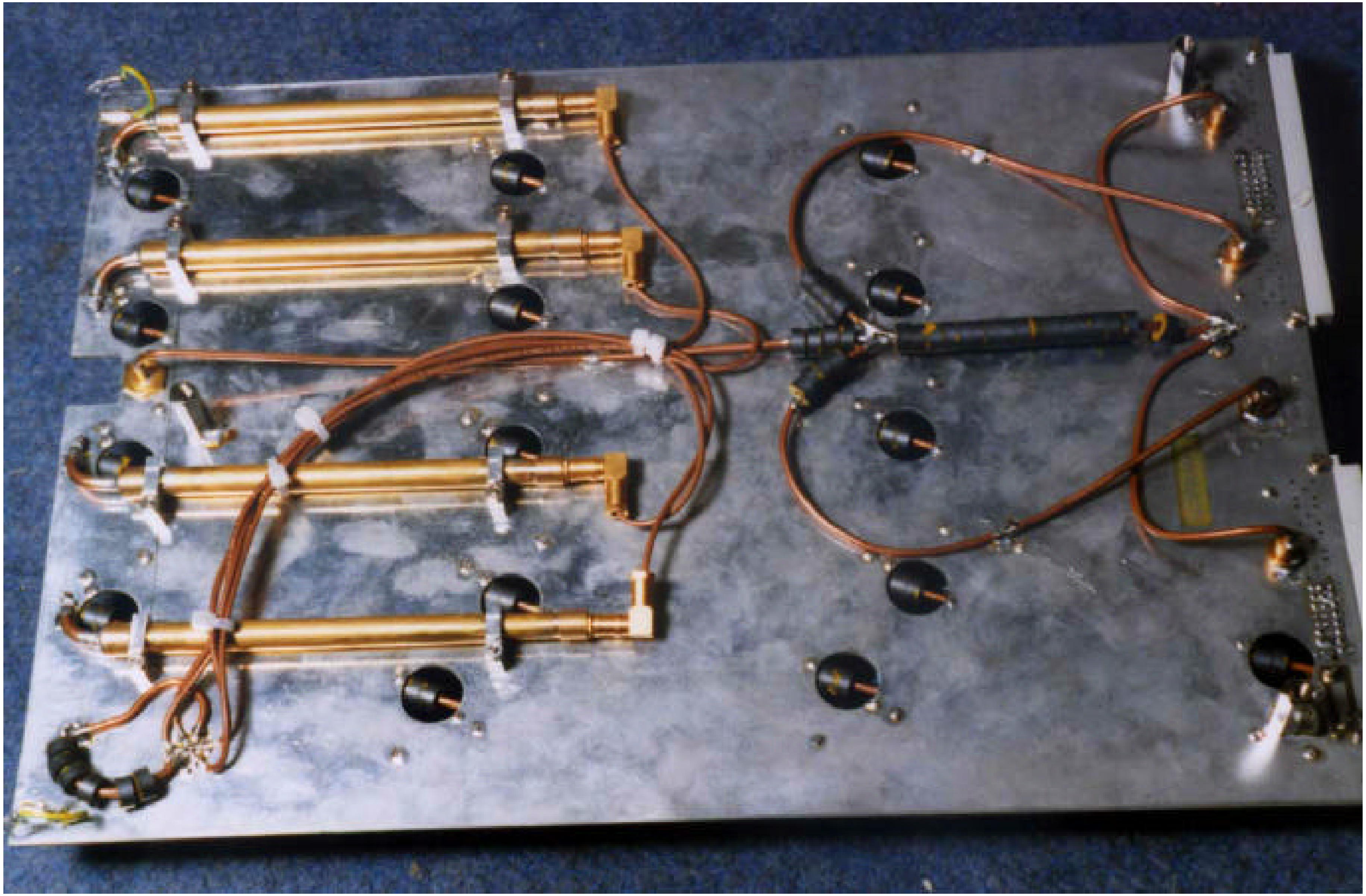
A better 1 into 4 transformer



The three intermediate cables have the same length

Can achieve around 10kV with 100ps rise time

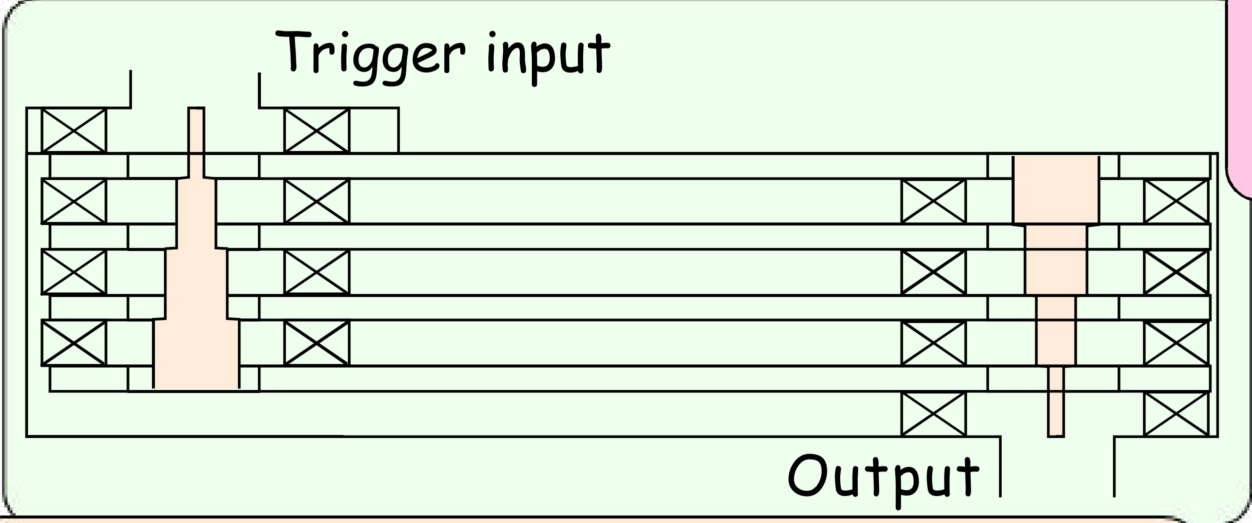
Impedance Transformers (The realisation)

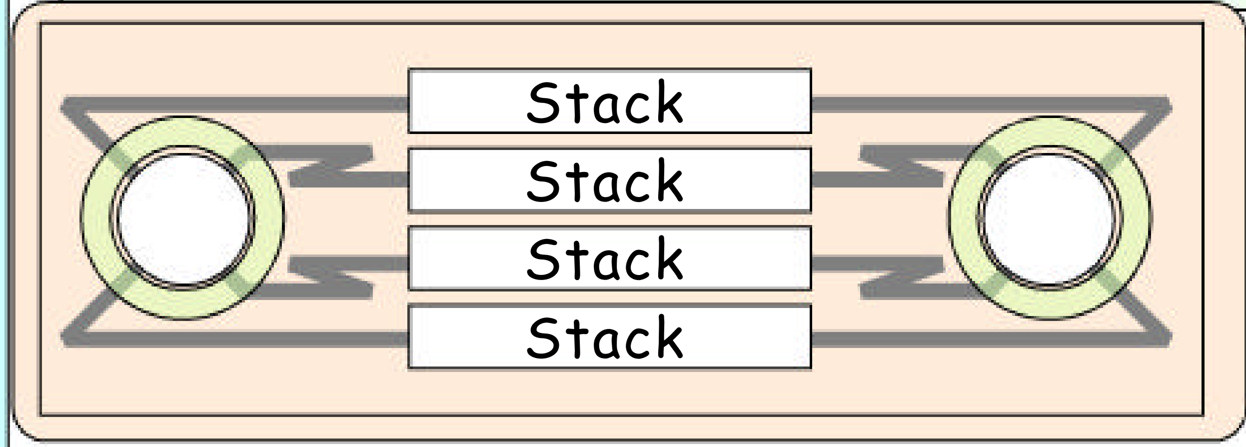


Distributed Pulse Transformers

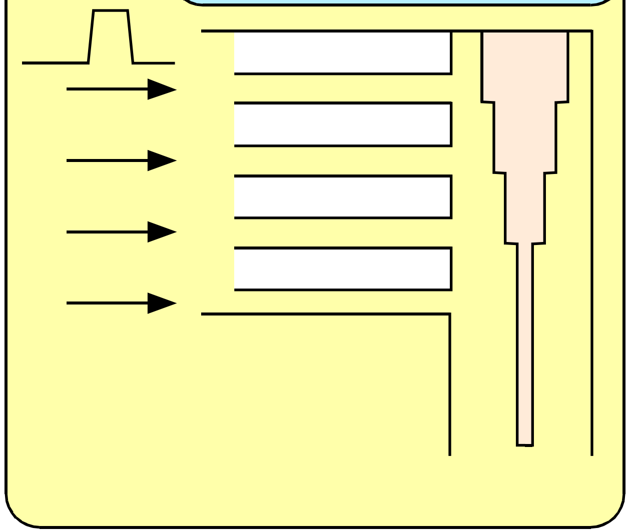
With a distributed system one can avoid having a high voltage on a dielectric interface except at the output

We have built units with 960 devices in the output stages

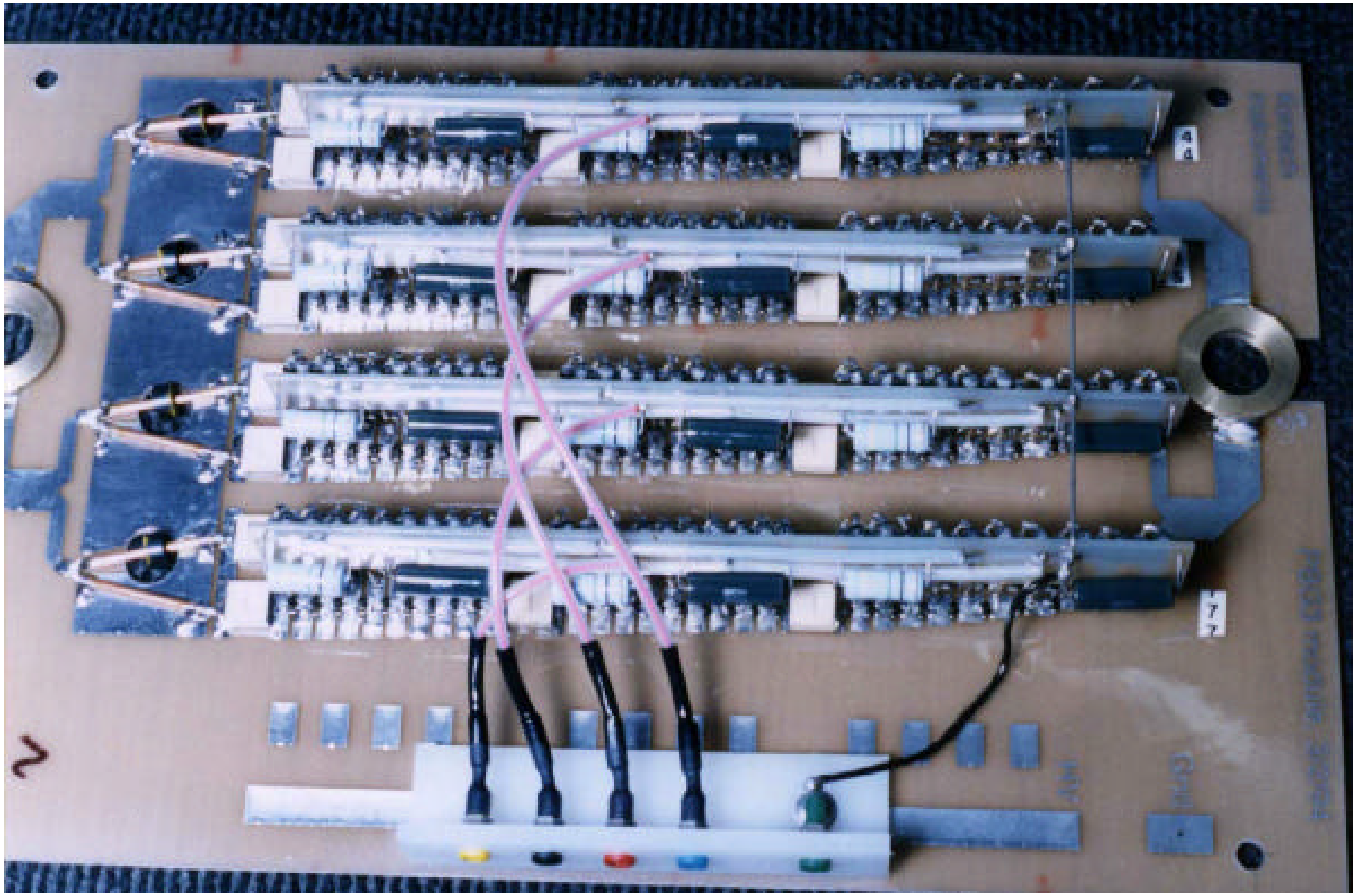




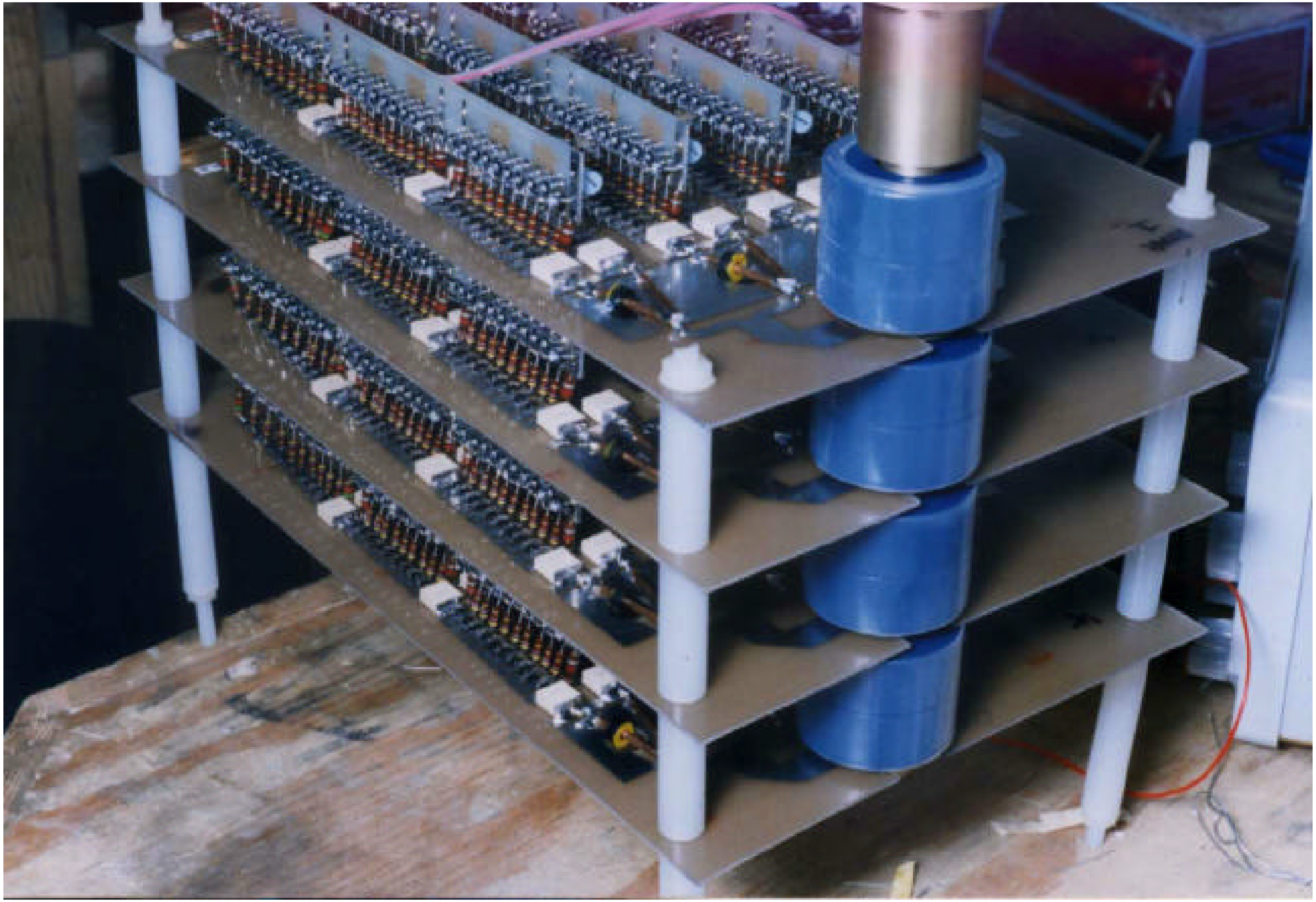
Equivalent Circuit



A 240 device card, 6kV into 12.5Ω output impedance

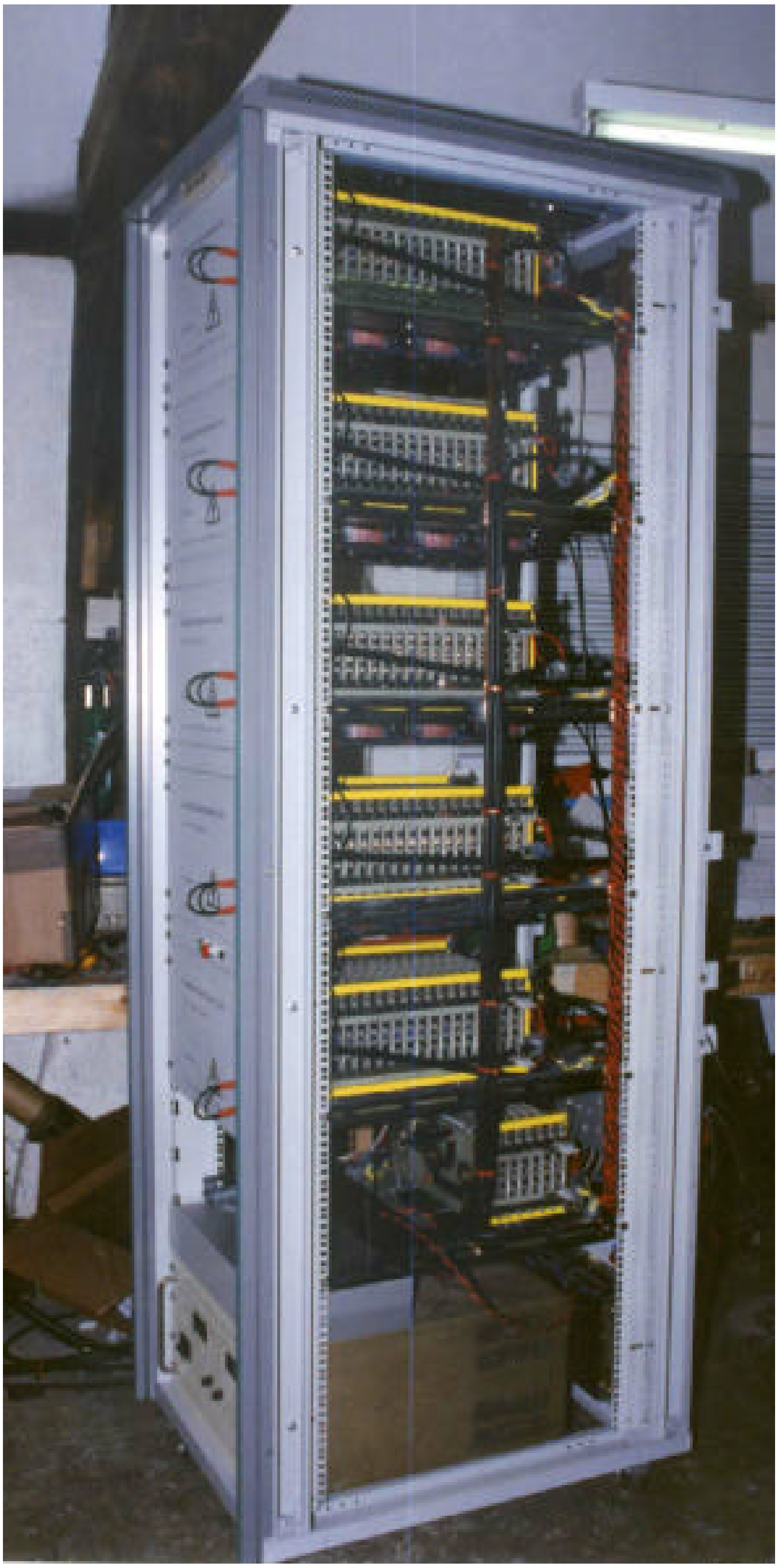


960 Avalanche devices



Large FET pulser

Arrays in series and parallel with a distributed coupling transformer.



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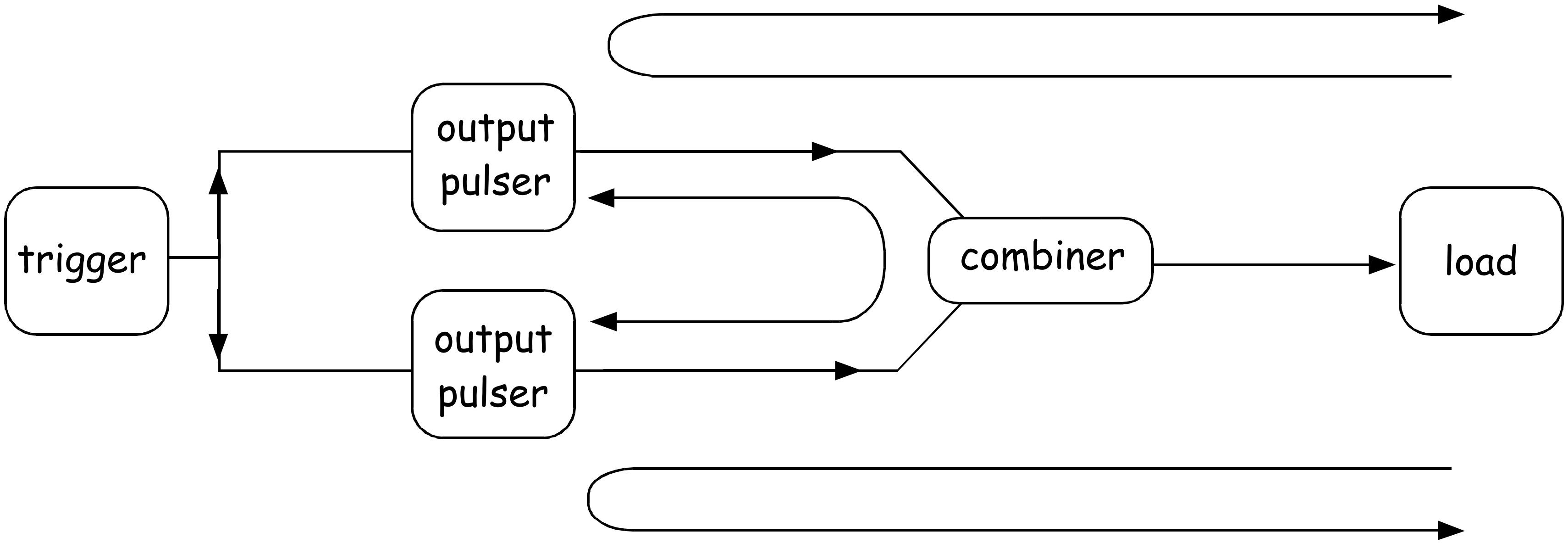
Desynchronised combining - dealing with reflective loads

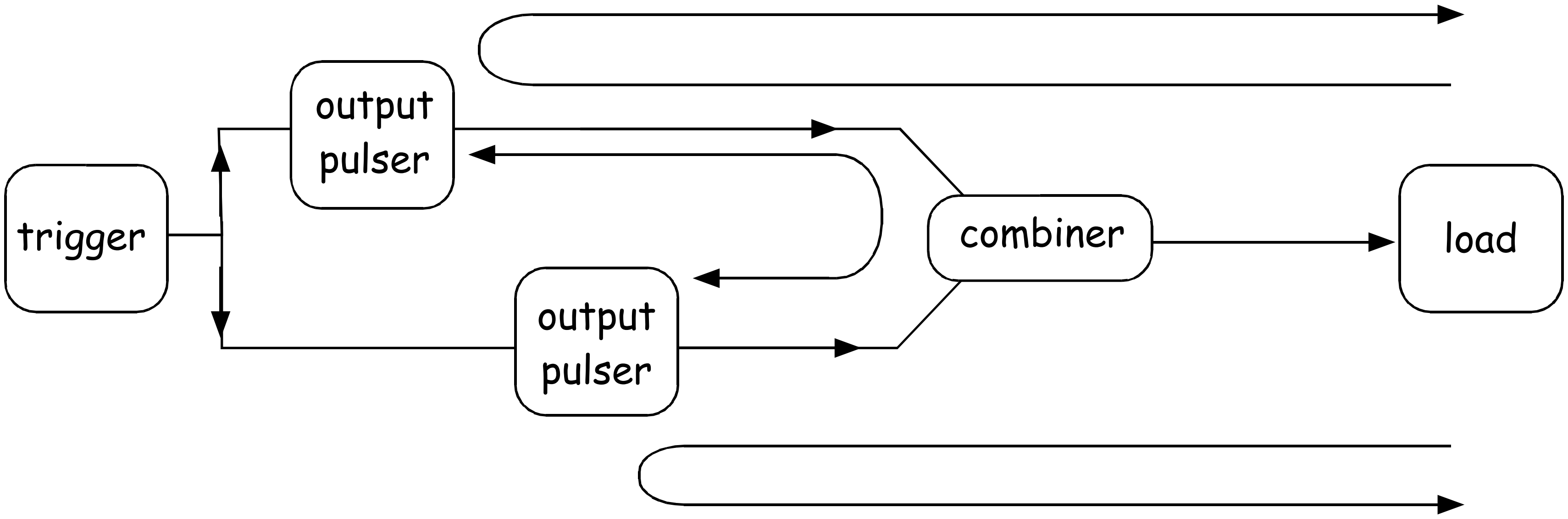
A regular system uses the following as all the parts are the same



Reflections from the load and then from the pulsers are all synchronous. Reflections from pulser to pulser cancel giving large reflections back to the load

Desynchronised coupling dealing with reflective loads

By using dissimilar cable lengths and correcting with trigger timing one can reduce the effected of reflected power.

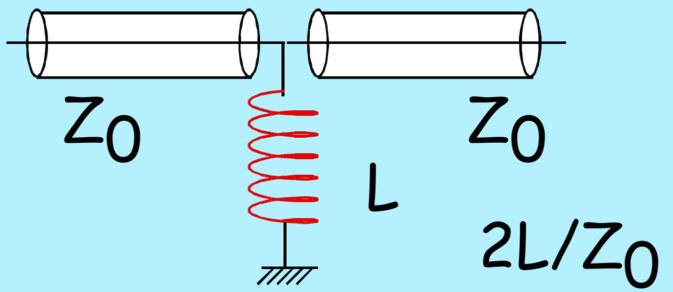


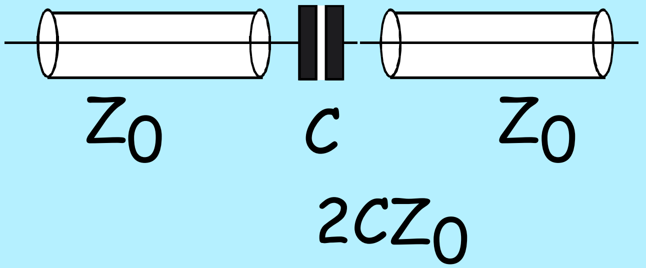
Reflections from the load and then from the pulsers are desynchronised Reflections from pulser to pulser and back to the load are distributed over many pulse lengths.

Pulse Forming techniques for Avalanche Pulsers

- Many applications require a formed pulse or possibly a spike.

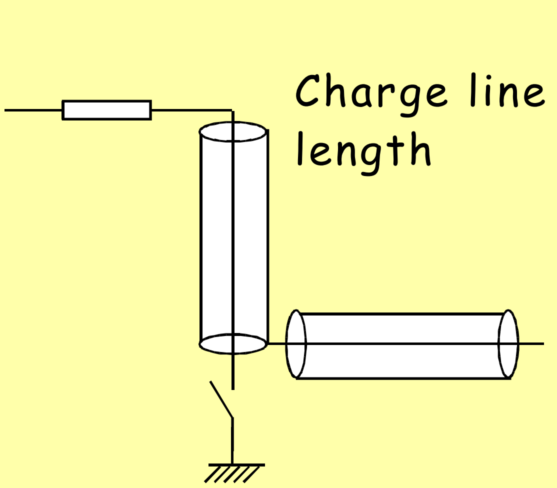
- Spikes are easily formed with differentiation.
- RC differentiators are good down to ~150ps but suffer from the required voltage hold off of the capacitor.
- Fast means small but High volts means big.
- Unless the rep. rate is high use L/R differentiators; faster.

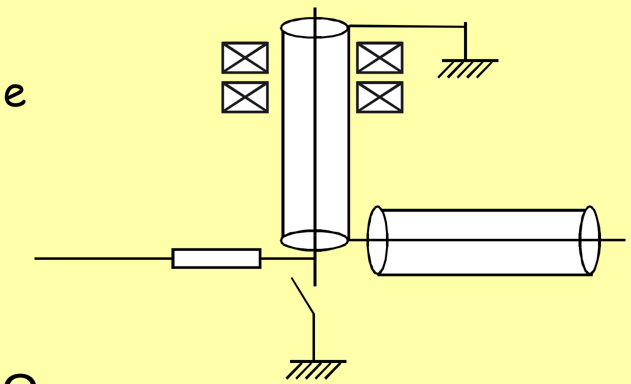




Pulse Forming techniques for Avalanche Pulsers

For shaped pulses into resistive loads cable pulse formers are often used.



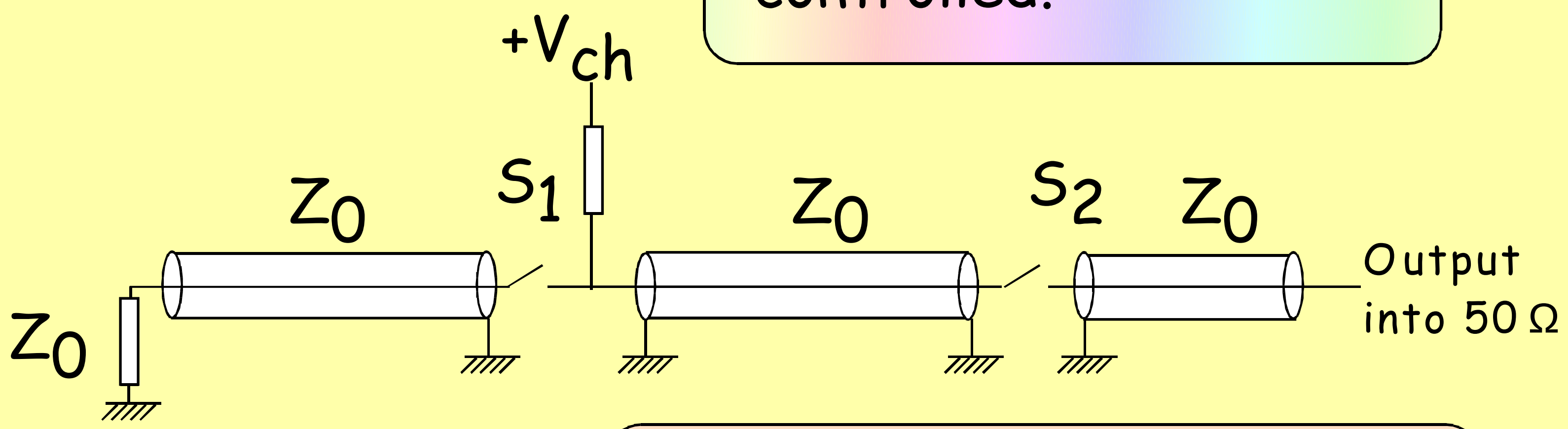


These techniques work close to the pulser output only

Programmable Pulse Length Control

Changing cable lengths under electronic control is possible but not simple.

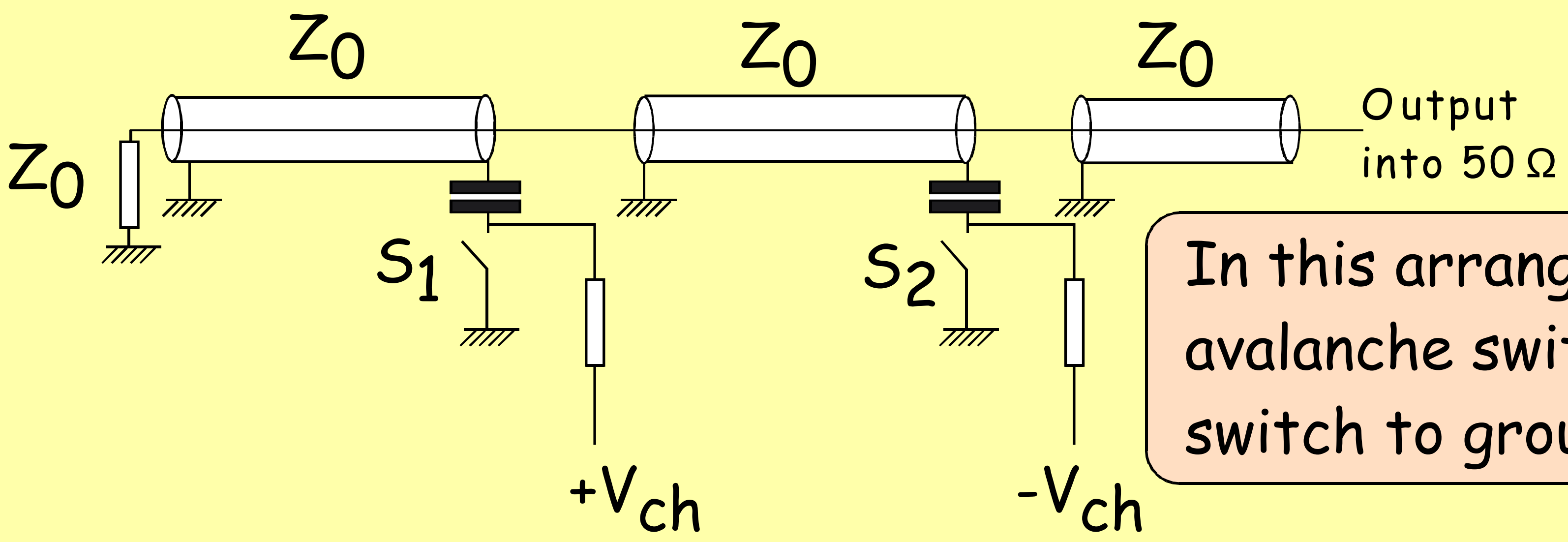
By adjusting the timing of the firing of S1 and S2 the pulse length is controlled.



This arrangement with floating switches is not easy to achieve.

Programmable Pulse Length Control

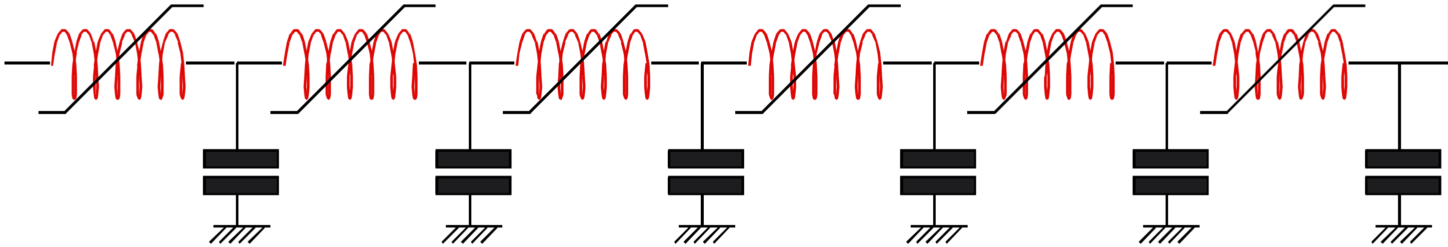
By adjusting the timing of the firing of S1 and S2 the pulse length is controlled.



In this arrangement the avalanche switches switch to ground only.

High Repetition Rate Pulsers.

Non Linear Lines To speed up Slow Pulsers



Standard Magnetic Shock Line

The capacitor can be non linear instead or as well.

Velocity = $1/\sqrt{LC}$

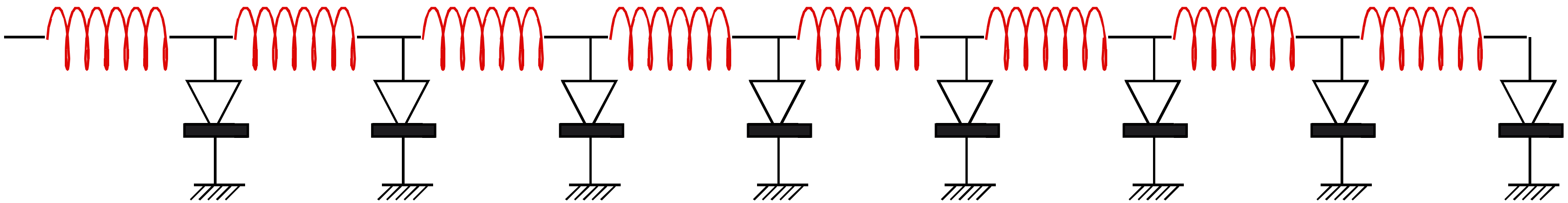
Works well above 5kV

If L or C falls with increasing voltage then the line supports shocks

High Repetition Rate Pulsers.

Non Linear Lines To speed up Slow Pulsers

Replacing the capacitor with diodes also gives non linear behavior



These lines work at a few hundred volts and can sharpen to ~200ps. Biasing the diodes allows control over the pulse characteristics

This technology has been extended to a few volts at a few ps pulses in monolithic GaAs structures