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DESIGN OF A 1 KV PULSE AMPLIFIER FOR THE 2.2 GEV LINAC BEAM CHOPPER

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Design of a 1 kV Pulse Amplifier for the 2.2 GeV Linac Beam Chopper

1. General Considerations

The 2.2 GeV Linac Beam Chopper has to be driven with a pulse having the following characteristics[1]

Pulse Amplitude	:	1kV
Load Resistance	:	50Ω
Rise and Fall Time (10% to 90%)	:	2ns
Pulse Length	:	10ns to 270ns
Repetition Rate	:	300ns
Burst Length	:	2.2ms
Burst Repetition Rate	:	13.3ms

Many devices have been considered for this application and rejected because of their insufficient performances. Power Mosfets get close to the voltage and current requirements but do not match the switching time limit. RF Mosfets are very fast but their power and voltage limitations make them better suited for a driver stage rather than to provide the whole output signal. Avalanche Mode Transistors can only provide a fraction of the required power with reasonable lifetime while Spark Gaps, Ignitrons and Thyratrons do not permit high pulse repetition frequencies. It seems therefore that only Vacuum Tubes can switch the needed voltage and current with the required speed and repetition rate.
The pulser could be implemented as a linear amplifier. To obtain ~60dB voltage gain one could expect to use n=5 cascaded stages, each providing 12dB gain. For rise and fall times t_r=2ns, the upper cutoff frequency of each stage should approximately be (Appendix A)

$$f_c \approx 1.21\frac{\sqrt{n}}{\pi \cdot tr} \approx 1.21\frac{\sqrt{5}}{\pi \cdot 2 \cdot 10^{-9}} \approx 430MHz$$

while the low frequency cutoff, dictated by the repetition rate, should be around 1 MHz. The maximum output power during the pulse burst being ~20kW and the wide required bandwidth would suggest to implement the amplifier in a distributed form. In such a case, the need of loading the anode line on both ends doubles the required power, increases the number of tubes and, at the same time, the amplifier's rise-time, which increments as $\sqrt[3]{n}$ where n is the number of cells in the lumped line[2].
As far as tubes with a sufficient gain-bandwidth product exist, it seems therefore more convenient to couple the signal of different devices using an output combiner rather than a distributed configuration.
Moreover, a distributed amplifier needs loading of the grid line. This prevents the implementation of standard semiconductors switching techniques that imply only charging and discharging a capacitive load. In fact, to relax the bandwidth constraint, the amplifier should be optimized for rise-time rather then linearity and have the minimum number of cascaded stages. As described in the following sections both conditions can be obtained implementing the amplifier with a tube connected in common cathode configuration directly driven by some fast Mosfets. As for Power Mosfets or IGBTs switching, if the grid voltage is kept below conduction, the driver stage only needs to provide or remove the capacitive input charge. This allows the use of small, fast devices. Unfortunately these items only exist for low working voltages (50V-70V) which limits the choice to medium power tubes that have to be combined to obtain the specified output voltage. With the selected tube, 16 units are needed to get 1 kV on 50 Ω. They will be combined using standard rf techniques and a delay compensated transformer.

2. Circuit Description

Among the available tetrodes, Siemens type YL1056 is probably the best suited for our application. Plate current is at very low values with Vgk of only –40V and it increases to ~5.5A at Vgk =0V. This parameter is fundamental to allow direct grid drive by means of small Mosfets. The tube main characteristics are listed in Table 1.

YL1056 Tetrode					
Plate DC Voltage	:	3.5kV	gm @Ia~5A and Va>1kV	:	0.2 A/V
Plate Dissipation	:	2kW	gm @Ia~0.5A and Va>1kV	:	0.055A/V
Screen Voltage	:	500V	Is @ Vgk=0V and Va=1.5kV	:	0.3A
Screen Grid Dissipation	:	30W	Cgk	:	42pF
Control Grid Dissipation	:	5W	Cgs	:	60pF
Ia @ Vgk=0 and Va>1kV	:	5.5A	Cag	:	0.05pF
Ia @ Vgk=-40 and Va>1kV	:	0.2A	Cas	:	8.4pF

Table 1 – YL1056 Main Characteristics

2.1. Plate Circuit

Assuming the tube plate capacitance C_a=10pF and a plate load R_a=50Ω the cutoff frequency would be ~320MHz. This limit can be further increased introducing a compensation series inductance. The widest bandwidth is obtained by setting the circuit quality factor to

$$Q_a = \frac{1}{R_a} \cdot \sqrt{\frac{L_a}{C_a}} = \frac{1}{\sqrt{2}} \quad \text{so that} \quad L_a = \frac{R_a^2 \cdot C_a}{2} = 12.5nH$$

The compensated circuit cutoff frequency and rise-time then are

$$f_c = \frac{1}{2 \cdot \pi \cdot \sqrt{L_a \cdot C_a}} = 450MHz \qquad t_r \approx \frac{0.35}{f_c} \approx 0.8ns$$

Shorter rise-time could be obtained with higher Q_a values but with more pronounced overshoot which is now limited to ~5%.
The plate current the tube can supply at Vgk=0V is 5.5A which gives a voltage swing on the plate load of 275V. Assuming the DC plate supply to be V_{HT}=1725V, the power dissipated on the tube, considering the maximum duty cycle (D_m) and a rest current $Ia_{o=}$0.2A, is

$$Dm = \frac{270ns}{300ns} \cdot \frac{2.2ms}{13.3ms} \approx 0.15$$

$$Pa = 1725V \cdot 0.2A \cdot (1 - Dm) + 1450V \cdot 5.5A \cdot Dm \approx 1.5kW$$

which is well within the maximum rating. When pulsed to 5.5A, the screen current is 0.3A so that the power dissipated on the screen grid with Vs=500V is ~23W against a 30W limit.
To provide the DC power supply to the tube anode without degradation of the frequency response, the self-resonance of the rf choke should lay above the plate circuit cutoff. This is quite unlikely to be obtained but the problem can be solved using the inverting, ferrite loaded, transmission line transformer shown in Figure 1.

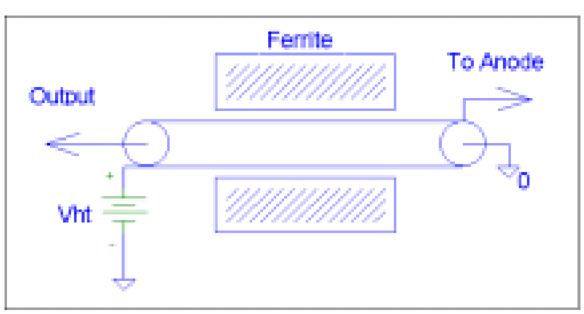

Figure 1 - Inverting, Ferrite Loaded, Transmission LineTransformer

The circuit provides AC de-coupling and, for a correctly implemented device, frequency response can extend to the GHz region. Tests have been made on 4L ferrite (μi~200) to evaluate the saturation effects due to the DC current component. They showed that with a section of ~16cm^2 one gets ~6μH at dc currents up to 5A. To limit the induction to 5mT at 250V and 3.3MHz (the repetition frequency we require) one needs two of these sections for a total inductance of 12μH. Using a line characteristic impedance of 50Ω, the low frequency cutoff will then be ~700kHz.

2.2. Grid Circuit

Since the tube Ia vs Vg characteristic is not linear, driving the grid with a linear function will result in a delayed and accelerated front on the output. To evaluate the transient times required from the driving signal, Pspice simulations of the circuit shown below have been done. The circuit is driven by a 40 V voltage generator with 5 Ω internal impedance. It includes a fairly representative tube model constructed from constant current curves. The tube-input capacitance, for grounded cathode configuration, is Cin~105pF and its internal construction (studied by opening an old tube) is such that the active region is connected to the contacts through coaxial lines having constant characteristic impedance. The grid-cathode line has Zo=25Ω and is 5cm long while the values for the control-grid screen-grid line are Zo=18.5Ω and 3cm. T1, TX1 and T2, TX2 represent these lines and their common mode inductance respectively. The tube cathode is DC biased to +40 V in order to obtain 200 mA anode current. On the plate side T4, TX3 represent the inverting, ferrite loaded, transmission line transformer while T3 is introduced because of the anode circuit physical layout. Better transient results require a 15nH compensation inductance instead of the computed 12.5nH. As shown in Figure 3, to obtain 2ns rise and fall times (10% to 90%) on the load resistance, the input signal requires a 2.2ns rise time and 2.8ns fall times. We must also notice that the input current peak is limited to ~2A.

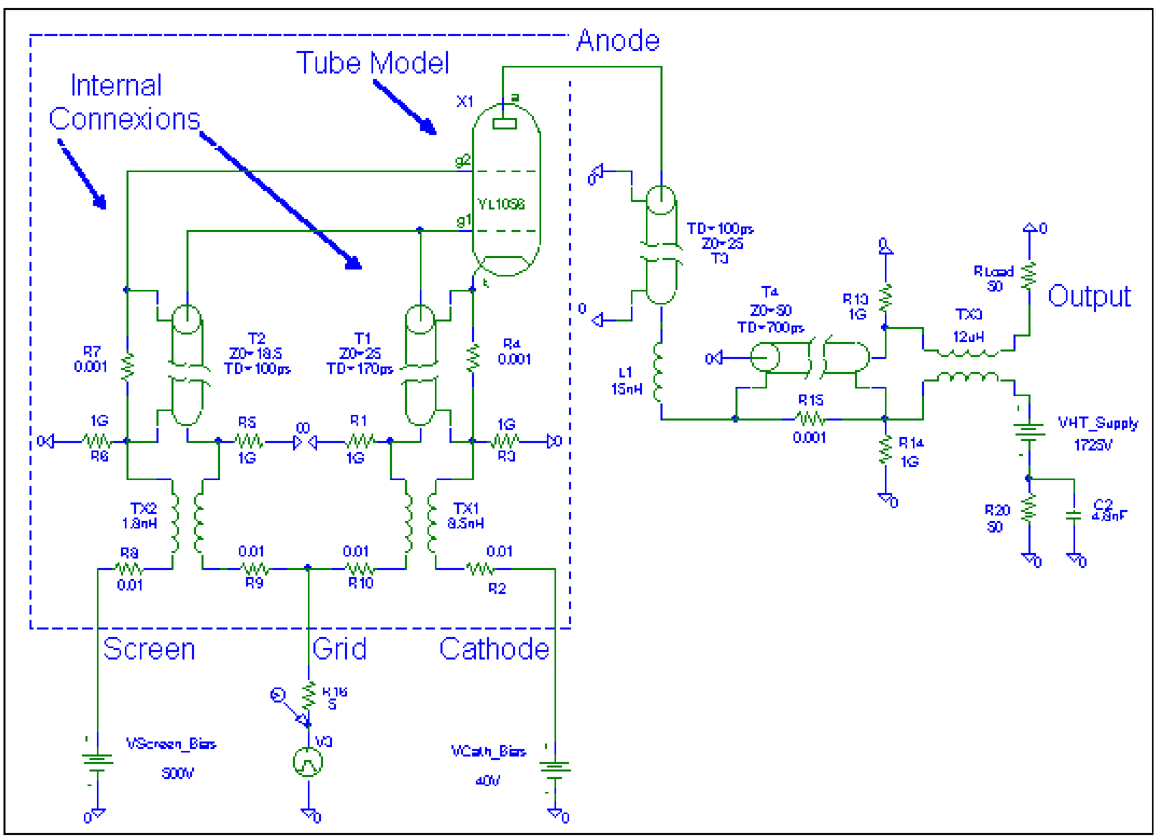

Figure 2 –Pspice Circuit

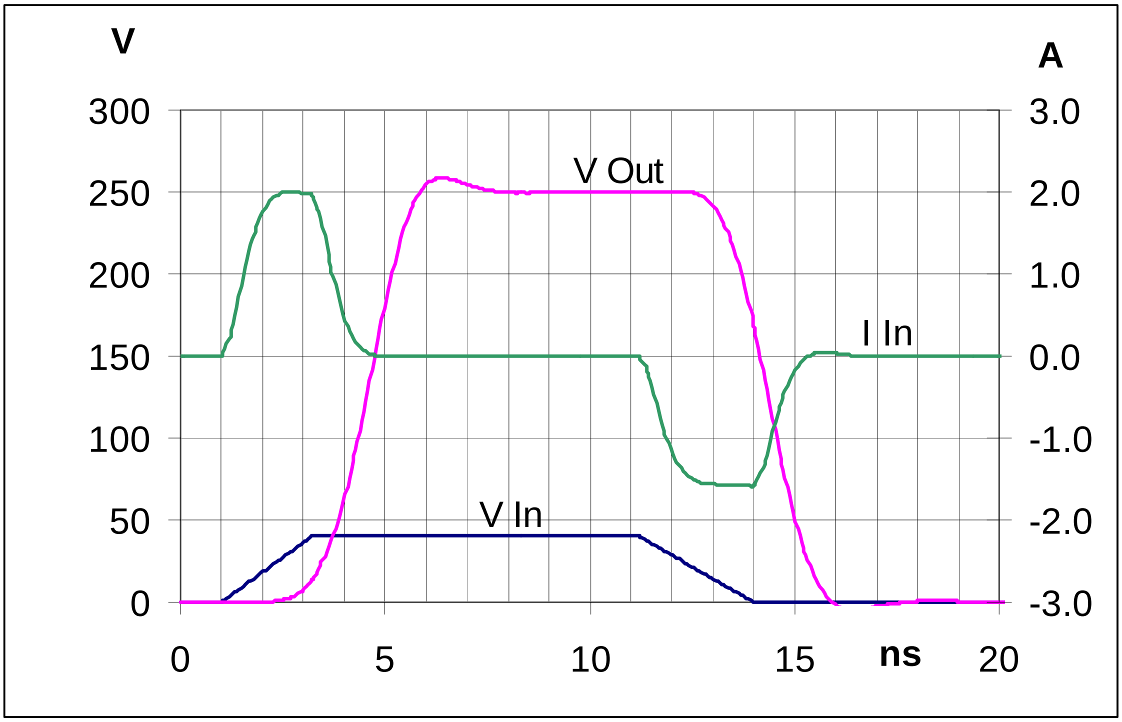

Figure 3 – Simulation Results

2.3. Grid Driver

Charge and discharge of the tube input capacitance could be done using 8 parallel cells as shown in Figure 4. The Mosfets typical characteristics are listed in table 2 and 3. Attention must be paid to prevent dissipating excessive power on the grid by driving it into conduction. This could destroy both the tube and the grid driver. The circuit should be spread around the tube in order to limit leakage inductance that could rapidly deteriorate the performances. Simulated results of the tube driven by the gate driver are shown in Figure 5.

BSN20 N-Channel Mosfet						
Max. Drain-Source Voltage V_{DSS}	:	50V		Input Capacitance Ciss	:	8pF
Max DC Drain Current I_D	:	0.1A		Output Capacitance Coss	:	7pF
Pulsed Drain Current I_{DM}	:	0.3A		Reverse Transfer Capacitance Crss	:	2pF
Turn On Time	:	2ns				

Table 2 – BSN20 Typical Characteristics

BSS84 P-Channel Mosfet						
Max. Drain-Source Voltage V_{DSS}	:	50V		Input Capacitance Ciss	:	25pF
Max DC Drain Current I_D	:	0.13A		Output Capacitance Coss	:	15pF
Pulsed Drain Current I_{DM}	:	0.52A		Reverse Transfer Capacitance Crss	:	3.5pF
Turn On Time	:	3ns				

Table32 – BSS84 Typical Characteristics

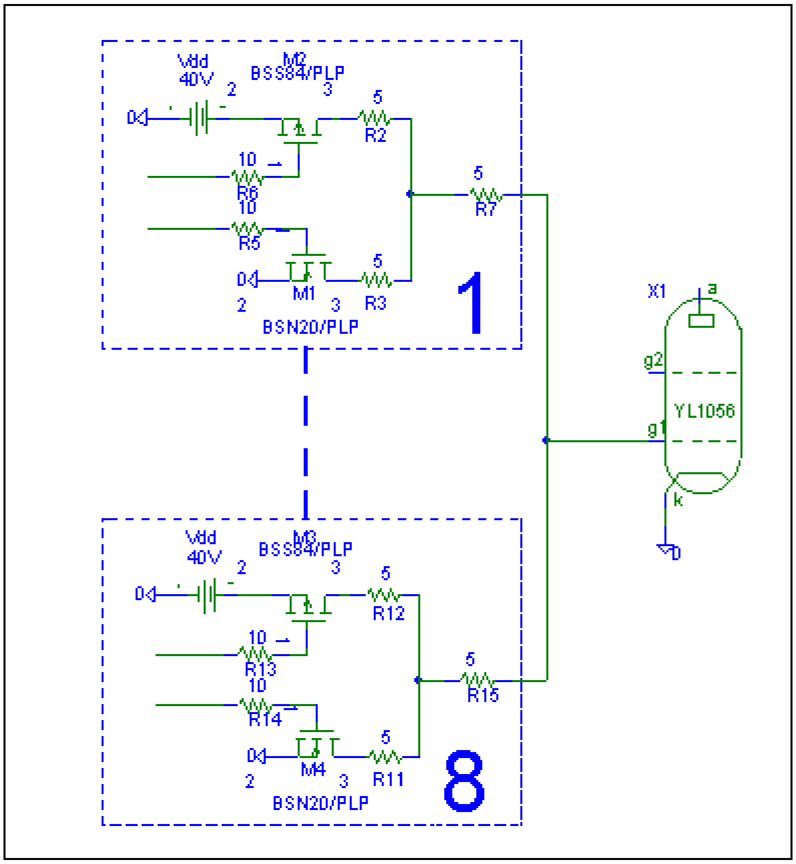

Figure 4 – Gate Driver Configuration

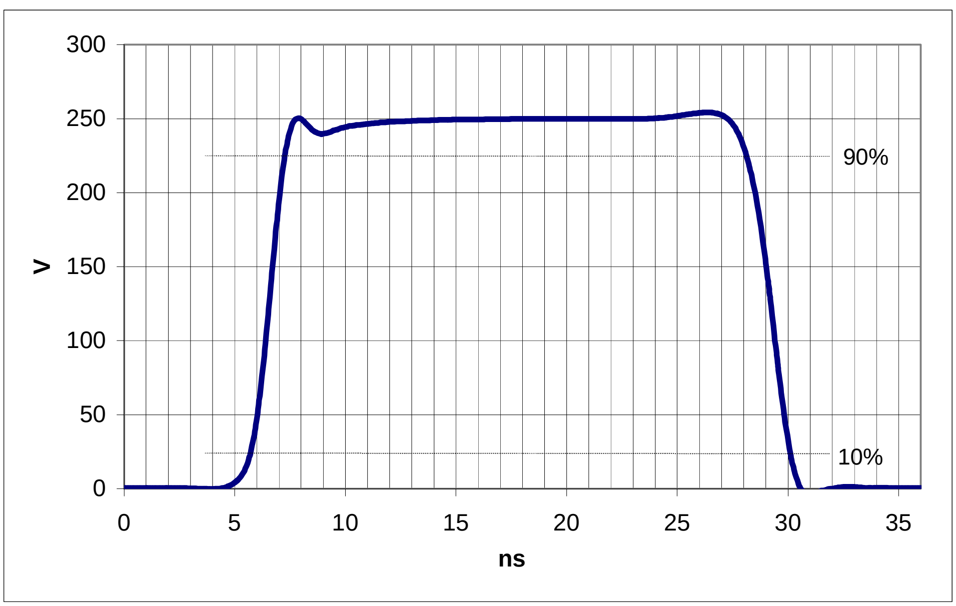

Figure 5 – Output Pulse Of The Circuit Shown In Fig. 2 Driven By The Gate Driver Of Fig. 4

2.4. Output Combiner

Coupling together 16 of the modules described above will give 250V on 3.125Ω that can be transformed into 1 kV on 50 Ω by a 1 to 16 transmission line transformer (Fig. 6). A delay compensated device can provide the required bandwidth and transformation ratio. No particular problems are expected from this circuit. AC coupling of the different modules imposes DC line restoration at load level adding extra complexity to the pulser.

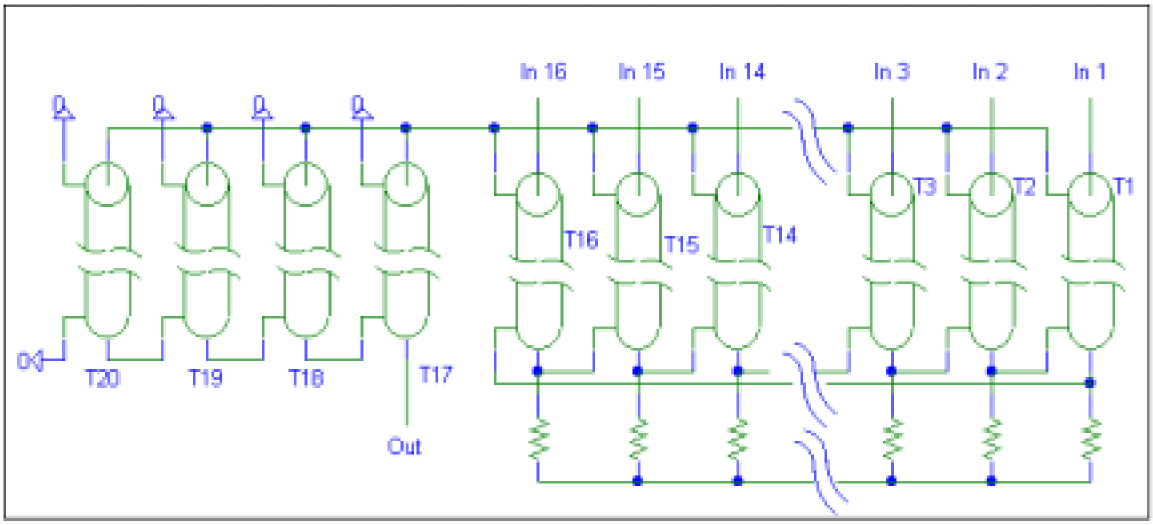

Figure 6 – Combiner and 1 to 16 Transformer Schematic

3. Price Estimation

Each of the 16 basic unit built around a tetrode and having all the power supplies can be estimated at ~20kCHF divided as follows:

Power Tube	:	5 kCHF
Ferrite	:	1 kCHF
Power Supplies	:	6 kCHF
Gate Driver and Ancillary Equipment	:	3 kCHF
Mechanics	:	5 kCHF
Total Price	**:**	**20 kCHF**

DC line restoration can be implemented for 50kCHF so the pulse generator price can be estimated to ~370kCHF.

4. Conclusion

Pspice simulations of the pulse generator for the 2.2 GeV Linac Beam Chopper provide encouraging results that must be verified by a real device. The required performance could possibly be achieved mixing solid state and vacuum tubes technologies but active devices are pushed close to their technological limits. Principle testing of the grid driver configuration proved that the required grid control voltage can be switched in about 2ns but mixing low voltage Mosfets with high voltage power tubes could prove critical. It seems therefore necessary to construct a 250V module prototype to verify that physical implementation of the circuit is possible.

Appendix A

As described in [3] the response of a current driven, parallel R-C network has a half power high-frequency cutoff $f_c = \frac{1}{2 \cdot \pi \cdot R \cdot C}$ while its time response to a step function is such that 10% to 90% rise-time is $t_r = 2.2 \cdot R \cdot C$. Cascading 'n' of such stages with adequate isolation, will produce a degradation of both the cutoff frequency and rise-time with a law given by

$$\frac{1}{\sqrt{2^{\frac{1}{n}} - 1}} \approx 1.1 \cdot \sqrt{n}$$

so that $f_{c_n} \approx \frac{f_c}{1.1 \cdot \sqrt{n}}$ and $t_{r_n} \approx t_r \cdot 1.1 \cdot \sqrt{n}$

Rearranging the above equations to obtain f_c as function of t_{r_n} gives

$$f_c \approx 1.21 \cdot \frac{\sqrt{n}}{\pi \cdot t_{r_n}}$$

1) R. Garoby, M. Vretenar, Private communications.
2) J. Millman, H. Taub, Pulse, Digital and Switching Waveforms, Appendix C, Mc Graw-Hill, New York,1965.
3) J. Millman, H. Taub, Pulse, Digital and Switching Waveforms, chap. 4, Mc Graw-Hill, New York,1965.