

ELECTRICAL DESIGN OF THE BEAM SWEEPING POWER SUPPLY

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This report describes the electrical design of the power supply for the beam sweeping system. Essentially all pulsed-power circuit components are identified and described in detail. The general features of the design follow the circuit described in Ref. 1. The details of the magnetic cores for the compression reactors are described in a separate pbar note.

The power supply circuit is a two-stage magnetic pulse compression circuit. Referring to Figure 1, the sequence begins when the SCR is triggered, transferring energy from the energy storage capacitor C0 to the first compression stage capacitor C1 through the high voltage step-up transformer TX1. L1 is the SCR protection choke. When the first compression reactor L2 saturates, the energy is transferred, through two RG-220 cables, to C2 in the target vault, which in turn discharges through the second stage reactor, to the resonant circuit C3 and L4. L4 represents the inductance of the sweep magnet. The most significant change since the writing of Ref. 1 is the splitting of the winding on the first stage reactor into two equal halves. Each half has 8 turns. The effect of splitting the reactor winding is that the circuit between the step-up transformer and the reactor becomes balanced, with peak voltages of ± 15 kV, instead of the 30 kV of an unbalanced circuit (compare Fig. 4 of Ref. 1). When the reactor saturates, the voltages on the two capacitor terminals approach 15 kV, and the voltage on one of the two output terminals approach 30 kV. The other terminal remains at ground potential until the second reactor saturates. It may be possible to wind the second stage reactor in a balanced manner, but, because of the nested arrangement of the capacitor box on the target module, no easy way was found to do it. Thus the circuit remains unbalanced at the second reactor. After the magnet is energized, all the voltages ring at half the voltage across the sweep magnet because the secondary circuit ground is at the center tap of the sweep magnet. Voltages calculated by Spice for the circuit with an initial charge on the energy storage capacitor of 3 kV are plotted in Figure 2. The behavior of the current waveforms remains essentially as reported in Ref. 1.

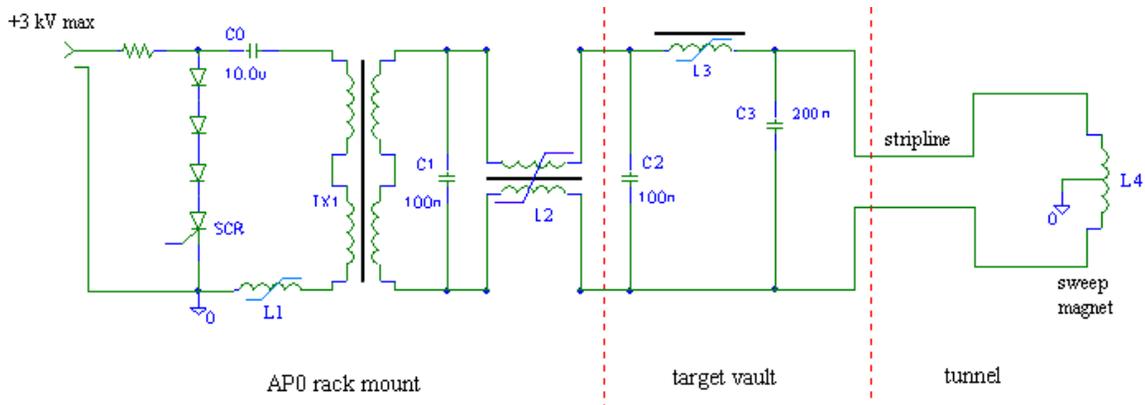


Figure 1. Simplified schematic diagram of power supply.

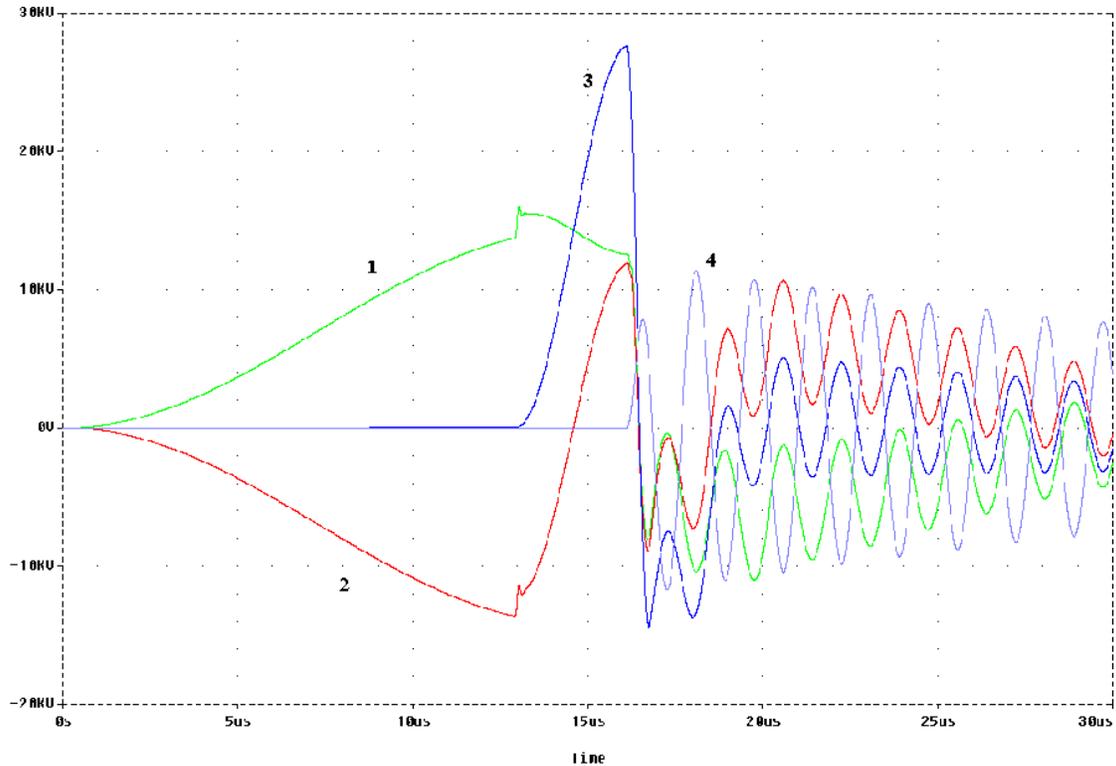


Figure 1. Spice model voltage waveforms. 1- First stage capacitor C1 voltage, positive side, 2 - capacitor C1 voltage, negative side, 3 - second stage capacitor C2 voltage, 4 - ringing circuit capacitor C3 voltage.

The final design of the trigger circuit is not completed. We expect that it will closely follow the design of the trigger circuit shown in Ref. 1.

The cable damping circuit (R8C2 in the circuit drawing POWER SUPPLY - RACK below) has not been tested. It may be necessary to break up its function into two RC circuits, one on each cable if the inductance of the leads to the circuit become too long. The optimal value of the transformer centertap resistor (R7) has not been determined. It should be the smallest possible without reducing the amplitude output pulse.

Pulse transformer.

The pulse transformer consists of two cylindrical G-10 spools mounted on a cut silicon-steel core with dimensions as listed in the table. The 9-turn primary winding is 1/2" copper strip wound on the inner spool, and the 90-turn secondary winding is #16 magnet wire (MWS Industries) wound on the outer spool. The spools are connected in series in both primary and secondary circuits. The total calculated stray inductance of the transformer is 2.8 μH , which is the largest single contribution to inductance of the primary circuit. The transformer leakage inductance was intentionally made large. The large inductance allows for a wide the insulation gap between the primary and secondary windings.

Assembly notes.

1. All the cores were filed to fit the spools, and then acid etched in a 85% phosphoric acid solution for 15 minutes. After etching, several of the cores no longer fit in the spools, indicating some swelling of the cores in the acid etching process. If necessary, the process can be repeated.
2. Take care to clean and sandpaper primary windings on the transformer.
3. Do winding with cotton or latex gloves (avoid the latex gloves that come with lubricant on them). General cleanliness is very important to maintain good adhesion of the epoxy fill.
4. Round edges of primary winding with deburring tool. Acid etch may also be helpful.
5. Carefully clean off solder flux with flux cleaner. Be extremely careful to remove all the flux. Using small quantities of alcohol or cleaner with a q-tip or kimwipe is preferable to just blasting it with an aerosol. This prevents flux from being spread around. Clean in ultrasonic cleaner.
6. Assemble spools using core as a guide. Epoxy parts together, paint on the same epoxy they use to pot with.
7. Vacuum pot both spool assemblies. Fill to top, with epoxy wetting the top of the assembly. Plastic/paper cones prevent dripping/overflowing of the epoxy.
8. Paint flange with epoxy, drop it on, pull a little vacuum, fill up with epoxy.
9. There is an option of using a pressure vessel, if one comes available. It may be necessary to do the entire potting procedure in the pressure vessel. Place a Plexiglas lid on tank for the vacuum pot part of the operation.
10. Probably place the primary and secondary high voltage connectors on opposite sides of the spool pieces.
11. Primary jumper: wrap/solder strip around copper rod to make the connection.
12. Use rubberized dip coating on primary jumpers and connectors.

Compression reactors.

The first stage consists of 8 + 8 turns on 4 tape wound cores. The second stage consists of 4 turns on three Metglas cores. The cores will be in aluminum cans, and potted in Sylgard in a Nalgene polycarbonate case.

Assembly notes

1. Put threaded holes in the top conductors. This serves 3 purposes.
 - prevent trapped air bubbles in the potting process
 - allow for easier removal of soldered pieces
 - for bolting to an alignment fixture on assembly
2. Preferable to do a 1-step potting procedure.
3. Order aluminum cans for 2nd stage Allied Metglas cores. These will be open cans. The cores will be RTVed inside the cans. Assemble using G-10 hooks to hang the cans from the middle-potential conductor, 4 places. Pot with a hard vacuum. Not a great problem if some air bubbles remain in mylar region, since electric field is not very large there. Back fill with nitrogen.
4. First stage. To prevent virtual leaks from the 'sealed' cans, pot in a soft vacuum (about 100 microns). Plastic spacers will be necessary.
5. First stage mounting pieces can be similar to the second stage (side mount on the conductor bars). The pieces should be attached near the middle turn on each side of the winding. At this location, the voltage difference between the conductors and the cores is at most 7.5 kV.

6. We decided to bolt the conductor pieces together. In addition, the bottom connections should be well soldered to prevent any possibility of sparking. The top pieces should be lightly soldered, to allow the possibility of disassembling the reactor.
7. Reactor conductor bars can be either copper/brass or aluminum. In either case they should be silver plated. You can't solder to tin plate, the tin melts at too low a temperature.

Bias circuit.

The bias circuit provides DC bias current through a single turn on the compression reactors. The choice to operate with DC bias current, rather than a pulsed reset, was made to take advantage of the simplicity and reliability of a DC bias circuit. The bias choke has a design inductance of 4 μ H which, together with the capacitor C1 and the parallel resistor R1, suppresses the pulse voltage at the DC current supply. The bias choke has a volt-second capability of 20 mV-sec (compared to the single-turn volt-second rating of the compression reactors of 10 mV-sec), at 8.7 A DC bias current. The bias choke is grounded at the center, so that, for a 7 kV loop voltage, the peak voltage to ground at the bias choke is 3.5 kV. There are two identical bias circuits, one for each compression reactor. They may be energized by two DC current supplies separately or by a single supply in series.

Table B1
Results of a thermal test of the bias choke spool, measured with infrared heat sensor.

Current	Winding temperature
6 A	137° F
8 A	166° F
10 A	243° F

The nylon spool is rated 130 °C = 266° F. The results of this test indicate that 8 A is probably the maximum acceptable operating current. Pulse tests of the Allied Metglas cores show that we would like to operate at about 5 A DC bias.

Parts lists and circuit diagrams for the power supply are shown below. Construction details follow for several of the components.

Table 1
List of circuit components of power supply

PART	FUNCTION	DETAILED DESCRIPTION
R1	charging resistor	HVR Type AB664, 1000 Ω
R2	charging resistor	HVR Type AB664, 3500 Ω
R3	discharge resistor	Caddock MX431, 6 M Ω
R4	varistor	Harris V480LA80B
R5	varistor	Harris V575LA80B
R6	diode grading resistor	18K, 2 Watt carbon comp.
R7	transf. centertap resistor	1000+ Ω , HVR Type AJ149, or Cesiwid
R8	cable damping resistor	Cesiwid 234AS101JD5, 100 Ω , 2.5 kV
C0	energy storage capacitor	Maxwell #30664, 10 μ F, 7.5 kV
C1	first stage capacitor	Maxwell #31981, 0.1 μ F, 40 kV, double ended
C2	cable damping capacitor	Murata DHS30 N4700 301M401K (300 pF, 40 kV)
C3	second stage cap. bank	52 parallel Murata DHS60-120N4700202K40K (2 nF, 40 kV)
C4	resonating cap. bank	54 parallel Murata DHS60-120N4700402K20K (4 nF, 20 kV)
L1	SCR protection choke	8 turns on Magnetics Hi-flux core #58438-A2
L2	first stage reactor	8+8 turns on 4 Magnetic Metals cores #501A4601P
L3	second stage reactor	4 turns on 3 Allied-Signal Metglas/mylar cores: see description
L4	sweep magnet	see description
D1	discharge rectifier	Fagor 7 kV plastic rectifier Type HVR3-7
D2	pulse rectifier	Westcode diodes SM12CXC314
SCR	switching thyristor	Westcode thyristor D315CH36F2D0
TX1	pulse transformer	18:180 turns on a 4-mil Si-steel National Arnold cut core 1.5" x 1.5" x 3.5" x 6.5"

Table 2.
List of components in voltage divider #1

PART	FUNCTION	DETAILED DESCRIPTION
R1	hv resistor	Victoreen Slim-mox 102 , 8.73 M Ω , 1%
R2	viewing resistor	30.1 k Ω , 1% thin film resistor
C1	hv capacitor	24 pF silver mica, 2500 V P/N CDV30EK240J03
C2	viewing capacitor	3300 pF, Mallory ceramic chip, temp. characteristic COG
C-trim	trim capacitor	300 pF typical
R3	cable damping resistor	51 Ω , 1/4-Watt carbon comp.
	spark gap	90V gas-tube surge protector Joslyn #2027-09-B

Table 3.
List of components in voltage divider #2

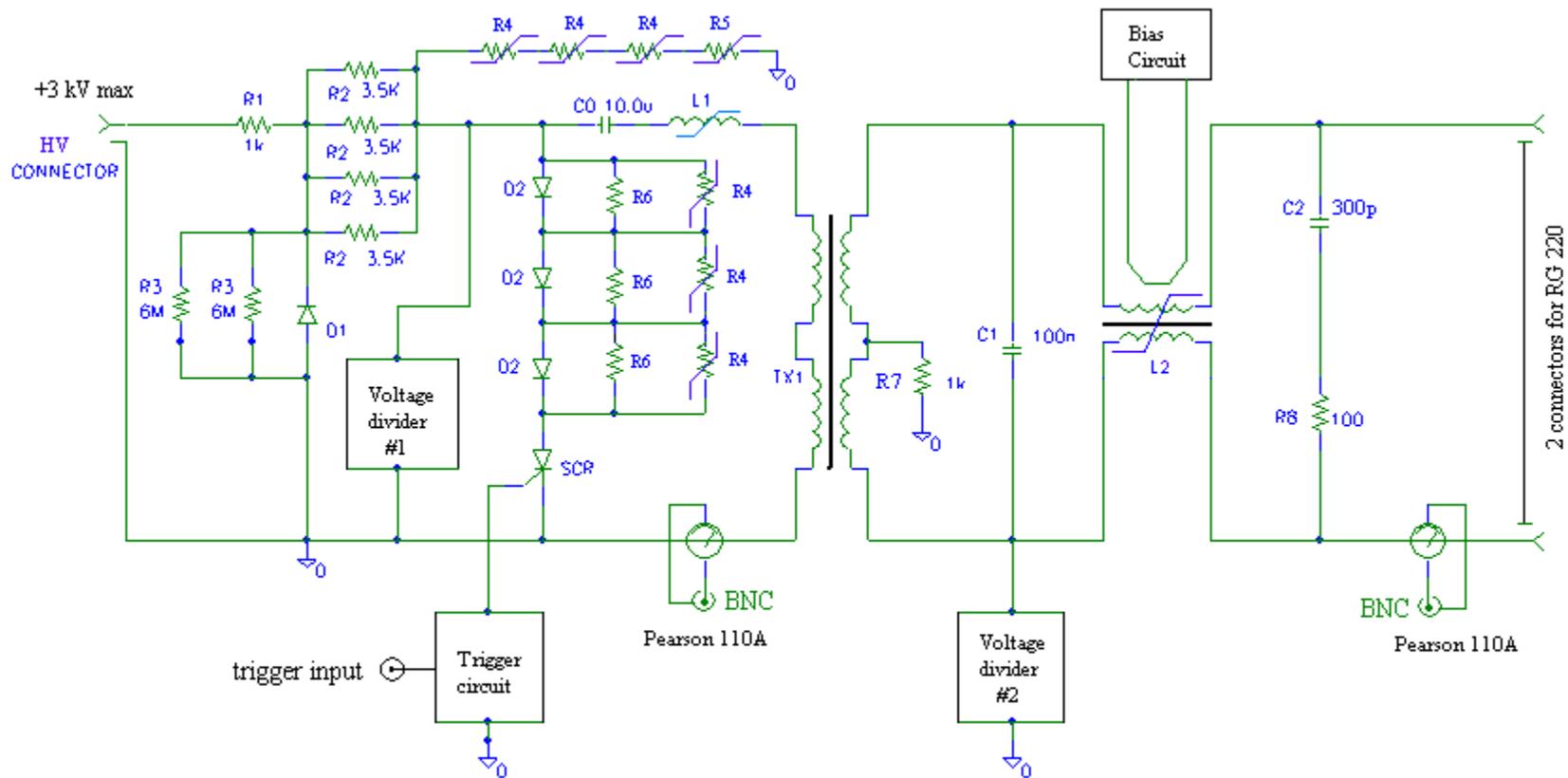
PART	FUNCTION	DETAILED DESCRIPTION
R1	hv resistor	Victoreen Slim-mox 102 , 285 k Ω , 1%
R2	hv resistor	Victoreen Slim-mox 102, 571 k Ω , 1%
R3	viewing resistor	1.0 k Ω , 1% thin film resistor
C1	hv capacitor	24 pF silver mica, 2500 V P/N CDV30EK240J03
C2	viewing capacitor	3300 pF, Mallory ceramic chip, temp. characteristic COG
C-trim	trim capacitor	300 pF typical
R3	cable damping resistor	51 Ω , 1/4-Watt carbon comp.
	spark gap	90V gas-tube surge protector Joslyn #2027-09-B

Table 4.
List of components in voltage divider #3 and #4

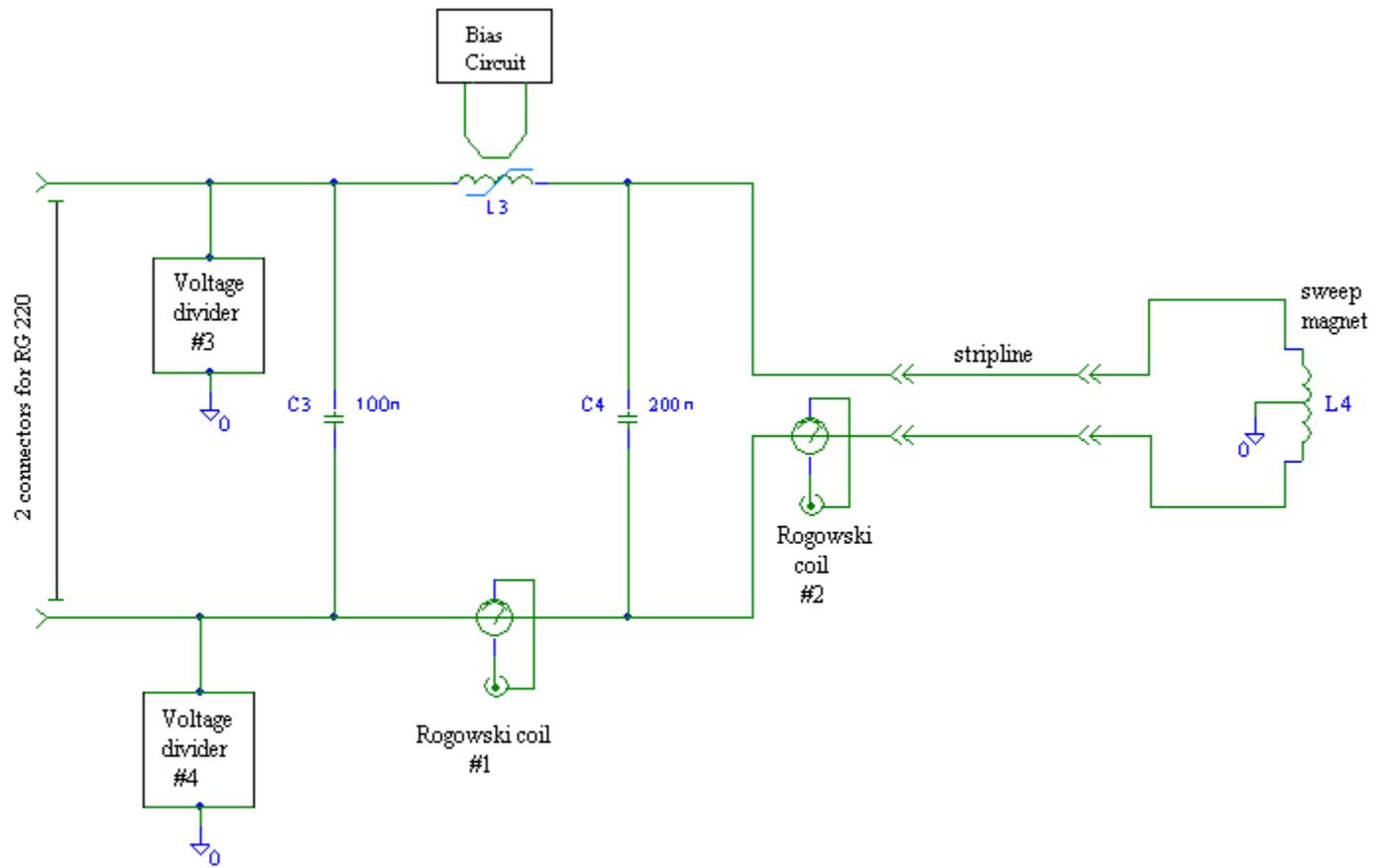
PART	FUNCTION	DETAILED DESCRIPTION
R1	hv resistor	25 k Ω , 1%, Victoreen Mox-4-13 (#3); Mox-2-13 (#4)
R2	viewing resistor	51 Ω 1/2 Watt, carbon comp.
	ferrite bead	from Bob Vargo's 'Joule box'
	spark gap	90V gas-tube surge protector Joslyn #2027-09-B

Table 5.
List of components in bias circuit

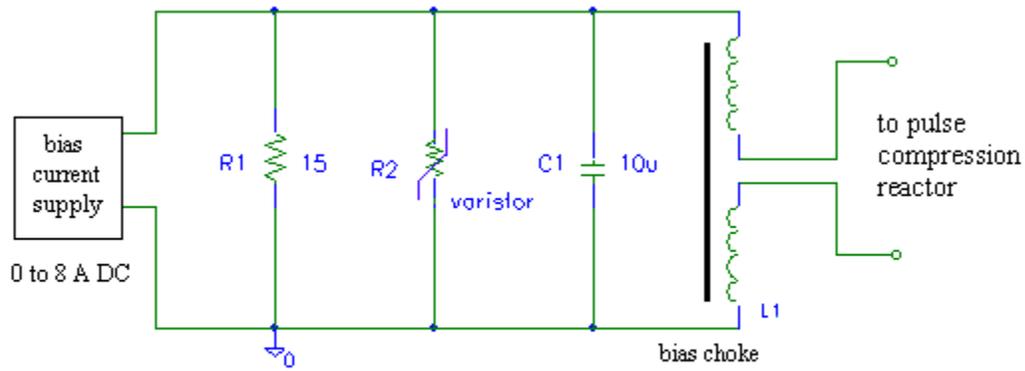
PART	FUNCTION	DETAILED DESCRIPTION
R1	damping resistor	15 Ω , 1 Watt, carbon comp.
R2	damping varistor	Harris V22ZA2
C1	damping capacitor	CDE polypropylene type DME2W10K (10 μ F, 250 V)
L1	bias choke	90 turns on 2 National-Arnold 4-mil Si-steel cut cores AH-24



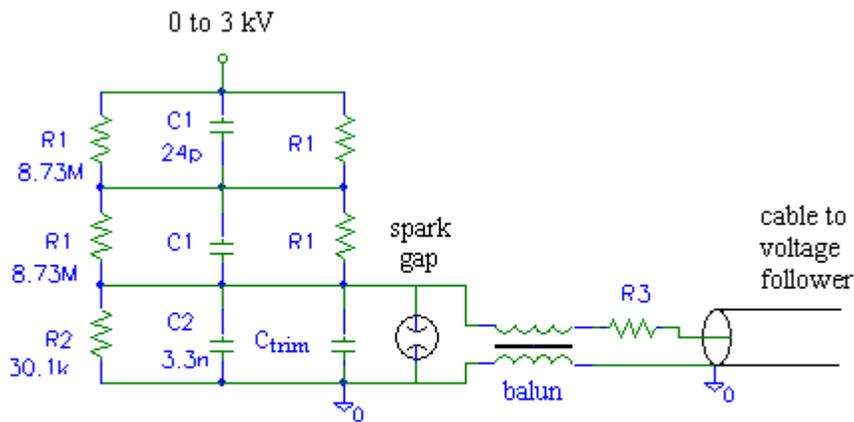
POWER SUPPLY - RACK



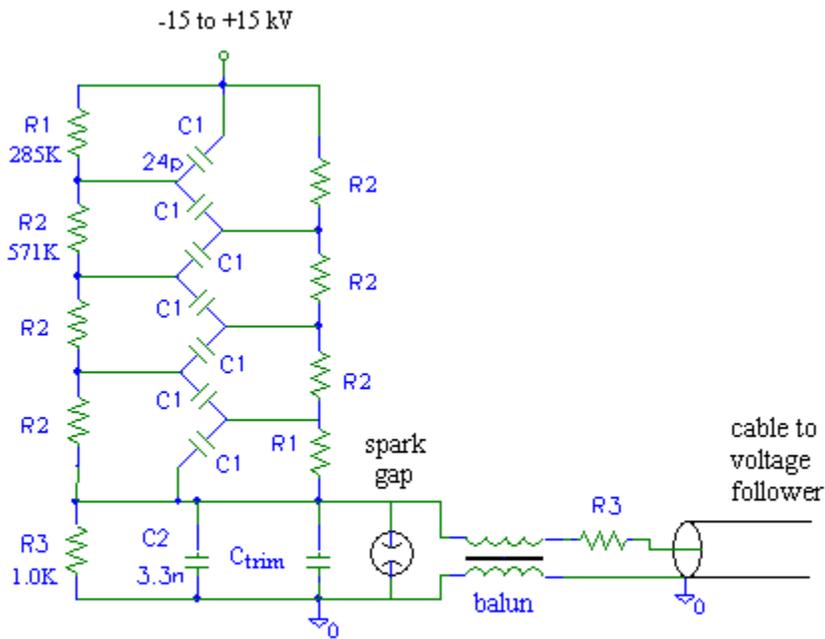
POWER SUPPLY - TARGET VAULT



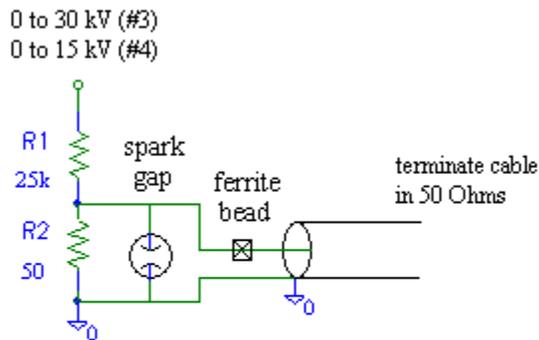
BIAS CIRCUIT



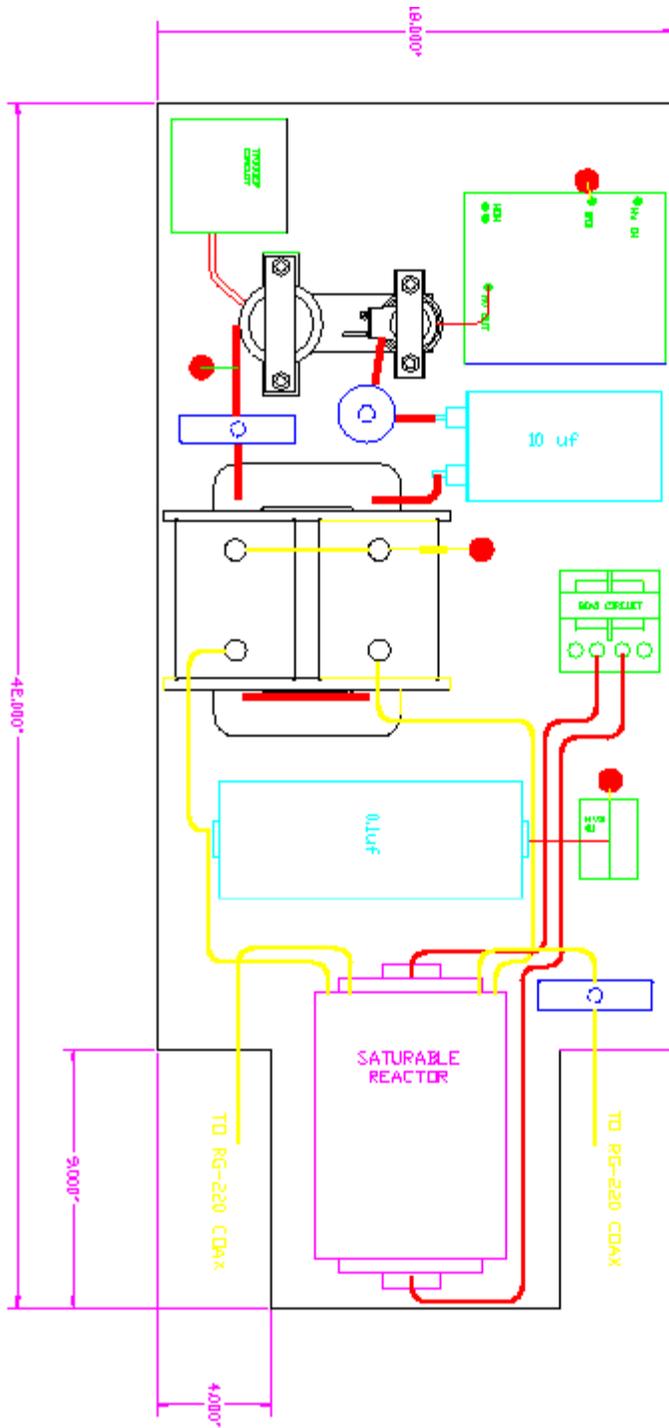
**Voltage divider #1 - charge circuit
(300:1)**



**Voltage divider #2 - first stage
(1000 : 1)**



**Voltage dividers #3 and #4
(1000:1)**



Power supply - rack layout.

Voltage dividers.

#1. Charge circuit.

The voltage divider in the charge circuit is installed as part of the charge circuit card. It has good frequency response from DC to 2 MHz. The mica capacitors have very low temperature and voltage coefficients. The viewing capacitor is a ceramic chip capacitor to minimize self-resonance effects. The COG temperature rating of the ceramic capacitor is very stable. The balun is a few turns on a ferrite core. The 51-Ohm output series resistor, combined with the capacitance of the cable, damps the cable ringing. The signal may be viewed at an oscilloscope or voltage follower input. The RC time constant is 100 μ s, so this is predominantly a capacitive divider on the time scale of power supply operation. The voltage ratio was chosen to be 300:1 such that the maximum signal would be 10 V, for input to controls equipment.

#2. First stage.

The voltage divider for the first compression stage has a ladder of seven mica capacitors. It should be installed on the low voltage side of the transformer/capacitor to properly observe the voltage swings on both charge and discharge. In addition careful grading of the voltage structure is desirable to minimize the amount of self-generated corona in the voltage divider. Circuit card should have the capacitors arranged in a compact ladder geometry, with the grading structure on both sides of the circuit components. A trim capacitor may also be installed if necessary. The RC time constant is 3.4 μ s.

#3. Second stage - inner capacitor box.

The voltage divider on the inner capacitor box in the target vault is designed to be simple and rugged. The resistance is low enough that the RC time constant is very short (<10 ns) and no compensation is required. The low resistance value is possible because the voltage pulse is very short. The output is protected by a spark gap surge protector. The ferrite beads damp high-frequency circuit oscillations. The long cable connects to a scope terminated in 50 Ohms.

#4. Output voltage - outer capacitor box

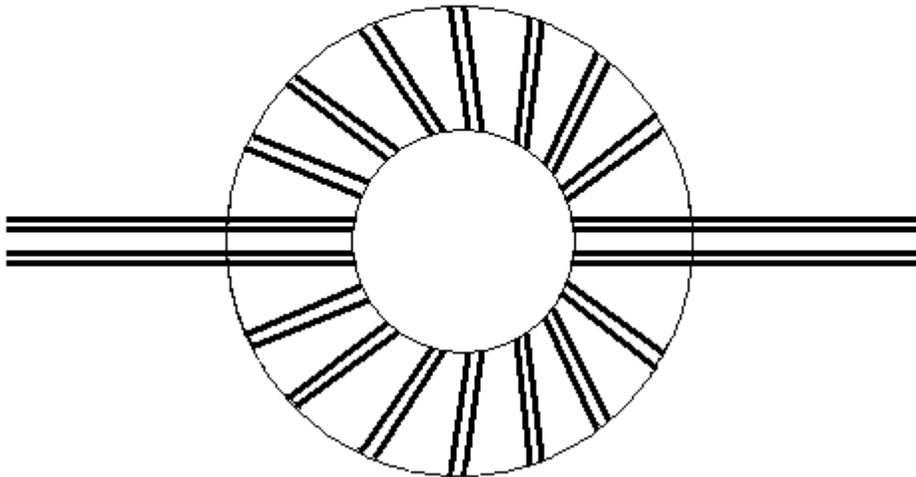
This voltage divider has the same circuit diagram as the second stage divider. The only difference is that the resistor is only rated for 20 kV.

SCR protection choke

The Westcode SCR chosen for use in this circuit has a repetitive dI/dt rating of $1000 \text{ A}/\mu\text{s}$. In order to maintain dI/dt to well below this value while the SCR is turning on, the SCR protection choke limits initial dI/dt to $100 \text{ A}/\mu\text{s}$. The protection choke saturates after roughly one microsecond. The inductance of the saturated choke is about $0.3 \mu\text{H}$.

Assembly

1. Use hi-flux core #58438A2 ($\mu=125$).
2. Double wrap fiberglass tape over the core.
3. Use 2 parallel windings of MWS Industries kapton- insulated #16 magnet wire.
4. Wind 8 turns, double, on each side of the core in opposing direction (2 parallel sets of 8 turns on each side, as shown).
5. Pot the entire assembly in potting compound.



Rogowski coil

The Rogowski coil for the output circuit (Rogowski coil #2) is a thin tube to be inserted into a special G-10 insulator structure between the two output conductors. Construction details of the Rogowski coil are given the Assembly section. The mechanical design for Rogowski coil #1 does not exist because the mechanical design of the capacitor boxes and the electrical connections between the capacitor boxes is not complete. It may be possible to adapt the Rogowski coil #2 design for use in this location between the upper and lower capacitor boxes. Note that Rogowski coil #1 is not absolutely essential, since the discharge current through the output switch can be ascertained from the measured voltages on opposite sides of the switch.

The coil consists of about $N = 210$ turns of #22 magnet wire, with inductance L given by

$$L = \frac{\mu_0 N^2 r^2}{\ell + 0.9r} = 4.5 \text{ mH}$$

where ℓ is the coil length (5.75"), and r is the wire radius. The effective resistance of the wire (taking into account skin depth of .0033") is $.303 \Omega$. If the viewing resistor is 0.25Ω , the L/R time of the Rogowski coil is $8 \mu\text{s}$. This is the low-frequency cutoff. An uncut steel shield ($\rho = 72 \mu\Omega\text{-cm}$) of thickness $0.010"$ has a resistance of $0.343 \text{ m}\Omega$ and an inductance of 0.22 nH , or an L/R time of 600 ns . This is the high-frequency cutoff for a closed shield. Since the Rogowski coil requires a flat frequency response up to at least 1 MHz , the shield must be cut, and no longer provides a high frequency cutoff. The prototype Rogowski coil was calibrated against a Pearson current monitor, and shows excellent amplitude and phase response in the range 80 kHz to 1 MHz .

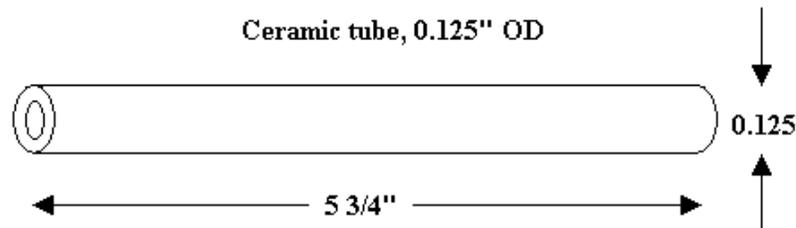
The amplitude response is just the voltage generated across the viewing resistor by the Rogowski coil current induced by the current in the stripline, I ,

$$V = RI / N$$

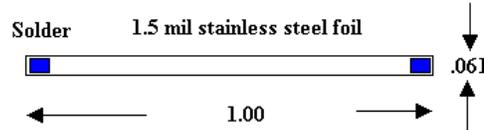
or about $1 \text{ V} / \text{kA}$.

Assembly

1. Cut/grind .125" OD ceramic tube to $5 \frac{3}{4}"$ length (ID= $1/16"$).

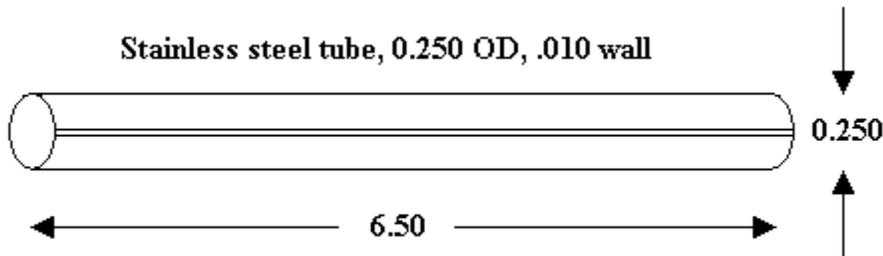


2. Wind ceramic tube with #22 magnet wire, covering the tube. The ends of the wire will be soldered to wires connected to the viewing resistor assembly, running through the center of ceramic tube.
3. Make current viewing resistor of 1.5-mil nonmagnetic 18-8 stainless steel foil. Remove adhesive backing. Cut a piece to length about 1 inch. Use stainless-steel flux to make solder pads on opposite ends of the foil. Adjust dimensions as necessary until the resistance is within 10% of 0.25 ohms.



The resistor should be electrically connected across the two ends of the coil. Solder output signal leads to the ends of the resistor, and place the viewing resistor inside the ceramic tube. Fix both ends of wire and the resistor with epoxy. Spray coat the winding with Aerodag. This acts as a first electrostatic shield, as an insulator, and as a lubricant.

4. Cut 1/4" OD nonmagnetic thinwall (.010" wall) 304 seamless stainless steel to 6.50" length. Make sure the tube is straight and round. EDM cut a thin slit lengthwise in the tube. Remove any burrs, so the wire insulation isn't scratched. Solder on a metal endcap or thin wires to one end of the tube. Insert the coil all the way into the metal tube, which acts as an electrostatic shield. Make sure the coil wires don't short to the steel tube or endcap. Solder a ground wire to the shield, which should be grounded locally. Fill the opening and the slit in the steel tube with epoxy.



6. Insert the Rogowski coil into the G-10 Rogowski coil support piece. (See drawings 322905.) Place tube such that the closed end is flush to the support piece, such that 1/2" of the open end of the tube extends out. Place slit halfway between (not facing) the two conductors. Use a small dab of epoxy to hold the tube in place, but don't pot it in place, to facilitate possible replacement of the Rogowski coil.
7. Take the signals out on a coax cable to an electrically isolated BNC connector mounted on the outside of the capacitor box. Run the cable into the steel tube, but don't make a direct connection between the signal leads and the shield.
8. Place a balun between the capacitor box and the viewing scope, for example 7 turns wound on a 3C85 ferrite core, to break up ground loop currents. The inductance of the balun must be much greater (400 μH is reasonable) than the inductance of the Rogowski coil, which is about 4 μH .
9. The signal strength of the Rogowski coil should be about 1 V/kA. Calibrate the coil in situ, using a Pearson current monitor as reference.

Unfinished work.

Details of the diagnostic signal buffering circuits, timing, and controls interface need to be worked out. The most important of these are the beam inhibit and timing stabilization circuits.

Beam inhibit. To provide information on whether the beam sweep power supply is operating normally, the beam sweeping system will provide an inhibit signal through the controls system to the Main Injector extraction kicker for pbar production. It will be an input to the controls system to pull down the Pbar beam permit locally at AP0. The fall of the permit would then be seen at MI60S and the Beam Sync clock transfer event would be inhibited. Since the time required for the signal to reach MI60 is at least 5 μ s, the inhibit signal would sample the first stage voltage at 5 to 10 μ s into the pulse, to determine whether the SCR switch and the first stage compression circuit are operating correctly.

Timing stabilization. For optimum performance of the sweeping system, the relative timing of the beam sweep power supplies should be maintained within about a 40-ns window. This requirement will be met by a timing stabilization circuit.

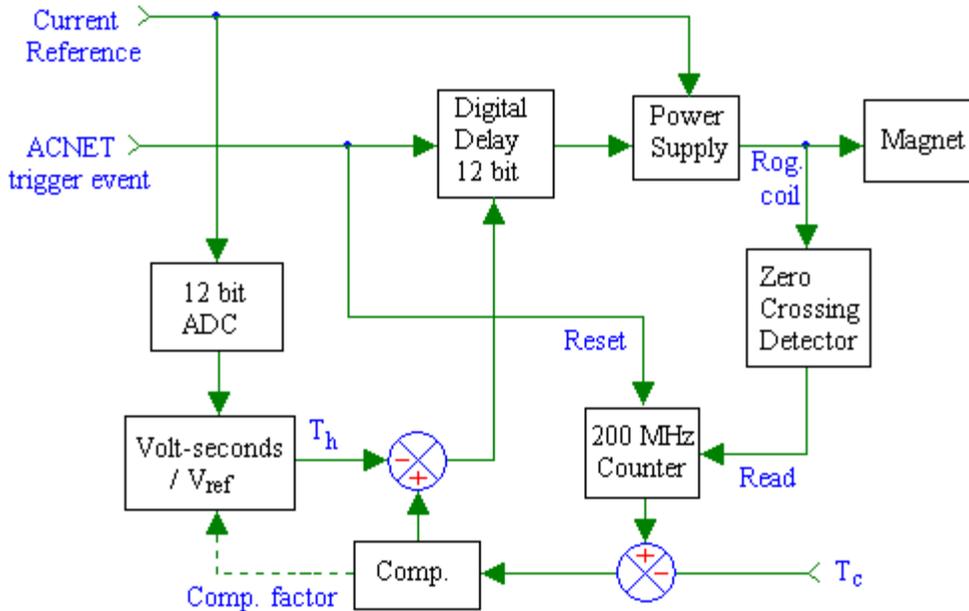
There are several sources of timing drift.

1. The saturation inductance of the Ni-Fe tape used in the first stage reactor has a temperature coefficient of -750 ppm/ $^{\circ}$ C. For a 160 mV-sec reactor and a peak inductive voltage drop of 30 kV, the thermal drift is -4 ns/ $^{\circ}$ C. Physically locating the power supply racks in adjacent locations will help reduce relative timing drift from this effect.
2. The temperature coefficient of the Maxwell plastic capacitors used in the first stage of the circuit is about -700 ppm/ $^{\circ}$ C. Thus, assuming a 15- μ s pulse length, the thermal drift of the capacitors is -5 ns/ $^{\circ}$ C. Again, adjacent locations will help reduce relative timing drift from this effect.
3. The temperature coefficient of the ceramic capacitors in the second stage is -4700 ppm/ $^{\circ}$ C. Thus, assuming a 3- μ s second stage pulse length, the thermal drift is -14 ns/ $^{\circ}$ C. Since the upstream capacitors will be located in the API tunnel, and the downstream capacitors will be located in the target vault, their relative temperatures are likely to change enough that the power supplies will drift out of the timing window without a stabilization circuit.
4. Pulse delay is inversely proportional to the charge voltage. Although relative voltage stability to 1 part in 10^3 is easily achievable with modern high voltage supplies, absolute voltage accuracy to this level is much more difficult to achieve. Maintaining timing stability is much easier with a feedback circuit.

Following is a conceptual scheme to do the timing stabilization.

We can monitor the current to the sweep magnet with a zero crossing detector which generates a pulse the instant the load current at the first zero crossing of the current when the load voltage is non-zero. This requires two inputs; load current and load voltage. It does not have to be ultra-fast, just stable. The system resets a counter which is clocked at a 200 MHz rate (5 ns/count). The zero-crossing detector reads this counter at the zero crossing to obtain the total system time delay. A fixed delay value represented by T_c is subtracted from the counter reading. The result is input

for a compensation routine which filters out pulse-to-pulse timing jitter. The reference voltage or energy storage capacitor voltage is digitized (12 bit resolution) to calculate the required delay compensation that must be added when the input voltage is raised. This represents the T_h portion of the delay. This value is subtracted from the compensation routine output.



A correction will certainly be required for this voltage correction scheme. This correction factor can be generated using data from the compensation routine. The arithmetic calculations can be carried out by either an embedded microprocessor or a central cpu which handles all power supplies. The latter would seem preferable.

Timing jitter. Under normal operation, the timing stability of the output pulse is limited only by the stability of the high voltage power supply. We expect, however, that a failing component, especially a compression reactor, will announce that fact by exhibiting jitter in output timing as partial breakdowns begin to occur. Thus a jitter monitor will be useful in early warning of a failing component. This CAMAC-based device, which is now installed on the Booster, will allow real-time monitoring on a histogram display, such a P87, of the output pulse jitter. Darren Qunell is looking into acquiring such a device for the sweeping system.

Temperature stabilization of ringing capacitor (C4). The temperature coefficient of the ceramic output capacitor that rings with the sweep magnet is 4700 ppm/ °C. In order to maintain the relative sweep rates of the circuits within 40 ns over the entire 1.6 μ s pulse, the downstream capacitors in the target vault and the upstream capacitors in the AP1 tunnel must track each other thermally within 20 °C. Although the tunnel tends to become warm during operation, it is unlikely that the temperature variation will be more than 20 °C. If the capacitors in the tunnel become very hot during operation, it may become necessary to install a water cooling circuit on the capacitor box in the tunnel to ensure tracking of the temperature.

¹ O. Kurnaev, A. Cherepakhin, Report on development of beam sweeping equipment, Pbar Note # 570 (1997).