P-BAR NOTE #570

REPORT ON DEVELOPMENT OF BEEM SWEEPING EQUIPMENT

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Introduction.

Intensity of the incident 120-GeV proton beam on the antiproton production target is scheduled to increase to 5×10^{12} protons per pulse. To prevent damage to the target, it is planned to spread hot spot on target with a beam sweeping system. The rotating-field magnets will be installed upstream and downstream of the target. These magnets will deflect the beam in a circular pattern on the target. The power supply, which is separated from the magnet by a distance of about 10 m, utilizes magnetic pulse compression by saturating inductors to drive the magnets through the transmission lines.

Three identical magnets will be used, the pair of upstream sweep magnets will be installed at the end of the AP1 beamline and a single downstream sweep magnet will be placed in a double module between the collection lens and the pulsed magnet .

It is known that rotating beam spot on the target can be created by two kickers, one vertical and one horizontal. The excitation sinewave currents should be 90 degree phase shifted (in qudrature). Another approach has been proposed by F.M.Bieniosek [1]. Vertical and horizontal kickers are combine in one magnet, which has two pairs of round conductors placed 90 degree apart inside circular magnet yoke. Because of poor field uniformity in circular aperture with round conductors, it was proposed to twist conductors in such a way that integrated current density distribution would be $\cos(\theta)$, where θ is conductor position to median plane. In this case integrated field is uniform. The main advantage of this design is that both vertical and horizontal kickers occupy full available length for installation , thus reducing required power for excitation.

Requirements:

<u>magnets:</u>

physical length	-	56 cm
nominal kick	-	440 G x m
Aperture	-	28 x 28 mm
sweep time	-	1.6 μs
repetition rate	-	0.5 Hz
winding	-	two-phase, 4conductors

current pulse synchronization with the beam pass - ±30 ns

Calculated inductance of the magnet coil is 0.2 μH, sweep time specified requires 625 kHz excitation frequency.

All this numbers lead to <u>power supply requirements:</u>

Nominal excitation current (amplitude)	-	7 kA
Maximum excitation current	-	12-14 kA
Current frequency	-	625 kHz
Voltage between magnet conductors terminals	-	5.5 kV (nominal)
conductor to ground	-	2.75 kV
number of power supply per magnet	-	2

Magnet design

Downstream magnet is located in severe radiation environment . This has two consequences: first, no organic insulation material can be applied, second, all magnet parts are heated by secondary particle showers. Total power dissipation in magnet body is estimated to be approximately 2 kW. Magnet is relatively small and this amount of heat can not be dissipated in air at reasonable temperature. So, water cooling seems to be necessary. The heating problem makes impractical the use of ferrite as magnet yoke material because of low Curie temperature and poor thermal

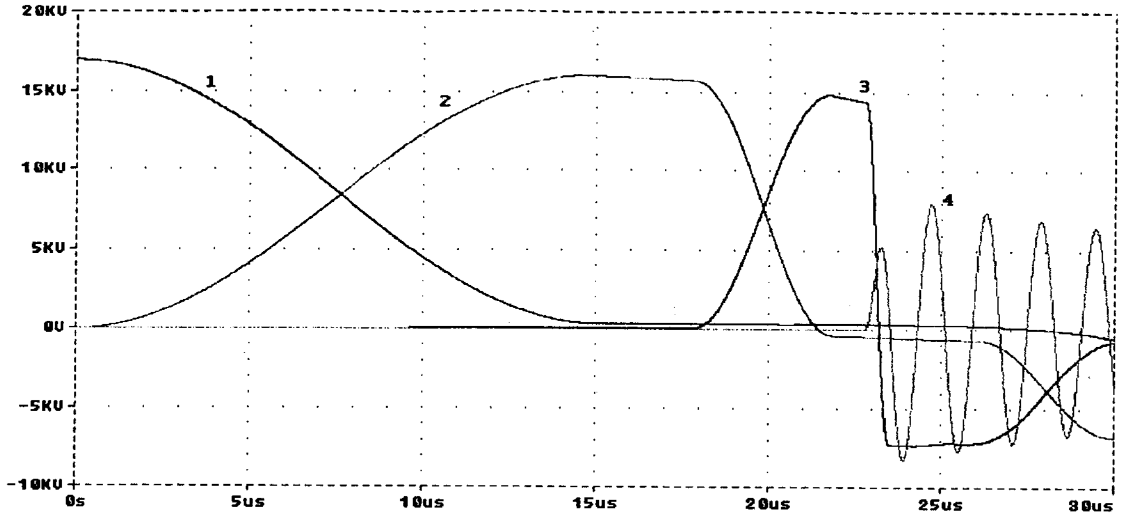


Fig. 4. SPICE model waveforms. 1 - Charging capacitor C0 voltage x 10. 2 - first compression stage capacitor C1 voltage. 3 - second stage capacitor C2. 4 - ringing circuit capacitor C3 voltage.

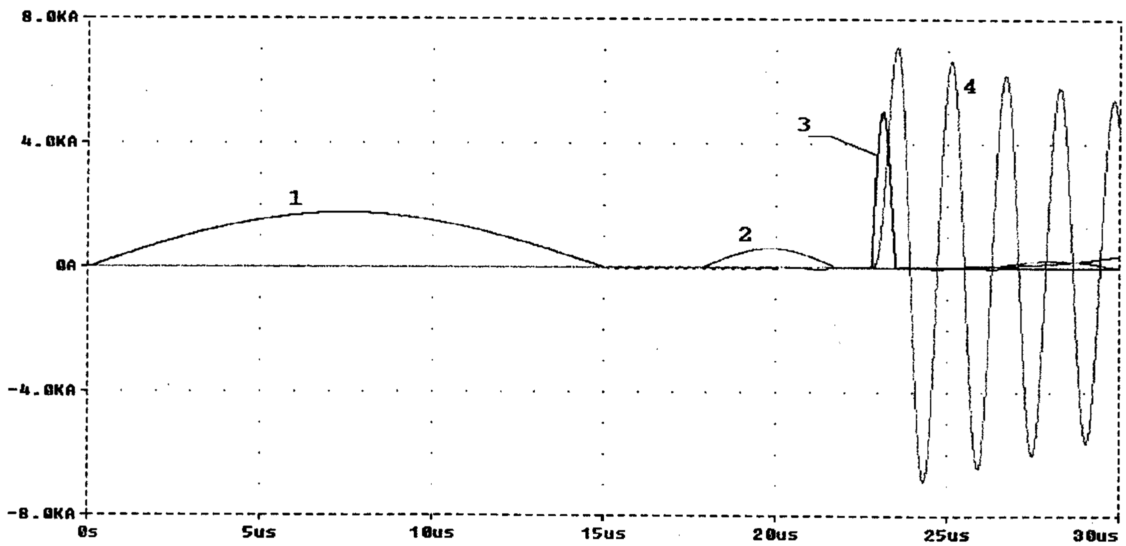


Fig. 5. SPICE model waveforms. 1 - SCR current. 2 - first compression stage current. 3 - second compression stage current. 4 - ringing circuit (magnet) current.

Prototype power supply test results

Power supply has been built and tested at varies voltages up to 3 kV of C0 charging voltage. Glasman WG-05P60 model is used for primary charging. Details of power supply built can be found in Appendix 1. Oscilloscope pictures of real voltages and currents are shown on fig. 6 and fig. 7. For comparison with SPICE simulation it is made for the same primary charging voltage 1.7 kV (fig.6) and for the same magnet current (fig.7) as used in the SPICE pictures.

Magnet test

The prototype of sweeping magnet has been run for about 0.5*E6 pulses with nominal current of 7 kA. High voltage behavior shows no trouble. Magnetic measurements have been done using stretch wire technique. Ribbon cable was used to pick up dB/dt signal along the whole magnet length and then was integrated to obtain voltage signal proportional to field flux through the measurement loop. The magnet had a possibility to be moved horizontally, thus giving integrated field distribution inside the aperture. For the local field distribution small coil has been used as a probe. Horizontal integrated field distribution for three Z position of the loop is shown on fig. 9. Local field distribution in median plain for two azimuthal small coil position is shown on fig. 10.

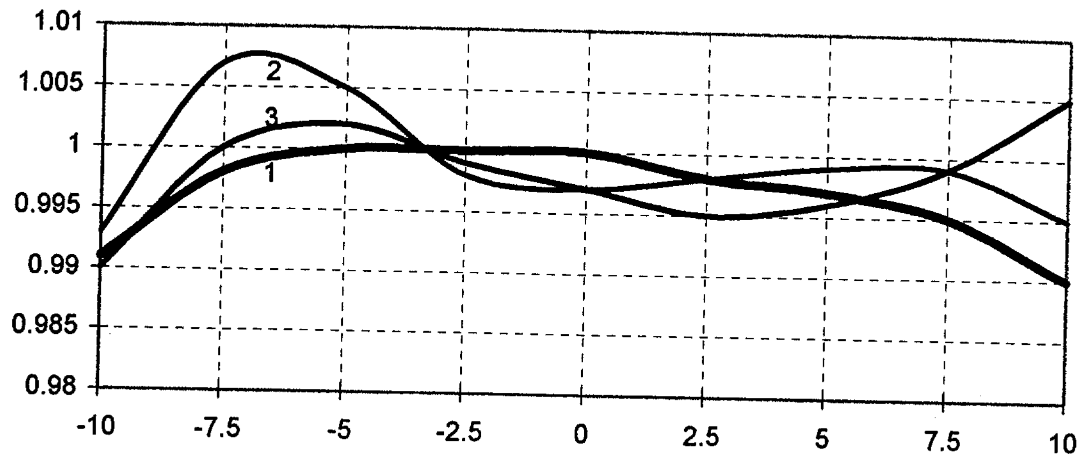


Fig. 9. **Integrated vertical field distribution in RFM aperture.**
0 in horizontal scale corresponds vertical magnet axis. Horizontal scale is mm.
Curve 1 is a distribution in median plane. Curve 2 is +7 mm over median plane and 3 is - 7 mm below.
Inhomogeniety is defined as BY(x)/BY(0,0).

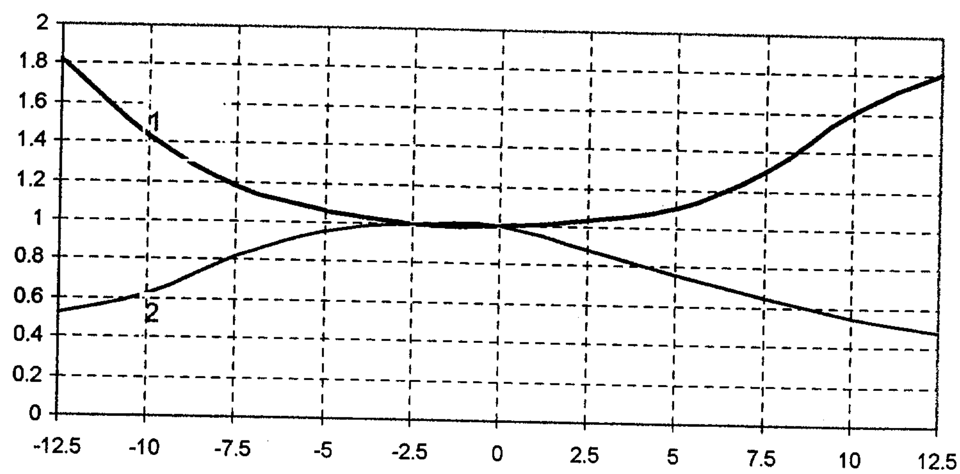


Fig. 10. **Local vertical field distribution in RFM median plane.**
Horizontal scale is mm. 0 - corresponds magnet vertical axis.
Curve 1 is a distribution when measuring coil is 2cm mm in from magnet end.
Curve 2 is with measuring coil 20 cm in .

Conclusion

1. Sweeping system prototype magnet and power supply have been built and successfully tested, although not all system components are finished (strip line, magnet fixture to the module, control etc.).
2. Up to now 50% more then nominal magnet current was achieved. It is well understood where the improvement and modification can be made to get more reserve for possible future increase of sweeping power.
3. Magnet field distribution is satisfactory and confirms well twisted conductors principles.
4. Power supply works as predicted by SPICE model and reliable. The main point of concern for the time being is a field swing in saturated cores, which should be improved with new material. The greater field swing will allow to run with higher voltage and at the same time diminish SCR peek current and di/dt.
5. Power supply jitter does not exceed ±2ns, while slow drift is about 20ns.
6. The total numbers of pulses made till now is about 0.5 million. It is important in view of high reliability requirements to continue with endurance test with maximum voltage up to at least few millions pulses.

Literature:

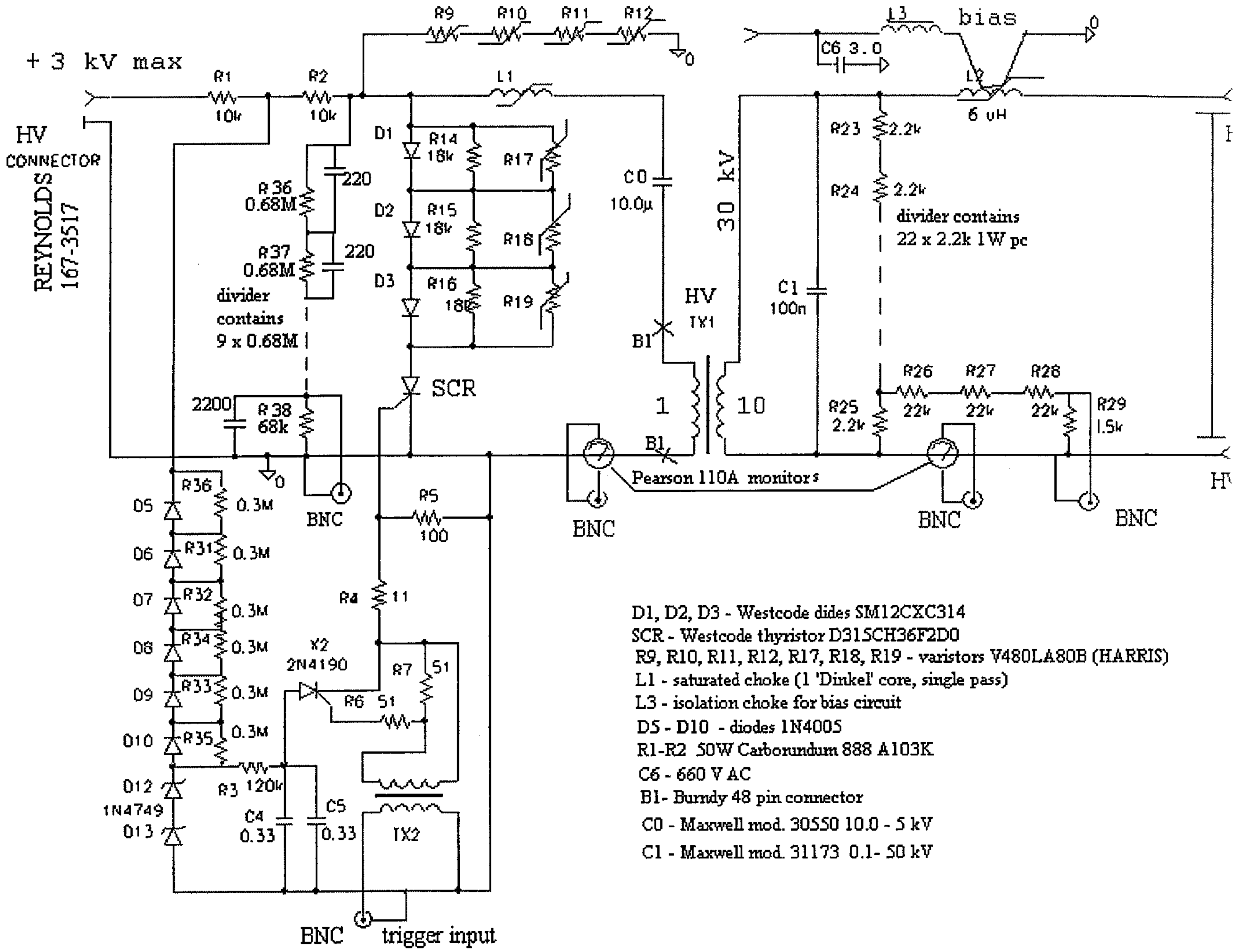
1. Beam-sweep magnet with rotating dipole field. P-bar note #561. (1997)
2. Scale model of a solid-state driver for the beam sweep magnet. P-bar note #557. (1995)

List of appendixes:

1. Power supply circuit diagram first stage details.
2. Westcode thyristors switching behavior.
3. Magnetic measurement numerical data.

Appendix 1.

Power supply circuit diagram first stage details

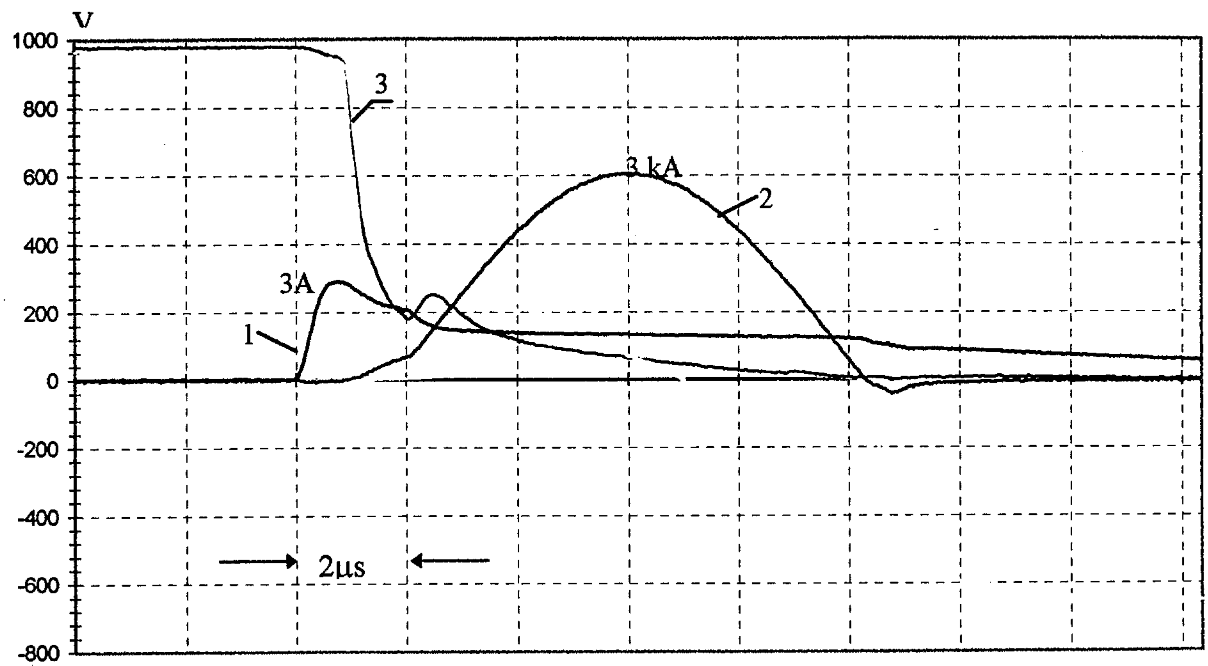


D1, D2, D3 - Westcode dides SM12CXC314
SCR - Westcode thyristor D315CH36F2D0
R9, R10, R11, R12, R17, R18, R19 - varistors V480LA80B (HARRIS)
L1 - saturated choke (1 'Dinkel' core, single pass)
L3 - isolation choke for bias circuit
D5 - D10 - diodes 1N4005
R1-R2 50W Carborundum 888 A103K
C6 - 660 V AC
B1- Burndy 48 pin connector
C0 - Maxwell mod. 30550 10.0 - 5 kV
C1 - Maxwell mod. 31173 0.1- 50 kV

Appendix 2

WESTCODE SCR switching behavior

The switching proprieties of Westcode SCR model SM12CXC314 has been investigated . Oscillogram shown down here is taken with short circuit at the step-up transformer input. The maximum thyristor current corresponds in real circuit to 3 kV charging voltage which is our maximum. SCR losses integrated from this pictures is about 1.8 J. The diodes losses, measured separately are order of magnitude less. It can be seen from the picture, that max di/dt is close to 1 kA/μs, but initial di/dt is about twice less due to saturated choke in thyristor circuit. The measurement made in real circuit with 3 kV charging voltage shows 3.8 J total thyristor losses. Obviously it is due to higher transition voltage at the beginning of the pulse.



Scope picture of thyristor's gate current (1), main current (2) and voltage drop (3) time scale - 2μs/division.

APPENDIX 3

Magnetic measurement of RFM sweeper prototype

Measurements of vertical field are made in three plains:
median plain, upper plain and lower plain as shown on fig. 1.

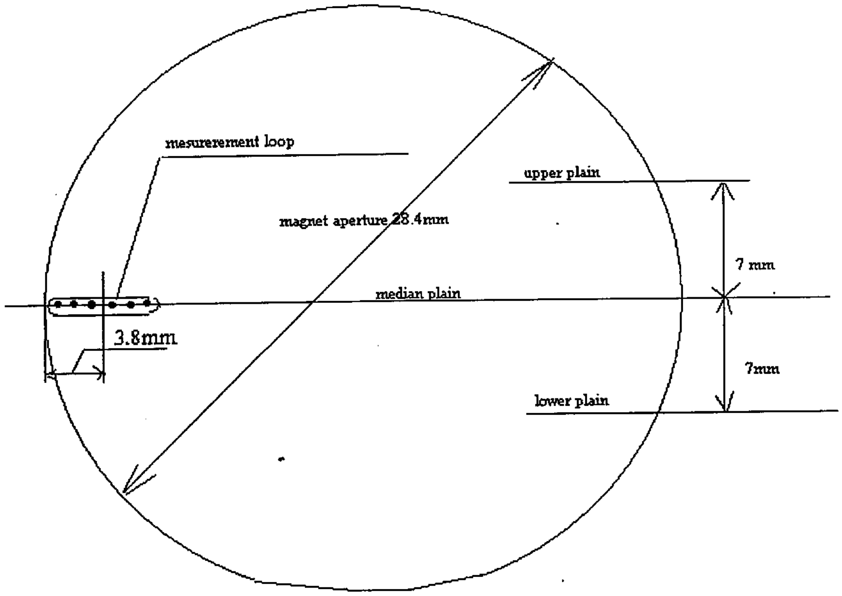


Fig 1. RFM aperture and measurement loop positions.

In down following tables 0 corresponds to extreme left position of measuring loop (the axes of the loop is 3.8 mm from aperture edge).
Nominal average field 880 Gs corresponds 2.722 V integrator output voltage.
All measurement are made at nominal field.

Median plain.

Loop position	Readings V
0	2.698
0.1''	2.718
0.2''	2.722
0.3''	2.722
0.4''	2.722
0.5''	2.718
0.6''	2.714
0.7''	2.708
0.8''	2.696

Upper plain (+7mm)

Loop position	Readings V
0	2.770
0.1''	2.748
0.2''	2.724
0.3''	2.716
0.4''	2.714

0.5"	2.718
0.6"	2.724
0.7"	2.716
0.75"	2.664

Lower plain (-7mm)

Loop position	Readings V
0	2.708
0.1"	2.730
0.2"	2.720
0.3"	2.718
0.4"	2.712
0.5"	2.710
0.6"	2.714
0.7"	2.728

Measurements with the small coil , local field profile.

Small measuring coil is in the magnet 20mm in from conductors end ring.
Coil was D = 2.0 mm and has 5 turns.

Loop position	Readings V
0	0.122
0.1"	0.093
0.2"	0.079
0.3 "	0.071
0.4 "	0.067
0.5 "	0.067
0.6 "	0.069
0.7 "	0.074
0.8 "	0.087
0.9 "	0.108
1.0"	0.125

Small measuring coil is 200mm in from conductors end ring.

Loop position	Readings V
0	0.040
0.1"	0.044
0.2"	0.056
0.3"	0.068
0.4"	0.068
0.5"	0.068
0.6"	0.060
0.7"	0.052
0.8"	0.044
0.9"	0.040
1.0"	0.036

Azimuthal distribution of local field

Zero corresponds measuring coil position near conductors end ring.
Minus means coil is out of magnet.

Position Z (cm)	Readings V
5	0.079
4	0.0785
3	0.0765
2	0.068
1.5	0.057
1.0	0.0415
0.5	0.0275
0	0.0145
-0.5	0.0055

Average field absolute value measurement (kick)

The next formula is used:
$E = d\Phi/dt = dB*S/dt = S*dB/dt$
$B = Bo * \sin(w*t)$
$Emax = Bo*w*S$
S = loop area (m^2) = 1.27mm * 0.5m = 0.635*E-3 m^2
w = round frequency ($2\pi f$); measured f = 552 kHz; w = 3.468*E6
Bo - nominal field = 0.088 T
Substitution gives that Emax should be 194 V at nominal field.
We have got this value at excitation current of 7 kA measured by Pearson, charging voltage was 2.2 kV.

Vertical field distribution while horizontal field is excited.

Position	readings mV (horizontal field reading is 2.72 V}
0	40
0.1"	38
0.2"	36
0.3"	34
0.4"	30
0.5"	28
0.6"	28
0.7"	22
0.8"	12

Vertical field distribution for the second pair of conductors.
To measure this magnet is turned 90 degree and power supply is reconnected to second pair of conductors.

Loop position	readings, V
0	2.716
0.1"	2.720

It can be seen from the fig. 2 that current leads are located at middle of conductors. The conductors are grounded all together by the end flange from both side of the magnet. This requires bipolar power supply but at the same time diminishes conductor to ground potential. By other words 5.5 kV between the conductors means that first conductor has +2.75 kV and second conductor has -2.75 kV to ground. Four ceramic bushings are used to support current leads and insulate it from magnet body. The copper tube spiral is wound around the magnet housing pipe to provide proper cooling of the whole structure. The spiral fingerstock is provided with copper spacer located between each two pairs of cores. It serves as a slide guide and stress relief for insulating ceramic pipes.

Power supply design

The sweeping magnet is located near antiproton production target. Severe radiation in that location will not allow to use any power supply component nearby. Therefore strip line will be utilized to connect magnet to ringing circuit capacitance which is placed on top of the target vault. In its turn the power supply is located in equipment hall about 10 m from top of the target vault. It has been proposed [2] to use magnetic pulse compression technique to facilitate problems of switch and shot high current pulse delivery over relatively long distance. Simplified circuit diagram of power supply is shown on fig. 3.

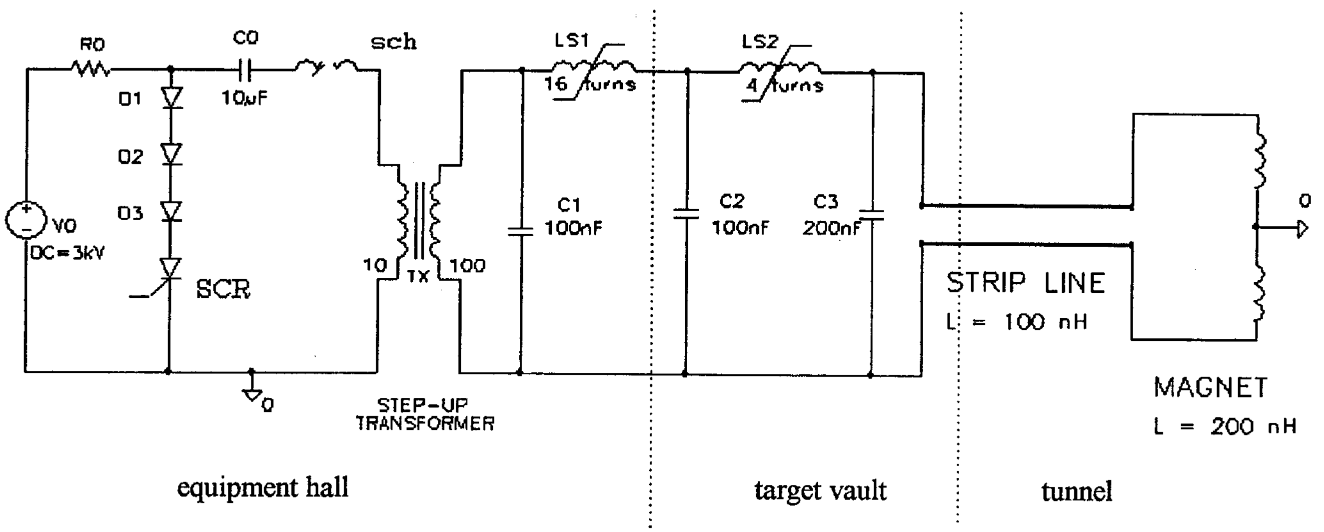


Fig. 3. Power supply simplified circuit diagram.

The first compression stage capacitor C1 is being charged via HV step-up transformer by closing the thyristor switch SCR. This initiates energy transfer from charged capacitor C0 to first stage capacitor C1. Time period for charge transfer is chosen to be about 15 μs taking into account the limitation imposed by switch di/dt. The total delay between switch trigger and magnet current pulse also allows time to disable proton extraction kicker in case of power supply failure. When the first saturated reactor LS1 becomes conductive the energy from C1 transfers to second stage capacitor C2. Second stage is located about 10 m away and connected to the first stage via a pair of coax cables (RG220/U). Saturating of LS2 initiates discharge of C2 into ringing circuit C3-stripline-magnet. Saturated inductances LS1, LS2 are made using the METGLAS cores, wound with 18 μm 2605SC material and 8μm kapton film as interlamination insulation. Three cores 51mm wide, 70 mm I.D. and 137 mm O.D. are used for each choke. To get the maximum ΔB swing (3.0T was assumed for calculation) bias current for each core is provided. The small saturated choke 'sch' is implemented only to decrease initial di/dt for thyristor switch. It is WESTCODE type D315CH36F2D0 device rated for 3.6 kV and 1kA/μs for di/dt. To limit the reverse current of this relatively slow turn-off device, the stack of fast recovery diodes is connected in series. It is WESTCODE type SM12CXC314. The SPICE simulation of the circuit has been done to find out the optimal solution and relations between different parameters. When calculating saturated chokes it was assumed that core cross-section is 34 cm^2 of Metglas and saturated field is 1.5 T.

The results of SPICE simulation is shown on Fig. 4 and Fig 5. The parameters are chosen to deliver nominal current to the magnet with 1.7 kV charging voltage at C0.

conductivity. Iron lamination can be used, but very thin lamination (<0.1mm) is needed, which makes it costly and difficult in handling. Pressed-powder Mo-permalloy (MPP) cores are chosen for the prototype magnet yoke. It features relatively high Curie temperature and good thermal conductivity. Prototype magnet cross section is shown on fig. 1.

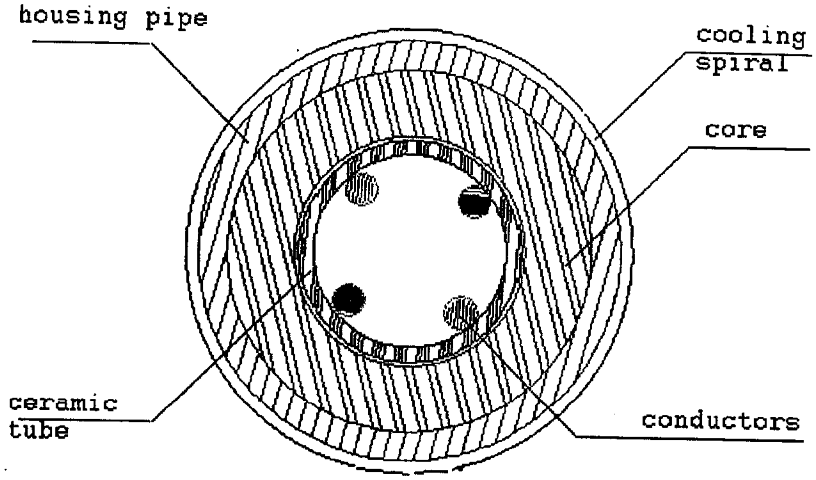


Fig. 1. Sweeping magnet cross section.

The cores are press fit into housing nickel pipe. Pipe material is chosen to have the same thermal expansion coefficient as the MPP core. Thus good thermal conductivity is provided at any temperature to outer cooling spiral. ¼" aluminum thin wall tubes is used as a material for conductors. Diameter of inscribed circle between conductors is 28.5 mm. Longitudinal cross-section of the magnet is shown on fig. 2. The magnet overall length is 560 mm.

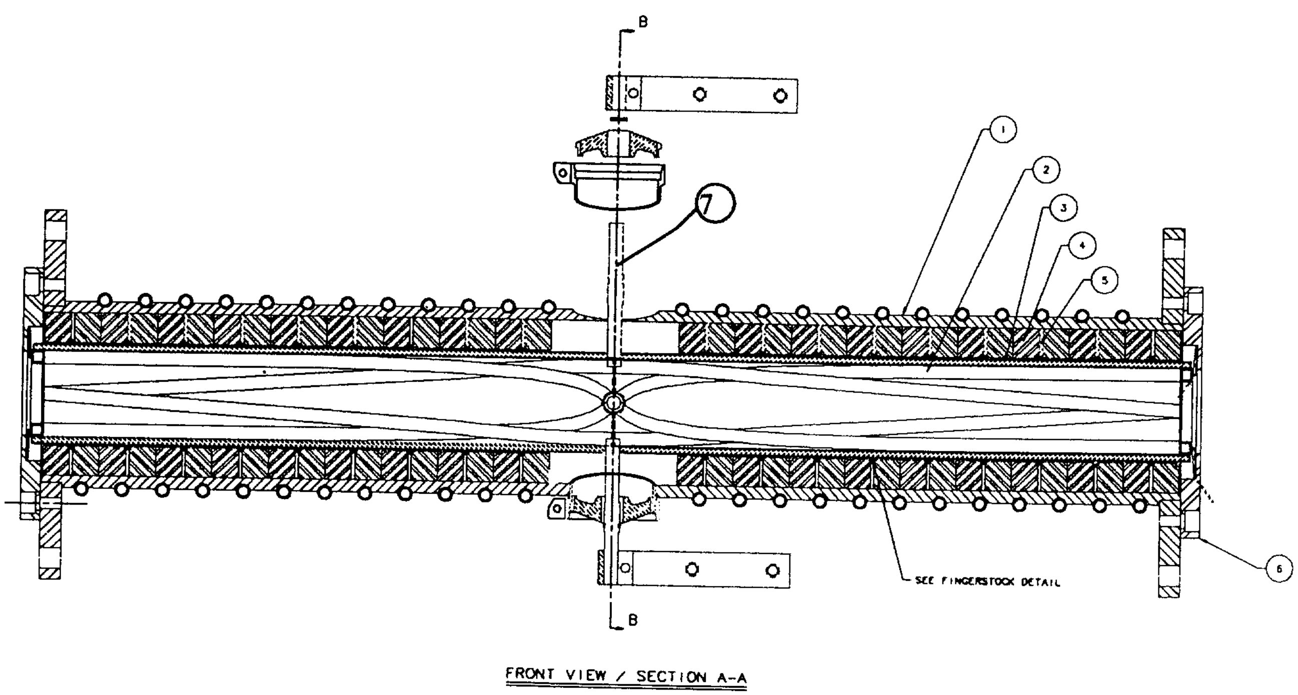


Fig. 2. Rotating field magnet longitudinal cross-section.
1 - housing pipe, 2 - twisted conductors, 3 - ceramic pipe, 4 - MPP core, 5 - spacer, 6 - end flange, 7 - current lead

It can be seen from comparison SPICE and scope pictures that real saturated inductances LS1 and LS2 have less Volt-Seconds area (voltages curves flat-top are shorter) versus calculated ones. By other words ΔB is smaller, 2.4 T versus 3.0 T, used for calculation). It has been figured out that origin of it is wrong procedure applied by core manufacturer (Allied Corp.). The actual cores were annealed after winding with kapton film, which destroy magnetic properties. Annealing should be done before winding kapton. Reduced Volt-Seconds area of the real saturated chokes still good to achieve nominal power supply parameters but it limits maximum for the magnet current on the level of 11 kA. The second drawback of reduced volt-seconds area at the present design is that at maximum output current, di/dt for thyristor switch is very close to the limit of 1 kA/ μs. To make thyristor pulse wider and thus lower di/dt for better reliability, one needs more volt-seconds for the first compression choke. It seems possible to increase chokes volt-seconds area considerably keeping the same design by using 2605CO material instead of 2605SC.

The energy losses in compression stages have been measured as follows:

- energy losses at 2.0 kV charging voltage while transfer from C0 to C1 - 16%
- C1 to C2 - 15%
- C2 to C3 - 0 % (magnet disconnected)

The C0 to C1 losses is due to SCR switch (10%) and step-up transformer (6%). C1 to C2 losses are hard to separate, but seems mainly due to reactor's conductor AC resistance.

The power supply for one conductor's pair is housed in two standard 19" wide and 20" depth chassis plus GLASMAN high voltage supply rack mounted. It is supposed to have two power supply in one rack and one control crate for both. The final compression stage and ringing capacitors are located in separate box.

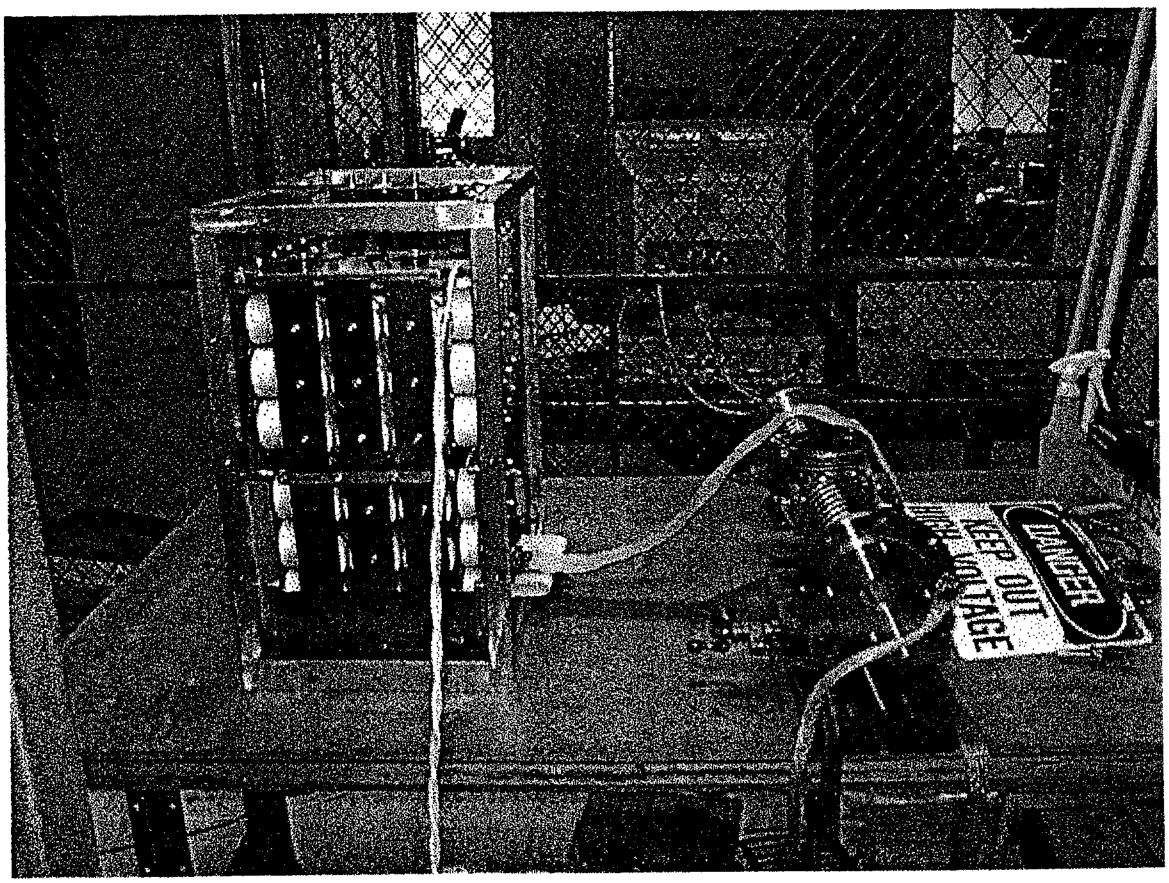


Fig. 8. PHOTOGRAF OF LAST STAGE (left) AND THE MAGNET (right)

of real voltages and currents are shown on fig. 6 and fig. 7. For comparison with SPICE simulation it is made for the same primary charging voltage 1.7 kV (fig.6) and for the same magnet current (fig.7) as used in the SPICE pictures.

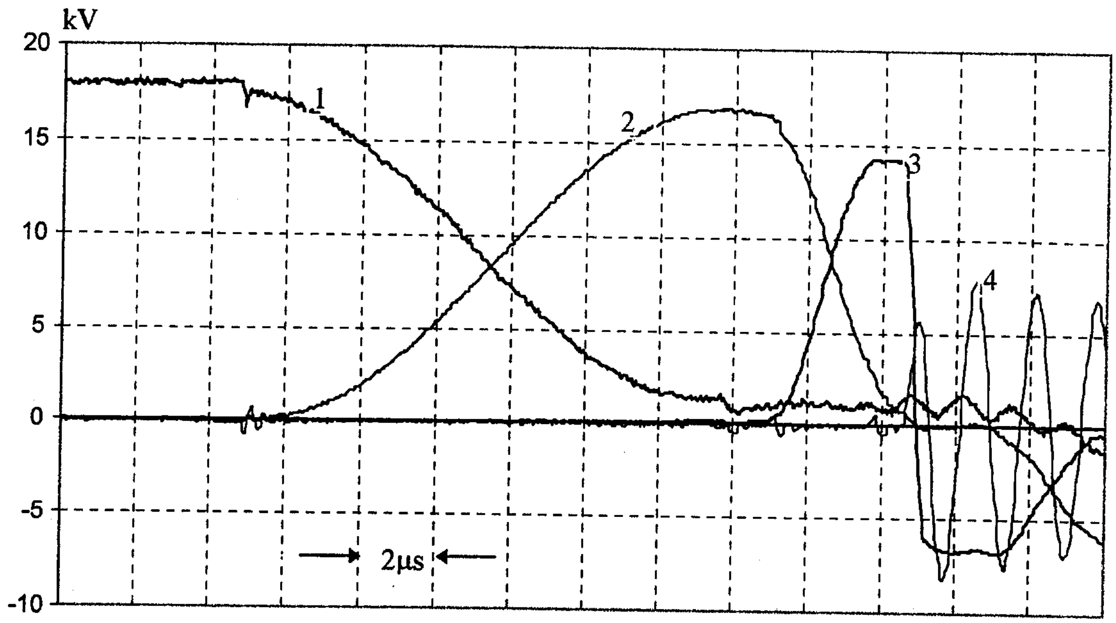


Fig. 6. Scope picture of voltages in compression stages. 1 - first charging capacitor x 10.
2 - first compression stage capacitor. 3 - second compression stage capacitor.
4 - ringing circuit (magnet) voltage.

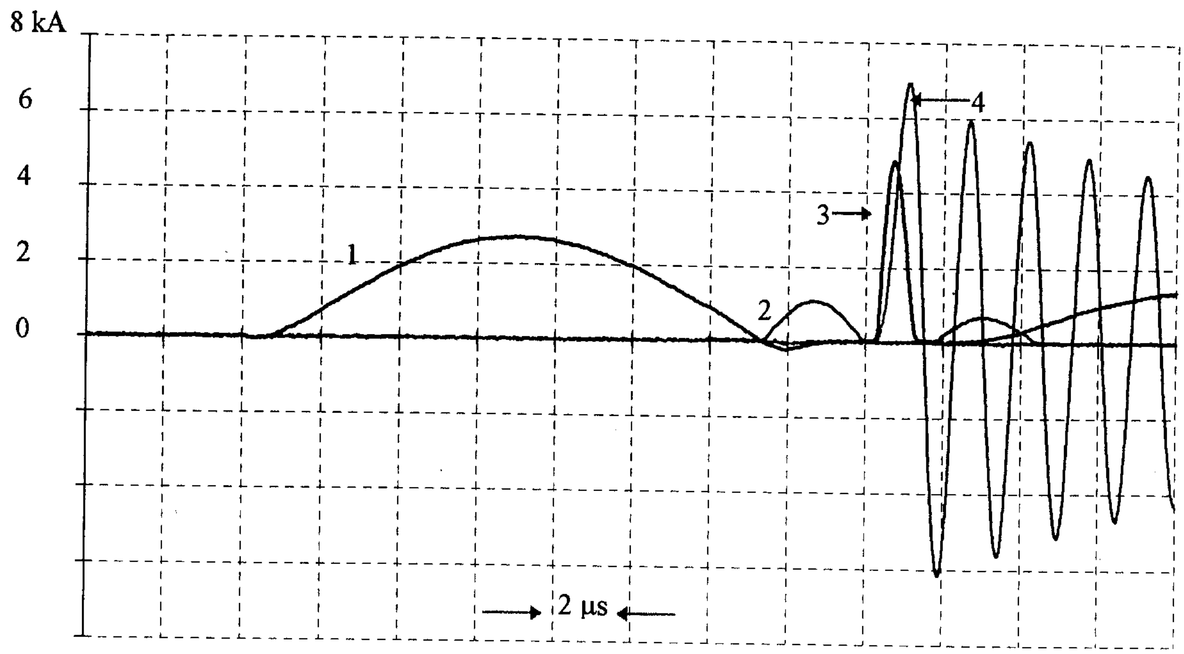


Fig. 7. Scope picture of currents in compression stages of power supply.
1 - SCR current. 2 - first compression stage. 3 - second compression stage.
4 - ringing circuit (magnet) current.

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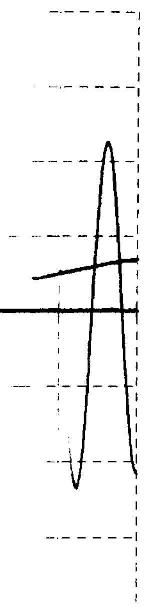

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