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Booster proton cavity with voltage reduction during the cycle

M. Plotkin

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Collider Accelerator Department
Brookhaven National Laboratory

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MARTIN PLOTKIN
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ACCELERATOR DEVELOPMENT DEPARTMENT
Brookhaven National Laboratory
Upton, N.Y. 11973

BOOSTER PROTON CAVITY WITH VOLTAGE REDUCTION DURING THE CYCLE

Martin Plotkin

The specification for the Booster proton accelerating cavity, Cavity III, is a frequency range of 2.4 - 4.2 MHz and a system peak voltage of 90 KV. To achieve 90 KV in a single cavity presents numerous problems: voltage breakdown, space limitations, excessive losses in available ferrites, etc. It was decided to use two cavity stations, each station comprised of two cavities (two accelerating gaps) requiring, for parallel operation from the amplifier, only 22.5 KV peak voltage.

Even with the two stations, the best ferrite tested to date, Philips Ferroxcube 4M2, would be marginal in terms of power loss and amplifier power. But, more importantly, the amount of ferrite required had an inductance which would require gap capacitances to be below the amount required for beam stability.

With 90 KV peak volts at the beginning of the cycle the stable phase angle is about 17°. If we allow the voltage to fall to 70 KV peak at the end of the cycle the phase angle moves only to about 22°. This difference in stable phase is actually better in terms of matching the AGS admittance and, since the ferrite exhibits the highest losses at the end of the cycle, less ferrite is required due to the lower voltage.

Assume, for this system, a linear voltage drop from 90 KV/system at 2.4 MHz to 70 KV/system at 4.2 MHz. For two stations the total voltage per station is 45 KV at the beginning of the cycle and 35 KV at the end of the cycle.

The specification on duty cycle for the proton accelerating system is 50%. Water cooling is capable of handling about 250 - 300 mw/cc. From small sample data on Ferroxcube 4M2 we can design a cavity for the highest ferrite loss frequency, 4.2 MHz. The designs will be done for 400 mw/cc (200 mw/cc average for 50% duty factor) and for 500 mw/cc. From measured data (see Fig. I) 400 mw/cc corresponds to a flux density of 101 gauss at 4.2 MHz; 500 mw/cc corresponds to 110 gauss.

Using the relationship:

$V = \omega B A \times 10^{-8}$

$B = 101$ gauss (400 mw/cc)
$A = (r_2 - r_1)\, N t$
N = number of rings
$t = 2.5$ cm ring thickness
r_2, r_1 = outer and inner radii of the ferrite in cm.

for 50 cm OD rings
23 cm ID rings
and $V = 35000$ volts
$N = 38.9$

Since there are four ferrite stacks/station N must be a multiple of 4. Let $N = 40$.

Similarly, for 500 mw/cc and 110 gauss N = 35.8 or 36. The actual flux density for 40 rings is B = 98 gauss with a power loss of ≈ 370 mw/cc and for 36 rings B = 109 gauss for a power loss of ≈ 480 mw/cc. We increase the number of rings for each case to build in a factor of safety 40 → 44 and 36 → 40 giving:

44 rings B = 89.2 290 mw/cc
40 rings B = 98.3 360 mw/cc

For each of these cases we can calculate the flux density at the low frequency end, 2.4 MHz. Since flux density varies inversely with frequency and directly with voltage, for 45 KV with 44 rings B = 201 gauss with losses of 275 mw/cc and for 40 rings B = 221 gauss with 420 mw/cc. We will assume an average power loss over the cycle which is weighted towards the 4.2 MHz end of the cycle, since the protons are relativistic. The average power losses are calculated here as 1/3 $(P_{2.4} + P_{4.2})$. Using this averaging the loss during the cycle is 285 mw/cc for 44 rings and 380 mw/cc for 40 rings. Applying a factor of two for a 50% duty cycle the time average losses are:

143 mw/cc for 44 rings
190 mw/cc for 40 rings

If, inadvertently, 90 KV total voltage was used for the entire cycle the time averaged loss would be:

44 rings, $B_{4.2}$=114.9, P=550 mw/cc=Time average with duty cycle=229 mw/cc.
40 rings, $B_{4.2}$=126.4, P=800 mw/cc=Time average with duty cycle=237 mw/cc.

We have sufficient room in the cavities to provide, for each cavity (2 per station), 24 ferrite rings. With 48 rings and 45 KV per station we can recalculate the flux densities and losses for rings 50x23cm and for 50x25cm.

For 50 x 23 cm at 2.4 MHz V = 5.09BN
at 4.2 MHz V = 8.9 BN

For 50 x 25 cm at 2.4 MHz V = 4.71BN
at 4.2 MHz V = 8.24BN

Using 48 rings and V = 45,000 (no reduction during cycle)

d_1	f	B	P
23 cm	2.4MHz	184 gauss	215 mw/cc
25	2.4	199	270
23	4.2	105	440
25	4.2	114	530

For 23 cm ID the time average over the cycle is 366 mw/cc and for 25 cm ID the time average is 443 mw/cc. Applying the duty factor of 50% these numbers become:

23 cm ID P = 183 mw/cc
25 cm ID P = 222 mw/cc

These numbers are even more favorable if we reduce the voltage at 4.2 MHz to 35 KV.

	d_1	f	B	P	
90 KV	23 cm	2.4 MHz	184 gauss	215 mw/cc	from previous table
90 KV	25	2.4	199	270	
70 KV	23	4.2	81.9	245	
70 KV	25	4.2	88.5	280	

For 23 cm ID the volume of 48 ferrite rings is 185,800 cc. Using the losses at 2.4 MHz and 4.2 MHz the power per station is

39950 watts at 2.4 MHz (supply V = 22.5 KV)
45520 watts at 4.2 MHz (supply V = 17.5 KV)

The impedance per station, from $Z_{res} = V^2{}_{pk}/2P$, is

$Z = 6336\ \Omega$ at 2.4 MHz
$Z = 3364\ \Omega$ at 4.2 MHz

For 25 cm ID the volume of ferrite is 176,715 cc. Using the losses from the table for 90 KV total voltage (22.5 KV supply) at 2.4 MHz and 70 KV total voltage (17.5 KV supply) at 4.2 MHz, the power per station is

47715 watts at 2.4 MHz, $Z = 5305\Omega$
49480 watts at 4.2 MHz, $Z = 3095\Omega$

For continuous 90 KV total voltage operation, the average losses, at either 23 cm or 25 cm ID, are acceptable but the amplifier power required increases considerably at 4.2 MHz.

23 cm ID $P = 81752$ $Z = 3096\Omega$
25 cm ID $P = 93660$ $Z = 2702\Omega$

We can calculate the amplifier supply current required <u>for the ferrite losses only</u>. The approximate Q is calculated, for a nominal $\mu = 130$, as

$$Q = \frac{Z_{res}}{\omega L}$$

For 23 cm ID: $L/_{cav} = 2\ \mu t\ \ell n \frac{d_2}{d_1} \times 10^{-3}\ \mu h$

where t = ferrite length = 24 x 2.5 cm/cavity.

At 2.4 MHz, $\mu = 130$ and $L = 260 \times 60\ \ell n \frac{50}{23} \times 10^{-3} = 12.1\ \mu h$

The total inductance for 2 cavities is parallel is 6.06 μh.

At 4.2 MHz, $\mu = 42.45$ $L = 1.98\ \mu h$
For 90 KV total, $Q\ 2.4 \cong 69$
For 70 KV total, $Q\ 4.2 \cong 64.4$

For 23 cm ID the peak feed current at 2.4 MHz, for 22.5 KV and $Z = 6336\Omega$ is 3.55 amperes. Similarly, at 4.2 MHz and 17.5K the peak current is 5.2A. With

Q values calculated as 69 at 2.4 MHz and 64.4 at 4.2 MHz, the peak circulating currents are 245 amperes at 2.4 MHz and 335 amperes at 4.2 MHz.

Similarly, for 25 cm ID at 2.4 MHz, for 22.5 KV and Z = 5305, I_{peak} = 4.24 amps and at 4.2 MHz and 17.5 KV peak Z = 3095 and I_{peak} 5.65 amperes. Corresponding L and Q values can be calculated as $L_{2.4} = 10.8$ µh/cav or 5.4 µh/station, and $L_{4.2} = 1.77$ µh/station.

$$90 \text{ KV total } Q_{2.4} = 65.1$$
$$70 \text{ KV total } Q_{4.2} = 66.3$$
$$I_{pk}\text{circ} = QI_{pk} = 276 \text{ A at } 2.4 \text{ MHz}$$
$$= 375 \text{ A at } 4.2 \text{ MH}_z$$

For 90 KV total voltage at 4.2 MHz:

ID = 23 cm, Z = 3096Ω, $I_{pk} = 7.27A$, Q = 59.3, $I_{circ} = 431A$
ID = 25 cm, Z = 2702Ω, $I_{pk} = 8.33A$, Q = 57.8, $I_{circ} = 481A$

See Table I for summary of results.

In summary, the advantages of decreasing the voltage to the end of the cycle are:

1. A more conservative ferrite design.
2. Lower power in the ferrite.
3. A greater gap capacitance.
4. Fewer ferrites required.
5. More axial space for gap clearance, cooling, valves, etc.
6. Almost uniform power in the ferrite over the cycle rather than the 2:1 increase over the cycle with uniform voltage.

APPENDIX I

If we wish to use the old AGS cavity shells we are restricted to a maximum ring diameter of 45 cm. For 45 x 23 cm rings, with 70 KV at 4.2 MHz the flux density for 400 mw/cc is 103 gauss. As before N can be calculated as 23.4 and 24 rings would be used. The actual B = 100 gauss for a power loss of 360 mw/cc. The 90 KV, 2.4 MHz, flux density is B = 175 gauss, powerloss = 180 mw/cc. The time average loss is 270 mw/cc, or 135 mw/cc with 50% duty cycle.

L calculates to 5.24 µh for the station or a resonant capacitance at 2.4 MHz of 420 pf.

The comparison between the 50 x 23 cm rings and the 45 x 23 cm rings (for the existing cavity shells) is:

	50 x 23	45 x 23
time avg. power loss	602 mc/cc	135 mw/cc
N/sta	44	48
L/sta	5.56 µh	5.24 µh
C/gap	396 pf	420 pf
Volume/sta	170,317 cc	141,000 cc
Total power at 4.2 MHz	49.4 KW	50.8 KW
Total length of ferrite	110 cm	120 cm

The two cases are very close with 50 x 23 cm rings allowing 30 cm for other uses, but the 45 x 23 could use the existing cavities. Mechanical design considerations must be closely investigated to determine the best choice.

2 RINGS: EACH 1.20 CM LONG
1.615 CM ID
2.77 CM OD

PHILIPS (FERROXCUBE)
FXC 4M2
DATA 4/21/87
4/20/87

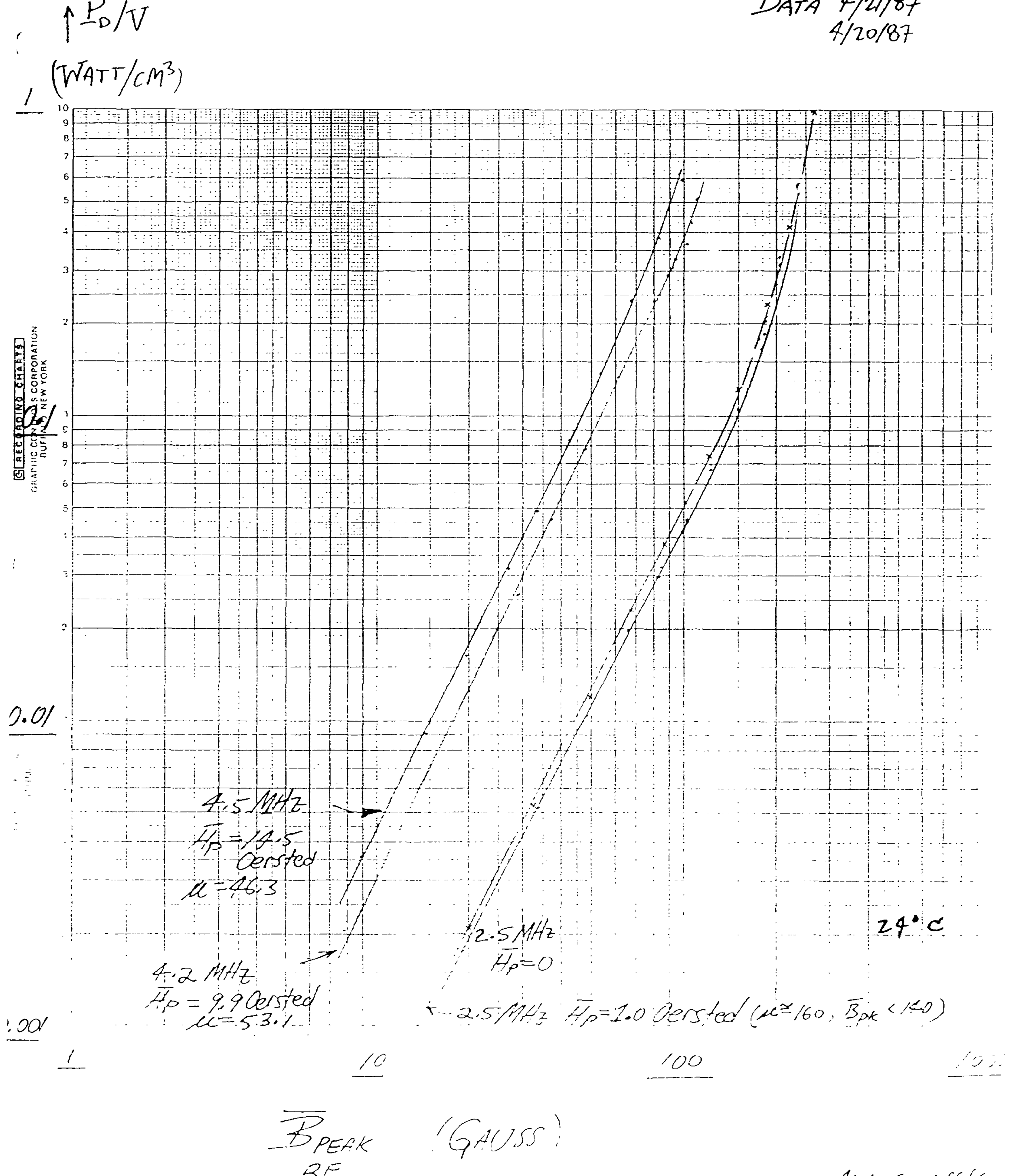

FIG. I

M.A. GOLDMAN
H. ZHANG

V·KV STA	N/STA	ID cm	F KHZ	B gauss	Pwr mw/cc	TIME AVG PWR. mw/cc	Vol. cc/STA	Pwr TOTAL/STA KW	Z-Ω STA.	L/STA μh (μ=130)	Q	I_{drive} (CAVITY ONLY)	I_{ARC}	C/gap·pf (μ=130)
35	44	23	4.2	89.2	290	143								
45	44	23	2.4	201	275	229								
45	44	23	4.2	114.7	550									
45	48	23	2.4	184	215	183	185800	39.95	6336	6.06	69	3.55	245	363
45	48	23	4.2	105	440		185800	81.75	3096	1.98	59.3	7.27	431	363
45	48	25	2.4	199	270	222	176715	47.7	5305	5.4	65.1	4.24	276	406
45	48	25	4.2	114	530		176715	93.7	2702	1.77	57.8	8.33	481	406
45	48	23	2.4	184	215	118	185800	39.95	6336	6.06	69	3.55	245	363
35	48	23	4.2	81.9	245		185800	45.52	3364	1.98	64.4	5.2	335	363
35	48	25	4.2	88.5	280	138	176715	49.5	3095	1.77	66.3	5.65	375	406
45	48	25	2.4	199	270	222	176715	47.7	5305	5.4	65.1	4.24	276	406
45	48	25	4.2	114	530		176715	93.66	2702	1.77	57.8	8.33	481	406

Summary of results

TABLE I