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CALCULATION OF MOTOR SPEED OF THE SIEMENS M.G. SET DURING A PULSE

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July 1984

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

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AGS Division Technical Note
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The motor generator system has been designed so that under normal circumstances the motor speed over the duration of an AGS magnet pulse varies by less than ± 2%. This is with a motor power input variation of less than ± 200 KW. Considering that the main magnet power supply output goes from +70 MW to -70 MW during the pulse, these power swings must be absorbed by the rotational energy of the MG set. This has been accomplished by designing the generator rotor with a large radius resulting in a large moment of inertia. At 1200 RPM, the stored energy is 310 MJ.

The motor speed at any time during a pulse can be determined by considering the electrical and mechanical relationships

$$1)\quad P_{in} = JW \frac{\partial W}{dt} + P_W + P_E$$

where

P_{in} = power into the motor
J = MG set moment of inertia $[40(10^3)\ \text{kg M}^2]$
W = rotational speed in radians/sec
P_W = windage and bearing losses (850 KW)
P_E = electrical power

Three types of elements contribute to the electrical power term (P_E). They are resistance (P_R), inductance (P_L) and arc drop (P_A). Let us discuss these items a little further.

The arc drop term is attributed to the arc drop across the excitrons. For each excitron this is equivalent to a 16 volt battery in series 13 mΩ. For the whole power supply, this is equivalent to 128 volts in series with 50 mΩ. For convenience, this 50 mΩ and other power supply resistances are lumped in with the load resistance of 0.25 Ω to comprise a total resistance of 0.3 Ω. This 0.3 Ω will be used for the determination of the "P_R" term. This 128 volts will be used for the "P_A" term.

Now, the inductive term is something somewhat special. The main reason is that the prime source of the system inductance is that of the magnet whose inductance varies with the current. This variation is from 0.5 to 0.8 Henries. The main value used in this note will be 0.7 H. This includes also the reactive drop in the transformer connections, etc. It should also be pointed out that the "P_L" term can be either positive or negative depending upon whether the current is increasing or decreasing.

In light of these comments, we can then conclude that

$$2) \quad W \frac{\partial W}{\partial t} = \frac{\left(P_{in} - P_W\right)}{J} - \frac{\left(P_E + P_R + P_L\right)}{J}$$

Integrating both sides from 0 to t yields

$$3) \quad W^2 - W_o^2 = \left(\frac{P_{in} - P_W}{J/2}\right)t - \frac{1}{J/2} \int_o^t \left(P_E + P_R + P_L\right)dt$$

4) $$W^2 = W_o^2 + \left(\frac{P_{in} - P_W}{J/2}\right)t - \frac{1}{J/2} \int_o^t \left(E_E\, I + RI^2 + LI\,\frac{dI}{dt}\right)dt$$

If "I" has form

5) $$I = I_o + \alpha\, t$$

then,

6) $$\frac{dI}{dt} = \alpha$$

and then

7) $$W^2 = W_o^2 + \left(\frac{P_{in} - P_W}{J/2}\right)t - \frac{1}{J/2} \int_o^t \left[(EI_o + \alpha LI_o + RI_o^2) + (\alpha E_E + L\alpha^2 + 2\alpha RI_o)t + \alpha^2 Rt^2\right]dt$$

and

8) $$W^2 = W_o^2 + \left(\frac{P_{in} - P_w}{J/2}\right)t - \left(\frac{E_E I_o + L\alpha I_o + RI_o^2}{J/2}\right)t - \left(\frac{E_E\,\alpha + 2R\alpha I_o + \alpha^2 L}{2(J/2)}\right)t^2 - \frac{\alpha^2 Rt^3}{3(J/2)}$$

During a pulse, four current segements can be identified. They are: injection porch, rectify, flattop, and invert. The current characteristics during each of these intervals are as follows:

Injection Porch

$$9)\quad I_{IP} = 2956\ t \Big|_{o}^{t\ 0.11\ sec}$$

Rectify

$$10)\quad I_{R} = 325.16 + 10{,}500\ t \Big|_{o}^{t_R}$$

Flattop

$$11)\quad I_{F} = I_{F}\ \text{(constant)}$$

Invert

$$12)\quad I_{I} = I_{F} - 11{,}250\ t \Big|_{o}^{t_I=0}$$

Therefore, during the injection porch,

$$13)\quad W^2 = W_o^2 + \left(\frac{P_{in} - 0.85(10^6)}{2(10^4)}\right)t - 162.4t^2 - 43.69t^3$$

Where W_o is approximately 1.5% above the synchronous (rotational) speed. The synchronous speed is 1200 RPM or 125.66 radians per second. 1.5% above this is about 128 radians per second. W_o^2 is then 16,384.

During rectify we get

$$14)\quad W_R^2 = W_{oR}^2 + \left(\frac{P_{in} - 0.85\ (10^6)}{2(10^4)}\right)t_R - 121t_R - 2014t_R^2 - 551t_R^3$$

Where t_R is reckoned from the end of the front porch (t - 0.11) and W_{oR} is the speed at the end of the front porch.

During flattop

$$15)\quad W_F^2 = W_{oF}^2 + \left(\frac{P_{in} - 0.85(10^6)}{2(10^4)}\right)t_F - \left(\frac{128\ I_{Fo} + 0.3I_{Fo}^2}{2(10^4)}\right)t_F$$

Where t_F is reckoned from the beginning of flattop and I_{Fo} is the current at the beginning of flattop.

For invert, the following relationship exists

$$16)\quad W_I^2 = W_{oI}^2 + \left(\frac{P_{in} - 0.85(10^6)}{2(10^4)}\right)t_1 + \left(\frac{7747\ I_{o1} - 0.3\ I_{o1}^2}{2(10^4)}\right)t_1$$

$$- (2179 - 0.1688\ I_{o1})t_1^2 - 632.8t_1^3$$

W_{o1} is the speed at beginning of invert at t_1 is reckoned from beginning of invert.

Assuming an M.G. set initial speed of 128 radians per second, the speed as a functin of time has been calculated over the duration of a typical 28 GeV/c AGS magnet current pulse. This corresponds to a current of 5050 amperes. This was done for a 1.0 second and a 2.0 second flattop. Two sets of calculations were made; one set for a motor net power input of four megawatts, the other for seven.

The results of these calculations are tabulated on the following pages. A plot is also included.

mvh

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Siemens Techs

INJECTION PORCH

$P_{IH} \cdot P_W$ = 4 MW   7 mw

4 MW	7 MW	
0.01	0.01	SEC
29.56	29.56	AMPS
128.0077487	128.0136075	RADS
0.02	0.02	SEC
59.12	59.12	AMPS
128.015369	128.0270858	RADS
0.03	0.03	SEC
88.68	88.68	AMPS
128.0228599	128.0404337	RADS
0.04	0.04	SEC
118.24	118.24	AMPS
128.0302205	128.0536503	RADS
0.05	0.05	SEC
147.8	147.8	AMPS
128.0374498	128.0667347	RADS
0.06	0.06	SEC
177.36	177.36	AMPS
128.0445466	128.0796858	RADS
0.07	0.07	SEC
206.92	206.92	AMPS
128.0515102	128.0925027	RADS
0.08	0.08	SEC
236.48	236.48	AMPS
128.058339[illegible]	128.1051844	RADS
0.09	0.09	SEC
266.04	266.04	AMPS
128.065033[illegible]	128.1177299	RADS
0.1	0.1	SEC
295.6	295.6	AMPS
128.0715906	128.1301382	RADS
0.11	0.11	SEC
325.16	325.16	AMPS
128.078010[illegible]	128.1424083	RADS
0.12	0.12	SEC
354.72	354.72	AMPS
128.08429[illegible]	128.1545393	RADS

RECTIFY

PIH-PW

SEC	AMPS	4mw RADS	7mw RADS
0.01	430.16	128.0865878	128.1626856
0.02	535.16	128.0872981	128.1692472
0.03	640.16	128.0864101	128.1742114
0.04	745.16	128.0839111	128.1775654
0.05	850.16	128.0797879	128.1792966
0.06	955.16	128.0740275	128.179392
0.07	1060.16	128.0666168	128.1778388
0.08	1165.16	128.0575426	128.174624
0.09	1270.16	128.0467917	128.1697346
0.1	1375.16	128.0343506	128.1631575
0.11	1480.16	128.020206	128.1548796
0.12	1585.16	128.0043445	128.1448876
0.13	1690.16	127.9867524	128.1331682
0.14	1795.16	127.9674161	128.1197081
0.15	1900.16	127.946322	128.1044937
0.16	2005.16	127.9234562	128.0875117
0.17	2110.16	127.8988048	128.0687483
0.18	2215.16	127.8723539	128.0481898
0.19	2320.16	127.8440895	128.0258225
0.2	2425.16	127.8139974	128.0016326
0.21	2530.16	127.7820634	127.975606
0.22	2635.16	127.7482731	127.9477288
0.23	2740.16	127.7126122	127.9179867
0.24	2845.16	127.6750661	127.8863657
0.25	2950.16	127.6356203	127.8528512

Pw-Pw 4MW	7MW	
0.26	0.26	SEC
3055.16	3055.16	AMPS
127.5942599	127.817429	RADS
0.27	0.27	SEC
3160.16	3160.16	AMPS
127.5509702	127.7800846	RADS
✓0.28	✓0.28	SEC
3265.16	3265.16	AMPS
127.5057363	127.7408032	RADS
0.29	0.29	SEC
3370.16	3370.16	AMPS
127.458543	127.6995701	RADS
0.3	0.3	SEC
3475.16	3475.16	AMPS
127.4093754	127.6563706	RADS
0.31	0.31	SEC
3580.16	3580.16	AMPS
127.358218	127.6111896	RADS
0.32	0.32	SEC
3685.16	3685.16	AMPS
127.3050555	127.5640121	RADS
✓0.33	✓0.33	SEC
3790.16	3790.16	AMPS
127.2498725	127.5148229	RADS
0.34	0.34	SEC
3895.16	3895.16	AMPS
127.1926532	127.4636067	RADS
0.35	0.35	SEC
4000.16	4000.16	AMPS
127.133382	127.4103482	RADS
0.36	0.36	SEC
4105.16	4105.16	AMPS
127.0720429	127.3550317	RADS

4MW	7MW	
0.37	0.37	SEC
4210.16	4210.16	AMPS
127.0086199	127.2976415	RADS
✓0.38	✓0.38	SEC
4315.16	4315.16	AMPS
126.9430969	127.238162	RADS
0.39	0.39	SEC
4420.16	4420.16	AMPS
126.8754577	127.1765771	RADS
0.4	0.4	SEC
4525.16	4525.16	AMPS
126.8056857	127.1128709	RADS
0.41	0.41	SEC
4630.16	4630.16	AMPS
126.7337645	127.047027	RADS
0.42	0.42	SEC
4735.16	4735.16	AMPS
126.6596773	126.9790292	RADS
✓0.43	✓0.43	SEC
4840.16	4840.16	AMPS
126.5834072	126.9088609	RADS
0.44	0.44	SEC
4945.16	4945.16	AMPS
126.5049373	126.8365056	RADS
✓0.45	✓0.45	SEC
5050.16	5050.16	AMPS
126.4242503	126.7619465	RADS
0.46	0.46	SEC
5155.16	5155.16	AMPS
126.3413289	126.6851665	RADS

.45
.12
.67

FLAT TOP

4MW	7MW	PIN-PW
0.03 126.3987523	0.03 126.7542686	SEC RADS
0.13 126.3137218	0.13 126.7286721	SEC RADS
0.23 126.2286339	0.23 126.7030704	SEC RADS
0.33 126.1434887	0.33 126.6774635	SEC RADS
0.43 126.058286	0.43 126.6518515	SEC RADS
0.53 125.9730257	0.53 126.6262343	SEC RADS
0.63 125.8877076	0.63 126.6006119	SEC RADS
0.73 125.8023316	0.73 126.5749843	SEC RADS
0.83 125.7168977	0.83 126.5493516	SEC RADS
0.93 125.6314057	0.93 126.5237136	SEC RADS
1.03 125.5458554	1.03 126.4980705	SEC RADS
1.13 125.4602469	1.13 126.4724221	SEC RADS

4MW	7MW	
1.23 125.3745798	1.23 126.4467686	SEC RADS
1.33 125.2888542	1.33 126.4211098	SEC RADS
1.43 125.2030699	1.43 126.3954458	SEC RADS
1.53 125.1172268	1.53 126.3697767	SEC RADS
1.63 125.0313247	1.63 126.3441023	SEC RADS
1.73 124.9453636	1.73 126.3184226	SEC RADS
1.83 124.8593433	1.83 126.2927378	SEC RADS
1.93 124.7732637	1.93 126.2670477	SEC RADS
2.03 124.6871246	2.03 126.2413525	SEC RADS

INVERT AFTER 1SEC I-FLAT TOP

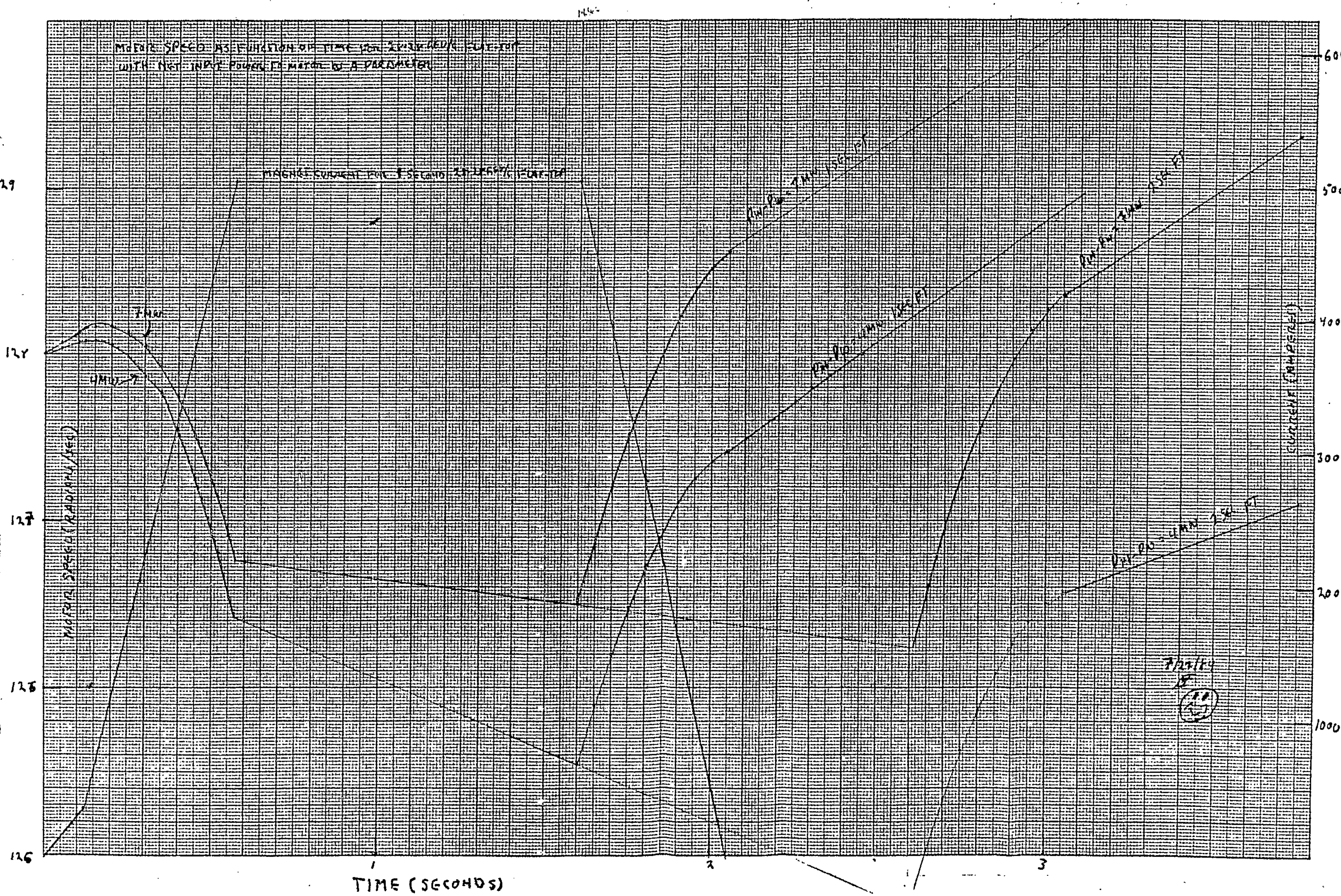
4MW	7MW	$(P_{IM}-P_W)$	4MW	7MW	
0.01	0.01	SEC	0.13	0.13	SEC
4937.66	4937.66	AMPS	3587.66	3587.66	AMPS
125.6159413	126.5735546	RADS	126.3666301	127.3892666	RADS
0.02	0.02	SEC	0.14	0.14	SEC
4825.16	4825.16	AMPS	3475.16	3475.16	AMPS
125.6849175	126.6479314	RADS	126.4212563	127.4493392	RADS
0.03	0.03	SEC	0.15	0.15	SEC
4712.66	4712.66	AMPS	3362.66	3362.66	AMPS
125.7527709	126.7211878	RADS	126.4746001	127.5081351	RADS
0.04	0.04	SEC	0.16	0.16	SEC
4600.16	4600.16	AMPS	3250.16	3250.16	AMPS
125.8194882	126.7933107	RADS	126.5266483	127.565641	RADS
0.05	0.05	SEC	0.17	0.17	SEC
4487.66	4487.66	AMPS	3137.66	3137.66	AMPS
125.8850562	126.8642873	RADS	126.5773874	127.6218439	RADS
0.06	0.06	SEC	0.18	0.18	SEC
4375.16	4375.16	AMPS	3025.16	3025.16	AMPS
125.9494615	126.9341045	RADS	126.6268041	127.6767306	RADS
0.07	0.07	SEC	0.19	0.19	SEC
4262.66	4262.66	AMPS	2912.66	2912.66	AMPS
126.0126909	127.0027492	RADS	126.6748848	127.730288	RADS
0.08	0.08	SEC	0.2	0.2	SEC
4150.16	4150.16	AMPS	2800.16	2800.16	AMPS
126.0747311	127.0702084	RADS	126.7216163	127.782503	RADS
0.09	0.09	SEC	0.21	0.21	SEC
4037.66	4037.66	AMPS	2687.66	2687.66	AMPS
126.135569	127.1364692	RADS	126.766985	127.8333623	RADS
0.1	0.1	SEC	0.22	0.22	SEC
3925.16	3925.16	AMPS	2575.16	2575.16	AMPS
126.1951911	127.2015184	RADS	126.8109774	127.8828527	RADS
0.11	0.11	SEC	0.23	0.23	SEC
3812.66	3812.66	AMPS	2462.66	2462.66	AMPS
126.2535842	127.2653431	RADS	126.85358	127.930961	RADS
0.12	0.12	SEC			
3700.16	3700.16	AMPS			
126.310735	127.3279302	RADS			

4MW	7MW	(PIN-PN)	4MW	7MW	
0.24	0.24	SEC	0.35	0.35	SEC
2350.16	2350.16	AMPS	1112.66	1112.66	AMPS
126.8947792	127.9776739	RADS	127.2514468	128.3956026	RADS
0.25	0.25	SEC	0.36	0.36	SEC
2237.66	2237.66	AMPS	1000.16	1000.16	AMPS
126.9345616	128.0229783	RADS	127.274738	128.4245263	RADS
0.26	0.26	SEC	0.37	0.37	SEC
2125.16	2125.16	AMPS	887.66	887.66	AMPS
126.9729135	128.0668606	RADS	127.2964466	128.4518795	RADS
0.27	0.27	SEC	0.38	0.38	SEC
2012.66	2012.66	AMPS	775.16	775.16	AMPS
127.0098212	128.1093077	RADS	127.3165585	128.4776483	RADS
0.28	0.28	SEC	0.39	0.39	SEC
1900.16	1900.16	AMPS	662.66	662.66	AMPS
127.0452712	128.1503061	RADS	127.3350598	128.501819	RADS
0.29	0.29	SEC	0.4	0.4	SEC
1787.66	1787.66	AMPS	550.16	550.16	AMPS
127.0792496	128.1898425	RADS	127.3519361	128.5243777	RADS
0.3	0.3	SEC	0.41	0.41	SEC
1675.16	1675.16	AMPS	437.66	437.66	AMPS
127.1117428	128.2279033	RADS	127.3671732	128.5453105	RADS
0.31	0.31	SEC	0.42	0.42	SEC
1562.66	1562.66	AMPS	325.16	325.16	AMPS
127.142737	128.2644752	RADS	127.3807569	128.5646034	RADS
0.32	0.32	SEC	0.43	0.43	SEC
1450.16	1450.16	AMPS	212.66	212.66	AMPS
127.1722184	128.2995447	RADS	127.3926727	128.5822425	RADS
0.33	0.33	SEC	0.44	0.44	SEC
1337.66	1337.66	AMPS	100.16	100.16	AMPS
127.2001731	128.3330981	RADS	127.4029063	128.5982137	RADS
0.34	0.34	SEC	0.45	0.45	SEC
1225.16	1225.16	AMPS	-12.34	-12.34	AMPS
127.2265872	128.3651219	RADS	127.4114432	128.6125029	RADS

INJECT AFTER 2SEC 28.28 GeV/c FLAT-TOP

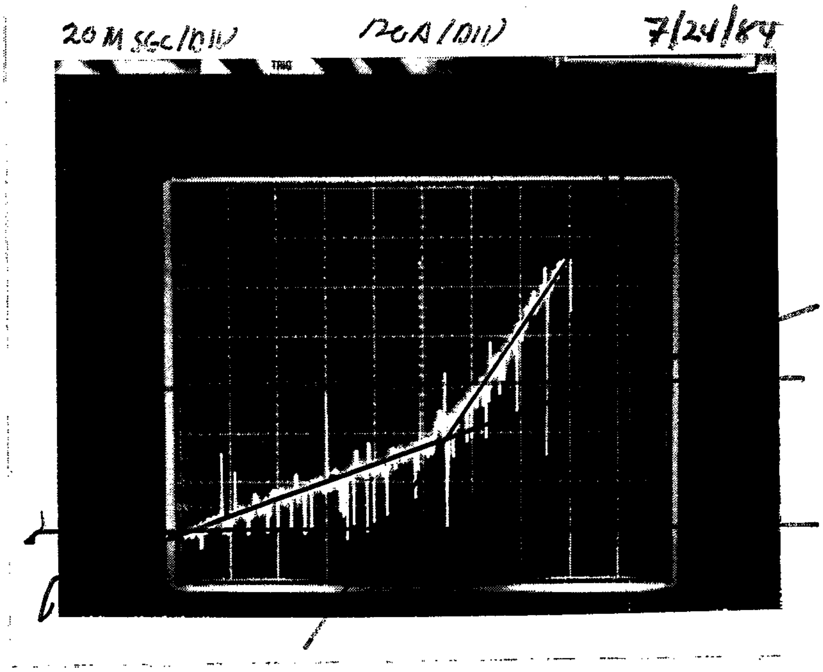
4MW	7MW		4MW	7MW	
0.01 4937.66 124.7576929	0.01 4937.66 126.31699	SEC AMPS RADS	0.12 3700.16 125.4572397	0.12 3700.16 127.0728887	SEC AMPS RADS
0.02 4825.16 124.8271434	0.02 4825.16 126.3915178	SEC AMPS RADS	0.13 3587.66 125.5135149	0.13 3587.66 127.1343481	SEC AMPS RADS
0.03 4712.66 124.8954628	0.03 4712.66 126.4649227	SEC AMPS RADS	0.14 3475.16 125.5685123	0.14 3475.16 127.1945412	SEC AMPS RADS
0.04 4600.16 124.9626378	0.04 4600.16 126.5371917	SEC AMPS RADS	0.15 3362.66 125.6222182	0.15 3362.66 127.2534548	SEC AMPS RADS
0.05 4487.66 125.0286551	0.05 4487.66 126.6083119	SEC AMPS RADS	0.16 3250.16 125.6746194	0.16 3250.16 127.3110757	SEC AMPS RADS
0.06 4375.16 125.0935013	0.06 4375.16 126.6782701	SEC AMPS RADS	0.17 3137.66 125.7257024	0.17 3137.66 127.3673909	SEC AMPS RADS
0.07 4262.66 125.1571632	0.07 4262.66 126.7470534	SEC AMPS RADS	0.18 3025.16 125.7754536	0.18 3025.16 127.4223873	SEC AMPS RADS
0.08 4150.16 125.2196273	0.08 4150.16 126.8146486	SEC AMPS RADS	0.19 2912.66 125.8238597	0.19 2912.66 127.4760516	SEC AMPS RADS
0.09 4037.66 125.2808804	0.09 4037.66 126.8810428	SEC AMPS RADS	0.2 2800.16 125.8709072	0.2 2800.16 127.5283706	SEC AMPS RADS
0.1 3925.16 125.3409091	0.1 3925.16 126.946223	SEC AMPS RADS	0.21 2687.66 125.9165823	0.21 2687.66 127.5793312	SEC AMPS RADS
0.11 3812.66 125.3997	0.11 3812.66 127.0101759	SEC AMPS RADS	0.22 2575.16 125.9608717	0.22 2575.16 127.6289201	SEC AMPS RADS

4MW SEC	4MW AMPS	4MW RADS	7MW SEC	7MW AMPS	7MW RADS
0.23	2462.66	126.0037618	0.23	2462.66	127.6771241
0.24	2350.16	126.0452388	0.24	2350.16	127.7239299
0.25	2237.66	126.0852892	0.25	2237.66	127.7693242
0.26	2125.16	126.1238994	0.26	2125.16	127.8132936
0.27	2012.66	126.1610555	0.27	2012.66	127.8558249
0.28	1900.16	126.1967438	0.28	1900.16	127.8969046
0.29	1787.66	126.2309507	0.29	1787.66	127.9365192
0.3	1675.16	126.2636622	0.3	1675.16	127.9746554
0.31	1562.66	126.2948645	0.31	1562.66	128.0112997
0.32	1450.16	126.3245438	0.32	1450.16	128.0464385
0.33	1337.66	126.352686	0.33	1337.66	128.0800582
0.34	1225.16		0.34	1225.16	128.1121453
0.35	1112.66	126.4043036	0.35	1112.66	128.1426861
0.36	1000.16	126.4277507	0.36	1000.16	128.1716669
0.37	887.66	126.4496047	0.37	887.66	128.199074
0.38	775.16	126.4698514	0.38	775.16	128.2248937
0.39	662.66	126.4884765	0.39	662.66	128.249112
0.4	550.16	126.5054657	0.4	550.16	128.2717151
0.41	437.66	126.5208048	0.41	437.66	128.2926891
0.42	325.16	126.5344793	0.42	325.16	128.3120201
0.43	212.66	126.5464748	0.43	212.66	128.3296939
0.44	100.16	126.5567769	0.44	100.16	128.3456965
0.45	-12.34	126.5653708	0.45	-12.34	128.3600138



129
128
127
126
6000
5000
4000
3000
2000
1000
7MW
4MW
1
2
3
TIME (SECONDS)

Injection Porch

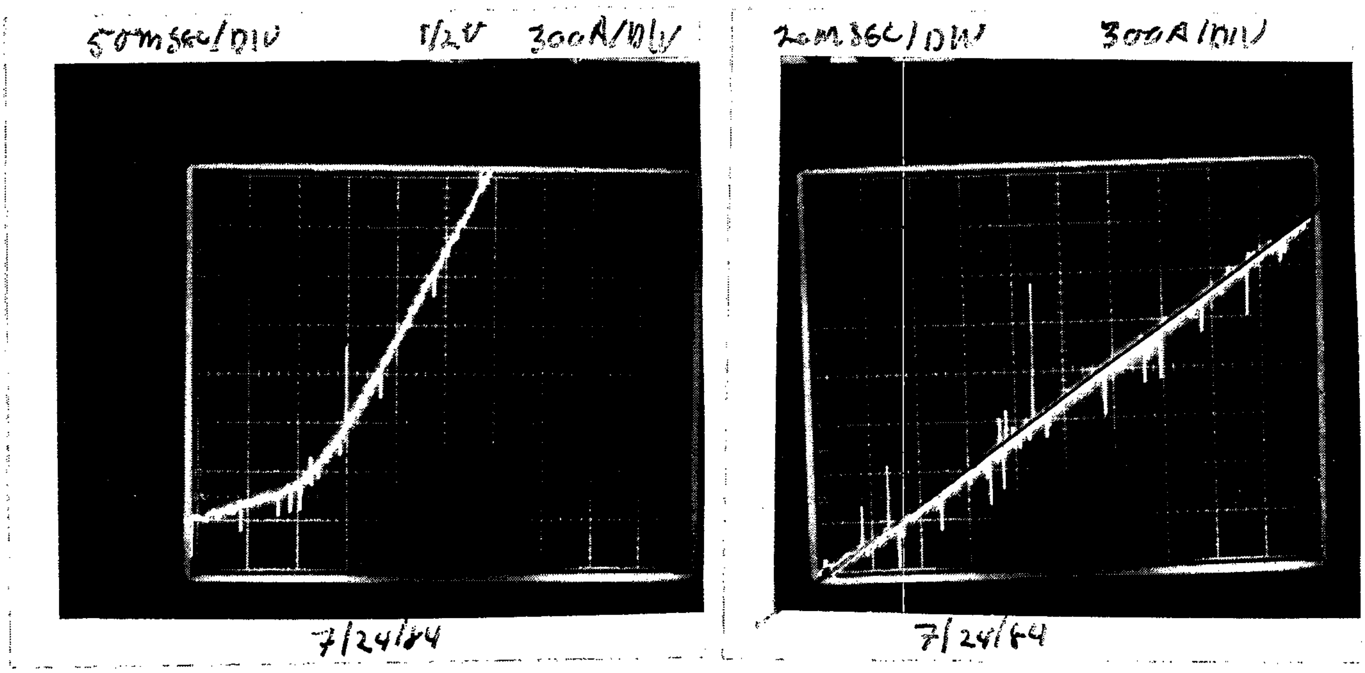


$$I = \frac{(120)(3)}{(0.02)(6.7)} = 2686.6t \cong 2687t \Big|_{o}^{0.11\ sec}$$

$$I_{0.11\ sec} = 295.6\ Amps$$

FIGURE 1

Rectify



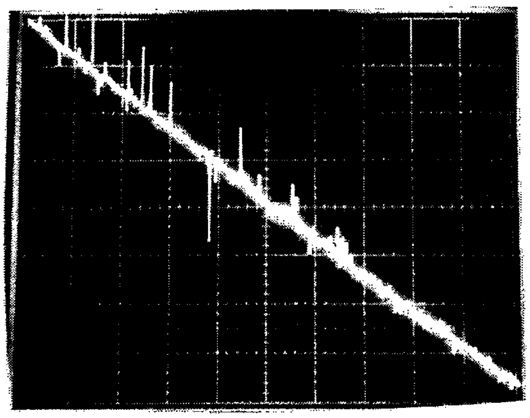
$$I = 295.6 + \frac{(300)(7)}{0.2} t^{-0.11} = 295.6 + 10{,}500\ (t - 0.11)$$

$$I = -860 + 10{,}500t \Big|_{0.11}^{t}$$

FIGURE 2

Invert

20 msec/Div 300 Amps/Div



$$I = I_F - \frac{(300)(7.5)}{0.2} = I_F - 11{,}250t$$

FIGURE 3