03 December 2004

To: Mike Zarnstorff

From: Wayne Reiersen

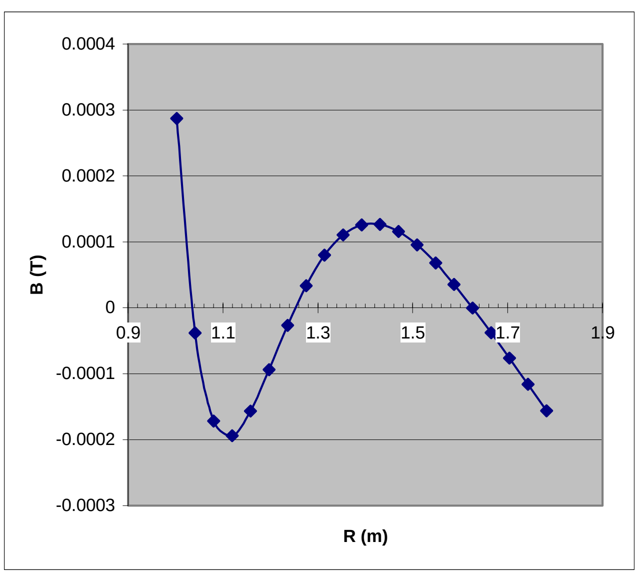
Subject: Re-using the NSTX PF1A coils

I took a quick look at using the two NSTX PF1A coils in place of new PF1-3 coils. The results actually look quite promising. The NSTX PF1A coil is a two layer solenoid coil that is 21.383” tall, 1.786” thick with 48 turns. The radius to the current centroid is 7.24”. It uses the same conductor that we were planning to use on PF1-3, namely a 0.787” square conductor with a 0.354” diameter cooling hole.

I located the current centroid 0.4m off the midplane. I get a fair OH distribution using just the new PF1, PF4, and PF6 coils. The following current distribution provides 1Vs of linked flux to a circular current loop at 1.4m.

Coil	I (MAT)	Turns	I (A)
PF1	6.49	48	135169
PF4	1.79	80	22397
PF6	0.03	14	1870

The stray field is less than 2 gauss on the midplane between 1.0m and 1.8m with the 1 Vs current distribution. At the maximum currents required for the First Plasma scenario (PF1 has a maximum current of 18279 A) the stray field is only 0.27 gauss.



I did not run the ENERGIES code to recalculate the new single turn mutual inductance between the new PF1 and the modular coils and plasma. Rather, I used the old PF1 values for the modular coils and I calculated the mutual between the new PF1 and a current loop at 1.4m for the PF1 to plasma mutual.

Running the scenario exactly as before resulted in problems with the current in PF1 (the max current was 20.2kA compared to the power supply capability of 5kA) and the voltage in PF4 (the voltage was 738V compared to the power supply capability of 500V). These problems can be addressed as follows:

1. Increase the current ramp time from 70ms to 100ms.

2. Decrease the assumed resistive consumption in the plasma from 1.0V to 0.6V. (With these two changes, the average applied loop voltage during the current ramp decreases from 2V to 1.3V which is still better than the maximum of 1V that W7AS was able to live.)

3. Put all four Robicon-5 units (5kA and 300V) – two from the old PF1/2 circuit, one from the old TF circuit, and one from the old PF3 circuit – in parallel for PF1, thus providing 20kA and 300V.

4. Move Robicon-10 (10kA and 200V) from PF6 to the TF.

5. Buy a tiny new power supply for PF6 that provides at least 253A and 32V. (Sounded like three car batteries to Raki if regulation was not critical. Alternatively, we could just get rid of the TF circuit for First Plasma as originally proposed and keep the Robicon-10 in the PF6 circuit.)

Please run these changes through your simulation code and see if you come to the same conclusions. If we could make this work, it could save big bucks. The new solenoid coils will cost perhaps $500K. The CS support structure which costs almost $200K could be greatly simplified to grab only these two coils. The incremental cost to Raki should be less than $100K. It is not unreasonable to expect a net savings on the order of $500K if we can make this work. More could be saved if we could get rid of the TF circuit altogether.

There are probably two things that concern you. One is dropping the loop voltage from 2V to 1.3V. We could probably get this back by reducing the ramp time back closer to 70ms but not pushing quite so much current through PF4. It changes the equilibrium but it would probably be OK. Your second worry might be not having enough volt-seconds. My vote for this would be to wind two new PF1A coils EXACTLY like the ones that were would for NSTX with no change in design or tooling or personnel. That would give us ample volt-seconds at minimum cost.

I attached my current waveforms and coil (not circuit) inductance matrices for your reference along with some graphs of my simulation. The TF and modular coil currents did not change. The simulation features a 10ms plasma current flattop. Your thoughts would be appreciated. Please let me know if you uncover any errors that would undermine my conclusions.

Old coil inductance matrix

Multi-turn coil inductance matrix	M1	M2	M3	PF1	PF2	PF3	PF4	PF5	PF6	TF	Plasma
M1	1.236E-02	2.825E-03	1.254E-03	-5.521E-05	9.153E-06	3.783E-05	1.219E-04	-2.287E-04	-2.818E-04	8.676E-03	-1.631E-05
M2	2.825E-03	9.234E-03	2.324E-03	2.214E-05	-1.035E-05	-5.070E-06	-1.274E-05	-4.515E-05	-6.266E-05	6.683E-03	-1.079E-05
M3	1.254E-03	2.324E-03	7.903E-03	1.023E-04	-8.504E-06	-3.480E-05	-1.656E-04	-2.030E-04	-6.188E-05	4.675E-03	-8.599E-06
PF1	-5.521E-05	2.214E-05	1.023E-04	3.030E-03	4.763E-04	7.205E-05	1.470E-04	1.679E-04	1.188E-04	0.000E+00	8.924E-06
PF2	9.153E-06	-1.035E-05	-8.504E-06	4.763E-04	2.626E-03	4.276E-04	3.222E-04	1.754E-04	1.141E-04	0.000E+00	6.785E-06
PF3	3.783E-05	-5.070E-06	-3.480E-05	7.205E-05	4.276E-04	2.613E-03	1.138E-03	1.817E-04	1.044E-04	0.000E+00	4.404E-06
PF4	1.219E-04	-1.274E-05	-1.656E-04	1.470E-04	3.222E-04	1.138E-03	1.529E-02	1.135E-03	5.895E-04	0.000E+00	1.816E-05
PF5	-2.287E-04	-4.515E-05	-2.030E-04	1.679E-04	1.754E-04	1.817E-04	1.135E-03	1.287E-02	3.493E-03	0.000E+00	4.805E-05
PF6	-2.818E-04	-6.266E-05	-6.188E-05	1.188E-04	1.141E-04	1.044E-04	5.895E-04	3.493E-03	6.259E-03	0.000E+00	3.968E-05
TF	8.676E-03	6.683E-03	4.675E-03	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.898E-02	1.510E-06
Plasma	-1.631E-05	-1.079E-05	-8.599E-06	8.924E-06	6.785E-06	4.404E-06	1.816E-05	4.805E-05	3.968E-05	1.510E-06	2.679E-06

New coil inductance matrix

Multi-turn coil inductance matrix	M1	M2	M3	PF1	PF2	PF3	PF4	PF5	PF6	TF	Plasma
M1	1.236E-02	2.825E-03	1.254E-03	-3.681E-05	0.000E+00	0.000E+00	1.219E-04	0.000E+00	-2.818E-04	8.676E-03	-1.631E-05
M2	2.825E-03	9.234E-03	2.324E-03	1.476E-05	0.000E+00	0.000E+00	-1.274E-05	0.000E+00	-6.266E-05	6.683E-03	-1.079E-05
M3	1.254E-03	2.324E-03	7.903E-03	6.823E-05	0.000E+00	0.000E+00	-1.656E-04	0.000E+00	-6.188E-05	4.675E-03	-8.599E-06
PF1	-3.681E-05	1.476E-05	6.823E-05	7.910E-04	-3.079E-11	-5.157E-11	8.583E-05	1.510E-09	5.486E-05	0.000E+00	4.057E-06
PF2	0.000E+00	0.000E+00	0.000E+00	-3.079E-11	2.610E-03	-3.308E-11	1.004E-11	1.667E-09	3.403E-10	0.000E+00	0.000E+00
PF3	0.000E+00	0.000E+00	0.000E+00	-5.157E-11	-3.308E-11	2.610E-03	-6.967E-11	1.967E-10	8.595E-11	0.000E+00	0.000E+00
PF4	1.219E-04	-1.274E-05	-1.656E-04	8.583E-05	1.004E-11	-6.967E-11	1.529E-02	2.053E-08	5.895E-04	0.000E+00	1.816E-05
PF5	0.000E+00	0.000E+00	0.000E+00	1.510E-09	1.667E-09	1.967E-10	2.053E-08	1.212E-02	9.688E-08	0.000E+00	0.000E+00
PF6	-2.818E-04	-6.266E-05	-6.188E-05	5.486E-05	3.403E-10	8.595E-11	5.895E-04	9.688E-08	6.259E-03	0.000E+00	3.968E-05
TF	8.676E-03	6.683E-03	4.675E-03	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.898E-02	1.510E-06
Plasma	-1.631E-05	-1.079E-05	-8.599E-06	4.057E-06	0.000E+00	0.000E+00	1.816E-05	0.000E+00	3.968E-05	1.510E-06	2.679E-06

Old current waveform

Current waveforms (A)											
	t(s)	M1	M2	M3	PF1	PF2	PF3	PF4	PF5	PF6	TF	Plasma
0.5T First Plasma Scenario												
	-1.550	0	0	0	0	0	0	0	0	0	0	0
	0.000	10000	10000	10000	0	0	0	0	0	0	93	0
	0.050	10000	10000	10000	0	0	0	0	0	0	93	0
	0.120	10000	10000	10000	4869	4869	4869	1478	0	385	93	-25999
	0.123	10000	10000	10000	4973	4973	4973	1510	0	393	93	-25999
	0.130	10000	10000	10000	5217	5217	5217	1584	0	413	93	-25999
Waveform max (A)		10000	10000	10000	5217	5217	5217	1584	0	413	93	0
Waveform min (A)		0	0	0	0	0	0	0	0	0	0	-25999

New current waveform

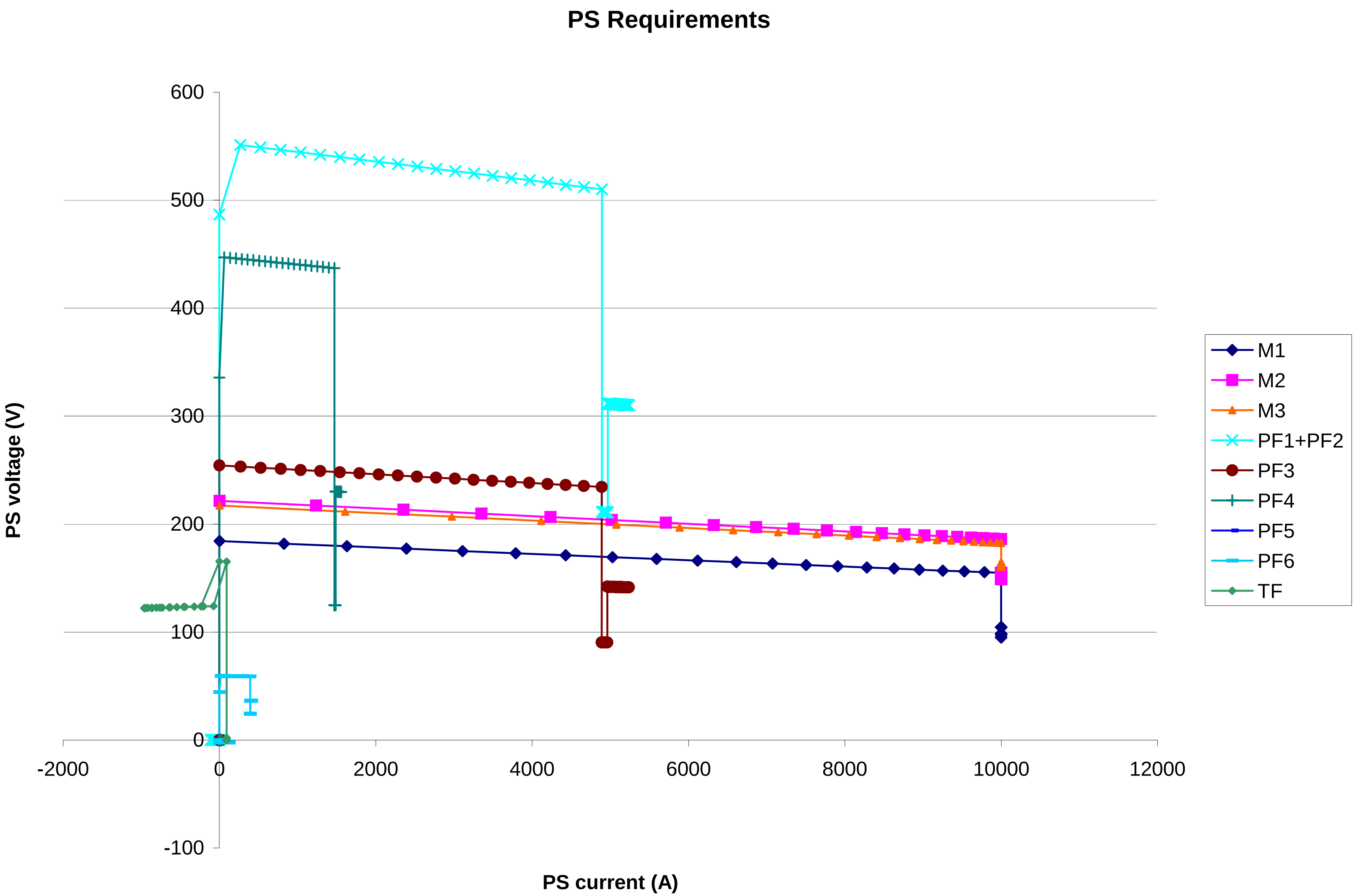
Current waveforms (A)												
	t(s)	M1	M2	M3	PF1	PF2	PF3	PF4	PF5	PF6	TF	Plasma
0.5T First Plasma Scenario												
	-1.550	0	0	0	0	0	0	0	0	0	0	0
	0.000	10000	10000	10000	0	0	0	0	0	0	93	0
	0.050	10000	10000	10000	0	0	0	0	0	0	93	0
	0.149	10000	10000	10000	17445	0	0	2891	0	241	93	-25999
	0.152	10000	10000	10000	17688	0	0	2931	0	245	93	-25999
	0.159	10000	10000	10000	18256	0	0	3025	0	253	93	-25999
Waveform max (A)		10000	10000	10000	5217	5217	5217	1584	0	413	93	0
Waveform min (A)		0	0	0	0	0	0	0	0	0	0	-25999

PF1a study

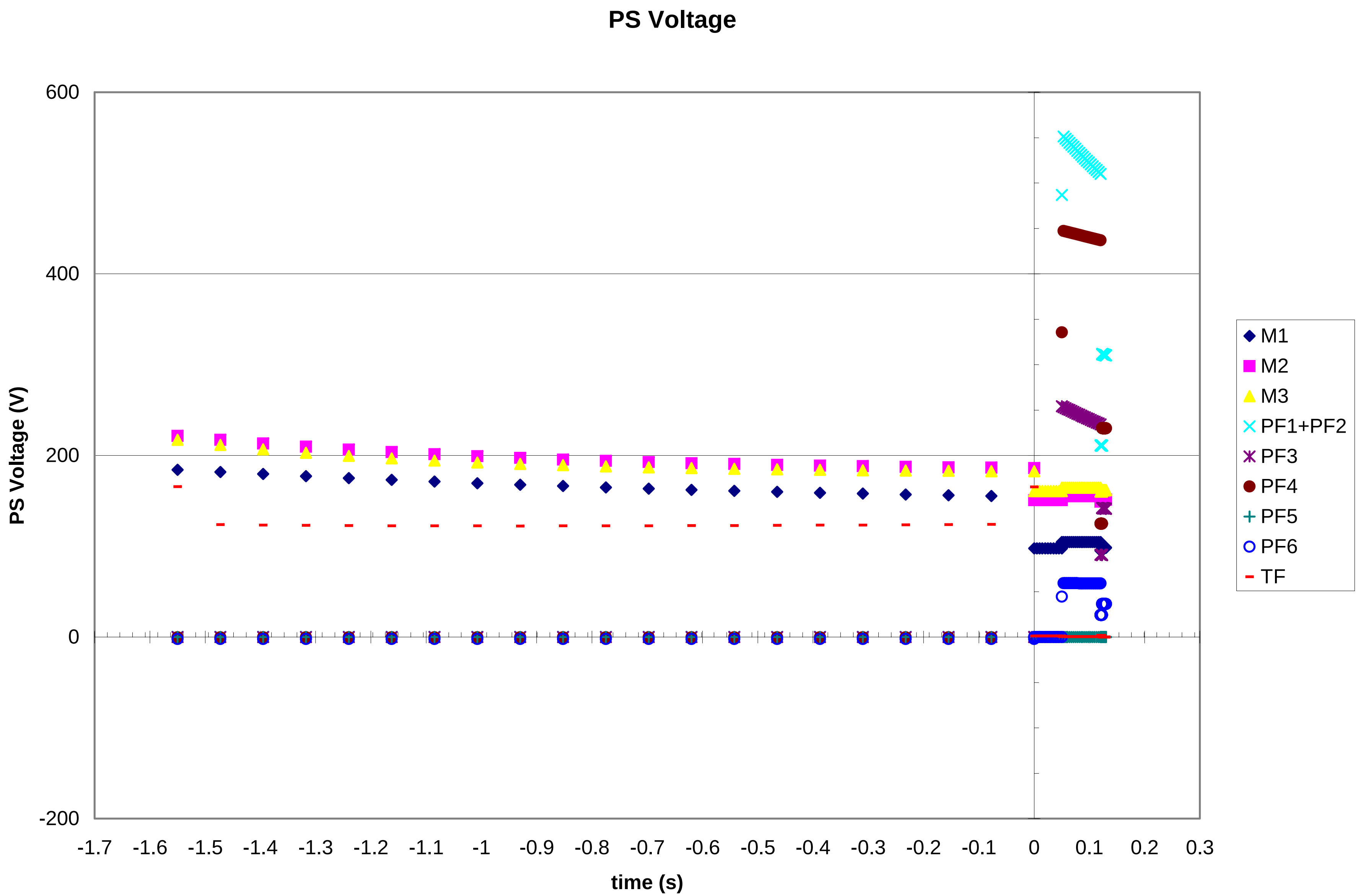
December 2004

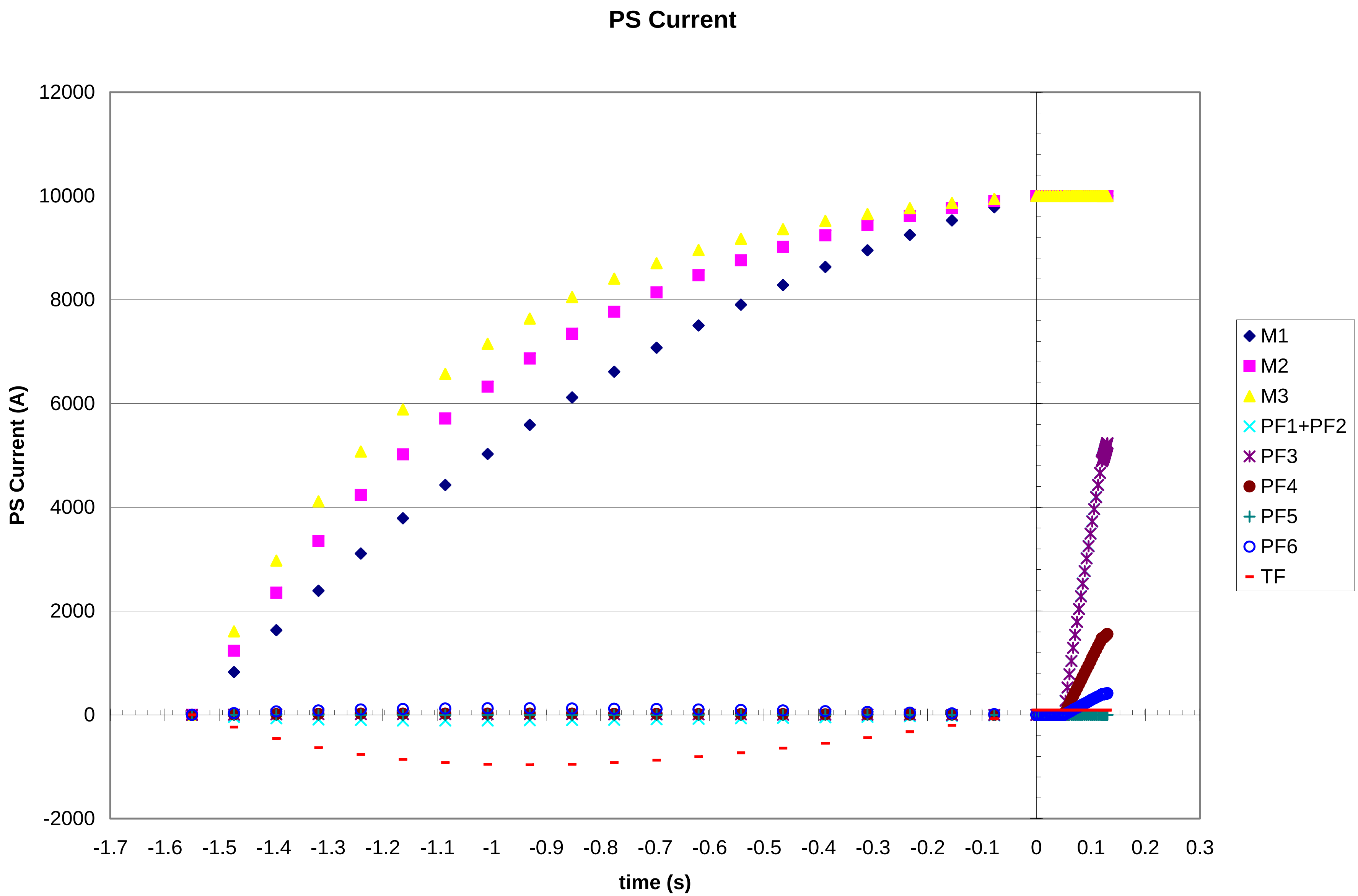
Baseline Coil Configuration

- First plasma scenario
- PF1-6 are powered independently in the model
- In actuality…
  - PF1-2 are in series. Need to add PS voltages to get right answer.
  - PF 5 is open circuited. Ignore PS voltage required to maintain zero current at breakpoints.

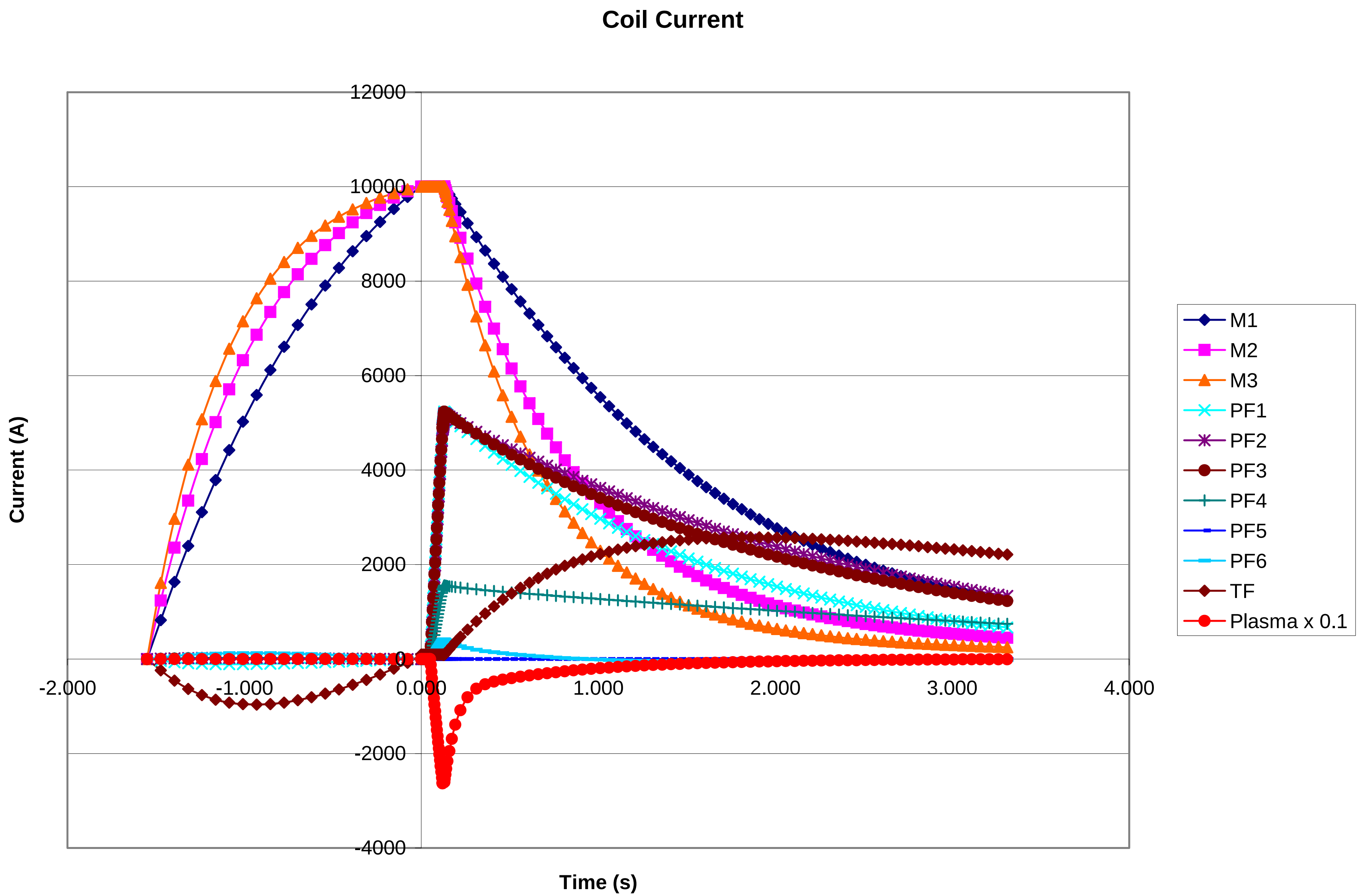


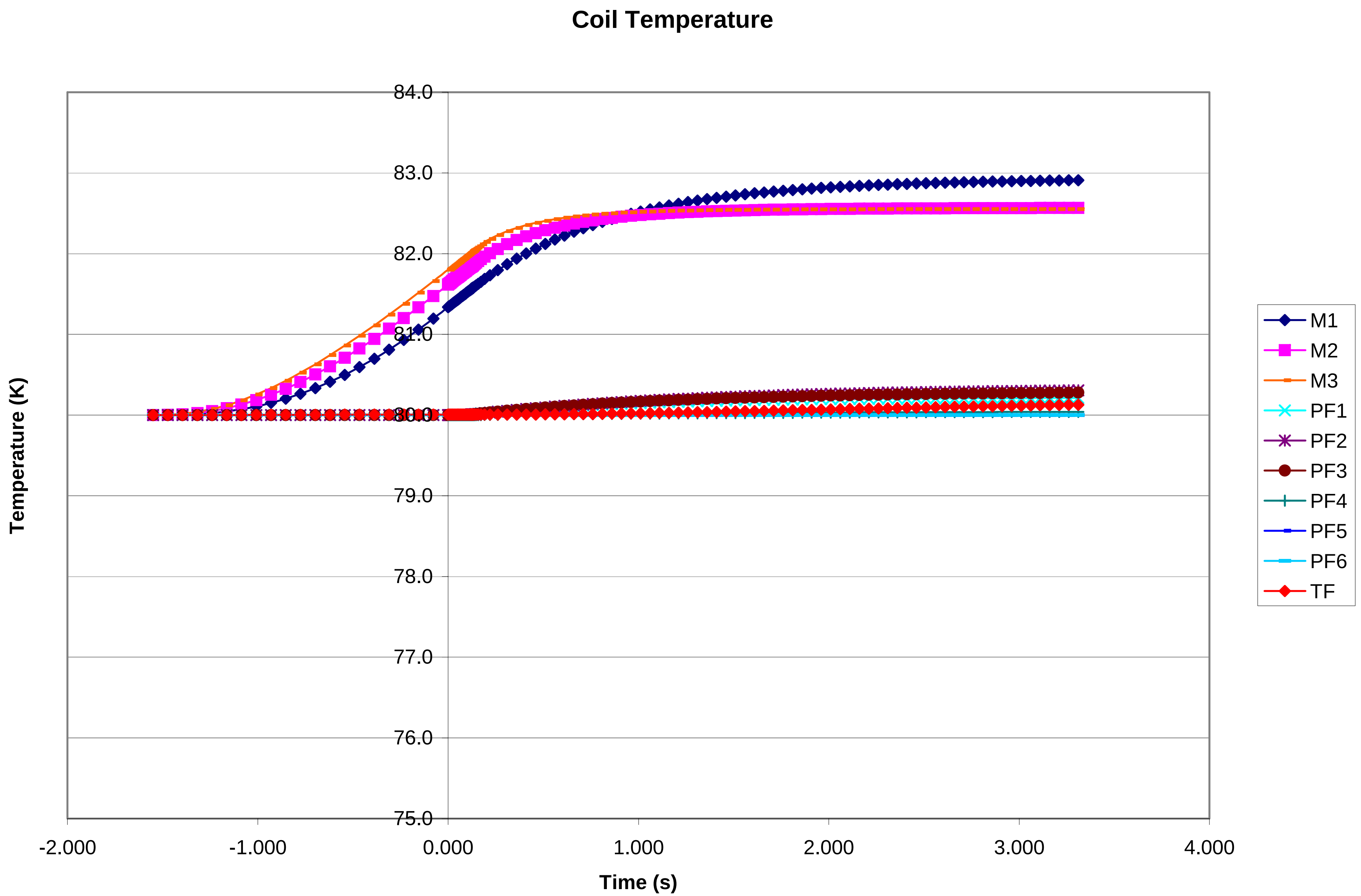
PS Requirements
PS voltage (V)
PS current (A)
600
500
400
300
200
100
0
-100
-2000
0
2000
4000
6000
8000
10000
12000
M1
M2
M3
PF1+PF2
PF3
PF4
PF5
PF6
TF


PS Voltage
PS Voltage (V)
600
400
200
0
-200
-1.7
-1.6
-1.5
-1.4
-1.3
-1.2
-1.1
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
time (s)
M1
M2
M3
PF1+PF2
PF3
PF4
PF5
PF6
TF



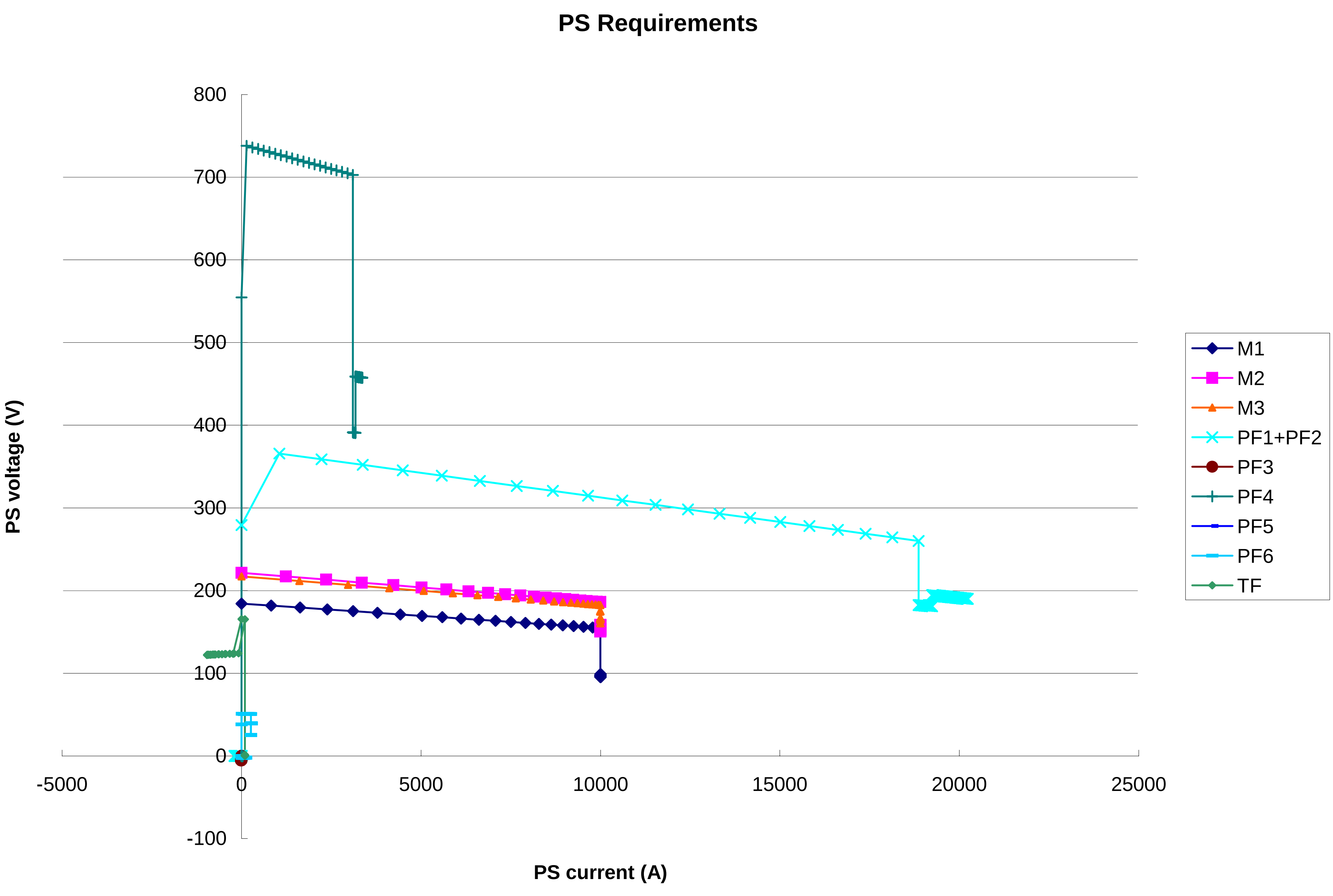
PS Current
PS Current (A)
12000
10000
8000
6000
4000
2000
0
-2000
-1.7
-1.6
-1.5
-1.4
-1.3
-1.2
-1.1
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
time (s)
M1
M2
M3
PF1+PF2
PF3
PF4
PF5
PF6
TF


Coil Current
Current (A)
Time (s)
12000
10000
8000
6000
4000
2000
0
-2000
-4000
-2.000
-1.000
0.000
1.000
2.000
3.000
4.000
M1
M2
M3
PF1
PF2
PF3
PF4
PF5
PF6
TF
Plasma x 0.1

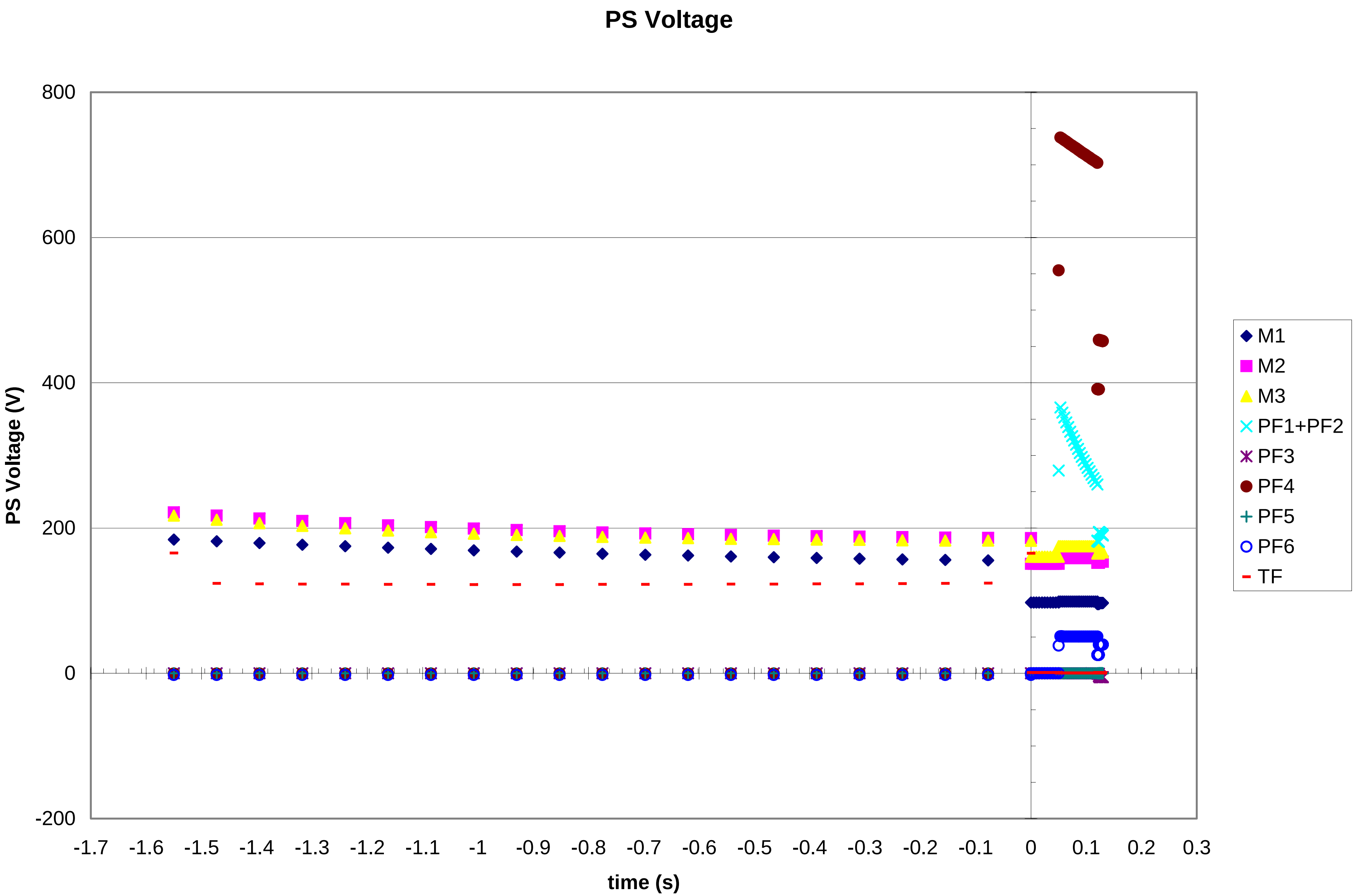

Coil Temperature
Temperature (K)
84.0
83.0
82.0
81.0
80.0
79.0
78.0
77.0
76.0
75.0
-2.000
-1.000
0.000
1.000
2.000
3.000
4.000
Time (s)
M1
M2
M3
PF1
PF2
PF3
PF4
PF5
PF6
TF

New configuration with NSTX PF1

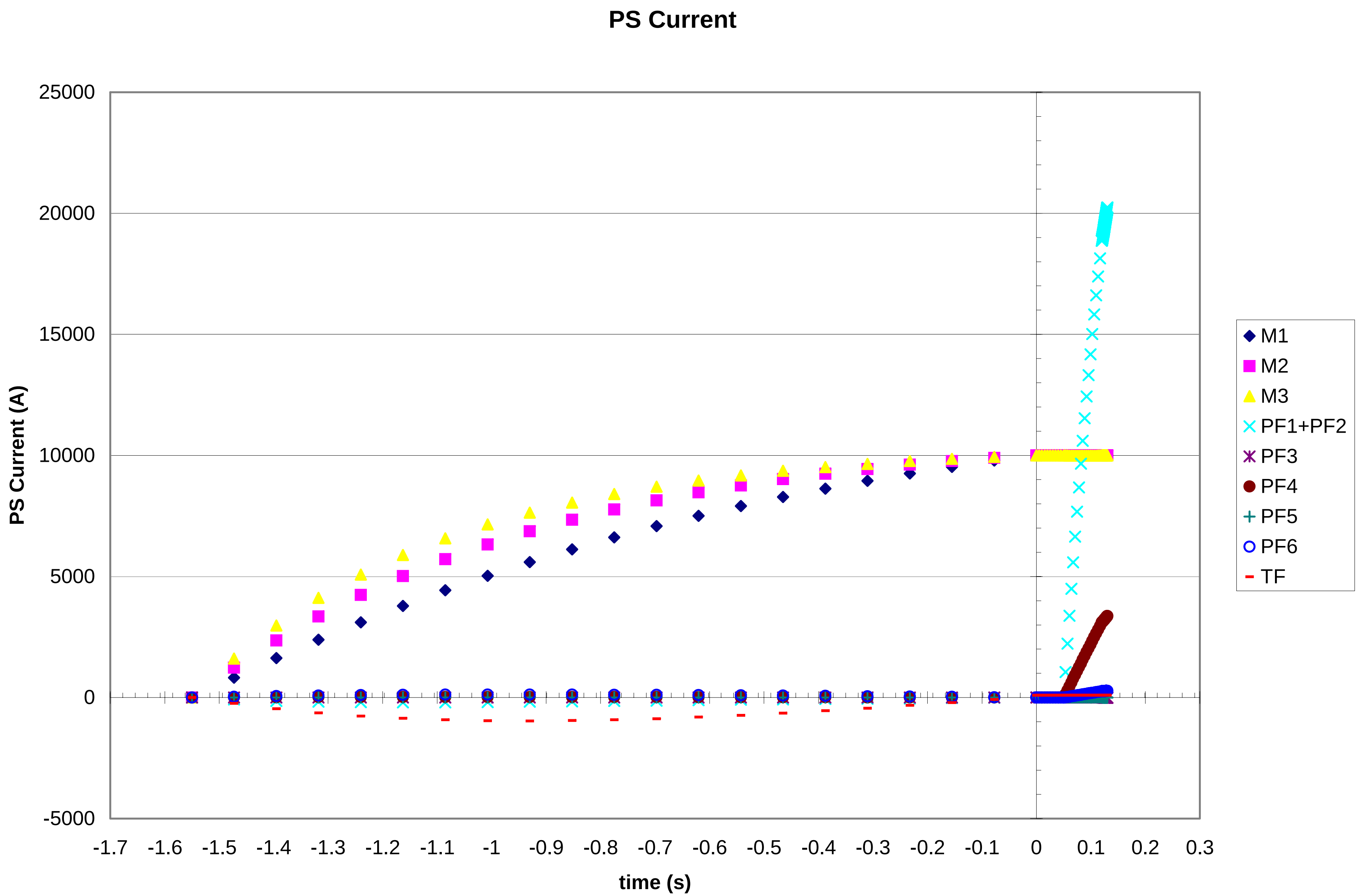
- PF1 centroid located 0.4m off midplane
  - Calculated single turn mutual inductance between plasma and new PF1 based on circular loop at 1.4m. Used same mutual between PF1 and modular coils. New calculation required.
- PF2-3 gone
  - In the model, power supplies targeted for zero current.
- Same scenario. Plasma IR drop of 1V assumed. Loop voltage is 2V.

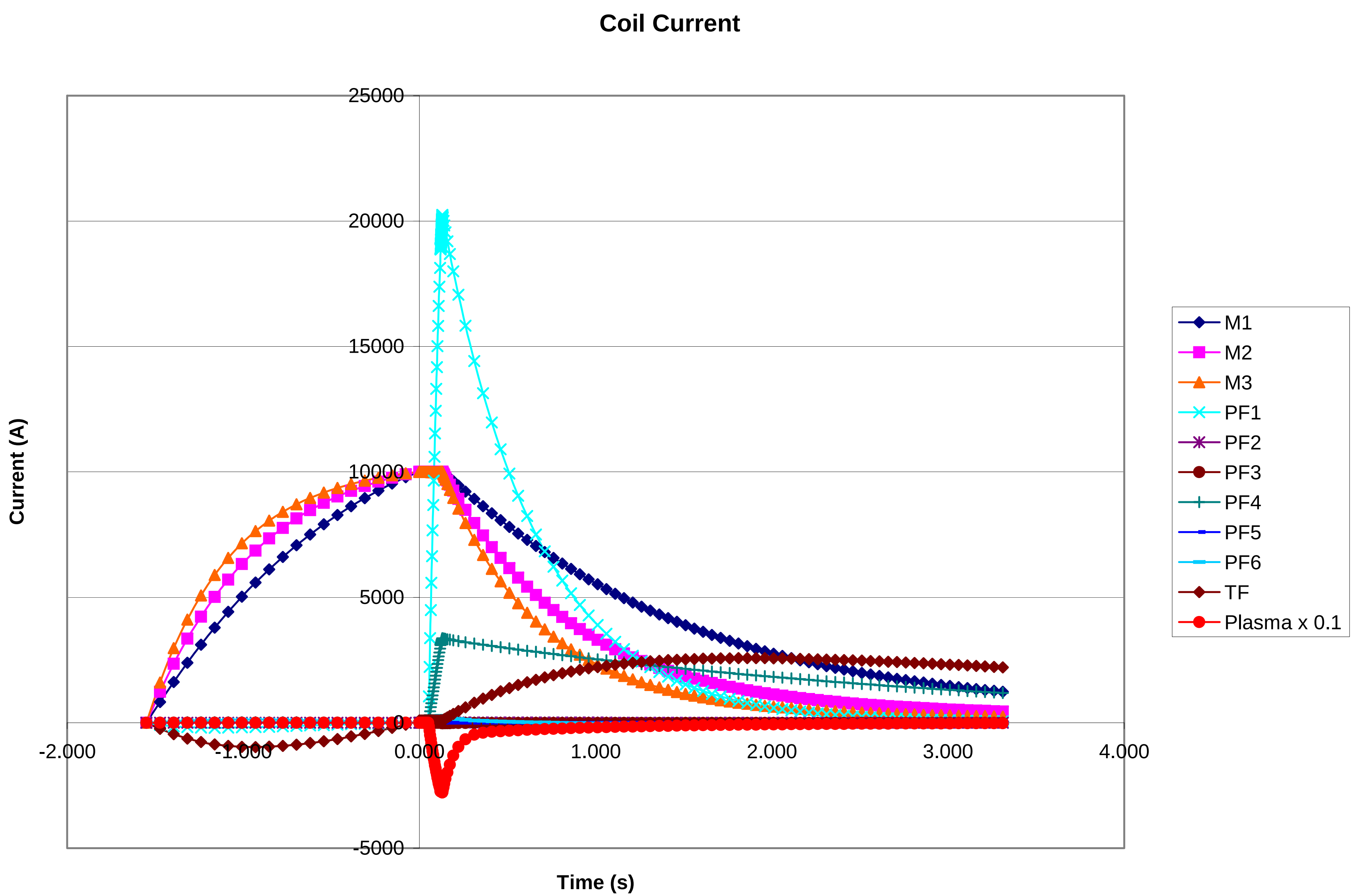


PS Requirements
800
700
600
500
400
300
200
100
0
-100
-5000
0
5000
10000
15000
20000
25000
PS voltage (V)
PS current (A)
M1
M2
M3
PF1+PF2
PF3
PF4
PF5
PF6
TF

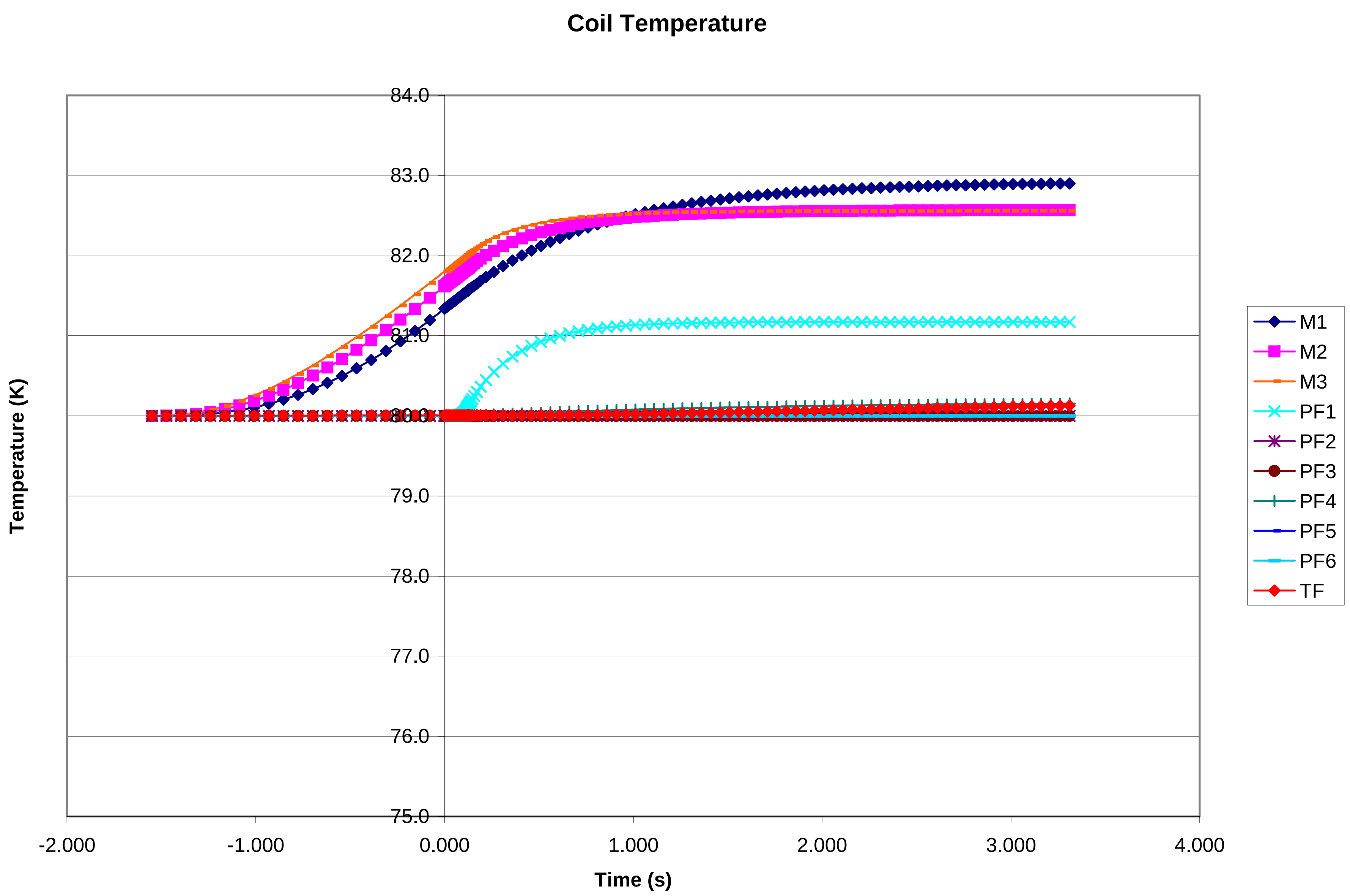


PS Voltage
PS Voltage (V)
800
600
400
200
0
-200
-1.7
-1.6
-1.5
-1.4
-1.3
-1.2
-1.1
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
time (s)
M1
M2
M3
PF1+PF2
PF3
PF4
PF5
PF6
TF


PS Current
PS Current (A)
25000
20000
15000
10000
5000
0
-5000
-1.7
-1.6
-1.5
-1.4
-1.3
-1.2
-1.1
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
time (s)
M1
M2
M3
PF1+PF2
PF3
PF4
PF5
PF6
TF



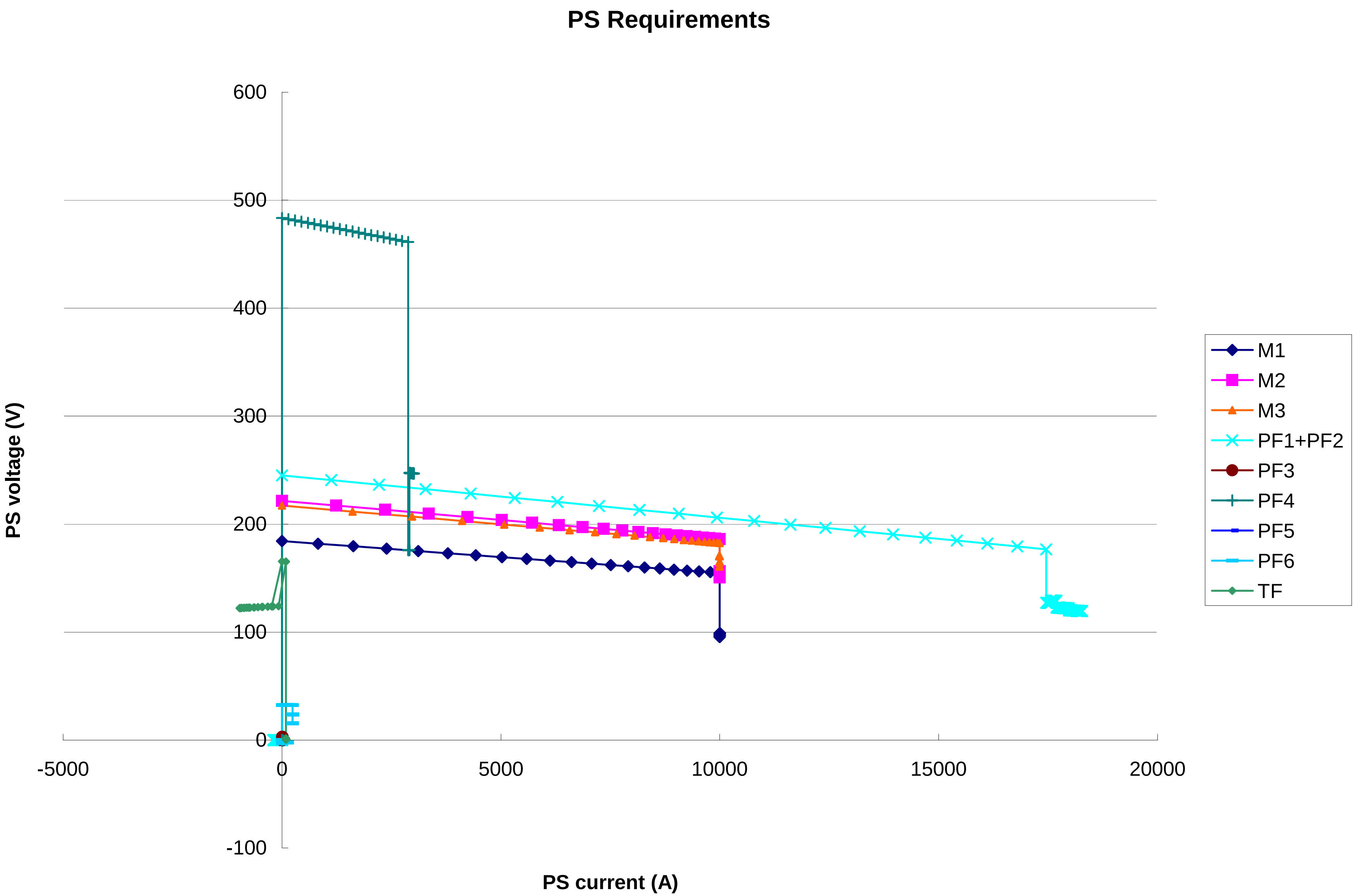
Coil Current
Current (A)
Time (s)
25000
20000
15000
10000
5000
0
-5000
-2.000
-1.000
0.000
1.000
2.000
3.000
4.000
M1
M2
M3
PF1
PF2
PF3
PF4
PF5
PF6
TF
Plasma x 0.1



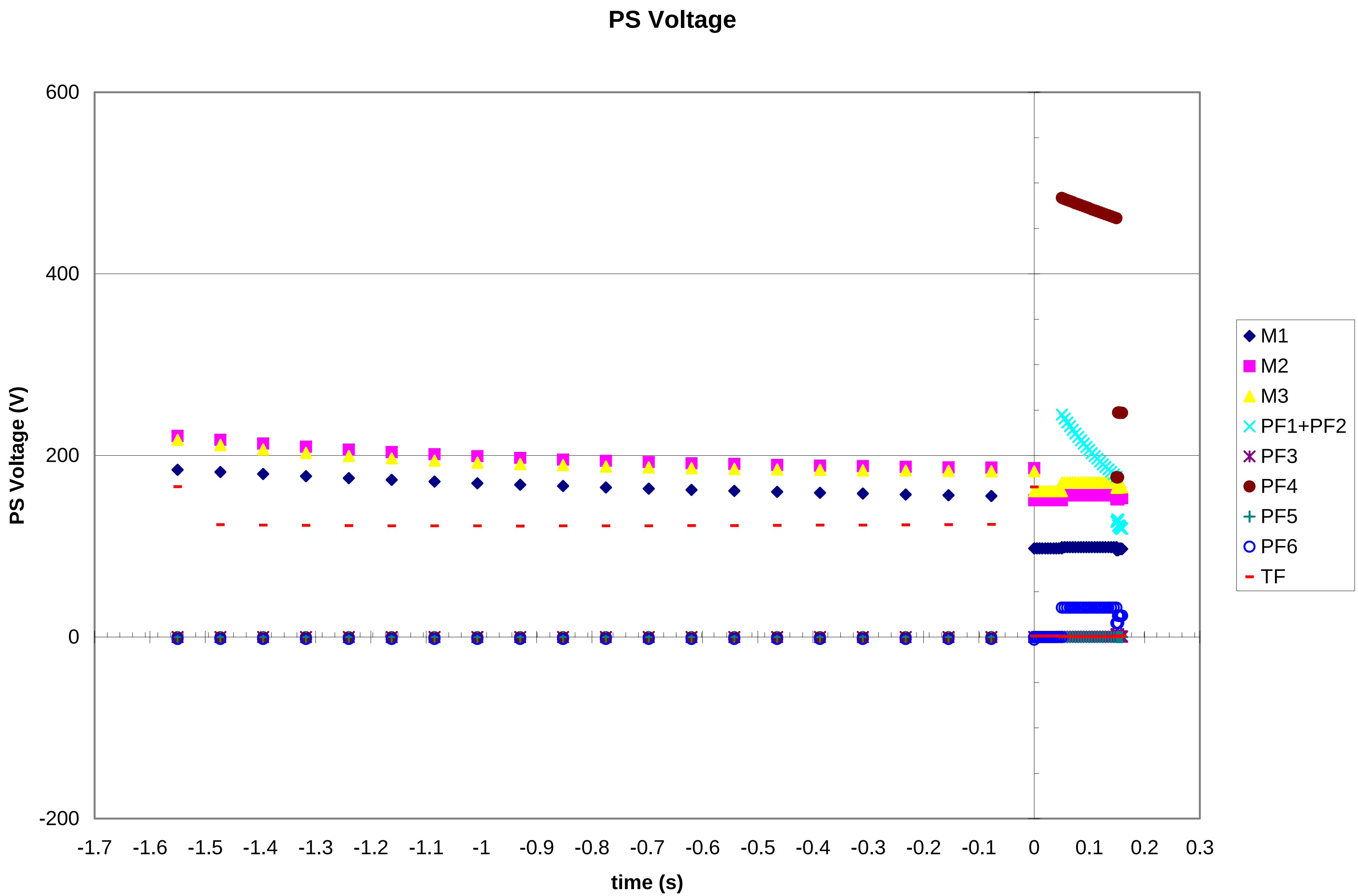
Coil Temperature
Temperature (K)
84.0
83.0
82.0
81.0
80.0
79.0
78.0
77.0
76.0
75.0
-2.000
-1.000
0.000
1.000
2.000
3.000
4.000
Time (s)
M1
M2
M3
PF1
PF2
PF3
PF4
PF5
PF6
TF

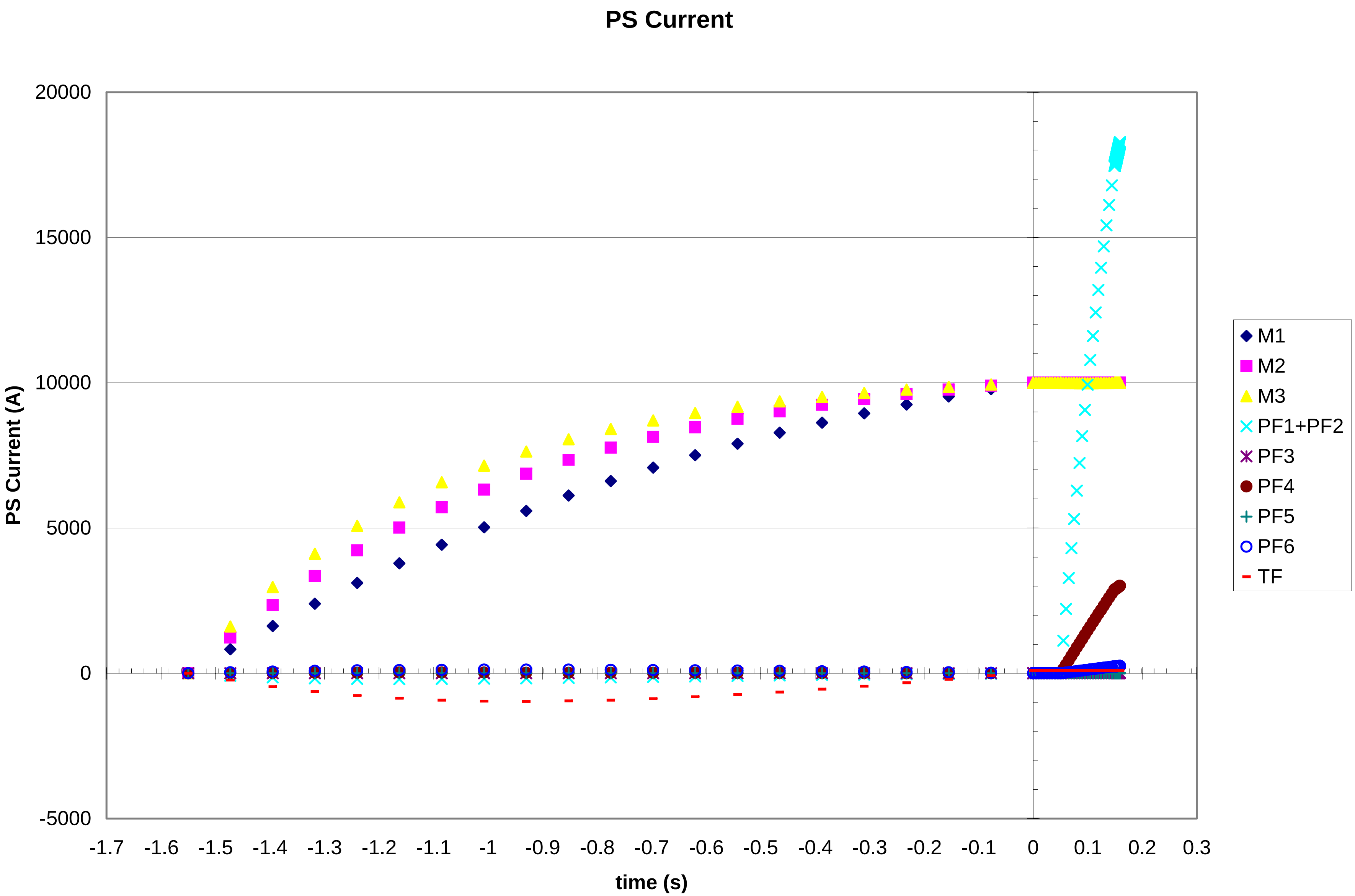
Problems…

- PF4 requires 4kA and 738V compared to the 5kA and 500V available from the UCLA supply
  - Decrease resistive consumption from 1V to 0.6V
  - Increase current ramp time from 70ms to 100ms (solves PF4 problem)
  - Net change in Vs is -0.01 Vs
- PF1/2 requires 21kA and 370V compared to the 5kA and 600V available from 2 Robicon-5 PS in series
  - Move Robicon-10 (10kA and 200V) from PF6 to TF
  - Put all four Robicon-5 units (5kA and 300V) in parallel for PF1/2 creating a 20kA 300V PS
  - Buy a new 50V 300A supply for PF6 (or better yet, get rid of the TF circuit and keep the Robicon-10 for PF6)

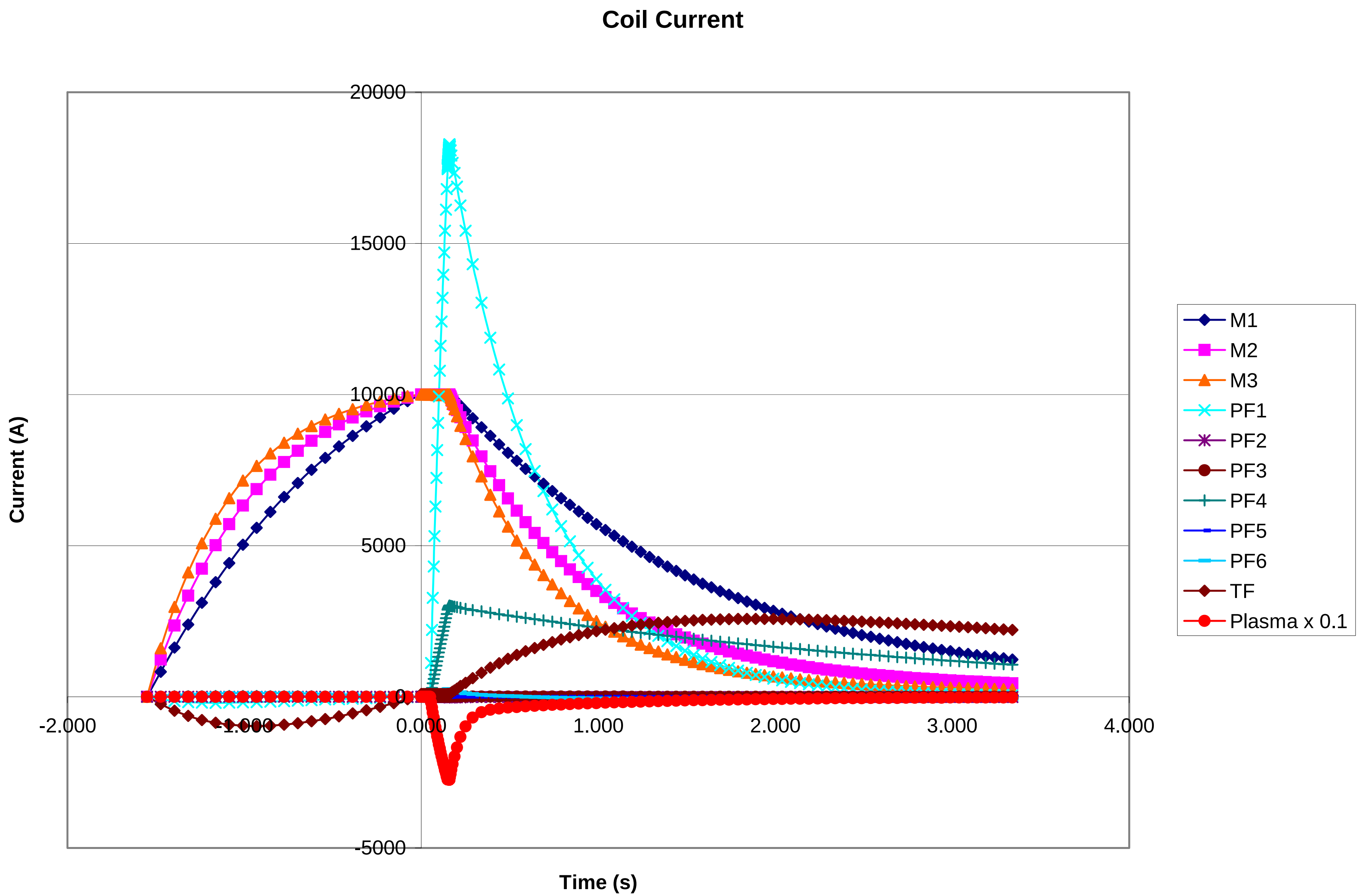


PS Requirements
PS voltage (V)
PS current (A)
600
500
400
300
200
100
0
-100
-5000
0
5000
10000
15000
20000
M1
M2
M3
PF1+PF2
PF3
PF4
PF5
PF6
TF

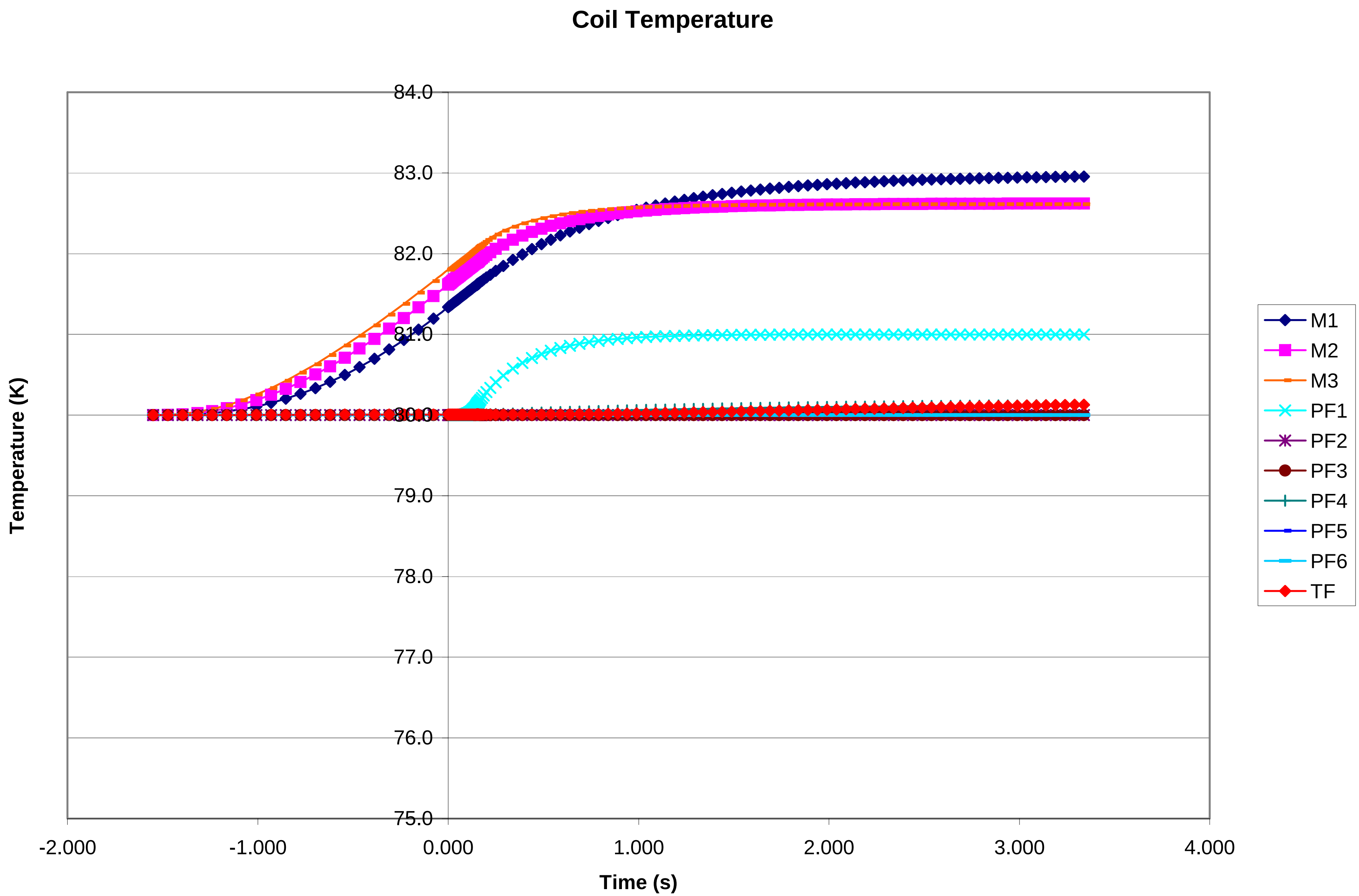

PS Voltage
PS Voltage (V)
600
400
200
0
-200
-1.7
-1.6
-1.5
-1.4
-1.3
-1.2
-1.1
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
time (s)
M1
M2
M3
PF1+PF2
PF3
PF4
PF5
PF6
TF



PS Current
PS Current (A)
20000
15000
10000
5000
0
-5000
-1.7
-1.6
-1.5
-1.4
-1.3
-1.2
-1.1
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
time (s)
M1
M2
M3
PF1+PF2
PF3
PF4
PF5
PF6
TF



Coil Current
20000
15000
10000
5000
0
-5000
-2.000
-1.000
0.000
1.000
2.000
3.000
4.000
Current (A)
Time (s)
M1
M2
M3
PF1
PF2
PF3
PF4
PF5
PF6
TF
Plasma x 0.1


Coil Temperature
Temperature (K)
84.0
83.0
82.0
81.0
80.0
79.0
78.0
77.0
76.0
75.0
-2.000
-1.000
0.000
1.000
2.000
3.000
4.000
Time (s)
M1
M2
M3
PF1
PF2
PF3
PF4
PF5
PF6
TF

Results

- PF1 – max I, V is 18.3kA and 240V compared to 20kA and 300V
- PF4 – max I, V is 3.0kA and 483V compared to 5kA and 500V
- PF6 – max I, V is 253A and 32V which can be provided by 3 car batteries (or by getting rid of the TF circuit and using the Robicon-10)