ENGINEERING CONSIDERATIONS FOR THE FF-1

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1. ABSTRACT

The present document analyses the working of the FF-1 from an external, Electrical Engineering standpoint, in order to examine several engineering aspects of the machine.

After a short description of the FF-1 experiment, the electrical system components are examined and the Electrode Assembly is treated as a Coaxial Transmission Line.

Using available experimental data, the apparent equivalent variable cell resistance due to plasma discharge is computed at 100 nS intervals and from this the operating and residual capacitor bank voltage is found. Finally the expended and the residual energies are found. With this procedure an unique set of resistance values fully defines the apparent variable $R_{(t)}$ of the cell in operation.

The above procedure is obviously a simplification , as the circuit inductance and its effect has not been taken into consideration, but the data found is then used for fully defining FF-1 operation under the effect of system inductance. Again a unique set of resistance values is found, which depends on circuit parameters and on fuel (and its concentration) used.

From all the above, limits to the operation of the FF-1 are found: the lower limit being defined by the total in-circuit inductance and the upper limit being defined by the operating voltage, all other parameters being equal.

In conclusion the procedures presented show ways to FF-1 system improvement in order to reach a reliable and repetitive test bed for Fusion operation.

2. GENERAL

A simplified block diagram for the FF-1 is shown in Figure 1 below.

A capacitor bank charge circuit feeds the capacitor bank, consisting of 12 High Voltage capacitors General Atomics type "C", to a top value of 45 kV. The capacitors are connected, through individual spark discharge switches, to a transmission line feed connected to a special electrode assembly enclosed in a vacuum chamber[1][1].

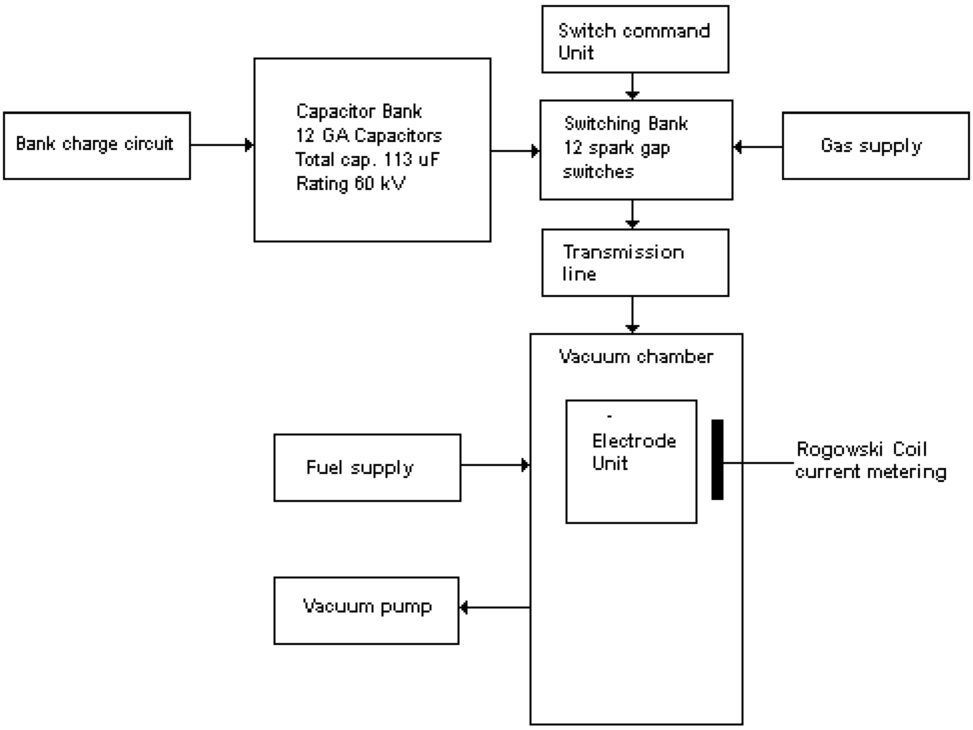

Figure 1 – FF-1 blocks diagram

The intended Plasmoid firing cycle is as follows: (**a**) the charge circuit charges the capacitor bank to a voltage of 45 kV, at an energy level in excess of 110,000 J; (**b**) at the same time the vacuum pump has emptied the chamber; (**c**) gaseous fuel (later to be mixed with Boron) is leaked into the chamber; (**d**) at the same time the gas supply saturating the spark gap switches is in operation; (**e**) the operator fires the switch command unit; (**f**) a command pulse simultaneously fires all 12 switches; (**g**) after a delay of the order of 100 nS, due to the out-circuit (external) inductance and the in-circuit (internal) inductance, plasma forms across the electrodes of the electrode unit and current starts flowing, being monitored by *ad hoc* Rogowski coils; (**h**) current rises for a time depending on fuel type and pressure (density). This time is in the order of 2,000 nS (2 µS); (**k**) currents are in the order of millions of Amperes (1 to over 2 MA) and generate a very strong magnetic field which confines the plasma; (**i**) an energy generating, fuel burning Plasmoid is formed, with a lifetime of approx. 20 nS; (**j**) current falls to zero leaving a residual charge in the capacitor bank.

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1 "Theory and experimental program for p-B^{11} Fusion with Dense Plasma Focus", E.H. Lerner et Al.

FF-1 has been designed as a test bed to achieve Fusion and to learn peculiarities and behaviour of the Plasmoid and as such is not operable as a repetitive machine. It is envisaged that future industrial generators based on DPF principles will operate at repetitive rates of up to 200 Hz, e.g. one Plasmoid cycle every 5 mS.

3. ELECTRICAL SYSTEM COMPONENTS

2.1 CAPACITORS

The Type “C” capacitors[2] forming the capacitor bank have a rated equivalent series inductance of approx. 40 nH and an equivalent series resistance of approx. 10 mΩ (both mainly due to internal wiring).[3,4] Thus the capacitor bank accounts for approx. 4 nH of external inductance and approx. 1 mΩ of external resistance.

Capacitor working life at rated voltage is 10^4 hours, or approx. 1 year. Life is extended by operation at a lower voltage, so the expected life of the capacitor bank (45 kV as compared to 60 kV) is expected to be in the order of 50 years. Another story is with repetitive pulse work, which will reduce useful life to only hundreds of hours, or less.

2.2 SWITCHES

Each R.E. Beverly III spark gap switch[5] is integrally mounted on its companion capacitor (Scyllac style terminals) thus reducing ohmic losses and minimizing series inductance[6]. Typical series resistance is in the order of 1 mΩ and series inductance is typically less than 30 nH per switch. Therefore the entire switching bank accounts for negligible series resistance and for a series inductance of approx. 3 nH.

Again only very low repetition rates are acceptable and useful lifetime is dependent on number of shots, as electrodes are worn out by switching action. The switches also require the continuous flow of purified gas for optimum operation and a purging interval after each shot.

The biggest problem with multiple parallel connected switches is triggering, because it is difficult to have all switches trigger exactly at the same time.

2.3 TRANSMISSION LINE

The transmission line should account for a total series inductance of approx.15 nH[7]. We shall look at this important aspect again later on.

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2 “Series C – High Voltage Energy Storage capacitors”, General Atomics Product Bulletin.
3 “Engineering Bulletin – Capacitors”, General Atomics Product Bulletin.
4 “Progress in the reduction of the inductance in standard 100 kV energy storage capacitors”, R.A. Cooper et Al, 2001.
5 “Specifications for S-G Series Spark Gap Switches”, R.E. Beverly III & Associates, Switch Specifications, 2013.
6 “Application notes 101, 102, 103 & 106”, R.E. Beverly III & Associates.
7 E.J.Lerner et Al. op. cit., page 9.

2.4 ELECTRODE ASSEMBLY

The electrode assembly is shown in Figure 2, below. The hollow anode is mounted on an insulator and has a diameter of 56 mm. The cathode consists of 16 copper rods, placed along a diameter of 100 mm. Tungsten studs are placed at the base of the anode to insure that plasma begins flowing at the base of the assembly.

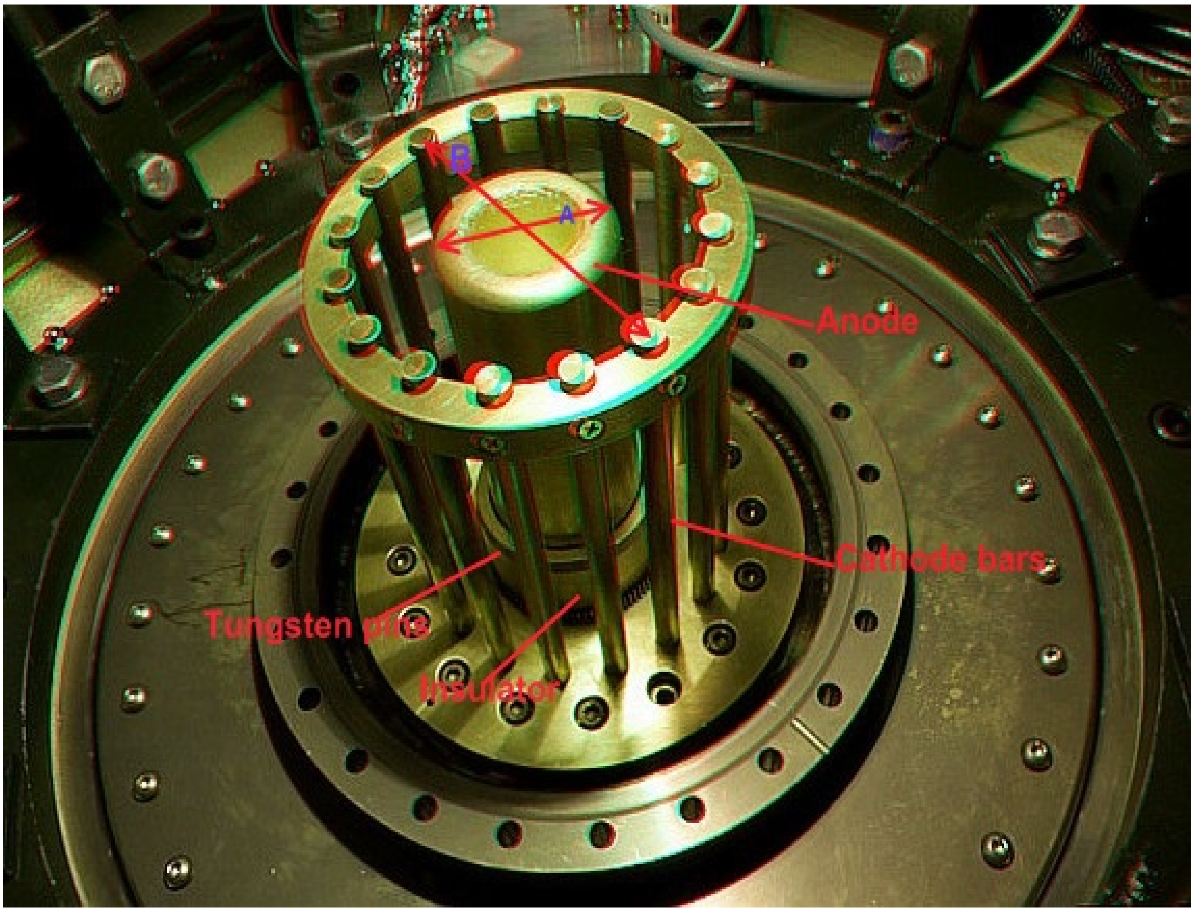


Figure 2 – The electrode assembly

The electrode assembly has the structure of a coaxial line section having a "cold" characteristic impedance Zo which can be approximated by jointly using the formulas of the five-line symmetrical structure and of the cylindrical transmission line. Line parameters are calculated as follows[8].

8 All numerical computations are done on EXCEL file "Basic Electrical 8", enclosed.

With the definitions:
D = B(fig.2) = 100 mm
d = A (fog. 2) = 56 mm
ε_r = 1.3 for compressed H, with diel. constant diminishing for increasing pressure.
$\varepsilon = 8.854*10^{-12}$
$\mu = 1.257*10^{-6}$
l''_a = 140 mm – Cathode assy. maximum length
l'_a = 70mm – Cathode assy. minimum length

Symmetrical five-line $Zo = (173/\varepsilon_r^{1/2})*Log_{10}(D/(0.933*d) = 41.22\ \Omega$
Coaxial line $Zo = (138/\varepsilon_r^{1/2})*Log_{10}(D/d) = 29.37\ \Omega$

Hence characteristic impedance of the electrode assy. should have an in-between value of approx. 32 Ω.

Unit length line capacitance $C'_\Phi = (2*\Pi*\varepsilon*\varepsilon_r)/Ln_e\ (D/d) = 1.247*10^{-10}$ Farad/meter
►Max. line capacitance C_Φ = 17.46 pF
►Min. line capacitance C_Φ = 8.73 pF

Unit length line inductance $L'_\Phi = (\mu o/(2*\Pi))*Ln_e\ (D/d) = 1.145*10^{-6}$ Henry/meter
►Max. line Inductance L_Φ = 16nH ► Corrected L_Φ = 22.50 nH
►Min. line Inductance L_Φ = 8 nH ► Corrected L_Φ = 11.25 nH

For line capacitance and line inductance the coaxial line formulas have been used, so that the calculated values only approximate physical values. Looking at the symmetrical five-line model, we can expect the line capacitance to be less than calculated, while the line inductance will be more than calculated. Using the impedance ratio as a correction parameter, more realistic values are as shown.

4. ANALYSIS OF EXPERIMENTAL CURRENT Vs. TIME DATA

In Ref. 1 experimental data of cell current versus time is given in two different diagrams.

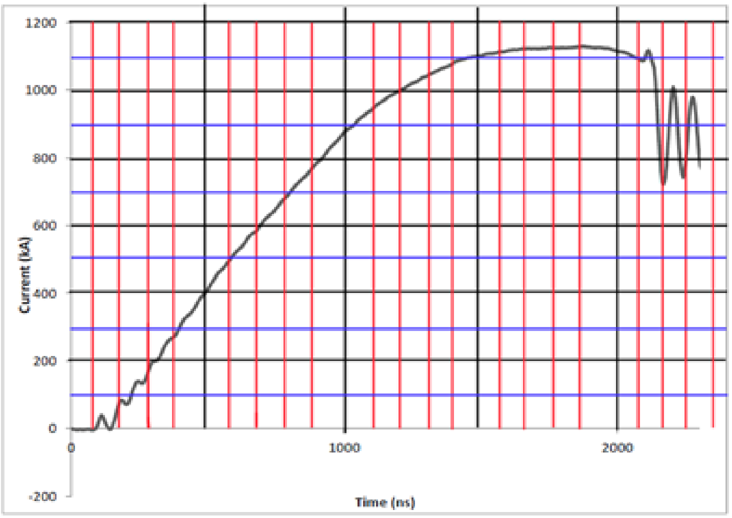


Figure 3 – “Long” current pulse to Pinch

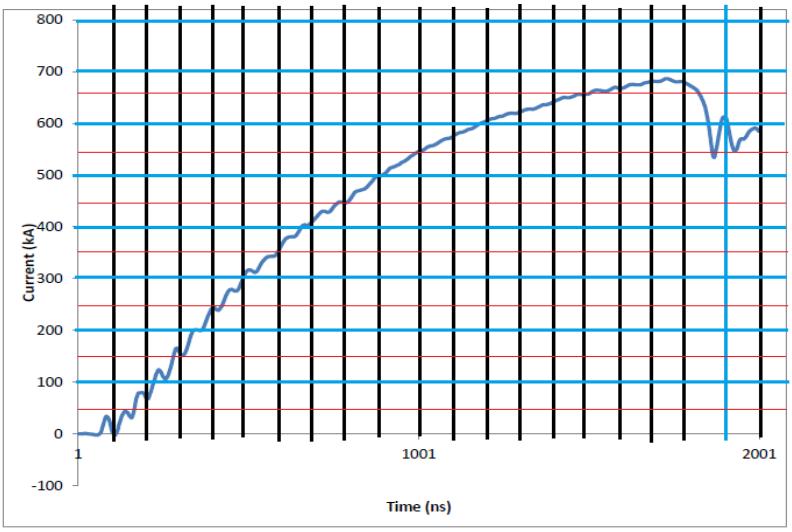


Figure 4 – “Short” current pulse to pinch

With the only assumption that the capacitor bank was initially charged to 45 kV, di/dt data was extracted from the graphs at 100 nS intervals, as described in a previous post[9]. This data illustrates the actual discharge current behaviour of the FF-1 as defined and influenced by all existing electrical parameters. It was later discovered[10] that the “long” pulse of Figure 3 was caused by plasma contamination due to electrode decomposition caused by the high level of energy present, while the“short” pulse represents a condition of sufficiently clean plasma environment.

9 “Work on the FF-1 Electrical Aspecys”, post by the Author on Focus Fusion Society Forum 3/1/2014.
10 “Presentation Script” – LPP presentation10/12/012

The following parameters are of great interest in this experimental data:

- The rate of rise of the current to Pinch;
- the time to Pinch;
- the equivalent load resistance and
- the energy delivered to the electrode assy.

Looking at the LPP-1 machine as a two terminal load fed by a capacitor bank, it must be understood that the current is **increasing** while, at the same time, the feed voltage is **diminishing**. In fact the capacitor bank has been supplied with fixed amount of energy that is being dissipated into the load and therefore the voltage is gradually falling.

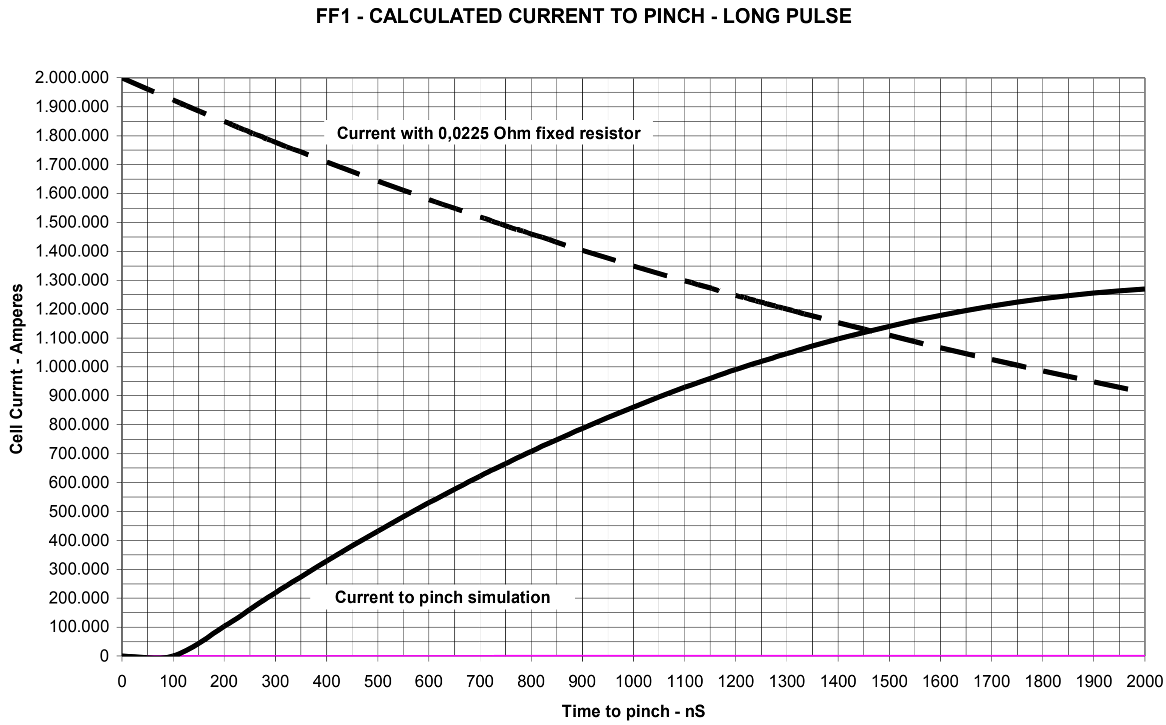


Figure 5 – "Long" current pulse to Pinch math simulation

The data of Figure 3 is approximated by the expression:

$I = -0{,}0003t^2 + 1{,}3082t - 146{,}62$

This expression is used to smooth out possible small errors in evaluating the curve of Figure 3 and is used to calculate current at intervals of 100 nS in Sheet 3, column B. Therefore it is the experiment itself that tells us that prior to Pinch, in that particular instance, the current out of the capacitor bank was 100 kA after 200 nS and 1.2 MA after 2100 nS. The dashed line curve shows the behaviour of the current with the bank discharging into a **fixed** resistor of 0.0225 Ω.

3.1 THE CASE FOR THE EQUIVALENT APPARENT RESISTANCE ONLY

What is happening here is that, to have the current **increasing** with a **falling** voltage we must have a complex load which can be represented by a fixed inductance in series with a variable resistance **decreasing** with time until Pinch. Considering initially the equivalent resistance (X_l+$R_{(t)}$) and current values every 100 nS, we can compute the residual voltage as follows:

$V_{(t)} = V_{(t-1)} * EXP((-dt)/(C * R(t-1))$

In other words we approximate the voltage level at the beginning of every 100 nS time period. Next the resistance value for the next Voltage/Current combination is computed, and so on[11]. Figures 6 & 7 show voltage and resistance variations to Pinch.

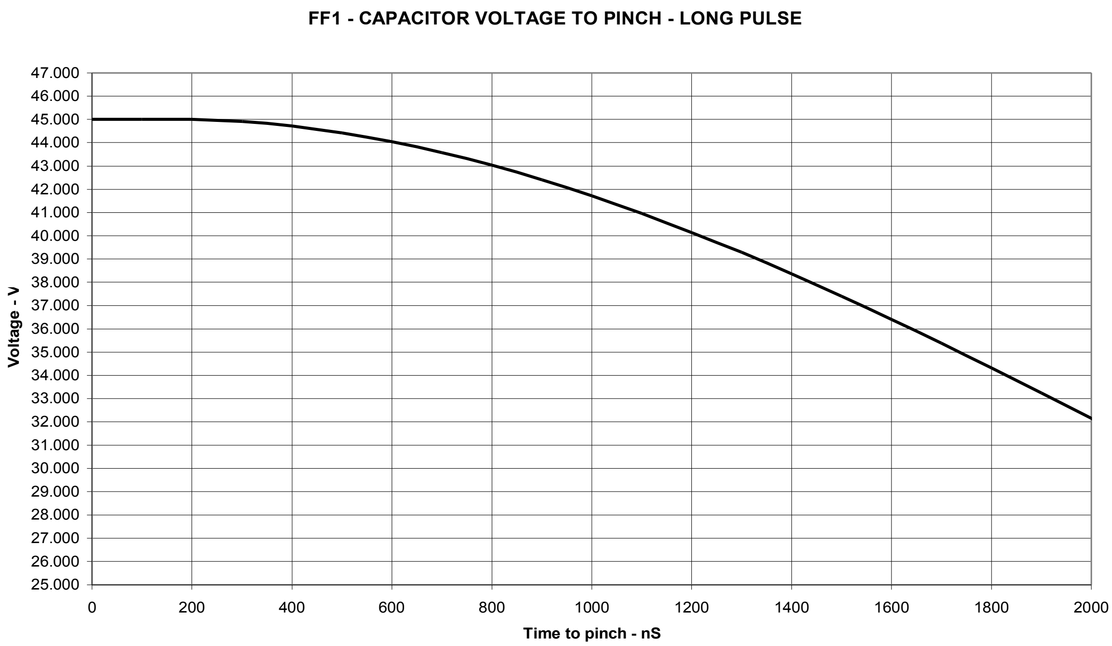


Figure 6 – Voltage variation across electrode assy. input

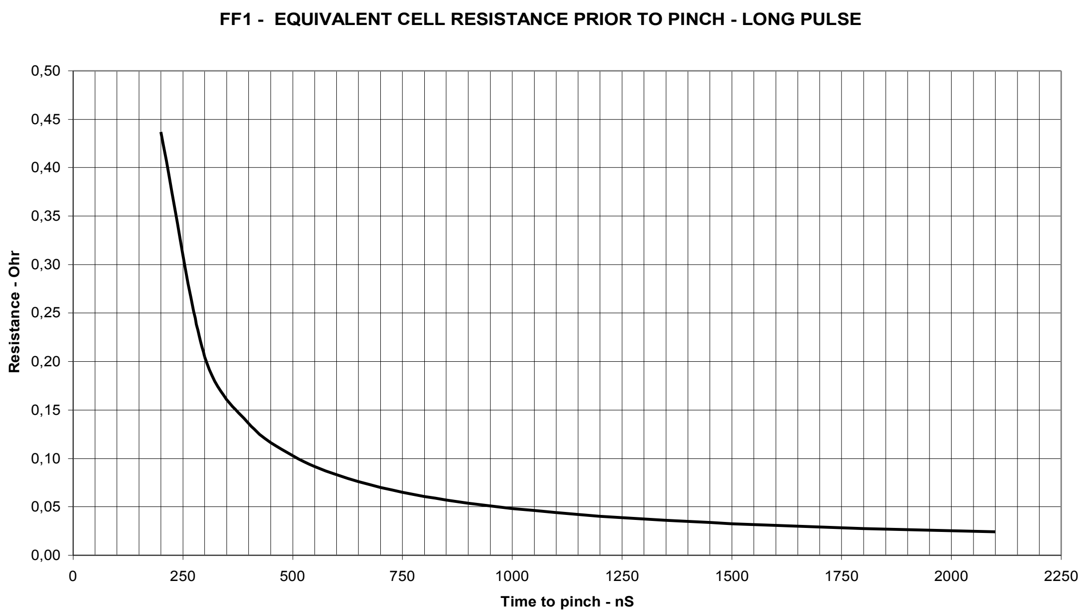


Figure 7 – Apparent equivalent cell resistance variation

11 See Note 8 page 3.

We can see at once that, in the time to Pinch, bank voltage had decreased from 45 kV to 32 kV approx., thus a significant amount of energy has not been used by the cell, as shown in Figure 8.

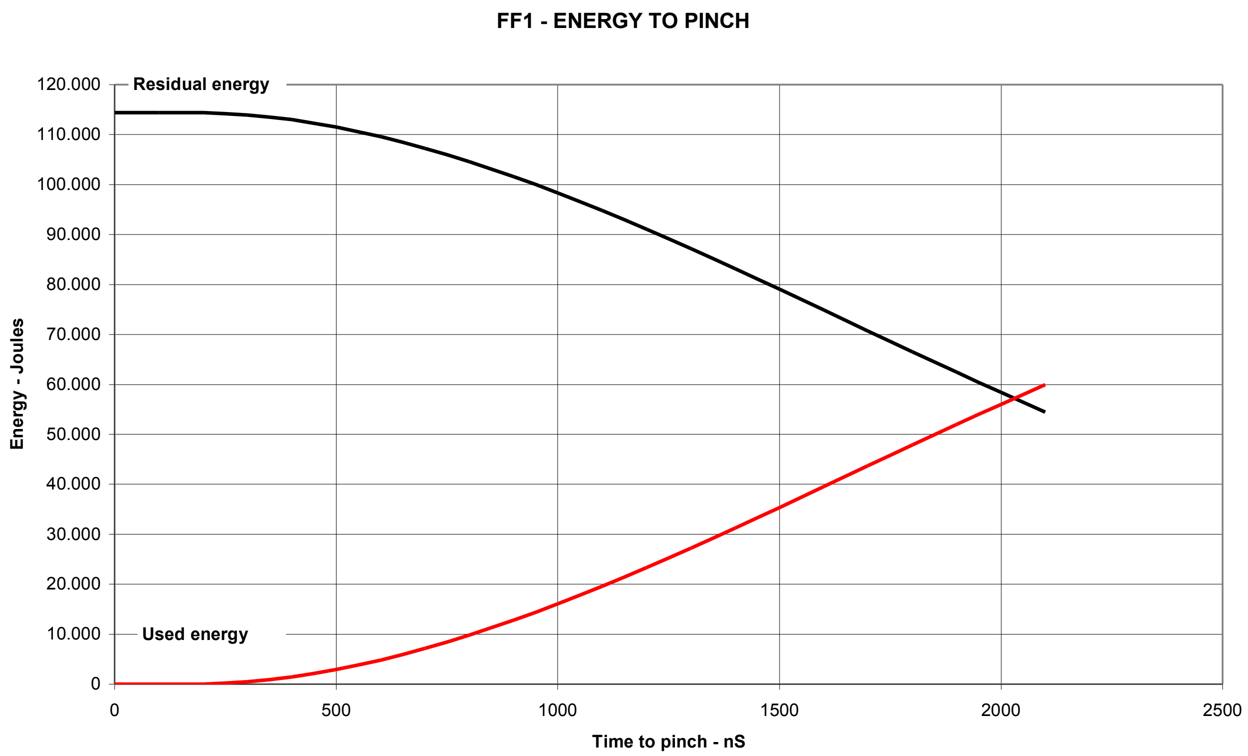


Figure 8 – Used energy and residual energy in capacitor bank

3.2 THE CASE FOR THE REAL SYSTEM: L + $R_{(t)}$

The mechanism described in the previous paragraph is a simplification. Furthermore we have no quantitative data on the parameter, or combination of parameters, which limit(s) current flow. As we have seen in 2.4, depending on length, the electrode assy. can have an inductance of 22.5 to 11.25 nH. Moreover we have seen from previous considerations that the series inductance of the capacitor bank amounts to 4 nH and that of the switch bank to 3 nH. The system inductance, excluding the connecting line, has a value of between 29.5 to 18.25 nH. Reference 1, page 7, guesses total system inductance at 45 nH. Therefore connection inductance is estimated at 15 nH.

By numerically solving the equation for the inductor's transient current,

$I_{(t)} = V_b/R_{(t)}* (1 – EXP((R(_t)/L)*t$

it is possible to find the exact value of $R_{(t)}$ at each 100 nS time interval for any value of system series inductance L. It then becomes possible to determine how critical this parameter is in obstructing system current flow. This computation has been done[12] for L = 40 nH and the result for L is shown in Figure 9. The experimental plot of Figure3 is the result of all the system design parameters, of the variable resistance shown above and of a total system inductance L = 40 nH.

12 See note 8, page 3.

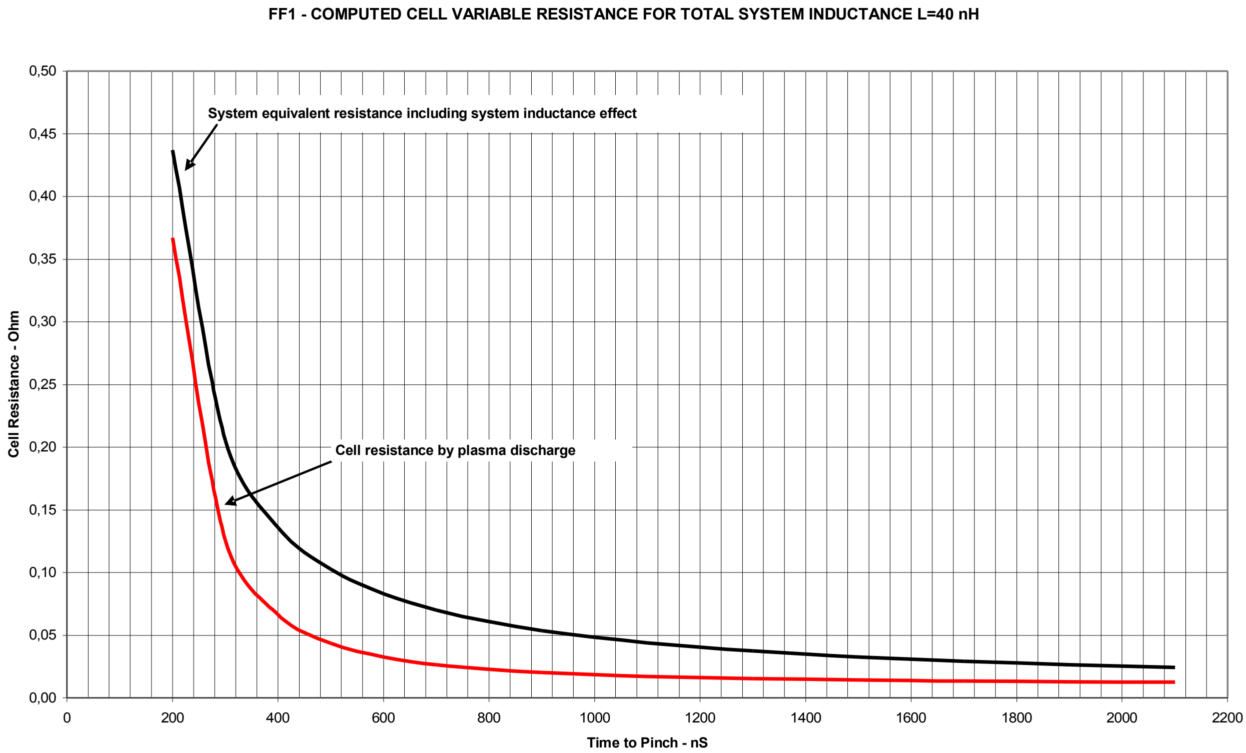


Figure 9 – Cell variable resistance compared with system apparent variable resistance

With these parameters current reaches a value of 1,200 kA after 1,500 nS and it is limited to this value, this value being good enough to start Pinch after approx. another 500 nS. Conversely, with the plot of Figure 4 the current starts limiting at below 700 kA.

Table 1 in the next page shows the original condition of L=40 nH ((blue) and a modified condition with L=30 nH (orange).

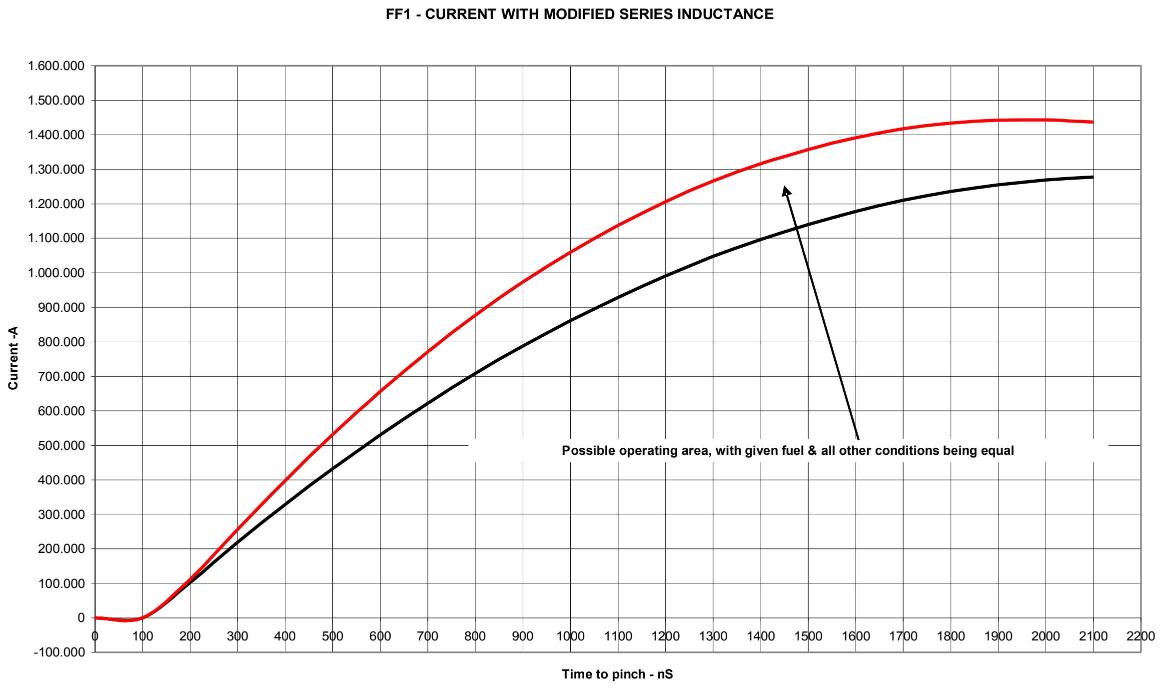
- Time nS
- Cell current as calculated from data taken from Figure 3.
- Rx: computed variable resistance.
- Spc. I: computed cell current from Rx and L = 40 nH.
- R: apparent equivalent resistance as described in 3.1.
- Cell current is limited to 1277 kA.

- Time nS
- Cell current increased by inductance reduction by 10 nH
- Rx: computed new variable resistance.
- Spc. I: computed cell current from Rx and L = 30 nH.
- R: new apparent equivalent resistance as described in 3.1.
- Cell current is limited to 1443 kA.

Table 1

t	I	Rx	Spc. I	R	Voltage	t	I	Rx	Spc. I	R	Voltage
uS	A	OHM	A	OHM	V	uS	A	OHM	A	OHM	V
			4,0E-08						3,0E-08		
0	0,00		0,00	Infinity	45.000	0	0,00		0,00	Infinity	45.000
100	0,00		0,00	Infinity	45.000	100	0,00		0,00	Infinity	45.000
200	103.020,00	0,3670	103.044,67	0,43681	45.000	200	111.999,52	0,3670	111.999,52	0,40179	45.000
300	218.840,00	0,1256	218.605,64	0,20521	44.909	300	256.245,29	0,1256	256.245,29	0,17523	44.901
400	328.660,00	0,0665	328.687,09	0,13605	44.716	400	397.876,54	0,0665	397.876,54	0,11228	44.675
500	432.480,00	0,0438	432.280,19	0,10272	44.426	500	531.114,19	0,0438	531.114,19	0,08345	44.324
600	530.300,00	0,0326	530.498,94	0,08306	44.045	600	656.414,34	0,0326	656.414,34	0,06681	43.857
700	622.120,00	0,0265	622.093,64	0,07005	43.578	700	771.336,43	0,0265	771.336,43	0,05611	43.279
800	707.940,00	0,0227	707.981,58	0,06078	43.031	800	877.233,62	0,0227	877.233,62	0,04856	42.602
900	787.760,00	0,0202	787.928,64	0,05383	42.409	900	973.727,07	0,0202	973.727,07	0,04296	41.833
1000	861.580,00	0,0185	861.296,64	0,04842	41.717	1000	1.059.896,36	0,0185	1.059.896,36	0,03866	40.980
1100	929.400,00	0,0172	929.222,04	0,04407	40.962	1100	1.137.669,52	0,0172	1.137.669,52	0,03521	40.053
1200	991.220,00	0,0162	991.221,67	0,04050	40.148	1200	1.206.405,33	0,0162	1.206.405,33	0,03238	39.059
1300	1.047.040,00	0,0154	1.047.380,66	0,03752	39.280	1300	1.266.408,51	0,0154	1.266.408,51	0,03001	38.005
1400	1.096.860,00	0,0148	1.096.705,59	0,03498	38.364	1400	1.316.267,36	0,0148	1.316.267,36	0,02803	36.901
1500	1.140.680,00	0,0143	1.140.113,25	0,03279	37.406	1500	1.357.583,16	0,0143	1.357.583,16	0,02634	35.754
1600	1.178.500,00	0,0139	1.178.219,31	0,03089	36.410	1600	1.391.446,53	0,0139	1.391.446,53	0,02485	34.573
1700	1.210.320,00	0,0135	1.210.634,71	0,02923	35.382	1700	1.417.451,02	0,0135	1.417.451,02	0,02354	33.363
1800	1.236.140,00	0,0132	1.236.161,13	0,02777	34.327	1800	1.433.965,09	0,0132	1.433.965,09	0,02241	32.132
1900	1.255.960,00	0,0129	1.255.500,08	0,02647	33.250	1900	1.442.206,05	0,0129	1.442.206,05	0,02142	30.888
2000	1.269.780,00	0,0127	1.269.534,03	0,02532	32.157	2000	1.443.630,84	0,0127	1.443.630,84	0,02053	29.638
2100	1.277.600,00	0,0126	1.277.016,28	0,02431	31.053	2100	1.436.643,37	0,0126	1.436.643,37	0,01976	28.387

It must be noted that reducing series inductance, with the plasma resistance considered here and derived from data in Figure 3, at 2100 nS bank voltage is decreased to the point that current begins to fall. Therefore the FF-1 system, at least with the fuel used for the data of reference 1, seems to be imprisoned in a balanced situation: if system inductance is kept at 40 nH the current is limited to approx. 1.3 MA, if inductance is decreased to 30 nH, then current is limited to approx. 1.4 MA because starting bank voltage is too low. This situation is shown is shown in Figure 10 (TOP). A straightforward way to increase operating current, all other parameters being equal, is to increase operating voltage, as shown in Figure 10 (BOTTOM).



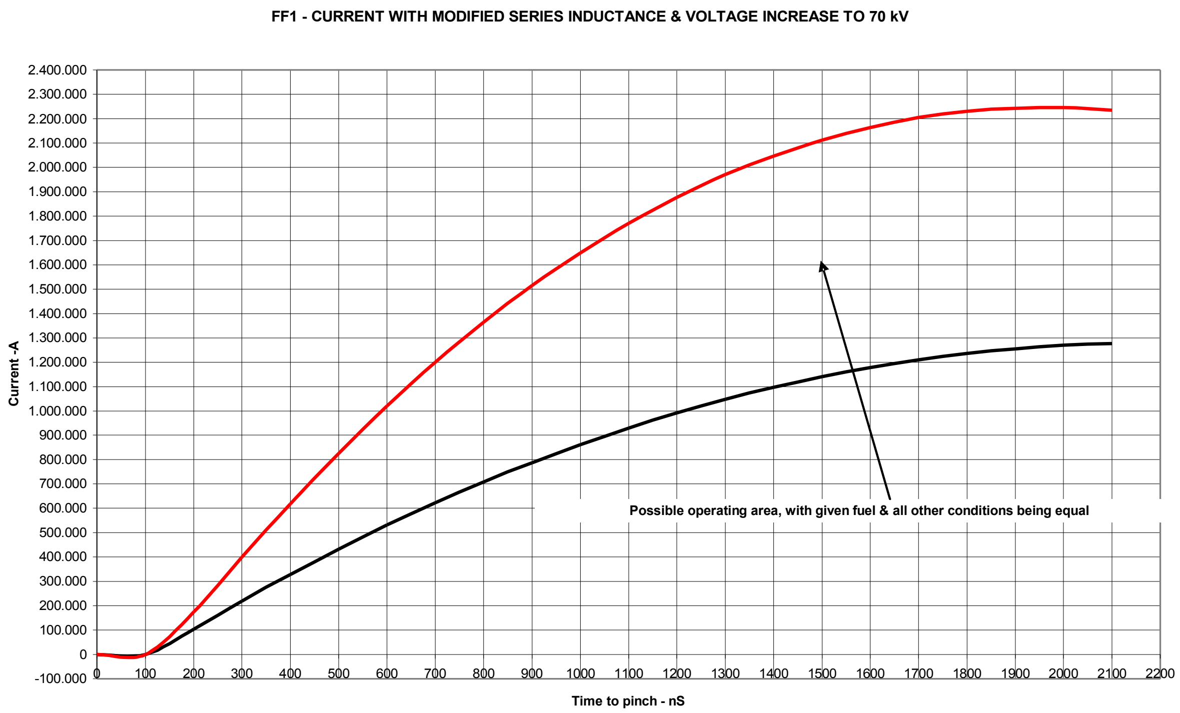


Figure 10 – Limits in current performance

5. THE FF-1 EQUIVALENT ELECTRICAL CIRCUIT

The simplified electrical circuit of the FF-1 is shown in Figure 11 below.

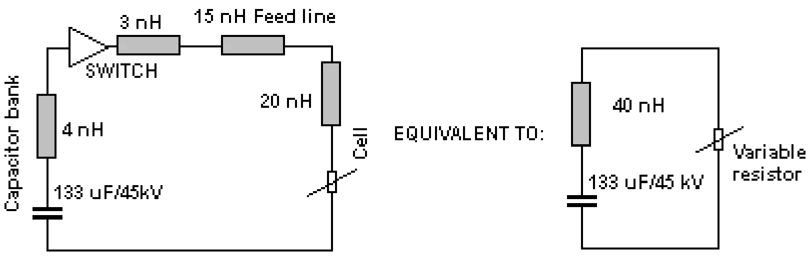


FIGURE 11 – Equivalent electrical circuit

Shown above is a classic resonant circuit, which can be underdamped, critical or overdamped, depending on the value of the circuit components. The value of the variable resistance, caused by plasma discharge, changes the state of the circuit from switch on to Pinch. In fact at switch-on resistance is at infinity and the circuit is certainly unerdamped, then the load resistance starts dropping, until a critical condition will be reached. Past this condition the resistance will drop more to a very low value (current peak) and the circuit will become overdamped.

The radian frequency $\omega_o = 1/(L*C)^{1/2} = 470{,}360$ rad/sec
The resonant frequency $F_o = \omega_o /(2*\Pi) = 75{,}000$ Hz
The period $T_o = 1/F_o = 13{,}36$ uS
The critical load $Rc = 2*(L/C)^{1/2} = 0.0377\ \Omega$

Looking at table 1, the equivalent circuit is underdamped all the way to 500 nS and becomes overdamped above 600 nS.

The “wobble” shown in the current plot of Figure 4 has no relation to the above, but looks like a parasitic system oscillation at approx. 20 Mhz.

6. CONCLUSION

According to published experimental data, it seems that improvements in fuel fusion performance could be obtained by reducing distributed system inductance, by increasing supply voltage, by increasing capacitor bank capacitance and by modification of the electrode assy, dimensions in order to achieve a lower characteristic impedance. All these questions may be examined in a subsequent paper.