

The Historical Development of HIPIMS Power Supplies: From Laboratory To Production

D. Ochs, Hüttinger Elektronik GmbH, Freiburg, Germany;
P. Ozimek, Huettinger Electronic Sp. z.O.O., Zielonka, Poland;
A. Ehasarian, Sheffield Hallam University, Sheffield, United Kingdom; and
R. Spencer, Alacritas Consultancy Ltd., Markfield, United Kingdom

ABSTRACT

This paper describes the development of HIPIMS power supplies from their earliest inception in Russia, described in 1974, to the present day. The work started in high-current glow discharges and moved to magnetron discharges in the 1980s. Various HIPIMS power supplies are described. In the earliest case we have a motor generator-charged capacitor bank with vacuum discharge tube switches to start and to end the pulse. Discharges with voltages up to 2-5 kV, currents up to 24 kA and pulse durations of up to 660 microseconds are described in these early results.

By the 1990s Kouznetsov had built a thyristor based unit, giving 2kV/0.8kA and a fixed frequency of 50 Hz. Christie et al describe an experimental unit with 3kV/3kA capability and frequency of 500 Hz. The first 19-inch rack HIPIMS unit was developed by Bugyi et al, in cooperation with Sheffield Hallam University in 2003. These HIPIMS supplies had 2kV/3kA capability and repetition frequency up to 500 Hz. It had a fast active arc suppression and was tested in production environment. In the latest units discharges with voltages up to 3kV/6kA and repetition frequency up to 1 kHz are described. Now various power supply configurations with voltages of 1-3kV and currents of 1-6kA have been realized in order to meet the process needs of numerous applications.

BACKGROUND

High Power Impulse Sputtering (HIPIMS or HPPMS) is a new sputter deposition technique that is causing much excitement due to the high ionization percentages it can produce in the sputter flux from standard magnetrons. Pulses of many MW lasting 100 microseconds or so are applied in a HIPIMS plasma. The high density plasma this causes leads to the high ionization that is of such interest. Such power supplies are non-trivial, and have to deal with current pulses of many kA. So where however did this technology of high power plasma pulses come from? This paper attempts to answer this question.

Helmersson et al [1]. detail the work of the last decade or so, however there was work done in Russia for the previous two decades or more. This relatively unknown Russian work is hard to obtain. So a full history is almost impossible to re-create. We have papers several years apart, by different authors.

We've attempted here to draw a coherent line through this, and link it to the more recent, better known work.

HISTORY

In 1974 O.A. Malkin [2], from the Moscow Engineering and Physics Institute, published "Pulsed current and gas relaxation" covering experiments carried out between 1968 and 1972, at the Institute in the department of E.S. Trekhov. The aim of research was not sputter deposition but light sources, lasers, spark erosion, and welding.

Their Plasmas were glow discharges (no applied magnetic field), and they ran these at very high current densities (up to 24kA into a 20 – 60mm diameter electrode). At such high current densities it would be normal for the plasma to collapse to an arc. However they found that this collapse to an arc took some time, and so their high current plasma could be maintained for some 100s of microseconds. They therefore termed these high current glow discharges as quasi-stationary discharges. Quasi-stationary discharge in that if maintained indefinitely the plasma will collapse to an Arc.

Malkin detailed two ways that the power supply for the plasma pulse can be designed. The first was a 'passive' design using an LC network, the second was a capacitor bank with switched output. They preferred the switched capacitor bank as the LC network had several disadvantages, namely:

- the values of L and C must be changed with the plasma characteristics (for example when changing the gas pressure).
- the pulse shape is poor
- for a high current pulse very high values of L are needed
- the switch off is very slow, i.e., the end of pulse is not well defined.

So they used a switched capacitor bank. The main features of this were:

- thyrotron switches (on only)
- switch plasma on with an on switch
- switch plasma off by closing an off switch to shunt the stored energy away from the plasma

To power the capacitor bank they used an engine or motor driven generator.

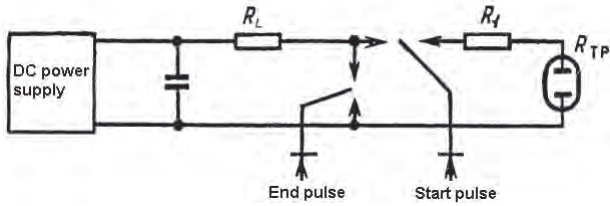


Figure 1: Pulsed power supply design published by Malkin.

One key difference with modern HIPIMS practice was that they used a short radio frequency pulse to start the plasma and pre-ionize the gas just before the current pulse.

An example of the resulting pulses, is shown below. In this instance they had currents of 12,000 to 16,000 Amps, and a voltage of 900V. The pulse power was therefore around $14000 \times 900 = 12.6 \text{ MW}$. They describe other pulses ranging from durations of 660 microseconds, at 2kA, to 50 microsecond at 24 kA.

The plasma created during the pulse shown in Figure 2 was highly dense. Malkin quotes $n_e = 10^{18} / \text{cm}^3$. Note that there is some anomaly, or unexplained behaviour, here as these plasma densities are higher than the gas density at these pressures [3]. N^+ and N^{2+} were seen in the emission spectra. These features are similar to those found in a HIPIMS plasma. Gas temperature of 38,000K was calculated from Boltzmann plots of intensity versus excitation energy of various emission lines.

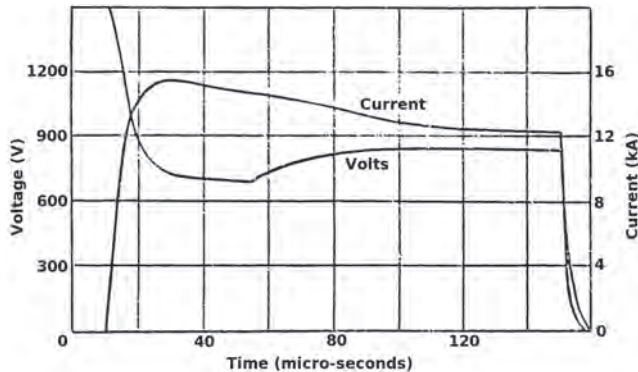


Figure 2: High Power Pulse into N_2 plasma at 1 Torr, as shown by Malkin.

These 13MW pulses were into a 20 – 60mm electrode, this is an incredibly high power density of 650 kW/cm^2 , that has never been approached since. This created plasmas so intense that their quartz chamber were strongly eroded by discharge and had to be regularly replaced. In comparison a modern HIPIMS plasma using 13MW pulses would probably be used on a magnetron of 1m or so length.

Makin doesn't give any details of the pulse repetition rate that could be achieved with their system.

INTRODUCING MAGNETIC CONFINEMENT

By 1981 Tyuryukanov et al [4], still working at the same Moscow institute had introduced a magnetic confinement to a similar pulsed discharge and investigated a magnetron like discharge (crossed electric and magnetic fields, circular racetrack). They used a 50mm diameter racetrack, and pulses of 120A (400V = 50kW), i.e., 2.5 kW/cm^2 . Their pulses were as long as 1 millisecond. Tyuryukanov investigated the plasma itself, the effects of magnetic field strength, and so on, however they still didn't use their system for depositing any coatings. They don't describe any details of their power supply either (pulse forming method, powers, pulse repetition rate, etc.,).

FIRST HIPIMS COATING DEPOSITION

In 1993 Mozgrin et al [5], still working at the same Moscow institute, published work describing the first coating deposition from these systems. They used a simple LC chain pulse supply driving a planar magnetron. They were still pre-igniting the plasma, this time using a 300mA 'static' plasma that was permanently present between pulses.

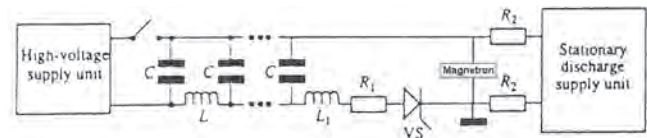


Figure 3: The LC chain power supply of Mozgrin et al.

In addition to the expected initial 'static' plasma, and the end point arc state, they identify two intermediate pulsed plasma states. They had a higher voltage 'magnetron mode' (i.e., our present day HIPIMS plasmas), and also a lower voltage 'diffuse plasma' mode.

In the higher voltage 'magnetron mode' pulsed plasmas they put 200 kW (200A) into a 120mm target (1.8 kW/cm^2). They also had the capability for very long pulses of upto 1.5 milliseconds, however the repetition rate of the pulses was only 10 Hz. They measured the plasma density in these pulses as $n_e = 10^{13} \text{ cm}^{-3}$.

Most importantly Mozgrin et al did use their system for sputter deposition of various materials (Cu, Ti, Mo, and Stainless Steel).

FIRST WESTERN PUBLICATIONS

The first publications in western Journals were in 1999 by Fetisov et al [6], and by independantly by Kouznetsov [7]. Fetisov was an author on the Tyuryukanov [4] paper from 1981, and also on the Mozgrin [5] paper of 1993, so there is a clear continuity here.

In their paper Fetisov et al discuss HIPIMS deposited Cu, Mo, Ti, Al, & Stainless Steel, oxides and nitrides. They don't give much detail on the film properties of these materials. They used Pulse durations up to 1.5ms, and powers of 200kW into a 120mm magnetron ($= 1.8 \text{ kW/cm}^2$). They identified key HIPIMS features as low heat load, better target utilization and lifetime, and high ionization of sputter flux. They describe in some detail HIPIMS coating of polymers.

No circuit diagram of power supply given, but it is described as a storage line with 5.5kJ accumulated energy, a high power switch, and a matching system. This is first mention of a matching system, but it is not clear what this was. They were also using a 'stationary discharge to pre-ignite the plasma. Fetisov also details the plasma regions, previously discussed by Mozgrin, that they identify in their pulses. Of most interest is a diffuse plasma region. This does not appear in more recent HIPIMS work.

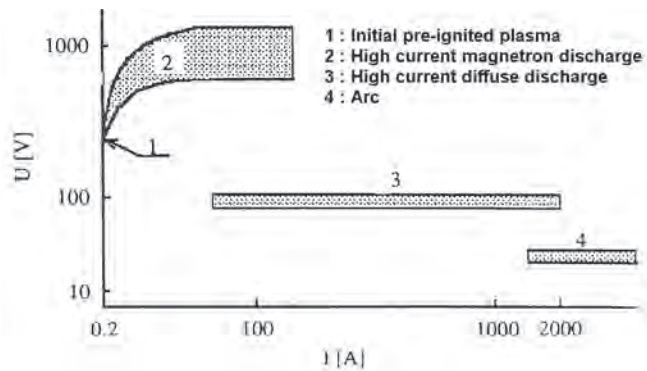


Figure 4: Pulse plasma regions identified by Fetisov [6].

Kouznetsov [7] removed the pre-pulse ignition plasma, their plasma was ignited every pulse, so that the current rise started about 50 microseconds after the voltage was applied. They put 500kW pulses into 150mm target (2.8 kW/cm^2). They sputtered Cu and demonstrated the ionization of the sputter flux and used this for directional deposition for improved trench filling.

Their power supply consisted of a storage capacitor, and high power switch, with an inductor for pulse shaping [8]. The pulse frequency was 50 Hz.

INDUSTRIAL SIZED POWER SUPPLIES

The previous works above had demonstrated pulse power densities of $1 - 3 \text{ kW/cm}^2$. If we want to use this on an industrial scale, the magnetrons are likely to be linear and have much larger areas than previously demonstrated. For example 1m magnetron would be around 100 - 150mm wide, this is an area of 1000 cm^2 , to get our typical 2 kW/cm^2 we therefore need pulses of 2 MW.

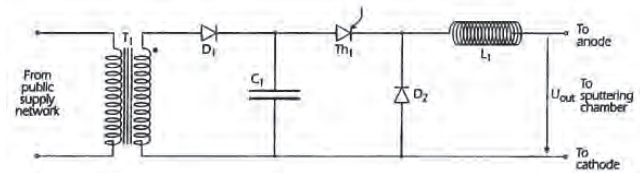


Figure 5: The power supply used by Kouznetsov [8].

In 2002 Ehiasarian [9] demonstrated the first use on linear magnetrons of 400 cm^2 area and by 2004 [10] had increased this to 1200 cm^2 . These supplies gave pulses of upto 6MW, had arc suppression and a pulse repetition rate of 100 Hz.

Even though arcs in theory take time to develop (thus allowing the short HIPIMS pulse at current densities that would not be stable as a DC plasma), arcs do still occur in HIPIMS plasmas. Ehiasarian and Bugyi [10] report arc detection as the current rises beyond a preset point. Once the arc is detected the applied power is cut and only the stored energy in the cables and matching network delivered to the Arc, quenched it in 100 microseconds or so.

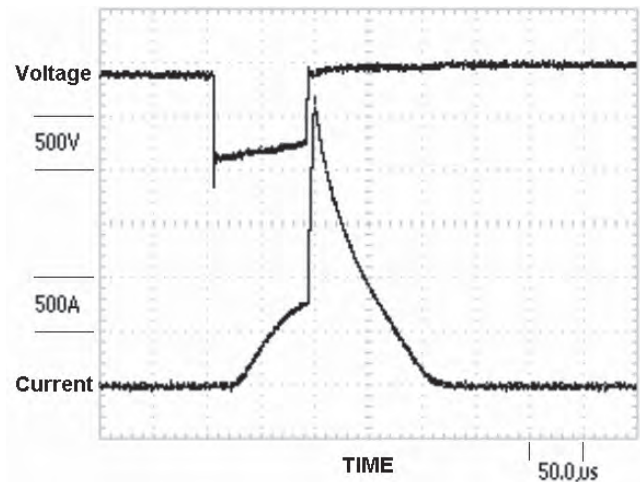


Figure 6: An arc in a HIPIMS pulse.

Simultaneously in 2004 Christie et al. [11] report a power supply capable of peak powers of up to 3 MW frequencies of 500 Hz, and having arc handling.

Key power supply features such as the maximum pulse power and pulse frequency show a strong trend of improvement over the last decade.

We now have HIPIMS supplies capable of driving large area sputter targets at $1 - 3 \text{ kW/cm}^2$. These have been in use in commercially available HIPIMS sputter systems since about 2006. These are predominantly in hard coatings where the ability to make dense coatings and engineer the coating/substrate interface has produced significant benefits [1]. Now that industrial HIPIMS supplies are commercially available, it will

Table 1: Timeline of HIPIMS development.

Date	Author	Key Features
1968 – 72, published 1974	O.A. Malkin	<ul style="list-style-type: none"> • 13 MW pulses, 120 μs duration • multiple ionization seen • N₂ plasma, 1 Torr • 20 – 60mm diameter parallel plate • no magnetic field (hence high pressure) • not for coating deposition
1981	Tyuryukanov	<ul style="list-style-type: none"> • magnetic field introduced • circular magnetron type plasma • Ar Plasma, 0.7 Pa pressure • 48 kW (120A) into 50mm diameter magnetron • not for coating deposition
1993	Mozgrin	<ul style="list-style-type: none"> • Planar magnetrons used for HIPIMS sputter deposition • Cu, Mo, Ti, Al, & Stainless Steel deposited • 200 kW (200A) into 120mm target
1999	Fetisov	<ul style="list-style-type: none"> • Continuation of Mozgrin work. • Deposition of Oxides and Nitrides
1999	Kouznetsov	<ul style="list-style-type: none"> • Removed pre-ignition plasma • Popularization in the west
2001	Kouznetsov	<ul style="list-style-type: none"> • first patent
2002	Ehiasarian	<ul style="list-style-type: none"> • First upscaling to linear magnetrons
2004	Ehiasarian, Christie	<ul style="list-style-type: none"> • First commercial industrial scale power supplies • First Arc handling
2006		<ul style="list-style-type: none"> • first commercial HIPIMS deposition systems

be interesting to see what other market areas are penetrated by HIPIMS technology in the next few years.

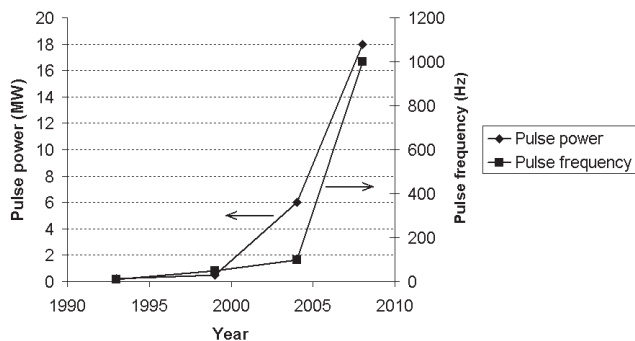


Figure 7: Recent development progress of HIPIMS power supplies (pulse energy and repetition rate).

CONCLUSIONS

- As long ago as 1970 Malikin could make HIPIMS like discharges (13 MW for 150 μ s), but they did not use these for sputter deposition. No magnetic field was used in these plasmas and so the pressure was high (1 Torr, 130 Pa).

- This work at the Moscow Engineering and Physics Institute, continued until at least 1999, developing into HIPIMS sputtered coatings.
- The timeline from Malkin, to date, is roughly:
 - ◇ 1968 - 1972 Malkin making HIPIMS like glow discharges
 - ◇ 1981 Tyuryukanov studied pulsed magnetron discharges
 - ◇ 1993 Mozgrin reports first HIPIMS sputtered metal films
 - ◇ 1999 Fetisov investigates HIPIMS sputtering further, reports first ‘matching network’, reports first oxides and nitrides.
 - ◇ 1999 Kouznetsov publishes ‘key paper’ in the west and starts technology growth
 - ◇ 2002 first upscaling to linear cathodes (400 cm²).
 - ◇ 2004 First industrial scale power supplies available (for magnetrons > 1000 cm²)
 - ◇ 2006 First HIPIMS production coatings systems available
- All power supplies basically comprise:
 - ◇ High voltage DC supply
 - ◇ Storage capacitor
 - ◇ High power switch

- It is also useful to have:
 - ◊ Matching network, (really a pulse shaping network), this prevents oscillations, and controls the current rise time.
 - ◊ Arc handling
- Typical HIPIMS pulse densities are 1 – 3 kW/cm², on a large linear magnetron this necessitates total pulse powers of many MW. HIPIMS supplies have recently developed to the point where pulse energies up to 18MW are available (1-3kV, 1-6kA). This makes HIPIMS feasible on many large scale industrial applications.

REFERENCES

Note: dates below refer to the publication date of the translation in English. In some cases the original publications in Russian may be a year or two earlier.

1. U. Helmersson, M Lättemann, J. Bohlmark, A.P. Ehiasarian, J.T. Gudmundsson, "Ionized physical deposition (IPVD): A review of technology and applications," *Thin Solid Films*, 513, Issue 1-2, 1-24, 2006
2. O.A. Malkin "Pulsed current and gas relaxation," published (in Russian), 1974
3. Prof. James Bradley, University of Liverpool, private communication
4. Tyuryukanov P.M., Nikol'skii A.D., Fetisov I.K., Tolstoi I.N., "Low-pressure pulsed discharge in a transverse axisymmetric magnetic field," *Sov. J. Plasma Phys.* 8(6), Nov-Dec., pp 693 - 697, 1982
5. Mozgrin D.V. , Fetisov I.K., and Khodachenko G.V., "High-Current Low-Pressure Quasi-stationary Discharge in a Magnetic Field: Experimental Research," *Plasma Physics Reports*, 51(5): pp 400 - 409, 1995
6. Fetisov I.K., Filippov A.A., Khodachenko G.V., Mozgrin D.V. and Pisarev A.A., "Impulse irradiation plasma technology for film deposition," *Vacuum*, 53, 133-136, 1999
7. V. Kouznetsov, K. Macak, J. M. Schneider, U. Helmersson and I. Petrov, "A novel pulsed magnetron sputter technique utilizing very high target power densities," *Surf. Coat. Technol.*, Vol. 122, Issues 2-3, pp 290-293, 1999
8. V. Kouznetsov, "Method and apparatus for magnetically enhanced sputtering," US patent 6296742, 2001
9. A.P.Ehiasarian, R.New , W.-D.Munz, L. Hultman, U. Helmersson, V.Kouznetsov, "Influence of High Power Densities on the Composition of Pulsed Magnetron Plasmas" *Vacuum* 65 (2), 147, 2002
10. A.P.Ehiasarian and R. Bugyi, "Industrial Size High Power Impulse Magnetron Sputtering," *47th Annual Technical Conference Proceedings of the Society of Vacuum Coaters*, pp. 486 - 490, 2004
11. D.J. Christie, F. Tomasel, W.D. Sproul, D.C. Carter, "A novel power supply with arc handling for high peak power magnetron sputtering," *J. Vac. Sci. Technol., A, Vac. Surf. Films* 221415, 2004