# PULSED POWER DRIVERS AND DIODES FOR X-RAY RADIOGRAPHY

K. J. Thomas, AWE Aldermaston, Reading RG7 4PR, United Kingdom


*Abstract*

Flash radiography has been used as a diagnostic for explosively driven hydrodynamics experiments for several decades following the pioneering work of J C Martin and his group at AWE. Relatively simple pulsed power drivers operating between 1 and 10 MV coupled to experimentally optimised electron beam diodes have achieved great success in a number of different classes of these experiments. The next generation of radiographic facilities will aim to improve even further the radiographic performance achievable by developing both the electron beam diodes used and the accelerators that drive them. The application of the rod-pinch diode to an Inductive Voltage Adder at 2 MV in the US has already advanced the quality of radiography available for relatively thin objects. For the thickest objects accelerators operating at up to 15 MV and diodes capable of focusing electron beams to intensities of ~ 1 MA/cm$^2$ for tens of nanoseconds will be required in the future. Since the various candidate diode configurations operate in both high and low impedance regimes there is a further challenge to design and engineer an accelerator capable of driving whichever one, or more, are eventually used.


## INTRODUCTION

Radiography records X-ray attenuation profiles through an object. Line of sight mass can then be unfolded from the images generated. A “flash” radiograph aims to freeze the object motion by reducing the X-ray pulse duration to the point where the object movement is minimal during that time. Spatial resolution is determined by a number of parameters – object motion during the exposure, the source size and detector blur. For the objects of interest to AWE the attenuation can be several orders of magnitude in which case X-ray scatter and quantum statistics can also contribute to the overall image resolution. Since those objects are explosively driven metal systems the source and detector must be protected which can constrain the radiographic geometry (Figure 1).

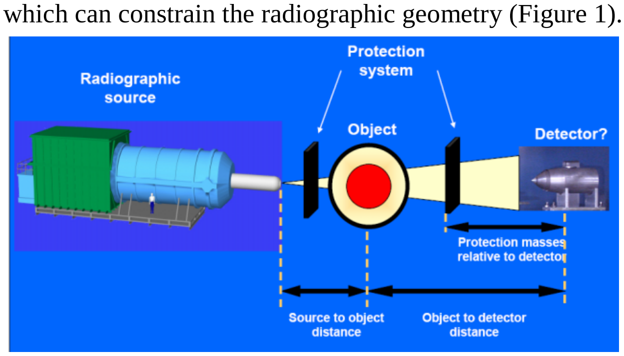


Figure 1: The geometry of a flash radiographic system.

The line of sight mass of the object (the “thickness”) is a major factor in determining what radiographic source is optimum for a particular experiment. For thin objects a relatively soft spectrum is best for ensuring high contrast. Thick objects require a high voltage to achieve sufficient penetration power. The specific aims of the experiment may also determine other parameters such as the desired spot size, pulse duration and number of views. No single system can satisfy the requirements of all radiographic applications.

For example, the flash radiographic sources at AWE range in voltage from under 1 MV (MEVEX) to 10 MV (Mogul E). In each case the X-ray source is a focused electron beam incident on a high atomic number target. The electron beam diode, which generates and focuses the electron beam, is driven by a pulsed power machine. Those currently in service at AWE were all built in-house by the group headed originally by J.C. (Charlie) Martin [1]. They pioneered this field of Pulsed Power with the goal, eventually successfully realised, of being able to perform flash radiography of simulated weapons systems.

This route for flash radiography offers high current compared to LINACS or LIAs. This has the advantage of generating a softer X-ray spectrum for a given dose (dose scales as ~ Voltage$^3$). For high Z objects a machine of ~10 MV produces the optimum Bremsstrahlung spectrum to maximise photons in the minimum absorption band between 2 and 5 MeV. For voltages below this level there is still the advantage that the lower energy photons produced by scattering processes are more attenuated than the unscattered photons that form the image.

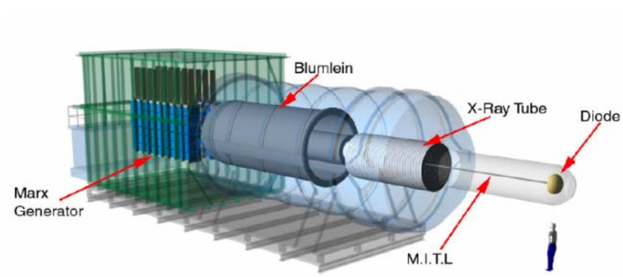


Figure 2: The Single (Blumlein) Pulse Forming Line Pulsed Power Machine.

All the machines in service at AWE have a Single Pulse Forming Line (SPFL) configuration (Figure 2). A Marx generator (a capacitor bank switched from parallel to series configuration) charges a single Blumlein pulse forming line to a voltage of the order of the final load voltage in approximately a microsecond. One self closing switch initiates the pulse forming action of the Blumlein sending a pulse (of duration determined by the double transit time of the line), typically of less than 100 ns duration, towards the load.

Since the final stage of the machine is a vacuum transmission line feeding the e-beam diode there is an insulator stack at the interface between the vacuum and the insulating medium (usually transformer oil) upstream.

This technology has the advantages that it is both simple and capable of delivering much higher currents than are available from more complex accelerators.

## THE E-BEAM DIODE

Four types of electron beam diode are currently in use or being investigated for future radiographic applications – the self magnetic Pinch (SMP), Rod Pinch (RP), Paraxial and Immersed B Field (Bz) diodes (Figures 3-6).

The SMP and paraxial diodes were developed at AWE in the 1960s and 70s based on simple analytical theories and extensive experimentation. The hope now is that an improved understanding of the plasma physics controlling diode behaviour can be incorporated in computational models, such as the LSP Particle in Cell code developed by Mission Research Corporation (MRC), to allow further improvement of all the diode types mentioned. In conjunction with that effort work is proceeding at many labs in a co-ordinated programme to develop diagnostics that will allow diode behaviour to be much better understood and hence benchmark the PIC models.

To field experiments aimed at improving these diodes, prior to the construction of new radiographic facilities, a number of pulsed power drivers are being, or will be, employed. These include the Gamble II and MERCURY machines at the Naval Research Lab. (NRL), RITS-3 and shortly RITS-6 at Sandia National Lab. (SNL), ASTERIX at CEA in France and the EROS and EMU machines at AWE.

### *Self Magnetic Pinch and Rod Pinch Diodes*

The self magnetic pinch (SMP) diode relies on the self magnetic field of the electron beam to focus it to an intense spot, once the proximity of the conducting anode removes the countering electrostatic forces. In the rod-pinch (RP) diode [2] the rod is the anode and the electrostatic and magnetic forces force the electrons to the tip which acts as the X-ray converter.

The self magnetic pinch is the diode currently used for thin object radiography at AWE while the rod pinch, which generates a smaller spot size (1 mm rather than 2-3 mm) is already in use in the US on the CYGNUS machines at the NTS. Future low voltage radiography (up to 3 MV) is likely to use the RP in its current state of development. The need then is simply to design the most suitable driver. These two diodes and variations are also being investigated for higher voltage applications.

A variation on the standard Rod Pinch is the Plasma Filled Rod Pinch [3], in which an externally generated plasma initially short circuits the RP AK gap. Once current flows from the pulsed power driver the AK gap opens up achieving a very low impedance and high current density diode. This allows higher doses to be produced at lower voltages, which could be useful for very thin objects as signal level at the detector can be increased without the hardening of the X-ray spectrum that would result if the voltage was simply raised to increase the dose.

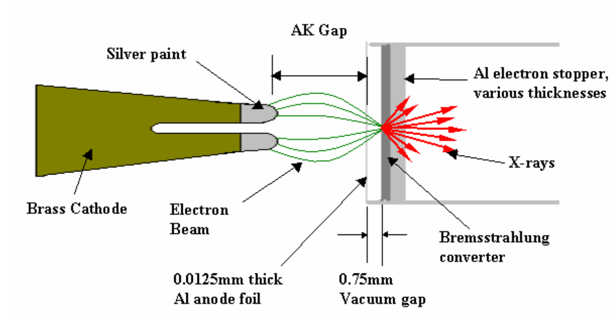


Figure 3: Self Magnetic Pinch.

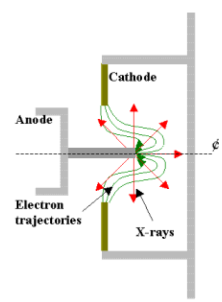


Figure 4: Rod Pinch (Positive Polarity).

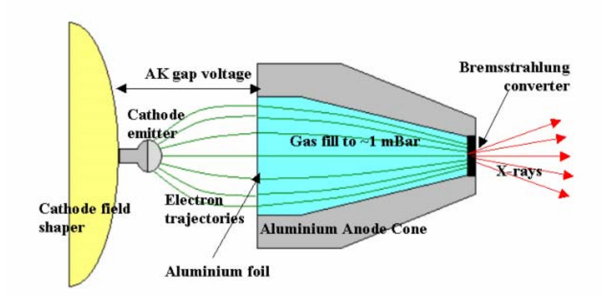


Figure 5: Paraxial Diode.

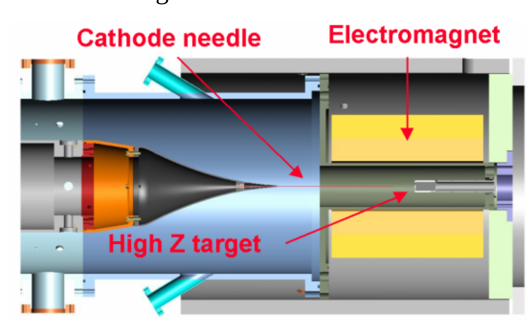


Figure 6: Immersed B Field Diode



0-7803-8859-3/05/$20.00 

### *Paraxial Diode*

In the paraxial diode [4] the electrons are accelerated across the anode cathode (AK) gap at a relatively low density. They then pass through a thin foil separating the diode vacuum chamber from a low pressure gas in a "drift" section a few centimetres long. Here, ionisation of the gas and induced currents act to almost completely neutralise both the electrostatic and magnetic forces. The residual forces cause a relatively gentle betatron oscillation of the electron beam. The X-ray converter is then positioned at one of the focii (usually the first) of that oscillation.

The paraxial diode is currently used for thick object radiography, and hence high voltage, radiography at AWE. Its spot size is 4-6 mm which is higher than desired for future applications. Experiments at SNL (with the collaboration of MRC, Univ. of New Mexico and AWE) are looking at externally generating a plasma in the drift region that will fully ionise the gas prior to the electron beam arriving with the aim of reducing the spot size [5].

### *Immersed B-Field Diode*

In the Immersed B-Field (Bz) diode [6,7] an externally generated pulsed magnetic field is used to force the beam down to a small diameter before impinging on the X-ray target. This diode is another possible candidate for high voltage radiographic facilities. The spot size is currently limited to greater than 4 mm by ion-hose instabilities caused by the interaction of heavy, multiply charged ions with the electron beam. Experiments at SNL are planned which will limit the ion species to one by cooling the target chamber and cryogenically depositing one element (e.g. Hydrogen) on the anode surface.

## PULSED POWER DRIVERS

The SMP and RP diodes would operate at a much lower impedance than the paraxial or Bz at the voltages needed for radiography of thick objects. Since the eventual choice of an optimum diode is not yet clear the driver design, which is proceeding in parallel [8], must be able to cater for either high or low impedance options.

The next generation of radiographic facilities will utilise a development of pulsed power technology pioneered by SNL and Titan Pulsed Sciences Division (Titan PSD). This is the Inductive Voltage Adder [9] which uses Induction Cells threaded by an adder stalk to add the voltages from a series of pulse forming lines all charged by a common Marx generator. Voltages in excess of 10 MV can therefore be obtained with pulsed power components operating at ~ 1.5 MV.

Another technology being developed by the HCEI at Tomsk in Russia for SNL is the Linear Transformer Driver [10]. This has already been applied to generating high current, long (500 ns) pulses but the production of the shorter pulse lengths suitable for flash radiography of hydrodynamics experiments has only recently been demonstrated. This technology dispenses with the Marx generator and pulse forming lines of the IVA. Instead, low jitter DC switches discharge low inductance capacitors directly into the bore of an inductive adder in individual stages operating at ~ 100 kV.

The IVA is currently the more mature of these two pulsed power architectures. The RITS (Radiographic Integrated Test Stand) IVA [11] at SNL is a test bed that has been used for developing IVA technology to the point where it can be used for radiography. Fig. 7 shows the 3 cell configuration of the RITS IVA. It has a complex succession of pulse compression and shaping stages, some of which have, thanks to the experience gained, been eliminated in subsequent designs.

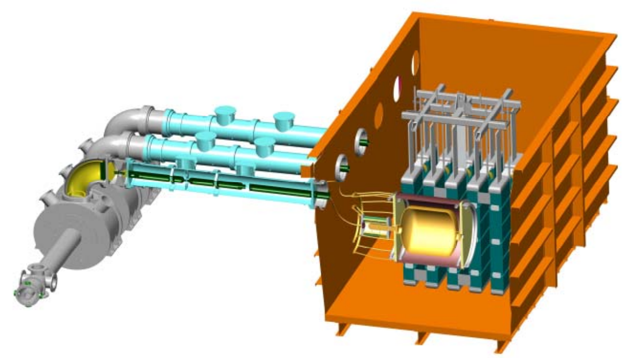

Figure 7: The RITS-3 IVA.

An example of this is the two CYGNUS IVAs [12] at the NTS (as shown in Fig. 8) which have achieved considerable success in thin object radiography. The intermediate storage capacitor and laser triggered switch used on RITS have been dispensed with in favour of directly charging a RITS PFL with a fast Marx generator. The one PFL then charges three induction cells to deliver 2.2 MV to a Rod Pinch diode.

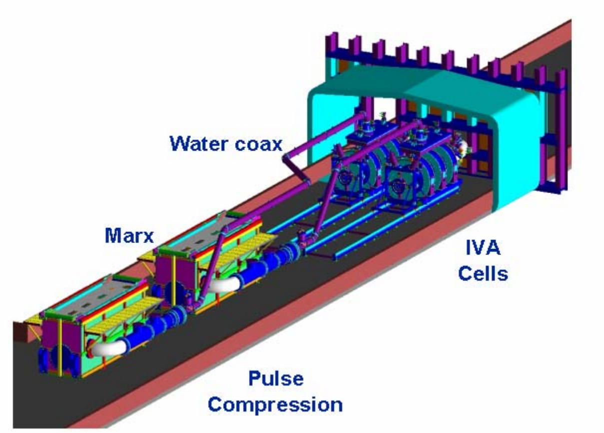


Figure 8: The two CYGNUS IVAs as configured at the NTS.

## MEETING FUTURE REQUIREMENTS FOR THICK OBJECT RADIOGRAPHY

AWE currently performs flash radiography on radiographically thick hydrodynamic experiments, which study the behaviour of explosively driven metal systems, using the largest of the SPFL machines mentioned previously. The requirements for future experiments of this type have been determined using information theory and uncertainty analysis [13]. There is a zone of performance which will meet those goals with the commonly accepted target being a source which generates 1000 R at 1 metre with a 2 mm spot size.

Since X-ray dose scales as ~ Voltage$^3$ the dose requirement points towards simply increasing the driver voltage. Achieving the spot size is more problematic, which is the reason for the work previously described. Nevertheless, the various diode technologies all currently show potential for achieving this goal.

The possible diodes for future core punch radiography have a wide range of predicted impedances at the voltages necessary to achieve the required performance. The vacuum transmission line that connects the pulsed power drive to the diode load must necessarily function in a magnetically insulated mode [14] since, at the required voltages, the fields on the electrodes exceed the level (~250 kV/cm) where electron emission from their surfaces will occur. In this case a sheath current of electron flow in the vacuum exists as well as the current flowing in the metal of the negative conductor. So long as the total current exceeds a critical value the magnetic field constrains the vacuum electrons sufficiently to prevent them reaching the positive conductor. The conventional approach to designing Magnetically Insulated Transmission Lines (MITLs) assumed that only the conducted current could be used in the diode and the sheath current would have to be dumped elsewhere. The driver then has to be capable of supplying the total current which is the sum of the conducted and sheath currents. The operating range of the accelerator in terms of diode impedance is consequently a linear function of voltage.

Recent work has shown that it may be possible to retrap MITL sheath current [15] and use it in the diode. The process that occurs reduces the diode voltage, but only modestly for a small amount of retrapping. An useful reduction in lost sheath current and increase in diode current can be obtained. If the low impedance diodes such as the SMP and RP are driven with a high impedance machine the retrapping has to be considerable and so is the consequent voltage drop. However, if the original driver voltage is high enough, the resulting diode voltage may be sufficient to deliver the desired performance. The benign consequence of this situation is that the dumped sheath current can be virtually eliminated. Not only does that improve the efficiency of the system but it removes the undesirable scattered X-ray background that the dumped current would generate. The phenomenon of retrapping means that the operating range of any machine becomes an extended area in impedance-voltage space. This eases the problem of catering for the varying impedances of prospective diodes when designing an accelerator.

A 10 stage IVA (Fig. 9) is being designed by Titan PSD for a new radiographic facility at AWE [16]. This develops the approach used on RITS by directly charging the 10 PFLs from the Marx (as in CYGNUS) to allow a more compact design configured such that three or more machines can be positioned around a common firing point for multiple views. Also, laser triggered switches are used to initiate the PFLs. This ensures the synchrony required for correct adder operation. With high impedance diodes this machine is designed to be capable of delivering an output voltage of 14 MV. With retrapping, a low impedance diode will reduce this to ~ 8 MV. The IVA design incorporates provision to add both an extra two stages (to increase the voltage) and to add a second parallel bank of PFLs doubling the available current. It is therefore well specified to meet the future radiographic goals whichever diode technology or technologies prove most effective. Three of these 14 MV IVAs will be installed in a new radiographic facility due to commence operation in 2010.

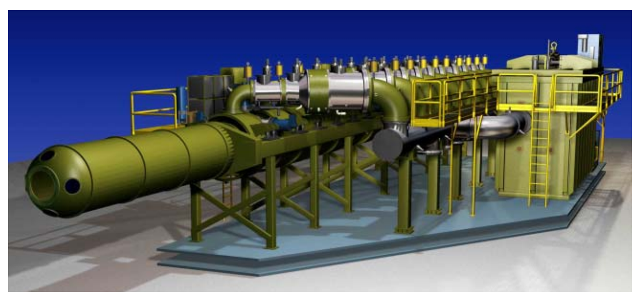

Figure 9: The 10 stage IVA for new AWE radiographic facilities.

## SUMMARY

Pulsed Power driven flash radiography has been used for many years to provide an important diagnostic tool for the hydrodynamics of explosively driven metal systems. A number of different types of these experiments are performed leading to the need for at least two distinct optimised sources. New technology and improved physics understanding is being applied to advance the performance of these systems. The benefits of this work have already been demonstrated for thin objects. An extensive collaborative programme between many laboratories is in progress to meet the major challenge of improving the radiographic performance available for the most attenuating objects [17]. The next generation of such facilities will be built in the next few years which will apply the results of these efforts.

 0-7803-8859-3/05/$20.00 ©2005 IEEE

## ACKNOWLEDGEMENTS

The author would like to stress that what is presented here summarises the work of a number of laboratories and organisations in the US, UK and elsewhere. Thanks are due to numerous people at AWE, SNL, NRL, Titan PSD, MRC, LANL, Bechtel-Nevada, UNM, CEA and HCEI.

## REFERENCES

[1] J.C. Martin, "J.C. Martin on Pulsed Power", T.H. Martin, A.H. Guenther, and M. Kristiansen, Eds. New York: Plenum, 1996

[2] G. Cooperstein et al, "Theoretical Modelling and Experimental Characterisation of a Rod-Pinch Diode", Phys. Plasmas, Vol. 8, pp 4618-4636, 2001

[3] B.V. Weber et al, "Ultra-high Electron Beam Power and Energy Densities Using a Plasma-Filled Rod Pinch Diode", Phys. Plasmas, Vol. 11,pp 2916-2927, 2004

[4] D. Short et al, "LSP Simulations of the paraxial diode and comparisons with experimental data", in Dig. Tech. Papers, 14th IEEE Int. Pulsed Power Conf., A. Neuber, Ed., pp744-747, 2003

[5] D.R. Welch et al, "Transport of a relativistic electron beam in gas and plasma-filled focusing cells for X-ray radiography", Phys. Plasmas, Vol. 11, pp. 751-760, 2004

[6] G.M. Cooper et al, "Recent Immersed Bz X-ray diode experiments", Proc. 14th Int. Conf. High Power Particle Beams, p. 155, 2002

[7] D. Rovang et al, "Recent progress in the development of immersed diodes", in Dig. Tech. Papers, 14th IEEE Int. Pulsed Power Conf., A. Neuber, Ed., pp. 487-490, 2003

[8] T.J. Goldsack et al, "Multimegavolt multiaxis high-resolution flash X-ray source development at AWE Aldermaston", IEEE Trans. Plasma Sci., Vol. 30, pp. 239-253, Feb. 2002

[9] J.J. Ramirez et al, "The four stage HELIA experiment", Proc. 5th IEEE Pulsed Power Conf., pp. 143-146, 1985

[10] A.A. Kim et al, "1 MV ultra-fast LTD accelerator", in Dig. Tech. Papers 14th IEEE Int. Pulsed Power Conf., A. Neuber, Ed., pp. 853-854, 2003

[11] I.D. Smith et al, "Design of a Radiographic Integrated Test Stand (RITS) based on a voltage adder, to drive a diode immersed in a high magnetic field", IEEE Trans. Plasma Sci., Vol. 28, pp. 1653-1659, 2000.

[12] D. Weidenheimer et al, "Design of a driver for the Cygnus X-ray source", Proc. 13th IEEE Int. Pulsed Power Conf., pp. 591-595, 2001

[13] J. O'Malley, "Optimisation of Diode Performance for deep penetration Flash Radiographic Applications at AWE", Proc. 14th Int. Conf. High Power Particle Beams, pp. 163-166, 2002

[14] J.M. Creedon, "Magnetic cut-off in high current diodes", J. Appl. Phys., Vol. 48, pp. 1070-1077, 1977

[15] K. Hahn et al, "Retrapping studies on RITS", in Dig. Tech. Papers, 14th IEEE Int. Pulsed Power Conf., A. Neuber, Ed., pp. 871-874, 2003

[16] I. Smith et al, "Induction voltage adder architectures and electrical characteristics", in Dig. Tech. Papers, 14th IEEE Int. Pulsed Power Conf., A. Neuber, Ed., pp. 371-378, 2003

[17] J.E. Maenchen et al, "Advances in Pulse Power-driven Radiography Systems", Proceedings of the IEEE, Vol. 92, pp. 1021-1042, 2004