Radiation Production Notes

Note 60

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x = Major Item

FAST CIRCUITS, DIODES AND CATHODES FOR e BEAMS

Fast Circuits:

a   Coax lines
b   Blumlein circuit
c   Stacked lines or Blumlein circuits
d   Tapered lines.

Feed from generator to e beam tube.

x Vacuum interface, gradients that can be held.

Parasitic emission from metal surfaces.

Magnetically cut coax feeds.

x Cathode types:

Physics of operation.

Brief look at instabilities of plasma blobs.

Brief look at electron optics and quality of electron beam.

X-ray diagnostics of beam quality.

EXTRA TOPICS POSSIBLY TO BE COVERED

High current beam diodes.

Diode pinch.

"Plasma filled" diode.

High current e beam propagation.

Examples of high current, high voltage pulse generators.

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The topics which should be covered in these notes represent the majority of the SSWA group activity over the past eight years or so. The material of the other four lectures represents peripheral or side issues which were necessary to tackle in order to work effectively in the desired area. Thus ideally these notes should and could be many times the length of the others combined. However, apart from e-beam triggered discharges Hull University is not too likely to have any need for data from this area, hence both the lecture and these notes will only briefly cover the topics involved. This is so that a properly balanced overall picture can be given and in the event that some new area does assume importance (such as direct pumping with e-beams) an appreciation can be made of what has been done and what sort of effort is required. For details of what is still a rapidly evolving field, we should be approached for the latest position as far as we know it. As ever the NPT note should be consulted for a general review of the high speed output lines of use and reference 1 (now sadly outdated) gives a popular resume of some of the systems we built years ago. Reference 2 gives a detail of a medium sized system of some five years ago. Reference 3 gives a detailed description of a pulse charge low impedance line using gas switching and also gives details of the real life performance of a strip line version of the Blumlein circuit in some of its variants.

The trend of recent years has been towards lower impedance systems with output voltages in the 1 MV range. Two sorts of approaches have been employed to achieve megamp outputs. In one solid mylar dielectric sheets are used to make Blumlein circuits and series parallel arrangements of these are used to provide the desired output voltage and current. These Blumlein circuits are pulse charged and graded by resistive films at the edges of the conductors and were initially switched with solid dielectric switches. Later these were replaced by multichannel pressurised SF_6 rail gaps which have performed well. Physics International of San Leandro California, have raised the state of the art of such systems to a high level. A number of groups in the states (including Physics International) have followed the route of a pulse charge water filled coaxial line. This of course needs to be charged to 2 MV to deliver 1 MV into its matching load but this is now a routinely used modest voltage. Those using this route are Naval Research Laboratories Washington DC, Maxwell Laboratories San Diego, Sandia Corporation Albuquerque and ourselves. It is probably fair to say that the later route has proved the most useful and least complicated for the working range mentioned above. Generally but not always high speed pulse lines are used to accelerate large currents of relativistic electron beams which are then used directly or are in their turn used to produce X-rays or sometimes microwave radiation. All of these and other applications require the high voltage pulse to be fed from the line to a vacuum filled diode. This involves two portions of the system, the output feeds and a vacuum envelope or diaphragm. The output feed is designed on transmission line concepts and can have a closer spacing than the original pulse charged lines, as the pulse duration it sees is much shorter than that applied to the main lines. Also in a matched coaxial line system it sees only half the voltage that the pulse charged line has to withstand. Thus in general the design problems in this area are not too severe.

The Diode Vacuum Interface

This represents an area of considerable concern to the high voltage pulse designer and in particular in low impedance systems, the design must be very good in order to keep the inductance of this portion of the system acceptable. Reference 2 describes a typical high voltage tube insulator of the multisection type, where the pulse voltage is applied along a carefully graded structure made out of perspex. Fortunately modern high current cathodes do not need a very high vacuum in order to operate and pressures of 0.1 to 1 micron are acceptable. Reference 4 summarises the available data and references on vacuum flash over of various materials for short pulses. Typically tubes to withstand high voltage pulses of 100 ns duration can work at gradients up to 2 MV per foot for pulses of a few million volts.

There is another version of the diode interface which was also developed at AWRE and that is the diaphragm tube. In this case a large disc of plastic is used usually without intervening rings and the adjacent metal surfaces are contoured so the electrons leaving the plastic surface do not re-enter it, and thus the field lines have to have the optimum angle to the surface on the vacuum side.

After the vacuum interface, a stalk carries the cathode which is located close to the anode. From the cathode a large current of electrons is extracted and directed at the anode or passed through a window for use in the region beyond.

Reference 5 describes a large X-ray machine built at Sandia Corporation some years ago while reference 6 covers some of the work at NRL on high current systems. Physics International have built a very wide range of systems, including the largest system to date a 5 megajoule stored energy one. In addition they have done much work on beam propagation as have the NRL group, Sandia Laboratories and a group at Cornell University. A considerable body of published literature exists on the machines and beam propagation from these and other groups working in the field. More complete references can be supplied if desired.

Cathodes

As will be described in the talk an enormous range of cathodes have been used at one time or another. Apart from very low current systems all of these have in common that they either intentionally or unintentionally get covered by plasma blobs early in the high voltage pulse. These plasma blobs originate from whiskers which vapourise by

$$\int j^2 dt$$

heating of the field emitted current and then the resulting debris gets heated to a few ev temperature. Provided they are not affected by the self magnetic fields of the current they are emitting, these blobs expand hydrodynamically at a velocity of about 2 cm per microsecond. Near the front of these plasma blobs at a density of about 10^{18} atom per cc the electrons run away and are emitted at surface of nearly zero work function.

The trick in making a good cathode is to provide many such blobs distributed over the area from which it is required to carry current. Reference 7 gives a description of some early-ish cathodes. This note also covers focusing and drifting of moderate level (~ 50 kilo amp) electron beams.

The plasma blobs, as was mentioned earlier, expand hydrodynamically unless the magnetic pressure becomes comparable with the particle pressure. When this happens the placid and usually acceptable velocity of expansion of 2 cm/sec increases by an order of magnitude or more in what we call the bulging instability. The plasma can then close across the anode cathode gap (typically a 1 cm or so for 1 MV) during the pulse and usually causes impedance collapse.

For some time now we have been using arrays of razor blades as cathodes and find we can produce hundreds of blobs, each of which carries a few kilo amps of current and hence does not go unstable. Such cathodes have a slowly decreasing impedance as the blobs expand but even in 1 cm like spacings can be used for 300 to 400 ns.

The current carried from the plasma covered cathode obeys the Child Langmuir space charge limited relation when allowance is made for the motion of the effective cathode surface, providing the total current in the diode is not too high.

However many systems produce a prepulse before the main pulse arrives, unless considerable care is taken to suppress this and this prepulse can cause the plasma blobs to form well before the onset of the main pulse, Reference 8 covers some of the effects of this prepulse. The prepulse while usually a disadvantage can be turned to advantage and, intentionally tailored, can give rise to a class of cathodes (the "plasma filled" ones) which can provide very large current densities of 1 MA/cm^2.

As was stated above space charge limited current flows in between the virtual cathode and the anode providing the self magnetic field of this current is not too large. As the current drawn from the cathode is increased eventually the radius of curvature of the electrons on the outside of the beam in the self field is so small that a simple treatment says that they cannot reach the cathode. However, nature is subtler than simplistic 2D calculations and indeed increasing current can still be drawn but now the current pinches into a region on the axis of the cathode and current densities up to 100 kilo amps/cm^2 result. Reference 9 gives a treatment of the conditions necessary to avoid the diode pinch. If one wishes to distribute the electron beam over a large area then it is necessary to arrange the cathode anode set up so that diode pinching does not occur, or alternatively to introduce an axial magnetic field whose strength is comparable to the self field of the electron beam in the anode cathode space. On the other hand the diode pinch (first observed by Mr. I. D. Smith of Physics International) provides simply large current densities. Various theories exist as to what is actually going on in a diode pinch, of which a model based on parapotential flow, is probably one of the best. In any event the current in the pinched anode is no longer proportional to the area of the cathode but goes as its radius, an observation in agreement with the parapotential theory predictions.

The resulting very large electron beams can be transported over several meters without too much loss and can be focused to some extent. Transport can be carried out in low pressure unionised gases ($p \sim 1$ torr) when a return current establishes in the back ground gas, which largely cancels the self magnetic field of the primary electron beam. Alternatively the electron beams can be controlled by B_Z or B_θ fields and transported at high efficiencies. The whole field of transport of large current relativistic electron beams is quite complex and much very good work has been done in this area mainly in the States. To even summarise it would be a time consuming business, but suffice it to say that there is a plethora of interesting plasma physics involved and a number of instabilities have been noted and in the case of plasma heating experiments exploited.

Large pulse microwave generators have been built at NRL by modulating a drifting relativistic beam with a rippled magnetic field. Also by making potential wells with focused electron beams, collective accelerations of ions achieved, producing ion currents of energy considerably larger than that of the original electron beam. Just recently current densities of several meg amps per cm^2 have been observed and while the total currents in such beams is quite small and only exist for 10 or so ns, it is to be expected that rapid advances will be made in high density high current beams in the very near future.

The transport and focusing of high current electron beams is closely related to their "temperature." This is the measure of the perpendicular momentum of the electrons. The cooler the beam the more paraxial are the electrons and the easier it is to transport or the more it can be focused. For very high current density beams, all materials placed in their path vaporise and this makes many methods of measuring the temperature of the beam difficult. The method which is still applicable is the analysis of the X-rays produced by the beam, both spacially, temporarily, and spectrally when it hits a target. Reference 10 summarises some of the techniques and also contains illustrative data on the behaviour of the beams from razor blade cathodes. For e-beam laser work it is unnecessary to go to such methods as the current densities are very low and the total currents modest and essentially unaffected by their self fields. However, as the reference shows razor blades backed by non emitting metal surfaces can produce beams whose mean angle of divergence is only a few degrees, also we have found X-ray techniques useful even in this case. Arrays of razor blades have been used to produce current densities down to a few amps per cm^2 for times essentially limited by the hydrodynamic velocity of expansion of the plasma blobs at 2 cm per μsecond. However it is probably necessary to have a reasonably fast rise to the high voltage pulse in order to light up the cathode edge in a large number of places. When this is done, good uniformity is achieved. Such beams can be drifted 10 cms or more in vacuum without any magnetic field, because the low current density involves little space charge blow up, and the initial trajectories can be made only weakly diverging. The great advantage of such cathodes is their robustness, simplicity and the fact that they can operate in relatively poor vacuo. However I do not know of their operation at current densities of fraction of an amp per cm^2. With sharp enough edges this should be possible but of course the velocity of expansion of the plasma puts a practical limit of some microseconds to the pulse length usable.

Not really relevant to this section are two further notes which are included for interest. These are a description of a cheap 1 megajoule low voltage (30 kV) bank using solid dielectric start switches (Ref. 11). Also included is some very early work with a much smaller bank, on which pulsed magnetic fields of 2.5 megajoules were achieved with simple coils (Ref. 12).

These notes describe low inductance banks which are typical of those built in SSWA and give some measure as to what is involved in low voltage high current megajoule systems. Of course in such banks the energy is delivered in a few microseconds, not tens of nanoseconds.

LECTURE NO. 4 REFERENCES

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