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Physics Options in the Plasma Code VOA

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ABSTRACT

A two dimensional relativistic plasma physics code has been modified to accomodate general electromagnetic boundary conditions and various approximations of basic physics. The code can treat internal conductors and insulators, imposed electromagnetic fields, the effects of external circuitry and non-equilibrium starting conditions. Particle dynamics options include a full microscopic treatment, fully relaxed electrons, a low frequency electron approximation and a combination of approximations for specified zones. Electromagnetic options include the full wave treatment, an electrostatic approximation and two varieties of magnetohydrodynamic approximations in specified zones.

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Introduction

This paper describes various physics approaches and conditions which the user may select for use in the code VOA. The basic code is described in UCID-16830¹, "VOA - A 2-D Plasma Physics Code". For completeness we recapitulate the properties of VOA here. The code uses a continuum approach to plasma physics in which nonthermal components of particle distribution functions are represented by moments in momentum space. The code also includes relativistic and collisional effects for a fully ionized plasma. VOA is based upon the same logical framework as the code BBC^{2,3} and utilizes the same generator, KEG,⁴ for problem startup. The code may be run with BBC executing concurrently or with plasma physics only on either 7600 or STAR machines at LLL. To the interacting user the code will appear to be a modified version of BBC, with most options to be selected at run time.

Originally the code was designed to run real plasma physics problems; that is to say, problems involving time scales on the order of inverse plasma periods and distance scales typically multiples of some characteristic Debye length. The full electromagnetic Maxwell equations were also used, which meant that the time interval Δt was restricted by $c \Delta t < \Delta x$, c being the speed of light and Δx being the smallest interval size for a problem. In this respect VOA treats the same physical domain as do simulation codes. Many prospective users, however, wished to relax the time and distance restrictions inherent in any full blown plasma physics treatment. Due to the fact that VOA has been formulated in terms of fluid-like variables, modifications to the code could be derived and implemented which would ease many of the restrictions upon the original version of VOA. For situations in which

the physics approximations are well taken, much machine time may be saved by the use of some of these options, as described below. Other options involving treatment of boundaries are also discussed.

Conductors and Insulators

Within any problem, arbitrary configurations of conductors and insulators may be included. These special electromagnetic regions, however, must have their borders coinciding with zone borders if the code is to represent the boundary conditions at their surface accurately. The conducting and/or insulating regions are set up when the problem is generated by KEG. All interior zones which have material number "35" will be treated as conducting. All interior zones which have material number "36" will be treated as insulating. The four exterior walls of the problem are specified separately by choice of boundary sentinels supplied to KEG. To obtain a conducting exterior border, one must specify an open ("vacuum" for BBC) boundary on that edge and also specify that no mass be in the outside zones along that edge. To obtain a transmitting exterior border, one must specify an open boundary on that edge and also that mass be present in the outside zones along the edge. To obtain an insulating exterior border one specifies a reflecting boundary on that edge. See Example 1 in Appendix.

An insulator has zero perpendicular E field and zero gradient of the tangential E field. No charge can be transmitted across an insulator. A conductor has arbitrary perpendicular E field (calculated by the code from initial conditions self consistently or from boundary conditions) and zero tangential E field. Charge can be transmitted across a conducting interface.

Electric charge may be advected out of a problem "onto" a conductor in the usual hydrodynamic manner. Electric charge may also be brought into a problem through a conductor but the amount of charge depends upon values placed in the conductor zone density (for interior conductors) or mass (for exterior conductors). Normally the charge thus brought into a problem is negligible, but the user may select any value he wishes. A transmitting interface has continuous fields across it.

Imposed E-M Fields

At the time of execution, values for the electromagnetic fields may be put into a problem. Uniform initial values may be inserted by the use of cards as shown in Ref. 1. In addition, self consistent values for Z pinches and E beams are calculated as part of initialization for those problems. Boundary values imposed for the duration of a problem are accomplished by the use of a special input card with mnemonic "EBDY", discussed in the Appendix, Example 2. At present the following geometries may be treated: conducting walls with a linear buildup of fields up to some cutoff time, internal conductor with an axis centered hole and a linear buildup of fields until a cutoff time, and a plasma focus configuration with specified field buildup. The plasma focus configuration is an internal truncated cylindrical conductor and an outer conducting sheath. Other configurations will be added as necessary.

External Circuit

The imposed fields may also be specified by an external circuit calculation, which is essentially a capacitor discharge across a specified inductance and resistance as well as the circuit element calculated in detail by VOA. See

Appendix, Example 3. Because the code is setup to handle E-M waves and not just simple field situations, the approach taken is not the usual one. In any situation involving rapid time variations, the common identification $\int_1^2 \vec{E} \cdot d\vec{\ell} = \phi_1 - \phi_2$ is not appropriate. Here $\vec{E}$ is electric field, $d\vec{\ell}$ is an element of path length and ϕ is potential. The code employs boundary conditions couched directly in terms of the fields and surface charges on conductors. By keeping track of current flow out of or into a problem the charge contribution of a specific geometry may be computed. The charge contribution of an external circuit may be computed consistently with the above using the given values of the circuit elements. The difficult aspect of this approach is how to model the charge distribution on the surface of the conductor. Over a long period of time the charge will be distributed to yield an equipotential. Over a short period of time the charge cannot move faster than an electron wave speed in the conductor. The procedure now used is to model the external circuit as if it were connected to a device devoid of plasma. The interior charge contributions are assumed to have effect only locally (i.e., they do not spread out instantaneously) and subsequent propagation is followed by the code.

Non-Equilibrium Conditions

Problems may be started with non-equilibrium electron distributions. Only a simple form of the distribution function is allowed. The basic density, velocity and temperature are specified in the normal way. Non-equilibrium components are characterized by a spread (temperature in keV), a density fraction (number of non-equilibrium particles compared to total) and momentum components (cm/shake). See Appendix, Example 4.

Particle Dynamics Options

Currently four different physical approaches toward particle motion are allowed. They are chosen by setting sentinel number 11 equal to different values. The default value is 0, in which case the code runs with the correct microscopic equations of motion for all species. This means that time constraints of electron plasma oscillations ($\Delta T < 1780/\sqrt{n}$ shakes) and ion plasma oscillations ($\Delta T < \frac{m_s}{m_D} \frac{2 \times 10^{-7}}{\sqrt{\rho}}$ shakes) must be observed. In the formulae above ΔT is the maximum time step, n is electron number density (cm^{-3}), m_s/m_D is the ratio of the ion species mass to deuterium mass and ρ is the ion mass density (gm cm^{-3}).

If sentinel number 11 is set to 9, the code calculates ions as usual, but electrons are assumed to follow the ions and relax about them with the form of their distribution function either equilibrium or non-equilibrium if so specified. The electric field calculated is that which is self consistent with the fully relaxed electron density distribution. The method of solution is by iteration of a back substitution solution for the net charge transfer from zone to zone. No attempt is made to follow the evolution of the non-equilibrium form of the electron distribution function, which remains as initially specified. This method bypasses time constraints having to do with the electrons and also, by virtue of the electron shielding, bypasses the ion plasma frequency time scale. Thus the code time interval just becomes the Courant limit for the ions, effectively a true hydrodynamic time scale. However, heating rates may also place different limits on a given problem. Because the electric field calculation is really that of the longitudinal field, the electromagnetic wave time constraint is also eliminated.

If sentinel number 11 is set to 8, ions are again calculated as usual, but electron velocities are calculated via a modified algorithm which averages out the high response frequency (i.e., plasma oscillation) to impressed forces. In essence the electrons are limited in the average so that the electron flux across a boundary is never much more than that necessary to yield Debye shielding of the zones being treated. The non-equilibrium components of the electron distribution are calculated consistently with the above processes. However it is important to note the temperature of the electron distribution cannot really be found self consistently within this approximation. One needs to know either the phase relation between electron current (which is really at plasma frequency) and electric field or a resistivity to calculate internal energy properly. Slow heating due to collisions is treated correctly, but the code at present ignores the high frequency effects when using this approximation. This approach clearly avoids restrictions from electron plasma oscillations, but is still limited by ion plasma oscillation time scales. This version is useful for investigating the dynamics of space charge effects and the like.

If sentinel number 11 is set to 7, a combination of approximations is allowed. All zones specified to the generator (KEG) as multi-fluid (as BBC would calculate them) are to be treated within the fully relaxed electron approximation. All zones not so specified are to be treated within the low frequency electron approximation. In this option non-equilibrium components of the distribution function are calculated in both types of zones. This version is useful for treating problems in which zones of high density (where relaxation is fast) are juxtaposed to zones of lower density.

Electromagnetic Field Options

Four different approaches to the calculation of electric and magnetic fields are in the code. This is in addition to the treatment used in zones for which the "fully relaxed electron" approximation applies. In those zones only, the default treatment of the fields amounts to an electrostatic approximation for the electric field and a consistent magnetohydrodynamic calculation of the magnetic field, since E is small.

The default treatment of the electric and magnetic fields is to follow their evolution from the two of Maxwell's equations involving time derivatives. The limit on time scale from that approach is $c \Delta T < \Delta x$, c being the speed of light, ΔT being the limiting time step and Δx being the smallest interval size. This treatment follows all electromagnetic waves capable of being resolved by the problem geometry.

By setting sentinel number 8 to 1, the code runs with a static magnetic field. This means that E-M waves cannot propagate and is equivalent to an electrostatic approximation. For this situation, the time scale is limited by $\Delta T \lesssim .1 \sqrt{\Delta x/E}$ (essentially a Courant type condition on the electrons) ΔT is in shakes, Δx in centimeters, E in statvolts per centimeter.

By setting sentinel 8 to 2, the code runs with the MHD approximation for the magnetic field. This means that E is ignored when compared to the current J . The electric field used in the code is that consistent with the change of B as calculated in MHD. Limit here is a Courant condition generalized to take account of the Alfvén speed.

By setting sentinel 8 to 3, the MHD approximation for the magnetic field is made and the electric field is ignored altogether.

Appendix

This Appendix collects examples of how to implement code options.

Example 1 - Electromagnetic boundary conditions.

In the KEG input the following cards are present.

```
  1  1 1 0 0  . . . Box T75 TEST                      (title card)
  :
35  KL  1  7  2 10
36  KL 20 30 20 30
WALL 1  7  2 10
WALL 21 29 21 29
  :
PL  0  3  0  0  0  1  0  1  0
```

The fourth through seventh characters in the first card (blank is considered a character) denote the velocity boundary conditions at the walls of the problem in order top, bottom, left, right. The r axis is vertical, the z axis is horizontal. The character 1 denotes a reflecting boundary (zero velocity across the wall), and the character 0 denotes an open boundary (arbitrary velocity across the wall).

The last four non-blank characters in the last card above denote the mass boundary conditions outside the walls in the same order as before. The character 1 denotes no mass in zones outside the wall. The character 0 denotes that zones with some mass are found outside the wall. As noted in the text, reflecting walls are treated as insulating, open walls into a "no mass" zone are treated as conducting, and open walls into zones with mass are treated as

transmitting. It should be noted that for the general case some further specifications of the boundary zones with mass are needed. The table below summarizes these conditions for our example.

<u>Location</u>	<u>Velocity Sentinel</u>	<u>Mass Sentinel</u>	<u>E-M Condition</u>	<u>Comments</u>
Top	1	1	Insulating	Reflecting wall
Bottom	1	0	Insulating	Not normally used
Left	0	1	Conducting	Conducting wall allowing some current through it
Right	0	0	Transmitting	Transmitting "wall"

In addition the two middle cards in this example specify that, for the interior of the problem, a conductor extends between K lines 1 to 7 and L lines 2 to 10 and an insulator extends between K lines 20 to 30 and L lines 20 to 30. The "WALL" cards are used to insure that no motion takes place inside either conductor or insulator.

Example 2 - Imposed fields

In the code execution file the following card may be present.

```
PL  EBDY  10  1.E+2  1.0E+1
```

The first two characters "PL" denote this as a special plasma card.

The characters "EBDY" denote that the card contains values for imposition of external fields.

The third item on the card, 10, denotes a plasma focus geometry.

<u>Value of Third Item</u>	<u>Meaning</u>
0	No boundary values are put in (default).
1	Outer walls conducting with E field and rise time specified in items four and five.
9	Internal conductor with hole centered on axis; E field specified between right hand border and internal conductor.
10	Plasma focus geometry with inner conductor extending to left border, E field specified between top (cylindrical) conductor and inner conductor.

The fourth item on the card, 1.0E+2, denotes that the final value of the imposed electric field in this problem, in the absence of any return currents, would be 100 statvolts per cm higher than any initial value (1 stat v/cm = 3×10^4 v/m). It has the same meaning for all possible geometries.

The fifth item on the card, 1.0E+1, denotes that the rise time for the increase of the electric field will be 10 shakes. It has the same meaning for all possible geometries. After the time has lapsed no further changes of the electric fields are imposed.

Example 3 - External Circuit

In the code execution file the following card may be present.

```
PL  EXCIR  1  1.0E+3  1.0E-2  1.0E+2  5.0E-8  1.0E-8  1.
```

The characters PL denote a plasma card.

The characters EXCIR denote this to be a card supplying values for an external circuit.

The third item "1" denotes the type of external circuit (series RLC). At present 1 is the only nonzero value recognized by the code. Zero is the default value for no external circuit.

<u>Item Number</u>	<u>Attribute</u>	<u>Value in Example</u>
4	Original capacitor potential	1000 volts
5	External resistance	.01 ohms
6	External capacitance	100 farads
7	External inductance	5.0×10^{-8} henries
8	Original internal inductance	1.0×10^{-8} henries
9	Time lapse between circuit closure and start of VOA calculation..	1.0 shake

Example 4 - Non-equilibrium conditions.

In the code execution file the following card may be present.

PL NONEQ 1 2.0 0.1 10. 20.

The characters PL denote a plasma card.

The characters NONEQ denote this to be a card supplying values for an initial non-equilibrium distribution.

The third item "1" denotes the application of the values, in this case to electrons only. Default is zero (initial equilibrium). No other values are now implemented.

<u>Item Number</u>	<u>Attribute</u>	<u>Value in Example</u>
4	Non-equilibrium component thermal spread	2.0 keV
5	Non-equilibrium component relative density (compared to equilibrium)	0.1 (dimensionless)
6	Non-equilibrium component drift velocity, z direction	10 cm/sh
7	Non-equilibrium component drift velocity, r direction	20 cm/sh

Example 5 - Sentinel choices.

In the code execution file the following card may be present.

```
SENTL   8   2   11   7   34   0.   42   1.0E-14   46   1.0E-20
```

The characters SENTL denote this to be a card for resetting sentinels in the code. The numbers following SENTL are to be taken pairwise, the first of a pair being the sentinel number and the second being its value. In this example sentinel number 8 is set equal to 2 (MHD approximation for B, consistent E); sentinel number 11 is set equal to 7 (combined fully relaxed and low frequency approximations for electrons); sentinel number 34 is set equal to 0.0 (turns off von Neumann "Q"); sentinel number 42 is set equal to 1.0×10^{-14} cm/sh (velocity floor) and sentinel number 46 is set equal to 1.0×10^{-20} g (mass in each boundary zone). A discussion of the BBC sentinels is found in UCIR-705 - Preliminary Users Manual for BBC.³

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1. Eltgroth, P. G. (1975), VOA-A 2-D Plasma Physics Code, UCID-16830, Rev. I.
2. Sutcliffe, W. G., BBC Hydrodynamics, UCID 17013 (1974).
3. Sutcliffe, W. G., Warshaw, S. I. and Litterst, R. F. (1973), Users Manual for DBC, UCIR-705.
4. Warshaw, S. I. (1974), KEG Manual, UCIR-646, Rev. I.

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