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Relevance of Plasma Science to Particle Accelerators⋆

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Abstract

In following the theme of this Symposium, "Plasma Science and Its Applications," we may be suggesting to some readers that the "other" applications of Plasma Science somehow justify the existence of a field traditionally devoted to fusion energy. In fact, we do not believe that plasma science can or should be justified for its spin-off contributions. Nevertheless, the unity of science would be seriously threatened by a precipitous decline in the support for plasma science. It is that unity which repeatedly has been verified as one looks for how advances in one field are crucial to several other seemingly fundamentally different fields. Thus it is in this case, as a representative of the community of Particle Accelerator Scientists, that we show four significant areas in which the methods and the results of plasma science have been applied to Accelerator Science. We have deliberately skipped plasma ion sources which are perhaps the most obvious application of plasmas to accelerators. Two of our four examples are cases in which the computational methods of plasma science have been adopted, and two are examples in which the plasmas themselves are employed. One of each category are now actively in use and the other one in each category is being used to develop or design new devices.

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Klystron Design

The material in this section is due to Arnold Vlieks and coworkers at SLAC. The application of the techniques know as PIC Codes, for Particle in Cell, to the subject of klystron design, was begun by Simon Yu[1] The status of high power klystrons for accelerators in 1984 was not seriously advanced from the tubes that were provided to the two–mile accelerator two decades earlier. Computer models were mostly based on one–dimensional disk models. This is a model which can be used successfully to design "low–power" klystrons but which fails seriously as beam perveance is increased.

The use of PIC programs for klystron design solves two shortcomings of other programs:

1. The "fully electromagnetic" characteristic accounts for electric and magnetic rf fields and their effects on the beam particles in ways that allow reasonable numbers of particles to be handled in acceptable computation time.

2. One glance at the figure of the Magic results shows that the beam dynamics is clearly not appropriate to a one–dimensional disk model. In fact, a model in which the beam is considered to be an incompressible fluid is more appropriate. Bunching is then more characterized by radial ripples than by longitudinal density variations.

From roughly 35 MW at S-band (3 GHz), which was the status in 1984, klystrons in use today on the Next Linear Collider Test Accelerator, are rated at above 75 MW at X-band, (four times higher in frequency).[2] In the Abstract, we noted that two of the applications would be cases of the use of the computational methods of plasma physics. The klystron design work is such a case in which the devices being designed are in wide–spread use. We next consider an application to the development of a computer program that is being used to design whole accelerator systems.

The WARP Code for Beam Transport Simulation

The material in this section was provided by A. Friedman and D. Grote and their colleagues at LLNL. Accelerators for Heavy Ion Fusion (HIF) Drivers require space–charge limited beams at velocities well below the relativistic conditions treated by the fully electromagnetic programs However, because of the need to treat pulsed beams with careful attention to emittance growth and pulse shape, it is necessary to include 3–D effects very carefully. One application in particular, the design of a circular configuration, led to conditions that required a new program with the name "WARP" referring to a warped or bent coordinate system.[3]

WARP has been developed into a generally used program that can handle acceleration and focusing in 3–D (quadrupole) systems. Both electric and magnetic quadrupoles are used in the HIF application. A particularly interesting accelerator application is the electrostatic quadrupole injector which combines an accelerating column with electrostatic quadrupole focusing elements. Results of beam measurements with the first model of this design match closely the predictions from WARP. The most complex and ambitious project to which WARP has been applied is to design the HIF Recirculation Induction Accelerator.[4] The extensive beam dynamics instrumentation that has been incorporated into the small recirculator experiment at LLNL will provide important calibration for the WARP simulations as well as a test of this new technology for HIF.

Measurements of Longitudinal Emittance Growth in the Tevatron

The material in this section was supplied by Pat Colestock of Fermilab. We turn now to examples of applications of plasma physics in which the plasma technology itself supports particle accelerator science. In a colliding beam facility, such as the Fermilab Tevatron, the longitudinal emittance, which is a measure of energy spread, grows slowly due to Coulomb scattering from residual gas and from adjacent beam particles. As it grows, the collision rates in the colliding beam interaction area are reduced.

The emittance growth is not normally a fast process, but after many hours of operation, the luminosity can be significantly degraded. A direct measure of the longitudinal emittance growth would find a time constant of around 10^9 *sec*. Dr. Colestock applied plasma physics measurement techniques to observe longitudinal kicks of the beam. Waves from these kicks progress like solitons, for large fractions of a second. Even more interesting are beats of these waves, caused when kicks of different subharmonics of the accelerating field are used together. These beats cause echo waves in the bunches that can be observed as rf voltages from the bunch.

Among the plasma phenomena observed in this way are solitary waves, nonlinear Landau damping, and wave–wave coupling.[5] These collective plasma effects are employed to study the mechanisms for the saturation of beam instabilities.

Beam–Plasma Interactions and the Plasma Lens

The material in this section was supplied by Pisin Chen of SLAC. Electron linear colliders provide the cleanest path for future High Energy Physics to study collisions of fundamental particles. Because the cross sections for collisions drop with increasing energy, it is necessary to provide higher density beams in order to achieve a reasonable luminosity. Improved beam density is achieved by extremely careful beam handling in the accelerator of beams that have as much transverse energy as possible removed by damping rings at injection. However, as beams reach the minimum size consistent with the residual beam emittance, any further reductions require a focusing mechanism right at the interaction point.

A plasma lens has been proposed as the device which will provide the extra focusing. Planned experiments at the SLAC Final Focus Test Beam[6] will reduce the beam cross section from a few microns to of the order of one micron. This experiment differs from previous plasma lens demonstrations in that it is the parameter range for future linear colliders. If the plasma density is greater than the beam particle density, then the space charge forces are fully neutralized and only the beam self field remains. This can result in a self–pinched beam mode unless with even greater density, it is possible to suppress all the beam self fields by providing a plasma return current that cancels the beam current. The more normal range is expected to be the one in which self pinch forces remain.[7]

Summary

There are many applications of plasma science to accelerator technology. We have seen only four in this presentation. If there is a moral to this story, it is that our fields have much in common. As Chairman of the Division of Physics of Beams of the APS, I join the previous speaker, Nat Fisch, Chairman of the Division of Plasma Physics, in urging all scientists active in either plasma science or accelerator science, to join both DPP and DPB, and let their voices be heard.

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Figure Caption: An example of graphic output from the PIC Program MAGIC, used in the design of X–band klystrons. Macroparticles are shown moving left to right in the high–power end of the klystron. Idler cavities and the output structure are shown as vertical slots in the wall.

Magic simulations on current and future 75 MW klystrons