Our group is working on advanced accelerator and beam dynamics at ANL, BNL, SLAC, UCLA and Pulse Sciences Incorporated. The following is a list of accomplishments:

I. WAKEFIELD ACCELERATION STUDIES AT ANL (D. CLINE, C.H. HO)

1989-1990 Description of Research and Progress

During 1989 UCLA participated in experiments in which the focusing effect on the electron beam, which was inferred from the nonlinear plasma wakefield accelerator measurements, was directly observed. A streak camera based diagnostic allowed time resolved measurement of the beam density transverse profiles at the end of the plasma column used in plasma wakefield accelerator experiments. These self-pinched profiles reflected the development of Bennett like equilibria with radii smaller than a plasma skin-depth. The experimental results and theoretical analysis of the self-focussing process are discussed in a paper entitled “Experimental Studies of Plasma Wakefield Acceleration and Focussing”. This paper is published in Physica Scripta and is part of the proceedings of the ITCP Spring College on Plasma Physics Meeting held in Trieste, Italy, May, 1989. An additional paper on similar work entitled “Demonstration of Electron Beam Self-Focussing in Plasma Wakefields” was prepared for the 1989 APS
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UCLA also worked on a compact optical system which can produce 100 nC bunches with bunch lengths of a few pico seconds in 1989. Space charge effects strongly influence beams at low energies blowing up beams in both the transverse and longitudinal directions. In the limit of large currents, space charge will cause divergencies of order 0.3 to 0.5 radians within a few centimeters of the photocathode. C.H. Ho, in collaboration with J. Norem and P. Schoessow, developed a coaxial bunch compressor system for a photocathode source. Research in 1990 was an extension of the research started in prior years. Simulation and modeling was performed to estimate the longitudinal space charge force near the photocathode.

It is possible to make an estimation of the longitudinal space charge force $-eE_z$ near the photocathode. Simulations using 'PARMELA' shows the kinetic energy of electrons is about 0.5 MeV ($\gamma \sim 2$) right after all the electrons are emitted from the laser photocathode. It is convenient to work in the rest frame of beam since $E_z$ is a Lorentz invariant. One assumes concave shape-like electron beams are moving together with uniform density and $\gamma \sim 2$.

For an axial symmetric system, $E_z(0,0,0)$ at the origin can be calculated in the beam frame as:

$$E_z(0,0,0) = \frac{\rho}{4\pi \varepsilon_0} \int_{0+}^{H} 2\pi r dr \int_{z_1(r)}^{z_2(r)} \frac{z}{(z^2 + r^2)^{3/2}} dz$$

$$= \frac{2\pi \rho}{4\pi \varepsilon_0} \int_{0+}^{H} \left[ \frac{r}{(z_1(r)^2 + r^2)^{1/2}} - \frac{r}{(z_2(r)^2 + r^2)^{1/2}} \right] dr$$

(1)
where

\[ z_1(r) = \gamma \left[ R_c - \sqrt{R_c^2 - r^2} \right] \]

\[ z_2(r) = z_1(r) + \gamma \tau \]

- \( R_c \) \( \equiv \) Curvature of beam radius in the laboratory frame \( \sim 1.13 \times 10^{-2} \) (m)
- \( H \) \( \equiv \) Beam height \( \sim 10^{-2} \) (m)
- \( \tau \) \( \equiv \) Beam thickness \( \sim 6 \times 10^{-3} \) (m)
- \( \gamma = 2 \)
- \( \rho = \frac{Q}{\pi H^2 \tau} \)
- \( Q = 100 \) (nC) = \( 10^{-7} \) (coul)
- \( \frac{1}{4\pi\varepsilon_0} = 9 \times 10^9 \) (\( \frac{\text{V}}{\text{m}} \))

Equation (1) can be evaluated easily by 'Mathcad'. Taking \( 0^+ = 10^{-20} \) (m), the result is \( E_z \simeq 24 \) (MV/m). One can also approach this result quickly by treating the beam as a thin pancake. Denoting the surface density as \( \sigma = Q/(\pi H^2) \), \( E_z \) is thus of the order \( \sigma/(2\varepsilon_0) \simeq 18 \) (MV/m).
On the other hand, for a pure drifting concave shape-like beam (as shown in the figure above) with initial kinetic energy being $0.511\text{ MeV} \ (\gamma = 2)$, the simulation result of 'PARMELA' gives $E_z \approx 26\text{ (MV/m)}$, which is in good agreement with the above estimations.

Work in 1990 also concentrated on a conceptual design of a high current, short bunch length, electron source for the proposed 1 GeV Argonne Wakefield Accelerator. The design is based on a laser-driven RF photocathode with a “cup-shape” incoming laser beam. The laser wavefront is shaped in such a way that the space charge effect is minimized in the early stage near the photocathode and the bunch length is optimized due to the compensation of the path length differences between radially inner and outer electrons of the bunch. The simulation code PARMELA has been modified to allow the use of arbitrarily shaped beam. The results show the feasibility of 100 nC electron beam with less than 10 ps bunch length. An abstract of this work was presented by C.H. Ho at the APS Spring Meeting in Washington D.C., April 1990.

II. PLASMA LENS RESEARCH AT SLAC (D. CLINE, S. RAJAGOPALAN)

1989-1990 Description of Research and Progress

Luminosity enhancement using an under dense plasma lens continued to be studied by simulation for the cases of the SLC and some proposed B-factory designs. Aberrations of the under dense plasma lens have been studied using simulation and analytic methods. Much of the research was carried out by S. Rajagopalan in collaboration with P. Chen and J. Rosenzweig. In the work, the viability of using an under dense plasma lens as a final focussing device for a linear $e^+e^-$ collider was examined. The under dense plasma lens is superior to the over dense lens in that it improves focussing linearity and background event rate but works well only for electrons. The interaction of an electron beam, which is smaller than the positron beam at the collision point, a situation which is termed bootstrap disruption, was investigated. Potential luminosity enhancement is
determined by analysis of the lens optics and simulation of the bootstrap disruption. A paper describing the research and entitled “Final Focussing and Enhanced Disruption from an Under dense Plasma Lens in a Linear Collider” was published in Physical Review D in August, 1989.

Subsequent work carried out by the UCLA group at SLAC included an investigation into the problems associated with the ionization of gasses by relativistic beams, the problem of measuring very small spot sizes in the design of the SLAC Final Focus Test Beam (FFTB) and the designs of proposed colliders at higher energies. Aberrations from a plasma lens and the effect of synchrotron radiation on the beam distribution and the consequences thereof in beam-beam collisions, have been investigated. The above research is further described in a paper entitled “Design of a Plasma Lens Test at the Final Focus Test Facility”, which was presented at the Washington D.C. APS meeting, April, 1990.

Calculations and studies were also performed during 1990 to test a plasma lens device at the SLAC FFTB.

In considering the use of a plasma, or a gas jet which is ionized by the front of the beam, as a focussing device, one needs to consider four aspects:

1) The optics of the plasma lens must be as simple as possible, particularly free from aberrations as far as one can do so.
2) The plasma production must be simple. Bulky and expensive devices (like lasers) are neither feasible or desirable.
3) The background produced for high-energy physics experiments by the beam interacting with the plasma must be tolerable.
4) In strong focussing of a beam, one has to avoid the blow-up of the beam by synchrotron radiation which defeats the purpose of focussing.

UCLA will continue to participate and contribute to the conceptual design for the test of a plasma lens at the SLAC FFTB in 1990.
Modeling and calculations were also performed for a plasma lens for a TeV Linear Collider (TLC) having the following parameters:

\[
\begin{align*}
N &= 8 \times 10^9 \\
\sigma_z &= 26 \times 10^{-4} \text{ cm} \\
\sigma_x &= 190 \times 10^{-7} \text{ cm} \\
\sigma_y &= 1 \times 10^{-7} \text{ cm} \\
\epsilon_{x_n} &= 2.6 \times 10^{-4} \text{ cm-rad normalized emittance} \\
\epsilon_{y_n} &= 2.3 \times 10^{-6} \text{ cm-rad normalized emittance}
\end{align*}
\]

Work on this topic had just begun at the time of this report and more extensive work has to be done in order to understand and have a clearer picture of the focusing properties from a plasma lens for flat beams and the range of parameters, fractional ionization, background gas (plasma) density and focal length to be specified for a realistic scheme to emerge.

III. HIGH GRADIENT RF CAVITIES AND BEAM DYNAMIC STUDIES AT THE BROOKHAVEN ACCELERATOR TEST FACILITY (D. CLINE, C. PELLE-GRINI, X. WANG)

1989-1990 Description of Research and Progress

During 1989 the computer program "Bunched Charge Particle Tracking" (BCPT) was developed to study beam emittance behavior in the injector system of the ATF at BNL. The program tracks N particles through magnetic lenses and a RF linac by solving initial value problems of coupled ordinary differential equations by numerical integration methods. BCPT includes higher order nonlinear magnetic fields and 2-D space charge effects. BCPT’s numerical integrators are designed in such a way that new features can be added by writing seven external functions. BCPT is designed for the transport line and injection system of the linac. X. Wang took major responsibility for this development work.

X. Wang also performed simulations, using the optimized computer program PERCY, of Smith-Purcell radiation from Edmund gratings. A paper authored by X. Wang and entitled "Smith-Purcell Radiation from Commercial Gratings" discusses the optimization of the computer program PERCY and simulation of Smith-Purcell
Radiation. It is expected that X. Wang will complete the requirements for a Ph.D. late 1990. Wang’s thesis topic is Smith-Purcell Radiation of Intense Electron Beams at the BNL ATF.

UCLA also participated in the development of a low emittance beam transport line and final focusing system for laser acceleration experiments at the BNL ATF. In order to preserve the low emittance \(10^{-10}\) m-rad 50 MeV electron beam, attention has to be paid to the higher order effects. The low emittance transport line consists of two parts. The first part performs an emittance selection. The second part provides the possibility of energy selection and beam transport to the experimental area. The beam transport line developed will perform emittance and energy selection without significant increment of the transverse emittance. The effectiveness of emittance selection is restricted by the quadrupole strength and the drift space length.

UCLA also helped prepare a proposal for the study of laser acceleration of electrons using micrograting structures at the ATF. The proposal is to investigate new methods of particle acceleration using a short pulse CO2 laser as the power source and grating-like structures as accelerator cavities. Phase I of the project is intended to demonstrate the principle of the method. UCLA was also involved in the calculations and experimental measurements of the Brookhaven RF gun. The performance of the gun will be described at the Particle Accelerator Conference of the European Physical Society, Nice, France, during June, 1990.

IV. RF PULSE COMPRESSION DEVELOPMENT PROJECT AT SLAC (D. CLINE, C. NANTISTA)

1989 – 1990 Description of Research and Progress

The experimental program in 1989 – 1990 has focussed on implementing rf pulse compression with a “Binary Energy Compressor (BEC). To this end, the collaboration has performed successfully a low-power (non-vacuum) test of a two-stage BEC, and has designed, engineered, fabricated, and is currently installing a three-stage high-power
(vacuum) BEC. The number of stages in BEC refers to the pulse-length compression factor, roughly the power amplification factor: the three-stage BEC being built is designed to compress the rf pulse-length by $1/2^3$, while amplifying the power by $2^3$ times the compression efficiency, which is about 75% for the device being built. The low-power test, and the plan for the high-power test are both described in the paper, SLAC-PUB-4911.

C. Nantista, a UCLA graduate student, is an active collaborator in the high-power BEC installation project. In addition to studying the related physics and engineering issues, he has been participating in mechanical installation of the high-vacuum rf system, through which he has been learning mechanical and electrical fabrication skills and high vacuum technique. He has regular and productive interactions with professional mechanical and electrical technicians and engineers. He is also becoming a group specialist for a specific aspect of the rf system: the high-power phase-shifters and their controls. He is assembling the phase-shifter control system, and is helping assemble the phase-shifters. It is anticipated that the BEC system will be fully installed and operational in the Spring, 1990 and that C. Nantista will be fully involved in the experimental program of microwave measurements with which the proper operation of the BEC design will be verified.

After the high-power BEC tests are complete, the BEC will serve as a high-power test-stand for accelerator structure development, and the collaboration will focus on a slightly different implementation of rf pulse compression which is similar in concept to the SLED technique (which is used at SLAC for increasing the power of the SLC klystrons by a factor of 2.5). It is believed that this SLED-related concept, which is called SLED-II, is better suited to the goal of engineering an efficient linac rf system at lowest cost, because multi-staged SLED-II systems utilize less high-power waveguide than comparable BEC systems. SLED-II involves storing klystron energy in long low-loss resonant cavities. These cavities discharge their energy as pulses of duration equal
to twice the cavity length. The final stage of compression to a 100 nsec pulse then would utilize a cavity approximately 50 nsec (50 feet) long and 3 inches in diameter. These storage lines can be reduced in length by a factor of 5 to 10 by periodic loading disks. C. Nantista has been working on this problem.

V. BUNCHER SYSTEMS FOR HIGH GRADIENT ACCELERATOR AND RELATIVISTIC KLYSTRON APPLICATIONS
(F. AGHAMIR, W. BARLETTA, D. CLINE, C. NANTISTA)

1989 – 1990 Description of Research and Progress

An industrially developed induction linac suitable for our experimental studies is available at Pulse Sciences Inc. in Agoura Hills, California. This accelerator provides a 1 kA beam at 1.6 MeV, delivered in 65 nsec pulses at an average power exceeding 20 kW. We have designed and constructed a bunching cavity operating at 5.7 GHz driven by 1 – 2 MW of RF power. Using the SUPERFISH simulation code, the reentrant cavity was designed to support the TM_{010} mode. In this cavity the large RF fields will produce an energy modulation on the high current beam. By drifting the beam over an appropriate distance one obtains a temporally modulated high current beam. At the point where the RF current becomes maximum, an output cavity can extract energy by decelerating the beam. The output cavity could also be replaced by traveling-wave structures or by a series of cavities. The combination of the buncher cavity followed by a high Q resonant structure provides a test bed that allows us to study a wide range of structure parameters.

An important parameter in buncher scaling is the beam plasma wavelength. The process of velocity modulation which bunches the beam and the space charge repulsion forces which cause the beam to debunch produce oscillations. For optimal bunching, the length of the drift tube between the input and output cavities are chosen to be approximately one quarter of the plasma wavelength. For a beam of radius, a, and
current, I, in a drift tube with radius, b, the plasma wavelength on axis is

\[ \lambda_p = \lambda_{rf} \sqrt{\left( \frac{17000}{I} \right)^5 \left( \frac{(\beta \gamma)^5}{1 + 2 \ell_n \frac{b}{a}} \right)} \]

where \( \beta = \frac{v}{c} \) and \( \gamma = (1 - \beta^2)^{-\frac{1}{2}} \). For our buncher system, the plasma wavelength is approximately 120 cm.

Another important parameter in scaling is the magnetic field required to confine the beam. For a beam of uniform cross section and radius, a, the necessary magnetic field is given by

\[ B = \frac{2mc^2}{ea} \sqrt{\left( \frac{2I}{17000} \right) \left( \frac{1}{\beta \gamma} \right)} \]

For our system, a magnetic field of approximately 1 K Gauss is required to confine the beam to a 5 mm radius.

Low power cavity experiments were performed with equipment on loan from the Electrical Engineering Department of UCLA. Figure 1 shows the experimental set-up for the cold tests. Our results confirm the code prediction for the resonant frequency. The radio frequency power was introduced inside the cavity through a small hole. Critical coupling was achieved by adjusting the hole size and monitoring the reflected power on a HP network analyzer. We used perturbation techniques to identify the mode structure and to evaluate the Quality factor. The results of these measurements are shown in Figures 2 – 4.
Plot of the electric field lines of $\text{TM}_{010}$ mode in the buncher cavity.
Figure 1.
Perturbation in the cavity
second measurements

Figure 4