**HEAVY ION FUSION ACCELERATOR RESEARCH (HIFAR)
HALF-YEAR REPORT***

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FOREWORD

The basic objective of the Heavy Ion Fusion Accelerator Research (HIFAR) program is to assess the suitability of heavy ion accelerators as igniters for Inertial Confinement Fusion (ICF). A specific accelerator technology, the induction linac, is being studied at the Lawrence Berkeley Laboratory and at the Lawrence Livermore National Laboratory.

The HIFAR program addresses the generation of high-power, high-brightness beams of heavy ions, the understanding of the scaling laws in this novel physics regime, and the validation of new accelerator strategies, to cut costs. Key elements to be addressed include: 1) Beam quality limits set by transverse and longitudinal beam physics; 2) Development of induction accelerating modules, and multiple-beam hardware, at affordable costs; 3) Acceleration of multiple beams with current amplification -- both new features in a linac -- without significant dilution of the optical quality of the beams; 4) Final bunching, transport, and accurate focussing on a small target.

Denis Keeffe died suddenly on March 11, 1990. His loss is strongly felt by his colleagues within the HIFAR Program as well as by his many friends and colleagues at LBL and throughout the world.

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HIGHLIGHTS

Thomas J. Fessenden

- 1,2 By very carefully controlling the experimental conditions of MBE-4 we are developing an excellent qualitative (almost quantitative) understanding of the beam emittance growth in MBE-4. As first predicted by the computer simulations of Celata in 1987, very strongly tune depressed and off-axis beams interact with image charges on the electric-quadrupole electrodes and with focus field imperfections to produce a strongly modulated and growing rms emittance which is stationary in the laboratory frame. The phase of the x and y emittance modulation is determined by the position of the beam with respect to the system axis as it enters the MBE-4 accelerator. Diagnostic access to the beams is only available at every 5th lattice period. Thus, the increase and decrease of measured emittance is explained by the sparse sampling of this complicated behavior. Over longer time periods the measured emittance at a specific point would often change to a different but reproducible value. We now know that this was caused by inadvertent changes in the initial conditions of the beam-offset at the entrance to MBE-4.
- 3,4. A very useful experimental technique (suggested by Denis Keefe) was to smoothly vary the zero current phase advance (σ_0) of the accelerator and observe the "coils" of the emittance and envelope oscillations as they slid by a fixed diagnostic station. In this way the beam behavior between diagnostic stations could be investigated. During these experiments we used the beam itself to detect and pinpoint imperfections in the MBE-4 transport structure to top and bottom. In particular we learned that the beams were receiving a large "kick" near L₁₁ that prevented us from continuing with other experiments. Attempts at locating the source of the trouble on-line were unsuccessful. After experiments indicated no significant other imperfections in the MBE-4 transport, we decided to remove the offending section and substitute for it one taken from the end of MBE-4. This allowed beam experiments to continue in parallel with investigations of the source of the trouble.
5. In preparation for acceleration experiments with 5 mA beams, the beam energy at the input to MBE-4 was measured. This information is required to initialize the SLID and SLIDE codes.

6. An improved 10 mA source for MBE-4 has been developed and experimentally investigated off line. Measurements compare favorably with EGUN calculations. We have also fabricated an assembly that will stabilize the MBE-4 injector geometry. We are awaiting the completion of experiments with the 5 mA beam to mount these improvements.
7. Simulations have suggested that only cold, off-axis beams increase in emittance as they are transported in electric-quadrupole lattices. With a technique for degrading the beam emittance used by Tiefenback on the SBTE experiments, we are planning to increase the initial emittance of the beams and experimentally study the saturation of emittance growth as seen in simulations.
8. Work toward improving the lifetime of the carbon ion source has continued. Many variations on the method of triggering the source discharge have been tried---so far without adequate success. Simulation work at Livermore suggests that the plasma switch can significantly degrade the source emittance if not optimized and that the design goal of 0.5π mm-mRad normalized emittance requires that the ion temperature of the plasma be less than ≈ 2 eV.
9. One half the high-voltage column of the 2 MV injector was tested with pulsed power to 980 kV before it began to break down in a non-recoverable manner. Inspection revealed that plastic debris, introduced during assembly, had lodged at the bottom of the column behind the electrodes and contributed to the breakdown. The diode was cleaned carefully and reassembled using all practical steps to keep the interior of the column as clean as possible. Half-column tests with one carbon beam are anticipated in April or May.
10. Tests of the 16-beam prototype electrostatic quadrupole designed for the ILSE sequence were completed. The challenging positional accuracy requirement of $\pm .002$ " for each quadrupole electrode was achieved as specified in the ILSE Conceptual Engineering Design Study. The assembly held a maximum of ± 52 kV after 8-10 hours of conditioning in high vacuum. This is more (but not comfortably so) than the ILSE requirement of ± 45 kV.

11. Metglas material of type 2605-S2 is available in quantity from Allied at the attractive projected cost of \$15/kg, as compared with 2605-CO at \$45/kg. Different from CO, S2 cores must be annealed after winding because the winding process changes the magnetic properties of the material. At this time, no insulation technique is available that would survive annealing and allow S2 to be effectively used for induction accelerator cores at interesting voltage levels. A simple test of a Kapton insulated test core showed no improvement in magnetic properties after annealing, presumably because of the difference in expansion coefficients of the two materials, which nullified the effects of annealing as the test core cooled.
12. One strategy of dealing with the longitudinal instability at driver parameters is to introduce adequate momentum spread ($\geq 1\%$) to stabilize the mode then perform a momentum analysis at final focus by splitting the beams into several (≈ 10) and directing each beam individually onto the target. Although perhaps possible, this scheme appears cumbersome and expensive.
13. Finally, the HILDA code is being used to study an intermediate facility that would provide a beam energy of 10-100 kJ using cost estimates based on presently available or "near-term" technology. These studies should be completed by the end of FY90. In parallel, work on completing the basic model for a full scale driver is continuing.

TRANSVERSE EMITTANCE STUDIES ON MBE-4

T. Garvey, S. Eylon, and T.J. Fessenden

Introduction

Previous investigations of the variation of the transverse emittance of MBE-4 with diagnostic station have shown that it is not, in general, constant.¹ The measured emittances normally show a gradual, but not monotonic, increase from the beginning to the end of the linac. In the light of recent simulation runs by K.D. Hahn² and by C. Celata³ it was suggested that the r.m.s. emittance might be continuously varying through the linac in an oscillatory fashion. This oscillation could not be confirmed by measurements made at the discrete points occupied by diagnostic stations. In order to simulate measurements at points immediately up and downstream of diagnostic stations it was suggested that one could vary the lattice quadrupole voltages (and, therefore, the zero-current tune) so changing the total accumulated phase advance experienced by the beam between the injector and some fixed diagnostic station. This is tantamount to allowing the coherent oscillation to slide past a stationary observer.

Experiments and results

Measurements were performed on the top (5 mA) beam of MBE-4 with the energy constant at its injection value (180 keV). We monitored both the emittance and beam centroid motion in the horizontal plane while varying the strength of the linac quadrupoles. The oscillation amplitude of the beam centroid is, according to the simulations of Hahn, a crucial parameter in determining the behavior of emittance variations. The dependence of the measured emittance on σ_0 , as measured at LP 25 is shown in Fig.1. One can immediately see that the emittance shows variations of 50% over the quadrupole range used in the experiment. This quadrupole range was limited by the desire to maintain the transported current constant for all measurements. The matching section for MBE-4 was not re-adjusted for each main linac quadrupole setting. However, we do not suspect the injection mismatch to be the cause of emittance growth. Indeed it is worth noting that some quadrupole settings above and below the matched setting ($\sigma_0=70^\circ$) result in emittance decrease from the matched beam.

Fig. 1 Variation of emittance with zero-current phase advance

The measured emittance variation at LP 20 shows a similar behavior to that at LP 25. In principle one might suspect that we could plot both data on a single graph showing emittance variation against an effective or "pseudo" LP. The pseudo period number for each data point would then be the ratio of the total accumulated phase to some reference σ_0 (the matched one, for example). In practice this is complicated by our discovery of a disturbance to the coherent motion of the beam during its flight through the linac so making the calculation of the total phase advance uncertain(4). Measurements and simulations of the beam centroid motion lead us to believe that the disturbance to the beam occurs at LP 11 and if one assumes that we should calculate the total phase advance from there we can generate the graph shown in Fig.2.

Discussion

The gross features of (Fig.2) are certainly similar to those found in the simulations of Hahn and Celata. Before concluding however that the observed phenomena is due to the large offset beams (4 mm in our experiments) or the strongly depressed tune ($\sigma=7^\circ$) we have to confirm that the emittance oscillations are absent in a well centered beam or a beam which is injected with a larger emittance (e.g by a factor of 2). This confirmation awaits further MBE-4 experiments and it is hoped that these will be completed by the next reporting period.

Fig. 2 Normalized emittance vs. pseudo lattice period

References

1. T. Garvey and S. Eylon, "Drifting beam studies on MBE-4", HIFAR year-end report, LBL-28264 December 1989.
2. K. Hahn and L. Smith, "MBE-4 Simulations", this report.
3. C.M. Celata, "The effect of nonlinear forces on coherently oscillating space-charge-dominated beams", LBL-2214, March 1987.
4. E. Henestroza, T. Garvey and S. Eylon, "Beam centroid motion and misalignments in MBE-4", this report.

MBE-4 SIMULATIONS

K. Hahn and L. Smith

This report summarizes the results of simulations of the 5-mA beam in MBE-4 and compares them to experimental results. The 10-mA beam previously used was subject to significant aberrations in the extraction region, leading to a distorted velocity profile and a hollow density distribution at the gun exit. By selecting only the central portion of the extracted beam, the density profile is almost uniform and the emittance is decreased more than in proportion to beam cross section area because the outer distorted velocity region in phase space is eliminated. Emittance variations in the 10-mA beam were largely due to the non-linear electrostatic energy of the hollow beam profile. This is no longer the case, and since the tune depression σ_0/σ is larger for the 5 mA beam (~ 10 instead of ~ 5), a new phenomenon begins to dominate. Namely, the excitation of coherent beam modes by external non-linear and image forces amplitude modulated by a coherent oscillation of the beam due to quadrupole misalignments or, in simulation work, by a deliberately imposed coherent oscillation.¹

First, a few words about the code, the image forces, previously occurring continuously, are now more realistically modelled by discontinuously replacing the electrode configuration by free space where there are no quadrupoles. This change has significantly altered the magnitude of the emittance variations. Also, the code has been checked again for accuracy in this new situation by decreasing time steps and increasing spatial resolution; it appears that the values regularly used to economize on computer time are adequate.

Simulation of a well centered beam with images and external non-linearities show negligible normalized emittance change for both coasting and accelerated beams. This is true also for a coherently oscillating beam if images and non-linear forces are turned off. The latter result is also a further demonstration that no anomalous numerical effects are influencing the results.

Fig. 1. Normalized emittance vs. lattice period. Solid dots emphasize the possible values at the measuring stations (not experimental data)

Fig. 1 shows the time histories of the x and y emittances along the channel. With an initial beam displacement of 3 mm in both the x and y directions, represented by the upper set of lines, the emittance shows rather large oscillations

imposed on a steady growth along the channel. The typical oscillation frequencies are observed; a fast oscillation frequency of approximately $(1+\sqrt{2})\sigma_0$, and a beating frequency of $\sim(\sqrt{2}-1)\sigma_0$. On the other hand, the beam without initial displacement shows essentially no growth. Runs made with 1.5 mm initial displacements showed about a factor of 3 less change in magnitude of emittance variations, suggesting quadratic rather than linear dependence on amplitude. The observed frequencies are the same for both cases. When the sum of squares of x and y emittances is plotted, a rather regular pattern is observed. This suggests that there are a few dominant collective modes that are operational, perhaps from the beginning. However, when x-only initial displacement of $\sqrt{18}$ mm is used, the emittance pattern is quite different from above suggesting that different type of modes are excited.

Fig. 2. Experimental emittance vs. total phase advance are plotted with squares and circles. Two other superimposed curves are x (broken line) and y (solid line) emittance from lattice period 0 to 14 of Fig. 1.

Fig. 2 shows the experimental emittance versus the total phase advance expressed in terms of the pseudo lattice period² Superimposed are the simulation emittance time traces from the Fig. 1. Both show similar frequency and amplitude in the region where the total phase advances from the onset of the coherent displacement are equal. Since the coherent oscillations in the experiments are different from the oscillations used in simulation, only qualitative conclusions are possible.

In summary, the recent MBE-4 simulations show interesting phenomena which are caused by the coupling of coherent beam displacement and non-linear field, external or induced. Rough parametric scaling of the effect of beam displacement, tune depression, and magnitude of external non-linear fields on the emittance is being explored for possible future implications. Initial comparison with experimental data is encouraging in terms of frequency and the magnitude, though indirect. Further detailed verification of experiments in terms of parametric scaling is desirable to rule out possible accidental coincidence.

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BEAM CENTROID MOTION and MISALIGNMENTS IN MBE-4.

E. Henestroza, T. Garvey and S. Eylon

In the course of studying the variation of emittance with phase advance per period (σ_0) on MBE-4 we monitored the mean position, $\langle X \rangle$, and mean angular offset, $\langle X' \rangle$, of the beam centroid at several positions along MBE-4. The variation of $\langle X \rangle$ with σ_0 at lattice point (LP) 25 is shown in Fig. 1. It is immediately obvious that the period of the observed oscillation is too long to be due to a betatron oscillation induced at the beginning of the linac. A 180° phase advance variation over 25 cells would require a change of 7.2° per cell whereas the corresponding observed change is much larger. In addition, the amplitude of the oscillation turns out to be much larger than one can account for on the basis of the initial offsets in $\langle X \rangle$ and $\langle X' \rangle$ and the lattice properties of the linac alone. Similar remarks apply to the oscillation in $\langle X' \rangle$ at LP 25 and to the position and angle data at LP 20. However, if one maps the data at LP 20 through 5 periods, one obtains good agreement with the data at LP 25 (Fig.1). It was quickly realised (A. Fallens and D. Keefe) that the discrepancy between experiment and prediction could be understood if one assumed that the beam had suffered a "kick" or "kicks" during its transport through the machine, perhaps due to a misaligned quadrupole. The observed oscillation would then consist of two (or more) waves of different frequencies and amplitudes and indeed this is qualitatively evident from the data.

In order to test this hypothesis we carried out similar measurements further upstream to see where the observed motion first departed from the expected and so to help locate the origin of the kick. Fig.2 shows the dependence of $\langle X \rangle$ and $\langle X' \rangle$ at LP 10 with σ_0 . The amplitude and period of this oscillation is much as one would expect from the initial condition except that it appears to be centered about a line -0.36 mm from the nominal linac axis. This is believed to be due to a small disturbance to the beam originating between LP 6 and LP 10. However similar measurements at LP 15 (Fig.3) show that the amplitude has already increased above the ± 1.4 mm seen at LP 10 and that the periodicity is destroyed. We believe this to be evidence of a significant mechanical misalignment or imperfection of the focussing quadrupoles between LP 11 and LP 15. The possibility of an electrical problem has been excluded following a fruitless search for stray deflecting fields or unpowered quadrupoles.

If one assumes that the disturbance in between LP 11 and LP 15 is due to a single kick then the measured data is best fitted by a kick at LP 11. It is of interest to note that data taken on the bottom beam of MBE-4 also indicates a problem in this area. At the time of writing we are making an extensive search to confirm the source of the misalignment before continuing with further beam measurements in MBE-4 [Ref. 1].

Reference

1. R. Jonsson, S. Eylon, and D. Vanecek. "Survey and Alignment of MBE-4", this report.

Fig. 1 Measured beam centroid displacement and angular offset at LP25 compared with measurements taken at LP20 and mapped into LP25.

Fig. 2 Measured beam centroid displacement and angular offset at LP10.

Fig. 3 Measured beam centroid displacement at LP15.

SURVEY & ALIGNMENT OF MBE-4

R. Johnson, E. Eylon, and D. Vanecsek

The alignment of the MBE-4 electrostatic quadrupole focusing lenses is checked 2 to 4 times a year (refs. 1 and 2). Optical targets are sequentially placed at each diagnostic station and surveyed with respect to a straight line using a least squares data fit. Then the machine is realigned to $\pm 0.005''$.

June 1989. A 2 week period was devoted to survey and alignment, measuring some 80 target positions in the north and south beam lines. Special attention was given to aligning the matching section right after the ion source. The results showed that $\pm 0.005''$ alignment was achieved through the transport sections and $\pm 0.008''$ in the matching section. Results for the top beam are shown in Fig. 1.

Fig. 1. Survey of quadrupole horizontal and vertical displacements along the top MBE-4 beam line (z) taken after June/89 realignment.

October 1989, (after the Santa Cruz earthquake). MBE-4 was in operation when the earthquake struck and was about 3/4 way through an emittance scan. The scan continued to completion with the loss of only 2 pulses. That and subsequent scans gave normal data. Nevertheless, a survey was made immediately and no large misalignments were observed except for a 0.015" horizontal offset where MBE-4 crosses from one floor slab to another in Bldg. 58. In the past horizontal movements of this floor joint as large as 0.030" have been detected. This survey indicates that the earthquake caused no large misalignments to MBE-4.

February-March 1990. The motion of the beam centroid reported in the previous paper³ prompted us to repeat the alignment survey of MBE-4. Since in a survey of MBE-4 access to the quadrupole lenses is only allowed at the end of each section we have to rely on the integrity of the original assembly alignment for the positions of the inner quadrupoles. We decided to try to check the position of all the quadrupole lens electrodes in the top beam line of sections "B" & "C". Three special targets were made; a) Thin uniform, b) thin tapered & c) long. No large misalignments were found using the thin targets in sections "B" & "C" [Fig. 2]. The long target was positioned with extension tubes in the top beam line of section "C". The measured displacements were $< \pm 0.010''$, but we were looking for errors 3 or 4 times larger. Positioning this target was quite tedious and time consuming, and we are not presently sure of the accuracy of this method.

Fig. 2. Top beam quadrupole alignment survey in sections B and C taken with a target along the beam line (z).

The results of our beam experiments still show section "C" to be anomalous whereas all other sections of MBE-4 act as predicted by theory. We therefore have decided to remove this section and exchange it with section "F". Once section "C" is removed we plan a thorough alignment check to find the cause of anomalous behavior of beams in this section.

The relative motion between the Bldg. 58 floor slabs is being monitored. Two stations with permanently placed measuring fixtures have been monitored daily for the past three months. Figure 3 shows the horizontal data. A slow differential drift of 0.010" is seen but more observation time is required to determine if this is permanent or cyclical.

Fig. 3. Relative movements of Bldg. 58 floor slabs at the north and south measurement stations.

References:

1. R. Johnson, S. Eylon, H. Meuth and W. Tiffany, "Survey and Alignment of MBE-4," HIFAR Half-Year Report, October 1, 1988-March 31, 1989.
2. R. Johnson, S. Eylon, and H. Meuth, "Survey and Alignment of MBE-4, Dec. '88-Jan. '89," HIFAR Note-237.
3. E. Henestroza, T. Garvey, and S. Eylon, "Beam Centroid Motion and Misalignments in MBE-4," This report.

ENERGY ANALYSIS OF THE 5mA MBE-4 BEAM

T. Garvey and E. Henestroza

Although recent work on MBE-4 experiments has concentrated heavily on studies of transverse beam dynamics we have devoted some time to investigations of the longitudinal energy spread of the 5mA beam. As the operating current in MBE-4 is now lower than previously, one might suspect that the acceleration schedule required to produce self similar bunch compression will be different. In order to check this we are bringing the SLID [Ref. 1] computer code in to use, as well as test-running the alternate version SLIDE [Ref. 2].

The temporal dependence of the beam current and energy have been measured at injection using the small electrostatic energy analyzer [Ref. 3]. These data were subsequently used as input parameters for SLID/SLIDE runs with no applied pulser schedule, i.e. for a drifting beam [Fig. 1]. The runs were done for a number of different values (between 2.5 and 4) of the electrostatic screening factor, g . The reduced transverse dimensions of the 5mA beam from the 10mA beam implies that the g factor required for 5mA SLID runs will be larger than for the 10mA case where $g=2.2$ [Ref. 4]. The resulting energy and current profiles predicted by SLID/SLIDE for a beam drifting to the end of the machine were then compared with the corresponding measured profiles. From the comparisons we were able to conclude that the experimental data is reasonably well fitted with $g=2.8$ although the best fit seems insensitive to small changes in g . The measured and computed profiles of energy and current at the end of the linac for the drifting beam are shown in Figs. 2 and 3. Notice that the SLIDE code appears to fit the experimental data slightly better than the SLID code.

Having obtained an estimate of g appropriate to a 5mA beam we are now in a position to input acceleration waveforms to SLID/SLIDE and determine a suitable schedule for future 5mA accelerated beam studies.

References:

1. C.H. Kim and L. Smith, "A design procedure for acceleration and bunching in an ion induction accelerator", Particle Accelerators, Vol.18, pp101-113, 1985.
2. E. Henestroza, "Study of the Longitudinal Ion Dynamics- Extended Version: SLIDE". HIFAR Year-End Report, LBL-27230.
3. H. Meuth and W.B. Ghiorso, "A compact energy analyzer for MBE-4", HIFAR Year-End Report, LBL-24519.
4. A.I. Warwick et al, "Preliminary report on MBE-4 - an experimental multiple-beam induction linear accelerator for heavy ions", HIFAR-NOTE 222.

Fig. 1 Current and energy profiles measured at linac input.

Fig. 2 Measured and computed (SLID) profiles of current and energy at end of linac (drifting beam).

Fig. 3 Measured and computed (SLIDE) profiles of current and energy at end of linac (drifting beam).

AN IMPROVED 10 mA ION SOURCE FOR MBE-4

E. Eylon, E. Henestroza, R. Johnson, W. Chupp, and D. Vanecek

Previous studies¹ revealed that observations in the MBE-4 injector were leading to excessive emittance growth as the beams were injected into the matching section of MBE-4. A quick solution² was to improve the beam dynamics by scraping the beam to 5 mA. Along with this solution we are in the process of developing a new improved 10 mA source.

The new source consists of a curved ion emitter, a modified Pierce electrode (graphic plate) and a new mechanical assembly. EGUN calculations using the new improved source shows (Fig. 1) a uniform current density and a lower emittance for a beam emerging from the new diode and scraped to 10 mA at the input to the MBE-4 matching section.

A new technique was developed and used to fabricate two curved emitters. The performances of the new emitters were evaluated in a test stand using a diode configuration with anode cathode spacing of 0.5" and voltages up to 20 kV. Figure 2 shows a temperature profile measurement of the emitter surface along a diameter and a current density measurement at 0.9" from the diode cathode grid. The current density measurements were found to be in agreement with EGUN calculations (Fig. 2) for the same geometry, thus qualifying the source for further tests in MBE-4.

A new mechanical assembly (Fig. 3) which stabilizes the diode geometry (especially when going from air to vacuum) and improves the alignment of the four MBE-4 sources was designed and fabricated. The new assembly uses four insulating posts connecting the graphic plate (anode) to the output aperture plate (cathode).

References:

1. H. Meuth, K.D. Hahn, S. Eylon, L. Smith, "A Detailed Study of Transverse Emittance in MBE-4," HIFAR Half Year Report, LBL-27230, p. 6, Oct.-Mar. 1989.
2. S. Eylon, E. Henestroza, H. Meuth, "A Improved Ion Source for MBE-4," HIFAR Year End Report, LBL-28264, p. 6 Apr.-Sep. 89.

Fig. 2 Test stand measurements of the current density profile J(DATA) compared with EGUN simulation J(EGUN), and the temperature profile taken at the emitter surface.

Fig. 1 EGUN calculations of source current density profile and divergence angle at the input to the MBE-4 matching section.

Fig. 3 Top and side views of the new source mechanical assembly.

EMITTANCE DEGRADATION VIA A WIRE GRID

W. M. Fawley and E. P. Lee

Following the recent observations of emittance growth in the (unaccelerated) MBE-4 beam, there has been interest in degrading the initial emittance of the beam to determine if the final value of the emittance more or less remains the same as predicted by particle simulations of the "Celata effect"[1]. (The reader should be cautioned that the emittance growth in these experiments observed between lattice point 15 and 30 is likely due to the kick in lattice cell C and may not be present following the substitution of cell F for C). These simulations indicated that the emittance of a misaligned beam would grow for early z due to the anharmonic forces present from the dodecapole moment of the electrostatic focussing field and the beam's image charge, and then reach an asymptotic value with little additional growth for large z . MBE-4 is thought to be too short for an initially low emittance beam to reach the predicted asymptotic final emittance. By raising the initial emittance to a larger value, we hope to decrease the necessary length in z to a small enough value that the asymptotic behavior of the emittance variation will be observable in MBE-4.

Fig. 1 Mesh configuration between anode and cathode plane

The most direct method of degradation is passing the beam through a closely spaced, wire grid just before the cathode plane (see Fig. 1). An earlier calculation performed by M. Tiefenbach in his Ph.D. thesis[2] suggested that the change in the angular spread of the beam scaled as

$$\Delta\theta^2 \sim \left(\frac{\Delta E_{\parallel}}{T}\right)^2 w^2$$

where $\Delta E_{\parallel}$ is the change of the longitudinal electric field across the grid wires, w is the wire spacing, and T is the beam's kinetic energy at the grid. We re-analysed this problem [3] using two different approaches: a Fourier series expansion and complex potential method. In the Fourier series approach, we presumed that the grid was held at a fixed potential V_0 relative to the anode. In the limit that the grid wire spacing w is small compared to the anode-grid separation d , the Fourier series results reproduced those of Tiefenbach, i.e.

$$\langle\Delta\theta^2\rangle = \left(\frac{eV_0}{T}\right)^2 \left(\frac{w}{d}\right)^2 \times \frac{1}{96}$$

For the general case, the increase in angular spread is an infinite Fourier series whose leading terms are equivalent to the above equation but whose higher transverse wavenumber terms fall off more rapidly due to interference effects from image charges on the anode and cathode planes. For equal wire spacing, a two-dimensional mesh produces half the angular spread change as does a one-dimensional grid.

The complex potential method involves writing the potential as a product

$$\Phi = \frac{-2\lambda}{4\pi\epsilon_0} \operatorname{Re} f(z)$$

where

$$f(z) = \ln\left[\sin\left(\frac{\pi(z-id)}{w}\right)\right] - \ln\left[\sin\left(\frac{\pi(z+id)}{w}\right)\right]$$

reproduces the logarithmic singularities of the potential on the grid wires ($=V_0$) and their images on the anode plane. In this case, λ is determined by forcing the potential to go to a specified value as z goes to infinity. In the limit w/d is much less than one, Tiefenbach's result is produced again.

Numerically, to double the emittance of MBE-4 from its unnormalized value of 12 mm-mrad at 200 kV requires a 96 mil wire mesh placed within the cathode-anode spacing of 4 inches.

References

- [1] C. M. Celata, "The Effect of Nonlinear Forces on Coherently Oscillating Space-Charge-Dominated Beams", LBL-22214, 1987.
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ION SOURCE DEVELOPMENT

H. L. Rutkowski

The main emphasis in the ion source program has been extension of source lifetime, remote reconditioning methods, emittance reduction, and investigation of the potential of arc sources for multi-charged ion extraction. Three sources with the conventional trigger design have been run in the 20-30 K shot lifetime region. One of these sources had copper trigger electrodes and two had tantalum trigger electrodes. The diagnostic used in these lifetime studies is the shot-by-shot emittance scan. The computer control has been modified to include an automatic misfire monitor which causes an X to appear on the emittance plots at a point where the source has failed to fire before the extraction pulse occurs. The normal failure mode of these sources is a gradual increase in the misfire rate starting in the 20-30 K shot region. The misfires are caused by a buildup of carbon deposits on the trigger surface which gradually degrades the trigger plasma. A healthy trigger plasma is necessary not only to achieve reliable firing but also to achieve high quality pulses in the emittance runs.

Several trigger designs were tried in an attempt to increase the lifetime. Also, several cleaning methods were tried with the conventional surface flashover trigger in an attempt to find a way to develop a remotely reconditionable design. The methods that were used were capacitor discharges and D.C. vacuum heating. The use of a repetitive trigger for many shots (18-30 K triggers) with the main arc pulser shut off cleaned the source trigger enough to get one or two thousand pulses before degradation occurred again. The repetitive triggering cleaned a narrow path between the trigger wires which was easily recoated with carbon. The ceramic ceramic rod in which the trigger wires reside was cut to provide only a narrow strip between the wires in the hope that this trigger cleaning method would be more effective by allowing carbon to deposit only in a narrow region between trigger wires. The source would not fire once we destroyed the flashover surface contact with the cathode. Evidently the trigger plasma closely hugs the ceramic surface and follows it to the cathode. The break in surface contact in this design must have caused the trigger plasma to flow down into the cathode interior. Attempts to use D.C. current heating created a glow between the wires but no real improvement in firing. A ten joule capacitor discharge produced temporary recovery. In an attempt to eliminate surface flashovers which are subject to surface contamination, one of the trigger wires was brought around the outside of the source and run backwards through the main arc anode aperture to create a volume breakdown. The two trigger wires inside the ceramic rod were connected electrically in parallel. The trigger discharge was between these wires and the wire in the anode hole. Another source was constructed with a single wire in the ceramic rod. Adequate plasma flux was not obtained from these versions of the source. Several wire positions were tried for the anode hole wire to no avail.

At the present time work has started with a source that does not have a separate trigger plasma generator but rather uses a pulsed overvoltage of the cathode - anode gap to initiate the

arc pulse. The main arc pulse generator is coupled to the gap through the secondary of a series pulse transformer. Since the trigger plasma has been an important factor in the quality of the output beam, it remains to be seen if this new design is a suitable solution to the problem. If the design is successful, the carbon cathode could be fed in as it erodes, and the trigger would not need cleaning.

Dennis Hewett at LLNL has been simulating the plasma switch on the computer in an attempt to find an optimum design of the plasma switch from the viewpoint of creating low emittance beams. His code is called GYMNAS. The results indicate that the plasma switch can be responsible for significant transverse energy content in the ions from the source, which translates into emittance in the beam. Unless the configuration is properly designed, the plasma switch can be responsible for much more emittance than the inherent ion temperature of the arc. By allowing electrons to penetrate partially through the switch grid at the time of beam extraction the ions can be shielded from the electric fields of the wires and thus acquire less transverse energy. So far the simulations indicate that with 2 eV initial ion temperature, a 1×10^6 m/sec transverse ion velocity might be obtained for a 2 inch diameter beam, this would give an intrinsic source emittance of $8.5 \times 10^{-7} \pi$ m-rad which is to be compared with our design goal of $5 \times 10^{-7} \pi$ m-rad normalized. The source would have to be tailored to the plasma properties required by the simulations. The assumed 2 eV ion temperature is not known from experiment, but this value would give an intrinsic emittance of $4.8 \times 10^{-7} \pi$ m-rad in the absence of the plasma grid effect. If the actual ion temperature is lower the source emittance will be lower. Work is underway to test these predictions experimentally.

Experiments have also been performed to study the multi-charged ion production capabilities of the source. In the past multi-charged ions have been observed from vacuum arcs that do not use the plasma switch and which use an applied B field. By contrast plasma switch sources without B fields have always yielded singly charged ions. Experiments have been performed to show the effect of biasing the plasma potential in the source to inhibit electron loss from the drifting source plasma.¹ This electron loss is responsible for creating a plasma potential that inhibits the transport of multiply charged ions in the conventional plasma switch source. By electrically separating the arc anode and the metal drift tube, and by applying a suitable bias voltage to the anode plate, enhanced production of Al^{++} , Mg^{++} , Pb^{++} and Pb^{+++} was observed. Using the same diagnostics it was confirmed that only C^+ ions are emitted from the carbon version of the source.

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2 MV INJECTOR

H. L. Rutkowski, D. Brodzik, and A. Faltens

After considerable difficulty in fabricating the titanium electrodes and large delays by the vendors, the electrodes were installed in the insulator module which had the best dimensional accuracy. Some difficulty was encountered with the liquid resistor mounting hardware and a couple of designs had to be tried before sufficient dimensional stability could be achieved. The water control system which regulates the conductivity of the water in the liquid column grading resistor was delivered by Millipore to LBL and performs satisfactorily. The high voltage system was fired near the end of calendar 1989 using the twelve tray subsection of the full inductively graded Marx generator. The column electrodes had been installed and aligned in the ceramic module while in a temporary clean room. No beam was used in these tests. The plan was to condition the column with pulsed discharges before installing the source and the associated electronics.

The column was ultimately subjected to 980 kV before it started to break down in a non-recoverable manner. Attempts to recondition led to breakdown at lower voltages. The target operating voltage for this first half of the full 2 MV column is 944 kV. After the tests the column was reopened and inspected. Burn marks appeared on the ceramic and the titanium conical sections. Most of the burns were located near the bottom of the cylindrical column, which is normally mounted with its axis horizontal. Considerable dusty debris was found inside, leading to the conclusion that the breakdown occurred mostly in the area where dirt had settled in the bottom of the column. Chemical analysis of the debris showed that it contained no aluminum or silicon which are both present in the ceramic but that it did contain polyester which was present in the plastic shims used during electrode assembly. Otherwise the analysis showed some sulfur, iron, titanium, calcium, and copper. The module was rechecked for vacuum leaks to see if SF_6 gas could have leaked in and caused the sulfur to be present in the residue. No leaks were found and no sulfur cutting oils were used in fabrication. The titanium could have come from the electrodes and the copper from TiCuSi brazing compound. We concluded that more care during the critical column assembly process was required.

As a consequence of the above findings the column assembly process was modified. First, the clean room was modified by adding an entrance area outside the assembly area. Hats and beard guards were worn during column assembly along with shoe covers and coveralls. Thinner plastic shims were used to avoid leaving plastic shavings behind after use. After assembly caps were put on the column to protect it from dirt in the experimental area. During assembly of the electron trap and the source sub-assembly some exposure was unavoidable. In short all practical steps to keep the interior of the column as clean as possible were taken. The titanium electrodes were repolished before assembly.

As an additional step to try to insure a minimum of damage during the conditioning process, the column was conditioned section by section with a high voltage D.C. supply with limited current. Since imperfections are inevitable and breakdowns during conditioning are thus inevitable, limiting the current to less than 1 mA offers a way to condition yet not inflict significant damage to the column. Using the 1 MV pulsed generator involves the potential for significant damage because of the higher energy involved in the breakdowns. All sections except the first were conditioned to 200 kV which is the limit of the supply. The design for these sections calls for 175 kV pulsed. The first section is a 69.8 kV section and it was conditioned to 20% above design.

The source and its associated plasma switch and pulser electrodes were installed before these conditioning runs so that the vacuum system would not have to be opened after conditioning. The electronics to drive the source, the pulser to inject the 1 μsec current pulse, and the rheostat to allow voltage adjustment on the first column section are all being installed. Also the fibre optics controls for the source are being installed. The next step is to test this half column section with beam up to the voltage we can achieve closest to the design value.

CBB 8912-10653

Fig. 1 First half of injector column with external high voltage shielding structure removed.

ELECTROSTATIC QUADRUPOLE PROTOTYPE DEVELOPMENT ACTIVITY

S. Mukherjee

The 16 beam electrostatic quadrupole¹ design and fabrication were completed by Sept. 30, 1989. The individual component was cleaned per LBL specification for high vacuum application and assembled with proper care to avoid organic contamination. The assembly task was performed by one person within a period of 7 hours. The assembled quadrupole array was ready for dimensional measurement on October 15, 1989.

DIMENSIONAL MEASUREMENTS:

The ILSE conceptual engineering design² indicated that the quadrupole array should hold position tolerances of $\pm .002$ inches in both X and Y direction for all the electrodes. We contracted Applied Dimensional Metrology Inc. at San Jose CA, for the measurement of critical dimensions. This work was performed on their Lietz Coordinating Measurement Machine (CMM) which is programmed for operation using DIN based computer software. This machine is able to measure complicated surfaces to accuracies less than 40μ inches over approximately a four foot cube. The outer ground plate of the assembly was taken as the reference datum plane of measurement. The quadrupole was kept in a constant temperature room for several days before actual measurements were performed. The measurement probe of the CMM took X-Y measurement at two depths, i.e. 2 inches and 7 inches from the reference plane. This method ensured measurement of true positions of the quadrupole electrodes in their spatial configuration.

The software of this CMM is capable of determining a best fit center of the entire quadrupole array based on the true measured position of the electrodes. The X - Y coordinates were rotated by 45 degrees so that the fiducial slots were parallel to these new coordinates X' - Y'. The virtual center of the true quadrupole and the fiducials were measured with reference to the new coordinates. This measurement established the fixed reference of the electrostatic field center and the fiducials for this particular quadrupole assembly.

The results of the measurements showed that the location accuracy for individual electrode was within the required specification of .000 to .004 inch and that the virtual center of the quadrupole was within .000017 to .00002 inch of the mechanical center of the array. More details of the CMM measurements are available in HIFAR note # 255.³

ELECTRICAL TEST:

The high voltage test was performed in a test tank which was pumped down to 2×10^{-6} torr pressure. Two power supply-units each of capacity of 80 kV DC were used to provide both positive and negative voltages. During conditioning, the maximum voltage reached was 104 kV DC within 7 hours of testing. Polishing the electrode's tip area eliminated excessive sparking that was noticed during earlier conditioning tests shows the rate of conditioning voltage rise.

The ILSE design requires a maximum of 45 kV on this quadrupole.

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MAGNETIC INDUCTION CORE STUDIES

A. Falten and C. Fong

Most of the future induction linac scenarios have been based on using amorphous metallic glass cores such as Allied's Metglas. The materials for these cores have gone from the research stage to the production stage, but considerable work remains in the areas of annealing, winding, and insulating. At the present time, the insulation requirements for the power industry are not severe, because of the relatively low voltage from lamination to lamination. Likewise, for induction acceleration use, the previously developed and tested silicon dioxide insulation is satisfactory for the longer duration pulses, say, a few microseconds in duration. For the submicrosecond pulses; however, there is not yet an economically acceptable solution.

The two most interesting candidate materials in the U.S. are the type 2605-S2 and the type 2605-CO made by Allied. The S2 is being made in commercial quantities, and has a projected cost of about \$15/kGm contingent on satisfactory insulation development. The CO is an existing material with an already developed insulation scheme, but has a projected cost of \$45/kGm. The scheme that works today is to select the CO material, which is not extremely sensitive to stresses, and to rewind the material with thin Mylar insulation after the material has been annealed. The only commonly available insulating material that can withstand the annealing temperature is Kapton, but in addition to its high cost, it also tends to stress the core material on cool-down after annealing. Most of these general features have been known for some time from earlier work. The number of annealing/winding possibilities is very large, and we wanted to explore at a low level some of the possibilities which might allow use of the less expensive material. At this early stage, we can only report that the nonannealed S2 material has significantly lower magnetic properties than the annealed material, and that our first attempt to anneal a wound core did not improve its properties.

Test cores were made of the new 4" wide and 6.7" wide 2605-S2 ribbons using 0.3 mil thick Kapton insulation, as shown in Fig. 1. The near term expected uses require only a 20 volt per lamination insulation, for which the Kapton is more than

adequate. The cores were wound at LLNL using winding apparatus developed for the laser isotope separation program. The cores were wound with 800 turns each. The actual ribbon thickness was a very good 0.75-0.80 mils, which together with the thin insulation resulted in a build-up of very nearly 1.0" for the 800 turns, for a packing factor of about 0.62. The 4" wide specimen was annealed at 380°C for over eight hours in a programmable controlled annealing oven. Heat-up and cool-down were therefore controlled. Both cores were electrically tested before annealing, and the 4" core was tested after.

The test procedure is to discharge a large capacitor through a suitable winding of a few turns. The induction field is measured with a separate winding and a high impedance voltage probe. The excitation current is measured with a current transformer on the low voltage side of the winding. The circuit is configured to produce a large amplitude half-sine after the core saturates, thereby reverse-charging the capacitor and turning off the thyatron switch used in the circuit. The capacitor rings back through the core and a linear inductor with a series diode, thereby restoring some of the charge to the capacitor and resetting the core. The adequacy of reset can be checked by alternating low-voltage and high-voltage pulses, or by reversing the drive leads. This mode of operation approximates the intended use conditions, where a separate pulser resets the core to a negative remanence.

The results of these preliminary tests are that the as-cast S2 cores had:

$$B^T = 700 \text{ gauss,}$$

$$B^S = 13,800 \text{ gauss,}$$

and a general behavior like that of a magnetically hard material with a sheared-over hysteresis loop. The first annealing effort gave virtually the same values. There are several possible explanations. First, it is possible that the difference in the coefficient of expansion between Metglas and Kapton would cause excessive stress, thus exceeding the anisotropy limit on cool down. Another would be that the annealing time was excessively long, thus causing partial recrystallization of the amorphous structure of the Metglas.

CBB 8911-9912

Figure 1. Metglas 2605 S2 were wound with 3 mil Kapton for these series of tests.

A PRELIMINARY CONSIDERATION OF BEAM SPLITTING IN MOMENTUM SPACE

David L. Judd

The conditions under which the longitudinal resistive-wall instability may create problems for heavy-ion induction-linac drivers for inertial-fusion power plants have been receiving consideration. Among the possible palliative measures is the increase of thermal velocity spread. Such a spread should perhaps be about an order of magnitude greater than is desirable to avoid excessive chromatic aberration in final-focusing lens systems. The lenses need spreads of order $\pm 1\%$ or less; thus beam pulses should have spreads of order $\pm 0.1\%$ or less preceding final drift compression by a factor of order ten in "standard" scenarios. However, a spread of order $\pm 1\%$ at that point (at the linac exit) could be tolerated by the final lens systems if each beam were to be momentum-analyzed into of order ten separate beamlets, each having a spread of order $\pm 0.1\%$, later to be increased by longitudinal drift compression.

It has been pointed out E. Lee that it is more effective to perform the splitting by introducing an ordered velocity tilt of order $\pm 10\%$ (about an order of magnitude greater than the thermal spread sought), which was previously required to drive the drift compression, and then perform a momentum analysis of each beam into, say, ten beamlets. Each of these would be "born" with a bunch length roughly one tenth that of the original bunch, thus removing the need for longitudinal drift compression. Also, each beamlet would have its own thermal velocity spread of order $\pm 1\%$, tolerable to the final lenses; there would be no increase by drift compression because none would be needed.

Here we summarize some aspects of a preliminary conceptual exploration¹ of the design of a momentum-analyzing system to accomplish such a task. A combination of "lenses" and "prisms" (realized by quadrupole singlets and uniform field (dipole) bending elements) bring incoming monoenergetic beams to foci at positions separated by momentum. Important parameters are the total path length L from linac exit to focus, and the dispersion parameter $D = \Delta x_p / (\Delta p/p) =$ transverse separation per unit fractional momentum spread. Thin septa will be needed between the beamlets, on which a fraction of the particles will impinge; an upper limit on this fraction, and thus a lower limit on D , is required to avoid

septum destruction and waste of too much beam energy. Lenses producing convergence in the bending plane will give divergence in the normal direction, making line images of height Δy in the focal plane at distance L for monoenergetic groups of ions; a lower bound on Δy is also required. A successful design must (1) make Δy large enough; (2) make D large enough; and (3) avoid unnecessarily long L . A lens with large focal power $1/f$ increases Δy and shortens L but reduces D . If the focal power represented by a single thin lens is divided into two or more separate lenses spread out along the path, the effect of spreading is to combat the dispersion we are trying to enhance, and also to produce a smaller Δy . Thus a single quadrupole at the system entrance is best. A sketch is shown in the figure. An analytic study is described in Reference 1. Representative values of the parameters indicated on the figure are: $\theta = 15^\circ$, $D = 5$ m, $R = 27$ m, $f = 27$ m, $s_1 = 7$ m, $s_2 = 16$ m, $L = 23$ m, and $\Delta y/r = 3.7$, with r the incoming beam radius. In the HIFAR Note it is shown that the system optics may be improved by choosing Δx_p larger than Δy , but at the expense of increasing the scale of lengths; the argument against this is an economic one.

A number of problems remain to be studied should such a scheme be needed. The focal plane of the analyzer is tilted from being normal to the central ray, by an amount which is impractically large in some designs. The containment of transverse space charge forces in the beamlets may prove difficult because of lack of space between them for a considerable distance downstream from the septa. Finally, longitudinal control of beamlets that are "all ends" may provide a challenge. In conclusion, this first look has not shown the task to be impossible, but it is certainly an unappealing option.

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Figure 1. Sketch defining several momentum-analyzer parameters.

STATUS OF THE OPTIMIZATION CODE HILDA

E. Lee, E. Close, and C. Fong

A near-term induction linac module design has been completed according to the following design philosophy. The machine is considered to be an intermediate facility, not a full scale power driver. The components and materials used are based on near-term technology. This is also true of their cost estimates. By "near-term" is meant that the materials and components will probably be current technology in the reasonably near future (within 5 years) and a reduction of unit cost will be taken only for mass production or a learning curve. The beam focusing uses pulsed magnetic quadrupoles having a pulse length of about 1.0 msec. The beam currents considered are on the order of 20 A per beam and thus load the pulsers lightly. The repetition rate is low, on the order of 1/10 Hz. The component life is assumed to be rather low compared to a full scale driver, around 10^6 pulses. This intermediate facility could provide a beam energy on the order of 10-100 kJ.

HILDA subroutines that design the focusing quadrupoles have been coded and tested. Also subroutines that design the accelerating cores and structures have been coded and tested. Subroutines for the costs of the pulsers have been coded and tested. Work is progressing on completing the remaining costing subroutines;

including magnet power supplies, vacuum, cooling, and conventional facilities. As these subroutines are completed, appropriate code drivers are built that enable the modules to be individually tested. This allows us to check that the model and the corresponding subroutines are accurate and give reasonable results over the expected parameter ranges. Preliminary cost studies using this intermediate facility should be available by October of this year.

In parallel, work is continuing on completing the basic model for a full scale driver. It is our intent that the experience we acquire using this intermediate facility model within the HILDA code structure will help serve as a guide to developing this full scale driver model.

Model development for special components such as the injector and combiner is underway. Documentation of HILDA is occurring concurrently with the program development. All corrections, additions, modifications are consistently made in the HILDA program document. This program document is used as the primary source of the FORTRAN source code, which is then down loaded from the document to the VAX mainframe for testing and running. Hence, up-to-date code documentation is automatically present whenever a computation is made.

Figure 1. Typical Near-Term Accelerating Core Module

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