UCRL--90395

DE84 012320

HIGH CURRENT ELECTRON LINACS (ADVANCED TEST ACCELERATOR/EXPERIMENTAL TEST ACCELERATOR)*

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Abstract

The high current induction accelerator development at the Lawrence Livermore National Laboratory will be described. The ATA facility is designed for 10 kA peak currents, 50 nsec pulse lengths and 50 MeV energies. At this time, half of the design current has been accelerated through the entire machine to particle energies of about 45 MeV. Current problem areas and operational experience to date will be discussed.

Several key technical areas required development for the ATA machine; this report will survey these developments. The control of transverse beam instabilities required an accelerating cavity design with very low Q. Electron sources capable of 10 kA operation at high rep rates were developed using a plasma "sparkboard" approach. The pulse power systems on ATA, using the same type of spark gap switches as ETA, have exhibited excellent operational reliability.

* Work performed jointly under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48 and for the Department of Defense under Defense Advanced Research Projects Agency ARPA Order No. 4395, monitored by Naval Surface Weapons Center under document number N60921-84-WR-W0095.

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I. Introduction

The development of multistage linear induction accelerators (LIA) was originally stimulated by applications requiring high peak current pulses at particle energies above the levels where acceleration in a single diode gap is practical.[1] In the U.S.A., the Lawrence Livermore National Laboratory (LLNL) pioneered electron induction accelerator technology in the early 1960's with the Astron accelerator, which in its final configuration produced 850 amp beam pulses of 300 nsec duration at 6 MeV.[2]

In the mid-1970's, development of multi-kiloamp LIA's at LLNL was initiated. The Experimental Test Accelerator (ETA) was completed in 1979; it has achieved its design current of 10 kA in 30-40 nsec pulses at 4.5 MeV. The ETA machine served as a testbed for the technology components required for the 10 kA, 50 MeV Advanced Test Accelerator (ATA). ATA construction was completed last year, and it has achieved 7 kA beam current levels at about 45 MeV in its initial operation. Some of the ETA technology, which benefited substantially from the earlier development of the Electron Ring Accelerator (ERA) injector at Lawrence Berkeley Laboratory,[3] was also applied in the construction of the 18 MeV, 2-4 kA Flash X-Ray (FXR) machine at LLNL.[4]

In this paper, we describe the engineering and beam physics developments involved in the ATA/ETA machines, and we summarize the initial operating experiences with ATA. Looking to the future, prospects for a broader range of LIA applications have been significantly enhanced by recent developments in magnetic power conditioning systems.[5] In particular, with these new power conditioning systems, LIA's may provide a reliable and inexpensive approach to the generation of high average power electron beams for a number of applications, including radiation processing.

II. Description of the Advanced Test Accelerator

The design goals of the ATA are a beam current of 10 kA, pulsewidth of 50 nsec, particle energy of 50 MeV, and an average rep rate up to 5 Hz. The system is also capable in "burst mode" operation of accelerating up to ten pulses at a 1 kHz rep rate, at the same average power output.

In its present configuration, the machine consists of a 2.5 MeV injector and 170 accelerator units, each designed for a nominal acceleration per unit of 250 kV (see Fig. 1). Pulse power systems for an additional 20 accelerator units (to be added in the future) are already in place. The power supplies and power conditioning equipment are located in the building area above the beam tunnel, as shown in Fig. 1, with the output of each pulse power unit delivered to an accelerator cell through two flexible, oil-filled transmission lines.

The electron beam is transported down the 80 meter accelerator by means of a continuous solenoidal magnetic field, following the beam's extraction from a magnetic field-free cathode in the injector. The maximum value of the solenoidal field is 3 kG through most of the accelerator (beyond 6 MeV). The main consideration determining the focusing field strength is adequate suppression of the coherent transverse interactions with the accelerator gaps discussed in the next section.

The power conditioning systems convert the power from the line into the short, high voltage pulses applied to the gaps of each accelerator cell. These systems are described in more detail in ref. 6. They consist of: (a) a main 18 kV capacitor bank (over 8 megajoules total storage and 1 megajoule delivered per burst); (b) a command resonant charge unit that charges the intermediate energy storage capacitors to 25 kV ± .025% in less than a millisecond; (c) a thyratron output switch that charges a 12 Ω water Blumlein to 250 kV through a 10:1 step-up transformer; and (d) a final coaxial pressurized gas-blown switch that delivers the output pulse of 250 kV, 20 kA, 70 nsec (FWHM) to the accelerator cell through the two parallel 24 ohm transmission lines. The round trip transit time of the drive pulse through these transmission lines is long enough to provide transit-time isolation of the accelerator cell load from the Blumlein circuit. The transmission lines connect to the cells as shown in Fig. 2. Since the impedance of the ferrite torroids is large compared to 12 ohms, the voltage at the drive point appears across the one inch accelerating gap. That is, the accelerator cell can be viewed as a 1:1 transformer electrically, with the electron beam acting as the secondary. Neglecting the electrical transients involved with gap capacitance and stray inductance of the drive blades, the electrical schematic shown in Fig. 3 is an adequate equivalent circuit to calculate the power input to the beam, which is properly represented in the circuit as a current source because current continuity at the gap is required at any gap voltage. As indicated in Fig. 3, compensation load resistors are also connected at the cell drive points, primarily to absorb some of the pulse energy under mismatched conditions and prevent long duration, high voltage "ringing" in the transmission lines. In ATA, a conservative approach was taken with a net compensation load resistance of 25 ohms per cell chosen for the "standard configuration" (it is easy to change the resistors). With a beam current of 10 kA, the transmission lines and Blumlein are then matched to the parallel combination of the beam and the load resistors, with equal power and current (10 kA) to each one. In the absence of beam, the overvoltage at the cell is then only 33%. The overall power conditioning system efficiency is about 50%; with the standard compensation resistors in place and a 10 kA beam, the resulting electrical efficiency from line to the beam is about 25 % (not including focusing power supplies and gas blowers, of course.)

The timing of the acceleration pulse with the beam pulse is provided by the trigger system on the Blumlein spark gaps. With trigger voltages of 150 kV or greater on the trigger electrodes, spark gap jitter of about one nanosecond or less is achieved. Cable lengths on the trigger system are adjusted to provide the proper time delay at different points in the machine.

The ATA injector consists of ten (larger diameter) induction units in series, driven by 20 pulse power units, to develop a net voltage of 2.5 MeV (nominal) across a single diode region.[7] This injector is similar in design to the ETA injector,[8] although many mechanical and electrical improvements were made. In the ETA development, ten inch diameter thermionic cathodes operating at 25 Amps/cm^2 with an extraction grid at 80-100 kV were used originally as the electron source. These thermionic sources proved impractical in the ETA vacuum environment, although a diode test stand had indicated adequate lifetime and reliability up to twice the design current density. For this reason, a plasma surface discharge source was developed for ETA that proved to have excellent reliability and lifetime at currents above 10 kA, and also demonstrated the capability for burst operation at rates greater than 1 kHz.[9] This electron source has been used in ETA for several years, and for the past year on ATA. The normalized RMS emittance of the beam extracted from the ATA injector with this source is about 0.5 πrad-cm for a wide range of operating conditions.[7] Operating experience with ATA, described in a following section, has recently motivated a search for even better sources and injector configurations. Recent tests of a smaller diameter, gridless, field emission configuration inserted in the ATA injector greatly improved the ATA performance, as described later.

The optics of beam extraction from the injector, and its matching to the solenoidal transport, is strongly dependent on both the cathode-anode voltage and beam current for a given setting of the focusing magnets.[10] For this reason, the leading and trailing edges of the beam pulse are inevitably mismatched in the transport system; some of the consequences of this feature of high current transport are described in the following sections. We note that at 10 kA beam current levels and normalized emittances of 0.5 π rad-cm, with typical magnetic tunes the transport system is in the space-charge dominated regime until the beam has been accelerated to about 4-5 MeV.

III. Beam Breakup Instability

Collective interactions between the beam and the accelerator structure are an important limit to beam intensity and/or pulse lengtn in many linacs. In electron induction machines, a coherent "snake-like" perturbation in the beam centroid (at wavelength λ) creates $m = 1$ components in the beam's self-fields and the beam tube wall currents ($\cos\phi$ variation in azimuth) that drive the accelerator gaps at a frequency $\approx c/\lambda$. A response function of the accelerator cavity to this excitation can be defined by the magnitude and phase of the transverse deflections of the beam electrons passing through the gap region (per unit of centroid displacement). The worst situation is when the cavity has high Q, $m = 1$ resonances represented by poles in this response function. On the other hand, it is important to realize that even a perfectly "matched" radial gap in the beam tube will have a resistive component in this response function, leading to exponential amplification of transverse perturbations down the machine.

In our ETA/ATA program, a substantial effort was made to reduce the Q's of all resonant modes as much as possible, and to quantify the peak of the resistive part of this response function by measurements of the amplification rate of driven oscillation in ETA.[11,12] The ATA cavities have ferrite absorbers on the drive blades and "back wall" of the cavity, and a "corner reflector" to match radial outgoing waves in the accelerator gap region to the vacuum insulator interface. With these devices in place, the Q's of all $m = 1$ modes were reduced to about 4 or less. From calculations of the respcnse function for a model of our radial line geometry,[13] we estimate an interaction impedance for the ATA cavities of about 30 ohms. This value is in good agreement with the observations of beam breakup amplification rates on ATA,[14] and the model is also consistent with measurements of the amplification rates on ETA where the Q of the most important mode (~800 MHz) is about 7. We also note that on the basis of this model, a perfectly matched radial line would have the instability growth rate reduced by less than a factor of two for the same current and gap width.

IV. . Initial Operating Experience with ATA

Tests of the injector were begun prior to the completion of the full machine. Reliable operation at the full 10 kA design current, and at voltages up to 3 MeV, were quickly achieved with relatively well-centered beams (~millimeter transverse displacement) and emittances in the expected range.[6,7]

When the 10 kA beam was accelerated to the 10 MeV point in the accelerator, we observed fluctuations in the current monitor waveforms developing down the machine. These fluctuations generally occurred on the rise and fall of the current pulse (see Fig. 4); and they were in a frequency range well below the peak growth rate for beam breakup oscillations (~800 MHz). They could also be observed on wall current difference signals (x-y monitors) as well as x-ray wires inserted into the beam pipe. Transport of even lower current beams through the entire machine was poor, with progressively larger time-dependent displacements of the beam and current loss down the machine. The expected beam breakup oscillation frequencies were sometimes observed, but these oscillations were much lower amplitude than the lower frequency fluctuations.

A number of experiments were carried out to determine the cause of these fluctuations and the cause of the limitations in beam transport (assumed to be related). Experiments with very low current beams transported through the accelerator, beams passed through different sized collimators at the injector output, and beams "conditioned" by sending them through a wire zone[15] at the 6 MeV point were carried out.

On the basis of these experiments we could conclude that: (a) the phenomena was not a collective effect (dependence on current was weak or absent), (b) that pulse power drive asymmetries were not important, and (c) that transverse error fields in the accelerator solenoid were minimal and within tolerance ($\leq 0.03\%$ average error field). The steering coils were found to be distorted in their profile and magnitude by small ferrite pieces in the current monitors, however, these coils are being repositioned to correct this problem. The data indicated that energy variation through the beam pulse (particularily on its rise and fall) leads naturally to a "corkscrewing" up in frequency of beam displacements and beam profile asymmetries as it propagates down the solenoidal field, and this is an important factor in the generation of the observed fluctuations (see ref. 16). At present, the main factor limiting beam transport is felt to be the presence of particles from the injector that exhibit large radial excursions in the (bumpy) solenoidal transport field. As pointed out earlier, the beam front and tail is inevitably mismatched to the solenoidal field if the magnetic tune is set for proper matching of the beam body. In addition, evidence is strong that a fraction of the beam body extracted from our plasma cathode/grid combination has poor optics as well.

Some of the evidence for the above conclusion is the marked improvement in beam transport when the beam was collimated at the injector output by a 4 cm diameter collimator. Motivated by these observations, a new smaller diameter (5 inch) field emission cathode in a gridless configuration was tried. This injector configuration lead to a substantial improvement in the performance. A 7 kA beam was transported through the accelerator (to ~45 MeV energy) with minimal loss of peak current and minimal beam centroid displacement (see Fig. 5). The beam centroid offset down the machine and beam profile data in Fig. 5 are displayed for a beam segment about 30 nsec into the pulse. At the 7 kA, level, the output pulse was shortened to about half the pulse length injected into the linac because of beam breakup oscillations. With a slow risetime pulse at a peak current of 5 kA, the total charge and peak current are both preserved through the linac.[14]

V. Conclusions and Future Prospects

The initial operating experience with ATA has clearly demonstrated the need for improvements in the injector. In addition, for many applications of LIA's improvements in the emittance (brightness) are desirable. For both of these reasons, a renewed effort is underway to look at alternative injector configurations and electron sources, with the goal of generating a beam with a very symmetric current profile and low emittance to inject into the linac.

Beam breakup instability continues to limit the performance of ATA at high currents. Reduction of the magnitude of the transverse interaction impedance has begun to approach fundamental limits in the current ATA cavities, which are reasonably well "matched" over a very broad frequency band (having very low Q's of the residual resonances). For substantial gains in the limits posed by beam breakup, stronger focusing systems will be needed, probably including implementation of phase mix damping schemes.[15]

The power conditioning systems on ATA have proved to be very reliable, with excellent jitter-free performance and relatively minimal maintanence burden. Nonetheless, the recent developments in magnetic power conditioning systems[5] offer a further qualitative improvement in LIA technology, with reduced power burden for the auxiliarly systems such as the gas blowers and the high voltage trigger system. In addition, high average power operation with long lifetime is much more practical with LIA's driven by these magnetic systems. In the future, it may even be reasonable to consider magnetically-driven LIA technology for applications where average power is the main system requirement. The extra cost of the power conditioning systems required to form the short high voltage acceleration pulses might be offset by other features of the LIA system when comparing it to D.C. accelerators or C.W. rf accelerators. In particular, the short duration of the voltage pulse, and its segmentation into a number of independent regions of beam acceleration, leads to relaxed requirements on the vacuum system, insulator surfaces, and electrode conditions for reliable performance at high average power.

Acknowledgements

This paper is an overview of the work of a large number of people. In addition to those Lawrence Livermore National Laboratory personnel cited by references, I am particularily grateful to Dr. Daniel S. Prono, Group Leader for the ATA Physics Team, for assistance in the preparation of the paper and the summary of ATA operations.

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Figure Captions

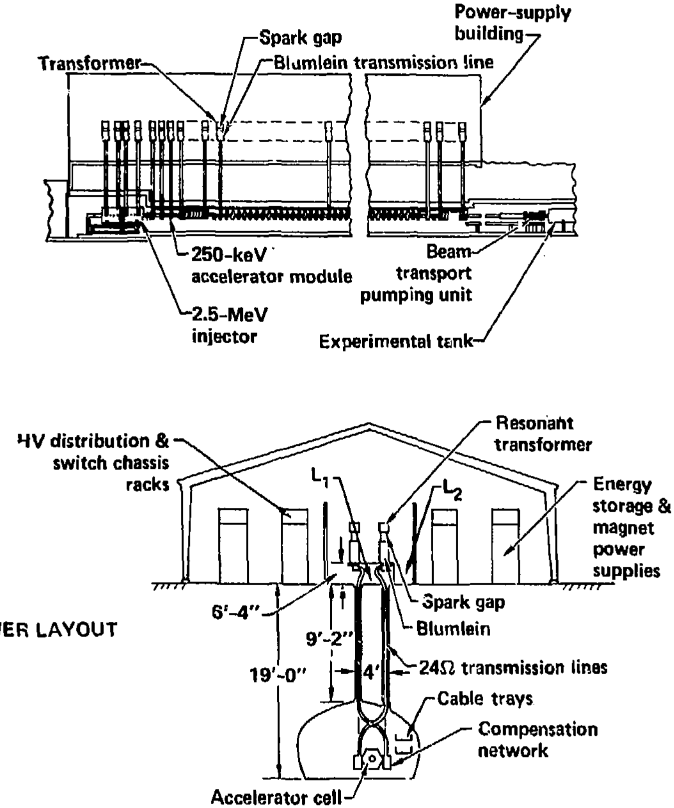
FIG. 1 Longitudinal and transverse cross sections of the ATA facility.

FIG. 2 ATA 250 kV induction cell.

FIG. 3 Simplified electrical schematic of induction unit. The pulse voltage $V_0(t)$ is the output of the blumlein, with risetime determined primarily by spark gap closure and inductance.

FIG. 4 Current and beam centroid versus time at 10 MeV. Current scale is 2 kA/div.

FIG. 5 Transport of 7 kA peak current through accelerator (~45 MeV).



PULSE POWER LAYOUT

FIG. 1

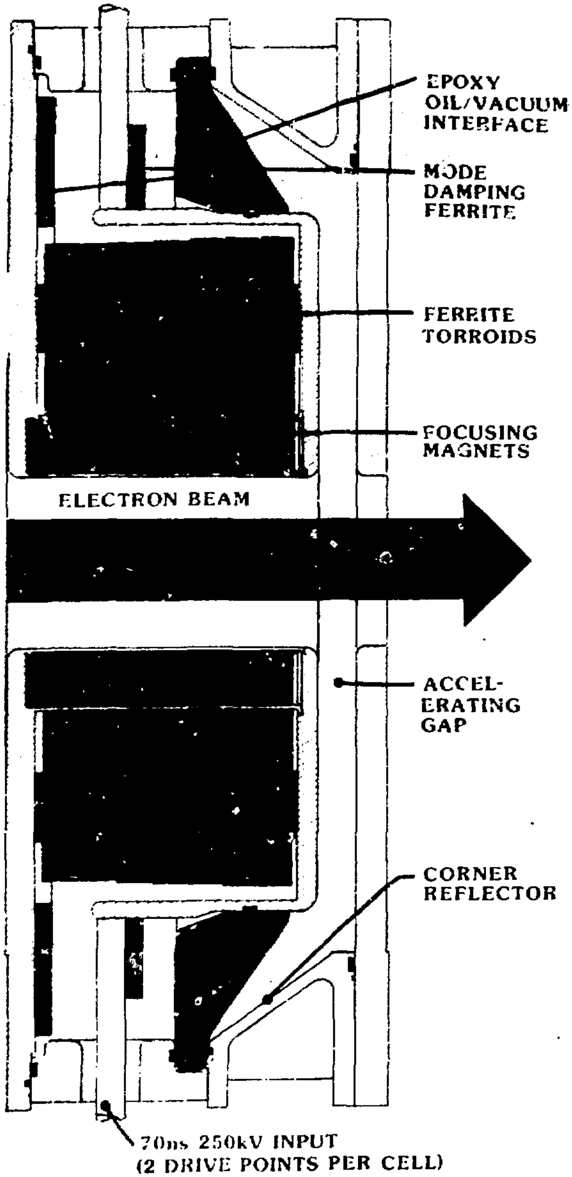
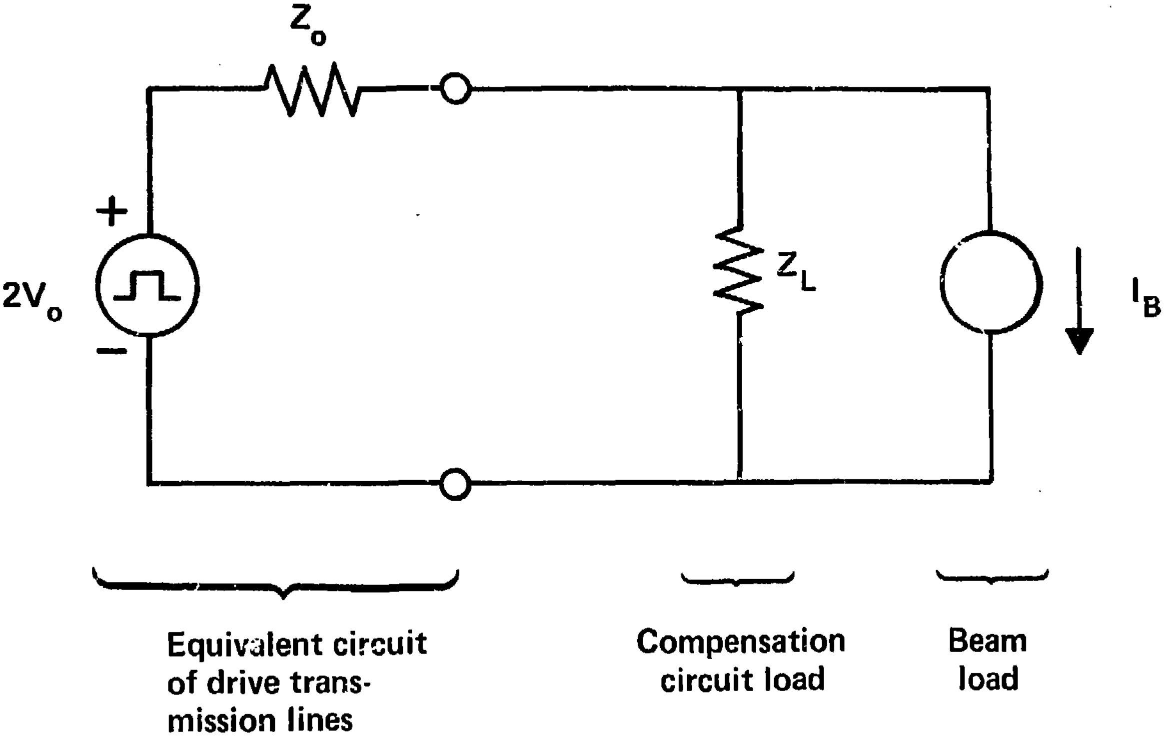

EPOXY
OIL/VACUUM
INTERFACE
MODE
DAMPING
FERRITE
FERRITE
TORROIDS
FOCUSING
MAGNETS
ELECTRON BEAM
ACCEL-
ERATING
GAP
CORNER
REFLECTOR
70ns 250kV INPUT
(2 DRIVE POINTS PER CELL)

FIG. 2



Z_o
+
$2V_o$
−
Z_L
I_B
Equivalent circuit of drive trans- mission lines
Compensation circuit load
Beam load

FIG. 3

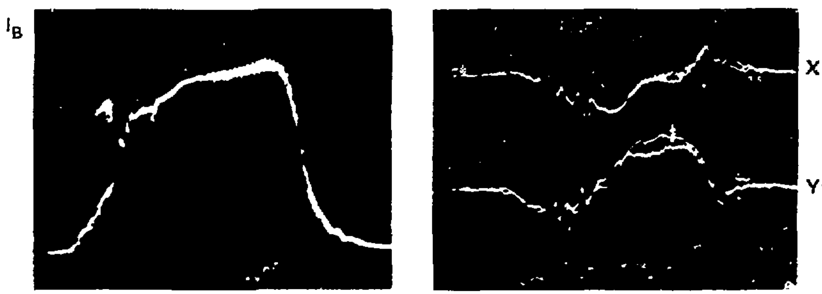


FIG. 4

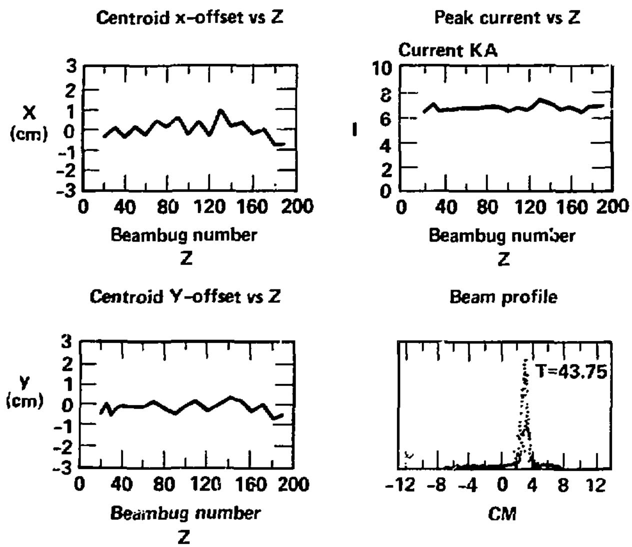

Centroid x-offset vs Z
X
(cm)
3
2
1
0
-1
-2
-3
0 40 80 120 160 200
Beambug number
Z
Peak current vs Z
Current KA
I
10
8
6
4
2
0
0 40 80 120 160 200
Beambug number
Z
Centroid Y-offset vs Z
Y
(cm)
3
2
1
0
-1
-2
-3
0 40 80 120 160 200
Beambug number
Z
Beam profile
T=43.75
-12 -8 -4 0 4 8 12
CM

FIG. 5