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Overview of Beam Conditioning

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13. ABSTRACT (Maximum 200 words) This report contains five short papers summarizing theoretical studies of various techniques for conditioning relativistic electron beams. Conditioning refers to processes that either damp transverse fluctuations of the beam, or provide a head-to-tail variation in its emittance. The studies were performed in support of beam propagation experiments being conducted at several laboratories.				
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OVERVIEW OF BEAM CONDITIONING

This report contains five short papers that were presented at the Annual DARPA/SDIO/Services Charged Particle Beam Review held at the Naval Postgraduate School in Monterey, California during 18-21 September 1989. The papers describe theoretical beam conditioning studies carried out at NRL in support of propagation experiments at several laboratories.

Since these papers were written, the ATA Multi-Pulse Propagation Experiment (ATA/MPPE) has been completed, and high-current propagation has been successfully demonstrated at NRL's Super-IBEX facility. Both experiments used a passive IFR cell to taper the beam from head to tail, resulting in improved stability during subsequent propagation. The ATA experiment was plagued by substantial initial beam sweep, in part because of problems with the Fast Corrector Coil (FCC) which was designed to suppress such fluctuations. Detailed analysis of these experiments will be reported elsewhere.

A brief description of each paper and a list of authors are given below.

Beam Conditioning Techniques: This paper contains an overview of NRL research on several post-accelerator techniques used either to center a beam or to introduce a head-to-tail variation in beam emittance. The techniques discussed are passive IFR cells, vacuum and gas-filled wire cells, multi-foil cells, and energy-ramp focusing cells. Proper use of these techniques can substantially reduce the growth of the hose instability after the beam is injected into air. Both analytical modeling and simulation codes have been employed in these studies. (Fernsler, Slinker, Hubbard, Joyce)

Wire Cells I: Vacuum: Vacuum wire cells include passive devices with a simple resistive wire charged by the beam, and active devices driven by an externally applied wire current. Wires can be used both to center the beam and to taper its radius. The major disadvantages are wire fragility, beam losses to the wire, and the production of radial wings in the beam profile. Passive wire cells, moreover, do not center the beam head and generally overheat the beam body. Active (current-carrying) wire cells center the

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entire beam without overheating it, provided the applied current is modest. An active cell can produce emittance tailoring if the beam radius is appropriately tapered prior to entering the wire cell. The analytical results are supported by particle simulations using the PEWW code. (Fernsler, Slinker)

Wire Cells II: Gas: An externally-driven gas-filled wire cell was examined as a possible conditioning technique for Super-IBEX. The additional pinch forces in the gas-filled cell suppress the formation of radial wings in the beam profile, but they also promote hose instability. Analytical calculations indicate that the wire current needed to damp hose will overheat the beam. In support of this prediction, SARLAC simulations showed that an externally applied wire current of 7.9 kA was insufficient to completely damp hose in a 30 kA beam, while 14.2 kA of wire current damped hose but overheated the beam. Gas-filled wire cells do provide some radius tailoring inside the cell, but it is inadequate for most propagation experiments and can be converted into emittance tailoring only at the expense of further overheating. (Slinker, Fernsler, Hubbard)

Foil Focusing for Transport and Conditioning: A thin conducting foil in a vacuum beam line focuses the beam like a thin lens. The focal length is proportional to $r_b I_A / I_b$ where r_b is the beam radius, I_b is the beam current, and $I_A = \gamma mc^3 / e$ is the Alfvén current. Analytic calculations of the focal length and emittance growth for various beam profiles have been confirmed by the FRIEZR particle simulation code. Some versions of FRIEZR impart a prescribed impulse to each simulation particle as it passes the foil location, while other versions solve the full electromagnetic field equations on a fine axial mesh. Both the analytical and simulation results predict that emittance growth from the anharmonic nature of foil focusing is a severe problem for beams with high I_b / I_A such as Super-IBEX. In addition, we have found that "matched" transport, in which the beam radius is constant at each foil, is not possible because the condition for matching violates the condition for stability in a periodic focusing system. Nevertheless, multi-foil transport can be useful for transport over limited distances and, in some cases, can provide emittance tailoring. (Fernsler, Hubbard, Slinker, Boris).

Beam Conditioning Options for the ATA Multi-Pulse Experiment: Stable propagation of the ATA/MPPE will require a substantial head-to-tail emittance variation. Three strategies have been considered for introducing this variation: a multi-foil cell, a differential focusing cell, and a passive IFR cell. All three have been analyzed using analytical models and axisymmetric FRIEZR simulations, and all are capable in principle of producing substantial emittance tailoring. The multi-foil cell, however, tailors the beam over too narrow a region and overheats the beam through scattering. The differential focusing cell provides considerable flexibility, but suffers from a need for fine tuning of the energy ramp. The passive IFR cell appears to produce the best tailoring, especially when operated at low gas pressures, provided the beam emittance is low at injection. (Hubbard, Slinker, Fernsler, Joyce, Ali)

BEAM CONDITIONING TECHNIQUES

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INTRODUCTION

A relativistic electron beam must be conditioned to achieve stable, long-range propagation. We identify four nominal conditioning goals. First is a centering requirement relating the beam offset, y_b , to the beam radius, r_b :

$$\frac{y_b}{r_b} \lesssim \begin{cases} 0.01 & \text{for high frequencies (BBU)} \\ 0.1 & \text{for low frequencies (sweep)} \end{cases} \quad (1)$$

Second, the normalized emittance, ϵ_n , should taper over 10-20 ns from a large value in the beam head to a small value in the body with a variation

$$\epsilon_n^{(\max)}/\epsilon_n^{(\min)} > 3. \quad (2)$$

Third, the value $\epsilon_n^{(\min)}$ in the body should be small to maintain a tight pinch. And fourth, the beam should exit the final conditioning cell well matched for propagation into air.

In this paper we briefly summarize theoretical predictions for several conditioning techniques. Papers 2-5 describe the results in more detail.

We begin with four observations. First, the emittance prior to conditioning should be small: $\epsilon_n^{(\text{inj})} < 0.5 \epsilon_n^{(\min)}$. Second, ϵ_n , rather than r_b alone, should be tailored to detune the hose instability (because past the pinch point, $\lambda_\beta \propto \epsilon_n/I_{\text{eff}}$). Third, using foil scattering to tailor ϵ_n works only if r_b is flared. And fourth, two cells generally work best using the first cell to flare r_b and the second cell to heat and center the beam; a thick exit foil is then unnecessary and undesirable.

PASSIVE IFR CELL

A passive IFR cell consists of a tube filled with low-density ($P < 1$ Torr), un-ionized gas. The beam ionizes the gas and electrostatically ejects

*Work supported by the Defense Advanced Research Projects Agency, ARPA Order No. 4395, Amendment 80, monitored by the Naval Surface Warfare Center

the plasma electrons, leaving the ions to pinch the beam. The developing ion pinch flares r_b and partially centers the beam. The principal concerns are ion motion, magnetic trapping of plasma electrons at high beam current, I_b , and gas heating and recovery. Our studies indicate that IFR cells flare r_b well, even at high I_b , provided $P \sim 10$ mTorr and $\epsilon_n^{(inj)} < 0.5 \epsilon_n^{(min)}$; see the example below. A thick exit foil or later heating cell would convert the radius flare into emittance tailoring. IFR cells additionally damp high-frequency offsets y_b in the beam body.

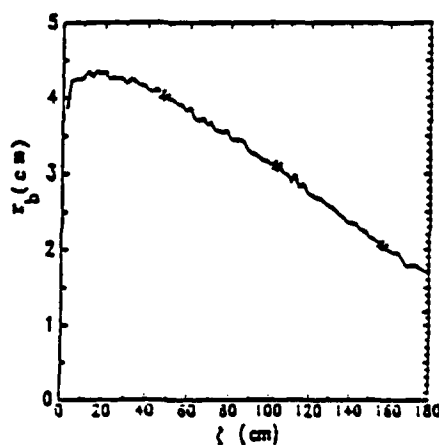


Fig. 1. IFR Cell (20 mTorr air): $I_b = 50$ kA, $\gamma = 8$, $z = 30$ cm.

WIRE CELLS

Several different wire conditioning schemes have been studied. Passive vacuum wire cells, consisting of a thin resistive wire in an evacuated pipe, flare r_b , center the body (though not the head), but inverse tailor the beam and overheat it by $\sim I_b/I_{eff} > 1$, where I_{eff} is the effective current in air. Adding a thick exit foil to tailor ϵ_n overheats the beam more. By contrast, an active vacuum wire cell, consisting of a highly conducting wire with external current, I_{ext} , centers the entire beam without overheating, provided $I_{ext} \leq I_{eff}/2$. Moreover, the active cell can convert a flare in r_b (from, say, a preceding IFR cell) into tailoring of ϵ_n . Vacuum wire cells suffer, however, from losses to the wire and from electron profiles with broad radial wings about a sharply peaked center. A small wire reduces the losses but is fragile and, at high I_b , must be replaced after each shot. See Ref. 3 for further discussion of vacuum wire cells.

An active gas-filled wire cell consists of a highly conducting wire with

I_{ext} but in gas. The self-pinch force from the beam improves beam profile but allows for hose instability, as illustrated below. I_{ext} must be large to suppress hose but small to avoid beam overheating. The best compromise is to damp hose but overheat the beam by a factor of 2 or less, depending upon I_b and the pulse length. Note that a gas cell inverse tailors ϵ_n , even with a γ -ramp, unless r_b is flared at injection. See Ref. 4 for further discussion.

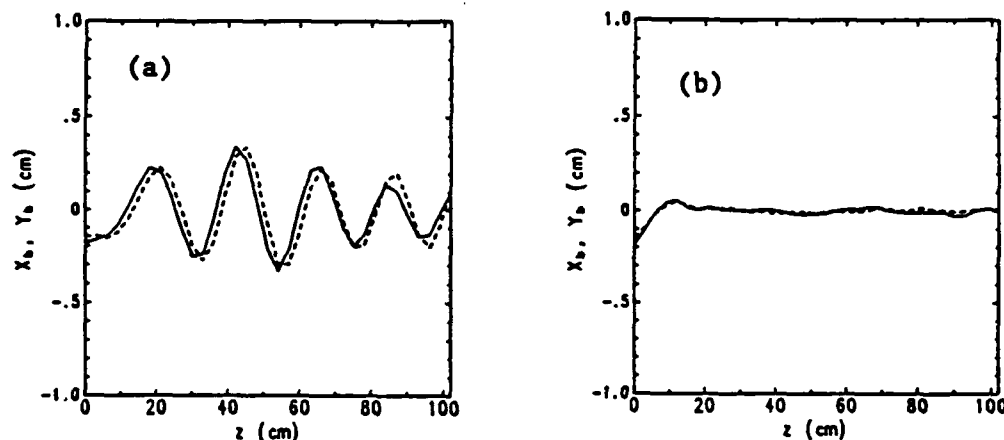


Fig. 2. Gas Wire Cell showing: (a) hose growth for $I_{\text{ext}} = 7.9$ kA, and (b) hose damping for $I_{\text{ext}} = 14$ kA. Here $I_b = 30$ kA, $\gamma = 10$, and $\zeta = 1080$ cm.

FOIL CELLS

Transverse conducting foils act in vacuum like thin lenses with a focal length proportional to $r_b \gamma / I_b$. A ζ -variation in beam impedance, γ / I_b , can therefore be used to flare r_b . Because foils are imperfect lenses, however, they quadratically increase ϵ_n by an amount proportional to $(r_b I_b)^2$. Foil scattering, if present, further increases ϵ_n quadratically by an amount proportional to r_b^2 times the foil thickness. Using foils to flare r_b , and ultimately tailor ϵ_n , is thus practical only for $I_b \ll I_A \approx 17\gamma$ kA. Moreover, tailoring occurs only where γ / I_b varies. See Ref. 5 for details.

ENERGY-RAMP FOCUSING CELL

An energy-ramp focusing cell consists of a solenoidal lens, a thick scattering foil, and a prescribed variation in γ with ζ . Because the focal length of a solenoidal lens varies as γ^2 , a 20% variation in γ can be converted into a large radius flare downstream of the lens. Passing the flared beam through a thick scattering foil (after allowing for foil focusing) produces emittance tailoring. This technique requires a highly

reproducible energy variation, $\gamma(\zeta)$, and a small energy spread, $\Delta\gamma/\gamma \ll 1$, at any given ζ . The latter condition necessitates $I_b \ll I_A$. Moreover, overall performance is sensitive to foil location, and the solenoidal field errors must be small. See Ref. 2 for discussion.

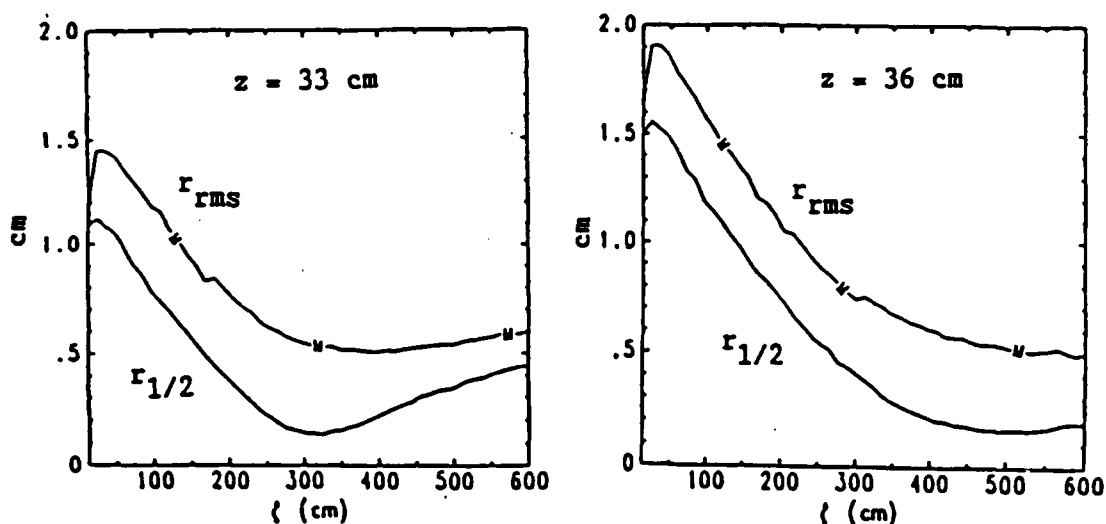


Fig. 5. Energy-Ramp Tailoring Cell: 6 kA, 8-10 MeV variation over 10 ns, perfect solenoidal lens with a nominal focal length of 30 cm.

CONCLUSION

IFR cells appear to be the best candidate for radius-flaring, in terms of emittance degradation and ease of control. The best technique for centering is the active wire cell, gas or vacuum, which provides control and rapid phase-mix centering. An attractive variation is a filamentary gas discharge which would eliminate wire losses and wire replacement (at low rep-rates).

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WIRE CELLS I: VACUUM*

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INTRODUCTION

In this paper we summarize our present theoretical understanding of active and passive vacuum wire cells as devices for centering or tailoring relativistic electron beams. The analytic theory is reviewed first, followed by numerical simulations. Gas-filled wire cells are considered separately in the companion paper, "Wire Cells II: Gas."

THEORY

In this section we present results from analytic calculations. We begin with a brief description of passive and active wire cells.

A passive vacuum wire cell consists of a thin resistive wire centered in an evacuated pipe with conducting end plates.¹ The beam induces a charge λ_w and current I_w on the wire. The wire resistance R_w resistively damps I_w in a time L_w/R_w , where L_w is the wire inductance. As a consequence, an electrostatic pinch force (from λ_w) develops with time.

An active vacuum wire cell uses a highly conducting wire with an external current.² Because $R_w = 0$, the attractive and repulsive forces from the induced wire charge and current nearly cancel, leaving the magnetic force from the external current, I_{ext} , to pinch and center the beam.

Away from the end plates and to order γ^{-2} , the only force on the beam electrons is the wire force, $F_w = -2T_w/r$ where $T_w \equiv e(I_w/c - \lambda_w)$. The large spread in electron oscillation frequency, $\omega_\beta \propto 1/r$, causes rapid phase-mix damping so that the beam quickly centers and equilibrates about the wire.

Inside the wire cell, the average equilibrium beam temperature is given, independent of injection conditions, by

$$T = -\frac{1}{2} \int_0^\infty dr \frac{2\pi r J_b}{I_b} r F_w(r) = T_w$$

*Work supported by the Defense Advanced Research Projects Agency, ARPA Order No. 4395, Amendment 80, monitored by the Naval Surface Warfare Center.

to order $a_w^2/a_b^2 \ll 1$. Here a_w is the wire radius, a_b is the beam radius, J_b is the beam current density, and I_b is the beam current. By contrast, the equilibrium temperature of a self-pinchd, self-similar beam in air is given by $T_B = eI_{\text{eff}}/2c$, where $I_{\text{eff}} < I_b$ is the effective current. An active wire cell thus does not overheat the beam ($T_w \leq T_B$) provided

$$I_{\text{ext}} \leq I_{\text{eff}}/2.$$

However, in a passive wire cell, $I_w \rightarrow 0$ while $\lambda_w \rightarrow \sim -I_b/2c$. Hence, a passive cell overheats the beam by a factor

$$T_w/T_B \approx I_b/I_{\text{eff}} > 1.$$

Adding a thick exit foil overheats the beam further.

The $1/r$ dependence of F_w produces beam profiles strongly peaked about the wire. For example, for an isothermal beam about a hollow wire,

$$J_b(r) \rightarrow J_b(0) (a_w/r)^{2x},$$

where

$$x = H(a_w - r)/(1 - a_w^2/a_b^2).$$

Here H is the Heaviside step function, and $a_b^2 \equiv I_b/\pi J_b(0)$. For $r > a_w$ and $a_b \gg a_w$, $x \approx 1$. For a beam that is injected cold and nearly flat-topped, the equilibrium beam current density still peaks about $r = 0$ but falls off more gradually with a sharp cut-off at the initial edge radius, $a_i \gg a_w$:

$$J_b(r) \rightarrow (I_b/\pi a_i^2) [(a_i - r)/(r + a_w)] H(a_i - r).$$

The minimum beam emittance can be estimated by showing that a cold beam at injection contracts according to

$$\langle r^n \rangle = (n+1)^{-1/2} \langle r_i^n \rangle,$$

where $\langle r_i^n \rangle$ is the n th radial moment at injection. Combining this result with the result for $T = T_w$ yields a minimum normalized emittance given by

$$\epsilon_n^{(\min)} \approx \gamma R_i [(I_w - c\lambda_w)/I_A]^{1/2},$$

where R_i is the rms radius at injection and $I_A = 17\gamma$ kA is the Alfvén current. The passive wire cell thus inverse tailors ϵ_n . On the other hand, the active wire cell tailors ϵ_n , for constant I_{ext} , only if R_i flares in the head (or γ falls with z). Note that a γ -ramp produces inverse tailoring for both cells and is therefore usually detrimental.

Losses to the walls and wire are a major concern for solid beams. By considering the turning radii of the electron orbits, we have concluded that the wall losses are small provided the beam temperature at injection is small, $T_i < T_w/2$, and the wall radius large, $b > 2 R_i$. Losses to the wire should be small provided $T_i \geq T_w/5$ and $a_w \leq 0.01 R_i$; here, finite T_i imparts angular momentum to the beam electrons, causing most to miss the wire (much as occurs for hollow, rotating beams such as RADLAC). A related concern is wire durability which typically is poor at high beam currents and long pulses; the wire must then be replaced after each shot.

SIMULATIONS

We have used the PEWW code to simulate both the passive and active wire cells. This code combines a fully relativistic particle pusher (courtesy of G. Joyce) and an ultrarelativistic circuit equation to compute I_w and λ_w . End-plate effects are not included in the simulations presented.

A passive wire cell of length $L = 1$ m and radius $b = 14.8$ cm, with a wire resistance $R_w = 1$ Ω /cm and radius $a_w = 0.05$ cm, is simulated below. The beam current I_b rose to 10 kA in 5 ns with $\gamma = 10$, half-radius $R_{1/2} = 1$ cm, and $\epsilon_n = 2.3$ rad-cm. The beam was injected off-axis at $\bar{x} = -0.5$ cm. Plotted at cell exit are $R_{1/2}$ and R , ϵ_n , and the centroid $\bar{x}$. Observe that the cell flares R , inverse tailors ϵ_n , and centers the beam body but not the head. The cell overheats the beam by $\sim 30\%$, relative to the Bennett temperature in air. Adding a thick exit foil to tailor ϵ_n would overheat the beam further.

We next show a simulation of an active cell with $L = 1$ m, $b = 20$ cm, $R_w = 0$, $a_w = 0.08$ cm, and $I_{\text{ext}} = 5$ kA. I_b rose to 20 kA in 12 ns with $\gamma = 10$ and a matching current $I_m = 1.7$ kA. The beam was injected off-axis at $\bar{x} = -0.5$ cm with R flared as shown. The beam at exit is well centered and emittance tailored.

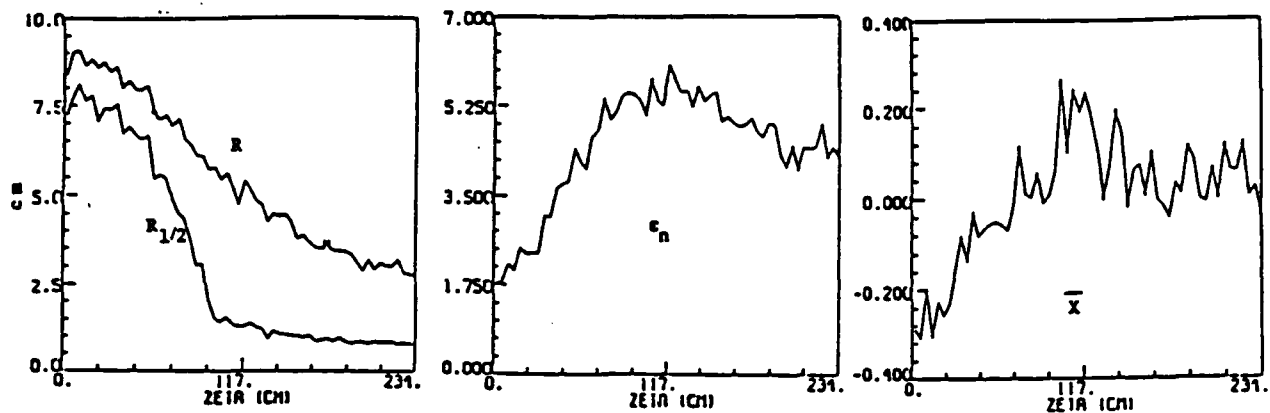


Fig. 1. A passive vacuum wire cell.

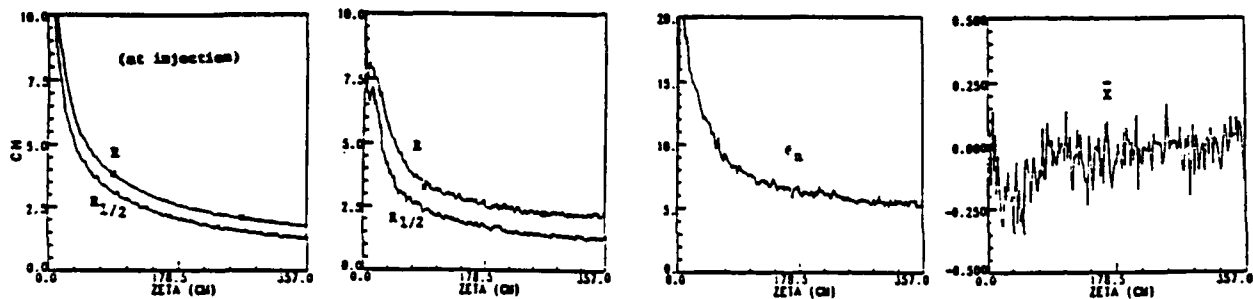


Fig. 2. An active vacuum wire cell (flared beam at injection).

CONCLUSION

A passive vacuum wire cell flares the radius, centers the body but not head, and overheats the body. The overheating becomes substantial at beam currents above 10 kA. An active cell centers the entire beam without overheating, and tailors the emittance if the beam is flared at injection.

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WIRE CELLS II: GAS*

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Introduction. An externally-driven, current-carrying wire immersed in a gas (normally ambient air) has shown promise as a technique for beam conditioning. Experiments on IBEX and RADLAC at SANDIA(1) verify the excellent centering and transport properties of these cells.

Theoretical modeling and numerical simulation of gas-filled wire cells has been performed by both SANDIA(2) and MRC(3). This paper investigates the feasibility of using gas-filled wire cells on the SUPERIBEX experiment.

Advantages of gas-filled wire cells. 1). These cells have strong centering and damping properties. The force, going inversely with r , is very anharmonic giving good phase-mix damping. The length of the cell need be only a few betatron wavelengths: $L \sim \text{a few } 2\pi r_b (17\gamma/I_{\text{eff}})^{1/2}$. By integrating the frozen field approximation to Maxwell's equations, one can show that the total current in the wire I_w , including the return current induced by the presence of the beam, is given approximately by $I_w \sim I_d - I_{\text{net}}/2$ where I_d is the current driven in the wire before the beam enters and I_{net} is net current the beam would have if the wire weren't there. This assumes the inductance in the external circuit is small compared to the cell. The minimum amount of driven current I_d for the cell to work is that which allows $I_w > 0$; that is, $I_d > I_{\text{net}}/2$ is required. If this requirement is not met, the wire will repulse the beam.

*Work supported by the Defense Advanced Research Projects Agency, ARPA Order No. 4395, Amendment No. 80, monitored by the Naval Surface Warfare Center.

Because of the plasma currents in the gas, the hose instability may occur in the cell. To damp hose the driven current I_d must exceed the requirement mentioned above. Certainly, if the force from I_w exceeds the repulsive force from the plasma current driven by the beam in the gas, then hose perturbations cannot grow. This requirement can be estimated by

$$I_w \sim -\pi r_b^2 \int_{r_w}^{\infty} dr \frac{2\pi r J_b}{I_b} \sigma E_z \approx -g I_p,$$

where g is a geometric factor which is $1/3$ for Bennett beams and 1 for flattop beams with self-similar plasma currents. With the relationship between I_w and I_d given above, this translates into an upper bound for the minimum driven current needed to completely damp hose: $I_d \sim g I_b + (.5-g)I_{net}$. For a 30 kA Bennett beam with a net current of 10 kA the minimum required driven current is between 5 kA and 12 kA, while a flattop may need up to 25 kA.

2). The gas-filled wire cell can generate some radius flaring which can be transformed to emittance tailoring by scattering in an exit foil. This results from variation of the effective current due to the rise in beam current and also from gas scattering in a beam with energy variation.

3). Because part of the pinch force is beam-generated, a better radial profile (smaller wings) is given to the beam in contrast to an externally-driven wire cell in vacuum.

4). The gas-filled cell is easier to implement experimentally than a vacuum cell.

Disadvantages of gas-filled wire cells. 1). The cell tends to heat the beam too much. The effective current in the cell is given by

$I_{eff} = 2I_d + I_{eff}^u$ where I_{eff}^u is the effective current of the beam in the presence of the wire without any driven current present. It is a fraction of the effective current in open air. For the 30 kA beams simulated below the effective current in open air was ~ 10 kA while

I_{eff}^u was ~ 4 kA. For the beam to be matched into air the effective current in the cell should match that in the open air. Clearly this requirement is incompatible with the requirements on I_d needed for centering and damping, so some mismatch has to be tolerated and the beam will expand at exit. Fortunately the equilibrium radius depends on the square root of the effective current. Note that using a thick exit foil to emittance tailor will enhance the mismatch. Also using a large inductance in the external circuit to clamp the driven current, while lessening the minimum stabilizing requirements, will overheat the beam.

2). Using the cell with solid beams (SUPERIBEX) will result in wire loss of beam electrons. This may not be a problem if there is "current to burn". In any case a possible solution may be to drive the external current through a filamentary discharge. This is also a possible solution for multi-pulse applications provided channel expansion is tolerable.

3). The radius tailoring achievable by this cell (probably not much better than 2:1) is not adequate for most applications. Consequently, this cell must be used with other conditioning means. The best configuration may be to emittance tailor the beam before it enters the gas-filled wire cell and use this cell mainly to center.

Simulation model. Propagation in the gas-filled wire cell was modeled with SARLAC. A large, but finite, conductivity σ_d was put in a narrow region, $r_w \sim .08$ cm, at the axis. An external current density, $J_d = I_d / \pi r_w^2$, is used as a source term in the field solver. For these runs the injected beam was Bennett with a small amount of tailoring. There was a γ ramp from 4 to 10 over the 13 ns rise of the beam. The peak beam current was 30 kA. The timestep had to be on the order of .125 cm in order to resolve motion near the wire.

Simulation results. With a wire radius of 0.079 cm and a solid SUPERIBEX beam of 30 kA, about 10 kA was lost in a 100 cm cell. Though this is an overestimate of wire loss, since any electron which hit the wire was discarded, it was decided to ignore the wire loss problem in

the rest of the simulations and assume they pass through without loss or deviation. In particular, wire losses can be minimized by using a fine wire or a discharge.

The main results consist of a scan of cell currents. Three values of I_d were tried: 3.16, 7.9 and 14.2 kA. The beam current rose to 30 kA over 13.3 ns. The nominal beam radius was 1 cm. There was a 2.5 to 1 emittance tailoring over 13.3 ns due to radius variation in the injected beam. The discharge radius was 0.079 cm and the cell length was 100 cm. The beam was injected with a low frequency hose perturbation of at most 0.28 cm off the discharge center.

The results are summarized in the following table along with code verifications of some of the simple scaling formulas.

CODE RESULTS

CASE	I_w @ 14ns	I_{eff} @ head	I_{eff} @ 14ns	I_{net} @ 14ns	$R_{1/2}$ @ exit	R_{rms} @ exit	ϵ_n @ exit
$I_d=0, \sigma_d=0$		0	9.7	10.2			
$I_d=0$	-5.6	0	3.9	8.8			
$I_d=3.16$	-1.9	4.2	10.2	12	2.4	3.6	11
$I_d=7.9$	2.8	16.2	19.8	16.6	1.2	2.7	8.7
$I_d=14.2$	8.8	25.2	32.3	23.8	1.1	2.6	10.9

For the 14 ns slice at entrance: $R_{1/2} = 1$, $R_{rms} = 2.9$ and $\epsilon_n = 5.4$.

Formula # 1:

$$I_w = I_d - I_{net}^*/2$$

Code gives:	I_d	I_{net}^*
	0	11.2
	3.16	10.2
	7.9	10.2
	14.2	10.8

Formula # 2:

$$I_{eff} = 2 I_d + I_{eff}^u$$

Code gives:	I_d	I_{eff}^u
	0	3.9
	3.16	3.9
	7.9	4.0
	14.2	3.9

Formula # 3:

$$\epsilon_n = \gamma R_{rms} (I_{eff}^*/17\gamma)^{1/2}$$

Code gives:	I_d	I_{eff}	I_{eff}^*
	3.16	10.2	15.9
	7.9	19.8	17.7
	14.2	32.3	29.7

Formula # 4: the minimum I_d for hose stability satisfies

$$I_{net}/2 \sim 5 < I_d^m < 11.7 \text{ for a Bennett}$$

Code gives:

$$7.9 < I_d^m < 14.2$$

For both the 7.9 and 14.2 values of the external current, the slice at 14 ns centered and damped at once, reaching a value about an order of magnitude down by the end of the cell, while the displacement grew for $I_d = 3.16$. A slice at 36 ns has its displacement grow to about 0.5 cm off axis before damping when $I_d = 7.9$. For 14.2 kA all slices damped immediately in the cell. Therefore, the minimum amount of I_d needed to completely damp hose growth was between 7.9 and 14.2 kA.

The beam exiting the 7.9 kA cell had an emittance fairly well matched at the 14 ns point to that in open air (without an exit foil). It was then propagated for 2 m and its stability was compared to that of a beam with the same parameters as that entering the gas cell but with a higher temperature in order to match open air. After a meter of propagation the gas-cell-conditioned beam showed much smaller hose growth, but the differences were not great at the 2 m propagation point. The beam radii at 2 m were comparable. This indicates that the major effect of the cell was to dampen the displacements at the expense of tailoring. Obviously a better tune, along with an exit foil, is needed.

Conclusions. The gas-filled wire cell shows promise as a centering and damping device for SUPERIBEX. The major disadvantages are beam overheat and current loss if a wire is used. Tailoring is not sufficient and so the cell must be used in conjunction with some other tailoring device.

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FOIL FOCUSING FOR TRANSPORT AND CONDITIONING*

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INTRODUCTION

Adler¹ and Humphries² have proposed foil focusing as a means of transporting electron beams, while Fawley³ has proposed foil focusing for conditioning. In this paper we address various issues relating to the use of foils for transporting and conditioning ultrarelativistic beams.

FOCAL LENGTH

An isolated foil may be treated as a thin lens of focal length f_ℓ provided $f_\ell \gg b$ and $b \partial/\partial \zeta \ll 1$, where the pipe radius b characterizes the axial range of the foil fields and $\zeta = ct - z$ measures distance behind the beam head. We have extended the analysis of Adler to compute f_ℓ for four beam profiles: flat-topped, Gaussian, parabolic, and Bessel. Plots of f_ℓ in units of $RI_A/(1-f_c)I_b$ versus r/R are shown below for three values of b/R ; here R is the rms beam radius, $I_A = 17\gamma$ kA is the Alfvén current, and $f_c (= 0$ in vacuum) is a plasma charge-neutralization fraction. We conclude from these plots that: (i) f_ℓ is relatively insensitive to beam profile; (ii) the

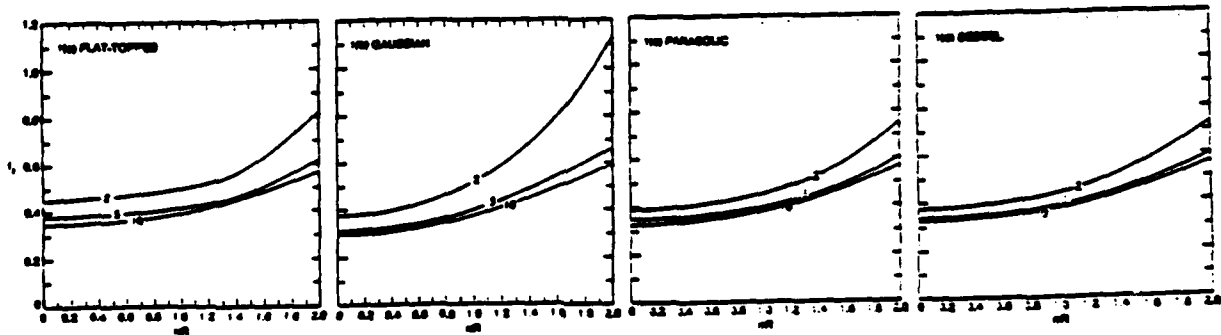


Fig. 1. Focal length f_ℓ in units of $RI_A/(1-f_c)I_b$ for $b/R = 2, 5, 10$.

* Work supported by the Defense Advanced Research Projects Agency ARPA Order No. 4395, Amendment No. 80, monitored by the Naval Surface Warfare Center.

paraxial treatment ($f_\ell \gg b$) is valid only if $(1-f_c)I_b/I_A \ll 0.2$; and (iii), foils are imperfect lenses with $\partial f_\ell / \partial r \neq 0$.

EMITTANCE GROWTH

We have found that a thin lens alters the normalized beam emittance ϵ by

$$\delta \epsilon^2 = \epsilon_{f0}^2 + \epsilon_{f1}^2$$

where

$$\epsilon_{f0}^2 = \gamma^2 [R^2 \langle (r/f_\ell)^2 \rangle - \langle r^2/f_\ell \rangle^2]$$

and

$$\epsilon_{f1}^2 = 2\gamma^2 [R^2 \langle u_r r / c f_\ell \rangle - \langle r^2 / f_\ell \rangle \langle u_r r / c \rangle].$$

Here $u_r(r)$ is the radial fluid velocity at r . Some general properties are: (i) $\delta \epsilon = 0$ for a perfect lens (constant f_ℓ); (ii) $\delta \epsilon$ is independent of the thermal velocity, $\delta v_\perp = v_\perp - u_r f$; and (iii), $\epsilon_{f1} = 0$ if the beam expands self-similarly ($u_r \propto r$). Hence, unless the beam profile changes radically, the emittance increases quadratically by ϵ_{f0}^2 .

Using the previous results for f_ℓ , we find that for foils

$$\epsilon_{f0} = g_3 R (1-f_c) I_b / 17 \text{ kA}$$

where $g_3 \approx 0.1$ for flat-topped profiles, $g_3 \approx 0.2$ for parabolic and Bessel profiles, and $g_3 \approx 0.5$ for Gaussian profiles. The use³ of flat-topped profiles may thus considerably underestimate the emittance increase produced by anharmonic foil focusing. Observe that ϵ_{f0} , like the emittance increase from foil scattering, is independent of beam energy γ . A foil thus tailors ϵ only if R (or I_b) varies with ζ .

MULTI-FOIL TRANSPORT:

Interactions between adjacent foils become important at foil spacings $d \lesssim b$. The preceding theory of foil focusing can, however, be readily adapted provided the focal length within each foil cell satisfies $f_\ell \gg d$. This condition becomes the new paraxial condition and allows the foil cells to be treated as separate thin lenses.

Simple ray optics⁴ shows that a beam passing through a series of lenses at fixed spacing d and constant f_ℓ is stable provided $d < 4f_\ell$. For a harmonic lens but with $f_\ell \propto R$, we find that stability requires $d < 2f_\ell$, twice as restrictive as for constant f_ℓ . At very large R , saturation occurs. We have also derived a general "matching condition" for a beam of given emittance ϵ :

$$d = 2f_\ell \{1 + [1 - (\gamma R_{\min}^2 / f_\ell \epsilon)^2]^{1/2}\} > 2f_\ell,$$

where $R_{\min}$ is the (minimum) radius between foils. Because this condition violates the stability criterion, we conclude that a matched, stable beam is not possible with foils - i.e., the beam must vary from one foil cell to another. Moreover, emittance growth from anharmonic focusing or foil scattering eventually causes the radius to grow linearly with foil number n .

FRIEZR SIMULATIONS

We have run two types of FRIEZR simulations: those that explicitly compute the foil fields, and those that use the thin-lens formalism. The former can treat a broader class of problems, but it requires small spatial and temporal steps to resolve the foil fields. The full code typically agrees with the theoretical calculations for the focal length and emittance growth to within 20%. Moreover, simulations of multi-foil transport are consistent with the analytical predictions for stability and radius growth, even at high I_b/I_A where the paraxial approximation and the analysis fail.

The use of foils for conditioning was examined using the thin-lens approximation in FRIEZR. Shown below are typical results for ATA using 2-mil carbon foils at $z = 0, 39, 60$ cm and 30-mil at $z = 78$ cm in an evacuated tank of radius 7 cm. The beam parameters were $\gamma = 21$, $I_b = 6$ kA with a 10 ns rise, $R = 1$ cm, and $\epsilon = 0.46$ rad-cm. Although R and ϵ are well tailored at exit, ϵ is higher than desired in the tail. Such overheating worsens at higher I_b/I_A .

CONCLUSIONS

Our analysis and simulations indicate that foil transport and conditioning work best at low I_b/I_A and short distances. At high I_b/I_A , emittance growth from scattering or anharmonic focusing becomes excessive,

and this growth accelerates as the beam expands. For transport, we have found that the foil spacing must be kept small to prevent unstable growth.

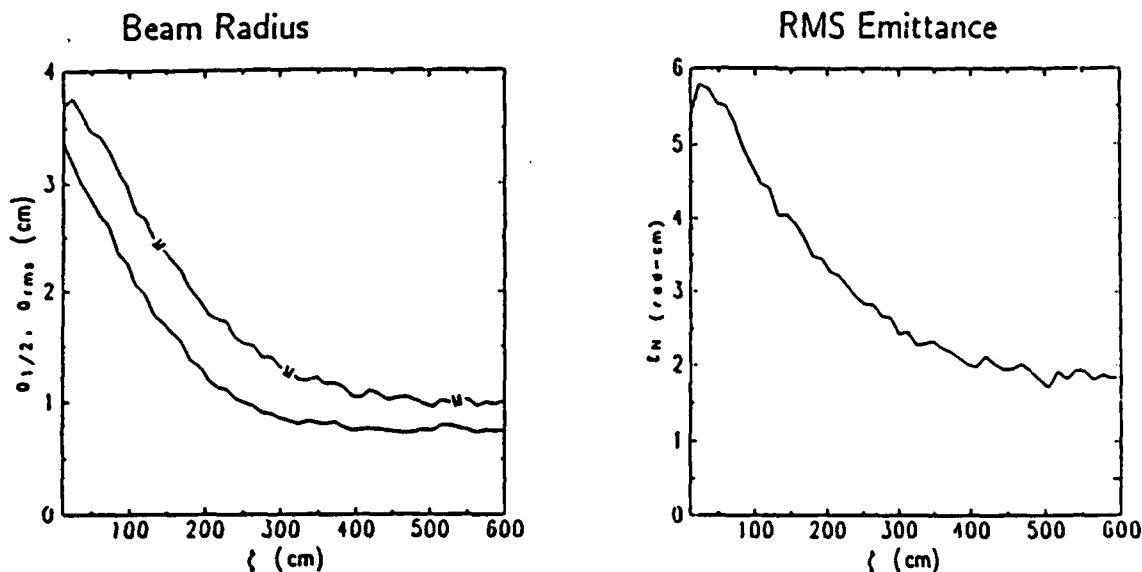


Fig. 2. ATA Multi-Foil Tailoring Cell ($z = 78$ cm).

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BEAM CONDITIONING OPTIONS FOR THE ATA MULTI-PULSE EXPERIMENT*

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I. INTRODUCTION

The ATA Multi-Pulse Propagation Experiment (MPPE) will be the first serious attempt to study beam stability, tracking and range extension for a WIPS-mode pulse train. The accelerator is expected to produce 5 beam pulses separated by 1.25 msec with peak current $I_0 = 6-8$ kA, radius $a_0 = 0.5$ cm and a nominal energy of 10 MeV. However, it is expected that the beam will be disrupted by the resistive hose instability unless a substantial head-to-tail variation in beam emittance is introduced.¹ This paper examines three emittance tailoring techniques which are currently being considered for ATA/MPPE: a multi-foil cell, a classical (passive) IFR cell and a differential focusing or energy variation system. All three techniques introduce a beam radius variation $a_b(\zeta)$ where $\zeta = ct - z$ is the distance from the beam head; the beam is then passed through a final scattering foil which converts much of this variation to a variation $\epsilon_n(\zeta)$ in the normalized emittance. Our studies have primarily been performed using the FRIEZR axisymmetric simulation code.

II. MULTI-FOIL TAILORING CELLS

Description of technique: When a relativistic beam passes through a thin conducting foil, the radial electric field is shorted out, and the beam experiences a focusing force similar to that produced by a solenoidal magnetic lens.^{2,3} The focal length f_L scales with $a_b \gamma / I_b$. Fawley⁴ has proposed using three thin foils positioned so that the beam body ($I_b = I_0$) is focused to a small radius while the lower current beam head expands to a larger radius. Since γ is nearly constant in ATA, the radius profile $a_b(\zeta)$ arises from the rise in beam current $I_b(\zeta)$ in the beam head.

Modifications to FRIEZR simulation code: The FRIEZR code has been upgraded to include foil focusing, scattering, and solenoidal lenses. Foils and lenses may be located anywhere in the beamline. Foil focusing is treated using a thin lens approximation:^{2,3} each beam electron is given an inward impulse with a focal length whose variation with r is shown in Fig. 1 of Ref. 3, assuming a Bessel beam profile. Foil scattering is treated by imparting an appropriate random kick to each simulation particle as it passes through the

foil. Solenoidal lenses are treated by specifying a focal length f_L at the lens location and adding an impulse $\delta p_x/p_z = -x/f_L$ and $\delta p_y/p_z = -y/f_L$.

Simulation results for multi-foil cell: A series of simulations were performed for a 6 kA, 10 MeV beam with an injection beam radius $a_b(0) = 0.8$ cm, wall radius $b = 7$ cm, beam rise length $\zeta_r = 360$ cm, initial normalized emittance $\epsilon_n(0) = 0.5$ rad-cm and an upstream lens placed so that $da_b/dz = 0.03$ at the first foil. Carbon foils 2 mils thick were placed at $z = 0, 39, \text{ and } 50$ cm with a thicker 30 mil foil at $z = 78$ cm. (Fawley suggested similar foil locations for a shorter three-foil cell). Figure 1 plots the half-current and rms beam radii (lower and upper curves, respectively) as functions of ζ at the final foil. The desired beam taper is produced with $a_{1/2}$ varying by a factor of 4.5. The corresponding emittance taper is shown in Fig. 2. At $\zeta = 600$ cm, ϵ_n is almost a factor of four above its injection value. This is due primarily to scattering, but a portion arises from weak variations in focal length length contained in Eq. (1). The latter effect is proportional to $a_b v_b/\gamma$ and can result in huge emittance increases for high v/γ beams such as SuperIBEX.

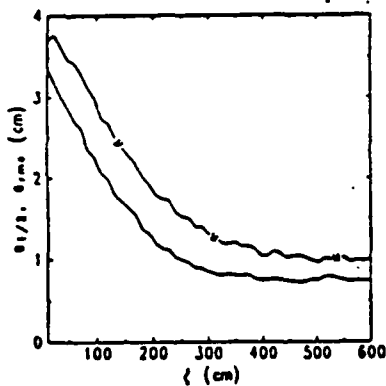


Fig 1. Beam $a_{1/2}$ and a_{rms} vs ζ at end of 78 cm long 2-2-2-30 mil carbon multi-foil cell.

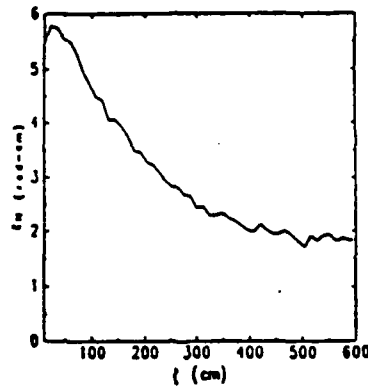


Fig 2. Emittance vs ζ for the cell used in Fig. 1. Location is just after final foil.

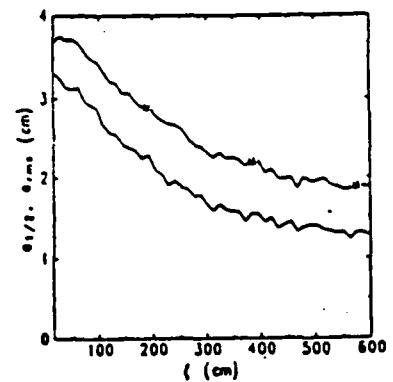


Fig 3. Beam $a_{1/2}$ and a_{rms} vs ζ at end of 78 cm long 5-5-5-30 mil carbon multi-foil cell.

When foil scattering is eliminated, the minimum half-current radius drops from 0.7 cm to 0.4 cm. However, even 2-mil foils are unlikely to survive multi-pulse ATA operation. When the first three foils are 5-mil, a_b rises to an unacceptable 1.3 cm, as shown in Fig. 3. Thus, foil scattering may severely limit the usefulness of this technique for ATA. Also, the relatively sharp radius taper in Fig. 1 is not favorable for hose stabilization.

III. PASSIVE IFR TAILORING CELL

Description of technique: Passive or classical IFR cells have been extensively used on ATA in the past to taper the beam. The beam is passed through a low pressure gas, producing a plasma column whose density, $n_i(\zeta)$, increases during the pulse. Provided $n_i < n_b$, the radial electric field produced by the beam density, n_b , expels plasma electrons, leaving behind an ion column which electrostatically pinches the beam. FRIEZR has been extensively used in the past to model such conditioning cells.⁵

IFR cells in multi-pulse operation: Although passive IFR cells have not been operated in a multi-pulse machine, we believe the beam will be tailored in the same manner as in single pulse operation. The dominant atomic physics process between pulses is expected to be charge exchange between fast ions and ambient neutral gas atoms or molecules. Hole boring should be insignificant because the collisional mean free paths are large at these gas densities. By the time the next pulse arrives, the plasma density is expected to be much too low to influence the beam. We believe that IFR cells on ATA have performed well, especially considering the inverse tailoring apparently produced by laser-ion guiding in the accelerator.

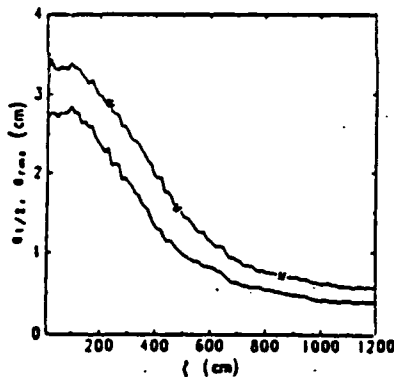


Fig 4. Beam $a_{1/2}$ and a_{rms} vs ζ at end of a 5 mtorr passive IFR cell.

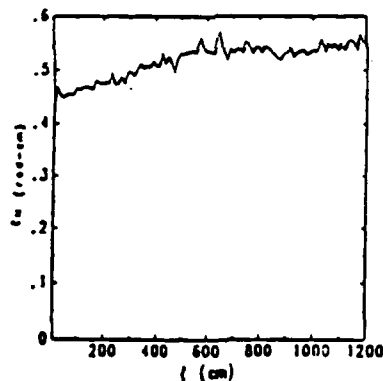


Fig 5. Beam emittance vs ζ just before final scattering foil for the IFR cell in Fig.4.

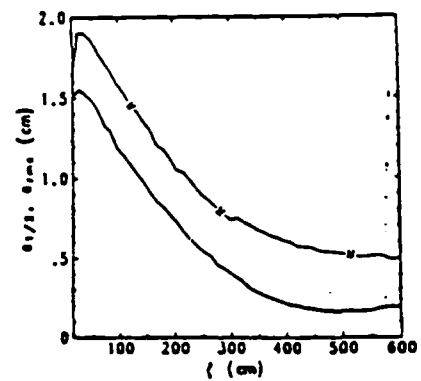


Fig. 6. Beam $a_{1/2}$ and a_{rms} for a differential focusing cell with a 20% energy variation.

Simulation results for a passive IFR cell: Although most experiments and simulations in the past have utilized IFR cell pressures of 20 mtorr or higher, lower pressures may be more effective if the beam emittance is not too large. Figure 4 plots $a_{1/2}(\zeta)$ and $a_{rms}(\zeta)$ at $z = 90$ cm for a beam similar to that described in the previous section. The gas was assumed to be air at 5

mtorr. Figure 5 plots $\epsilon_n(\zeta)$ just before the exit foil, showing essentially no emittance growth from the injected value. When the same beam is propagated in 20 mtorr, the beam tapers more quickly, and ϵ_n rises during the pulse, reaching a maximum value of 1.1 rad-cm. The results are in approximate agreement with a simple analytical model which assumes free expansion at the beam head and an equilibrium pinch in the beam body.

IV. ENERGY VARIATION (DIFFERENTIAL FOCUSING) TAILORING CELL

Description of Method: This scheme involved deliberately introducing a 10-20% energy variation in the beam and passing it through a magnetic lens tuned to focus the highest energy portion in the beam body onto a scattering foil.⁴ Lower energy portions are overfocused and expand before striking the foil. FRIEZR uses the thin lens approximation to model this approach.

Simulation results for differential focusing cell: Figure 6 plots the beam radius at the nominal focal point (30 cm) of a beam injected through a lens at an initial radius of 5 cm. The desired beam taper is attained, although the difference between $a_{1/2}$ and a_{rms} indicates an undesirable core-halo current density profile. The system must be tuned very accurately; a shift in the scattering foil position of only 3 cm in either direction alters the taper dramatically.

V. SUMMARY AND REFERENCES

All three conditioning techniques are capable of producing the desired radius taper although the multi-foil method may not be acceptable because of foil scattering. The IFR cell can in principle produce an excellent beam taper for stabilizing hose, but the differential focusing method is more compatible with the ATA fast corrector coil and can produce similar beam tailoring profiles if carefully tuned.

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