IFR CELL RADIUS TAILORING ON SUPERIBEX[$]

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Abstract

Radius tailoring is an important step towards intense relativistic electron beam (IREB) conditioning. A well conditioned beam propagates relatively stably in a self pinched mode in high neutral pressure gas environments. Low pressure Ion Focus Regime (IFR) cells are simple but very versatile radius or emittance tailoring cells since they allow flexibility in the adjustment of all major conditioning parameters. In addition they provide an efficient beam transport medium as well as some weak centering and sweep damping. The SuperIBEX beam was used to characterize the performance of the IFR low pressure gas cell as a radius and emittance tailoring device for variations in fill gas pressure, gas species, input beam temperature and exit foil.

INTRODUCTION

Beam conditioning can extend the range of "stable" propagation of high power electron beams in high pressure neutral gas environments dominated by the resistive hose instability by reducing its growth. Beam conditioning consists of two parts: emittance tailoring and current centroid oscillation (beam sweep) damping. Since the beam equilibrium radius in high pressure neutral gas is proportional to the emittance, emittance tailoring results in a smoothly varying radius as a function of time in the beam pulse. For stable propagation the most effective emittance tailoring profile is monotonically decreasing. The result is a beam with a radius which asymptotically approaches the equilibrium value with an adjustable radius decay time constant.

Figure 1 shows a typical radius variation of a tailored beam at the exit of a tailoring cell as well as the parameters needed to quantify the tailoring:

- Tailoring ratio (n): The ratio of the beam head to tail radius. Typically it is 2–10.
- Tailoring Time (t_c): The time constant for beam radius equilibration.
- Equilibrium Radius (R_{eq}): The asymptotic limit of the beam radius.

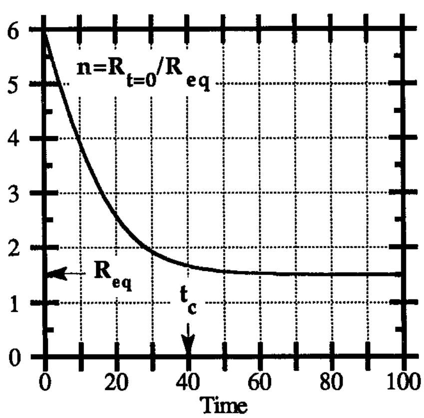

Figure 1 Idealized IFR radius tailoring profile. The three main parameters i.e. tailoring ratio, tailoring time and asymptotic final radius are indicated.

Table 1 lists some of the most common analytical models that result in the profile of figure 1. These models are used in analytical and numerical studies of these beams. Fitting experimental data to any of these profiles provides an unambiguous way of characterizing its tailoring.

IFR Tailoring Models

$$R_{beam}(t) = R_{eq}\left\{1+(n-1)e^{-\frac{t}{t_c}}\right\}$$

$$R_{beam}(t) = R_{eq}\left\{n+(n-1)\tanh\left(\frac{t}{t_c}\right)\right\}$$

$$R_{beam}(t) = R_{eq}\left\{1+\frac{\alpha}{\left(\frac{t}{t_c}\right)^{\kappa}}\right\}$$

R_{beam} = beam half-current radius
n= head-to-tail tailoring ratio
R_{eq} = final asymptotic radius
t_c = tailoring time constant
α,κ = radius variation parameters

Table 1 Common functions that can model the time dependent radius for a low pressure IFR cell. The polynomial function is not well behaved near the head, but is very useful for analytical treatments of the resistive hose instability.

A variety of passive and active techniques ranging from single or multiple IFR cells, current carrying or resistive wire cells, transverse conducting foil arrays and other hybrid cells have been used to tailor electron beams. In addition to radius tailoring, the transport efficiency, beam centering , sweep reduction, sweep damping and radius to emittance tailoring conversion properties of the cell must be considered in the conditioning cell selection for each specific application. This work concentrates primarily on the radius and emittance tailoring abilities of a single low pressure IFR cell. The conversion of radius to emittance tailoring is accomplished by using a relatively thick titanium foil at the exit of the IFR cell.

IFR cells are simple conditioning to operate and they are very versatile. An IFR cell is a passive, low pressure gas filled tube with a foil at each end. As a relativistic electron beam travels through the neutral fill gas it generates a quasineutral plasma due to impact ionization of the ambient neutrals by the beam electrons. Because of the electric field generated inside the beam by its own space charge, the plasma electrons are be ejected very quickly

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14. ABSTRACT
Radius tailoring is an important step towards intense relativistic electron beam (IREB) conditioning. A well conditioned beam propagates relatively stably in a self pinched mode in high neutral pressure gas environments. Low pressure Ion Focus Regime (IFR) cells are simple but very versatile radius or emittance tailoring cells since they allow flexibility in the adjustment of all major conditioning parameters. In addition they provide an efficient beam transport medium as well as some weak centering and sweep damping. The SuperiBEX beam was used to characterize the performance of the IFR low pressure gas cell as a radius and emittance tailoring device for variations in fill gas pressure, gas species, input beam temperature and exit foil.

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from the interior of the beam unless the beam current is approaching the Alfvèn current or the beam is fully charge neutralized. The ions are left behind forming a positive channel which partially neutralizes the beam space charge resulting in a net increase of the pinch force on the beam. The channel ion density in an IFR cell increases monotonically in time. In IFR cells the fill pressure is low enough so that the space charge neutralization ratio ($f_e = n_{channel}/n_{beam}$) remains below 1. If f_e exceeds 1 return currents are generated in the excess channel plasma modifying the favorable beam radius profile.

The evolution of the beam envelope in an IFR is described by the envelope equation[1]. To simplify the analysis we first consider the beam perveance and emittance terms only. For $f_e \leq 1/\gamma^2$ both terms result in defocusing forces and expansion of the beam envelope. When $f_e \geq 1/\gamma^2$, the perveance term becomes focusing partly reducing the emittance driven radius growth. The equilibrium time is reached when f_e reaches the value that equalizes the perveance and emittance terms. But f_e continues to increase resulting in a net focusing force on the beam which should continue to reduce the beam radius. For an IFR cell it has been shown that as the beam radius decreases below its injection radius, the focusing force results in beam emittance increase rather than any significant radius reduction. This corresponds the slow variation of radius in figure 1 after time=t_c. Inductive erosion of the beam is ignored in this analysis, whose main effect is to further increase the beam size and current loss particularly near the beam head as well as decrease the effective beam pulse width.

EXPERIMENT DESCRIPTION

The beam used for the conditioning study was produced by NRL's SuperIBEX accelerator. The nominal beam energy is 4.5 MeV and the pulse width is 40 nsec FWHM. The beam originates from a 0.3cm radius flat cathode. The anode is a 2.5 μm thick Ti foil. The emittance selector consists of a 5 cm long, 18 mm diameter evacuated stainless steel tube and an exit foil allows us to control the current and input beam emittance. The typical beam current injected into IFR cell ranges from 15-27 kA. The input beam emittance is estimated below 50 mrad–cm so the input beam emittance is primarily due to the emittance selector exit foil.

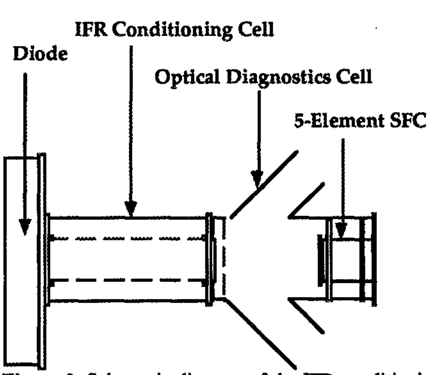

Figure 2 Schematic diagram of the IFR conditioning cell used in the SuperIBEX experiments. The optical diagnostics cell with the Cerenkov target and the segmented Faraday collector is also shown.

The IFR cell is a 40 cm long, 10 cm in diameter. Both the input and output foils are interchangeable. The input foils used were 6 μm thick double-sided aluminized mylar and 12 μm, 38 μm and 125 μm titanium foils. The exit foil was maintained at 38 μm titanium. Figure 2 is a schematic of the IFR cell indicating the position of the main radius tailoring diagnostics.

The main diagnostics used to measure the parameters relevant to beam conditioning were:

- Beam bugs measuring beam current and centroid position near the entrance and exit of the IFR cell.
- 5 element concentric segmented Faraday (SFC) collector measuring beam current distribution 5 cm and 26 cm away from the exit foil [3]. The SFC is located at 26 cm to allow simultaneous use of the optical and electrical diagnostics as well as observe the equilibrium beam profile in full density air from which we can infer the actual beam emittance tailoring.
- 4 frame gated optical imager with 100 picosecond resolution measuring time resolved 2-dimensional beam current distribution from Cerenkov emission of a thin FEP Teflon foil.
- Optical streak camera for time resolved 1-D measurements of beam current distribution, radius and centroid position from Cerenkov emission of a thin FEP Teflon foil.

The Cerenkov foil for the optical diagnostics was placed 1cm from the exit foil to measure the actual beam radius tailoring at the IFR cell exit foil.

RESULTS AND DISCUSSION

The IFR cell offer several "knobs" which give it its versatility. The IFR cell pressure, input foil, output foil and fill gas species allow precise tuning of the beam radius profile for each application. For pressures between 3 and 10 mTorr, input emittance of 0.05–0.3 mrad–cm and Argon fill gas we were able to achieve tailoring ratios 2–10, tailoring times 3–40 ns and final radius from 0.5– 3 cm.

The **IFR pressure** affects the tailoring in the following ways:

- **Pressure too low** — f_e never reaches the equilibrium value within the pulse since the characteristic time for the increase in f_e is inversely proportional to pressure. The head of the beam is almost freely expanding while the beam tail remains larger than the injection radius. The conditioning time in this case is longer than the beam and the radius profile is a decreasing ramp with the final radius never reaching its asymptotic value.
- **Pressure too high**— Equilibrium is reached early in the pulse but f_e continues to increase overheating the beam tail without much radius decrease. If the beam exits through a thin foil the beam tail could be inversely tailored since the emittance is inversely tailored near the beam tail inside a high pressure IFR cell.
- **Optimum pressure**— Produces a beam suitable for propagation experiments. The tailoring time is comparable to the beam current risetime to not only tailor the high current portion of the beam but to achieve small radius and high current density beams without significant tail overheating. The proper thickness exit foil then dominates the beam emittance directly converting radius tailoring to emittance tailoring.

Figure 3 shows the equilibrium radius profiles of the same input beam when the IFR pressure is changed from 3 to 9 mTorr of argon. The measurement is made with the SFC after 26 cm of propagation in air, so the profile depends on the total emittance tailoring. The final radius for the two high pressures is the same indicating that they were high enough to reach equilibrium for the beam input emittance. For lower pressures the beam radius decreases slower at early times as expected.

The **fill gas species** is important primarily because the ionization cross section and consequently the plasma production rate vary with gas species. The plasma production rate governs the increase of f_e ultimately determining the tailoring time. If a heavy gas is used an

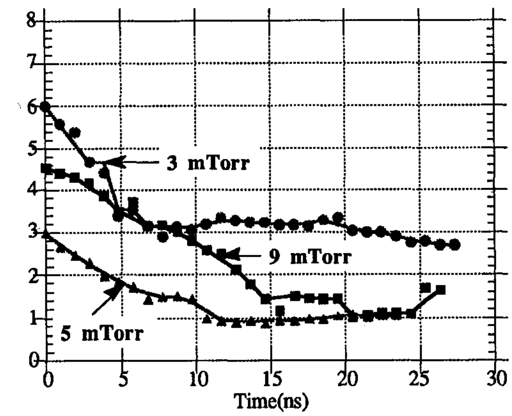

Figure 3 IFR pressure variation effect on radius tailoring. Low pressure extends conditioning time past the beam current peak. Increased pressure increases the slope of the decrease of radius and reduces beam current head erosion.

additional benefit is derived from the increased ion inertia which can reduce beam sweep growth and for long pulses it can delay the onset of the ion hose instability.

The **accelerator** and the **cell entrance foil** determine the emittance of the injected beam. If the injected beam emittance increases without a corresponding increase in gas pressure, the equilibrium slice moves further towards the tail of the beam. Thus the tailoring time increases and tail overheating decreases. The disadvantage of using this knob to control the beam profile is that warm beams suffer head erosion due to rapid beam expansion and loss at the walls of the IFR cell. If the IFR cell diameter increases, it does not directly affect the radius profile and it improves beam transport at the expense of the already limited beam centering force which decreases as (r_b^2/r_w^2). Such weak centering can lead to enhanced beam sweep and instabilities accompanied by severe beam heating or loss. Figure 4 shows the effect of the change of the input beam temperature on the tailoring of the beam after 26 cm of propagation in full density air. Thus the actual exit beam emittance profiles are compared. The hot beam produced by the 5 mil entrance foil not only has the largest tail radius but shows the effect of the beam tail overheating because the exit foil is thinner than the entrance foil and does not dominate the output emittance so any inverse tailoring inside the cell is maintained. The exit foil section below discusses this effect in more detail.

The **total beam current** does not have a very strong effect on the tailoring for our parameters because the beam radius expansion is dominated by the emittance term which is not current dependent instead of the perveance term which depends on the beam current. The radius tailoring profile for a low current (14 kA) and a high current (21 kA) is plotted in figure 5. The time history of the radius is virtually unchanged by the increase in beam current.

The **cell exit foil** is a key piece of the IFR puzzle. The exit beam emittance profile determines the stability of the beam during further propagation experiments. A thin metallic foil results in emittance increase $\Delta\varepsilon \approx R_b \langle\delta\theta\rangle$ where R_b is the beam radius and $\langle\delta\theta\rangle$ is the mean scattering angle given by $\langle\delta\theta\rangle \approx \sqrt{t}/\gamma$ with t the foil thickness in mils. If the foil is thick enough so that its emittance contribution dominates the total emittance, the radius tailoring is converted directly into emittance tailoring. If the exit foil is not thick enough to dominate the exit beam emittance the inverse emittance tailoring of the IFR cell could lead to an inversely tailored beam. The thick exit foil may conflict with requirements that the total exit beam emittance does exceed a certain value for beam radius considerations. Proper choice of exit foil has a profound effect on beam stability in atmospheric propagation experiments [4].

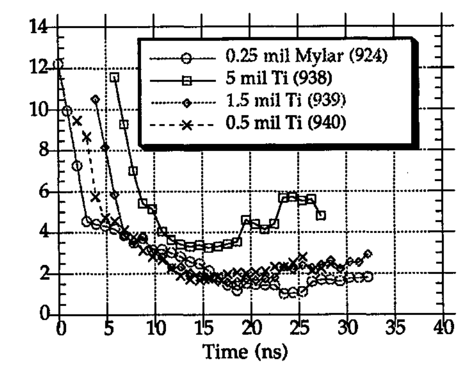

Figure 4 Effect of input beam temperature changes in the emittance tailoring in an IFR cell. Cell pressure is 5 mTorr argon and the exit foil is 1.5 mil Ti.The delay in radius decrease is due to higher emittance. The hot beam has tail flare from overheating in the cell maintained due to the thin exit foil.

CONCLUSIONS

IFR cells are simple passive conditioning cell that allow control over all of the important beam tailoring parameters i.e. equilibrium radius, tailoring time and tailoring ratio. Tailoring is effective over a large current range and is relatively insensitive to beam current variations. The tailoring ratio can be varied over an order of magnitude and tailoring can be extended to match or exceed the beam current risetime. The output beam radius is as small as 5 mm with on-axis current density as high as 5 kA/cm^2.

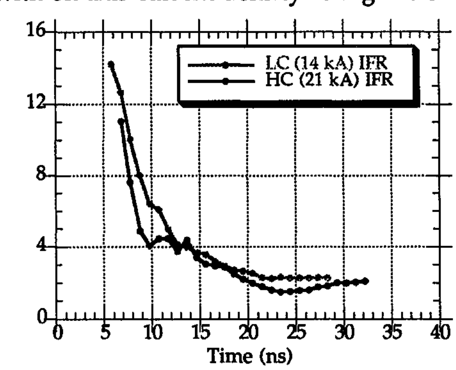

Figure 5 The beam current does not have a significant effect on tailoring characteristics for these parameters since the profile is depends primarily on emittance.

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