2.18: Control of Beam Loss and Improving Efficiency in High-Repetition-Rate High-Power Klystrons

(Progress Report)

Accelerator Physics

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Control of Beam Loss and Improving Efficiency in High-Repetition-Rate High-Power Klystrons

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Project Overview

A major thrust in the International Linear Collider (ILC) program is the development of high-power klystrons to power a TeV-class LC. The high construction and operating costs of the ILC rf power system drive the need for research and development on Alternative Configuration Design (ACD).

For ILC, the choice of Base Configuration Design (BCD) is the L-Band Multi-Beam Klystron (MBK). The required specifications for the L-Band power source are: 10 MW power output, 1.5 ms pulse length, 10 Hz repetition rate, 65% efficiency, and several years of lifetime.

Much progress has been made in Europe, US and Japan on L-Band MBK (Adolphsen, 2006). At Thales, 4 tubes were produced, and gun arcing problem occurred and seemed to be corrected in last two tubes after fixes applied. However, Thales tubes recently developed other arcing problems above 8 MW. Thales is to build two more without changes and two with changes after problem is better diagnosed. At CPI, one tube was built and factory-tested to 10 MW at short pulse. During full pulse testing at DESY, it developed vacuum leak after 8.3 MW was achieved. It has been repaired and will be tested again. At Toshiba, one tube was built, and after a vacuum problem was fixed, ran at full spec for one day – has been shipped to DESY for further evaluation. Despite these efforts, the ILC community and industry still needs to develop an L-Band klystron that meets the full specifications for ILC.

A leading choice of Alternative Configuration Design (ACD) is a ribbon-beam (or sheet-beam) klystron (RBK) powered by an electron beam with a large-aspect-ratio elliptic cross section. The ribbon-beam klystron (RBK) has the following advantages over the conventional multiple cylindrical-beam klystrons:

a) Higher efficiency (75% vs. 65%),
b) Single beam (1 vs. 6 or 7),
c) Lower magnetic field (1.4 kG rms vs. 5 kG rms),
d) Energy-free permanent magnet vs. energy-consuming pulsed magnet.

These advantages would reduce the construction and operating costs of ILC and improve the reliability of the rf power system. RBKs could provide the following savings:

a) Klystron hardware: 66% (or $60M) saving.
b) RF system electricity: 20% (or $20M/year) saving.

These attractive features motivated MIT to pursue the R&D on a RBK. In FY06, SLAC began to establish a sheet-beam klystron R&D program with internal funding. SLAC hopes to receive support from GDE in FY07 to accelerate its sheet-beam klystron R&D.

The goal of MIT R&D program is to continue our innovative research on ribbon-beam klystrons, building upon the experience we gained in the past several years in the theory, design, fabrication and testing of ribbon beams and ribbon-beam devices.

Progress Report

Our recent accomplishments in our Ribbon-Beam Klystron research were:

(a) Developed an award-winning design for an elliptic electron gun in 2004-2005 (Bhatt and Chen, 2005; Bhatt, Bemis, and Chen, 2005 and 2006);
(b) First experimental demonstration of a 6:1 elliptic electron gun in 2005 (Chen, 2006);
(c) Developed a cold-fluid equilibrium theory of a periodically twisting elliptic beam in 2005 (Zhou, Bhatt and Chen 2006);
(d) Published a kinetic equilibrium theory of a periodically twisting elliptic beam, which showed that thermal effects are negligibly small (Zhou and Chen, 2006);
(e) Developed a kinetic equilibrium theory of nearly non-twisting elliptic beams (Bhatt, 2006);
(f) Developed a cold-fluid equilibrium theory of nearly non-twisting elliptic beams (Zhou and Chen, 2007);
(g) Designed a ribbon-beam transport system for the development of ILC ribbon-beam klystron (Zhou and Chen, 2007).

A brief description is given below for each of the 2006-2007 accomplishments (d)-(g), while our accomplishments (a)-(c) prior to 2006 were reported earlier.

Accomplishment (d): A Vlasov equilibrium of the Kapchinskij-Vladimirskij form was obtained for a periodically twisted ellipse-shaped charged-particle beam in a non-axisymmetric periodic magnetic focusing field. The single-particle Hamiltonian dynamics was analyzed self-consistently. A constant of motion analogous to the Courant-Snyder invariant was found. The equilibrium distribution function was constructed. The statistical properties of the beam equilibrium were studied. In the zero-temperature limit, the generalized envelope equations derived from the kinetic equilibrium theory recover the generalized envelope equations obtained in the cold-fluid equilibrium theory. Examples of periodically twisted elliptic beam equilibria were considered, and potential applications were discussed. For ribbon-beam klystron applications, the kinetic equilibrium theory predicted that the effect of beam temperature on the beam envelopes is negligibly small. Detailed results were published (Zhou and Chen, 2006).

Accomplishments (e) and (f): Both cold-fluid and kinetic equilibrium theories of nearly non-twisting elliptic beams were developed (Bhatt, 2006; Zhou and Chen, 2007). In paraxial approximation, the focusing field is expressed as

$$\mathbf{B} = \left\{ B_z(s)\mathbf{e}_z - \frac{dB_z(s)}{ds}\left[\frac{k_{0x}^2}{k_0^2} x\mathbf{e}_x + \frac{k_{0y}^2}{k_0^2} y\mathbf{e}_y \right] \right\} + B_q'\left[y\mathbf{e}_x + x\mathbf{e}_y \right]. \qquad (1)$$

with $B_q' \equiv \partial B_x^q / \partial y\big|_{(s,0,0)} = \partial B_y^q / \partial x\big|_{(s,0,0)}$. The paraxial cold-fluid equations, which consist of the continuity equation, the Poisson equation, and the force balance equation, are solved with the density and transverse velocity of the form

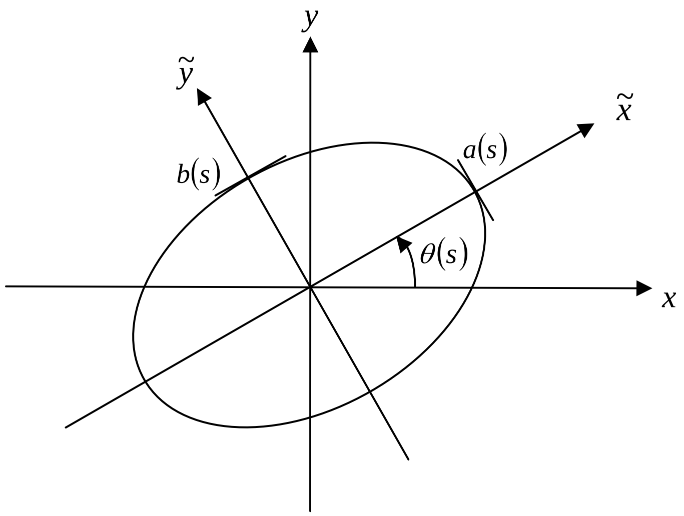

Fig. 1 Coordinate systems.

$$n_b(\mathbf{x}_\perp, s) = \frac{N_b}{\pi a(s) b(s)} \Theta\left[1 - \frac{\tilde{x}^2}{a^2(s)} - \frac{\tilde{y}^2}{b^2(s)}\right], \tag{2}$$

$$\mathbf{V}_\perp(\mathbf{x}_\perp, s) = [\mu_x(s)\tilde{x} - \alpha_x(s)\tilde{y}]\beta_b c \hat{\mathbf{e}}_{\tilde{x}} + [\mu_y(s)\tilde{y} + \alpha_y(s)\tilde{x}]\beta_b c \hat{\mathbf{e}}_{\tilde{y}}, \tag{3}$$

In Eqs. (2) and (3), $\mathbf{x}_\perp = \tilde{x}\hat{\mathbf{e}}_{\tilde{x}} + \tilde{y}\hat{\mathbf{e}}_{\tilde{y}}$ is a transverse displacement in the twisted coordinate system illustrated in Fig. 1. $\theta(s)$ is the twist angle of the ellipse. $\Theta(x) = 1$ if $x > 0$ and $\Theta(x) = 0$ if $x < 0$. The functions $a(s)$, $b(s)$, $\mu_x(s)$, $\mu_y(s)$, $\alpha_x(s)$, $\alpha_y(s)$ and $\theta(s)$ obey the generalized envelope equations, which will be presented elsewhere (Zhou and Chen, 2007). Equations (1)-(3) together with the generalized envelope equations provide a theoretical framework for the design of elliptic electron beams in RBKs.

Accomplishment (g): Using the cold-fluid equilibrium theory, we determined the parameters for the realization of an elliptic electron beam for an ILC ribbon beam klystron. Table 1 shows the progress we made in our consideration of beam design options for RBK. Figure 2 shows the simulation results (Zhou and Chen, 2007).

Table 1. System parameters for an elliptic beam design for ILC RBK

Parameter	Value
Current (A)	111.1
Voltage (kV)	120
S (cm)	2.2
k_{0x}/k_{0y}	0.158
B_0 (kG)	2.0
a/b	20
a (cm)	1.0
θ_{max} (deg)	0.75

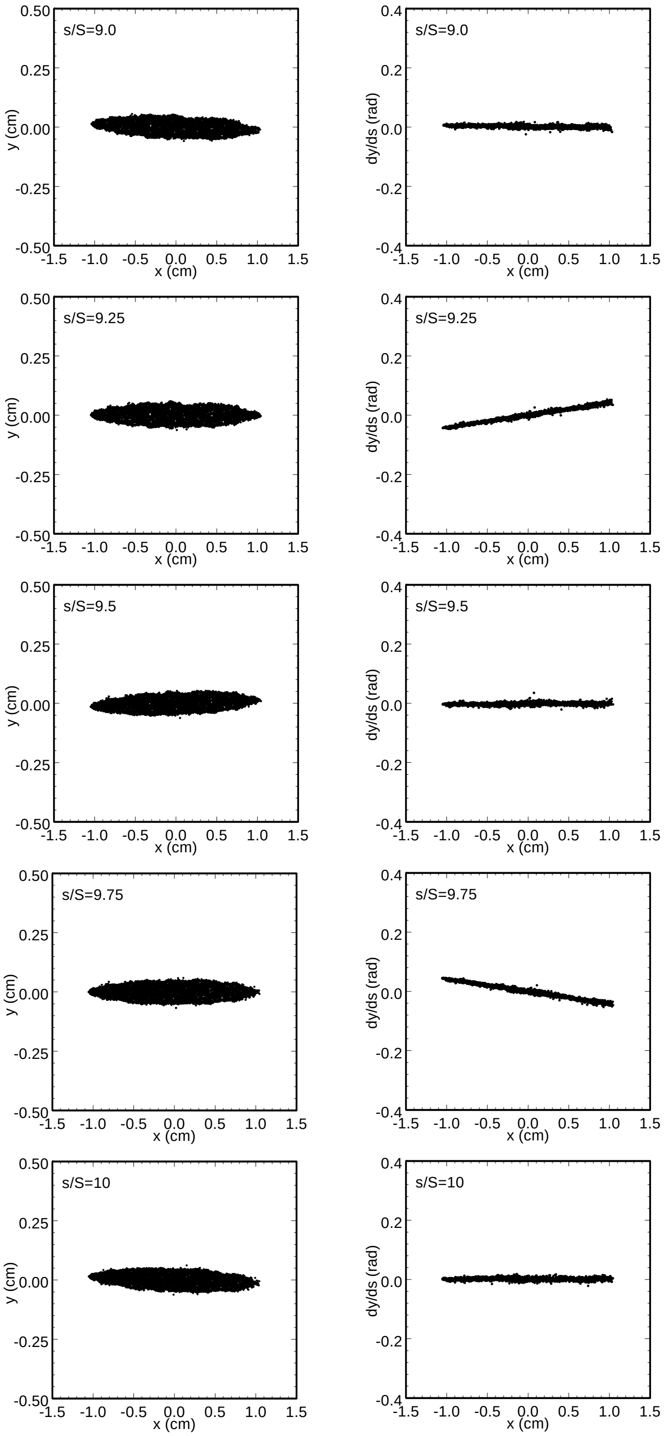

Fig. 2 Plots of 5,000 particles (a sample of the 5×10^5 particles in the PFB2D simulation) in the (x,y) plane and $(x,dy/ds)$ plane for five snapshots within one period: $s/S = 9.0, 9.25, 9.5, 9.75$ and 10.0 for the parameters listed in Table 1 (Zhou and Chen, 2007).

Plans for 2007 and Beyond

We plan to study how to form elliptic electron beams, apply the knowledge we gain to forming the elliptic electron beam, and participate in the engineering design, fabrication, and testing of ILC RBK in collaboration with SLAC and industry. Deliverables include:

a) Design of the formation of a relativistic elliptic beam from an elliptic diode (2007);
b) Design of the transformation of a relativistic round beam from a round diode into a relativistic elliptic beam (2007);
c) Design the focusing magnets (2007-2008);
d) Design the rf system including beam tunnel and rf cavities (2007-2008);
e) Participate in the fabrication and testing of ILC RBK (2008-2009).

We plan to submit a supplemental request to Department of Energy to support these actives in FY07. Beyond FY07, we plan to submit a research proposal directly to Global Design Effort (GDE) to participate in the engineering design, fabrication, and testing of ILC RBK. The estimate cost for FY07-FY09 is given in Table 2, which is modest for the proposed research efforts.

Table 2. Approximate breakdown of estimate costs for 2007-2009

Item	FY07	FY08	FY09	Total
Chiping Chen (PI)	$30,000	$32,000	$35,000	$97.000
Postdoctoral Research Associate	$45,000	$47,000	$49,000	$141,000
Student	$7,000	$7,000	$7,000	$21,000
Travel	$3,000	$4,000	$4,000	$11,000
Total	$85,000	$90,000	$95,000	$270,000

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