

To the Graduate Council

I am submitting herewith a thesis written by Dirk A. Bartkoski entitled “The Development of Computational Tools for Halo Analysis and Study of Halo Growth in the Spallation Neutron Source Linear Accelerator.” I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Physics.

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**THE DEVELOPMENT OF COMPUTATIONAL TOOLS FOR HALO ANALYSIS
AND STUDY OF HALO GROWTH IN THE SPALLATION NEUTRON SOURCE
LINEAR ACCELERATOR**

A Thesis
Presented for the
Masters of Science
Degree
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Abstract

The Spallation Neutron Source (SNS), being built at the Oak Ridge National Laboratory, utilizes a high intensity particle accelerator for neutron production. One of the challenges in SNS, as with all high intensity accelerators, is to minimize the amount of beam lost. High beam losses can cause costly damage and lead to residual activation of accelerator components, which complicates routine maintenance.

One of the key components in beam loss at SNS is the development and propagation of beam halo. Halo particles are those driven to large amplitudes by space charge forces between the beam particles or by mismatch between the beam and the accelerator optics. The research presented seeks to develop computational tools to quantify the halo in a beam by analyzing beam profiles and identifying the halo using the Gaussian area ratio and kurtosis methods. Simulations of various configurations using three types of initial simulated distributions, along with an analysis of their phase space and rms properties, provides insight into the development of halo in the SNS linear accelerator. Finally, comparisons with machine beam profile data, taken at the same conditions as that of the simulated data, shows how accurately the simulations model the beam and its halo development and provides a better understanding of the best machine configuration with which to minimize beam halo and losses.

Results of simulated data are independent of the initial distribution for strongly mismatched cases; however, even relatively well matched cases generate some halo. Core analysis reveals an increase in beam size as halo decreases for simulated cases. Experimental comparison with simulation results shows poor correlation between halo plots but moderate agreement in profile plots.

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1 Introduction

Since the beginning of time, Man has pondered the mysteries of the natural world. Whether it is to stare into heavens, marveling at its vastitude or wonder at the complexity of the simplest elements of life, the curiosity to understand the created universe has driven humanity to its greatest achievements.

Particle accelerators are among the top technological modern marvels. With new machines being built to probe the fundamental structure of matter and with medical uses of accelerated particles to help treat tumors, accelerators are helping to advance all areas of humanity. The class of accelerators used as neutron sources is recognized for its potential in study of materials science. Many of the most powerful neutron sources are currently located in Europe and Japan with some reactor and accelerator based sources in the U.S. The new Spallation Neutron Source (SNS) being built at the Oak Ridge National Laboratory will be the most powerful pulsed neutron source in the world when it is completed in 2006.

Machines like SNS will not only be tools for neutron scattering study but will also allow accelerator physicists to study the physics of high-intensity beams. One of the main challenges present in more powerful accelerators is the control of beam loss as the beam is accelerated. Excessive beam loss and subsequent activation of accelerator components is a limiting factor in the performance of high-intensity accelerators. Radioactivation created when high-energy particles collide with the accelerating structure not only delays necessary maintenance, but high concentrated losses can damage components beyond repair. Beam losses can arise from many types of errors but, for a well tuned machine, the main contributing factor comes from outlying particles known as beam halo. If a beam is

injected into the accelerator with a phase-space orientation that is mismatched to the design orientation a fraction of the particles are forced to the outside of the beam forming a “halo” of large amplitude particles that can hit the walls of the machine.

It is the goal of this research to analyze the halo development in the SNS linear accelerator (linac) by developing a computational model to compare measured particle distributions with computer simulations for different machine settings which reflect the actual machine settings at the time the data was accumulated. Compare simulations with experimental data to determine simulation accuracy. Simulations for different initial distributions will be compared in order to understand which parameters are sensitive to the halo development. Use experimental data to provide guidance for machine settings to minimize halo and control beam loss. SNS will be an excellent platform to expand the current understanding of halo production allowing for the operation and design of more efficient particle accelerators.

2 Accelerator Background

2.1 Accelerator History

In the early 1900's, physicists were looking for new ways to probe the atom. The atomic structure was known to consist of electrons and a nucleus thanks to J. J. Thompson and Ernest Rutherford, but there was suspicion that the nucleus itself was composed of smaller particles. The need for high energy particles to bombard the nucleus was quickly realized and therein began the development of the particle accelerator. John D. Cockcroft and Ernest Walton built one of the first accelerators and work done by Robert Van de Graaff showed that higher voltages could be reached. While Rolf Wideroe was building linear accelerators in 1928, Ernest Lawrence was using the same principle to build circular accelerators. The highest energy machines are used primarily for colliding protons or electrons with their antimatter particles for high-energy particle physics. Halo has been observed since scientists began building high-intensity accelerators. Beam losses in the 100 mA continuous wave Accelerator Production of Tritium project gave more motivation into the study of beam halo [1] along with more powerful computers and developments in nonlinear dynamics. The Low-Energy Demonstration Accelerator (LEDA) was the first study solely devoted to halo development [2].

2.2 The Spallation Neutron Source

The Spallation Neutron Source is a third generation pulsed neutron source. Because they have no charge, neutrons can penetrate atomic structures unlike electrons and protons. Neutron scattering is a process in which scientists scatter beams of neutrons off a sample of material to understand its internal structure. Many neutrons will pass through the material, but some will interact with nuclei in the structure and be scattered.

By measuring the angles and energies of the scattered neutrons, scientists can determine the structure of the material [3].

Neutrons in SNS are produced in a spallation reaction. Spallation refers to the nuclear process that occurs when a high-energy particle strikes a heavy atomic nucleus. Some neutrons are ejected immediately, but most are released as the atom is excited in energy. For every incoming proton, 20 to 30 neutrons are emitted [3].

The production of neutrons begins in the Front-End, as shown in Figure 2.1, with an ion source that generates negative hydrogen ions (H^-). The particles are formed into bunches and accelerated to an energy of 2.5 MeV using a Radio Frequency Quadrupole (RFQ). They are further bunched and matched into the remainder of the linac in the Medium Energy Beam Transport (MEBT) shown in Figure 2.2 (a). The first part of the linear accelerator, the warm linac, operates at room temperature, while the later portion of the linac which is composed of Superconducting (SCL) cavities cooled to 2° kelvin.

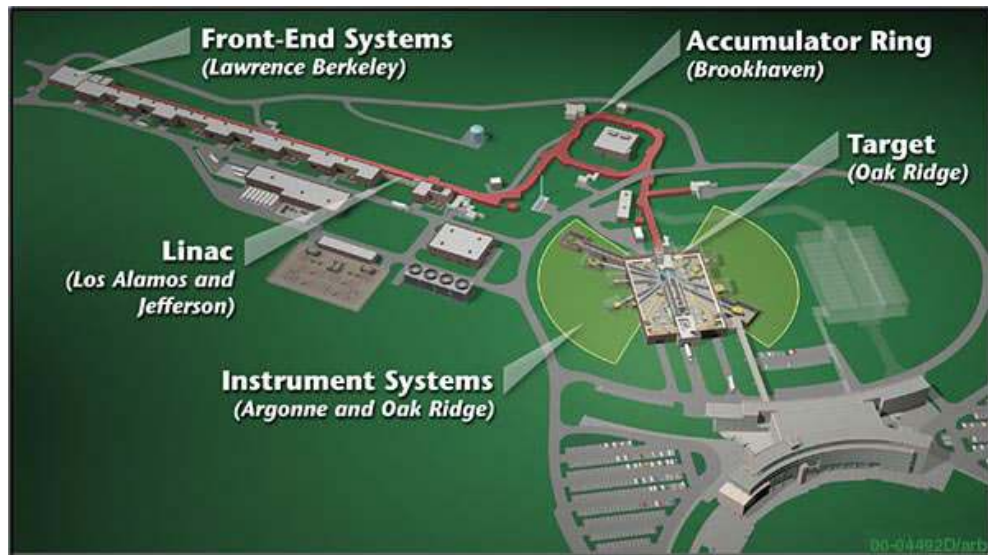
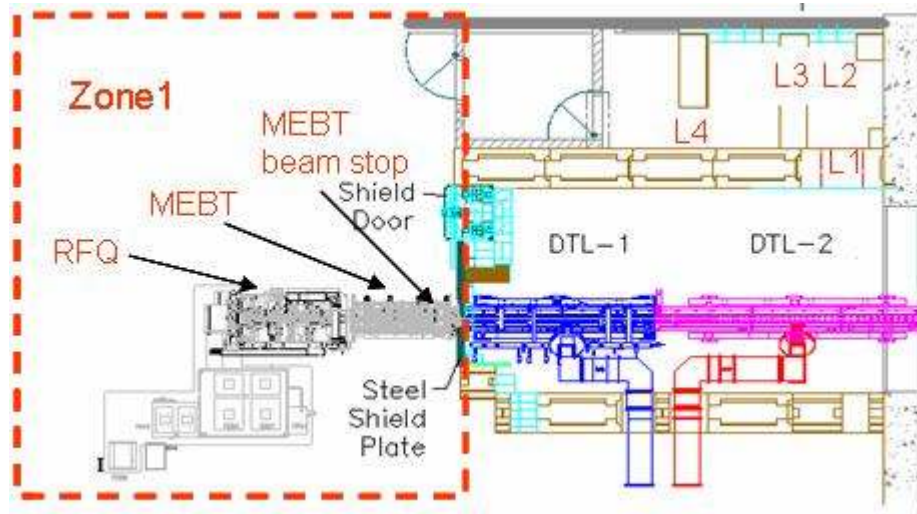
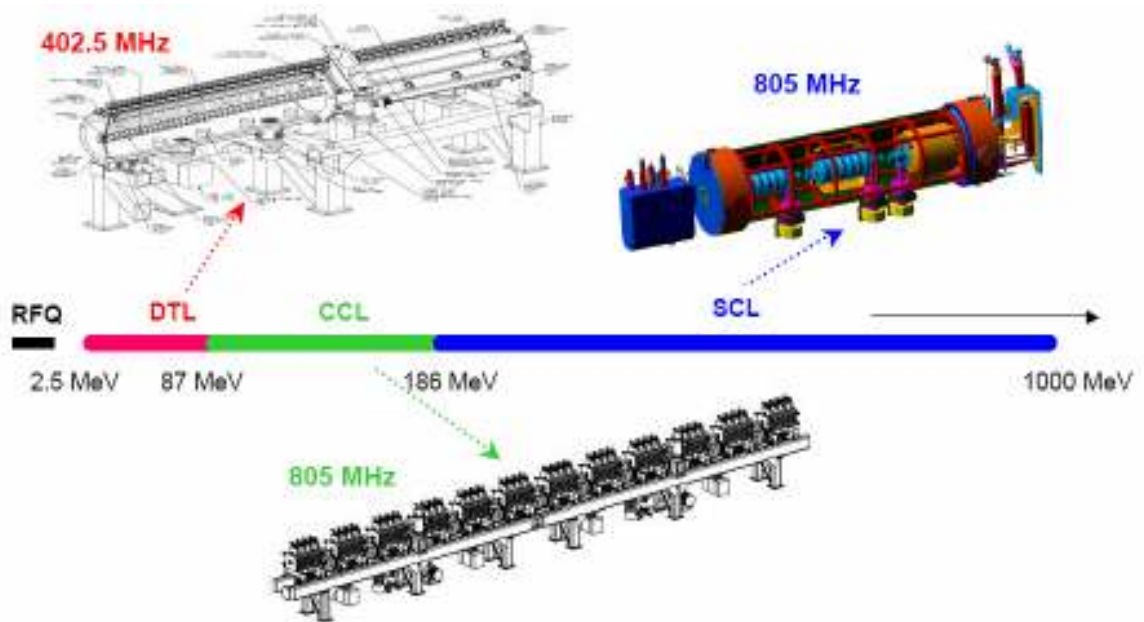


Figure 2.1 Spallation Neutron Source overall setup with collaborator references [3].



(a)



(b)

Figure 2.2 (a) MEBT and first two DTL tanks. (b) Main linac DTL, CCL, and SCL structures [4].

There are 6 Drift Tube Linac (DTL) tanks, shown Figure 2.2 (b), immediately following the MEBT. A DTL uses radio frequency (RF) power to set up electromagnetic waves inside a cylindrical cavity. A series of drift-tubes shield the beam particles so they only see the RF electric field in the gap during that part of the RF cycle when the field is accelerating. Some drift tubes also contain quadrupole magnets used to focus the beam in the transverse direction.

Klystrons provide the RF power to all of the cavities. A klystron uses bunched electrons to excite microwave frequency oscillations in an evacuated tube to produce a large amount of RF power [5]. Waveguides then deliver the waves to resonant cavities that set up standing waves or propagate traveling waves.

The H^- ions are accelerated to an energy of 87 MeV at the end of the DTL tanks, at which they enter the four Coupled-Cavity Linac (CCL) modules. A coupled-cavity module is a linear array of resonant cavities into which RF power is provided from the klystron gallery. Each cavity is designed to support a standing wave mode. Particles passing through the cavity see an accelerating electric potential when they enter with the correct phase.

The rest of the SNS linac structure consists of superconducting niobium cavities, shown in Figure 2.2 (b), that are cooled with liquid helium allowing for much higher electric fields. After its acceleration to a final energy of 1 GeV the beam is then injected into the accumulator ring, which takes the 1 millisecond pulse and delivers a 1 micro-second beam pulse to the target. The electrons are stripped off the H^- ions leaving H^+ before injection into the ring. The target uses liquid mercury as the nuclear material for the spallation reaction. The emitted neutrons are moderated and delivered in at room

temperature and 20° K to different research areas. Basic parameters for SNS can be found in Table 2-1.

There are many diagnostic tools used to analyze the position and characteristics of the beam. The wirescanner is the most useful tool implemented in SNS to study halo. Wirescanners are devices placed inside the beam pipe that pass metallic wires through a beam. The amount of current generated in a wire is proportional to the number of charged particles striking the wire. The wirescanners are used to generate beam profiles along a given axis with three wires; vertical, horizontal, and diagonal.

The SNS will be the world's highest power proton accelerator. Therefore, consideration of beam loss is of paramount importance. SNS is designed to run with losses of 1 W/m in the warm linac and less in the superconducting section. Figure 2.3 shows the losses predicted for SNS at the full power of 1.4 MW. This goal strengthens the need to control all forms of loss especially in the warm linac, where halo is expected to develop. Since beam halo is a key component to the losses in SNS, understanding its development and control is a high priority.

Table 2-1 SNS basic parameter list [3].

Parameter Description	Parameter
Proton beam on target	1.4 MW
Proton beam kinetic energy on target	1.0 GeV
Average beam current on target	1.4 mA
Pulse repetition rate	60 Hz
Protons per pulse on target	1.5×10^{14} protons
Charge per pulse on target	24 μC
Energy per pulse on target	24 kJ
Proton pulse length on target	695 ns
Ion type (Front end, Linac, HEBT)	H minus
Average linac macropulse H-current	26 mA
Linac beam macropulse duty factor	6%
Front end length	7.5 m
Linac length	331 m
HEBT length	170 m
Ring circumference	248 m
RTBT length	150 m
Ion type (Ring, RTBT, Target)	proton
Ring filling time	1.0 ms
Ring revolution frequency	1.058 MHz
Number of injected turns	1060
Ring filling fraction	68%
Ring extraction beam gap	250 ns
Maximum uncontrolled beam loss	1 W/m
Target material	Hg
Number of ambient/cold moderators	1/3
Number of neutron beam shutters	18
Initial number of instruments	5

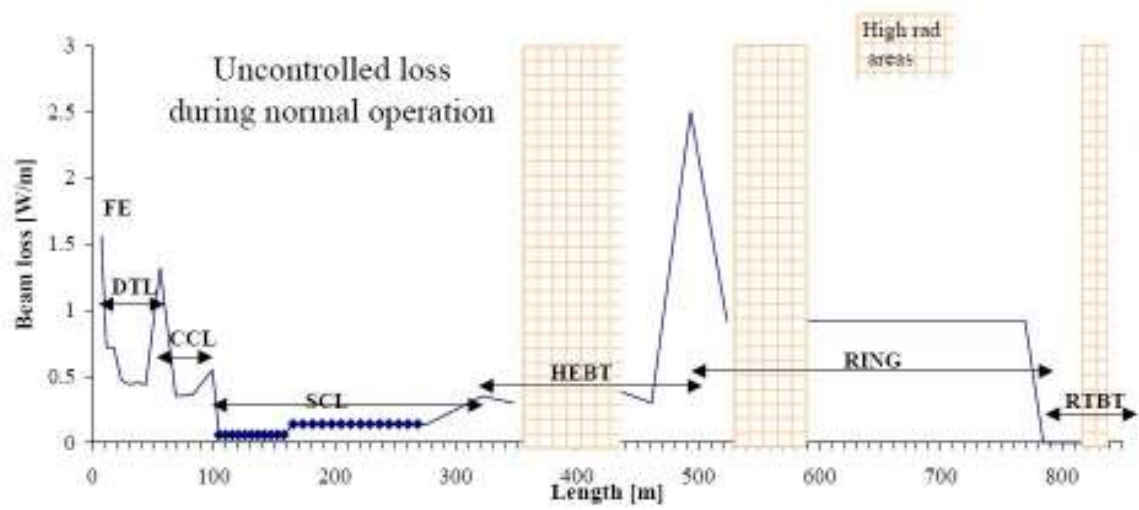


Figure 2.3 Loss diagram for SNS running at full power.

3 Linac Beam Dynamics Theory

3.1 Longitudinal Particle Dynamics

To understand halo development it is necessary to be familiar with the dynamics acting on a particle when propagating along an accelerator. There are numerous types of accelerators, but since SNS utilizes an RF linear accelerator, the theory presented will focus on this type of device.

To accelerate an object, a force must be applied for a long enough time that the desired energy transfer can occur. A particle of velocity $\mathbf{v}$ feels a force

$$\mathbf{F} = e(\mathbf{v} \times \mathbf{B} + \mathbf{E}), \quad (1)$$

known as the Lorentz force when passing through a region containing a magnetic field $\mathbf{B}$ and an electric field $\mathbf{E}$. As the particle moves from point r_1 to r_2 , its energy changes by the amount

$$\Delta E = \int_{r_1}^{r_2} \mathbf{F} \cdot d\mathbf{r} = e \int_{r_1}^{r_2} (\mathbf{v} \times \mathbf{B} + \mathbf{E}) \cdot d\mathbf{r}. \quad (2)$$

During the motion the path element $d\mathbf{r}$ is always parallel to the velocity vector $\mathbf{v}$ [6]. The vector $\mathbf{v} \times \mathbf{B}$ is perpendicular to the plane formed by $\mathbf{v}$ and $\mathbf{B}$ and therefore perpendicular to $d\mathbf{r}$. Since $(\mathbf{v} \times \mathbf{B}) \cdot d\mathbf{r} \equiv 0$, the magnetic field $\mathbf{B}$ does not contribute to the change in energy of the particle, meaning only electric fields can produce acceleration. The energy gain then becomes

$$\Delta E = e \int_{r_1}^{r_2} \mathbf{E} \cdot d\mathbf{r} = eV, \quad (3)$$

where V is the potential difference crossed by the particle.

Considering that power requirements for producing dc voltages large enough to

accelerate particles to high energies are unrealistic for a single accelerating potential, high frequency electromagnetic waves with angular frequency ω can be employed to establish alternating voltages $V(t)$ of the form

$$V(t) = V_{\max} \sin \omega t , \quad (4)$$

in a radio-frequency cavity. The sinusoidally varying fields in RF accelerators mean that the particle can gain or lose energy depending on when the beam encounters the wave crest. The beam of particles is bunched as in Figure 3.1 so there is a net acceleration for all particles.

Once the beam has begun to accelerate, the bunch will tend to spread apart in the longitudinal and transverse directions due, mainly, to space charge but also to finite beam divergence and energy spread. Space charge describes the Coulomb forces felt by particles on one another within a bunch. In order to propagate the beam any reasonable distance, focusing must be applied to the beam to overcome its divergence and space charge.

For longitudinal focusing, an ideal particle in a bunch that arrives at an

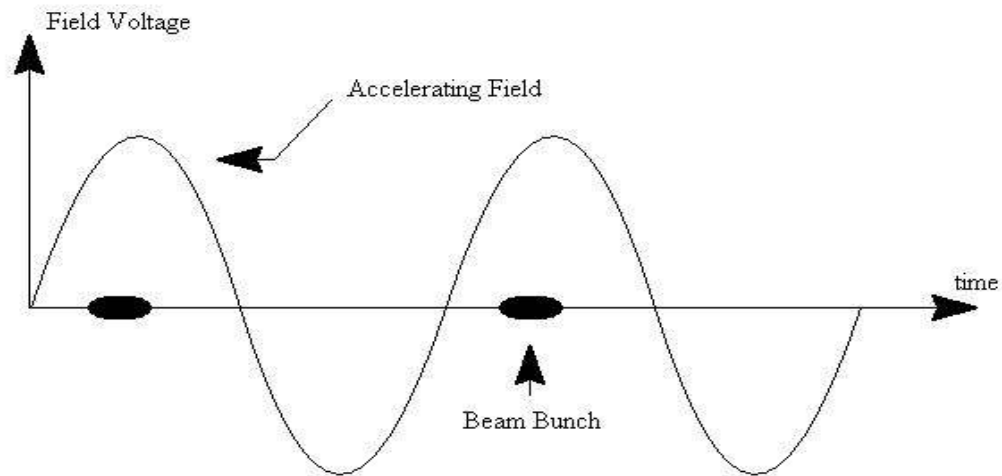


Figure 3.1 Beam bunches in an RF linac [7].

accelerating gap at the design phase is called the synchronous particle. It sees an energy gain of

$$E = qV_{\max}T \sin(\phi_s), \quad (5)$$

where q is the charge on the particle, ϕ_s is the phase of the RF voltage seen by the synchronous particle and T is the transit-time factor defined as the ratio of the energy gained by a particle passing through the cavity to the energy that would be received if the field were constant in time at the design value. The synchronous phase also describes a point in the sense that particles arriving earlier than the synchronous phase experience a smaller accelerating field, and particles that arrive later experience a larger field. The middle plot in Figure 3.2 shows that particles near the synchronous phase are confined in a potential well so that they oscillate around the stable point ϕ_s providing stability and phase focusing. Unfortunately, transverse focusing of off-axis particles is not as simple as the longitudinal phase focusing.

3.2 Transverse Particle Dynamics

It has been shown [8] that the RF fields needed for longitudinal focusing, are generally incompatible with local radial focusing. Earnshaw's Theorem states that the electrostatic potential in free space cannot have a maximum or a minimum [9, 10]. In the rest frame of the particle the magnetic forces are zero and only the electrostatic forces can act. From Laplace's equation

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0. \quad (6)$$

For a potential minimum all three partial derivatives $\partial^2 V / \partial x^2$, $\partial^2 V / \partial y^2$, and $\partial^2 V / \partial z^2$ must be positive, and for a potential maximum they must all be negative. Both

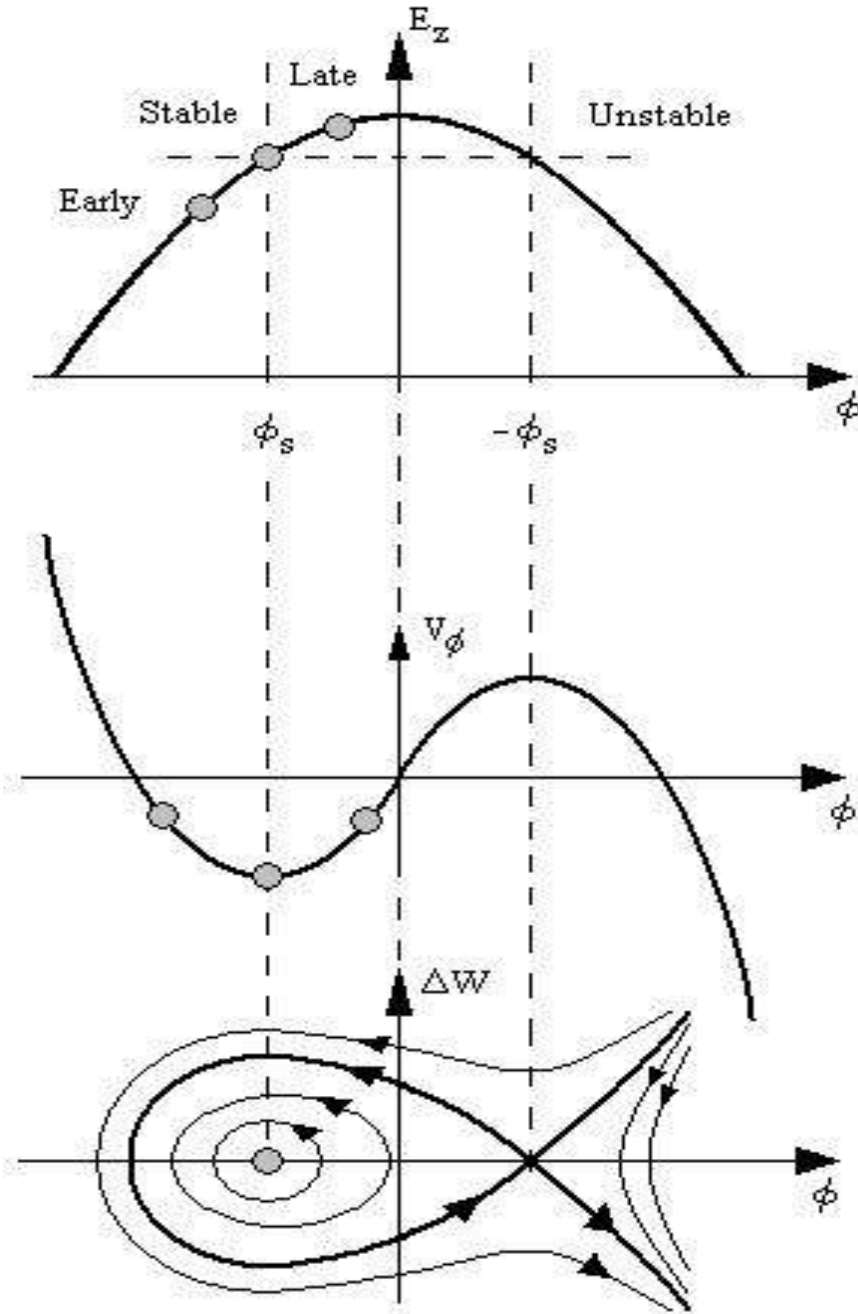


Figure 3.2 Top: Accelerating field with synchronous particle. Middle: Potential for accelerating field. Bottom: Phase-space trajectories showing stable region [11].

requirements are incompatible with equation 6. At no point in time are all of the terms focusing [7]. Since the forces that focus the beam longitudinally also, push particles radially outward, another method of transverse focusing is needed.

Although magnetic fields do not contribute to the energy of the particle, they will affect the component of the particle's motion perpendicular to the s direction as defined in Figure 3.3. For a particle of velocity v_s in the s direction through a magnetic field $\mathbf{B}$ the force is the Lorentz force $F_x = ev_s B_y$. Since the transverse dimensions of the beam are small compared to the radius of curvature of the particle trajectory, the magnetic field may be expanded in a Taylor Series in the vicinity of the nominal trajectory:

$$B_y(x, y) = B_y(0) + \frac{\partial B_y}{\partial x} x + \frac{\partial B_y}{\partial y} y + \dots \text{Higher Order Terms} . \quad (7)$$

$$B_x(x, y) = B_x(0) + \frac{\partial B_x}{\partial x} x + \frac{\partial B_x}{\partial y} y + \dots \text{Higher Order Terms} . \quad (8)$$

The magnetic field may be regarded as a sum of multipoles, where the lowest two poles are used for beam steering and focusing. The dipole $B(0)$ is used for bending and is

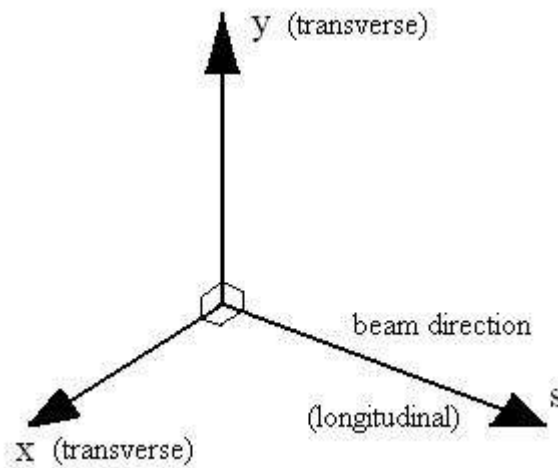


Figure 3.3 Left-handed accelerator coordinate system.

zero in linear accelerators leaving only linear quadrupole fields as the main source of transverse focusing. Higher multipoles (sextupole, octupole etc.) arise either as unwanted field errors or are deliberately introduced for compensation and field correction [6].

Overall focusing is accomplished by alternating the gradient between successive quadrupole magnets. Four quadrupoles at the end of the MEBT, like the one shown in Figure 3.4, are used to match the beam to the design phase space orientation of the main accelerating structure. Along the accelerating structure in the longitudinal direction s , the quadrupole strength varies with position and can be represented by $k(s)$. It can be shown that the fundamental equation of motion in the transverse direction for a particle traveling through a linear optical system is where $x(s)$ is the distance in the x direction as a function of longitudinal position and $x''(s) = d^2x/ds^2$. Assuming no beam bending $1/R(s) = 0$

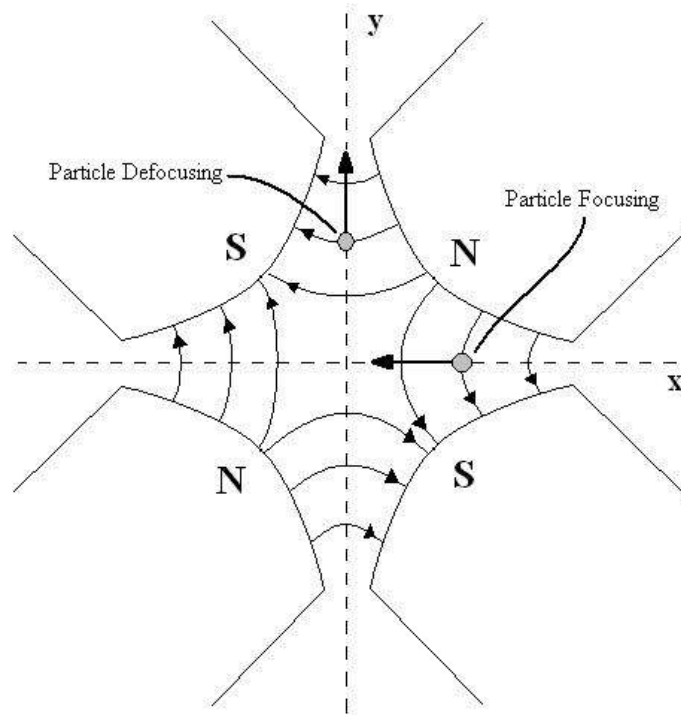


Figure 3.4 Example of a quadrupole magnet with field lines [6].

(equation 9) and that, $\Delta p/p \ll 1$ the transverse equation of motion becomes a differential equation known as Hill's equation

$$x''(s) + \left(\frac{1}{R^2(s)} + k(s) \right) x(s) = \frac{1}{R(s)} \frac{\Delta p}{p}. \quad (9)$$

The general solution is similar to that of the harmonic oscillator

$$x''(s) + k(s)x(s) = 0 \quad [12]. \quad (10)$$

The equation can be solved using the trial solution

$$x(s) = A u(s) \cos[\Psi(s) + \phi], \quad (11)$$

which describes the transverse oscillation of a particle about a trajectory that does not deviate in the transverse direction. Such oscillations are known as betatron oscillations

[6] and are illustrated in Figure 3.5. Replacing A with $\sqrt{\varepsilon}$ and $u(s)$ with $\sqrt{\beta(s)}$ and

noting that $\Psi(s)$ is the phase as the particle travels, the final form of equation 11 is

$$x(s) = \sqrt{\varepsilon} \sqrt{\beta(s)} \cos[\Psi(s) + \phi]. \quad (12)$$

Equation 12 describes the trajectory of a particle through focusing and defocusing elements. The $\beta(s)$ in equation 12 is called the “beta function.” The beta function $\beta(s)$ describes an envelope that contains all particle trajectories and modulates the transverse size of the beam, $E(s) = \sqrt{\varepsilon\beta(s)}$, as seen in Figure 3.5 [6]. The ε also has a special importance in describing the characteristics of a beam, as shown below. Taking the derivative of the trajectory $x(s)$ gives

$$x'(s) = -\frac{\sqrt{\varepsilon}}{\sqrt{\beta(s)}} [\alpha(s) \cos(\Psi(s) + \phi) + \sin(\Psi(s) + \phi)], \quad (13)$$

where $\alpha(s)$ is

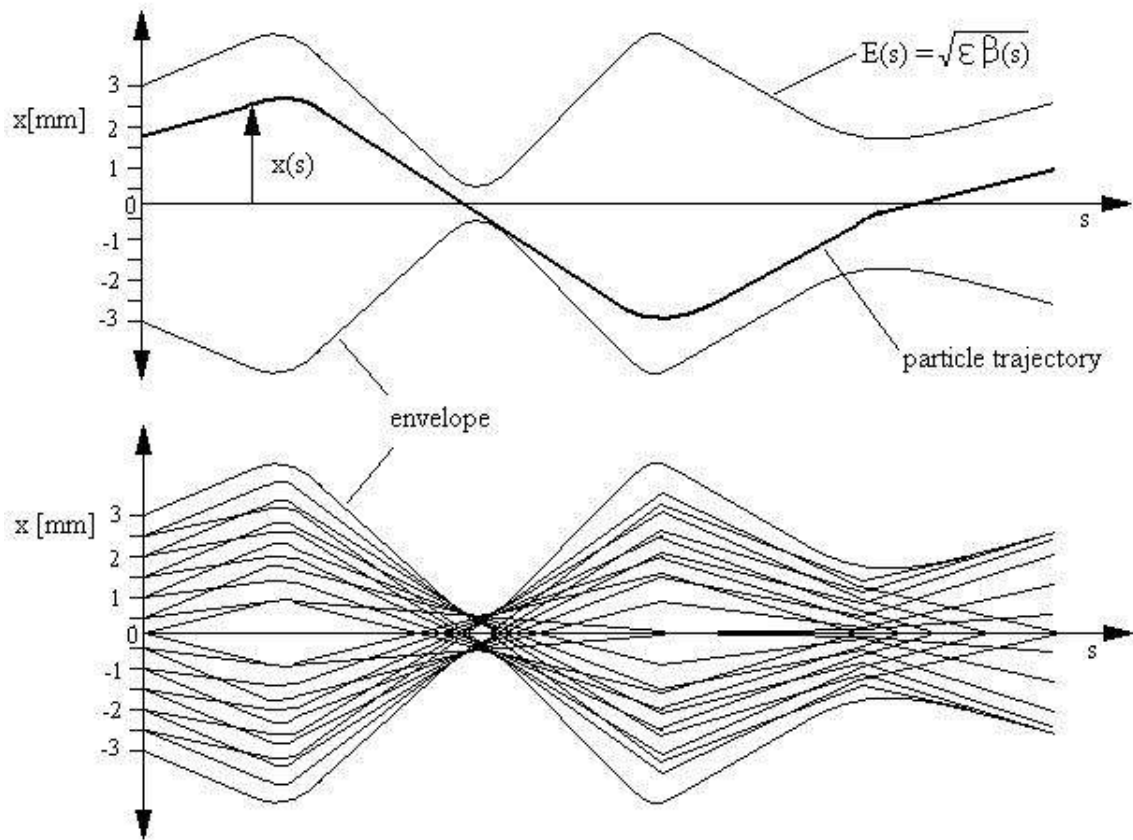


Figure 3.5 Particle trajectories within envelope $E(s)$. The upper plot shows a single trajectory while the lower shows multiple trajectories of individual particles in a beam. [6]

$$\alpha(s) = -\frac{1}{2} \frac{d\beta(s)}{ds},$$

(14) and $\Psi(s)$ is

$$\Psi(s) = \int \frac{1}{\beta(s)} ds. \quad (15)$$

Substituting

$$\cos(\Psi(s) + \phi) = \frac{x}{\sqrt{\varepsilon\beta(s)}} \quad (16)$$

into equation 16 yields

$$\sin(\Psi(s) + \phi) = \frac{\sqrt{\beta(s)}x'}{\sqrt{\varepsilon}} + \frac{\alpha(s)x}{\sqrt{\varepsilon\beta(s)}} \quad (17)$$

and using the relation $\sin^2 \theta + \cos^2 \theta = 1$ gives

$$\frac{x^2}{\beta(s)} + \left(\frac{\alpha(s)}{\sqrt{\beta(s)}} x + \sqrt{\beta(s)} x' \right)^2 = \varepsilon. \quad (18)$$

Defining

$$\gamma(s) \equiv \frac{1 + \alpha^2(s)}{\beta(s)} \quad (19)$$

gives

$$\gamma(s)x^2(s) + 2\alpha(s)x(s)x'(s) + \beta(s)x'^2(s) = \varepsilon. \quad (20)$$

Equation 20 is important for transverse measurements because it provides a conservation law for the motion of a particle. The variables $\alpha(s)$, $\beta(s)$, and $\gamma(s)$, which are known as Twiss parameters, describe the motion of a particle in the $x - x'$ plane. The importance of equation 20 can be seen in the fact that it describes an ellipse of area ε , as illustrated in Figure 3.6. This area is conserved for the motion of each particle. The beam

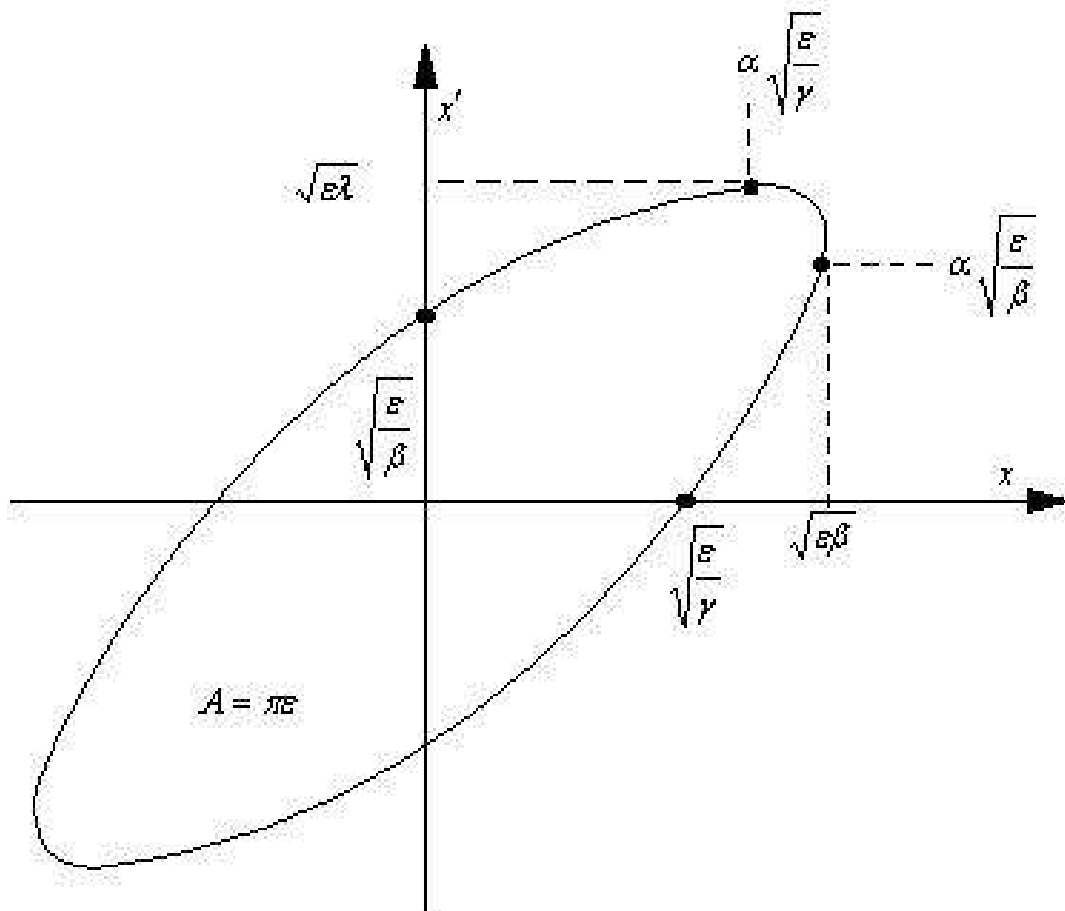


Figure 3.6 The phase space ellipse of particle motion in the x - x' plane.

consists of a distribution of particles each with its own emittance. Beam emittances are defined relative to this distribution. Mismatch or matching depends on the distribution, not individual particles. The emittance and phase space are widely used constructs for analyzing beam characteristics. The phase space ellipses along with beam profile plots are the best ways to graphically analyze halo.

Defining a new set of variables from equation 18 as

$$\omega = \frac{x}{\sqrt{\beta}} \quad (21)$$

and

$$\omega_p = \frac{\alpha}{\sqrt{\beta}} x + \sqrt{\beta} x', \quad (22)$$

transforms the ellipse described in Figure 3.6 to a circle with radius $\sqrt{\varepsilon}$. These normalized coordinates in equations 21 and 22 are useful for quantifying the phase space mismatch of a beam. A perfectly matched beam distribution will be a circle in normalized coordinates while mismatched beams will not. A mismatch factor can be defined by

$$M = \frac{R_{\omega}}{R_{design}} \quad (23)$$

where R_{ω} is the half the major axis of the ellipse of a mismatched beam in normalized coordinates and R_{design} is the radius of the circle for a perfectly matched beam in normalized coordinates.

4 Halo Definition

4.1 Halo Representation

Qualitatively, halo particles are those described as being outside a central beam core. To make this definition quantitative, it is necessary to define what is meant by the beam core. Typically the particle density decreases continuously toward the edges. The core of the beam is not easily defined and will vary from case to case. Nevertheless, as beam profiles tend to be Gaussian in nature, non-Gaussian tails are due to halo particles. When dealing with tens of thousands of particles in simulations, it is necessary to develop a model for the core using graphical representations of the beam.

Profile plots, like the ones shown in Figure 4.1, are projections of the 2-D phase space ellipse onto the position axis. The left plots in Figure 4.1 shows a distribution taken from the horizontal direction in $x - x'$ space that resembles a Gaussian core with little halo. Halo can be understood by looking at the right plots in Figure 4.1 that show a core phase space ellipse with a Gaussian profile plot containing non-Gaussian tails that arise from large amplitude particles in phase space. The particles populating the tails in the right profile plot in Figure 4.1 are halo particles.

4.2 Halo Theory

The physics behind halo production is not completely understood. Much progress has been made in obtaining analytical models [13] to explain the halo phenomena seen in simulation and experiments. The simplest current theory of halo production is based on the particle-core model. It simplifies a beam to a particle interacting with a core of uniform space-charge. The particle-core model assumes a uniform space-charge ellipsoid because the forces present inside the bunch are linear.

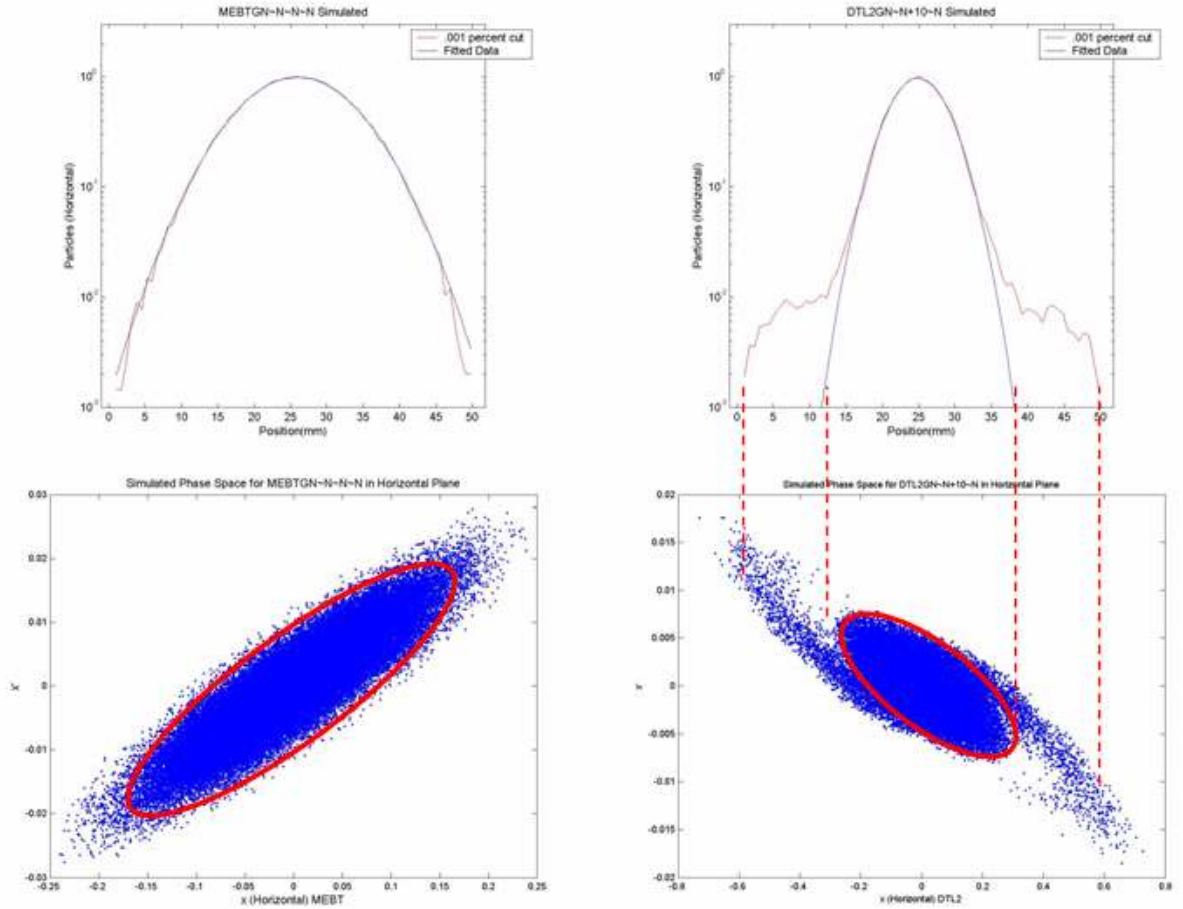


Figure 4.1 Left: Gaussian distribution with phase profile showing Twiss parameter ellipse in red. Right: Gaussian distribution with halo particle tails showing corresponding phase space tails with actual halo particle positions.

For the simple case of a cylinder of length L and radius R with constant charge-density ρ_o , Gauss's law gives

$$\vec{\nabla} \cdot \vec{E} = \frac{1}{\epsilon_o} \rho, \quad (24)$$

or in integral form

$$\int \vec{E} \cdot d\vec{s} = \frac{1}{\epsilon_o} \int \rho dV. \quad (25)$$

For a uniformly charged cylinder of radius R , integrating equation 25 over the surface of a cylinder of radius $r < R$ and length L one obtains

$$E_r 2\pi r L = \frac{1}{\epsilon_o} \rho_o V = \frac{1}{\epsilon_o} \rho_o L \pi r^2, \quad (26)$$

where V is the volume of the cylinder of radius r . The electric field inside the cylinder is

$$E_r = \frac{\rho_o L \pi r^2}{\epsilon_o 2\pi r L} = \frac{\rho_o}{2\epsilon_o} r, \quad (27)$$

which is linear with r . Similarly for a sphere of radius R with constant charge-density ρ_o , integrating equation 25 over a sphere of radius $r < R$ is

$$\int \vec{E} \cdot d\vec{s} = E_r 4\pi r^2 = \frac{1}{\epsilon_o} \rho_o V = \frac{1}{\epsilon_o} \rho_o \frac{4}{3} \pi r^3. \quad (28)$$

consequently

$$E_r = \frac{\rho_o}{3\epsilon_o} r. \quad (29)$$

The electric fields, equations 27 and 29, for spherical and cylindrical charge distributions are linear inside the boundaries. It has been shown that three dimensional uniform space-charge ellipsoid also have inner space-charge forces that are linear inside

the charge boundaries [14]. Since the space charge force is linear with displacement, the effect of linear space charge is identical to quadrupole focusing, so we expect it to modify the beam envelope.

The beam envelope, including both quadrupole focusing and linear space charge follows the model outlined in [15], the equation describing its maximum oscillation amplitude or envelope equation for a core of radius R is

$$\frac{d^2 R}{dz^2} + k_0^2 R - \frac{(4\varepsilon_{rms})^2}{R^3} - \frac{K}{R} = 0 \quad (30)$$

where

$$K = \frac{qI}{2\pi\varepsilon_0 mc^3 \beta^3 \gamma^3} \quad (31)$$

contains the effect of space charge, k_0 represents the focusing force and the wave number or phase advance per unit length of the transverse individual particle oscillations at zero current, and the $1/R^3$ term prevents the beam from being squeezed to zero radius. The constants q , m , and βc are the charge, mass, and axial velocity, γ is the relativistic Lorentz factor, c is the speed of light, I is the beam current (charge per unit length times axial speed), and ε_{rms} is the root mean square, for the distribution, of the emittance defined in equation 20.

In a uniform focusing channel the individual particles oscillate uniformly inside the bunch and the core envelope remains constant: $d^2 R/dz^2 = 0$ and $R = R_o = \text{constant}$. Each focusing lattice, in this case the quadrupole magnets, is designed to accept a beam with a phase space ellipse (see in Figure 3.6) with a particular orientation. The ideal or matched case is when the incoming bunch is perfectly aligned with the ellipse, in which case the focusing structure will equally focus and defocus in all directions and R is

constant.

When the beam is mismatched in phase space, the initial radius R does not equal R_o , $d^2R/dz^2 \neq 0$, and the core oscillates. Generalizing the ellipsoidal geometry the symmetric or breathing mode shown at the top of Figure 4.2 has a beam core that expands and contracts in all three planes simultaneously but with different amplitudes in the transverse and longitudinal planes. It has the highest oscillation frequency of all three modes and is usually the most ‘harmful’ mode in terms of halo development. The quadrupole or antisymmetric mode, shown in the bottom of Figure 4.2, has a core oscillating only in the transverse planes with 180 degree phase difference between x and y [17].

The equation of motion for a single particle moving through a uniform charge-density cylindrical coasting beam core of radius R is

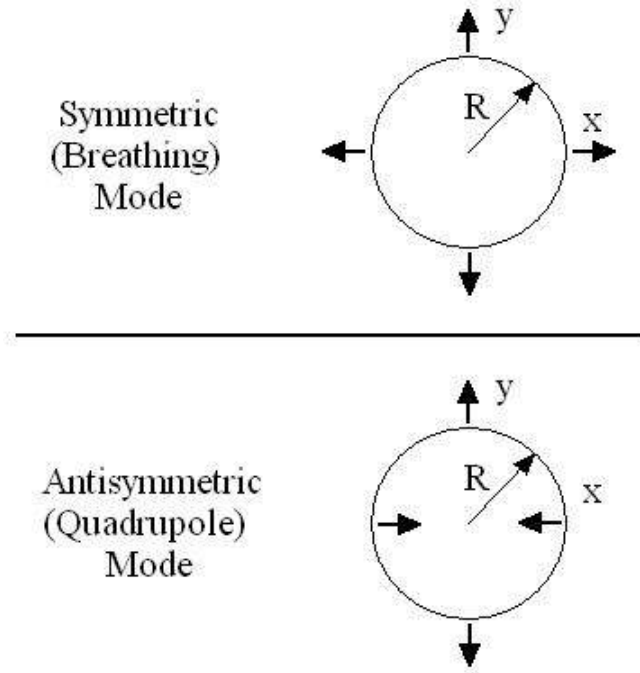


Figure 4.2 Collective modes of mismatched beams [16].

$$x'' + k_o^2 x = \begin{cases} Kx/R^2, & |x| < R \\ K_x/r^2, & |x| \geq R \end{cases}, \quad (32)$$

where k is the wave number of the transverse motion in the absence of space charge. The equation of motion for the vertical motion is the same as for horizontal. Analyzing equation 32 shows that the left hand side is similar to equation 10 but there is an extra driving term on the right hand side that is due to the linear space charge force inside the core and the nonlinear force outside the core. Wangler describes the particle-core mechanism by which a particle is driven to halo amplitudes in the following way.

“For the matched case, the core radius is constant, and there is no net change in particle energy averaged over a complete period of the particle motion. For the mismatched case, the core radius oscillates, and particles can either gain or lose energy with each transit through the core. The particles experience a nonlinear force proportional to K/x when they are spatially outside the core and from Gauss’s law this force is independent of the instantaneous size of the core. When the particles pass through the core, they are decelerated by the space charge force as they approach the core, and accelerated by the space charge force as they leave the core. The net space charge impulse delivered to the beam may be described as the sum of a core entrance contribution plus a core exit contribution. These impulses may be either diminished or enhanced relative to the matched case depending on whether the core radius is larger or smaller than the equilibrium value at the time the particle passes through. For example, if a particle enters the core when it’s radius is larger than the matched value and exits when the radius is smaller than the matched value a net energy impulse is delivered to the particle. [15]”

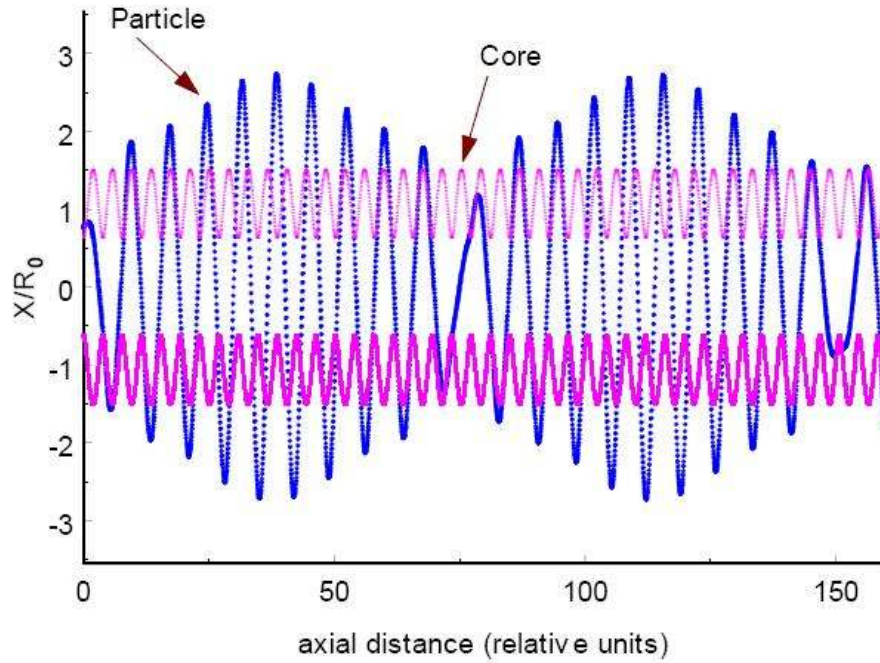
It has been shown [13] that there is a parametric resonance between a halo particle and an oscillating core in a breathing mode that arises from the nonlinear force outside the core such that there is only a significant contribution of energy exchange when

$$f_{particle} = \frac{f_{core}}{2} . \quad (33)$$

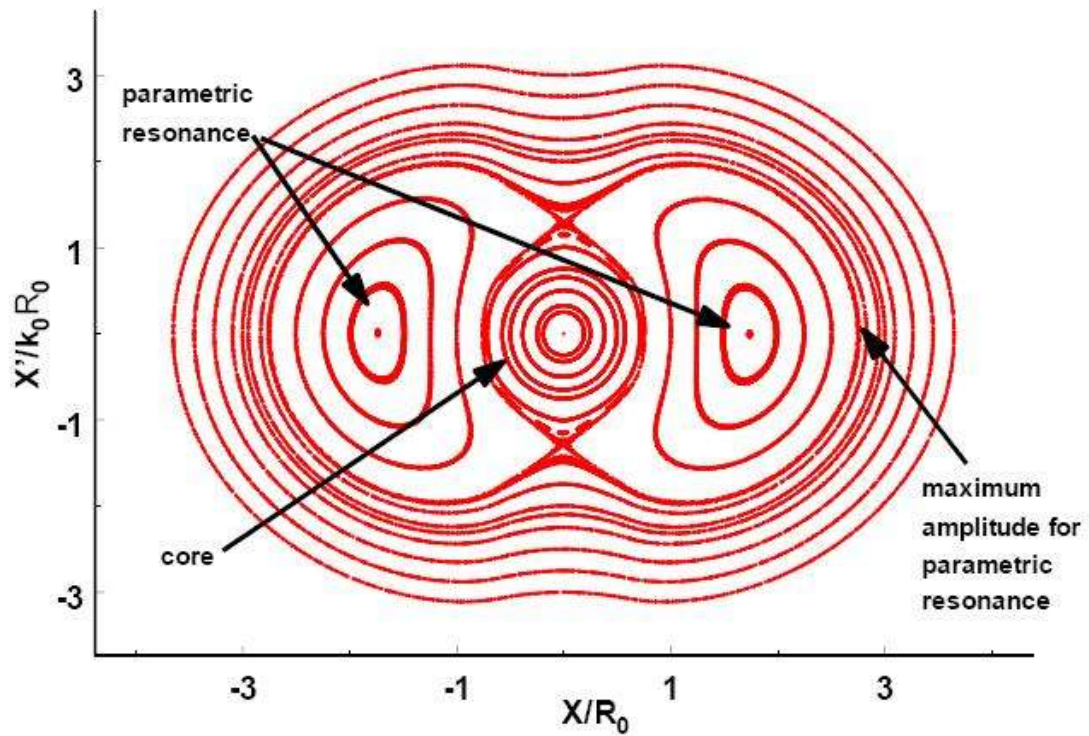
Integrating equations 30 and 32 for mismatched initial conditions and plotting the results using two graphical techniques shows (Figure 4.3 (a)) a core that oscillates twice as fast as the halo particle and (Figure 4.3 (b)) regions of resonance [15]. Figure 4.3 (b) is a stroboscopic plot or Poincaré plot taken by tracking a particle and overlaying its position in phase space as it passes through the same phase in a periodic structure, such as a focusing lattice. The curves in the figure describe the particle orbits in phase-space. The stroboscopic view shows a central core region of closed surfaces with two islands to the left and right of the inner separatrix and regions beyond the outer separatrix.

The particle-core model predicts, looking at Figure 4.3 (b), that particles initially inside the core will not leave unless they are forced out past the inner separatrix boundary. Particles in the islands outside the core will oscillate about the resonant stable fixed points, thus populating a halo. Another important result can be deduced from figure 4.3 (b). The close curves throughout the diagram lead to the idea that halo particles cannot grow in amplitude indefinitely. This can be explained by realizing that the space charge field around the core decreases the further from the core boundary. The resonant condition required for a particle to oscillate with the breathing mode cannot be sustained once the particle is too far from the core.

The development of halo is compensation by the beam to equalize the extra



(a)



(b)

Figure 4.3 (a) Particle and core oscillations (displacement versus time). (b) Stroboscopic plot of breathing mode excitation of uniform core [16].

energy gained due to the oscillations acquired through mismatch [17]. The transfer of the “free energy” in the oscillating core to particles passing through it is the principle mechanism for the production of halo particles. In order to equalize its energy the core size will increase absorbing the halo particles. Although not all emittance growth is necessarily associated with generation of halo, halo formation is always accompanied by emittance growth [16]. Simulations done for the SNS accelerator have that trend of decreasing halo with an increase in core size.

5 Development of Computational Tools

5.1 Simulations and Program Outline

Before the tools developed for halo analysis could be implemented it was necessary to create data by performing simulations for a variety of machine settings. The Phase and Radial Motion in Ion Linear Accelerators code (PARMILA) [22] was used to simulate the acceleration of particles in the SNS linac. Parmila uses a particle-in-cell (PIC) space-charge routine. The PIC represents a particle distribution with a collection of macroparticles. The space-charge from all the macroparticles is calculated and binned onto a grid of cells. The forces acting on each particle are then the sum of the fields from the binned charges in each cell [7]. Simulations were run for nine machine configurations using three types of initial distributions at two beam currents.

The development of computational tools for analyzing halo in the simulations and in experimental data began with rewriting of earlier software. There is not currently a standard software package for halo analysis. Existing software [18] includes a package to analyze beam profiles and wirescan data, isolate the halo, and quantify the amount to allow comparison of simulation and experimental data. In order to analyze the halo from simulations and machine data, the software [18] was converted into the Matlab programming language and expanded upon Using Matlab's large graphical toolbox. In this way, the data can be analyzed more efficiently with greater options for expansion.

The program processes profile data from simulations or wirescanners and disregards points below a threshold value to eliminate noise. After fitting the data using a Gaussian model to define the core, the data is analyzed using two methods to quantify the amount of halo present. The halo data and beam sizes are accumulated and used to

analyze beam characteristics. A mismatch parameter is also created from the profile data.

5.2 Profile Data Analysis

The halo analysis requires the data to be filtered and fitted. Due to the number of large particles, there will always be a small number of individual particles that will populate extreme regions of tails of the distribution. This data is not representative of halo and it increases the statistical error of the analysis. Data points below 0.1% of the maximum signal are removed since this is the expected resolution of the wirescanner signals. Figure 5.1 shows a simulated profile showing fluctuations at large amplitudes due to the finite number of macroparticles used in the simulation.

Simulated profile plots, like those in Figures 4.1 and 5.1, are histograms of horizontal position. All histogram data is normalized to 1 to assure comparability

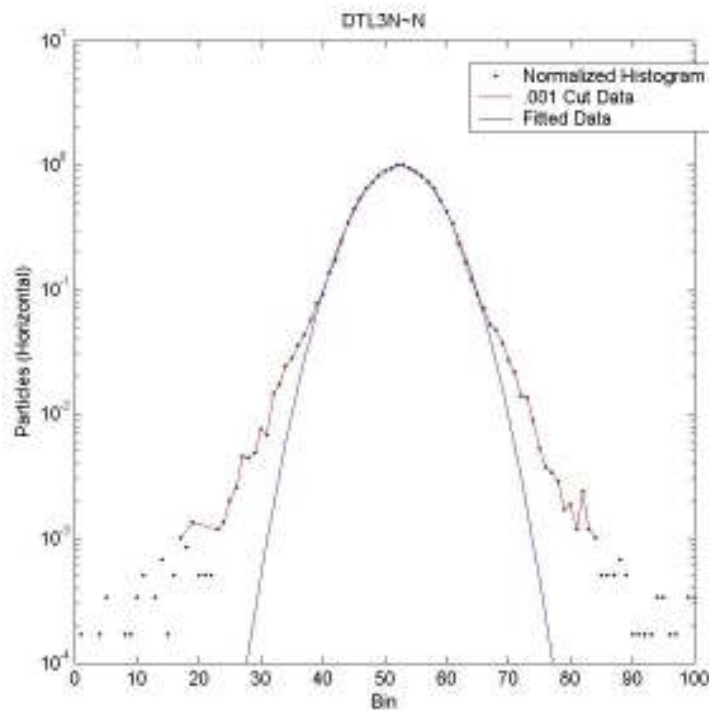


Figure 5.1 Simulated profile showing all data, 0.001 cut data, and 0.01 fitted data.

between cases. In order to select only the part of the profile above 0.001 a filter was created. Starting from the center of the profile peak, the profile is traversed down both sides comparing each y value of the histogram to the cutoff of 0.001 and recording the index of point in the array until the data is not greater than the cutoff. All of the profile data corresponding to the normalized profile values below the 0.001 threshold is cut and the remaining profile is kept.

Beam profiles are the simulation equivalent of wirescan profiles. Wire scanners provide histogram data of particle density along a given axis, perpendicular to the beam direction. Pre-processing of the simulated data is simpler than that of experimental results because each axis can be considered separately. In the case of wirescan profiles, there is a considerable amount of cross-talk between the wires meaning there will be one large peak corresponding to the primary signal and two smaller peaks arising from the beam striking the other two wires in the three wire assembly. Figure 5.2 shows a wirescan

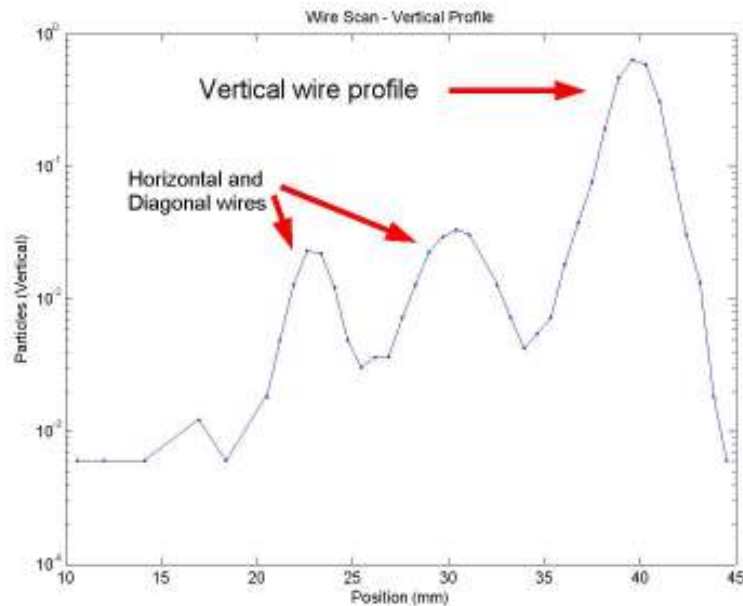


Figure 5.2 Unprocessed wirescanner data show wire overlap.

profile for the vertical direction showing the “cross-talk” between wires. There are also occasional missing data points where the wirescan profile is zero, and those are removed entirely based on an empirical knowledge of the measuring device.

In order to isolate the correct profile peak, the experimental data is analyzed by first finding the highest peak. The profile points are traversed down each side as in the simulated case except that here the criterion for cutoff is when the slope between points switches signs. When the program approaches another peak, the slope changes and all subsequent values are excluded. One problem with this method is that if the other peaks are close enough to the main peak the profiles will interfere and make it difficult to distinguish the halo tails. Profiles of this nature are handled on a case by case basis.

5.3 Gaussian Area Ratio Method

Two analysis methods have been utilized to quantify beam halo. The first, the Gaussian area ratio method attempts to quantify the “non-Gaussian” component of the beam profile. Even if the initial distribution is non-Gaussian it will tend toward a Gaussian as it evolves. After the data is filtered, it is fitted to a Gaussian of the form

$$f(x) = Ae^{\frac{-(x-\mu)^2}{2\sigma^2}}. \quad (34)$$

where A is the amplitude, μ is the mean value, and σ is the standard deviation. The fit is done using a least squares method which finds the best fitting curve by minimizing the sum of the squares of the offsets of the data points from the curve. However, because squares of the offsets are used, outlying points can have a disproportionate effect on the fit, a property which may or may not be desirable depending on the problem at hand [19].

In order to represent the core, the Gaussian is only fitted to the top (90 percent) of the

profile since most profiles greatly resemble Gaussian's in this region at the beam core. Once a Gaussian fit has been generated, the profile data and Gaussian fit data are used in the method.

The area ratio method consists of finding the area of the core profile and the area of the whole profile and dividing the two, giving a ratio and subsequently a quantification of halo. First, the range over which the profile is summed is decreased using data outside 1σ which corresponds to 0.6826895. It is sufficient to say that tails do not form until outside approximately 70% from the center of the profile. The areas on the left and right are summed using the midpoint method as in Figure 5.3. This process is repeated for both the fractional fitted and profile data. The fractional data is divided by the fitted to give a ratio with a value of 1 for no halo.

5.4 The Kurtosis Method

A second method used to quantify halo is the kurtosis method. Wangler [20] defines the beam profile parameter h_x as

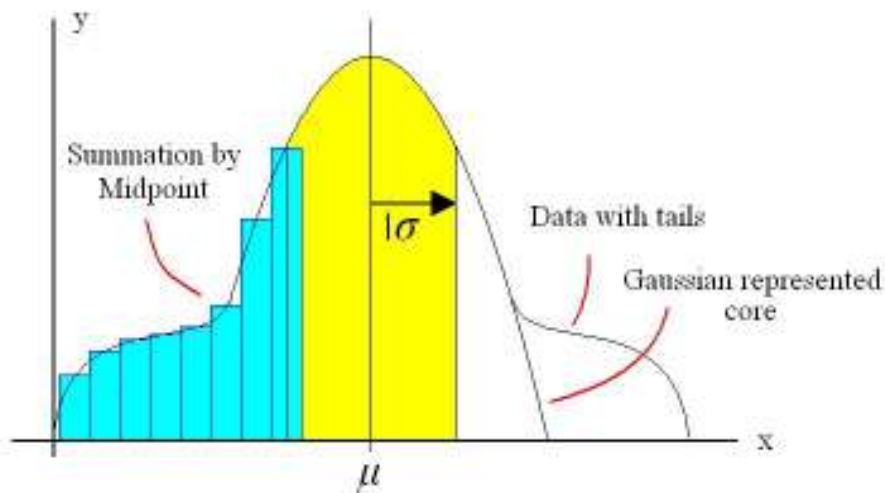


Figure 5.3 Fictitious halo profile with Gaussian core.

$$h_x = \frac{\langle x^4 \rangle}{\langle x^2 \rangle^2} - 2. \quad (35)$$

The h parameter uses the raw moments $\langle x^n \rangle$ of the distribution x to quantify halo by using, more generally, a property of the distribution known as kurtosis;

$$kurt(X) = \frac{\langle (X - \mu)^4 \rangle}{\sigma^4}, \quad (36)$$

where

$$\sigma^2 = \langle x^2 \rangle - \langle x \rangle^2 \quad (37)$$

is the variance. A perfect Gaussian will have a kurtosis of 3 so that $h_x=1$

It is difficult to tell which of the Gaussian distributions in Figure 5.4 has a higher standard deviation. While the one on the left is wider about the mean, the right distribution has fatter tails. Kurtosis is a measure of how “peaked” a distribution looks with values greater than 3 being leptokurtic, which means more peaked with fatter tails, while values less than 3, are platykurtic, or less peaked with thinner tails. This method does quantify the halo characteristics of a beam but is more sensitive to noise at large amplitudes than the area ratio method. Even after cutting data points below a certain

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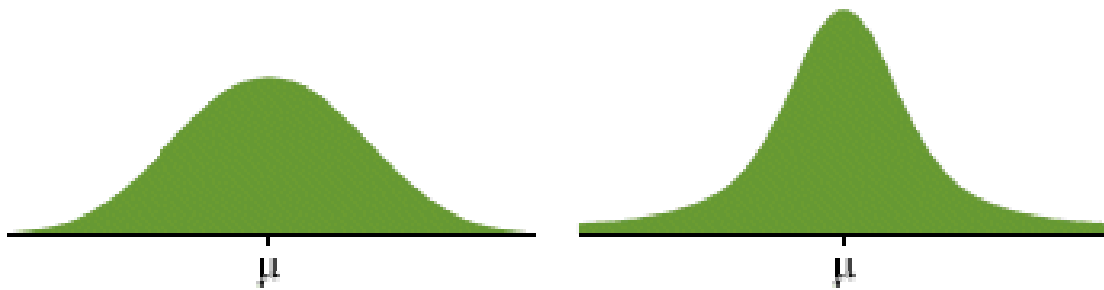


Figure 5.4 Distributions presenting kurtosis with the right one having a higher kurtosis value. [21]

threshold, the noisiness of the data can cause a large discrepancy between the two methods. Figure 5.5 shows halo calculated using both methods with kurtosis halo in blue twice as high as the area ratio method not showing the same trends. It was decided that the kurtosis method was too sensitive to noise and it was disregarded as a reliable source of halo quantification and not used in any of the final analysis.

The area ratio method code was tested for accuracy by benchmarking with a perfect Gaussian distribution and with a distribution that had known halo and had been independently analyzed. The code gave a halo number of 1 for the Gaussian and the exact same value obtained previously for the distribution with halo. Even with the success of the area ratio method, its results are at best guidelines due to the inherent difficulty in separating the core from the tails. Halo quantification is taken more as an estimate of real halo.

5.5 Emittance Growth

The size of the core along with the halo analysis is important to fully describe a beam's characteristics. Depending on the orientation of the halo particles in phase space, halo may or may not be observable in a profile, for example when the halo particles are primarily oriented along the x' axis. Furthermore, since halo particles oscillate through the core, depending on where the phase space distribution is observed, a halo particle may or may not be seen outside the core. These issues complicate the analysis of quantifying the halo in profile plots. The problem of projection onto the position axis was taken into consideration in the accelerator design, so that the wire scanners are positioned at optimal phase space ellipse orientations.

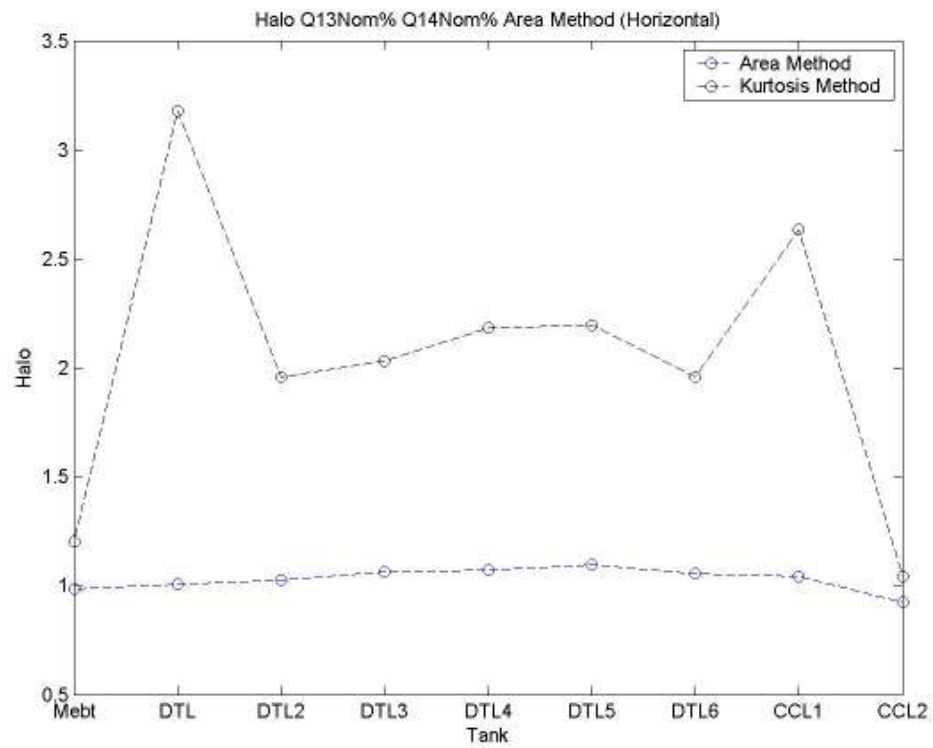


Figure 5.5 Halo analysis results, comparing the two the analysis methods.

The rms σ from the Gaussian fit in equation 34 is related to the emittance and can be interpreted as the radius of the core. Plotting the sigma from each fit gives a measure of how the core grows. A ratio of the simulated rms to the experimental rms is used to show the difference in emittance growth.

5.6 Mismatch Parameter

The mismatch parameter defined in equation 23 requires the core sizes of a matched and mismatched beam. The radius of the circle in normalized coordinates for a matched beam is found by projecting the distribution onto the position axis and finding the variance. The variance is sigma squared. For mismatched beams, the distribution is rotated so that the semi-major axis of the core ellipse is parallel to the position axis to ensure an accurate profile of the core. Particles less than 70% of the maximum are used in an attempt to isolate the core from the tails. The size of the core is found using the variance. The mismatch parameter gives a dimensionless ratio for how matched a distribution is compared to the design phase-space orientation.

6 Results

The analysis of halo production in the SNS linear accelerator began with a study of simulation data for different matching quadrupole configurations. The four quadrupoles at the end of the MEBT are labeled Q11, Q12, Q13, Q14 (shown in Figure 6.1), and are the last elements to control the matching of the beam from the front end of the accelerator into the main linear accelerator. In order to get a complete understanding for the behavior of these quadrupoles on the beam halo, nine configurations were simulated. Table 6-1 shows the cases for the quad strength in which each is varied separately $\pm 10\%$. Each case was simulated in PARMILA for a reference distribution designed to represent the distribution coming from the RFQ. The simulated distributions are recorded after each DTL and CCL tank and analyzed using the halo analysis program.

6.1 Halo Analysis

Figure 6.2 shows the simulated halo values generated using the area ratio method for each of the nine cases labeled according to Table 6-1. For the horizontal case, the distributions right after the MEBT have varying degrees of halo. As these distributions propagate down the accelerator, the halo tends to increase until DTL5 and then decreases thereafter. The vertical direction shows a similar trend with the exceptions that the distributions right after the MEBT quadrupoles vary much more in their halo values and

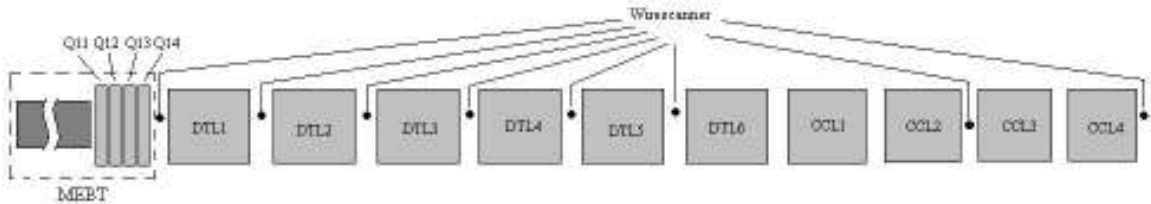
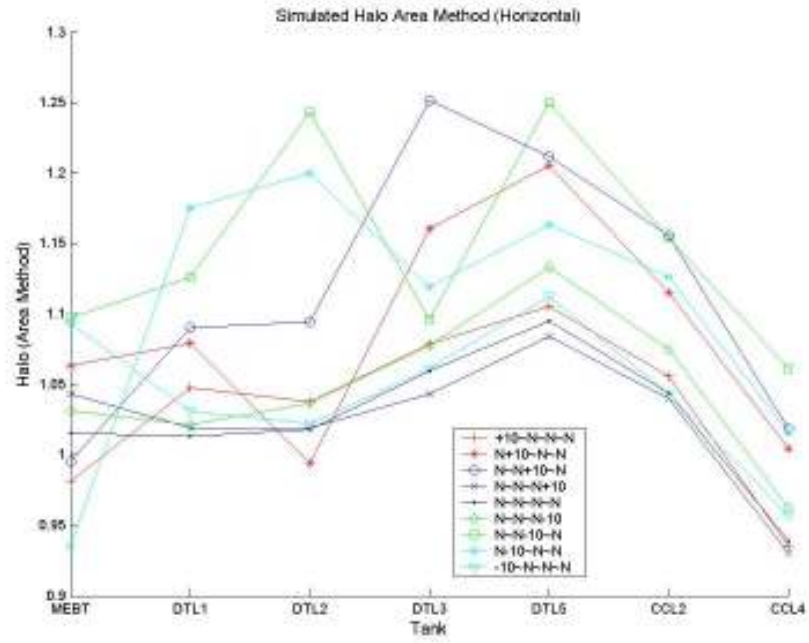


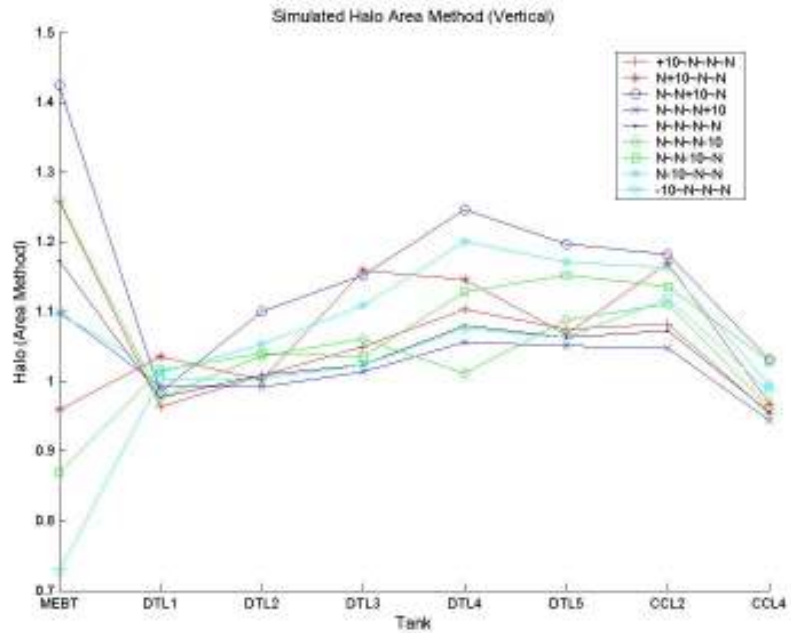
Figure 6.1 Quadrupole and wirescanner positions in the warm linac.

Table 6-1 Quadrupole Mismatch Cases

Case Number	Case Name
Case 1	+10~N~N~N
Case 2	N+10~N~N
Case 3	N~N+10~N
Case 4	N~N~N+10
Case 5	N~N~N~N
Case 6	N~N~N-10
Case 7	N~N-10~N
Case 8	N-10~N~N
Case 9	-10~N~N~N



(a)



(b)

Figure 6.2 (a) Horizontal and (b) vertical simulated halo data for nine quadrupole settings using the reference distribution.

the subsequent halo growth is much more uniform. Certain cases, in both the horizontal and vertical direction, produce more errant particles than others; meaning that halo development is more sensitive to certain quadrupoles than others. A similar observation was made by accelerator physicists in the control room during commissioning runs when tuning the front end of the accelerator. Preliminary analysis would suggest that the nominal case, where all quads are set to the design settings, is one of the best configurations for minimizing beam halo.

6.2 Mismatch Analysis

Analysis of the halo growth for the different distributions shows that certain cases consistently produce more or less halo. Since it is known that mismatch produces halo, it would appear certain cases are more mismatched than others. Figure 6.3 shows the mismatch parameter for the horizontal and vertical direction. Clearly the $N \sim N+10 \sim N$ case has the worst mismatch. Analyzing 6.3 show that mismatch is more sensitive to quadrupoles 12 and 13. The worst halo would be expected to come from set point errors in these quadrupoles.

6.3 Distribution Dependence

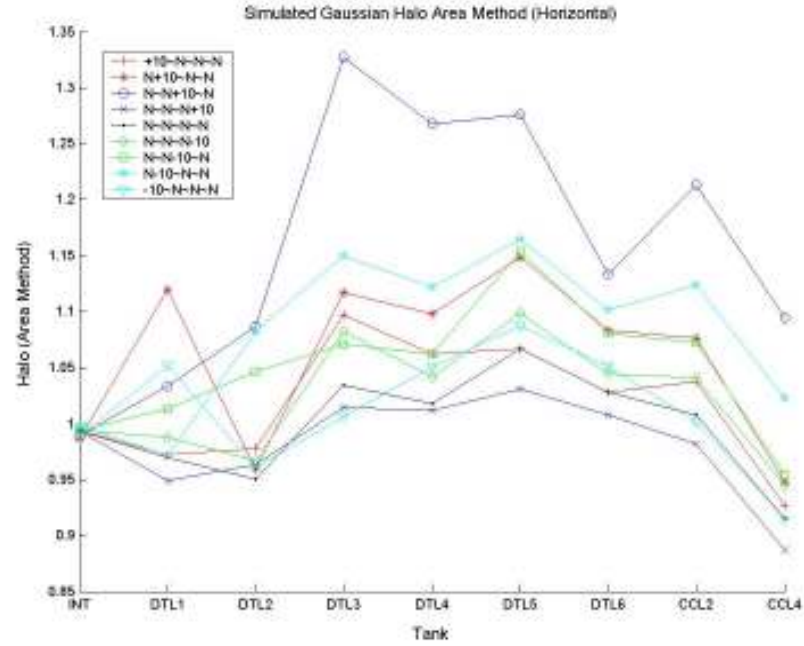
The first question that arises when analyzing the reference distribution halo is whether the observed halo is primarily generated by the quadrupole mismatch or by the halo in the initial distribution itself. If it is more mismatch dependent, then a beam will generate halo for all cases regardless of the initial distribution. In order to answer this question, two other initial distributions designed to have the same parameters as the reference distribution were simulated for the same nine cases in Table 6-1. A Gaussian initial particle distribution was used because it has very small tails. The other distribution

used is called a 6-D Waterbag, which is described by particles generated uniformly within a six-dimensional ellipse [22], and, therefore, has no tails.

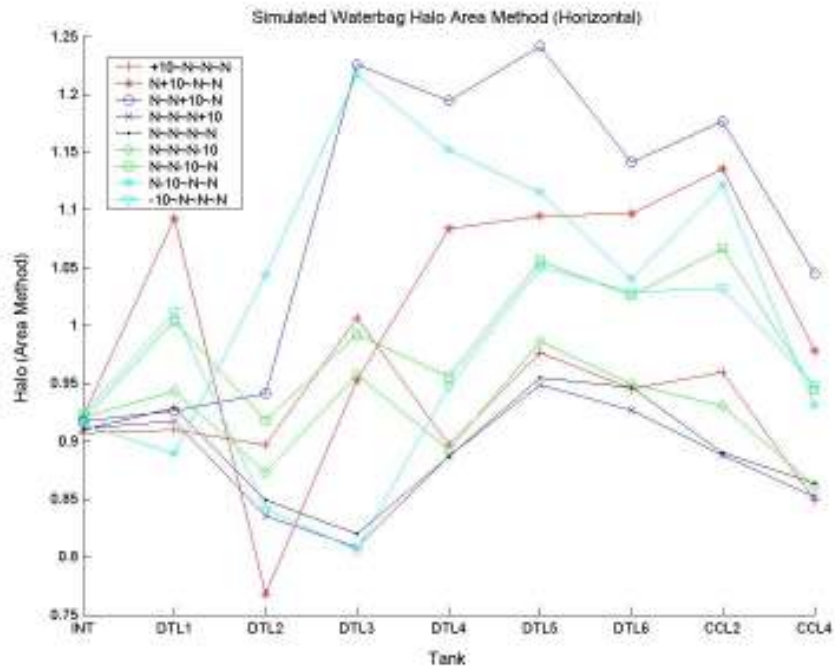
The results for the halo analysis of the horizontal direction for the Gaussian and Waterbag distributions are shown in Figures 6.4 and reveal that the halo production is primarily independent of the initial distribution. Both Gaussian and Waterbag distributions generate halo even for the nominally matched case. Analyzing Figures 6.4 and A.1 (b) show that for matched cases, particularly $N \sim N \sim N+10$, $N \sim N \sim N$, and $N \sim N \sim N-10$, there is little to no halo development. The halo that does exist propagates relatively unchanged to the end of the CCL. For mismatched cases, $N \sim N+10 \sim N$, $N-10 \sim N \sim N$, and $N \sim N-10 \sim N$, halo is produced even when no previous halo exists. The Gaussian distribution generates halo growth similar to the reference distribution in both directions (horizontal Figures 6.2 (a) and 6.4, vertical Figures 6.2 (b) and A.1 (a)) which leads to the conclusion that the reference distribution is approximately a Gaussian with tails.

6.4 Phase Space Analysis

There is a definite trend among all of the halo plots (Figures 6.2 and 6.4). The halo tends to disappear at the end of CCL4 in all cases. Looking at the phase space distributions along the linac for different cases will reveal phase space orientation and, subsequently, whether the halo particles are being covered in phase space or whether there is an actual decrease in large amplitude particles. Choosing the $N \sim N+10 \sim N$ case, which is typically the worst case for halo, the phase space plots of the reference and Waterbag distribution in the horizontal direction are shown side by side in Figure 6.5 for the initial, DTL1, DTL5, CCL2, and CCL4 positions.



(a)



(b)

Figure 6.4 Simulated halo data for a (a) Gaussian and (b) Waterbag distribution in the horizontal direction using the area ratio method.

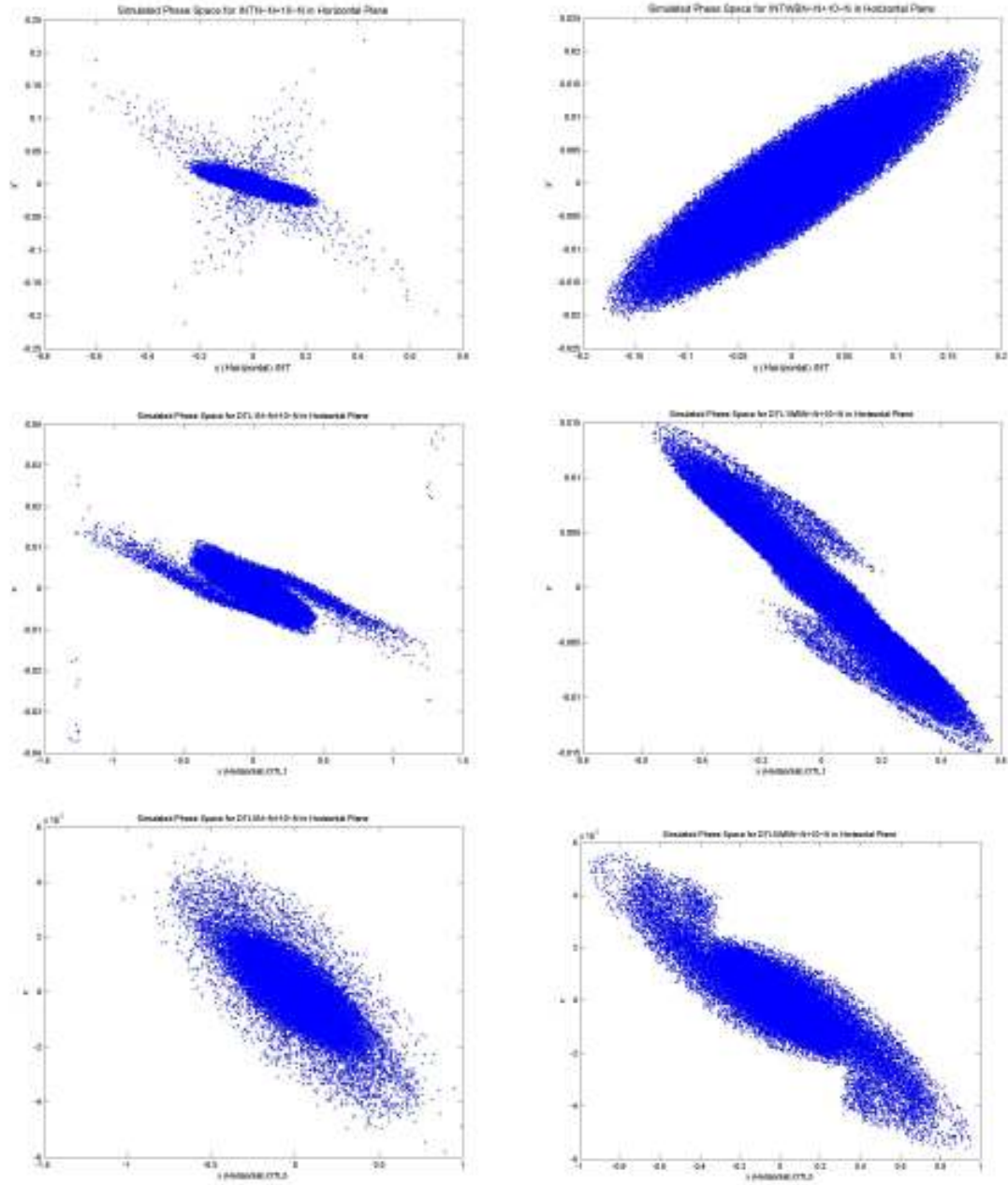


Figure 6.5 Left Column: Reference distribution phase space for the $N \sim N+10 \sim N$ at INT, DTL1 & 5, and CCL2 & 4. Right Column: Waterbag distribution phase space for the $N \sim N+10 \sim N$ at INT, DTL1 & 5, and CCL2 & 4

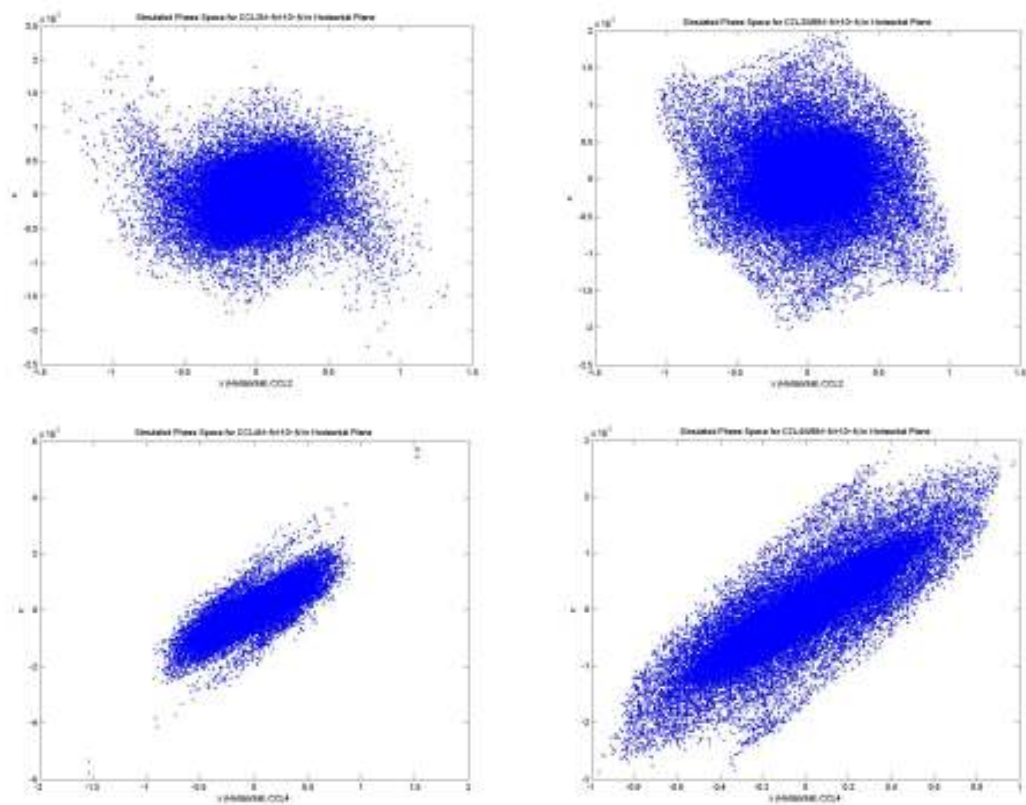


Figure 6.5 (continued)

It can be seen that tails develop around the core ellipse and rotate until CCL2 where the beam core engulfs the tails with the CCL4 distribution having relatively small tails. While it could be said that some halo particles are not seen in Figure 6.5 because they are inside the core at the moment this distribution was observed, this is unlikely because the profile has grown. The scale of the phase space position axis at the initial position is -0.15 to 0.15 cm and -0.8 to 0.8 cm for the width of the core. This growth in core size would suggest that the halo decreases as the size of the core or emittance increases. This is consistent with beam relaxation models [15], which predict that a beam will tend to equalize its energy by converting the free energy of the initial mismatch oscillations into thermal energy of the beam [16]. A larger beam core with little halo is not necessarily better than a small core with large halo. It still remains that a mechanism of halo control is important. Figure 6.6 shows the halo tails corresponding to the phase space plots in Figure 6.5 for the reference distribution. The distribution can be seen to become mostly Gaussian at the end of the CCL. The plots in Figure 6.6 are normalized to have the same rms in order to compare the tails. The size of the core is lost when this normalization is performed.

6.5 RMS Analysis

Quantifying the core growth is necessary in order to know how the core size and halo are related. The rms of the Gaussian fit to the data profile is a measure of the size of the core and is easily obtained. Figure 6.7 shows an increase in core size in the CCL. This increase in rms corresponds to the decrease in halo in Figures 6.2 in the CCL and decrease in rms and increase in halo in the DTL.

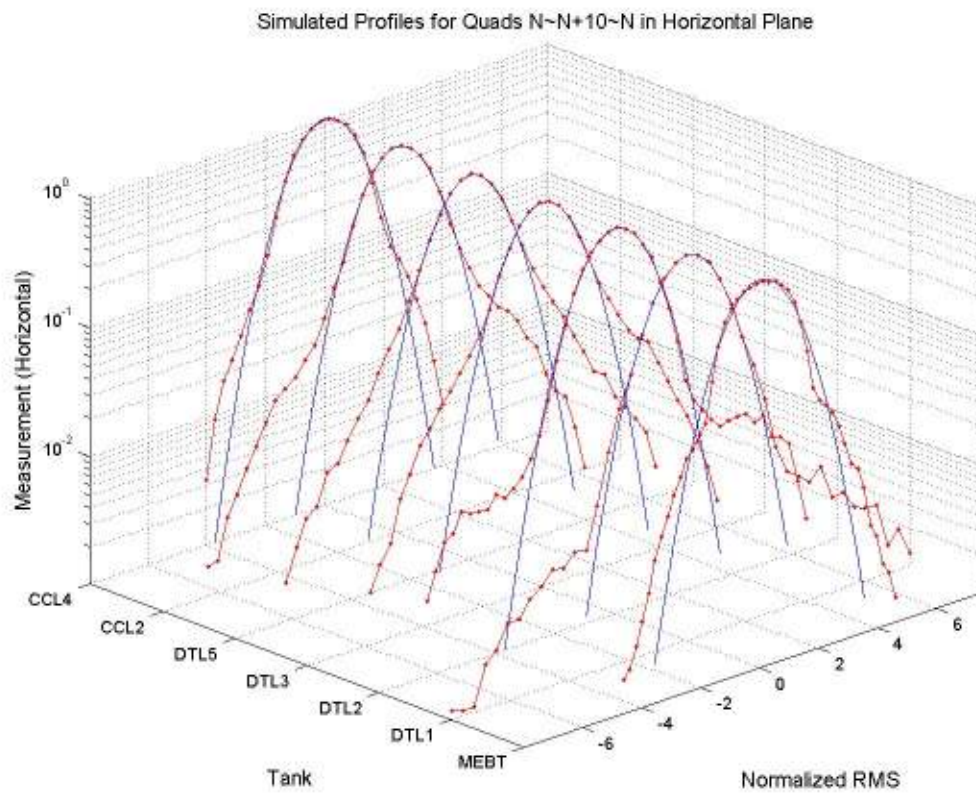
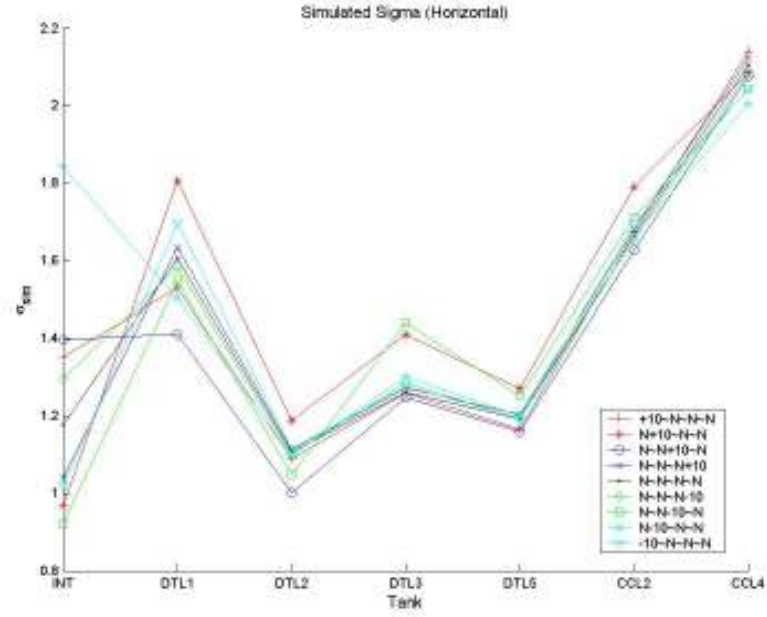
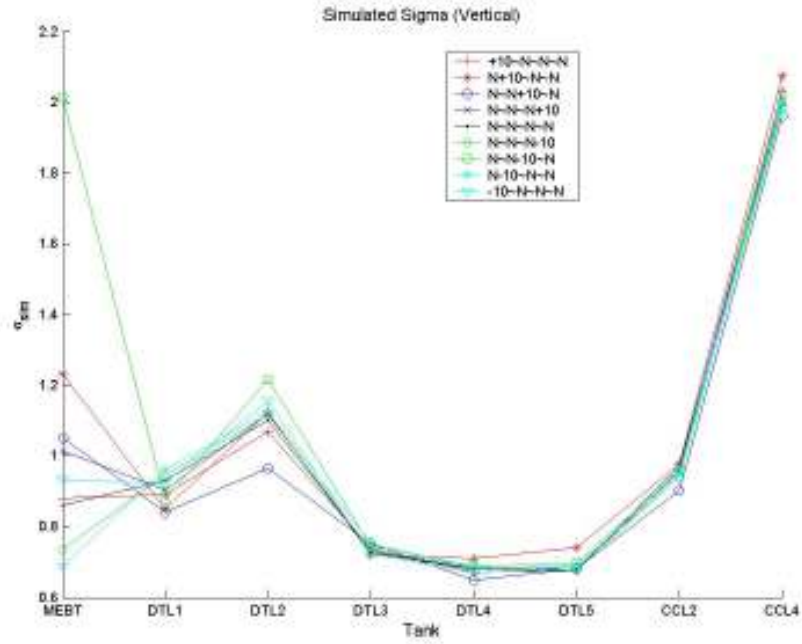


Figure 6.6 Horizontal profiles the N~N+10~N reference distribution.



(a)



(b)

Figure 6.7 (a) RMS values for the simulated reference distribution for all quadrupole settings in the horizontal direction. (b) RMS values for reference distribution in the vertical direction. RMS values are in centimeters.

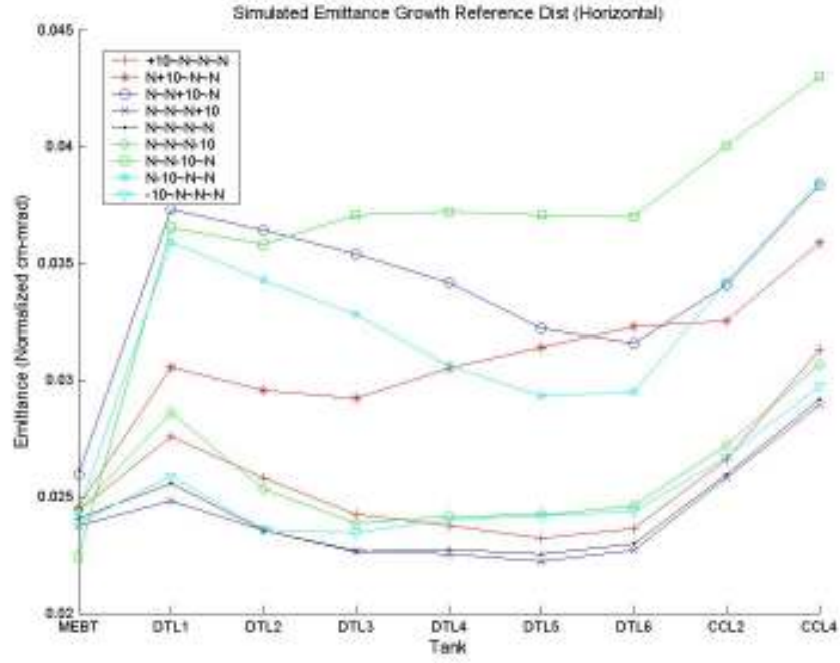
The simulation results of the rms, halo, and phase space analysis suggest that the halo increases in the DTL for mismatched cases and then decreases in the CCL toward a Gaussian accompanied by emittance growth with little halo for simulation data. The particle-core model attributes the increase in emittance growth and halo to the space charge of the beam. It would appear that space charge is one of the main factors contributing to the development of halo as the particles are driven to higher amplitudes by the space charge and overall size of the beam increases in order equalize the energy.

6.6 Emittance Analysis

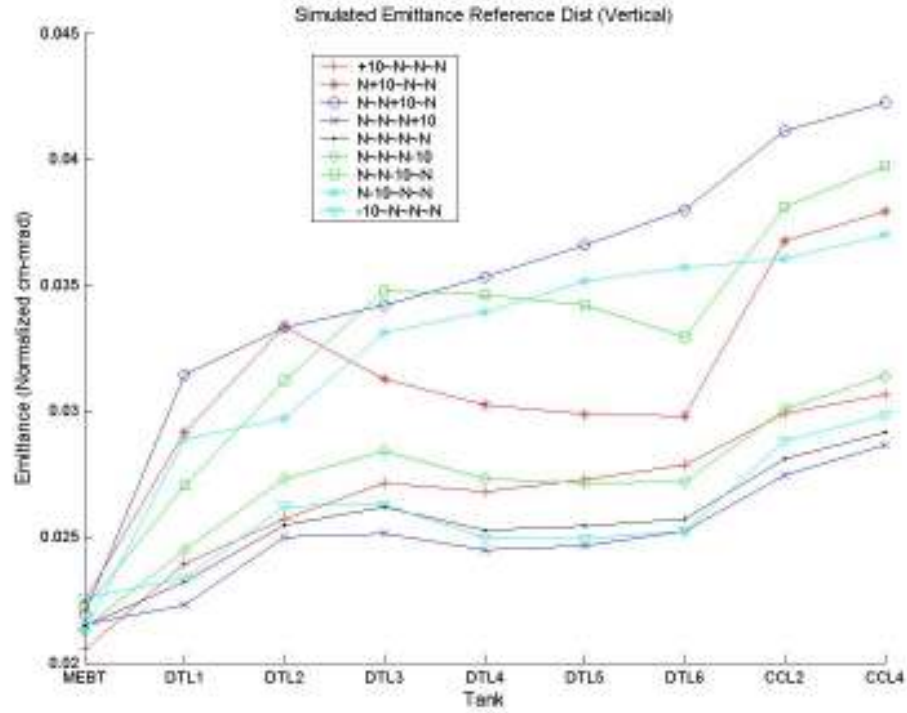
While analyzing the phase-space and rms properties of a distribution can be useful, phase-space does not give quantitative measurements about the core and the rms from a distribution may not be an accurate representation of beam size. Depending on the orientation in phase-space of the particle distribution, the projection onto a particular axis could hide the true size of the core phase-space area. The best core representation is that of emittance. Emittance gives the area of the core distribution regardless of orientation in phase-space. Figure 6.8 shows a growth in emittance for both horizontal and vertical directions. The horizontal case shows emittance decreasing around DTL5 and increasing in the CCL. These results show a definite relation between halo and emittance growth for simulation data.

6.7 Experimental Comparison

Wirescan data was taken for the nine quadrupole settings in Table 6-1 in order to compare with simulated data. The machine was operating at a peak beam current of 25 mA when the data was taken. Simulations were carried out for the reference distribution at 25 mA in PARMILA. Figure 6.9 shows two cases of wirescan horizontal profiles.

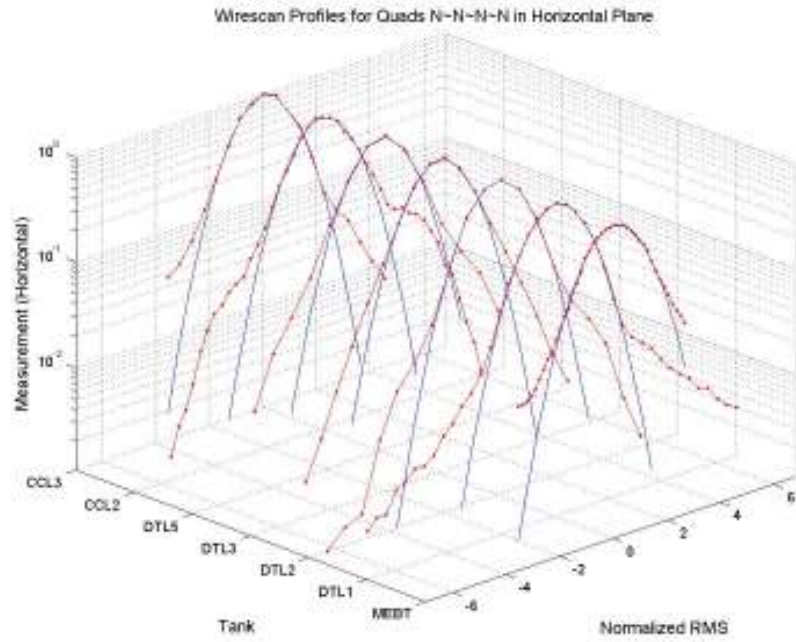


(a)

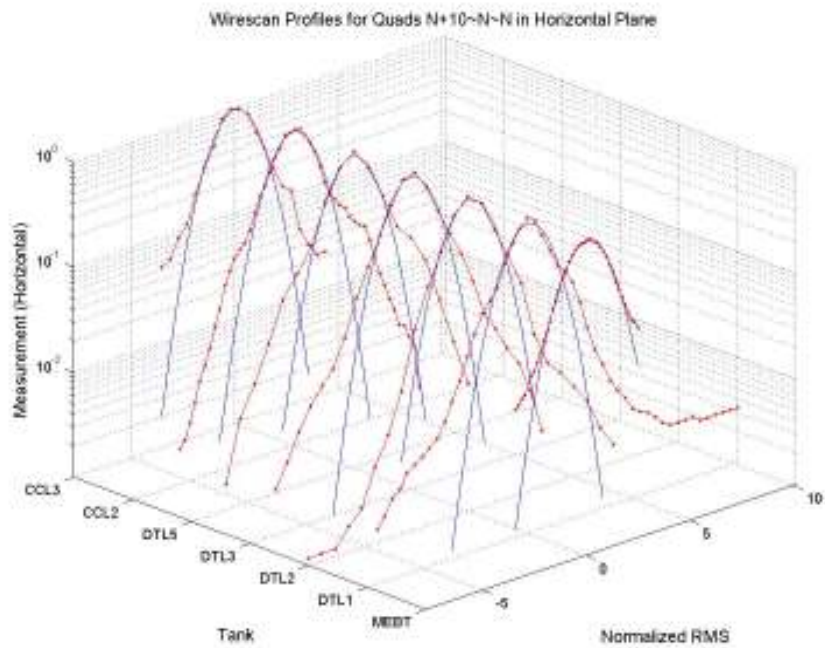


(b)

Figure 6.8 Emittance growth plots for the reference distribution in the (a) horizontal and (b) vertical planes.



(a)



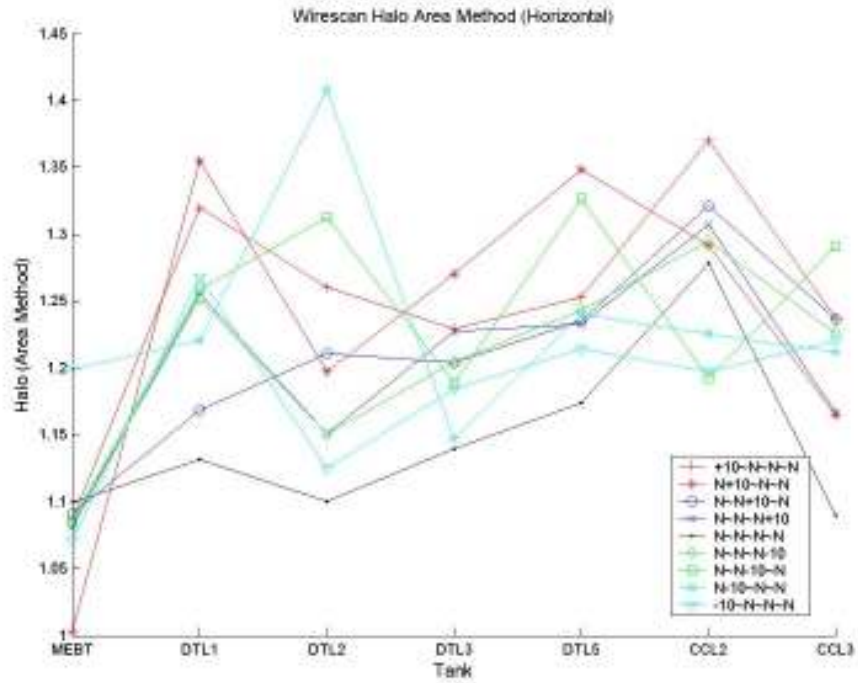
(b)

Figure 6.9 Wirescan profile plots: (a) N~N~N~N Horizontal, (b) N+10~N~N Horizontal.

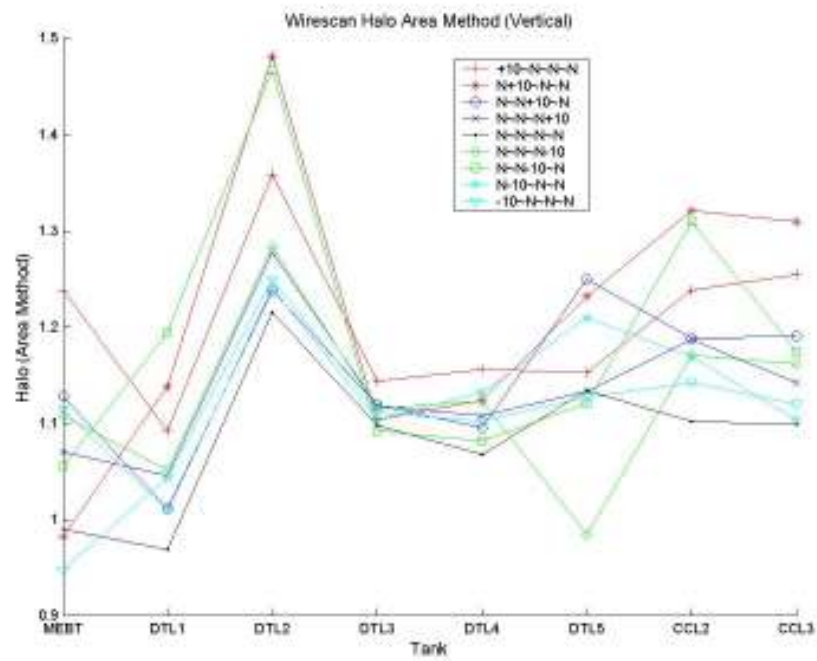
The halo analysis for all wirescan data is shown in Figure 6.10, and the simulation results are shown in Figure 6.11. Comparing Figure 6.10 with 6.11 shows that the overall halo values in both directions are larger for experimental data, than for simulation data. The machine halo data does not match the simulated except in the fact that the vertical experimental halo data, Figure 6.10 (b), is more correlated than the horizontal experimental halo data, Figure 6.10 (a). The wirescan data show an overall peak of halo growth in CCL2 in the horizontal direction and DTL2 in the vertical direction as opposed to DTL5 in the horizontal simulated case and DTL4 in the vertical case.

Even though the experimental halo data do not agree perfectly with simulation, many of the profiles are very similar as seen in Figure 6.12. The simulations accurately reproduced many of the features of the profiles but underestimate their halo production. In Figure 6.12, all of the profiles are normalized by their rms values, thus making it easier to compare the tail regions. To compare rms core growth, Figure 6.13 shows simulated rms divided by measured rms values.

RMS analysis reveals some core growth in experimental data but not to the degree it is seen in simulation data. Vertical rms values in both the wirescan and simulated data spiked in DTL2. Experimental growth decreased in CCL4 in most cases but not the same as in simulations and the vertical wirescan data saw no decrease in halo in CCL2 or CCL4. The discrepancy between simulation and experimental data is not understood at this time. One possible answer is that the beam entering the quadrupoles at the end of the MEBT has considerably more halo than anticipated. Even with the differences, both simulated and wirescan halo data show certain cases that produce more halo than others. The $N \sim N+10 \sim N$, $N-10 \sim N \sim N$, $N \sim N-10 \sim N$, and $N+10 \sim N \sim N$ cases produce the most halo.

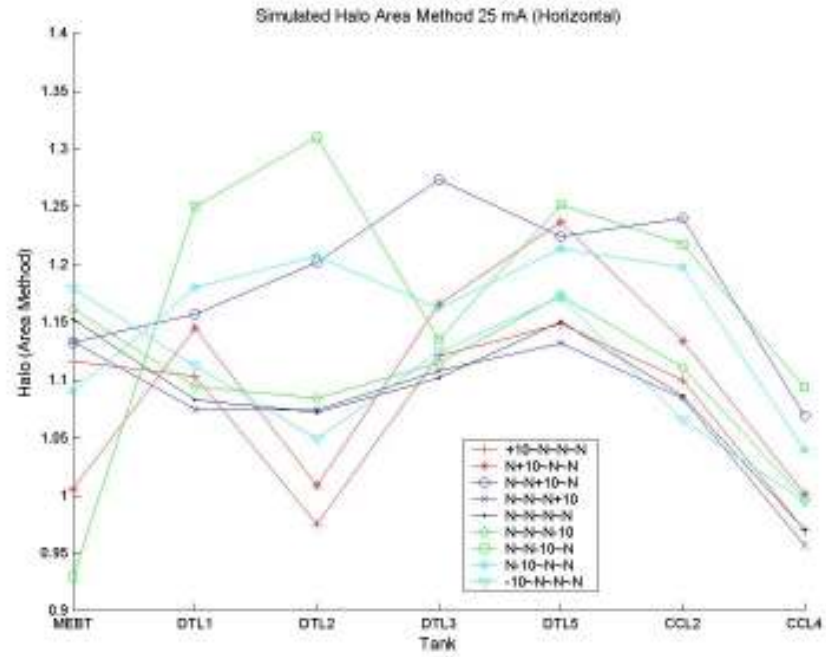


(a)

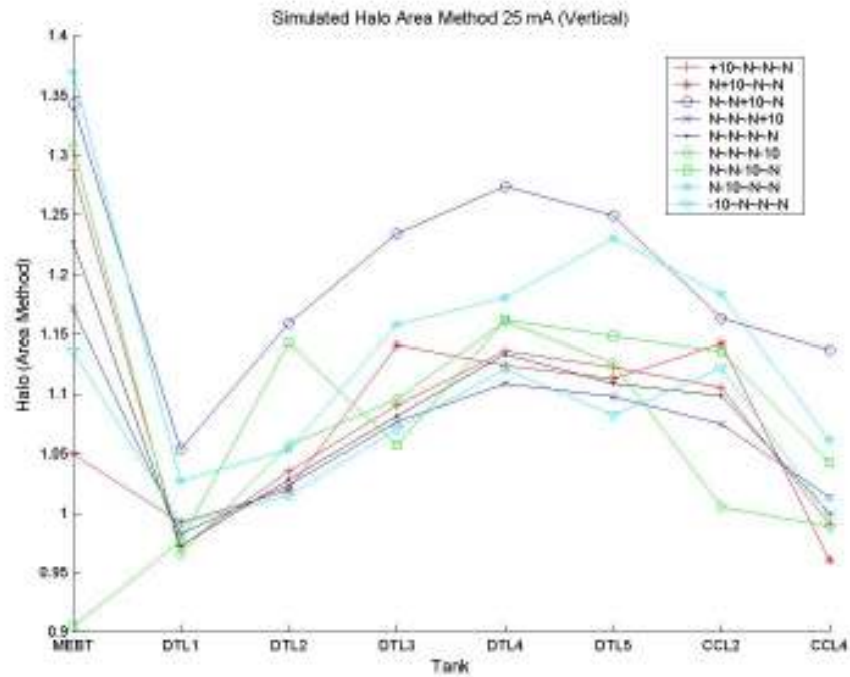


(b)

Figure 6.10 (a) Wirescan halo plots in the horizontal direction. (b) Wirescan halo plots in the vertical direction.



(a)



(b)

Figure 6.11 (a) Horizontal reference distribution simulated at 25 mA. (b) Vertical reference distribution simulated at 25 mA.

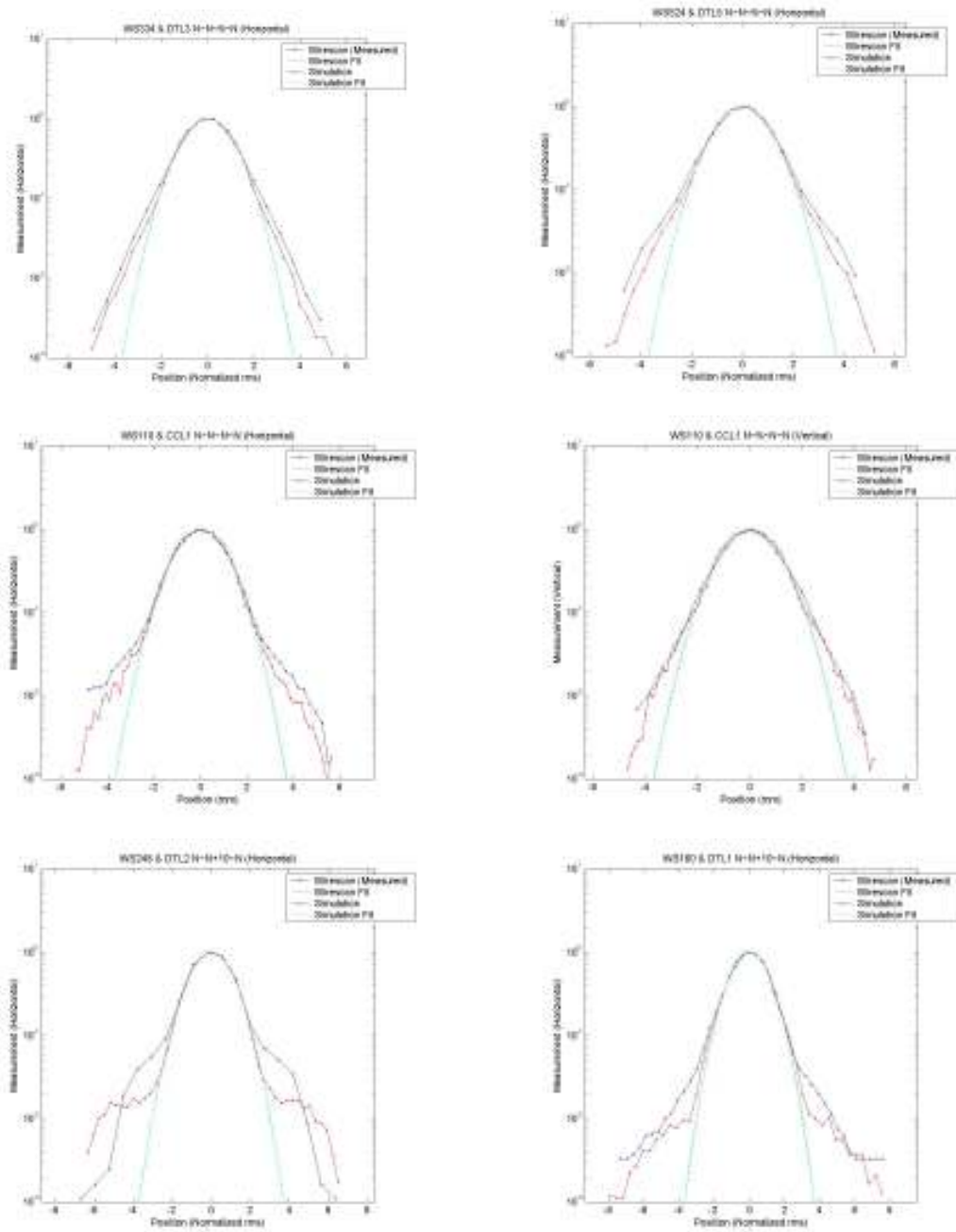
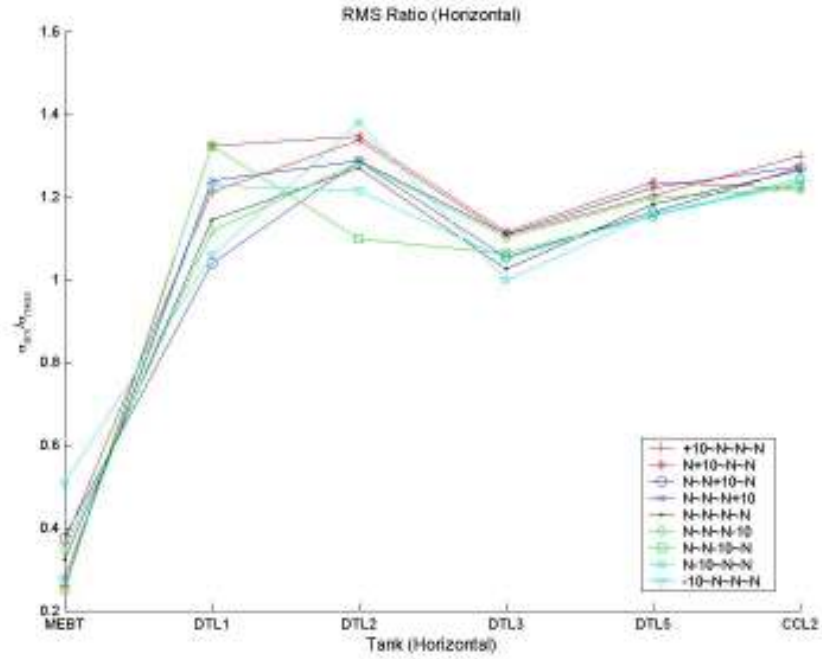
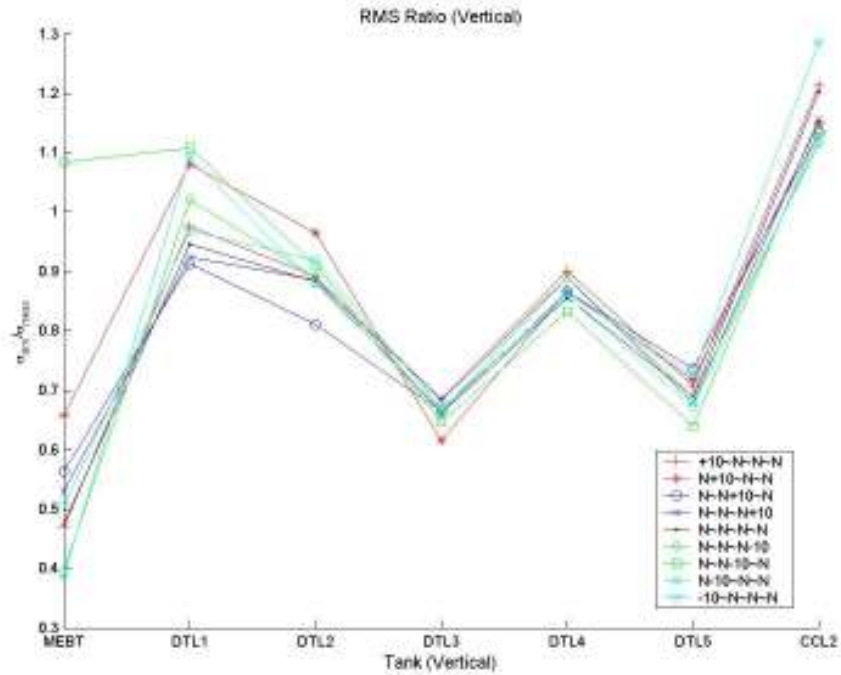


Figure 6.12 Various simulated plots overlaid with wirescan plots, all with normalized rms.



(a)



(b)

Figure 6.13 RMS ratio values comparing the simulated to experimental core in the (a) horizontal and (b) vertical direction.

This would suggest that MEBT quadrupoles 12 and 13 affect halo growth more than 11 and 14. All cases conclude that the nominal setting is one of the lowest halo generating configurations. The low rms ratios in the MEBT mean that the experimental beam is considerably larger than the simulation distribution. If the nominal case is indeed the minimal halo case, then methods for decreasing halo inside the MEBT are of greater importance than optimizing the quadrupoles at the end of the MEBT.

Further study into the production of halo is needed to say whether the nominal configuration is the optimal one. PARMILA can generate an input distribution with two Gaussians overlapped. By choosing a “core” Gaussian plus one with broad tails, more initial halo can be created allowing for modeling a case with larger tails at the input to the linac. There is much research that can be done on the simulation data to study the energy transfer between the core and halo particles.

7 Conclusions

The Spallation Neutron Source will be the most powerful pulsed neutron source in the world and will be a powerful tool for materials science. The SNS linac is designed to accelerate H^- ions to an energy of 1 GeV which are then stripped, accumulated as protons, and collided with a mercury target producing neutrons through a spallation reaction. In order to produce the maximum of neutrons the amount of beam lost along the accelerator has to be carefully controlled. High beam losses cost research time and money, making loss control elimination a high priority.

One of the key contributors to beam loss is beam halo. According to the particle-core model, a particle distribution approximated by a uniform charge density ellipsoid that enters a focusing lattice with an orientation that is mismatched with the design orientation will oscillate in the longitudinal and transverse planes. A particle outside the core can gain energy as it passes through the oscillating core and can be driven to large amplitudes, populating the beam halo. The core compensates for this transfer of free-energy by increasing its size and absorbing the halo particles.

The four matching quadrupoles at the end of the MEBT are the last method of mismatch control before the beam is injected into the main accelerating structure and, therefore, optimizing these quadrupoles is necessary in order to control halo production.

Simulations using the accelerator simulation package PARMILA were used to study nine quadrupole cases for three initial distributions. Computational tools were developed with Matlab to analyze a beam profile either from simulation or experimental data, isolate the core, and quantify the halo using two methods. The Gaussian Area Ratio method compares the core, approximated with a Gaussian fit, to the non-Gaussian tails.

The Kurtosis method uses the moments of the distribution to determine to what degree the distribution is peaked. The Kurtosis method was found to have a large statistical error and, therefore, only the Area Ratio Method was finally used.

Results from the simulations revealed an increase in halo for all cases around DTL5 and a decrease in halo at the end of CCL4. Quantifying the beam mismatch showed that certain cases, $N \sim N+10 \sim N$ in particular, had the worst mismatch. In order to determine whether the core size had increased or the halo particles were being hidden when their phase placed them inside the core, a study of phase space, the rms properties of the core, and emittance growth was done. Examining the phase space of a simulated distribution revealed that the core was becoming larger and more Gaussian toward the end of the CCL. This was confirmed with an analysis of the core size using the rms of the fitted Gaussian and the emittance growth.

A Gaussian along with a Waterbag distribution, both having little to no initial halo, were simulated and found to produce halo even when none was present before the matching quadrupoles. This led to the conclusion that halo is initial distribution independent for highly mismatched cases or that, for low mismatch, halo will be created and propagate unchanged.

Simulations were carried out for a reference distribution designed to resemble the distribution from the machine at the current of 25 mA and compared to wirescan profiles of a 25 mA beam for the same nine quadrupole configurations. While simulations showed a decrease in halo in the CCL experimental data did not support this. Simulations tended to underestimate the halo actually present and halo behavior did not show good agreement between simulations and measurement. Core size did increase in experimental

data but not to the same degree seen in simulations. Despite the discrepancies, halo production was generally more sensitive to quadrupoles 12 and 13 and the quadrupole settings $N \sim N+10 \sim N$, $N-10 \sim N \sim N$, $N \sim N-10 \sim N$, and $N+10 \sim N \sim N$ tended to generate more halo. The nominal case typically had the lowest halo.

More research is needed in order to understand the discrepancy between experimental and simulation data. Simulated data showed halo produced through mismatch with subsequent emittance growth but machine data did not support this. For the experimental data, it was discovered that the beam at the end of the MEBT had more halo than predicted by the simulations. It can be concluded that halo could be controlled by setting the quadrupoles to their nominal settings and working to create an initial beam with less halo before injection into the linear accelerator.

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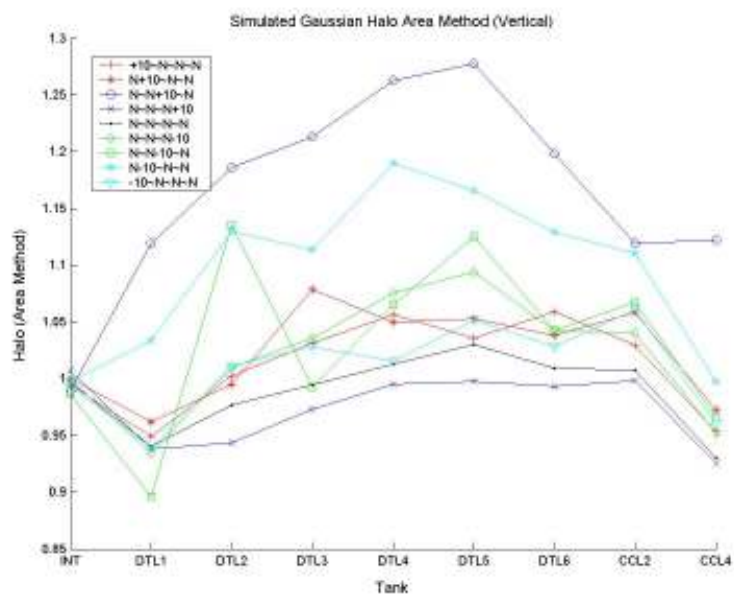
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Appendix

Appendix



(a)



(b)

Figure A.1 Halo data for a Waterbag distribution in the (a) horizontal and (b) vertical directions using the area ratio method.

Vita

Dirk Alan Bartkoski was born in Christiansburg, VA., on April 30, 1982. His father moved the family to Blacksburg, Co. to pursue a career in mine management. The Bartkoski family moved to Kentucky, where Dirk spent his childhood years being homeschooled. In 1996, he moved to Belmont, Ohio where he graduated high school through homeschooling and received his GED. After spending one year at the Ohio University Eastern Campus in a general engineering degree, he went to Oral Roberts University in Tulsa, OK. where he graduated with a B.S. in Engineering Physics and a minor in Math.

Dirk is currently pursuing his Master's in Physics at the University of Tennessee in Knoxville, TN. while working as a research assistant at the Spallation Neutron Source in the Oak Ridge National Laboratory. He plans on continuing his education toward a Doctorate in Physics.