Plasma Considerations in the IPNS RCS

Jeffrey C Dooling
Argonne National Laboratory

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Introduction

IPNS Rapid Cycling Synchrotron (RCS)—Parameters:

3×10^{12} protons per pulse, 50 MeV to 450 MeV, 30 Hz

Ave. current in the single harmonic ring reaches 2.5 A

Peak current may be as high as 13 A.

Background pressure typically of 1 μTorr nitrogen

Ionization cross section 5×10^{-22} m^2 at injection

neutralization folding time 0.5 ms.

In comparison, the PSR typically runs with an average background pressure of 5×10^{-8} Torr

With an injection energy of 800 MeV, the neutralization time in the PSR is in excess of 20 ms.

Measurements presented by R. Macek at this workshop suggest that the neutralization fraction in PSR is on the order of 1 percent, consistent with its longer folding time.

Bunching Factor

BF changes significantly during the acceleration period: 0.5 near injection—0.2 near extraction.

The increase in beam density leads to higher space-charge electric fields as the charge density increases.

Plasma Formation

Significant plasmas should be generated in the IPNS RCS based on several arguments that will be presented here.

Anecdotal evidence—Profile And Position monitoring System (PAPS) shows transverse beam profile information to be unusable 3-5 ms after injection

Data collected in 1999 shows profiles which move with steering as expected from inside to outside. However, after 5 ms, all channels of the device saturate and the profiles become useless. Since that time the device has internally shorted.

Beam potential.

A simple calculation of voltage potential generated by the RCS beam: round, single bunch beam of radius, a=1 cm circulates in a beam pipe of radius, b=3 cm with $3\mathrm{x}10^{12}$ protons (Q=0.48 μC).

The RCS has a circumference of 43 m of which the bunch, near injection, is assumed to uniformly occupy 50 percent, i.e., L_b=21.5 m. The initial line density, λ(t=0), is then $1.4\mathrm{x}10^{11}$ m^{-1}.

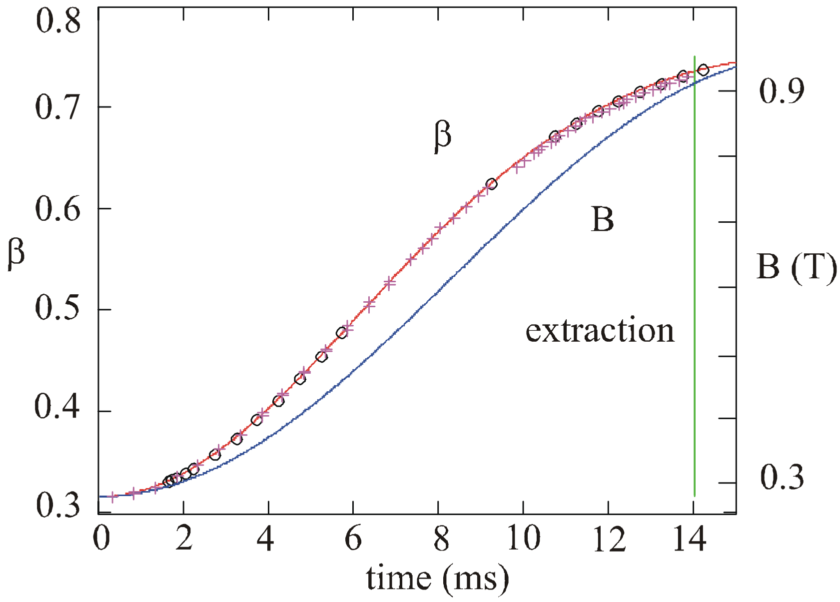
From $\nabla \bullet \mathbf{D} = \rho$,

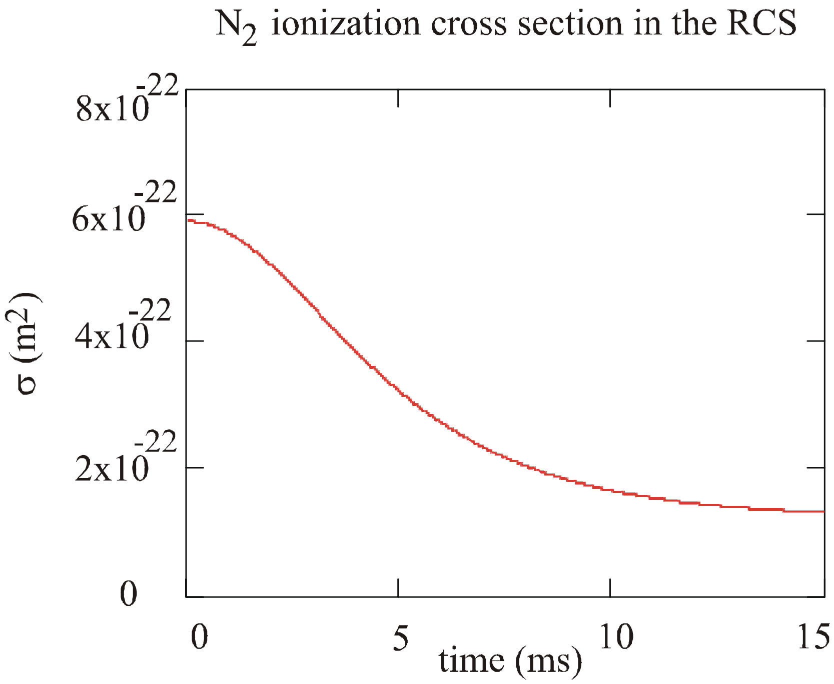
$$V(r,t) = \begin{cases} \dfrac{\rho(t)}{4\varepsilon_o}\left[\left(a^2 - r^2\right) + 2a^2 \ln\left(\dfrac{b}{a}\right)\right], & r < a \\ \dfrac{\rho(t)a^2}{2\varepsilon_o}\left(\ln\left(\dfrac{b}{a}\right) - \ln\left(\dfrac{r}{a}\right)\right), & a < r < b \end{cases}$$

As an example, shortly after injection with local charge density $\rho(t=0)=\lambda/\pi a^2$, the potential at the edge of the beam is +441 V, while the potential at the beam center is 200 V higher.

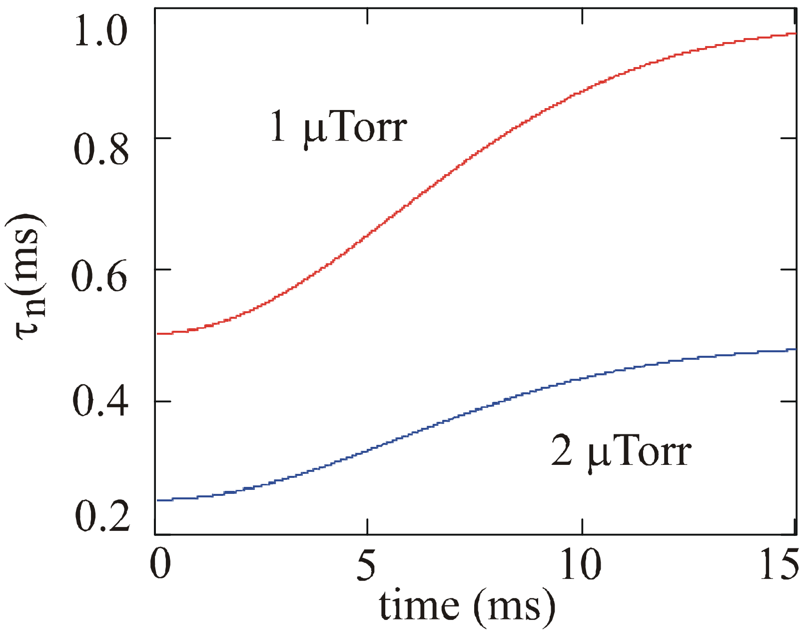
This potential will grow as the beam is accelerated and further bunched as will be shown shortly.

Magnetic field, ion velocity, and ionization cross section within the RCS



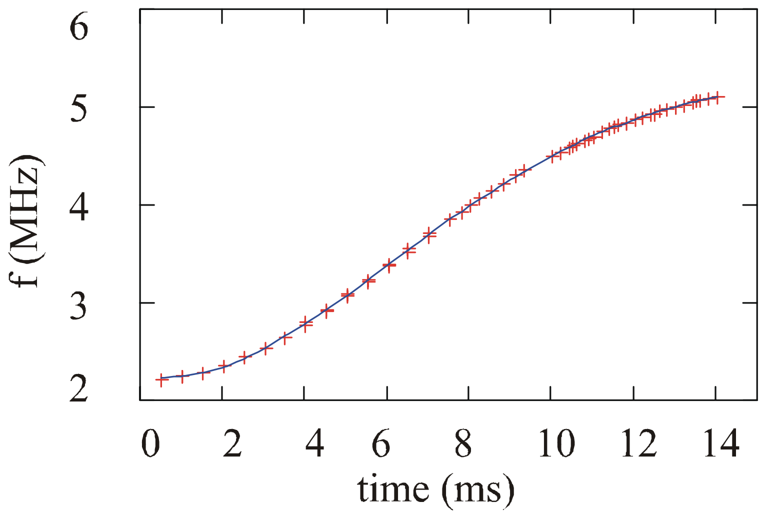


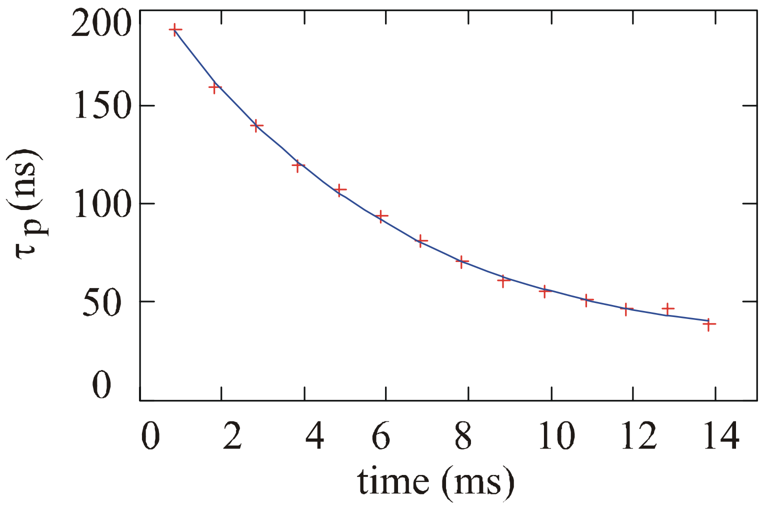
Neutralization folding time in the IPNS RCS



The neutralization time is relatively short compared with the acceleration period; therefore a quasi-neutral plasma establishes itself quickly in the RCS.

RCS Frequency and Pulsewidth--Data and Fit





Bunching Factor in the RCS

Fit of bunching factor from frequency and pulsewidth data fits:

frequency fit:

$b_o := 2.255210^{6}$ $b_1 := -9.102610^{7}$ $b_2 := 7.704210^{10}$

$b_3 := -5.932210^{12}$ $b_4 := 1.378610^{14}$

$$f(x) := b_o + b_1 \cdot x + b_2 \cdot x^2 + b_3 \cdot x^3 + b_4 \cdot x^4$$

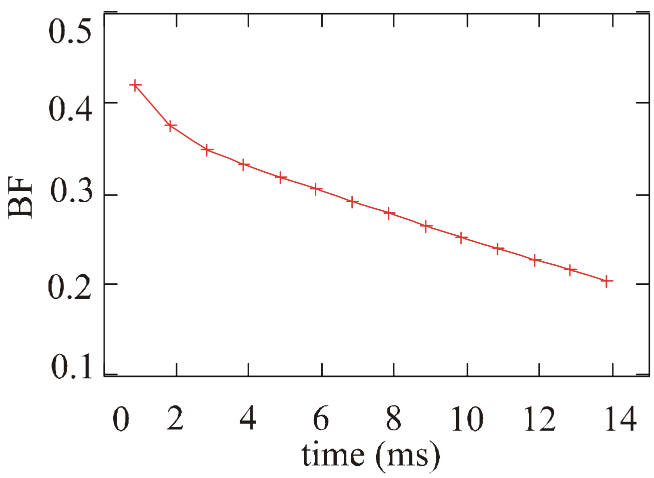
pulsewidth fit:

$a_o := 2.116810^{-7}$ $a_1 := -3.062110^{-5}$ $a_2 := 2.073210^{-3}$

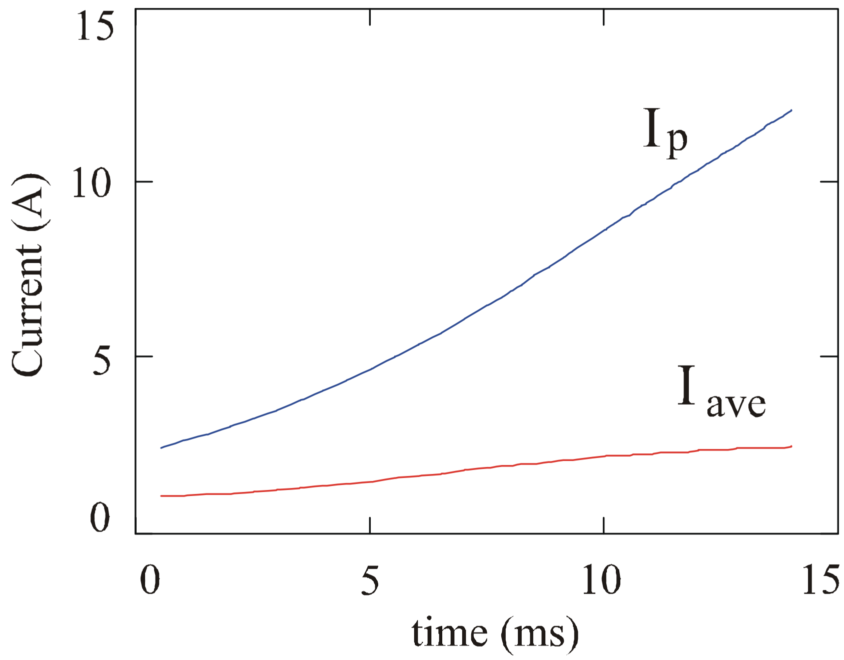
$a_3 := -0.0638$ $a_4 := 0.6629$

$$\tau(x) := a_o + a_1 \cdot x + a_2 \cdot x^2 + a_3 \cdot x^3 + a_4 \cdot x^4$$

Bunching Factor, BF = $\tau_p(x) f(x)$



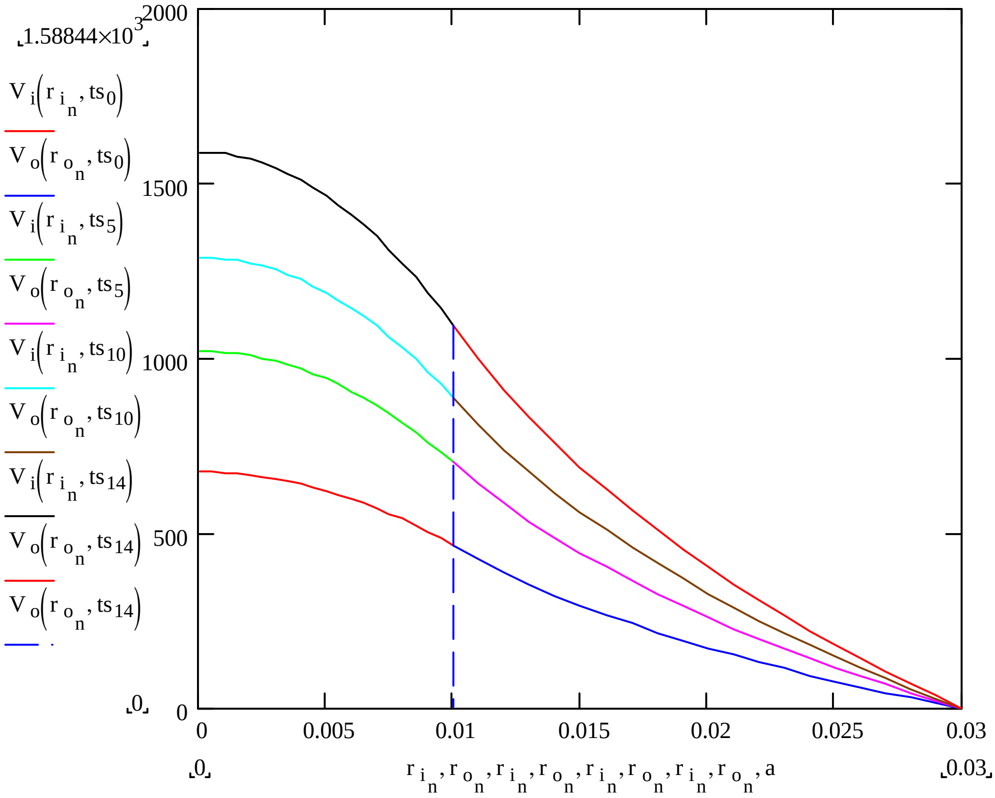
Average and Peak Current in the RCS



The large ratio of peak to average current, in conjunction with a fast neutralization time, indicates substantial non-neutrality in the plasma formed along the beam path.

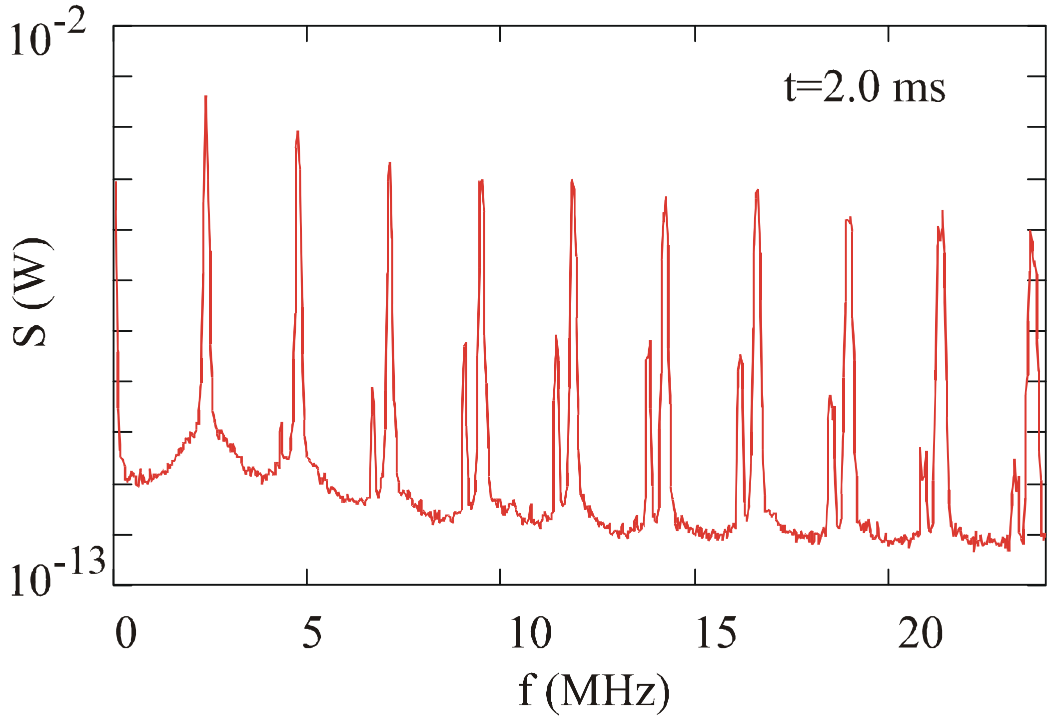
Radial voltage profiles, revisited

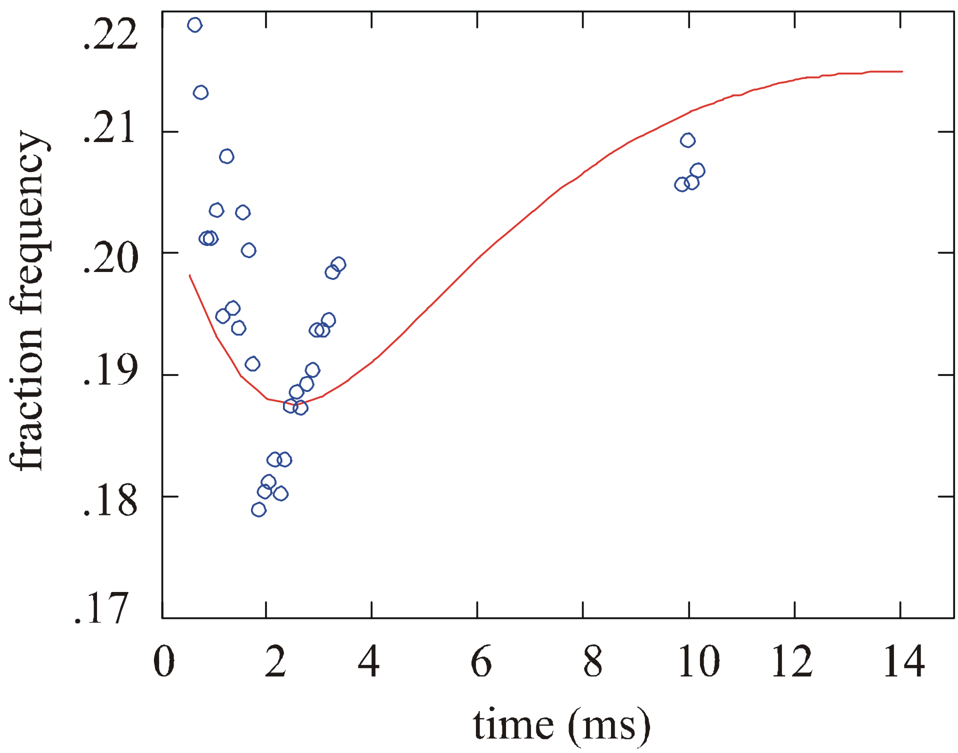
Beam space charge generates in excess of 1.5 kV between beam center and grounded wall near extraction. Plasma will certainly modify the profiles.



time (s)

Fractional Tune Shift in the RCS





Tune Shift

From Reiser, p. 290 the expression for tune shift,

$$\Delta\nu(\tau) = -\frac{I_p R\left(1-\gamma^2 f_e(\tau)\right)}{I_0 \varepsilon_n \beta^2 \gamma^2}$$

Have interpreted this as,

$$\Delta\nu(t) = -\frac{I_p R\left(1-\gamma^2 BF(t)\right)}{I_0 \varepsilon_n \beta^2 \gamma^2}$$

Where I had assumed neutralization proceeds only up until the average current. This result is plotted above.

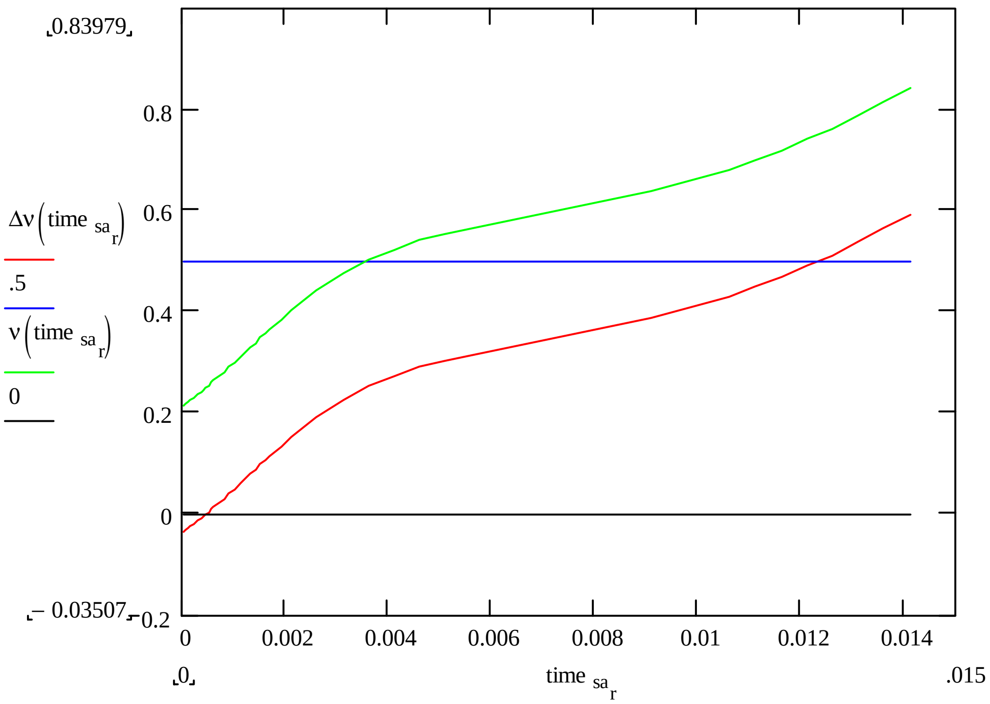
However, upon rereading Reiser (p. 279), this is not correct. In the IPNS RCS the background density is much greater than the beam density , the beam channel should become OVER NEUTRALIZED.

In this case the expression should be written as,

$$\Delta\nu(t) = -\frac{I_p(t) R\left(1-\gamma^2 \frac{t}{\tau_n}\right)}{I_0 \varepsilon_n \beta^2 \gamma^2}$$

Tune Shift

Now using $f_e(t) = t/\tau n$, we obtain the following:



Horizontal tune shift is actually positive!

This conclusion is supported by other tune shift data and says that the beam is self-focussing. This needs to be verified.

Conclusions and Further Work

Significant plasma formation and neutralization must be occurring in the RCS during the 14 ms acceleration period.

Measurements of the electron cloud and plasma adjacent to the beam should be made. It may be possible to resurrect the PAPS, but with dead channels and shorted leads, it may make more sense to completely replace it.

In addition to the RFA and Swept Analyzer diagnostics, other techniques might be attempted. If plasma is present, then perhaps a small biased probe might be useful (e.g., a Langmuir probe) or with the proper choice of geometry, an optics-based measurement for line density (e.g., an interferometer).

Is self focussing occurring the IPNS RCS? It appears so.

Acknowledgment

This work would not be possible without the dedication of the IPNS Accelerator Operations staff.