Electron Clouds in Present and Future High Intensity Hadron Machines

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SNS/BNL Accelerator Physics

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Hadron Machines with Electron Clouds

	LANL **PSR**	**CERN** **PS**	**CERN** **SPS**	**BINP** **PSR**	**CERN** **ISR**	**BNL** **RHIC**
Main Symptom	**Instability**	**Diagnostic problems**	**Instability**	**Instability 1966**	**Pressure rise +**	**Pressure rise**
$I_{peak}(A)$	**70**	**7**	**7**	**0.5**	**20**	**2**
$s(f)/f$	**6.3e-4**	**1.9e-5**	**2.6e-6**	**1.3e-2**	**1.4e-4**	**4.e-6**
$s_{\perp}(mm)$	**7.6**	**6.3**	**2.5**	**2.5**	**2**	**2**
Kinetic energy	**787 MeV (storage)**	**26 GeV (extraction)**	**26 GeV (injection)**	**1 MeV (storage)**	**30 GeV**	**11 GeV/A (Au inj)**
$r_{pipe}(mm)$	**50**	**h=70,v=35**	**h=70, v=23**	**h=60,v=40**	**h=70,v=35**	**30**
Q_b	**2.2**	**6.25**	**26.6**	**0.7**	**8.9**	**28.2**

High Intensity Hadron Machines under construction

	ORNL SNS	J-PARC 3 GeV	J-PARC 50 GeV
Primary concern	Instability	Instability Pressure rise?	Instability Pressure rise?
$I_{peak}(A)$	80	• injection 38 extraction	• injection 196 extraction
$s(f)/f$	5.5e-4	5.9e-3 injection 3.2e-4 extraction	4.1e-4 injection 3.3e-6 extraction
$s_{\perp}(mm)$	14	19 injection 12 extraction	11 injection 5 extraction
Kinetic energy	1 GeV	375 MeV inj 3 GeV ext	3 GeV inj 50 GeV ext
$r_{pipe}(mm)$	100	125	65
Q_b	6.3	4.2	22.2

Origin of Electron Cloud

Primary electrons due to losses and gas stripping.

Loss generated electrons more likely to multipactor

$$m_e \frac{d^2 y}{dt^2} = -e \frac{Z_0 I(t)}{2\pi\beta} \frac{y}{y^2 + \sigma^2}$$

Approximate conservation of adiabatic invariant (long bunch)

$$E_{\text{strike}} = -\pi m_e c^2 \left(\frac{b}{c}\right)^2 \dot{\omega}_e / 2.$$

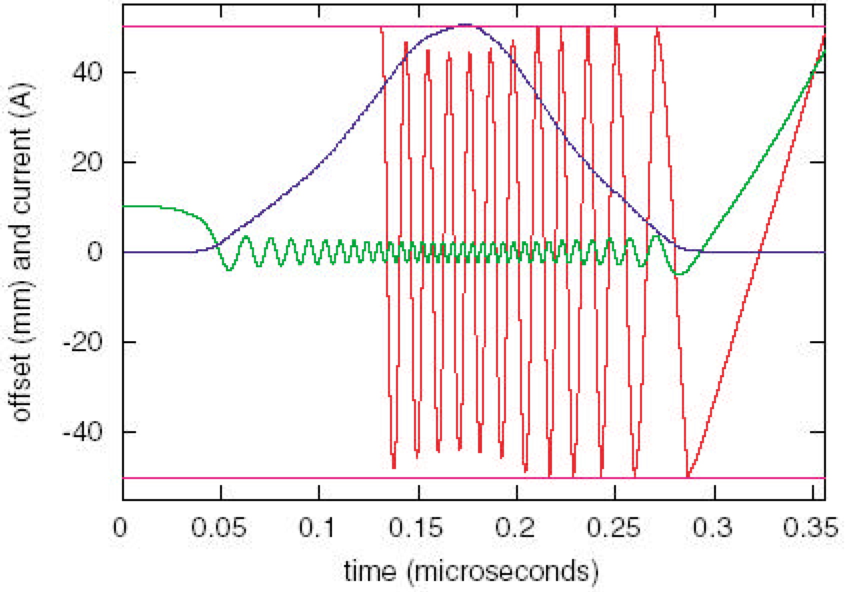


FIG. 4. (Color) Proton beam current (blue) and positions for captured (green) and loss created (red) electrons. The beam pipe radius is 50 mm (violet).

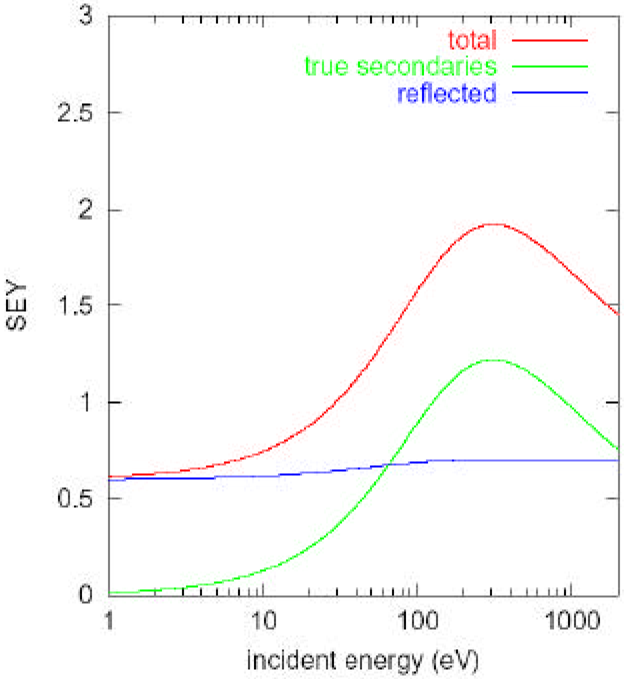
For sufficient strike energy multiplication occurs.

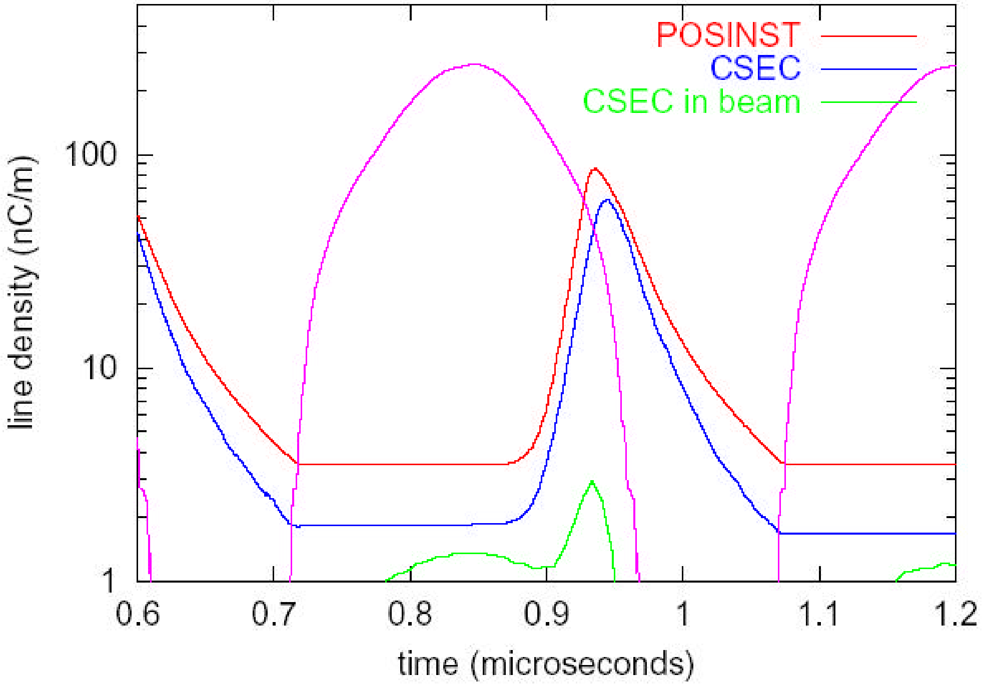
Secondary Emission Yield = $\dfrac{N_{out}}{N_{in}}$

Simulations for PSR

CSEC compared with M. Furman's POSINST.

POSINST is 3 dimensional and shows a larger number of electrons surviving the gap.



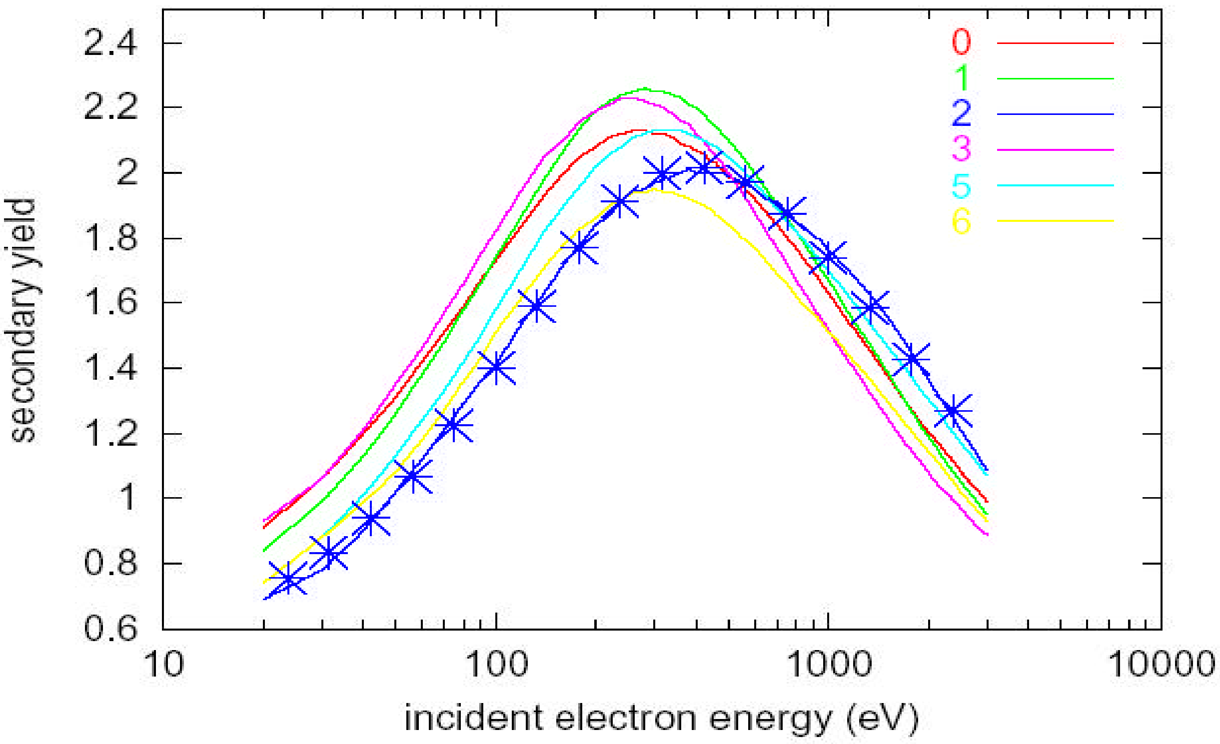


SEY is a distribution of distributions

Coupons manufactured by BNL vacuum group, High pressure magnetron DC sputtering. Measurements done by CERN vacuum group during January 2001

No baking or electron beam conditioning.

Fit CSEC model to data. Symbols are worst fit.

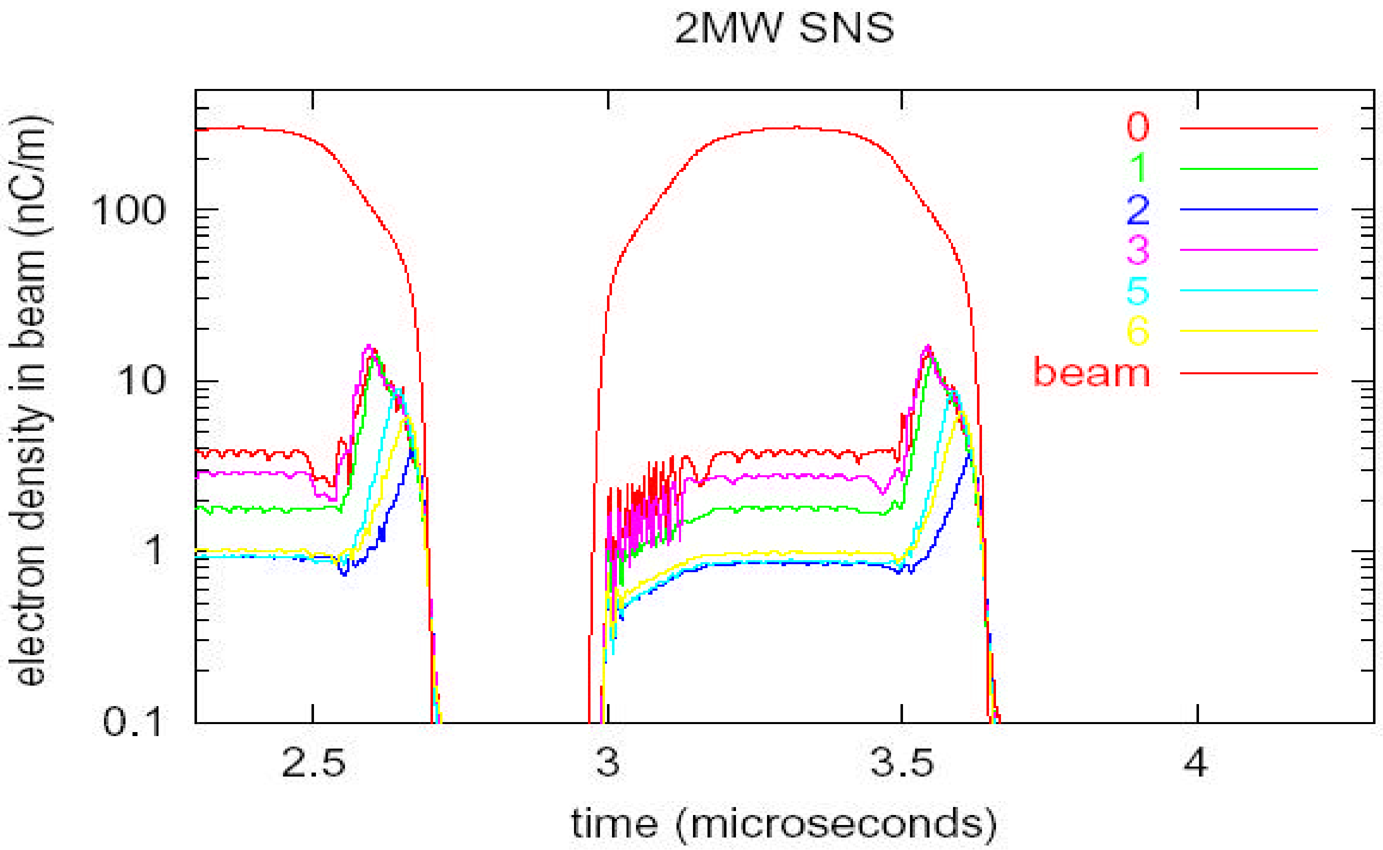


SNS electron clouds in straight sections

CSEC uses cylindrical symmetry and variable charge macroparticles (2D)

Loss rate ∝ I(t), 20 electrons per lost proton and 1% loss gives 2.e8 e/m/turn

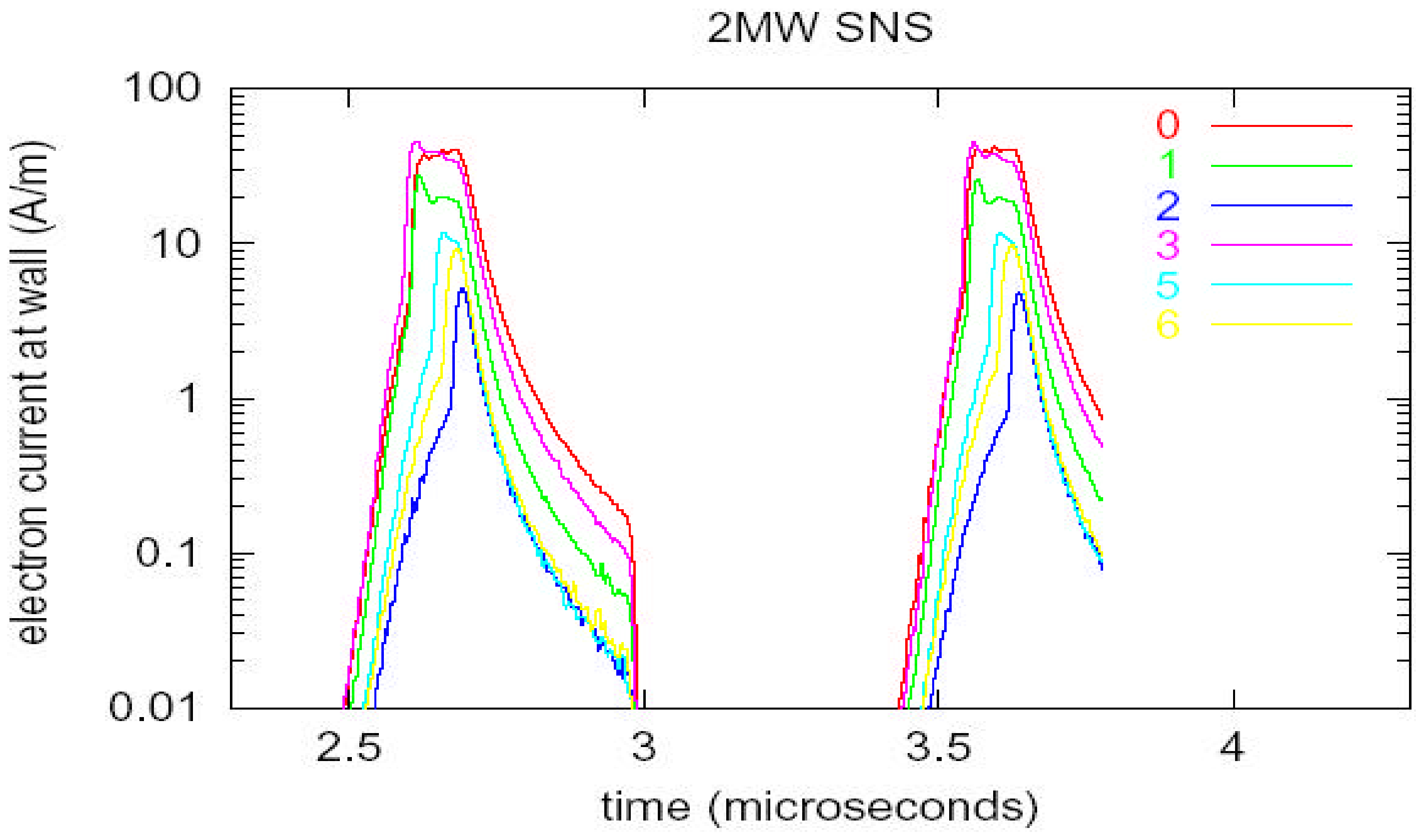
Also done by Furman and Pivi in PRSTAB 034201 with smaller SEY.



Electron current into wall for 2 MW SNS

Total charge deposited ranges from 40 to 700 pC/cm^2/turn

Between 10 and 50 pC/cm^2/turn for energy > 100 eV

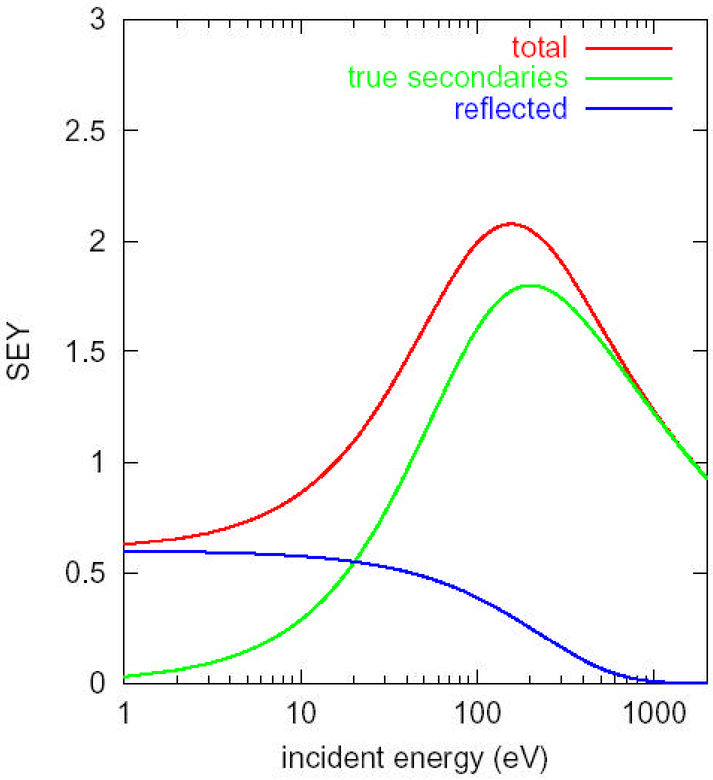


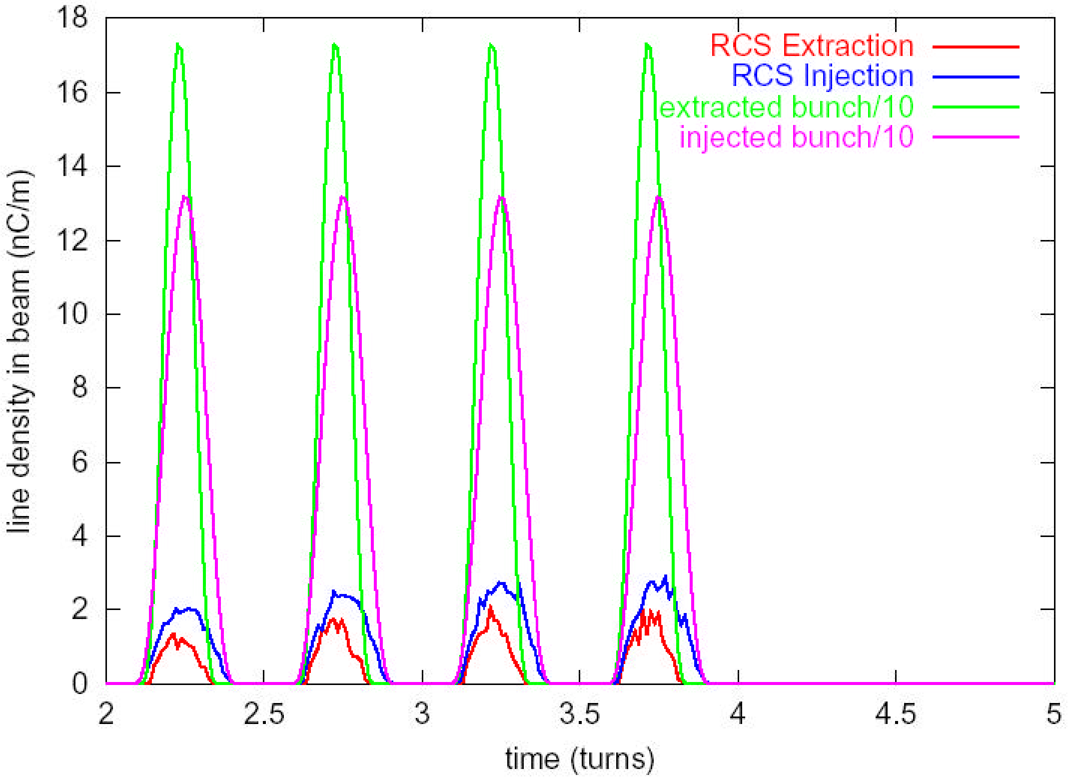
Calculations for J-PARC 3 GeV RCS

Did simulations using CSEC for SEY shown and 0.1% loss over 2000 turns.

Larger losses had little effect on electron density in beam; saturation.

Ohmi, Toyama, and Ohmori did a similar calculation neglecting electron-electron forces and reflected electrons, A_e





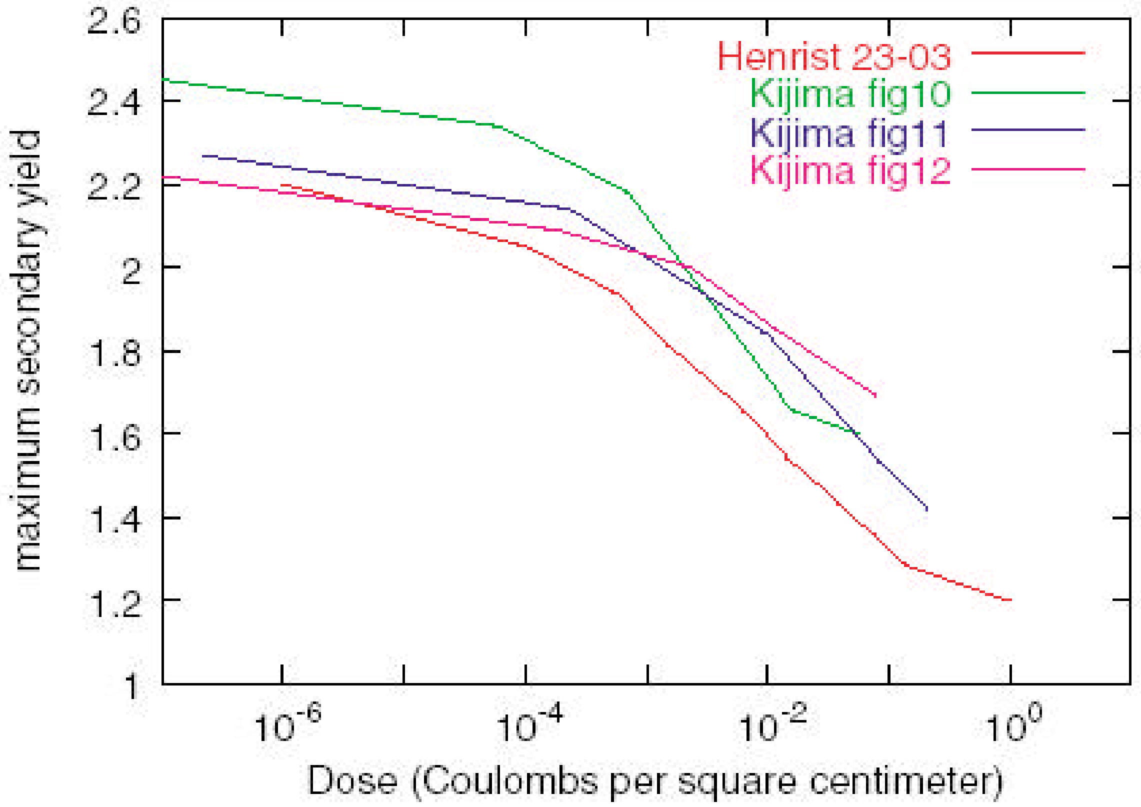
SEY conditioning rates

Henrist et. al. in EPAC02 report conditioning rates for Cu

Kijima et. al. in SRF2001 shows data for wetted then e- conditioned TiN

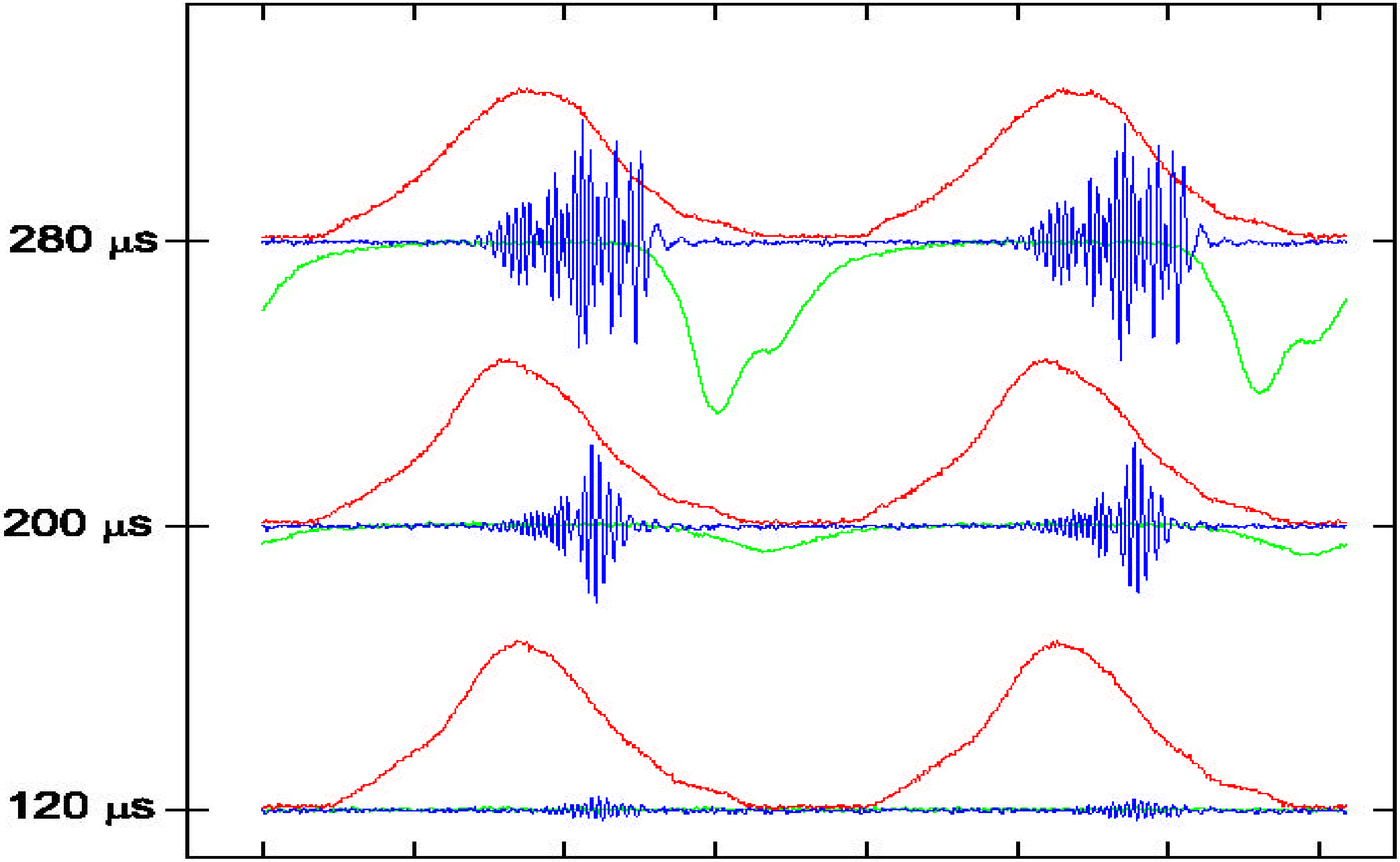
Substrates of OFHC , Cu plated SS, and Nb (600 eV data)

Hilleret finds that the dependence on electron energy is at most linear (SF00)



The last question is whether machines will be stable enough to allow for significant conditioning.

Evolution of PSR instability, beam current, stripline difference signal, electron flux at wall. Note timing



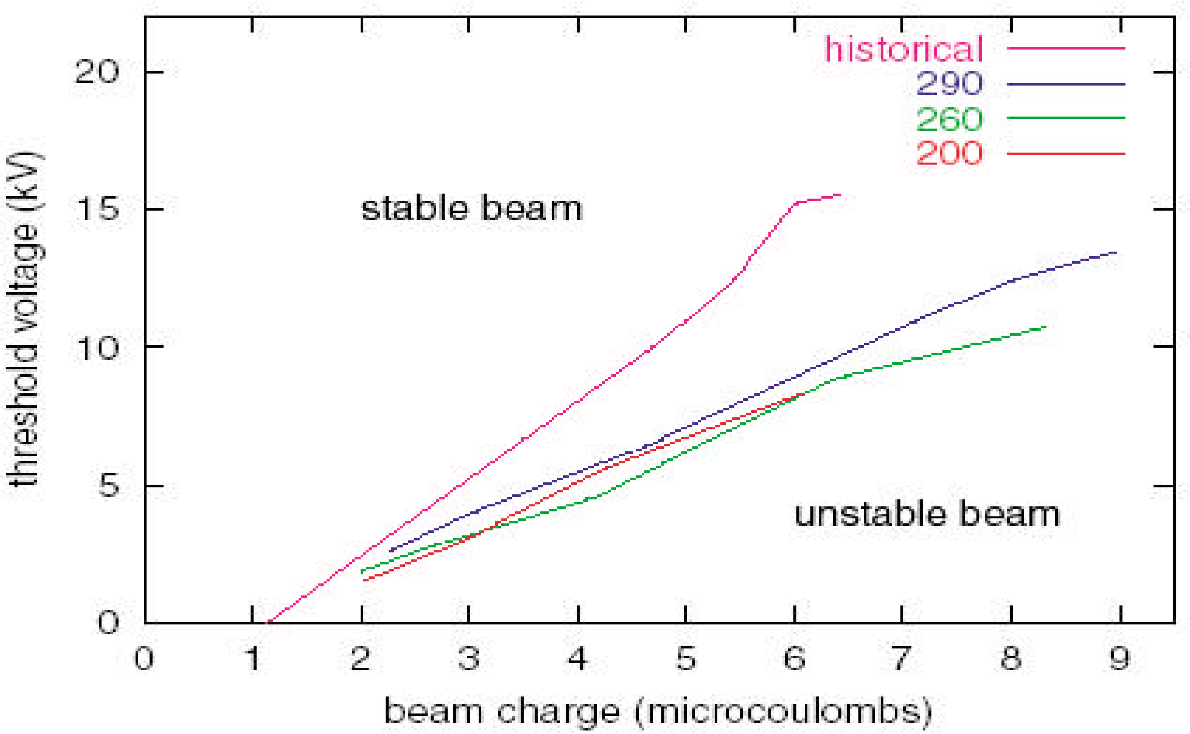
PSR Stability Scaling Law

Maximum number of stored protons scales linearly with RF Voltage.

Very weak dependence on bunch length (major theoretical challenge)

In earlier work, shortening bunches increased maximum stored protons

Significant conditioning after a month of operation



Simple picture of ep instability

Tune shift for cold coasting beam,
Keil and Zotter notation
simplified formula

$$\Delta Q_b = \Delta Q_{sc} + i\,\frac{Q_p^2}{2Q_b}\left(\frac{Q_e}{dQ_e}\right)$$

Q_p is the betatron tune for electron focusing alone

$$Q_p^2 = \frac{\left| e\, l_{e,inbeam} \right|}{2pe_0 g m_p w_0^2 a_p^2}$$

Tune spread in vicinity of carrier frequency

$$dQ_b = Q_e\,\frac{s\,(f\,)}{f} \propto \sqrt{I_b V_{rf}}$$

Dispersion relation

$$1 = \frac{\Delta Q_{thresh}(u)}{dQ_b}\int \frac{r\,(v)dv}{u + i0 - v}$$

For a cold beam the growth rate depends on beam current only through electron generation.

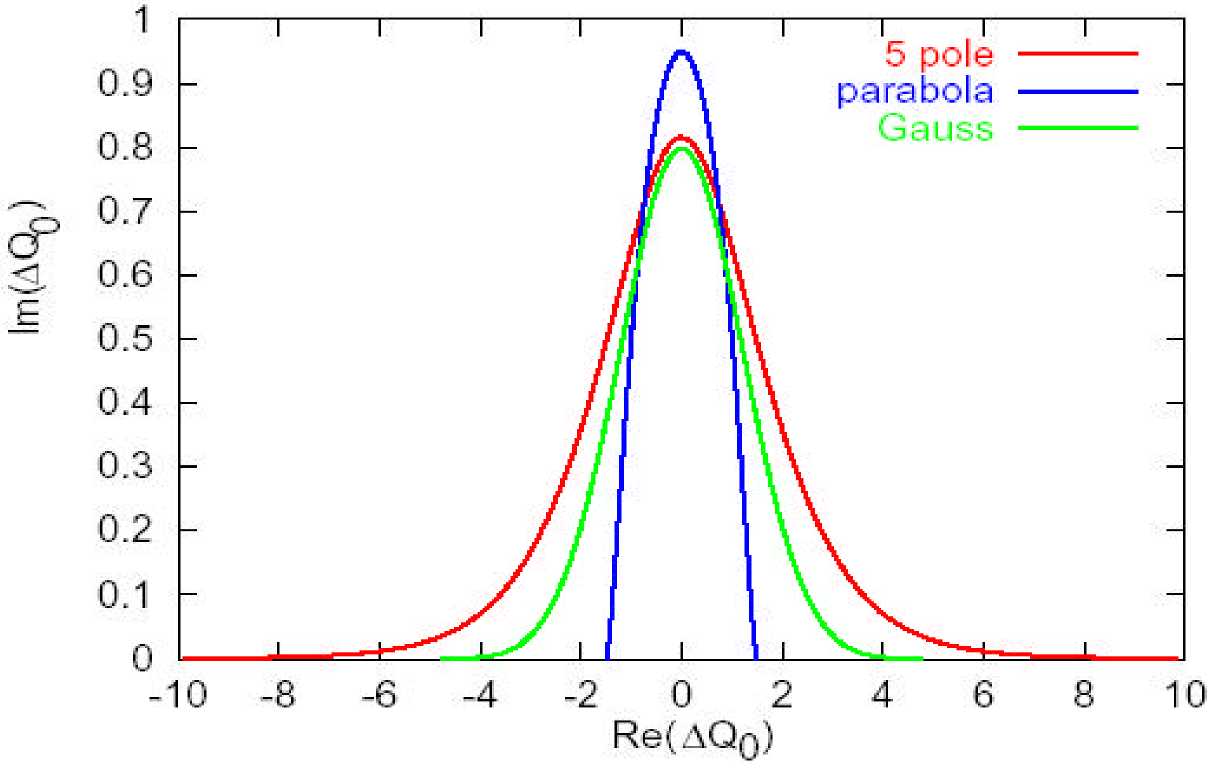
Effect of different momentum distributions

$$r(v) = C\prod_{j=1}^{5}(v_j^2 + v^2)^{-1}$$ for a 5 pole distribution.

stability diagrams for $s(v)=1$ Points below curves are stable.

$$\Delta Q_{sc} > \frac{Q_p^2}{2Q_b}\left(\frac{Q_e}{dQ_e}\right)$$

Tails of the tune distribution are important



Bunched Beam Eigenvalue Problem

For typical PSR conditions the bunch length is 40 electron oscillation periods.

Polynomial basis expansion techniques require at least 3000 by 3000 matrices.

Solution:

Approximate RF by a barrier cavity, yielding: 1) a rectangular bunch profile

2) momentum distribution independent of longitudinal position within bunch

Linearize the electron-proton force. Model electron frequency spread using a damped harmonic oscillator (convenience).

$$\frac{\partial Y(\phi,\upsilon,\theta)}{\partial\theta}+\upsilon\frac{\partial Y}{\partial\phi}-\frac{dU(\phi)}{d\phi}\frac{\partial Y}{\partial\upsilon}=i\Delta Q_{\mathrm{sc}}[Y(\phi,\upsilon,\theta)-\bar{Y}(\phi,\theta)]$$
$$+\,i\frac{Q_p^2 Q_e^2}{2Q_0\tilde{Q}}\int_0^{\phi}\bar{Y}(\phi',\theta)\sin(\tilde{Q}[\phi-\phi'])e^{-\alpha[\phi-\phi']}d\phi'$$

$$\rho(\upsilon)=\rho_0\prod_{j=1}^{M}\frac{1}{\upsilon^2+\alpha_j^2}$$

Get a matrix of dimension 40*M

Need a good desktop cpu

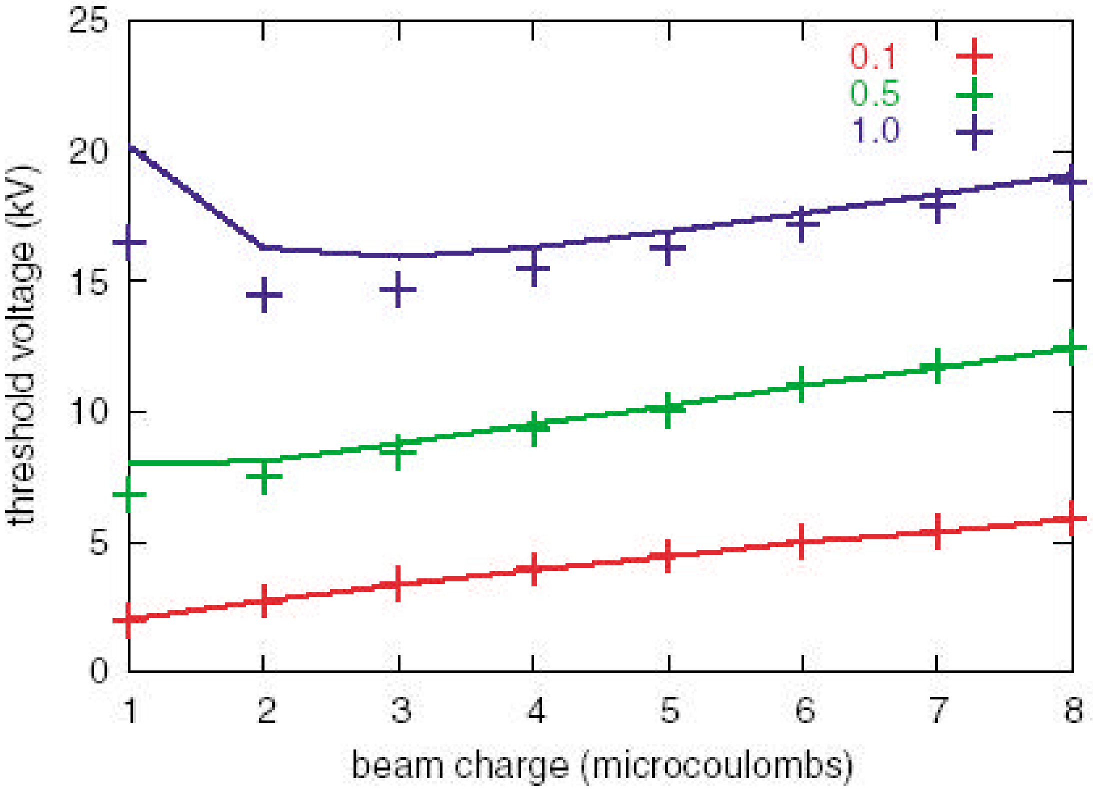
PSR stability threshold: 1st pass

PSR with varying amounts of electron line density (nC/m)

Crosses are from bunched beam eigenvalue problem with 5-pole distribution.

Lines are from coasting beam and 5-pole distribution.

Verifies coasting beam approximation.



PSR with finite momentum aperture

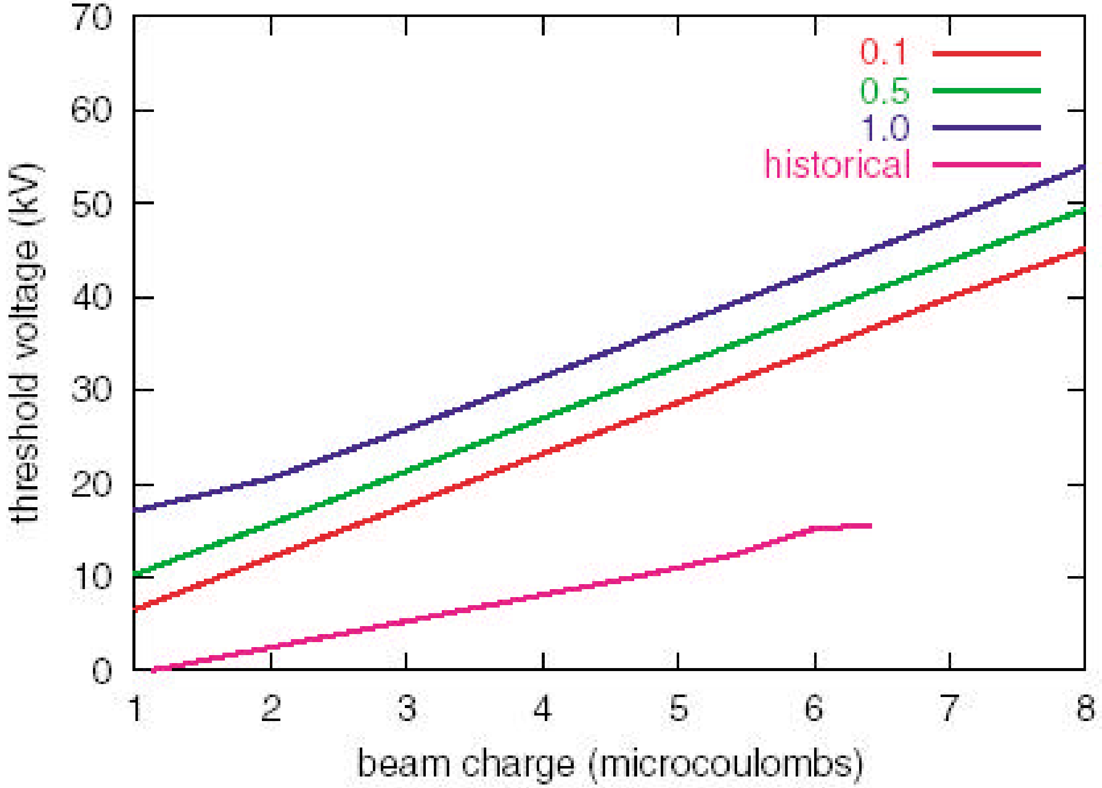
Used a parabolic momentum distribution and coasting beam dispersion relation.

Weak dependence on electron line density (nC/m)

Threshold dominated by large space charge tune shift.

Nominal PSR bunch length shown. Error is larger for shorter bunches.

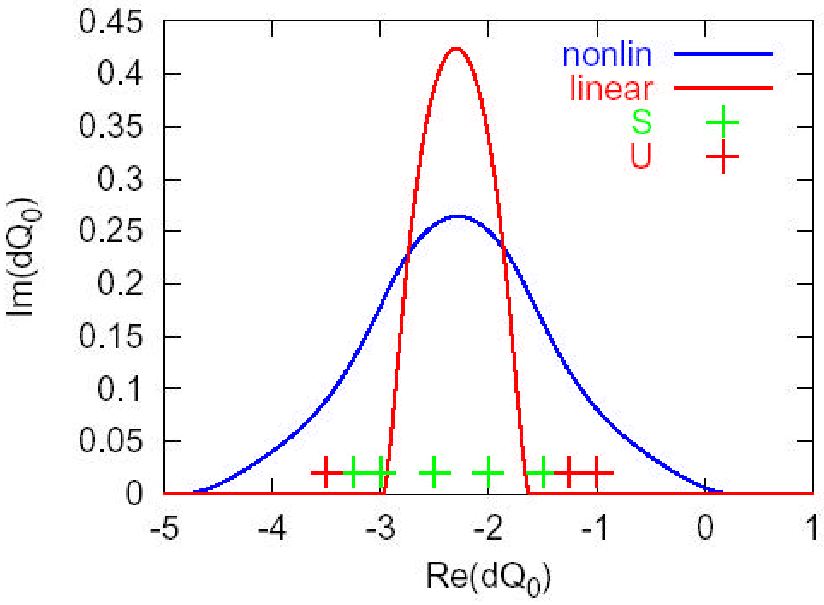
1 nC/m, Q_e / dQ_e =3, and cold beam gives 9 microsecond growth time



Nonlinear space charge effects remain an issue

Simple 1D analytic model (left) suggests that space charge tune spread from betatron amplitude can reduce the impact of space charge tune shift on the stability threshold. Simulations with 2D coasting beam (+) show a 30% effect.

PPPL code on right from PRSTAB 014401 shows significant damping from nonlinearity. Serious monetary implications.



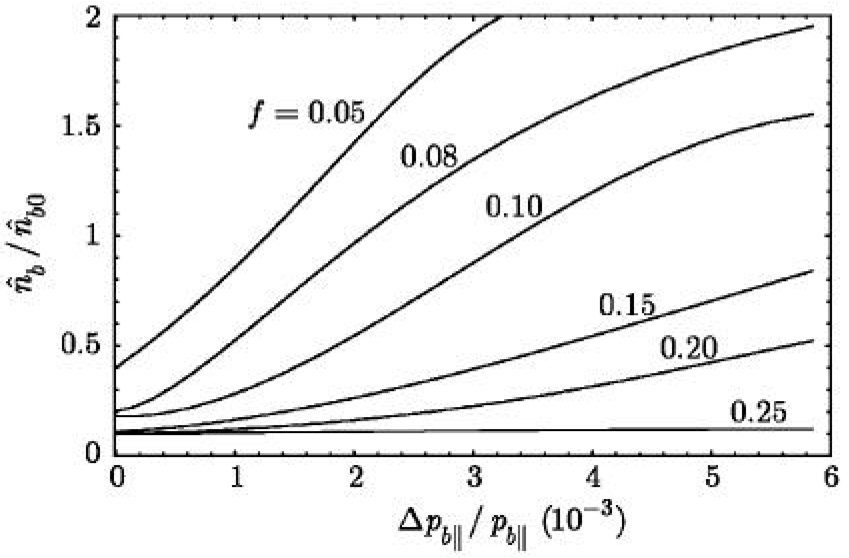


FIG. 3. Density threshold for the two-stream instability as a function of beam axial momentum spread for different values of fractional charge neutralization.

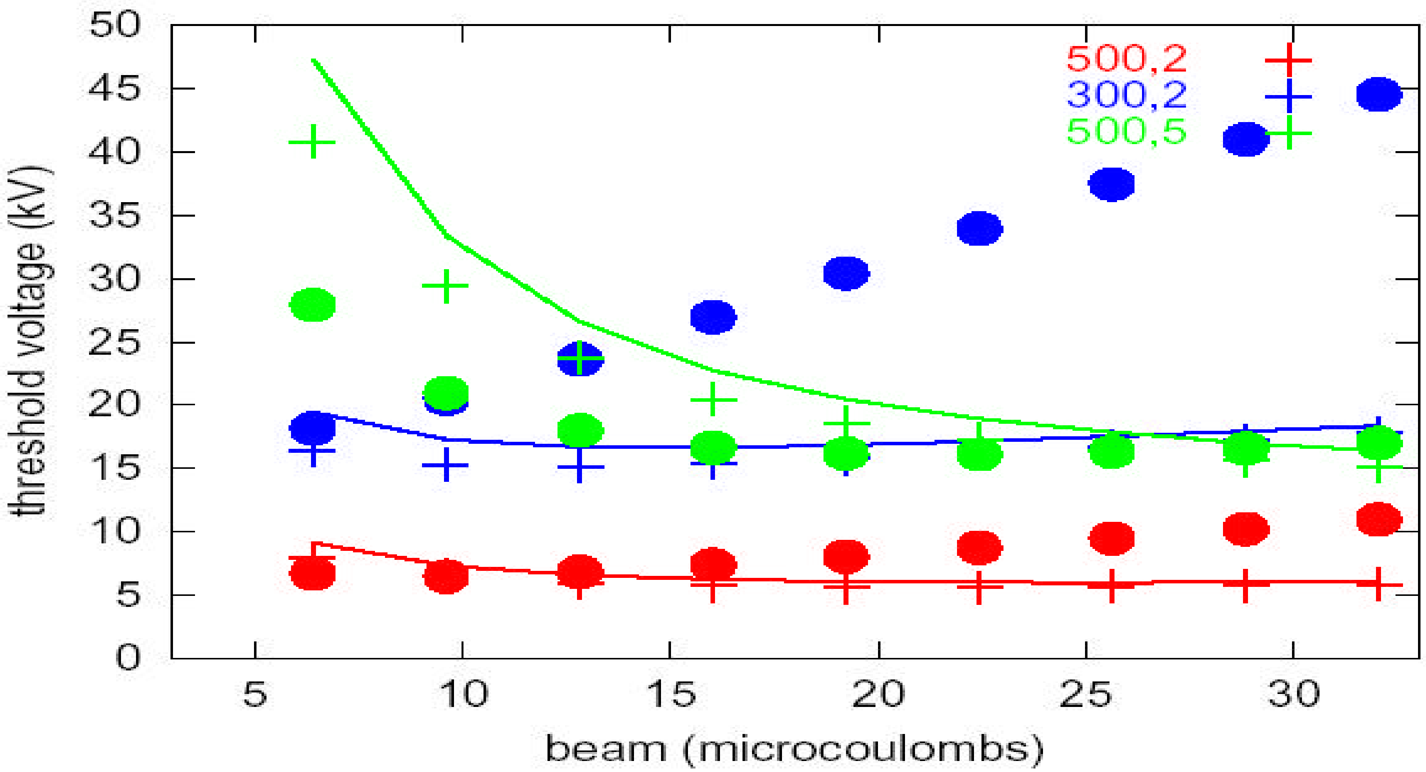
SNS stability threshold estimates: 1^{st} pass

rms bunch length is 500 ns (700 ns true), $l_e = 2$ and 5 nC/m

Took Gaussian beam cross section and thin electron cloud (same as PSR)

Lines are coasting beam 5-pole, crosses are BB eigenmode analysis, circles are coasting beam with parabolic momentum density, design voltage is 40 kV

5 nC/m is present only at high intensity

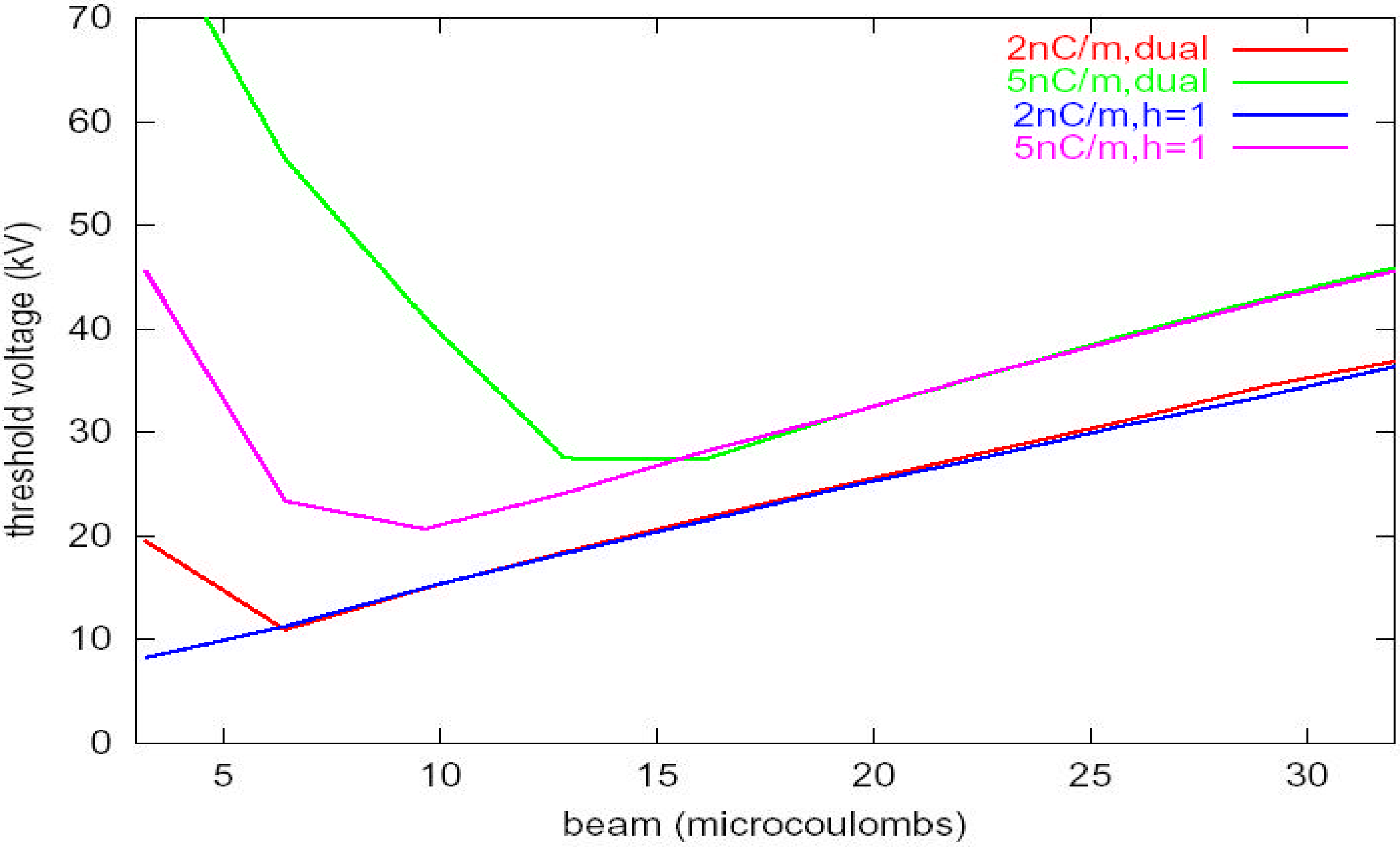


SNS stability thresholds 2nd pass

Used coasting beam estimates with peak current and momentum distributions from full RF simulation.

Took equal radii for proton beam and electron cloud.

Calculated for dual harmonic RF (h=1 and h=2) and for h=1 alone.

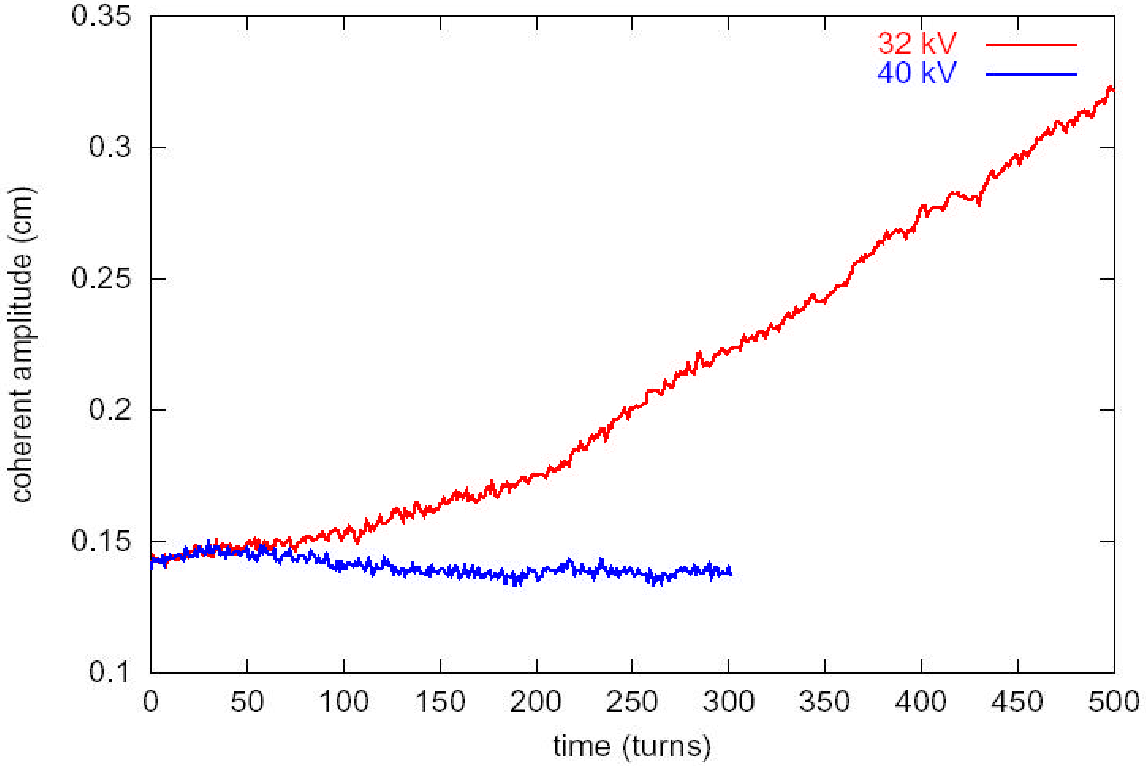


Simulations for SNS with 32 microcoulombs

SNS simulations for single harmonic RF with 2 nC/m. Same bunch length, peak current and rms momentum spread as RF design simulations.

No multipacting (transparent walls) or loss driven electron generation.

Coasting beam estimate is 37 kV.



Simulations for SNS with multipacting and loss driven e-

beam charge in mC

Most unstable bunch shown.

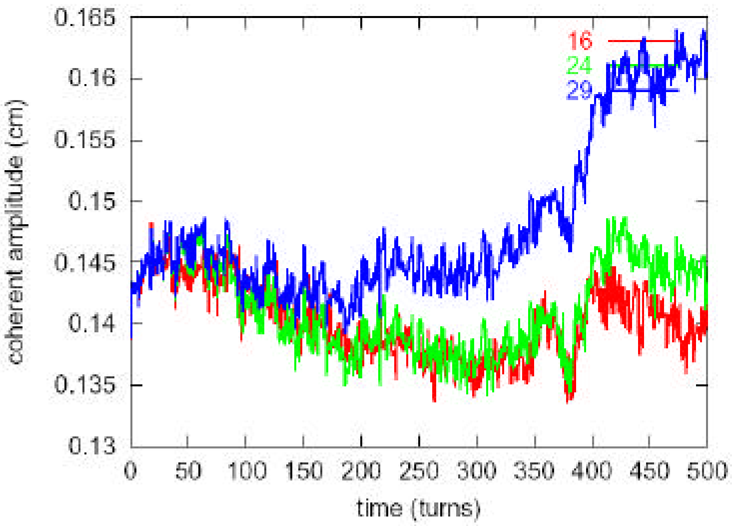
Transverse size at b_{avg}

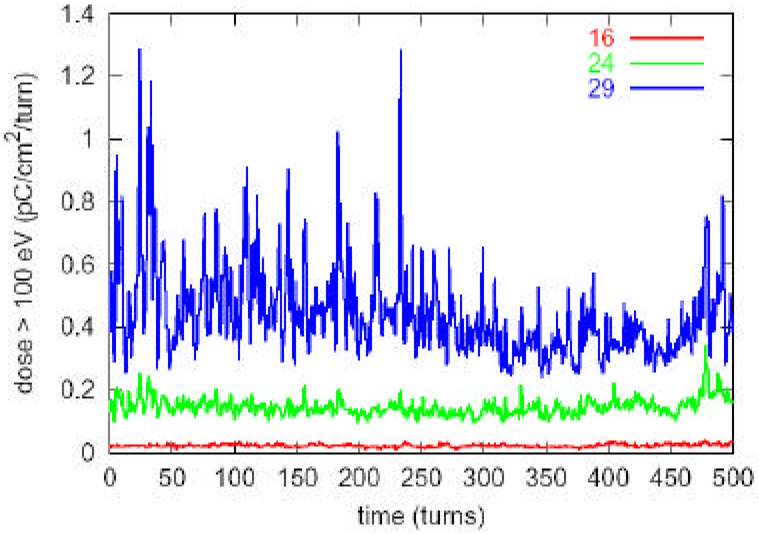
2 nC/m surviving gap

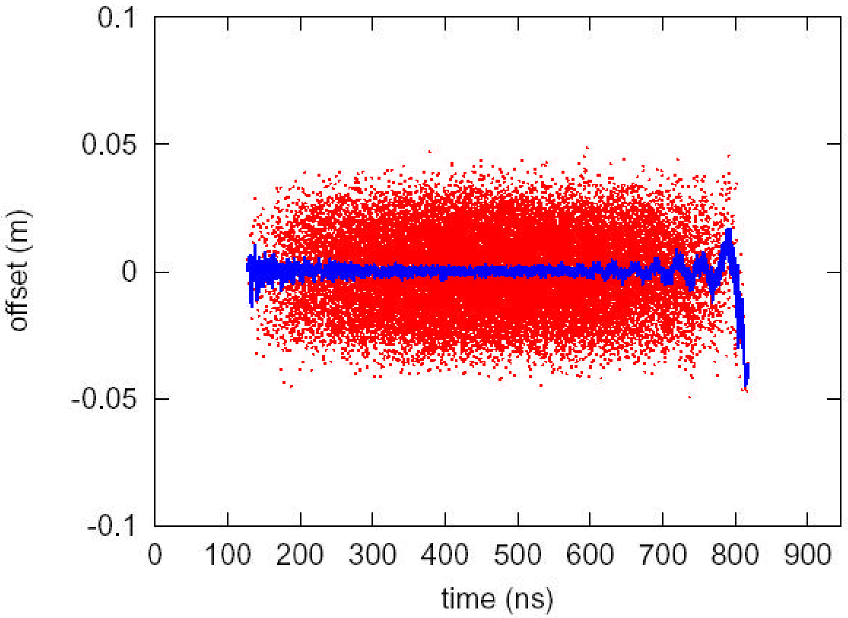
40 kV on h=1, 0 kV on h=2

Scrubbing has strong intensity dependence

Flash on tail is small here, but still fairly effective







Conclusions

Analytic estimates for SNS, based on equivalent rms quantities, predict stability for an electron line density of 2 nC/m. The threshold is around 5 nC/m.

Similar estimates for PSR give threshold voltages 3-4 times the observed values

SNS estimates using peak beam current and simulated momentum distributions give threshold voltages around 40 kV, the design value.

The electron flux at the wall with energy > 100 eV is around 10 pC/cm^2/turn with 2 nC/m line density

Taking the 60 Hz rep rate, 10 pC/cm^2/turn, and 400 turns/cycle gives

0.14 C/cm^2/week

0.1 C/cm^2 reduces the peak SEY below 1.8 which gives no more than 1 nC/m of electrons surviving the gap.

Simulations with loss generated electrons show that the electron burst at the tail destabilizes the beam. This may reduce the intensity threshold but scrubbing will reduce the SEY. Stability at 2 MW should be obtained within a few weeks.

The weak dependence on bunch length for the PSR stability threshold is still unresolved. The calculated intensity thresholds are smaller than the experimental values. Linear threshold estimates for SNS should be conservative.

Electron Cloud Generation

Primary electrons are generated via losses and collisions with gas

Loss created electrons at the pipe wall produce many secondaries

Model loss rate proportional to instantaneous current

Along with secondary emission there is also the possibility of reflection

$$R = R_0 \exp(-E / E_{char})$$

$$SEY_t(E) = SEY_{\max} \frac{s(E / E_{\max})}{s - 1 + (E / E_{\max})^s}$$

$$SEY = R + SEY_t$$

Reflection can be elastic or rediffused

For true secondaries

$$P(E) \propto \frac{(E / E_r)}{(1 + (E / E_r)^2)^2}$$