Simulation of the electron-cloud effect in the Proton Storage Ring PSR and Spallation Neutron Source SNS

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“POSINST” Simulation code features

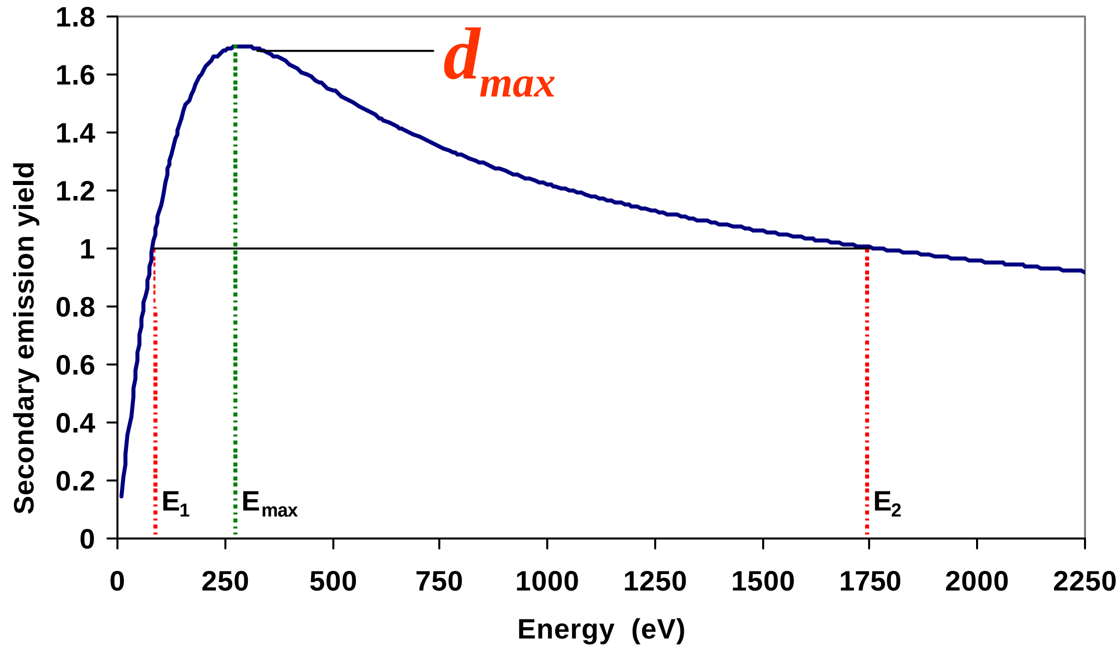
single or multi-bunch passages, short or long bunches, and effective bunch profile

the electron cloud is dynamically generated from:

- proton losses: important for PSR and SNS
- secondary electron yield (SEY), detailed model included
- residual gas ionization, (switched OFF for these simulation).
- photoelectron emission LHC

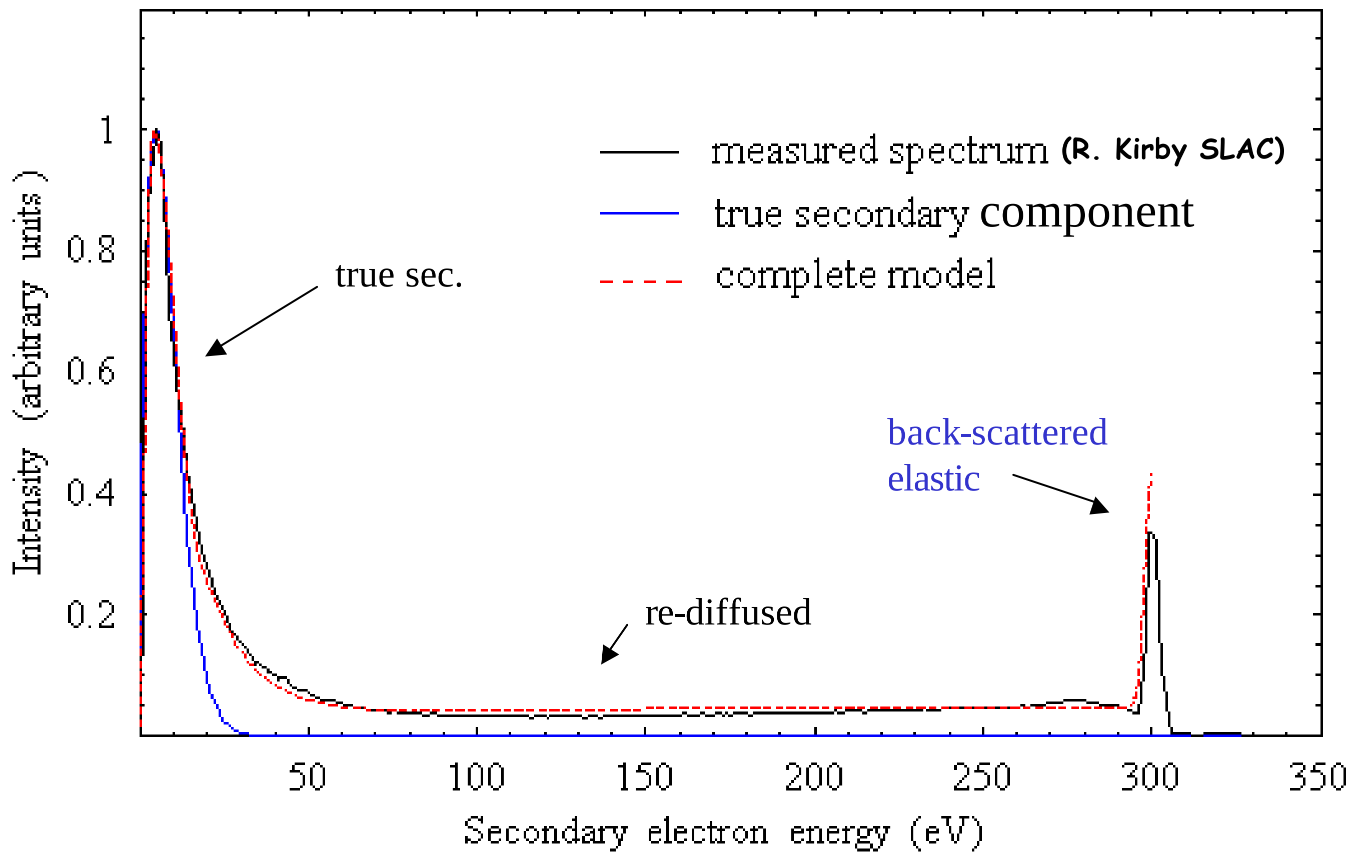
- field-free region, or dipole field region
- bunch divided longitudinally into N_k kicks (typ. 5000)
- 3D electron kinematics
- 2D (purely transverse) electron space-charge effects
- 2D (purely transverse) beam-electron forces
- round or elliptical vacuum chamber geometry, with a possible antechamber
- perfect-conductor BCs (surface charges included)

Secondary electron yield (SEY)



Secondary electron yield as a function of the incident electronenergy, universal curve for most of the accelerator technical surface materials. When specified, we set the SEY at low energy ?(0) ~ 0.5, or reflected component of 50%.

Secondary emitted-electrons energy spectrum model



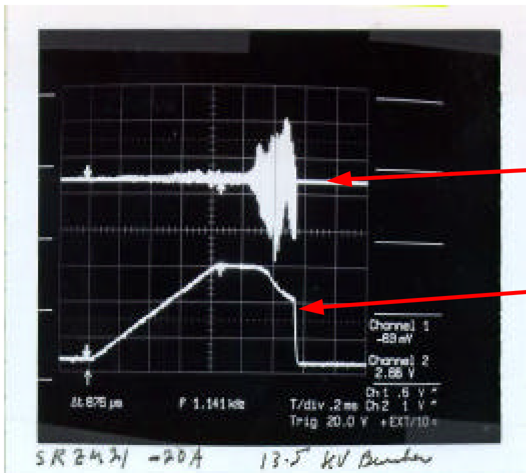
PSR recent simulations: benchmarking with experimental data

PSR	Symbol	params
beam energy	*E, GeV*	1.735
dipole field	*B, T*	1.2
ring circumference	*C, m*	90
bunch population, ppb	N_b	5×10^{13}
total bunch length	*bl, nsec (m)*	~250 (64)
revolution period	?, *nsec*	350
transverse bunch size	r_x, r_y *mm*	10
beam pipe radius *round*	r_w, *mm*	50 x 50
proton losses rate	plr*	4×10^{-6}
peak sec. electron yield stainless steel	??max	~2.0
yield - electrons per incident proton	Y_{ep}	100

used actual longitudinal bunch profile

*proton losses = proton loss per proton per turn

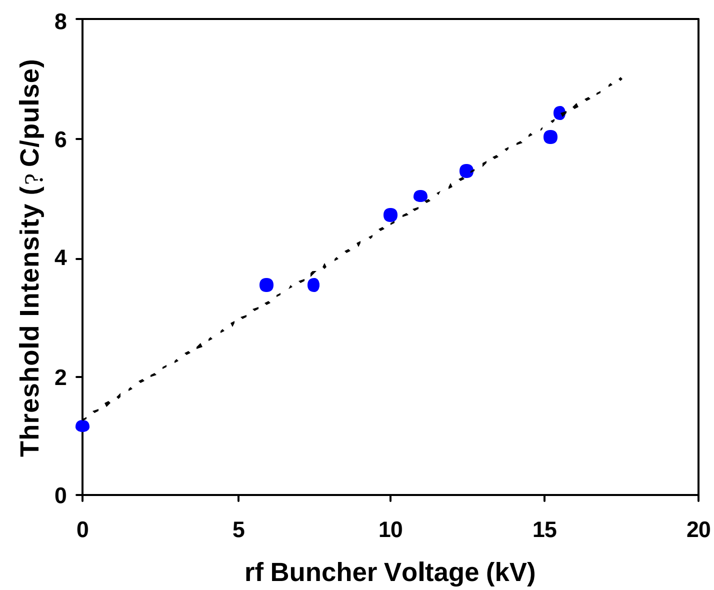
Well Established PSR Instability Characteristics
(R. Macek Courtesy)



Instability Signals

BPM ? V signal

CM42 (4.2 ? C) (Circulating Beam Current)



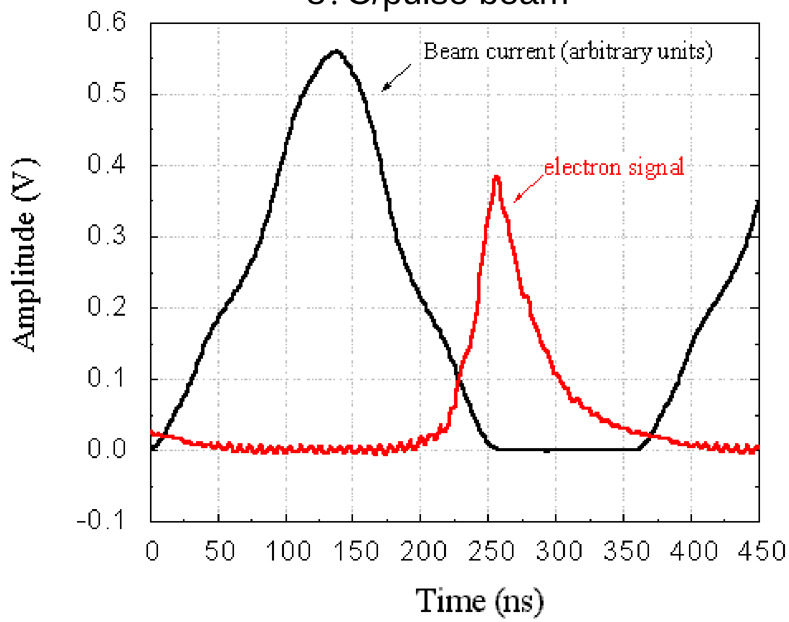
- **Growth time ~ 75 ? s or ~200 turns**
- **High frequency ~ 70 – 200 MHz**
- **Controlled primarily by rf buncher voltage**

Bk86, p98

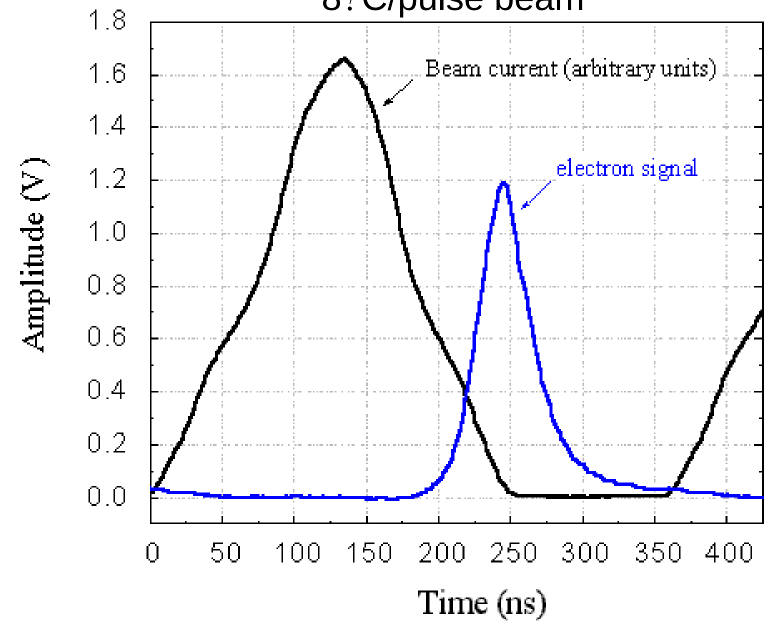
Electron Detector Signals at PSR (R. Macek courtesy)

- **ED02X located just <u>after stripping foil</u> in section 0, and ED42Y in straight portion of section 4**

ED02X electron detector signal
8?C/pulse beam

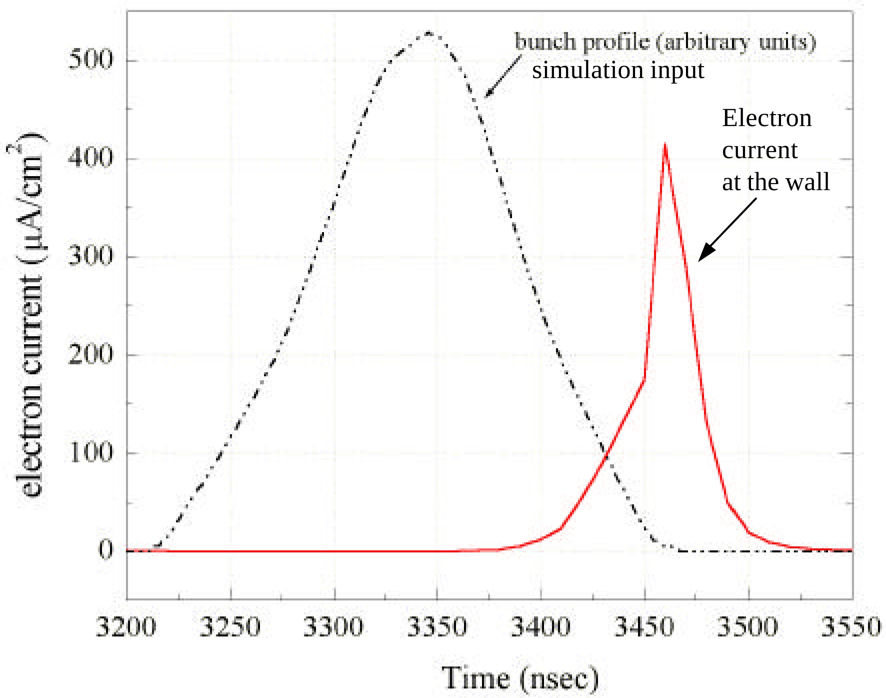


ED42Y electron detector signal
8?C/pulse beam



The electron current in *A/cm²* is obtained dividing the voltage signal by a factor ~2.75x10³.

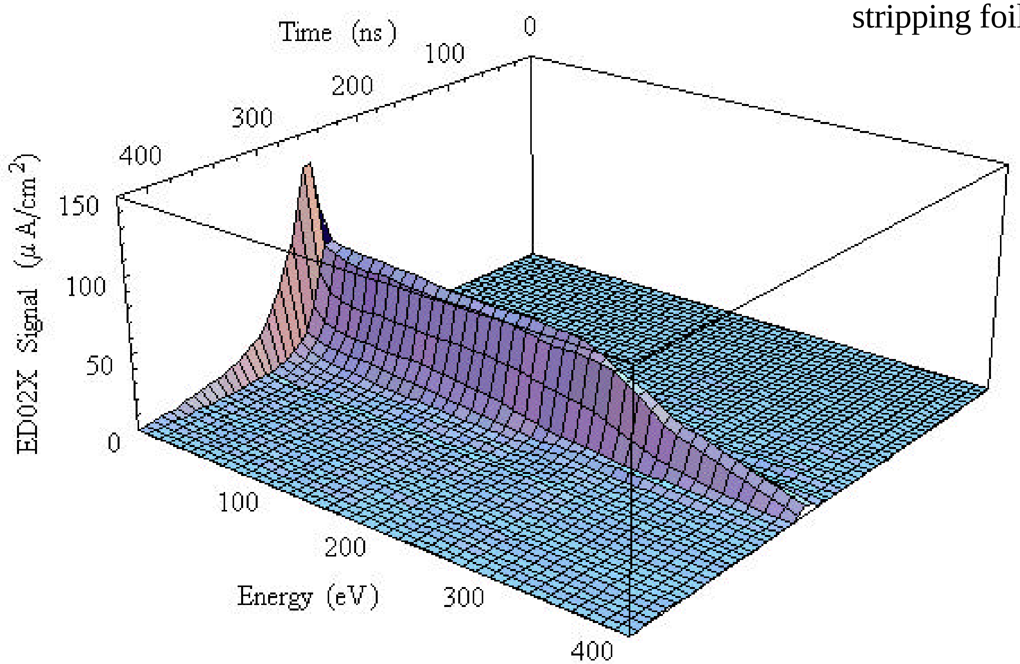
Simulated electron wall current



Simulated electron wall current in ? *A/cm*^{2}, for a stainless steel chamber surface assuming $?_{max}$=2.05, E_{max}=300 *eV.* Emitted-secondary electron model: reflected and rediffused electrons were not included in this simulation.

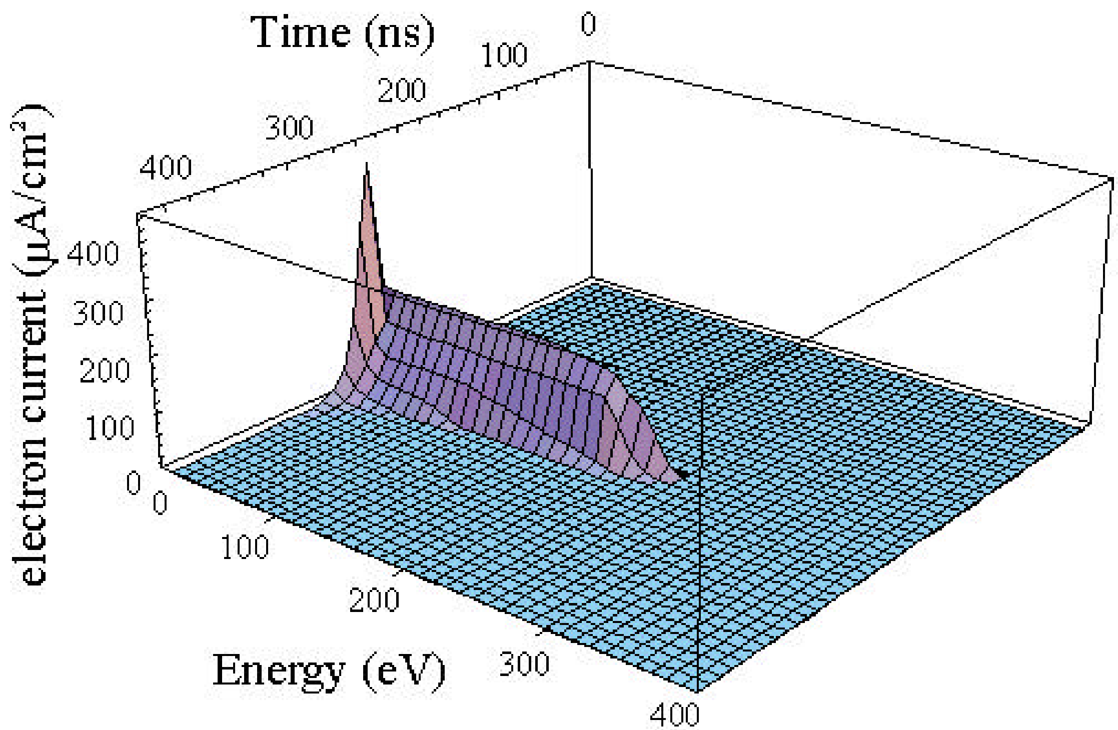
Electron energy cumulative spectrum (3D profile)

(ED02X detector, near stripping foil)



ED02X e^- detector <u>near stripping foil</u>, measured cumulative energy spectrum of the electrons hitting the wall as a function of time. The origin of time corresponds to the passage of the head of the bunch. Electron current in micro*A/cm*^{2} *.*

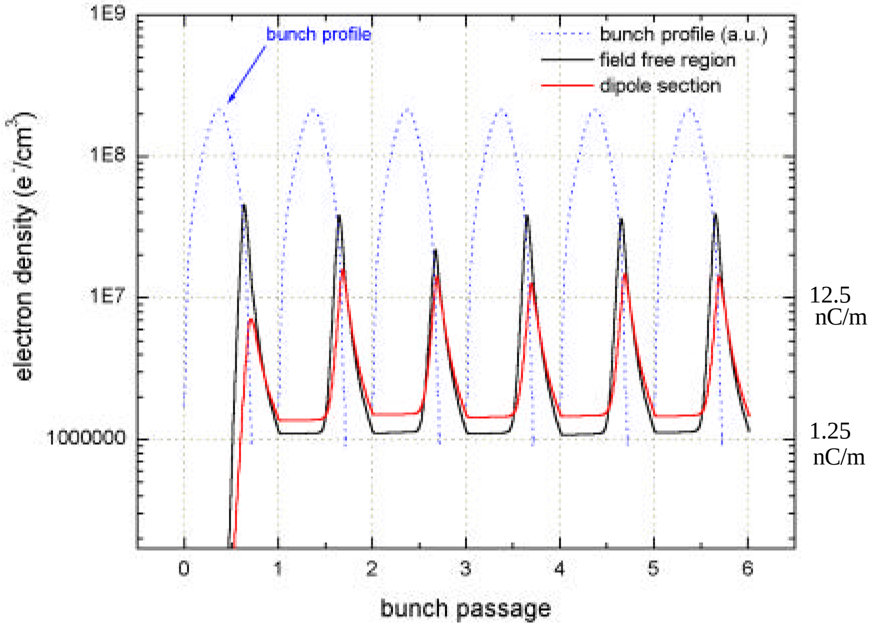
Simulated cumulative energy spectrum

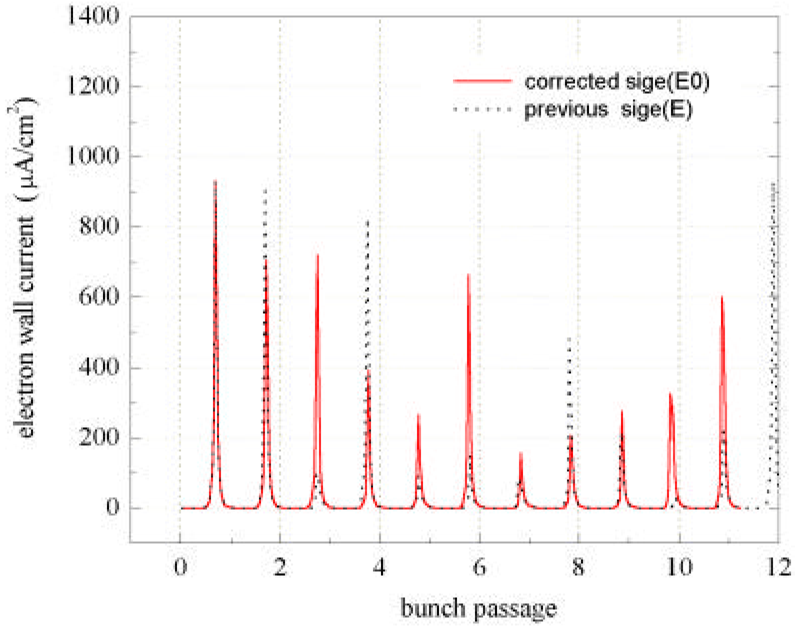


Simplified detector geometry

Simulated cumulative energy spectrum of the electrons hitting the wall of a stainless steel field-free region, in ?A/cm^2, assuming ?$_{max}$=2.05, E_{max}=300 *eV.* Vacuum pressure turn off in simulations. Emitted-secondary electron model: reflected and rediffused electrons were not included in this simulation.

PSR simulations: e^- density and e^- wall current



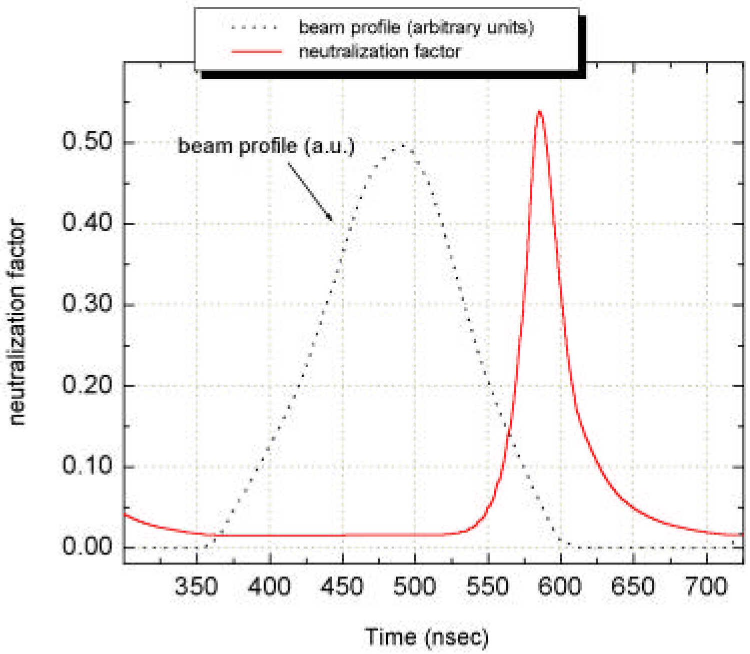


Simulated electron density in the PSR, bunch population 5 10^{13} ppb, proton losses 4 10^{-6} proton loss per proton per turn, circumference 90 meters. Emitted-secondary electron energy spectrum model includes true secondary, rediffused and backscattered electrons (Hilleret fit, Cu).

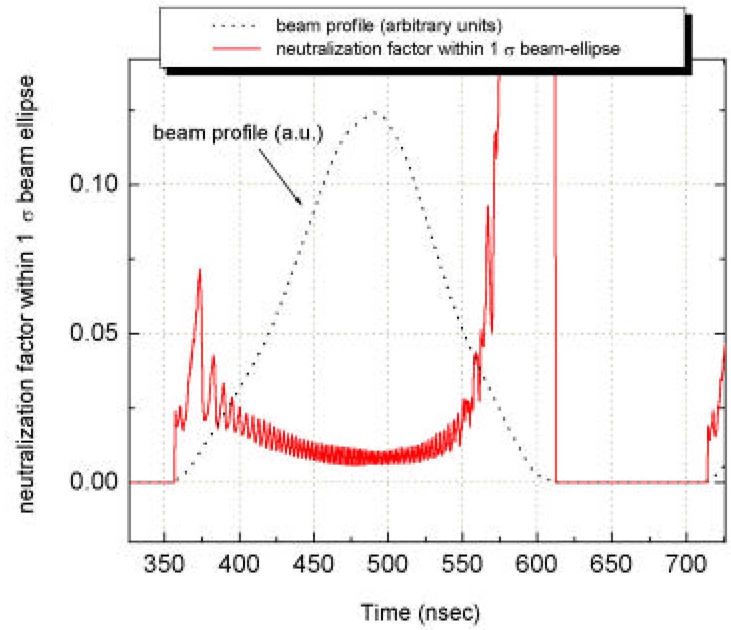
Simulated Electron current at the wall, averaged over the beam pipe circumference, in a PSR field free region, with bunch population 5 10^{13} ppb. Eemitted-secondary electron energy spectrum model includes true secondary, rediffused and backscattered electrons (Hilleret fit, Cu). Now current increases consistently.

Neutralization factor e^-/p

within vacuum pipe

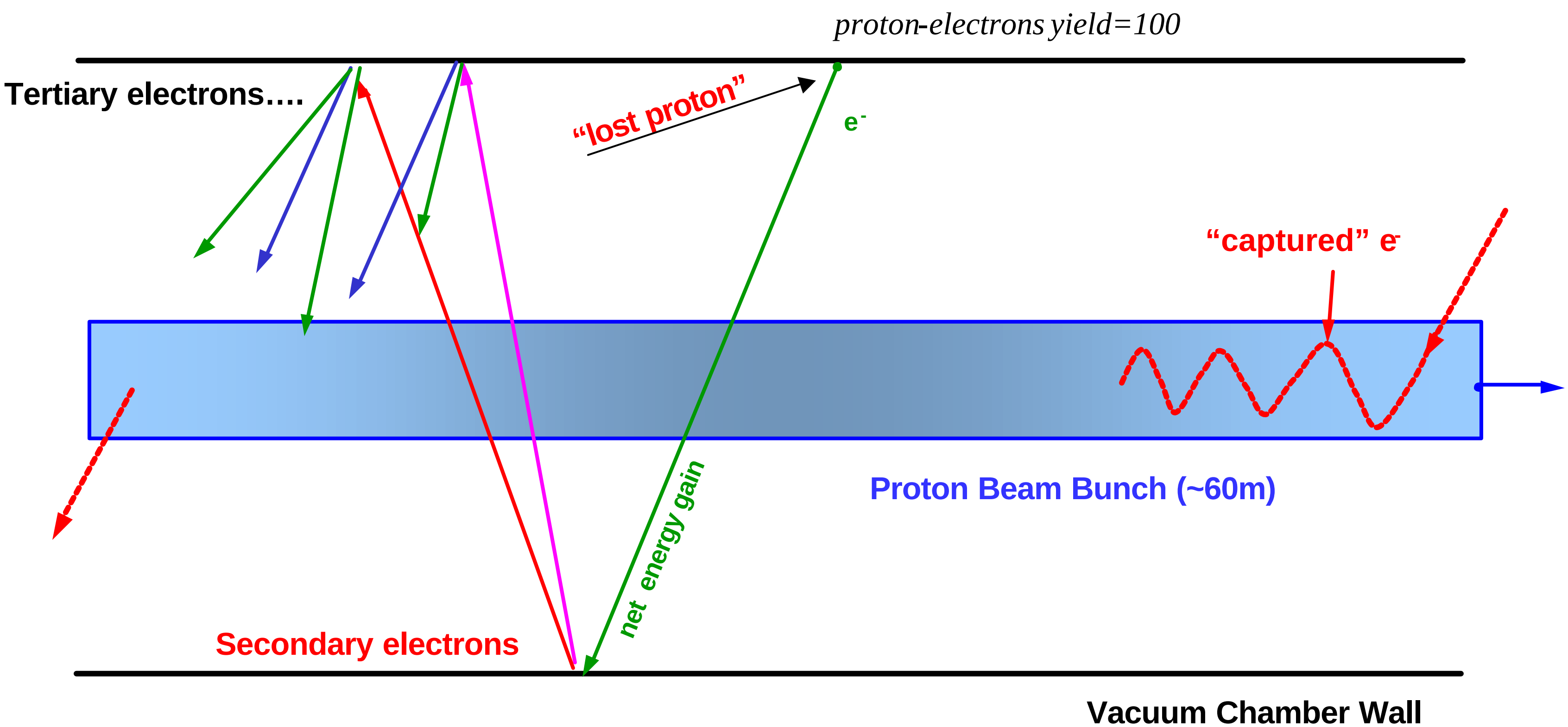


within 1 ? beam-ellipse



Simulated neutralization factor, ratio e^-/p^+, in an PSR field free region. The fractional neutralization within the 1 ? ?beam-ellipse (right side), reaches values > 5% at the tail of the bunch. The ripples give an indication of the average oscillation frequency of the electrons in the proton beam well potential. Emitted-secondary electron energy spectrum model includes true secondary, rediffused and backscattered electrons (Hilleret fit, Cu).

Electron multiplication mechanism (PSR-SNS)

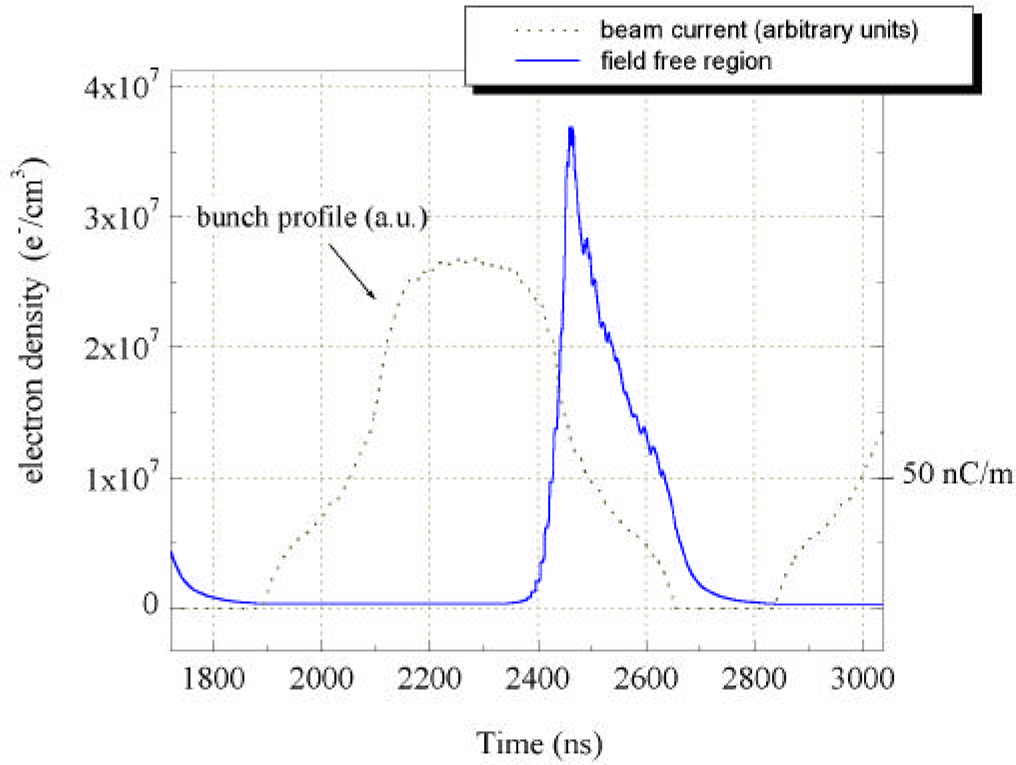


SNS	Symbol	params
beam kinetic energy	*E, GeV*	1.0
dipole field	*B, T*	0.78
ring circumference	*C, m*	248
number of particles per bunch	N_b	2.048 x10^{14}
total bunch length (> 1A)	*bl, nsec*	~760
revolution period	? , *nsec*	945
transverse bunch size, *unif. distribution*	r_x, r_y cm	2.8
beam pipe radius *round*	r_w , *cm*	10 x 10
proton losses rate (0.01%)	plr*	1.1 x10^{-7}
peak secondary electron yield	??max	~2.0
electron per incident proton yield	Y_{ep}	100

used actual longitudinal bunch profile

Note: *proton losses ~ 0.01% in 1000 turns, plr = proton loss per proton per turn (in PSR is plr = 4 X10^{-6})

SNS simulations: e^- density and e^- wall current

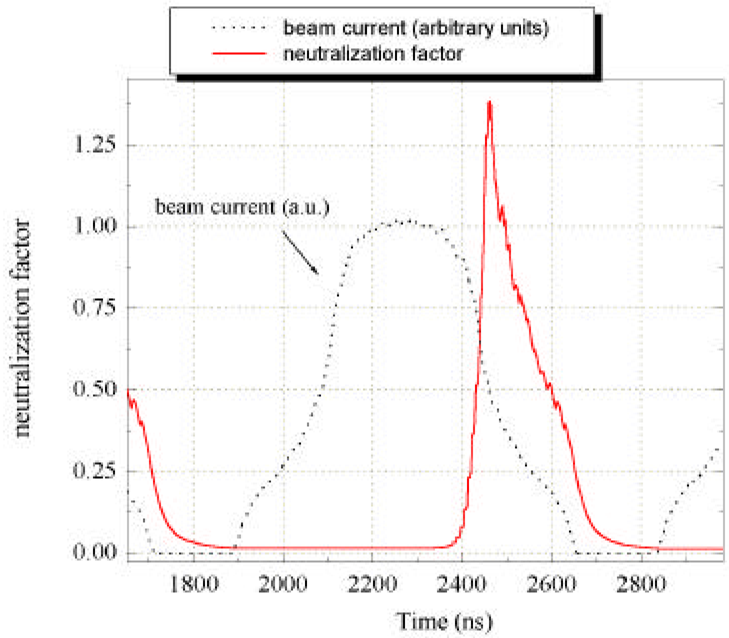


Simulated electron density in a SNS field free region. Secondary yield ~2.

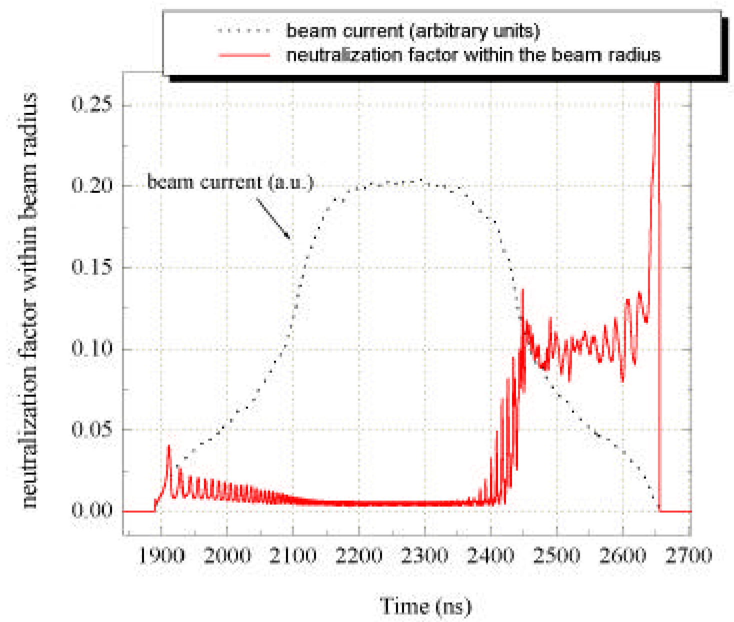
Note: in all the following SNS simulation results we have included the complete model for the emitted-secondary electron energy spectrum with true secondary, rediffused and reflected electrons (Hilleret fit, Cu), see slide no. 5.

Neutralization factor e^-/p

within vacuum pipe



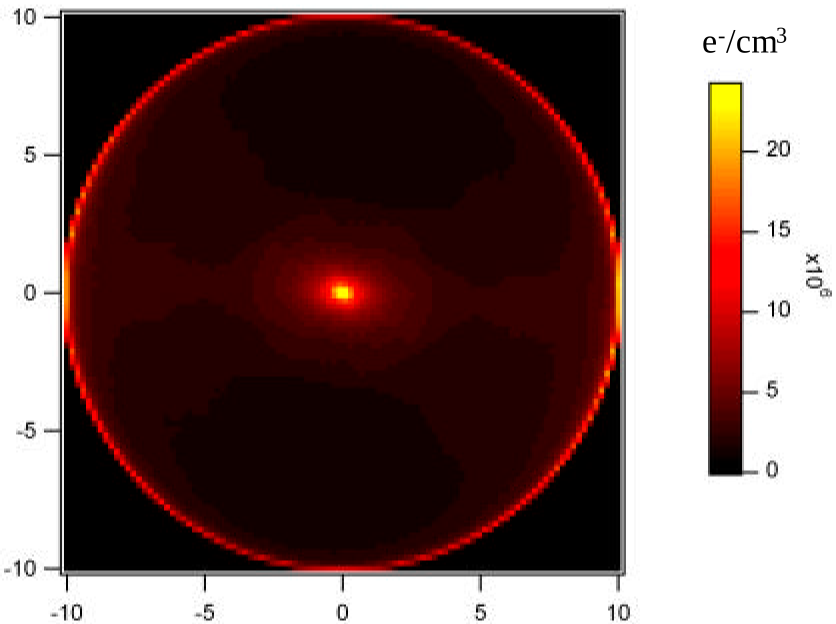
within beam radius

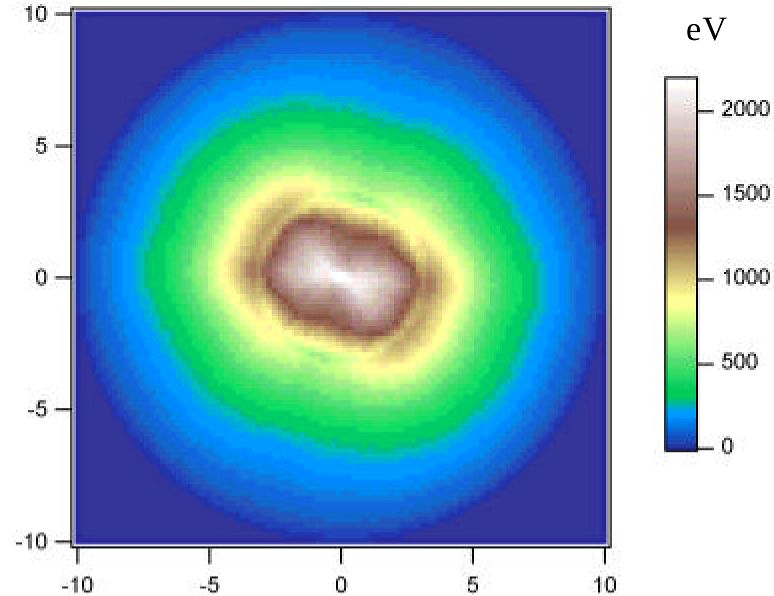


tail particles tune shift: $dQ_{sc} \sim 0.2$ $dQ_{ec} \sim -0.4$

Neutralization factor, ratio e^-/p^+, in an SNS field free region. The fractional neutralization within the beam (right side), reaches values > 10 % at the tail of the bunch. The ripples give an indication of the average oscillation frequency of the electrons in the proton beam well potential.

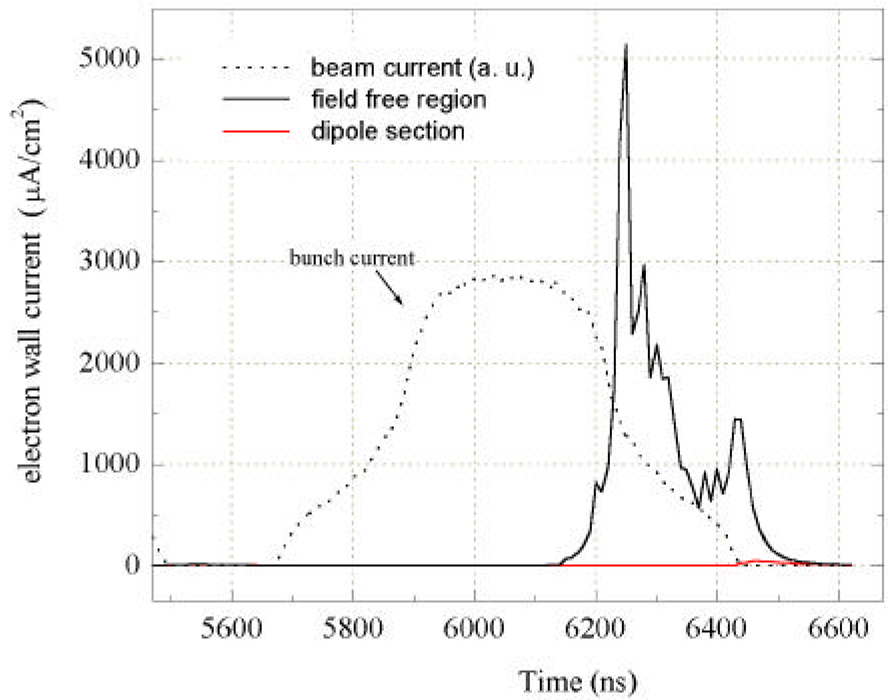
time-averaged electron distribution in a field free region





(Left) histogram of the electron distribution, averaged over the all bunch passages, in an SNS field free region. In units of 10^6 e^-/cm^3. (Right) histogram of the electron energy averaged over the all bunch passages.

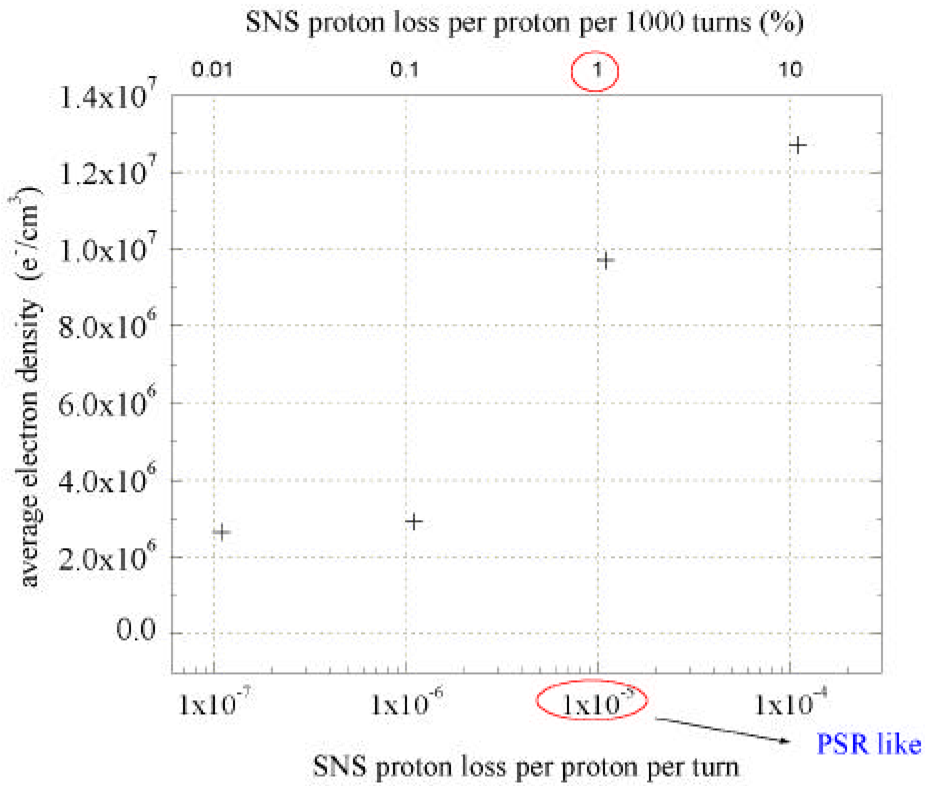
electron wall current (contd')



Note: PSR peak ~ 400 ?A/cm²

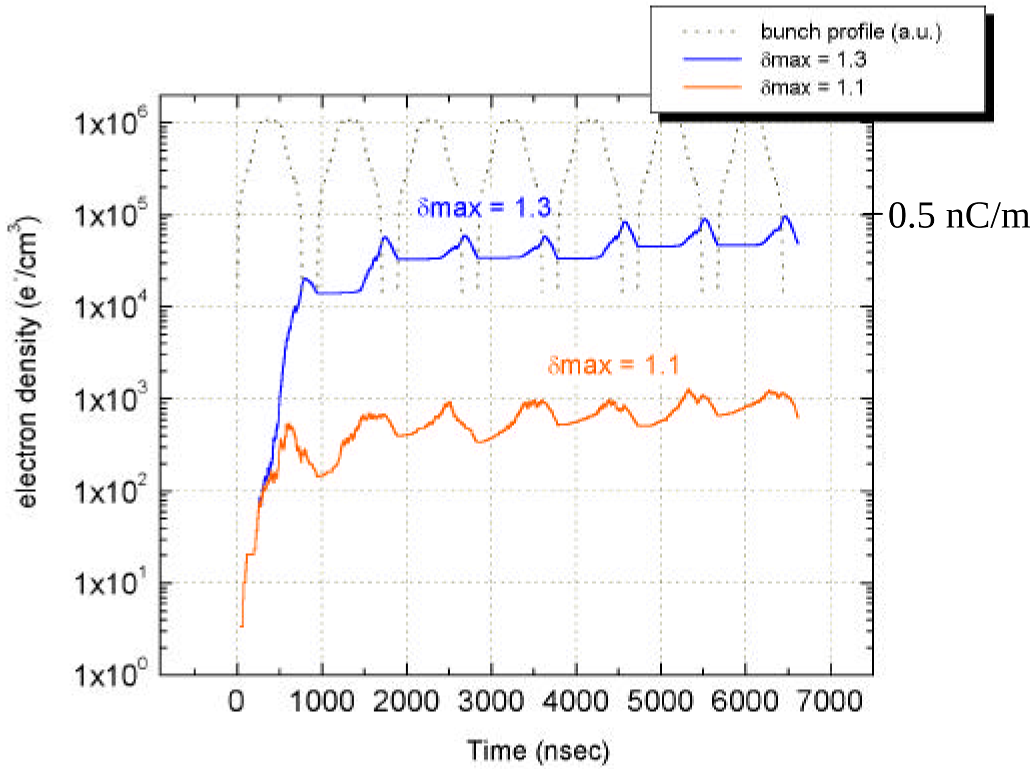
Electron current at the wall, averaged over the beam pipe circumference. The electron wall current depends strongly on the bunch current profile. In particular, rote the presence of the two peaks due to the particular bunch current profile. Secondary electron yield ~2.

Comparing different proton losses: e⁻ density



SNS: Average electron density (over whole run). SNS proton losses are expected to be in the order of 10^{-7} protons loss per proton per turn, to be compared with the typical proton loss for PSR in the order of 10^{-5}. Secondary electron yield ?max~2.

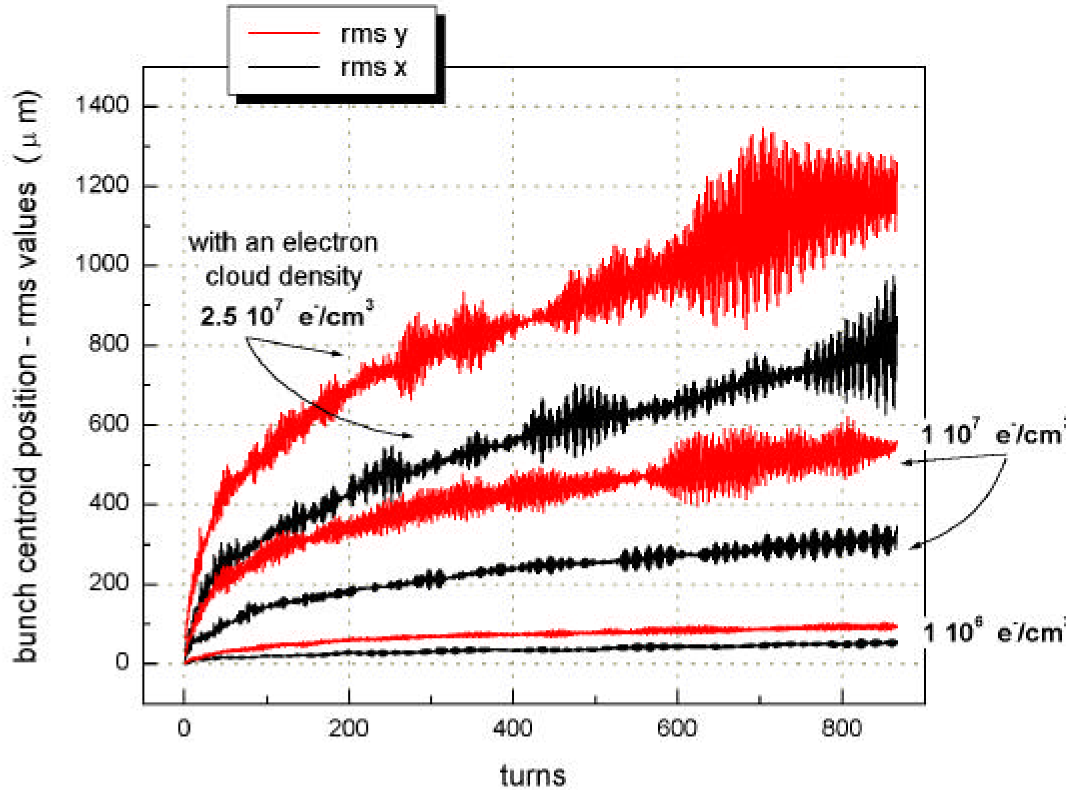
variation of the secondary e- yield SEY



Simulated electron density in the SNS, first bunch passages, bunch population 2.048 10^{14}ppb. Varying the secondary electron yield 1.1 < ?max < 2. All simulation are for proton losses ploss=1.1 10^{-7} proton loss per proton per turn, or ~0.01% loss in 1000 turn. Problem: in the particular case of SNS simulations the number of macroparticles reaches soon very high values due to high electron multiplication. Limit in the computations. To increase code performances more work is needed to implementing, space charge calculation ..

Future development of the electron-cloud studies.
Simulations of the single bunch instability (strong-head tail) preliminary tested for "short" bunches, for the Next Linear Collider NLC.

NLC Damping Ring: Y.H. Cai head-tail simulation code preliminary results



Evolution turn by turn of the bunch centroid position (in ?m), rms values of all slices, for different electron cloud densities and zero chromaticity. NLC actual bunch size ?$_x$= 41 ?m, ?$_y$= 5 ?m, synchrotron tune= 0.0035. In figure plotted 3 synchrotron oscillations.

Conclusions and future work

- Detailed model of the secondary electron emission included in the simulation code.
- simulated electron-cloud density and current at the wall for PSR, overall good qualitative agreement with measurements
- Simulation of the electron-cloud features for the SNS

  peak electron density > 10^7 e^-/cm^3 (50 nC/m), neutralization factor > 10%

  for different proton losses and secondary yield*
- Single bunch instability code simulations for short bunches - NLC

Future plans:

*Improve space charge calculations to improve code performances in simulating SNS

- Implement single-bunch head-tail instability code
- parallelization of the codes