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

Mauro Pivi - Miguel A. Furman  
LBNL

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We are particularly grateful to our colleagues of the PSR Instability Studies Program for many stimulating discussions, M. Blaskiewicz, K. Harkay, R. Davidson, H. Qin, P. Channell, T. S. Wang.

We are especially grateful to R. Macek for discussions and for providing us the experimental data.

Thanks to Frank Zimmermann, Noel Hilleret, J. Wei, Andrzej Wolski, Sam Heifets, Tor Raubenheimer, Robert Kirby, A. Alexandrov, V. Danilov.



# “POSINST” Simulation code features

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

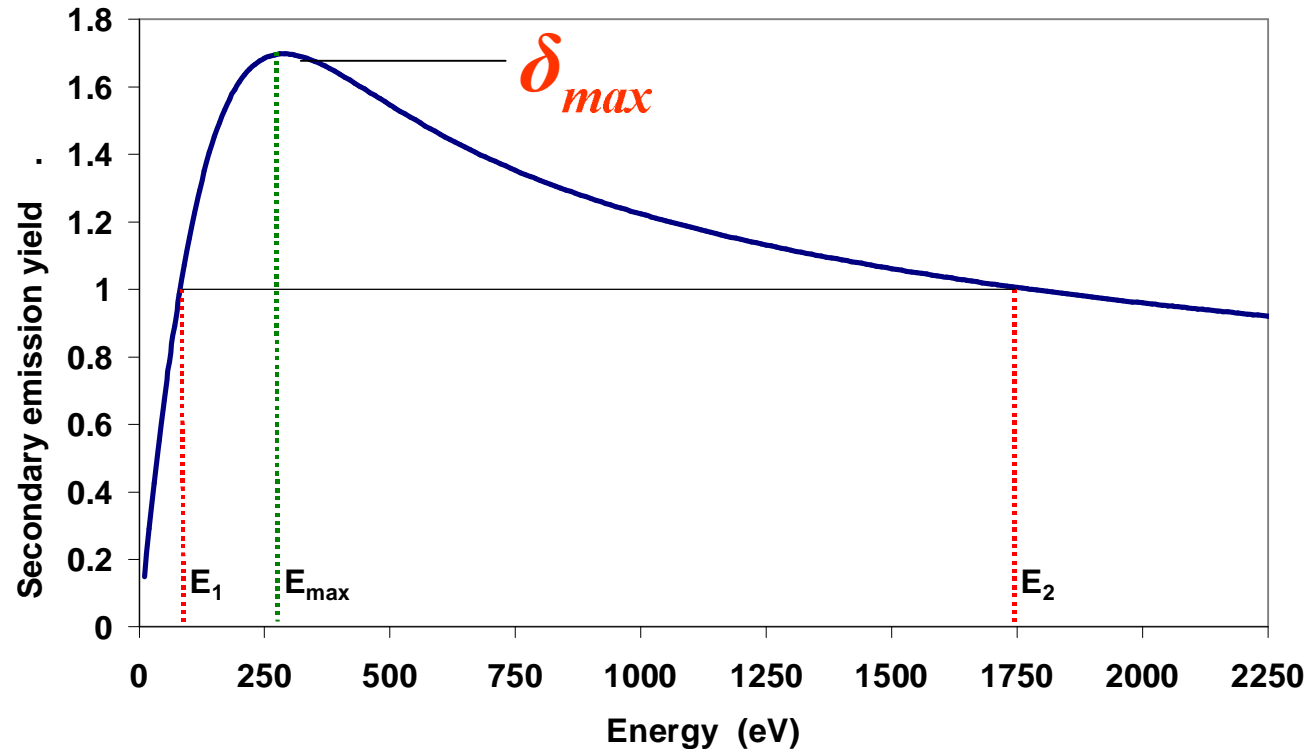
the electron cloud is dynamically generated from:

- 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)



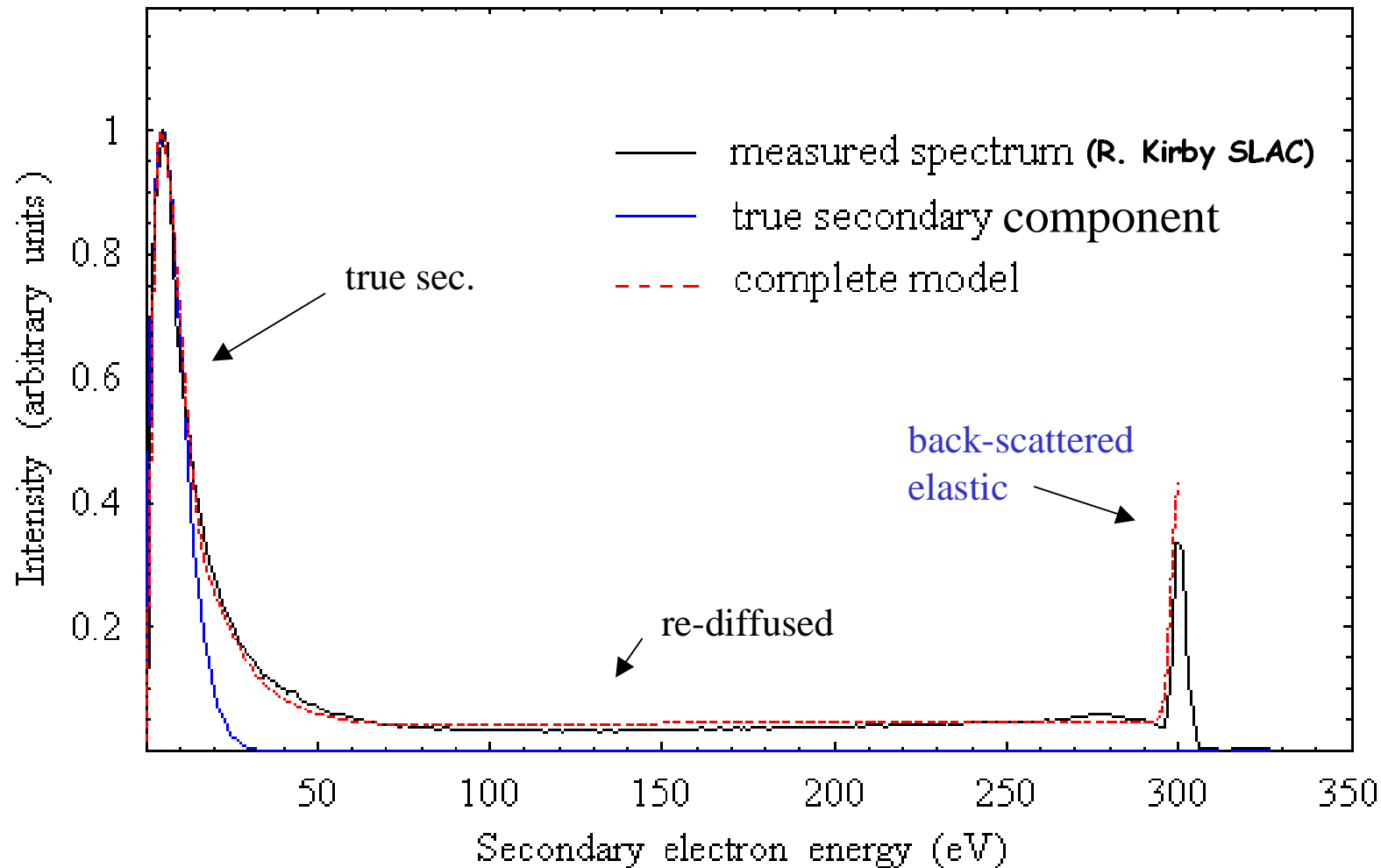
# Secondary electron yield (SEY)

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

# Secondary emitted-electrons energy spectrum model



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# PSR recent simulations: benchmarking with experimental data



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# PSR

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## Symbol

## params

beam energy	$E, GeV$	1.735
dipole field	$B, T$	1.2
ring circumference	$C, m$	90
bunch population, ppb	$N_b$	$5 \times 10^{13}$
total bunch length	$bl, nsec (m)$	~250 (64)
revolution period	$T, nsec$	350
transverse bunch size	$r_x, r_y mm$	10
beam pipe radius <i>round</i>	$r_w, mm$	50 x 50
proton losses rate	plr*	$4 \times 10^{-6}$

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peak sec. electron yield stainless steel	$\delta_{max}$	~2.0
yield - electrons per incident proton	$Y_{ep}$	100

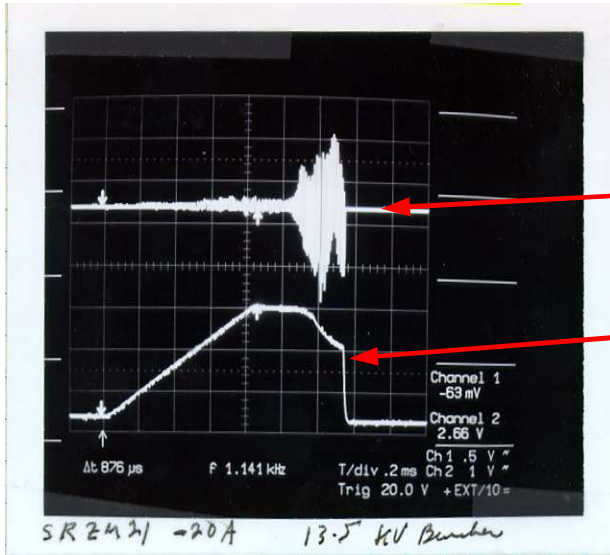
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used actual longitudinal bunch profile

\*proton losses = proton loss per proton per turn



# Well Established PSR Instability Characteristics (R. Macek Courtesy)

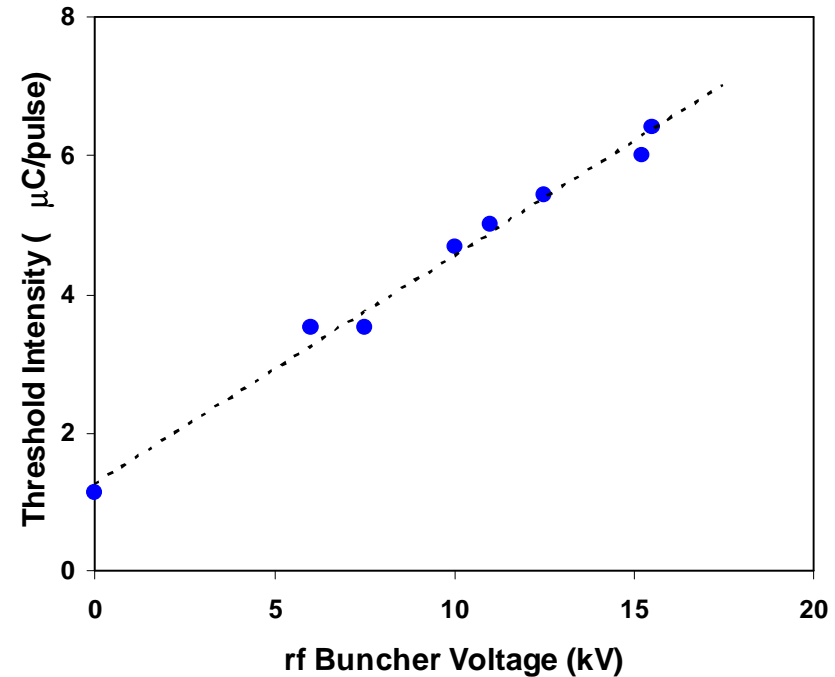


Instability Signals

BPM  $\Delta V$  signal

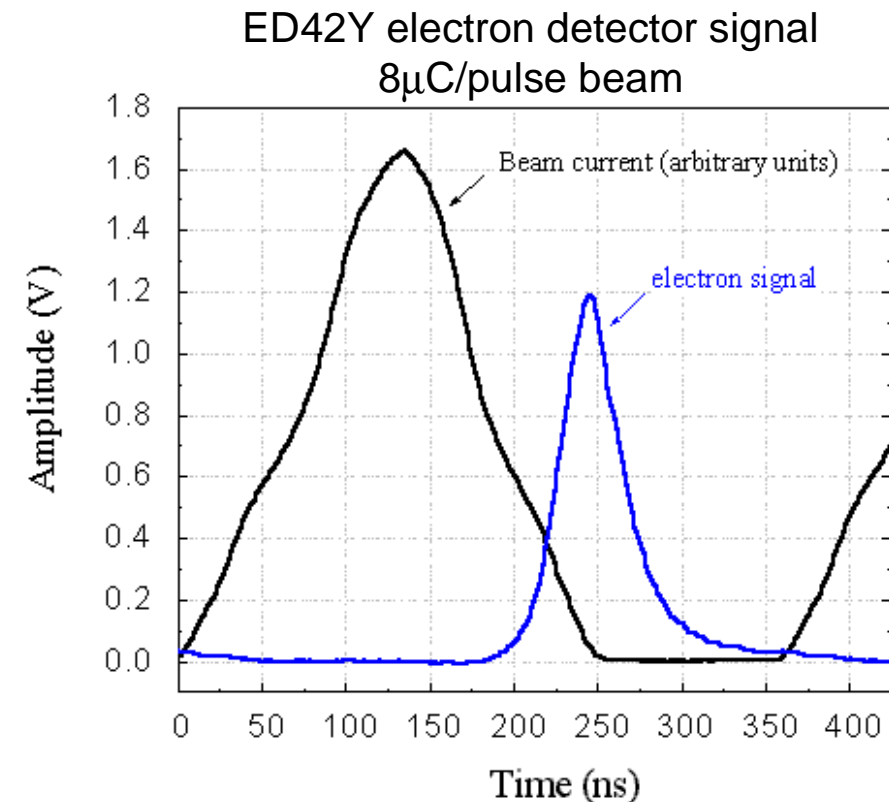
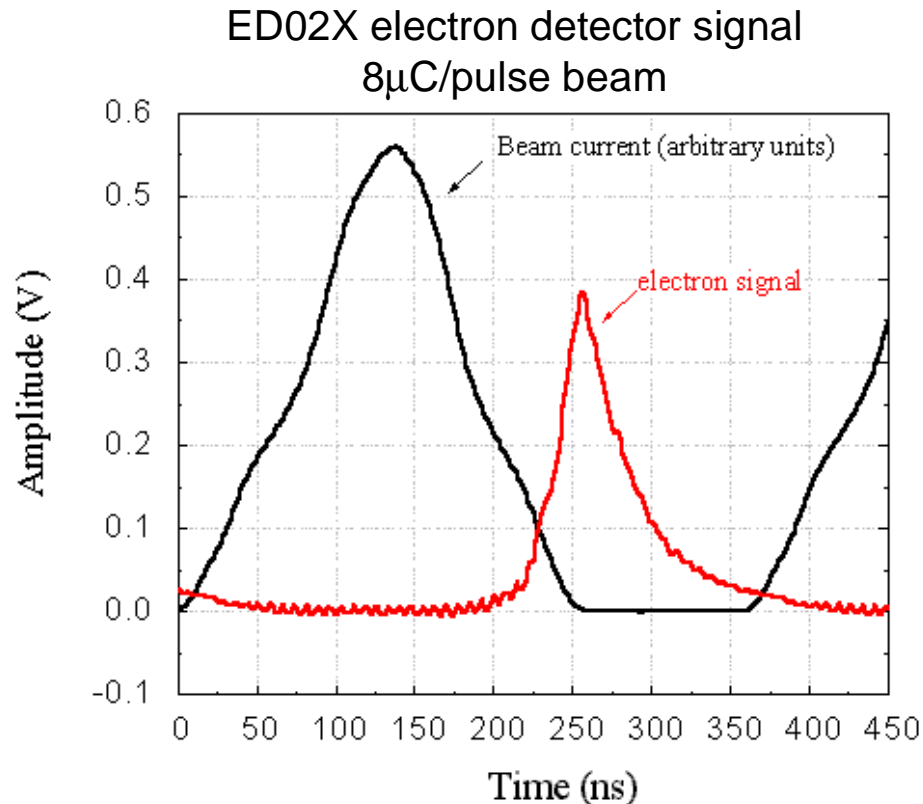
CM42 ( $4.2 \mu\text{C}$ )  
(Circulating Beam  
Current)

- Growth time  $\sim 75 \mu\text{s}$  or  $\sim 200$  turns
- High frequency  $\sim 70 - 200$  MHz
- Controlled primarily by rf buncher voltage



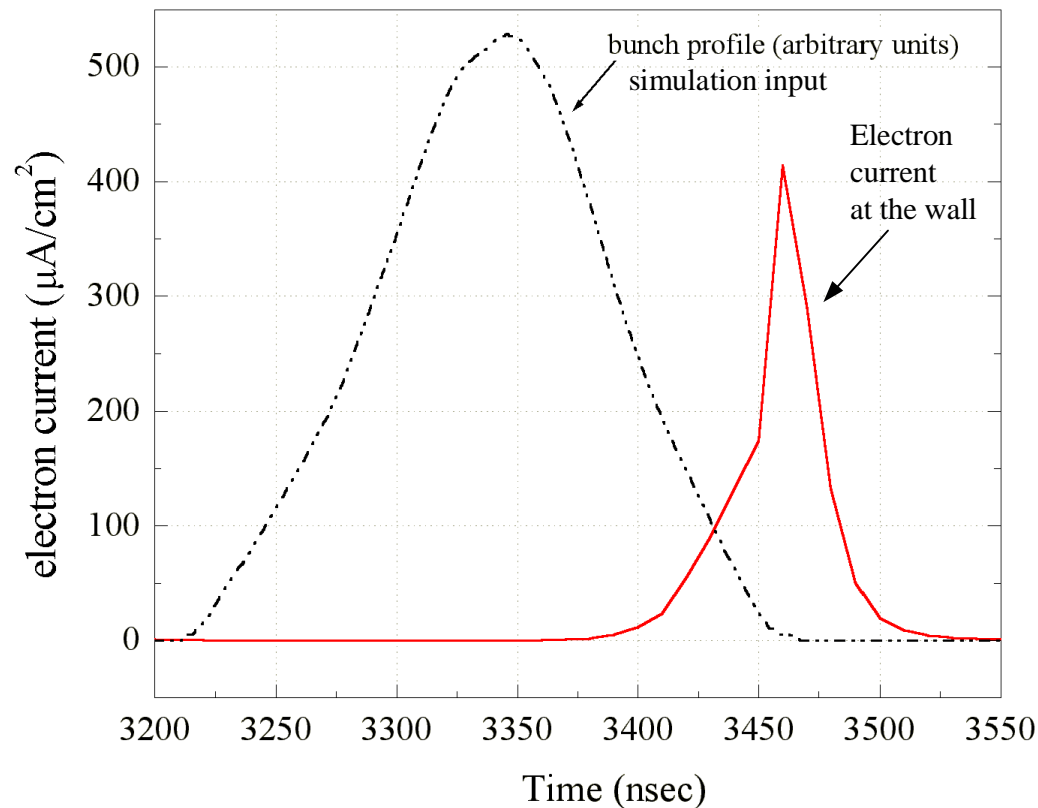
# Electron Detector Signals at PSR (R. Macek courtesy)

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



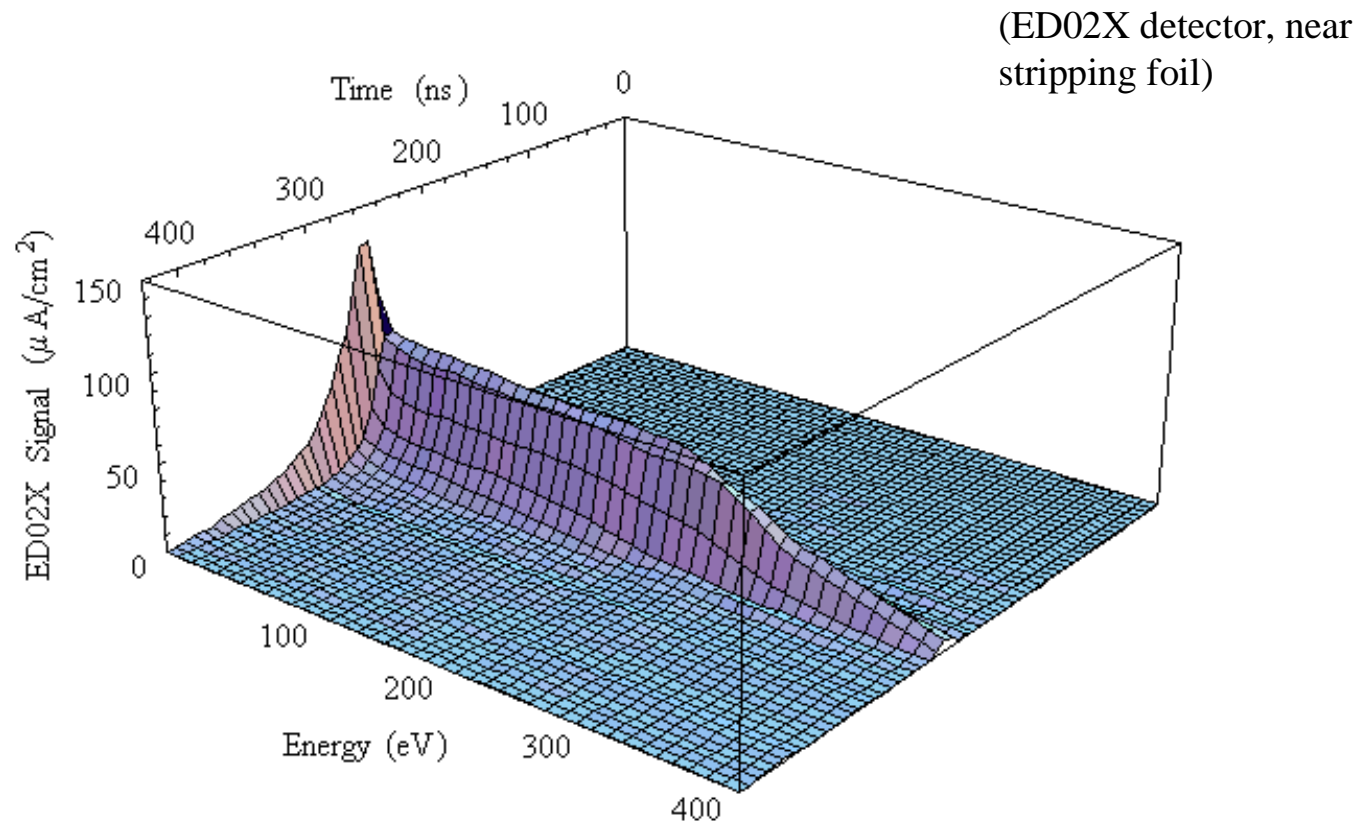
The electron current in  $A/cm^2$  is obtained dividing the voltage signal by a factor  $\sim 2.75 \times 10^3$ .

# Simulated electron wall current



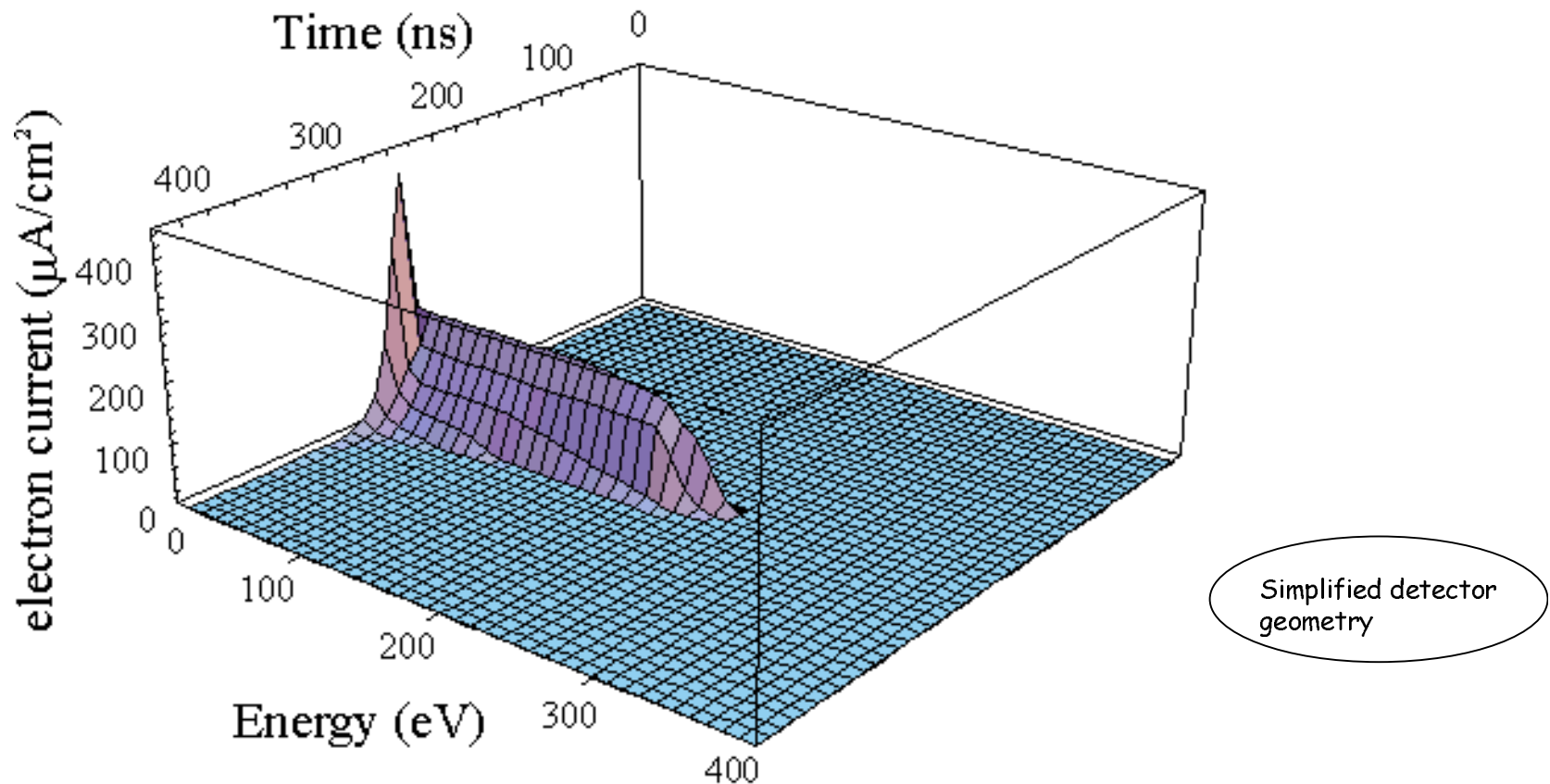
Simulated electron wall current in  $\mu\text{A}/\text{cm}^2$ , for a stainless steel chamber surface assuming  $\delta_{max}=2.05$ ,  $E_{max}=300$  eV. Emitted-secondary electron model: reflected and rediffused electrons were **not included** in this simulation.

# Electron energy cumulative spectrum (3D profile)



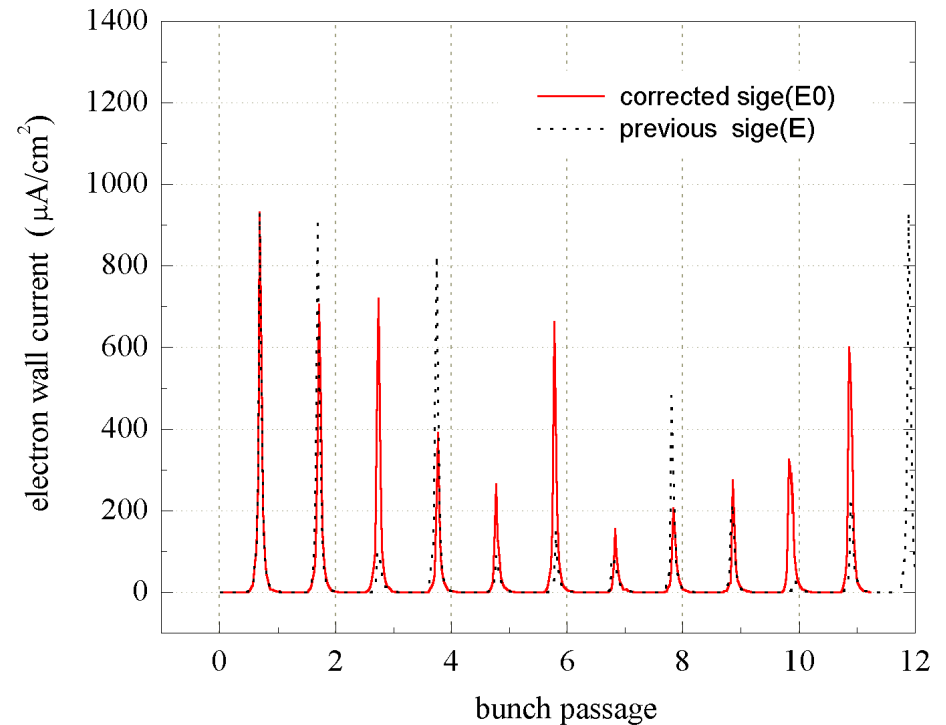
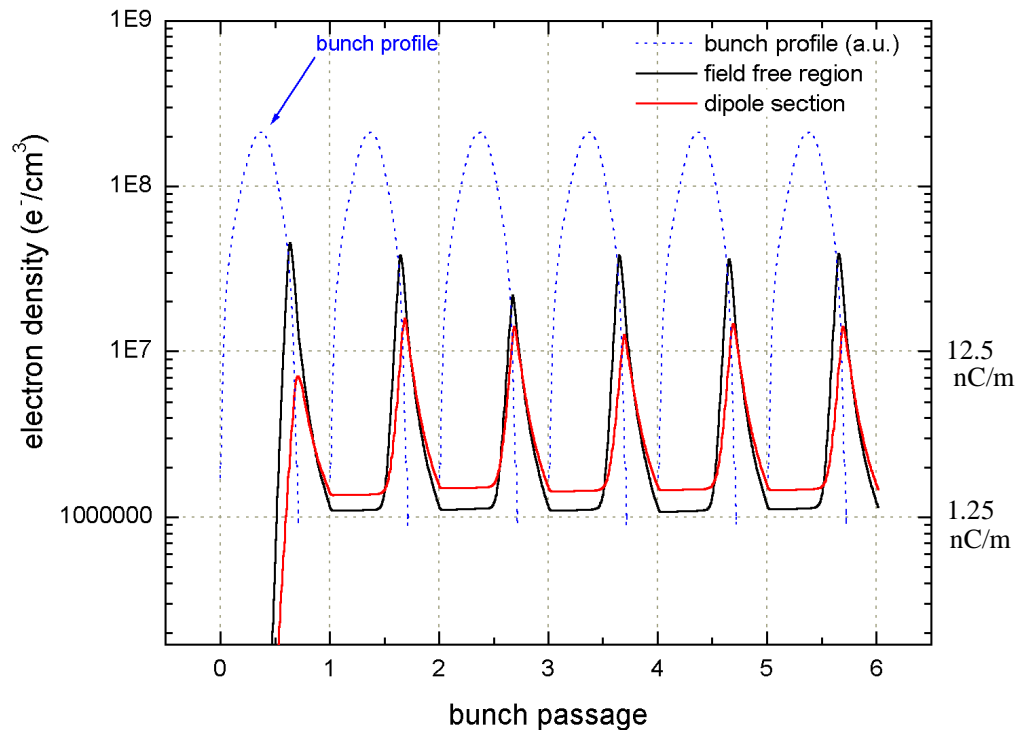
ED02X e<sup>-</sup> detector near stripping foil, measured cumulative energy spectrum of the electrons hitting the wall as a function of time. The origin of time corresponds to the passage of the head of the bunch. Electron current in  $\mu\text{A}/\text{cm}^2$ .

# Simulated cumulative energy spectrum



Simulated cumulative energy spectrum of the electrons hitting the wall of a stainless steel field-free region, in  $\mu\text{A}/\text{cm}^2$ , assuming  $\delta_{max}=2.05$ ,  $E_{max}=300$  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

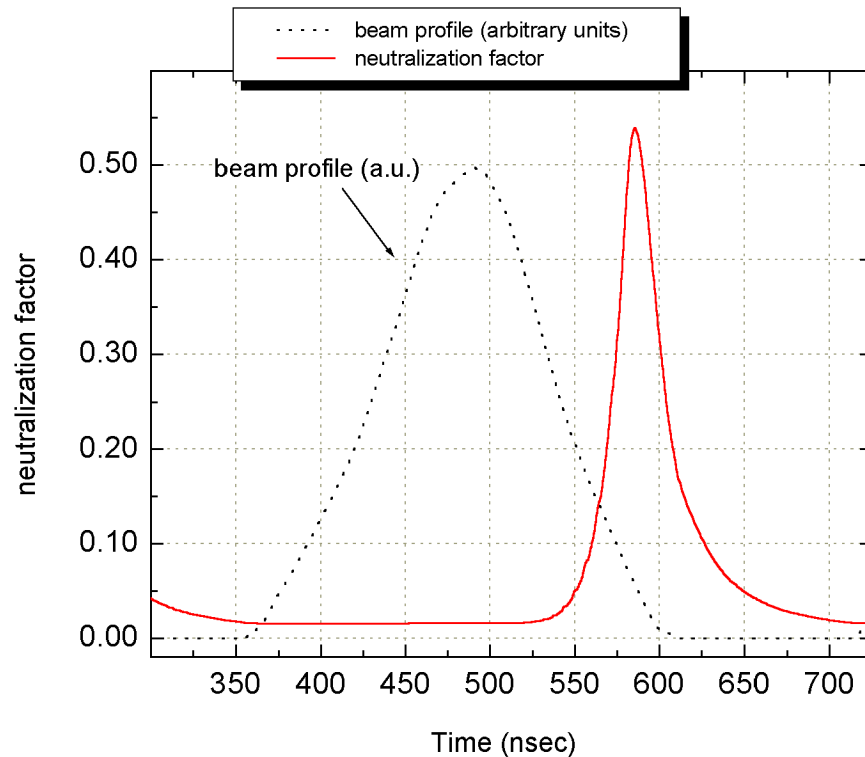


Simulated electron density in the PSR, bunch population  $5 \cdot 10^{13}$  ppb, proton losses  $4 \cdot 10^{-6}$  proton loss per proton per turn, circumference 90 meters. Emitted-secondary electron energy spectrum model includes true secondary, rediffused and backscattered electrons (Hilleret fit,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

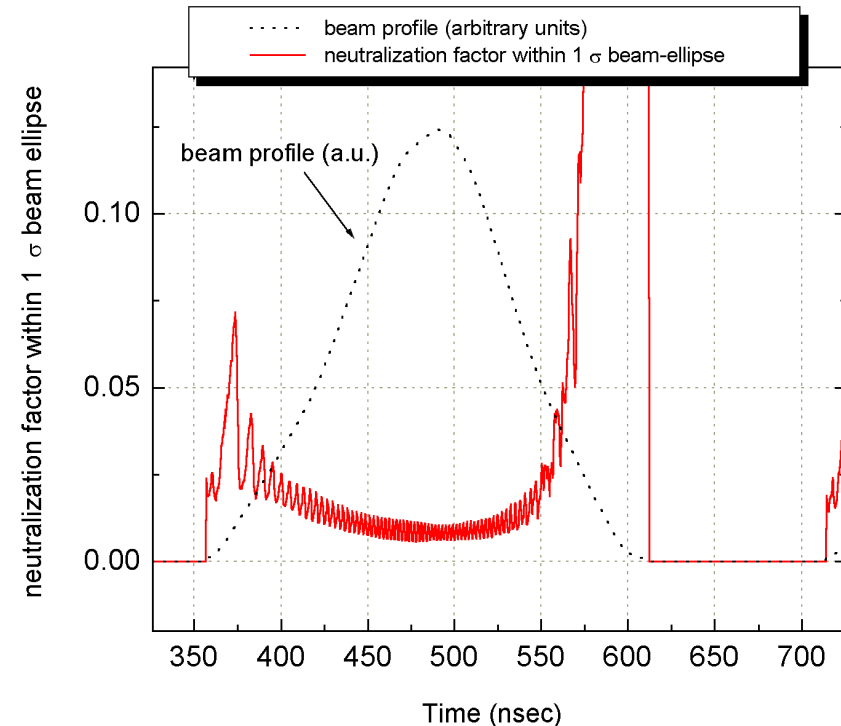
Simulated Electron current at the wall, averaged over the beam pipe circumference, in a PSR field free region, with bunch population  $5 \cdot 10^{13}$  ppb. Emitted-secondary electron energy spectrum model includes true secondary, rediffused and backscattered electrons (Hilleret fit, Cu). Now current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

# Neutralization factor $e^-/p$

within vacuum pipe

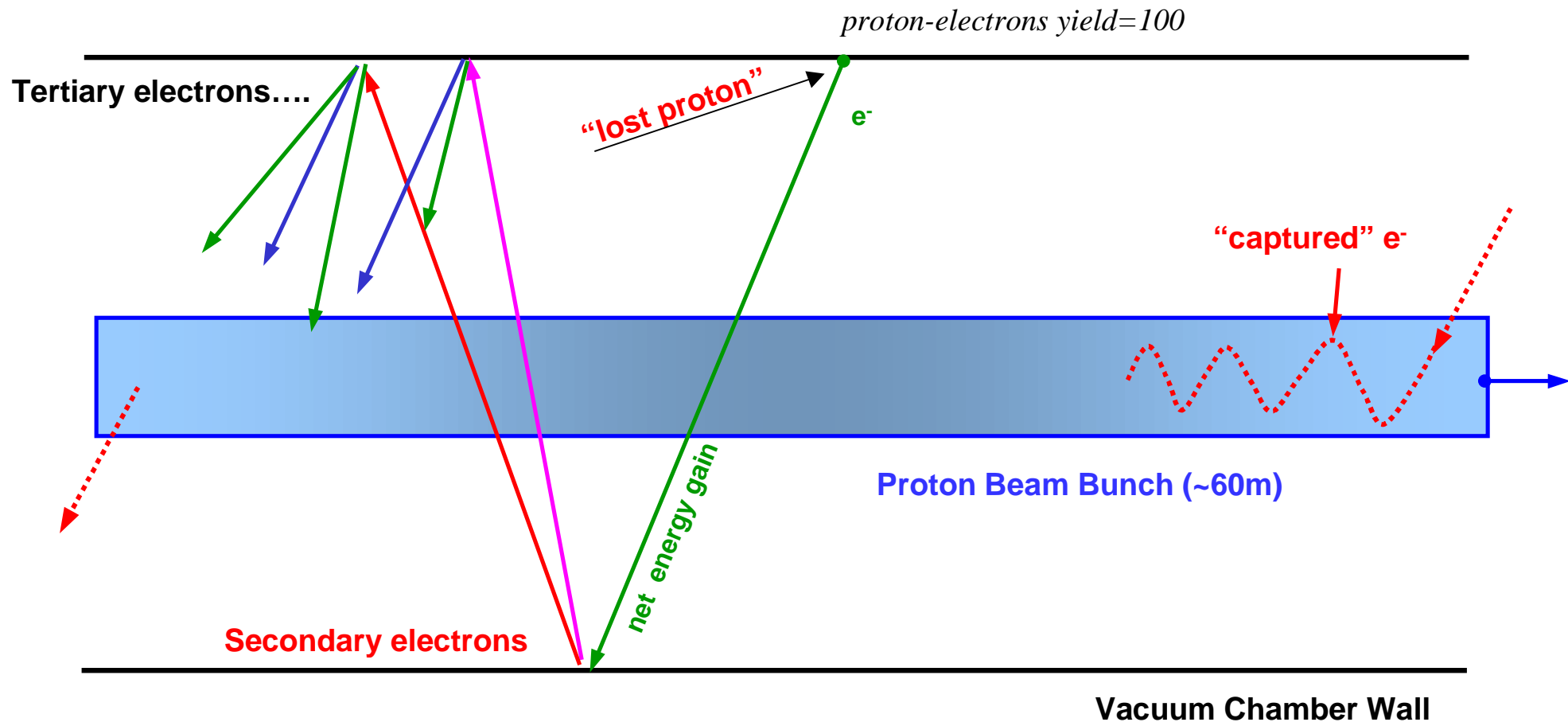


within  $1 \sigma$  beam-ellipse



Simulated neutralization factor, ratio  $e^-/p^+$ , in an PSR field free region. The **fractional neutralization** within the  $1 \sigma$  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

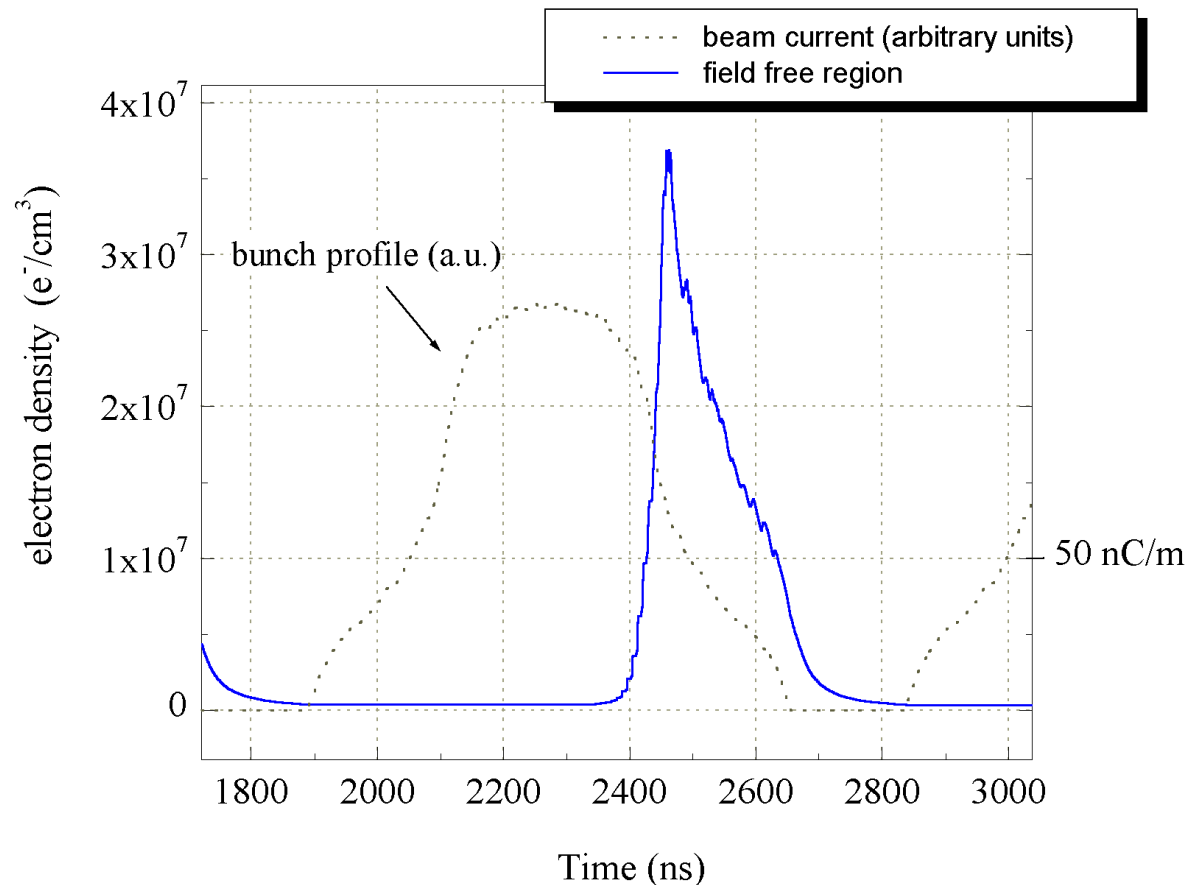
beam kinetic energy	$E, GeV$	1.0
dipole field	$B, T$	0.78
ring circumference	$C, m$	248
number of particles per bunch	$N_b$	$2.048 \times 10^{14}$
total bunch length (> 1A)	$bl, nsec$	~760
revolution period	$T, nsec$	945
transverse bunch size, <i>unif. distribution</i>	$r_x, r_y, cm$	2.8
beam pipe radius <i>round</i>	$r_w, cm$	$10 \times 10$
proton losses rate (0.01%)	$plr^*$	$1.1 \times 10^{-7}$
peak secondary electron yield	$\delta_{max}$	~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  $plr = 4 \times 10^{-6}$ )



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



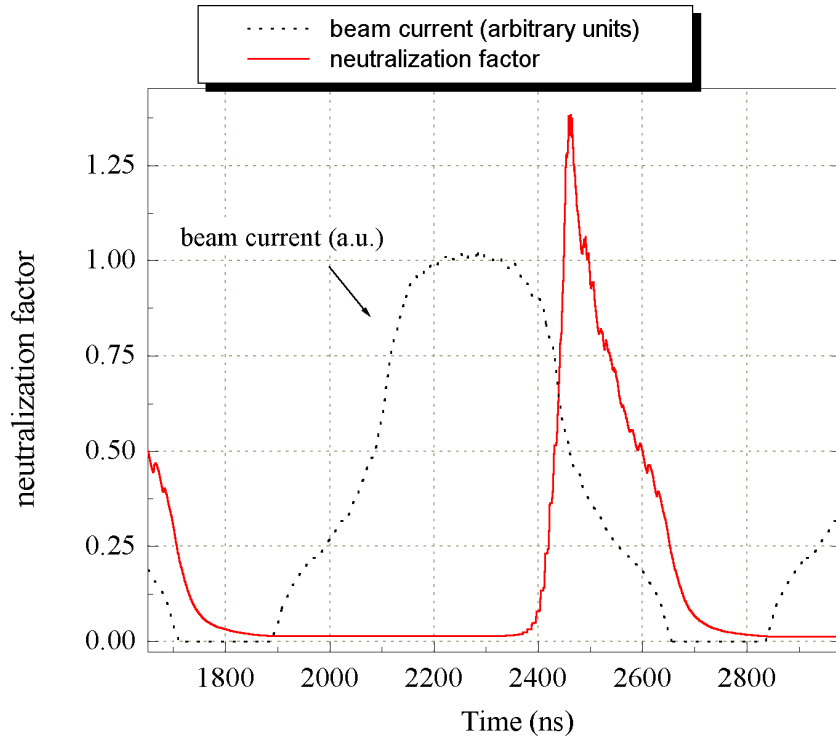
Simulated electron density in a SNS field free region. Secondary yield  $\sim 2$ .

**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.

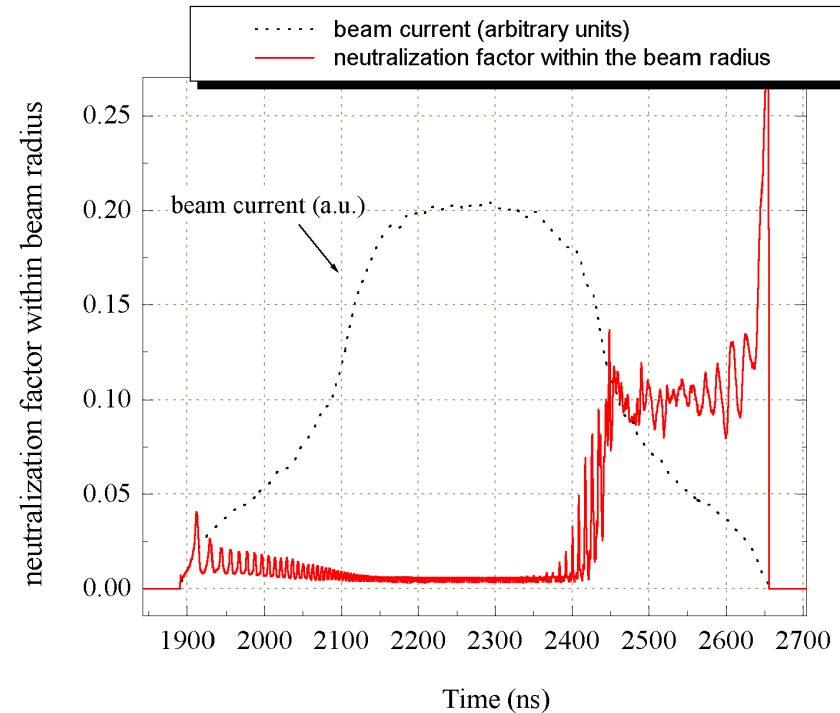
# Neutralization factor $e^-/p$

SNS

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

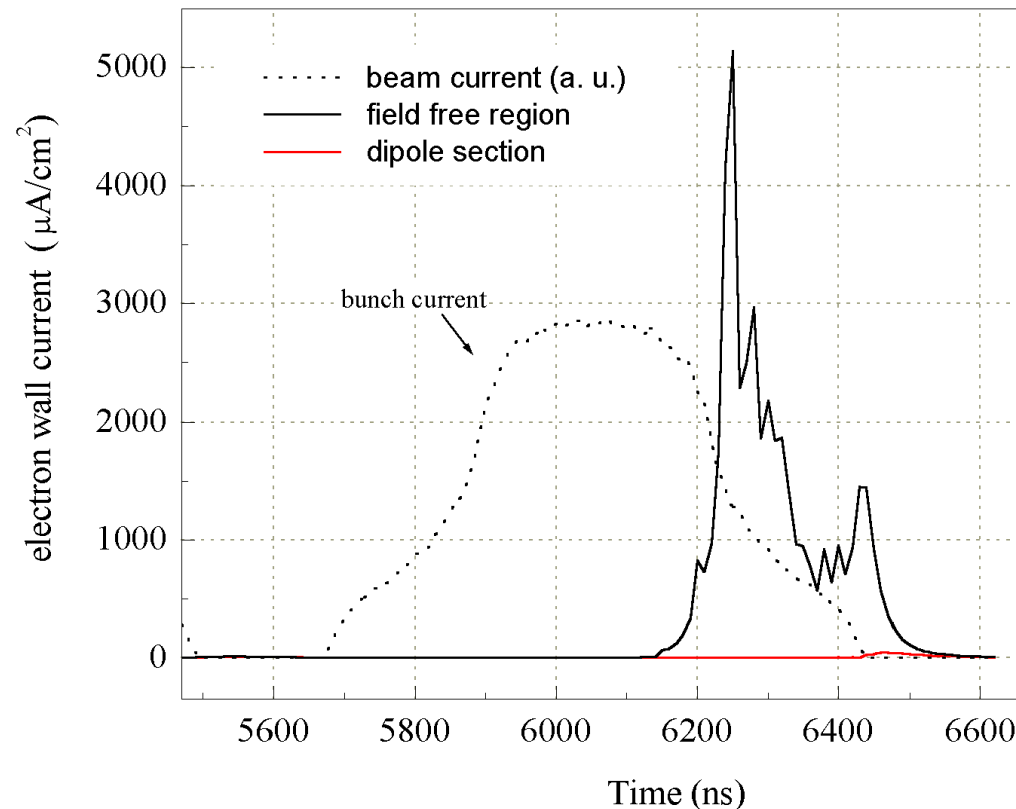
SNS



(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<sup>3</sup>. (Right) histogram of the electron energy averaged over the all bunch passages.

# electron wall current (contd')

SNS



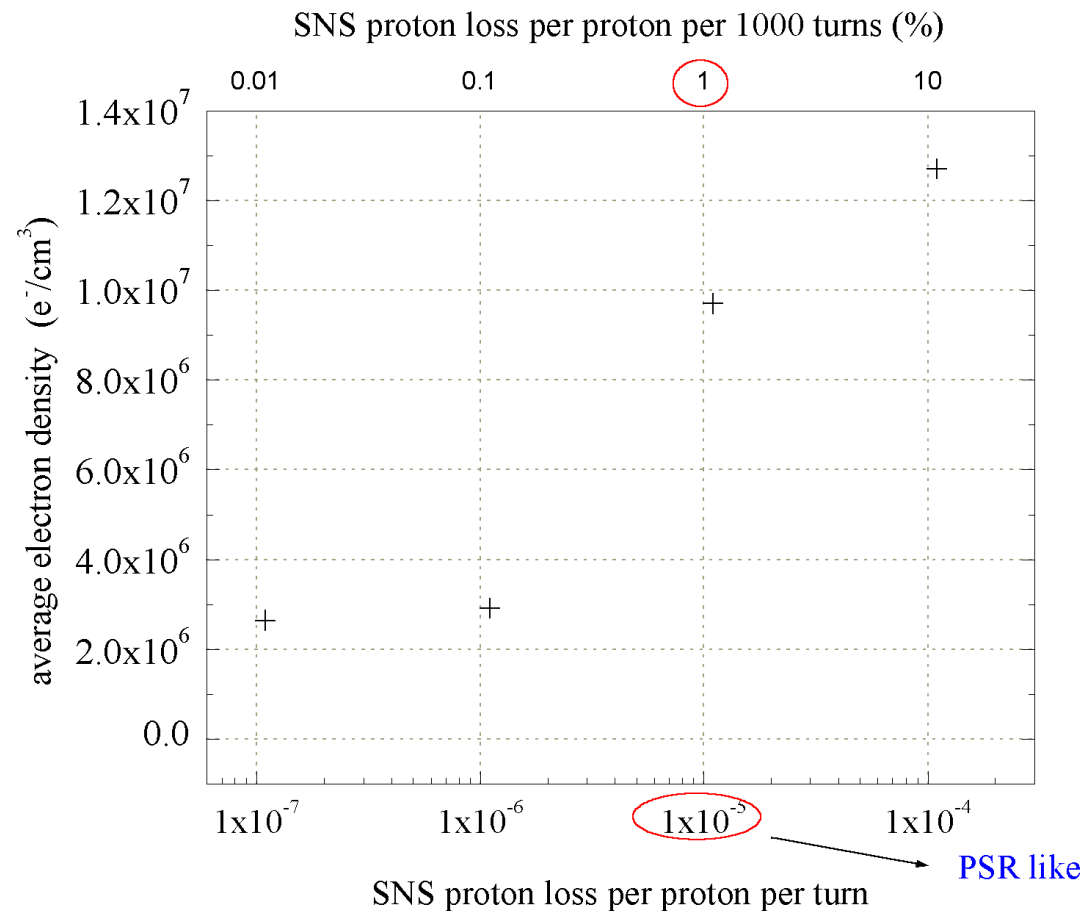
Note: PSR peak  
 $\sim 400 \mu\text{A}/\text{cm}^2$

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



# Comparing different proton losses: $e^-$ density

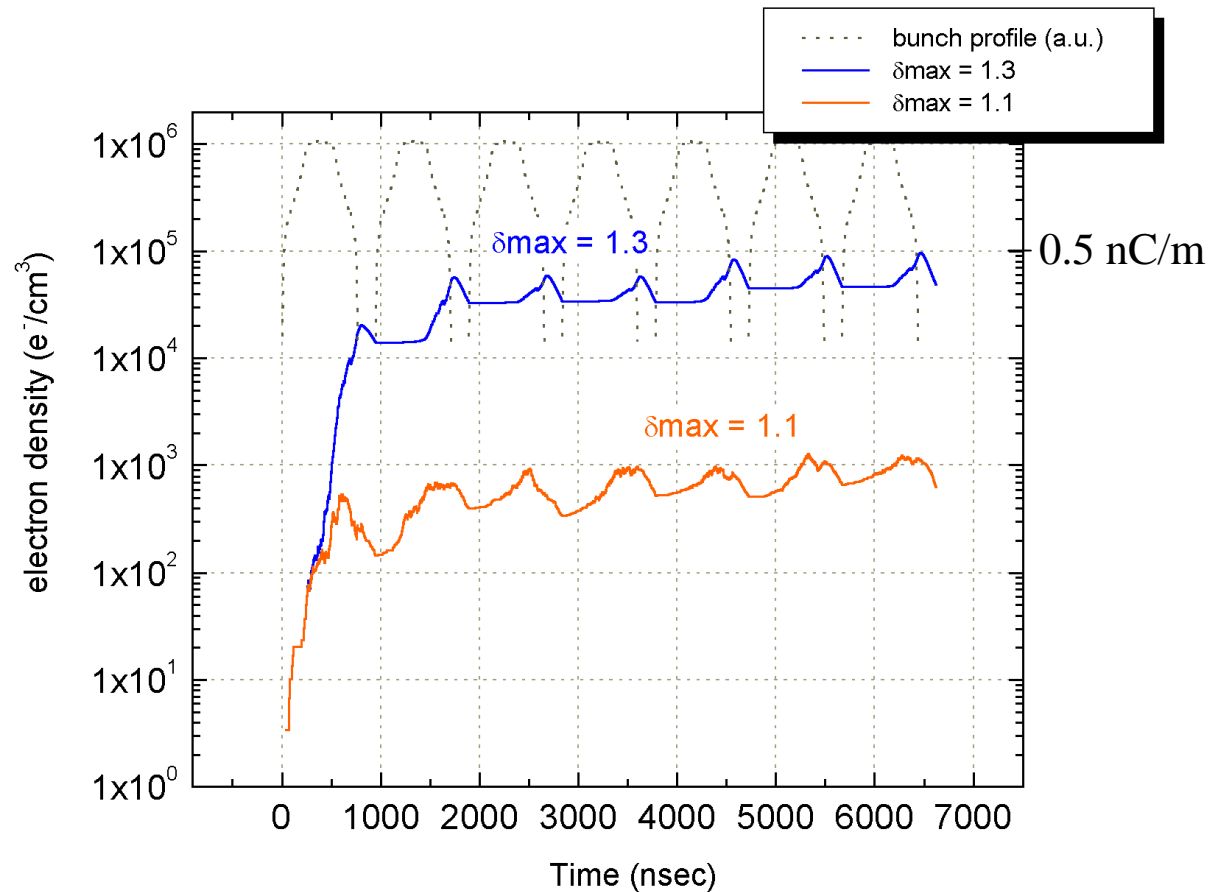
SNS



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  $\delta_{\text{max}} \sim 2$ .

# variation of the secondary $e^-$ yield SEY

SNS

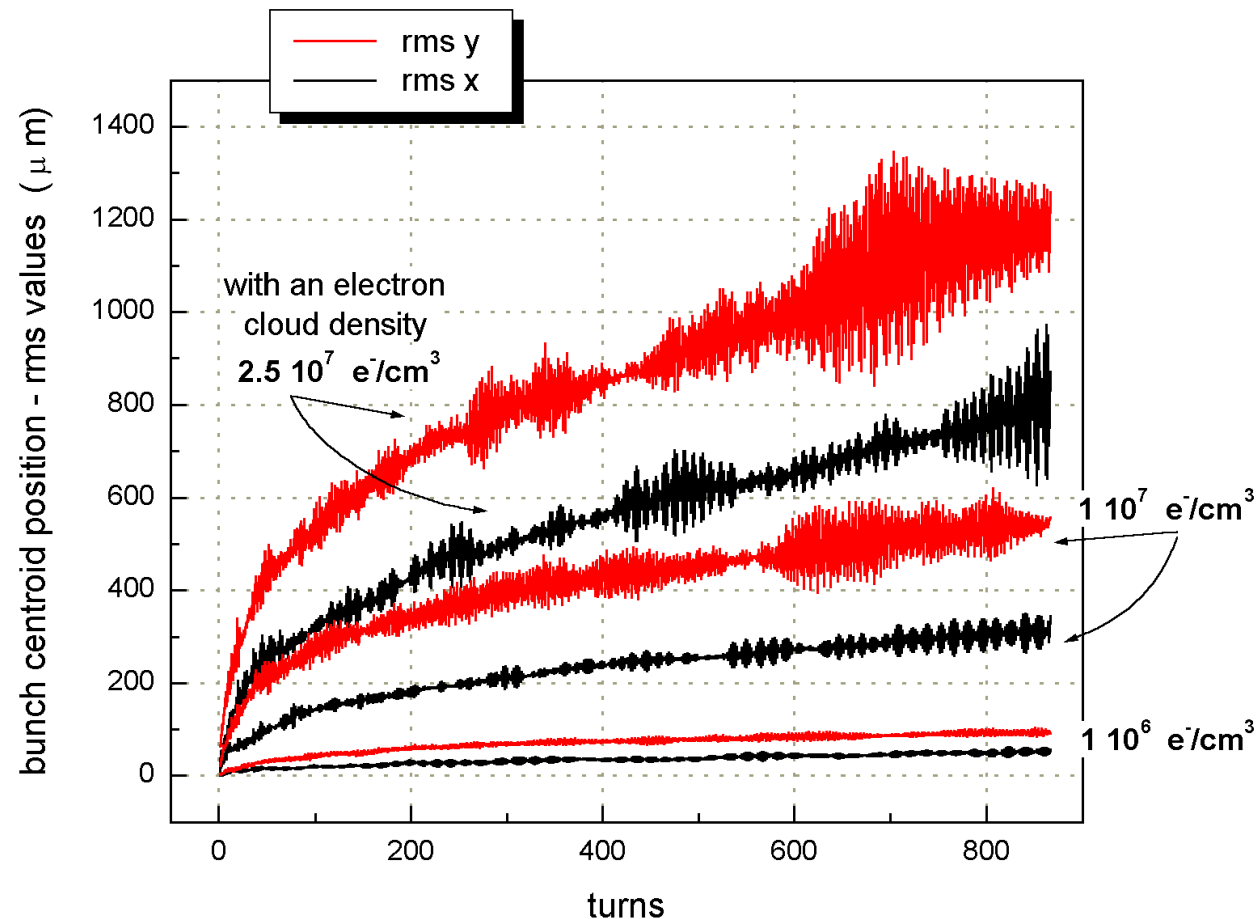


Simulated electron density in the SNS, first bunch passages, bunch population  $2.048 \cdot 10^{14}$ ppb. Varying the secondary electron yield  $1.1 < \delta_{\max} < 2$ . All simulation are for proton losses  $\text{ploss} = 1.1 \cdot 10^{-7}$  proton loss per proton per turn, or  $\sim 0.01\%$  loss 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 ..

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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  $\mu\text{m}$ ), rms values of all slices, for different electron cloud densities and **zero chromaticity**. NLC actual **bunch size**  $\sigma_x = 41 \mu\text{m}$ ,  $\sigma_y = 5 \mu\text{m}$ , **synchrotron tune** = 0.0035. In figure plotted 3 synchrotron oscillations.

# Conclusions and future work

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- 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**  $> 10^7 \text{ e}^-/\text{cm}^3$  (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

