ECloud 04 Workshop

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Simulation of e-Cloud using ORBIT: Benchmarks and First Application

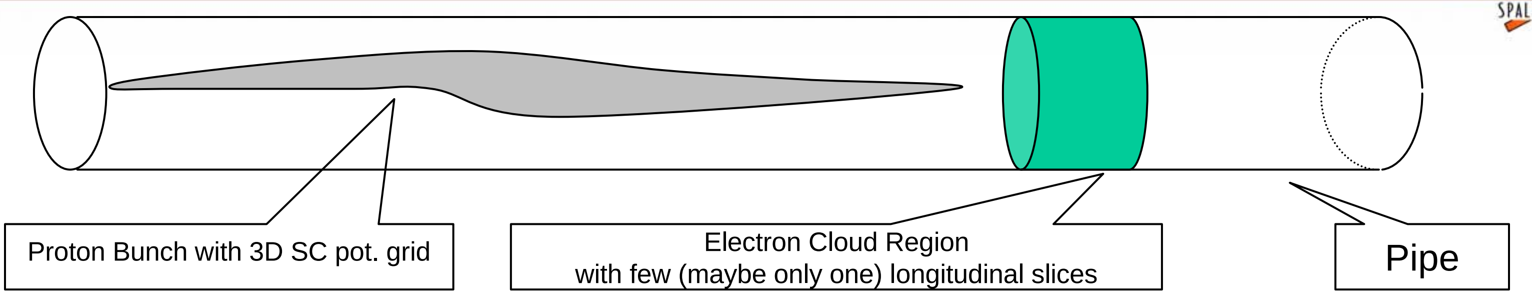
Yoichi Sato

SNS/ORNL; Indiana University, Bloomington

A. Shishlo, S. Danilov, J. Holmes, S. Henderson

SNS/ORNL

Outline


Proton Bunch with 3D SC pot. grid

Electron Cloud Region
with few (maybe only one) longitudinal slices

Pipe

- Benchmark of secondary emission surface model in ORBIT
  - Implementation of Furman and Pivi's Model (with simplifications to save calculation time)
  - Secondary energy spectrum
  - Electron cloud development in a cold proton bunch

- Benchmark of instability for two stream model
  - Analytically solvable model
  - Setup in ORBIT
  - Instability and growth rate

- Estimation of computational requirements for PSR bunched beam case

Surface Model

BASIC FEATURE

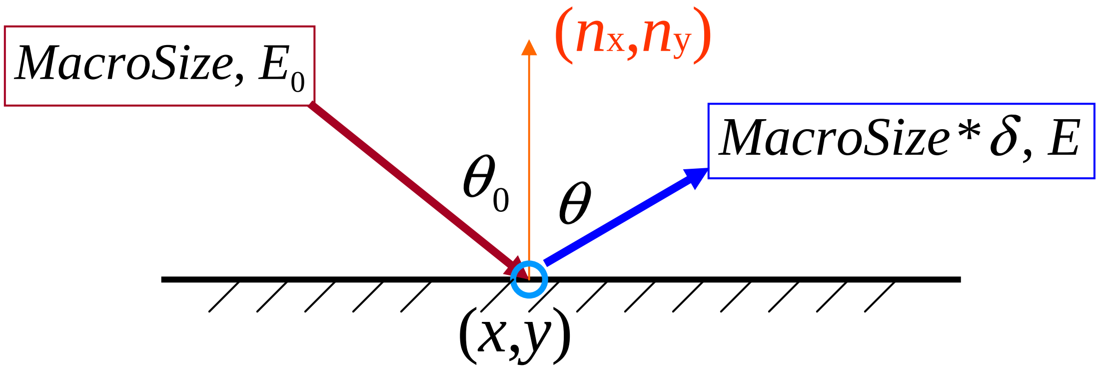
Removes electron-macroparticle hitting the surface from the electron bunch data

Adds electron-macroparticle using ORBIT implementation of Furman and Pivi's model: PRST-AB 5 124404 (2002)

- its macrosize is the original one multiplied by the secondary emission yield:

$$\boxed{\delta(E_0,\theta_0) = (\text{secondary current})/(\textit{incident electron beam current})}$$

- its energy is determined by model spectrum with transformation method



We use a flexible Monte Carlo scheme to control the number of macroparticles and their macrosize (weight of macroparticle) without changing physics

Surface Model, cont.

The surface model divides SEY into 3 components

$$\delta(E_0) = \delta_{el} + \delta_{rd} + \delta_{ts}$$
$$\delta_{el} = (\text{elastic backscattered current})/(\textit{incident electron current})$$
$$\delta_{rd} = (\text{rediffused current})/(\textit{incident electron current})$$
$$\delta_{ts} = (\text{true secondary current})/(\textit{incident electron current})$$

Each component has its own particular model spectrum. With the following probabilities we choose the type of emission and obtain the emitted energy from its spectrum through the transformation method.

Elastic backscattered emission: $\boxed{\delta_{el}/\delta}$

Rediffused emission: $\boxed{\delta_{rd}/\delta}$

True secondary emission:

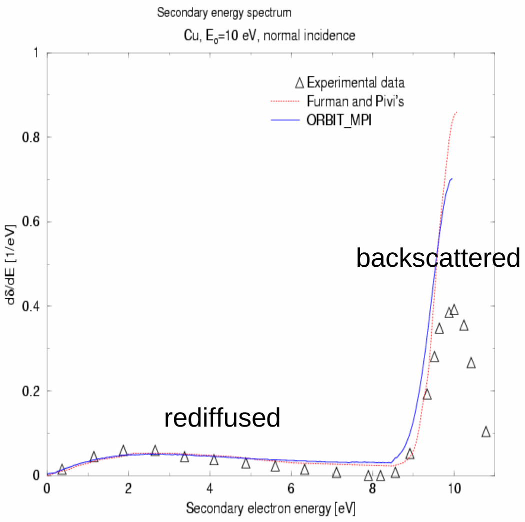
$$\boxed{\frac{(\delta_{ts}/\delta)P_{n,ts}}{\sum_{i=1}^{M_{emiss}} P_{i,ts}}}$$

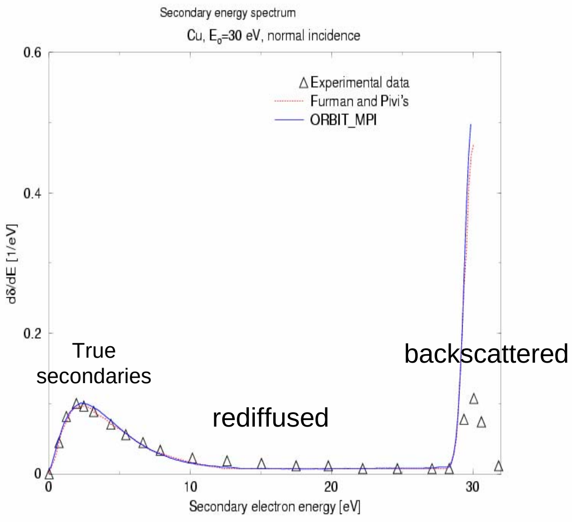
$$n = \text{number of emitted electrons per event}: \quad 1 \le n \le M_{emiss}$$

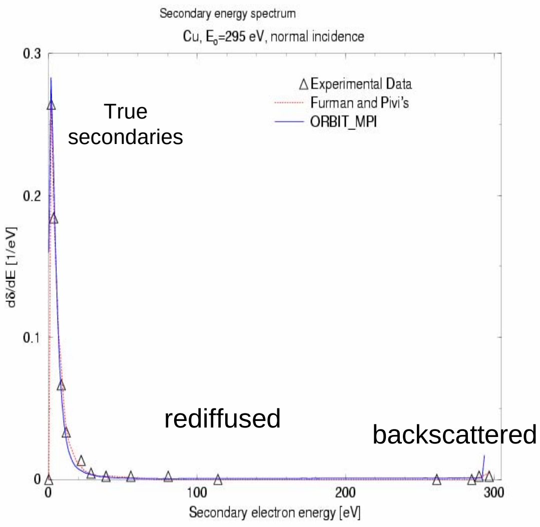
$$; P_{n,ts} = \binom{M_{emiss}}{n}\left(\frac{\delta_{ts}}{M_{emiss}}\right)^{n}\left(1-\frac{\delta_{ts}}{M_{emiss}}\right)^{M_{emiss}-n}$$

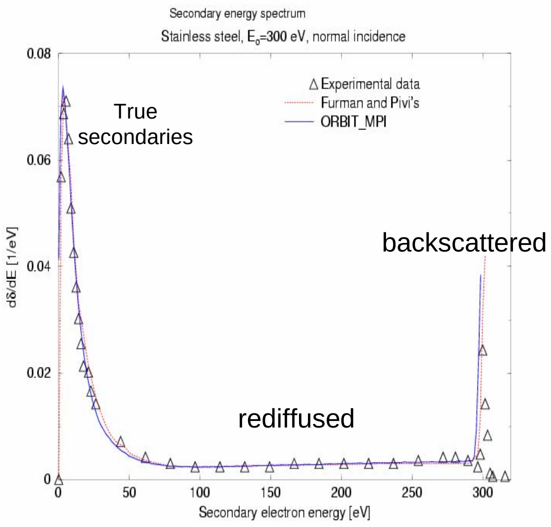
For getting energy of true secondary, we assume $E_0 >> E$ to simplify the model

Secondary Emission Surface Spectrum







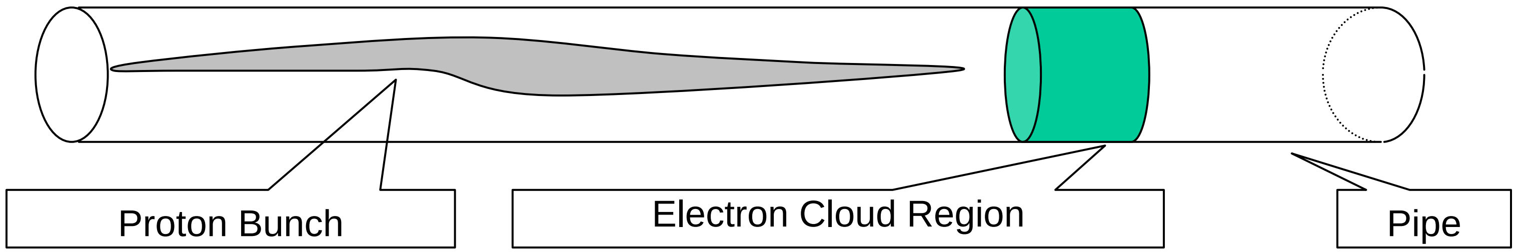


The secondary electron energy spectra from normal incidental electrons on copper and stainless steel surfaces

The ORBIT spectra (E0=10,30,295eV for copper, 300eV for stainless steel) match Furman and Pivi's simulation, PRST-AB 5 124404 (2002),

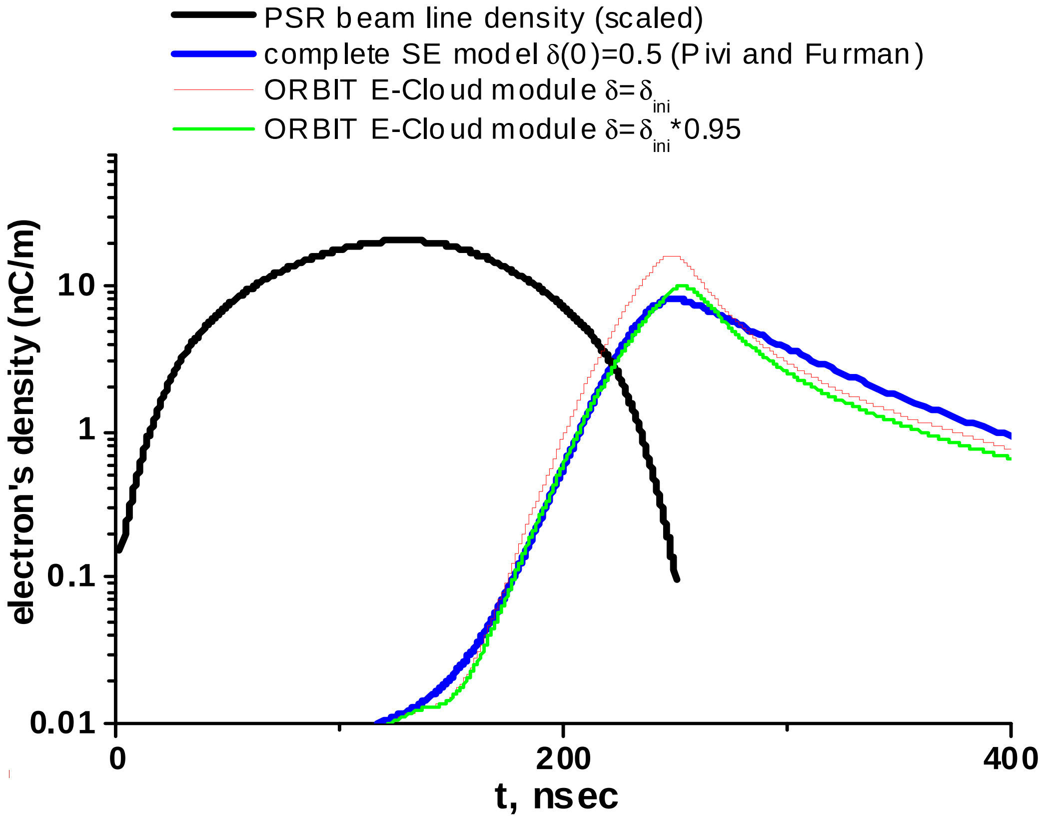
Gaussian distribution around E0 in the data corresponds to energy resolution of the detector

E-Cloud Development (ORBIT Simulation)


Proton Bunch

Electron Cloud Region

Pipe

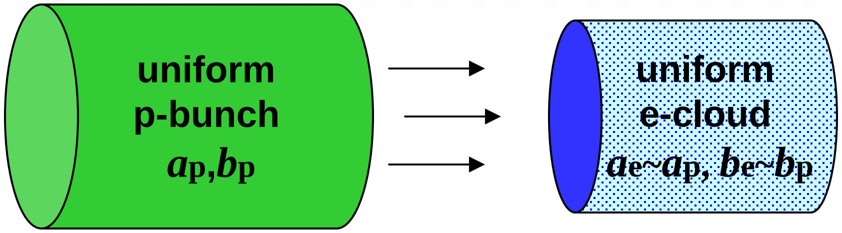


No kick on the proton bunch to compare the results with Pivi and Furman's PRST-AB 6 034201 (2003)

EC peak height is sensitive to SEY

The same parameterization with Furman and Pivi's but the different Monte Carlo scheme from theirs

Analytically Solvable Electron Cloud Model



Ref: D. Neuffer *et. al.* *NIM* **A321** p1 (1992)

Centroid oscillation model of uniform line densities of proton and electron

$$y_{p,c} = A_p Exp[i(n\theta - \omega t)], \quad y_{e,c} = A_e Exp[i(n\theta - \omega t)] \qquad ;\ A_e/A_p = \frac{\omega_e^2}{\omega_e^2 - \omega^2}$$

Dispersion relation (no frequency spread)

$$(\underbrace{\omega_e^2}_{\text{ep freq.}} - \omega^2)\{\underbrace{\omega_\beta^2}_{\text{betatron freq.}} + \omega_p^2 - (n\underbrace{\omega_0}_{\text{rev. freq.}} - \underbrace{\omega}_{\text{ep freq.}})^2\} = \omega_e^2 \omega_p^2$$

n = longitudinal harmonic of ep mode

$$\omega_{p,V}^2 = \frac{4\lambda_e r_p c^2}{\gamma b_e (a_e + b_e)}, \quad \omega_{e,V}^2 = \frac{4\lambda_p r_e c^2}{b_p (a_p + b_p)}$$

The relation is valid under **linear force** inside the streams

The dispersion relation has complex solutions (instability) near $\omega \sim \omega_e$ and $\omega \sim (n\omega_0 - \omega_\beta)$, slow wave, and satisfies the threshold condition:

$$\omega_p \underset{\approx}{>} \sqrt{\omega_\beta / \omega_e}\,\left| n\omega_0 - \omega_e - \omega_\beta \right| = \omega_0 \sqrt{Q_\beta / Q_e}\,\left| n - Q_e - Q_\beta \right| \qquad ;\ Q_e \equiv \omega_e/\omega_0 \quad ;\ Q_\beta \equiv \omega_\beta/\omega_0$$

Two Stream Model in ORBIT

To study the two stream model in ORBIT, we use SNS parameters

$$a_e = b_e = a_p = b_p = 30\,\mathrm{mm},\ 1\,\mathrm{GeV\ protonbeam},\ \mathrm{betatron\ tune}\ \underline{Q_x = Q_y = 6.2}$$

$$\omega_0 = 2\pi/T = 6.646[\mu s^{-1}],\ \lambda_p = \frac{1.5*10^{14}}{248\mathrm{m}*0.65} * \left(Bunchfactor = 2.5\right) = 2.326*10^{12}\,[\mathrm{m}^{-1}]$$

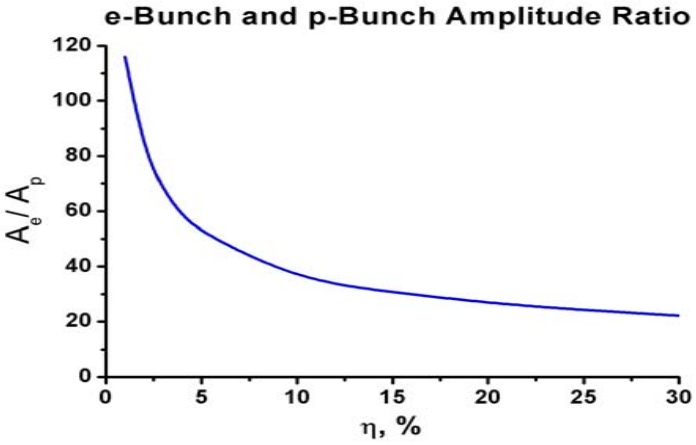
$$\underline{Q_e = \omega_e/\omega_0 = 172.171}$$

$$Q_p = \omega_p/\omega_0 = 2.79616\sqrt{\eta} \quad ; \eta = \lambda_e/\lambda_p = \mathrm{neutralization\ factor}$$

which is most unstable at the longitudinal harmonic number n = 178.
For sufficient electron cloud, exceeding the threshold, the dispersion relation for n = 178 has a growth mode as one of 4 roots of ω:

$$\omega_2/\omega_0 = 171.961 - 0.716\,i\,, \quad \left|A_e/A_p\right|_{\omega_2} = 116.1 \qquad \mathrm{for}\ \eta = 0.01$$

So, if we initialize the electron cloud and proton beam as slow waves with n=178 modulation and proper phase relationship, we can expect EC centroid oscillation to grow.



Two stream model in ORBIT, cont.

To reduce the calculation time, we adopt the periodic structure of L=248m/178=1.393m having 20 longitudinal nodes. $N_p = \lambda_p L = 3.241\times 10^{12}$

Initial proton bunch

KV distribution (R_p=30mm) –needs **very** (32 points) symmetric structure

0.01mm centroid modulation (slow wave) in vertical direction

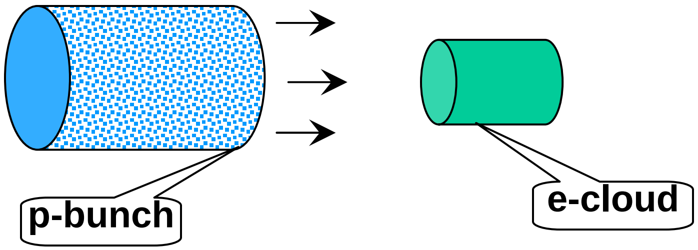
more than 400,000 macroprotons to satisfy at least 10 particles/grid-cell

Initial electron cloud

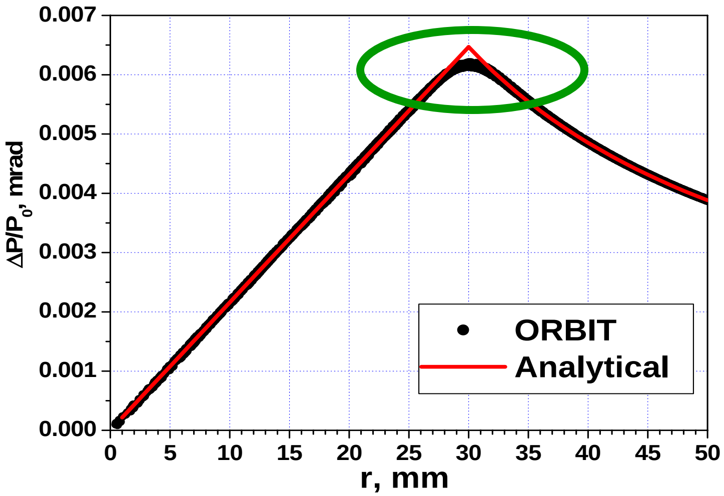
KV distribution (R_e=26mm) –needs to receive **linear** force inside p-bunch

400,000 macroelectrons with $\lambda_e = \eta \left(\frac{R_e}{R_p}\right)^2 \lambda_p$

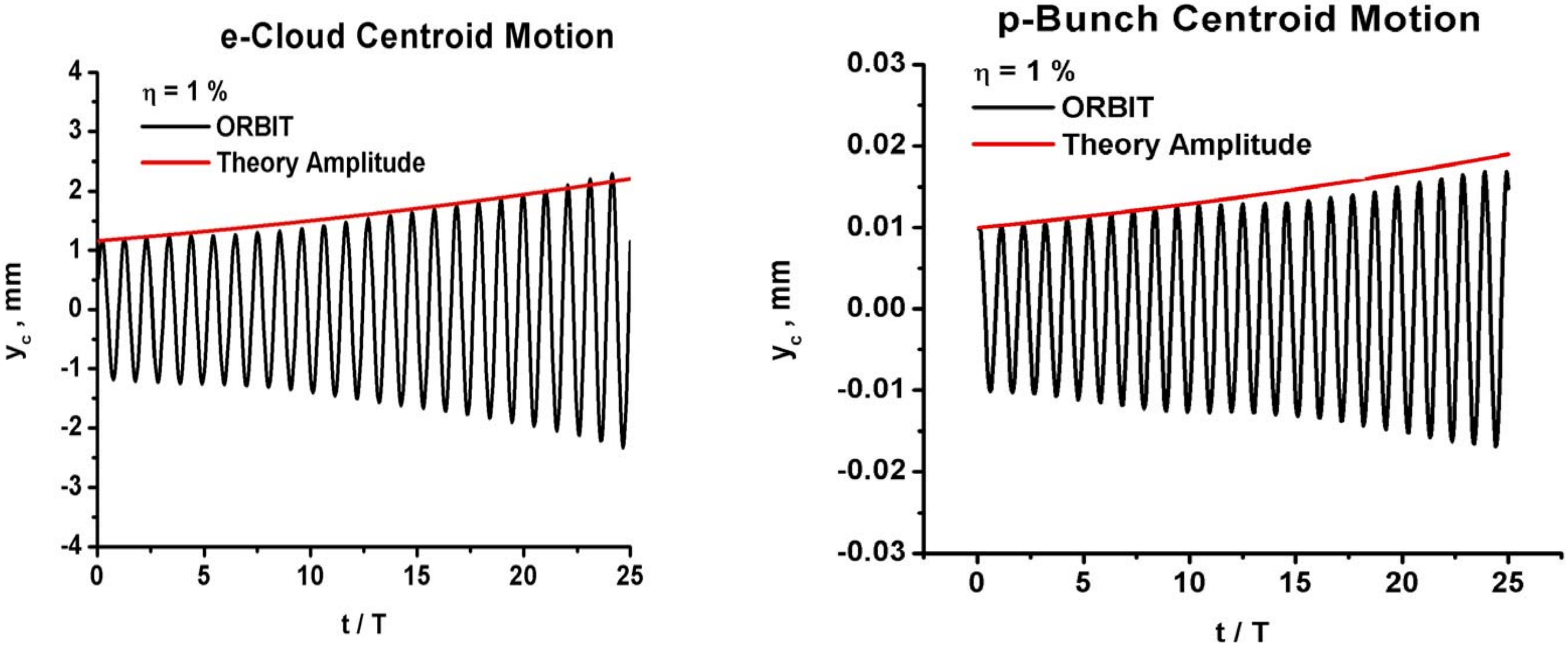
$\left(A_e/A_p\right)_{\eta,\text{ growth mode}} \times 0.01\text{mm}$ centroid modulation in vertical direction



The change in the transverse momentum of protons is in perfect agreement with analytic calculations except for the round shoulder



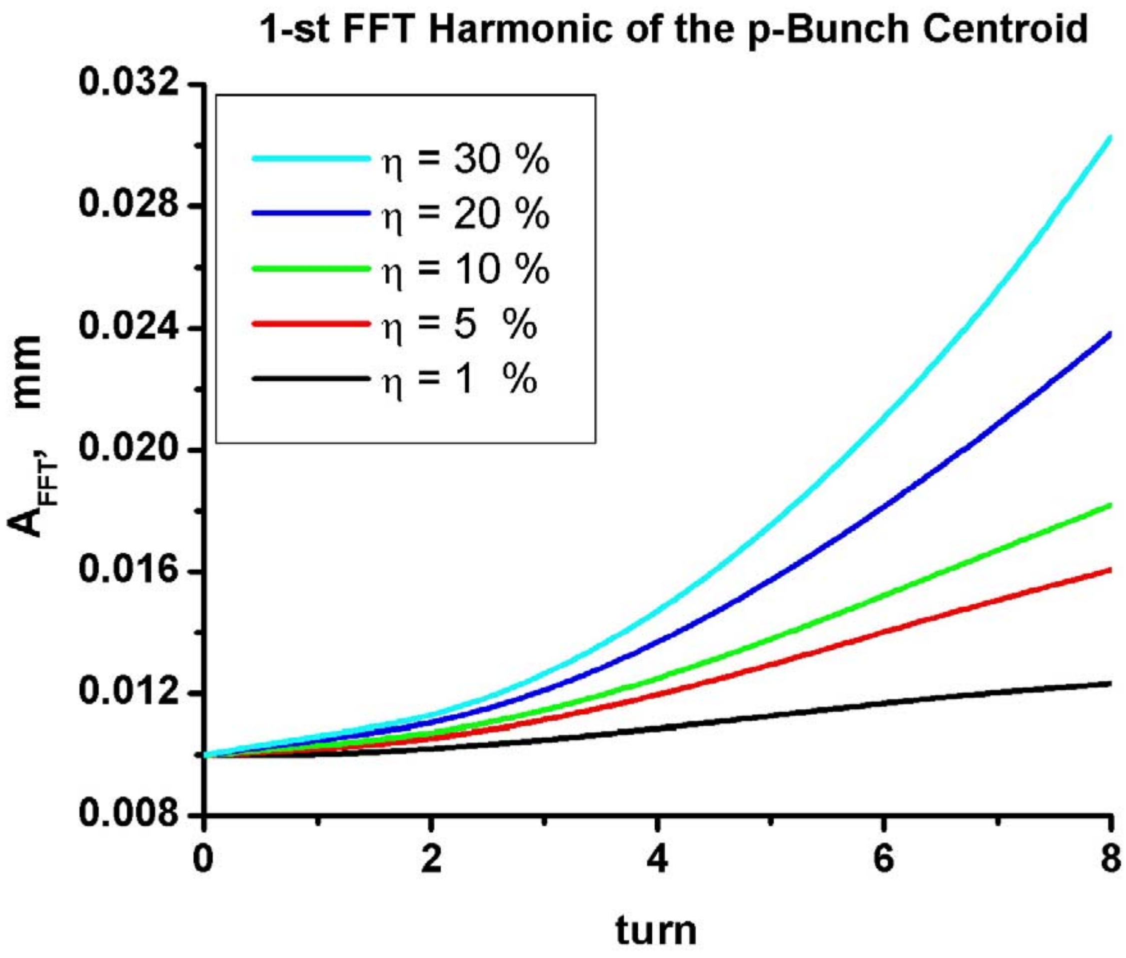
Two stream benchmark (ORBIT Simulation)



10 turns in the periodic structure requires about 10 min in SNS 16 CPUs

The growth of both electron and proton centroids matches for first several turns

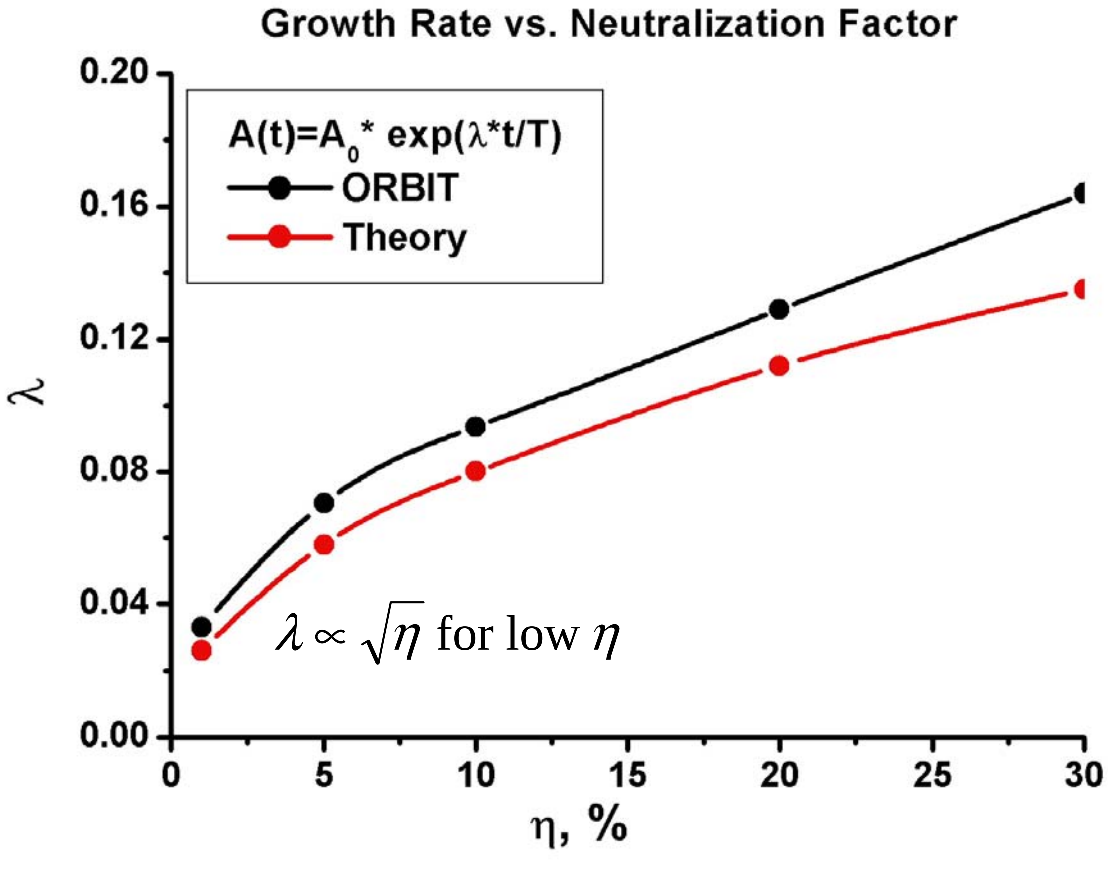
Two stream benchmark (ORBIT Simulation), cont.



The larger neutralization factor, the sooner e-cloud exceeds p-bunch radius.

We can apply the analytic two stream model for the first several turns

Two stream benchmark (ORBIT Simulation), cont.



$\lambda \propto \sqrt{\eta}$ for low η

The ORBIT growth rate is about 20% lager than the theory.

$$\frac{1}{\tau} \approx \frac{Q_p\omega_0}{2}\sqrt{\frac{Q_e}{\left|n-Q_e\right|}} \approx \frac{Q_p\omega_0}{2}\sqrt{\frac{Q_e}{Q_\beta}} \propto \sqrt{\eta}$$

Initial centroid modulation is for [Re=Rp=30mm]
However, we use Re=26mm to ensure linear force

Each proton spends outside of the e-cloud in some part of its trajectory

Estimation of computational requirements for PSR bunched beam case

Two stream model for PSR:

$$a_e = 12\text{mm},\ b_e = 15\text{mm},\ a_p = 16\text{mm},\ b_p = 20\text{mm},\ \ 0.793\,\text{GeV protonbeam}$$

$$\lambda_p = \tfrac{1.0\times10^{14}}{90.261\text{m}} = 1.108\times10^{12}\,[\text{m}^{-1}],\quad \text{betatron tune}\ Q_x = 3.21,\quad Q_y = 2.19$$

$$Q_{e,x} = 79.516,\quad Q_{e,y} = 71.121,\quad Q_{p,x} = 1.82\sqrt{\eta},\quad Q_{p,y} = 1.63\sqrt{\eta}\quad ;\eta = \lambda_e/\lambda_p$$

$$\boxed{\text{most unstabale at}\quad n_x = 83,\quad n_y = 73}$$

For PSR bunch we need to think:

- About 80*20 longitudinal nodes to simulate the PSR ring
- Ignoring boundary and no 3D proton on proton space charge will require about 80 times as much CPU time as our benchmark calculation (80 min. for 1 turn with SNS 16 CPUs)
- Setting primary electron production and secondary emission surface instead of linear neutralization factor

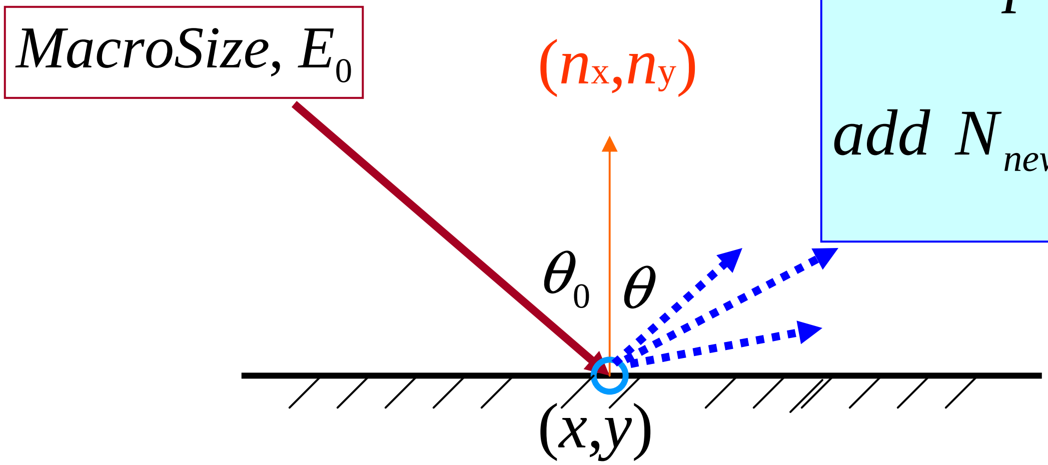
Conclusion

The secondary emission surface model integrated into ORBIT, which is based on M. Pivi and M.Furman's, matches their spectrum results. PRST-AB 5 124404 (2002), PRST-AB 6 034201 (2003)

A benchmark of the code with an analytic model for two stream instabilities has been successfully done.

We are going to simulate a PSR bunched beam case.

Attachment for page 3 “different Monte Carlo scheme”



In the probability of $P_{newborn}$,

$$add\ N_{newborn}\ of \left[\frac{MacroSize*\delta}{P_{newborn}N_{newborn}}, E_i\right]$$

We are having different Monte Carlo scheme to control the number of macroparticles and their macrosize (weight of macroparticle) without changing physics feature

Attachment for page 9 “32 points” symmetry