Electron Clouds in the PSR and SNS

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Collaborators

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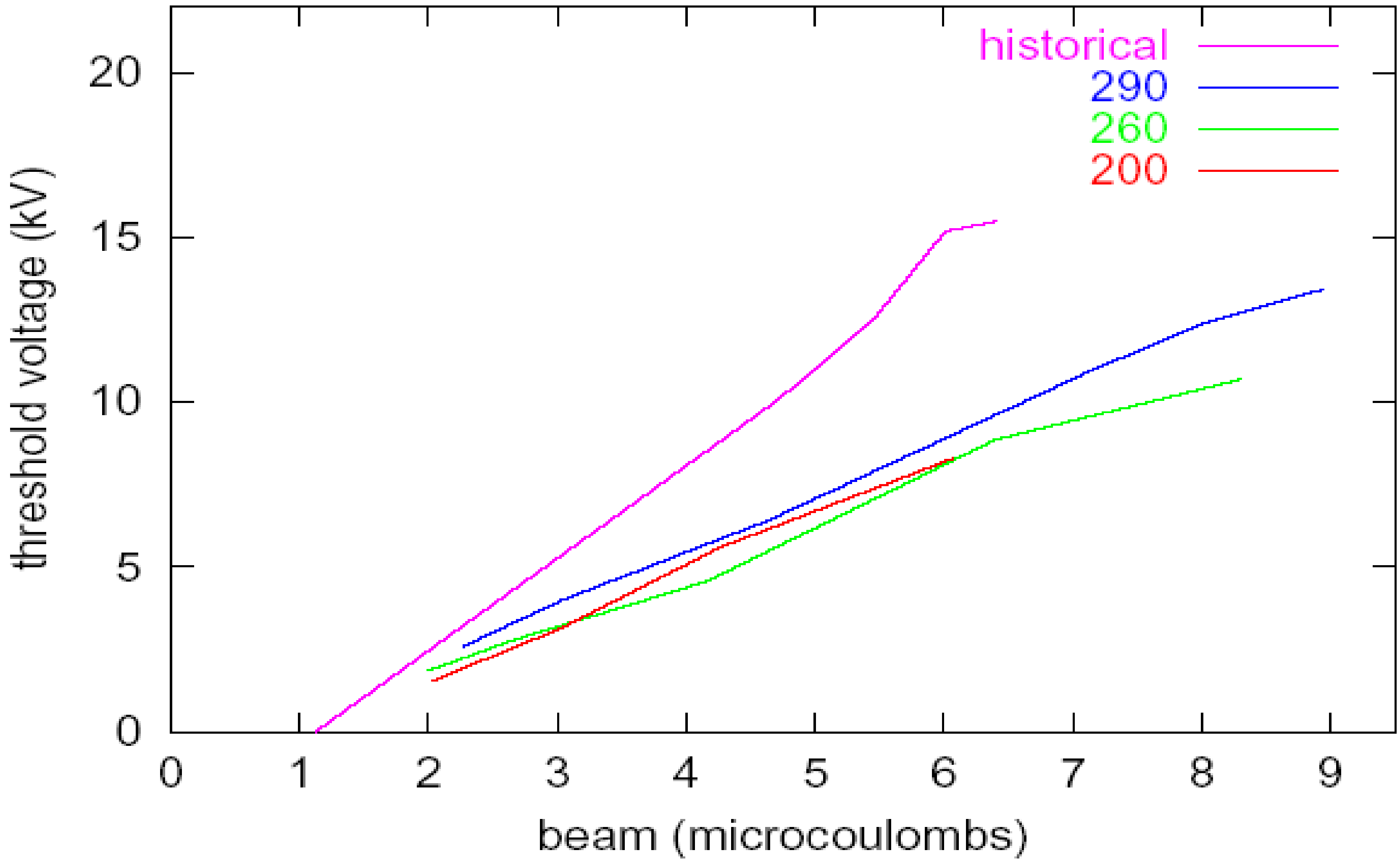
Outline

- Accelerator physics issues
  - Electron cloud generation
  - Stability simulation
  - Stability eigenmode analysis

PSR Threshold before and after long run for a range of bunch lengths (Courtesy R. Macek)



Electron Cloud Generation

Primary electrons are generated via losses and collisions with gas
Model loss rate proportional to instantaneous current
Along with secondary emission there is also the possibility of reflection
Microphysics gets very complicated
A simple parameterization is given by

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

$$\delta(E) = \delta_{\max} \times 1.1 \frac{1 - \exp[-2.3(E/E_{\max})^{1.35}]}{(E/E_{\max})^{0.35}}$$

If not reflected then use a Lorentzian distribution for secondary energy.

SNS electron clouds in straight sections

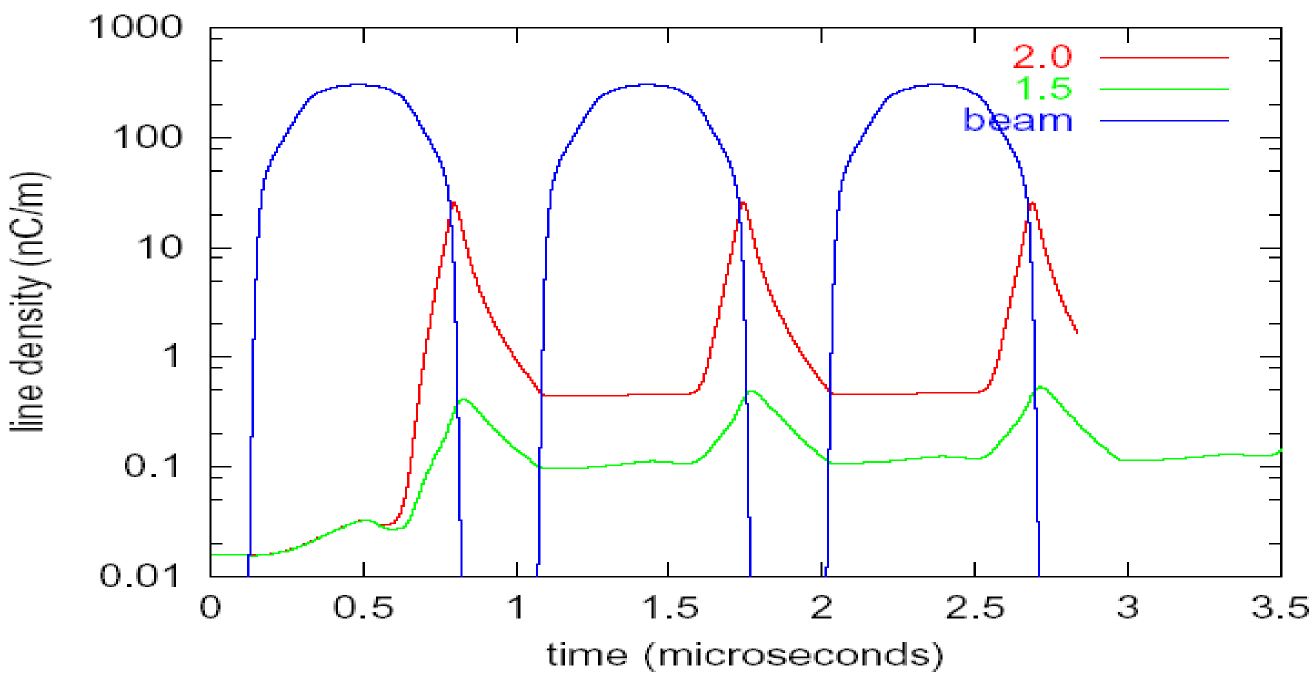
Wall conditions are somewhat uncertain for SNS

electron generation rates and reflectivity are important

Uses a fast cylindrically symmetric algorithm and simple SEY model

2 MW SNS, with E_{max}=300 eV, δ_{max}=1.5 and 2.0, loss rate $\propto$ I(t)

200 e per lost proton and 0.1% losses gives 2E8 e/m/turn



Electron-Proton Instability coasting beam scaling

- Characteristic tunes $$Q_e^2 = \frac{e\lambda_p}{2\pi\varepsilon_0 a^2 m_e \omega_0^2}, Q_p^2 = \frac{e\lambda_e}{2\pi\varepsilon_0 a^2 \gamma m_p \omega_0^2}$$
- Coasting beam tune shift $$\Delta Q_0 = \Delta Q_{sc} + i\frac{Q_p^2 Q_e}{2Q_\beta \delta Q_e}$$
- Coasting beam tune spread $$\delta Q_\beta = |\eta| Q_e \left.\frac{\Delta p}{p}\right|_{hwhm}$$
- Threshold assuming SC dominates magnitude of tune shift $$N_p \propto V_{rf} \tau_b^3$$
- For production length PSR beams the proportionality constant is reasonable
- Observed PSR threshold is roughly independent of bunch length
- Scaling with bunch length and inclusion of realistic clouds have been focus of simulations

Stability Simulations

- 20 to 200 electron cloud macroparticles and space charge kick implemented ≈10 times per betatron oscillation
- Cloud density at head of bunch is an input parameter
- Only vertical coherent forces on protons and linear RF force
- Contribution from straight sections greater than dipoles, model straights
- Electrons can multipactor, no loss driven production
- Macroparticle equations of motion

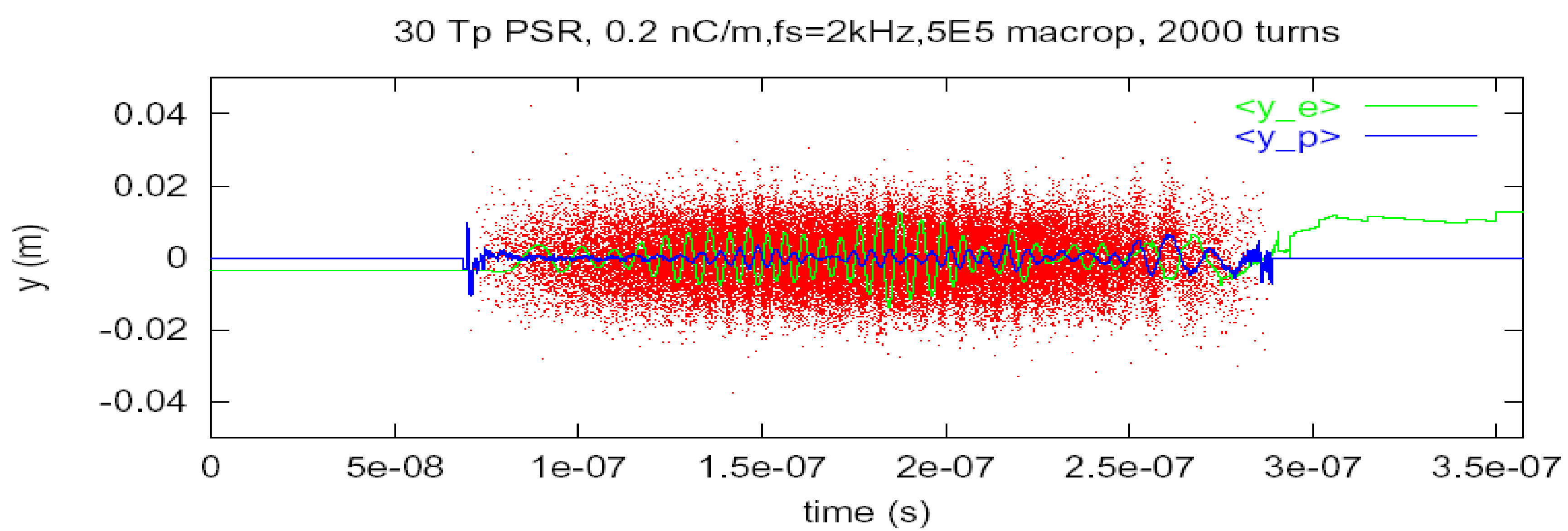
$$\frac{d^2 y_p}{d\theta^2} = -Q_y^2 y_p + C_{sc}\lambda_p(\theta,t)(y_p - < y_p(\theta,t) >) + F_e(\theta, y_p, t)$$

$$F_e = -\frac{e\lambda_e(\theta,t)}{2\pi\varepsilon_0}\frac{y_p - < y_e(\theta,t) >}{\sigma^2(y_e(\theta,t)) + \Delta x^2 + \Delta y^2}\frac{1}{\gamma m_p \omega_0^2}$$

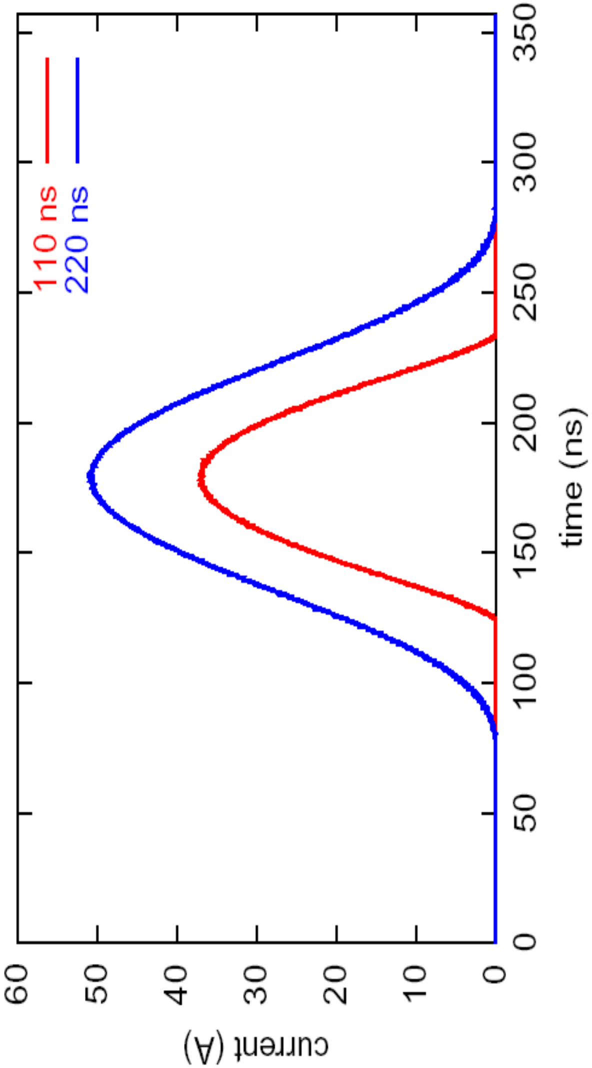
$$m_e\frac{d^2 y_e}{dt^2} = -\frac{e\lambda_p(\theta,t)}{2\pi\varepsilon_0}\frac{y_e - < y_p(\theta,t) >}{\max(a^2, \Delta x^2 + \Delta y^2)}$$

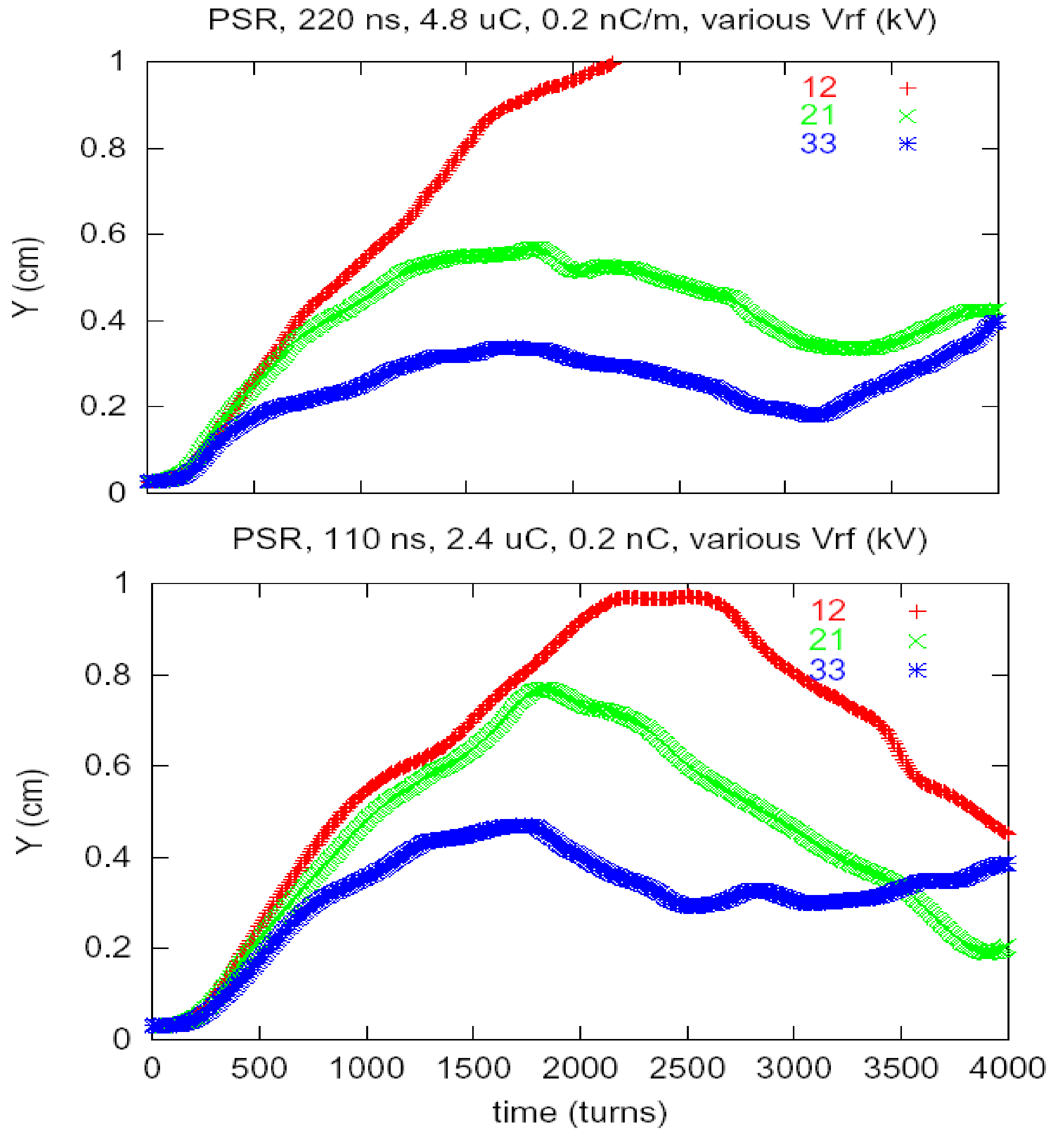
PSR simulations

- Did simulations for a range of bunch lengths, intensities, RF voltage, and electron densities.
- Electron densities of 1nC/m generally led to an explosive instability when other parameters were well below thresholds observed in the PSR.
- For smaller electron densities, found that beams that were unstable at small amplitude could reach a saturation amplitude and continue oscillating without filamentation.
- Data taken by R. Macek in PSR suggest a similar behavior in real beams with saturation amplitudes of order a millimeter



PSR simulations $Y^2 = \int (<y(t)>^2 + <y'(t)/Q_y>^2)\rho(t)dt$





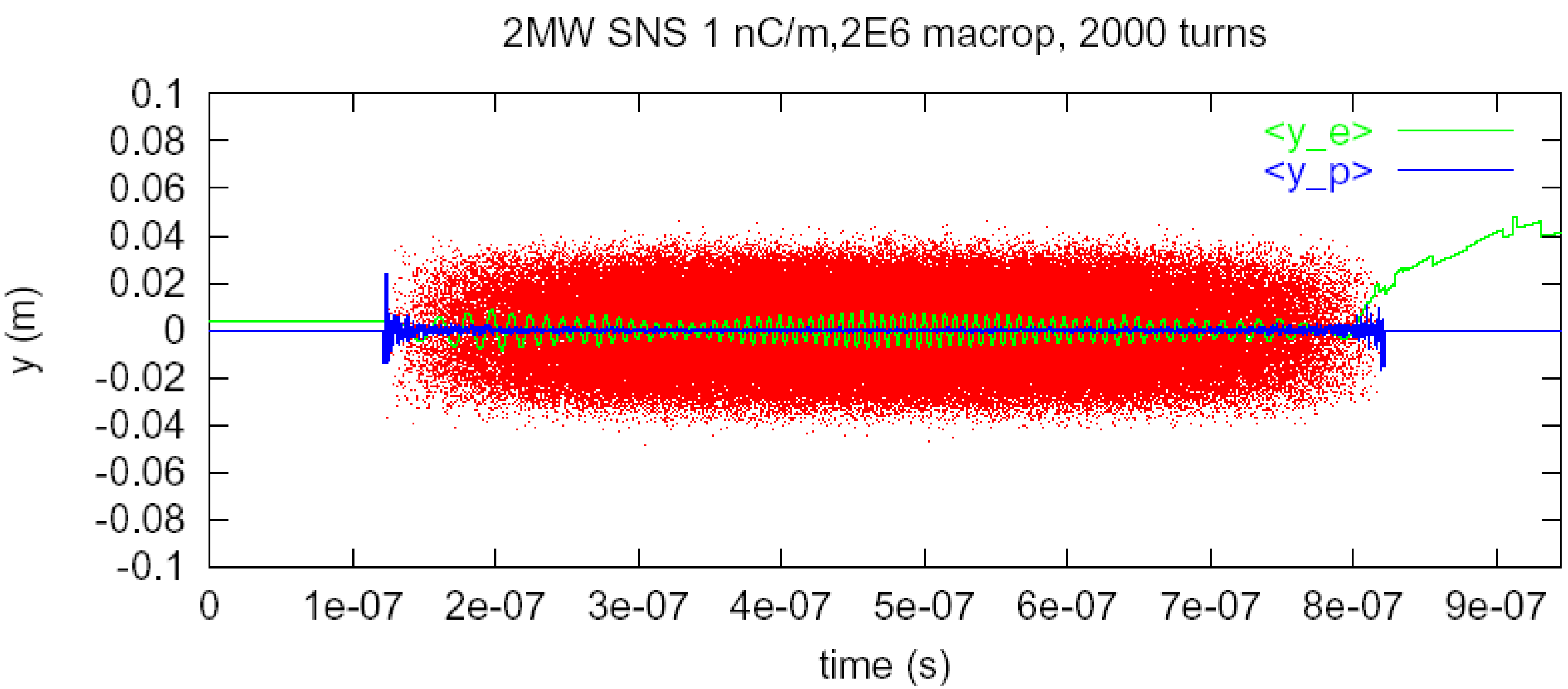
Comments on PSR simulations and SNS results

Simulations give threshold electron densities 20% of observed

Simulations need about 50% more RF than observed (11μH inductor)

Unclear where additional damping comes from

SNS predictions should be conservative



Eigenmode analysis

$$\frac{\partial x(\varphi,v,\theta)}{\partial\theta}+v\frac{\partial x}{\partial\varphi}+F_{well}(\varphi)\frac{\partial x}{\partial v}=i\Delta Q_{sc}[x(\varphi,v,\theta)-\overline{x}(\varphi,\theta)]$$

$$+i\frac{Q_p^2Q_e^2}{2Q_x\widetilde{Q}}\int_0^{\varphi}\overline{x}(\varphi_1,\vartheta)\sin[\widetilde{Q}(\varphi-\varphi_1)]\exp[-Q_e(\varphi-\varphi_1)/2Q_r]d\varphi_1$$

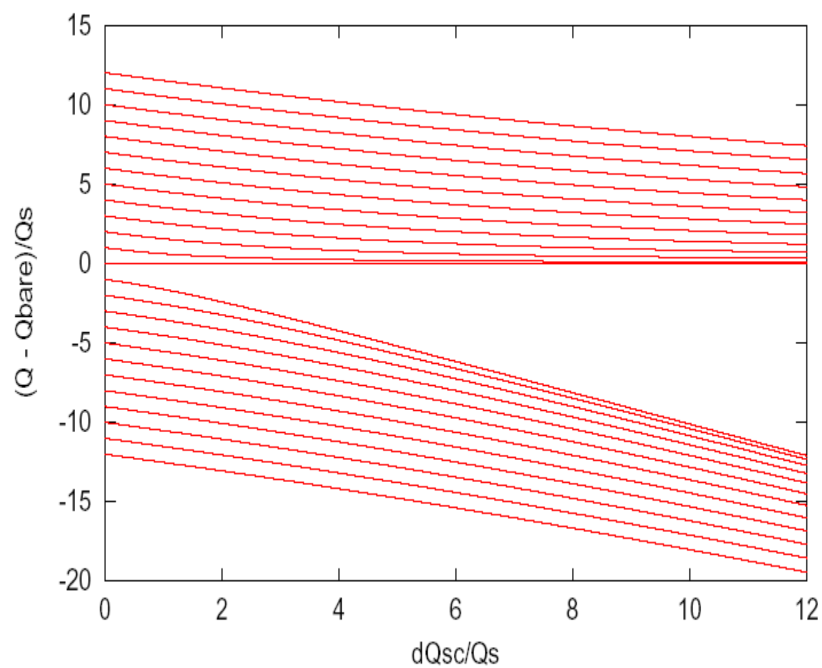
Approximate RF by a square well potential

Need tune eigenvalues of the PDE

This is fairly involved

Details in upcoming article

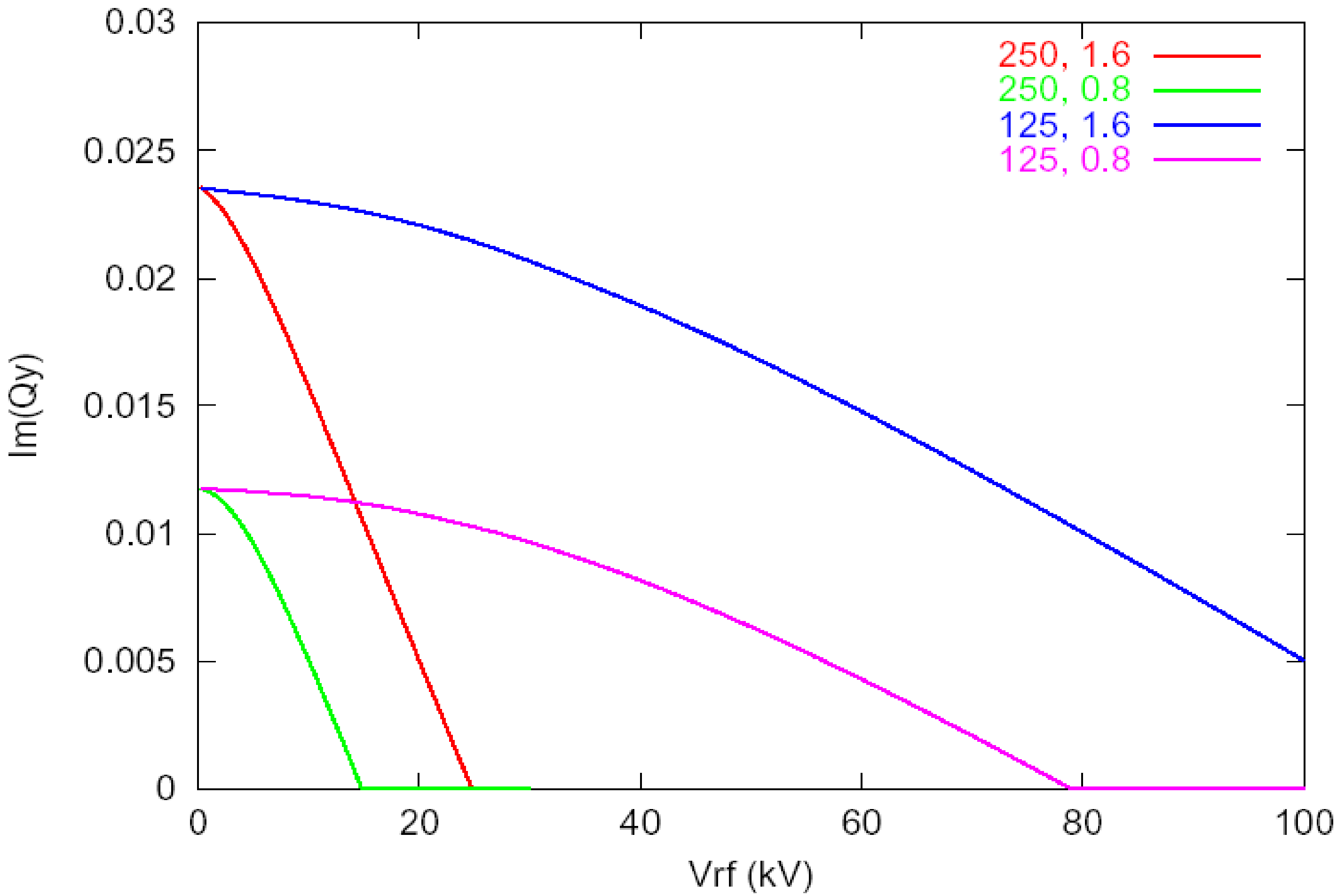
$$\Delta Q_{sc}\approx 100Q_s$$



Growth rates versus rf voltage

PSR growth rates

For various bunch lengths (ns) and electron densities (nC/m)



Coasting beam versus eigenmodes

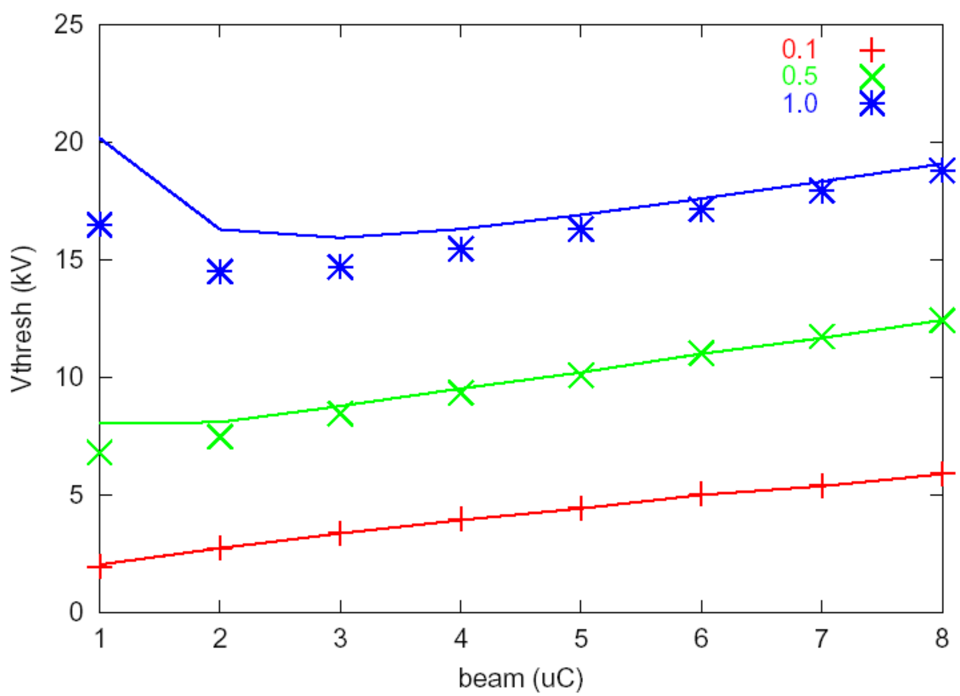
The symbols are the threshold from the eigenmode analysis for various electron densities (pure TMCI)

The solid line is the coasting beam threshold with same tune distribution

$$\Delta Q_0 = \Delta Q_{sc} + i\frac{Q_p^2 Q_e}{2Q_\beta \delta Q_e}$$

$$\delta Q_\beta = |\eta| Q_e \frac{\Delta p}{p}\bigg|_{rms}$$

$$1 = \Delta Q_0 \int \frac{\rho_{norm}(v)dv}{\Delta Q + i0 - v\delta Q_\beta}$$

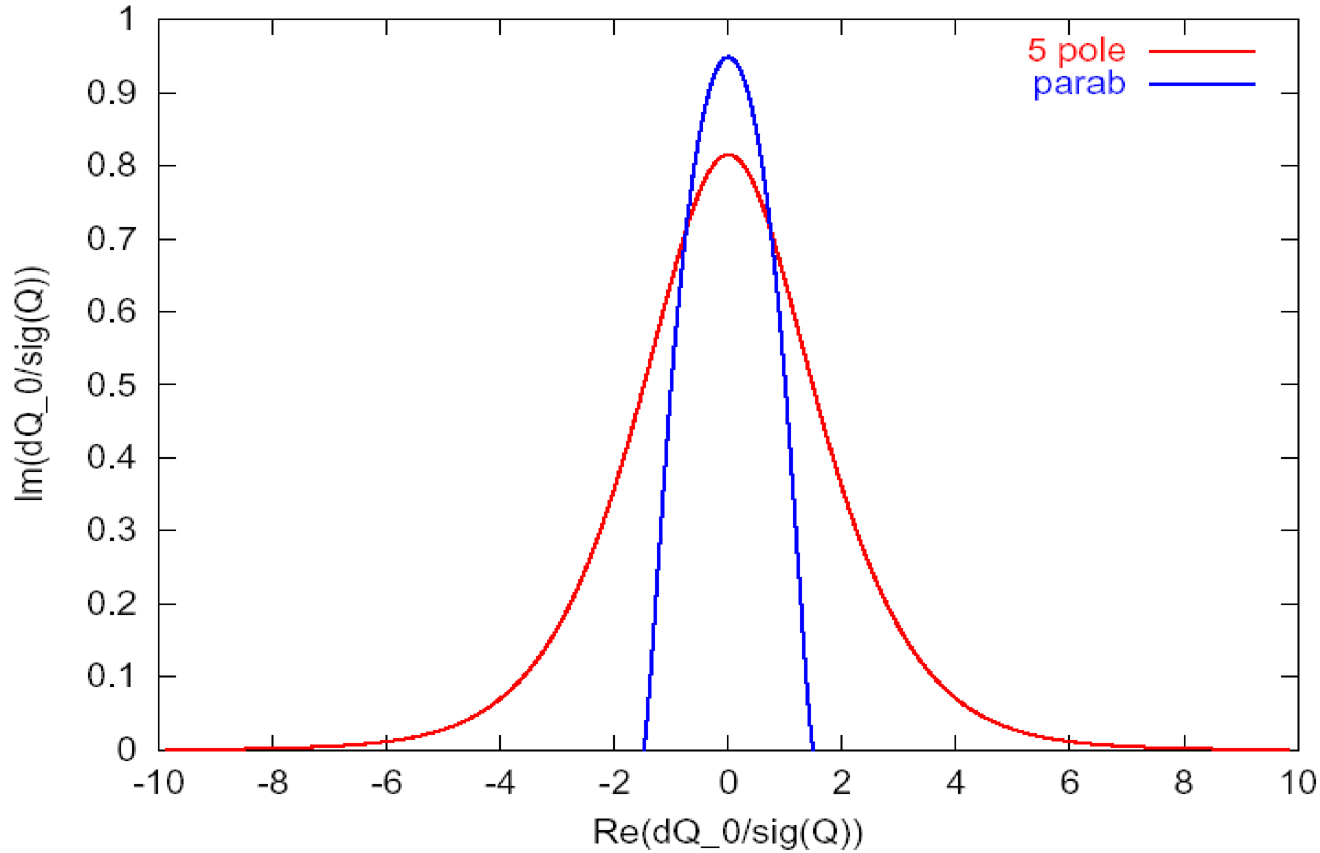


Devil is in the details

The momentum distribution used in the eigenmode analysis has long tails.

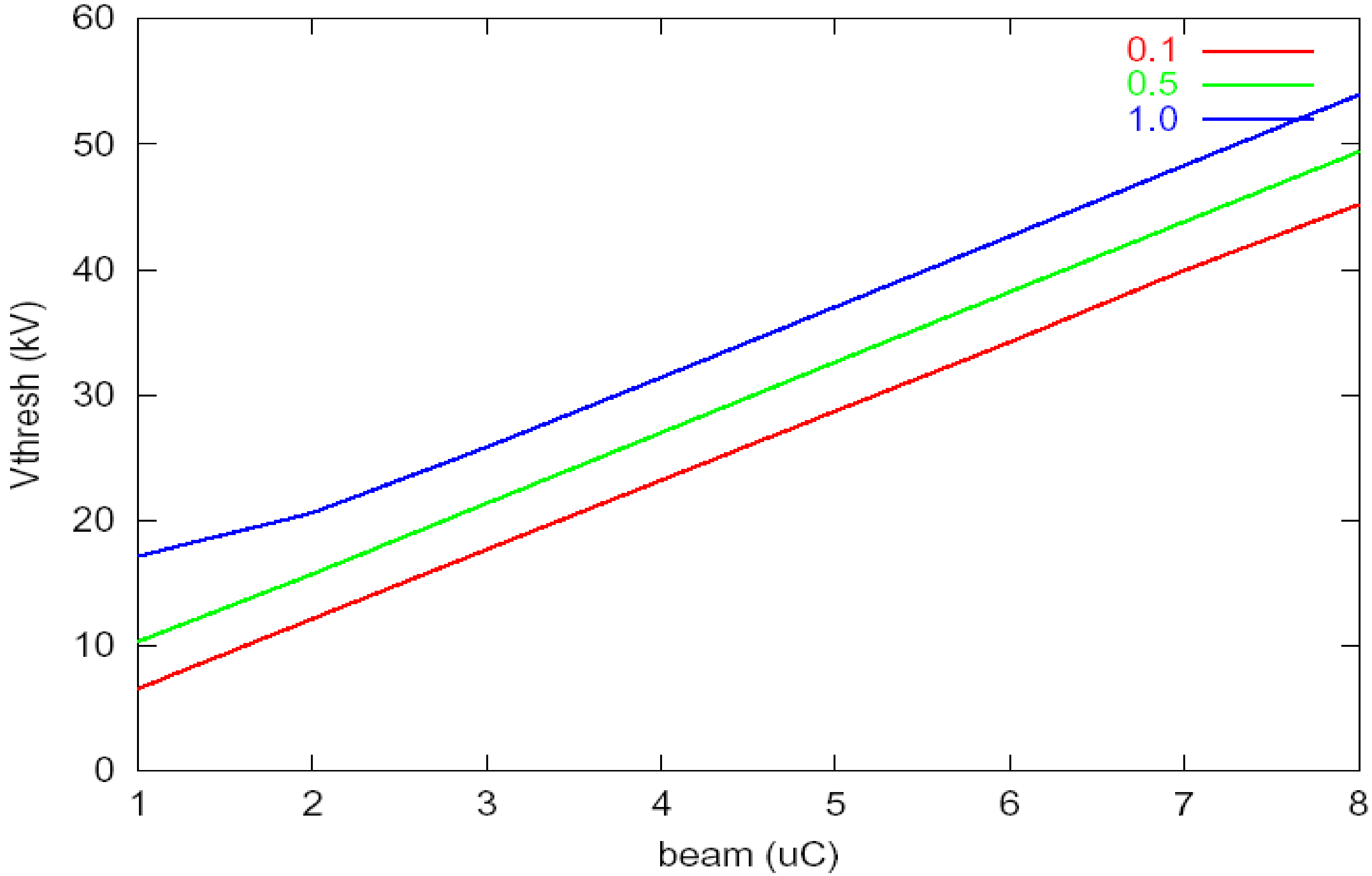
This has a strong effect on the coasting beam dispersion relation.

Compare eigenmode distribution to parabolic with same RMS tune spread



PSR is less stable with parabolic

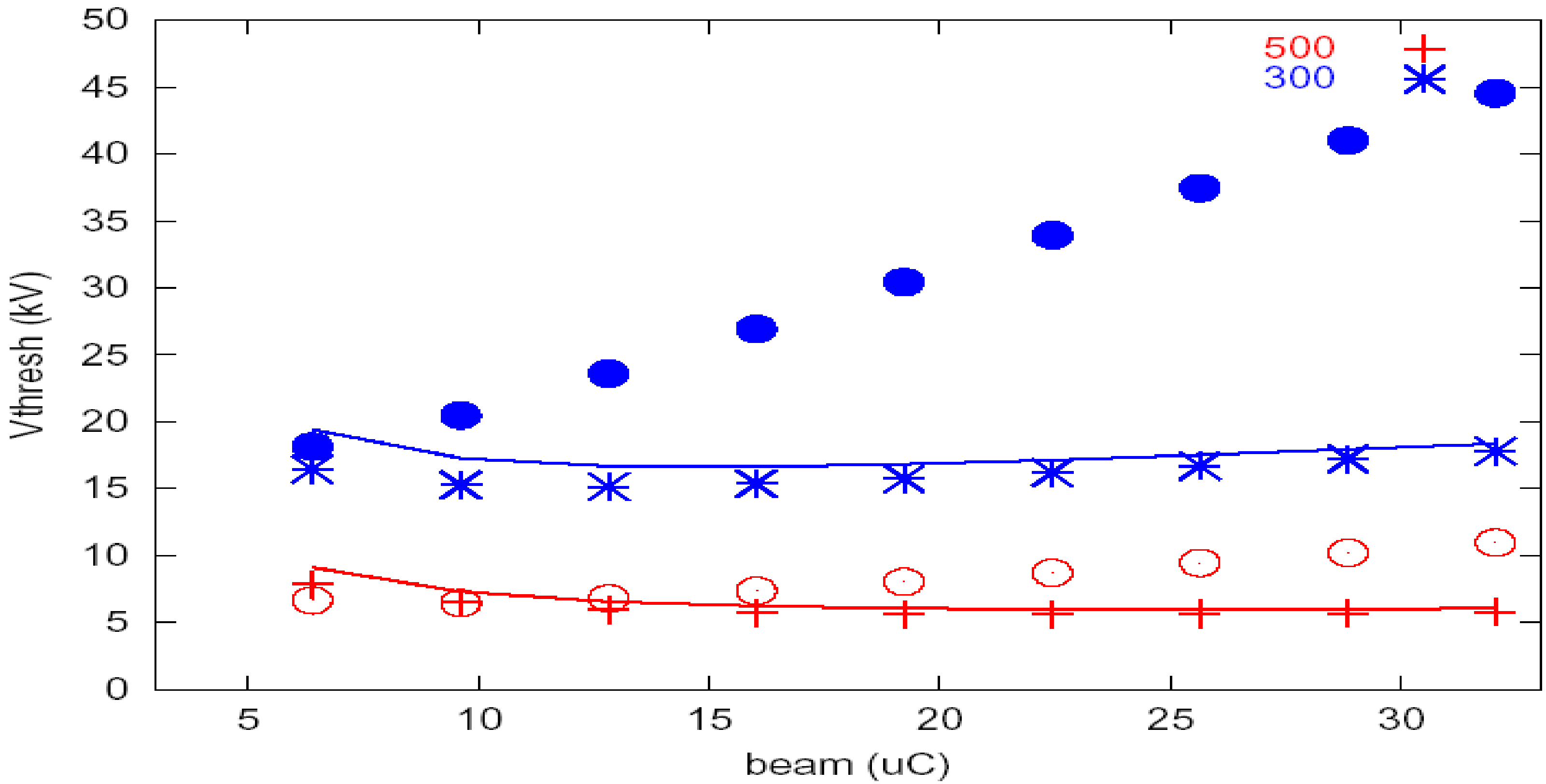
PSR with same inputs as previous page except using a parabolic momentum distribution



SNS still looks good

2 nC/m, for nominal bunch equivalent square has 500 ns length (700 ns true)

Lines are coasting beam 5-pole, stars are eigenmode analysis, circles are coasting beam with parabolic momentum density



Summary and Conclusions

Electron cloud simulations and measurements in PSR are in fair agreement, around 1 nC/m of electrons survive gap

Simulations of e-p instability in PSR show threshold for 0.2 nC/m, the reason for the discrepancy is unclear

Simulations of 2MW SNS are stable for 1 nC/m

1 nC/m is for fairly large reflectivity and SEY.

Eigenmode analysis for SNS looks good with >2 nC/m

Scrubbing effects will improve things even more.

Convergence test

$$\omega_e \tau_b = 5\pi$$

$$\Delta Q_0 = 0.10 + i0.05$$

$$\omega_0 \tau_b = 2\pi / 35$$

Needed many modes to see the beam breakup limit

Far fewer modes needed for reasonable threshold estimate

Coasting beam dispersion relation gave a good threshold estimate