PS2 Electron-Cloud: Status

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- **CERN contacts:** M. Benedikt, G. Rumolo, I. Papaphilippou, F. Zimmermann

Previous results (~CM13)

ecloud build-up:

- ecloud density in field-free regions larger by ~1-10 relative to dipoles
- 1–σ density: (a few)x10^{11} – (a few)x10^{12} m^{-3}
- LHC50 beam clearly favored over LHC25 in f.f. regions
- There is a generic non-monotonic dependence of ecloud density n_e as a f. of bunch intensity N_p
  - n_e is larger at N_p~(1–3)x10^{11} than at the higher (nominal) N_p
- Sensitivity to chamber radius in f.f. sections is strongly dependent on N_p
  - weak dependence at nominal N_p

Effects of ecloud on the beam:

- Clear threshold of instability at n_e~0.5x10^{12}
  - This value is in the mid-range predicted by the build-up simulations
- Clear beneficial effect of negative chromaticity: increases threshold in n_e
  - And detrimental effect of positive chromaticity
- Simulation variables: spot-checked for numerical stability
- Excellent agreement with HEADTAIL code

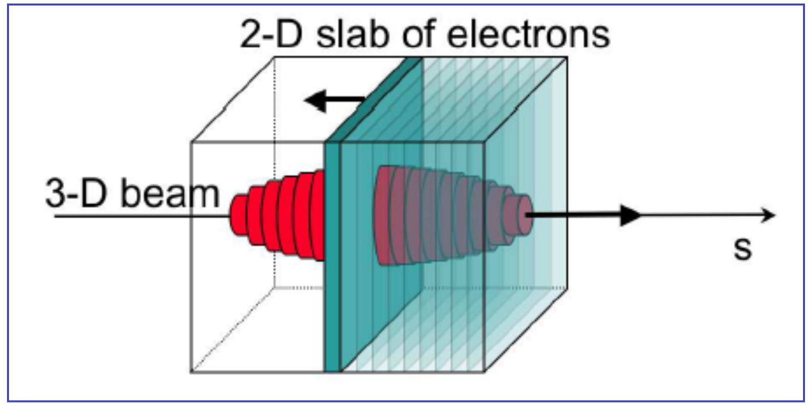
Progress since then

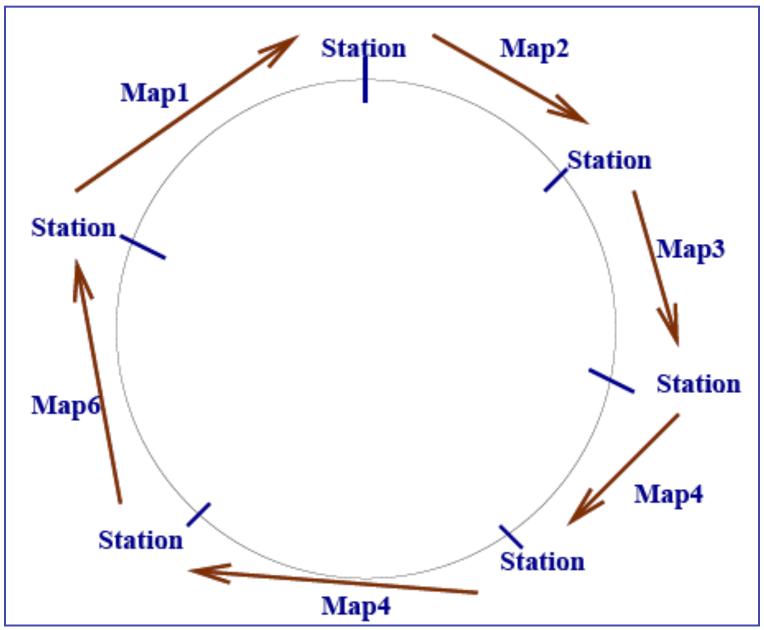
- Ecloud build-up:
  - A few odds and ends (numerical checks, computation of beam neutralization,...)
  - Continuing comparisons with FNAL Main Injector

- Effects of ecloud on the beam (work by Marco Venturini):
  - Most of recent effort
  - Numerical model refinements
  - Apply linear theory of TMCI to ecloud instability
    - Applicability is much more restrictive than simulations, but may provide insights
    - Casting ecloud-induced instability allows contact with , and profit from, conventional instability analysis and lore

Model for beam-ecloud interaction (single bunch) as implemented in Warp/POSINST

- Smooth approximation assumed for lattice
- Beam-cloud interaction localized at stations uniformly distributed along lattice





- Beam-cloud interaction is strong-strong, in the quasi-static approximation (beam particles don't move while interacting w/ cloud).
- Gaussian longitudinal charge density
- Electrons confined to 2D transverse slab, with initial uniform density. Same e-density assigned to each station; refreshed after each beam passage
- Electron motion confined to vertical lines (models e^- orbit in magnetic field).

Parameters used in simulations

Beam, lattice parameters(*)

~Injection

Energy	5 GeV
γ_T	35i
N_p	$5.9(4.2)\mathrm{x}10^{11}$
ν_x	13.25
ν_y	8.2
ν_s	$1.2\mathrm{x}10^{-2}$
σ_x	6 mm
σ_y	5.7 mm
σ_z	0.9 m

Extraction

Energy	50 GeV
γ_T	35i
N_p	$5.9(4.2)\mathrm{x}10^{11}$
ν_x	13.25
ν_y	8.2
ν_s	$7.7\mathrm{x}10^{-4}$
σ_x	1.9 mm
σ_y	1.7 mm
σ_z	0.3 m

(*) These parameters might not be the most recent

Other parameters

Chamber sizes (rectangular)	a=6 cm b=3.5 cm
No. macroelectrons	16k
No. beam macroparticles	>300k(**)
No. long slices	64
Grid size	128*128
No. beam-ecloud stations N_{st}	40(***)

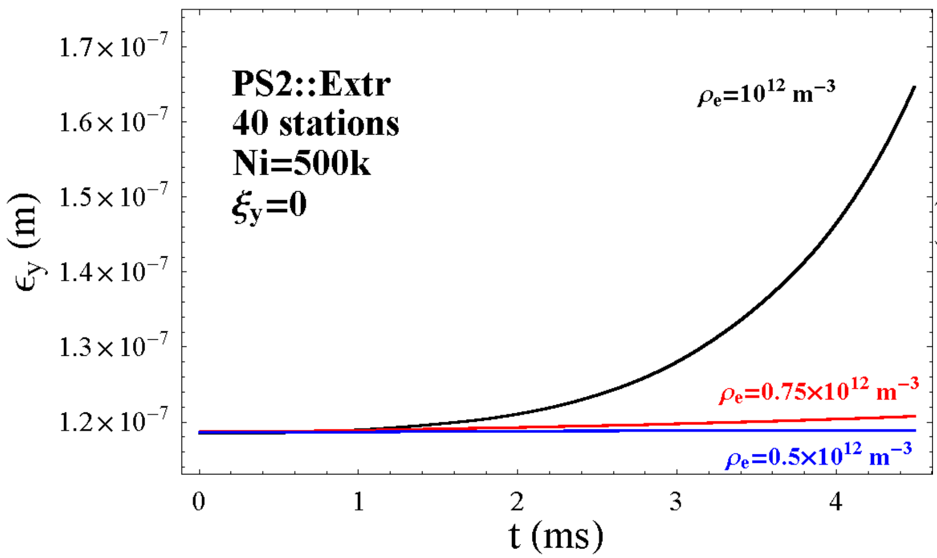
(**) old value=10k

(***) old value=10. Note: new value of N_{st} is >4 stations per $\lambda_{\beta y}$, ie., well resolved

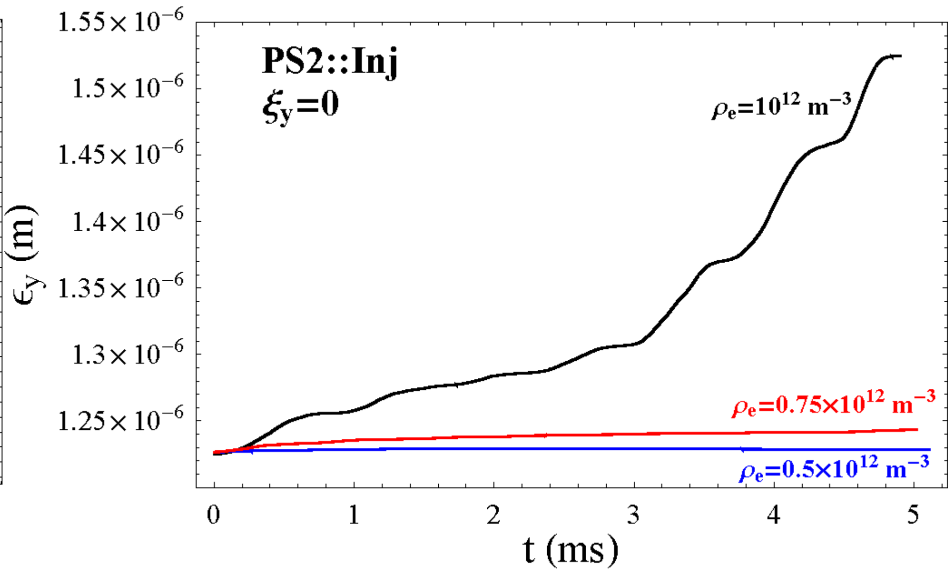
Simulations identify an instability threshold at $\rho_e \approx (0.5\text{-}0.75) \times 10^{12}\ m^{-3}$ for $N_p = 5.9 \times 10^{11}$

- Instability develops for e-cloud density $\rho_e \approx (0.5 \sim 0.75) \times 10^{12}\ m^{-3}$ (at zero chromaticity)
- Large number of macro-protons (>300k) insures numerical stability
- Same e-cloud density assumed at all interaction stations

Extraction

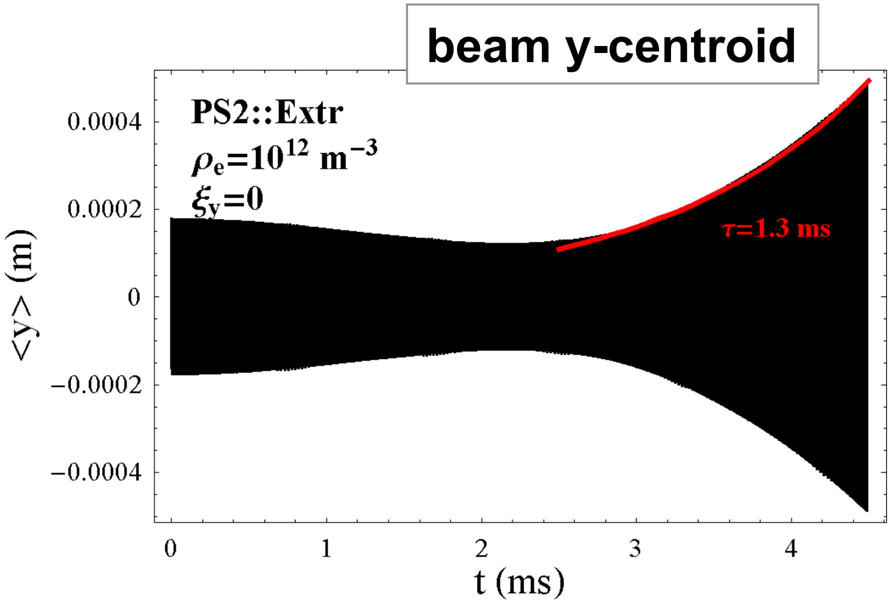


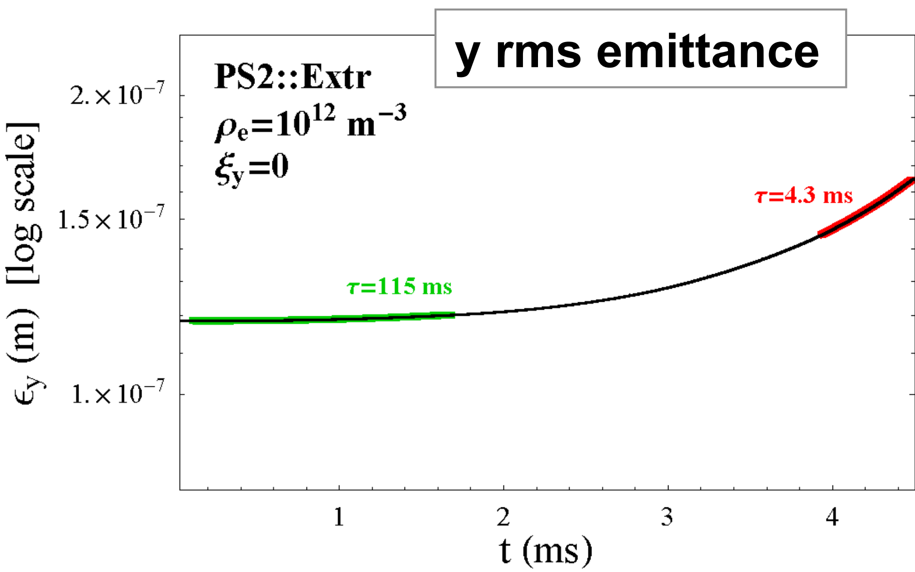
Injection



- Thresholds are surprisingly similar at extraction and injection.

Emittance growth correlated with unstable centroid motion



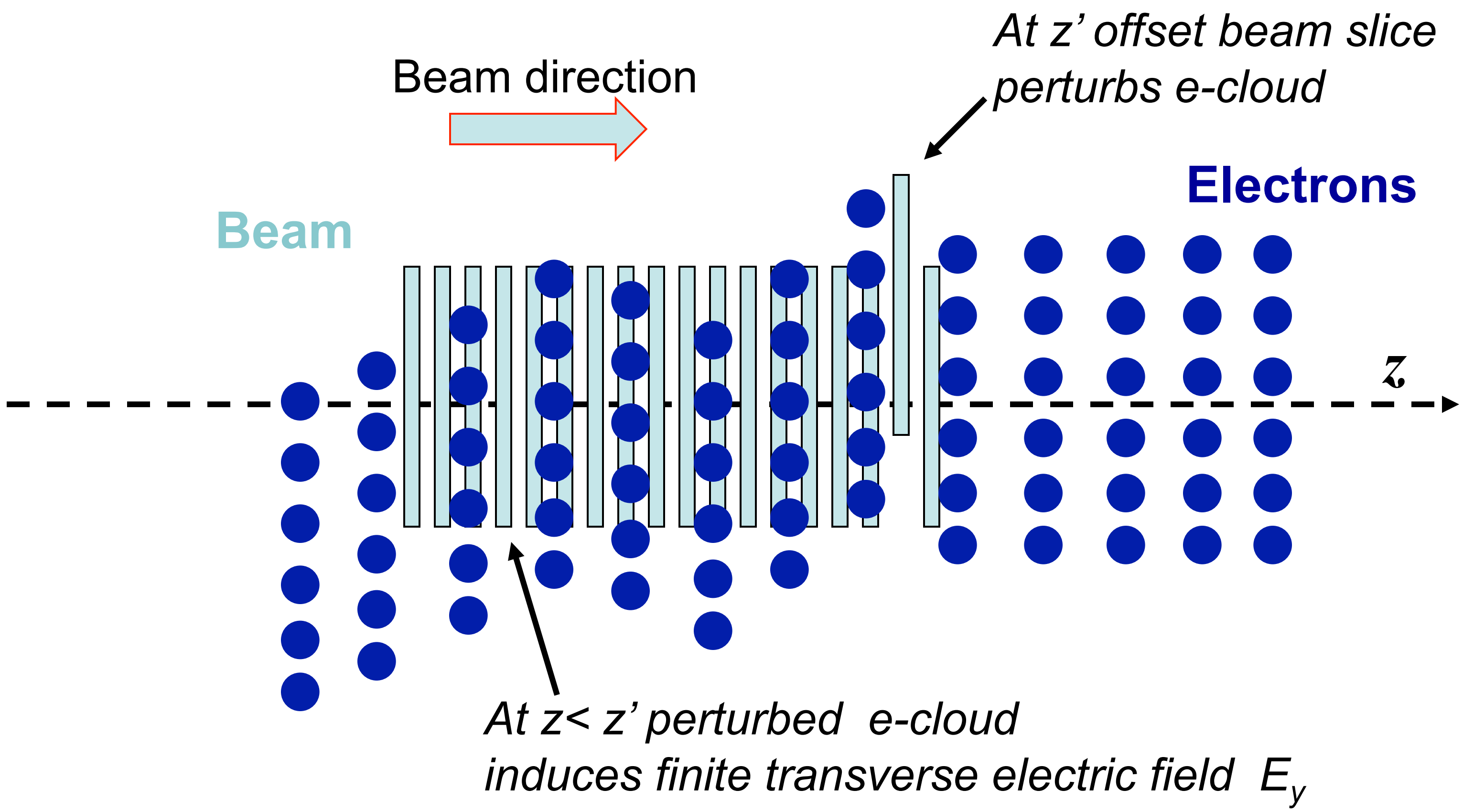


- Exponential growth in amplitude of beam centroid sets in after ~2 ms
- Instability appears to be main drive emittance growth but some emittance growth already apparent at < 2 ms
- NB: simulated instability is seeded by Δy_0=0.0002 m to "get it going" quickly

← **4.5 ms ≈ 1000 turns**

Attempt to apply TMCI theory to the determination of instability threshold

- TCMI theory requires a model of wake potential to describe the effect of electrons on beam



Dipole wake potential induced by e-cloud:

$$W_y(z,z') = -\frac{eE_y(z)}{mc^2 r_e}\frac{L}{\langle y(z')\rangle N_b \rho(z')\Delta z'}$$

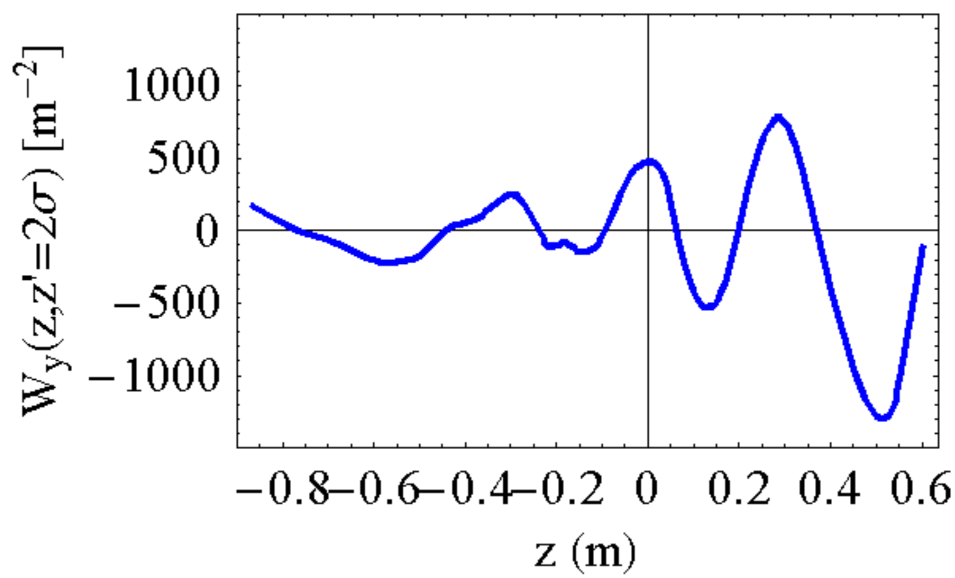
Broad-Band resonator model for e-cloud induced wake

So far attempts to apply TMCI theory to e-cloud have made use of a simplified model of wake potential forcing the wake to be in the form of a BB resonator $W_y = W_y(z - z')$:

$$W_y(z-z') \propto e^{\alpha(z-z')/c} \sin\left(\frac{\varpi(z-z')}{c}\right)$$

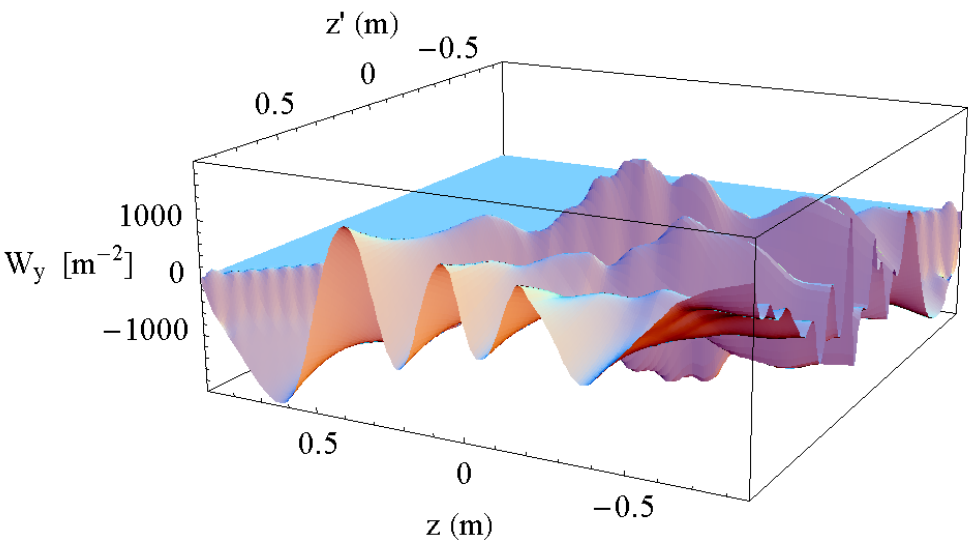
Example of e-cloud induced wake as calculated from POSINST (z' fixed, vary z).

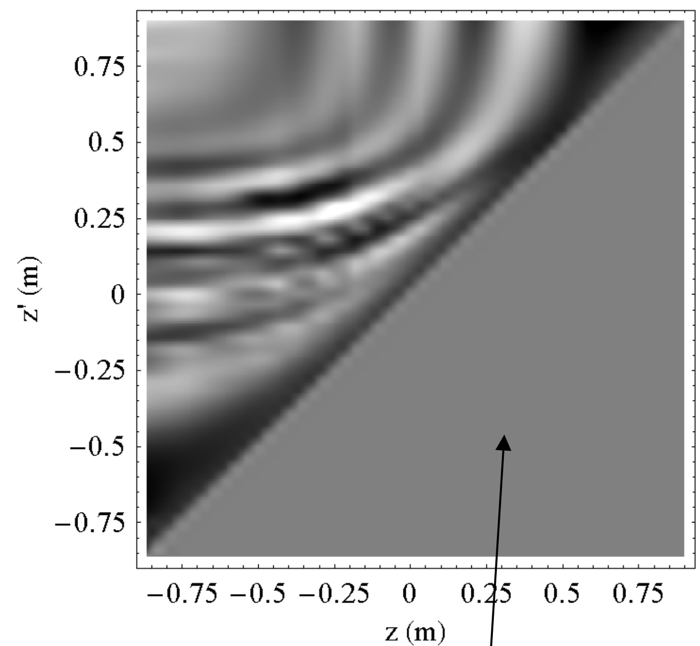
wake is reminiscent of BB model but in general does not exhibit a simple dependence on (z-z')
-- see next slide



E-cloud induced wake potential is more complex than BB resonator model

- You can't expect W_y to be a function of z–z' because, unlike wakes produced by the chamber, the electron cloud is dynamical
- Indeed, plots of W_y in the (z,z') plane shows that it is a function of z, z' separately rather than z-z'





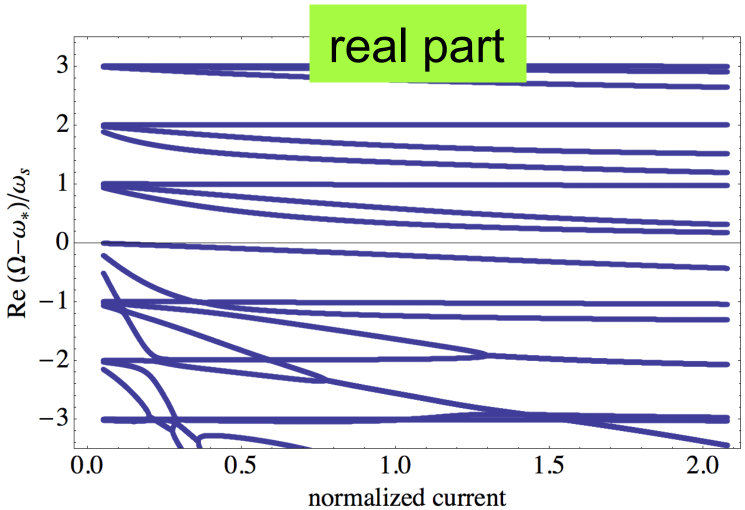
- Wake calculated using POSINST with PS2 beam parameters at extraction
- Gaussian proton beam (51 slices)
- Initially uniform e-density (10^{12} m^{-3})

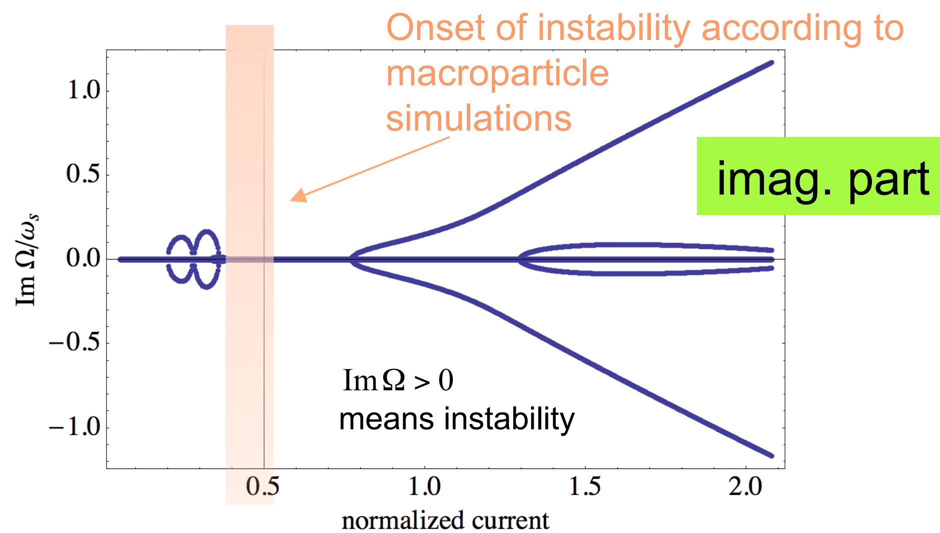
W_y~0 here because of causality

Apply e-cloud induced wake W(z, z') to linear theory for TMCI

- Perevedentsev (ECLOUD'02) generalized TMCI linear theory to include the case of a generic wake W(z,z'), rather than W(z-z')
  - … but to the best of our knowledge this theory has never been applied.

Linear analysis for PS2 beam parameters at extraction with assumed e-density $n_e = 10^{12}$ m^{-3}: eigenfrequencies of the beam density modes





Normalized current: $I = \dfrac{N_b r_e c}{2\gamma \nu_y \omega_s} \sim 0.52\ \mathrm{m}^2$ for $N_b = 5.9 \times 10^{11}$

Conclusions

Ecloud build-up

- nothing qualitatively new; previous results seem stable against computational parameter checks

Effects of ecloud on the beam

- We improved the numerical stability of simulations
  - more beam macroparticles
  - more beam-ecloud stations
- PS2 parameters at extraction:
  - Newer results basically confirm preliminary finding reported at CM13. Onset of instability is predicted for e-density right below $\sim 10^{12}$ m^{-3}.
  - Instability threshold in n_e at injection comparable to that at extraction.
- We applied the TMCI theory to predict the instability threshold
  - Used a realistic model of e-cloud induced wake potential (computed numerically using POSINST)
  - Model is an improvement over BB resonator wake used in the past
  - The threshold from linear theory is within 50% of value obtained from macroparticle simulations

What's next (pre-Chamonix list)

Ecloud build-up:

- Numerical refinements
- Increase understanding from side-by-side comparisons with Main Injector
- Simulate ecloud in quads and other regions

Ecloud effects on the beam:

- Improve macroparticle simulation, e.g. remove vertical-motion constraint
- Better analysis of macroparticle simulations
  - Compute tunes for all beam slices
  - Apply FFT techniques to connect simulations to more conventional analytic theory (e.g., similar to SPS feedback simulation work; talks by J. Fox, C. Rivetta, J.-L. Vay tomorrow)
- Use updated PS2 parameters
- Make n_e vary from station to station
- Make $dn_e/(dxdy)$ non-trivial (use ecloud build-up code output)
- Improve lattice description (true optics vs. constant focussing)
- Multibunch simulation: 2-3 bunches seems realistic