PS2 Electron-Cloud Build-Up Studies: Status

LARP CM13
Danford's Inn (Port Jefferson), November 4-6, 2009

Miguel A. Furman
LBNL
mafurman@lbl.gov

- **Team:** M. Furman, M. Venturini, J.-L. Vay, G. Penn, J. Byrd, S. de Santis (LBNL); M. Pivi, L. Wang, J. Fox, C. Rivetta (SLAC); R. de Maria (BNL).
- **CERN contacts:** M. Benedikt, G. Rumolo, I. Papaphilippou, F. Zimmermann, J. M. Jiménez, G. Arduini, F. Caspers.

Summary

- Previous results presented at CM12 (Napa, April 2009):
  - Examined ecloud density build-up in dipoles only
  - Considered LHC25 or LHC50 beams, at injection or extraction energy
  - Checked numerical convergence of simulations
  - Quantified sensitivity to peak SEY $\delta_{max} = \delta(E_{max})$ for δ_{max} =1.2, 1.3, 1.4, while keeping E_{max} = 293 eV = fixed

- New results (this presentation):
  - Examined build-up simulations in field-free regions
  - Studied sensitivity to chamber radius in field-free regions
  - Studied sensitivity to E_{max} in dipoles
  - Obtained first results on <u>effects from the ecloud on the beam</u>
    - With 3D code WARP
    - Studied single-bunch effects only
    - Studied sensitivity to certain numerical parameters and to chromaticity
    - For detailed questions, please ask Marco Venturini

Goals of PS2 ecloud studies

1. Predict as closely as possible the EC density n_e and its distribution
2. Use n_e and its distribution as inputs to understand effects on the beam
   - Coherent single- and multi- bunch instabilities
   - Emittance growth
3. Assess mitigation mechanisms if necessary
   - Low-SEY coatings
   - Grooved surfaces
   - Clearing electrodes
   - Feedback system (similar to SPS (*) if necessary and feasible)
4. Possibly combine EC with space-charge studies
   - EC provides a local, dynamical, neutralization of the beam
5. Maintain an ongoing side-by-side comparison against MI upgrade
   - Measurements and code validation at the MI are likely to bolster PS2 studies

(*) See talk by J. Fox

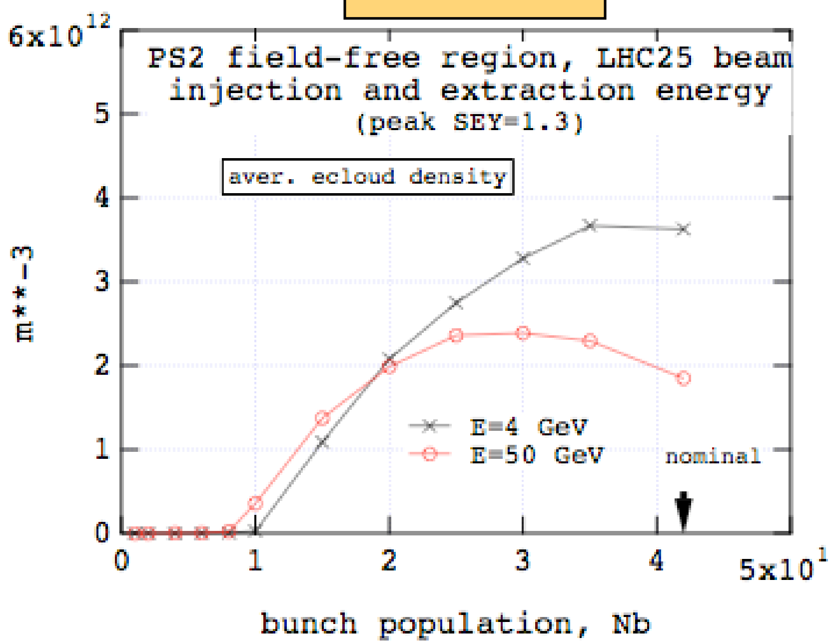
Assumptions for build-up simulations

1. C=1346.4 m, h=180, f_{RF}=40 MHz
2. Beam energy: KE_{inj}=4 GeV, KE_{extr}=50 GeV
3. Dipole bending magnet: B=0.136 T @inj., 1.7 T @extr.
4. Beam fill patterns:
   - "LHC25": 168 full consecutive + 12 empty buckets, s_b=25 ns, $N_b=4.2\times10^{11}$
   - "LHC50": 84 full every other + 12 empty buckets, s_b=50 ns , $N_b=5.9\times10^{11}$
5. Bunch length: σ_t=3 ns @ inj., σ_t=1 ns @ extr.
6. $\varepsilon_x=\varepsilon_y=6.5\times10^{-6}$ m–rad (RMS, normalized)
7. (β_x, β_y)=(30, 26) m at dipole magnet (neglect bunch dispersive width)
8. Bunch shape: 3D gaussian
9. Elliptical chamber cross section semi-axes:
   - Dipole: (a,b)=(6, 3.5) cm
   - Field-free region: a=b=4, 5 or 6 cm
10. Peak SEY: $\delta(E_{max})$=1.3=fixed, but E_{max} ranged in 200–400 eV
11. Computational parameters:
    - Macroelectrons=20k (for build-up simulations)
    - Integration time step: $\Delta t=3\times10^{-11}$ s
    - Space-charge grid: 64x64 [just enough to cover (2a)x(2b) area]

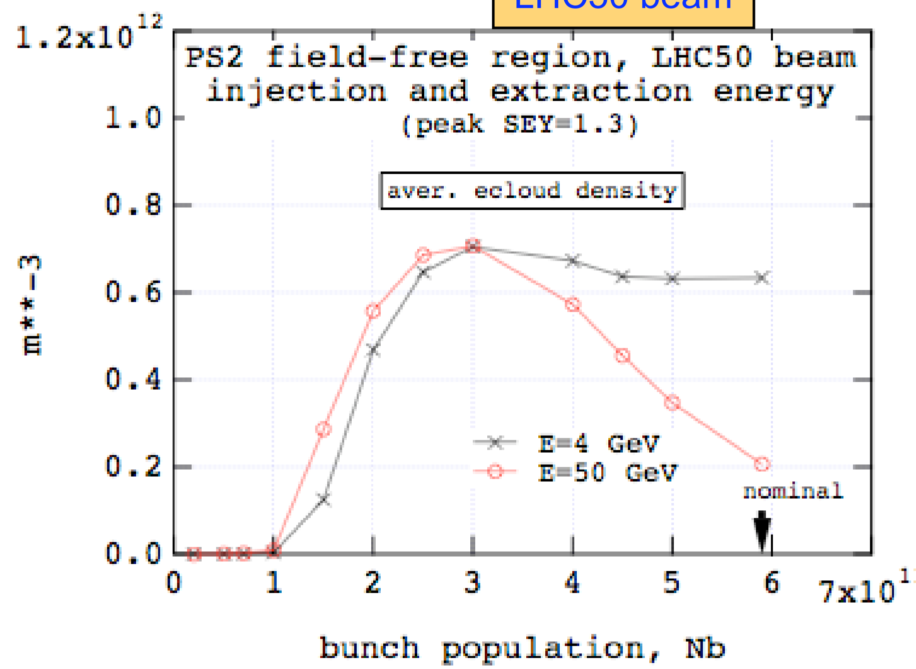
Field-free section: ecloud density n_e at 4 & 50 GeV

δ_{max}=1.3, E_{max}=293 eV

LHC25 beam



LHC50 beam

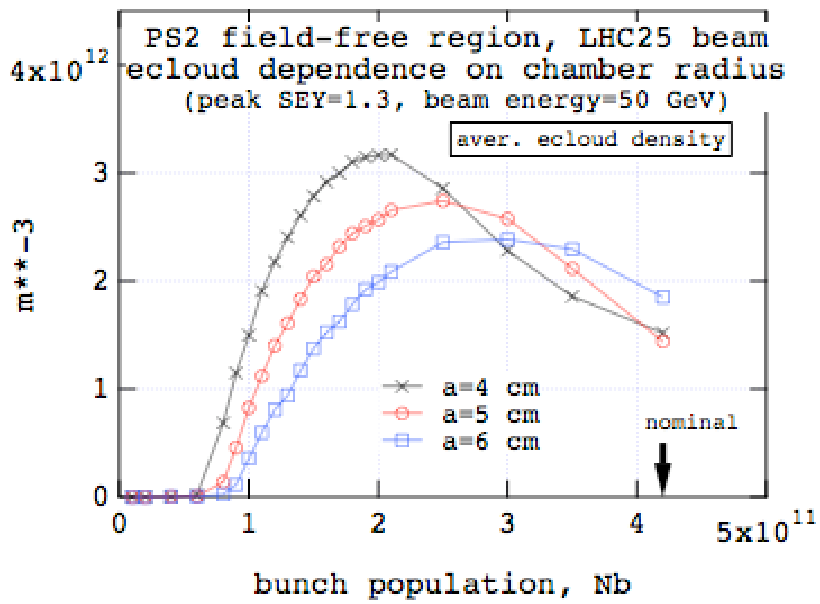


- Ecloud density higher in f.f. sections than in dipoles (see slide #8)
- LHC50 beam better (lower n_e by x2-4) than LHC25
  - not a surprise; similar to dipole case
- Non-monotonic behavior of $n_e(N_b)$ qualitatively understood as being due to e^--wall impact energy $\langle E_{wall} \rangle$ crossing E_{max} at N_b~(1-3)x10^{11}

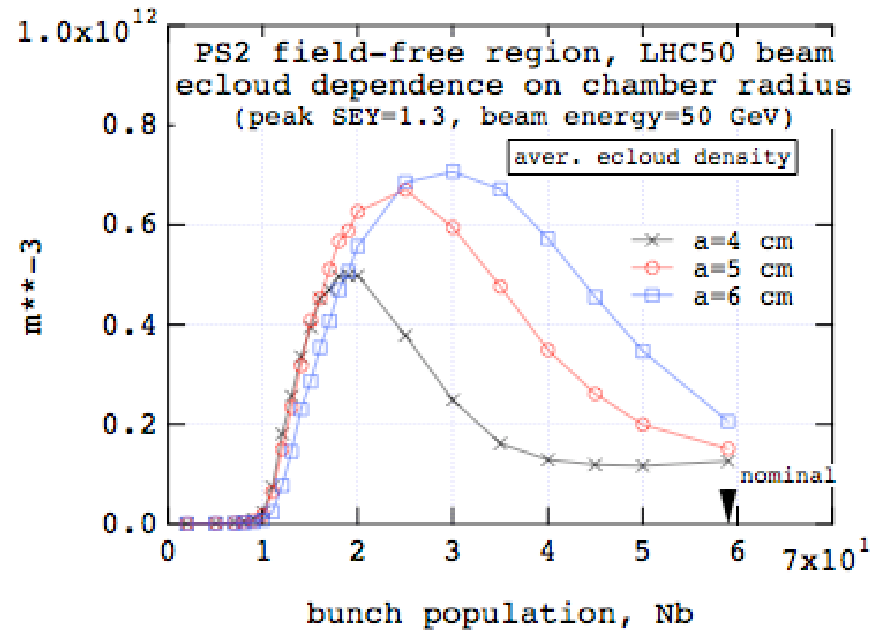
Field-free section: sensitivity to chamber radius

E_b=50 GeV, δ_{max}=1.3, E_{max}=293 eV

LHC25 beam



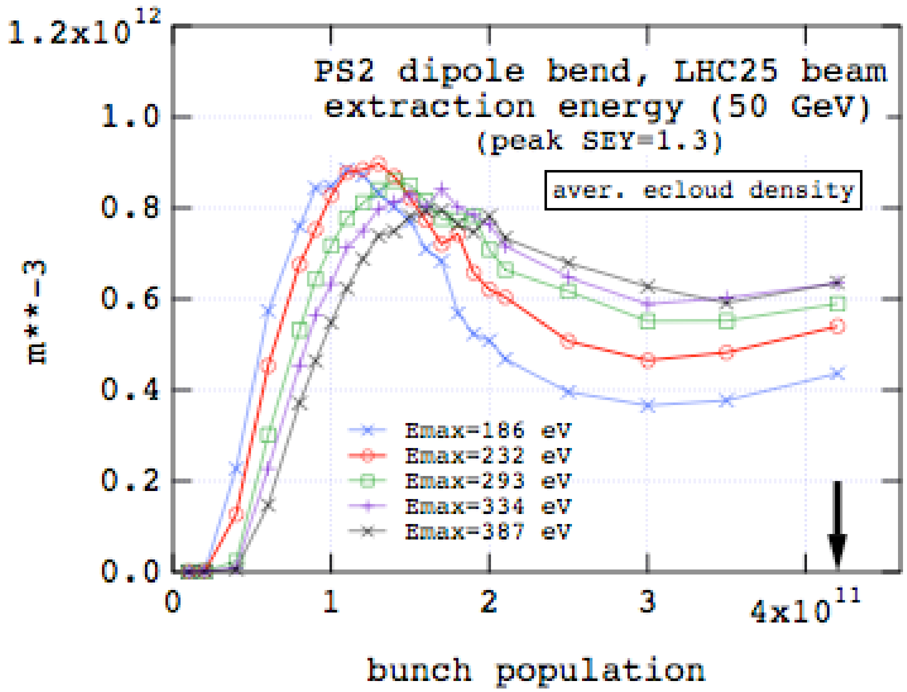
LHC50 beam

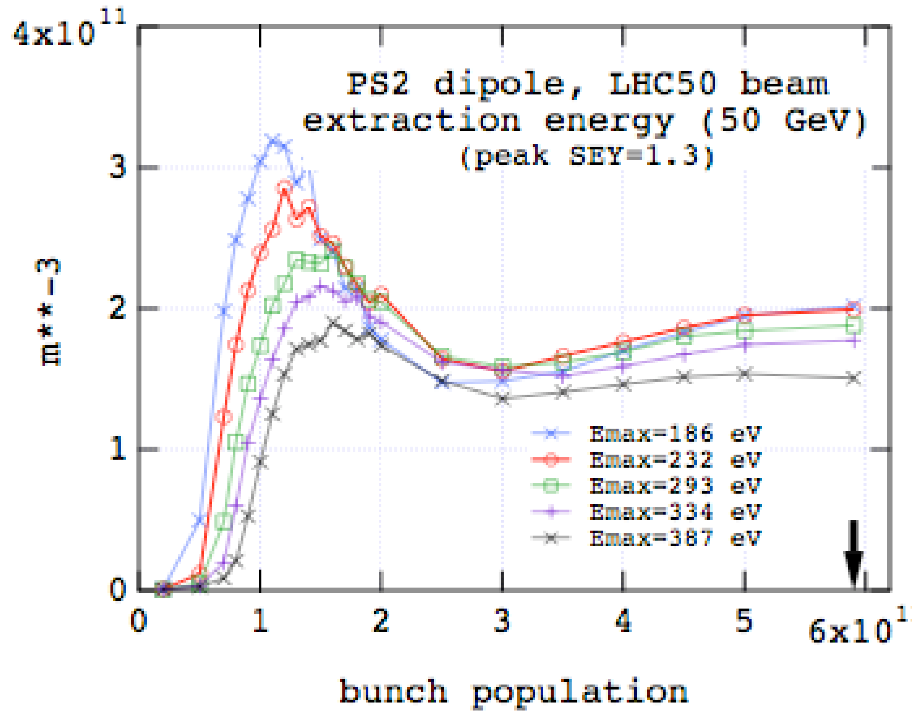


- Not much sensitivity to chamber radius at low N_b nor at nominal N_b, but possibly significant at intermediate values of N_b
- Only E_b=50 GeV looked at so far

Dipole: sensitivity to E_{max}

E_b=50 GeV, δ_{max}=1.3



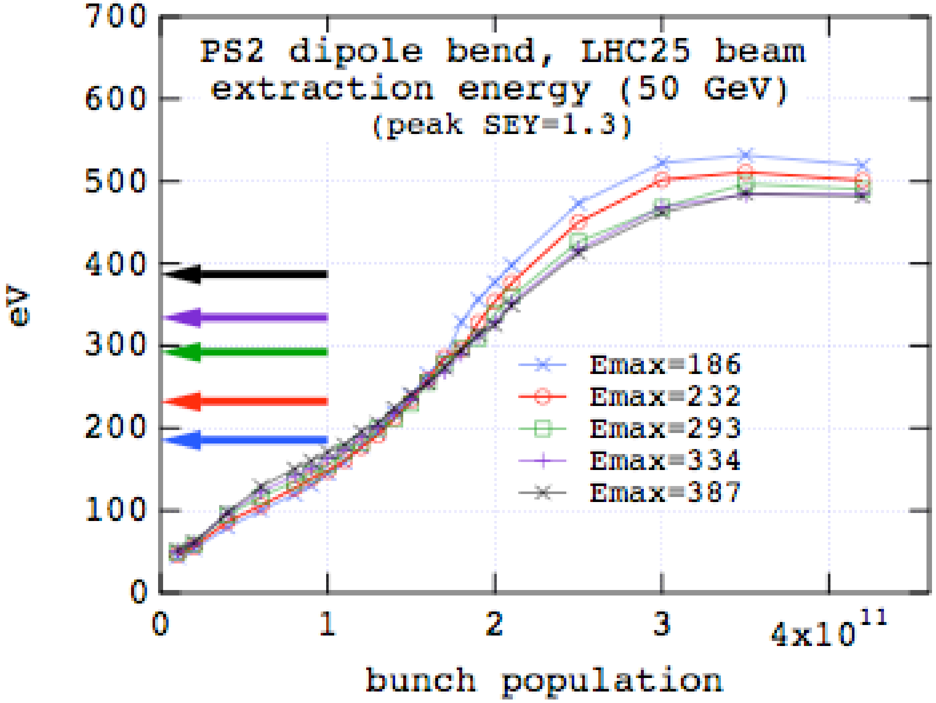


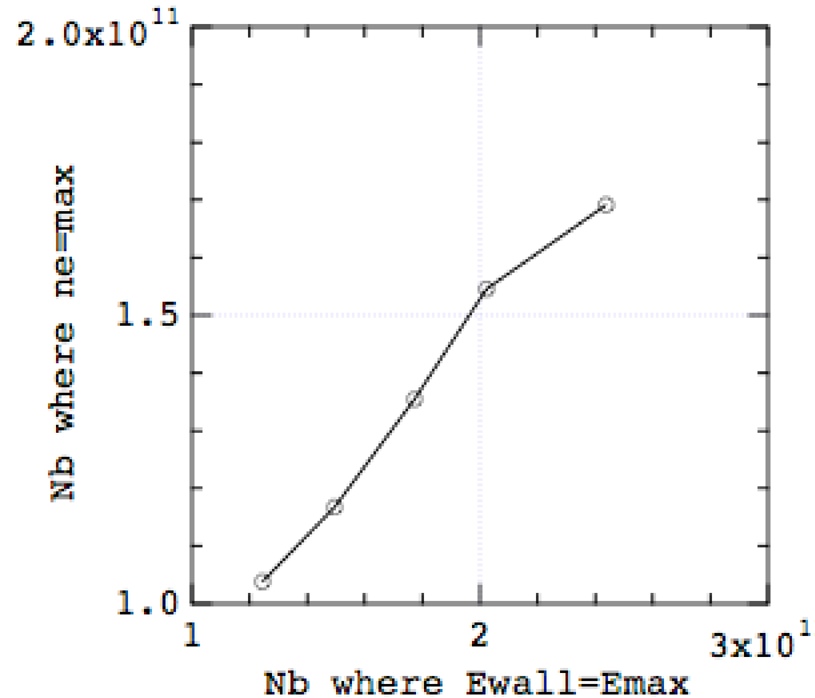
- Some sensitivity at intermediate values of N_b, especially for LHC50 beam
- Explanation: strong correlation between the value of N_b where aver. e^--wall collision energy $\langle E_{wall} \rangle = E_{max}$ and the value of N_b where n_e is maximum
    - See following slide

Dipole: sensitivity to E_{max}

LHC25 beam, E_b=50 GeV, δ_{max}=1.3

Electron-wall collision energy vs. N_b





- Clear correlation between electron-wall impact energy and peak of density
- The turnover of E_{wall} vs N_b at large N_b is likely due to significant neutralization of the beam-electron kick (R. Zwaska's argument)
- This sensitivity is less clear for field-free sections
  - Awaits a conclusive explanation

Time-averaged ecloud density [m^{-3}]

δ_{max}=1.3, E_{max}=293 eV; field-free chamber radius=6 cm

Average over whole chamber

	E_b=4 GeV dipole / field-free	E_b=50 GeV dipole / field-free
LHC25 @ $N_b=4.2\times10^{11}$	$\sim6\times10^{11}$ / $\sim4\times10^{12}$	$\sim6\times10^{11}$ / $\sim2\times10^{12}$
LHC50 @ $N_b=5.9\times10^{11}$	$\sim5\times10^{10}$ / $\sim6\times10^{11}$	$\sim2\times10^{11}$ / $\sim2\times10^{11}$

Average within 1 beam σ

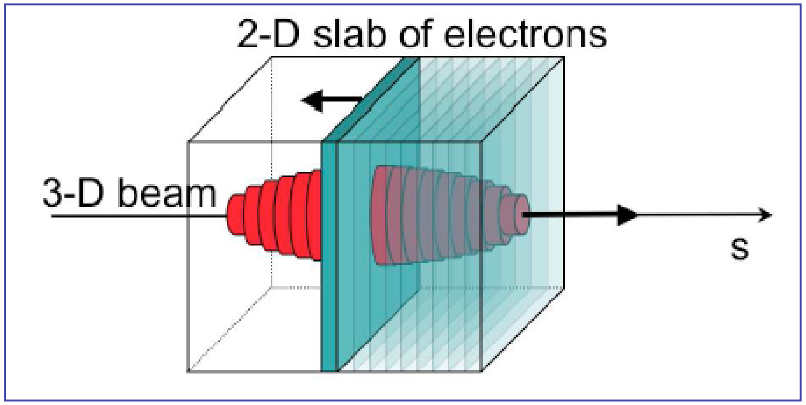
	E_b=4 GeV dipole / field-free	E_b=50 GeV dipole / field-free
LHC25 @ $N_b=4.2\times10^{11}$	$\sim5\times10^{12}$ / $\sim8\times10^{12}$	$\sim5\times10^{12}$ / $\sim6\times10^{12}$
LHC50 @ $N_b=5.9\times10^{11}$	$\sim5\times10^{11}$ / $\sim2\times10^{12}$	$\sim3\times10^{12}$ / $\sim6\times10^{11}$

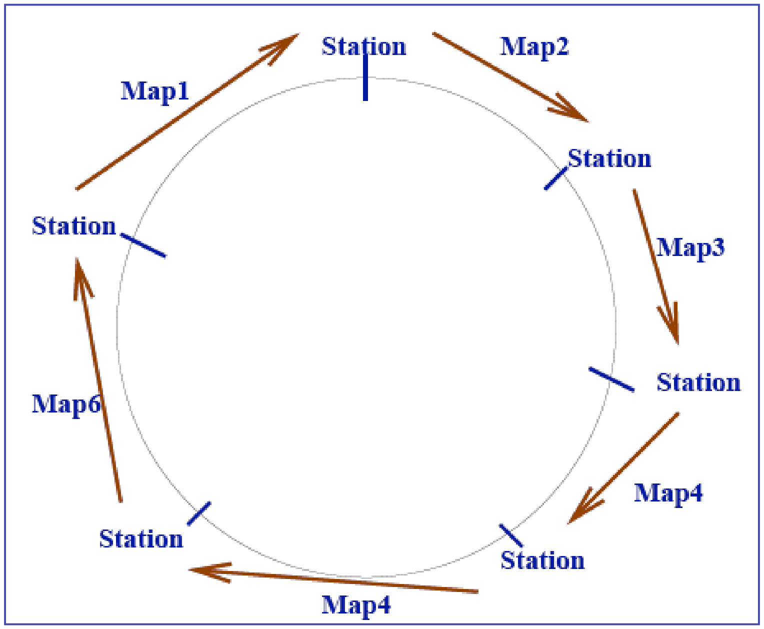
- Within the whole chamber, density range is (a few)x10^{10} – (a few)x10^{12} m^{-3}
- Within 1σ, density range is (a few)x10^{11} – (a few)x10^{12} m^{-3}

N.B: these estimates are *rough*; they are provided for relative comparisons only. Also, in most cases the ecloud density is higher at intermediate values of N_b than at the nominal value.

Effects on the beam: model for beam-electron interaction (single bunch) implemented in Warp/POSINST

- Lattice: continuous focusing model
- Beam-ecloud interaction localized at discrete “stations” uniformly distributed along lattice
- An assumed value of the ecloud density is fed as *input* to the WARP simulation
  - Eventually, will do fully self-consistent





- Beam-cloud interaction is strong-strong, in the quasi-static approximation (beam particles don’t move while interacting w/ cloud).
- 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 (mimics e^- orbit in magnetic field).

Parameters used in simulations

Selected beam, lattice parameters (PS2 extraction)

E_b	50 GeV
γ_T	35i
N_b	(4.2 or 5.9)x10^{11}
ν_x	13.25
ν_y	8.2
ν_s	7.7x10^{-3}
σ_x	1.9 mm
σ_y	1.7 mm
σ_z	0.3 m
$\lambda_{\beta y}=C/\nu_y$	164 m

Chamber & other parameters

Chamber (a , b) (rectangular)(*)	(6 , 3.5) cm
No. macroelectrons	10k
No. macroprotons	15k – 65k
No. long. slices	64
Grid size	128x128
Beam-ecloud stations: N_{st}	8–80

(*) Required by present Poisson solver

Typical simulation length:
~1000 turns ~ 5 ms

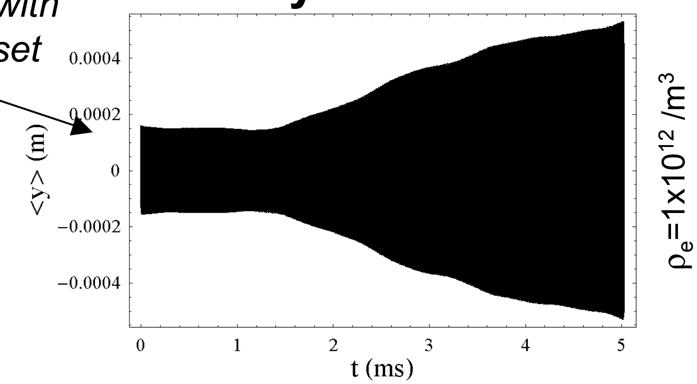
NB: in this exercise the only difference between LHC25 and LHC50 beams is the value of N_b (recall that we are looking at a *single* bunch only)

Simulations identify an instability threshold at $n_e \sim 0.5\times10^{12}$ m^{-3} for N_b=5.9x10^{11}

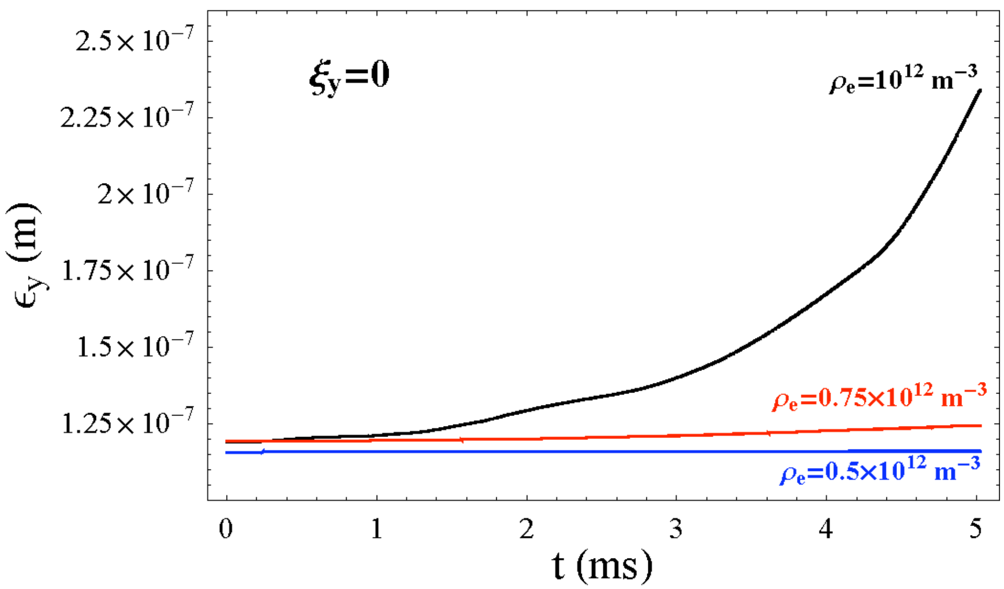
- Fast instability (time scale shorter than synch. period) develops for e-cloud density slightly above $n_e=0.5\times10^{12}$ m^{-3} (at zero chromaticity)

Beam launched with Initial small y-offset

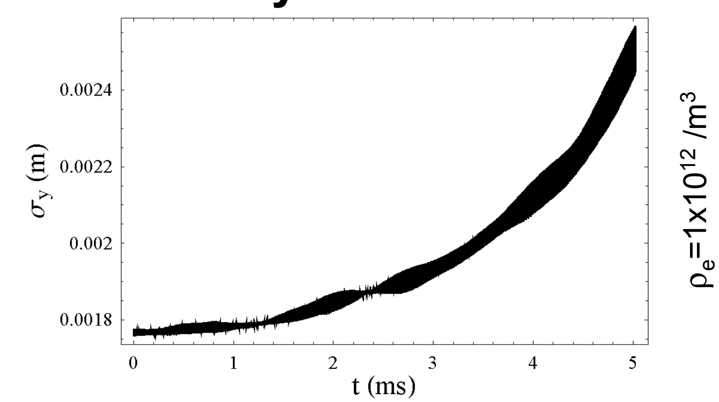
y-centroid



Evolution of Emittance

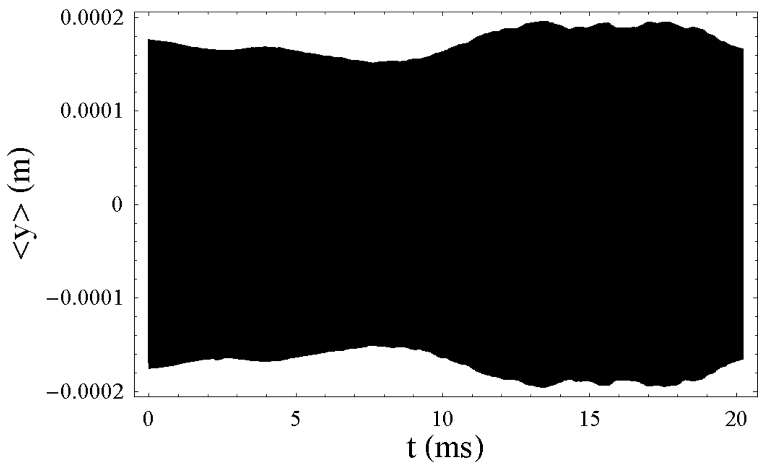


y rms size

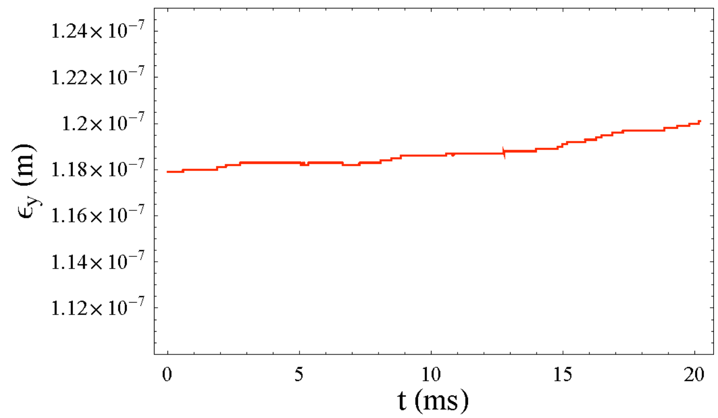


Stability at ρ_e=0.5x10^{12} m^{-3} over longer time scale (20ms)

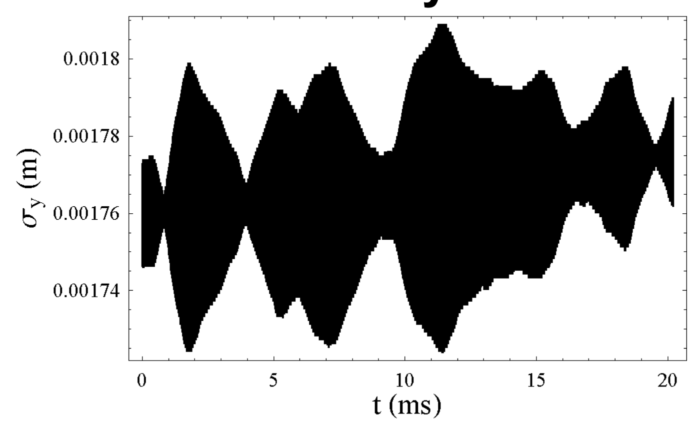
y-centroid



y-emittance



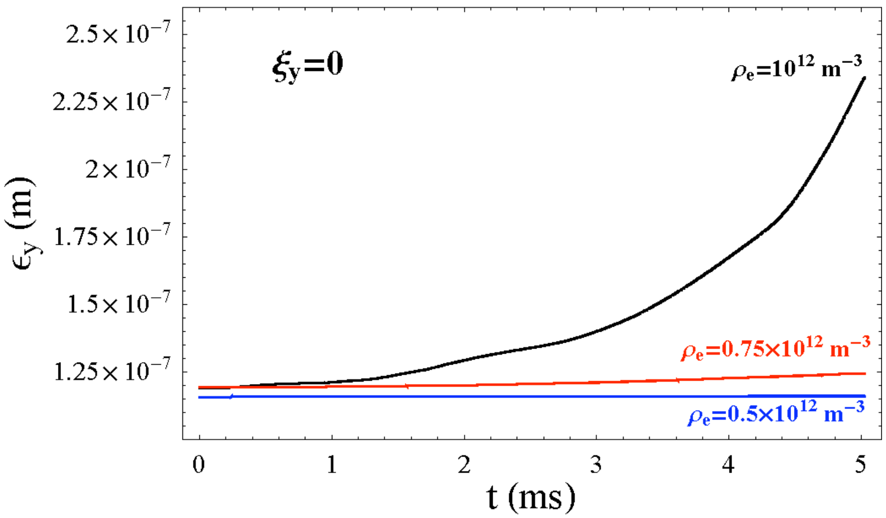
rms y-size



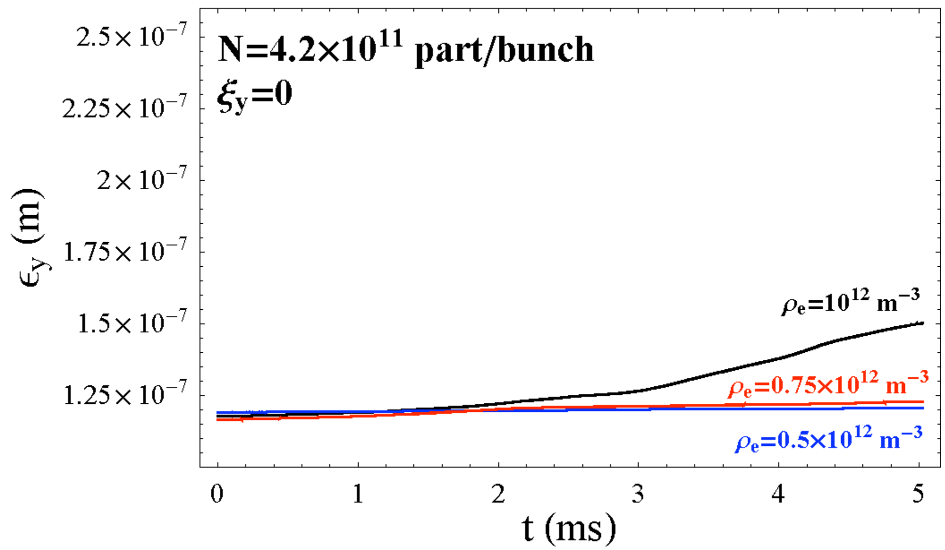
- Evolution of centroid suggests absence of instability
- Small growth apparent in evolution of emittance, size.
  - Numerical?
  - Slow (physical) diffusive effect?

For $N_b=4.2x10^{11}$ see modest increase of instability threshold

N=5.9x10[11] [nominal for "LHC50"]



N=4.2x10[11] [nominal for "LHC25"]

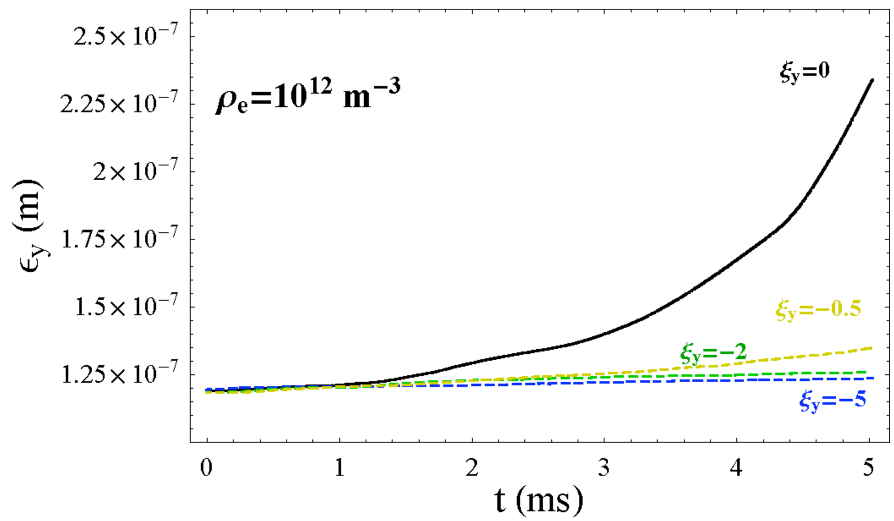


- Instability threshold close to $\rho_e=0.75x10^{12}$ m^{-3} when $N_b=4.2x10^{11}$ instead of $5.9x10^{11}$

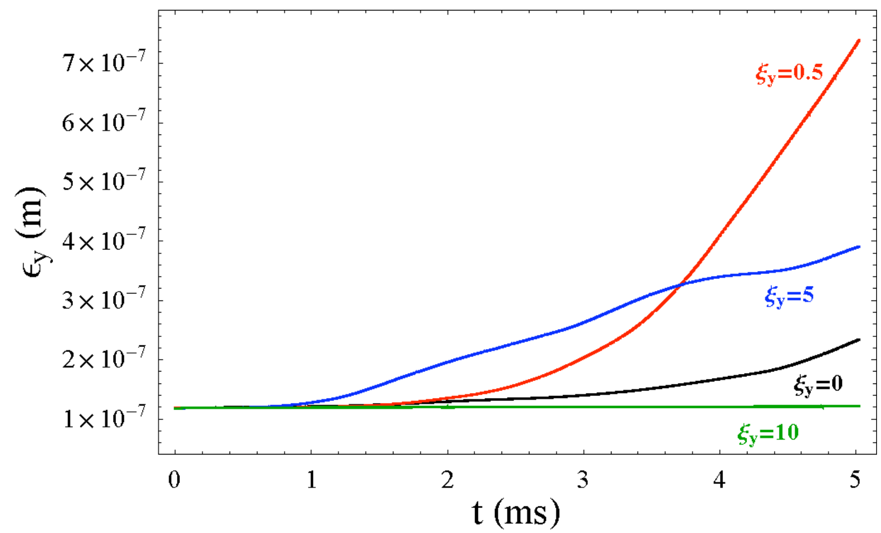
Small negative chromaticity stabilizes motion

- Motion above threshold stabilized by negative chromaticities
- Small positive chromaticities have the opposite effect

Negative chromaticities

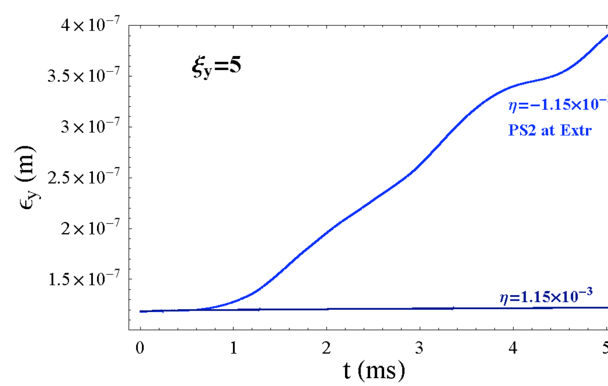


Positive chromaticities



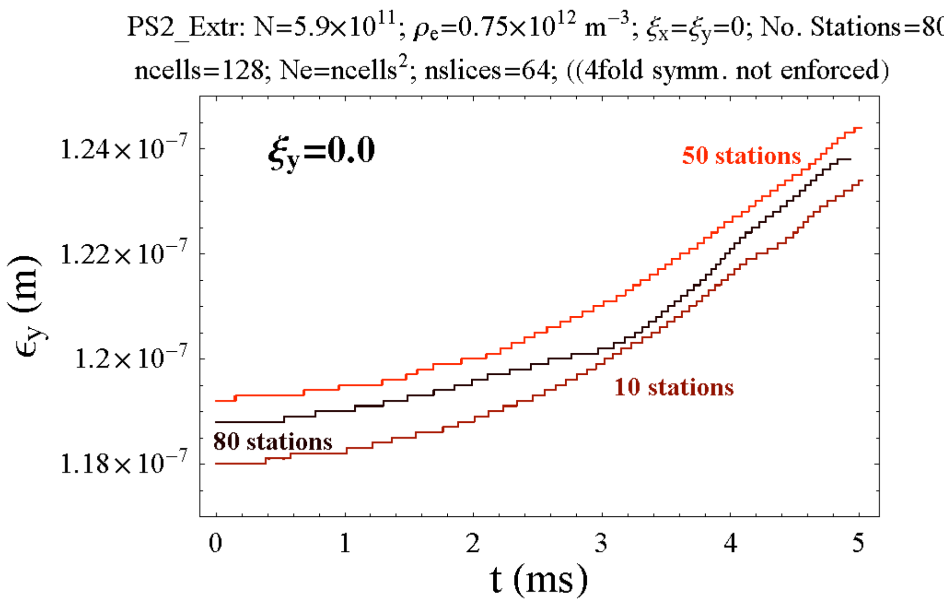
NB: PS2 slippage factor η is <0 for all E_b because γ_t=imaginary

– Artificially setting $\eta>0$ <u>*reverses*</u> the effects of positive/negative chromaticity
– Consistent with prior simulations (which have $\eta>0$ and require $\xi>0$ to suppress instability)

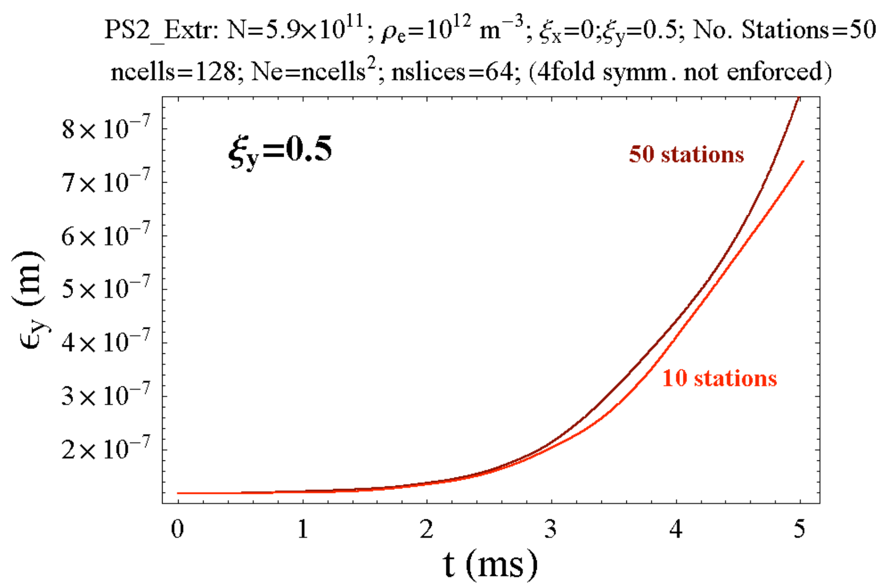


Checking numerics: no. of stations

- Theoretical minimum: $N_{st} \sim \nu_y \sim 8$ (in order to resolve λ_β)
- N_{st}=10 have been used in most of the simulations. Increasing up to 80 does not result in significant differences



Slightly above threshold

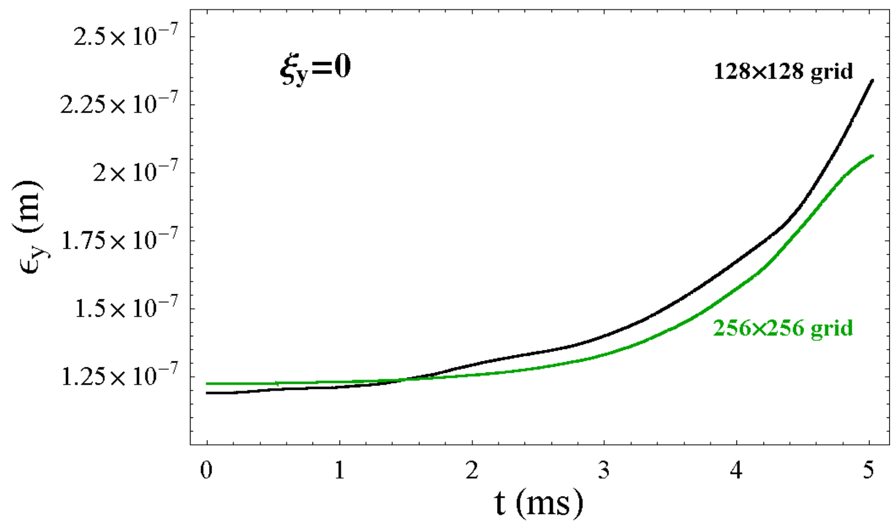


Above threshold w/ positive chromaticity (enhancing instability)

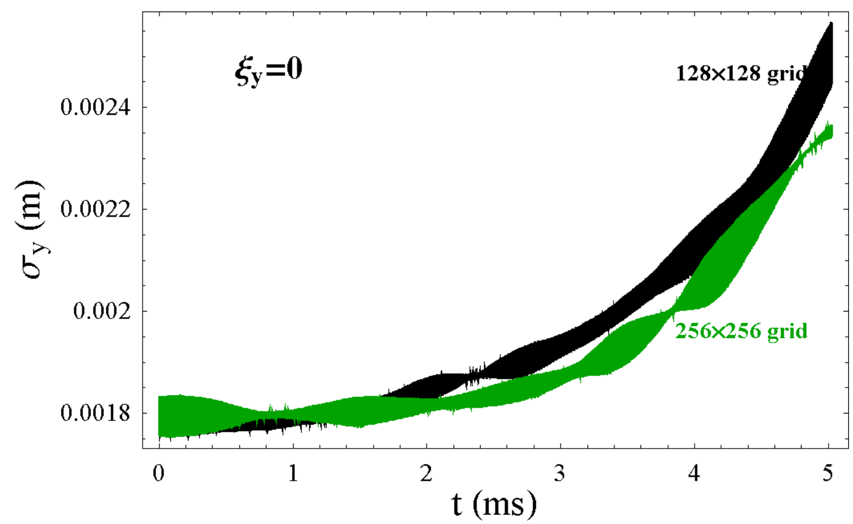
Check numerics: grid resolution

N_{st}=10, n_e=1x10^{12} m^{-3}

y-emittance



y-rms size

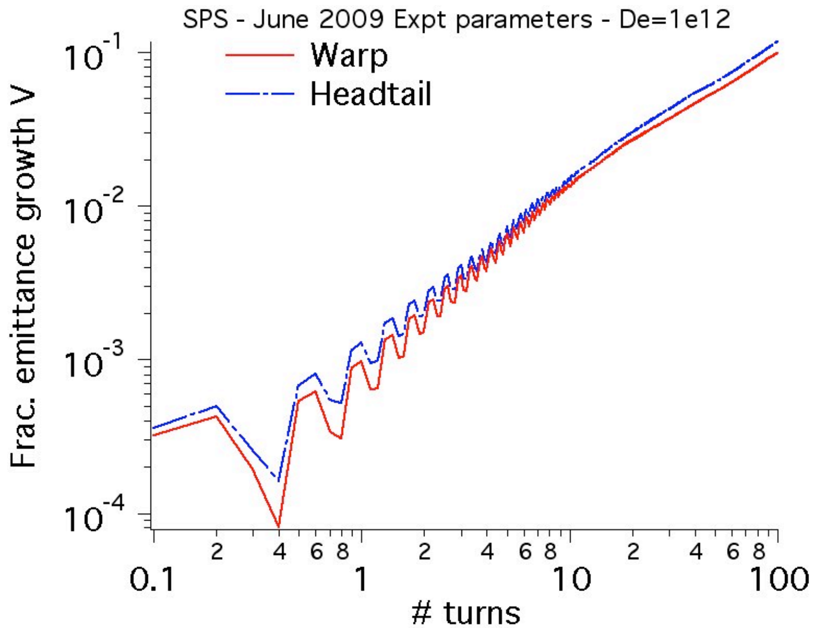


- In most simulations we used 128x128 grid (for solving Poisson eq.)
- Refining grid to 256x256 results in small difference in growth rate

Cross-check against other codes

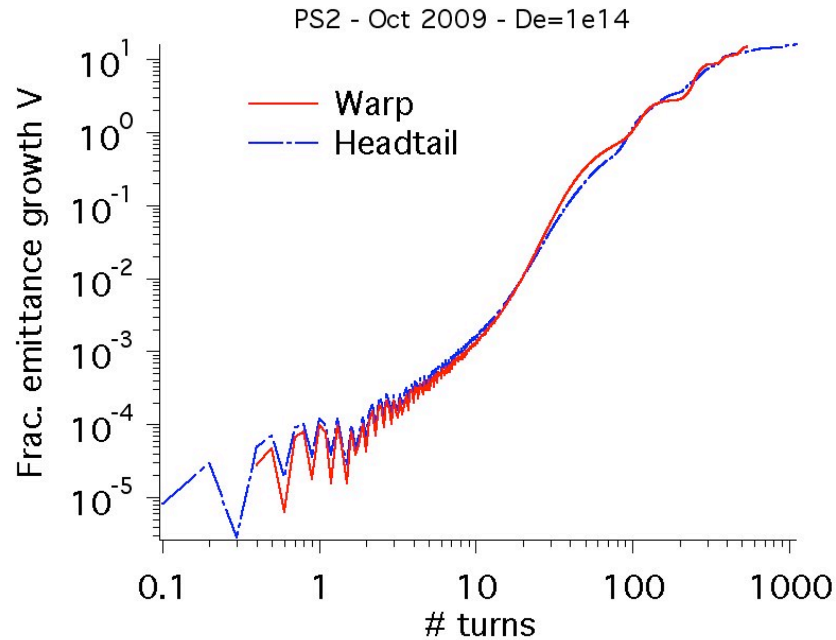
- Comparison against HEADTAIL (CERN, Zimmerman, Rumolo, et al.) shows good agreement (similar physics model)

Emitance growth WARP vs. HEADTAIL



Just above threshold

$\rho_e = 10^{12}$ /m^3



Well above threshold

$\rho_e = 10^{14}$ /m^3

Conclusions for ecloud build-up

- Aver. EC 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 field-free regions
  - By a factor ~2-4 in average n_e; similar to previous result for dipoles
- In most cases (dipoles and f.f. sections), ecloud density n_e is larger at N_b~(1–3)x10^{11} than at the larger (nominal) N_b
  - Because $\langle E_{wall} \rangle \approx E_{max}$ at N_b~(1–3)x10^{11}
  - This non-monotonicity of $n_e(N_b)$ is especially clear in dipoles
- Sensitivity to chamber radius in f.f. sections (in range 4-6 cm):
  - Especially clear at N_b~(1–3)x10^{11}
  - LHC25 beam: weak sensitivity
  - LHC50 beam: significantly lower n_e at 4 cm relative to 6 cm at N_b~(1–3)x10^{11}, but weak dependence at N_b=5.9x10^{11}
- Sensitivity to E_{max}
  - Especially clear at N_b~(1–3)x10^{11}
  - Especially clear in dipoles
  - Weak at 50 GeV and nominal N_b
  - Clear correlation of N_b-value when $\langle E_{wall} \rangle = E_{max}$ and N_b-value when $n_e(N_b)$=max.

What's next on ecloud build-up

- Refine understanding of observed dependencies on N_b and E_b
- Simulate ecloud build-up during the ramp
  - Especially around bunch coalescing time
- Examine other regions of the chamber
  - e.g., quads
- Re-examine physical parameter values, esp. SEY model
- Complete assessment of numerical convergence
- Maintain side-by-side comparison with MI upgrade

Conclusions for ecloud effects on the beam

- This is a first pass at estimating effect of ecloud in PS2 on single-bunch
- Simplified physical model:
  - Single bunch in a constant-focusing lattice
  - But has already been used with some success to simulate experiments (HEADTAIL code).
- Simplified computational model: “quasi-static approximation”
  - Good theoretical underpinnings, widely used by now
  - Beam-ecloud interaction occurs at several discrete points along the circumference
  - Ecloud is cold and uniform just before bunch arrival, and is refreshed at every encounter
- Simulations show existence of threshold for fast instability for n_e~$0.5x10^{12}$ m^{-3}
  - This value is in the mid-range predicted by the build-up simulations
  - Therefore interesting
- Clear beneficial effect of negative chromaticity in increasing the threshold
  - And detrimental effect of positive chromaticity
- Spot-checked that estimate of threshold is robust against choice of numerical parameters:
  - no. of ecloud stations, grid size
- Very good agreement between codes WARP and HEADTAIL in spot-checks

What’s next on ecloud effects on the beam

- Will continue checking for robustness against computational parameters
  - Especially no. of macroparticles and beam slices
  - Will run for >> 1000 turns
- Look at beam energies other than 50 GeV
- Allow for mix of ecloud distributions along ring
  - to reflect expected differences in drift, dipoles, etc
- Use more realistic e-cloud density distribution in 4D phase space (as determined by POSINST runs)
- Go beyond smooth-focusing approximation for lattice model
- Analyze multibunch instability
- Explore mitigation mechanisms if necessary
  - Low-SEY coatings, feedback system, …
- Fully self-consistent calculation
  - New computational techniques now make possible, in principle, fully self-consistent calculations within reasonable CPU time (J.-L. Vay)
  - We might attempt spot-checks during 2010

Extra material (from my CM12 talk, April 2009)

Tasks and effort level

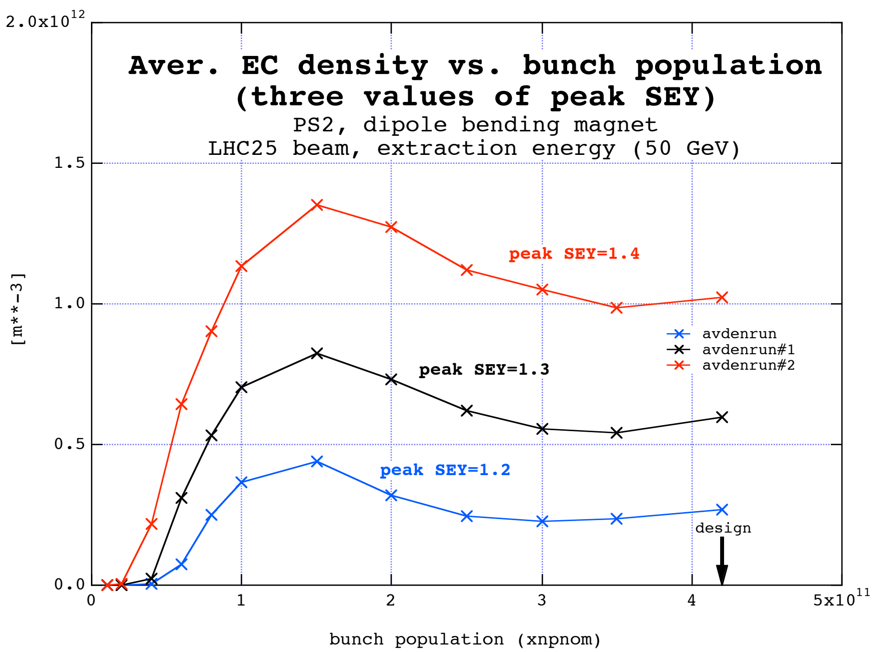
1. Refine assessments of electron-cloud build-up (4 EPM(*)). Estimated completion: end of CY09
2. Compare electron-cloud build-up at the PS2 against MI upgrade (3 EPM). Commence in April 2009, complete at end of CY09.
3. Explore parameter space (4 EPM). Commence in Oct. 2009, complete in April 2010.
   - Secondary emission model
   - PS2 design parameters are changing
4. Assess ecloud mitigation mechanisms (4 EPM). Commence Jan. 2010, complete Oct. 2010.
5. Assess need to combine space charge with ecloud simulations (2 EPM). Commence in April 2009.
   - If yes, complete code augmentation/integration at end of CY2010, with final benchmarking validation in June 2011.
6. Assess impact of ecloud on the PS2 beam (12 EPM). Commence Oct. 2009. Initial assessment ready by June 2010. Final report Sep. 2011. Ongoing re-assessments to continue as needed.
7. If above indicate a single-bunch instability, design a BB FDBK system (4 EPM). Commence April 2011. Initial assessment Dec. 2011. Ongoing re-assessments to continue as needed.

(*) EPM=experienced-person-month

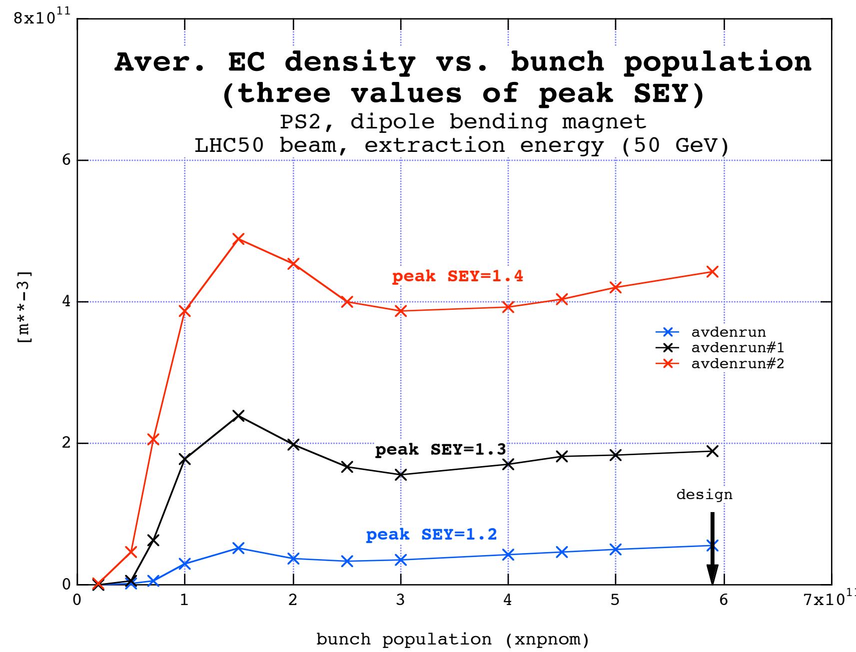
Sensitivity to peak SEY: aver. n_e vs. N_b in dipole

trigaussian bunch, E_b=50 GeV, δ_{max}=1.2, 1.3 and 1.4

LHC25 beam



LHC50 beam

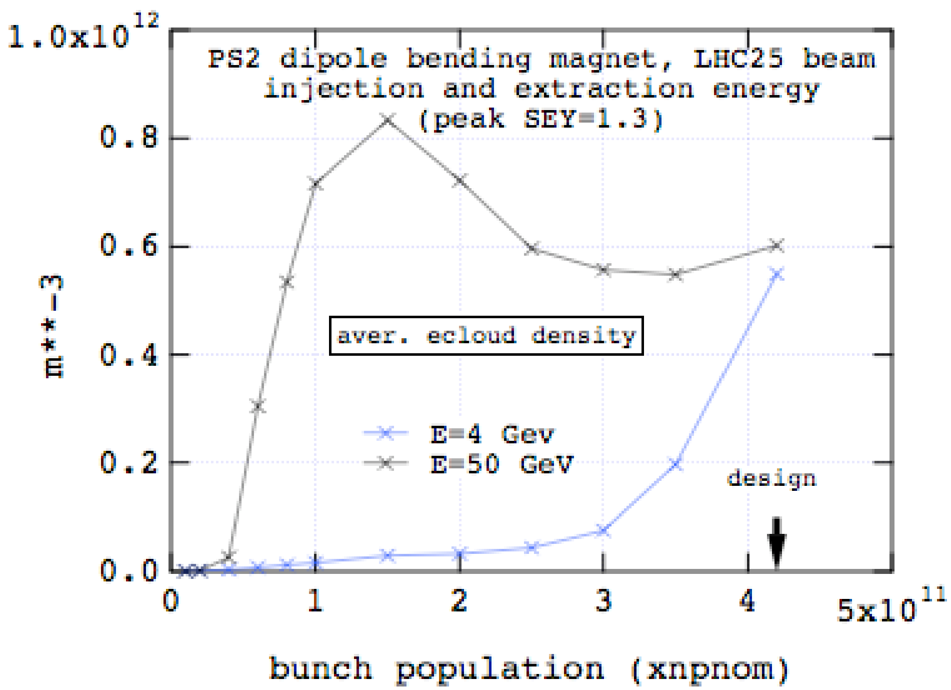


- Strong sensitivity to δ_{max}
  - Not a surprise
  - Used to calibrate EC build-up simulations against measurements at FNAL MI:
    - δ_{max}~ 1.3 is a reasonable value (after conditioning)
    - Awaits further confirmation, but various measurements are nicely consistent

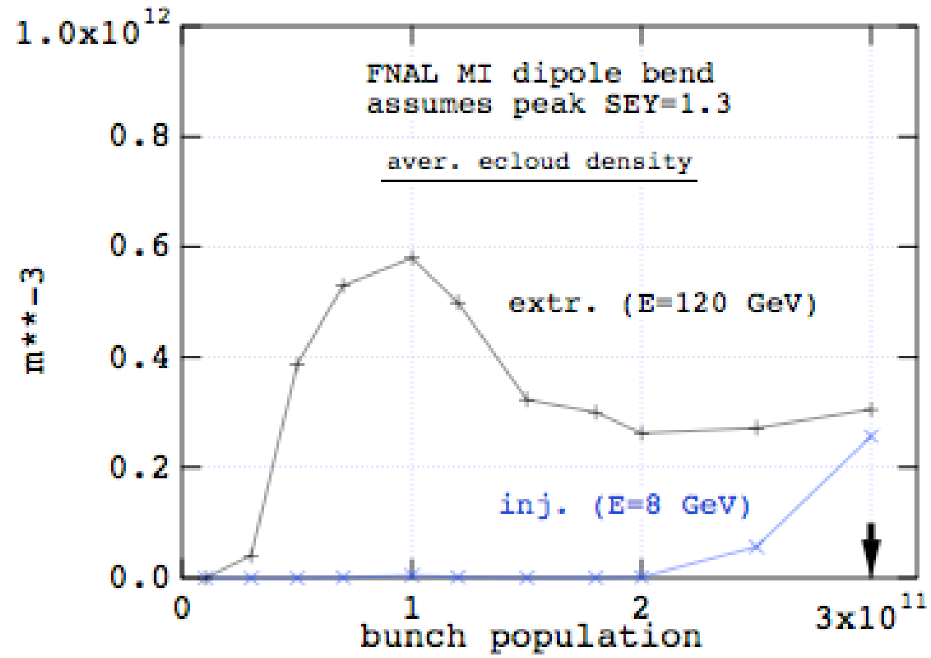
PS2 vs. MI upgrade: aver. n_e vs. N_b in dipole(*)

trigaussian bunches, dipole bend, δ_{max}=1.3

PS2, LHC25 beam



MI upgrade



- Similar ecloud features in both machines
  - PS2 stands to profit from current ecloud program at MI
- See table on next page for parameters I actually used in the MI simulations

(*) These plots are slightly different from those in my CM12 talk as a result of fixing a computer bug in ~Sept. 2009. These results are current as of Nov. 1st, 2009

PS2 and MI upgrade

main parameters used in dipole ecloud simulations*

	PS2	MI upgrade
C [m]	1346.4	3319.419
h	180	588
(a,b) [cm]	(6, 3.5) (ellip.)	(6.15, 2.45) (ellip.)
f_{RF} [MHz]	40	53
K.E. [GeV]	4 – 50	8 – 120
B [Tesla]	0.136 – 1.7	0.1022 – 1.391
t_b [ns]	25 or 50	19
no. bunches	168 or 84	~ 500
N_b	(4.2 or 5.9)x10^{11}	3x10^{11}
(σ_x, σ_y, σ_z) [mm]	(6.3, 5.9, 1000) @ inj. (1.95, 1.83, 330) @ extr.	(2.29, 2.81, 560) @ inj. (0.62, 0.76, 150) @ extr.
no. macropart.	20,000 max	20,000 max
Δt [s]	3x10^{-11} typ.	3x10^{-11} typ.
grid size	64 x 64 typ.	64 x 64 typ.

(*) **NB**: actual parameters are evolving; see https://twiki.cern.ch/twiki/bin/view/Main/PS2Collaboration for PS2 current design, and http://projectx.fnal.gov for MI upgrade.