Issues with Electron Cloud for Long-Term R&D and Possible Beam Tests

Future Directions for Accelerator R&D at FNAL
Lake Geneva, WI, 11–13 May, 2009

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Summary

1) Electron-cloud basics
2) ecloud program at the FNAL MI
3) Simulation fits to ecloud measurements with RFA (~mid-2007)
4) Extrapolation of simulations
    - High beam intensity
    - Beam energy dependence
    - Compare f_{RF}=53 MHz vs. 212 MHz
5) Effects on the beam (very preliminary)
6) Comparison of MI vs. proposed CERN PS2
7) CESR-TA results
8) MI future plans and proposals
9) Conclusions

My gratitude to I. Kourbanis and R. Zwaska

Electron cloud basics

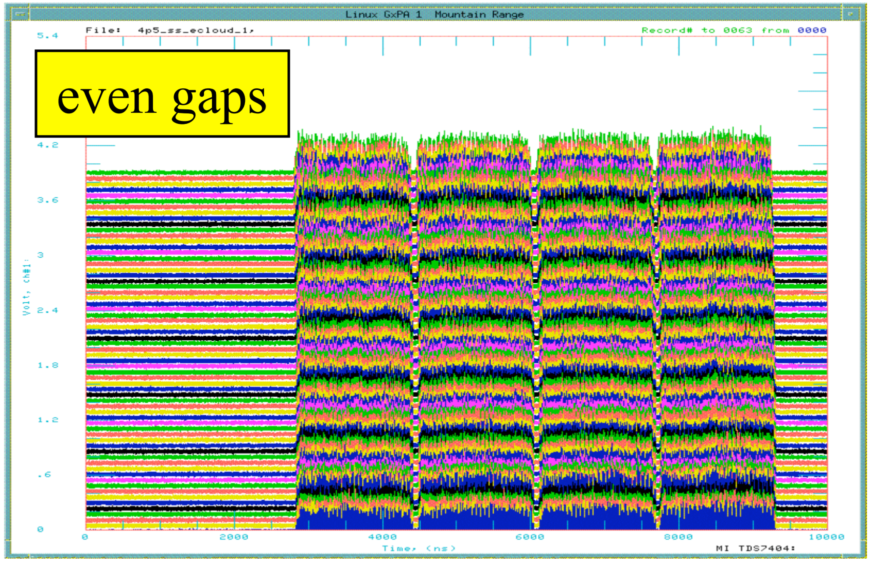
- Intense beams lead to an electron cloud in the chamber
  - — Particularly for positively-charged beams
- Typical average e$^-$ density: $n_e \sim 10^{10} - 10^{12}\ \mathrm{m}^{-3}$
- Significant limitation at PEP-II, KEKB, SPS, PSR,…
  - — Average luminosity
  - — Particle losses
  - — Emittance growth
  - — Instabilities
  - — Interference with diagnostics
  - — Excessive cryogenic heat load, …
- Almost always: the main ingredient is the SEY of chamber surface
  - — But this is strongly coupled with chamber geometry, beam fill pattern, …
- Typically, divide effort into two:
  - — Ecloud build-up (95% of this talk), obtained with LBNL/SLAC code “POSINST”
  - — Effects from ecloud on the beam, obtained with LBNL code “WARP/POSINST”

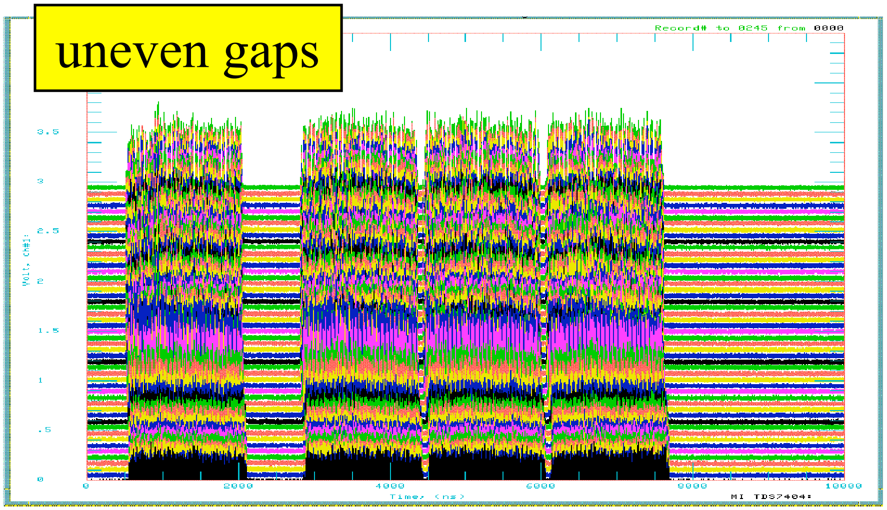
ecloud program at the MI

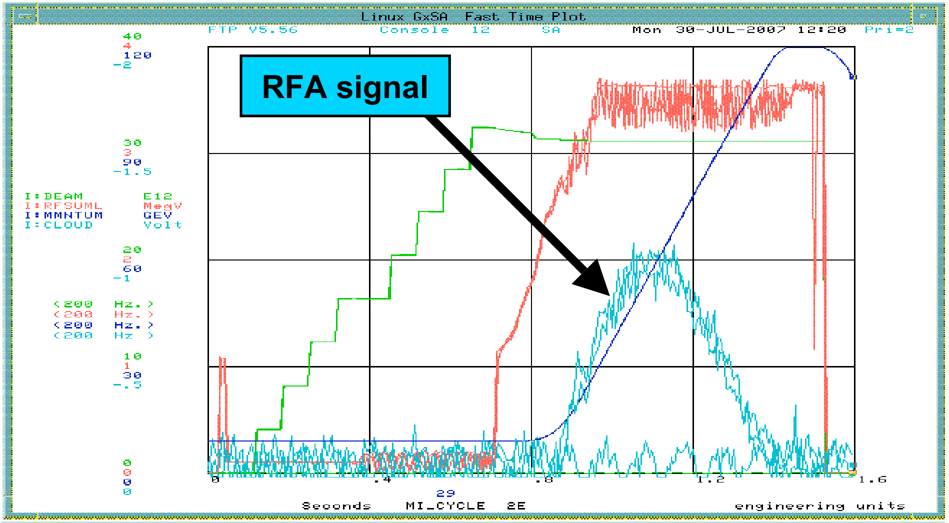
- Measurements and simulations for the past 2-3 years
  - — In support of the MI upgrade goal:
    - $N_b=3x10^{11}$ per bunch
    - $N_{tot}=1.6x10^{14}$ per pulse (~540 bunches)
- Presently:
  - — N_b~$1x10^{11}$ (but <500 bunches)
  - — e^- cloud observed, but is not an operational limitation
- Program goal: will e^- cloud be a limitation at $3x10^{11}$?
  - — If so: mitigate
    - Low-SEY coatings, clearing electrodes,…
- New test chambers and instrumentation to be installed this year

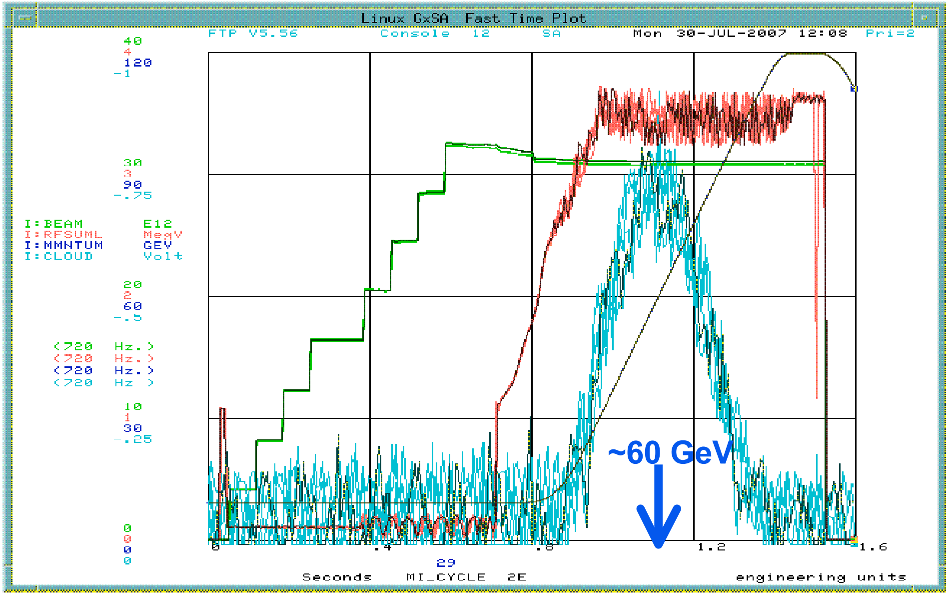
Sample RFA signals at MI(*)

4 booster trains, N_b=(9.1–9.5)e10





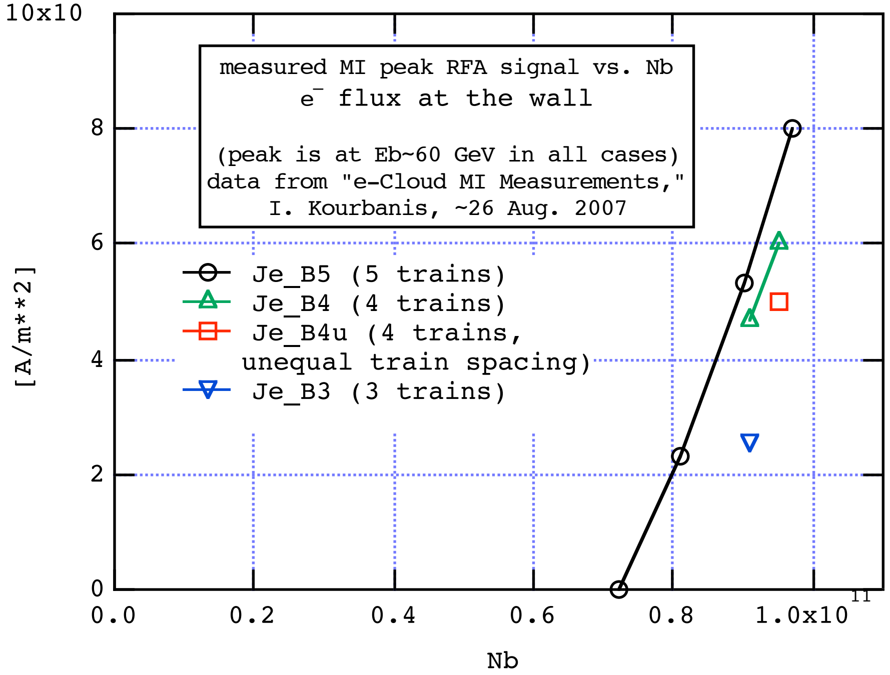




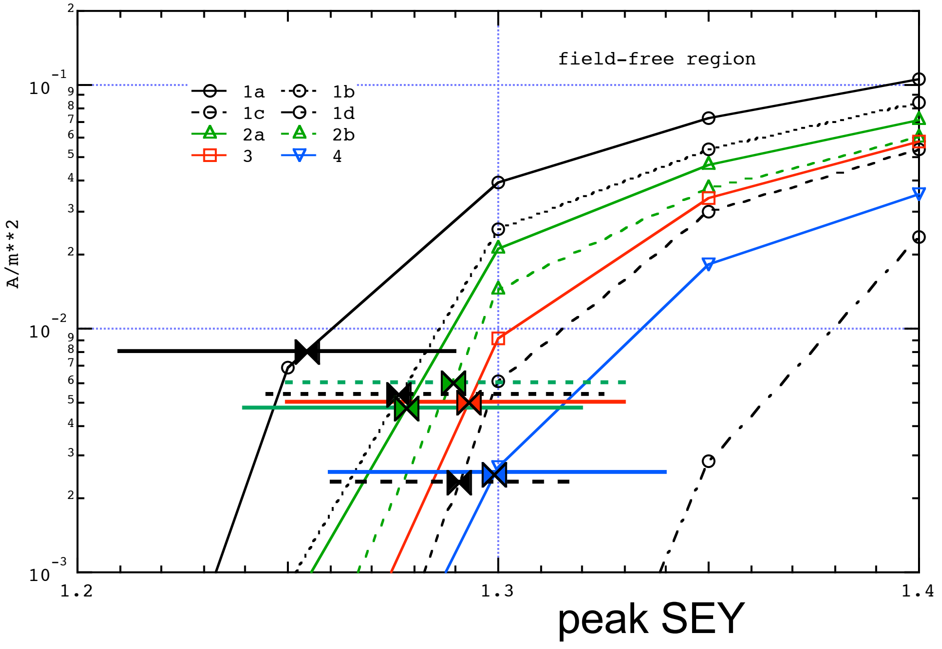
(*) I. Kourbanis report, ~26 Aug. 2007

RFA measurements and fits

e⁻ flux J_e at RFA vs. N_b for various fill patterns (E_b=60 GeV all cases)



Simulation fits: J_e vs. δ_{max}



Conclusion:

- Nicely consistent solution with peak SEY δ_{max}≈1.3

Caveats:

- we fixed E_{max}=300 eV

(you can usually trade off δ_{max} for E_{max} to some extent)

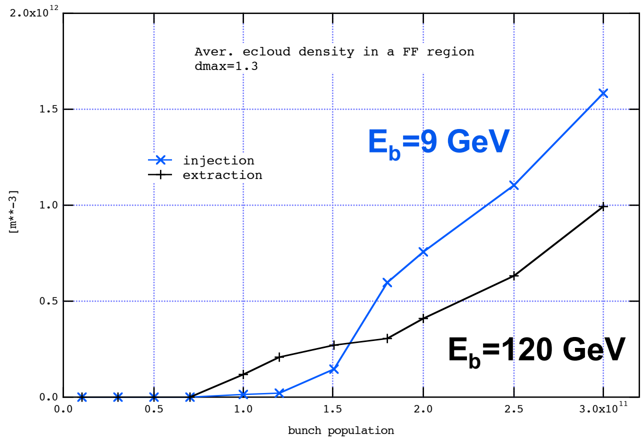
- RFA data not quite consistent with microwave dispersion data

⇒ need to re-examine

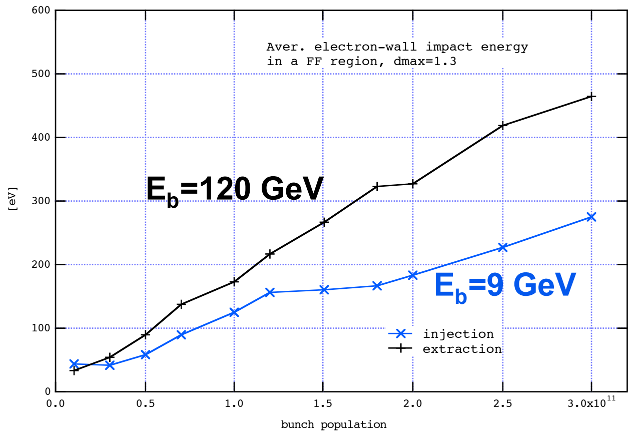
Extrapolate average n_e vs. N_b

assumes: 500 consecutive bunches and peak SEY δ_{max}=1.3

Aver. ecloud density

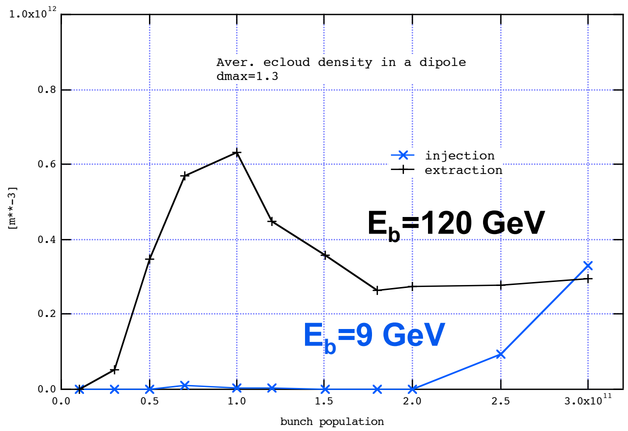


e⁻-wall impact energy

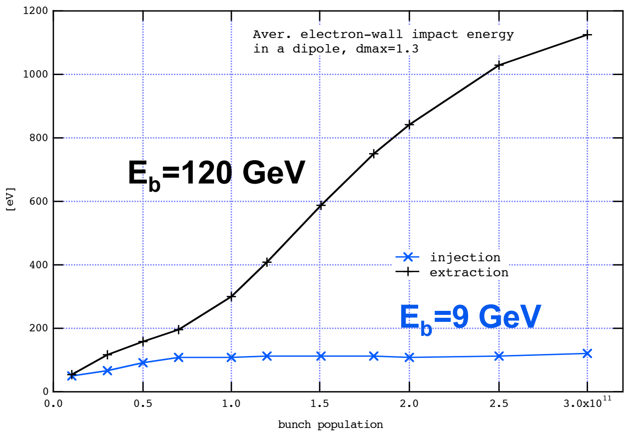


RFA (field-free) region

Aver. ecloud density



e⁻-wall impact energy



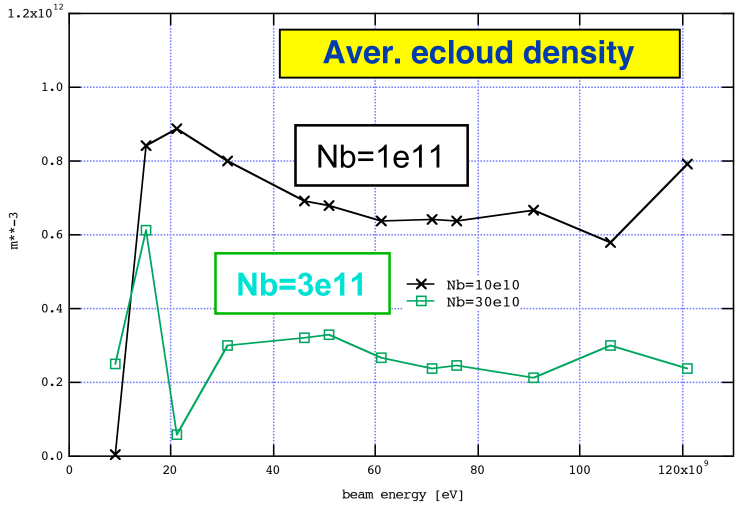
Dipole bending magnet

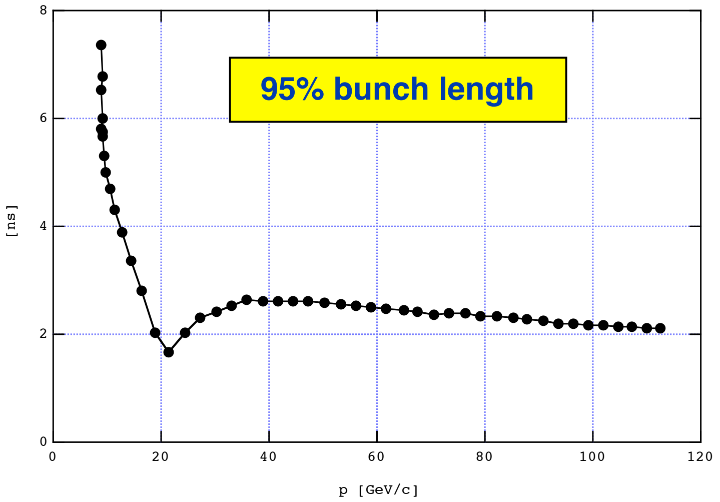
Conclusions:

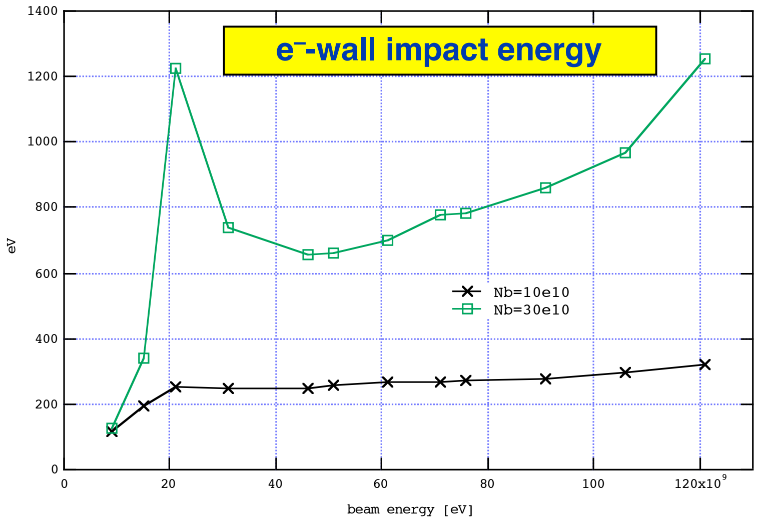
1) n_e~10^{12} m^{-3}
2) Threshold behavior in FF region
3) But not in dipole
4) Peak at N_b~10^{11} due to ~300 eV e⁻-wall impact energy
5) Why does n_e increase at high N_b at injection energy?

E_b dependence of n_e in MI dipole

assumes: 500 consecutive bunches and peak SEY δ_{max}=1.3





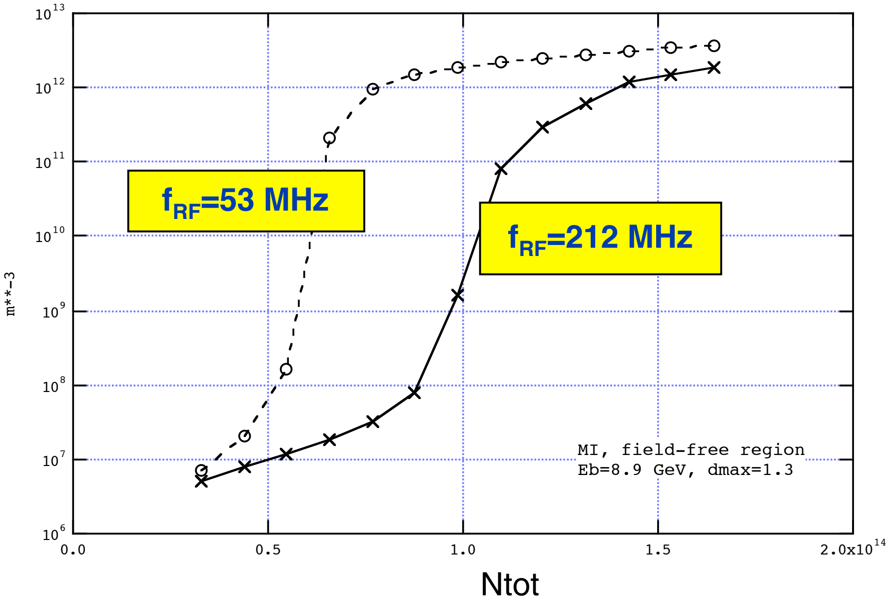


Conclusions:

1) Mild dependence on beam energy, except at transition crossing
    - Consistent with microwave dispersion measurements (N. Eddy et al, PAC09 paper WE4GRC02), but not with RFA measurements
2) Large e⁻-wall impact energy leads to lower n_e at high N_b

f_{RF}=53 MHz vs 212 MHz in MI FF region

n_e vs. N_{tot} at E_b=9 GeV, assumes δ_{max}=1.3



Compared 2 fill patterns:

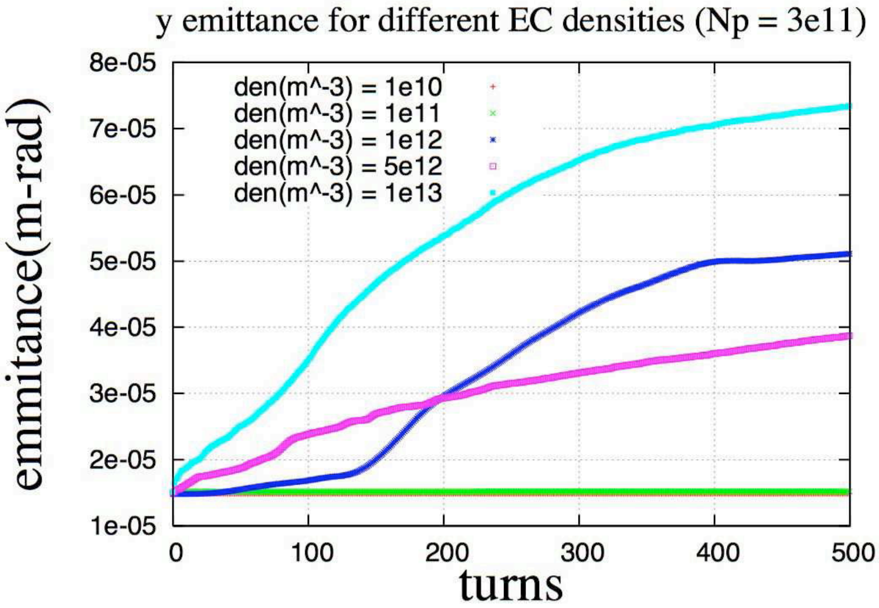
- 500 bunches at N_b and σ_z
- 2000 bunches at N_b/4 and σ_z/4

Conclusions:

1) Higher threshold at 212 MHz by factor ~2 relative to 53 MHz
2) Above threshold, n_e lower by factor ~2-4
3) In <u>dipole</u>: no such beneficial effect of higher f_{RF} (not shown here)
4) Need to examine other beam energies

Effects on the beam

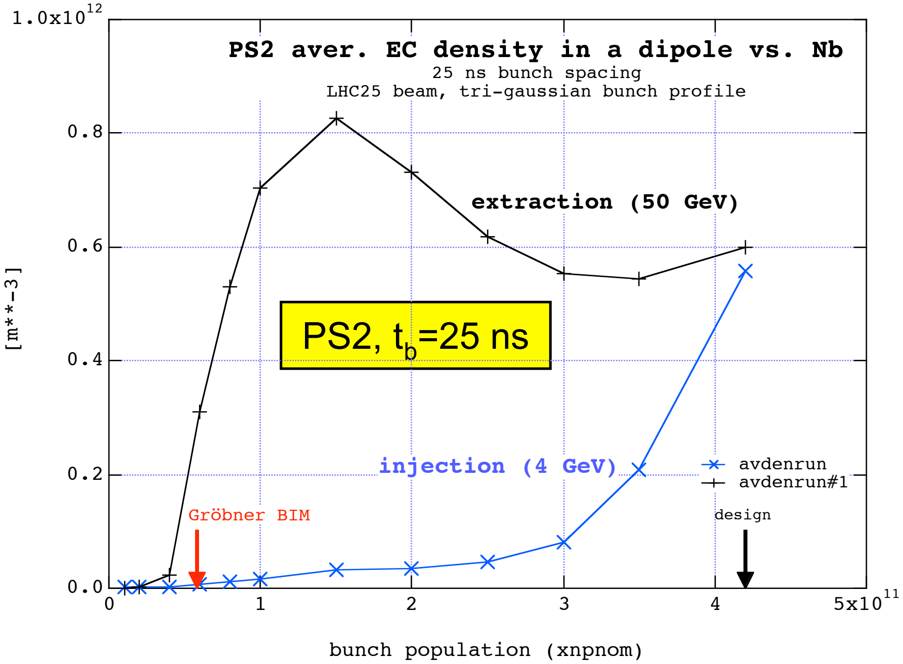
- Preliminary rough estimate of threshold for emittance growth:
  - — n_e~(0.1–1)x10^{12} m^{-3}
- This is ~the same range of our build-up simulations + measurements
- Examine multi-bunch effects (not even started)
- Need to pursue this!

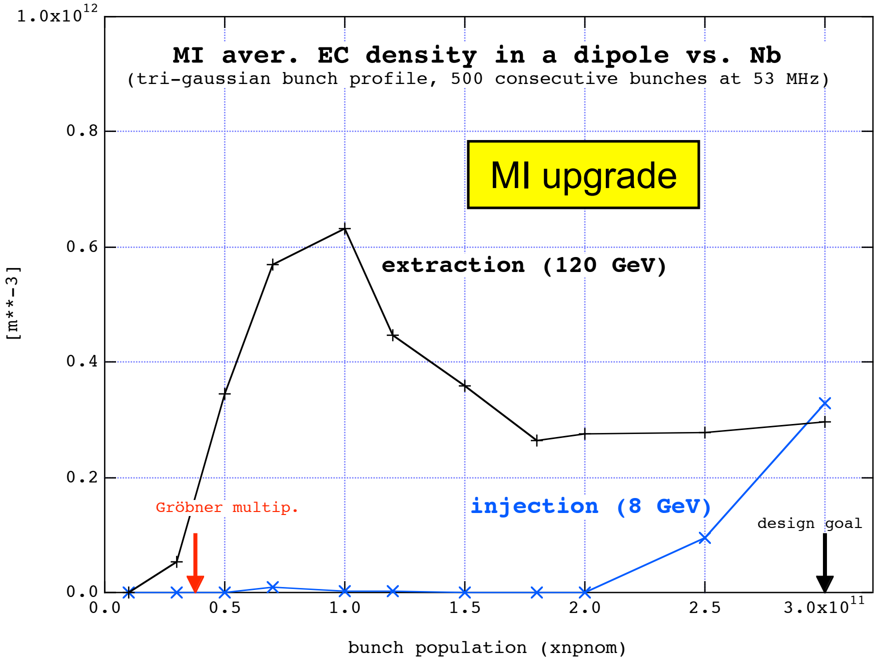


K. G. Sonnad, M. A. Furman and J.-L. Vay, "Progress on electron cloud effects calculations for the FNAL main injector," LBNL-767E, 9 June 2008

PS2 vs. MI upgrade: average n_e vs. N_b in a dipole

assumes: trigaussian bunches, peak SEY δ_{max}=1.3





- Very 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 simulations

PS2 and MI upgrade

main parameters used in dipole ecloud simulations*

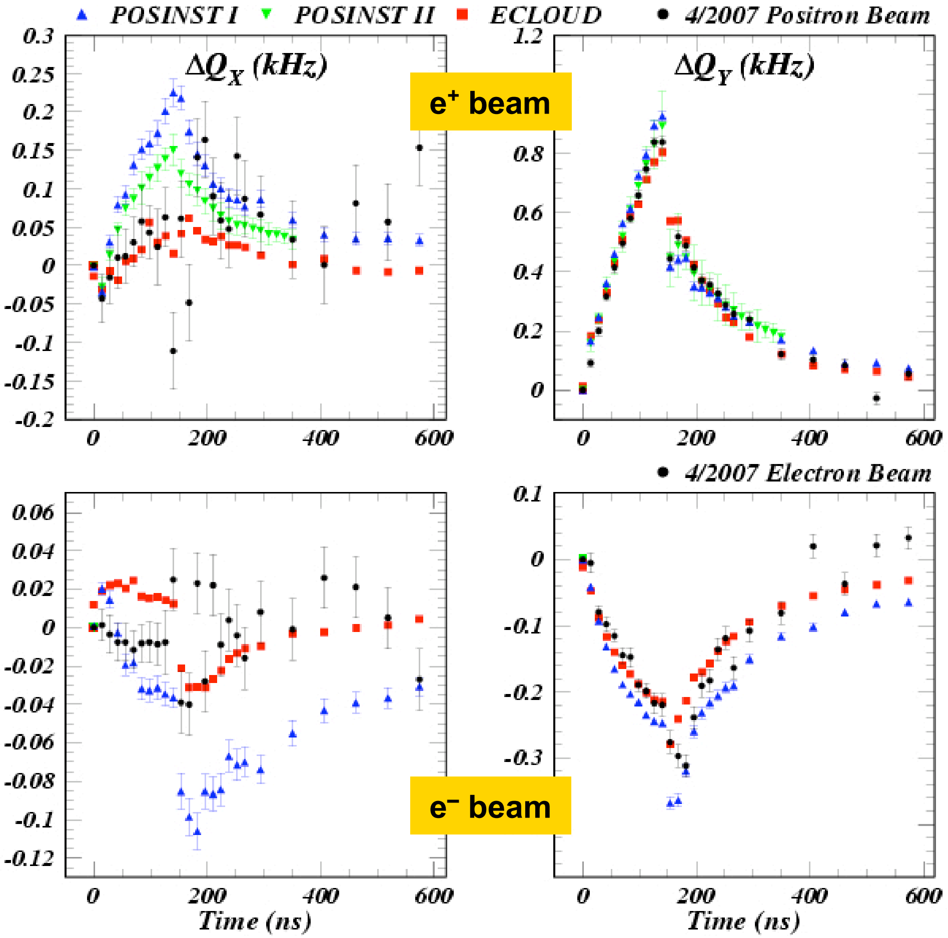
	PS2	MI upgrade
C [m]	1346.4	3319.419
h	180	588
(a,b) [cm]	(6, 3.5) (ellip.)	(6.15, 2.45) (ellip.)
f_{RF} [MHz]	40	53
K.E. [GeV]	4 – 50	8 – 120
B [Tesla]	0.136 – 1.7	0.1022 – 1.391
t_b [ns]	25 or 50	19
no. bunches	168 or 84	~ 500
N_b	4.2×10^{11}	3×10^{11}
$(\sigma_x, \sigma_y, \sigma_z)$ [mm]	(6.3, 5.9, 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]	3×10^{-11} typ.	3×10^{-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.

CESR-TA sample results:

tune shifts along bunch train

- CESR-TA = dedicated facility to study ecloud and ultra-low beam emittance (for ILC damping rings)
- Systematic program of ecloud measurements and simulations is ongoing:
  - — Both e^+ and e^- beams
  - — Both RFA and microwave dispersion techniques
  - — Possible direct measurement of SEY
  - — Several simulation codes
- Current results are providing useful measurements of photoelectric and secondary emission data
- Near future: beam instability studies



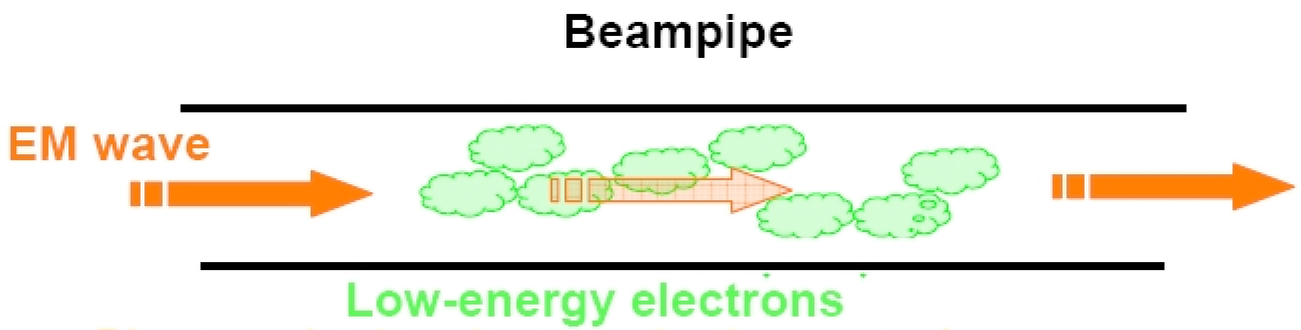
from J. Crittenden et al., PAC09 paper FR5RFP077

MI plans

- Two new test chambers will be installed soon
  - 1 m long each
  - one bare StSt, the other TiN-coated
  - 3 new RFA's (plus one old ANL RFA)
- Will continue microwave dispersion measurements
  - New antennas
- BBB tune measurements?
  - Similar to CESR-TA
  - Train of M bunches followed by a "witness bunch" H buckets behind the train, then measure coherent $\Delta\nu_x$ and $\Delta\nu_y$ as a function of M and H for every bunch
- New measurements should allow better fits and more robust extrapolations to high intensity
  - Hopefully will resolve existing discrepancy between RFA and microwave dispersion measurements

Microwave Transmission

(slide courtesy of N. Eddy, PAC09-WE4GRC02)



Phase velocity changes in the ec region

From plasma physics, expect a microwave travelling down a waveguide to experience a phase shift due to a homogeneous plasma

From the microwave dispersion relation

$$k^2 = \frac{\omega^2 - \omega_c^2 - \omega_p^2}{c^2} \quad \Longrightarrow \quad \frac{\Delta\phi}{l} = \frac{\omega_p^2}{2c\sqrt{\omega^2 - \omega_c^2}}$$

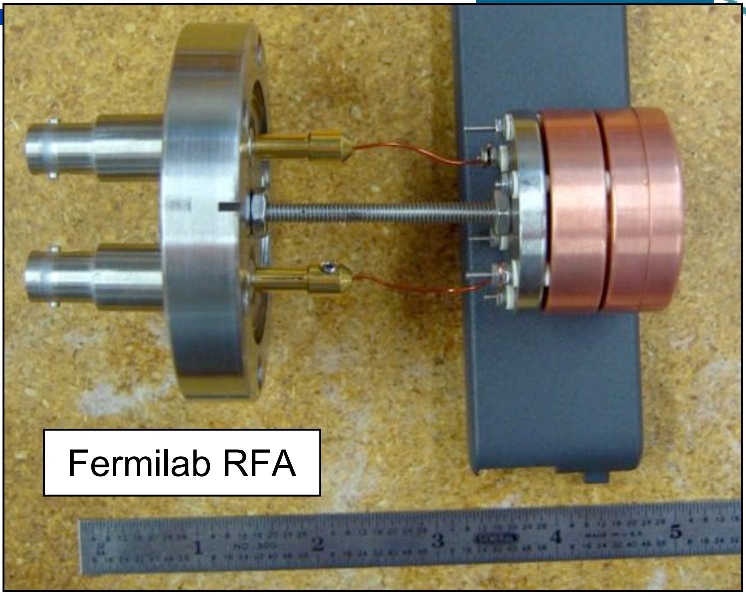
For an electron cloud $\omega_p^2 = 4\pi\rho_e r_e c^2$ is proportional to *e* density

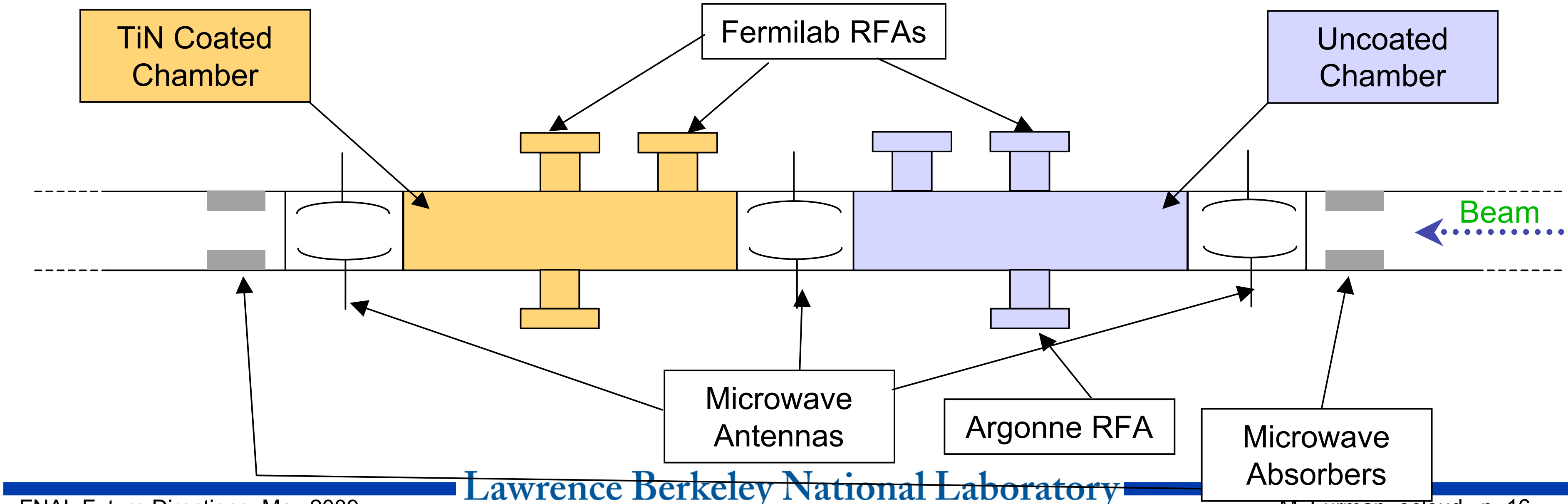
Electron Cloud Experimental Upgrade - 2009

(slide courtesy of R. Zwaska)

To be installed in Main Injector, Summer 2009 :

- **2 New experimental Chambers**
  - **— Test TiN coating for ECloud suppression**
  - **— Measure spatial extinction of ECloud**
- **3 Fermilab and 1 Argonne RFA**
  - **— Retarding Field Analyzers**
  - **— Directly measure electron flux**
    - **Compare designs**
- **3 microwave antennas and 2 absorbers**
  - **— Measure ECloud density by phase delay of microwaves**





TiN Coated Chamber

Fermilab RFAs

Uncoated Chamber

Beam

Microwave Antennas

Argonne RFA

Microwave Absorbers

Conclusions

1) Fits of simulations to measurements show nicely consistent results for peak SEY ~1.3
    - Caveat 1: SEY changes with time (conditioning, venting, …)
    - Caveat 2: we fixed E_{max}=293 eV; probably OK, but need to pin down with broader, simultaneous, fits
2) e-cloud density in range ~(0.1–1)x10^{12} m^{-3} in steady state
3) On average, beam neutralization ~few %
    - Caveat: near beam, n_e is much higher, typically by x10
4) Qualitatively different behavior in field-free region and dipole magnets as a function of N_b
    - Looks like effect will be <u>weaker</u> in dipoles at N_b=3e11 than at 1e11 by a factor ~2 (but see caveat 2 above)
5) Higher f_{RF} is beneficial in FF region but perhaps not in dipole
    - There may be an optimal value for f_{RF}
6) Most important variable is SEY
    - Surest way to reduce ecloud effects is to lower SEY
7) MI and PS2 remarkably similar, at least thus far in the exercise

<u>What next:</u>

a) Complete set of simulations for FF region and dipole as a function of N_b, f_{RF} and E_b
b) Explore dependence on other SEY parameters (especially E_{max}) and other model variables
c) Explore other regions of the chamber (quads,…)
d) Analyze expected new data
e) Simulate beam train/winess bunch tune shifts
f) Ascertain numerical convergence (most likely okay)
g) Resolve why RFA and microwave dispersion measurements show qualitatively different dependencies on E_b
h) Quantify effects on the beam and validate !

Extra material

MI ecloud-related LBNL publications

M. A. Furman, "A preliminary assessment of the electron cloud effect for the FNAL main injector upgrade," LBNL-57634/CBP-Note-712/FERMILAB-PUB-05-258-AD, June 28, 2005. Revised: June 26, 2006.

M. A. Furman, "A preliminary assessment of the electron cloud effect for the FNAL main injector upgrade," LBNL-57634-JArt/CBP Note-737, June 22, 2006; New Journal of Physics Focus Issue: Accelerator and Beam Physics, New J. Phys. 8 (2006) 279 (this article is a condensed version of LBNL-57634)

M. A. Furman, "HINS R&D Collaboration on Electron Cloud Effects: Midyear Progress Report," CBP-Technote-364/FERMILAB-TM-2369-AD, 22 September 2006.

M. A. Furman, "Studies of e-cloud build up for the FNAL main injector and for the LHC," LBNL-60512/CBP Note-736, June 15, 2006; Proc. HB2006, paper TUAX05

M. A. Furman, K. Sonnad and J.-L. Vay, "HINS R&D Collaboration on Electron Cloud Effects: Midyear Report," LBNL-61921/CBP-761/FERMILAB-TM-2370-AD, Nov. 7, 2006.

M. A. Furman, "HINS R&D Collaboration on Electron Cloud Effects: MI ecloud build-up simulations at the electron detector location," CBP Technote-367, Dec. 5, 2006.

M. A. Furman, "Electron-Cloud Build-up in the FNAL Main Injector," LBNL-62738, June 4, 2007. Proc. ECLOUD07, p. 97.

K. G. Sonnad, M. A. Furman, J.-L. Vay, M. Venturini, C. Celata and D. Grote, "Electron Cloud Induced Instabilities in the Fermilab Main Injectors (MI) for the High Intensity Neutrino Source (HINS) Project," LBNL-63754, Sept. 2007; Proc. ECLOUD07, p. 114.

K. Sonnad, M. Furman, S. Veitzer, P. Stoltz and J. Cary, "Preliminary Analysis and Simulation Results of Microwave Transmission Through an Electron Cloud," LBNL-863E, Sept. 2007; Proc. ECLOUD07, p. 100.

K. G. Sonnad, M. Furman, J. R. Cary, P. Stoltz, S. A. Veitzer, "Simulation and Analysis of Microwave Transmission Through an Electron Cloud, a Comparison of Results" LBNL-63752, CBP-803; Proc. PAC07, paper THPAS008.

K. G. Sonnad, C. M. Celata, M. Furman, D. Grote, J.-L. Vay, M. Venturini, "Simulations of Electron Cloud Effects on the Beam Dynamics for the FNAL Main Injector Upgrade," LBNL-63753; Proc. PAC07, paper FRPMS028.

Kiran G. Sonnad, Miguel A. Furman and Jean-Luc Vay, "A preliminary report on electron cloud effects on beam dynamics for the FNAL main injector upgrade," CBP Technote-369, January 16, 2007.

M. A. Furman, "Electron-cloud build-up simulations for the MI RFA: A status report," CBP Technote-387, 12 Nov. 2007.

M. A. Furman, "Main Injector Upgrade R&D Collaboration on Electron Cloud Effects: Comparing the RF frequency of 53 MHz vs. 212 MHz," CBP-Technote-386, 17 March 2008.

Kiran G. Sonnad, Miguel A. Furman and Jean-Luc Vay, "Progress on electron cloud effects calculations for the FNAL main injector," LBNL-767E, 9 June 2008.

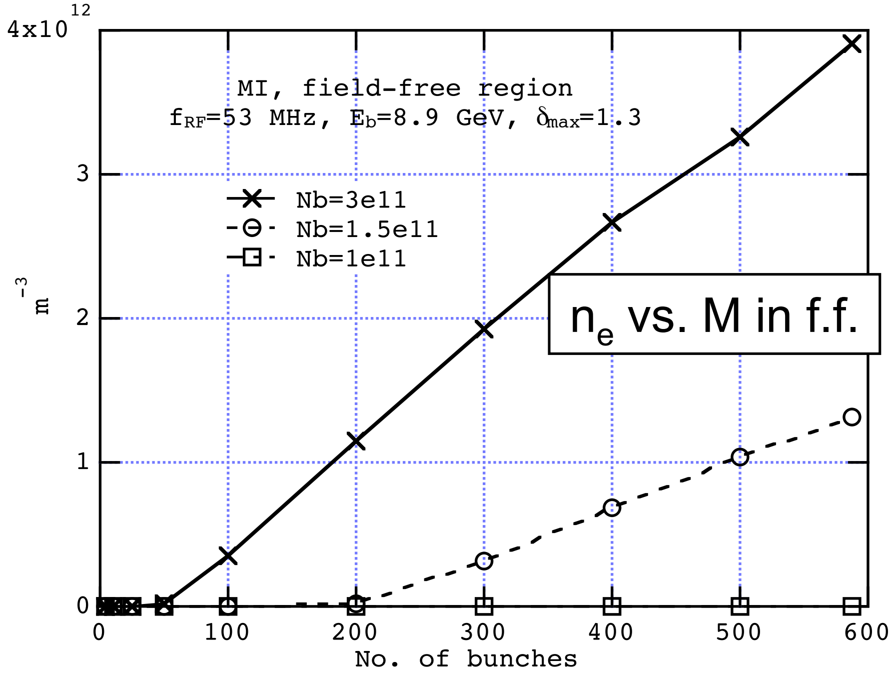
M. A. Furman, "Electron-Cloud Build-Up Simulations for the FNAL Main Injector", LBNL-1402E/CBP Tech Note 387, Sept. 19, 2008. Proc. HB2008.

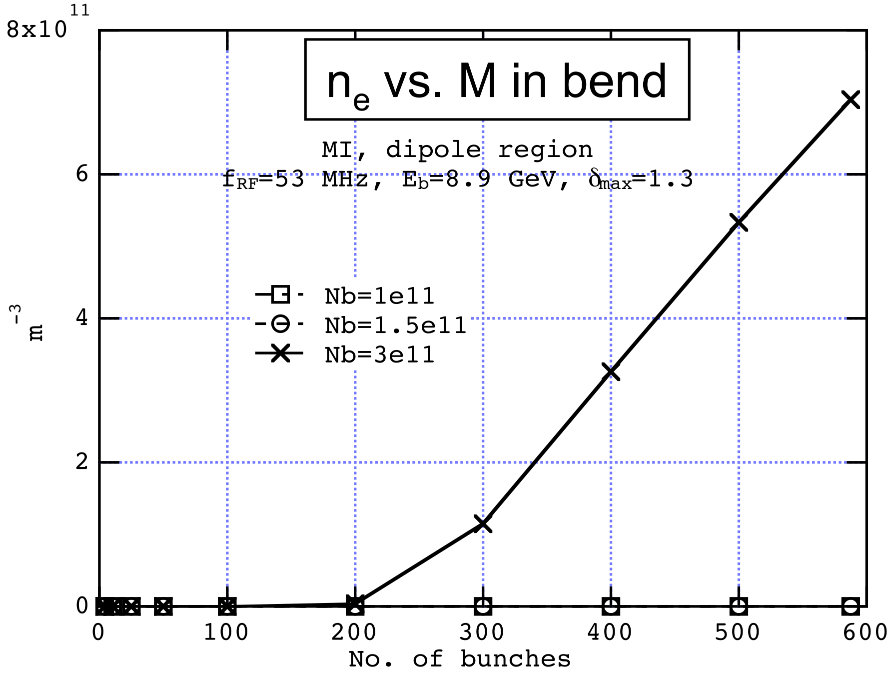
M. A. Furman, "Electron-Cloud Build-Up Simulations for the FNAL Main Injector: 400-ns Bunch Spacing," CBP-Technote-390, 3 Oct. 2008.

M. A. Furman, I. Kourbanis and R. M. Zwaska, "Status of Electron-Cloud Build-Up Simulations for the Main Injector," LBNL-xxx; Proc. PAC09, paper TH5PFP032.

M-dependence at N_b=(10-30)x10^{10}

n_e vs. M (KE_b=8 GeV, continuous train of bunches)

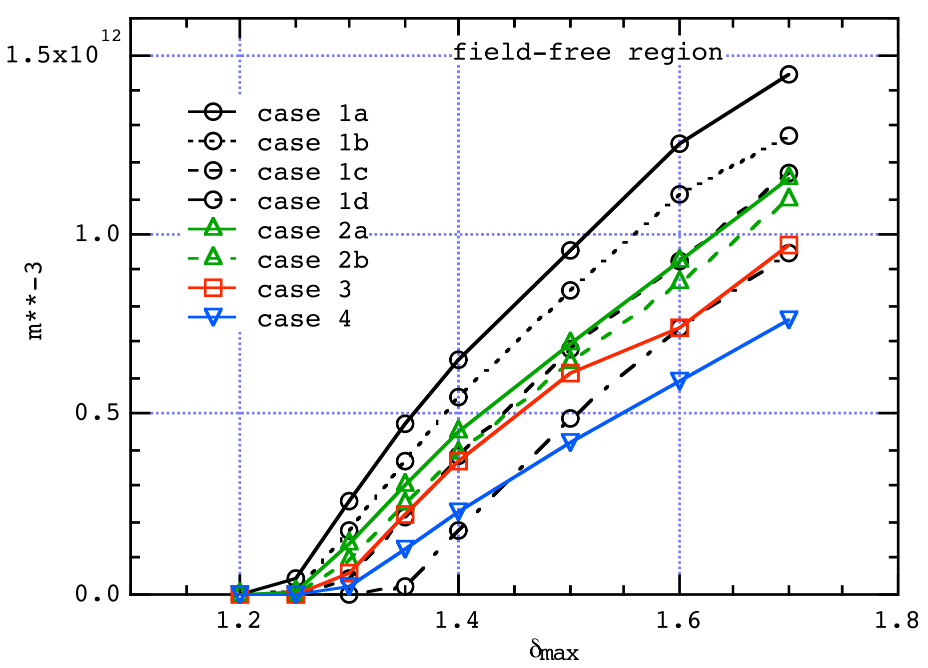

n_e vs. M in f.f.

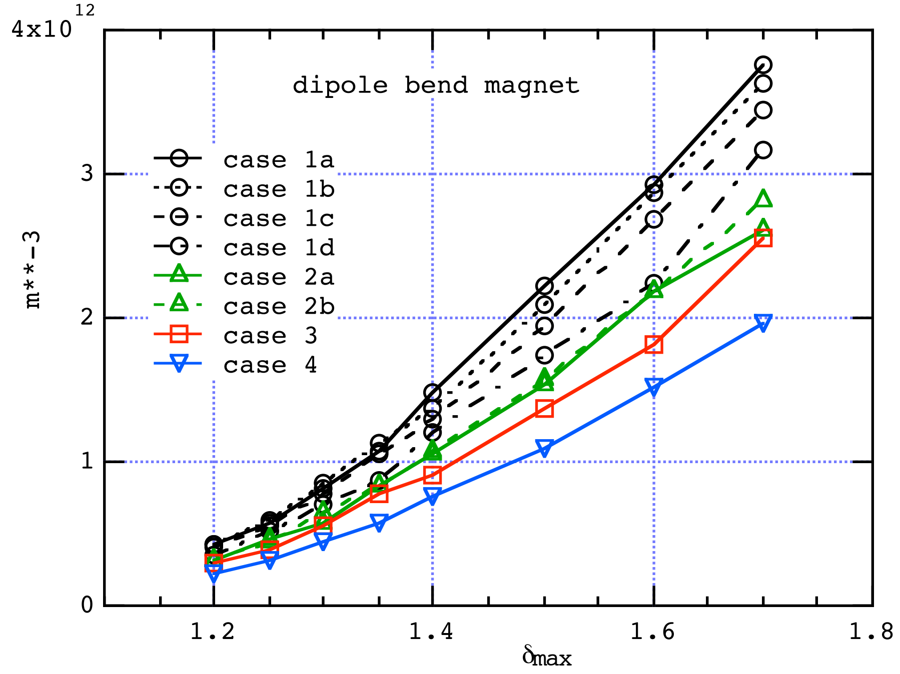

n_e vs. M in bend

- Threshold in M strong function of N_b:
  - —M_{th}=50 for N_b=30x10^{10}
  - —M_{th}=200 for N_b=15x10^{10}
- For a dipole, M_{th}=200 for N_b=30x10^{10}

Compare field-free vs. dipole bend

n_e vs. δ_{max} (E_b=60 GeV, same fill patterns, σ_z=19 cm)





- Threshold as a f. of δ_{max} in field-free region
- No threshold in dipole
- n_e in dipole ~3 times larger than in F.F. region

  —not yet explained