Electron-Cloud Physics

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Summary

- Description of the electron-cloud effect (ECE)
- R&D work at LBNL
- Plans for the future
- Conclusions

I am grateful for collaboration and discussions over time with: A. Adelmann, G. Arduini, V. Baglin, M. Blaskiewicz, O. Brüning, Y. H. Cai, R. Cimino, R. Cohen, I. Collins, F. J. Decker, A. Friedman, O. Gröbner, K. Harkay, S. Heifets, N. Hilleret, U. Iriso, J. M. Jiménez, R. Kirby, G. Lambertson, R. Macek, A. Molvik, K. Ohmi, M. Pivi, C. Prior, A. Rossi, G. Rumolo, D. Schulte, P. Stoltz, J.-L. Vay, S. Y. Zhang, A. Zholents and F. Zimmermann.

What is the ECE

- Beam produces electrons
  - — photoelectrons from SR radiation (beam going through bends)
  - — ionization of residual gas
  - — stray beam particles striking the chamber
- Electrons get rattled around the chamber from multibunch passages
  - — especially for intense positively-charged beams
  - — this may lead to significant secondary electron emission from the chamber walls (esp. aluminum)
- Possible consequences:
  - — dipole multibunch instability (bunch-to-bunch coupling)
  - — emittance blowup
  - — gas desorption from chamber walls
  - — excessive energy deposition on the chamber walls (important for superconducting machines, eg. LHC)
  - — particle losses, interference with diagnostics,…
- In summary: the ECE is a consequence of the interplay between the beam and the vacuum chamber
  - — many ingredients: beam intensity, bunch shape, fill pattern, photoelectric yield, photon reflectivity, secondary emission yield (SEY), vac. chamber size and geometry, …

Observations

- ECE has been observed at many machines:
  - — PF, PEP-II, KEKB, BEPC, PS, SPS, APS, PSR, RHIC
    - undesirable effects on performance, and/or
    - direct observation (dedicated e^- detectors)
  - —expected at LHC, SNS, NLC DRs
- For bunched beams: ECE encompasses:
  - — beam-induced multipacting (BIM) (ISR, mid 70's)
    - multibunch effect
  - — trailing-edge multipacting (PSR, since mid 80's)
    - single-long-bunch effect
- For coasting beams: ECE encompasses two-stream instability (since mid 60's at BINP, Bevatron, …)

Importance

- ECE was significant at PEP-II and KEKB
  - — dominant sources:
    - photoelectrons (KEKB)
    - secondary electrons (PEP-II)
  - — decision to TiN-coat the PEP-II e^+ vacuum chamber (aluminum has high SEY!)
  - — current performance level could only be reached after controlling the ECE
- ECE limits performance of PSR at high current
- Future machines:
  - — LHC, SNS, ILC damping rings

Importance (contd.)

- **1997: realization that the LHC would be subject to an ECE**
  - **first proton machine with significant synchr. radiation:**

    critical energy of photon spectrum: $E_{\rm crit}=\frac{3\hbar c}{2\rho}\gamma^3=44.1\ {\rm eV}$

    intensity: $N_{\gamma/p,\rm tot}=\frac{5\alpha\gamma}{2\sqrt{3}}\Delta\theta=0.4$ photons/proton/bend
  - **main concern: excessive power deposition**
  - **initial estimates: ~a few W/m, vs. 0.5 W/m cryo capacity**
  - **"LHC crash program" started 1997**
  - **main sensitivity: SEY**
  - **current consensus: peak SEY must be <~ 1.1–1.3**
    - **but parameter sensitivity not fully explored**

- **ILC: damping rings subject to ECE**
  - **main concern: wiggler regions**
  - **peak SEY must be <~ 1.2**

Controlling the ECE

- **Weak solenoidal fields (~20 G)**
  - — B field confines electrons near the chamber, away from the beam
    - used extensively at KEKB and PEP-II
    - significant improvement in performance
- **Tailoring bunch fill pattern**
  - — add strategic gaps in the train
    - used at PEP-II for a while, before solenoids
- **Vacuum chamber geometry**
  - — transverse grooves (LHC beam screen): suppress photoemission (by ~x2)
  - — longitudinal grooves (SLAC tests): suppress effective SEY (~x2)

Lowering the SEY

- Low-SEY coatings
  - TiN (used in PEP-II, SNS; tested at PSR)
  - TiZrV: studied at CERN
    - fully suppresses multipacting after activation (SPS tests)
    - used in RHIC warm sections ("works better than solenoids")
    - will be used in LHC warm straights
    - drawback: cannot be used in cold regions (needs activation ~160-200 C)
- SEY decreases with e^- bombardment: "<u>scrubbing</u>"
  - self-conditioning effect
- SPS ECE studies:
  - ~5 years of dedicated EC studies with dedicated instrumentation
  - scrubbing very efficient; favorable effects seen in:
    - vacuum pressure
    - in-situ SEY measurements
    - electron flux at wall

Work at LBNL

- LBNL is an early player in the field of ECE simulations and analysis
  - — since 1995: have developed code "POSINST"
    - incorporates a detailed SE model
    - in good agreement with measurements at APS and PSR
      - – but many input parameters not well known
    - code is 2D, and not self-consistent
      - – EC is dynamical, beam is not
      - – OK for stable (or mildly unstable) beam, and short sections of a ring
  - — applied to PEP-II since 1995
    - results led to TiN coating decision of LER vacuum chamber
- ILC damping rings (A. Wolski's talk)
  - — simulations (started by M. Pivi, now at SLAC)
    - concern: wiggler sections
  - — low-SEY coatings (TiN, TiZrV, TiCN)
    - coupons prepared at SLAC, we do the coating, SLAC analyzes
  - — grooved surface bench tests
- Measurements at PEP-II (J. Byrd's talk)
  - — microwave transmission through e-cloud

Work at LBNL: collaborations

- APS, PSR, RHIC and PEP-II
  - code benchmarking and analysis of data
- CERN (since 1997)
  - within the context of the US-LHC program "LARP"
  - we are the lead lab for EC physics within LARP
  - code comparisons
  - analysis of SPS measurements
- AMAC group (here at LBNL) (R. Ryne's talk)
  - 3D self-consistent code "PARSEC"
    - A. Adelmann (now at PSI)
- Tech-X Corp. via an SBIR
  - CMEE library: general-purpose modules for:
    - SE, based largely on our SEY model
    - ion-wall emission,…
    - license agreement: free for non-commercial applications
- Lead institution for ECLOUD'04 workshop (April '04)

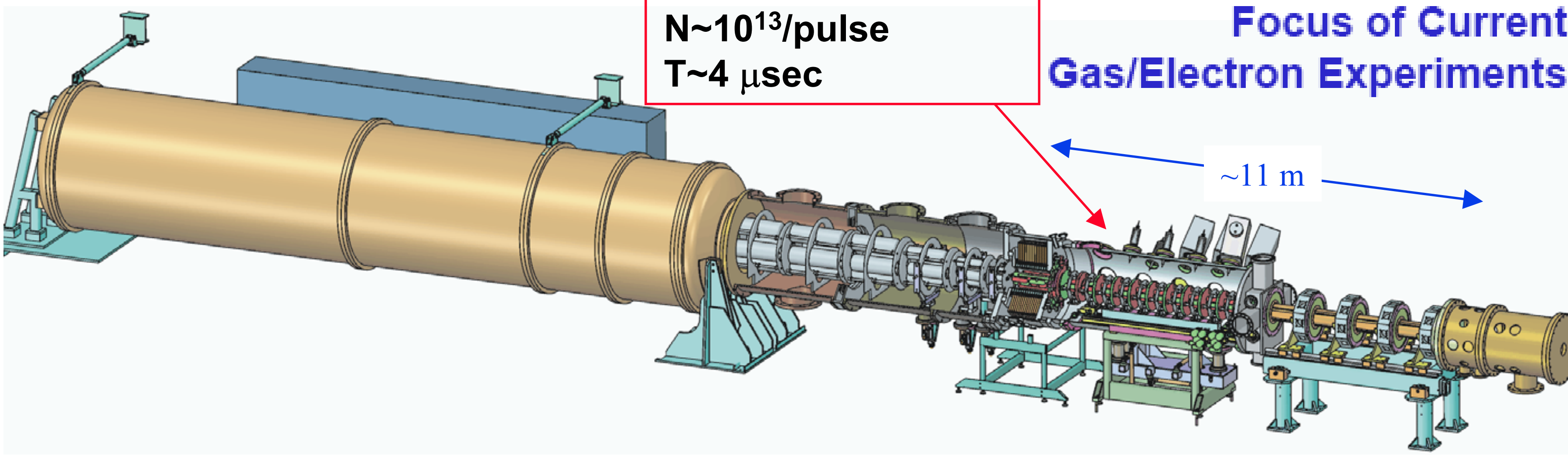
http://icfa-ecloud04.web.cern.ch/icfa-ecloud04/

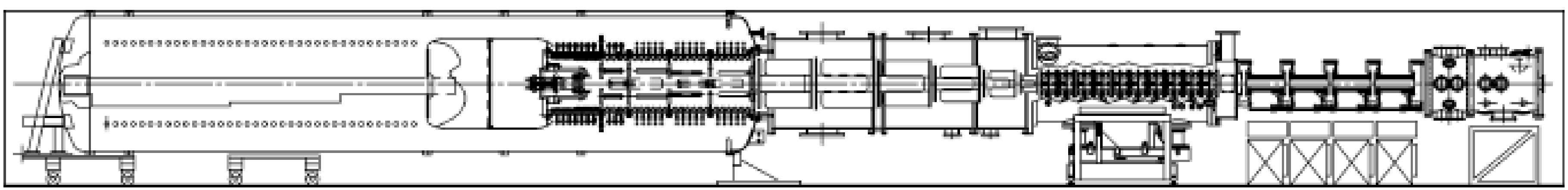
Work at LBNL: LDRD

"Electron Production and Collective Field Generation in Intense Particle Beams"

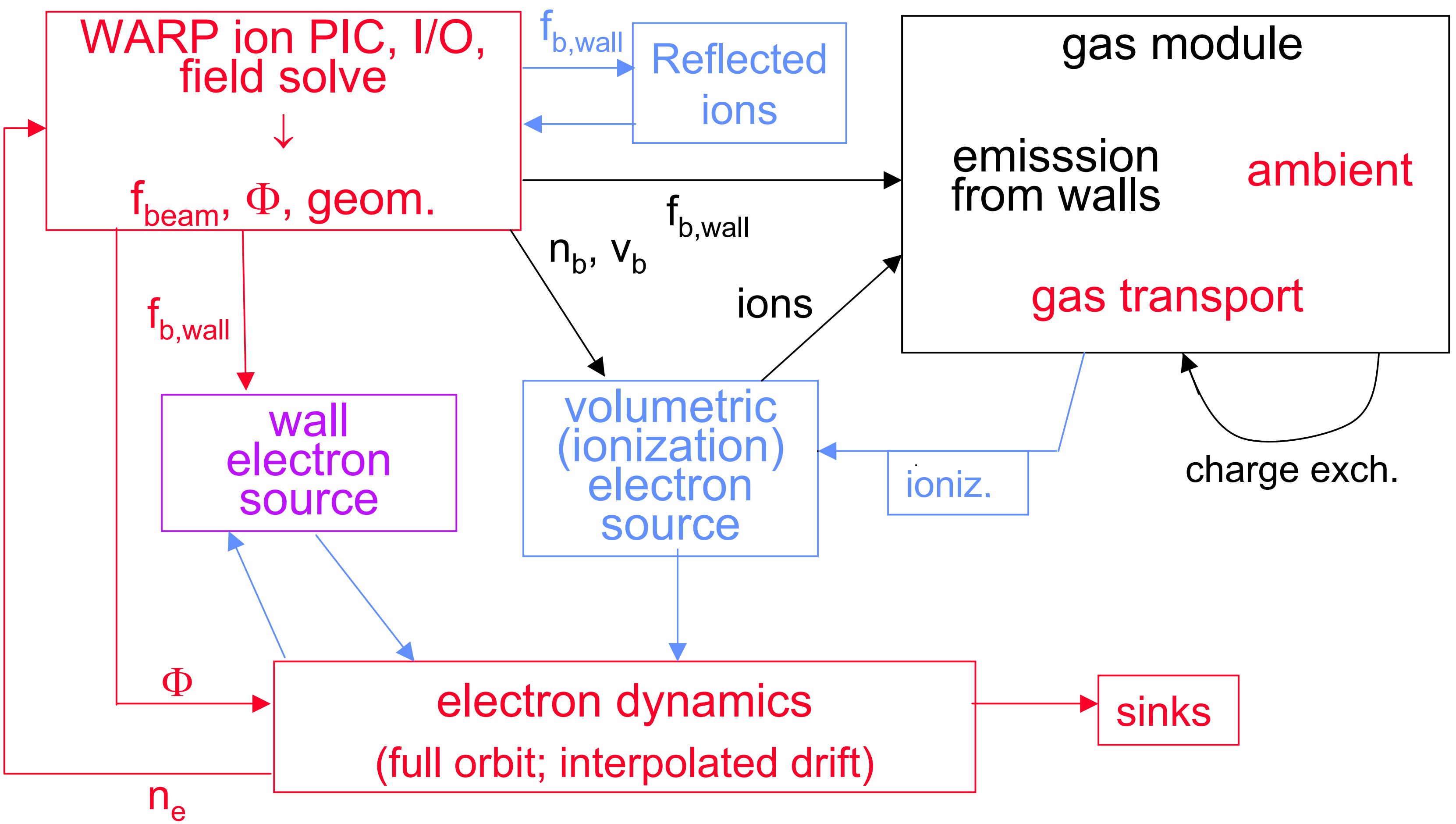
- LDRD (coordinated LBNL-LLNL) since Oct. '02
  - — ~$120k/yr (LBNL) + ~$180k/yr (LLNL)
  - — supports EC work at CBP and HIF, and LLNL
  - — FY05 is 3rd (and last) year
  - — integrated program (simulation, diagnostics and measurements)
  - — produce a 3D self-consistent code
    - based on code "WARP" (self-consistent, parallel, MAD input,…)
    - add POSINST e^- emission models, gas, ionization,..
  - — centered around the HCX driver at LBNL
    - E=1.8 MeV K^+ ions, ~10-m long machine
    - detectors: electrons, gas, ions at the wall
  - — HCX can be simulated end-to-end!
  - — main goals:
    - measure various quantities (e^- and gas yields, ion-wall scattering,…)
    - validate code and understand EC details via comparisons against expts
    - ultimately: <u>predictive simulation tool</u> of general applicability

The HCX driver for HIF





WARP+POSINST code structure



Key: operational; implemented, testing; partially implemented; active offline development

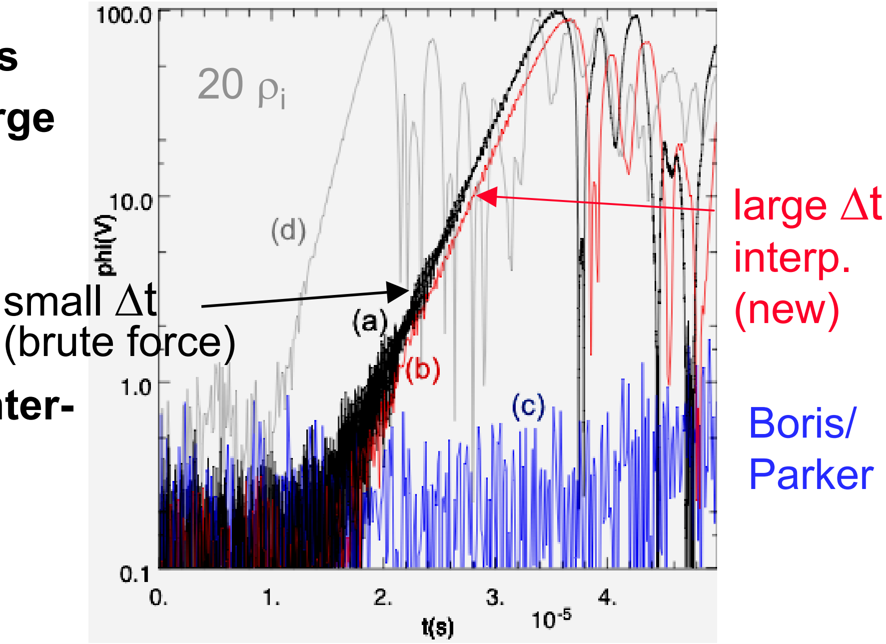
Invention of an efficient electron integrator
(R. Cohen et al.)

- Problem: wide range of time scales (electrons move fast!)
- ⇒ brute force integration requires small Δt when *B* ≠ 0 ⇒ slow
- Our solution: interpolation between full-particle dynamics (Boris mover) and drift kinetics (motion along B plus drifts).

$$\mathbf{v}_{new} = \mathbf{v}_{old} + \Delta t \left(\frac{d\mathbf{v}}{dt}\right)_{Lorentz} + (1-\alpha)\left(\frac{d\mathbf{v}}{dt}\right)_{\mu\nabla B}$$

$$\mathbf{v}_{eff} = \mathbf{b}(\mathbf{b}\cdot\mathbf{v}) + \alpha\mathbf{v}_\perp + (1-\alpha)\mathbf{v}_d$$

- Particular choice: $\alpha=1/[1+(\omega_c\Delta t/2)^2]^{1/2}$ gives
  - — physically correct "gyro" radius at large $\omega_c\Delta t$
  - — correct drift velocity and parallel dynamics
- Ref. Cohen et al, Phys. Plasmas May '05
- Test problem: 2 stream instability of counter-streaming pencil (10 gyroradii) beams

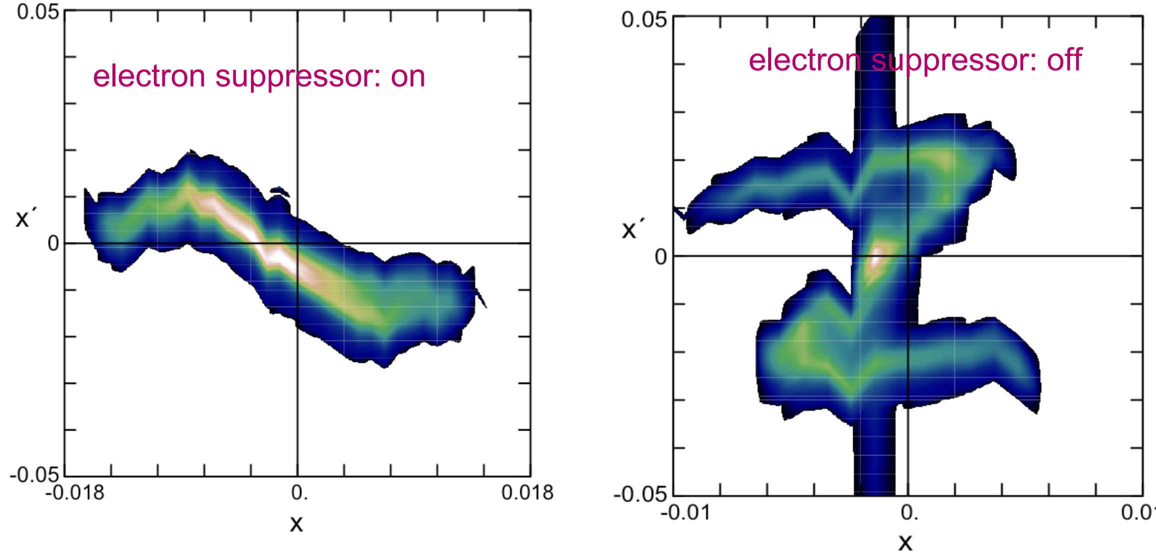


Speed-up by ~x25, ~no loss of accuracy

WARP/POSINST e-i simulations of the 4 magnet section of HCX show ion phase space similar to the experiments

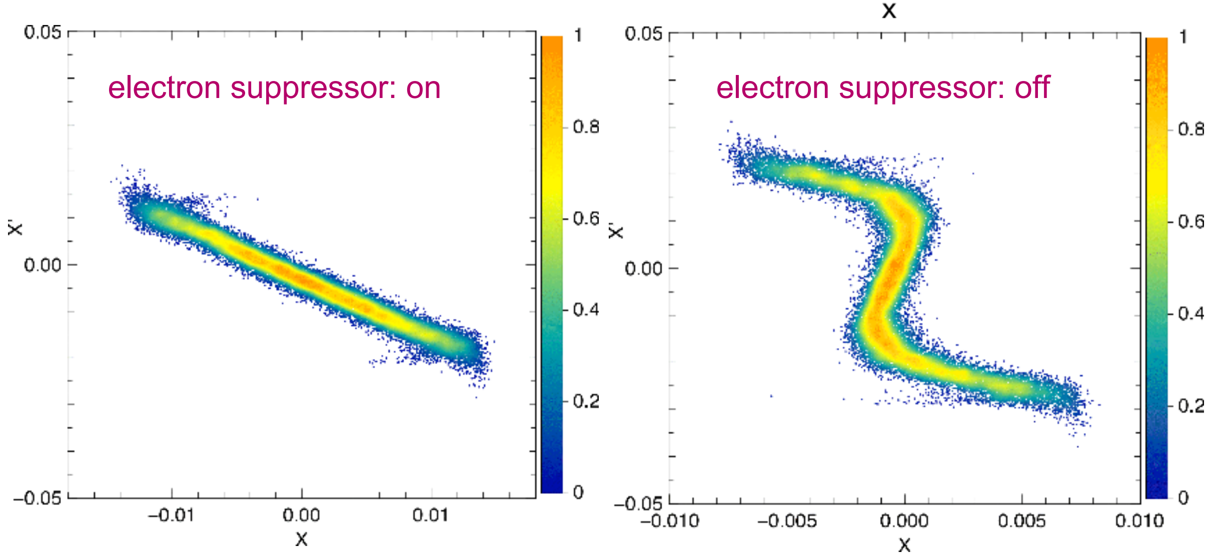
HCX measurement

Phase space reconstruction from scintillator images of slit scan



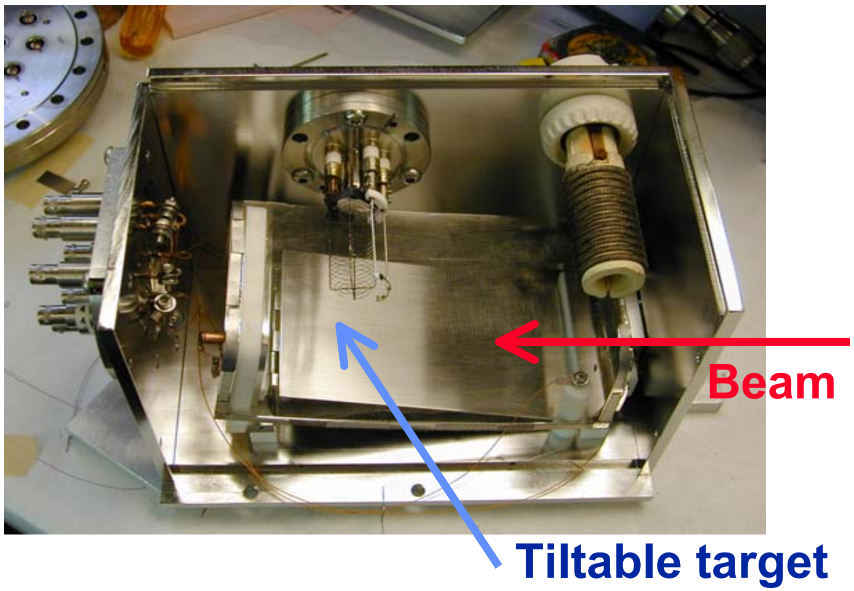
3-D WARP simulation with:

Electron desorption at end wall matching desorption rate from separate experiments.
Secondary emission when electrons hit radial pipes.
NO local sources of electrons

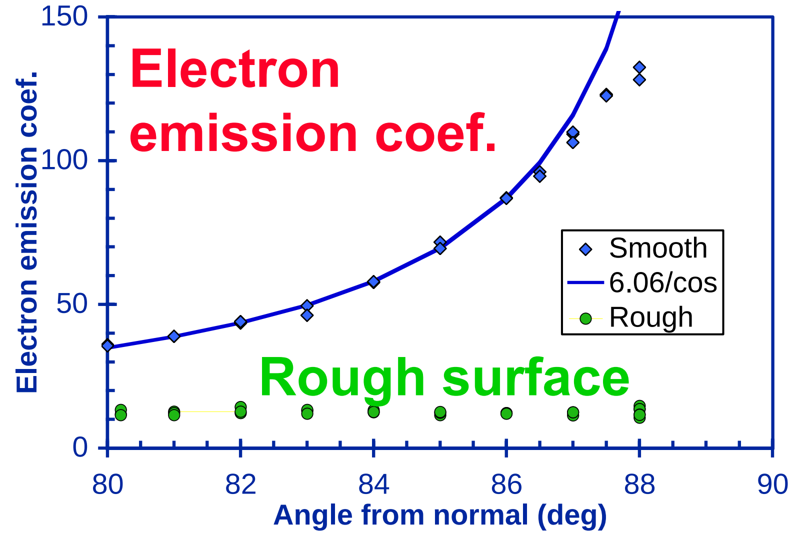


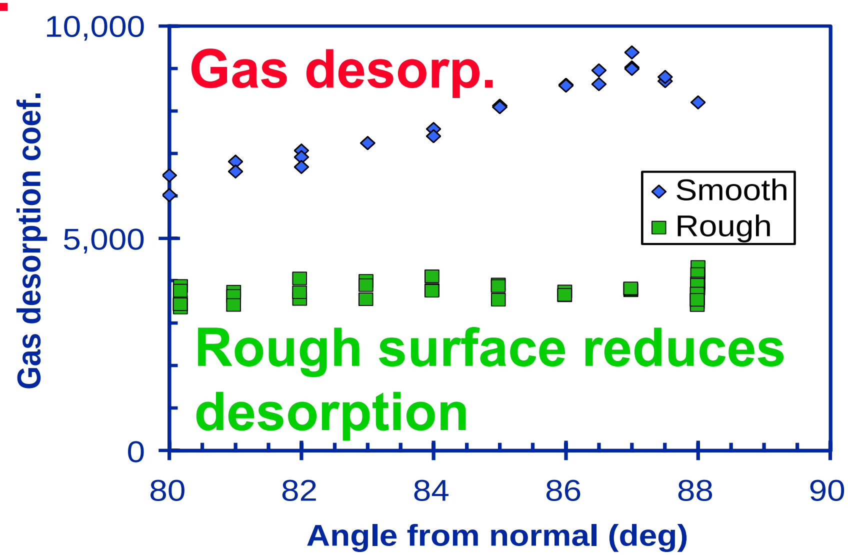
Gas desorption / electron emission measurements

Gas-Electron Source Diagnostic (GESD)



Target surface roughened by glass-bead blasting – grazing incidence ions now hit rims of craters.





Future Plans

- More thorough simulations for reliable predictions
  - — even with 2D code POSINST
  - — explore parameter dependencies and sensitivities
    - eg., LHC power deposition is sensitive to the spectrum, not just the yield
  - — remaining questions here and there
    - why was TiN coating at PEP-II not enough?
    - EC at Tevatron (?)
    - …
- Predict LHC heat deposition and optimal "conditioning scenario"
- Predict and analyze RHIC measurements
  - — CERN-style detector to be installed this summer
- Tech-X CMEE library needs to be expanded:
  - — parameterize more materials, fix many variables (so far, SEY model only for Cu and St.St., and even these are not fully analyzed)

Future Plans-contd.

- 2nd generation simulation codes (3D, self-consistent)
  - — WARP+POSINST, PARSEC
    - many pieces exist; need to integrate and validate
    - “QUICKPIC” code (UCLA/USC) is half-way there
    - we can do better!
- These codes will allow:
  - — realistic model (beam, electrons, gas, magnetic lattice, surface effects, magnetic edge effects,…)
  - — e.g., simulate a portion of the LHC arc (1 FODO cell coming soon!)
    - keen interest from CERN people
  - — assess effects from the 3rd (z) dimension:
    - electrons survive for ~1 s at SPS! (quadrupole trapping? dissipation?)
    - clearly important for PSR and other long-bunch machines
  - — assess interplay between gas desorption, ionization and secondary emission
    - circumstantial evidence from SPS
    - is secondary ionization important?

Conclusions

- The ECE is an ubiquitous phenomenon for intense beams
- Spans broad range of charged-particle machines
- Significant investment in our work from non-HEP:
  - e.g., APS, PSR, RHIC and HIF
- Significant institutional investment (LDRD support for ~2.5 yrs now)
  - LDRD ends this FY
- Main goal for next ~2 yrs:
  - continue with applications (tests at RHIC, predict LHC, …)
  - deliver a validated, reliable, predictive simulation tool
  - lots of parameters in the model; need to <u>test methodically</u>
- Beyond 2 yrs:
  - apply to LHC and ILC in more detail
    - ECEs should be understood before LHC commissioning at full intensity
    - incorporate mitigation/control techniques in the ILC design if possible
- HCX is a unique test resource
  - developments have been important to field of EC as a whole
  - highly desirable to continue this effort

LBNL ECE publications Since Oct. '02

Invited Papers

A. W. Molvik, R. H. Cohen, A. Friedman, M. Kireeff Covo, S. M. Lund (LLNL); F. Bieniosek, P. Seidl, J.-L. Vay (LBNL), "Electrons and Gas Versus High Brightness Ion Beams," invited talk, 25th International Workshop on Physics of High Energy Density in Matter (Hirschegg, Austria, Feb. 2-7, 2003). UCRL-PRES-209447.

A. W. Molvik, D. Baca, F. M. Bieniosek, R. H. Cohen, A. Friedman, M. A. Furman, E. P. Lee, S. M. Lund, L. Prost, P. A. Seidl, J.-L. Vay, "Experimental Studies of Electron Effects in Heavy-Ion Beams," invited talk, International Workshop in Physics of High-Energy Density in Matter, Session on Gas/Electron Effects in High-Ion-Current Accelerators (Hirschegg, Austria, Feb. 2-7, 2003).

M. A. Furman, "Formation and Dissipation of the Electron Cloud", LBNL-51829; invited talk, Proc. PAC03 (Portland, OR, May 12-16, 2003), paper TOPC001.

A. W. Molvik, J. J. Barnard, E. M. Bringa, D. A. Callahan, C. M. Celata, R.H. Cohen, A. Friedman, M. A. Furman, J. W. Kwan, B. G. Logan, W. R. Meier, A. Sakumi, P.A. Seidl, W. Stoeffl, S. S. Yu, "HIF (Heavy Ion Fusion) Gas Desorption Issues", invited talk, ICFA Workshop on Beam-Induced Pressure Rise in Rings (BNL, Dec. 9-12, 2003). UCRL-PRES-202004.

M. A. Furman, "Issues in the Formation and Dissipation of the Electron Cloud," (unpublished invited talk), 13th ICFA Beam Dynamics Mini-Workshop on Beam-Induced Pressure Rise in Rings (BNL, Dec. 9-12, 2003).

R. H. Cohen, A. Friedman, S. M. Lund, A. W. Molvik, E. P. Lee, A. Azevedo, J.-L. Vay, P. Stoltz and S. Veitzer, "Modelling Electron Cloud Effects in Heavy-Ion Accelerators", invited talk, 31st ICFA Advanced Beam Dynamics Workshop on Electron-Cloud Effects "ECLOUD '04" (Napa, CA, 19-23 Apr 2004).

A. W. Molvik, F. M. Bieniosek, J. J. Barnard, D. A. Calahan, R. H. Cohen, A. Friedman, M. Kireeff Covo, J. W. Kwan, W. R. Meier, L. Prost, A. Sakumi, P. A. Seidl, S. S. Yu, "Experimental Studies of Electron and Gas Sources in a Heavy-Ion Beam," invited talk, 31st ICFA Advanced Beam Dynamics Workshop on Electron-Cloud Effects "ECLOUD'04" (Napa, CA, 19-23 Apr 2004). UCRL-PRES-203920 and UCRL-CONF-207208.

M. A. Furman, "Goals for the Workshop," invited talk, 31st ICFA Advanced Beam Dynamics Workshop on Electron-Cloud Effects "ECLOUD'04" (Napa, CA, 19-23 Apr 2004). LBNL-57166.

M. A. Furman, "Closing Remarks," invited talk, 31st ICFA Advanced Beam Dynamics Workshop on Electron-Cloud Effects "ECLOUD'04" (Napa, CA, 19-23 Apr 2004). LBNL-57166.

P. Stoltz, S. Veitzer, R. Cohen, A. Molvik, J.-L. Vay, "The CMEE Library for Numerical Modeling of Electron Effects," invited talk, 31st ICFA Advanced Beam Dynamics Workshop on Electron-Cloud Effects "ECLOUD04" (Napa, California, April 19-23, 2004).

Invited Papers (contd.)

W. Molvik, P. A. Seidl, F. M. Bieniosek, R. H. Cohen, M. Kireeff Covo, L. Prost, "Experimental Studies of Electrons in a Heavy-Ion Beam", invited talk, HIF-2004 - International Heavy-Ion Inertial Fusion Symposium (Princeton University, Princeton, NJ, June 7-11, 2004). UCRL-PRES-204889.

R. H. Cohen, A. Friedman, S. M. Lund, A. W. Molvik, A. Azevedo, J.-L. Vay, P. Stoltz and S. Veitzer, "Simulating Electron Cloud Effects in Heavy-Ion Accelerators", invited talk, HIF Symposium (Princeton, NJ June 7-11, 2004).

R. Macek and M. A. Furman, "Summary of the ECLOUD'04 Workshop," invited talk by R. Macek, Proc. 33rd ICFA Advanced Beam Dynamics Workshop on High Intensity and High Brightness Hadron Beams "ICFA-HB2004" (Bensheim, Germany, October 18-22, 2004), LA-UR-04-8606/LBNL-57160, Feb 24, 2005.

R. H. Cohen, A. Friedman, M. Kireeff Covo, S. M. Lund, A. W. Molvik, F. M. Bieniosek, P. A. Seidl, J. L. Vay, P. Stoltz, S. Veitzer, "Simulating Electron Clouds in Heavy-Ion Accelerators, invited talk, APS-DPP meeting (Savannah Georgia, Nov. 15-19, 2004).

Refereed Publications

M. A. Furman and M. T. F. Pivi, "Probabilistic Model for the Simulation of Secondary Electron Emission", LBNL-49771, CBP Note-415, Nov. 6, 2002; PRSTAB/v5/i12/e124404 (2003).

M. T. F. Pivi and M. A. Furman, "Electron Cloud Development in the Proton Storage Ring and in the Spallation Neutron Source", LBNL-51618, Oct. 16, 2002; PRSTAB/v6/i3/e034201.

M. Blaskiewicz (BNL), M. A. Furman, M. Pivi (LBNL) and R. J. Macek (LANL), "Electron-Cloud Instabilities in the Proton Storage Ring and Spallation Neutron Source", LBNL-51661, Dec. 11, 2002; PRSTAB/v6/i1/e014203 (2003).

Y. Cai, M. Pivi (SLAC), M. A. Furman (LBNL), "Buildup of Electron Cloud in the PEP-II Particle Accelerator in the Presence of a Solenoid Field and with Different Bunch Pattern," SLAC-PUB-10164/LBNL-54689, Sep. 2003; PRSTAB/v7/i2/e024402.

R. Cimino (Frascati and CERN), I. R. Collins (CERN), M. A. Furman (LBNL), M. Pivi (SLAC), F. Ruggiero (CERN), G. Rumolo (GSI), and F. Zimmermann (CERN), "Can Low Energy Electrons Affect High Energy Physics Accelerators?," CERN-AB-2004-012 (ABP), LBNL-54594, SLAC-PUB-10350, Feb. 9, 2004; Phys. Rev. Lett. 93, 014801 (2004).

Cohen, R. H., Friedman, A., Lund, S. M., Molvik, A. W., Lee, E. P., Azevedo, A., Vay, J.-L., Stoltz, P., and Veitzer, S., "Electron-Cloud Simulation and Theory for High-Current Heavy-Ion Beams," PPRSTAB 7, 124201, (2004), UCRL-JRNL-205555.

LBNL ECE publications Since Oct. '02

Refereed Publications (contd.)

Cohen, R. H., Friedman, A., Kireeff Covo, M., Lund, S. M., Molvik, A. W., Bieniosek, F. M., Seidl, P. A., Vay, J.-L., Stoltz, P. and Veitzer, S., "Simulating Electron Clouds in Heavy-Ion Accelerators," accepted by Phys. Plasmas, (2004), UCRL-JRNL-207978.

R. H. Cohen, A. Friedman, S. M. Lund, A. W. Molvik, A. Azevedo, J.-L. Vay, P. Stoltz, and S. Veitzer, "Simulating Electron Cloud Effects in Heavy-Ion Beams", NIMPRA, to be published (2005).

Stoltz, P. H., Veitzer, S., Cohen, R. H., Molvik, A. W., Vay, J.-L., "Simulation of Heavy Ion Induced Electron Yield at Grazing Incidence," PRSTAB 7, 103201, (March 2004).

Conference Papers and Formal Reports

A. Adelmann and M. A. Furman, "PARSEC: Parallel Self-Consistent 3D Electron-Cloud Simulation in Arbitrary External Fields", LBNL-51797; Proc. PAC03 (Portland, OR, May 12-16, 2003), paper FPAG030.

Y. Cai, M. Pivi, and M. A. Furman, "Buildup of Electron Cloud with Different Bunch Pattern in the Presence of Solenoid Field", LBNL-51832; Proc. PAC03 (Portland, OR, May 12-16, 2003), paper WOAA004.

R. H. Cohen, A. Friedman, M. A. Furman, S. M. Lund, A.W. Molvik, P. Stoltz, J.-L. Vay, "Stray-Electron Accumulation and Effects in HIF Accelerator", LBNL-53100; Proc. PAC03 (Portland, OR, May 12-16, 2003), paper TOAA010.

A. W. Molvik, D. Baca, F. M. Bieniosek, R. H. Cohen, A. Friedman, M. A. Furman, E. P. Lee, S.M. Lund, L. Prost, A. Sakumi, P. A. Seidl, J.-L. Vay, "Initial Experimental Studies of Electron Accumulation in a Heavy Ion Beam", LBNL-52532; Proc. PAC03 (Portland, OR, May 12-16, 2003), paper TOPC004.

M. Pivi and M. A. Furman, "Mitigation of the Electron-Cloud Effect in the PSR and SNS Proton Storage Rings by Tailoring the Bunch Profile", LBNL-52709; Proc. PAC03 (Portland, OR, May 12-16, 2003), paper RPPG024.

M. Pivi, T. O. Raubenheimer and M. A. Furman, "Recent Electron-Cloud Simulation Results for the Main Damping Rings of the NLC and Tesla Linear Colliders", LBNL-52710; Proc. PAC03 (Portland, OR, May 12-16, 2003), paper RPPG023.

Conference Papers and Formal Reports (contd.)

J. Wei, M. Blaskiewicz, J. Brodowski, P. Cameron, D. Davino, A. Fedotov, P. He, H. Hseuh, Y. Y. Lee, H. Ludewig, W. Meng, D. Raparia, J. Touzzolo, S. Y. Shang, A. Aleksandov, S. Cousineau, V. Danilov, S. Henderson, M. Furman, M. Pivi, R. Macek, and N. Catalan-Lasheras, "Electron-Cloud Mitigation in the Spallation Neutron Source Ring", LBNL-51828; Proc. PAC03 (Portland, OR, May 12-16, 2003), paper WPPG004.

Y. Cai, M. Pivi (SLAC), M. Furman (LBNL), "Buildup of Electron Cloud with Different Bunch Pattern in the Presence of Solenoid Field," SLAC-PUB-9813, LBNL-54688, May 2003; Proc. PAC03 (Portland, OR, May 12-16, 2003), paper WOAA004, p. 350

M. A. Furman and M. T. F. Pivi, "Simulation of Secondary Electron Emission Based on a Phenomenological Probabilistic Model", LBNL-52807/SLAC-PUB-9912, Jun. 2, 2003.

M. A. Furman and M. T. F. Pivi, "A Preliminary Comparative Study of the Electron-Cloud Effect for the PSR, ISIS and the ESS," LBNL-52872/CBP Note 516, Jun. 23, 2003.

J.-L. Vay, M. A. Furman, A. W. Azevedo, R. H. Cohen, A. Friedman, D. P. Grote, P. H. Stoltz, S. A. Veitzer, "Status Report on the Merging of Electron-Cloud Code POSINST with 3-D Accelerator PIC code WARP," 31st ICFA Advanced Beam Dynamics Workshop on Electron-Cloud Effects "ECLOUD04" (Napa, California, April 19-23, 2004). LBNL-57173.

A. W. Molvik, F. M. Bieniosek, J.J. Barnard, D. A. Calahan, R. H. Cohen, A. Friedman, M. Kireeff Covo, J. W. Kwan, W. R. Meier, L. Prost, A. Sakumi, P.A. Seidl, S. S. Yu. "Experimental Studies of Electron and Gas Sources in a Heavy-Ion Beam," 31st ICFA Advanced Beam Dynamics Workshop on Electron-Cloud Effects "ECLOUD04" (Napa, California, April 19-23, 2004). UCRL-CONF-207208.

M. A. Furman, "ECLOUD04 Workshop (Napa, California, April 19-23, 2004)", LBNL-56110, Aug. 2004. ICFA Beam Dynamics Newsletter No. 33 (Apr. 2004), Sec. 5.2.1 (p. 215) http://www-bd.fnal.gov/icfabd/

LBNL ECE publications Since Oct. '02

Conference Papers and Formal Reports (contd.)

M. A. Furman, "Electron Cloud Build-Up in Hadron Machines," LBNL-56109, Aug. 2004, ICFA Beam Dynamics Newsletter No. 33 (April 2004), Sec. 2.9 (p. 70) http://www-bd.fnal.gov/icfabd/

F. Zimmermann, E. Benedetto, F. Ruggiero, D. Schulte (CERN); M. Blaskiewicz, L. Wang (BNL); G. Bellodi (CCLRC/RAL/ASTeC); G. Rumolo (GSI); K. Ohmi, S. S. Win (KEK); M. Furman (LBNL); Y. Cai, M. T. F. Pivi (SLAC); V. K. Decyk, W. Mori (UCLA); A. F. Ghalam, T. Katsouleas (USC), "Review and Comparison of Simulation Codes Modeling Electron-Cloud Build Up and Instabilities", Proc. EPAC04 (Lucerne, Switzerland, 5-9 July 2004), paper THPLT017. LBNL-55239, July 2004.

P. A. Seidl, A. W. Molvik, F. M. Bieniosek, R. H. Cohen, A. Faltens, A. Friedman, M. Kireeff Covo, S. M. Lund, L. Prost, J.-L. Vay, "Intense Ion Beam Transport in Magnetic Quadrupoles: Experiments on Electron and Gas Effects," 33rd Advanced Beam Dynamics Workshop on High Intensity & High Brightness Hadron Beams "ICFA HB2004" (Bensheim, Germany, Oct. 18-22, 2004).

P. Stoltz, S. Veitzer, A. Prideaux, M. Furman, J.-L. Vay, R. H. Cohen, A. W. Molvik, "The CMEE Library for Computer Modeling of Ion-Material Interactions," 33rd Advanced Beam Dynamics Workshop on High Intensity & High Brightness Hadron Beams "ICFA HB2004," (Bensheim, Germany, Oct. 18-22, 2004).

Selected Meetings and Websites

Meetings Fully or Partially Dedicated to Electron-Cloud Physics

Santa Fe Workshop on Electron Effects in High-Current Proton Rings, SNS/LANL (Santa Fe, NM, Mar 4-7, 1997); LA-UR-98-1601.

Workshop on Multibunch Instabilities "MBI97" (KEK, Tsukuba, Japan, July 15-18, 1997); KEK Proc. 97-17 (1997);
http://www-acc.kek.jp/www-acc-exp/Conferences/MBI97-N/MBI97.html

ICFA Workshop on Two-Stream Instabilities in Particle Accelerators and Storage Rings (Santa Fe, NM, Feb 16-18, 2000); http://www.aps.anl.gov/conferences/icfa/two-stream.html

Int'l Workshop on Two-Stream Instabilities in Particle Accelerators and Storage Rings (KEK, Tsukuba, Japan, Sept 11-14, 2001); http://conference.kek.jp/two-stream/

20th ICFA Advanced Beam Dynamics Workshop on High Intensity High Brightness Hadron Beams "HB2002" (Fermilab, April 8-12, 2002); http://www-bd.fnal.gov/icfa/workshops/20/

Mini-Workshop on Electron-Cloud Simulations for Proton and Positron Beams "ECLOUD02" (CERN, April 15-18, 2002); http://slap.cern.ch/collective/ecloud02/

13th ICFA Beam Dynamics Mini-Workshop on Beam-Induced Pressure Rise in Rings (BNL, Dec. 9-12, 2003);
http://www.c-ad.bnl.gov/icfa/

31st ICFA Advanced Beam Dynamics Workshop on Electron-Cloud Effects "ECLOUD04" (Napa, California, April 19-23, 2004); http://icfa-ecloud04.web.cern.ch/icfa-ecloud04/

33rd ICFA Advanced Beam Dynamics Workshop on High Intensity and High Brightness Hadron Beams "ICFA-HB2004" (Bensheim, Germany, October 18-22, 2004)
http://www.gsi.de/search/events/conferences/ICFA-HB2004/index_e.html

First CARE-HHH-APD Workshop on Beam Dynamics in Future Hadron Colliders and Rapidly Cycling High-Intensity Synchrotrons "HHH2004" (CERN, 8-11 November, 2004);
http://care-hhh.web.cern.ch/care-hhh/HHH-2004/

Some Websites Dedicated to Electron-cloud Physics

Electron Cloud in the LHC (CERN):
http://wwwslap.cern.ch/collective/electron-cloud/electron-cloud.html

Two-stream instability studies at PPPL:
http://w3.pppl.gov/~nnp/TwoStream.htm

Electron Cloud Studies at the Advanced Photon Source (ANL):
http://www.aps.anl.gov/asd/physics/ecloud/ecloud.html

Comparison of Electron-Cloud Simulations (CERN):
http://wwwslap.cern.ch/collective/ecloud02/ecsim/index.html

Our mission…

"PARTICLES, PARTICLES, PARTICLES."

Backup material

Electron Cloud Effect (ECE)

- **First seen for a e⁺ beam at PF (KEK) in 1994:**
  - **qualitative difference in coherent spectrum of e⁺ vs. e⁻ multibunch beams under otherwise identical conditions:**

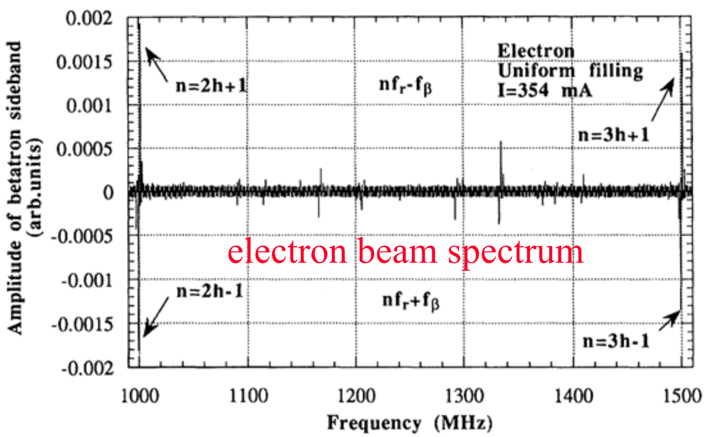


FIG. 1. Distribution of the betatron sidebands observed during electron multibunch operation with uniform filling.

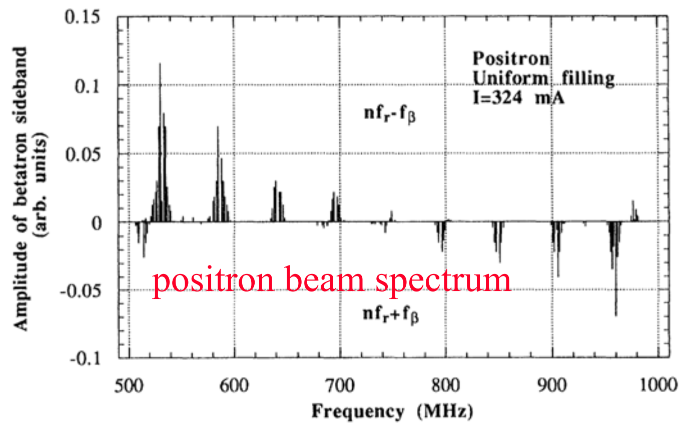


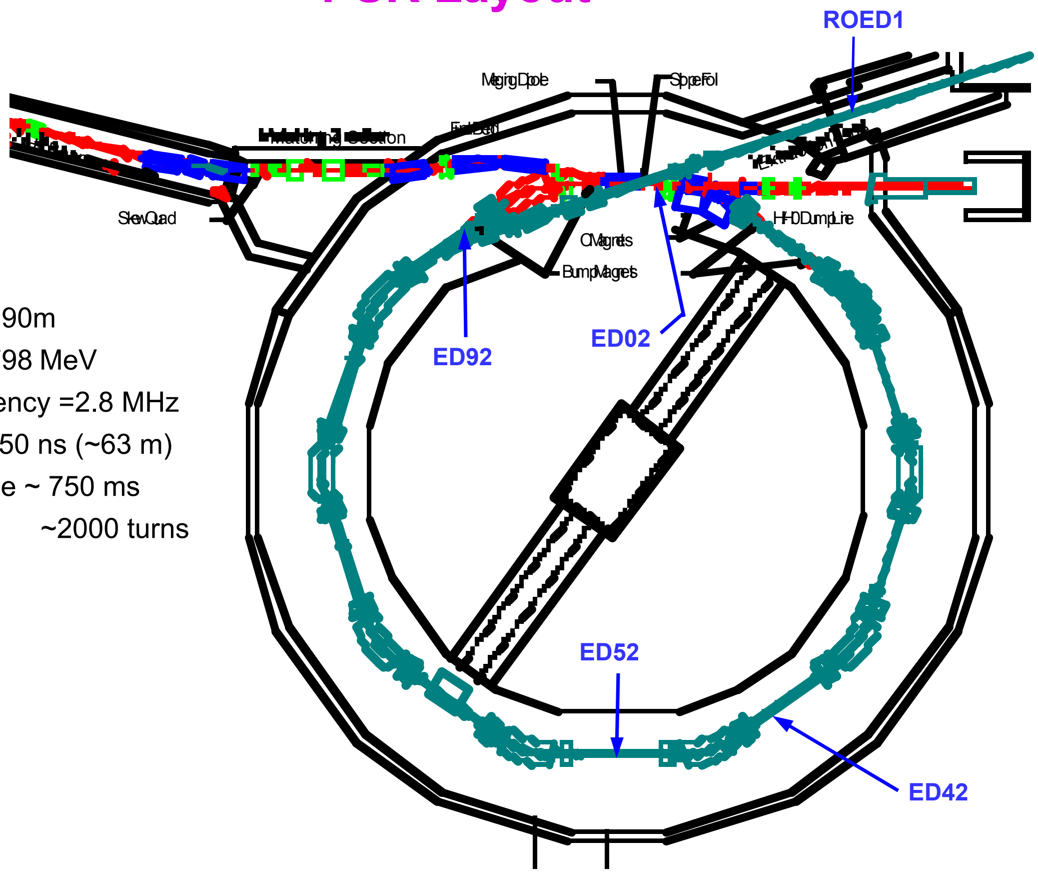
FIG. 2. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling.

Izawa, Sato & Toyomasu, PRL **74**, 5044 (1995)

- **Fast multibunch instability for e⁺ beam:**
  - **insensitive to "clearing gap"**
  - **sensitive to bunch spacing**
  - **electrons in the chamber were immediately suspected**

PSR Layout

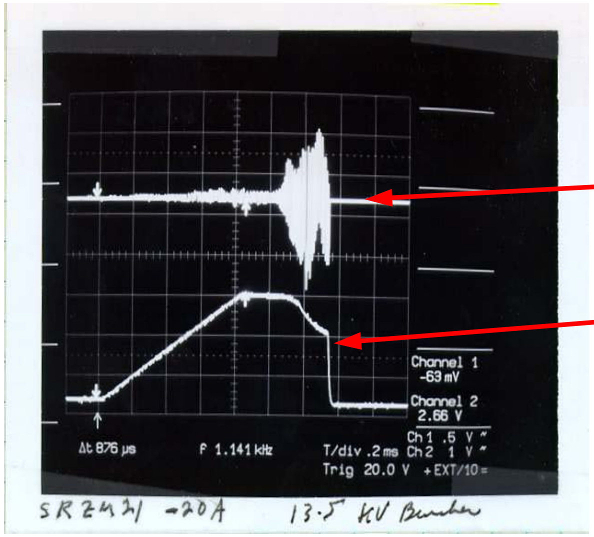
PSR Layout



Circumference = 90m
Beam energy = 798 MeV
Revolution frequency =2.8 MHz
Bunch length ~ 250 ns (~63 m)
Accumulation time ~ 750 ms
~2000 turns

PSR instability

(R. Macek)



BPM ΔV signal

CM42 (4.2 μC)
(Circulating Beam
Current)

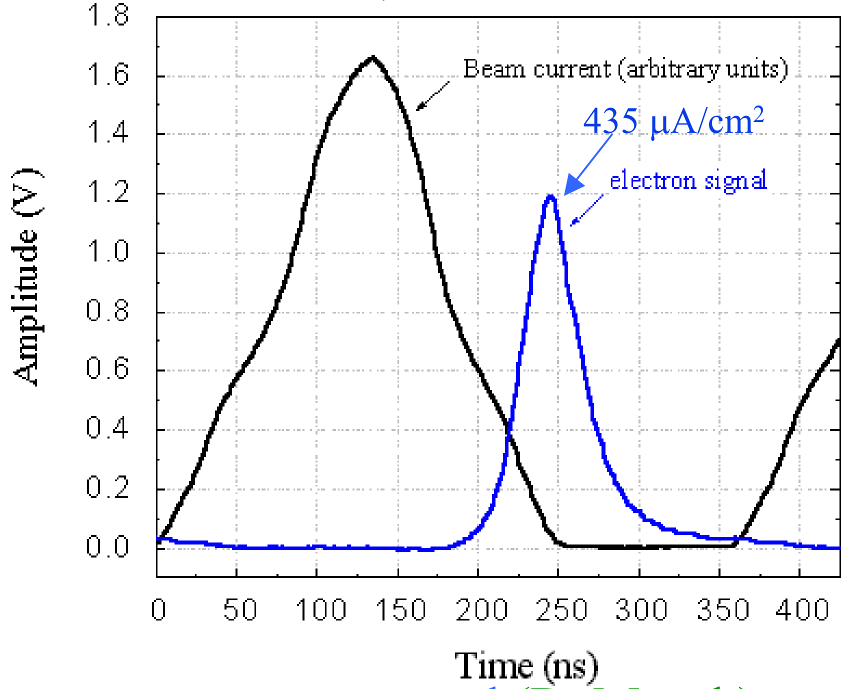
(200 μs/div)

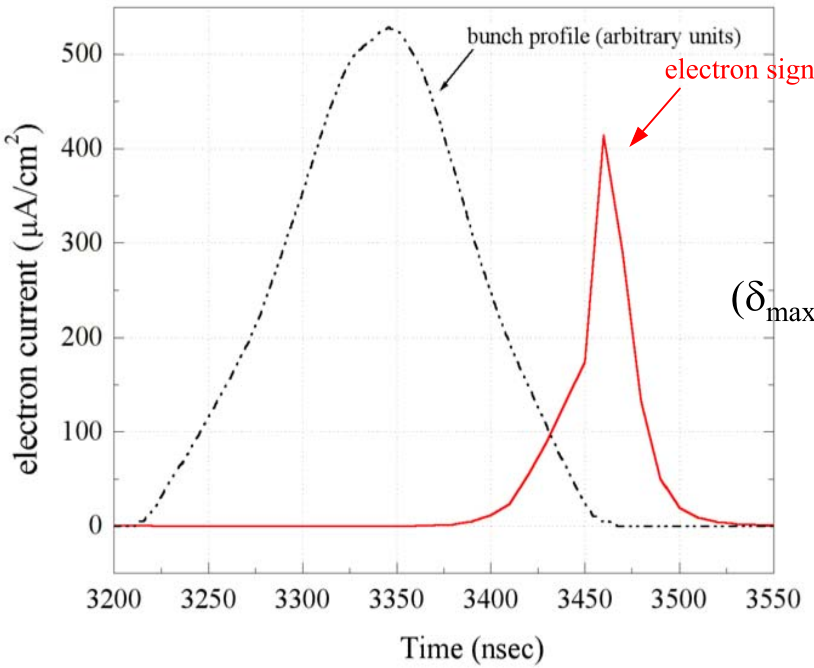
Growth time ~ 75 μs or ~200 turns
High frequency ~ 70 – 200 MHz
Controlled primarily by rf buncher voltage

PSR: benchmark code POSINST

- **Bunch length >> Δt**
  - **— a portion the EC phase space is in resonance with the "bounce frequency"**
  - **— "trailing edge multipacting" (Macek; Blaskiewicz, Danilov, Alexandrov,…)**

ED42Y electron detector signal
8μC/pulse beam

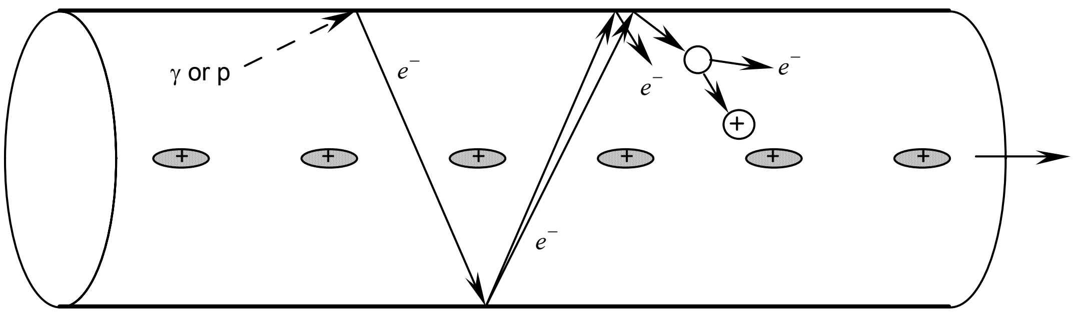




(δ_{max}=2.05)

measured (R. Macek) simulated (M. Pivi)

Beam-induced multipacting (BIM)



- train of short bunches, each of charge $Q=NZe$, separated by s_b
- Δt = e⁻ chamber traversal time
- b = chamber radius (or half-height if rectangular)

The parameter $G = \dfrac{ZNr_e s_b}{b^2}$ defines 3 regimes:

$$\left(r_e = \frac{e^2}{mc^2} = 2.82 \times 10^{-15} \text{ m} \right)$$

$$G \begin{cases} < 1 & \text{short bunch spacing } (s_b/c < \Delta t) \\ = 1 & \text{resonant (BIM) } (s_b/c = \Delta t) \\ > 1 & \text{long bunch spacing } (s_b/c > \Delta t) \end{cases}$$

If $G = 1$ and $\delta_{eff} > 1$, EC can grow dramatically (O. Gröbner, ISR; 1977)

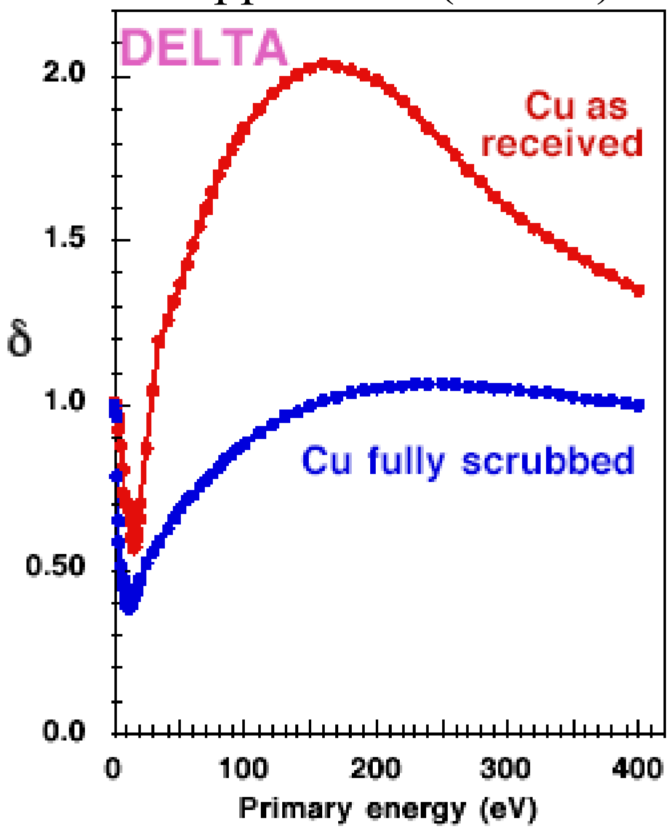
Conditioning effects: beam scrubbing

- **PSR "prompt" e^- signal (BIM) is subject to conditioning:**
  - —signal is stronger for st.st. than for TiN
  - —sensitive to location and *N*
  - —signal does not saturate as *N* increases up to ~8×10^{13}
  - —conditioning: down by factor ~5 in sector 4 after few weeks (low current)
- **PSR "swept" e^- signal is not:**
  - —signal saturates beyond *N*~5×10^{13}
  - — electron decay time $\tau \approx$ 200 ns, independent of:
    - *N*
    - location
    - conditioning state
    - st. st. or TiN
- **Tentative conclusion: beam scrubbing conditions δ_{max} but leaves $\delta(0)$ unchanged**

Conditioning effects–contd.

- **Consistent with bench results for Cu found at CERN!**
  - — **the result $\delta(0)\approx 1$ seems unconventional**
  - — **if validated, it could have a significant unfavorable effect on the EC power deposition in the LHC**
    - **because $\delta(0)$ controls the *dissipation rate* of the EC**
    - **large $\delta(0)$ ←electrons survive longer in between bunches**

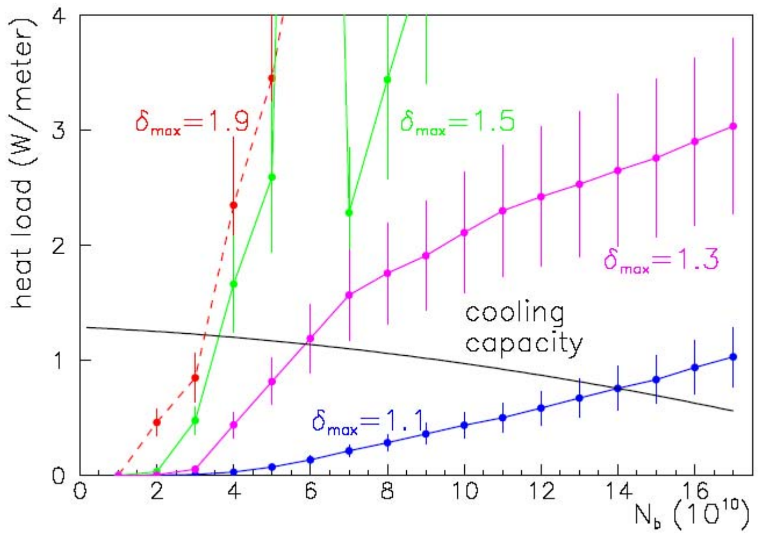
Copper SEY (CERN)



(R. Cimino and I. Collins, proc. ASTEC2003, Daresbury Jan. 03)

LHC EC power deposition

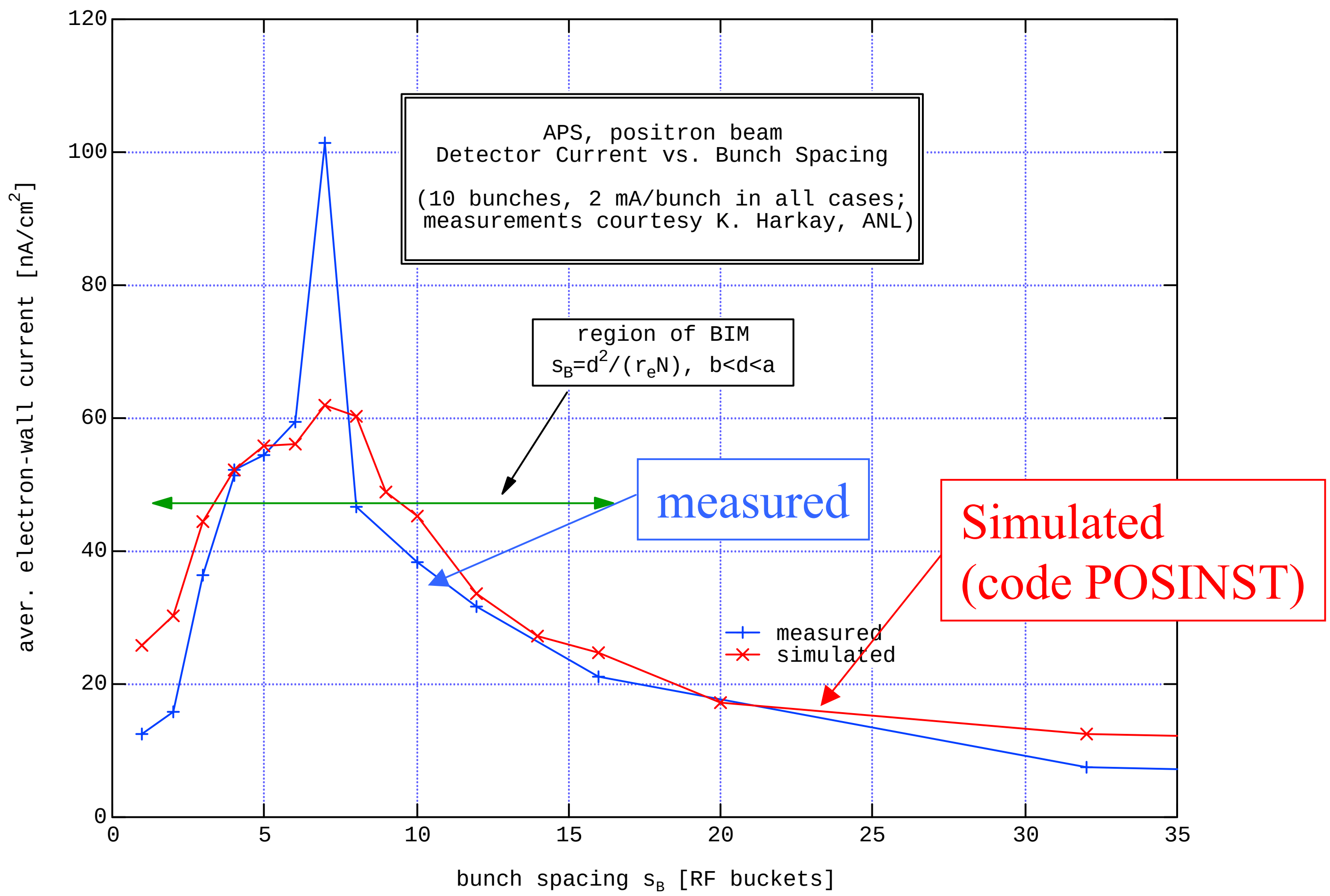
(F. Zimmermann - ECLOUD'02)



Simulated average LHC arc heat load and cooling capacity as a function of bunch population N_b, for various $\delta_{\rm max}$. Other parameters are $\epsilon_{\rm max} = 262$ eV, $R = 5\%$, $Y = 5\%$, and elastic electron reflection included. Average: $l_{\rm dip} = 3 \times 14.3$ m, $l_{\rm drift} = (3 \times 1.36 + 2.425)$ m, $l_{\rm quad} = 4.045$ m.

Sensitive to model for secondary emission (peak SEY, spectrum, fraction of elastics/rediffused/true secondaries)

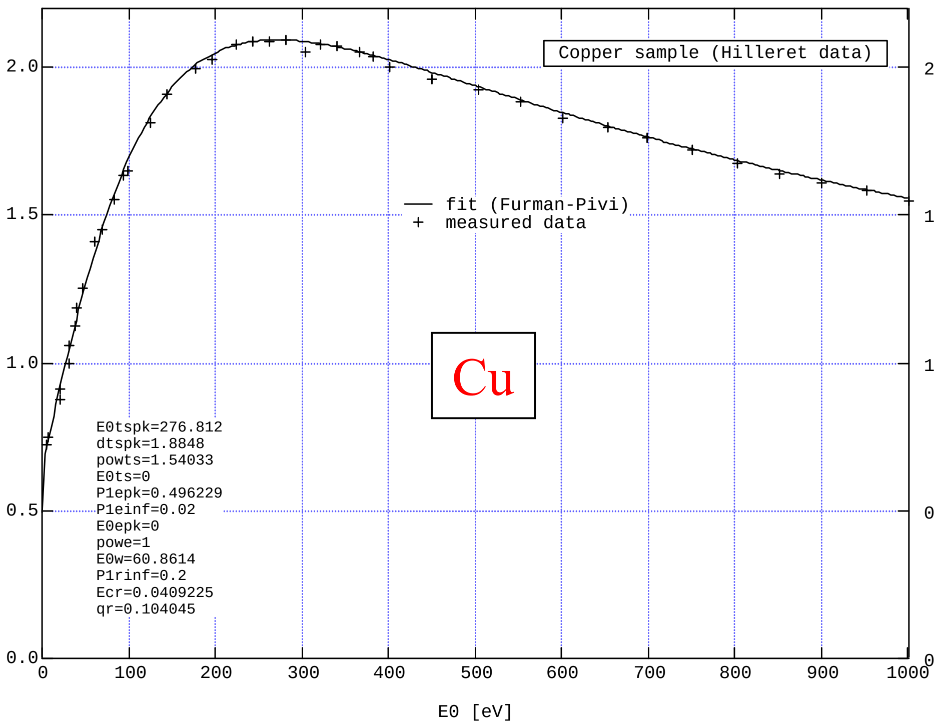
BIM in the APS: benchmark code POSINST

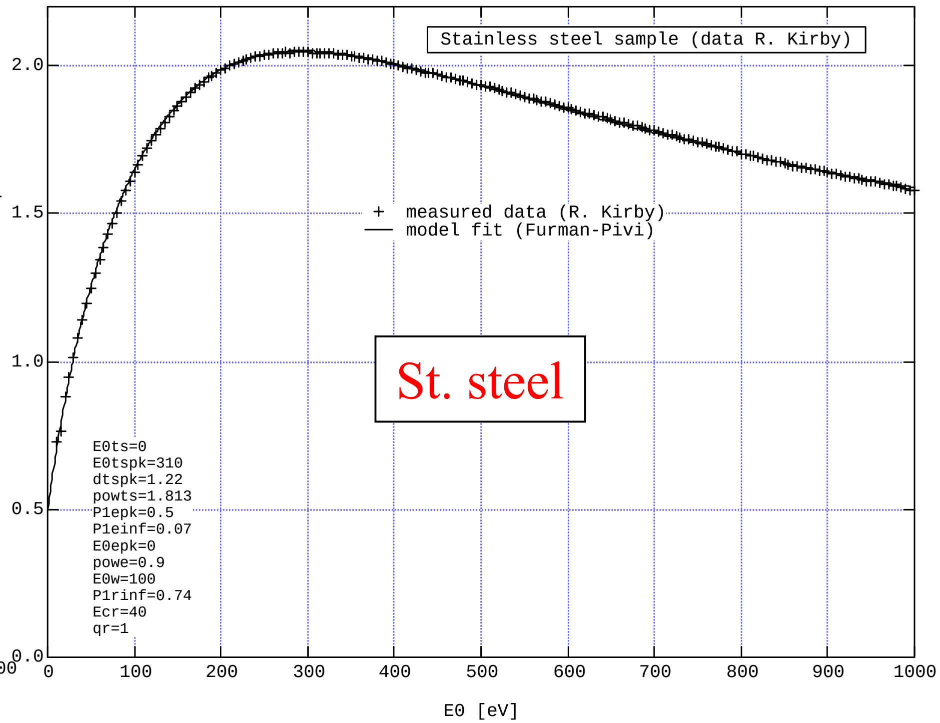


e^+ beam, 10-bunch train, field-free region

(Furman, Pivi, Harkay, Rosenberg, PAC01)

Two sample measurements of the SEY



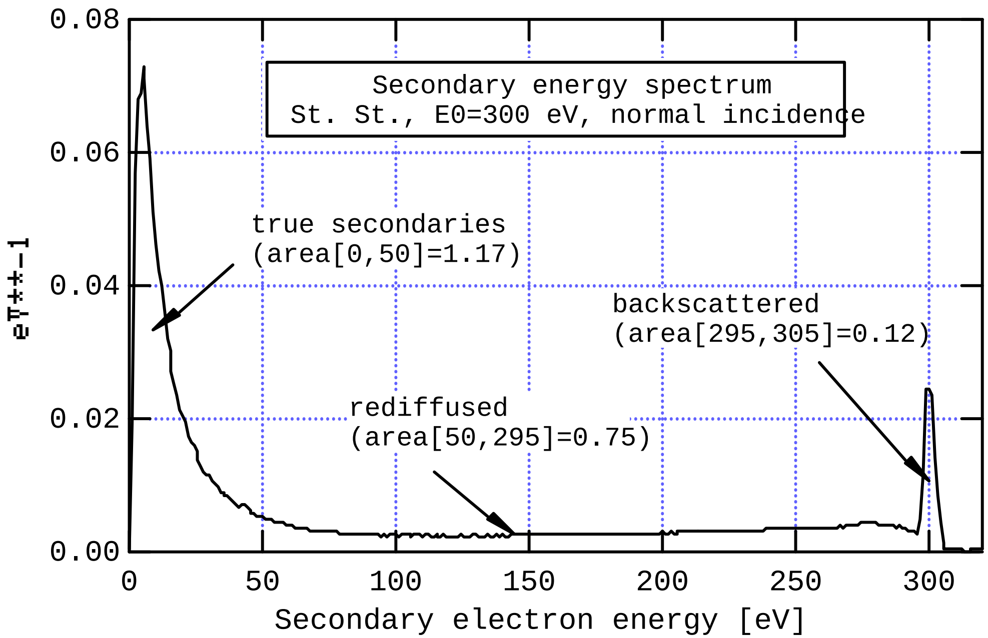


caveat: samples not fully conditioned!

(N. Hilleret; R. Kirby)

Secondary emission spectrum

- **Depends on material and state of conditioning**
  - **St. St. sample, E_0=300 eV, normal incidence,** **(Kirby-King, NIMPR A469, 1 (2001))**



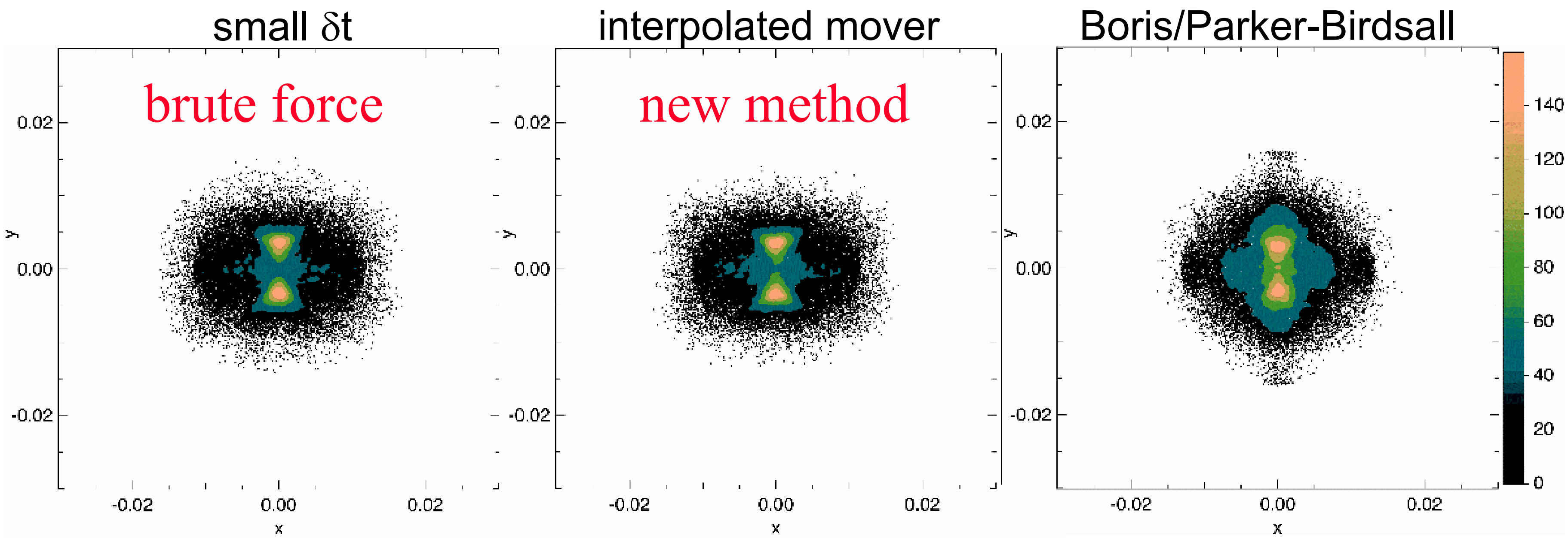
st. steel sample	Cu sample
$\delta = 2.04$	$\delta = 2.05$
$\delta_e = 6\%$	$\delta_e = 1\%$
$\delta_r = 37\%$	$\delta_r = 9\%$
$\delta_{ts} = 57\%$	$\delta_{ts} = 90\%$
$\delta_e + \delta_r = 43\%$	$\delta_e + \delta_r = 10\%$

– Hilleret's group CERN: Baglin et al, CERN-LHC-PR 472.

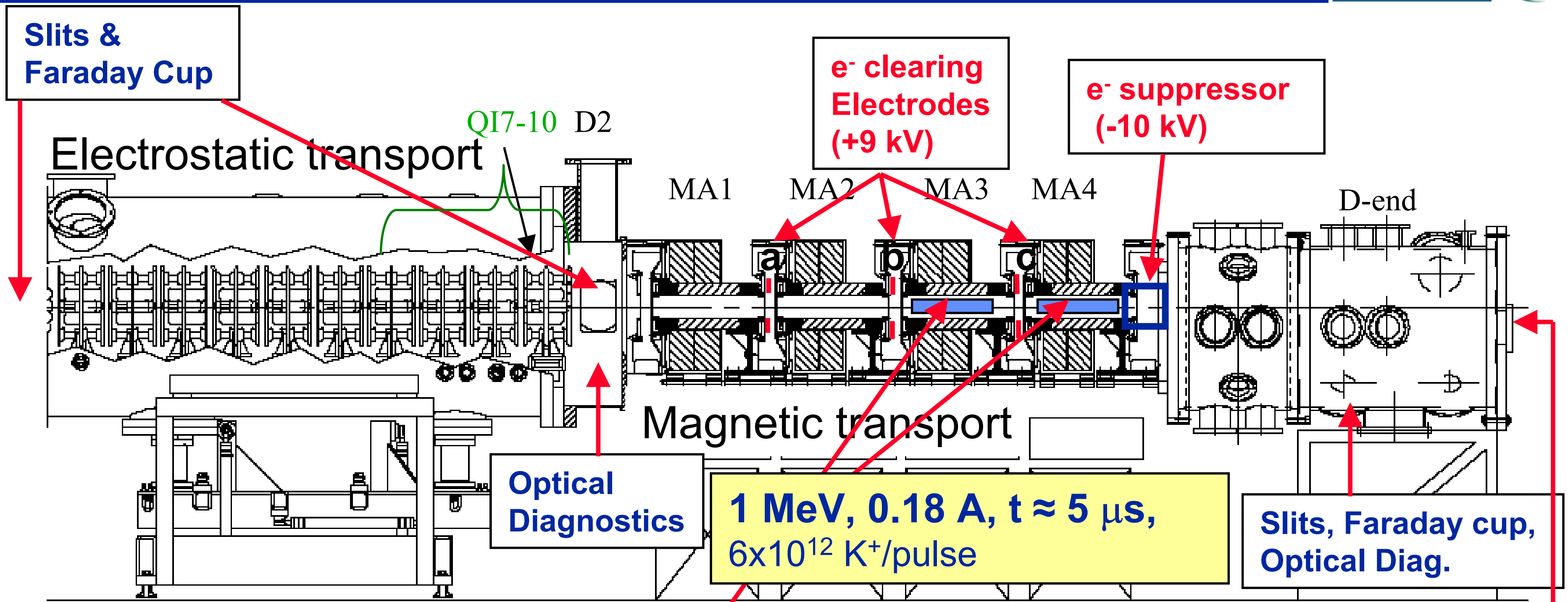
– Other measurements: Cimino and Collins, 2003)

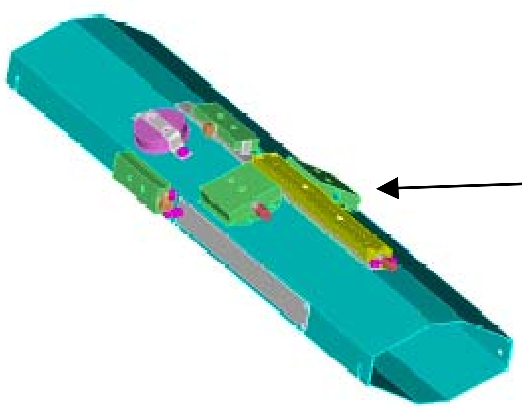
Key simulation invention: large Δt electron pusher for non-uniform B-fields (eg., quads) (R. Cohen)

- **Choice $\alpha=1/[1+(\omega_c\Delta t/2)^2]^{1/2}$ gives physically correct "gyro" radius at large $\omega_c\Delta t$ and also produces correct drift velocity and parallel dynamics.**
- **E-cloud produced by injection (at t=0) of T=10 eV electrons uniform out to nominal beam radius (e.g. ionization of neutral gas). Not stationary. Snapshot at fixed time (~50 τ_{bounce}):**
- **Factor ~25 increase in speed, little degradation of accuracy**



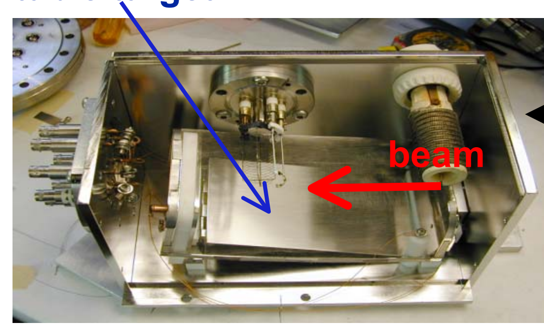
HCX instrumentation to carry out electron cloud (and gas desorption) experiments





Diagnostics Inside beam tube: capacitive monitors, e⁻ probes,…

tiltable target



Gas-Electron Source Diagnostic (GESD)