Observation and Modeling of Electron Cloud Instabilities

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managed by The University of Chicago

Study of electron cloud effects remains very active:

- **EPAC06: 23 abstracts mention “electron cloud”**
- **Over 20 publications in PRST-AB, PRL, PRA since 2003**

Outline

- Early observations, measurements
- Modeling development
- EC generation, amplification processes
- Surface science with protons, ions
- Cures
- Active study
  - Trapping in quads
  - LHC heat deposition, single bunch instability
- New observations
- Summary

First experimental observations

- Early observations of instabilities correlated with pressure attributed to EC in **proton** rings, coasting beam or single-bunch (BINP, CERN ISR, possibly others (ZGS, AGS, Orsay, Bevatron); ~1965-72)
- Similar observations and systematic experiment study in LANL PSR **proton** ring (~1988 – today)
- First observations in **positron** rings
  - Multibunch (KEK PF, BEPC, CESR; ~1989-97)
  - Single-bunch (KEKB, PEP-II; 1999-2000)

[see V. Dudnikov, Proc. 2001 PAC, 1892; F. Zimmermann, PRST-AB 7, 124801 (2004)]

- First detailed ***in-situ*** **measurements** of multipacting and EC distribution using dedicated diagnostics (RFA)
  - Positron, electron ring (APS, 1997-99)
  - Proton ring (PSR, 2000)

“PSR instability” story

Evidence pointed to e-p, but many questions lead to skeptisicm

- Experimental observations first, vertical instab. (~1988)
- Data consistent with e-p theory
- The problem: Where do all the electrons come from? Why doesn’t threshold change with vacuum pressure variation? How do electrons survive the gap?
- Many remained unconvinced until electron cloud measured directly with RFA, RFA sweeper (~2000)

RFA data lead to new understanding

- “Trailing edge multipacting” (R. Macek)
- Proton beam loss an important source of electrons
- Very low energy electrons survive the gap without beam

Story is not finished: new questions (first turn instability)…

Electron cloud (EC) modeling

Ca. 1995, **PEPII and KEKB** factories both under development; became concerned about EC effects

Calculated predictions of a **multipacting resonance in LHC**, also under development, resulted in a **crash program** at CERN to study EC effects

Modeling:

- 1st gen codes (2D analytical, PIC) developed to model EC generation and instabilities (M. Furman, K. Ohmi, F. Zimmermann, and colleagues)
- Detailed semi-empirical secondary electron emission model developed (POSINST) **[M.A. Furman, M.T.F. Pivi, PRST-AB 5, 124404 (2002)]**
- 2nd gen codes (2-3D) developed for more realistic modeling for positron, proton, heavy ion beams

A survey of codes (incomplete)

	Dim	Electron Model	Particle Pusher	Parallel (max cpu)	Fieldsolver
Quick-PIC, W. Mori et al.	2– 3		LeapFrog 4th order	YES(128), 32 regular	EM- PIC
CLOUDLAND, L.F. Wang	2– 3	SE	Adaptive	NO	FEM
POSINST, M. Furman et al.	2	SR,IS,SE	Analytic	NO	Analytic
Head-Tail, Rumolo et al.	2– 3	-	Map	NO	PIC
Ecloud, Rumolo et al.	2– 3	RS,SE,IS	Leap Frog, Analytic	NO	Analytic,FFT
Warp, Friedman et al.	1,2,3	SR,IS,SE,US	Leap Frog, hybrid drift	YES	ES-PIC,AMR
Orbit*, Holmes et al.	2– 3	SE, US	Leap Frog, Analytic	YES	ES-PIC
Best, Qin et al.	3		Symplectic	YES 512	DeltaF
CSEC etc. Blaskiewicz			Symplectic	NO	Analytic
PARSEC*, Adelmann et al.	3	SR,IS,SE	Leap Frog, RK-x,Analytic	YES (4048)	FEM MG ES

CMEE, Stoltz

Library for computational methods for electron cloud effects

Courtesy A. Adelmann et al., ECLOUD04

Extensive benchmarking study launched after ECLOUD02, ECLOUD04, spearheaded by F. Zimmermann

Std. params for single-bunch instab: Build-up, thresh. vary by 3-100

[E.Benedetto et al., Proc. 2004 EPAC, 2502] [see also HB2006, benchmark session]

Modern study of EC effects

Electron cloud effects have been very difficult to predict

- Surface science is complex for technical materials and accelerator environment
- Low-energy electrons notoriously difficult to characterize – experimental uncertainties

Most advances have occurred when modeling is benchmarked against detailed measured data. Notable examples:

- APS and PSR vs. POSINST
- HCX (at LBNL) vs. WARP/POSINST
- SPS (LHC) vs. ECLOUD/HEADTAIL
- KEKB vs. PEHT/PEHTS
- RHIC vs. CSEC, ECLOUD, maps

EC cures for: LHC, SNS, JPARC, ILC, …

Electron cloud generation and surface science

Electron cloud generation

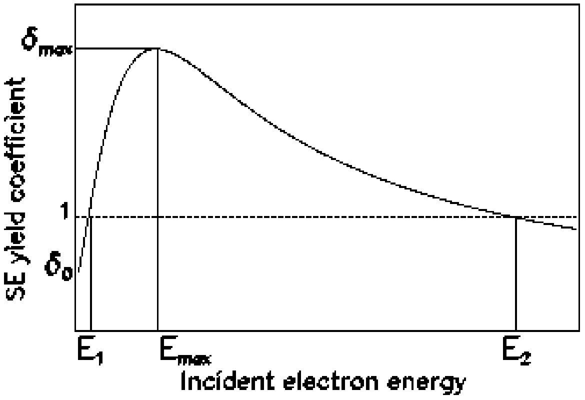
- Ionization of residual gas
- Photoemission
- Secondary emission, δ
  - Electrons accelerated by beam
  - Beam losses, protons and ions (grazing incidence on walls, collimators)

Secondary EC processes

- Electron-stimulated molecular desorption, vacuum pressure rise/runaway (PEP-II, APS, SPS, RHIC)
- Electron cloud trapping in magnetic fields (dipoles, quadrupoles, ion pump fringe field, etc) (HCX, PSR, CESR)
- Interference with standard beam diagnostics (SPS)

Secondary electron emission, multipacting

- **Universal δ curve, peak values surface dependent**
- **EC lifetime depends strongly on δ_0 ~0.5 (CERN, PSR)**
- **True SE distribution peaks 1-3 eV, surface independent; rediffused contrib. varies/sensitive**



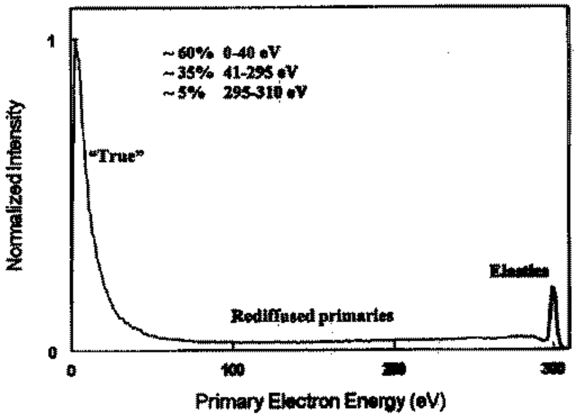
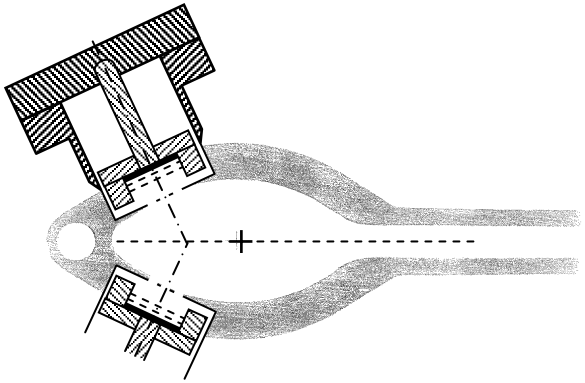


Fig. courtesy of R. Kirby



APS RFA

LHC, SPS=25ns

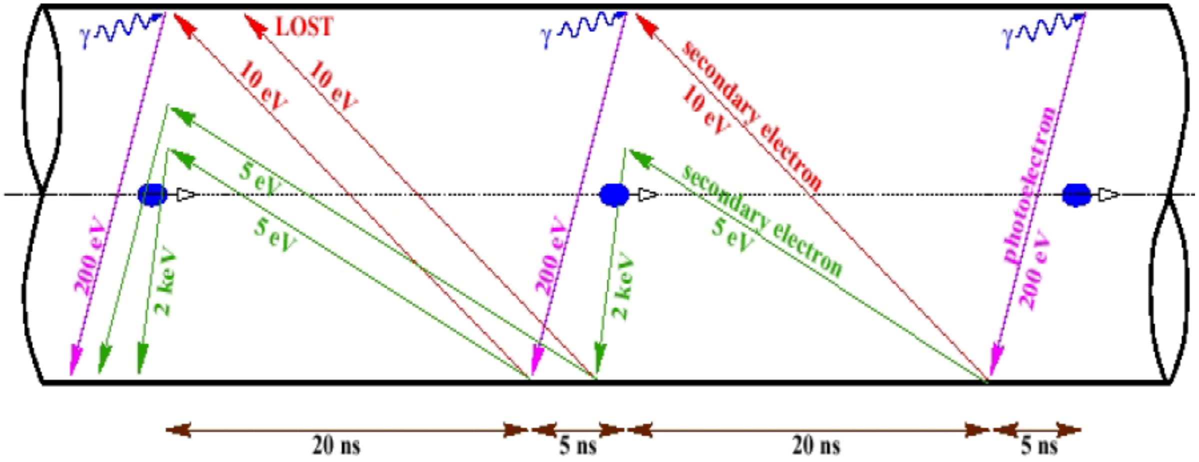


Fig. courtesy of F. Ruggiero, G. Arduini

EC amplification processes

Dominant source of EC can vary: KEKB vs PEPII

- Photoemission alone can be sufficient if no antechamber (KEKB, KEK PF, BEPC)
- Beam-induced multipacting can lead to large amplification if $\delta > 1$ (PEP-II, APS)

[APS vs BEPC: K. Harkay et al., Proc. 2001 PAC, 671 (2001)]

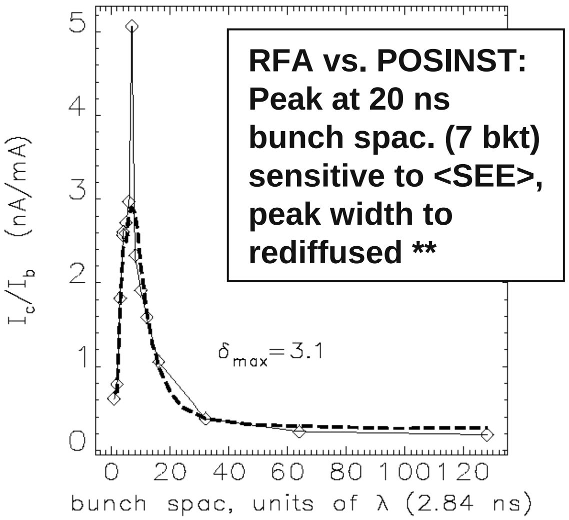
Multipacting condition vs. EC distribution: short bunches

- Cold-electron model **[O. Gröbner, Proc. 10th HEAC, Protvino, 277, 1977]**
- Multiple kicks, energy distribution (Zimmermann, Ruggiero)
- “General” condition: dependence on EC distribution (Furman, Heifets) **[K. Harkay, R. Rosenberg, PRST-AB 6, 034402 (2003); L.F. Wang, A. Chao, H. Fukuma, Proc. ECLOUD04 (2004)]**

Trailing-edge multipacting can occur in long proton bunches

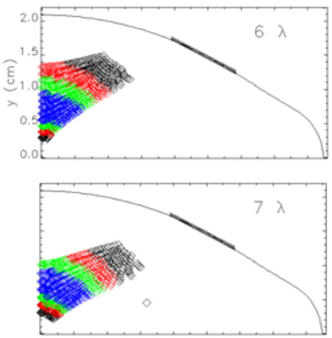
General multipacting condition vs. EC distribution

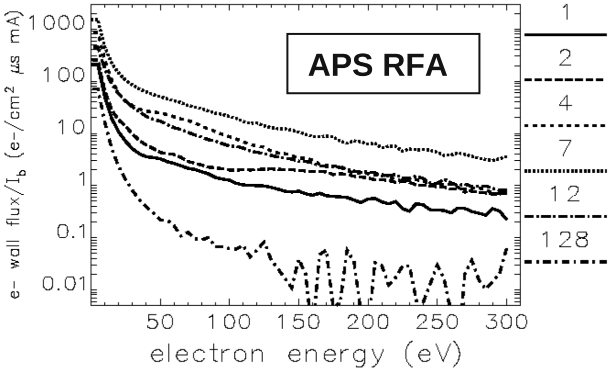
APS: K. Harkay, et al., Proc. 2003 PAC, 3183; ICFA BD Newsletter 33 (2004)



RFA vs. POSINST: Peak at 20 ns bunch spac. (7 bkt) sensitive to <SEE>, peak width to rediffused **

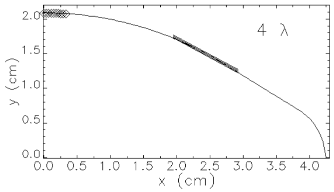
Most resonances for 6 – 7 bkt when 1.2 < SEE < 3.8 eV for 1.0 ≤ δ < 3.0





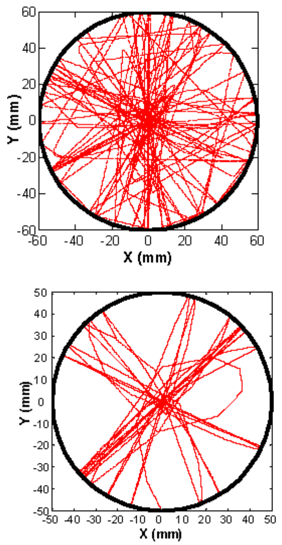
APS RFA

Cold SE predicts 4 bkt



****U. Iriso, also for RHIC (CSEC and ECLOUD), MOPCH135**

L. Wang et al., ECLOUD04: RHIC. KEKB. SNS



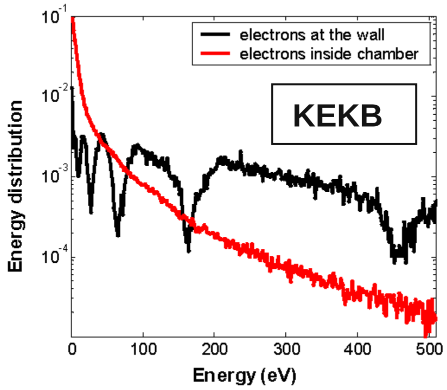


Figure 3: Energy distributions of the electrons at the wall and inside the beam chamber in the KEKB LER's beam. Bunch spacing is 2 ns.

Modeled EC distrib; RFA agrees

Figure 1: Electron's orbit (left column) and energy at the wall (right column). RHIC beam with bunch spacing 108 ns (top row); KEKB LER beam with bunch intensity 3.3×10^{10} and bunch spacing 8ns (bottom row).

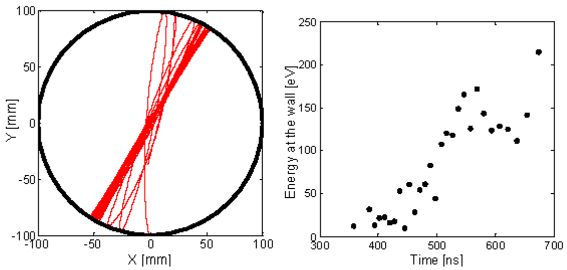
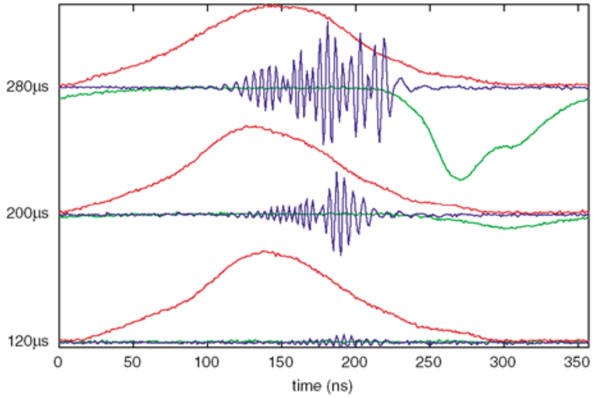
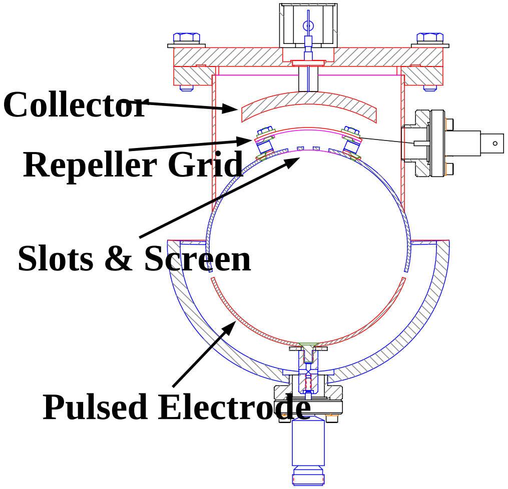


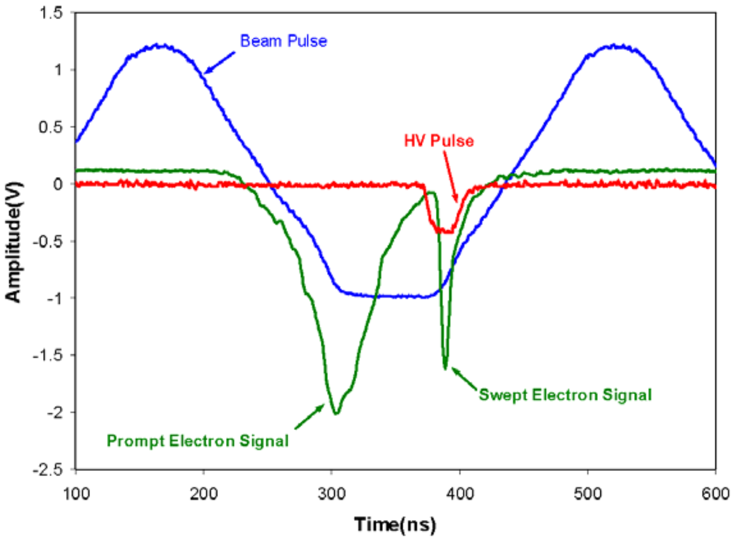
Figure 2: Electron's orbit (left column) and energy at the wall (right column) in the SNS accumulator ring. Bunch length is 700 ns.

Trailing edge multipacting at Proton Storage Ring



Wideband coherent motion 50-300 MHz (4.4 μC/pulse)





7.7 μC/pulse

LANL Electron Sweeper RFA (~500 V pulse, 80MHz fast electronics added)

Prompt electron signal due to trailing-edge multipactor; swept electrons survive gap

bunch length = 280 ns

Figs. courtesy R. Macek A. Browman, T. Wang

References and workshops

Review talks at Accelerator Conferences: J.T. Rogers (PAC97), F. Ruggiero (EPAC98), K. Harkay (PAC99), F. Zimmermann, K. Harkay (PAC01), G. Arduini, F. Zimmermann (EPAC02), M. Furman, M. Blaskiewicz (PAC03), M. Pivi, L. Wang (PAC05) http://www.jacow.org

ICFA BD Newsletter No. 33, Apr. 2004: special edition on Electron Cloud Effects in Accelerators http://www-bd.fnal.gov/icfabd

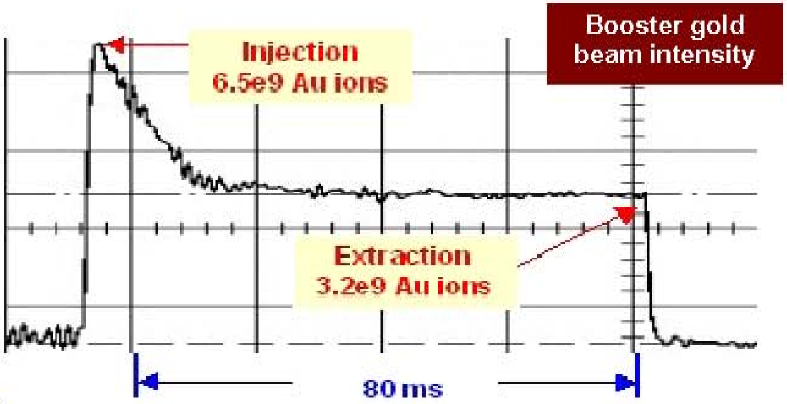
Workshops, past:

- ***Multibunch Instabilities Workshop***, KEK, 1997 KEK Proc. 97-17
- ***Two-Stream ICFA Mini Workshop***, Santa Fe, 2000 http://www.aps.anl.gov/conferences/icfa/two-stream.html
- ***Two-Stream Workshop***, KEK, 2001 http://conference.kek.jp/two-stream/
- ***ECLOUD02***, CERN, 2002 http://slap.cern.ch/collective/ecloud02/
- ***Pressure Rise Workshop***, RHIC/BNL, Dec. 2003 http://www.agsrhichome.bnl.gov/AP/PressureRise/Page1.htm
- ***ICFA ECLOUD04***, Napa, CA, Apr. 2004 http://www.cern.ch/icfa-ecloud04/
- ***ICFA High Brightness Hadron Beams***, KEK/JAEA, May 2006 *ftp://ftp.kek.jp/kek/abci/ICFA-HB2006*

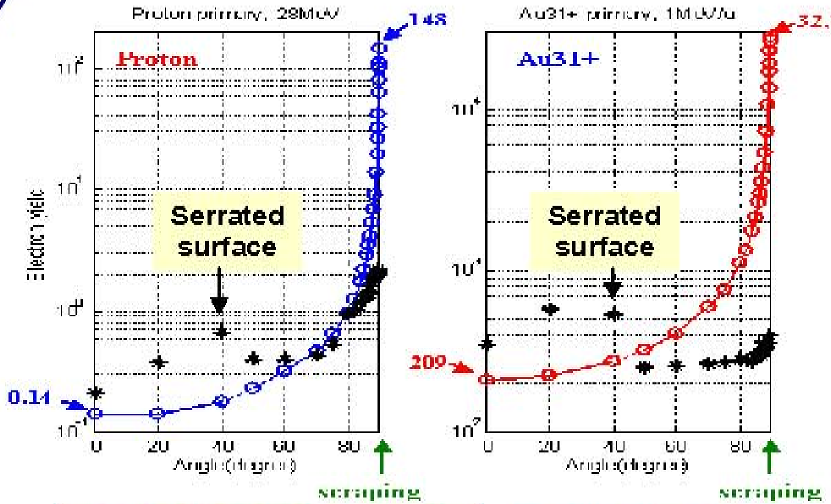
Effect of grazing incidence ions, protons

2. Non-perpendicular incident

- Beam injection and charge exchange caused beam loss are with the incident angles of mrad or less.
- At the time of AGS Booster was designed, ion desorption rate was believed to be 1 - 10.
- More than 1e5 molecules can be generated per lost Au ion. The gold beam injection loss induced pressure rise has caused > 40% loss during the acceleration at high beam intensity.
- Similarly, in early design of SNS, SEY was believed to be 0.1 - 1 per lost proton.
- SEY of proton impact is measured to be larger than 100 at grazing angles.



Booster gold beam intensity

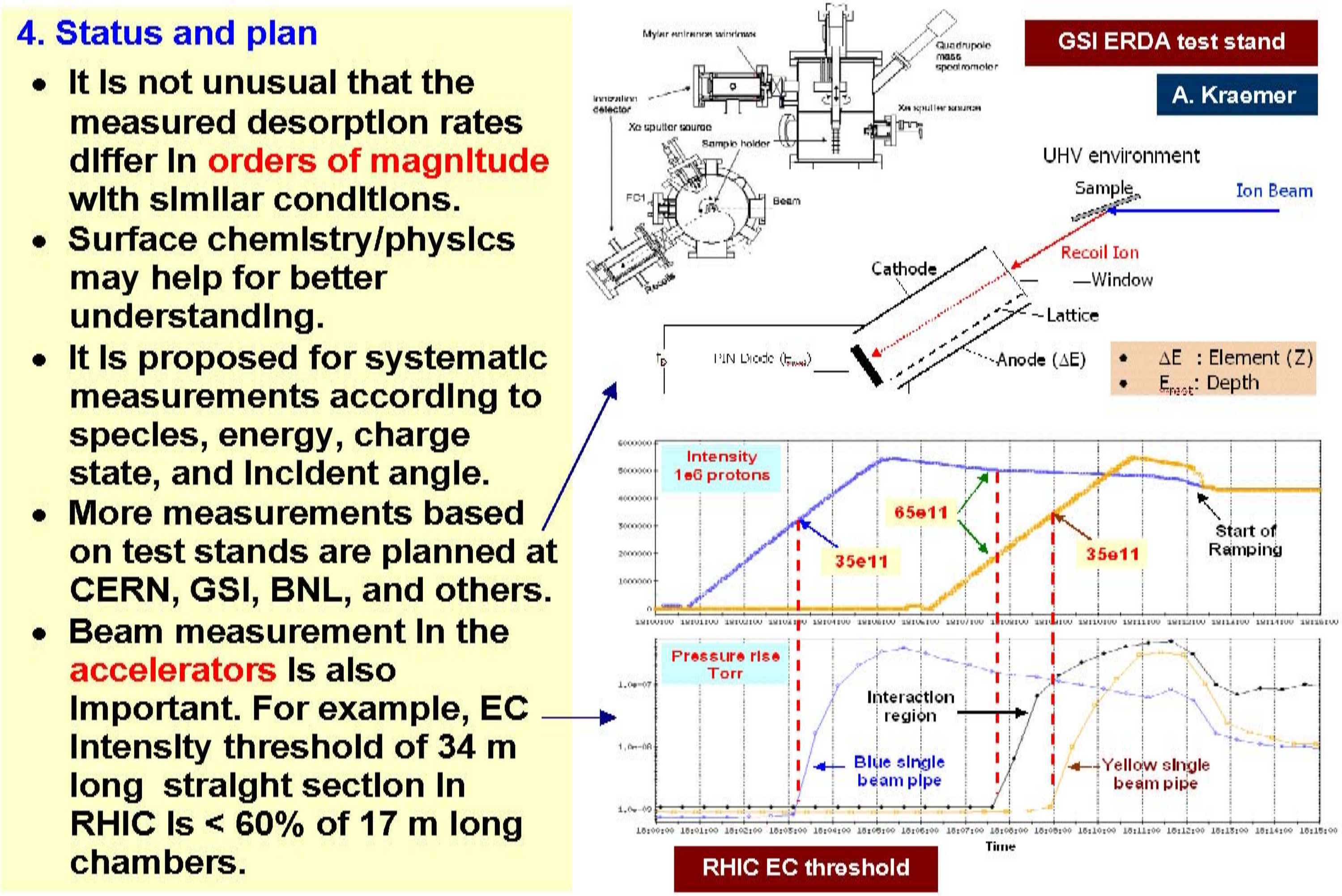


SEY of proton and Au impact

P. Thieberger et al

Electron impact gas desorption msrd at RHIC: 0.05 (0.01 after scrubbing) U. Iriso, W.Fischer, EPAC06, MOPCH134

S.Y.Zhang, T. Roser,[6] *Pressure-Rise Workshop Summary*



4. Status and plan

- It is not unusual that the measured desorption rates differ in **orders of magnitude** with similar conditions.
- Surface chemistry/physics may help for better understanding.
- It is proposed for systematic measurements according to species, energy, charge state, and incident angle.
- More measurements based on test stands are planned at CERN, GSI, BNL, and others.
- Beam measurement in the **accelerators** is also important. For example, EC intensity threshold of 34 m long straight section in RHIC is < 60% of 17 m long chambers.

GSI ERDA test stand

A. Kraemer

- ΔE : Element (Z)
- E_{rest}: Depth

RHIC EC threshold

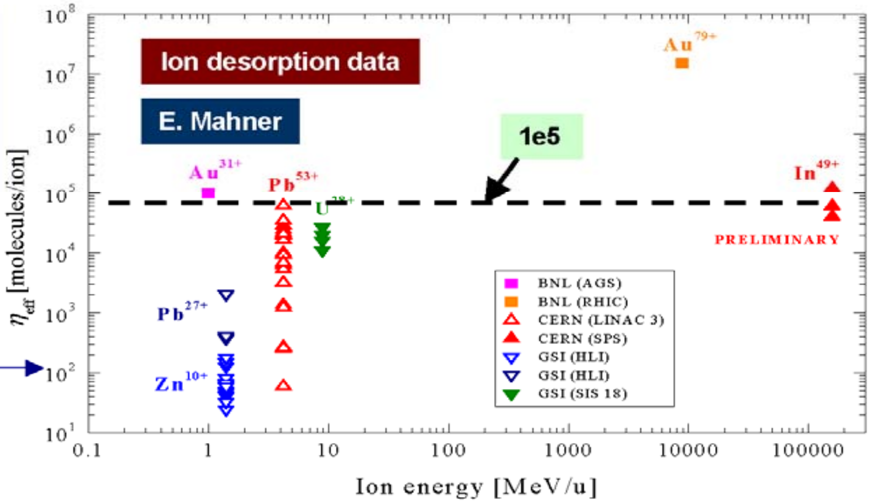
8

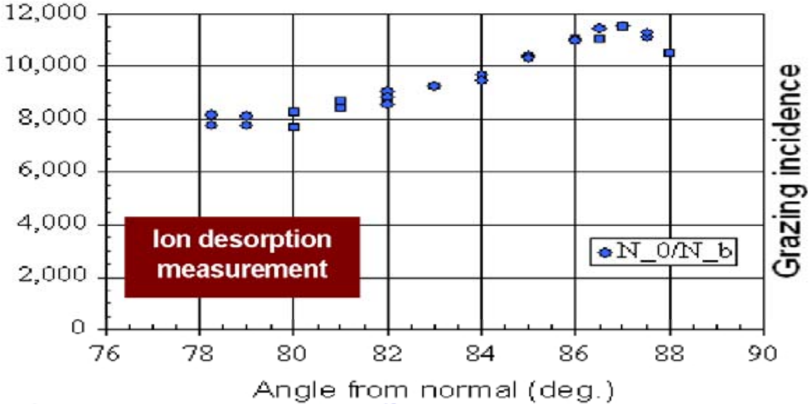
S.Y.Zhang, T. Roser, Pressure-Rise Workshop Summary

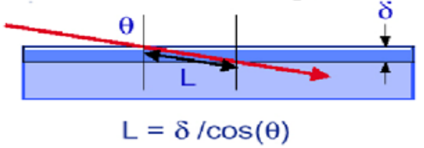
3. Progress in ion desorption measurement

- Measurement at AGS Booster, RHIC, LEAR, SPS, LINAC3, SIS and GSI HLI shows ion desorption rate of 10 - 1e7, under different conditions.
- The ion desorption rate of around 1e5 was measured at several accelerators.
- For low energy machine, the relevant incident angle is in mrad or less. For high energy machine, it may go to µrad or less.
- A bunch measurement shows peak desorption rate at 87 deg.
- The adequate length of surface relevant to grazing angle measurement?

PRST-AB 9, 063201 (2006); PRST-AB 8, 113201 (2005); PRST-AB 8, 053201 (2005); PRST-AB 7, 093201 (2004); PRA 61, 042901 (2000); PRST-AB 6, 013201 (2003)







A. Molvik

S.Y.Zhang, T. Roser, Pressure-Rise Workshop Summary

Grooves, antigrazing surfaces (collimation)

Int'l R&D Effort (SLAC, KEK, CERN, LANL, Frascati):
M. Pivi et al., Proc. 2005 PAC, 24; G. Stupakov, ECLOUD04

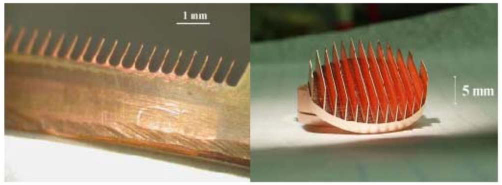


Figure 7. Samples with two different rectangular groove profiles, 1 mm or 5mm depth.

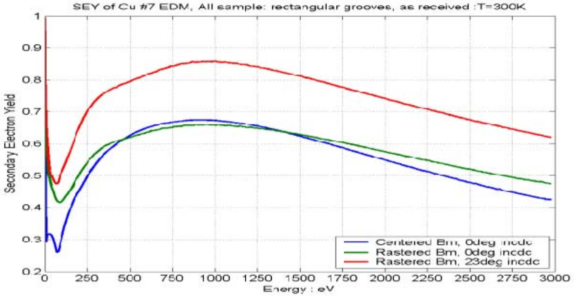


Figure 8. Measured SEY for a rectangular groove Cu sample at different angles. The smooth part of the sample has a δmax=1.65.

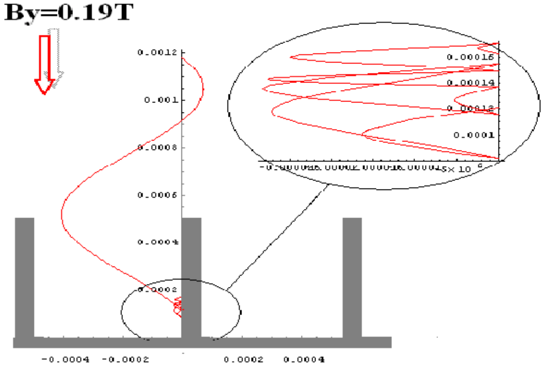


Figure 9. Electron dynamics in proximity of a rectangular groove surface in the presence of a dipole magnetic field. The electron is absorbed.

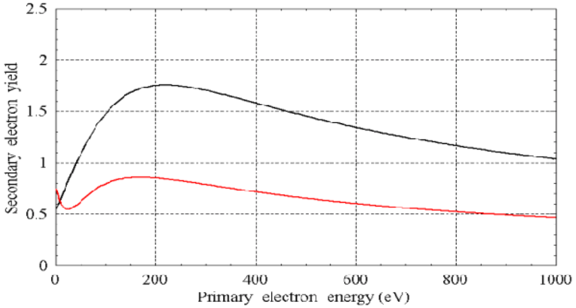
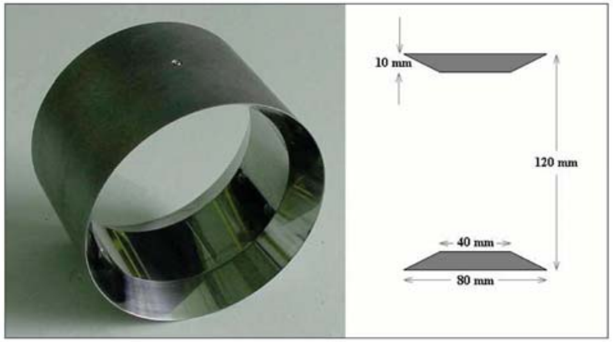
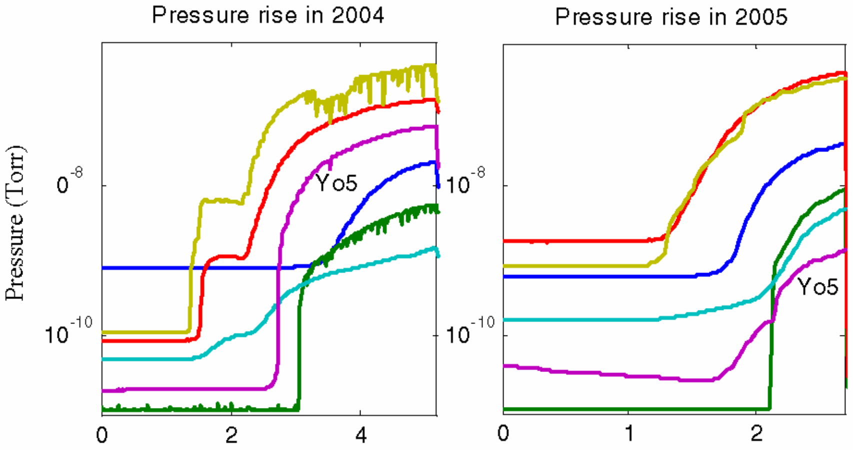


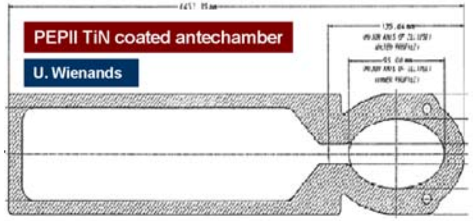
Figure 10. Simulated SEY for a smooth (above) and for a rectangular grooved surface (below) in a dipole field.

RHIC: S.Y. Zhang et al., PRST-AB 8, 123201 (2005)



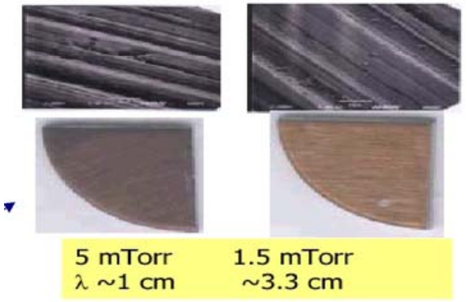


TiN, NEG coatings, surface roughness



PEPII TiN coated antechamber

U. Wienands

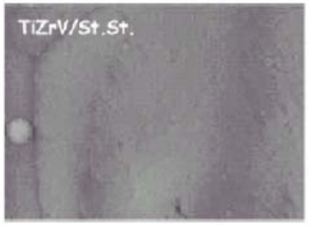


5 mTorr
λ ~1 cm

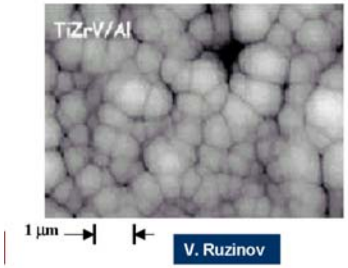
1.5 mTorr
~3.3 cm

TiN surface comparison

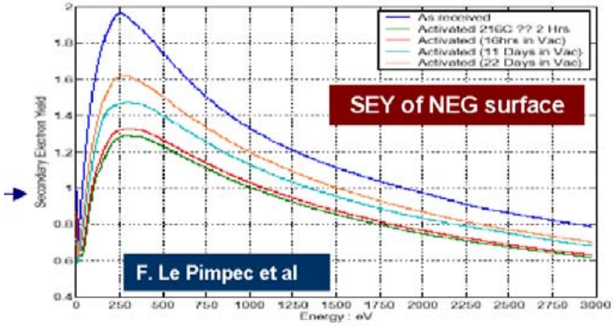
H.C. Hseuh



NEG surfaces on St. St. & Al



V. Ruzinov



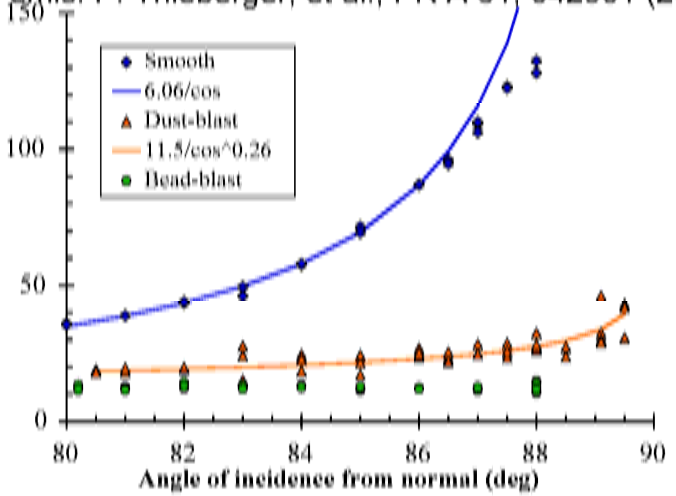
SEY of NEG surface

F. Le Pimpec et al

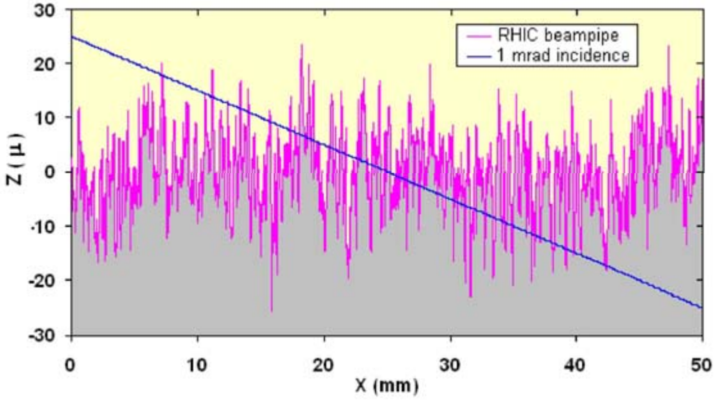
Pressure-Rise Workshop (2003)

A. W. Molvik, et al., PRST-AB 7, 093202 (2004).
Earlier e⁻ emis: P. Thieberger, et al., PR A 61, 042901 (2000).

Electron emis. 1 MeV K+ ions vs. dust/bead blasting; ion range must be << roughness



P. THIEBERGER *et al.*, PRST-AB 7, 093201 (2004)

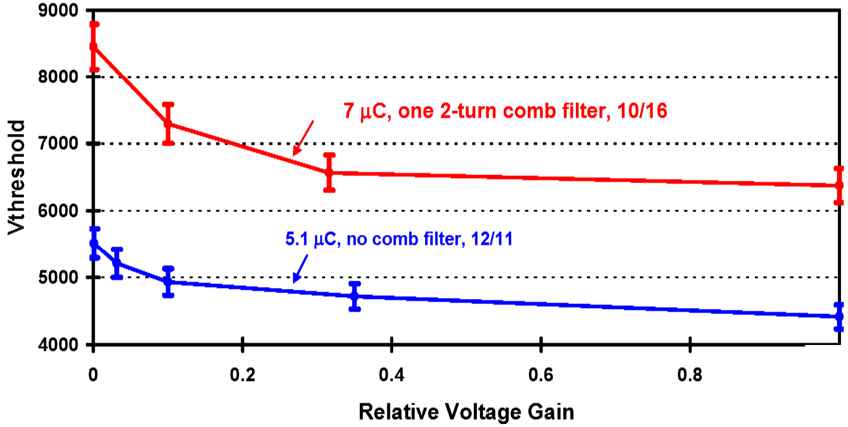


Prototype fast beam feedback for e-p

PSR/LANL, SNS/ORNL, LBNL, IU, SLAC collaboration

[see R. Macek, Proc. HB2006; C. Deibele THPCH13]

- **Instability threshold rf voltage as function of feedback gain**



25% reduction in threshold 10/16/05 for 7 µC beam, 2-turn comb filter

20% reduction in threshold 12/11/05 for 5.1 µC beam, no comb filter

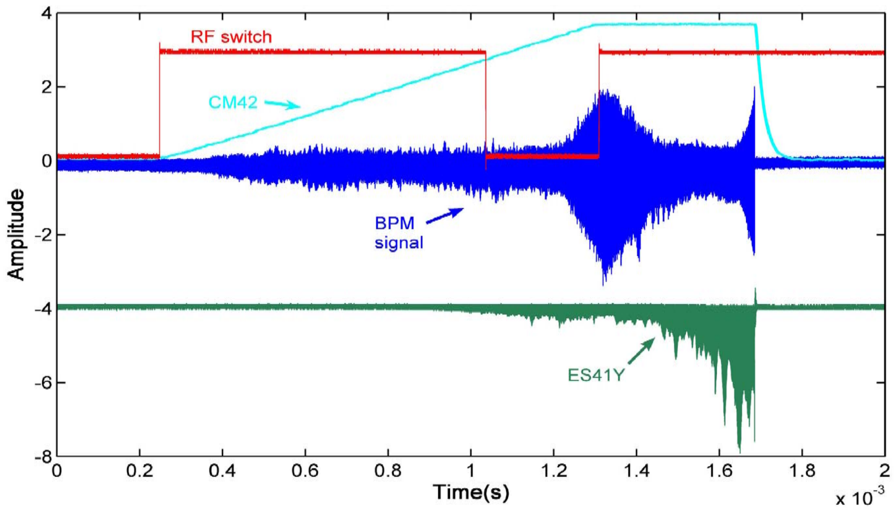
Grow-damp-grow measurements:

1st phase: growth $1.03\times10^4\ s^{-1}$

FB damping rate: $1.75\times10^4\ s^{-1}$

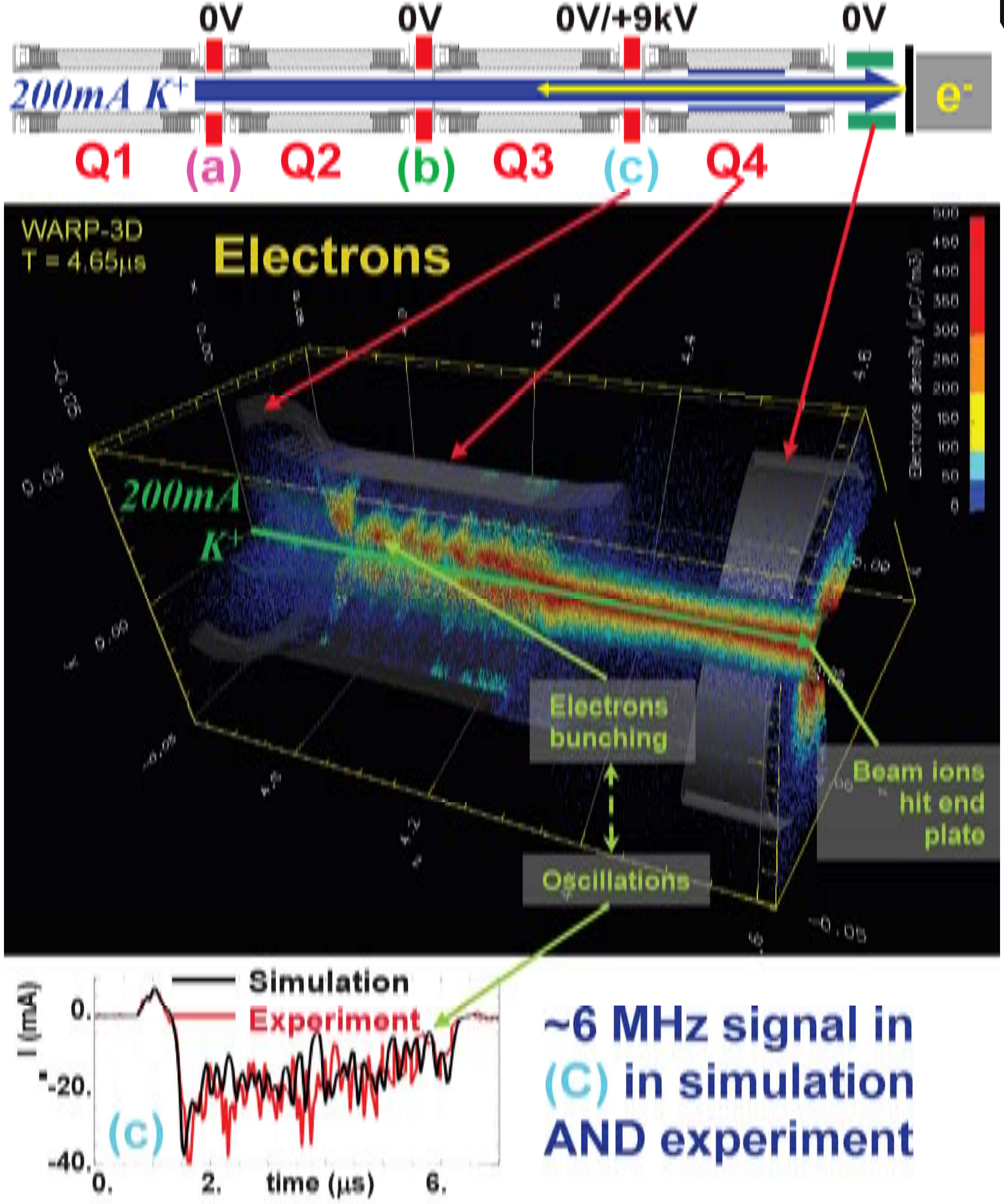
2nd phase: e-p growth $3.35\times10^4\ s^{-1}$

Beam in gap believed responsible



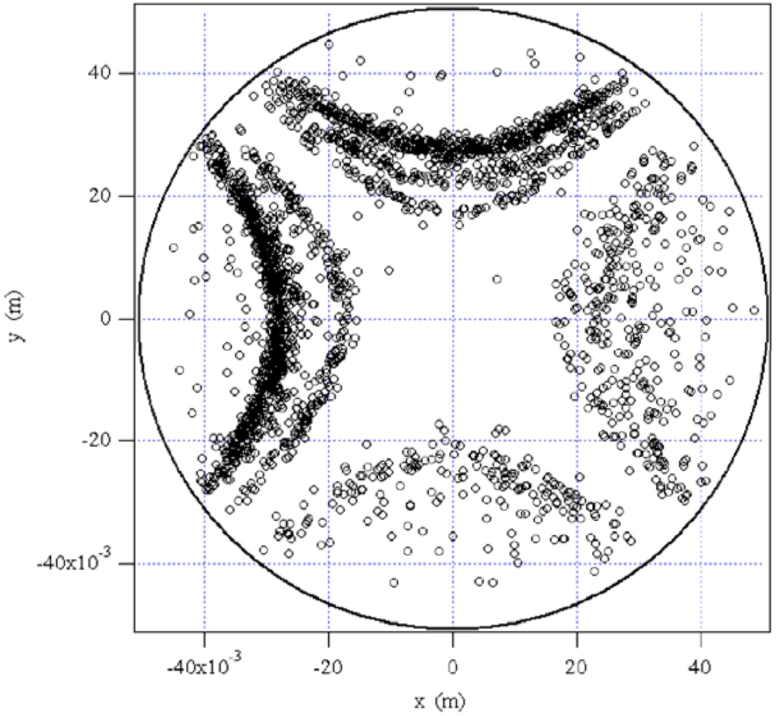
Trapping in quadrupoles

- **PSR, HCX: Large beta functions in quads, high beam loss (halo)**
- **KEKB: blowup with 3.27 bkt spacing, where are electrons (solenoids)?**
- **Self-consistent 3D modeling (WARP/POSINST), measurements** [J-L Vay et al., Proc. HB2006; Proc. 2005 PAC, 525 and 1479]
- **Cures? Clearing electrodes** [L. Wang, H. Fukuma, et al., MOPLS143]

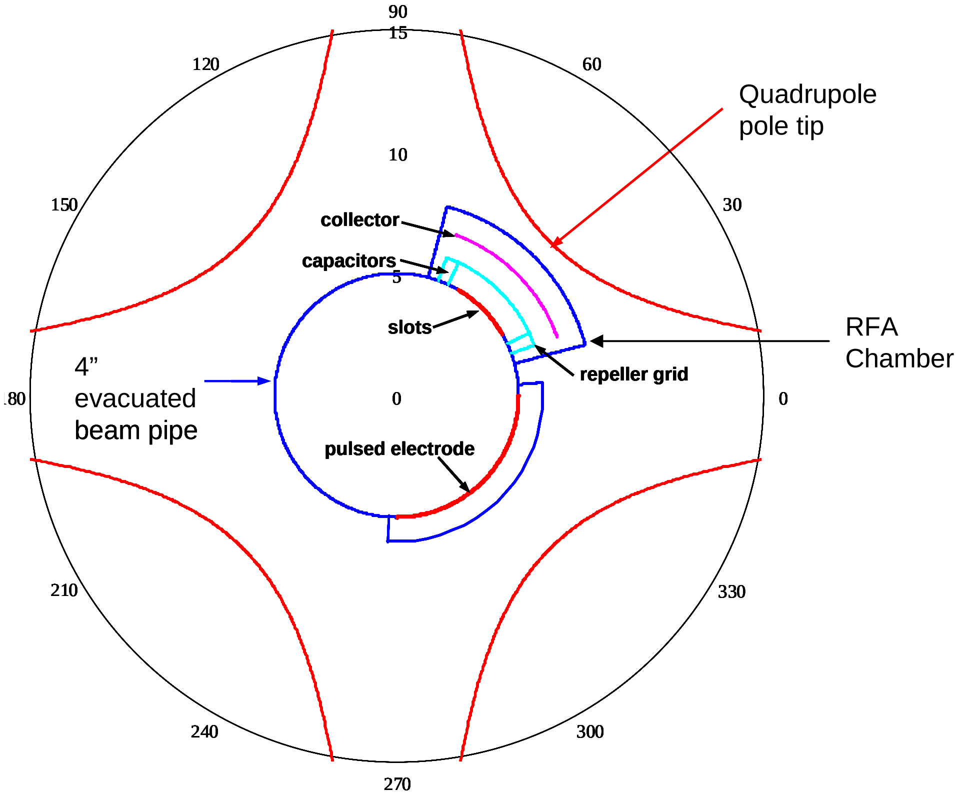


~6 MHz signal in (C) in simulation AND experiment

Proposed electron sweeper for quadrupoles (PSR)



Snapshot of trapped electrons in a PSR quadrupole 5 μs after passage of the beam pulse. (Courtesy M. Pivi)

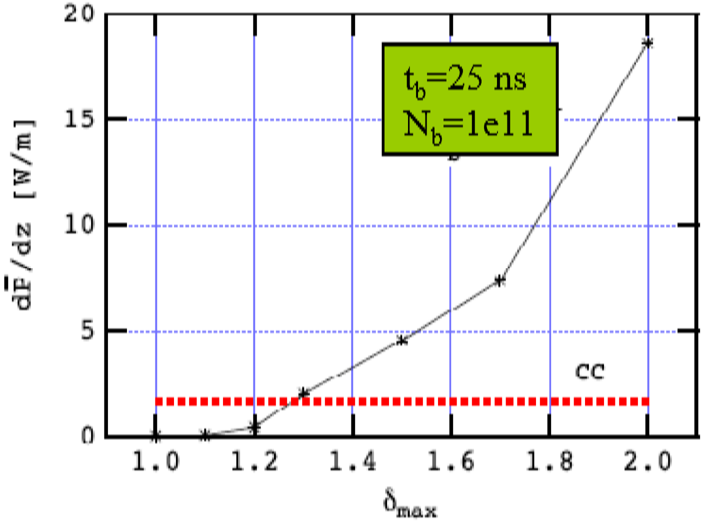


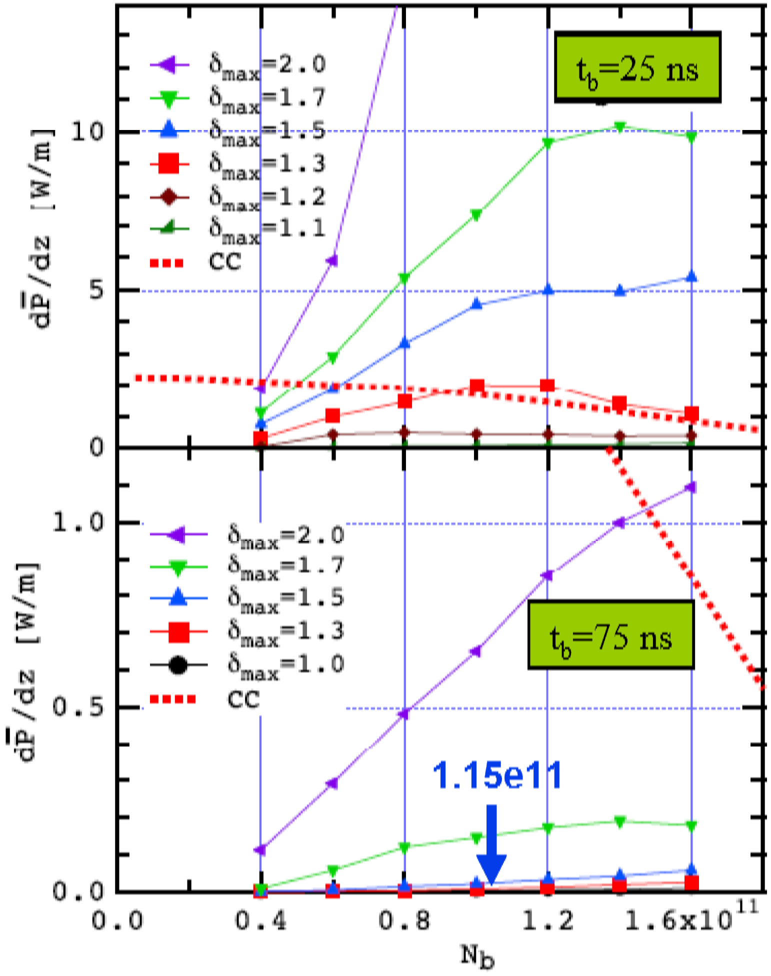
Schematic cross section of a proposed electron sweeping detector for a PSR quadrupole. (Courtesy R. Macek, M. Pivi)

Simulation: EC at LHC dipoles

M. Furman and V. Chaplin, PRST-AB **9**, 034403 (March 2006)

- EC power deposition $d\bar{P}/dz$
  - Simulation code POSINST
  - LHC arc dipole magnet
  - key parameters: N_b, t_b, δ_{max}
  - current result: δ_{max} must be <~1.2
    - conditioning scenario needs to be formulated to achieve this
  - CERN simulations: δ_{max}~1.3 is OK
    - owing to simpler SEY model used





1.15e11

▪▪▪▪▪▪▪ : cooling capacity available for EC power deposition (F. Zimmermann, LHC MAC mtg. #17 (2005))

TUAX05: M. Furman, "Electron Cloud Buildup: MI and LHC" p. 8

Maps

- Codes can predict 2nd order transitions
- 1st order transitions, e.g. vacuum pressure rise in RHIC, cannot be modeled – physics missing
- 3D modeling computationally expensive
- Maps proposed by U. Iriso and S. Peggs
- Maps can predict 1st order transitions and identify good bunch patterns in RHIC in a fraction of computation time [for appl to LHC: T. Demma et al., THPCH047]

U. Iriso, S. Peggs, PRST-AB 8, 024403 (2005); Proc ECLOU04; MOPCH132, MOPCH133

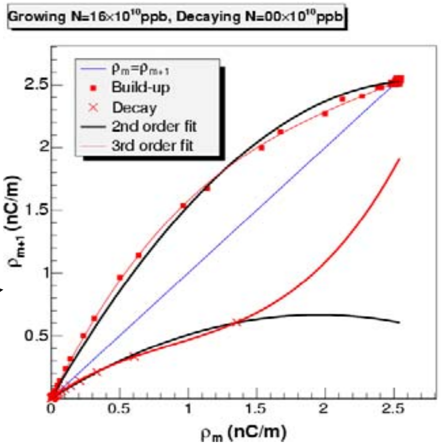
$$\rho_{m+1} = a_1 \cdot \rho_m + a_2 \cdot \rho_m^2 + a_3 \cdot \rho_m^3$$

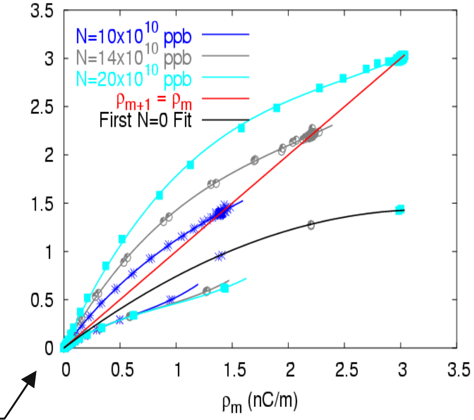
N=N build up

First N=0

N=0 decay (gap)

- For a given surface, for the EC build up the only thing changing between the bunch ***m*** and bunch ***m+1*** is ρ_m and ρ_{m+1}. That is… ρ!
- Plot ρ_{m+1} vs ρ_m
- CSEC (shown) + ECLOUD, diff SEY models





New observations, modeling continues…

Single bunch effects:

- KEKB: Sidebands observed due to EC, fast head-tail instab; modeling comparison good **[J. Flanagan et al., PRL 94, 054801 (2005); K. Ohmi et al., HB2006; THPCH050]**
- LHC: Incoherent single bunch instab, blowup modeling; potentially more a concern than heat load **[E. Benedetto et al., PRST-AB 8, 124402 (2005); Proc. 2005 PAC, 387 and 1344; THPCH018]**

Others:

- SNS: Efforts to control EC have paid off **[V. Danilov, S. Cousineau, Proc. HB2006]**
- FNAL: MI, Booster, Recycler **[R. Zwaska; V. Lebedev; A. Burov, Proc. HB2006]**
- ANL IPNS: Signature very similar to PSR, RFA data TBD **[G.E. McMichael et al., MOPCH126]**
- CESRc: ILC damping ring test bed **[M. Palmer, MOPLS141]**

Summary

- Electron cloud effects important in high performance rings; continue to surprise us
- Much progress on cures for positron rings; recent focus on proton, ion beams
- Surface science is complex: primary, secondary effects
- Benchmarking of models against measured data is absolutely critical to advance understanding
  - RFA and variations (APS, PSR, SPS, KEKB, …)
  - GESD, gridded electron collector (HCX)
  - Other beam diagnostics: spectra, centroid, tune shift, etc
- Modeling effort driving towards massively parallel 3D
- Simplified models: maps, multipacting, impedance

- Much work has been done: talk only touches the surface…

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P. Thieberger, L. Wang, T-S. Wang, F. Zimmermann,…

Teams at APS, BEPC, HCX, PEPII, PSR, RHIC, SPS/LHC,…

Next workshop:
ECLOUD07, early 2007, Asia
organizers: K. Ohmi, H. Fukuma (KEK), E-S. Kim (PAL)