

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 skepticism

- 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, **PEP-II** 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 4 th 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

CME, Stoltz Library for computational methods for electron cloud effects

Courtesy A. Adelmann et al., ECLLOUD04

Extensive benchmarking study launched after ECLLOUD02,
ECLLOUD04, 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]



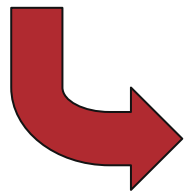
Modern study of EC effects

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. ELOUD/HEADTAIL
- KEKB vs. PEHT/PEHTS
- RHIC vs. CSEC, ELOUD, 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 $\delta_0 \sim 0.5$ (CERN, PSR)
- True SE distribution peaks 1-3 eV, surface independent; rediffused contrib. varies/sensitive

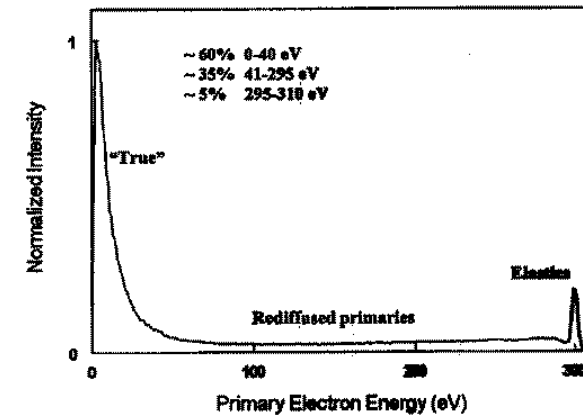
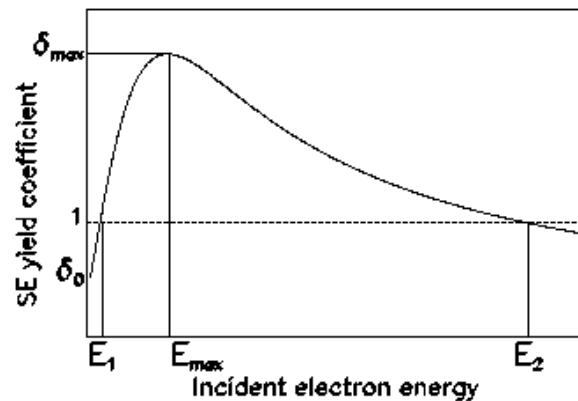
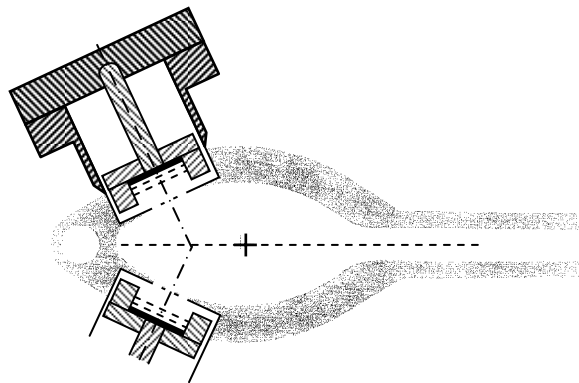


Fig. courtesy of R. Kirby

LHC, SPS=25ns



APS RFA

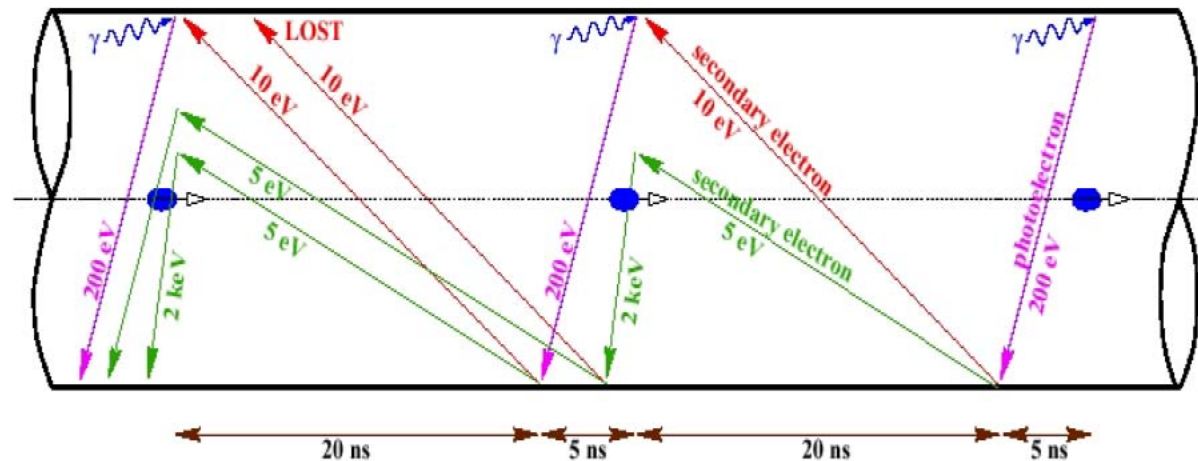


Fig. courtesy of F. Ruggiero, G. Arduini

EC amplification processes

Dominant source of EC can vary: KEKB vs PEP-II

- 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

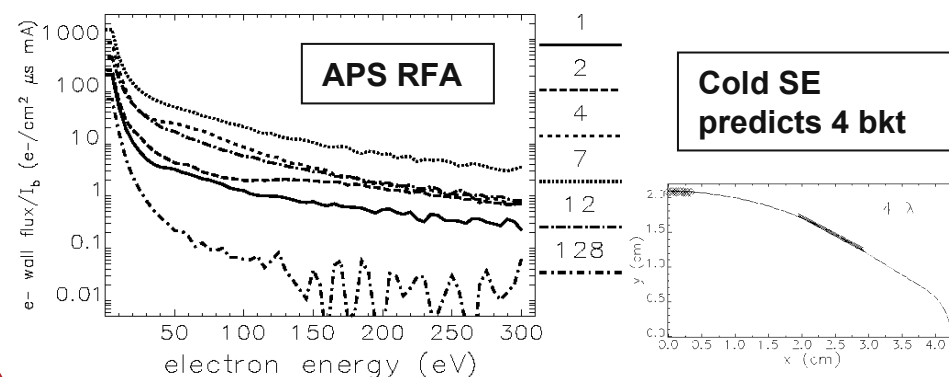
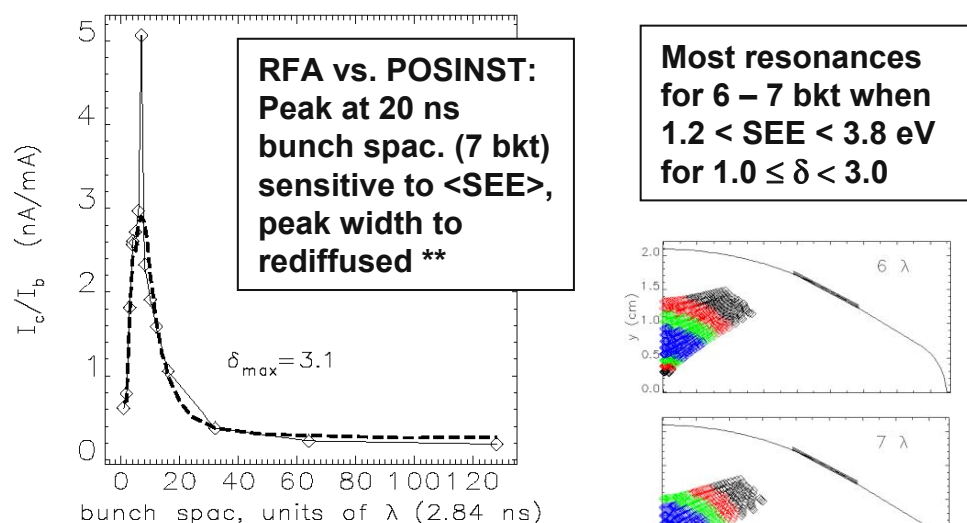
- Cold-electron model **[O. Gröbner, Proc. 10th HEAC, Protvino, 277, 1977]**
- Multiple kicks, energy distribution (Zimmermann, Ruggiero)
- “General” condition: dependence on EC distribution (Furman, Heifets)
[K. Harkay, R. Rosenberg, PRST-AB 6, 034402 (2003); L.F. Wang, A. Chao, H. Fukuma, Proc. ELOUD04 (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)



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

L. Wang et al., ECLoud04: RHIC. KEKB, SNS

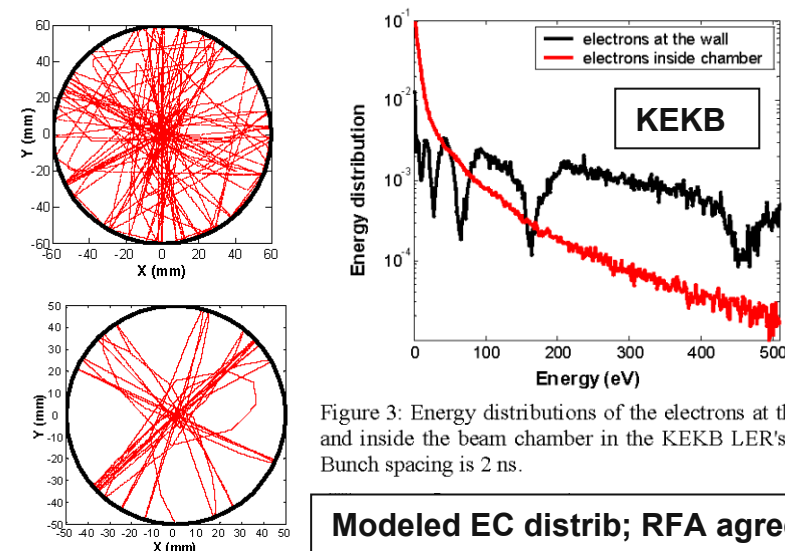


Figure 1: Electron's orbit (left column) and energy at the wall (right column). RHIC beam with bunch spacing 108 ns (top row); KEKB LER beam with bunch intensity 3.3×10^{10} and bunch spacing 8 ns (bottom row).

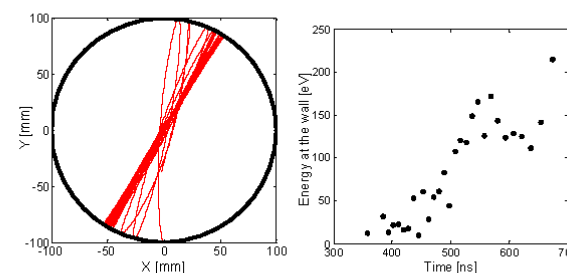
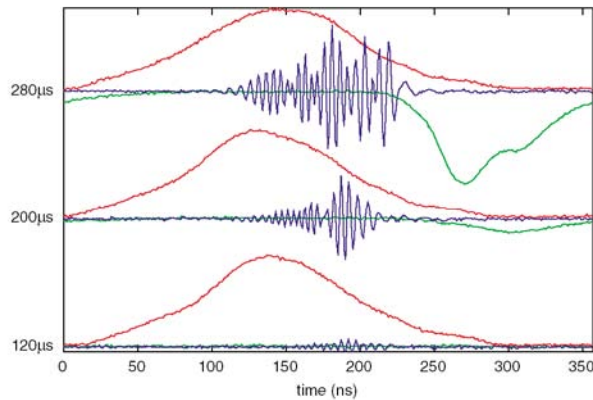


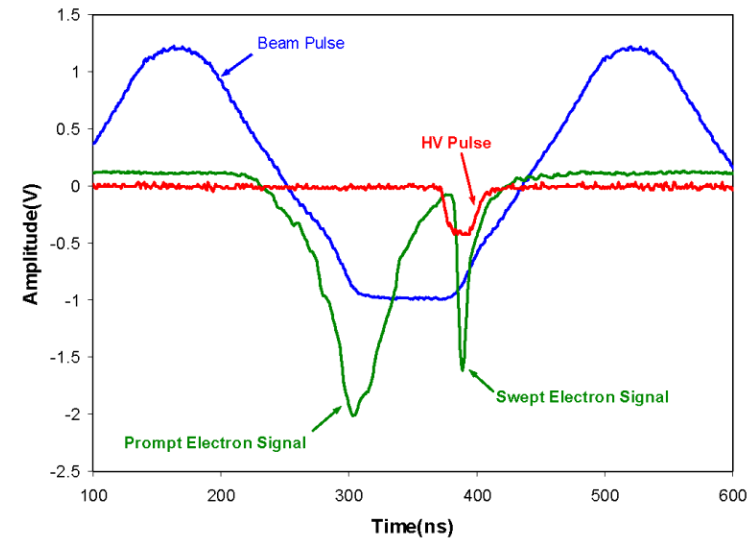
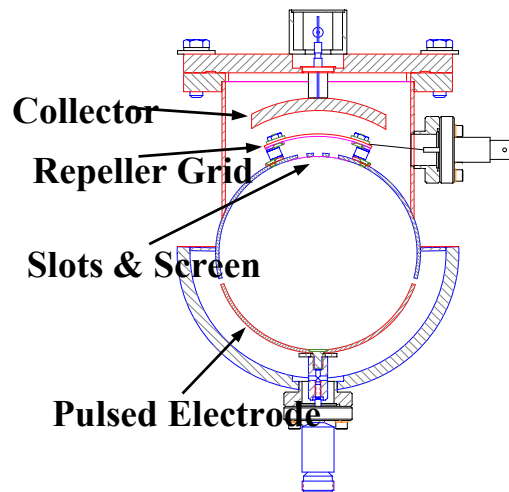
Figure 2: Electron's orbit (left column) and energy at the wall (right column) in the SNS accumulator ring. Bunch length is 700 ns.



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:

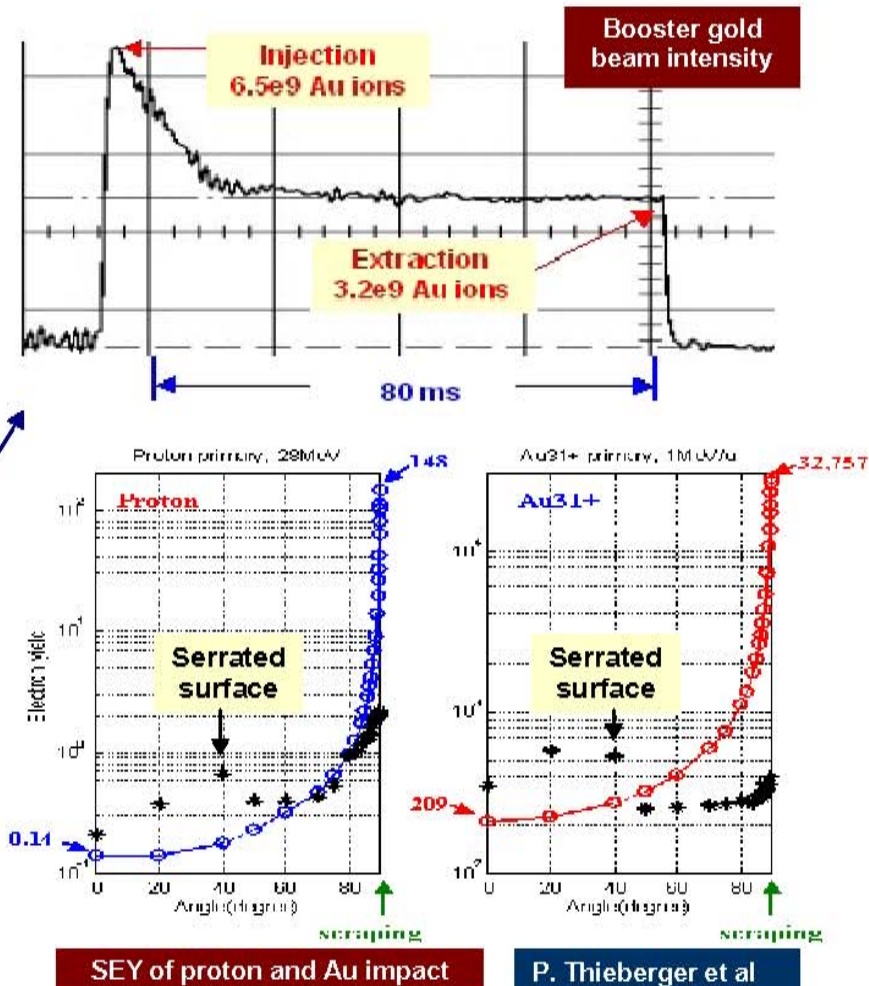
- **Multibunch Instabilities Workshop**, KEK, 1997 [KEK Proc. 97-17](#)
- **Two-Stream ICFA Mini Workshop**, Santa Fe, 2000
<http://www.aps.anl.gov/conferences/icfa/two-stream.html>
- **Two-Stream Workshop**, KEK, 2001 <http://conference.kek.jp/two-stream/>
- **ELOUD02**, CERN, 2002 <http://slap.cern.ch/collective/eloud02/>
- **Pressure Rise Workshop**, RHIC/BNL, Dec. 2003
<http://www.agrhichome.bnl.gov/AP/PressureRise/Page1.htm>
- **ICFA ELOUD04**, Napa, CA, Apr. 2004 <http://www.cern.ch/icfa-eloud04/>
- **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.

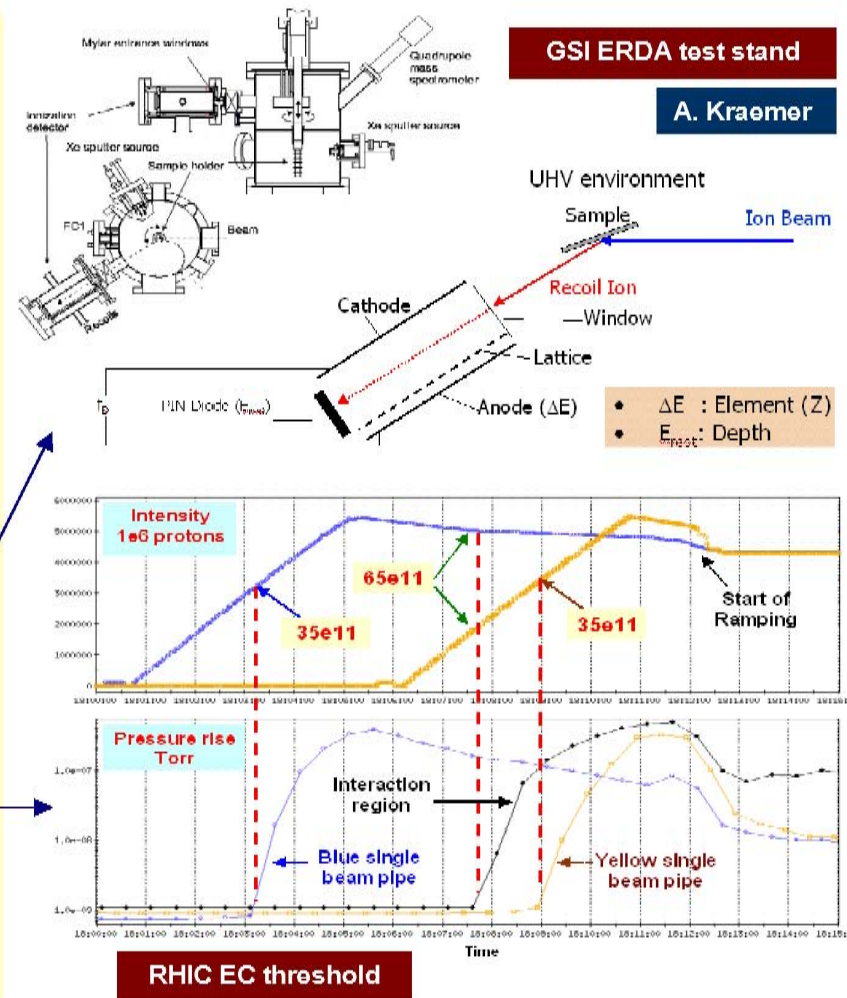


Electron impact gas desorption msrd at RHIC: 0.05 (0.01 after scrubbing) U. Iriso, W.Fischer, EPAC06, MOPCH134

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

4. Status and plan

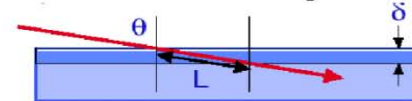
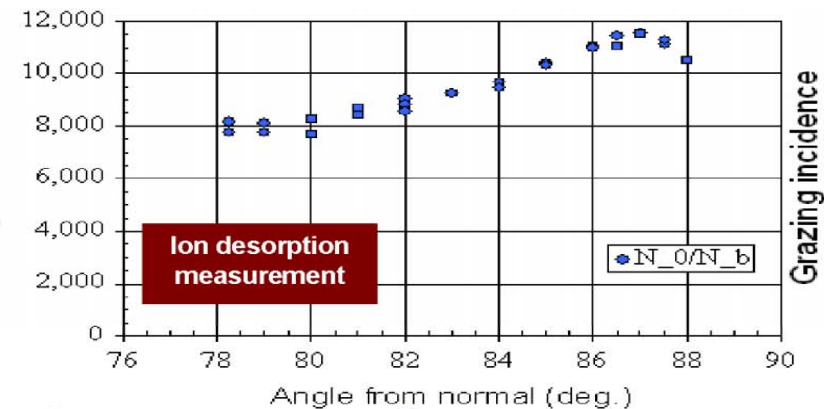
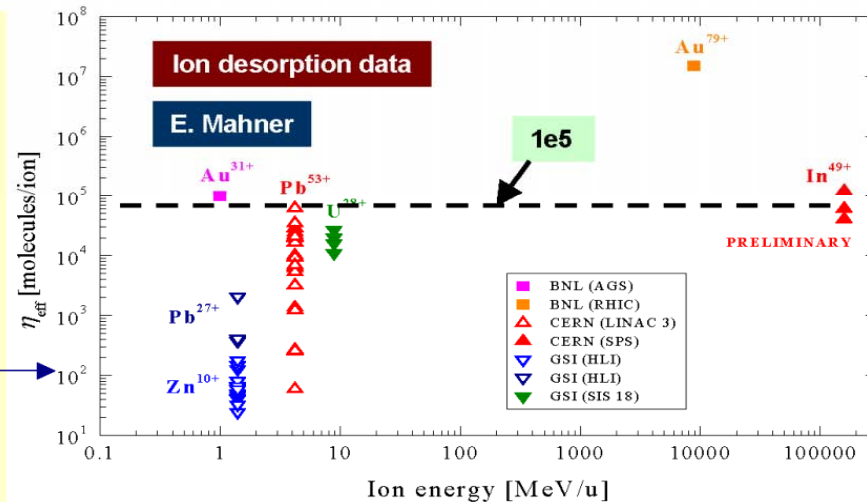
- It is not unusual that the measured desorption rates differ in **orders of magnitude** with similar conditions.
- Surface chemistry/physics may help for better understanding.
- It is proposed for systematic measurements according to species, energy, charge state, and incident angle.
- More measurements 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.



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?



$$L = \delta / \cos(\theta)$$

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)

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

Grooves, antigrazing surfaces (collimation)

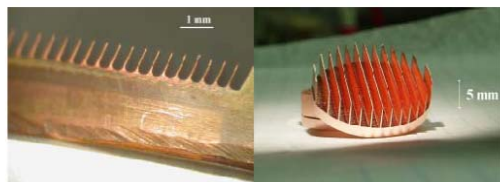


Figure 7. Samples with two different rectangular groove profiles, 1 mm or 5mm depth.

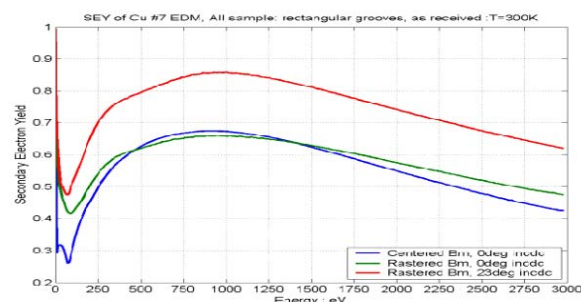


Figure 8. Measured SEY for a rectangular groove Cu sample at different angles. The smooth part of the sample has a $\delta_{max}=1.65$.

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

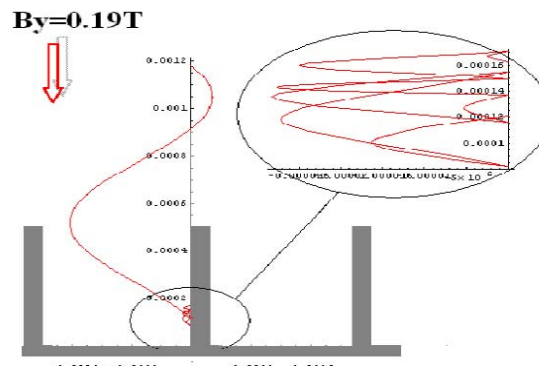


Figure 9. Electron dynamics in proximity of a rectangular groove surface in the presence of a dipole magnetic field. The electron is absorbed.

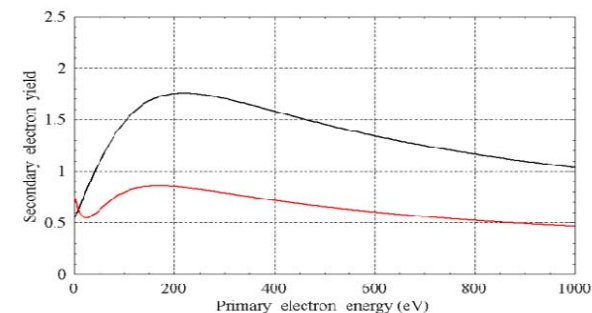
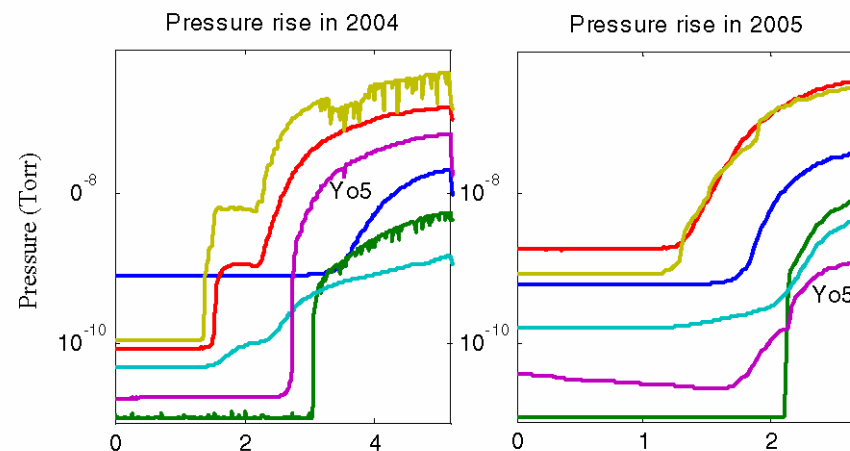
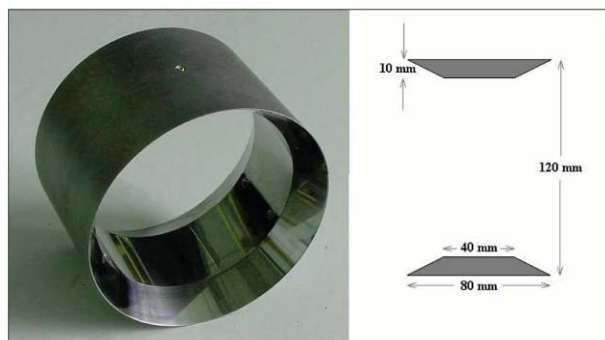
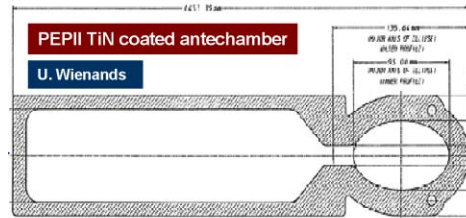


Figure 10. Simulated SEY for a smooth (above) and for a rectangular grooved surface (below) in a dipole field.

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



TiN, NEG coatings, surface roughness

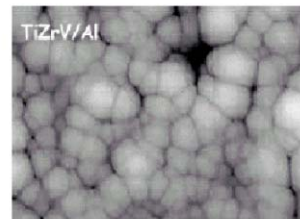


5 mTorr $\lambda \sim 1$ cm 1.5 mTorr ~ 3.3 cm

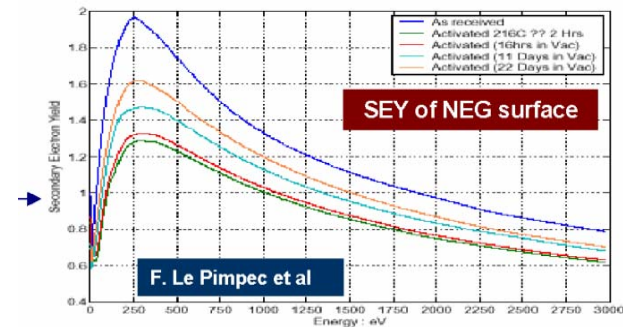
TiN surface comparison H.C. Hseuh



NEG surfaces on St. St. & Al



1 μ m V. Ruzinov

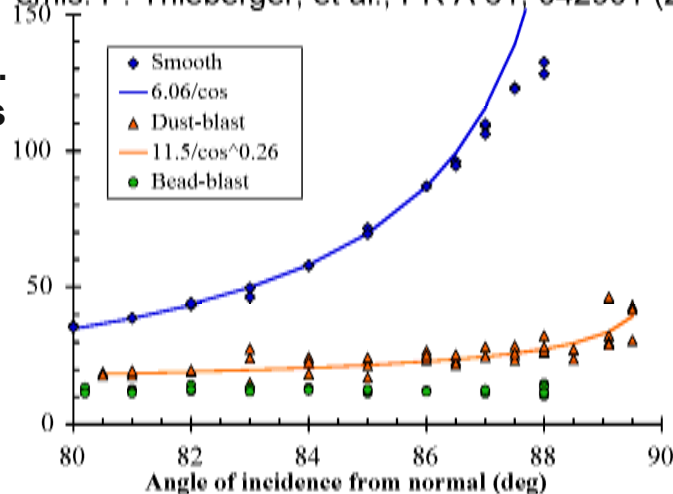


Pressure-Rise Workshop (2003)

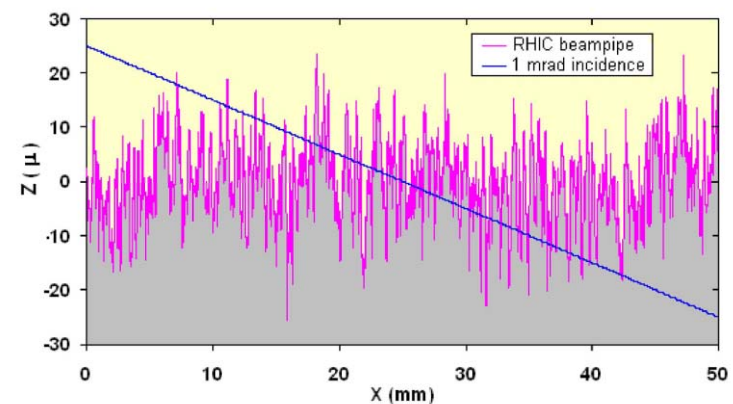
A. W. Molvik, et al., PRST-AB 7, 093202 (2004).

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 $\ll$
roughness**



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

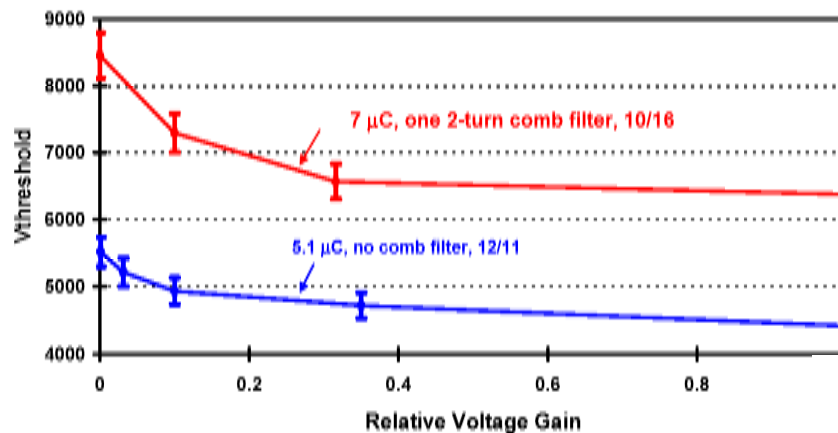


Prototype fast beam feedback for e-p

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

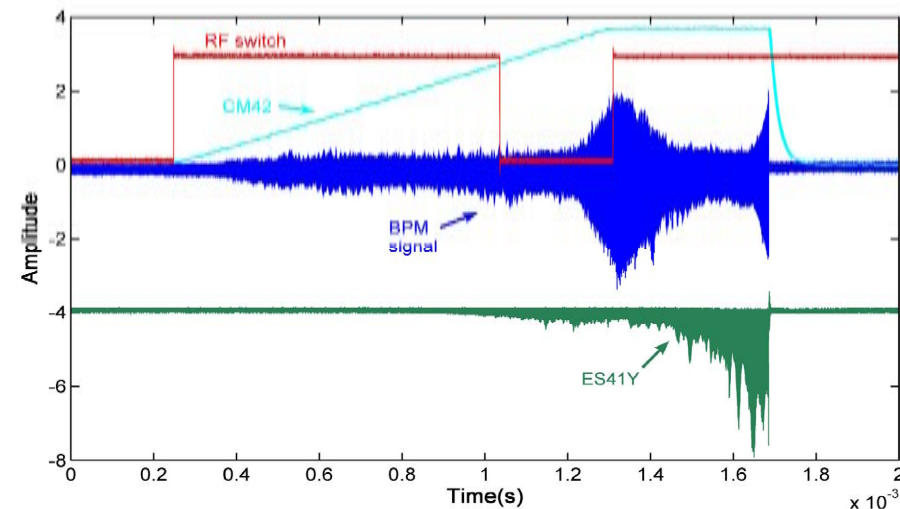
Grow-damp-grow measurements:

1st phase: growth $1.03 \times 10^4 \text{ s}^{-1}$

FB damping rate: $1.75 \times 10^4 \text{ s}^{-1}$

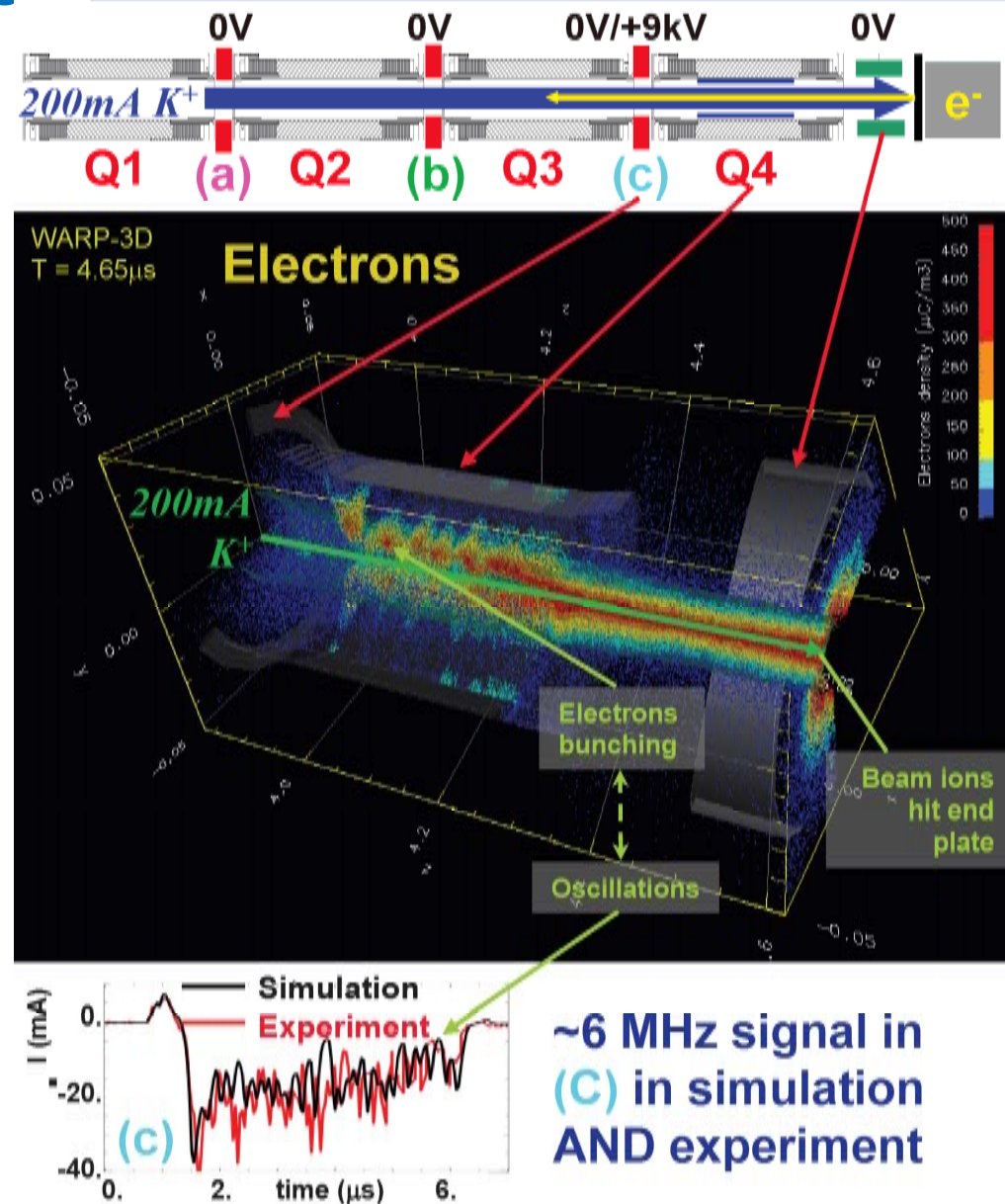
2nd phase: e-p growth $3.35 \times 10^4 \text{ s}^{-1}$

Beam in gap believed responsible

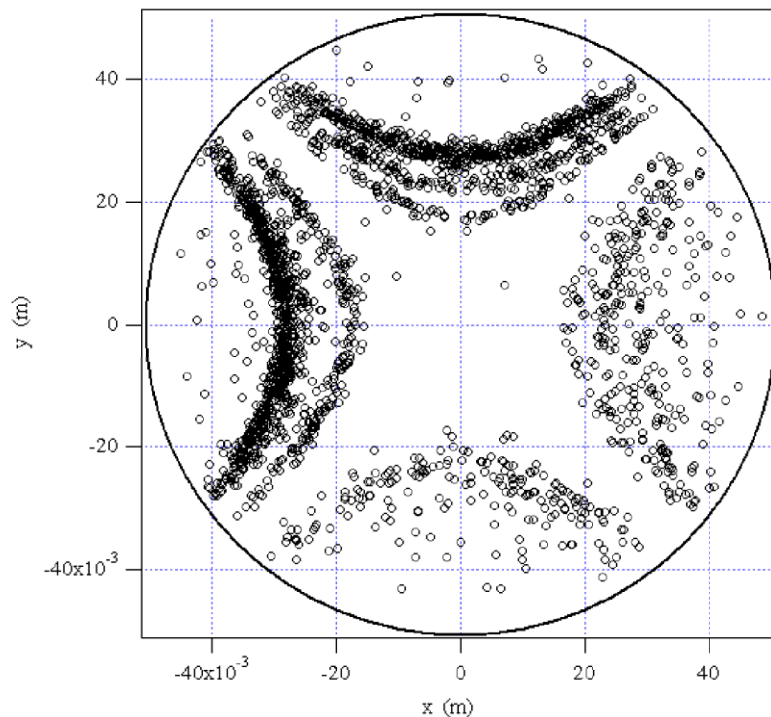


Trapping in quadrupoles

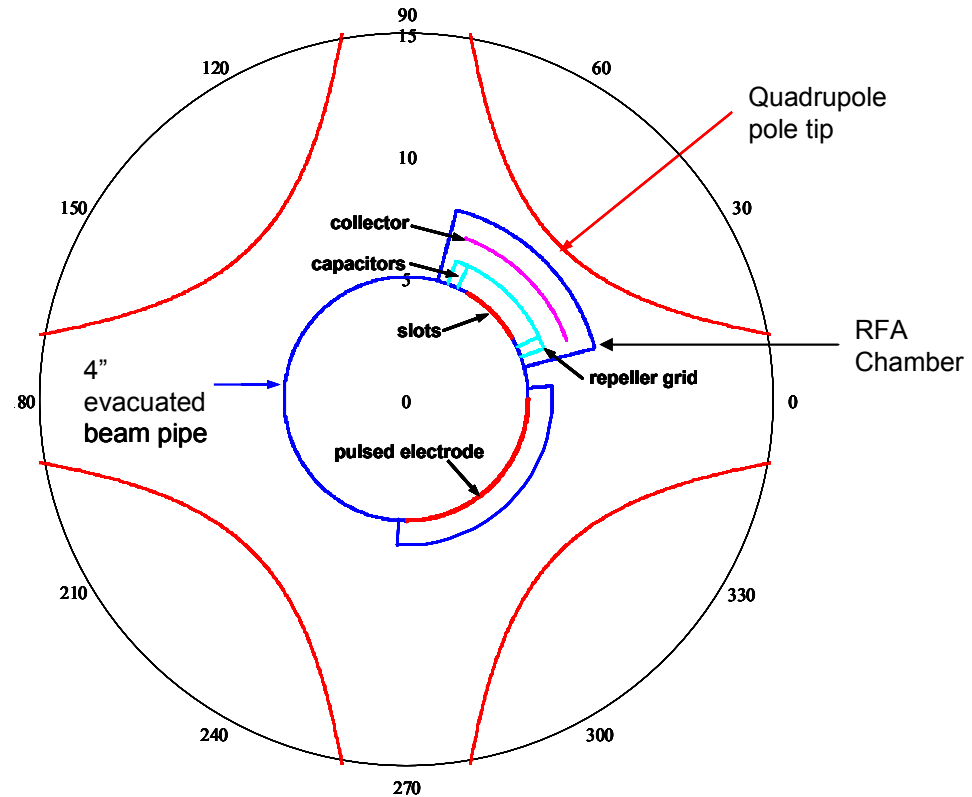
- PSR, HCX: Large beta functions in quads, high beam loss (halo)
- KEKB: blowup with 3.27 bkt spacing, where are electrons (solenoids)?
- Self-consistent 3D modeling (WARP/POSINST), measurements [J-L Vay et al., Proc. HB2006; Proc. 2005 PAC, 525 and 1479]
- Cures? Clearing electrodes [L. Wang, H. Fukuma,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



Proposed electron sweeper for quadrupoles (PSR)



Snapshot of trapped electrons in a PSR quadrupole $5 \mu\text{s}$ 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)



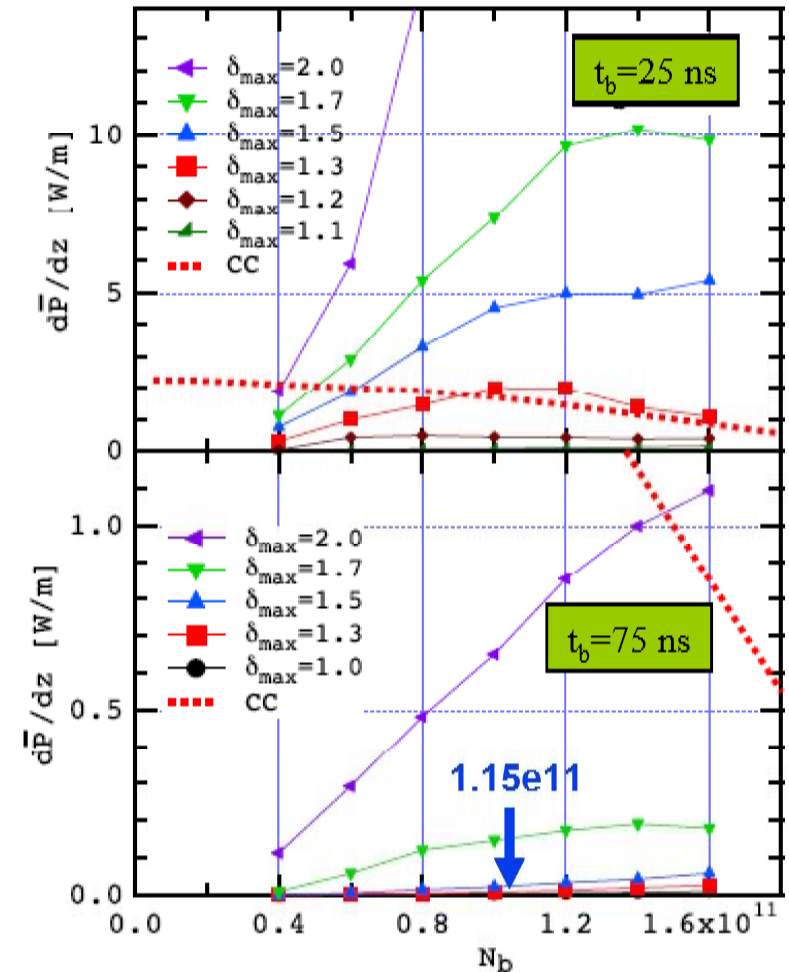
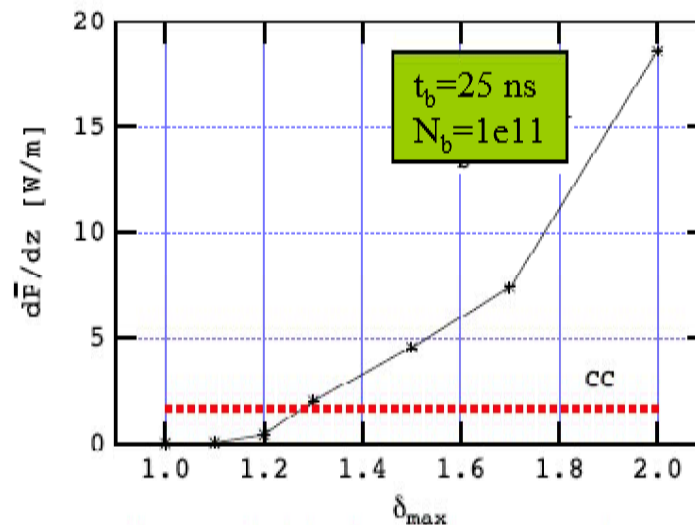
Simulation: EC at LHC dipoles

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 , $\delta_{\max}$
- current result: $\delta_{\max}$ must be ~ 1.2
 - conditioning scenario needs to be formulated to achieve this
- CERN simulations: $\delta_{\max} \sim 1.3$ is OK
 - owing to simpler SEY model used



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

Maps

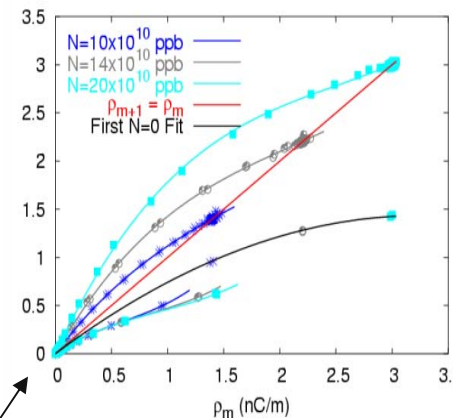
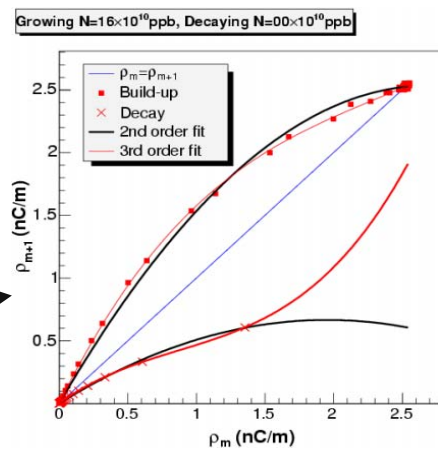
- Codes can predict 2nd order transitions
- 1st order transitions, e.g. vacuum pressure rise in RHIC, cannot be modeled – physics missing
- 3D modeling computationally expensive
- Maps proposed by U. Iriso and S. Peggs
- Maps can predict 1st order transitions and identify good bunch patterns in RHIC 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

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

- 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



N=N build up

First N=0

N=0 decay (gap)



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...



Acknowledgements – an incomplete list...

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