Electron Clouds in e^+ Storage Rings

(Report from the ECLOUD02 workshop)

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Accelerator Physics Seminar

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Outline

- Motivation
- Introduction
- Experimental Observations / Electron Cloud Diagnostics
- Secondary Emission Yield
- Electron cloud build-up : a simple model
- Simulation codes
- Conclusion

Reference: Proceedings ECLOUD'02, CERN-2002-001
CERN, Geneva, 15-18 April 2002, Eds.: G. Rumolo, F. Zimmermann

Motivation

- KEK, SLAC
  - B-factories
  - NLC/JLC damping ring
- CERN
  - LHC heat load on cold shielding
- DESY
  - TESLA e+ Damping Ring
  - PETRA III, Synchrotron Ligth Source
    - e+ versus e- runing
- SNS
  - Beam losses in acumulator ring
- ...

Motivation (cont.)

The winner is:

3rd price of the ecloud competition for the TESLA DR ?
(ECLOUD02 talk by A. Wolski)

	Incoherent tune shift	Single bunch threshold / nominal	Coupled bunch growth time /μs
PEP II LER	0.16	0.6	16
NLC MDR	0.019	0.8	20
TESLA	0.114	0.5 - 5	30 - 170
KEK B LER	0.022	3	180
DAΦNE	0.0068	3	20
NLC PPDR	0.0025	10	370
HERA-e	0.0057	20	2000

International Linear Collider Technical Review Committee (ILC-TRC)
Ranking 2: R&D needed to finalize design choices and ensure reliability of the machine
Items Common to All Machines
Luminosity
Damping Rings
• For all the damping ring designs, further simulation studies are needed to understand the magnitude of the electron cloud effects and to explore possible means of suppressing these effects. Experiments in existing rings are needed to test the electron cloud simulations.

Introduction

Electron cloud

Primary source:

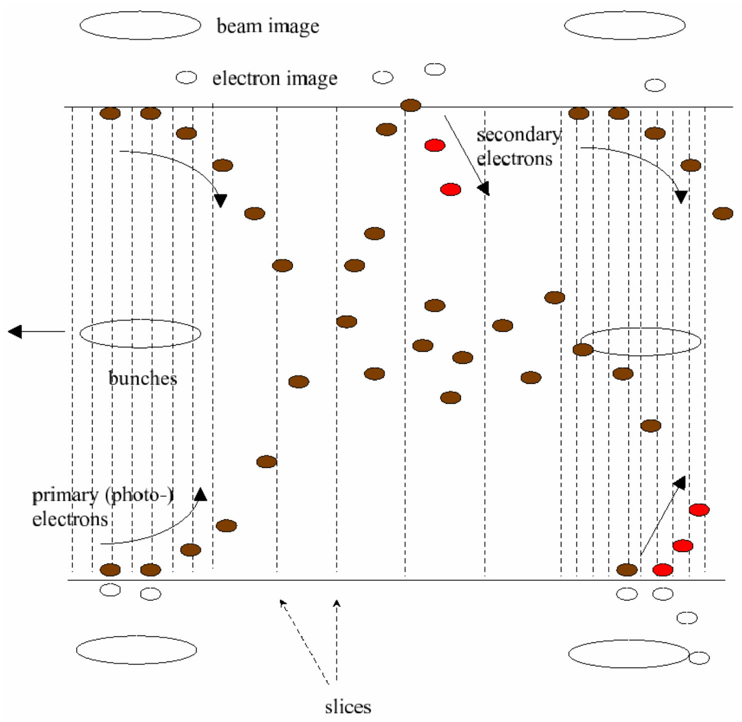
Photoemission

Residual gas ionization

Beam loss on the wall

Secondary source:

Field emission



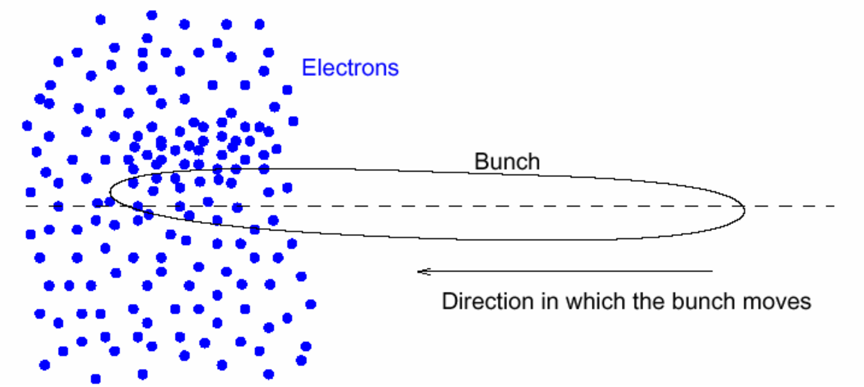
Experimentally observed in positron and Proton storage rings:

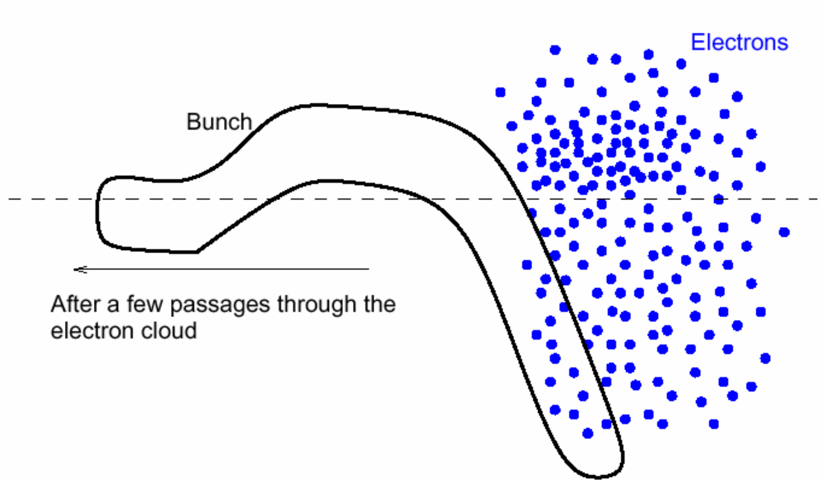
KEKB, PEP II, APS, SPS, ...

Introduction (Cont.)

- Secondary electrons
- Beam-induced multipacting (BIM)
- Build-up of an electron cloud
- Vacuum degradation
- Asymmetry in electron cloud:"wakefield"

The electrons are attracted by the slightly displaced head of the bunch and kick the coming bunch particles in that direction.



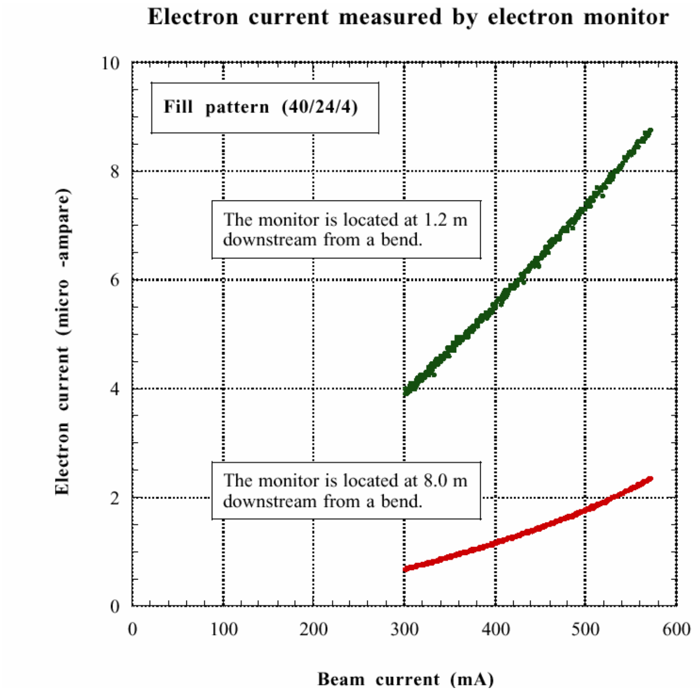


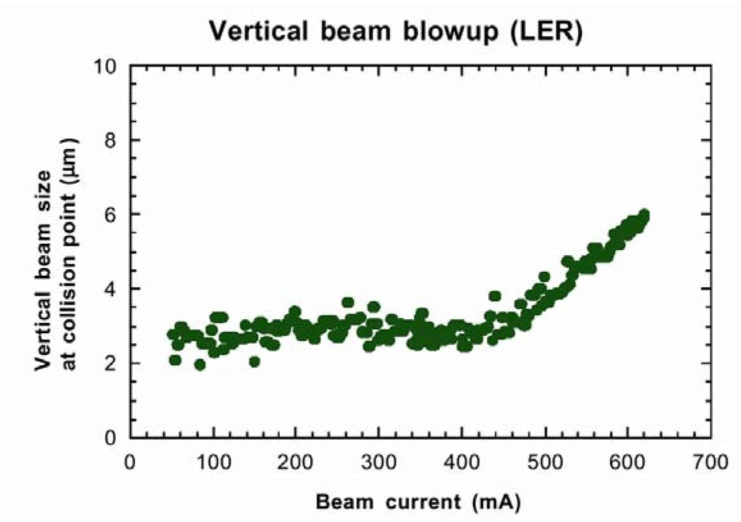
(from G. Rumolo's ECLOUD02 talk)

Experimental Observations

- KEKB LER
  - Single and multibunch effect
  - Threshold is determined by the charge density (Bunch current/bunch spacing)

Beam energy (GeV)	3.5
Circumference (m)	3016
Bunch length (mm)	4
Bunch spacing (ns)	8
Beam current (mA)	1400
Particles / bunch (10^{10})	3 -7
Emittance $\varepsilon_x / \varepsilon_y (10^{-8}$m)	1.8 / 0.036
Average beta function (m)	15

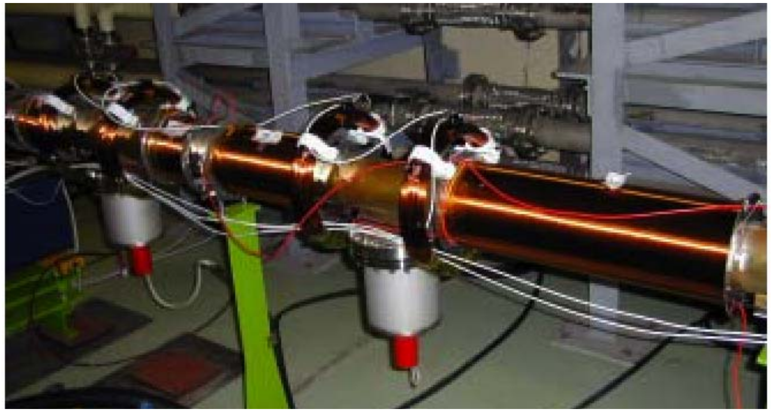


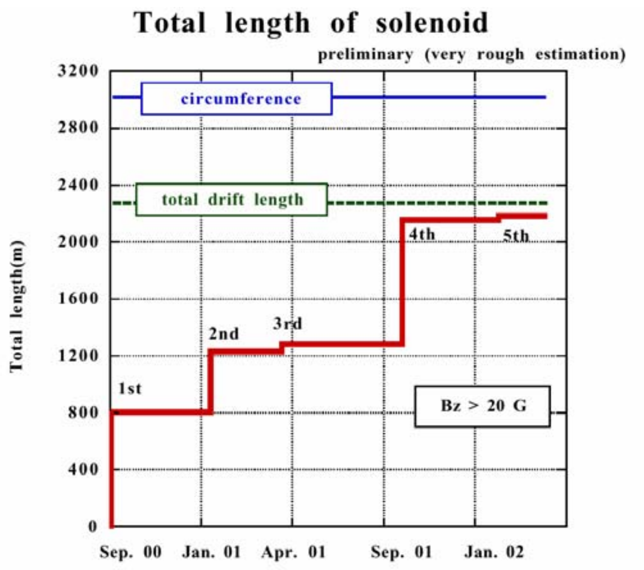


(talk by H. Fukuma)

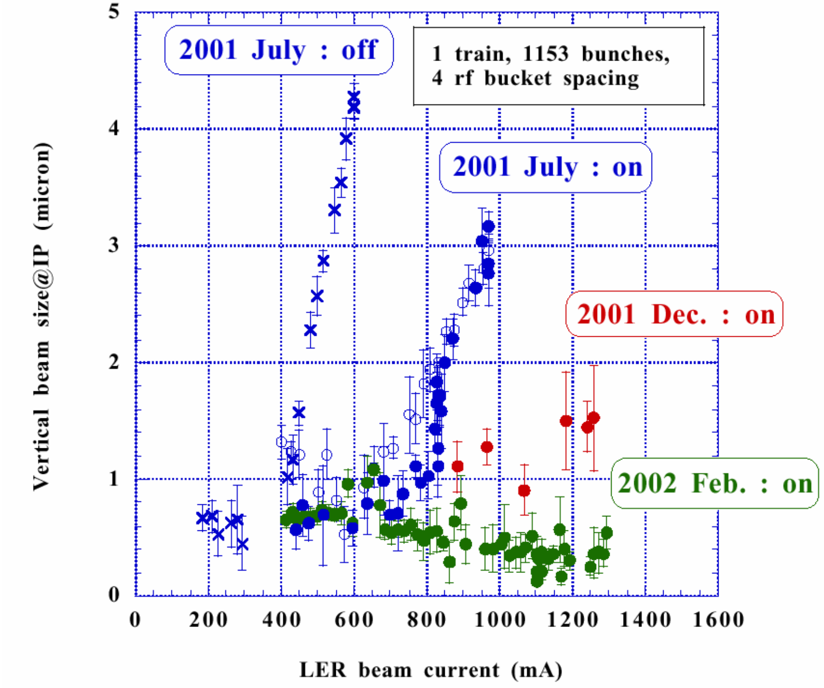
Experimental Observations: Cures

Solenoids (from H. Fukuma's talk)



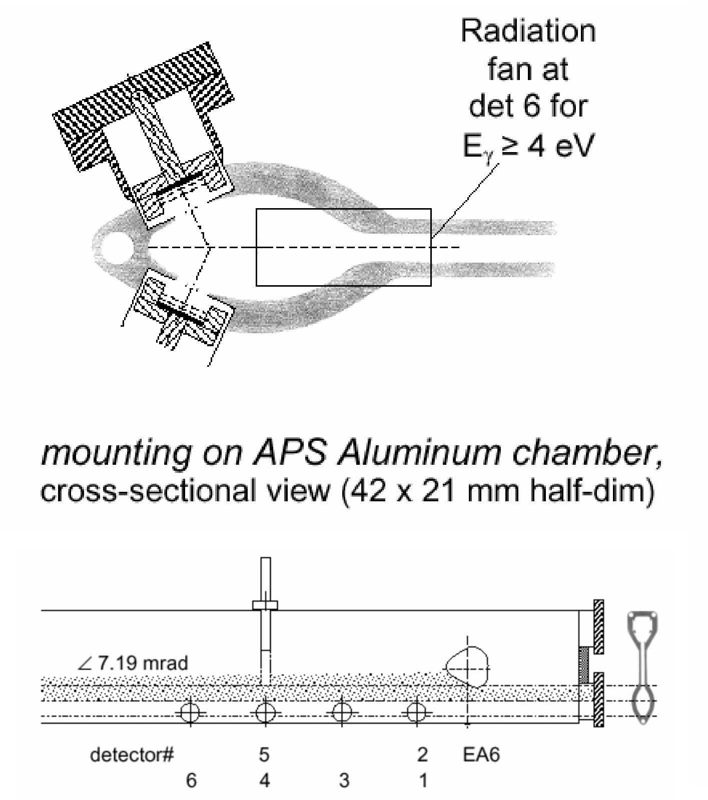


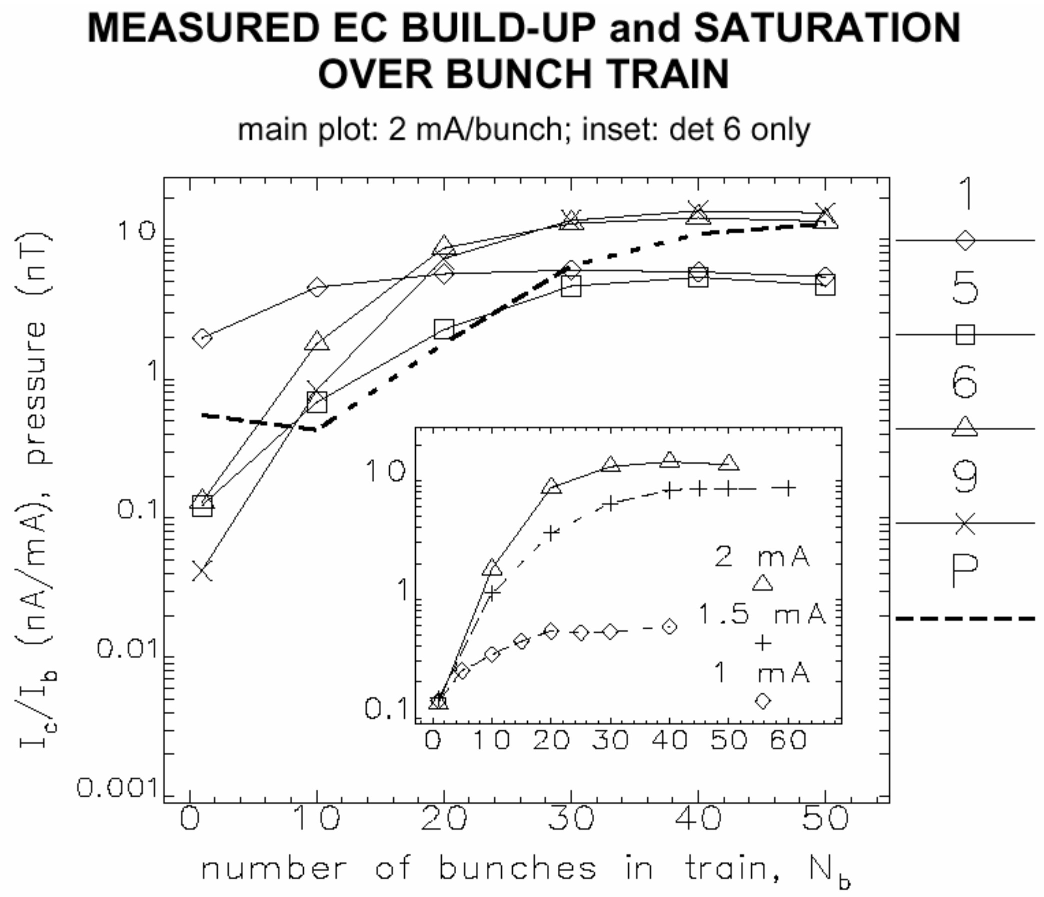
Effect of the solenoids
in physic run fill pattern



Electron cloud diagnostics

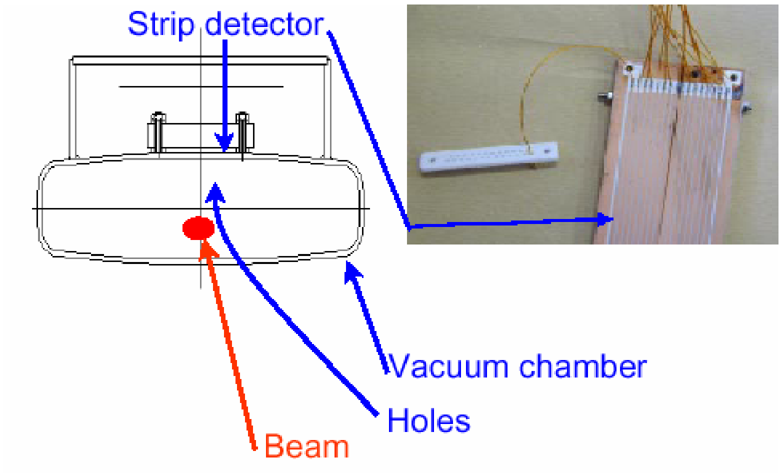
- Retarding Field Analyser (RFA)
  at the APS (Argonne)
  (talk by K. Harkay)





Electron cloud diagnostics (Cont.)

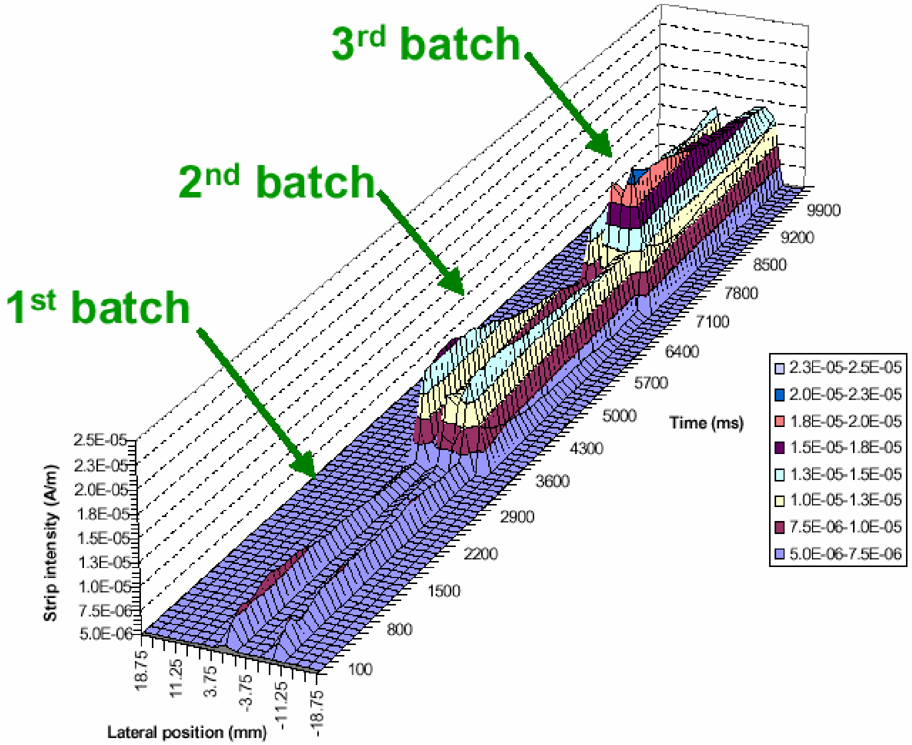
- CERN SPS strip detector



the spatial distribution of the electron cloud versus time is measured

(from J.M. Jimenez's talk)

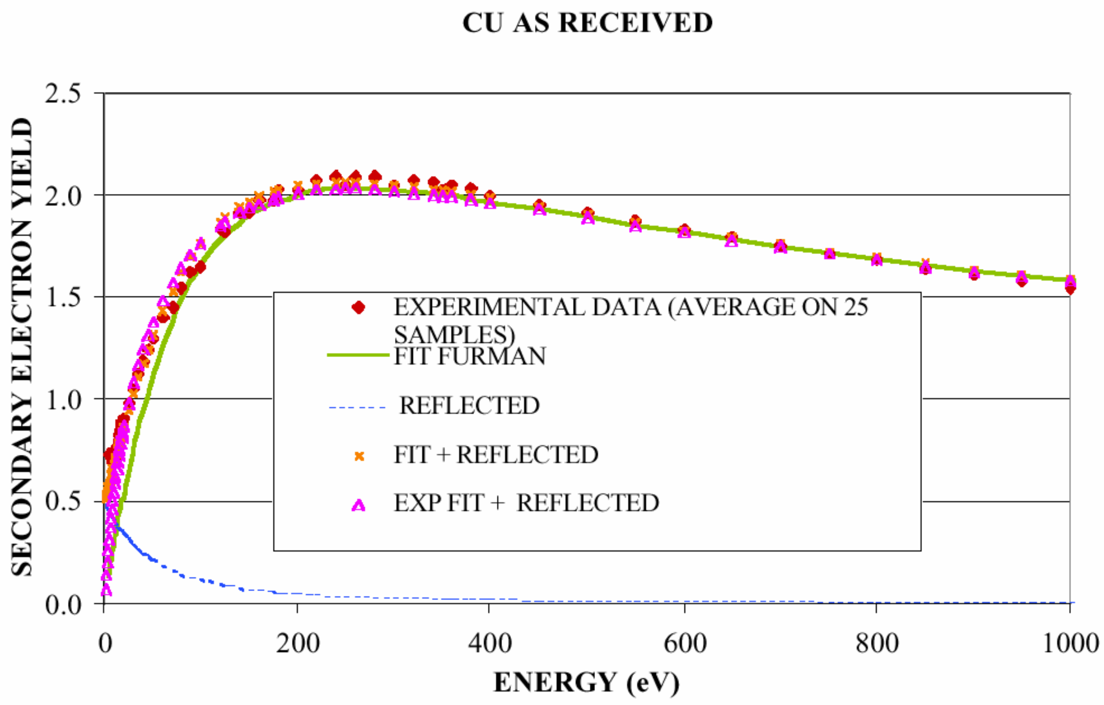
Electron cloud activity during the injection of 3 LHC batches (6 x 12 bunches) into the SPS:



at high p intensities (6 x10^{10} p/bunch)
two strips in the e-cloud

Secondary Emission Yield (S.E.Y.)

- Measurements at CERN (talk by N. Hilleret)



maximum Yield δ_{max} at energy E_{max} of primary electron $E_{max} \sim 300$ eV

	$\delta_{max} \sim$
Stainless Steel	2.0
Cu	2.1
Al	3.5
Ti	1.9
TiN	1.066

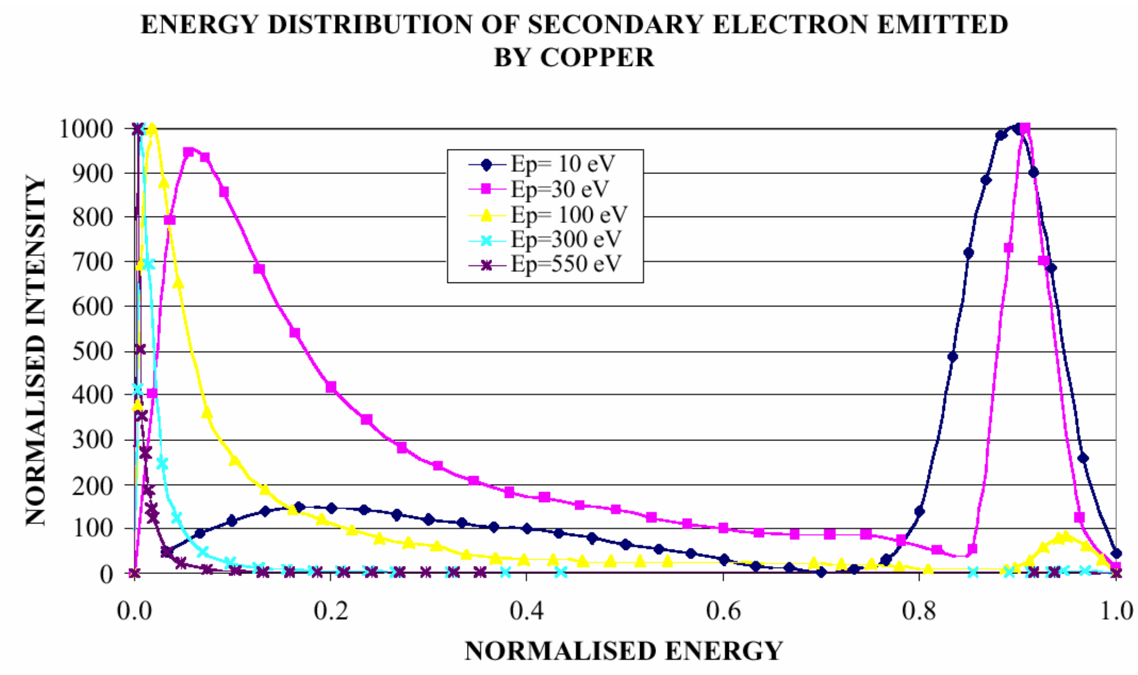
(after bombardment with electrons)

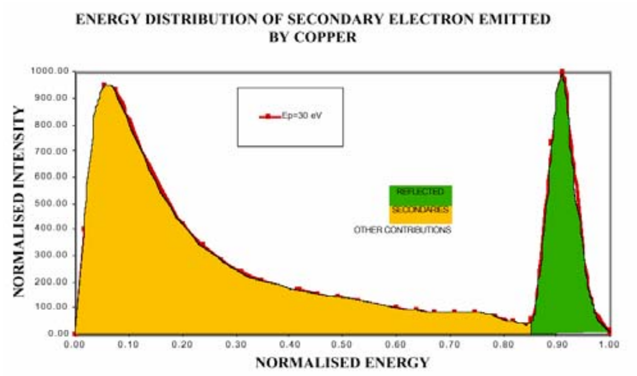
Fit to data:
δ_{max}=2.03
E_{max}=262 eV
s = 1.39

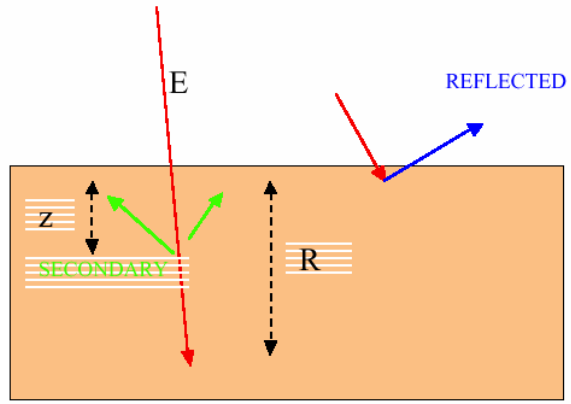
$$\delta(E) = \delta_{max} \frac{s\ (E / E_{max})}{(s-1) + (E / E_{max})^s}$$

Secondary Emission: Energy distribution

Energy distribution for different energies of the primary electron







The reflected contribution is negligible for primary energies above 300 eV

Fit for true secondaries:

C = 0.126

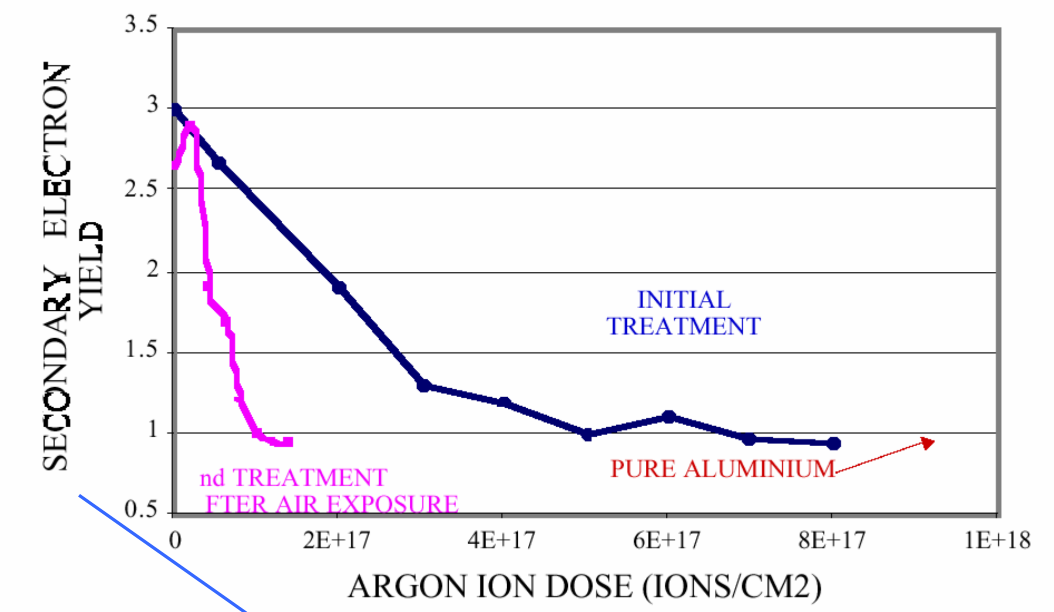
E_0= 1.58 eV

τ=1.16

$$D(E) = C \exp\left(- \frac{[\ln(E/E_0)]^2}{2\,\tau^2} \right)$$

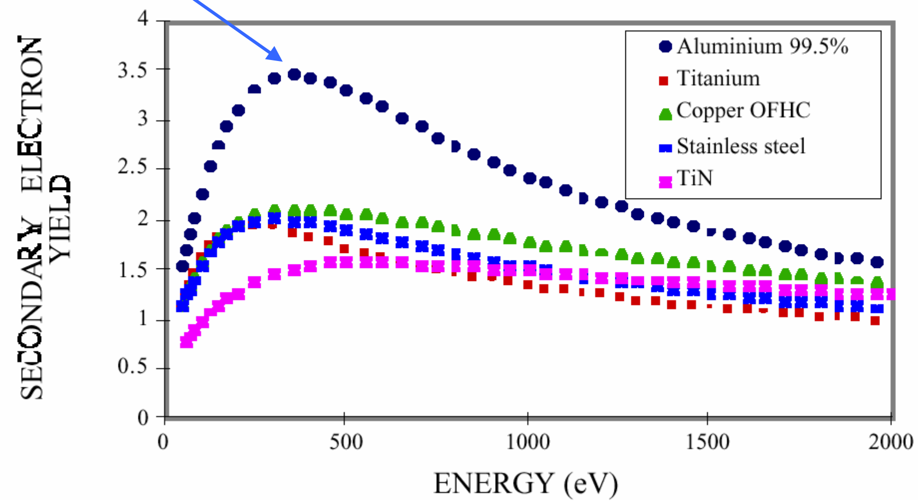
S.E.Y of Al

SEY (max) of Al after cleaning with Argon Ions



max. SEY

SEY of various as received materials:

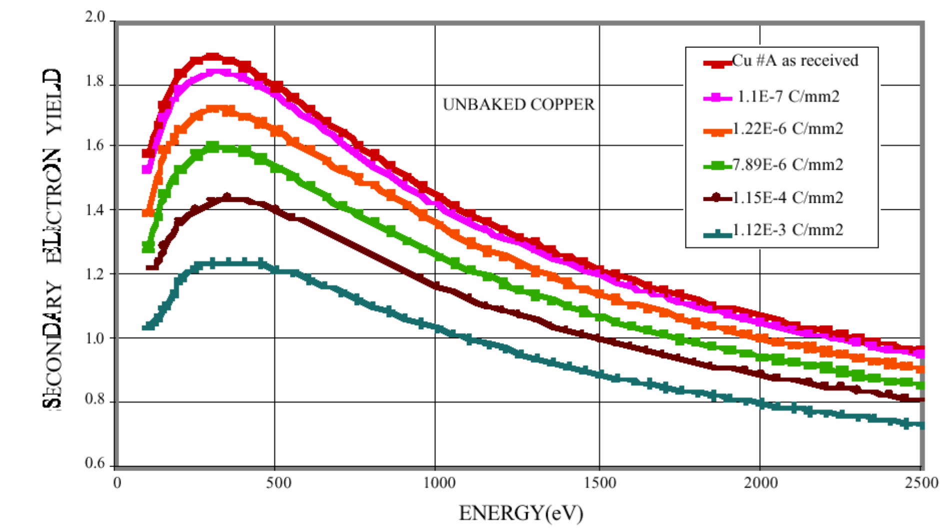


(from N. Hilleret et al. EPAC 2000 paper)

Processing of Cu (S.E.Y.)

a) with electon beam:

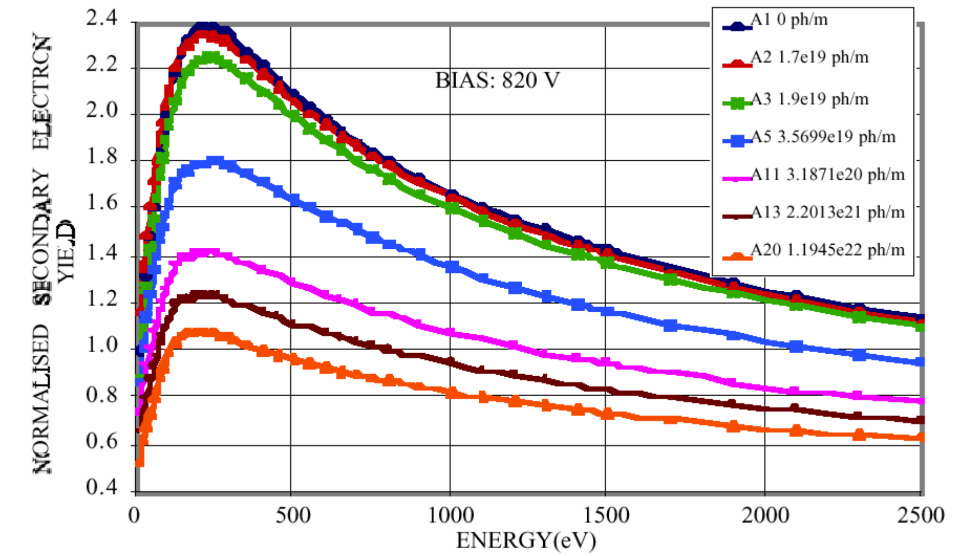
the effect is permanent
if the surface is kept
under vacuum (< 1 x 10-5)



b) with synchrotron light:
(820 eV photon energy)

SEY saturates at 1.6
for diffuse photons

(from N. Hilleret
et al. EPAC 2000
paper)



Electron cloud build-up : a simple model

Photoelectrons:

$$\frac{dN_{e^-}}{ds} = Y \frac{dN_\gamma}{ds}$$

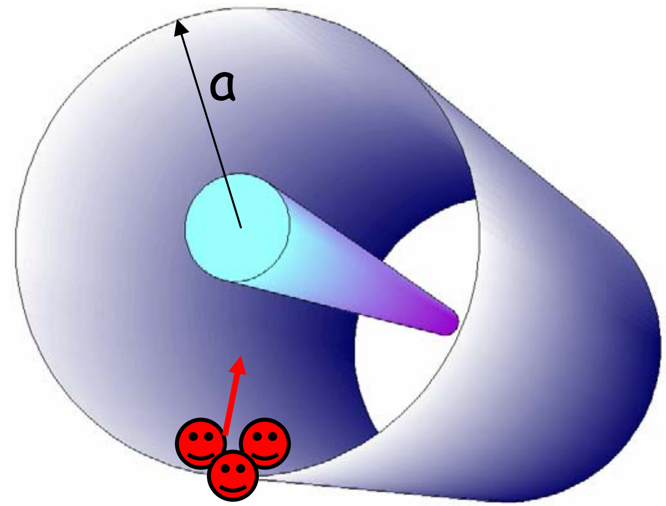
$$\frac{dN_\gamma}{ds} = \frac{5}{2\sqrt{3}} \frac{1}{137} \frac{E}{mc^2} \frac{1}{\rho}$$

$$Y \approx 0.1$$

Parameter	KEKB LER	APS Studies	PETRA II	TESLA DR Arc
Energy /GeV	3.5	7	7	5
Circumference /m	3016	1104	2304	2460
Bunch population/ 10^10	3.1	4.6	5	2
Bunch spacing /ns	8	20	96	20
Bending Radius /m	16	30	192	83
Photoelectrons/m /e+	**0.454**	**0.37**	**0.075**	**0.124**
Chamber	Cu	Al	Al	Al
a / mm	47	21	28	18
b /mm	47	42.5	55	22
Energy after kick / eV	**20**	**78**	**60**	**33**
Drift time through chamber	35	8	12	10

Kick at the chamber wall:

$$\Delta p = e \frac{1}{2\pi\varepsilon_0} \frac{N e}{l} \frac{1}{r} \Delta t = \frac{e^2}{2\pi\varepsilon_0 c} \frac{N}{r}$$



Please note:
the energy of the electrons
is calculated after **one** kick !

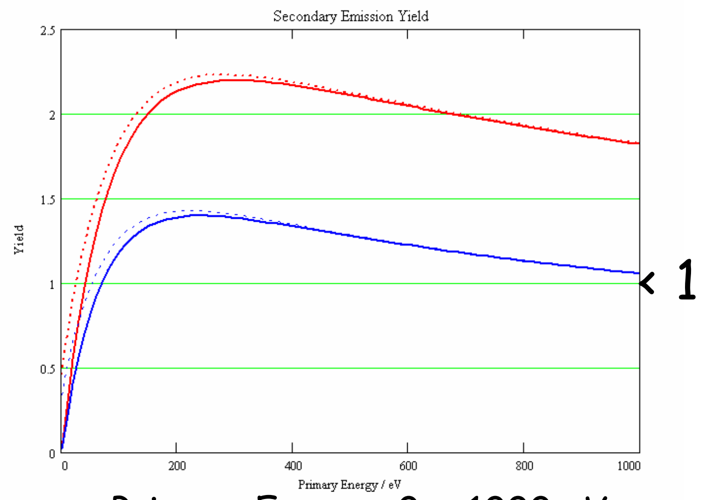
Electron cloud build-up : a simple model (cont.)

Secondary emission: SEY < 1

SEY = 1	Al	Al (true)	Cu	Cu (true)
Energy / eV	**27**	**42**	**54**	**70**

$$\frac{e^2}{2\pi\varepsilon_0}\frac{N}{a} \leq \sqrt{(E_{SEY})^2 + 2E_{SEY}\, m_0\, c^2} - \sqrt{(E_0)^2 + 2E_0\, m_0\, c^2}$$

$$\text{S.E.Y.} < 1: \quad E_{SEY}, \qquad E_0 = 7 \text{ eV}$$



Primary Energy: 0 … 1000 eV

"Save" bunch distance - only one kick

$$\frac{2}{c\,\beta(p)} \leq \frac{\Delta t}{a}$$

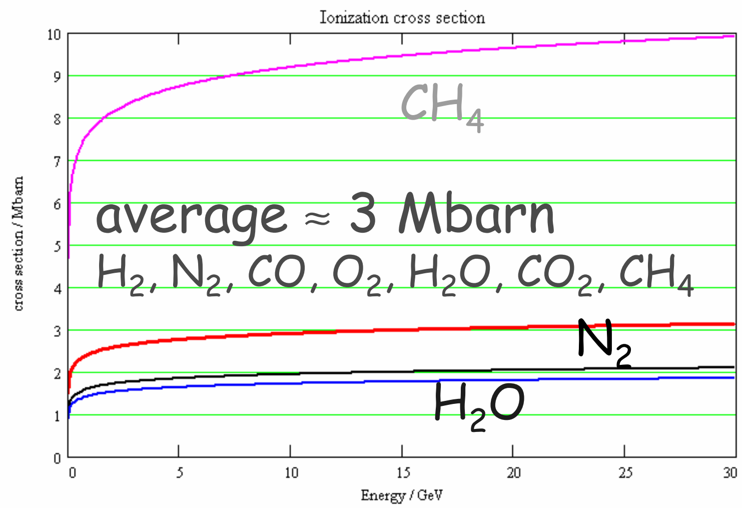
Parameter	KEKB LER	APS Studies	PETRA II	TESLA DR Arc
Bunch population/ 10^10	3.1	**4.6**	**5**	**2**
Bunch spacing /ns	**8**	20	96	**20**
Chamber	Cu	Al	Al	Al
a / mm	47	21	28	18
Energy after kick / eV	**20**	**78**	**60**	**33**
Limit Al/ 10^10	6.4	2.8	3.8	2.4
Limit Cu/ 10^10	9.5	4.2	5.6	3.6
Δt > / ns Al	30	14	18	12
Δt > / ns Cu	21	10	13	8

Limit calculated for true SEY<1

Electrons from Gas Ionization

cross section for gas ionization
(A. Poncet in CAS, CERN 99-05)

$$\sigma(a,b) = 4\pi\left(\frac{\hbar}{m_0 c}\right)^2 \left[a\left(\frac{\gamma^2}{\gamma^2-1}\ln(\gamma^2-1)\right)+b\,\frac{\gamma^2}{\gamma^2-1}\right]$$



TESLA DR	Arc	**Straight**	Wiggler
Energy /GeV	5	5	5
Circumference /m	2460	**14000**	540
Bending Radius /m	83		
Bunch population /1.0E10	2	2	2
Bunch spacing / ns	20	20	20
Chamber	Al	Al	Al
a / mm	18	48	9
b /mm	22	48	16

Arc: e- from photons $\frac{dN_{e^-(photo)}}{ds} = N\,Y\,\frac{dN_\gamma}{ds}$
$2.48 \cdot 10^9$/m/bunch
long straight section:
e- from ionization
145 /m/bunch $\frac{dN_{e^-(ion)}}{ds} = N\,\sigma(a,b)\,\frac{p}{k_B T}$
(design pressure: $1 \cdot 10^{-9}$ mbar)

primary e- arc/ e- straigth = $3 \cdot 10^6$ (14 km / 2.46 km = 5.7)
but there are secondary e- => total cloud density may determined by the neutralization condition

$$\rho_{cloud} = \frac{N}{\pi\, a\, b\, \Delta t\, c}$$

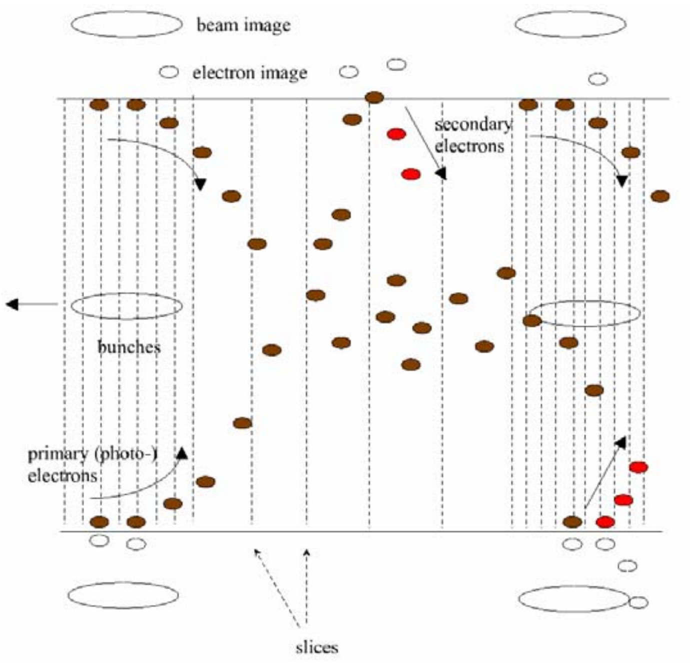
Simulation codes

•Electron build-up codes

- •LBL, M. Furman (POINST)
- •CERN, F. Zimmermann (ECLOUD)
- •KEK, K. Ohmi (PEI),
- •...

•Instability codes

- •CERN, G. Rumolo (HEADTAIL)
- •KEK, K. Ohmi
- •SLAC/LBL, Y. Cai,
- •...



simulation: (1 m of chamber)
•macro electrons
•periodic boundary conditions in z
•external magnetic fields
•space charge fields
•image charges
•secondary emission

Benchmarks of codes (POINST)

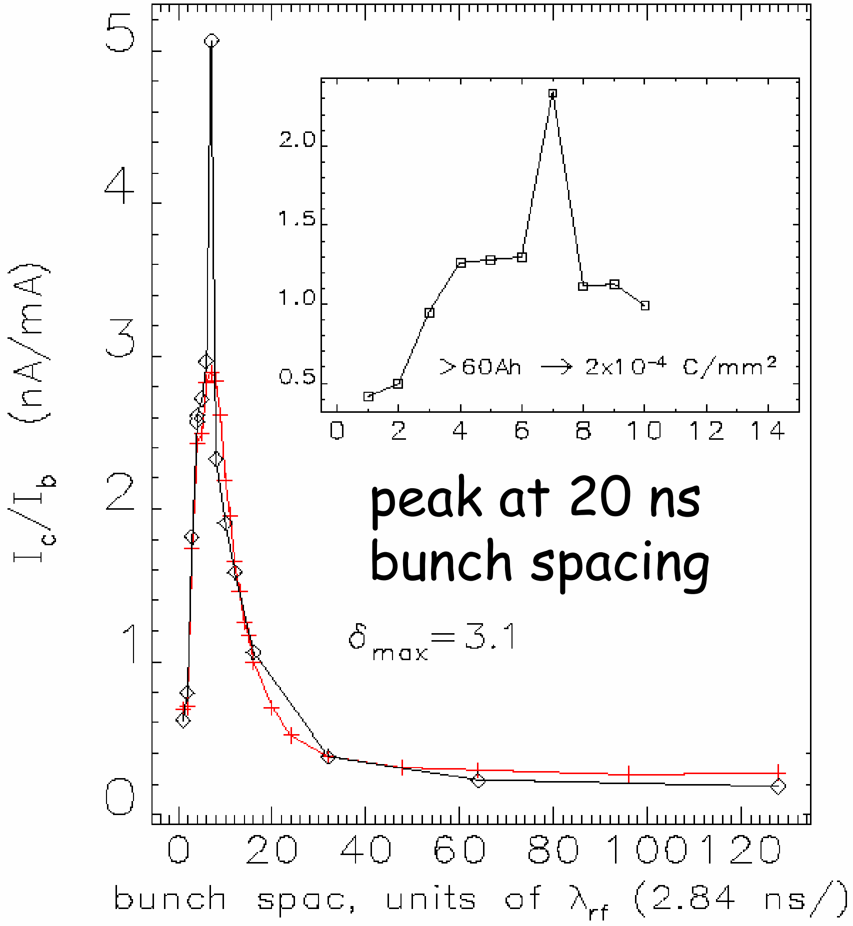
Simulation for APS:
(from K.Harkay's talk)
Comparison:
Measured and simulated current at the RFA

Parameters:

Circumference	1104	m
Harmonic no.	1296	
Rf frequency	351.93	MHz
Bunch population	4.6×10^{10}	(2 mA)
rms bunch length	5	mm
Transverse rms sizes	300, 50	µm
Vacuum chamber semiaxes	4.25, 2.1	cm
Antechamber slot height	1	cm
Eff. photoelectron yield	0.1	
No. of photons per e+	0.07	
SE params: δ_{max}; E_{max}	3.3; 280	eV
Number of kicks over bunch	5	

Electron Detector Current:

10 e+ bunches; 2 mA/bunch (4.6×10^{10} e+/bunch); vary bunch spacing



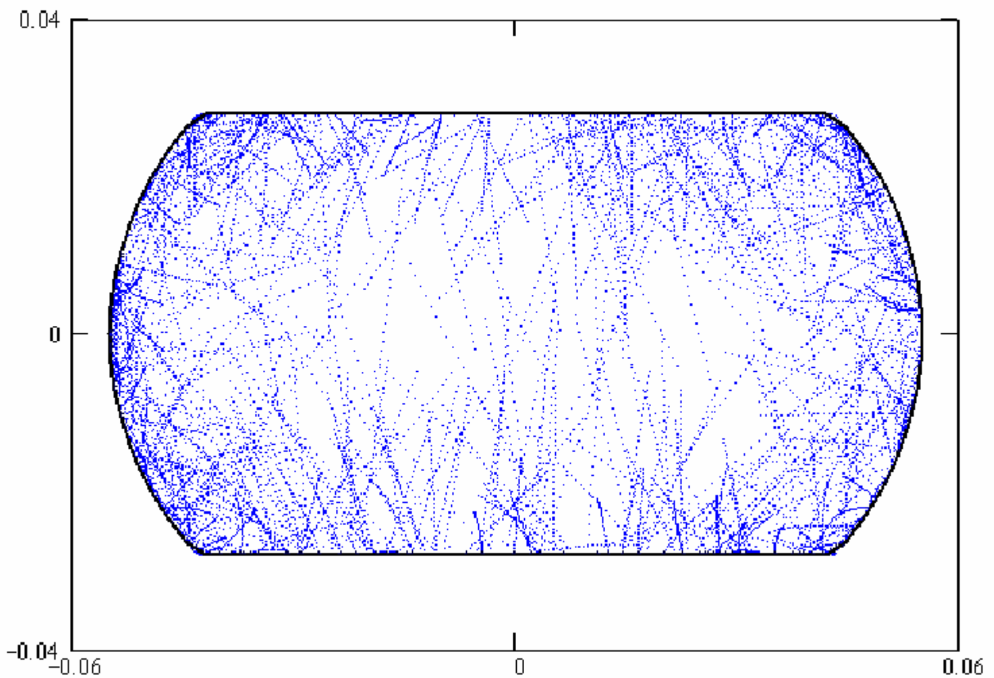
position of peak in modeled I_c/I_b vs bunch spacing (red) ***very sensitive*** to secondary electron energy spectrum, especially mean energy

Note: User operation with e+ beam typically at 1 λ_{rf} or 54 λ_{rf} bunch spacing; never observed BIM until dedicated EC study

Simulation of PETRA III

	PETRA III a	PETRA III b
Energy (GeV)	6	
Bending radius (m)	191.729	
Circumference (m)	2304	
Total current (mA)	200	200
Bunch charge (10^10)	**0.5**	**24**
Number of bunches	1920	40
Bunch separation (m)	1.2	57.6
(ns)	**4**	**192**
Emittance (nmrad) Hor. /Vert.	1 / 0.01	

Simulation with ECLOUD:
PETRA field free region



Simulation of PETRA II/III (cont.)

Reference:
Petra II: typical fill for HERA
Petra II 10 ns: study

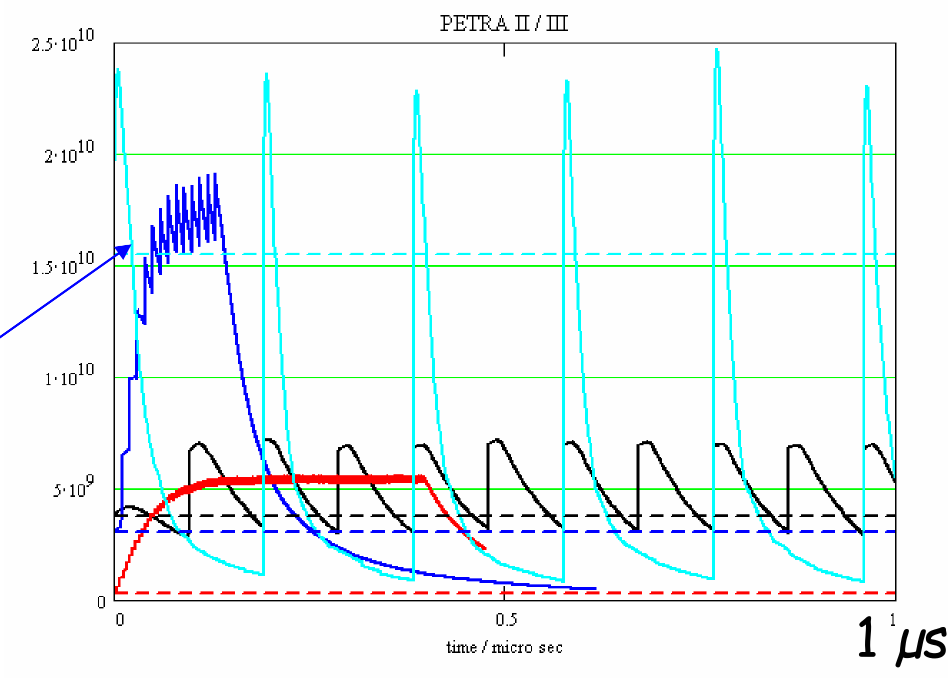
Petra III a: 1920 bunches, $0.5 \bullet 10^{10}$
Petra III b: 40 bunches, $24.0 \bullet 10^{10}$

simulation with S.E.Y for Cu

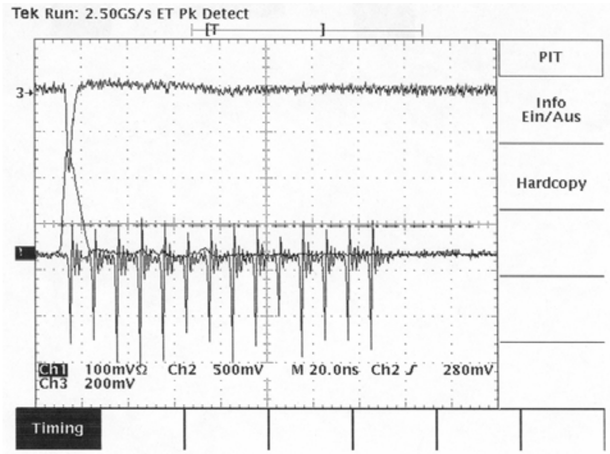
	PETRA II	PETRA II 10ns	PETRA III a	PETRA III b
Energy (GeV)	7		6	
Bending radius (m)	191.729		191.729	
Circumference (m)	2304		2304	
Total current (mA)	44	12	200	200
Bunch charge (10^10)	**5**	**4.1**	**0.5**	**24**
Number of bunches	42	14	1920	40
Bunch separation (m)	28.78	3	1.2	57.6
(ns)	**96**	**10**	**4**	**192**
Photoelectron emission yield (1/m)	0.075	0.075	0.065	0.065
Simulation with				
Secondary emission yield (Cu)	1.4		1.4	
maximum SEY at Energy (eV)	240		240	
Emittance (nmrad) Hor. /Vert.	23 / 0.3		1 / 0.01	
Chamber width (mm)	110		80	
Chamber hight (mm)	56		40	

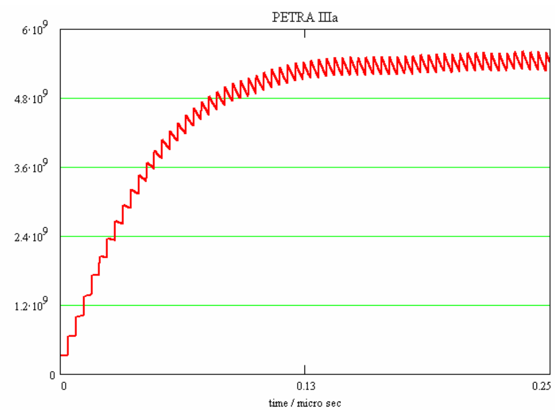
Simulation of PETRA II/III (cont.)

Total population of the electron cloud / meter versus time:
ECLOUD 2.2.1 results



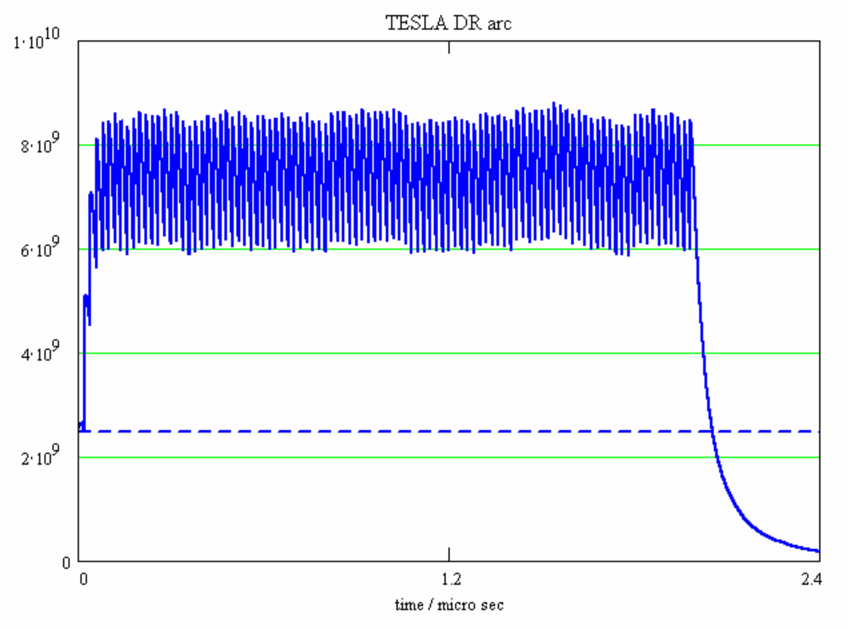
PETRA 4.2.03: 12 mA
14 bunches, Δt = 10 ns



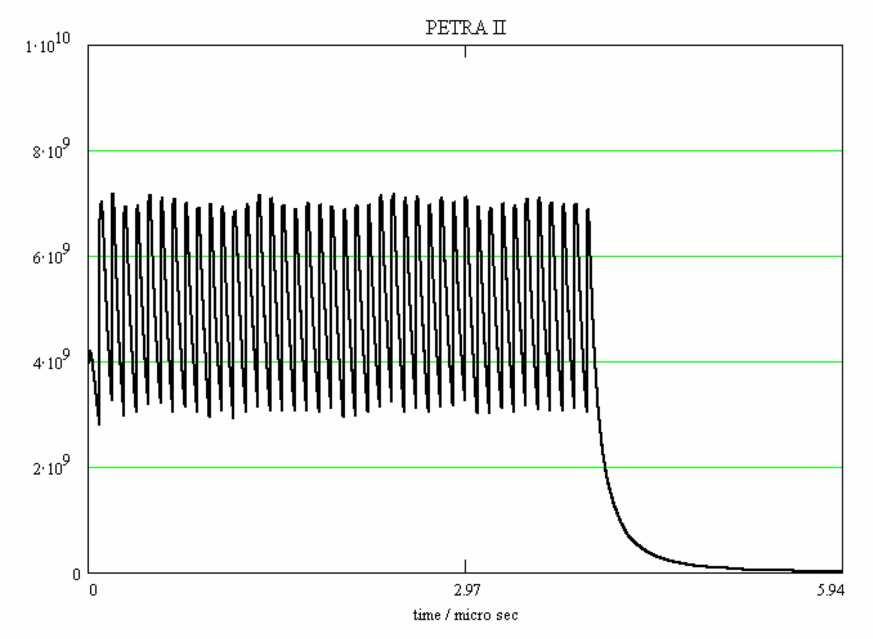


Simulation of the TESLA DR (arc)

TESLA Damping Ring:
simulation with 100 bunches,
Δt=20 ns



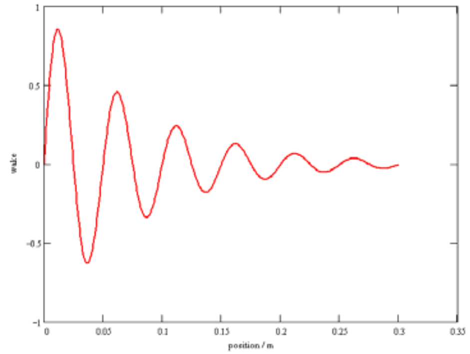
PETRA as injector for HERA:
simulation with 42 bunches,
Δt=96 ns



Further studies are required to calculate an effective ecloud impedance from the cloud density in the center of the chamber.

Instabilities/ Broad Band Resonator Model

Broad Band Resonator Model
(Ohmi, Zimmermann, Perevedentsev
CERN-SL-2002-011 AP)



$$W_1(s) = \hat{W}_1 \ \sin(\omega_c \tfrac{s}{c}) \ \exp(-\tfrac{1}{2Q_r} \omega_c \tfrac{s}{c})$$

Assumptions
- density of the cloud based on the neutralization condition $\rho_{cloud} = \dfrac{N}{\pi \, a \ b \ \Delta t \, c}$
- distribution of the cloud Gaussian with width equal to the that of the beam

$$\lambda_{cloud} = 2\pi \ \sigma_x \sigma_y \ \rho_{cloud}$$

	Incoherent Tune Shift	Single Bunch Threshold /Nominal	Coupled Bunch Growth Time /μs
NLC MDR	0.019	0.8	20
NLC PDR	0.003	10	370
TESLA	0.06	2.6	170
KEK-B	0.02	3	180
PEP-II	0.16	0.6	16
DAΦNE	0.007	6	20
HERA-e	0.006	20	1750

(A. Wolski, Proc. ECLOUD'02, CERN-2002-001)

PETRA III Single bunch threshold/nominal
(K. Balewski) ~7.6

Conclusion

- Ecloud effects are observed at B-factories
  At PEP-II an beam blow up occurs in the horz. plane
  not in the vert. plane as simulated

- Ecloud detectors have been successfully used at various Laboratories

- SEY has been measured at CERN in great detail for Cu and other technical materials

- Several codes have been developed to simulated the cloud build-up
  There exist some benchmarks against experiments. The results a sensitive with respect to the SEY (yield **and** energy distribution).

Conclusion (cont.)

- The Computer code ECLOUD 2.2.1 has been applied to PETRA and theTESLA DR arc. Further investigations are needed (SEY, Al chamber).

- The electron cloud build-up seems to be moderate for PETRA III and the TESLA DR but further simulations are needed

- Experimental Ecloud studies with the present PETRA ring are possible (with a bunch spacing of about 10 ns)

But this requires the

- installation of an RFA in PETRA (**R**etarding **F**ield **A**nalyzer)