Vacuum in Accelerators 16-24 May 2006, Platja d'Aro, Spain

# Beam vacuum interactions II

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# Specific ionisation of the residual gas

Ionisation of the residual gas by the high energy beam

$\sigma_p$ is the ionisation cross section

$$I_p = \sigma_p \frac{P_{gas}}{kT} I_{beam}$$

Ionisation cross-sections for high energy particles in units of $10^{-18}$ cm$^2$

| Gas | 26 GeV | 7 TeV |
|---|---|---|
| $H_2$ | 0.22 | 0.37 |
| He | 0.23 | 0.38 |
| $CH_4$ | 1.2 | 2.1 |
| CO | 1.0 | 1.8 |
| A | 1.1 | 2.0 |
| $CO_2$ | 1.6 | 2.8 |

e.g. LHC arc: $I_p$~ 20 nA/m at nominal current and density ($10^{15}$ $H_2/m^3$)

# Power loss by nuclear scattering

Particles lost by nuclear scattering along the arcs of a machine can not be collimated and their losses occur uniformly distributed around the arcs

$$P(w/m) = \frac{1}{c}\frac{IE}{\tau} = 0.93\frac{I(A)E(TeV)}{\tau(h)}$$

LHC design requires a nuclear-scattering life time of ~ 100h

LHC -> 0.1 W/m for two beams at ultimate current required gas density equivalent to $10^{15}$ $H_2/m^3$

Each W at 1.9 K ~ 500 W at RT (Ph.L. lecture)

# Space charge potential of the beam

Line density (particles/m), total current $I$

$$\lambda = \frac{I}{e\beta c}$$

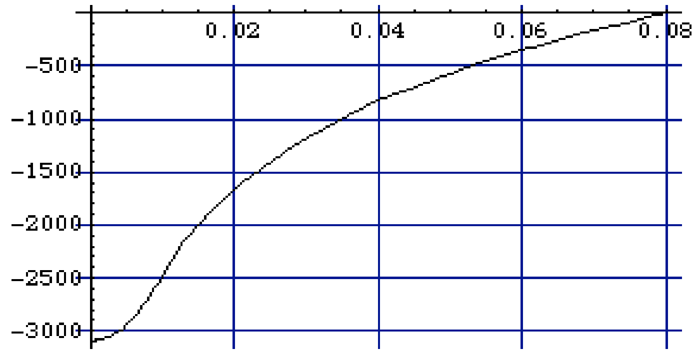
$$\varepsilon(r) = \frac{e\lambda}{2\pi\varepsilon_0}\frac{r}{a^2} \qquad r \le a$$

$$\varepsilon(r) = \frac{e\lambda}{2\pi\varepsilon_0}\frac{1}{r} \qquad r \ge a$$

Circular, concentric geometry, beam with uniform charge and radius $a$ .
Electric field follows from Gauss law

Integrating the field gives the potential in the centre of the beam

$$V_b = \frac{e\lambda}{2\pi\varepsilon_0}\left[\frac{1}{2} + \ln\left(\frac{r_p}{a}\right)\right]$$




ISR: I = 20 A, $r_p$ = 0.08 m
a = 0.01 m
Electrons remain trapped in the potential well

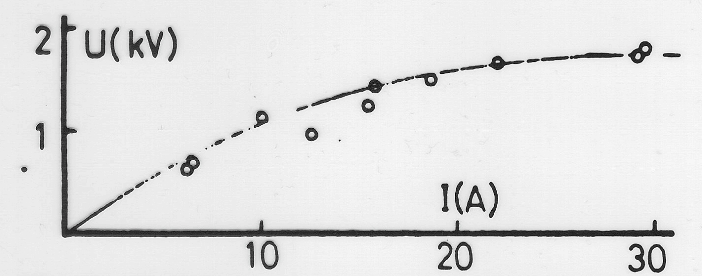



Fig. 5 Beam Potential versus Stacked Current as Determined from the Clearing Electrode Potential at Saturated Electron Current.

# Record book: the largest ionisation gauge

Ionising beam current 10 - 60 A
Gauge length 2 x 1km
Current resolution 20 pA
1-300 collectors & true <P> seen by beam

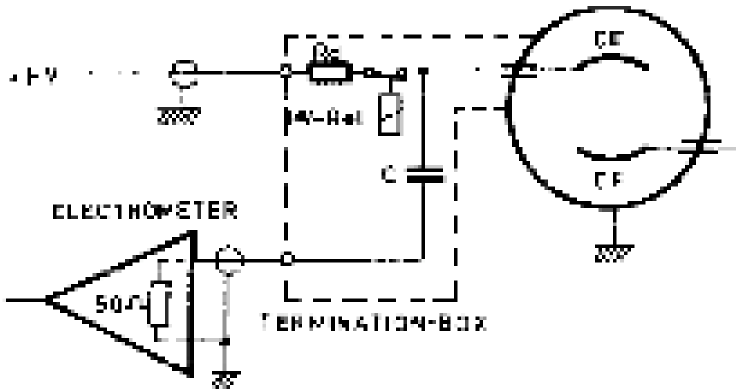



Fig. 1 Principle of Current Measurement on a Clearing Electrode.

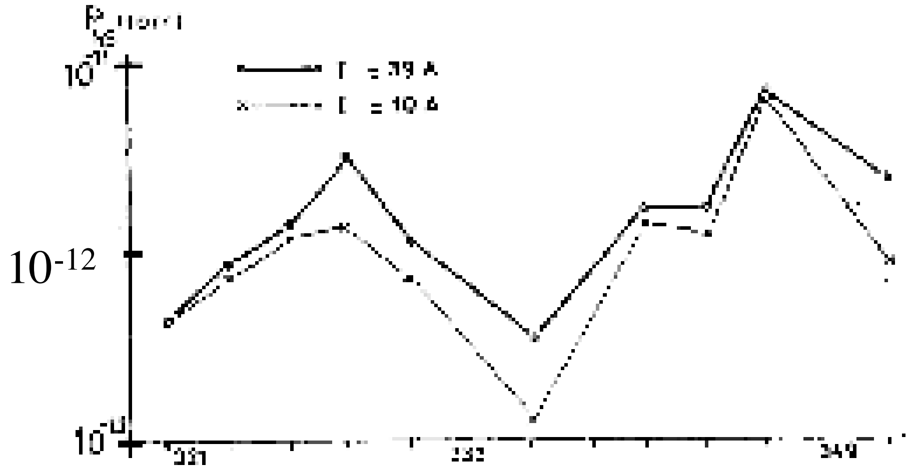



Fig. 4 Pressure Profiles in ISR Sector 51 Measured at Beam Intensities of 10 A and 39 A and Showing Local Beam Induced Pressure Rises.

The integrated pressure around the whole machine requires a **single** electrode only

!! LHC has a **bunched** beam therefore this system can not be used.

Further reading: ISR clearing current monitoring system, O. Grobner, P. Strubin, PAC1977_1376

# Beam space charge neutralisation

Trapped charges neutralise the beam space charge and cause a tune shift and beam instabilities

The neutralisation factor is defined as $$\eta = \frac{n_i}{N_b} \leq 1$$

$N_b$ is the number of beam particles

$n_i$ is the neutralising charge, i.e. electrons trapped in a proton beam, or positive ions trapped in an electron or antiproton beam.

Production rate ($s^{-1}$ $m^{-1}$) depends on gas density $$R_p = \beta c n_g \sigma_i$$

Equilibrium neutralisation $$\eta_{equ} = \frac{R_p}{R_c}$$ prop. to pressure!

The clearing rate $R_c$ depends on the specific mechanism

# Space charge neutralisation tune shift

Space charge due to neutralisation changes the focussing

$$\vec{F} = \vec{F}_e\left(\frac{1}{\gamma^2} - \eta\right)$$

$$\frac{\vec{E}_x}{dx} = \frac{I_b}{2\pi\varepsilon_0\beta c}\frac{1}{a^2}$$

$$d_i = \frac{1}{2\pi R}\frac{N_b}{\pi a^2}\eta$$

$$\boxed{\Delta Q = \frac{1}{4\pi}\int \beta(s)k(s)ds}$$

$$k(s) = \frac{e}{\gamma m_0 c^2}\frac{d\vec{E}}{dx}$$

$$\Delta Q = -r_0 R\langle\beta_x\rangle\frac{I_b}{e\beta c}\frac{1}{a^2}\frac{\eta}{\gamma} = r_0\frac{R}{Q_x}\frac{N_b}{2\pi a^2}\frac{\eta}{\gamma}$$

For most accelerators a few $10^{-3}$ neutralisation are harmful

For ISR-> $\Delta Q \sim 20\dfrac{\eta}{\gamma}$

# Ion stability in a bunched beam

Positive ions can be trapped in a bunched electron beam-> successive bunches give kicks to the ions

$$\begin{pmatrix} y \\ \dot{y} \end{pmatrix}_{after} = M \begin{pmatrix} y \\ \dot{y} \end{pmatrix}_{before}$$

$\alpha$ attractive kick given by a bunch, n number of bunches, T revolution time

$$M = \begin{pmatrix} 1 & t \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \alpha & 1 \end{pmatrix}$$

Drift * Kick

$$\alpha = \frac{4cr_0}{b(a+b)} \frac{1}{A} \frac{N_b}{n} = \frac{2cr_0}{a^2} \frac{1}{A} \frac{N_b}{n}$$

The ion motion is stable if

$$-2 < Tr(M) < 2$$

Ions with masses larger than a critical mass $A_c$ accumulate

$$-1 < (1 - \alpha \frac{T}{2n}) < 1 \quad \Rightarrow \alpha_c = \frac{4n}{T}$$

LHC: $A_c$ ~10 -> electrons are ejected

LEP: 4 intense e- bunches $A_c$ > 200

$e^-$ rings all require a 'clearing gap'

$$A_c = \frac{cr_0}{2a^2} \frac{N_b}{n} \frac{T}{n} = \pi r_0 \frac{RN_b}{a^2 n^2}$$

# Proton-electron instability

Electrons oscillate in the potential well of protons -> excite protons to oscillate: coupled oscillators

$$\ddot{z}_p + (Q^2 + Q_p^2)\omega^2 z_p = Q_p^2 \omega^2 \bar{z}_e$$

$$\ddot{z}_e + Q_e^2 \omega^2 z_e = Q_e^2 \omega^2 \bar{z}_p^2$$

Bounce frequencies:

$$Q_e^2 \omega^2 = \frac{N_p r_e c^2}{\pi R a^2} \qquad Q_p^2 \omega^2 = \frac{r_p c^2 N_e}{\gamma \pi R a^2}$$

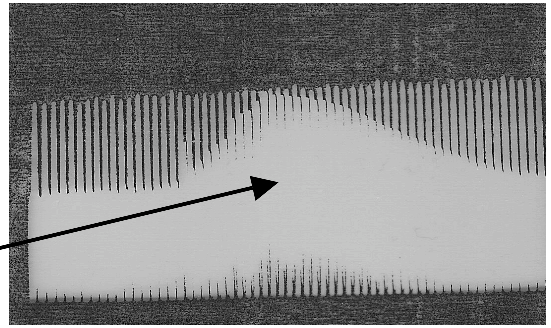
Stability limit for protons a few % neutralisation

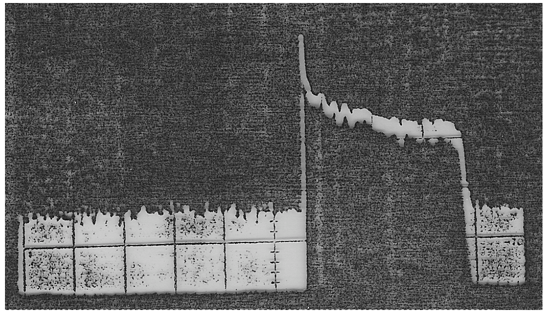
$$Q_p = \frac{(n - Q_e)^2 - Q^2}{2\sqrt{Q_e (n - Q_e)}}$$

e-p oscillations observed in the ISR and in many accelerators: ~ 80 MHz -> beam size increases!

Spectral lines -> harmonics of the revolution frequency.

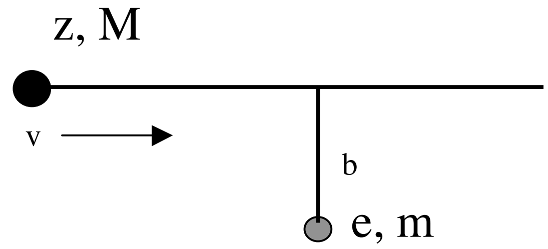
With bad vacuum electron oscillations cover a wide frequency range





Single instability ~20 ms

# Coulomb heating of trapped electrons




Multiple collisions with the beam -> beam heating

Momentum transfer depends on the velocity and the charge, not on the mass of the beam particle

$$\Delta p(b) = \int_{-\infty}^{+\infty} eE(t)dt = \frac{2mc}{\beta}\frac{r_e}{b}$$

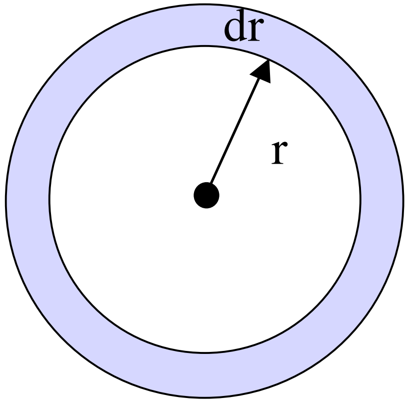
Physical limits on b: maximum allowed energy transfer and the condition that the electron can be considered stationary.

$$\Delta E(b) = \frac{(\Delta p)^2}{2m} = \frac{2mc^2}{\beta^2}\frac{r_e^2}{b^2}$$

Energy transfer is inversely proportional to the mass of the particle -> for ions heating is very inefficient

$$\Delta E_{\max} \Rightarrow b_{\min} = \frac{r_e^2}{\beta^2\gamma}$$

# Electron heating by multiple scattering (ISR)




Beam section

$$I_b = eN_b \frac{c}{2\pi R}$$

$$\Delta E(b) = \frac{2mc^2}{\beta^2} \frac{r_e^2}{b^2}$$

$$\rho = \frac{N_b}{2\pi R \pi a^2}$$

$$\frac{d^2 N_b(r)}{dt} = \frac{N_b}{2\pi R \pi a^2} \beta c \, 2\pi r dr$$

$$\frac{d^2 E(r)}{dt} = \frac{2r_e^2 mc^2}{\beta} \frac{cN_b}{R\pi a^2} \frac{dr}{r}$$

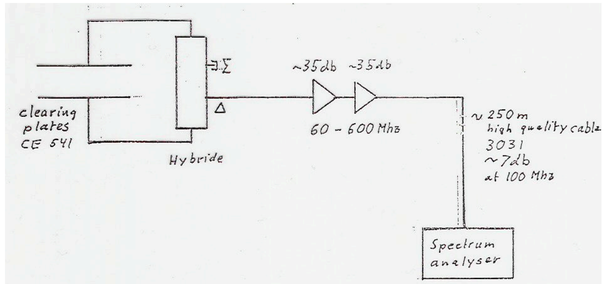
$$b_{\min} = \frac{r_e}{\beta^2 \gamma}$$

$$\frac{dE}{dt} = \frac{4r_e^2 mc^2 I_b}{ea^2} \ln\left(\frac{r_{\max}}{r_{\min}}\right)$$

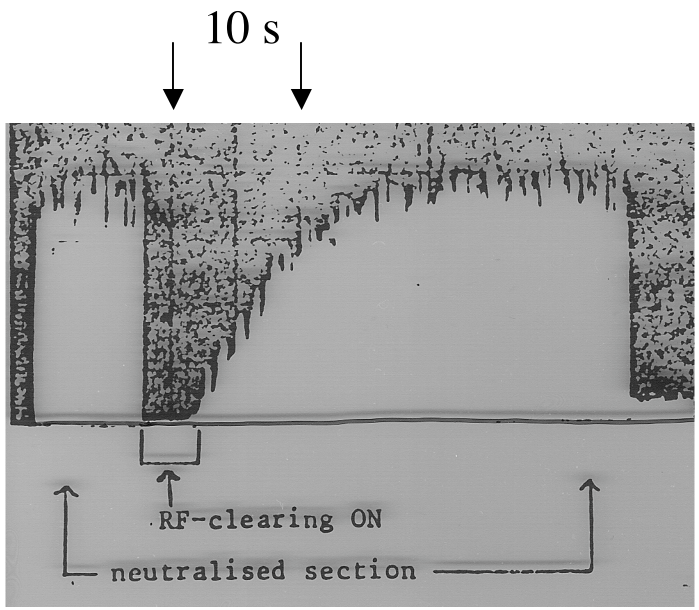
Numerical example ISR:
I = 20 A, R= 150 m, a = 0.01 m
$R_{max}$ = vacuum chamber = 0.04m
γ= 28. beam potential ~ 2kV
Heating rate ~ 680 eV/s
Clearing rate ~0.3/s

# Electron clearing by a bunched beam

Electrons have 1/2000 the mass of a proton -> are not trapped in a bunched proton and positron beam




ISR: e-cloud build-up in a section with bad vacuum and without electrostatic clearing electrodes.



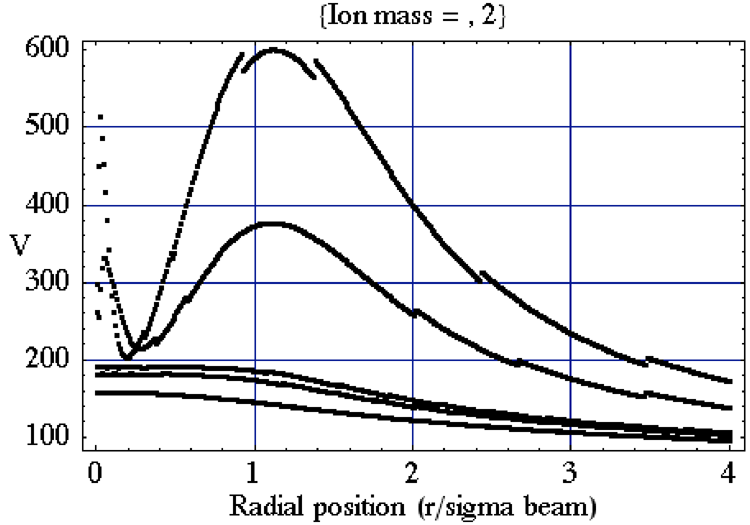

Bunching the ISR beam clears electrons

# Ion impact energy

Ions are repelled by the positive space charge and hit the wall with a significant energy -> several keV

Ion energy in LHC

M = 2, 4, 28, 44, 500




Bunched beams: heavy ions integrate the passage of many bunches and see an average field.
Light ions gain a more energy, since they see the peak field.
Final energy depends on the initial position in the beam

# Density increase by ions

Ions trapped in the beam contribute to the gas density

$$d_g = \frac{P_g}{kT}$$

The ion density for a given degree of neutralisation will add to the neutral gas density

$$d_i = \eta d_b$$

The beam density and the residual gas densities add up to give

$$d_b = \frac{I_b}{e} \frac{1}{\beta c a^2 \pi}$$

$$d_{total} = \eta \frac{I_b}{e} \frac{1}{\beta c a^2 \pi} + \frac{P_g}{kT}$$

$e^-$ ring: $I_b$= 1A
a = 0.002m
$P_g$ = $10^{-7}$ Pa

$d_b \sim 1.6\ 10^{15}\ m^{-3}$
$d_g \sim 2.4\ 10^{13}\ m^{-3}$

few% neutralisation will be a dominating contribution

# Dust particle trapping

Trapping of 'macroscopic' (<$10^{-6}$ m size) dust particles has caused problems in several machines with negative beams: Antiproton accumulator, $e^-$ ring in HERA and Super-ACO

Dust charges positively due to loss of electrons ~$10^6$ charges

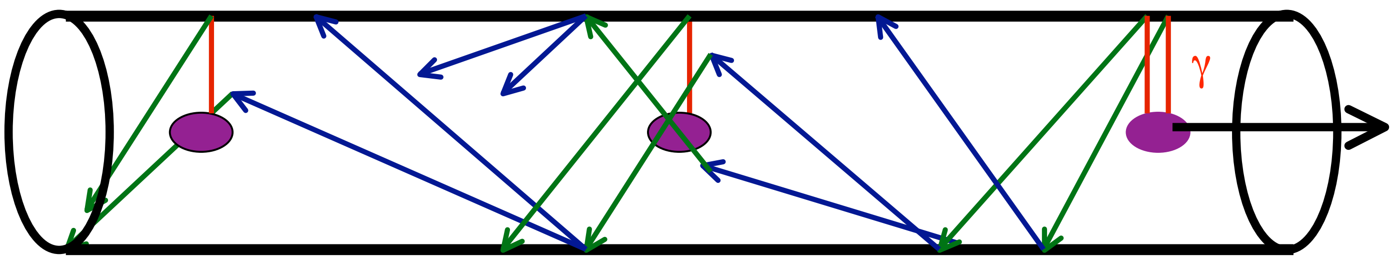
Dust can remain trapped in the intense beam and cause lifetime degradation

Remedies are fast beam shaking to eject the 'slow' dust from the potential well

Origin of dust is not clear but evidence points to integrated sputter ions pumps in HERA $e^-$ ring and to ion pumps mounted above the beam in LEP

HERA dust problem solved by replacing IP's with linear NEG pumps.

# Electron cloud




## Key parameters

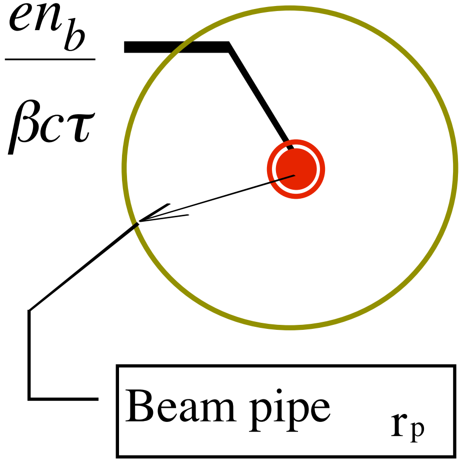
Synchrotron radiation
Y(E,ϕ) photoelectric yield
δ(E,ϕ) second. electron Y
Second. electron energy
residual gas ionization

Photon reflectivity
Beam pipe shape
Bunch intensity and spacing
External fields (magnetic, electric, space charge)

# Electron cloud multipacting

The electric field of a bunch with the line density $\lambda$ *and* $\beta$~1

$$E(r) = \frac{\lambda}{2\pi\varepsilon_0 r} \qquad \lambda = \frac{en_b}{\beta c\tau}$$




Momentum transfer by the bunch is independent on the bunch length $\tau$

$$\Delta p = eE\tau = \frac{e^2 n_b}{2\pi\varepsilon_0 cr}$$

Velocity gained by an electron

$$\Delta v = \frac{\Delta p}{m} = 2cr_e \frac{n_b}{r}$$

Condition for wall-to-wall multipacting

$$\frac{2r_p}{v} = t_{bb}$$

With $L_{bb} = ct_{bb}$ particles per bunch

$$n_b = \frac{r_p^2}{r_e L_{bb}}$$

>> can occur also in a beam transfer line with a single pass

# Gaussian beam

Gaussian density distribution

$$E(r) = const \, \frac{1 - e^{-\left( r / r_b \right)^2}}{r}$$

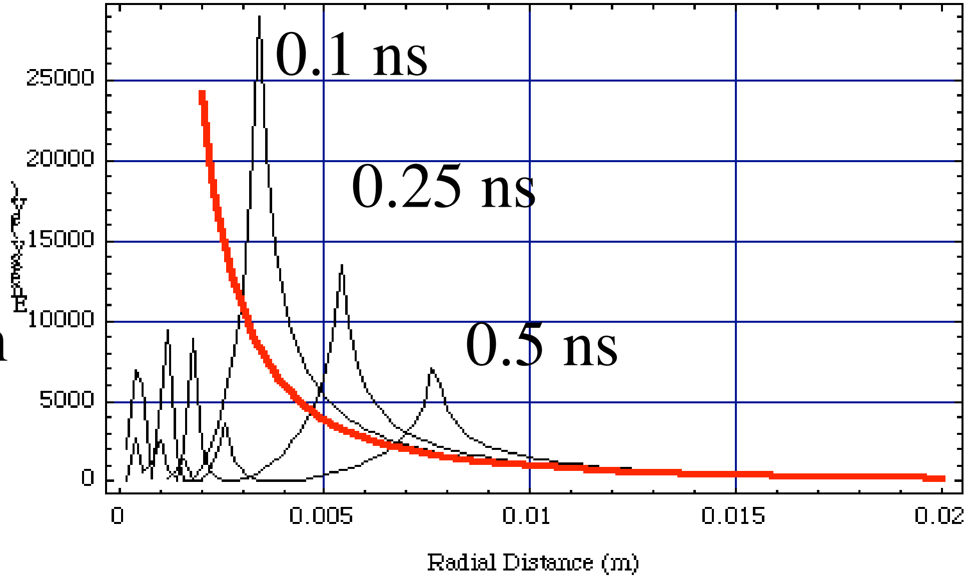
Electrons move during the kick of a bunch

$$m \ddot{r} = e E(r)$$

Integrating the equation of motion gives *r(t)*, the velocity and energy

$$\Delta W = \frac{m \ \dot{r}(\tau)^2}{2} = \frac{2mc^2}{e} r_e^2 \left( \frac{n_b}{r} \right)^2$$

Energy (eV) of a stationary (red) and moving electron versus the initial radial position for different bunch length

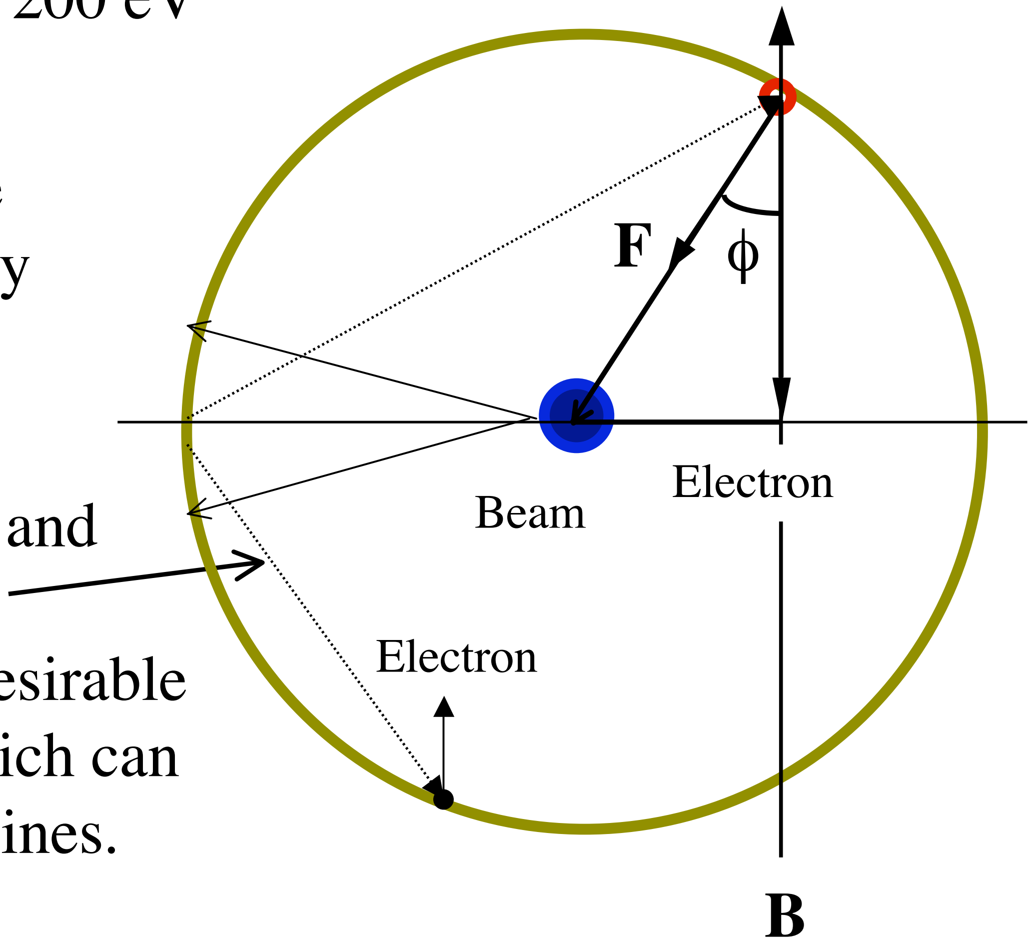


# Effect of a dipole magnetic field

Cyclotron oscillations/bunch ~120
Cyclotron radius ~ 6 μm for 200 eV
F force by the proton bunch

SR photons -> median plane
Photoelectrons suppressed by
the magnetic field.

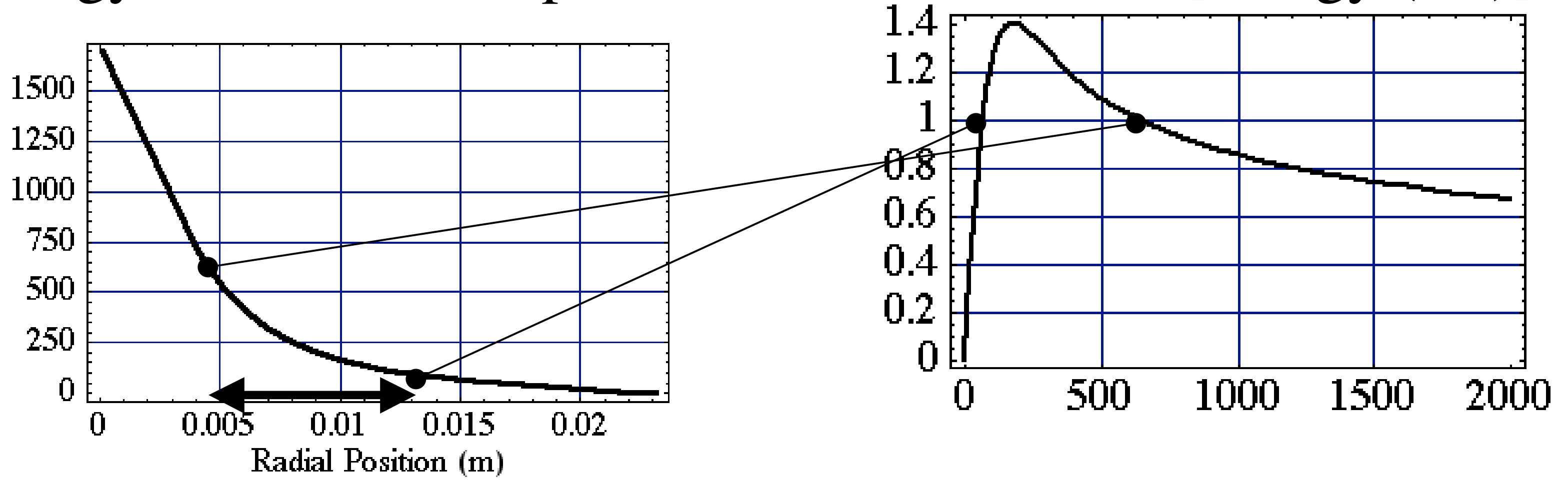
Reflected photons reach top and
bottom of the beam pipe ->
Low photon reflectivity is desirable
to reduce photoelectrons which can
move freely along the field lines.



# Electron cloud in a dipole beam screen

Energy vrs. horizontal position

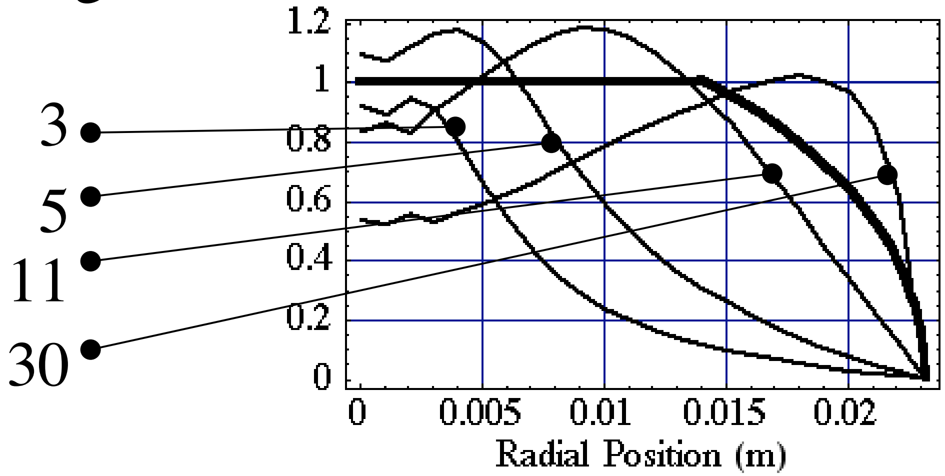
Yield [energy (eV)]



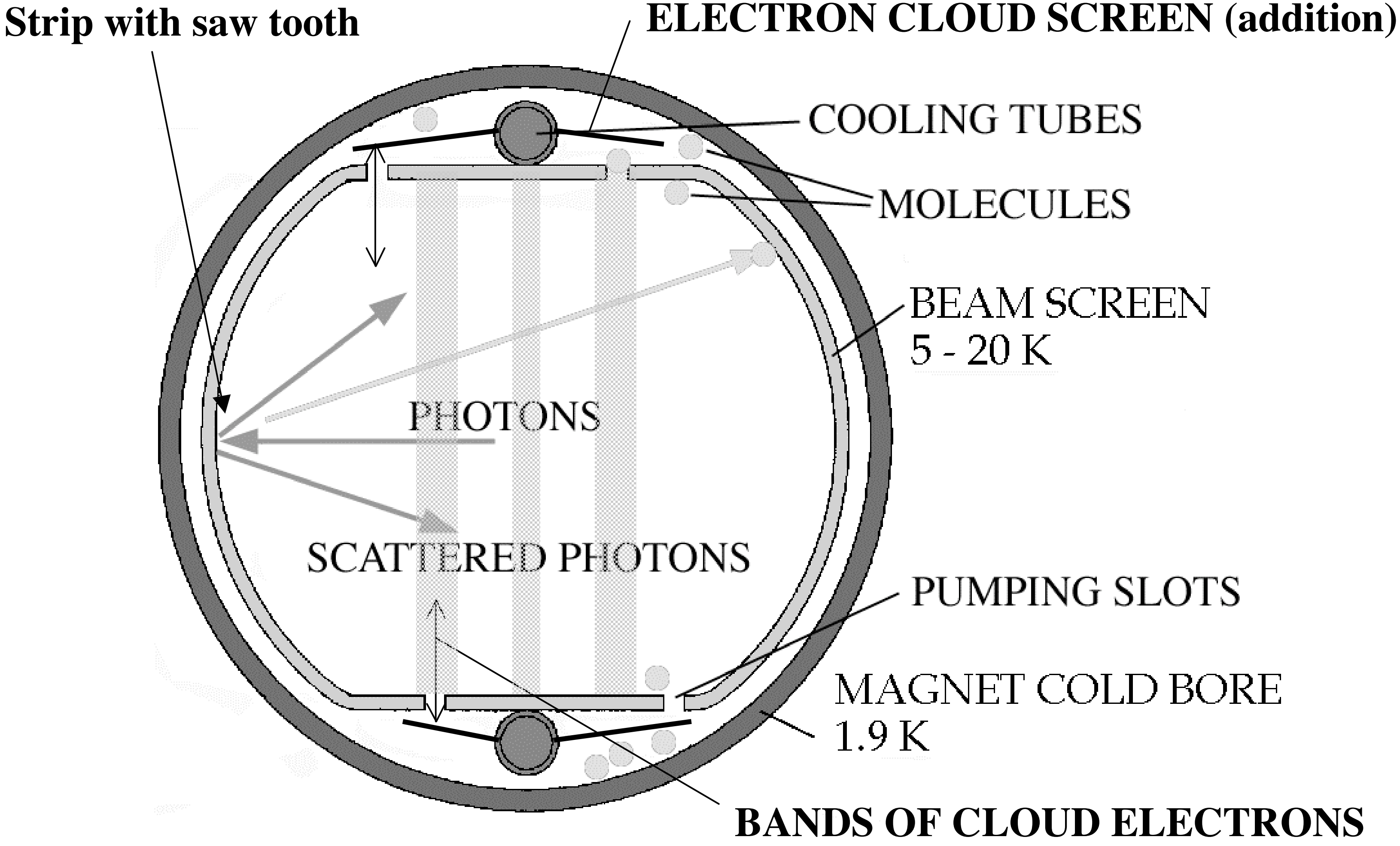

Horizontal multipacting range

Yield for different $n_b$

Bunch intensities $10^{10}$ per bunch

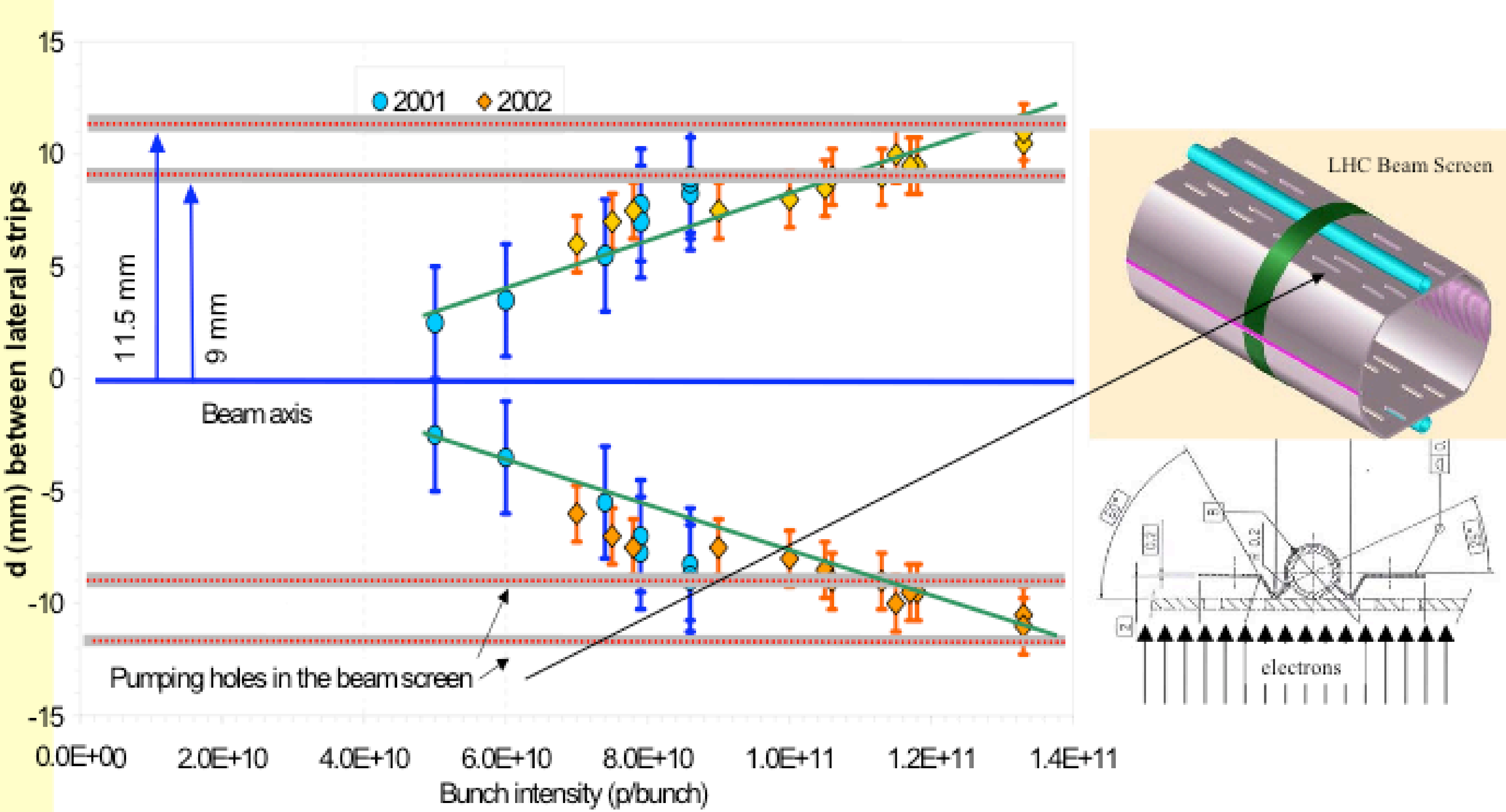


# Beam screen in an LHC dipole



# e⁻ cloud build up @ 25 ns bunch spacing

## *Spatial distribution / baffles to intercept electrons*

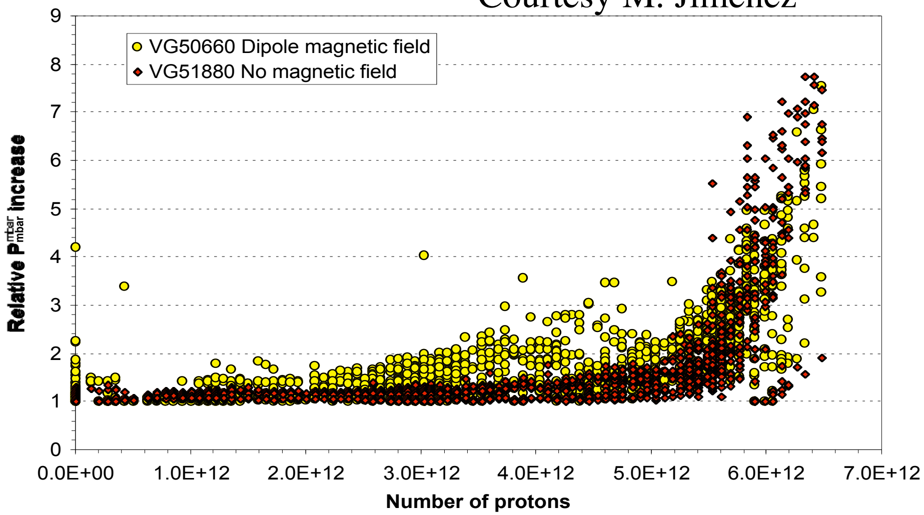


# Pressure increase due to BIM

Gas load, $Q_{cloud}$ is related to the power deposited by the electrons, $P_{cloud}$, to the molecular desorption yield, $\eta_e$ and to the average energy of the electrons in the cloud, $<E_{cloud}>$.

Courtesy M. Jimenez

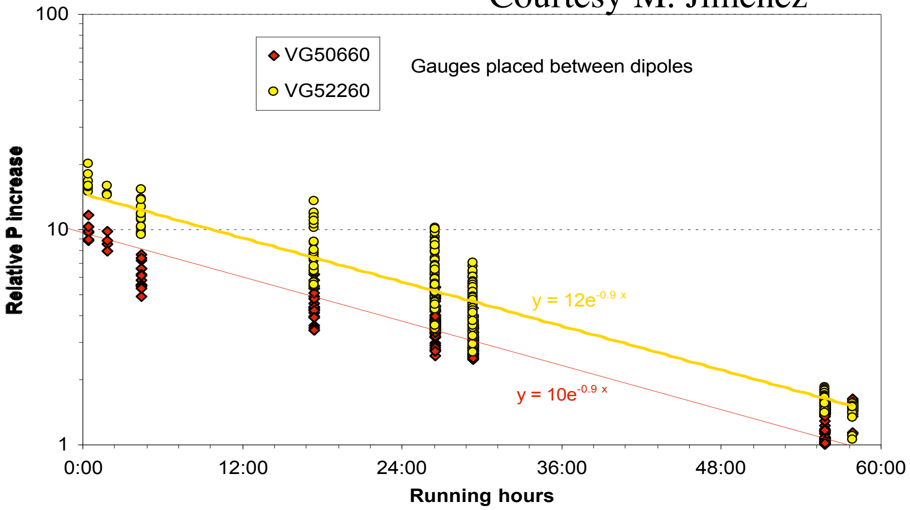
$$Q_{cloud} = k \frac{\eta_e P_{cloud}}{< E_{cloud} >}$$




LHC cooling limit: $P_{cloud}$ ~ 1 W/m -> $10^{-6}$ mbar l/s/m

# Reduction of BIM with beam dose

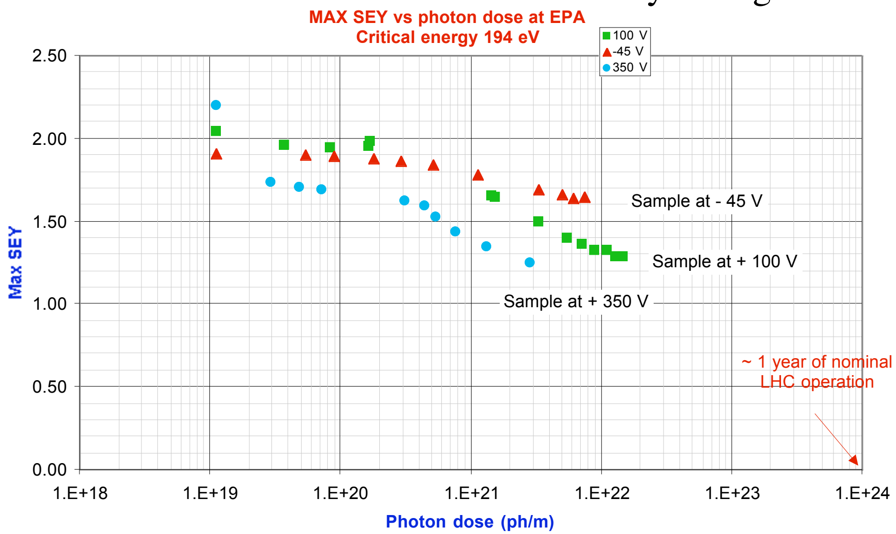
Courtesy M. Jimenez




Running hours SPS

Beam scrubbing reduces the secondary electron yield and pressure rise

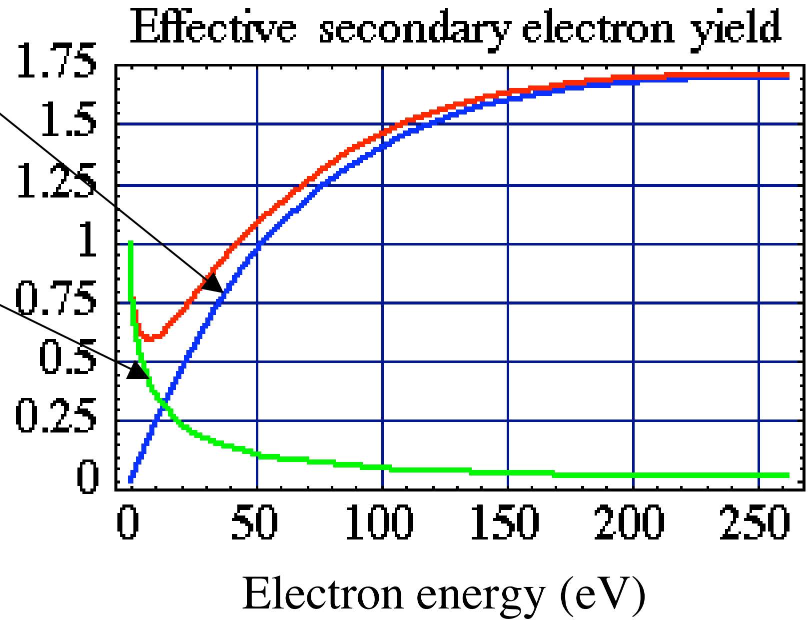
Courtesy V.Baglin




Photon dose in EPA

# Suppression of secondary electrons

True secondary electrons reflected electrons E < 50 eV are trapped by a weak solenoid field.



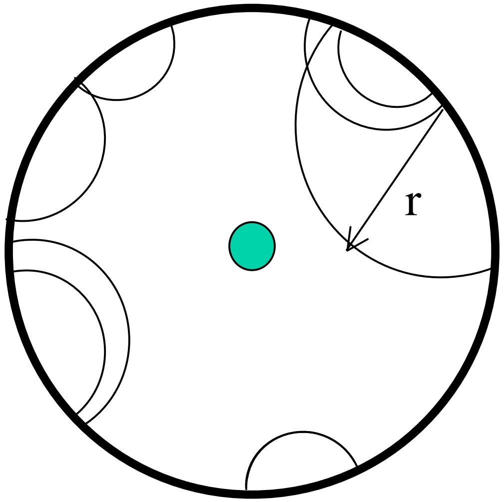

Between bunches, low energy electrons are confined close to the vacuum chamber walls by a weak external solenoid field

R. Cimino et al. Phys.Rev.Lett. 93 (2004) 014801/1-4

# Solenoid field in drift chambers

$$r = \frac{mv}{eB}$$

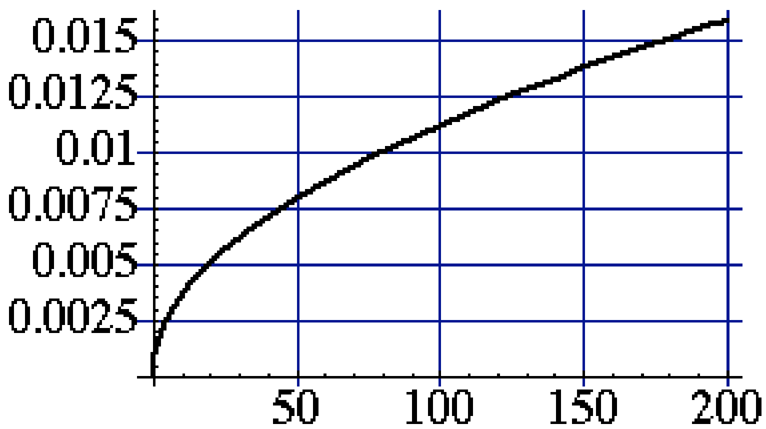
$$t_{cycl} = 2\pi \frac{m}{eB}$$




$$r(m) = \frac{\sqrt{2 \, {}^{m}\!/_{e} \, E(eV)}}{B(T)}$$

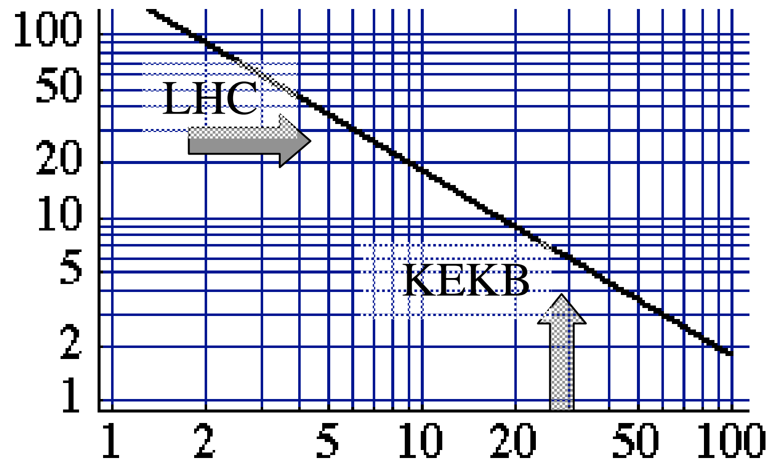
$$t_{wall-wall} \sim \frac{\pi m}{eB} < bunch\ spacing$$

Radius (m) at 30 Gauss




Energy (eV)

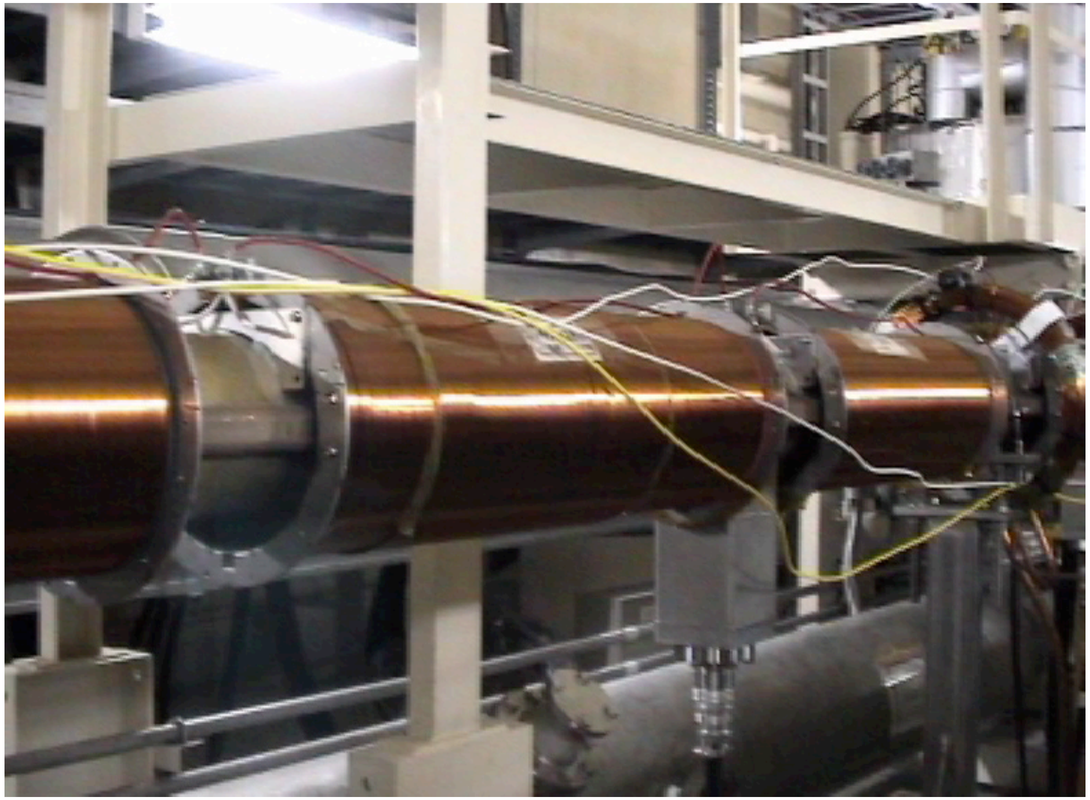
Trajectory time (ns)




Field (Gauss)

# KEKB

Drift chambers with solenoids



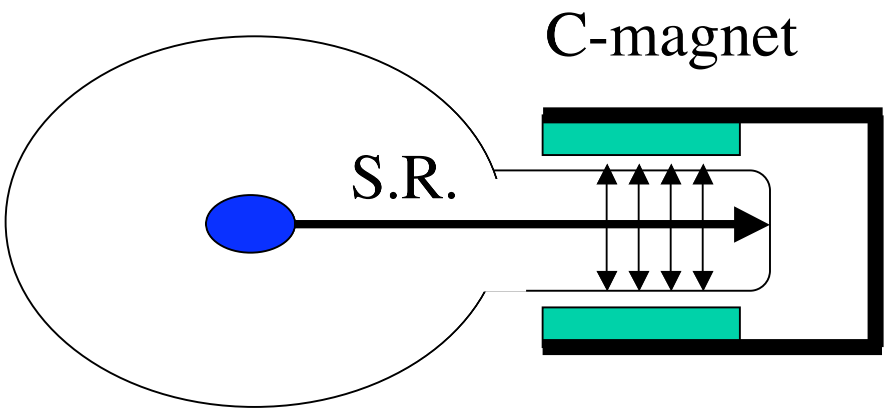
Solenoids in quadrupoles are ineffective -> would require a much higher field

# Beam pipe with antechamber

Synchrotron radiation is captured in the ante-chamber section.

C-magnet around antechamber traps photoelectrons.

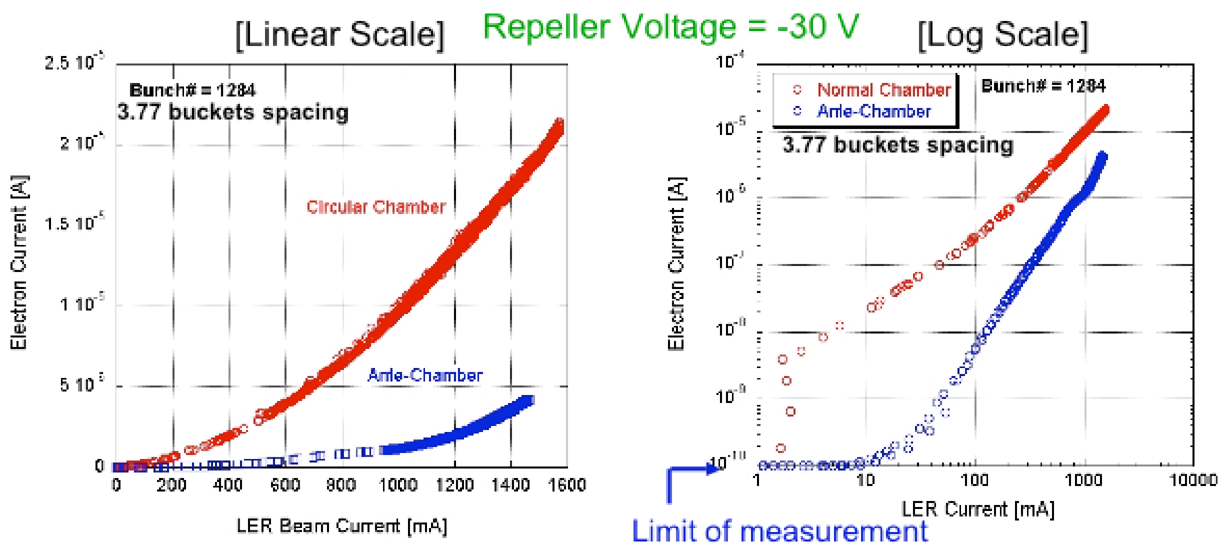
Residual gas ionisation in the beam duct remains as an electron source



# KEKB (Y. Suetsugu)

## Beam Duct with Ante-chamber _3

- Electrons in the beam channel
  - Photoelectrons decreased by factors at high current ($I_b \geq 1\,000$ mA).
  - The reduction was by orders at low current ($I_b \leq 100$mA).
  - Multipactoring seems to become important at higher current.
- Combination with solenoid field, and an inner surface with a low SEY will be required at higher current.

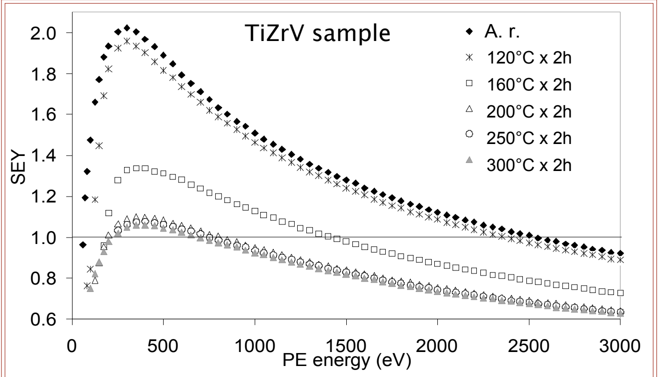



2005.02.22 KEKB Review 2005 @KEK 7

# Surface coating (A. Rossi)

## The Secondary Electron Yield of TiZr and TiZrV NEG thin film coatings

- Normal PE (Primary Electrons) angle of incidence, 60 eV to 3 keV. PE ~ $5 \cdot 10^{-9}$ A, pulsed, giving a total dose < $10^{-8}$ C/mm$^2$ [1].
- TiZr and TiZrV thin film (1μm) deposited onto chemically polished copper substrates [2].
- An important $\delta_{max}$ decrease from above 2 to <1.4 already occurs after 2h at 200°C (TiZr) and 160°C (TiZrV), i.e. below the activation temperature [2].
- $\delta_{max}$ ~ 1.1 after 2h at 250°C (TiZr) and 200°C (TiZrV) [2].




Courtesy of C. Scheuerlein

A. Rossi, presented at E-Cloud 04

Surface coatings have been applied to many vacuum systems

# Conclusions

Numerous processes exist by which the beam and the residual gas interact. The walls and surface characteristics of the vacuum system have a vital influence.

In addition to static and dynamic out-gassing properties, also generation of electrons: photo- and secondary electrons are important

Electron cloud effect with its consequences on beam dynamics has become a performance limiting effect in many accelerators

Future vacuum system designs must put emphasis on surface properties of vacuum chambers and incorporate remedies for e-cloud effects to enable very high bunch currents and short bunch spacing

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