Electron Cloud in IRs?

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Many thanks to Elias and Stephane for stimulating discussions

CERN, ICE meeting, 12-12-12

Main Factors

- E-cloud influences incoherent and coherent oscillations of beam particles in various aspects.
  - It works as a static lens, shifting up all coherent and incoherent tunes.
  - It gives a significant tune spread. With the size of the e-cloud similar to the proton beam size, the nonlinear tune spread is comparable to the tune shift. The tune spread is defocusing with the amplitude.
  - As a reactive medium, e-cloud works as a sort of low-Q impedance at the electron bounce frequency ω_e which phase advance on the bunch rms length is

$$\psi_e \cong 0.5\sqrt{N_b r_e \sigma_z / \sigma_x^2}$$

- Note that number of e-cloud pinches per p-bunch is $\sim \psi_e$. Thus, for $\psi_e \gtrsim 1$ the effective size of the electrons within the proton beam is ~2-3 times smaller than the proton bunch radius.

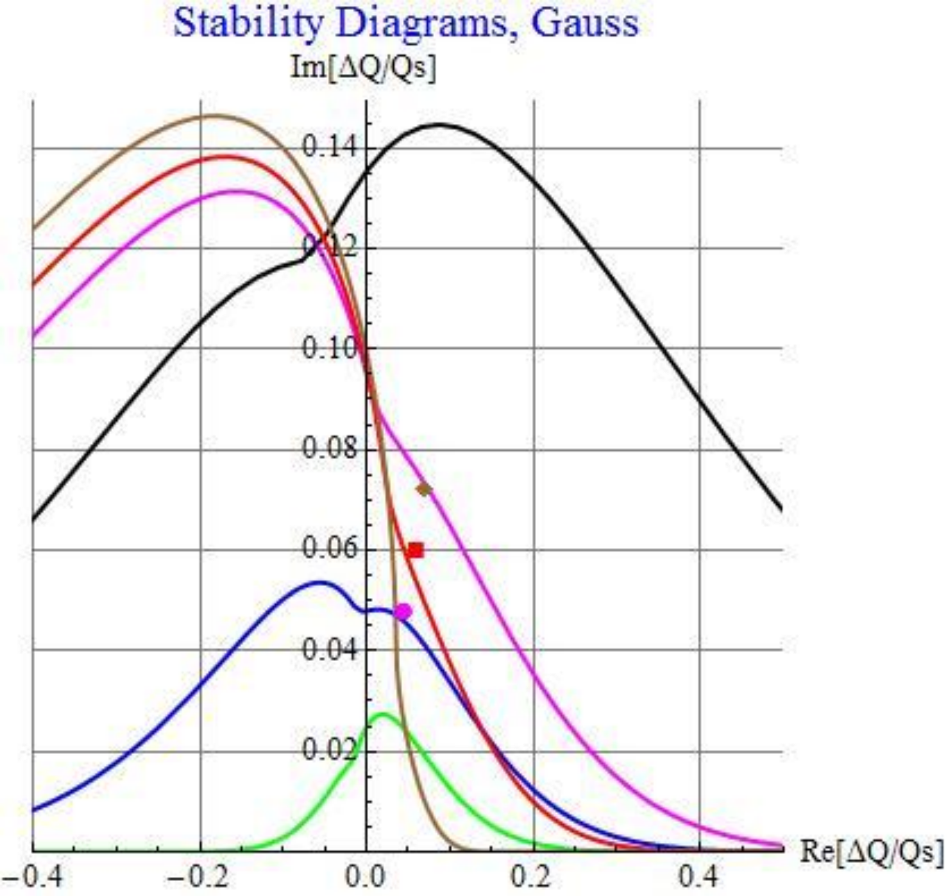
Stability Diagrams, LO+

Assuming e-cloud transverse profile same as for the beam, the incoherent tune follows:

$$\Delta Q_e = \Delta Q_e^{(0)} + \Delta Q_e^{(1)} + \ldots$$

$$\Delta Q_e^{(0)} = \frac{N_e r_p}{4\pi\varepsilon_n}$$

$$\Delta Q_{ex}^{(1)} = -\frac{3\Delta Q_e^{(0)}}{8}\,\frac{J_x + 2J_y/3}{\varepsilon}; \quad \left\langle J_{x,y} \right\rangle = \varepsilon.$$



LO=140A – computed threshold

BB only, LO=0

BB and LO=500A

BB, LO=500A, dQe0=6.0E-4

BB, LO=500A, dQe0=8.0E-4

BB, LO=500A, dQe0=1.0E-3

Markers – MUMs, colors correspond

$$\Delta Q_e^{(0)} = 8\cdot 10^{-4} \Leftrightarrow N_e = 1.3\cdot 10^{10}\ \text{total}$$

Wake function

- Following [Burov & Dikansky,1997], e-cloud wake can be modeled as a low-Q resonator:

$$W(\tau) \simeq W_0 \sin(\omega_e \tau) \exp\left(\omega_e \tau / 2Q\right);$$

$$W_0 = \frac{2N_e r_e c}{\sigma_\perp^4 \omega_e}, \quad Q \sim 2-3, \;\; \tau < 0$$

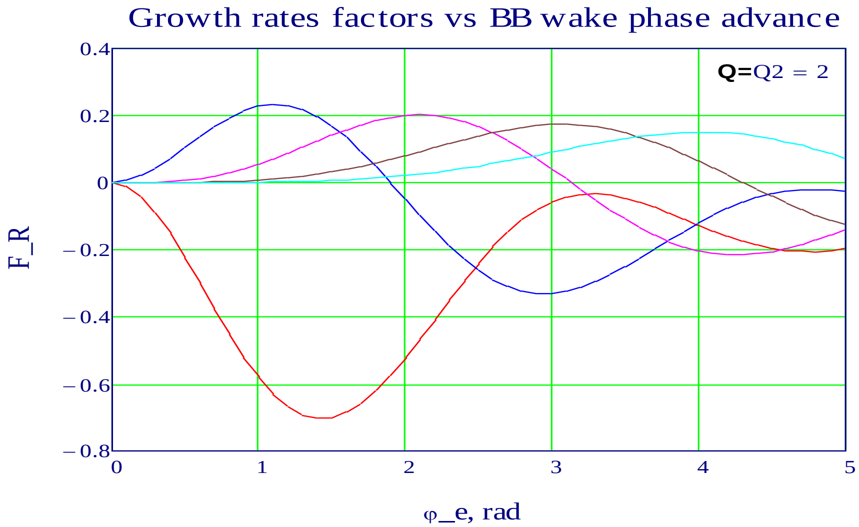
equivalent to a shunt impedance $\frac{R_s}{Q} \simeq Z_0 \frac{N_e r_e c}{2\pi\sigma_\perp^4 \omega_e}; \;\; Z_0 = \frac{4\pi}{c} = 377\,\mathrm{Ohm}$

Here N_e is number of electrons seen inside the proton beam size of the radius $\sigma_\perp$ per revolution.

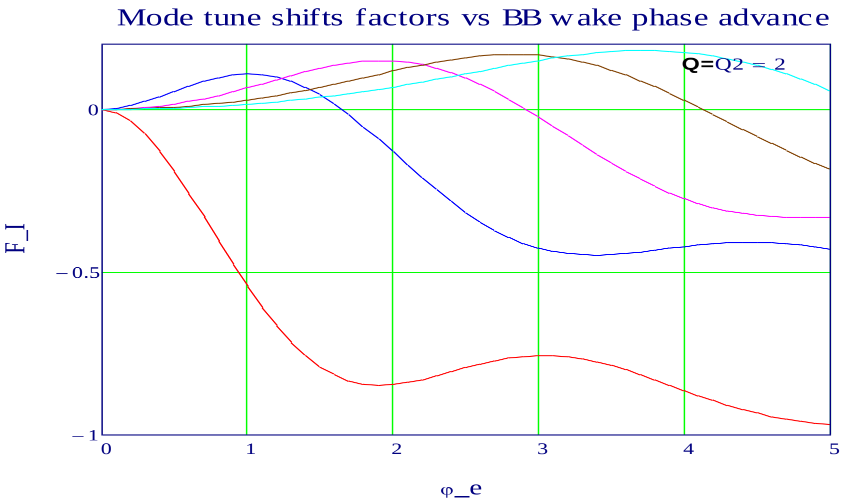
Weak Head-Tail (WHT)

- Application this wake function to the WHT tune shift and growth rate (A. Chao, Eq. 6.213, air-bag) results in (HT phase $\chi \le 1$) :

$$\mathrm{Im}[\Delta Q] = \chi \Delta Q_{e0} F_R(m,\phi_e); \quad \mathrm{Re}[\Delta Q] = \Delta Q_{e0} F_I(m,\phi_e); \quad \phi_e = \sqrt{2}\omega_e \sigma_z / c$$



Growth rates factors vs BB wake phase advance



Mode tune shifts factors vs BB wake phase advance

$$F_R(m,Q,\phi) = 3\int_0^{\infty} \frac{J_m(x\phi)J'_m(x\phi)}{1+Q^2(x-1/x)^2}\frac{dx}{x}; \quad F_I(m,Q,\phi) = \frac{3}{2}\int_0^{\infty} \frac{Q(x-1/x)J_m^2(\phi x)}{1+Q^2(x-1/x)^2}\frac{dx}{x}$$

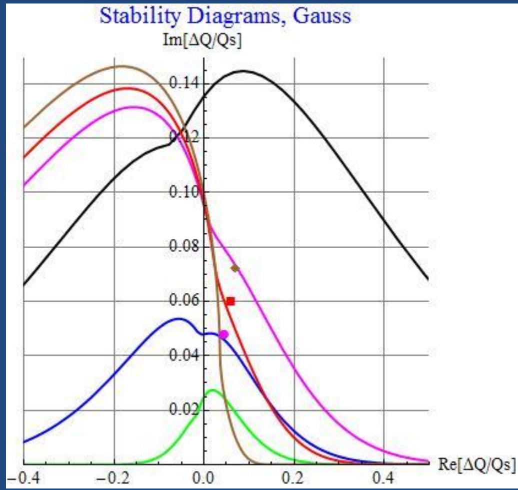
Unstable modes have positive tune shift – thus, they are not L-damped after the SD shift s to the left due to e-cloud unharmonicity!

At $\chi \simeq 1$, for the MUM: $\mathrm{Im}[\Delta Q] \approx \mathrm{Re}[\Delta Q] \approx 0.2\Delta Q_{e0}$ (used for markers at p.3 plot)

Why End of the Squeeze?

- According to the air-bag plots of p.5, the most unstable mode (MUM) number $l \cong 1.4\psi_e$. To be not suppressed from the longitudinal L-damping this number cannot be too high, $\psi_e \lesssim 1-2$. For the growth rate do not be too low, the electron phase advance cannot be too small as well, $\psi_e \gtrsim 1$. Thus, to drive the instability, the phase has to be about 1:

$$\psi_e \sim 1$$



BB, LO=500A, dQe0=8.0E-4

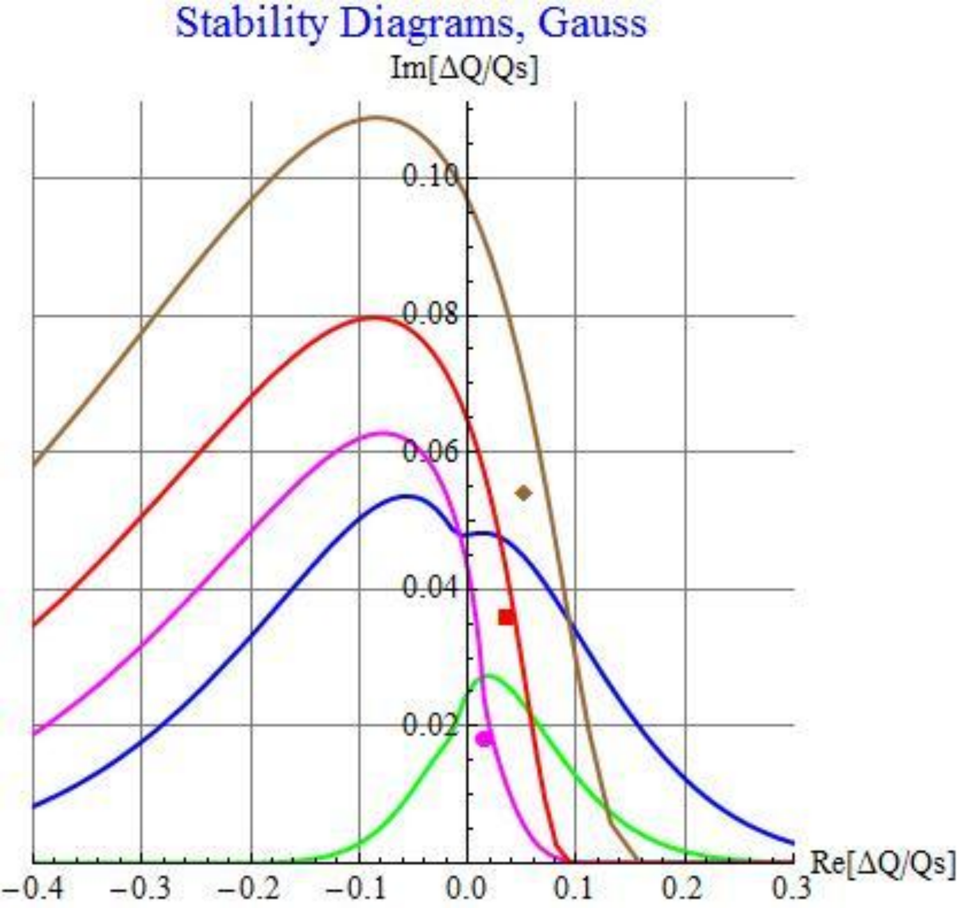
$N_e = 1.3 \cdot 10^{10}$ total

- During the squeeze, the phase advance ψ_e significantly changes:

$$\psi_e = \begin{cases} 9 \text{ rad for } \beta\text{=300m} \\ 2 \text{ rad for } \beta\text{=4km} \end{cases}$$

- Thus, the effective number of electrons N_e has to be shared between 4 high –beta regions of IR1 and IR5, requiring ~4E9 e per every ~25m region.
- Due to the e-pinches, this number has to be expected 2-10 times lower.

SD Focusing-Collapse for LO=0



LO=+140A – computed threshold

BB only

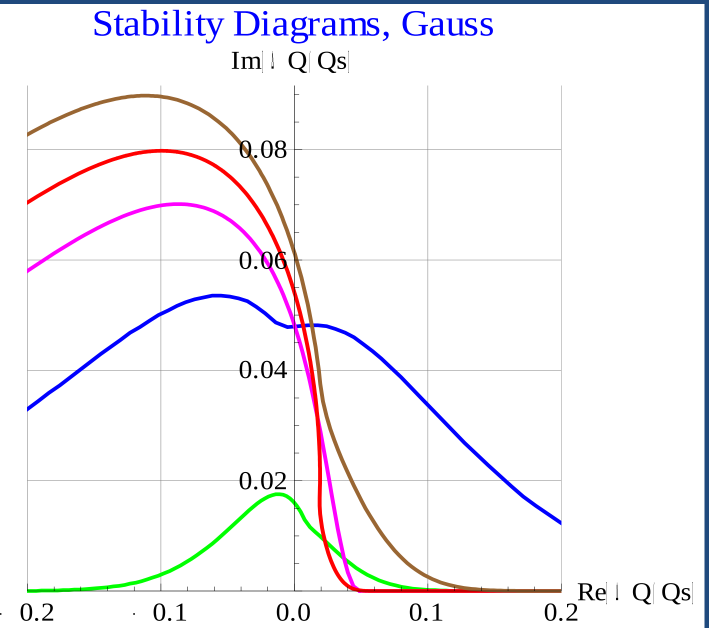
BB, LO=0, dQe0=2.4E-4

BB, LO=0, dQe0=4.8E-4

BB, LO=0, dQe0=7.2E-4

For zeroed LO, it takes twice less electrons for the instability than for +500A.

SD Collapses and Reductions for LO=-500A, No EC



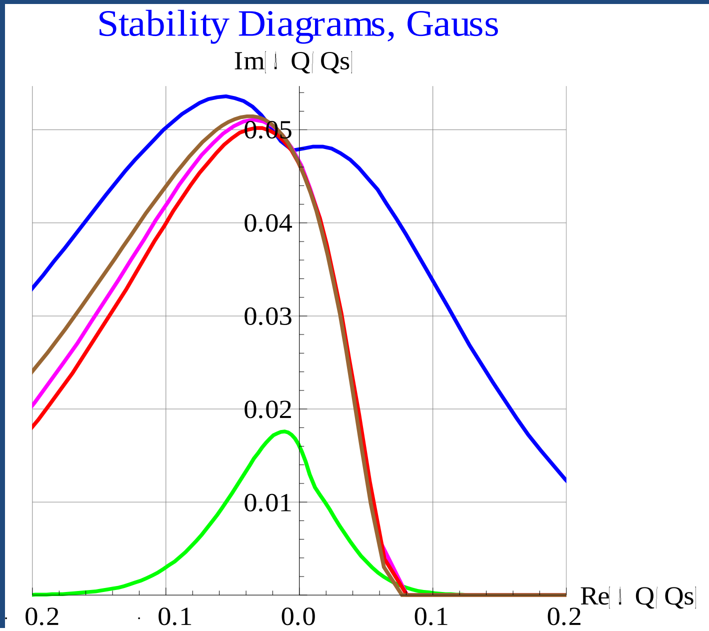
LO=-90A – threshold, LO- only

BB=2.5E-3 /IR,   LO=0

BB=5.8E-3 /IR, LO=-500

BB=6.3E-3 /IR, LO=-500 (F-collapse)

BB=6.8E-3 /IR, LO=-500



LO=-90A – threshold. LO- only

BB=2.5E-3 /IR,   LO=0

BB=3.0E-3 /IR, LO=-500,

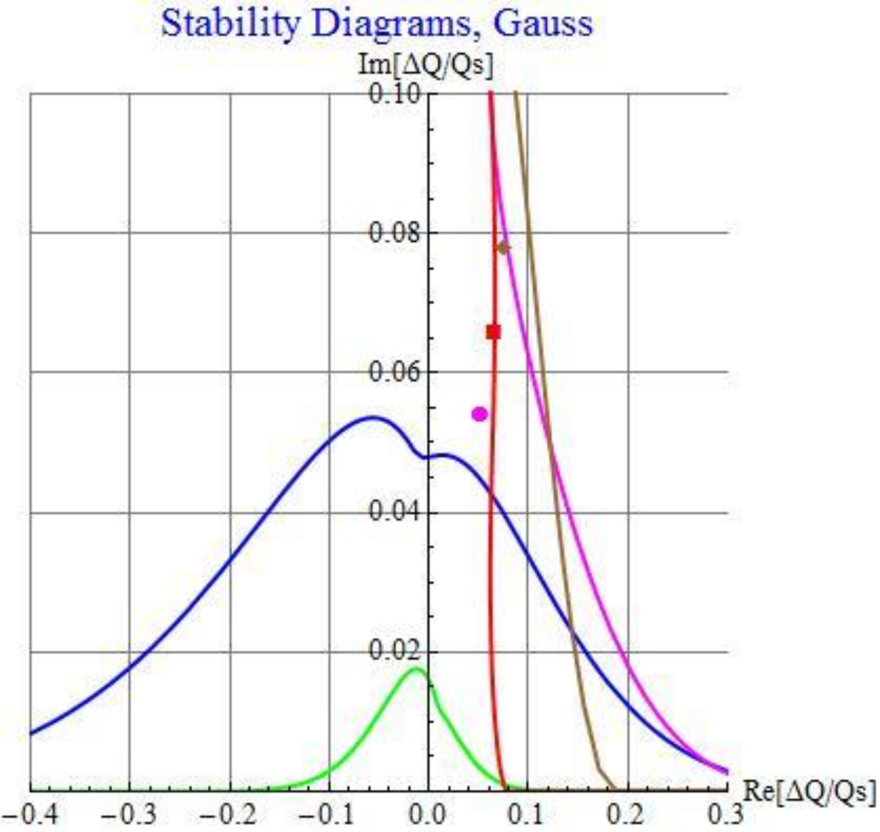
BB=3.8E-3 /IR, LO=-500, (SD D-reduction)

BB=4.3E-3 /IR, LO=-500, dQe0=5.0E-4

No D-collapse, just a minor reduction… This may be enough to drive the instability at Jura - but not at the Plateau.

AB

SD Collapses and Reductions for LO=-500A



LO=-90A – computed threshold for LO- only

BB=2.5E-3 /IR, LO=0

BB=1.4E-2 /IR, LO=-500, dQe0=7.2E-4

BB=1.4E-2 /IR, LO=-500, dQe0=8.8E-4

BB=1.4E-2 /IR, LO=-500, dQe0=1.0E-3

- The instability may develop at adjust only – not at the squeeze.
- With that polarity, the beam is stable both **at too low** **and too high** e-cloud.
- Instead, **for LO>0, there is no stabilization with increase of e-cloud**.

Arguments for IR e-cloud hypothesis

- IR e-cloud gives an instability mechanism, sensitive to 2 beams and not requiring coupled-beam oscillations.
- This instability appears only at the end of the squeeze, which is consistent with decrease of the phase advance ψ_e during the squeeze:

$$\psi_e = \begin{cases} 9 \text{ rad for } \beta = 300\text{m} \\ 2 \text{ rad for } \beta = 4\text{km} \end{cases}$$

- It takes only a few E9 e/IR to make the instability possible.
- Coupled-beam is refuted both conceptually and experimentally, and we do not know any other 2-beam instability mechanism.
- It is reasonable to expect only one beam oscillating (which was observed).
- It is reasonable to expect both emittances degrading (observed at cogging MD)
- This hypothesis is consistent with LO<0 observations (S. Fartoukh)

Questions

- What assumptions have to be taken for the IR vacuum chamber to make possible accumulation of a few E9 e/IR with 2 beams there?
- Can this Ne/IR be consistent with our knowledge about the IR?
- In case of no-refutation from the build-up simulations, can we install anti-cloud solenoids outside the IR quads?

Many thanks!