Studying the Nature of UFOs 2:
Dust Charging and Orbital Dynamics

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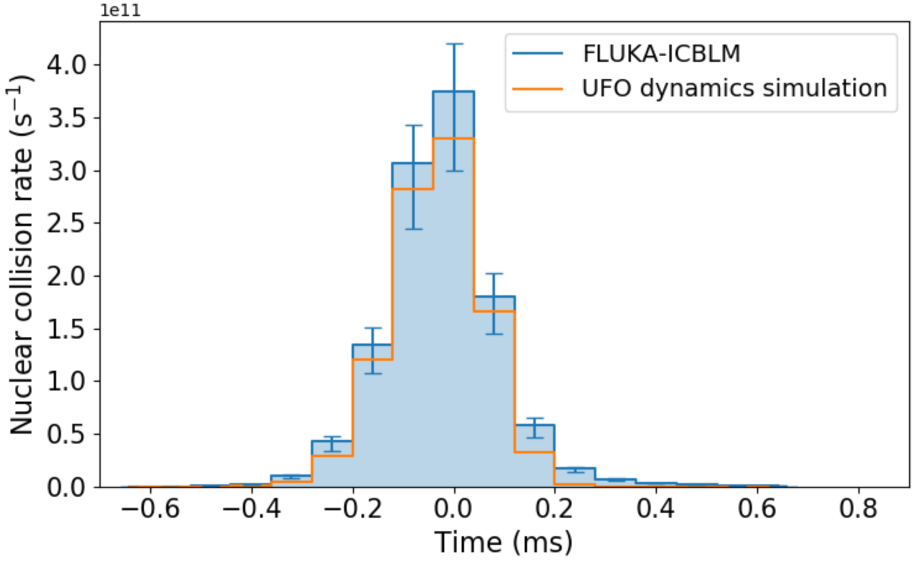
Quick Recap

Since the end of Run II, multiple studies on UFO Dynamics:

- **P. Bélanger et al.: Charging mechanisms and orbital dynamics of charged dust grains in the LHC (to be submitted, PRAB)**
- B. Lindstrom, P. Belanger et al.: Dynamics of the interaction of dust particles with the LHC beam (PRAB, 2020)
- B. Lindstrom et al.: Results of UFO Dynamics Studies with Beam in the LHC - CERN Document Server (IPAC, 2018)
- P. Bélanger et al.: Progress report : UFO Dynamics studies - CERN Document Server

Validated beam loss simulations with FLUKA



Validated UFO dynamics with b-by-b measurements

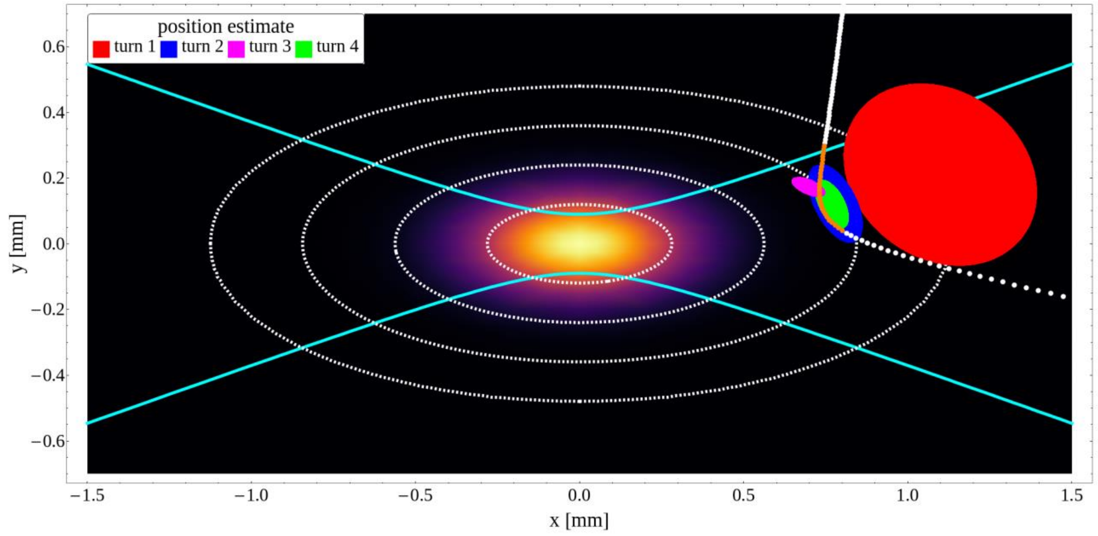
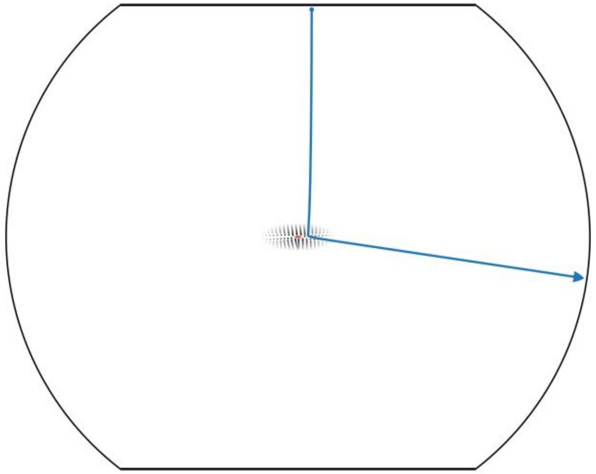
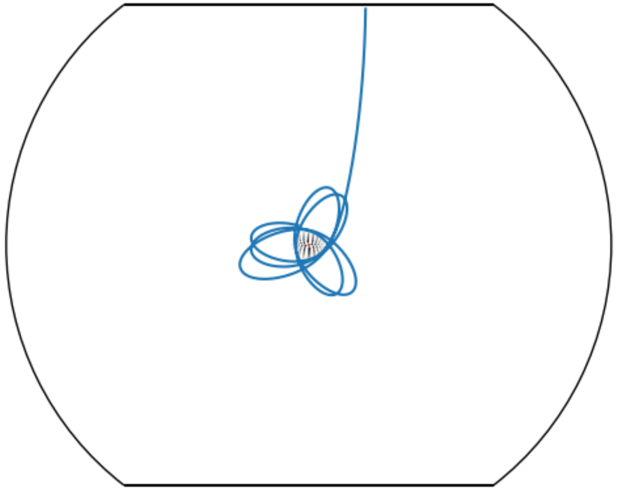


FIG. 14: Trajectory of the best fitting event from the simulations, compared to the estimated UFO position on a turn-by-turn basis.

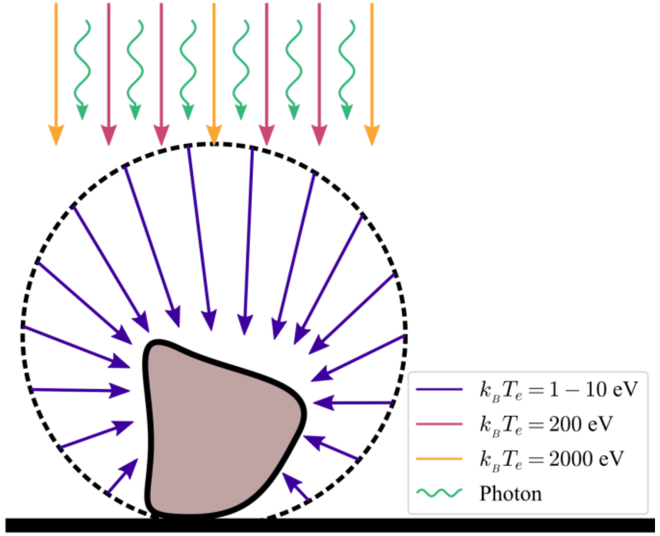
The UFO problem in the LHC

Beam-dust interactions
(**well understood**)

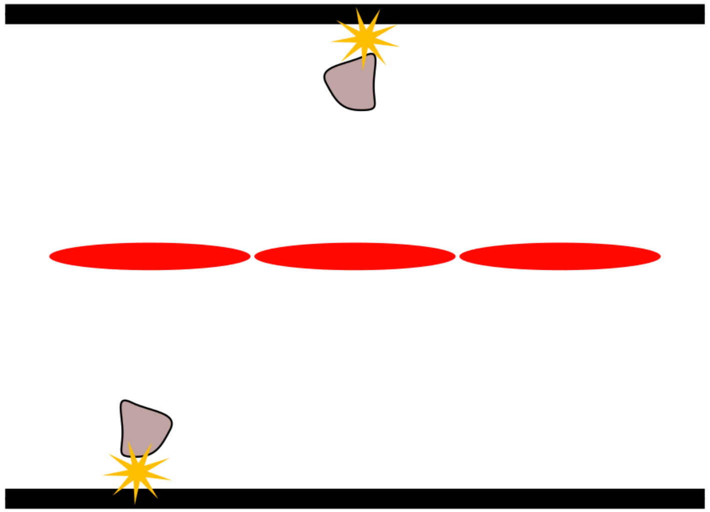




Alternative dynamics
(**following slides**)



Charging (**following slides**)



Release (**unknown**)

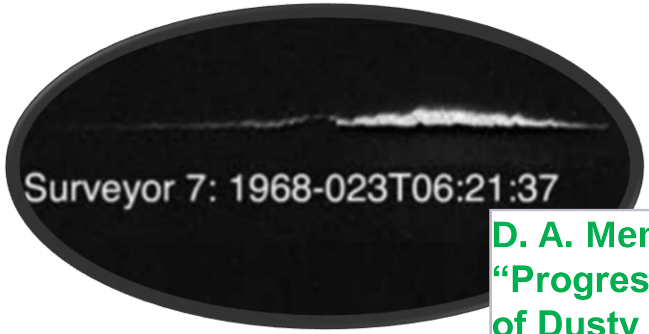
Dust grains in particle accelerators

- Intensity drops in electron storage rings (TRISTAN, CESR, HERA, DORIS)
- Pressure bursts in the SuperKEKB positron storage ring
- Sporadic beam losses as well as magnet quenches in the LHC proton beam

What can explain their interaction with both p^+ and e^- beams?

Dust grains outside of accelerators (i.e. in outer space)

Lots of research on the charging of cosmic dust.
Can it equally apply to particle accelerators?

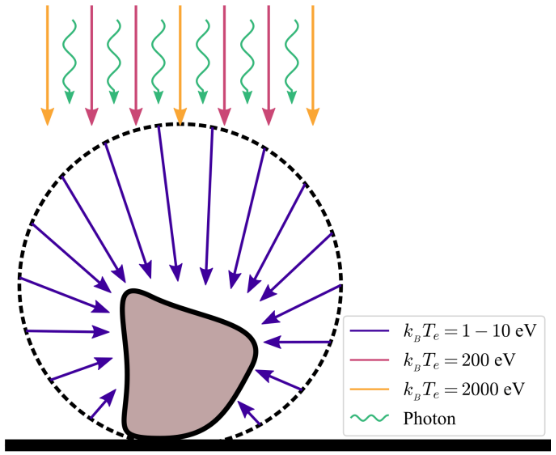


D. A. Mendis (2002) "Progress in the Study of Dusty Plasmas"

Ultra-high vacuum	Yes	Yes
High energy photons	Synchrotron Radiation	Mostly from the Sun
Free electrons	Electron clouds	Yes (plasma sheet)
Free ions	No	Yes (plasma sheet)

Dust Charging Mechanisms

$$\Phi = \frac{Q}{4\pi\varepsilon_0 R}$$



- **Electron collection, negative current**

$$J_e(\Phi, n_e, T_e) = -en_e \left(\frac{k_B T_e}{2\pi m_e}\right)^{1/2} \cdot \begin{cases} \exp\left(\frac{e\Phi}{k_B T_e}\right) & \text{for } \Phi < 0 \\ \left(1 + \frac{e\Phi}{k_B T_e}\right) & \text{for } \Phi \geq 0 \end{cases}$$

- **Secondary electron emission, positive current**

$$J_s(\Phi, n_e, T_e) = en_e \left(\frac{k_B T_e}{2\pi m_e}\right)^{1/2} \cdot \frac{\exp\left(\frac{e\Phi}{k_B T_e}\right)}{(k_B T_e)^2} \cdot \eta(\Phi)$$

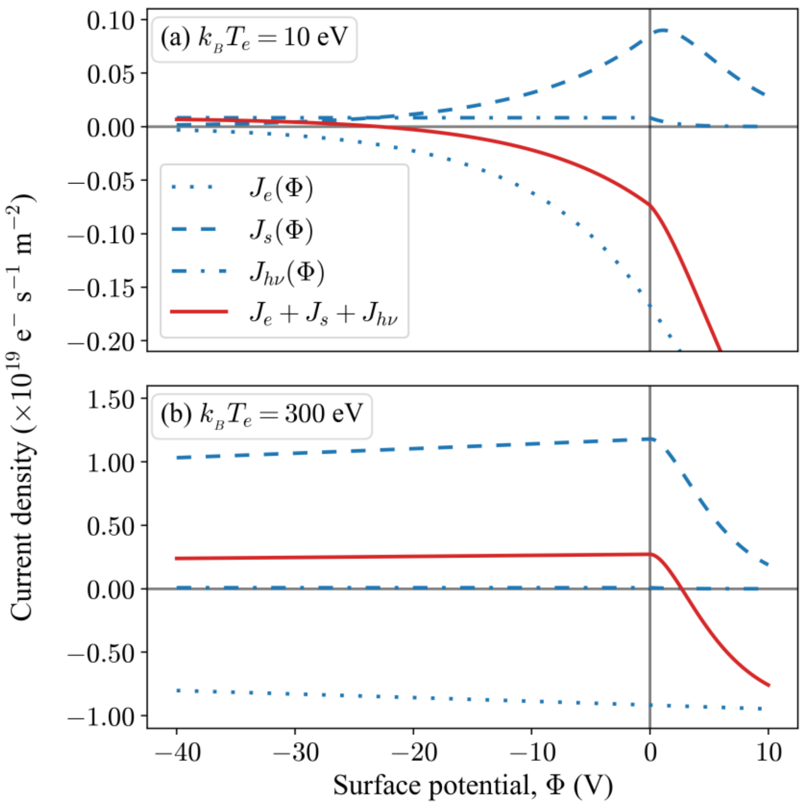
- **Photoelectric emission current, positive current**

$$J_{h\nu}(\Phi) = e\dot{\Gamma} Q_{h\nu}\delta_{h\nu} \cdot \exp\left(-\frac{e\Phi}{k_B T_{h\nu}}\right) \quad \text{for } \Phi \geq 0$$

- **Contact discharging with the beam screen?**

$$J_{\text{ind}}(\Phi) = \frac{1}{\pi R^2 \cdot 2\varepsilon_{r,\text{ox}}} \left(\frac{\sigma_{\text{ox}} A_c}{\ell_{\text{ox}}}\right) \left[\Phi_{\text{ind}} - \Phi\right]$$

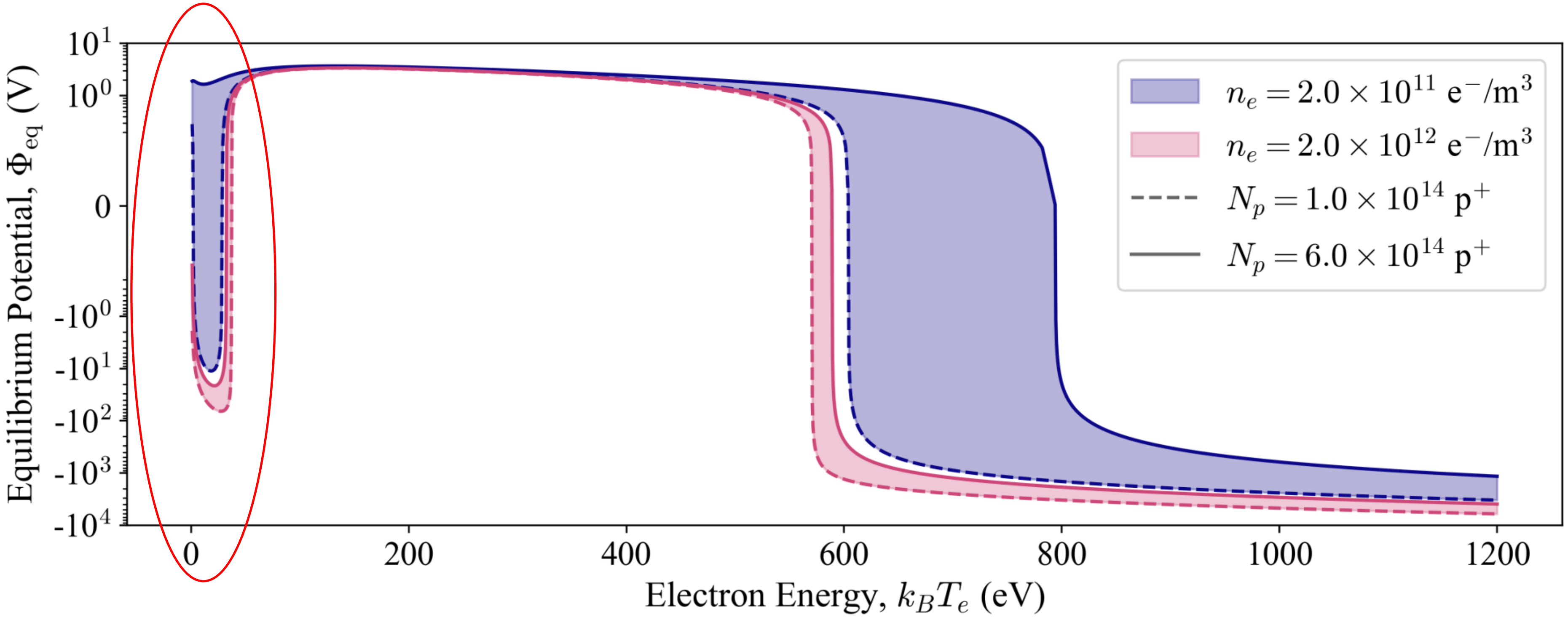
~ 5 orders of magnitude smaller



Equilibrium surface potential

- **Equilibrium** is found from the balance of the currents
- With fixed environmental conditions (synchrotron rad + e-cloud), depends **electron energy spectrum**
- In most conditions, **low energy electrons** will dominate

$$J_e + J_s + J_{h\nu} = 0$$



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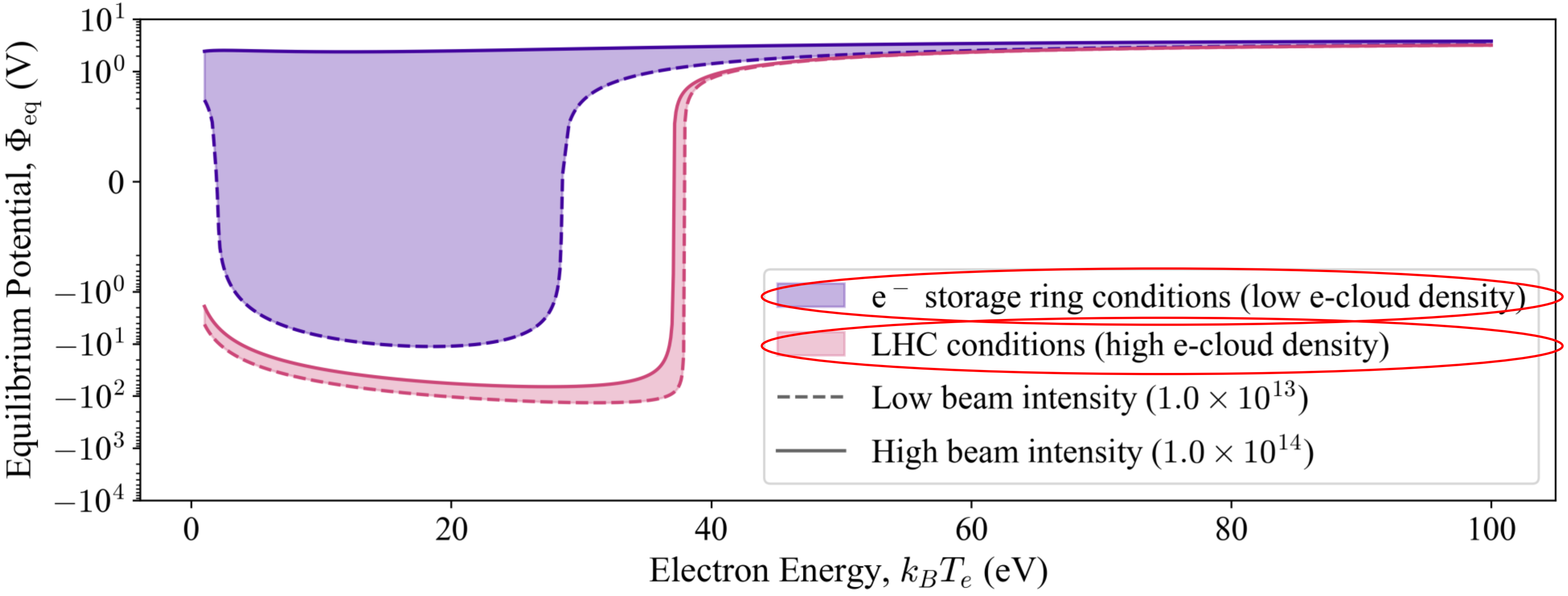
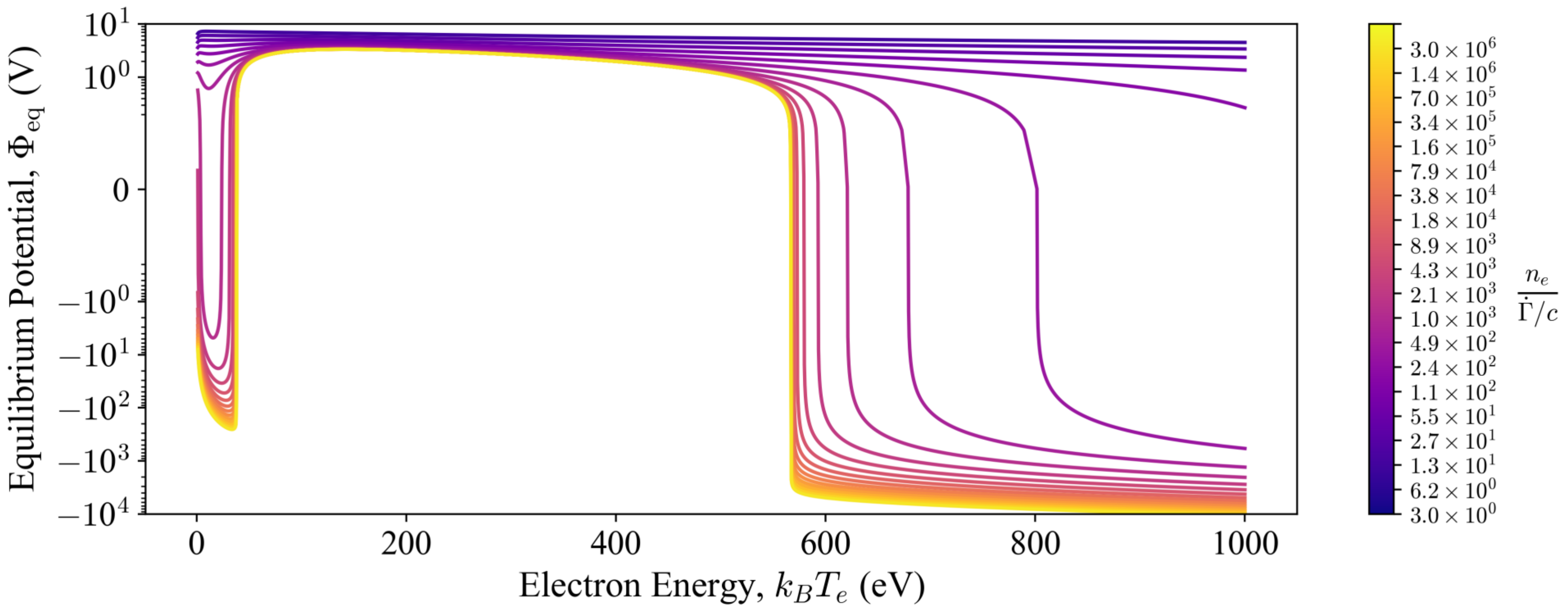


Equilibrium surface potential (take 2)

$$J_e + J_s + J_{h\nu} = 0 \;\longrightarrow\; -n_e + n_e + \dot{\Gamma} = 0 \;\longrightarrow\; \frac{n_e}{\dot{\Gamma}/c}$$

Recall slide 6

Which removes the dependence on beam intensity



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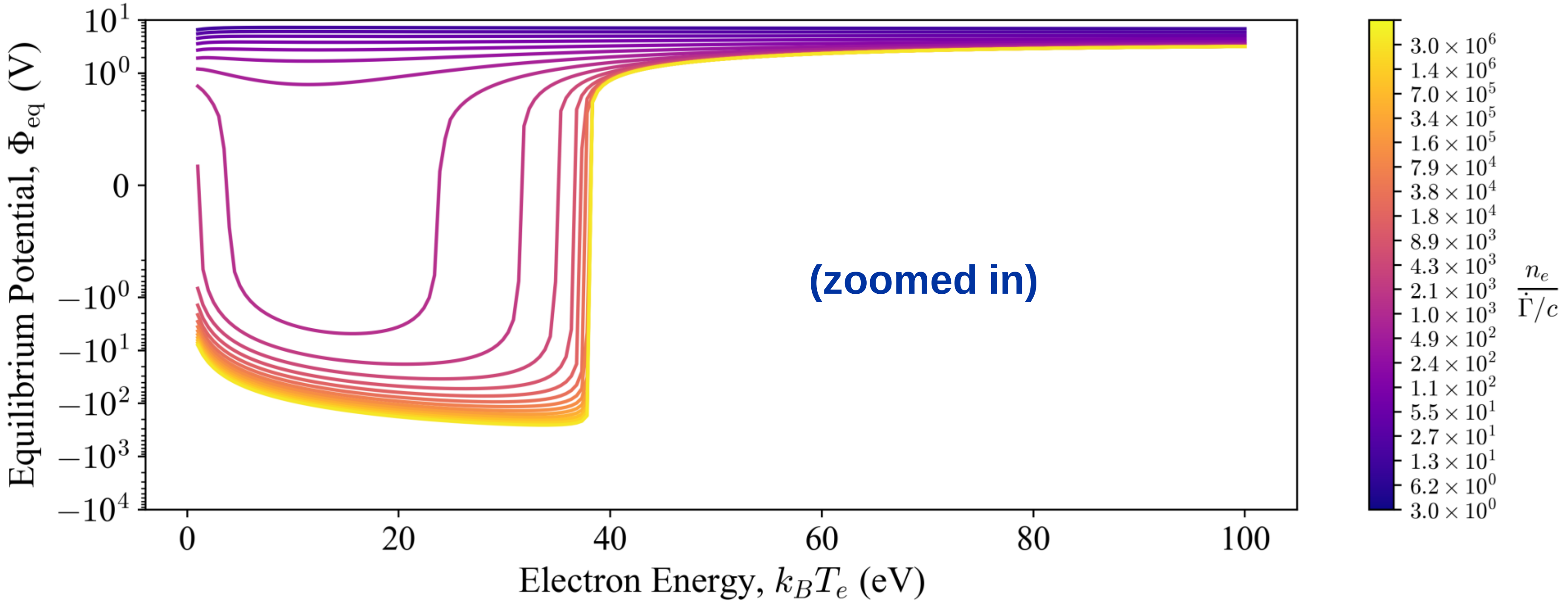
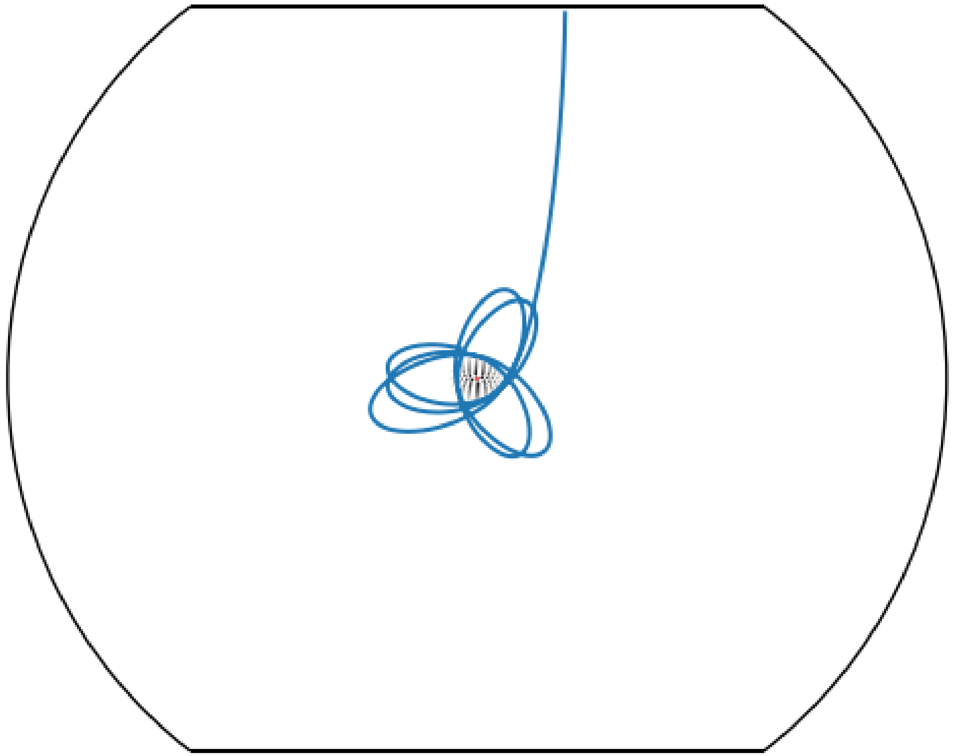


Orbiting Dust grains

From previous slides, the conclusion is that grains become:

- **Positively charged** in presence of low density e-cloud **(e- storage rings)**
- **Negatively charge** in presence of high density e-cloud **(LHC)**

Hence, the charge accumulated tends to be **opposite to the one of the beam**!

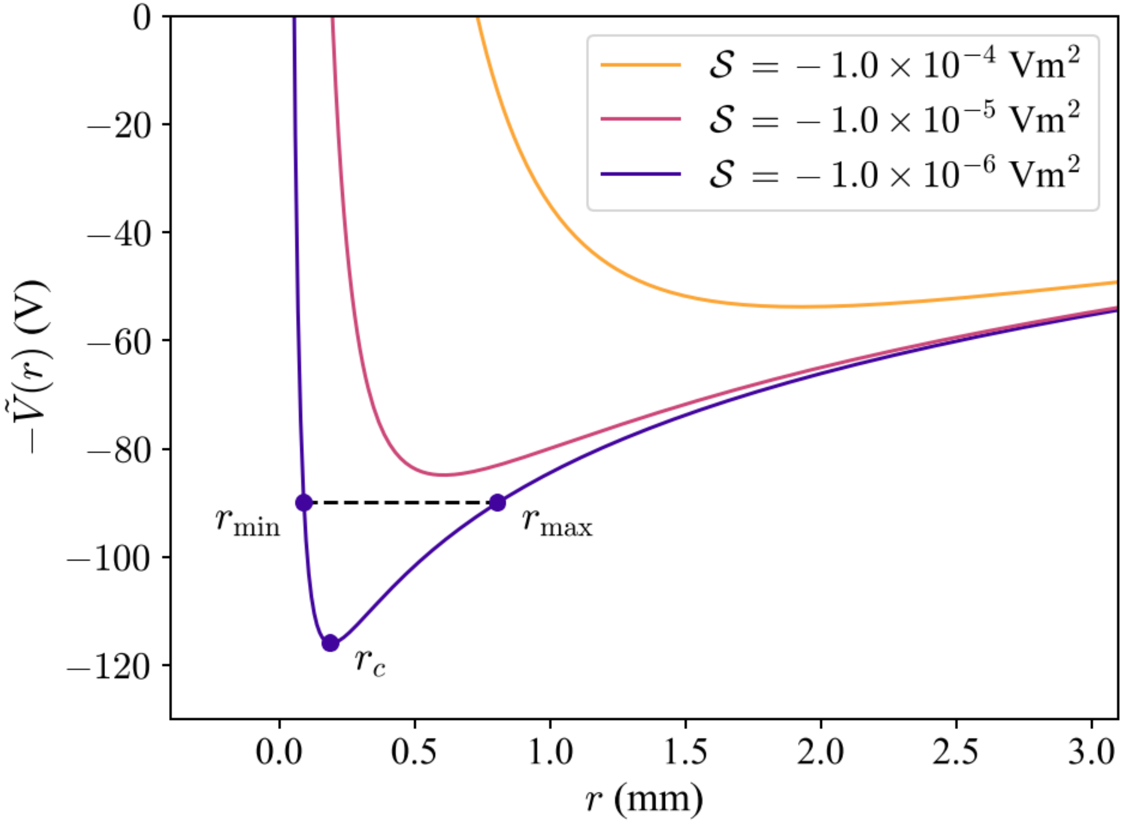


Logarithmic potential

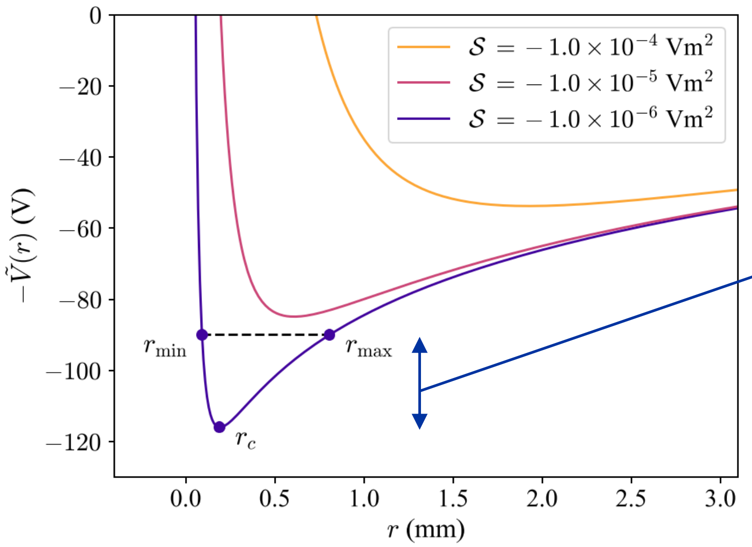
Looking for defining parameters (stiffness):

$$\mathcal{S} \equiv \frac{h^2}{Q/m}$$

$$\begin{aligned}\mathcal{H}_0 &= \frac{P_r^2}{2m} + \frac{P_\phi^2}{2mr^2} + QV(r) \\ &= \frac{P_r^2}{2m} + Q\left[\frac{\mathcal{S}}{2r^2} - V_0 \ln(r/r_\infty)\right] \\ &= \frac{P_r^2}{2m} + Q\tilde{V}_0(r)\end{aligned}$$

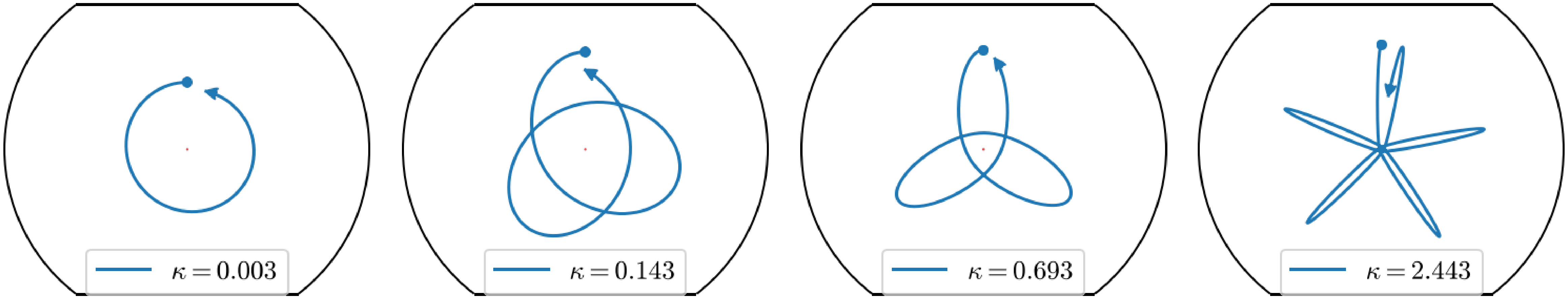


Shape parameter



$$\kappa \equiv \frac{E - E_c}{2K_{\phi,c}}$$

Can be used to describe circular orbits as well as trajectories falling into the beam (typical UFO assumption)!



Adding beam-dust interactions

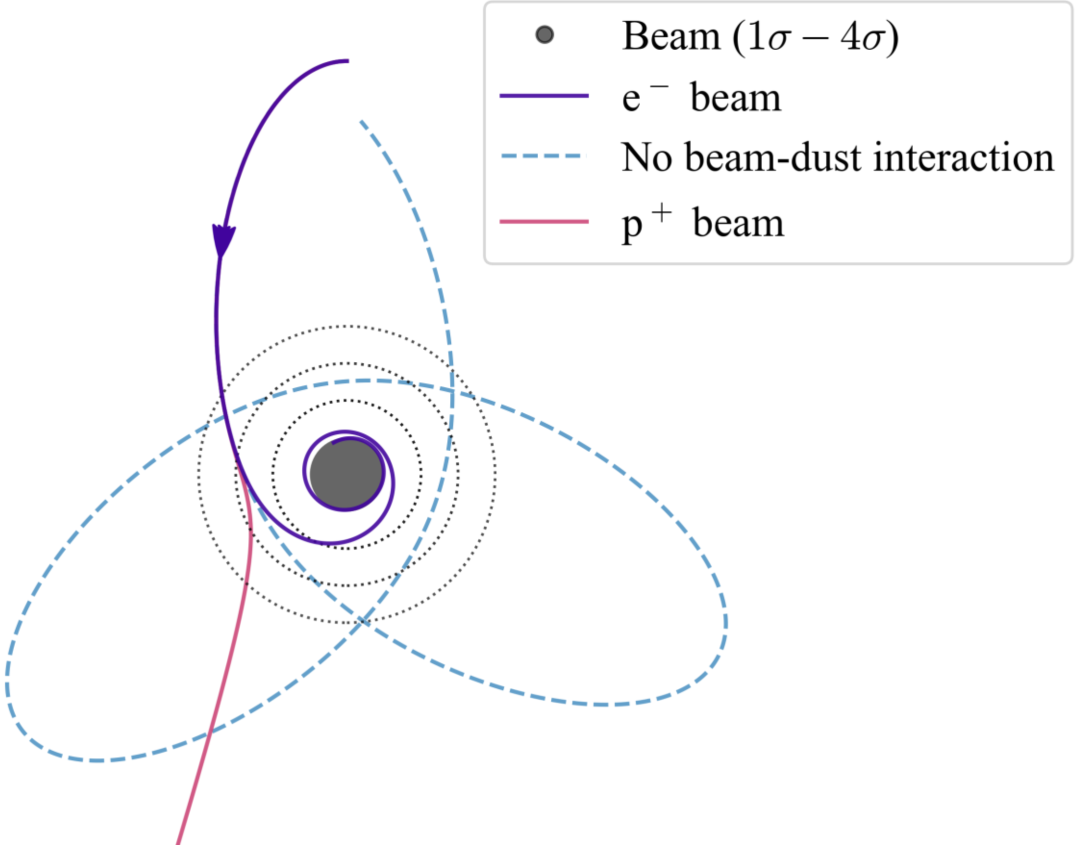
The grain is ionized (positive current).

Dynamics is consistent with historical observations in:

- e- storage rings
- The LHC

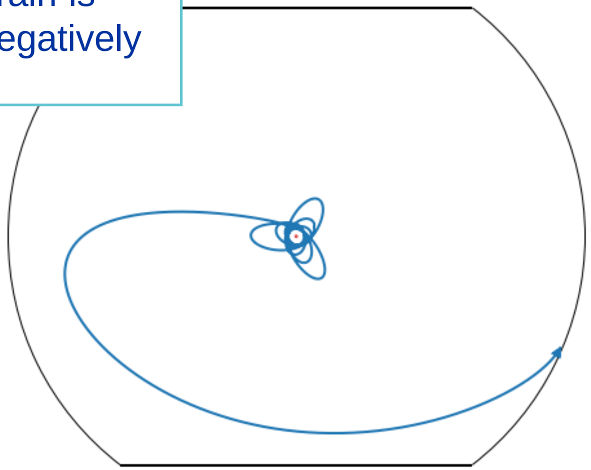
Note: In this p+ example, the grain switches polarity due to beam-dust interactions

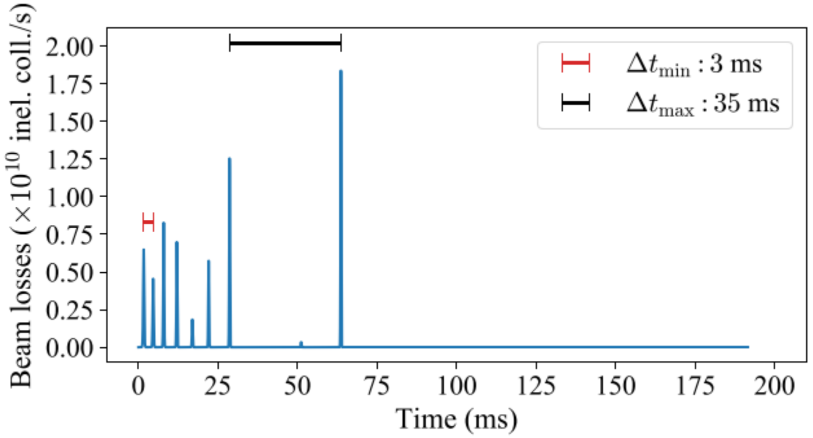
Important result: the trajectory can be described by a succession of orbits with instantaneous stiffness and shape parameter!



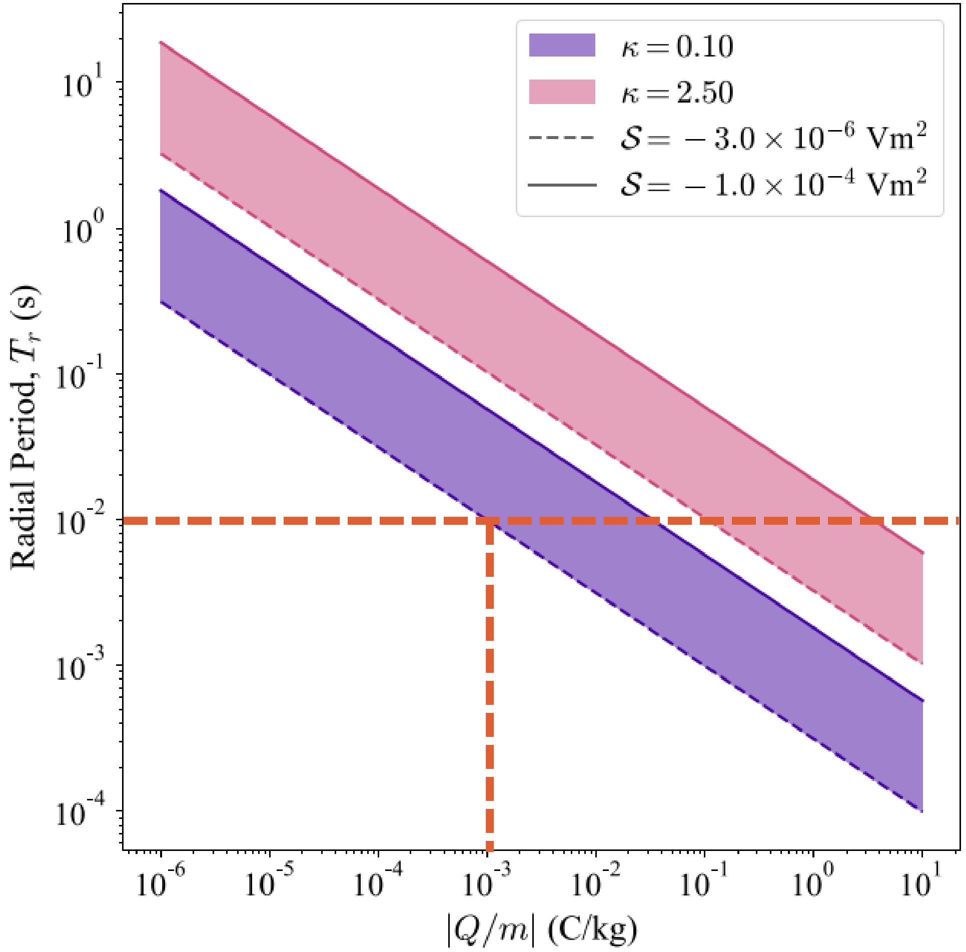
Beam losses

In this example, the grain is ionized but remains negatively charged!



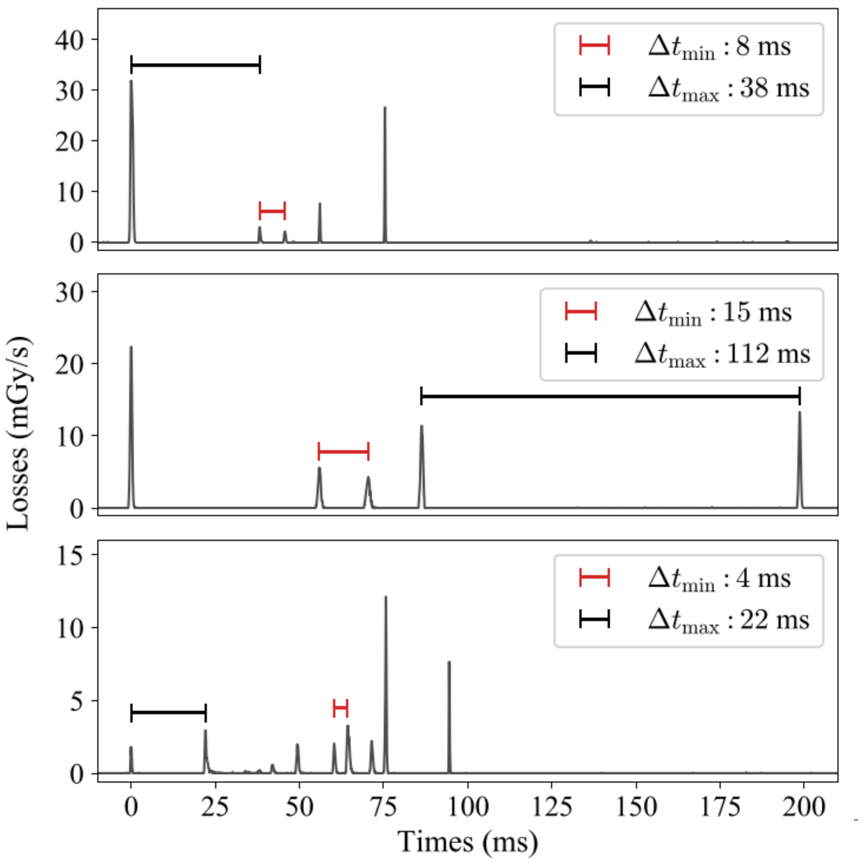


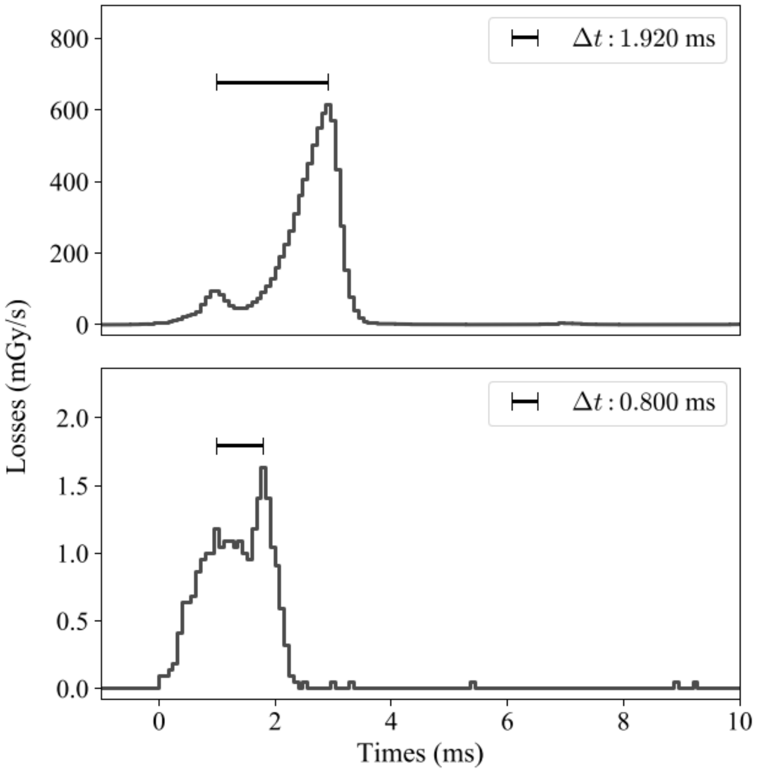
Analytical result without beam-dust interaction (instantaneous value)



Beam losses in the LHC?

- **Comparable amplitude** (1e10 inelastic collisions/s)
- **Comparable time separation** between loss peaks
- **35% of Run II** measurements have multiple peaks
- Example from **5 independent measurements** from Run II





Conclusion

- **There are hundreds of papers treating charged dust grains in vacuum environments outside of the LHC. Let's use them.**
- **Charging currents from e-clouds and synchrotron radiation allows to obtain:**
  - Positive dust grains in low e-cloud density environments (e- storage rings)
  - Negative dust grains in high e-cloud density environments (LHC)
- **Orbital dynamics can be well described with:**
  - Grain Stiffness
  - Shape parameter
- **Orbital dynamics is consistent with historical observations in e- storage rings and the LHC!**
- **With charge-to-mass ratios above 10^{-3} C/kg, radial period of oscillation is consistent with multipeak events from LHC Run II**

CERN