Dust Charging Mechanisms in Accelerators

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P. Belanger, R. Baartman, A. Lechner, B. Lindstrom, R. Schmidt, D. Wollmann

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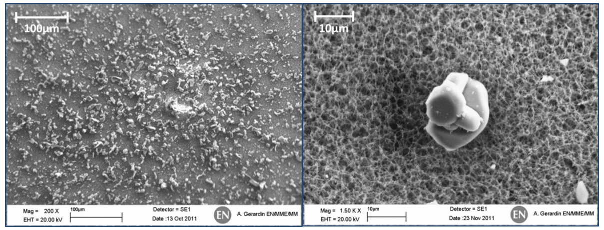
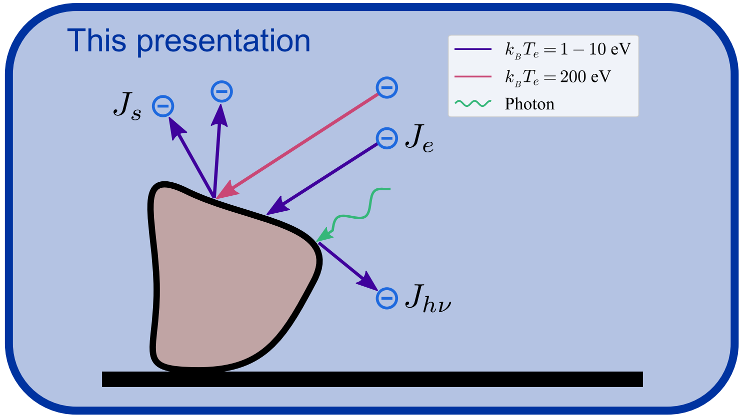
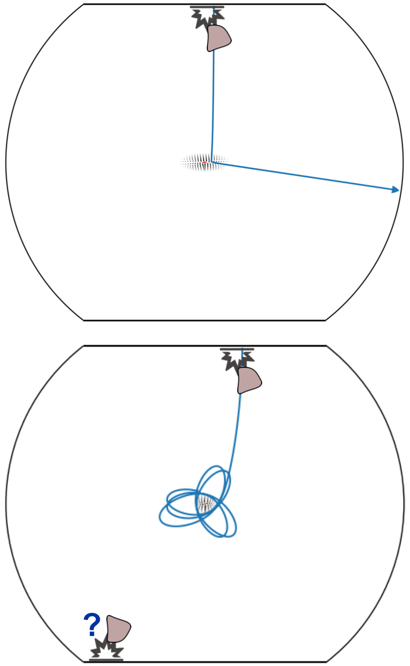
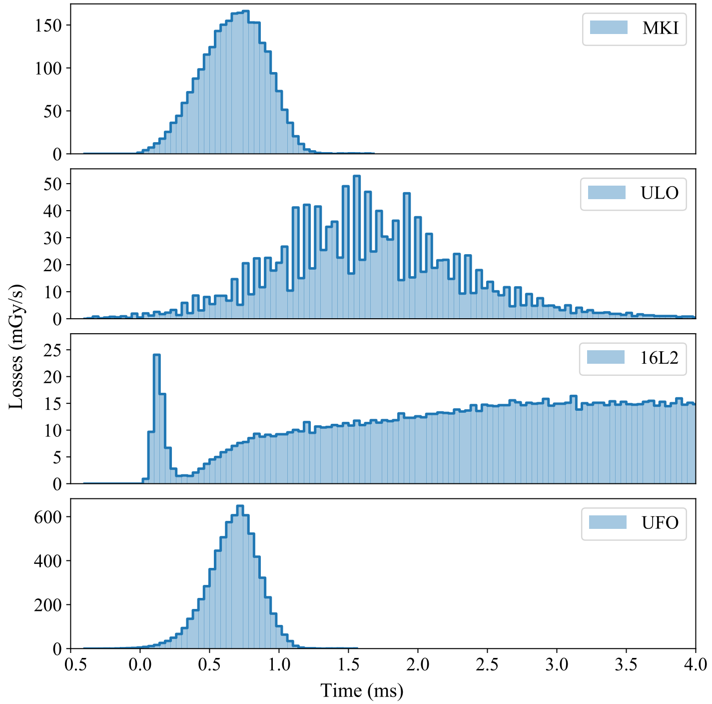
Dust problem in the LHC









M. Barnes (Wednesday)

L. Mether (Tuesday)

B. Lindstrom (Wednesday)

1. Dust charging → Release (ns scale)

2. Release → Dynamics (µs scale)

3. Dynamics → Beam losses (µs scale)

From first principles: what is the polarity of dust grains in the LHC?

Dusty Plasma, Cosmic Dust and Accelerator Dust

Ultra-high vacuum	Yes	Yes
High energy photons	Synchrotron Radiation	Solar radiation
Free electrons	Electron clouds	Yes (plasma sheet)
Free ions	No	Yes (plasma sheet)

Some examples

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

Negative

Environment	n_e (cm^{-3})	$k_B T$ (eV)	n_d (cm^{-3})	R (μm)	- Q/e	Carbon Q/m (C/kg)
Saturn's E-ring	10	10-100	10^{-7}	1	$\sim 10^4$	$\sim 10^{-1}$
Saturn's F-ring	10	10-100	< 10	1	$\sim 10 - 10^2$	$\sim 10^{-3} - 10^{-4}$
Saturn's spokes	0.1-10^2	2	1	1	~ 10	$\sim 10^{-4}$
Zodiacal dust disc	5	10	10^{-12}	10	$\sim 10^4$	$\sim 10^{-4}$
Lab-plasma (DA-wave)	10^8	2-4	10^4	5	$> 10^3$	$> 10^{-4}$
Lab-plasma (Dust-Ball)	10^8	2-4	10^3	5	$\sim 10^3$	$\sim 10^{-4}$
Coulomb dust crystal	10^9	2	$10^4 - 10^5$	5	$\sim 10^4$	$\sim 10^{-3}$
Large Hadron Collider	**10^6**	**1-10**	**-**	**1-35**	**$\sim 10^3$ - 10^5**	**$\sim 10^{-1}$ - 10^{-3}**

* assuming 5 μm C *

- **Charging** → **Surface Potential** → $\Phi = \dfrac{Q}{4\pi\varepsilon_0 R}$
- **Dynamics** → **Charge-to-mass ratio** → $Q/m = \dfrac{3Q}{\rho \cdot 4\pi R^3}$

Charging mechanisms in the LHC

- Electron capture
- Secondary electron emission

Electron clouds

- Photoelectric emission

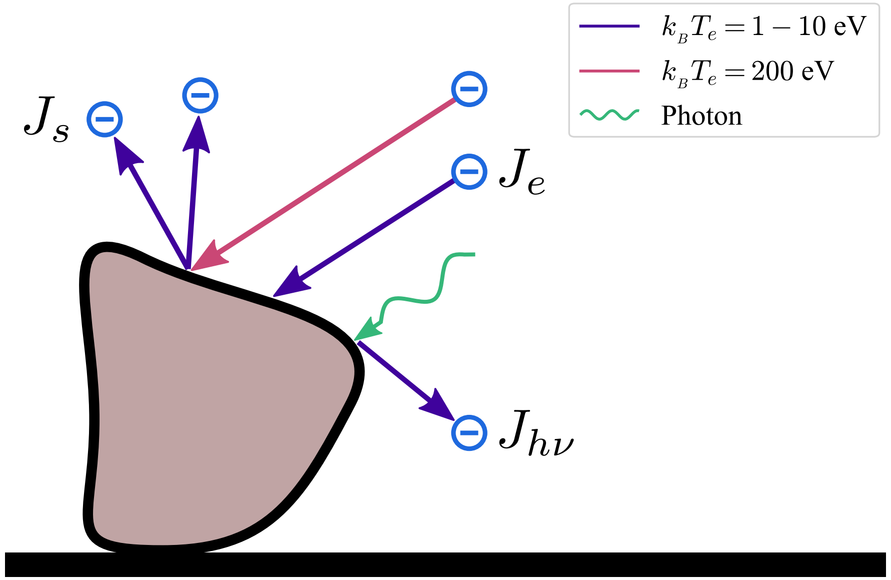
Synchrotron radiation

- Contact with conductive surfaces

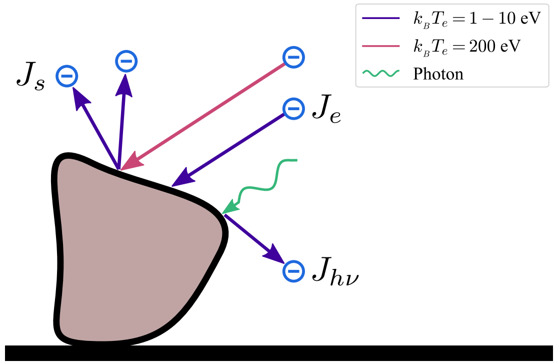
Beam screen contact

Assumed negligible

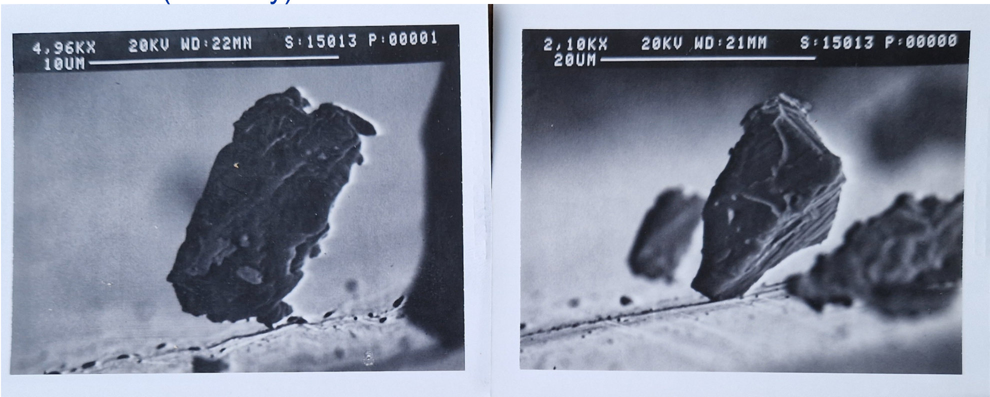
- Thermionic emission
- Triboelectrification (rubbing of two surfaces)
- Field emission

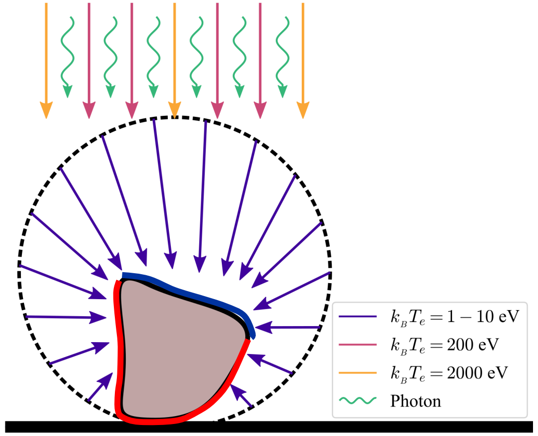


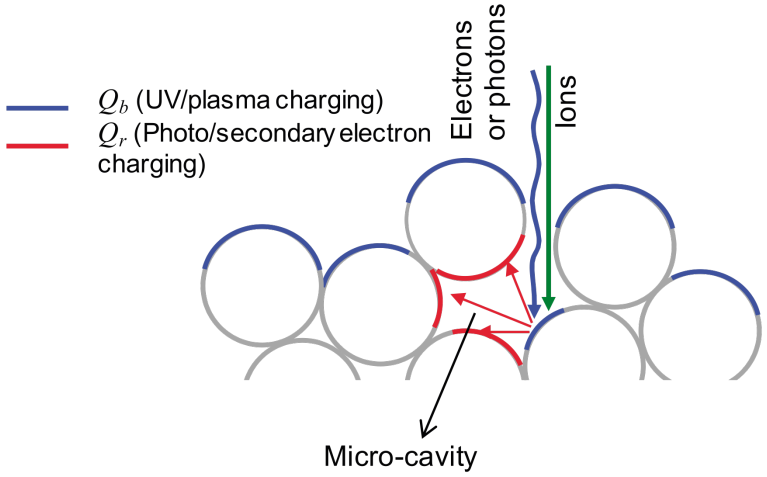
A conservative model



M. Jimenez (Tuesday)







X. Wang
M. Horanyi

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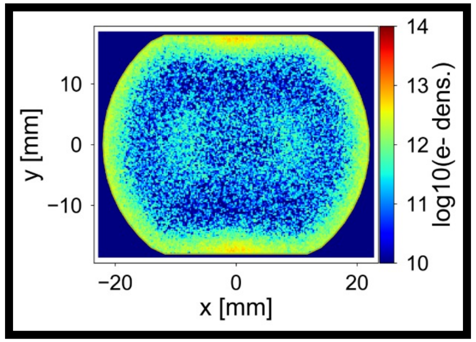
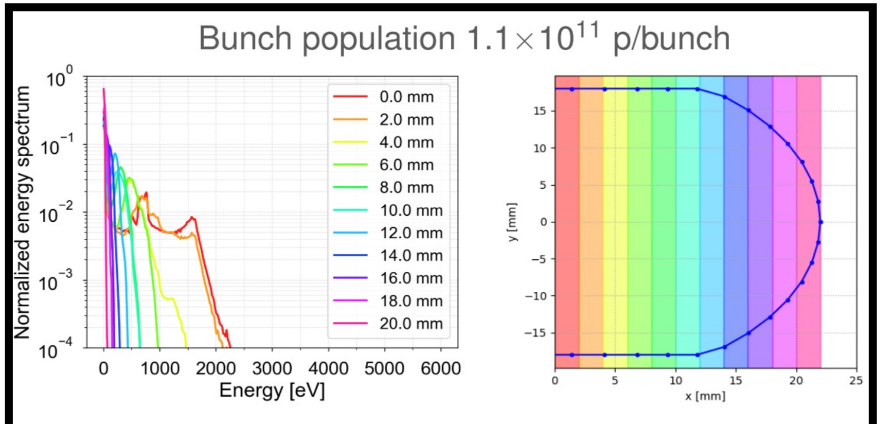
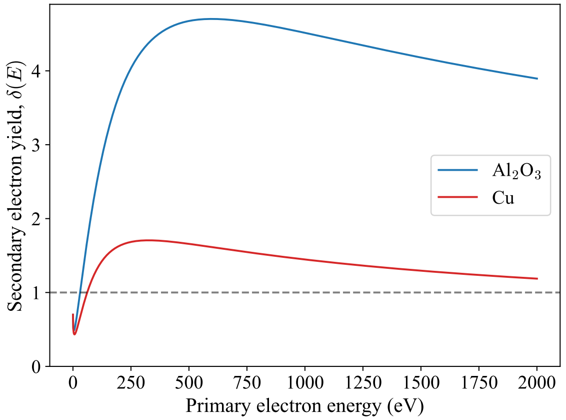
Assumptions

- **Electron cloud:**
  - Maxwellian energy distribution of low energy: 1-10 eV
  - High concentration of electrons near the beam screen
- **Synchrotron radiation**
  - Total power of synchrotron radiation distributed over the LHC ring
  - Only photons with energy above the work function of the material
- **Dust grain**
  - Conductivity expressed in the SEY
  - SEY follows the one of infinite planar slab (valid for >1 μm grain)
  - Resistive contact with the beams screen (oxide layer)





From Galina Skripka, Giovanni Iadarola, Electron cloud Meeting #71



Charging currents

- **Electron collection (negative)**

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

- **Secondary electron emission (positive)**

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

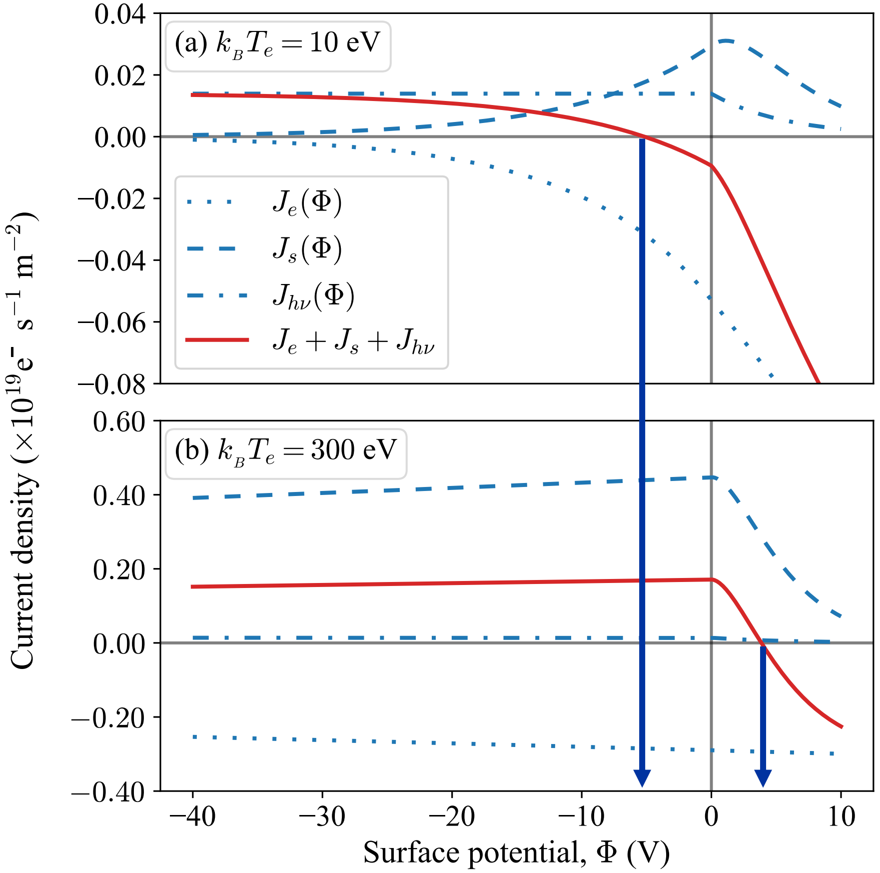
- **Photoelectric emission current (positive)**

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

- **Contact discharging with the beam screen**

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

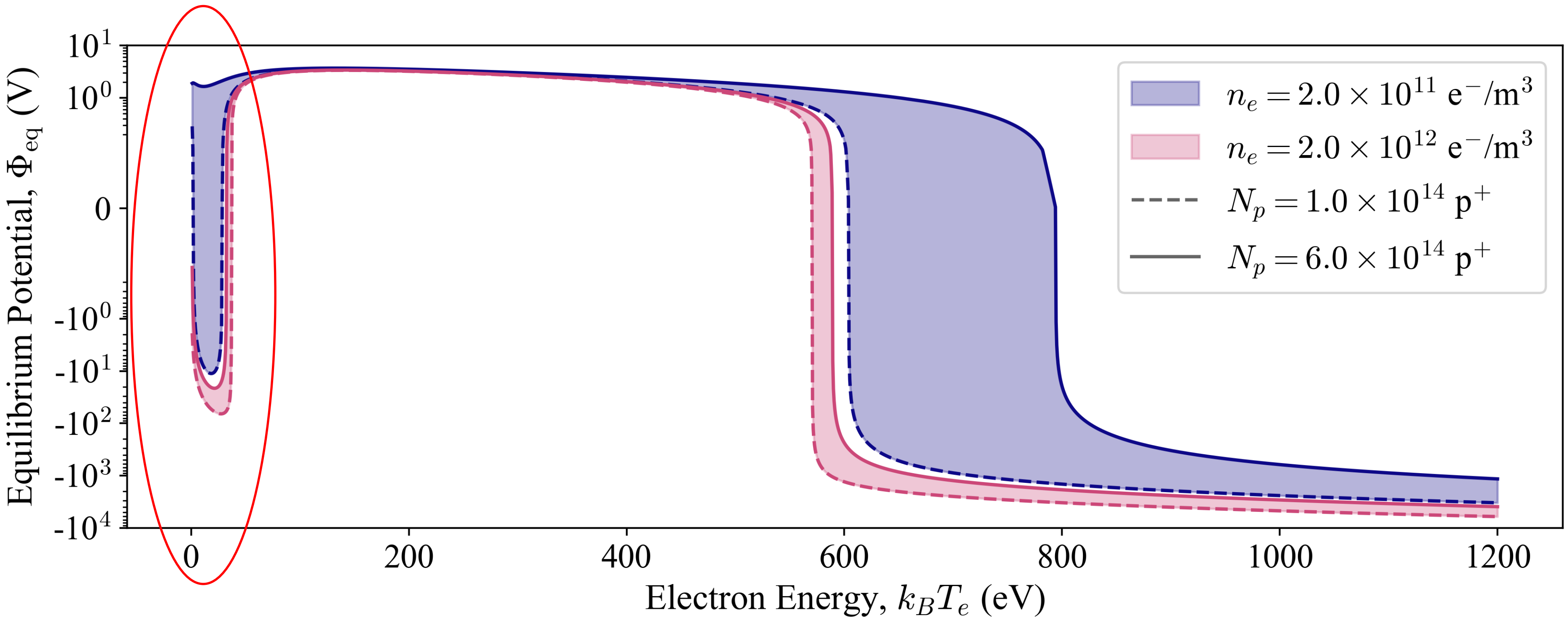
~ 5 orders of magnitude smaller



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

Equilibrium surface potential

- Equilibrium is found from the balance of the currents
- With fixed environmental conditions: depends on electron energy



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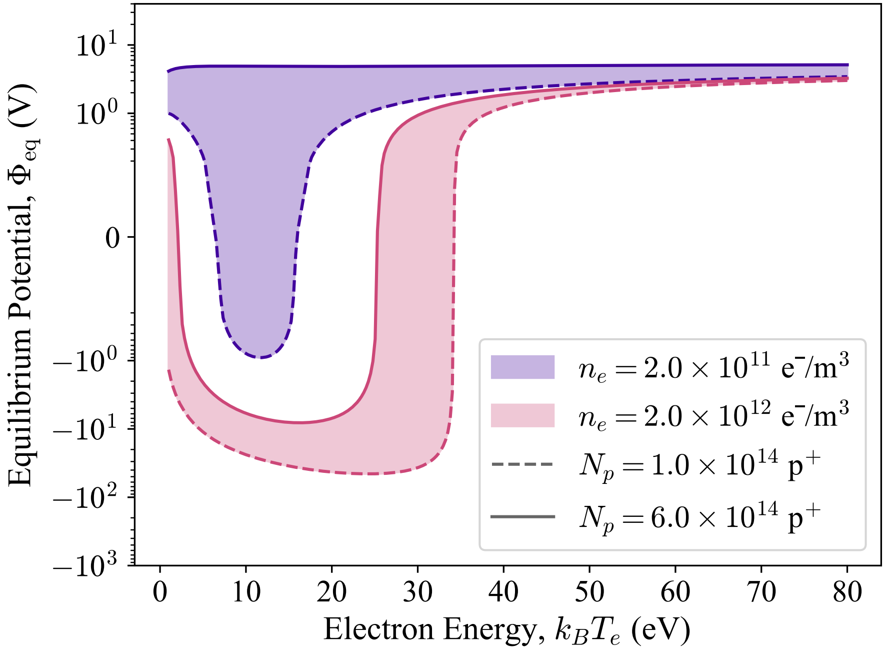
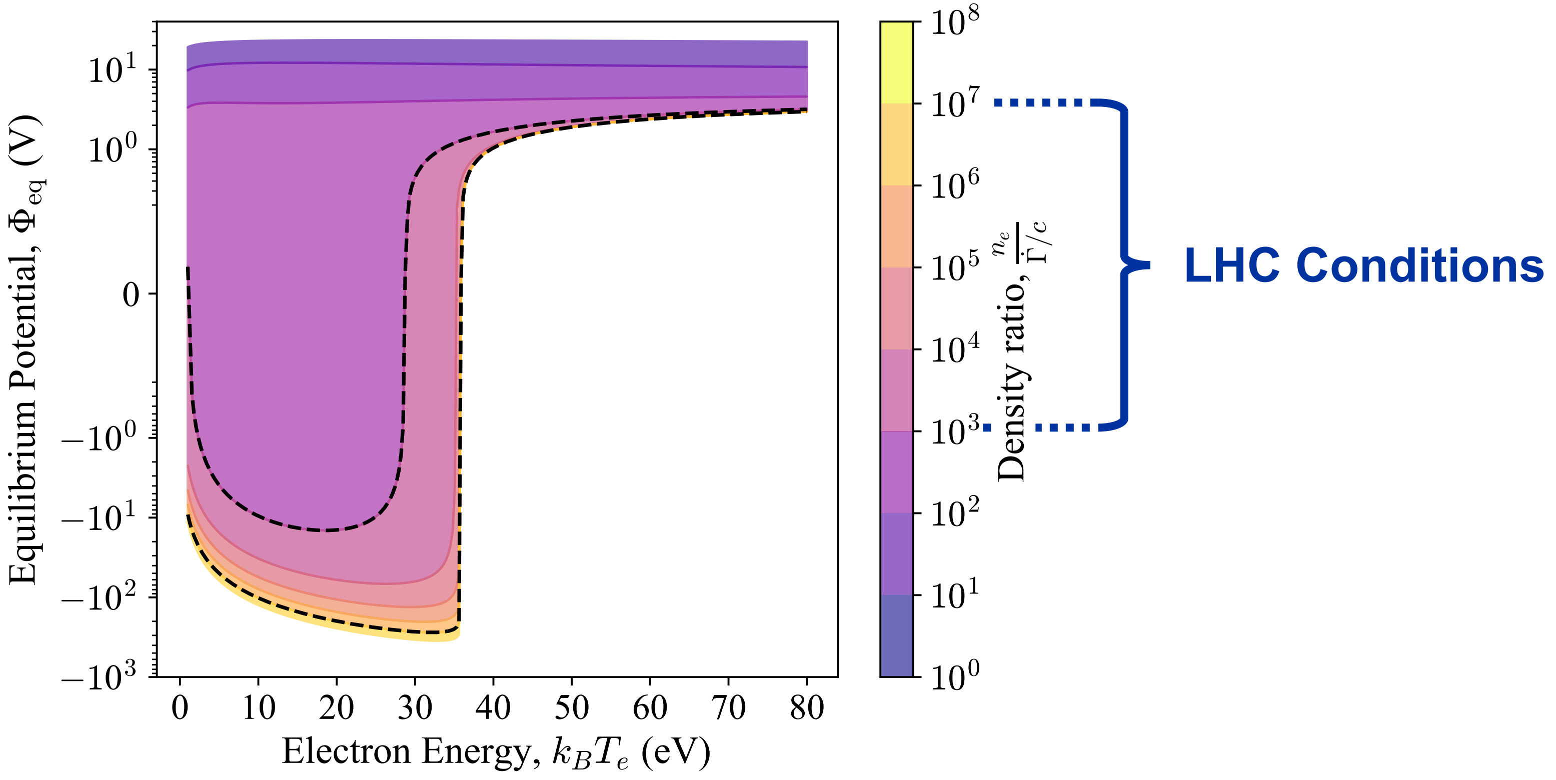


Equilibrium surface potential (density ratio)

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

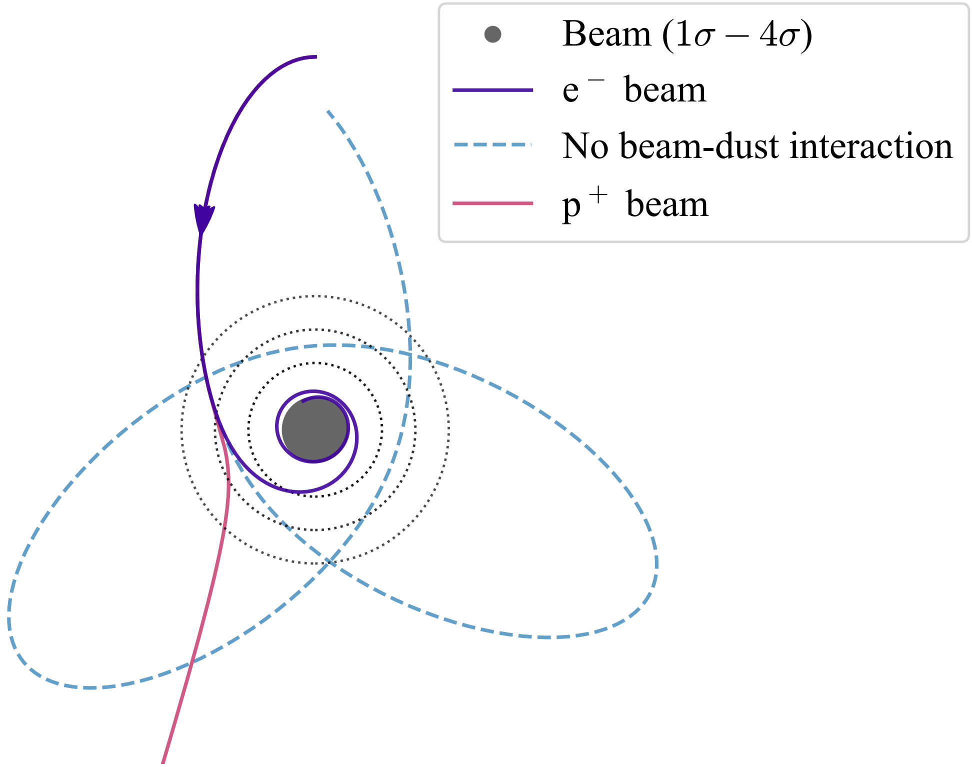


Electron machines:
- Density ratio much lower
- Patch model need to be taken into account

Trapped dust grains

From previous slides, the main conclusion is:

- Negatively charged grains in presence of high density e-cloud (LHC)
- Positively charged grains in presence of low density e-cloud (e- storage rings)
- Let's not forget: precise calculation would be highly dependant on the shape of the grain. Dust events are a stochastic process



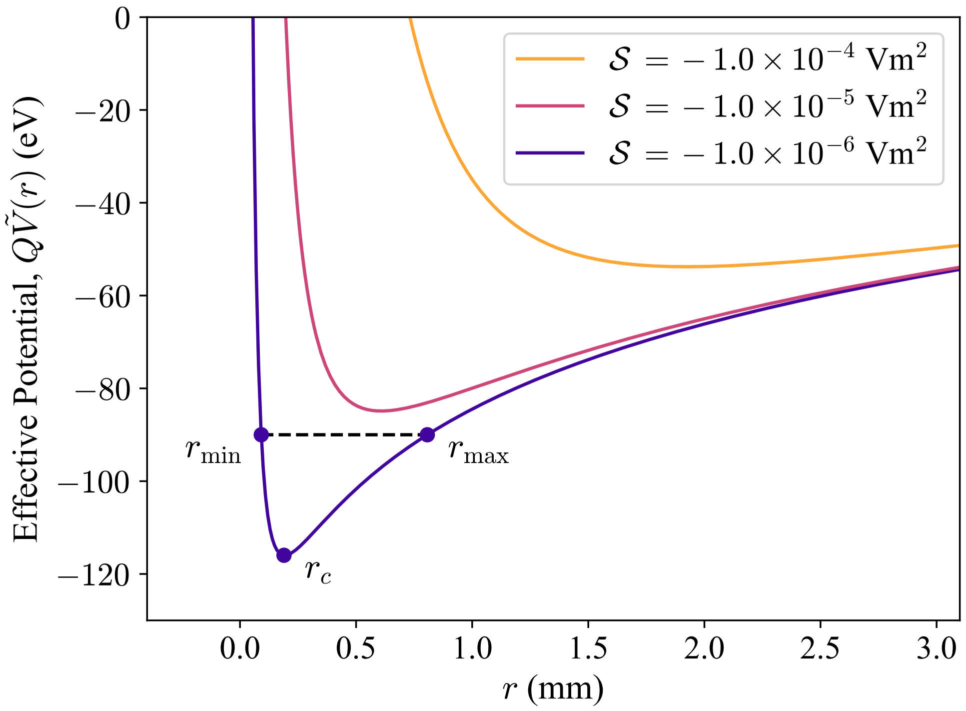
Opposite charge from the beam implies: orbiting motion!

Logarithmic potential

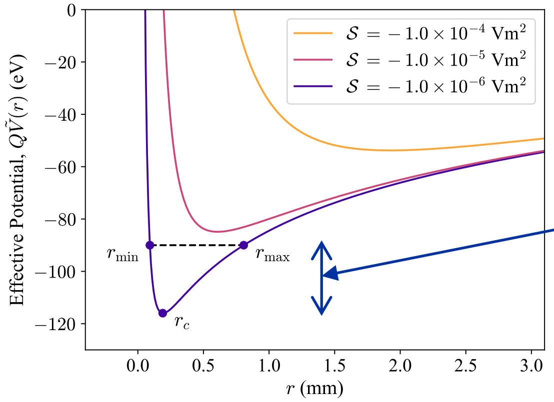
Relevant parameter: orbital stiffness

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

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



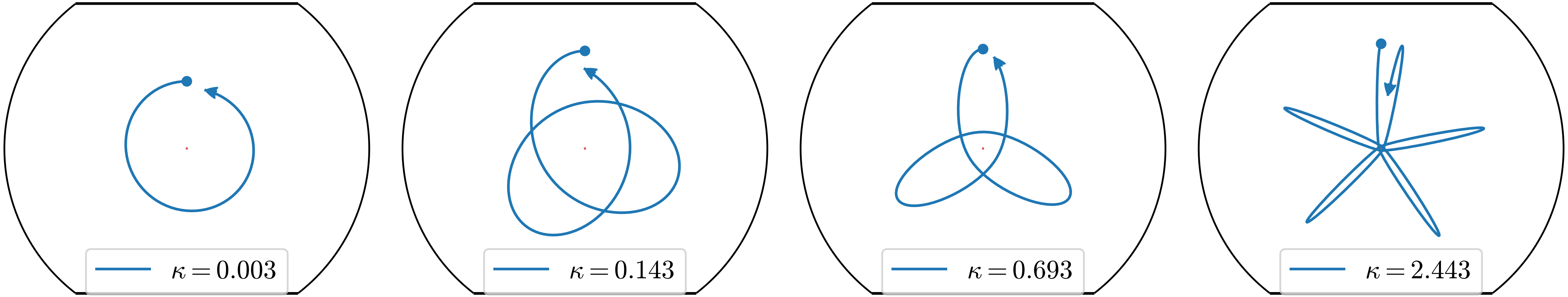
Shape parameter



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

Can be used to describe **circular orbits**, as well as trajectories falling into the beam (**typical UFOs**)

Based on: H. Hooverman, Charged particle orbits in a logarithmic potential, J. Appl. Phys. 34, 3505 (1963).

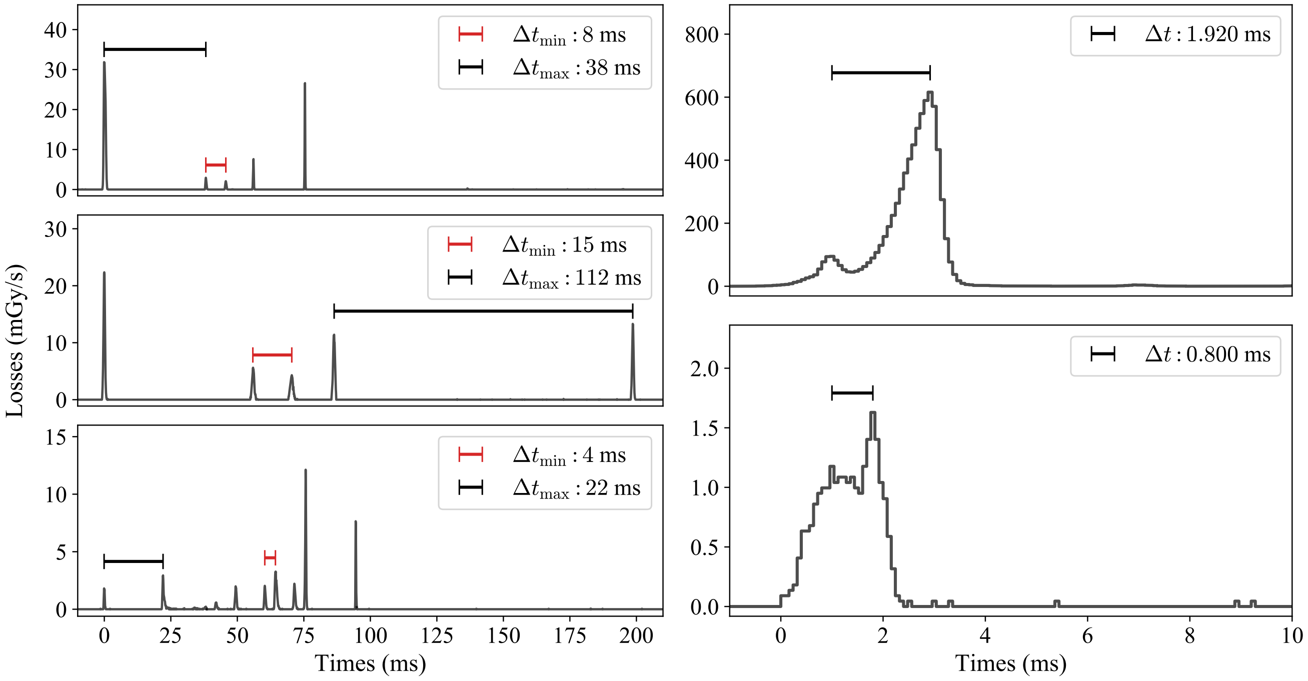


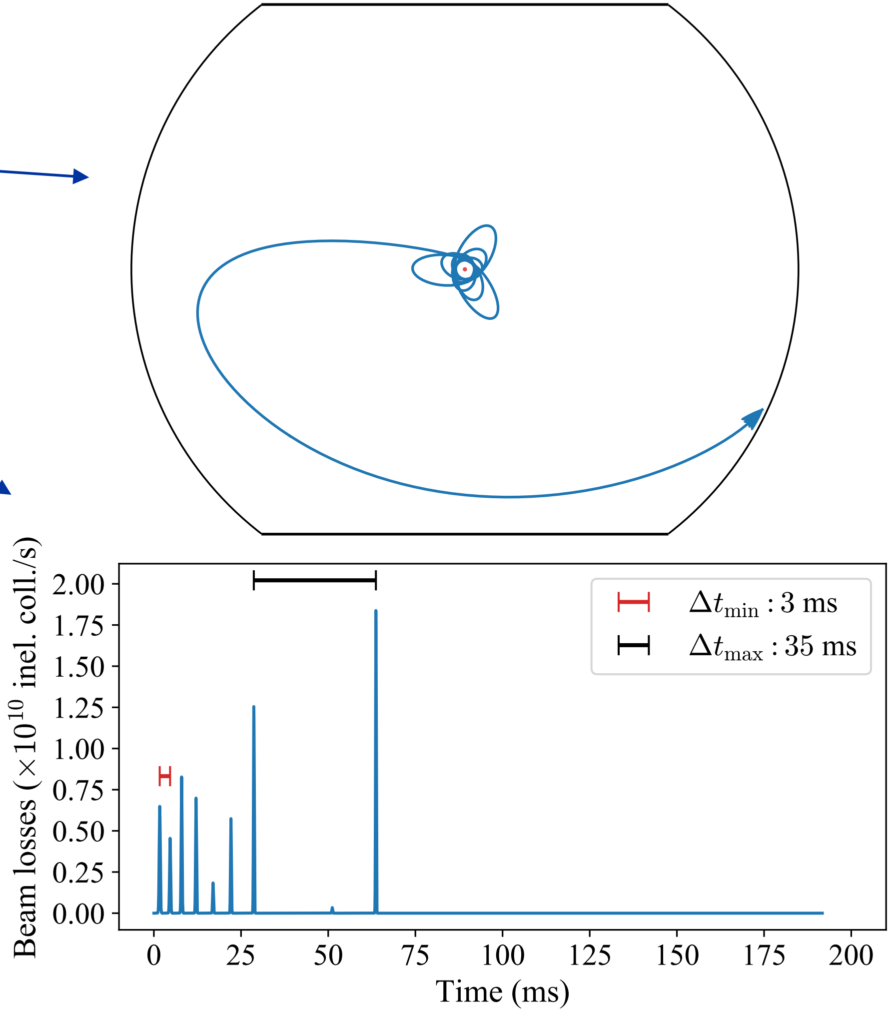
Multipeak measurements

Simulated losses can be found with:

- Similar time scale
- Similar proton losses

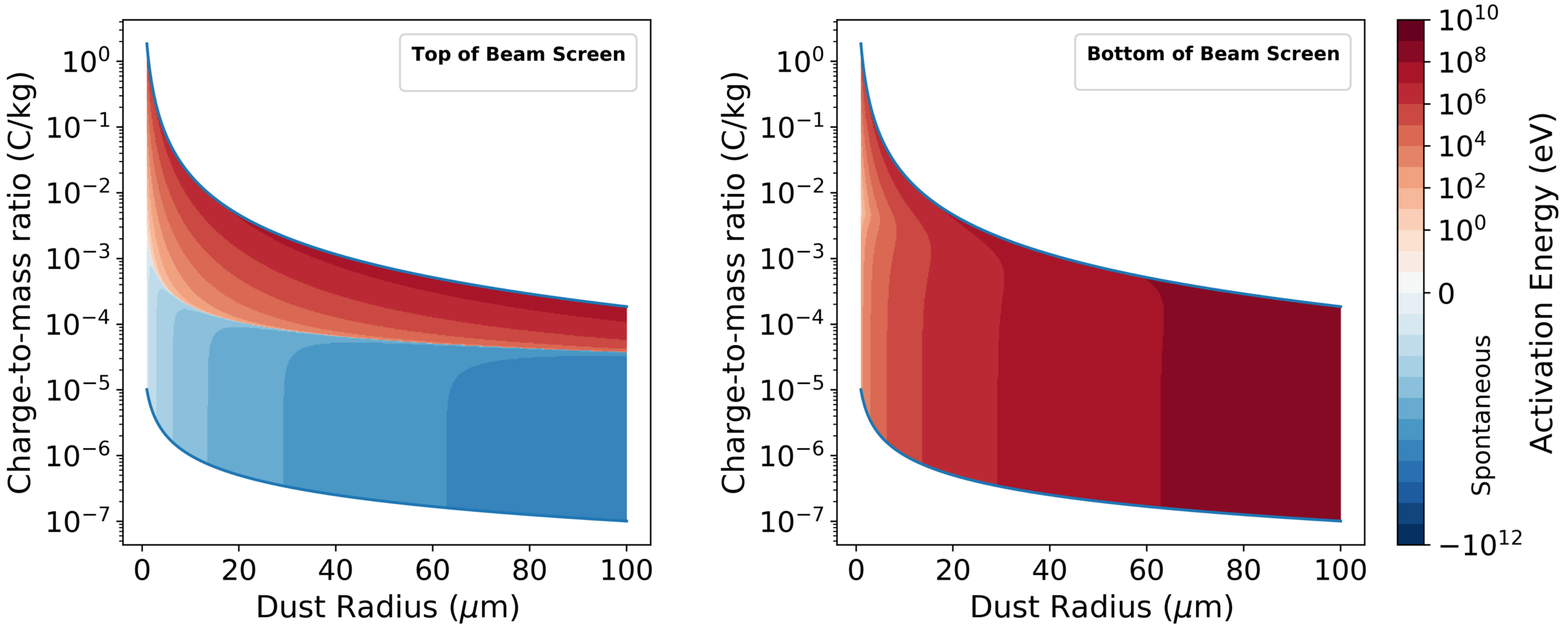
Measurements





Excitation Energy

- **Impossible** to pick up dust from the bottom?
- More appropriate to discuss the **energy required** to reach beam core



* Ex.: 200 nm initial separation. M. Barnes : 60-300 Hz, 10 nm vibration: 1-40 eV for UFO mass

Summary and outlook

- **Polarity of dust grains in particle accelerators can be explained from first principles**
  - Balance of charging currents lead to equilibrium potential
  - Patch charge model highlight the importance of grain geometry
  - **Simulations (PyECLOUD, MIGRAINe, TPG3D [LASP]) could be used to cross check and extend**
  - **LASP measurements could be used for validation**
- **Dynamics can be described with orbital parameters both in e- and p+ machines**
  - Multipeak measurements in the LHC
  - Dust trapping measurements in e- ring
- **Release mechanisms and dust migration**
  - Obviously of the biggest unknow for dust in particle accelerators
  - **Adhesive forces need to be studied**
  - **Dust collectors and/or mitigation strategies need to be studied**

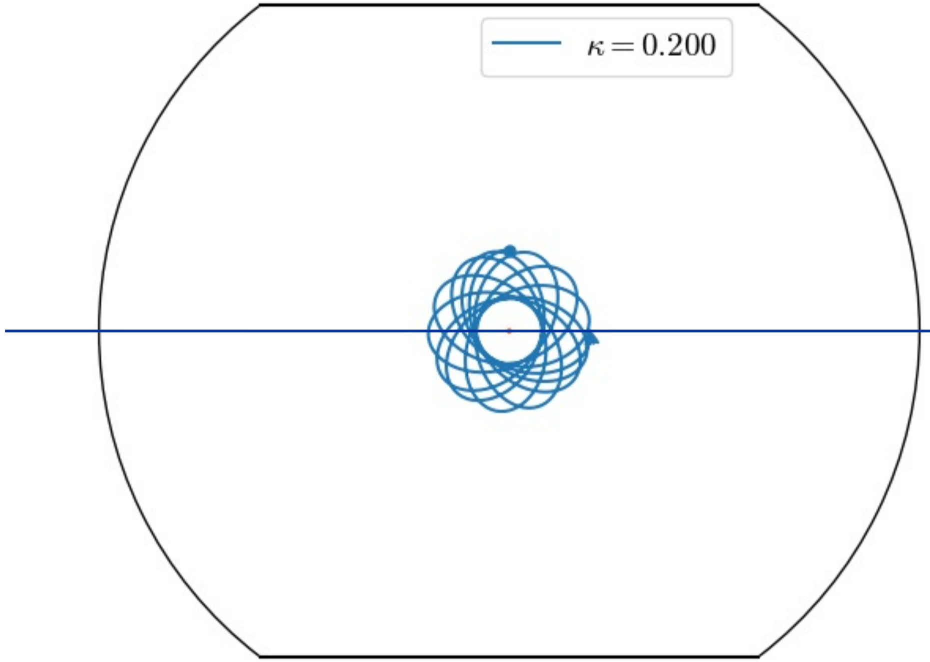
Thank you!

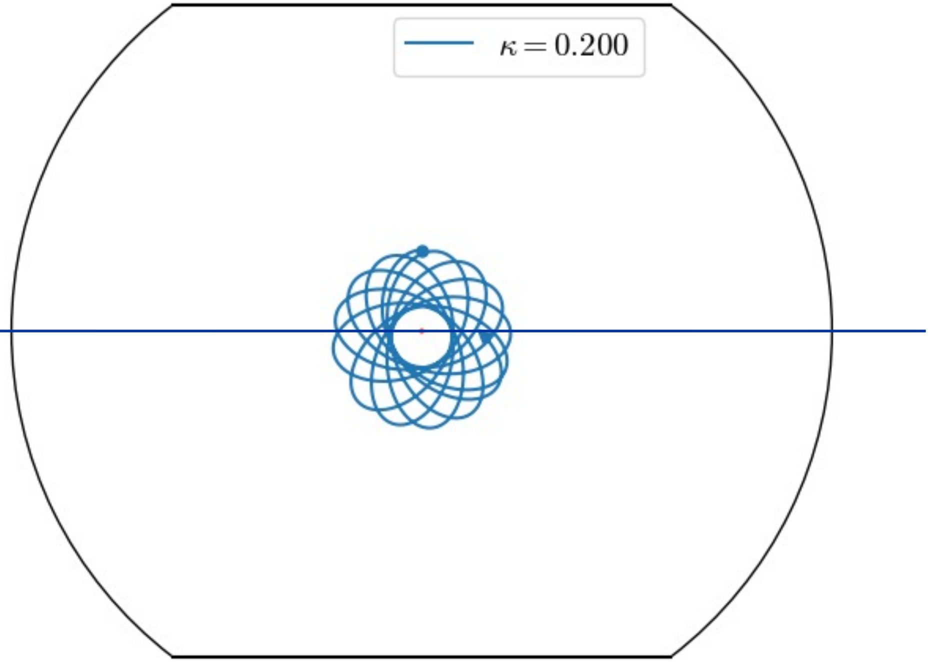
Questions?

Effect of gravity

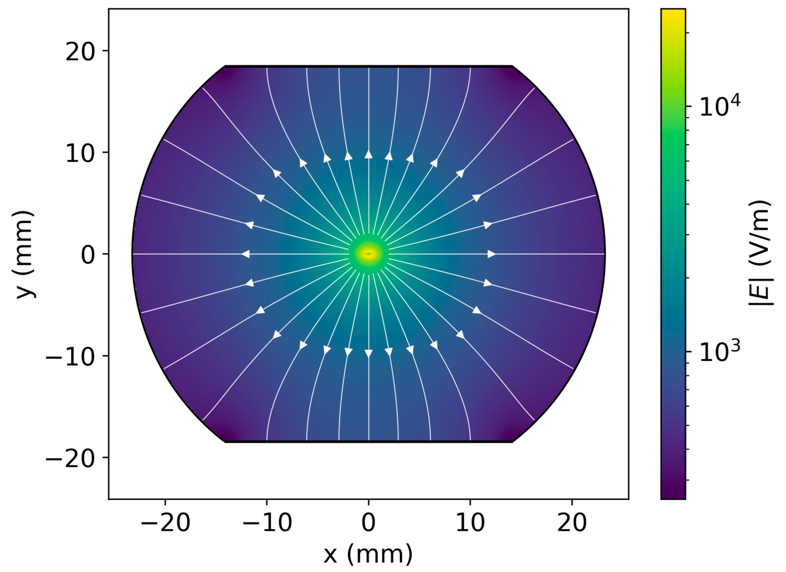
One can formally show that gravity can be neglected if: $\frac{1}{|Q|/m} g \ll \frac{2V_0}{r_c}$ where $V_0 = \frac{N_p e/C}{2\pi\varepsilon_0}$

To First order : only deforms the orbits down.





Adhesive forces



Considered:

1. Van Der Waals
2. Image charges from the dust grain
3. Beam electric field
4. Gravity

Not considered:

1. Effect of plasma sheet!!! ()