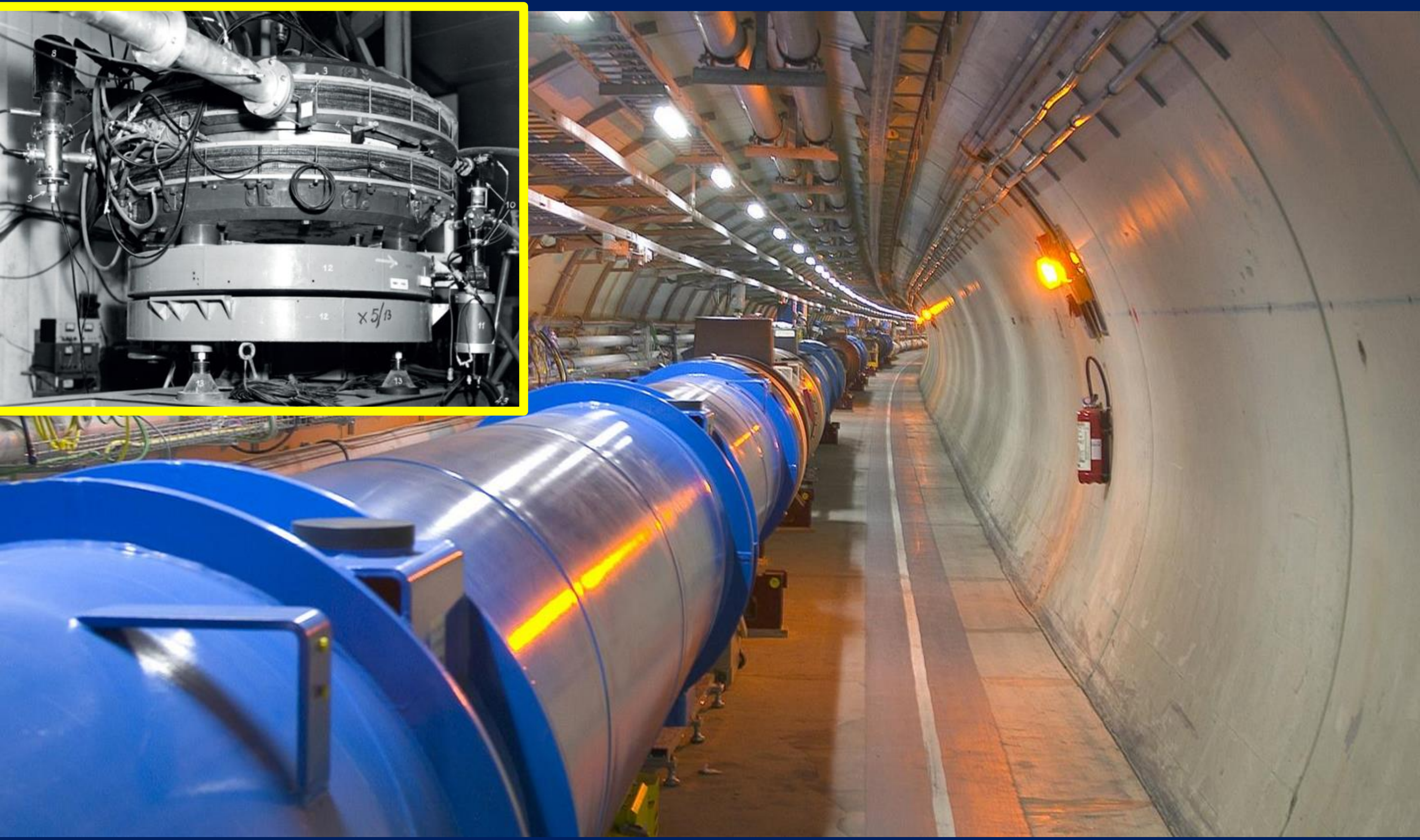
Overview of beam-dust issues in accelerators: From AdA, the first e+e- collider, to LHC



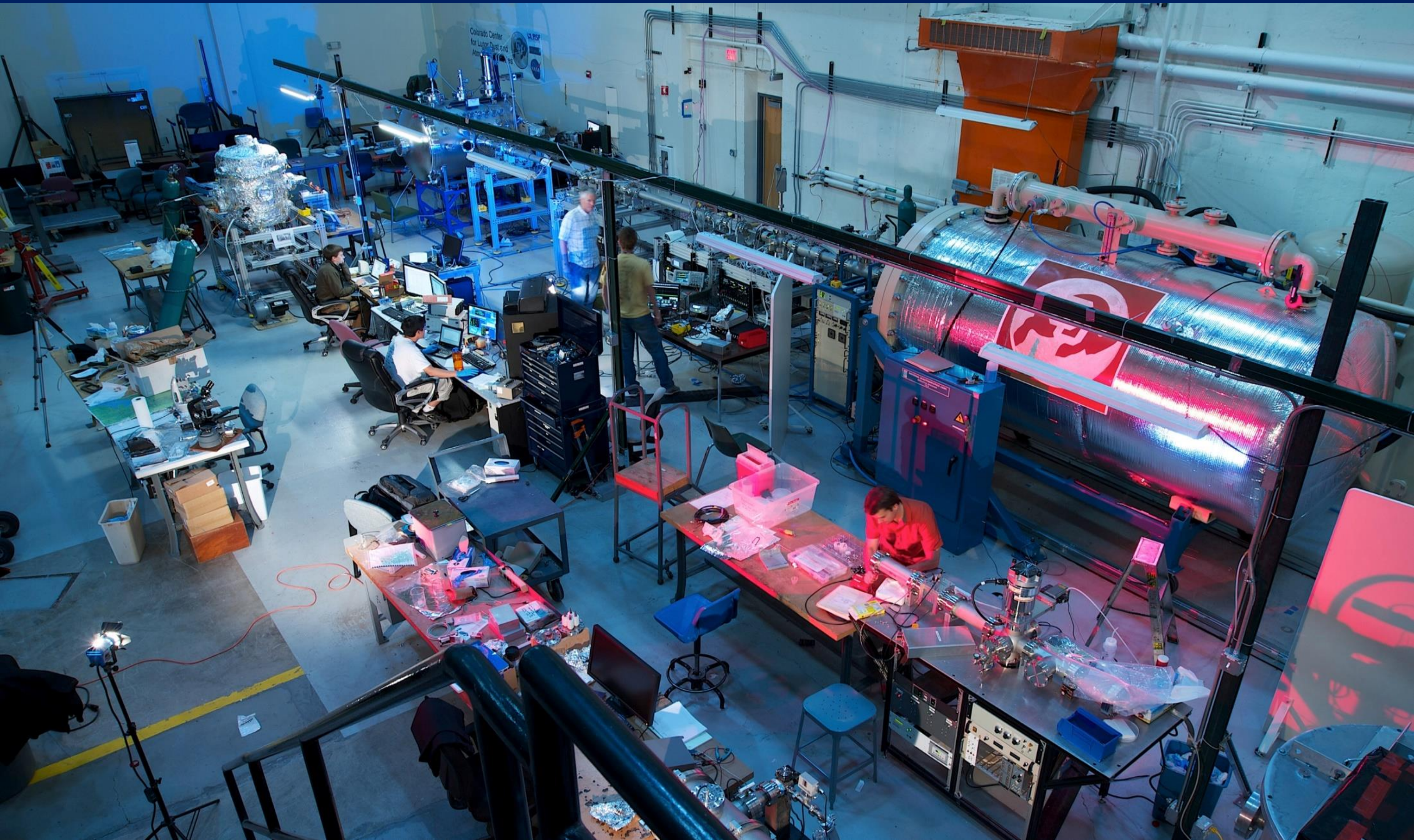
R.Schmidt, TU Darmstadt, GSI and CERN-user


DUS


WE ARE NOT ALONE
PT.1

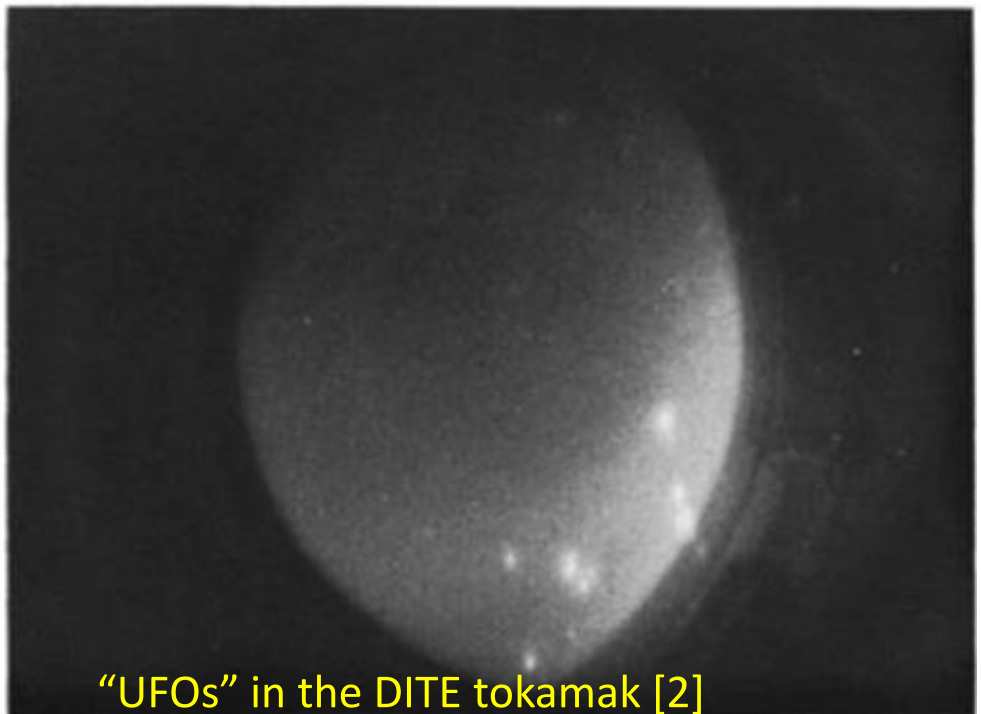
An accelerator for accelerating dust grains

LASP (Laboratory for Space Research), University of Colorado, Boulder, CO, USA



UFOs in tokamaks ... and at LHC

- As early as 1970s scientists knew that "particulate matter" exist in tokamaks
  - Early images of dust events in the DITE tokamak at JET, called "UFOs = **U**nidentified **F**alling **O**bjects"
  - At present dust is commonly observed with fast cameras in current major fusion devices



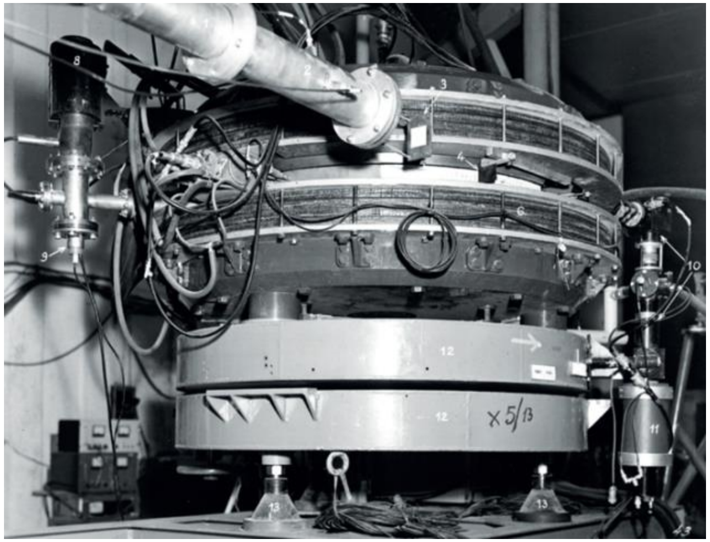
"UFOs" in the DITE tokamak [2]

[1] Modeling dust effects in plasmas of magnetic fusion devices, R.Smirnov, University CA San Diego (2020)
[2] D.H.J. Goodall, J. Nucl. Mater. 111-112 (1982)

Dust in accelerators: The story starts in 1961

1961	AdA (Frascati, Italy): First e+e- collider - observation of dust in an accelerator
1969	Apollo 11 misson landed on the moon
1971	ISR (CERN): Dust in first proton-proton collider
1974	Surveyor observations of lunar horizon-glow
1982	Bright moving macroscopic particles have been observed in many tokamaks **(called UFOs)**
1983	PHOTON FACTORY (KEK): Sometime sudden partial loss of beam (not understood)
1984	Antiproton Accumulator at CERN: Thorough theoretical analysis of dust issues in the AA
1985	NSLS (Brookhaven, USA): Beam lifetime occasionally changes abruptly for several hours to five minutes during operations. This has begun at a current above 100 mA.
1991	DCI and SUPER-ACO (Orsay, France): Bremsstrahlung production from dust was observed when operating with electrons (positron source broke down during a month)
1991	Tristan Accumulation Ring (Tsukuba, Japan): Observation of lifetime drops in electron beam led to several experimental
1992	ESRF (Grenoble, France): Change of undulators gaps produced sometimes intensity losses
1992	HERA (DESY, Hamburg, Germany): Sudden breakdown of e-beam lifetime with low intensity threshold, finally solved by operation with positrons
1993	CESR (Cornell, USA): Change of beam current lifetime in e-ring
1995	Tristan Accumulation Ring (Tsukuba, Japan): Experiment by dropping dust grains into beam
1999	KEKb HER e-ring (Tsukuba, Japan): Observation of dust trapping
2010	LHC (CERN): First observation of UFOs - dust-beam interactions
2016	SuperKEKb e+ ring (Tsukuba, Japan): Observations of beam dust interactions

AdA - first observation of dust in accelerators ...by eye



AdA was the first-ever electron–positron particle collider, measuring approximately 1.3 metres in diameter and designed to store beams of 250 MeV, build at Frascati, Rome, Italy. It started operation in **1961**.

"The stored beam sometimes was suddenly lost. There, by sheer chance, Bruno Touschek and Pierre Marin were looking through the porthole in the donut searching for the malefic elf's who were destroying the beam – and found them in the form of **fluttering diamagnetic dust left over from the welding of the donut** and moving under gravity along the magnetic field lines and passing through the beam."

https://link.springer.com/article/10.1007/s00016-003-0202-y

CERN-ISR proton-proton collider 1970-1971

- Pressure bumps and beam loss in the ISR during running in of the machine
  - **No dust:** The proton beam ionizes residual gas molecules. The space charge accelerates the ions towards the wall. The ions desorb molecules. A pressure instability has been a limitation for the maximum circulating beam current.
  - **Dust:** During the initial two years, **some of the pressure bumps were explained by dust grains**, possibly introduced by thermal insulation material for bakeout when opening the bellows.

E-6

ISR-VA/EJ/cc

8th November, 1973

ISR PERFORMANCE REPORT

"Dust" and Bakeout Insulation

ISR-MA/BWM/EEK

8th June, 1971

ISR RUNNING-IN

A note on the dust wall model of E. Fischer

(ISR-VA/EF/ck, 3rd June, 1971)

ISR-VA/EF/ck

3rd August, 1971

ISR RUNNING-IN

Run 94, 28th July, 1971

Test with a dust shaker in Straight Section 117

ISR-BWM/ls

15th July, 1971

ISR RUNNING IN

More about the dust wall model

CERN Antiproton Accumulator (AA), 1985: Trapped dust grains

IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

TRANSVERSE INSTABILITIES DUE TO BEAM-TRAPPED IONS AND CHARGED MATTER IN THE CERN ANTIPROTON ACCUMULATOR

E. Jones, F. Pedersen, A. Poncet, S. van der Meer, E.J.N. Wilson
CERN, CH-1211 Geneva 23, Switzerland

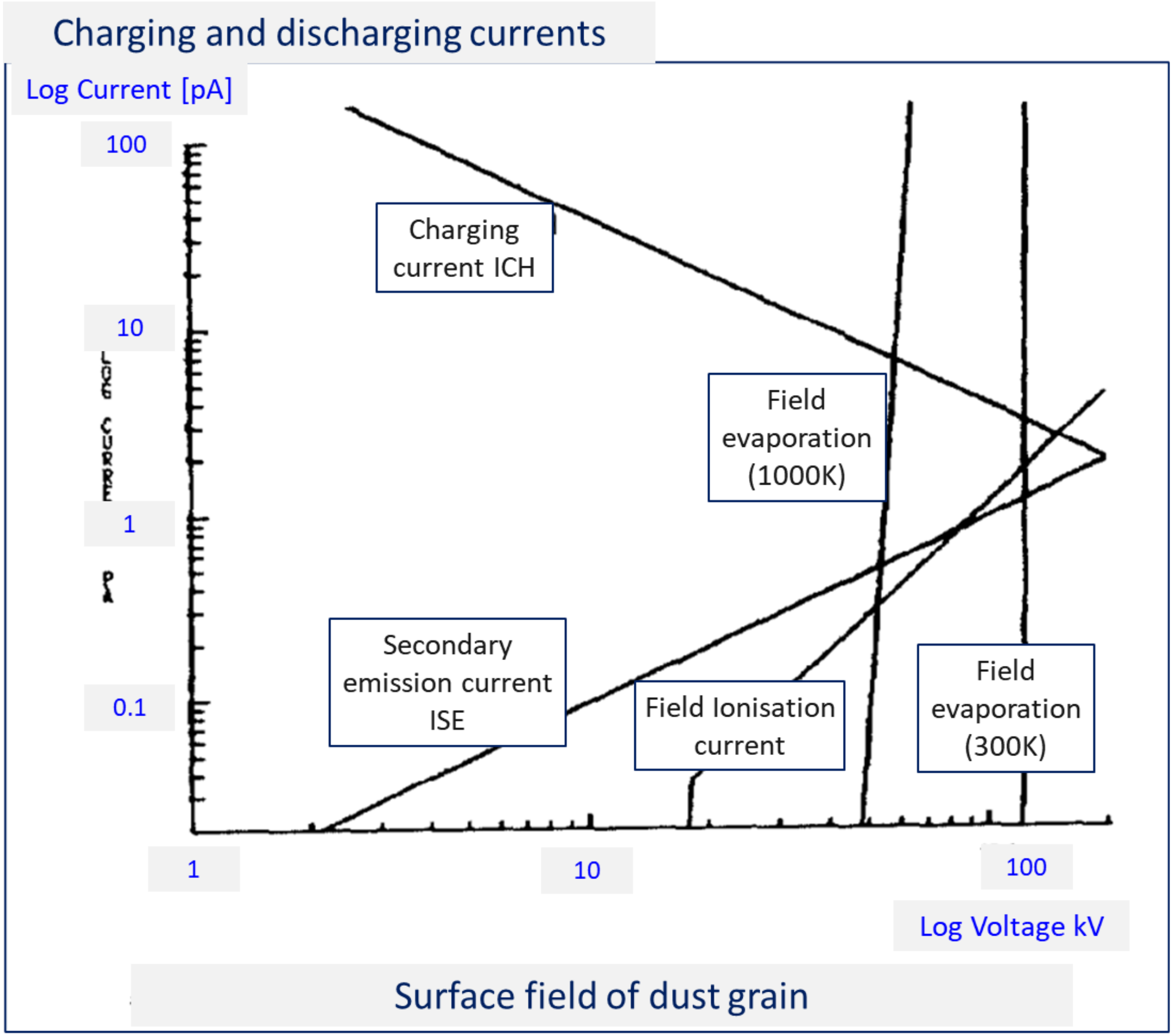
- Issues with dust grains in the CERN proton antiproton accumulator, beginning of the 80^{th}
- Intermittent and often violent growth of the beam (T = 1 min to 1 h).
- Associated beam loss rate, typically 10^9/h to 10^{10}/h.
- Occasionally, the onset coincides with an accidental trip of the shutter servos, an event provoking a mechanical shock in the beam pipe.
- This spooky phenomenon has been called the **AA “Ghost”**.

CERN AA: Transverse instabilities due to beam-trapped ions and charged matter

- Could be explained by a tiny, highly positively charged dust grains captured in the beam potential.
- The material is not precisely known (and probably differs from case to case).
- There is no synchrotron light, nor electron clouds in the AA.
- **Charging current** of dust grains by collisions of antiprotons with electrons in the grain. Electrons escape the grain, the grain becomes positively charged.
- **Discharging currents**
  1. The interaction of the beam with residual gas molecule creates free electrons that are collected by the dust grain (secondary electron discharge current)
  2. Ionisation of residual gas close to the dust grain above a surface field of 20 GV/m (H_2), leading to the capture of electrons (field ionisation current)
  3. Field emission of ions in dust grain above a threshold of about 50-100 GV/m (field evaporation current)

Effects of highly charged solid microparticles captured in negatively charged circulating beams, F.Pedersen, CERN, PAC1987

CERN AA: Charging and discharging currents



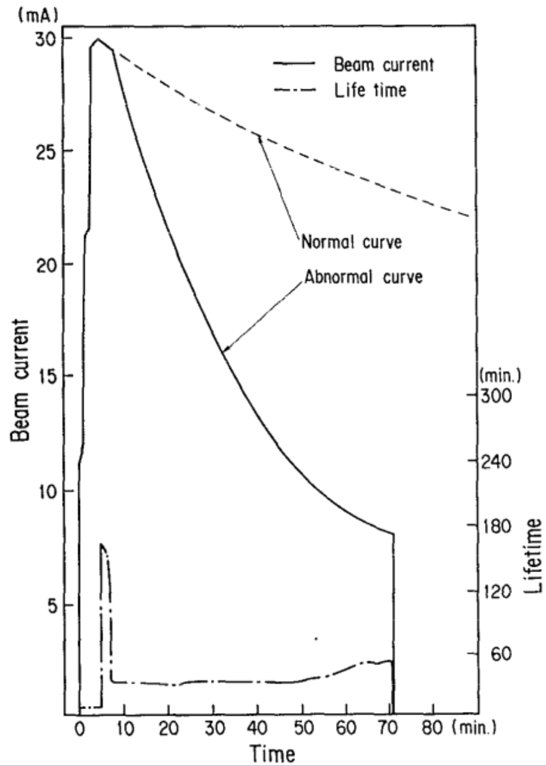
After 1987, there has been no documented case of micro-particle capture in the beam. There may be several reasons:

- Limited use of the AA shutters: less dust to be stirred up
- Higher beam densities (due to improved stochastic cooling) may reduce the maximum size of thermally stable microparticles to a harmless value
- Improved clearing has reduced the number of uncleared potential well pockets.

Very large surface fields of dust grains, up to several 10 GV/m

Tristan AR (Accumulation Ring) at KEK (1991)

- For several years, sudden decay of lifetime for stored electron beam has been observed at least once per day, leading to extensive studies
  - Observations of beam lifetime and bremsstrahlung from beam-dust collisions
  - Theoretical analysis: trapping of dust grains, grains moving in transverse and longitudinal direction
  - Three types of experiments



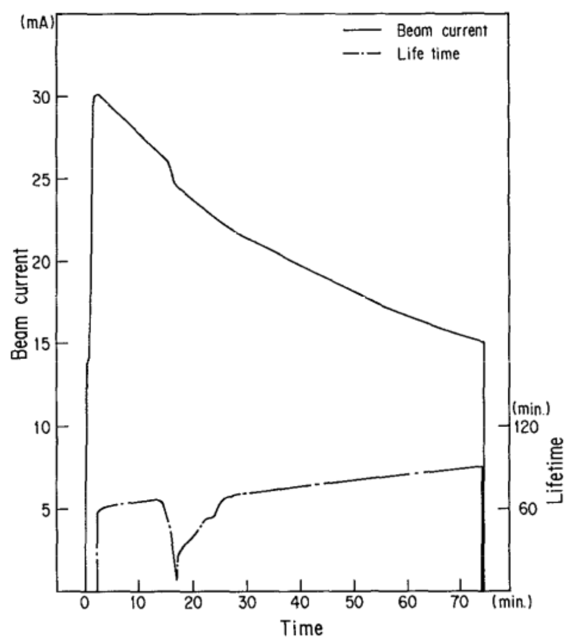
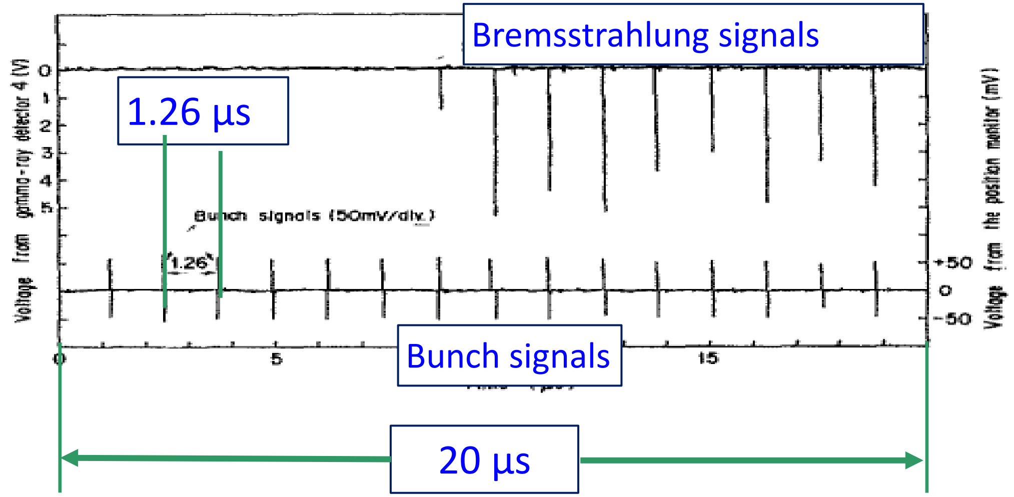
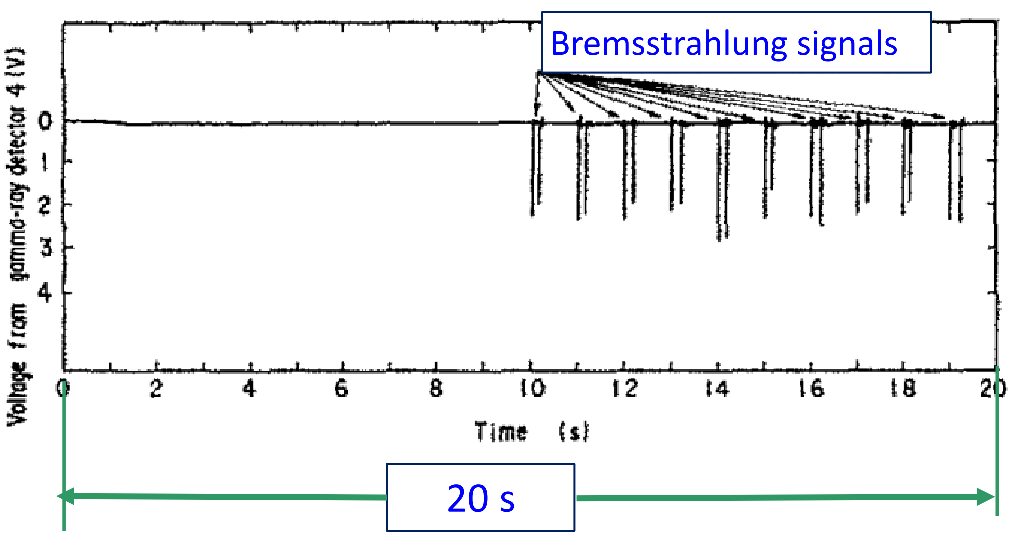


FIG. 2. Sudden decrease in the lifetime and decay of the beam current for a stored electron beam at a beam energy of 6.5 GeV. However, the lifetime of the electron beam recovered within 15 min.

H. Saeki, T. Momose, and H. Ishimaru, Rev. Sci. Instrum. 62, (1991). https://doi.org/10.1063/1.1142024

Tristan AR: Bremsstrahlung from beam-dust interaction synchronised with the bunch signal



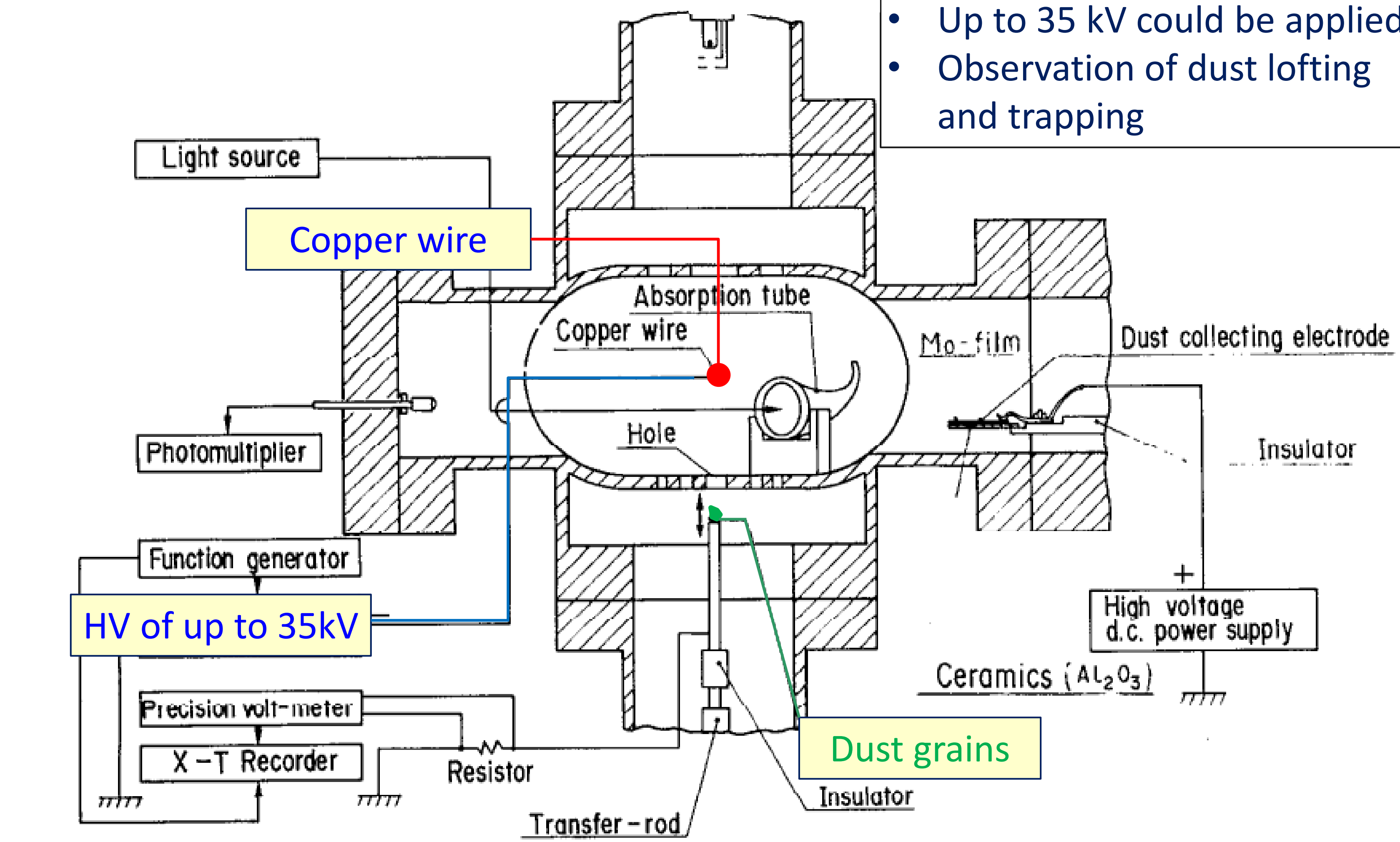


- Bremsstrahlung and bunch signal are synchronised. Each turn, collision between bunch and dust grain leads to emission of bremsstrahlung (Fig. 4).
- The dust grain made a horizontal oscillation and a vertical oscillation perpendicular to the orbit of the electron beam. The half period of the horizontal oscillation is about 200 ms and the time interval of the vertical oscillation is 1 s (Fig. 5).

Motions of trapped dust particles around the electron beam in the TRISTAN accumulation ring, H.Saeki et al., https://doi.org/10.1063/1.1142230

Tristan AR: Experiment A with a wire simulating the beam potential

- Different samples were placed
- Up to 35 kV could be applied
- Observation of dust lofting and trapping



Tristan AR: Experiment A with a wire simulating the beam potential

- Organic and metal dust was used, with sizes from 0.1 – 100 µm
- The voltage for trapping was measured, and compared with theoretical considerations

Voltages required to trap sample dust particles			
Material	**Size [micron]**	**Applied voltage to be collected [kV]**	**Theoretical value [kV]**
Organic matter	10-100	12	-
Ti	50-70	16	14.5-17.2
Ti	0.5-1.0	8.6	2.1-2.9
Al	50-70	17.3	11.3-13.3
Al2O3	2.6-6 .0	16.5	-
Cu	50-70	16.7	20.0-24.2

An enhancement factor of 4 is assumed

Tristan AR: Experiment B with / without vertical magnetic field

- Organic and Al dust placed on bottom of beam pipe, size of 0.4 – 0.6 mm
- Voltage applied up to -17.5 kV
- A charged dust grain picked up from under the wire mainly makes a vertical oscillation when there is no magnetic field; and mainly a horizontal oscillation with a small vertical oscillation when there is a bending magnetic field

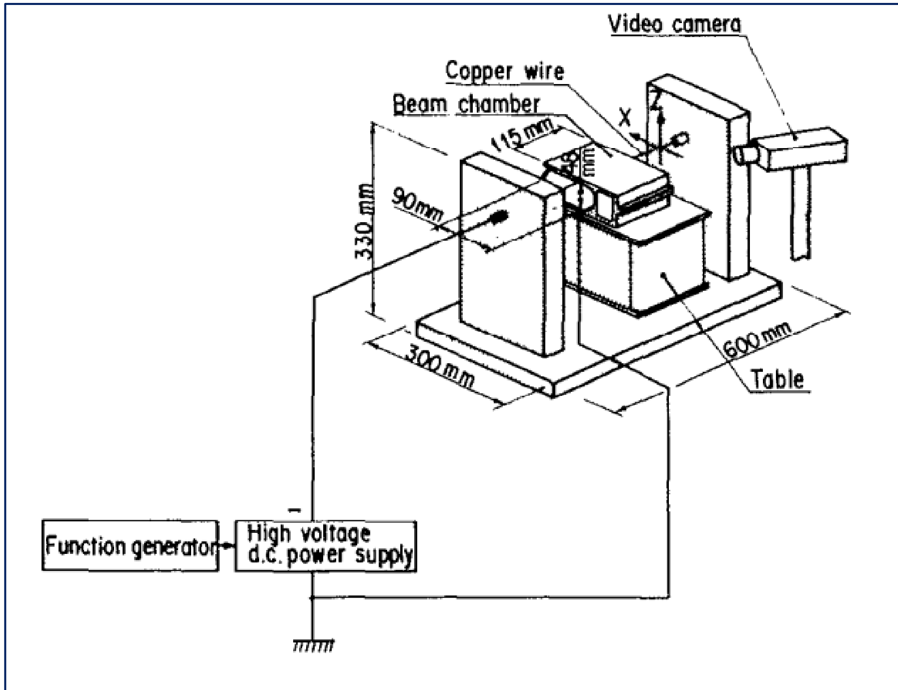


FIG. 1. Schematic drawing of the experimental apparatus using the Cu wire and no magnetic field.

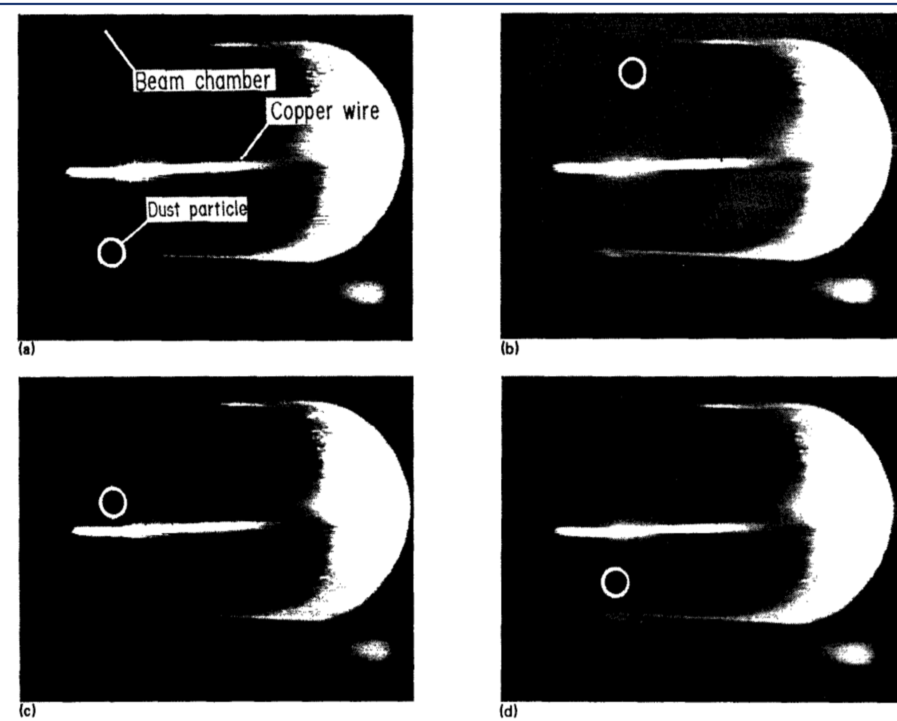
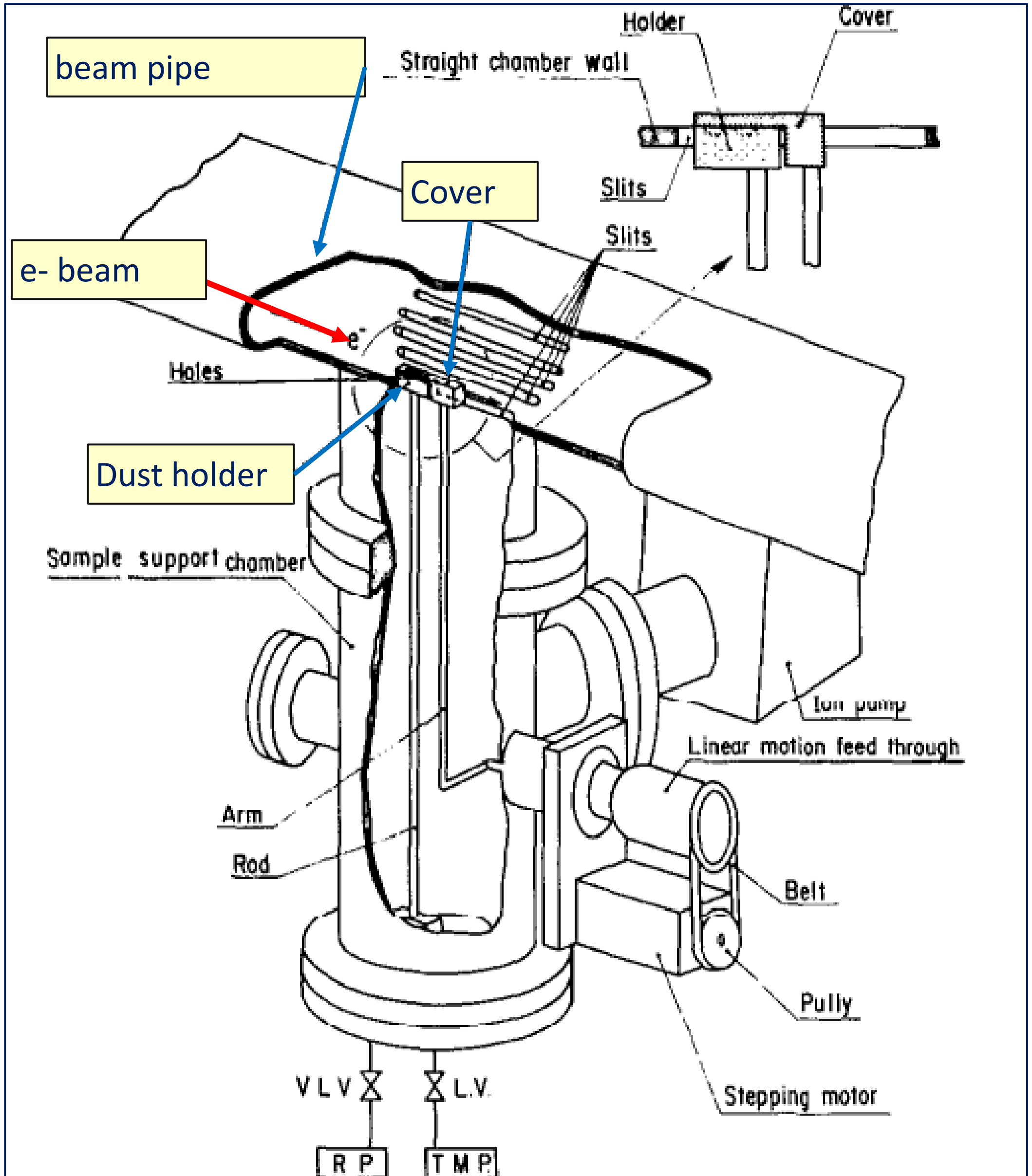


FIG. 2. Vertical motion of the charged dust particle made ... the peak of its vertical oscillation. (c) The dust particle is

https://doi.org/10.1063/1.1142231

Tristan AR– Experiment C with dust entering the beam



Sample dust grains ranging from 0.05 to 1 mm in size were put on a holder below the beam in a straight section.

The total number of dust grains was about 20. Half of the dust grains were made of organic matter and the other half made of aluminium alloy.

The beam lifetime suddenly decreased when the cover was removed and the dust grains directly under the electron beam were caught up into the beam.

Such experiments were carried out nine times, high-energy bremsstrahlung was observed four times.

After the operation of the ring was stopped, it was found that the sample dust grains had disappeared from the holder.

https://doi.org/10.1063/1.1142230

CESR Storage Ring, Cornell 1993: Mass and charge measurement of trapped dust

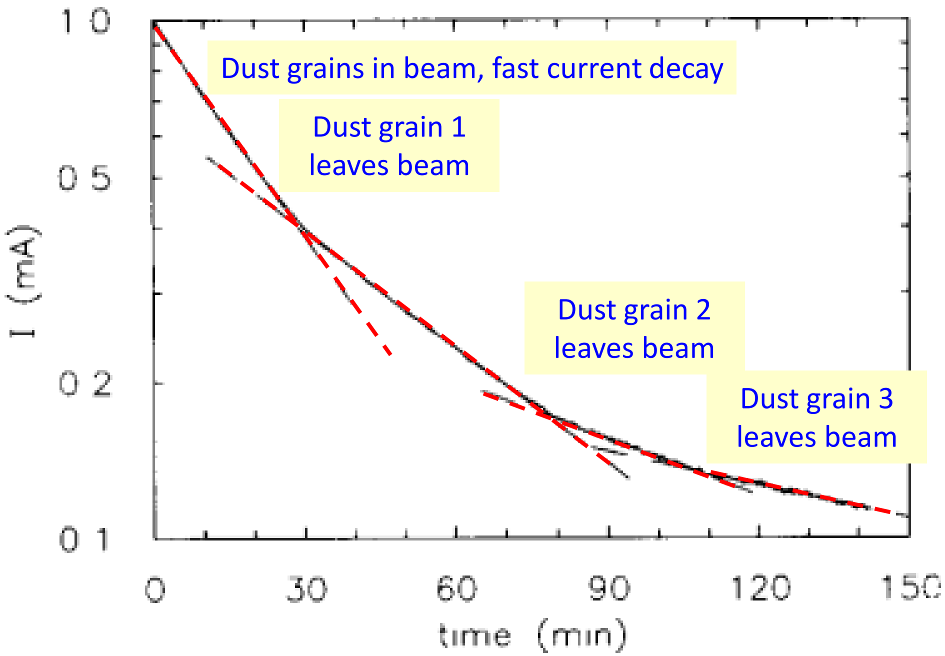


Fig. 1. Beam current as a function of time The four dashed lines are fits to the four straight sections where the lifetime is approximately constant. The kinks in the curve indicate where individual dust particles fall out of the beam

- Sudden drop in lifetime and/or a sudden increase in radiation as observed by radiation detectors near the ring: trapping of dust grains.
- Experiments to measure the mass of trapped dust grains using changes in beam lifetime – grain size in the order of a few µm.
- Calculation of charge
  - Observe the lifetime
  - Assume that the electric field of the beam is not strong enough to capture the grain when the current decreases

Mass and charge measurement of trapped dust in the CESR storage ring, D.Sagan, NIM A330 (1993) 371-379

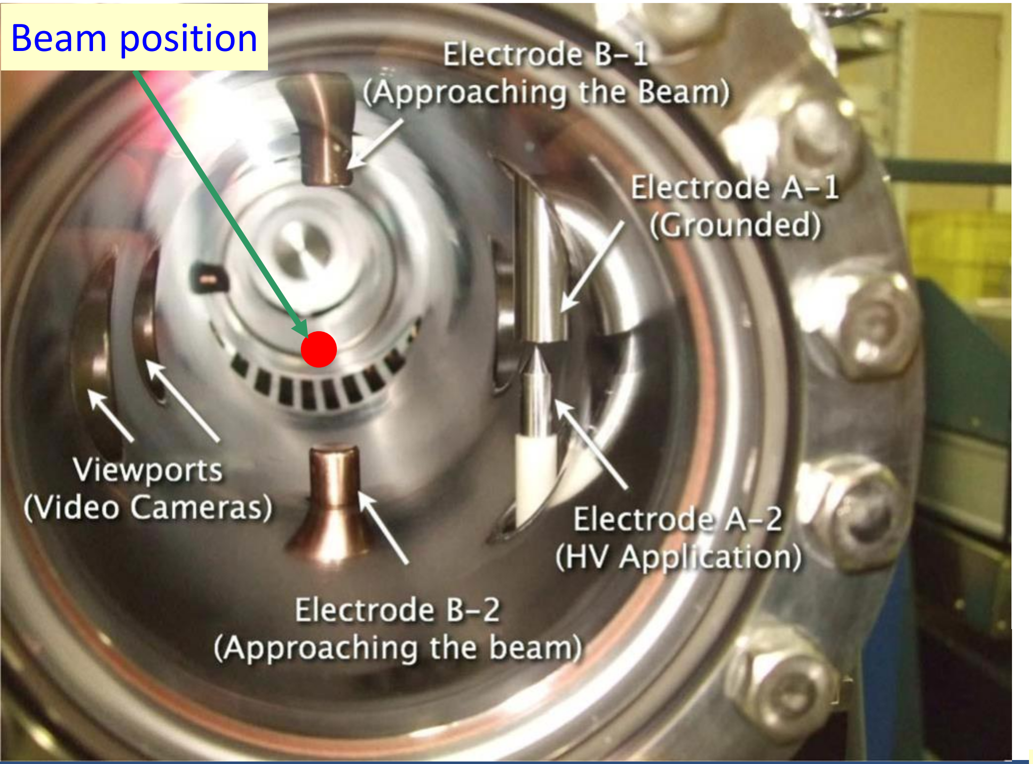
CESR: Considerations on dust charging and discharging

- D.Sagan based his work on the paper of F.Pedersen.

- Main charging process: knocking out of electrons from the dust grain due to Coulomb collisions with electrons of the beam.
- The electric field of the beam in CESR and other storage rings is at least about 2 orders of magnitude less than E_{min} for lofting: **dust grains lying on a conducting surface cannot be picked up by the electric field of the beam due to the image charge forces.**
- Several **possible mechanisms** that can cause a dust grain to be transported to the beam (.e.g. movement of devices).
- At CESR it has not been possible to associate the majority of the dust trapping events with any observable cause.
- The calculated surface fields for the three dust grains is in the range of 30 to 50 GV/m.

Photon Factory Advanced Ring (PH-AR), KEK 2009: Electric discharges for dust generation near stored beam

- Two types of electric discharges near the stored beams. The device was equipped with two types of movable electrodes and two viewing ports for video cameras
- Electrodes A1-A2 simulated discharges by applying a 5–7 kV to the lower electrode
- Electrode B (grounded) was used to simulate the discharge due to beam-induced electro-magnetic fields by moving the top and/or bottom electrodes closer to the beam



- Electric discharges caused by the applied DC HVs and the beam-induced RF fields and mechanical movement of the electrodes in the vacuum device produced dust grains
- The grains were observed with a video camera, and the interaction observed with gamma ray detectors downstream
- Dust grains travelled downstream by at least 15-20m

Y. Tanimoto et al., Phys. Rev. ST Accel. Beams 12, 110702 – 2009

PH-AR: Direct dust observation with a video camera

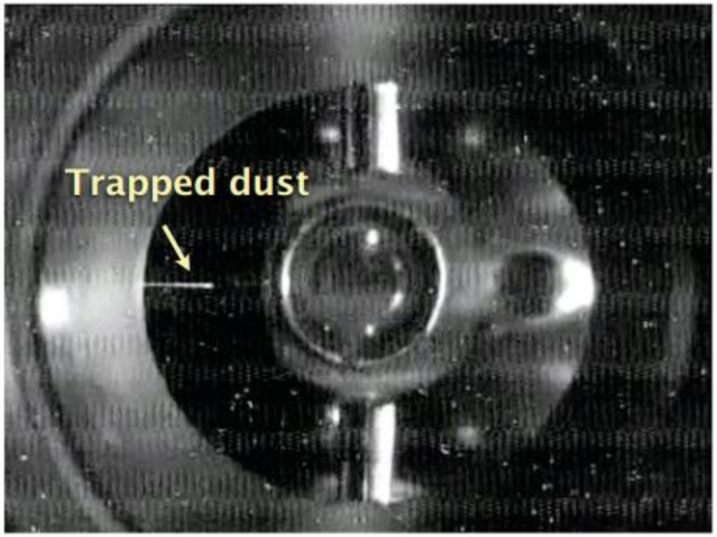


Figure 12: Direct observation of trapped dust that stayed at the same position for 40 min.

- In some cases, dust grains got into the beam due to the movement of the mechanism (no discharge).
- In one experiment, video cameras captured by chance the trapped dust particle as a luminous object.
- Evidence that dust particles can be produced at distributed ion pumps and discharge-prone vacuum devices.

- Electric discharges in vacuum can produce dust particles.
- Multiple dust particles could be simultaneously trapped.
- Thermally stable dust particles can reach thermal equilibrium.
- Detailed analysis of the cause of the light emission: the temperature of the trapped dust exceeded 1300 K.

CERN-LHC UFOs

- First observation of UFO events at LHC in 2010 (T.Bär et al, 2011)
- Large number of UFO events around injection kickers MKI (M.Barnes et al., 2010 and 2011)
  - 58 protection beam dumps of LHC beam from 2010 to 2012, 21 due to MKI UFOs
  - UFOs from MKI: solved by modifying kickers in the shutdown 2013/2014
- First simulations model (F.Zimmermann, T.Bär et al., 2011)
  - Sufficiently heavy macroparticles give rise to a maximum beam loss rate at or above the quench threshold – came as a surprise!
- A new type of UFO events was observed, UFO type 2, at one location in LHC (Grob 2017, L.Mether 2018)
- Presence of a lying object at the bottom of the beam pipe (ULO). When the beam position moved towards the ULO, UFO type beam losses were triggered.
- The UFO observations are not compatible with a dust grain falling from the top into the beam by gravity (B.Lindstrom, 2020)

Overview: A.Lechner, other LHC talks: V.Baglin, K. Paraschou, C.Garion, M.Himmerlich, A.Fontenla

Dynamics of dust grain movement close to the beam

- **Electron /antiproton beams: T**rapping of dust grains in the beam potential for long time (many minutes to hours)
  - Oscillations around the beam
  - Movement along the beam
  - Melting / vaporisation of dust grain due to beam heating
    - Thermal stability of dust grains to be considered

- **Proton beams:** Very short interaction with the (µs .... ms), e.g. LHC
  - Dust grain charged by the beam halo to positive potential
  - Dust grain expelled from the beam (UFO type 1)
  - Possibly magnet quenches due to collisions of protons with dust nuclei
  - In some cases, multiple radiation peaks are observed within some 100 ms
    - Movement of dust grain around the beam potential is possible also for proton beams)

How does a dust grain get detached from the wall of the beam pipe?

Accelerator Physics to Atmospheric and Space Physics

- Charging mechanisms of dust grains in accelerators (P.Belanger 2022)
  - Referring to papers from research groups on Space Physics: Mechanisms that dust grains can be lofted from a surface
  - Very interesting to understand charging mechanisms in accelerators
- Visiting the Laboratory for Atmospheric and Space Physics (LASP), University of Colorado, Boulder, USA, 2022
  - All about dust: similar questions in both research areas
  - Proposal to use an experimental setup at LASP for some experiments
  - Dust grains can be lofted from a surface!

Since then, scientific exchange between CERN and LASP which led to this workshop

Dust charging and transport on airless planetary bodies (**X. Wang**, J. Schwan, H.-W. Hsu, E. Grün, and **M. Horányi**), 2016

Known release mechanisms of dust grains

- Magnetic dust grains move into beam due to magnet fields
- Creation of dust via flaking from titanium sublimation pumps or ion pumps
- Firing of injection kicker magnets
- Sparking of electrostatic separators
- Discharges inside the beam pipe
- Dust from movable devices, during movement
  - CESR sparking of the electric separators and scraper movement
  - CERN-AA: actuation of mechanical shutters installed in the beam pipe
- Dust from fibres enter the beam pipe when it is open (ISR)
- Vibration of the beam pipe. Dust trapping could be provoked by mechanically knocking on the beam pipe
  - for PEP2 HE e-Ring with a remotely powered solenoid (“thumper”) in 2001
  - for SuperKEKb with a beam pipe knocker in 2016

..... release mechanisms that are not understood

Most of the time there is no correlation between a release mechanism and a beam dust event (e.g. most events in the LHC)

- Dust events are more common after maintenance of the accelerator
- Dust inside the beam pipe, lying on the bottom or attached to the surface ?
- Picking up dust grains from the bottom of the beam pipe ?
- Peeling off of dust grains from the top of the beam pipe ?
- Some release mechanisms rely on charges of the dust grain

Dust grain size

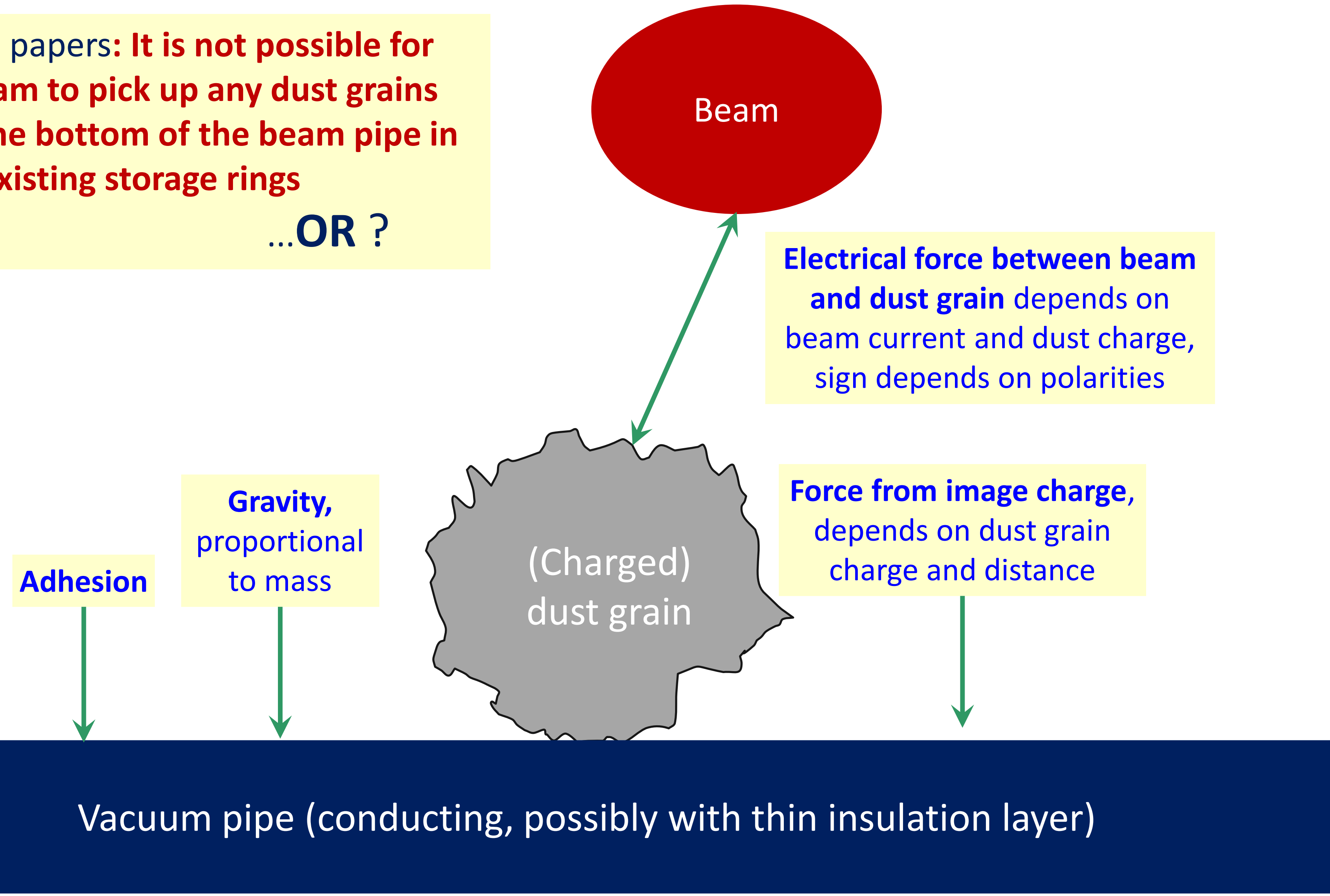
- Reported to be a few micron (e.g., p-pbar, CESR, ...), about one micron (e.g., LHC), up to several 100 micron (TRISTAN AR wire tests)
- Dust grain material: large variety, metallic, organic, ...

Controlling Particulates and Dust in Vacuum Systems, L.Lilje, Proceedings of the 2017 CERN–Accelerator–School course on Vacuum for Particle Accelerators, Glumslov, (Sweden)

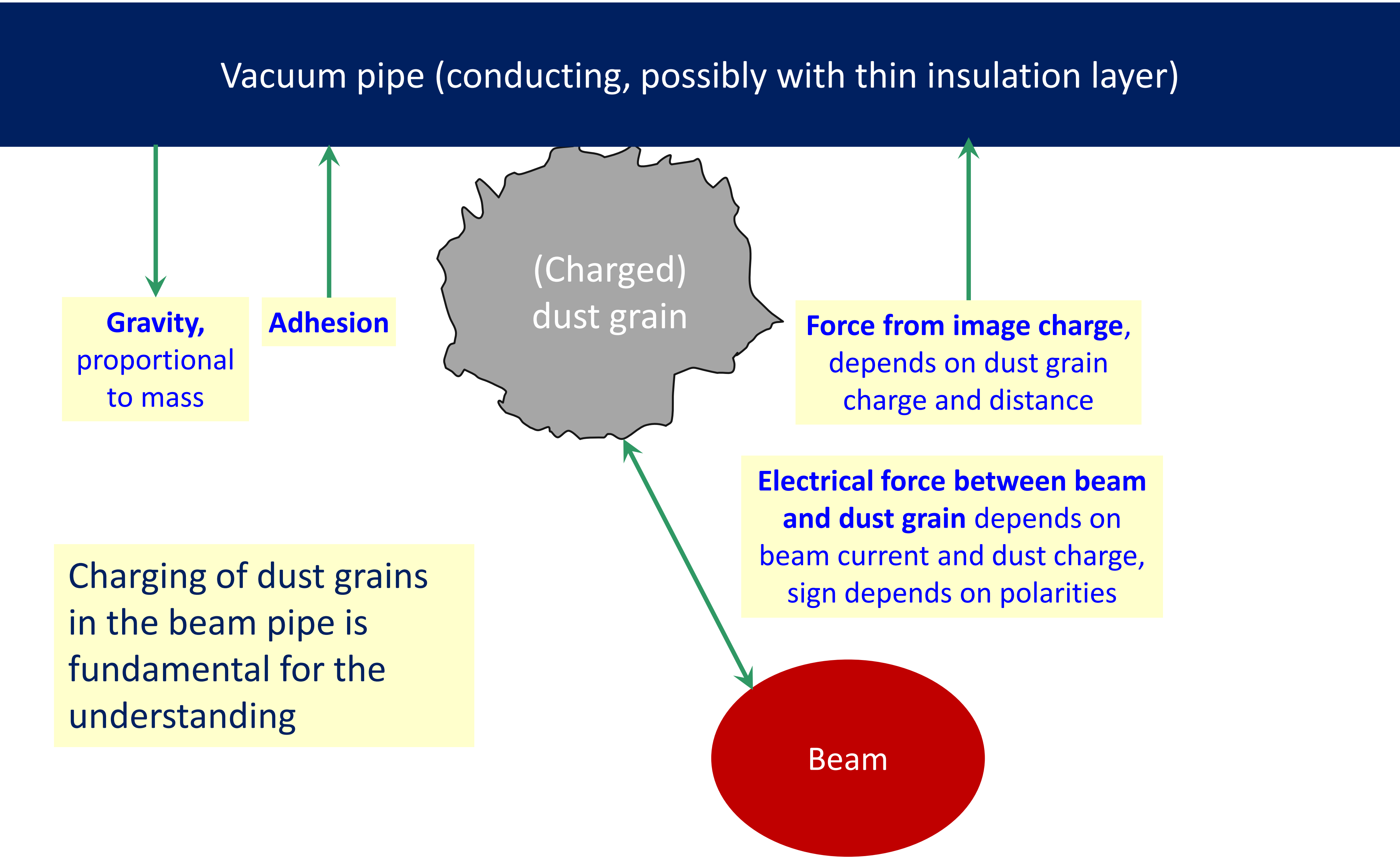
Forces on dust grain on the bottom of the beam pipe

Several papers: **It is not possible for the beam to pick up any dust grains from the bottom of the beam pipe in most existing storage rings**

…**OR** ?

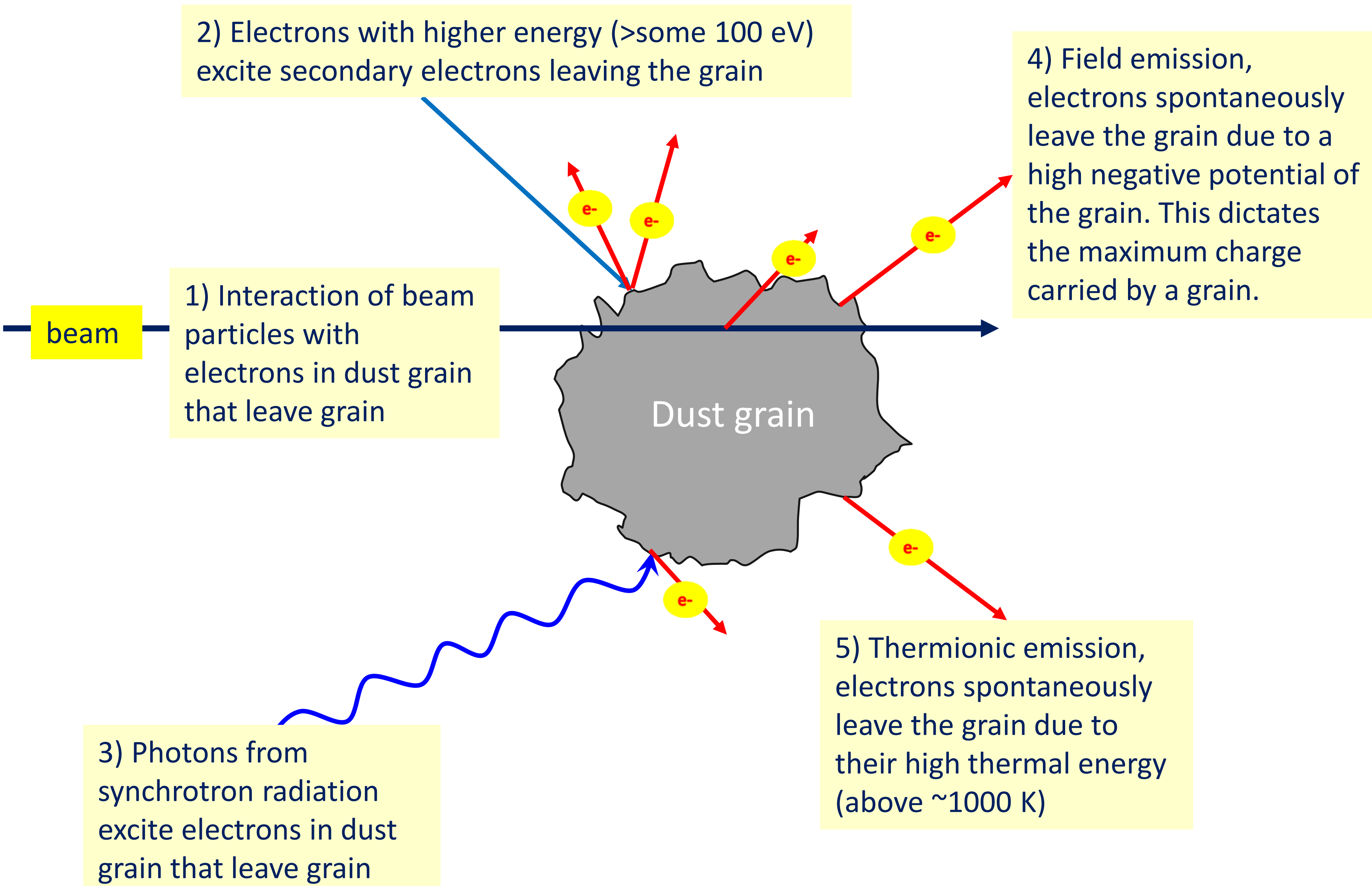


Forces on dust grain on the top of the beam pipe

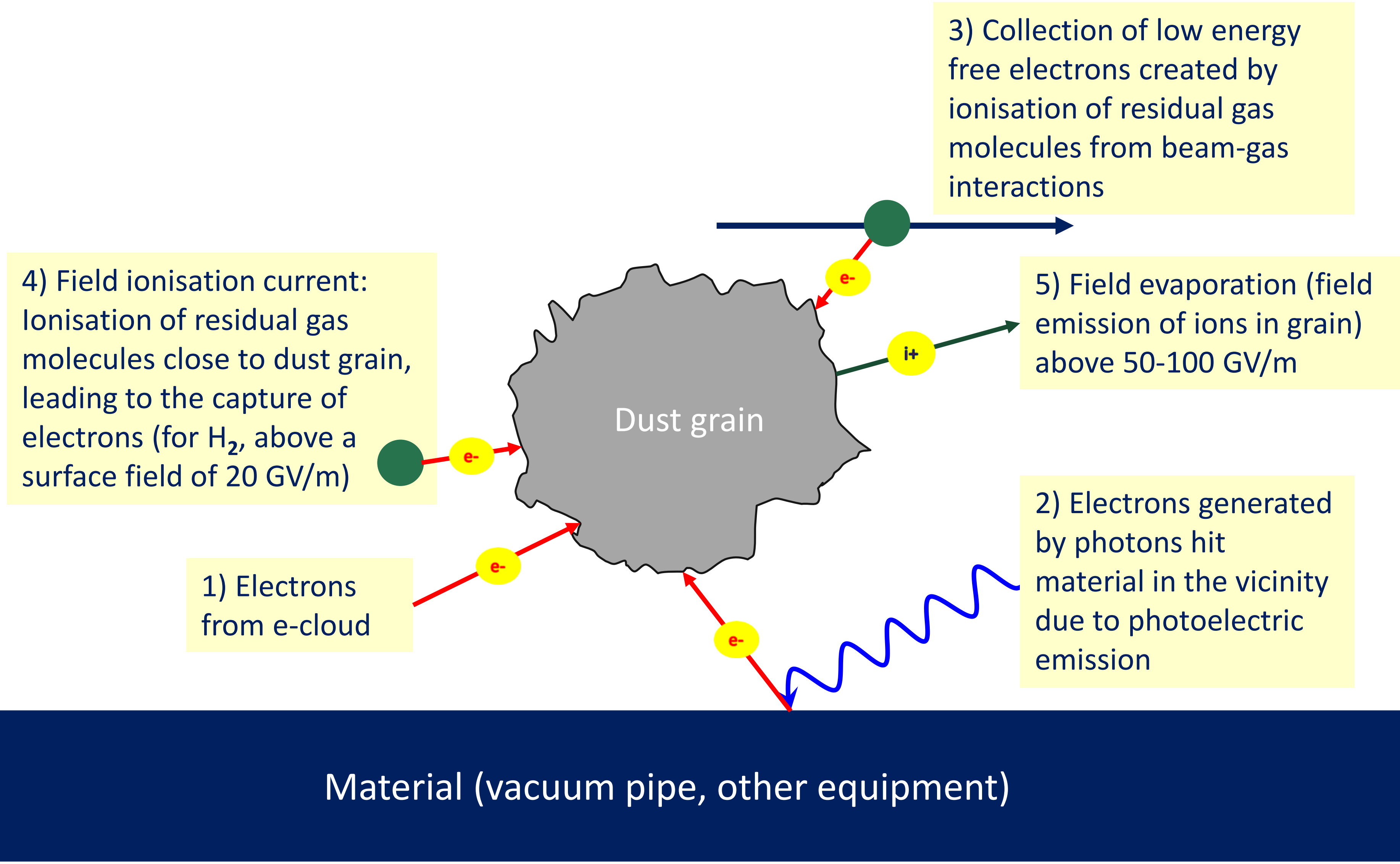


Charging of dust grains in the beam pipe is fundamental for the understanding

Positive charging current of dust grains



Negative charging current of dust grains



Final remarks

- Observation of dust-beam interactions in many accelerators, operating with negatively charged beams (electrons and antiprotons), but also for proton and positron accelerators (positively charged beams)
- In some cases, dust-beam interactions have a significant impact on the accelerators performance
- It is not well understood.....
  - How the dust leaves the surface of the beam pipe (release mechanism).
  - Random nature of beam-dust interactions.
  - Why dust-beam interactions are observed in some accelerators, in others not (PETRA, LEP, ...).
- Today, research on dust in accelerators is mainly motivated by LHC and SuperKEKb. For the future, FCC and other accelerators – an improved understanding is required.

So far there has been little collaboration on this topic. I hope that this workshop will change that.

Thanks and have a great workshop

Reserve

DCI and SUPER-ACO, 1991

RT/91-03

OBSERVATION OF BREMSSTRAHLUNG ON DUST PARTICLES TRAPPED IN ELECTRON BEAMS AT DCI AND SUPER-ACO

P. Marin

I. INTRODUCTION

Due to a major failure on the focusing system of the positron converter, the Linac injector at LURE could only provide electron beams during the full month of January 1991. Both Super-ACO and DCI were reversed in polarity so as to be operated with electrons. This opportunity was seized to look for the Bremsstrahlung production on the dust particles trapped in the beam. A brief summary of the observations recorded over 2 to 3 weeks is reported below.*

ESRF 1992

- Change of gaps of undulator vessels 1992 sometimes produced stored intensity losses.
- Several vessels were dismounted and examined with an endoscope equipped with a miniature camera. The 707 YEG strips installed inside the vacuum vessels produce lose fine magnetic grains which can form a chain of small dipoles under the influence of the magnets.
- These chains could short circuit the ID vessel gap and interact with the stored beam.
- Further investigation showed that ID vessels arc sometimes contaminated by metallic debris produced during vessel manufacture.
- SAES, the 707 NFG manufacture was alerted and discovered that the NEG magnetic dust arc coming from the carbon steel tooling used to crush the Zi V Fe NEG alloy into powder.

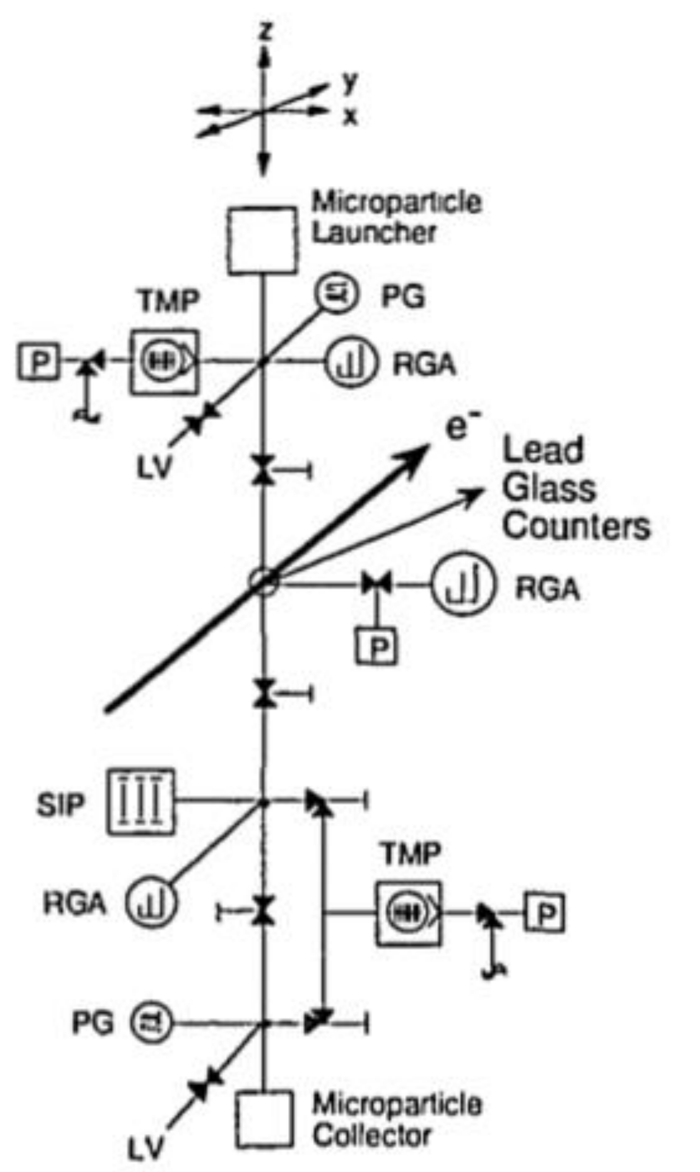
HERA@DESY

- The Lepton–Proton collider HERA (Hadron–Elektron Ring Anlage) operated between 1991 and 2007.
- Early operation with electrons suffered from **sudden breakdowns of beam lifetime with low intensity threshold**. The beam lifetime would not recover even for the smallest beam currents but would be restored after a beam dump and new injection. This was attributed to dust in the vacuum system.
- Explanation: Dust grains on the positively charged plates of the integrated getter pumps get ionized by synchrotron radiation and then accelerated and captured inside the beam leading to massive beam loss due to bremsstrahlung.
- Resolved by running with positrons until 1998.
- The vacuum system was cleaned in 1997. Ion pumps were replaced by NEG pumps.
- After 1998, operation with electrons was possible, though occasional dust trappings were observed in later years as well.

F.Zimmermann et al. (1995): https://ieeexplore.ieee.org/document/504705

F.Willeke (2021): https://www.worldscientific.com/doi/pdf/10.1142/9789814436403_0015

Tristan Accumulation Ring, KEK 1995: Dust trapping experiments



- Species of dust grains with sizes from 0.1 µm to 50 µm were dropped and fall through the electron beam.
- The bremsstrahlung and the lifetime of the beam was measured.
- For some dust species, a sudden drop of the beam current was measured for a short moment, with a short peak of the bremsstrahlung.
- For other dust species, trapping of the grain was observed

DUST TRAPPING EXPERIMENTS AT TRISTAN AR, S.Kato et al., JAERI-Conf 95-021

Mechanisms on charging and discharging dust grains

Positive charging current

1. Interaction of beam with electrons in dust grain: electrons leave the dust grain
2. Photons from synchrotron radiation excite electrons in dust grain that leave the grain
3. Higher energy electrons (> some 100 eV) excite secondary electrons leaving the grain
4. Thermionic emission, electrons spontaneously leave the grain due to their high thermal energy (above ~1000 K)
5. Field emission, electrons spontaneously leave the grain due to a high negative potential of the grain. This dictates the maximum charge carried by a grain.

Negative charging current

1. Collection of low energy free electrons created by ionisation of residual gas molecules from beam-gas interactions
2. Electron capture: incoming low energy electrons are captured by the dust grain
   - Electrons from electron cloud
   - Electrons generated by photons hitting material in the vicinity due to photoelectric emission
3. Field ionisation current: Ionisation of residual gas molecules close to dust grain, leading to the capture of electrons (for H_2, above a surface field of 20 GV/m)
4. Field evaporation (field emission of ions in grain) above a threshold of 50-100 GV/m

Observations and Questions

- Order of 50 GV/m in Field-Ion-Microscope Tips (Müller, from Pedersen)
- Average field of beam – maximum field of bunch (H.Saeki et al, 1991)
- Dielectric breakdown
- Very large difference between dust grain size has been reported
- What are the consequences for operation, for todays accelerators and for future accelerators?

Lunar Surface Innovation Initiative (LSII) to coordinate cross-agency teams and spur the creation of novel technologies needed for lunar surface exploration. Dust mitigation is one of the key capability areas LSII addresses.

Jun 8, 2021

Dust: An Out-of-This World Problem

Dust is a nuisance on Earth. Thankfully, we can simply pull out a vacuum or grab a rag to rid ourselves of the concoction of dust mites, fibers, soil, pollen, and other tiny bits.

Beyond Earth's atmosphere, dust is insidious. On the Moon, it's made of crushed rock and is damaging to everything from lunar landers to spacesuits and human lungs if inhaled. As NASA readies to return to the Moon with the Artemis program, a team at NASA's Glenn Research Center in Cleveland is working to mitigate dust's dangers.

Houston, We Need a Vacuum

Dust mitigation has been an issue for NASA since Apollo. When astronauts were entering and exiting the lunar module, dust got everywhere – it clogged mechanisms, interfered with instruments, caused radiators to overheat and even tore up their spacesuits.

https://www.nasa.gov/feature/glenn/2021/dust-an-out-of-this-world-problem

https://www.colorado.edu/today/2020/08/31/researchers-develop-dustbuster-moon

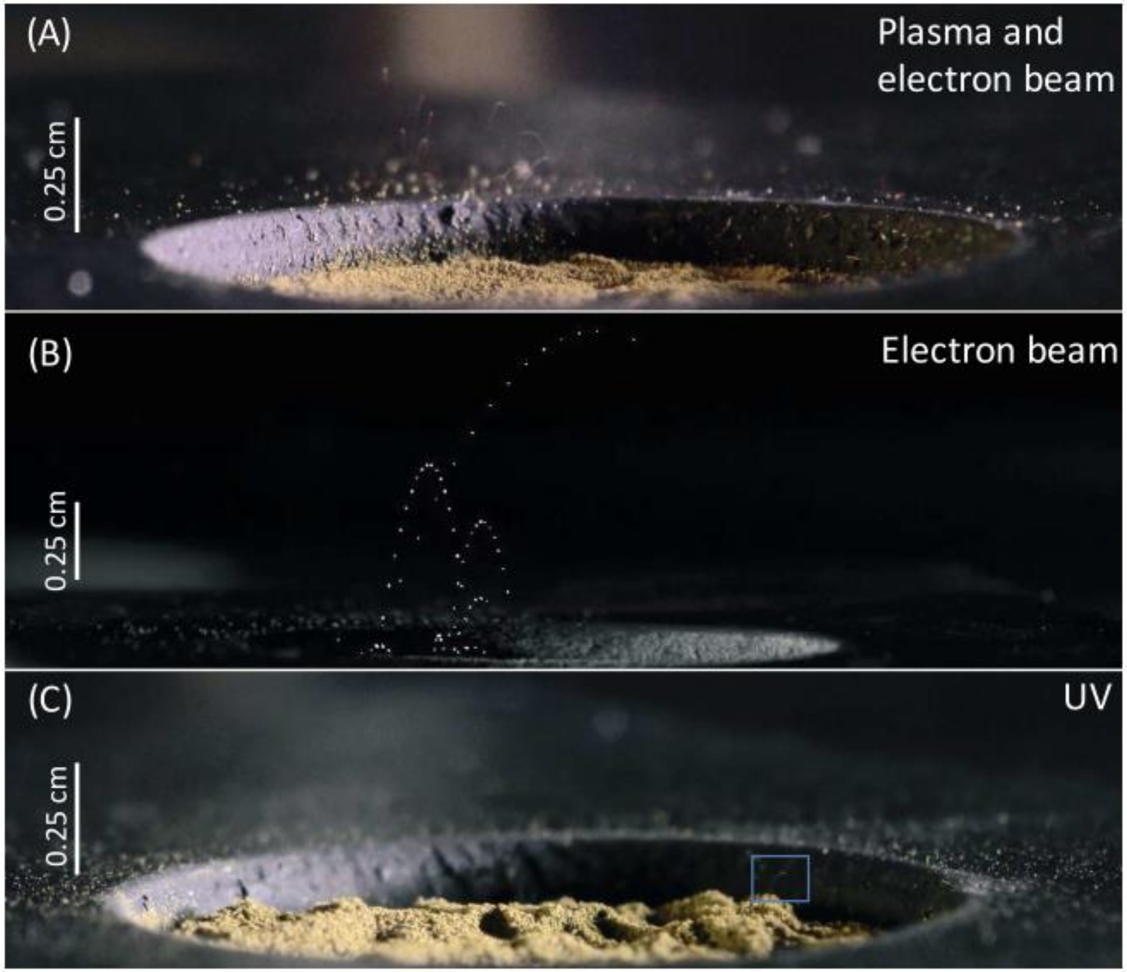


Figure 3. Images of dust transport and hopping trajectories in (a) plasma and electron beam, (b) electron beam, and (c) UV experiments. A blue square in Figure 3c indicates a hopping trajectory captured under UV illumination. Deposits of dust particles on the surface outside the crater also indicate their hopping motions in all three images. Large aggregates up to 140 μm in diameter are lofted in addition to individual particles (38–45 μm in diameter).

KEK accelerators

- Photon Factory (PF)
- Tristan AR (Accumulation Ring)
  - Length of 377 m
  - Injection 2.5-3 GeV, extraction 6-8 GeV
- Tristan MR (Main Ring)
- KEKb
- SuperKEKb

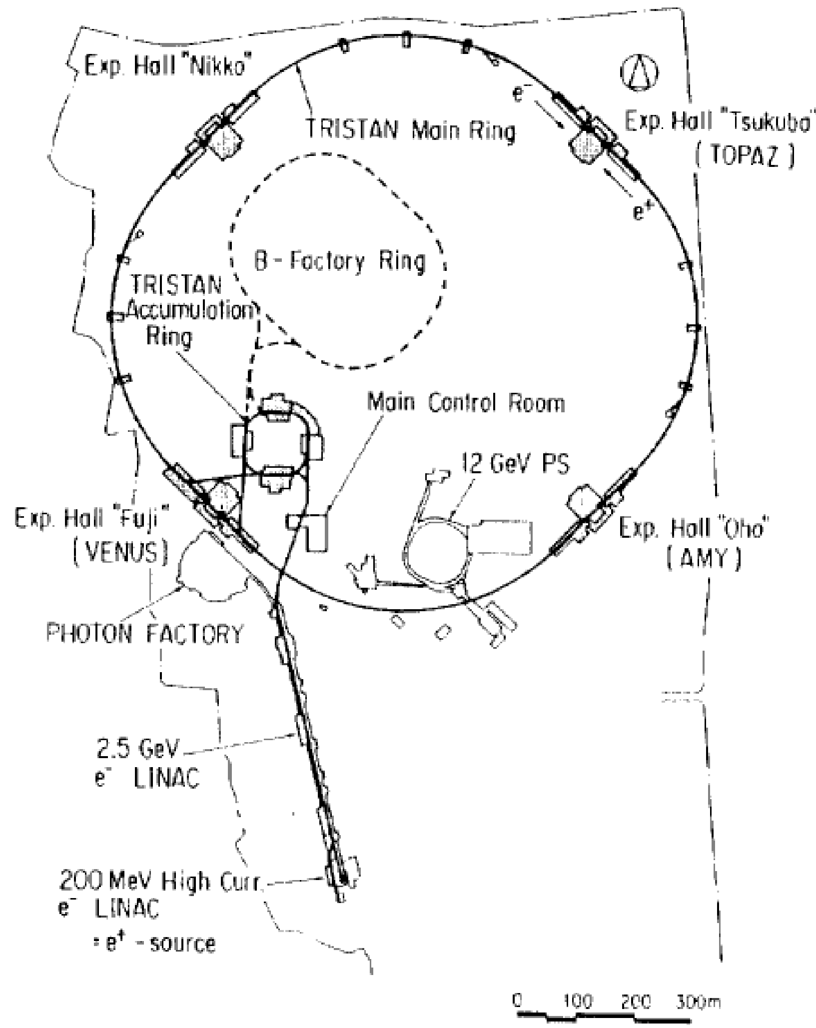


Fig. 1 Site layout of the TRISTAN accelerator complex and an asymmetric B-factory planned.

Field map for AA

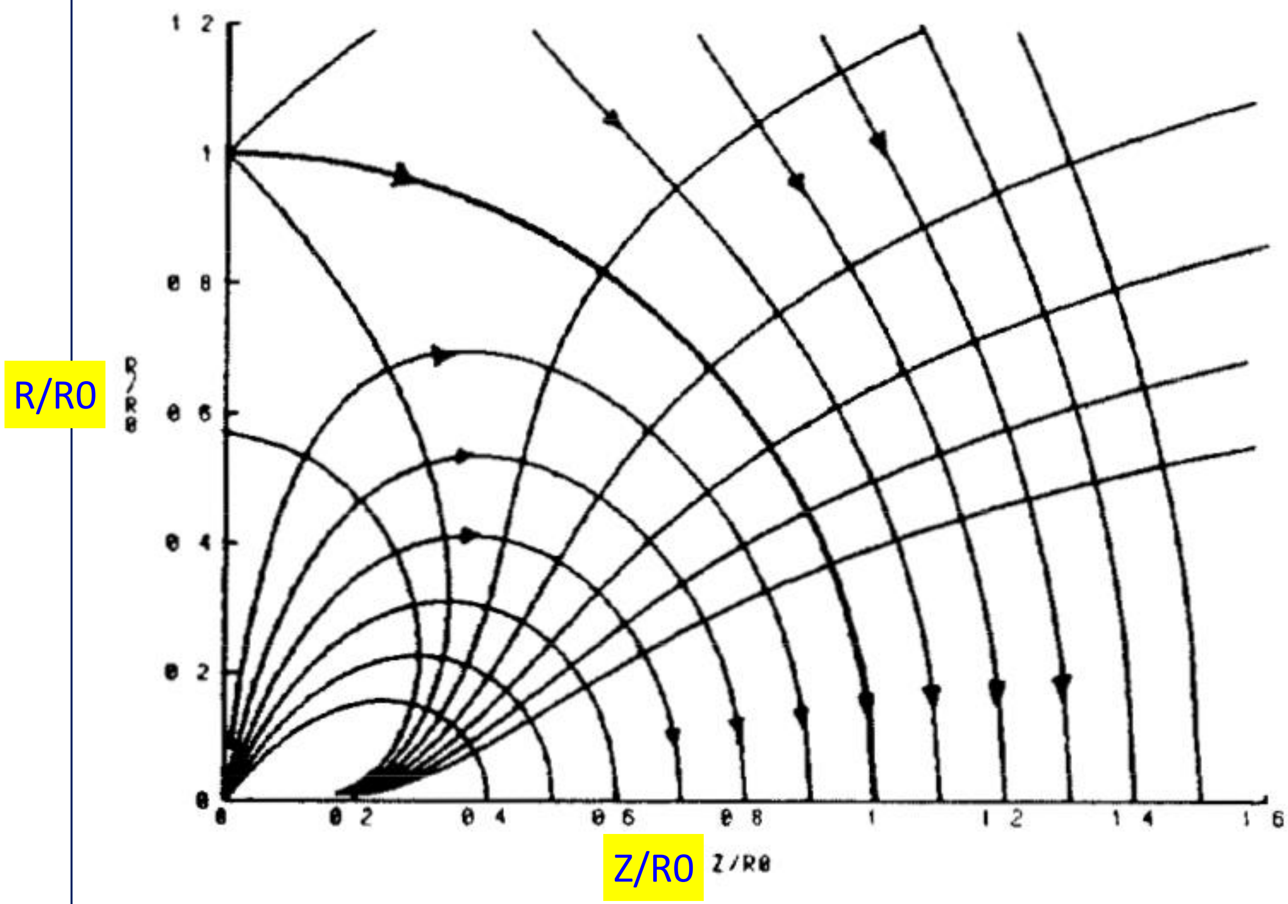
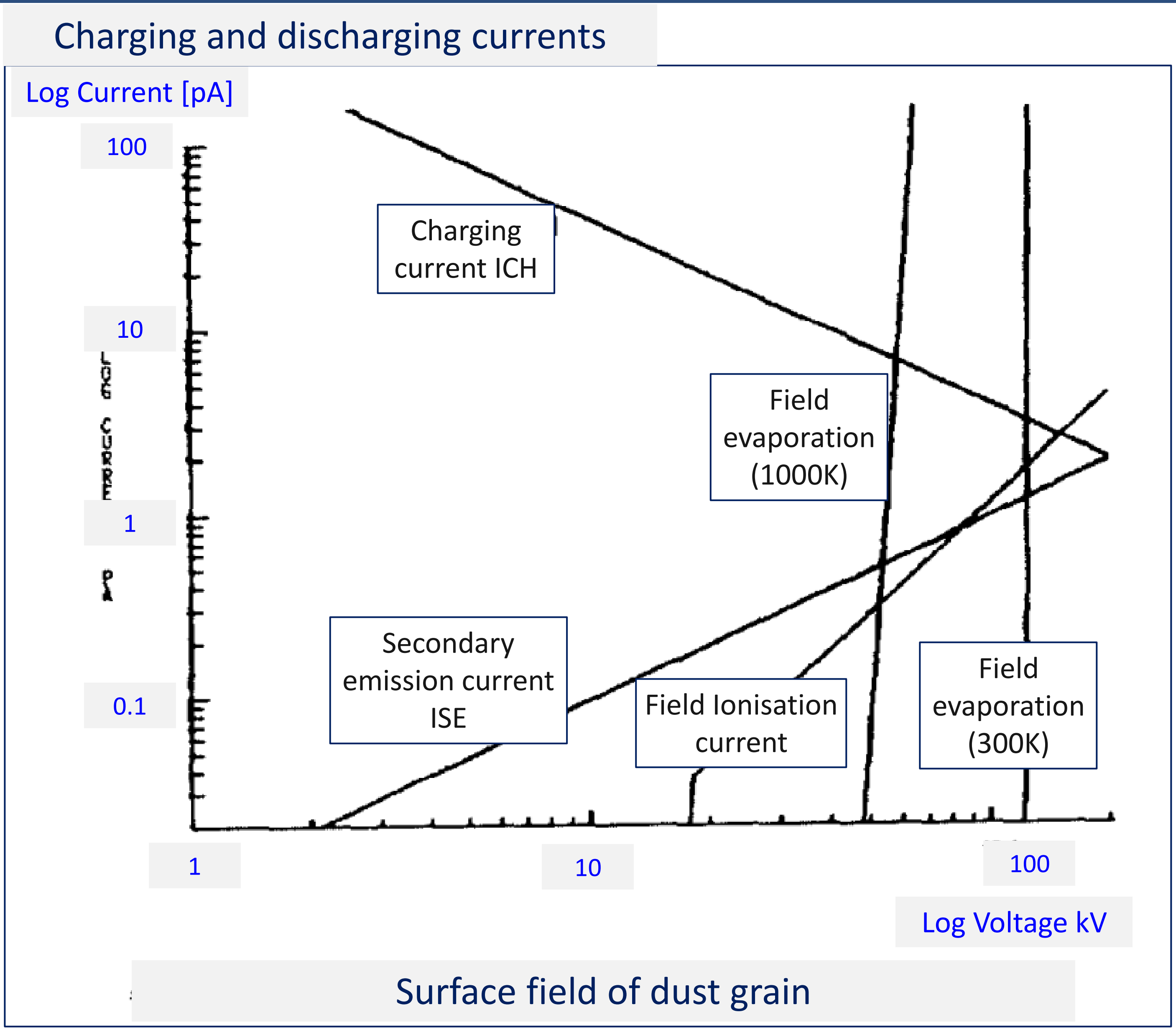


Fig. 1 - Field from point charge and line charge.

Charging and discharging currents for the AA



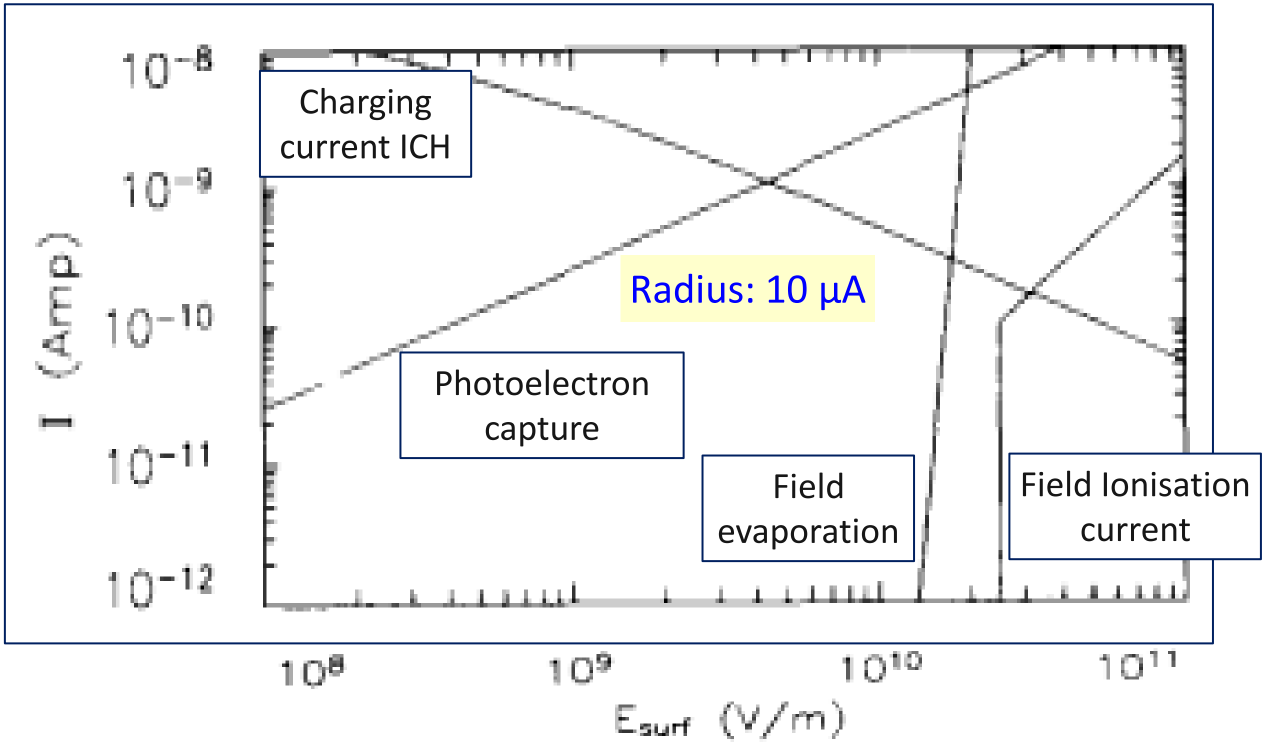


Fig. 2. Charging and discharging currents as a function of surface field for a beam current of 1 mA and particle radii ranging from 0.1 μm to 10 μm. (a) 10 μm radius particle, (b) 10 μm radius particle, (c) 0.1 μm radius particle.