Direct Observation of the Dust-trapping Phenomenon

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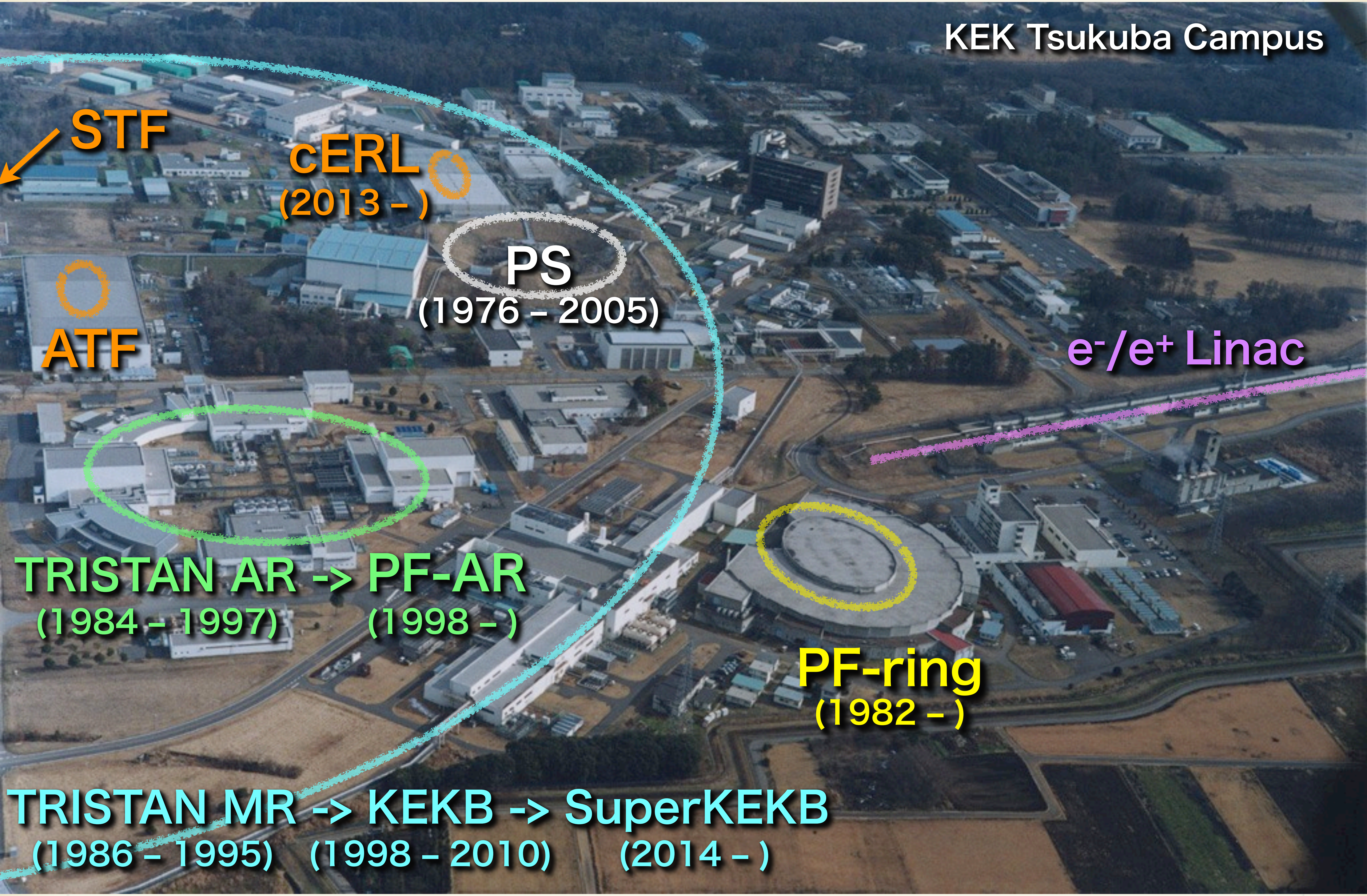

KEK Tsukuba Campus
STF
cERL
(2013 –)
PS
(1976 – 2005)
ATF
e⁻/e⁺ Linac
TRISTAN AR -> PF-AR
(1984 – 1997)
(1998 –)
PF-ring
(1982 –)
TRISTAN MR -> KEKB -> SuperKEKB
(1986 – 1995)
(1998 – 2010)
(2014 –)

Outline

1. Review of the dust-trapping phenomenon

2. Dust-trapping problem at PF-AR

3. Dust-trapping experiment at PF-AR

1. Review of the dust-trapping phenomenon

Dust-trapping Phenomenon

- observed at AA, PF-ring, NSLS, PF-AR(TRISTAN AR), DCI, Super-ACO, HERA, DORIS, PETRA, CESR, ESRF, KEKB, PEP II, BEPC, etc.
- gives rise to a sudden decrease in electron beam lifetime (without corresponding increase in vacuum pressure) or a sudden increase in antiproton beam emittance
- yields a gamma-ray burst ahead of electron beam orbit
- never lasts stably in positron or proton storage rings
- more frequently observed directly after accelerator constructions or large-scale reconstructions

These observations can be explained by the dust-trapping hypothesis claiming that positively charged dust particles can be stably trapped by electron or antiproton beams, and emit bremsstrahlung gamma-rays as a result of the interaction with electron beams.

Estimation of Dust Size from Reduced Lifetime

During the dust trapping, stored electrons lose their energy mainly through **the bremsstrahlung process**, and electrons that fall out of the energy acceptance will be lost from the bunch.

Dust diameter d can be estimated from **reduced beam lifetime τ**, assuming that the amplitude of transverse oscillation of the trapped dust is immediately damped within 1σ of the beam size.

(ref. F. Zimmermann, SLAC-PUB-6788, 1995)

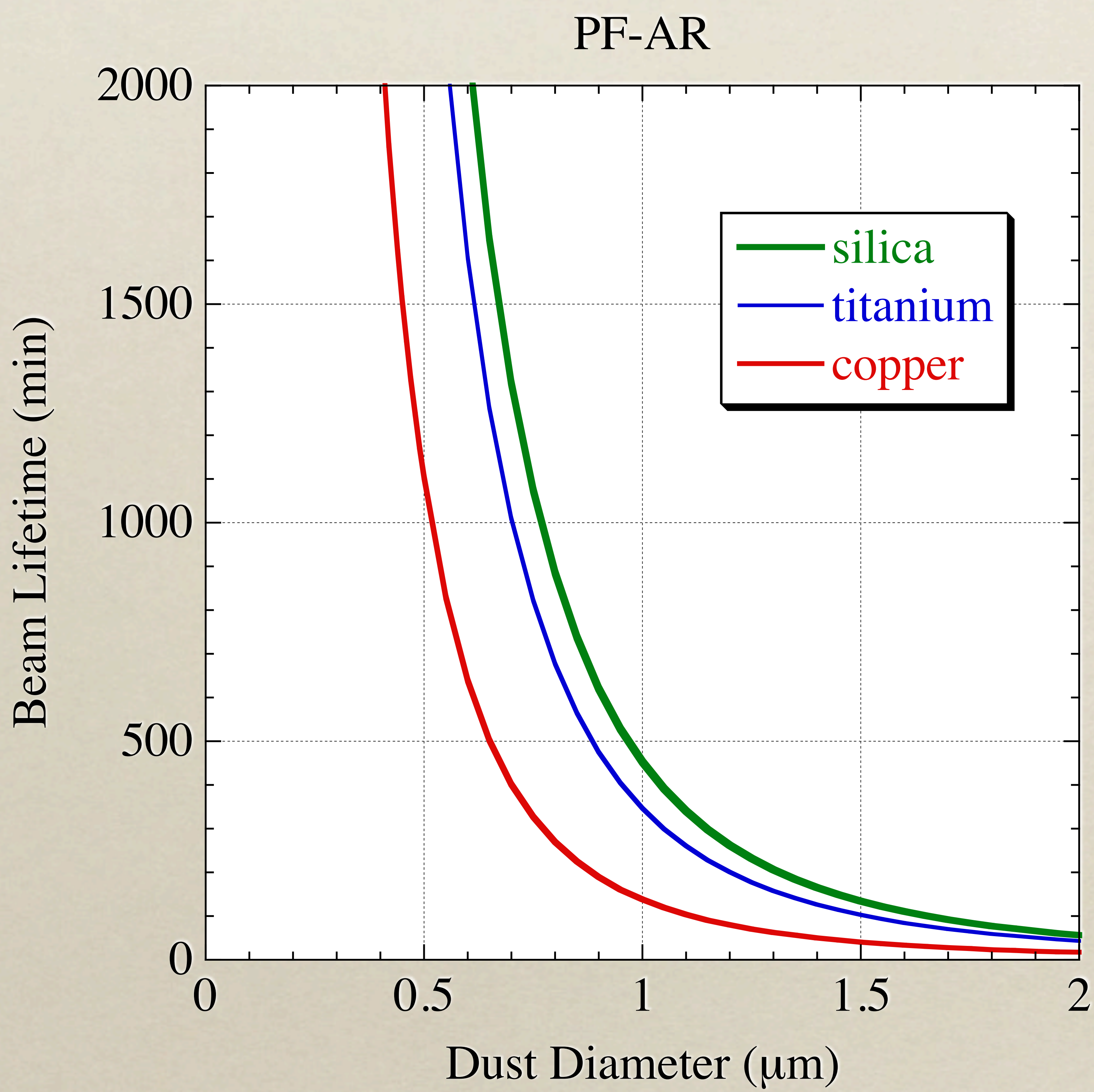
$$\frac{1}{\tau} = \frac{\sigma_b \, c \, \rho}{12 A_{atom} m_u \sigma_x \sigma_y L} d^3$$

σ_b : bremsstrahlung cross section (see below)
c : velocity of light (electron beam)
ρ : density of dust
A_{atom} : mass number of the dust atom
m_u : atomic mass constant
$\sigma_{x,y}$: transverse rms beam size
L : ring circumference

$$\sigma_b = \frac{16 r_e^{\,2}}{3 \cdot 137} Z^2 \ln\left(\frac{E}{\Delta E}\right) \ln\left(\frac{183}{Z^{1/3}}\right)$$

r_e : classical electron radius
$\Delta E/E$: energy acceptance
Z: atomic number of the dust atom

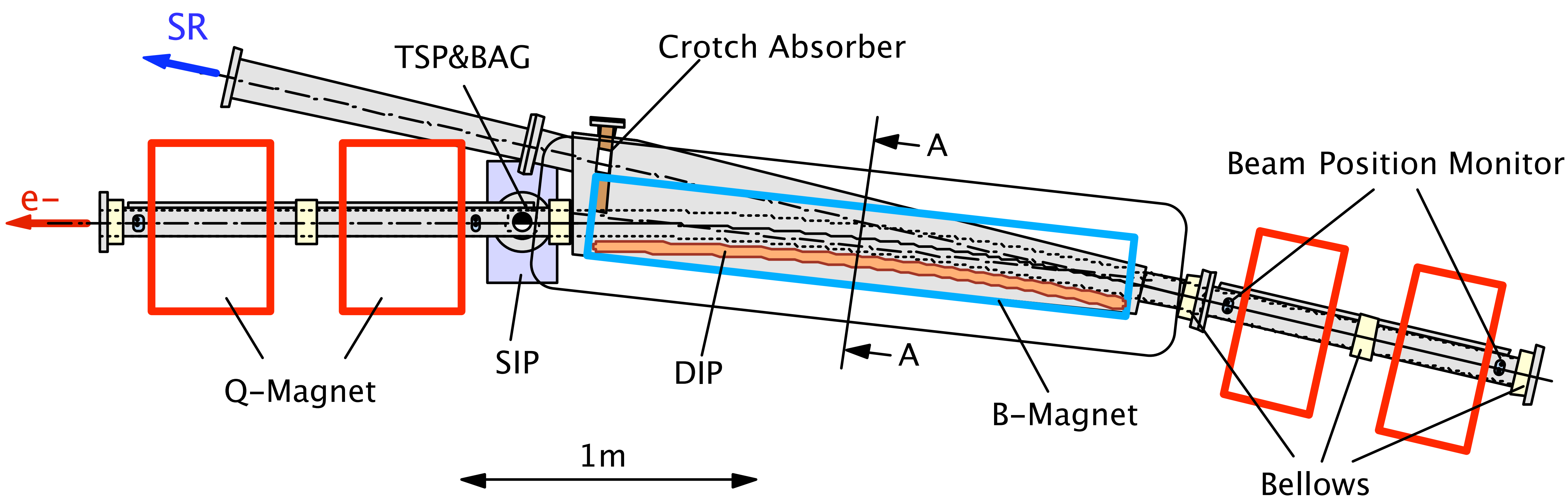
Dust Size vs. Reduced Lifetime



Known Dust Sources

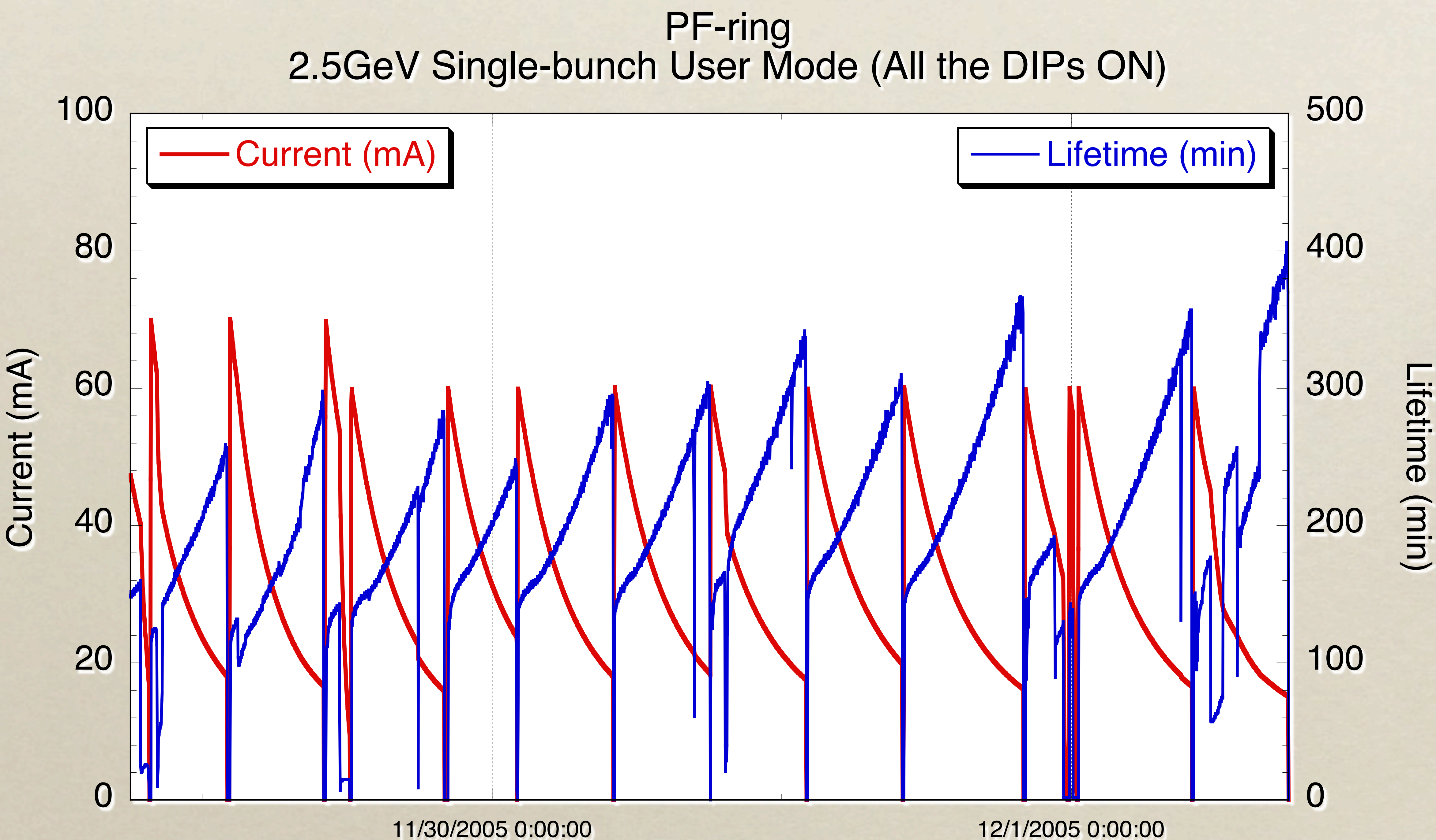
- Distributed ion pumps (DIP)

Production of Dust Particles in DIP

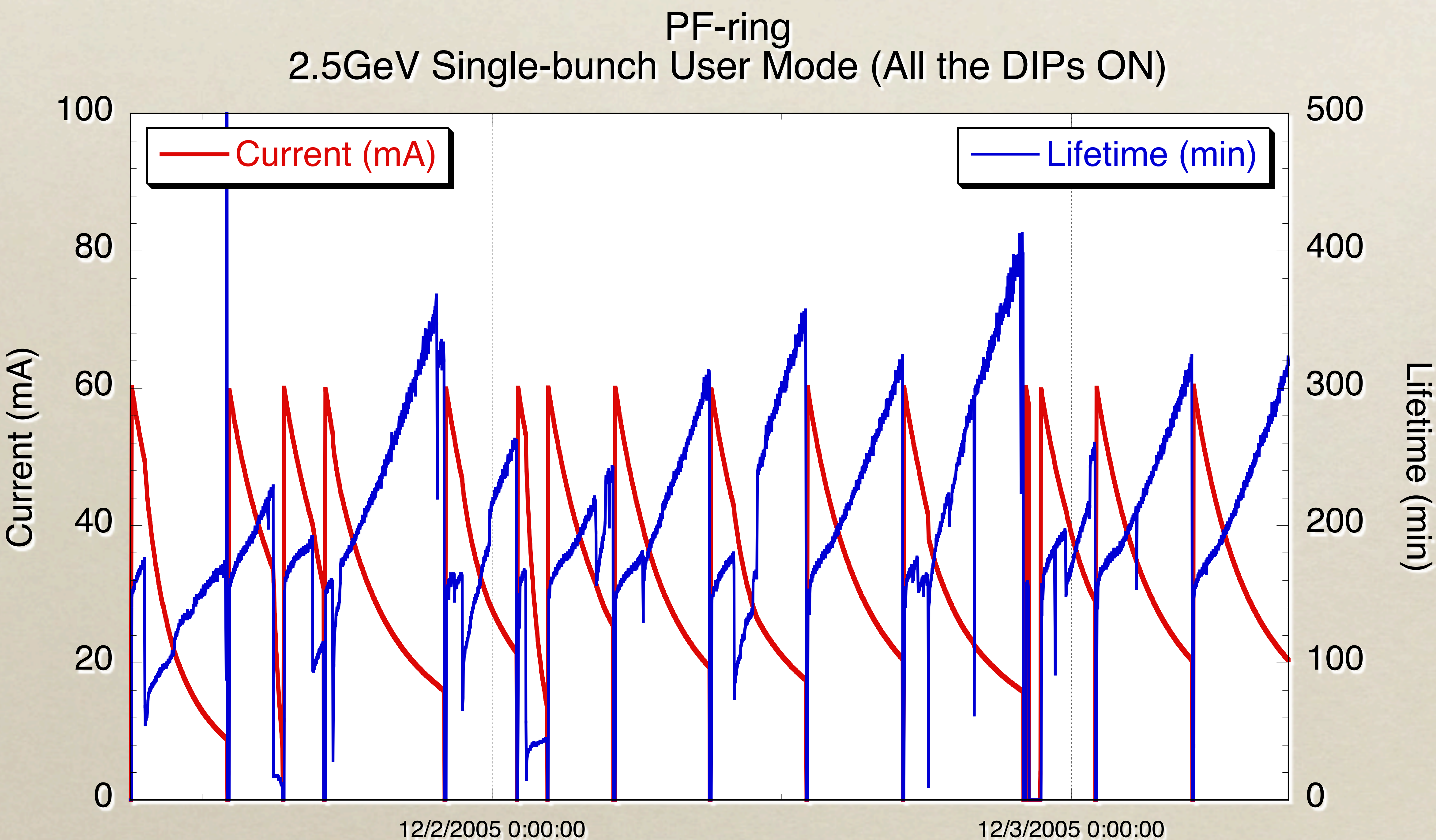


Typical configuration of the vacuum components in PF-ring

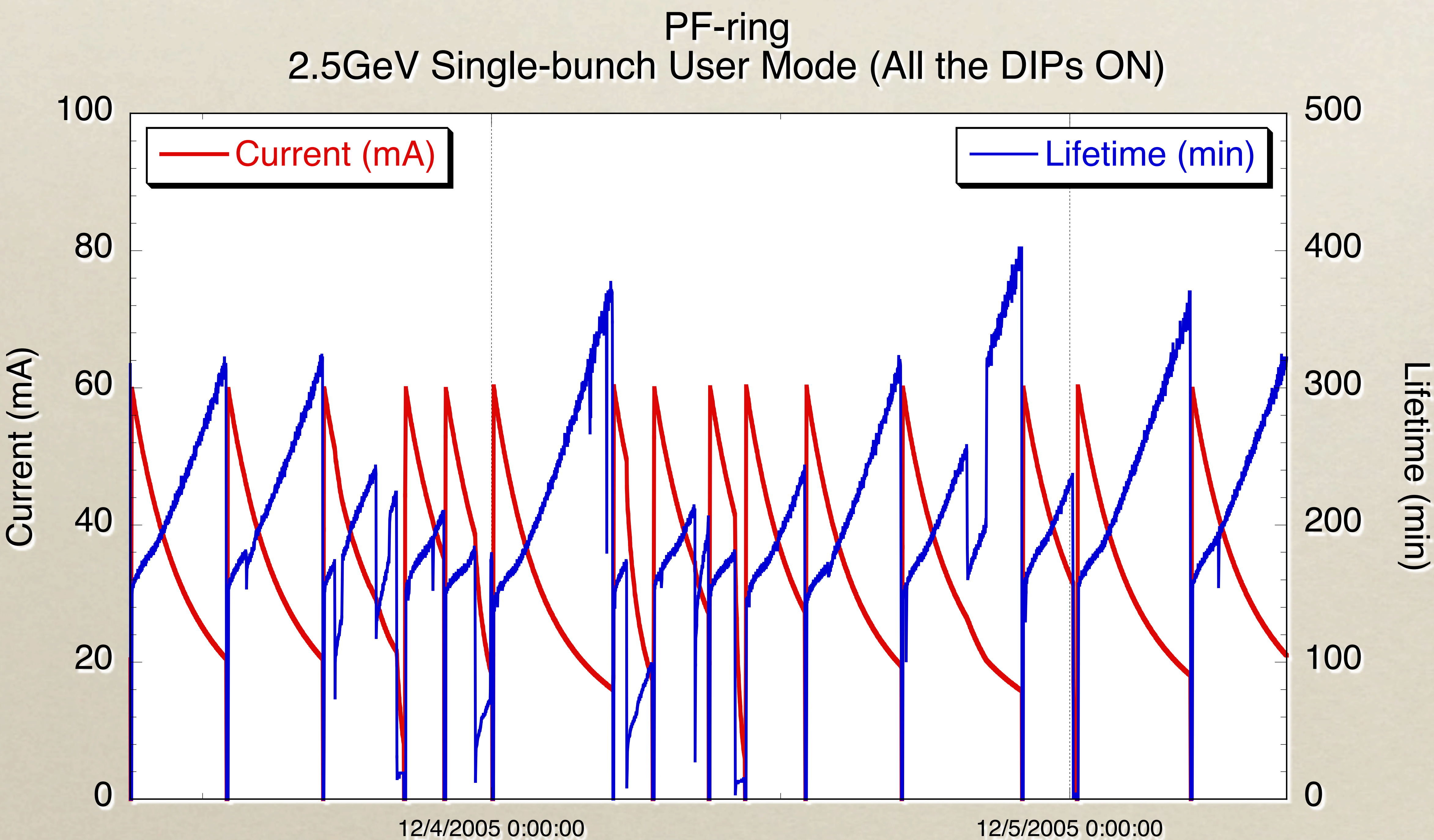
Evidence of Dust Production in DIP (1/7)
(obtained just after the PF-ring reconstruction in 2005)



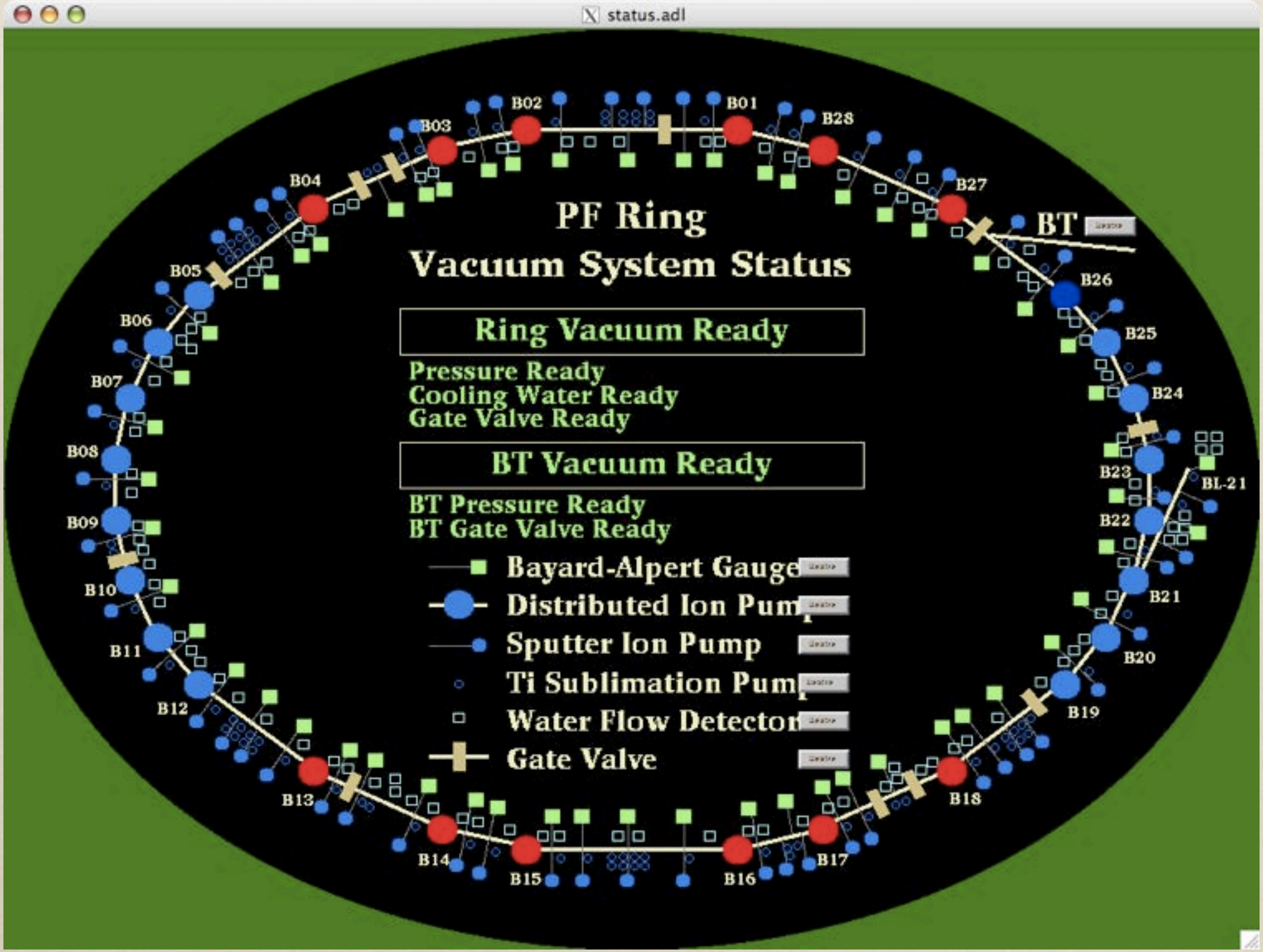
Evidence of Dust Production in DIP (2/7)
(obtained just after the PF-ring reconstruction in 2005)



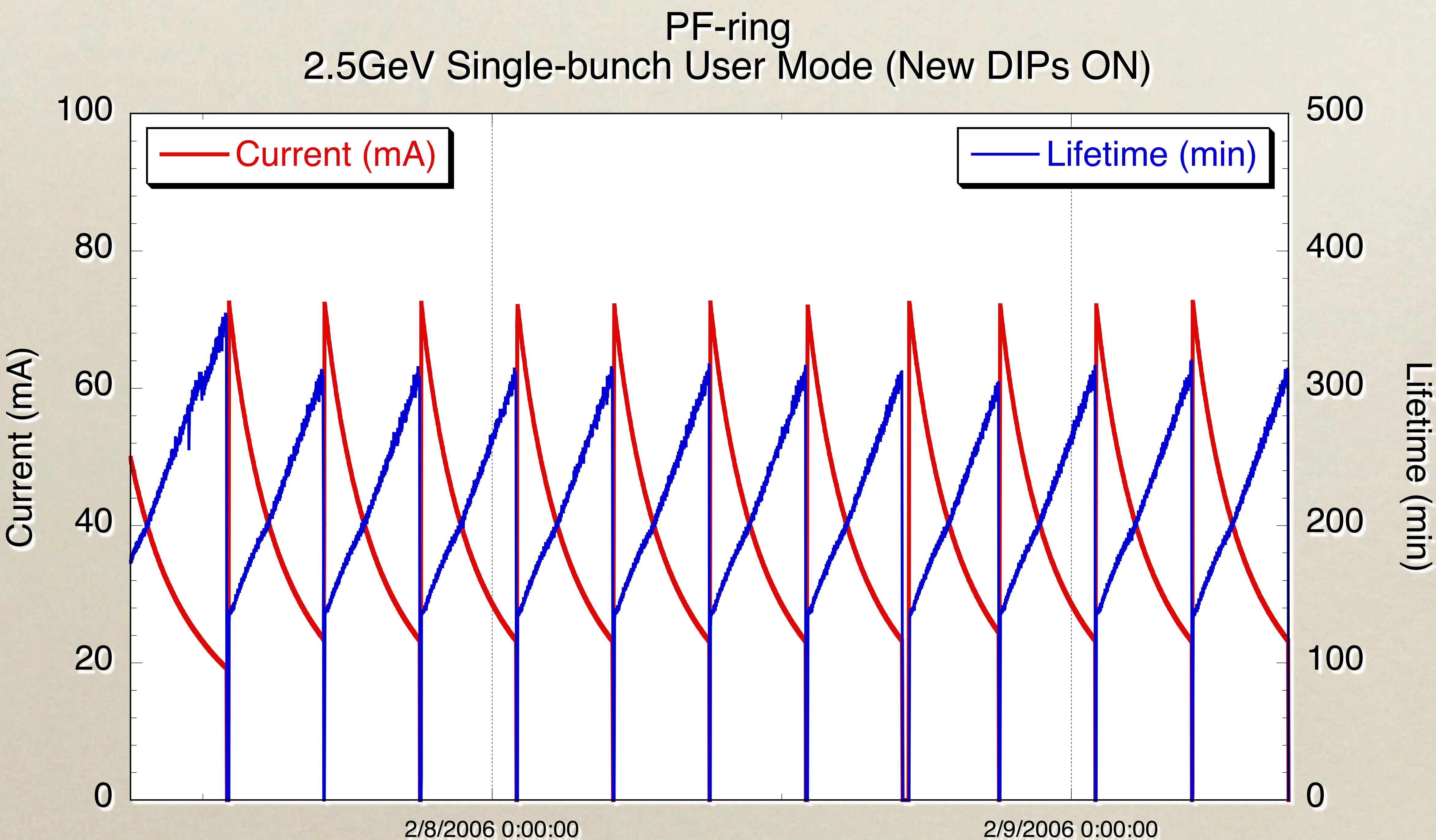
Evidence of Dust Production in DIP (3/7)
(obtained just after the PF-ring reconstruction in 2005)



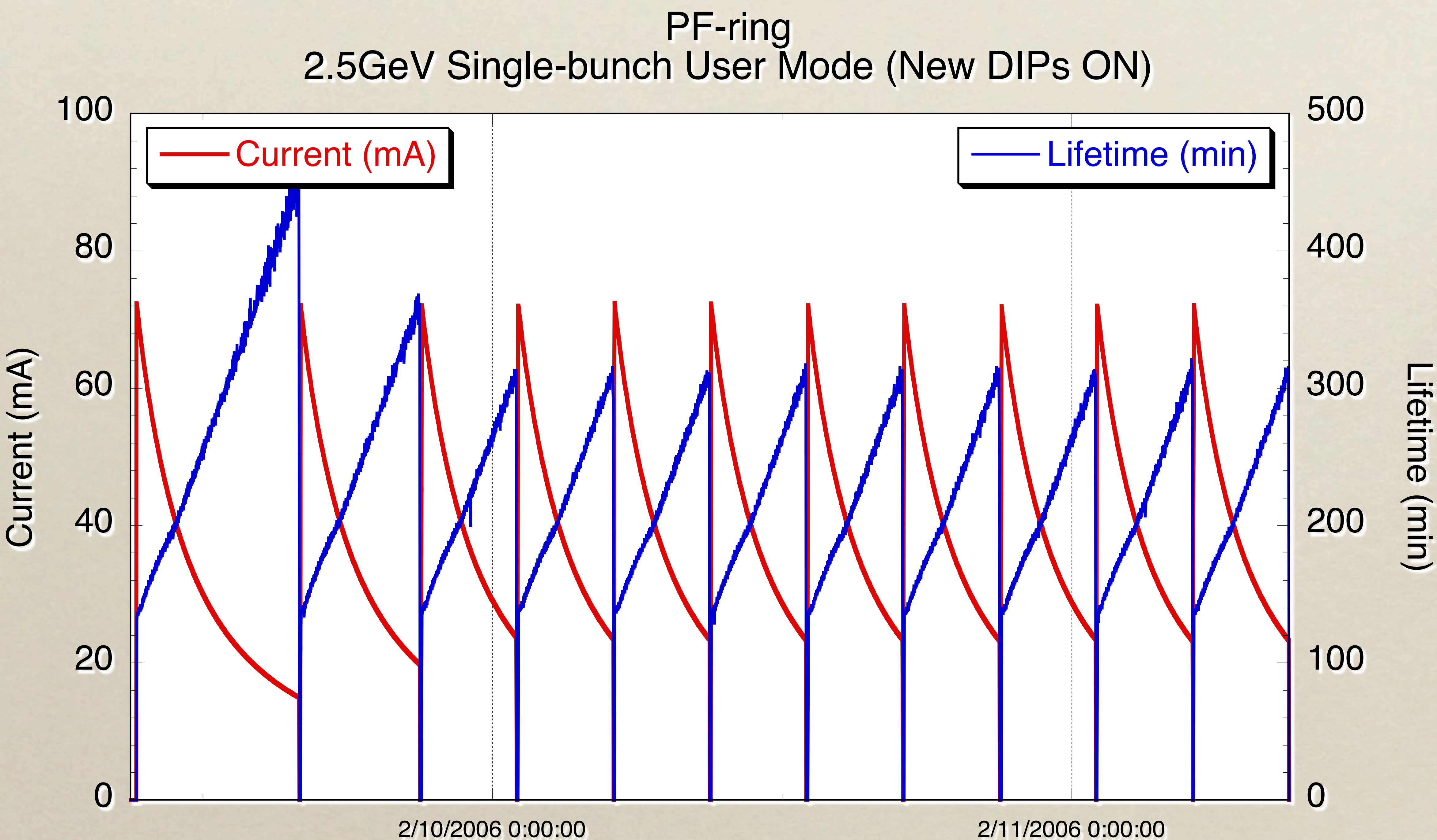
Evidence of Dust Production in DIP (4/7)
(obtained just after the PF-ring reconstruction in 2005)



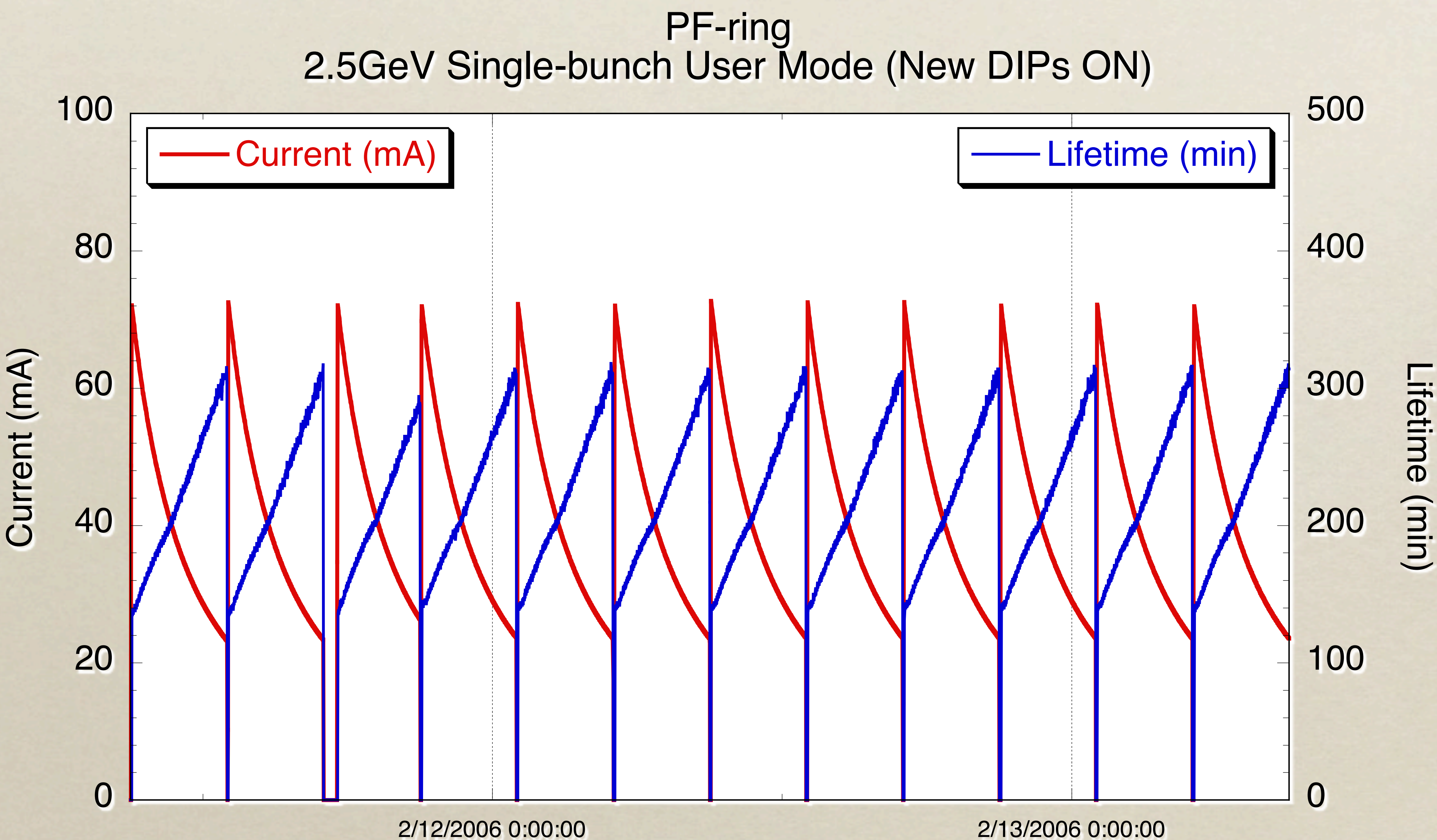
Evidence of Dust Production in DIP (5/7)
(obtained just after the PF-ring reconstruction in 2005)



Evidence of Dust Production in DIP (6/7)
(obtained just after the PF-ring reconstruction in 2005)



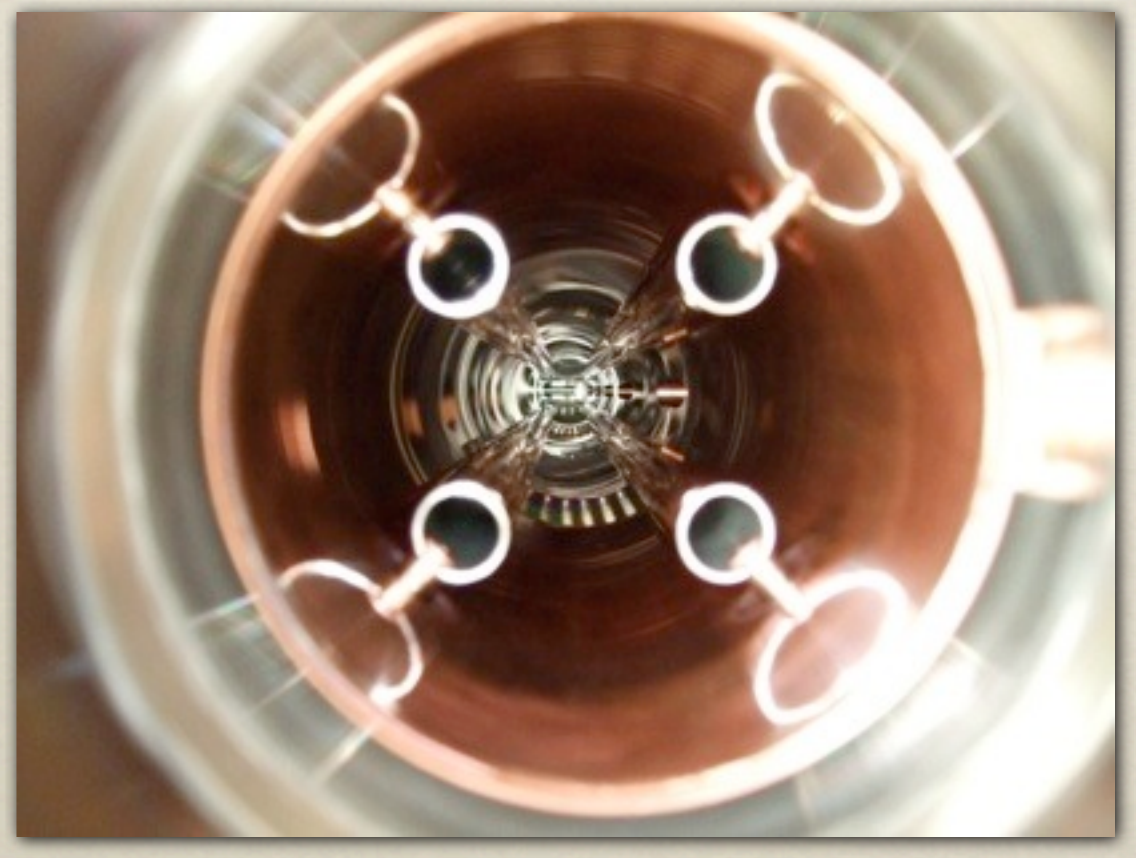
Evidence of Dust Production in DIP (7/7)
(obtained just after the PF-ring reconstruction in 2005)



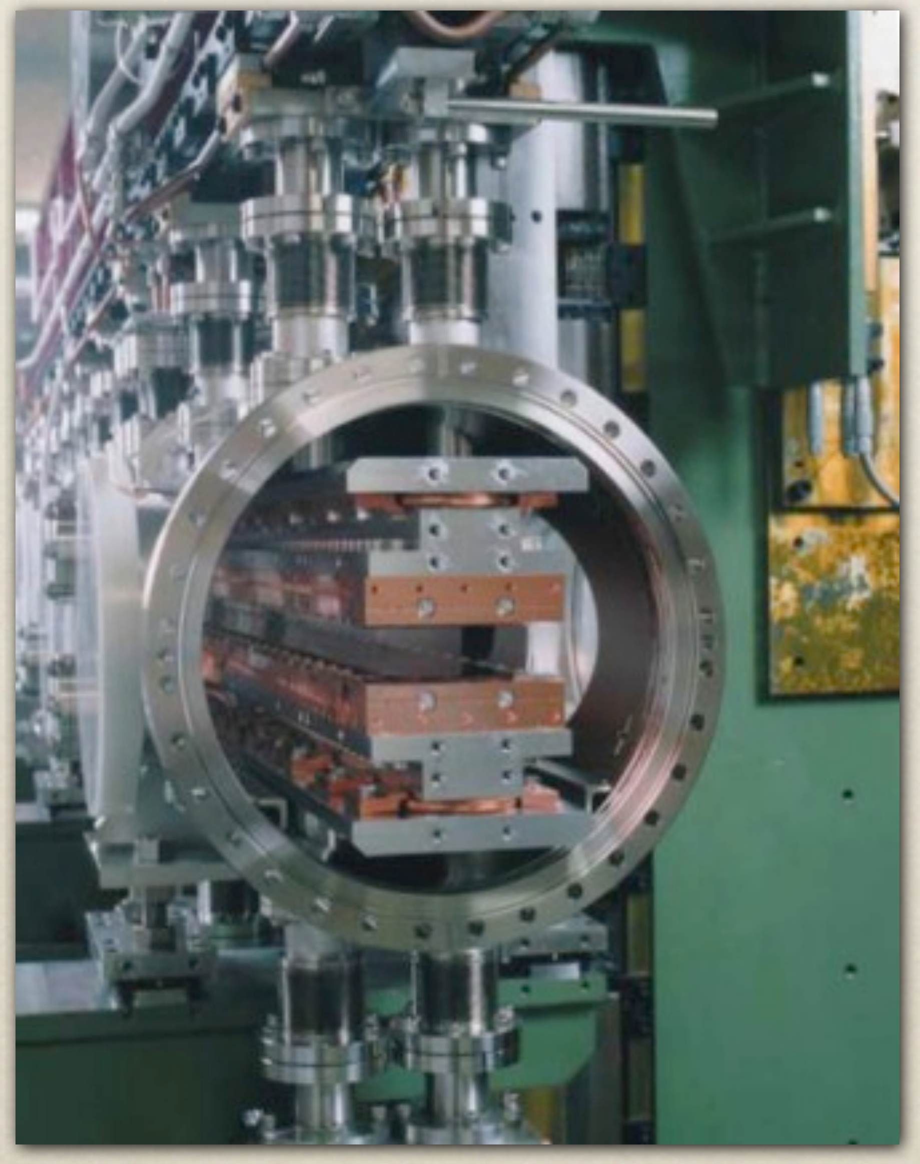
Known Dust Sources

- Distributed ion pumps (DIP)
- Discharge-prone vacuum devices

Discharge-prone Vacuum Devices in PF-AR

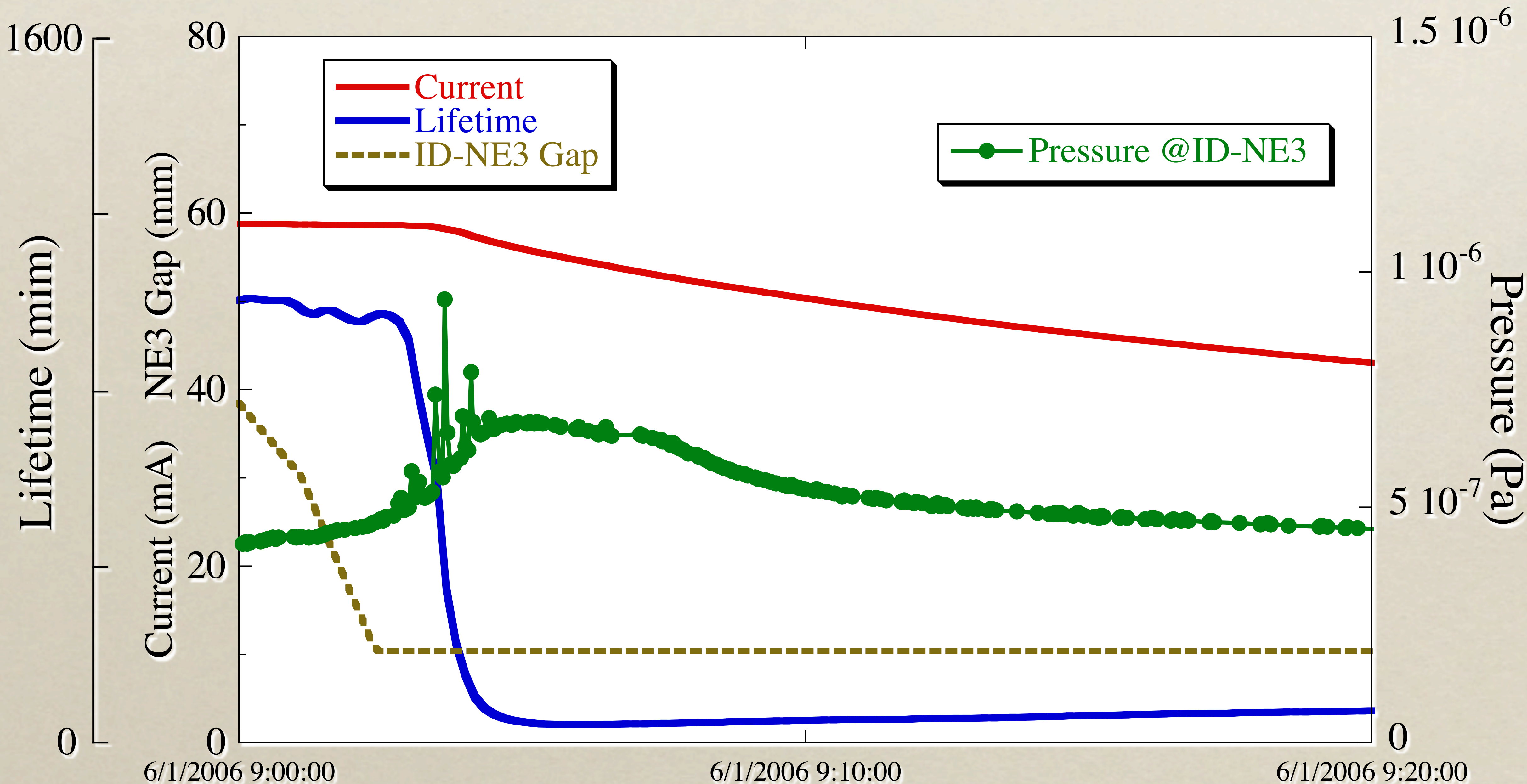


Feedback rf kicker
(oscillation damper)
with four tubal electrodes



In-vacuum insertion device (ID)
Min. gap of magnet arrays ~ 10 mm

Lifetime Drop Triggered by Electric Discharge at In-vacuum ID



Known Dust Sources

- Distributed ion pumps (DIP)

- Discharge-prone vacuum devices

- Movable devices (shutters, scrapers, valves, ...)
  mechanical movement, shock, vibration, and friction

  E. Jones, F. Pedersen, A. Poncet, S. van der Meer, E.J.N. Wilson, Proc. PAC'85, 2218
  J.M. Jimenez, J.L. Dorier, N. Hilleret, Vacuum 53 (1999) 329
  U. Wienands, Proc. PAC'01, 597

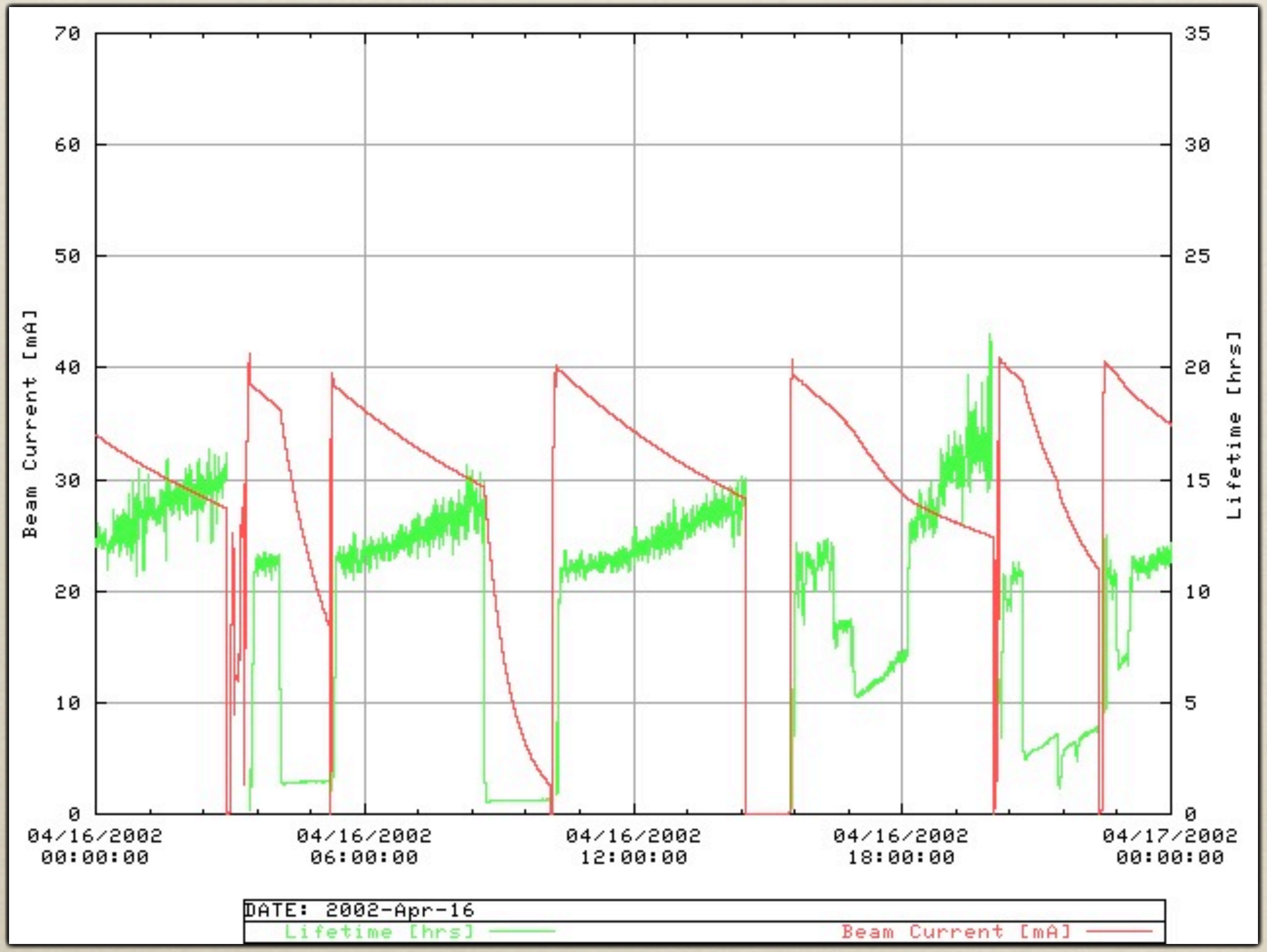
- Dust particles lying on the chamber wall ?

  Calculations conclude that positively charged dust particles lying on a conducting surface cannot be picked up because of the image charge force.

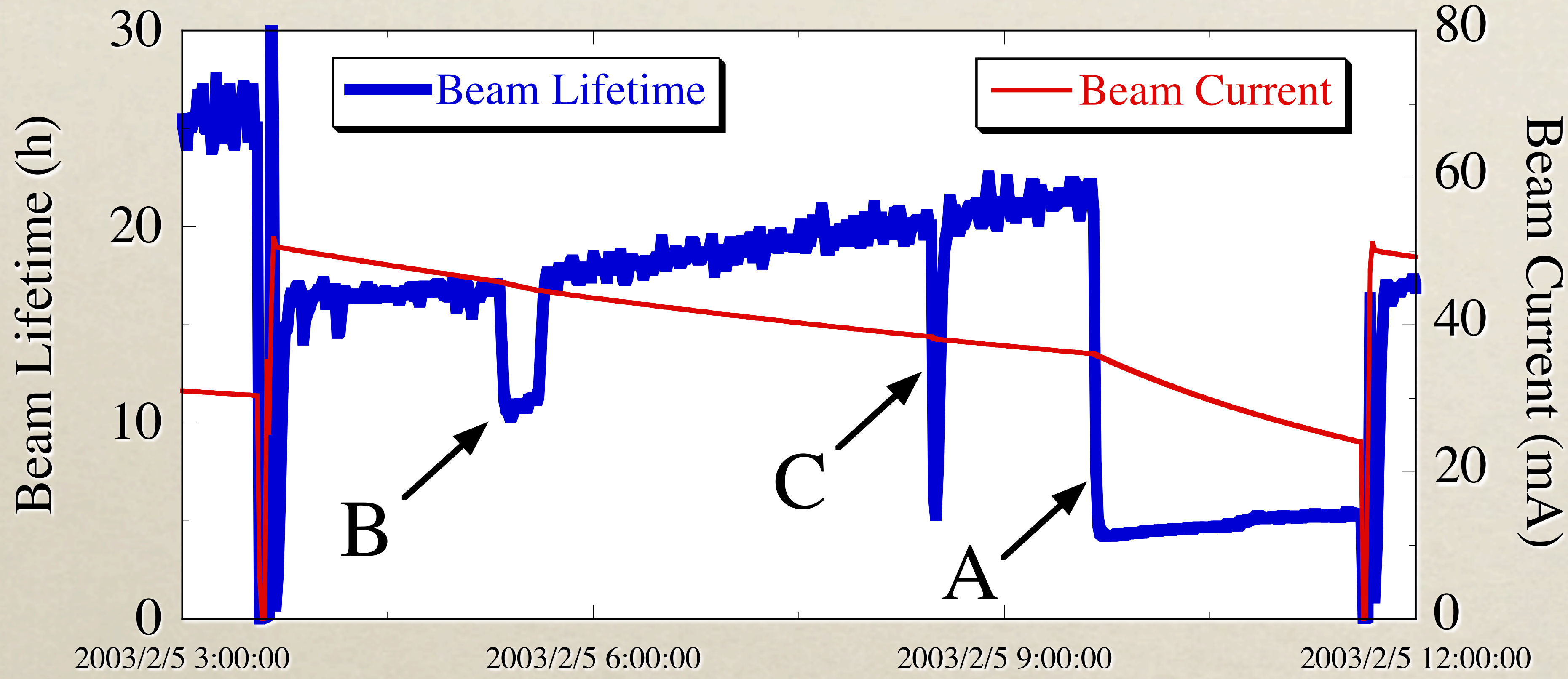
  D. Sagan, NIM A330 (1993) 371
  F. Zimmermann, PEP-II AP Note No.: 8-94

2. Dust-trapping problem at PF-AR

Sudden Lifetime Drops at PF-AR (directly after the reconstruction in 2001)



Classification of Sudden Lifetime Drops by their Duration



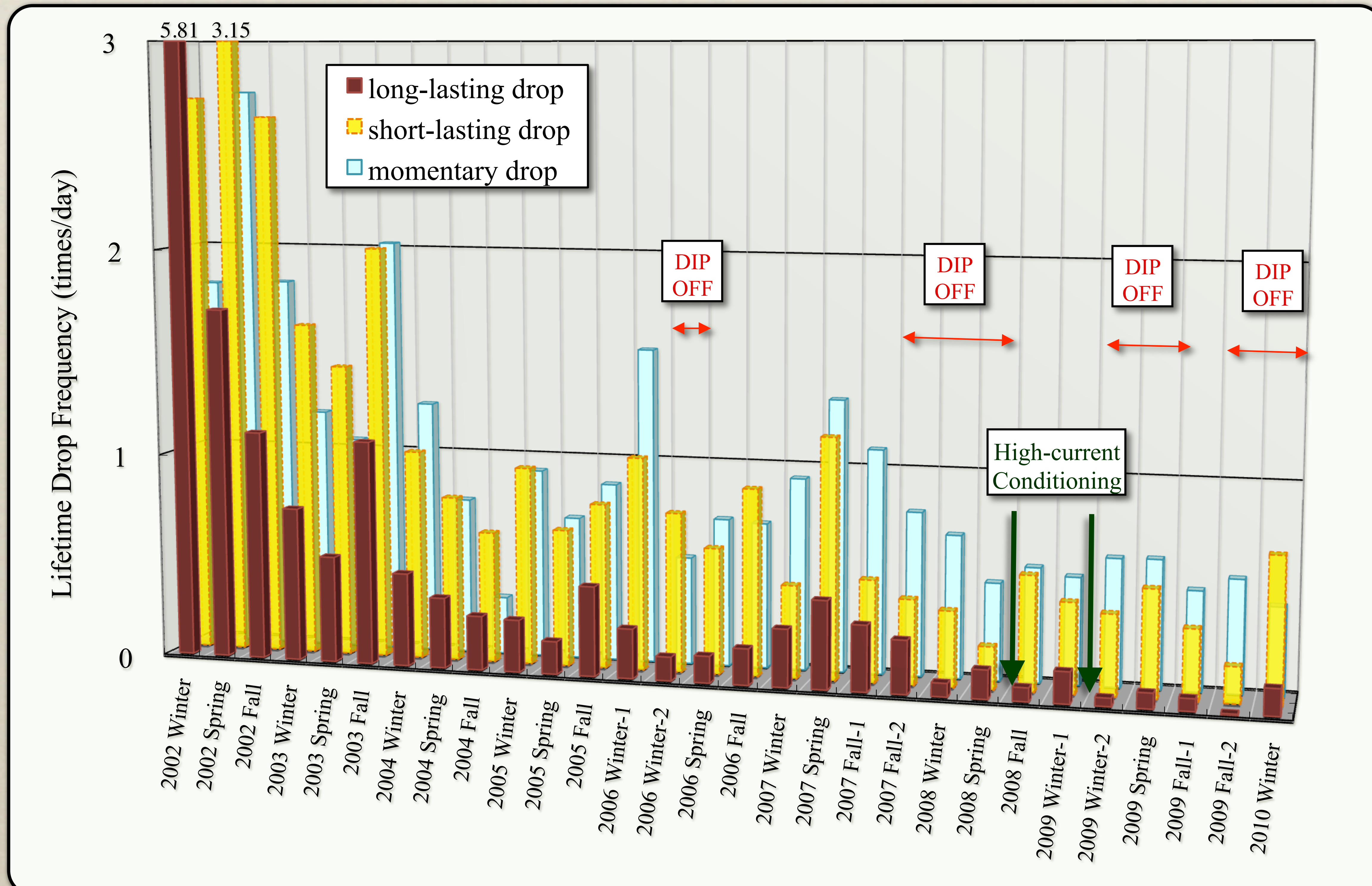
A: **Long-lasting drop** that continues for hours.

B: **Short-lasting drop** that recovers in minutes.

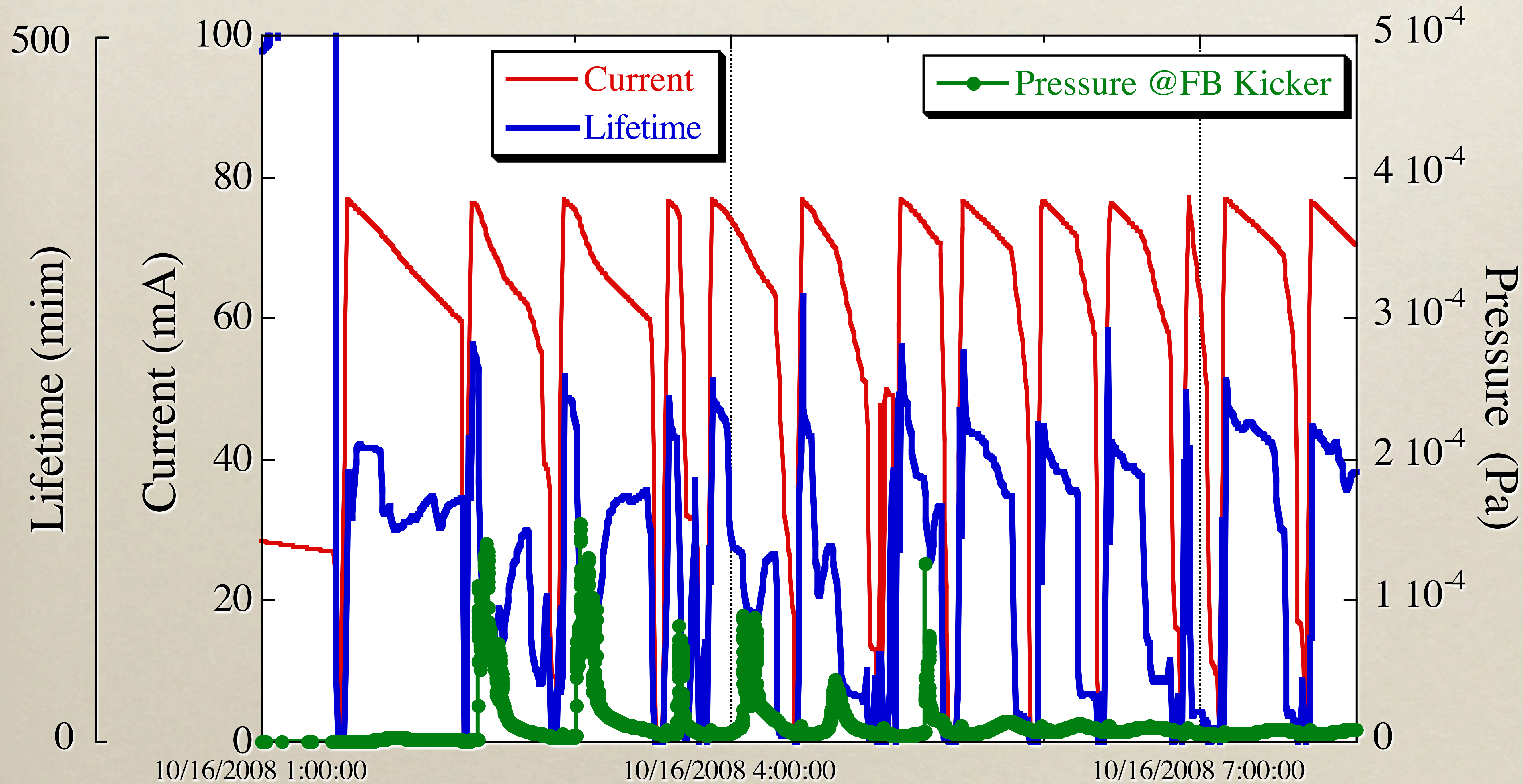
C: **Momentary drop** due to a small beam loss.

Difference in material and size of dust particles may result in different behaviors of the lifetime drops.

Statistics of Lifetime Drop Events at PF-AR since 2002 (directly after the reconstruction in 2001)



Discharge Conditioning with Higher Current Beams
(76 mA, 3 GeV, 2 bunches, Oct. 2008)



Effect of Measures to Mitigate Dust Trapping (statistics of long-lasting drops)

	DIP-ON			DIP-OFF			DIP-ON & Hi-Cur.			DIP-OFF & Hi-Cur.		
	Ope. Time (h)	event	Event Freq. (times/day)	Ope. Time (h)	event	Event Freq. (times/day)	Ope. Time (h)	event	Event Freq. (times/day)	Ope. Time (h)	event	Event Freq. (times/day)
2006 Winter1	580	6	0.25									
2006 Winter2				773	4	0.12						
2006 Spring	1560	9	0.14									
2006 Fall	1823	14	0.18									
2007 Winter	1001	12	0.29									
2007 Spring	1110	20	0.43									
2007 Fall1	1103	15	0.33									
2007 Fall2				632	7	0.27						
2008 Winter				966	3	0.07						
2008 Spring				1460	9	0.15						
2008 Fall							1588	5	0.08			
2009 Winter1							597	4	0.16			
2009 Winter2										967	2	0.05
2009 Spring										1422	5	0.08
2009 Fall1							1726	5	0.07			
2009 Fall2				131	0	0.00						
2010 Winter				1396	8	0.14						
Total	7177	76	0.25 (100%)	5358	31	0.14 (55%)	3911	14	0.09 (34%)	2389	7	0.07 (28%)

High-current (76 mA) Conditioning

Is it possible to completely suppress the dust trapping at PF-AR?

Thermal Equilibrium in Dust Particle

A dust particle explodes after trapped if the heating by energy deposition from the beam exceeds the cooling by thermal radiation. However, if the dust has a high melting point and a low vapor pressure, it can reach thermal equilibrium, which results in a long-lasting lifetime drop.

Since the size of trapped dust is far smaller than the size of beam, energy deposition on the dust is proportional to the beam flux. One can calculate that minimum beam flux that exceeds the thermal radiation power from a silica (SiO_2) sphere of 1 μm and 1900 K is 7×10^4 A/m^2.

(ref. F. Zimmermann, SLAC-PUB-6788, 1995)

	PF-AR	PF-ring		SPring-8	KEKB HER
Beam Current (mA)	60	30	450	100	1300
Beam Emittance (nm·rad)	290	36		3.4	24
Beam Flux (A/m^2)	4×10^4	2×10^5	3×10^6	5×10^6	7×10^6
Lasting Lifetime Drop	Yes (often)	Yes	No	No	No

Is it possible to completely suppress the dust trapping at PF-AR?

No, as long as we operate the ring with the present beam parameters.

3. Dust-trapping Experiment at PF-AR

Dust-trapping Experiment at PF-AR

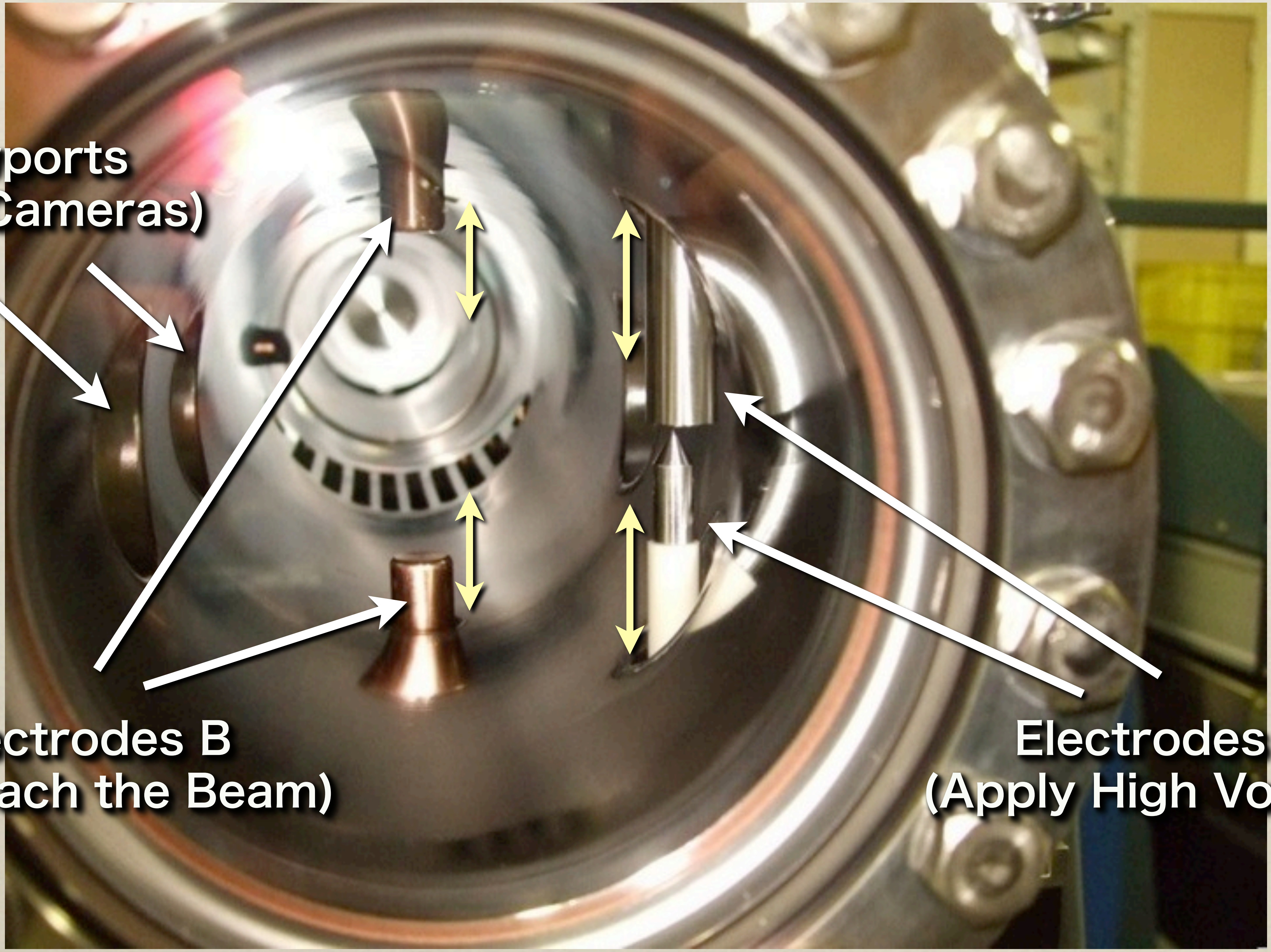
Aims:

1) to demonstrate that two kinds of electric discharges can cause dust trapping:

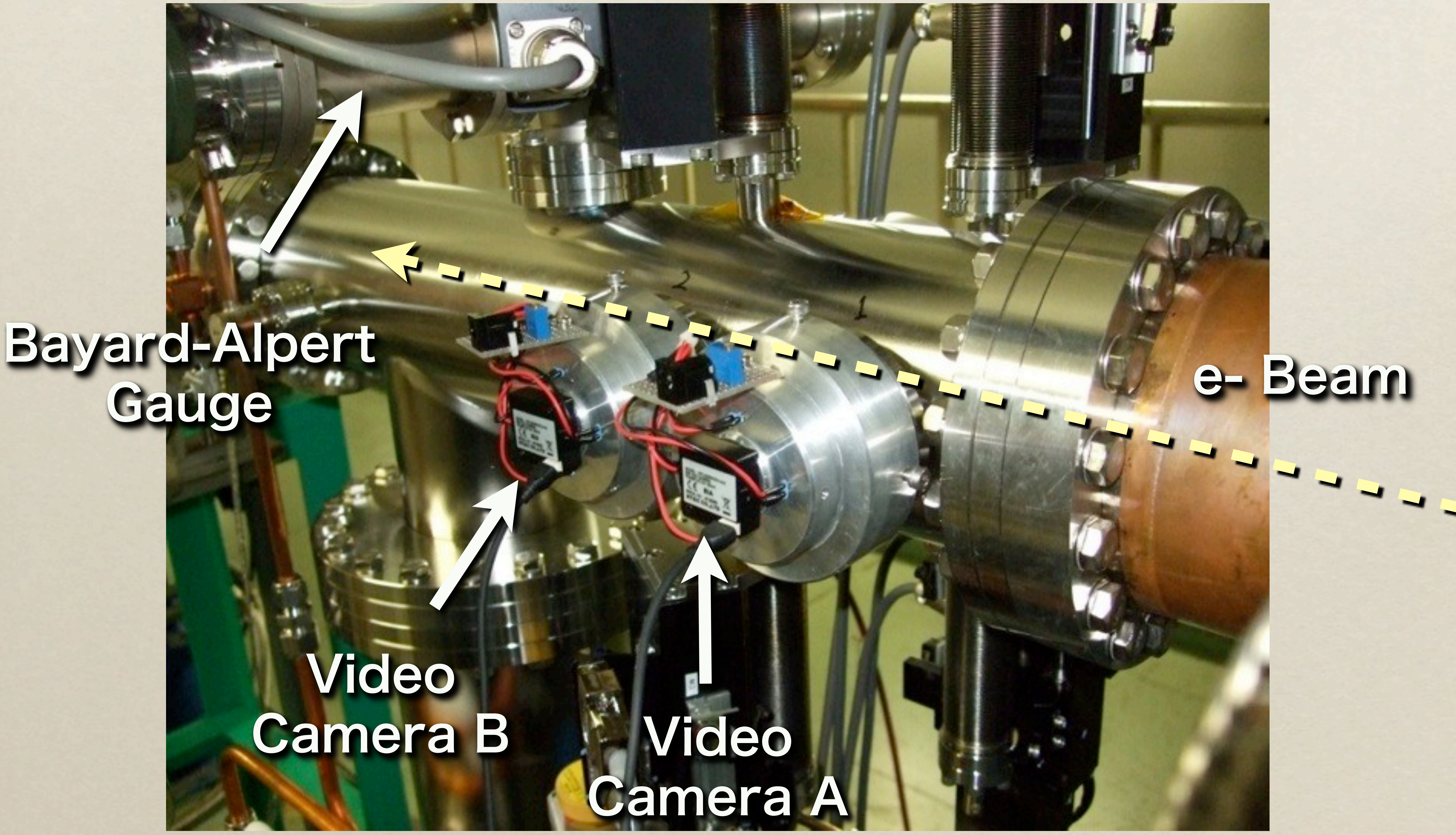
- discharge by applied DC high voltage (ex. DIP)
- discharge by beam-induced electro-magnetic fields (ex. in-vacuum ID, rf kicker electrodes)

2) to accumulate knowledge toward further understanding of the dust-trapping mechanism

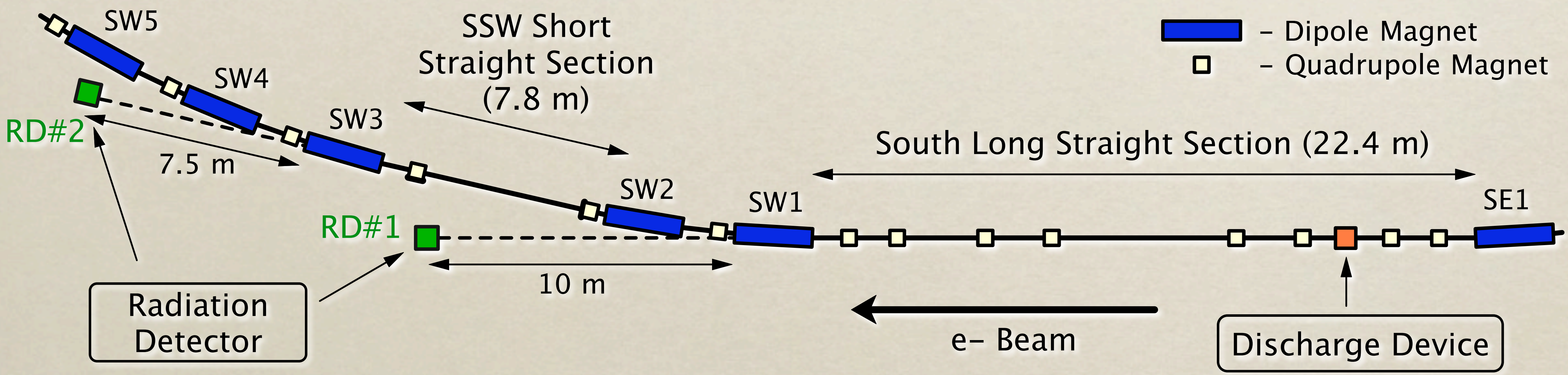
Experimental Setup (1/3)



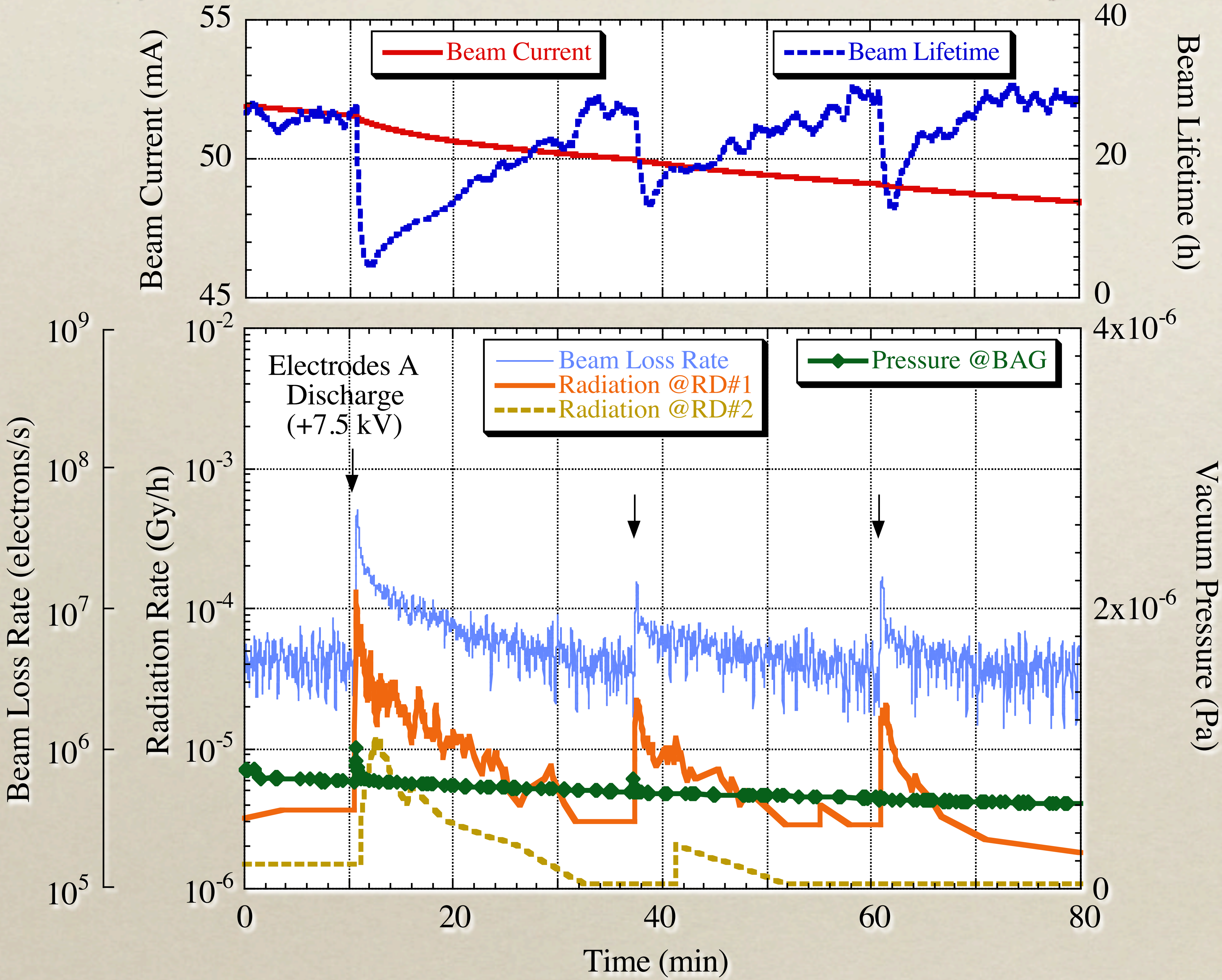
Experimental Setup (2/3)



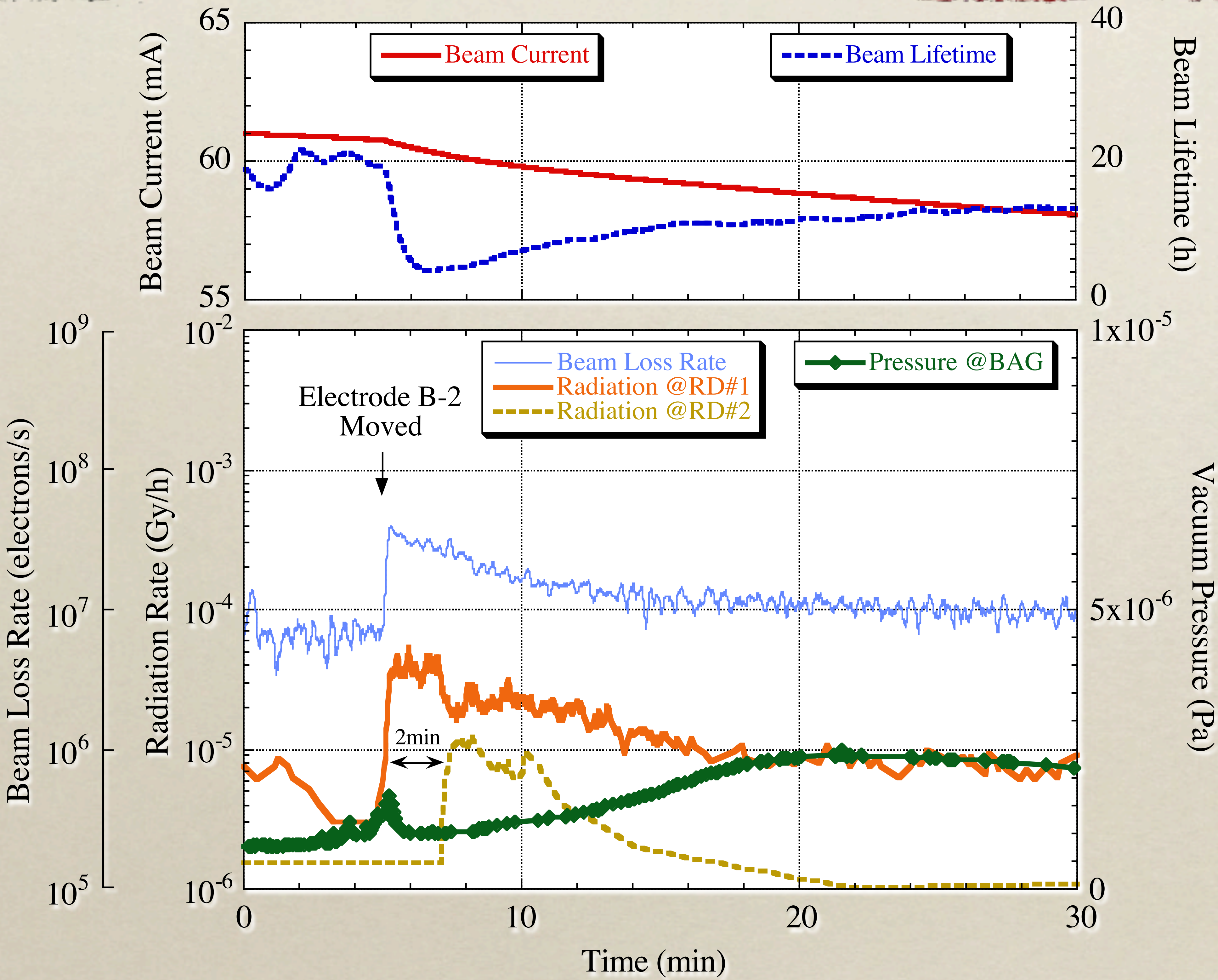
Experimental Setup (3/3)



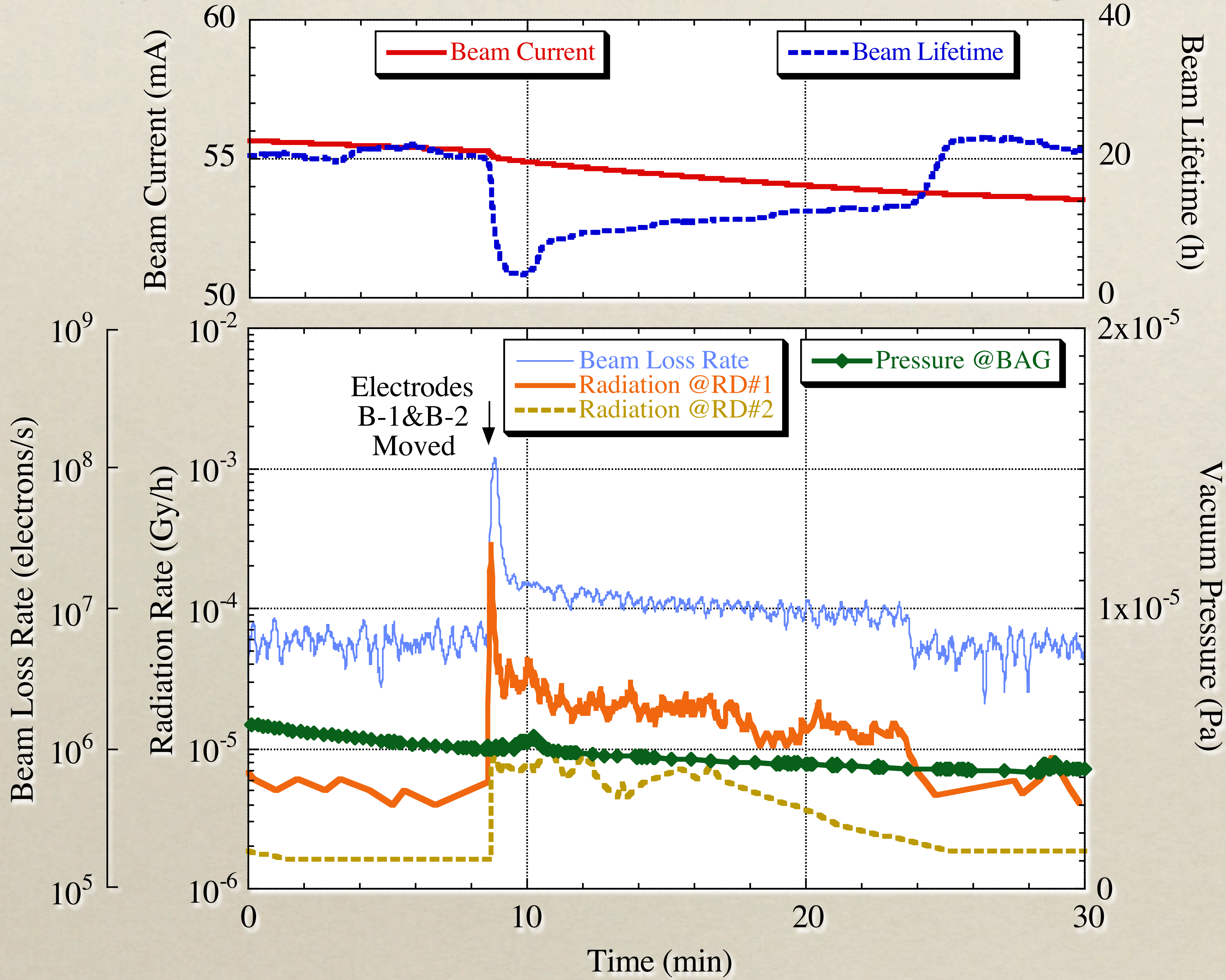
Example of Experimental Results (1/3)
(apply +7.5 kV to Electrode A-2)



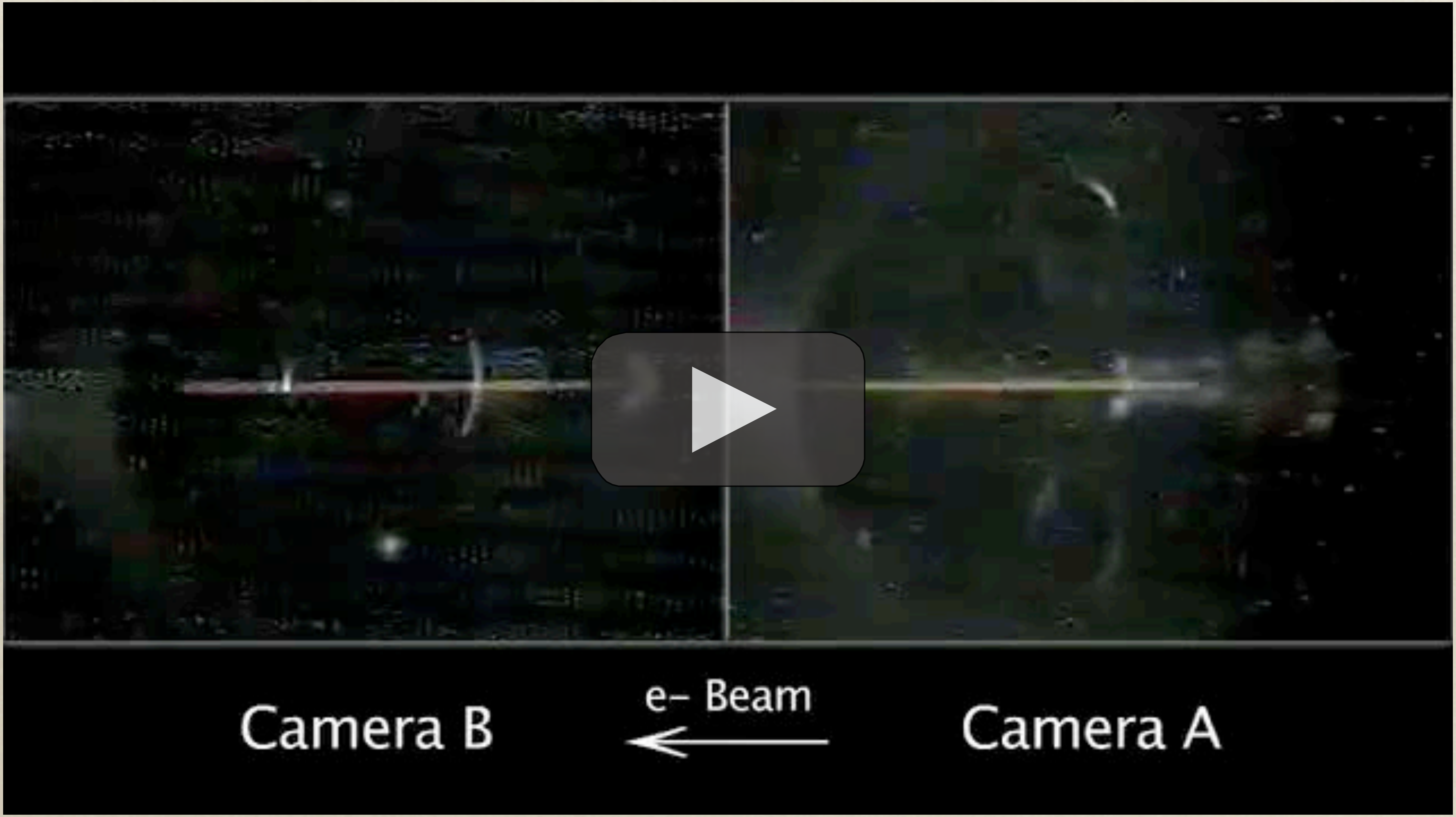
Example of Experimental Results (2/3) (bring Electrode B-2 close to the beam)



Example of experimental results (3/3)
(bring Electrodes B close to the beam)



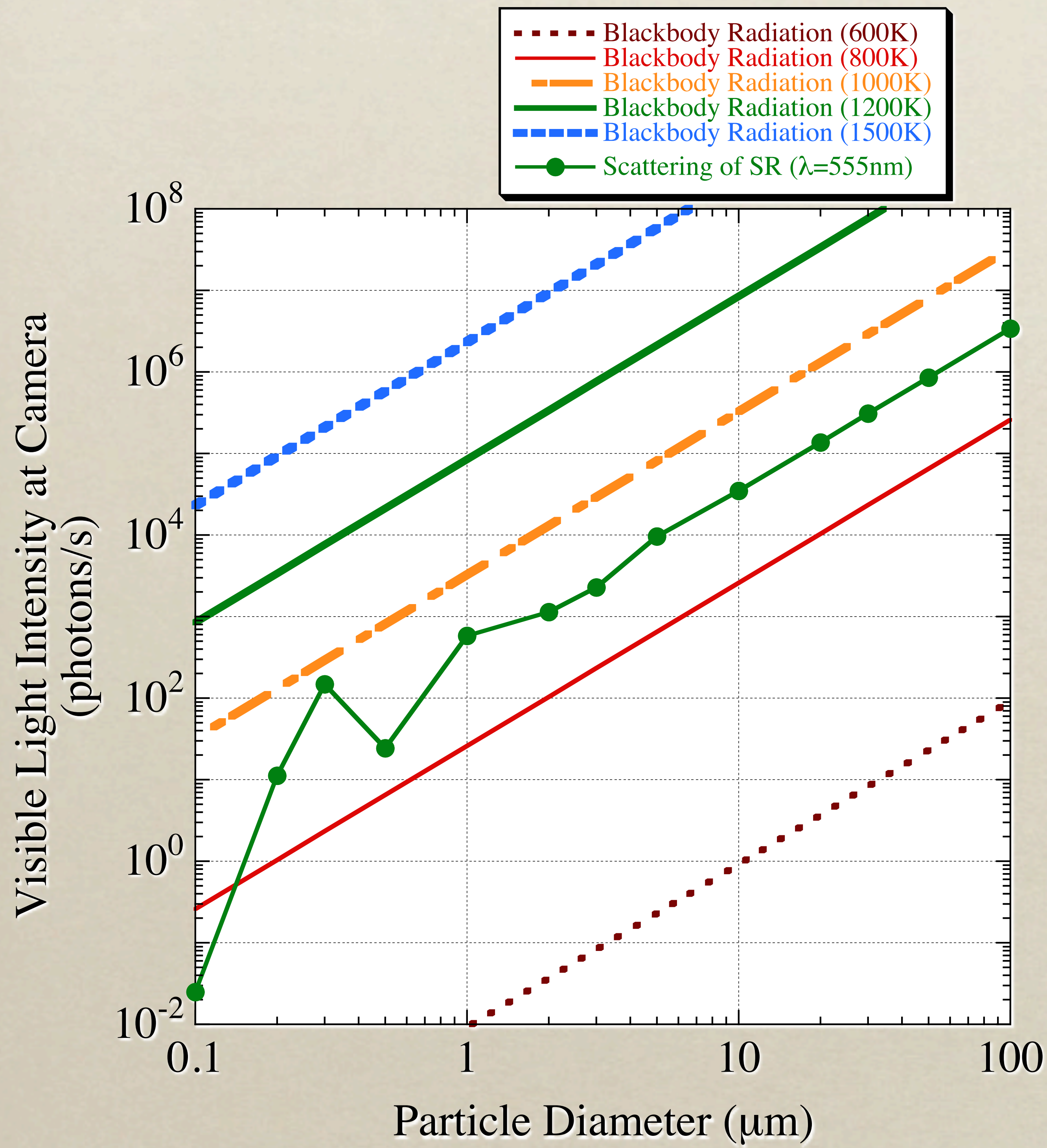
First Direct Observation of Dust Trapping



First Direct Observation of Dust Trapping (playback in half speed)

This is the first direct observation of a dust particle trapped by an electron beam, and visually confirmed the dust-trapping hypothesis proposed nearly 30 years ago.

Estimation of light-emission intensities from a dust particle (blackbody radiation and scattering of SR)



- roughly proportional to square of dust diameter

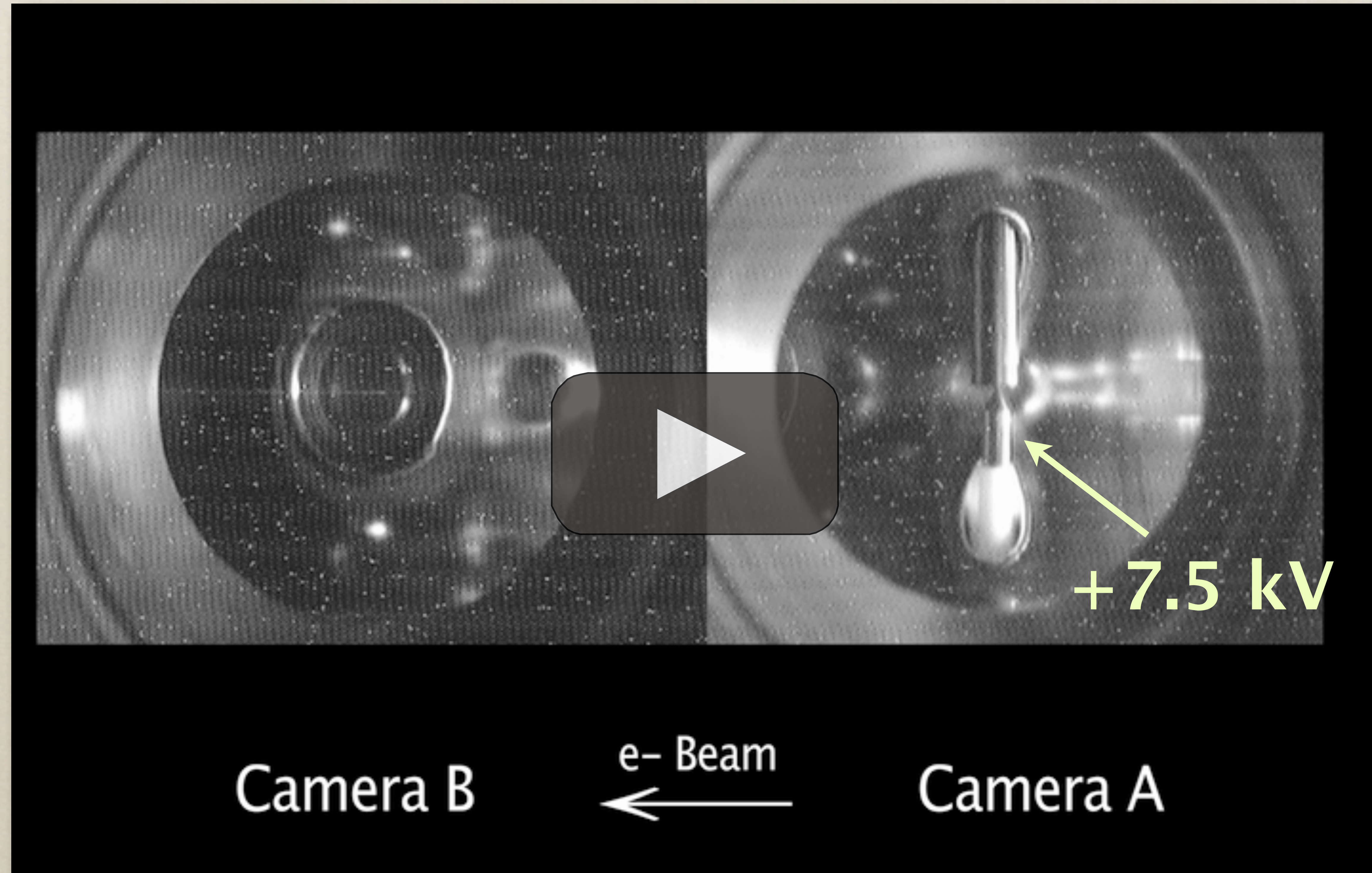
- blackbody radiation prevails against scattering of SR at 1000 K or higher

- sensitivity of the CCD is around 10^6 photons/s

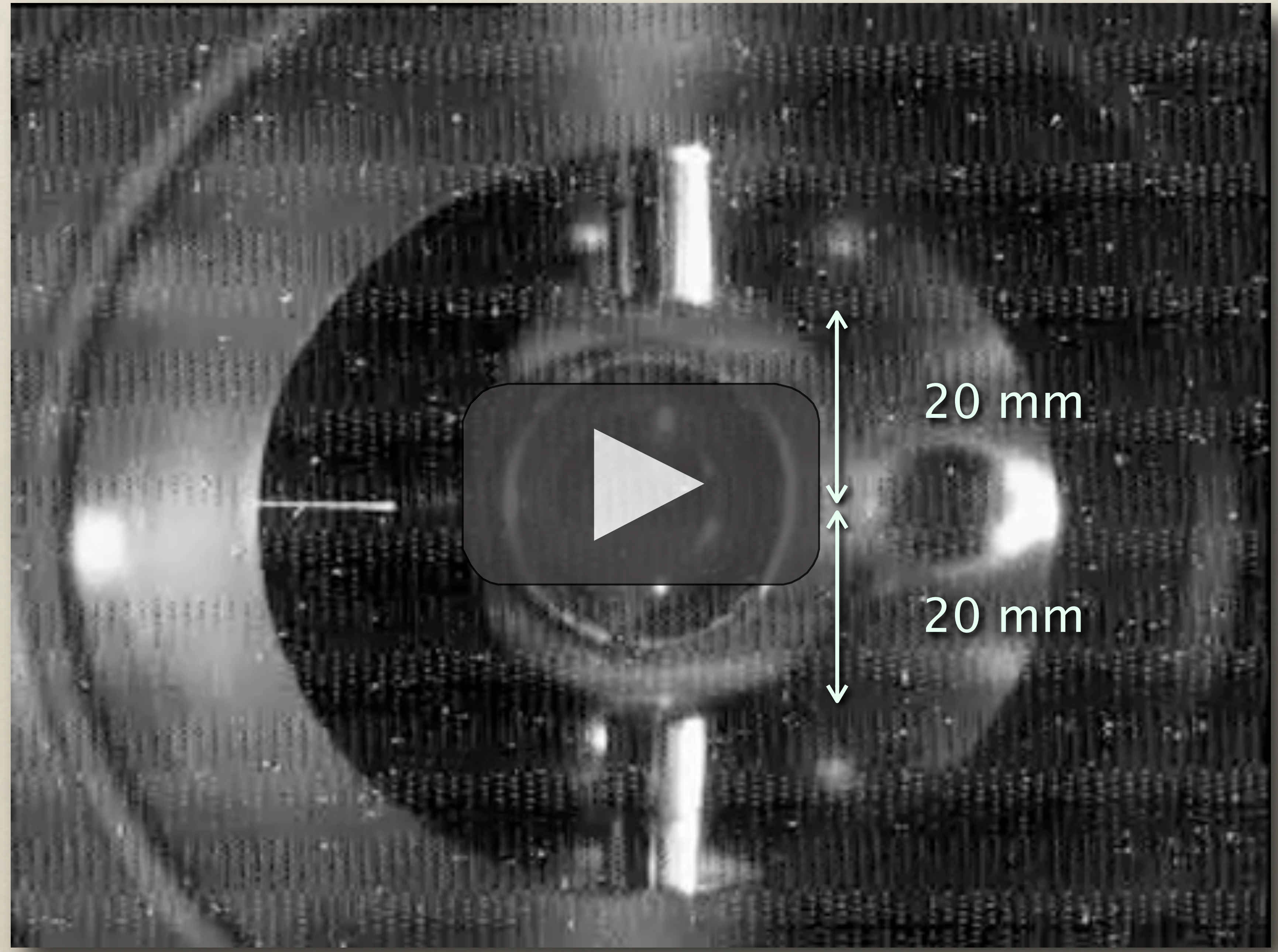
- estimated diameter from the observed lifetime (1 h) is 2 μm (assuming the dust to be silica)

Most probable reason of the light emission is blackbody radiation from a particle of 1200 K or higher

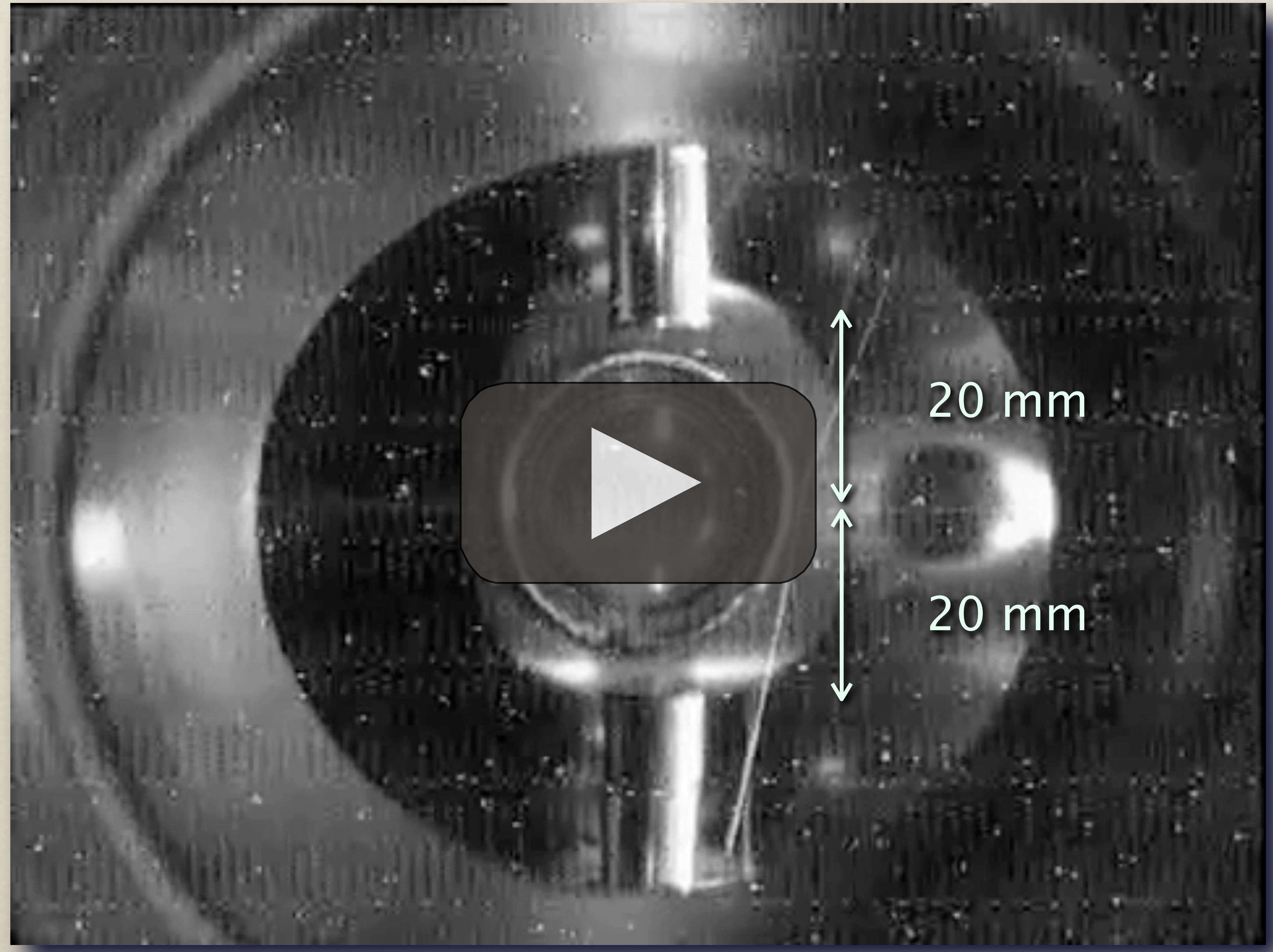
Observation of dust trapping with supersensitive cameras (1/5)



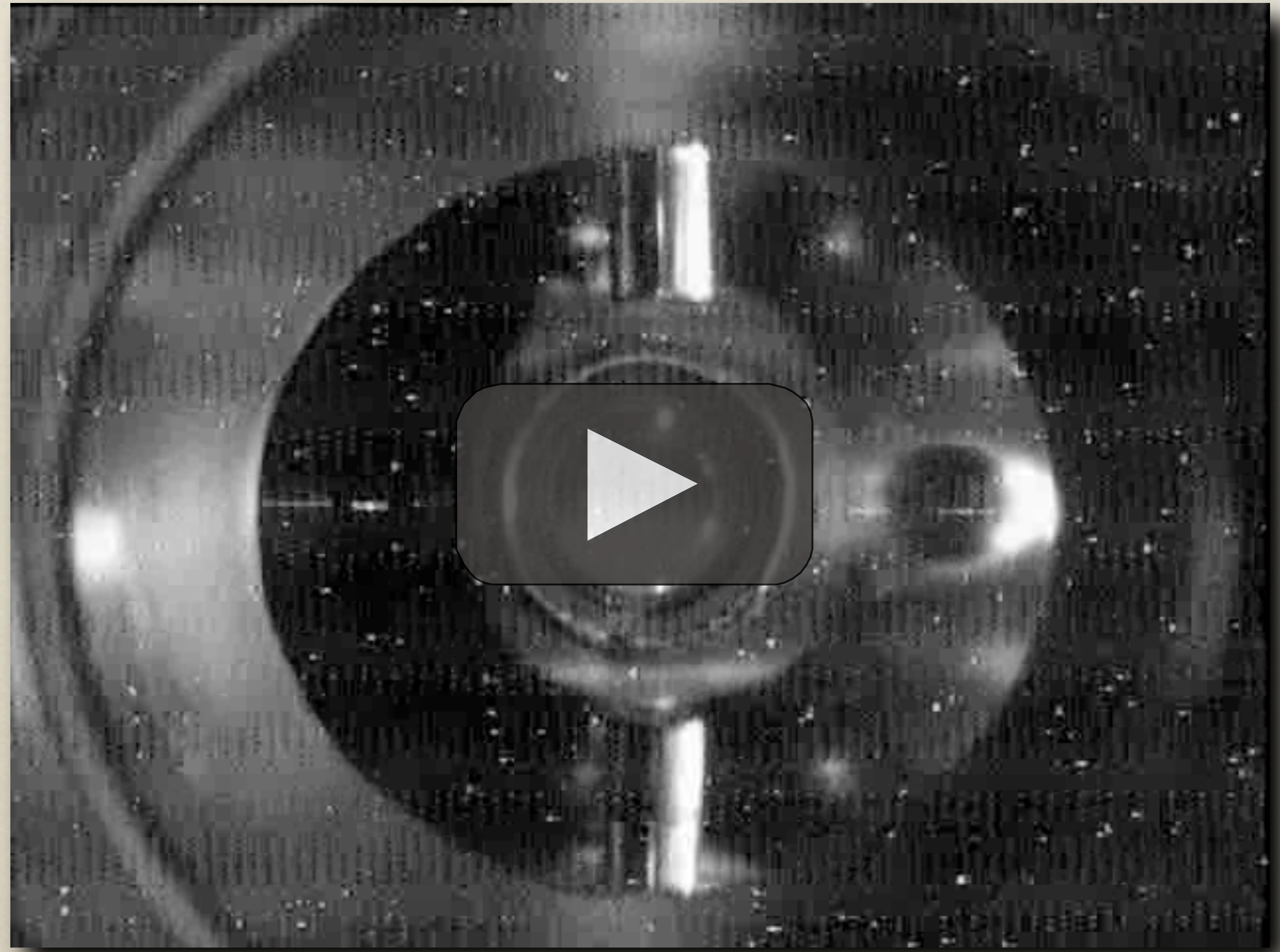
Observation of dust trapping with supersensitive cameras (2/5)



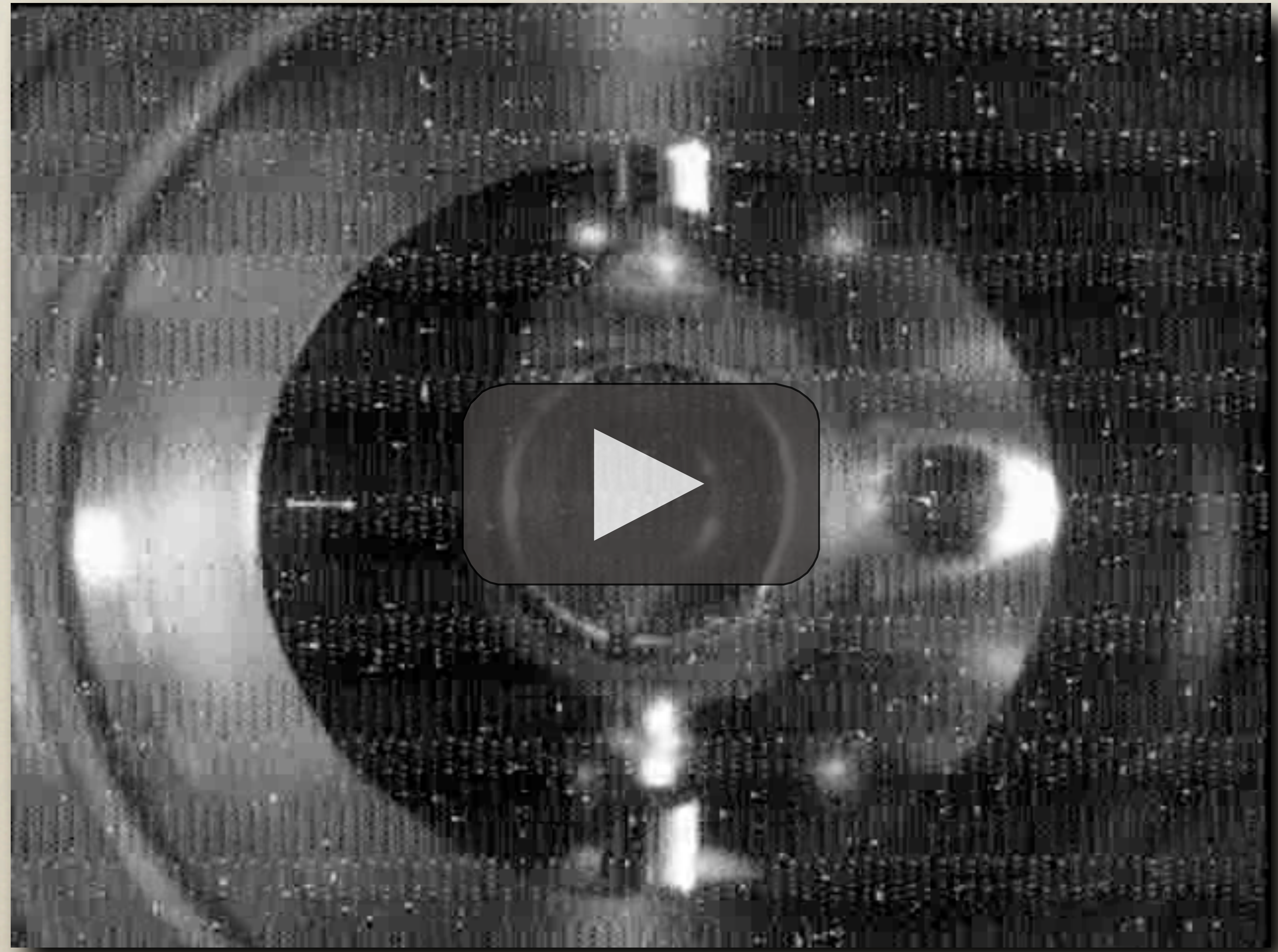
Observation of dust trapping with supersensitive cameras (3/5)



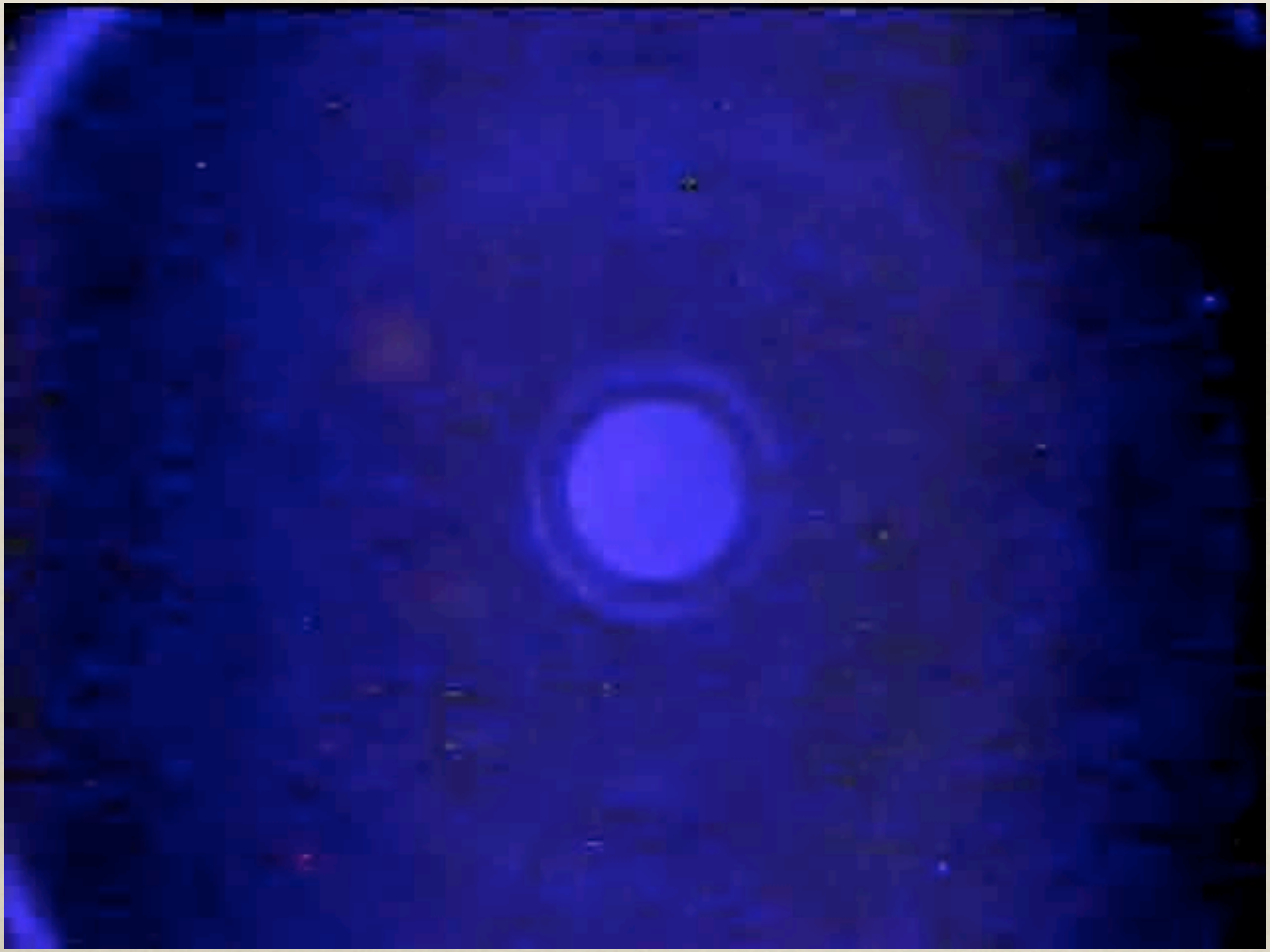
Observation of dust trapping with supersensitive cameras (4/5)

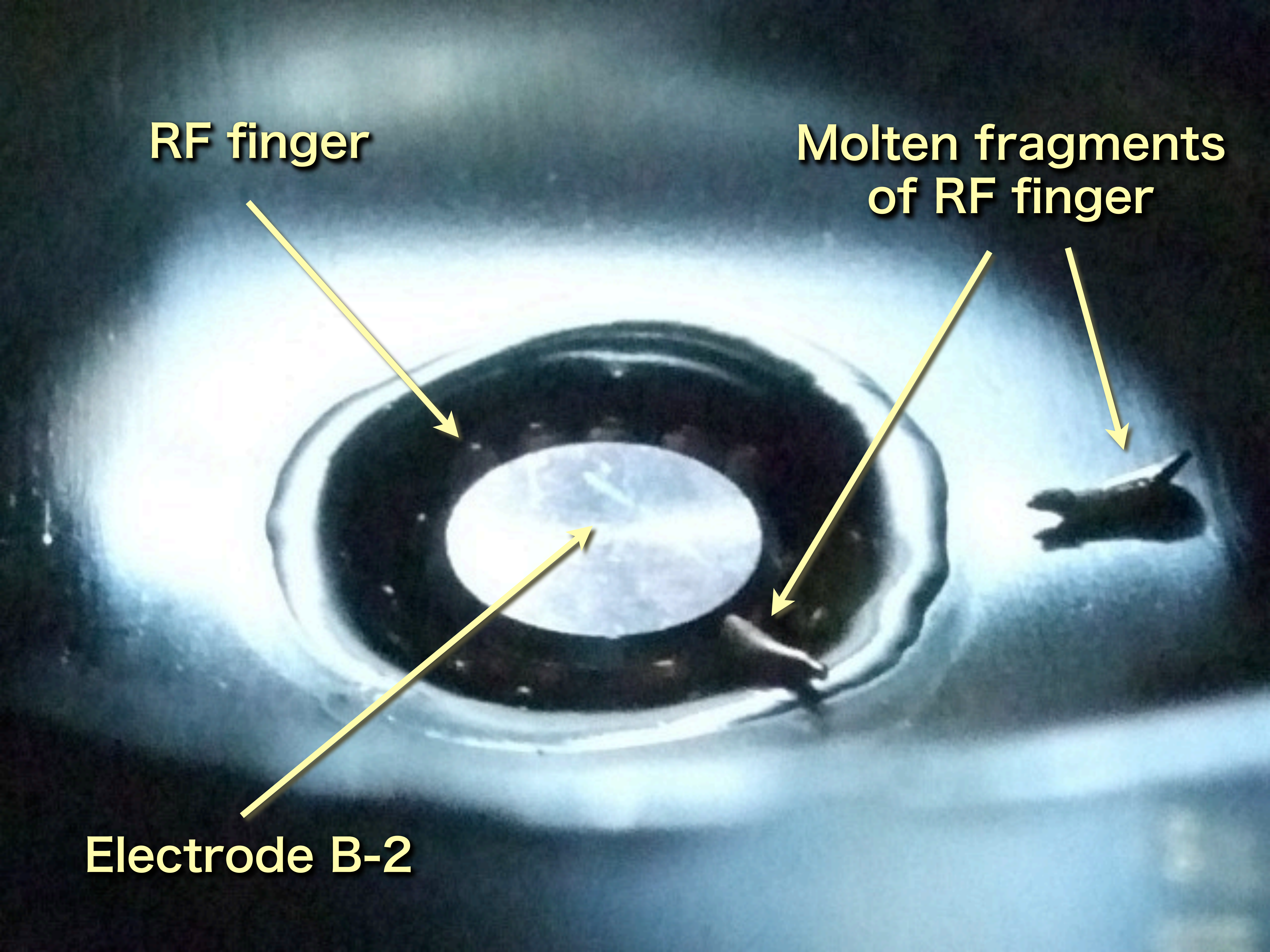


Observation of dust trapping with supersensitive cameras (5/5)



Beam Dump




RF finger
Molten fragments of RF finger
Electrode B-2

Summary

1) Experimental demonstration of the dust trapping

- Two types of electric discharge: DC high voltage and beam-induced fields

2) First direct observation of the dust trapping

- Dust-trapping hypothesis was visually confirmed.
- Temperature estimation (1200 K or more) supports the essential dust-trapping theory ---- trapped dust can reach thermal equilibrium.
- It revealed that the trapped dust can move longitudinally or stay still, suggesting that the dust is trapped in a longitudinal potential well.

Direct observation of the trapped dust was proved to be an effective and promising method for the dust-trapping research.

Acknowledgements

Experimental research on the dust trapping presented here was founded on many instructive suggestions and valuable discussions with **Tohru Honda, Shogo Sakanaka, Yoichiro Hori, Toshio Kasuga, Yoshio Saito, and Ken-ichi Kanazawa.**

I am also grateful to **Takashi Nogami, Takashi Uchiyama, and engineers at Mitsubishi Electronics System Service and Seiwa Works** for their professional contribution to the preparations of the experimental setup.