The Science and Technology of Electrophotography

or

Benjamin Franklin and Electrophotography

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Electrophotography

Technology used in

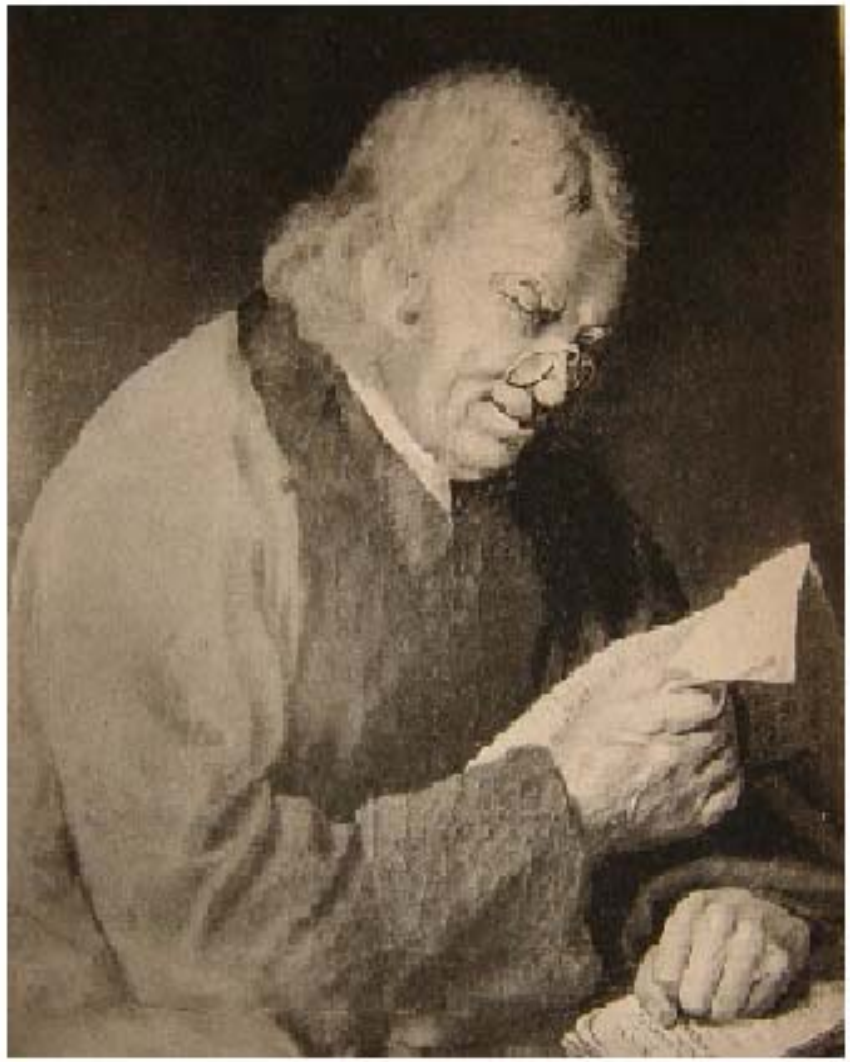
- Copiers
- Laser Printers

Multibillion Dollar Industry Based on

- Electrostatics

It's Roots go back to experiments of Benjamin Franklin

Woodcut illustrating the Leyden experiment
from Park Benjamin, A History of Electricity, 1898 - reproduced from Winckler, 1746.



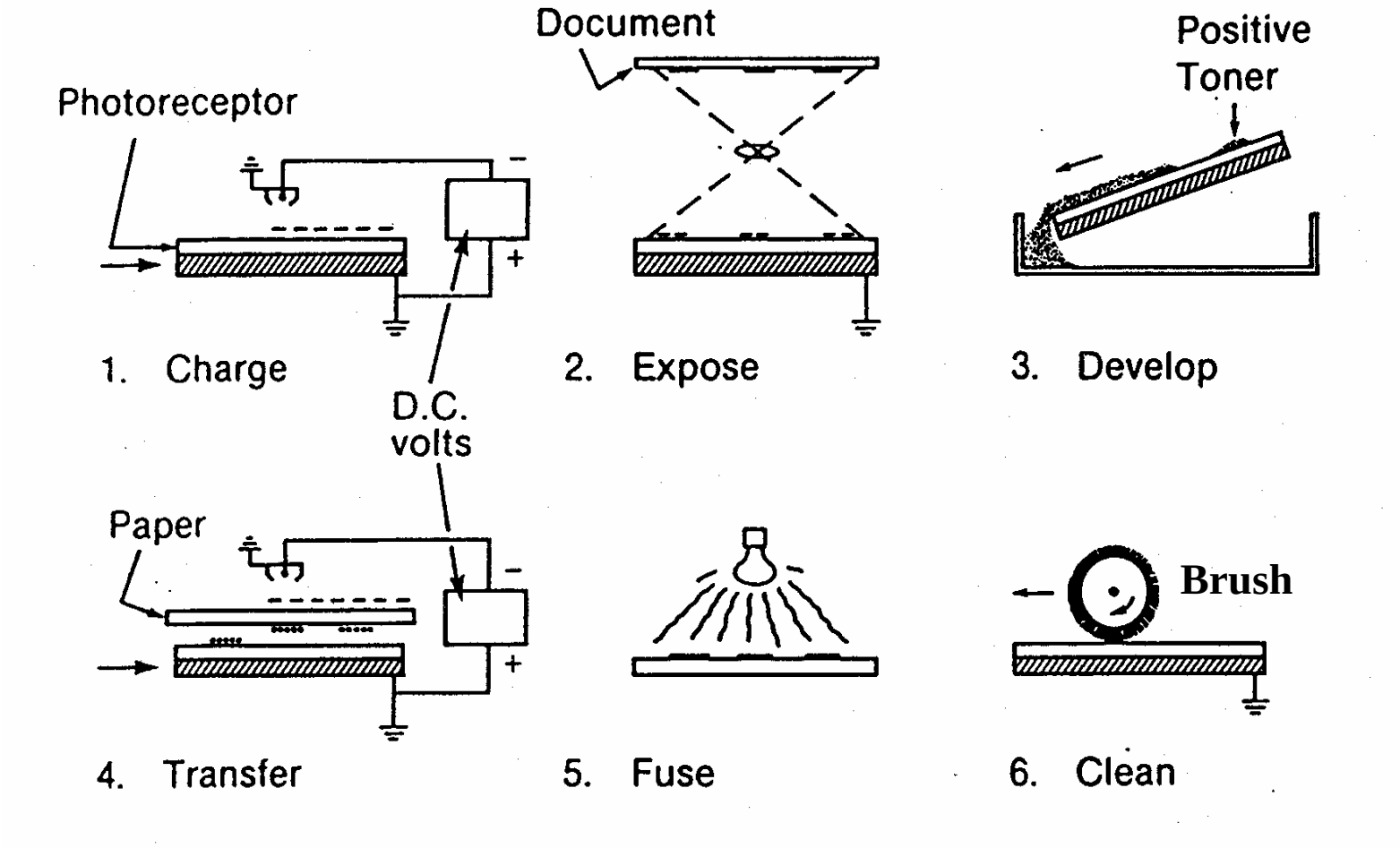
Franklin- from a painting by Stephen Elmer Bigelow 1904 Vol. VI frontispiece
(public domain)

(From www.tufts.edu/as/wright_center)

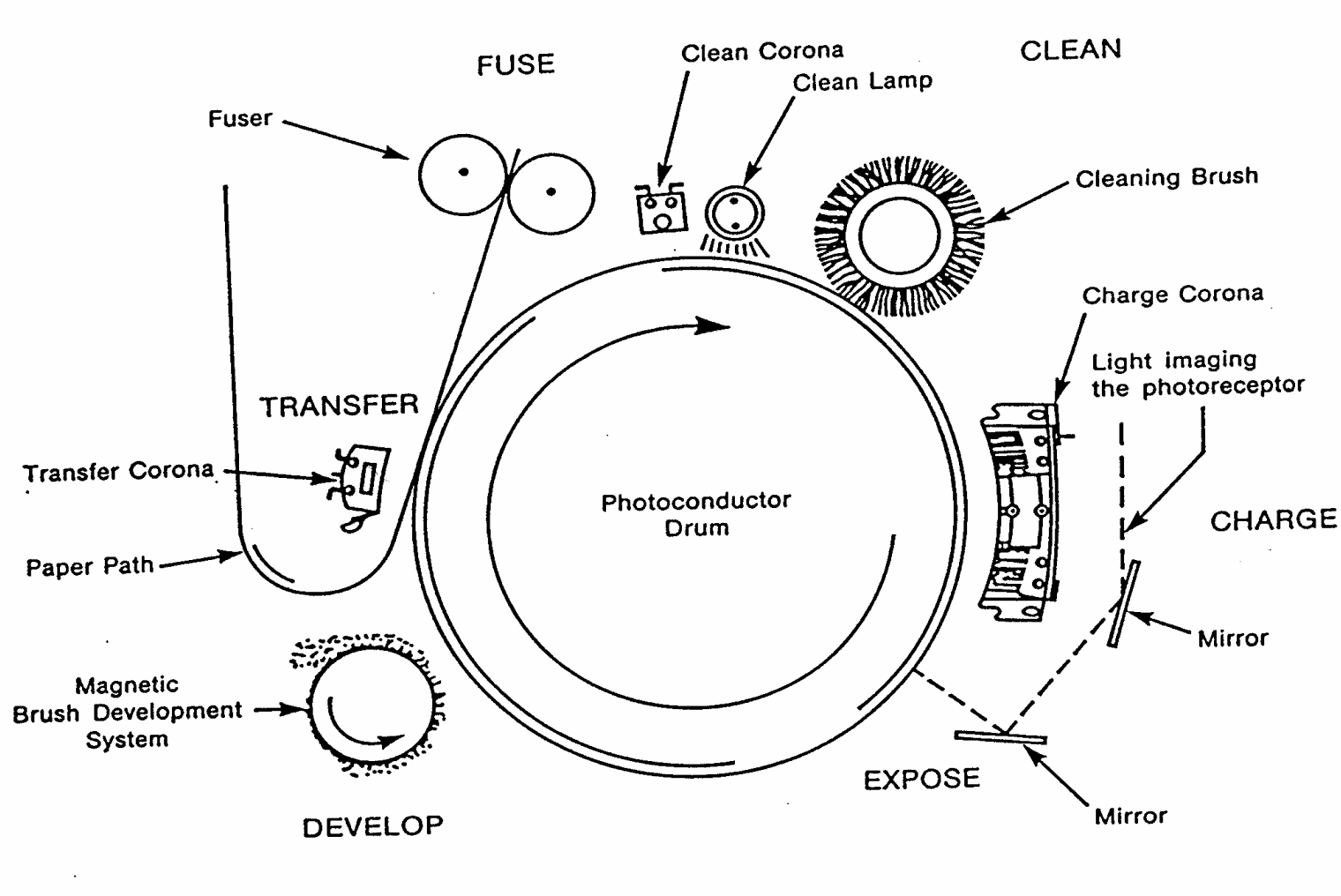
Franklin's Experiments

- Rubbed glass rod with wool or silk to generate electrostatic charges – (2) insulator charge exchange. Used rod to charge a Leiden jar – first capacitor
- Observed sharp points work better than blunt points in drawing off the fire - electric field concentration
- Noted that the amount of "electrical fire" added to glass was lost by the wool. Introduced the one fluid theory of electricity, i.e. charge conservation
- Noted the attraction or repulsion of charged surfaces to each other – (3) electrostatic adhesion
- Defined the glass's charge as positive, thereby defining the electron charge as negative
- Showed lightening is electrical in origin and designed the first lightening rods. This later led to (1) coronas

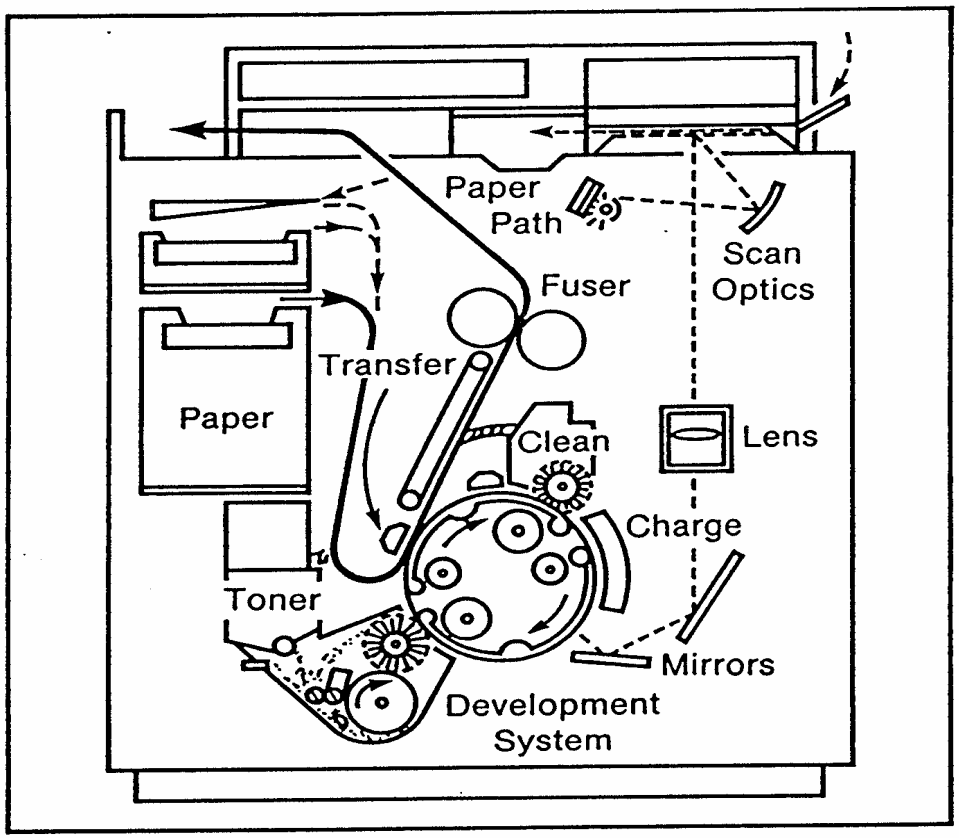
6 Steps of Electrophotography



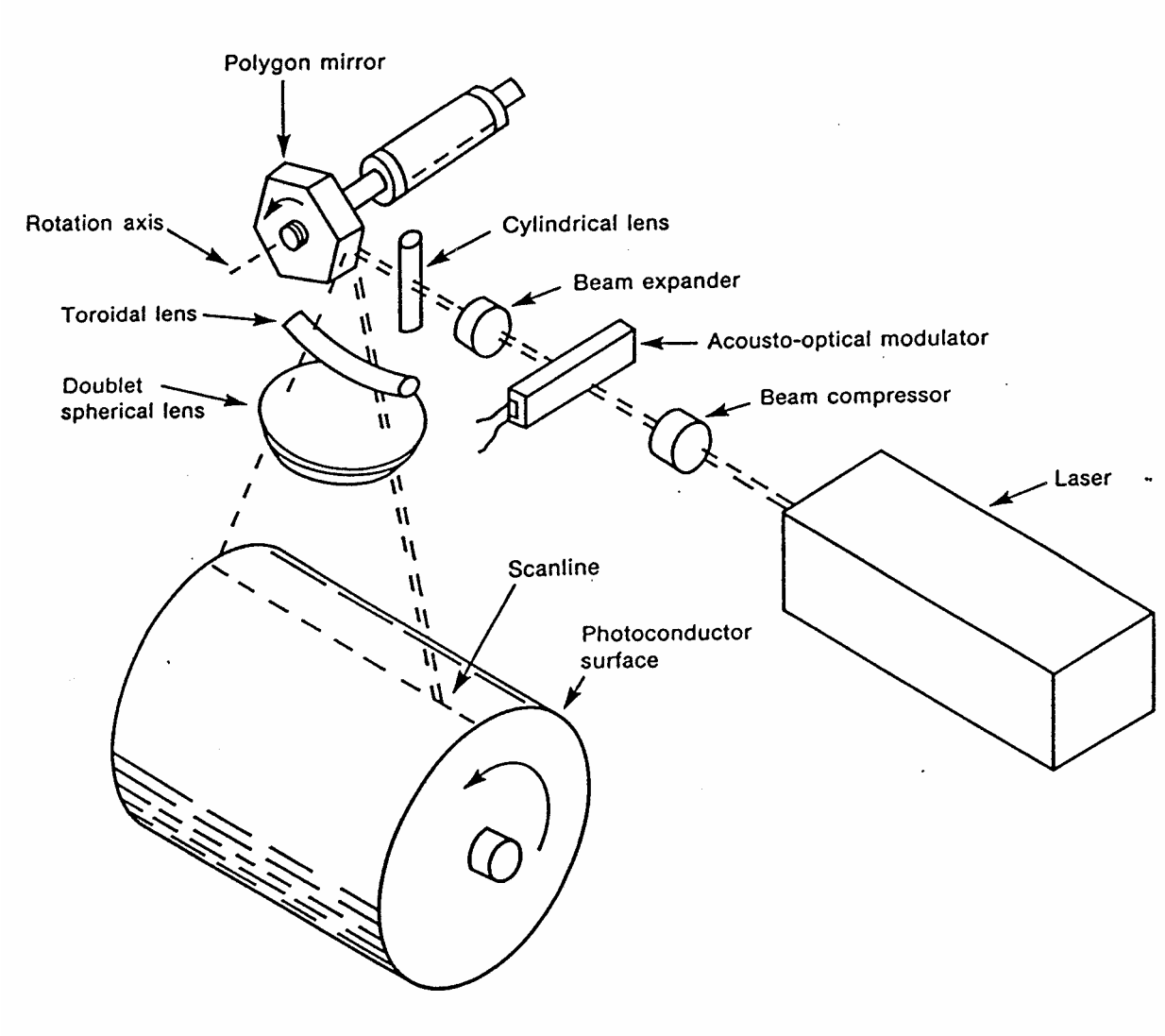
Electrophotographic Process



IBM Series III



Schematic of a HeNe Laser Printer



Short History of Electrophotography (EP)

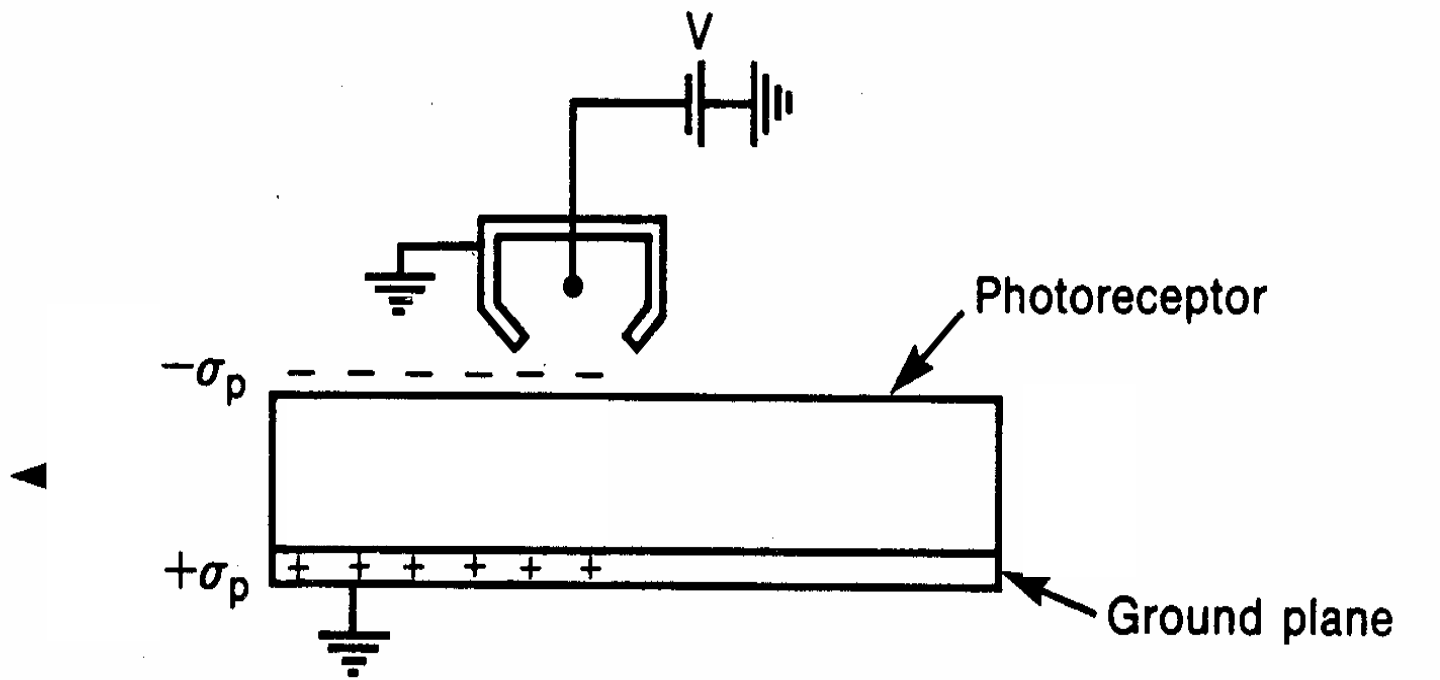
- **1938 – Invented by Chester Carlson**
- **Mid 1950s – Xerox (Haloid) - Battelle collaboration. Invented**
  - a-Se Photoreceptor
  - Corona charging
  - Two component development
  - Electrostatic transfer
- **1959 – Xerox 914 copier introduced**
- **Mid-60s – Organic photoreceptor introduced by IBM led to IBM Copier I (1970) and first laser printer (1975)**
- **1980 – Canon introduced magnetic toner, monocomponent development and cartridge (1983)**
- **1985 – Ricoh introduced NON-magnetic toner, monocomponent development – used extensively in color EP**
- **1986 – Canon introduced digital color**
- **2001 – Xerox introduced image-on-image (IOI) architecture**
- **2005 – Aetas introduced small volume, low cost IOI system**

Lightning

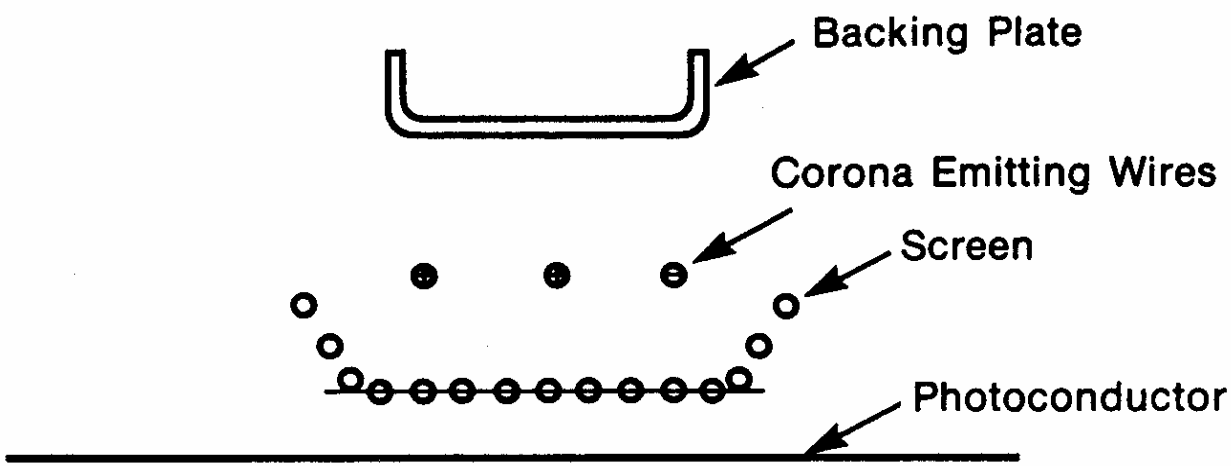
Lightning and (1) Coronas

- **Lightning**
  - Franklin showed lightning is electrical in origin – electrical fire.
  - Source of charge separation in clouds still under investigation.
  - Consider the cloud and ground as a capacitor – 2 parallel plates.
  - When the electric field in air is high enough (3 V/micron) for electrons to gain enough energy to ionize molecules by collision - creates a conductive path.
  - Lightning (discharge of the cloud) follows the conductive path
- **Corona**
  - Consider a wire – plane geometry. Field is non-uniform - highest at the wire surface.
  - Air is ionized near the wire. But far from the wire the field is too low to ionize the air.
  - This creates a plasma near the wire, which can be used as a source of charged particles.

Corotron

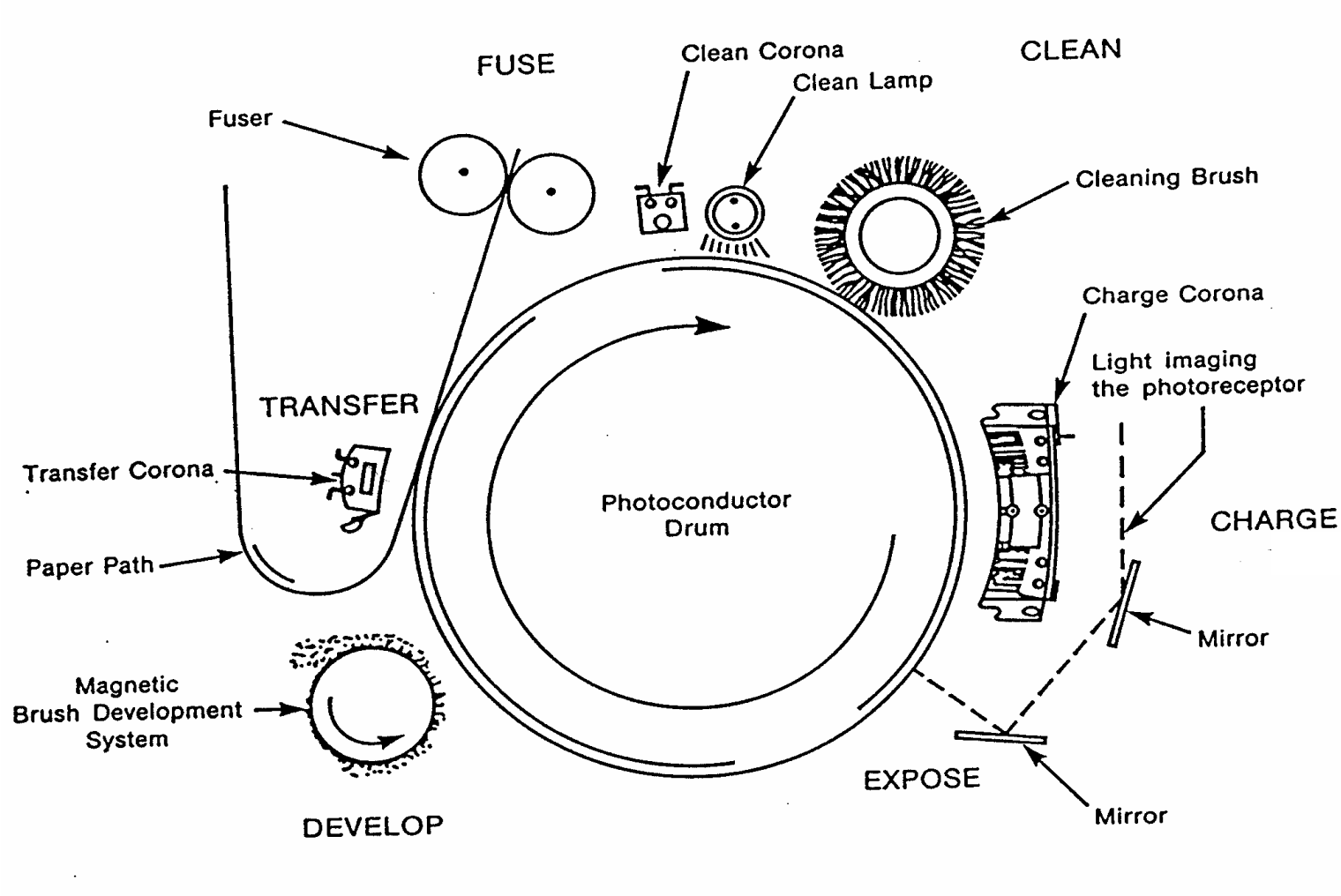


Scorotron



Charging is self limited

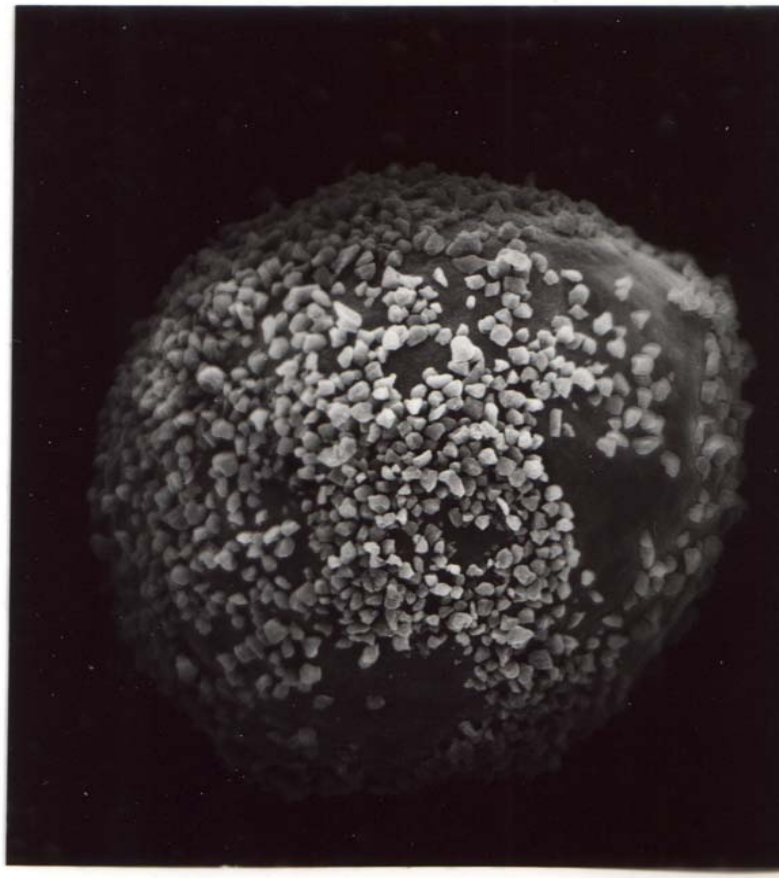
Electrophotographic Process



2. Insulator Charge Exchange
Charging Toner Particles

5 μm

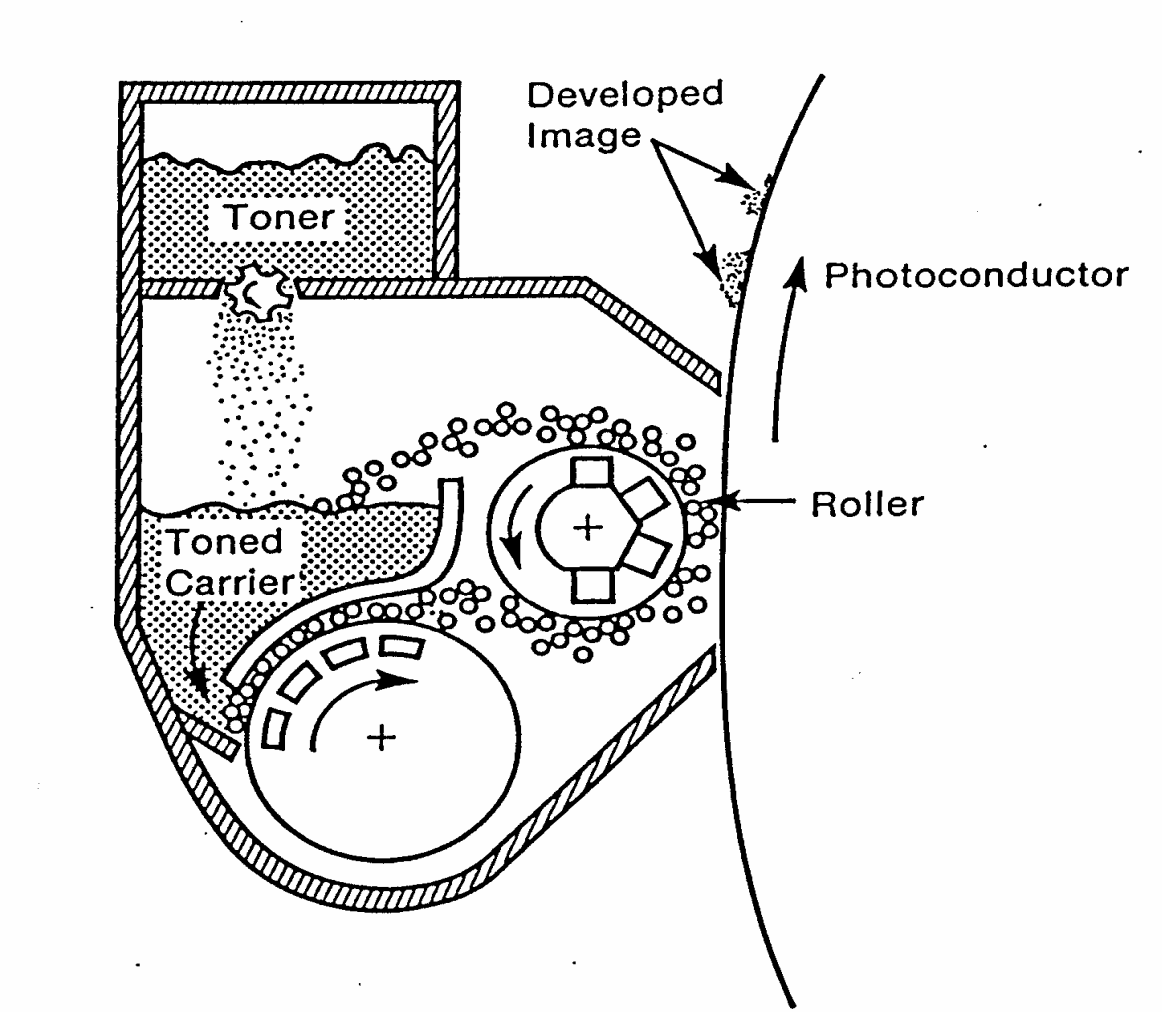
Toner



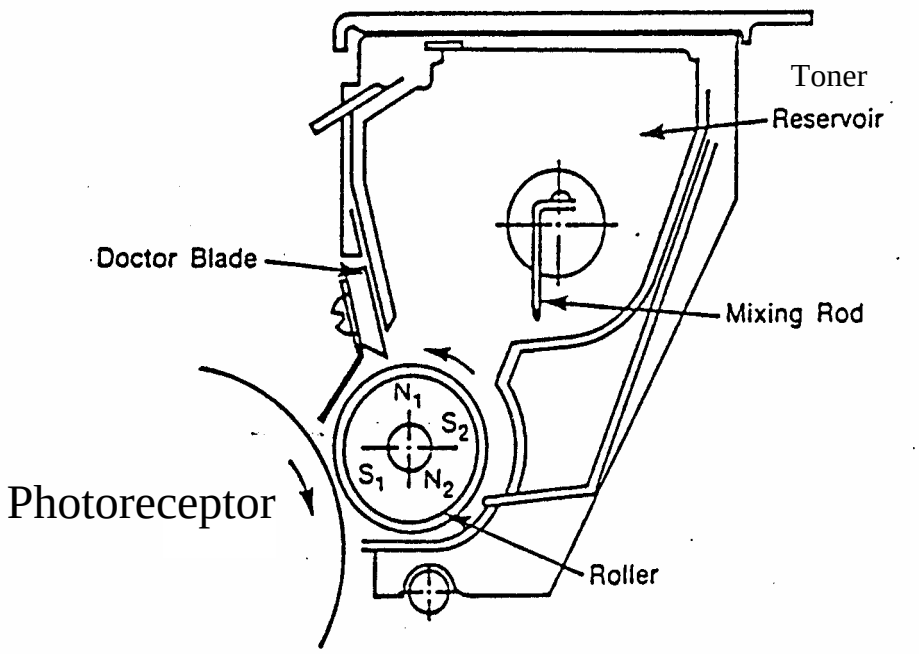
50 μm

Toner on Carrier

Two Component Development

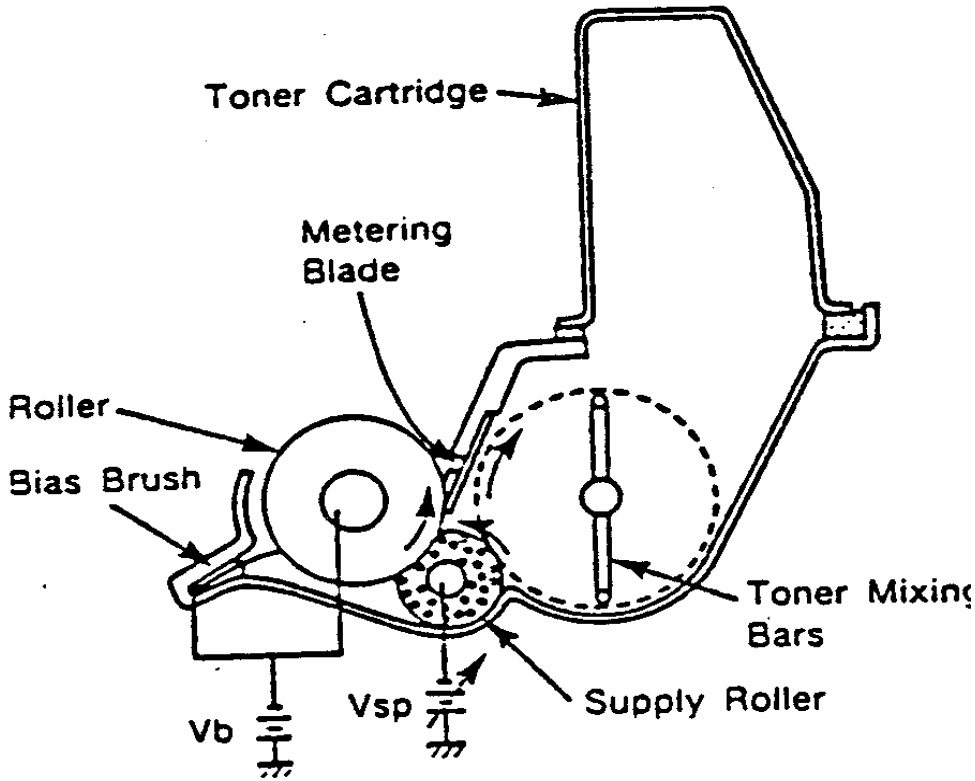


Canon's Magnetic Toner, Monocomponent Development System (1980)



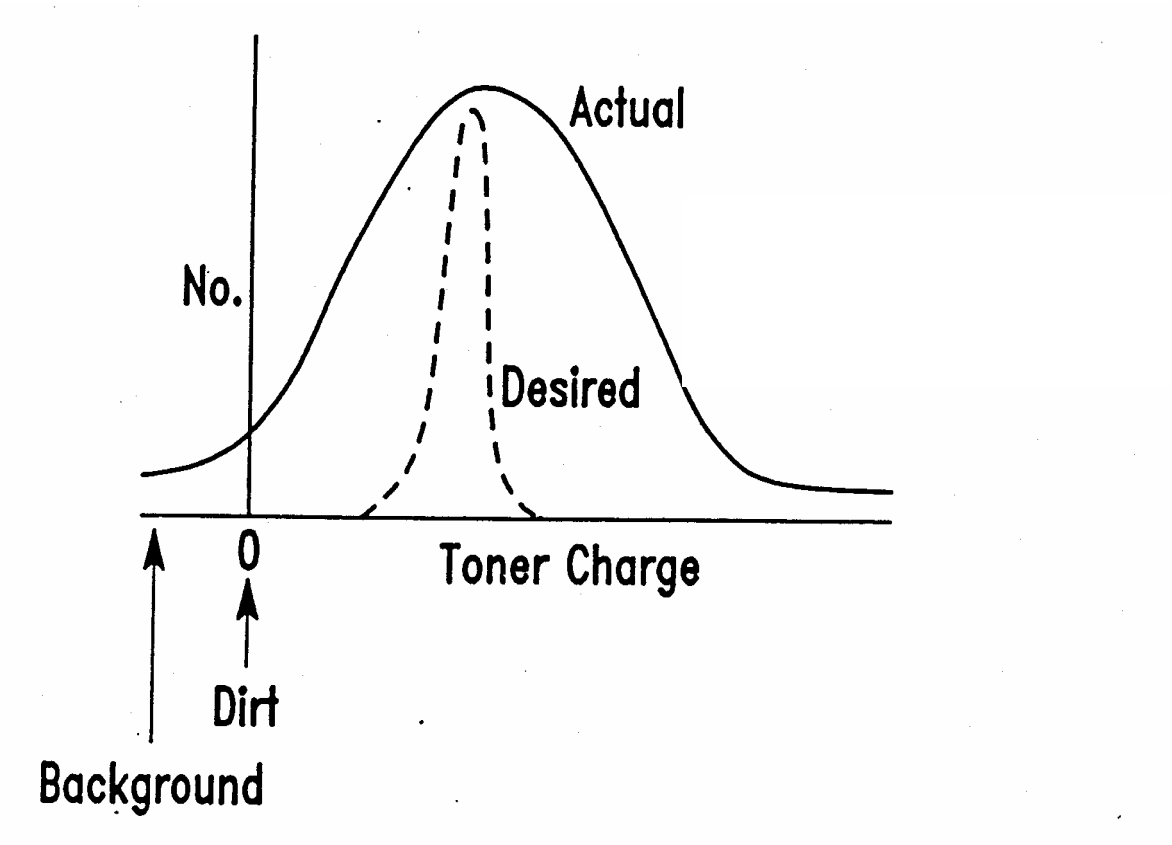
Uses ac electric fields

Ricoh's NON-magnetic Toner, Monocomponent Development System (1985)



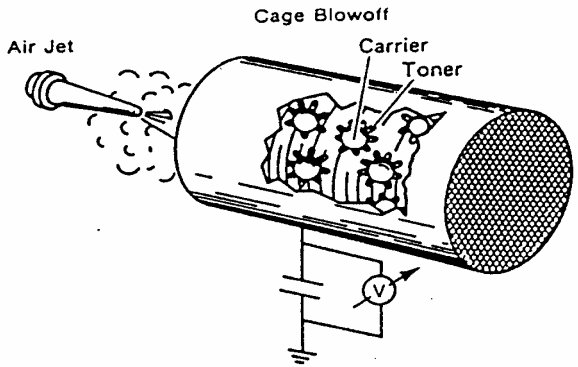
Uses contact development

Toner Charge Distributions

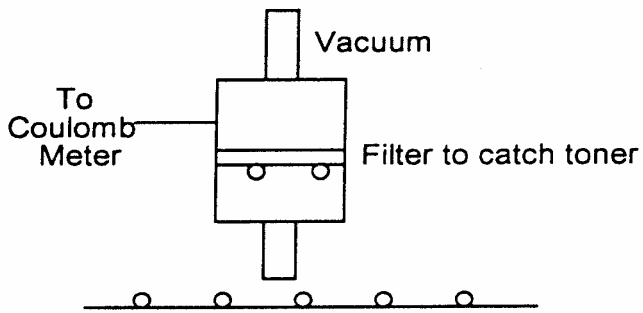


Charge Measuring Tools

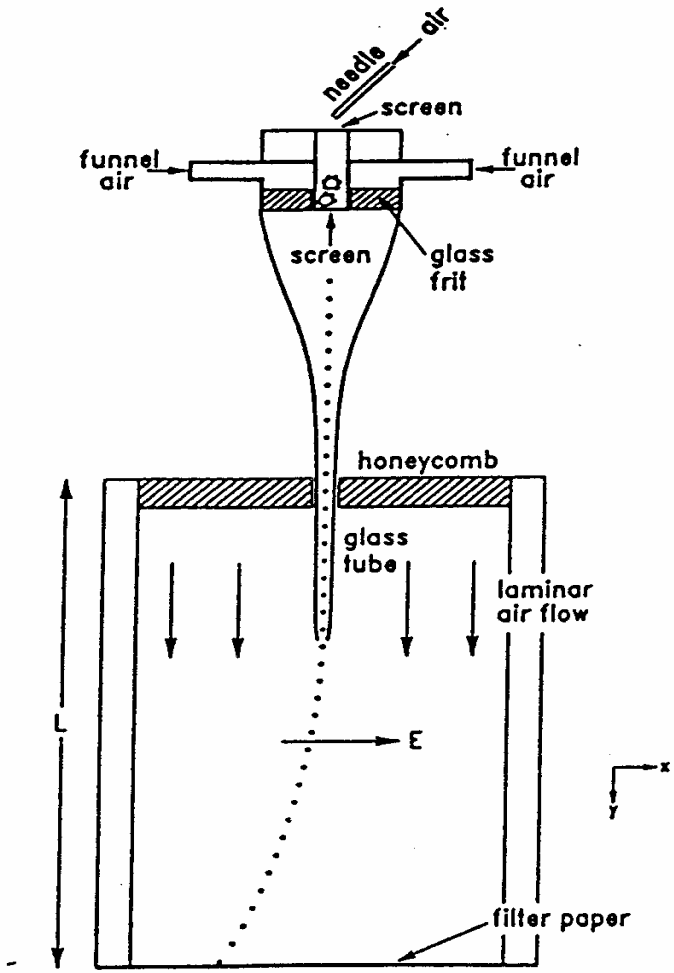
Cage Blowoff: Q/M

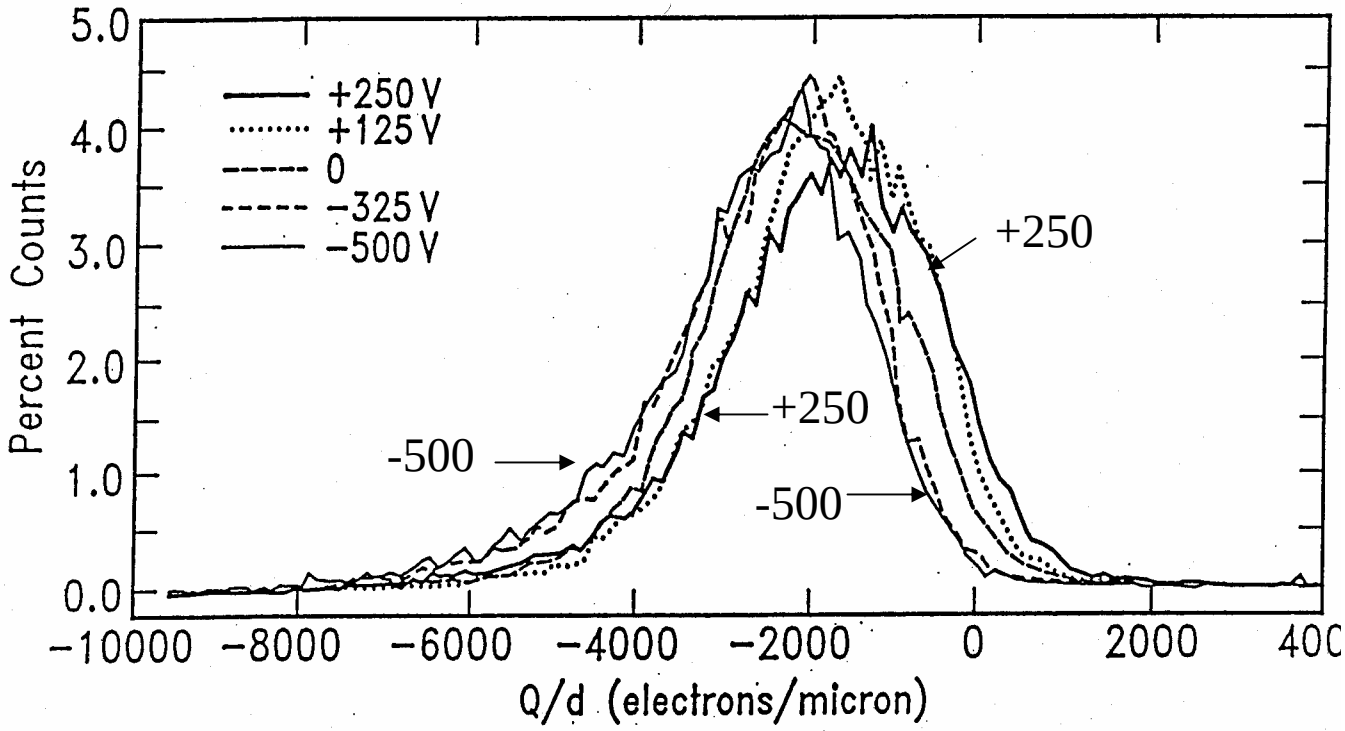


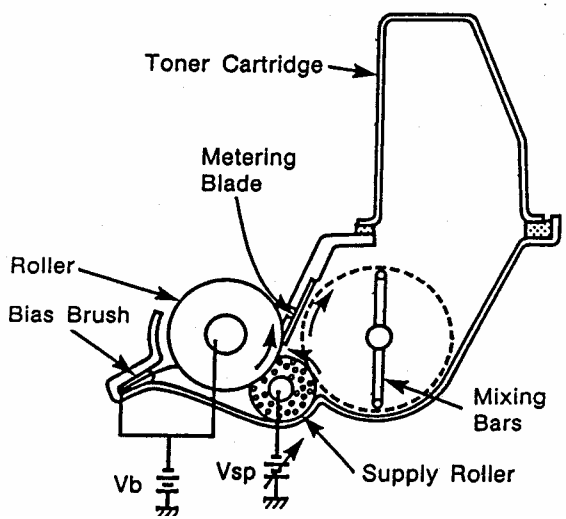
Vacuum Liftoff, Plate Blowoff: Q/M



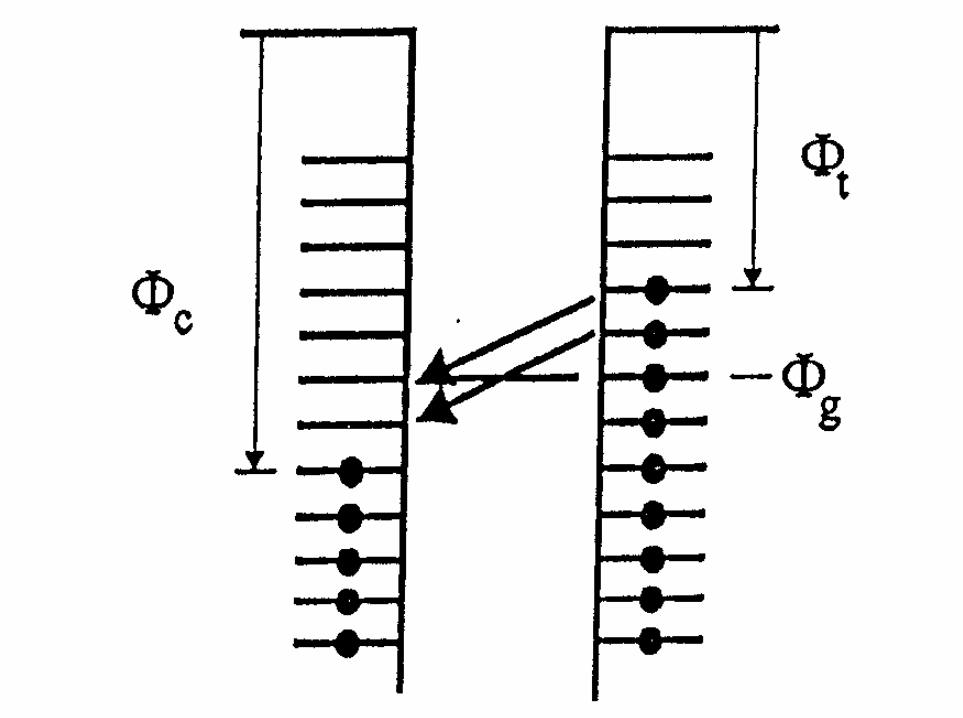
Toner Charge Spectrometer



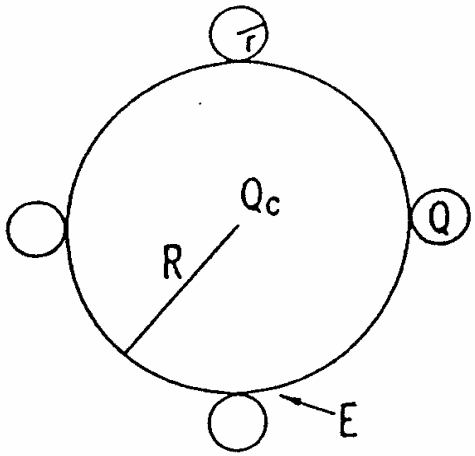

5.0
4.0
3.0
2.0
1.0
0.0
Percent Counts
+250 V
+125 V
0
−325 V
−500 V
+250
+250
-500
-500
−10000
−8000
−6000
−4000
−2000
0
2000
400
Q/d (electrons/micron)


Toner Cartridge
Metering Blade
Roller
Bias Brush
Mixing Bars
Supply Roller
Vb
Vsp

Low Density Surface State Model Inconsistent with Data



Electric Field Theory
Consistent with all Experiments

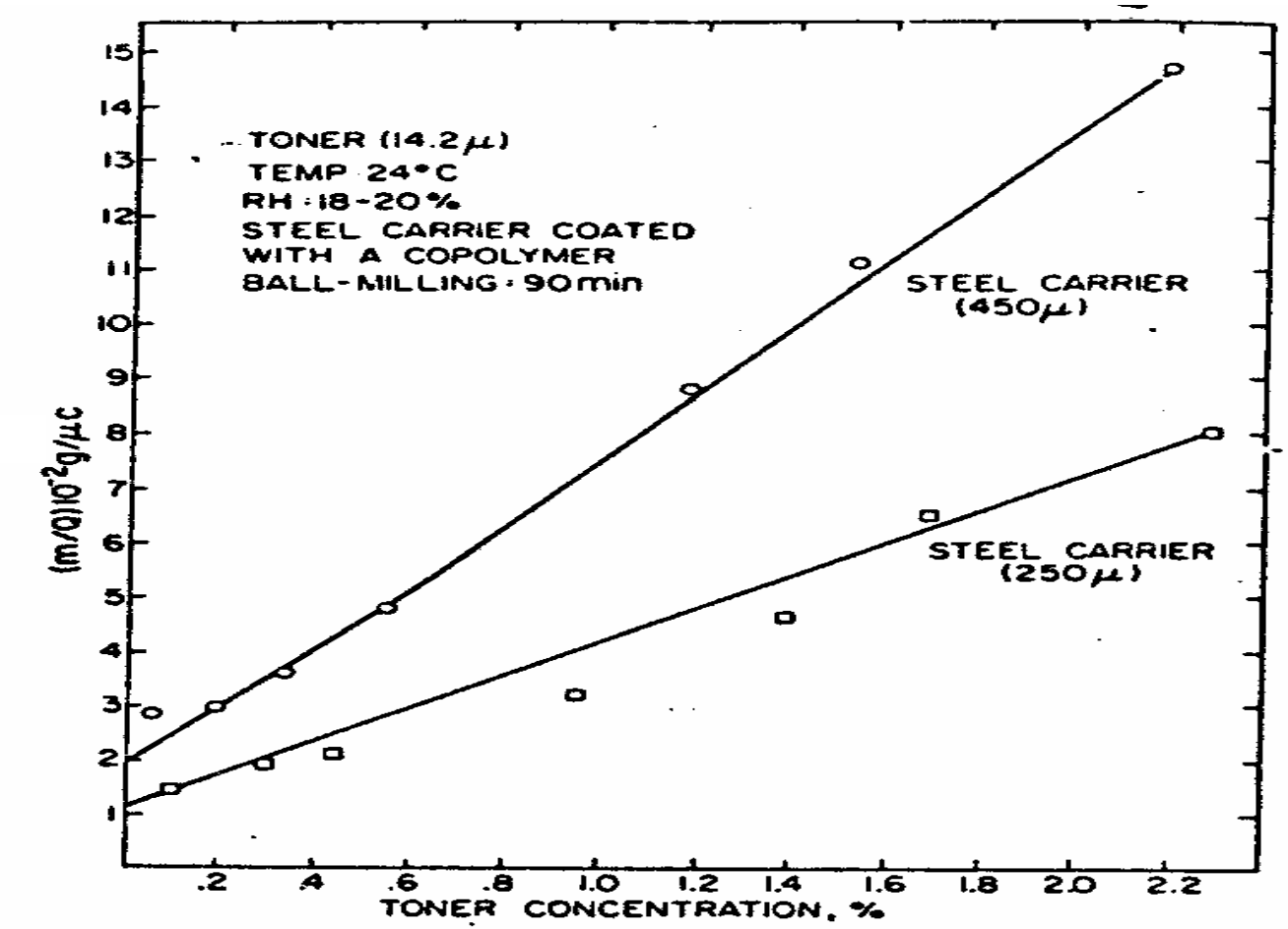


$$E = \frac{1}{4\pi\varepsilon_0}\left(\frac{Q}{r^2} + \frac{Q_c}{R^2}\right)$$

Toner charges until $E=E_e$

M/Q vs. C_t

(from Lee, Photo.Science, and Eng. 22, 228, 1978)



Comparison of Low Density and Electric Field Theories

- **Electric Field**

$$\frac{M}{Q} = RC_t\left(\frac{\rho_c}{3eE_e}\right) + r\left(\frac{\rho_t}{3eE_e}\right)$$

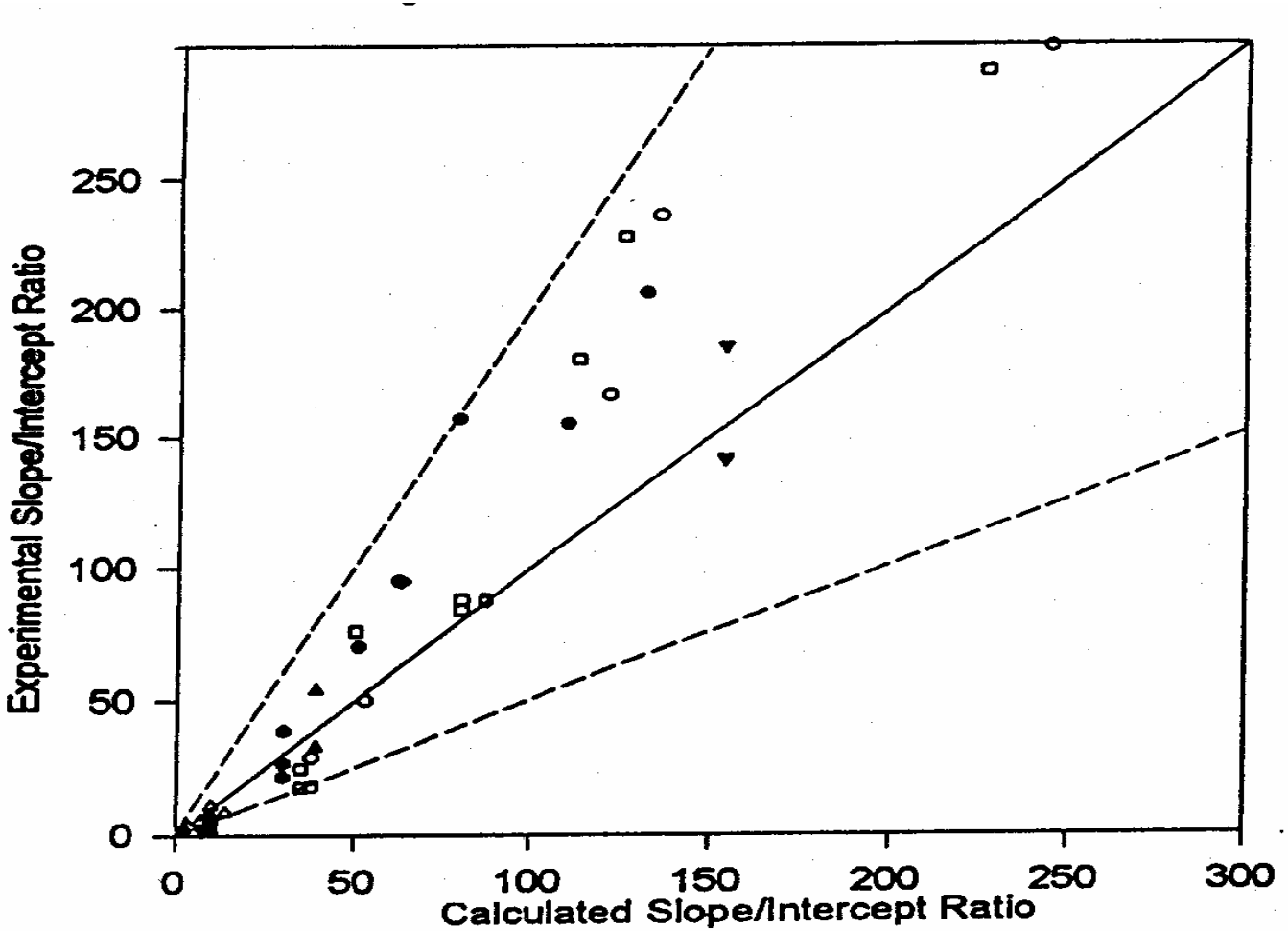
$$\frac{S}{I} = \frac{R\,\rho_c}{r\,\rho_t}$$

- **Low Density**

$$\frac{M}{Q} = RC_t\left(\frac{\rho_c}{3\Delta\phi eN_c}\right) + r\left(\frac{\rho_t}{3\Delta\phi eN_t}\right)$$

$$\frac{S}{I} = \frac{R\rho_c}{r\rho_t}\frac{N_t}{N_c}$$

Data Supporting Electric Field Theory



Theories of E_e (10V/μm)

- If E_e is associated with a work function or chemical potential, then $E_e = \Delta\Phi/ez$. E_e=1000 V/μm for z=1 nm, $\Delta\Phi$= 1 eV.
- Correlation with "work functions" determined by charge exchange with metals. But the range of Φ small and z not accounted for.
- Correlation with density of states of polymers suggested. But requires communication with bulk states and experiments could not be repeated.
- Correlations with Inverse Gas Chromatography recently shown. But z=30 nm is not unaccounted for.
- Basic understanding of E_e is needed.

3. Electrostatic Adhesion and Color Electrophotography

- **Markets**
  - Low cost, desktop - $400, 4ppm - Canon, Samsung, Konica-Minolta
  - Midrange - $20-100K, 6-30 ppm – Many manufactures
  - Digital Production Printing - $500K, 100 ppm - Xerox, Kodak, HP
- **Technical Challenges**
  - Image Quality
  - Image Accumulation

Phaser 740 (Matsushita)
(IOI means accumulation on the photoreceptor)

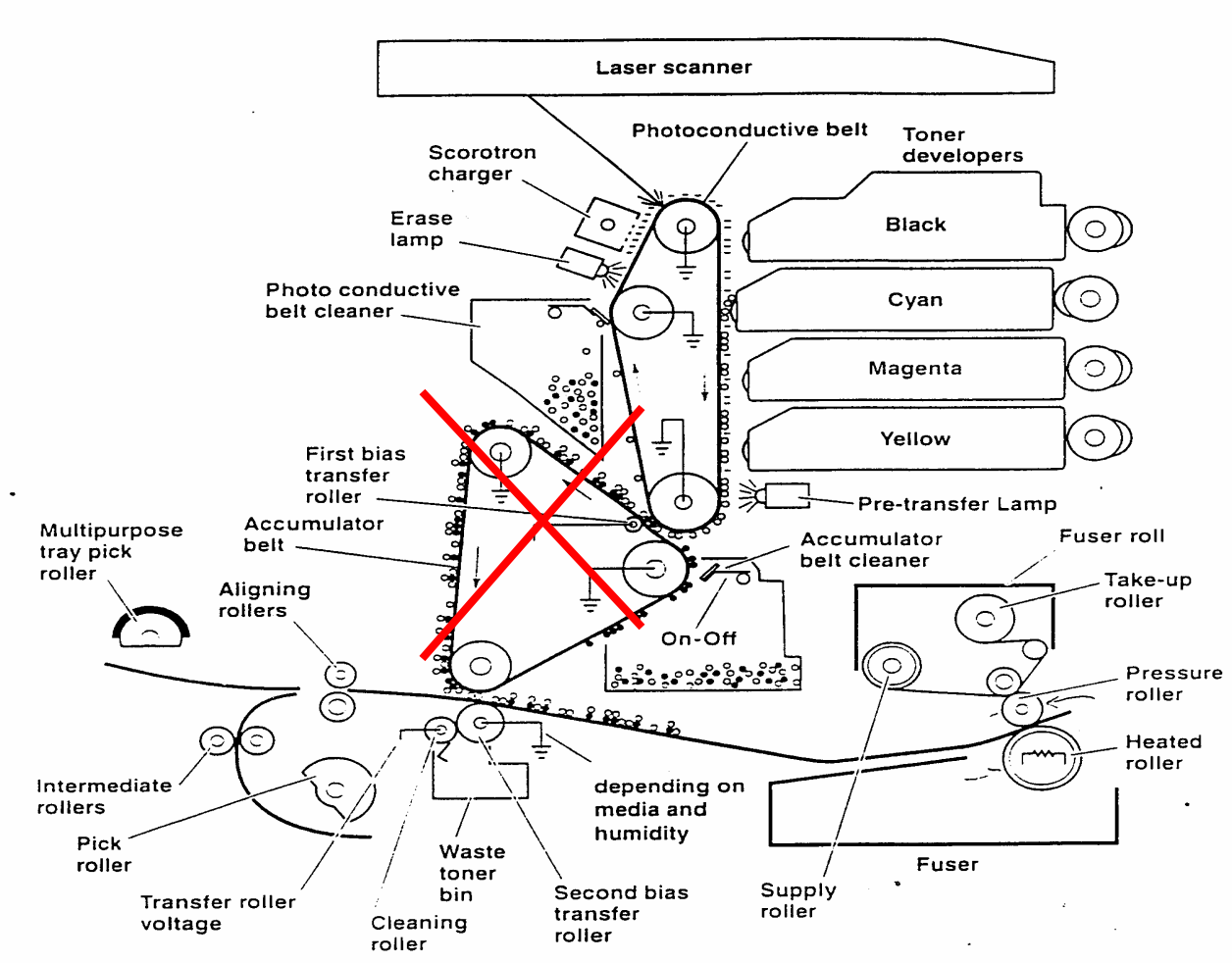
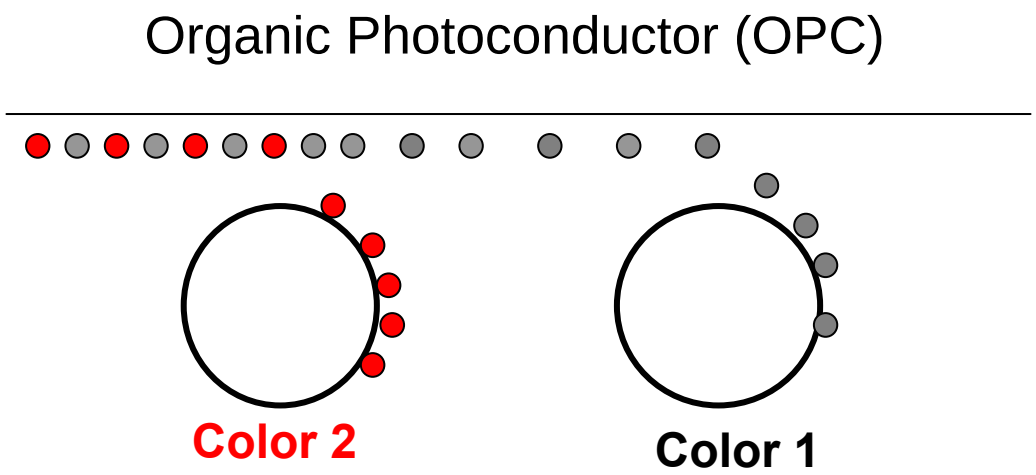


Image-on-Image (IOI) Technology Requires dc-Jump

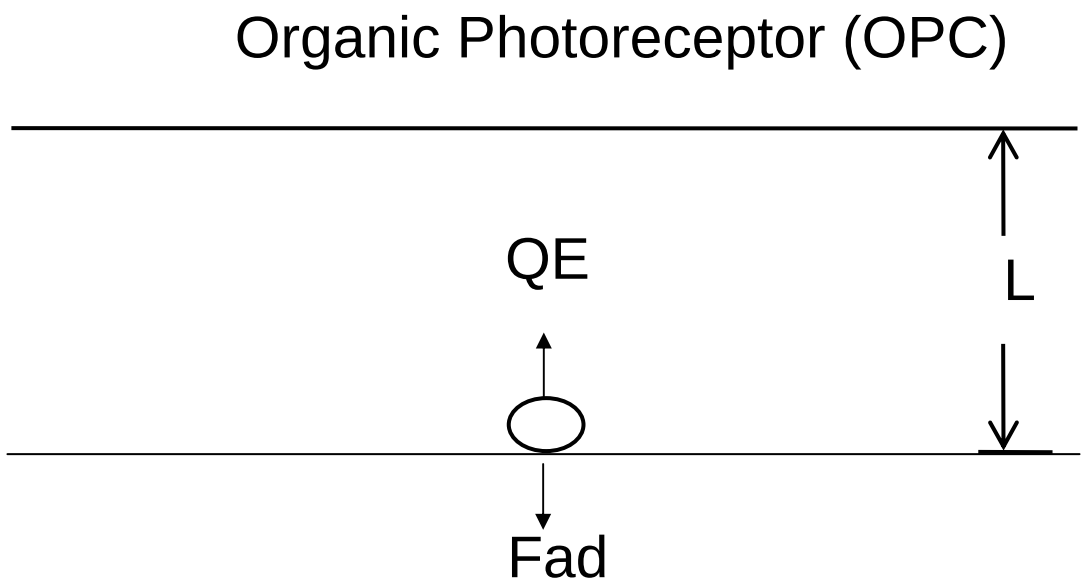


Cannot use ac electric fields because of contamination

Cannot use contact development due to image disturbance

Can only use dc electric fields

Physics of dc-Jump



Development occurs when QE > Fad
OPC charged to 700 volts, normally
Toner must be released at E=700 volts/gap
For IOI, release must be at E=400 volts/gap

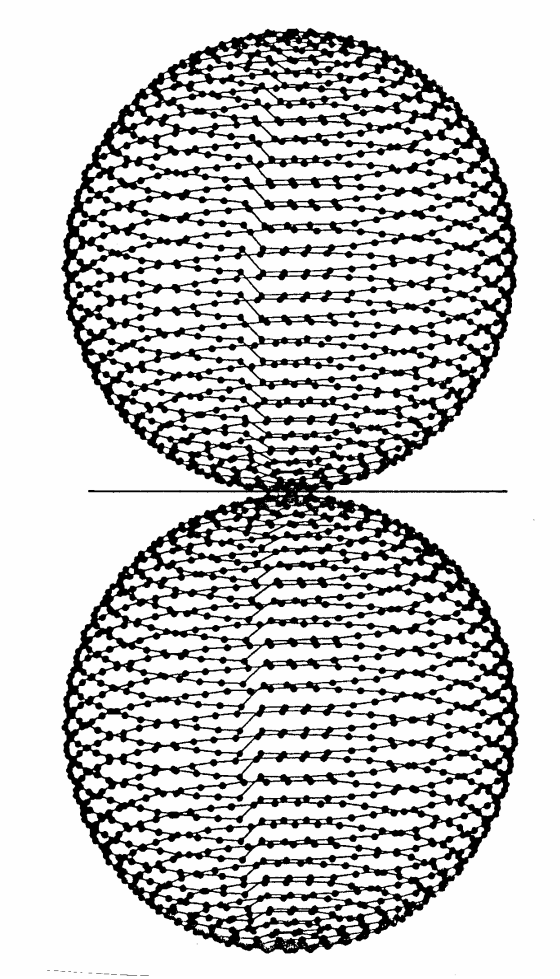
Toner Adhesion from Literature

(Hays, J. of Adhesion, **51,** 41, 1995)

$QE=Q(V_w/L)>F_{ad}=2[Measure(50\%)]$

Diameter	Q/M	Adhesion Calculated	Measure(50%)/ Calculated	V_w (at 150 µm)
µm	µC/g	nN	ratio	volts
20	5	17	47	11400
20	10	68	29	14100
20	30	610	7	10200
10	12	6.6	45	14200
10	5	1.2	36	4950
10	8	4.6	12	3950
10	16	12	12	5160

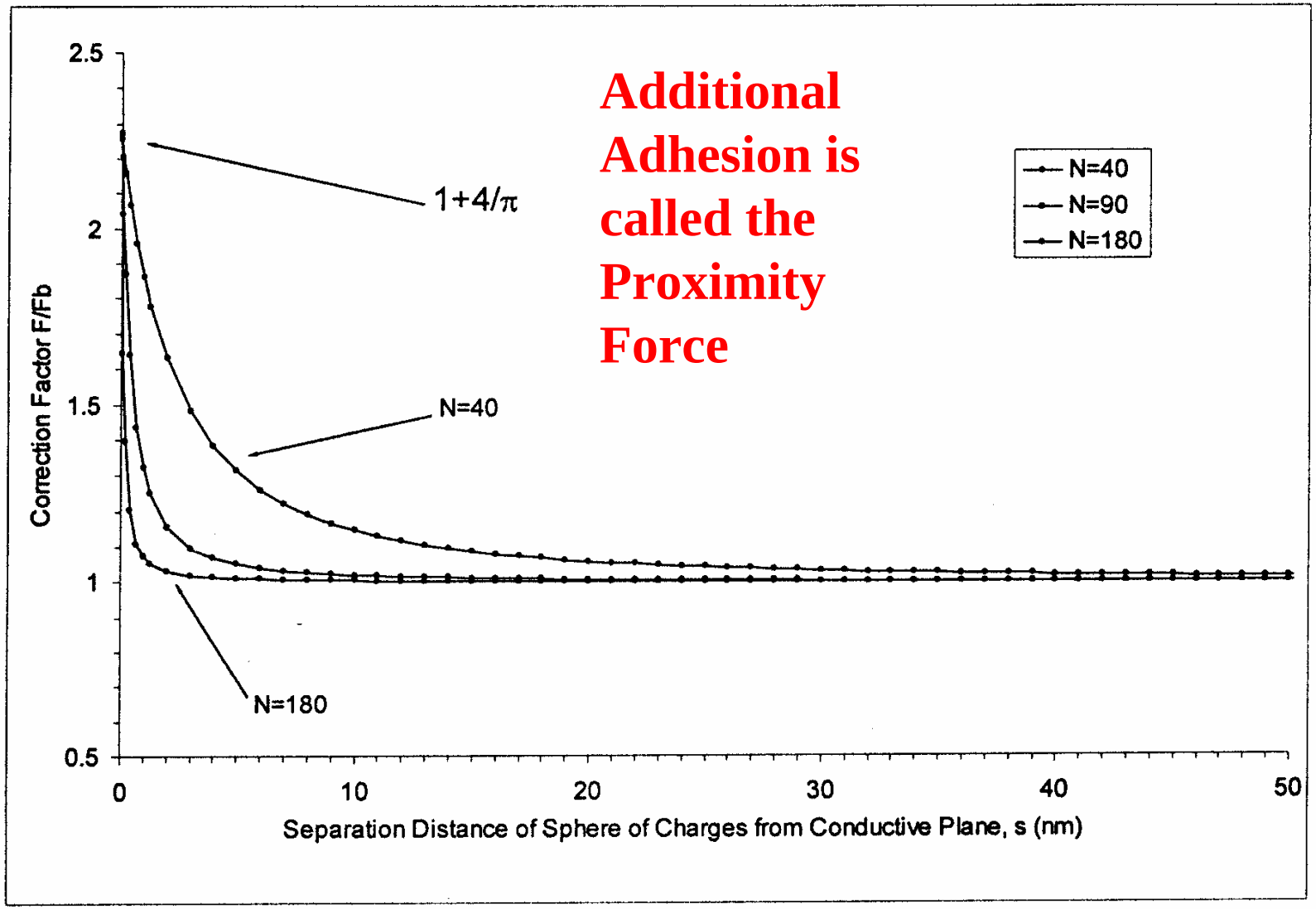
Numerical Calculation



$$F = \frac{1}{4\pi\varepsilon_0}\frac{Q^2}{(2r)^2}$$

Underestimates adhesion

Numerical Calculation



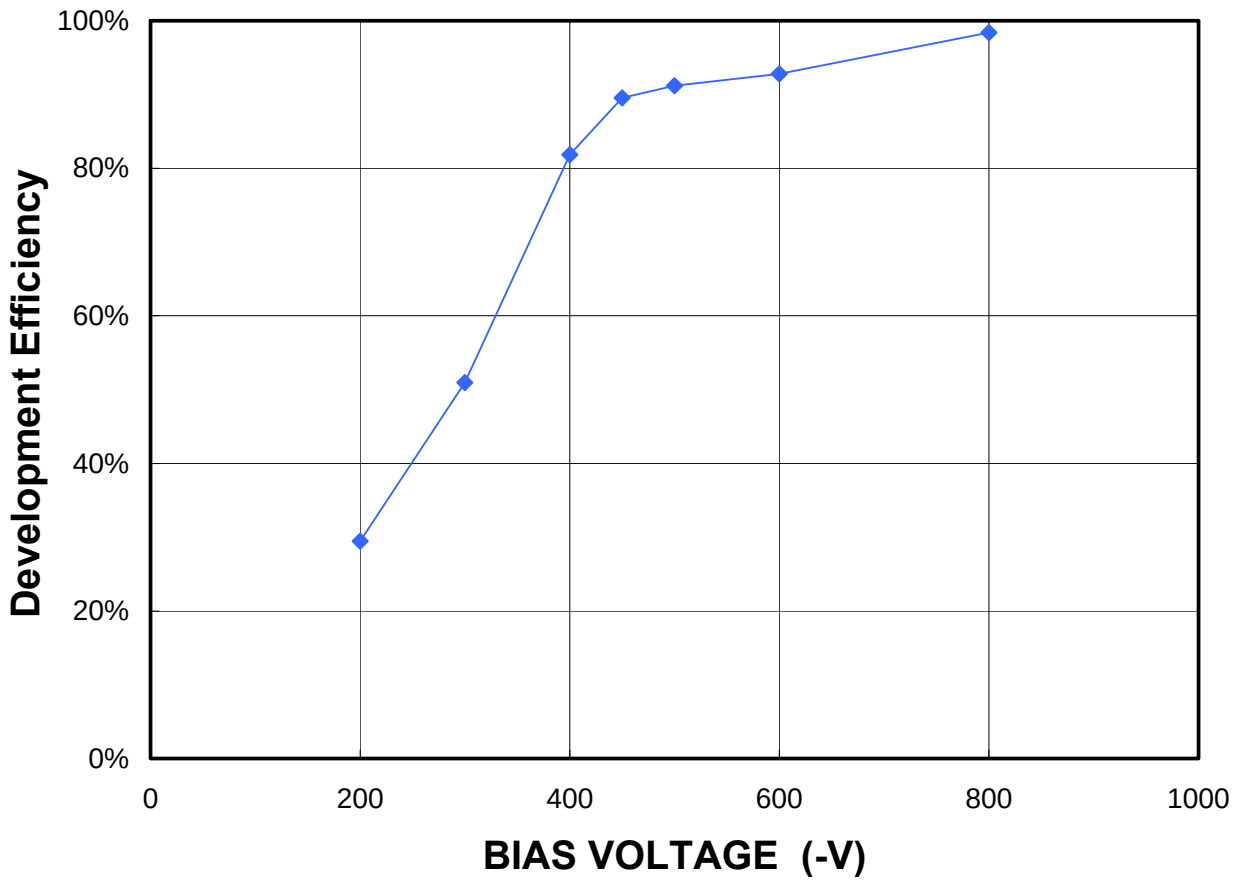
Technology/Science Challenge: Minimize Toner Adhesion

Published Idea: Toner adhesion due to nonuniform charge distribution around the toner particle

Aetas Discovery: Source of toner adhesion: Charge distribution on toner is uniform, but discrete.

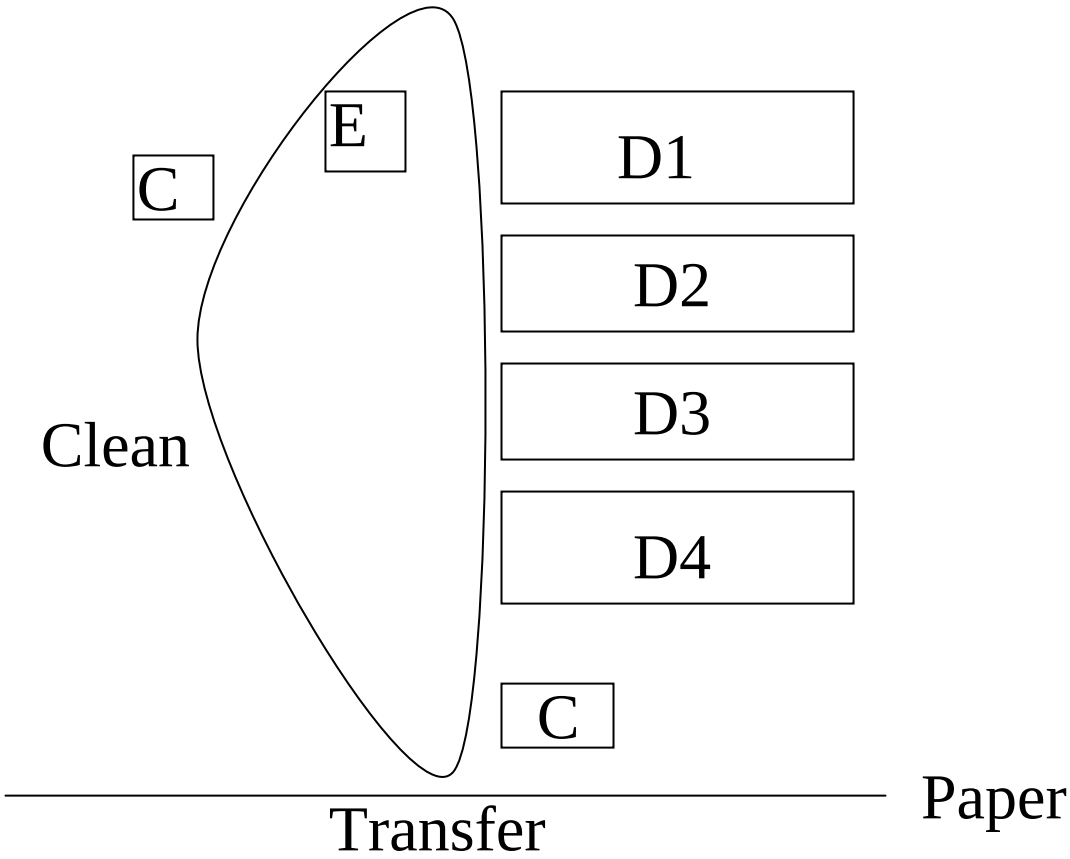
1. Toner adhesion is due to electrostatic proximity force (due to charge discreteness) -
2. Acting at each contact point (7-47 possible).
3. **Toner adhesion is minimized if number of contact points is minimized. Control with nanoparticles (e.g. 10 nm silica) on surface.**

Development Curve for 8 Micron Toner Measured at 150 µm Gap



Aetas Data

New dc-Jump Development System in a 4-Pass Printer



Aetas Printer

Volume = 27 liters

2.8 point Red

(magenta + yellow)

Ben Franklin and Electrophotography
Franklin Studied:

- **Lightning – in a non-uniform geometry the same mechanism creates a corona (a plasma near the wire) which is useful as a source of charged particles. Used in two steps of EP.**
- **Insulator Charge Exchange – critical for toner charging. Insulators charging is described by Electric Field Theory. Need a theory of E_e.**
- **Electrostatic Adhesion – It's understanding (based on proximity force) has led to its minimization and a new EP dev. system that allows a small volume, low speed IOI system – a true desk-top color laser printer.**

- **Franklin, who was a printer, would have been proud to know that his electrostatic experiments evolved into a new printing technology called Electrophotography.**