ACTRIS

CAIS-ECAC
Center for Aerosol In-Situ -
European Center for Aerosol Calibration and Characterization

ITINERIS

Charging, CPC & DMA - ITINERIS Training III

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Director ACTRIS CAIS-ECAC

WCCAP
World Calibration Centre
for Aerosol Physics

OGTAC-CC

European
Reference
Laboratory
for Air
Pollution

A C M C C
Aerosol Chemical Monitor Calibration Center

EMC2
Elemental Mass
Calibration Centre

CCC
Cluster
Calibration
Center

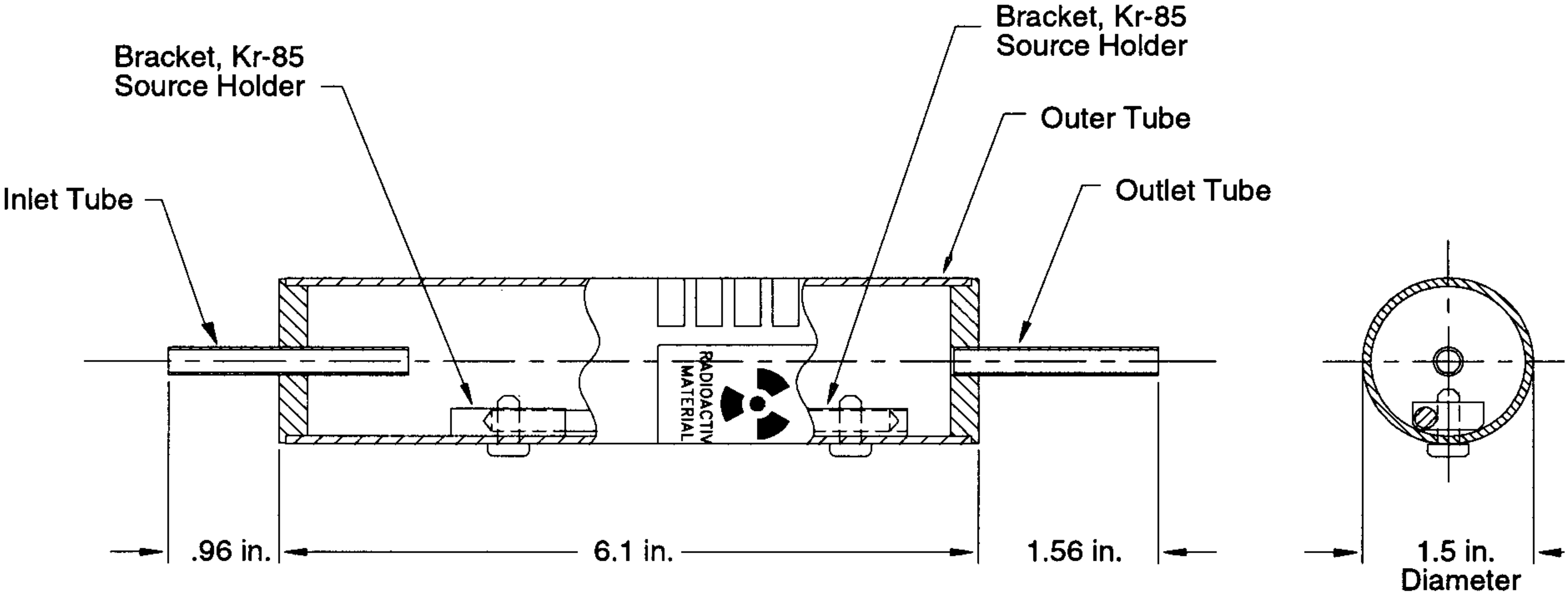
Bipolar Charge Equilibrium

Bipolar Diffusion Charging

- Particles are charged by positive and negative gas ions.
- The ions are produced and transported to the particles in a neutralizer or bipolar diffusion charger.
- The ions are produced due to ionization of gas molecules by radioactive alpha or beta radiation or X-ray
- Kr^{85}, Am^{241}, Ni^{63}, Po^{210}
- The ions are transported to the particles surface due to

- Diffusion	→ ion transport towards the particle by Brownian motion
- Coulomb force	→ attracting or repulsing force due to charged particle
- Force by Image charge	→ attracting force due to image charge in the particle

Example: Bipolar Charger TSI 3077A



(Manual: Neutralizer TSI 3077A)

Bipolar Charge Distribution - Equilibrium

- A single uncharged particle can be charged negatively by a negative ion at one moment.
- In the next moment, it can be neutralized by a positive ion.
- Each particle can be recharged several times during the bipolar charging process.
- The entire particle population, however, reaches a constant bipolar charge equilibrium with:
  - constant fractions of negatively and positively charged particles
  - constant fractions of uncharged, singly and multiple charged particles (size dependent)
- The different charge fractions of a certain particle size is constant (e.g., fraction of singly charged 100 nm particles).
- The fraction of negatively charged particles is greater than the fraction of positively charged particles (the mean mobility of negative ions is higher than the mobility of positive ions).

Bipolar Charge Distribution - Equilibrium

Advantages of the bipolar charge distribution

- time independent
- narrow for particles smaller than 300 nm
- known for the entire submicrometer size range
- simple to calculate

Disadvantages of the bipolar charge distribution

- broad for particles larger than 300 nm
- very low charging rate for particles smaller than 10 nm

Applications

- Particle number size distribution measurements
- generation of fine and ultrafine particles
- neutralization of highly charged particles

Gunn Charge Distribution

- The Gunn bipolar charge distribution takes the different electrical mobilities of positive and negative ions into account.
- The Gunn equation is however only valid for particles larger than 100 nm (mean free path of the ions much greater than the particle diameter).
- To describe the ion transport, the Gunn equation takes only the diffusion process into account.

$$F(n)=\frac{\mathrm{e}}{\sqrt{4\pi^{2}\cdot D_{\mathrm{P}}\cdot k\cdot T}}\cdot\exp\left(-\frac{\left(n-\left(\frac{2\pi\cdot\varepsilon_{0}\cdot D_{\mathrm{P}}\cdot k\cdot T}{e^{2}}\right)\ln\frac{N_{I+}\cdot Z_{\mathrm{I+}}}{N_{I-}\cdot Z_{\mathrm{I-}}}\right)^{2}}{\left(\frac{4\pi\cdot\varepsilon_{0}\cdot D_{\mathrm{P}}\cdot k\cdot T}{\mathrm{e}^{2}}\right)}\right)$$

Fuchs Charge Distribution

- The Fuchs theory describes the ion transport for the continuum and free molecular regime.
- Diffusion process as well as electrostatic forces between particles and ions are considered.
- The Fuchs theory describes the bipolar charge distribution for the entire submicrometer particle size range.
- There is no analytical solution for the Fuchs theory.
- The bipolar charge distribution is described by an approximation formula.
- This formula is used to calculate the fraction of uncharged and singly charged particle in the size range 1-1000 nm.
- The fraction of doubly charged particle can be calculated in the range 20-1000 nm.

$$\boxed{F(n) = 10^{\sum_{i=0}^{5} a_i(n)(\log D_\mathrm{P}/\mathrm{nm})^i}}$$

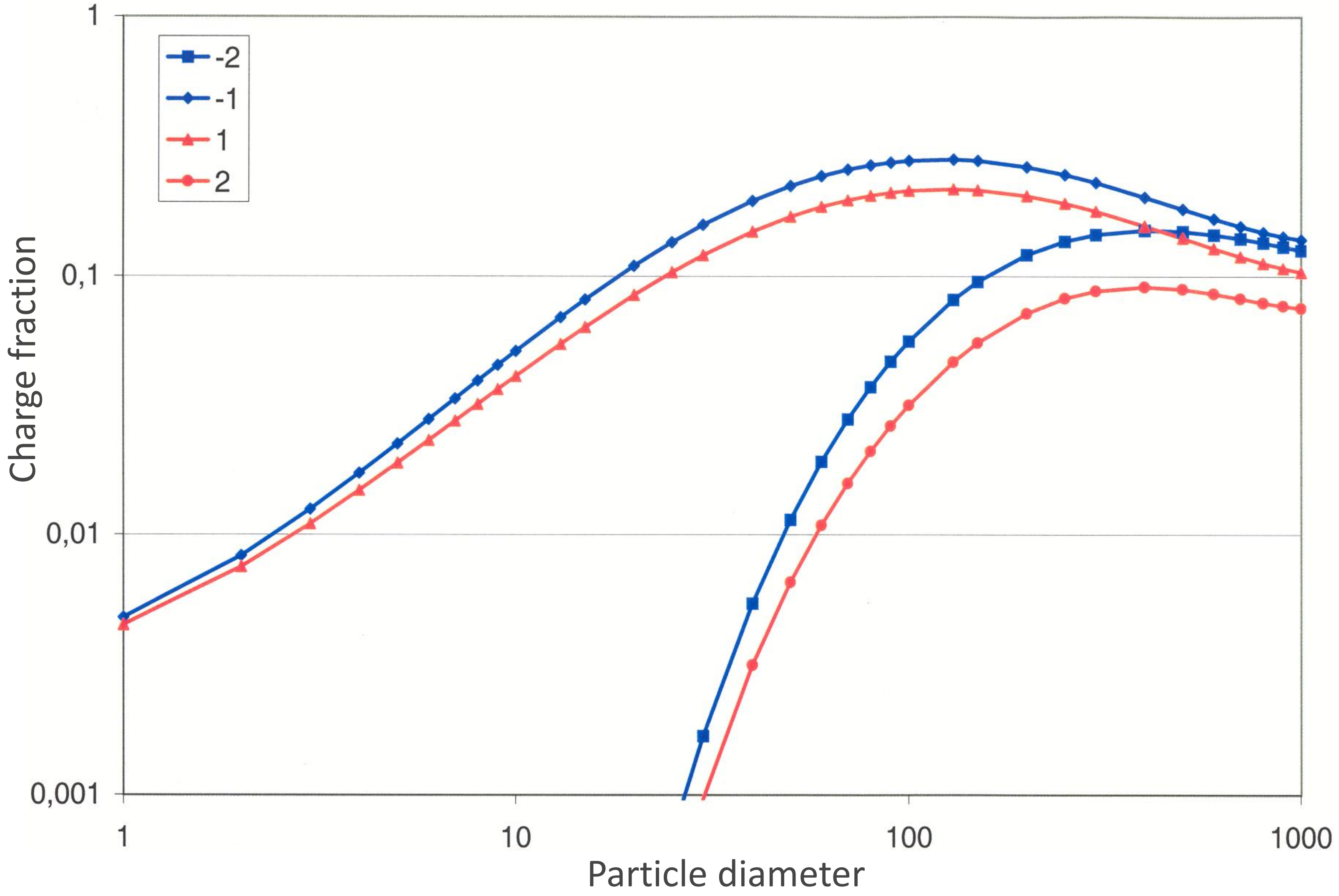
Approximation Coefficients

	Approximation coefficients $a_i(n)$				
i	n=-2	n=-1	n=0	n=+1	n=+2
0	-26.3328	-2.3197	-0.0003	-2.3484	-44.4756
1	35.9044	0.6175	-0.1014	0.6044	79.3772
2	-21.4608	0.6201	0.3073	0.4800	-62.8900
3	7.0867	-0.1105	-0.3372	0.0013	26.4492
4	-1.3088	-0.1260	0.1023	-0.1553	-5.7480
5	0.1051	0.0297	-0.0105	0.0320	0.5049

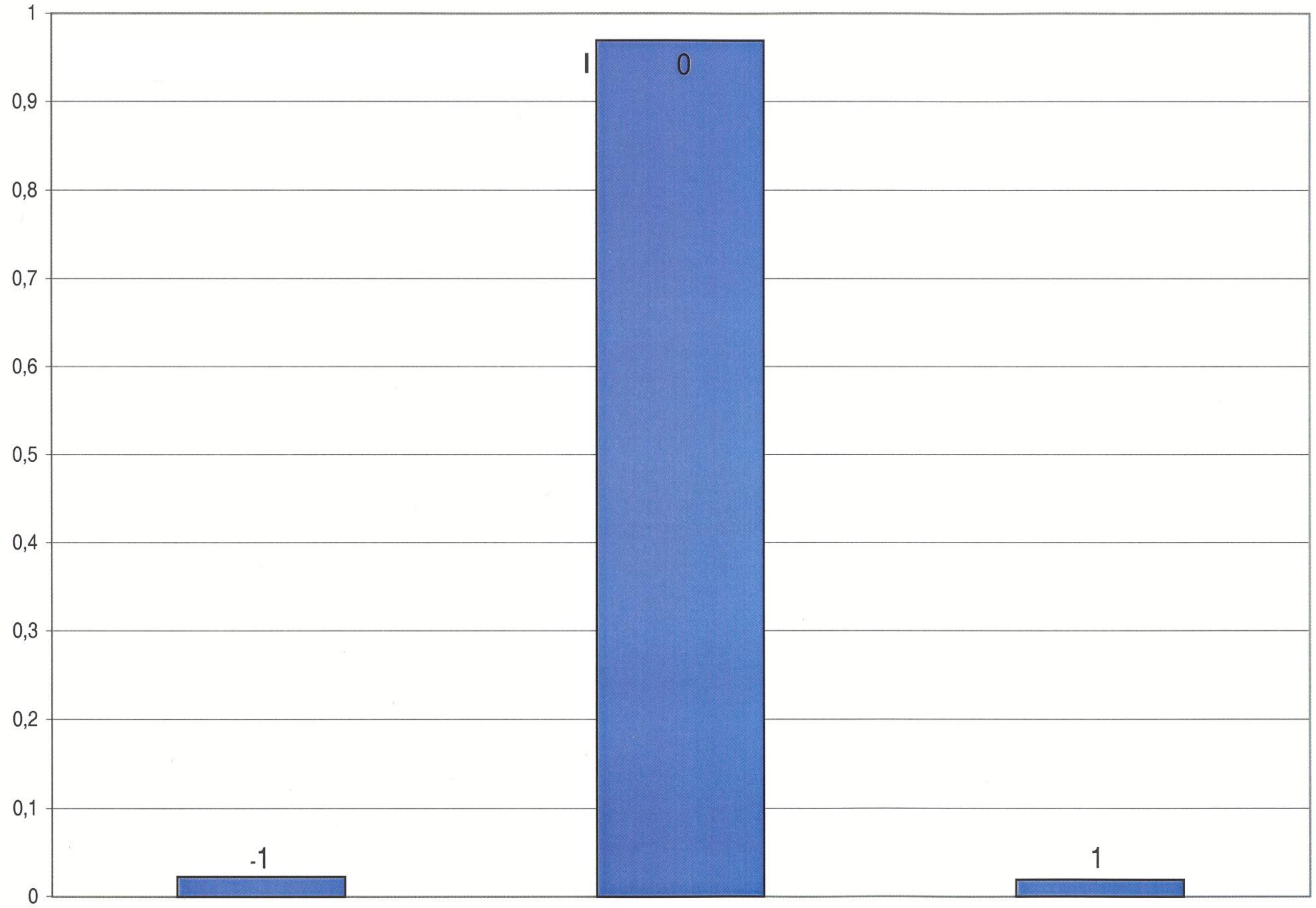
The fractions of multiple charged particles (-2, -1, 0, +1, +2) can be calculated using the approximation formula.

Wiedensohler, A. (1988). J. Aerosol Sci. 19, 387-389

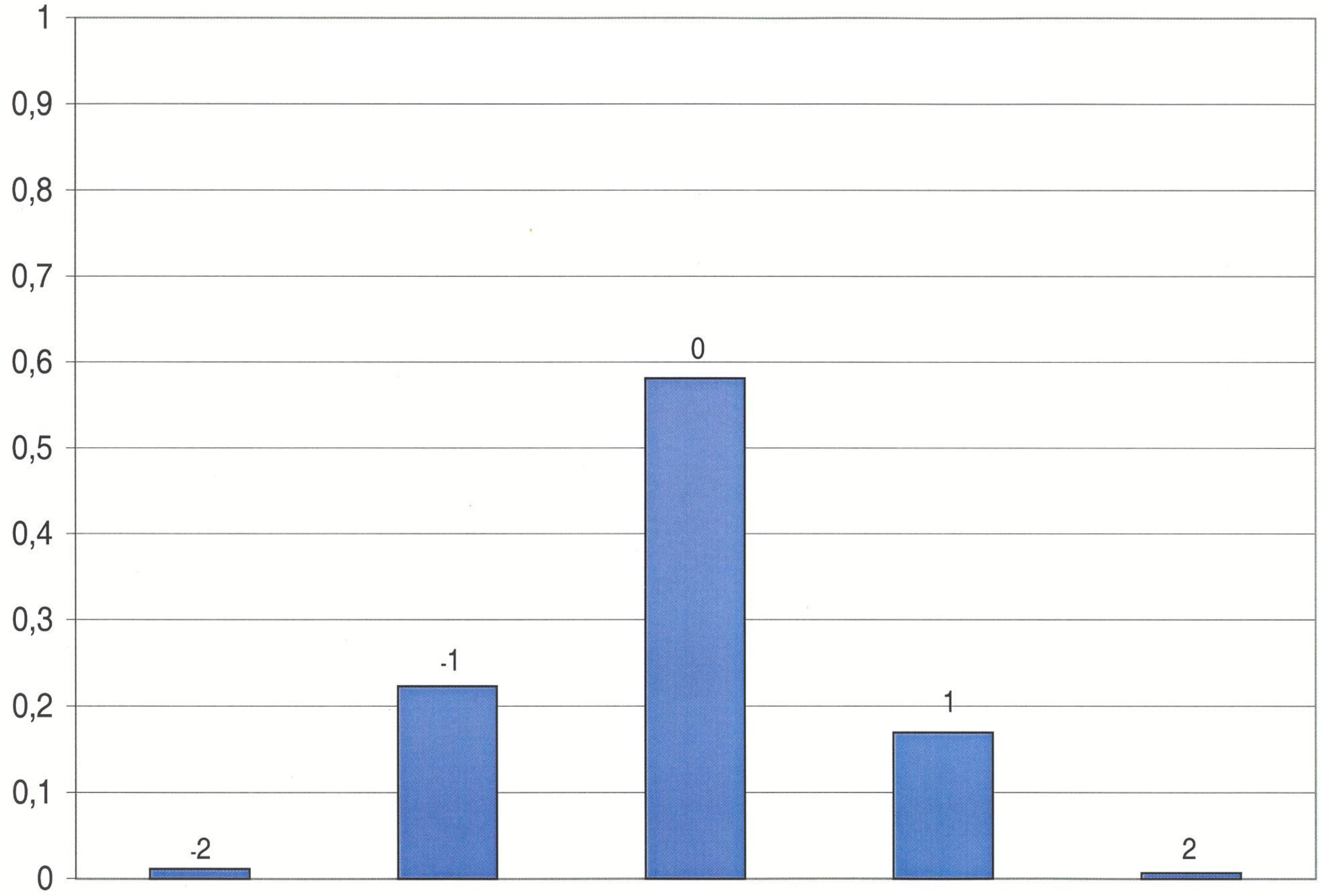
Bipolar Charge Distribution: Singly and Doubly Charged Particles



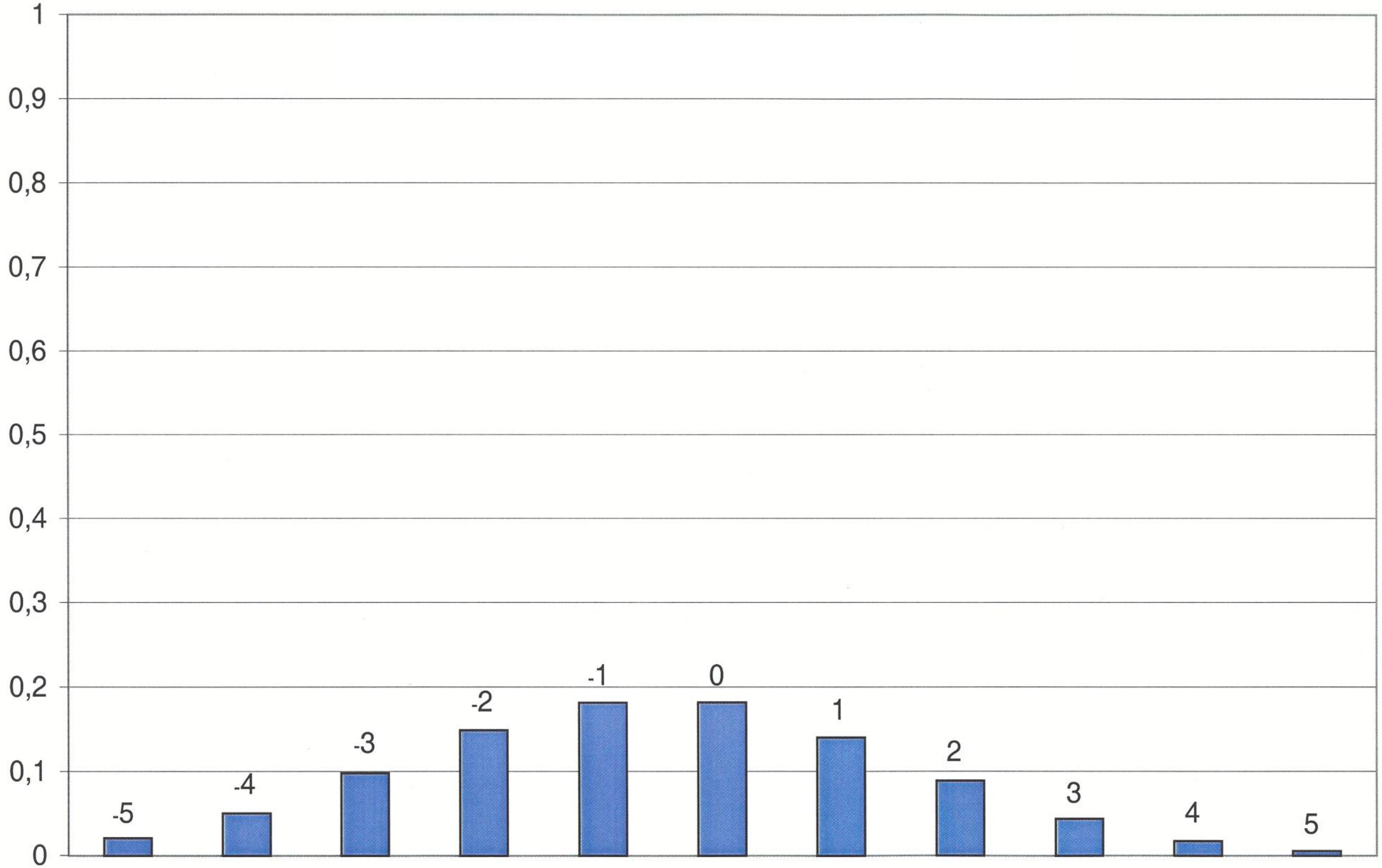
Bipolar Charge Distribution: 5 nm Particles



Bipolar Charge Distribution: 50 nm Particles



Bipolar Charge Distribution: 500 nm Particles

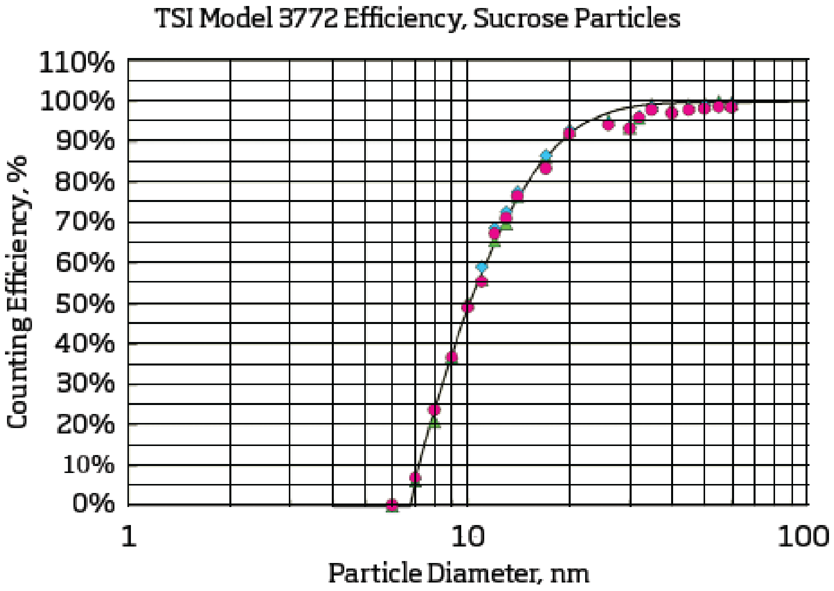


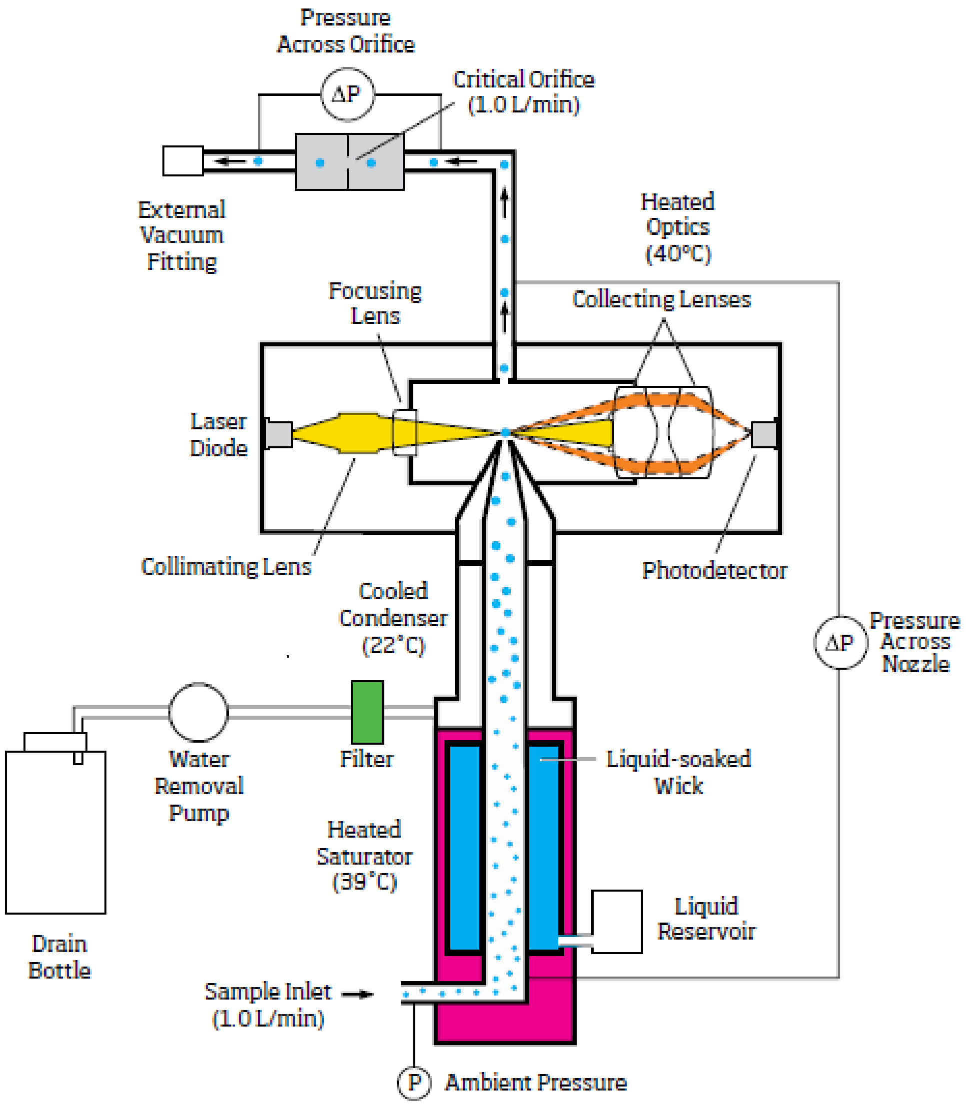
Bipolar Charge Distribution: Submicrometer Size Range

Dp	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	sum
1	0	0	0	0	0	0	0	0	0	0,00479	0,999309	0,004483	0	0	0	0	0	0	0	0	0	1,008582
2	0	0	0	0	0	0	0	0	0	0,008287	0,974178	0,007514	0	0	0	0	0	0	0	0	0	0,989979
3	0	0	0	0	0	0	0	0	0	0,01254	0,976545	0,011019	0	0	0	0	0	0	0	0	0	1,000103
4	0	0	0	0	0	0	0	0	0	0,017319	0,97513	0,014855	0	0	0	0	0	0	0	0	0	1,007305
5	0	0	0	0	0	0	0	0	0	0,022491	0,969338	0,018936	0	0	0	0	0	0	0	0	0	1,010765
6	0	0	0	0	0	0	0	0	0	0,027958	0,960507	0,023193	0	0	0	0	0	0	0	0	0	1,011658
7	0	0	0	0	0	0	0	0	0	0,03364	0,949754	0,027577	0	0	0	0	0	0	0	0	0	1,010971
8	0	0	0	0	0	0	0	0	0	0,039476	0,937844	0,032047	0	0	0	0	0	0	0	0	0	1,009367
9	0	0	0	0	0	0	0	0	0	0,045416	0,92529	0,036568	0	0	0	0	0	0	0	0	0	1,007274
10	0	0	0	0	0	0	0	0	0	0,051416	0,912431	0,041115	0	0	0	0	0	0	0	0	0	1,004962
13	0	0	0	0	0	0	0	0	0	0,069473	0,873928	0,054707	0	0	0	0	0	0	0	0	0	0,998108
15	0	0	0	0	0	0	0	0	0	0,081332	0,849282	0,063585	0	0	0	0	0	0	0	0	0	0,994199
20	0	0	0	0	0	0	0	0	0,0002	0,109565	0,793069	0,084648	0,000101	0	0	0	0	0	0	0	0	0,987583
25	0	0	0	0	0	0	0	0	0,000696	0,135157	0,744591	0,103716	0,000387	0	0	0	0	0	0	0	0	0,984546
30	0	0	0	0	0	0	0	0	0,001681	0,157867	0,702788	0,120661	0,000966	0	0	0	0	0	0	0	0	0,983962
40	0	0	0	0	0	0	0	0	0,005419	0,195066	0,634651	0,148553	0,003141	0	0	0	0	0	0	0	0	0,98683
50	0	0	0	0	0	0	0	3,11E-05	0,011424	0,222862	0,581445	0,169587	0,006552	1,4E-05	0	0	0	0	0	0	0	0,991915
60	0	0	0	0	0	0	0	0,000157	0,019157	0,243233	0,538606	0,185178	0,010879	7,05E-05	0	0	0	0	0	0	0	0,997281
70	0	0	0	0	0	0	0	0,000493	0,027975	0,257873	0,503249	0,196538	0,015794	0,000221	0	0	0	0	0	0	0	1,002145
80	0	0	0	0	0	0	0	0,001154	0,037325	0,268121	0,473478	0,204626	0,02103	0,000518	0	0	0	0	0	0	0	1,006252
90	0	0	0	0	0	0	3E-05	0,002217	0,04679	0,275007	0,447998	0,210188	0,026384	0,000995	1,03E-05	0	0	0	0	0	0	1,00962
100	0	0	0	0	0	0	7,84E-05	0,003719	0,056079	0,279319	0,425893	0,213796	0,03171	0,001669	2,69E-05	0	0	0	0	0	0	1,012289
130	0	0	0	0	0	1,24E-05	0,000564	0,01064	0,081327	0,282142	0,373956	0,216832	0,046649	0,004775	0,000194	0	0	0	0	0	0	1,017091
150	0	0	0	0	0	4,98E-05	0,001336	0,016745	0,095379	0,279019	0,347619	0,214917	0,055304	0,007515	0,000459	1,31E-05	0	0	0	0	0	1,018356
200	0	0	0	0	2,29E-05	0,000463	0,005275	0,033989	0,12113	0,264091	0,299086	0,204259	0,071865	0,015254	0,001812	0,000122	0	0	0	0	0	1,01737
250	0	0	0	0	0,000159	0,001716	0,011707	0,050601	0,136493	0,246477	0,265483	0,191075	0,082131	0,02271	0,004023	0,000451	3,21E-05	0	0	0	0	1,013059
300	0	0	0	5,5E-05	0,00057	0,004038	0,019563	0,064792	0,145008	0,229754	0,240558	0,178281	0,08781	0,029079	0,006722	0,001062	0,000115	0	0	0	0	1,007408
400	0	0	6,53E-05	0,000485	0,002711	0,011388	0,035967	0,085403	0,150602	0,202036	0,205575	0,15664	0,091014	0,038329	0,012359	0,002996	0,000546	7,48E-05	0	0	0	0,99619
500	0	5,91E-05	0,00036	0,001742	0,006718	0,02062	0,05038	0,097974	0,149	0,181581	0,181804	0,140331	0,089098	0,04397	0,017311	0,005425	0,001353	0,000269	4,25E-05	0	0	0,988037
600	4,69E-05	0,00025	0,0011	0,004006	0,012066	0,030045	0,061859	0,105306	0,144743	0,166668	0,164351	0,128212	0,085601	0,047261	0,021255	0,007904	0,00243	0,000618	0,00013	2,26E-05	0	0,983875
700	0,000167	0,000689	0,00241	0,00716	0,018074	0,038759	0,070618	0,109314	0,139729	0,155806	0,150849	0,119196	0,082039	0,04906	0,024265	0,010197	0,00364	0,001104	0,000285	6,23E-05	1,16E-05	0,983435
800	0,00043	0,00146	0,004293	0,010948	0,024206	0,046407	0,077146	0,1112	0,134759	0,147932	0,140006	0,112483	0,079024	0,049906	0,026508	0,012209	0,004876	0,001688	0,000507	0,000132	2,98E-05	0,986149
900	0,000889	0,002595	0,006669	0,015099	0,030118	0,052923	0,081922	0,111713	0,130165	0,142315	0,131047	0,107515	0,076776	0,050136	0,028149	0,013923	0,006066	0,002328	0,000787	0,000235	6,15E-05	0,991431
1000	0,001578	0,004081	0,009418	0,01939	0,035617	0,05837	0,085344	0,111328	0,126067	0,138452	0,123481	0,103896	0,075353	0,049963	0,029325	0,015356	0,007174	0,00299	0,001112	0,000369	0,000109	0,998771

Condensation Particle Counter

Sketch of a CPC TSI model 3772/3750





ACTRIS Recommendation
Condensation Particle Counter

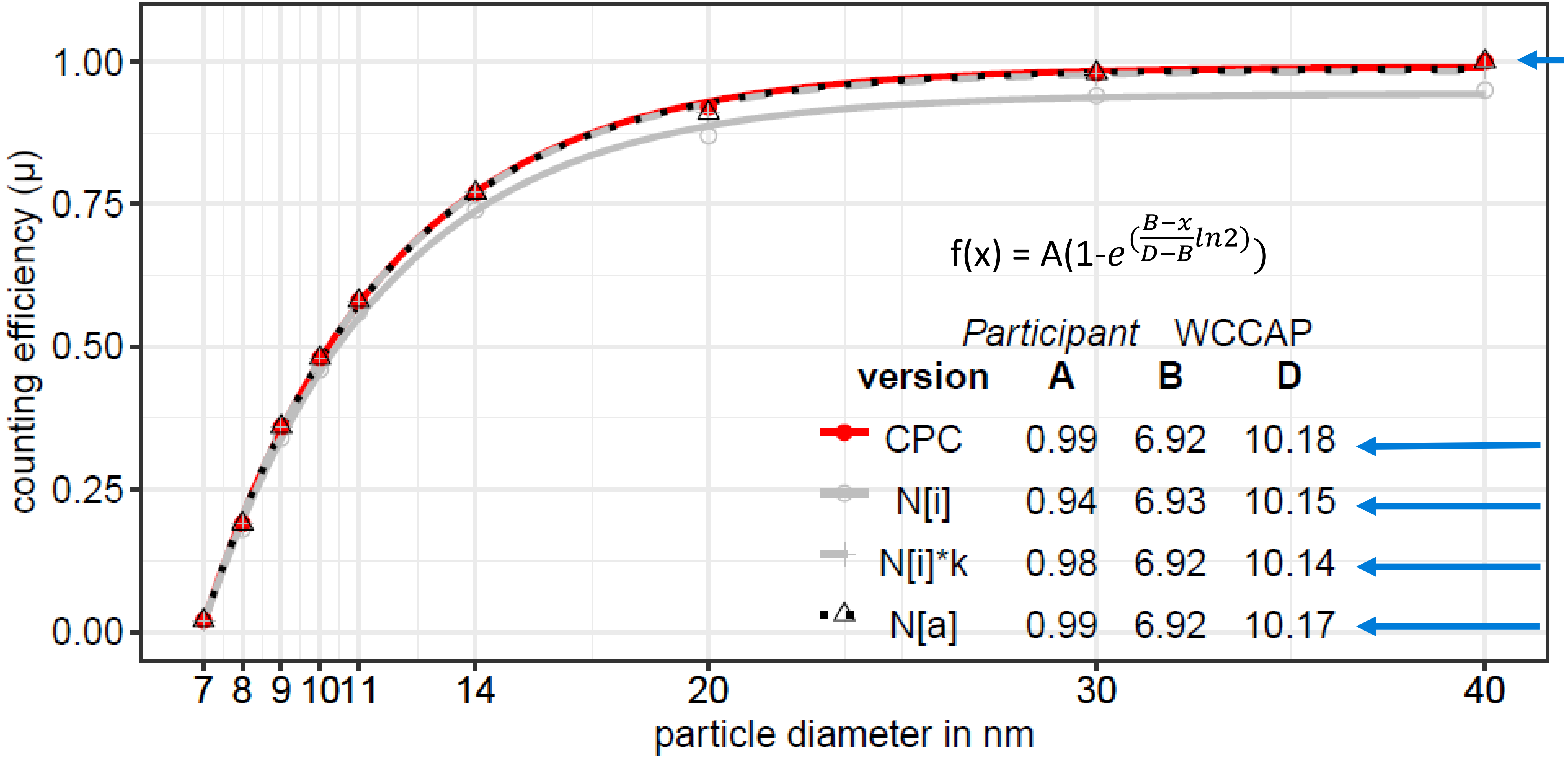
Condensation Particle Counter (CPC) - EN16976 – 10 nm

The EN 16976 recommends following:

- Full flow (inlet flow rate equal to detection flow rate
- Butanol as working fluid
- D_{P50} = 10 nm (+/-10%)
- Pulse Output (raw data) plus USB or ethernet port (corrected data)
- Frequent calibration according specific criteria
- Calibration aerosol = monodisperse Silver Nano Particles (7 – 40 nm)
- Uncertainty after calibration factor & coincidence corrections +/-5%

Condensation Particle Counter - Calibration

CPC Calibration – Detection Efficiency Curve



$$f(x) = A(1-e^{(\frac{B-x}{D-B}ln2)})$$

	Participant	WCCAP	
version	**A**	**B**	**D**
CPC	0.99	6.92	10.18
N[i]	0.94	6.93	10.15
N[i]*k	0.98	6.92	10.14
N[a]	0.99	6.92	10.17

Internal correction for the calibration factor

CPC internal output

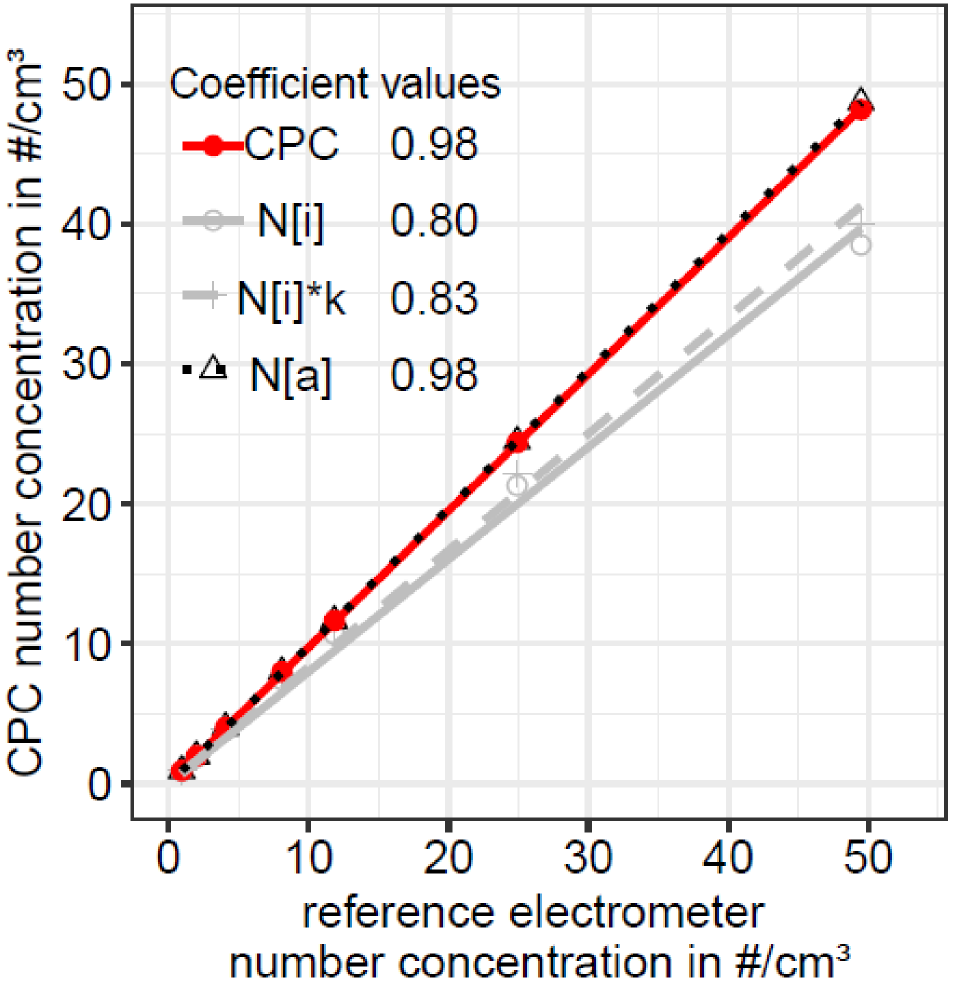
Pulse output

Pulse output with k-factor

Pulse output with k-factor and coincidence correction

Example of a CPC Calibration – Linearity

Example TSI CPC 3750-10



$$N_a = k\left(\frac{1}{c^2}\left(\frac{1}{N_i} - c\right) - \sqrt{\left(\frac{1}{c^2}\left(\frac{1}{N_i} - c\right)\right)^2 - \frac{2}{c^2}}\right)$$

N_a = corrected concentrations (particles/cm^3)

N_i = pulse concentrations (particles/cm^3)

k = k-factor: 1.04 for TSI CPC model 3750-10

c = coincidence parameter: $4.2e^{-06}$

Example: TSI CPC model-specific parameter

Principle of a Differential Mobility Analyzer-

Electrical Particle Mobility

The mobility of aerosol particles in an electrostatic field is called electrical particle mobility.

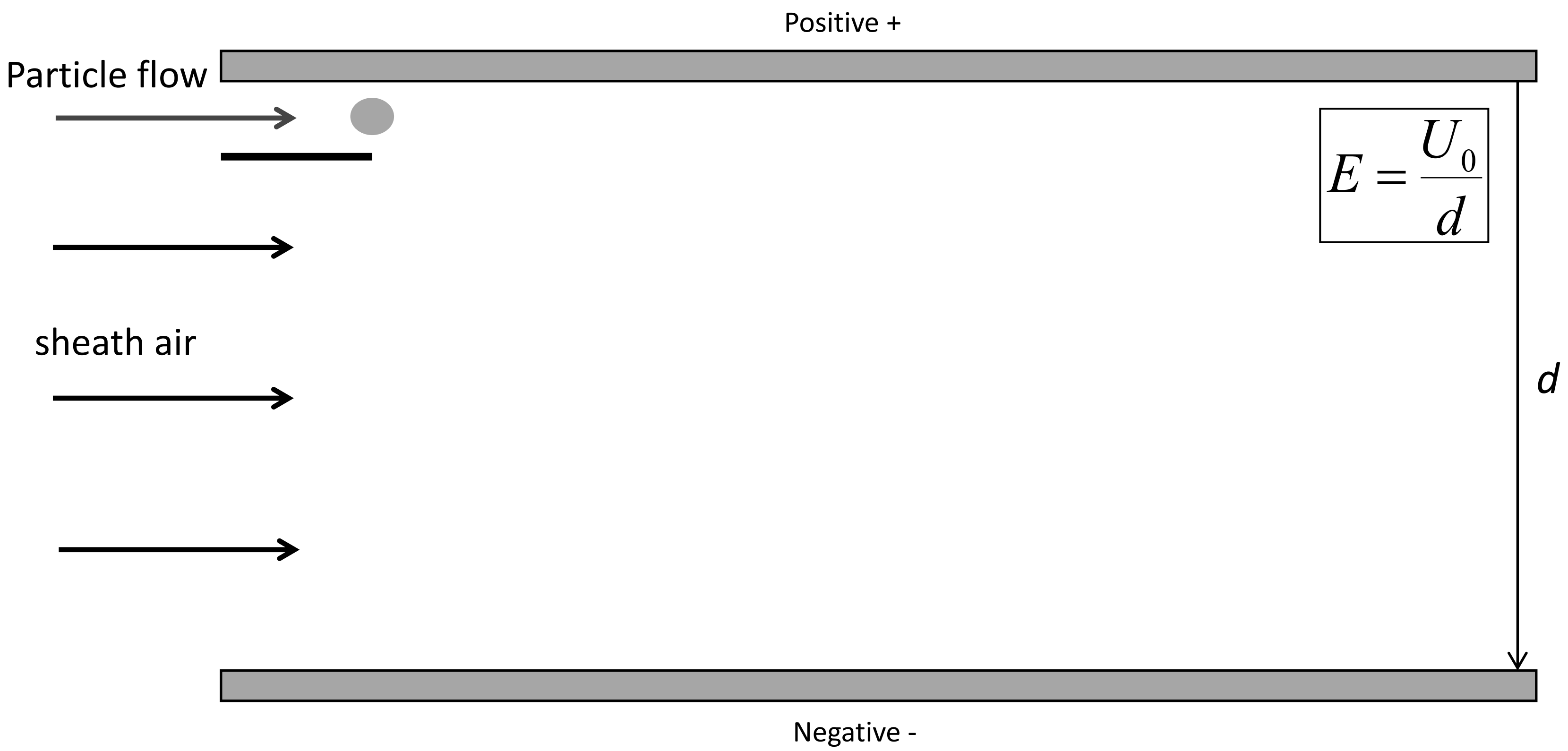
The electrical mobility Z_P of a particle with a certain electric charge is defined to:

$$\boxed{Z_\mathrm{P} = \frac{\vec{u}_e}{\vec{E}} = n_e \cdot \mathrm{e} \cdot \frac{C_C}{3\pi \cdot \eta \cdot D_\mathrm{P}}}$$

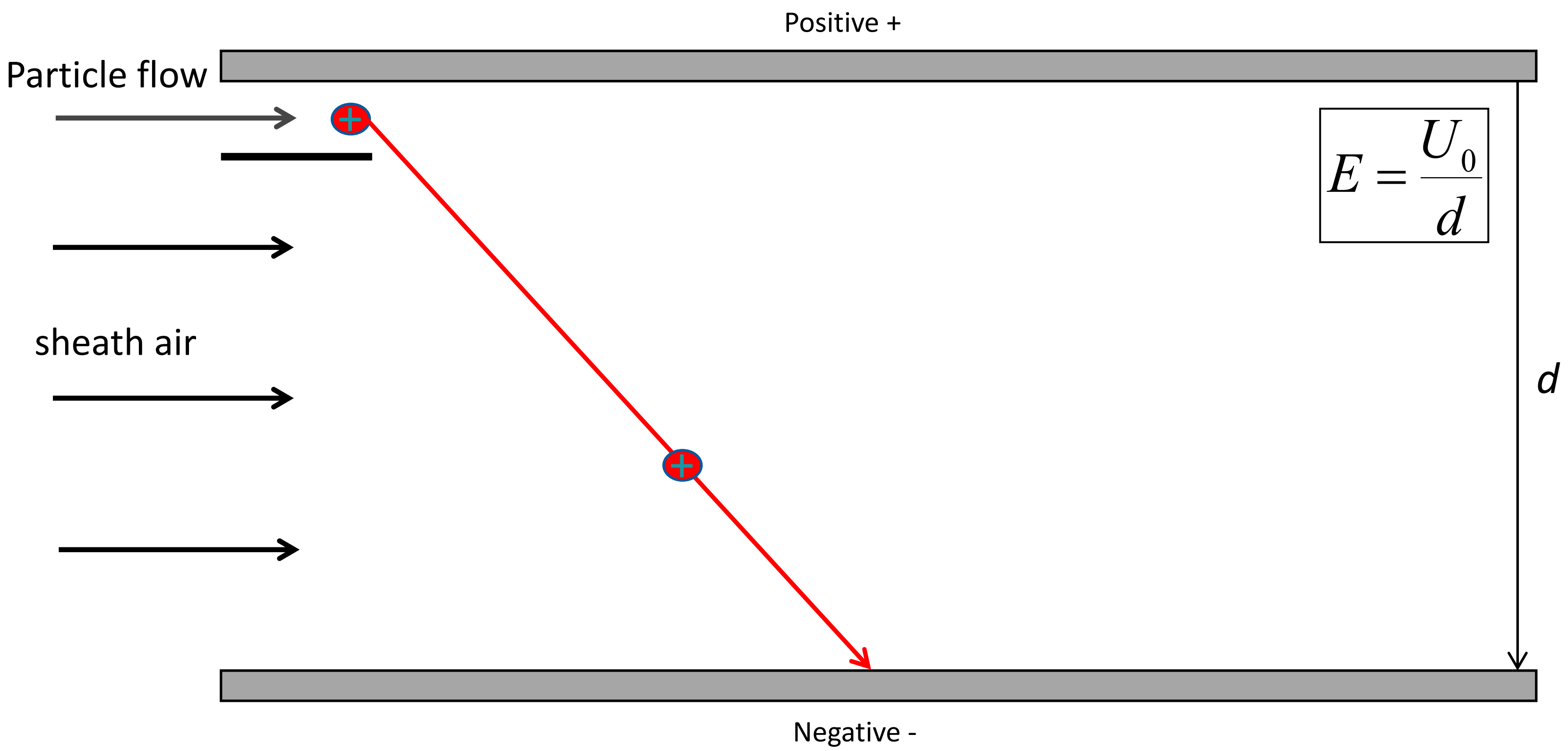
Plate capacitor

$$\boxed{E = \frac{U_0}{d}}$$

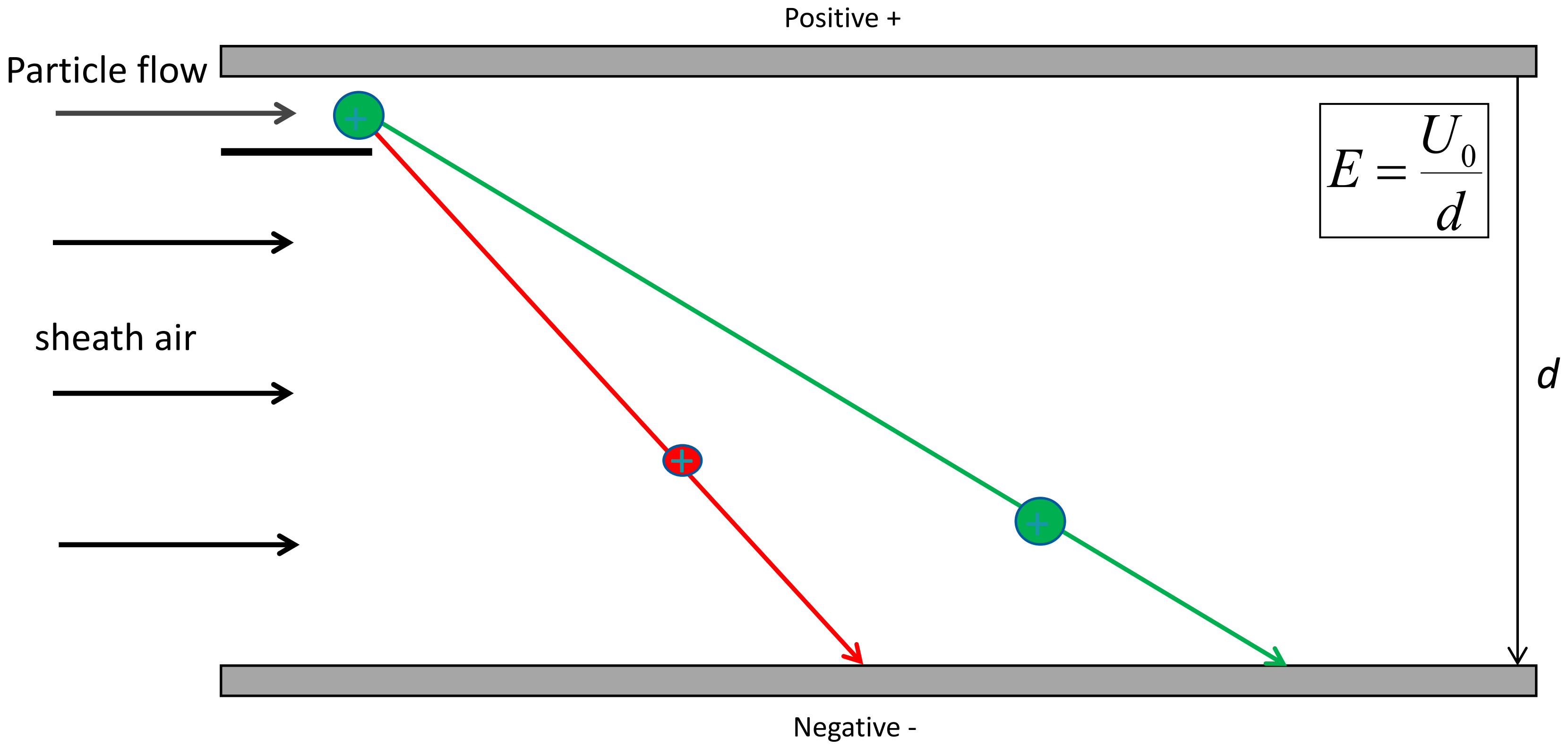
d … distance between the plates



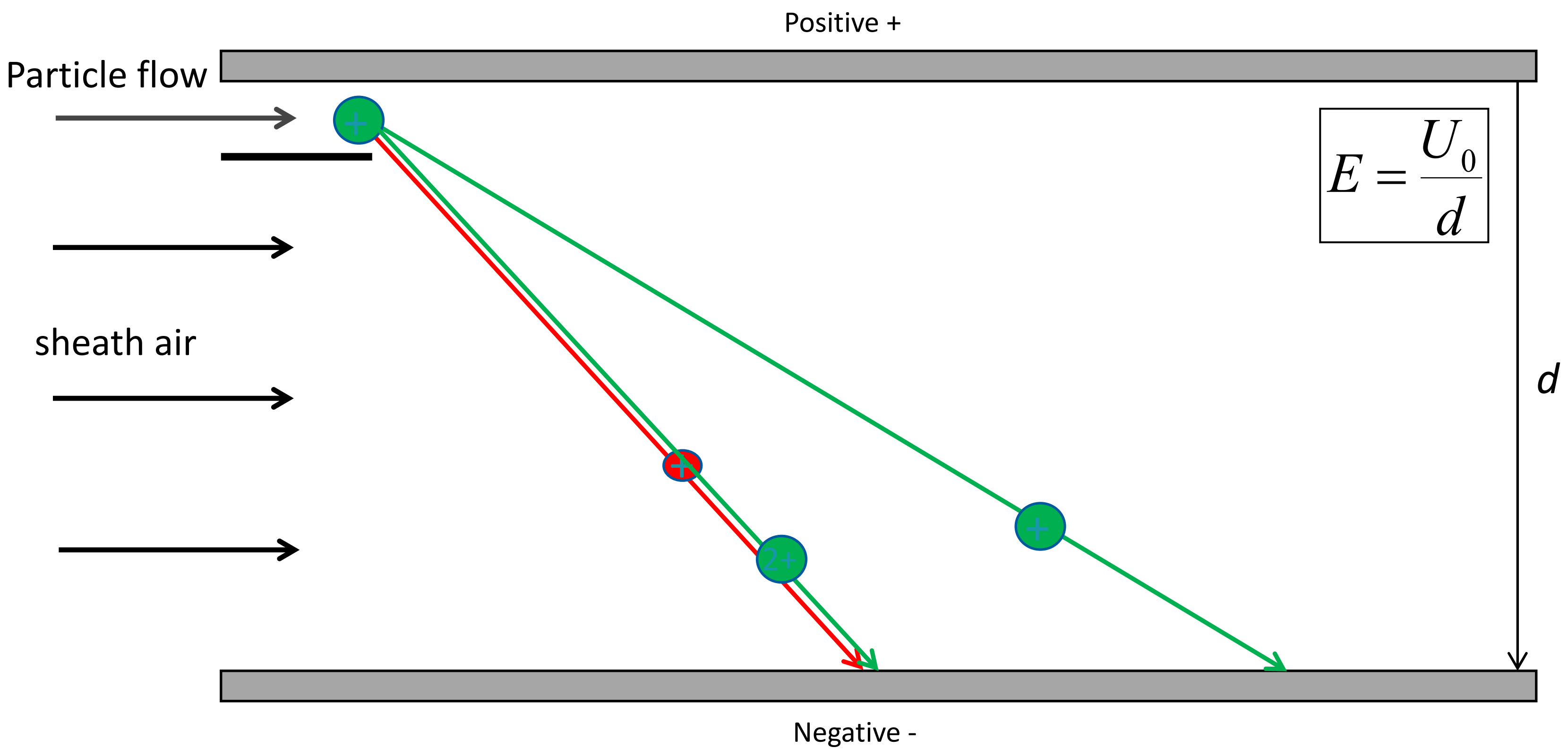
$$E = \frac{U_0}{d}$$



$$E = \frac{U_0}{d}$$

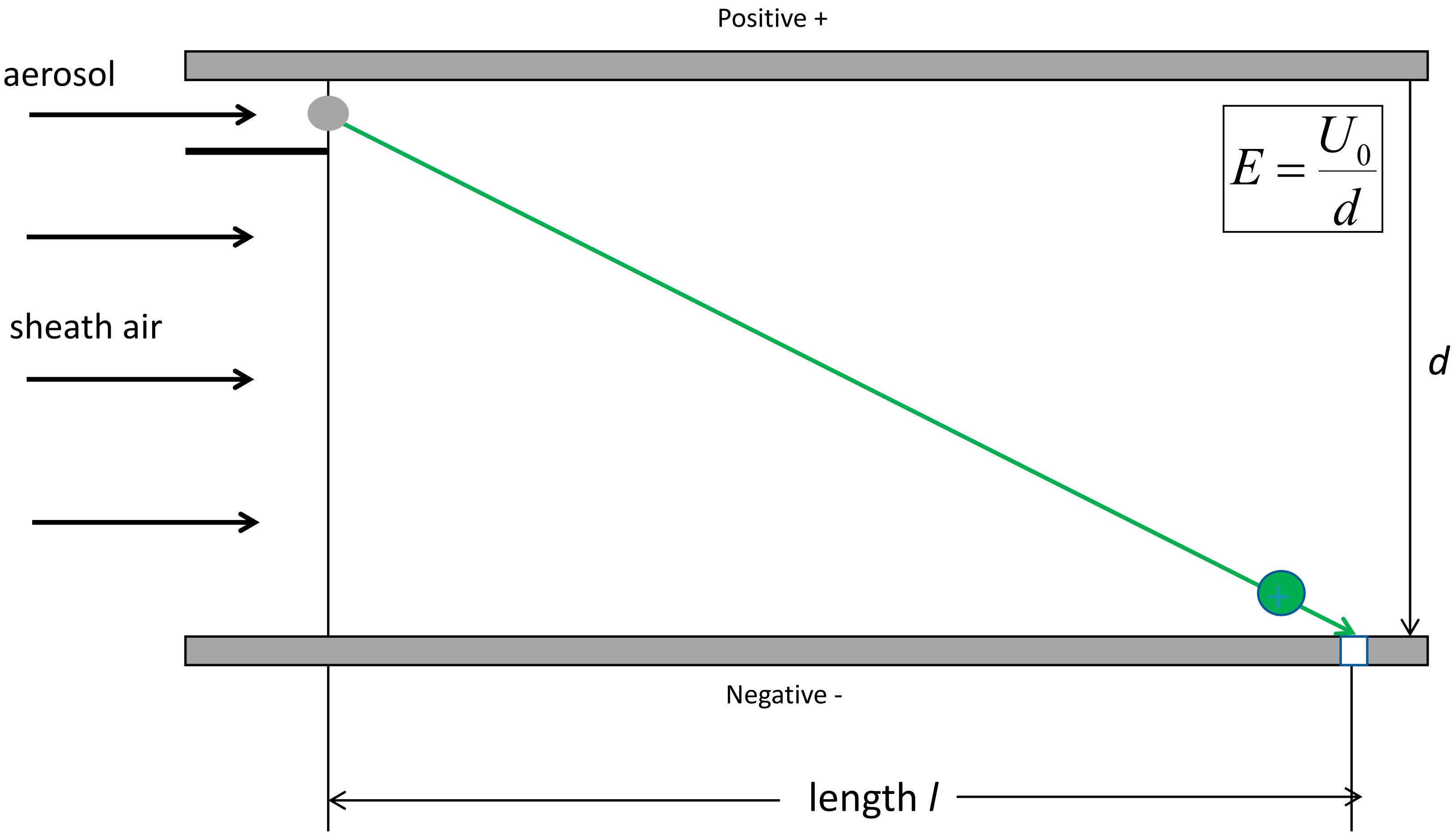


$$E = \frac{U_0}{d}$$



$$E = \frac{U_0}{d}$$

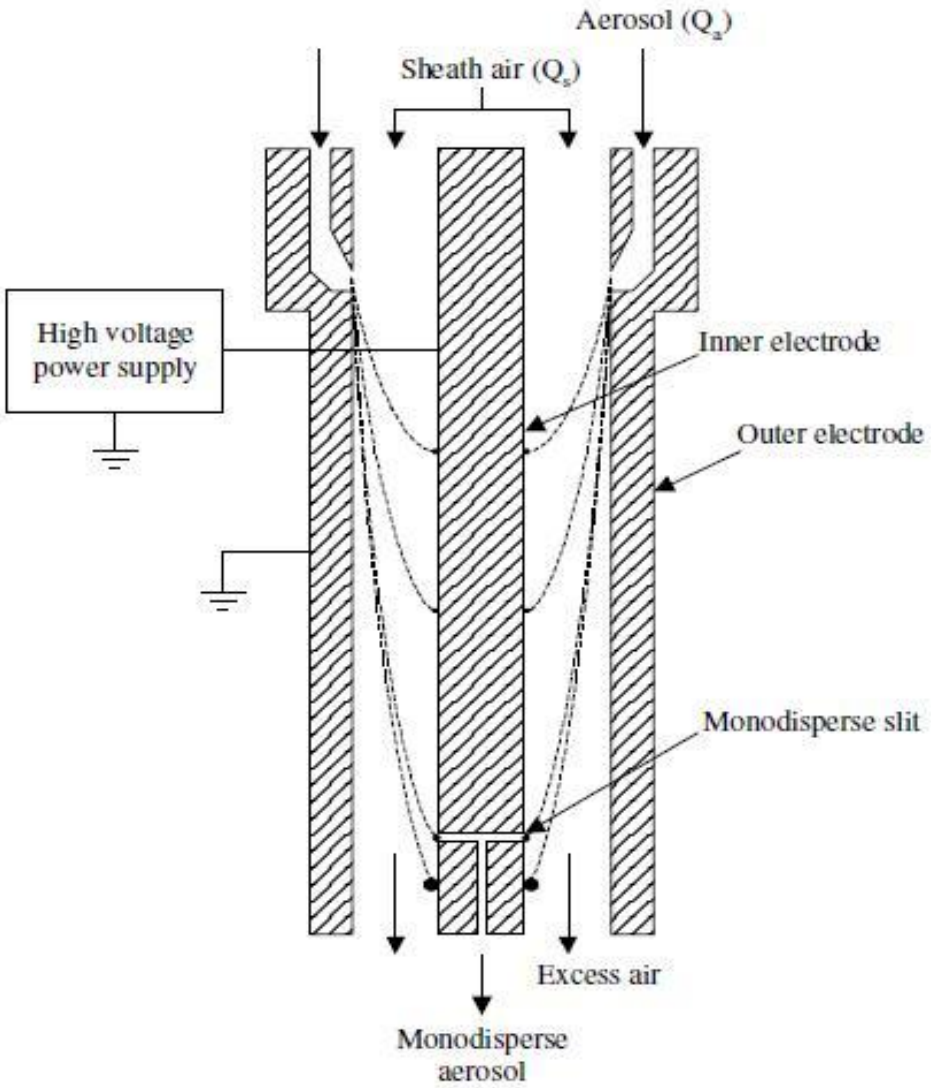
Plate differential mobility analyzer



$$E = \frac{U_0}{d}$$

Cylindrical
Differential Mobility Analyzer-

Vienna-Type Differential Mobility Analyzer



$$E = \frac{U_0}{\ln(r_o/r_i) \cdot r}$$

DMA – General Equations

The voltage to select the mean electrical particle mobility can be calculated to:

$$\boxed{\frac{n_e \cdot \mathrm{e} \cdot C_\mathrm{C}}{3\pi \cdot \eta \cdot \bar{D}_\mathrm{P}} = \frac{Q_{Sh} \cdot \ln(\mathrm{r_o}/\mathrm{r_i})}{2\pi \cdot U \cdot 1}}$$

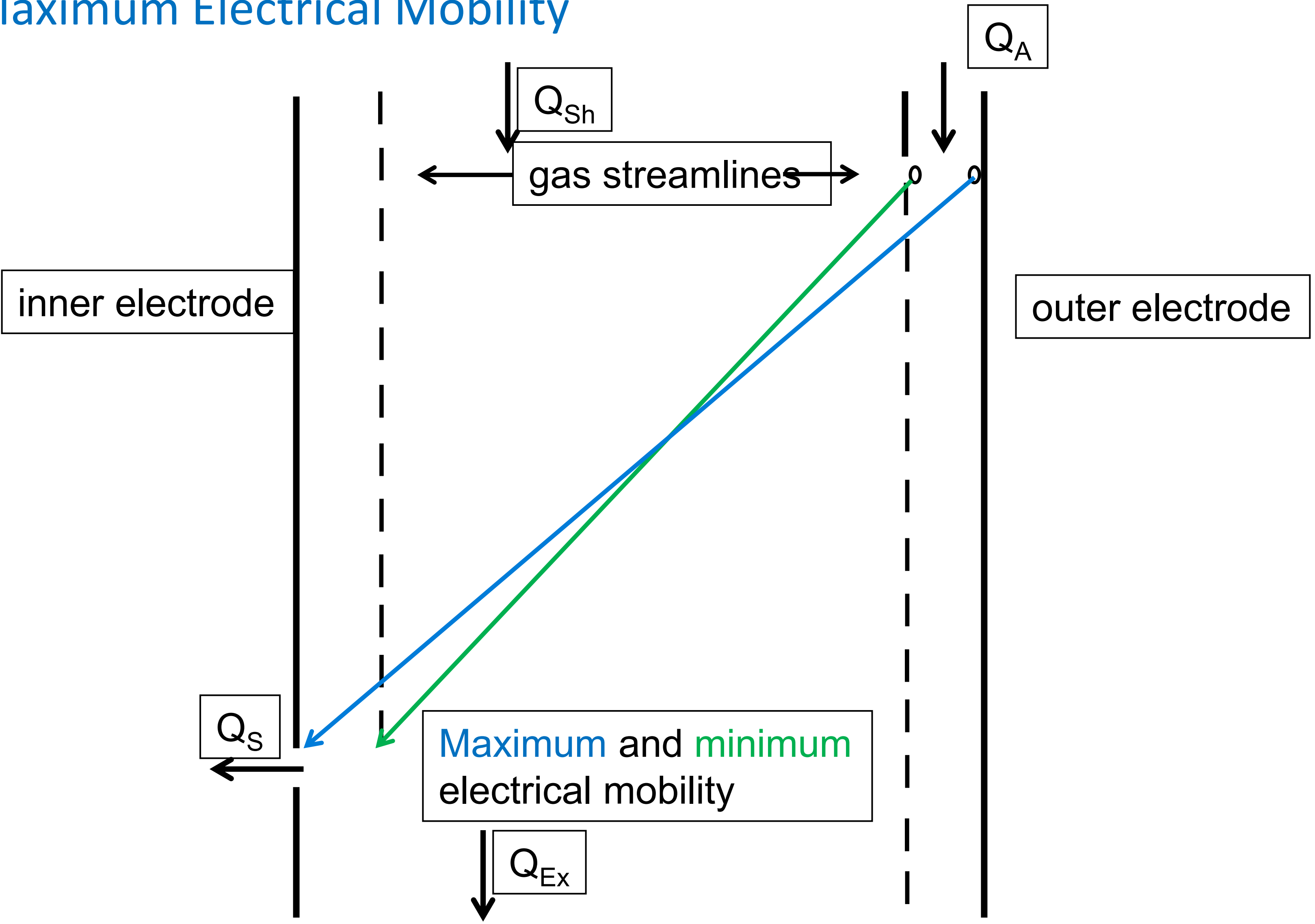
$$\Rightarrow \quad \boxed{U = \frac{3\eta \cdot \bar{D}_\mathrm{P} \cdot Q_{Sh} \cdot \ln(\mathrm{r_o}/\mathrm{r_i})}{2 \cdot 1 \cdot n \cdot \mathrm{e} \cdot C_\mathrm{C}(\bar{D}_\mathrm{P})}}$$

The mean particle diameter can be calculated as follows, but it cannot be analytically solved:

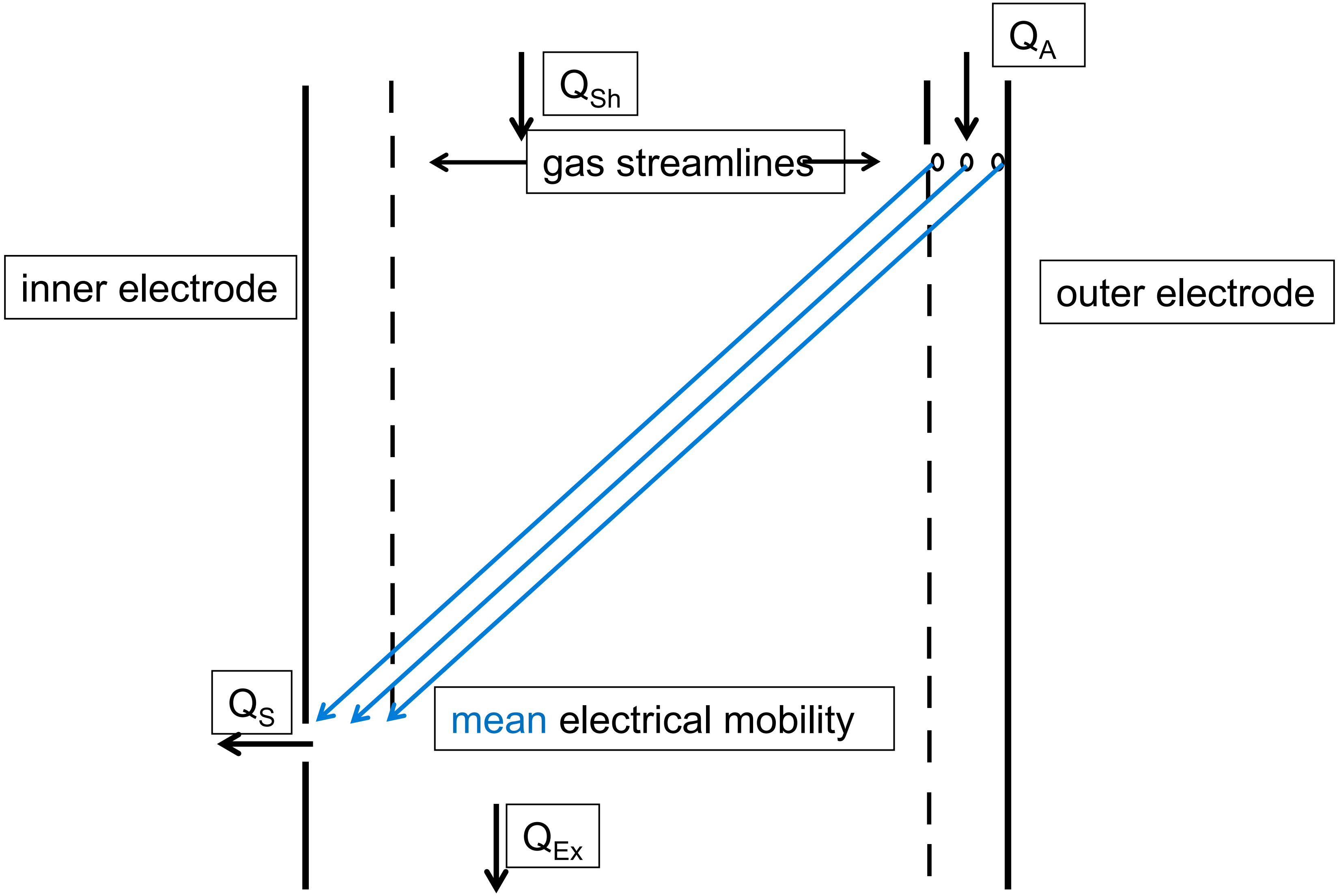
$$\Rightarrow \quad \boxed{\bar{D}_\mathrm{P} = \frac{2 \cdot U \cdot 1 \cdot n_e \cdot \mathrm{e} \cdot C_\mathrm{C}(D_\mathrm{P})}{3\eta \cdot Q_{Sh} \cdot \ln(\mathrm{r_o}/\mathrm{r_i})}}$$

DMA - Transfer Function

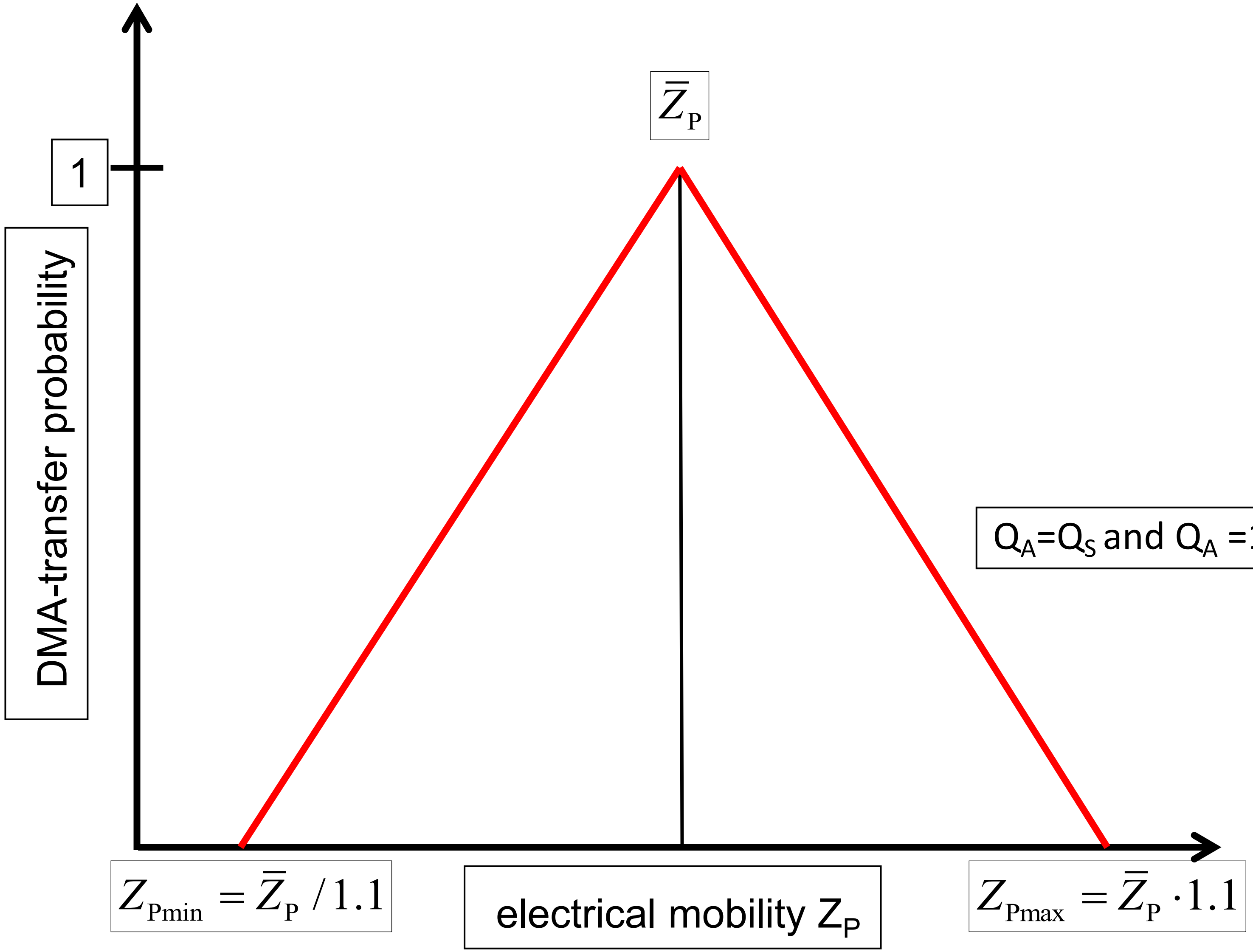
Minimum & Maximum Electrical Mobility



Mean Electrical Mobility



DMA - Transfer Function



DMA - Transfer Function

The flow rate Qs is taken out of the DMA through a slit at the end of the inner rod, carrying particle with a certain electrical mobility.

The mean electrical mobility of these particles can be calculated to:

$$\boxed{\bar{Z}_{\mathrm{P}} = \frac{(Q - \frac{1}{2}(Q_A + Q_S)) \cdot \ln(\mathrm{r_o}/\mathrm{r_i})}{2\pi \cdot U \cdot 1}}$$

$$\boxed{\bar{Z}_{\mathrm{P}} = \frac{Q_{Sh} \cdot \ln(\mathrm{r_o}/\mathrm{r_i})}{2\pi \cdot U \cdot 1}}$$

The ideal width and selectivity of the electrical mobility bin is described to:

$$\boxed{\Delta Z_{\mathrm{P}} = \frac{(Q_A + Q_S) \cdot \ln(\mathrm{r_o}/\mathrm{r_i})}{2\pi \cdot U \cdot 1}}$$

$$\boxed{\frac{\Delta Z_P}{\bar{Z}_P} = \frac{Q_A + Q_S}{Q_{Sh}}}$$

If $Q_A = Q_S$ and $Q_A = 1/10\ Q_{Sh}$

$$\boxed{\frac{\Delta Z_P}{\bar{Z}_P} = \frac{1}{5}} \quad \boxed{Z_{\mathrm{P}} = \bar{Z}_{\mathrm{P}} \pm 0.1 \cdot \bar{Z}_{\mathrm{P}}}$$