A new method to minimise charge uncertainty in condensation particle counter calibration when using a Faraday-cup aerosol electrometer

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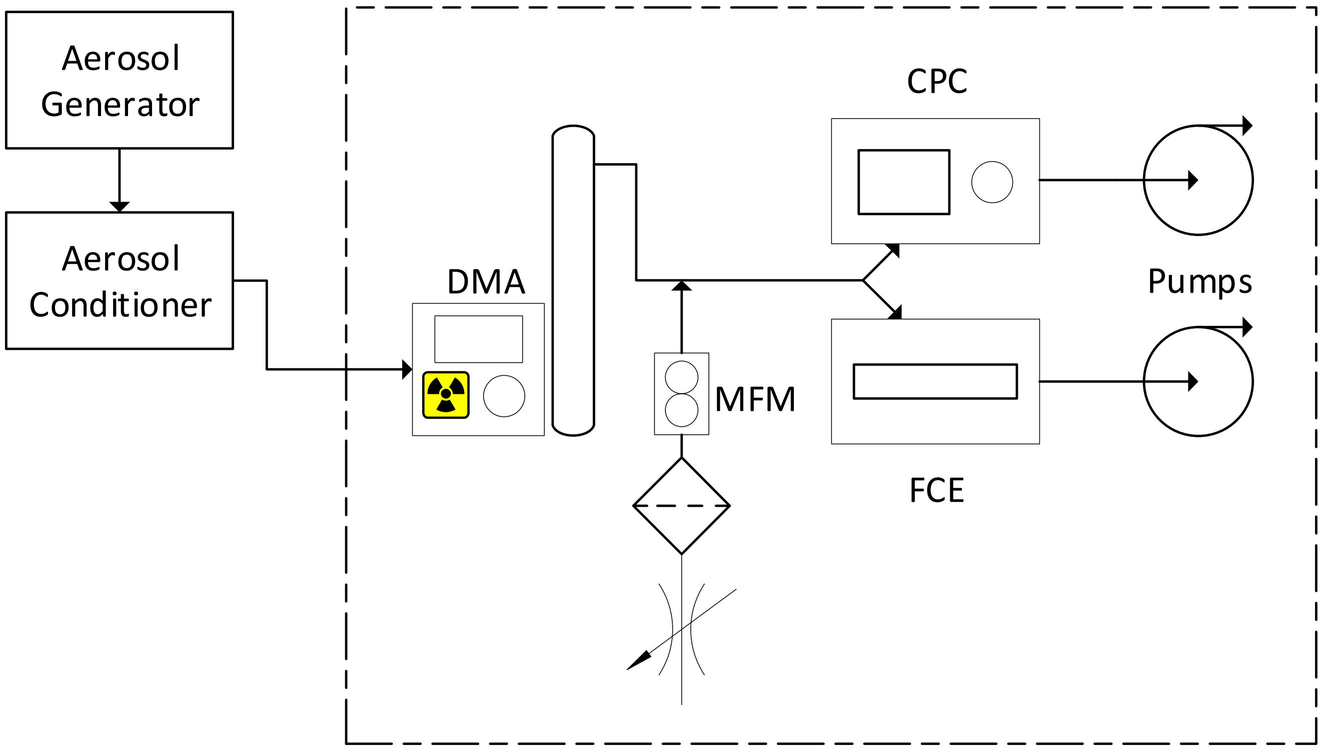
ISO27891:2015
"*Calibration of Condensation Particle Counters*"

"*This International Standard sets out two distinct methods of CPC calibration: the characterization of a CPC by comparison with an FCAE, …….. and by comparison with a reference CPC*."

"*Two major sources of errors are known in CPC calibration: **the presence of multiply charged particles** and the bias of the particle concentrations between the inlet of the CPC under calibration and that of the reference instrument. Evaluation of these factors and corrections for them shall be included in the calibration procedure, the methods of which are specified in this International Standard.*"

FCAE Method

Slightly simplified from ISO27891:2015

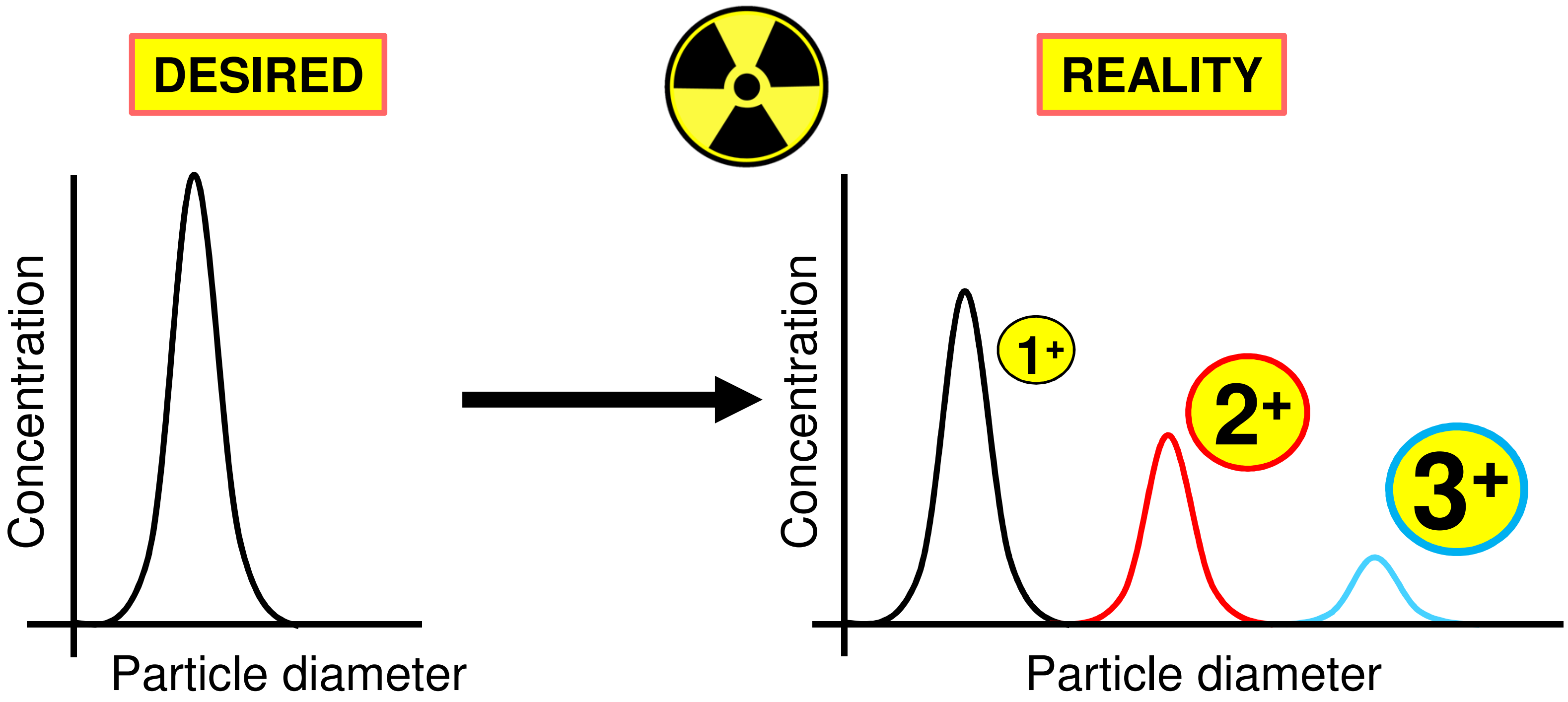


1. Size select particles with "DEMC" (DMA)
2. *Assuming* each particle has 1 elementary charge:

   FCAE particle number = current / elemental charge / flow

Uncertainty in charge state

DMA produces ***multiple peaks***



Leads to:

- Increased count on the FCAE
- Bias in the actual size at which that count is made

Minimising the single-charge uncertainty

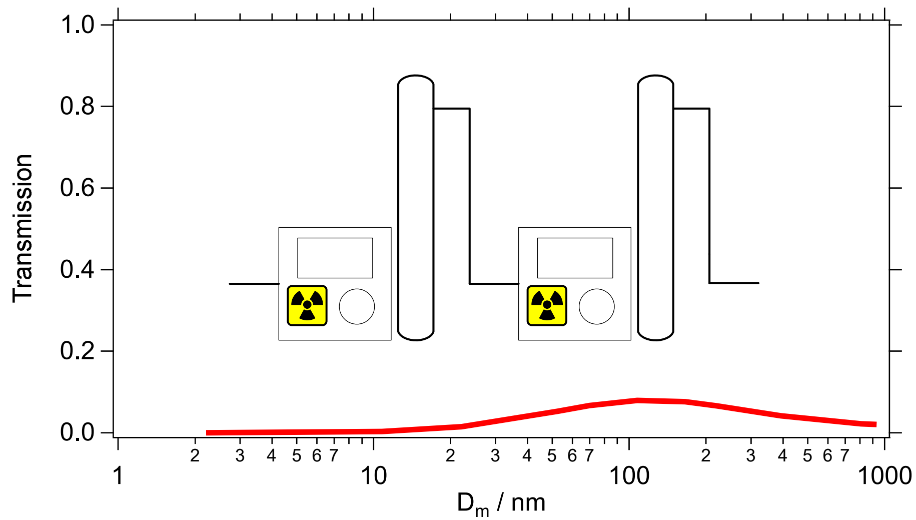
ISO27891 recommends you:

- Determine and correct for the uncertainty
- Minimise by experimental technique:
  - Charge small particles, then grow them larger – "Single Charged Aerosol Reference" (SCAR, Yli-Ojanperä *et al.*, 2010)
  - **Minimise the population of larger-than-desired particles in the source aerosol.**

One way of achieving this is to use a second DMA to pre-select particles at the same (or similar) desired size to provide an initial monodisperse aerosol – a Tandem DMA arrangement.

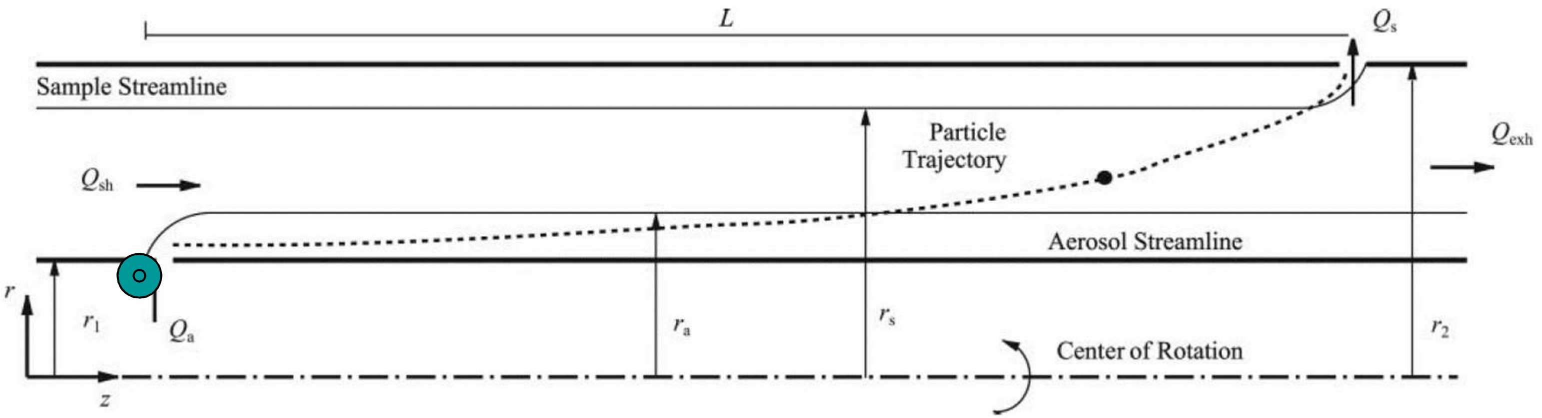
However, tandem transmission efficiency (mainly charging in 2x neutralisers) very poor, <10%:

Not a problem for CPC (can count singly), but can be for FCAE (~ 10^3 #/cc minimum)



Aerodynamic Aerosol Classifier (AAC)

- Can be thought of like a “rotating DMA” – has axial sheath flow, but radial force is centrifugal not electrical

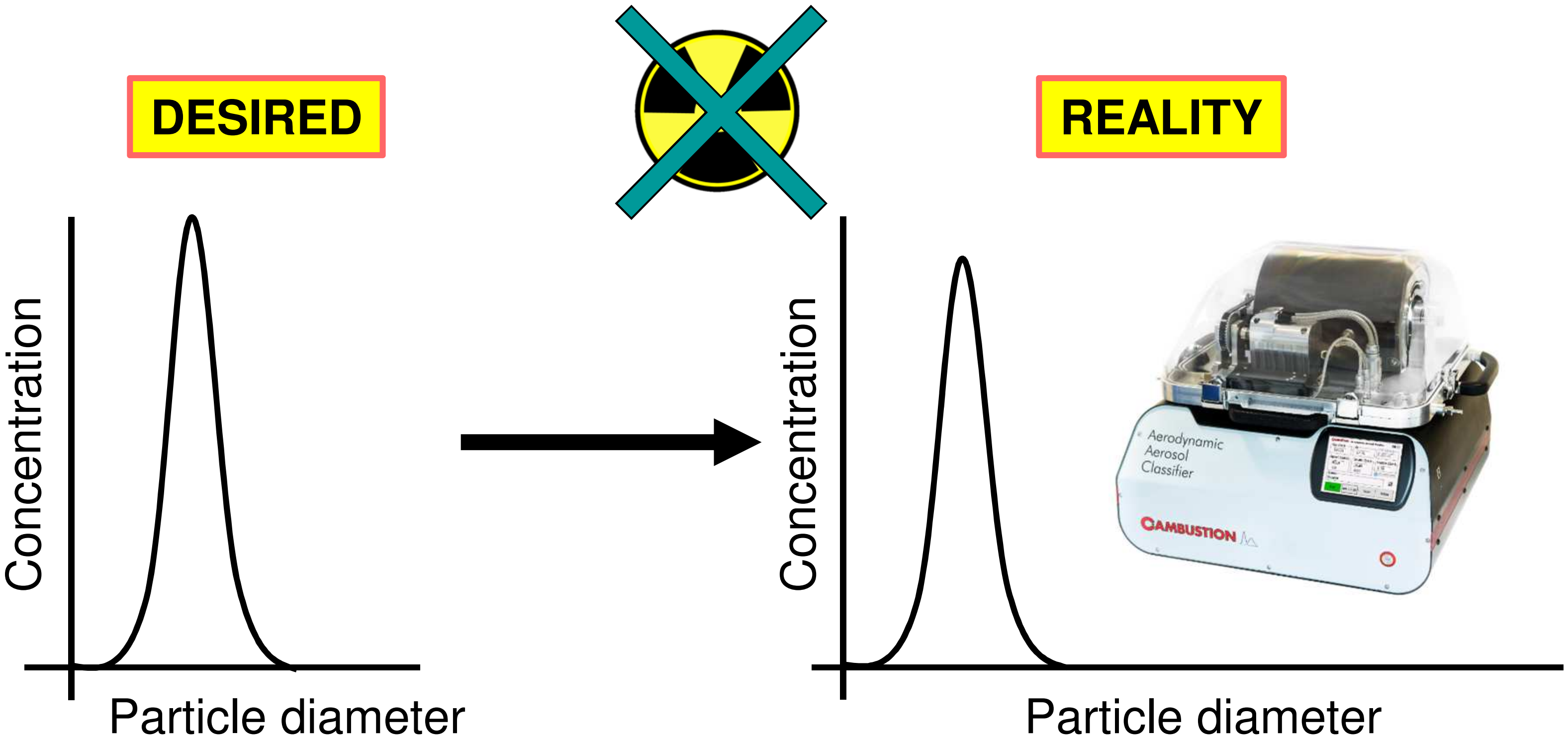


- Classifies aerosol particles by their relaxation time – the time taken for a particle to match the flow to which it is introduced
    - Smaller particles match the sheath flow sooner
    - Larger particles do not match the sheath flow
- <u>Doesn’t</u> rely on particle charging—true monodisperse aerosol

F. Tavakoli & J. S. Olfert (2013).

True monodisperse aerosol using AAC

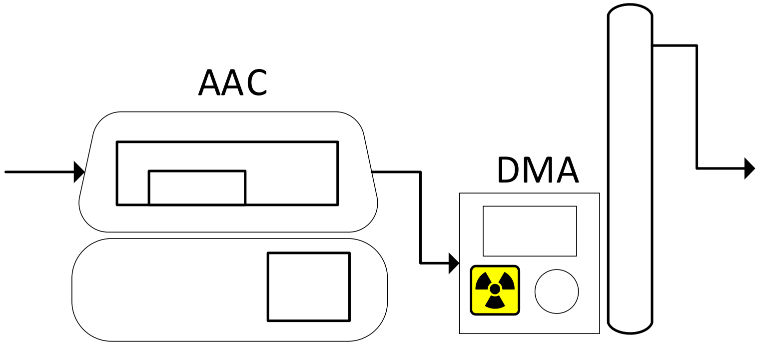
The AAC produces a ***truly*** ***monodisperse*** *aerosol*

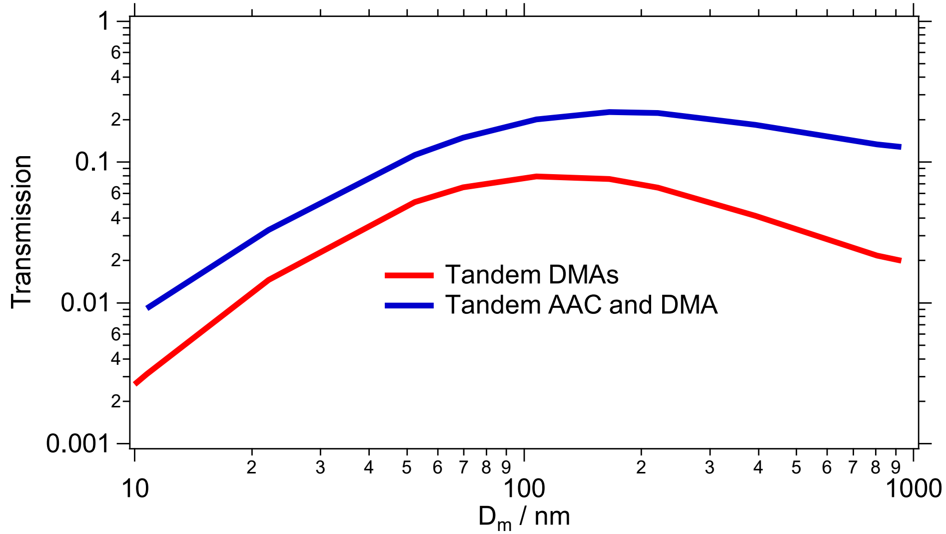


BUT….!

- AAC doesn't use charging – how will the FCAE count particles?!
  - Yes, you still need a DMA and neutraliser, the AAC and DMA are used in tandem.
- AAC classifies by aerodynamic diameter, we're interested in mobility diameter!
  - For a test aerosol of known density, the conversion is easy and can be made seamless

But you still need a neutraliser and a DMA!





- DMA column here effectively acts as a filter for uncharged particles
- Resolution (and size accuracy) of AAC is comparable to DMA – so DMA can be run at low resolution / low sheath flow
  - This means that the DMA can classify much larger particles than usual
  - At 1.2 lpm sheath, a TSI 3081 column can go as large as 1.8 μm at 10 kV

Mobility to Aerodynamic Diameter Conversion (1)

Mobility diameter (d_m) and aerodynamic diameter (d_a) are related by the following relationship:

$$\rho_{\text{eff}} \cdot d_{\text{m}}^2 \cdot C_{\text{c}}(d_{\text{m}}) = \rho_0 \cdot d_{\text{a}}^2 \cdot C_{\text{c}}(d_{\text{a}})$$

Fundamentally, the AAC classifies by particle relaxation time, τ

$$\frac{2Q_{sh}}{\pi\omega^2(r_i+r_o)^2L} = \tau \equiv mB = \frac{C_c(d_a)\rho_0 d_a^2}{18\mu} = \frac{\rho_{\text{eff}}\, C_c(d_m)\, d_m^2}{18\mu}$$

T.J. Johnson *et al*. 2018

for (balanced) AAC sheath flow Q_{sh}, rotational speed ω, classifier inner and outer radii r_i and r_o and length L, gas viscosity μ and effective density ρ_{eff}

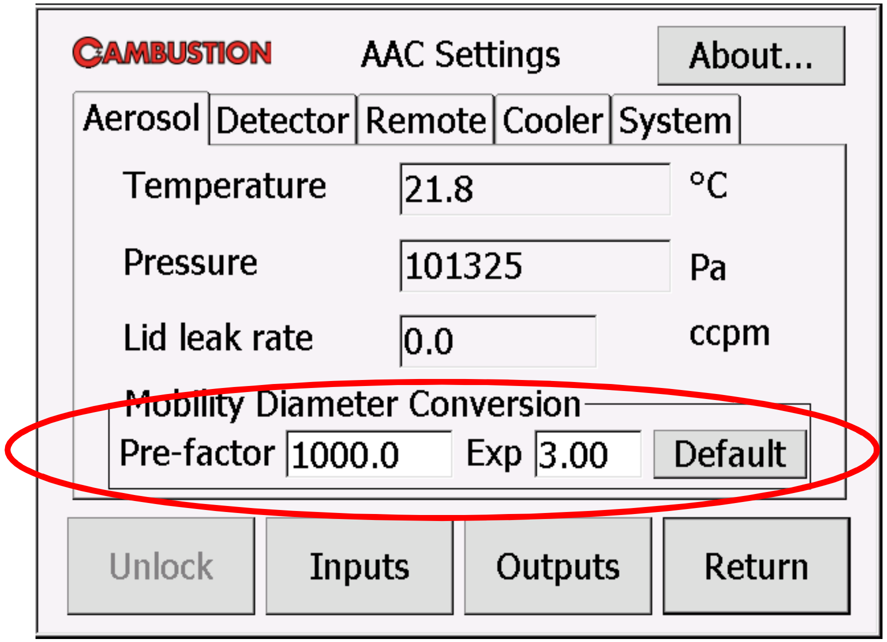
Resolution parameter (R), as for a DMA, is $Q_{sh}/Q_{aerosol}$

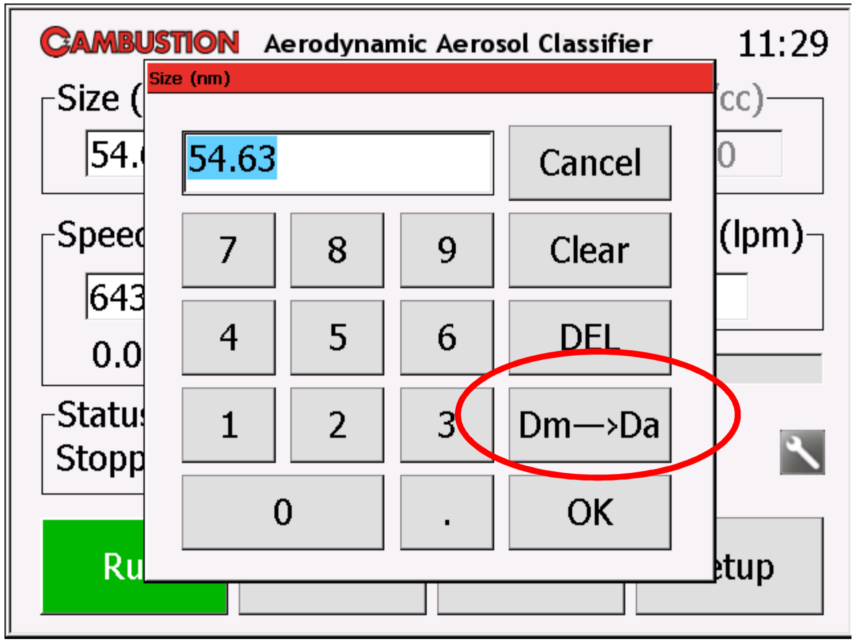
Required resolution sets Q_{sh}, then solve for ω for a given d_m

Mobility to Aerodynamic Diameter Conversion (2)

Conversion is solved numerically by the AAC software

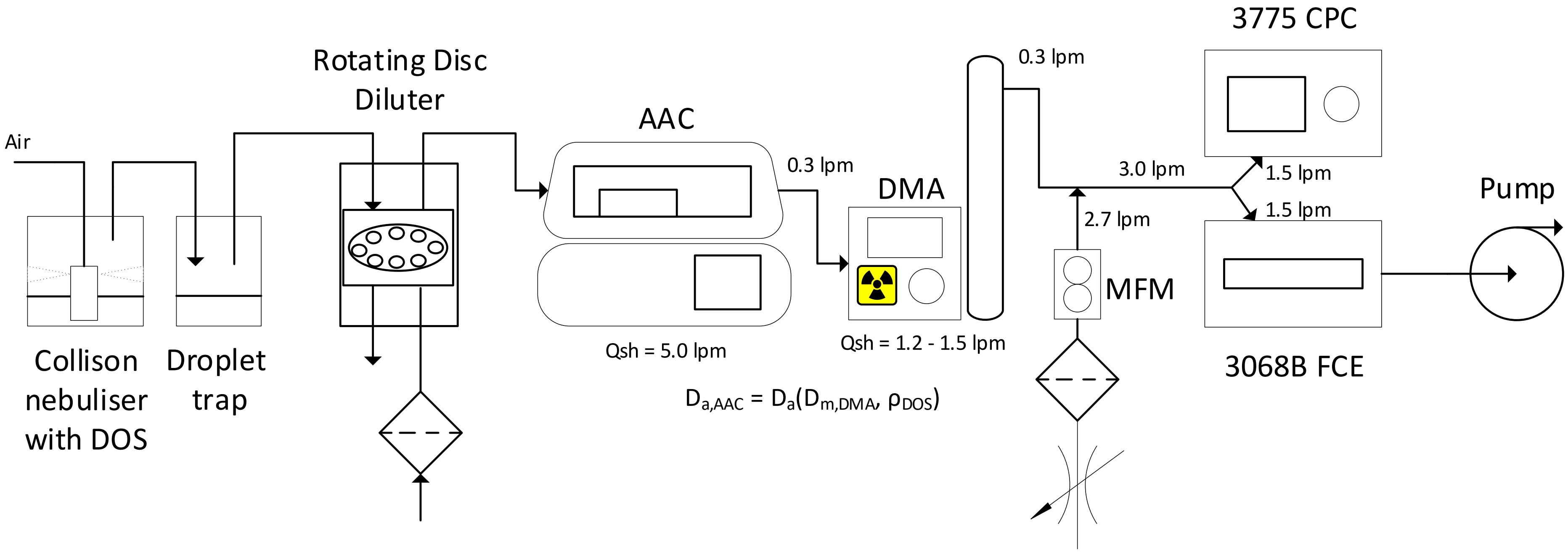
For DOS, ρ_{eff} = 914 kg m^{-3}

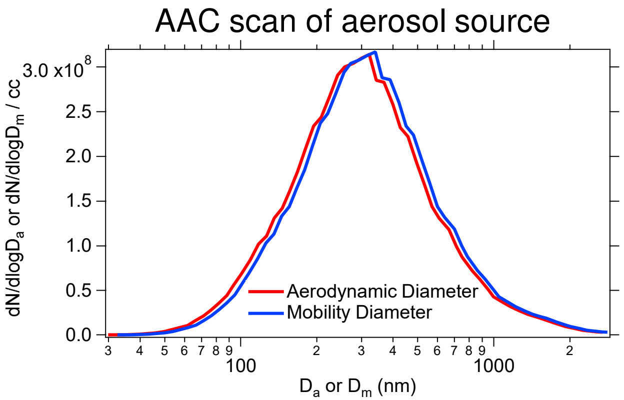




Possible for AAC to control DMA, or both to be controlled from PC

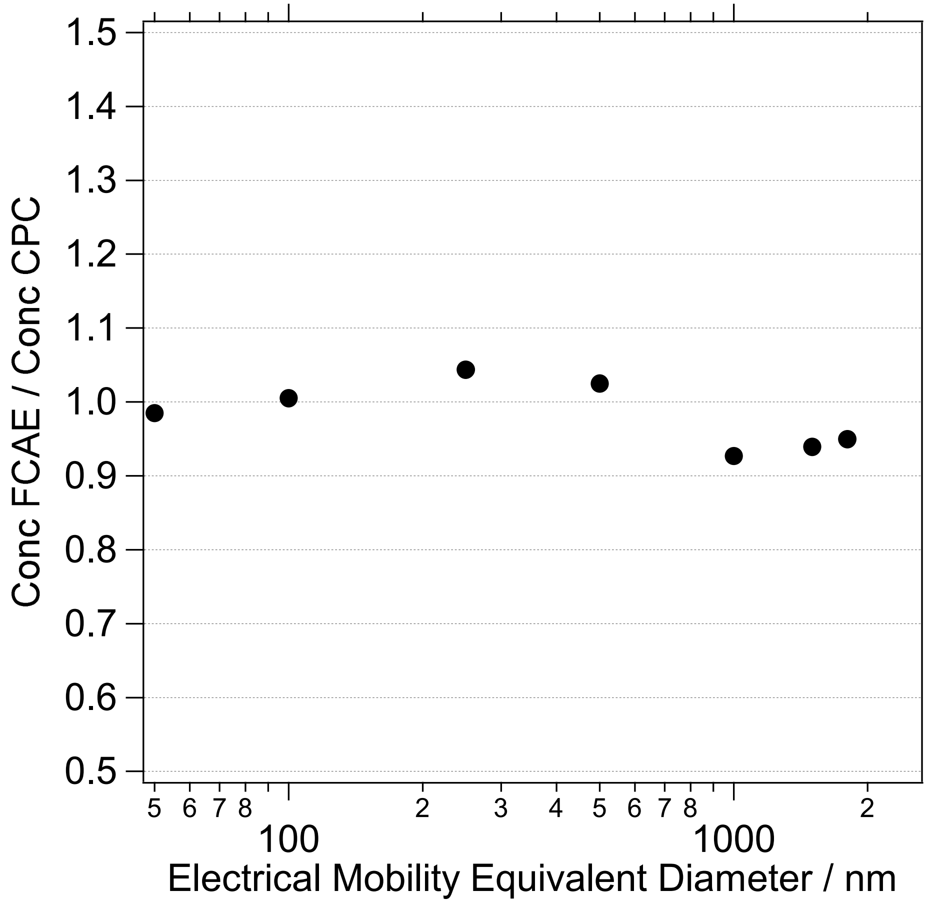
Experimental Setup





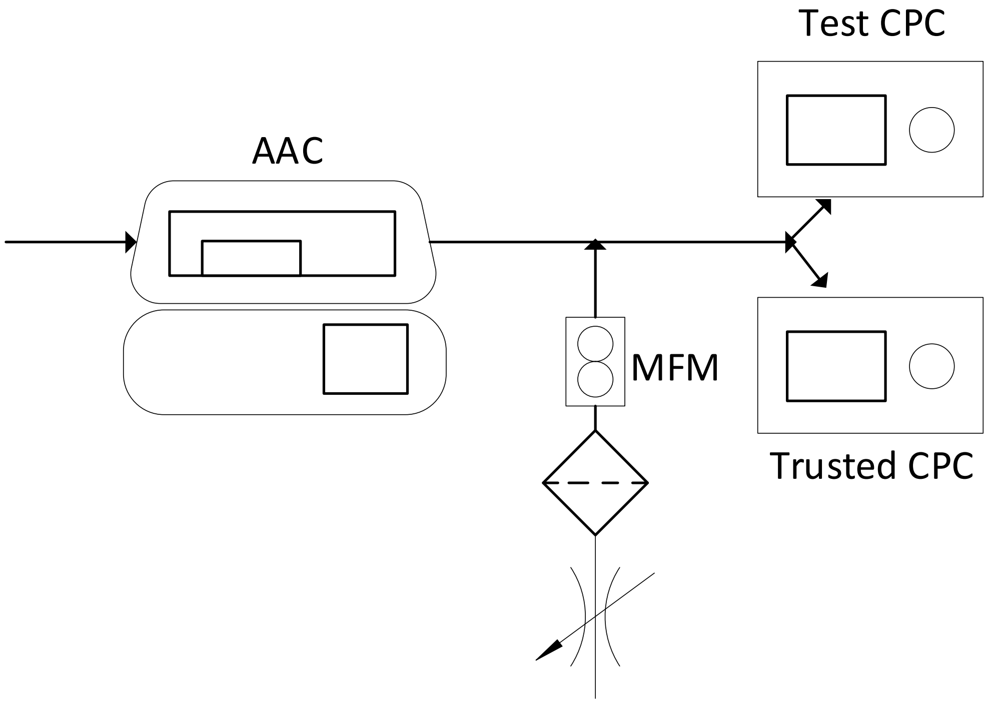
- DMA set to desired D_m
- AAC set to desired equivalent D_a to D_m
- Diluter set to keep concentration in range of FCAE
- One aerosol source; Process is automatable

Results



1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
Conc FCAE / Conc CPC
5 6 7 8
100
2 3 4 5 6 7 8
1000
2
Electrical Mobility Equivalent Diameter / nm

CPC to CPC calibration



- ✓ Don't need a neutraliser
- ✓ Higher concentrations possible
- ✓ Can calibrate up to much larger sizes
- ✓ Even with no FCAE, multiple charges from DMA still affect sizing accuracy
- ✗ AAC can't go as small as a DMA (currently >25 nm)?
  - CPC small size cut for solid engine particle measurements legislated in Europe (PMP) (d_{50} = 23 nm, possibly 10 nm soon…)

Or can it….?

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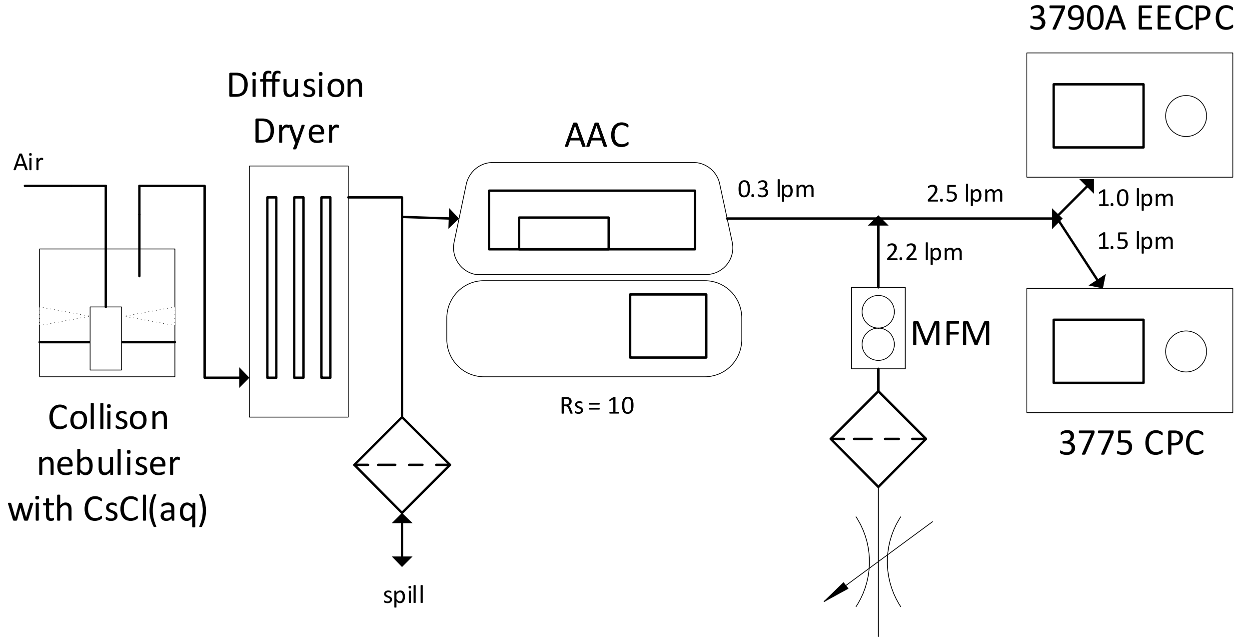
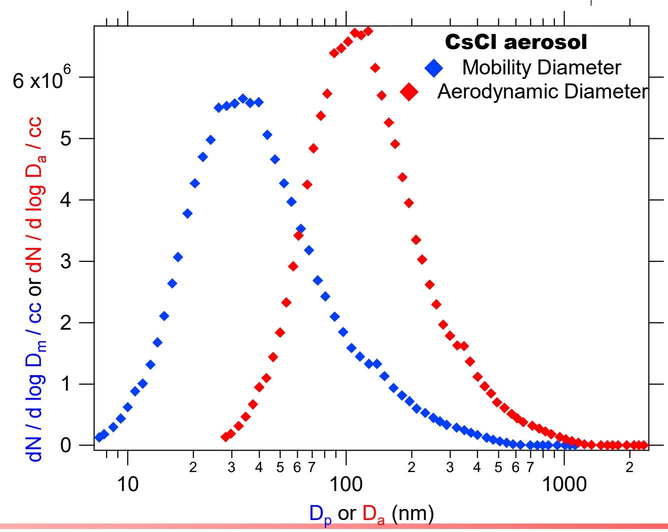
What about smaller sizes?

- 25 nm D_{ae} limit is due to maximum speed – not just mechanically but also fluid dynamic issues
- But this is for aerodynamic diameter….
  - So **use a denser aerosol to get to smaller mobility diameters**

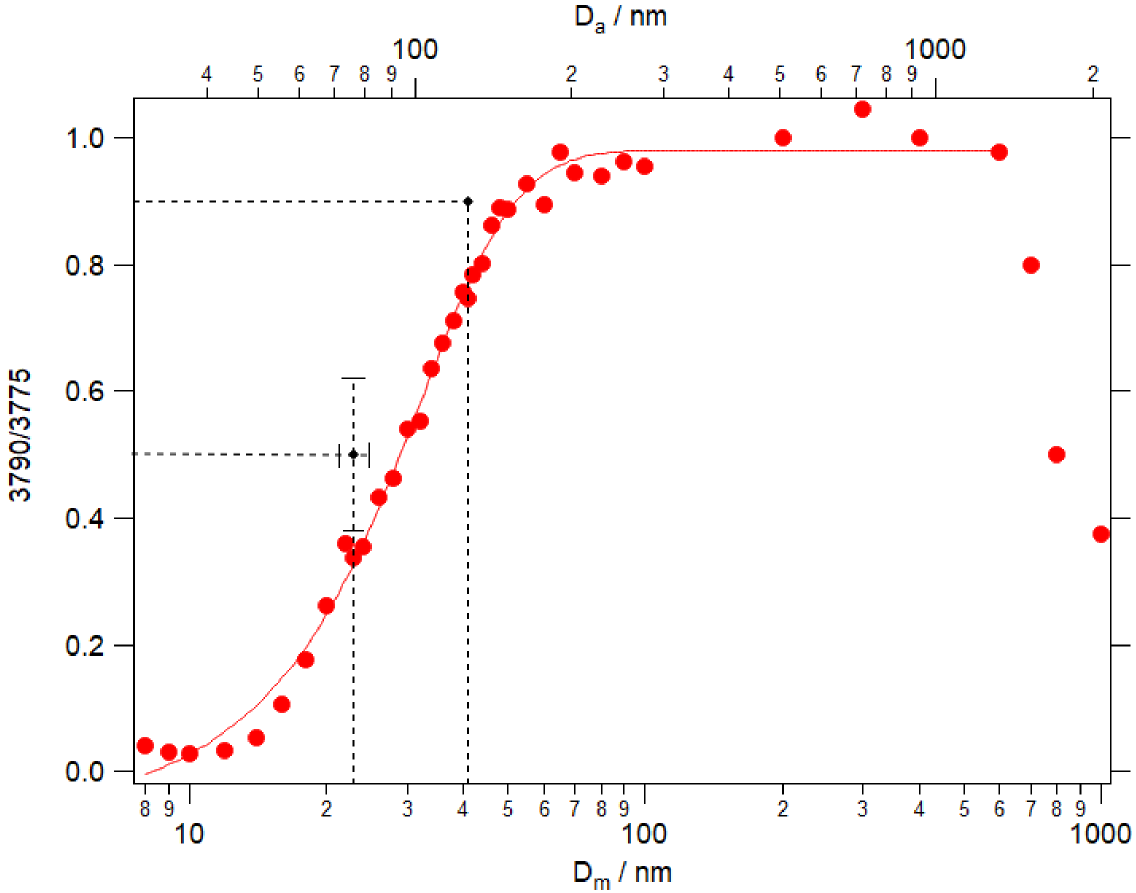
- Gold, ρ = 19200 kg/m^3, gets you to D_m = 1.5 nm (in theory!)
  - But requires evaporative generator
- Caesium Chloride, CsCl, ρ = 3999 kg/m^3, gets you to 7 nm
  - Can be dissolved in water and nebulised, just like salt
  - Fairly benign, just like salt

Example: TSI 3790A Engine Exhaust CPC





Results:



Doesn't quite fit on the "PMP" requirements of 50% at 23 nm and >90% at 41 nm.

A few caveats:

- This EECPC has previously been recalibrated in the field with CAST soot, not as Emery oil from the factory
- We don't know the butanol "wettability" of CsCl – humidity probably a factor as for NaCl
- The roll-off of CPCs may not be a function of only D_m…
- … Note the EECPC starts to "roll-off" at large sizes – this may well be an inertial effect at large D_a
- The 3775 itself has a D_{50} of 4 nm

Conclusions

- The AAC can be used to prepare a monodisperse aerosol for use with the neutraliser-DMA-FCAE method for CPC calibration.
- Much higher transmission than tandem DMAs
- A single aerosol source can cover a wide range – easily automatable
- Large particle sizes are possible by running the DMA at low resolution
- Small particle sizes are possible by using a dense test aerosol
- The AAC could replace the DMA in the reference CPC method for CPC calibration – with some caveats. No radioactive or X-ray source is needed, so more suitable for field calibration.
- Technique is suitable for aerosols of uniform morphology and known density – use of fractal aerosols such as soot would rather complicate matters…

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- Kingsley Reavell, Cambustion

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Any questions?

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