Design of Exposure Systems and Bioagent Inactivation Devices: Aerosol Generation, Measurement and Characterization

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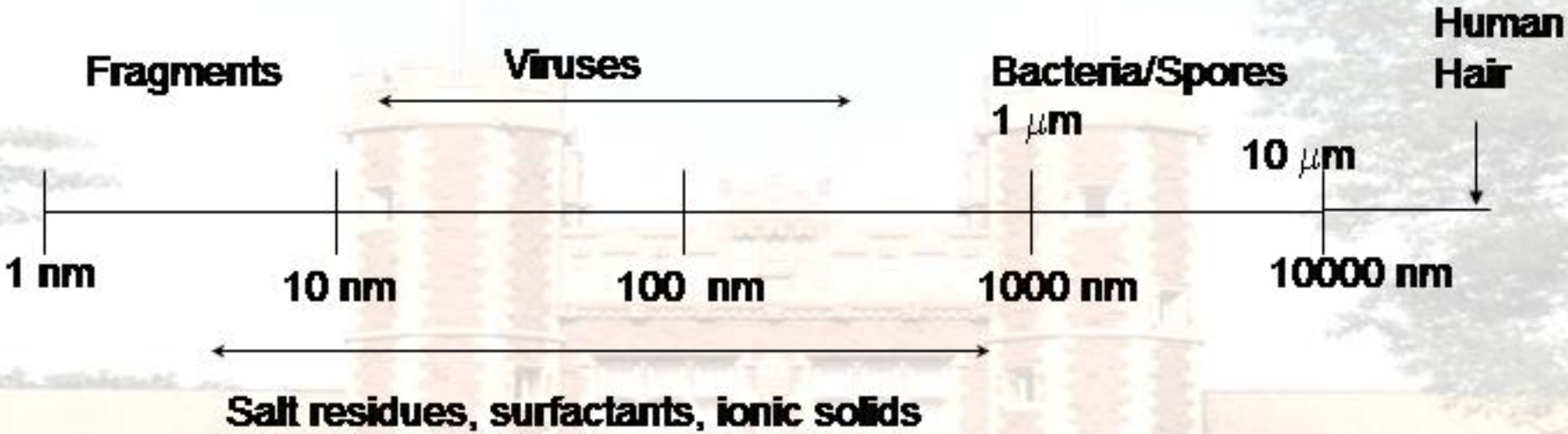
Outline of Presentation

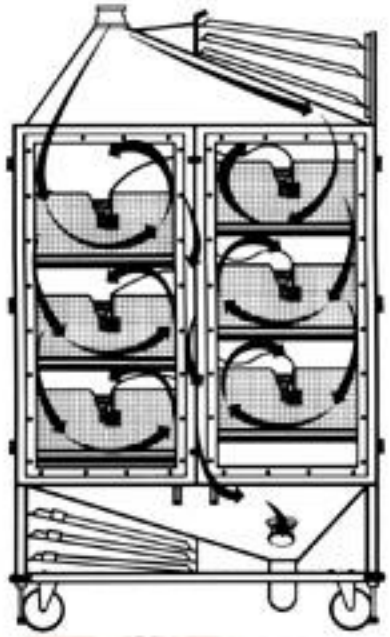
- Aerosol Generation
- Aerosol Measurement for bacteria and viruses; protein molecules and fragments.
- Characterization of Exposure Chambers – are the aerosols well distributed, flow modeling, transport in respiratory system and deposition
- Inactivation of Bioagents in Airborne Streams – just brief mention.

EVEN BIOAEROSOLS COVER A BROAD RANGE



PHYSICS OF TRANSPORT, GROWTH

- Size (aerodynamic size?, shape is also important)
- Concentration (number based metric, # / cm^3)
- Morphology – shape, agglomerate state
- Biological particles generally carry a surface charge, very important
- Other surface characteristics – hydrophobic, hydrophillic, etc.



EXPOSURE CHAMBER

AEROSOL MEASUREMENT

AEROSOL GENERATOR

OTHER IMP. CONSIDERATIONS
- Transport Modeling
- Aerosol dynamics (size change)
- Resipratory Deposition

Aerosol Generation

- Aerosolize suspension in liquid without changing viability (considerations: fragmentation, charge distribution, etc)
- Role of other constitutents – surfactants, ionic salts, etc.
- Resultant throughput and size distribution

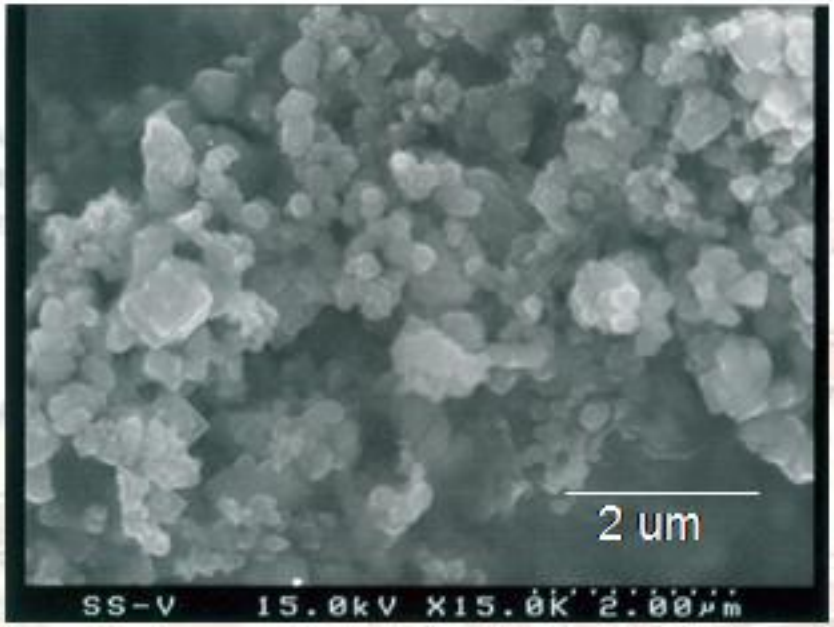
ATOMIZATION

- Uses a high velocity air jet to create a pressure difference that pulls liquid w/suspension from a reservoir
- Air jet breaks up liquid stream into droplets
- Impaction results in size selectivity – only smaller droplets are aerosolized. Larger droplets drop back into reservoir
- Possible disadvantage: damaging of organism on impaction. Re-design will result in gentler impaction, and non-reuse of larger droplets generated

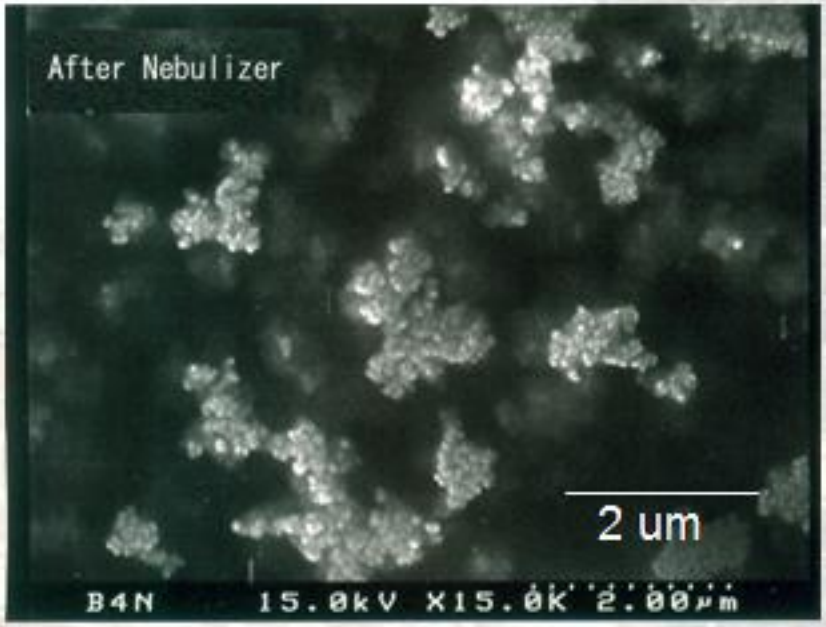
NEBULIZERS

- Similar principle as atomizer – gentler aerosolization
- Can have higher throughputs, lesser control on size
- Designs (such as BANG, etc to minimize foaming)

SEM images of MS2 bacteriophage (polio virus surrogates) aerosolized with a Collison Nebulizer



(a) Virion particles in suspended solution



(b) Virion particles after nebulizer

Nebulized Particles Tend to Clump Together !

Hogan, Lee, Biswas (2003) In review, *Aerosol Sci. Technol.*

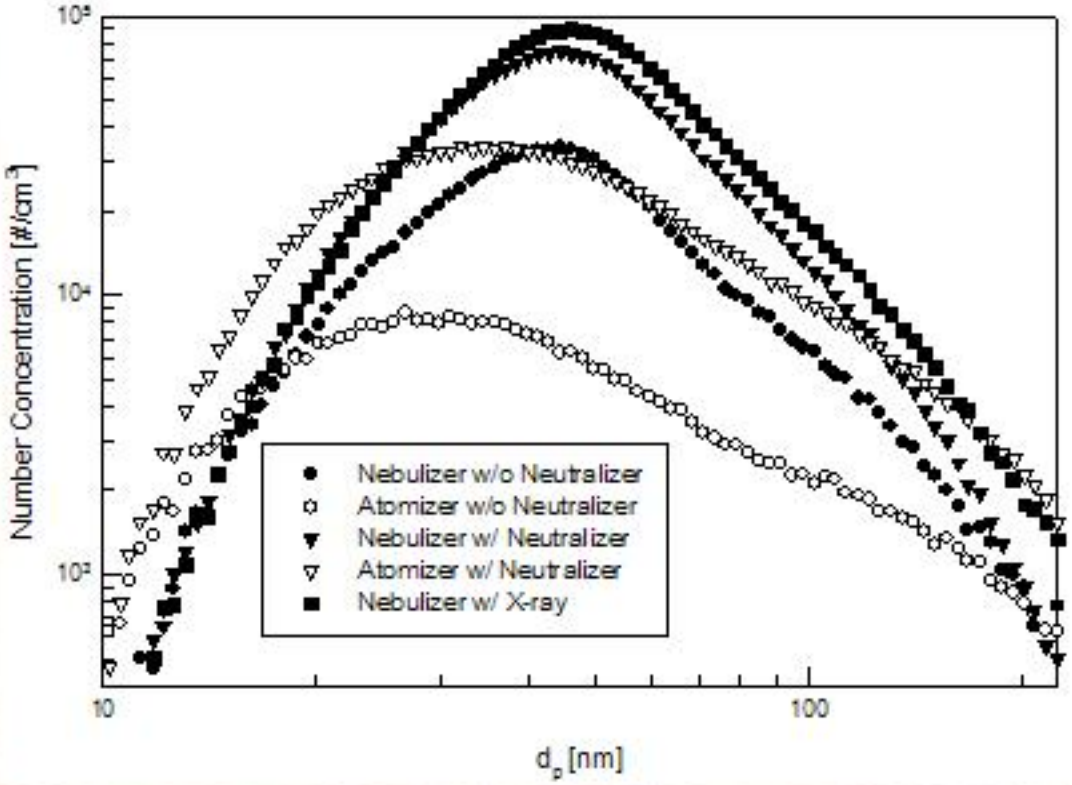
Though the viral particles are 25 nm in diameter, we measure a broader size distribution

Smaller particles are due to fragments of the particles – either due to nebulization or due to breakup as a result of surface charges

Larger particles due to tendency to aggregate

Our systems have allowed us to conduct fundamental studies on charge distributions on these viral particles – NEVER DONE BEFORE.

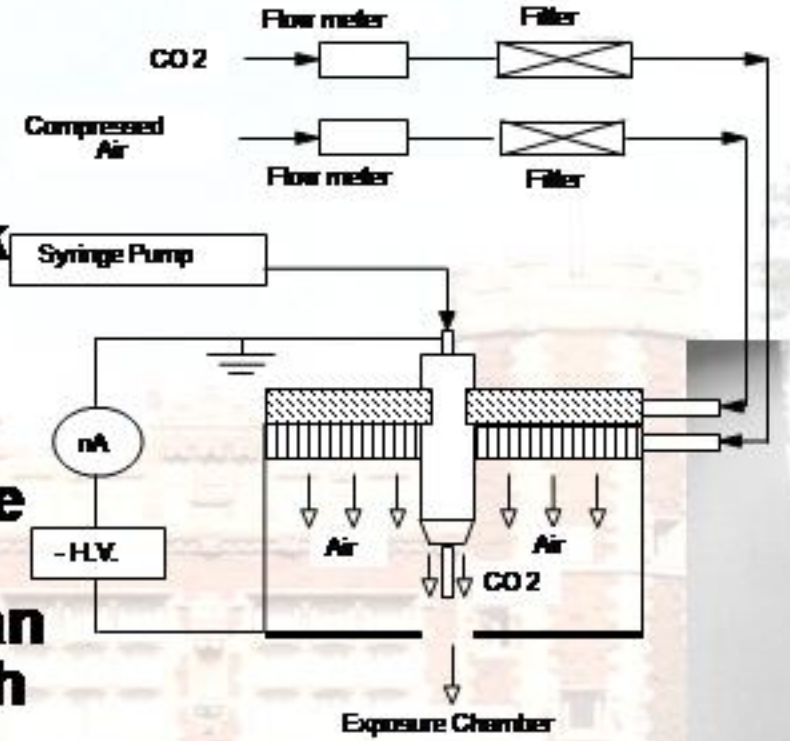
Why are such fundamental studies Important? – To better design control methodologies, scale up, ensure byproducts are not formed

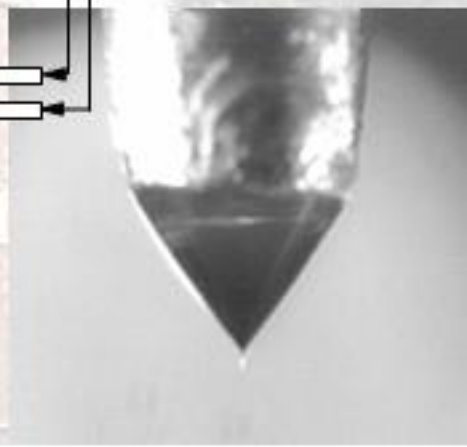


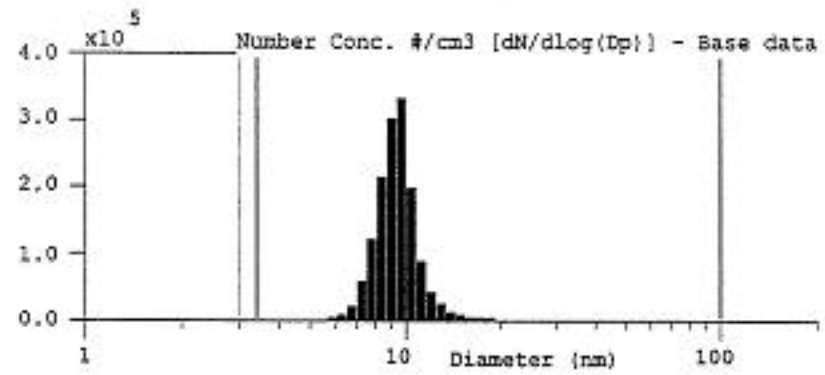
REAL TIME MEASUREMENT OF VIRAL PARTICLE SIZE DISTRIBUTIONS.

ELECTROSPRAYS

- Use an applied electrical field to break up droplets
- Ability to manipulate size in very narrow ranges and hence state of the resultant particles (overcome van der Waals forces which tend to hold particles together causing clumping)
- Can eliminate role of other additives in the solutions







POST GENERATION CONDITIONING

Can also use
real time size selection
devices

AEROSOL CONDITIONING
(e.g. Diffusion Dryer)

Choice of Filling
To selective remove
Liquid constituent
e.g. desiccant silica
For water

AEROSOL GENERATOR

Summary of "Aerosol Generation"

- Nebulizers may not be able to produce single units of the bioagent; even if starting material is "ultra-pure". Atomizers maybe better in size control, but may alter viability
- Post conditioning is a viable means of obtaining a well characterized aerosol, and maybe essential
- Electrosprays one of the best ways of generating particles in a large range of sizes

Aerosol Measurement

- Real time instruments that measure size distributions
- Most reliable are the electrical mobility techniques – especially for particles in the submicrometer and nanometer size ranges
- Optical instruments based on light scattering are also feasible – need some prior knowledge of organisms
- As real time instruments are well developed, routine monitoring in chambers using probes are advisable

GOVERNING EQUATIONS OF PARTICLE MOTION

- Equations for transport
- External force fields – gravity, electrical forces
- Other modes of transport: diffusion
- Important non-dimensional parameters

$$m\frac{d\overline{v_p}}{dt} = \frac{3\pi\mu d_p}{C}(\overline{u} - \overline{v_p}) + \overline{F_{ext}}$$

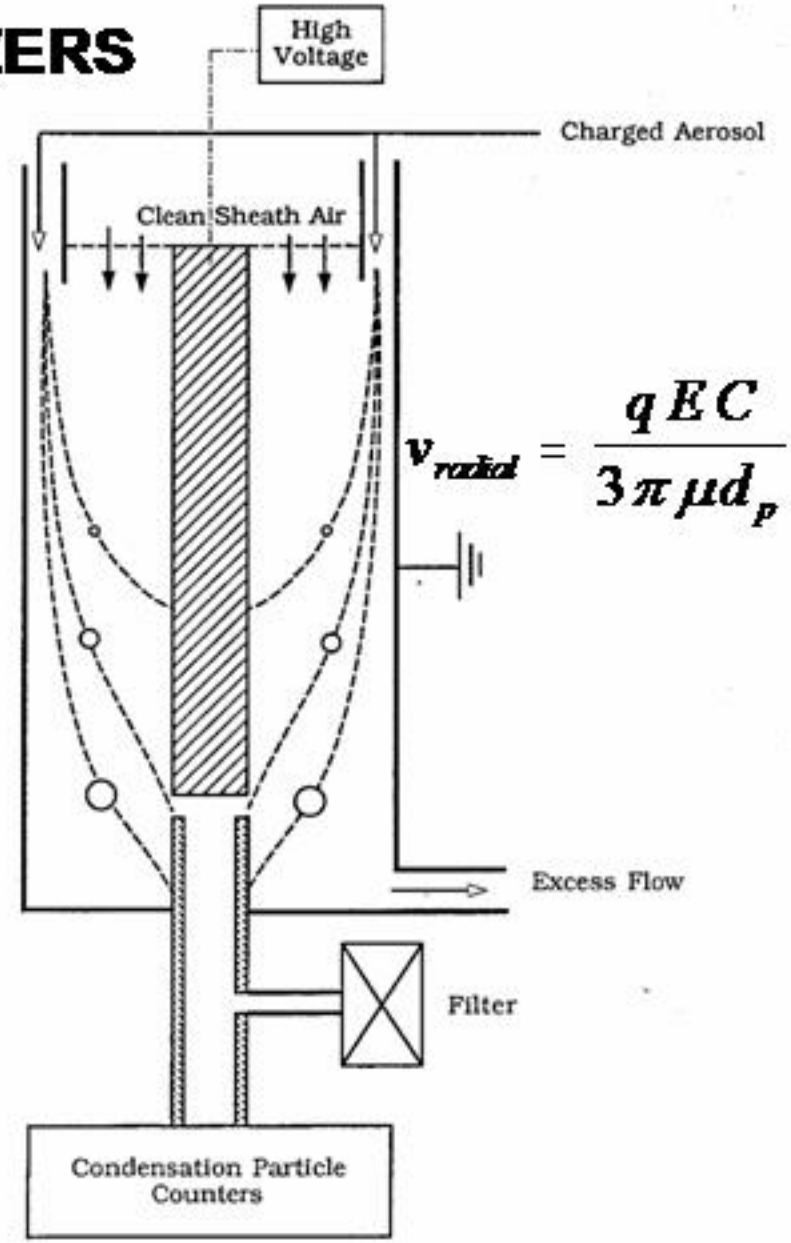
$$F_{electrical} = qE$$

$$D = \frac{kT}{3\pi\mu d_p} \quad ; Diffusion\ Coefficient$$

$$St = \frac{\rho_p C d_p^2 U_0}{18\mu L}$$

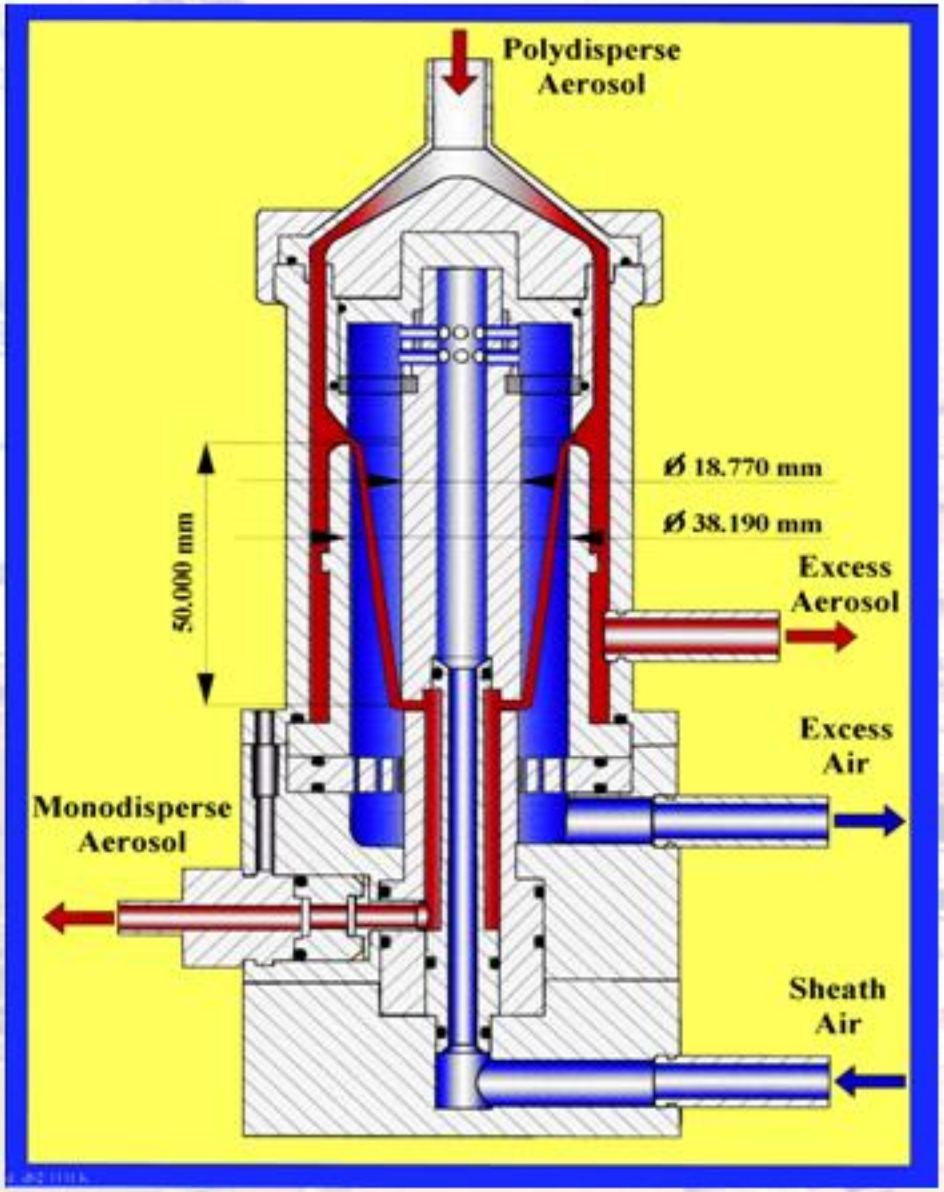
DIFFERENTIAL MOBILITY ANALYZERS

- Differential Mobility Analyzer – known charge on particles that are then classified in an electrical field
- Based on tuned electrical field (applied voltage) – a very narrow size of the particles can be selected
- The monodisperse stream can be used for further studies, or can be sent to a Condensation Particle Counter for counting
- Sequential change in voltage allows mapping the entire size distribution – Instrument called the Scanning Mobility Particle Sizer (SMPS)



$$v_{radial} = \frac{qEC}{3\pi\mu d_p}$$

Overall system layout (SMPS)

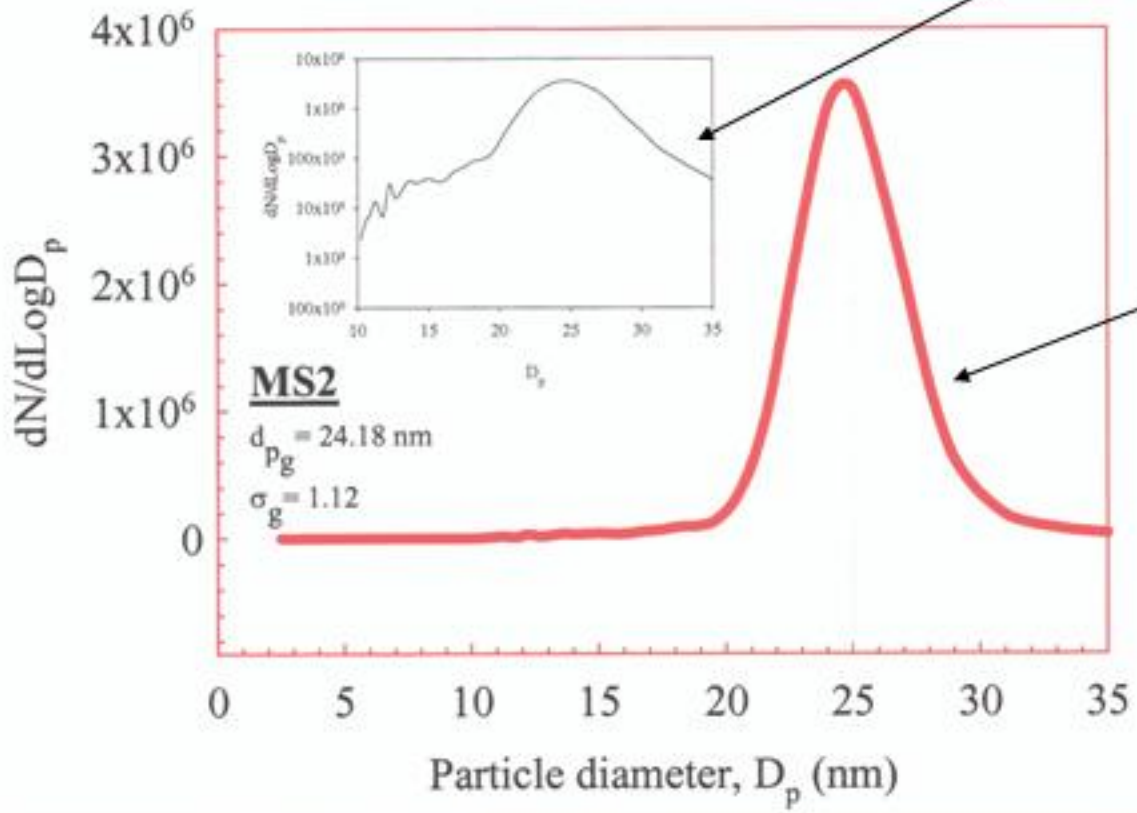


NANO - DMA

- Need to measure and classify real small particles – nanometer sized, such as viruses, protein fragments, etc
- Diffusion losses preclude effective measurement
- Modify DMA to minimize flight time and losses of nanoparticles – the NANO- DMA.

INSTRUMENTATION FOR QUICK DETECTION OF VIRUSES & PROTEIN FRAGMENTS

MS- 2 BACTERIOPHAGE (POLIO VIRUS SURROGATE)



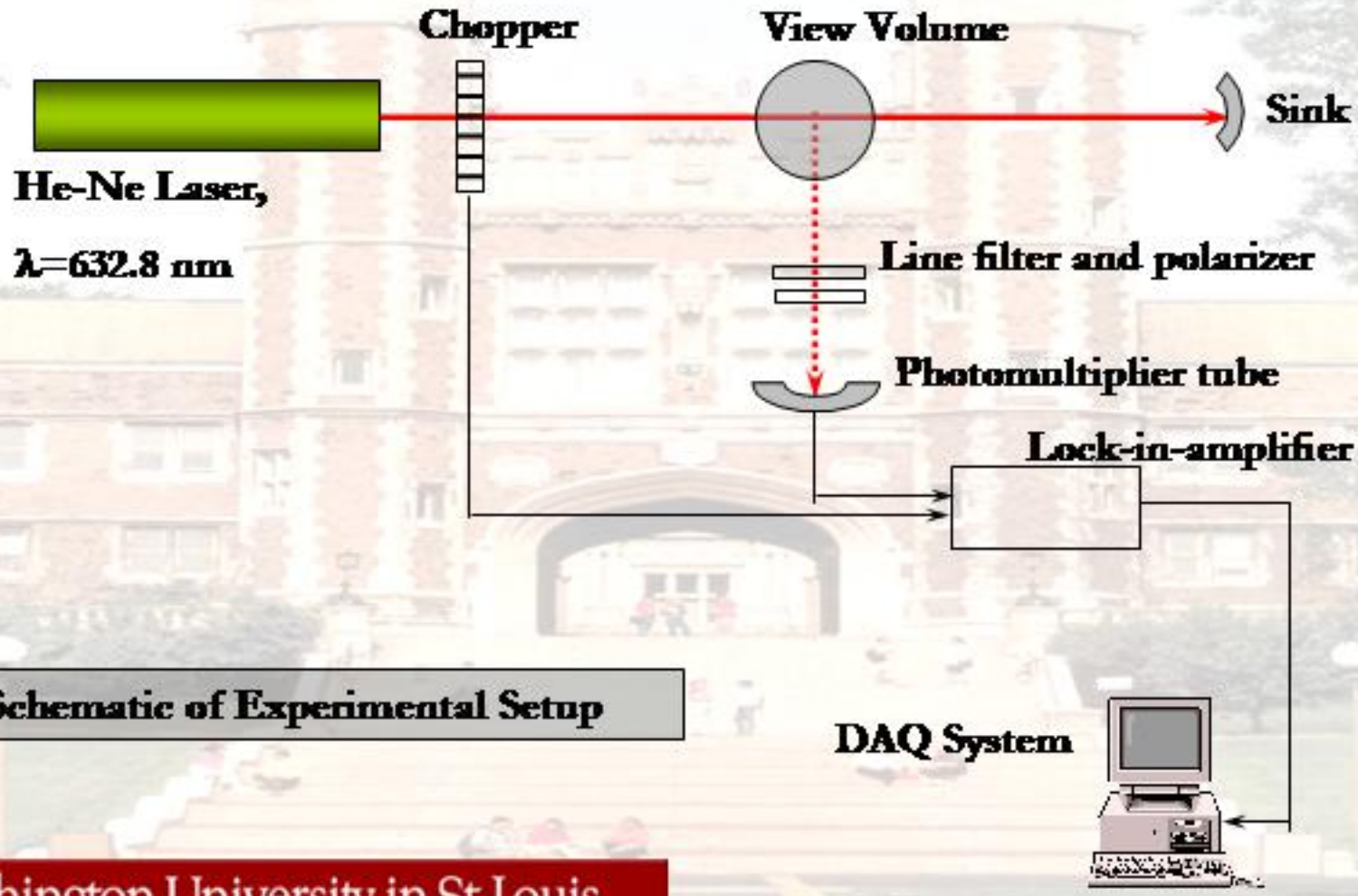
Routinely used atomizers
And DMA

Improved accuracy,
and reduced time,
Using Electrospray
System
(Kulkarni, Chen, Biswas, 2003)

System can also measure
Protein fragments - selectivity

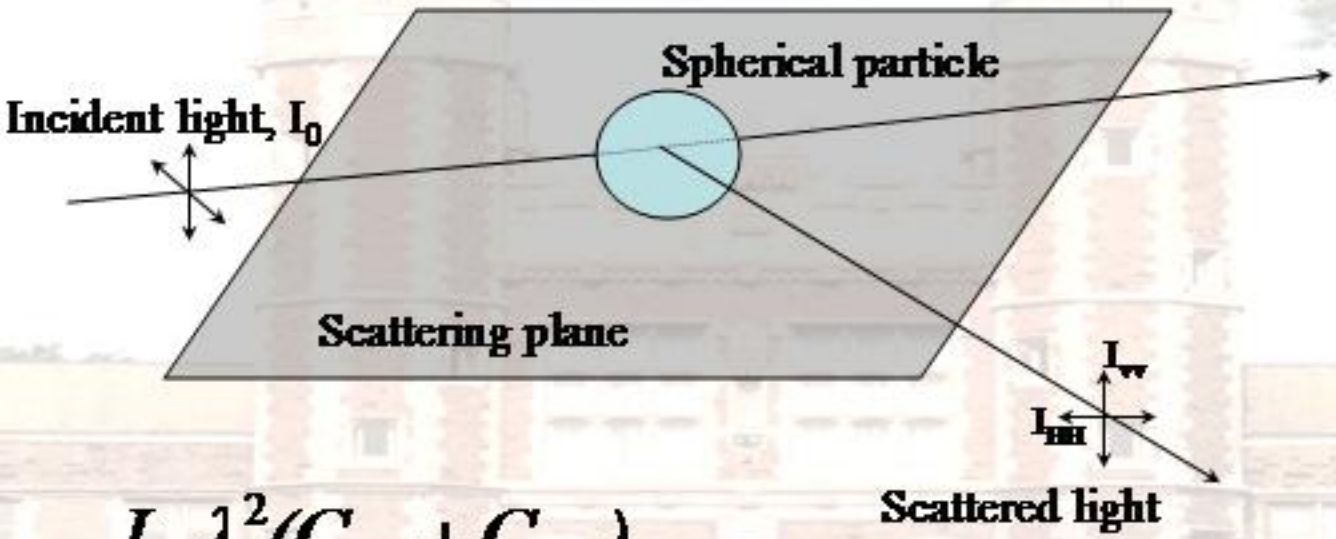
APPLY TO BIOAGENT DETECTION SYSTEMS

OPTICAL MEASUREMENT SYSTEMS



Schematic of Experimental Setup

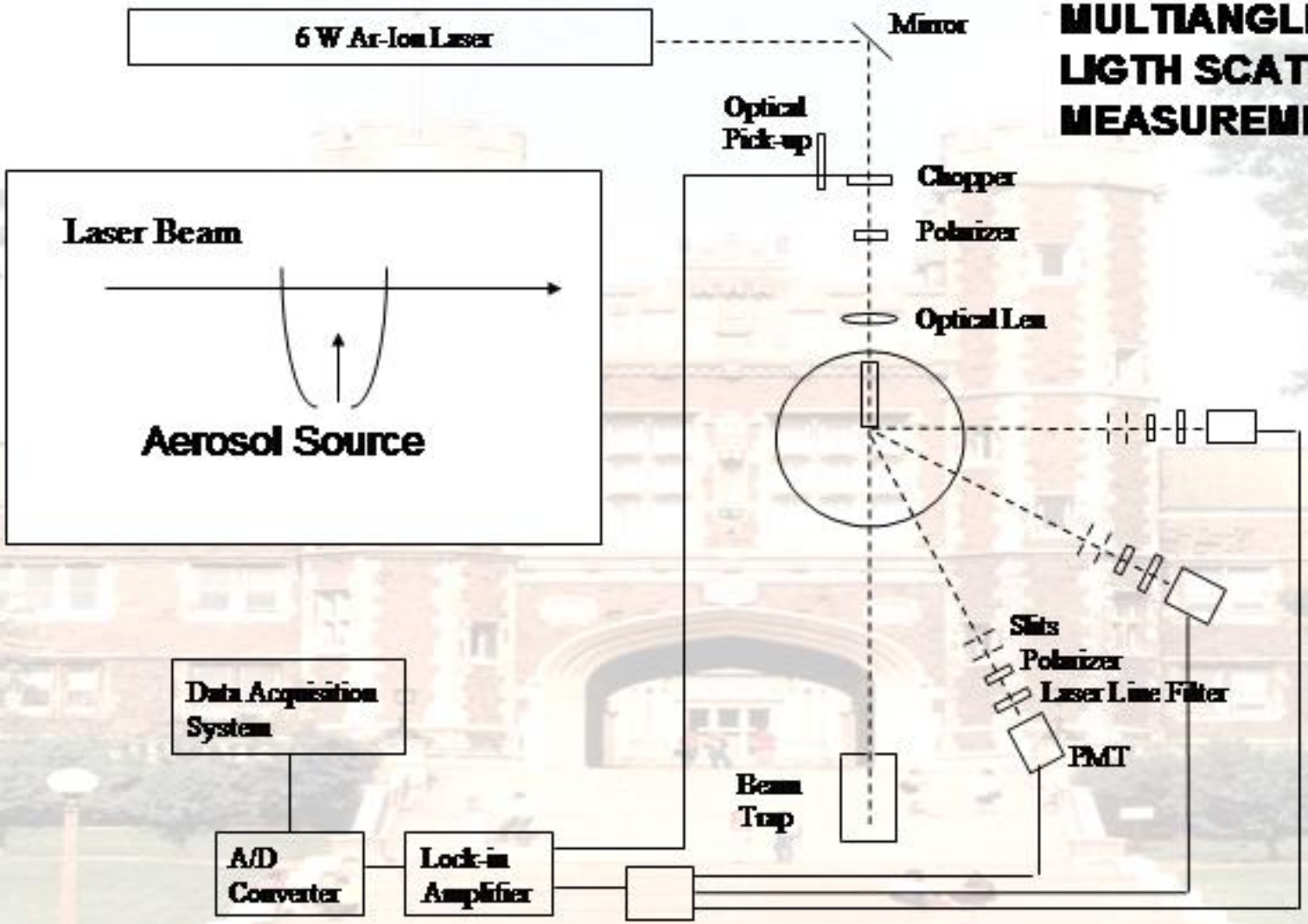
Rayleigh and Mie Scattering Theories

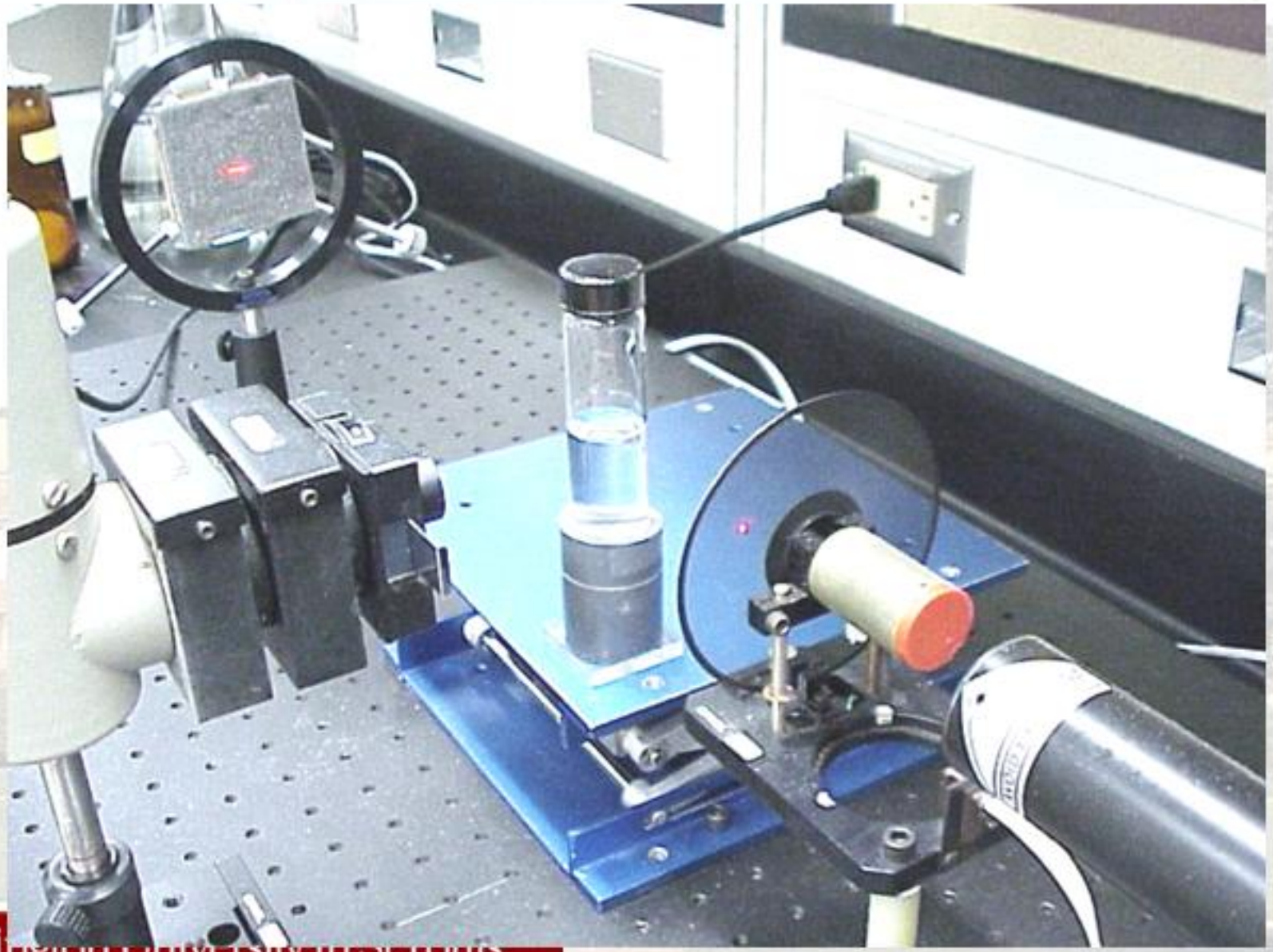


$$I(\theta) = \frac{I_0 \lambda^2 (C_{vv} + C_{hh})}{8\pi^2 R^2}$$

Scattered Intensity is a function of particle size, refractive index, angle of detection

MULTIANGLE LIGTH SCATTERING MEASUREMENTS

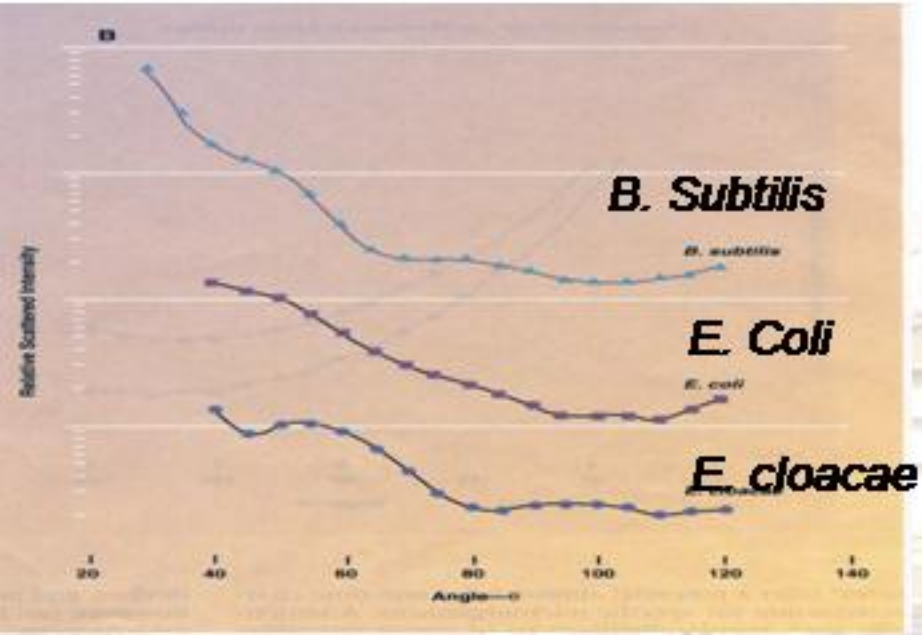




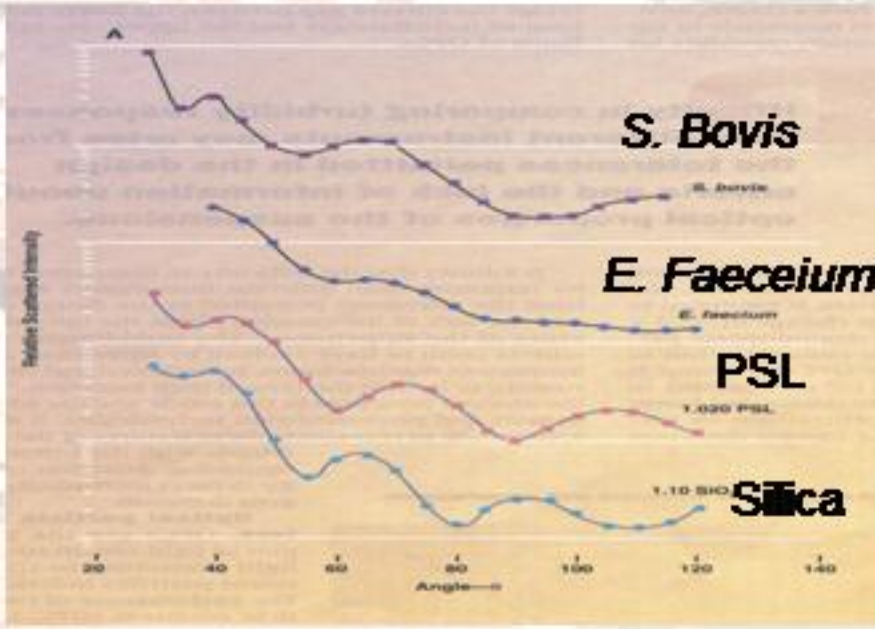
Detection of Micro-Organisms

- There is a renewed interest in quick and robust methods of detection of micro-organisms
- Laser based optical scattering systems offer a potential method of identifying larger bacteria – depending on shape, size and viability, they have unique light scattering patterns as a function of angle
- Can also modify to measure uv-vis absorption, or fluorescent signal to improve selectivity of detection.

ANGULAR DISTRIBUTION OF SCATTERED INTENSITY FOR ROD SHAPED MICRO-ORGANISMS



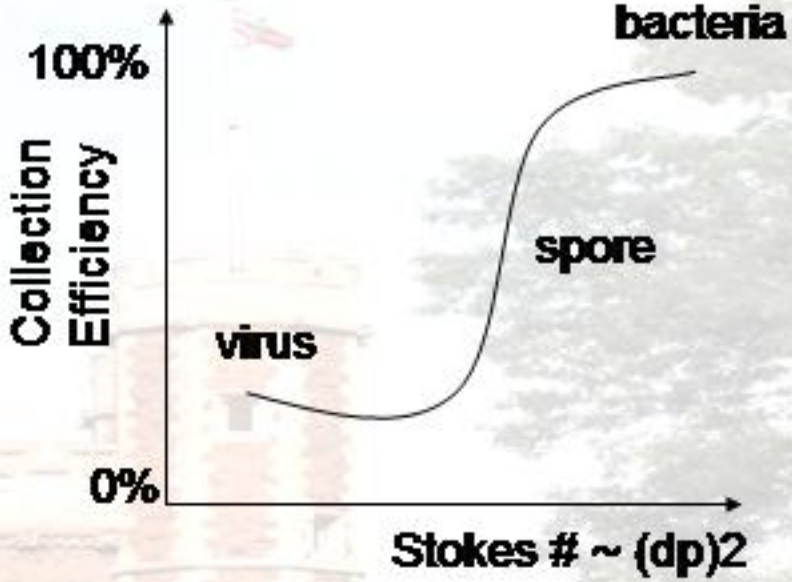
ANGULAR DISTRIBUTION OF SCATTERED INTENSITY – OTHER MICRO-ORGANISMS



DETECTION OF BIOLOGICAL PARTICLES

AGIs – How effective are they?

$$St = \frac{\rho_p C d_p^2 U_0}{18 \mu L}$$

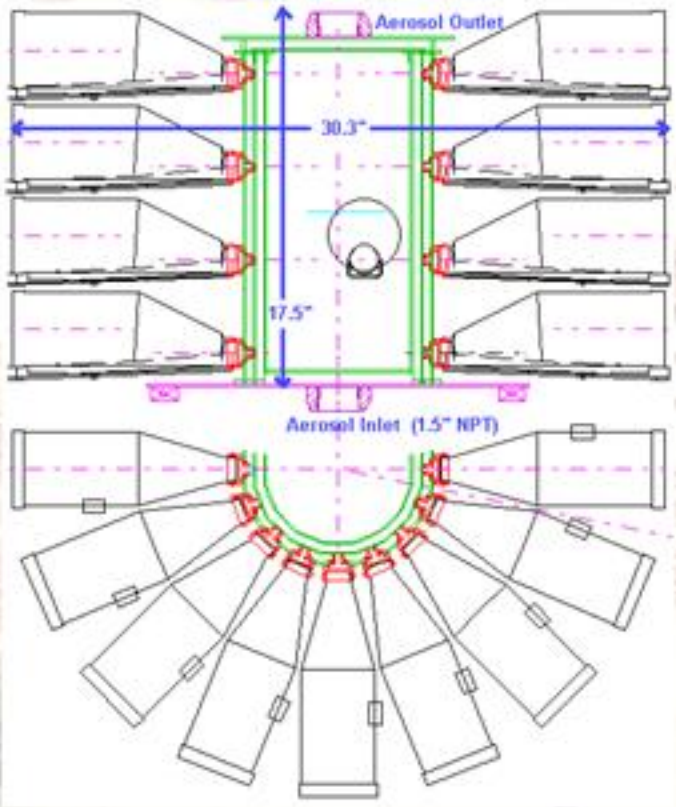


- AGI – Impinger designed for collection based on impaction of bioaerosols onto liquid surface
- Impaction efficiency increases with Stokes Number, St; which is proportional to square of diameter
- Bacteria which is in 1 to 10 um range Is 100 times larger than viruses. Hence St is 10,000 times smaller. Collection Efficiency is not going to be 100%
- Increasing velocity may help – but may alter viability of organism during collection
- Need to design more effective collection systems for viruses and fragments

Summary of Aerosol Measurement Devices

- Total particle counts – best instrument is the Condensation Particle Counter (CPC)
- Particles less than 100 nm – use the NanoDMA – CPC system
- Particles between 100 and 1000 nm – use the DMA (SMPS system)
- Particles greater than 1000 nm (1 um) – use Optical Particle Counters (OPC) or Aerodynamic Particle Sizers
- Characterize systems such as AGI's for the system in which they are to be used

Exposure chambers



- Is measuring the viable organisms by AGI's at the outlet good enough to calculate dose??
- Due to complex flow patterns there is a spatial variation of aerosol concentration, and hence may have localized regions – especially near animal intake ports
- Have the tools to characterize this – both experimentally and theoretically!

Flow modeling, distribution in chamber

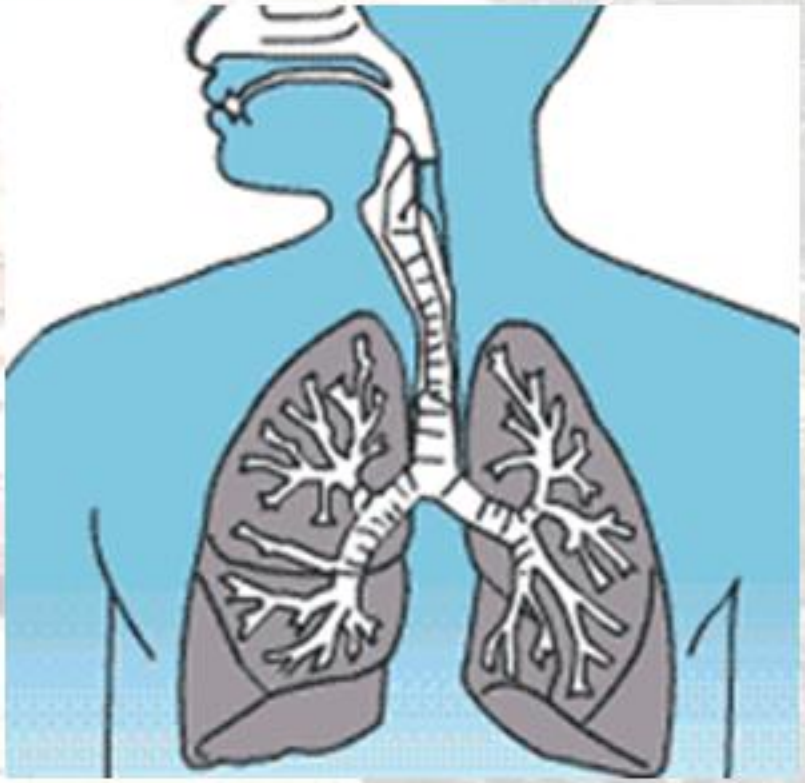
- Governing equation for particle transport

$$\frac{\partial n}{\partial t} = \underbrace{D\nabla^2 n}_{\text{Diffusion}} - \underbrace{\vec{u} \bullet \nabla n}_{\text{Convection}} + \underbrace{\frac{D}{kT}\nabla \bullet (\vec{F}_{EXT} n)}_{\text{External Forces}}$$

- Need flow field – can solve Navier Stokes equations, or use CFD codes
- Use velocity field, u, to solve particle size distribution, n, variation as a function of space and time
- Particle spatial distribution will be a function of size, geometry of chamber

Respiratory deposition

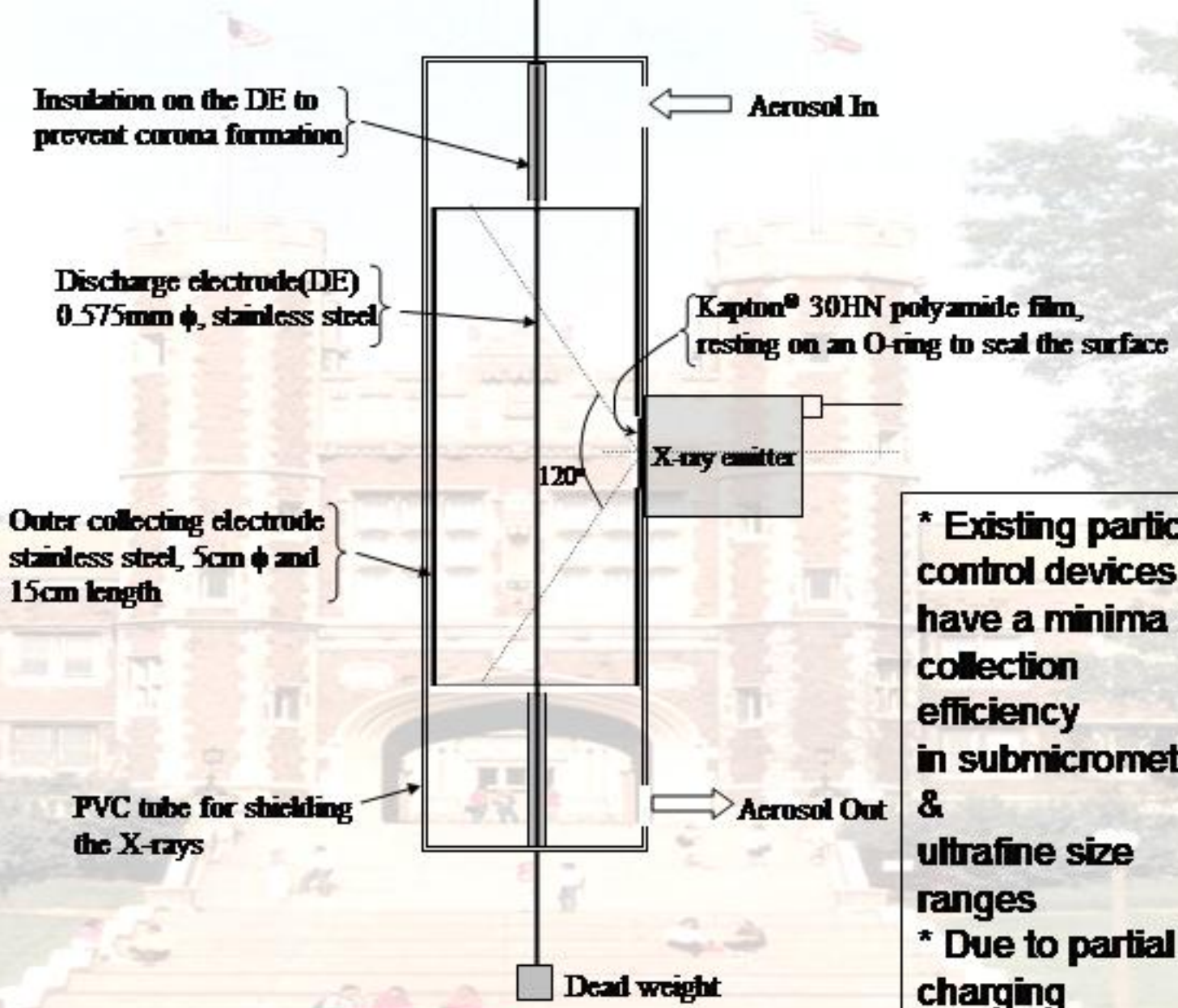
- Using spatial and time variation of size distribution function in respiratory chamber, can calculate size dependent deposition in respiratory system
- Importance of particle morphology (aggregates) and charge distribution very critical for accurate estimation
- http://www.aerosols.wustl.edu/aaqrl/courses/cycopcresp/



BIOAGENT INACTIVATION STUDIES: DEVELOPMENTAL PROJECT

- Capture and inactivation of bioagents, such as viruses and bacteria, from air streams important in many applications
  - Applications in aircraft cabin air filtration, indoor building ventilation systems, chem-bio agent inactivation (counter measures to bioterrorism)
- Several agents of interest – SARS virus, Small pox virus, spores, anthrax
- Several technologies in various stages of development (Alving, 2002). Most are based on filtration systems which are plagued with high pressure drops, maintenance and operational problems

NOVEL CORONA-SOFT XRAY SYSTEM FOR HIGH EFFICIENCY PARTICLE CAPTURE



* Existing particle control devices have a minima in collection efficiency in submicrometer & ultrafine size ranges
* Due to partial charging

US Patent Pending, 2002

- High voltage generates a corona, that produces an ion rich environment. Due to irradiation from Soft x-ray unit, there is a cascading effect that results in much higher ion concentrations
- Difficult to charge particles (ultrafine sizes) - are readily charged, and trapped in electrical field
- Due to high ion concentrations, and oxidizing environment, organic species are readily converted to carbon dioxide.
- Can further promote this with an nanostructured catalyst coating
- Very compact unit
- Can be readily mounted on existing duct work
- More than "4 to 5 logs" removal demonstrated for surrogates such as polio virus

Currently funded by the NIH Bio-Defense Project

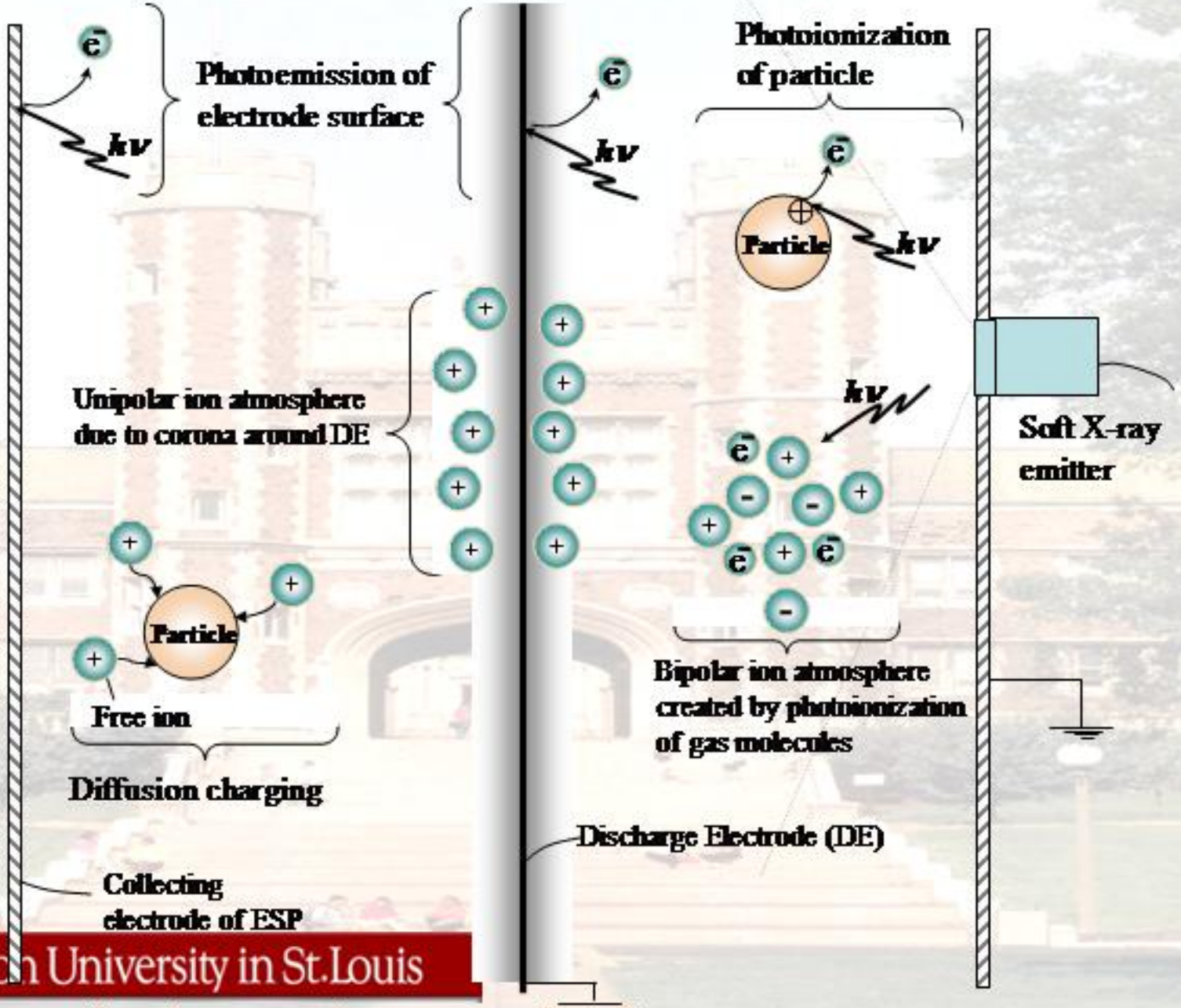
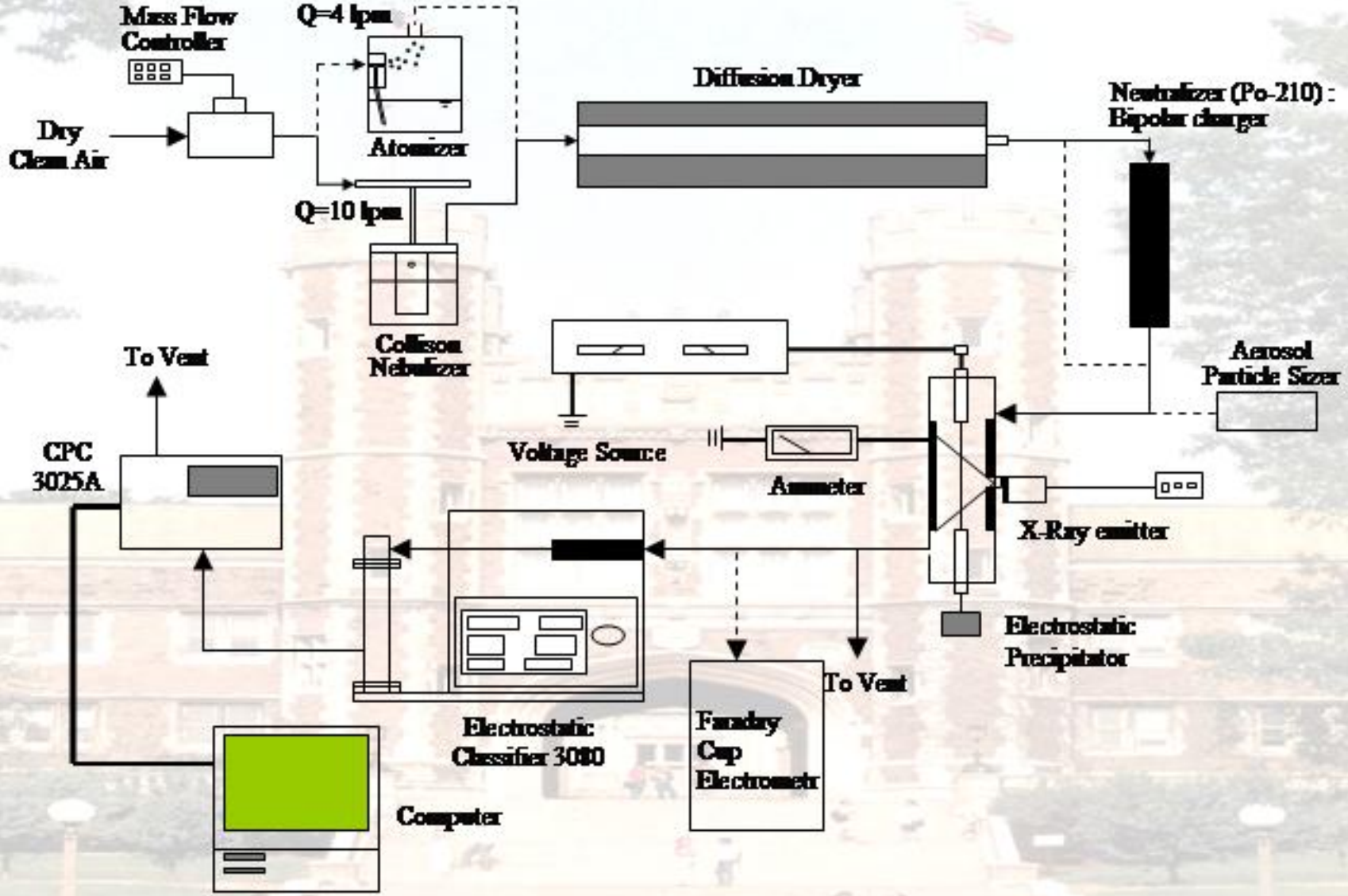
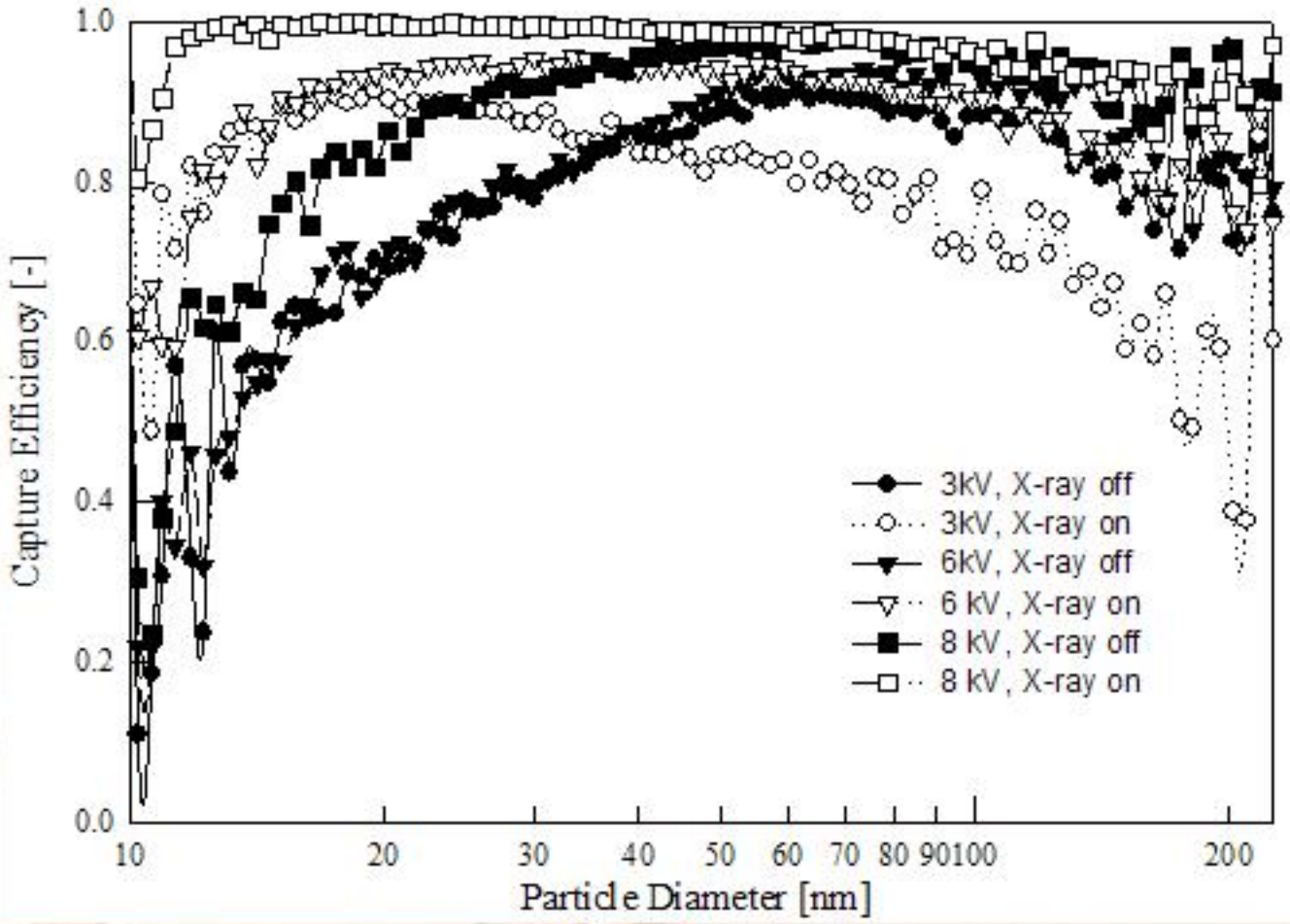

Photoemission of electrode surface
hν
Photoionization of particle
Particle
Unipolar ion atmosphere due to corona around DE
Soft X-ray emitter
Particle
Free ion
Diffusion charging
Bipolar ion atmosphere created by photoionization of gas molecules
Discharge Electrode (DE)
Collecting electrode of ESP

Figure 2



EXPERIMENTAL SYSTEM FOR AEROSOLIZING VIRUSES FOR CAPTURE TESTS IN CORONA-SOFT X_RAY UNIT

Capture efficiency at different particle diameters from 10 –225nm without neutralization with a Po-210 bipolar charger(Q=10lpm).



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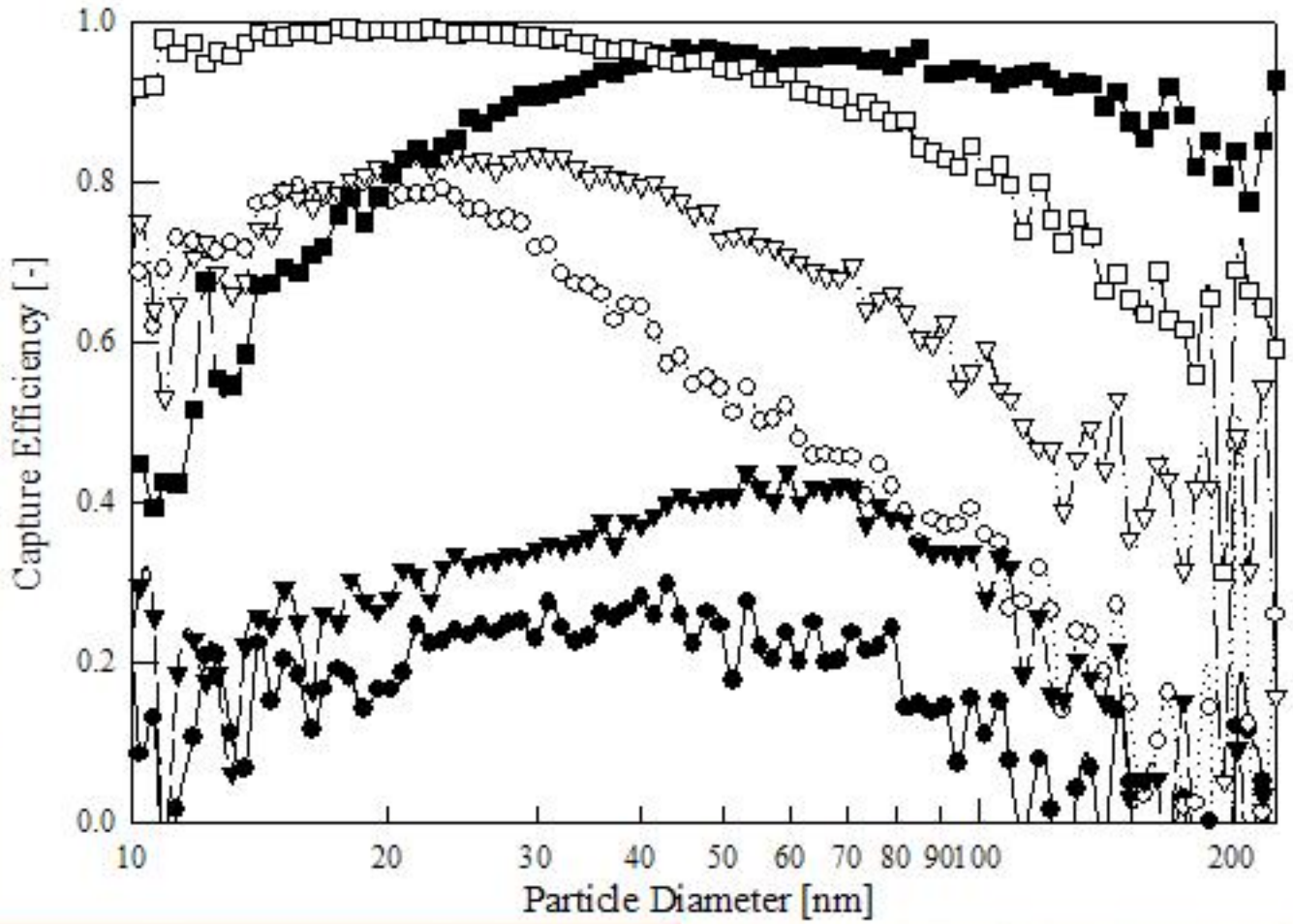
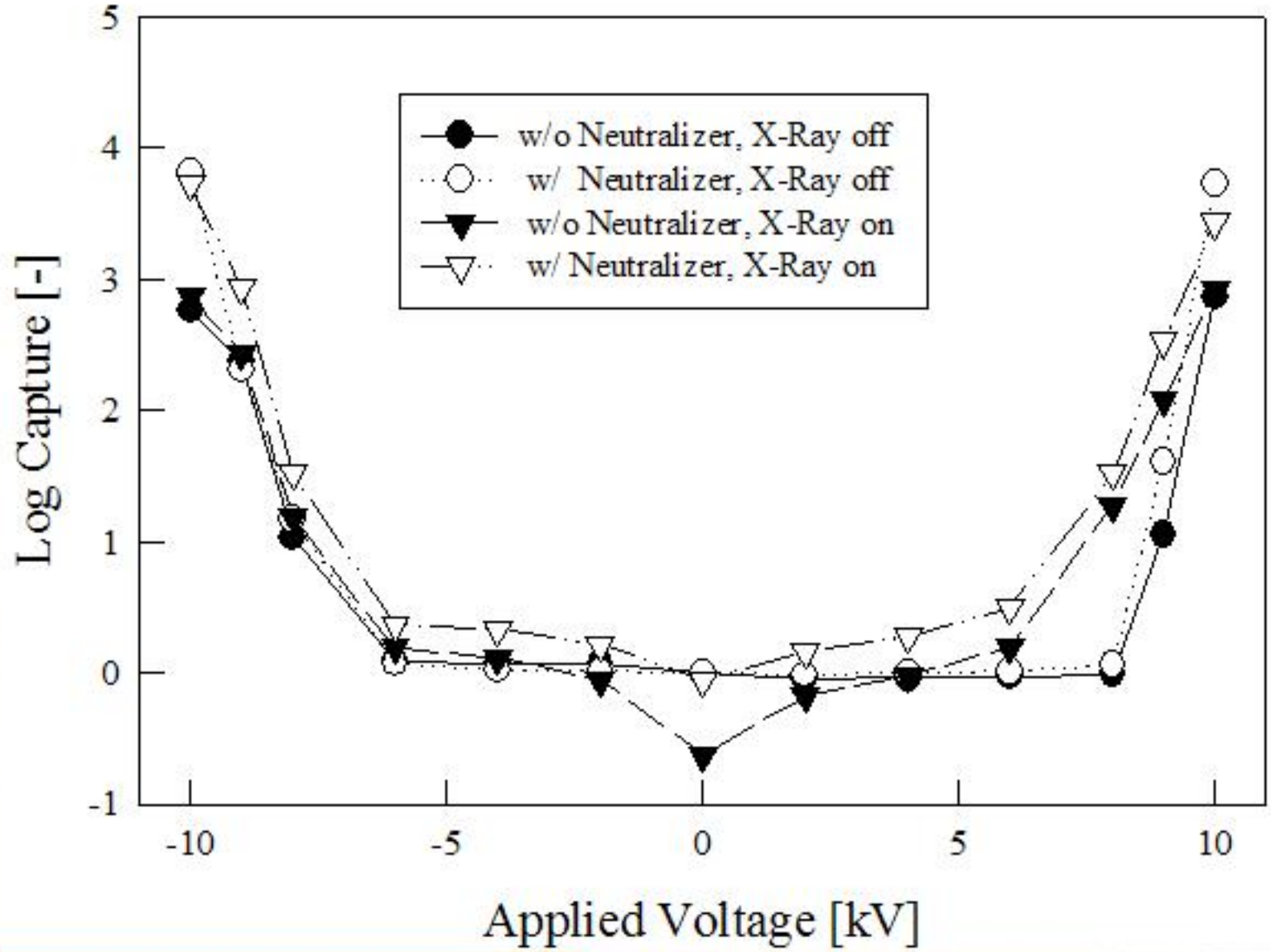


LOG CAPTURE OF VIRAL PARTICLES AS A FUNCTION OF APPLIED VOLTAGE



Aerosol aspects of aerobiology quite complex; but aerosol science and engineering is sufficiently advanced to address and resolve these issues.
Collaboration with main stream aerosol scientists strongly recommended

- Thank you for your attention
- Questions?

Aerosol and Air Quality Research Laboratory
Washington University in St. Louis

www.aerosols.wustl.edu/aaqrl

Particle Formation and Capture

SYNTHESIS & PROCESSING

- Aerosol Flame Reactors
- Aerosol Furnace Reactors
- Pristine and Doped TiO_2
- Nanostructured Coatings
- Magnetic Oxides

CONTROL & CAPTURE

- Soft X-Ray/Unipolar Coronas for Particle Charging & Capture
- Capture in Magnetic Fields
- Photocatalysis using TiO_2 – inactivation of bioaerosols and organic species
- Oxygen Enriched Coal Combustion/Hg Capture

Ambient Aerosols and Air Quality

- Diesel Engine Exhausts & Children's Health
- Morphology of Ambient PM
- Health Effects of Nanoparticles

Colloids/Bio-colloids

- Detection of Micro-organisms
- Electrostatic Filtration
- Inactivation of bio-agents

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AERODYNAMIC PARTICLE SIZER

- Particles are accelerated in a flow field
- Velocity is a function of the Stokes Number
- Use two laser system to time movement along a fixed distance, and then back calculate particle size
- Detection method good for large particles, as Stokes number goes as particle size^2. Can measure > 1 micrometer very effectively