DEVELOPMENT OF MULTIPLE-PARTICLE POSITRON EMISSION PARTICLE TRACKING FLOW MEASUREMENT

Dr. Cody Wiggins
Virginia Commonwealth University, USA; University of Tennessee, USA

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Meet the Presenter

Dr. Cody Wiggins is currently employed as a postdoctoral research associate at Virginia Commonwealth University (VCU) in the Department of Mechanical and Nuclear Engineering.

He earned his B.S. from the University of Tennessee, Knoxville (UTK) in Nuclear Engineering in 2014 and his Ph.D. from UTK in Physics in 2019.

Dr Wiggins's research has focused on experimental fluid dynamics, including pure and applied research components. His primary interest has been in the development and deployment of positron emission particle tracking (PEPT) – a radiotracer-based method for flow measurements in opaque systems. He is now studying thermal hydraulics for advanced energy applications, while maintaining a focus on the advancement of PEPT.

Dr. Wiggins was the winner of the American Nuclear Society's «Pitch your PhD» competition 2019

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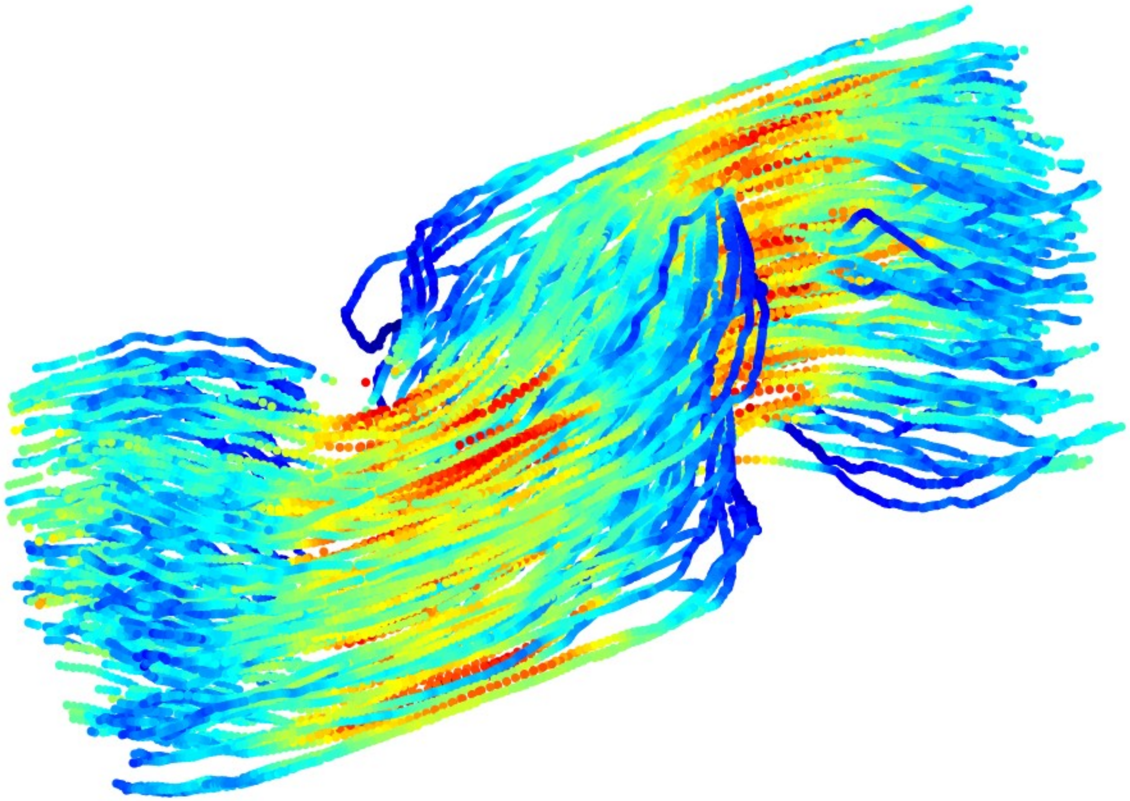
DEVELOPMENT OF MULTIPLE-PARTICLE POSITRON EMISSION PARTICLE TRACKING FOR FLOW MEASUREMENT



Cody Wiggins

Virginia Commonwealth University, USA
University of Tennessee, USA

OVERVIEW

- Motivation
- Positron Emission Particle Tracking
  - What is PEPT?
  - Historical PEPT methods
- Multiple-Particle PEPT
  - Novel Reconstruction Methods
- PEPT Experiments
  - Experimental Methods
  - Measurement Highlights
- PEPT Future

GEN IV International Forum[SM]

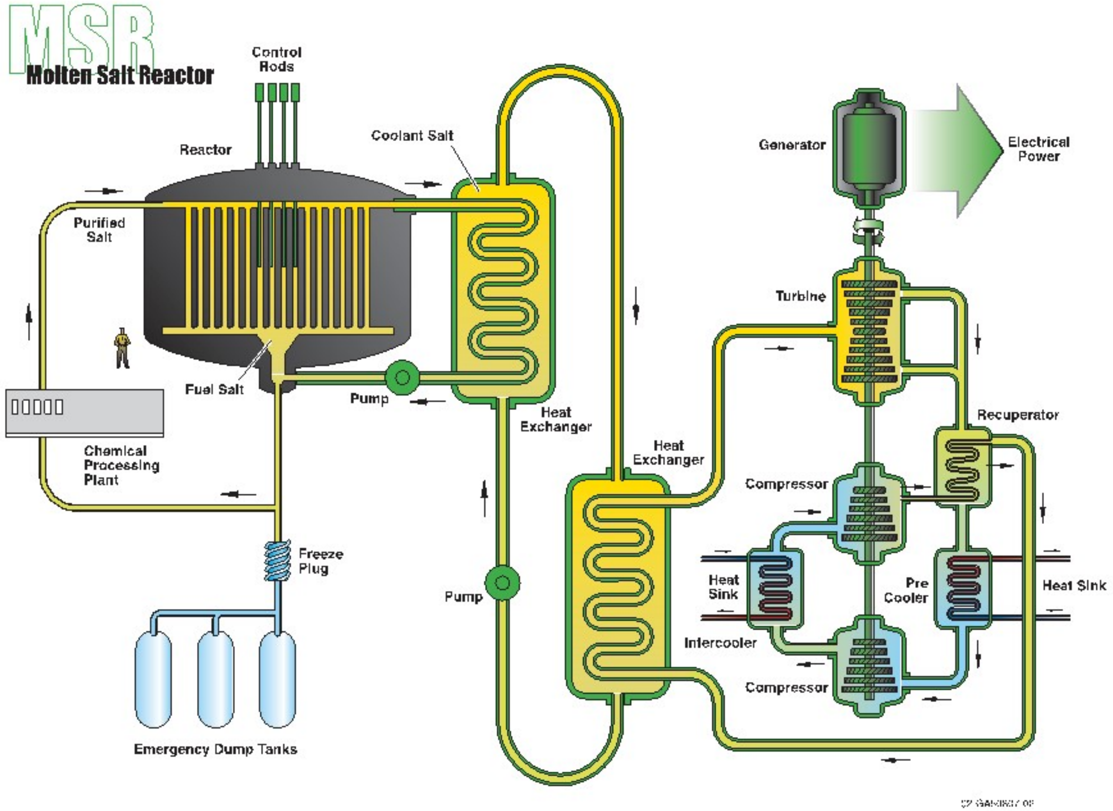
VIRGINIA COMMONWEALTH UNIVERSITY

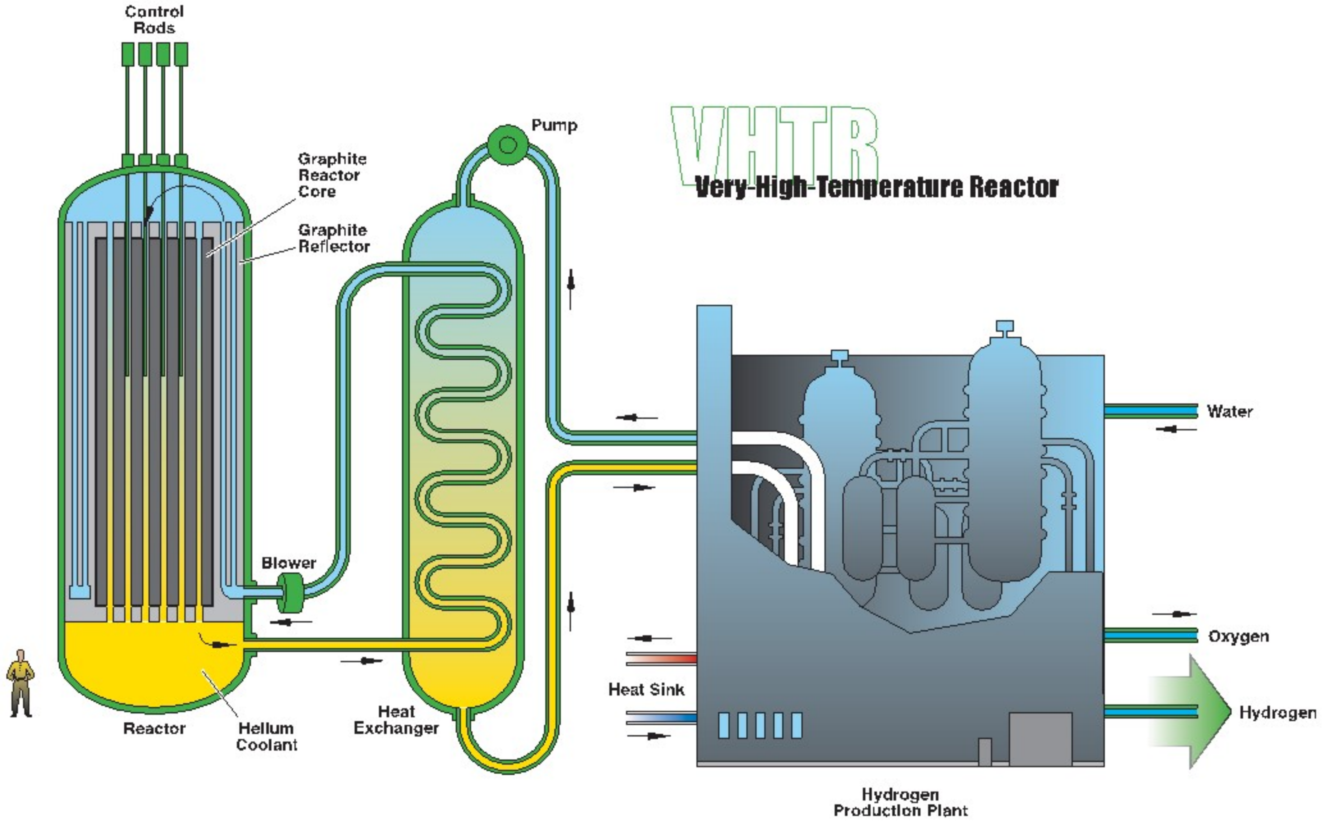
IUP Integrated University Program
U.S. Department of Energy

NNSA National Nuclear Security Administration

Challenge: Flows in Opaque Systems

- Flows in opaque systems are ubiquitous in reactor designs

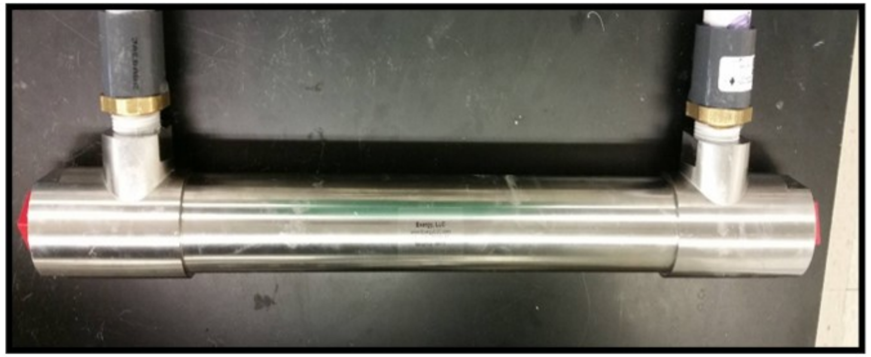


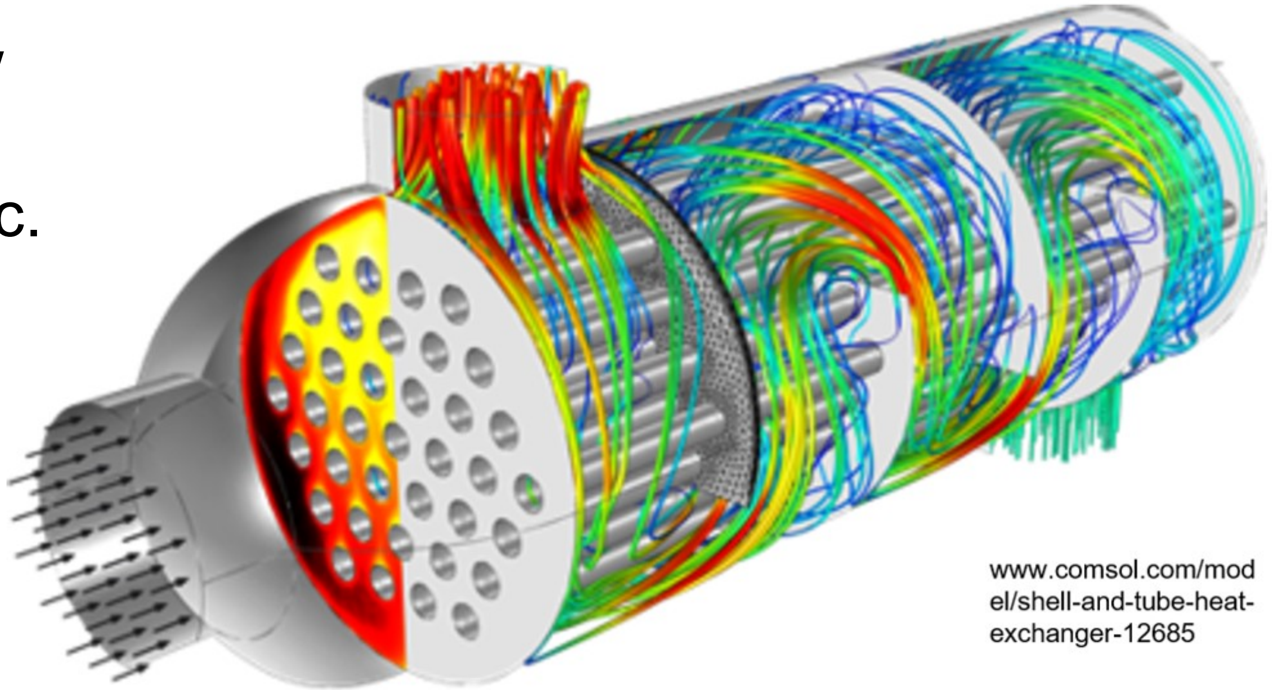


GIF *Technology Roadmap*, 2002.

Challenge: Flows in Opaque Systems

- Warrants use of CFD
  - Requires experimental data for validation
- Experimental options
  - Surrogate fluids, materials to allow optical access
  - Alternative methods: UVP, MRI, etc.





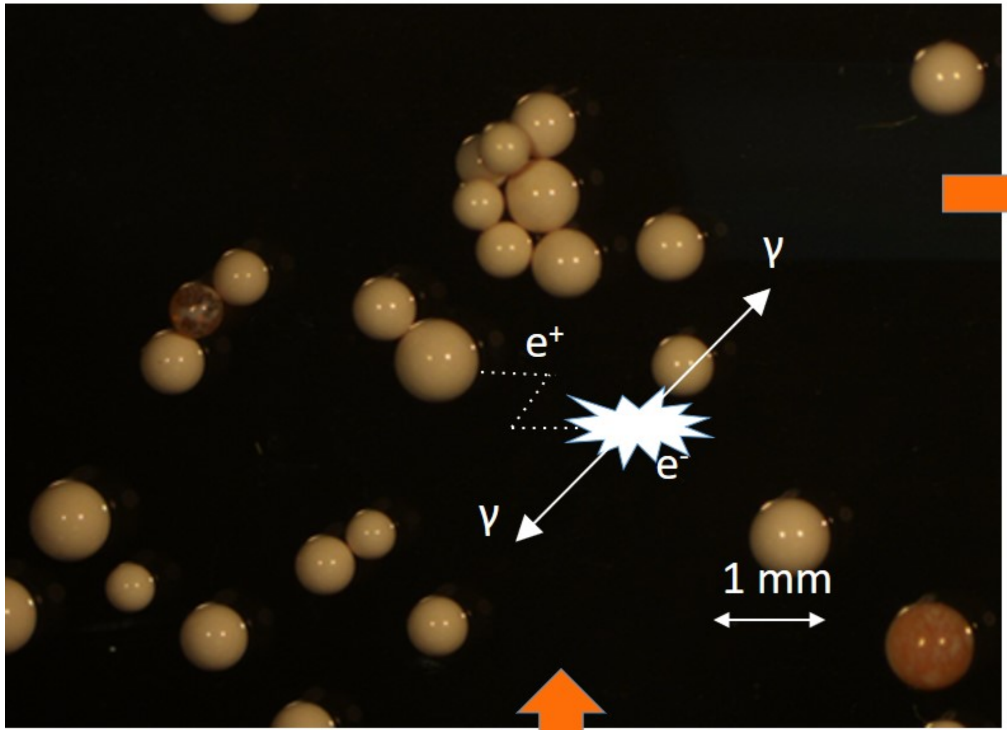
www.comsol.com/model/shell-and-tube-heat-exchanger-12685

Positron Emission Particle Tracking

- Particle tracking based on the detection of coincident gamma rays from radiolabelled tracer particles[1]
- PEPT allows generation of time-resolved, Lagrangian 3D fluid flow data inside of complex geometries.
- Detection of 511 keV gammas allows for imaging in opaque systems[2,3].
- Current technology[4] allows spatial resolution ~0.1 mm and temporal resolution of ~1 ms.

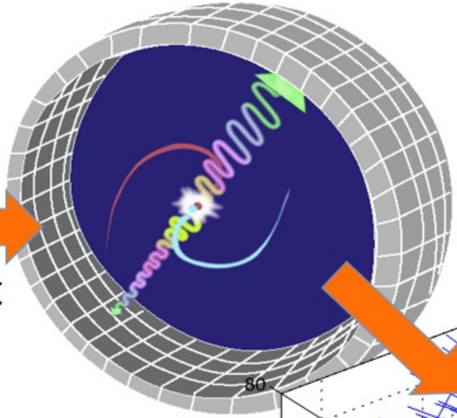
1. Parker, D., et al., 1993, *NIMA*, **326**, 592.
2. Perez-Mohedano, R., et al., 2015, *Chem Engr J,* **259**, 724.
3. Parker, D., et al., 2008, *Meas Sci Tech*, **094004**.
4. Chang, YF. and Hoffman, AC., 2015, *Exp. Fl.* ***56****:4*.

How PEPT Works

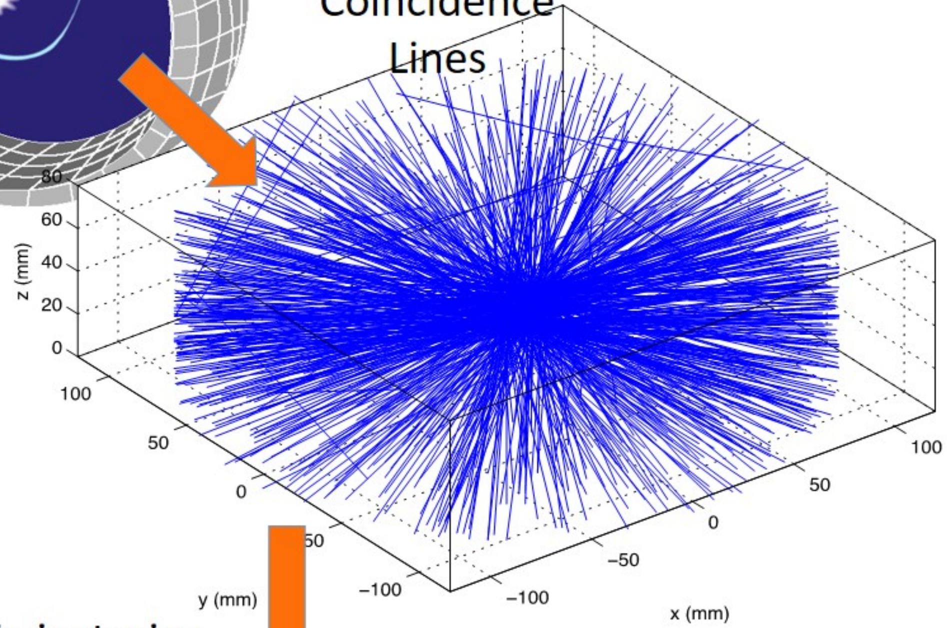


Activate

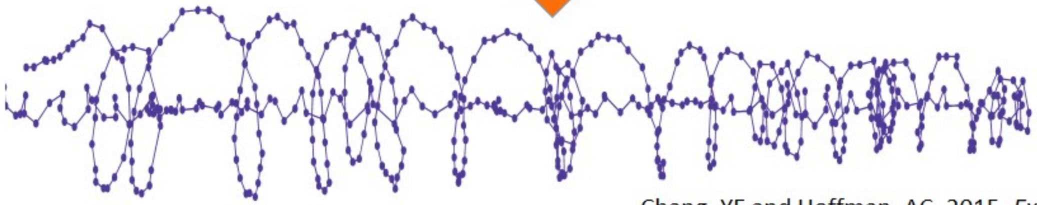
Detect



Coincidence Lines



Trajectories

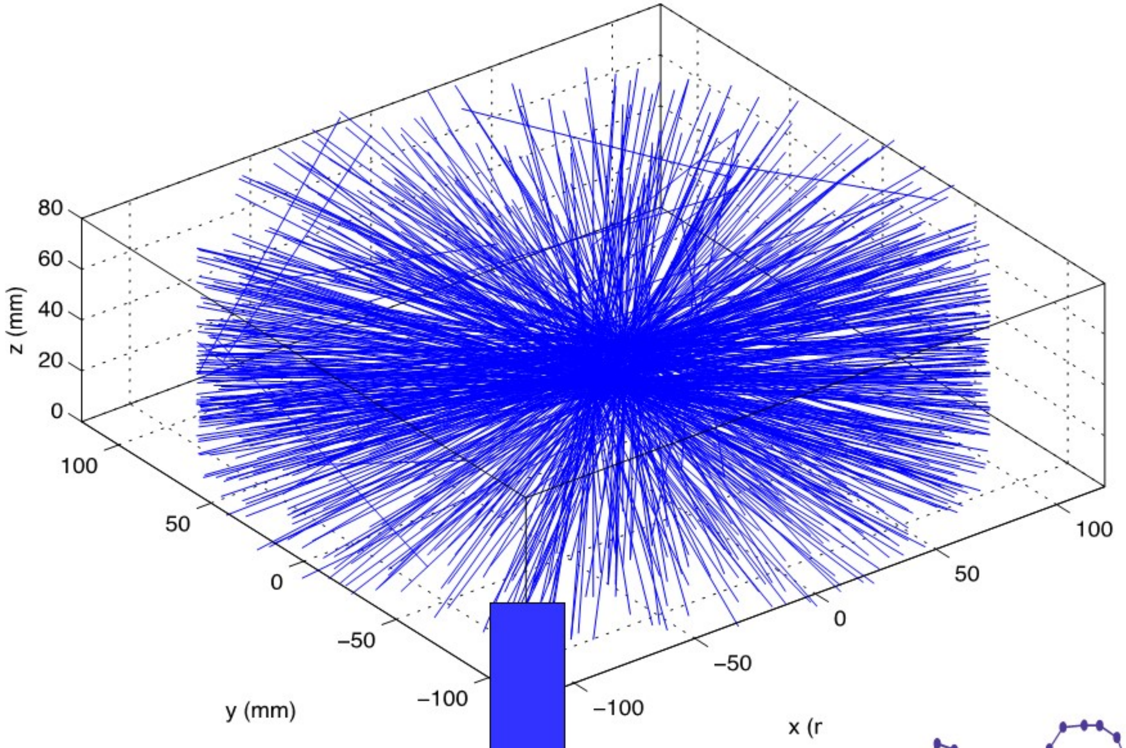


Isotope	$T_{1/2}$	E_{mean} (keV)	E_{max} (keV)	R_{mean} (mm)	R_{max} (mm)
^{18}F	109.8 min.	252	635	0.66	2.6
^{11}C	20.3 min.	390	970	1.1	4.5
^{22}Na	2.6 yr.	220	674	0.53	2.3
^{64}Cu	12.7 h.	278	653	0.56	2.9
^{68}Ga	68 min.	844	1899	3.6	10.3

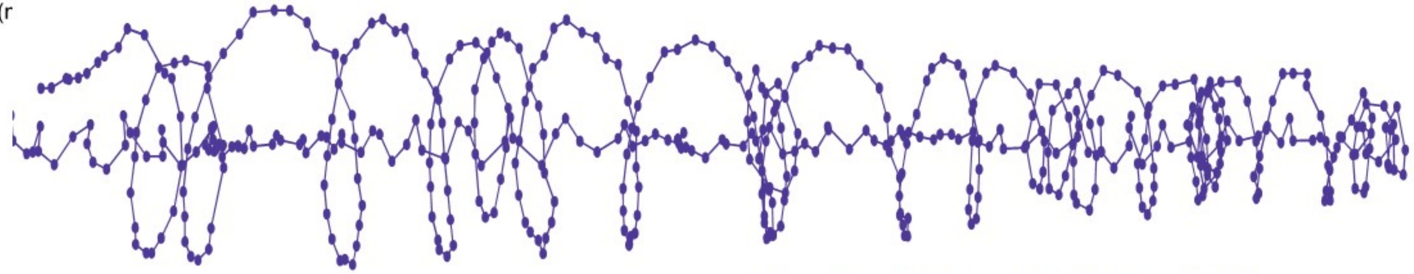
Chang, YF and Hoffman, AC, 2015, *Exp. Fl*, **56**:4.

PEPT Reconstruction

- Raw PEPT data is location of coincident detections, visualized as coincidence lines (CL)
- Must triangulate tracers from time series of CL

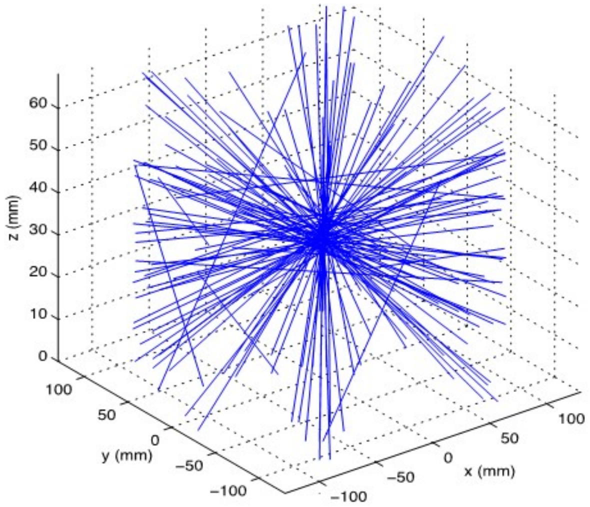


How?



Chang, YF and Hoffman, AC, 2015, *Exp. Fl*, **56:4**.

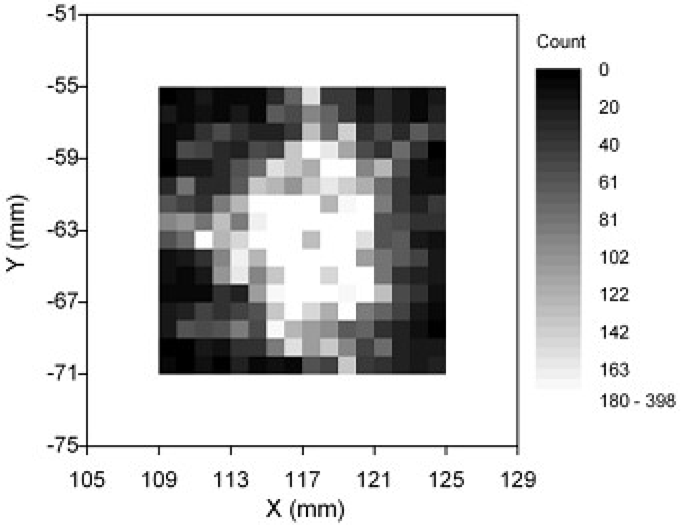
PEPT Reconstruction



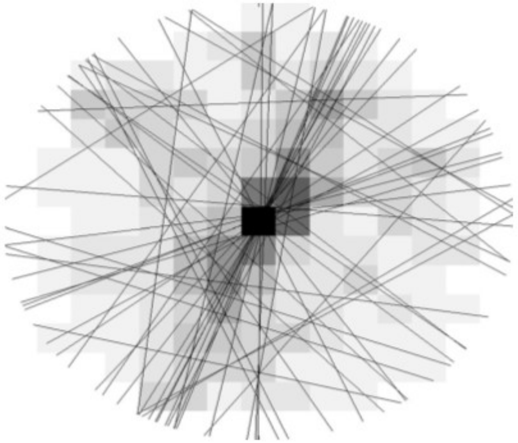
Birmingham Method[1]

- Find point in space that minimizes sum of distances to CLs
- Iterative triangulation rejections noise.

Bergen Method[2]



- “Cutpoints” (points of intersection) examined in 2-D projections.
- Iterative process used to remove cutpoints and find position in plane of interest.
- Out-of-plane component found by examine CLs contributing to final cutpoints.



Cape Town Method[3]

- Count CL crossings across superimposed grid
- Gaussian fit of 2D slices through “voxel” with greatest number to find particle

1. Parker, D., et al., 1993, *NIMA*, **326**, 592.
2. Chang, Y.F., et al., 2012, proc. *IEEE IMT*.
3. Bickell, M., et al., 2012, *NIMA*, **682**, 36

Multiple-particle PEPT (M-PEPT)

- We seek a method for PEPT reconstruction that allows tracking of an arbitrary number of tracers.

Birmingham Method

- Multiple particle tracking for tracers of very different activity (up to 3)[1]

Bergen Method

- Single- particle only[2]

Cape Town Method

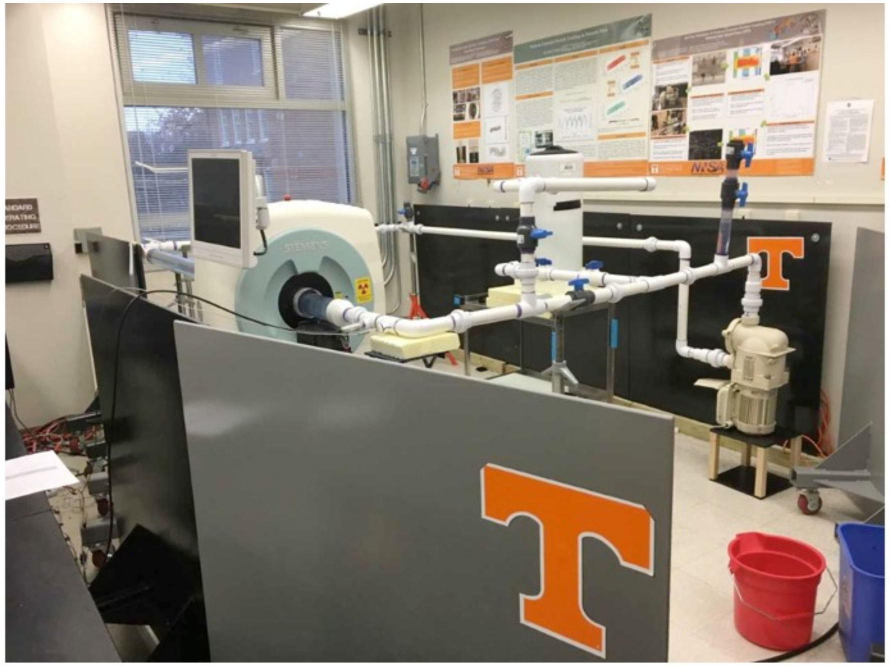
- Multiple-particle tracking for tracers of known initial positions (up to 16)[3]

} Criteria not satisfied

1. Yang, Z., et al., 2006, *NIMA,* **564**, 332.
2. Chang, Y.F., et al., 2012, proc. *IEEE IMT*.
3. Bickell, M., et al., 2012, *NIMA,* **682**, 36

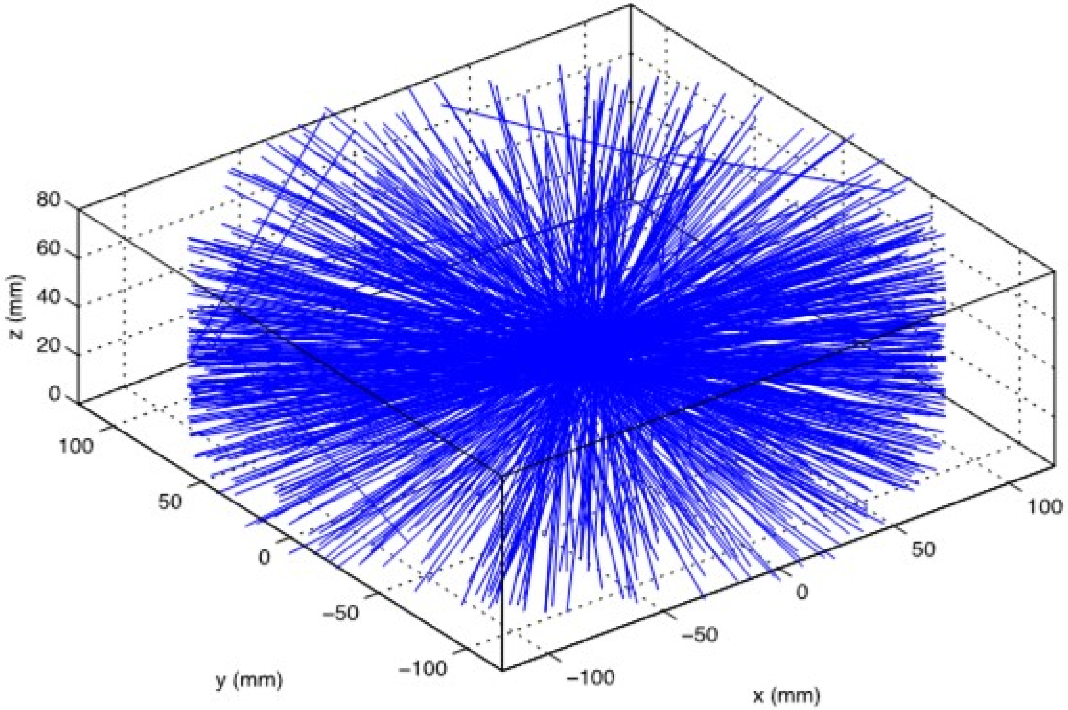
M-PEPT at UTK

- Developing novel PEPT techniques for understanding flow in complex systems



M-PEPT: Feature Point Identification (FPI)[1]

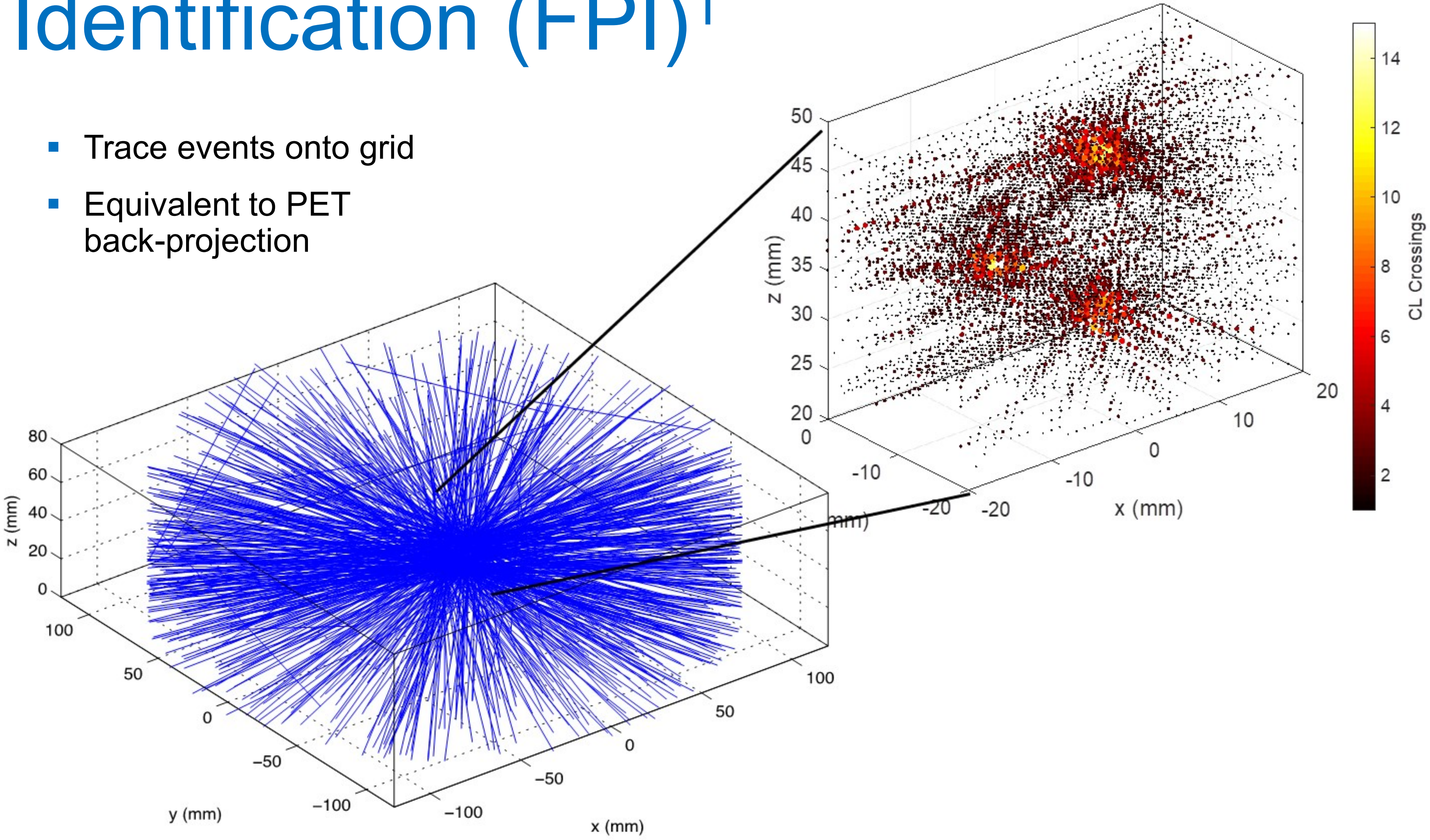
- Consider coincidence lines from an individual time frame
  - Typically ~ 1ms



1. Wiggins, C., et al, 2017, *Nucl. Instr. Meth. Phys. Res. Sec. A*, **843**, 22.

M-PEPT: Feature Point Identification (FPI)[1]

- Trace events onto grid
- Equivalent to PET back-projection



1. Wiggins, C., et al, 2017, *Nucl. Instr. Meth. Phys. Res. Sec. A*, **843**, 22.

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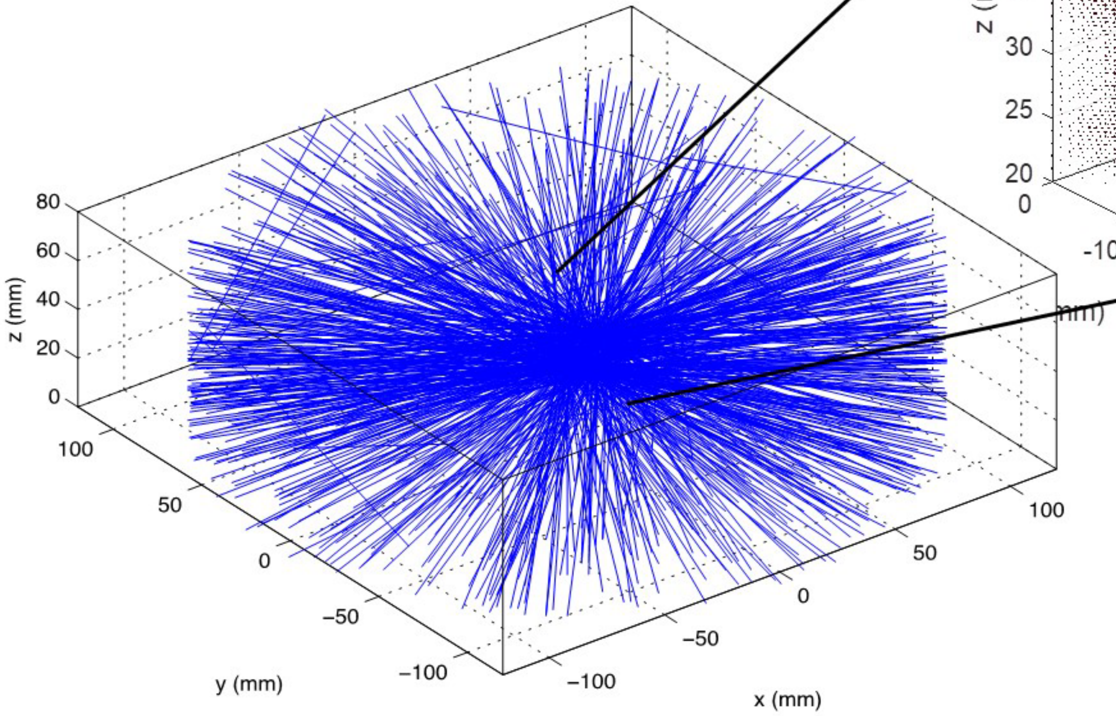
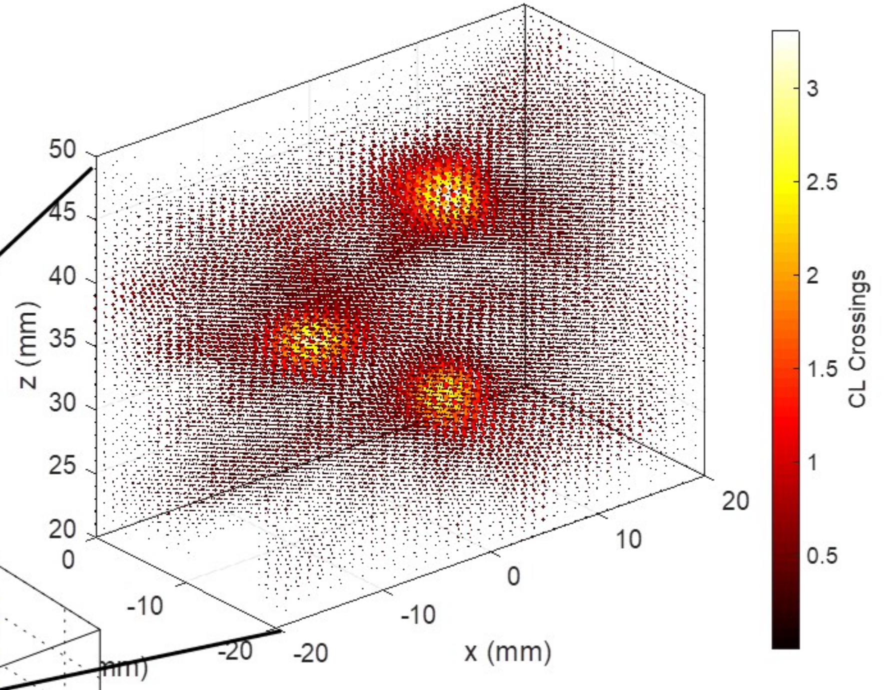
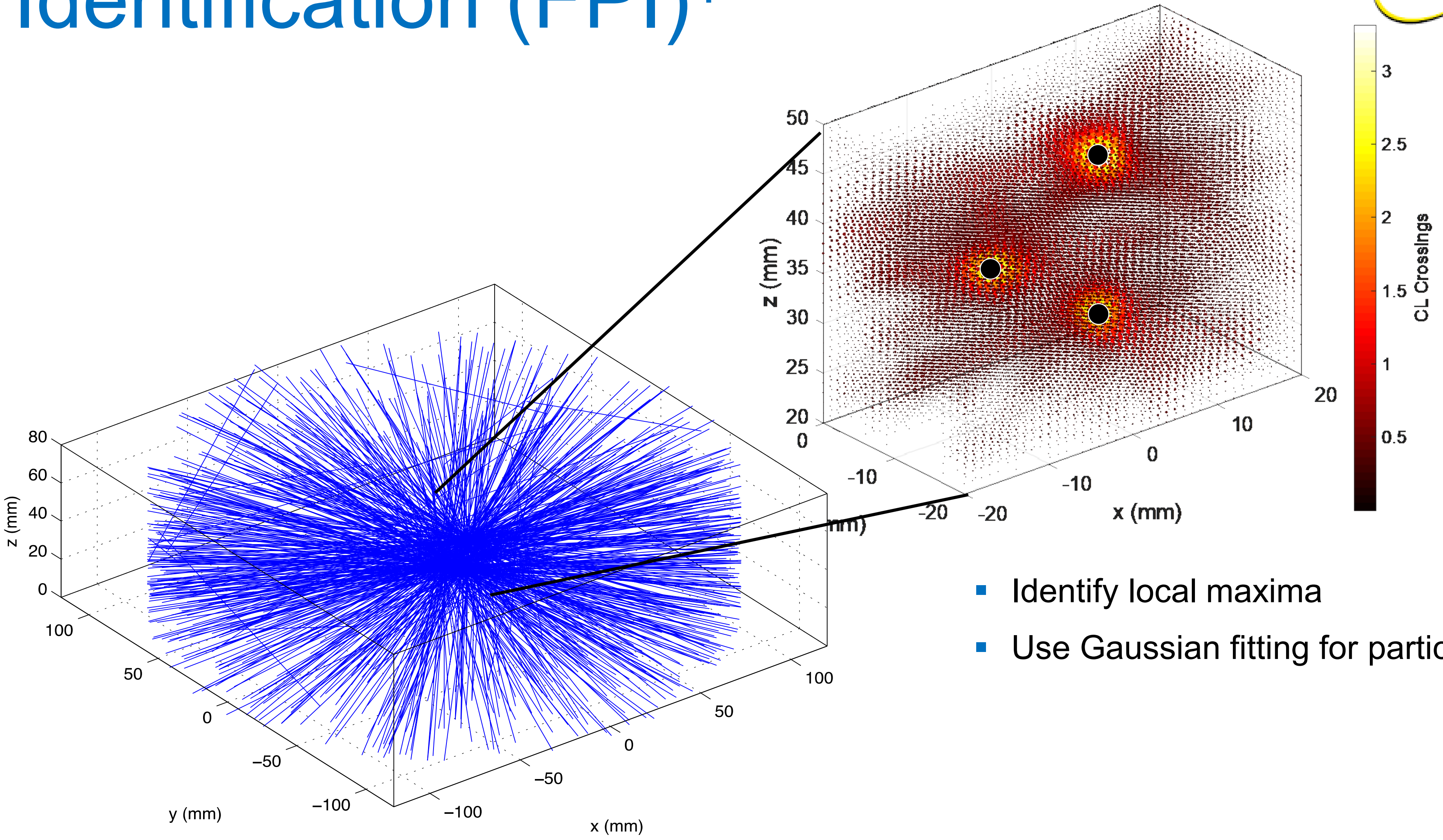




- Filter the “image”
  - Long wavelength background removal
  - Gaussian smoothing kernel

1. Wiggins, C., et al, 2017, *Nucl. Instr. Meth. Phys. Res. Sec. A*, **843**, 22.

M-PEPT: Feature Point Identification (FPI)[1]

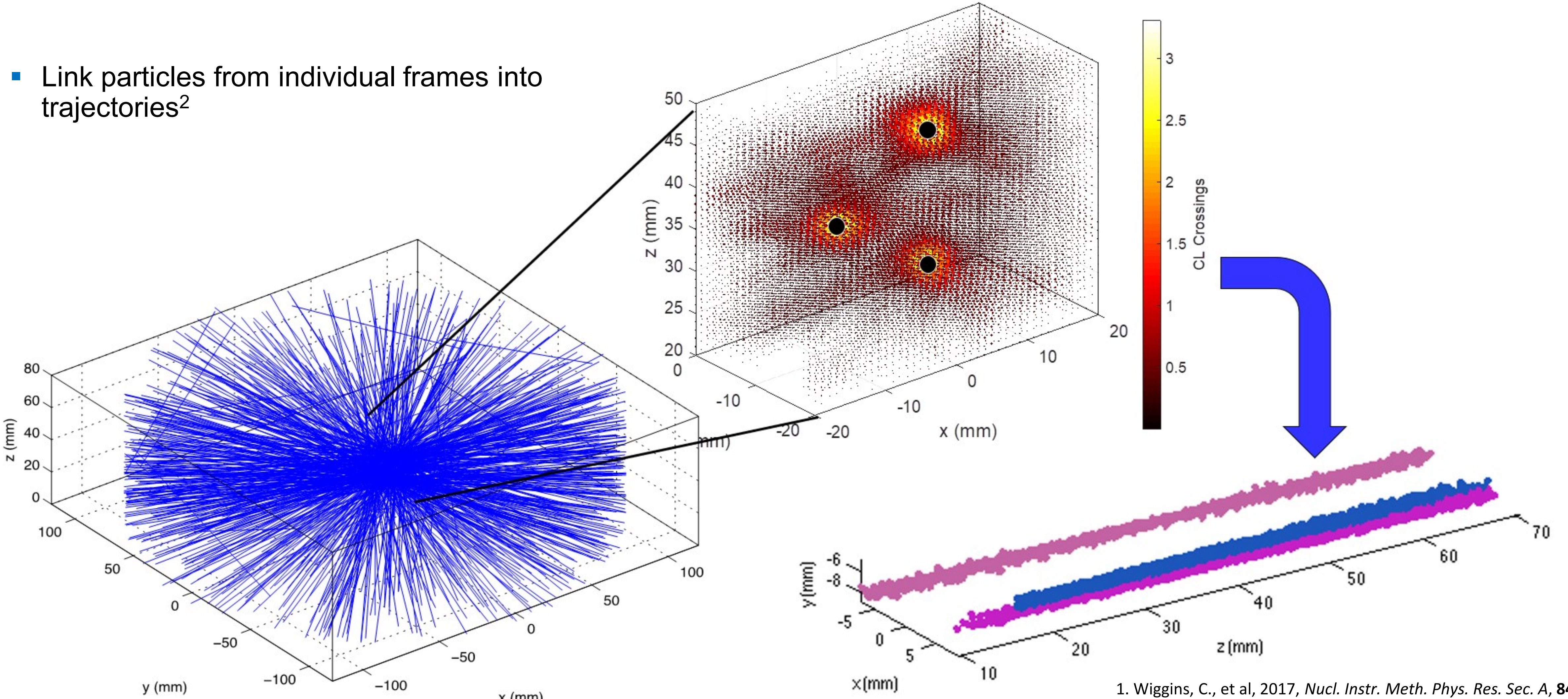


- Identify local maxima
- Use Gaussian fitting for particle positions

1. Wiggins, C., et al, 2017, *Nucl. Instr. Meth. Phys. Res. Sec. A*, **843**, 22.

M-PEPT: Feature Point Identification (FPI)[1]

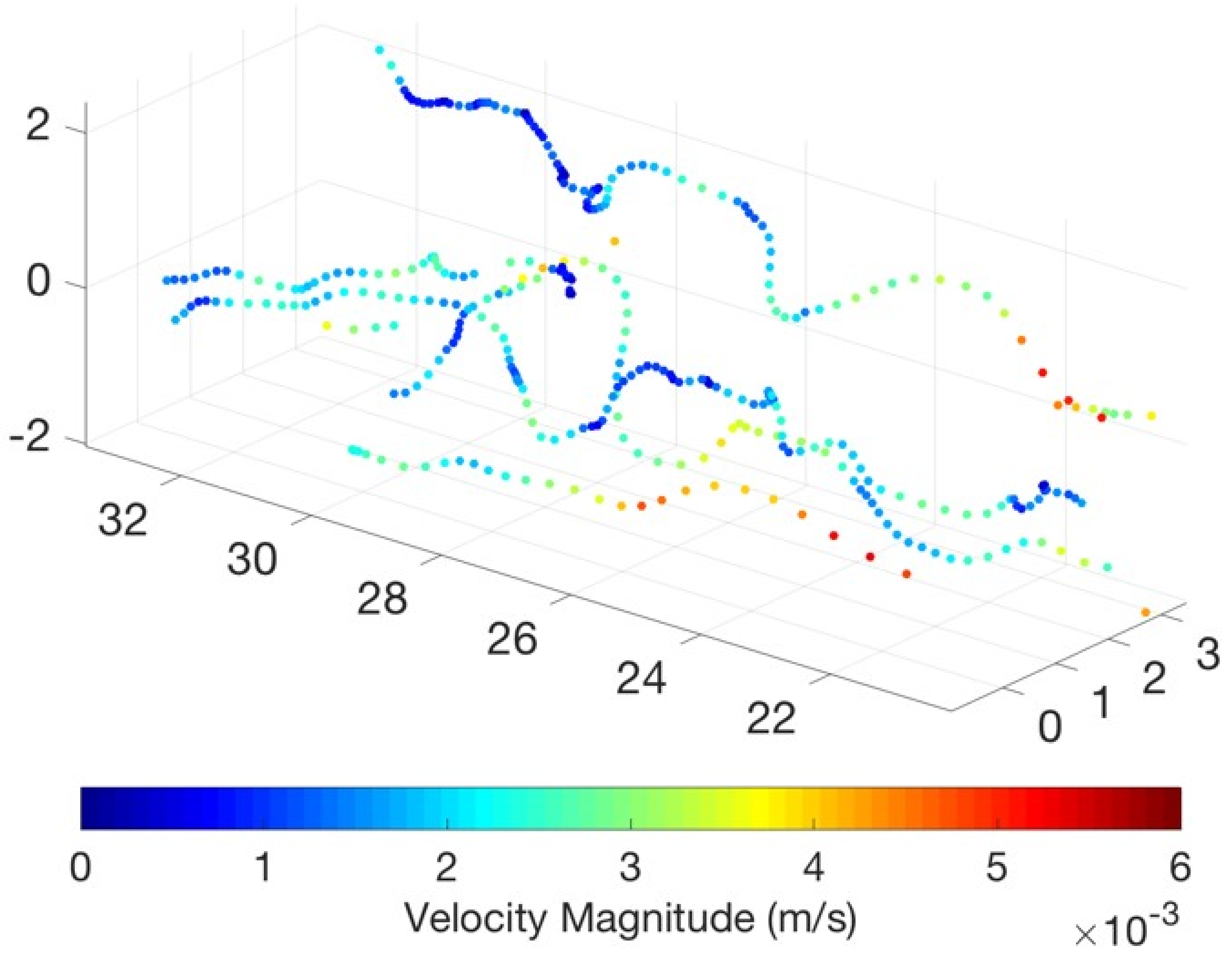
- Link particles from individual frames into trajectories[2]



1. Wiggins, C., et al, 2017, *Nucl. Instr. Meth. Phys. Res. Sec. A*, **843**, 22.
2. Wiggins, C., et al, 2016, *Nucl. Inst. Meth. Phys. Res. Sec. A*, **811**, 18.

M-PEPT Performance

- Typical spatiotemporal resolution: 1 ms, 0.5 mm
  - Depends on tracer activity, attenuating medium
- Tracking >80 particles simultaneously
  - Up to 100 in simulation
- Enables a number of novel PEPT experiments
  - Tracers can enter and leave field of view of scanner



PEPT Experiments: Activation

- Direct Activation
  - Volumetric activation via accelerator

- **Indirect Activation**
  - Surface activation via chemical means

Isotope	$T_{1/2}$	E_{mean} (keV)	E_{max} (keV)	R_{mean} (mm)	R_{max} (mm)
^{18}F	109.8 min.	252	635	0.66	2.6
^{11}C	20.3 min.	390	970	1.1	4.5
^{22}Na	2.6 yr.	220	674	0.53	2.3
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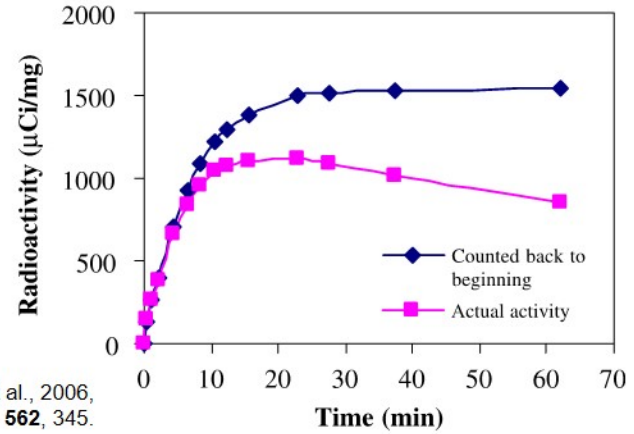
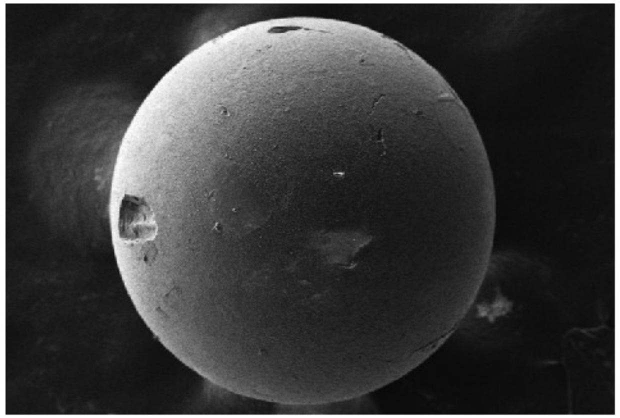
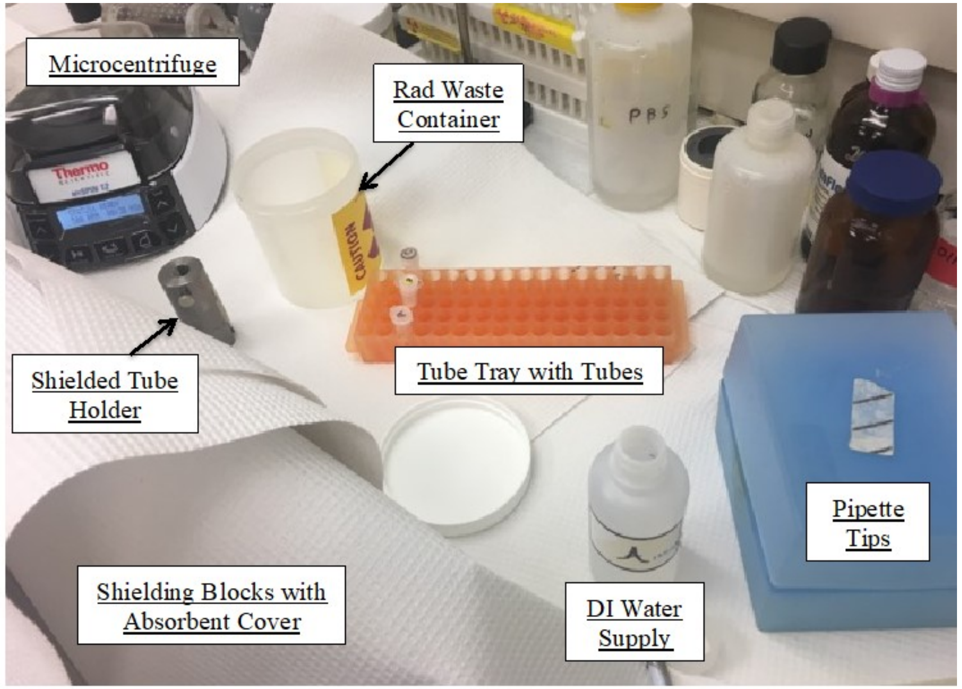


Fan, X., et al., 2006, *NIMA*, **562**, 345.

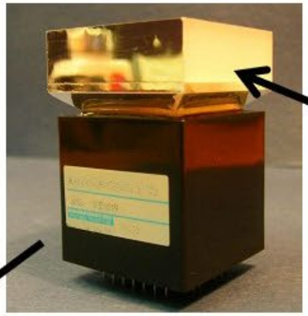


Anion exchange resin beads activated via soaking in ^{18}F aqueous solution (D = 0.1 -1 mm), final activity 50 – 1000 µCi

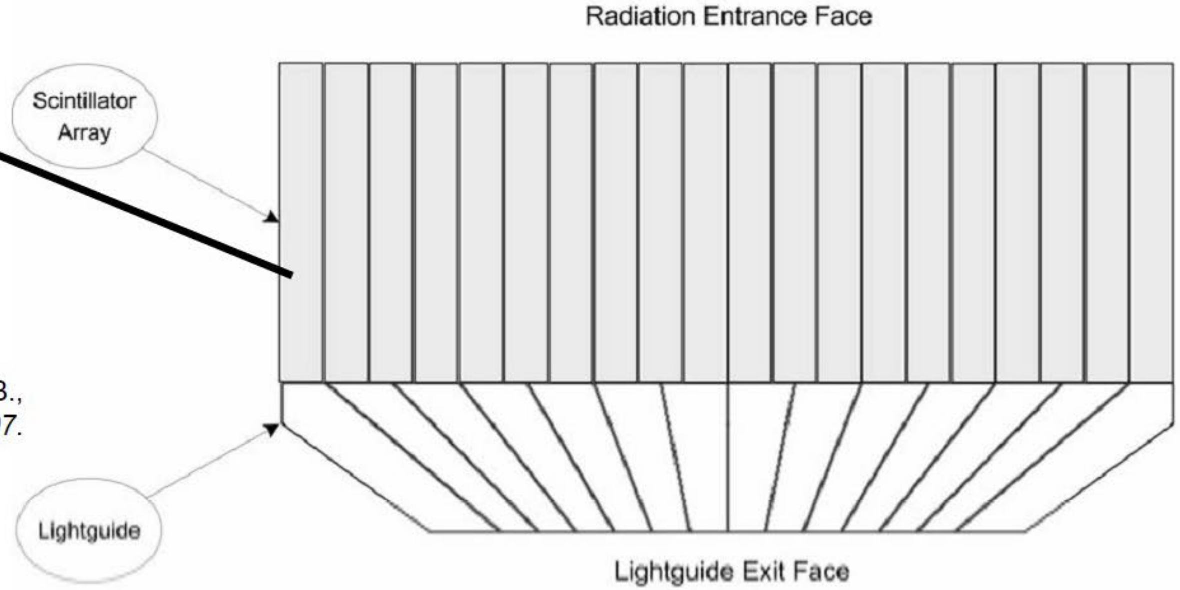


PEPT Experiments: Detectors

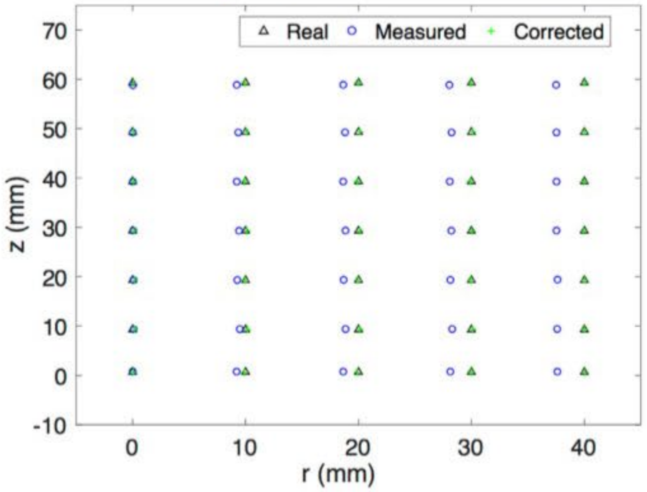
- PET scanners consist of a fixed array of segmented detectors
- Allows easy calibration, repeatability of experiments



Mintzer, R.A. and Siegel, S.B., 2007, proc. of *IEEE NSS 2007*.



PEPT Dewarping[1]



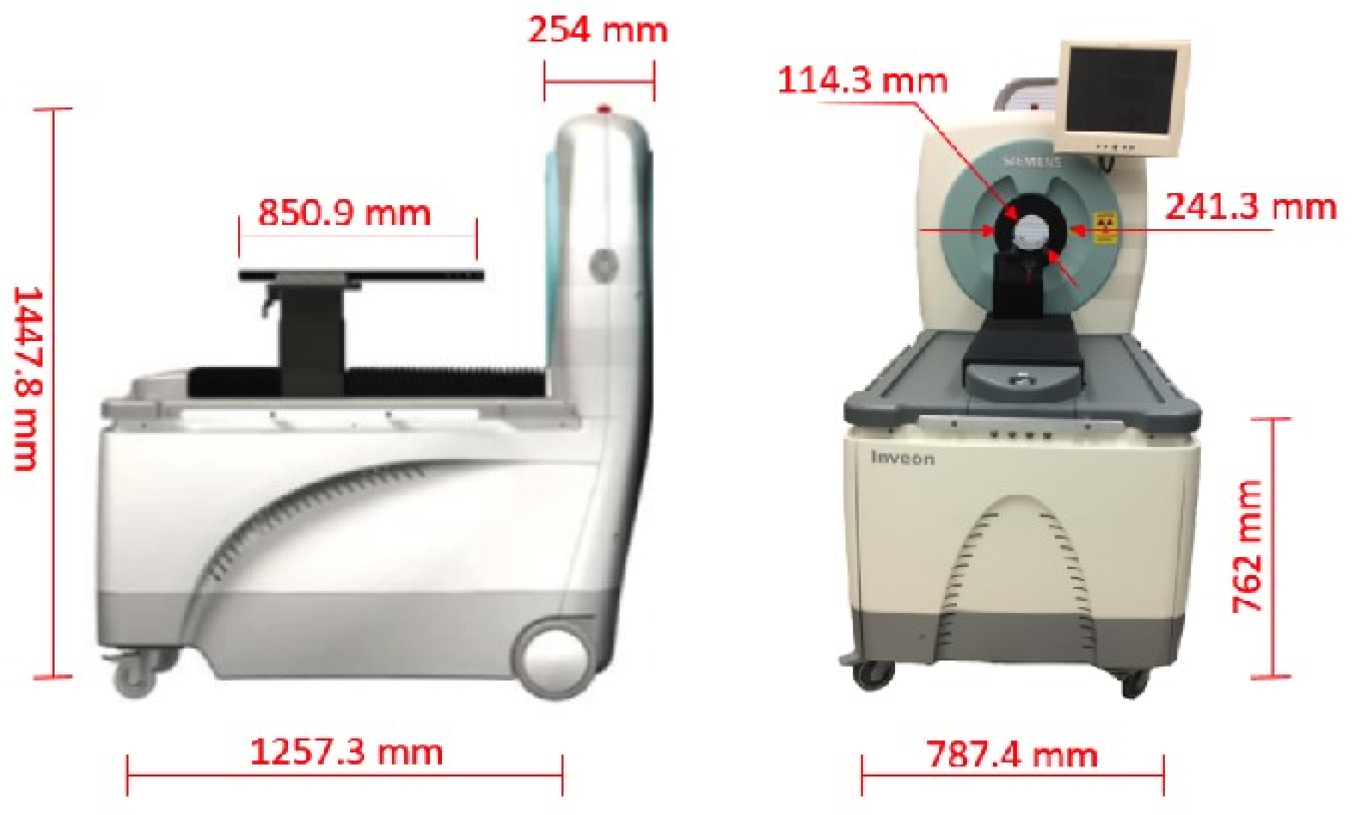
Alternatives: panel detectors[2], modular array[3]

1. Wiggins, C., et al., 2019, *Chem. Engr. Sci*, **204**, 246.
2. Perez-Mohedano, R., et al., 2015, *Chem Engr J*, **259**, 724
3. Parker, 2017, *Rev. Sci. Instr.*, **88**, 051803.

PEPT Experiments: Detectors – Siemens Inveon[1]

- Ring-type preclinical PET scanner
  - Designed for mouse, rat imaging
- Allows PEPT reconstruction up to 5 kHz
- Peak sensitivity 5.2% at 425-625 keV energy window

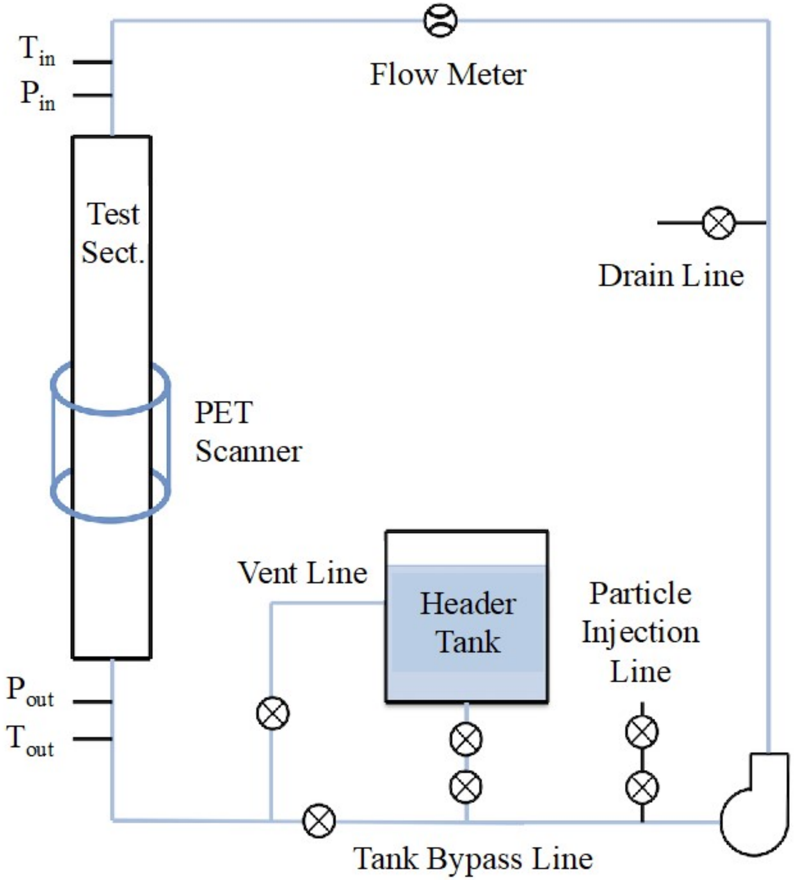
Detector	Crystal Material	LSO
	Crystal Size (mm)	1.51 x 1.51 x 10
	Crystal Pitch (mm)	1.59
	Crystal Array	400 (20 x 20)
System	No. of Detectors	64
	No. of Crystals	25,600
	No. of Rings	80
	No. of Crystals per Ring	320
	Ring Diameter (cm)	16.1
	Axial FOV (cm)	12.7
	Transaxial FOV (cm)	10.0



1. Bao, Q., et al., 2009, *J. Nucl. Med.*, **50**, 401.

PEPT Experiments: Measurement

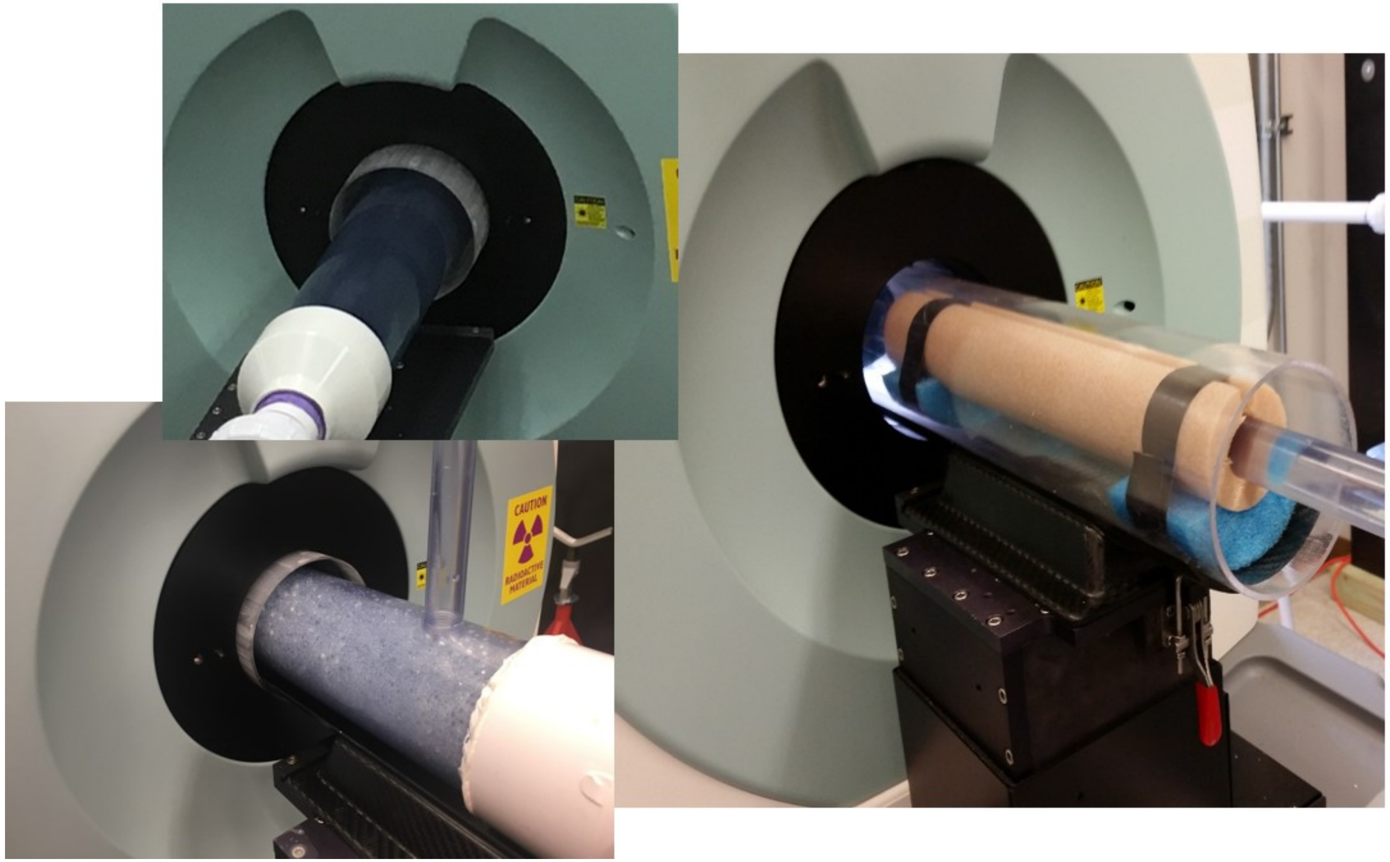
- Experiments carried out using deionized water
- Test section region of interest placed in bore of PET scanner

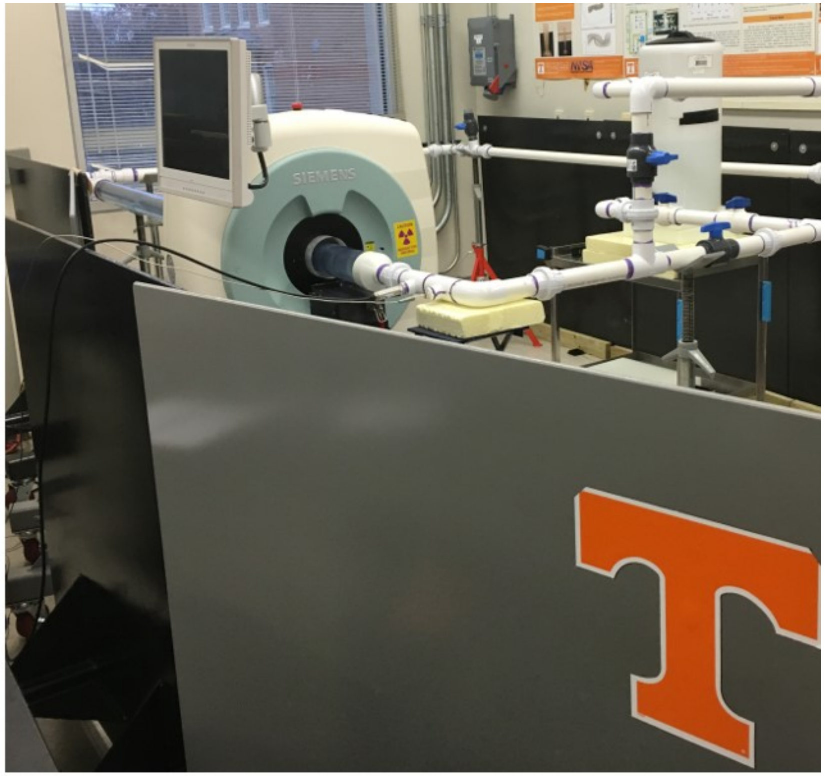


Typical PEPT measurement flow loop

PEPT Experiments: Measurement

- Experiments carried out using deionized water
- **Test section region of interest placed in bore of PET scanner**

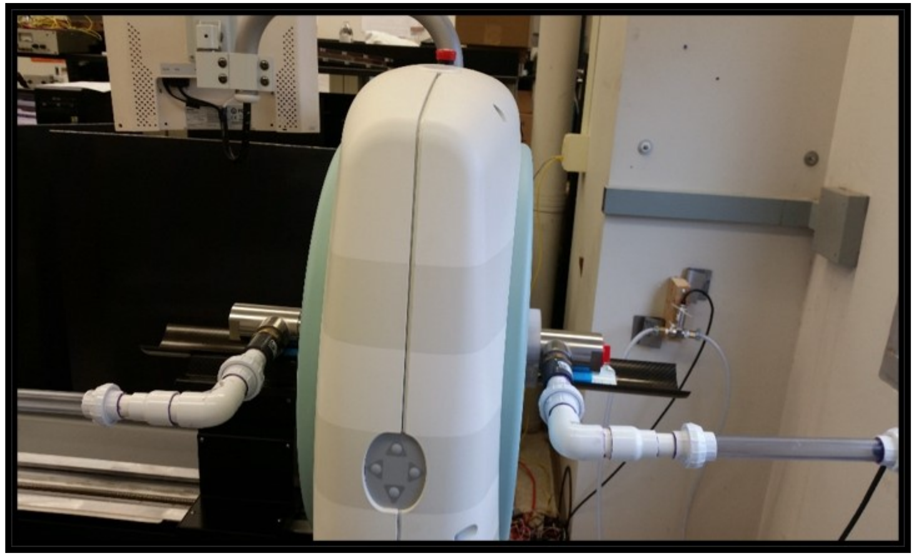


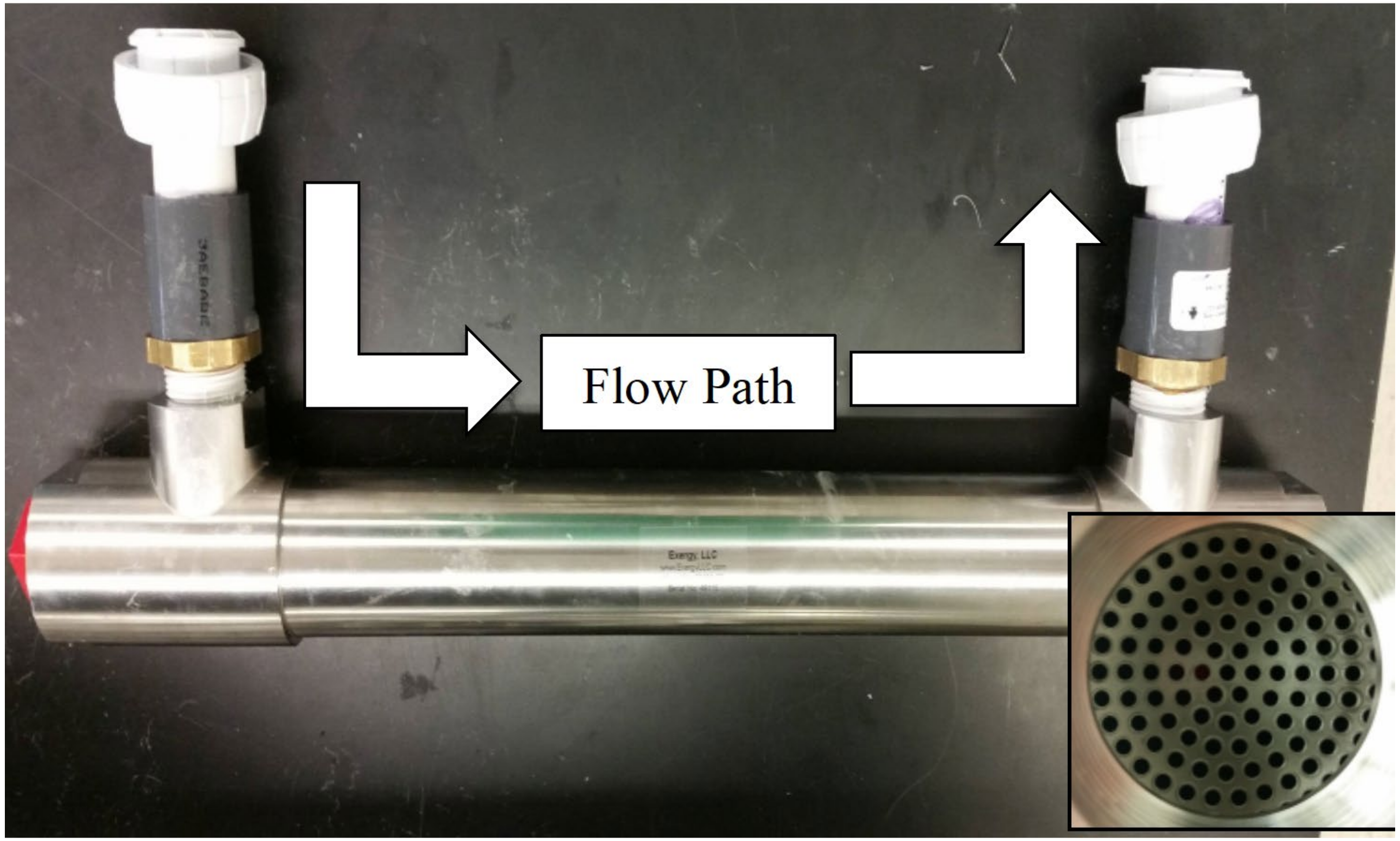


Experimental apparatus remains behind shielding during data collection.

Experiment Highlights: Heat Exchanger[1]

- Flow imaged in shell-side of tube-in-shell HX
  - Stainless steel, ¼-in. thick
  - Mean velocity 0.5 m/s

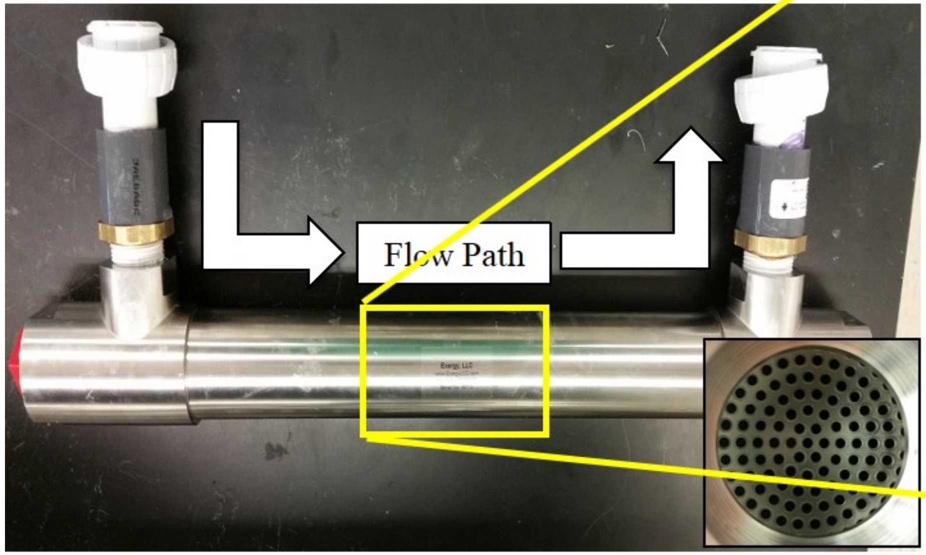


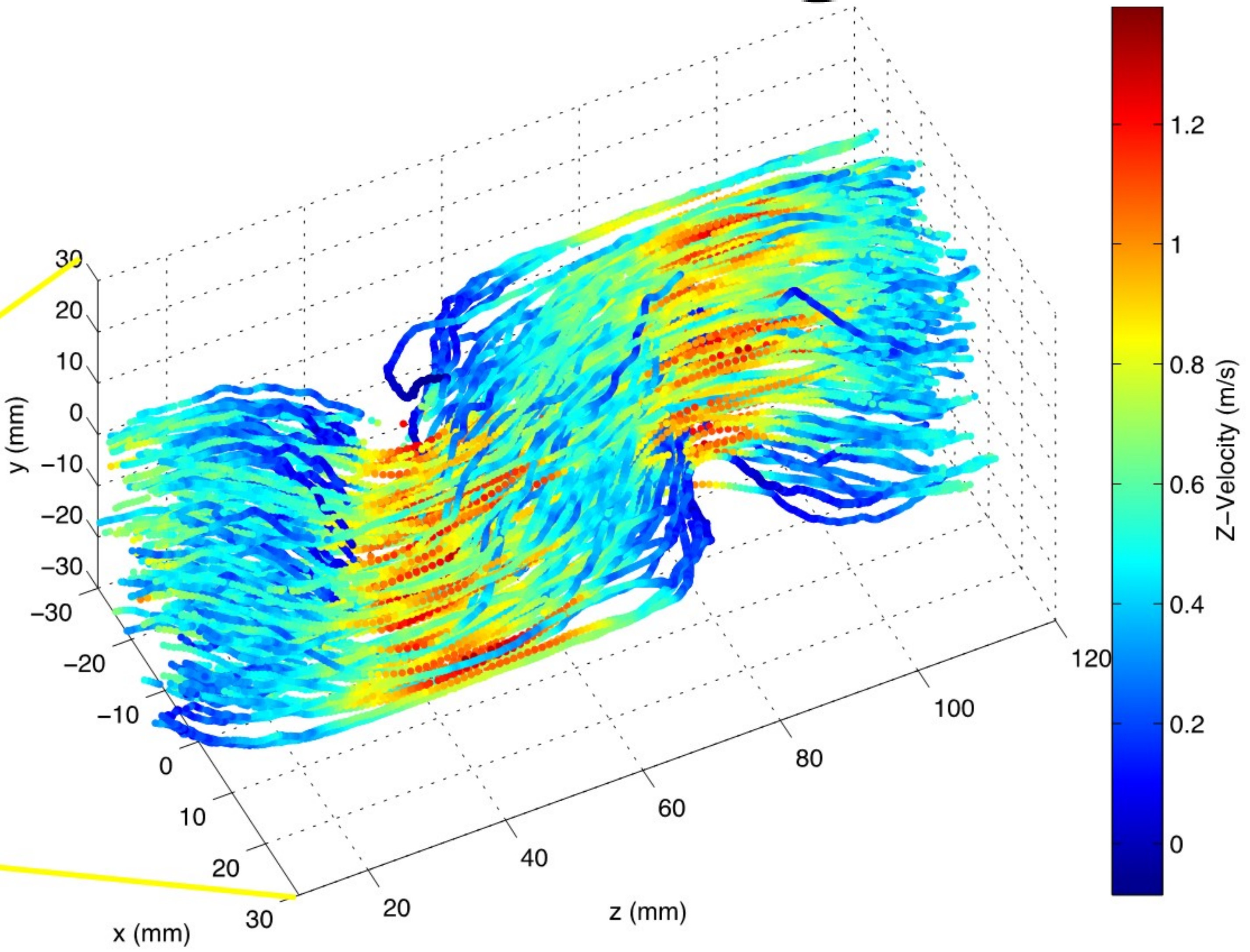


1. Buttrey, M., et al., *ANS Winter 2015.*

Experiment Highlights: Heat Exchanger

- Flow imaged in shell-side of tube-in-shell HX
  - Stainless steel, ¼-in. thick
  - Mean velocity 0.5 m/s
  - Resolves flow around tubes, baffles

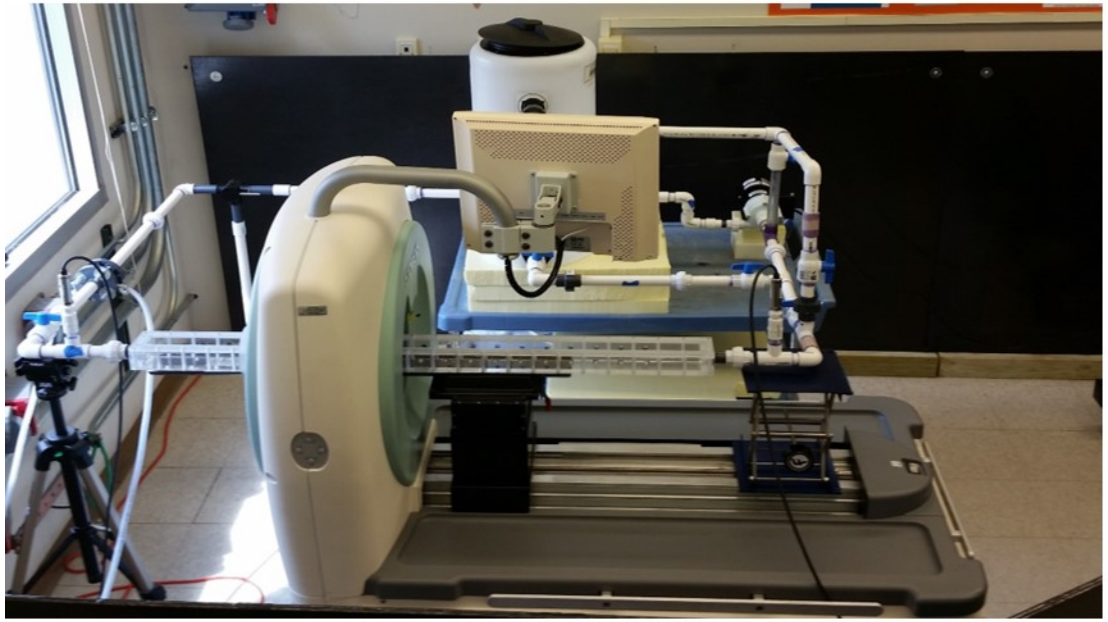


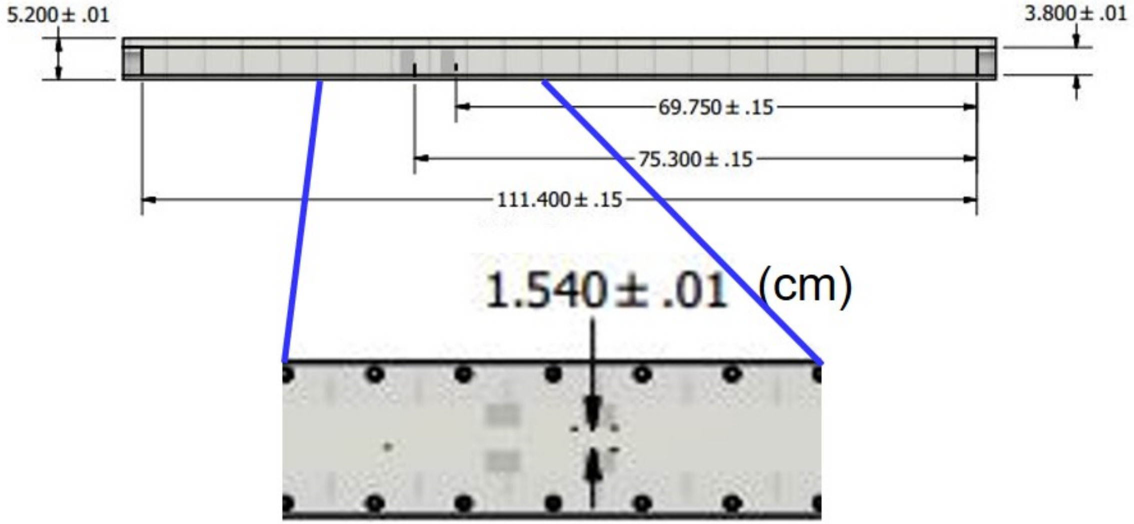


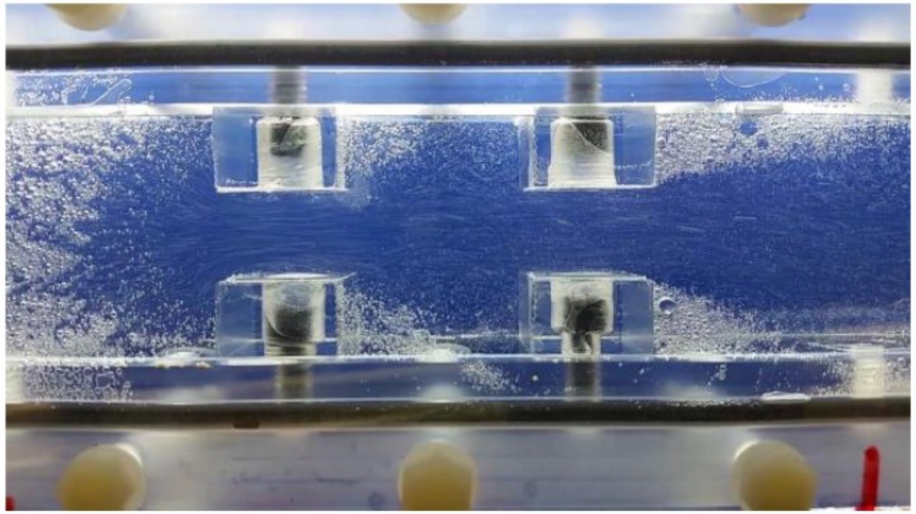
1. Buttrey, M., et al., *ANS Winter 2015*.

Experiment Highlights: Baffle Flow[1]

- Study flow in complex geometry with acceleration, recirculation
    - Compare to optical methods

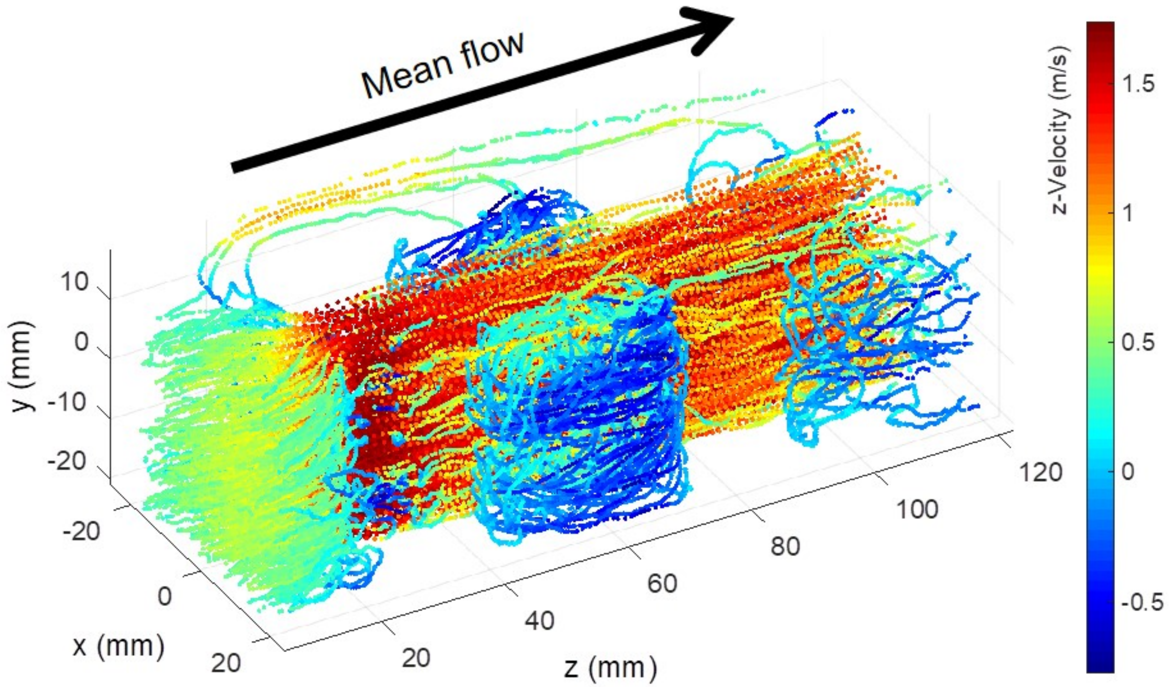


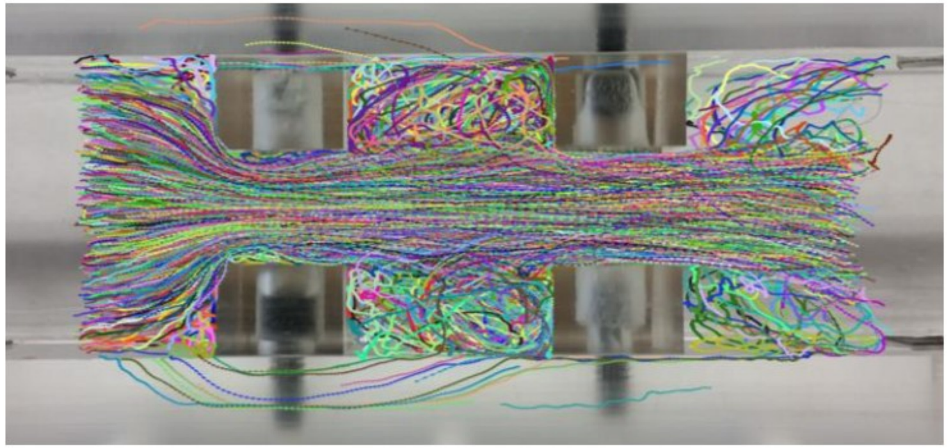


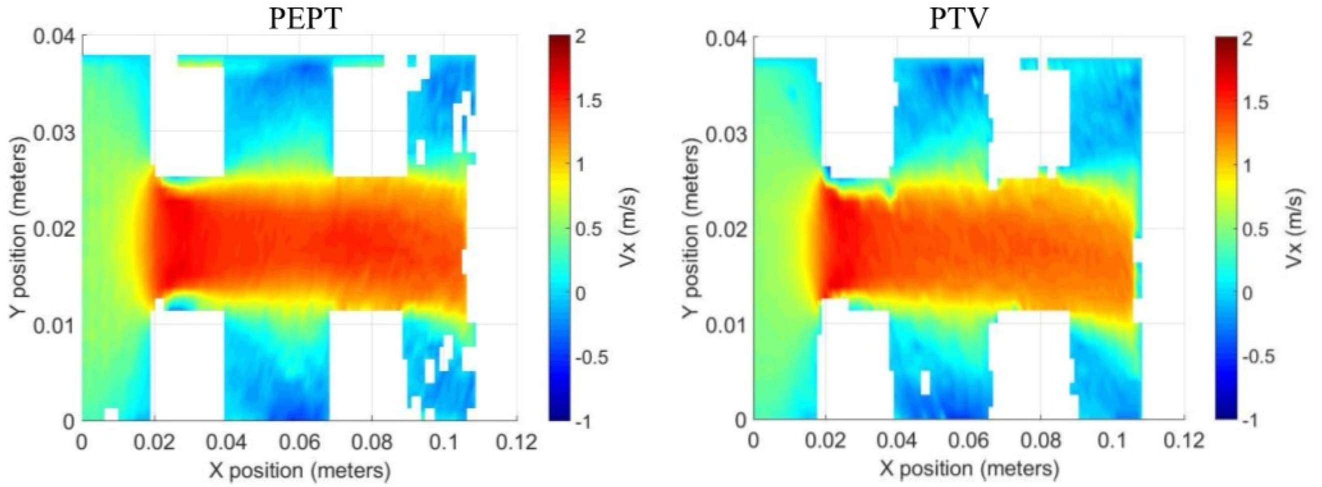


1. Langford et al, proc. *ICONE* 2016.

Experiment Highlights: Baffle Flow[1]





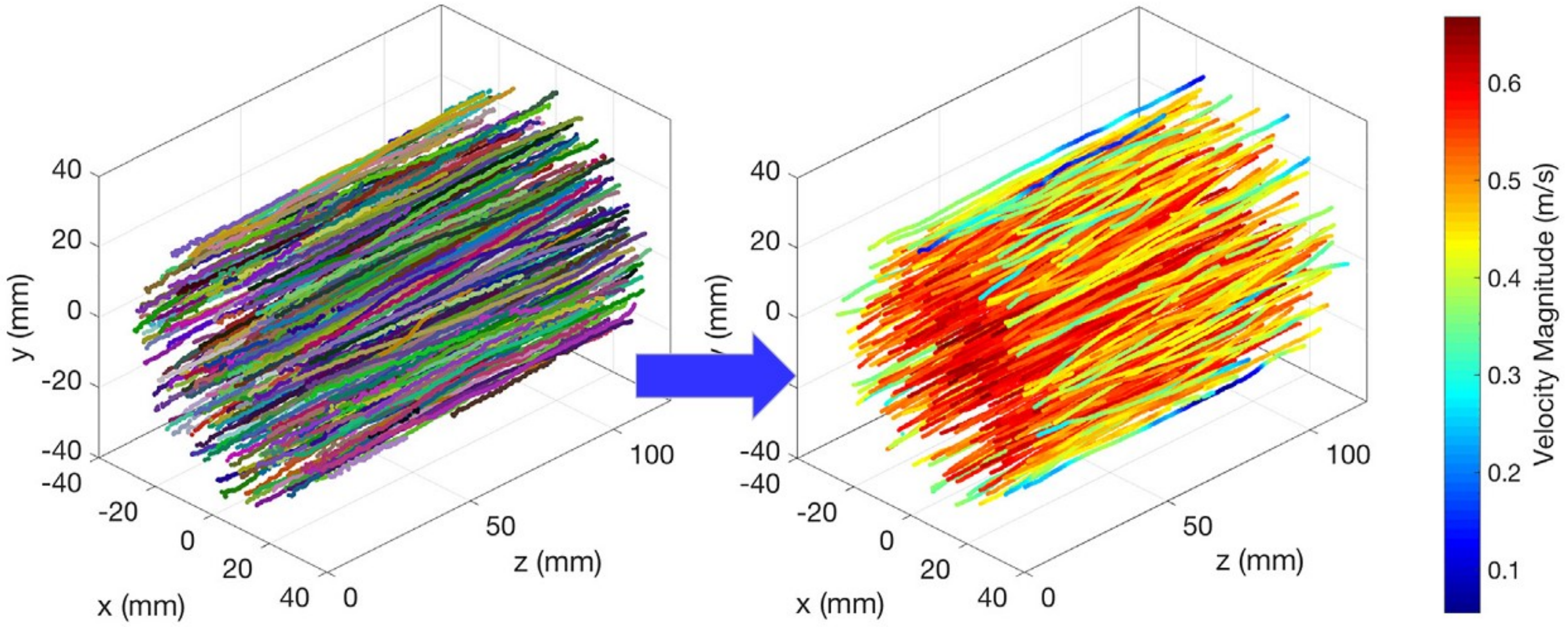


Results validated against optical PTV

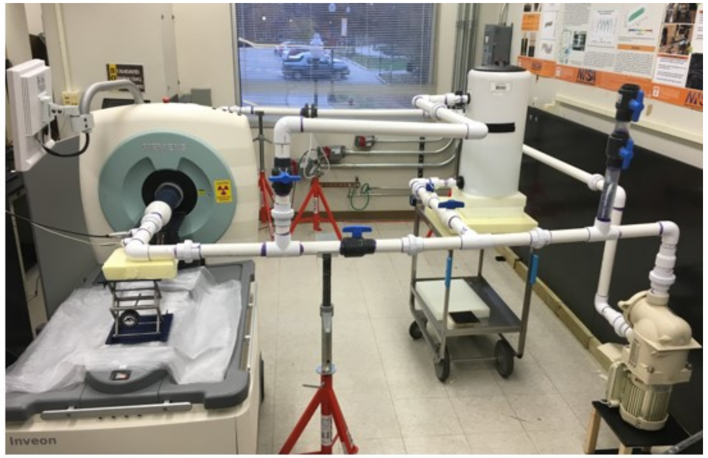
1. Langford et al, proc. *ICONE* 2016.

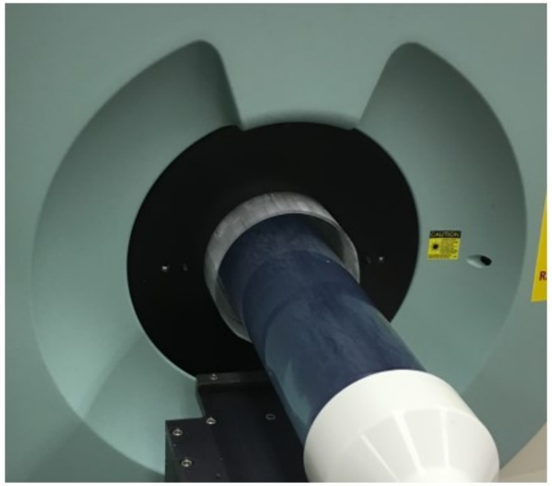
Experiment Highlights: Pipe Flow[1]

- Pipe Flow, D = 74 mm
  - Re = 42,600 (mean vel. 0.5 m/s)



Developed procedure to dewarp trajectories near radial edges of scanner

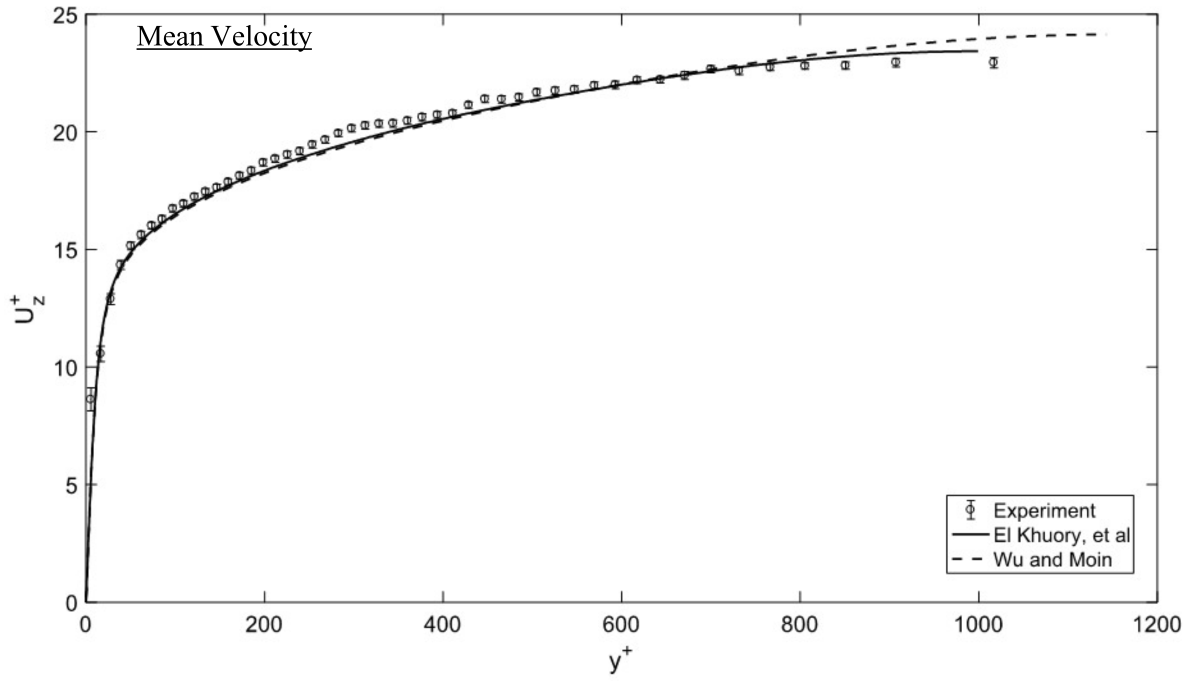


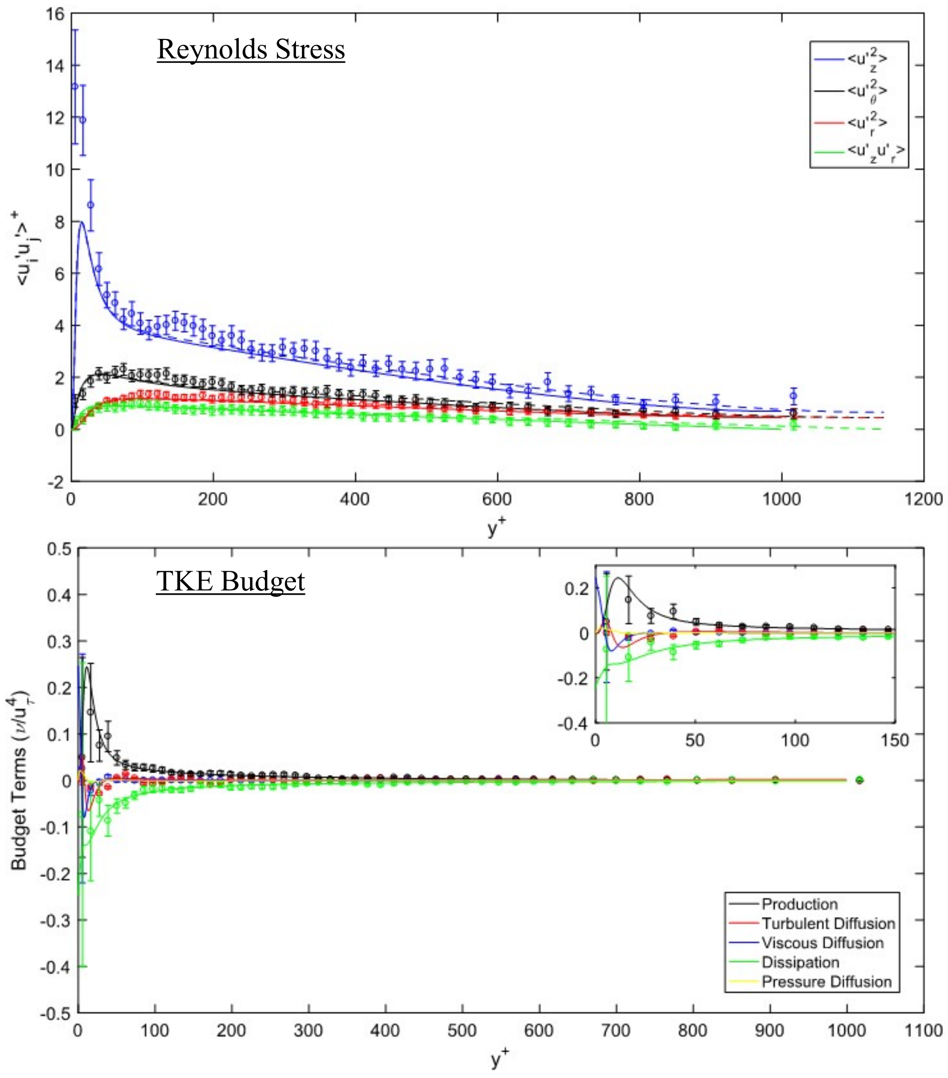


1. Wiggins, C., et al., 2019, *Chem. Engr. Sci*, **204**, 246.

Experiment Highlights: Pipe Flow

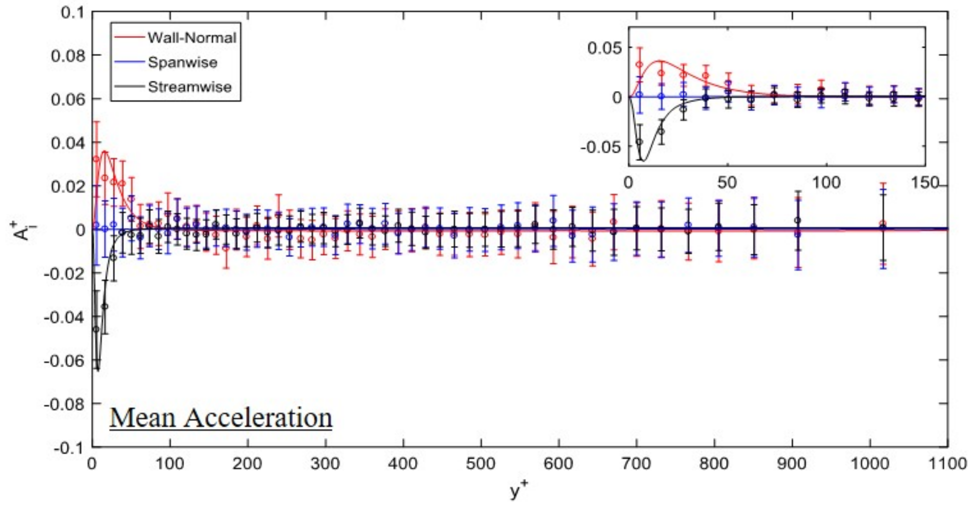
- Compare results to direct numerical simulation data[1-3]
  - Shows efficacy of PEPT for turbulence measurement, CFD validation

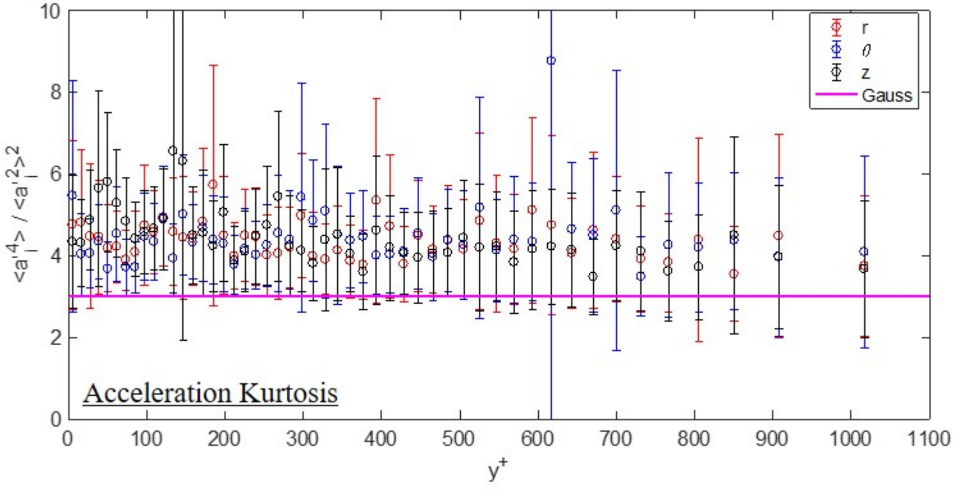




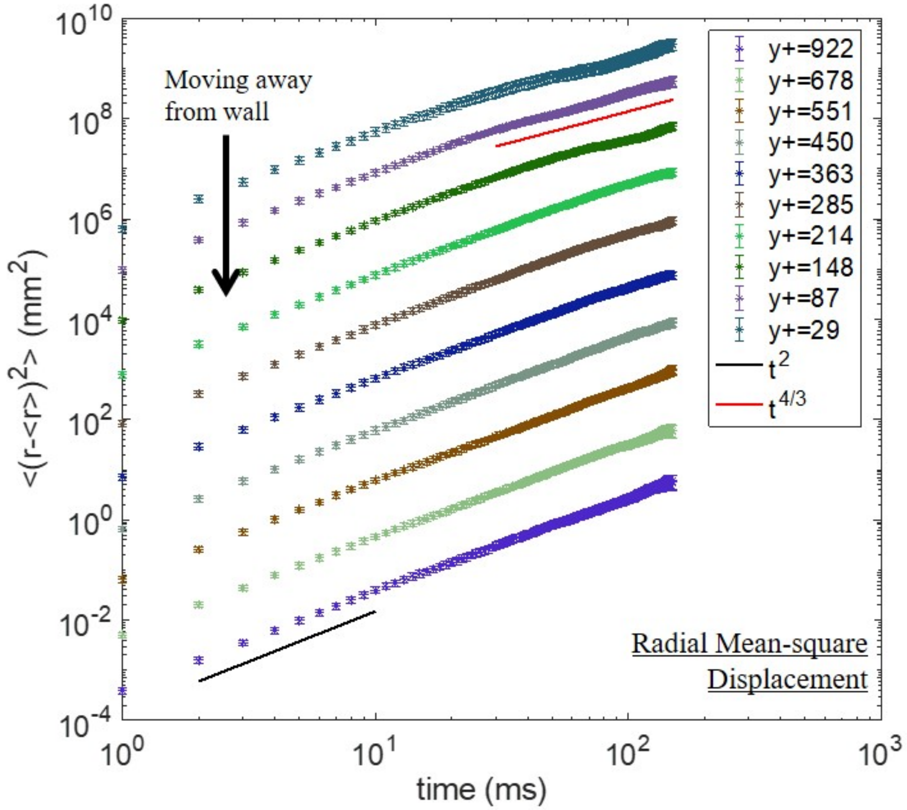
1. El Khuory et al., 2013, *Flow Turb. Combust.*, **91**, 475. 2. Wu and Moin, 2008, *J. Fluid Mech.*, **608**, 81. 3. Stelzenmuller et al., 2017, *Phys. Rev. Fluids*, **2**(054602).

Experiment Highlights: Pipe Flow





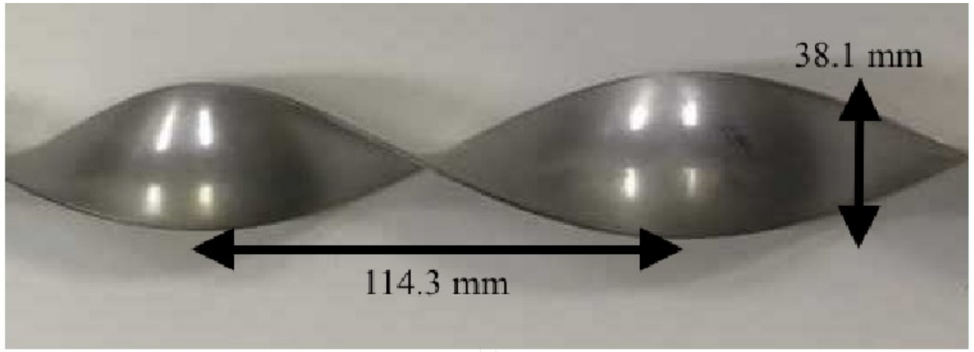
- Use particle tracking ("Lagrangian") data to understand acceleration, diffusion[1]

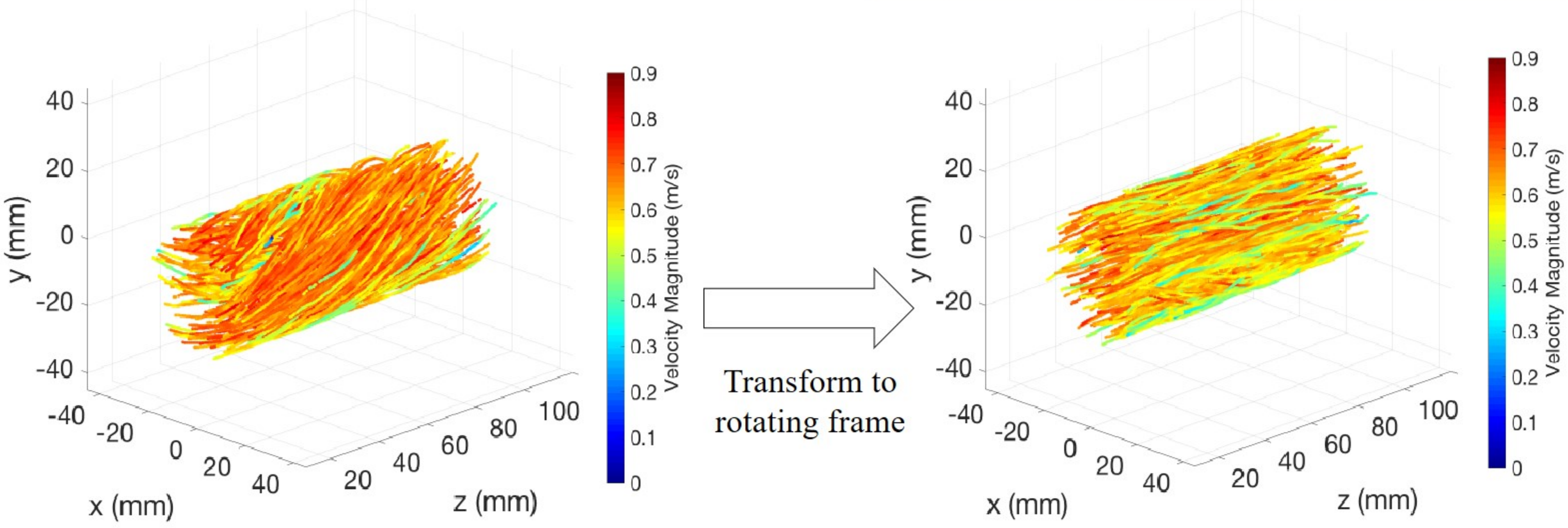


1. Wiggins et al., proc. *ANS Winter 2019*

Experiment Highlights: Swirl Flow[1]

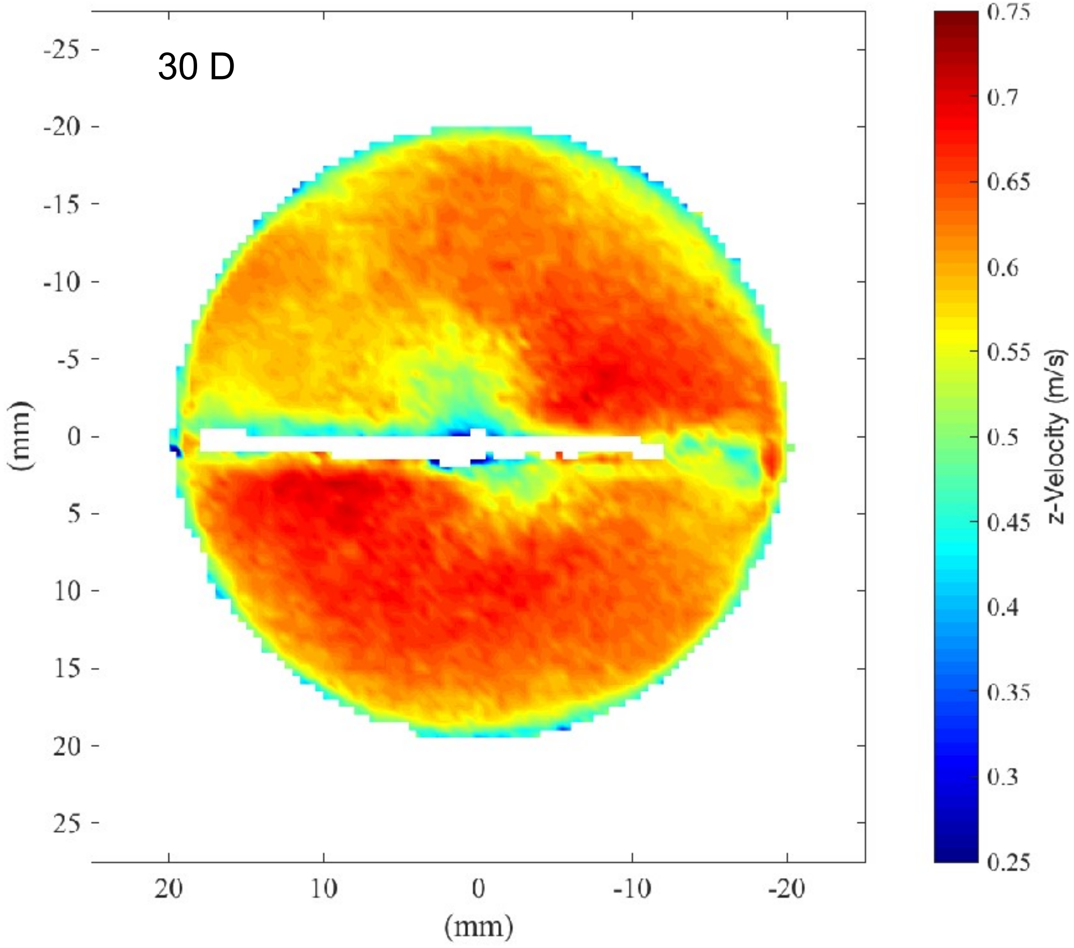
- Pipe flow with twisted tape insert
  - TT is common heat transfer enhancement
  - Study secondary flow, asymmetry



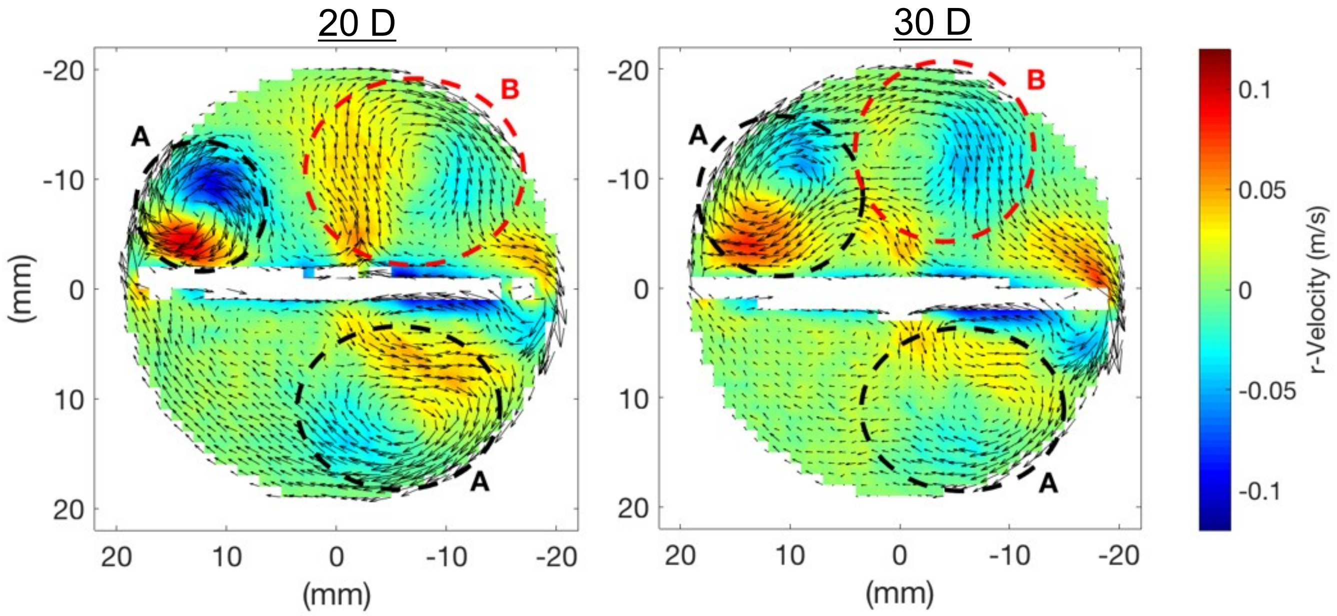


1. Wiggins et al., proc. *Adv. Therm. Hydraul.* 2020.

Experiment Highlights: Swirl Flow[1]



Asymmetric axial velocity profile



- Identified secondary flows in rotating frame
  - Flows still developing at 20 to 30 diameters

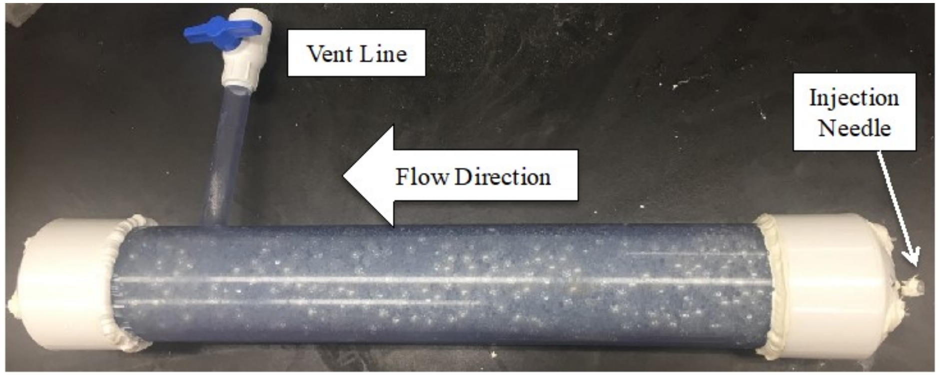
1. Wiggins et al., proc. *Adv. Therm. Hydraul.* 2020.

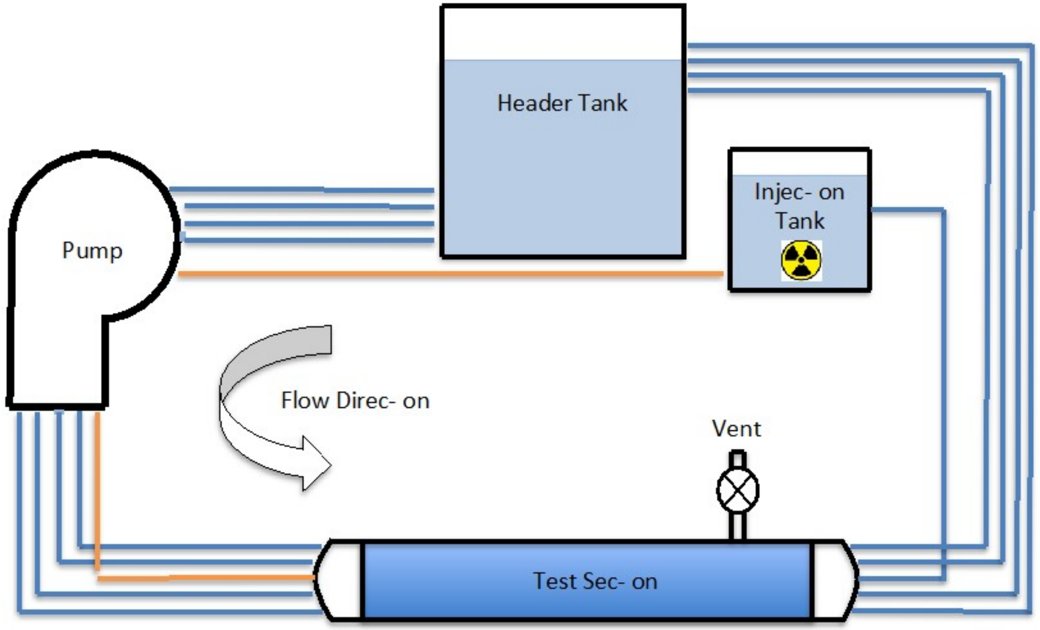
Experiment Highlights: Packed Bed[1]

- Study velocity, acceleration, and transport in porous media, low-Re flow
- Test sections constructed of packed glass spheres, diameter 2, 4, 8 mm

Bead Sizes (mm)	Re
2	0.135
2	0.27
2	0.54
2, 4	0.27
2, 4, 8	0.27

- Show capability of PEPT imaging in packed bed systems

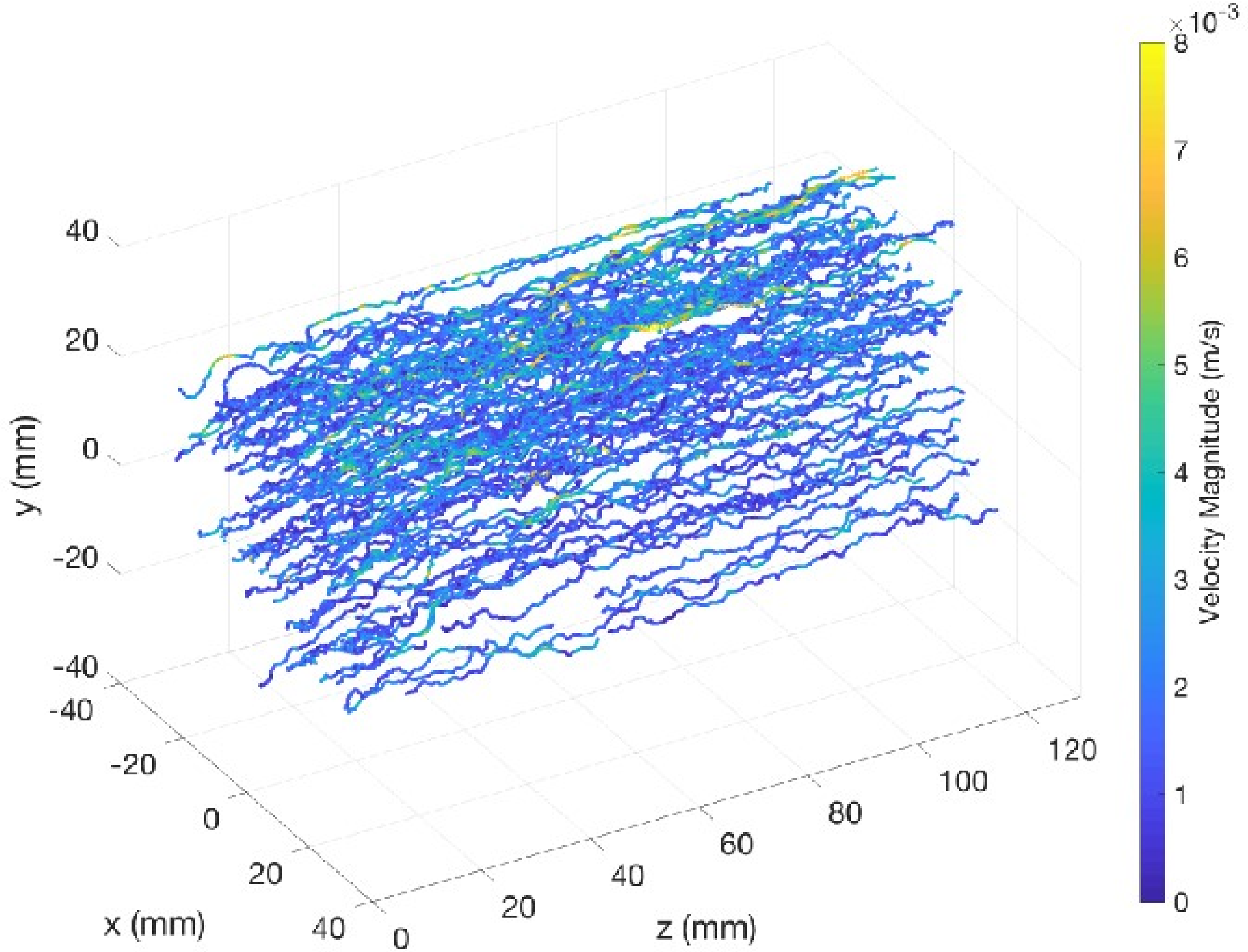




1. Wiggins, 2019, Ph.D. Dissertation.

Experiment Highlights: Packed Bed[1]

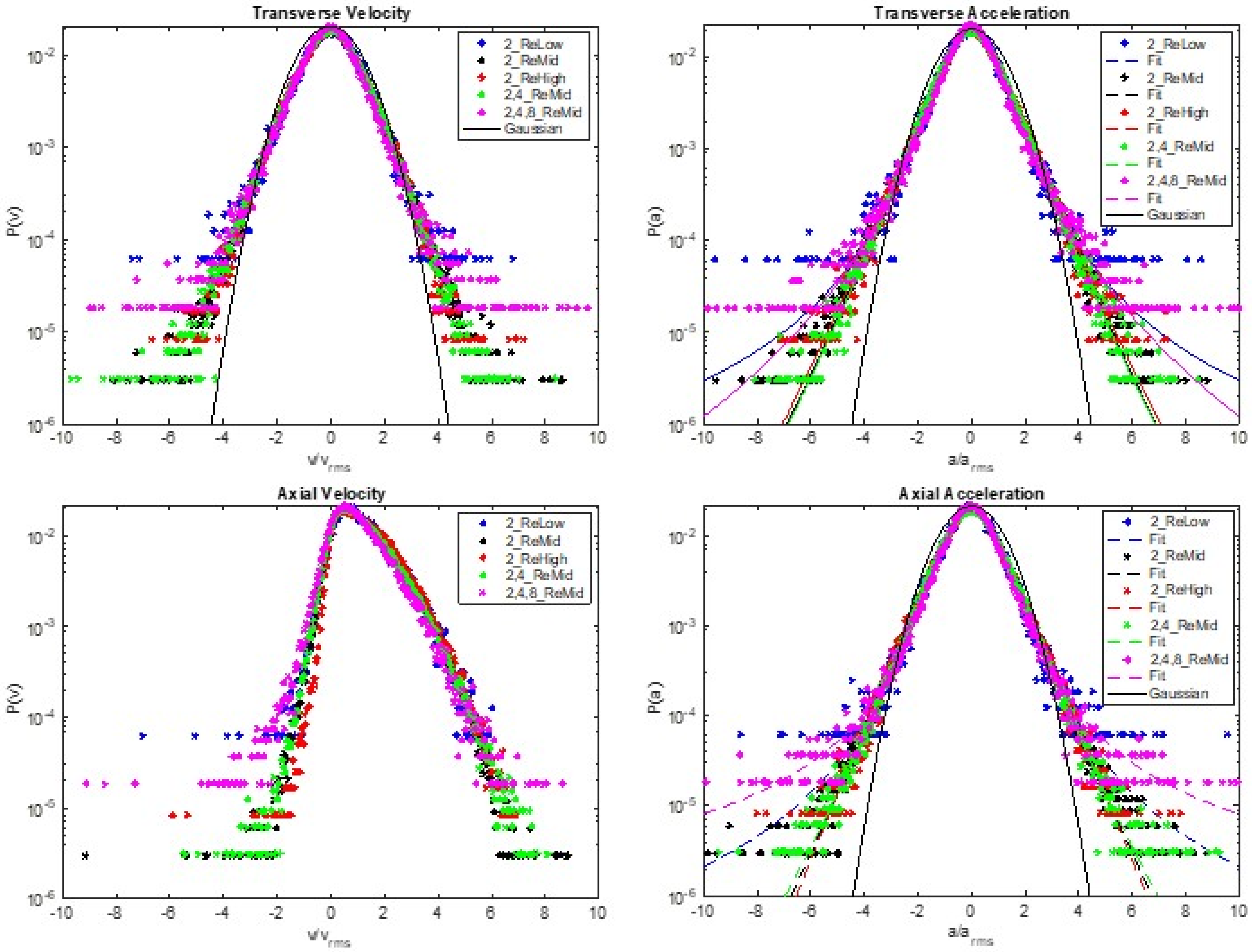
- Demonstrated capability for packed bed systems
  - Over 80 tracers tracked simultaneously



1. Wiggins, 2019, Ph.D. Dissertation.

Experiment Highlights: Packed Bed[1]

- Demonstrated capability for packed bed systems
  - Over 80 tracers tracked simultaneously
- Measurement of pore-scale velocity and acceleration distributions



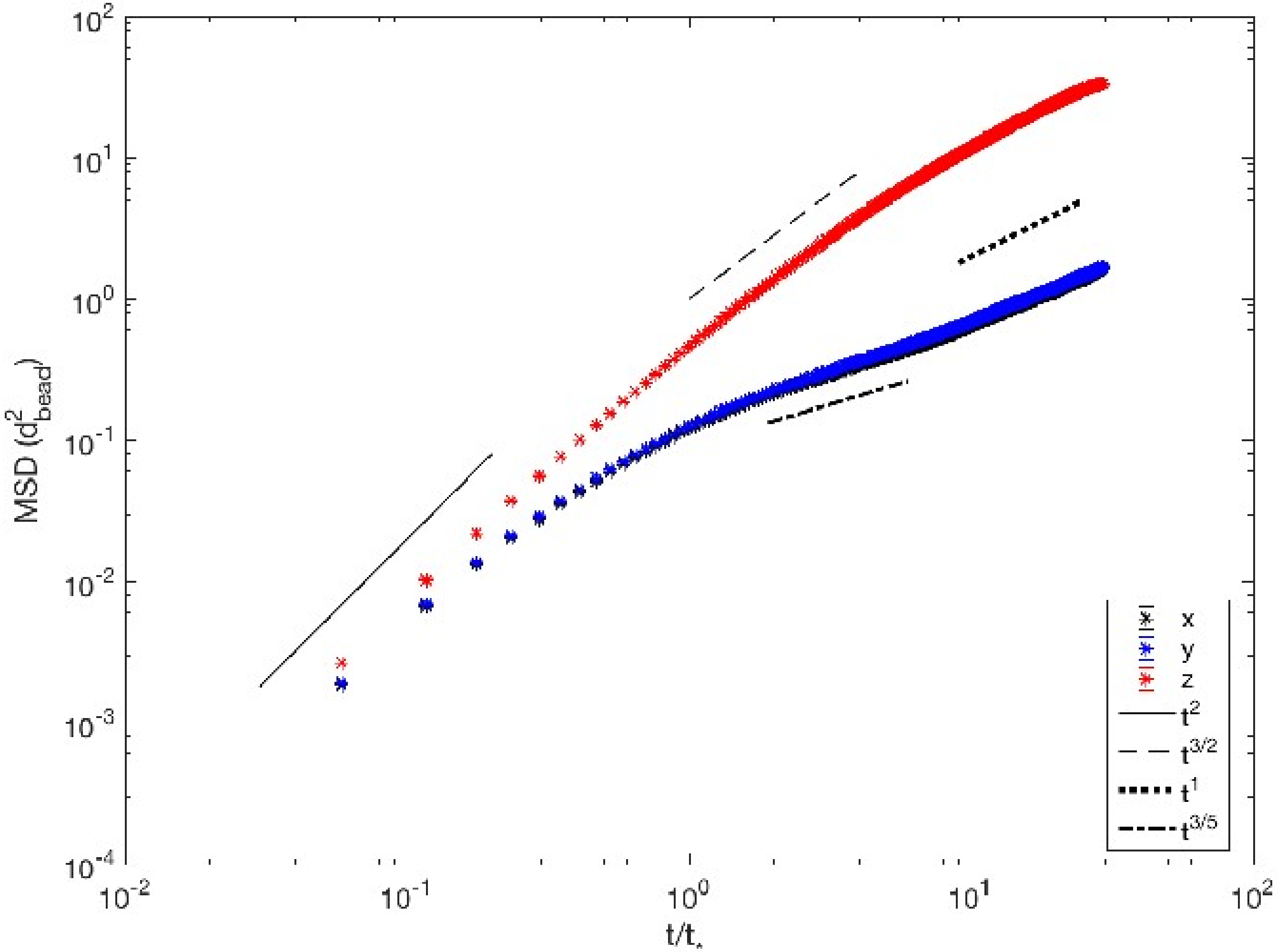
1. Wiggins, 2019, Ph.D. Dissertation.

Experiment Highlights: Packed Bed[1]

- Demonstrated capability for packed bed systems
  - Over 80 tracers tracked simultaneously

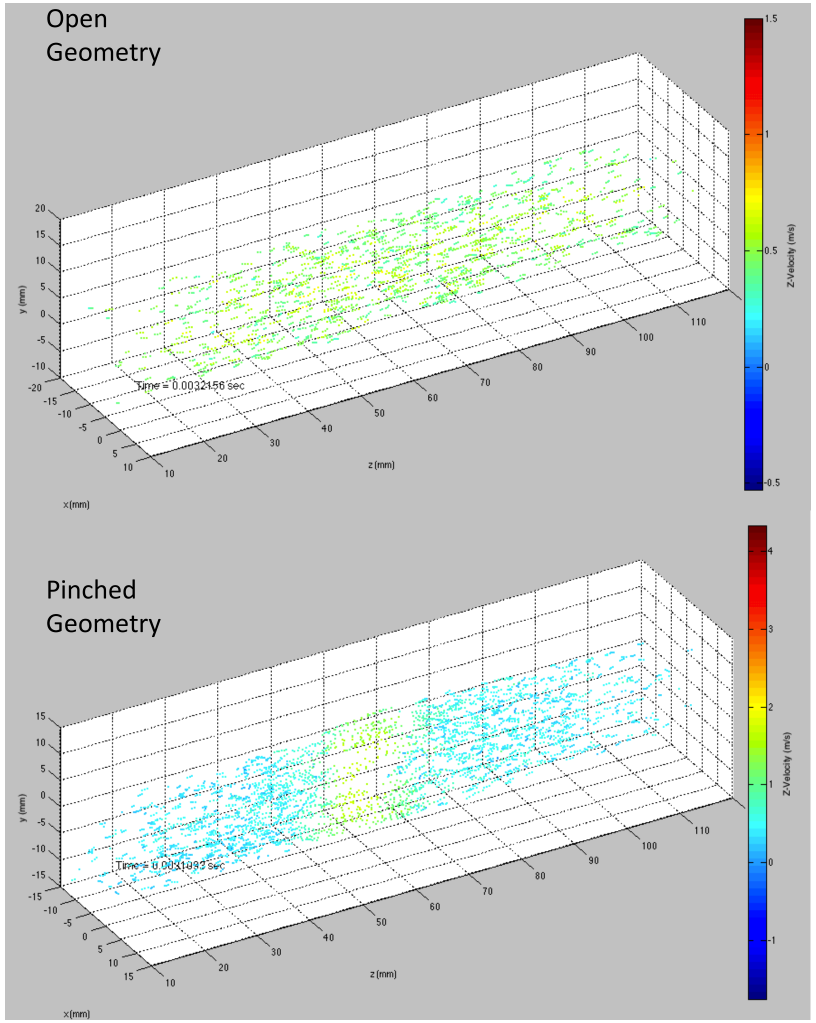
- Measurement of pore-scale velocity and acceleration distributions

- Mean-squared displacement measurements may be used to infer diffusion characteristics

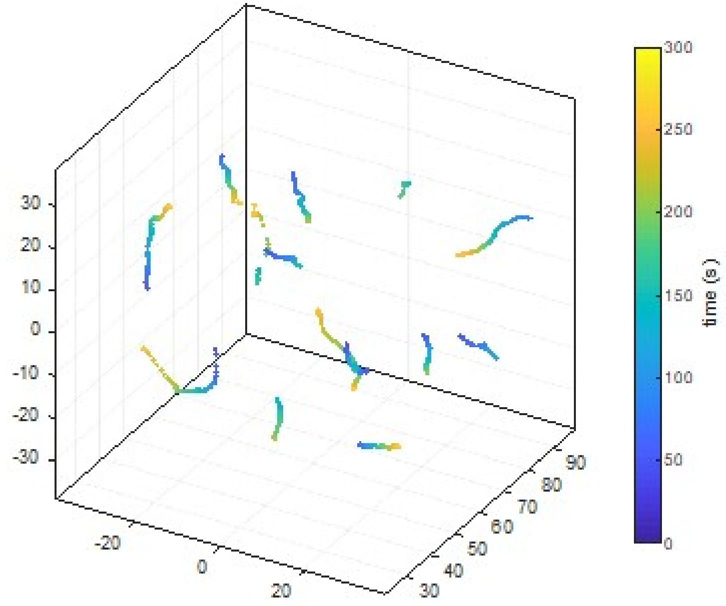


1. Wiggins, 2019, Ph.D. Dissertation.

Experiment Highlights: Biological Applications



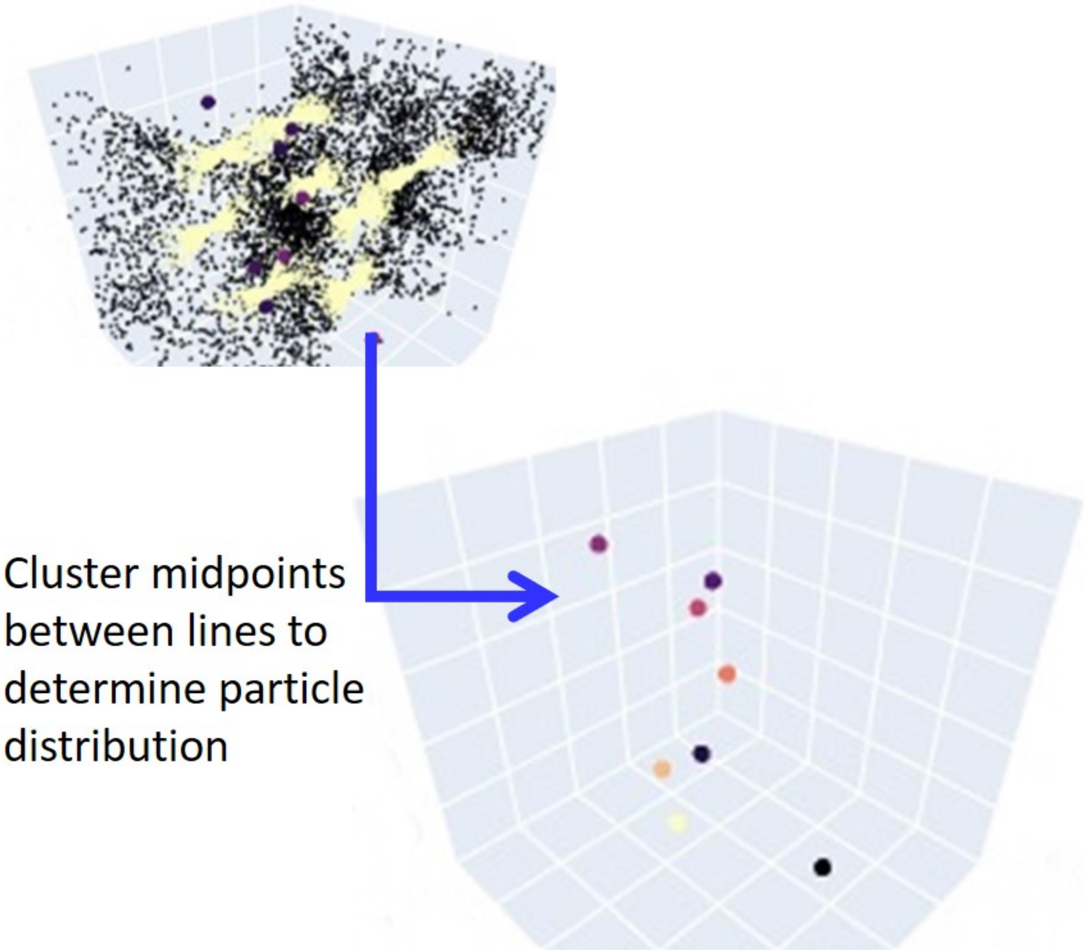
- PEPT utility also demonstrated for measurements of biological concern:
  - Pulsatile flow elastic tubing – open and restricted geometry[1]
  - In vitro tracking of individual yeast cells[2]



1. Patel, N., Wiggins, C., et al., 2017, *Exp. Fl.,* **58**:42
2. Langford, S., et al., 2019, *PLoS ONE,* **12(7)**.

PEPT Future: Reconstruction

- PEPT reconstruction development is an ongoing line of research.
  - Seek to improve spatial, temporal resolution, number of simultaneous tracers
  - Utilize prior research in optical particle tracking
- Recent advances at Univ. Birmingham using clustering methods[1]
  - Demonstrated reconstruction of 128 tracers in simulation



Cluster midpoints between lines to determine particle distribution

1. Nicusan and Windows-Yule, 2020, *Rev. Sci. Instr.*, **91**, 013329.

PEPT Future: Technology

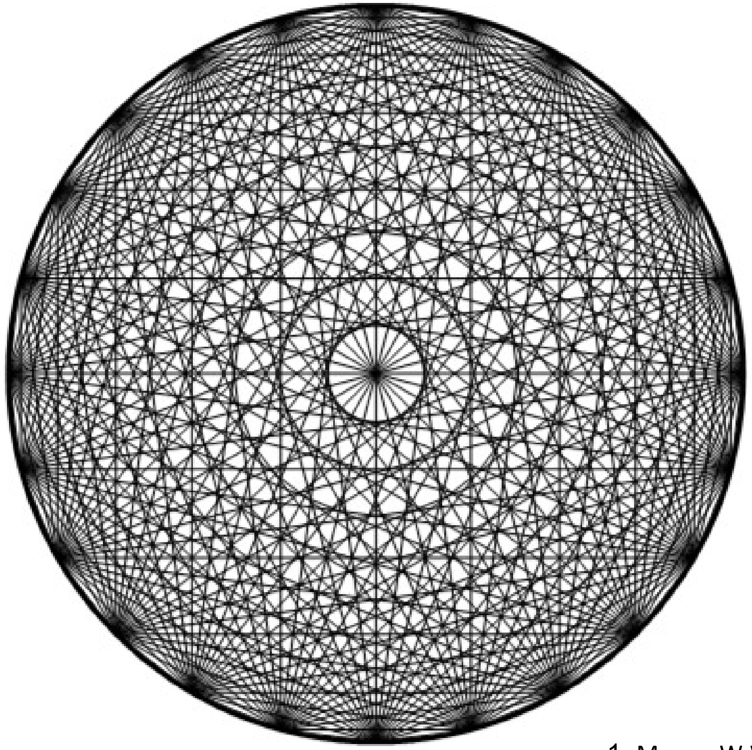
- PEPT advancement requires 2 major technology advancements:

- Tracers
  - Smaller size, Higher activity
  - Mechanical toughness

- Detectors
  - Modularity
  - Higher resolution (finer crystals, improved electronics, time of flight, etc.)

Isotope	$T_{1/2}$	E_{mean} (keV)	E_{max} (keV)	R_{mean} (mm)	R_{max} (mm)
^{18}F	109.8 min.	252	635	0.66	2.6
^{11}C	20.3 min.	390	970	1.1	4.5
^{22}Na	2.6 yr.	220	674	0.53	2.3
^{64}Cu	12.7 h.	278	653	0.56	2.9
^{68}Ga	68 min.	844	1899	3.6	10.3

May require moving away from F-18

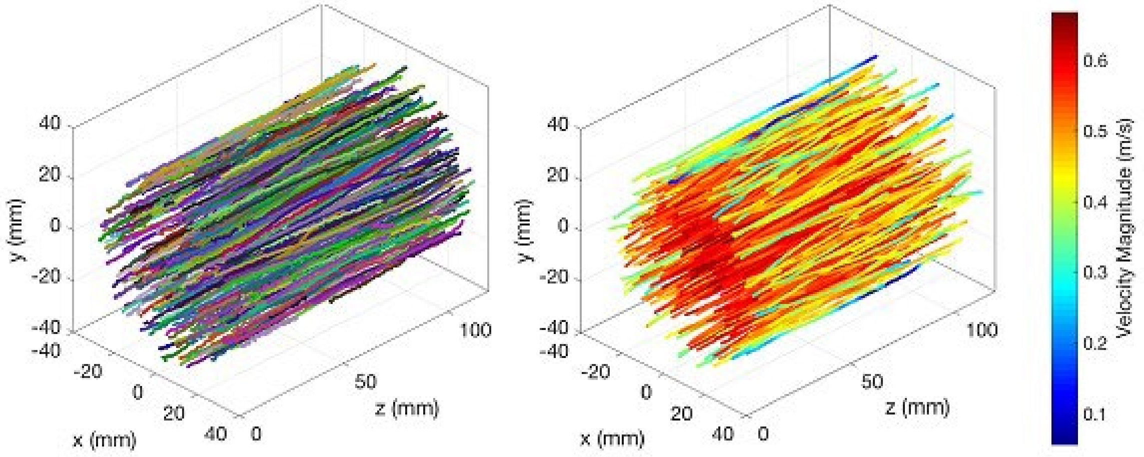


Typical line of response array in cylindrical PET scanner[1]

1. Moses, W.W., 2011, *Nucl. Instr. Meth. A*, **648**, S236

PEPT Future: Deployment

- PEPT is useful for flow measurements in opaque, complex geometries
  - Applications in science, engineering, medicine, etc.



- Requirements to establish PEPT facility:

PET Scanner / Detectors

Radioisotopes / Tracers

Available at many medical centers and research institutions

PEPT at VCU

- PEPT facilities being established at Virginia Commonwealth University under Dr. Lane Carasik and the FAST Research Group
- https://fastresearchgroup.weebly.com/

GEN IV International Forum

VIRGINIA COMMONWEALTH UNIVERSITY

Department of Mechanical and Nuclear Engineering

VCU Center for Molecular Imaging

PEPT at VCU

- Utilize Mediso LFER housed at VCU Center for Molecular Imaging

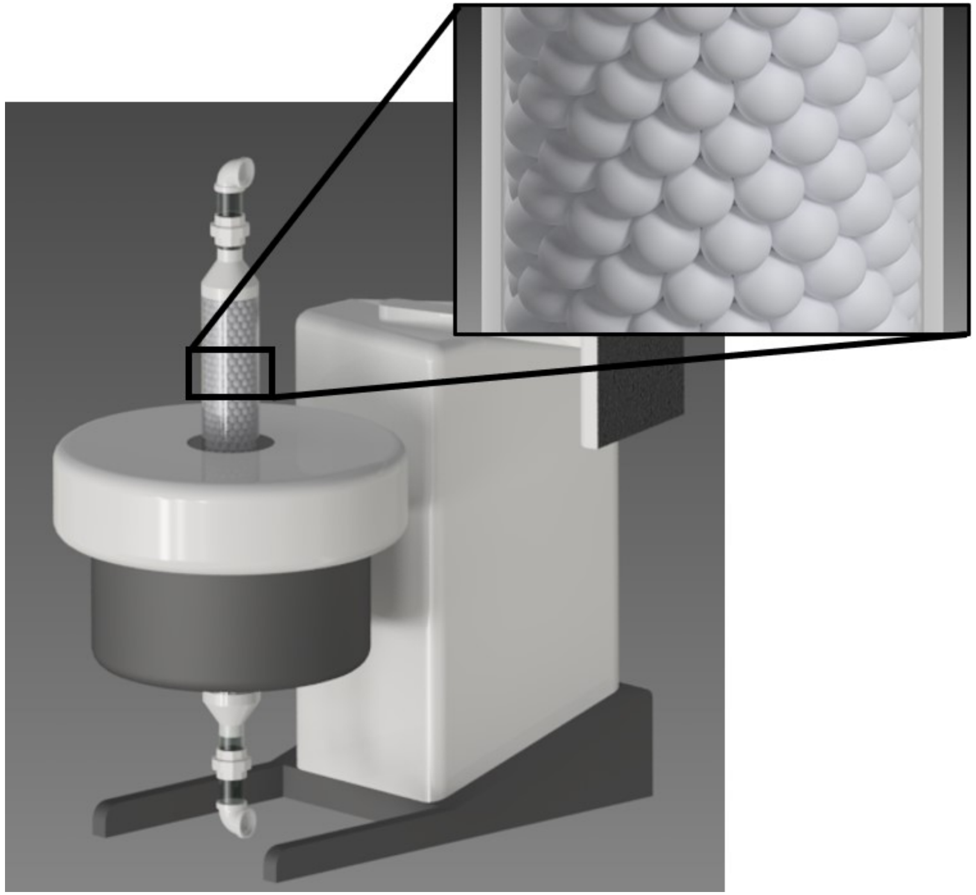
www.medisousa.com/multiscan/lfer

- LFER offers pivoting detector bore
- Enables measurements in new geometries

PEPT at VCU

- First experiments are planned to study flow in a vertical packed bed
  - Applicable to pebble bed reactor design
  - Plan to begin operation in early to mid 2021
- Continue experiments to support thermal design aspects of advanced reactors

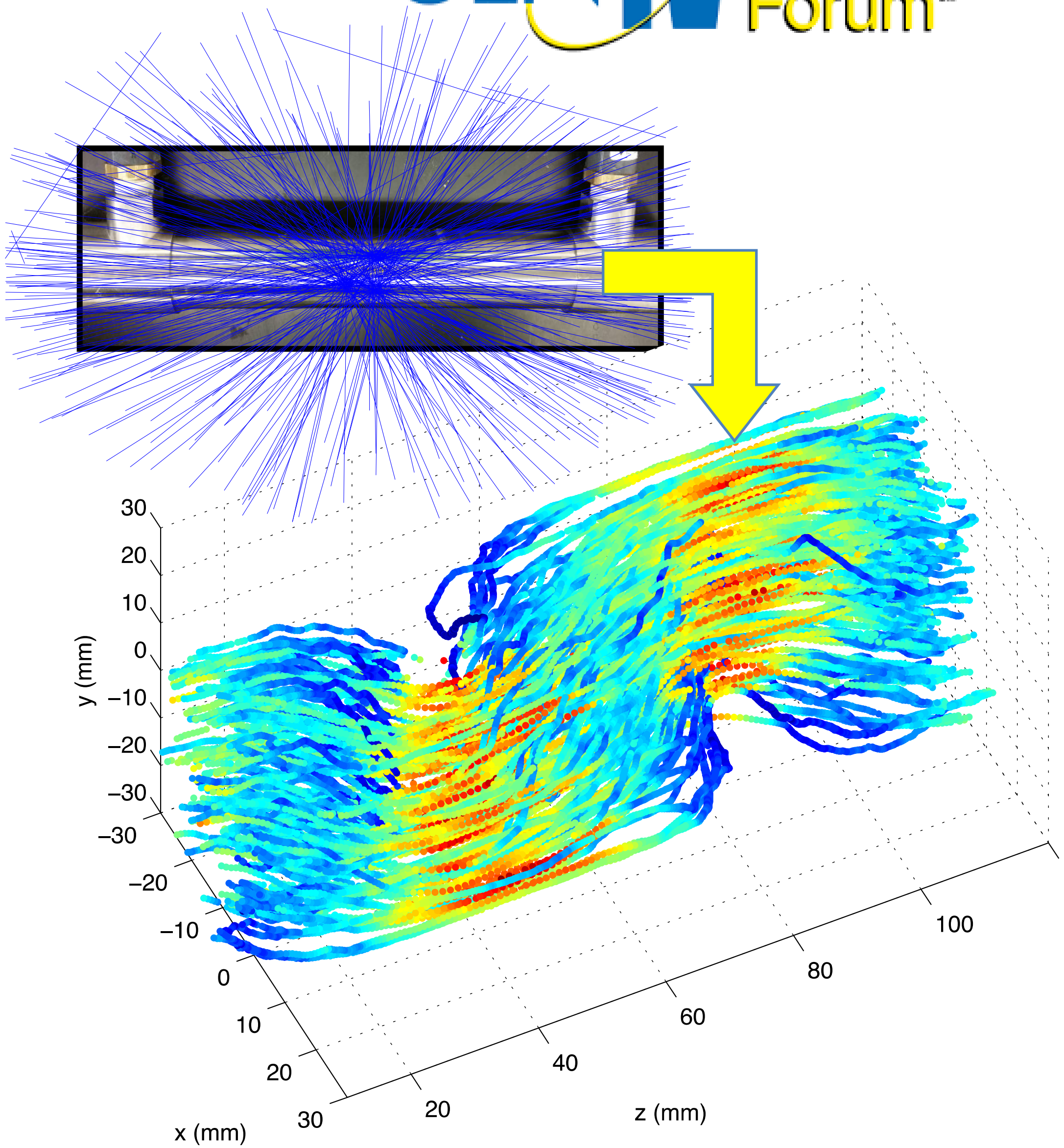
Use existing PET infrastructure to support PEPT experiments



- Build off prior packed bed PEPT work
- Study porous media flow at higher-Re

Summary

- The utility of PEPT has been demonstrated for measuring flows in opaque systems
    - Enables novel measurements for science and engineering
- Multiple-particle reconstruction methods developed at UTK allow new experiments, improved statistics
- PEPT at VCU to continue methods research and perform measurements for advanced reactor systems



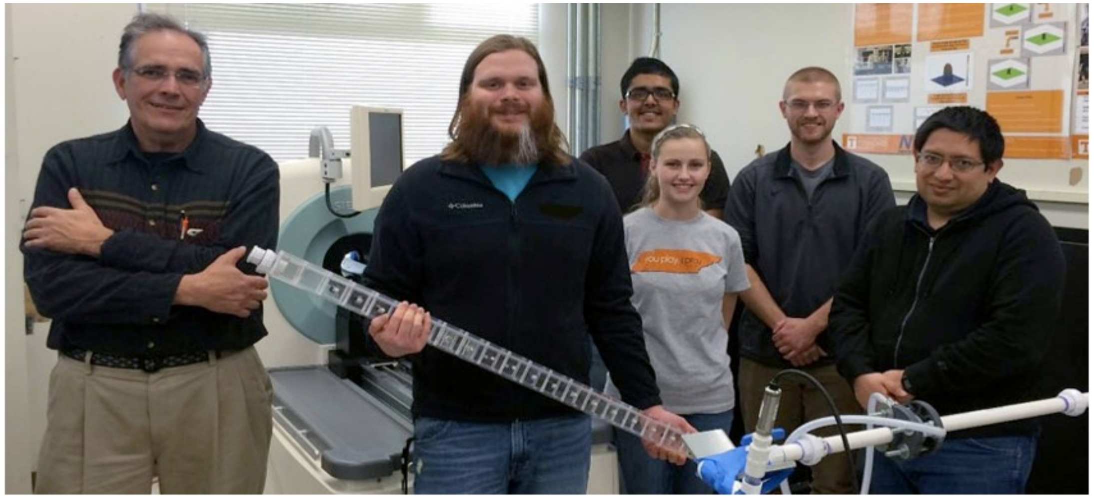
THANK YOU FOR YOUR TIME.

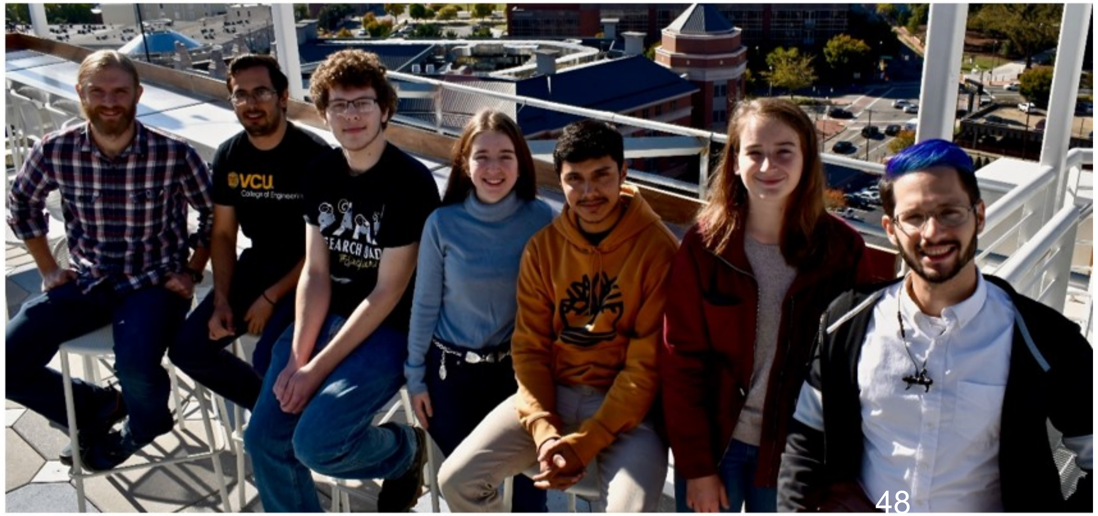
QUESTIONS?

Special thanks to:

Kate Jones (UTK Phys), Art Ruggles and the Thermal Hydraulics Research Group (UTK NE)

Lane Carasik and the FAST Research Group (VCU MNE)





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National Nuclear Security Administration

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GEN IV International Forum[SM]

Upcoming Webinars

28 January 2021	MOX Fuel for Advanced Reactors	Dr. Nathalie Chauvin, CEA, France
25 February 2021	Overview of Waste Treatment Plant, Hanford Site	Dr. David Peeler, PNNL, USA
25 March 2021	Introducing new Plant Systems Design (PSD) Code	Dr. Nawal Prinja, Jacobs, UK