Fluid Flow Measurements for Design, and for CFD Validation in Complex Geometries and Opaque Fluids

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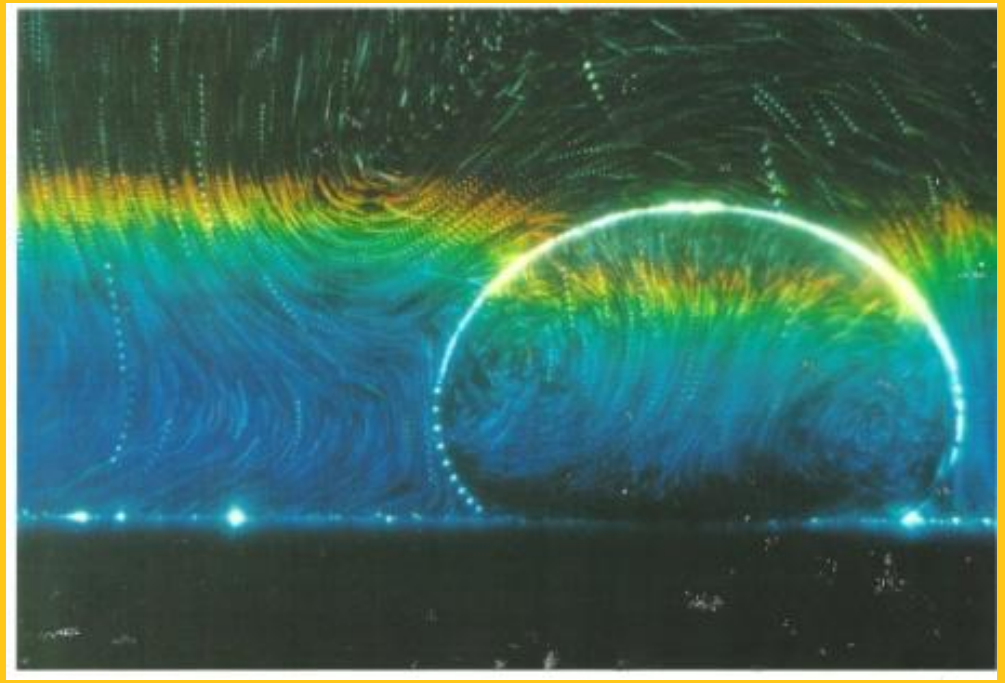

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Overview of Methods and Capabilities

Legacy Methods
Current Optical Methods, Transparent Fluids
Methods for Opaque Fluids and Opaque Structures

1. Computed Tomography, Gamma, Density Distribution
2. Neutron Radiography, Density Distribution in Time
3. Neutron Radiography with Seeds, PIV and Density vs Time
4. Ultrasonic Imaging, PIV and/or Doppler, time resolved particle trajectories.
5. Positron Emission Tomography (PET), diffusivity and velocity, with time resolution
6. Path Forward

Legacy Methods for Mean and Turbulent Fluctuation measurement, Prior to Laser Based measurements, and Digital Data Acquisition (i.e., before around 1980).

Film Video with:

- smoke, electrolysis bubbles, tufts and fibers, etc.

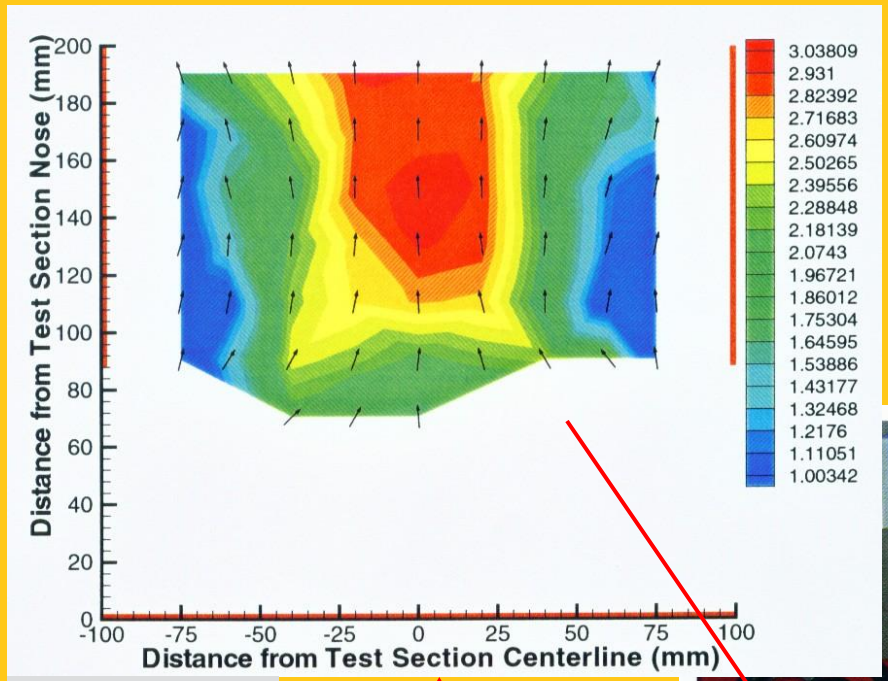
Hot wire anemometer and variants:

- high speed resistive thermometers
- high speed thermocouples

High speed conductivity/concentration probes with “salt” addition*

High speed pressure measurement

$$\vec{v} = \bar{u} + u'\,\hat{i} + \bar{v} + v'\,\hat{j} + \bar{w} + w'\,\hat{k}$$



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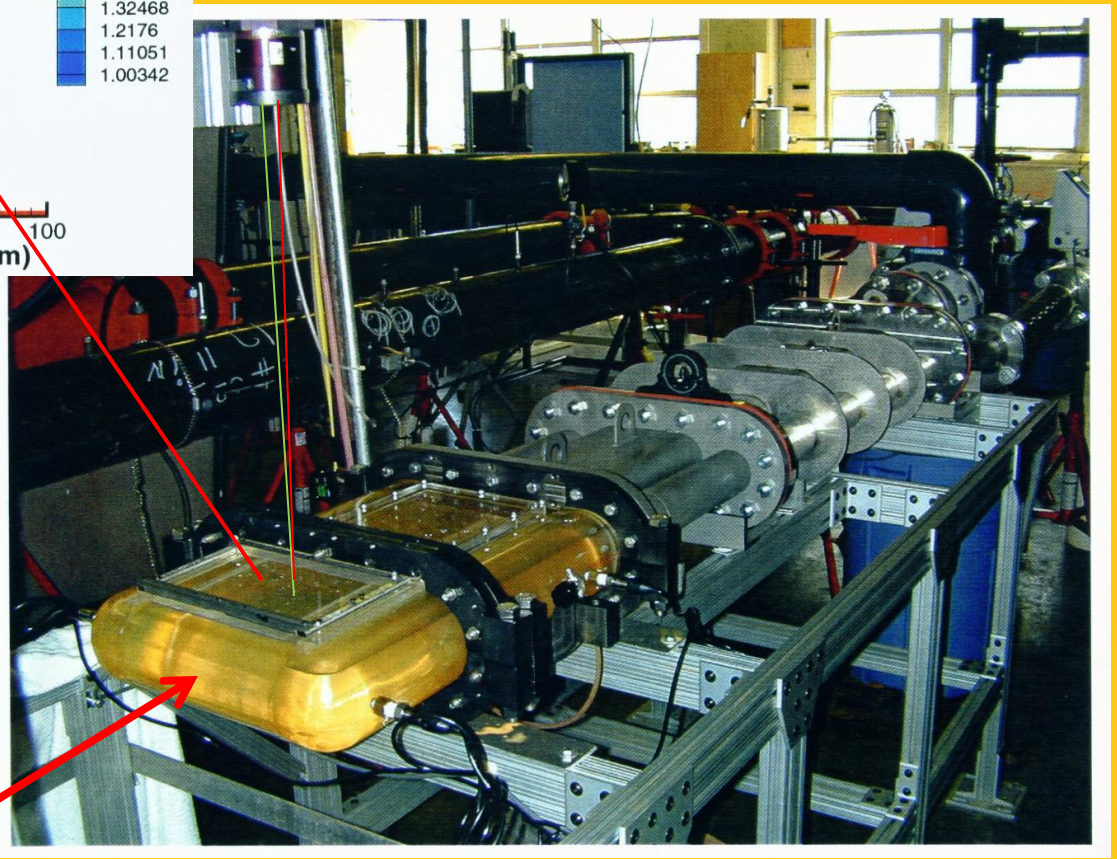
Beam

SNS Target Flow Characterization 1996.

Beam

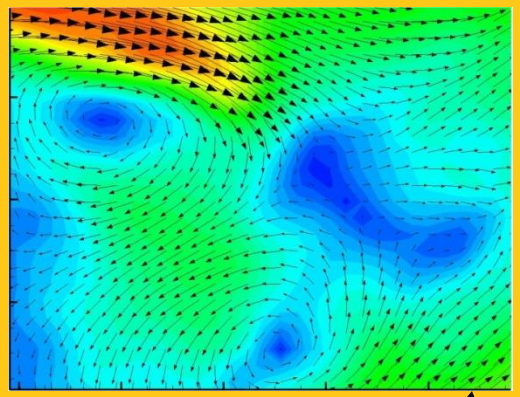
History:

Laser Doppler Velocimetry (LDV) Time Resolved, Single Point Measurement of Velocity in Transparent Fluids (80's-present).

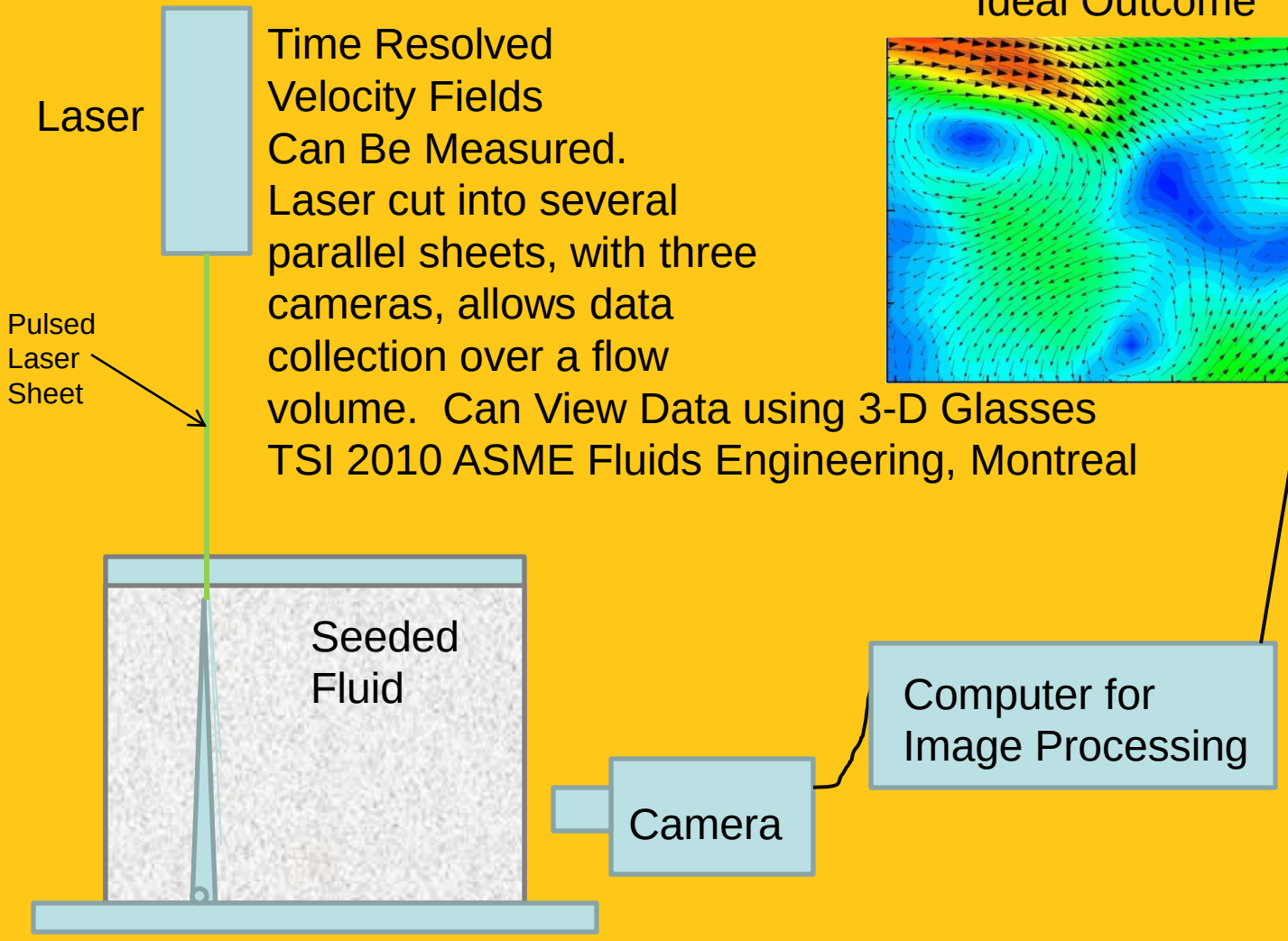


Particle Image Velocimetry (PIV), in current use, requires seeded transparent fluid (90's to present).

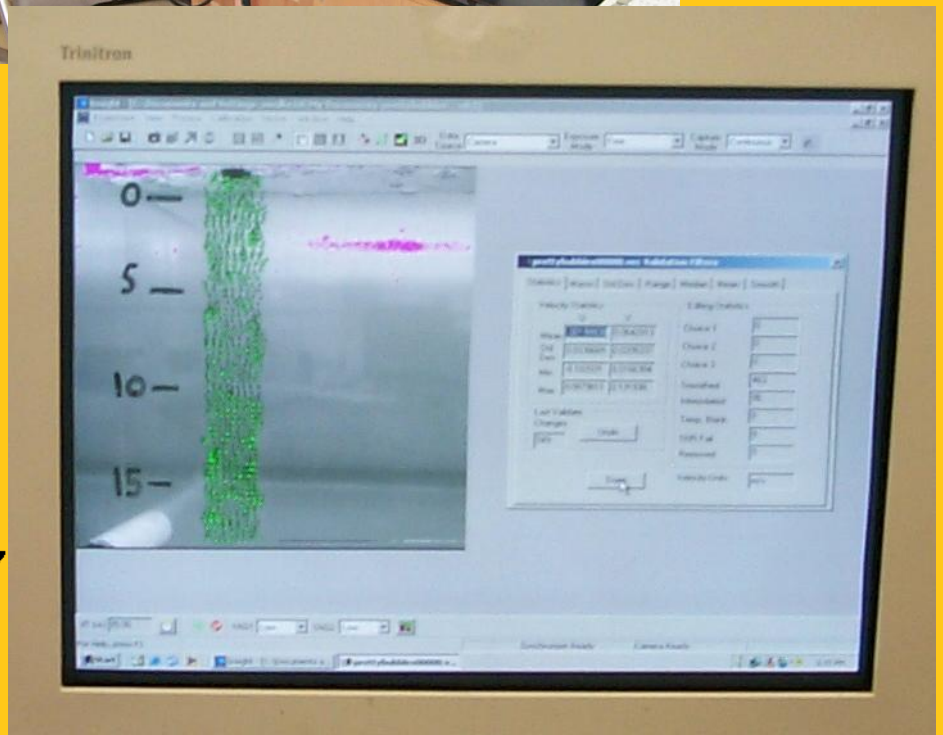
Ideal Outcome



Time Resolved Velocity Fields Can Be Measured. Laser cut into several parallel sheets, with three cameras, allows data collection over a flow volume. Can View Data using 3-D Glasses
TSI 2010 ASME Fluids Engineering, Montreal

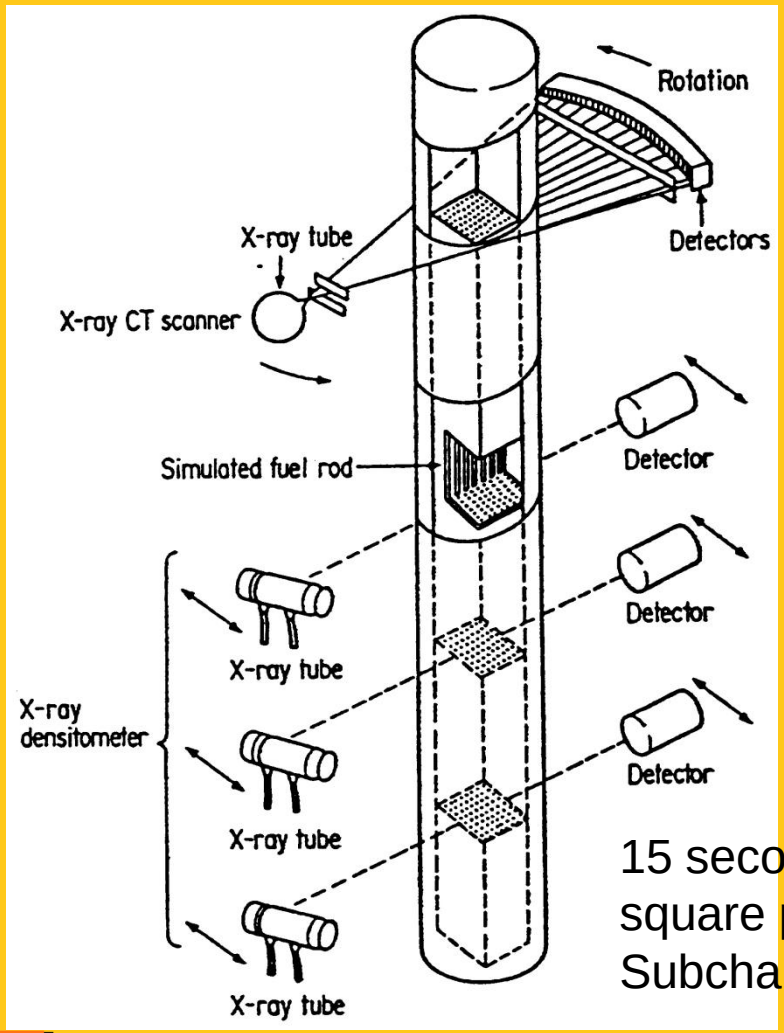


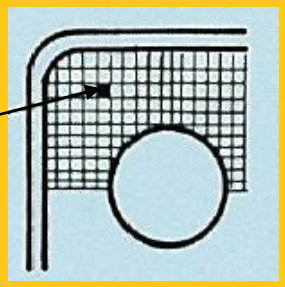
PIV used to Validate Ultrasonic Doppler Measurements For Bubble Rise Velocities.

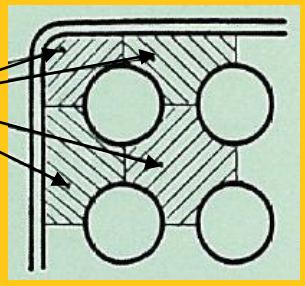


Laser Sheet illuminates particles in Flow Field In Pulsed Mode to Produce Multiple Exposures in Camera Image. Movement of Illuminated Particles (bubbles) used to Evaluate Velocity. Validation of Ultrasonic Doppler for Later use in opaque fluids (mercury).

BFBT Benchmark, IAEA with NRC Purchased Data from 1990's For Code V & V.



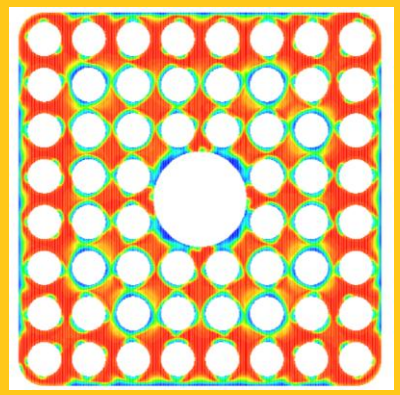




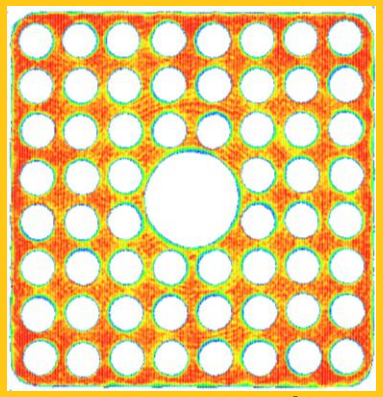
15 second average gamma count data for mm square pixel void topology. Conventional 1-D Subchannel methods can be refined to 3-D CFD.

BFBT Benchmark Simulation Results
Test 4101-61, Exit Quality = 25%
Baseline

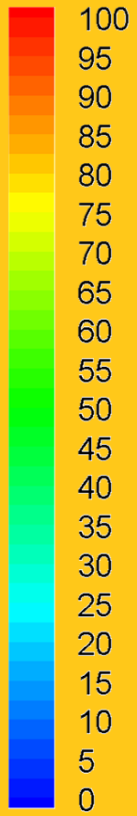
Microscopic Distribution



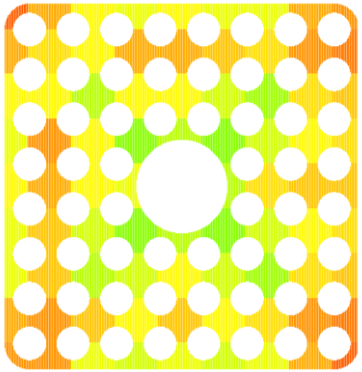
Predicted void fraction



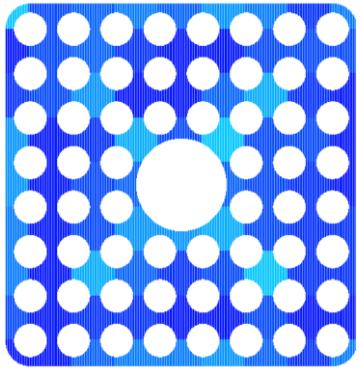
Measured void fraction



Channel Averages



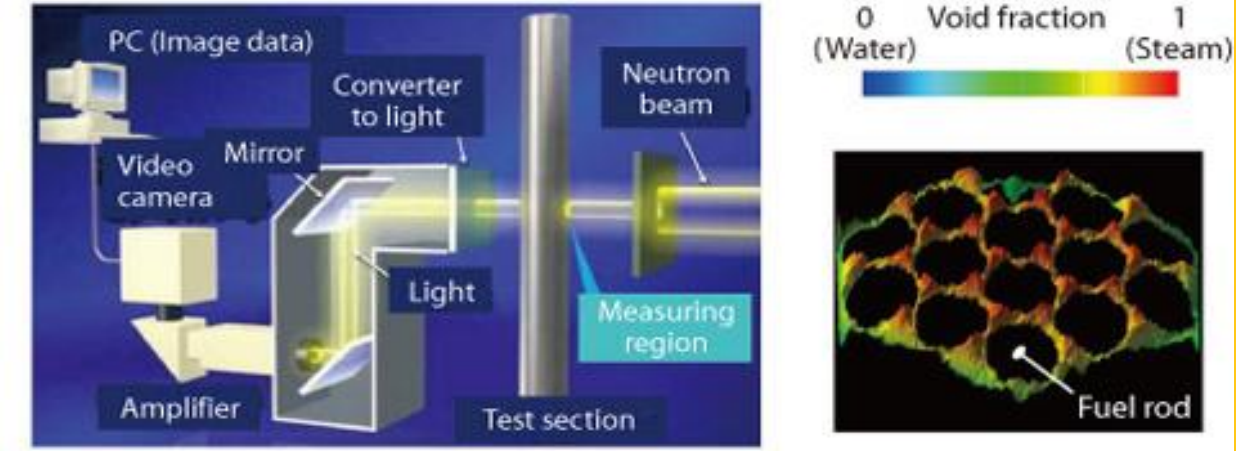
Predicted void fraction



Percent Error

ICONE 17-Tentner and Pointer
ANL and CD-Adapco, 2009

Proposed Neutron Radiography Capability for CHF Testing, and Methods Development.



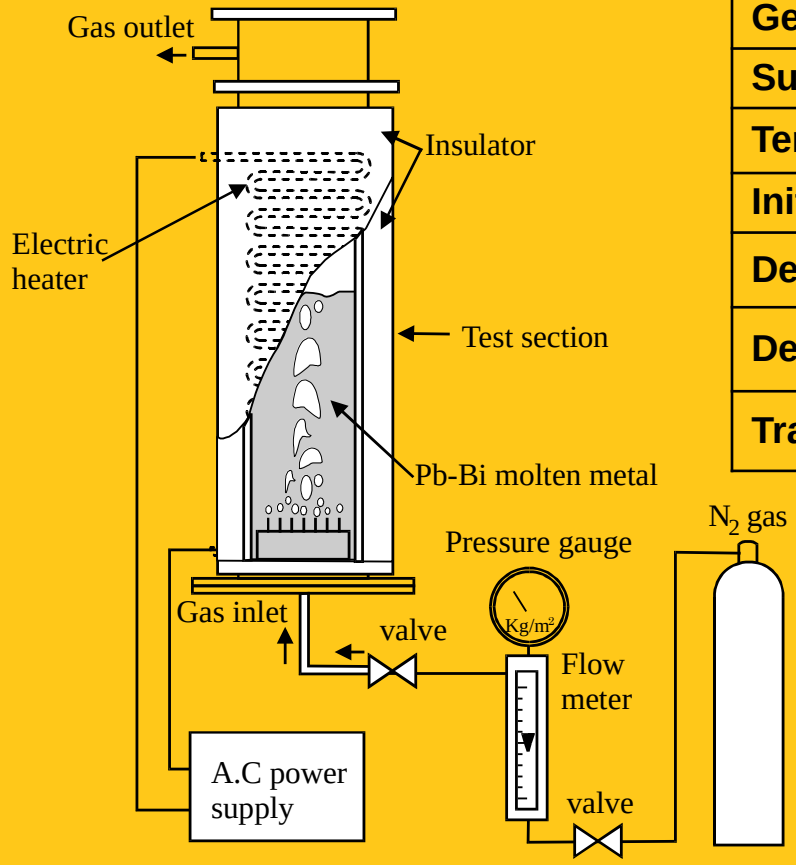
(a) Principle of neutron radiography

(b) Measured result

JAERI, Annual 2000

The principle shown here requires the rod bundle to turn, or the neutron beam and camera rotate around the bundle.

Neutron Radiography/PIV



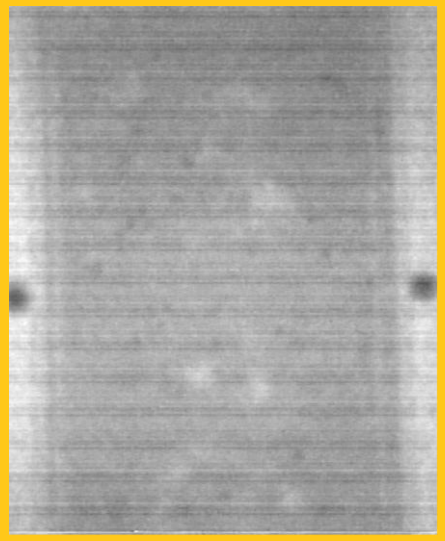
Schematic of the flat bubble column

Geometry	**100(W)×10(D) ×200(H)**
Superficial gas velocity	**0~15cm/s**
Temperature	**150°C**
Initial liquid height	**12cm**
Density of PbBi	**1057 kg/m^3**
Density of $AuCd_3$	**1070 kg/m^3**
Tracer diameter	**1~1.5mm**

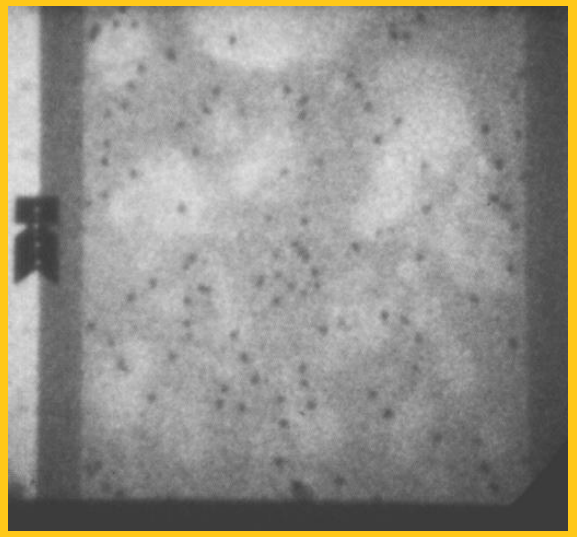
Neutron Source: JRR-3M in JAERI
Camera: Super10K 512×480pixels
HG-100K: 1504×1152pixels
I.I. : GaAsP 1MCP & Inverter type I.I.
Rec.speed: 250fps; T_G=1ms
Resolution: 250μm/pixel

K. Mishima, with permission

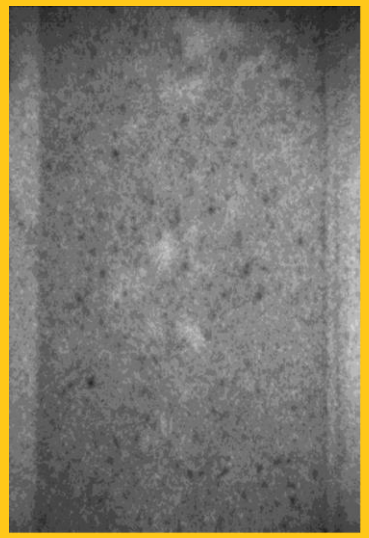
Comparison of Neutron imaging systems



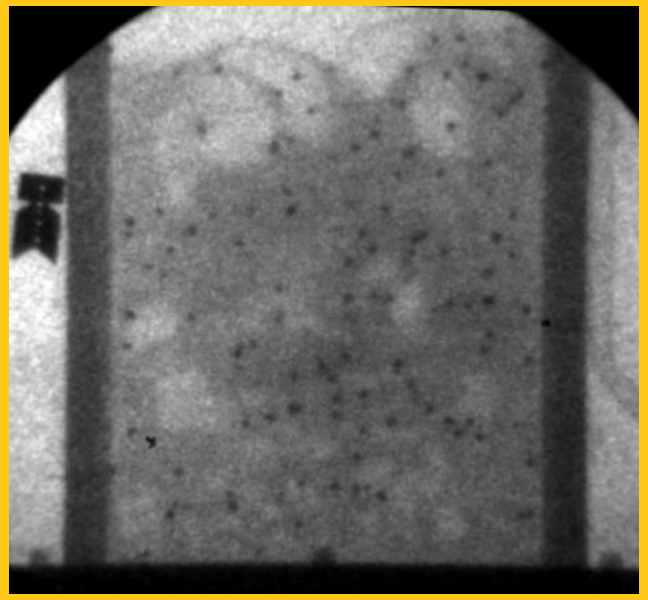
Photoron ultima (256×256) S20 2MCPs



Photoron Super10K (512×480) GaAsP 1MCP



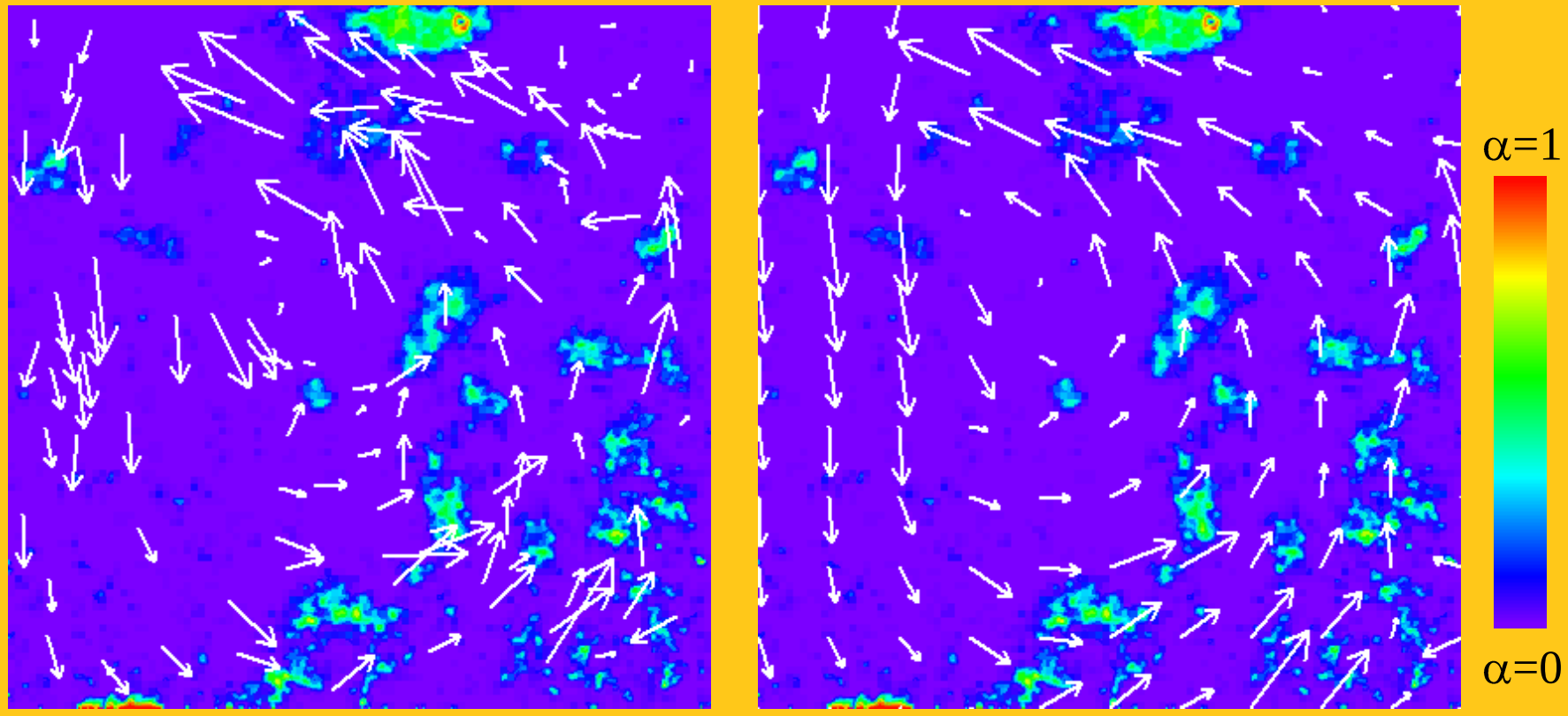
Photoron Super10K (512×480) S20 2MCPs



RedLake HG-100K (1504×1128) S20 1MCP

Combined Void and Liquid Velocity Data

j_g=3.4cm/s



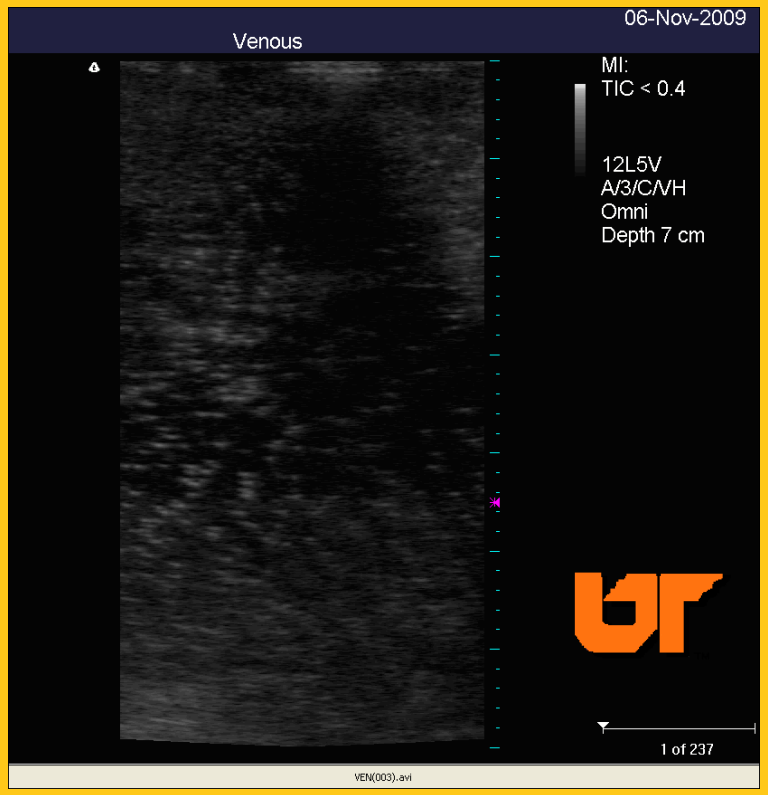
a) Raw data

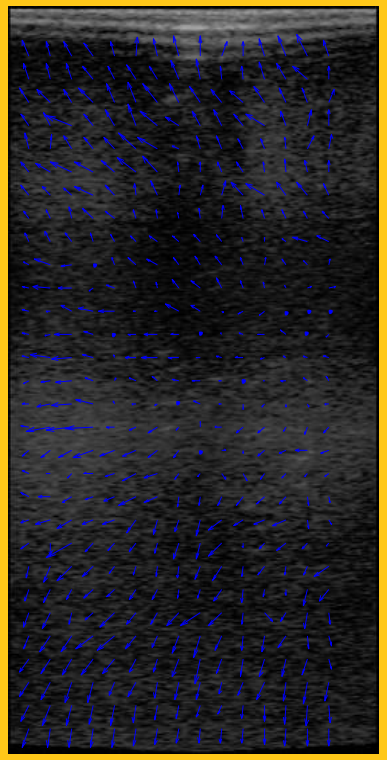
b) After griding

Ultrasonic Imaging used for PIV, and Image Doppler Measurements in Water and Mercury

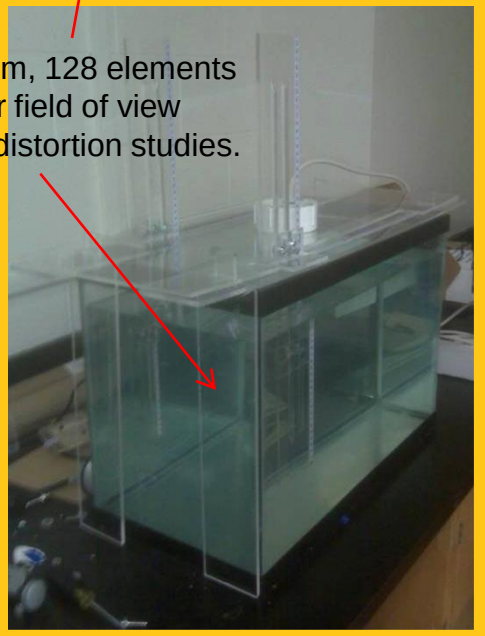
Terason Probe

Some success in PIV application for mercury. Targets are required for good echoes, and frame rate is slow (30 fps). However, with more effort this could work well in liquid metals.





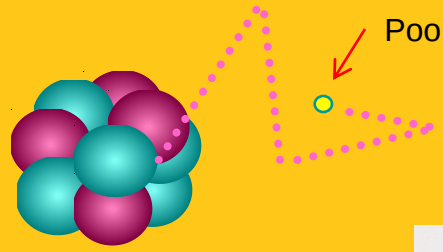
Probe bottom, 128 elements
Mounted for field of view
and image distortion studies.

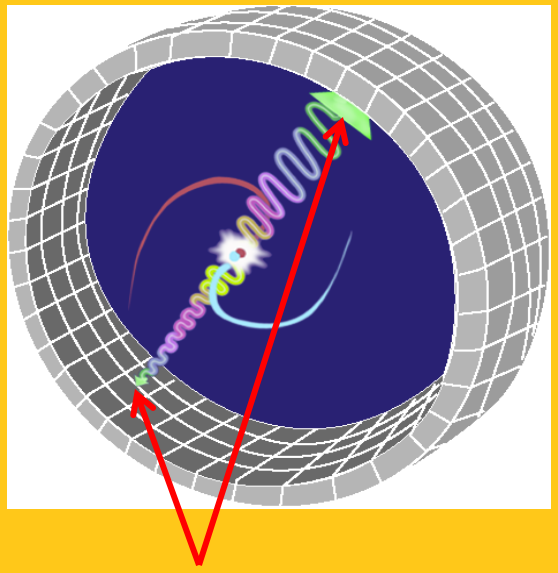


Cyclotrons for PET Isotopes and Neutron Production

Some Candidate Isotopes to Produce for Flow PET: O18 to F18 (100 min); N14 to O15 (2 min); O16 to N13 (10 min); N14 to C11 (20 min). 6 Ci of O15 in 10 seconds*, 2 Ci of F18 in 60 min. Ship ½ Ci F18 in 70 lbm casks in PET Net*.

Positron Emitters used in Positron Emission Tomography (PET) imaging Applications. F18 is most commonly used.

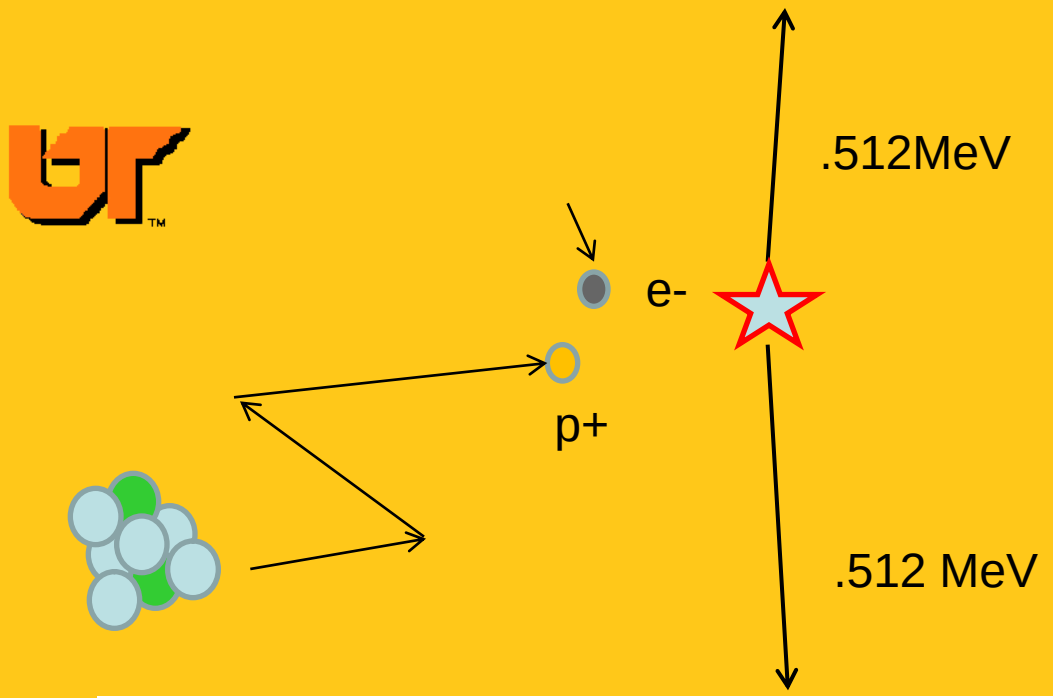




Coincident Events Counted to Speed Image Reconstruction relative to SPECT.

Rod Bundle

Fundamental PET Resolution Limitations from Physics

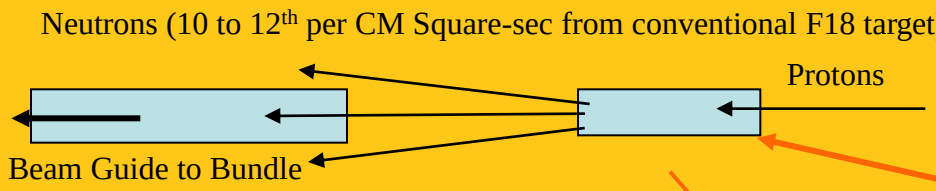


Some imaging systems use time of flight to locate annihilation along the chord.

a. Positron will travel some distance from nucleus prior to annihilation
    1. initial energy, Isotope dependent
    2. media

b. Twin Gammas not perfectly aligned in Lab Reference. Inferred annihilation position uncertainty grows with detector separation.

Cyclotron also produces Neutrons unused in medical PET, but possibly useful to engineering applications.

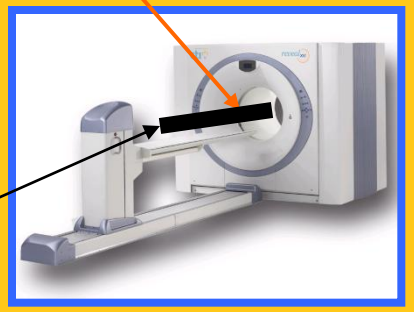


Cyclotron Target

Cyclotron Target can Produce PET Isotopes and Neutrons Simultaneously.

Positron Emitting Isotope, F18 Delivered to Bundle

Rod Bundle Replaces Patient


PET Imaging

Cyclotron

Turbulent Mixing Downstream of Spacer Grid, diffusivity and dispersion available in PET Image.

Rod Bundle figure from TTF data Campaign at ornl in 1980's.

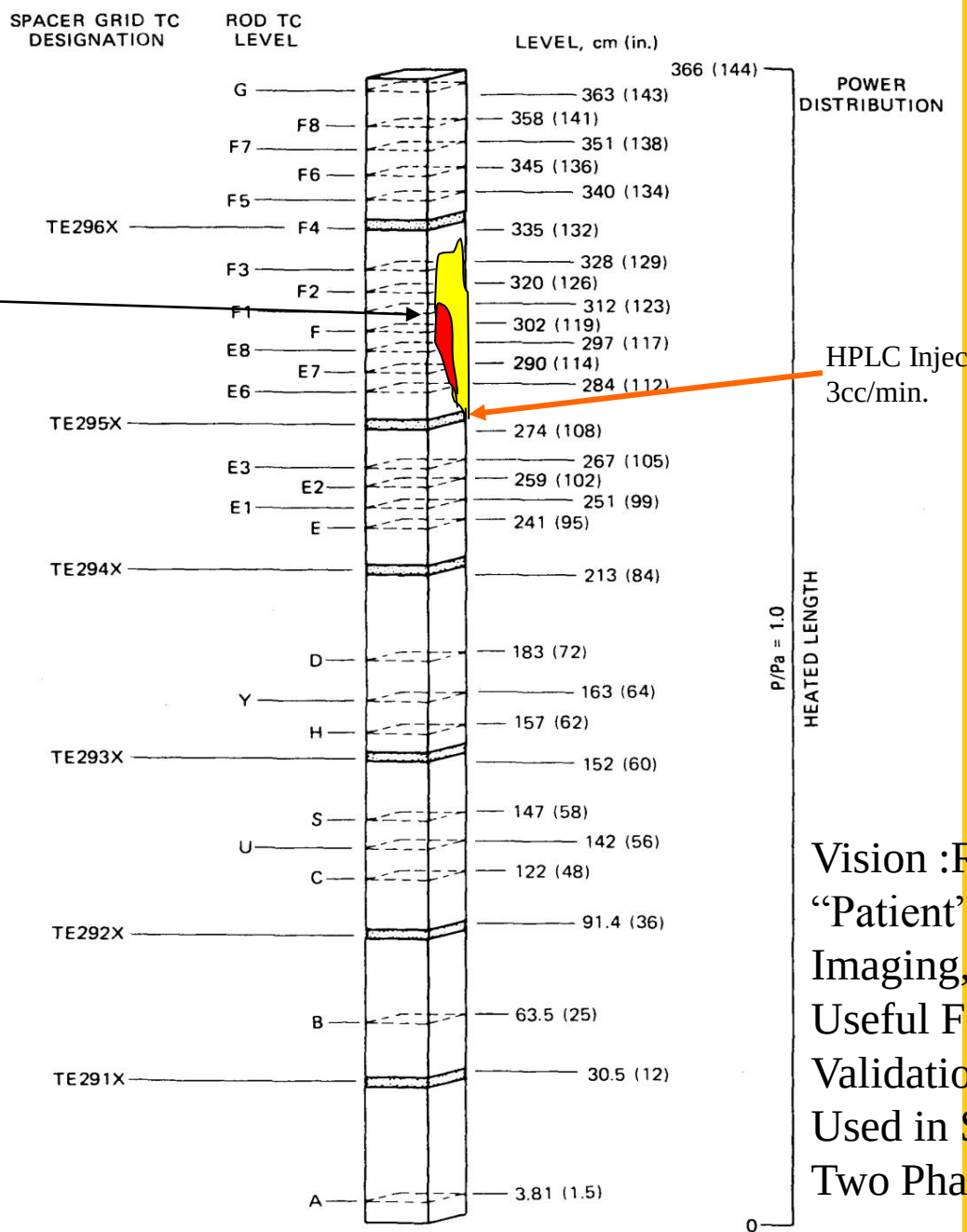


Fig. 3. Location of spacer grids and rod TCs.

HPLC Injection of PET Isotope, 3cc/min.

Vision :Rod Bundle as "Patient" for PET Imaging, Data are Useful For Method Validation. May be Used in Single and Two Phase Flows

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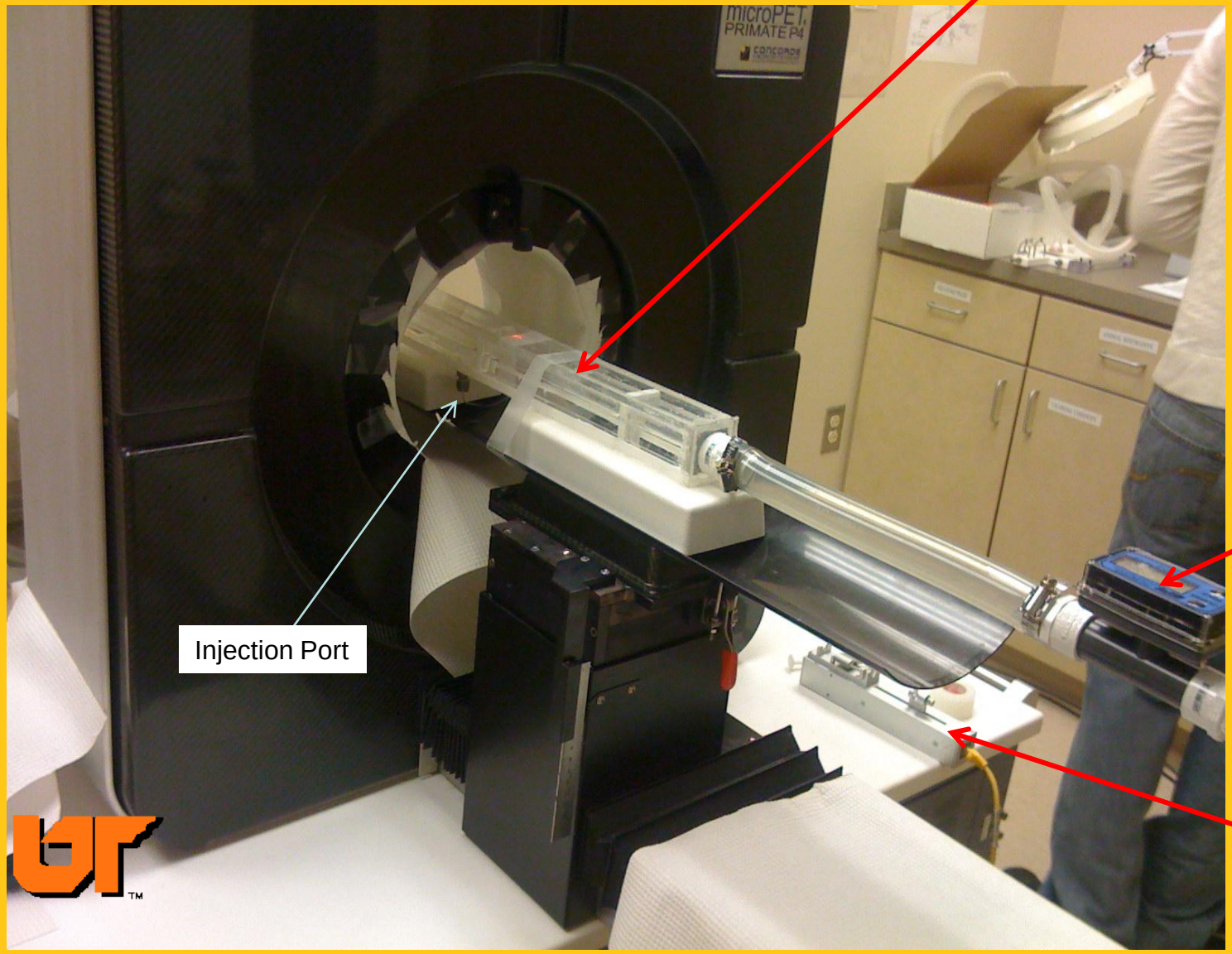
Flow Pet Image Test using Micro-PET Primate P4



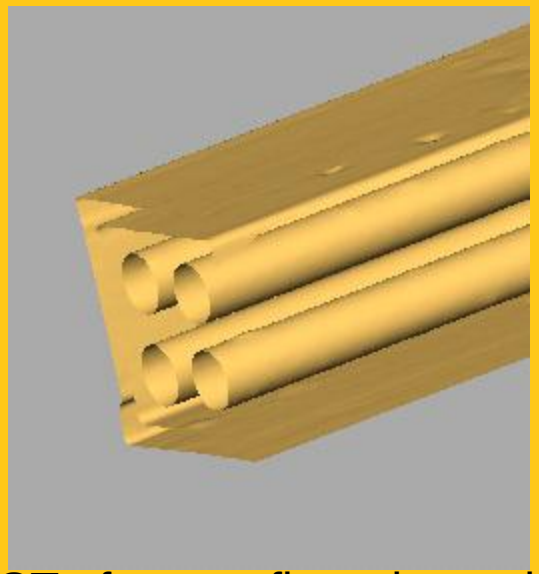
Flow Pet Image Test using Micro-PET Primate P4

Once thru flow, 29 mCi activity
in F18 in 3cc volume injected
through a hypodermic tube
into main flow over 60 seconds.

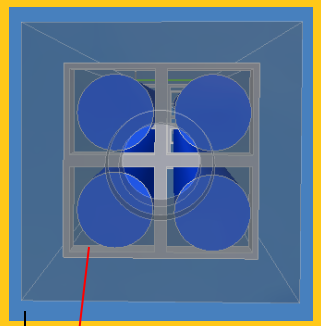
P4 resolution is 1.8mm, Full Width
Half Maximum (FWHM).
P4 is underutilized since the next
generation imaging machine
is 100 times faster capturing counts
and has FWHM resolution 1.4mm.

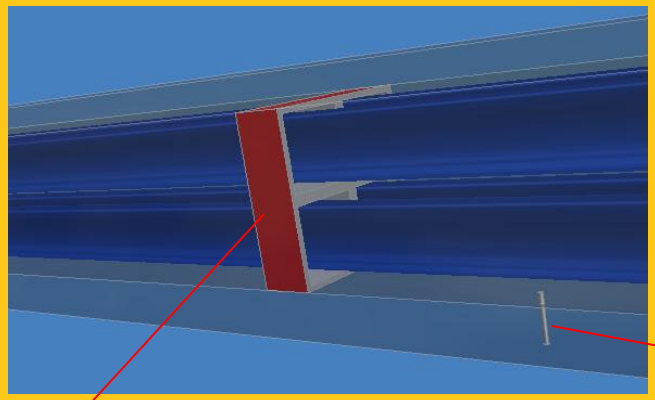
Exhaust Tank, F18 100 min half life allows us to pour this down the drain the next day.

Four pin bundle, 3 solid spacer grids, 28 gage needle injection for F18, Re=1200.
Flow cross-section is 2 inches square
Pins are ½ inch diameter.



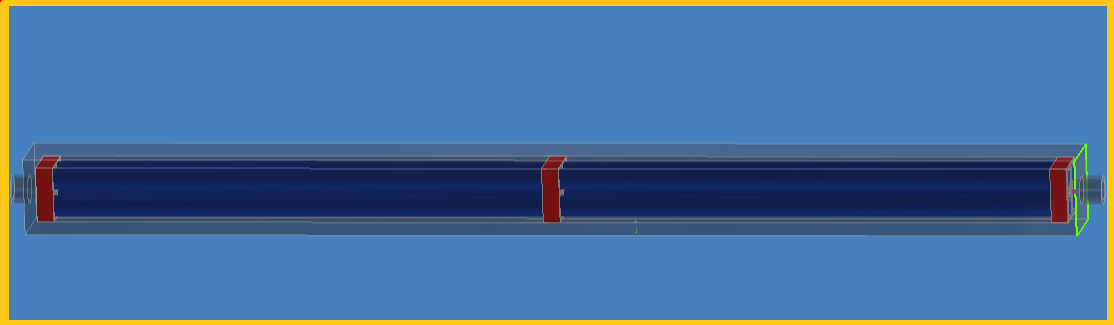
CT of empty flow channel
PET-CT often combined
In conventional scanners.

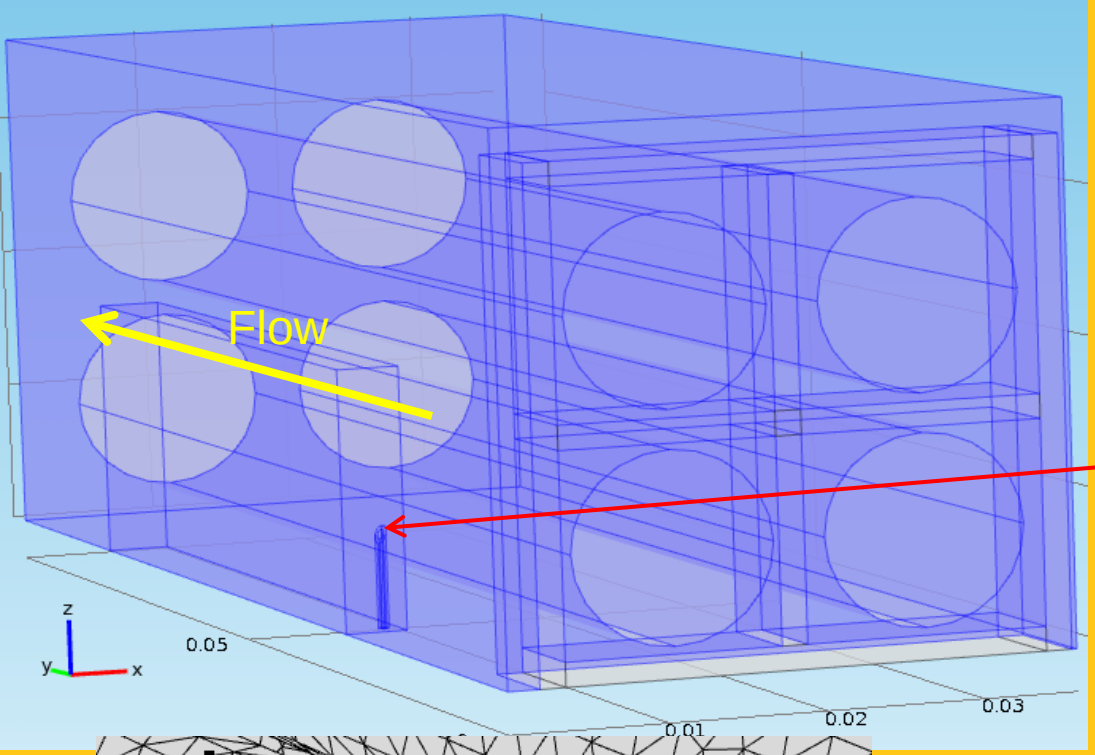




Injection Point

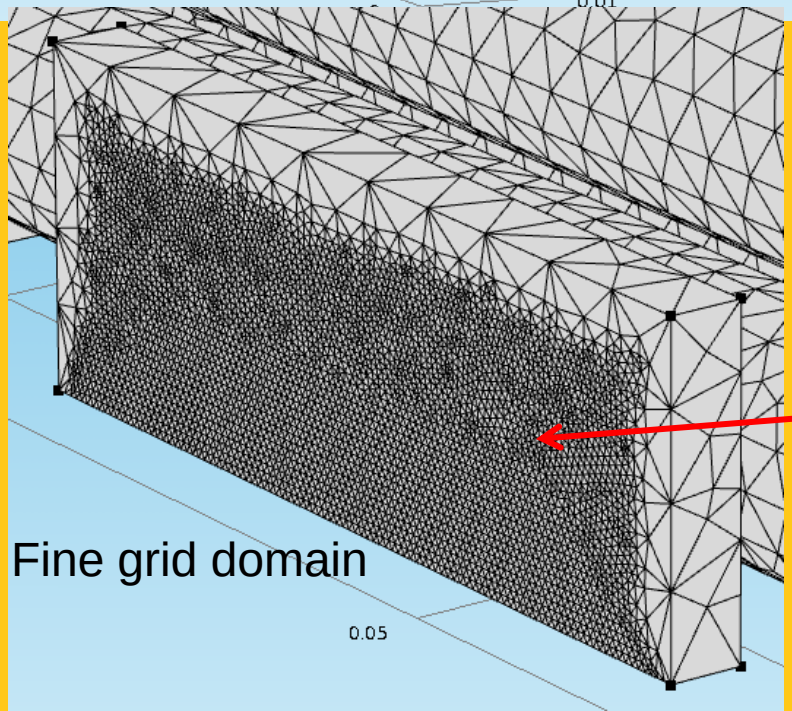
Solid Spacer Grid





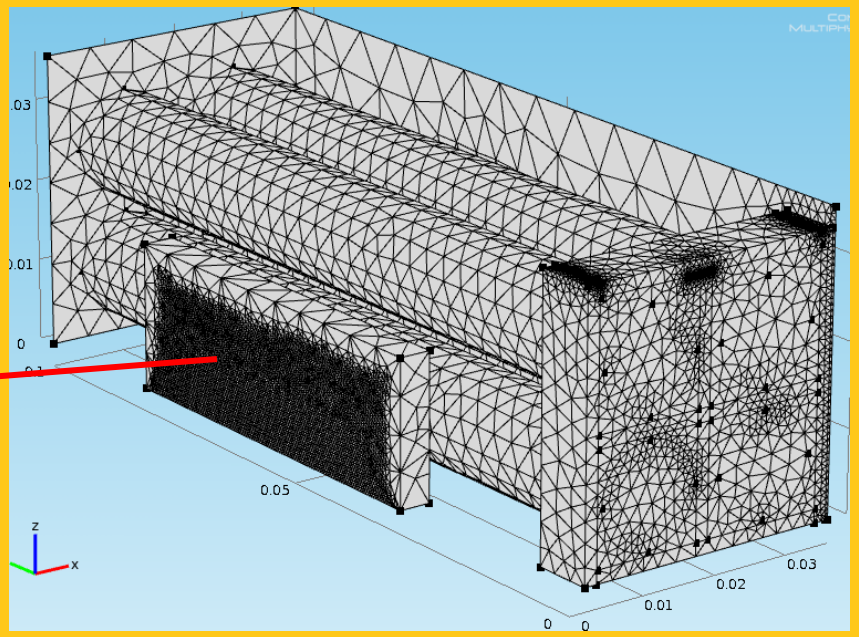
COMSOL Model: 513,000 mesh, 3.5 E6 DOF, k-ε, 10 Hours on dual quad processor, 64 Bit workstation.

Injection point

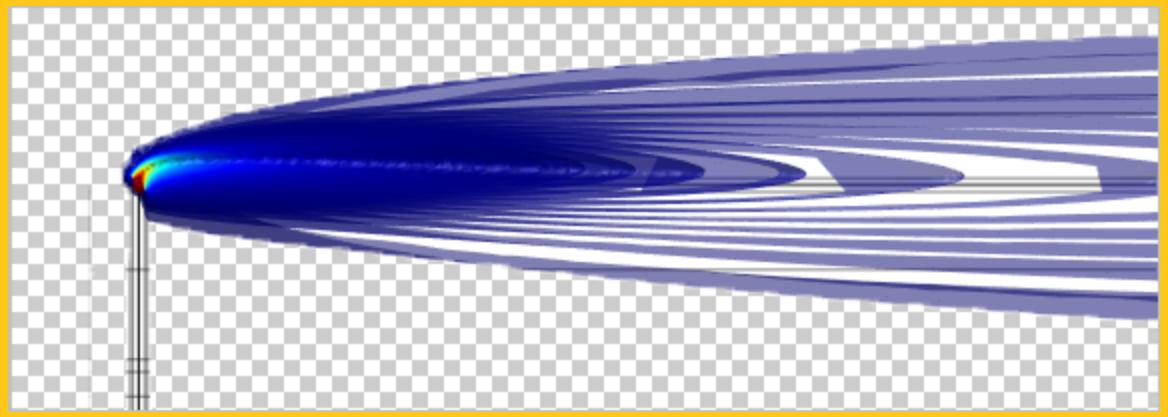


Fine grid domain

Mesh

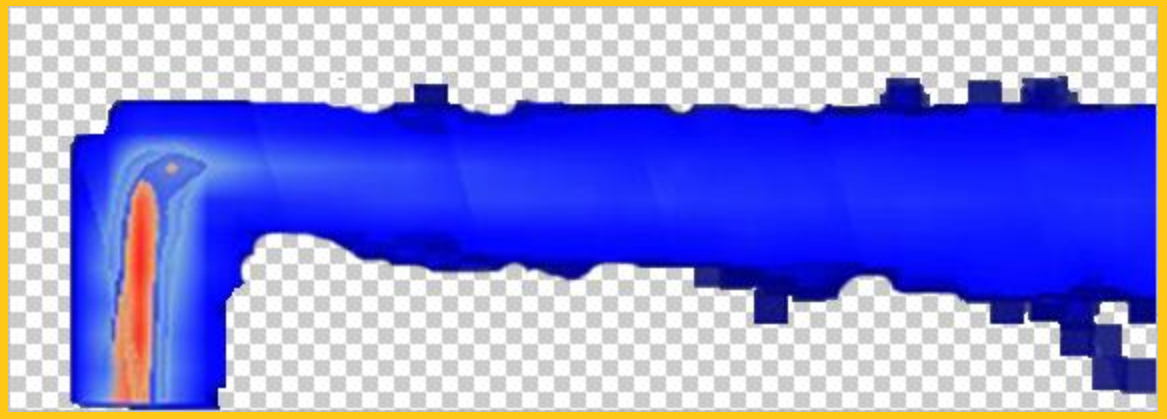


Result from
Dye test



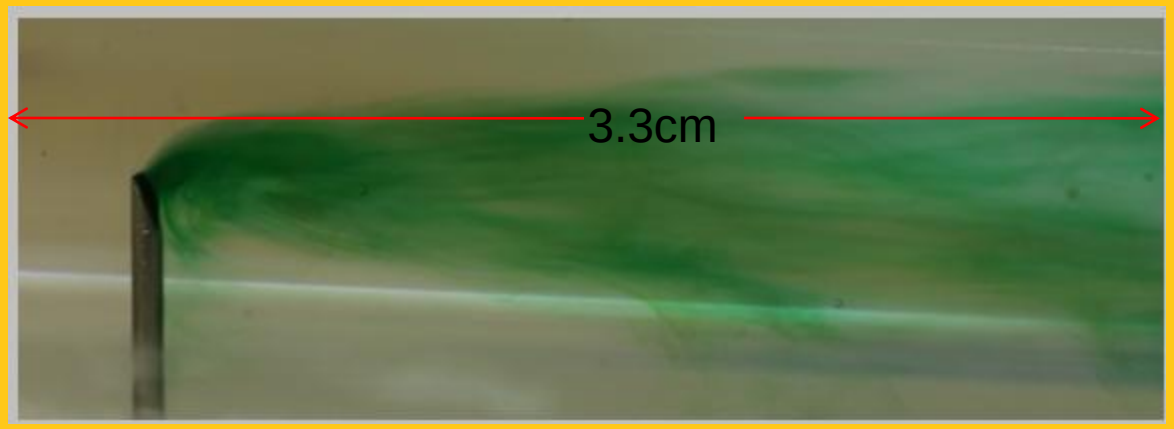
Result form
COMSOL

Superimposed
image



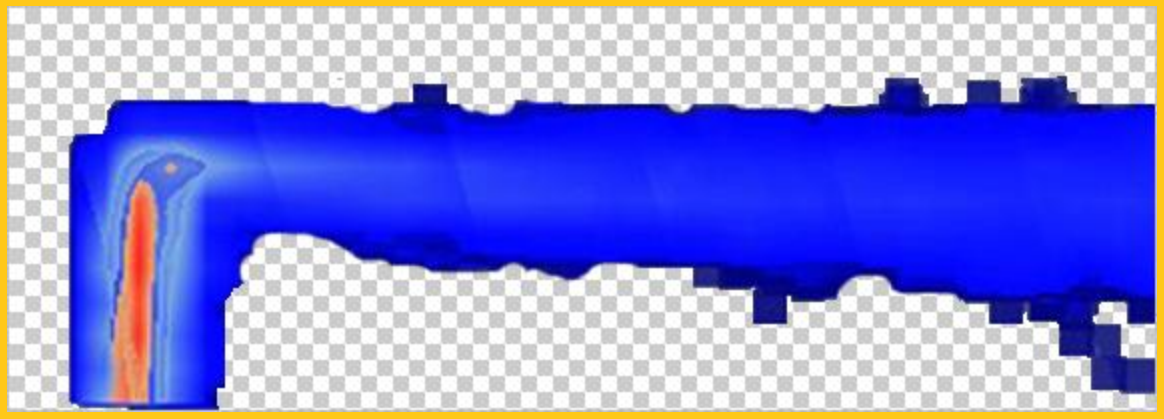
Result from PET Image

Amira is used to select 2D image from 3-D data to import to Photoshop

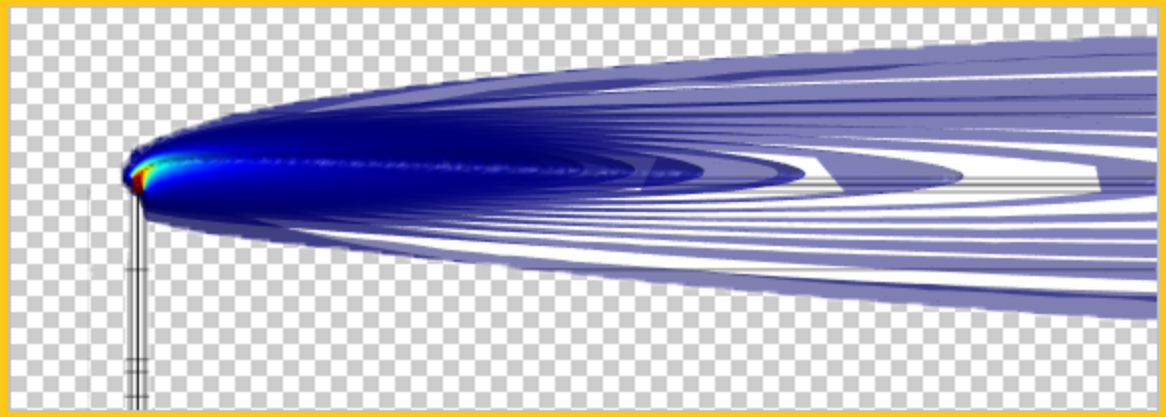


Result form Dye test

Superimposed Images



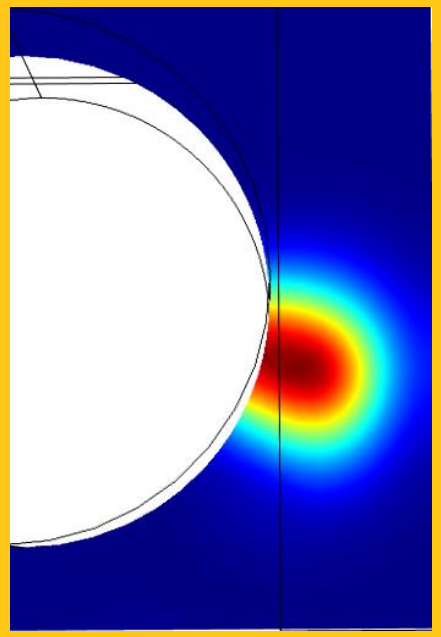
PET Data



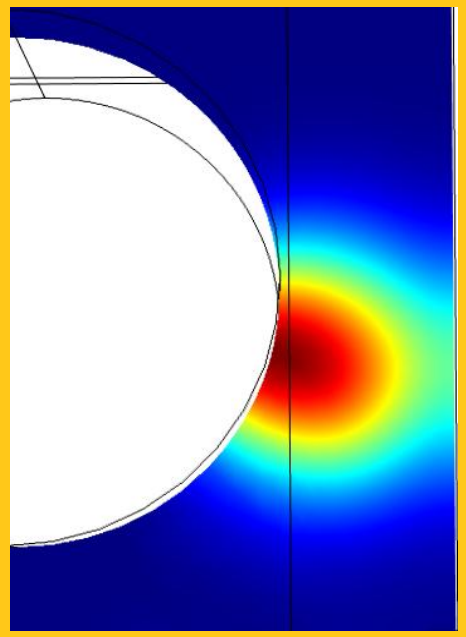
COMSOL

PET Data
Versus
COMSOL

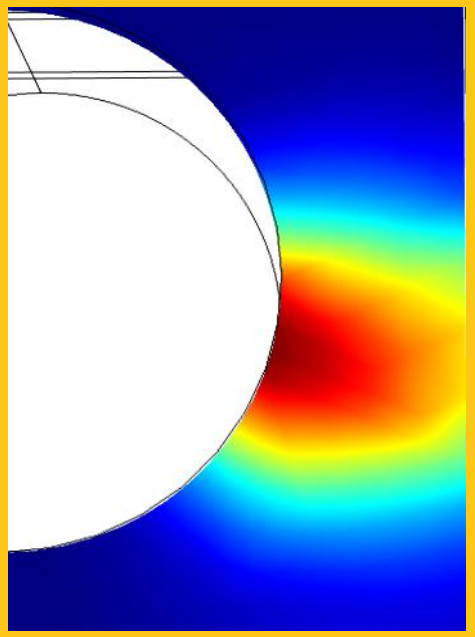
COMSOL Plume Axial Slices at Three Positions Downstream of Injection



2 cm

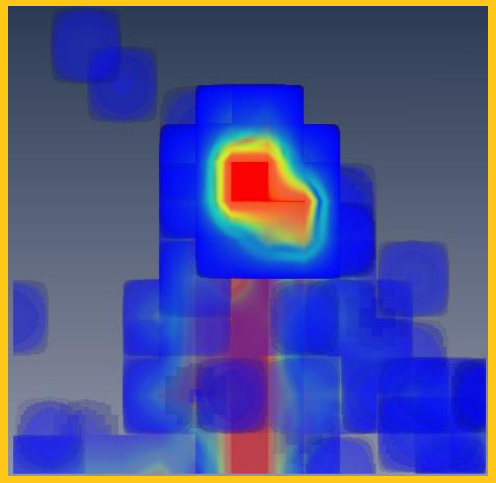


4 cm

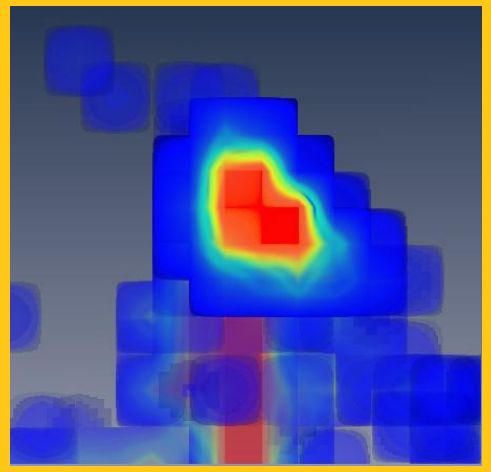


6 cm

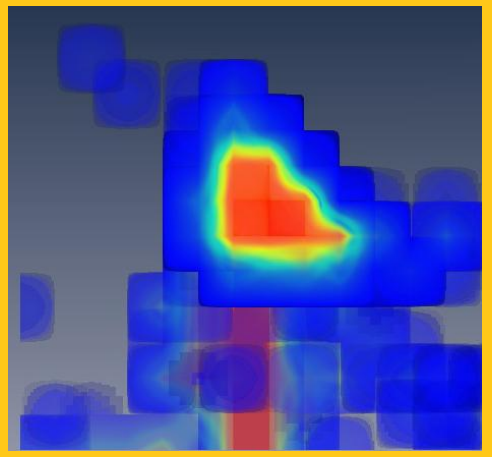
PET Plume Slices at Three Positions Downstream of Injection (Note Upstream Data is Ghosted)



2 cm

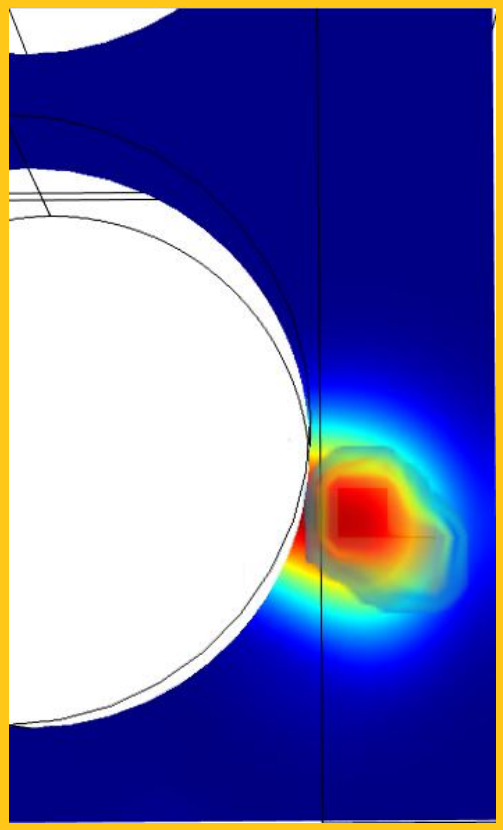


4 cm

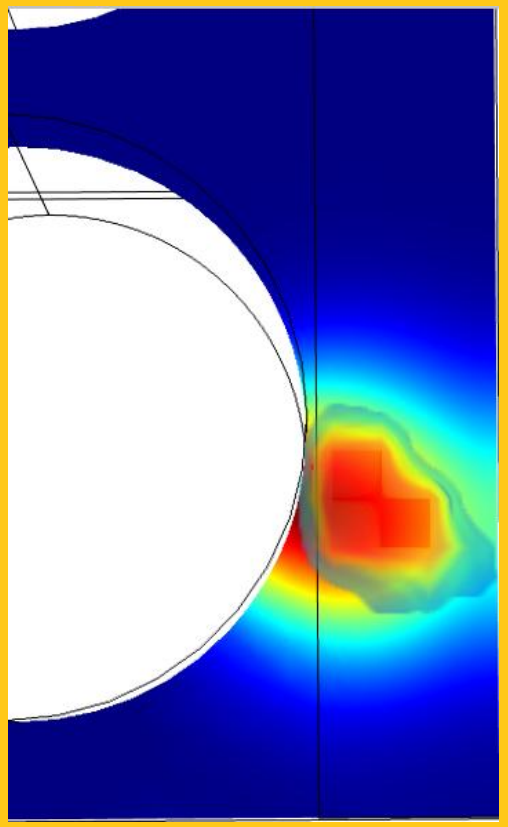


6 cm

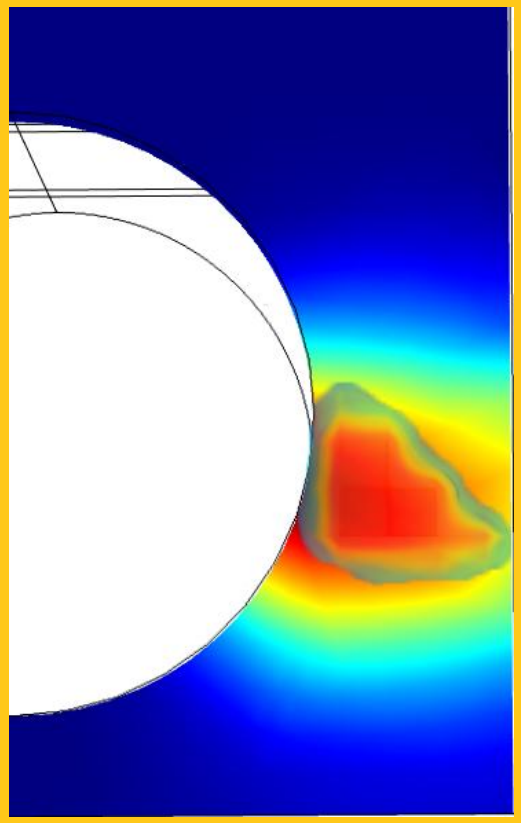
COMSOL & PET Superimposed Images



2 cm



4 cm



6 cm

More Details of Metrology and Visualization

Note the turbulence here is driven by upstream spacer and inlet flow distribution screen. Action is mostly “dispersive”.

Concentration variation is distinct, driven by stretching of inlet stream and action of large eddies formed by the spacer.

Analogue of Activity per unit volume to concentration: 10 mCi/cc equal to 10 μCi per μ liter. Voxel volume in bore is 5.8 μ liters. New machine volume of pixel is 2.7 μ liter.

Activity is reported as 3D image output scalar. Some magic seems to occur in the image rendering programs (smoothing plus….)

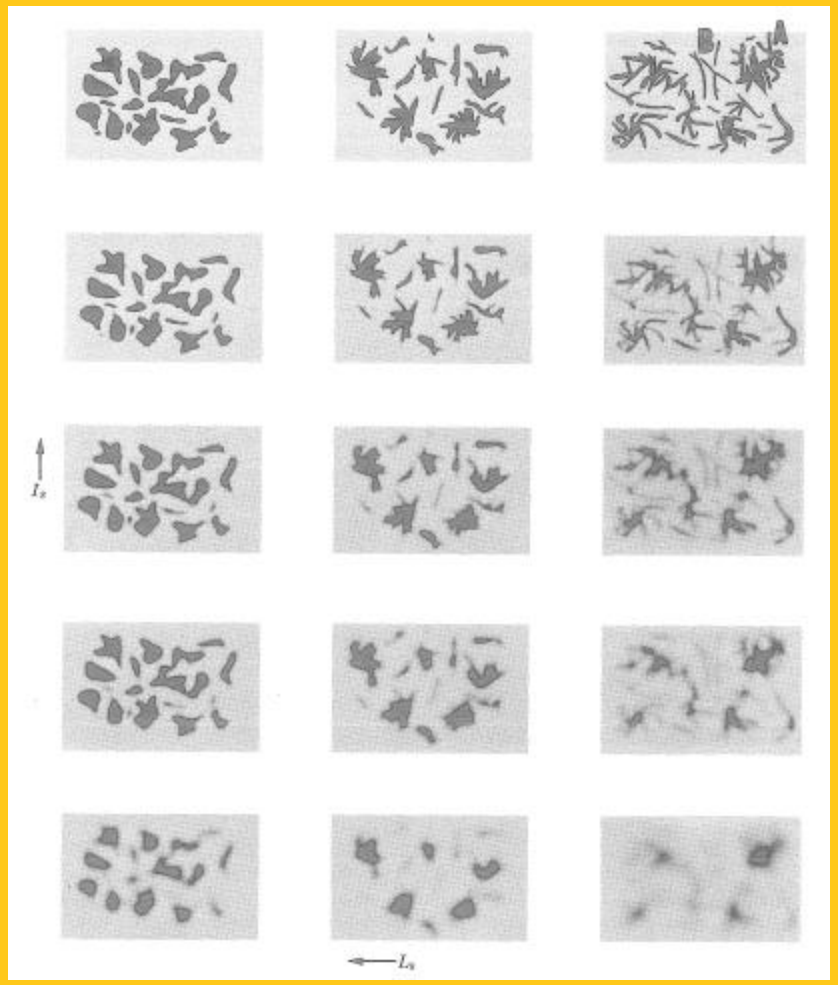
Creating 2D images offers several degrees of freedom (e.g., ghosting of background, chord average, slice average, 3-D translucent and rotating).

Normally would exclude injection needle from field of view as it saturates image with undiluted F18 activity, limiting resolution downstream in the plume, but these images better tell the story.

Dispersion versus Diffusion, “Tracking” Temperature and Concentration In Turbulent Flows

Dispersion

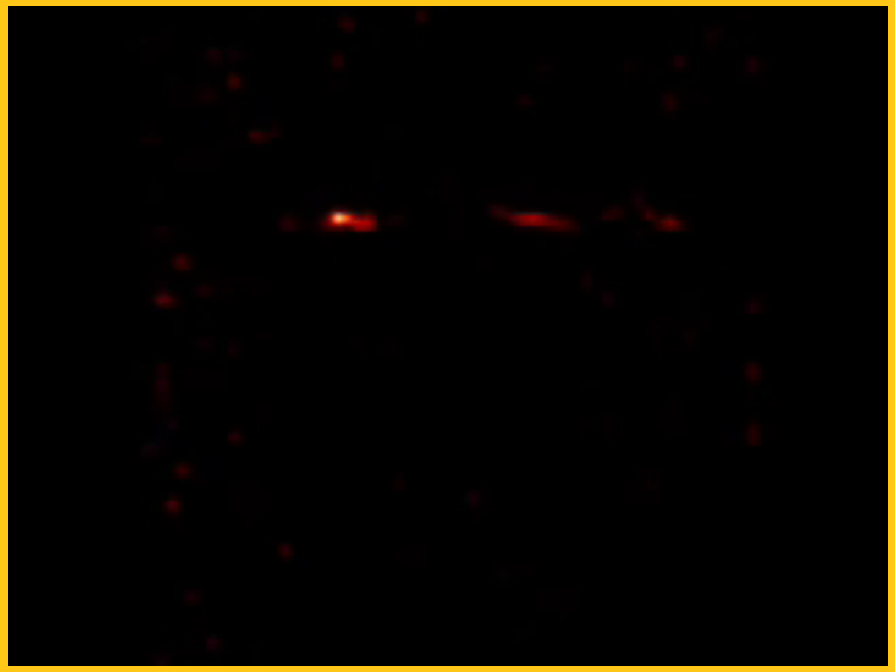
Diffusion



Large eddies disperse fluid, Small eddies and molecular diffusion smear concentration along gradients.

Brodkey, 1967

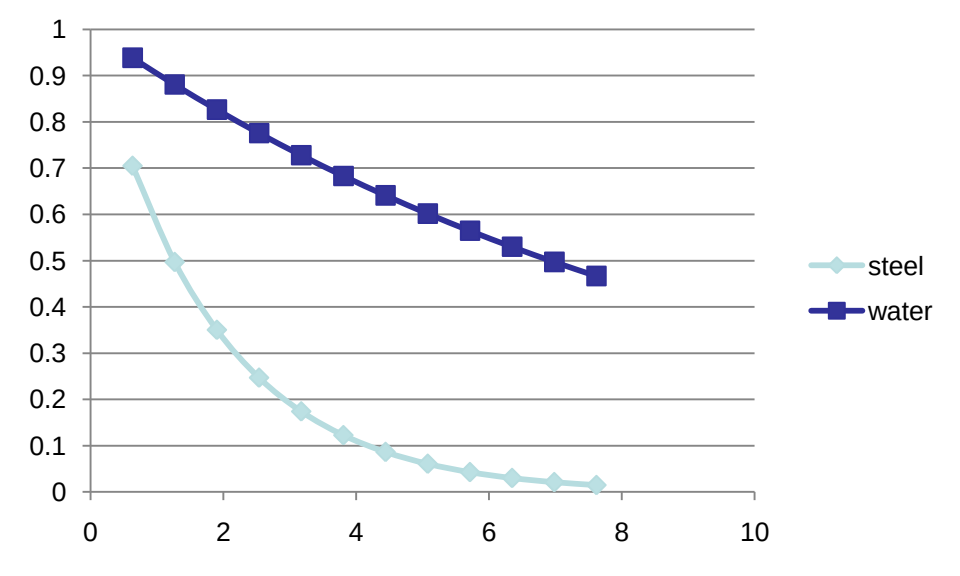
Time Resolved Data. This video is a cut through the center of the plume along the major axis in direction of flow. Injection needle is cur from field of view. UTNE does not own software for creating video from 3D data. Jon Wall and Alan Stuckey, UT Hospital, have graciously shared their equipment and software for these proof of concept studies. Much method development remains.



Time resolved, ½ second segments, 60 second injection of 29.8 mCi in 3cc. Note this is 3-D data, we are viewing center plane activity of plume in this Video.

The 0.512 MeV Gammas Attenuate, Steel versus Water

Fractional Attenuation



Penetration Distance, cm.

CT Scans are integral to new Scanners-Facilitates structural mapping

Flow volume may be flooded with uniform activity and imaged to map effect of structural attenuation and flow self shielding.

Synergy of Medical PET Imaging and PET for Flow Measurement

Detector Development motivated by Medical Applications is also good for Flow imaging:

1. Faster counting, plus time of flight, reduce activity or time required for image construction.
2. Some additional resolution improvements are possible.

Isotopes are commercially available and have relatively short half life. This helps defray barrier to entry costs associated with cyclotron, and mitigates radioactive material waste storage concerns.

Hot cells for remote isotope handling are commercially available.

Business models for medical imaging suites are well developed at major Medical research and clinical installations.

Unique Attributes of PET for Flow Measurement

Image Reconstruction for Engineering

1. Flow volume is only volume requiring image reconstruction, CT, or preliminary flooding of flow volume with isotope for a PET image, can identify flow volume, and allow exclusion of scatter from structure.
2. Attenuation from structure and self shielding can also be evaluated with PET image of isotope flooded flow volume. This facilitates correction of activity versus position measurement in complex geometries.

Path Forward: User Facility Marketing and Design

Need more test protocol development and investigation of details of transfer function from gamma detections to visualization of activity in flow measurement volumes.

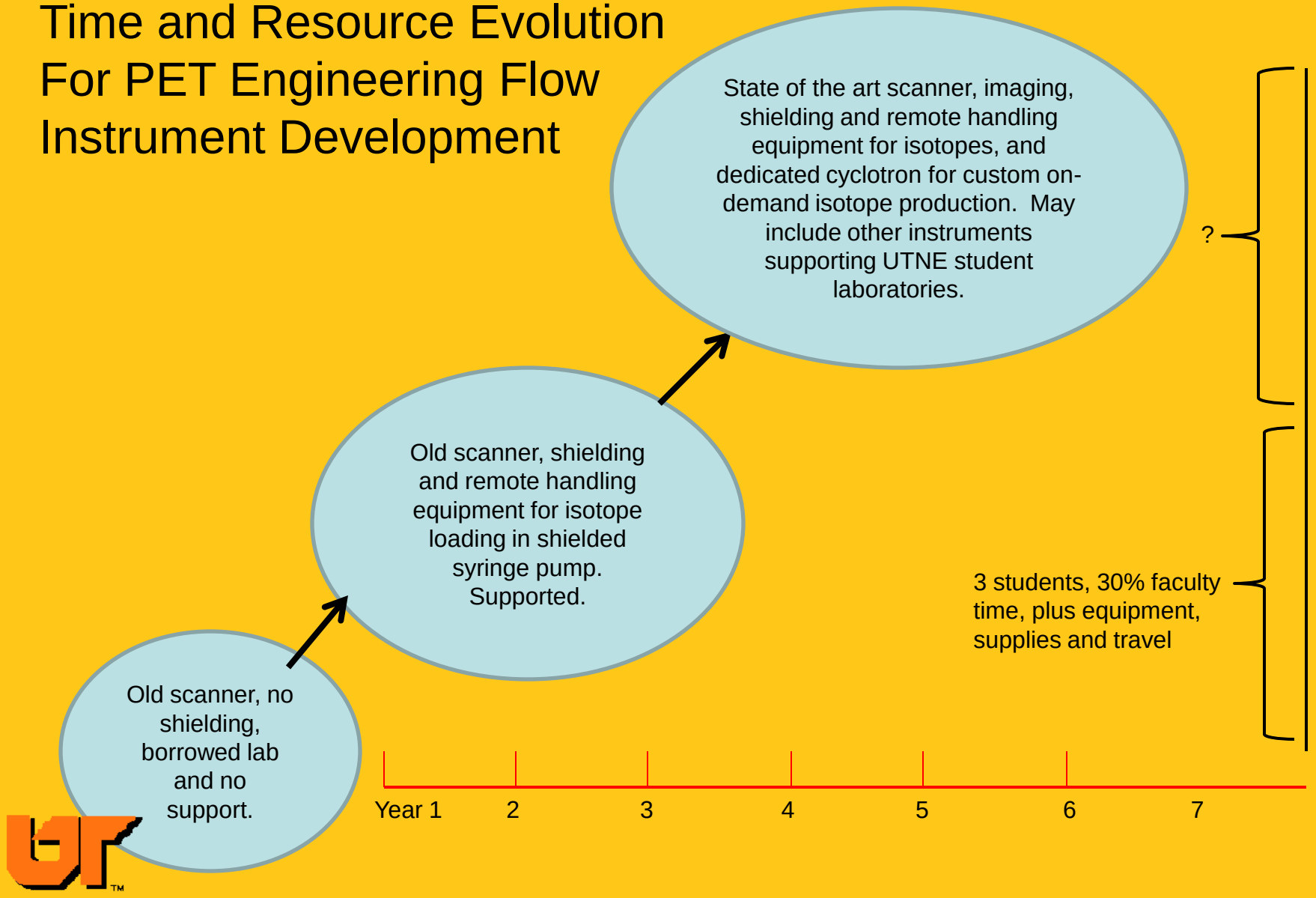
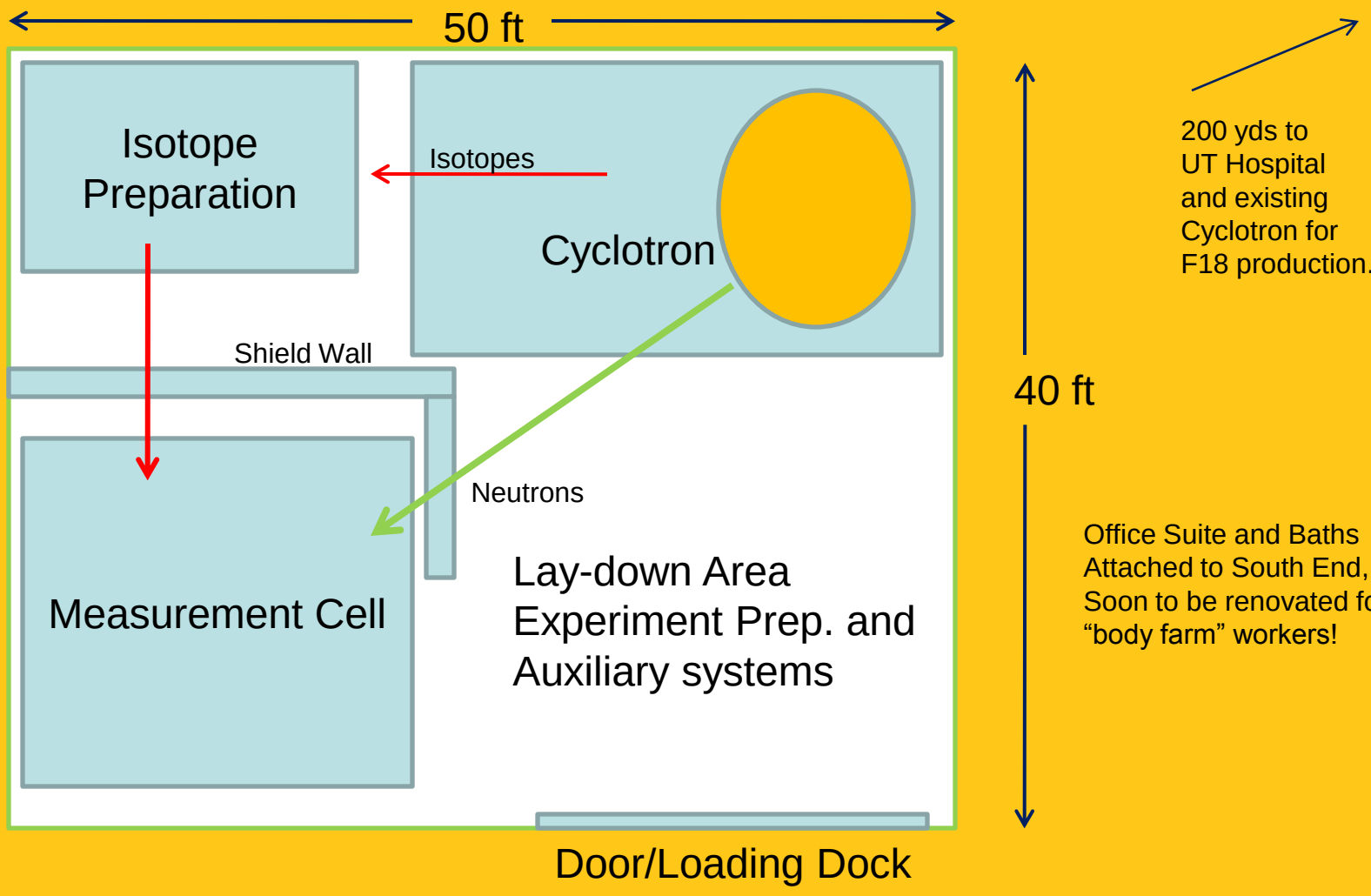
Protocol development will better define Ci amounts and injection rates required to make measurements in high Re flows, or in complex higher Z flow geometries.

CFD 3D diffusivity or eddy structure prediction may be compared with 3D Diffusivity Data, allowing validation formalisms to be developed.

Flow in Rod Bundles, Tube Bundles, and in Stacked Plate Exchangers may be evaluated using techniques similar to those presented here. (pulsed injection, multiple injection sites, PET particles)

Alternate detector geometries, such as multiple portable flat box detectors that can be placed around locations of interest. Flexible Image reconstruction approaches will also be required. (DHS)

Time and Resource Evolution For PET Engineering Flow Instrument Development



User Facility Vision: Current Home of UTNE Graphite Pile, and Hospital Waste, Beside UT Hospital and “Body Farm”