Simulation and Theory Summary

1. **Particle Yields, Energy Deposition and Radiation (N. Mokhov, L. Waters)**
   - Needs and Specs
   - Codes
   - Uncertainties
   - Benchmarking
   - Future Work

2. **Structural Analyses of Solid Targets and Li-lenses (N. Simos, P. Hurh, B. Riemer)**

3. **Magnetohydrodynamics in Liquid Targets (R. Samulyak, Y. Prykarpatsky)**

4. **Misc (L. Waters)**
   - Materials Handbook
   - Hydraulics

Targetry Issues

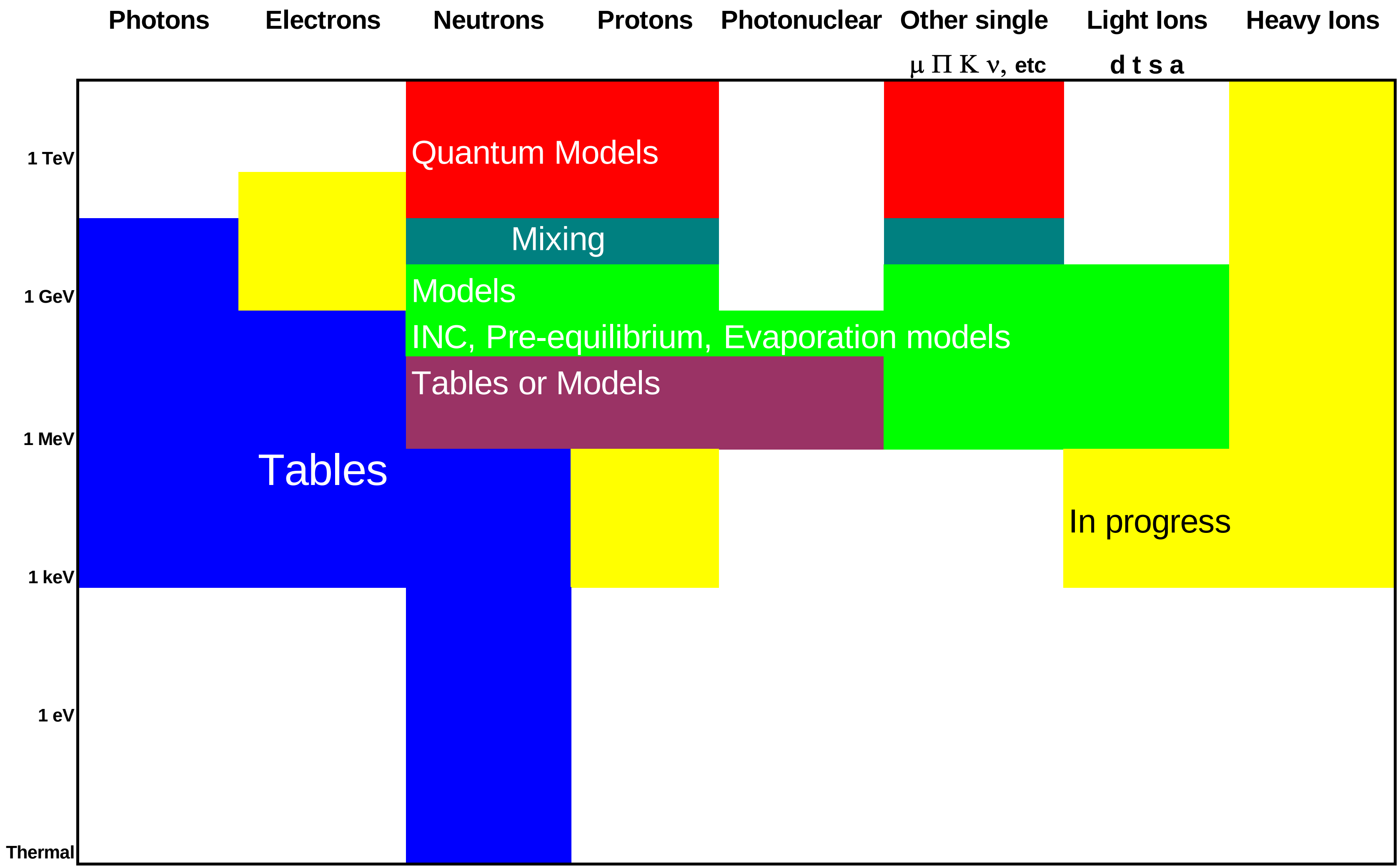
- Production and collection of maximum numbers of particles of interest: neutrons at SNS, positrons at linear colliders, *pbar* at Tevatron, and pions/kaons in ν -experiments.
- Survivability, heat loads, radiation damage and activation to target materials and those of near-beam components.
- Compatibility, fatigue, stress limits, erosion and remote handling.
- Suppression of background particles transported down the beamline.
- Protection of a focusing system including provision of superconducting coil quench stability.
- Spent beam.
- Shielding issues from prompt radiation to ground- water activation.

Most of these issues are addressed in detailed Monte Carlo simulations.

Particle Yields, Energy Deposition and Shielding Code Reqs

- Reliable description of x-sections and particle yields from a fraction of eV to many TeV.
- Accurate transport from 10% of min(σ, d) to 20-30 nuclear interaction lengths.
- Leading particles (elastic, diffractive and inelastic).
- Multiple Coulomb scattering (not a simple Gaussian or Molier!).
- Low-p_t π^0 production.
- Hadron, muon and heavy- ion electromagnetic processes with knock- on electron treatment and – at high energies – bremsstrahlung and direct pair production (not a simple dE/ dx!).
- Full accurate modeling of electromagnetic showers generated in two processes above.
- Accurate tracking in magnetic field.
- Stopped hadrons and muons.
- Residual dose rates.
- User-friendly geometry, histograming and GUI.
- Effective interfaces to MAD lattice description, ANSYS and hydrodynamics codes.

MCNPX Code Acceptance



General-Purpose Codes (2003)

Consistent soft and hard multiparticle production in *hA* , (*AA*), γ *A* and ν *A* at MeV to many TeV **(** *EG* **)** and corresponding full transport codes **(** *TC* **)** at a fraction of eV to many TeV in target/ accelerator/ detector/ shielding systems of any complexity:

DPMJET- III (EG) by J. Ranft et al, (*AA*)

MARS14 (EG+ TC) by N. Mokhov et al

FLUKA (EG+ TC) by A. Ferrari et al, (not GFLUKA or FLUKA86)

CEM2kph (EG) by S. Mashnik et al (<3 GeV)

LAQGSM (EG) – LANL (*AA*) (currently <100 GeV)

MCNPX (TC) – LANL (currently < a few GeV)

GEANT4 (TC) – CERN (promising)

MCNPX Applications as of 8/25/03

• **Medical**	**70 groups**	**201 people**
• **Space reactors, cosmics**	**54 groups**	**115 people**
• **Fuel Cycles**	**50 groups**	**140 people**
• **Threat Reduction**	**47 groups**	**124 people**
• **ADS**	**45 groups**	**185 people**
• **Accelerator HP**	**33 groups**	**101 people**
• **Applied Physics***	**31 groups**	**83 people**
• **Neutron scattering**	**16 groups**	**81 people**
• **Code development**	**18 groups**	**28 people**
• **Physics models, data eval.**	**9 groups**	**18 people**
• **Nuclear, HE, Astrophysics**	**8 groups**	**56 people**

*** Radiography, oil well logging, irradiation facilities, isotope production, detector development, environmental, high density energy storage**

Uncertainties in Yields and Energy Deposition

1. In most applications particle yields are predicted with <30% accuracy.

2. Energy deposition at shower core:
   – Source term: 30% in well-defined cases
   – Simplifications in geometry, materials and magnetic fields: unknown, but up to a factor of 2 to 3 typically
   – Good simulation code physics and algorithms: a few % to 30% typically

3. Prompt dose and fluxes in thick shielding: a factor of 2.

4. Residual dose rate: within a factor of 2 to 3.

Hadronic Codes: Future Work

1. Better, faster electromagnetic shower algorithms coupled to hadron transport codes (MCNPX and SHIELD first of all!).

2. Heavy-ion transport capability!

3. DPA, hydrogen and helium production as a standard option.

4. Better, faster nuclide production and residual dose rate options.

5. International benchmarking on energy deposition in targets at the level of “neutronic” activity.

Solid Target Structural Analyses

1. Simulations of pressure waves in targets and windows.

2. Benchmarking Dynamic Strain Predictions of Pulsed Mercury Spallation Target Vessels.

3. Antiproton collection lithium lens developments.

Targets and Windows at BNL

- Verification of fundamental modes of target response.
- Carbon-carbon composite over ATJ graphite superiority.
- E951 window strain tests and calculations.
- Good agreement between measurements and ANSYS calculations.
- Irradiation tests.

Issues and Material Matrix selection

• FAST proton beam interacting with window and depositing energy in small spot inducing shock waves

• Based on a 24 GeV/ 16 TP/ 0.5 mm rms beam MOST materials could fail with a single pulse

• Though thin, failure in window governed by through- thickness response

• **Sound spee**d, **material thickness** and **pulse structure** are critical elements

• Material search combined with analytical predictions led to the following

materials for testing

– Inconel 718 (1mm and 6mm thickness to study the effect)

– Havar

– Titanium Alloy (highest expectation of survivability)

– Aluminum

• Aluminum (3000 series) selected as the one that COULD fail under

realistic expectations of AGS beam during E951 (~ 8 TP and 1mm rms)

Simulations and Benchmarking at ORNL

- Design of the SNS target module requires an estimate of induced stress from beam pulses.
- Historically, while simulations have predicted the response of solid targets to short pulses well, simulating liquid metal target response has significant additional difficulties:
  - Dense fluid-structure interaction
  - Cavitation greatly changes behavior
- A credible simulation technique ABAQUS has been developed benchmarked to experimental data obtained as part of R&D.
- Proton irradiation performed at LANSCE-WNR.

Large Effects and Prototypic Targets

Two target types used in experiments to obtain relevant strain data

1. **Large Effects (LE) target (pure agreement with simulations).**

- Axisymmetric: modeling advantage.
- Flange end thinned to ~ 1 mm.
- Strains close to yield: easier to measure & more sensitivity to test parameters.

2. **Prototypic Shape (PS) target (good agreement with simulations).**

- ½ scale of SNS target.
- Thin beam window region.
- Internal baffles.
- Induced strains are driven by fluid structure interaction … not wave propagation in steel.

PS simulations compare well to data

- Generally good prediction of dynamic response.
- Predicted strain magnitudes are good match to data, although fatigue analysis could use better.
- A few locations matched poorly; it's hard to tell what could be wrong: experiment data setup, gravity or stand effects.
- It will have to do for now for application to SNS. There is no better benchmark available.

Solid Target Structural Studies

• Prove that solid target options can take 1 to 2 MW beams taking into account irradiation and environment (simulate energy deposition, structural behavior, beam tests, benchmarking, estimate lifetimes).

• Scrutinize new (and exotic) materials (carbon-carbon, Toyota Ti-alloy, Vascomax etc).

• Bring the resources together and identify a path forward for all the groups.

• Continue simulation studies and model developments into the “fuzzy” area of material behavioral changes due to irradiation and long expose to shocks.

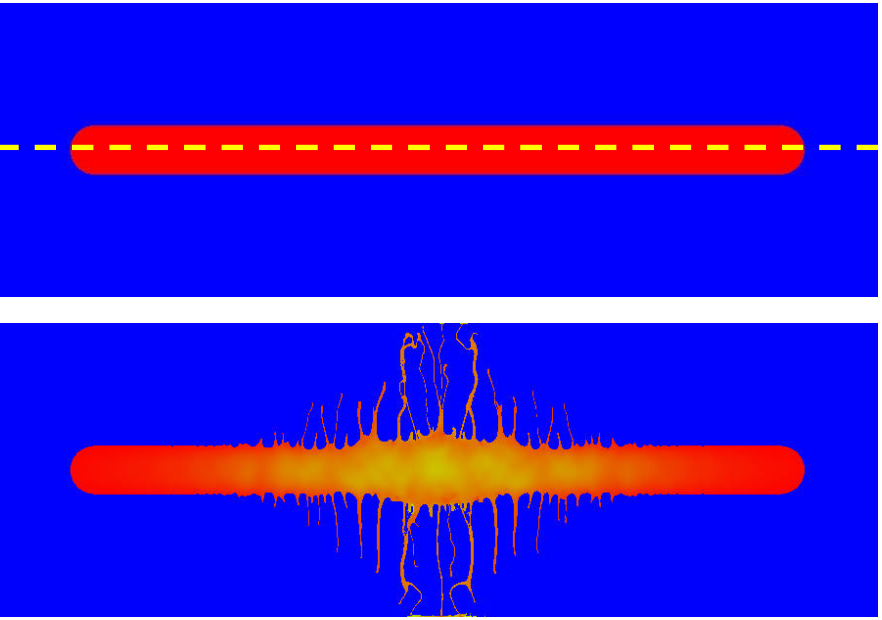
• Collaborate closer in the new initiatives (conventional neutrino beam upgrades etc).

Modeling of Free Surface MHD Flows and Cavitation

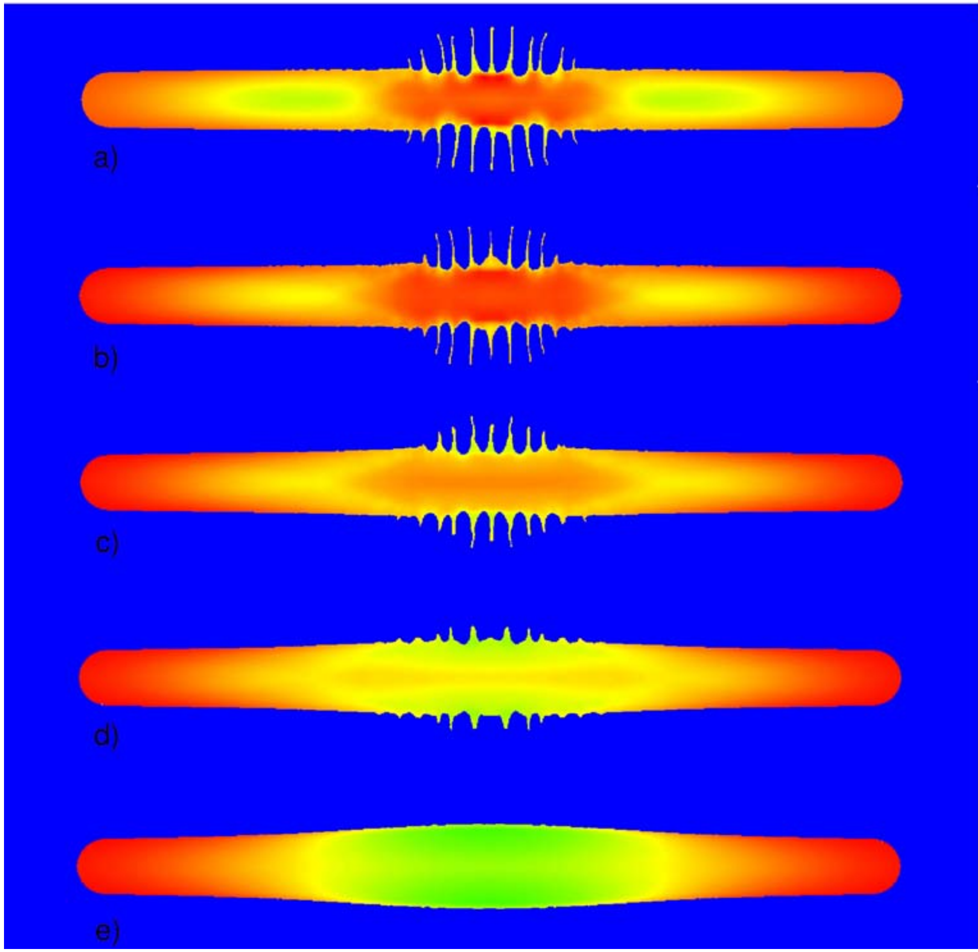
by R. Samulyak and Y. Prikarpatsky

- Theoretical and numerical ideas implemented in the FronTier-MHD, a code for free surface compressible magnetohydrodynamics.
- Some numerical examples in particular related to Neutrino Factory/Muon Collider Target.
- Bubbly fluid/cavitation modeling and some benchmark experiments. Possible application for SNS target problems.
- Future plans

Richtmyer-Meshkov instability and MHD stabilization

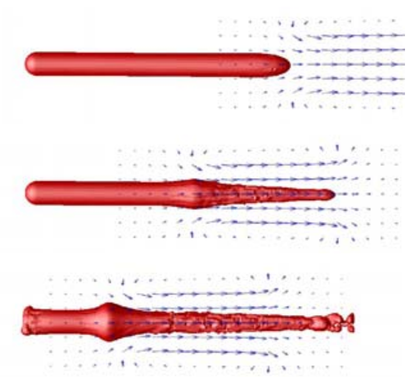


Simulation of the mercury jet – proton pulse interaction during 100 microseconds, B = 0

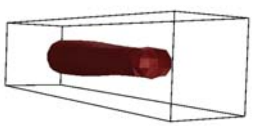


a) B = 0 b) B = 2T c) B = 4T
d) B = 6T e) B = 10T

Other applications

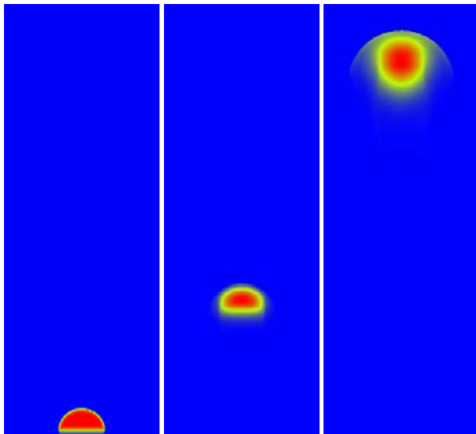


Conducting liquid jets in longitudinal and transverse magnetic fields. Left: Liquid metal jet in a 20 T solenoid. Right: Distortion (dipole and quadruple deformations) of a liquid metal jet in a transverse magnetic field. Benchmark problem: Sandia experiments for AIPEX project, experiments by Oshima and Yamane (Japan).



Laser ablation plasma plumes. Plasma plumes created by pulsed intensive laser beams can be used in a variety of technological processes including the growth of carbon nanotubes and high-temperature superconducting thin films.

Our future goal is to control the plasma expansion by magnetic fields.

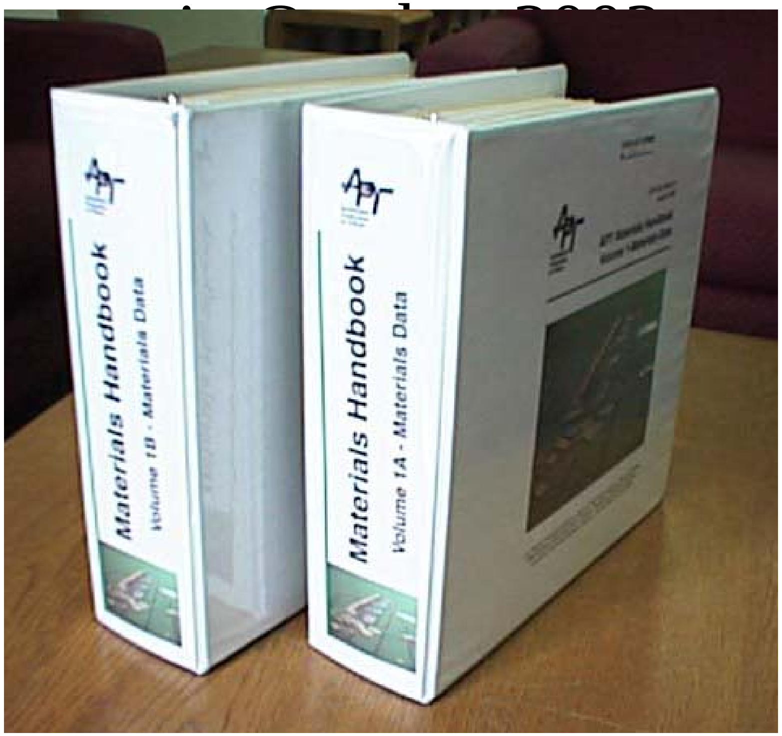


Numerical simulation of laser ablation plasma plume

CFD/MHD Simulations: Conclusions

- Recently developed simple homogeneous EOS for two phase mixtures significantly improved the quantitative agreement of numerical simulations and Muon Colider/Neutrino Factory mercury target experiments.
- Direct numerical simulation of bubbly fluids and homogeneous EOS models based on the Rayleigh-Plesset equations agree quantitatively with several shock tube experiments in gas-liquid mixtures.
- The use of new EOS models with bubbly fluid/cavitation support will be beneficial for both Neutrino Factory and SNS.
- It is necessary to incorporate terms accounting for the mass transfer due to phase transition in these EOS models.
- Numerical simulations show stabilizing effect of the magnetic field on the free mercury jet target surface deformations in 2D approximation. Since 2D approximation is not accurate for the problem geometry, it is necessary to perform full 3D numerical simulations to study the stabilizing effect of the magnetic field on the mercury target.

Rev. 4 of the Materials Handbook will be ready for distribution



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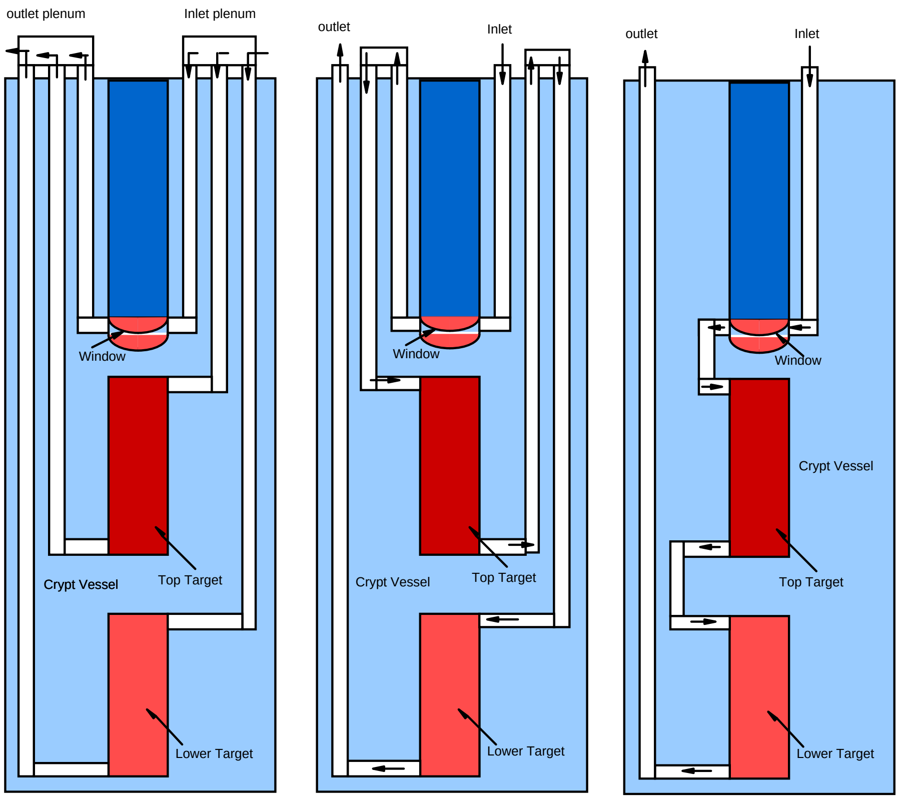
TRACE Characteristics and Capabilities

- Modular, object-oriented F95 standard coding
- Generalized two-phase thermal-hydraulic modeling capability (plants & test facilities)
  - Two-fluid model - 6 equation model
  - Multi-dimensional VESSEL component
  - All other components modeled in one dimension
    - Pumps, pipes, valves, etc.
  - Primary, secondary, and containment may be simulated

- Multiple fluid modeling capability
  - Primary and secondary loops can be modeled with different working fluids
  - Available fluid models include H_2O, D_2O, He, Pb-Bi, Na, N_2, air, oil, and RELAP5 H_2O
- Non-condensable gas model (H_2, air, etc.)
- Trace species tracking capability
  - Track trace gas and/or liquid species
  - Includes solubility models for trace species
- Fluid volumetric heating and fluid decay heat models

Three Piping Layouts in the Crypt



Parallel Connection outside the crypt vessel

Series Connection outside the crypt vessel

Series connection inside the crypt vessel