Development of a High Brightness Source for Fast Neutron Imaging

2016 North American Particle Accelerator Conference THBIO01

October 13, 2016

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LLNL-PRES-704386
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

LLNL has been developing a system to do fast neutron imaging for well over a decade and we are now in the hardware building phase

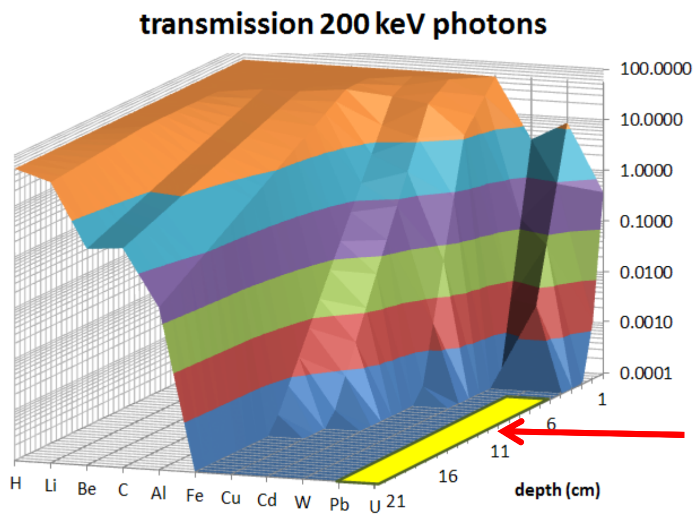
- Neutron imaging requires a very bright source of fast neutrons (10 MeV) to produce high resolution images through very thick, dense objects (ρl>100-150 g/cm^2, e.g., ~2-3" of Ta)

- Approach is to use a deuteron ion accelerator at 7 MeV and deuterium gas to create ~10 MeV neutrons

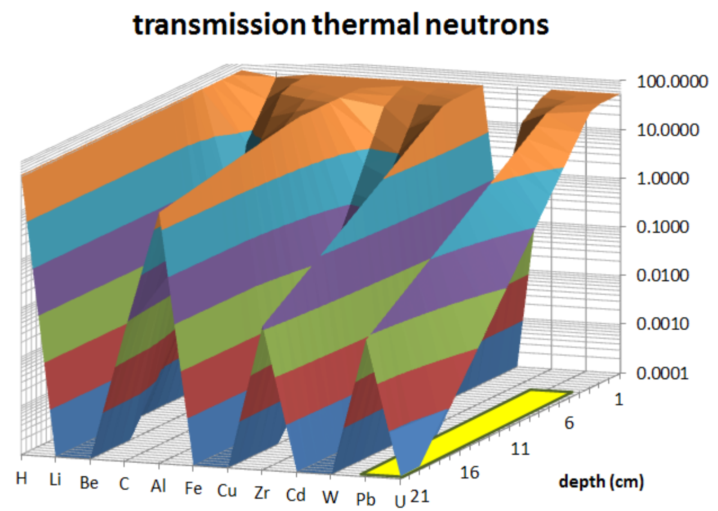
- Work across a number of subsystems is proceeding:
  - 4 and 7 MeV deuteron ion accelerator procurement
  - Beamline development, manufacturing, and assembly
  - Gas target testing and development
  - Differential pumping line
  - Process gas system installation
  - Imaging optics system development
  - Authorization basis work

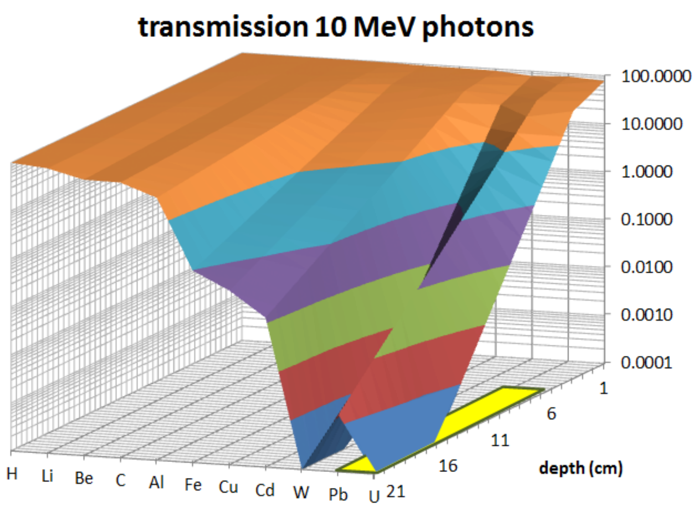
- If all goes according to plan:
  - In mid CY 2017, we should be producing ~10^{10} n/s/sr at 0 deg
  - In late 2017 to early 2018 we increase to 10^{11} n/s/sr at 0 deg

Comparing x-ray and neutron transmission shows fast neutrons are superior for penetrating massive objects

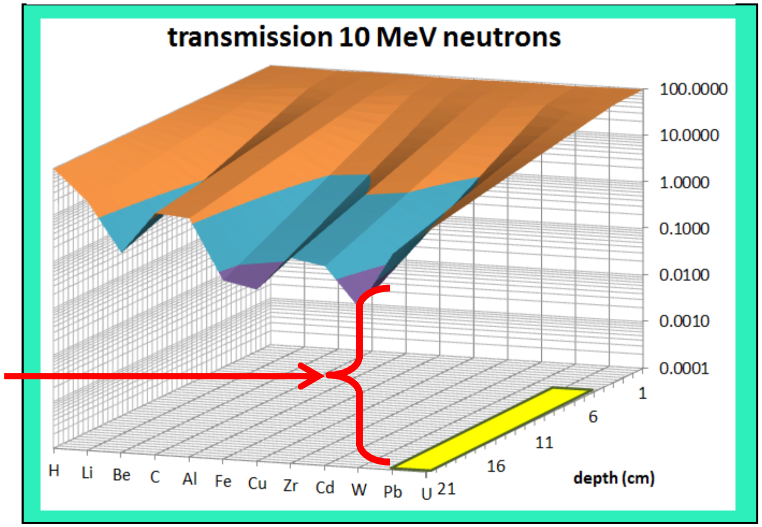


Yellow area depicts imaging challenge presented by dense objects

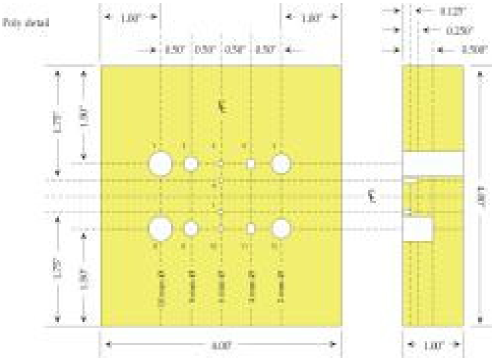




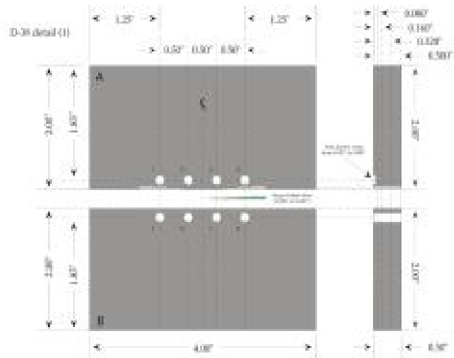
Fast neutrons are >10,000x more penetrating in thick objects allowing us to see what x-rays and thermal neutrons cannot



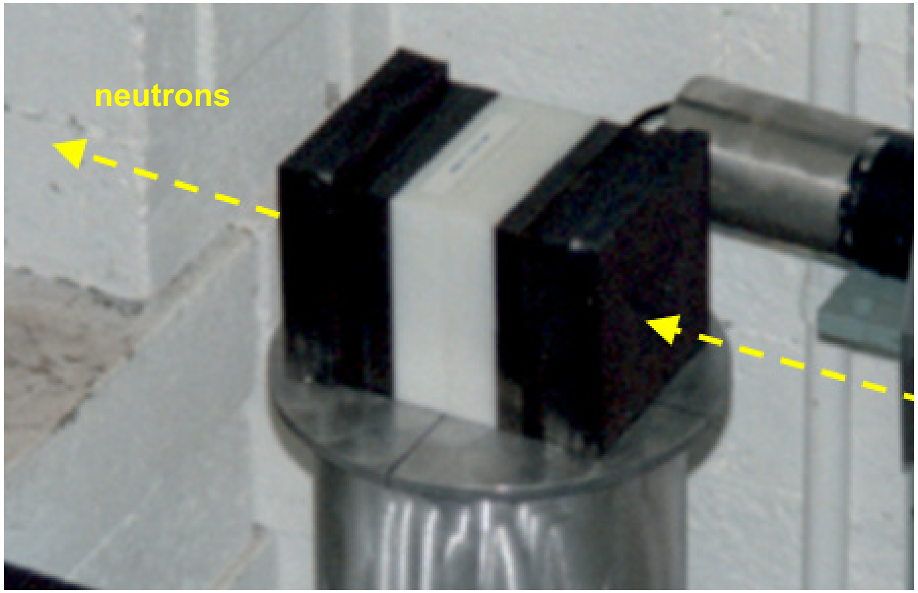
Over 25 experiments confirm fast neutron imaging readily images details through 4” of uranium that x-rays cannot penetrate enough to even create an image



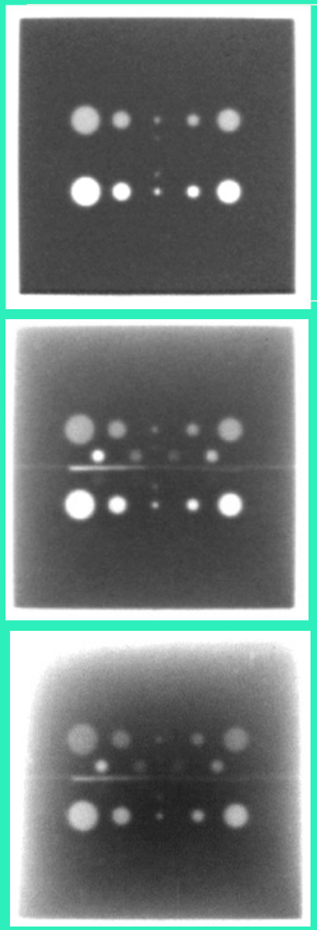
structure of poly block



structure of D-38 half-plate



10 MeV neutron image



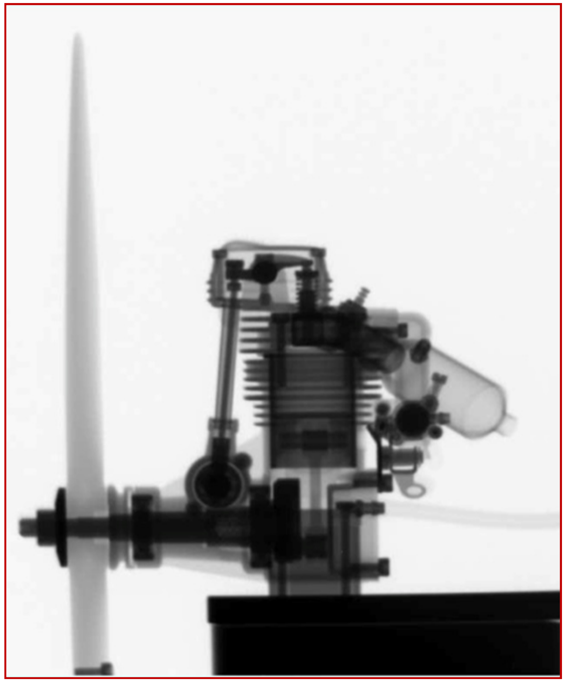
9 MeV x-ray image

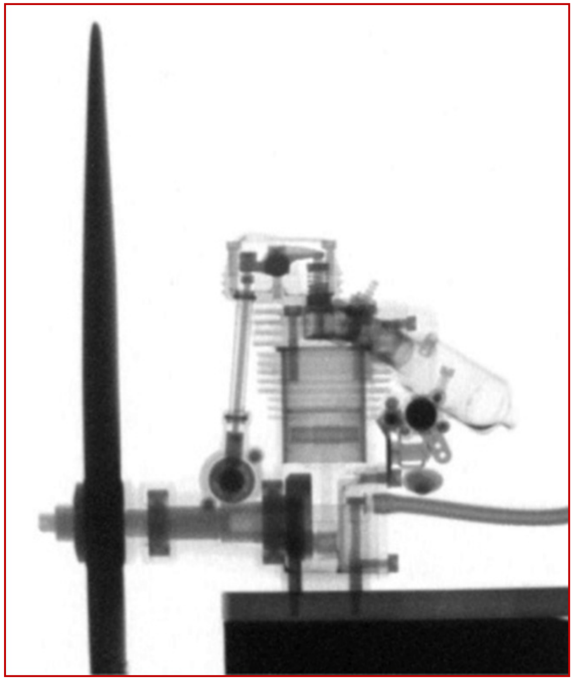
0” U238 shielding

2” U238 shielding

4” U238 shielding

Fast Neutron Imaging creates different radiographic data than X-rays and is being pursued as an advanced NDE diagnostic technique that could benefit research and industry

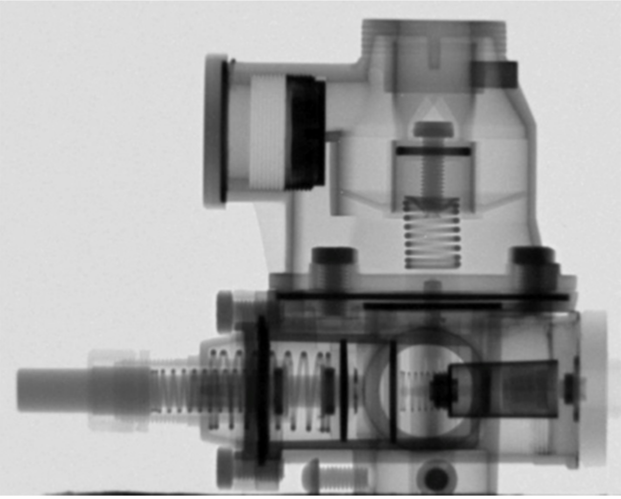




Model plane engine (left):
- X-ray image on left
- Neutron image right

Pressure reducer (below right):
- Neutron radiograph

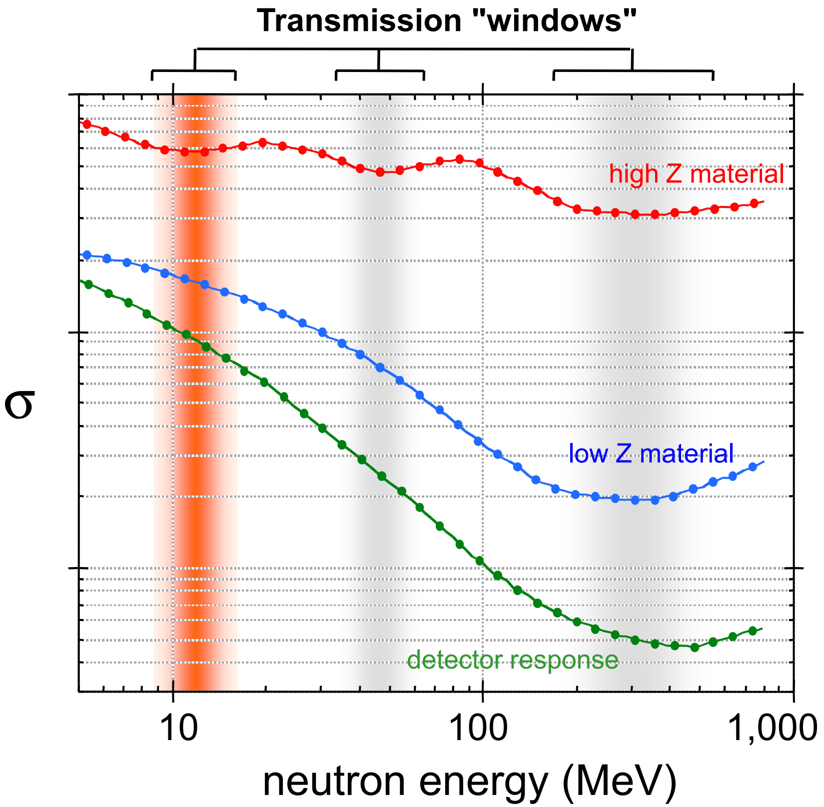
B. Schillinger – TUM, Germany



Most neutron imaging applications require a modest sized nuclear reactor for the neutron source; our proposed solution is much smaller, less costly, and easier to create

Rationale for choosing 10 MeV for neutron imaging and the associated benefits

- Energy range is most efficient for imaging and allows for using modest technology
- Allows developing a lab-scale instrument as a new NDE diagnostic for laboratory and larger scientific and industrial use
- Goals is to have instrument be “user friendly” as much as possible
  - Use COTS subsystems as much as possible
  - “Lab scale” should correspond to a standard x-ray radiography bay size
  - Needs to operate as an NDE instrument, not an experimental device



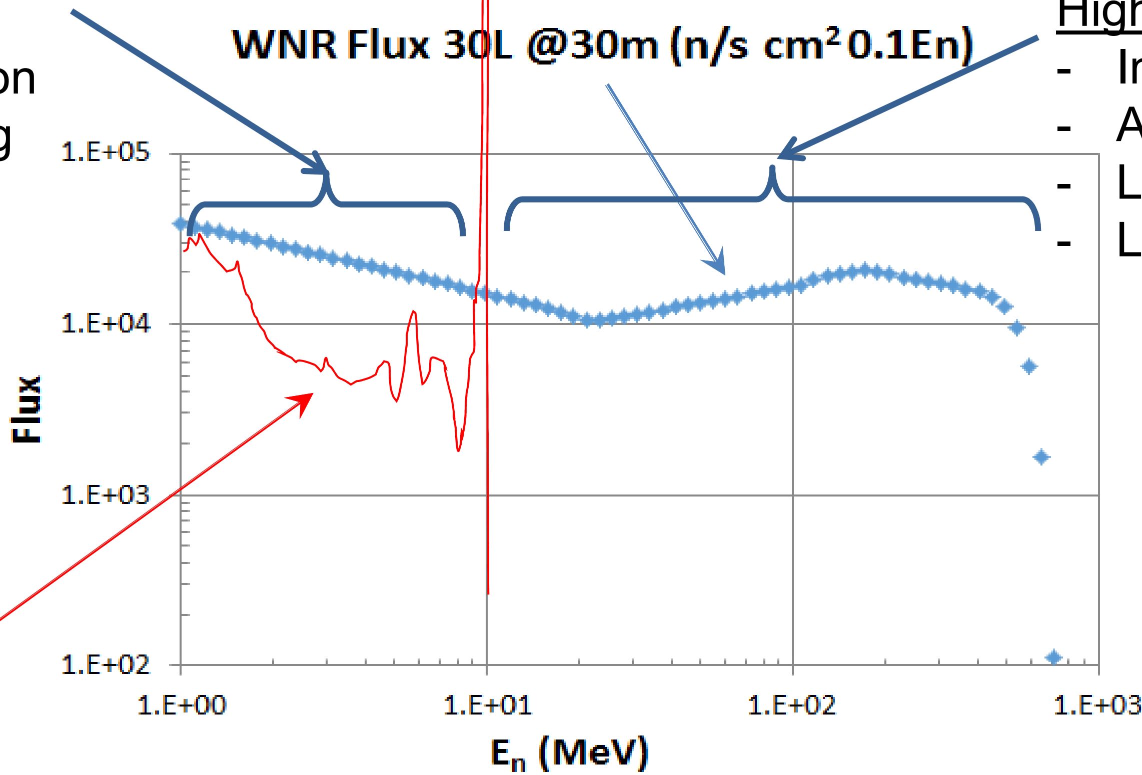
The juxtaposition of favorable cross sections and the ready accessibility to fast neutrons in the ~10 MeV range by modest-sized commercial accelerators formed the basis of the development effort

A quasi-monoenergetic source of fast neutrons is an ideal balance of good penetrability, minimized scattering, and minimum dose

- Fast neutron imaging has been done at WNR at LANSCE – and it works
  - Was a poly-energetic fast neutron beam (0.1-700 MeV neutrons)
  - Ours is a quasi-monoenergetic neutron beam (10 +/- 0.113 MeV neutrons)
- But…a spallation source is not ideal for imaging

Lower energy n:
- Less penetration
- More scattering

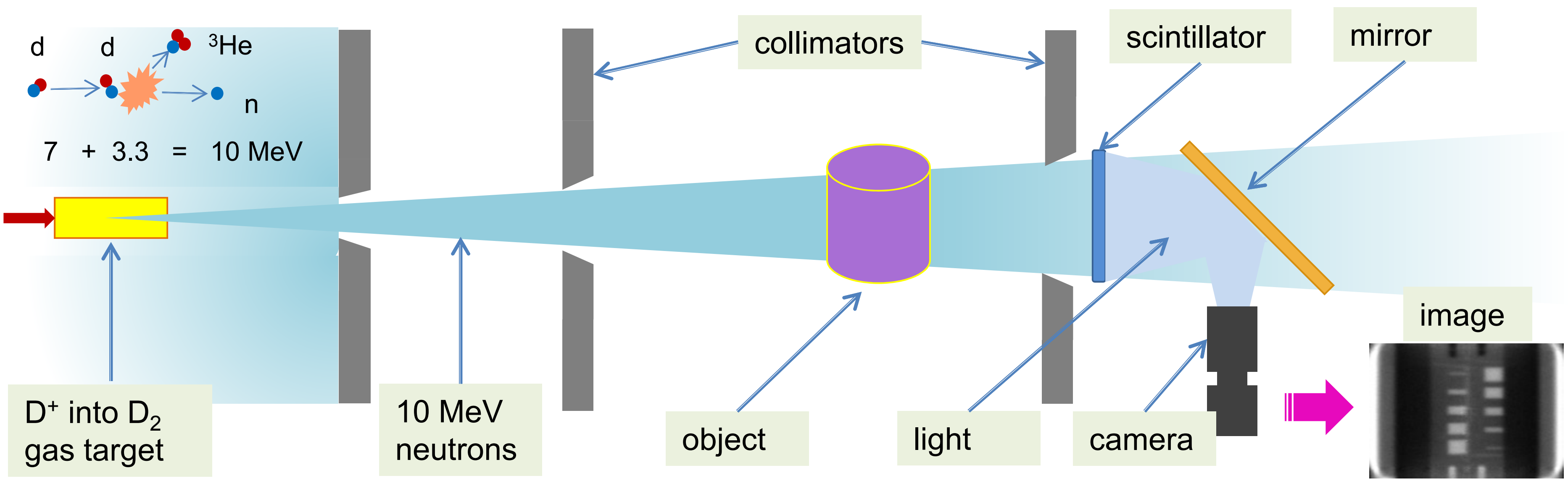
Higher energy n:
- Increases dose
- Air activation
- Low interaction
- Little benefit



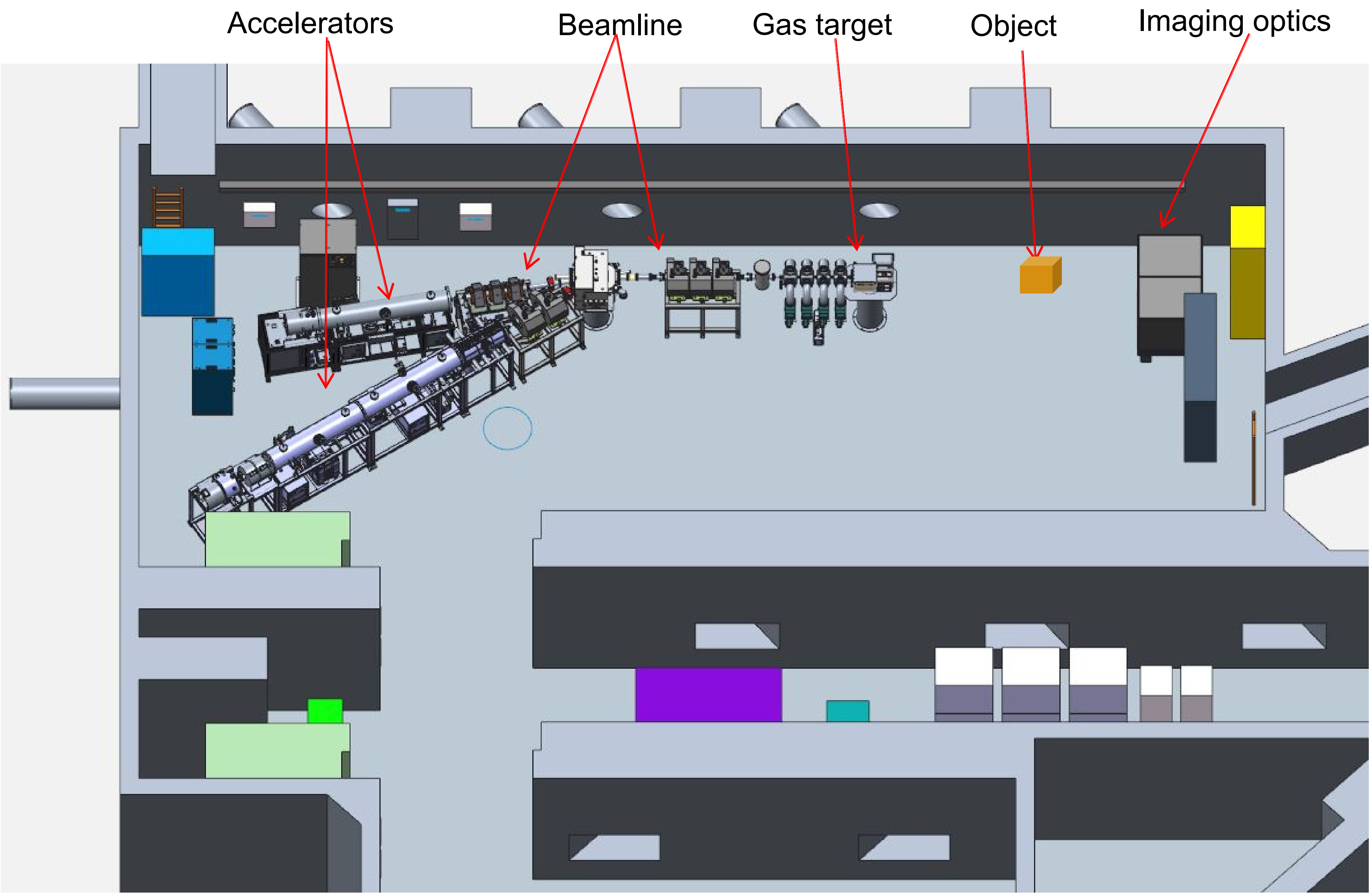
Approximate overlay of calculated NI flux

Neutron imaging uses quasi-monoenergetic fast neutrons to create radiographs analogous to X-ray imaging

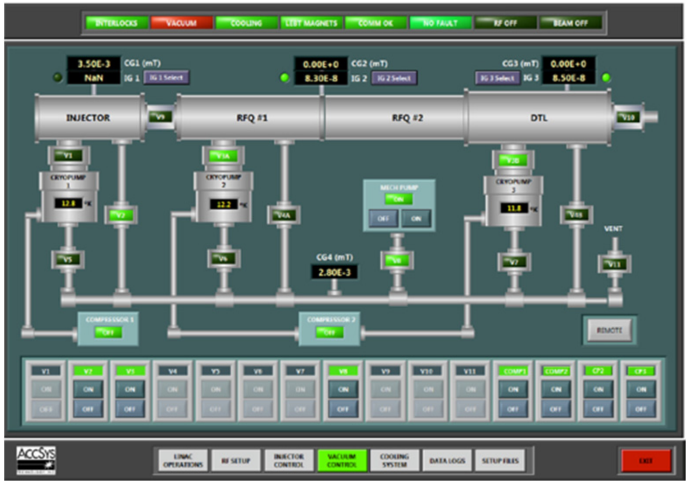
- System is based on commercial technologies
  - An intense accelerator-driven D(d,n)^{3}He neutron source for making 10 MeV neutrons
  - A digital radiographic and full CT imaging capability
- Neutron imaging compliments and extends radiography beyond x-rays
  - X-rays provide high resolution imaging of objects they can effectively penetrate
  - Neutrons provide slightly lower resolution images in thick, dense (ρl > 100 g/cm^2) objects that x-rays cannot penetrate efficiently

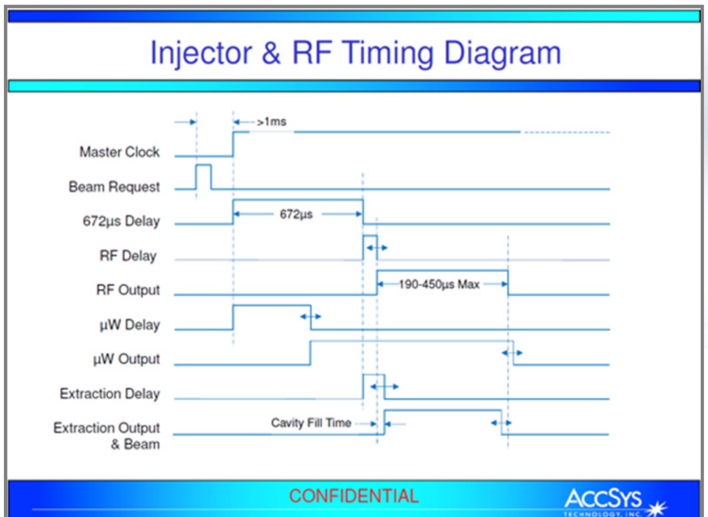


Developing layouts for the LLNL B194 North Cave, a 40 ft x 70 ft heavily shielded accelerator vault



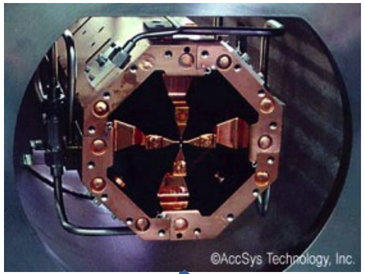
Deuteron accelerator system for full power imaging : 7 MeV deuteron Accsys DL7



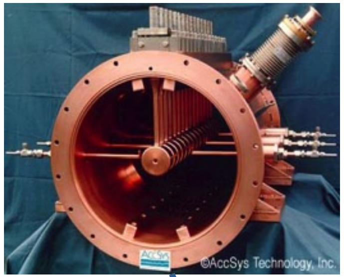


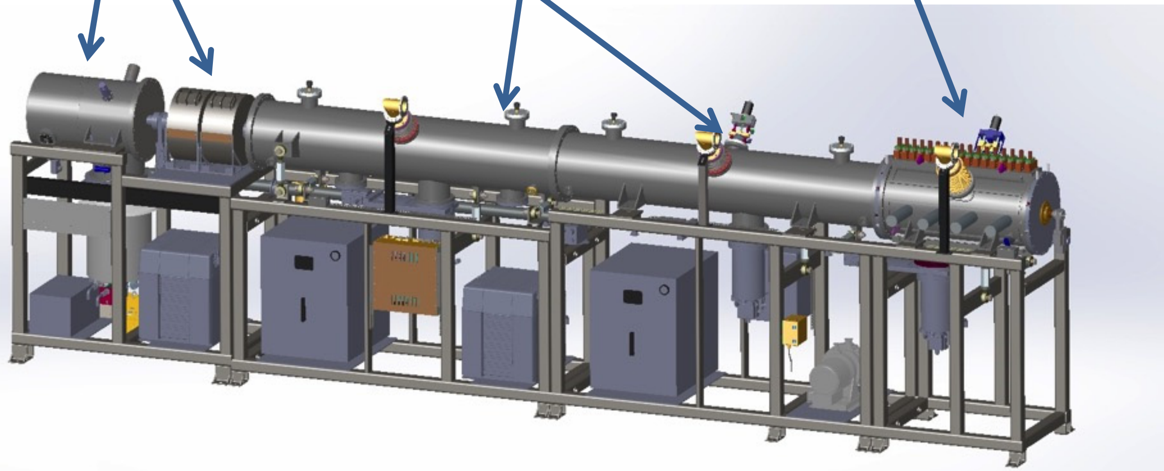
ECR driven ion source and magnetic low energy beam transport

RFQs are the first two acceleration structures



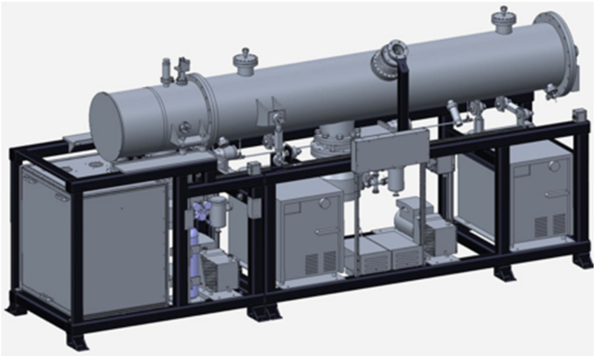
A DTL is the third acceleration structure

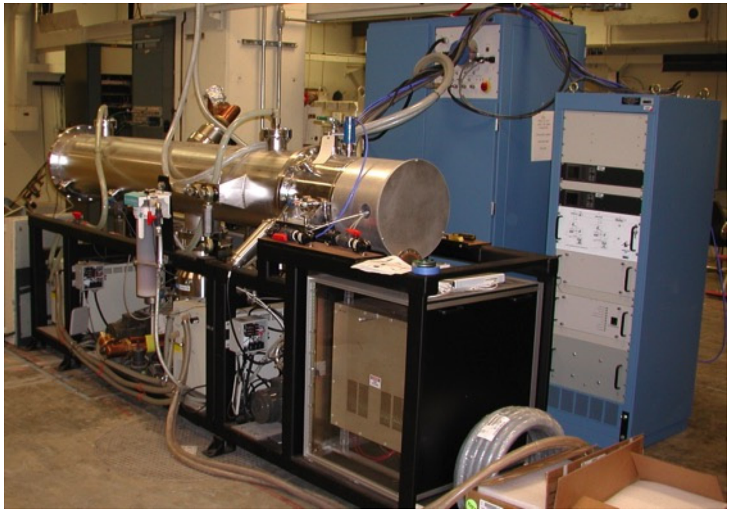




- Accsys progress > 80% complete
- Completed all design reviews this year
- Entering into assembly and integration phase
- Production on track
- DL7 scheduled for delivery April 2017

Additional peak power testing accelerator: 4 MeV deuteron Accsys DL4





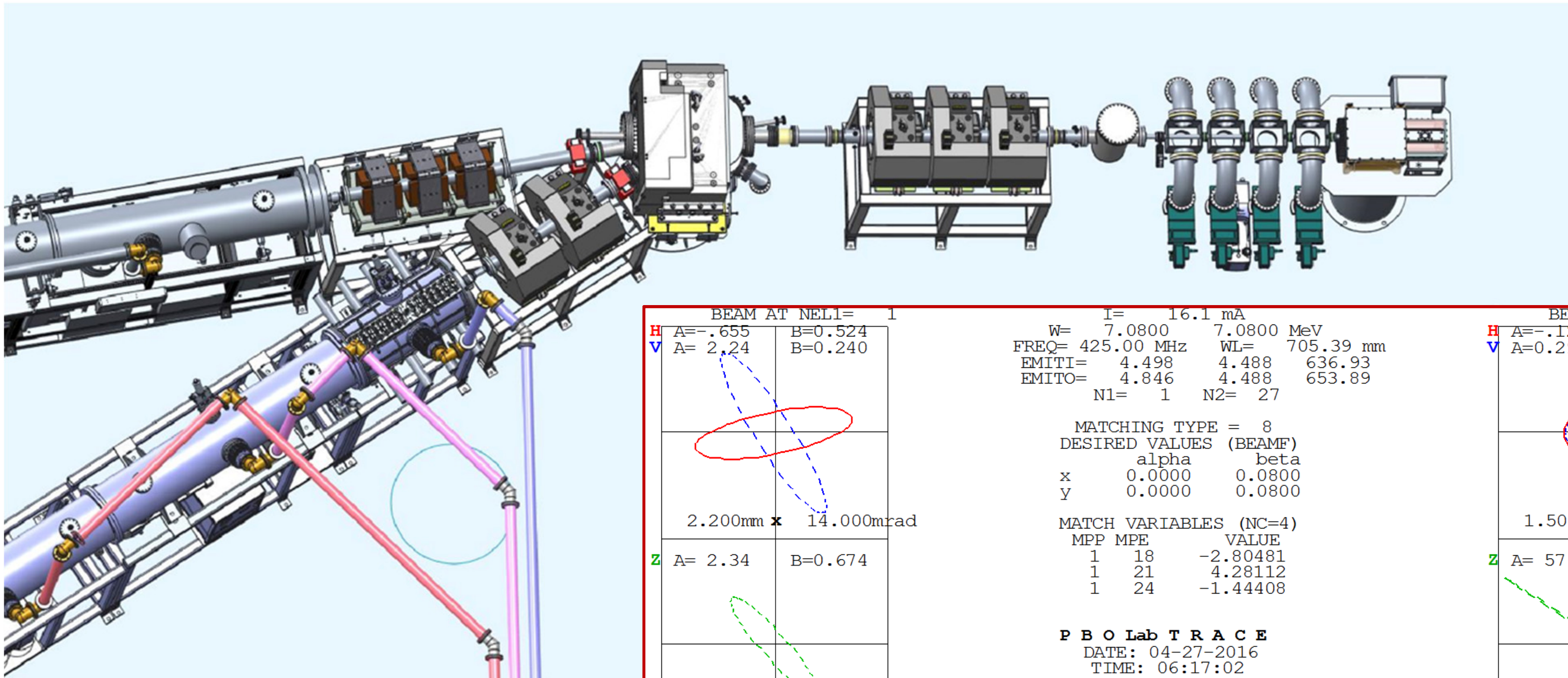
The DL7 machine will give the high average current needed to achieve the required integrated fluence

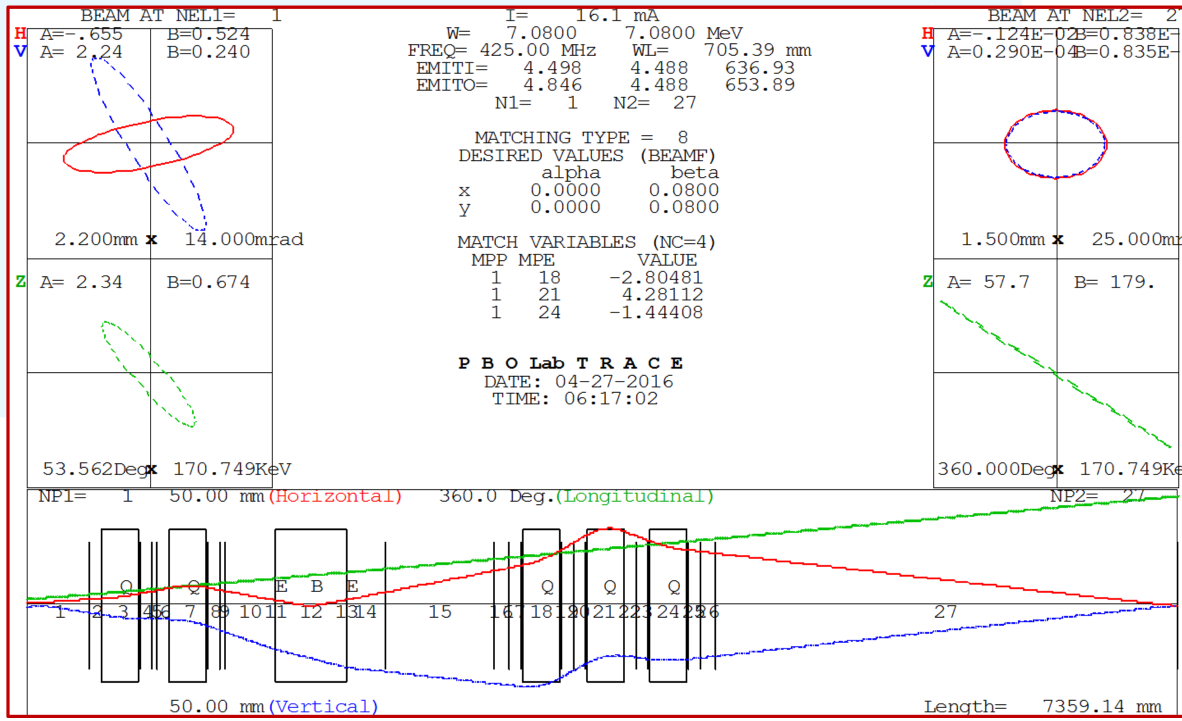
metric	DL7	DL4
energy (MeV)	7.07	4.1
ave current (uA)	300	100
peak current (mA)	17	15
duty factor (%)	2.1	1.0
ave beam power (W)	2100	400
peak beam power (kW)	120	61

The DL4 machine allows for early high peak power testing of the target and components, but lacks the average power suitable for imaging testing

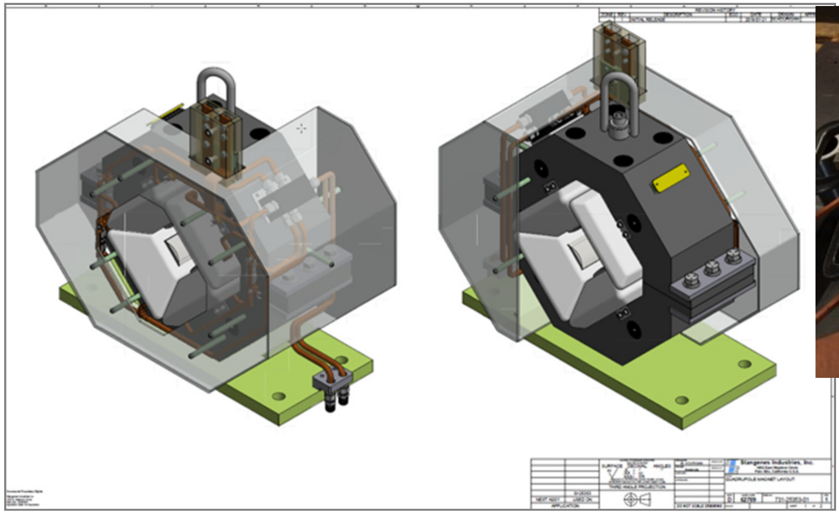
- DL4 refurbishment >95% complete
- Fixed beamline diagnostic being fabricated to allow testing DL4 to full spec at factory
- DL4 to be returned October 2016

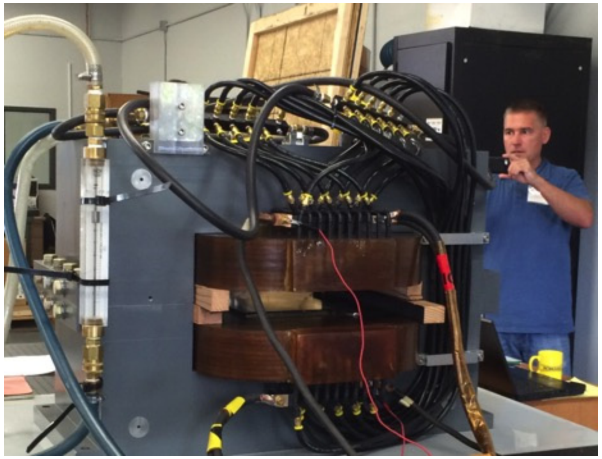
Beamline physics design completed that should achieve ~1.5 mm spot size using 5 quadrupoles and 1 dipole

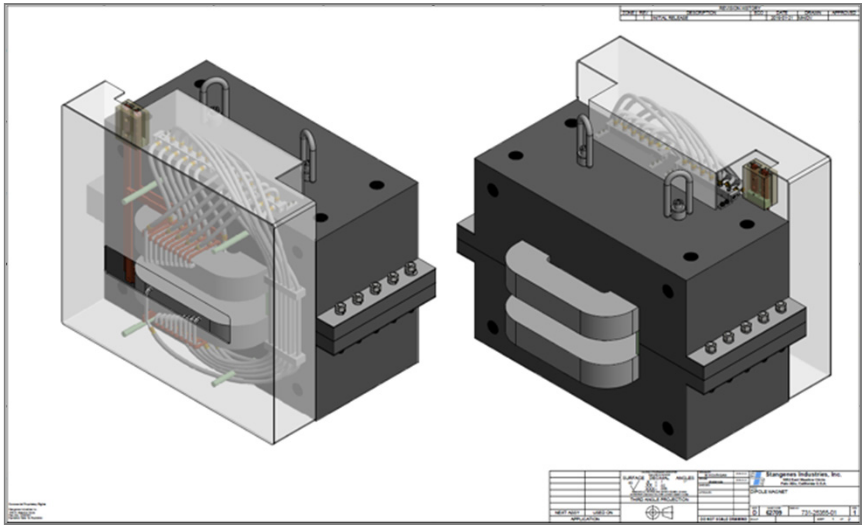


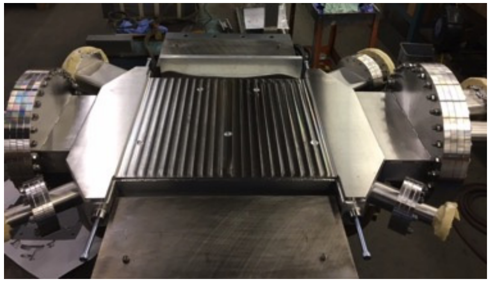


Beamline optics development is well along with magnetic dipole and quads being made by Stangenes Industries





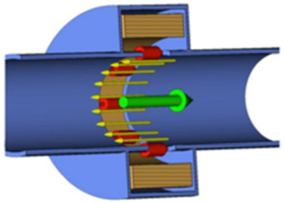




- Contract awarded to Stangenes Industries
- Completed CDR and FDRs
- Order included power supplies matched to magnets
- Dipole being finished, quad production started
- Magnet delivery scheduled for Oct-Dec 2016

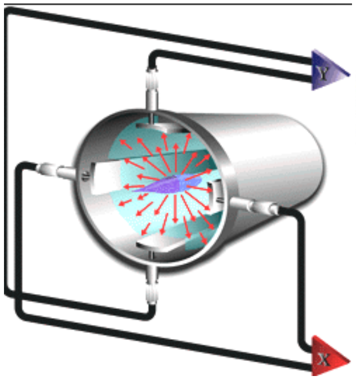
Various diagnostics will be used to measure and characterize the intense low-energy ion beam

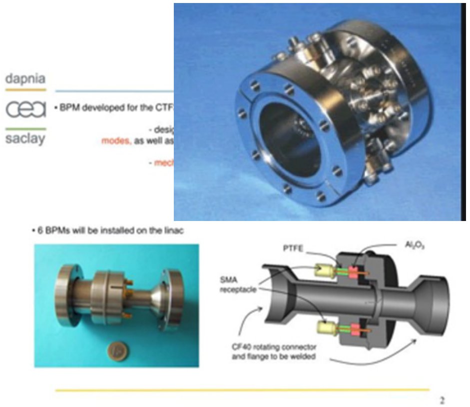
Beam current, non-intercepting - straightforward



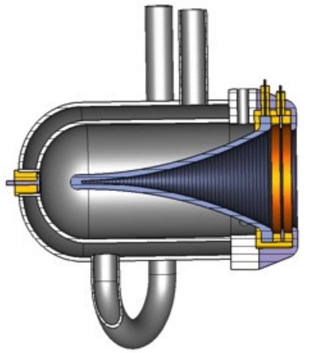
Bergoz coil typical

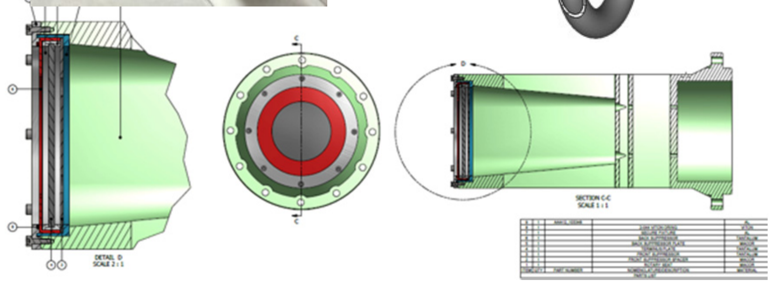
Beam position, non-intercepting - straightforward



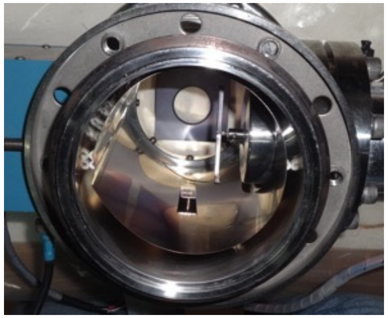


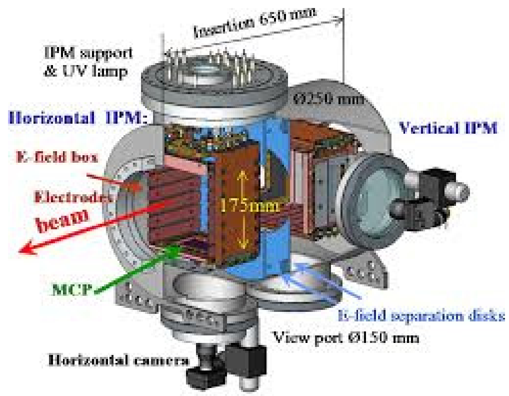
Beam current, intercepting Faraday cups – modest challenge





Beam profile, intercepting – bigger challenge





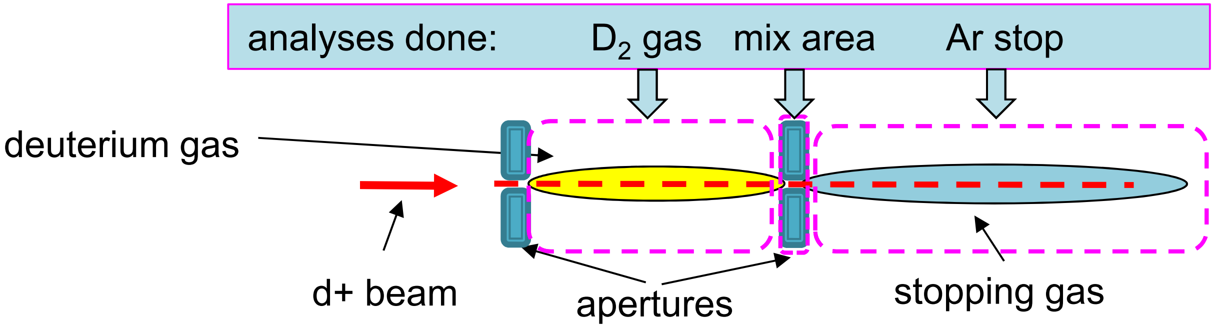
Beam produces ~12 kW/mm^3 power densities from ions stopping in 10's of um in solid materials…a challenge!

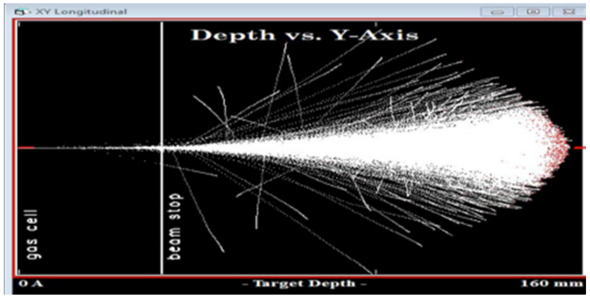
A high brightness source of fast neutrons is achieved by impinging a tightly-focused deuteron beam onto fixed-length deuterium gas column

- A transmission-type deuterium gas cell will produce the desired neutron spectrum and intensity with:
  - A nominal 7 MeV and 300 uA average current deuteron beam, pulsed at a 2% duty factor with 17 mA in a macrobunch
  - A deuterium gas cell target operating at 3 atm-gauge will produce 10 MeV neutrons at ~10^{11} n/s/sr at 0^o

- As this machine is for imaging, a small source spot size is needed (1.5 mm diam x 40 mm long = 71 mm^3 =) for sub-mm image resolution

- To prevent knock-on neutrons and damage due to deuterium buildup in a solid beam stop, an argon gas beam stop is being developed

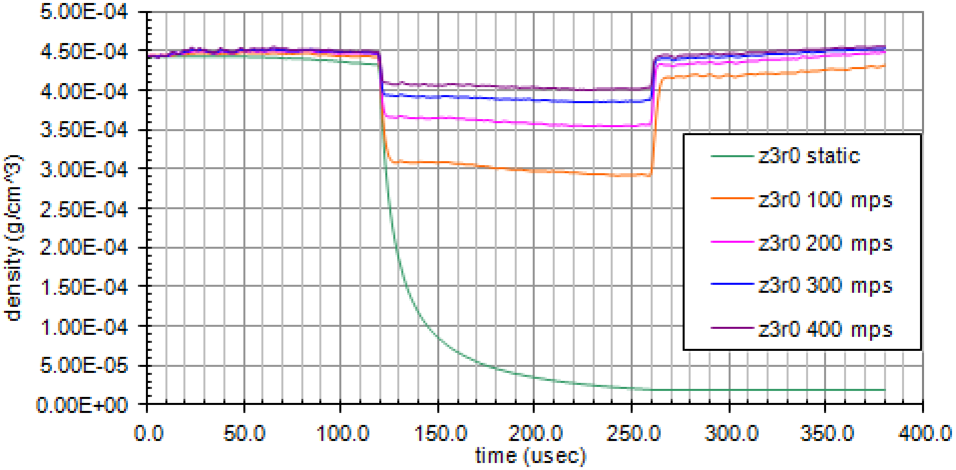


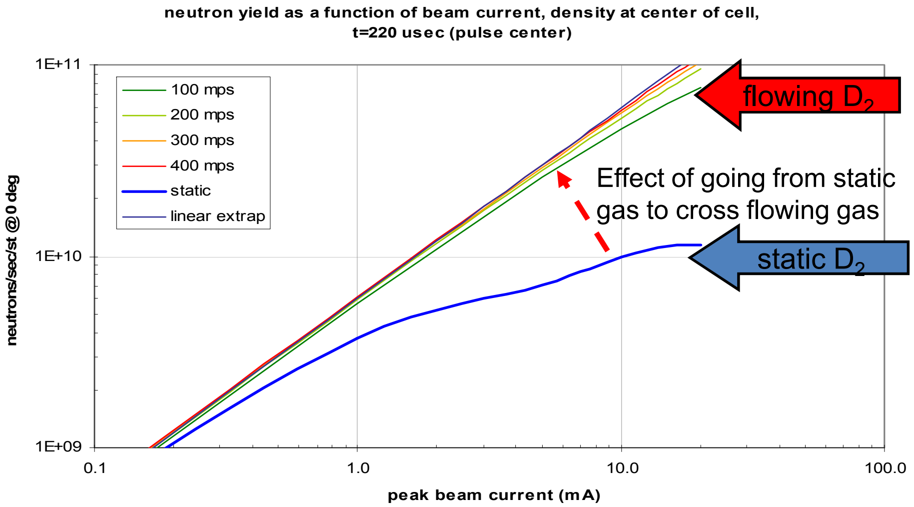


TRIM calc of stopping

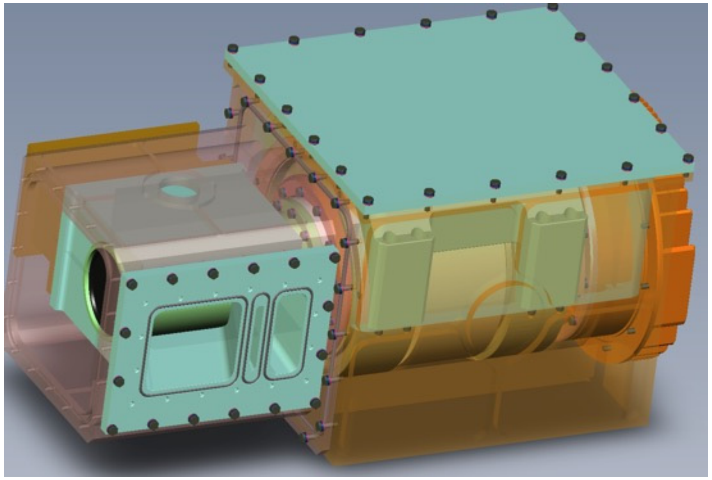
Due to the low energy, high peak beam power, and small spot size, this is a significant technical challenge

- With **113 kW peak power** in the macrobunch, the beam burns a hole in static gas in ~10 usec and limits neutron intensity, well short of the 150+ usec beam pulse length
- With upwards of **12 kW/mm³ average** power density deposited in a thin window, the beam will also quickly destroy any solid window
  - most windowed targets can do 20-30 uA average max, we're at 300 uA
- These high power densities have driven the design of a novel windowless gas cell that minimizes target gas from reaching the accelerator and that can move gas in front of the beam

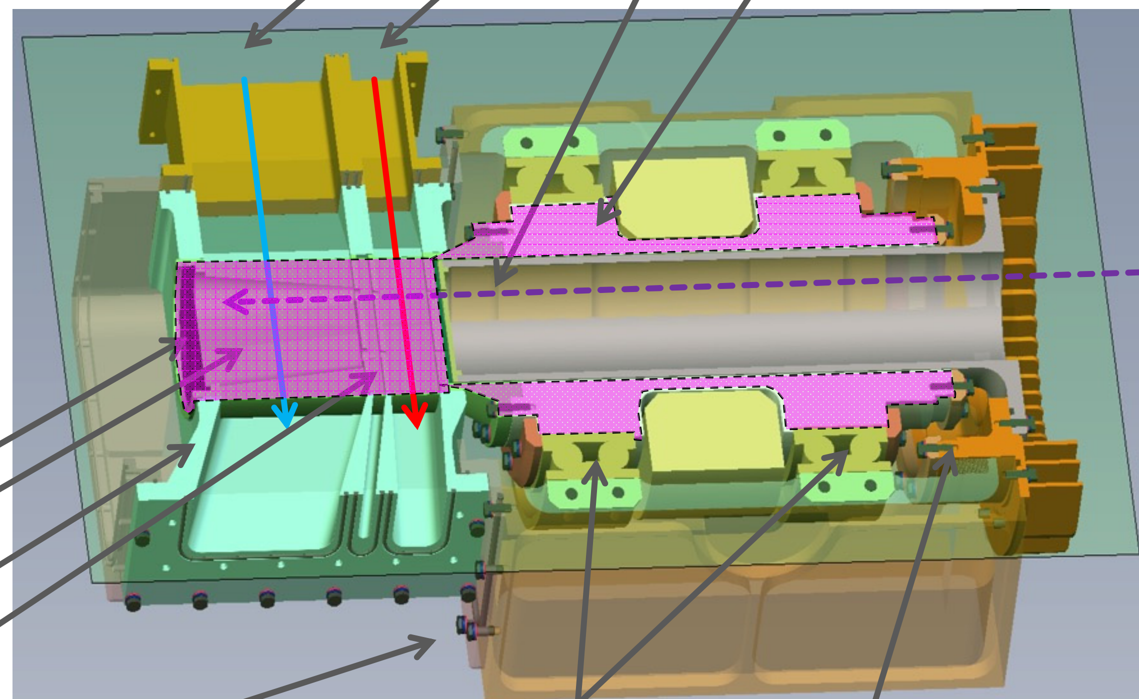




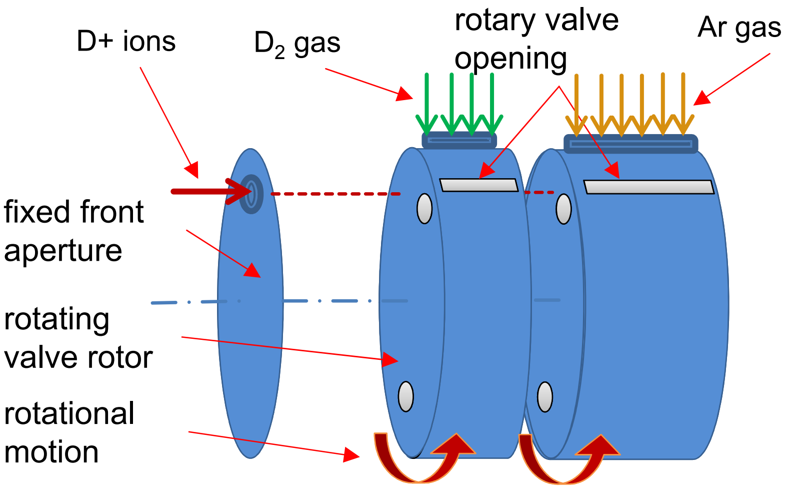
The rotary valve design will meter pressurized gas flow, aperture-restrict gas leakage to the beamline vacuum, and reduce leakage to the chamber with close gap tolerances

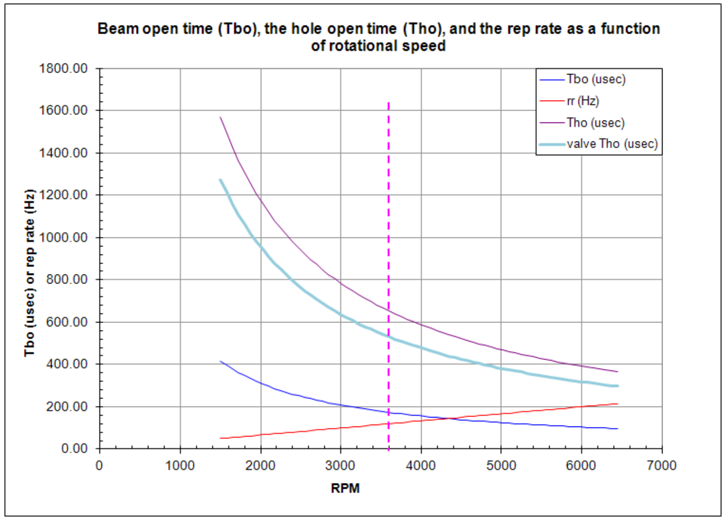


rotary valve assembly:
- ~12”x12”x24” in size and 300 lbs.
- rotates up to ~3,600 rpm
- made mostly of 7075 series aluminum to minimize activation products

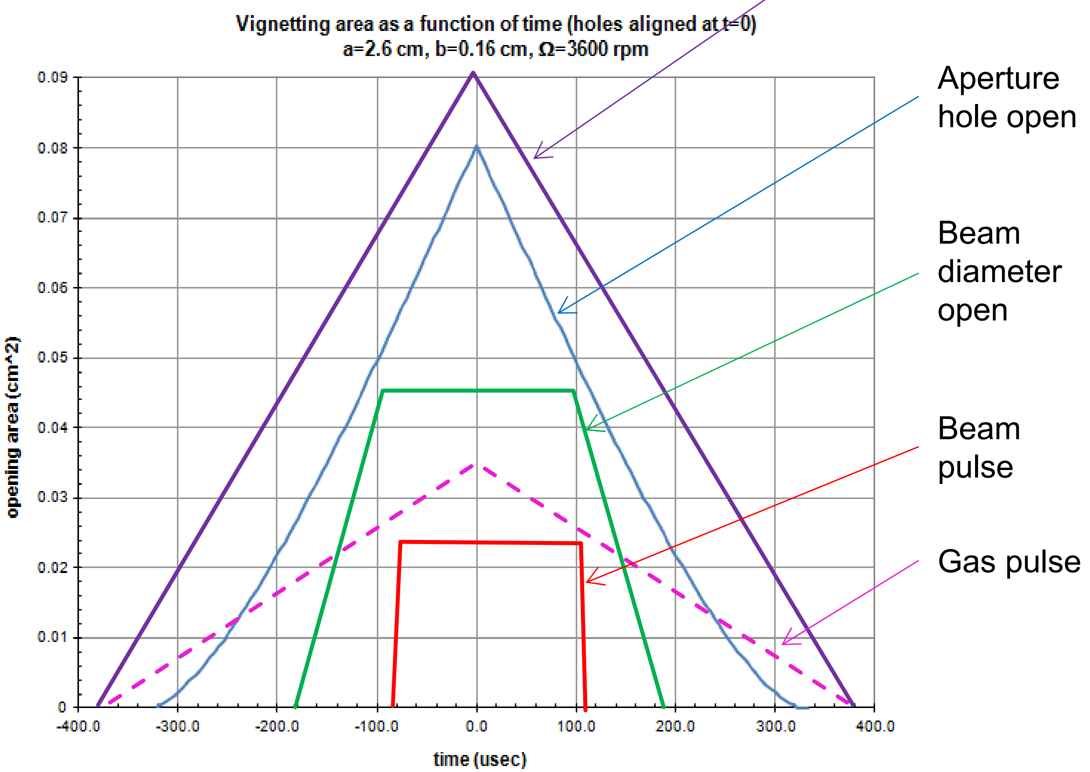


The valve geometry generates a number of coupled vignetting motions corresponding to beam aperture, gas inlet, and gas exhaust functions

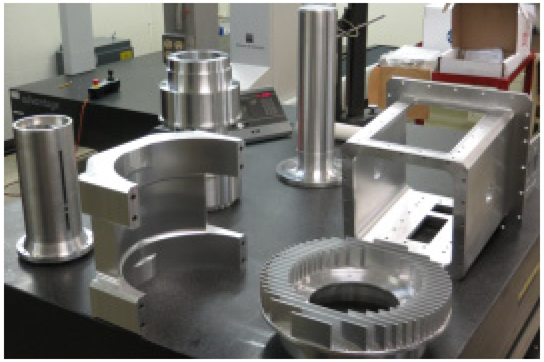


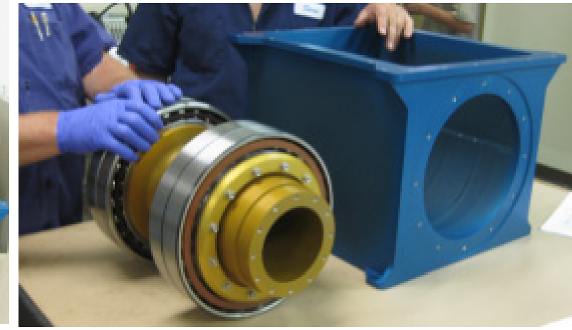


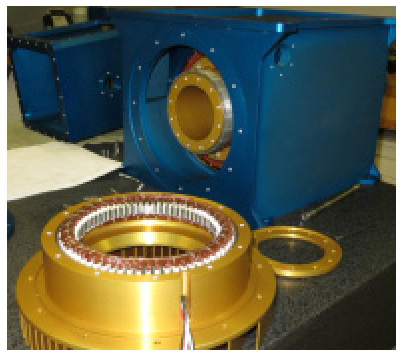
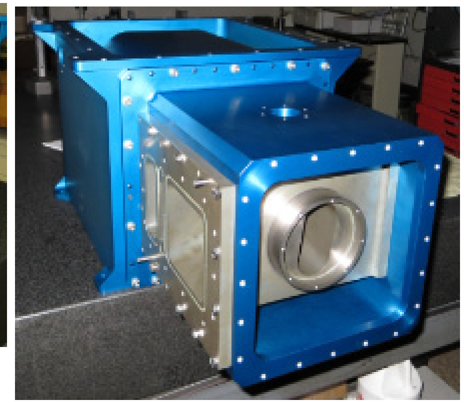
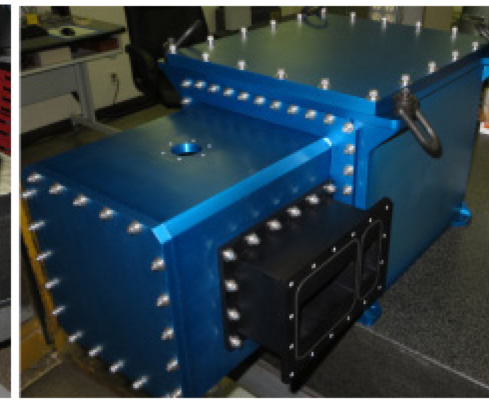
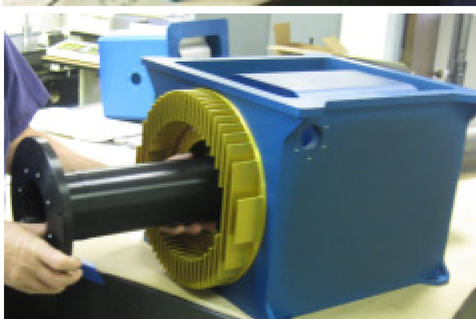
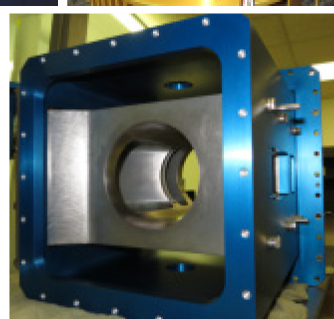
The geometry and rotational dynamics of the rotary valve system was configured to accommodate a 2% duty factor pulsed linac



Assembly of the rotary valve has been completed, and achieved precision 0.001-0.002” radial clearances between the rotor and valve head assembly



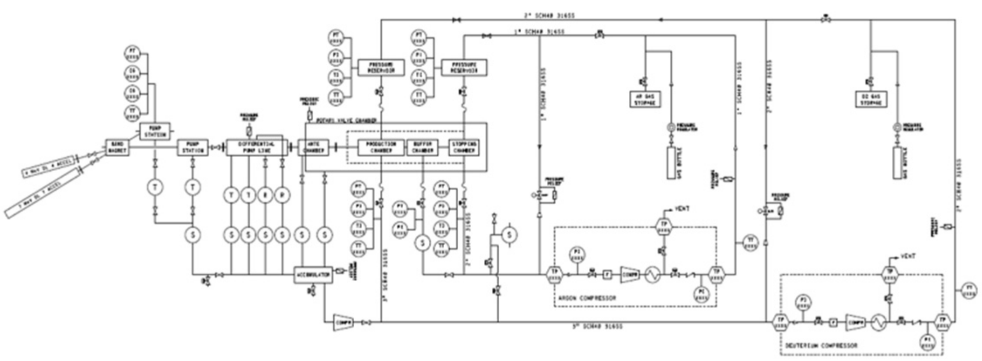






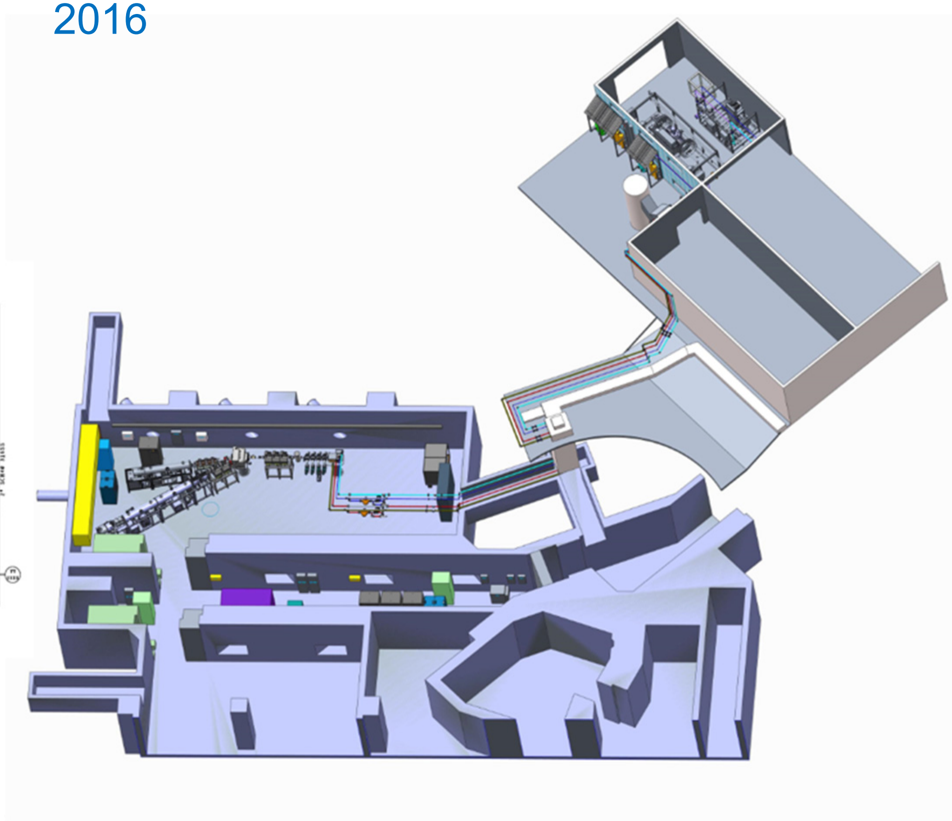
Machining and assembly was done by CHAMP Industries in Campbell, CA

Testing continues to measure performance and validate models

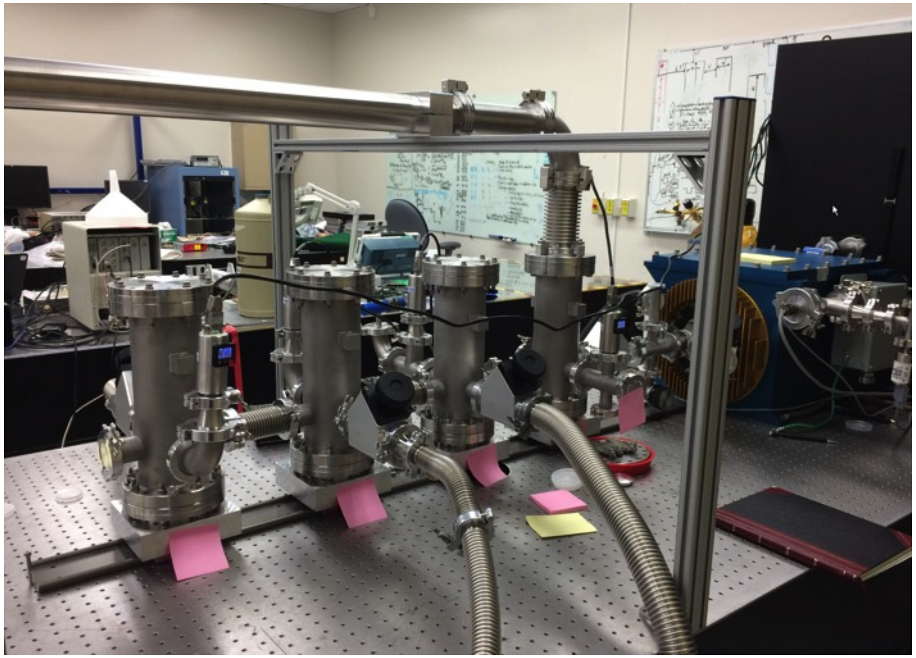
Process gas compressor installation is a significant undertaking

- Completed compressor anchoring calculation and process
- Completed initial safety analysis
- Completed updated P&ID diagram to guide piping installation
- Completed detailed piping layout design
- Installation completion expected by October 2016





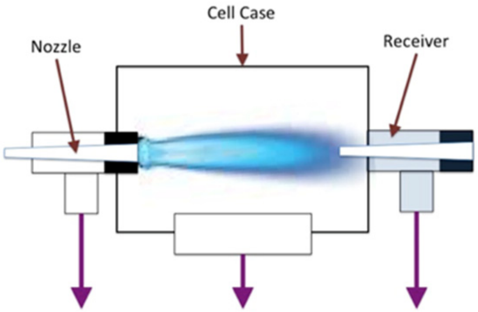
Significant effort going into the understanding and modeling of the differential pumping line for gas capture



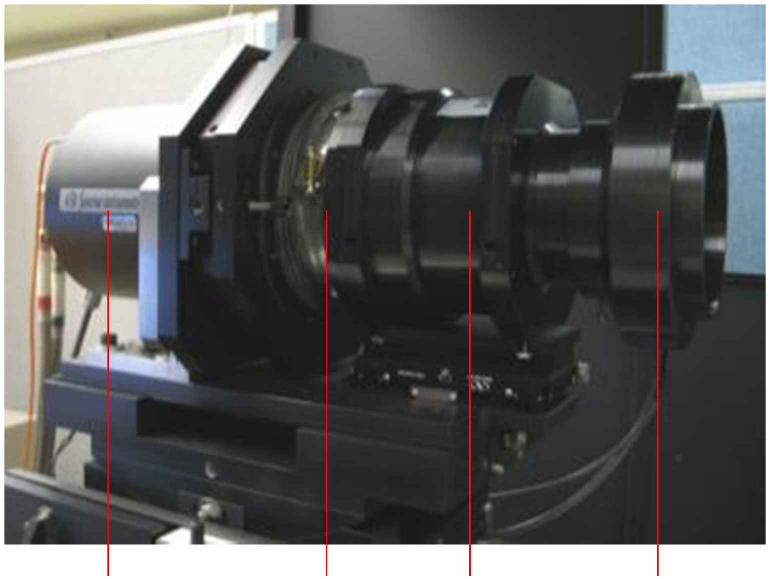
Characterizing gas propagation, mixing, and flow regimes across 6 orders of magnitude a complicated modeling problem

A preliminary testing apparatus was created to benchmark model

Want to avoid gas jetting regime which enhances transport



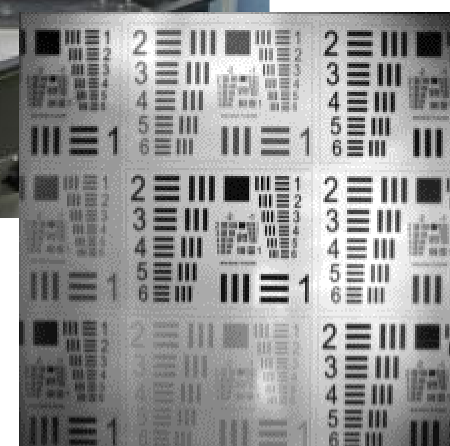
The lens-coupled imaging optics system uses a fast (f~2) lens with short focal length (<1m) and large viewing area (60x60cm) to focus light from the scintillator onto a 4096x4096 cooled CCD camera



The lens was built by Optics 1, and the camera by Spectral Instruments

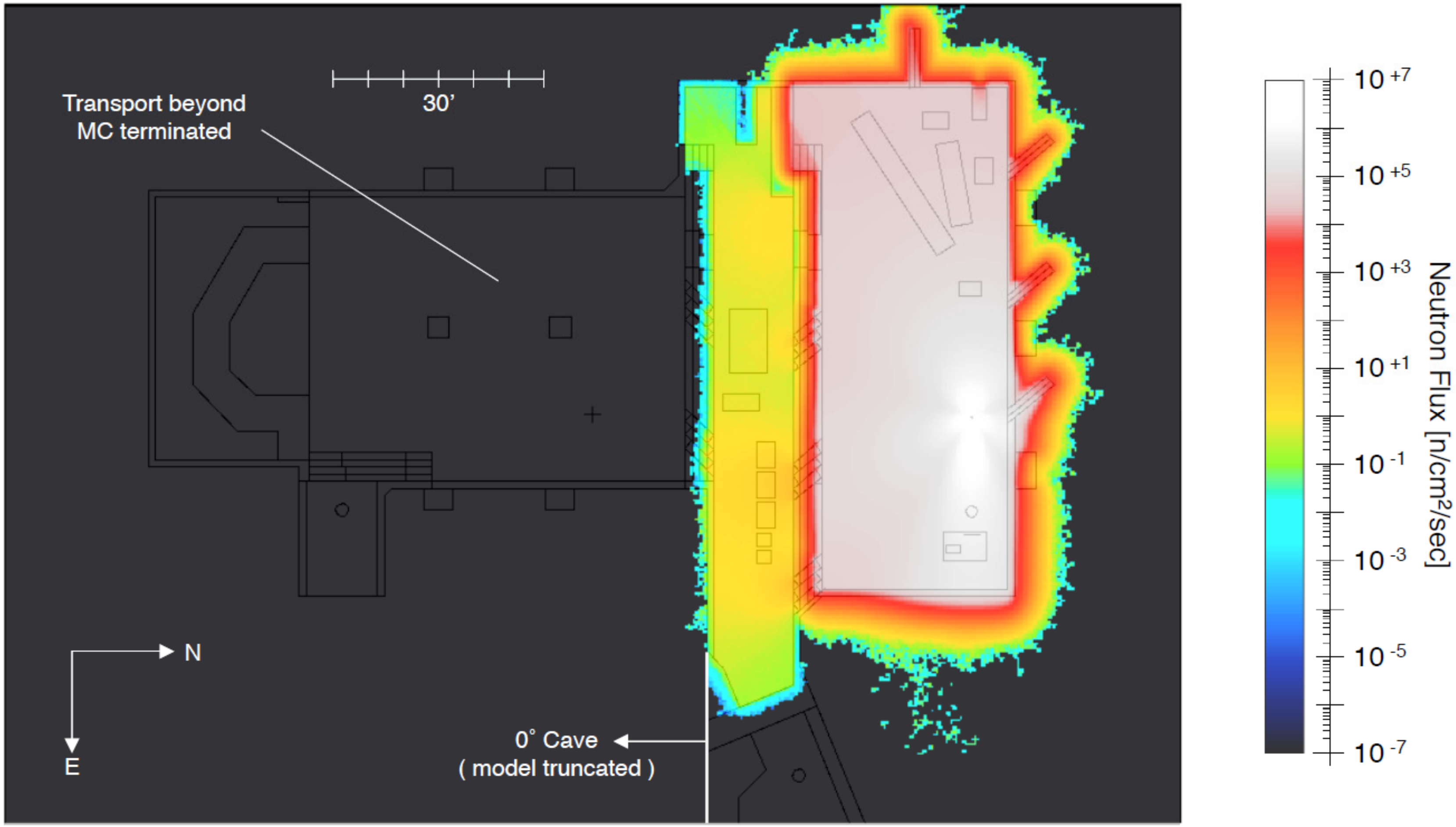
Both have performed well in initial testing

Test pattern image taken by system



Predicted neutron dose map with no local shielding shows high radiation flux in cave – a major concern for electronics

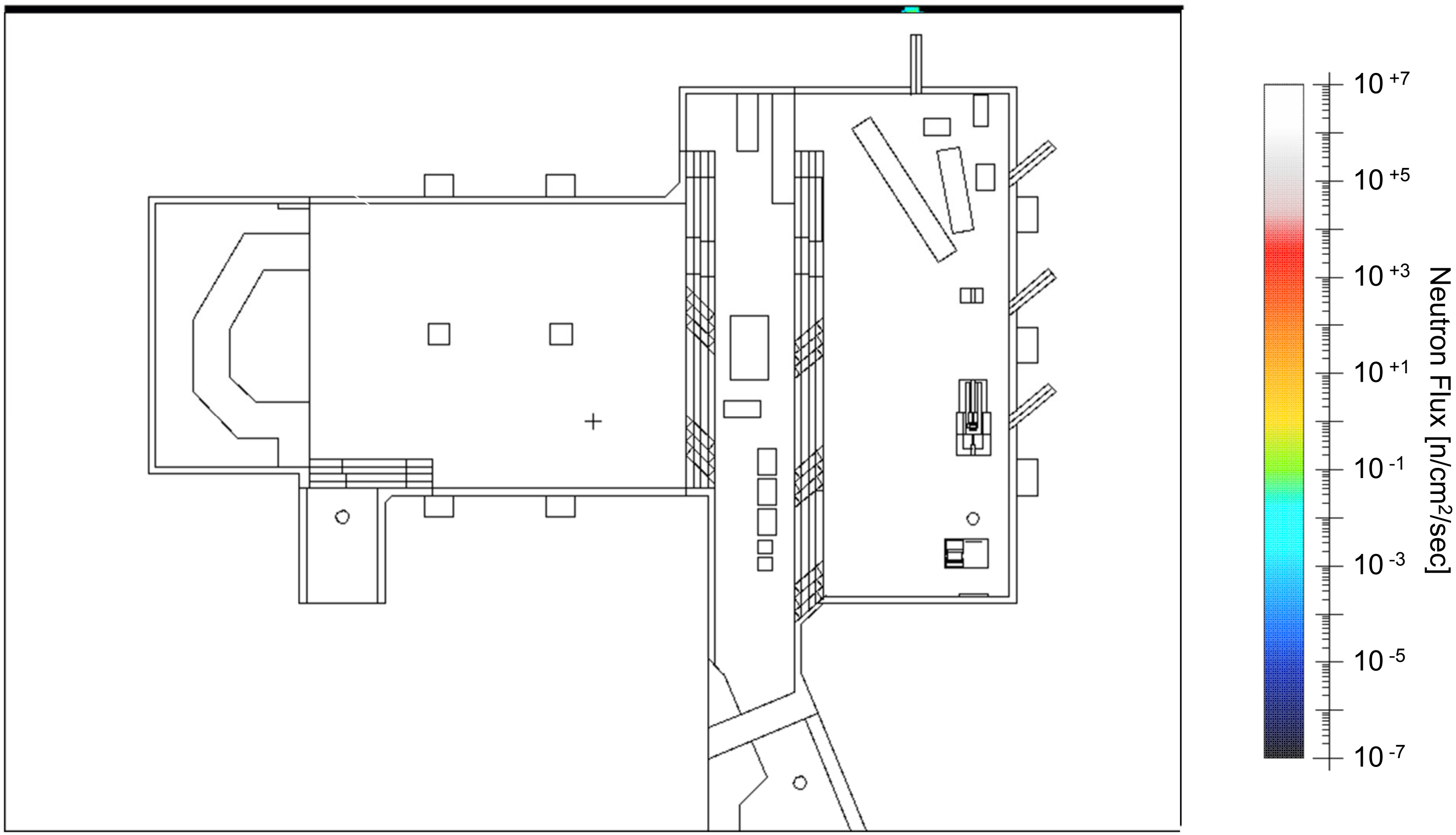
Unshielded / uncollimated neutron source (reference run) *



* Note: Results shown here are rendered at the same contrast level as the sad703 results (nominal intensity) to facilitate comparison.

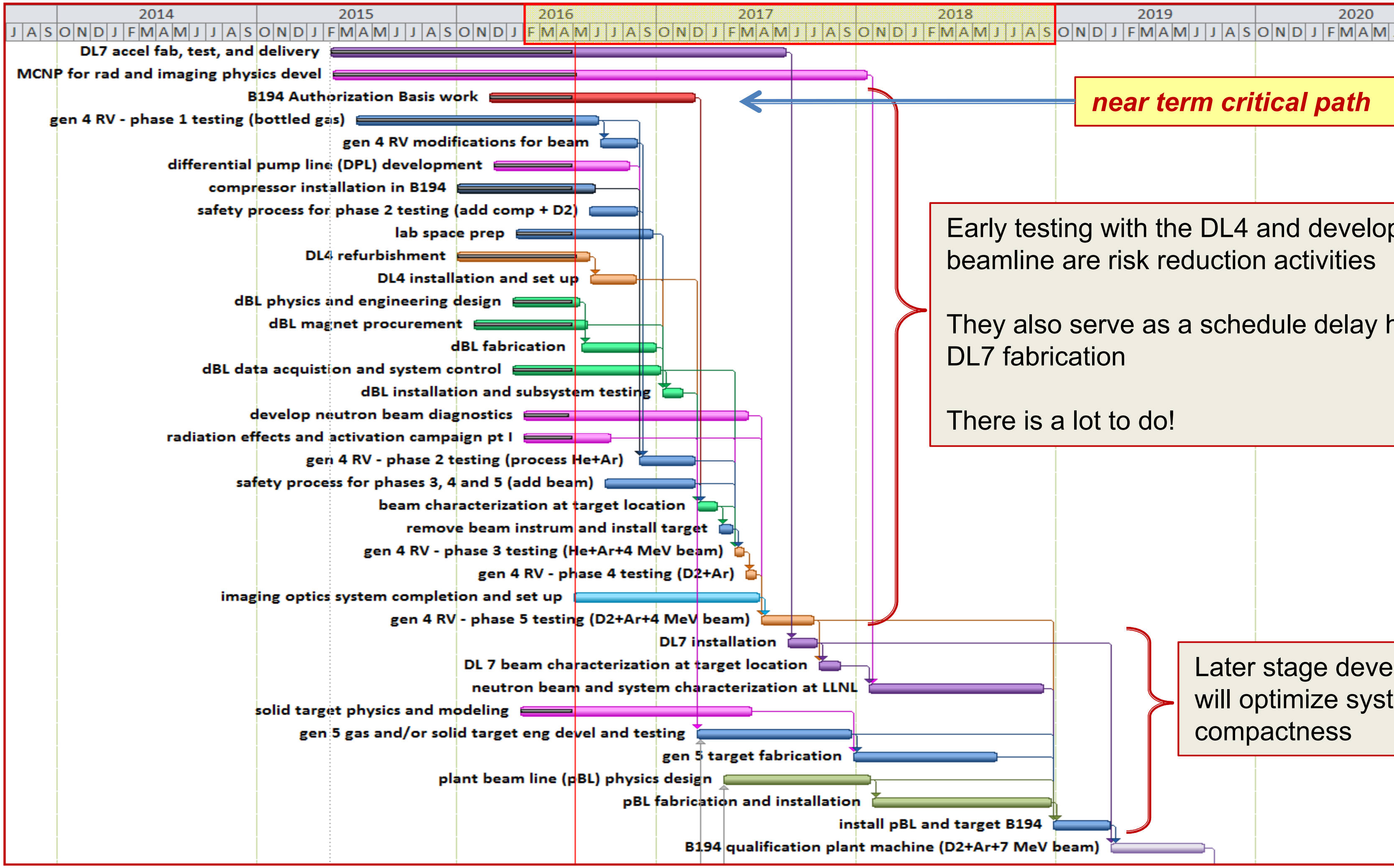
Installing localized iron and borated poly shielding around the production source lowers neutron fluxes by ~10^4

SST & BPE sarcophagus surrounding RV assembly; SST & BPE ± 3.6° collimator; max cred. doghouse; 4" BPE beam dump



* Note: Results shown here are rendered at the same contrast level as the sad703 results (nominal intensity) to facilitate comparison.

Technology development roadmap



near term critical path

Early testing with the DL4 and developmental beamline are risk reduction activities

They also serve as a schedule delay hedge on DL7 fabrication

There is a lot to do!

Later stage development will optimize system for compactness

Conclusions for source development for neutron imaging

- Approximately 15 years of development work has allowed ample time for the overall technology approach to mature
- A Fast Neutron Imaging Demonstration machine is well within reach using the current design concepts and technologies
- We are well positioned to complete the remaining development work, build, and test this novel high brightness source
- With the commissioning of the accelerators and beam line, we will be able to do actual beam testing of targets to better understand and advance target technology – a very important next step!
- The current development path will allow for advancing the technique of fast neutron imaging as well as allow for a variety of nuclear physics measurements

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