Advancement of an Accelerator-Driven High-Brightness Source for Fast Neutron Imaging

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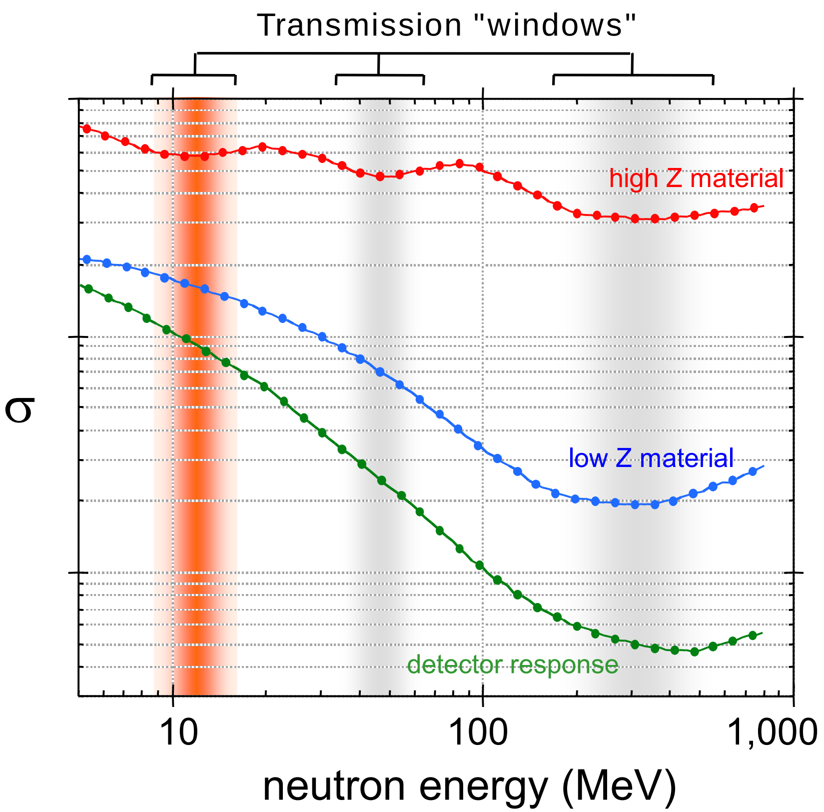
Neutron Imaging development has been ongoing at LLNL for 16 years and we are well along in building a demonstration capability

- Neutron imaging requires a very bright source of fast neutrons (10 MeV) to produce high resolution images through very thick, dense objects (rl>100-150 g/cm^2)
- 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:
  - Machine should be assembled by early CY2018
  - By mid CY2018, should be producing ~10^{10} n/s/sr at 0 deg
  - Sometime in 2018-2019, increase to ~10^{11} n/s/sr at 0 deg

Objectives of LLNL neutron imaging development effort

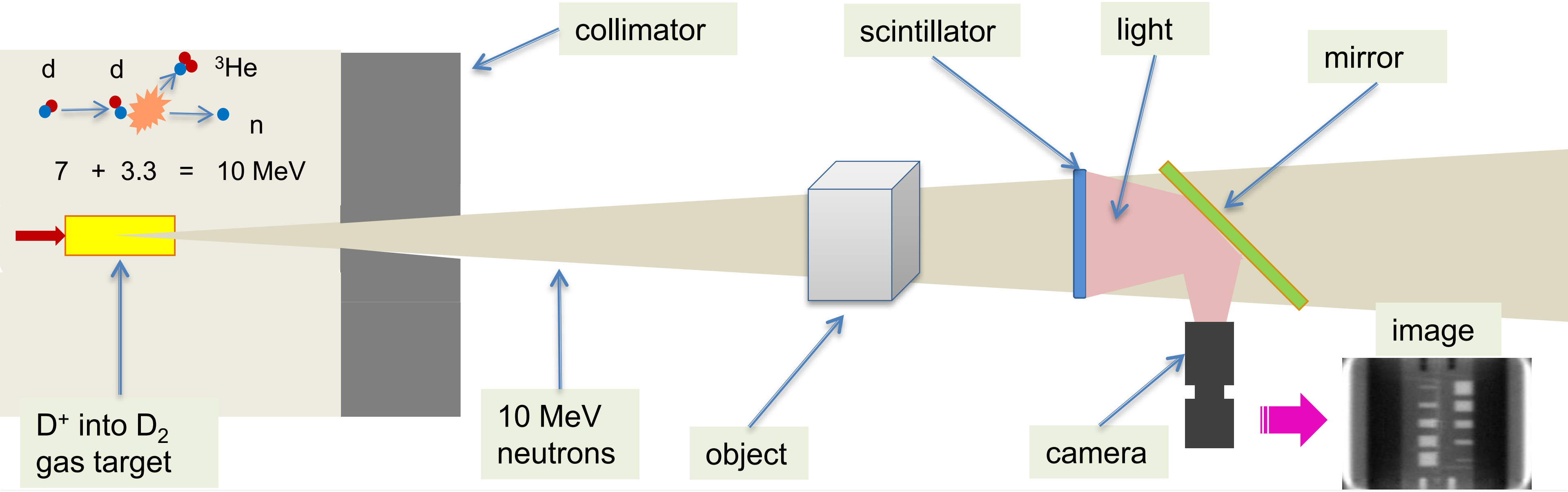
- Evaluate NI technique and its applicability as non-destructive-evaluation (NDE) diagnostic
- Develop a lab-scale fast neutron imaging instrument as a new NDE diagnostic for laboratory and larger scientific and industrial use
- Have the machine be user friendly
  - Use COTS subsystems as much as possible
  - “Lab scale” should correspond to a standard x-ray radiography bay size
  - Needs to operate as an NDE instrument, not an experimental device



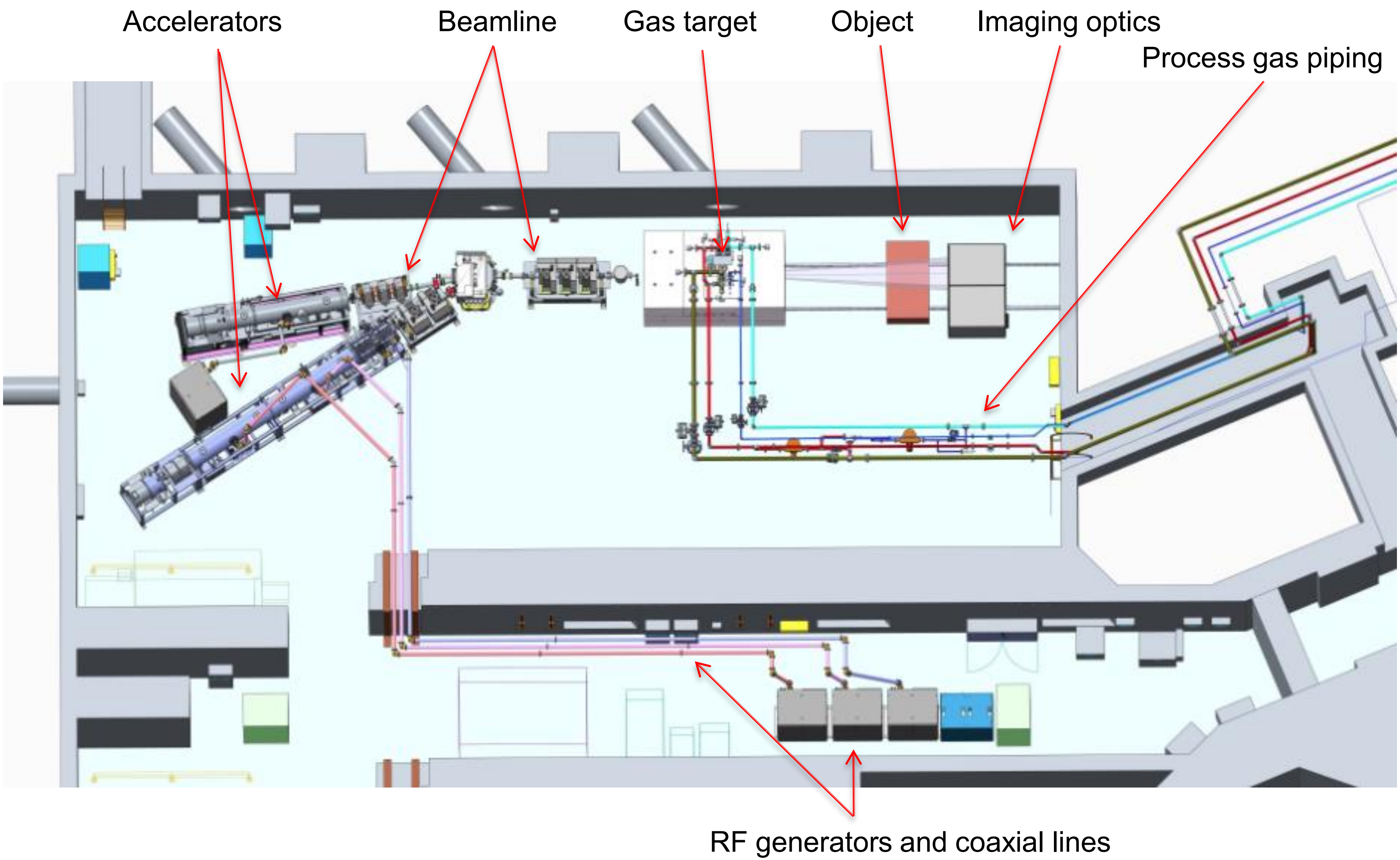
The combination of favorable cross sections and the ready accessibility to fast neutrons in the ~10 MeV range by modest-sized commercial accelerators form the basis of the development effort

Neutron imaging uses quasi-monoenergetic fast neutrons with much greater penetrating power to create radiographs

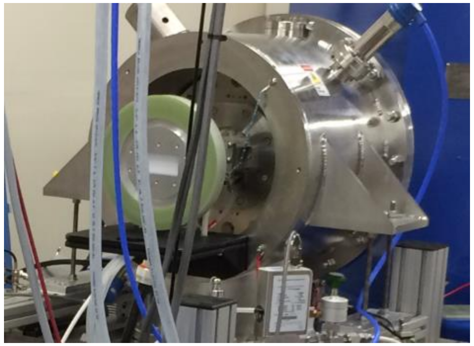
- Proposed system is based on commercial technologies
  - An intense accelerator-driven D(d,n)^{3}He neutron source for making 10 MeV neutrons
  - A digital radiographic and full CT imaging capability
- Neutron imaging compliments and extends radiography beyond x-rays
  - X-rays provide high resolution imaging of objects they can effectively penetrate
  - Neutrons provide slightly lower resolution images in thick, dense (ρl > 100-150 g/cm^2) objects that x-rays cannot penetrate efficiently

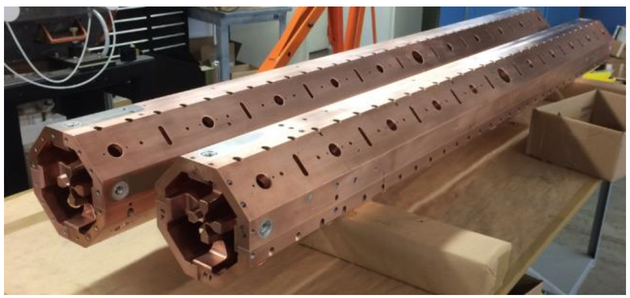


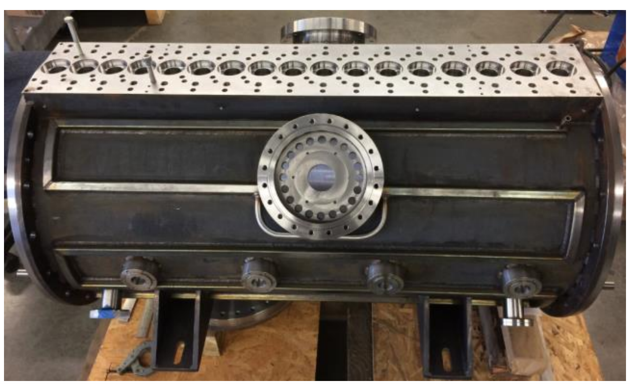
Currently layout of system in the LLNL B194 North Cave



Accelerator system being procured for full power imaging : 7 MeV DL7 deuteron accelerator built by Accsys Technology

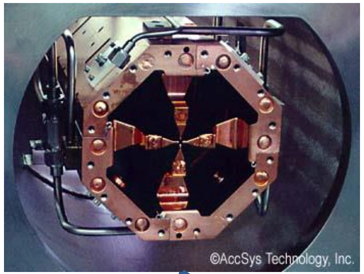




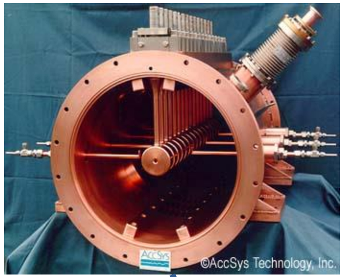


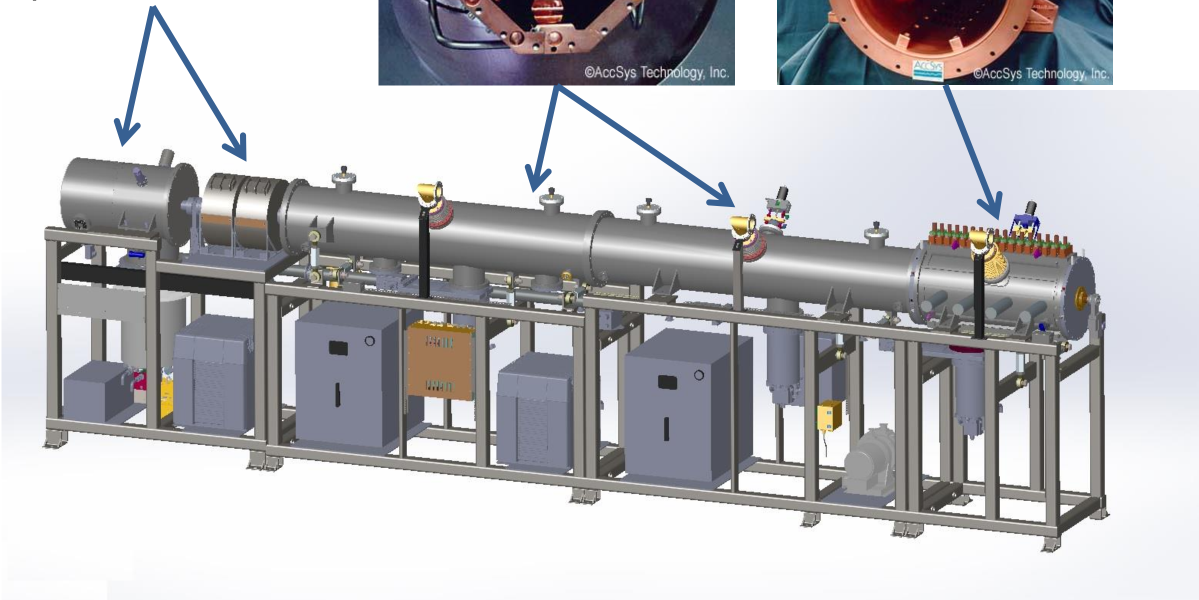
ECR driven ion source and magnetic low energy beam transport

RFQs are the first two acceleration structures



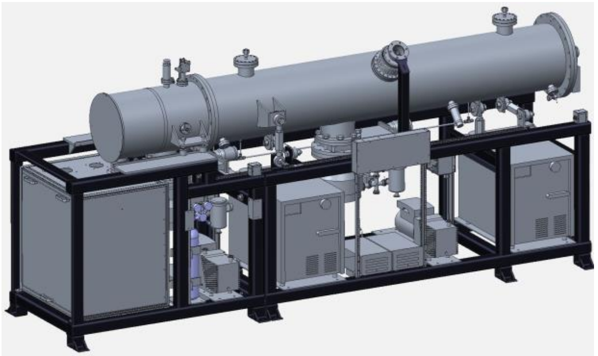
DTL is the third acceleration structure

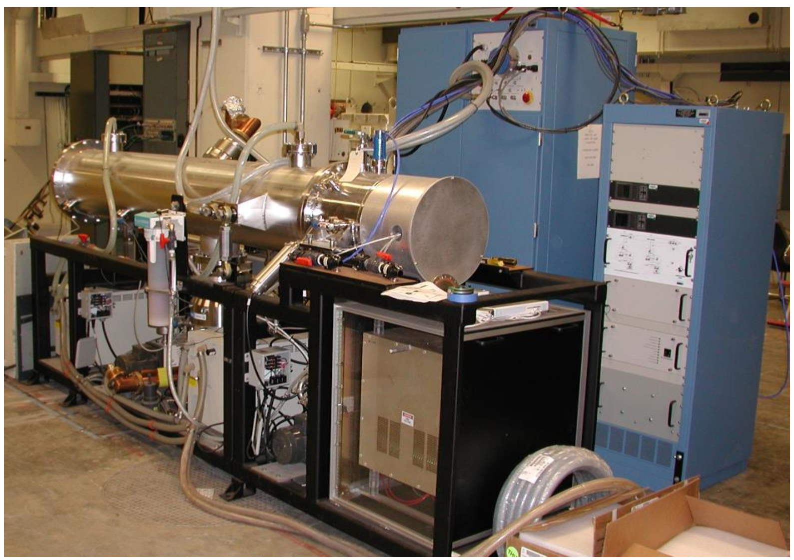




- Manufacturing > 80% complete
- Entering into assembly and integration phase
- DL7 scheduled for delivery August 2017

Peak power testing accelerator: 4 MeV deuteron Accsys DL4





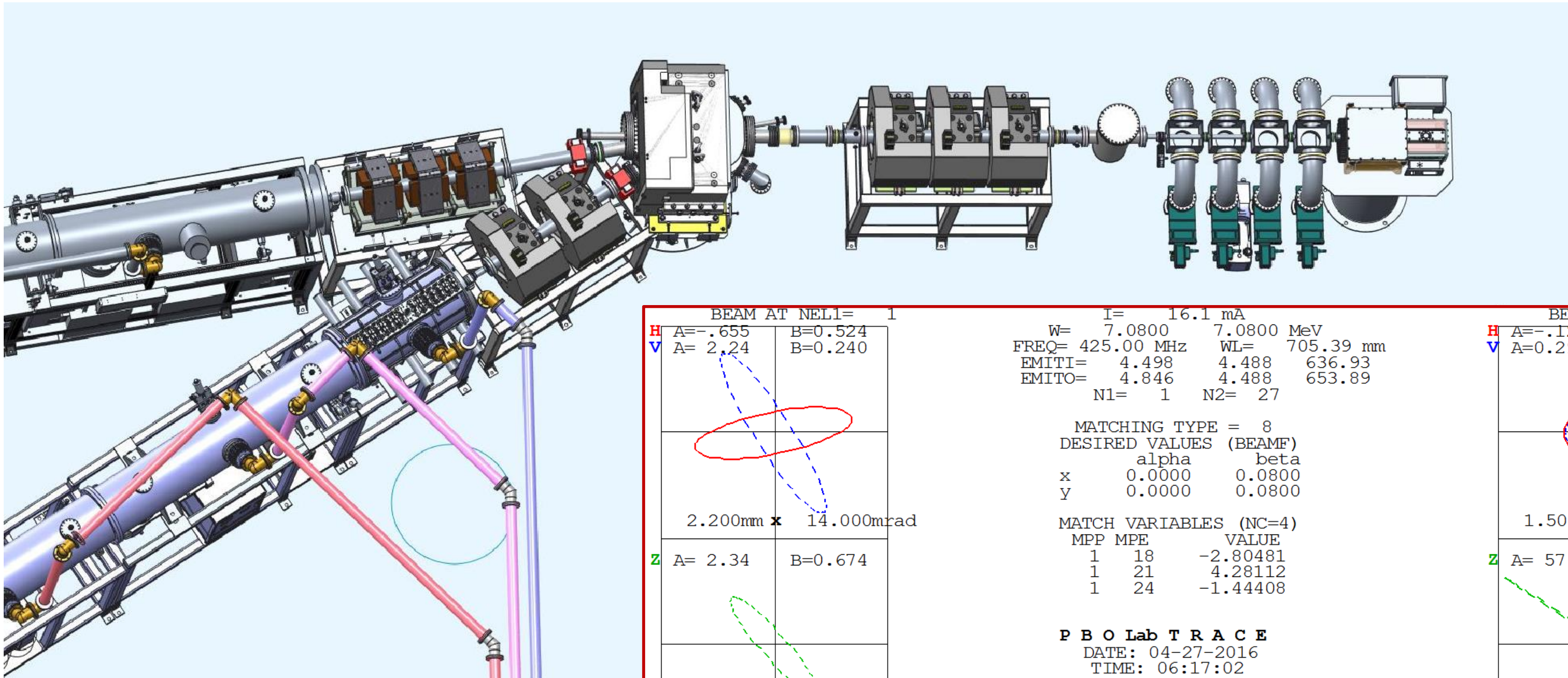
- DL4 refurbishment complete
- DL4 awaiting installation

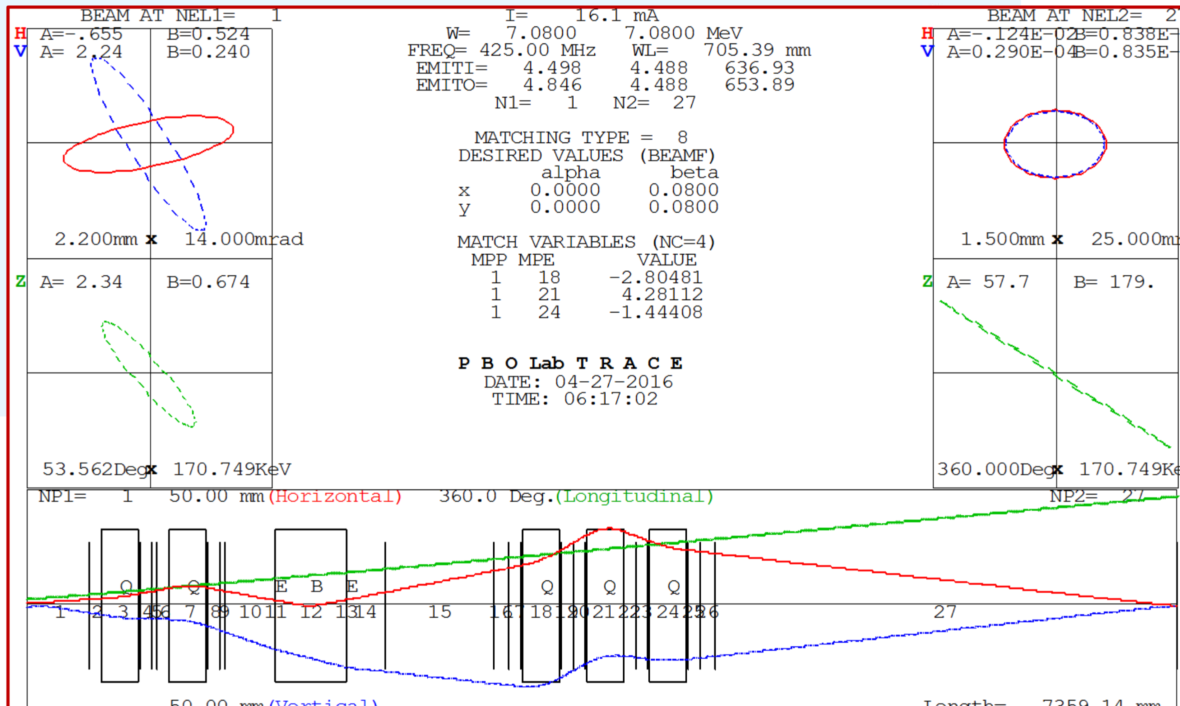
The DL7 machine will give the high average current needed to achieve the required integrated fluence

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

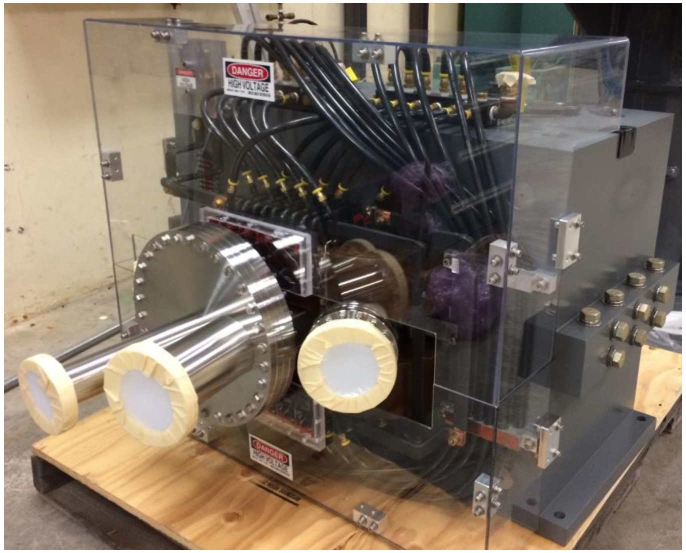
Beamline physics design completed that should achieve ~1.5 mm spot size using 5 quadrupoles and 1 dipole

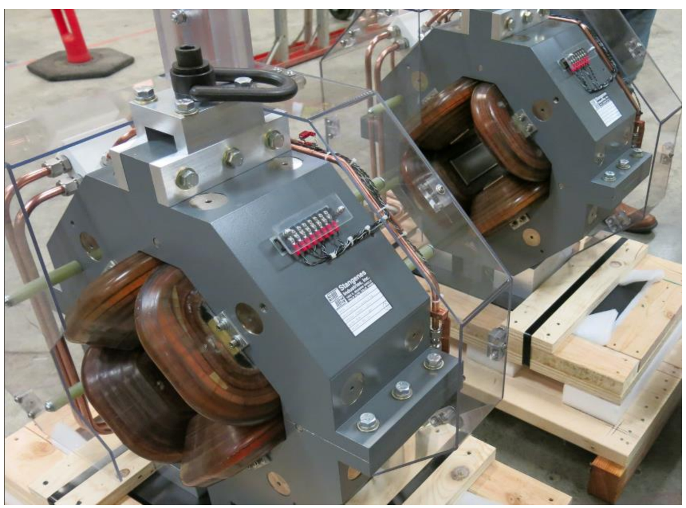


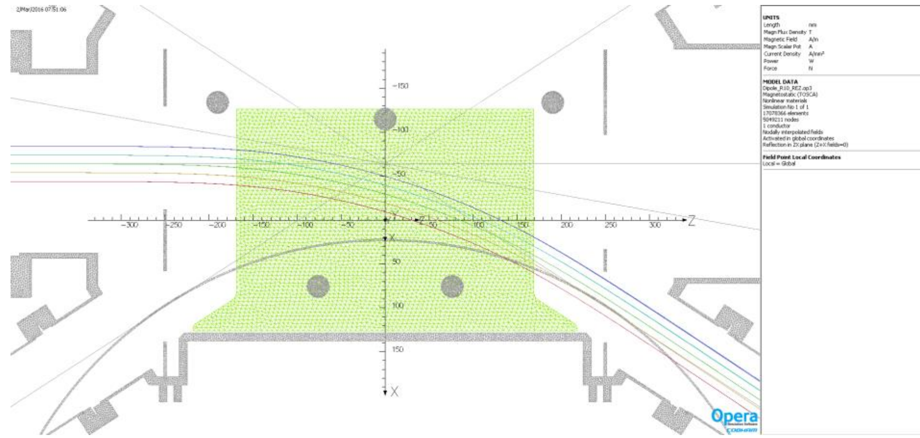


Beam final focus size based on 5xRMS values

Beamline optics development is nearing completion with magnetic dipole and quads being made by Stangenes Industries







- Magnets were designed to have significant margin
- Beamline will be used to characterize the beam to enable designing more compact machine
- Dipole and quad fabrication finished
- Magnets delivered and being inspected

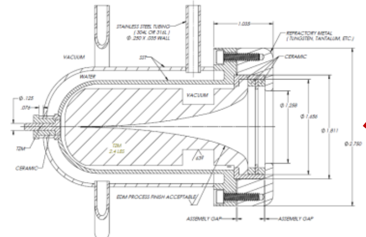
Dipole gap (cm)	6.6
Dipole operating current (A)	270
Dipole field strength (T)	1.27
Quadrupole bore (cm)	10.1
Quadrupole operating current (A)	240
Quadrupole field gradient (T/m)	11

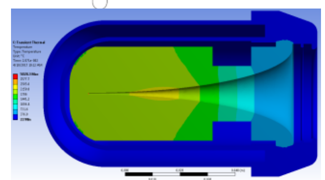
Beamline diagnostics an engineering challenge due to high power density of beam deposition in solids

current toroid

beam position

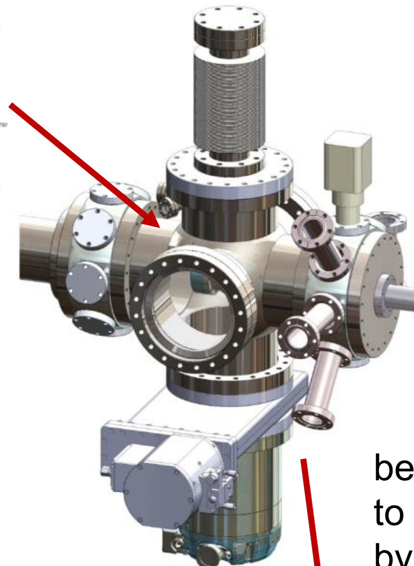
fixed stop



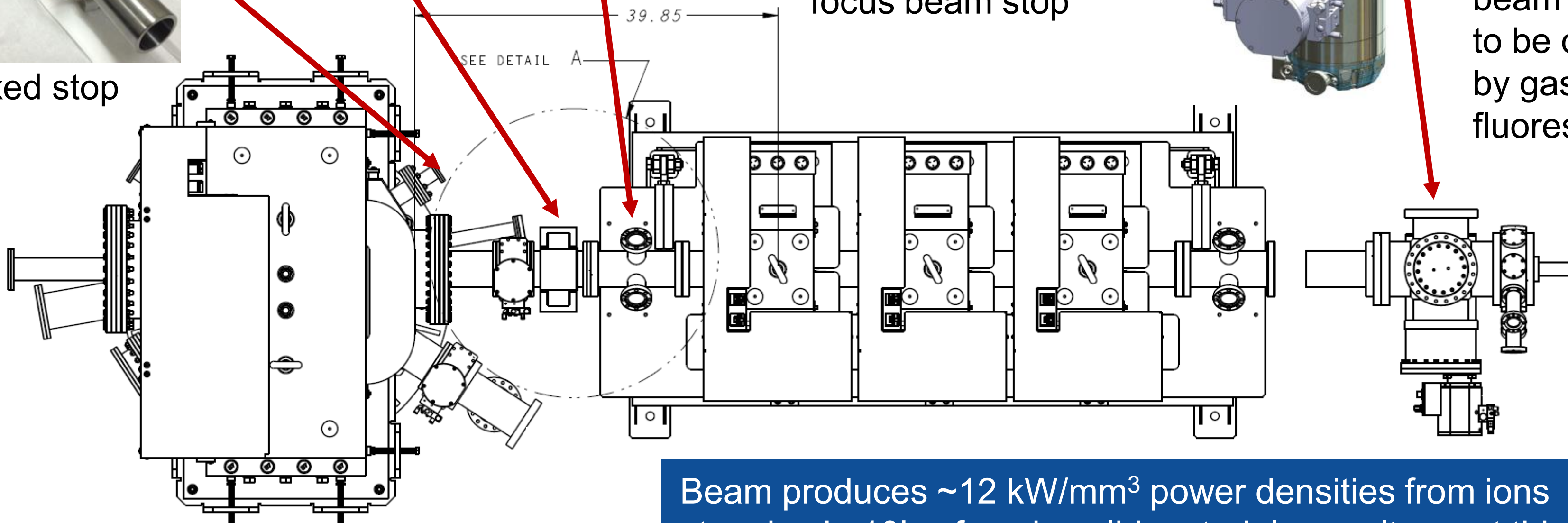


full power at focus beam stop

beam intercepting diagnostic



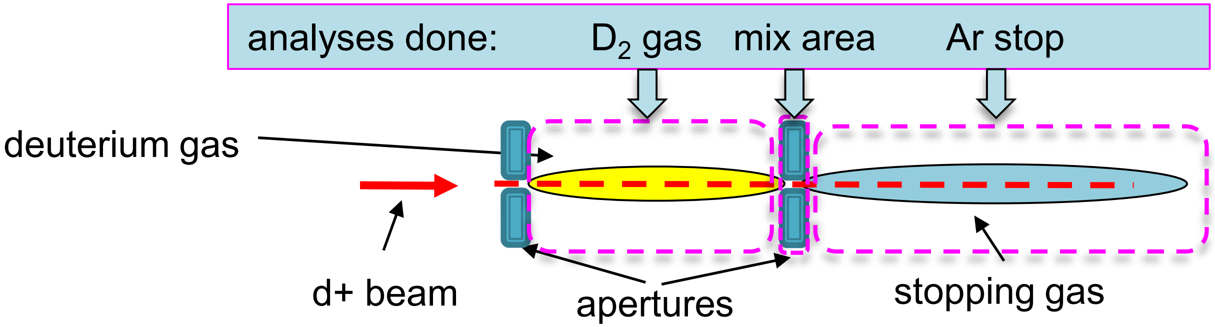
beam profile to be done by gas fluorescence

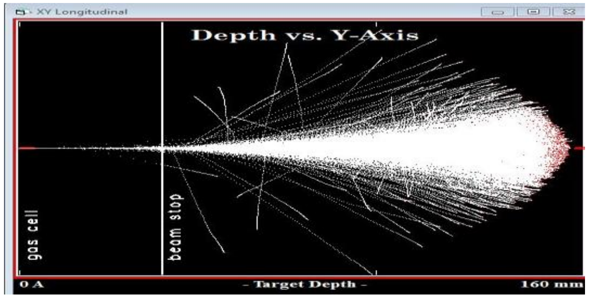


Beam produces ~12 kW/mm^3 power densities from ions stopping in 10's of um in solid materials…melts most things

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

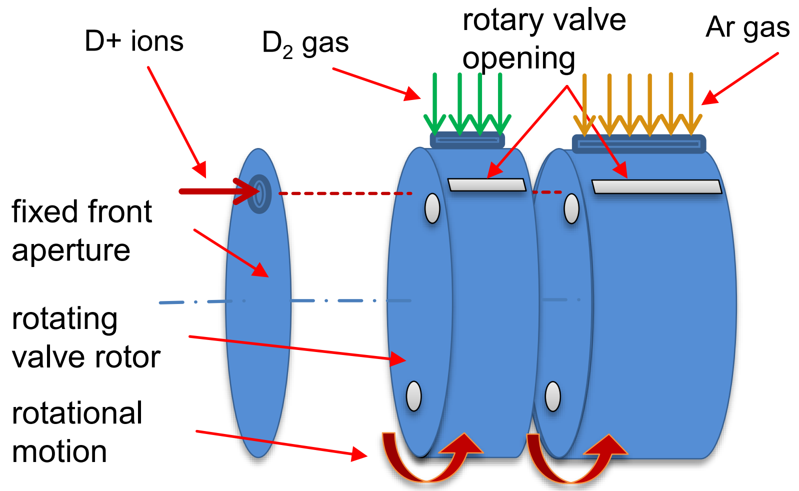
- A transmission-type deuterium gas cell will produce the desired neutron spectrum and intensity with:
  - A nominal 7 MeV and 300 uA average current deuteron beam, pulsed at a 2% duty factor with 17 mA in a macrobunch
  - A deuterium gas cell target operating at 3 atm-abs will produce 10 MeV neutrons 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 used



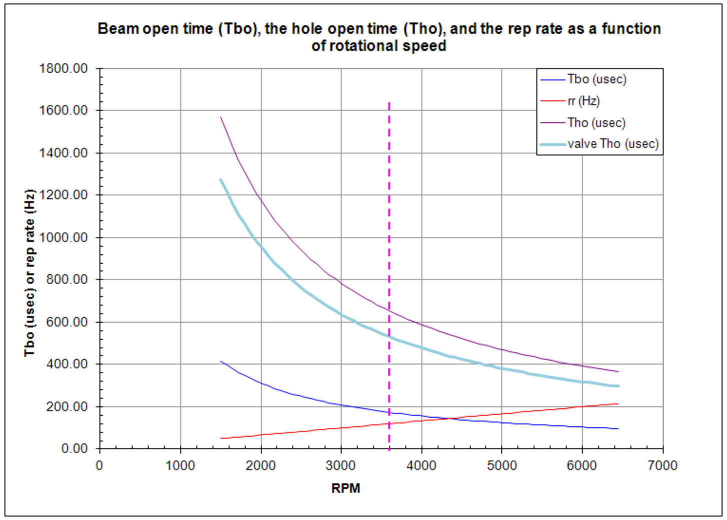


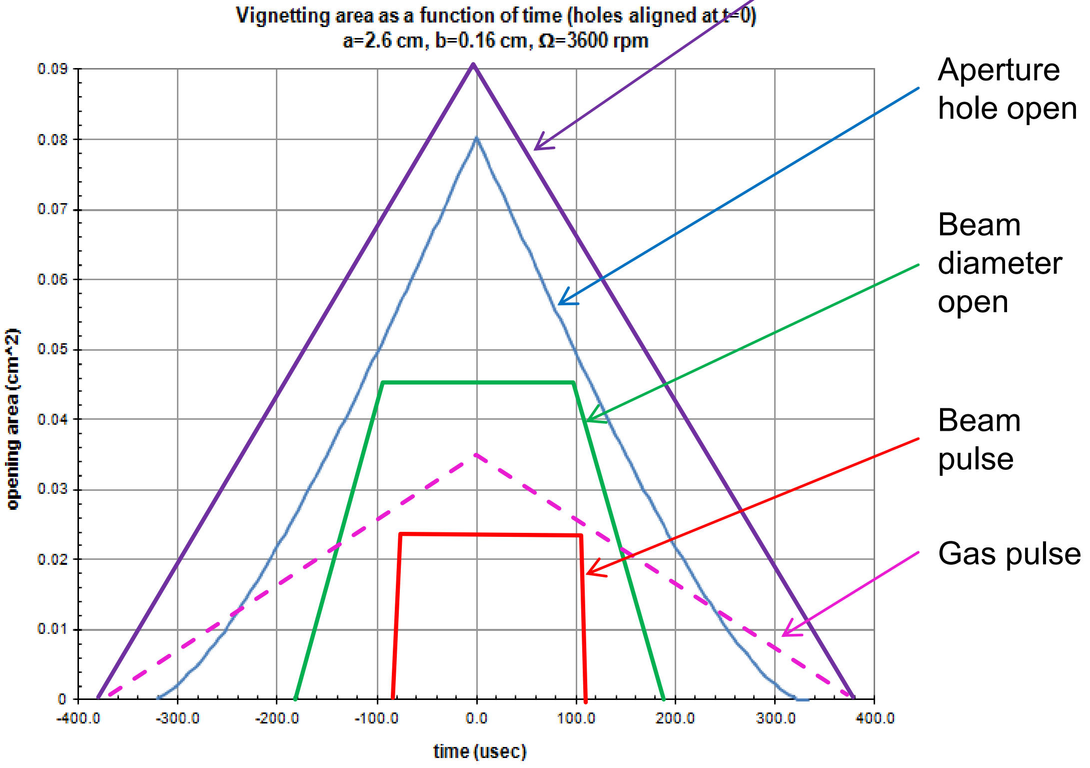
TRIM calc of stopping

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

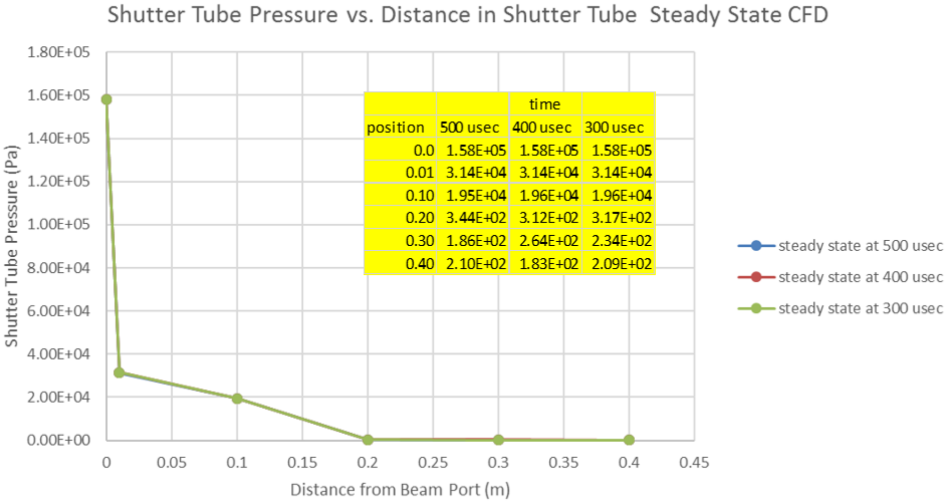


The geometry and rotational dynamics of the rotary valve system was configured to accommodate a 2% duty factor pulsed linac





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

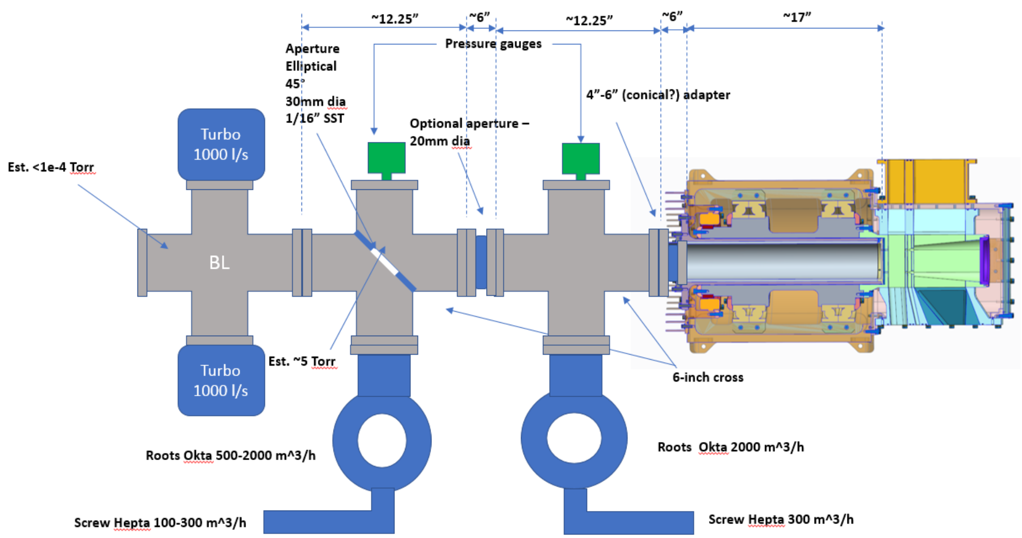


	time		
position	500 usec	400 usec	300 usec
0.0	1.58E+05	1.58E+05	1.58E+05
0.01	3.14E+04	3.14E+04	3.14E+04
0.10	1.95E+04	1.96E+04	1.96E+04
0.20	3.44E+02	3.12E+02	3.17E+02
0.30	1.86E+02	2.64E+02	2.34E+02
0.40	2.10E+02	1.83E+02	2.09E+02

Capturing gas properties, propagation, mixing, and flow regimes across six orders of magnitude is a complicated modeling and experimental problem

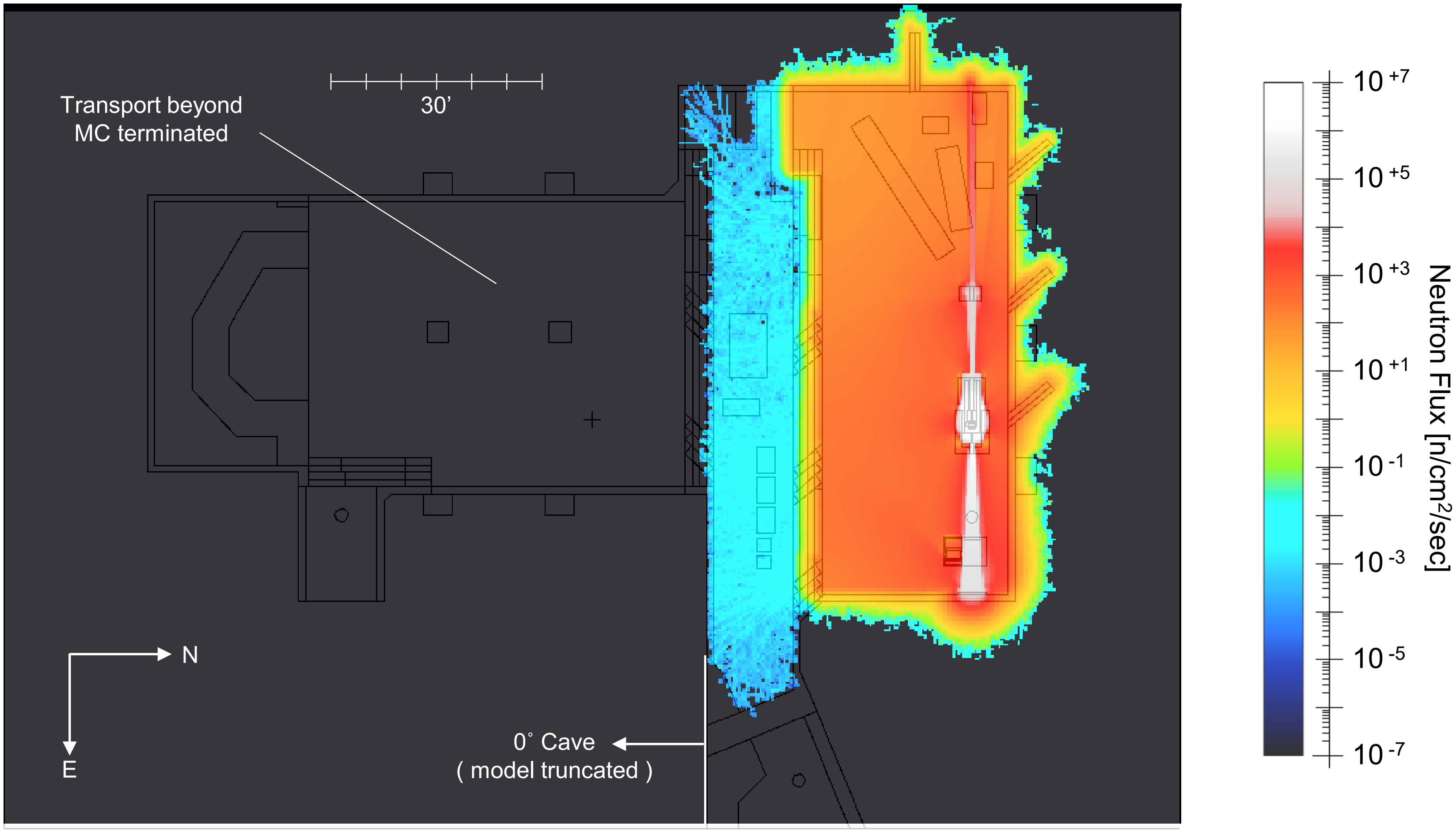
Currently assessing free expansion versus small volume capture and pumping

Testing underway to evaluate and optimize design approach



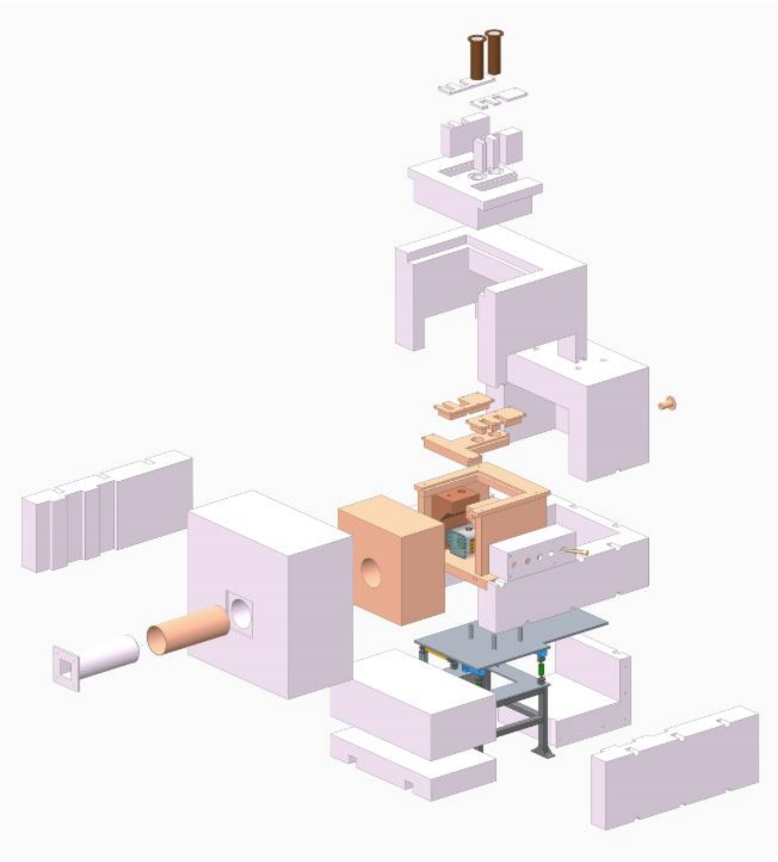
Installing localized iron and borated poly shielding around the production source lowers neutron fluxes ~10^4

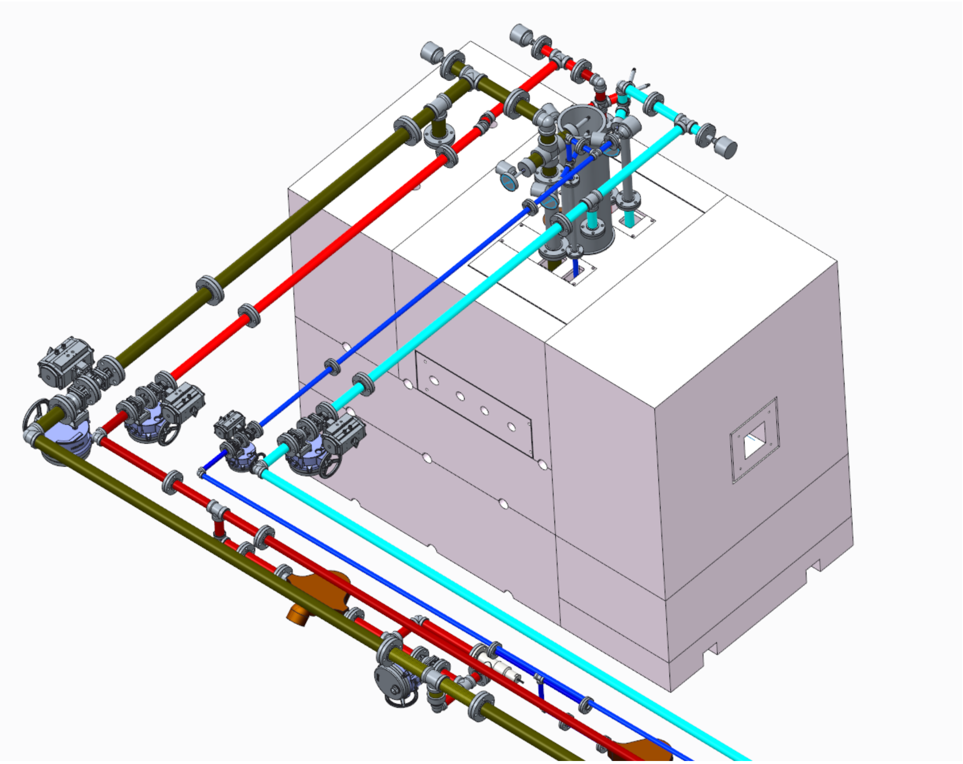
SST & BPE sarcophagus surrounding RV assembly; SST & BPE ± 3.6° collimator; max cred. doghouse; 4" BPE beam dump



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

Design of fast neutron target steel and borated poly collimator and overall shielding system is underway

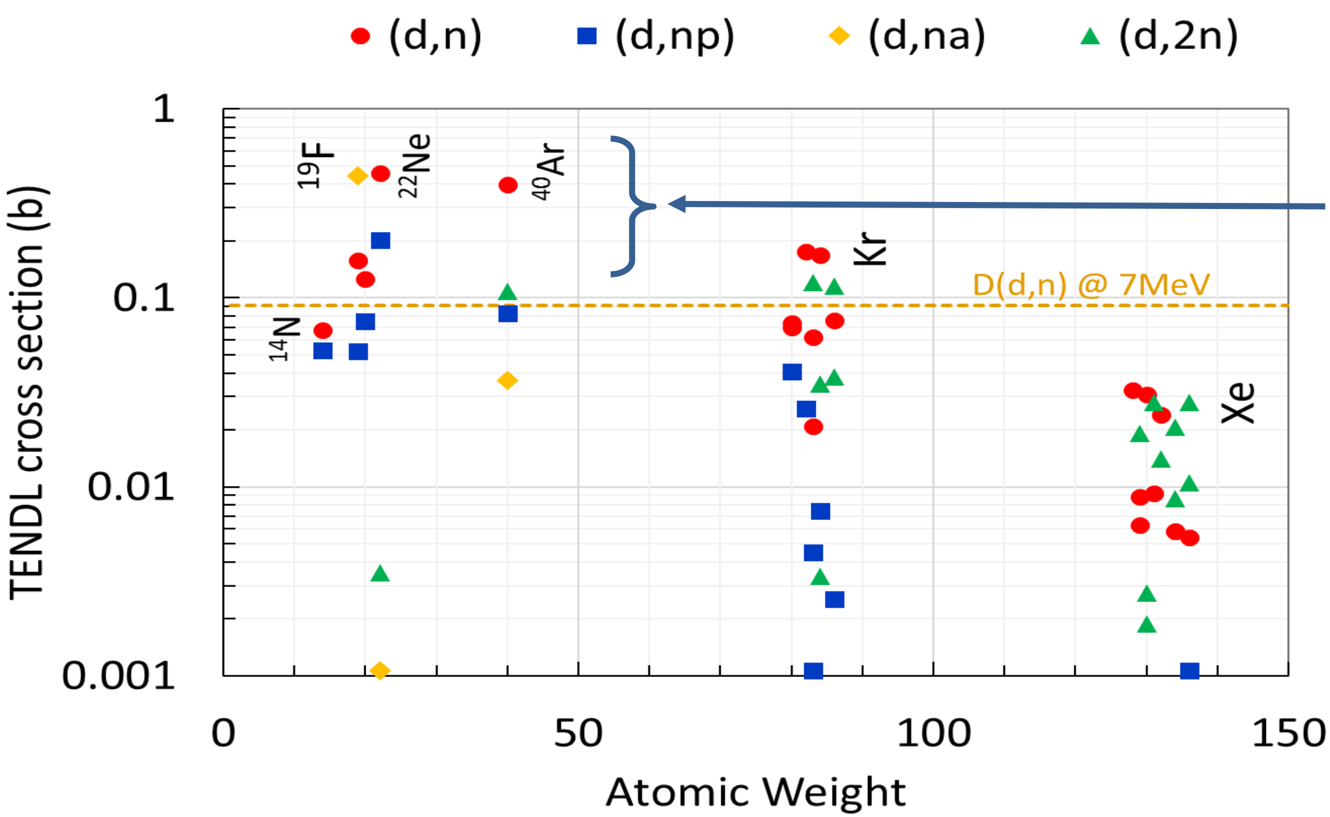




Assembly, accessibility, and seismic considerations are driving the design approach

Shielding assembly nominally 66” x 120” x 96” high and weighs approximately 40,000 lbs

Target nuclear physics studies are underway for next generation gas and solid targets



Some lighter gases offer intriguing alternatives to deuterium for producing neutrons,

We will be evaluating associated neutron spectra for imaging effectiveness

Initial survey of TENDL data (above) shows significant inconsistencies and gaps – planning on performing more extensive measurements in the coming months

Conclusions for neutron imaging machine development

- The extended LLNL development effort 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 have made solid progress in developing the overall concept and in advancing certain high risk areas
- We are now working on the remaining under developed technology areas to reduce risk and uncertainty further
- We are well positioned to complete the remaining development work, build, and test this novel and unique NDE demonstration machine
- The current development path will allow for advancing the technique of fast neutron imaging as well as allow for a variety of nuclear physics, activation, calibration, and scintillator development measurements to be done

Summarized machine parameters for 7 MeV D+ DL7

Neutron Production (averages)

- 1.0 x 10^{11} n / second / steradian at 0 degrees (imaging beam in ~14° forward cone)
- 1.2 x 10^{12} n / second into 4π
- max. neutron energy: 10.29 MeV energy width: 227 keV
- neutron pulse structure: 2% duty factor, 60-130 Hz rep rate, 330-150 usec pulse length

Accelerator System

- D+ ion energy: 4.5 and 7.07 MeV
- beam current: 300 μA average current, up to 25 mA peak current
- beam power: 2.1 kW average, 175 kW peak
- accelerator: 2 (RFQs) + 1 (DTL)
- operating frequency: 425 MHz
- RF power: planar triode combiner: 350 kW peak power, 7 kW average,
- pulse structure: 2% duty factor, 60-130 Hz rep rate, 330-150 usec pulse length
- beam emittance: $< 4\pi$ mm-mrad (5xRMS un-normalized)
- spot size in target: 1.5 mm diameter over 40 mm length, viewed end on

Gas Target System

- neutron production deuterium gas: 3 atm-gauge pressure, crossflow velocity > 400 m/s
- beam stopping argon gas: 1-2 atm-gauge pressure, crossflow velocity >200 m/s
- rotational speed: 2000-3000 rpm
- construction material: 7000 series aluminum to minimize activation
- motor: linear induction inside chamber vessel
- beam terminus behind gas stop, beam apertures: tungsten or tantalum

Gas Compressor System

- deuterium compressor: PDC 13-300-300, 700 SCFM at 3 atm-g
- argon compressor: PDC 4-150-150, 100 SCFM at 2 atm-g