ACCELERATOR-PATHWAY FOR ^{99}MO PRODUCTION WITHOUT HIGHLY ENRICHED URANIUM

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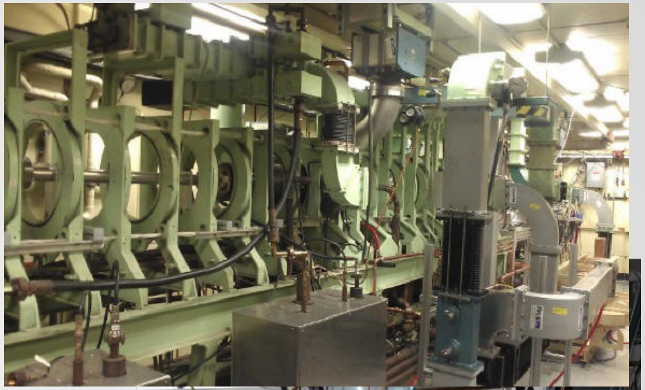
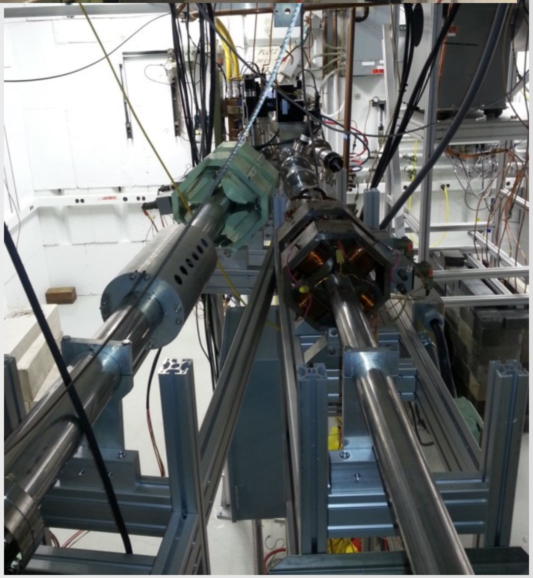
Mo-99 Topical Meeting
St. Louis, Missouri
September 14, 2016

OUTLINE

- Support for SHINE Medical Technologies
  - Phase 1 mini- and micro-SHINE experiments gas generation results
  - Transition to mini-SHINE phase 2 experiments
- Support for NorthStar Medical Isotopes
  - Beamline design
    - Beamline configuration
    - Beam diagnostic
    - High power targets
  - Van de Graaff testing for product development





SHINE SUPPORT: ARGONNE MINI-SHINE EXPERIMENT

- Argonne's mini-SHINE experiment use fissioning of uranyl-sulfate solutions using photo-neutron target at Argonne electron linac to produce Mo-99, this experiment is designed to:
  - Study the effects of fission on target-solution chemistry and radiolytic off-gas generation
  - Demonstrate the recovery and purification of Mo-99 from an irradiated target solution
  - Produce Mo-99 to ship to potential Tc-99m generator manufacturer partners

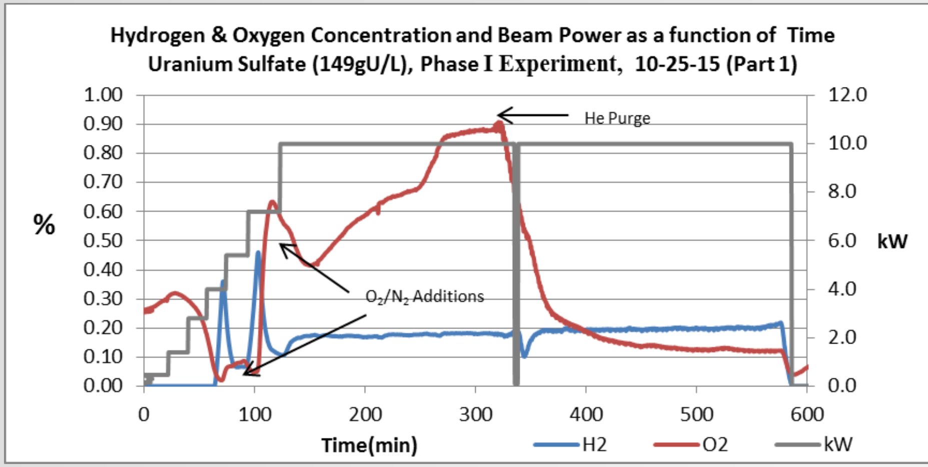
Phase 1 (completed January 2016)

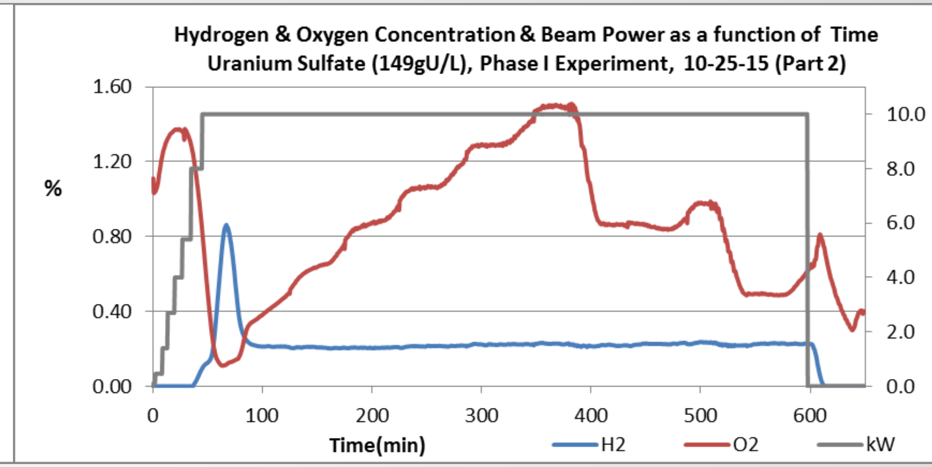
  - Linac was operated at 35 MeV and 10 kW beam power on the Ta target
  - 5 L solution (140 g-U/L) were irradiated with neutrons generated through gamma-n reaction in tantalum target
  - Maximum solution fission power was $\leq$ 0.05 kW/L
  - Up to 2 Ci of Mo-99 was produced per run

Phase 2

  - Experiment will be conducted at 35 MeV beam energy and up to 20 kW beam power
  - 20 L solution will be irradiated with neutrons generated in a depleted-uranium (DU) target (Zr clad DU discs were manufactured at LANL)
  - Maximum solution fission power will be $\leq$ 0.5 kW/L
  - Up to 20 Ci of Mo-99 will be produced

GAS GENERATION IN MINI-SHINE EXPERIMENT



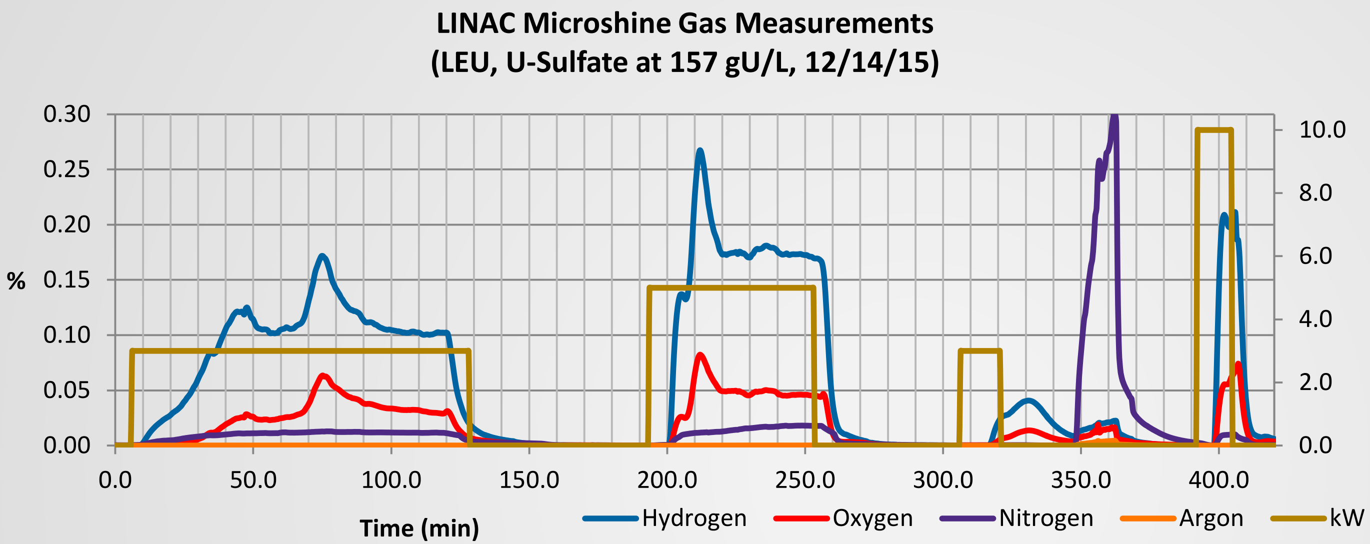


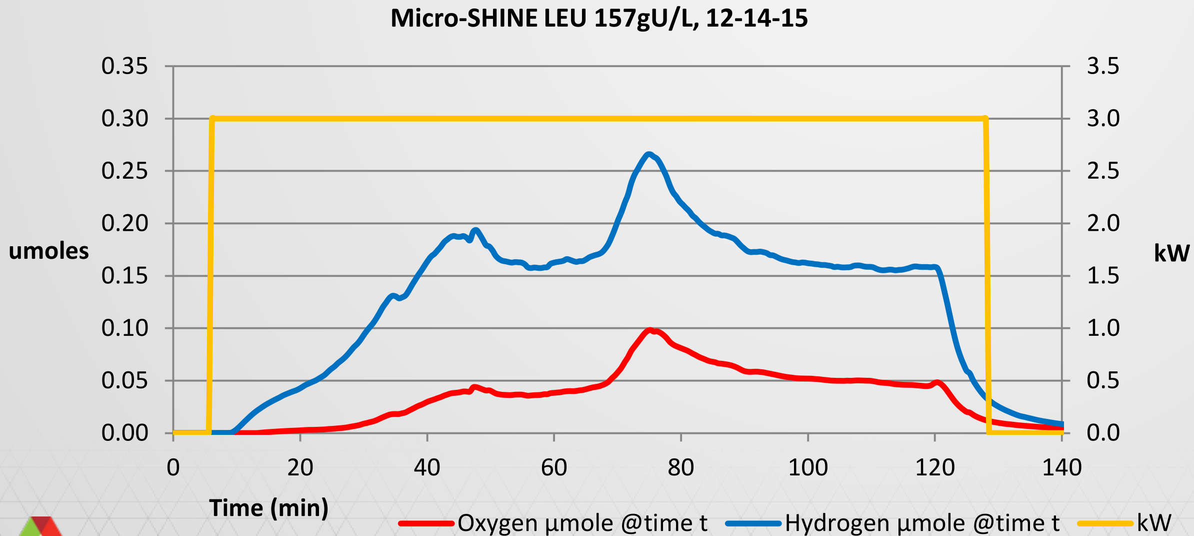
- 1% safety limit for maximum hydrogen gas concentration in head space of mini-SHINE experiment has significantly constrained gas generation measurements. Oxygen addition had to start 30-60 min into irradiation. Hydrogen concentration reached steady-state in ~100 min. After that time no addition of oxygen to the headspace was necessary.

GAS GENERATION IN MICRO-SHINE EXPERIMENTS

- Small samples ~2 ml were irradiated in dry tubes of the mini-SHINE experimental setup
- Gas generation rates were measured using flow through approach, which kept concentration of hydrogen below 1%
- Irradiation of the samples with different enrichments allowed separation of gas generation due to fission and photon radiolysis
- Fraction of gas production due to fission fragment radiolysis in LEU solution to total gas production is ~67%

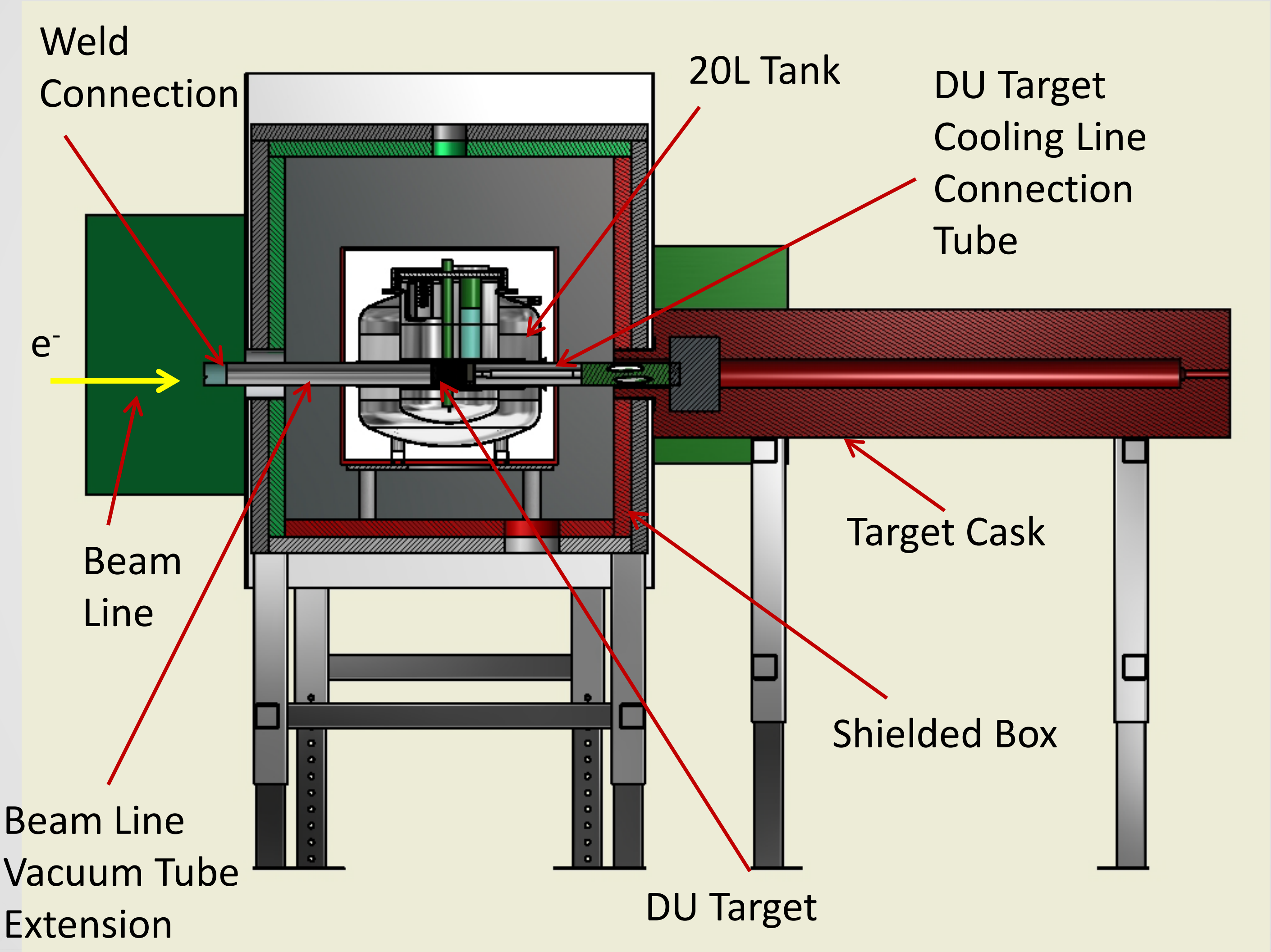
GAS GENERATION IN MICRO-SHINE EXPERIMENTS LEU



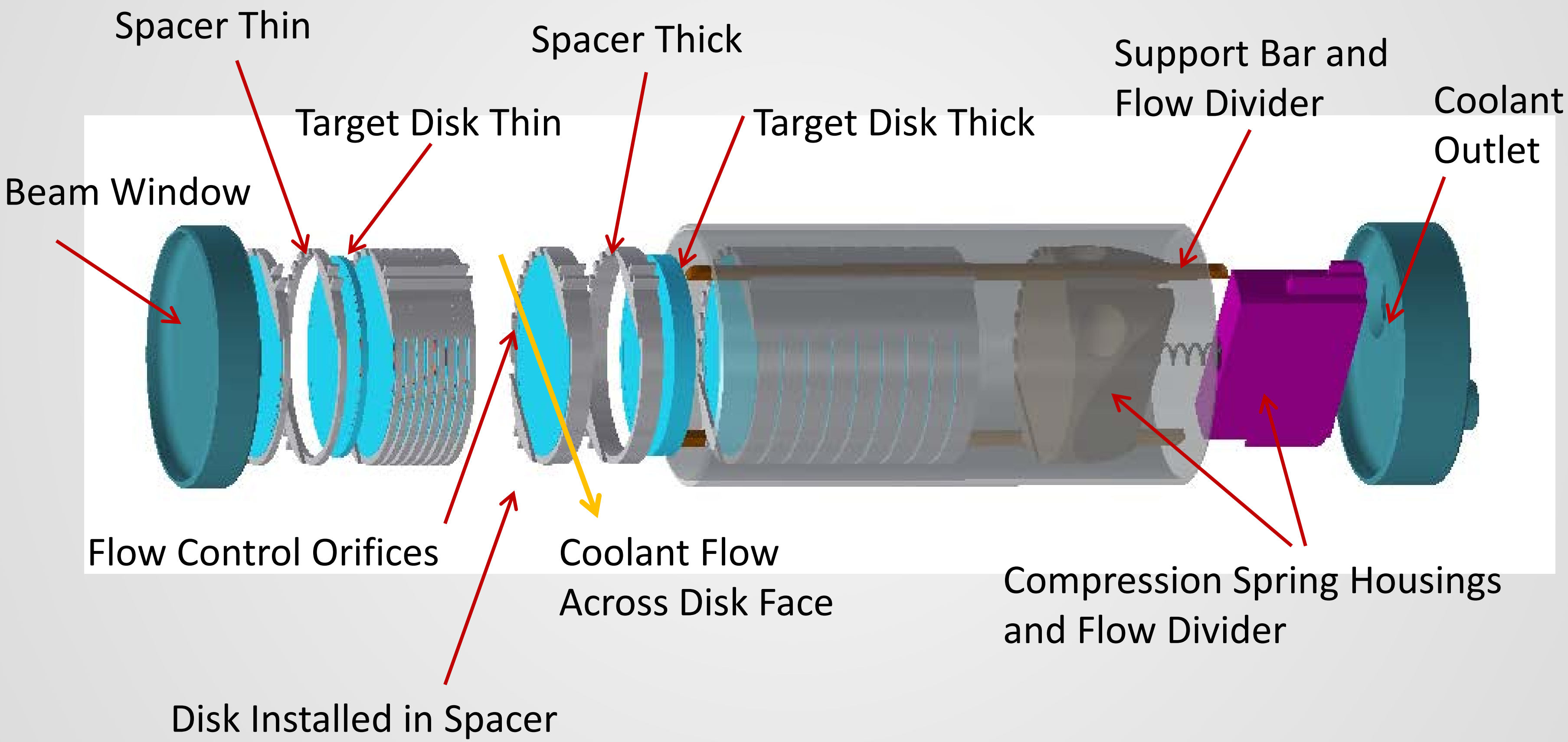


- Hydrogen generation rate for LEU ~75 mole/kWh of fission power in solution

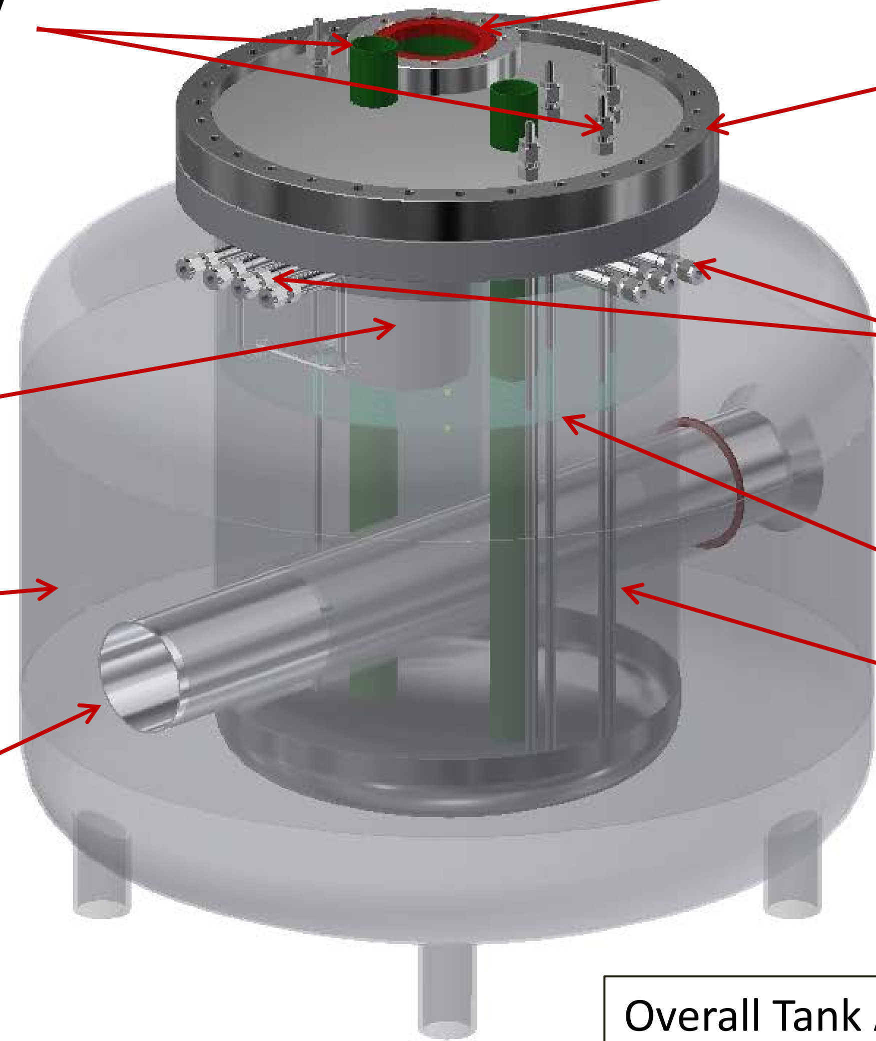
PHASE 2 MINI-SHINE IRRADIATION SETUP



DU TARGET DESIGN



OVERVIEW OF 20 L PROCESS TANK DESIGN



View Port

Instrument and Dry Well Penetrations

Removable Flange

Connections for Top Cooling Coil and Condenser/Heat Exchanger and Process

Heat Exchanger/ Condenser Inside of Tank

Outer Cooling/ Moderator Tank

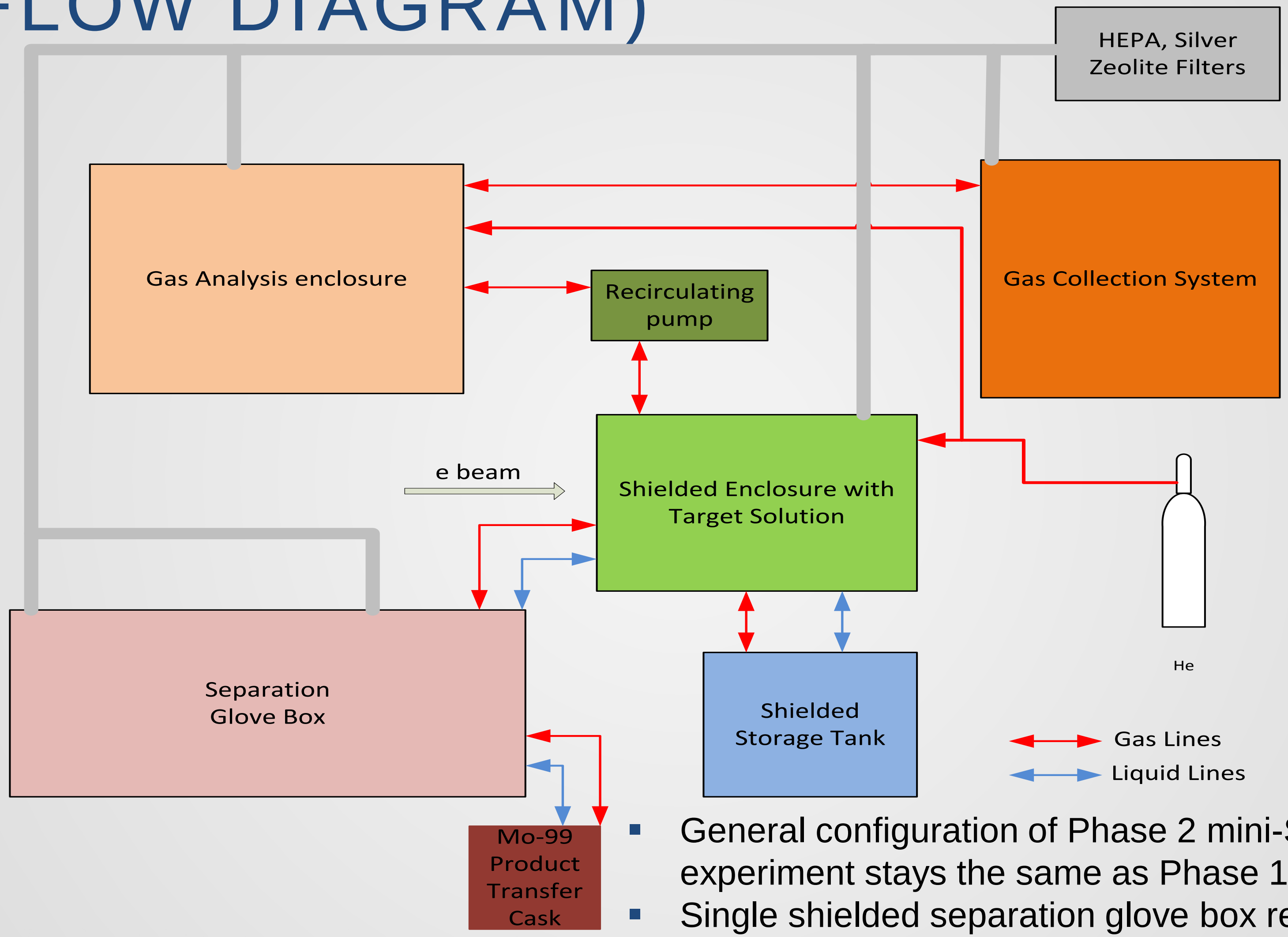
Process Fluid Level

Inner Process Tank

Target Sleeve Thru both Tanks

Overall Tank Assembly Size: ø22” x 22” H

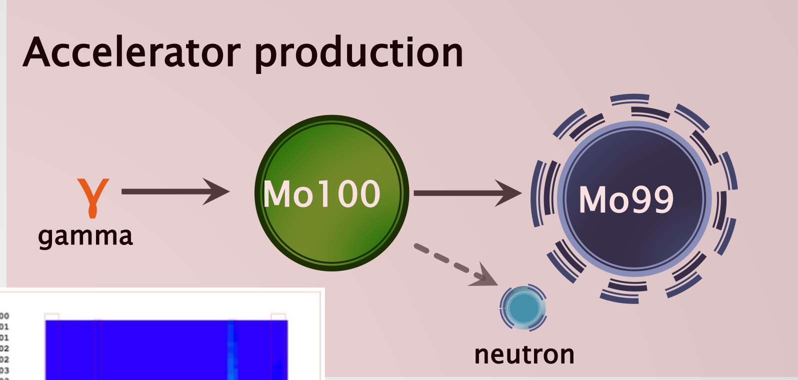
MINI-SHINE PHASE 2 EXPERIMENT (FLOW DIAGRAM)

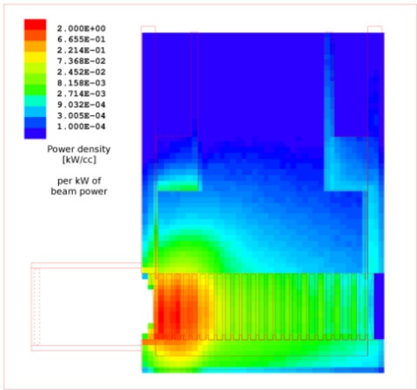


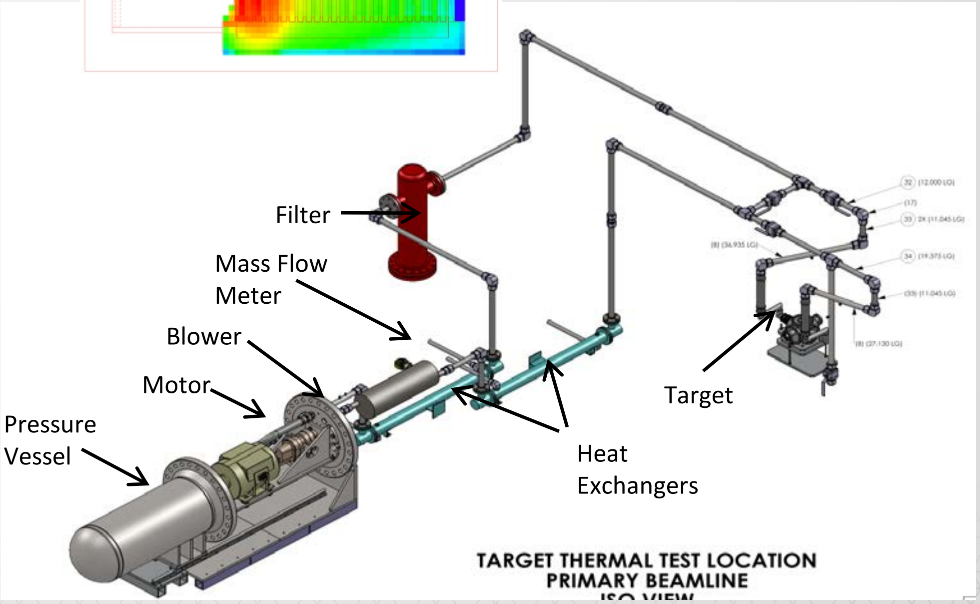
- General configuration of Phase 2 mini-SHINE experiment stays the same as Phase 1 experiment
- Single shielded separation glove box replaces two glove boxes used in Phase 1
- Relocation of equipment based on lessons learned from Phase 1

SUPPORT FOR NORTHSTAR MEDICAL RADIOISOTOPES

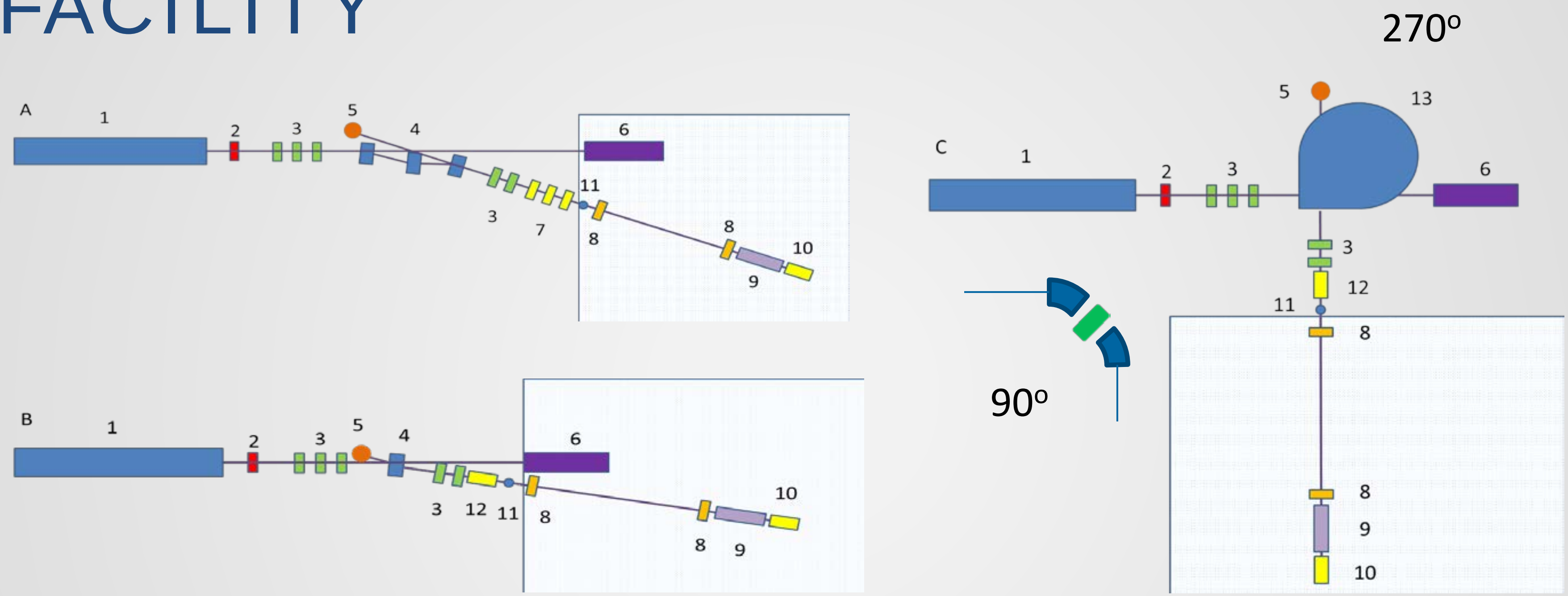
- Major challenges
  - Efficient delivery of high power electron beam to the target
  - Stability of the beam position on the target
  - High power beam tune-up and diagnostic
  - Cooling of high power density target





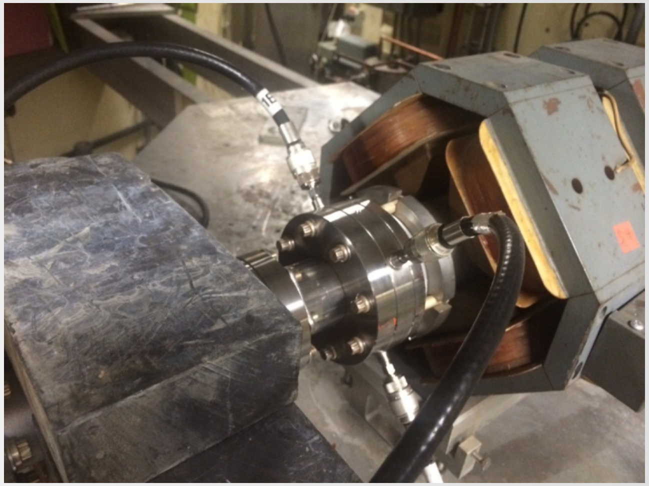


BEAM LINE CONFIGURATIONS FOR ACCELERATOR BASED PRODUCTION FACILITY



- Beam line elements: 1-linac, 2-fast acting gate valve, 3-quad magnets, 4-bending magnets, 5-OTR and IR cameras, 6-Beam stop, 7-non-linear beam optics, 8-beam position monitors, 9-collimator, 10-target, 11-gate valve vacuum sensor, 12-rastering magnet, 13-270º magnet

BEAM LINE COMPONENTS DEVELOPMENT AND TESTING



- 20º two bend achromatic magnet system was designed and will be installed and tested in October 2016.
- Beam position monitors were installed and tested during multiple production runs. Software for control and data acquisition was developed.
- Performance of the fast acting beam valve system was evaluated in a facility relevant configuration.
- High power collimator and beam stop was designed and fabricated. Those components will be tested in September 2016.

MATERIALS SELECTION FOR HIGH POWER TARGET

Material	Density (Kg/m³)	Thermal Conductivity (W/m-°C)	Maximum Stress (MPa)	Minimum Window Thickness (mm)	Maximum Temperature (°C)	Figure of Merit (FOM)
INCONEL 718	8,221	17.3	456	1.15	403	1
Hastelloy X	8,221	26.0				*Disqualified
INCONEL 706	8,055	22.5	75	2.87	1,280	2.45
Waspaloy	8,193	17.3	357	1.30	481	1.13
Rene 41	8,249	17.3	507	1.09	388	0.96
L-605 Haynes Alloy 25	9,134	19.0				*Disqualified
316 SS	7,806	22.5				*Disqualified
250 Maraging Steel	7,916	29.4	706	0.93	269	0.78
AerMet 100	7,889	31.2	793	0.87	249	0.73
2024-T81 Aluminum	2,768	173.1				*Disqualified
6061-T6 Aluminum	2,713	173.1				*Disqualified
Titanium alloy AMS 4910	4,484	13.9	175	1.88	497	0.90
Beryllium Standard grade	1,855	138.5	147	1.96	131	0.39
Magnesium alloy	1,800	77.0				*Disqualified

$$FOM = \frac{\rho t}{\rho_I t_I}$$

ρ = density of material to be evaluated

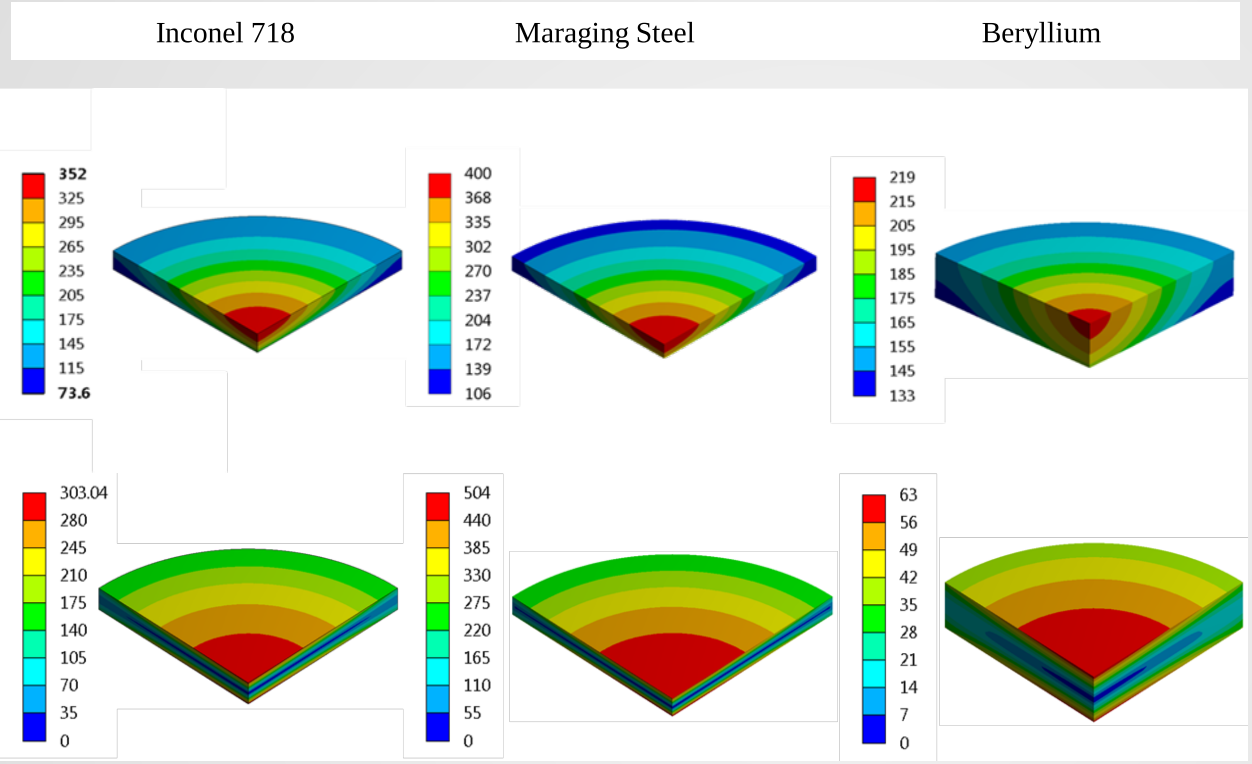
t = minimum acceptable thickness of material to be evaluated

ρ_I = density of INCONEL 718

t_I = minimum acceptable thickness of INCONEL 718

FOM = Factor of Merit

FINAL MATERIAL CANDIDATES FOR TARGET WINDOW



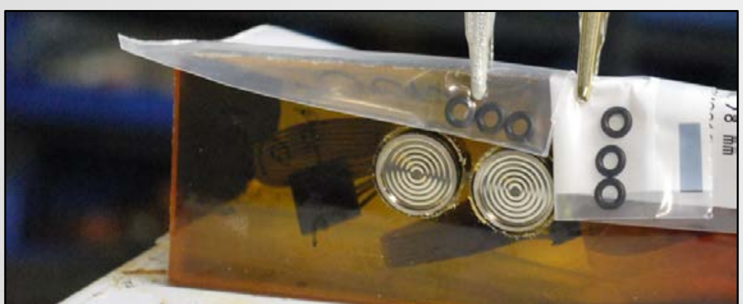
- Results of the thermal modeling are shown here as plots of temperature (°C)
- Stress due to pressure loading plotted as stress intensity in MPa

Material	Maximum Beam Power (kW)
Inconel 718	18
Beryllium	40
250 Maraging Steel	39

VAN DE GRAAFF (VDG) ACCELERATOR

Testing of radiation stability of process equipment

- Radiation damage tests using the VDG
- Effects of photon radiation on HDPE bottles containing K_2MoO_4 in 6 M KOH
- Zero to 6.5 MRad shown (up to twice calculated dose expected)
- Testing of RadioGenix generator components



SUMMARY

- Scope of phase 1 mini-SHINE experiment was completed in January 2016.
- Gas generation rates were measured in phase 1 micro-SHINE experiments and results are in good agreement with literature data.
- Installation of phase 2 mini-SHINE equipment is nearly complete. Commissioning of the phase 2 mini-SHINE experimental setup will start in September 2016.
- Different configurations of the beam line were evaluated. 90° or 270° configuration is proposed for the production facility.
- Beam position monitors and the fast acting gate valve system were tested in plant relevant conditions.
- High power beam dump and collimator were designed and built and will be tested in September 2016.
- Components of the RadioGenix system were tested at Van de Graaff accelerator. Results of those tests are helping NorthStar in developing a more robust system and in the FDA approval process.

ACKNOWLEDGEMENTS

- George Vandergrift
- Mandy Youker
- Peter Tkac
- John Krebs
- Mike Kalensky
- David Rotsch
- Alex Brown
- Andy Hebden
- Thad Heltemes
- Dominque Stepinski
- Jim Byrnes
- Jim Jerden
- Roman Gromov
- Chuck Jonah
- Vakho Makarashvili
- Brad Micklich
- Lohman Hafenrichter
- Kurt Alford
- Ken Wesolowski
- Kevin Quigley
- Jim Bailey
- Momen Abdul
- Tom Brossard

- This work is done in collaboration with LANL and ORNL

- Work supported by the U.S. Department of Energy, National Nuclear Security Administration's (NNSA's) Office of Defense Nuclear Nonproliferation, under Contract DE-AC02-06CH11357.