LBNE Target R&D/Conceptual Design Activities and Opportunities

Path to a 2 MW LBNE Target

P. Hurh
9/9/09
Updated 10/14/09

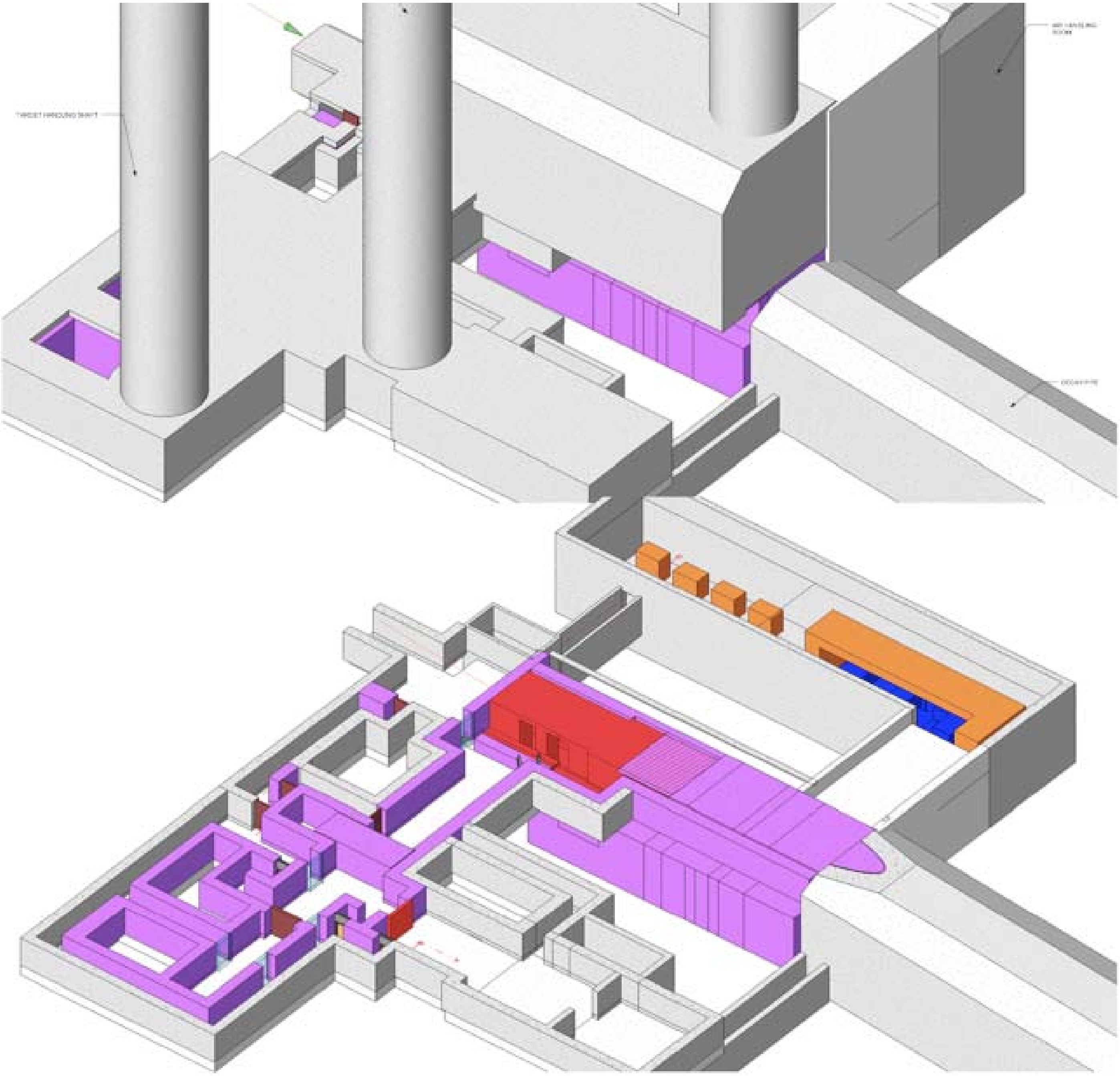
Overview

- 2 MW Target Challenges
- Possible Work Packages
- Other Target Related Issues
- Path to 2 MW Target

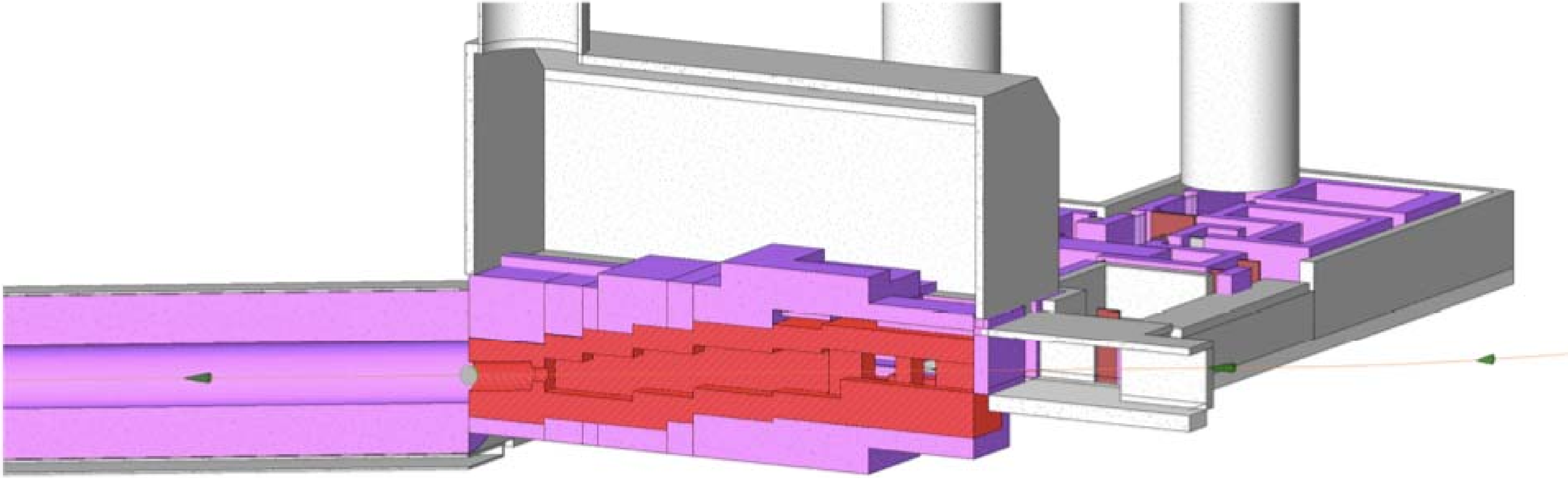
Facility	Status	Target Material	Beam Pulse		Energy (GeV)	Time Ave Power in Beam (MW)	Peak Time Ave Power Density (MW/m^3)	Peak Energy Density (MJ/m^3/pulse)
			Duration (μs)	Rep Rate (Hz)				
BNL Neutrino Superbeam	Under Study	C-C Composite	2.6	2.5	28	1	4,060	1,630
ESS - short pulse	Under Study	Hg	1.2	50	1.334	5	2,500	50
ESS - long pulse	Under Study	Hg	2,000	16.7	1.334	5	2,500	150
EURISOL	Under Study	Hg	3	50	2.2	4	100,000	2,000
IFMIF	Under Study	Li	CW		0.04 (D_2)	10	100,000	NA
JPARC - Hadron beam line	Under Const	Ni	7.E+05	0.3	50	0.75	7,600	5,300
JPARC - Neutrino bean line	Under Study	C	5	0.3	50	0.75	83	300
LANSCE - APT irradiation tests	Dismantled	W	1,000	20	0.8	0.8	800	40
LANSCE - Lujan	Existing	W	0.25	20	0.8	0.1	350	18
LANSCE - Mats Test Station	Under Study	Pb-Bi	1,000	120	0.8	0.8	2,400	20
LEDA as fusion mats test facility	Under Study	Li	CW		0.04 (D_2)	2	100,000	NA
MiniBoone	Existing	Be	150	5	8	0.032	120	24
NLC - conventional	Under Study	W Re	0.26	120	6.2	0.086	334,800	2,790
NLC - undulator	Under Study	Ti alloy	0.26	120	0.011	0.126	1,110,000	9,200
NuMI	Existing	C	8.6	0.53	120	0.4	320	600
ANU/NOvA	Under Study	C	10	0.75	120	0.7	450	600
Project X	Under Study	C	10	0.7	120	2.3	630	900
Pbar	Existing	Inconel 600 + É	1.6	0.5	120	0.052	7,650	15,300
RIA	Under Study	Li, Be, Hg, W, É	CW		1-96 (p to U	0.4	< 4,000,000	NA
SINQ/Solid Target	Existing	Pb, SS-clad	CW		0.575	0.72	720	NA
SINQ/MEGAPIE	Under Const	Pb-Bi	CW		0.575	1	1,000	NA
SNS	Under Const	Hg	0.7	60	1	2	800	13
US Neutrino Factory	Under Study	Hg	0.003	15	24	1	3,800	1,080

From: 1st HP Targetry Workshop in Long Island NY in 2003.

Putting 2 MW into perspective:



Putting 2 MW into perspective:



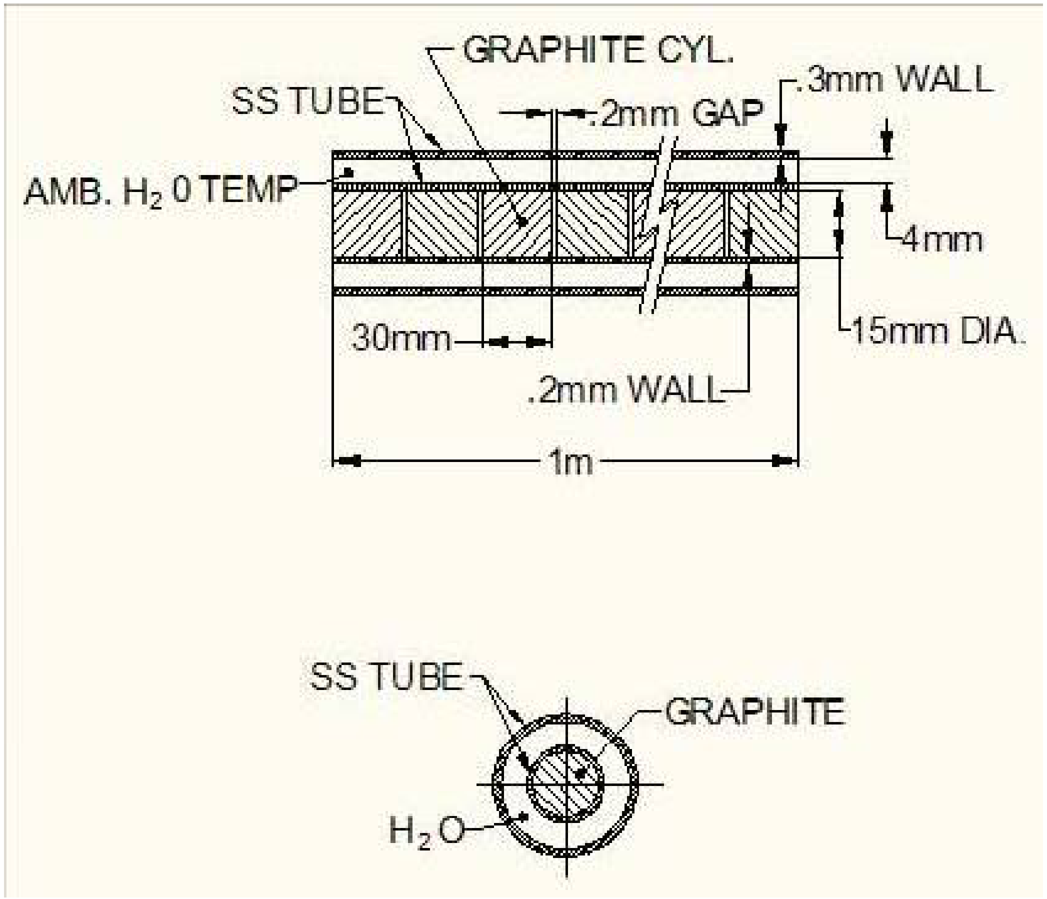
Note: Very early conceptual design stage (for civil construction estimating purposes)!

2 MW Target Challenges

- Heat removal
- Thermal shock (stress waves)
- Radiation damage
- Oxidation & Rad Accelerated Corrosion
- Spatial constraints
- Residual radiation
- Physics optimization

Heat Removal

- 25-30 kW total energy deposited (IHEP)
- Easy to remove with water

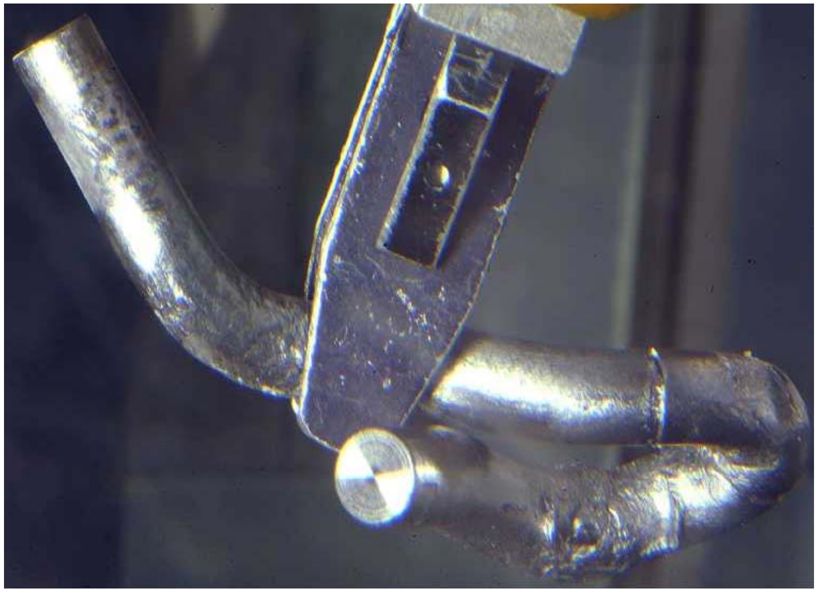


- Tritium production
- Hydrogen gas production
- Thermal shock in water (Water Hammer)
- 150 atm IHEP report

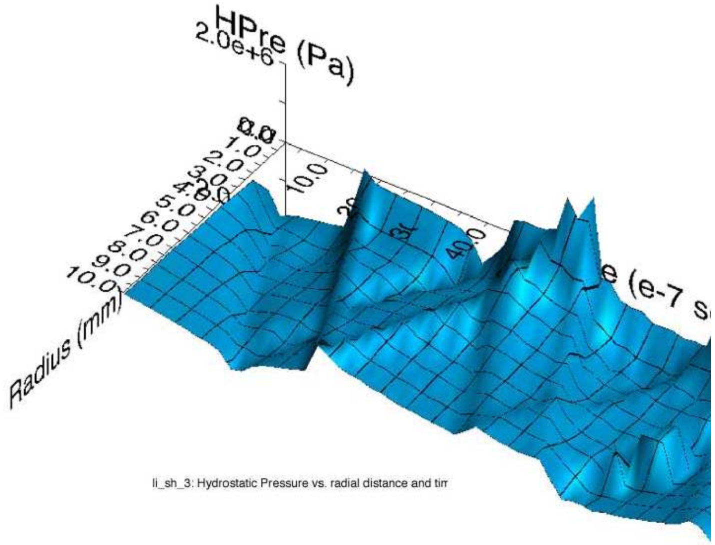
Heat Removal

- 2 Phase cooling (bubbles)
- 2 Phase cooling (heat pipe)
- Spray cooling (NuMI horn)
- Helium cooling (T2K 750 kW target)

Thermal Shock



Ta-rod after irradiation with 6E18 protons in 2.4 μs pulses of 3E13 at ISOLDE



Simulation of stress wave propagation in Li lens (pbar source, Fermilab)

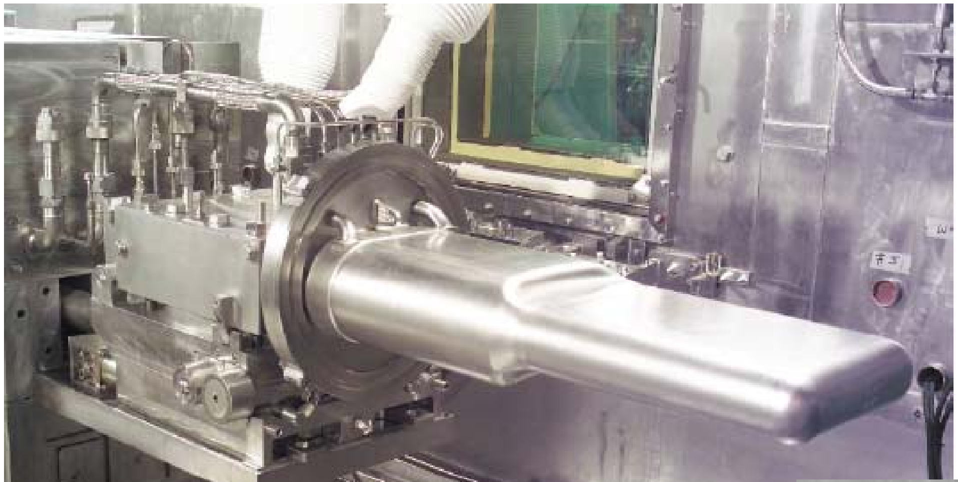
- Sudden expansion of material surrounded by cooler material creates a sudden local area of compressive stress
- Stress waves (not shock waves) move through the target material
- Plastic deformation or cracking can occur

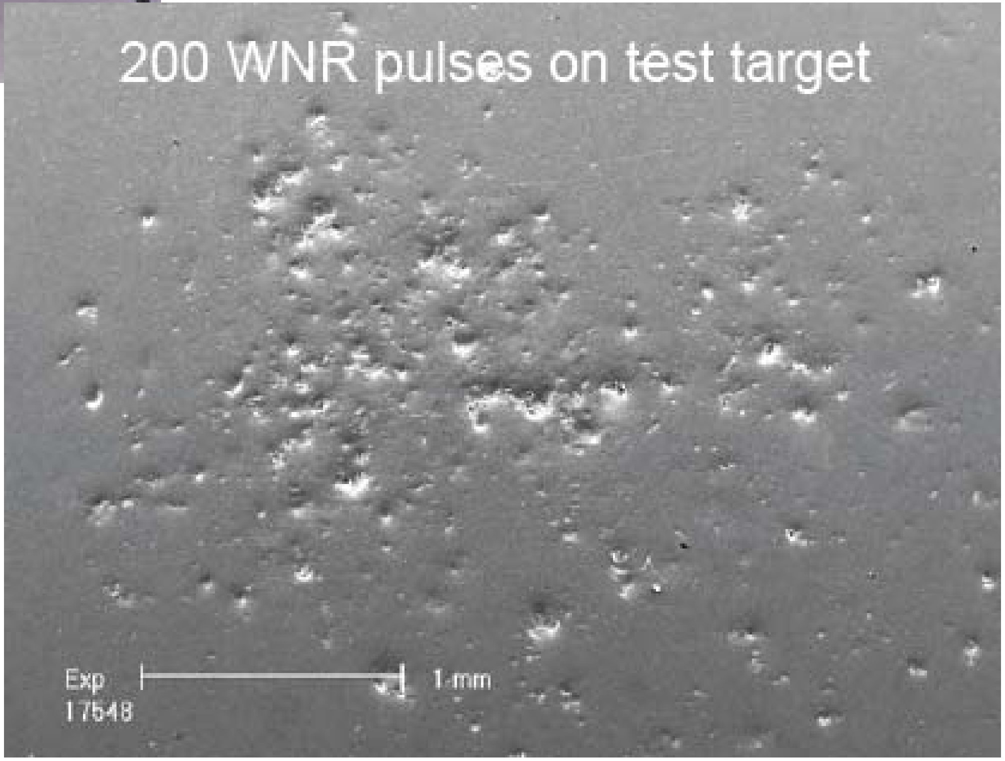
Thermal Shock

- Graphite materials particularly good for thermal shock (lower Cp, lower CTE, very low E, high strength at elevated temps)
- Beryllium is not as good, but perhaps survivable
- Pre-loading either in compression is favorable to reduce the effect
- Shorter “slugs” reduce cumulative effects in the longitudinal direction
- Remember radiation damage changes properties!
- Must design for accident conditions
  - Max intensity and smallest spot size
  - Max rep rate
  - Off-axis (asymmetric) beam on target

Thermal Shock

- SNS Hg Target Cavitation problems





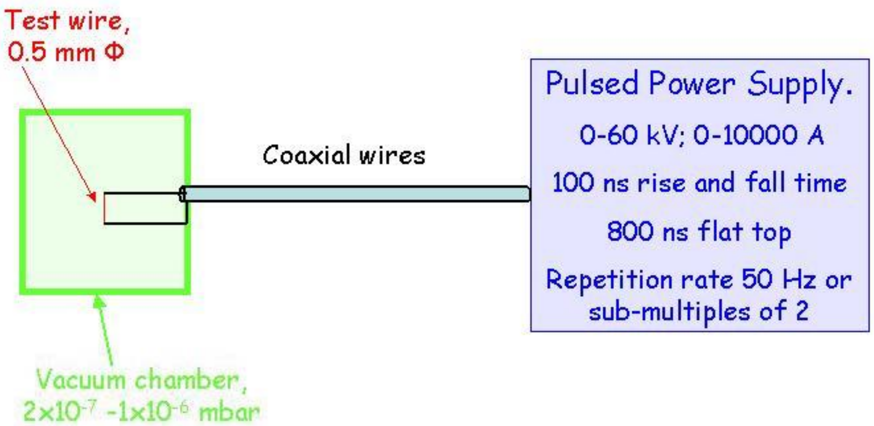
B. Riemer, ORNL

Thermal Shock

- Ongoing work at RAL-Sheffield by R. Bennett and G. Skoro to study solid targets for NuFact
  - Pulsed W wire testing
  - Benchmark simulation techniques
  - Show promise of solid W at 4 MW

Introduction Current pulse – wire tests at RAL

Schematic circuit diagram of the wire test equipment

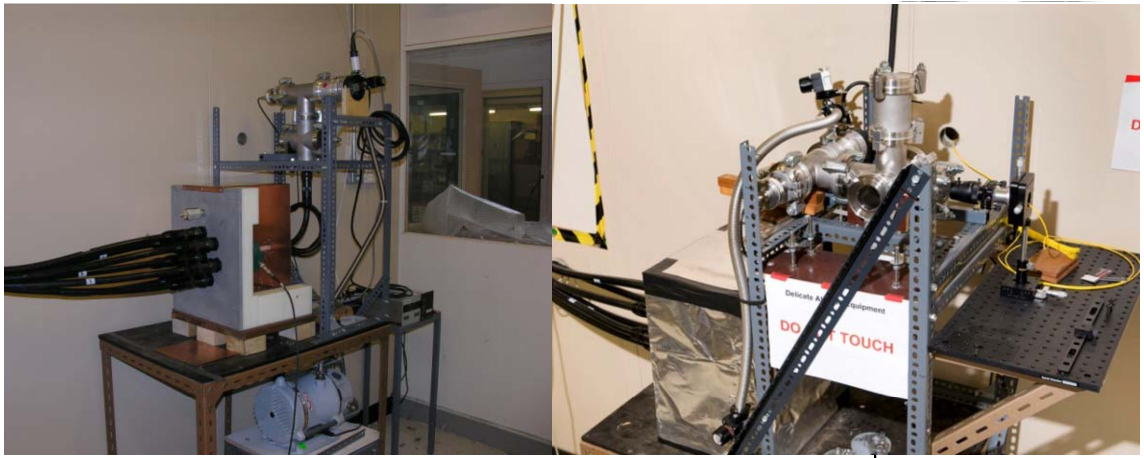


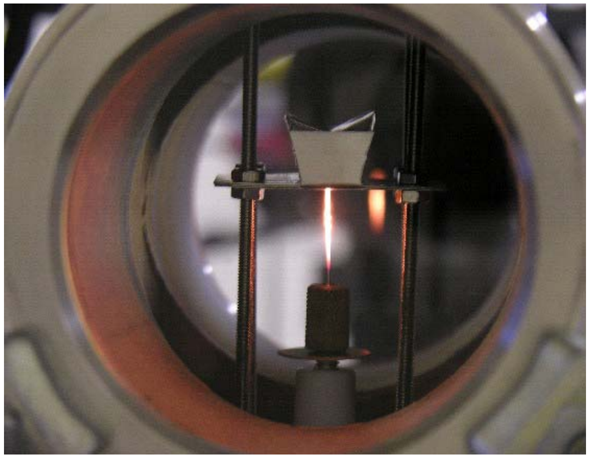
Test wire, 0.5 mm Φ

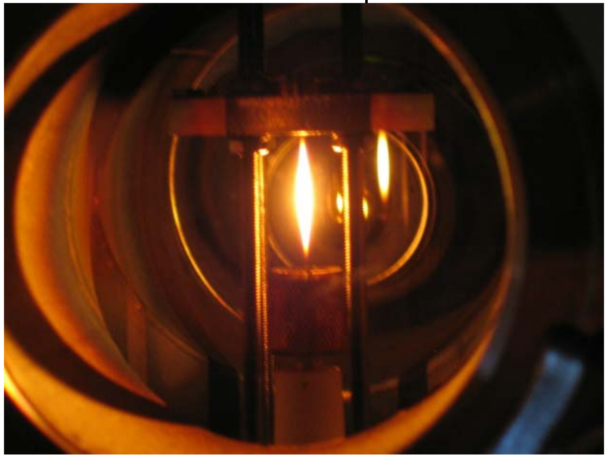
Coaxial wires

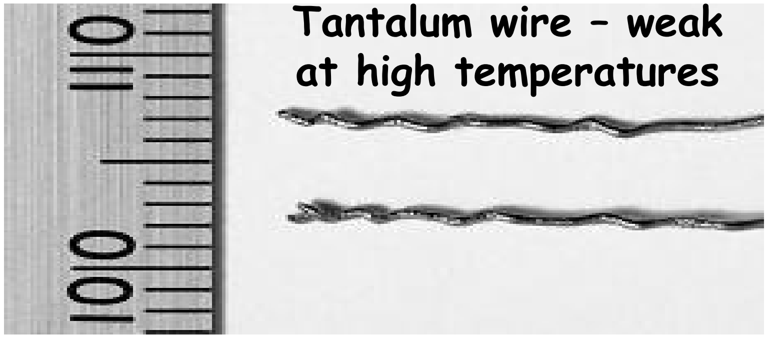
Pulsed Power Supply.
0-60 kV; 0-10000 A
100 ns rise and fall time
800 ns flat top
Repetition rate 50 Hz or sub-multiples of 2

Vacuum chamber, 2×10^{-7} -1×10^{-6} mbar







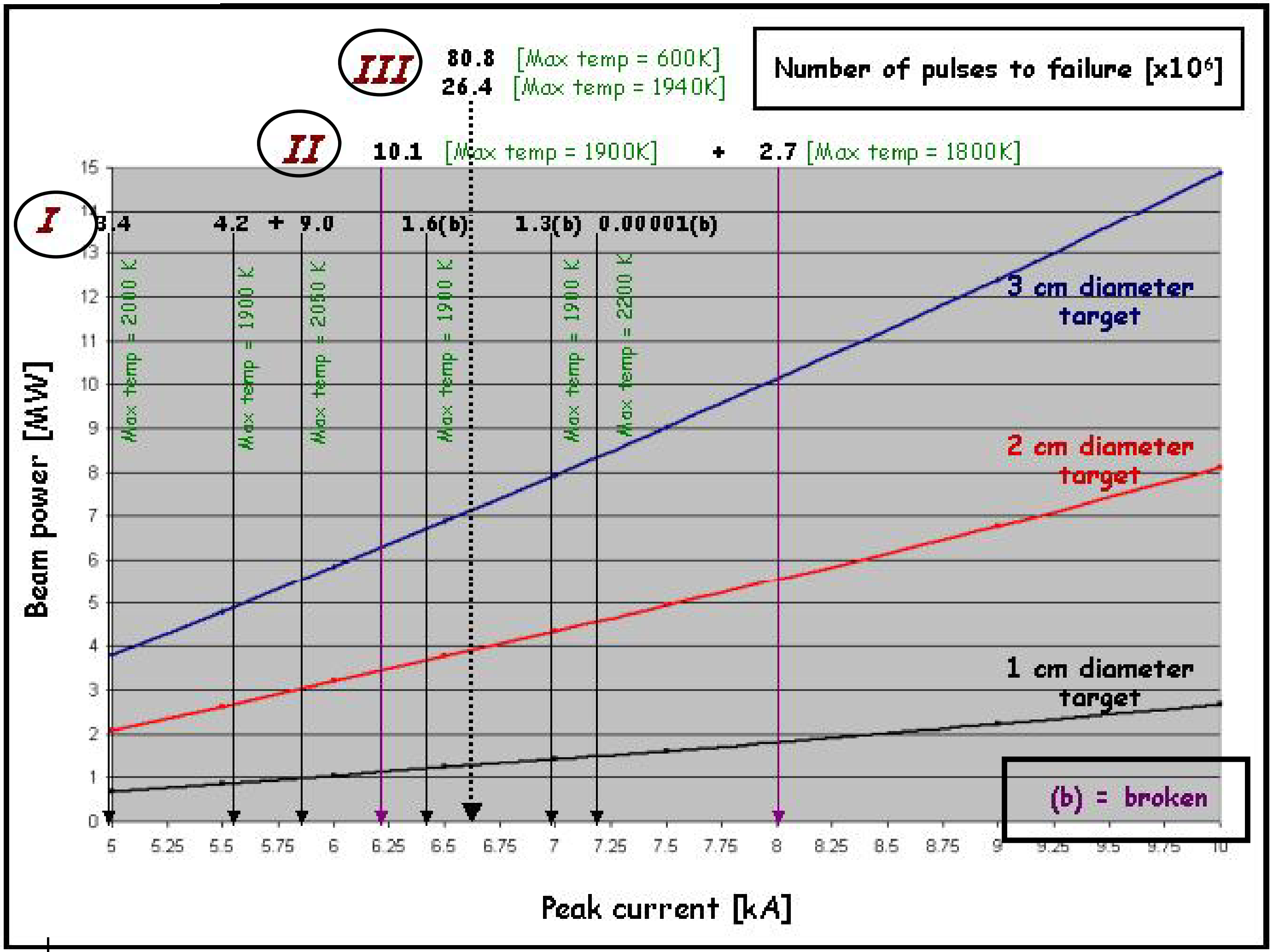


Tantalum wire – weak at high temperatures

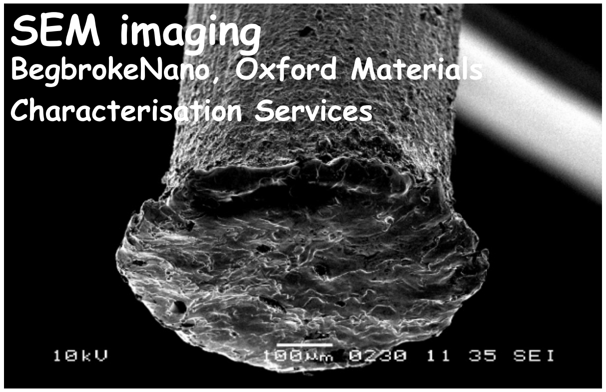
Tungsten – much better!!!

<u>The Finite Element Simulations have been used to calculate equivalent beam power in a real target and to extract the corresponding lifetime.</u>

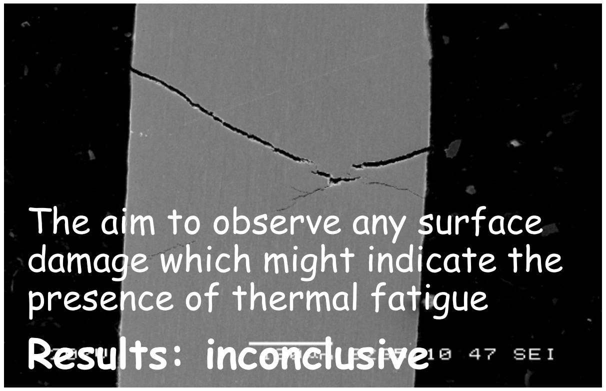
Lifetime/fatigue tests results



I, II, III -> 'chronology'. We have got better with the tests over time (better clamping of the wire; better understanding of 'violin modes' -> better alignment of the wire)


SEM imaging

BegbrokeNano, Oxford Materials Characterisation Services


The aim to observe any surface damage which might indicate the presence of thermal fatigue

Results: inconclusive

More than sufficient lifetime demonstrated:

> 10 years for 2cm diameter target

> 20 years for 3cm diameter target

Focus now:

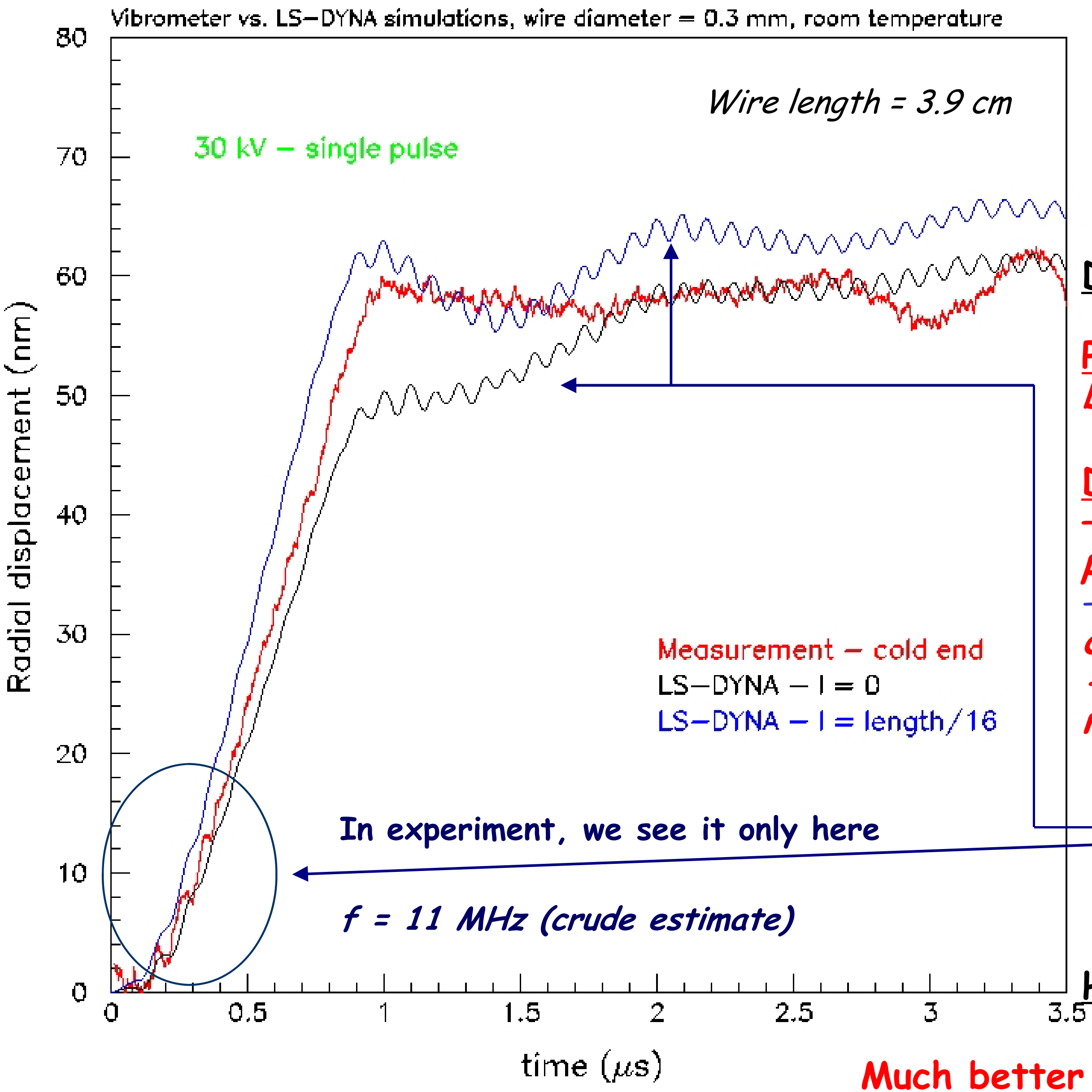
Measure stress;

Confirm modelling.

Better at lower temperature!

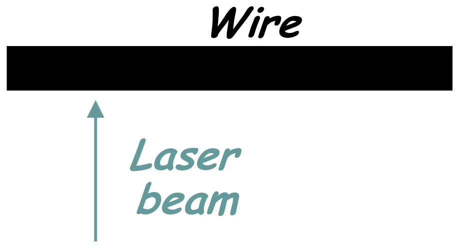
Results

Radial displacement as a function of energy deposition (0.3 mm diameter wire)



In experiment, we see it only here

f = 11 MHz (crude estimate)



Different wire, different diameter

Peak displacement value – *nice agreement between experiment and simulation*

Different shape (as a function of time)
- strongly depends on measurement's position along the wire
-we don't know exactly where we were during the measurements
- as can be seen from simulations, a few mm difference make a big change

Frequency of radial oscillations

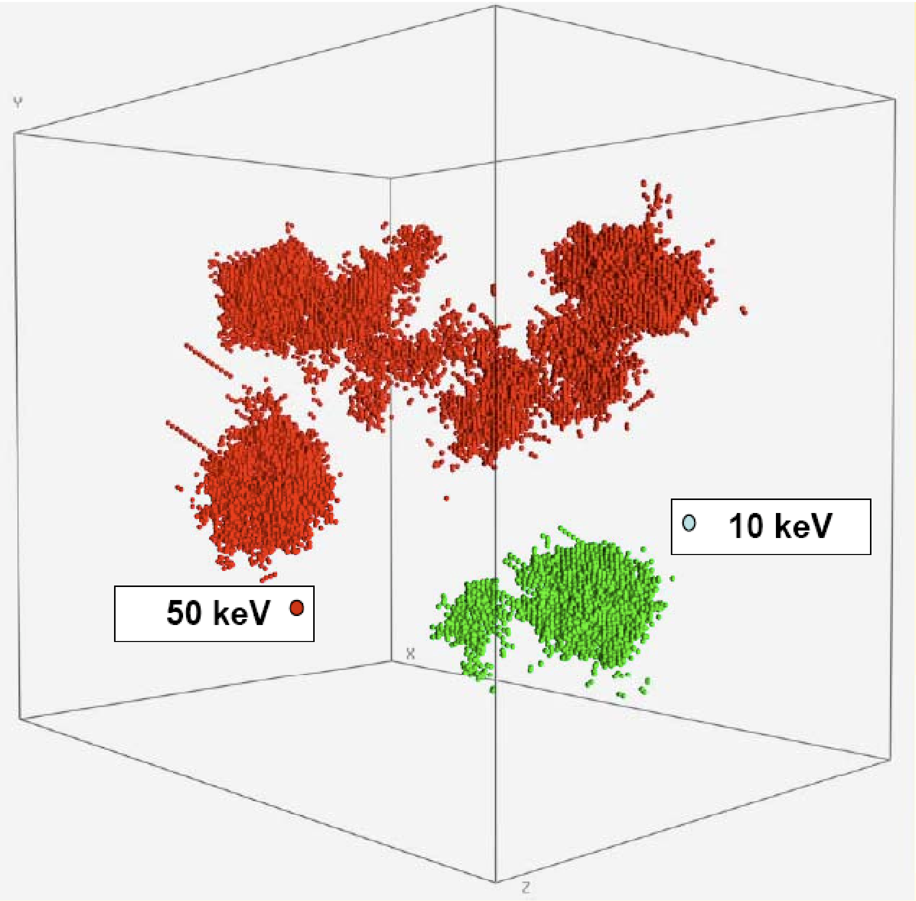
f = 11.3 MHz (LS-DYNA)

Hard to measure it for such a tiny wire!

Much better for 0.5 mm diameter wire (next Slide)

Radiation Damage

- Displacements in metal crystal lattice
  - Embrittlement
  - Creep
  - Swelling
- Damage to organics/plastics
  - Cross-linking (stiffens, increase properties)
  - Scission (disintegrate, decrease properties)

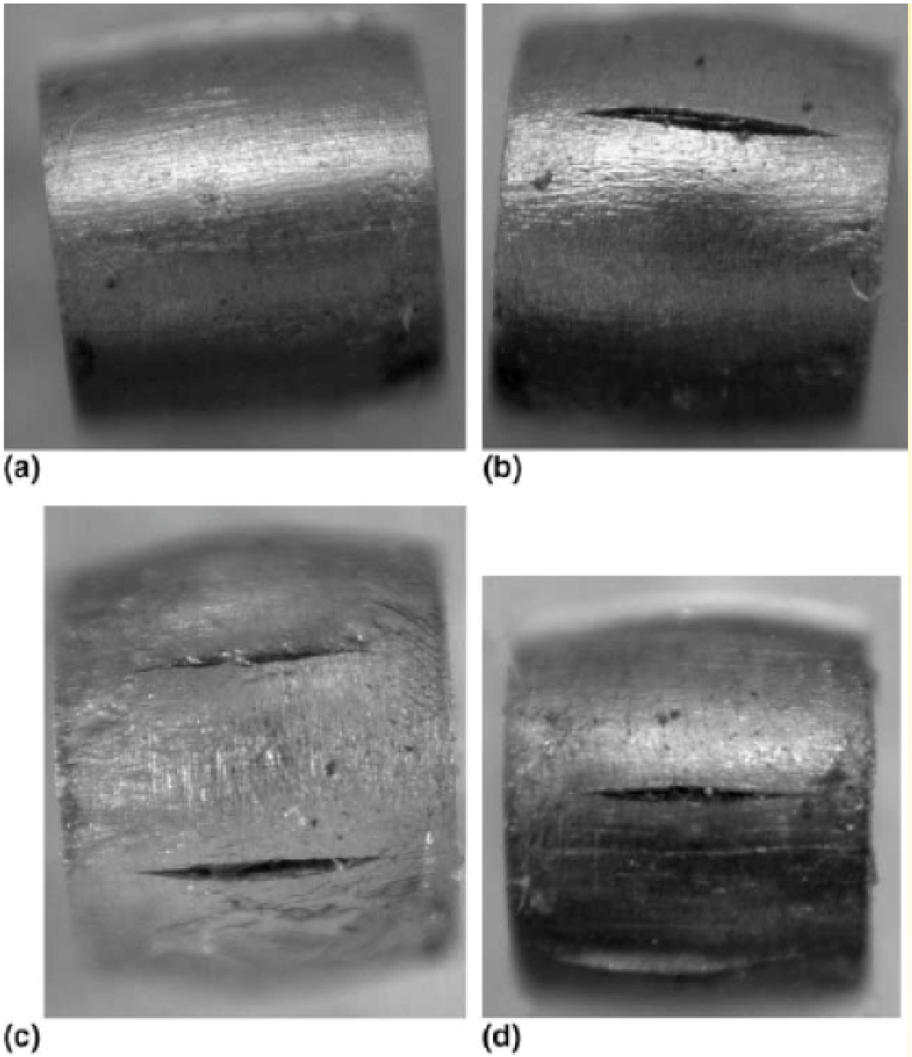


Molecular Damage Simulations of peak damage state in iron cascades at 100K.

R. E. Stoller, ORNL.

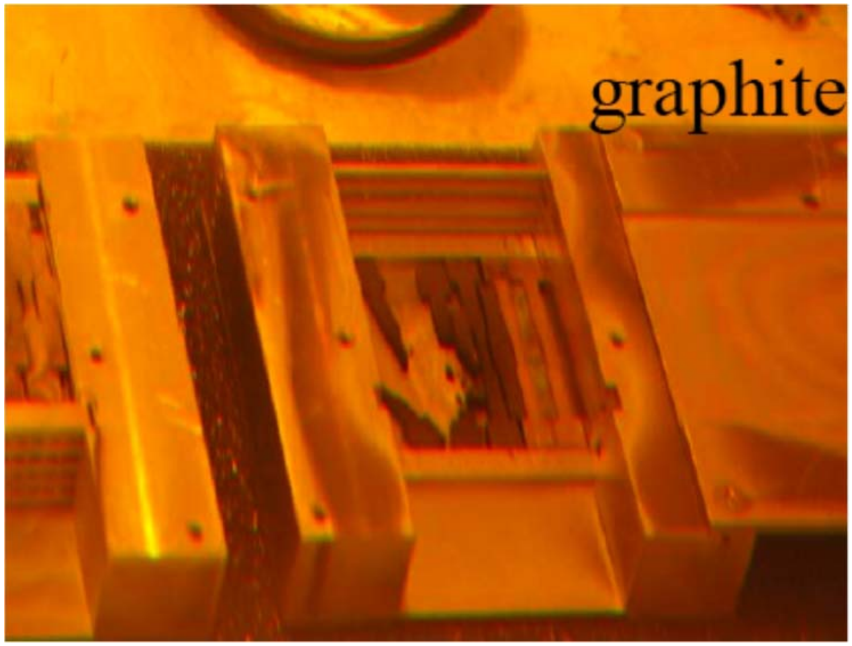
Radiation Damage

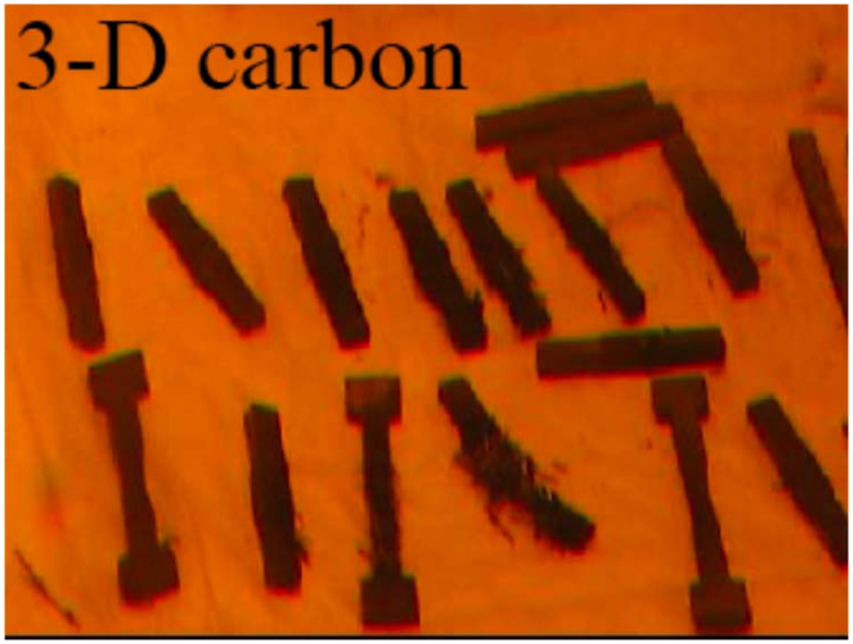
- Tungsten cylinders irradiated with 800 MeV protons and compressed to 20% strain at RT.
    - A) Before irradiation
    - B) After 3.2 dpa
    - C) After 14.9 dpa
    - D) After 23.3 dpa



S. A. Malloy, et al., Journal of Nuclear Material, 2005. (LANSCE irradiations)

Radiation Damage





- Atom displacement causes changes in material properties
- Not much literature on high energy proton irradiation of materials
- Lots of information on low energy neutron irradiation (nuclear reactors)

Pictures from N. Simos talk

Radiation Damage

- Tests at BLIP (BNL) by N. Simos indicate total failure of graphite and c-c at about 10^{21} protons/cm^2
- If correct, LBNE target lifetime would be 3-4 months, necessitating quick change-out mechanisms
- NT-02 showed reduction in yield more or less consistent with the BNL test
- IG-430 (nuclear grade) may be promising
- Metals such as Be and Ti also are affected but not as catastrophically for the same fluence (windows, target casing, not just for target)

Oxidation

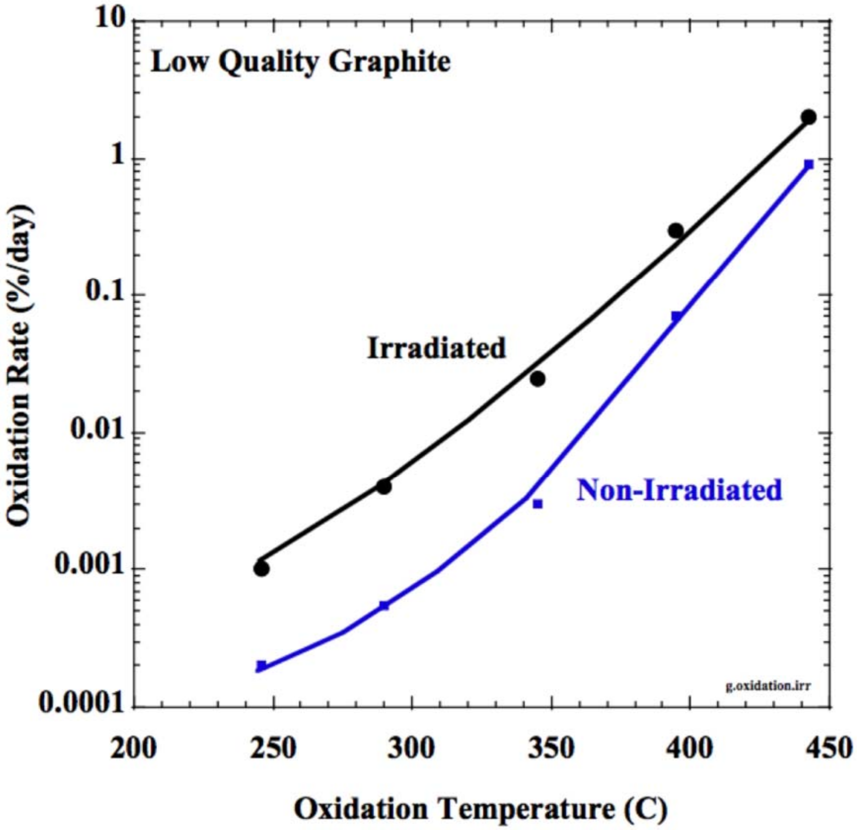


Figure 2 : Effect of irradiation on poor quality graphite. Kosiba and Dienes USAEC RID-7565 Ppart 1) 1959.

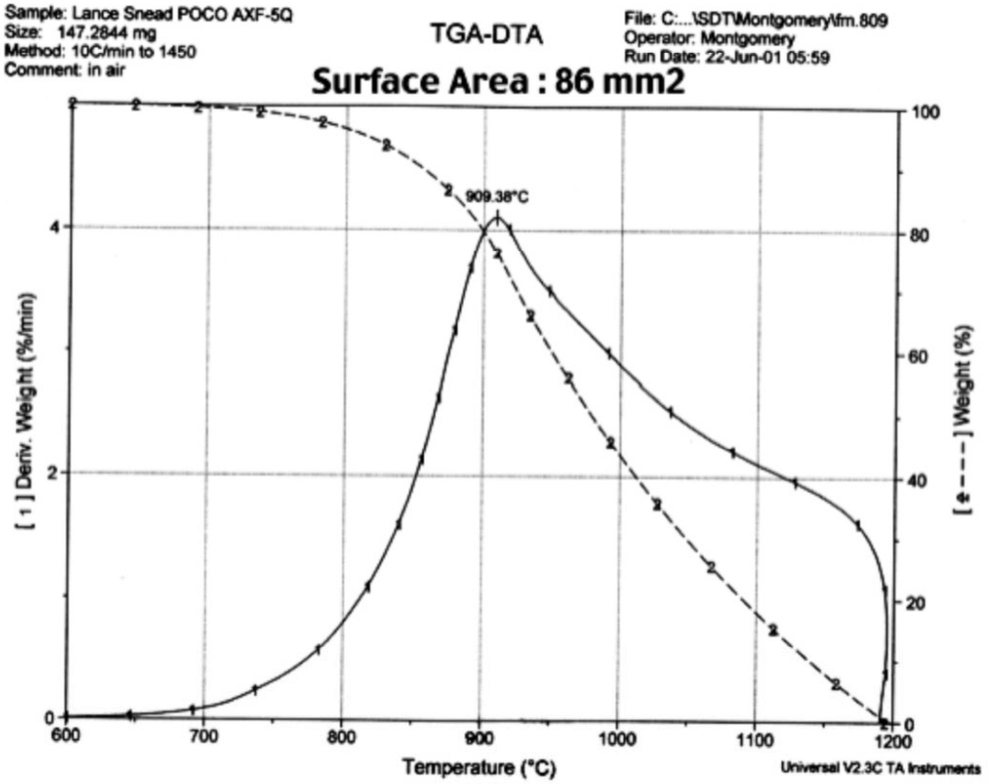


Figure 3a :Oxidation of Poco AXF-5Q in flowing air.

- Oxidation reaction is very fast for carbon at high temperatures
- Need sealed target jacket with beam windows and pump/purge system
- Beryllium avoids this?

Lance Snead and Tim Burchell
Oak Ridge National Laboratory

Radiation Accelerated Corrosion

- Al 6061 samples displayed significant localized corrosion after 3,600 Mrad exposure.
- Enhanced tritium uptake and permeation through austenitic Stainless Steel (300 series)

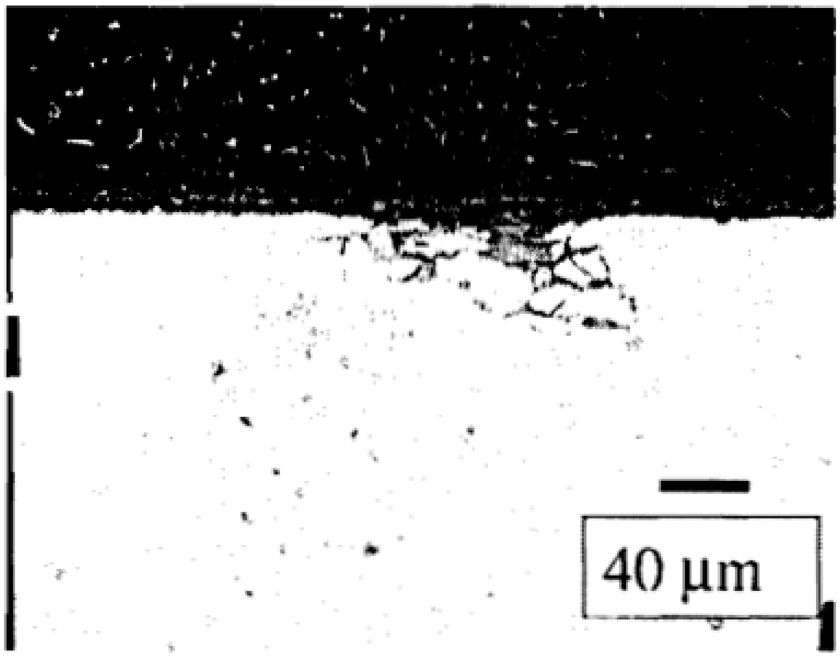


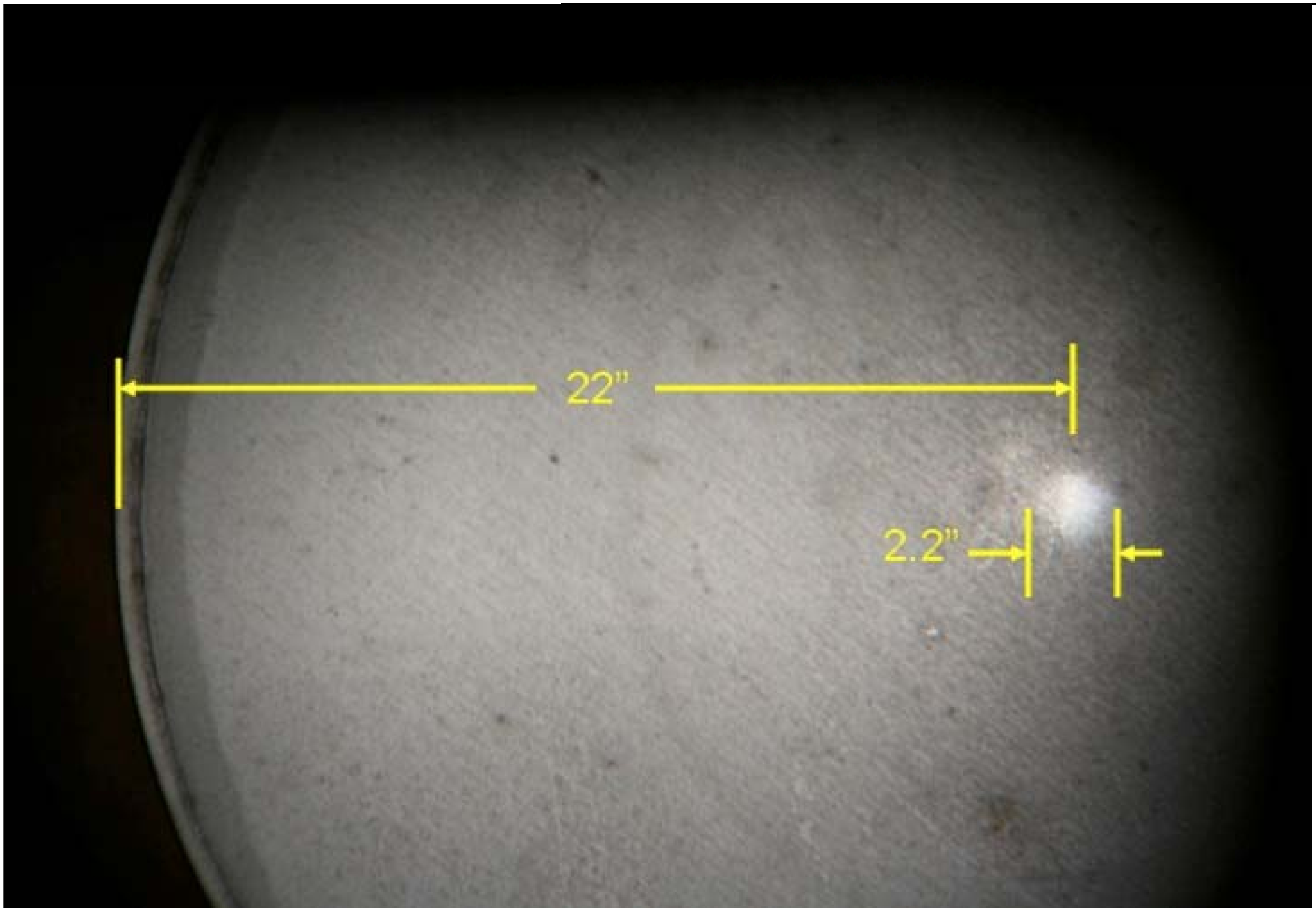
FIG. 8. Localized corrosion on 6061 Al sample exposed 12 weeks to saturated water vapor at 200°C and gamma irradiation.

R.L. Sindelar, et al., *Materials Characterization* 43:147-157 (1999).

Radiation Accelerated Corrosion

- MiniBooNE 25 m absorber HS steel failure (hydrogen embrittlement from accelerated corrosion).
- NuMI target chase air handling condensate with pH of 2.
- NuMI decay pipe window concerns.

Radiation Accelerated Corrosion

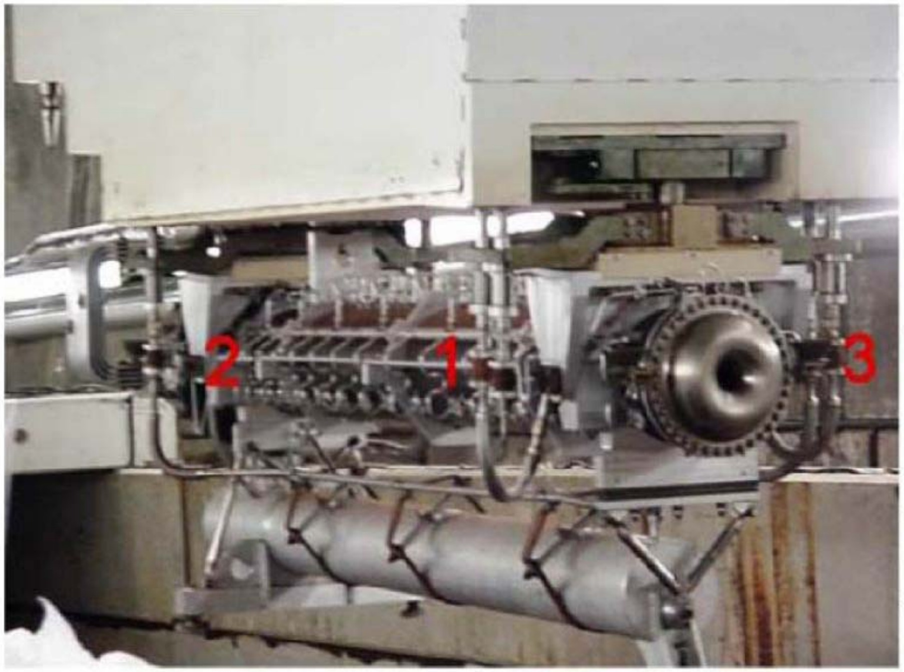


- Photograph of NuMI decay pipe US window showing corroded spot corresponding to beam spot

Spatial Constraints

- Low energy optics mean target must be inserted in throat of horn
- Little room for cooling (greater water hammer effect)
- Mount target to horn?
- Integrate target into horn inner conductor (Be target material)?
- If so, target design tied much more closely to horn design (high current, magnetic forces)

Residual Radiation

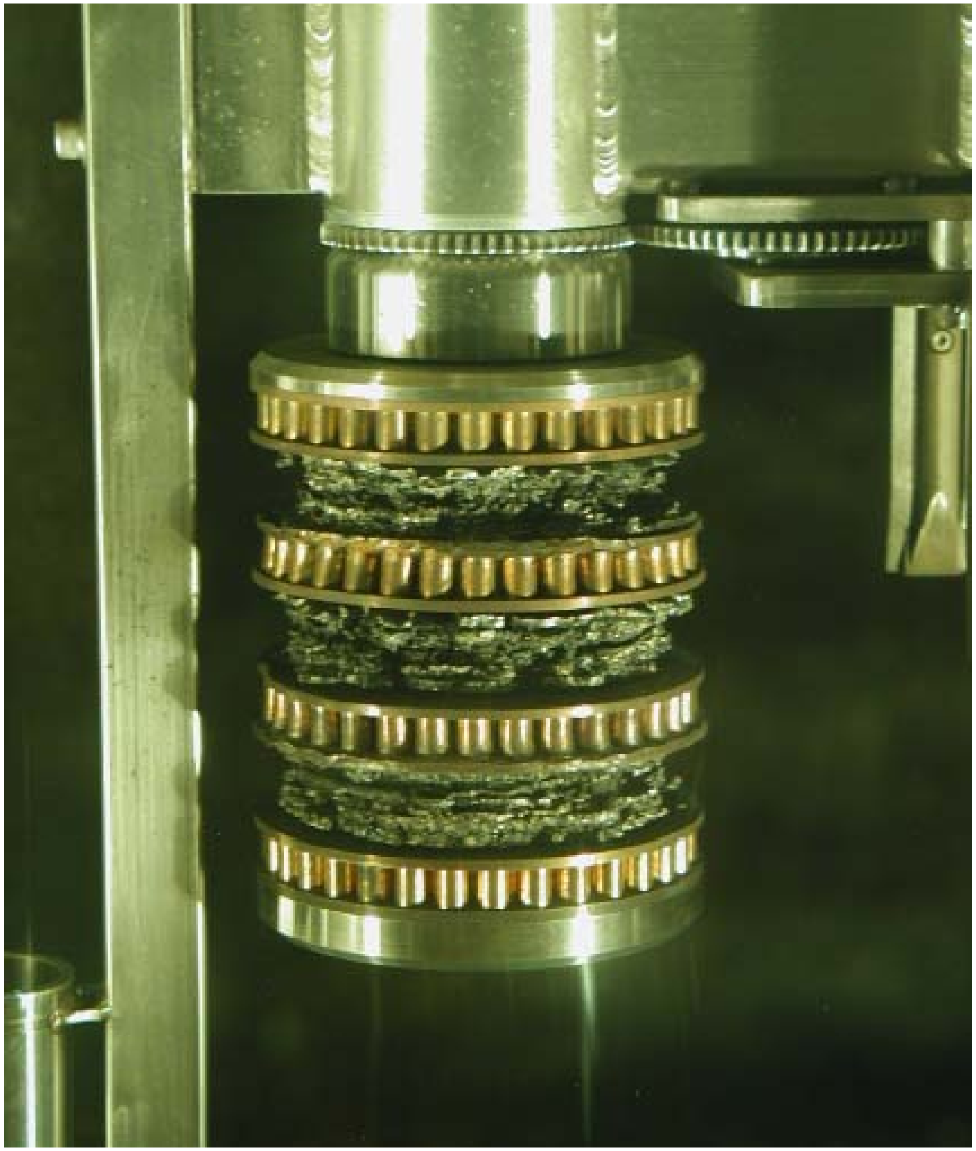


Measured dose rates for Horn 1 water line repair

Point	Doserate @ 1 foot (mr/hour)	Doserate On Contact (mr/hour)
1	35000	75000
2	40000	75000
3	35000	80000

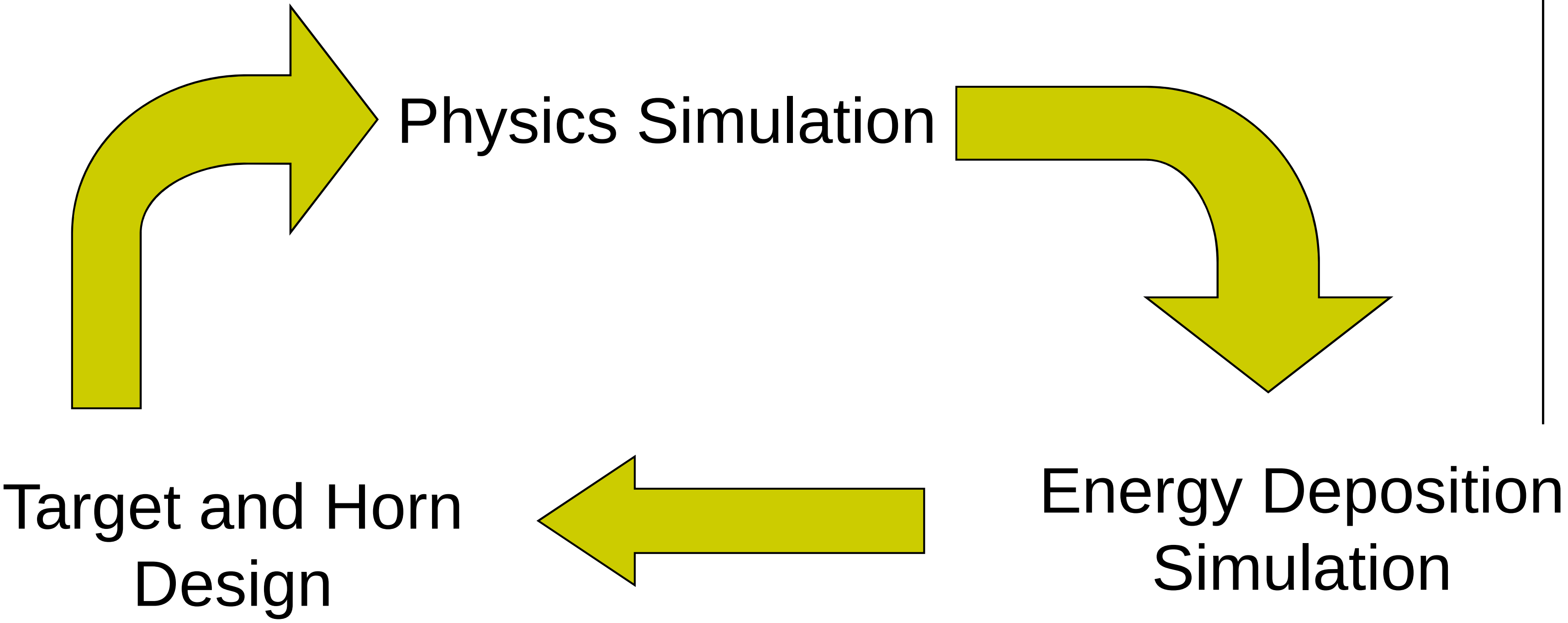
- Dose rates for 2 MW beam components estimated at 300-400 Rad/hr
- Systems for component change-out and repair must be developed (IE Remote Handling)
- Operations activities must be integrated into the conceptual design of target components

Survivability is relative



- P-bar consumable target
  - Ran in consumable mode for 2 plus years
  - Change-out time 12 hours maximum
  - Over-heating, oxidation, thermal shock led to damage

Physics Optimization



Physics Simulation

Energy Deposition Simulation

Target and Horn Design

Iterative process makes it difficult to isolate the design efforts

Possible Work Packages

- Water hammer investigation/experiment
- Radiation damage investigation/experiment
- Beryllium thermal shock investigation
- Integrated target/horn conceptual design
- 700 kW target design (using IHEP 2 MW core concept)
- Beam window conceptual design

Water Hammer

- Analysis and simulation to investigate water hammer effect
- Benefit - Single phase water cooling
- Who - ANL, RAL?
- Status - Contract for 4 weeks of Engineering time with ANL in place. Preliminary results indicate that pressure spike is 50 atm (instead of 150 atm)
- Future - Design test to confirm?

Radiation Damage

- Irradiation test at BLIP with new promising materials in vacuum (instead of water bath)
- Investigate radiation damage in candidate materials
- Benefit - Longer target lifetime
- Who - BNL, ANL?, ORNL?
  - BNL for irradiation and sample characterization
  - ANL/ORNL for correlation of neutron irradiation with high energy proton irradiation
  - ORNL for consult on irradiated properties of graphite?
- Status
  - Meeting with BNL (no funds committed) to design test
  - Contract with ANL for 1 week material scientist
  - Have not contacted ORNL

Radiation Damage

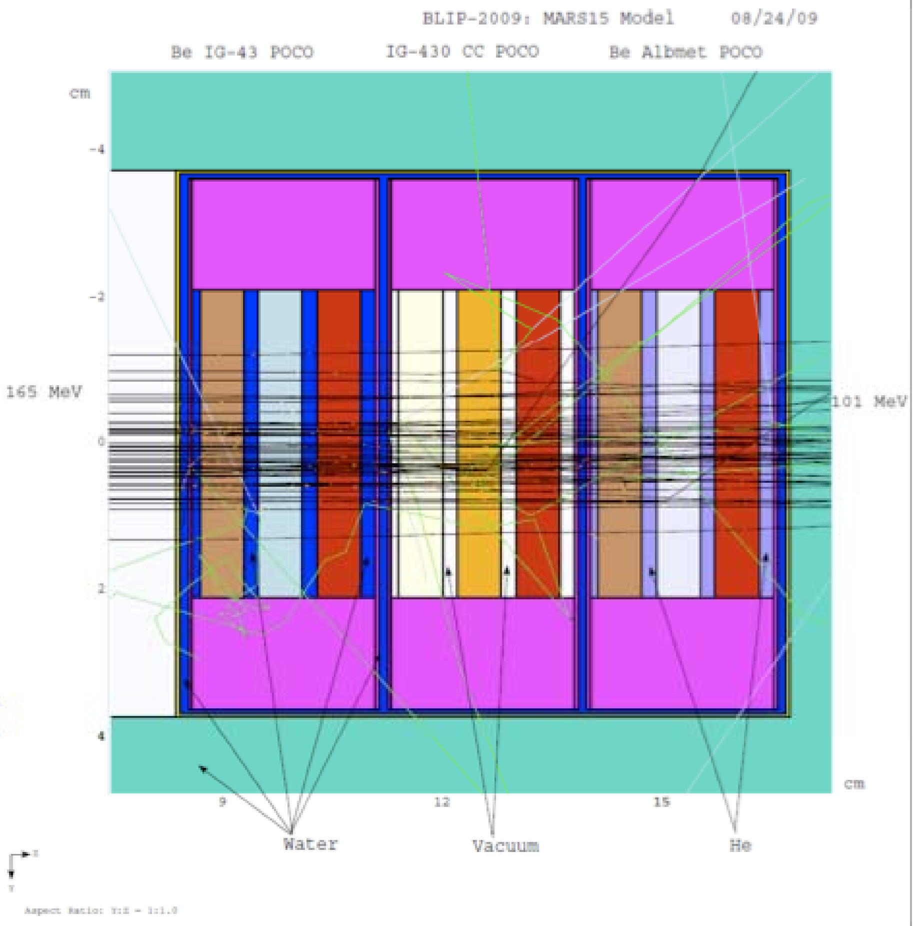
BLIP Target

165-MeV proton beam
to get 101 MeV downstream
$_x$ = $_y$ = 4.233 mm

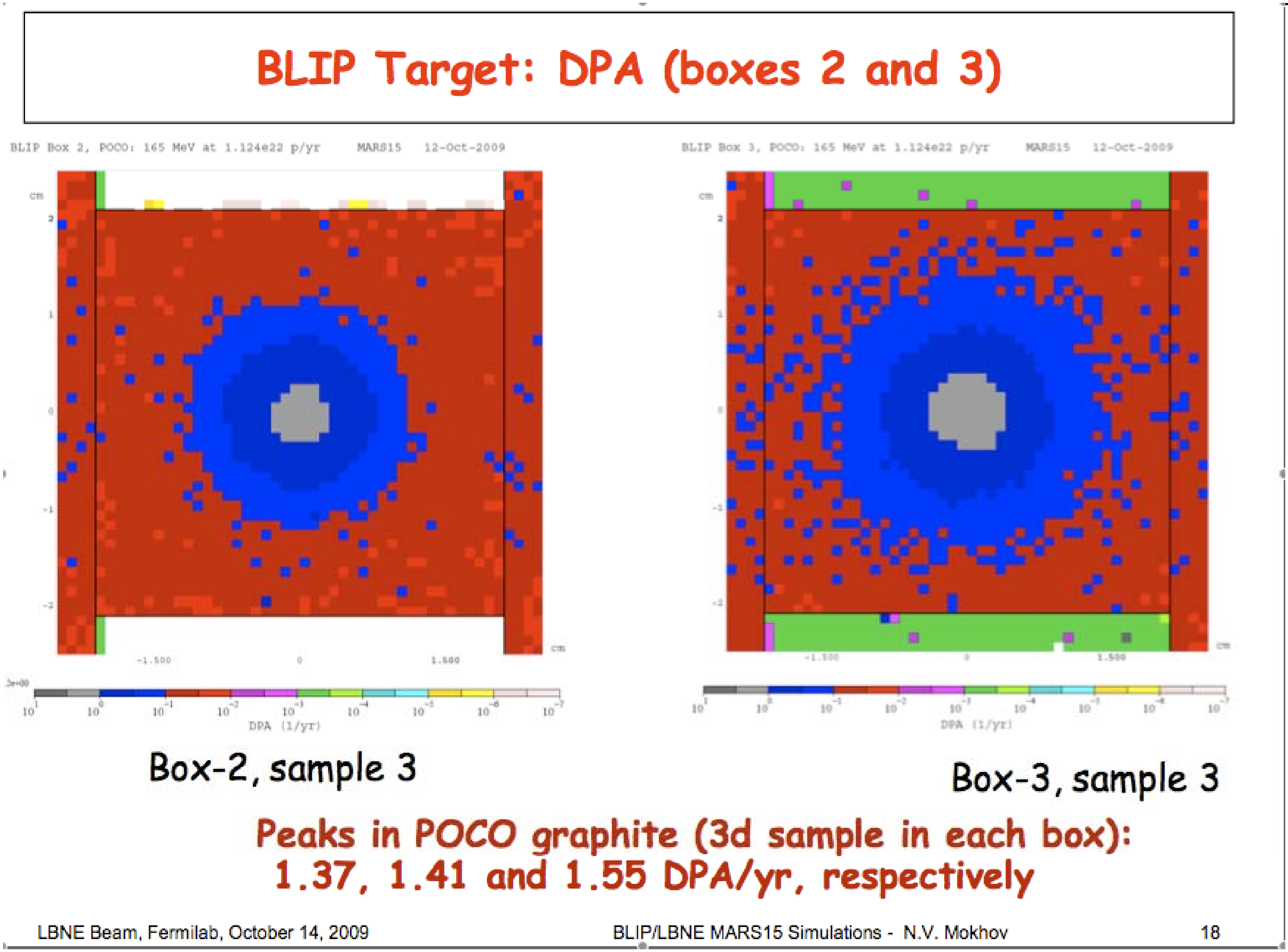
90 A: 5.62e14 p/s × 2e7 s/yr
= 1.124e22 p/yr

Nine 6-mm thick samples,3 per box

First run
Box-1: Be + IG-43 + POCO (Water)
Box-2: IG-430 + CC + POCO (Vacuum)
Box-3: Be + Albmet +POCO (He)



Radiation Damage



BLIP Target: DPA (boxes 2 and 3)

Box-2, sample 3

Box-3, sample 3

Peaks in POCO graphite (3d sample in each box):
1.37, 1.41 and 1.55 DPA/yr, respectively

LBNE Beam, Fermilab, October 14, 2009 BLIP/LBNE MARS15 Simulations - N.V. Mokhov 18

Radiation Damage

DPA Composition

Physics process contribution (%) at beam axis:
z=15 cm (NuMI) and Box 2 POCO graphite (BLIP)

Target	Nuclear	EM elastic	L.E. neutrons	$e^{\pm}$
NuMI	50.8	43.3	1.5	4.4
BLIP	43.5	53	3.5	0.02

In summary, DPA/yr = 0.45 (NuMI) and ~1.5 (BLIP) for 4.e20 p/yr and 1.124e22 p/yr, respectively.

Beryllium Thermal Shock

- Analysis to explore the use of Be as a target material
- Benefits
  - Longer target lifetime
  - Elimination of windows and pump/purge system
  - Possible integrated target/horn design
- Who - RAL (T2K target engineering team)?
- Status - Talking with C. Densham at RAL. No funds committed.

Integrated Target/Horn

- Analysis and conceptual design to use the target as the inner conductor of Horn 1
- Benefit - Identifies difficulties with that design solution early.
- Who - RAL?, ANL?, IHEP?
- Status - No contacts have been initiated for this task yet

700 kW Target Design

- Using 2 MW target “core” design, complete conceptual design of an LBNE baseline target assembly capable of 700 kW beam power
- Benefits
  - Facilitates baseline cost/schedule estimate
  - Provides experience with the IHEP 2 MW design concept
- Who - IHEP, RAL?
- Status - Initiating contact on this task (currently IHEP is working on the ME target for NOvA)

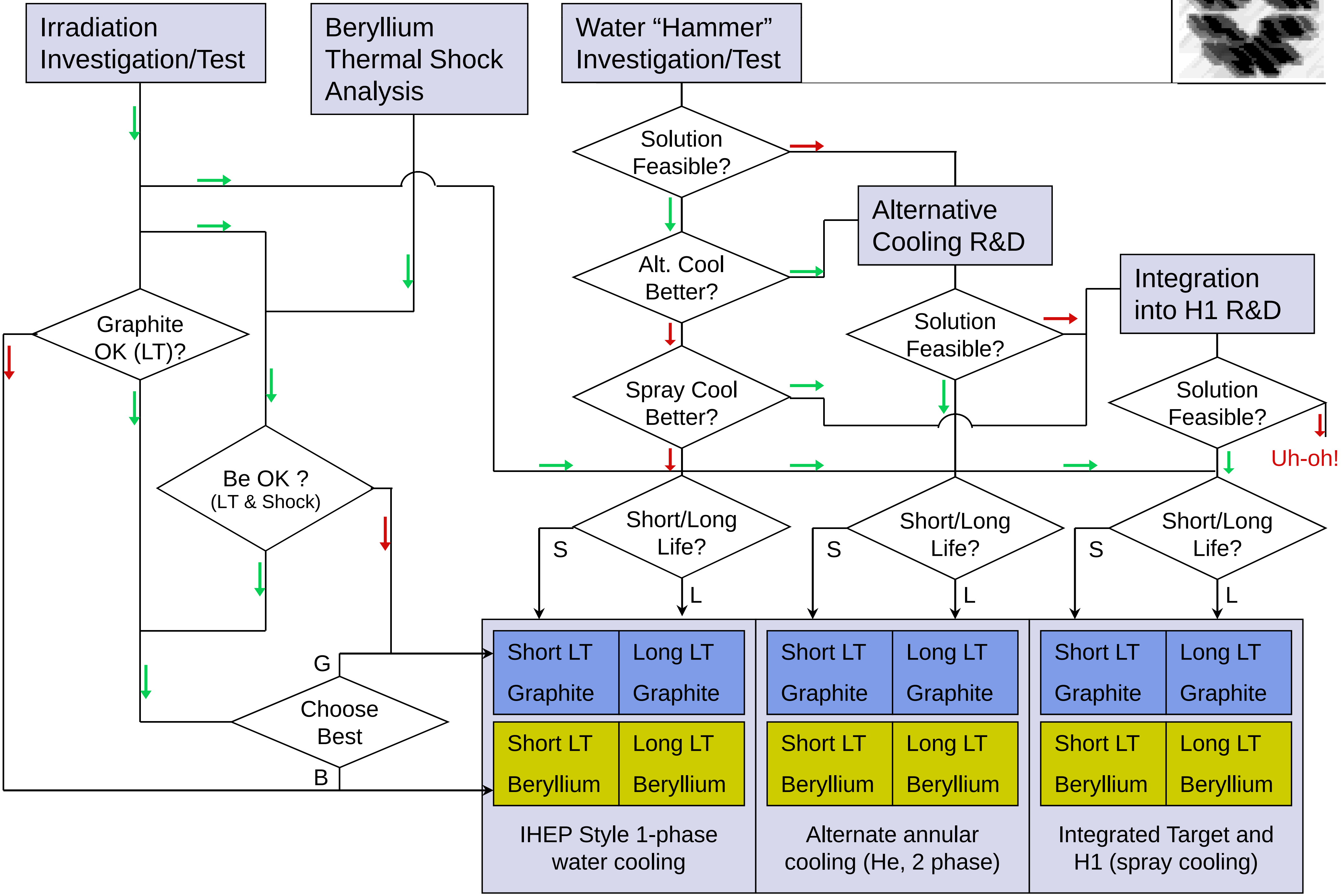
2 MW Beam Window

- Analysis and conceptual design of a replaceable beam window capable of 2 MW beam power
- Benefit - Facilitates baseline cost/schedule estimate
- Who - RAL?, ANL?, IHEP?
- Status - No contacts have been initiated for this task yet

Other Target Hall Issues

- Remote stripline connection (ORNL, RAL, ANL)
- Radioactive component handling (ORNL)
- Radiation accelerated corrosion (ANL, BNL)
- Air versus water cooled decay pipe (ANL, ORNL)
- High current horn conceptual design (??)
- Water cooled chase steel shielding (ANL, ORNL)
- Heat pipe target cooling (IHEP)

Path to 2 MW Target Flow Chart



Irradiation Investigation/Test

Beryllium Thermal Shock Analysis

Water “Hammer” Investigation/Test

Solution Feasible?

Alternative Cooling R&D

Alt. Cool Better?

Integration into H1 R&D

Solution Feasible?

Spray Cool Better?

Solution Feasible?

Uh-oh!

Graphite OK (LT)?

Be OK ?
(LT & Shock)

Short/Long Life?

S

L

Short/Long Life?

S

L

Short/Long Life?

S

L

G

Choose Best

B

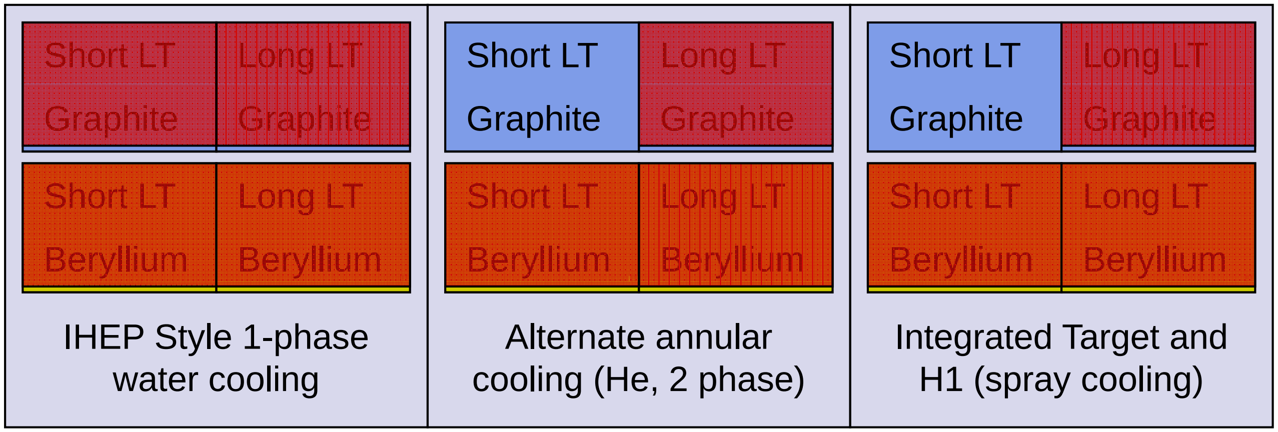
Short LT Graphite	Long LT Graphite	Short LT Graphite	Long LT Graphite	Short LT Graphite	Long LT Graphite
Short LT Beryllium	Long LT Beryllium	Short LT Beryllium	Long LT Beryllium	Short LT Beryllium	Long LT Beryllium

IHEP Style 1-phase water cooling

Alternate annular cooling (He, 2 phase)

Integrated Target and H1 (spray cooling)

Eventual Solutions?



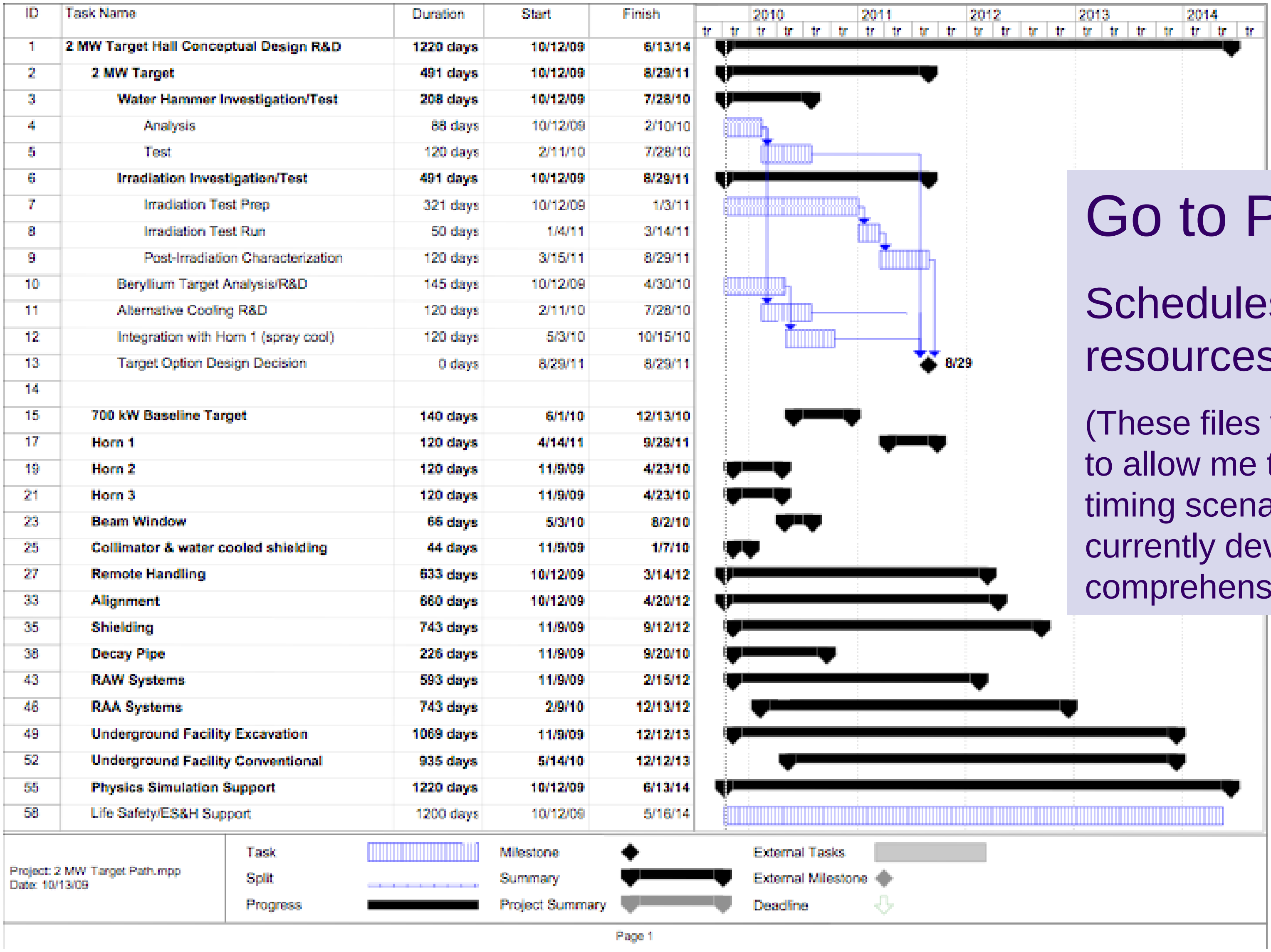
Short LT Graphite	Long LT Graphite	Short LT Graphite	Long LT Graphite	Short LT Graphite	Long LT Graphite
Short LT Beryllium	Long LT Beryllium	Short LT Beryllium	Long LT Beryllium	Short LT Beryllium	Long LT Beryllium
IHEP Style 1-phase water cooling		Alternate annular cooling (He, 2 phase)		Integrated Target and H1 (spray cooling)	

- Long Lifetimes are preferable (obviously)
- Be only considered if Long Lifetimes are confirmed
- Want to be well on path to defining design concept by CD-1
- Remote Handling issues (and thus civil work) cannot be reasonably estimated until target (and other components) conceptual designs are solidified
- Until then, must assume most conservative solution (most costly and time consuming) and work on these issues in parallel as much as possible!

Looking at it another way…

Option #	Target Material	Short or Lon Lifetime	Cooling	Water Hammer Inv/Test	Irradiatio Inv/Test	Beryllium Analysis	Alternativ Cooling	Integrate Horn (spr cool)	700 kW IHEP Targ Design	Remote Handling - Conceptua Design
1	Graphite	Short	Water, 1 phase	x		x			x	x
2	Graphite	Short	Alternative	x		x	x			x
3	Graphite	Short	Spray			x		x		x
4	Graphite	Long	Water, 1 phase	x	x	x			x	x
5	Graphite	Long	Alternative	x	x	x	x			x
6	Graphite	Long	Spray		x	x		x		x
7	Beryllium	Short	Water, 1 phase	x		x			x	x
8	Beryllium	Short	Alternative	x		x	x			x
9	Beryllium	Short	Spray			x		x		x
10	Beryllium	Long	Water, 1 phase	x	x	x			x	x
11	Beryllium	Long	Alternative	x	x	x	x			x
12	Beryllium	Long	Spray		x	x		x		x
	Primary bear window			x	x	x				x

And yet one more way…



ID	Task Name	Duration	Start	Finish
1	**2 MW Target Hall Conceptual Design R&D**	**1220 days**	**10/12/09**	**6/13/14**
2	**2 MW Target**	**491 days**	**10/12/09**	**8/29/11**
3	**Water Hammer Investigation/Test**	**208 days**	**10/12/09**	**7/28/10**
4	Analysis	88 days	10/12/09	2/10/10
5	Test	120 days	2/11/10	7/28/10
6	**Irradiation Investigation/Test**	**491 days**	**10/12/09**	**8/29/11**
7	Irradiation Test Prep	321 days	10/12/09	1/3/11
8	Irradiation Test Run	50 days	1/4/11	3/14/11
9	Post-Irradiation Characterization	120 days	3/15/11	8/29/11
10	Beryllium Target Analysis/R&D	145 days	10/12/09	4/30/10
11	Alternative Cooling R&D	120 days	2/11/10	7/28/10
12	Integration with Horn 1 (spray cool)	120 days	5/3/10	10/15/10
13	Target Option Design Decision	0 days	8/29/11	8/29/11
14				
15	**700 kW Baseline Target**	**140 days**	**6/1/10**	**12/13/10**
17	**Horn 1**	**120 days**	**4/14/11**	**9/28/11**
19	**Horn 2**	**120 days**	**11/9/09**	**4/23/10**
21	**Horn 3**	**120 days**	**11/9/09**	**4/23/10**
23	**Beam Window**	**66 days**	**5/3/10**	**8/2/10**
25	**Collimator & water cooled shielding**	**44 days**	**11/9/09**	**1/7/10**
27	**Remote Handling**	**633 days**	**10/12/09**	**3/14/12**
33	**Alignment**	**660 days**	**10/12/09**	**4/20/12**
35	**Shielding**	**743 days**	**11/9/09**	**9/12/12**
38	**Decay Pipe**	**226 days**	**11/9/09**	**9/20/10**
43	**RAW Systems**	**593 days**	**11/9/09**	**2/15/12**
46	**RAA Systems**	**743 days**	**2/9/10**	**12/13/12**
49	**Underground Facility Excavation**	**1069 days**	**11/9/09**	**12/12/13**
52	**Underground Facility Conventional**	**935 days**	**5/14/10**	**12/12/13**
55	**Physics Simulation Support**	**1220 days**	**10/12/09**	**6/13/14**
58	Life Safety/ES&H Support	1200 days	10/12/09	5/16/14

Project: 2 MW Target Path.mpp
Date: 10/13/09

Go to Project Files

Schedules assume infinite resources available!

(These files were only developed to allow me to investigate various timing scenarios. LBNE is currently developing the comprehensive WBS/RLS)

Path to 2 MW Target

The scheduling exercises show:

- Although irradiation damage questions may be unanswered, progress on the path to a 2 MW Target may be satisfactory for CD-1 at the end of CY2010?
- Parallel tasks in 2010 will require many resources. Even if “out-sourced”, significant oversight and support effort is required from FNAL scientists and engineers.
- Dependencies on 2 MW Target choices drive “informed” conceptual design activities until late in 2012. So early “worst-case” assumptions will be used for Civil Construction conceptual design (cost estimates).
  - This risks driving costs and contingencies even higher.
  - This risks “boxing” the component technical designs “in a corner”.

Path to 2 MW Target

The scheduling exercises show:

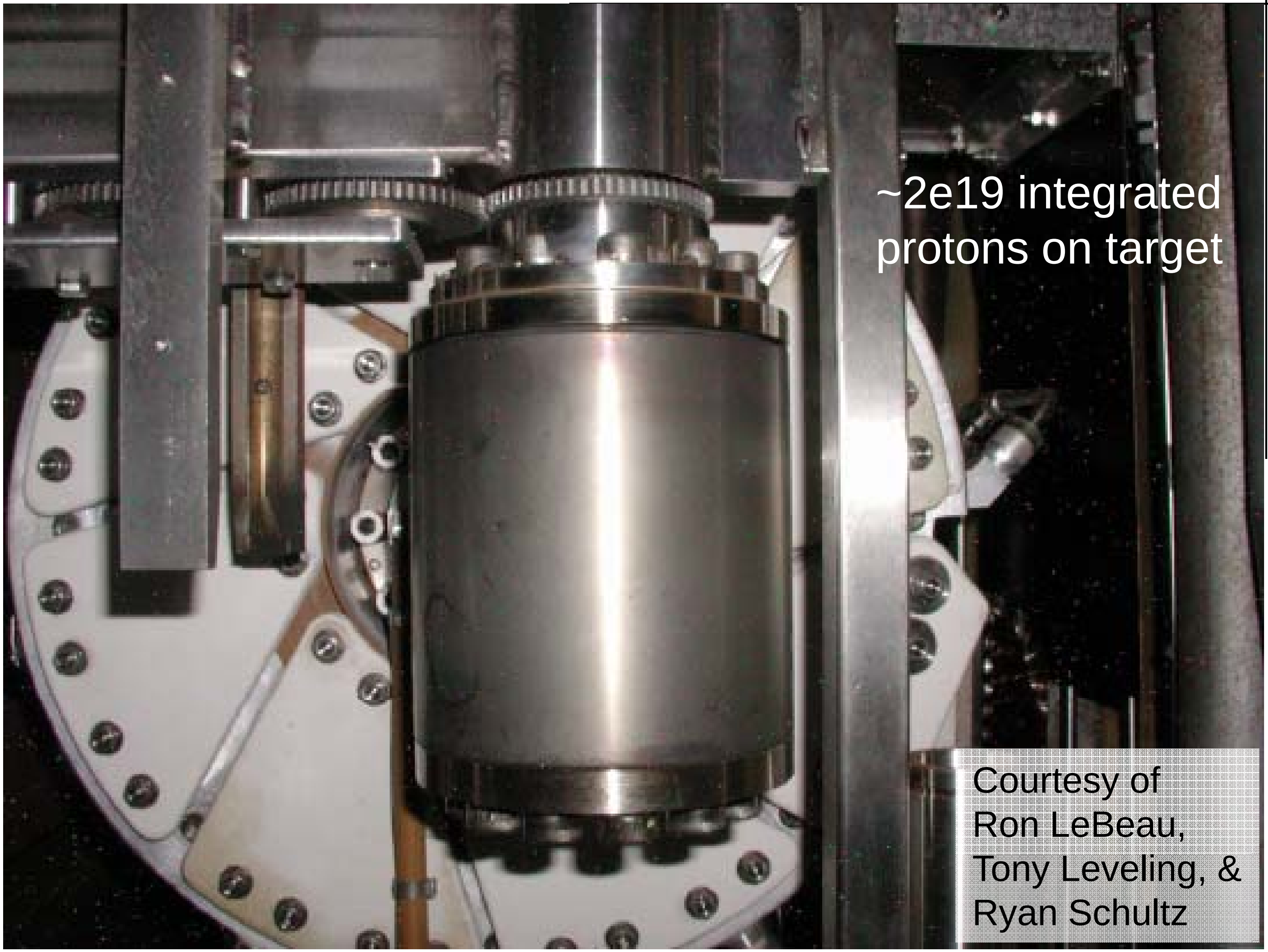
- If the BLIP irradiation test can be pushed up to the 2010 spring run without sacrificing quality, significant gains can be realized.
    - Conceptual Design for 2 MW Target defined by end of CY2010.
    - Conceptual Design of other components 9 months earlier.
    - “Informed” conceptual design activities completed for Target Hall infrastructure and civil construction 9 months earlier.

Path to 2 MW Target

In Conclusion:

- Much work to be done in a short amount of time with limited engineering resources
- Will concentrate on:
  - Irradiation testing of candidate target materials
  - Investigation of “water hammer”
  - Analysis of Be as target material
  - 700 kW baseline design
- We will also pursue:
  - Correlation of neutron to proton radiation damage
  - 2 MW primary beam window
  - Remote handling issues
  - Decay pipe cooling
  - Integrated Target/Horn 1 concept

New P-bar Target



~2e19 integrated protons on target

Courtesy of
Ron LeBeau,
Tony Leveling, &
Ryan Schultz