Radiation Protection at SLAC's Future MEC-U Laser Facility

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Overview

- Introduction to MEC-U Project
- Radiation Hazards and Source Terms
- Prompt Radiation and Its Mitigation
- Activation and Its Mitigation
- Other Considerations

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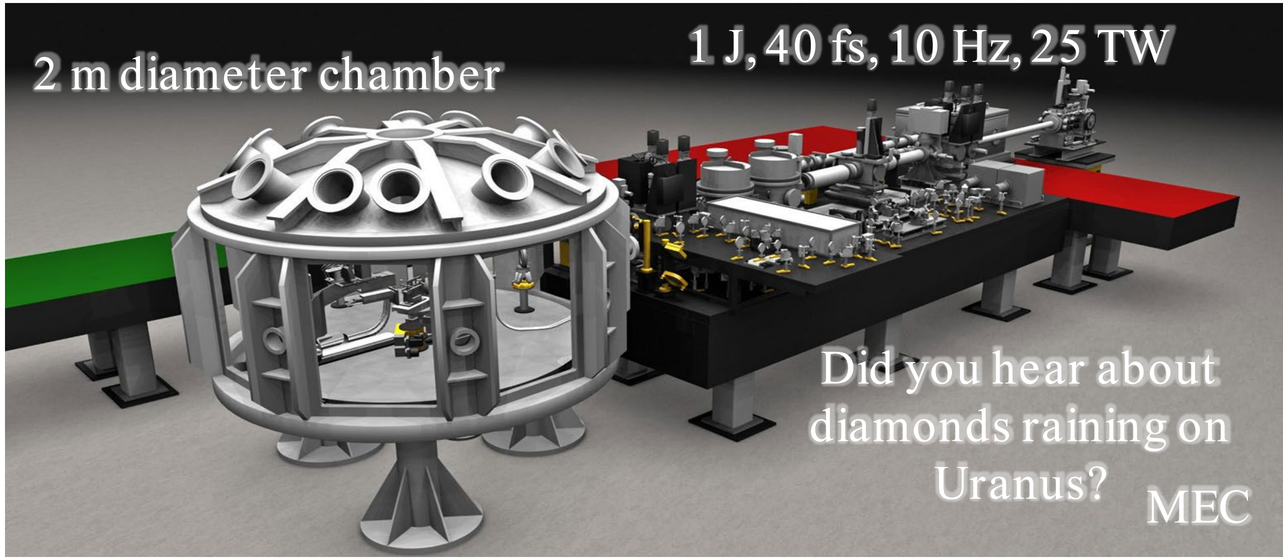
Introduction to MEC-U Project

Upgrade to MEC

Matters in Extreme Conditions at LCLS

- Hutch 6 at LCLS combines X-ray FEL with tightly focused laser light (up to 10^{20} W/cm^2)
- Radiation hazard from interaction of laser light with matter
- Talk at RadSynch17 in Taiwan



Did you hear about diamonds raining on Uranus?

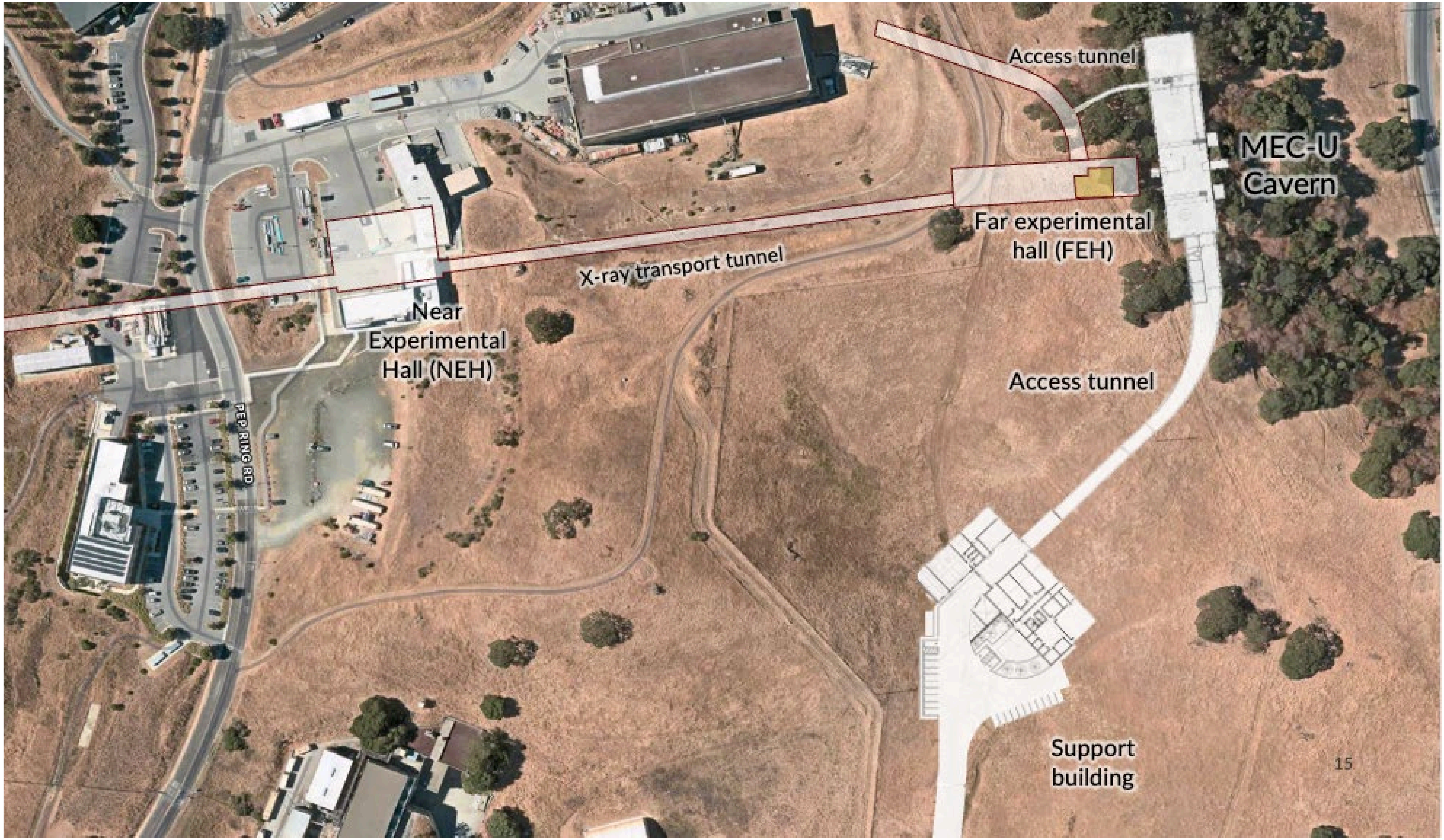
New Project MEC-U to replace MEC

- Underground Cavern behind last LCLS Hutch
- One hutch for laser-FEL experiments, one hutch for laser-only experiments
- Conceptual Design Report issued mid-2021
- Preliminary Design Review scheduled for Early 2024
- → all results shown are preliminary

MEC-U plans to study

- Conditions inside planets, stars
- Ion acceleration (short pulse multi-MeV)
- Relativistic plasma physics (e.g., cosmic ray acceleration)
- Ion stopping in plasmas (fusion science, astrophysics)

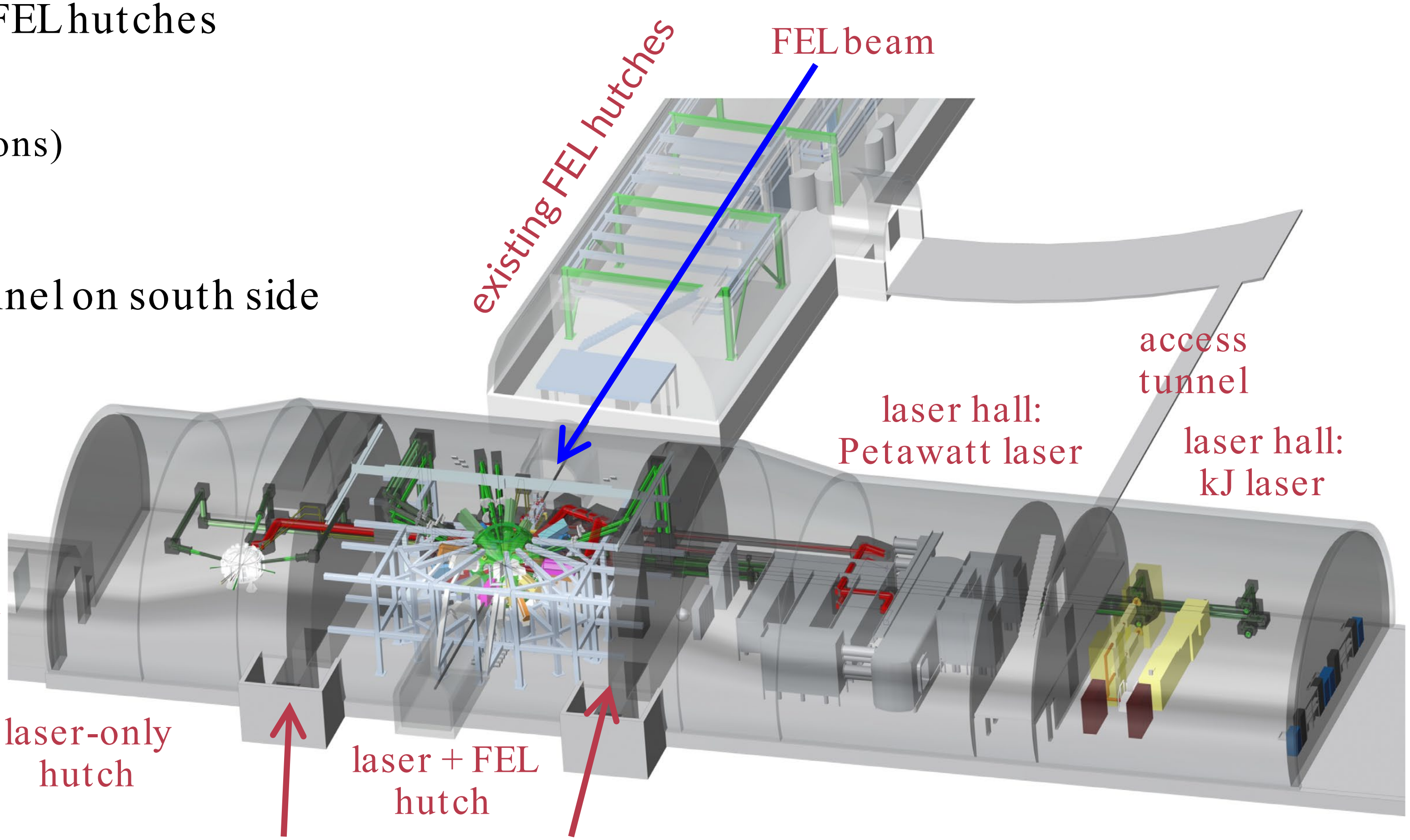
MEC-U and LCLS



MEC-U Layout

Underground cavern

- 80 m long
- Separated by earth from other FEL hutches
  (small FEL beam pipe)
- Shield walls (with maze, penetrations)
- Personnel access on north side
- Long equipment / personnel tunnel on south side connecting to …
- …support building at hill



existing FEL hutches

FEL beam

access tunnel

laser hall: Petawatt laser

laser hall: kJ laser

equipment / personnel access tunnel

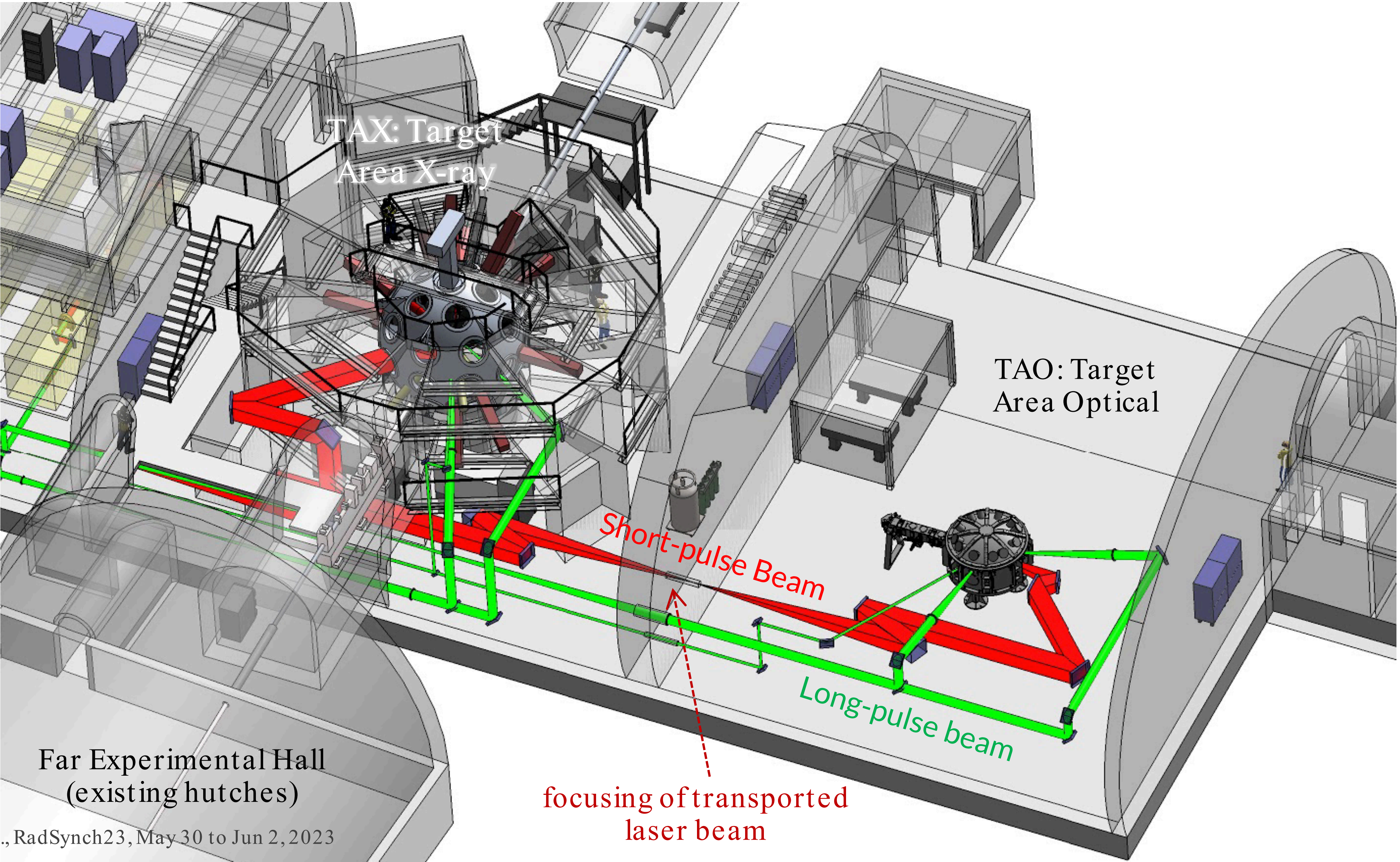
laser-only hutch

laser + FEL hutch

shield wall with maze

support building >150 m away

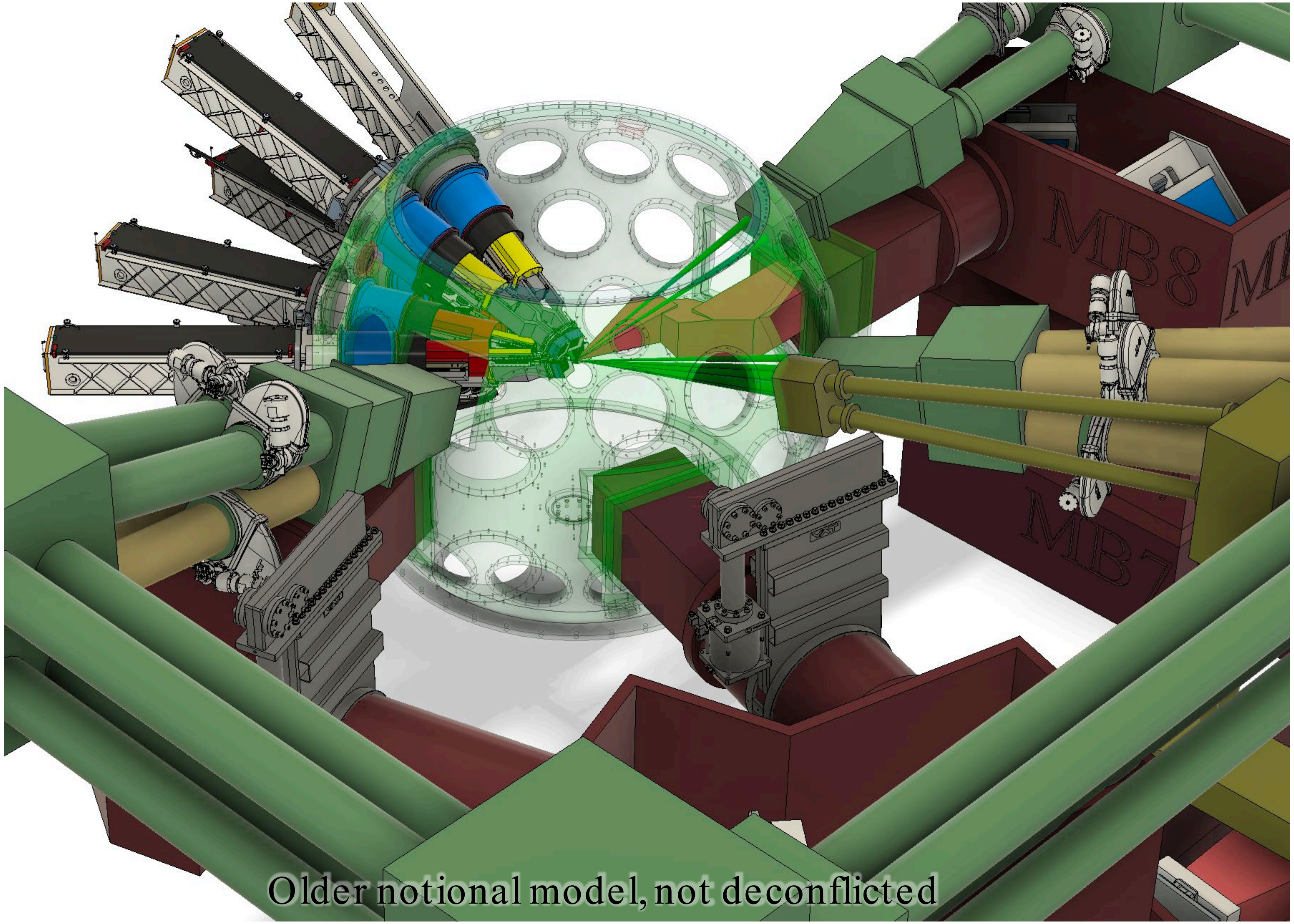
MEC-U Hutches



MEC-U Layout

Target Chamber

- Vacuum Chamber, 4.5 m diameter, 10 cm thick aluminum
- Large holes for laser light
- SLIMs (SLAC Insertion Modules): Moving devices in/out without breaking vacuum
    - diagnostics, targets, etc. moved in, *e.g,* for one experiment
    - starting with a few, more over time
- Goal: Personnel access to inside of target chamber only few times a year



Older notional model, not deconflicted

MEC-U Laser Operation

Lasers, Irradiance

High-Energy Long Pulse (HE-LP):	1 kJ, 20 ns, 2 shots / hour
High-Rep-Rated Long Pulse:	200 J, 20 ns, 10 Hz
High-Rep-Rated Short Pulse (RR-SP):	150 J, 150 fs, 1 um, 10 Hz ← laser with radiation hazard

with focusing: 3 x 10^{21} W/cm^2

Operation

- Facility to operate year-round
- About 27 experiments

Timeline through the year		
HE-LP (no RR-SP)	RR-SP and HE-LP	RR-SP only
Jan-Apr	May-Aug	Sep-Dec

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Radiation Hazards and Source Terms

Laser-Target Interactions

Creation of Plasma with Particle Acceleration

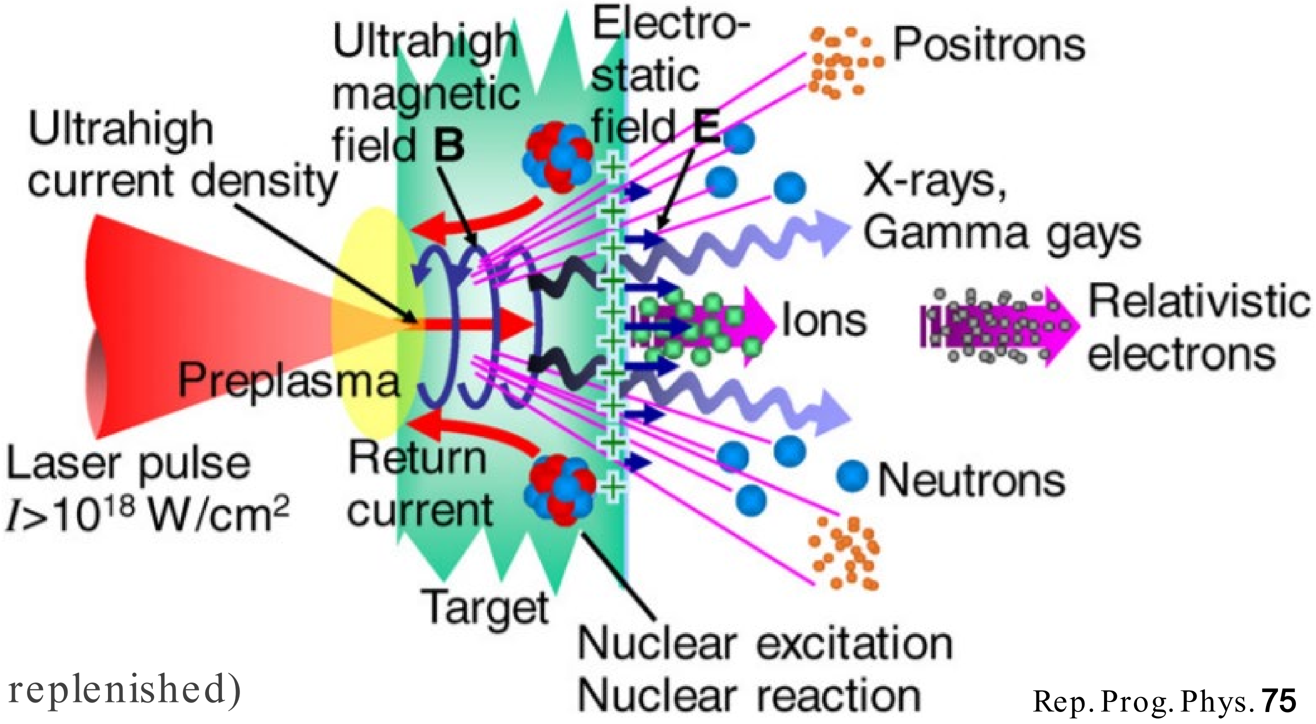
Laser light focused to small area while compressed in time

High electromagnetic fields create plasma and accelerate electrons and ions

Different acceleration schemas depending on laser strength, targets, etc.

Radiation of concern:
- hot electrons
- protons

Targets
- metals (mainly acceleration of electrons)
- carbohydrates (more protons/some ions)
- liquid/frozen targets (more protons, target easily replenished)

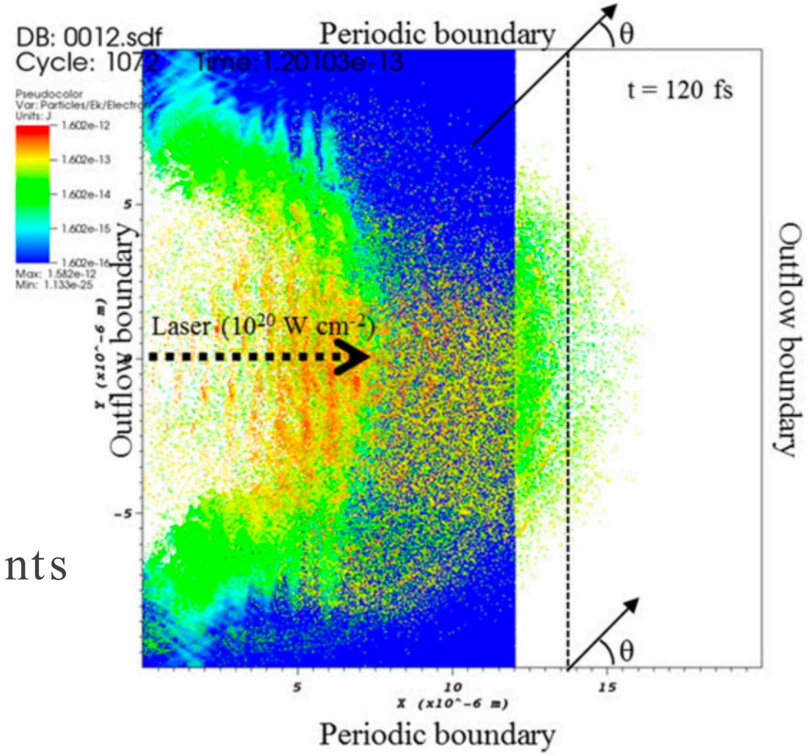


Rep. Prog. Phys. **75** (2012) 056401

Source Term for Hot Electrons

Source term into FLUKA taken from SLAC Study (Ted Liang’s thesis)

https://doi.org/10.1093/rpd/ncw325



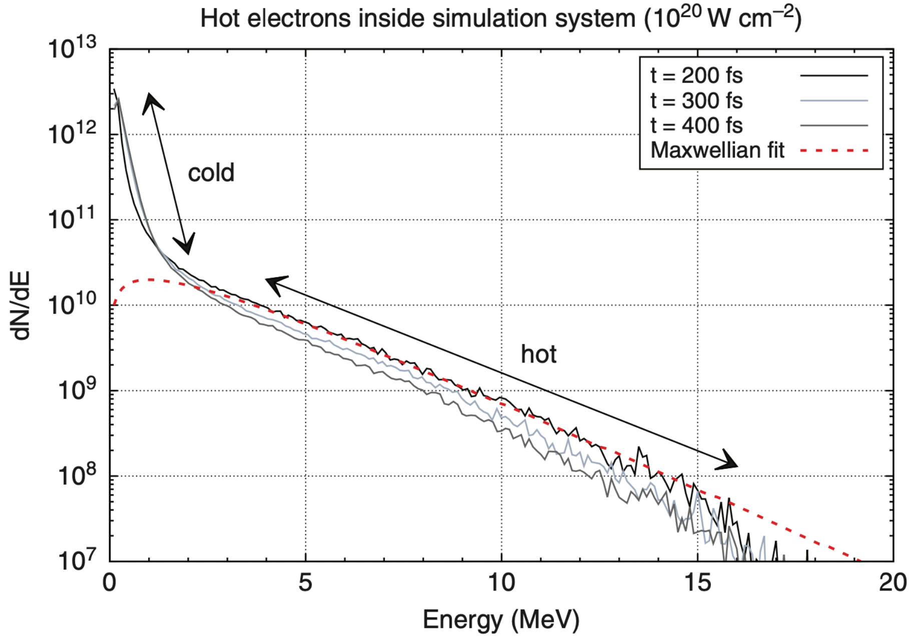
Study based on PIC code (EPOCH)

simulates interaction → obtain hot electron spectrum

Spectrum → source term for FLUKA → confirmed w/radiation measurements

Applied to MEC-U (assuming all shots at highest energy & irradiance)

- Hot electron temperature of Maxwellian distribution 23 MeV
- 60% conversion efficiency of laser energy to accelerated electrons
- Forward-backward ratio 27:1
- ± 45° opening angle
- Solid Targets: 1 mm thick Cu (conservative, but for thinner targets electrons circulate several times in plasma)
- Liquid targets: 300 μm thick He
  = reducing Cu target conversion efficiency from 60% to 6%
  10 liquid target shots = 1 solid target shot



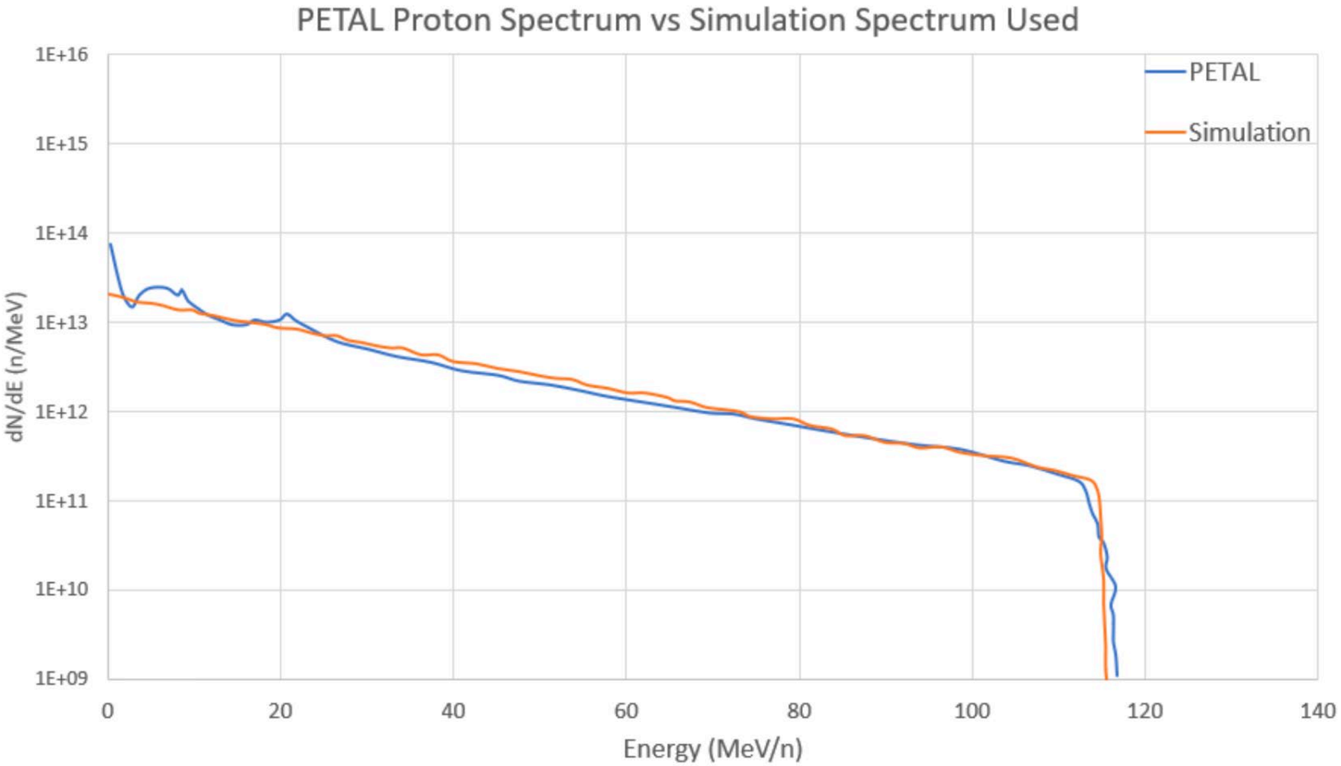
Source Term for Protons

Based on PIC Simulation for LMJ-PETAL at CEA/Cesta https://arxiv.org/abs/2105.11094

Similar parameters: 150 J, 1 PW, 2×10^{21} W/cm^2

Input to FLUKA

- Spectrum up to 115 MeV
- Average energy 23 MeV
- 5% conversion of laser energy to accelerated protons
- Same amount backward as forward (confirmed with PIC simulation)
- ± 20° opening angle (tighter than for electrons)
- Source term is already effective radiation = no target simulated in FLUKA
- Same radiation amount for both solid and liquid targets



Number of Shots in 1 Year and 1 Hour

Input from project

Upper limit, but reasonable
since goal of operation

Conservative since

- assuming all shots at highest energy and highest irradiance
- usually (so far) most shots not perfect
- usually (so far) time spent on setup

Note:

- 54,000,000 shots at 10 Hz → 1,500 hours if running straight
- Question once raised why goal is not 10 Hz operation all the time (6,000 hours)
- Above numbers for shield wall calculations (about 60 W through year)
- Assuming 10% of shots for activation calculations (about 6 W through year)

RP-Shot Estimate for Shielding Wall

Target	Number of Shots	
	1 year	1 hour
Solid (high Z)	4,000,000	24,000
Liquid (low Z)	50,000,000	36,000

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Prompt Radiation and Its Mitigation

Bulk Shield Walls

Big investment, cannot be easily upgraded

Shielding criterion:

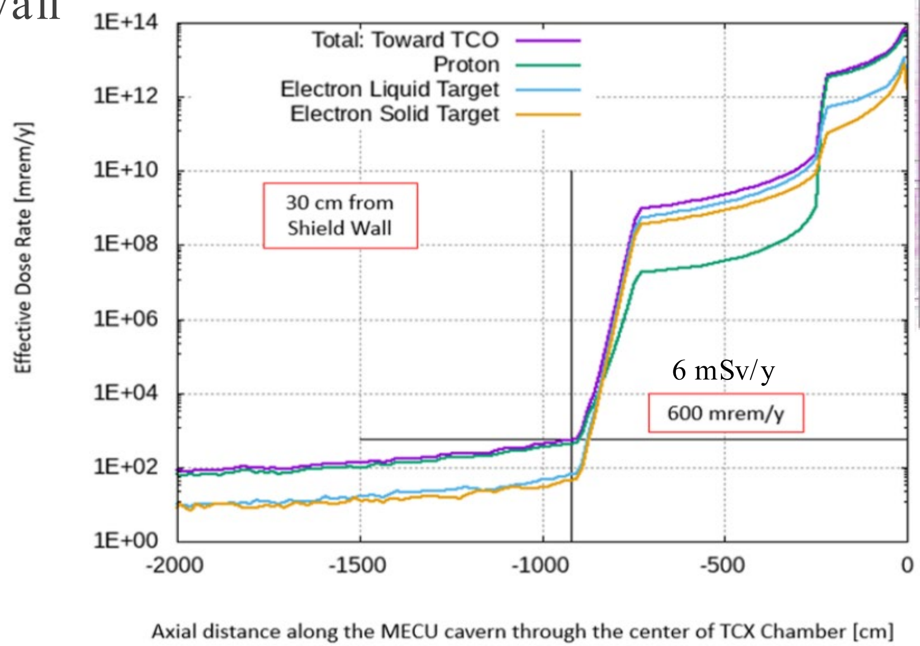
- 1 mSv in 1 year, 50 µSv in 1 hour
- assuming operation spread over 6,000 hours with each person for 1,000 hours at wall

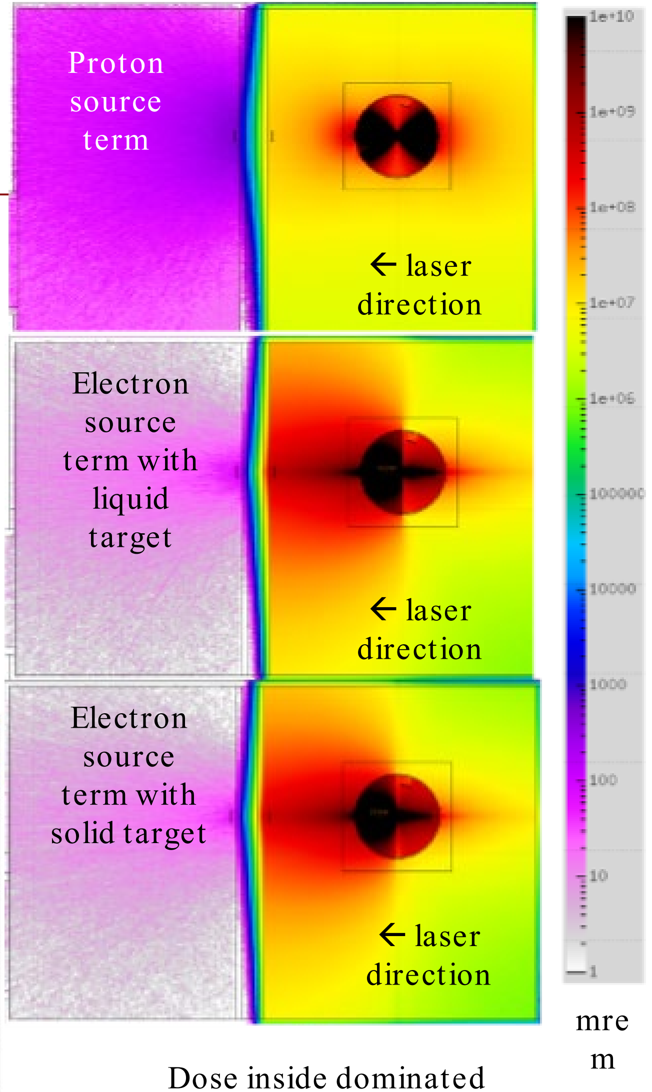
→ limit is 6 mSv for all shots in 1 year

Conservatively assuming all shots into wall

Proton source term dominant

→ 1.6 m heavy concrete (4.0 g/cm^3)



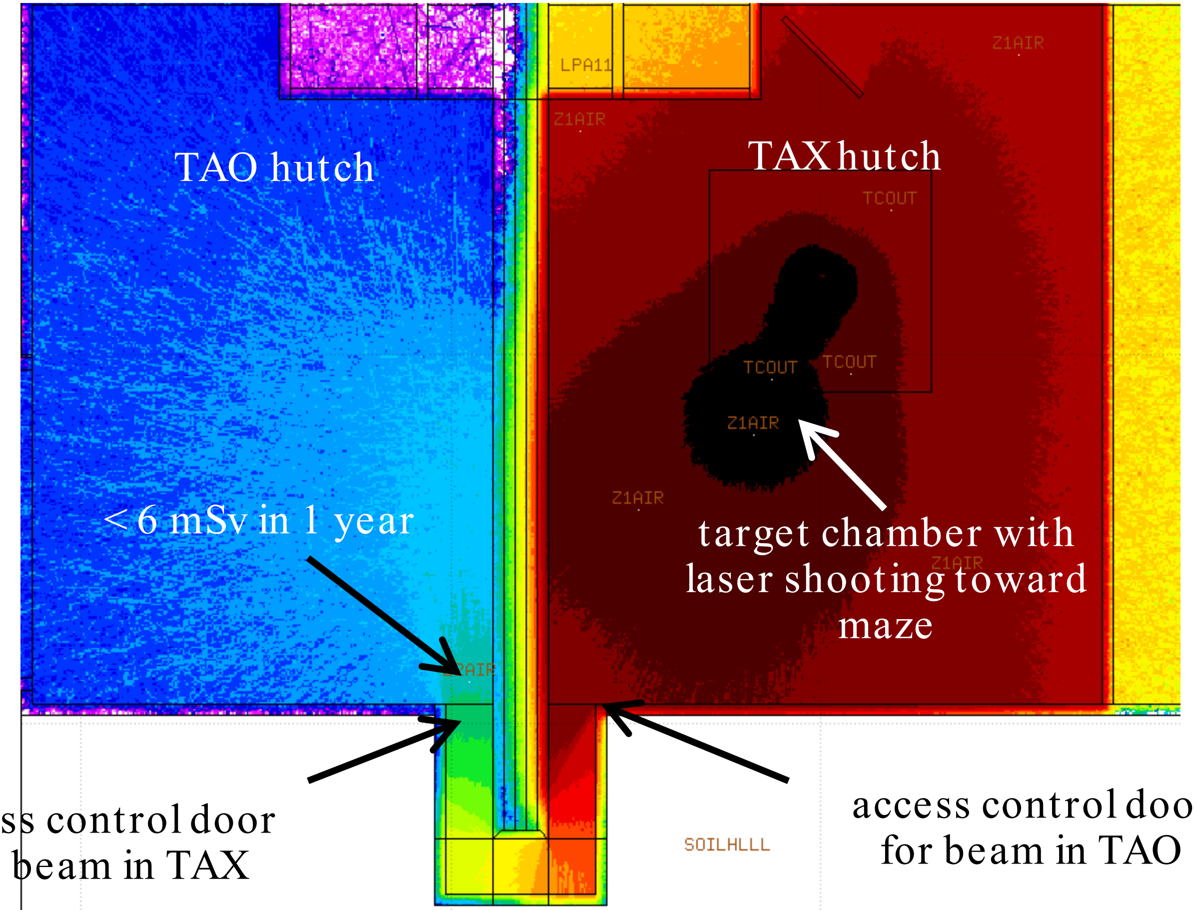


Dose inside dominated by electron source term, outside by proton source term

Entrance Mazes at Shield Wall

For access to hutch

Maze reduces dose rate to <6 mSv in 1 year



TAO hutch

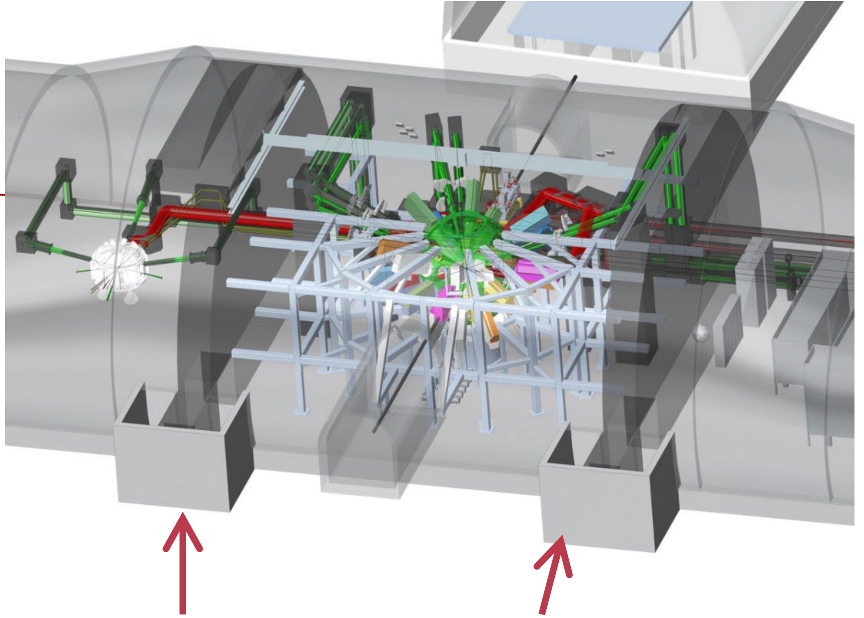
TAX hutch

< 6 mSv in 1 year

target chamber with laser shooting toward maze

access control door for beam in TAX

access control door for beam in TAO



shield wall with maze

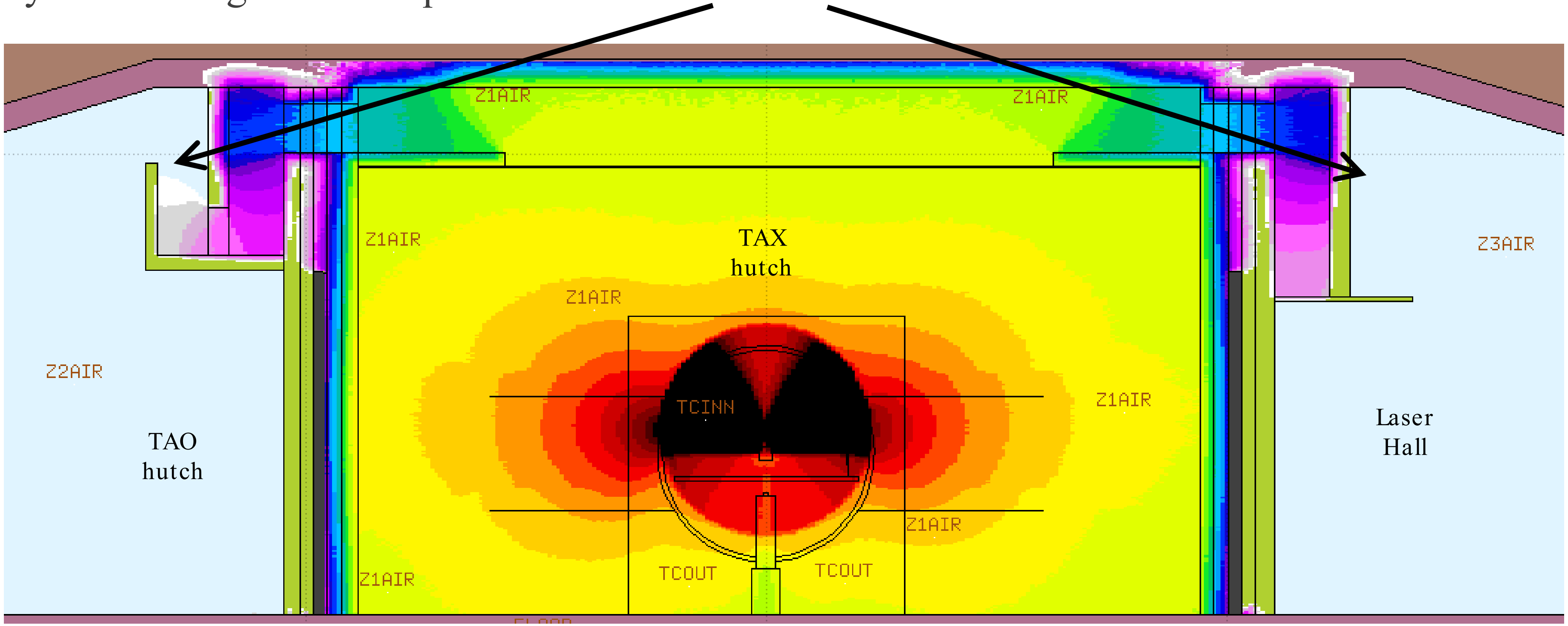
HVAC etc. Penetrations through Shield Wall

Large HVAC penetrations to TAX and Laser Hall

Worked with engineers for good solution

Maze-style shielding meets requirements

< 6 mSv outside
from 1-year shots



Dominant proton source term only

Laser Penetrations through Shield Wall

How to get a 50 cm laser beam through a small hole?

Laser engineers planned anyway to focus laser in vacuum while transporting

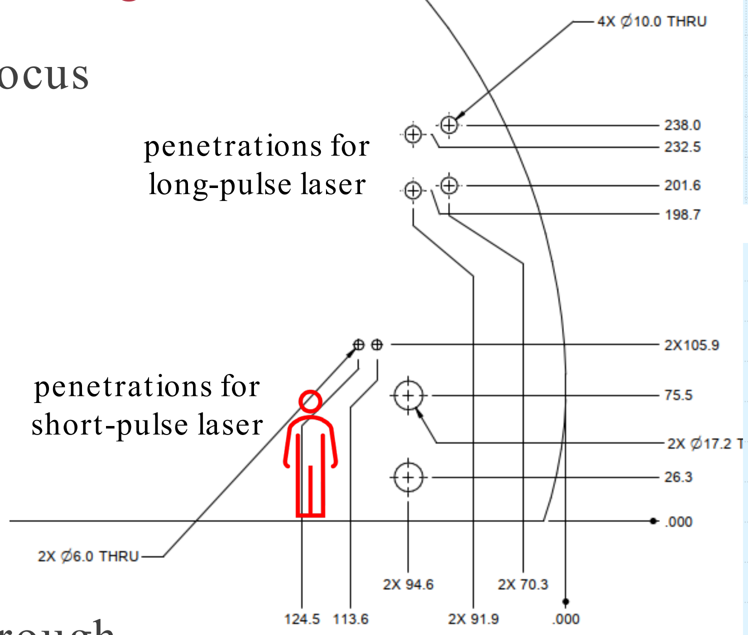
We asked the focal spot to be where laser light crosses the wall

→ penetrations can now be 44 cm diameter

Not a real maze

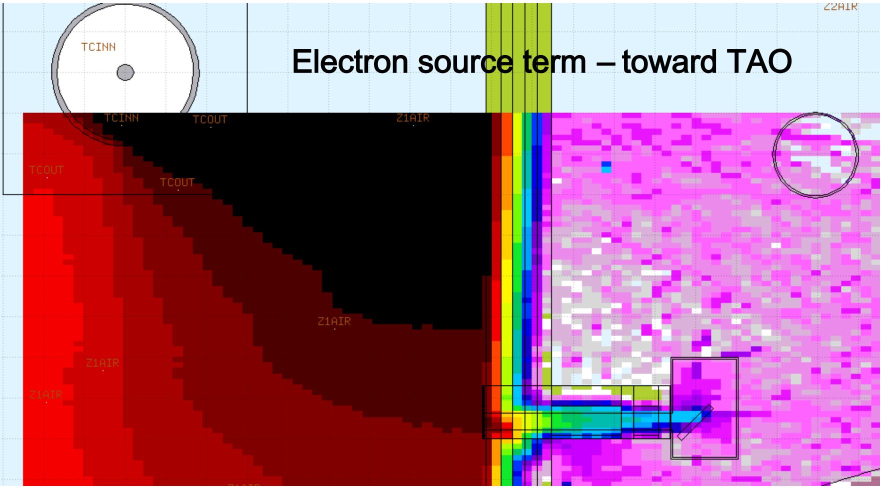
→ some radiation going straight through

→ need to keep people off path until next scatter point

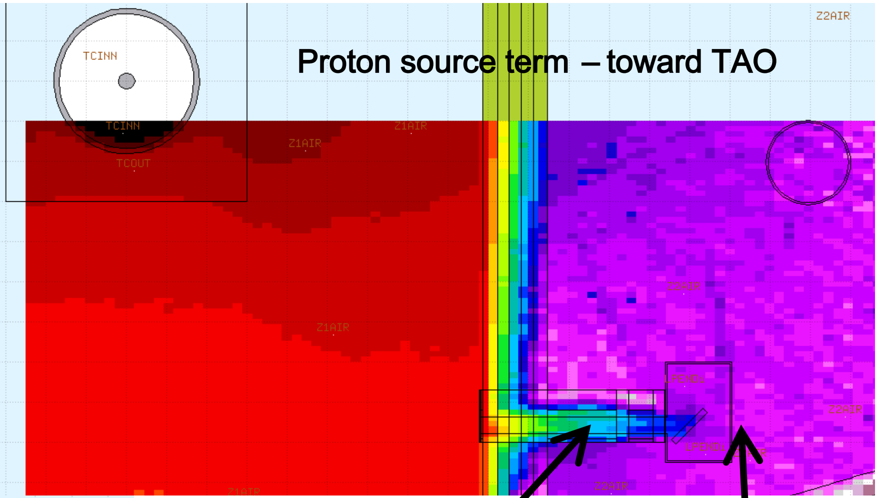


penetrations for long-pulse laser

penetrations for short-pulse laser



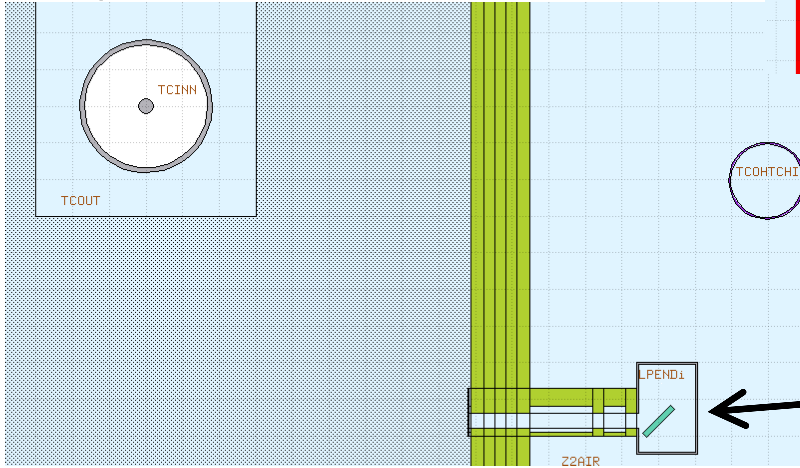
Electron source term – toward TAO



Proton source term – toward TAO

Still too high

Below limit



Optical element intercepts radiation from penetration

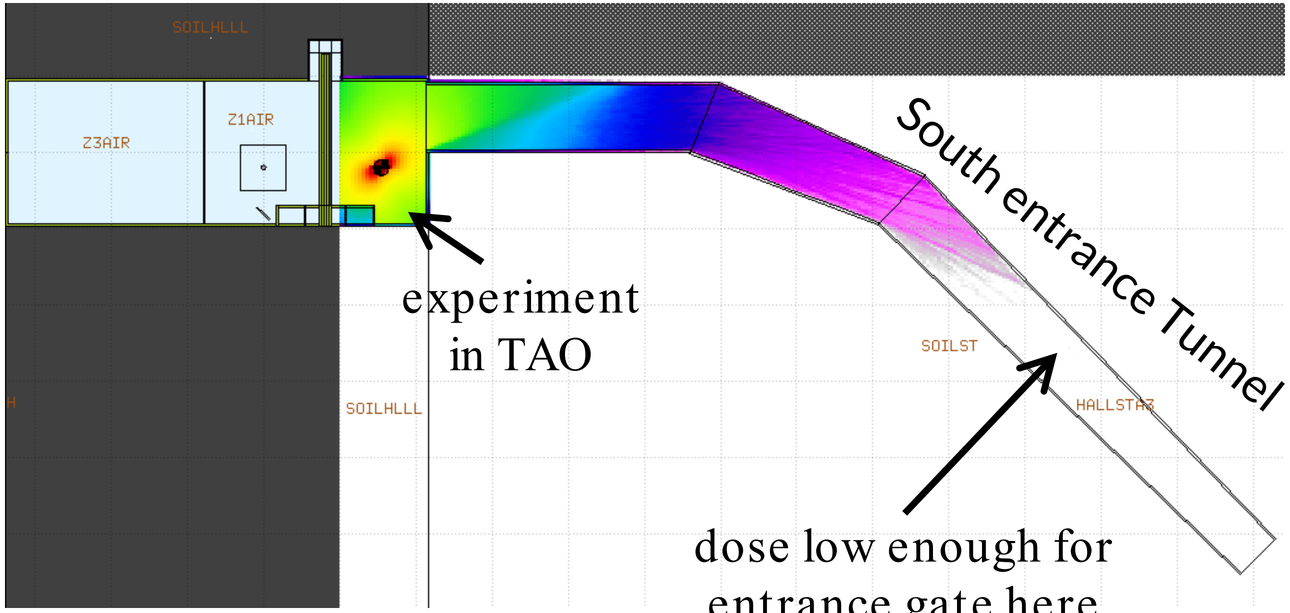
No Maze at South Entrance Tunnel

Currently in Deferred Scope

Need Access Control Gate for TAO hutch

Project wants to keep south entrance tunnel open for equipment access

→ partial maze with distance instead of shielding
  - o.k. to place gate far from hutch



rough simulation

South entrance Tunnel

experiment in TAO

dose low enough for entrance gate here

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Activation and Its Mitigation

Activation Hazard

Operation at up to 6 W (= 10% of shots)

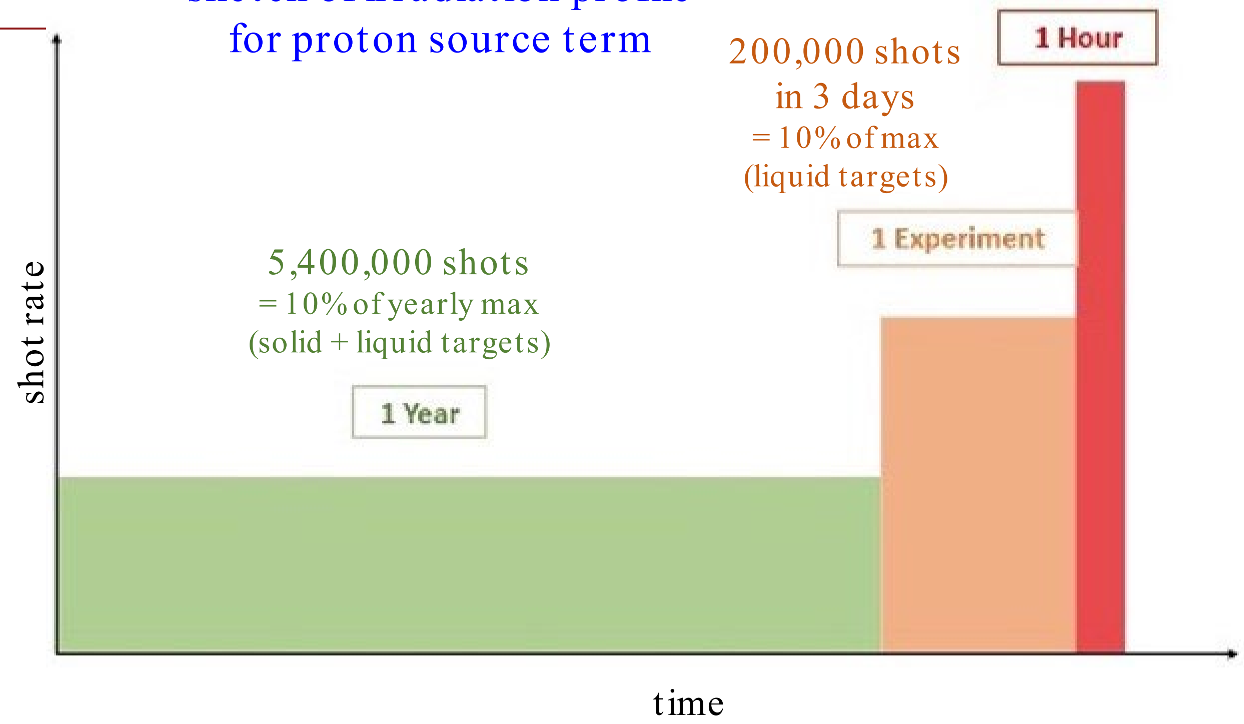
If MEC-U operates as designed,
significant activation created

Unlike accelerators
- Frequent access needed to area of activation
- Challenging to implement shielding

Analysis to understand hazard, to guide engineers

Assumptions for FLUKA irradiation profile:

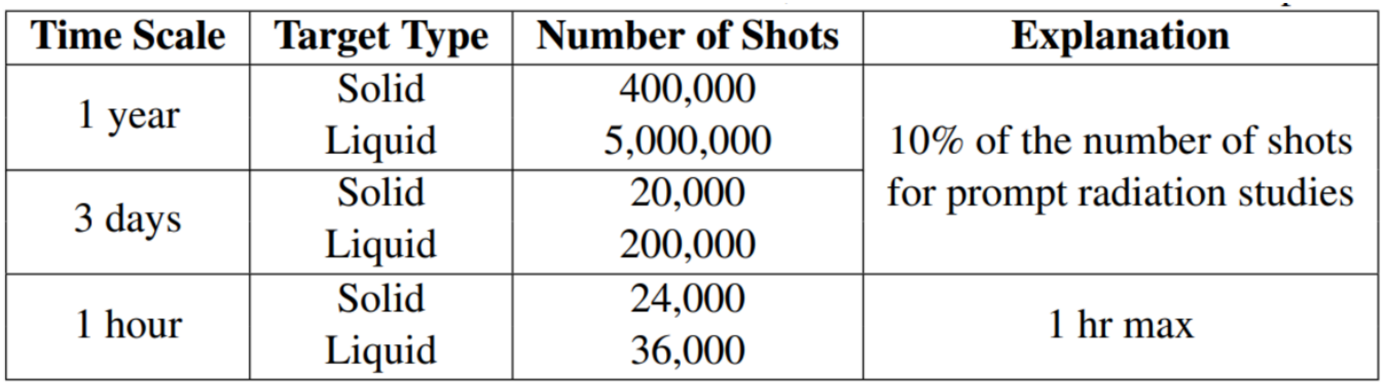
sketch of irradiation profile for proton source term



36,000 shots (liquid target)

200,000 shots in 3 days = 10% of max (liquid targets)

5,400,000 shots = 10% of yearly max (solid + liquid targets)



Time Scale	Target Type	Number of Shots	Explanation
1 year	Solid	400,000	10% of the number of shots for prompt radiation studies
	Liquid	5,000,000	
3 days	Solid	20,000	
	Liquid	200,000	
1 hour	Solid	24,000	1 hr max
	Liquid	36,000	

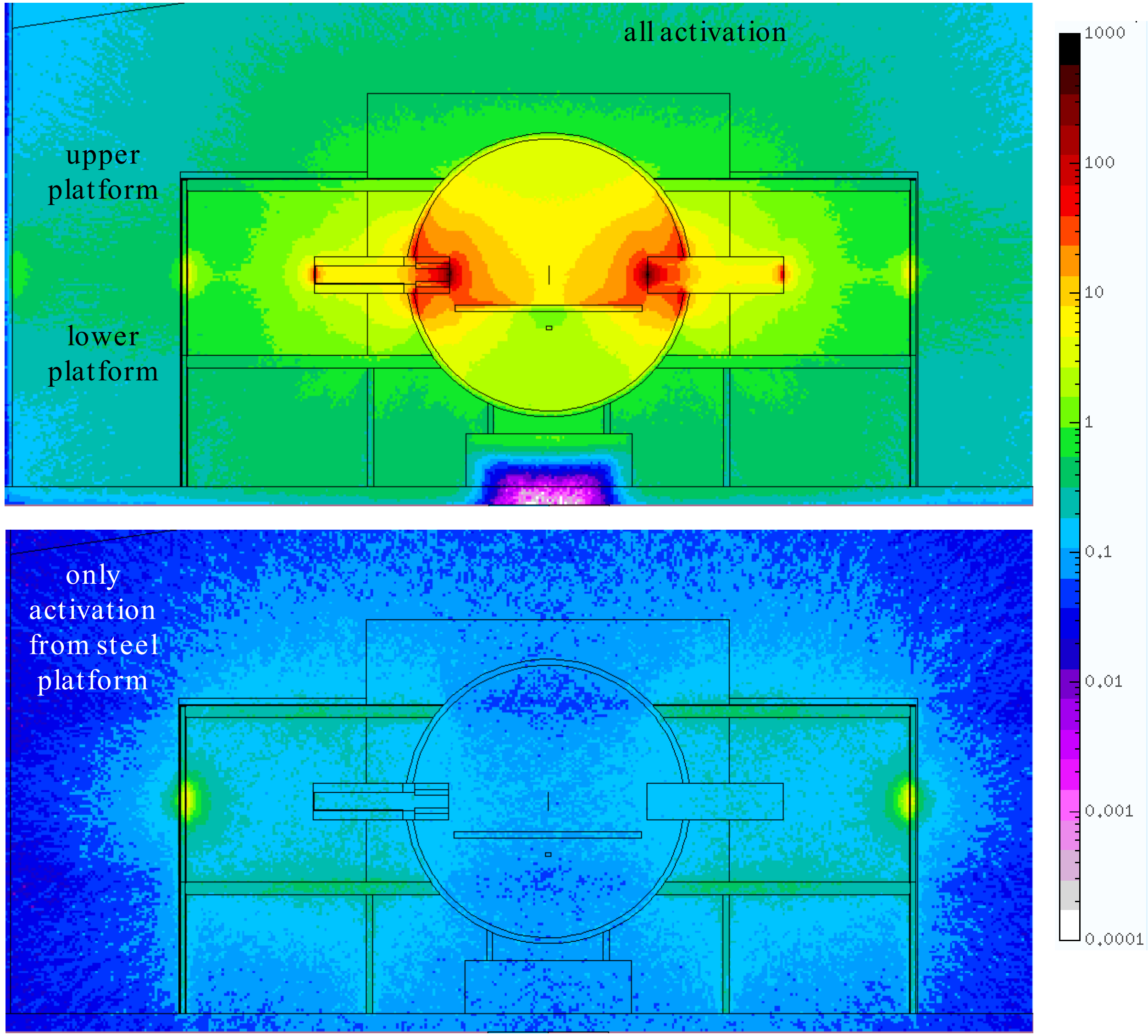
Platform around Target Chamber

Question from Engineers: Steel or Aluminum?

Simulation tells us:

- Steel activates more than aluminum, but …
- activation of aluminum chamber dominates over activation of steel platform

→ steel o.k.



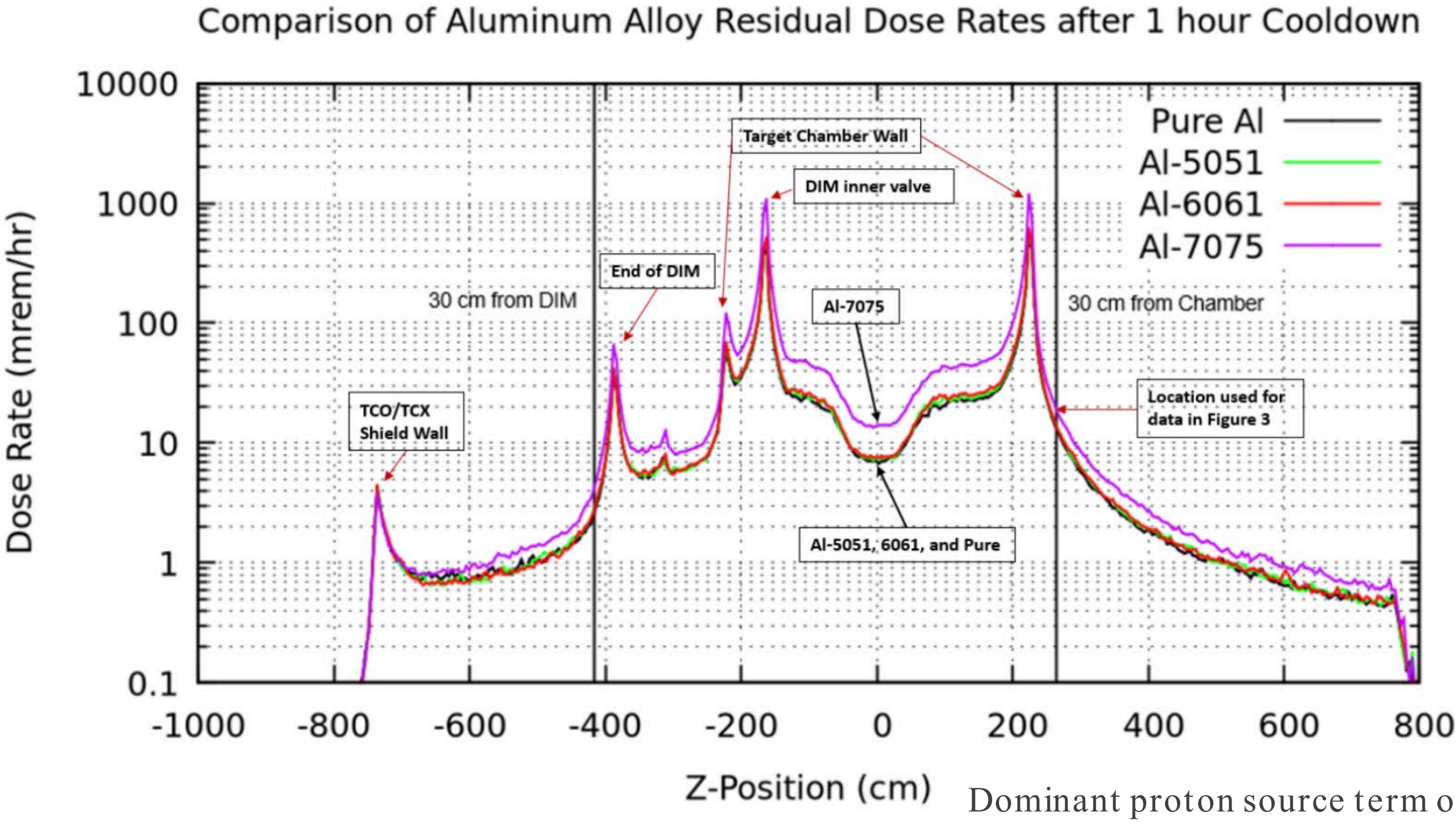
Aluminum Alloy

Questions from Engineers: Which alloy acceptable regarding activation? How much cobalt content?

- 5000- and 6000-series comparable activation
- 7000-series about x2 higher (no plans to use 7000-series)

no significant difference after ~1 day cool-down

- up to 0.15% cobalt → no significant change

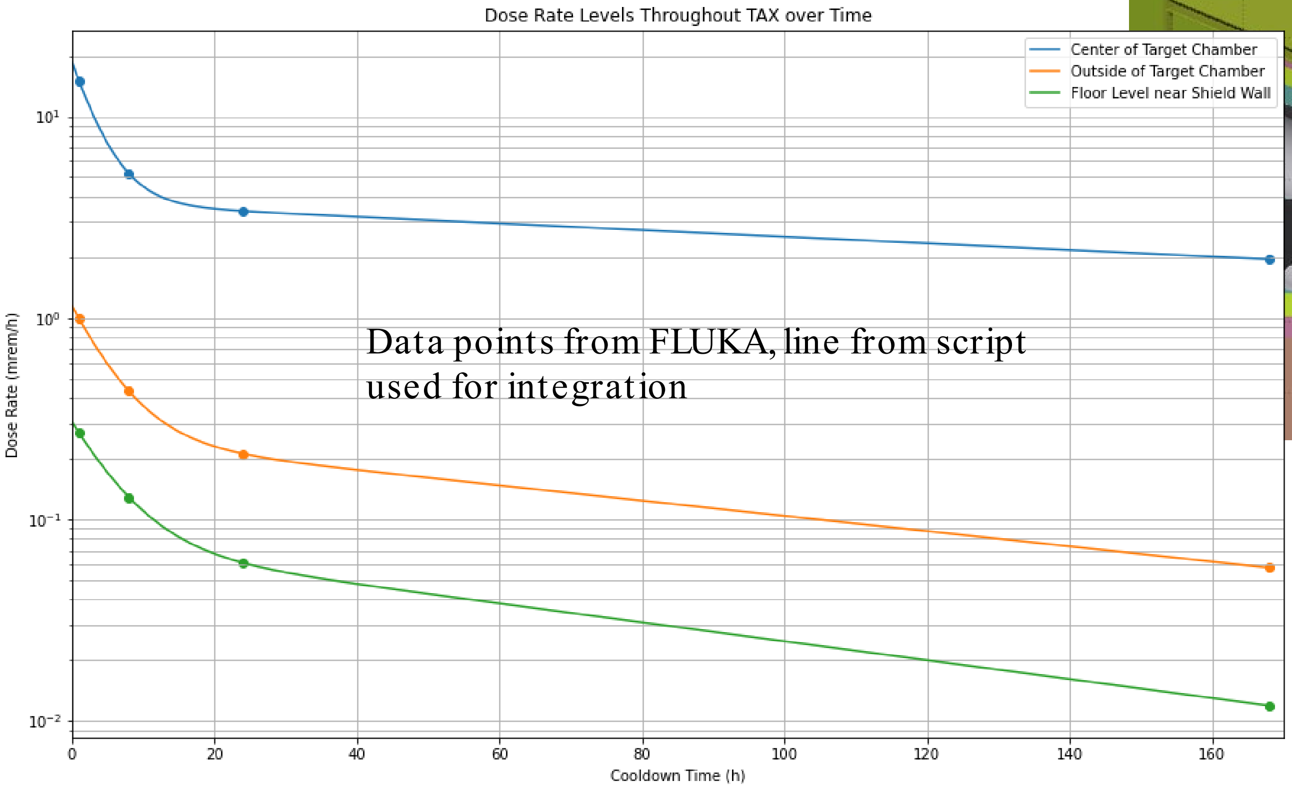


Dominant proton source term only

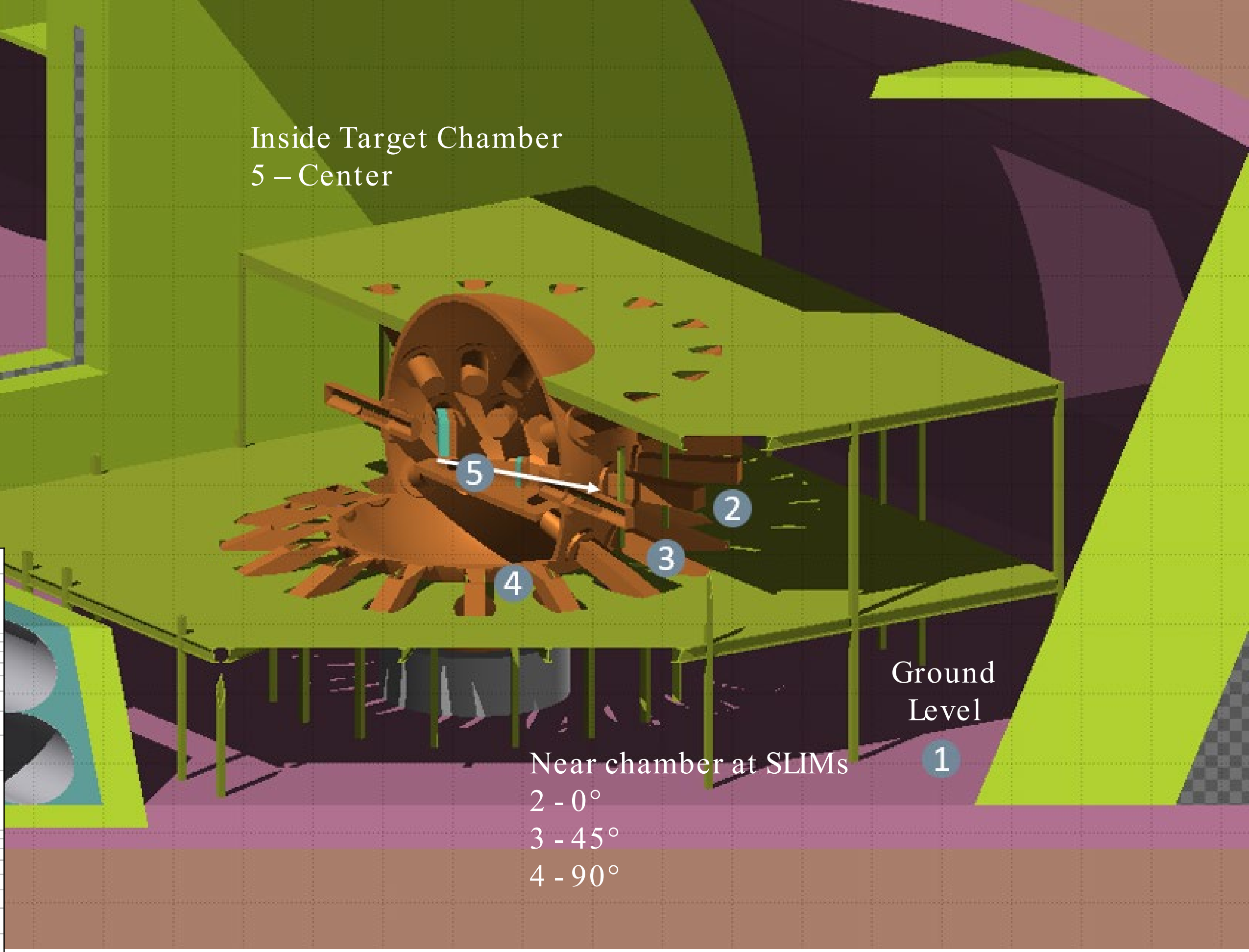
Dose to Personnel (1)

Simulations of activation

- Various points in hutch
- Various times after beam stopped



Data points from FLUKA, line from script used for integration



Inside Target Chamber
5 – Center

Near chamber at SLIMs
2 - 0°
3 - 45°
4 - 90°

Ground Level

Combine with estimates who will be where when

- Script interpolates between points
- Integration of dose

Dose to Personnel (2)

Working with project to estimate

- Where personnel works
- How long they work there
- How long after beam stopped

→ determine pattern for experiment for instrument scientists, users, instrument technicians

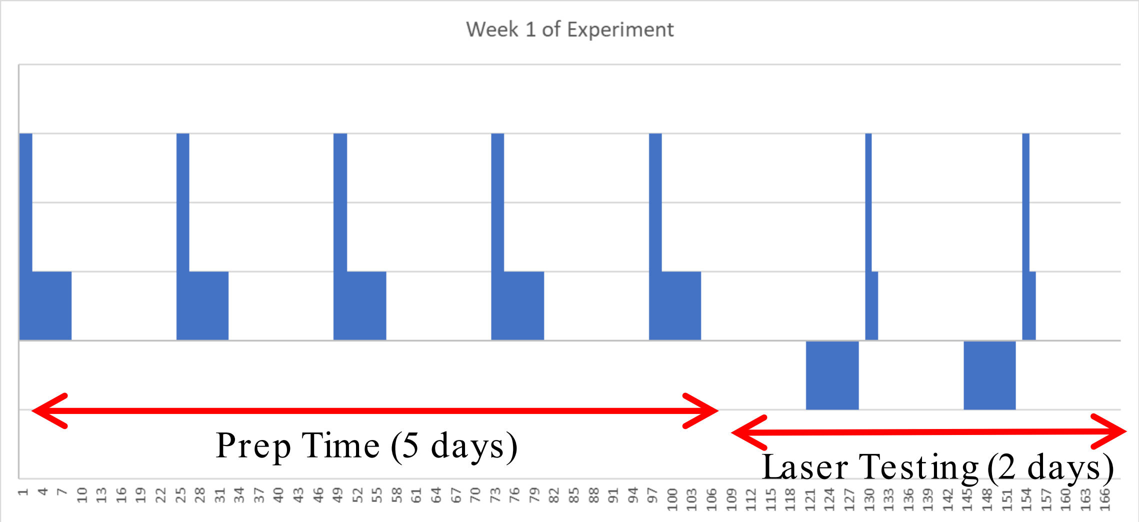
Still working out details

Caveats

- Estimated pattern only
- Assuming 10% of maximum number of shots
- Need to cover work on activated detector, optics, targets
- Need to cover work inside target chamber

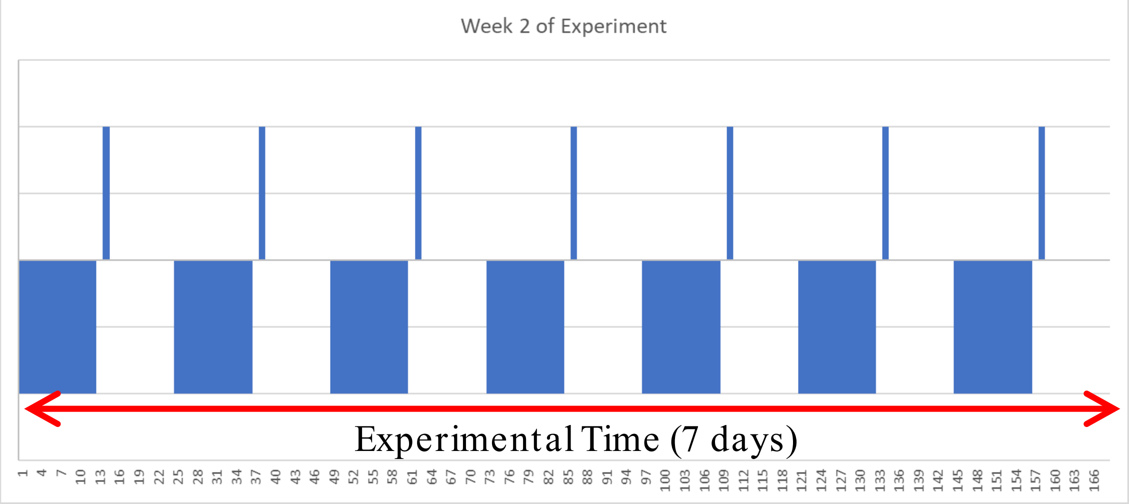
vertical axis indicates:

- beam operation
- cool-down
- location of work in hutch


Week 1 of Experiment

Prep Time (5 days)

Laser Testing (2 days)


Week 2 of Experiment

Experimental Time (7 days)

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Other Considerations

HVAC / Exhaust / Ground Water

Air Activation

Dose to personnel low enough: With 1 hour cool-down, DAC < 1

Dose to public low enough: With < 0.1 mrem/year for maximum exposed individual no need for continuous air monitoring

Exhaust

Possibility for activated target material pumped out → require HEPA filters

Ground Water

Water in activated soil and concrete

Main activation from laser light going east, colinear with FEL

Tritium o.k., Na-22 requires more detailed analysis

Access Control, Laser Control, Radiation Monitors

Access Control

Hutch access only with

- X-ray FEL stopped
- and laser hazards off

Laser Hazard Control: prompt radiation hazards off during access

Options:

- attenuate laser light (like at MEC)
- turn off amplification during access
- only use small alignment laser

Radiation Monitors

- Interlocked Prompt Radiation Monitors outside
- Interlocked Residual Radiation Monitors inside hutch

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Schedule and Outlook

Schedule

Lots of Work left

- Decision on shape of cavern coming within weeks
- Final Design Review Fall 2024
- Construction starting 2025
- First Light end of 2027

Additional Changes

- Deferred scope: Operation in TAO hutch
- Possible Multi-kJ laser
- Possible operation of second short-pulse Laser
  (only few experiments, same irradiance)

Thank You