High-Irradiance Optical Lasers: Radiation Hazards and Controls

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Introduction

- Previous Presentation
  Measurements from MEC Short-Pulse Laser at LCLS
- **This Presentation**
  Protocols to evaluate hazards and develop controls
  Examples of hazards and controls for MEC + future PW facility
  for solid, gas, and liquid targets

- Lasers are "cheap," used for variety of purposes
  >150 Laser Systems at SLAC, about 10 with short pulses >20 mJ
- Hazard only from specific lasers
  Compressor (fs pulses) and focusing optics (microm spotsize)
  with vacuum chamber

Classification as Radiation Generating Device

SLAC

From when on are radiological controls needed?

S10 Laser

5 mJ, 120 Hz

→ restricted to 10^{16} W/cm^2

50 mJ (this summer)

→ up to 5×10^{18} W/cm^2

MEC Laser (LCLS)

4 TW:	150 mJ, 10 Hz
25 TW:	1 J, 5 Hz
200 TW:	8 J, 1 shot / 8 min

Future PetaWatt Facility (LCLS)

1 PW:	200 J, 1 shot / 1 min
10 PW:	2000 J, 1 shot / 1 min

Classify as **Radiation Generating Device (RGD)** if

- capable of reaching 10^{16} W/cm^2,
- shooting on target (including gas) in vacuum,
- and using focusing optics

Three Types of Experiments

- Solid Targets:
  - Metals (Au, Cu, Ni, *etc.*); plastics
  - Mainly study of Matter in Extreme Conditions (warm dense matter like in Jupiter, confinement for NIF)
  - Also proton acceleration

Hot electrons to MeV level creating Bremsstrahlung

Protons up to 100s of MeV

- Liquid (Frozen) Targets
  - Stream of Liquid H_2, D_2, *etc.*, freezes in vacuum
  - Main goal ion (proton) acceleration
- Gas Targets
  - Few mm to tens of cm long gas cells; gas jets (puffs)
  - Mainly electron acceleration with X-ray generation

Laser Wakefield Acceleration of electrons to a few GeV

Photons at 100s of keV

Protocol to Determine Controls

(1) Ask about laser parameters and targets

- Laser energy, duration, focusing lens

  → source term for electrons, protons

(2) Ask about use factor

- Number of shots in experiment
- Number of shots in 1 hour
- Not used continuously, rather shots in clusters

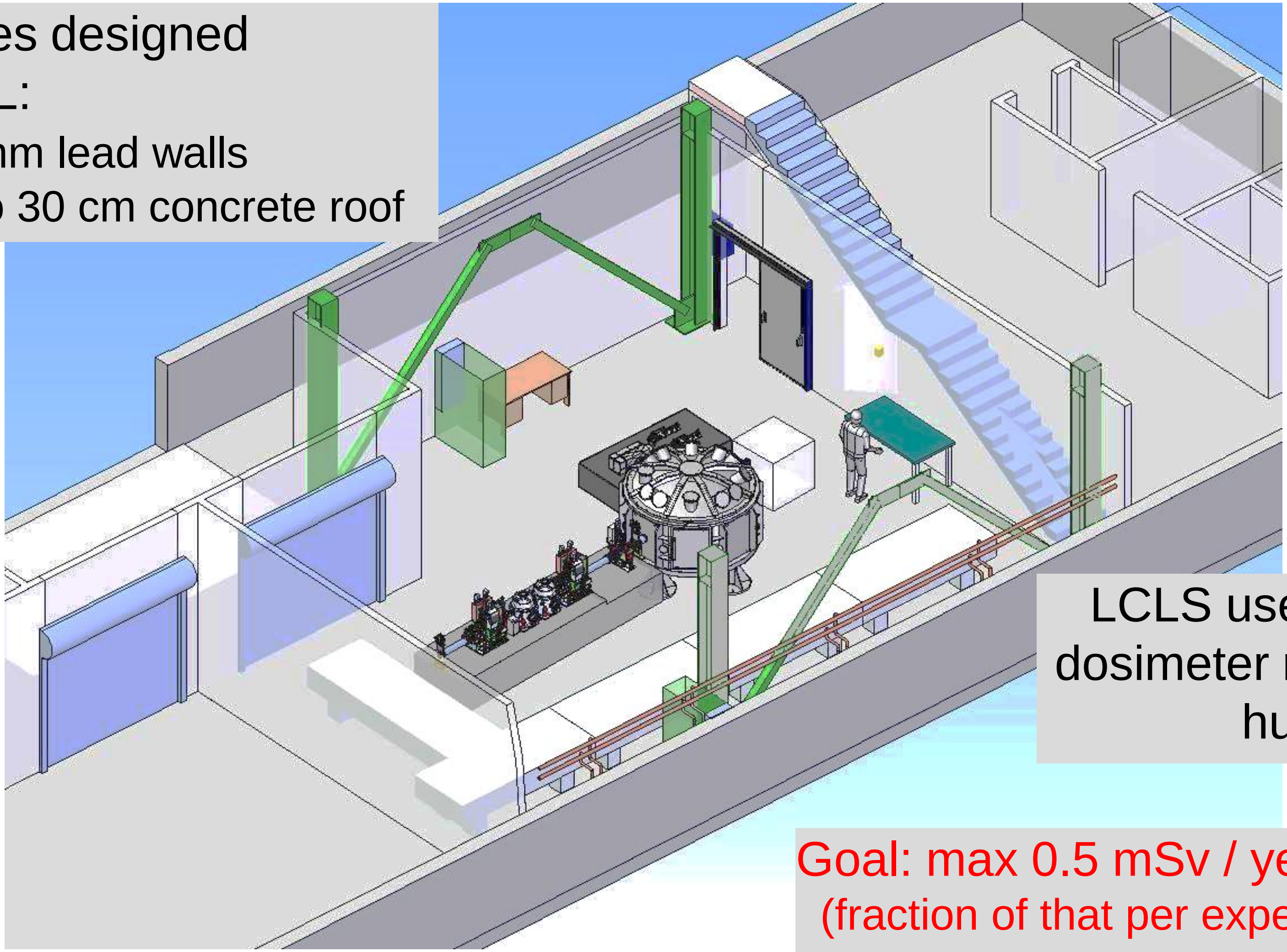
  → few day experiment can have all shots in just a few hours!

(3) Require controls

- Shielding
- Attenuators
- Radiation Monitors
- Access Controls
- Administrative Controls

Challenging Environment at LCLS

Hutches designed for FEL:
1.6 mm lead walls
10 to 30 cm concrete roof



LCLS users without dosimeter right outside hutch

Goal: max 0.5 mSv / year
(fraction of that per experiment)

Bulk Shielding

- Bulk shielding:
  - Concrete/lead bunker permanently installed
  - Concrete hutch walls, concrete/steel/lead doors

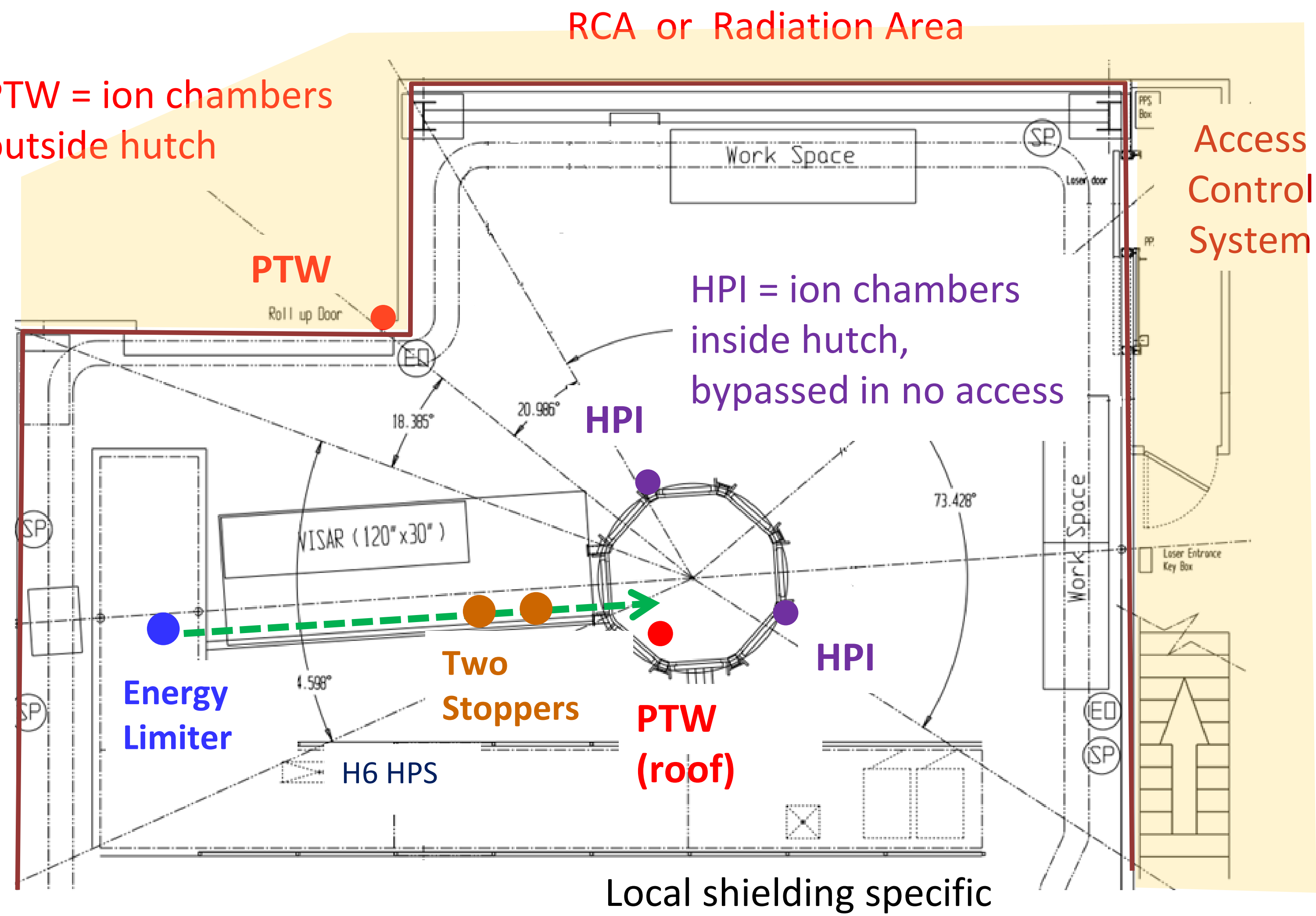
    → Independent of experiment = preserves flexibility, but very expensive investment

Gemini at RAL:
~1 m concrete,
steel door

2x15 J in 30 fs
10^{21} W/cm^2

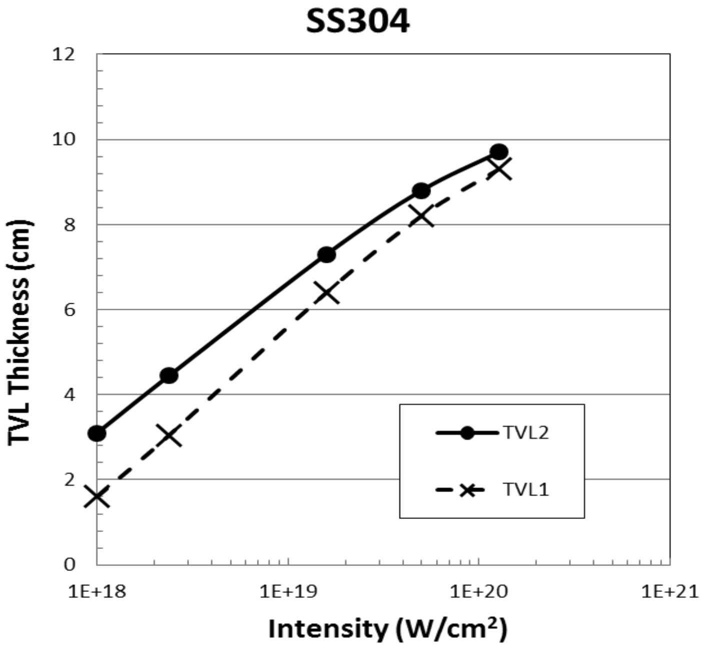
1 shot/min

Controls at MEC



Local Shielding

- Local shielding
  - Low irradiance: Target chamber sufficient,
  - High irradiance: Local shielding inside or outside target chamber,
    (e.g., ~12 cm steel in forward and backward directions, 1 inch tungsten plates)

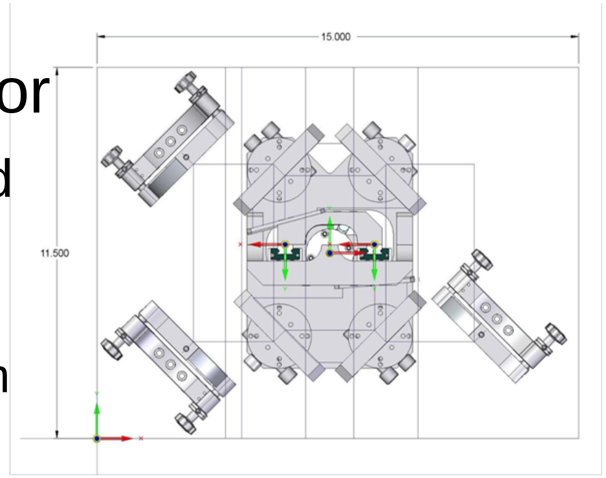


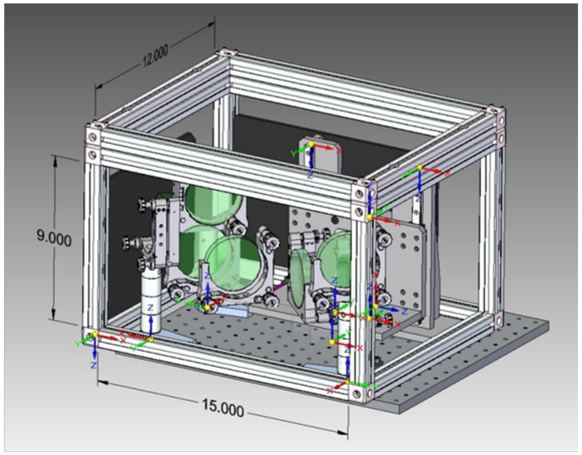
→ Cost (analysis, engineering for specific experiment, material cost)
Restrictions on experiment (direction, placement of diagnostics, flexibility)

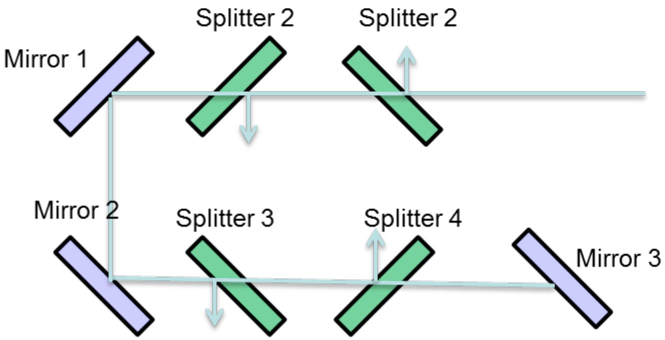
Energy Control

- Fixed attenuator: locked with Safety Office lock
  (*e.g.*, polarizer/waveplate/polarizer, mirrors, beam splitter)
  → Limit to low irradiance, robust, but limits experiments

- Moveable attenuator
  Automatically inserted in access
  → Needs interlock with Access Control System







Splitter	20% Transmission
Mirror	100% Reflectivity

Energy Transmission	$0.2^4 = 0.16\%$
Phase 1	1 J x 0.16% = 1.6 mJ
Phase 2	8 J x 0.16% = 13 mJ

Access Control System and Detectors

- Radiation Monitors

- Access Control System

  MEC connects to existing ACS for FEL

    Inserts stoppers on radiation

    Requires stopper or attenuator in during access

Administrative Controls

- Control on optics: administrative, safety officer countersigns
  (allow only longer focal lengths, or require measurement of beam spot)
  → Limits experiments, administrative only

- Limits on shots
  → Engineering limit difficult to implement:
  shots in air, without target don't count against quota

- Posting

  Radiologically Controlled Area or Radiation Area

  → Users don't like Radiation Worker Training,
  Users without dosimeters in vicinity (LCLS!),
  High doses/dose rates never desired

Solid Targets: Expected Dose Yield

Conservative estimate of yield, checked against measurements

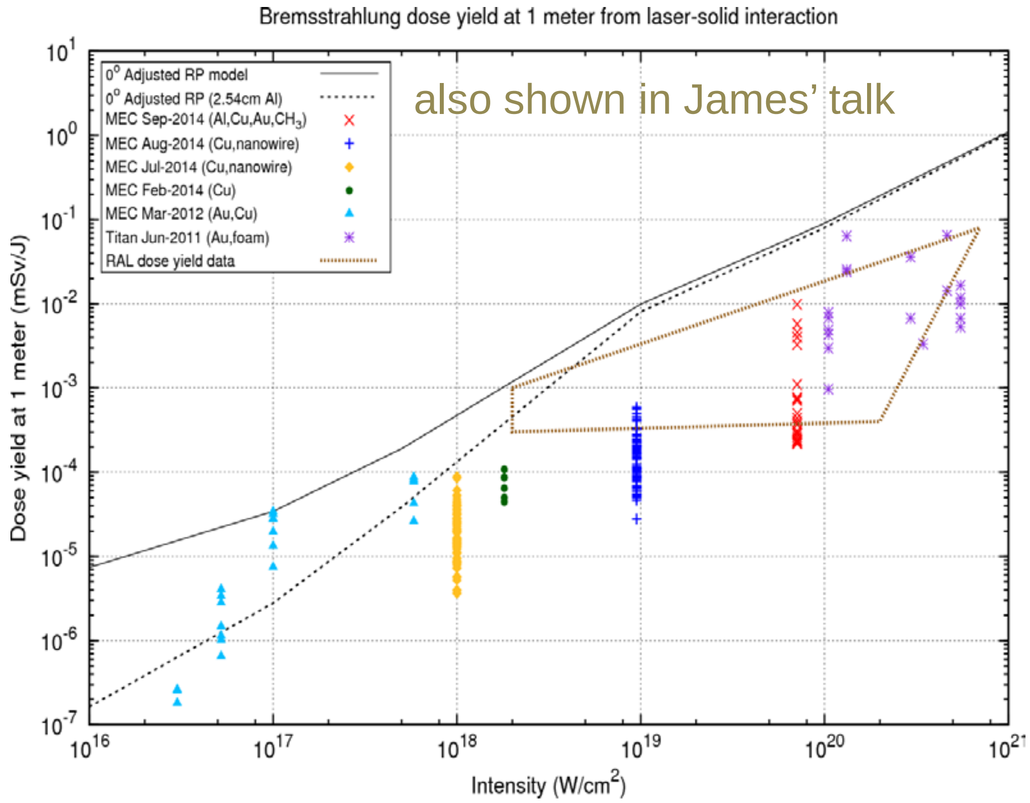
Used to estimate dose
in 1 hour and in experiment

Rough example of 'exponential' rise:

If pulse energy 10x higher:

- 10x higher dose yield
- 10x more energy in pulse
- (at low irradiance) 10x less attenuation by target chamber

→ 100x to 1000x increase in dose



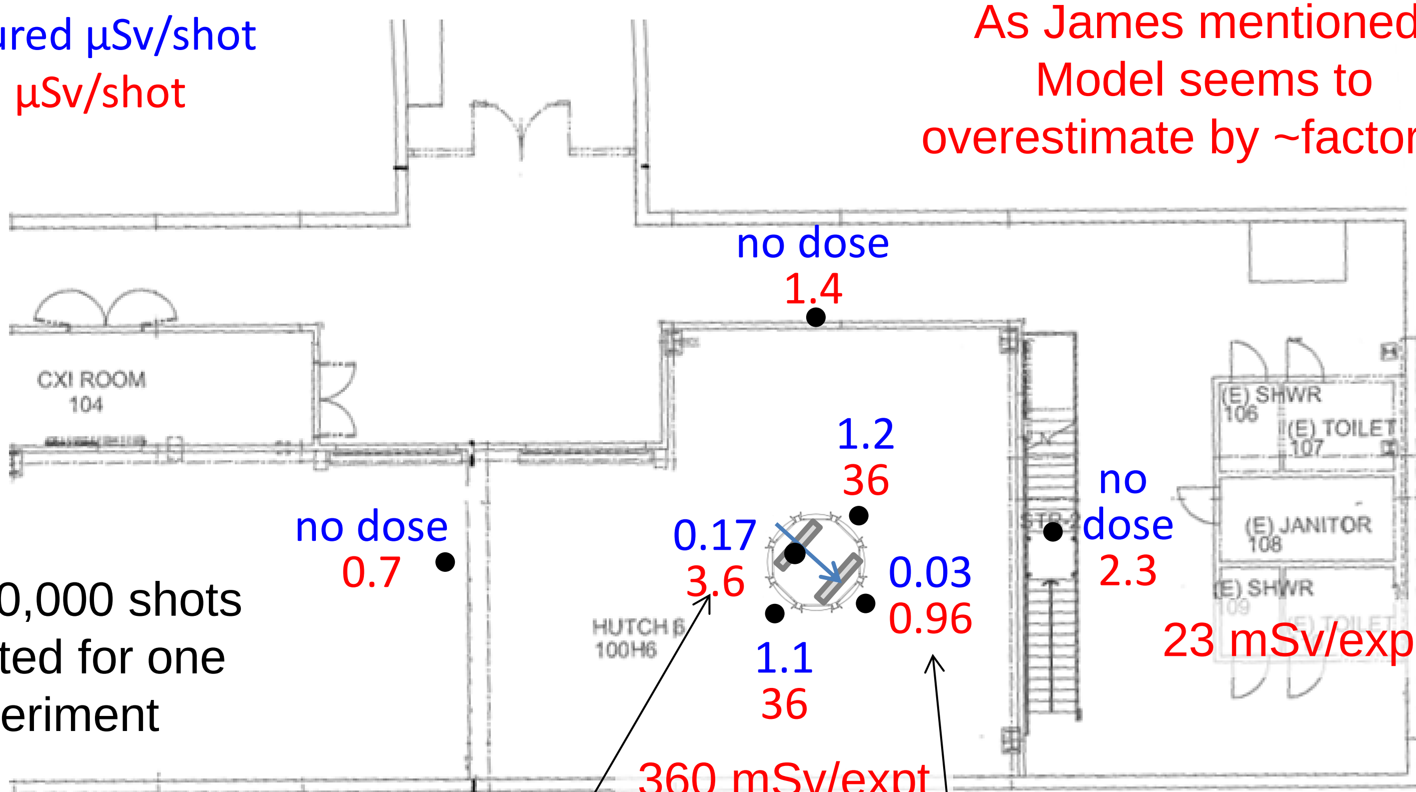
Solid Targets: at $7x10^{19}$ W/cm^2

25 TW: $7.1x10^{19}$ W/cm^2, 0.5 J in 50 fs on solid target

Measured μSv/shot

Model μSv/shot

As James mentioned:
Model seems to
overestimate by ~factor 10



Up to 10,000 shots estimated for one experiment

this location above target chamber

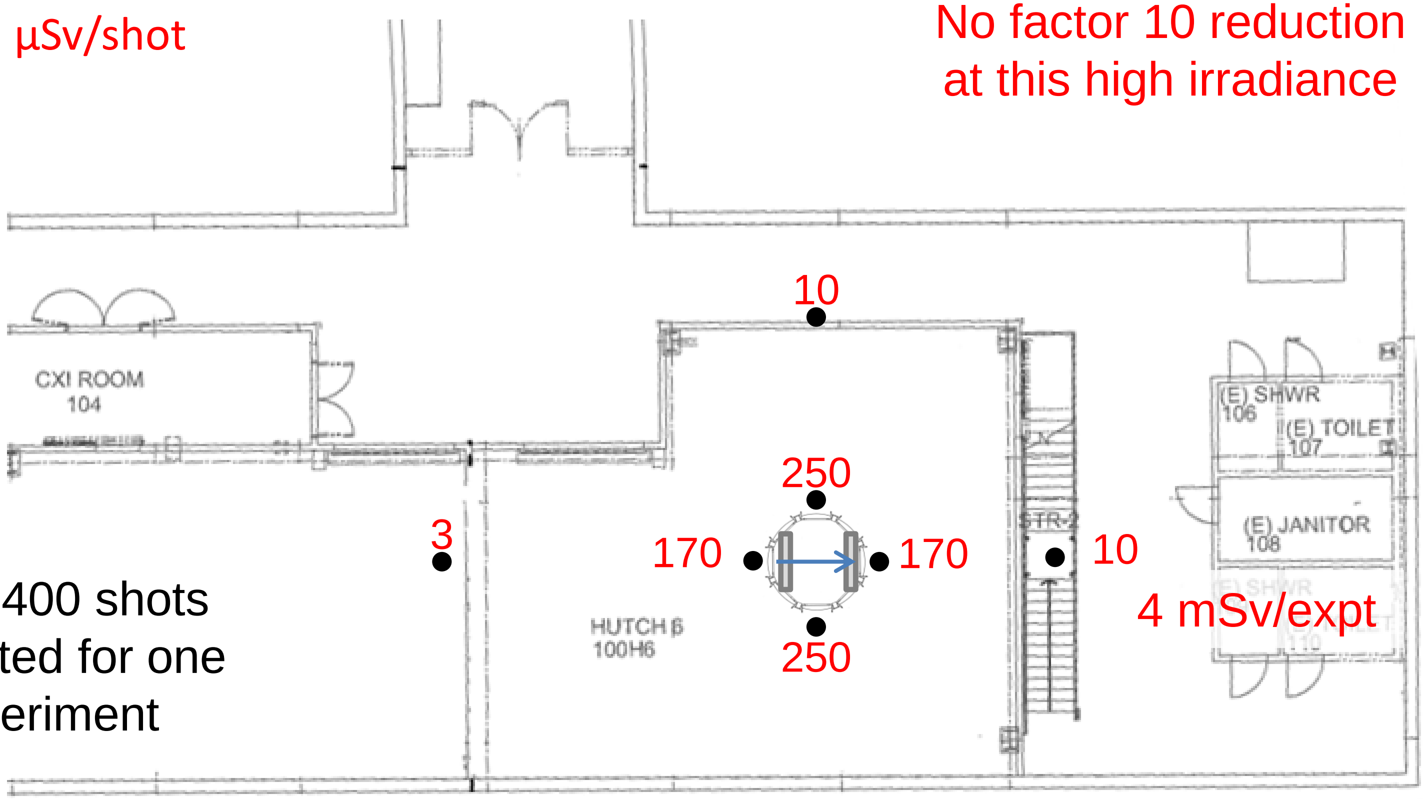
this location shielded locally by 12 cm steel

Solid Targets: at 10^{21} W/cm^2

200 TW: $\underline{10^{21}}$ W/cm^2, 8 J in 40 fs

Model µSv/shot

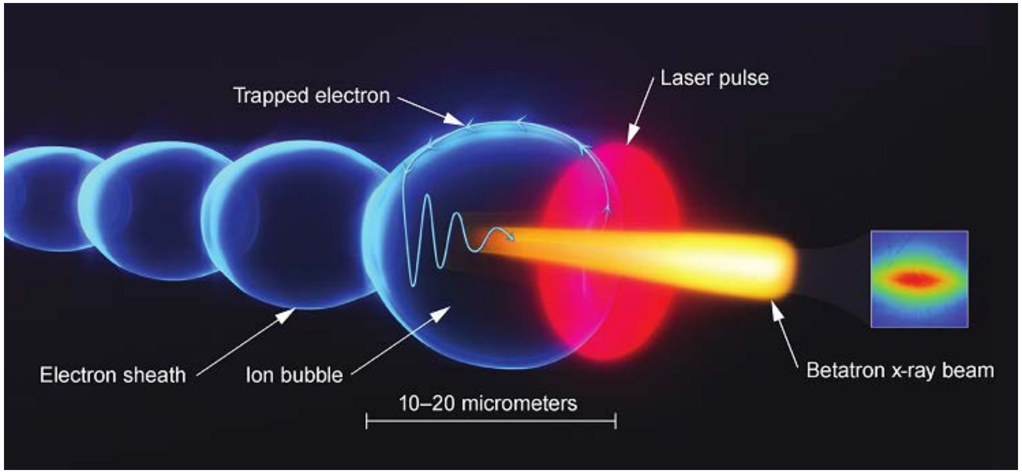
No factor 10 reduction at this high irradiance



Up to 400 shots estimated for one experiment

Gas Targets: Experiments

At higher irradiance usually Laser Wakefield Acceleration (LWFA)



→ electron acceleration
→ Betatron oscillation in electric field
→ short-pulse X-rays used in experiments

At other facilities: often only at low rep rate (minutes between shots)
At MEC: at high rep-rate (upcoming experiment 0.1 Hz)

Gas Targets: Source Term

Experimenters themselves want to characterize beam
→ measurements of electrons and X-rays exist

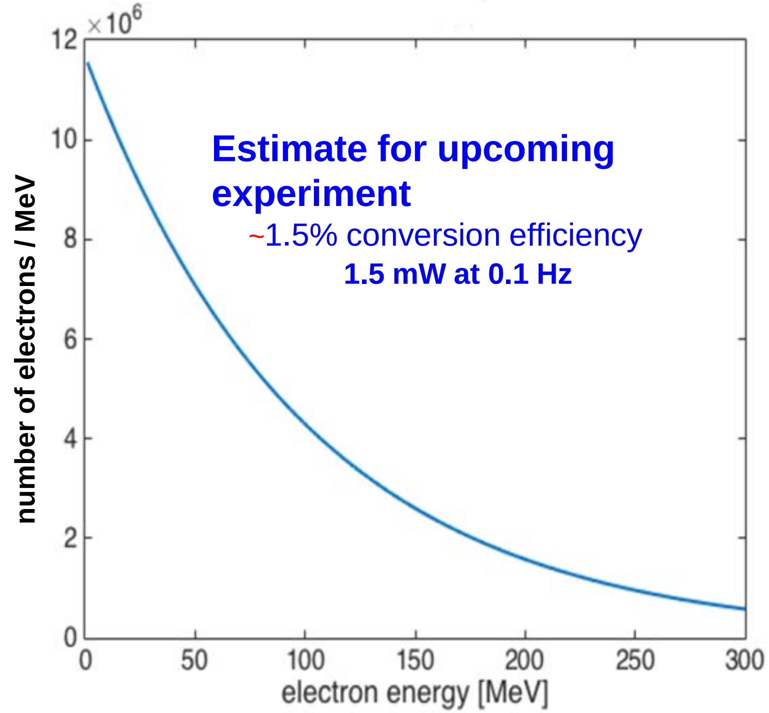
X-rays similar to FEL, but weaker = hutch wall sufficient

Electron source term from experimenters:
"conservative, not implausible"

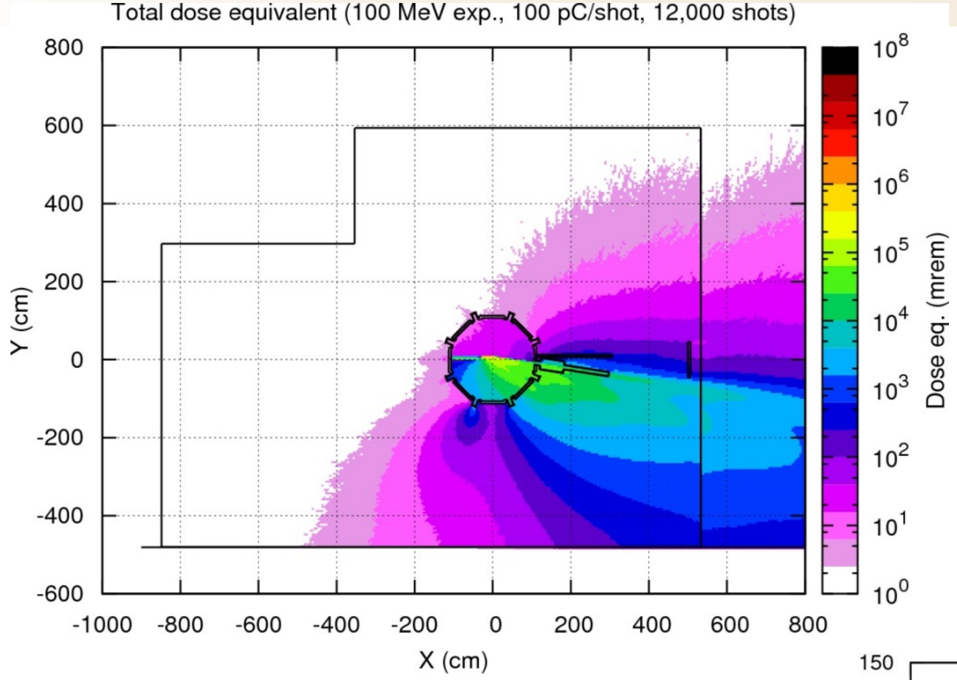
Experimental spectrum
30 TW laser
LOA – Salle Jaune

Spectrum used for 2014 experiment

~ 1% conversion efficiency laser-to-electron energy
10 mW at 1 Hz



Gas Targets: FLUKA Simulation

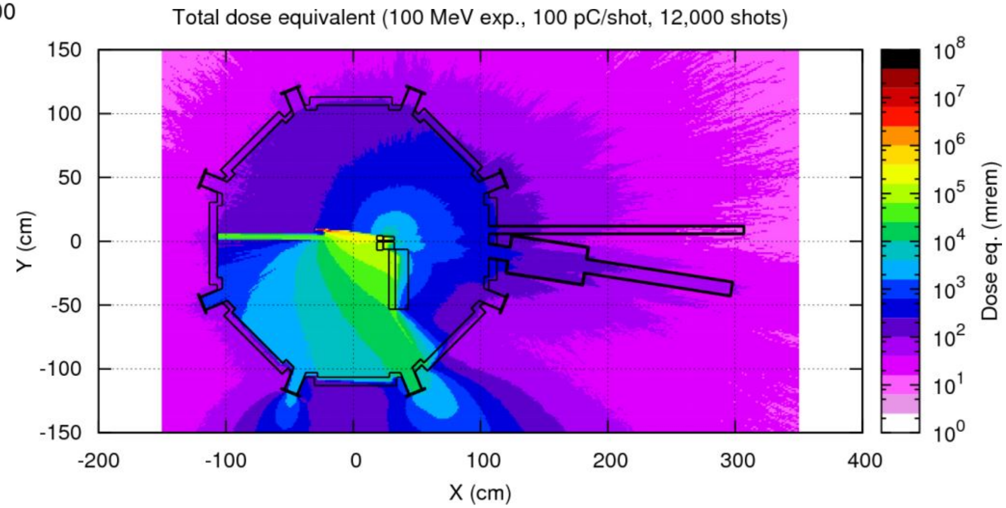


12,000 shots without shielding: up to 100 mSv outside hutch

Agreement with NCRP 144

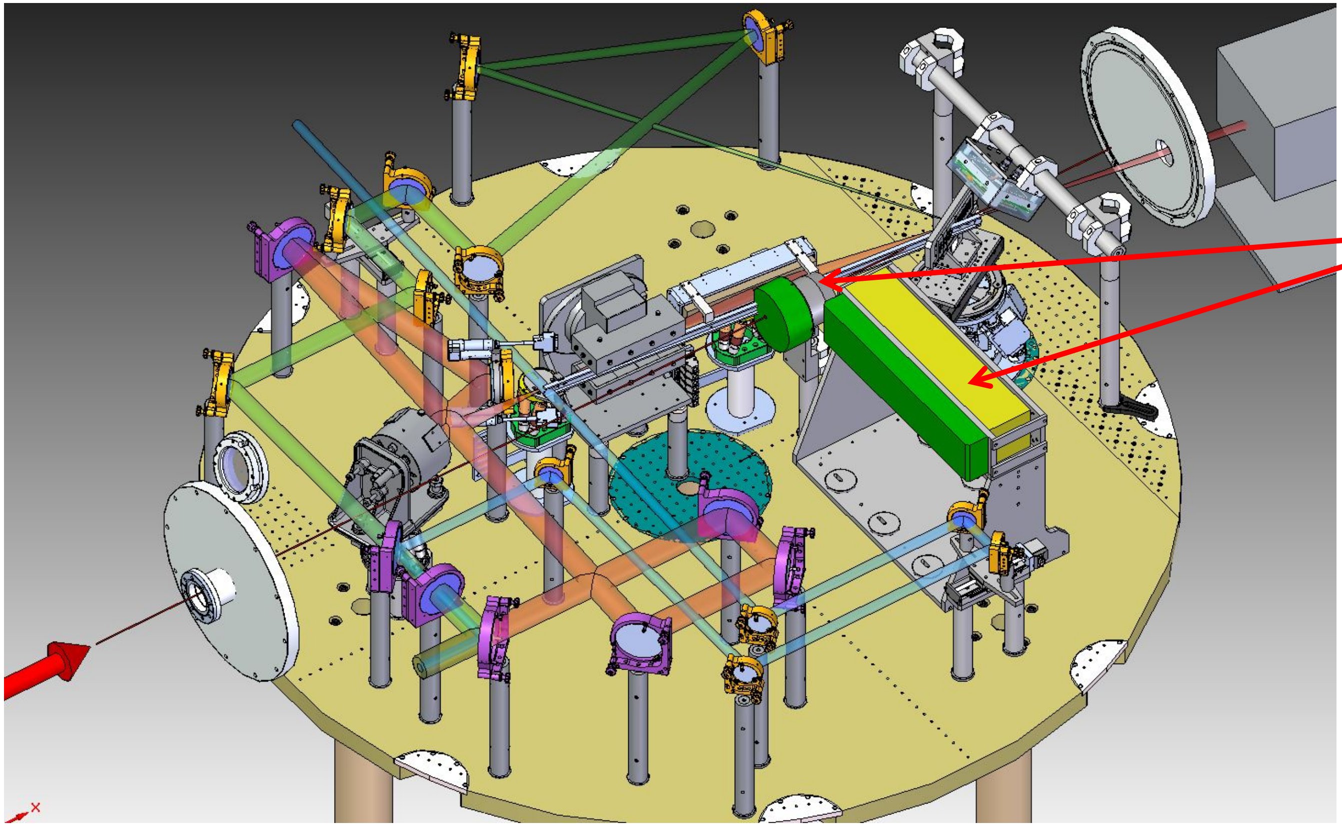
3 TVL = 10 cm lead
or 8 cm tungsten

~0.1 mSv maximal outside hutch



Gas Targets: Shielding

Upcoming Experiment: 1 J, 12,000 shots in few weeks



8 cm tungsten
10 cm lead

Shielding tightly integrated into experiment

→ Need substantial shielding, but only in forward direction

Liquid (Frozen) Jets: Hazards

SLAC

Focusing beam on stream of liquid hydrogen (or similar)

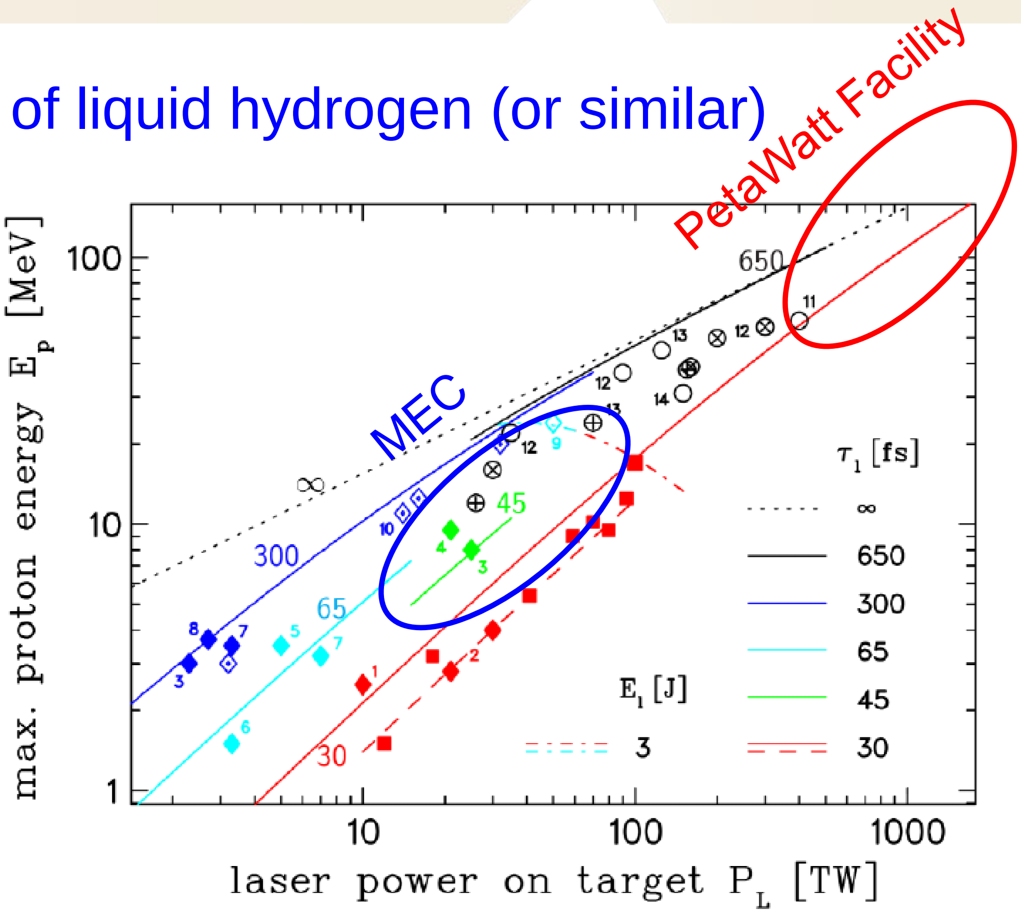
Protons:

- Ejected in forward direction
  1 J, 10^{20} W/cm^2: ~10^9 p/shot
  at ~7 MeV → negligible dose

Hot electrons: (dominant)

- Low Z → electron density low
  → dose yield at least 10x
  less than solid target

Jet operates continuously
→ high rep rate possible

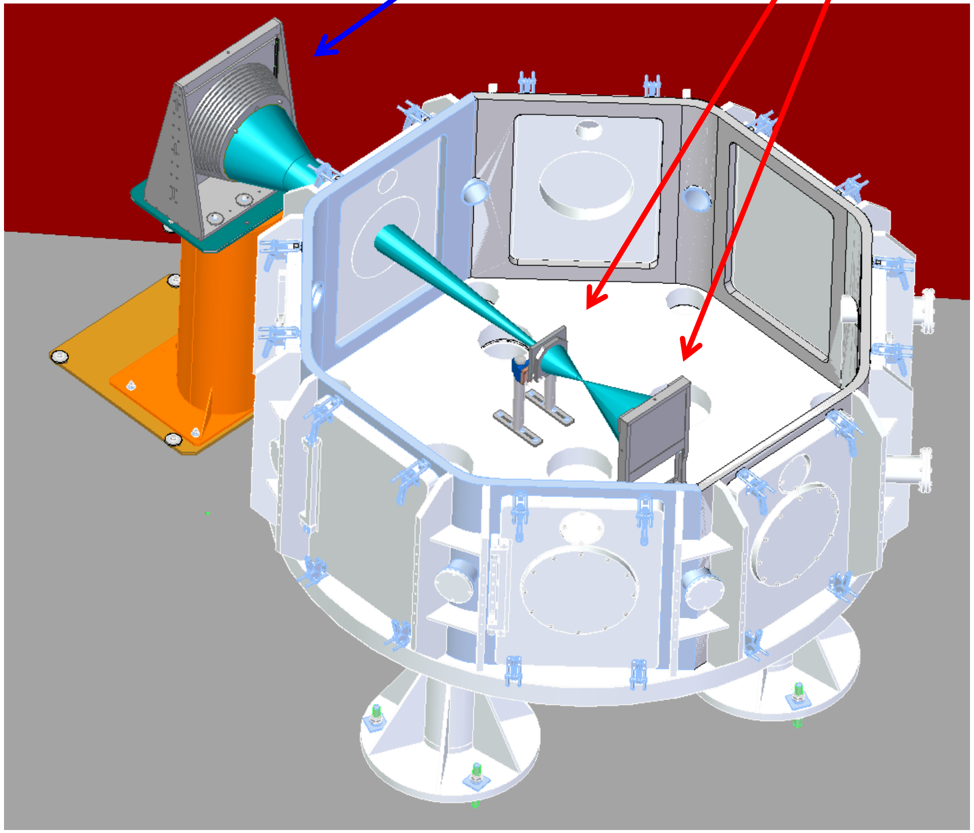


A. Macchi et al., *Ion acceleration by superintense laser-plasma interaction*, Rev. Mod. Phys. **85**, 751 (2013)

Liquid (Frozen) Jets: Experiments

MEC Laser with 1 J on LH_2 $5x10^{19}$ W/cm^2

- Assumed only 1/10 of solid target dose yield (but possibly even less)
- Local shielding installed
- Not measured any dose outside with LH2 (experiment challenging)
- Up to 400 mrem/h at target chamber with solid targets



PetaWatt Laser Facility at LCLS

Input from Siegfried Glenzer

Laser Power (10 PW)	Non-Acceleration	Proton Acceleration	Electron Acceleration
Target type	solids, liquids	Liquid H_2	He gas cell
Max laser intensity (W/cm^2)	$6.4x10^{21}$	$1.6x10^{23}$	$6.4x10^{21}$
Pulse energy (J)	2000	2000	2000
Pulse duration (fs)	20 to 2e7 (200 used)	200 – 1000 (200 used)	200
Min $1/e^2$ radial spotsize (µm)	10 – 1000	2	10
Max repetition rate (Hz)	1 shot/min	1 shot/min	1 shot/min
Dose per shot at 1 m (mSv/shot)	10^3	$6.1x10^2$	$2.1x10^3$
Total number of shots per year	9600	500	1000
Dose in 1 year at 1 m (mSv)	10^7	$3.1x10^5$	$2.1x10^6$
Number of TVL needed for 0.5 mSv per year dose goal at 5 m	6	4.5	5

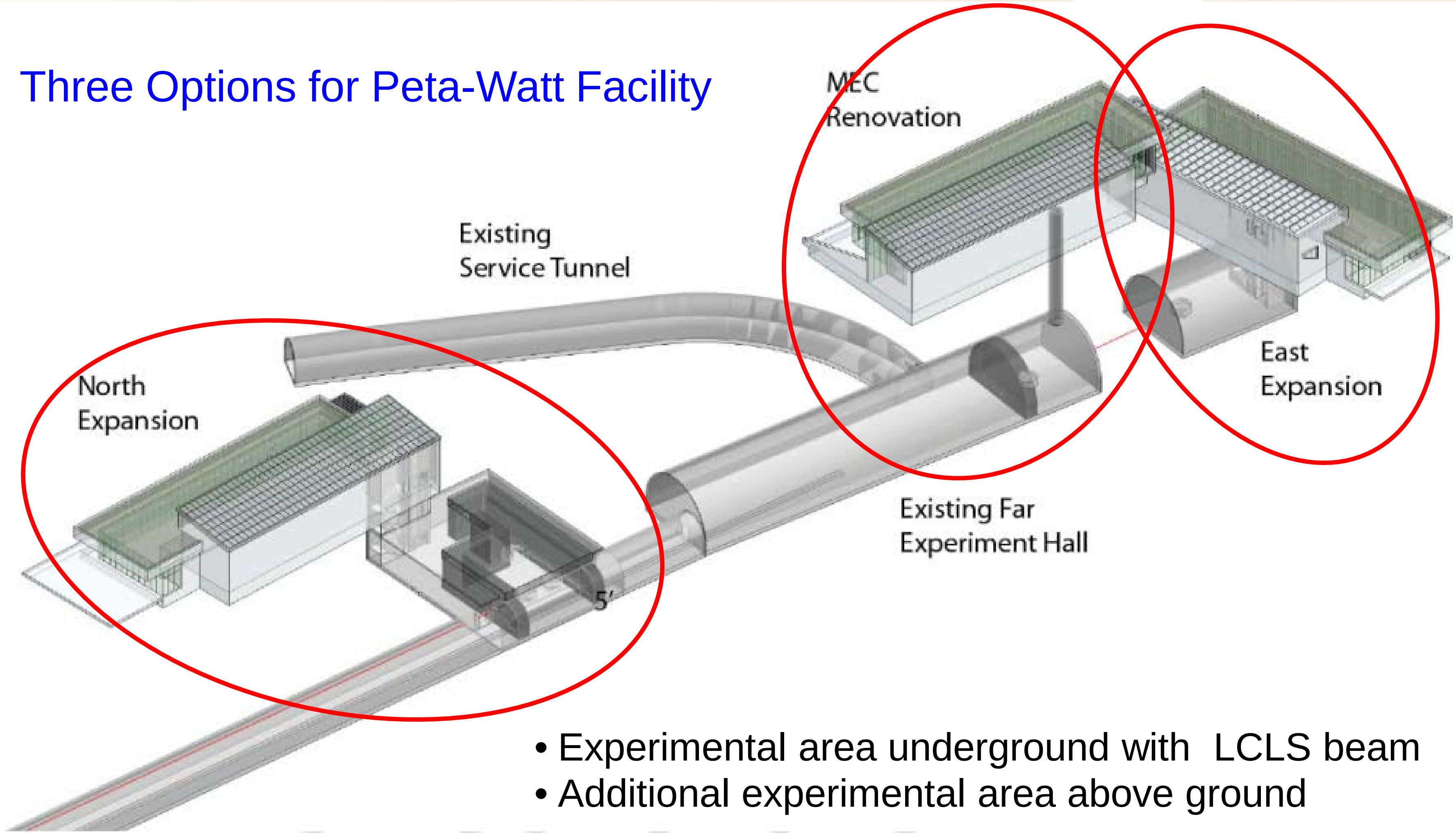
Likely conservative

2.4 m concrete or
0.66 m steel + 0.5 m polyethylene

also needs beam dumps

PetaWatt Laser Facility at LCLS (cont.)

Three Options for Peta-Watt Facility



- Experimental area underground with LCLS beam
- Additional experimental area above ground

Conclusion

- Short-pulse Laser capabilities at SLAC increasing:
  - From few mJ up to kJ level + increasing rep-rates
  - First 200 TW experiment this summer
- MEC hutch was built for FEL

  → nearly no shielding for radiation from laser-target interactions
- Several experiments now each year at MEC
- SLAC RP developed protocol to determine hazard mitigations
  - Studied the source terms, compared with measurements
  - Hazard analysis based on laser and target parameters
  - Use experimenter's estimate of number of shots
- Depending on experiment, combination of engineering controls, radiation monitoring, administrative controls
- New PetaWatt Laser Facility to be built with Radiation Protection in mind