Radiation Safety at LCLS:
Maximum Credible Beam, B4C Damage Threshold, Configuration Control

Johannes Bauer , Alyssa Prinz, James Liu, Sayed Rokni

SLAC National Accelerator Laboratory

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

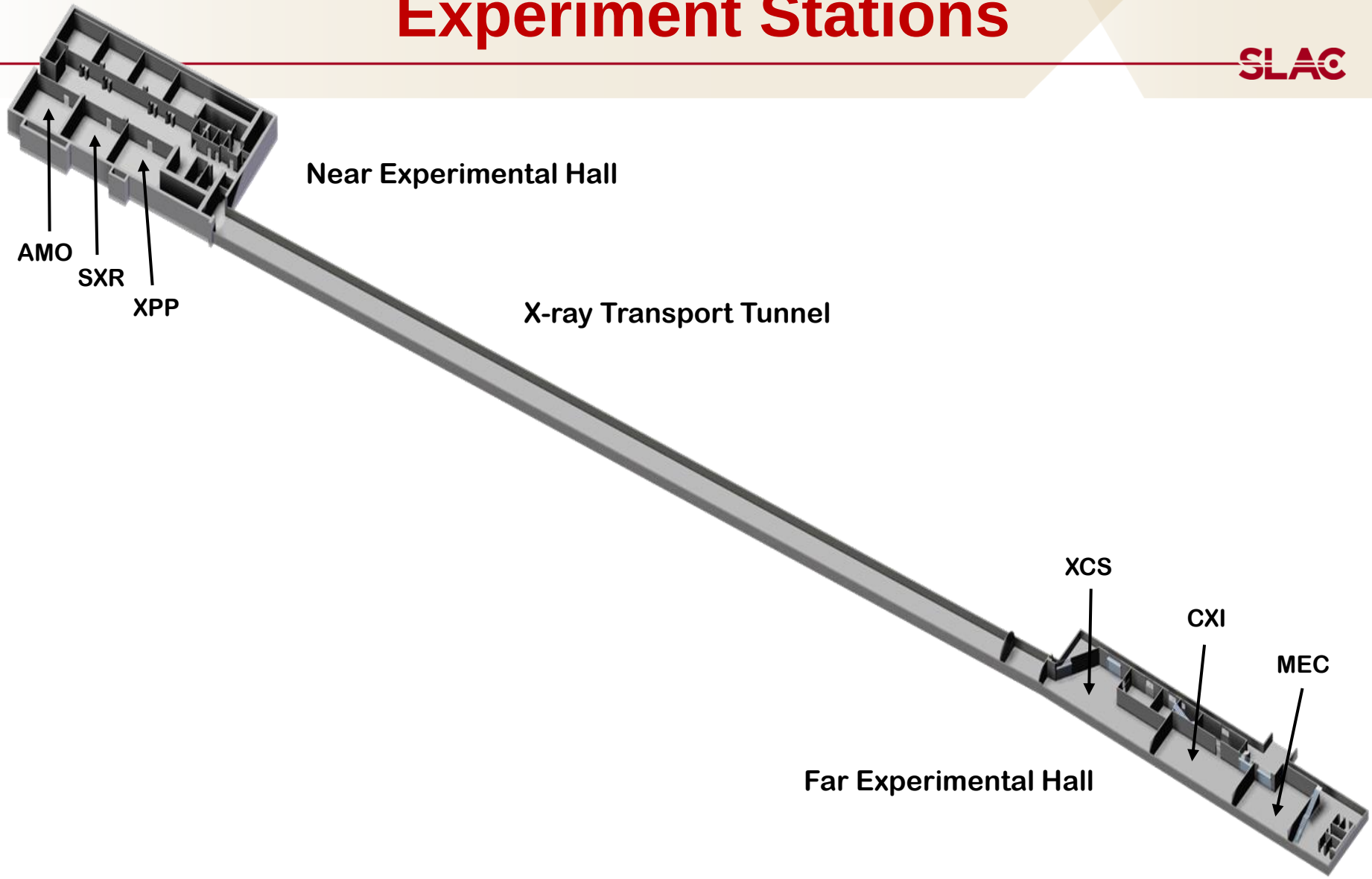
Linac Coherent Light Source (LCLS)

- Hard X-ray Free Electron Laser at SLAC National Accelerator Center
- 1 km e- Linac, 112 m Undulator
- Operational since October 2009

Photon Beam Parameters

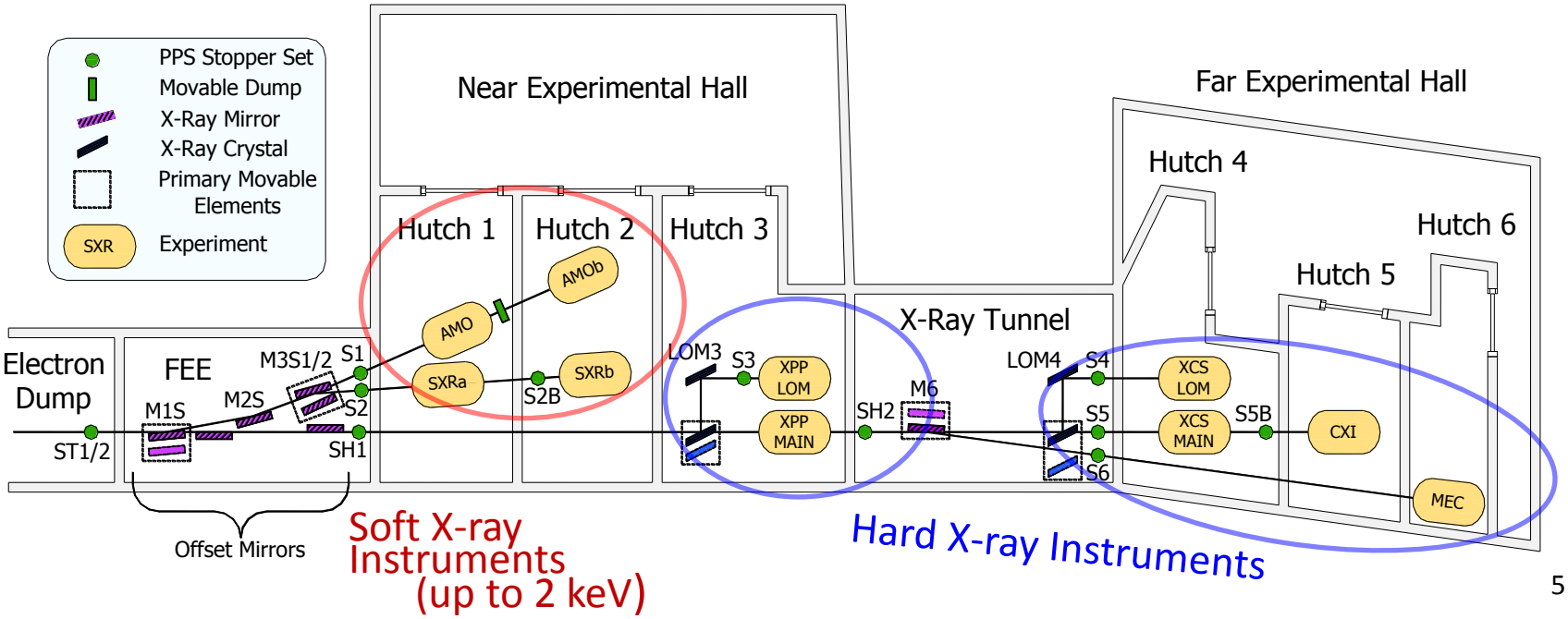
- FEL energy tunable 0.25 – 10 keV
- Spontaneous spectrum soft – 25 keV
- Pulse rate 120 Hz
- Pulse duration <10 – 500 femto seconds
- Beam width 1 mm (unfocused)
  to 1 µm (w/mirrors or Beryllium lenses)

Experiment Stations



Experimental Stations (cont.)

Beam pipes through occupiable areas



Beam Containment Challenges

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- Damage to Material
  - Unfocused beam burns through steel (vacuum chamber)
  - Focused beam burns through any solid
  - Ray trace, collimators, beam stoppers
- Mirrors & glancing-incidence crystals steer beam
  - Analysis of reflection, hard stops, etc.
- Crystals diffract beam (larger fraction at seeded beam)
  - No argument so far given that 'incredible'

    → special analysis

Beam Containment Challenges (cont.)

- For Damage to Material
  - Solution for Soft X-rays (<2 keV):

    Unfocused beam: Boron carbide ("B_4C")

    Build air gap into stoppers, into collimators

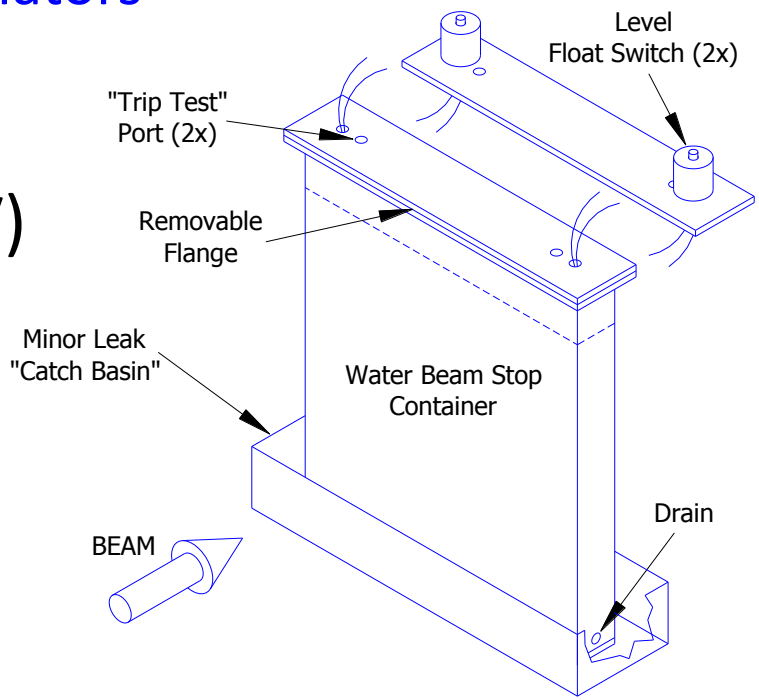
    But focused beam at Stopper S2B without air-gap
  - Solution for hard X-rays (> 2 keV)

    Unfocused beam: B_4C

    Focused beam: Water dump

    Diffracted focused beam:

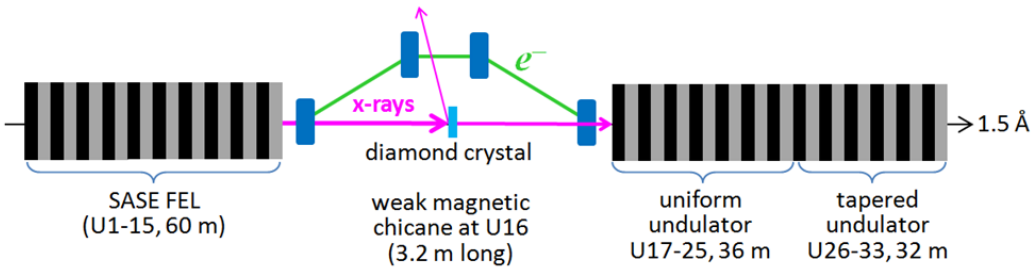
    Special analysis



Beam Containment Challenges (cont.)

Another Challenge: Hard X-ray Self-Seeding

- Chicane in undulator with thin diamond crystal



- FEL bandwidth reduced to below Si(111) bandwidth acceptance

  → crystal diffraction could redirect full beam

How Strong can Photon Beam be?

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"Maximum Credible Beam"

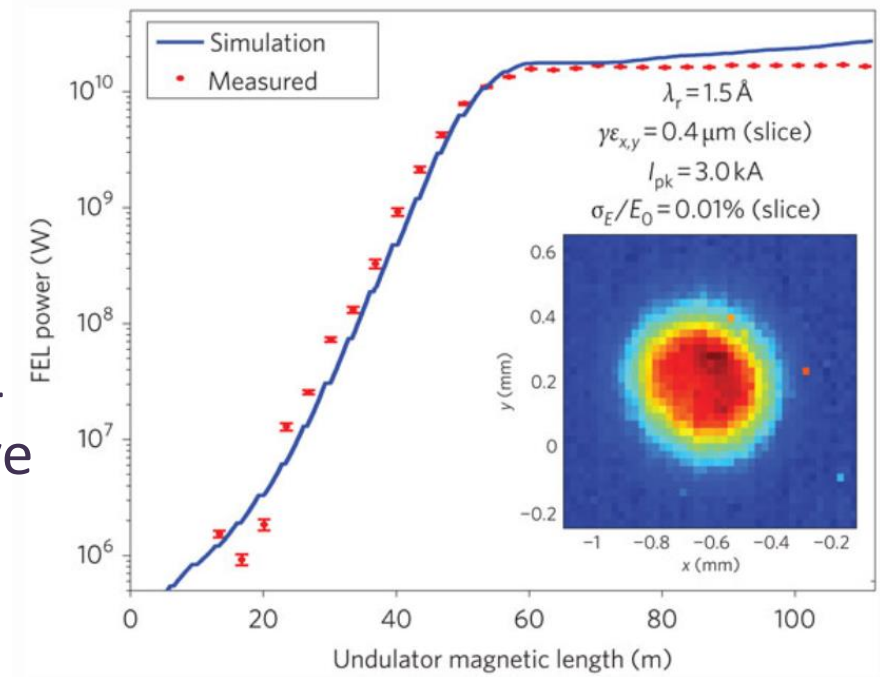
- What machine could in worst case do
- Since RP set no engineering limits on undulator settings: Photon MCB = allowed beam
- New ideas being tried out
- Cannot be too conservative
- MCB estimated from
  - Physics principles
  - Simulations
  - Operational experience

Analysis by Heinz-Dieter Nuhn (SLAC)

SASE MCB

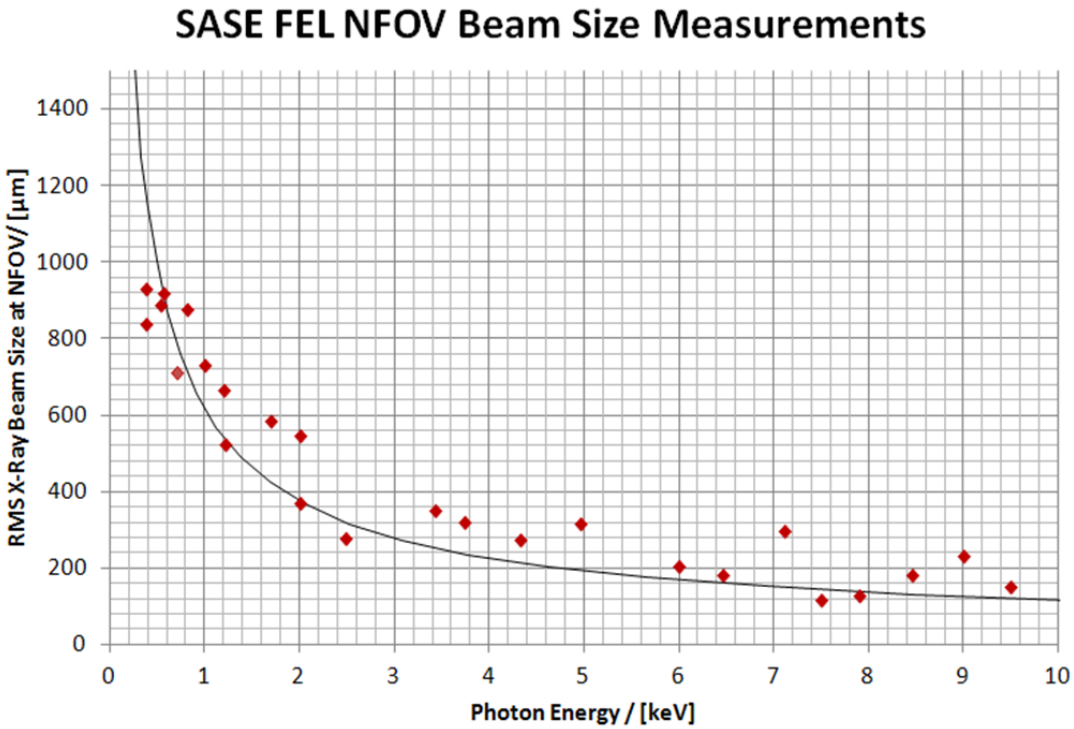
- Consists of
  - SR: Spontaneous Radiation, normal uncoherent undulator radiation (wide, no damage potential, but shielding needed)
  - SASE: Self-amplified Stimulated Emission = coherent FEL radiation (smaller in size, damage potential)

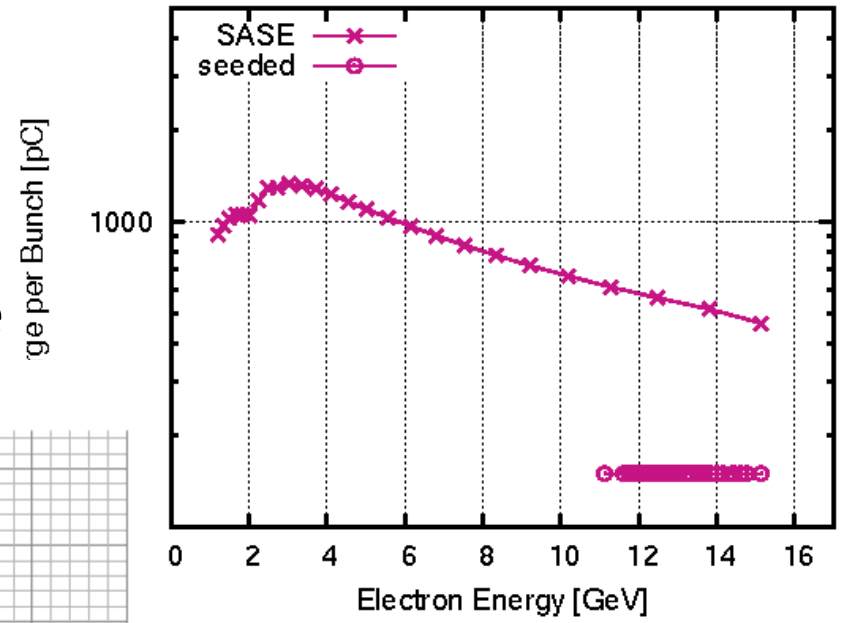
Normal FEL Gain Curve



SASE MCB (cont.)

- SASE Beam Size
  - Measurements consistent with simulations
  - Divergence difficult to measure

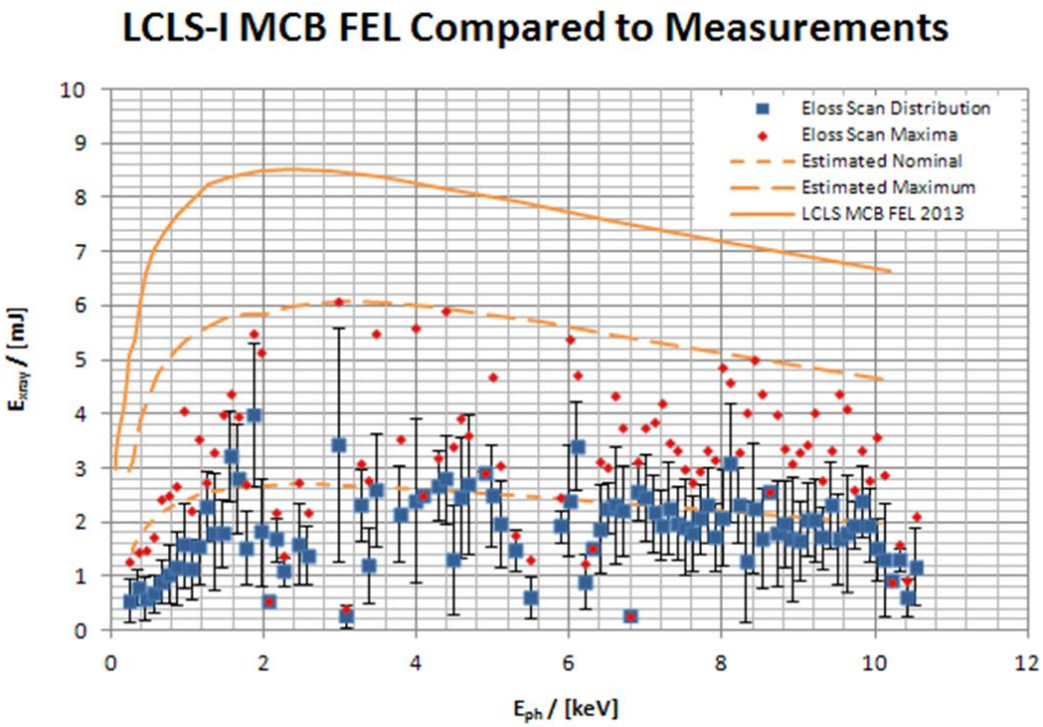




- Charge in pulse
  - Highest charge not giving most photons

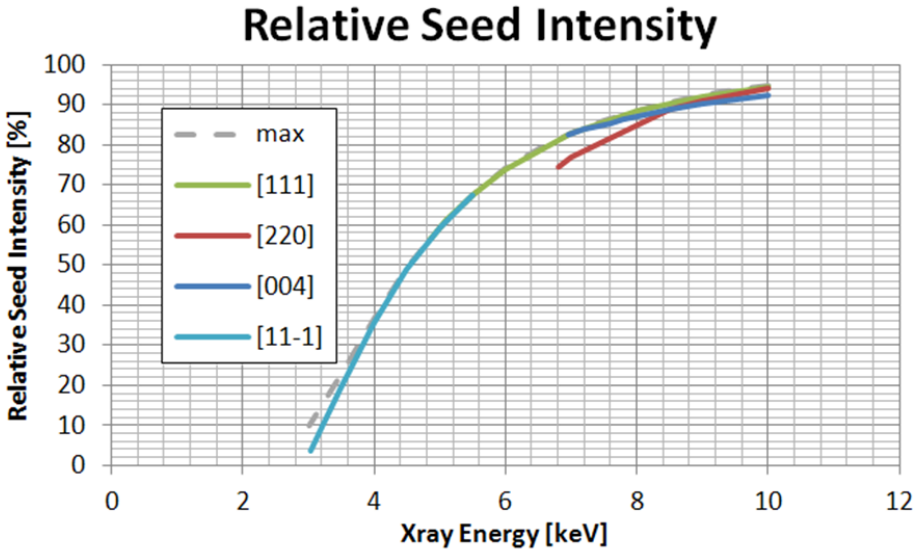
SASE MCB (cont.)

- Total energy in pulse
  - Measurements available (average & maximum)
  - Consistent w/simulations
  - MCB determined from those with 'reasonable' space to grow



Seeded Beam MCB

- Consists of
  - SR = Spontaneous Radiation
  - SASE FEL radiation
  - Seeded FEL radiation = stimulated emission by slice of seeding pulse (same size and divergence as SASE, but smaller bandwidth than SASE)
- Hard X-rays Seeded:
  - Earlier seeded beam "is not possible" < 5.5 GeV
  - Now "is possible" > 3 GeV
  - Overall power lower than unseeded SASE beam



Seeded Beam MCB (cont.)

- Soft X-rays Seeded
  - Starting end of year
  - SXRSS simulation 30% higher than SASE simulations

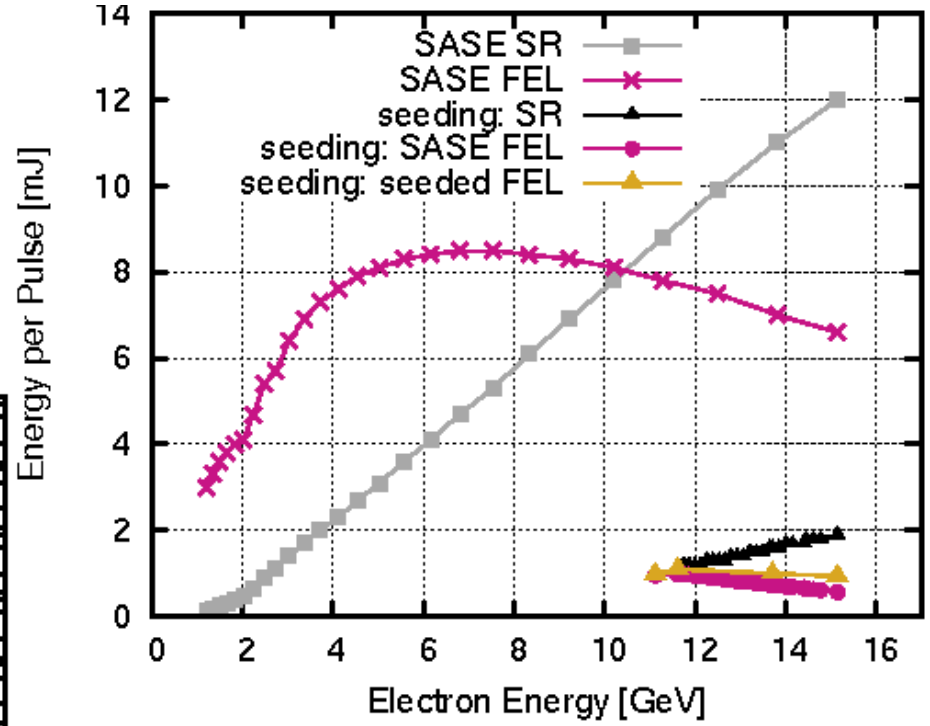
    → SXRSS MCB = 1.3 * SASE MCB

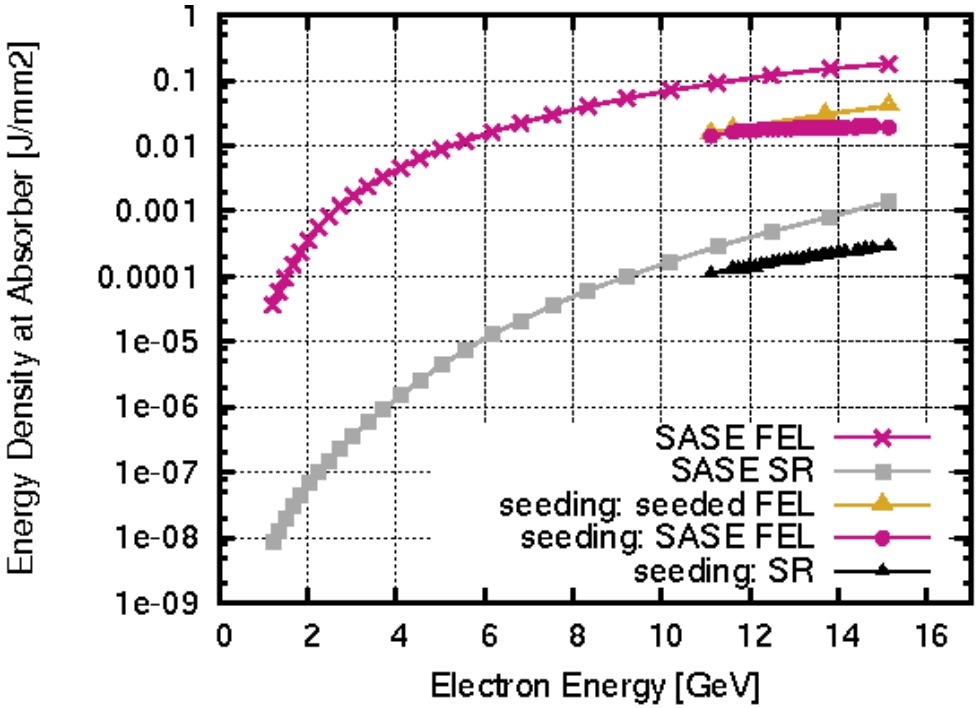
    + need to re-evaluate every year

- Special Cases: Two Color Beam, iSASE, …
  - Between SASE and Seeded, sometimes using seeding chicane
  - Always lower than MCB SASE or seeded beam
  - New ideas coming
  - With new hardware → all changes

Summary Plots on MCB

Energy per pulse →





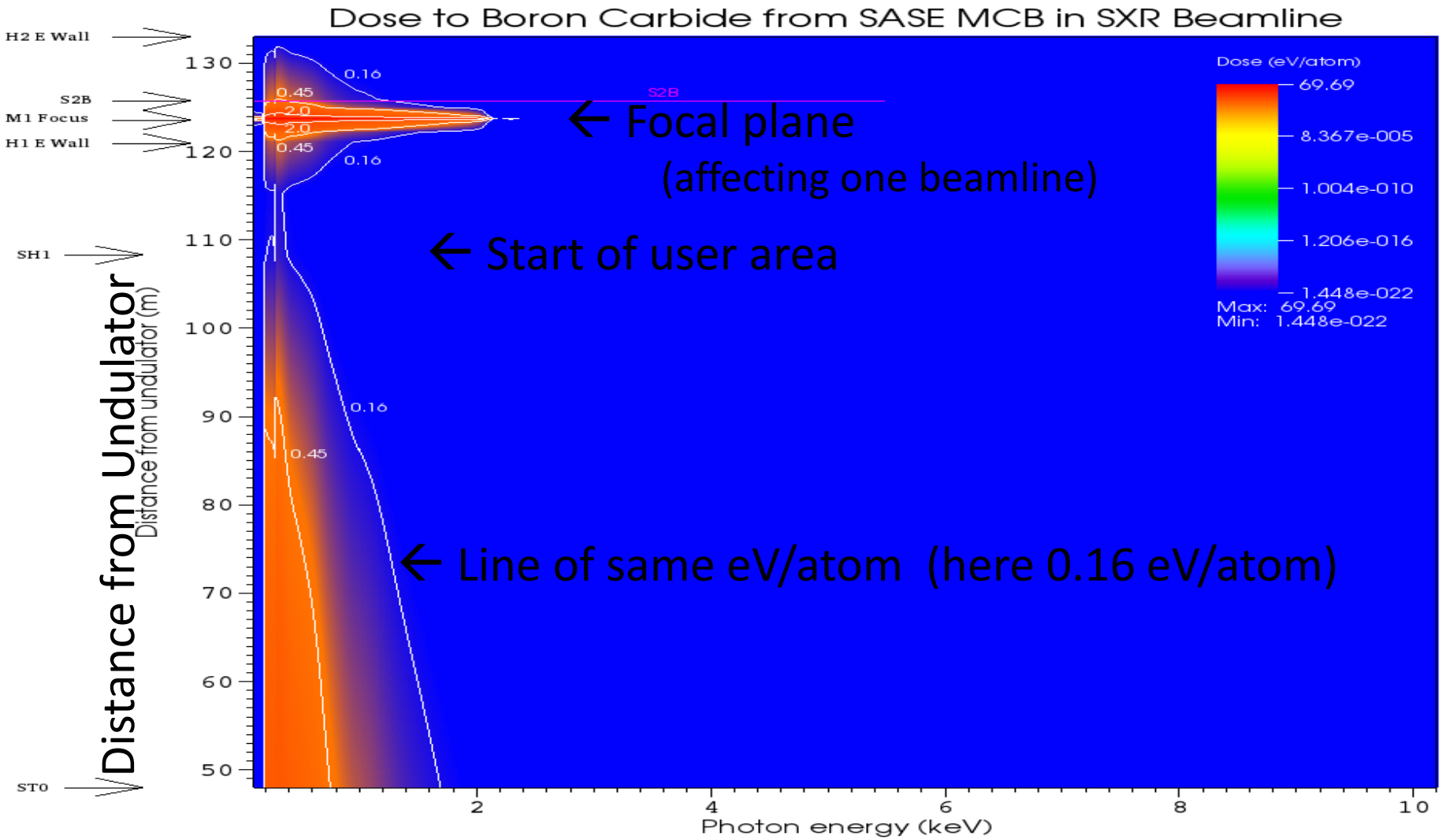
← Energy density

(unfocused at specific location)

Damage Potential

- Based on MCB estimates
- Lots of formulas to get from MCB to damage potential: depends on geometry, on focusing, on material
- Alyssa turned the crank (Details in Alyssa's talk)
- Thresholds given in eV/atom for given material
- Comparison with known damage thresholds

Sample Result from Calculation



Photon Energy (0 to 10 keV)

B4C Damage Studies

B4C Measurements at SLAC from LCLS Group

(esp. Stefan Moeller and Jacek Krzywinski)

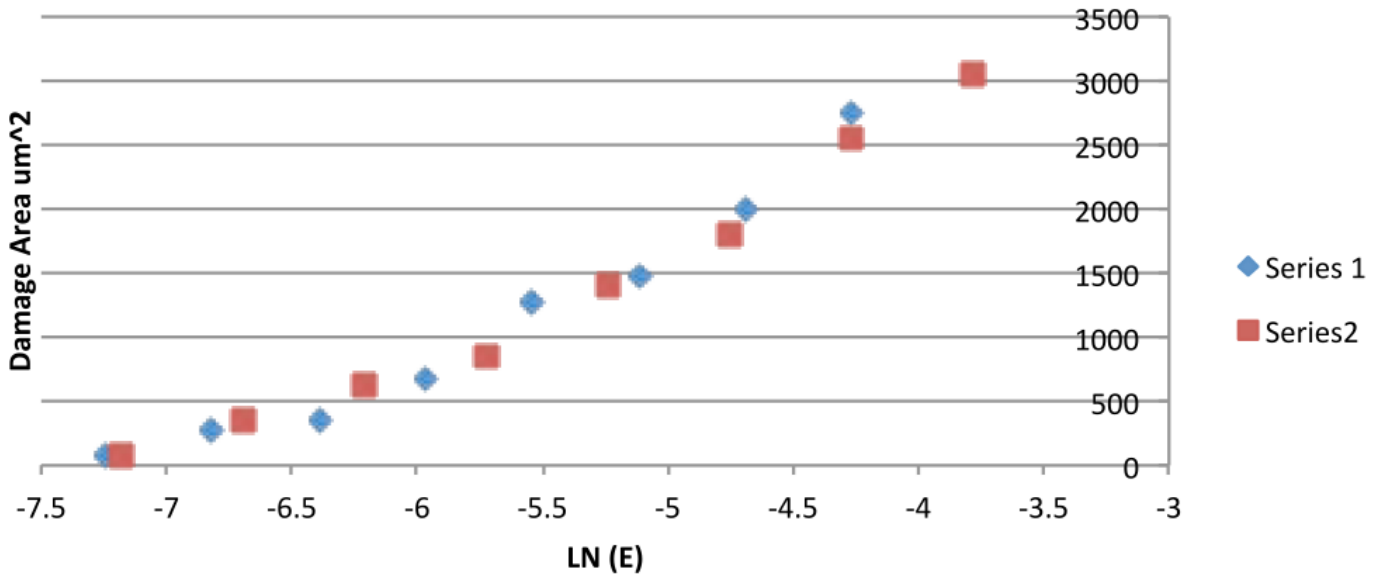
Recent preliminary results

- Pulse energy from
  - Gas Detector (pulse-by-pulse)
  - Loss in KB Mirror
    (between gas detector & focal spot)
- Pulse shape from
  - Imprints on PbW
    (good material for such imprints)

Interference pattern
b/c mirrors
too small for beam

B4C Damage Studies (cont.)

- Plot area of imprints versus pulse energies: "Liu plot"



- Extrapolation to zero gives damage threshold
  → consistent with known PbW threshold

B4C Damage Studies (cont.)

- Similar damage imprints on B4C

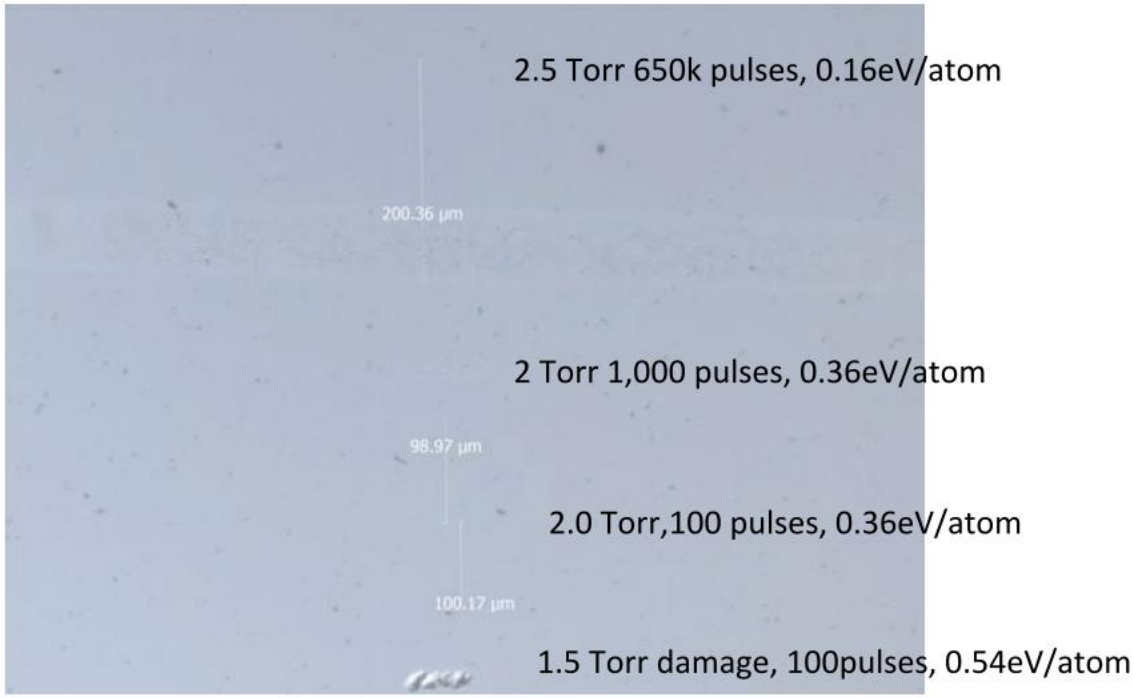
- Again plotting area vs energy and extrapolating to zero
- Single-pulse threshold

PRELIMINARY: 0.49 ± 0.02 (stat.) eV/atom for B4C

(better than & consistent with previous measurements)

B4C Damage Studies (cont.)

- Running on B4C for
  - 650,000 pulses @ 0.16 eV/atom
  - 1100 pulses @ 0.36 eV/atom
    → No Damage seen
  - 100 pulses @ 0.54 eV/atom
    → Damage (consistent w/Liu plot extrapolation)



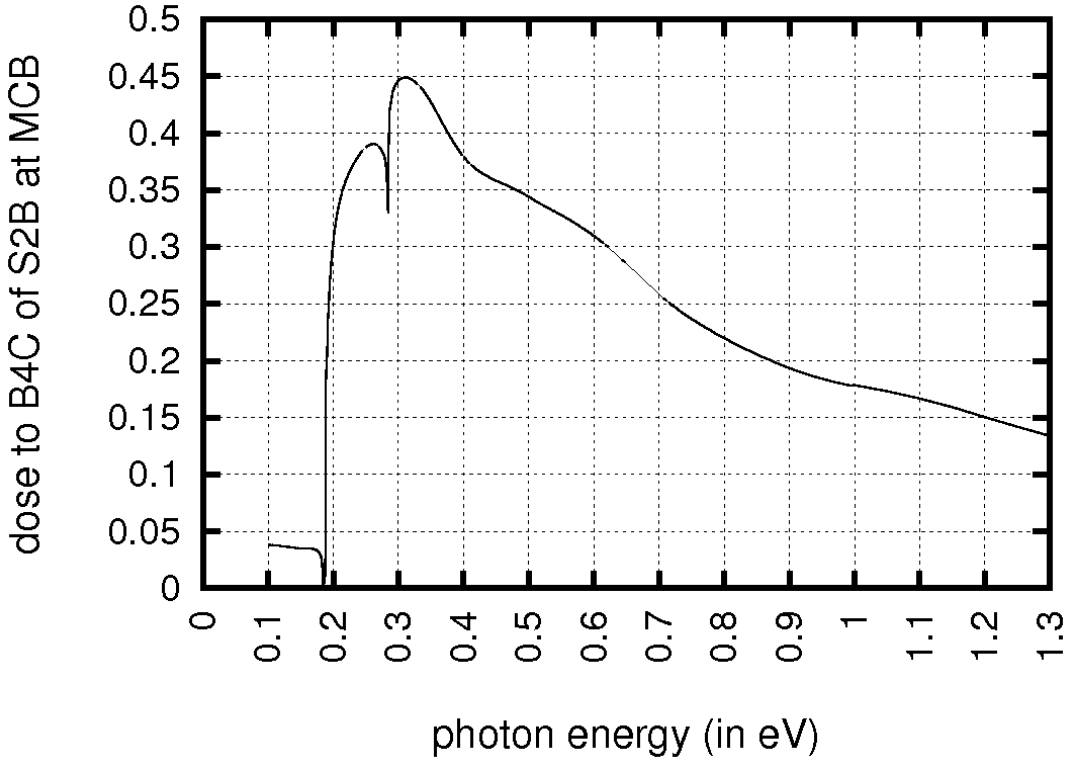
Planning to accept 0.16 eV/atom (preliminary) as new safe threshold

Applying Thresholds to Unfocused Beam

- B4C needs to hold up right upstream of hutches:
  - MCB dose from hutch stoppers (S1, S2, SH1) at about safe threshold
- Safety shutter upstream (ST1/ST2):
  - Could be damaged at MCB, but sacrificial B4C in front, observation for damage, special tests to be done once operation reaches high enough power

Applying Thresholds to Focused Beam

- Focused Beam at Stopper S2B:
  - Up to 0.45 eV/atom (close to single-pulse damage)
  - B4C might be damaged below 1.2 keV



- So far not allowing focused beam on S2B when energy low

  (operational burden)

Applying Thresholds to Focused Beam (cont.)

- S2B = pair of stoppers
  - Each stopper = B4C + Burn-through Monitor (BTM) + Heavimet
  - BTM = pressured air pocket
- If < 310 Torr above atmosphere:
  - BTM trip in < 1 sec
- If > 310 Torr above atmosphere and hole too small in BTM:
  - Photons < 1.2 keV reduced to 39% or less
  - Sufficient that B4C of second stopper holds up

    → no burn-through possible with both stoppers in
- And even with burn-through:
  - 410 eV photons (worst case) easily attenuated by air

    → very localized hazard, more like laser burn

Diffraction by Crystals

- Diffraction from good-quality crystals
  (mirrors, diagnostics, experimental samples)
- Large-angle deflections possible
- Lots of effort to prove that safe, often with geometry-dependent arguments:
  - No simultaneous damage of vacuum chamber & wall, but might need restriction on focal length
  - If no vacuum chamber or if wall too close:
    Extra dry wall (gypsum) sometimes helps
    (steel damaged easier than dry wall)
  - Crystal might melt first before damaging dry wall
  - Below 2 keV: only exotic material can diffract

Diffraction by Crystals (cont.)

- Requires configuration control:
  - Some Be lenses only with short focal length
  - Some seeded beam needs dry wall installed
- LCLS always finds new configurations, e.g.,
  - Beam twice focused
  - Beam split with gratings kept in PVC tubes, sample across room
- We hear that "it's improbable" that beam diffracts and damages wall
- Work ongoing to prove that

Conclusion

- New MCB estimates for this new FEL beam
- New B4C damage tests
- Detailed Calculations

  → Evaluating hazards
- Will keep eye on operation, since machine might once approach the limit