Accelerator Challenges for XFELs with Very High X-Ray Energies

Bruce Carlsten

Los Alamos National Laboratory

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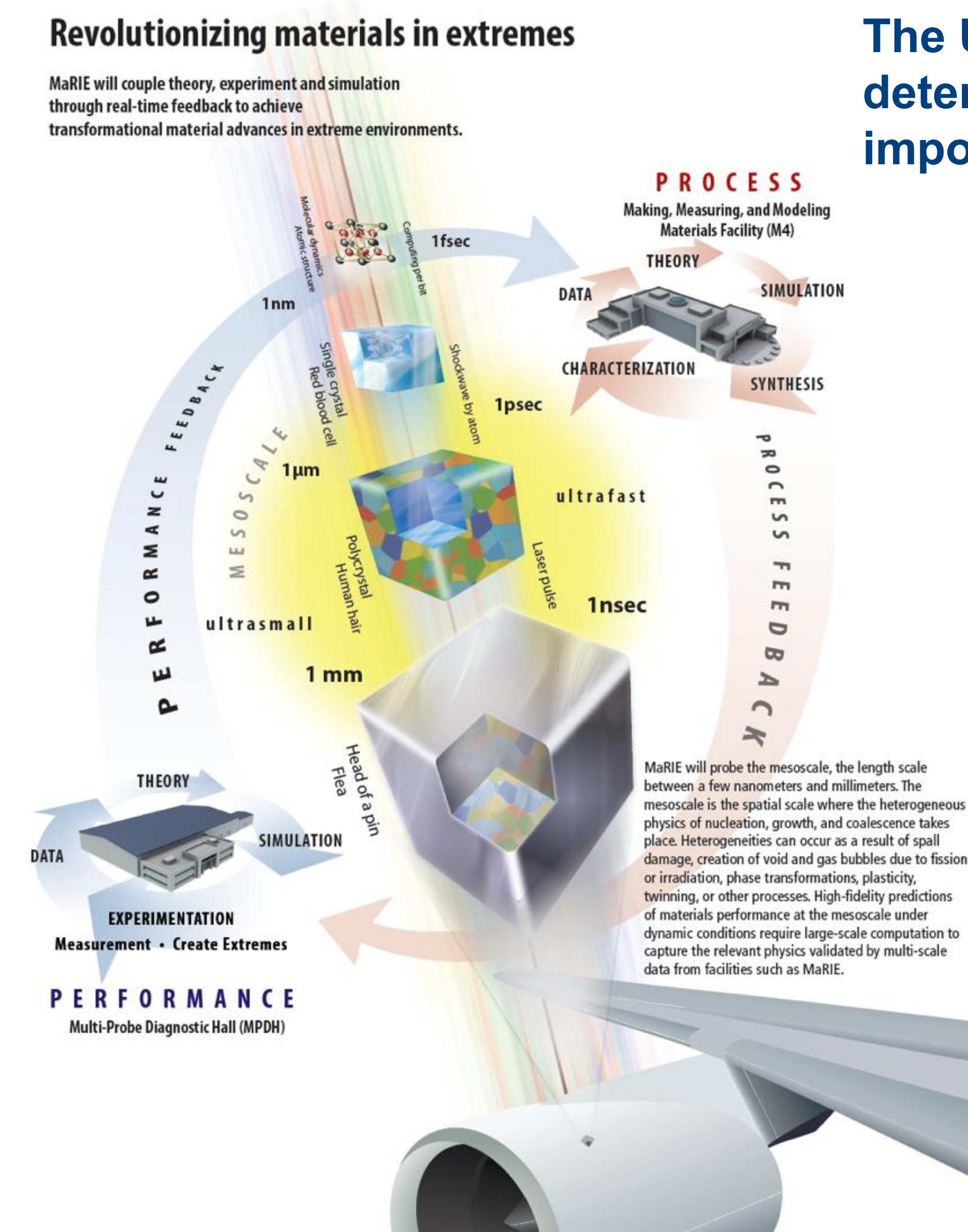
- MaRIE XFEL team
  - Photoinjector – Steve Russell, Leanne Duffy
  - Linac – John Lewellen, Nikolai Yampolsky, Quinn Marksteiner
  - Undulator and SASE – Dinh Nguyen, Petr Anisimov
- MaRIE team
  - Cris Barnes, Rich Sheffield, Rich Sandberg
- ***Laser-assisted microbunched electron bunch***
  - ***Petr Anisimov, Quinn Marksteiner, River Robles***
- ***High-gradient NCRF technology***
  - ***Jamie Rosenzweig, Sami Tantawi, Frank Krawczyk, Jenya Simakov***

Outline

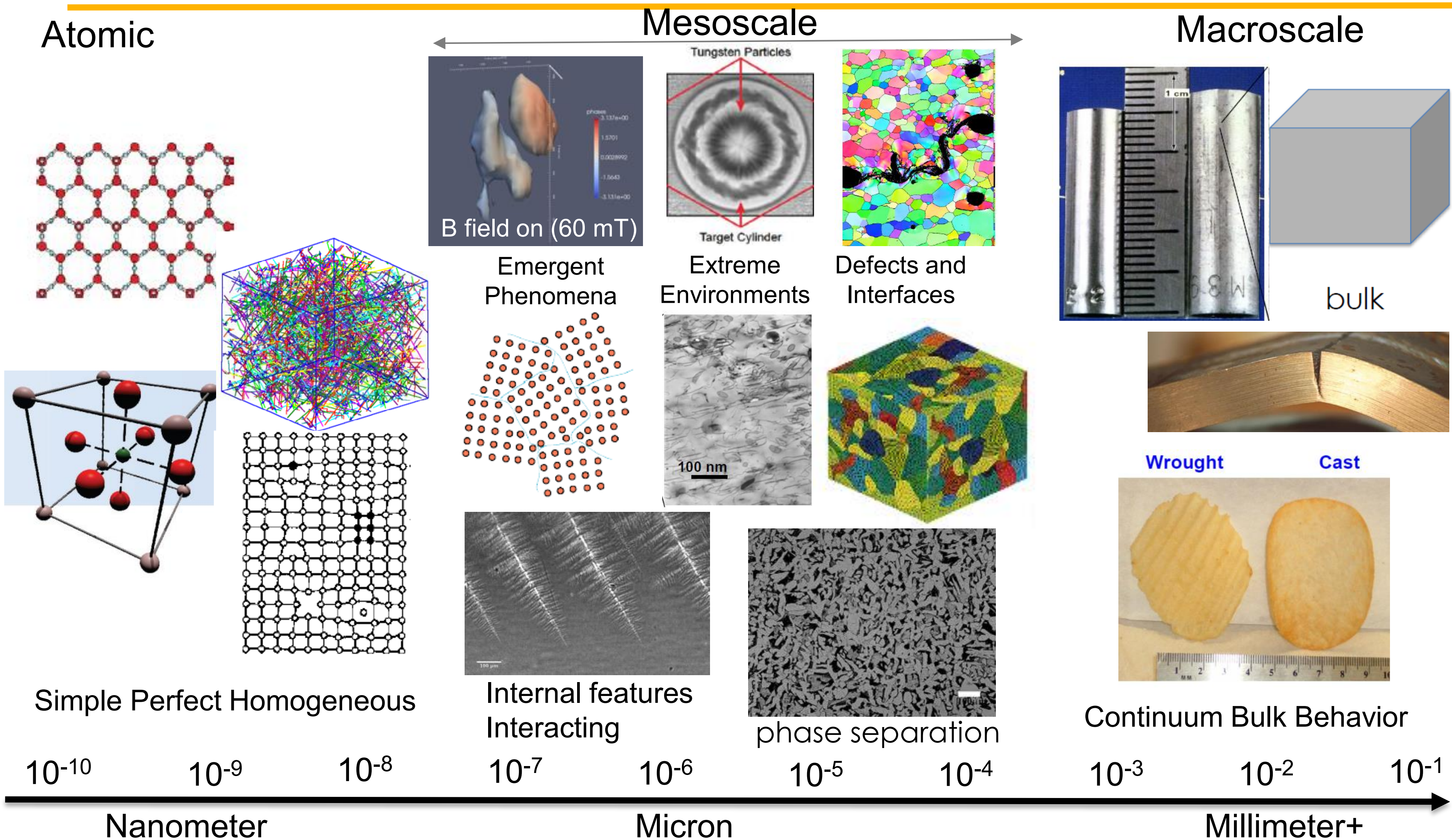
- DMMSC – the science need driving a high X-ray energy XFEL
- The Los Alamos MaRIE XFEL concept
- Challenges of ultra-short wavelength XFELs at moderate beam energies (MaRIE is 0.3 Å at 12 GeV)
  - Achieving low emittance comes at the risk of too high an energy spread
- High-brightness beam technology development for reducing the design risk
  - High-gradient cyro-cooled NCRF structures
  - Novel microbunched beam architecture (laser-assisted bunch compression – LABC)



The US Dept of Energy has determined there is a important science gap

- This science gap is in understanding dynamic materials: **Dynamic Mesoscale Materials Science Capability (DMMSC)**
- An XFEL light source could be used to close this gap

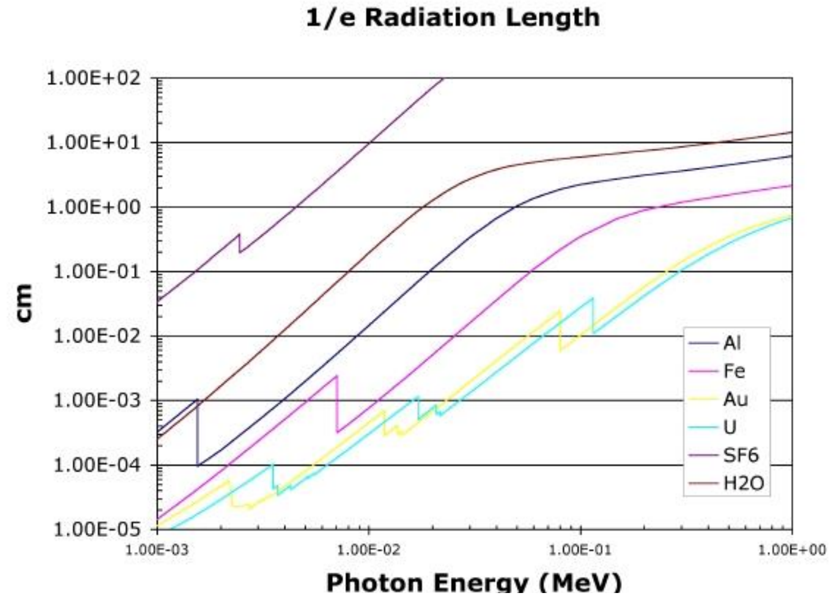
Revolutionizing materials in extremes requires understanding material behaviors at the mesoscale

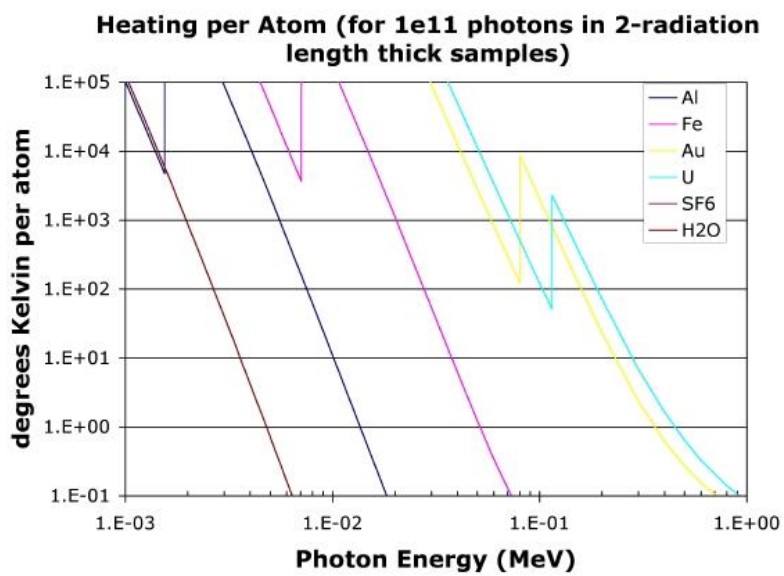


50-keV-class photons are needed for the DMMSC mission

MaRIE seeks to probe *inside* multigranular samples of condensed matter that represent bulk performance properties with sub-granular resolution. With grain sizes of tens of microns, "multigranular" means 10 or more grains, and hence samples of few hundred microns to a millimeter in thickness. For medium-Z elements, this requires photon energy of 50 keV or above.

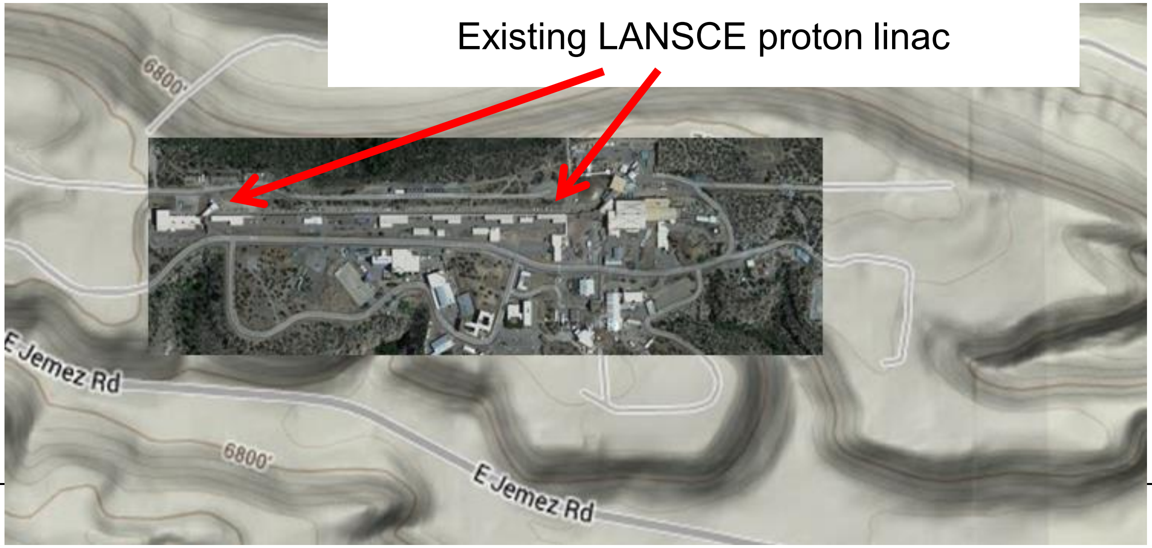
This high energy also serves to reduce the absorbed energy per atom per photon in the probing, and allows multiple measurements on the same sample. Interest in studying transient phenomena implies very bright sources, such as an XFEL.





Los Alamos has developed a "pre-conceptual" design for a 42-keV XFEL (MaRIE) for supporting Critical Decision 0 (CD-0)

- **It's an acronym – Matter-Radiation Interactions in Extremes**
- **The MaRIE experimental facility will eventually incorporate:**
  - Capabilities of Los Alamos Neutron Science Center (LANSCE)
    - Pulsed proton radiography
    - Pulsed neutron source
  - 12 GeV electron accelerator
    - 42-keV X-ray free-electron laser
    - Pulsed electron radiography



42-keV X-rays with a 12-GeV accelerator requires an exceptionally small emittance and energy spread

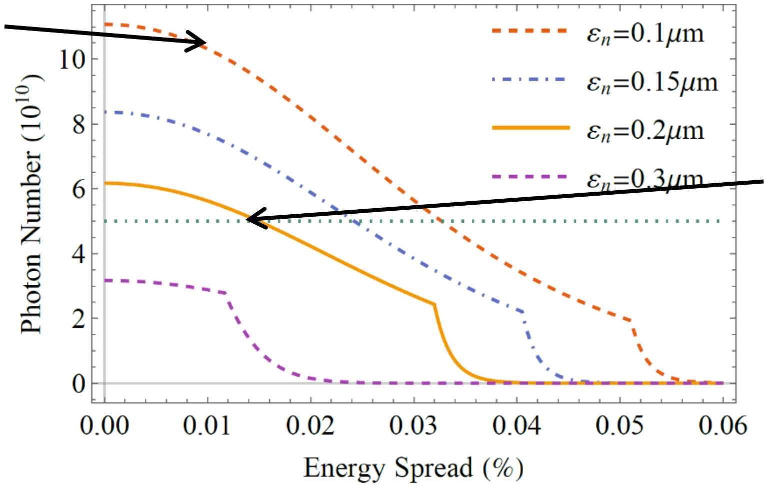
- Both the emittance and energy spread requirements become harder at low energy

$$\varepsilon_n < \frac{\gamma \lambda_{x-ray}}{4\pi} \qquad \delta\gamma_{\max} \le \frac{\rho\gamma}{2} = \gamma^{3/2} \frac{\lambda_{x-ray}}{8\pi\varepsilon_n} \sqrt{\frac{I}{2I_A}\left(\frac{K}{1+K^2/2}\right)JJ}$$

Linac target:
ε_n= 0.10 μm, $\delta\gamma/\gamma$ = 0.01%
100 pC

Photon requirements:
5×10^{10} 42-keV photons
0.02% bandwidth

(about 10-15% decrease in flux in plot from being time dependent)



XFEL requirement:
E_n < 0.2 μm, , $\delta\gamma/\gamma$ ~ 0.015%
(*factor of 2 decrease in flux*)

ΔE=1.8 MeV
$\delta\gamma$=3.5

Pre-conceptual design for “CD-0” was based on TESLA-style superconducting RF cyromodules

DMMSC

Beam parameters for lasing

- 12 GeV beam energy
- 100 pC bunch charge
- 13 fs bunch duration
- 3 kA peak current
- 0.015% energy spread
- 0.2 um rms emittance

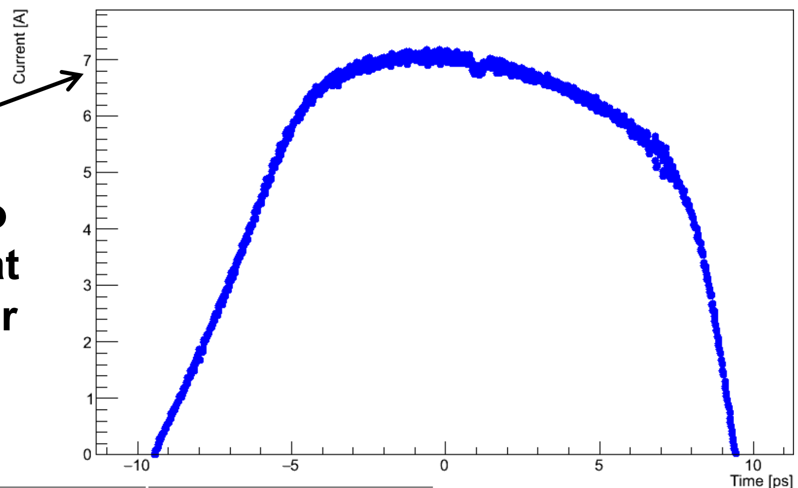
SRF LINAC parameters

- 1.3 GHz operating frequency
- 31.5 MV/m accelerating gradient
- 20:1 compression ratio, BC1
- 25:1 compression ratio, BC2
- 1 msec RF pulse duration

Other requirements

- Multiple bunches per RF macropulse (up to 100s total over 1 msec, up to 10s in ~ 20 nsec burst mode)
- 5×10^{10} X-rays/pulse
- 2-nC bunches interleaved for radiography

We can achieve the low emittance but the resulting low bunch current requires high total compression ratio



Implies 450:1 compression to achieve 3.5 kA at MaRIE undulator

In our current design, we suppress the thermal emittance by keeping the RMS beam size σ very small, which makes a very long, low current bunch

We might be able to have twice the current (and need only half the compression) at the same total emittance if the thermal emittance contribution vanished

Property	Value
Energy	195 MeV
Charge	100 pC
Thermal ε_n (copper*)	41 nm
Residual ε_n	60 nm
Total RMS ε_n	73 nm
RMS Length	5.5 ps
RMS Energy Spread	0.08%

$$\varepsilon_{therm} \sim \sigma\sqrt{\frac{W}{mc^2}}$$

Excess energy from emission process

$$\varepsilon_{total}^2 = \varepsilon_{thermal}^2 + \varepsilon_{residual}^2$$

(WEA02 – Nathan Moody's talk on photocathode research)

MaRIE XFEL compression ~ 450:1 leads to tight energy spread requirements

- **Designing the photoinjector for the required emittance increases the risk of achieving the required energy spread**
- Maximum energy spread at 12 GeV of 0.015% is 1.8 MeV
- Using 20:1 and 22:1 for BC1 and BC2 compression ratios
  - *We can tolerate 81 keV before BC2*
  - *We can tolerate 4 keV before BC1 (~ 200 eV from RF gun)*
- This puts constraints on several $\delta\gamma$ growth mechanisms
- If we need a laser heater to suppress micro-bunch instability, it can only put on a few keV onto the beam or it needs to be reversible

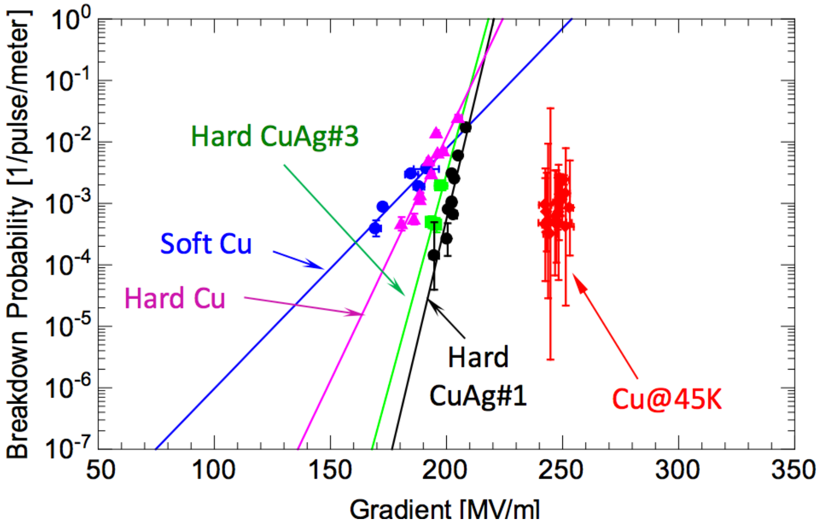
We would really like an energy spread of <1 MeV at 12 GeV

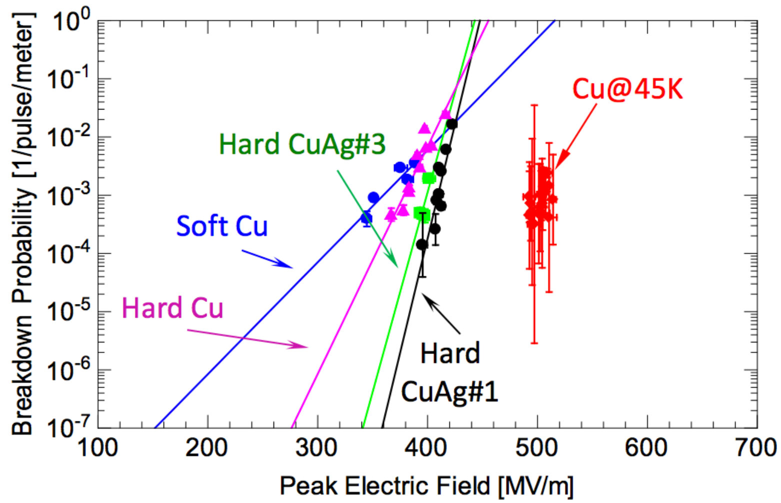
High-brightness beam technology development in two key areas can add significant design margin

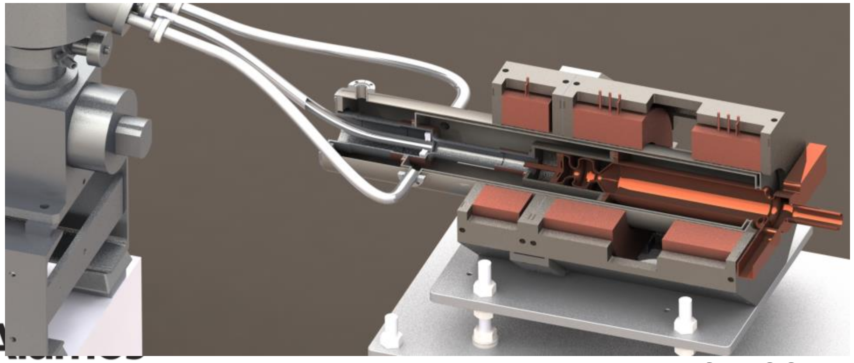
- Cyro-cooled NCRF technology:
  - Higher gradient in photoinjector will reduce the required total compression ratio
  - Higher gradient in linac (120 MV/m real-estate gradient) will suppress LSC and transverse emittance growth
- Microbunched electron bunch
  - Can suppress:
    - Undulator resistive wall wake (for sure)
    - Microbunch instability (partially)
    - CSR-induced emittance and energy spread growth (open research question)

Cryo-cooled NCRF technology can reduce the required total compression ratio and suppress LSC/transverse emittance growth

20-A RF gun (UCLA's TOPGUN at 240 MV/m – 55 nm at 100 pC)







Simulations show it can produce up to 20 A with our emittance requirement

Target linac gradient: 120 MV/m real-estate gradient

Cryo-cooled NCRF technology development is a multi-institutional effort

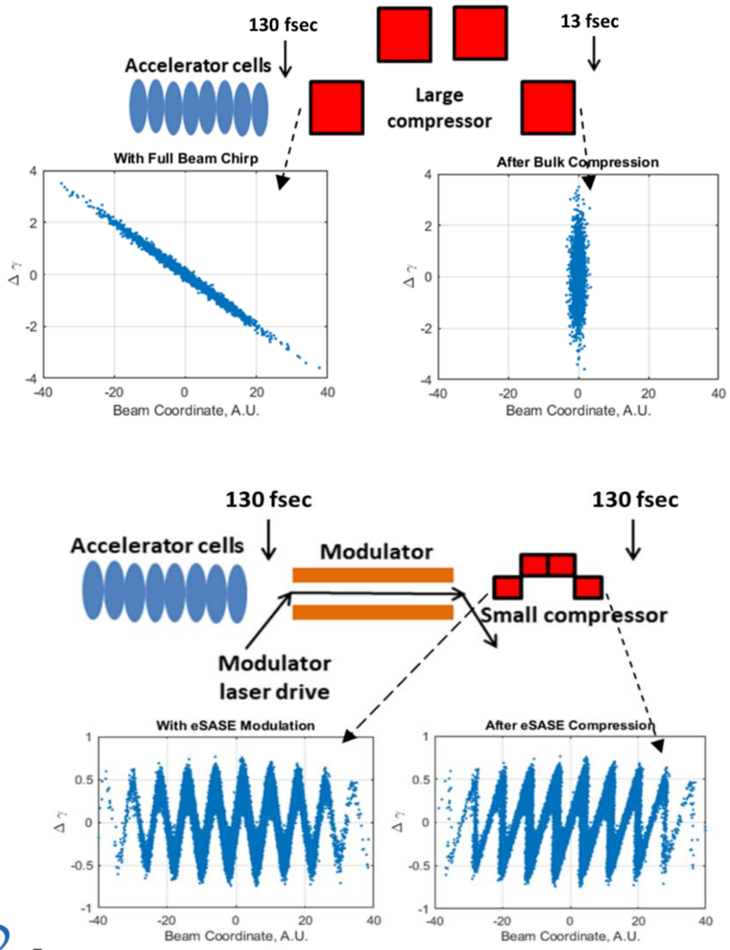
- Joint SLAC/UCLA/LANL/INFN effort
  - SLAC – core DOE accelerator R&D program
  - UCLA – DOE stewardship
  - LANL – LDRD program
- LANL focus areas
  - Materials development for RF breakdown suppression (custom copper alloys)
  - Advanced manufacturing for compatibility with material properties
  - Cryo-cooled operation for long pulse (*10s of μs*) operation
  - Established extension of Molecular Dynamics simulation tools to include RF fields and study macroscopic materials
  - *We have identified C-band as best compromise for efficiency, wakes, FEL operation*

C-band is likely the best frequency compromise for cyro-cooled NCRF

- *C-band (5.712 GHz) was identified as the most suitable RF operation frequency for XFELs.*
- RF performance metrics for RF structures (efficiency, gradient and multi-bunch decoupling) favor higher frequencies (C and X).
- Coupling between an RF structure and the transported beams (wake fields and control of the energy spectrum within a particle bunch) favor lower frequencies (S and C).
- Ease of fabrication and RF-transport losses also favor the lower range (S and C).
- C-band is the only established frequency that has favorable properties on all these criteria.

Bold=good, grey=FYI only	**L-band**	**S-band**	**C-band**	**X-band**
Shunt impedance [MΩ/m]	9.E+6	85	**120**	**170**
Wakes longitudinal [V/pC]	10.2	26.4	36.4	50.4
Energy change @ 1 GeV	0.3%	**2.5%**	**3.5%**	8.0%
Wakes transverse [V/pC/m]	15.1	155	835	4420
Deflection @1μm [kV]	0.0	**1.5**	**8.0**	67.4
Gradient [MV/m]	30	50	**100**	**150**
Dechirper length @ 1 GeV	N/A	2.9	**1**	0.8
Fabrication tolerances	good	**good**	**good**	hard
Long range wakes for burst	bad	bad	**good**	**good**

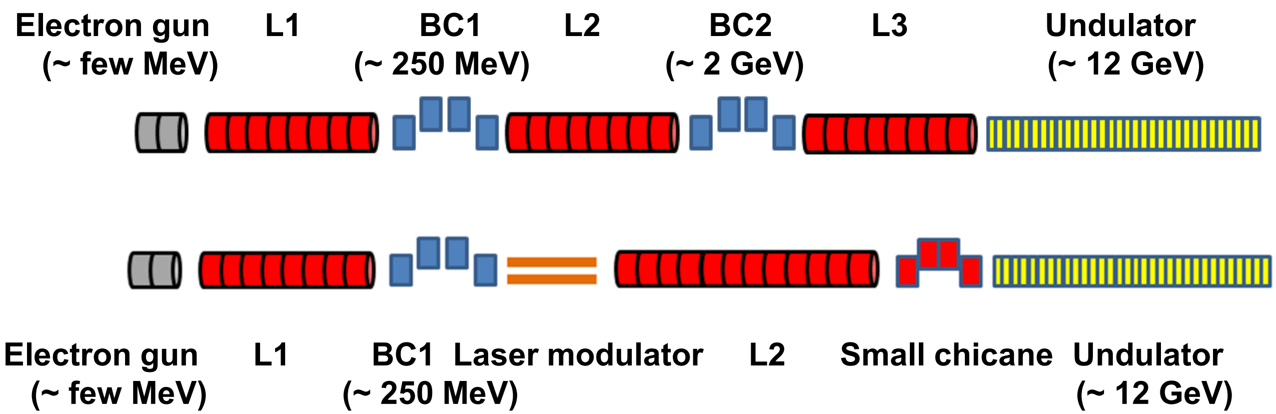
Laser-assisted microbunched electron bunch is the second area of high-brightness beam research

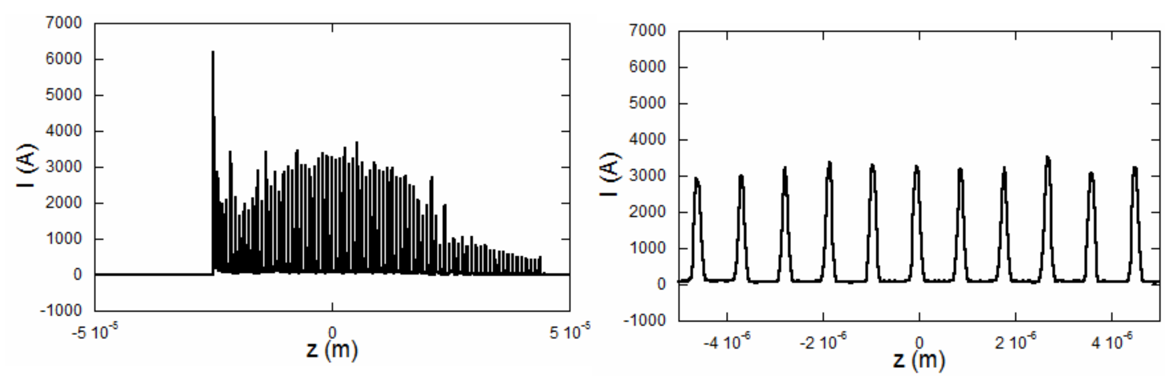


- The idea is to use a laser to eliminate the second BC. Our final current is the same current as before, 3 kA.
- Lack of second BC reduces CSR, minimizes the microbunch instability, and suppresses undulator resistive wall wake

More details in THB01 – Petr Anisimov: "Using an E-SASE Compression to Suppress Microbunch Instability and Resistive-Wall Wake Effects"

Laser-assisted microbunching allows more efficient operation of the RF

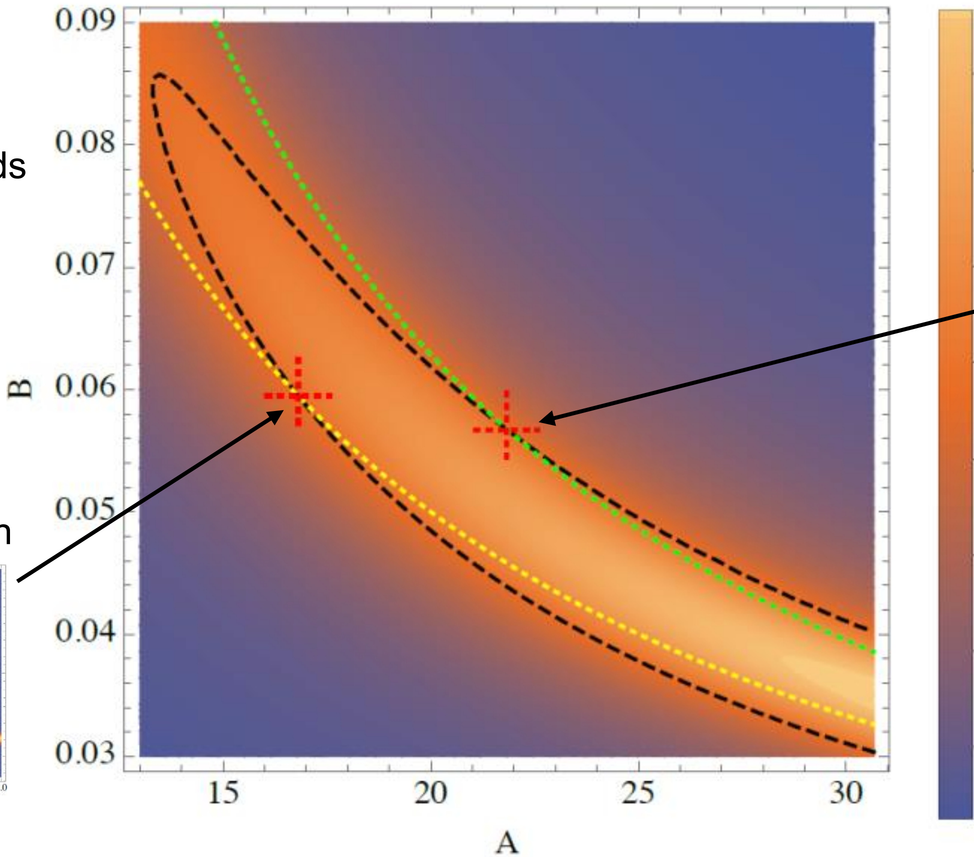




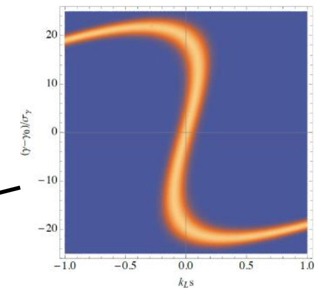
Simulation of microbunched beam

Laser-assisted bunch compression maximizes captured current while the eSASE condition maximizes compressed current – *more details in Petr's talk*

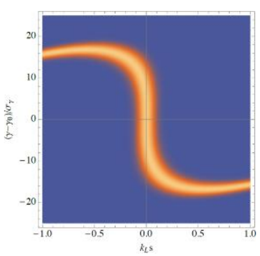
Dashed black line corresponds to 10:1 compression

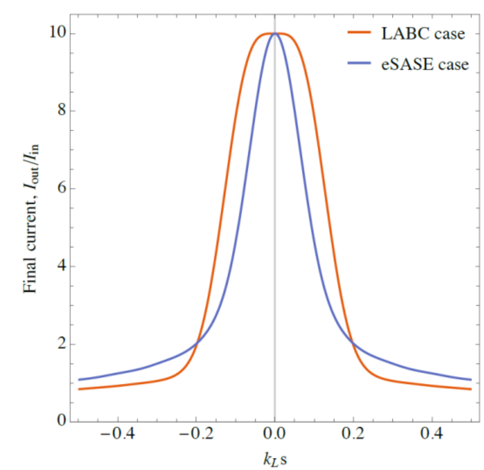


LABC condition



eSASE condition





Compression as a function of normalized modulation amplitude A and normalized momentum compaction B

LABC estimates indicate we can achieve a low energy spread

BC compression factor

Initial energy spread

LABC compression factor

Hemsing et al., Rev. Mod. Phys., 86, 2014

$$\sigma_{E,final} = \frac{2}{\sqrt{27}} \sigma_{E.initial} C_{BC} (C_{LABC})^{3/2}$$

Final energy spread induced by LABC (scaling comes from needed a large enough modulation on the beam)

$$\Delta s \approx 0.5 \frac{\lambda_L}{A}$$

Microbunch length formed by LABC

Δs has to be at least as long as the slippage through the undulator

With compression ratios of 15/10 the formulas predict a final energy spread of ~ 450 keV

Conclusions

- Our baseline MaRIE parameters are very ambitious – we want to generate 0.3 Å light with a 12 GeV electron beam.
- We have a pre-conceptual baseline design that will likely work – *we can always reduce risk by increasing the beam energy*
- With international partners, we have started to work on novel high-brightness beam technologies as an alternative to higher beam energy for reducing design risk
- *Better cathode thermal emittance can provide additional margin*
- Still a lot of questions to work out:
  - A 1 μm laser is too small because of slippage, while a 10 μm laser is probably too large, because you still need a large R56. What is the optimum wavelength, maybe 3 or 4 μm?
  - How much can we actually reduce both 1D and non-1D CSR and microbunching effects by using LABC?
  - Is it practical to use higher harmonics of the laser to get more than ½ the particles compressed? How would this be done?