# Fusion Energy Sciences at Berkeley Lab – a perspective


Thomas Schenkel

Fusion Science and Ion Beam Technology Program

Accelerator Technology and Applied Physics Division

Lawrence Berkeley National Laboratory


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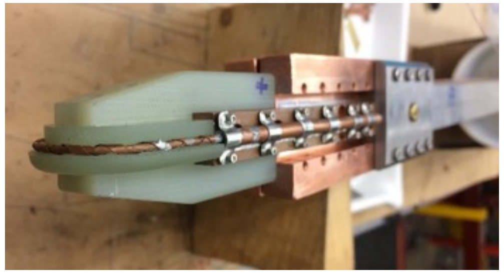
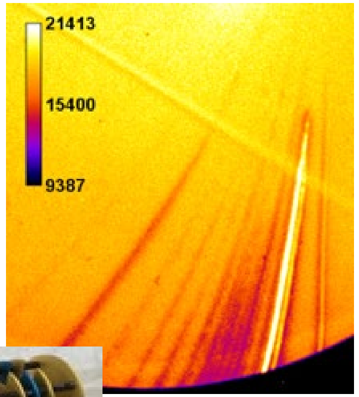
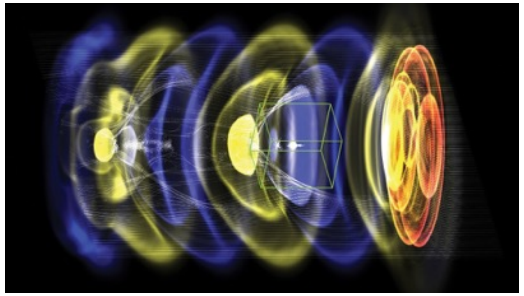
# Our R&D portfolio to advance fusion energy sciences at Berkeley Lab

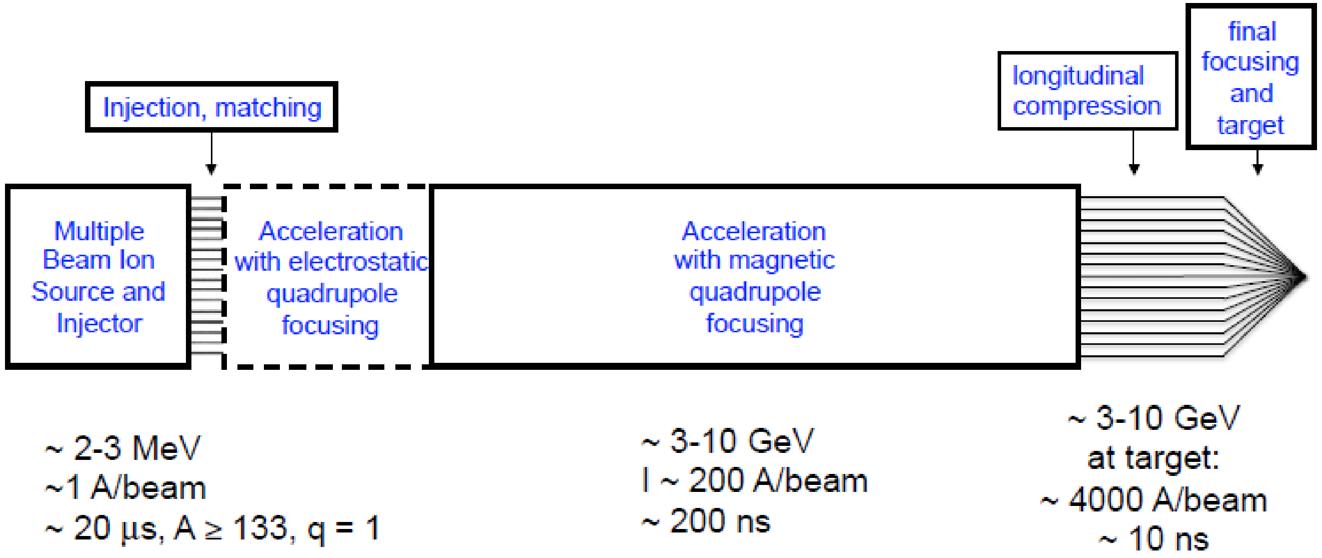
1. High Tc superconducting magnets for high-field tokamaks
2. High Energy Density Physics with lasers and particle beams
3. MEMS-based accelerators for nuclear materials testing and plasma heating
4. Modeling and Simulations of beams and plasmas
5. New ideas for Inertial Fusion Energy

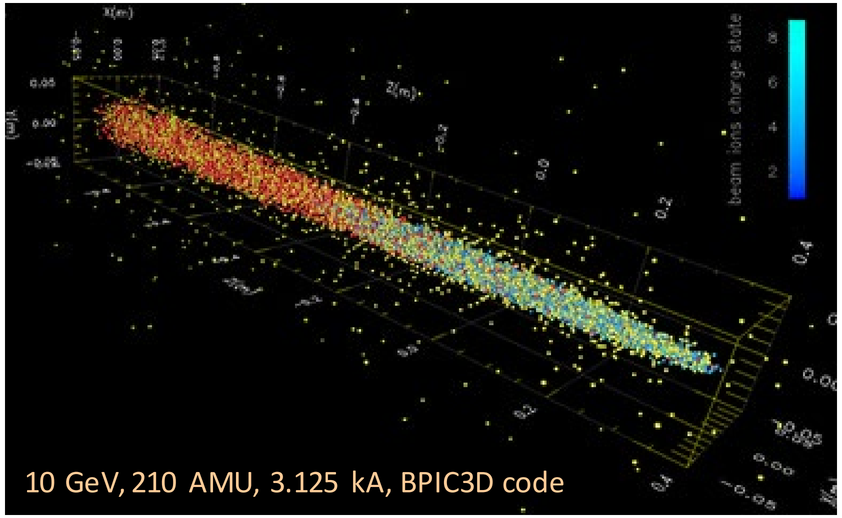




# Ion beams are a driver option that can complement pulsed power and lasers for Inertial Fusion Energy



10 GeV, 210 AMU, 3.125 kA, BPIC3D code

J. L. Vay (LBNL), W. Sharp (LLNL), et al., (2010)

- Heavy ion fusion drivers, 1 MJ per 1 GeV * 100 kA in 10 ns
- High accelerator efficiency (30-50% wall plug to beam), protection of final focus optics from neutrons, promising target and reactor chamber designs, …
- The heavy ion fusion program in the US was stopped in about 2012 – what has changed since then to re-consider ion beam drivers ?
- **Exciting opportunities or too little too late ?**

- P. A. Seidl, Encyclopedia of Nuclear Energy 3, https://doi.org/10.1016/B978-0-12-819725-7.00172-0
- R. Bangerter, A. Faltens, P. Seidl, Rev. Accel. S&T 6, 85 (2013) https://doi.org/10.1142/S1793626813300053

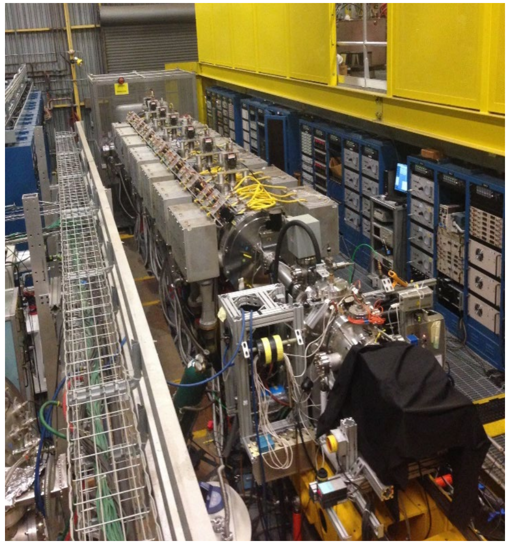
# Ion Beams and Inertial Fusion Energy R&D

- **Heavy Ion Fusion - HIF**
  - Opportunity to revisit heavy ion driver options in light of recent developments
    - Multi-beam RF linacs
    - Induction linacs
    - Laser-plasma based heavy ion drivers

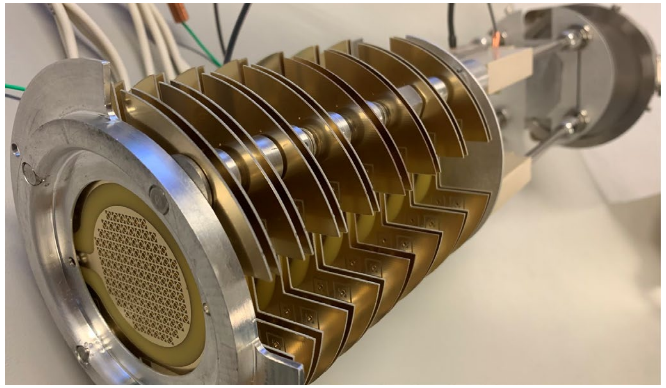
- **High Energy Density Physics for IFE**
  - Laser-plasma acceleration of heavy ions
  - Proton fast ignition
  - Ion stopping in plasmas
  - Equation of state studies
  - Diagnostic development
    - X-rays, gammas from laser-plasma interactions, …
  - LaserNetUS opportunities
  - Experiments at facilities like FAIR (kJ heavy ion pulses)
  - …

- **Modeling and Simulations of beams and plasmas**

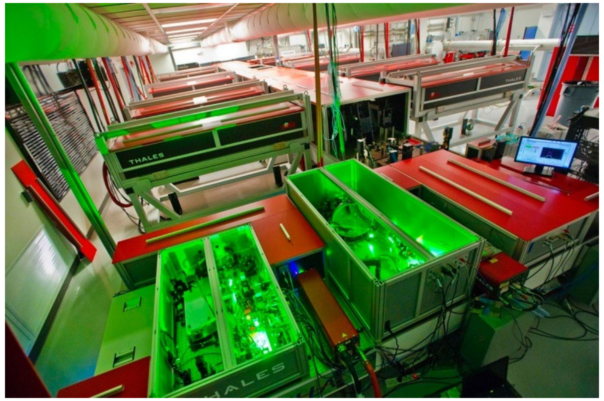
- Target design, gain and hybrid driver options
- Target fab, target control
- Chambers and reactor design, liquid metal walls, tritium breeding
- Dt, other fusion reactions ?
- Connection to private sector investments



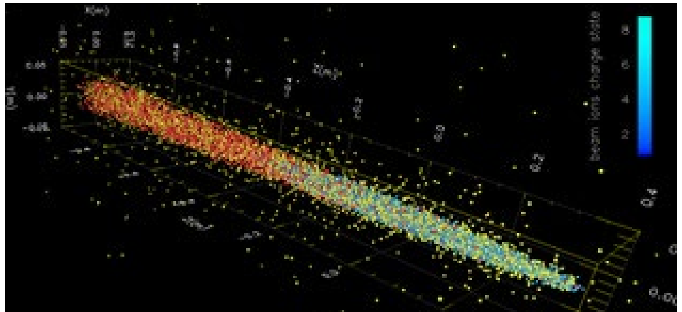
P. Seidl, et al., Laser and Particle Beams 35, 373 (2017)



Q. Ji, et al., Rev. Sci. Inst. 92, 103301 (2021)



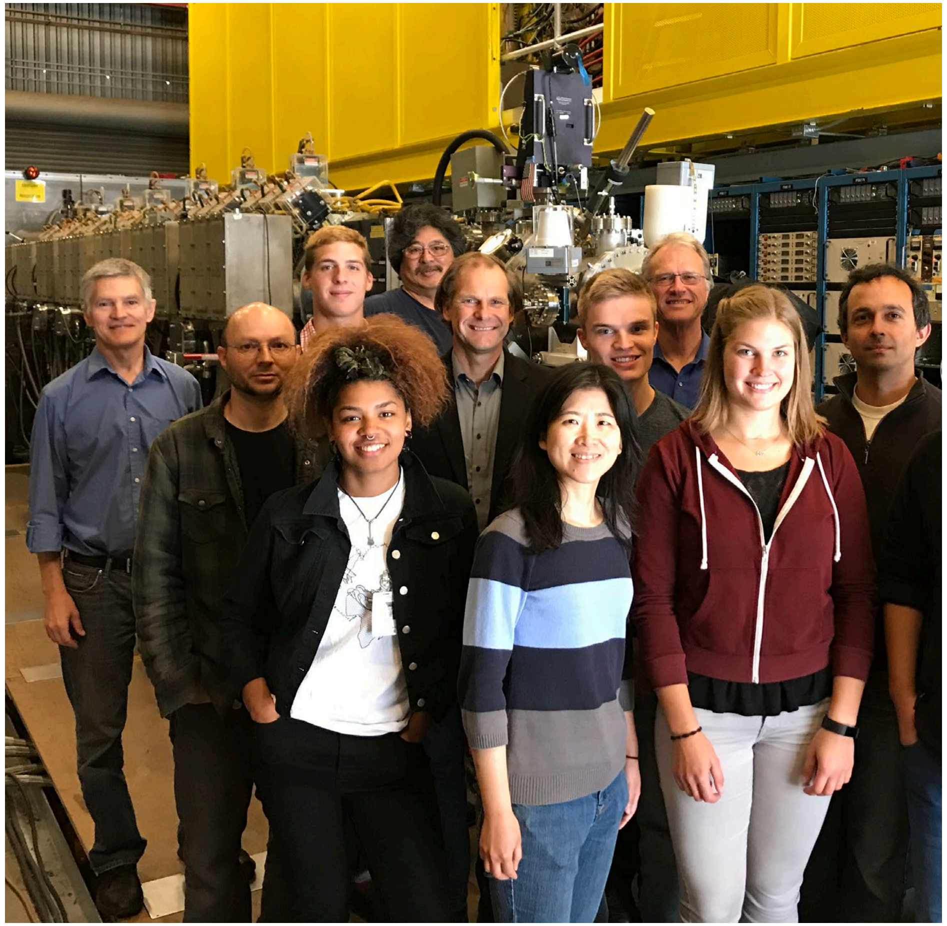
S. Steinke, et al., Phys. Rev. Accel. Beams 23, 021302 (2020)



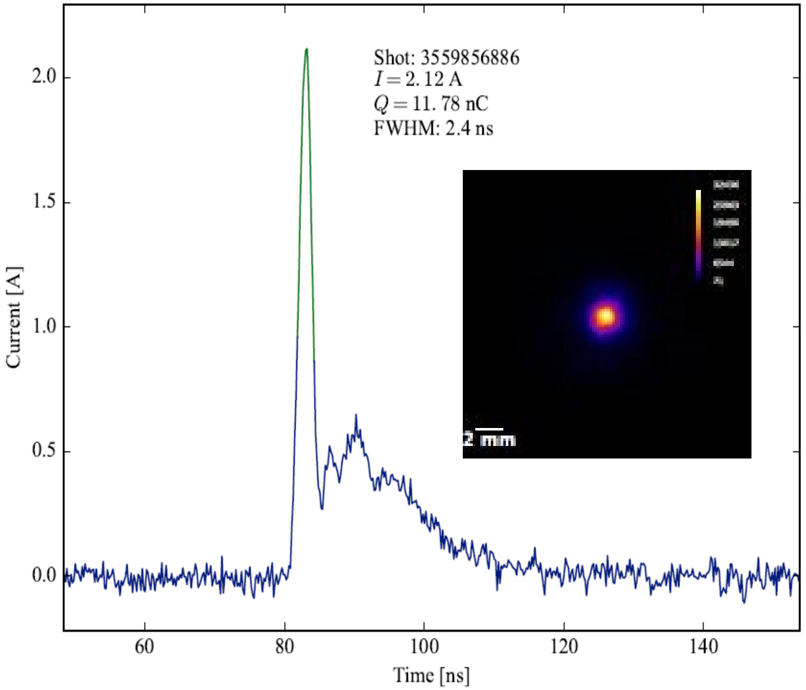
10 GeV, 210 AMU, 3.125 kA, BPIC3D code then, now in WarpX

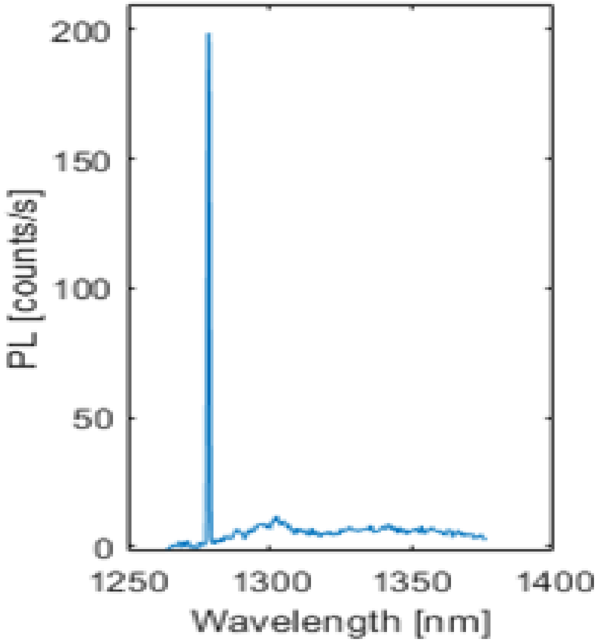
J. L. Vay, W. Sharp, et al., (2010)

# Intense, pulsed ion beams by neutralized drift compression in an induction linac – NDCX-II



- Pulse compression from ~1 us to a few ns
- Spot size with 1-2 mm radius
- 1 MeV protons, $He^+$, …
- Peak current up to 2 A (to date, AI/ML tuning in progress)
- Repetition rate 1 shot / 45 s

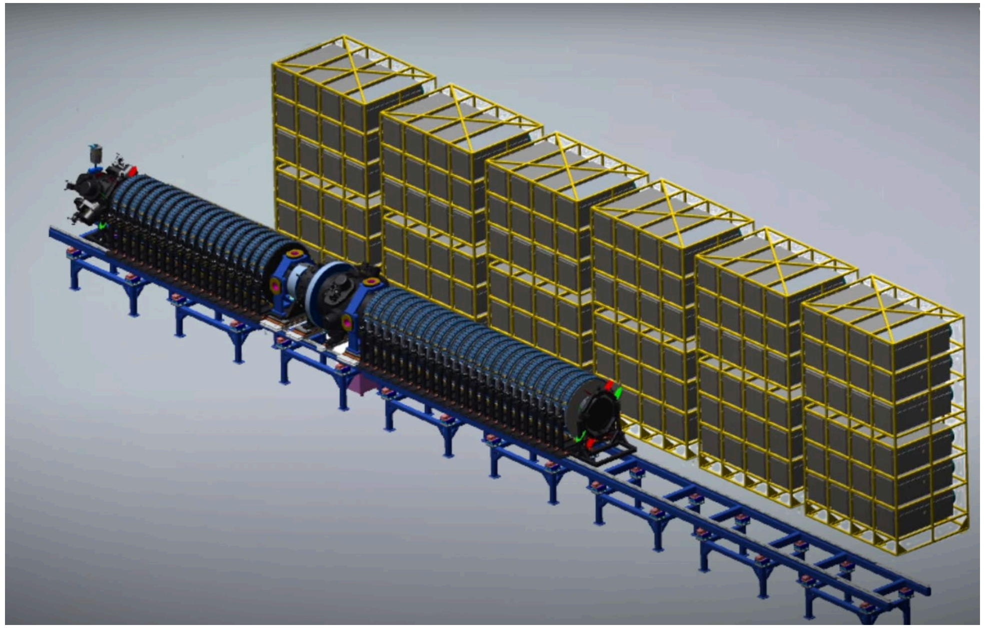



- Mid: Example of a shot with 1.1 MeV $He^+$, 12 nC ($7.5\times10^{10}$ ions/shot), 2 A peak current, 13 mJ
- Right: low temperature (3 K) photoluminescence spectrum showing G-centers in silicon formed with proton pulses at NDCX-II (W. Redjem, B. Kante, T. Schenkel, et al., in preparation)


- P. Seidl, J. J. Barnard, E. Feinberg, A. Friedman, E. P. Gilson, D. P. Grote, Q. Ji, I. D. Kaganovich, B. Ludewigt, A. Persaud, C. Sierra, M. Silverman, A. D. Stepanov, A. Sulyman, F. Treffert, W. L. Waldron, M. Zimmer, and T. Schenkel, "Irradiation of materials with short, intense ion pulses at NDCX-II", Laser and Particle Beams 35, 373 (2017)
- Q. Ji, et al., Rev. Sci. Instr. 87, 02B707 (2016); F. Treffert, et al., Rev. Sci. Instr. 89, 103302 (2018); A. D. Stepanov, Matter and Rad. at Extremes 3, 78 (2018); J.-H. Bin, et al., Rev. Sci. Instr. 90, 053301 (2019)

# New induction accelerator developments relevant to HIF: Scorpius



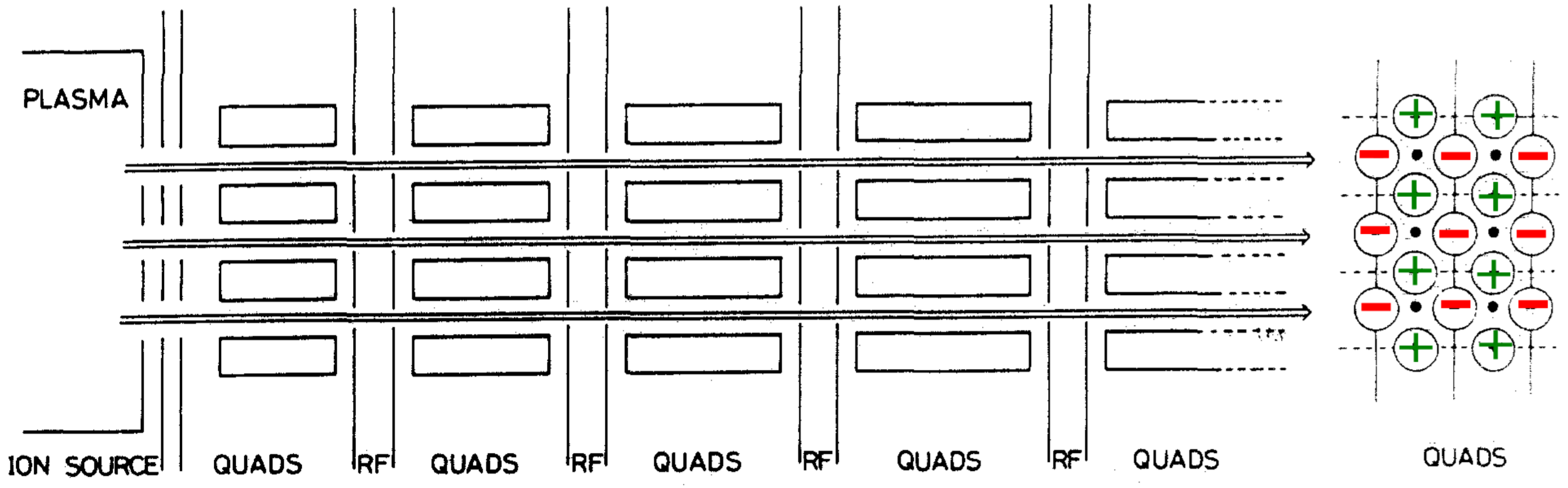
- Next generation induction linacs
  - ~100 **solid-state pulsed-power 200-kV cells**
  - 1.4 kA $e^-$ beam – high electrical efficiency
  - Advances and lower cost of SiC Mosfets make this pulsed power possible.
- HIF relevance: performance, economics
  - Instead of Blumlein/spark gaps with fixed shape and duration

  → solid state units with variable amplitude and shape, modular, less down time, long life
  - Flexible waveforms possible e. g. for optimized beam compression
  - Longer unit life means lower cost of operation and less down time
  - Fast rise and fall times → shorter pulses, lower driver cost

References:

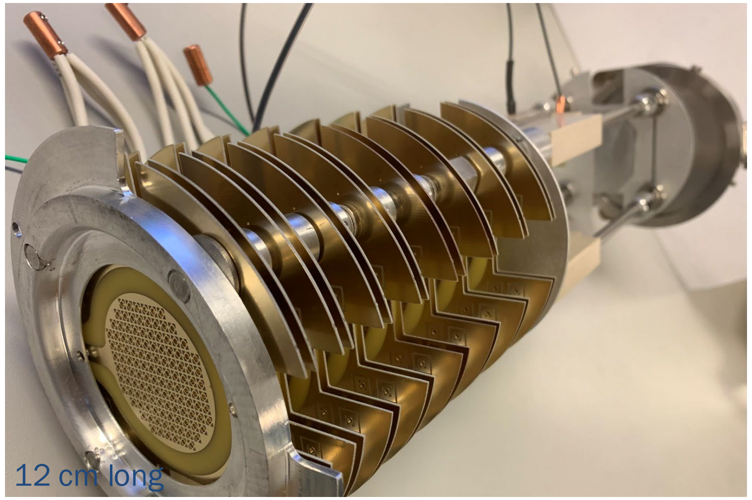

- M. Crawford and J. Barraza, "Scorpius: The development of a new multi-pulse radiographic system," 2017 IEEE 21st International Conference on Pulsed Power (PPC), 2017, pp. 1-6, https://doi.org/10.1109/PPC.2017.8291266
- C. Ekdahl, "Cathode to Target Simulations for Scorpius: Simulation Codes and Models" (2021) https://arxiv.org/pdf/2104.14593.pdf
- Youtube, LLNL 2021 https://youtu.be/ZONgho0jBYM

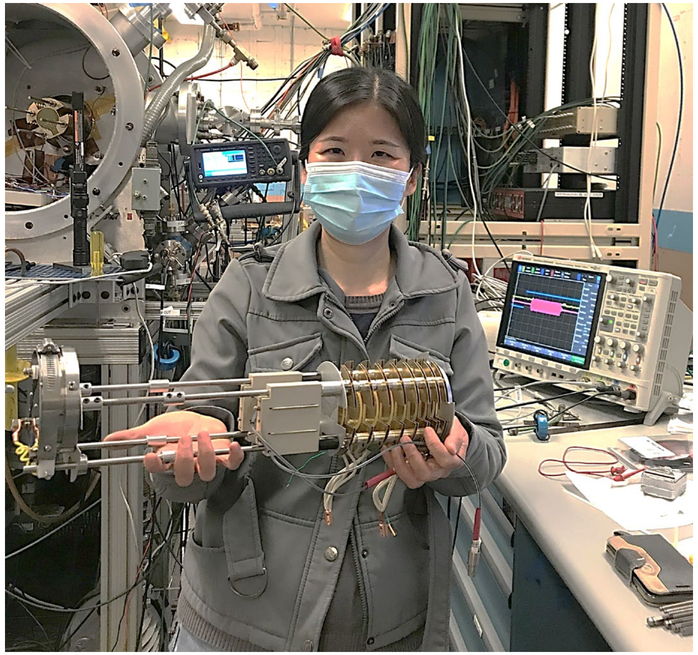
# Multiple-Electrostatic-Quadrupole-Array Linear Accelerator (MEQALAC)

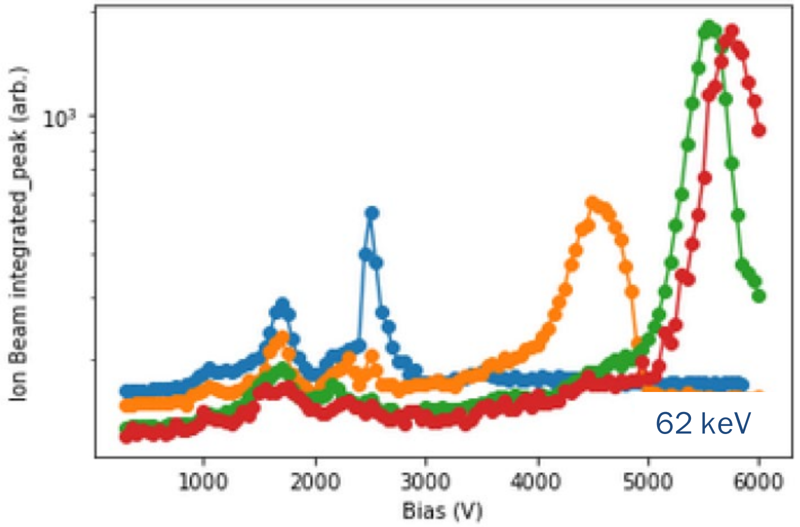



- A high current beam from many small beams for higher beam power and current densities
- 1980s: ~ 1 cm beam apertures, lattice period a few cm
- Al Maschke et al., early 1980s; also e. g. R. Thomae et al., Mat. Science & Eng., B2, 231 (1989)

# MEMS-based accelerators for (nuclear) materials and plasma heating. Can we scale accelerators to high beam power at much lower cost ?

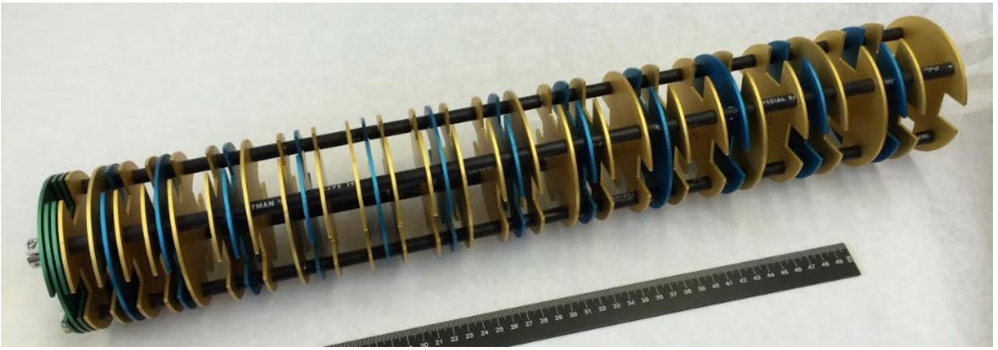





- Multi-beam RF linacs with 100 beams made from low-cost wafers
- Acceleration by 7 kV/RF-gap, 0.4 MV/m, 0.5 mA peak current, to date
- Next steps - beam power scaling
  - >1 MeV and average currents >1 mA per module
- Collaboration Berkeley Lab and Cornell, started with ARPA-E ALPHA

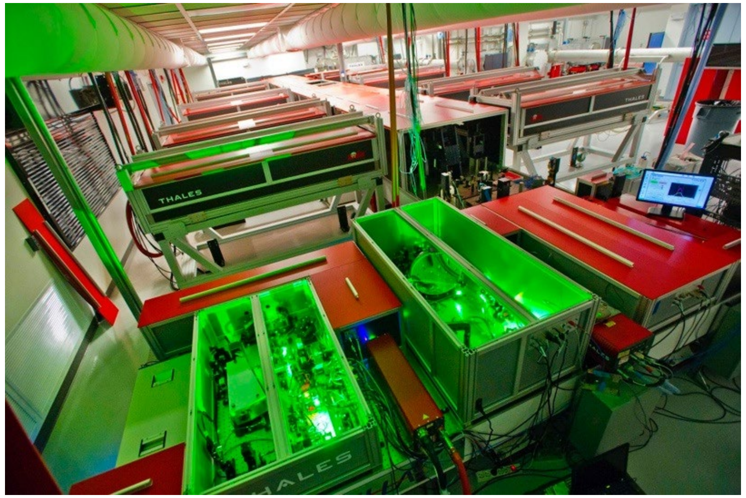
arpa·e
CHANGING WHAT'S POSSIBLE

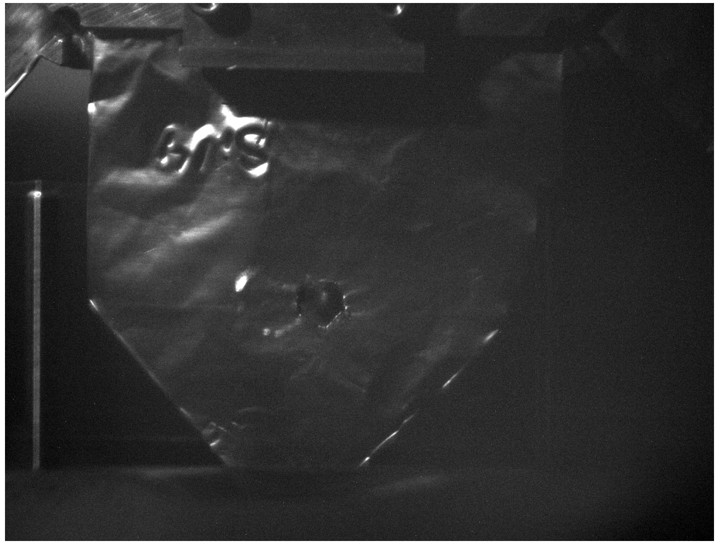


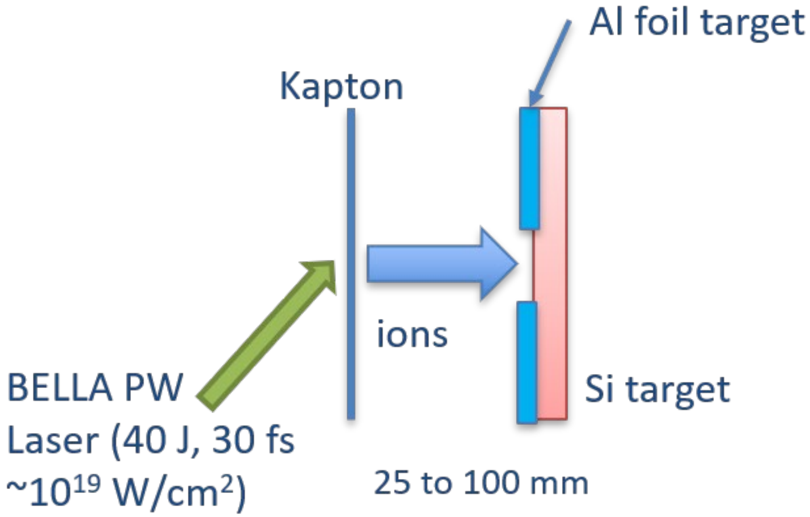
Model of a multi-beam RF linac scaled to 300 keV

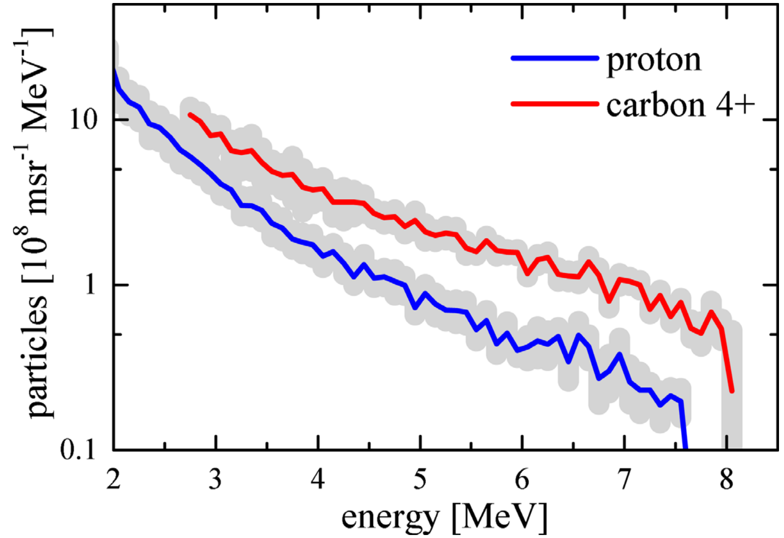
Qing Ji, et al., Rev. Sci. Inst. **92**, 103301 (2021)

# Opportunities for IFE relevant High Energy Density Science with lasers and ion pulses from laser-plasma acceleration








- BELLA PW at Berkeley Lab, 40 J, 30-100 fs, 1 Hz
- Protons and ions to 8 MeV with 2x$10^{19}$ W/cm$^2$, >$10^{21}$ W/cm$^2$ soon
- **"HEDP for IFE" experiments at high rep rate**
  - Fast ignition, coupling of ions to plasmas, EOS, …
  - Protons and heavy ions
  - Diagnostics development with x-rays, gammas, ions, neutrons
  - Part of LaserNetUS (www.lasernetus.org)

S. Steinke, et al., Phys. Rev. Accel. Beams 23, 021302 (2020)

**Contact**: Eric Esarey, BELLA Center, LBNL, EHEsarey@lbl.gov
https://atap.lbl.gov/berkeley-lab-laser-accelerator-bella/

# Accelerator Modeling with new and continuously developing computational tools and expertise for fusion and plasma sciences

BLAST
BERKELEY LAB ACCELERATOR SIMULATION TOOLKIT

## Broad toolset of plasma & accelerator codes

BeamBeam3D, IMPACT, FBPIC, HiPACE++, Warp/WarpX

Applicable to the modeling of
- Plasma acceleration.
- Laser-plasma interactions and plasma mirrors.
- High-field physics (with QED).
- Collisionless shocks.
- Pulsars.
- Magnetic reconnections.
- Intense particle beams.
- Accelerator designs.
- Light sources and particle sources.
- **Beam – plasma interactions for IFE**
- ...

**Contact: Jean-Luc Vay, JLVay@lbl.gov**
https://atap.lbl.gov/accelerator-modeling-program/

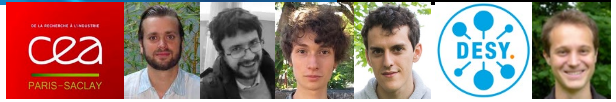
## New generation plasma code

WarpX

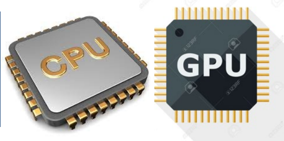
ECP EXASCALE COMPUTING PROJECT

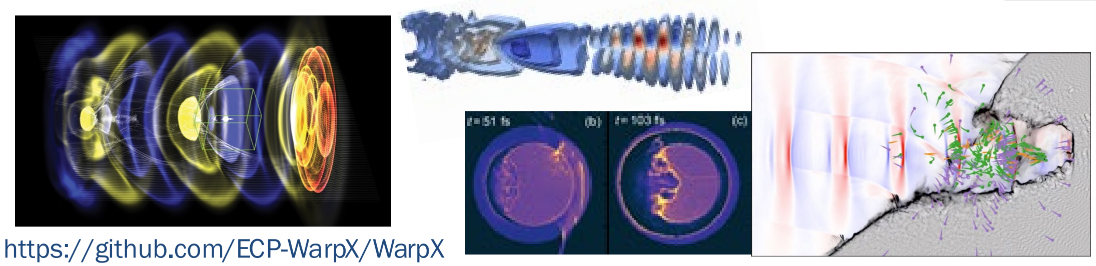
Open source, developed by tightly integrated team of physicists + applied mathematicians + computer scientists


and international collaborations




Runs on single user desktops/laptops up to largest CPU or GPU-based supercomputers



https://github.com/ECP-WarpX/WarpX

# Ion Beams and IFE R&D

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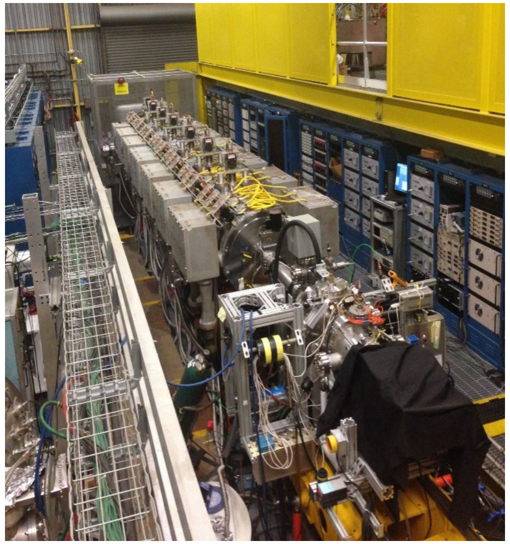

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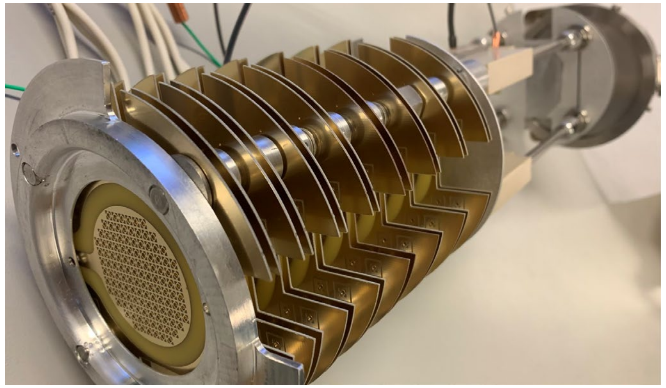
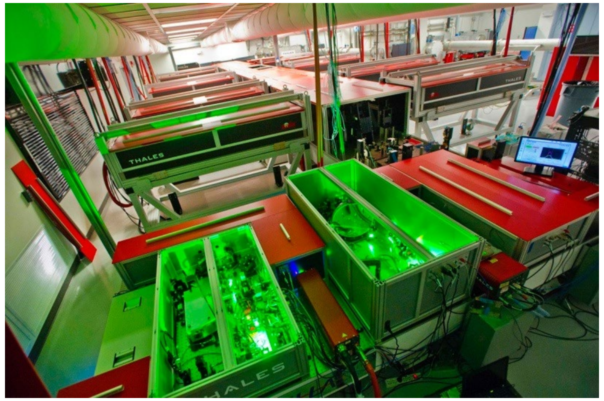


Q. Ji, et al., Rev. Sci. Inst. 92, 103301 (2021)



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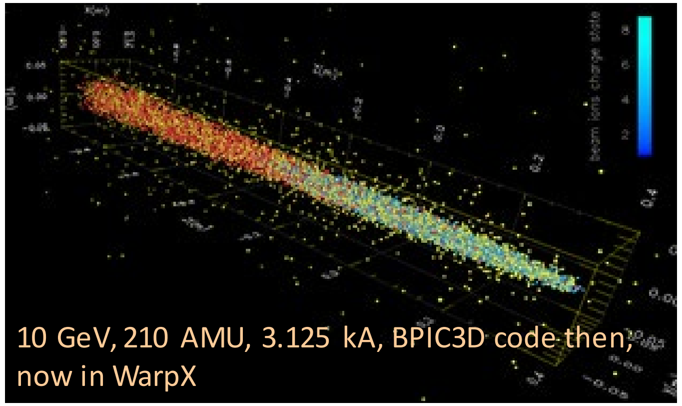


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