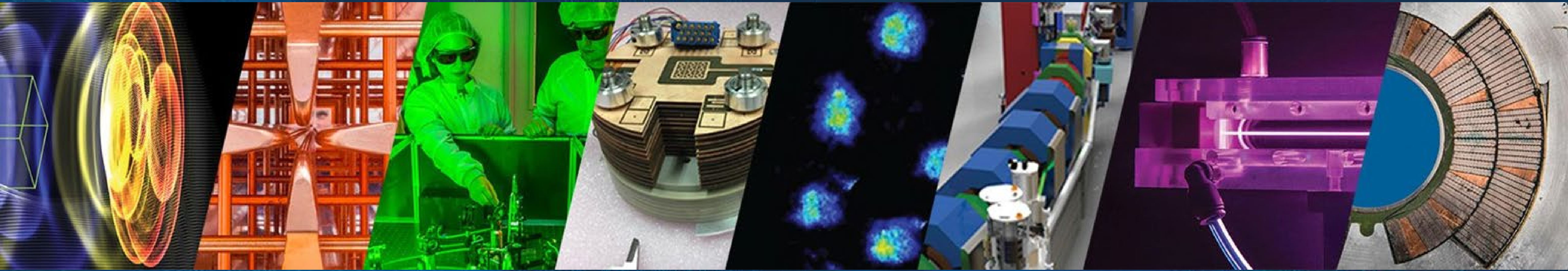
Fusion Energy Sciences at Berkeley Lab – a perspective

Thomas Schenkel, LBNL



Fusion Power Associates, 43rd annual meeting and symposium Dec 7, 2022

BERKELEY LAB

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

U.S. DEPARTMENT OF ENERGY | Office of Science

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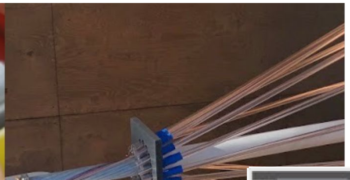
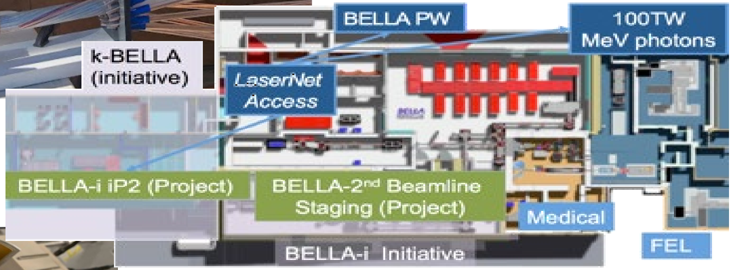
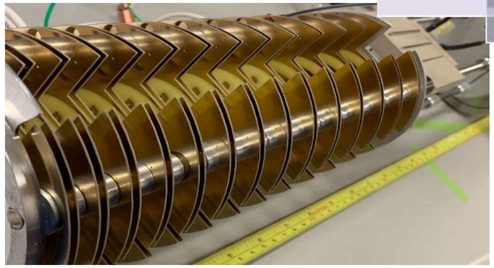
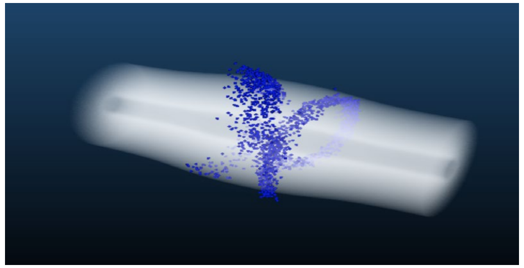
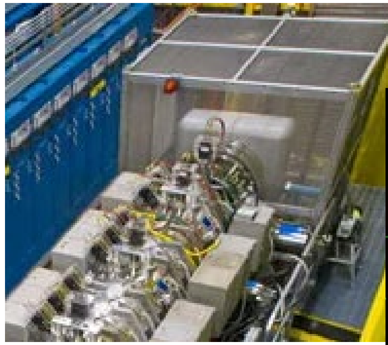
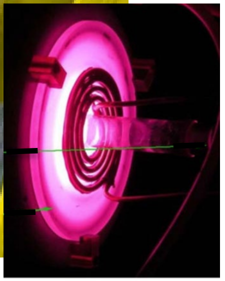
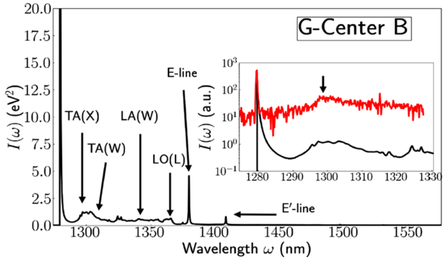
Our R&D portfolio to advance fusion energy sciences at Berkeley Lab

We are developing magnets, lasers and ion beams to advance fusion

1. High Tc superconducting magnets for high-field tokamaks
2. High Energy Density Physics and Inertial Fusion Energy driver R&D with lasers and particle beams
3. Multi-beam ion accelerators for nuclear materials development and plasma heating
4. Modeling and Simulations of beams and plasmas
5. New ideas to develop neutral beam injectors for the burning plasma era
6. Emerging Quantum Information Science capabilities that can support the quest for fusion and benefit from it

https://atap.lbl.gov/

High Field Magnet Leadership for Compact Fusion Plants

- Magnetic field strength is key to fusion reactor size: High Temperature Superconductors (HTS) have potential for 2x field
- LBNL leads the High Energy Physics US Magnet Development Program → leverage for fusion
  - Started: FES Test Facility Dipole + commercial partnerships (Commonwealth, General Atomics…)

FES Magnet Program @ LBNL

Understand and mitigate the degradation in HTS fusion cables → Design and develop technologies for robust fusion magnet systems → **Enable the next FES facility**

- Advanced diagnostics
- Demountable joints
- Radiation effects
- Other emerging needs, e.g., system-level protection

Cable and magnet R&D | Enabling R&D

Vision:

Leverage Berkeley Lab's expertise and experience to deliver on the FES Long Range Plan for fusion power

https://bcmt.lbl.gov/

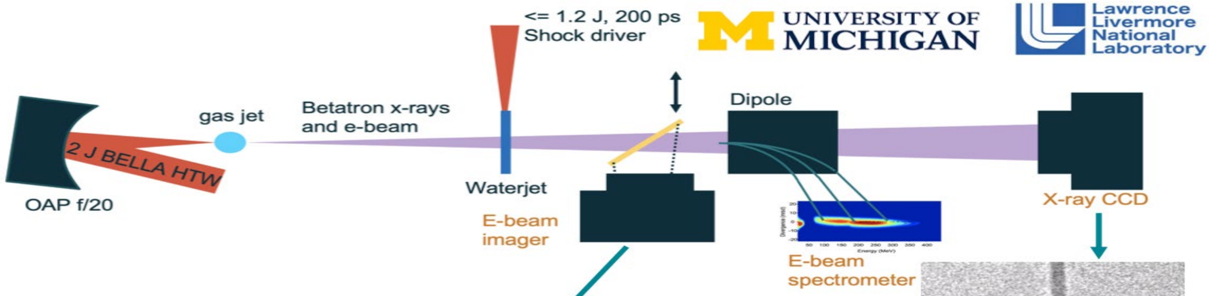
Contact: SOPrestemon@lbl.gov

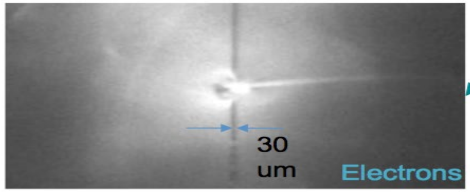
Ultra-intense Lasers and Ion Beams for Inertial Fusion Energy

- Inertial fusion requires high gain
  - Precision physics – diagnostics
  - Fast particle beam ignitors can reduce driver energy requirements and increase gain
- LaserNetUS & user programs at BELLA Lasers can advance solutions
  - Precision photon sources and hydrodynamic measurements
  - Multi-MeV, intense ion beam pulses at our new FES short focal length, high contrast, dedicated line

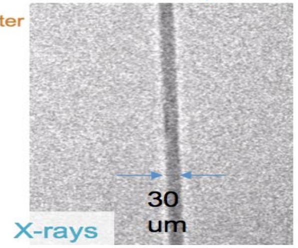
- **Contact: EHEsarey@lbl.gov**

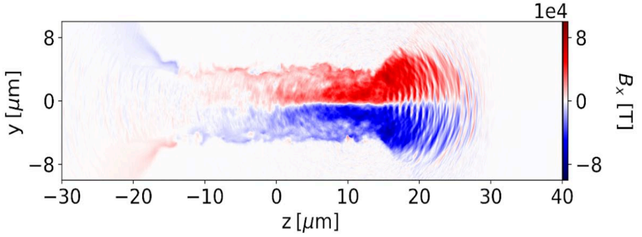
- Sahel Hakimi, et al., “Laser–solid interaction studies enabled by the iP2 BELLA PW”, Phys. Plasmas 29, 083102 (2022)

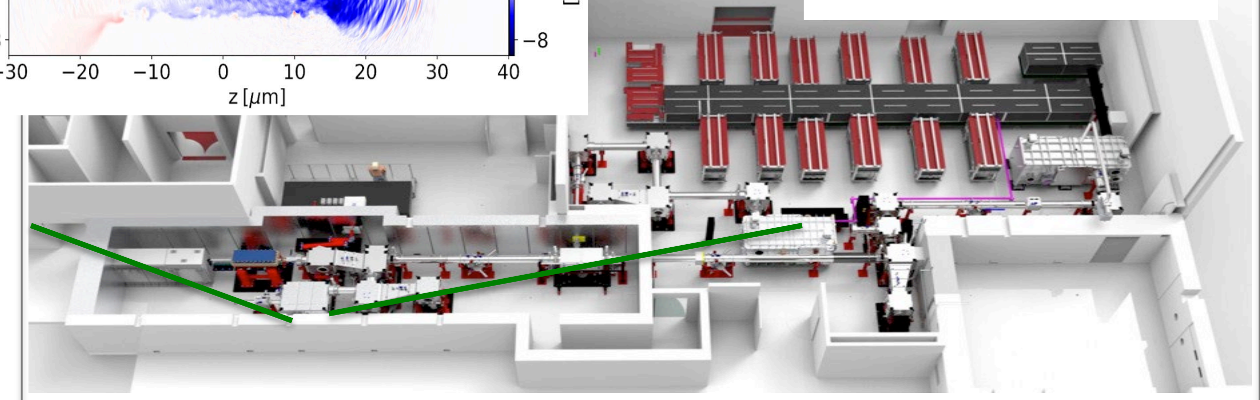




Precision photon source probes & hydrodynamics

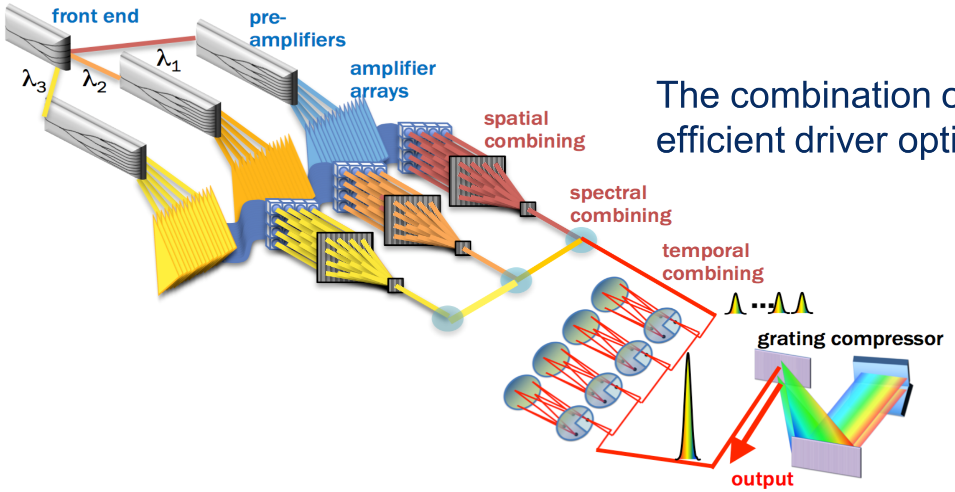




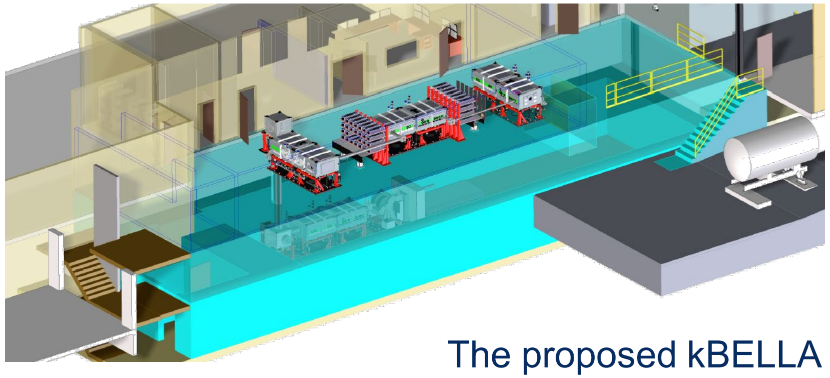


Development of efficient Laser and Ion Beam Drivers for Inertial Fusion

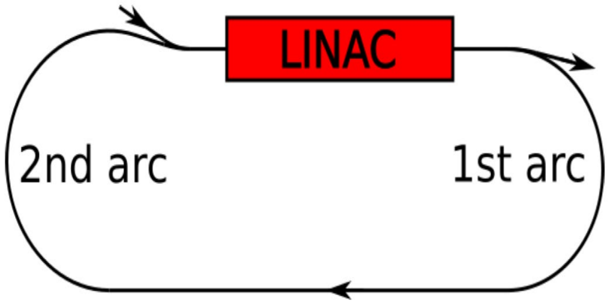
- Driver at 10’s of percent efficiency are required for IFE
  - But current laser drivers < 1% (flash lamps)
- High efficiency laser technology leverages our development of lasers for particle accelerators (electrons and ions)
  - Diode pumping, fiber combination, paths to ≥30%
- Historical leadership in heavy ion driver development (HIF) at Berkeley Lab, HIF is (still) an attractive future option
  - Ion accelerators are efficient (>30%), mitigate risk of damage to final optics from fusion targets
  - New opportunities, new ideas for low cost heavy ion accelerator architectures



The combination of fibers offers efficient driver options

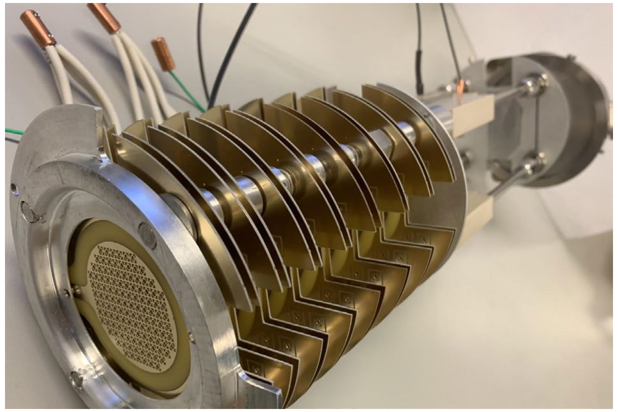


The proposed kBELLA high average power laser

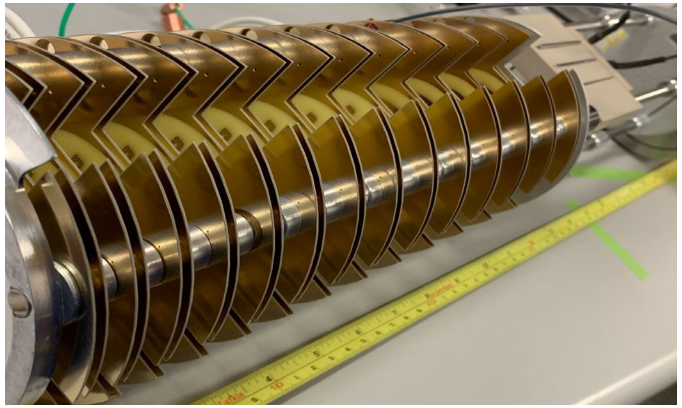


K. Hwang, J. Qiang, PR AB 20, 040401 (2017)

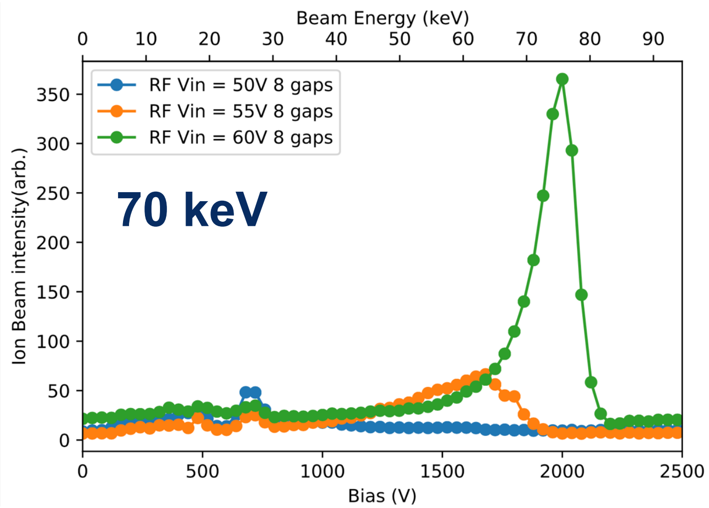
We are developing a new class of multi-beam ion accelerators for nuclear materials development and plasma heating

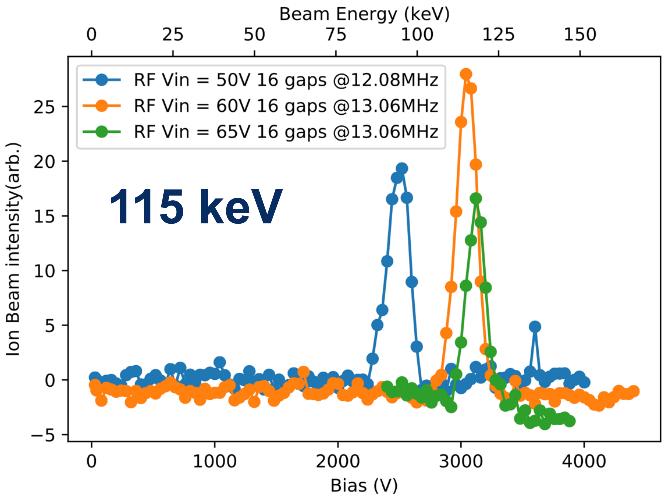


8 RF gaps, 16 wafers (4”), 112 beamlets, 12 cm



16 RF gaps (28 cm)





Next steps:

- ≥150 keV
- 13 MHz, 27 MHz, 54 MHz, …
- >1% duty factor
- beam power scale-up …

- Qing Ji, et. al., Rev. Sci. Instr. 92, 103301 (2021)

- **Funded by ARPA-E**

arpa·e CHANGING WHAT'S POSSIBLE

BERKELEY LAB ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP U.S. DEPARTMENT OF ENERGY Office of Science

Modeling and Simulations of beams and plasmas –
WarpX is highly relevant to many fusion and plasma physics topics

WarpX

ECP EXASCALE COMPUTING PROJECT

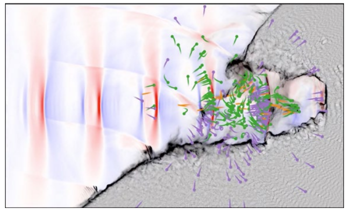
- WarpX is **an advanced Particle-In-Cell code**
  - Winner of the 2022 Gordon Bell Prize
- Fully **open-source & documented**
  `github.com/ECP-WarpX/WarpX`
  `warpx.readthedocs.io`
- Runs on largest **CPU or GPU-based supercomputers**, as well as on single-user laptops or desktops

Large team of contributors from worldwide institutions

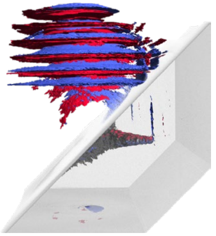
BERKELEY LAB · Lawrence Livermore National Laboratory · SLAC · cea PARIS-SACLAY · DESY. · CERN

Many fusion-relevant features in WarpX

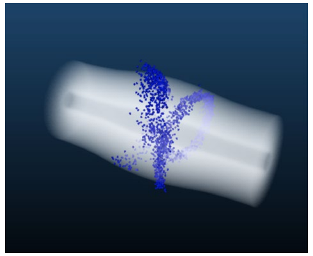
- Full support for **laser-plasma** interactions



- Monte-Carlo modules for:
  - fusion reactions
  - Coulomb collisions
  - ionization physics
  - …



- Support for arbitrarily-shaped **metallic boundaries** (e.g., from STL files)



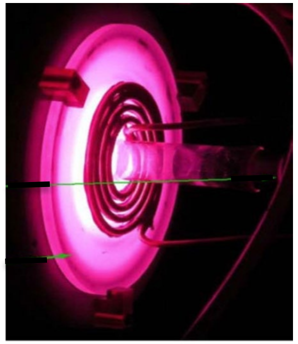
- **Python interface** allows coupling with **custom user code/modules**.

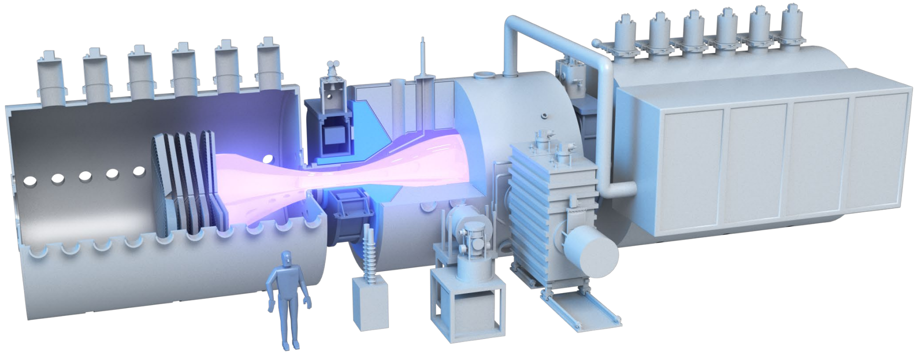
Contact: Jean-Luc Vay (LBNL, jlvay@lbl.gov)

New ideas to develop neutral beam injectors for the burning plasma era

- Berkeley Lab has developed ion beams and neutral beam injectors for plasma heating back in the 1980s
- We are active in the development of novel high power ion beams (positive and negative)
- Efficient neutral beam injectors are needed for plasma heating and control in the burning plasma era
- Opportunities for new private-public partnerships and collaborations
  - Emerging partnership with REALTA Fusion

REALTA FUSION

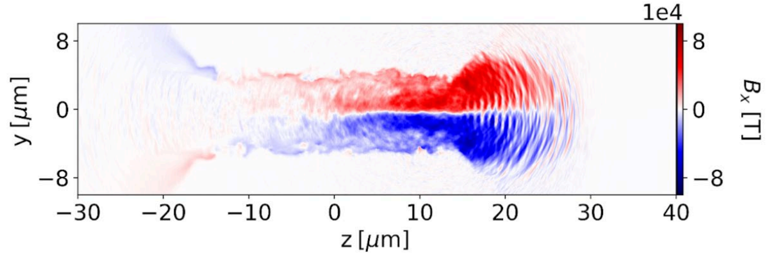


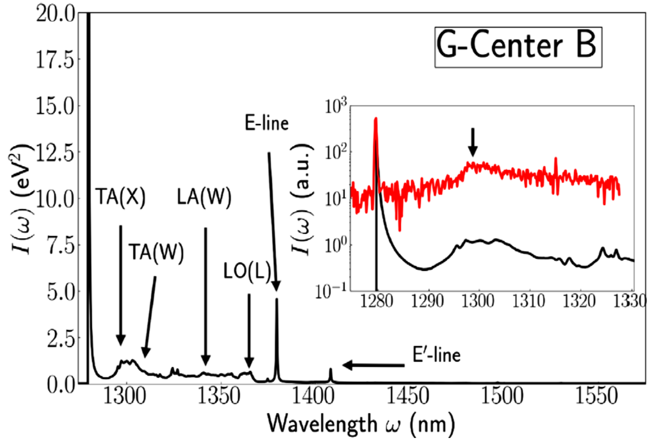


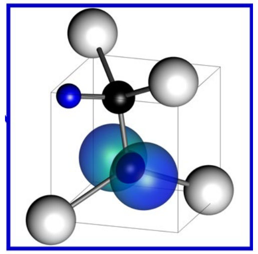
- Photos of the 150 kV injector with R&D ion beamline at Berkeley Lab, and an RF driven hydrogen ion source with external antenna (top). Bottom: Graphic of WHAM++, the Wisconsin HTS Axisymmetric Mirror.

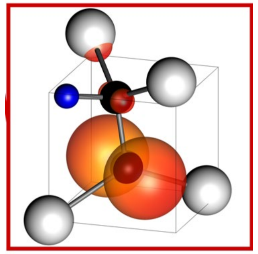
Emerging Quantum Information Science capabilities can support the quest for fusion and benefit from it

- Advances in quantum sensing, communication, and simulations can be adapted to advance fusion
- Beams and plasmas from fusion energy sciences can support advancements in quantum information science









- W. Redjem, et al.,“Defect engineering of silicon with ion pulses from laser acceleration”, https://arxiv.org/abs/2203.13781
- S. Hakimi, et al., “Laser–solid interaction studies enabled by the iP2 BELLA PW beamline”, Phys. Plasmas 29, 083102 (2022)
- V. Ivanov, et al., “Effect of Localization on Photoluminescence … of Silicon Color Centers”, https://doi.org/10.1103/PhysRevB.106.134107
- E. Albertinale, et al., “Detecting spins by their fluorescence with a microwave photon counter”, **Nature** 600, 434 (2021)
- https://quantnet.lbl.gov/, https://quantumsystemsaccelerator.org/

Outlook: R&D to advance fusion energy sciences at Berkeley Lab

We are developing magnets, lasers and ion beams to advance fusion

1. High Tc superconducting magnets for high-field tokamaks
2. High Energy Density Physics and Inertial Fusion Energy driver R&D with lasers and particle beams
3. Multi-beam ion accelerators for nuclear materials development and plasma heating (IFE, MFE, MTF, …)
4. Modeling and simulations of beams and plasmas
5. New ideas to develop neutral beam injectors for the burning plasma era
6. Emerging Quantum Information Science capabilities

- **Let's work together to advance fusion, through collaborations, private-public partnerships, Infuse, LaserNetUS, …**