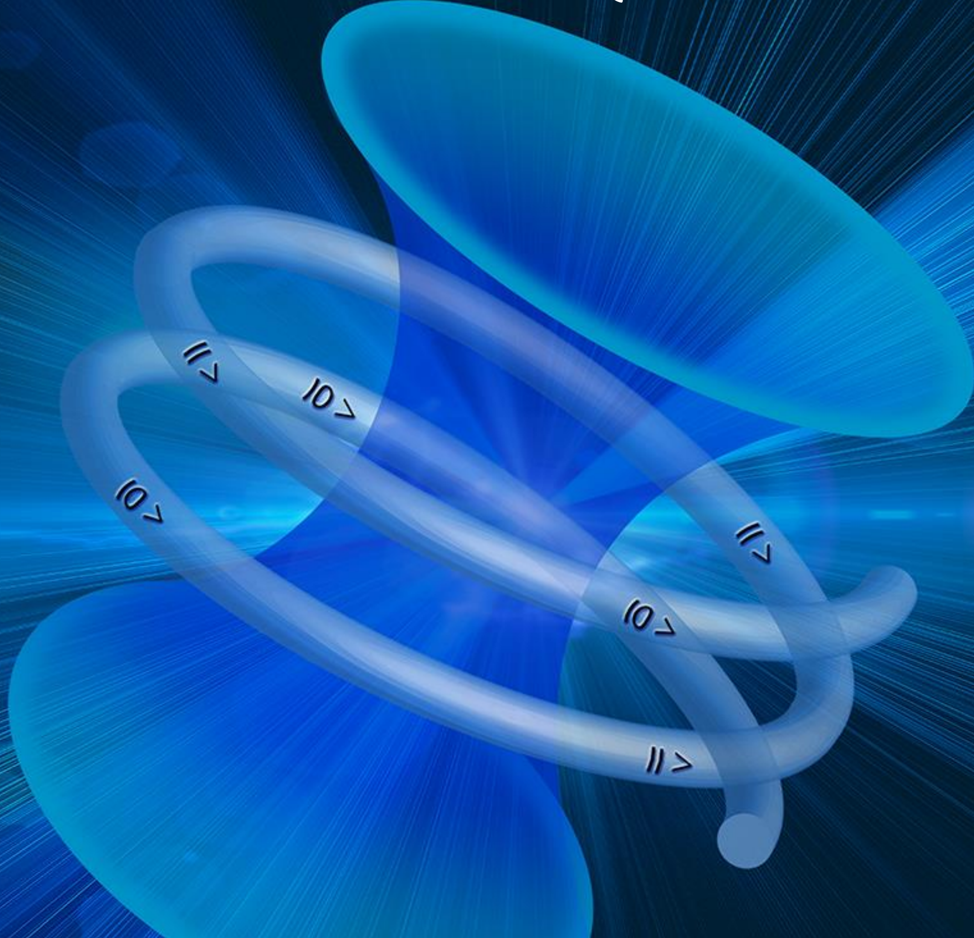
Report on the FES Roundtable on Quantum Information Science



Thomas Schenkel[1] and Bill Dorland[2]

[1]Lawrence Berkeley National Laboratory, [2]University of Maryland

FESAC meeting, Dec. 06, 2018

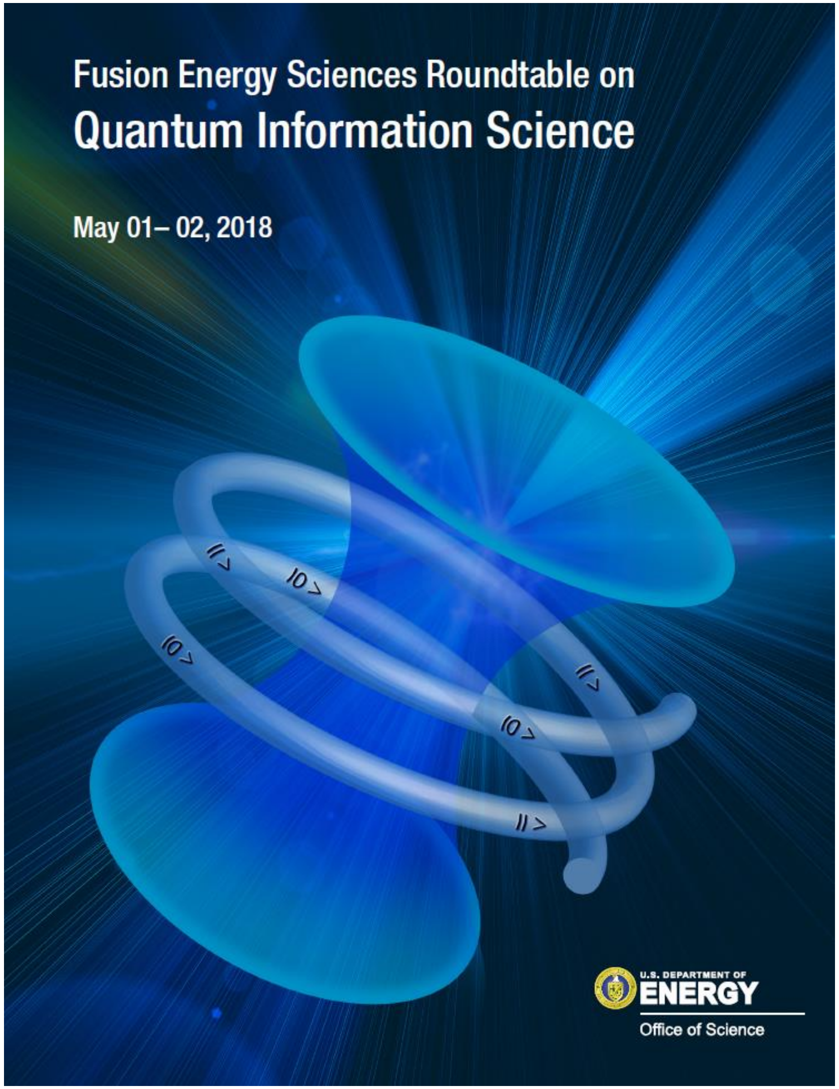
FES Roundtable on Quantum Information Science
May 1-2, 2018, Gaithersburg, MD 20877

Chair: Thomas Schenkel, Lawrence Berkeley National Laboratory
Co-Chair: Bill Dorland, University of Maryland

Roundtable Charge: The purpose of this roundtable is to explore the unique role of FES in the rapidly-developing interdisciplinary field of Quantum Information Science (QIS). Among the objectives of the meeting are to:

- Identify fundamental science supported by FES that could advance QIS development; and
- Explore QIS applications that could have a transformative impact on FES mission areas, including fusion and discovery plasma science.

The goal is to provide FES with a set of priority research opportunities that can inform future research efforts in QIS and build a community of next-generation researchers in this area. The findings of this roundtable meeting will be summarized in a report that should be submitted to FES within a month after the meeting.



https://science.energy.gov/fes/community-resources/workshop-reports/

Executive summary

- FES has long been a key driver in high performance computing
- There is broad interest and enthusiasm in the Fusion Energy Sciences community to deeply engage in Quantum Information Science
- Emerging QIS offers many opportunities to advance the mission of FES
  - quantum algorithm development for classical physics and quantum problems
  - opportunity for early success cases of QIS applications in the near term
  - quantum sensing for advanced plasma diagnostics
- FES research can impact QIS
  - techniques from high energy density science expand our reach in quantum materials synthesis and qubit formation
  - and can lead to new forms of ultrafast, plasma based optics for QIS
  - plasma science tools can advance simulations and control of quantum systems
- Workforce development – QIS themes will attract talent to support the mission of FES

- **Can emerging Quantum Information Science advance Fusion Energy Sciences ?**
  - **Quantum for Fusion**

- **Can research in Fusion Energy Sciences advance Quantum Information Science ?**
  - **Fusion for Quantum**

- Priority Research Opportunities for Quantum Information Sciences to advance Fusion Energy Sciences (Quantum for Fusion)

- Priority Research Opportunities for Fusion Energy Sciences to advance Quantum Information Science (Fusion for Quantum)

Panel members from academia, national labs and industry

• Andrew Baczewski	Sandia National Laboratory	
• Bill Dorland	University of Maryland	co-chair
• Malcolm Boshier	Los Alamos National Laboratory	
• Rip Collins	Laboratory for Laser Energetics, Rochester	
• Jonathan Dubois	Lawrence Livermore National Laboratory	
• Andrew Houck	Princeton University	
• Travis Humble	Oak Ridge National Laboratory	
• Nuno Loureiro	MIT	
• Chris Monroe	University of Maryland	
• Francis Robicheaux	Purdue University	
• Thomas Schenkel	Lawrence Berkeley National Laboratory	chair
• Scott E Parker	University of Colorado	
• Edward Startsev	Princeton Plasma Physics Laboratory	
• Matt Trevithick	GOOGLE	
• George Vahala	College of William and Mary	
• **John Mandrekas**	**FES, POC**	

Priority Research Opportunities for Quantum Information Sciences to advance Fusion Energy Sciences (Quantum for Fusion)

PRO 1: Reconceptualizing classical plasma physics problems for quantum computation

PRO 2: Quantum simulation for fusion problems (near term)

PRO 3: Quantum sensing for plasma diagnostics

Priority Research Opportunities for Fusion Energy Sciences to advance Quantum Information Science (Fusion for Quantum)

PRO 4: High energy density laboratory plasmas science for novel quantum materials

PRO 5: Relativistic plasma science for qubit control and quantum communication

PRO 6: Plasma science tools for simulation and control of quantum systems

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PRO 1: Reconceptualizing classical plasma physics problems for quantum computation (long term)

Scientific challenges

- Opportunity to re-conceptualize classical plasma physics problems for quantum computation
- Identify computational advantage vs. classical computing (exponential, like Shor, polynomial, or none, …)

Barrier to overcome

- Not clear at all yet how to do this mapping and what the impact will be
- There are already early quantum algorithms for sets of (non-homogeneous) linear differential equations that could be applied to plasmas and we can develop these further for high impact plasma problems

Quantum system requirements

- Challenge to find quantum algorithms that provide speed-up for plasma problems that are multi-scale, linear and non-linear, driven, dissipative,…
- General challenge to have access to error corrected quantum computers
- Specific quantum computer architectures for plasma problems?

Potential impact

- Potential for large increases in computational power with quantum algorithms that run on error corrected quantum computers
- Examples: Can problems of magneto-hydrodynamic stability be restated in the language of quantum gates ?
- Can we use quantum algorithms for faster full-wave modeling of (RF) plasma heating ?

PRO 1: Reconceptualizing classical plasma physics problems for quantum computation (long term)

- Not known what physical platform will scale to the required number of well connected, error corrected qubits
- Current estimate is that we will need ~100 to 1000 physical qubits per logical qubit and >1000 logical qubits
- Time line to “quantum supremacy” ?
- Time line to error corrected, “universal” quantum computer era ?
- General purpose or specialized quantum computer architectures ?
- Opportunity to map high impact problems in plasma physics and Fusion Energy Sciences into the language of future quantum computers
- **By aiming for the long-term now, we will also enable short-term progress because we will develop the language and experience required to participate in the quantum information transformation fully**

PRO 2: Quantum simulation for fusion problems (near term)

Scientific challenges

- What can we achieve with 50 to 100 noise qubits in the next 5 to 10 years ?
- Identify selected problems in classical plasma physics and quantum problems with high near term impact potential in plasma science and fusion research, including fusion materials

Barrier to overcome

- Co-design algorithms with the QIS community
- We should engage now so that plasma physics (our fundamental primitives) are expressed in a language that enables plasma quantum simulations

Quantum system requirements

- Build community of users and developers, in plasma - QIS
- Plasma science and fusion energy sciences can be part of the larger QIS community as it emerges

Potential impact

- Advances in simulations of transport properties, equations of state, plasma – wall interactions
- Two-dimensional electron gas in Jellium model as a stepping stone ?
  - R. Babush, et al., PR X 8, 011044 (2018)

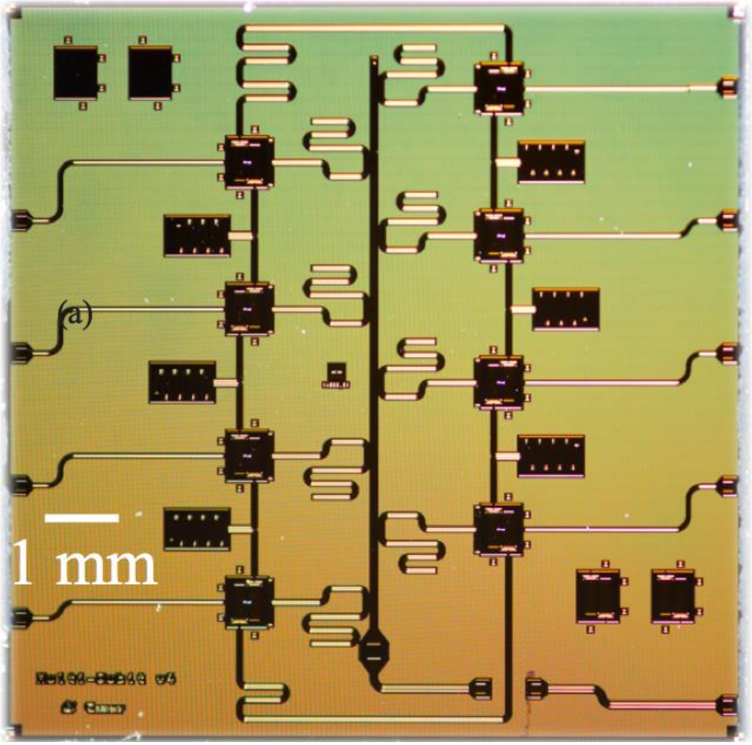
PRO 2: Quantum simulation for fusion problems (near term)

"Quantum algorithm for non-homogeneous linear partial differential equations"

J. M. Arrazola, T. Kalajdzievski, C. Weedbrook, S. Lloyd

- Example: application to Poisson's equation

https://arxiv.org/abs/1809.02622



8 qubit chip, Irfan Siddiqi, UC Berkeley and LBNL

http://berkeleyquantum.org

PRO 3: Quantum sensing for plasma diagnostics

Scientific challenges

- Quantum sensing is rapidly developing and is an early high impact area of QIS
- Opportunity to identify quantum sensing approaches that can advance plasma diagnostics

Barrier to overcome

- Communication between communities to connect emerging quantum sensing techniques with plasma diagnostics needs
- Explore impact potential for series of plasma environment

Quantum system requirements

- Adapt quantum sensing for plasma diagnostics
  - Quantum optics utilizing quantum correlations and squeezed states
  - Spin based magnetometry for fusion materials development
  - …

Potential impact

- Quantum sensing is highly promising for adaptation to selected problems in plasma diagnostics to enhance sensitivity, selectivity and speed

PRO 3 – Quantum sensing for plasma diagnostics

- Quantum sensing is highly promising for adaptation to selected problems in plasma diagnostics to enhance sensitivity

- Broad opportunity to tap into and connect to the Quantum Sensing communities
  - Use of quantum properties such as squeezed light can enhance sensitivity and enable faster measurements with increased specificity
  - Quantum optics for diagnostics of Tokamak plasmas, (lab)-astro, …

- While we identified this opportunity, we had less expertise on the panel. Another effort would be required to flesh this out properly

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PRO 6: Plasma science tools for simulation and control of quantum systems

PRO 4: High energy density laboratory plasmas science for novel quantum materials

Scientific challenges

- Unique capability to explore a new generation of quantum matter, "quantum communities" just starting to recognize capabilities of high energy density facilities.
- Dynamic synthesis, recovery, kinetic barriers, path (P,T,r,s) control. Real time monitoring-reaction pathways, structure, bonding, "thermodynamic" state, transport from linear response and beyond.

Barrier to overcome

- Need a community of plasma/HEDP scientists, chemists, computational and materials scientist to develop a new generation of experiments, theory and simulations, to characterize atomic- to meso-scale, understand, recover, and synthesize these new quantum states of matter.
- Rapid data collection/analysis to explore phase space

FES system requirements

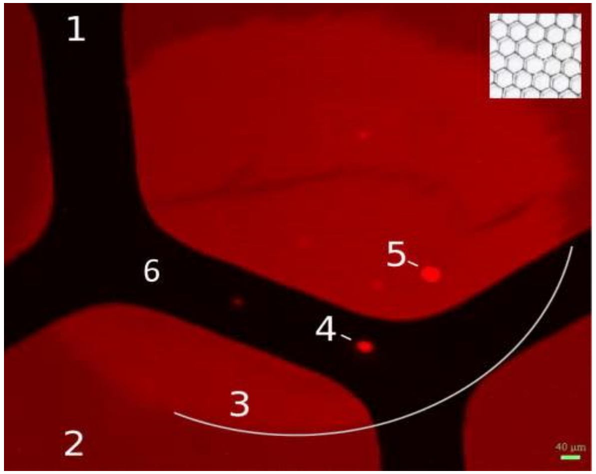
- High energy density facilities can now access new "quantum regimes", now not only at low temperature.
- Novel capabilities to form of new quantum matter phases by synthesis, recovery, kinetic barriers, path (P,T,r,s) control.
- Real time monitoring of reaction pathways, structure, bonding, "thermodynamic" state, transport.

Potential impact

- Synthesis of advanced color center qubits
- A new window into quantum materials and processes, e. g. higher temperature superconductors and topological insulators
- Super hard/strong lightweight materials
- High temperature version of Bose-Einstein condensate
- Quantum nuclear reactions (pycnonuclear)
- Periodic table for extreme conditions

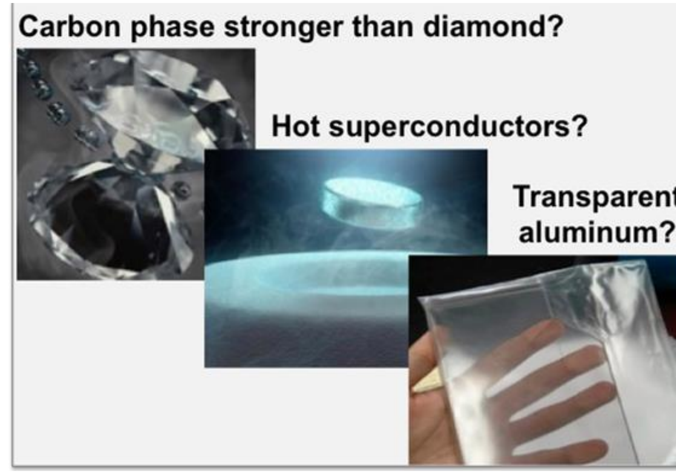
PRO 4: High energy density laboratory plasmas science for novel quantum materials

Advanced spin-photon qubits

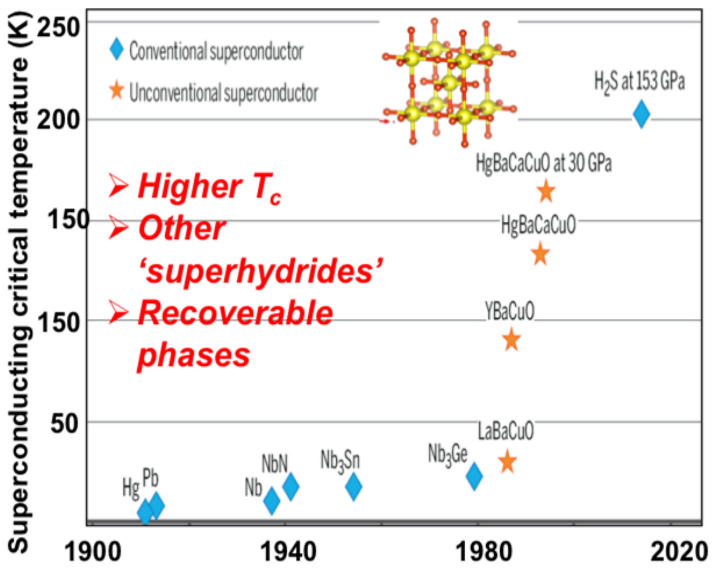


Nitrogen -vacancy color centers in diamond formed by local heating to 0.5 eV (J. Schwartz, et al., JAP 116, 214107, 2014)

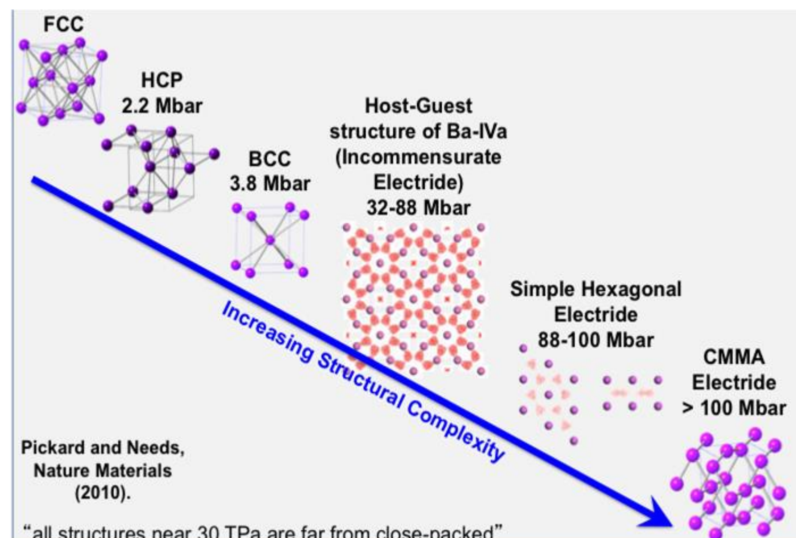
New quantum materials



Very high temperature superconductors



New basic quantum material science



PRO 5: Relativistic plasma science for qubit control and quantum communication

Scientific challenges

- Quantum sensing offers promise of 1/N vs 1/sqrt(N) scaling in error
- Quantum communication can double classical channel capacity
- However, reaching large N limit with quantum is hard with weak light matter interactions
- Optical computing requires nonlinearity

Barriers to overcome

- Quantum light (squeezed/entangled) is a scarce commodity, sources generally in the few photon regime.
- Crystal-based nonlinear optics have low parametric conversion efficiency and place limits on maximum incident power/intensity
- Manipulation of quantum states of light in the optical and above requires strong light matter interactions.

FES system requirements

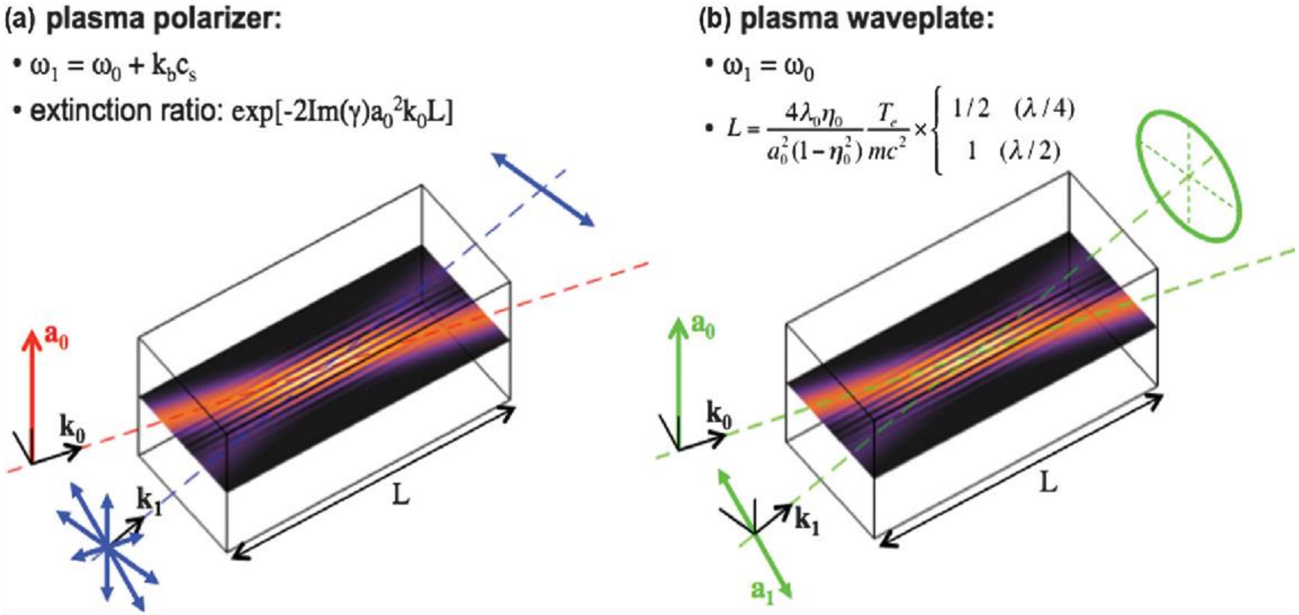
- Nonlinearity is a key part of efficiently preparing, addressing, & accessing quantum states
- Nonlinearity generates distinct energy level spacings & ensures that each energy level can be uniquely addressed
- Controllable strong light matter interactions
- Able to operate at high powers

Potential impact

- Light-plasma interactions may provide a route to high amplitude and highly entangled / squeezed states of light.
- Potential for high intensity beams of coherent states, squeezed states and entangled states from plasma-light interaction
- Especially useful for the high-power regime needed for high-bandwidth communications

PRO 5: Relativistic plasma science for qubit control and quantum communication

- Plasma-based mirrors, diffraction gratings, and wave-plates
  - Ultrafast optical switches based on laser-plasma interactions
- Absorption resonances in plasmas could have the potential to slow light
  - Plasmas could be more efficient than crystals at parametric down-conversion



” Dynamic Control of the Polarization of Intense Laser Beams via Optical Wave Mixing in Plasmas” P. Michel, L. Divol, D. Turnbull, J. D. Moody, Phys. Rev. Lett. 113, 205001 (2014)

PRO 6: Plasma science tools for simulation and control of quantum systems

Scientific challenges

- Enable high fidelity quantum simulations using ion traps with 100-1000 ions
- Realistic Doppler and sub-Doppler cooling to theoretical limits (0.1 mK). Infrequent neutral collisions and dynamics of ion crystal/plasma.

Barrier to overcome

- Ions with 0.1 mK or lower temperatures.
- Improved laser cooling models. Collisions with background neutrals. Variational integrator. Impurity species occupying a lattice location.

FES system requirements

- FES can provide first principle nonlinear classical and semi-classical simulation of the ions in the trap. Information important for quantum simulation studies (planar eigenmode spectrum).
- FES theory well positioned with tools available and has a research culture dedicated to developing first-principle plasma models.

Potential impact

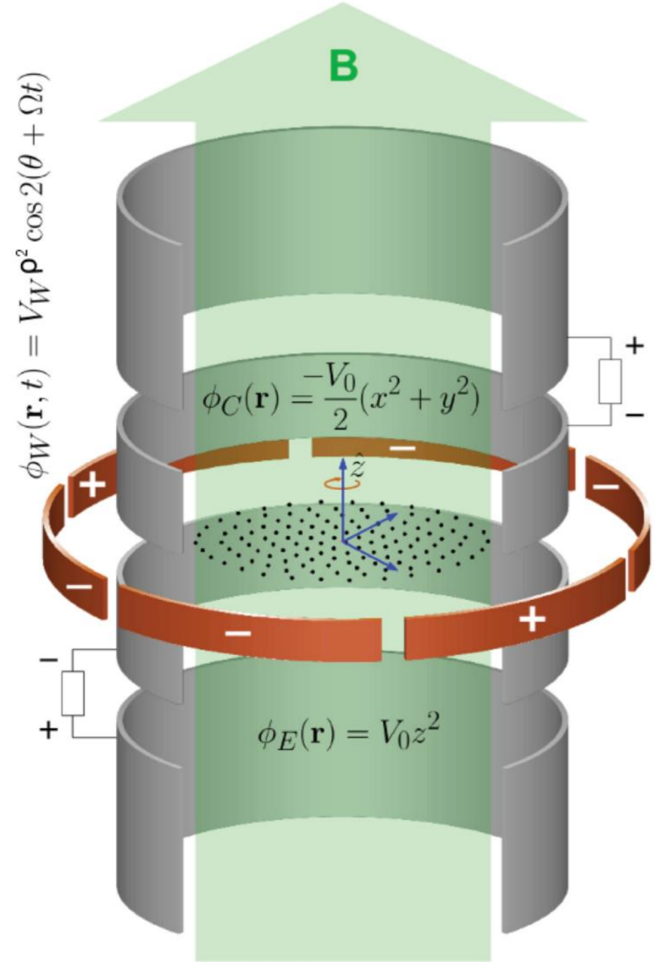
- Enable high fidelity quantum simulations and study viability of ion traps for future systems and scaling.
- Follow-up to recent high impact examples:

Many-body entanglement. Bohnet et al. Science (2016)

Measurement of 1/40th of zero point quantum fluctuations. Gilmore et al. PRL (2017)

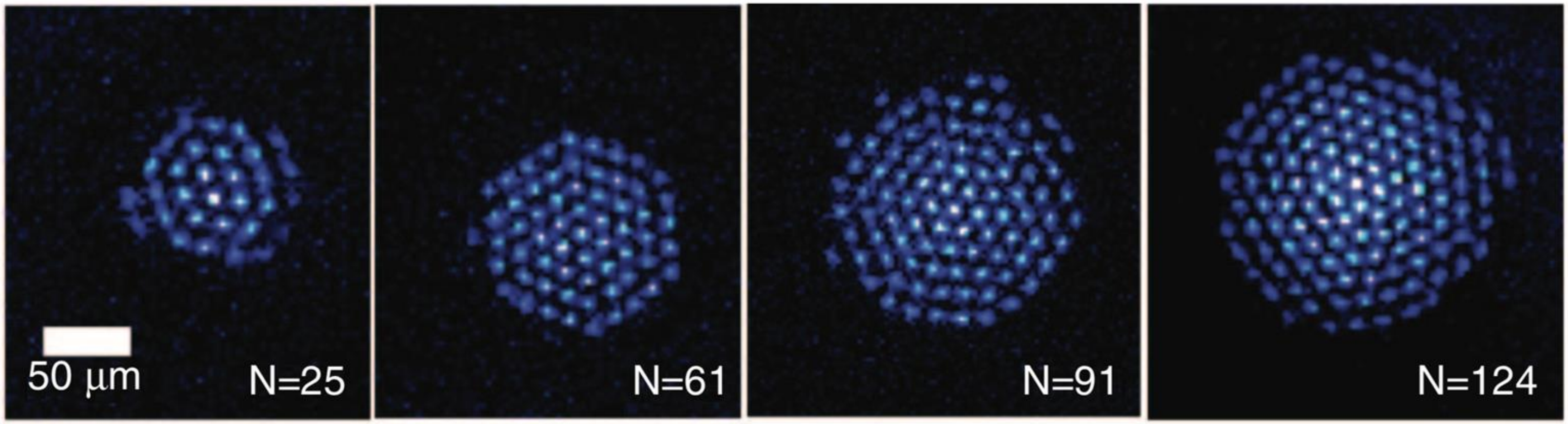
PRO 6: Plasma science tools for simulation and control of quantum systems

- Ion traps are used for quantum simulation and other potential QIS applications.
- Laser cooling of normal modes can be modeled accurately using nonlinear classical and semi-classical simulations.
- Simulation provides very useful information for trap operation and development.
- FES theory provides expertise in advanced numerical methods for modeling coupled nonlinear ion equations.

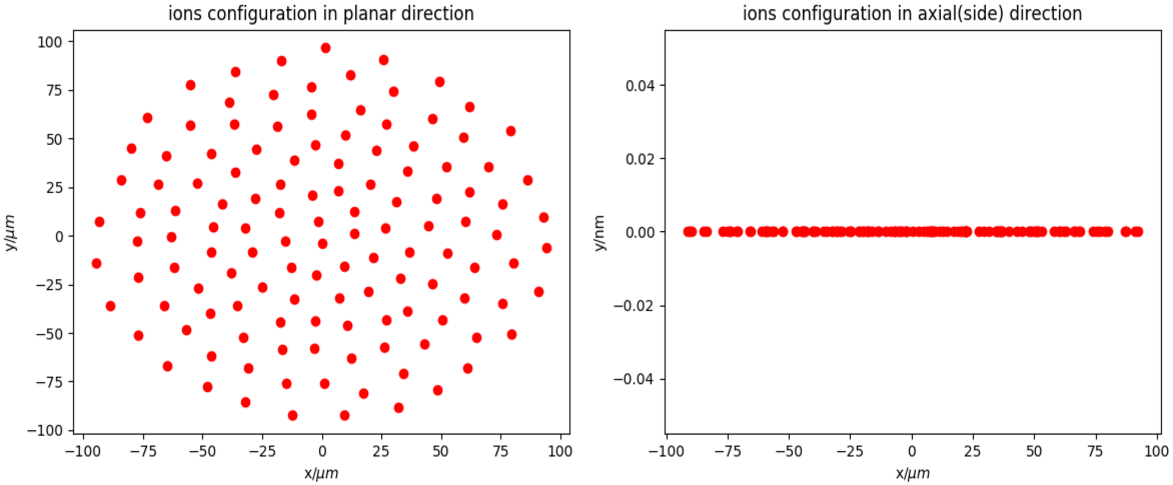


Wang, PRA 2013

PRO 6: Plasma science tools for simulation and control of quantum systems



Bohnet et al., Science 352, 1297 (2016)



Top and side view of ion configuration simulated (127 ions)

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Outlook

- The questions of QIS are long term and have great scientific depth as well as technology impact potential across many areas

- Opportunity for FES to deeply engage where QIS dimensions can become an integral part of the research portfolio

- Avoid hype, lead with science (as always)

- Basic research needs workshops ?
  1. QIS for FES
  2. FES for QIS

- Pilot program ?
- FOA ?
- …