Fusion, beams and qubits

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Outline

1. Beams
2. Qubits
3. Fusion
4. Outlook

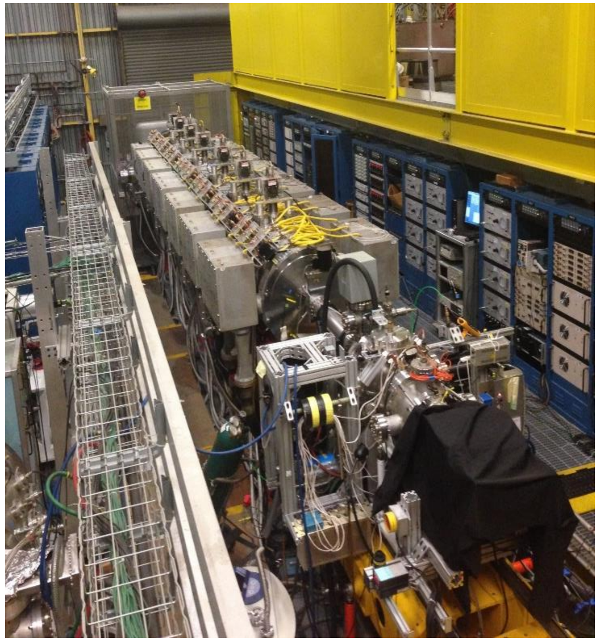
Beams

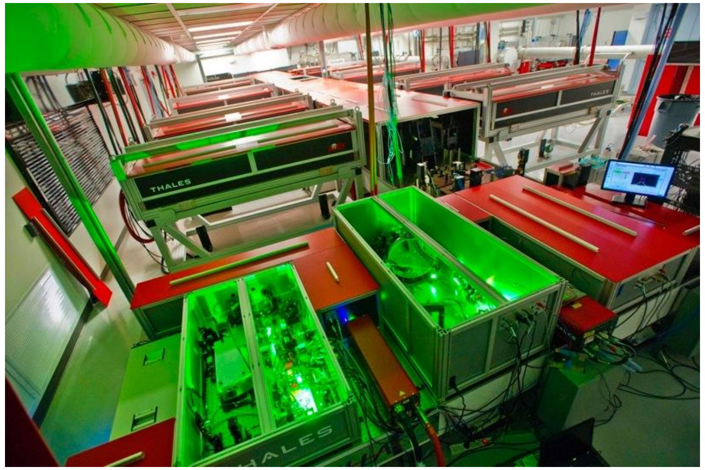
Outline - Beams

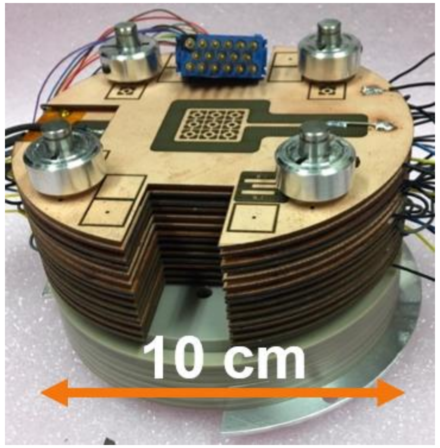
a. Induction linac, NDCX-II

b. Laser-plasma acceleration, BELLA

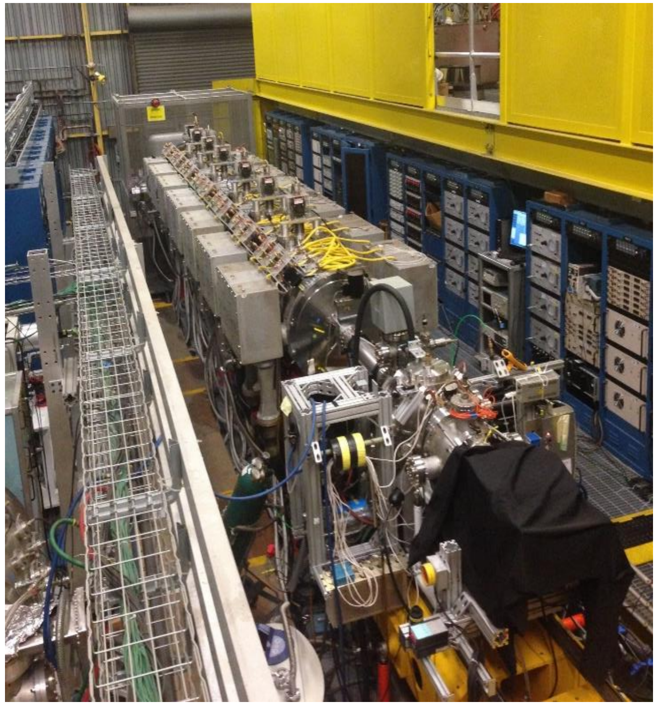
c. MEMS based RF-linacs

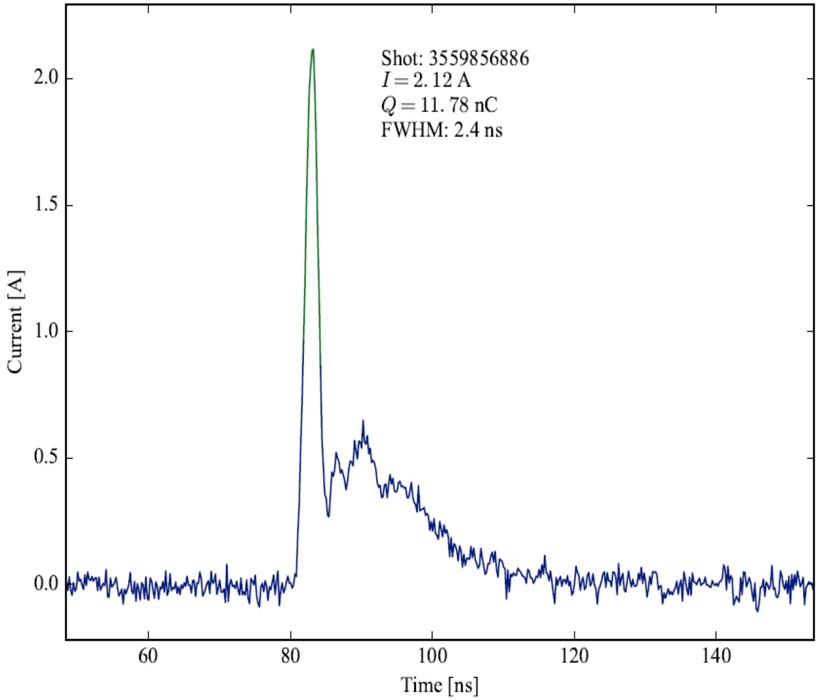


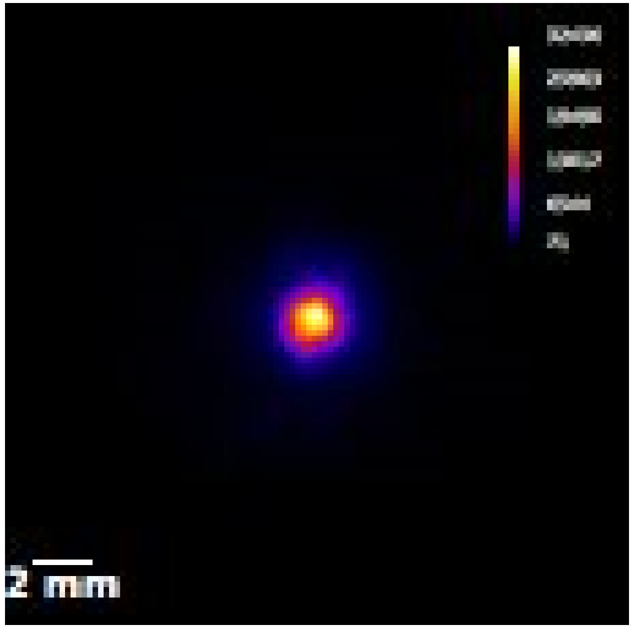




Intense, pulsed ion beams by neutralized drift compression in an induction linac – NDCX-II







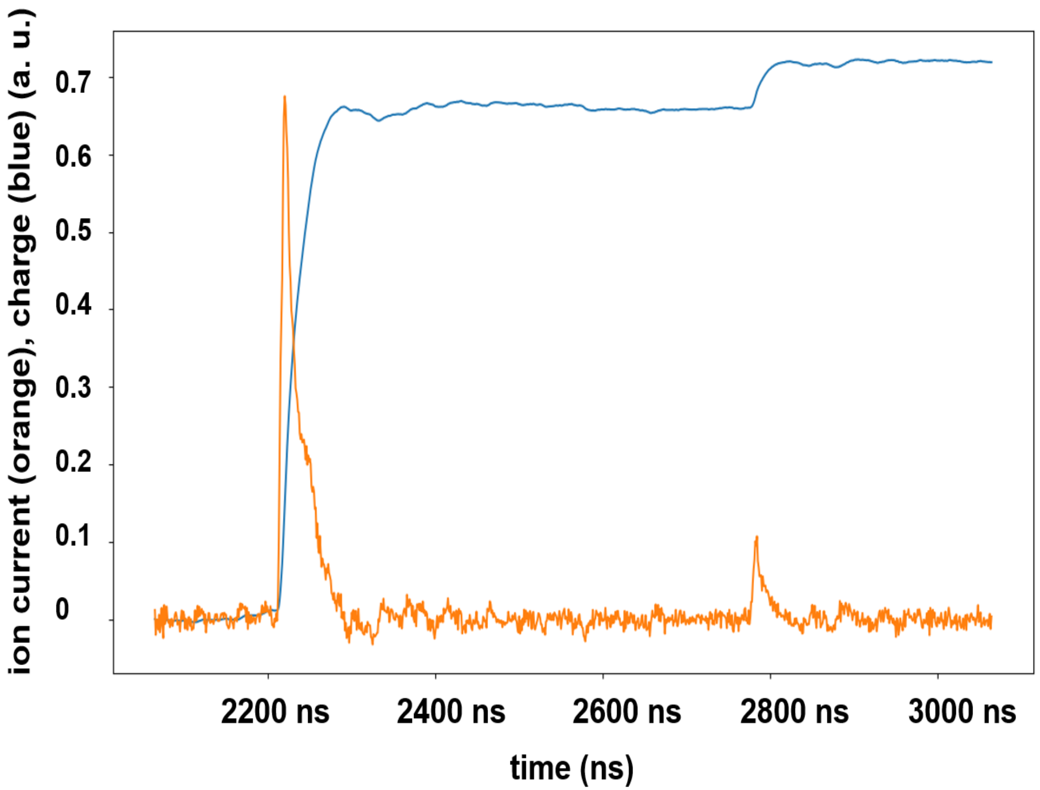
- NDCX-II at Berkeley Lab

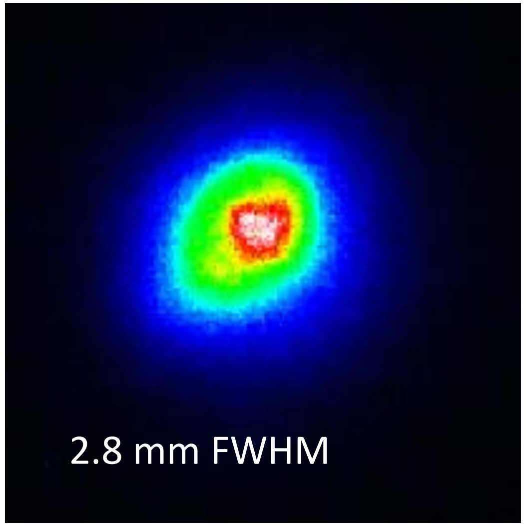
- 1.1 MeV (He^+), 12 nC (7.5×10^{10} ions), 13 mJ
- Routinely ~5×10^{11} ions/cm^2/pulse

- Pulse length: 2 to 10 ns, spot size ~1 to 5 mm radius, 1 MeV protons, He^+, Li^+, …
- Peak current: ~0.1 to 2 A
- Repetition rate ~1 shot / minute

- **P. A. Seidl, et al., NIM A (2015)**

Pulses of 1 MeV protons from NDCX-II

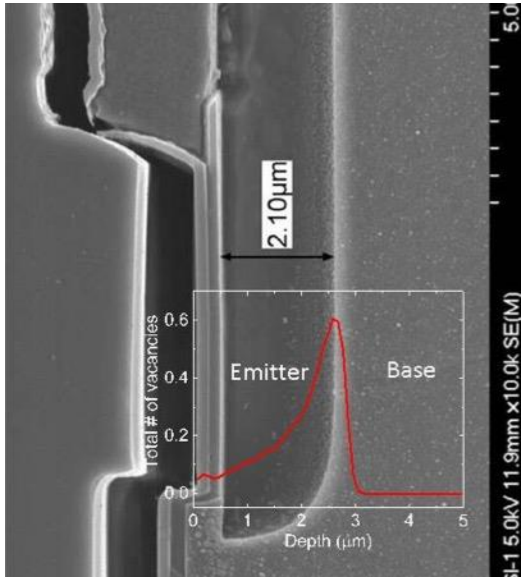




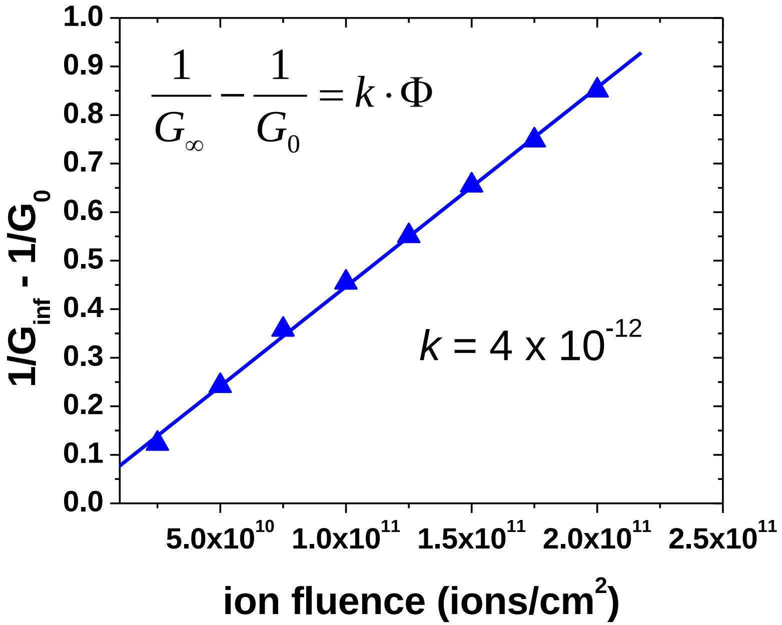
- Proton pulses with peak currents of 0.1 to 1 A, 10 to 20 ns FWHM, ~1 to 5E10 protons/pulse.
- The proton energy is 1 MeV with a range in silicon of 16 um.

J.-H. Bin, et al., Rev. Sci. Instrum.90, 053301 (2019)

Pulsed ion irradiation of electronic devices



B. Aguirre, et al., IEEE Trans. Nucl. Sci. (2017)



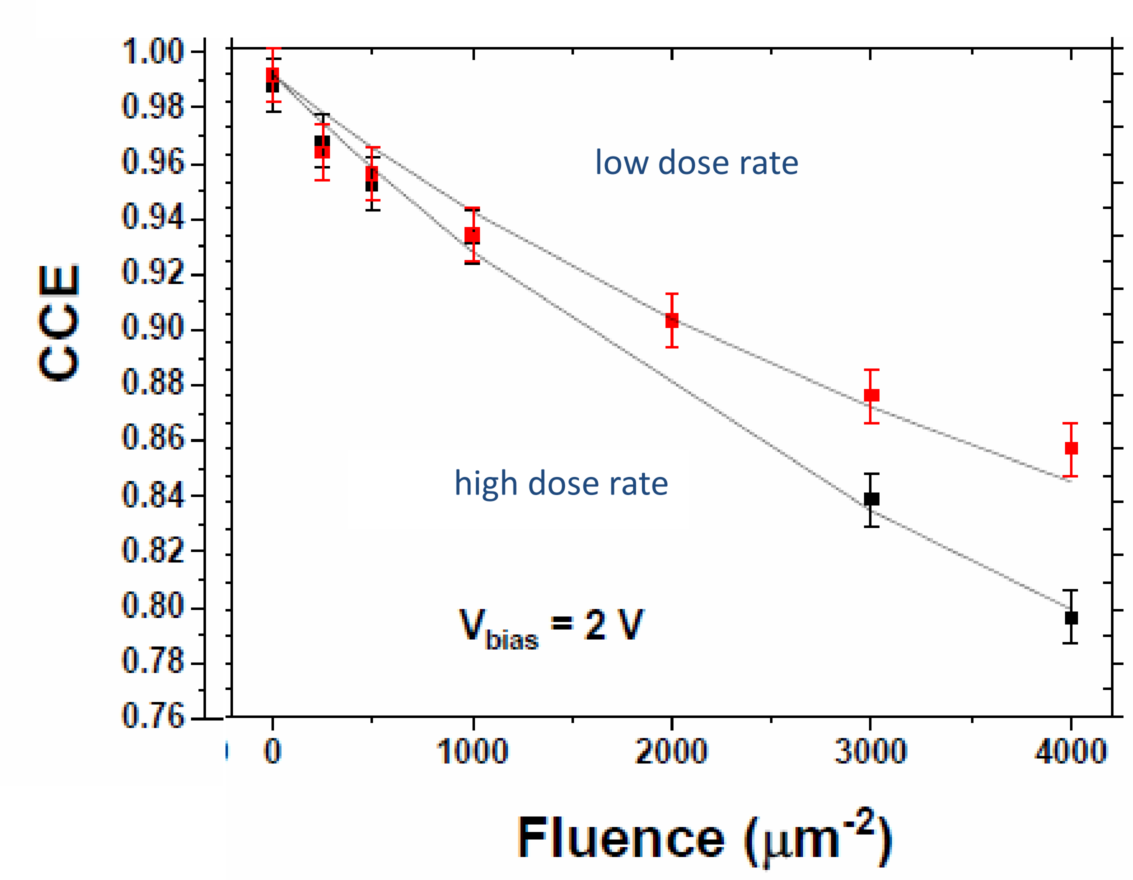
Example of a measured Messenger-Spratt curve to determine the damage constant.

- B. A. Ludewigt, et al., Journal of Radiation Effects, Research and Engineering Vol. 36, No. 1, April 2018

- Flux = $10^{18} - 10^{19}$ ions/cm^2/s per ~10 ns long helium ion pulse (1 MeV).
- Measured late-time gain degradation as a function of ion fluence for a series of shots up to 2.5×10^{11} ions/cm^2.

- At higher dose rates, $>10^{11}$ ions/cm^2/shot, we observe increased damage factors, changes in DLTS defect signatures and evidence for enhanced defect annealing, *B. Aguirre, et al, submitted; co. E. Bielejec, Sandia National Lab*

We probe dynamic annealing and dose rate effects on damage accumulation and charge collection efficiency with diodes



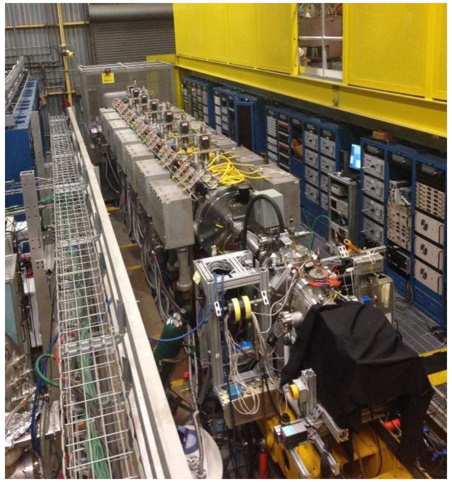
- S5821 Hamamatsu pin diodes, NDCX-II shots (high dose rate) compared to experiments at other labs with low dose rate
- 1 MeV Helium ions, 1E11 ions/cm^2/shot
- Balance of defect formation, annealing and formation of extended defects
- Co. E. Vittone, J. Garcia-Lopez, G. Vizkelethy, E. Bielejec, et al., IAEA_CRP_F11020 (2018)

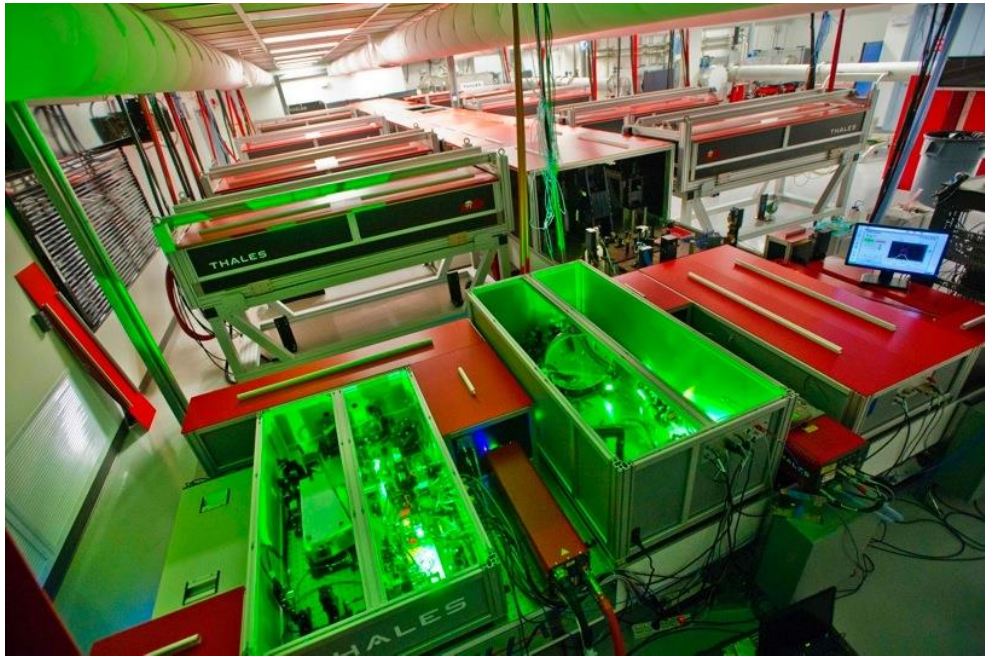
Outline - Beams

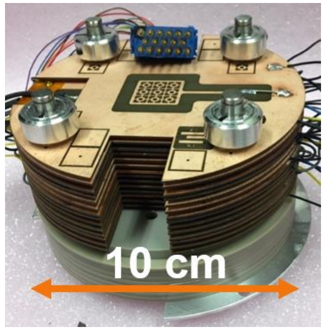
a) Induction linac, NDCX-II

b) Laser-plasma acceleration, BELLA

c) MEMS based RF-linacs





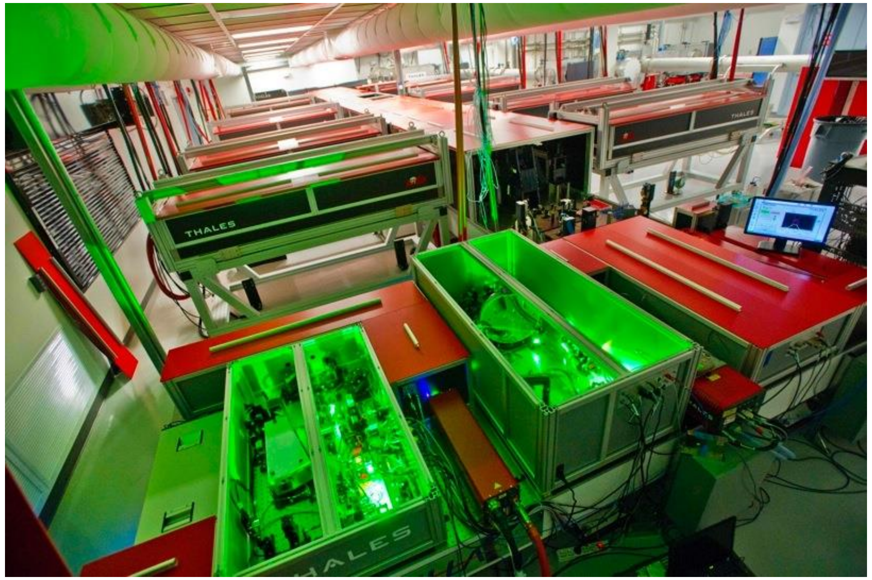


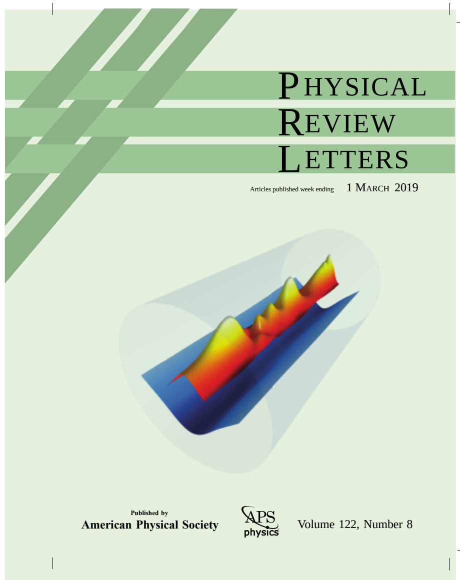
We use the BELLA PW laser to form pulses of high energy electrons (GeV) and now also ions (MeV)

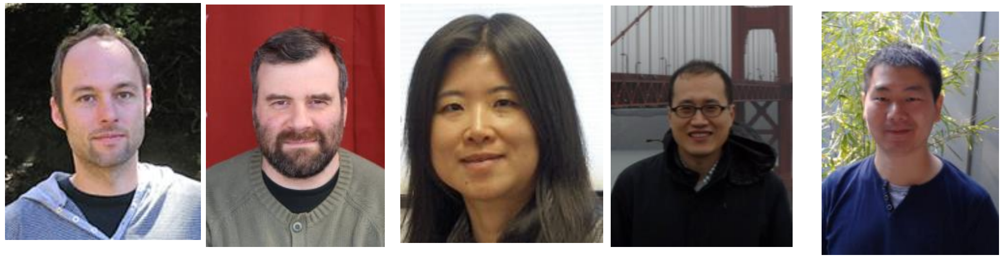
- BELLA – 1 PW at 1 Hz
- 40 J, 33 fs, ~2x10^{19} W/cm^2

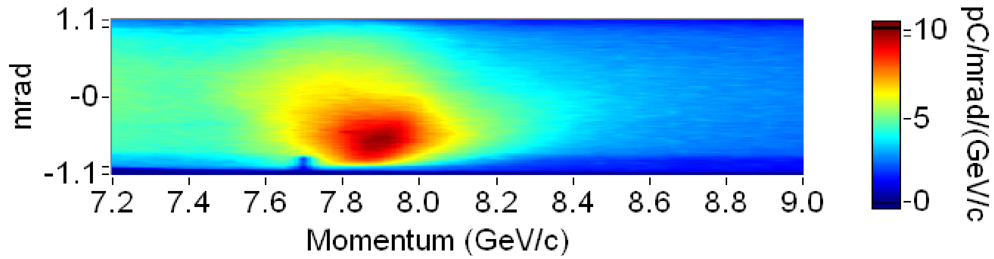
- The primary mission of BELLA is to master laser-plasma acceleration of electrons

- The BELLA Center is now part of LaserNetUS, a network of collaborative user facilities, (www.LaserNetUS.org)



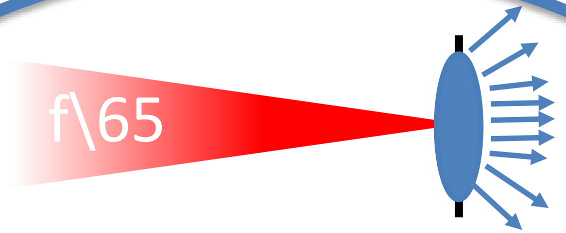




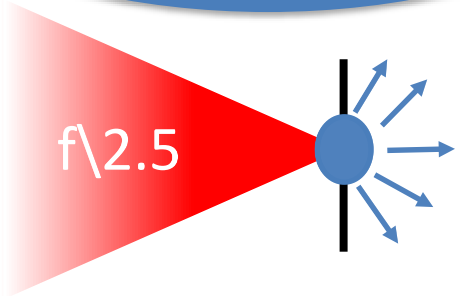


A. J. Gonsalves, et al. Phys. Rev. Lett. 122, 084801 (2019)
K. Nakamura et al., IEEE J. Quant. Electr. 53, 1200121 (2017)

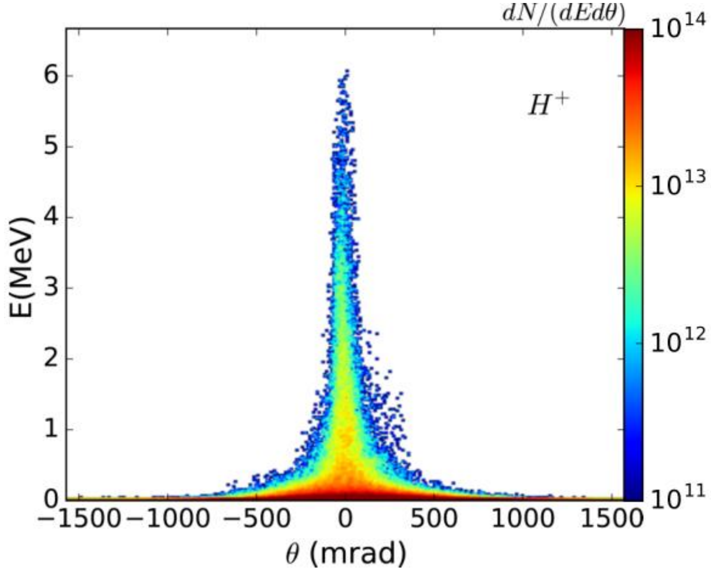
PW Laser Operating with Long Focal Length: Short Focal Length Beamline with a Dedicated Target Chamber in Progress HEDLP in LaserNetUS

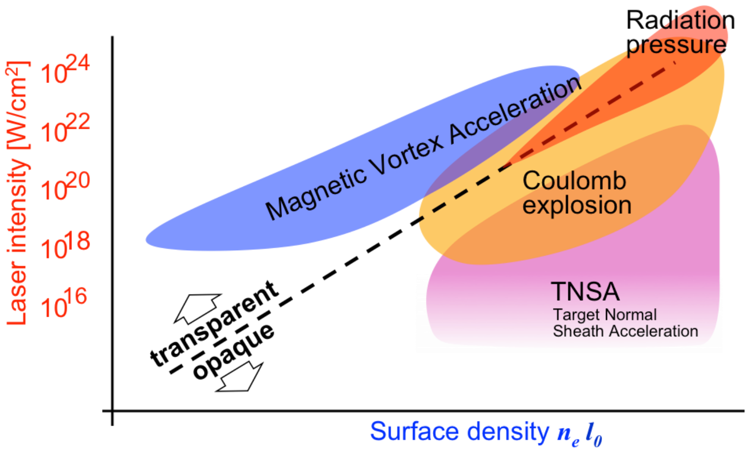


in operation now, 2x10^{19} W/cm^2 , large laser spot, 100 μm, low divergence ion pulses with 10^{12} protons

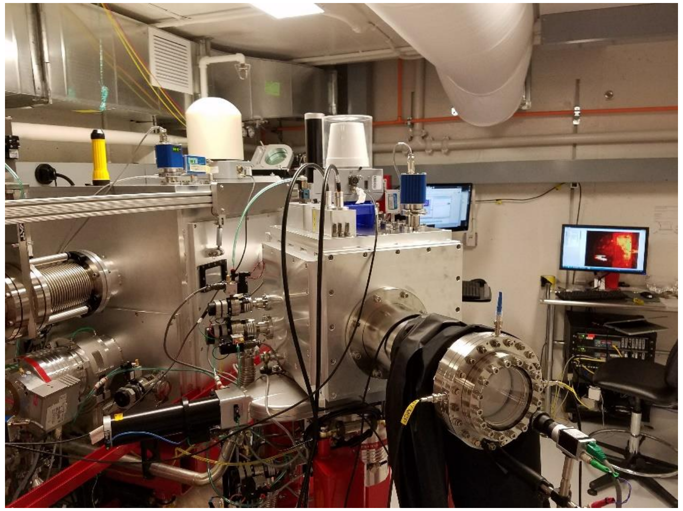


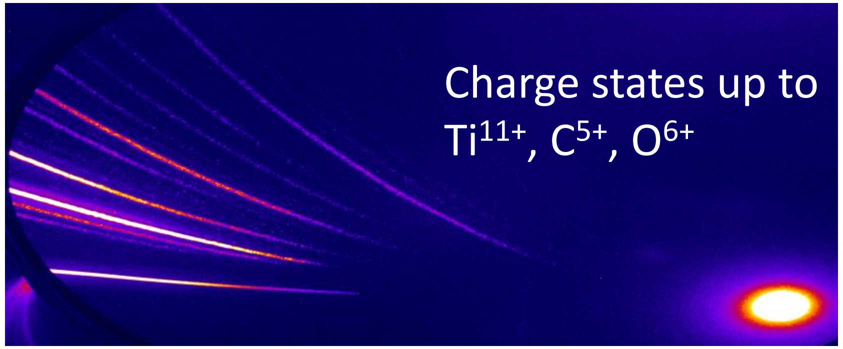
Under construction, >10^{21} W/cm^2, small laser spot, ~10 μm, (ultra)-relativistic plasma science at 1 Hz, advanced ion acceleration, high energy ions (>100 MeV)

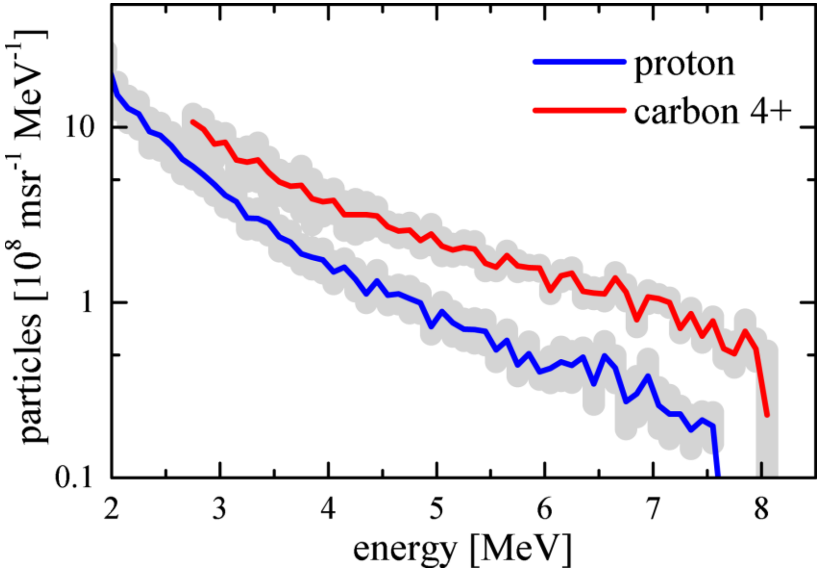


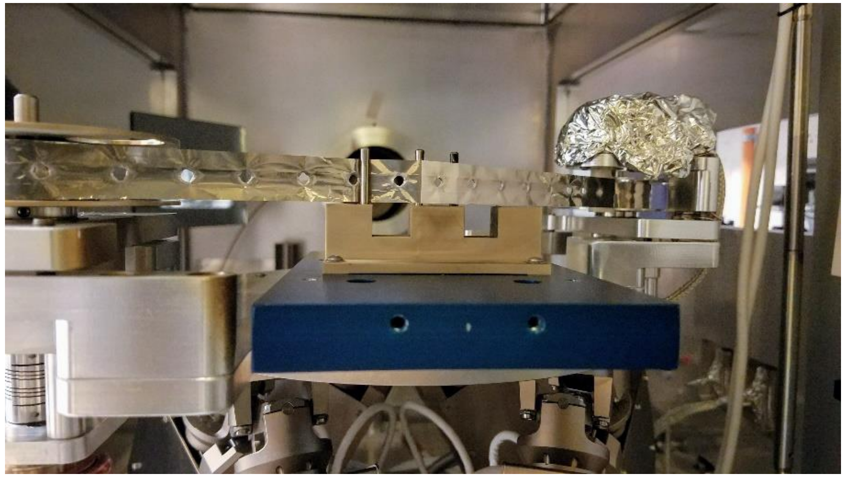


Ion acceleration at BELLA



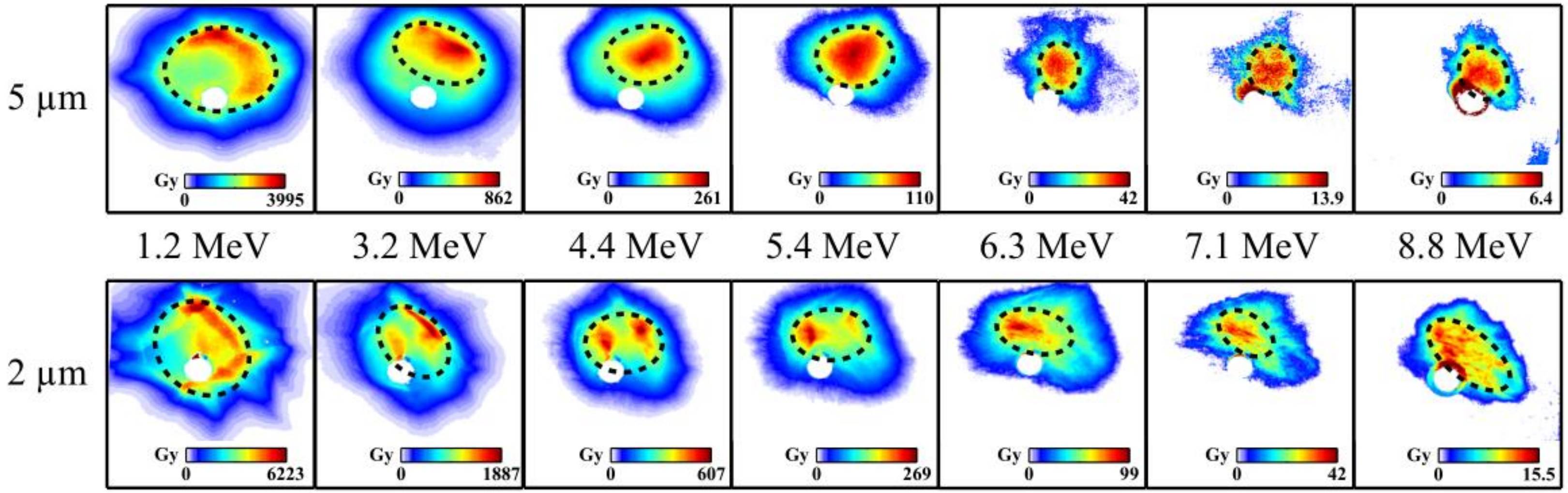


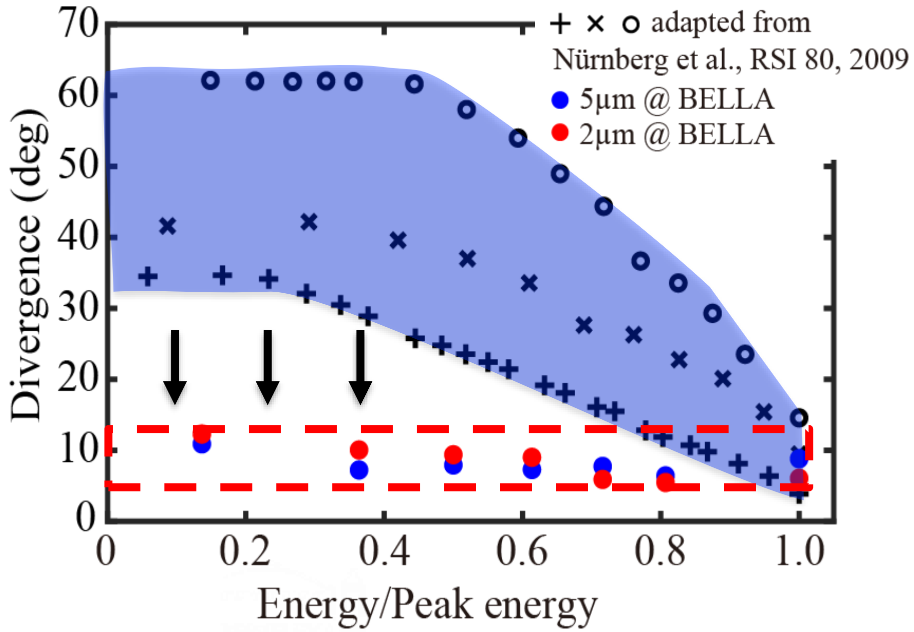




- ~10^{12} total number of MeV ions (from Thomson parabola) and >10^{13} lower energy ions (from ex situ sample analysis by Secondary Ion Mass Spectrometry, SIMS)
- tape drive targets for extended 1 Hz operation
- Bin et al., Rev. Sci. Instr. (2019)
- Steinke et al, in preparation

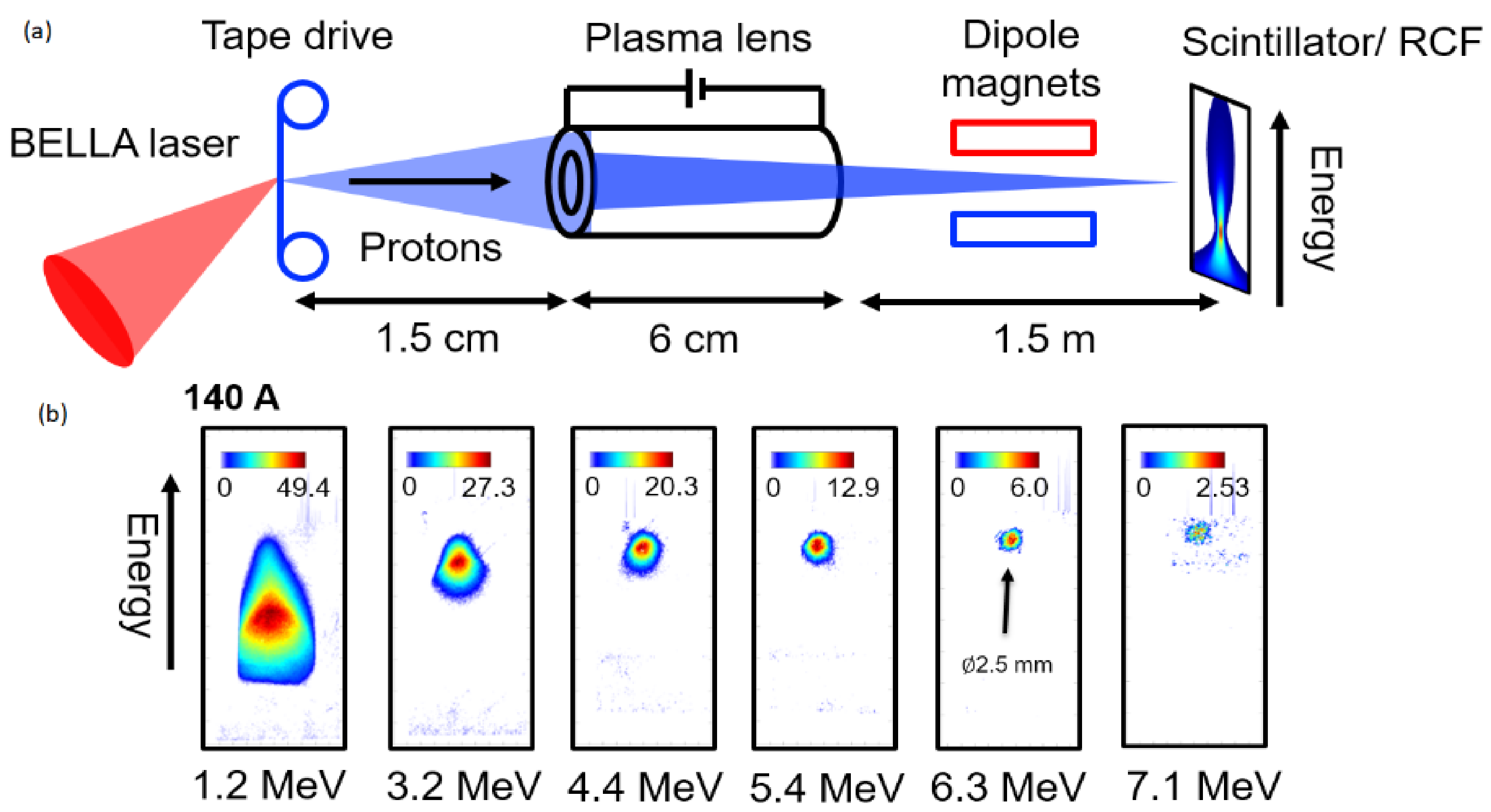
Larger laser spot size leads to achromatic divergence and high number of protons





- High number of protons: 10^{12} above 1 MeV
- Relatively low proton beam divergence independent of proton energy
- Processed RCF data: we used proton pulses form NDCX-ii for calibration of the films, J. Bin et al., RSI (2019)

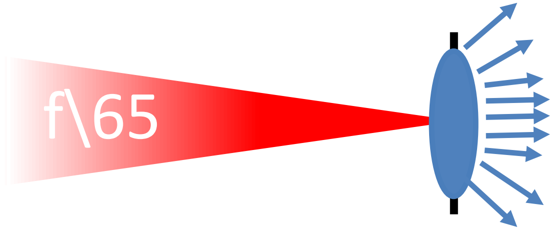
We have now demonstrated capture and transport of proton pulses



- Experiments with >1000 petawatt shots per day enable tuning, alignment, parametric studies
- Laser driven ion pulses for rad effects studies, …

Sven Steinke, et al., in preparation

PW Laser Operating with Long Focal Length: Short Focal Length Beamline with a Dedicated Target Chamber in Progress HEDLP in LaserNetUS



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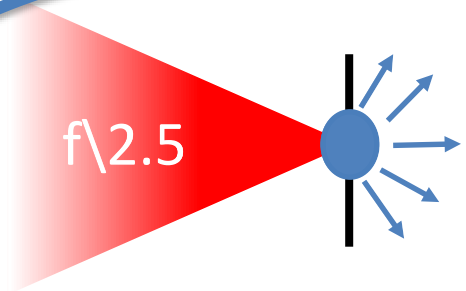

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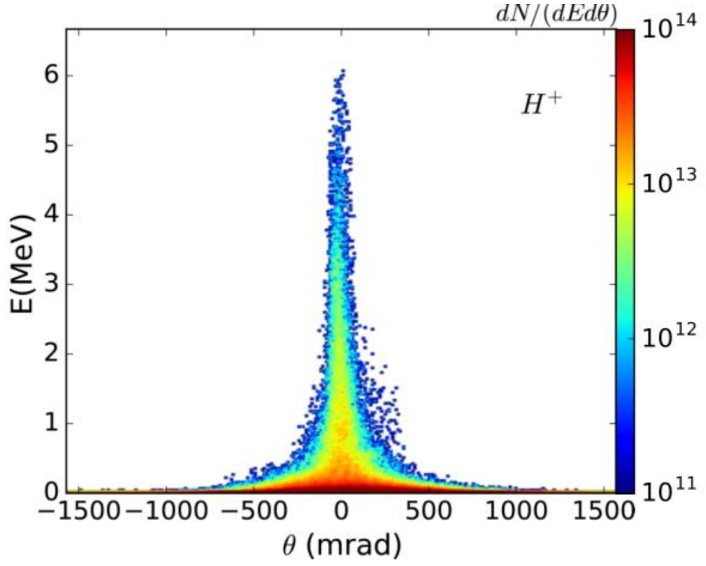
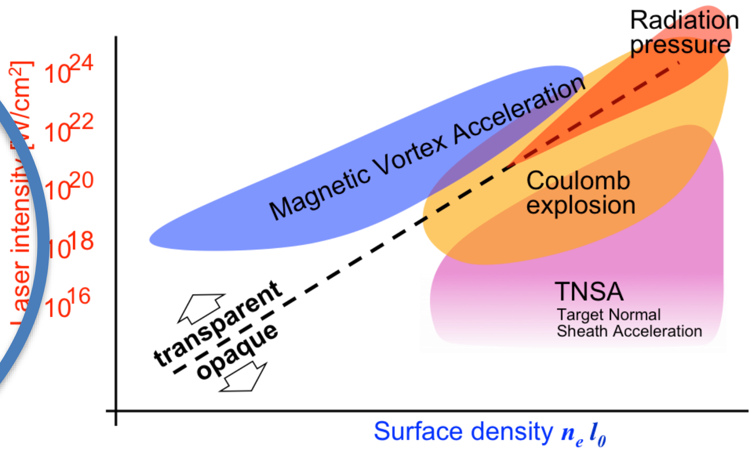
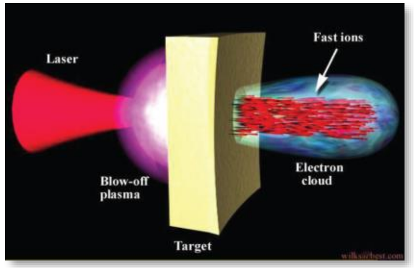




The Short Focal length Beamline Will Enable Ultra-Relativistic Plasma Physics with >10^{21} W/cm^2 at 1 Hz

Baseline: Target Normal Sheath Acceleration



Target: Thick solid density foils
Protons: E_{max}=50 – 60 MeV
Number of particles: ~10^8 - 10^9

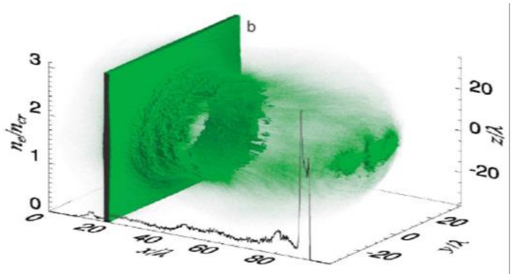
BELLA-i	short focal length
peak intensity (W/cm^2)	5 x 10^{21}
peak pulse energy	40 J in 30 fs
laser spot size	5 µm

Contrast enhancement methods

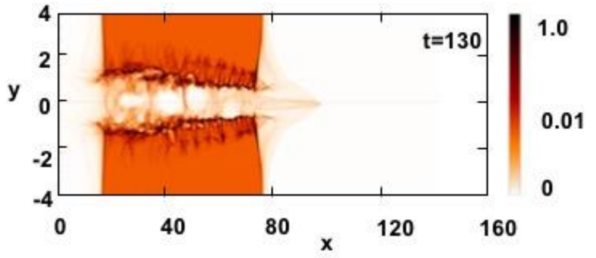
- Plasma mirrors
- Composite targets
- Controlled laser pre-pulse interaction
- Near critical density targets

Advanced ion acceleration

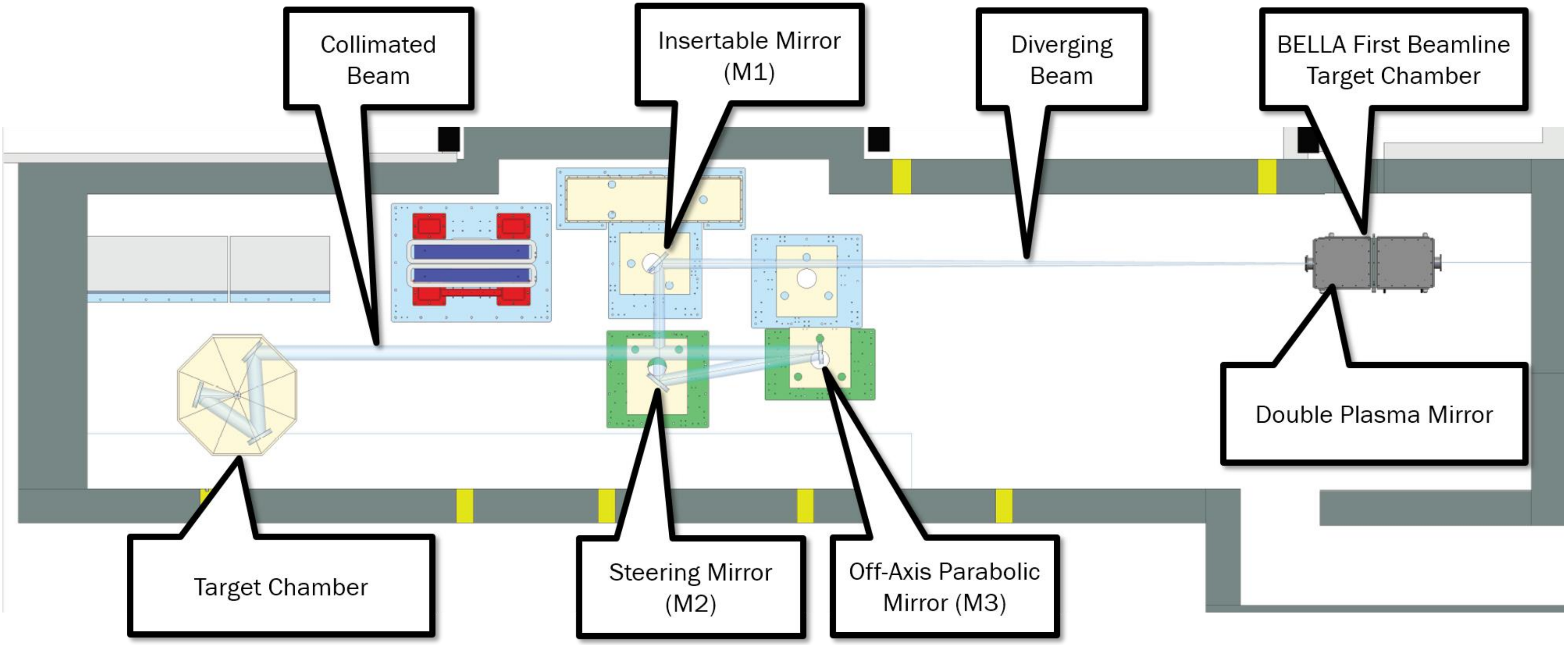
Radiation Pressure Acceleration:
Target: Thin solid density foils
Protons: E_{max}=150 – 200 MeV
Number of particles: ~10^{10} - 10^{11}



Magnetic Vortex Acceleration:
Target: Near Critical Density slab
Protons: E_{max}=100 – 300 MeV
Number of particles: ~10^8 - 10^9



Short focal length beamline layout with high contrast from plasma mirrors



S. Steinke et al.

Two Plasma Mirrors centered around the focus of the f\65 beamline enable ultra-high contrast experiments at intensities exceeding 10^{21} W/cm^2 in the main target chamber.

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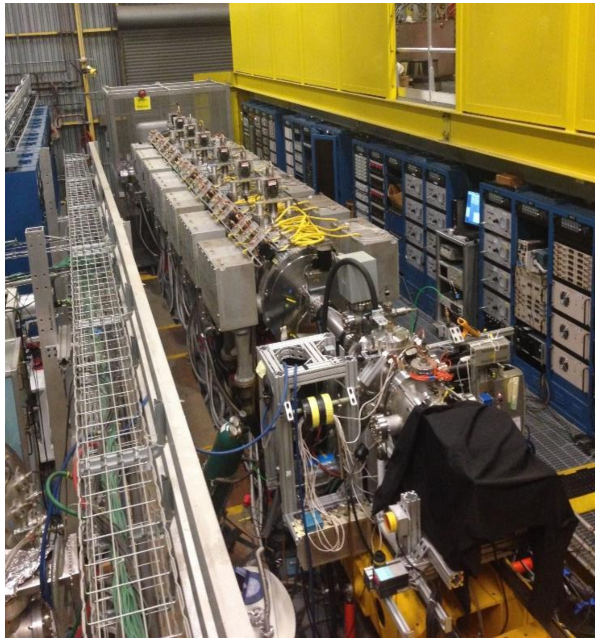
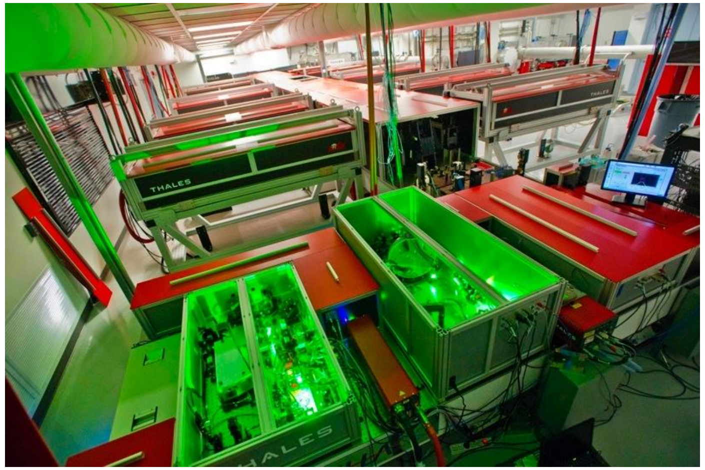
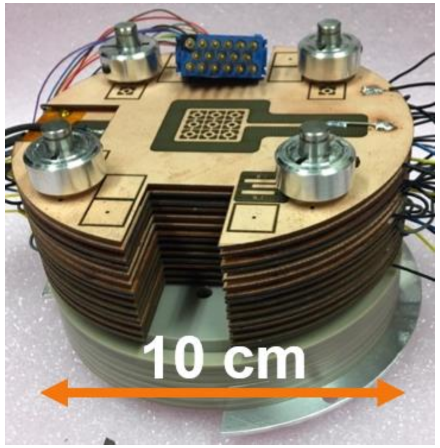
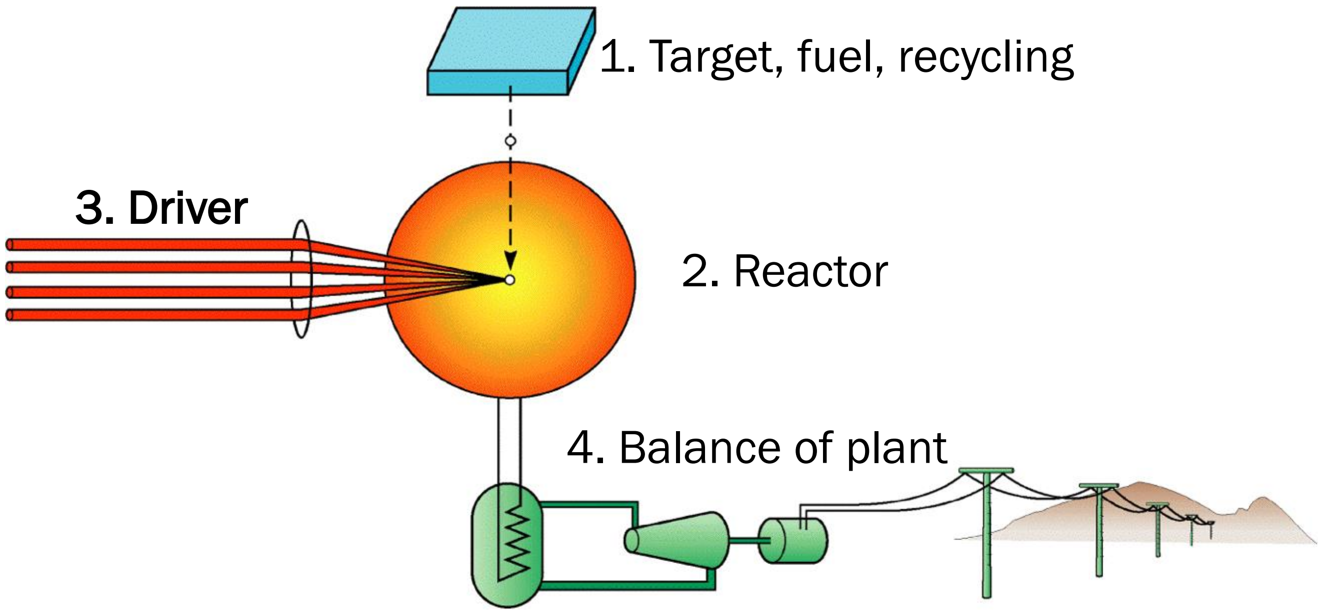




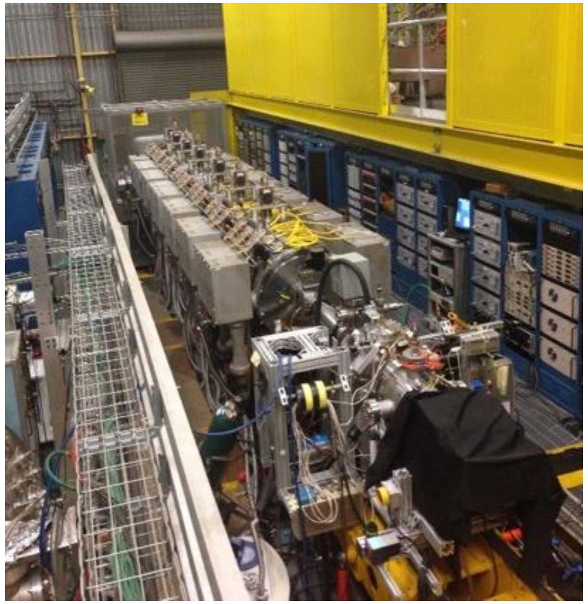


Comeback for IFE ?

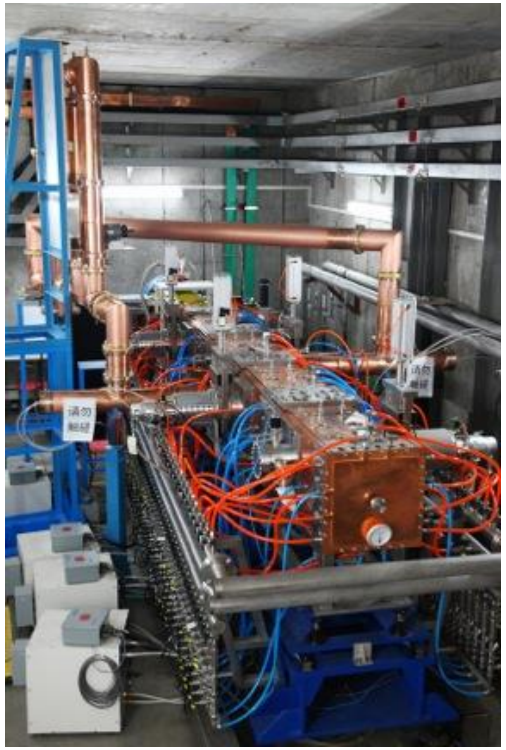


New ideas for heavy ion fusion drivers ?

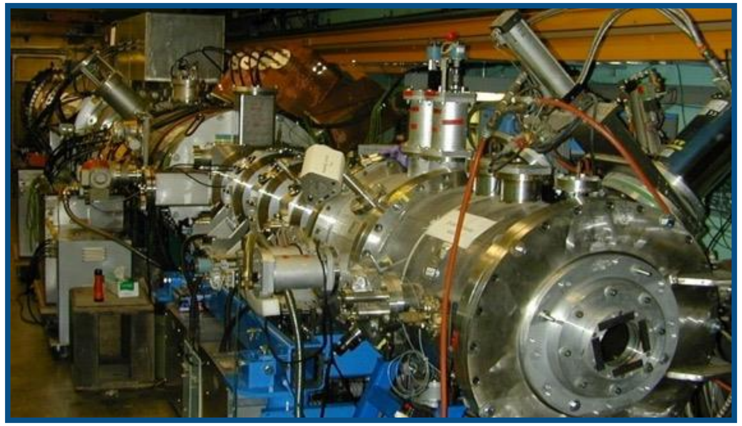
Examples of high power ion accelerators at Berkeley Lab



- Pulsed induction linac (12 m)
- 1 MeV, 2 ns, mm, ≥2 A peak
- 200x drift compression
- P. A. Seidl et al. NIM A (2015)



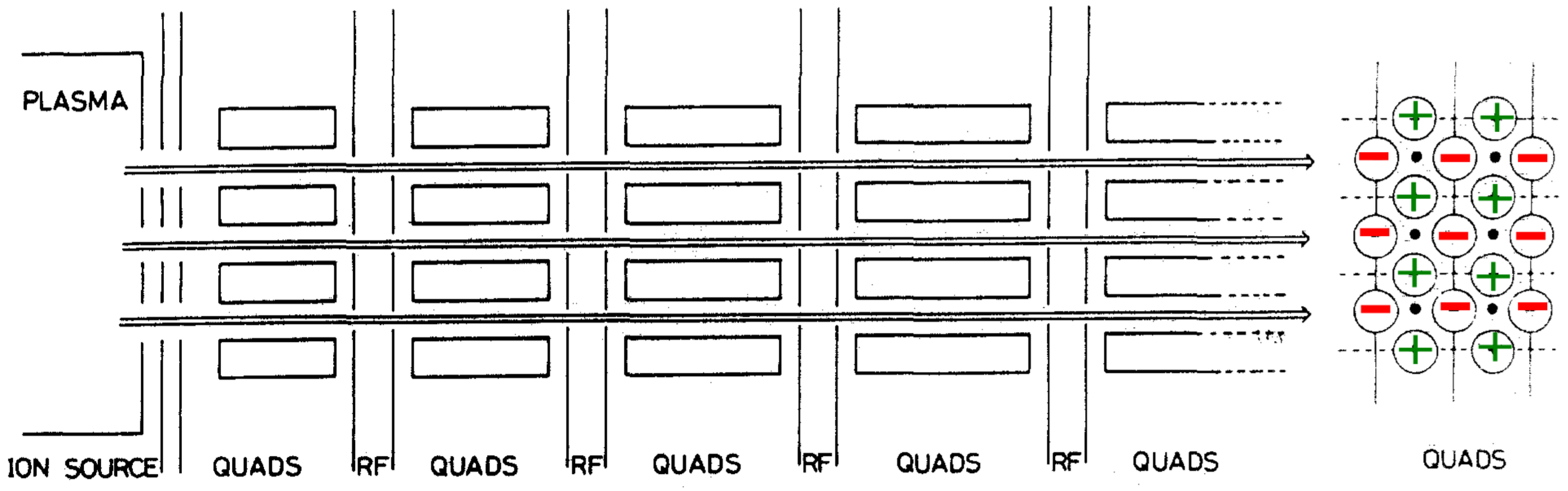
- Radio frequency quadrupole (RFQ)
- 2 MeV, 0.01 A, cw
- 4 m long, 0.4 m cross section
- Z. Zouhli, D. Li et al. IPAC2014



- High Current Experiment
- injection, matching and transport at heavy ion fusion driver scale
- 1 MeV, 0.2 A, 5 μs, ~12 m
- 0.4 m cross section
- M. Kireeff-Covo, et al., PRL (2006)

How can we scale ion beams to >1 MJ at lower cost?

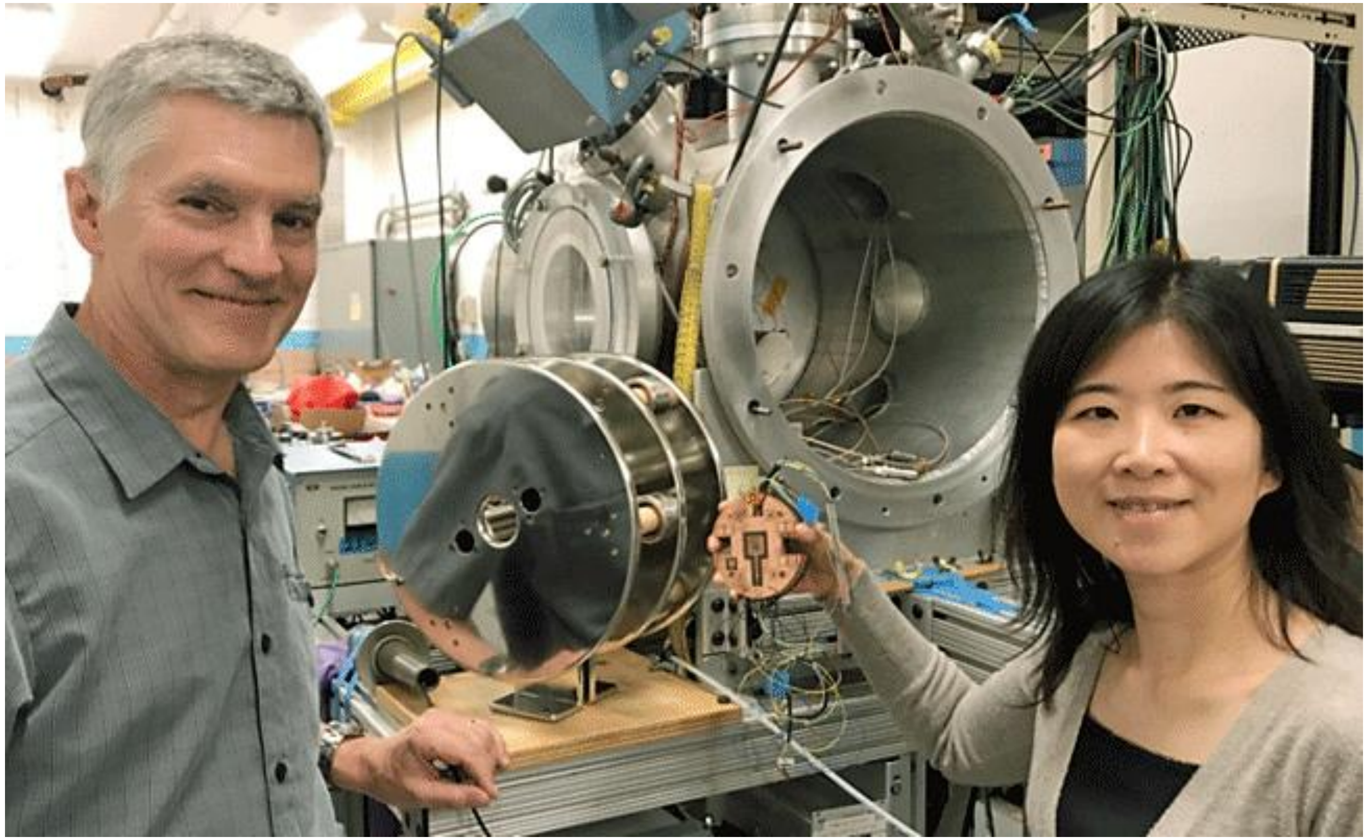
Multiple-Electrostatic-Quadrupole-Array Linear Accelerator (MEQALAC)

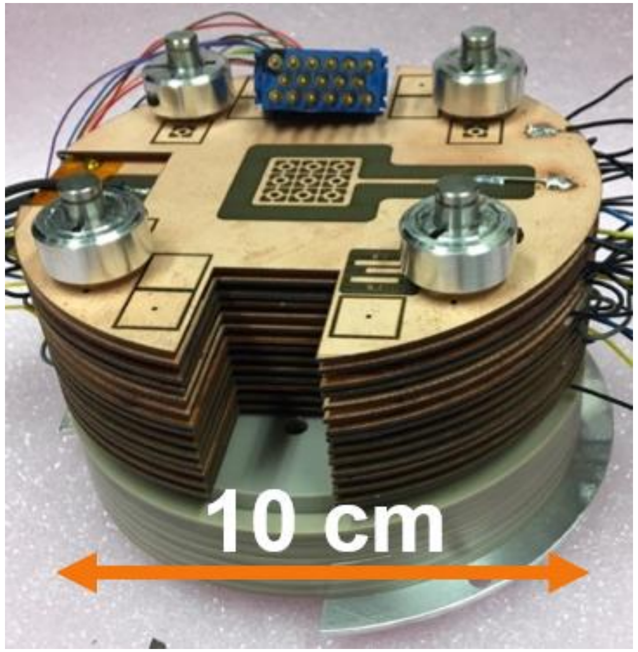


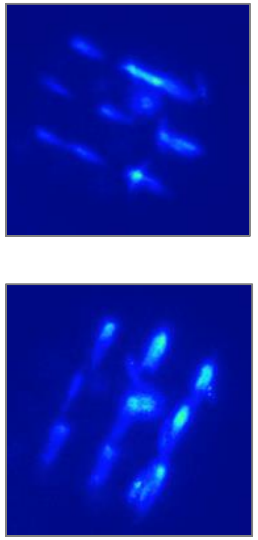
- A high current beam from many small beamlets for higher beam power and current densities
- 1980s: ~ 1 cm beam apertures, lattice period a few cm

- Thomae *et al.*, Mat. Science & Eng., B2, 231 (1989)
- Al Maschke et al., early 1980s

New ideas for high power ion beams







- MEMS based multi-beam RF linacs

A. Persaud, et al., RSI 88, 063304 (2017)
P. A. Seidl et al., RSI (2018)

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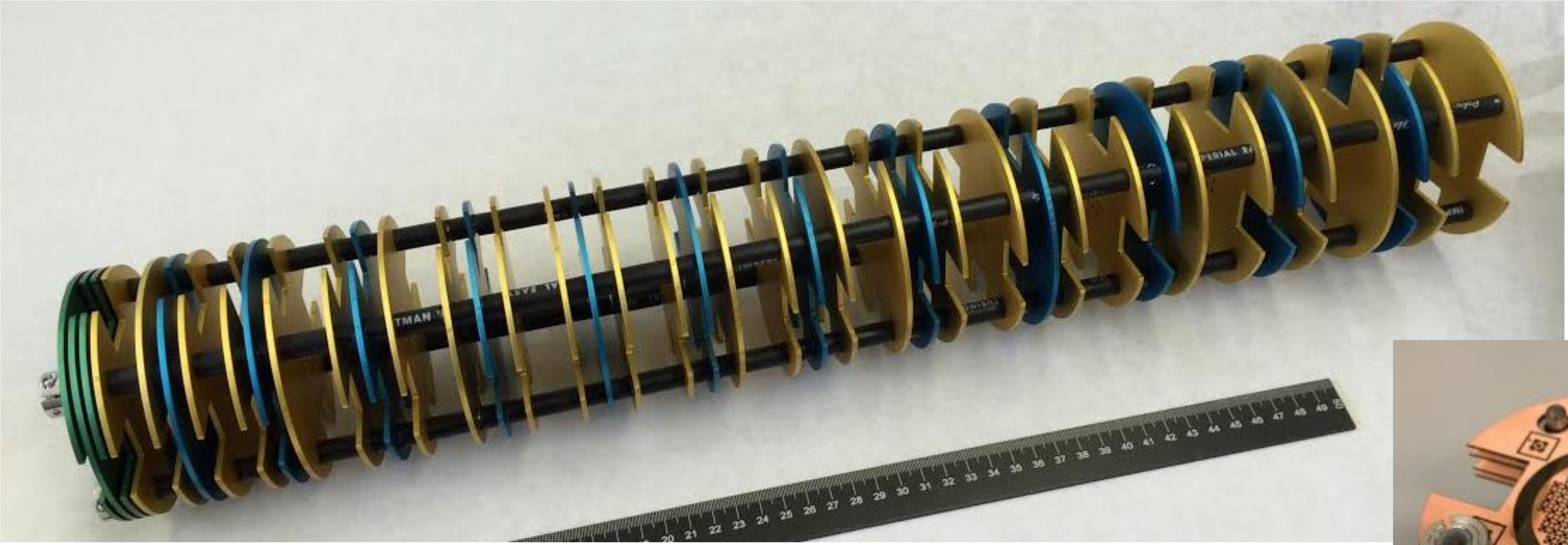
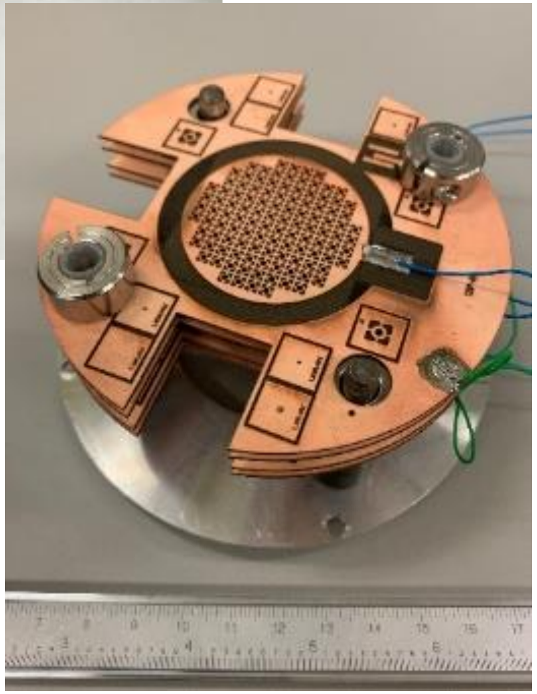
MEMS based multi-beam RF linacs

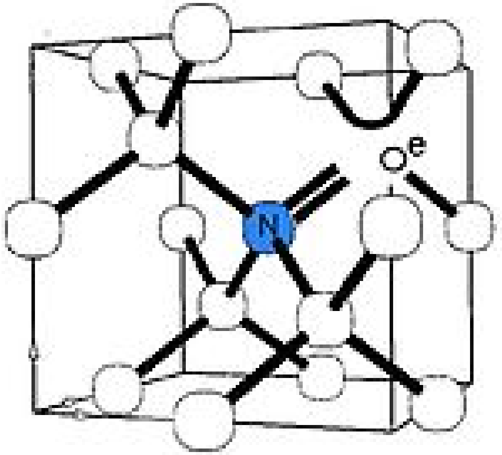




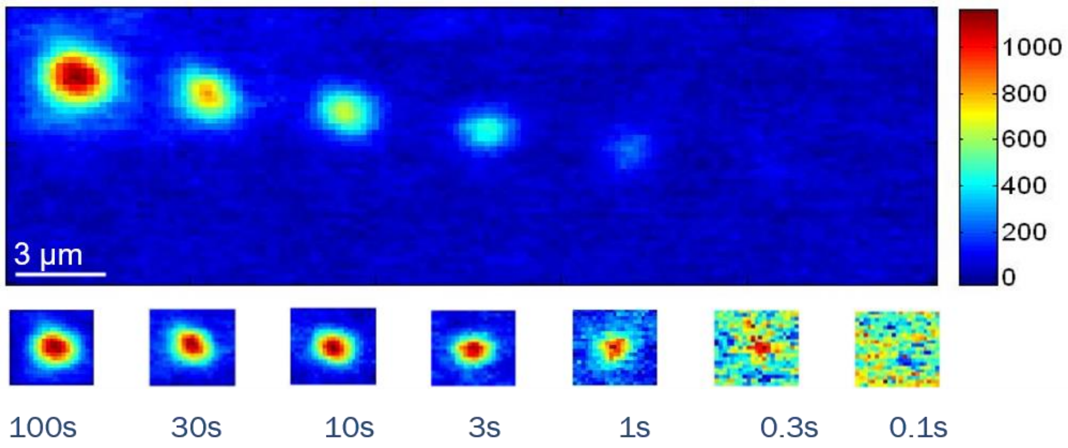
- Following proof-of-concept demos we are now scaling beam power
  - More beams: 3x3 → 10x10
  - Increase acceleration gradient: 2.5 kV/gap → 10 keV/gap
  - Add acceleration stages
- Next step: >1 MV/m, >100 keV, > 1 mA

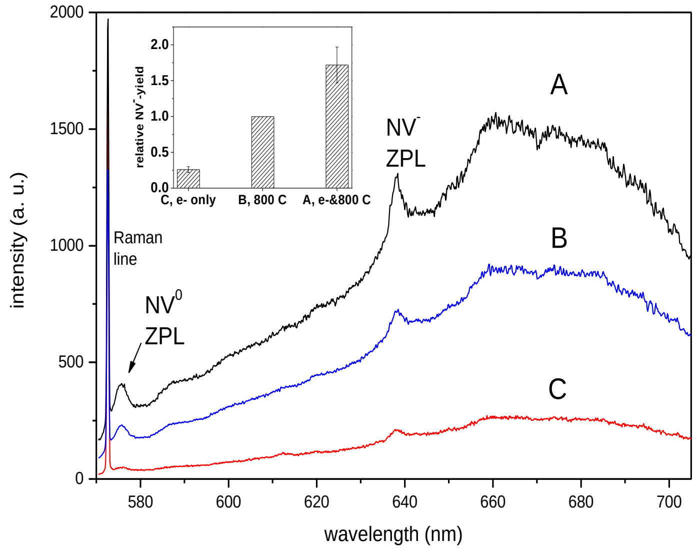
Qubits

NV-centers form during local exposure to low energy electrons at room temperature



https://en.wikipedia.org/wiki/nitrogen-vacancy center





- confocal PL image of NV^- centers (635–642 nm) at room temperature, recorded following exposure of 1 µm squares to a 9 pA, 2 keV electron beam. Insets show locally auto-scaled spots.

- **local, beam driven color center formation without thermal annealing**

- **can we learn how to reliably form and place color center qubits ?**

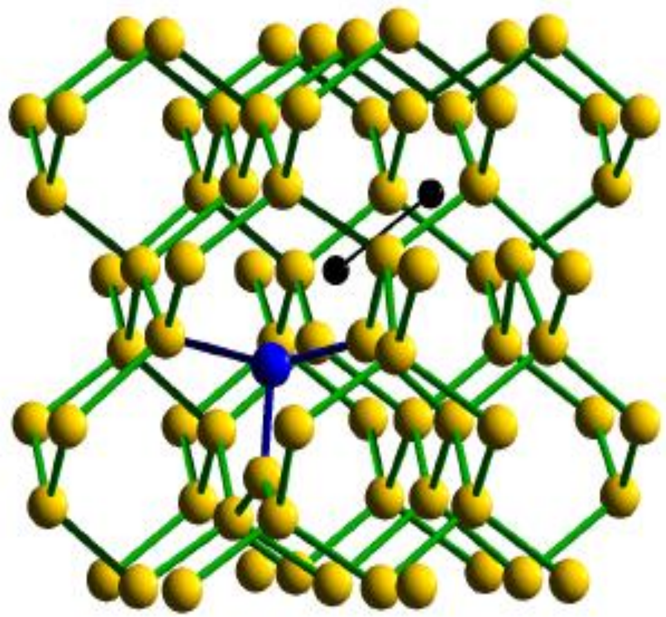
- J. Schwartz, et al., NJP (2012)
- J. Schwartz, et al., JAP (2014)
- J. J. Barnard, T. Schenkel, JAP (2017)

Mechanisms of NV-center formation in diamond?

$N_{substitutional} + V \rightarrow NV^{0,-}$

vs.

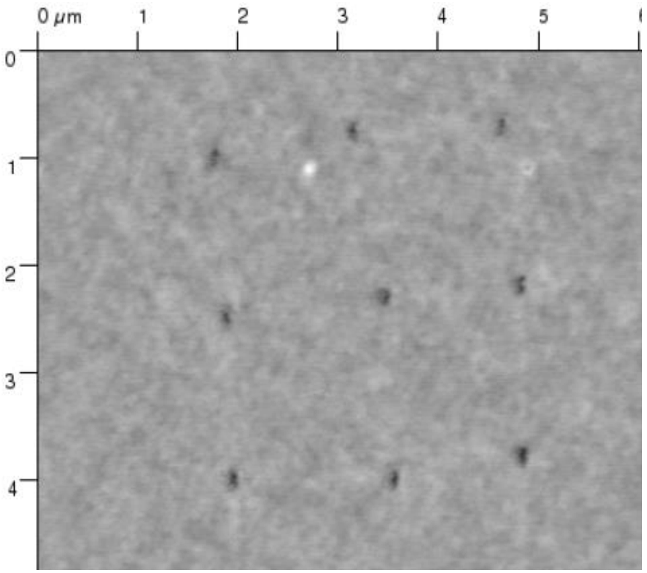
$N_{interstitial} + V_n \rightarrow NV^{0,-}$

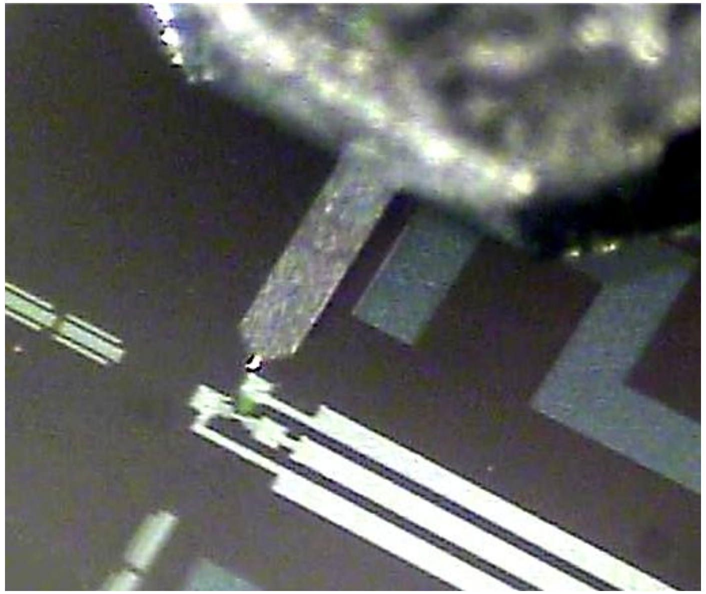


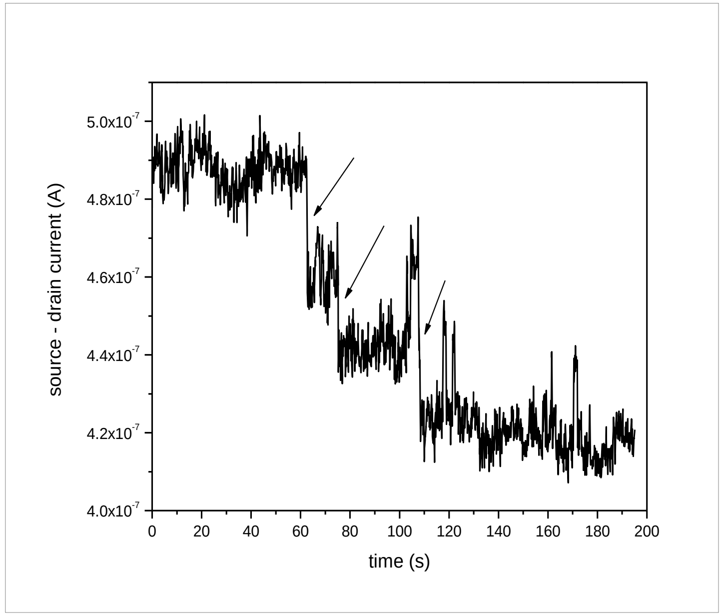
- A nitrogen atom on a split interstitial site (blue), close to two vacancies (black). Carbon atoms in yellow. NV's form during annealing at >300°C
- J. Adler, R. Kalish, et al., J. of Physics, 2014
- P. Deak et al. PRB 2014: di-vacancy formation favored over NV formation during annealing of N rich diamond after vacancy producing irradiation

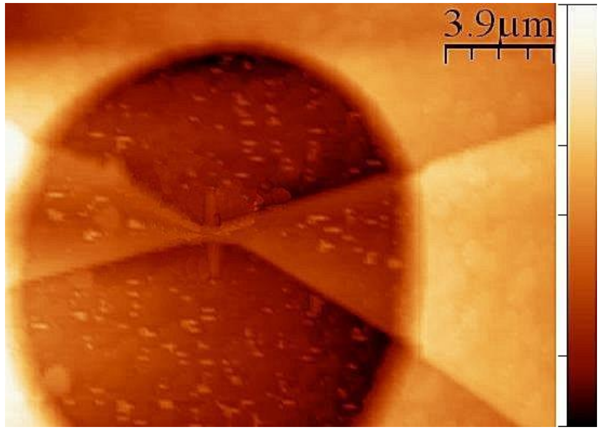
J. Schwartz, et al., NJP 2012, JAP 2014

Single ion implantation with scanning probe alignment









Single Bi^{+} ions (10 keV) implanted into 80 nm x 4000 nm devices, ion current: 0.1 pA/mm^2, single ion detection ΔI/I ~5%

T. Schenkel, et al., Nucl. Instr. Meth. B 267, 2563 (2009)
C. D. Weis, et al., NIM B 267, 1222 (2009)
A. Batra, et al., APL 91, 193502 (2007)
M. Ilg., et al., JVST B (2012)
T. Schenkel, et al., AIP (2014)

Development dark matter detectors based on spin coherence

- Ensemble of paramagnetic centers: N, NV^- in diamond, group IV donors in silicon
- In a high Q microwave cavity at low temperature and an external magnetic field
- Sensing of DM induced spin flips by detection of (single) microwave photons

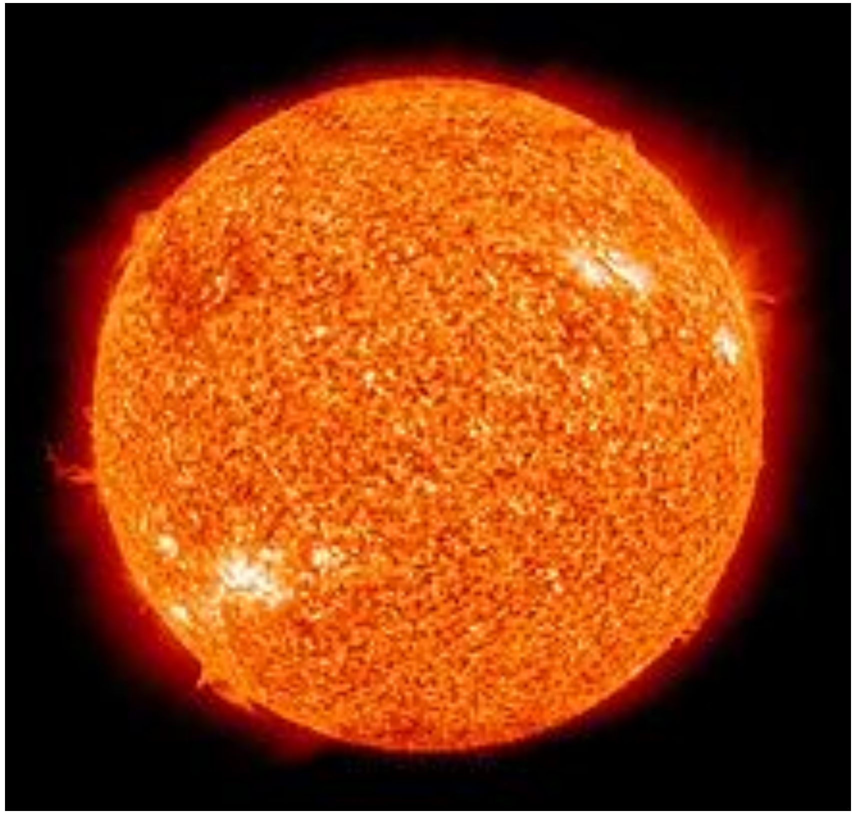
Outline

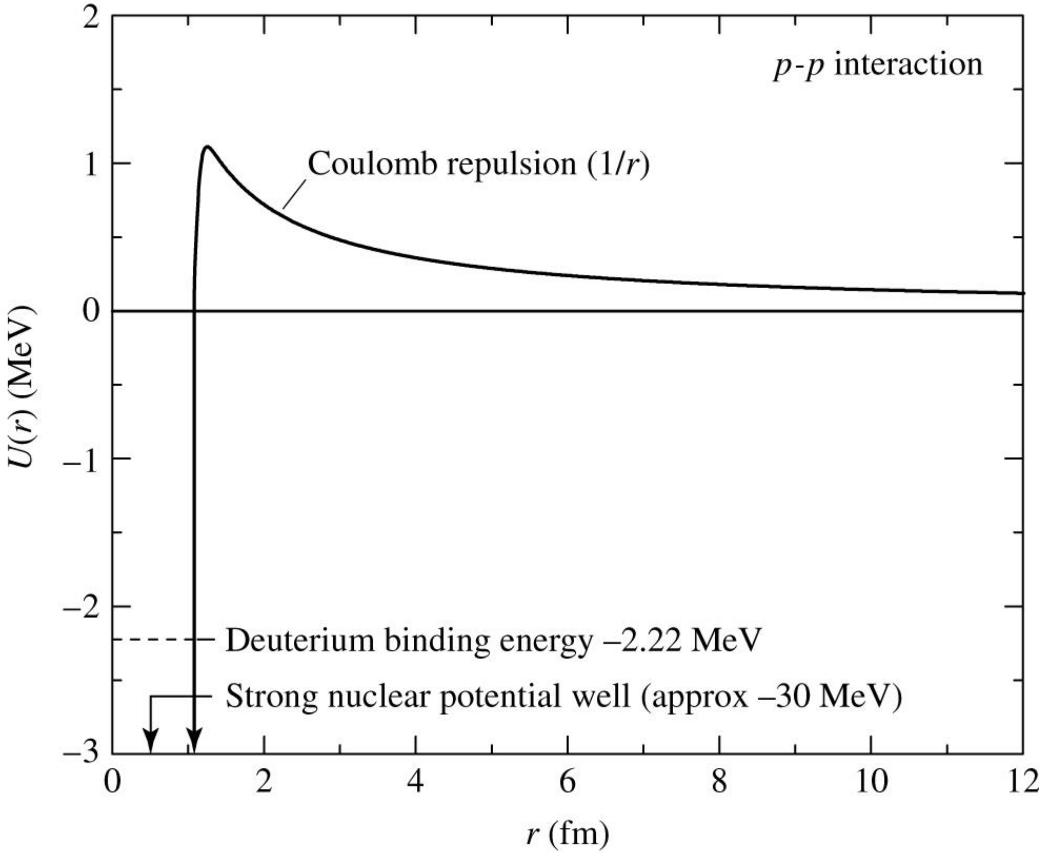
1. Beams
2. Qubits

3. Fusion

4. Outlook

Fusion

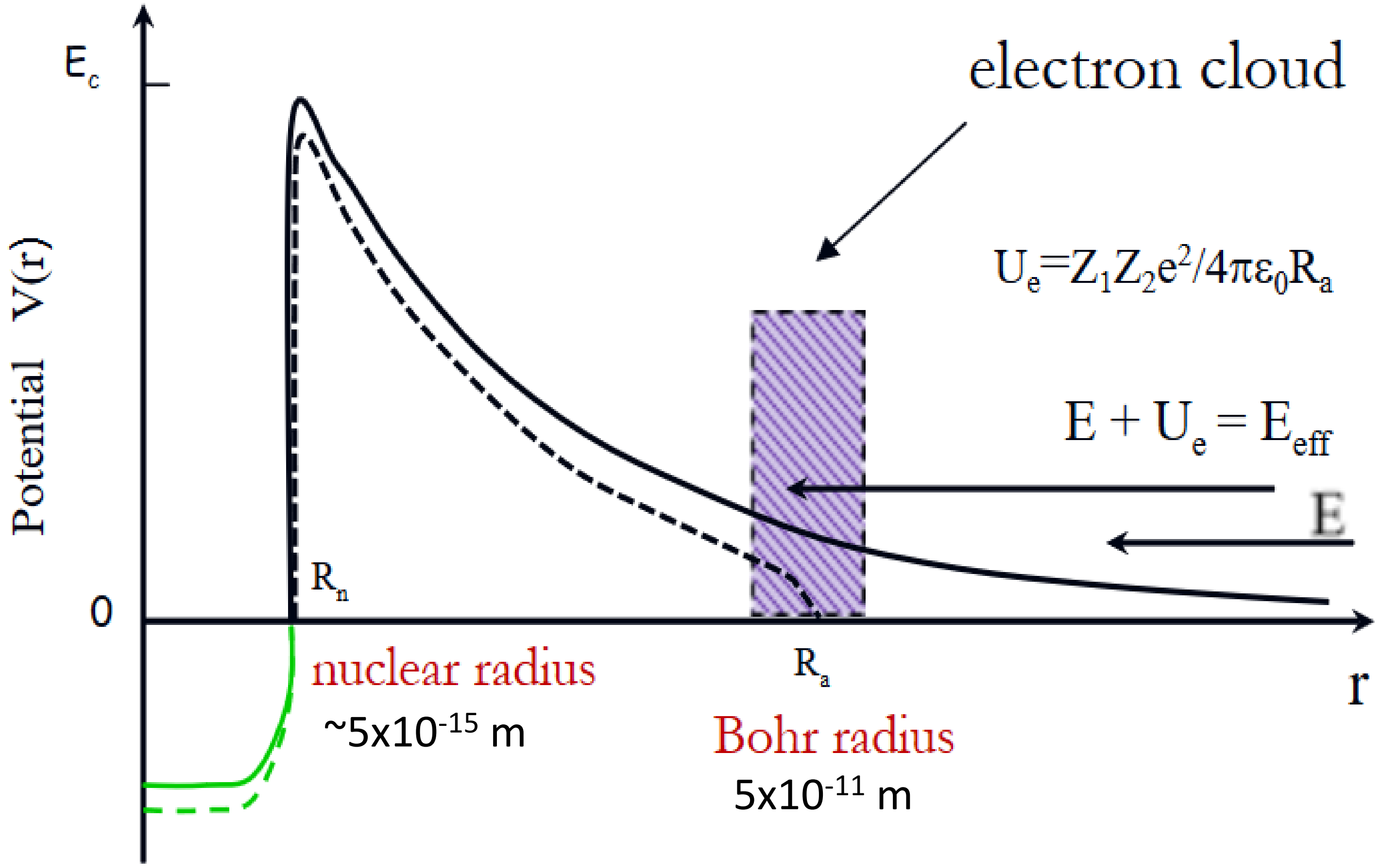




- temperature in the center of the sun is ~16 Million Kelvin
- corresponding average ion energies are ~2 keV
- the height of the Coulomb barrier for hydrogen fusion is ~600 keV
- fusion is possible due to tunneling through the repulsive Coulomb barrier

https://en.wikipedia.org/wiki/Sun
http://burro.cwru.edu/academics/Astr221/StarPhys/coulomb.html
http://hyperphysics.phy-astr.gsu.edu/hbase/NucEne/coubar.html

Electron screening affects low-energy fusion cross sections



$$\sigma_f(E, U_e) = \frac{1}{\sqrt{E(E+U_e)}} e^{-\sqrt{E_g/(E+U_e)}} S(E)$$

D-D, gas phase:
U_e = 27 eV

figure adapted from Matej Lipoglavšek, https://slideplayer.com/slide/10339372/

H. J. Assenbaum, K. Langanke and C. Rolfs, Z. Phys. A **327** (1987) 461.

Solid state environments affect nuclear reaction rates

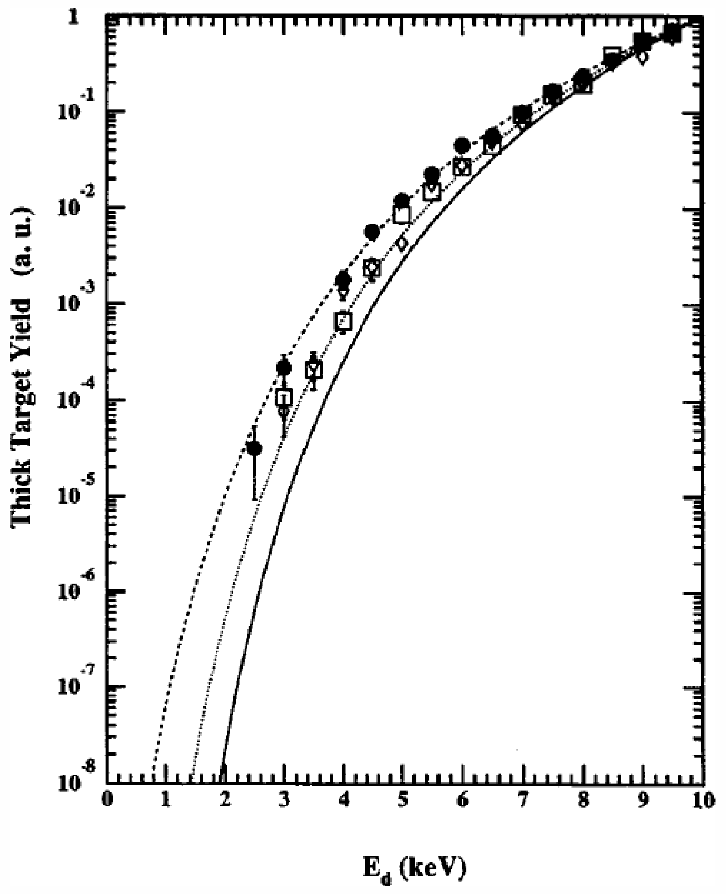
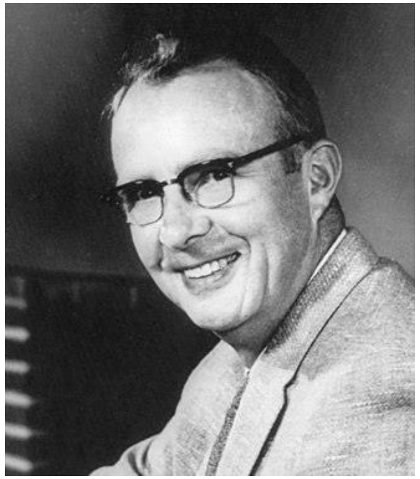


FIG. 2. Experimental yields of the $D(d,p)T$ reaction: in Pd under cooled conditions, $\langle T\rangle = 190.1$ K (open squares); in Pd at $\langle T\rangle = 313.0$ K (open diamonds); and in an Au/Pd/PdO heterostructure at $\langle T\rangle = 193.3$ K (solid circles). The solid curve is the calculated bare yield without enhancement. The dotted and dashed curves are parametrizations of the experimental yields with screening potentials $U_s = 250$ eV and $U_s = 600$ eV, respectively.

- example of Yuki, et al., JETP Lett. 68, 827 (1998)

- D-D fusion, relative thick target yields
- deuterium ion beam on beam loaded solid targets
- materials dependence of apparent electron screening potentials
  - 25 eV to 600 eV
  - Greife et al., 1995
  - Yuki et al., 1998
  - Czerski et al., 2001
  - Kasagi et al., 2002
  - Raiola et al., 2002
  - Lipson et al., 2005
  - …

Cold fusion: catalysis of nuclear reactions by μ mesons (muons)



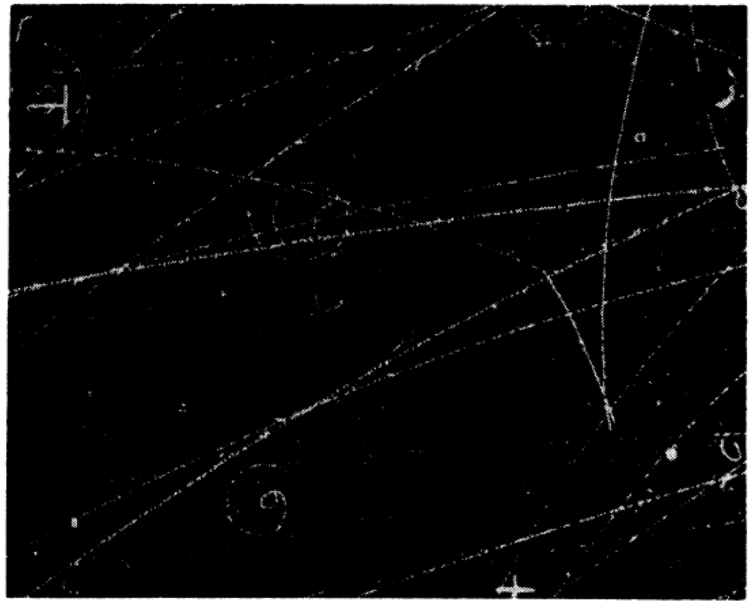


FIG. 1. Example of H-D reaction catalyzed by μ^- meson. The incident meson comes to rest, drifts as a neutral mesonic atom, is ejected with 5.4 Mev by the H-D reaction, comes to rest again after 1.7 cm, and decays.

“We had a short but exhilarating experience when we thought we had solved all of the fuel problems of mankind for the rest of time,” 1968 Nobel Prize acceptance lecture.

L. W. Alvarez, et al., Phys. Rev. 105, 1127 (1956)

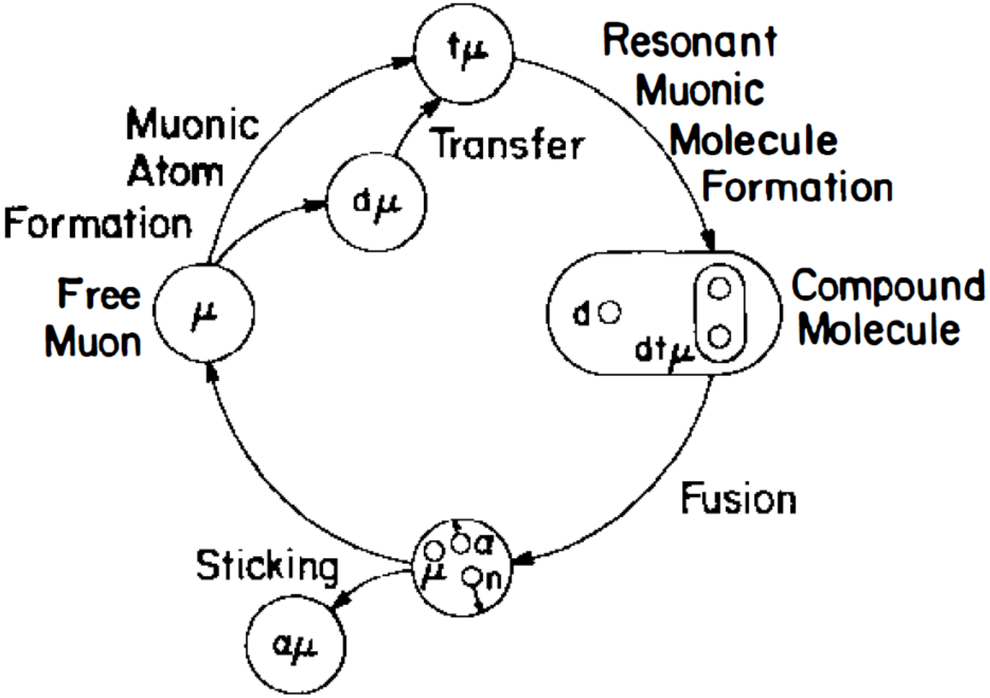


Figure 1 Simplified μCF cycle for a dt target.

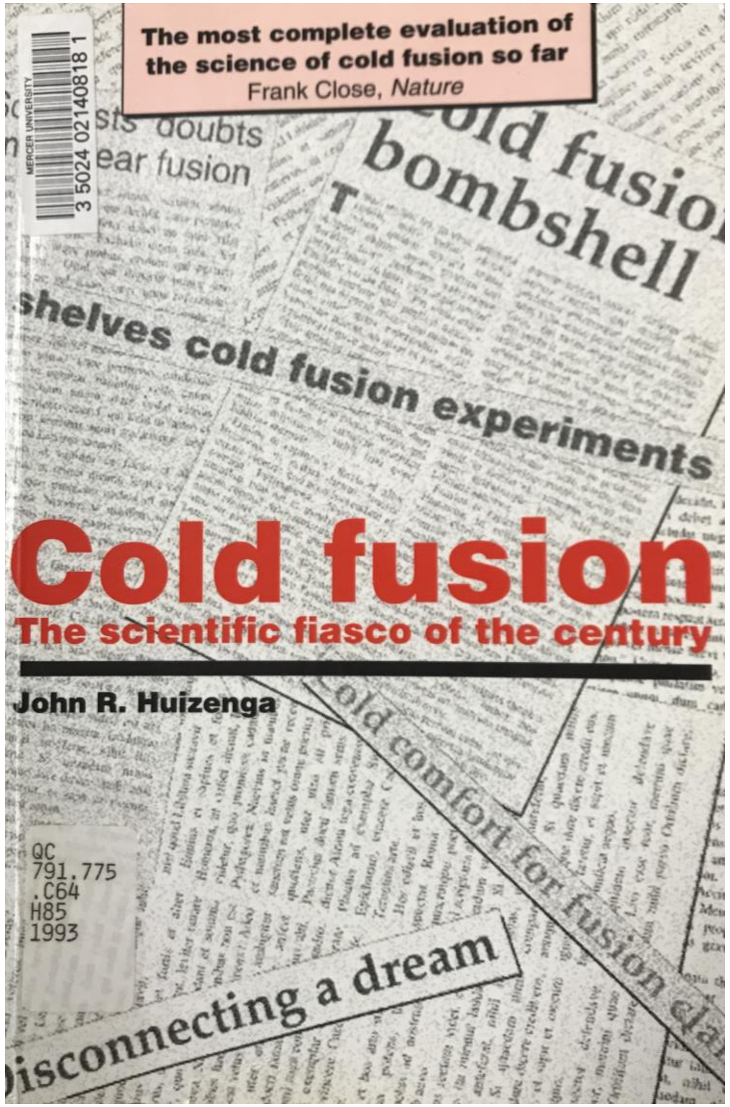
- J. D. Jackson, Phys. Perspect. 12, 74 (2010)
- Breunlich, Kammel, Ann. Rev. Nucl. Part. Sci. 39, 311 (1989)

- muon capture enables hydrogen fusion at room temperature
- at relatively low rates
  - limited by the number of muons and
  - limit of ~100 fusion reactions/muon (He-sticking problem)
- same nuclear radiation as in hot hydrogen fusion

- Cold fusion claims by Fleischmann and Pons in 1989
  - heating of palladium by fusion reactions in electro-chemistry experiments with heavy water
  - at room temperature and
  - with very little radiation

- No accepted theory predicts this
- Results were not reproducible
- Other claims of observation of "cold fusion" have followed since

M. Fleischmann and S. Pons, "Electrochemically induced nuclear fusion of deuterium", J. Electroanal. Chem., 261 (1989) 301-308



Responses to the Pons – Fleischmann cold fusion claims

"Three miracles of cold fusion" (Huizenga, 1993, p. 111 – 114)

1. **fusion rate**
   - normal fusion rate in D-D at distance of ~0.2 nm in palladium at room temperature is 10^{-64} 1/s (Koonin, Nature, 1989)
   - cold fusion claim requires increase by ~10^{50}

2. **branching ratio**
   - normal D-D fusion branching ratio is ~1:1 for the p+T and ^{3}He+n channels, ~10^{-7} for the ^{4}He + gamma channel
   - cold fusion claim is very few neutrons

3. **few nuclear products, direct coupling of released energy to the lattice**
   - normal D-D fusion is accompanied by protons (3 MeV) + tritium (1 MeV); or neutrons (2.5 MeV) + 3He (0.8 MeV); or in rare cases by ^{4}He + gamma (24 MeV)
   - cold fusion claims direct lattice heating without emission of nuclear radiation

- pattern of highly surprising observations and difficulty to reproduce the experimental results

MENU

nature
International journal of science

Perspective | Published: 27 May 2019

Revisiting the cold case of cold fusion

Curtis P. Berlinguette, Yet-Ming Chiang, Jeremy N. Munday, Thomas Schenkel, David K. Fork, Ross Koningstein & Matthew D. Trevithick

University of British Columbia, Vancouver, British Columbia
Massachusetts Institute of Technology, Cambridge, MA
University of Maryland, College Park, MD
Lawrence Berkeley National Laboratory, Berkeley, CA
Google LLC, Mountain View, CA

Nature **570**, 45–51 (2019)

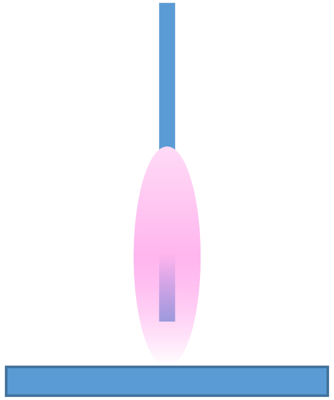
https://doi.org/10.1038/s41586-019-1256-6

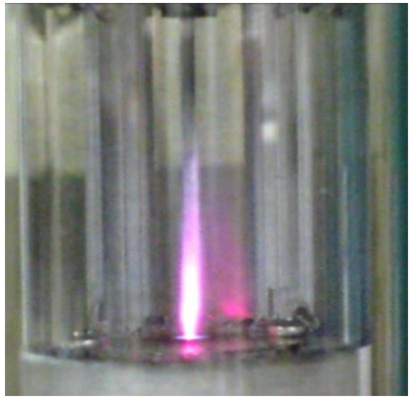
LA-UR- 95- 2687

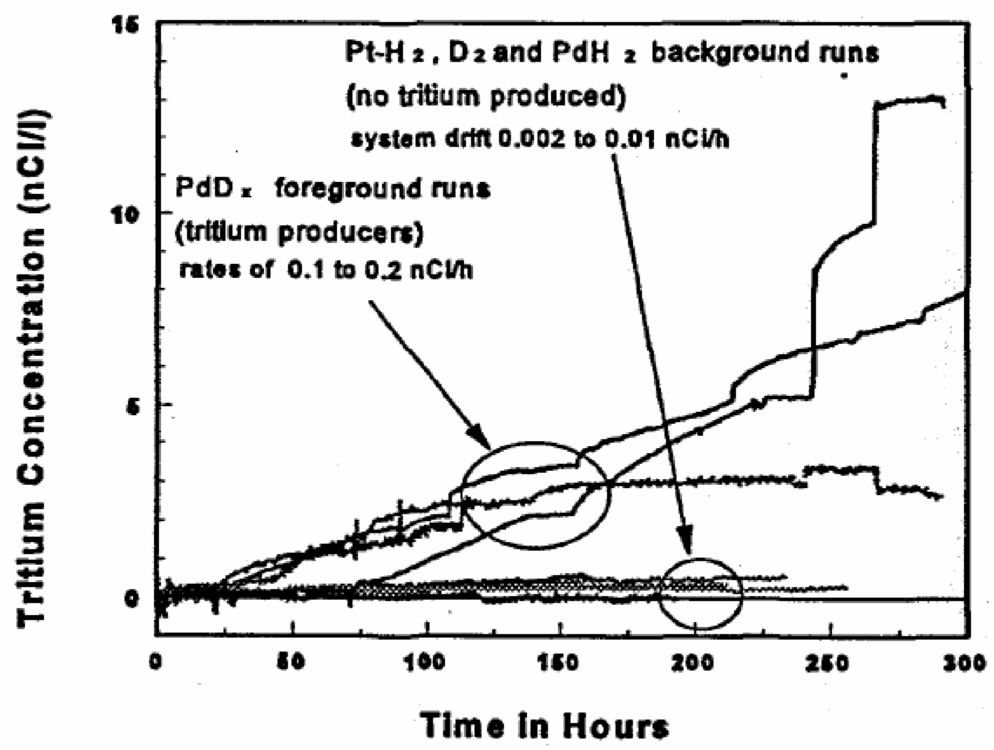
CONF-9506255--1
CONF-9504195--1

Title: TRITIUM PRODUCTION FROM A LOW VOLTAGE DEUTERIUM DISCHARGE ON PALLADIUM AND OTHER METALS

T. N. Claytor, D. G. Tuggle, D. D. Jackson, 5th Intern'l Conf. Cold Fusion, Monaco; Proceedings of Low Energy Nuclear Reactions, 1995







- Pd wire, 0.1 to 0.25 mm diameter
- 200 to 300 Torr D_2
- plasma discharge:
  - 2 kV, 3 to 5 A, 20 us, 50 Hz
- tritium detection with in line Femtotech tritium gauge

- 25x tritium enhancement over control experiment

- T/n > 10^8 ?!

Investigation of light ion fusion reactions with plasma discharges

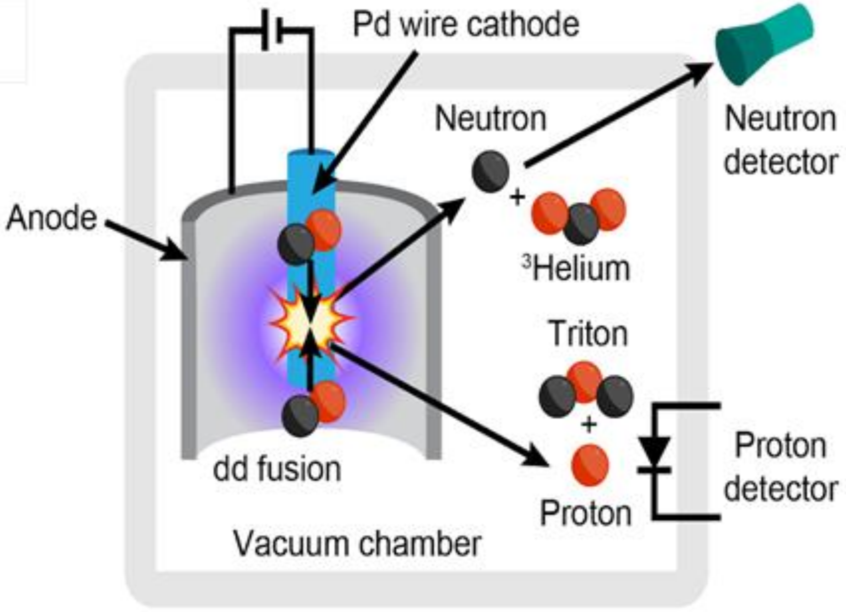
T. Schenkel[1], A. Persaud[1], H. Wang[1], P. A. Seidl[1], R. MacFadyen[1], C. Nelson[1], W. L. Waldron[1], J.-L. Vay[1], G. Deblonde[2], B. Wen[3], Y.-M. Chiang[3], B. P. MacLeod[4], and Q. Ji[1]

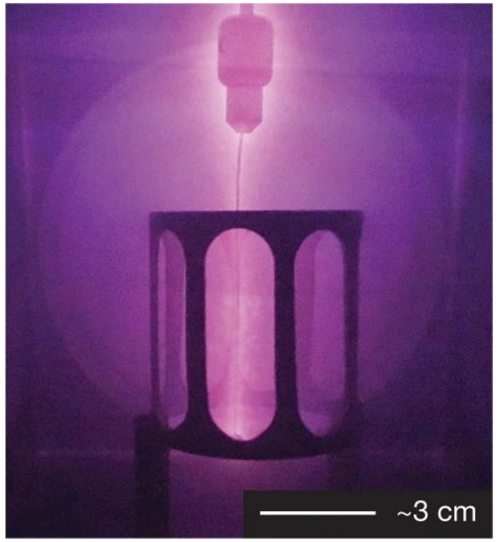
[1]Accelerator Technology and Applied Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

[2]Chemical Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

[3]Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[4]Department of Chemistry, University of British Columbia, Vancouver, British Columbia, Canada





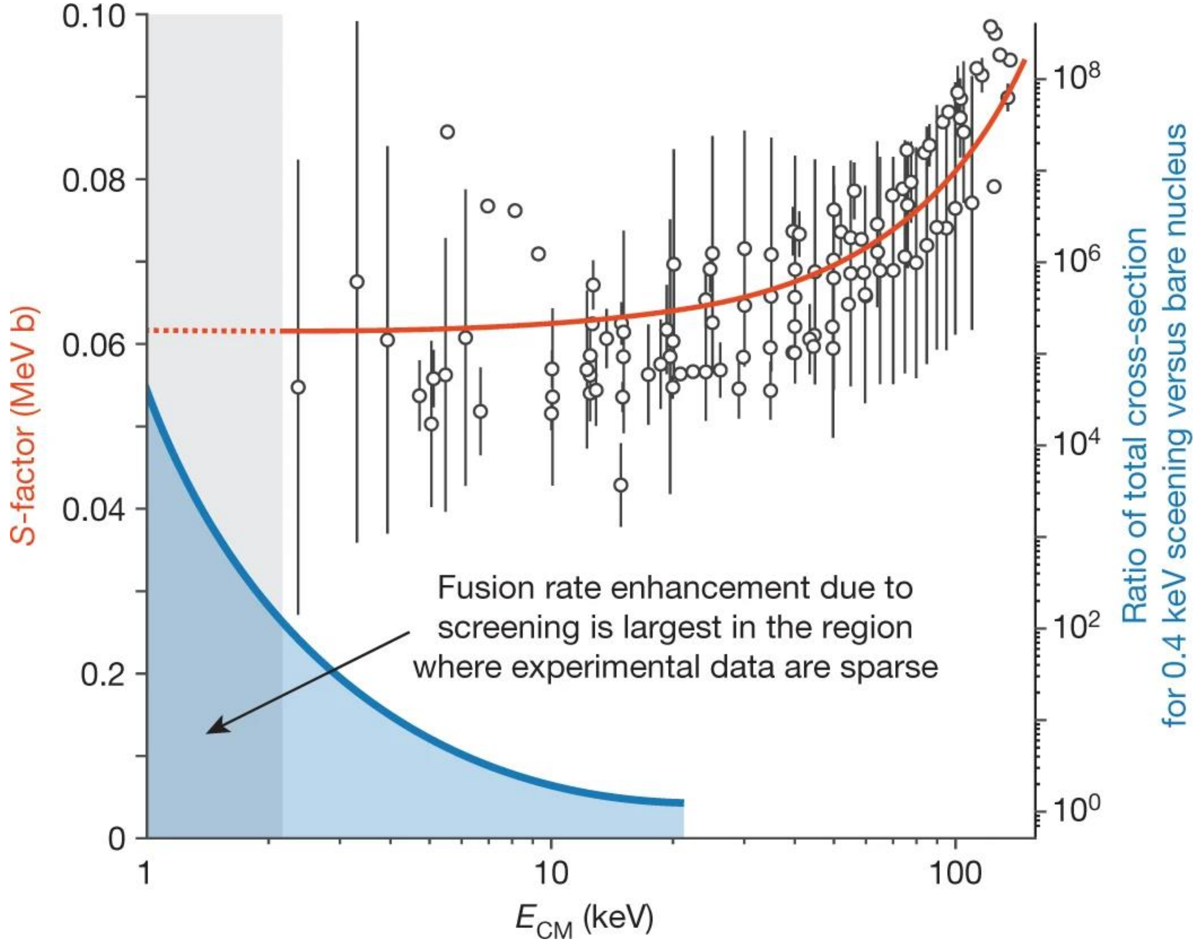
- deuterium ion pulses from a plasma discharge impinge on metal wires, inducing fusion reactions
- ~1 - 12 keV ion energies, peak currents 0.1 - 1 A
- ~ 0.1 to 1 Torr D_2 pressure

- **are fusion yields and branching ratios affects by ion flux and deuterium loading levels in Pd ?**

T. Schenkel, et al., https://arxiv.org/abs/1905.03400, J. Appl. Phys. 126, 203302 (2019)

C. P. Berlinguette, et al., Nature (2019)

Our goal was to test claims of high tritium production and D-D fusion rates at energies of a few keV



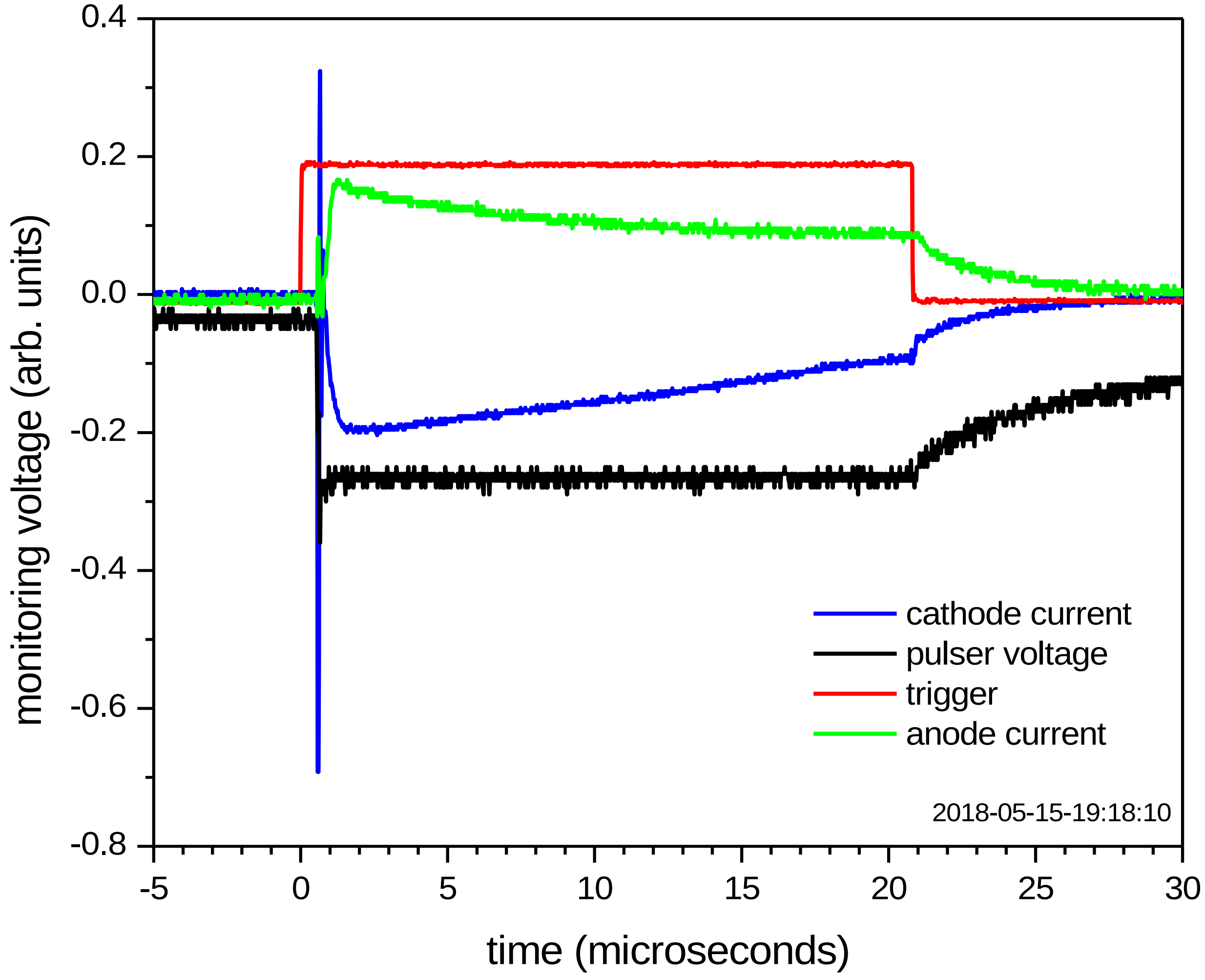
$$\sigma_f(E, U_e) = \frac{1}{\sqrt{E(E+U_e)}} e^{-\sqrt{E_g/(E+U_e)}} S(E)$$

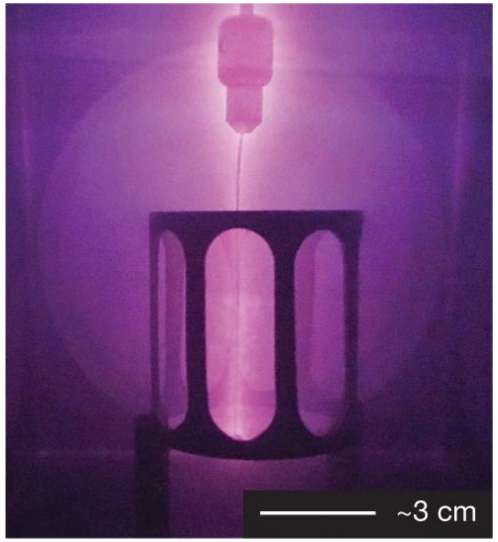
Plot adapted from D. T. Casey, et al. "Thermonuclear reactions probed at stellar-core conditions with laser-based inertial-confinement fusion", Nat. Phys. 13, 1227 (2017).

Data points show the *S*-factor for the D–D fusion reaction (left-hand vertical axis, red) as a function of centre-of-mass energy (E_{CM}). The thick red line shows the best fit extracted from the ENDF/B-VII.1 data library. The thick blue line shows the ratio of the calculated fusion cross-section for 0.4 keV screening potential (U_e) versus a bare nucleus (right-hand vertical axis, blue) as a function of E_{CM}, with the shaded blue region illustrating the increase in probability of an enhanced fusion rate.

C. P. Berlinguette, et al., Nature (2019)

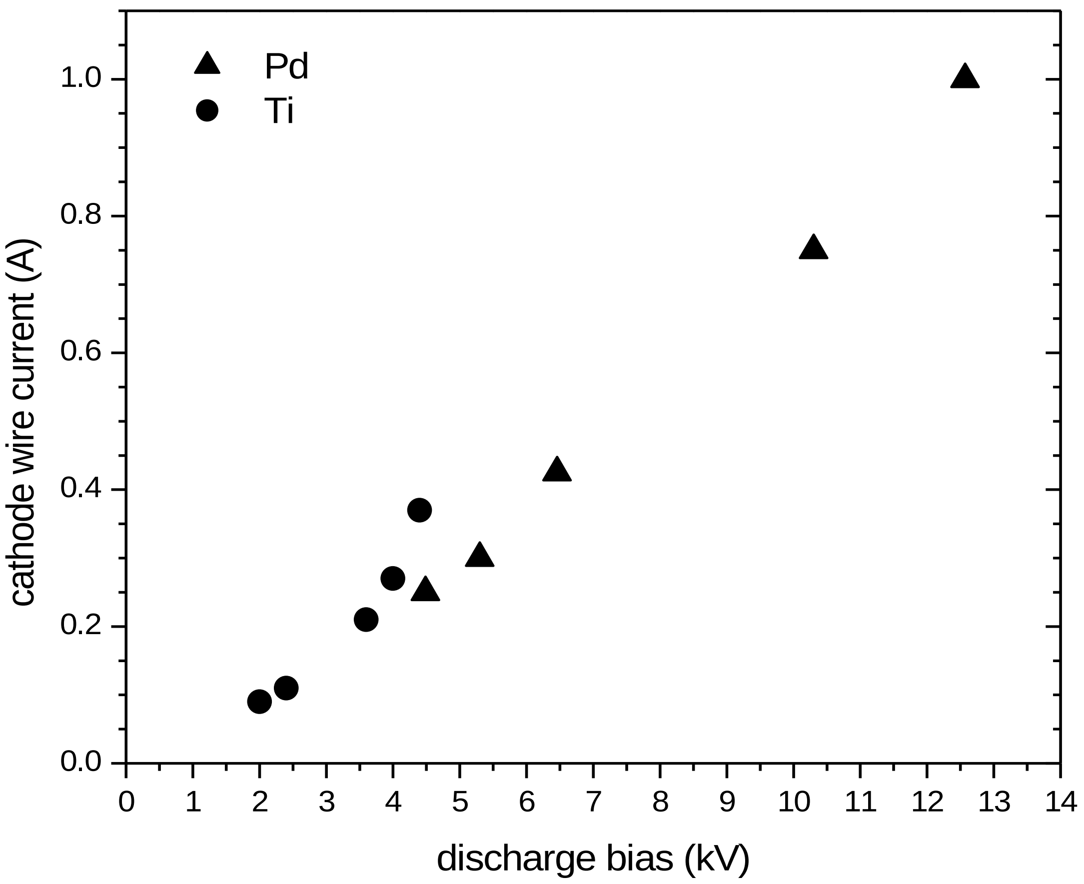
Plasma pulses in the glow discharge regime

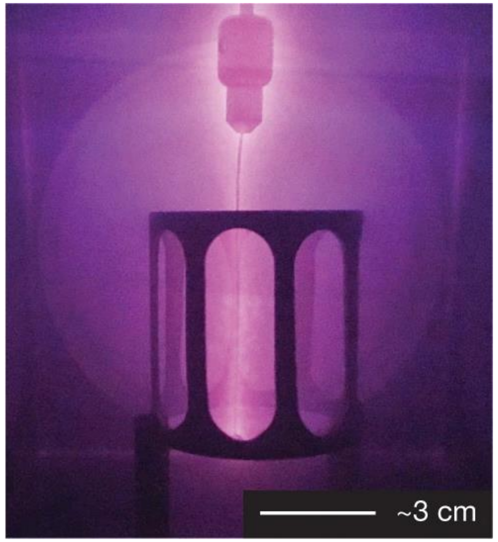




T. Schenkel, et al., https://arxiv.org/abs/1905.03400

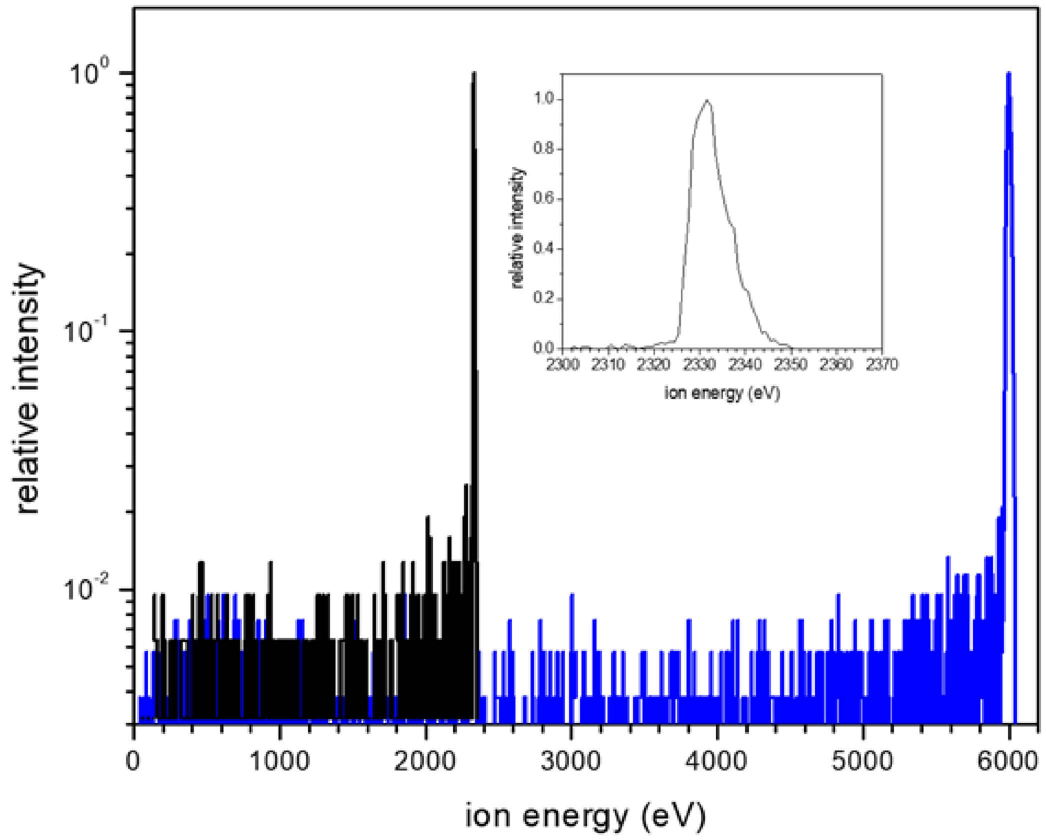
Plasma pulses in the glow discharge regime

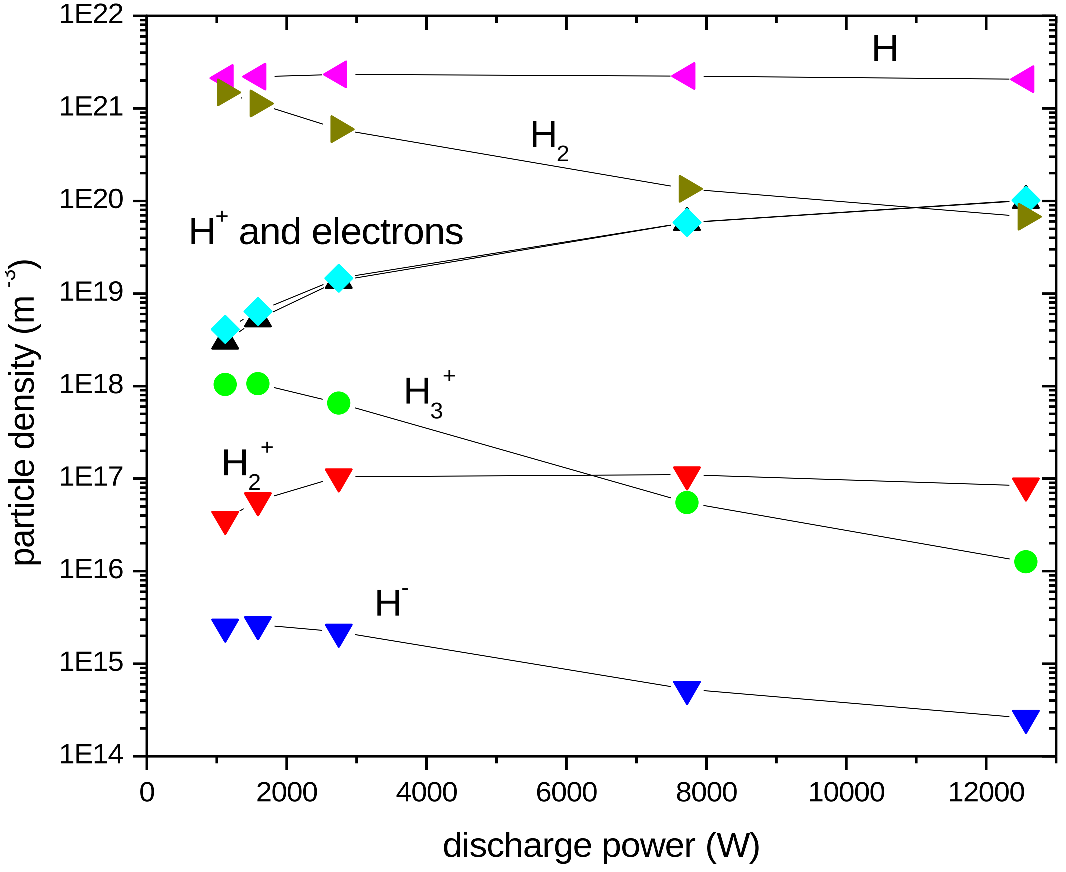




T. Schenkel, et al., https://arxiv.org/abs/1905.03400

We modeled particle collisions in the plasma with particle in cell codes

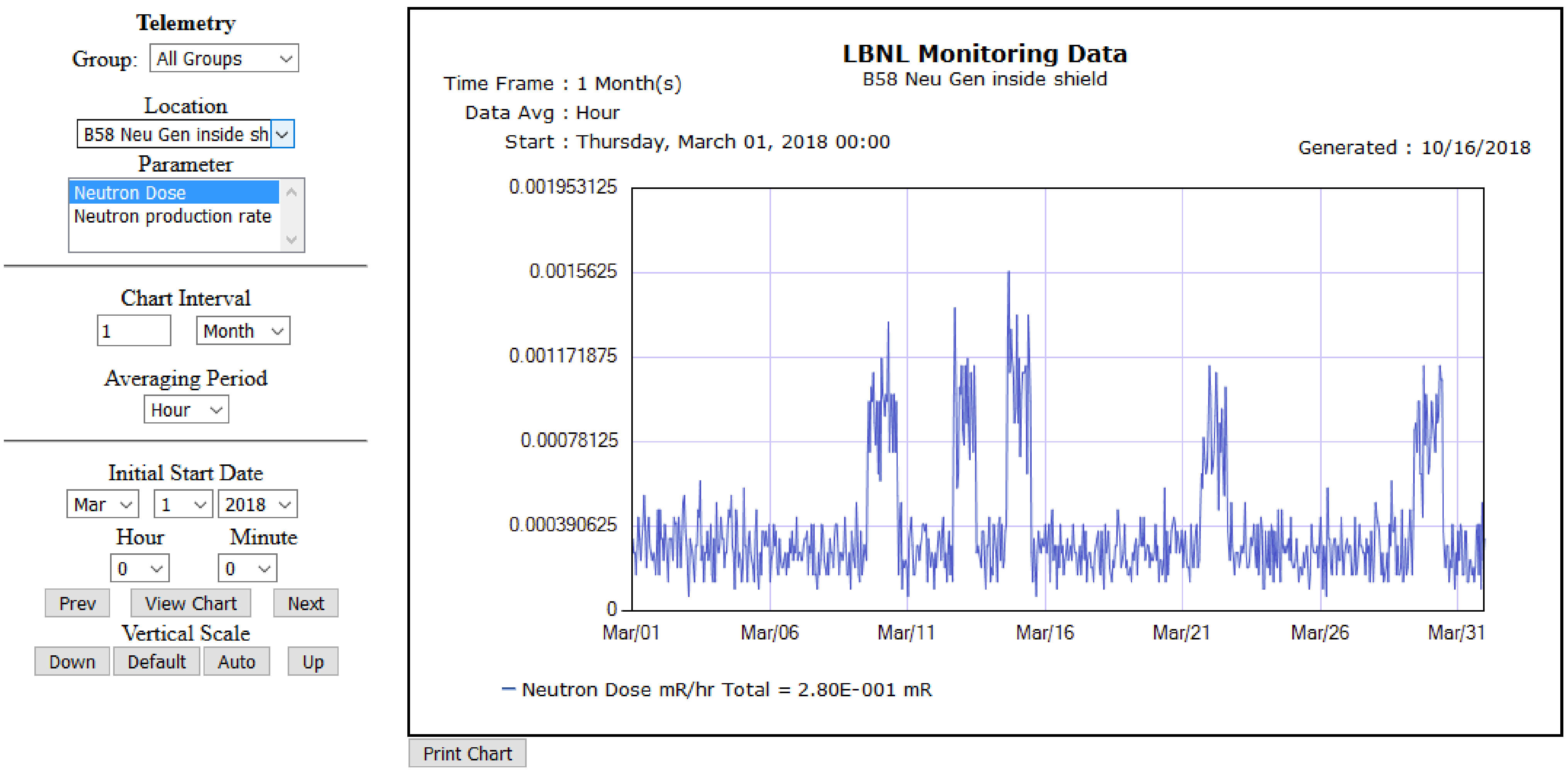




- important to understand the distribution of ion species and ion energies

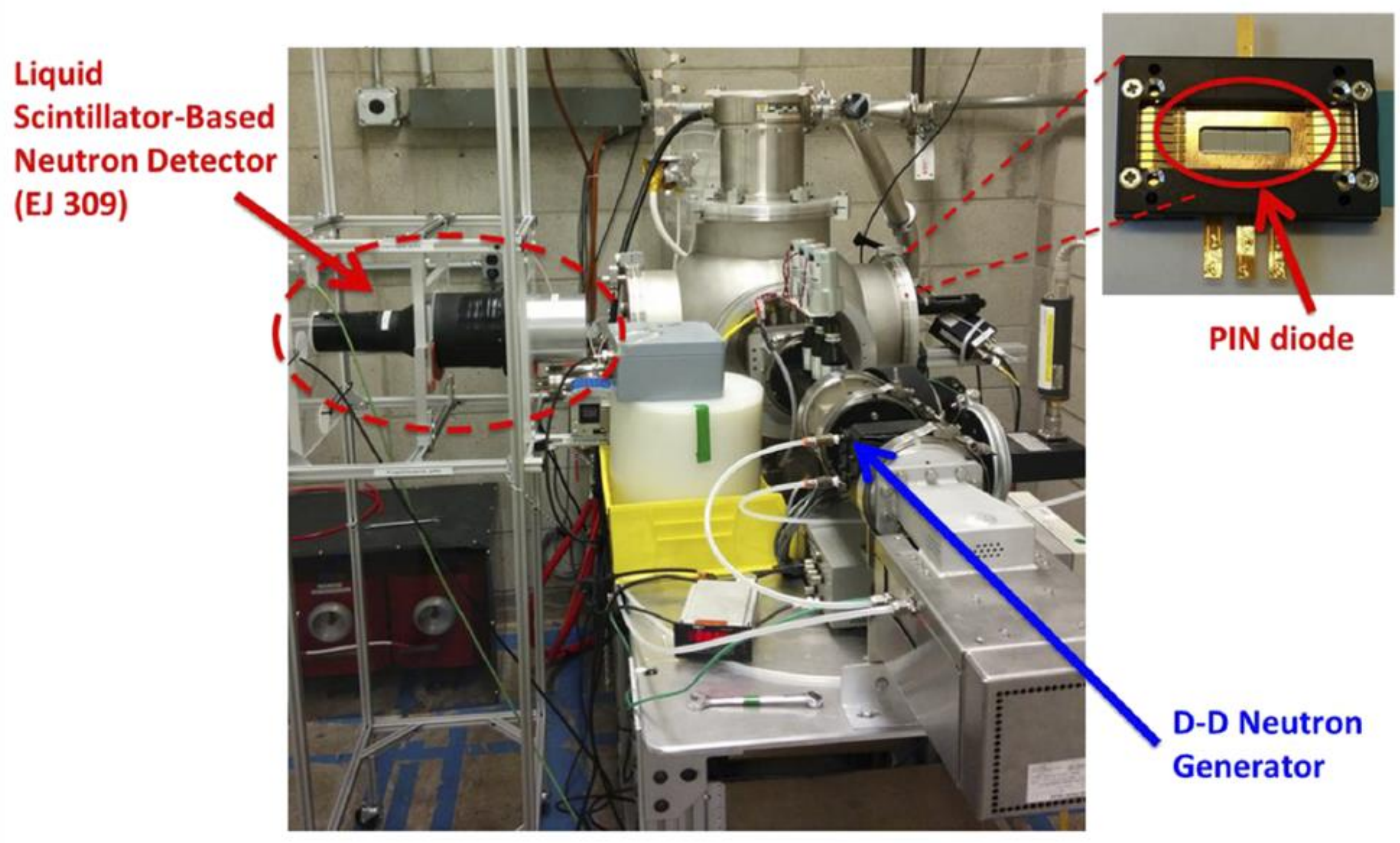
T. Schenkel, et al., https://arxiv.org/abs/1905.03400

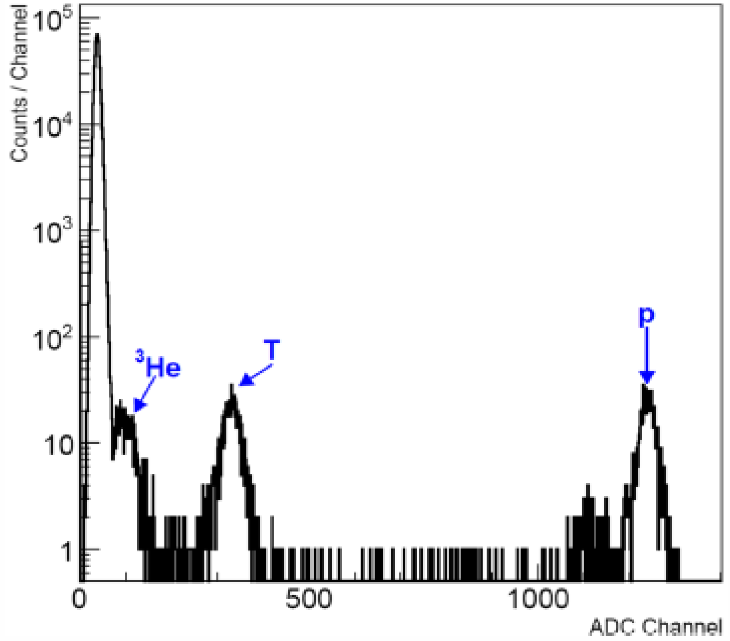
EHS TELEMETRY

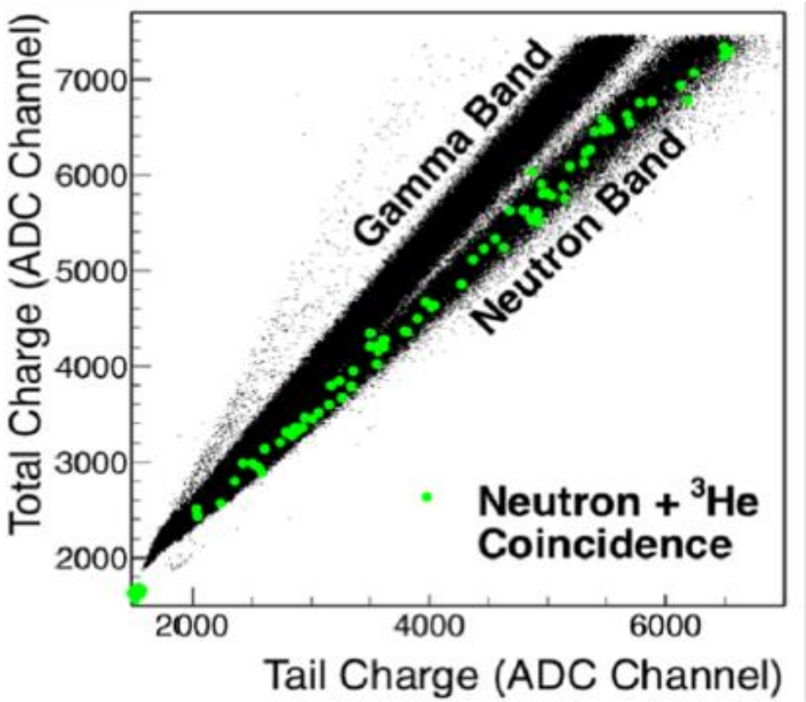


- Monitoring of neutron production is mandatory in our shielded experimental area
- Helim-3 based scintillation type neutron detector – ^{3}He + n → T + p

D-D fusion and neutron detection

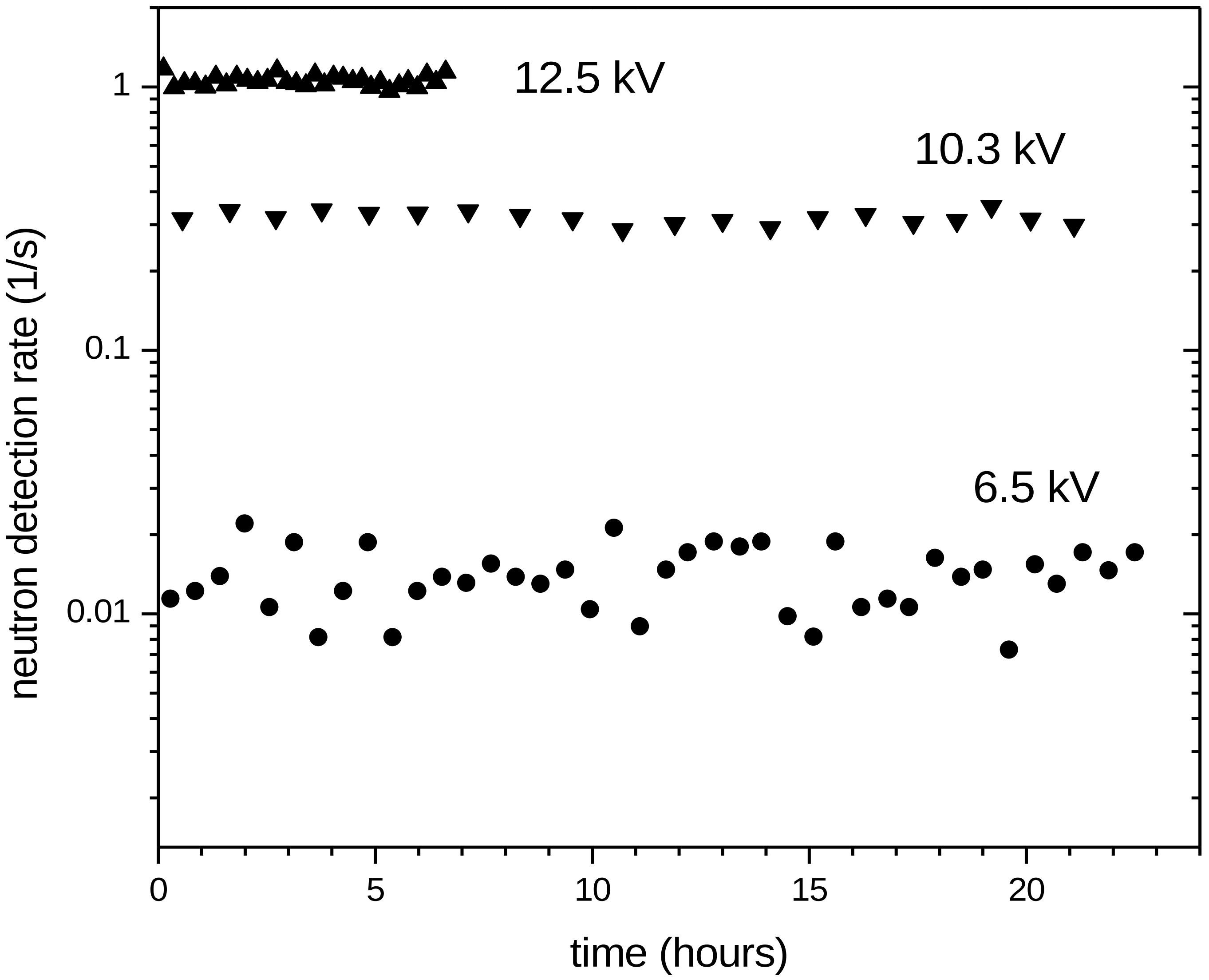


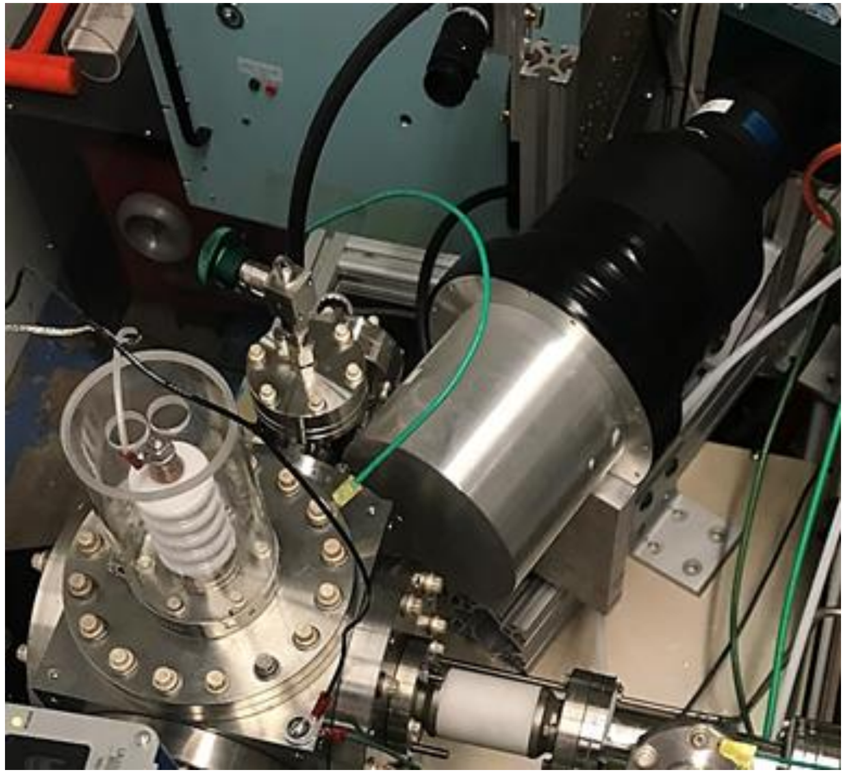




Q. Ji, C.-J. Lin, C. Tindall, M. Garcia-Sciveres, T. Schenkel, B. A. Ludewigt, "Coincidence measurements of ^{3}He and neutrons from a compact D-D neutron generator", Rev. Sci. Instr. 88, 056105 (2017)

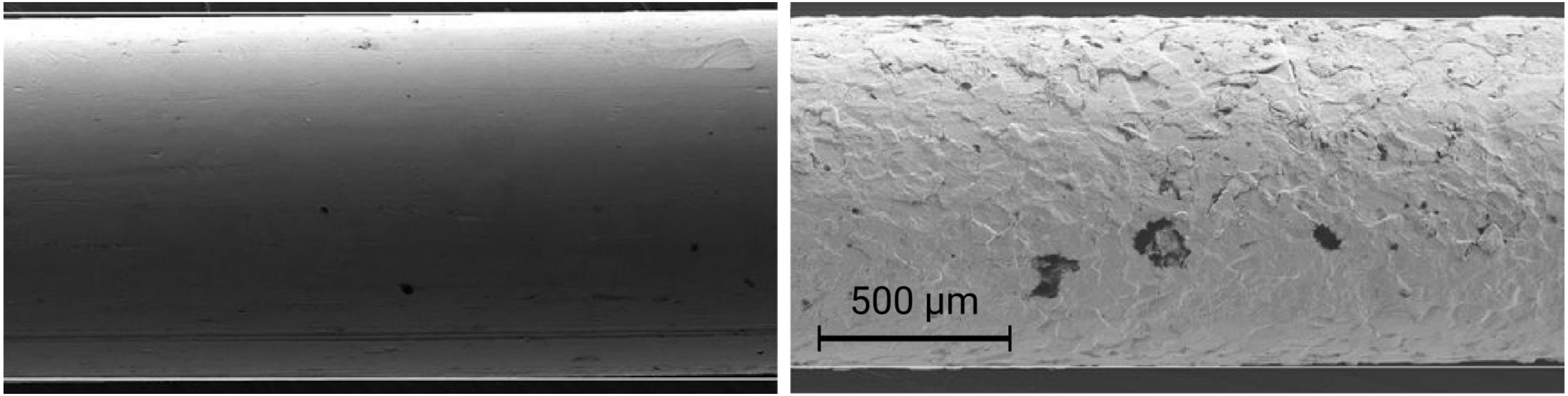
We ran the plasma discharges continuously for hours and days





T. Schenkel, et al., https://arxiv.org/abs/1905.03400

Ex situ electron microscopy shows roughening and increase of carbon and oxygen in palladium wires after exposure to deuterium ions in a glow discharge for hours



Scanning electron micrographs of an as-received Pd wire (left) and a Pd wire that had been exposed to deuterium ions in extended discharge plasma runs (right), imaged using an 15kV, 1 nA electron beam at 57x (done at MIT). Total deuterium ion fluence ~10^{21} d/cm^2.

Ex situ screening for tritium in deuterium implanted Pd wires shows no activity above background

d+d → tritium (1 MeV) + proton (3 MeV)
d+d → neutron (2.5 MeV) + ^{3}He (0.85 MeV)

- We analyzed aluminum catcher foil samples and palladium wires in a scintillation counter (Perkin Elmer Tri-Carb 2910TR)
- Tritium beta decay: T → ^{3}He + electron + neutrino
- Beta emission up to 18 keV (average 5.7 keV) into liquid scintillator and detection of scintillation photons
- Tritium half live, 12 y, specific activity 3.6×10^{14} Bq/g or 3.6×10^{-9} Bq/atom

- **We did not detect activity above the background of 0.2 Bq**

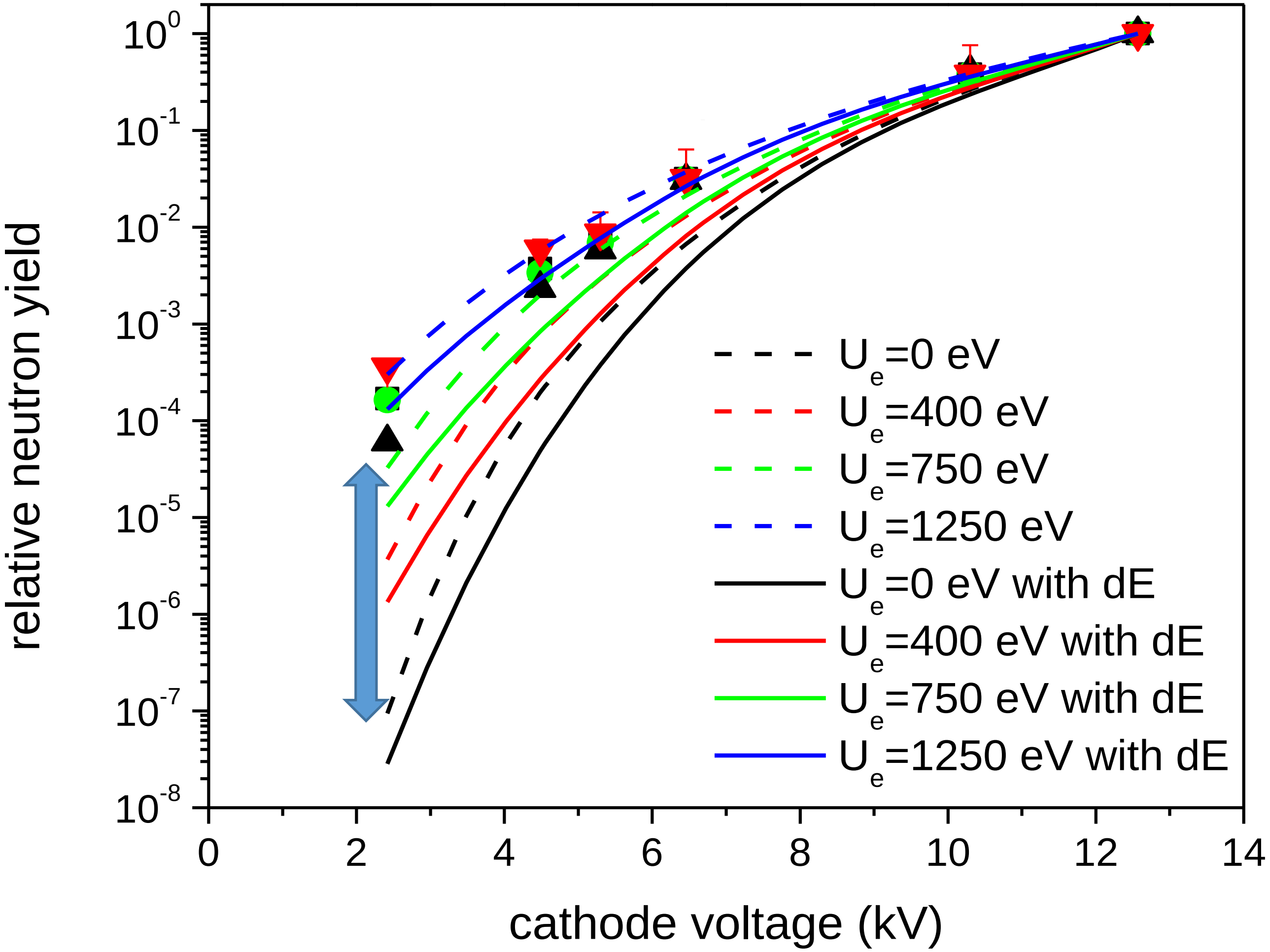
→ Fewer than 10^8 tritium atoms near the surface of samples

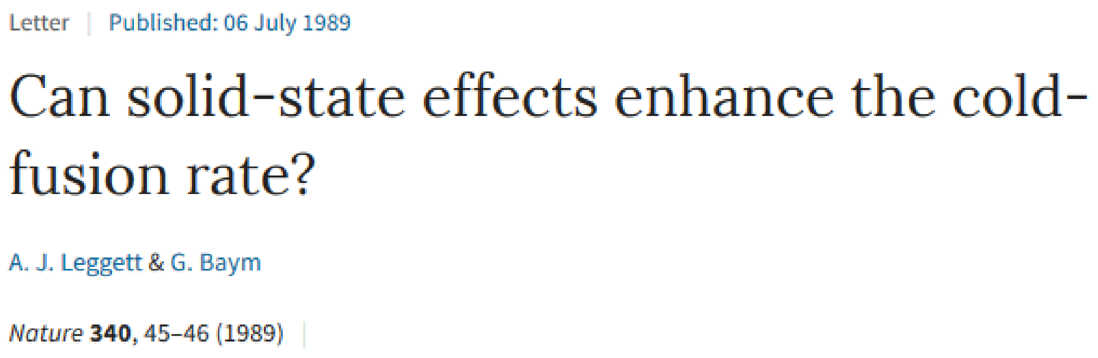
- But unknown sticking, diffusion and loss function, …

- Next steps:
  - catcher targets that can be dissolved into the liquid scintillator right after plasma exposures
  - in situ collection of tritium from Palladium foils
  - …

- beta-counting setup of Rebecca Abergel
- analysis of our samples by Gauthier Deblonde

We observe fusion rates that are > 100 times higher than expected for ion energies of below 5 keV





Letter | Published: 06 July 1989

Can solid-state effects enhance the cold-fusion rate?

A. J. Leggett & G. Baym

Nature **340**, 45–46 (1989)

- our work:
  - solid-state effects strongly enhance D-D fusion rates at reaction energies below a few keV (center-of-mass)

Schenkel, et al., https://arxiv.org/abs/1905.03400

Acknowledgments

The team working on the fusion experiments included (left to right) Qing Ji, Tak Katayanagi, Will Waldron, Peter Seidl and Arun Persaud. Photo by Marilyn Chung, Berkeley Lab.

Jean-Luc Vay contributed with plasma modeling and simulations

Gauthier Deblonde (now LLNL) conducted the tritium counting measurements

Work at Lawrence Berkeley National Laboratory was funded by the US Department of Energy, DOE, Office of Science and ArpaE, by Sandia National Laboratory, and in part by Google LLC under CRADA between LBNL and Google LLC. LBNL operates under U.S. Department of Energy contract DE-AC02-05CH11231.

Outlook – Fusion, Beams and Qubits

- Ion pulses from NDCX-II are used for rad effects studies with Sandia
- The BELLA Center is now part of LaserNetUS, high energy density science and ion acceleration
- We are learning about the formation of center qubits and are curious about quantum sensing
- MEMS based multi-beam linacs look promising for scaling to high beam power, possibly as HIF drivers
- We are exploring fusion processes at relatively low reaction energies
- Opportunities for collaboration