Fusion, beams and qubits

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Outline

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

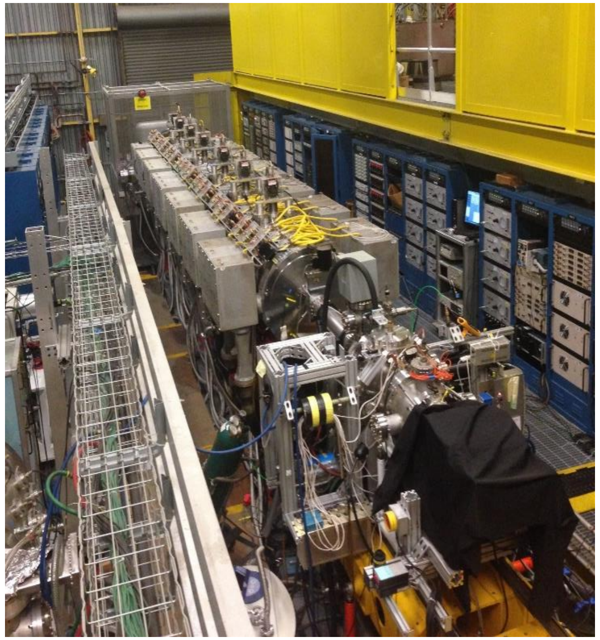
Beams

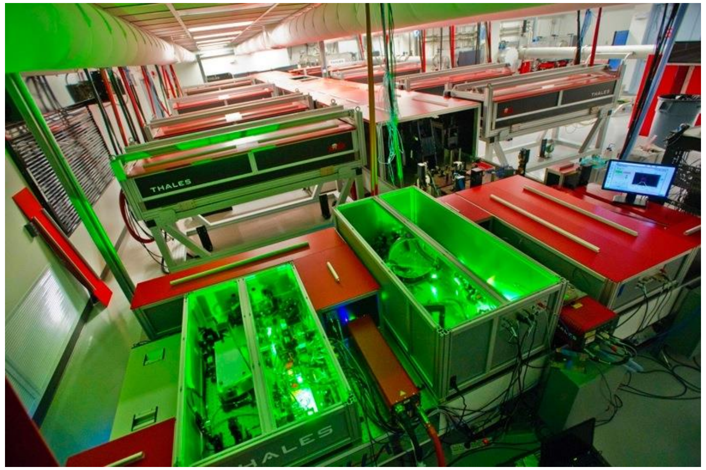
Outline - Beams

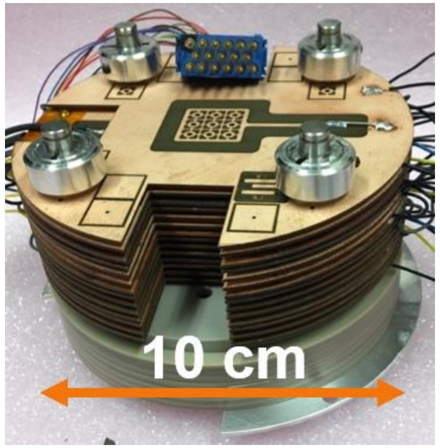
a. Induction linac, NDCX-II

b. Laser-plasma acceleration, BELLA

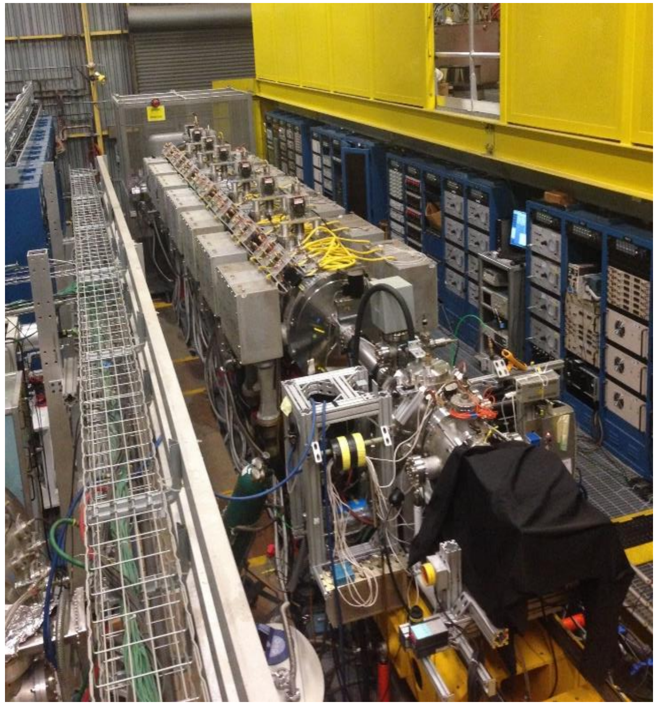
c. MEMS based RF-linacs

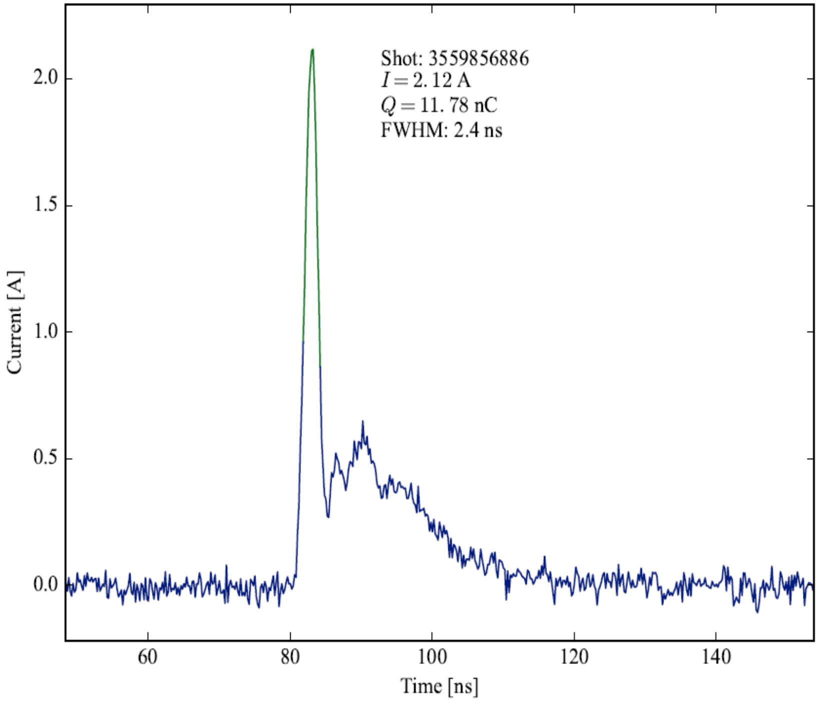


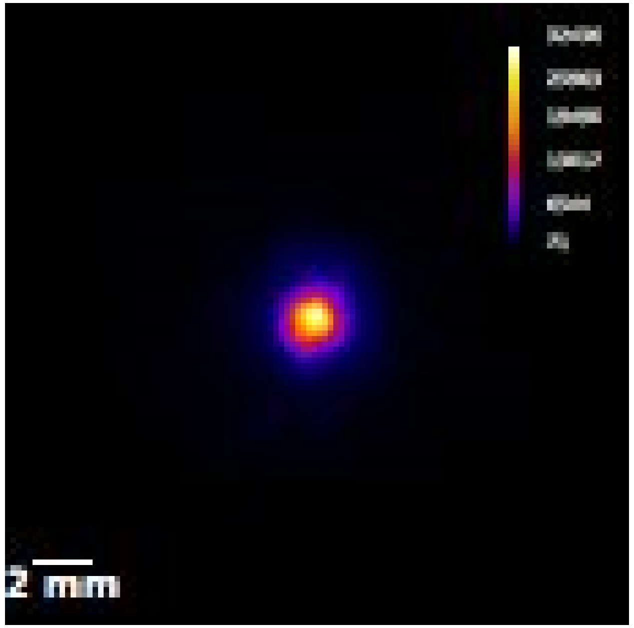




Intense, pulsed ion beams by neutralized drift compression in an induction linac – NDCX-II







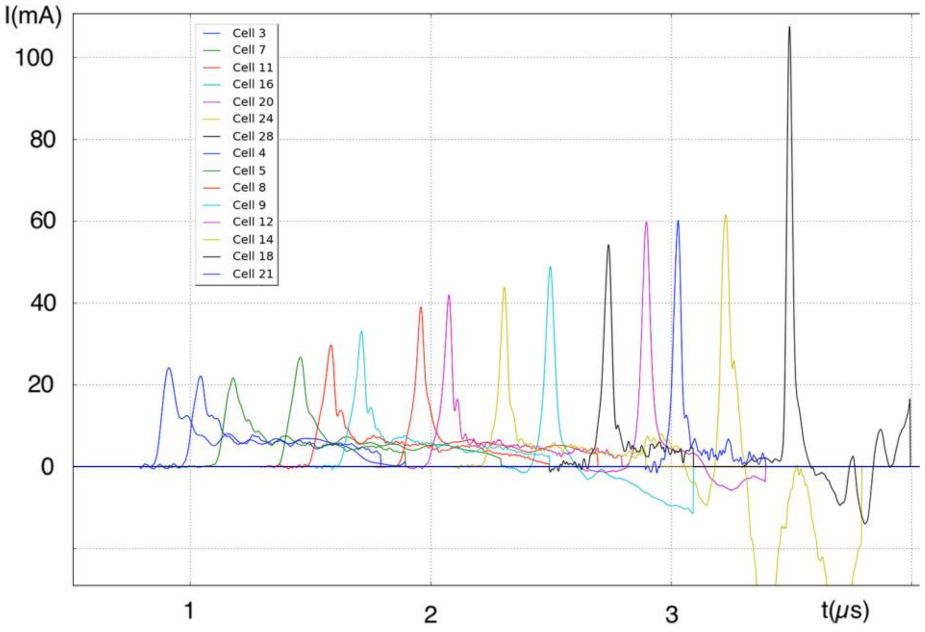
- NDCX-II at Berkeley Lab

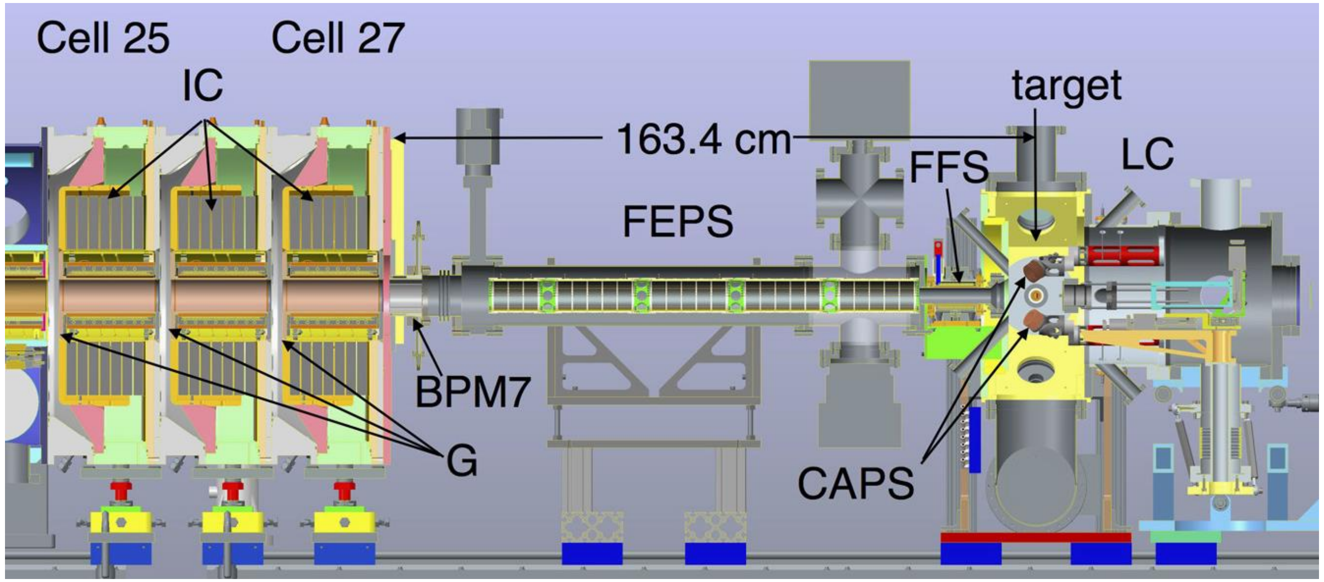
- 1.1 MeV (He^+), 12 nC (7.5×10^{10} ions), 13 mJ
- Routinely ~5×10^{11} ions/cm^2/pulse

- 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

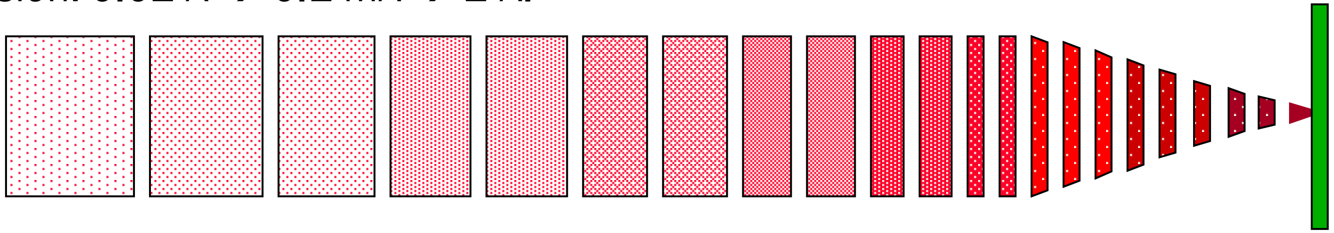
- P. A. Seidl, et al., NIM A (2015)

NDCX-II – the neutralized drift compression experiment to make intense, short ion pulses





- beam spots size with radius r ~ 1 mm within 2 ns FWHM and 10^{10} – 10^{11} ions/pulse.
- Compression: 0.02 A → 0.1 mA → 2 A.



Ion source and injector, 500ns

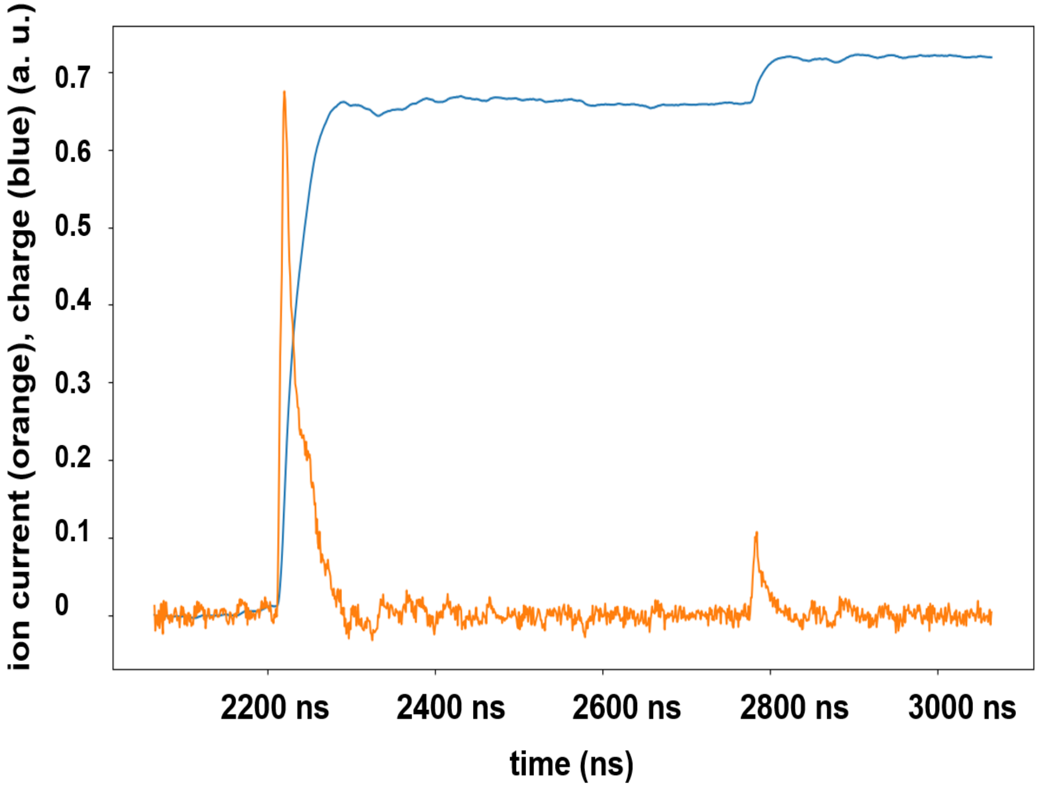
Linac custom waveforms for rapid beam compression

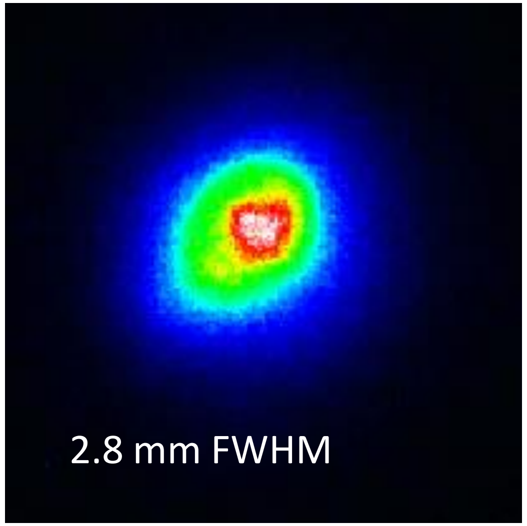
Neutralized drift compression and final focus

Target

P. A. Seidl, W. G. Greenway, S. M. Lidia, A. Persaud, M. Stettler, J. H. Takakuwa, W. L. Waldron, J. J. Barnard, A. Friedman, D. P. Grote, R. C. Davidson, E. P. Gilson, I. D. Kaganovich, T. Schenkel, “Short intense ion pulses for materials and warm dense matter research”, Nucl. Instr. Meth. A 800, 98 (2015)

Pulses of 1 MeV protons from NDCX-II

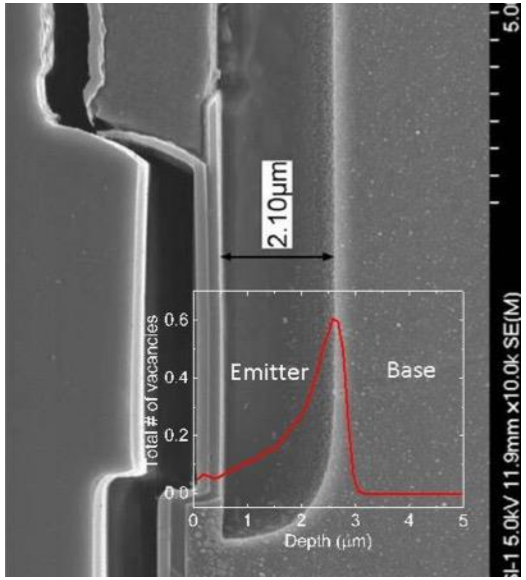




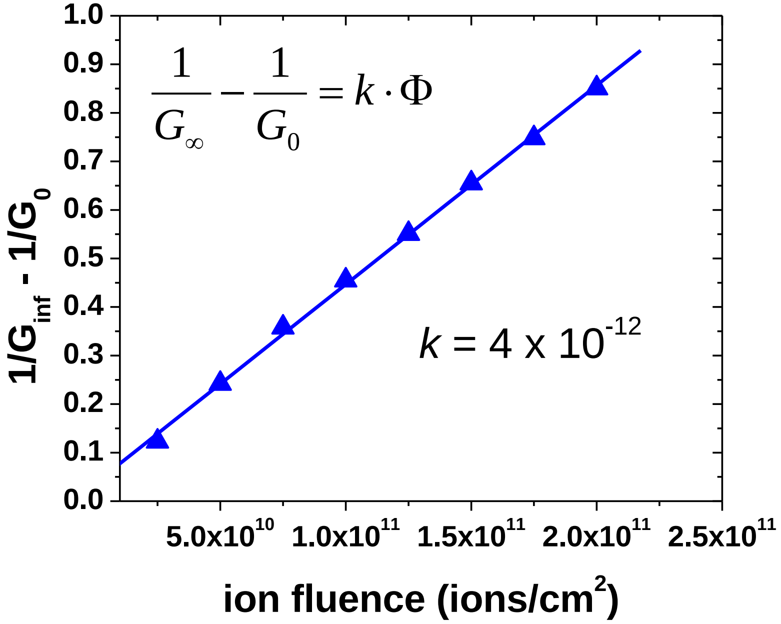
- Proton pulses with peak currents of 0.1 to 1 A, 10 to 20 ns FWHM, ~1 to 5E10 protons/pulse.
- The proton energy is 1 MeV with a range in silicon of 16 um.

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)



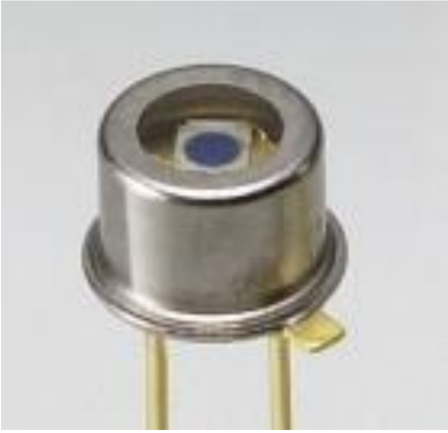
Example of a measured Messenger-Spratt curve to determine the damage constant.

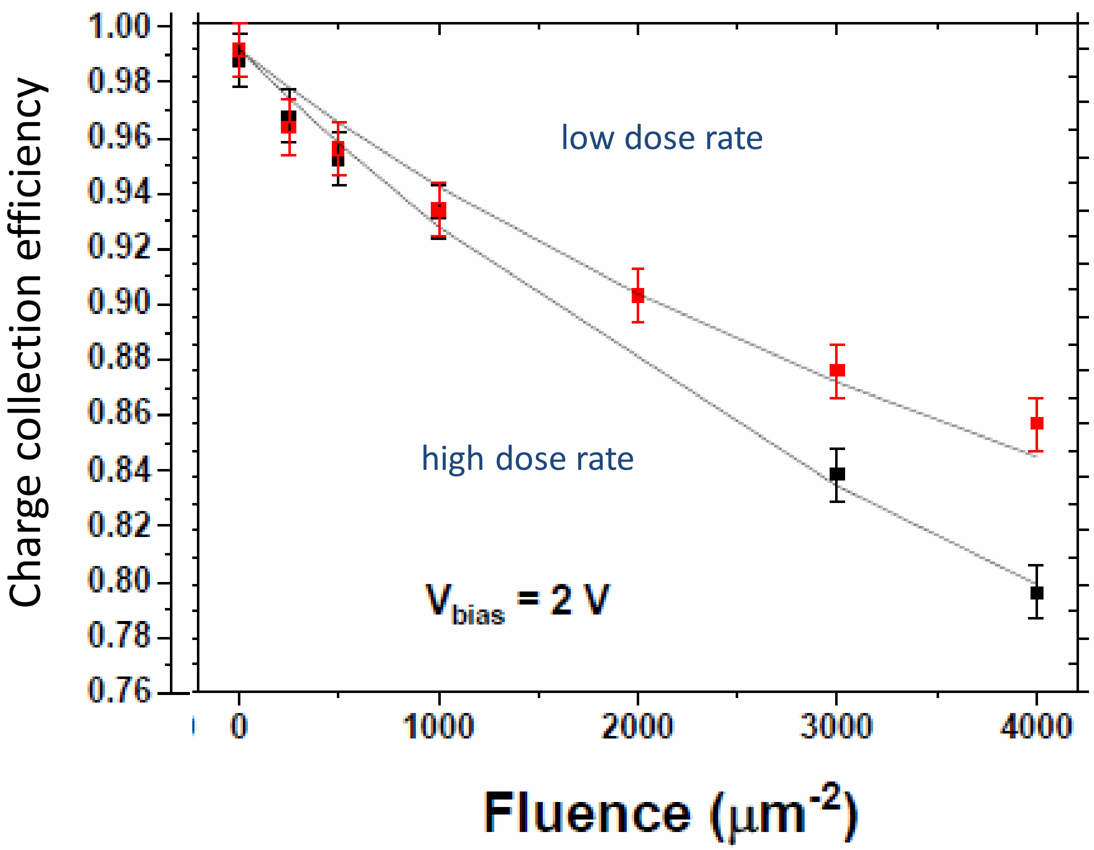
- B. A. Ludewigt, et al., Journal of Radiation Effects, Research and Engineering Vol. 36, No. 1, April 2018

- 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





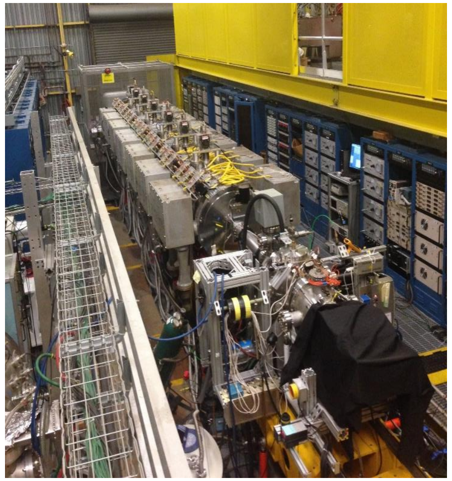
- S5821 Hamamatsu pin diodes, NDCX-II shots (high dose rate) compared to experiments at other labs with low dose rate
- 1 MeV Helium ions, 1E11 ions/cm^2/shot
- Balance of defect formation, annealing and formation of extended defects
- Co. E. Vittone, J. Garcia-Lopez, G. Vizkelethy, E. Bielejec, et al.,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

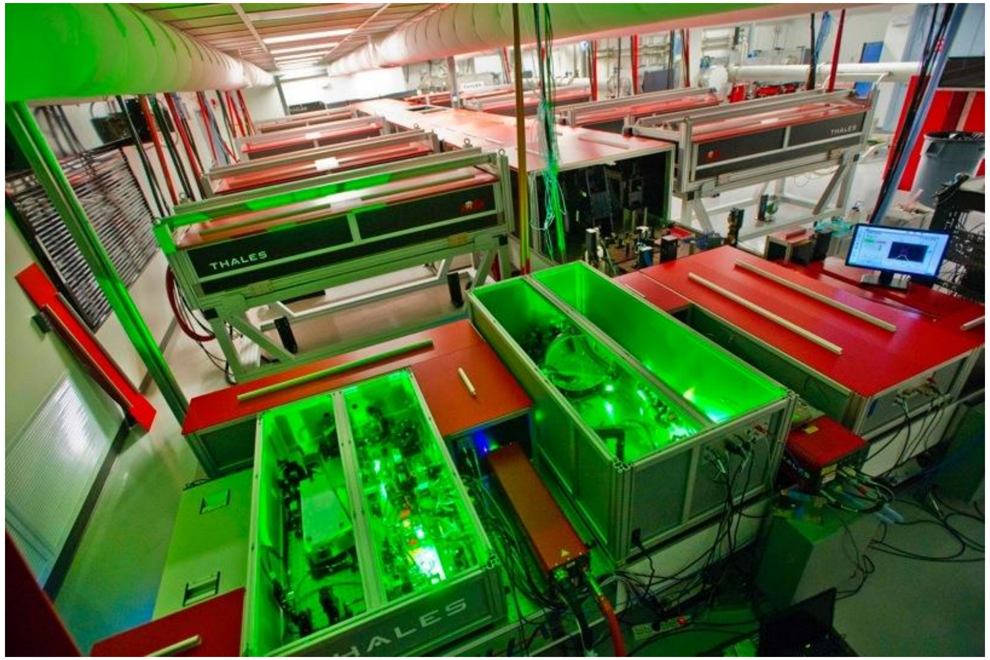
Outline - Beams

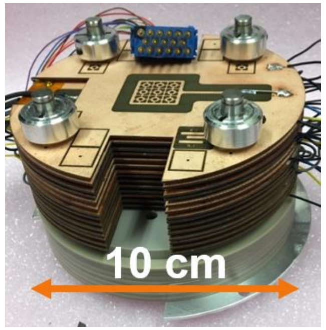
a) Induction linac, NDCX-II

b) Laser-plasma acceleration, BELLA

c) MEMS based RF-linacs





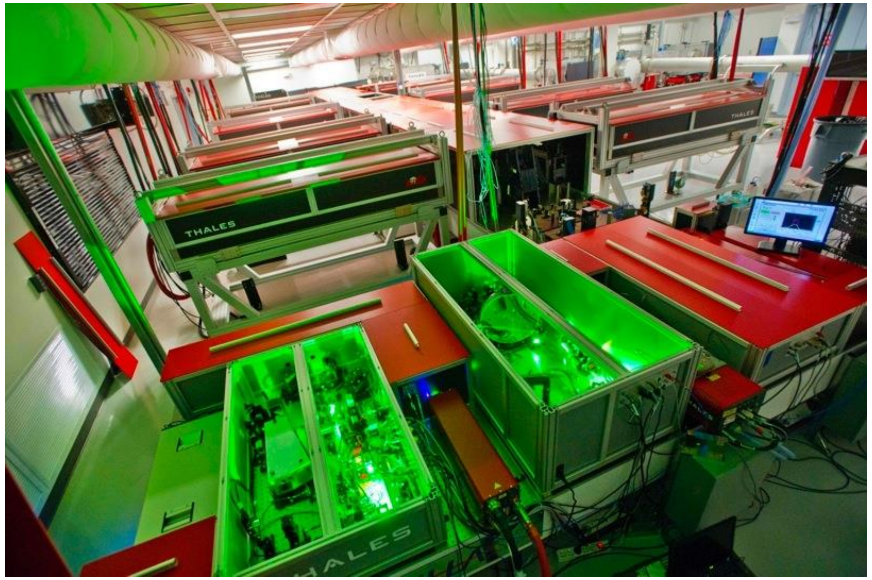


We use the BELLA PW laser to form pulses of high energy electrons (GeV) and now also ions (MeV)

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

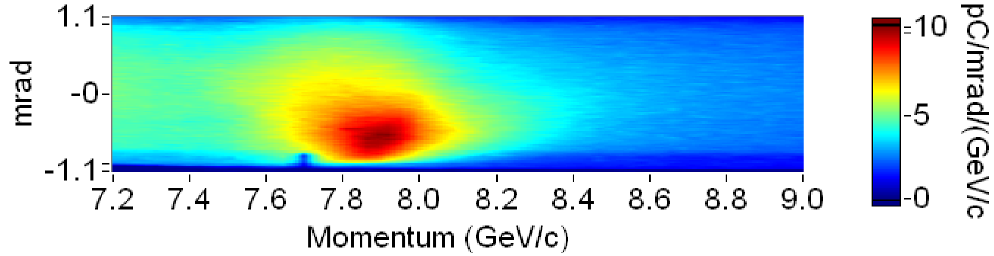
- The primary mission of BELLA is to master laser-plasma acceleration of electrons

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



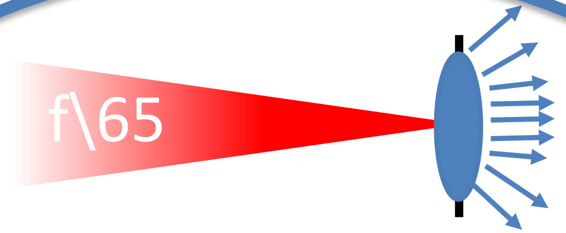




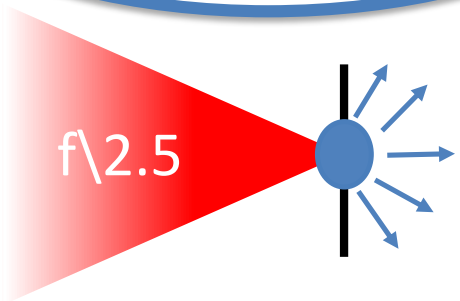


A. J. Gonsalves, et al. Phys. Rev. Lett. 122, 084801 (2019)
K. Nakamura et al., IEEE J. Quant. Electr. 53, 1200121 (2017)

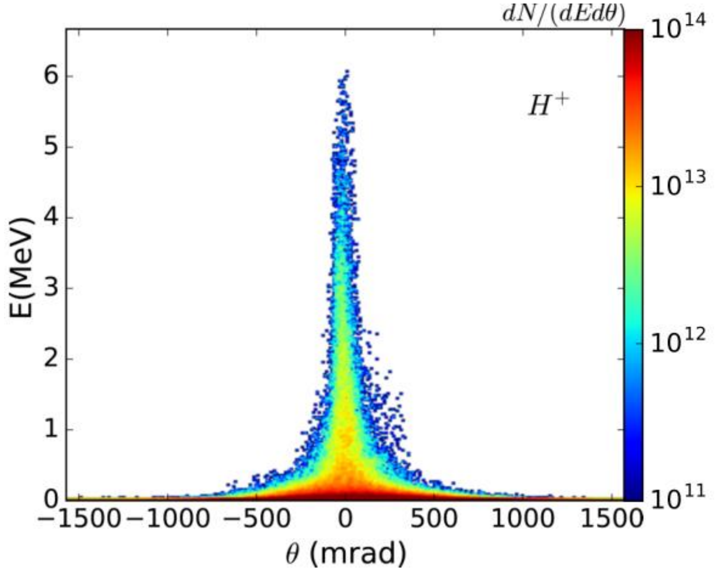
PW Laser Operating with Long Focal Length: Short Focal Length Beamline with a Dedicated Target Chamber in Progress HEDLP in LaserNetUS

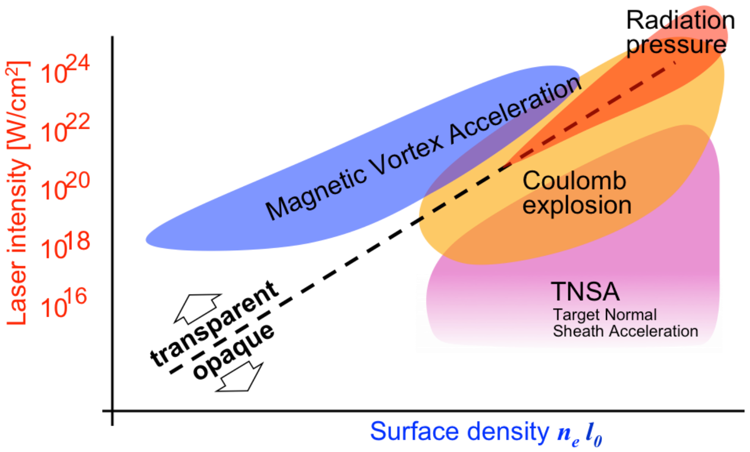


in operation now, 2x10^{19} W/cm^2 , large laser spot, 100 μm, low divergence ion pulses with 10^{12} protons

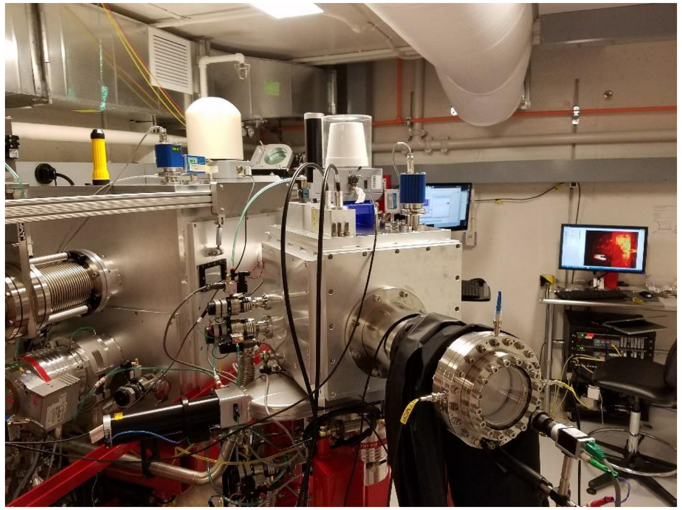


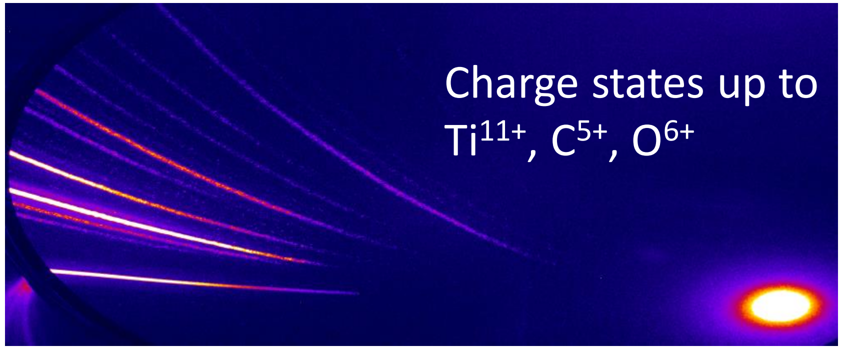
Under construction, >10^{21} W/cm^2, small laser spot, ~10 μm, (ultra)-relativistic plasma science at 1 Hz, advanced ion acceleration, high energy ions (>100 MeV)

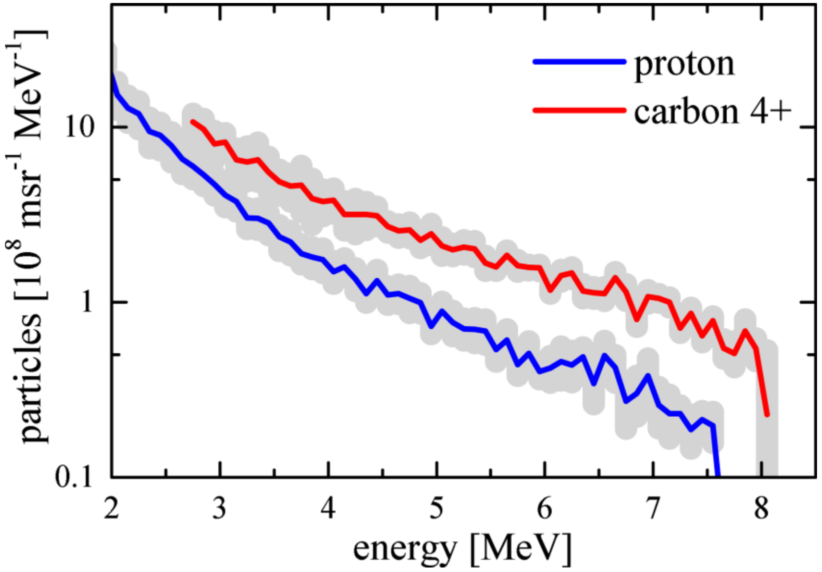


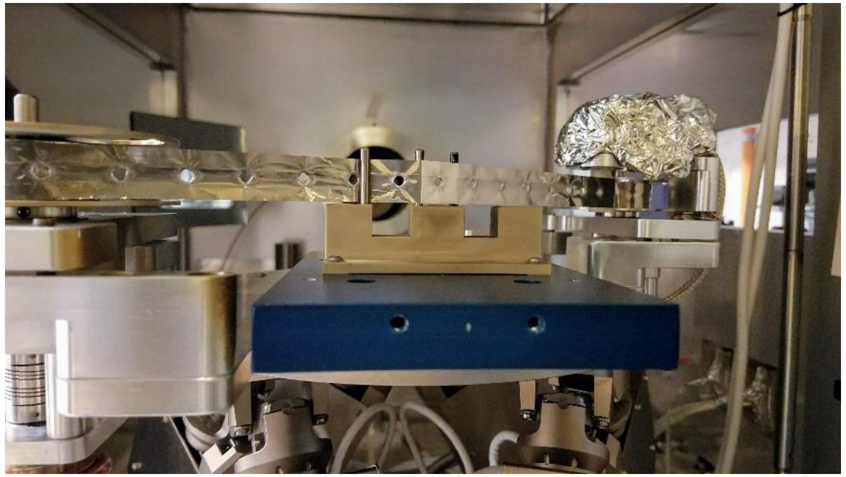


Ion acceleration at BELLA



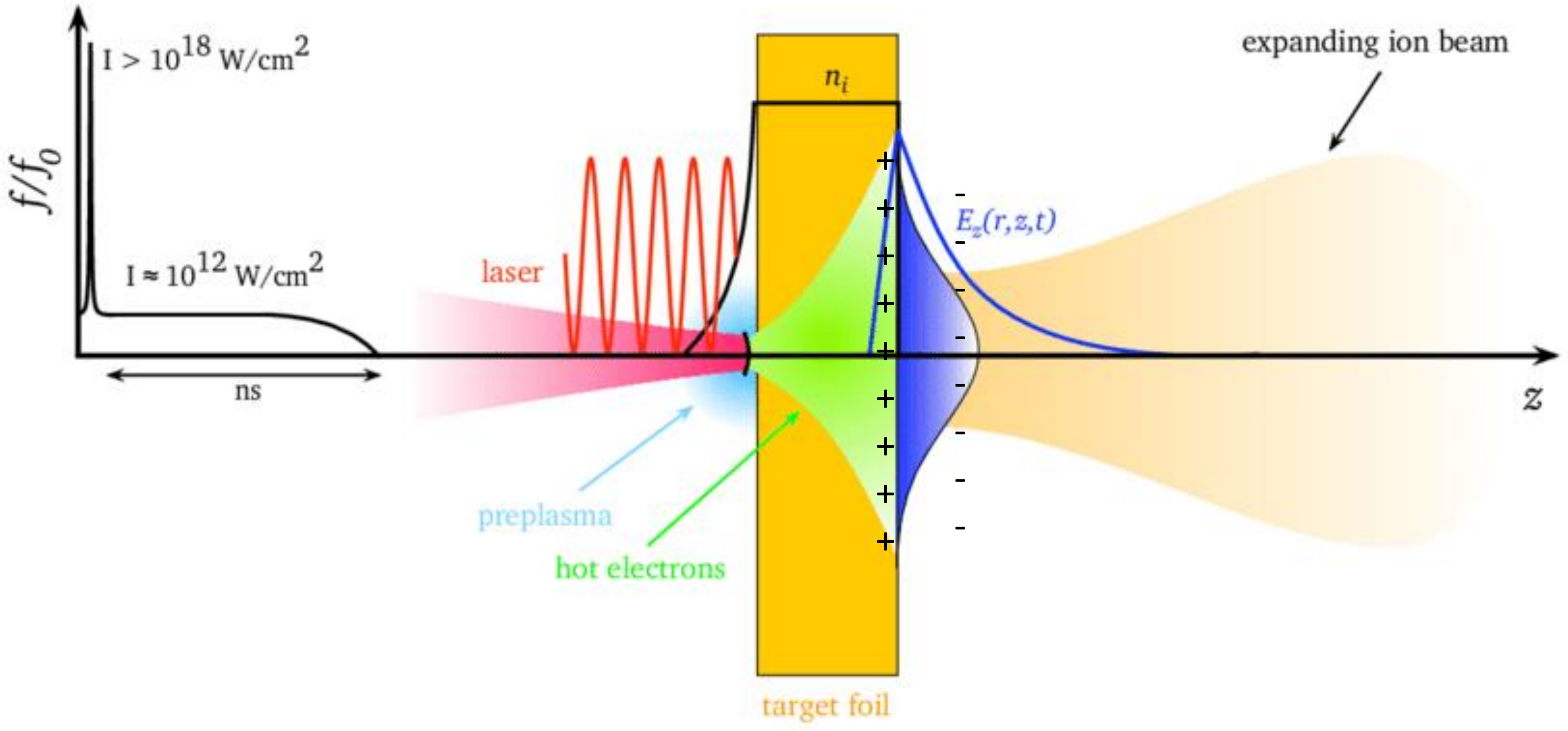






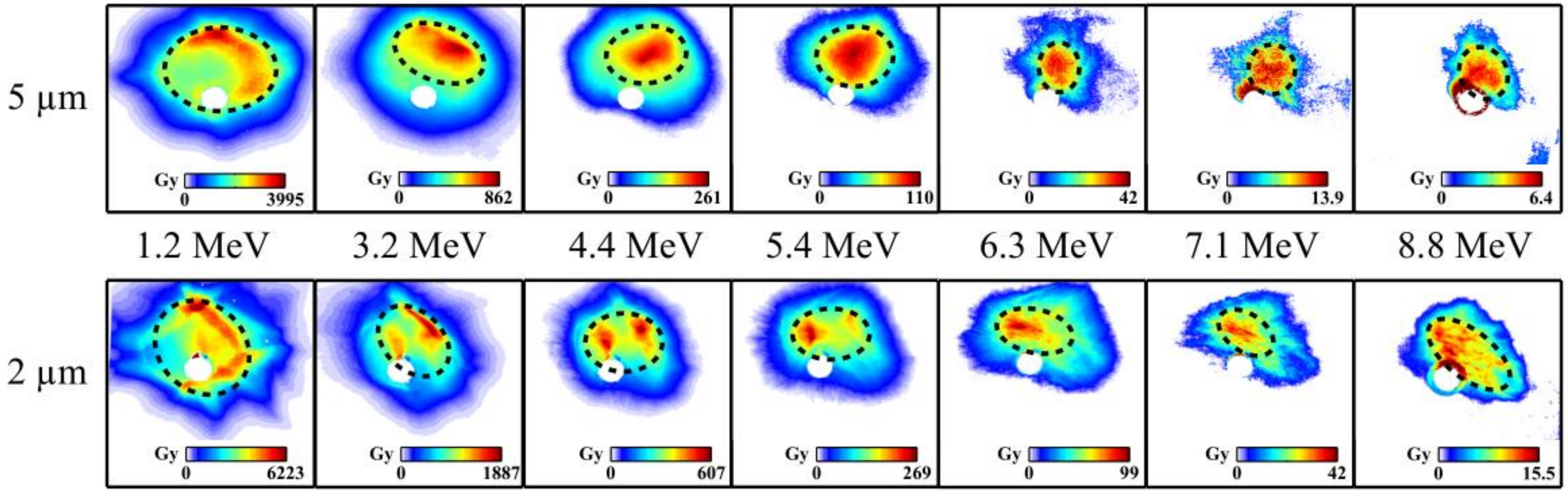
- ~10^{12} total number of MeV ions (from Thomson parabola) and >10^{13} lower energy ions (from ex situ sample analysis by Secondary Ion Mass Spectrometry, SIMS)
- tape drive targets for extended 1 Hz operation
- Bin et al., Rev. Sci. Instr. (2019)
- Steinke et al, in preparation

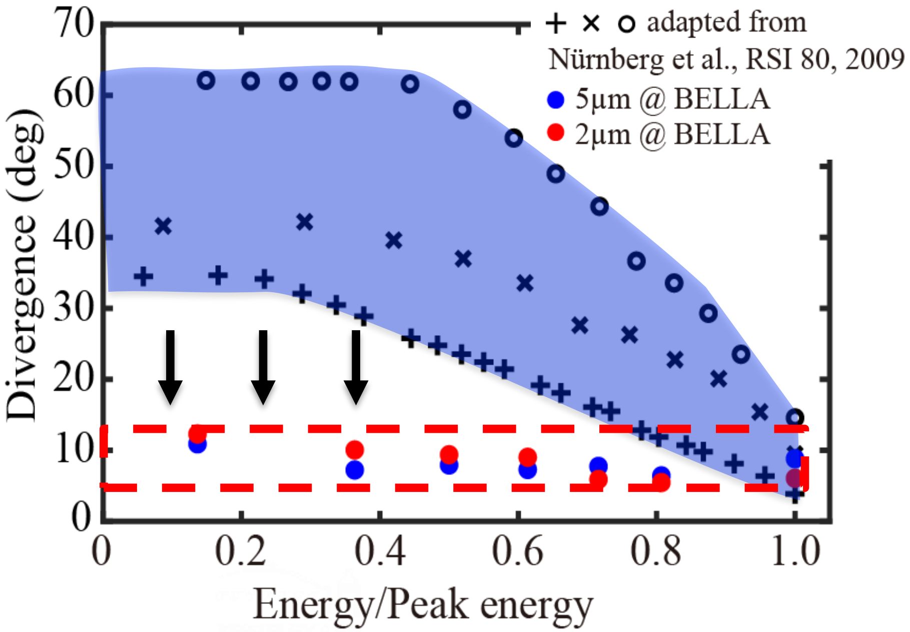
Target normal sheet acceleration (TNSA)



Markus Roth and Marius Schollmeier, 2016

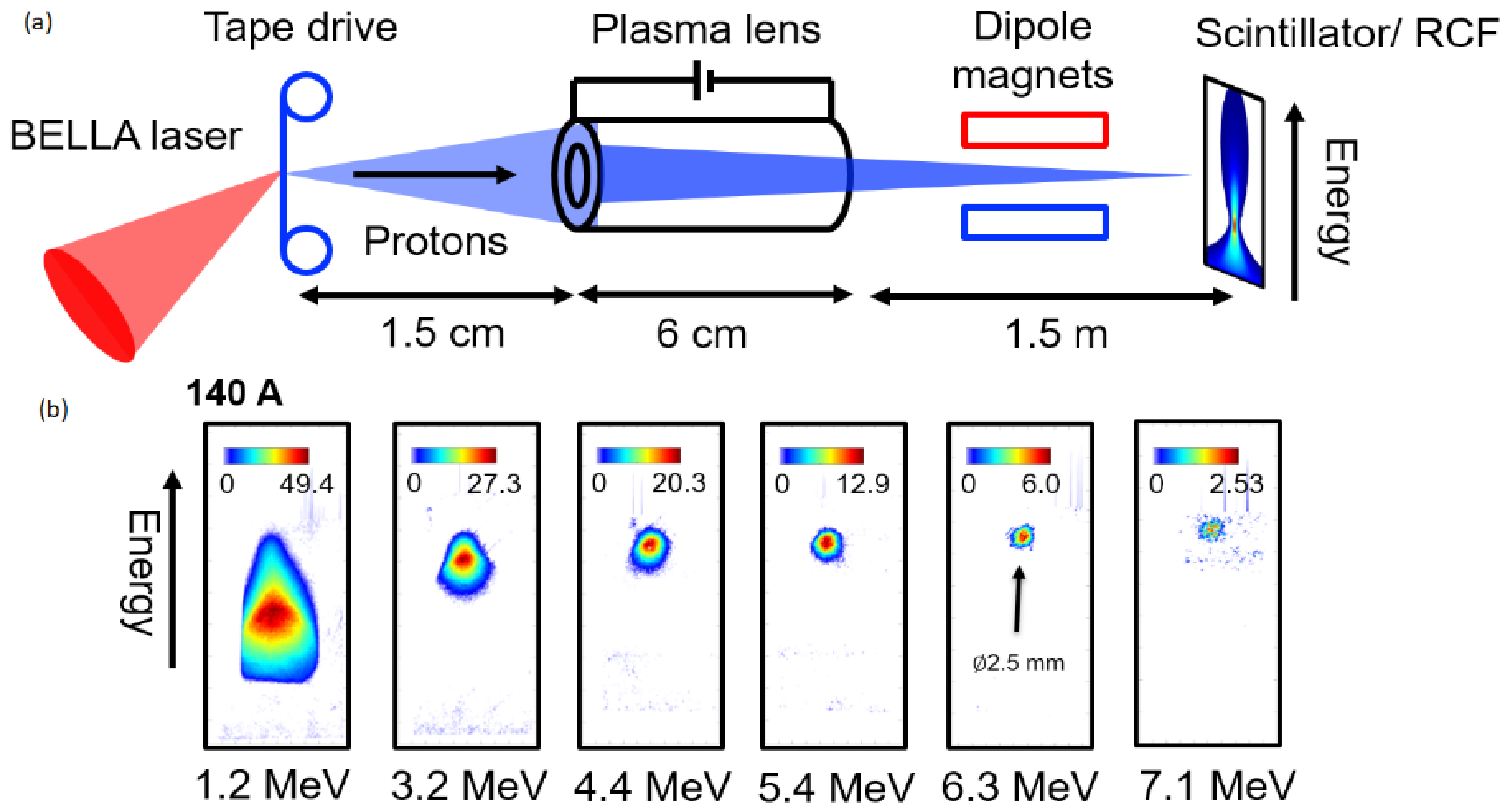
Larger laser spot size leads to achromatic divergence and high number of protons





- 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)

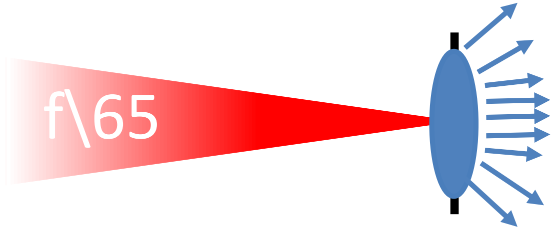
We have now demonstrated capture and transport of proton pulses



- 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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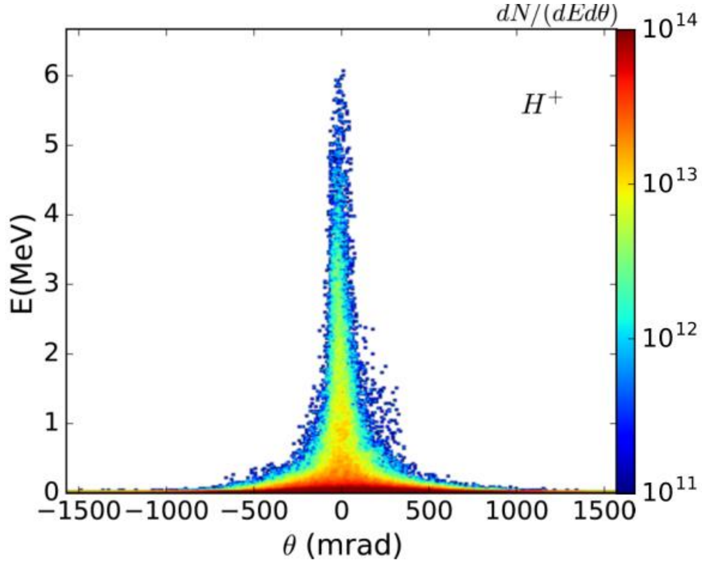
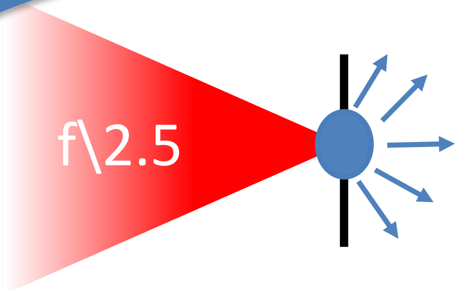
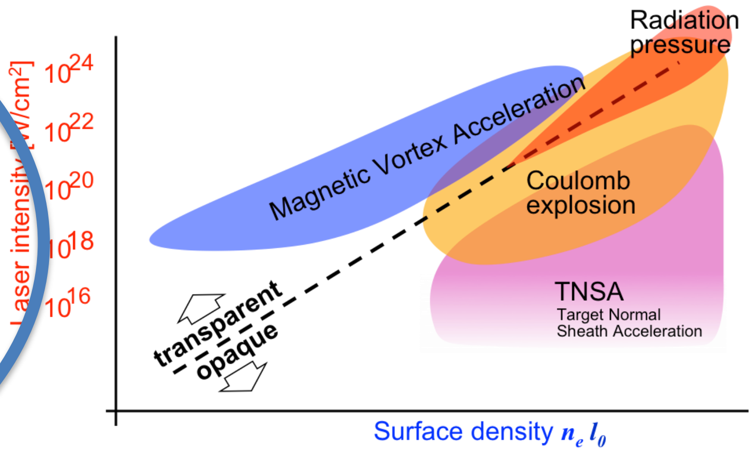


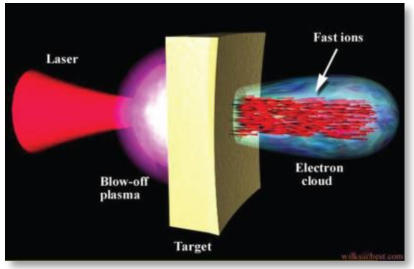


Under construction, >10^{21} W/cm^{2}, small laser spot, ~10 μm, (ultra)-relativistic plasma science at 1 Hz, advanced ion acceleration, high energy ions (>100 MeV)



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

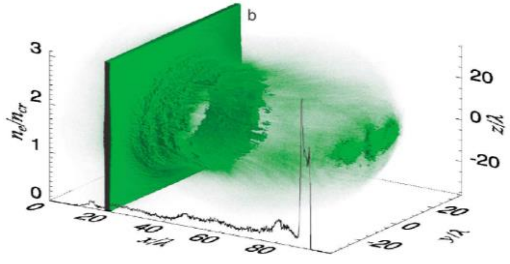
BELLA-i	short focal length
peak intensity (W/cm^2)	5 x 10^{21}
peak pulse energy	40 J in 30 fs
laser spot size	5 µm

Contrast enhancement methods

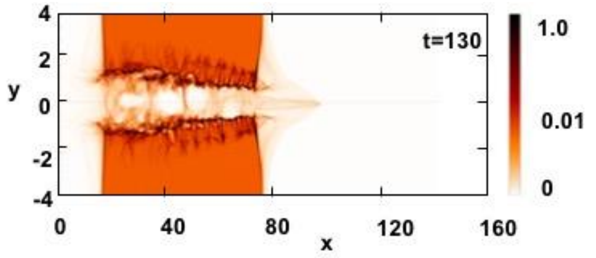
- Plasma mirrors
- Composite targets
- Controlled laser pre-pulse interaction
- Near critical density targets

Advanced ion acceleration

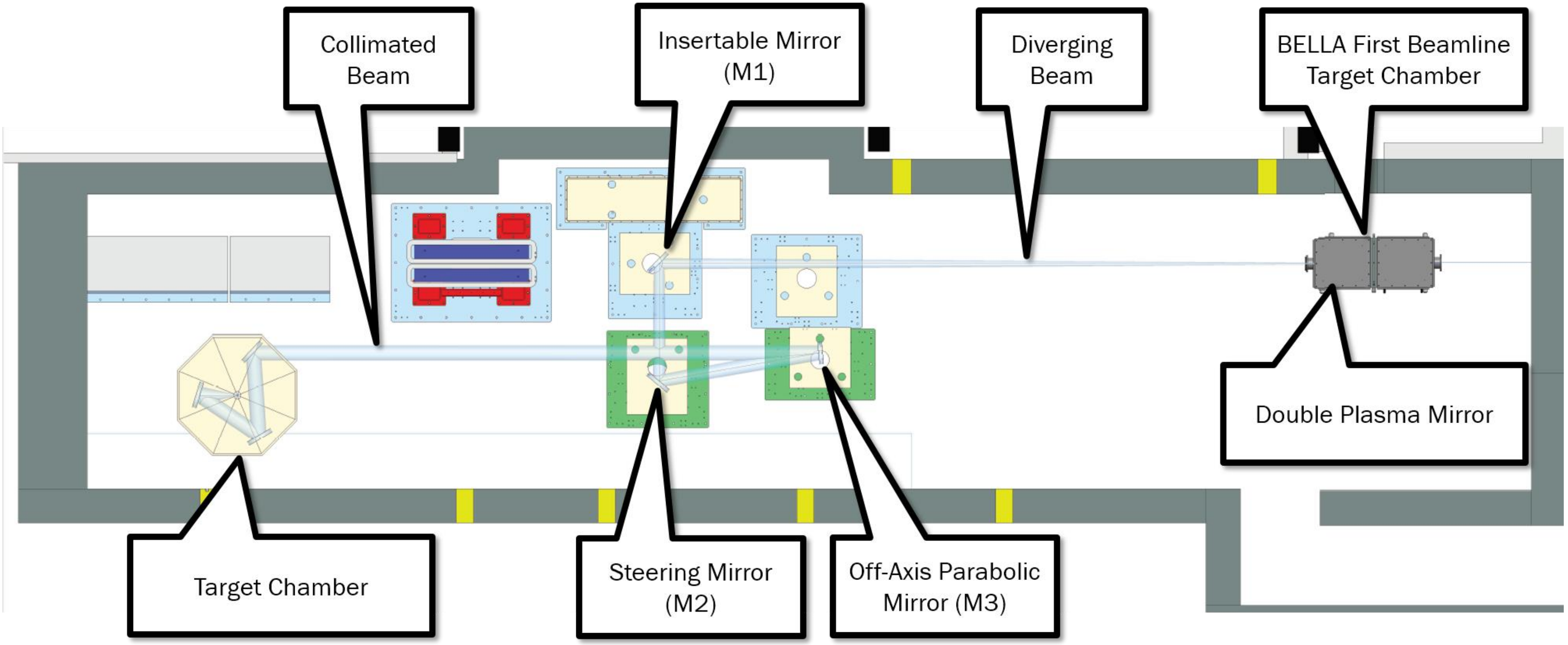
Radiation Pressure Acceleration:
Target: Thin solid density foils
Protons: E_{max}=150 – 200 MeV
Number of particles: ~10^{10} - 10^{11}



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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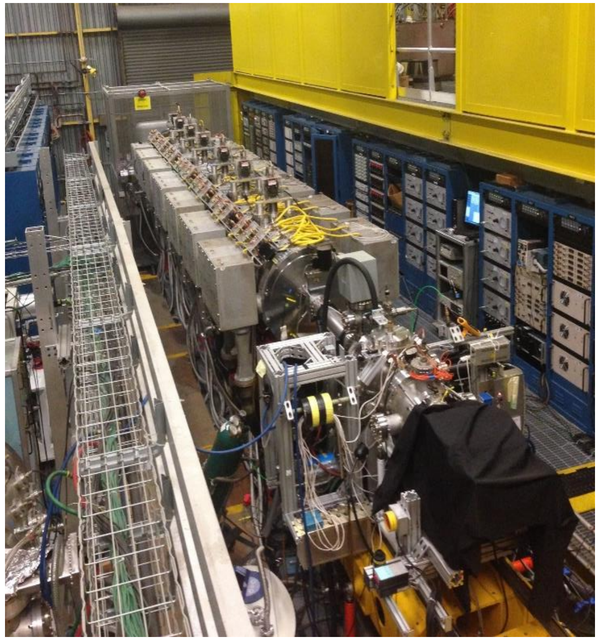
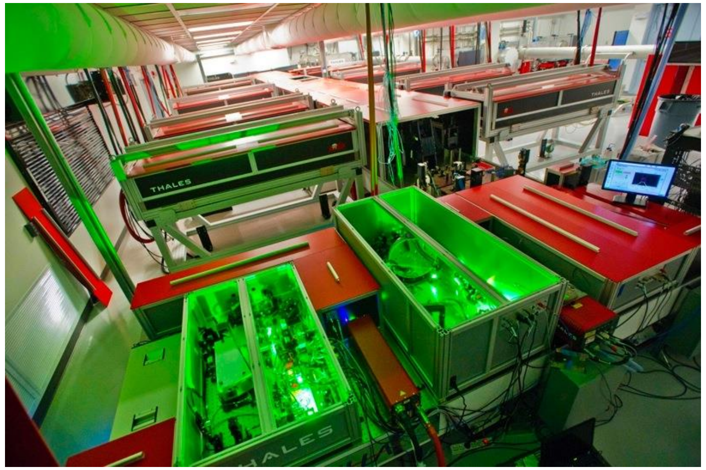
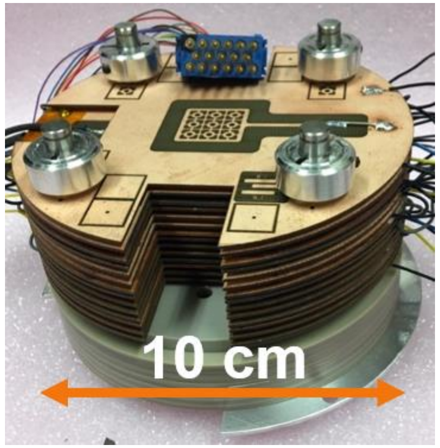
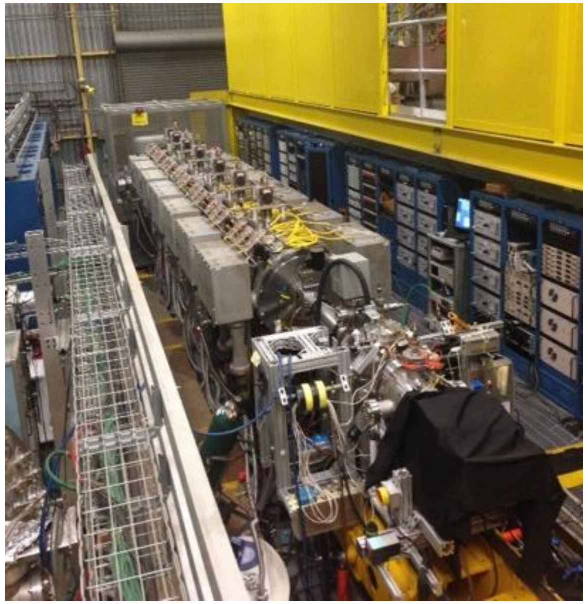


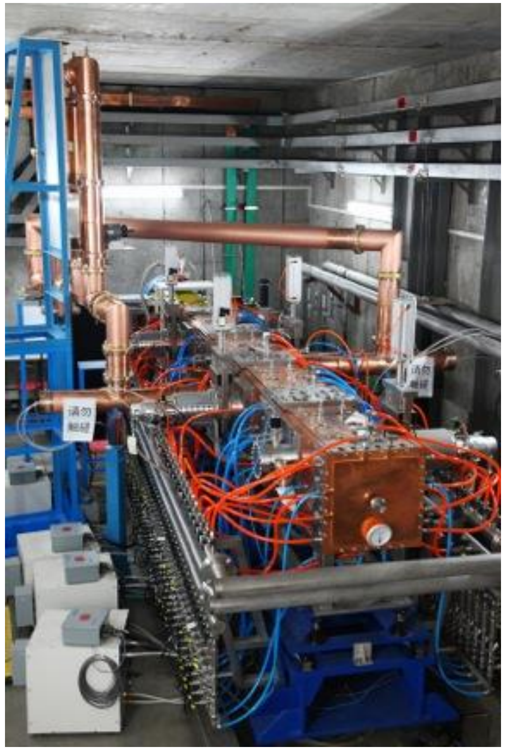




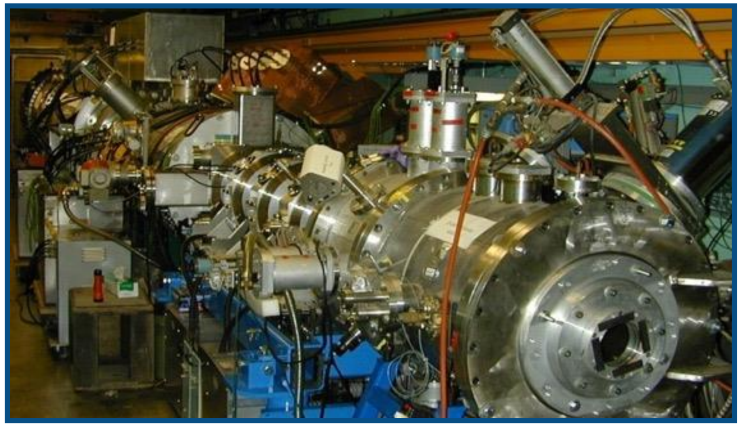
Examples of high power ion accelerators at Berkeley Lab



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



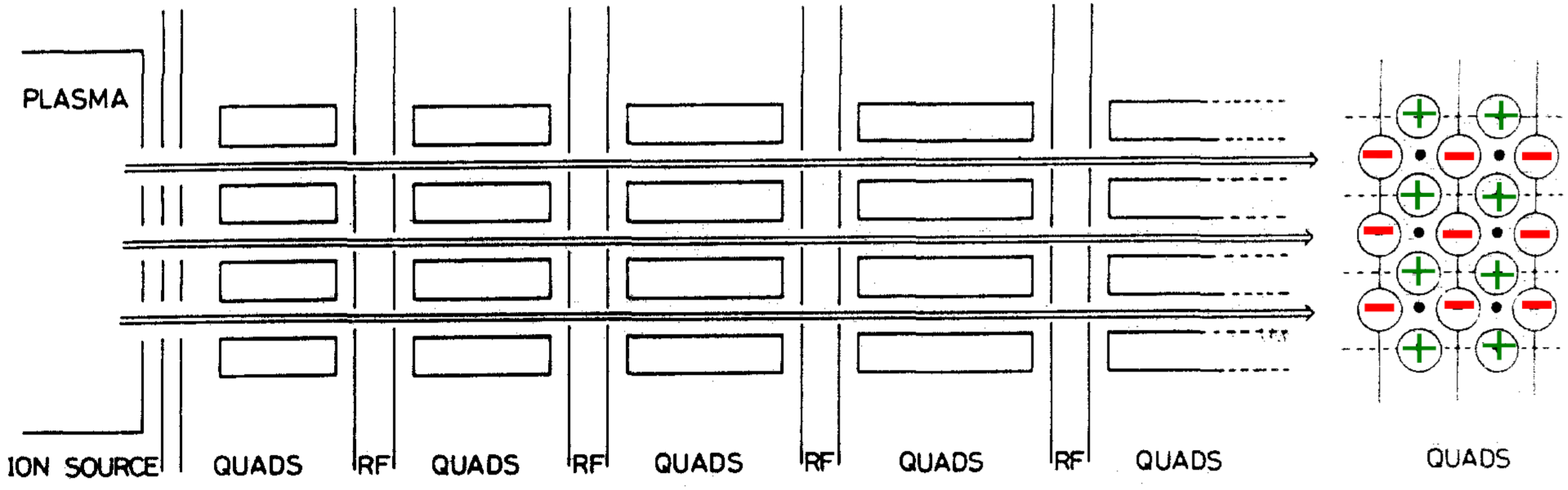
- Radio frequency quadrupole (RFQ)
- 2 MeV, 0.01 A, cw
- 4 m long, 0.4 m cross section
- Z. Zouhli, D. Li et al. IPAC2014



- 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?

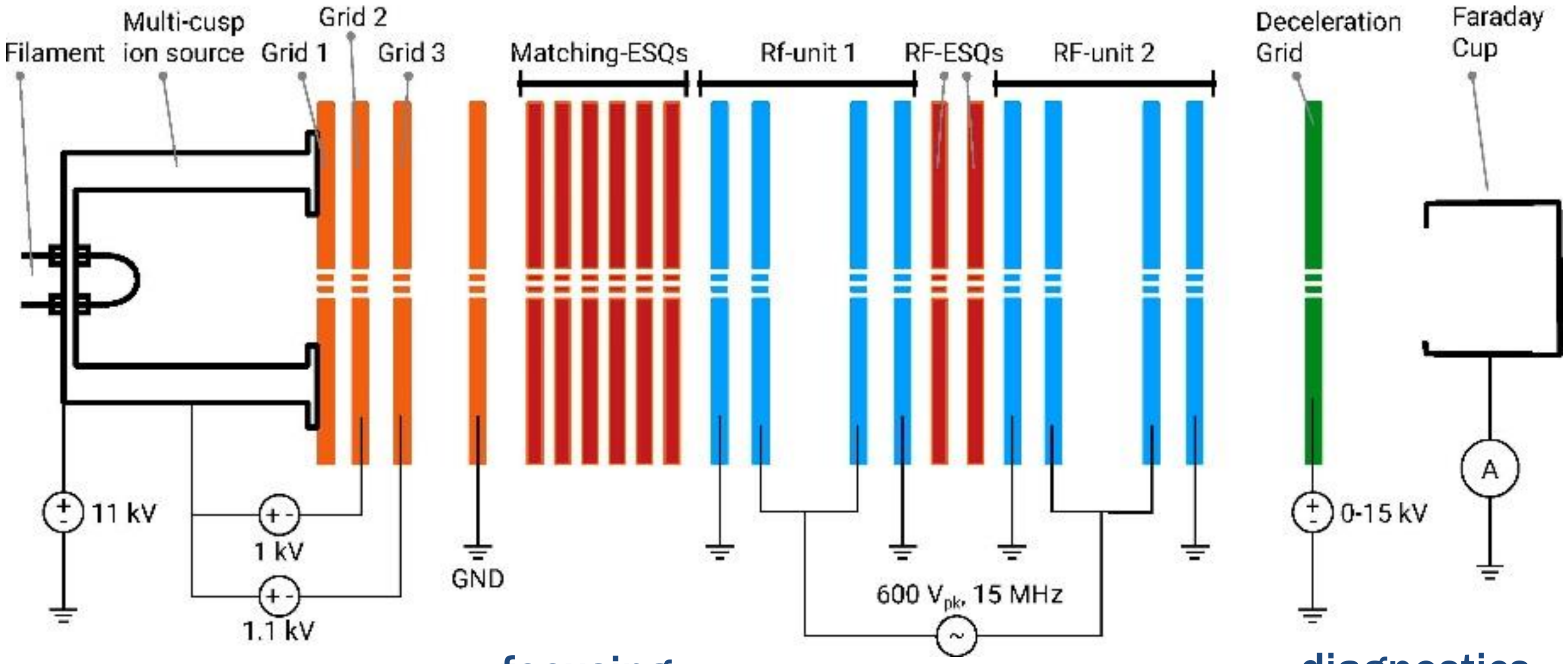
Multiple-Electrostatic-Quadrupole-Array Linear Accelerator (MEQALAC)



- 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

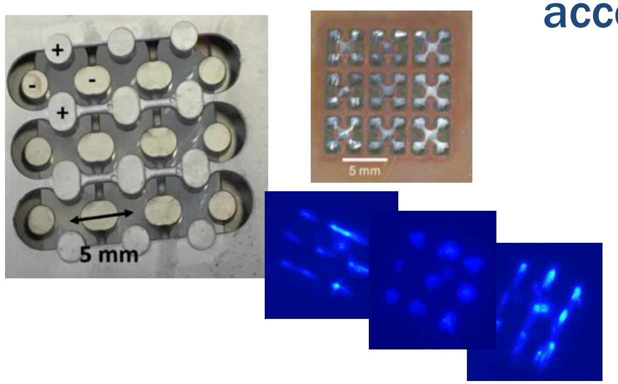
- **Thomae *et al.*, Mat. Science & Eng., B2, 231 (1989)**
- **Al Maschke et al., early 1980s**

Multi-beamlet Ion acceleration and focusing have been demonstrated using a stack of wafers

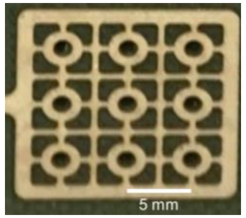


ion source

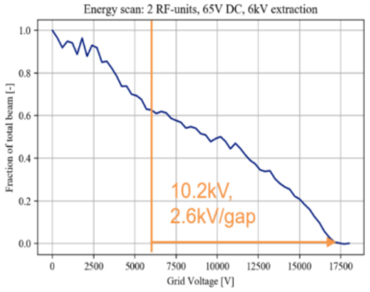
focusing



acceleration

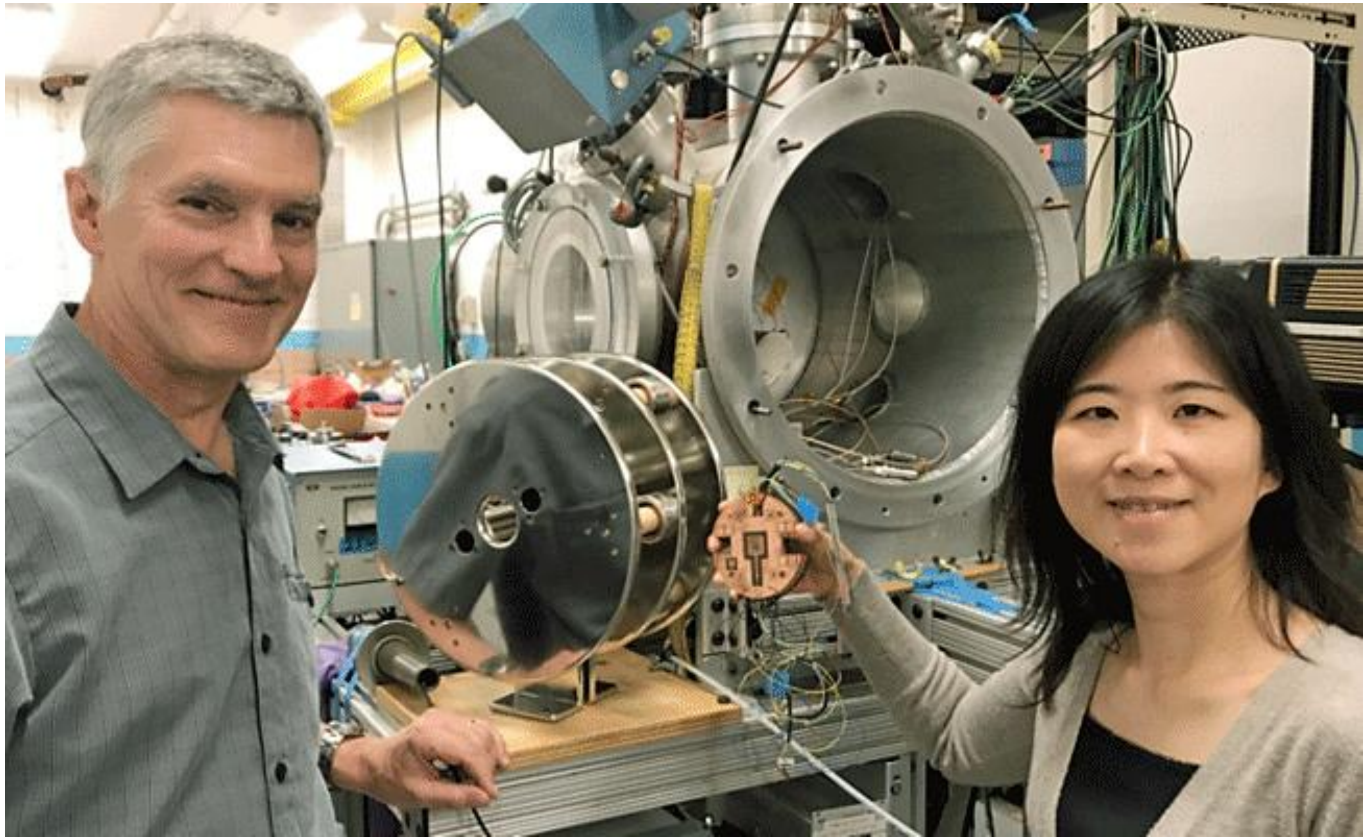


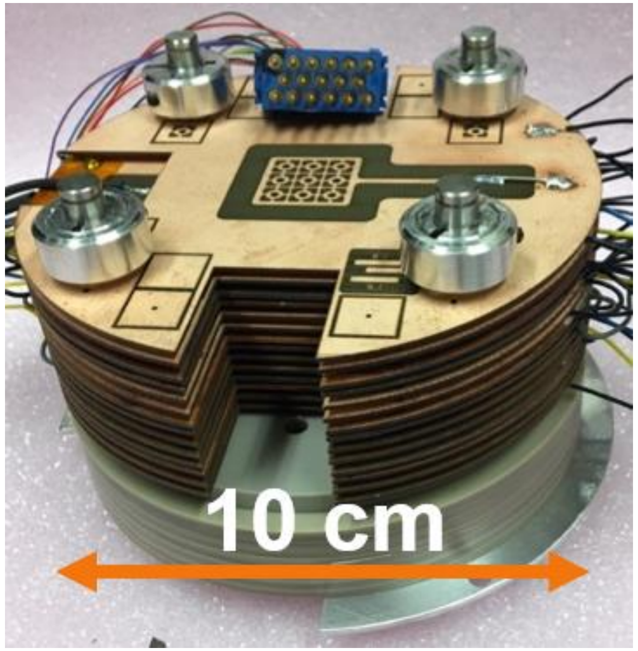
diagnostics

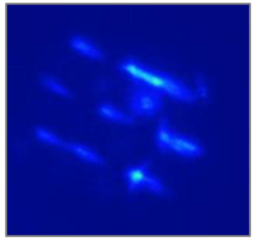


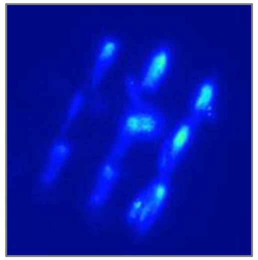
~ 0.01 mA/beamlet

New ideas for high power ion beams







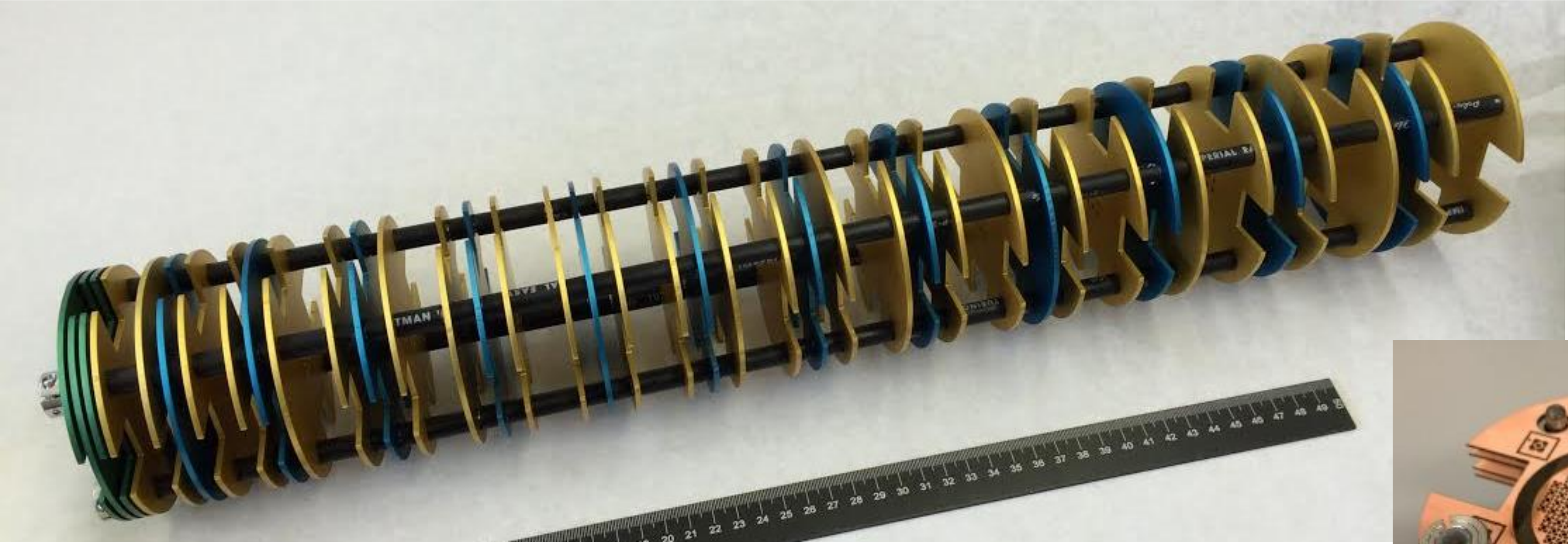


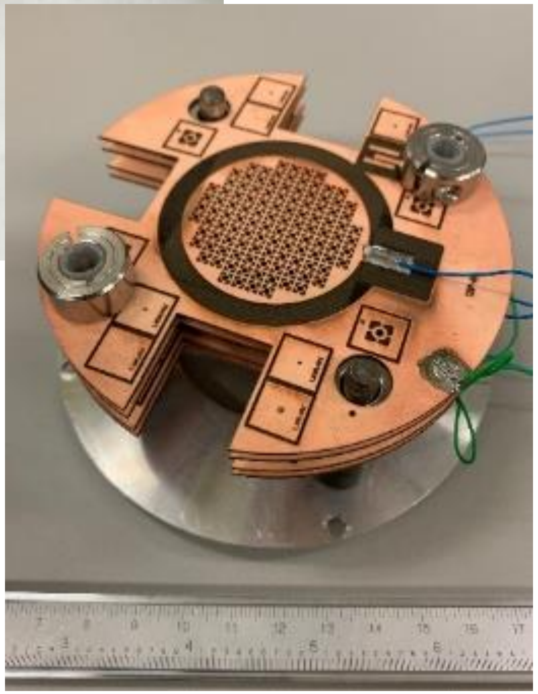
- MEMS based multi-beam RF linacs

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

arpa·e U.S. DEPARTMENT OF ENERGY

MEMS based multi-beam RF linacs



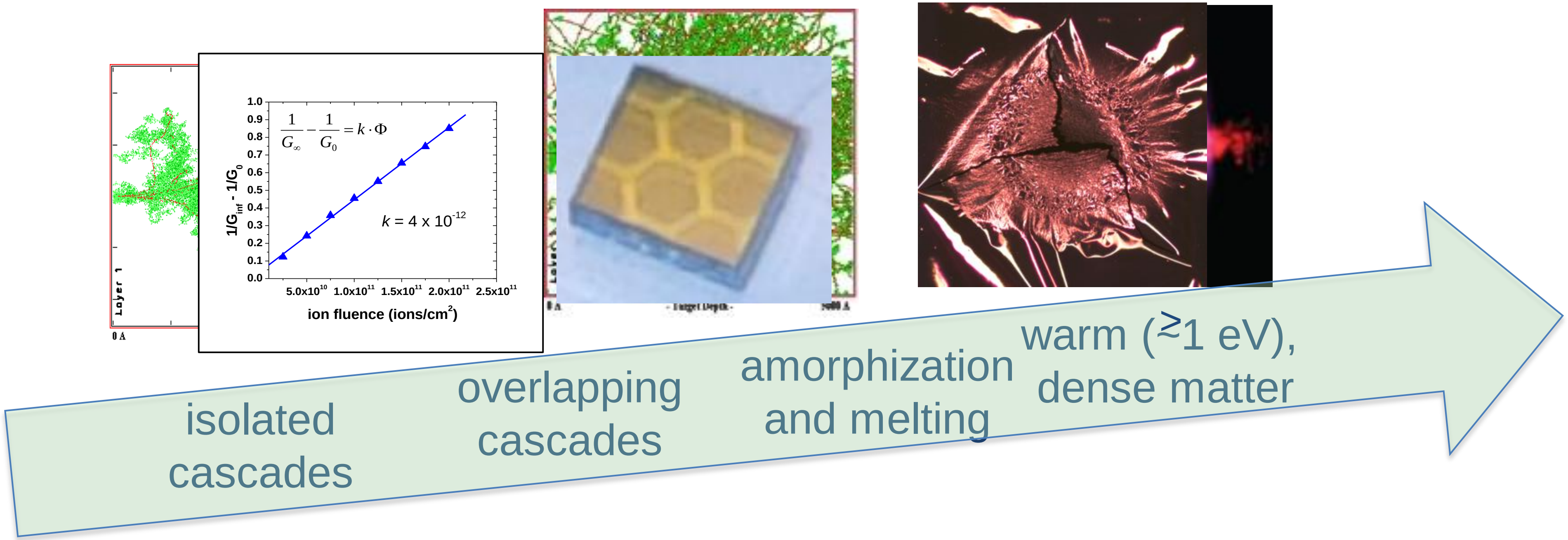


- Following proof-of-concept demos we are now scaling beam power
  - More beams: 3x3 → 10x10
  - Increase acceleration gradient: 2.5 kV/gap → 10 keV/gap
  - Add acceleration stages
- Next step: >1 MV/m, >100 keV, > 1 mA

Intense, short ion pulses are a unique tools for (bio)-materials science, studies of phase-transitions and warm-dense matter research

Lower intensities:
defect dynamics in materials

Higher intensities:
phase transitions and warm dense matter

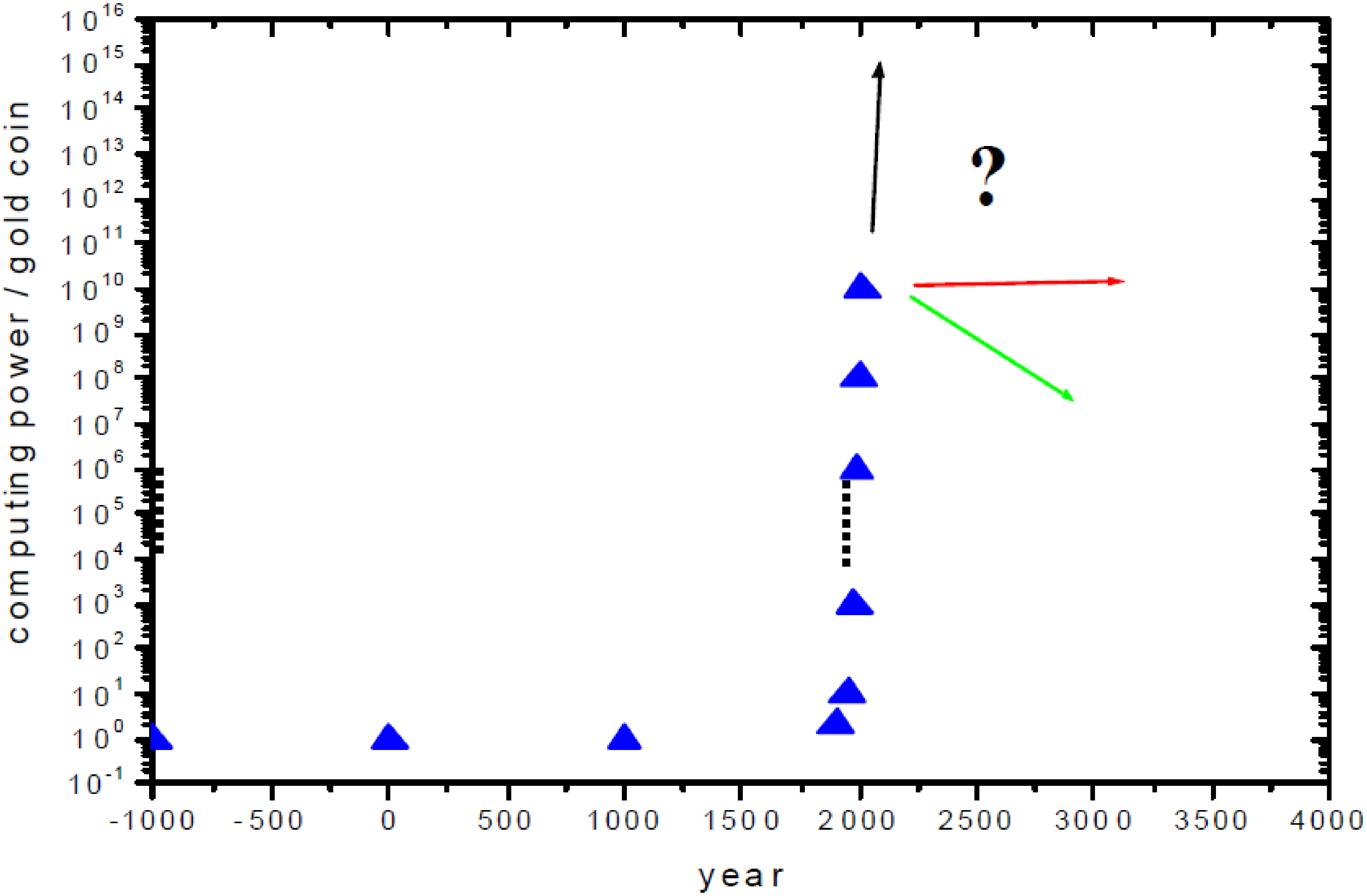


- Short ion pulses enable access to dynamics of rad effects experiments
- Intense ion pulses enable access to phase transitions, materials processing far from equilibrium and warm dense matter with uniformly heated materials

- A. Persaud, et al., Physics Procedia 66, 604 (2015)
- J. J. Barnard, T. Schenkel, J. Appl. Phys. 122, 195901 (2017)
- P. Seidl, et al. Laser and Particle Beams 35, 373 (2017)
- J. Schwartz et al., J. Appl. Phys. 116, 214107 (2014)

Qubits

Evolution of computational power



“Quantum Computing in the NISQ era and beyond”

John Preskill, Caltech

- **Noisy Intermediate-Scale Quantum (NISQ) technology**

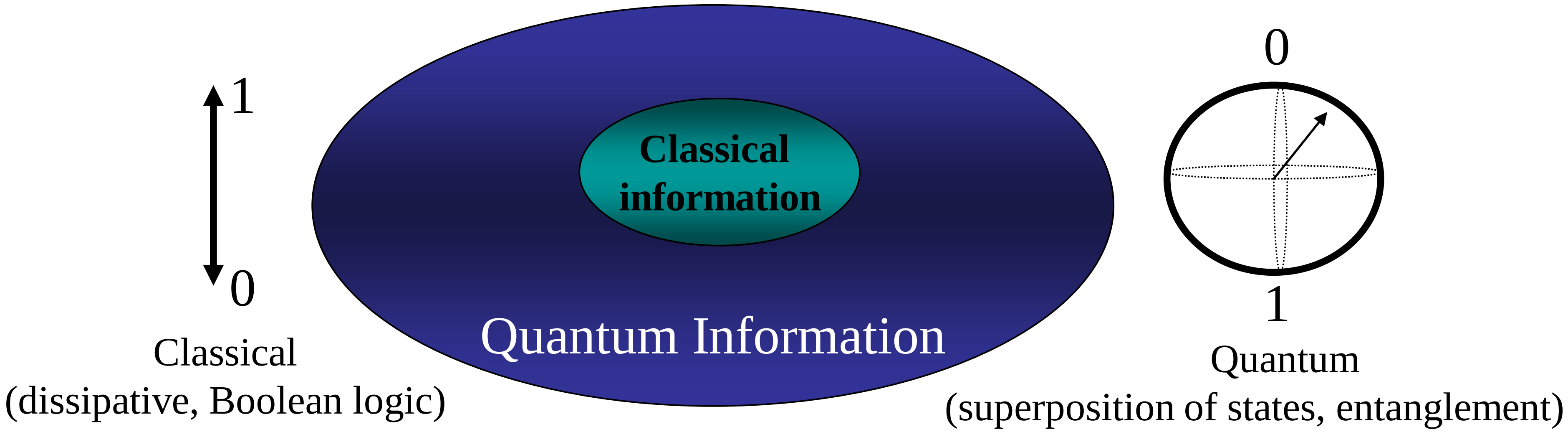
- Quantum computers with 50-100 qubits may be able to perform tasks which surpass the capabilities of today’s classical digital computers, but noise in quantum gates will limit the size of quantum circuits that can be executed reliably.

- NISQ devices will be useful tools for exploring many-body quantum physics, and may have other useful applications, but the 100-qubit quantum computer will not change the world right away — we should regard it as a significant step toward the more powerful quantum technologies of the future.

- Quantum technologists should continue to strive for more accurate quantum gates and, eventually, fully fault-tolerant quantum computing.

John Preskill, Quantum 2 (31 July 2018), p. 79; https://doi.org/10.22331/q-2018-08-06-79

Quantum Information Science



- “Information is a physical entity”, R. Landauer, 1999
- Flavors of quantum computing approaches[1]
  - Quantum circuit model
  - Measurement based quantum computing
  - Adiabatic quantum computing
  - Topological quantum computing
  - …

[1]see e. g. “Quantum computers: Definition and implementations”, C. A. Perez-Delgado and P. Kok, Phys. Rev. A 83, 012303 (2011)

Qubits

- Quantum bits
  - Capacity scales as 2^N
  - Bloch sphere representation
  - Superposition of states
  - Multi-qubit entanglement

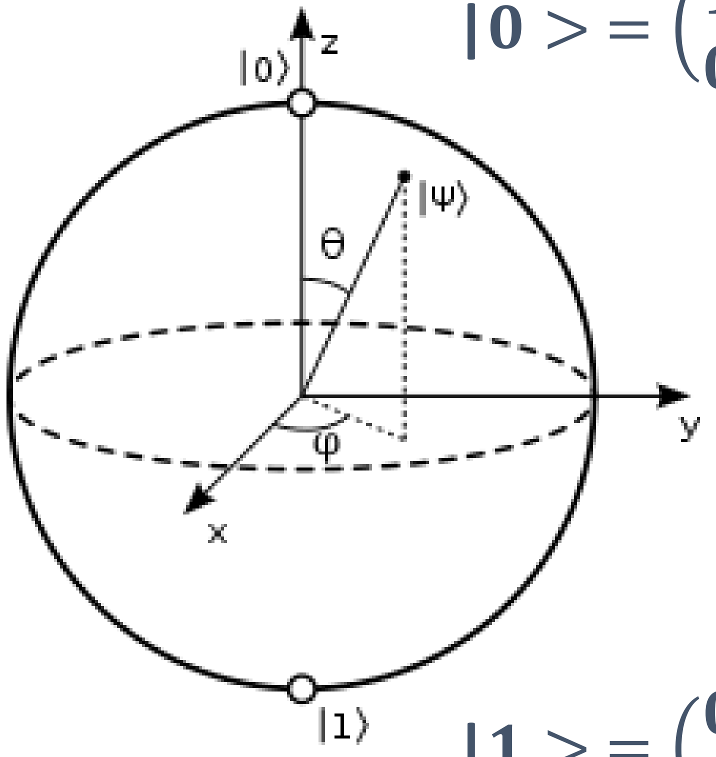
  $|\psi \geq= \alpha|0> +|\beta>$

  $|\alpha|^2 + |\beta|^2 = 1$

  $\frac{1}{\sqrt{2}}(|00>+|11>$

- Classical bits
  - Capacity scales as N
  - Boolian logic, and/or/not
  - Digital, 0 or 1

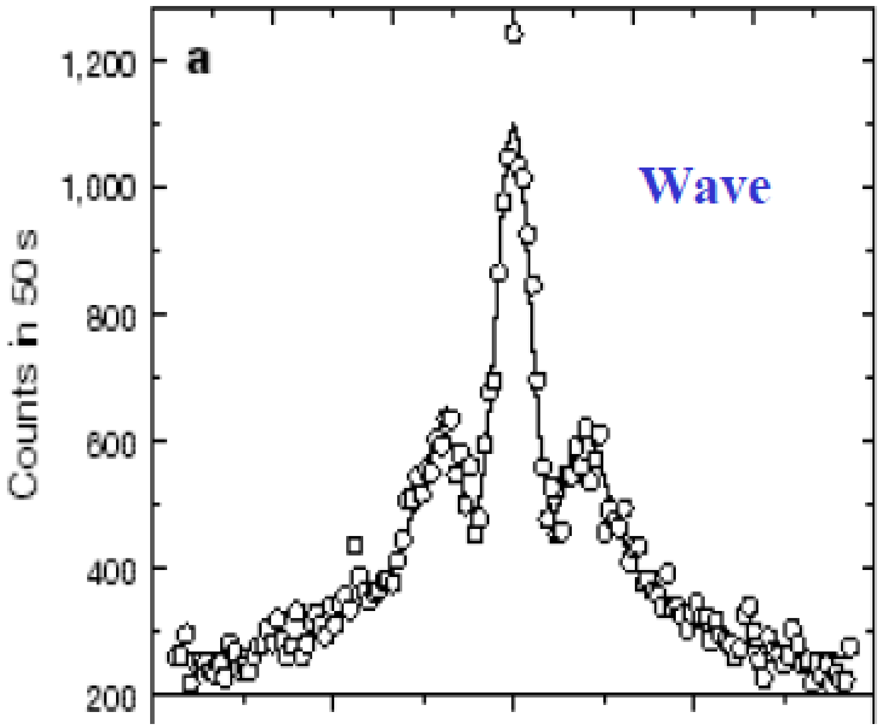
$$|\mathbf{0}> = \begin{pmatrix} \mathbf{1} \\ \mathbf{0} \end{pmatrix}$$



$$|\mathbf{1}> = \begin{pmatrix} \mathbf{0} \\ \mathbf{1} \end{pmatrix}$$

https://en.wikipedia.org/wiki/Qubit

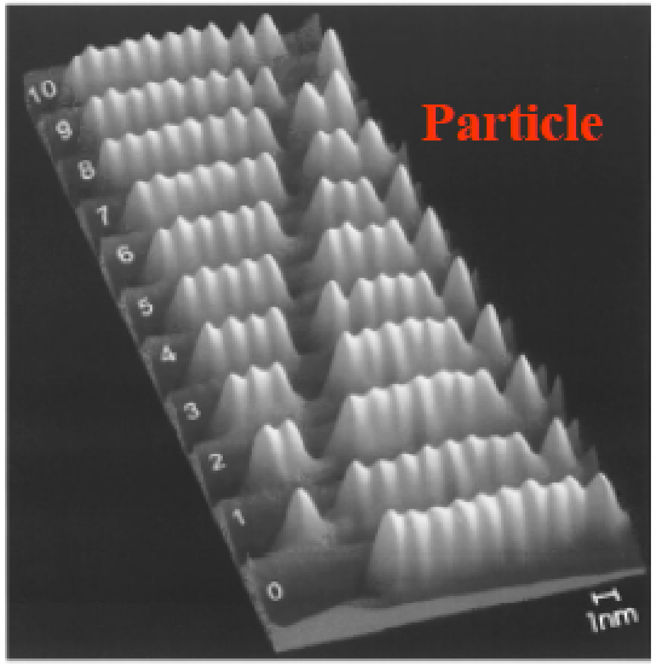
Wave-particle duality of C_{60} molecules



Markus Arndt, Olaf Nairz, Julian Vos-Andreae, Claudia Keller, Gerbrand van der Zouw & Anton Zeilinger

Institut für Experimentalphysik, Universität Wien, Boltzmanngasse 5, A-1090 Wien, Austria

NATURE | VOL 401 | 14 OCTOBER 1999 |



Room-temperature repositioning of individual C_{60} molecules at Cu steps: Operation of a molecular counting device

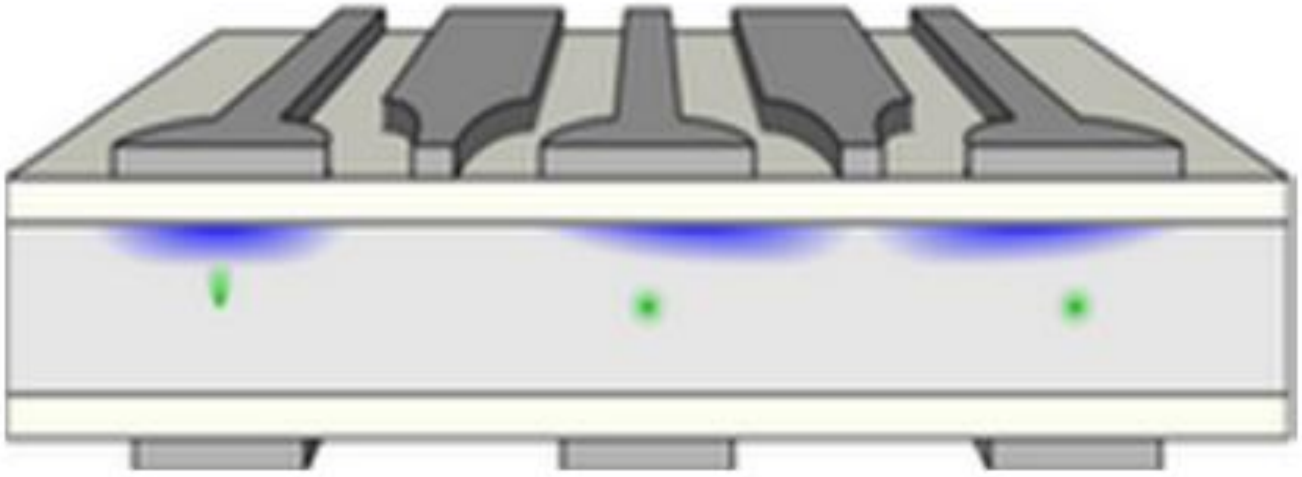
M. T. Cuberes,[a] R. R. Schlittler, and J. K. Gimzewski

IBM Research Division, Zurich Research Laboratory, 8803 Rüschlikon, Switzerland

Appl. Phys. Lett. **69** (20), 11 November 1996

- Wave - superposition of "which path" states in double slits leads to interference
- Particle - interaction of molecules with environment destroys interference, de-coherence, and "classical" behavior
- Quantum info processing requires the coherent superposition of N qubits while gates are applied until a measurement is made

Spins of electrons and nuclei are promising qubits

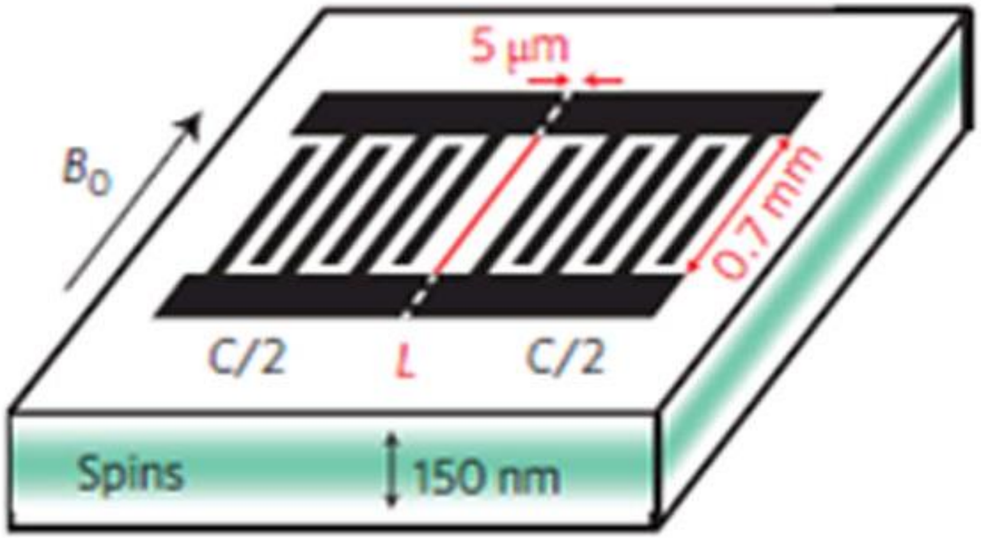


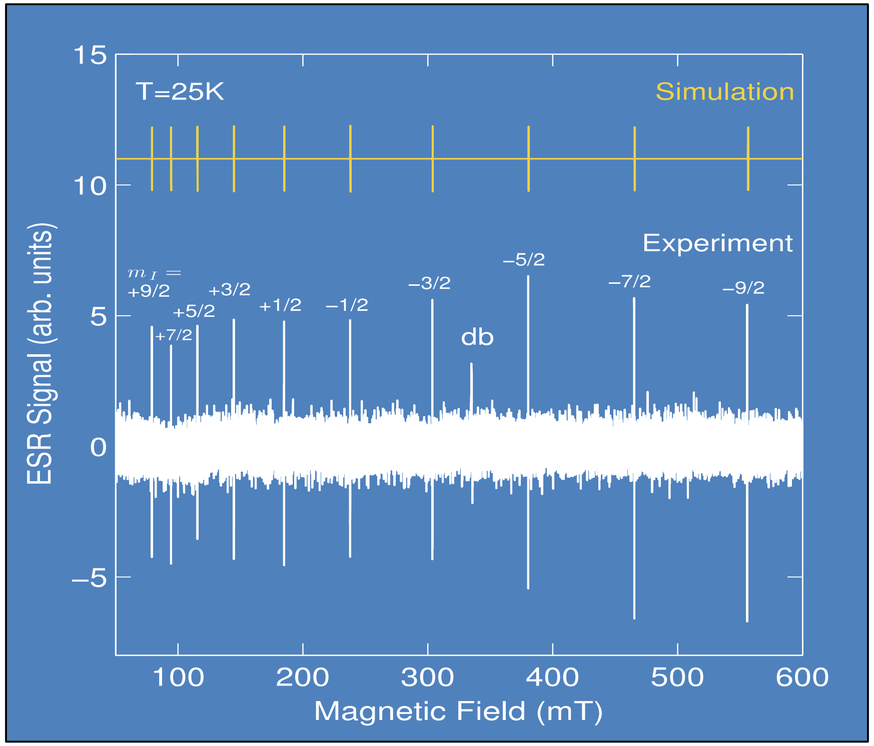
- Long coherence times, > 1 s
- Single shot single donor spin readout (A. Morello et al., Nature 467, 687, 2010)
- Fast single and two qubit gates (Y. He, et al., Nature 571, 371 (2019)
- Connectivity beyond nearest neighbor coupling not yet demonstrated
- Transducer to photons not demonstrated (early steps: C. M. Yin, et al., Nature 497, 91 (2013))
- Scaling has proven tricky to date

- New ideas to use spins to extend range in searches of light Dark Matter candidates

"Surface code architecture for donors and dots in silicon",
G. Pica, B. W. Lovett, R. N. Bhatt, T. Schenkel, S. A. Lyon, Phys. Rev. B **93**, 035306 (2016)

Can we extend the parameter space for qubit synthesis with intense beams ?





- Bismuth doped ^{28}Si enabled the demonstration of the Purcell effect with spins
- But only 60% of the bismuth atoms were electrically active

→ Opportunity to improve with processing under "extreme conditions"?

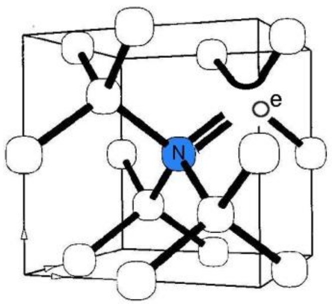
→ Opportunity for quantum sensing applications using spins

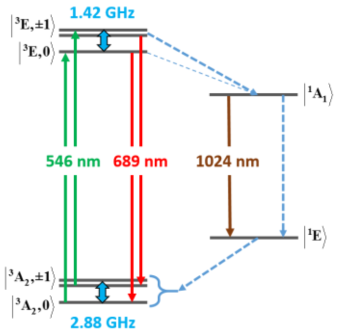
"Controlling spin relaxation with a cavity", A. Bienfait, J. Pla, Y. Kubo, X. Zhou, M. Stern, C. C. Lo, C. D. Weis, T. Schenkel, D. Vion, D. Esteve, J. J. L. Morton, P. Bertet, Nature 531, 74 (2016)

Can we make better color center qubits ?

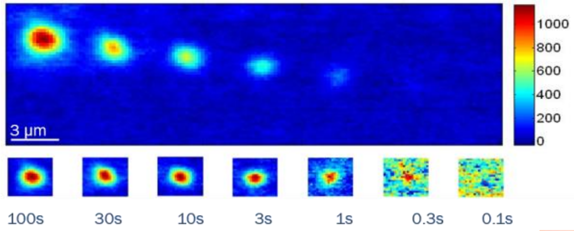
- The nitrogen-vacancy center in diamond is a very promising spin-photon qubit, but it also has limitations
- Can we find a better multi-function color center ?
  - Logic with the electron spin
  - Memory in the nuclear spin
  - Photon emission in the telecom band
- Could form the basis of a quantum repeater and enable more quantum sensing modes
- We form color center with lasers and ion beams

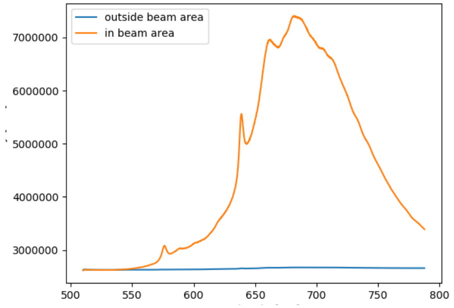
J. Schwartz, …, T. Schenkel, NJP (2012); JAP (2014)
J. H. Bin, …, T. Schenkel, RSI (2019)

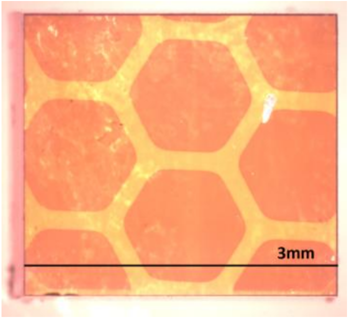


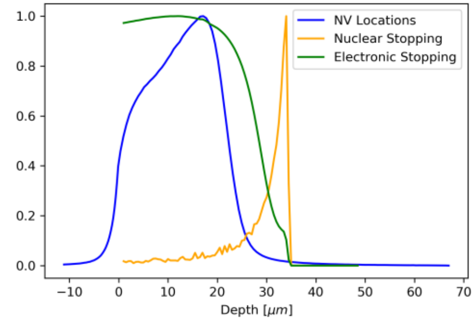


https://en.wikipedia.org/wiki/Nitrogen-vacancy_center

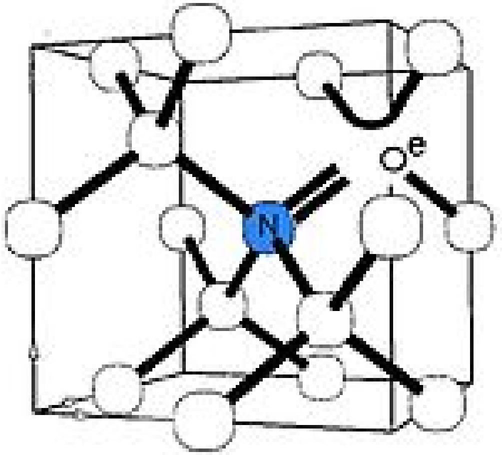




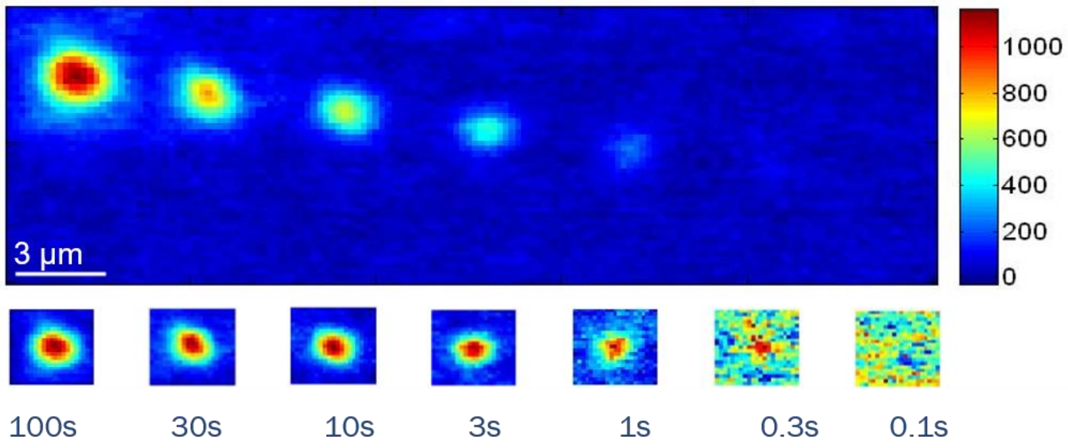


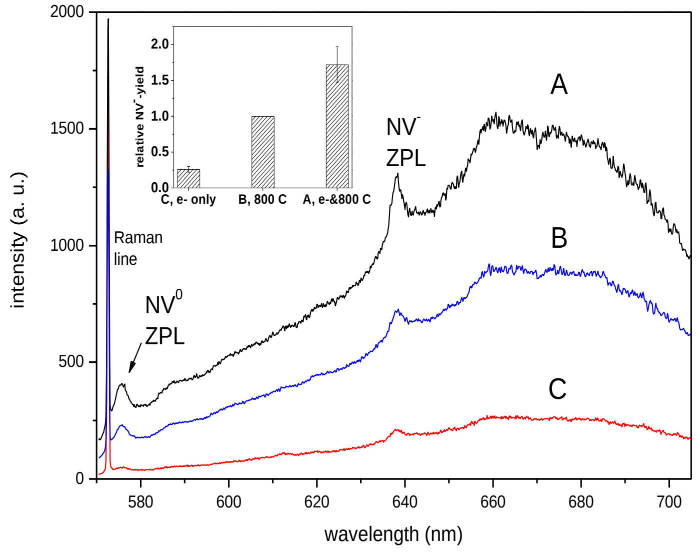


NV-centers form during local exposure to low energy electrons at room temperature



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 ?**

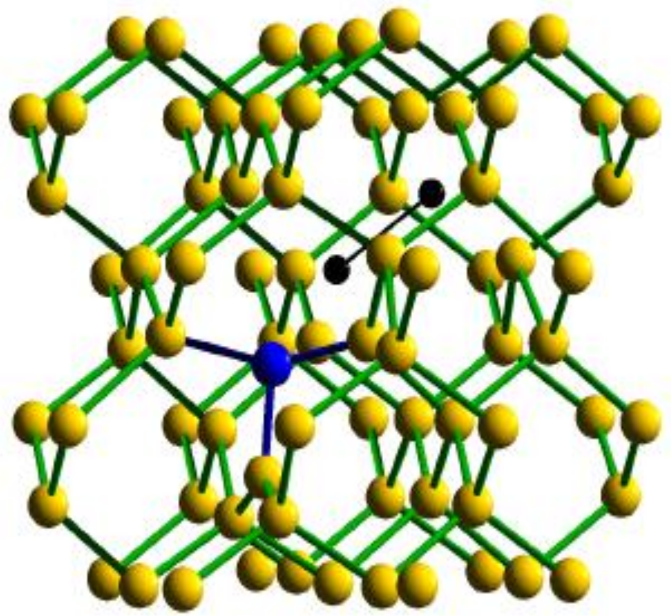
- J. Schwartz, et al., NJP (2012)
- J. Schwartz, et al., JAP (2014)
- J. J. Barnard, T. Schenkel, JAP (2017)

Mechanisms of NV-center formation in diamond?

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

vs.

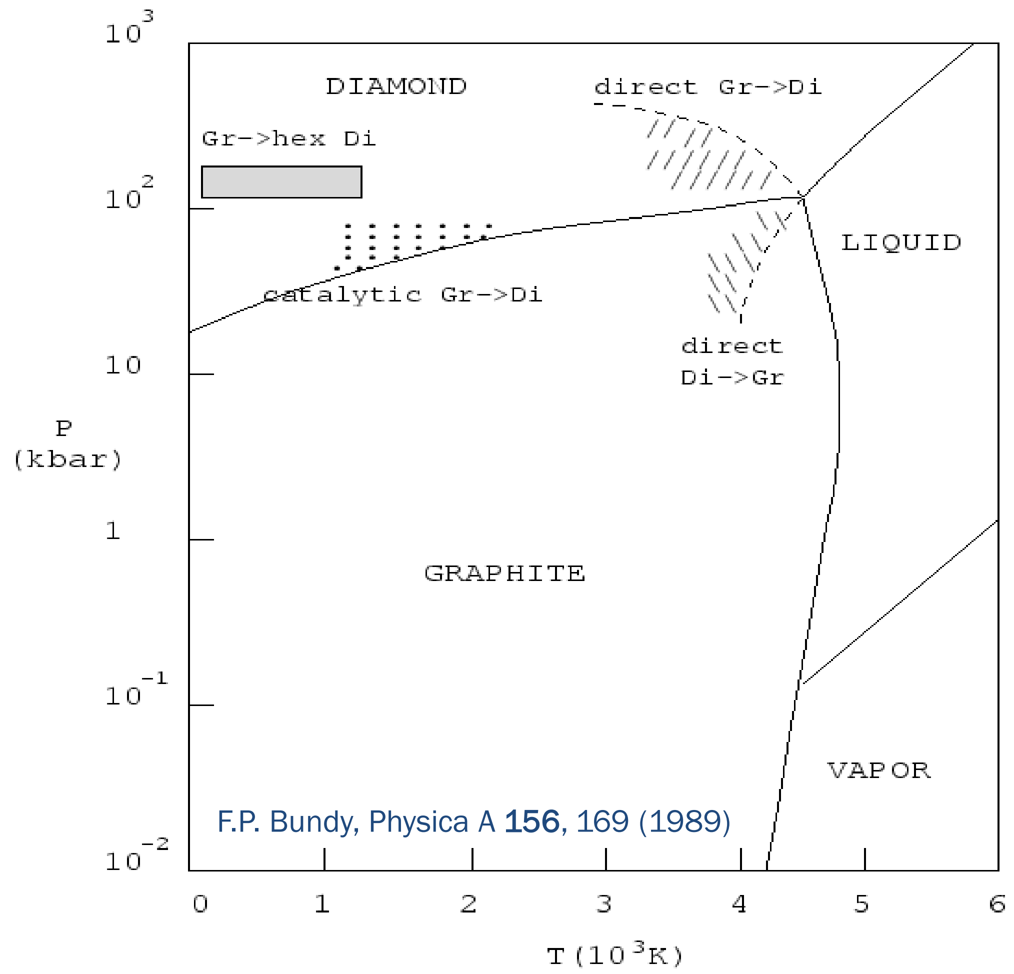
$N_{interstitial} + V_n \rightarrow NV^{0,-}$



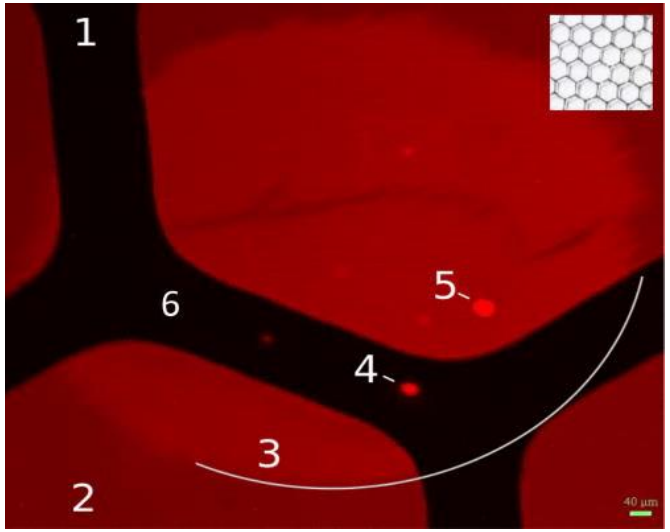
- A nitrogen atom on a split interstitial site (blue), close to two vacancies (black). Carbon atoms in yellow. NV's form during annealing at >300°C
- J. Adler, R. Kalish, et al., J. of Physics, 2014
- P. Deak et al. PRB 2014: di-vacancy formation favored over NV formation during annealing of N rich diamond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

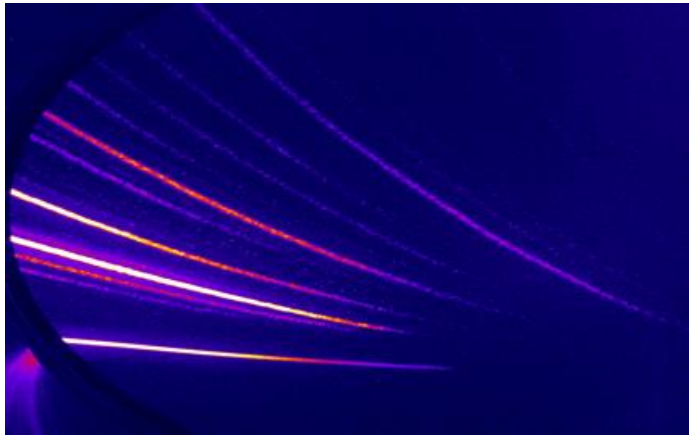
J. Schwartz, et al., NJP 2012, JAP 2014

Qubit synthesis with intense beams



F.P. Bundy, Physica A **156**, 169 (1989)





- NV-centers in diamond a great, but …
- Can we form color center qubits that emit light in the telecom bands ?
- Local melting, intense excitation, rapid re-crystallization

J. Schwartz, et al., JAP (2014)
J. H. Bin et al., RSI (2019)

Development dark matter detectors based on spin coherence

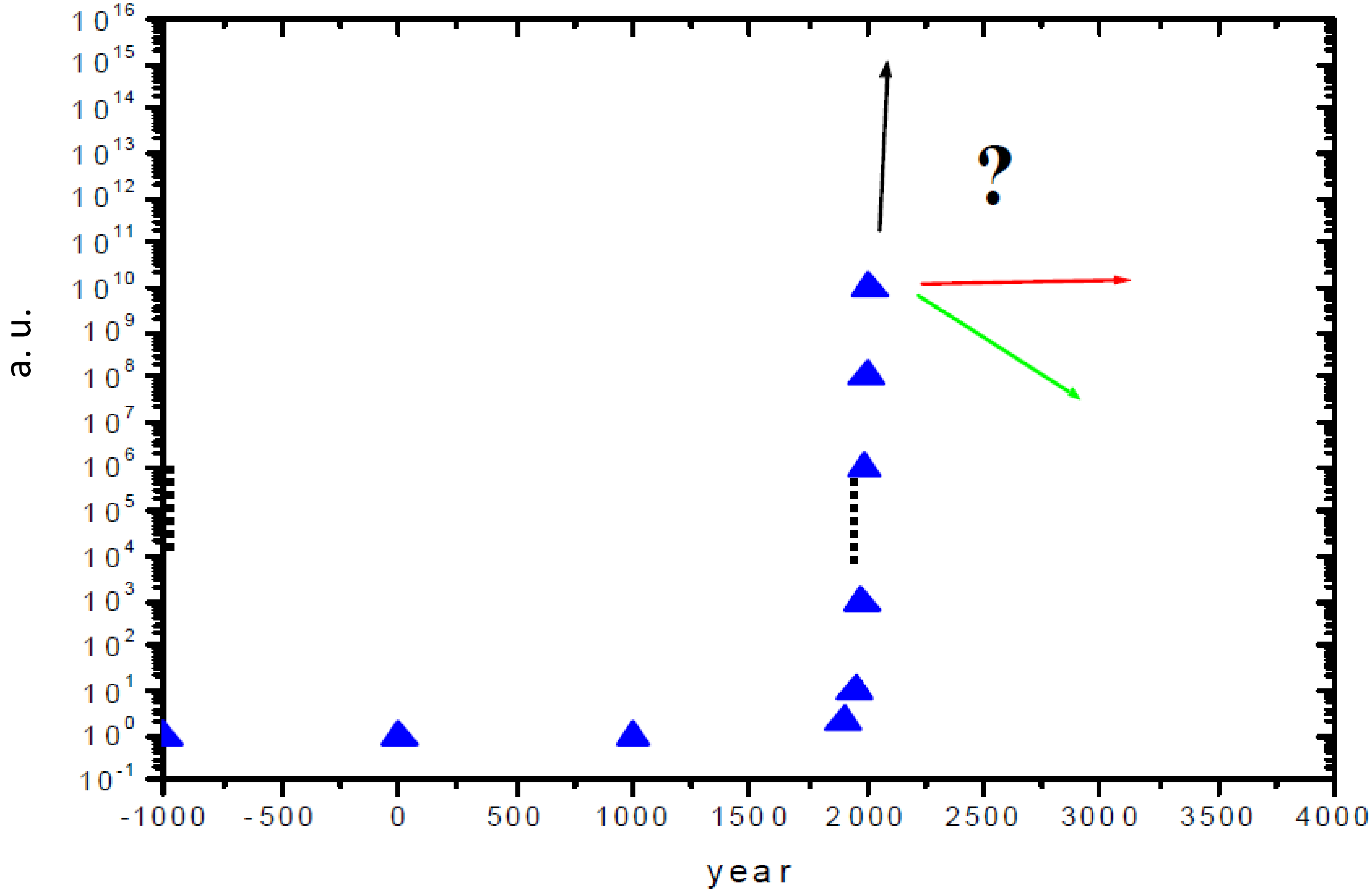
- Search for light dark matter between axions and WIMPS

- 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 (or phonons)

Outline

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

Evolution of energy consumption



Grand challenge: Energy gain from fusion (Lawson criteria)

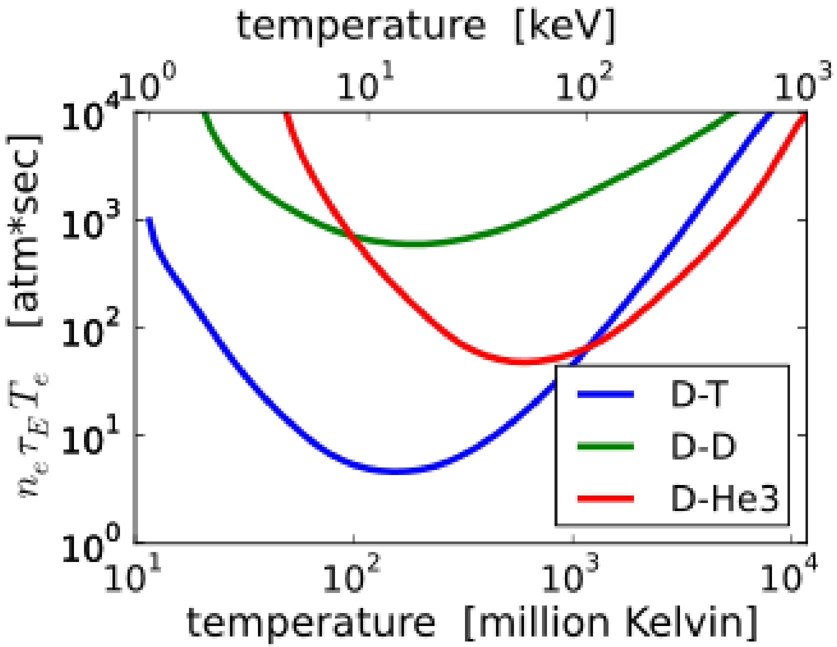
- **to achieve energy gain in a fusion reactor, the fuel has to be dense enough and hot enough for long enough**

- triple product of density, temperature and confinement time

- Sun – gravity
- Tokamak – magnetic confinement
- NIF, HIF – inertial confinement
- MIF – magneto-inertial confinement

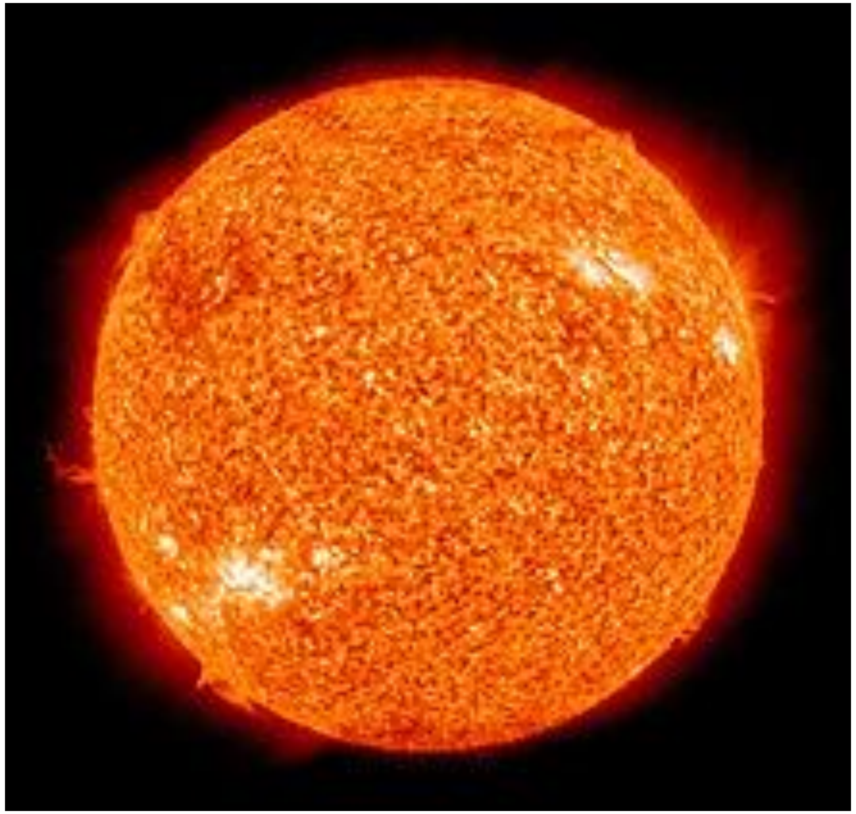
- Steady progress internationally to reach the burning plasma era

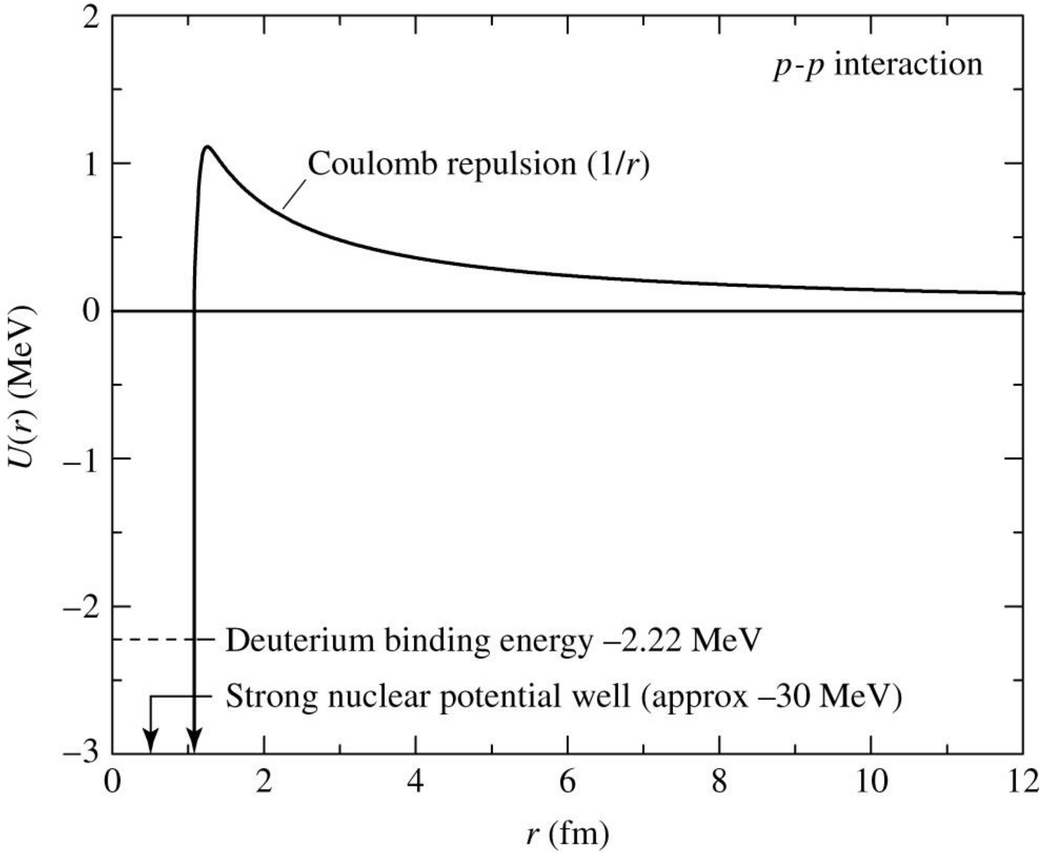
- https://www.energy.gov/science/fes/burning-plasma-science-long-pulse-and-high-power



https://en.wikipedia.org/wiki/Lawson_criterion

Fusion

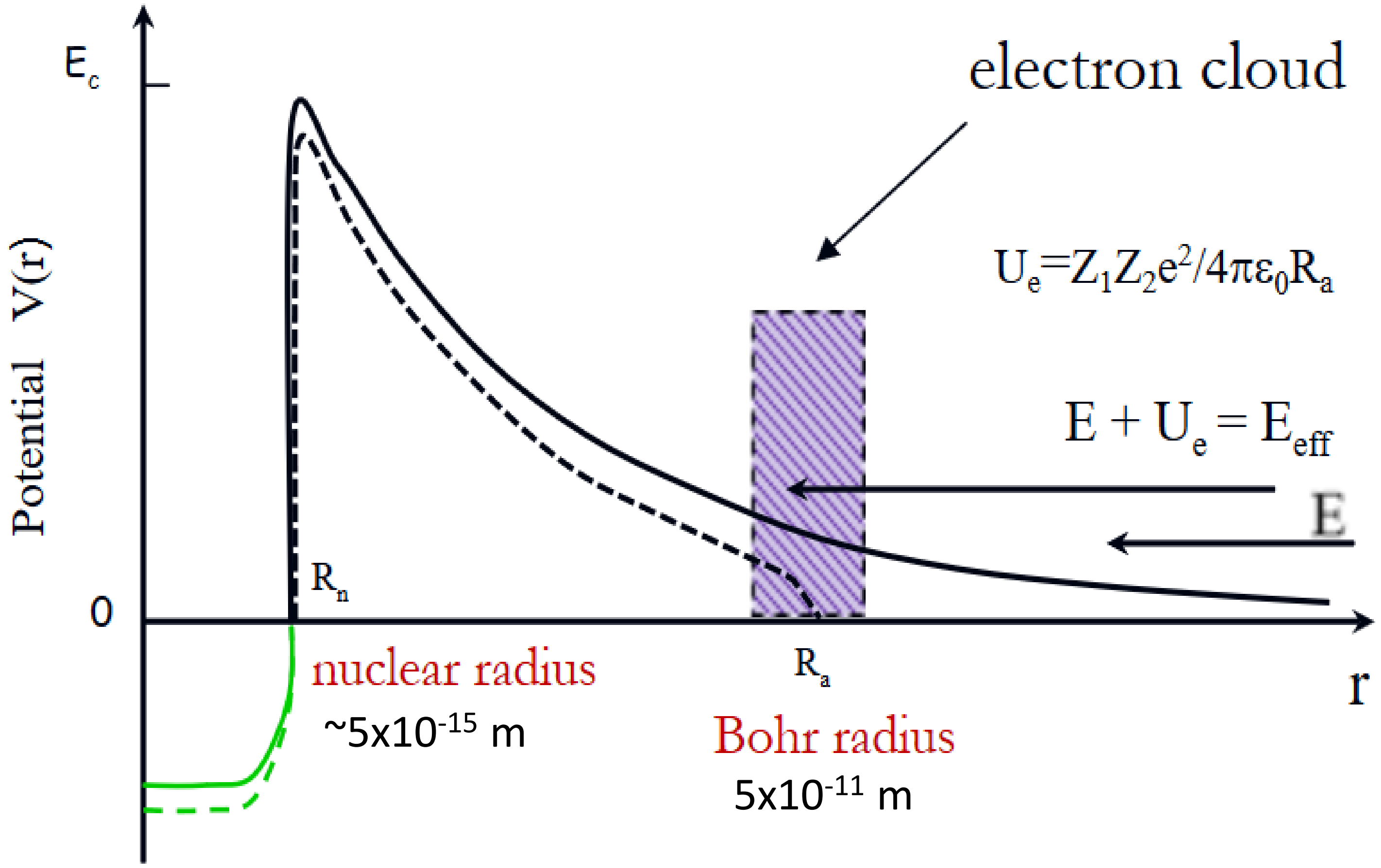




- temperature in the center of the sun is ~16 Million Kelvin
- corresponding average ion energies are ~2 keV
- the height of the Coulomb barrier for hydrogen fusion is ~600 keV
- fusion is possible due to tunneling through the repulsive Coulomb barrier

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

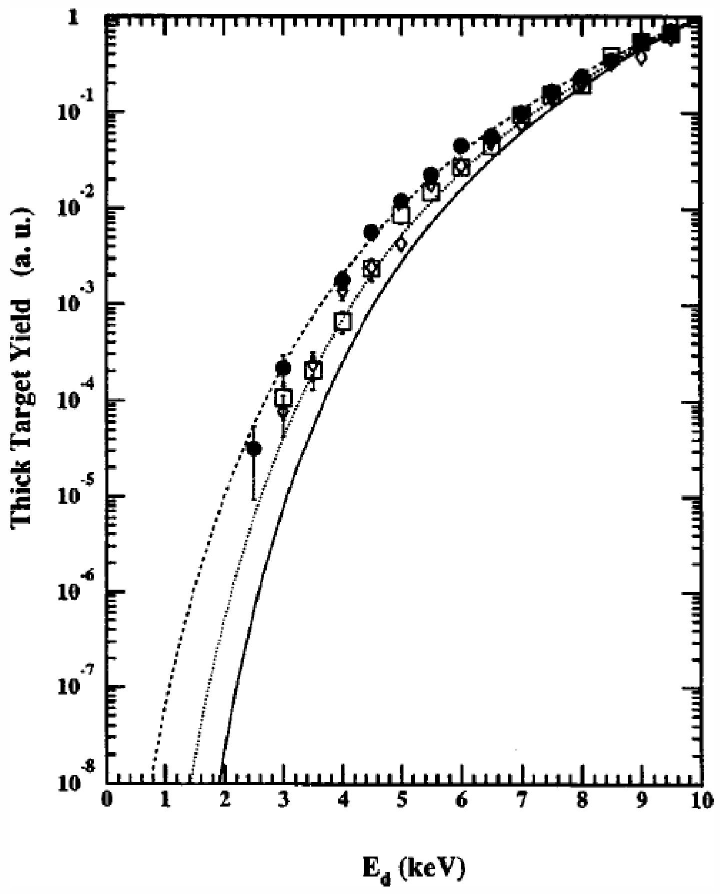
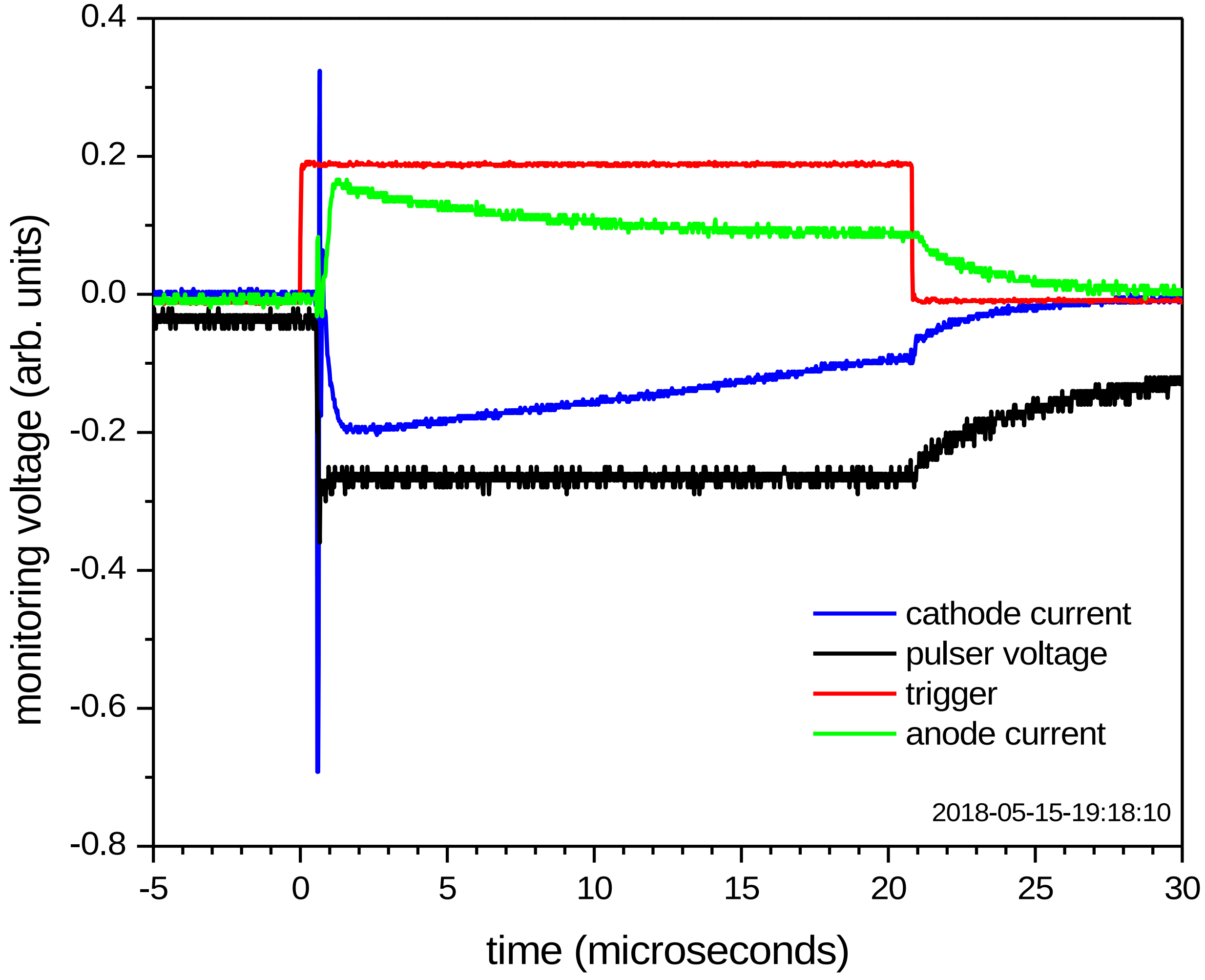


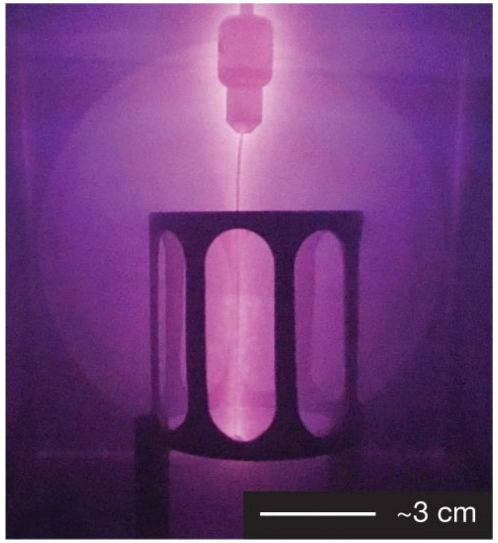
FIG. 2. Experimental yields of the $D(d,p)T$ reaction: in Pd under cooled conditions, $\langle T\rangle = 190.1$ K (open squares); in Pd at $\langle T\rangle = 313.0$ K (open diamonds); and in an Au/Pd/PdO heterostructure at $\langle T\rangle = 193.3$ K (solid circles). The solid curve is the calculated 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
  - …

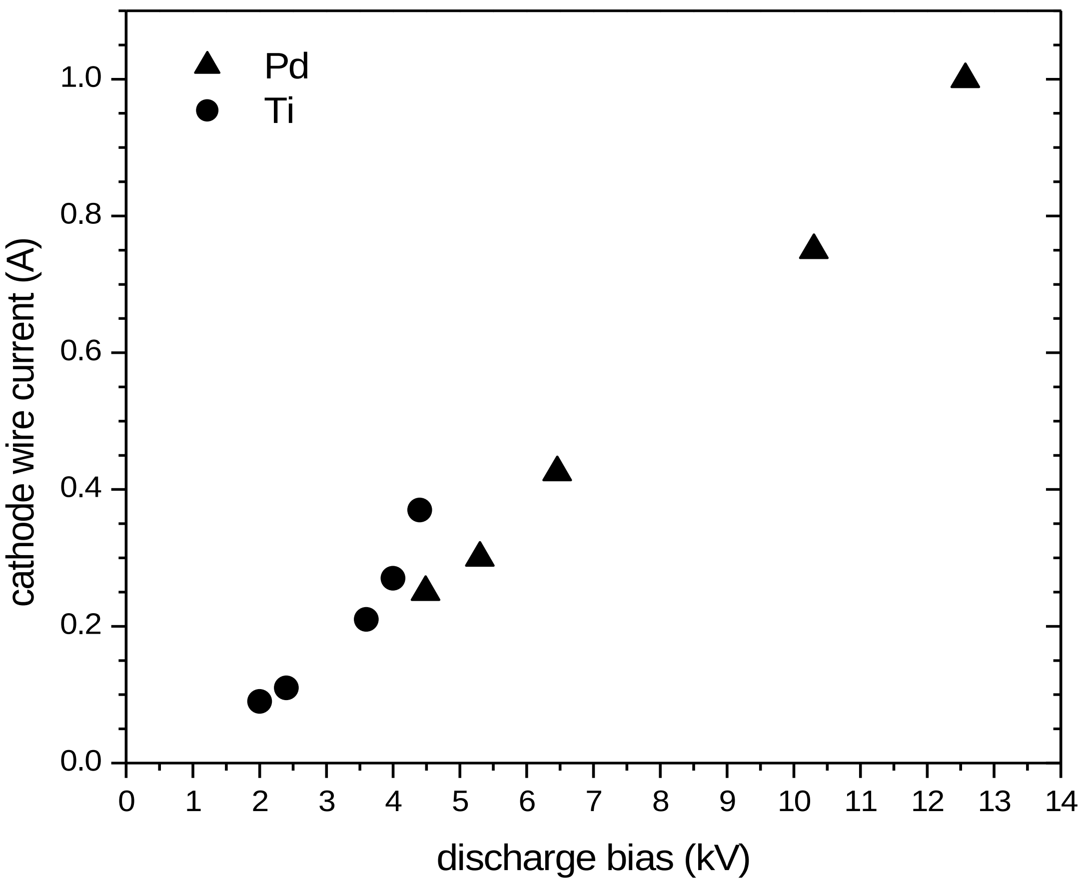
Plasma pulses in the glow discharge regime

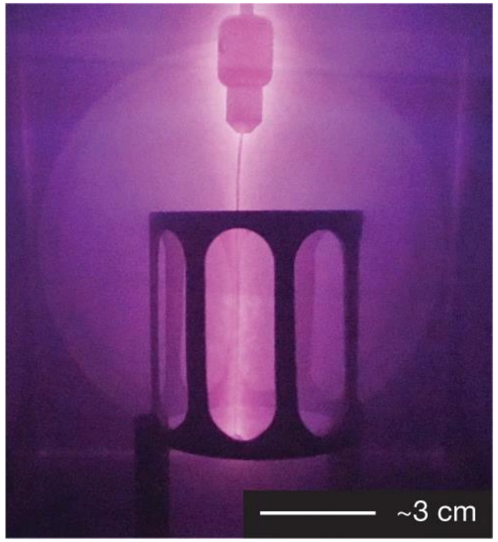




T. Schenkel, et al., https://arxiv.org/abs/1905.03400

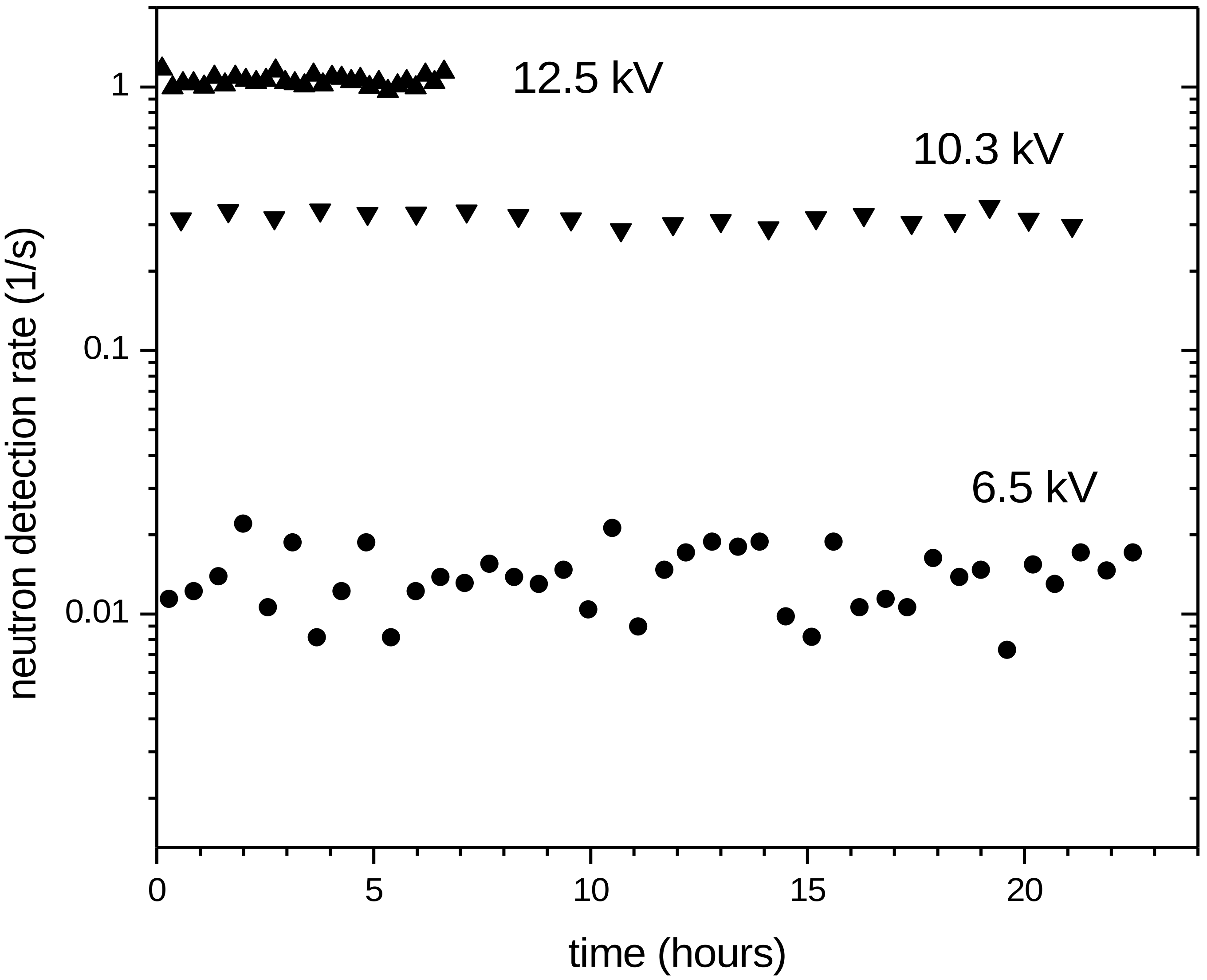
Plasma pulses in the glow discharge regime

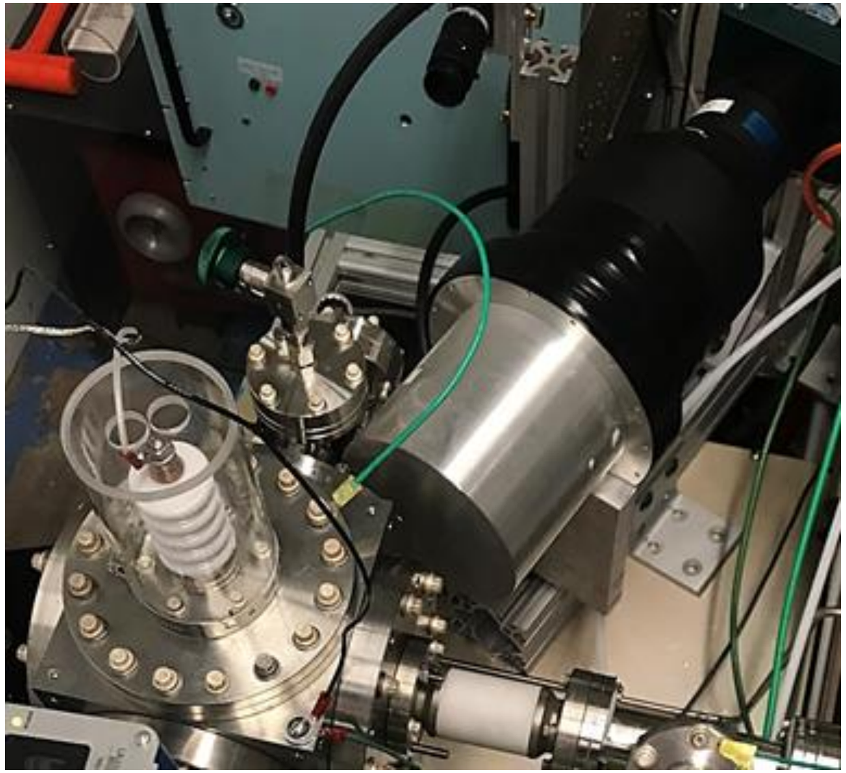




T. Schenkel, et al., https://arxiv.org/abs/1905.03400

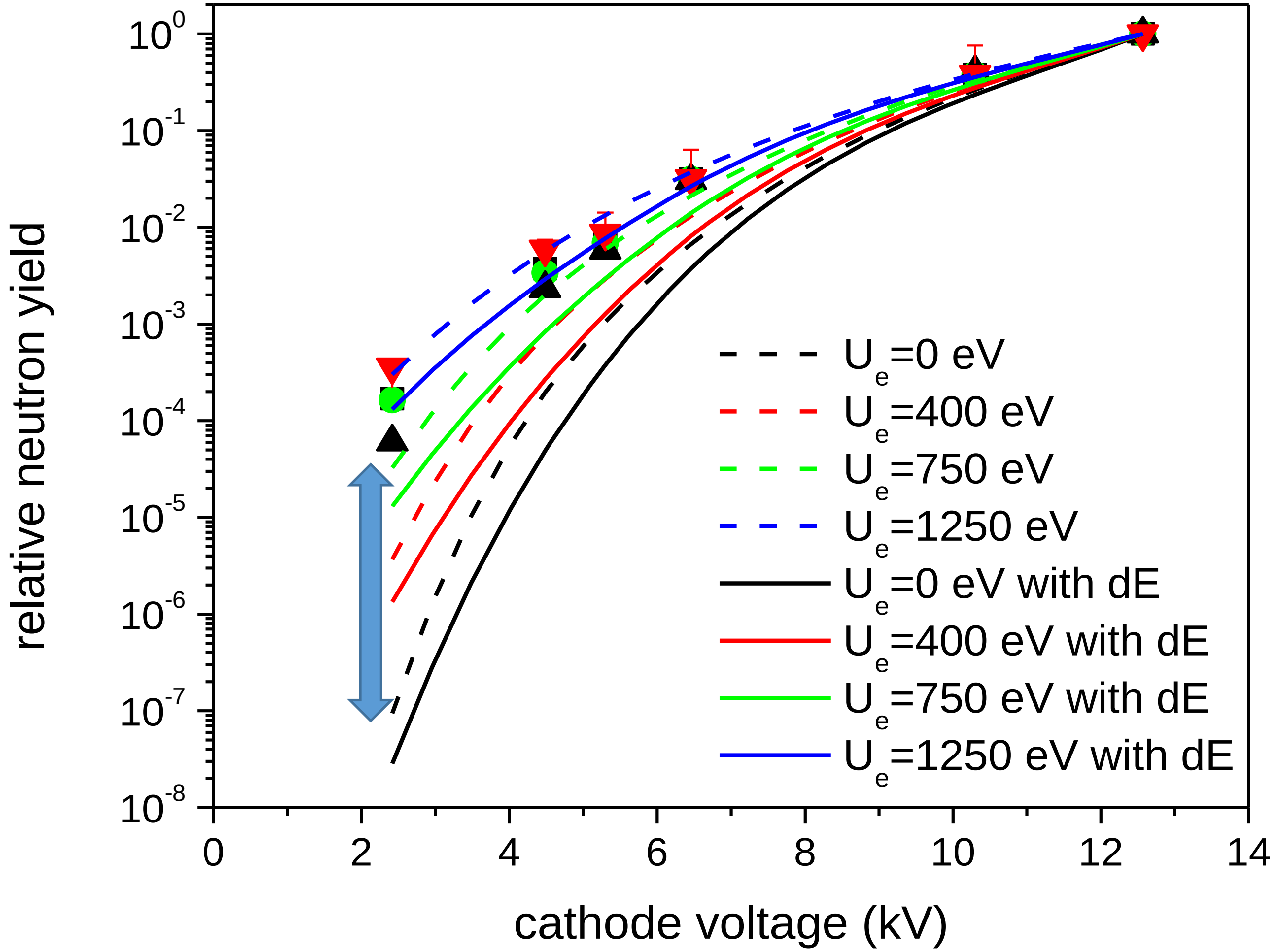
We ran the plasma discharges continuously for hours and days





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

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



- solid-state effects strongly enhance D-D fusion rates at reaction er ow a few keV (center-of-mass)
- can we use the well known D-D reaction to probe solid state environments like disordered metal hydrides ?

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

Acknowledgments

Jean-Luc Vay contributed with plasma modeling and simulations

Gauthier Deblonde (now LLNL) conducted the tritium counting measurements

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.

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

- We are using ion pulses from NDCX-II 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 part of HIF drivers
- We are exploring fusion processes at relatively low reaction energies
- Opportunities for collaboration