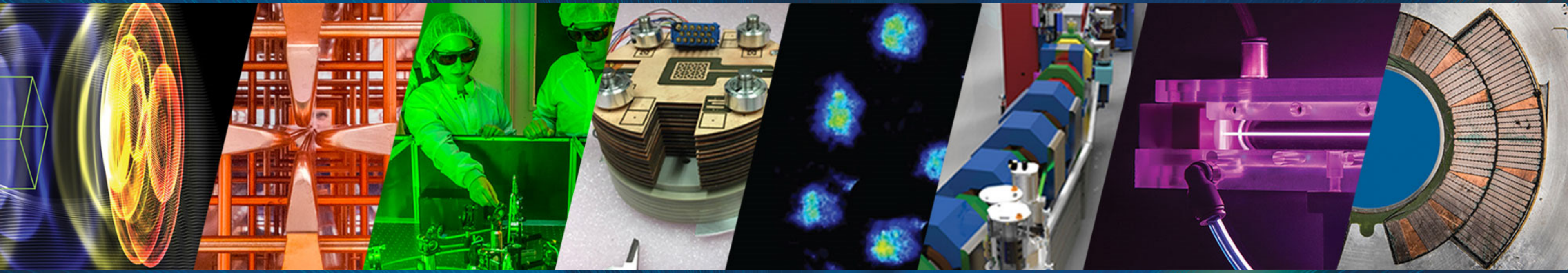
2022 North American Particle Accelerator Conference NAPAC 2022

Micro-electromechanical systems based multi-beam ion accelerators

Qing Ji[a], Ariel Amsellem[a], Nicholas Valverde[a], Arun Persaud[a], Zhihao Qin[a], Peter A. Seidl[a], Thomas Schenkel[a], Yuetao Hou[b], Di Ni[b], Ved Gund[b], Khurram K. Afridi[b], Amit Lal, Steve Lund[c] , and Thomas Schenkel[a]

[a]Lawrence Berkeley National Laboratory
[b]Cornell University
[c]Michigan State University



8/10/2022

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This R&D work has been a collaborative effort between LBNL and Cornell University.

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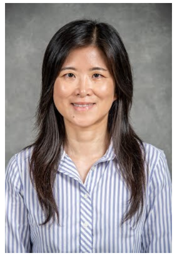
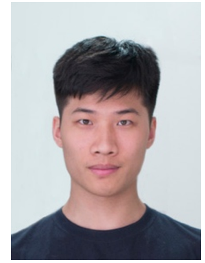
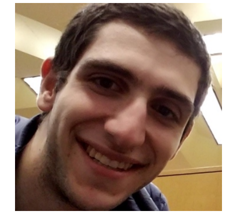
T. Schenkel (PI)


Q. Ji


A. Persaud


P. Seidl,


Z. Qin,


A. Amsellem,


N. Valverde

- **Accelerators, beam physics, ion sources and beam transport, RF, …** **http://atap.lbl.gov/**

Cornell University


A. Lal (co-PI)


K. K. Afridi


D. Ni


Y. Hou


V. Gund

- **MEMS fabrication, Chip-scale particle accelerators, RF power amplifier …** **http://www.sonicmems.ece.cornell.edu/**

Examples of high power ion accelerators at Berkeley Lab

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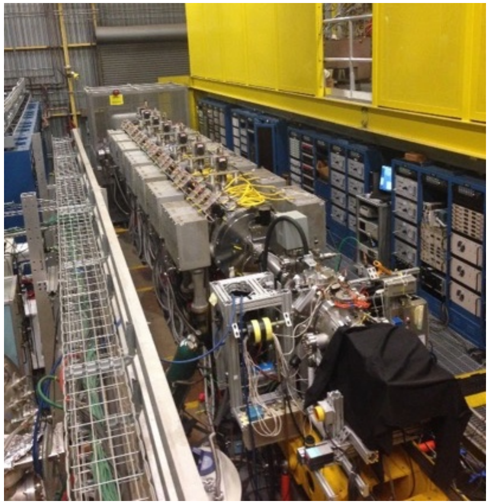

- Pulsed induction linac (12 m)
- 1 MeV, 2 ns, mm, ≥2 A peak
- 200x drift compression
- P. A. Seidl et al. NIM A (2015)

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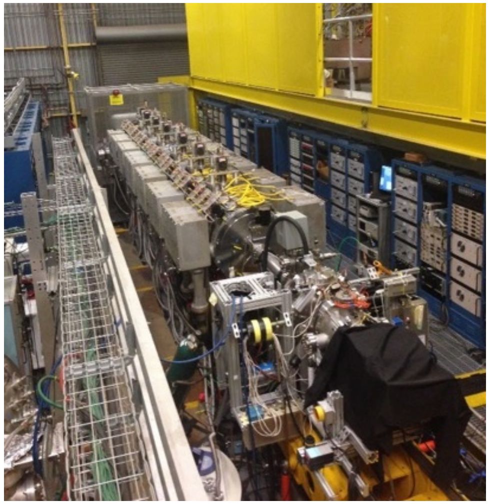

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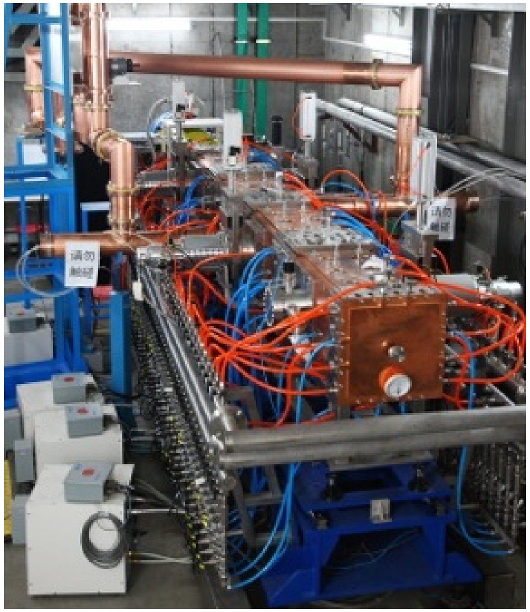

- Radio frequency quadrupole (RFQ)
- 2 MeV, 0.01 A, cw
- 4 m long, 0.4 m cross section
- Z. Zouhli, D. Li et al. IPAC2014

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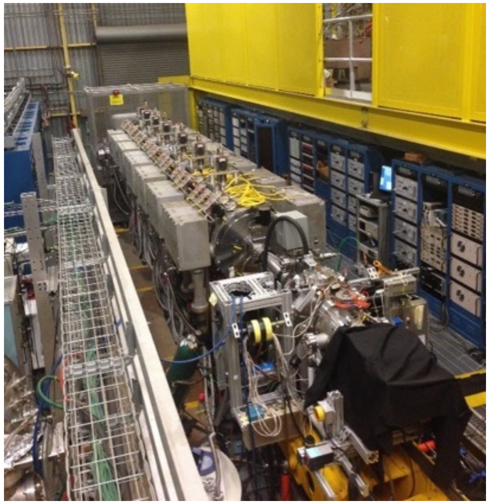

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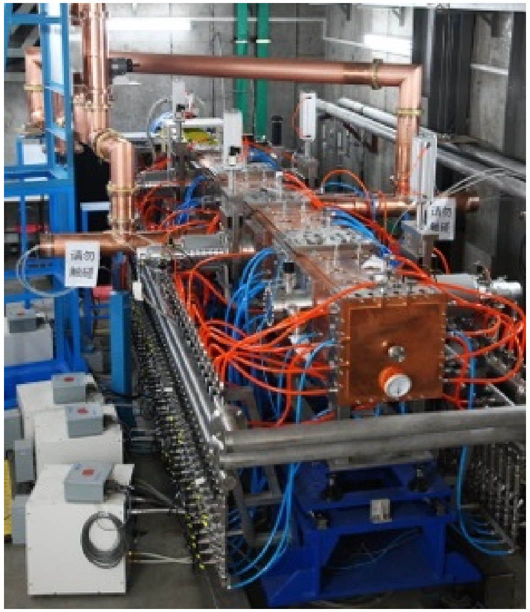

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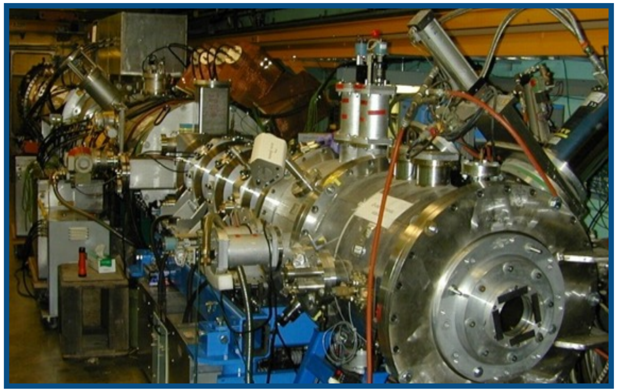

- High Current Experiment
- injection, matching and transport at heavy ion fusion driver scale
- 1 MeV, 0.2 A, 5 μs, ~12 m
- 0.4 m cross section
- M. Kireeff-Covo, et al., PRL (2006)

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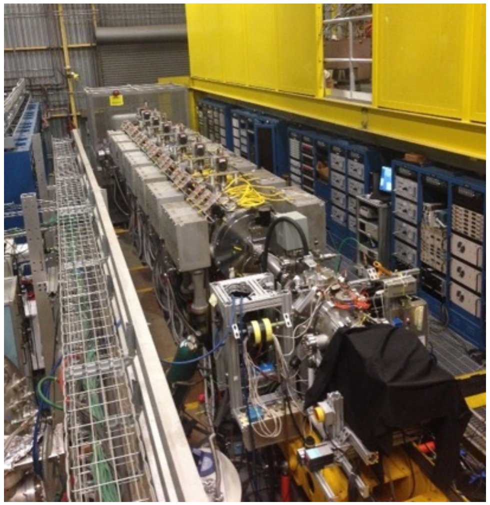

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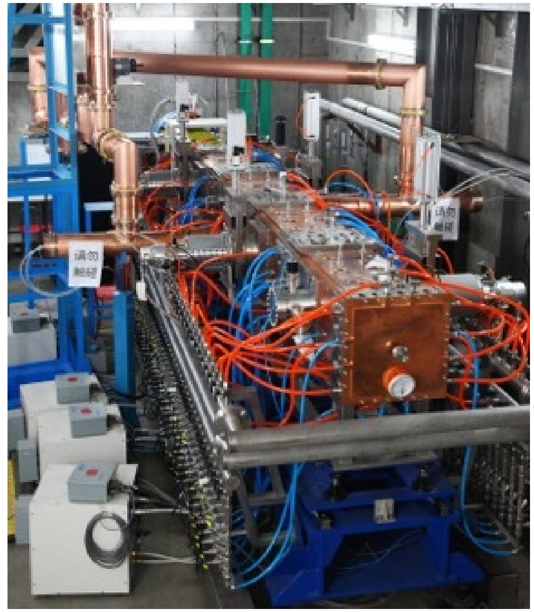

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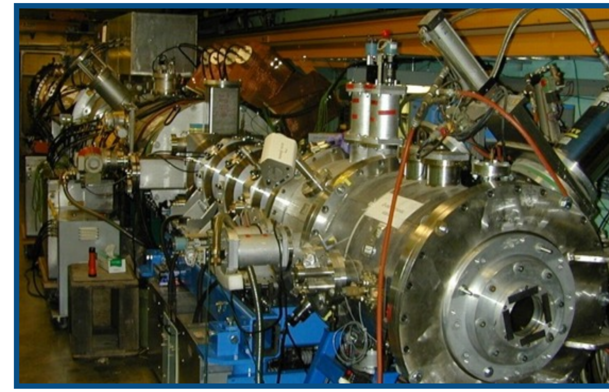

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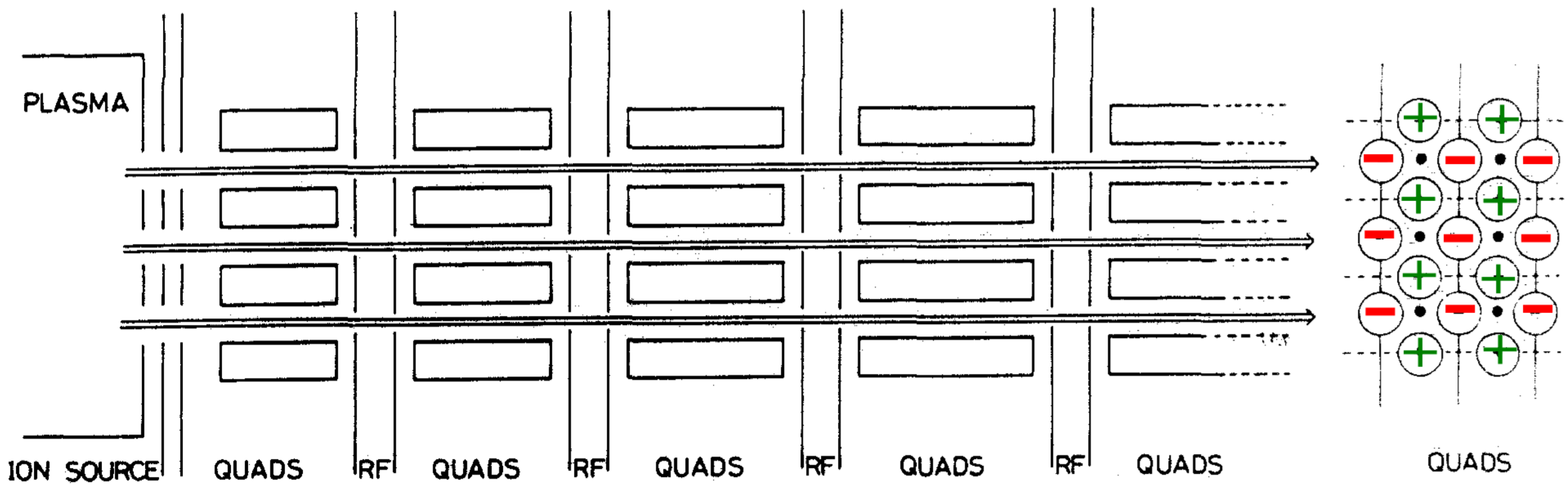
Can we scale ion beams to higher power at lower cost?
MEMS based multi-beam linacs

Multiple-Electrostatic-Quadrupole-Array Linear Accelerator (MEQALAC) concept from 1980s

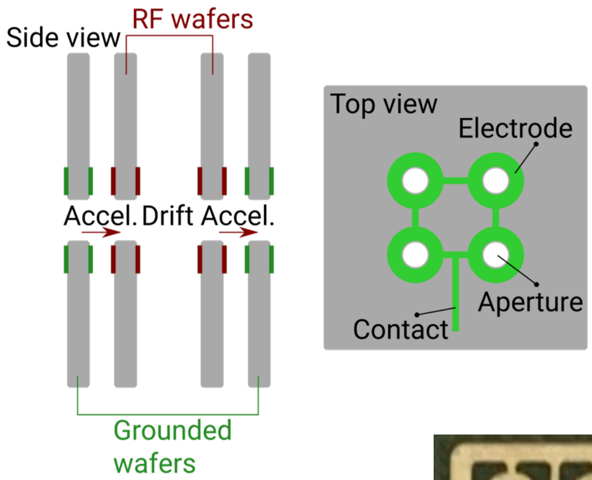


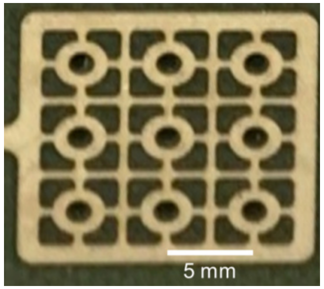
- Accelerator with many beamlets enables higher total ion currents, higher beam power and higher current densities
- ‘80s: ~ 1 cm beam aperture, electrostatic quadrupole (ESQ), ~15 MHz RF cavities

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

We achieved miniaturization of acceleration and focusing elements using MEMS technology.

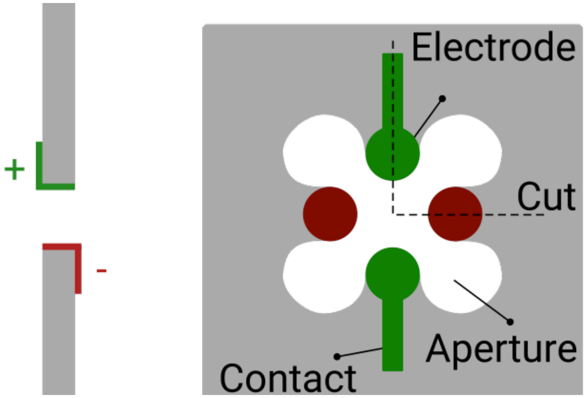
RF - acceleration
Drift = $\beta\,\lambda/2 = ½\, v_{ion}/f_{RF}$

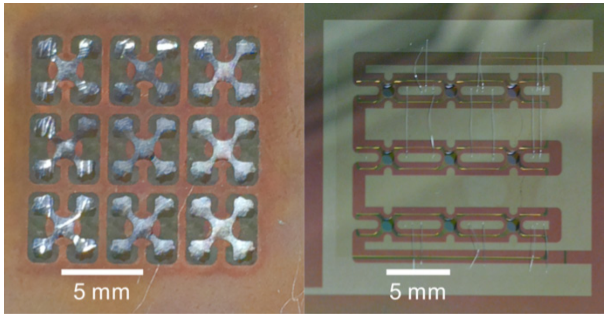




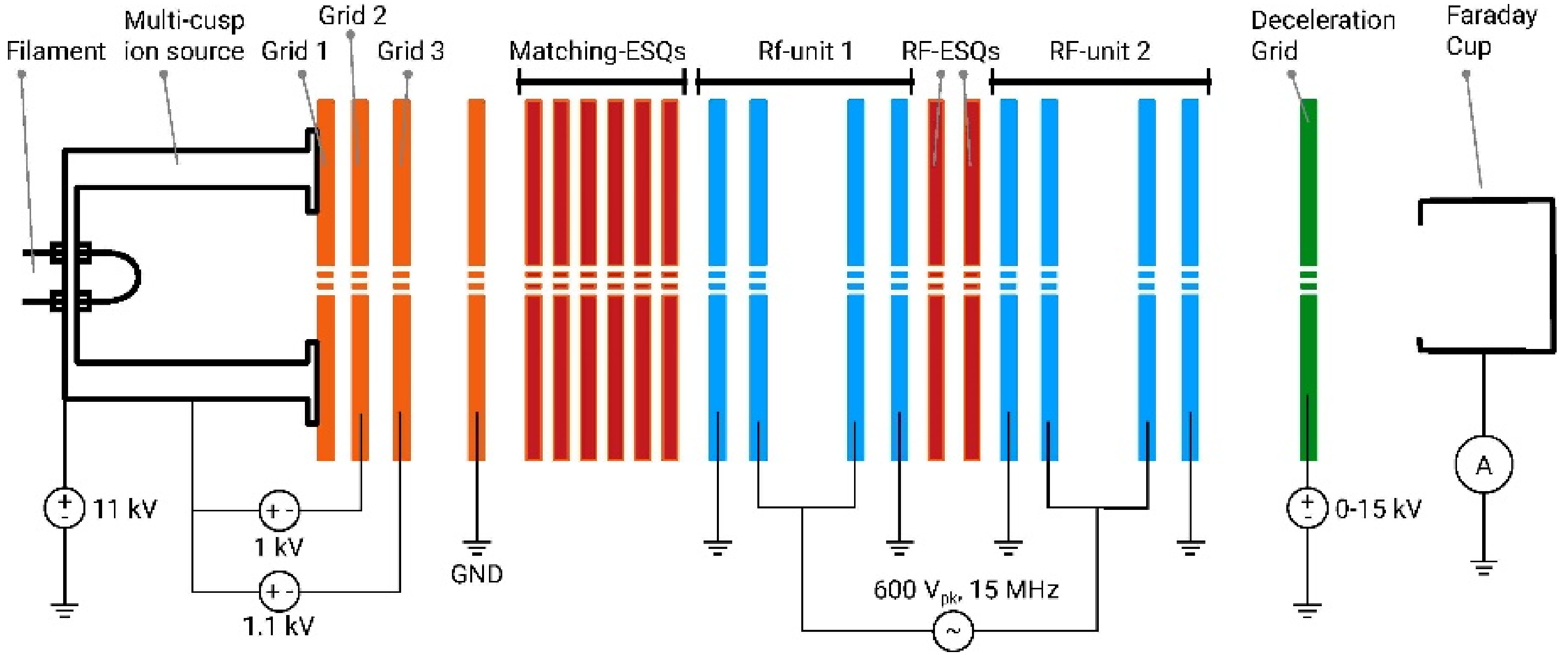
- Persaud, et al., Rev. Sci. Instr. 88, 063304 (2017)
- Persaud, et al., Phys. Procedia 90, 136 (2017)
- Seidl, et al., Rev. Sci. Instr. (2018)
- Vinayakumar, et al, J. Appl. Phys. 125, 194901 (2019)

Electrostatic Quadrupoles



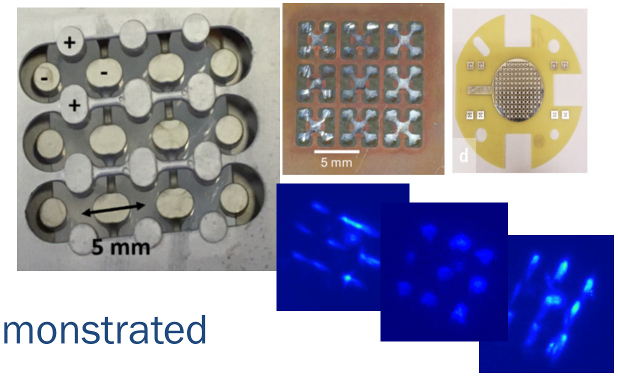


Ion acceleration and focusing have been demonstrated using a stack of wafers. The total ion current is scaled with more beamlets.

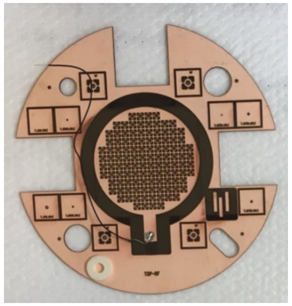


Beam extraction

Focusing



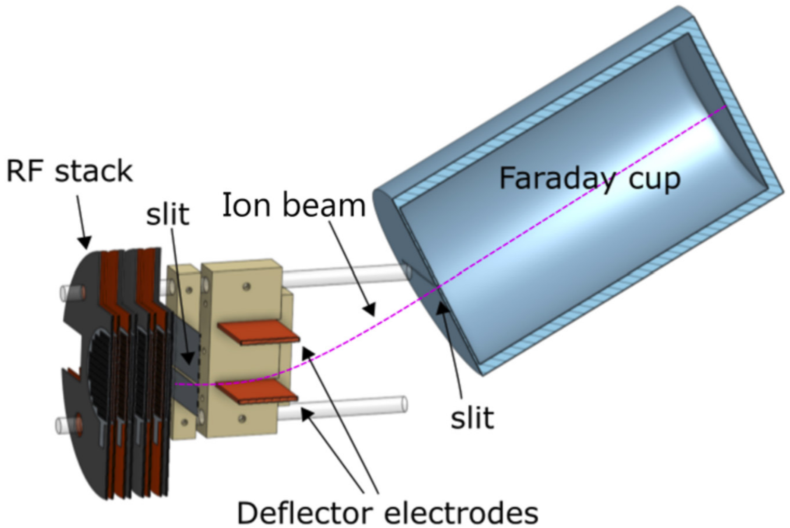
Acceleration

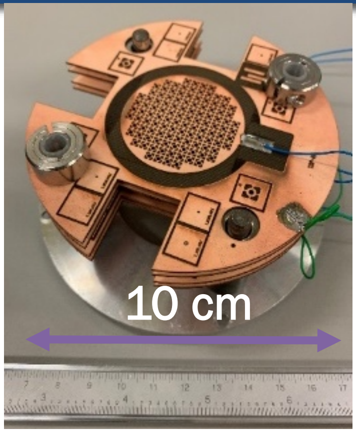


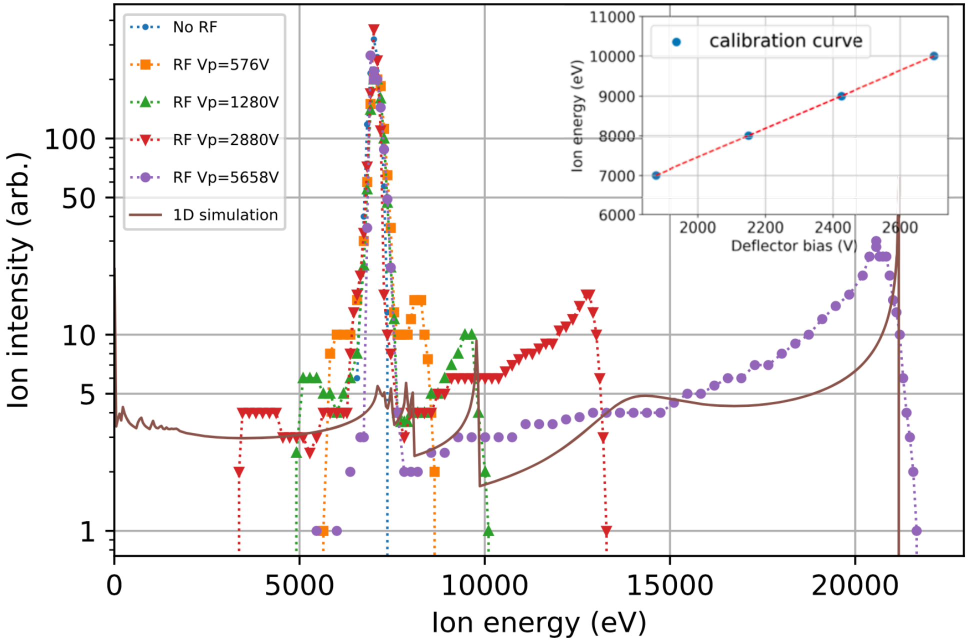
RF amplifier

up to 0.5 mA of Ar^+ demonstrated

Beam energy analyzer with parallel plates have been tested and calibrated with injected ions with known beam energy.



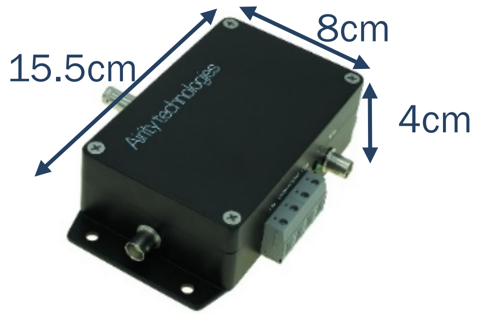


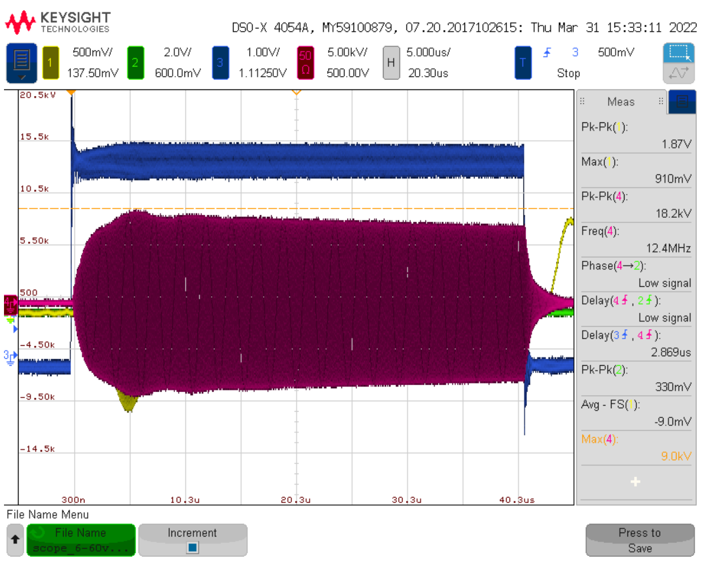


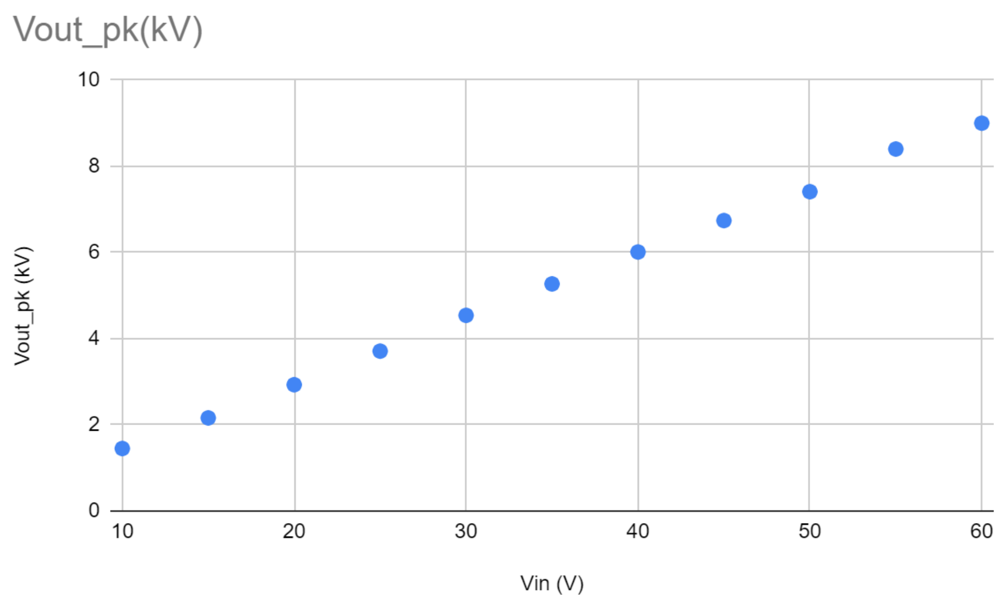
Q. Ji et al, Rev. Sci. Instrum. **92**, 103301 (2021); https://doi.org/10.1063/5.0058175

Near board compact RF amplifier enables acceleration > 6 keV/gap.

RF (13.5MHz) amplifier

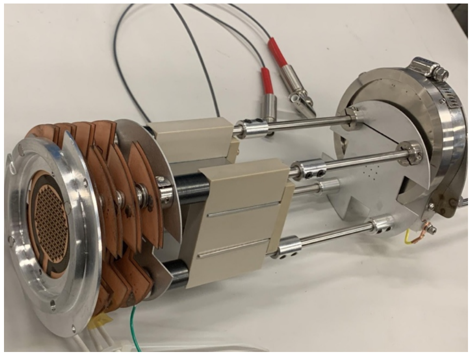






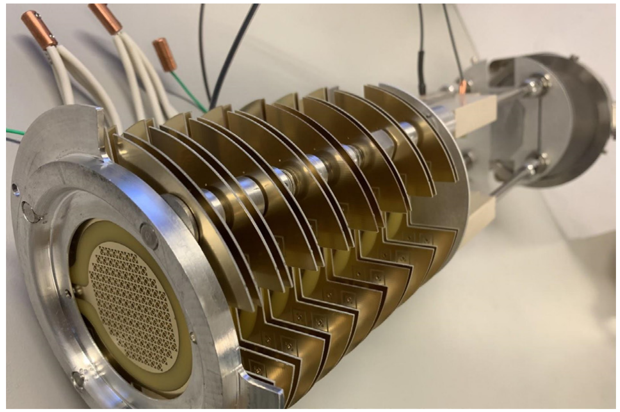
We've made steady progress to achieve ion energy over 100 keV.

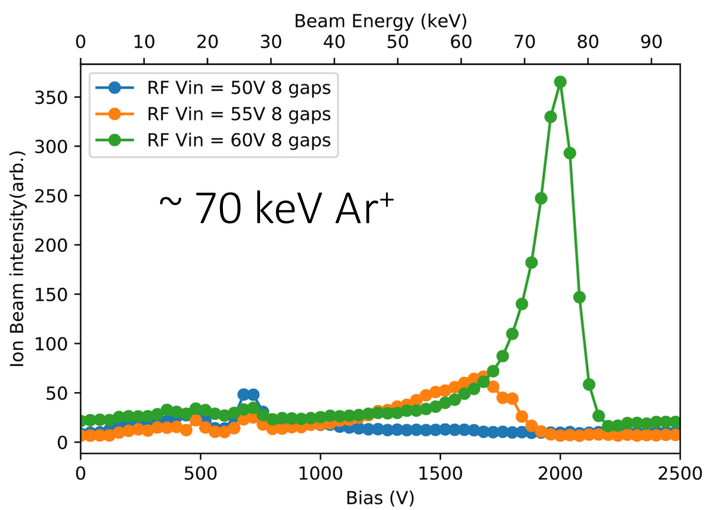
4 RF gaps



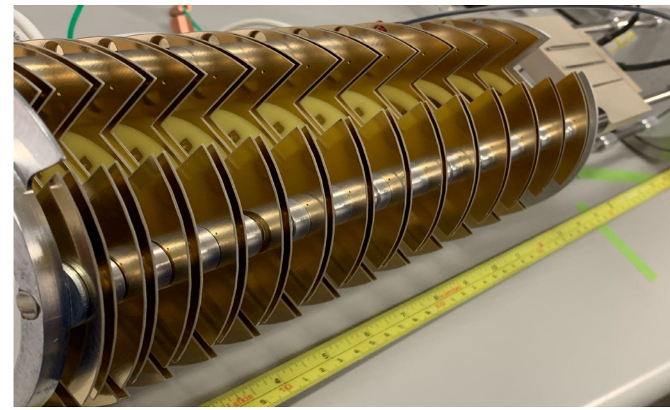
~ 33 keV Ar^+

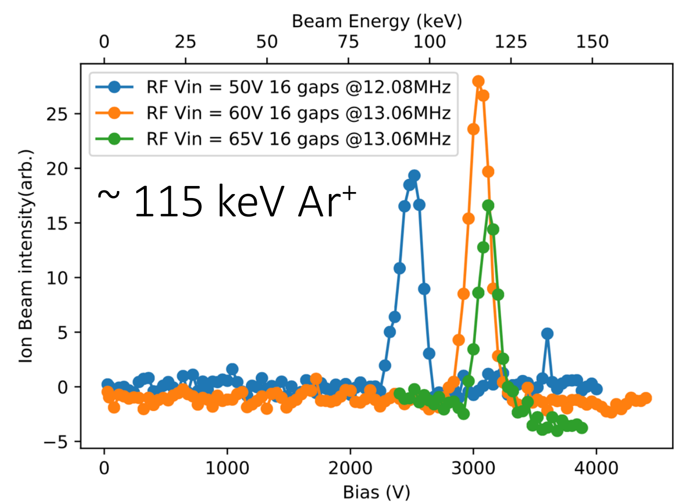
8 RF gaps



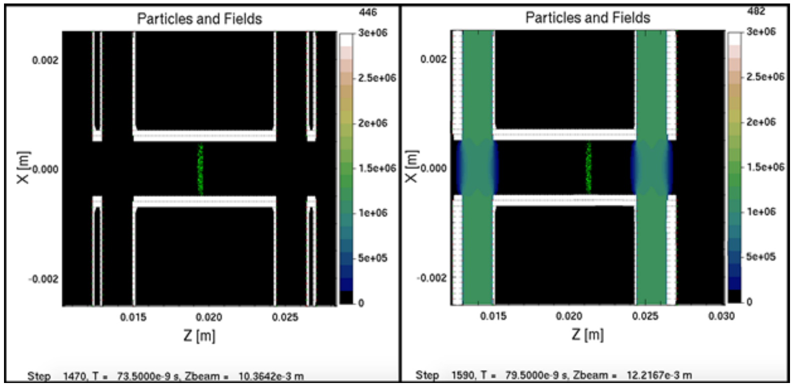


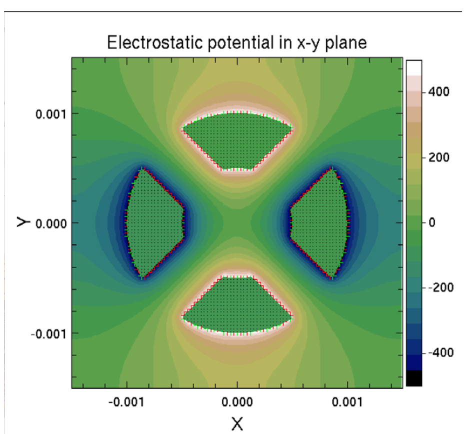
16 RF gaps

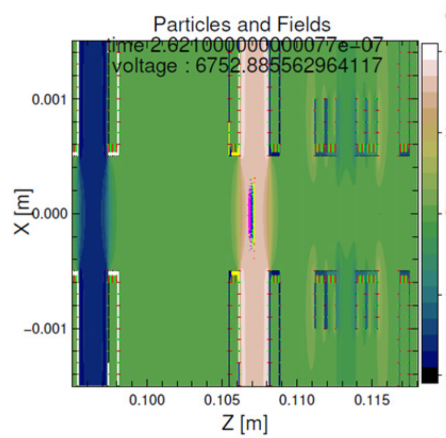


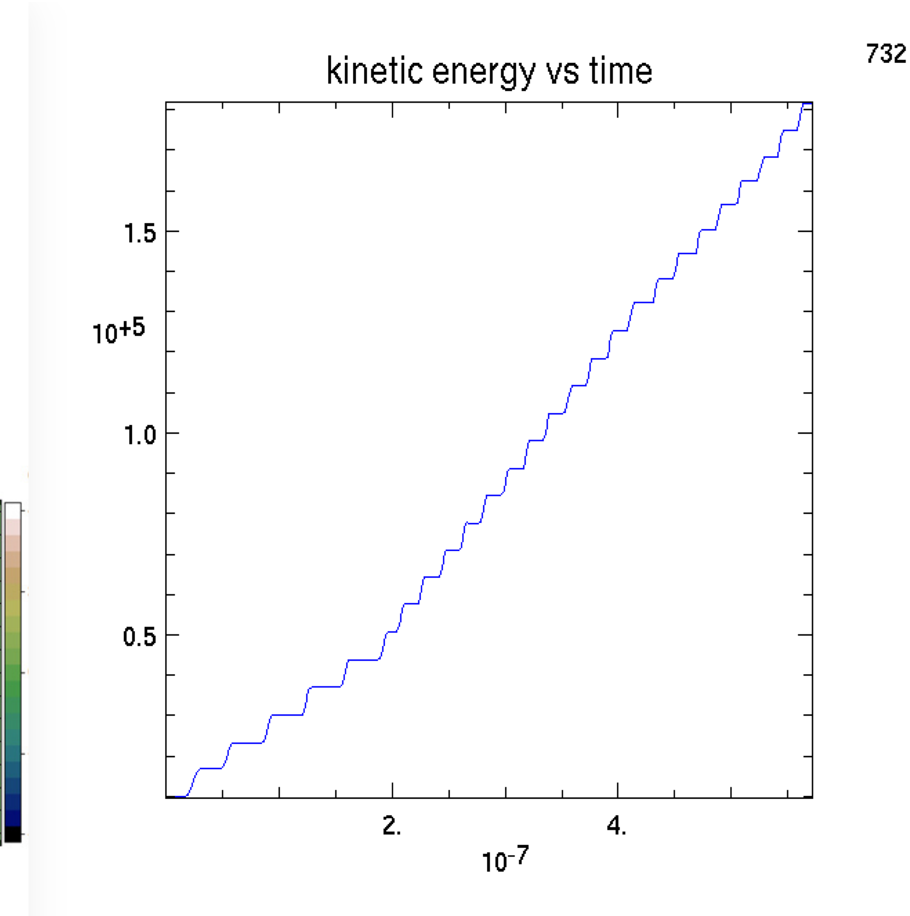


WARP PIC simulations are set up to optimize ESQ parameters and help understanding of beam acceleration and transport.

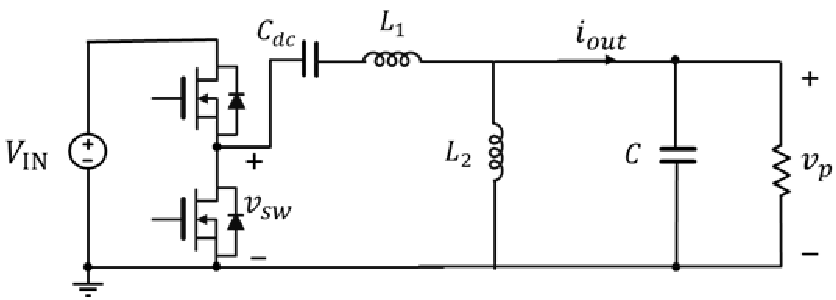


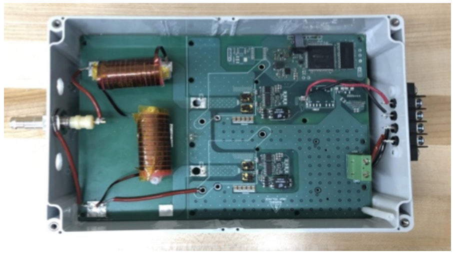




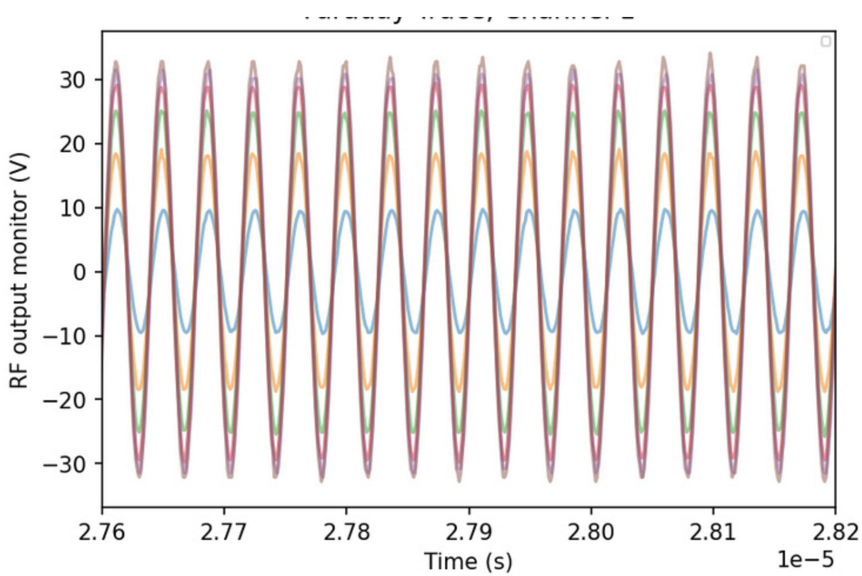


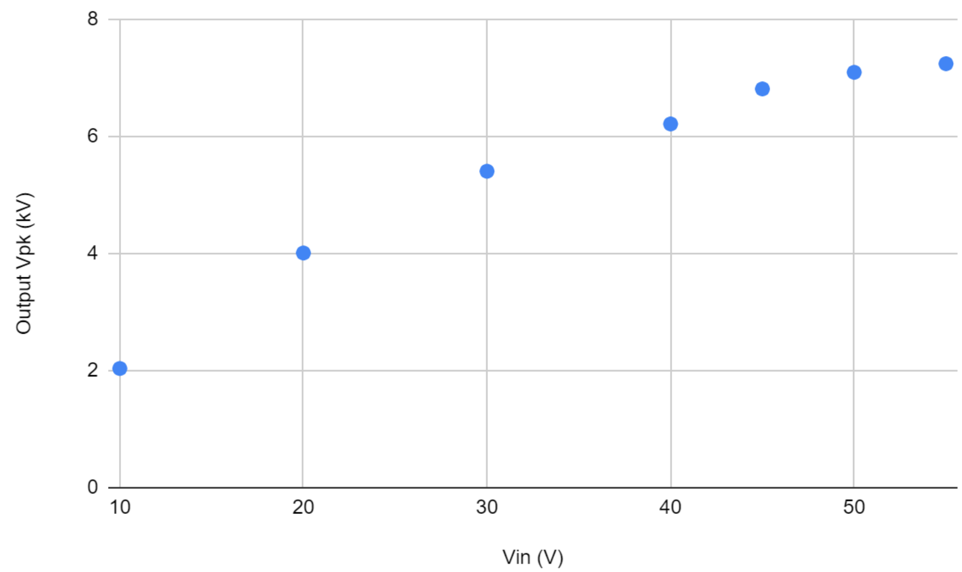
RF amplifiers at higher frequency are needed to improve the acceleration gradient.



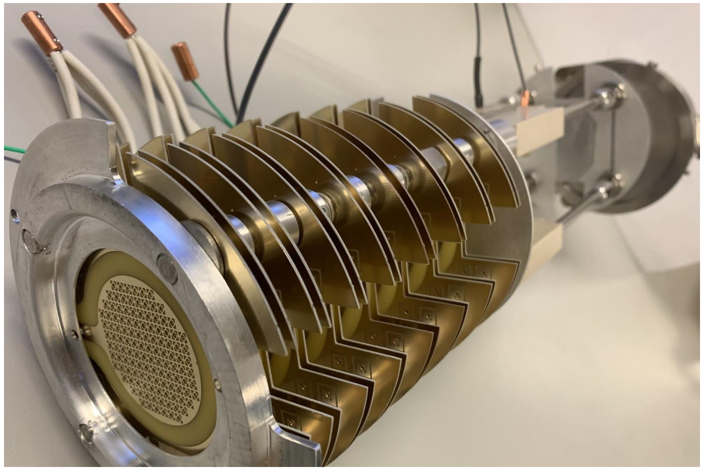


Half-bridge class-D circuit topology has been adopted for the 27MHz amplifier.





Summary and outlook



- We are developing a new class of particle accelerators that can deliver more ions on target at lower cost.
  - 32 wafers (4”), 16 acceleration gaps, cost per wafer is less than 1$
  - Injection energy 7 keV, up to 120 beamlets, peak argon ion current up to 0.5 mA
  - Acceleration by ~6.5 to 7.5 kV/gap, total energy added: ~100 keV, gradient 0.4 MV/m
- Minimal x-ray hazard, no large insulators to stand off high voltages
- Next steps is scaling to higher ion beam energy and ion current (>150 keV, >1 mA)
- This new class of particle accelerators can be applied to surface modification of materials, ion implantation, ion beam analysis, …

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CHANGING WHAT'S POSSIBLE

Acknowledgements

Special thanks Takeshi Katayanagi for his dedicated technical support.

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Thank you