Time-Resolved Transmission Electron Microscopy From 1 Hz To 10 GHz In Stroboscopic Mode

NIST

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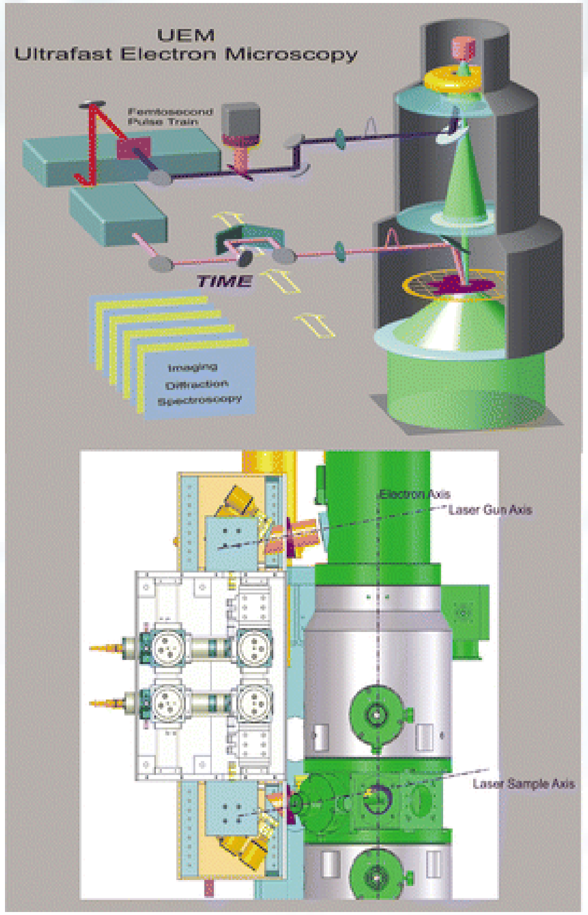
Housekeeping

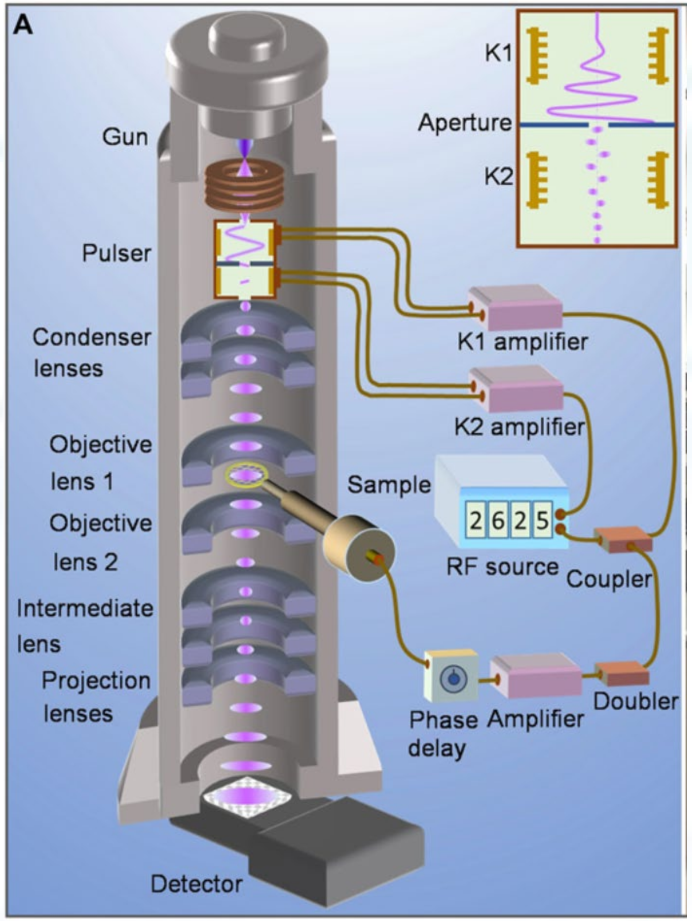
- Certain commercial equipment, instruments, or materials are identified in this presentation to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

- We ♥ publicly funded science! This work was supported by DOE BES SBIR program grant no. DE-SC0013121, and NIST award SB1341-16-CN-0035.

NOT a photoemission UEM…



- A. Zewail (Ann. Rev. Phys. Chem. 2006) https://doi.org/10.1146/annurev.physchem.57.032905.104748
- D. Flanngan (Acc. Chem. Res. 2012) https://doi.org/10.1021/ar3001684



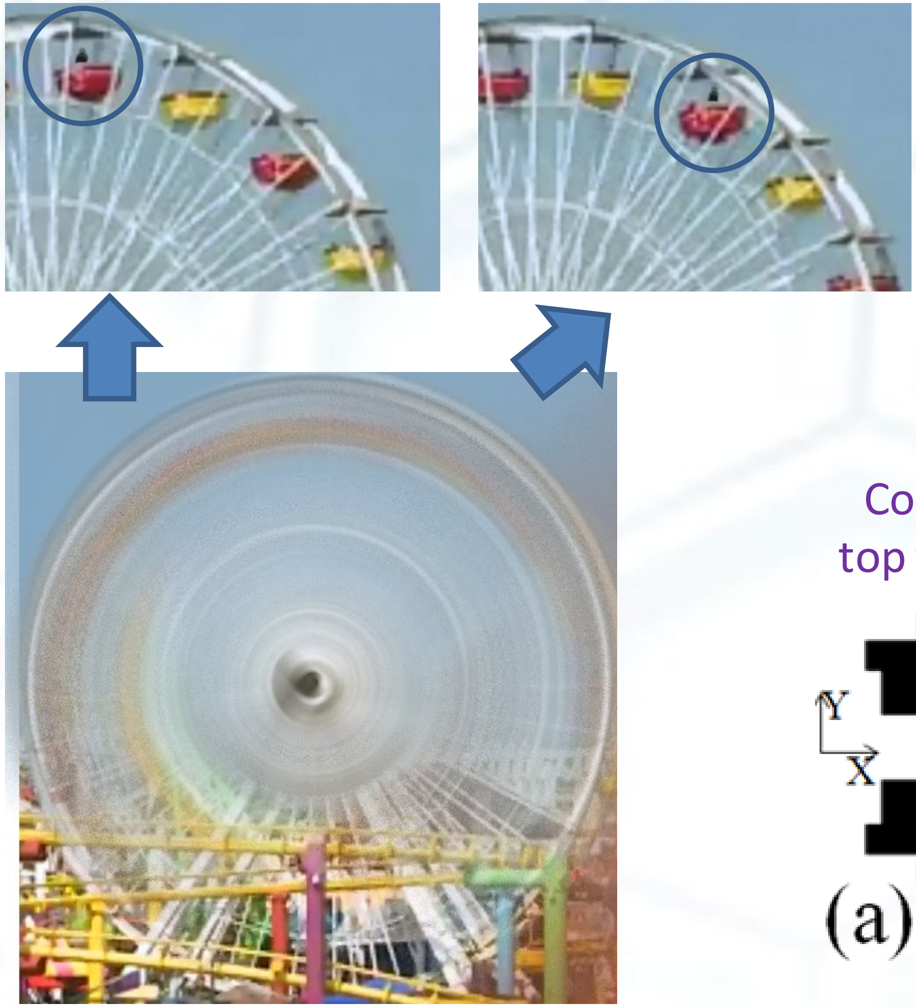
… but a pair of metallic comb strip-line beam pulsers

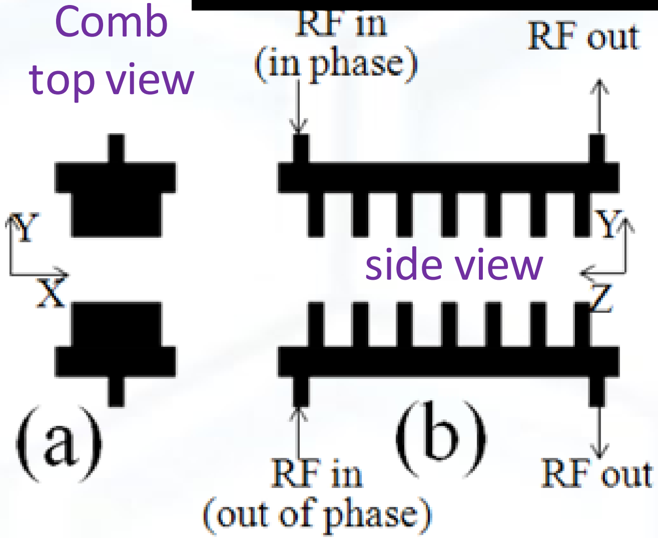
(Cover Article) Rev. Sci. Instrum. https://doi.org/10.1063/1.5131758

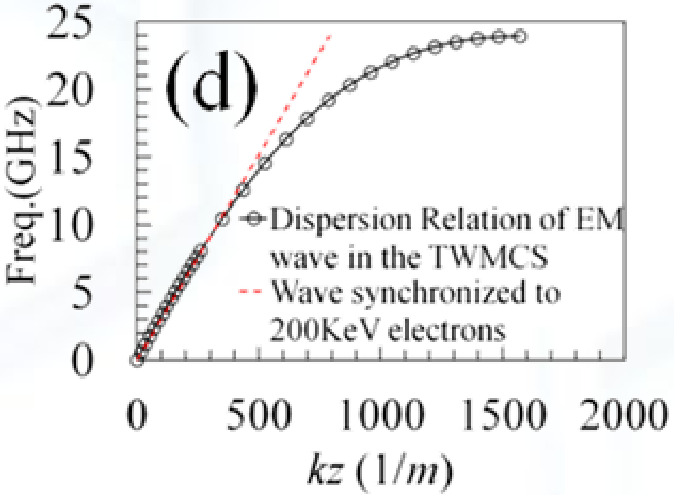
Microscopy TODAY 2020 Innovation Award

R&D 100 AWARDS

The stroboscopic appro



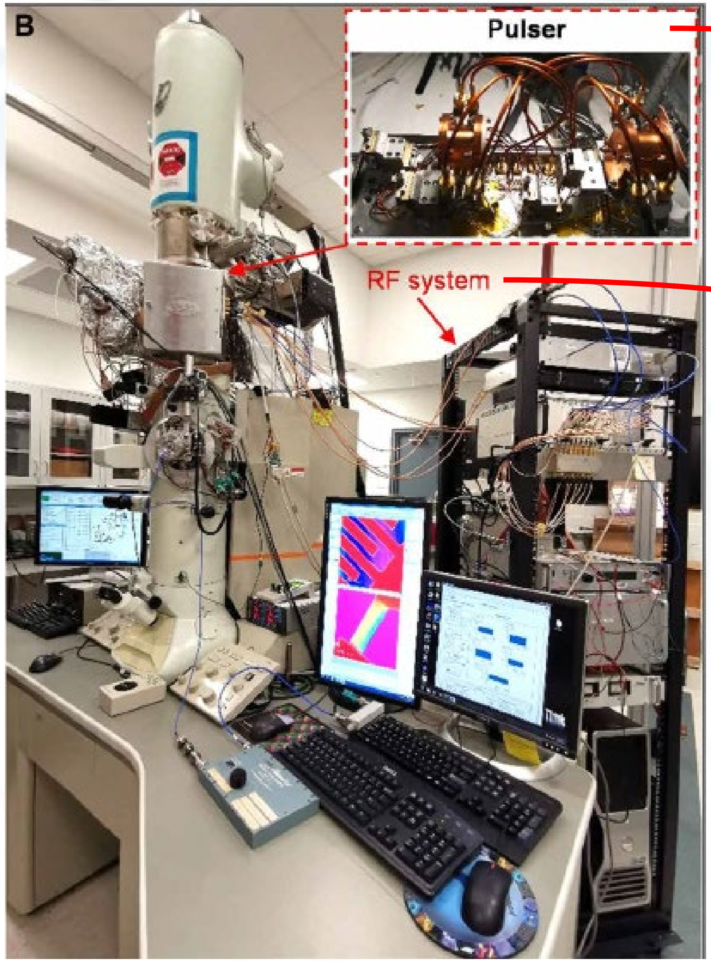


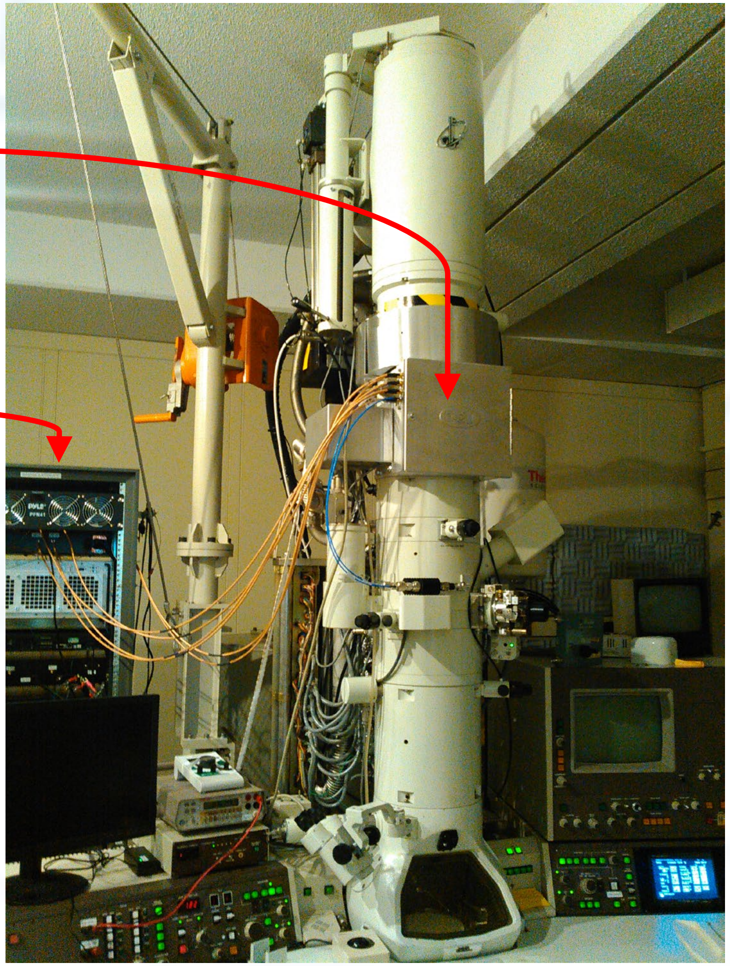


<u>Disclaimer</u>: for repeatable and cyclical phenomenon only. Not meant to be a replacement for single-shot techniques

Beam chopping in two microscopes

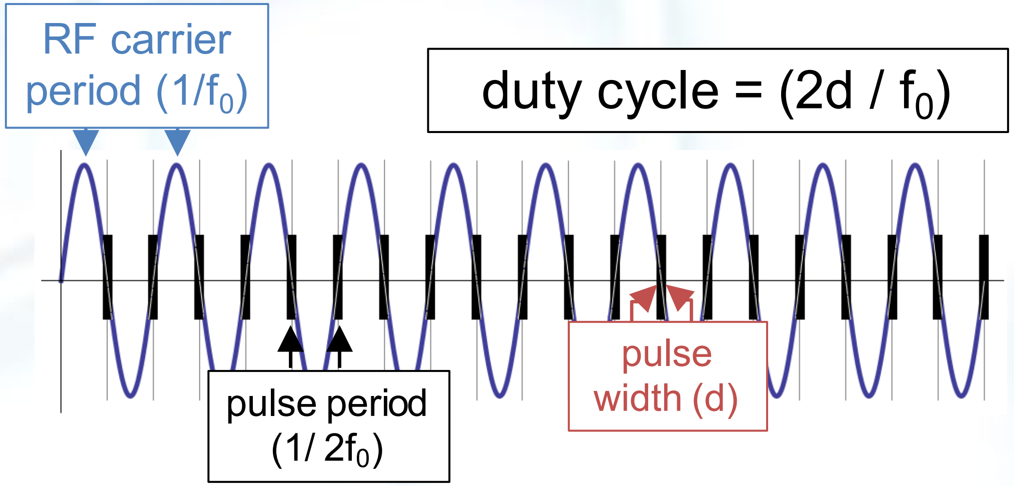
200-keV Schottky TEM (JEM2100F) at BNL





300 keV thermionic TEM (JEM3010) at NIST

Original microscope installed in 1994

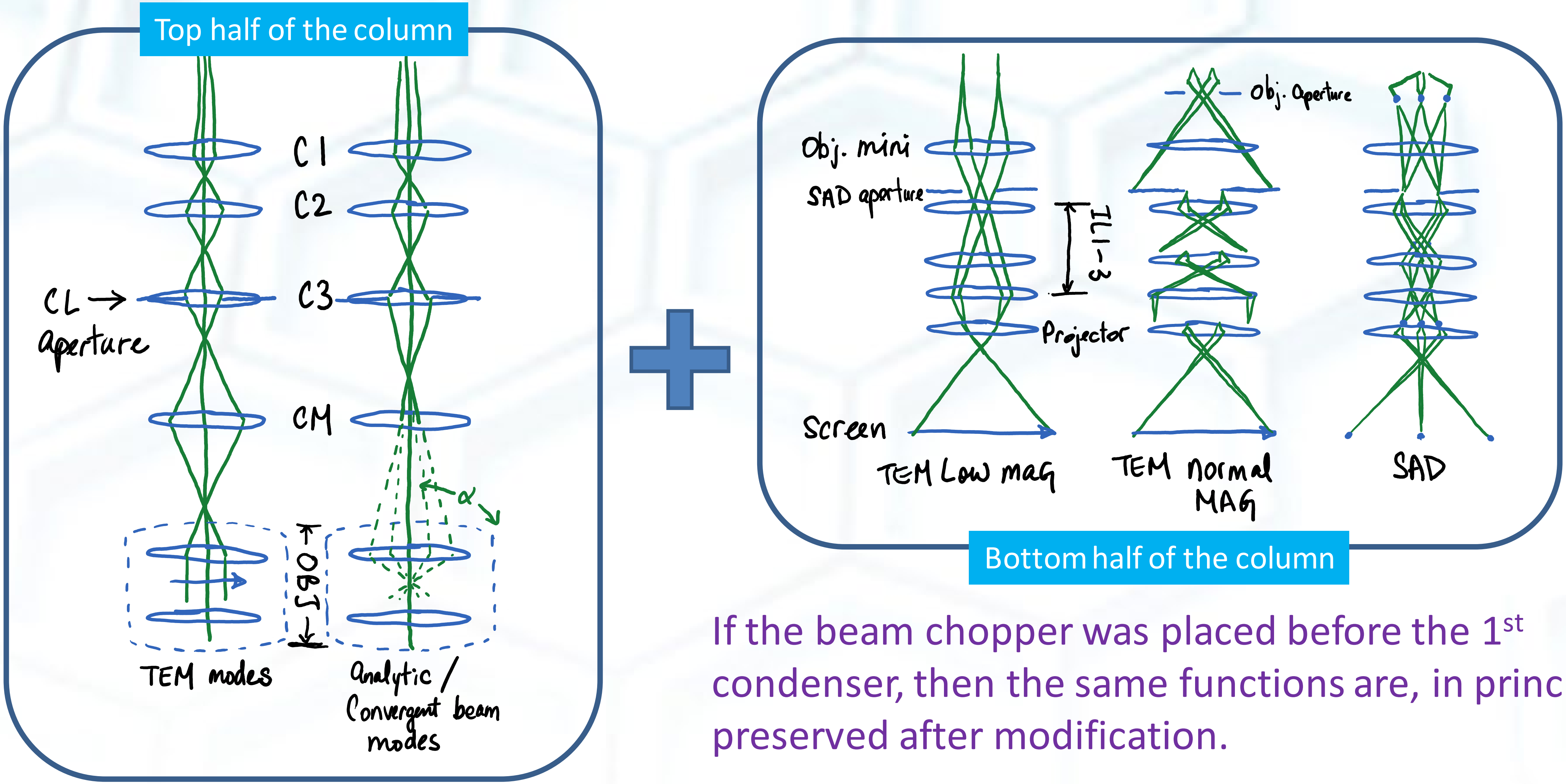


Broadband continuously tunable strobe-frequency 20 MHz < f_0 < 6.0 GHz

- Pulsed frequency is always ($2f_0$)!
- Pulse widths @ 10% duty demonstrated

Preservation of native modalities

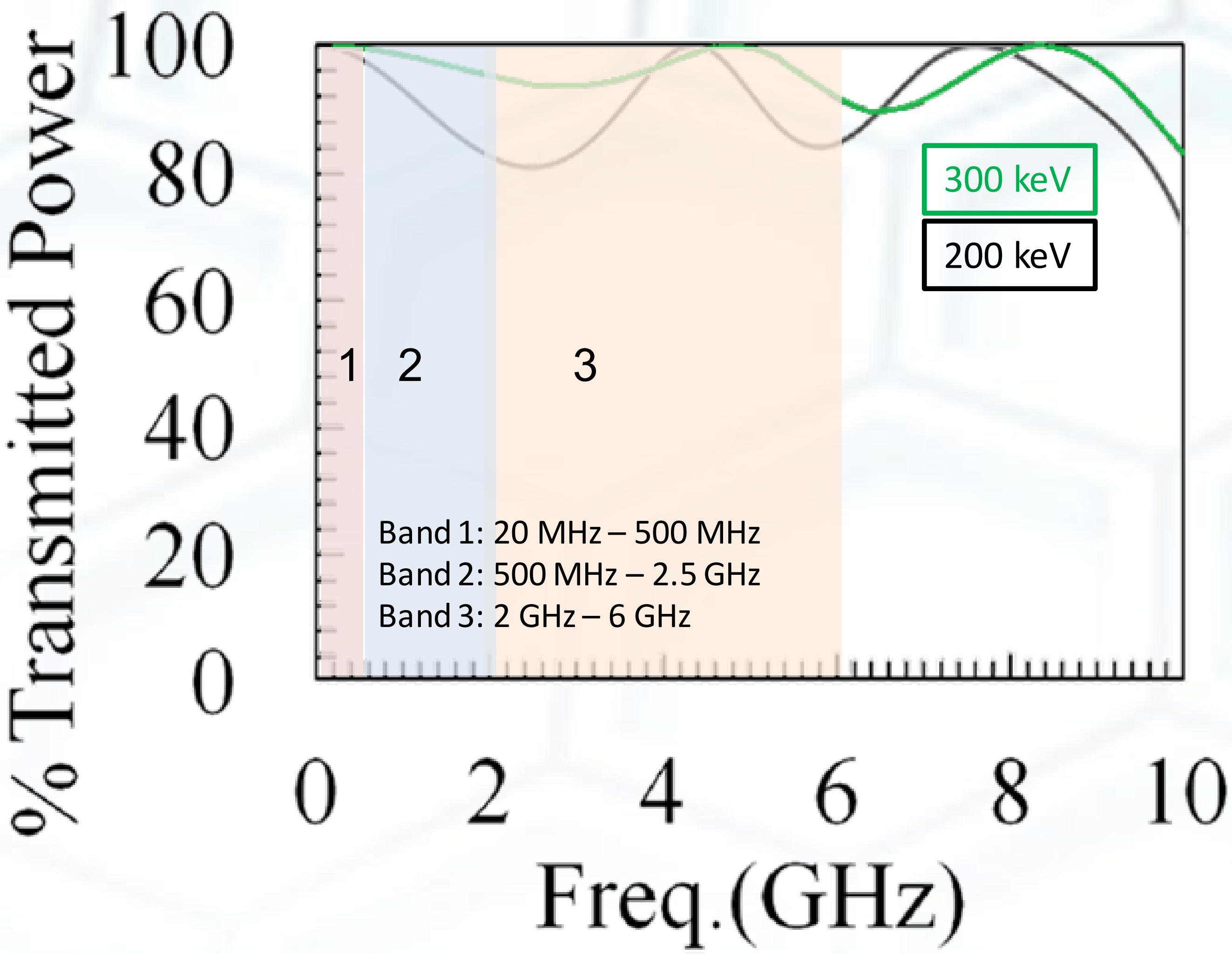
Ray diagrams of typical modes

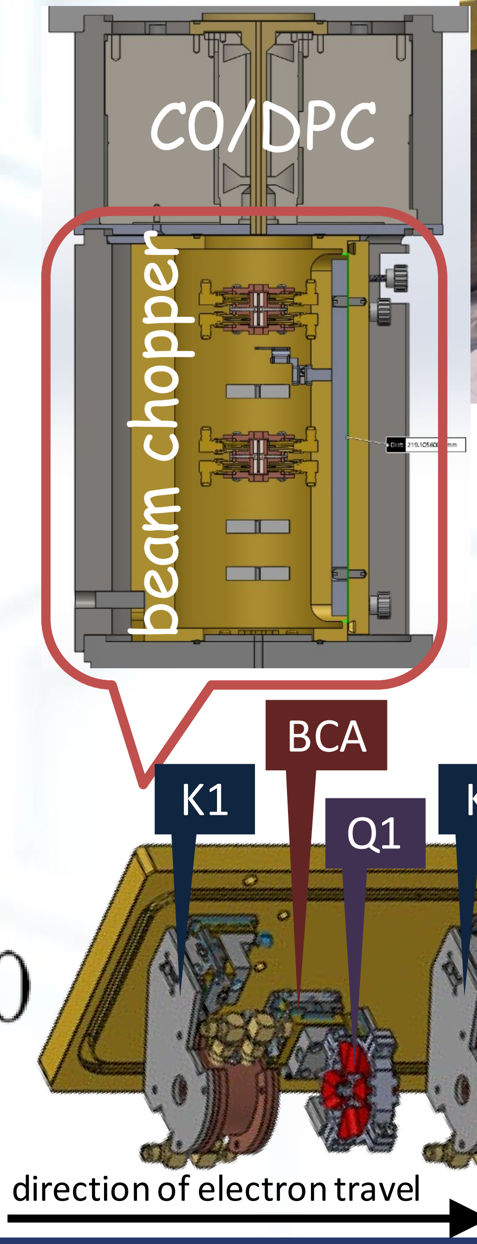


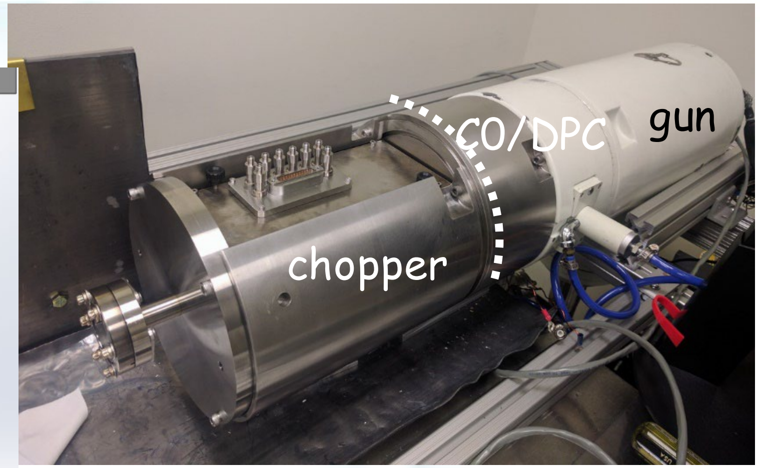
If the beam chopper was placed before the 1st condenser, then the same functions are, in principle, preserved after modification.

Basic Operation 40 MHz – 12 GHz

The basics



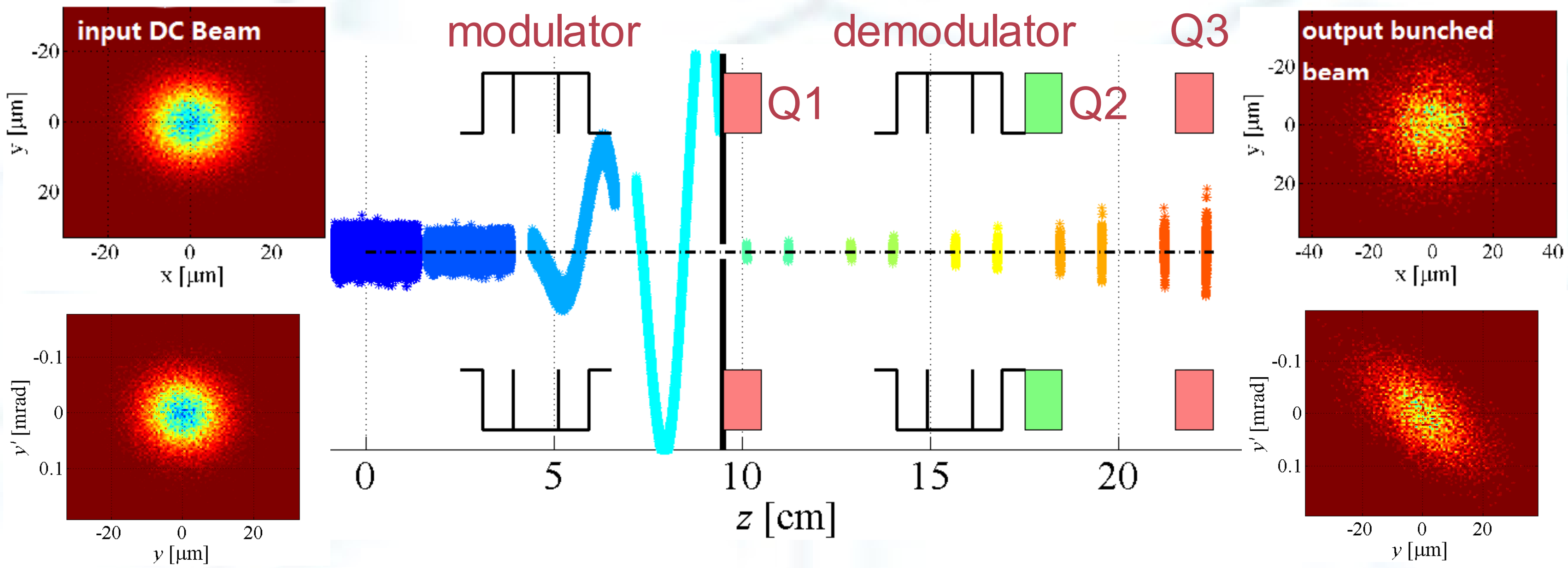




Parts nomenclature

- C0: pre-condenser lens
- DPC: differential pumping chamber
  - K1/K2: modulator/de-modulator
  - Q1-3: Quadrupole magnets
  - BCA: beam chopping aperture

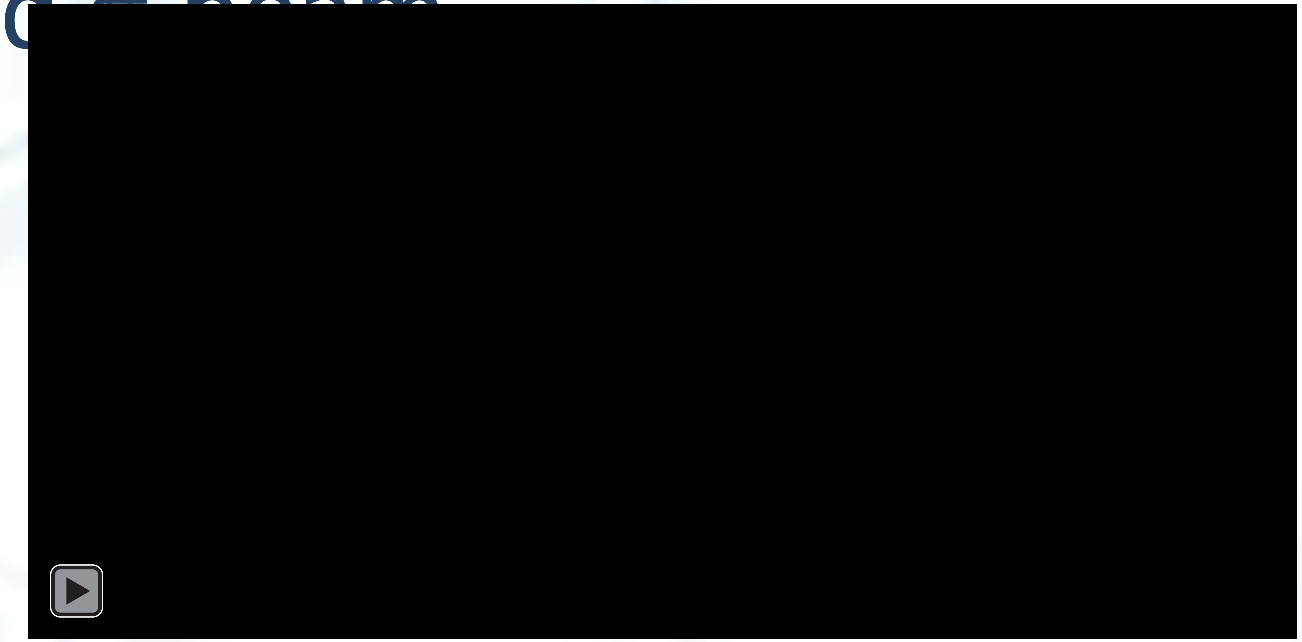
Transverse particle tracking

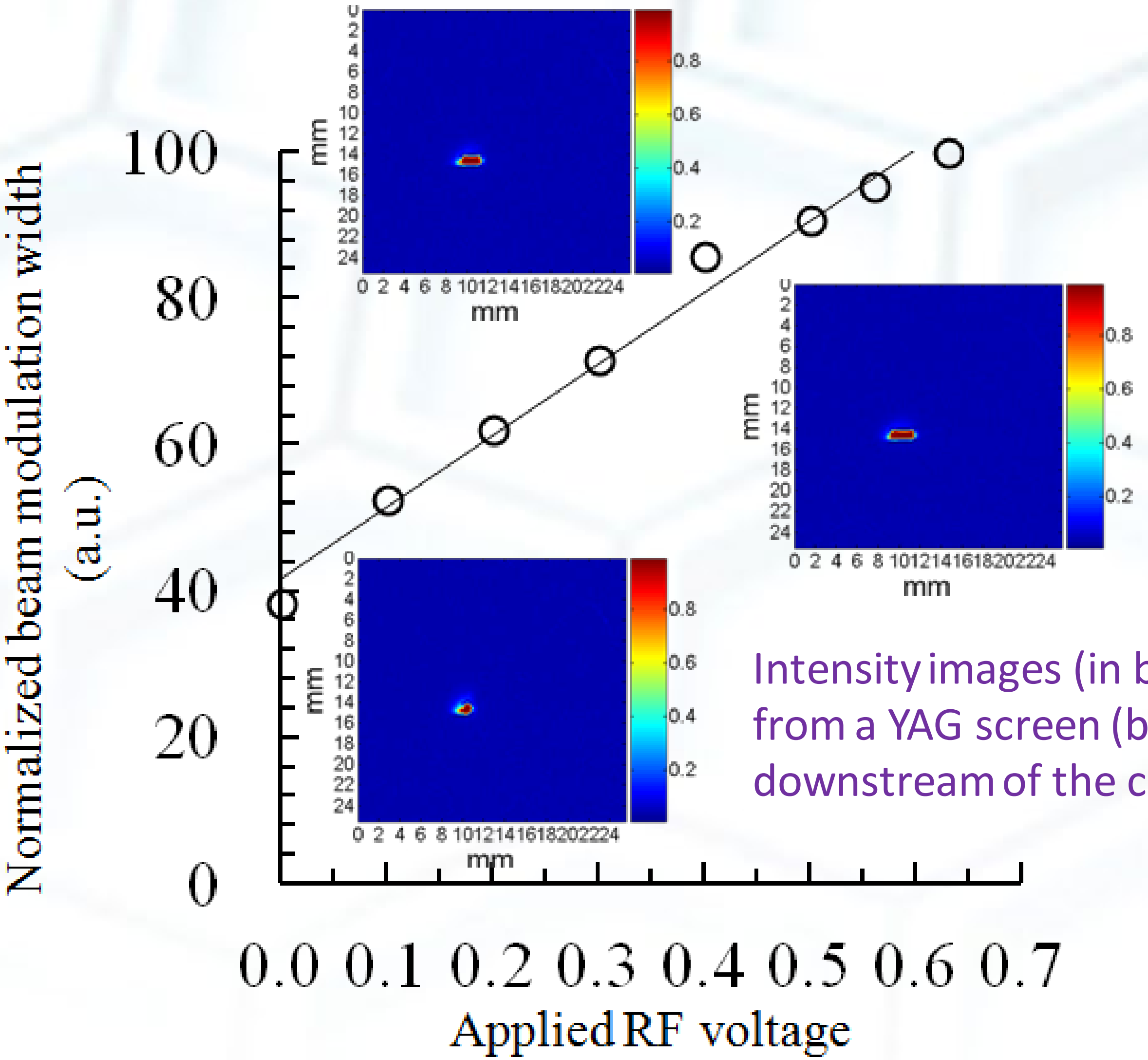


Frequency f_0	Aperture radius (μm)	Simulated pulse length (ps)	Emittance x	Emittance y	Energy spread introduced (eV)
3 GHz	5	16	0.18	0.32	0.02
	10	29	0.27	0.32	0.02
	20	65	0.30	0.32	0.03
6 GHz	5	6.8	0.21	0.30	0.02
	10	13	0.28	0.30	0.03
	20	28	0.30	0.30	0.06

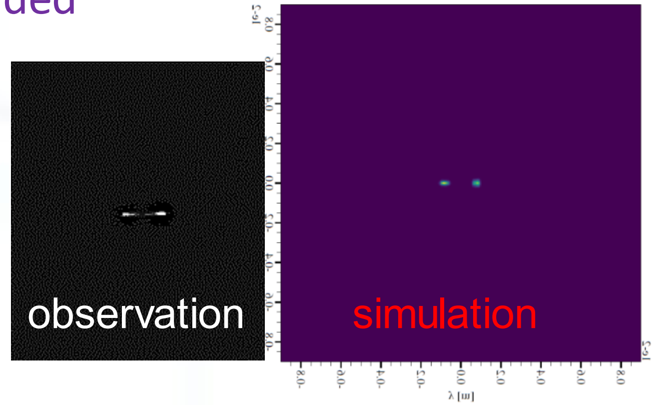
https://doi.org/10.1063/1.5131758

Dual-beam mode: 0 and





Intensity images (in blue), recorded from a YAG screen (bottom) downstream of the chopper



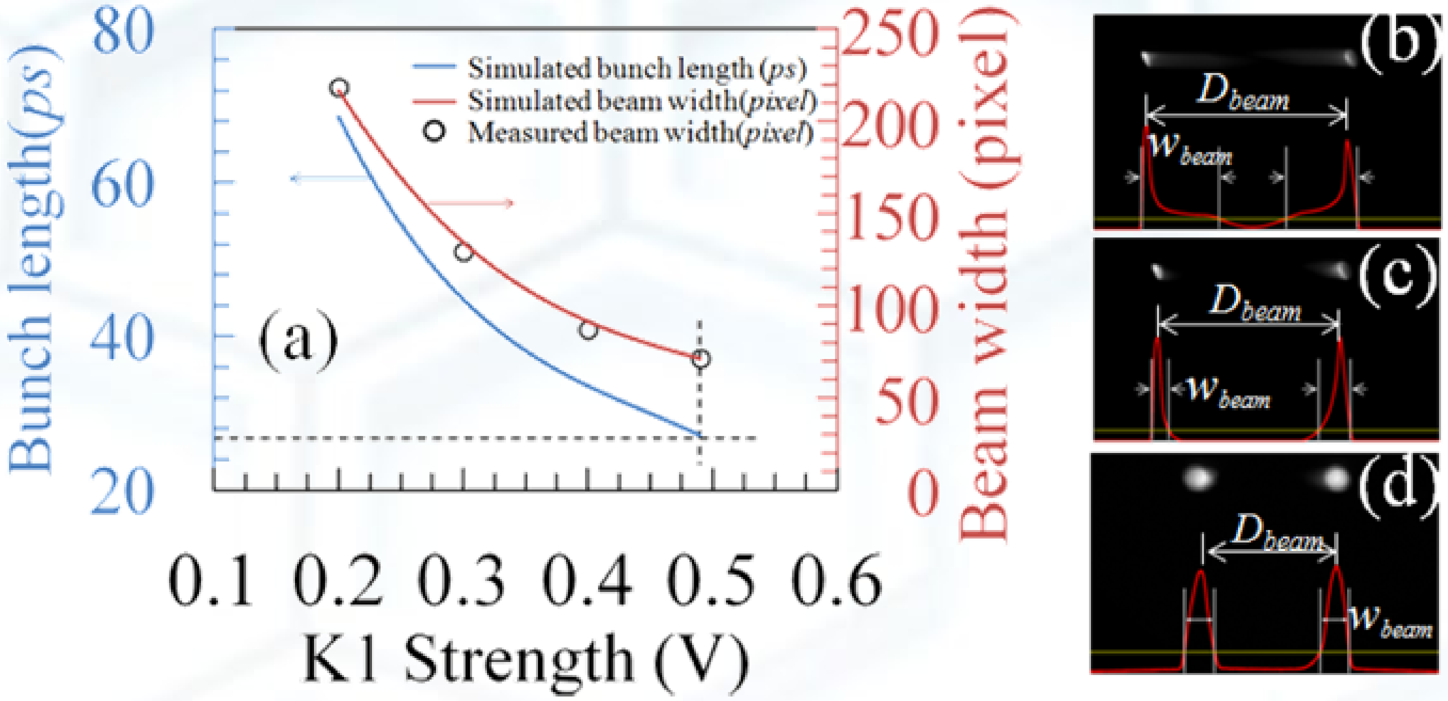
Time structure of the beam

Temporal resolution = D/f_0

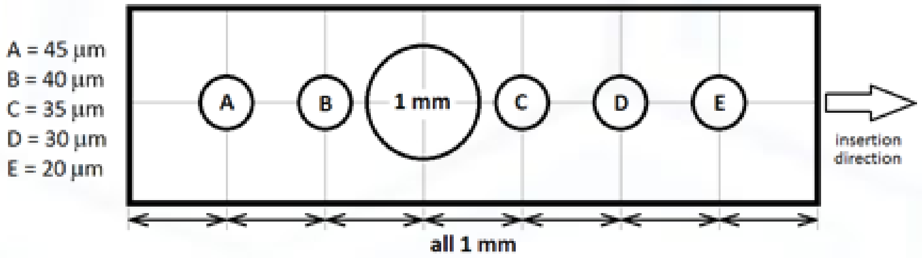
D = beam duty cycle ≈ w_{beam}/D_{beam}

Knobs at our disposal:

1. Beam chopping aperture
2. RF carrier frequency (f_0)
3. RF amplitude (V)



BCA = Beam chopping aperture

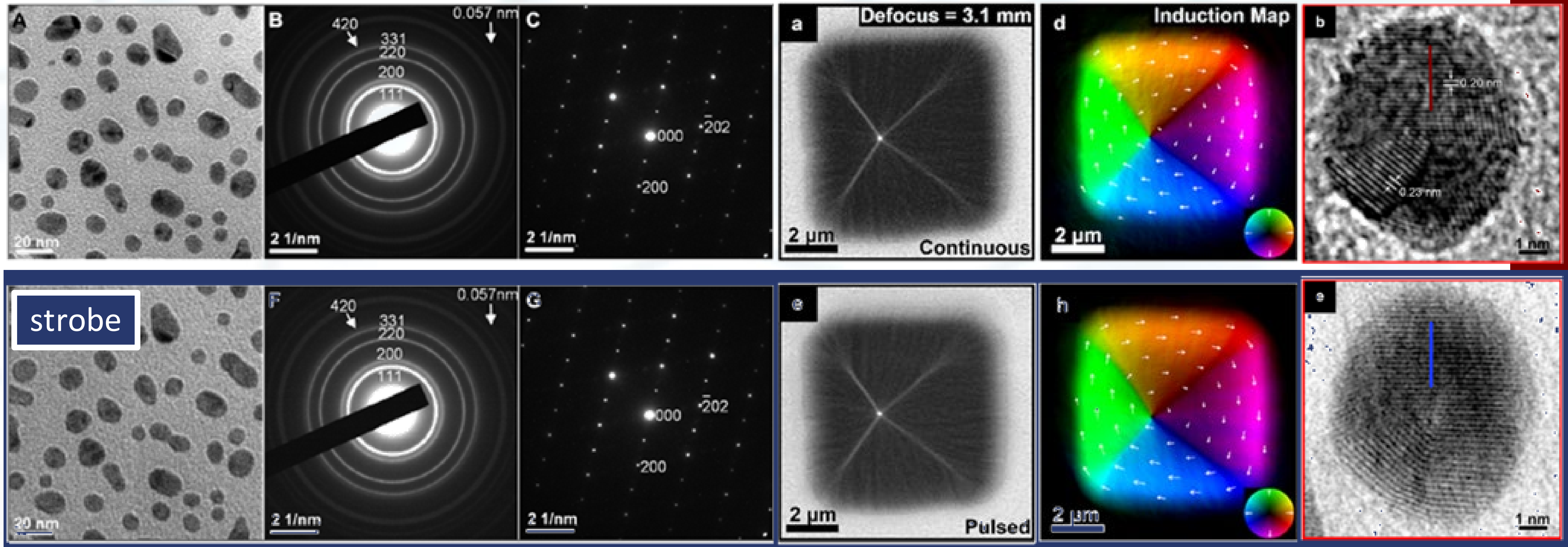


At f_0 = 5 GHz, using the 25 µm BCA, we obtained D = 0.11, which gives t_{res} = 11 ps

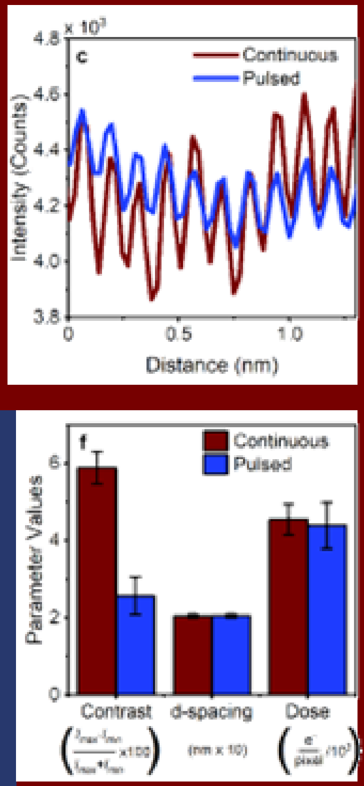
Continuous vs. stroboscopic mode

continuous

strobe



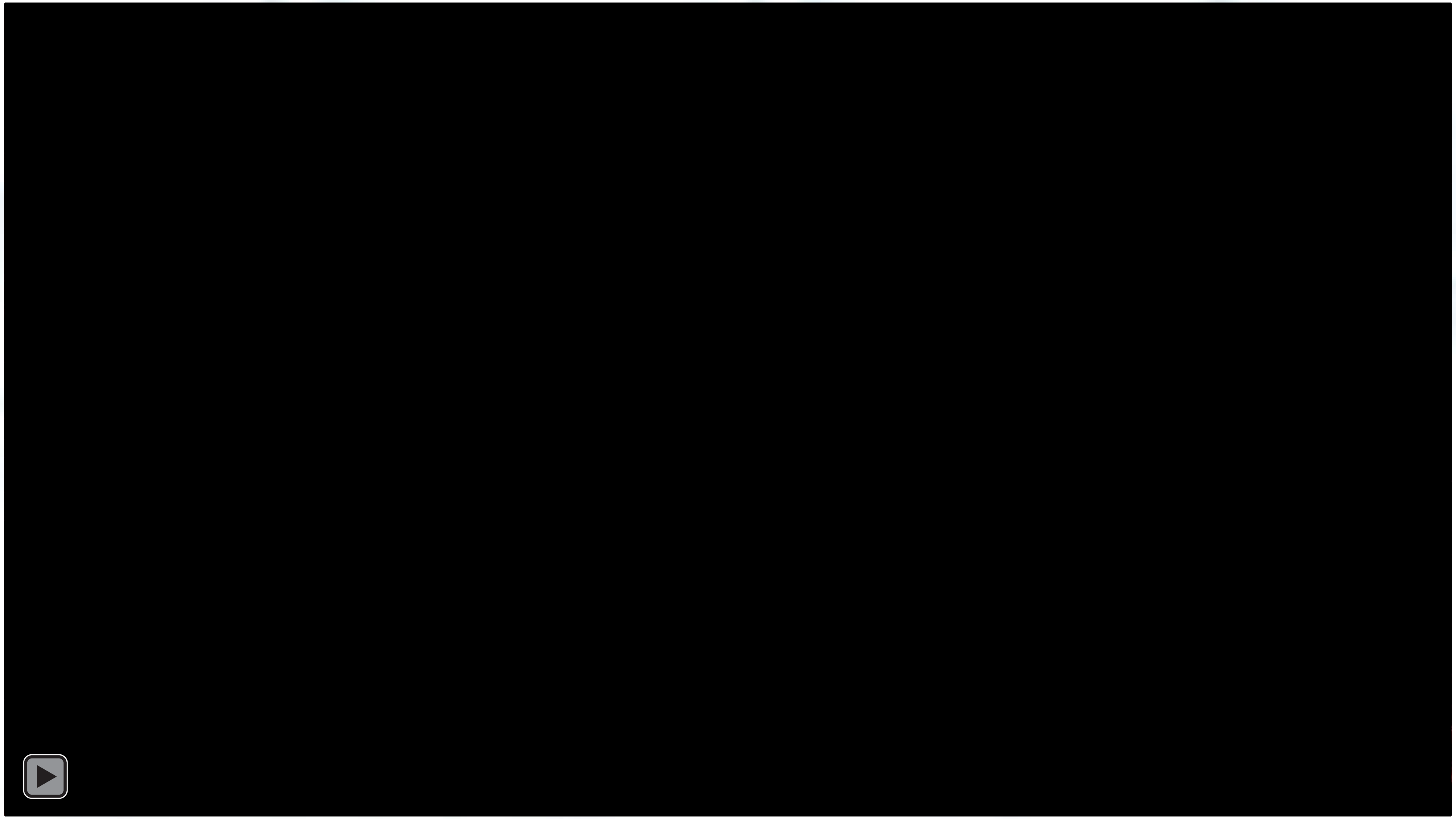
Beam statistics comparison



https://doi.org/10.1126/sciadv.abc3456

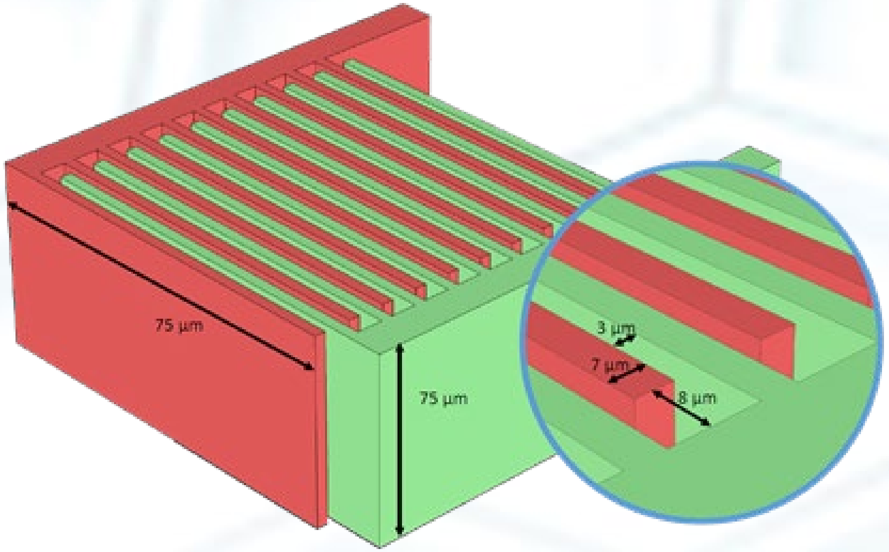
https://doi.org/10.1016/j.ultramic.2022.113497

Stroboscopic STEM mode



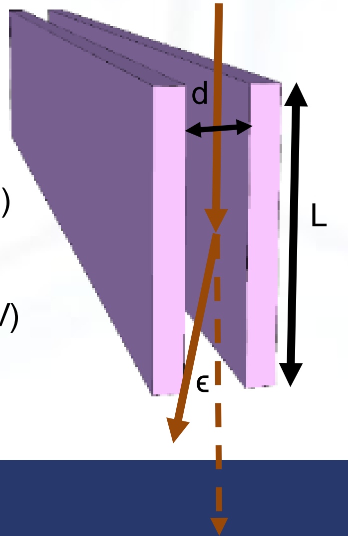
Strobo STEM-EELS… Strobo 4D STEM… Strobo cathodoluminescence…

Traveling wave along MEMS combs



$$\epsilon = \frac{euL}{2Ed} \cdot \frac{1 + \frac{E}{E_0}}{1 + \frac{E}{2E_0}}$$

ϵ = electron deflection (mrad)
e = electron charge
u = plate voltage (200 V)
E = electron energy (300 keV)
E_0 = rest energy

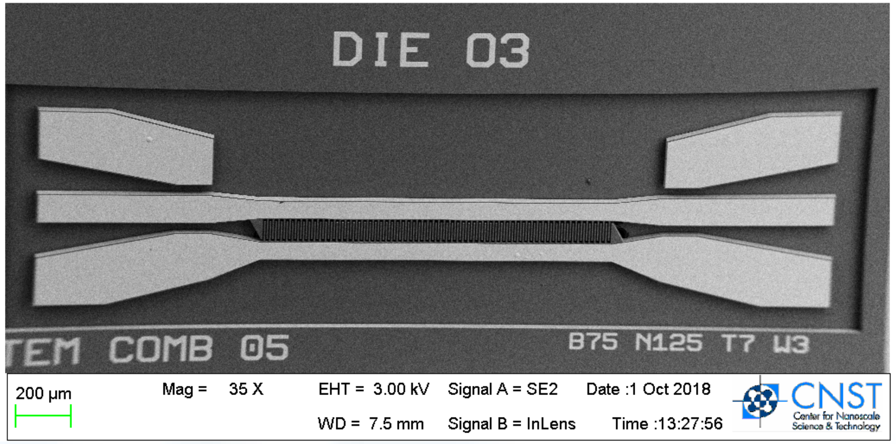


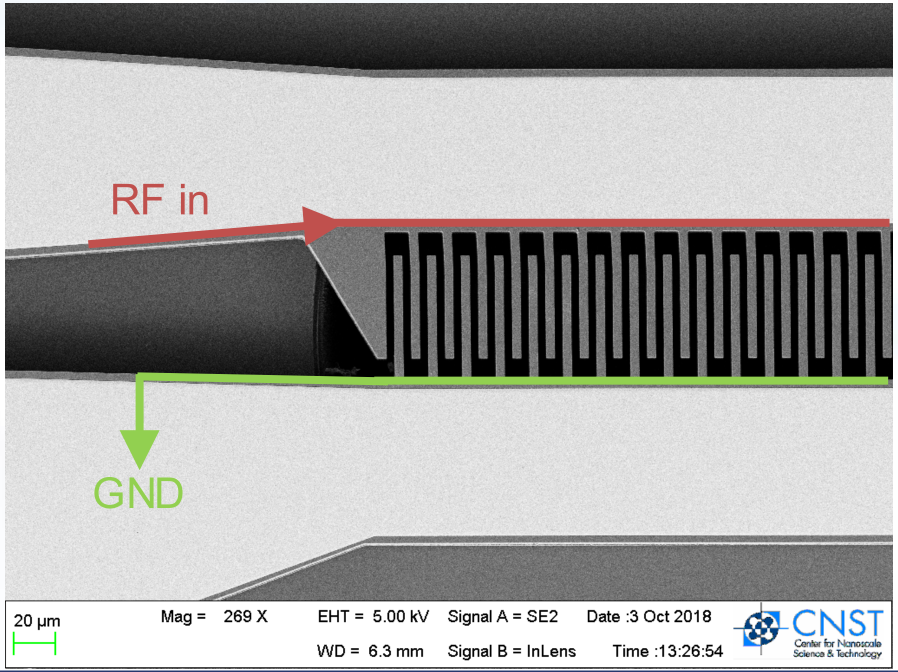
Comb characteristics:

- Tine length = 75 µm
- Tine width = 7 µm
- Pitch = 10 µm
- Comb length = 1.25 mm
- L: d :: 25: 1 (75 µm trenches)
- ρ = 0.01 Ω-cm
- $\varepsilon_r \approx 12$
- C ~ 1 pF
- @ 40V, ϵ = 2 mrad

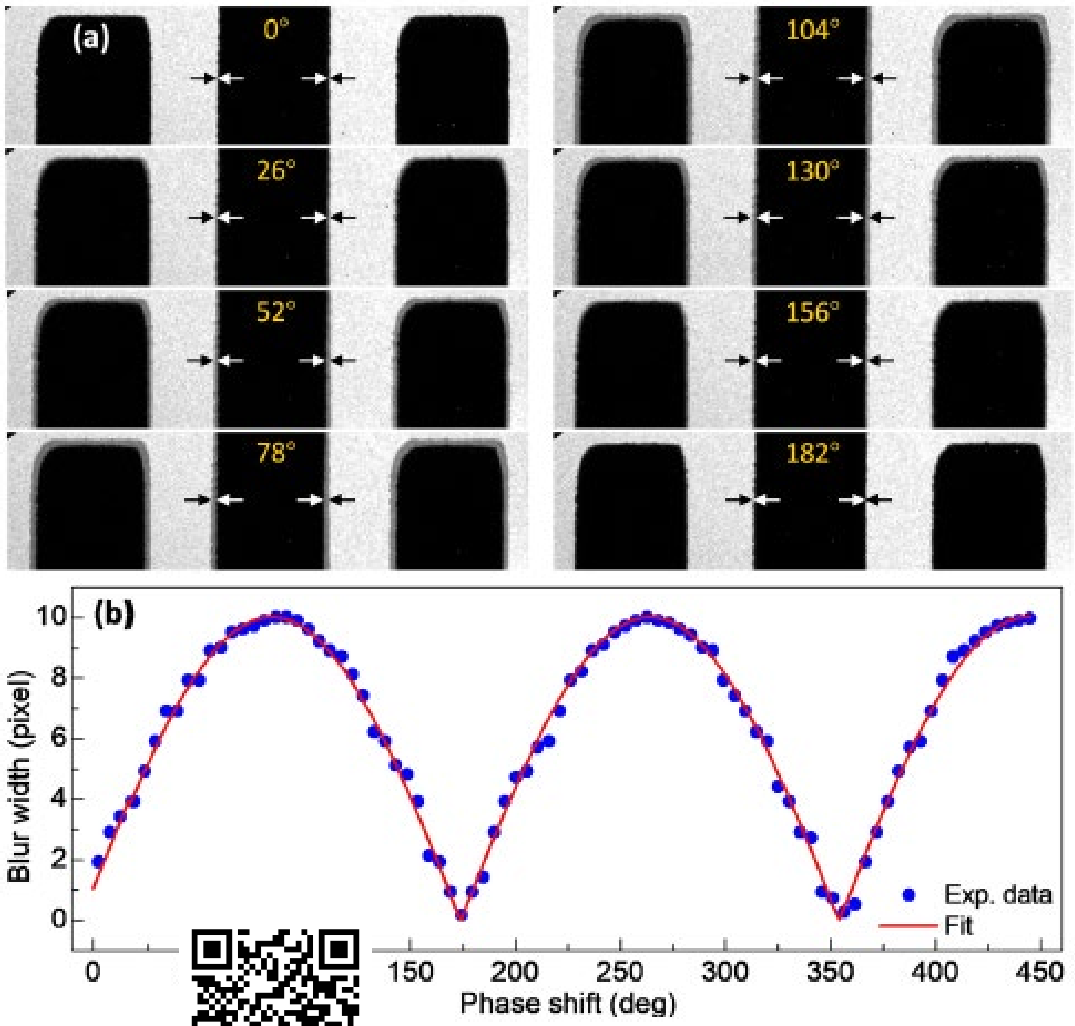
Microwave characteristics:

- $\lambda = \frac{c}{\nu\sqrt{\varepsilon_r}}$
- @ 2.6 GHz, λ ≈ 3 cm
- @ 6 GHz, λ ≈ 1.4 cm





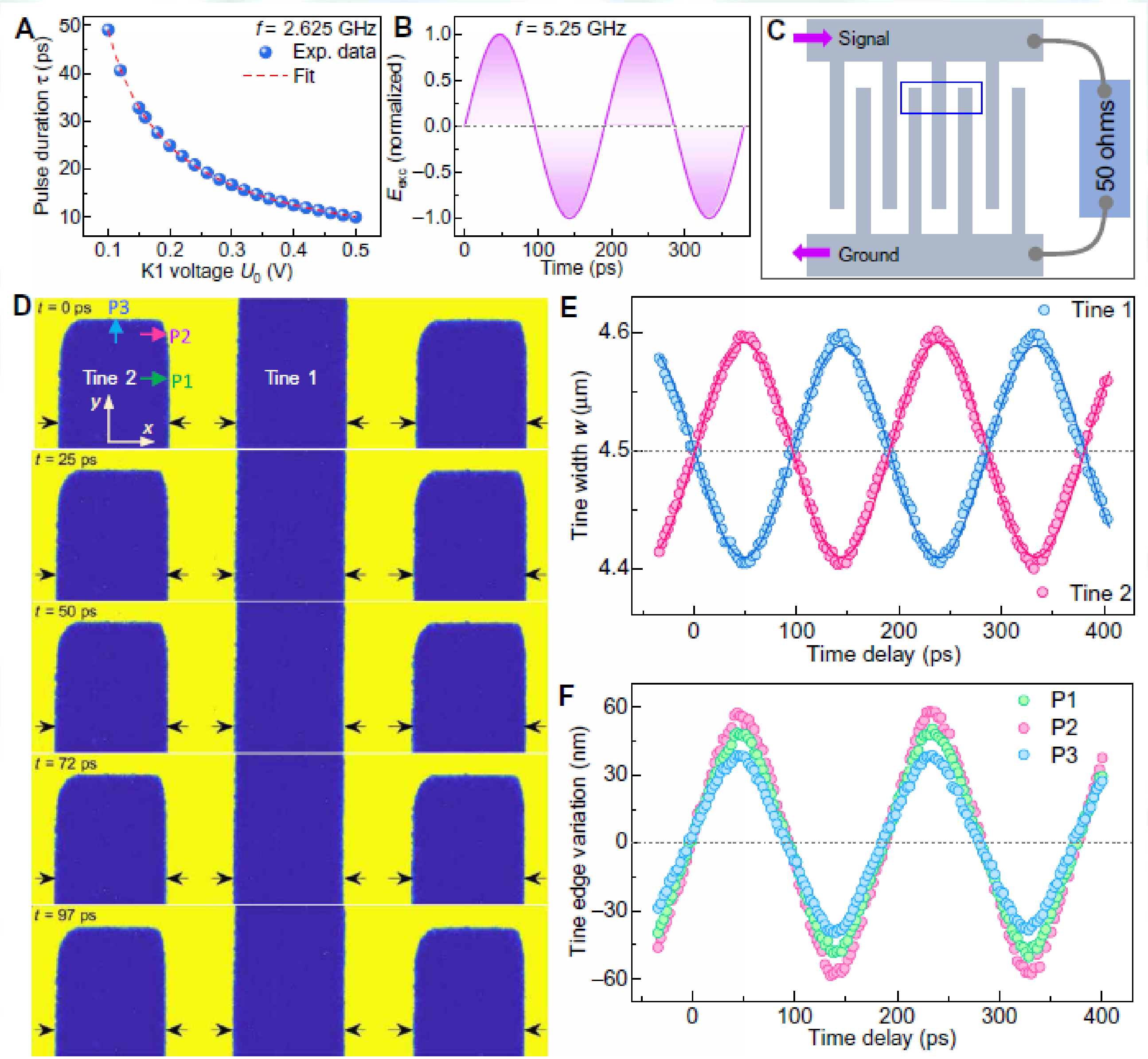
Direct visualization of a traveling wave

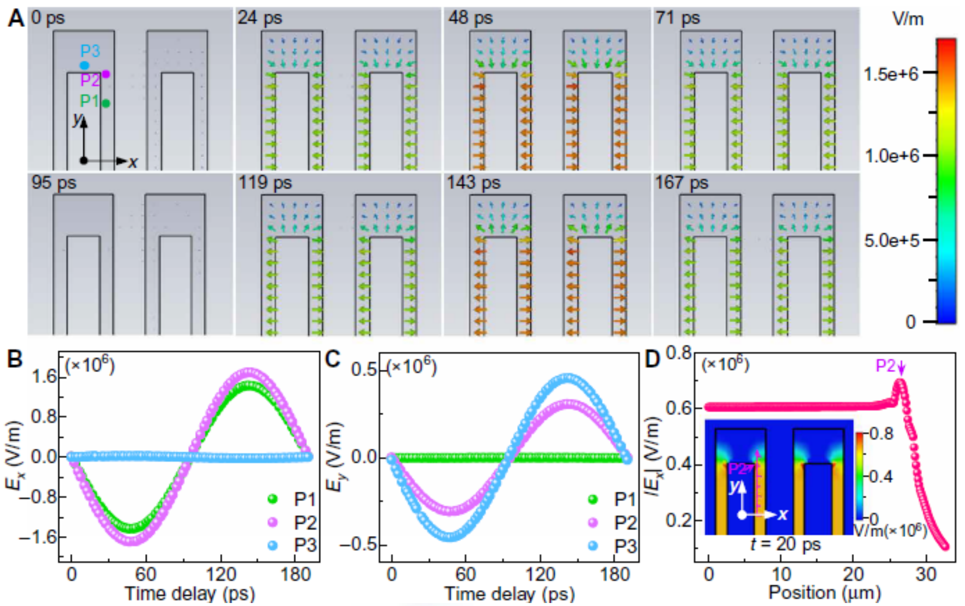


$W = B -$ [redacted]

https://doi.org/10.1063/1.5131758

Results replicated in the 200 keV microscope





Modeled behavior of electric fields in agreement with observations

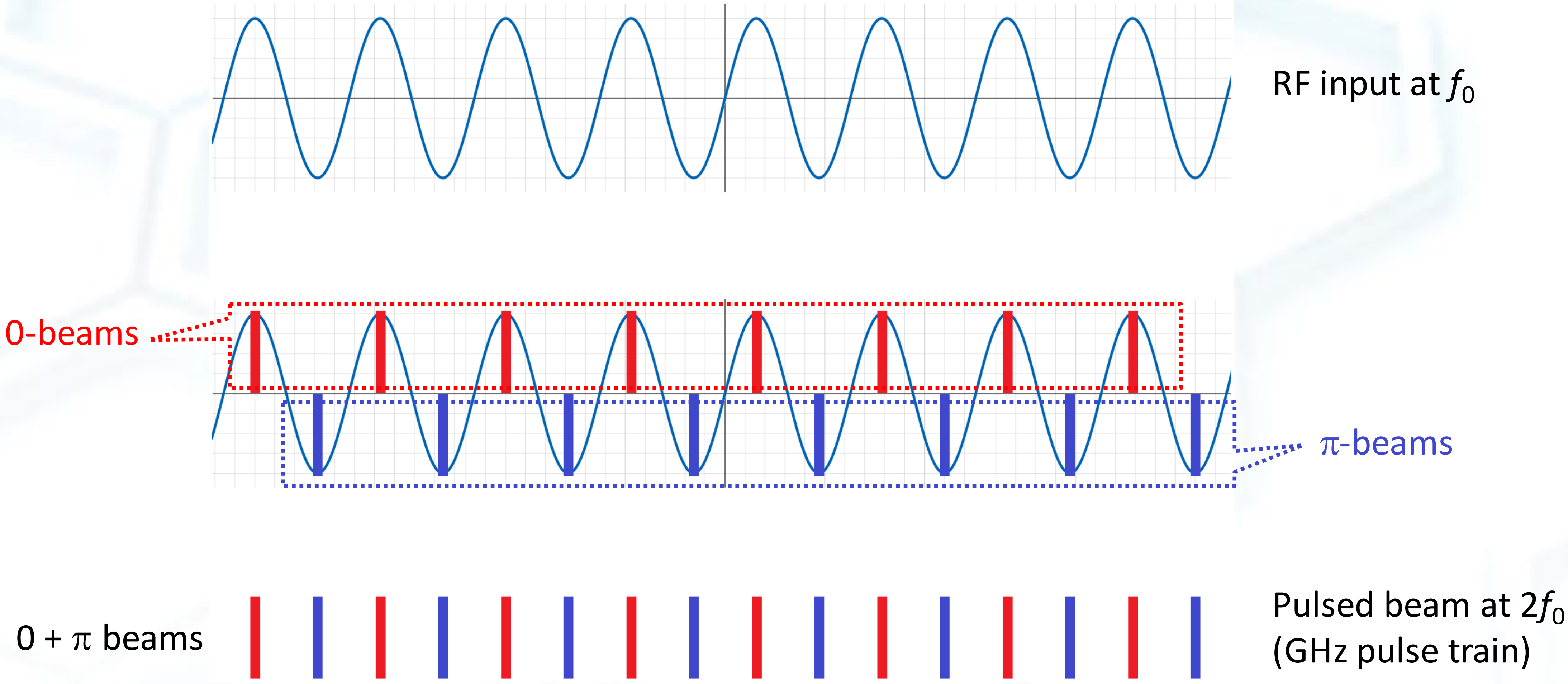
https://www.science.org/doi/10.1126/sciadv.abc3456

Basic Operation 40 MHz – 12 GHz

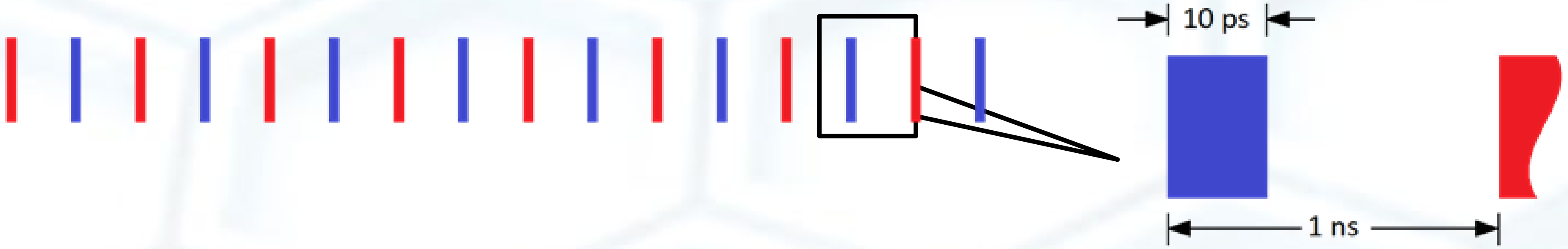
Range extender: 1 Hz – 25 MHz

(with present configuration)

General thinking on pulse trains

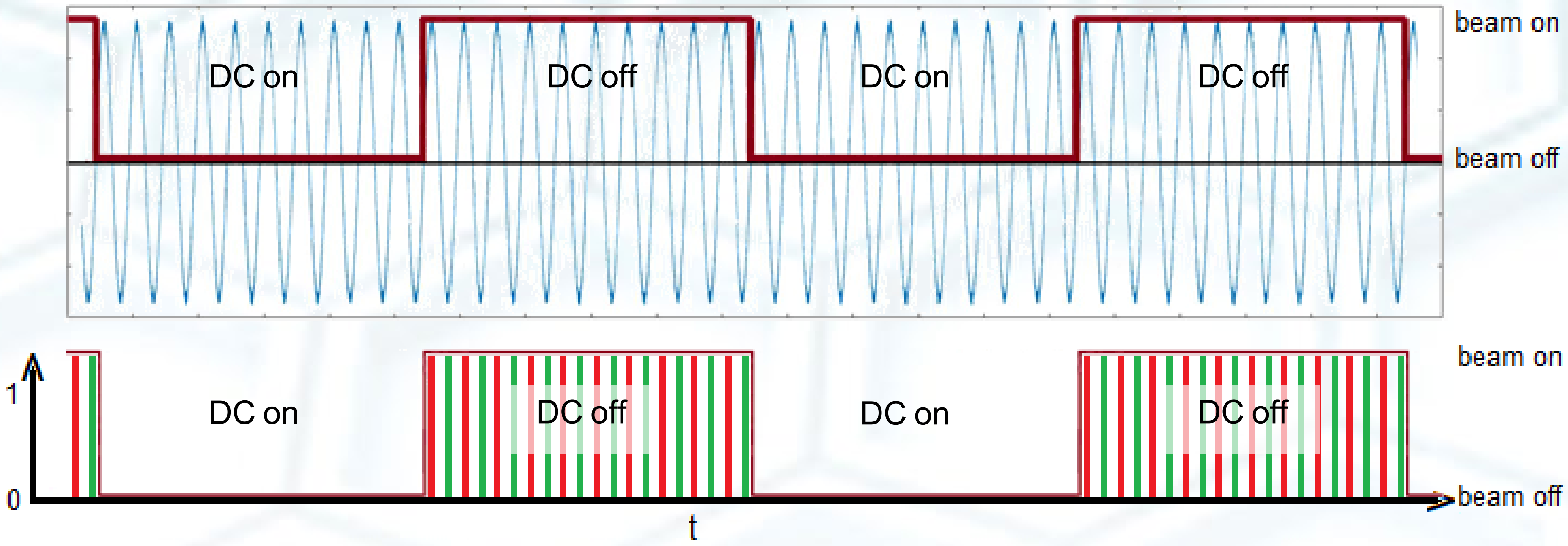


We don’t always want GHz pulse trains



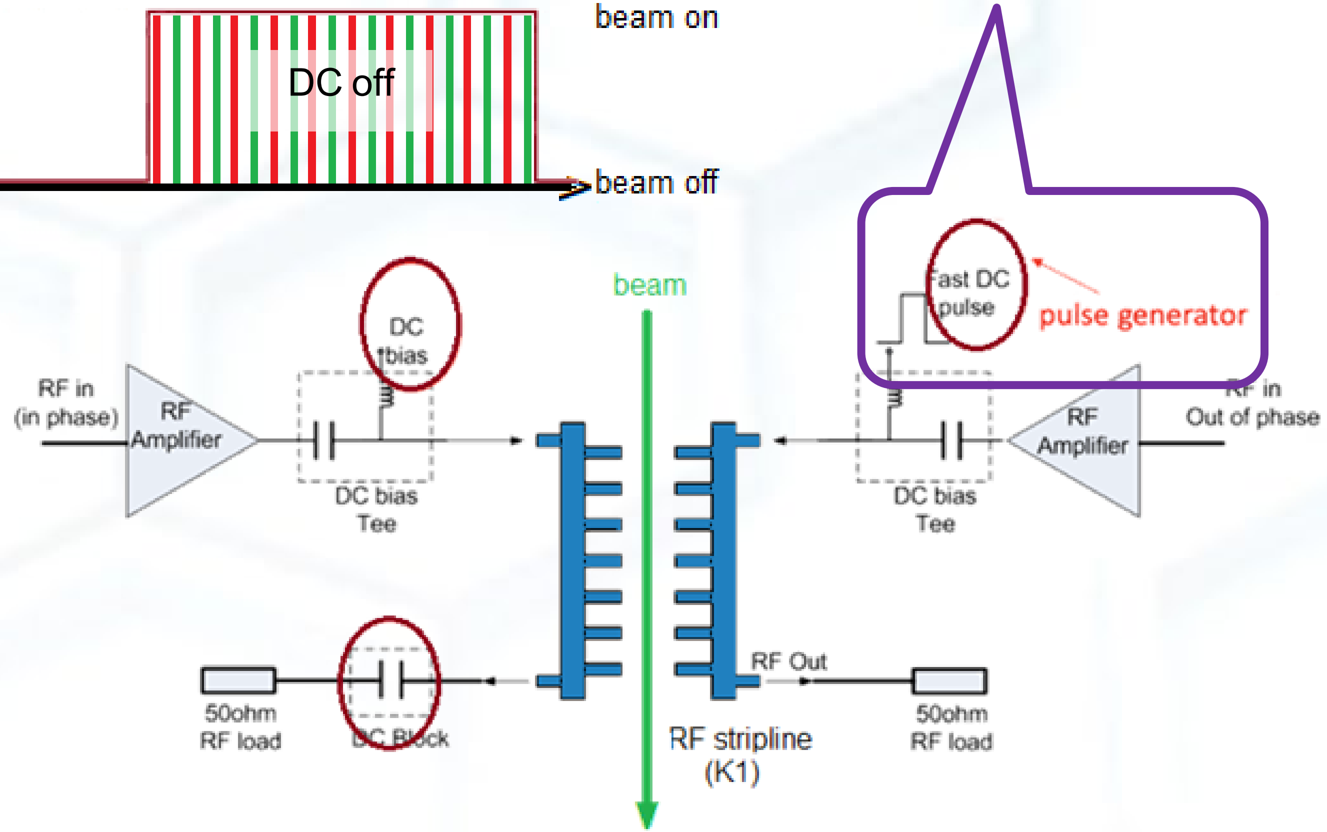
- What if you had a 1 MHz process, and needed 10 ps resolution?

- What if you had a 1 kHz process, but needed only 10 ns resolution?



DC pulse generator:
You get what you pay for

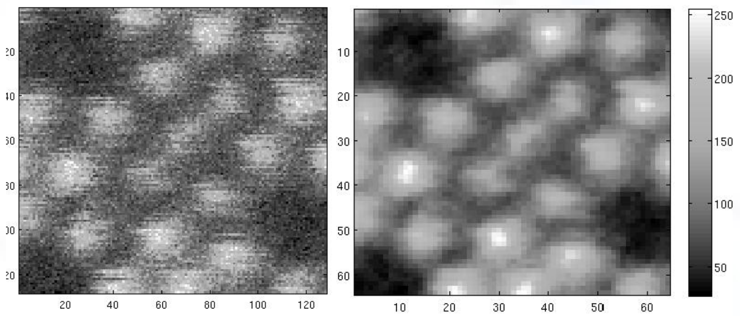
Arbitrary pulse(s) selection



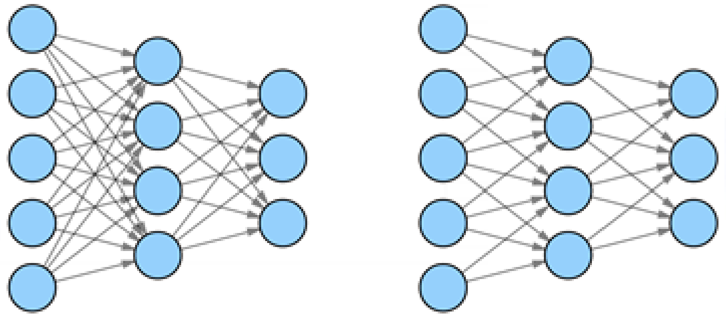
Limitations

- Temporal profile depends on your function generator
- To pick-off a single pulse, rise and fall time of the function generator matters a lot ($$$).
- Range extension means even less signal will reach detector(s)

Mitigation



- Compressive sensing



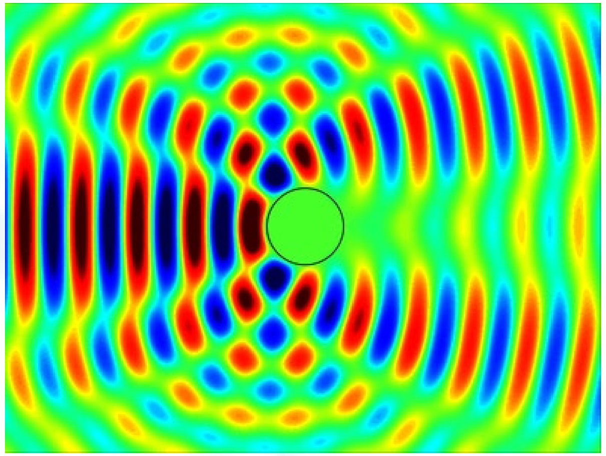
- Machine Learning

- KHz frame-rate cameras

GHz and high rep-rate science

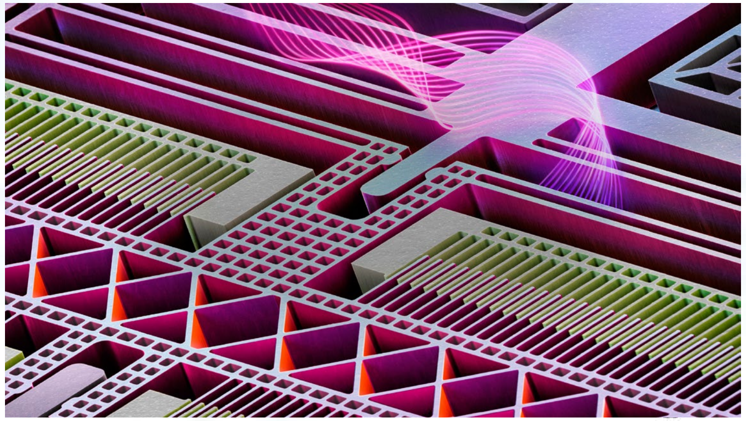
- Cyclical, repeatable phenomena
- Waves
  - Electromagnetic
  - Spin
  - Acoustic
- Resonant systems
  - Fundamental
  - Harmonics
  - Non-harmonic overtones

KHz



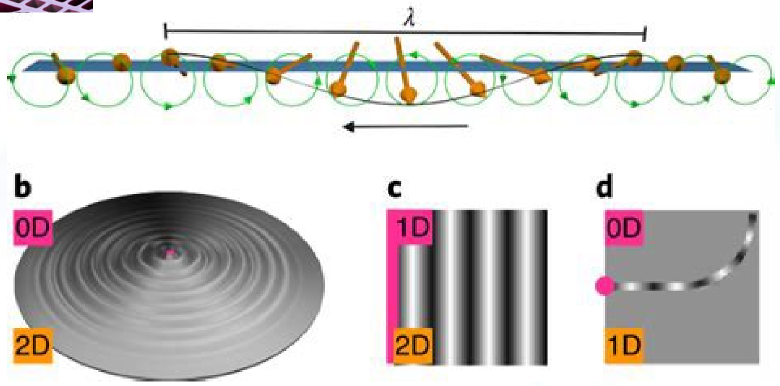
Acoustic metamaterials (source: comsol.com)

MHz



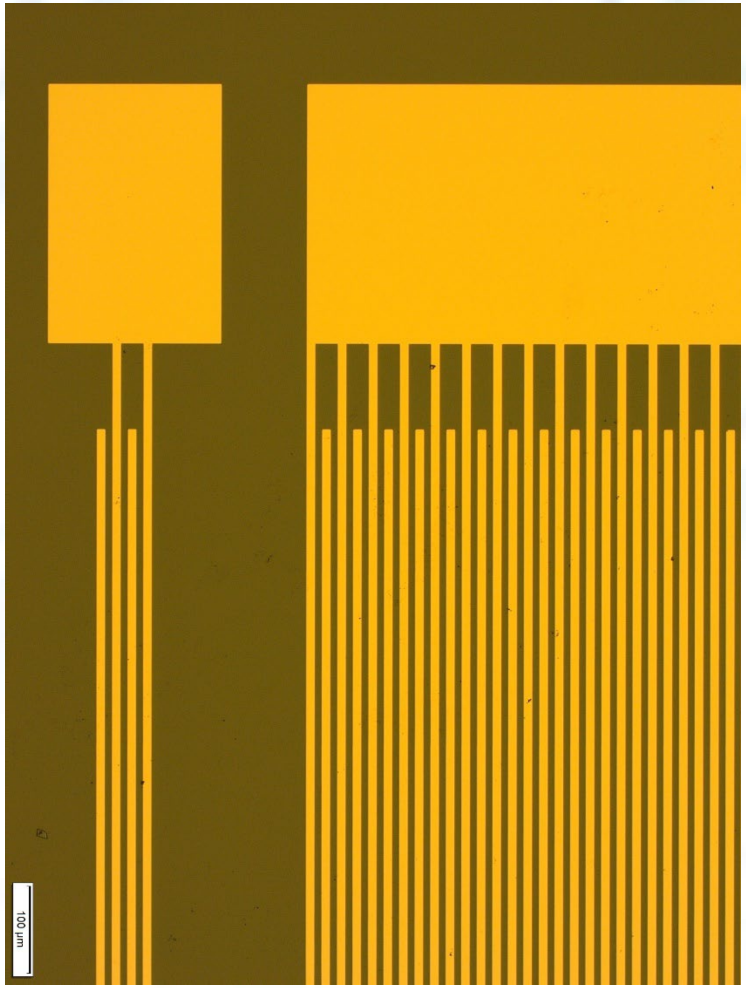
MEMS resonators (source:bosch.com)

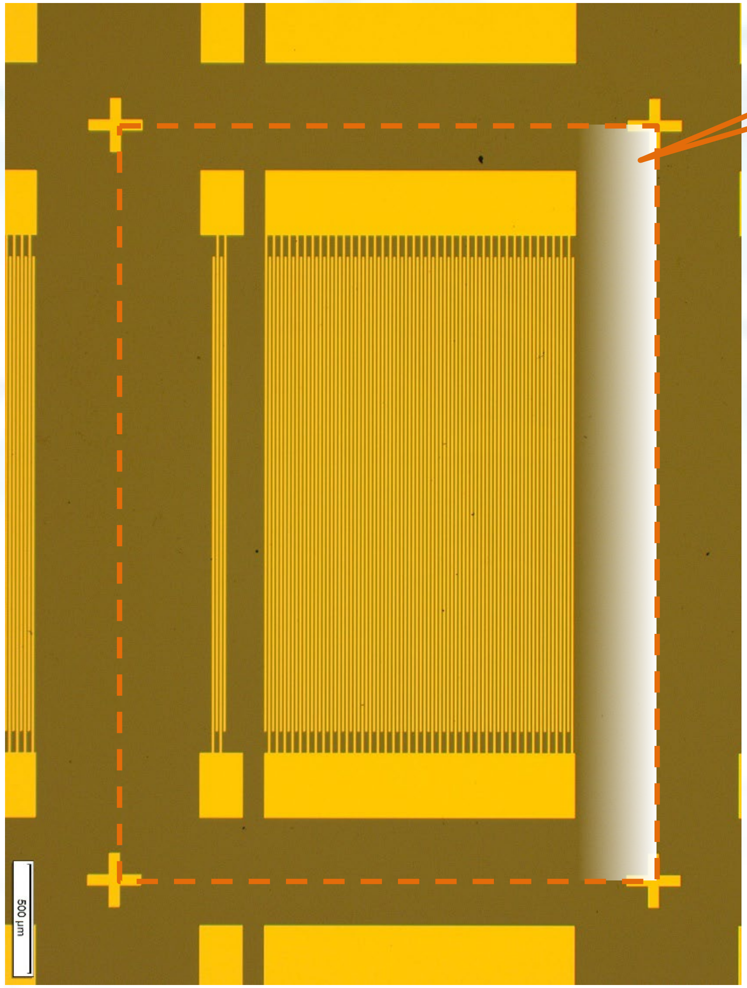
GHz



Spin waves (source: nature.com)

SAW in $LiNbO_3$





- Electron transparent area
- High-angle wedge polish + FIB

IDT properties:

- Resonance at 100 MHz
- Wavelength = 36 mm
- Finger width = 9 mm
- Finger spacing = 9 mm

Harmonics and non-harmonic overtones expected

How does sample thickness affect SAW?

Charge transport by SAW?

Research opportunities

Stroboscopic TEM: https://bit.ly/3zO7s9U

Machine learning with facility-scale data: https://bit.ly/39KVseG

Thank you!

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