Waferscale Accelerators for High Energy Ions and Electrons

Amit Lal
School of Electrical and Computer Engineering
Cornell University

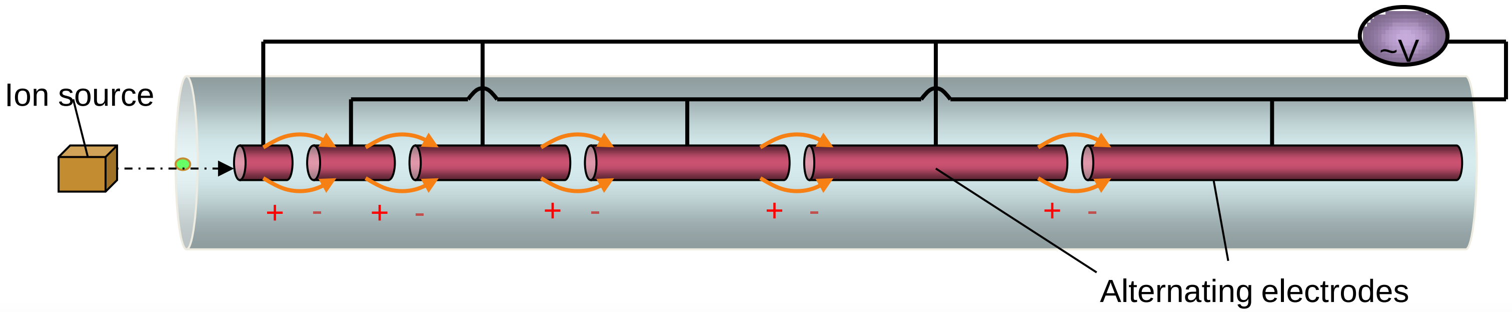
10/20/2013
ARPA-E Workshop on Fusion Drivers
Berkeley, CA

Outline

- <u>**Electric fields for Ion Manipulation**</u>
- **Fabrication process flow for wafer-scale accelerators**
- **Einzel Lens, LINAC**
- **CMOS Electronic Detection**
- **Conclusions**

To Target KeV - MeV Energy…

Linear Accelerator



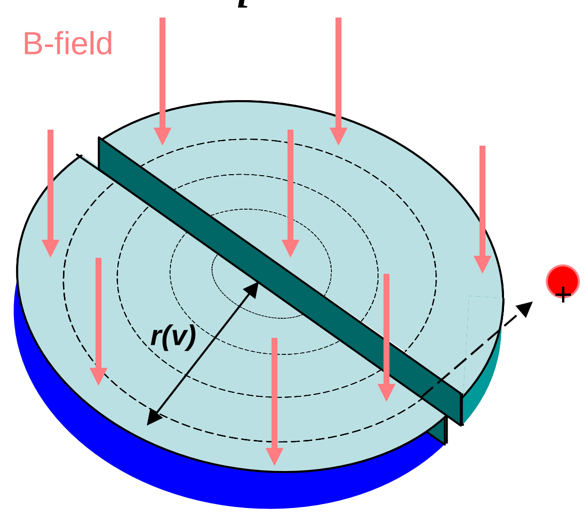
Cyclotron

$$q \cdot \vec{v} \times \vec{B}$$

- Magnetic field confine ions in circular path :

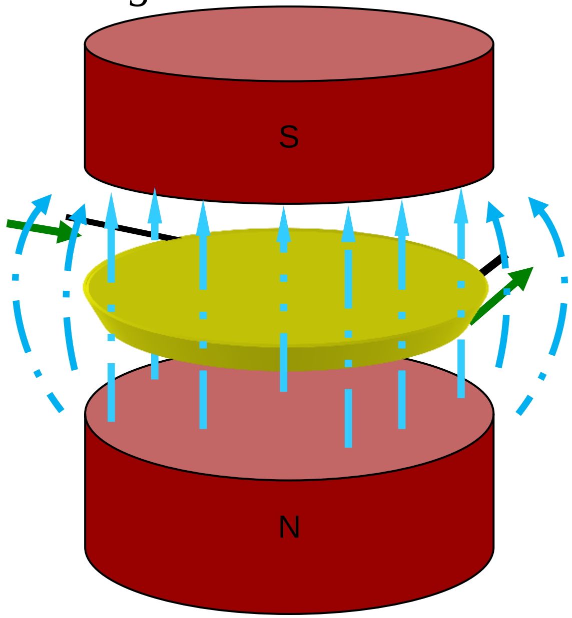
$$r = \frac{mv}{Bq} = \frac{v}{\omega_{cycl}}$$

- Ion is accelerated at gap between the "dees".
- Radius of cyclotron depends on final energy only
- Trade-off between B-field strength and cyclotron size

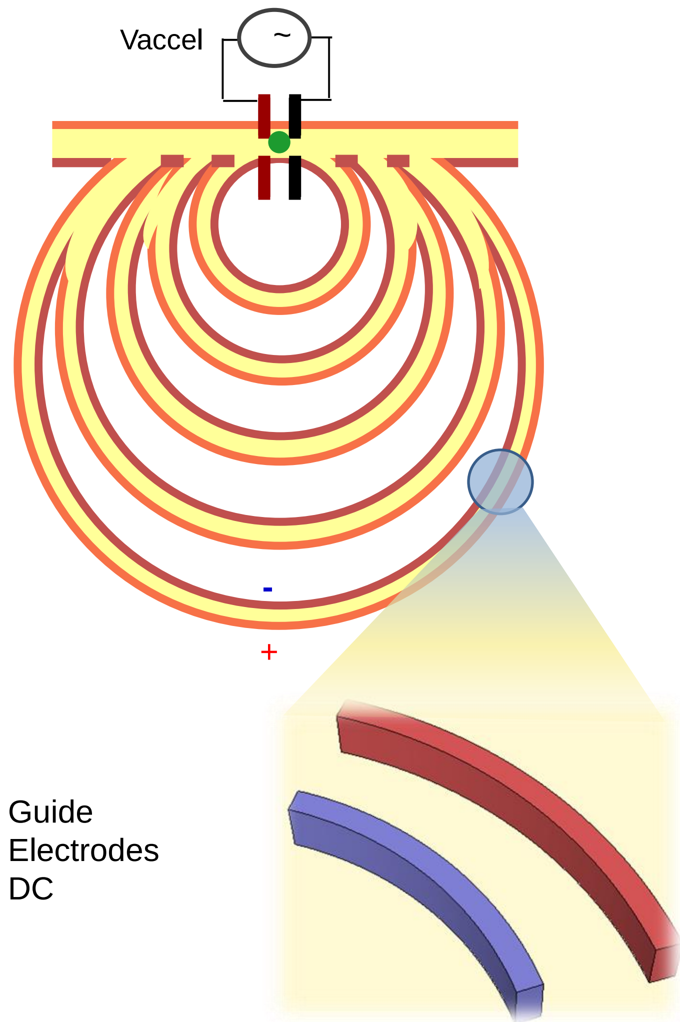


To Target KeV - MeV Energy…

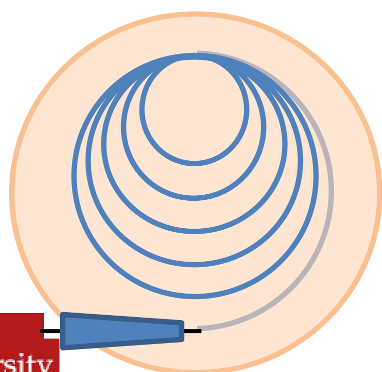
$$\vec{F}_{magnetic} = q \cdot \vec{v} \times \vec{B}$$



$$\vec{F}_{electric} = q \cdot \vec{E}$$



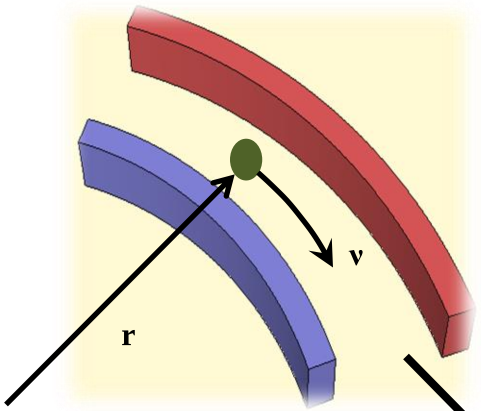
Microtron

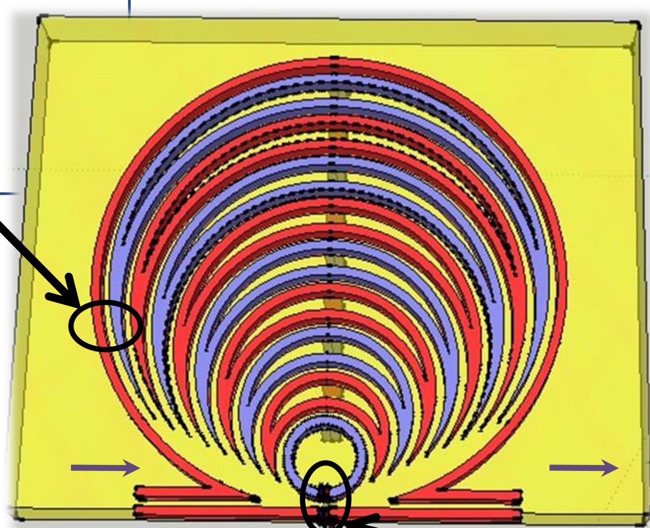


Guide
Electrodes
DC

THE GOAL

Guide Electrodes



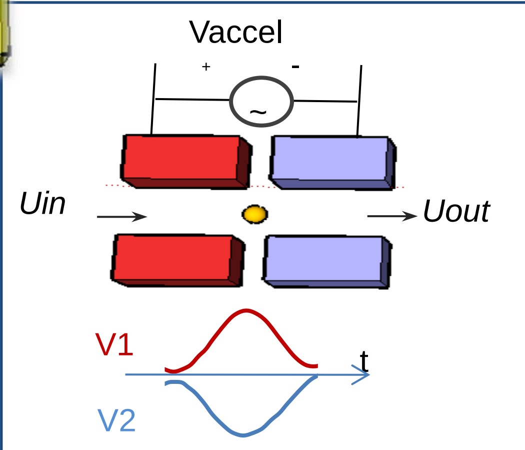


Ion Guidance

$$\vec{F}_{guide} = \vec{F}_{centripetal}$$

$$qE_{field} = \frac{mv^2}{r}$$

Ion Accelerator

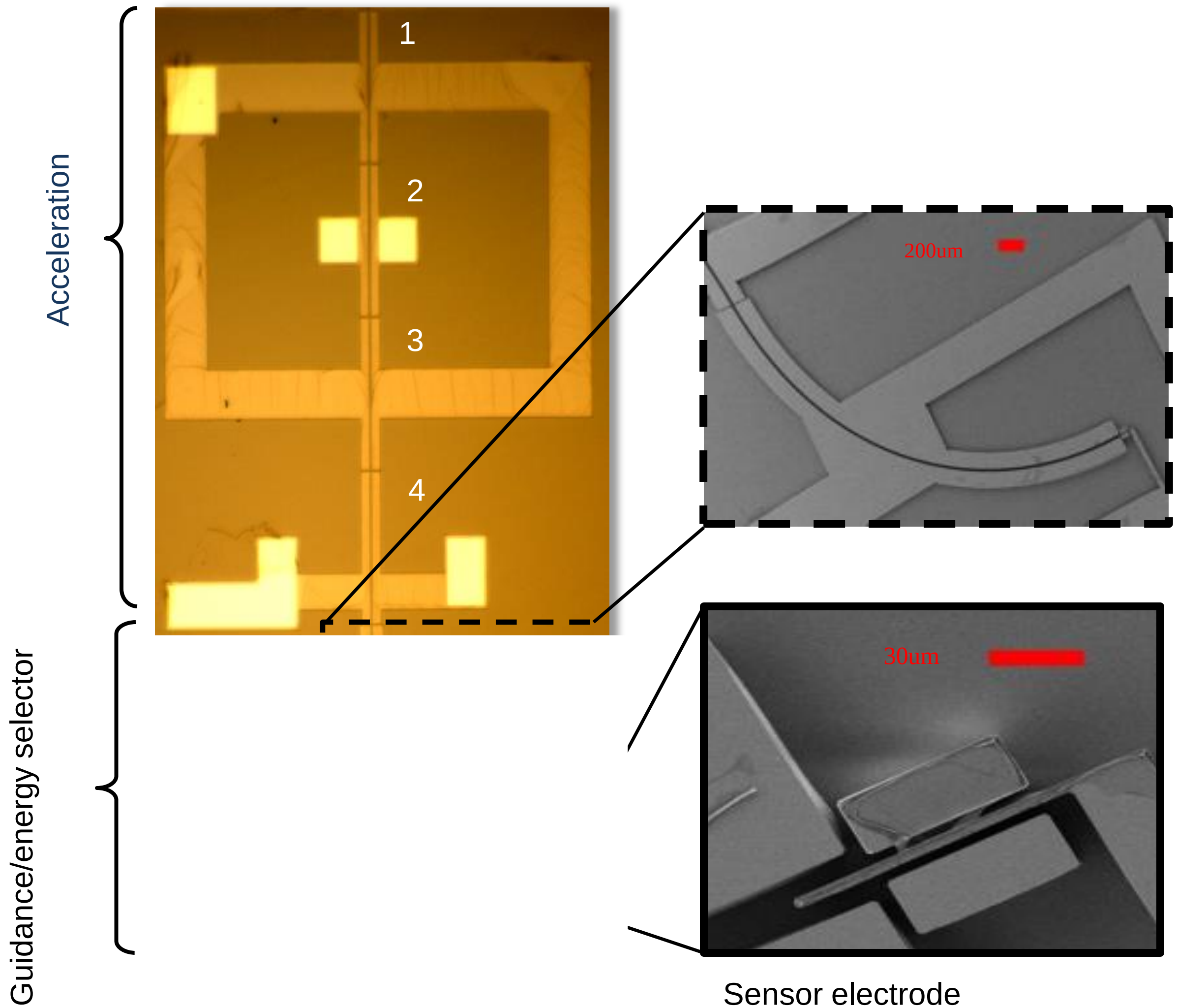


ION ACCELERATION

Driven at 35MHz

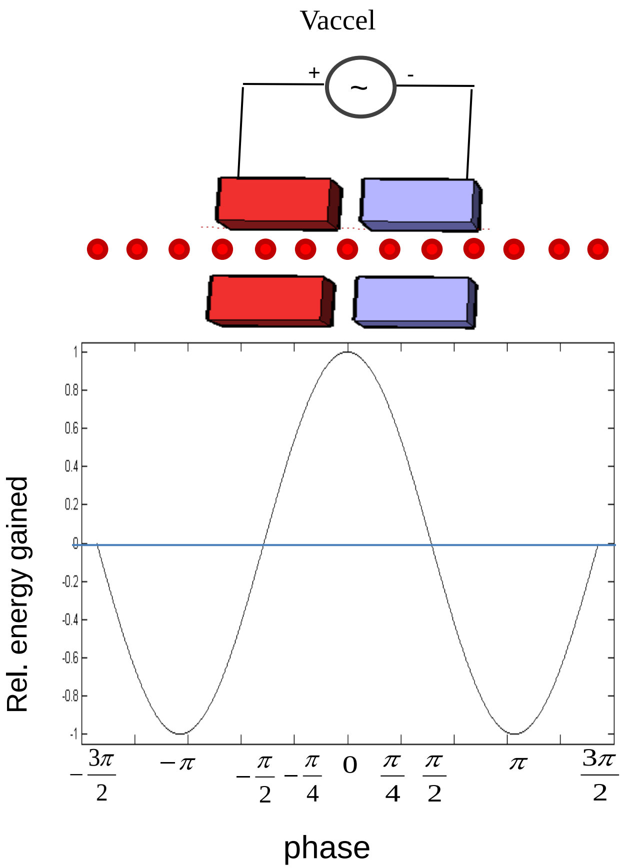
Gap gain:20eV

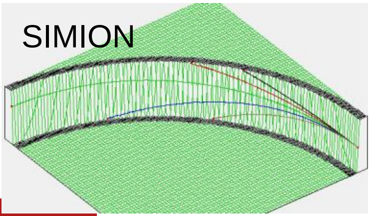
Total gain: 60eV

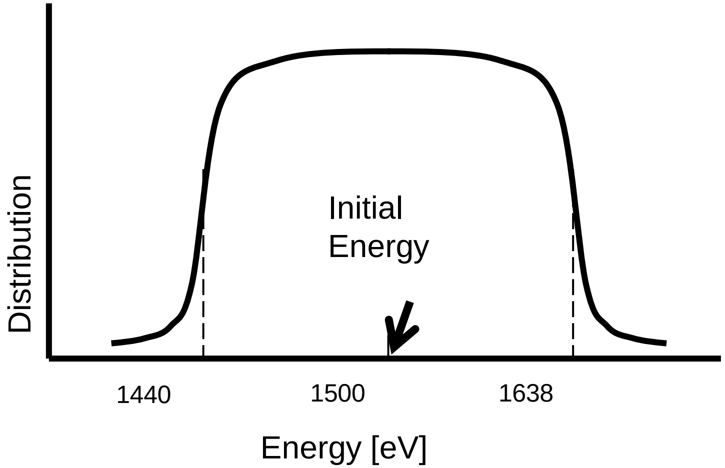


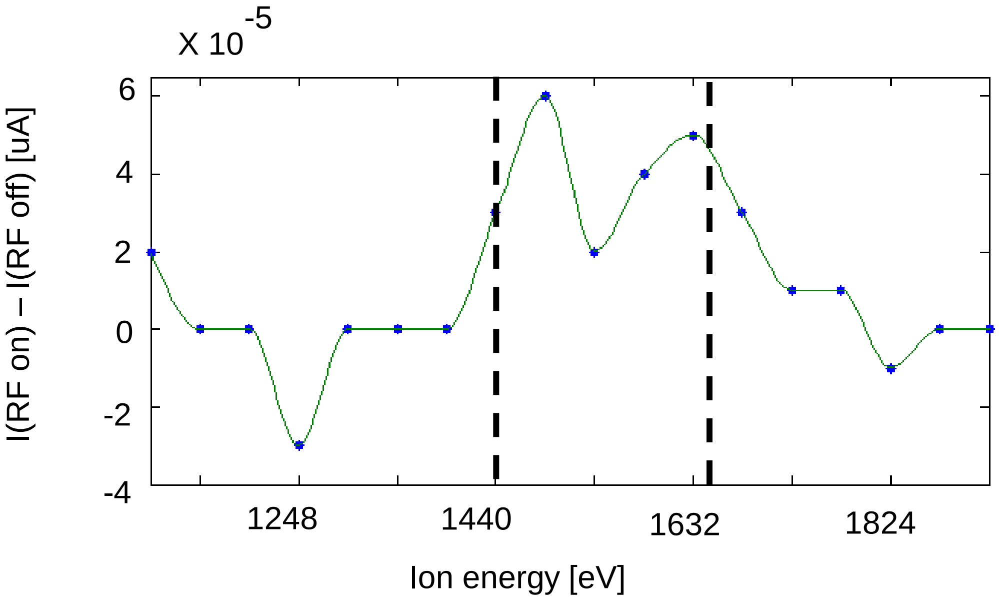
Cornell University

ION ACCELERATION





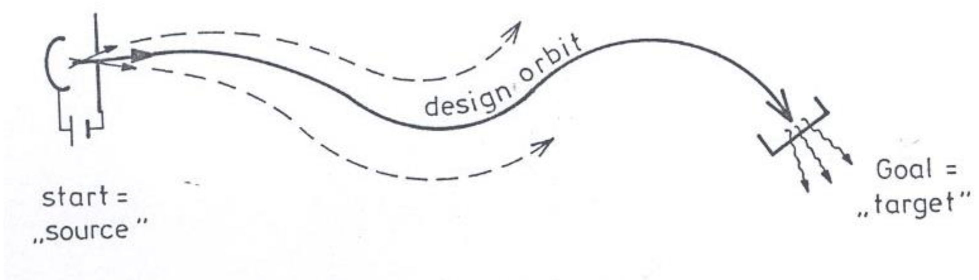




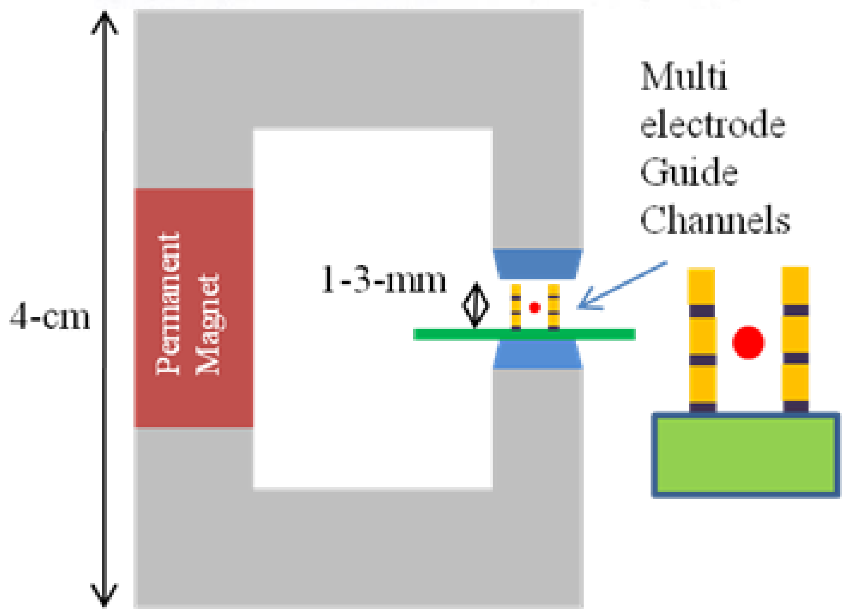
Outline

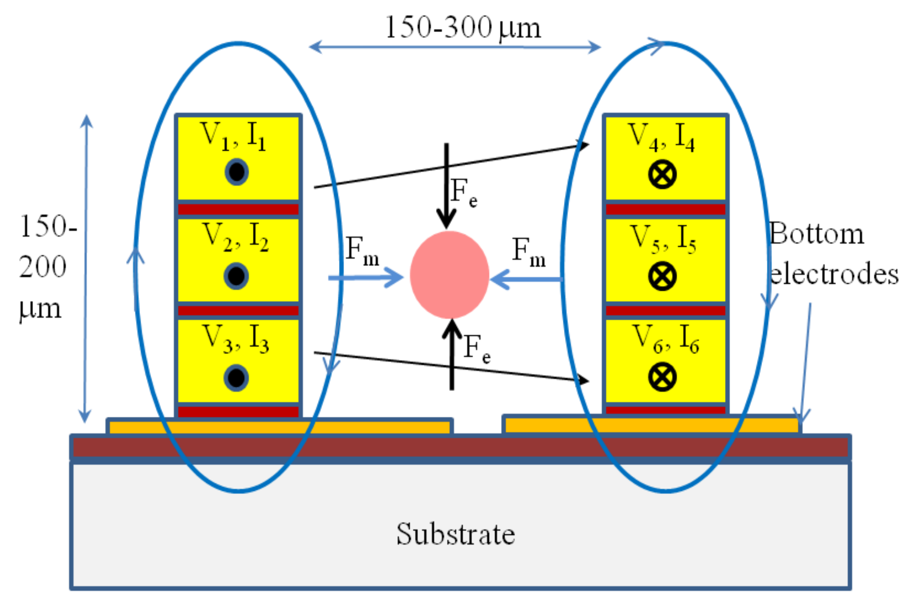
- **Electric fields for Ion Manipulation**
- **Fabrication process flow for wafer-scale accelerators**
- **Einzel Lens, LINAC**
- **CMOS Electronic Detection**
- **Conclusions**

Multi Electrode Planar Accelerators



$$\mathbf{F} = e\,(\,\mathbf{E} + \mathbf{v} \times \mathbf{B})$$





1. Permanent magnets for bulk of control force
2. Micro-structured electrodes for fine tuning and motion control

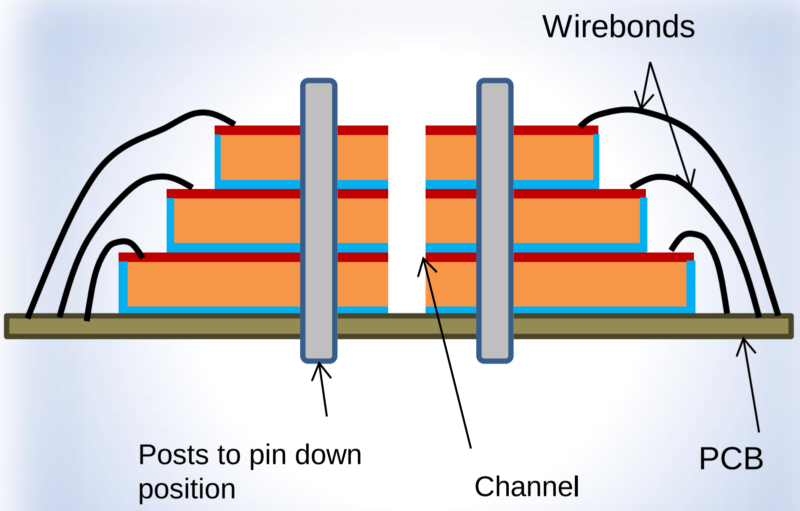
Cornell University

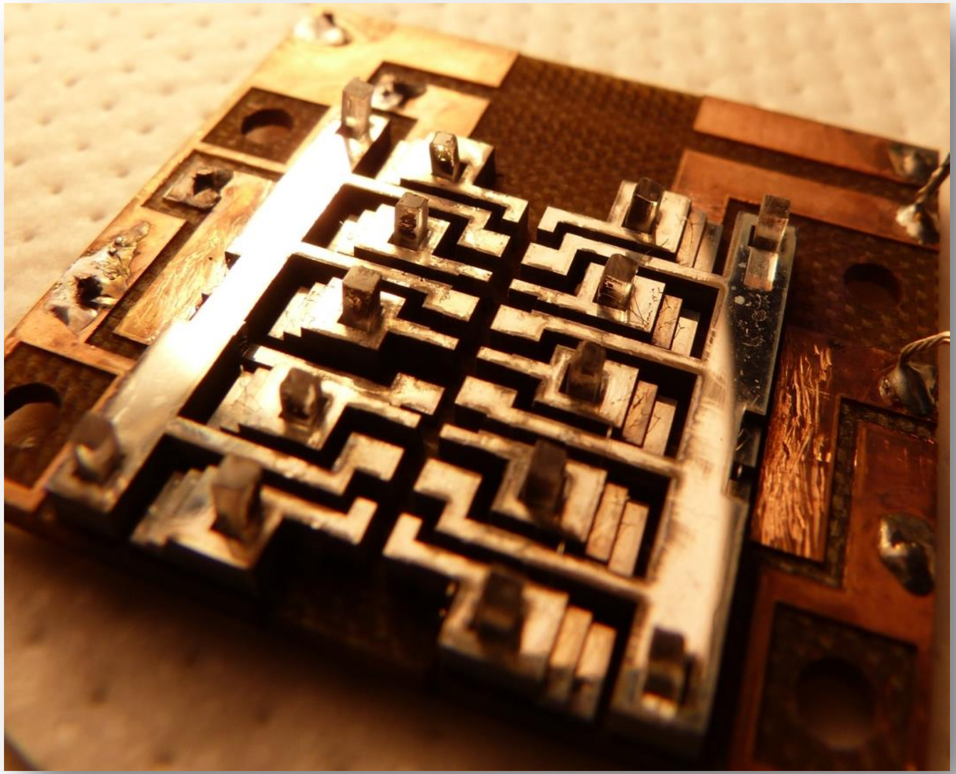
Assembly

5) Posts glued through layers to pin them down.

6) Tethers on Si are cut so that each “pinned” piece is disconnected to others

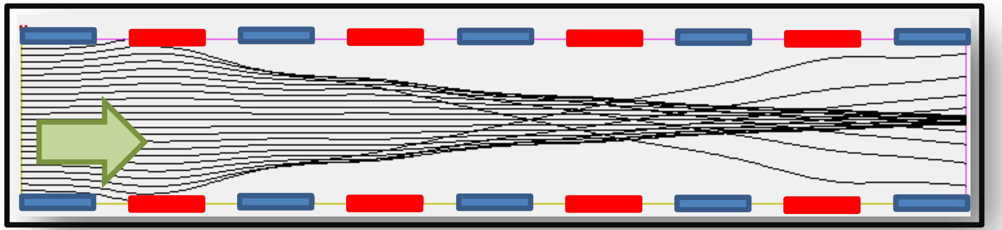
7) Wire bonds from Al on Si to Cu pads on PCB

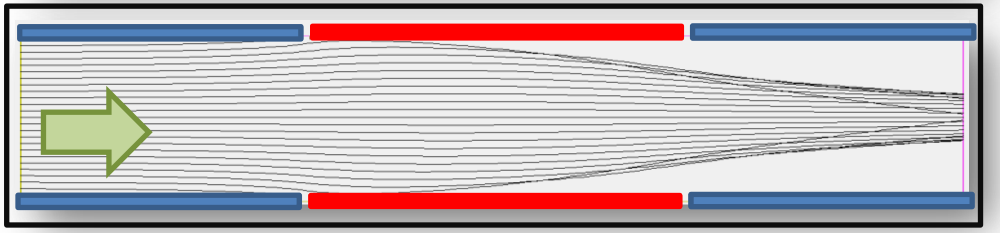


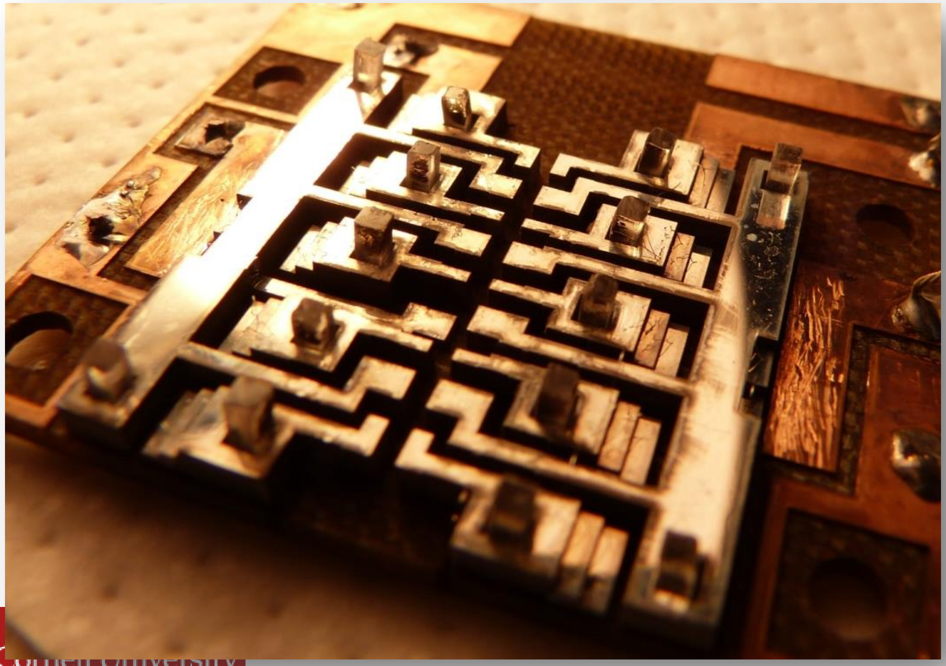


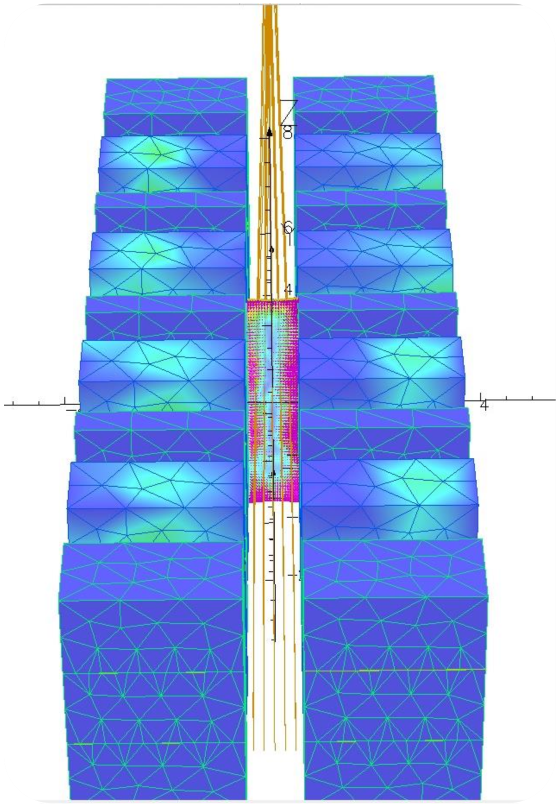
- Si dust accumulate on bottom of channels to form electrical short.
- Careful cleaning with water solved issue

Consecutive Series of Einzel Lens



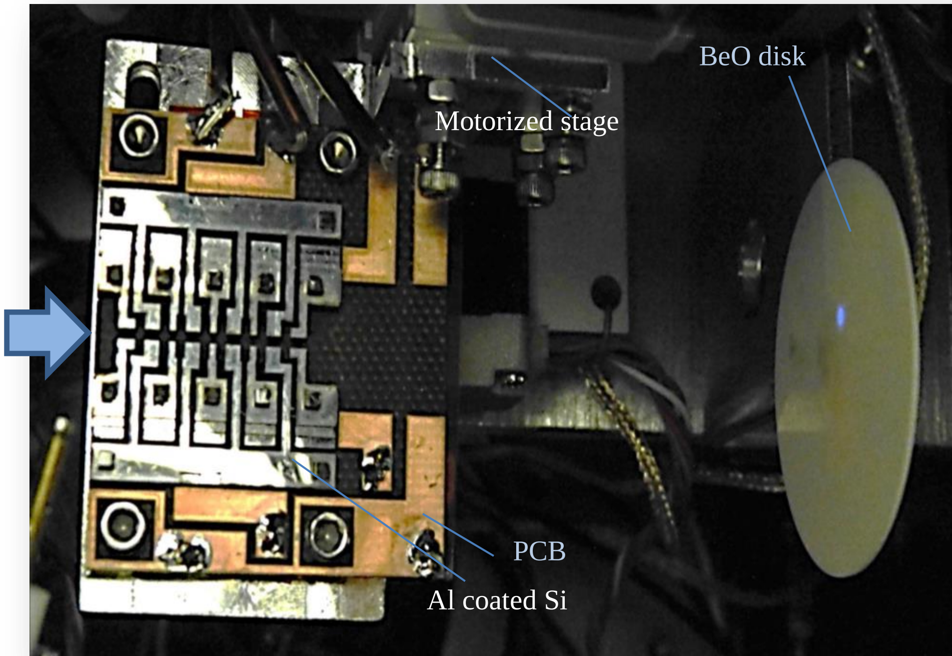


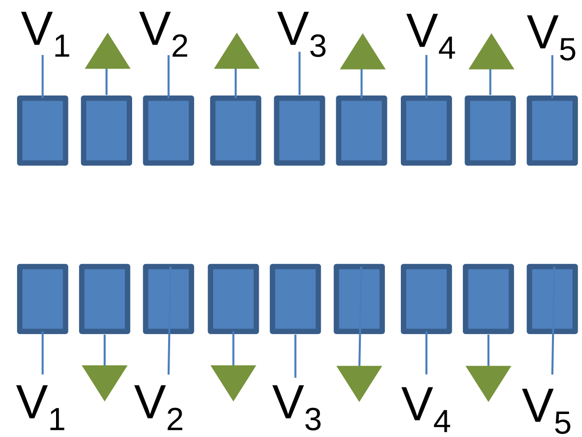


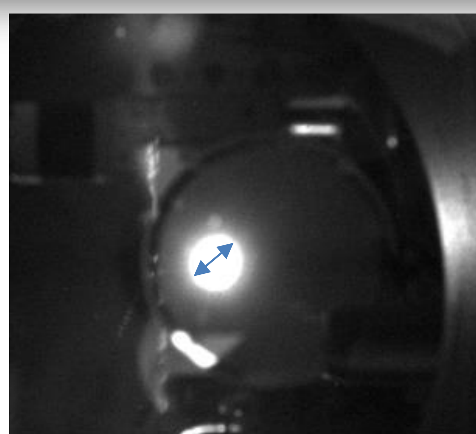


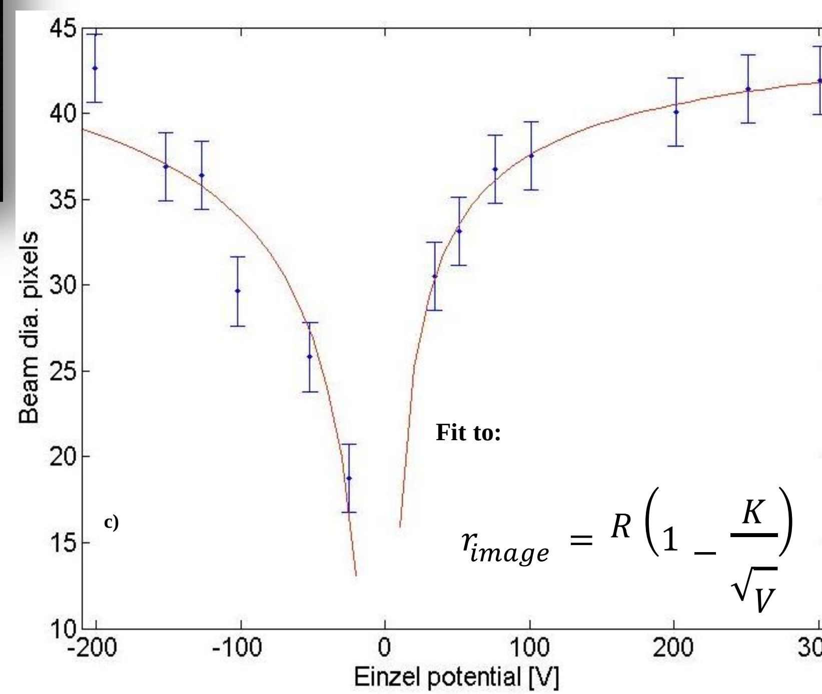
OPERA (June)

Experimental Operation of Einzel Lens

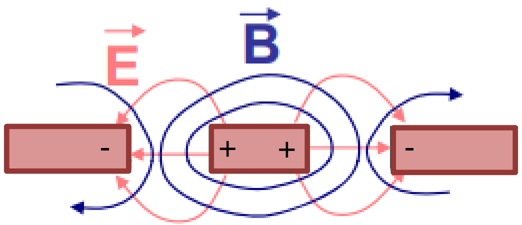


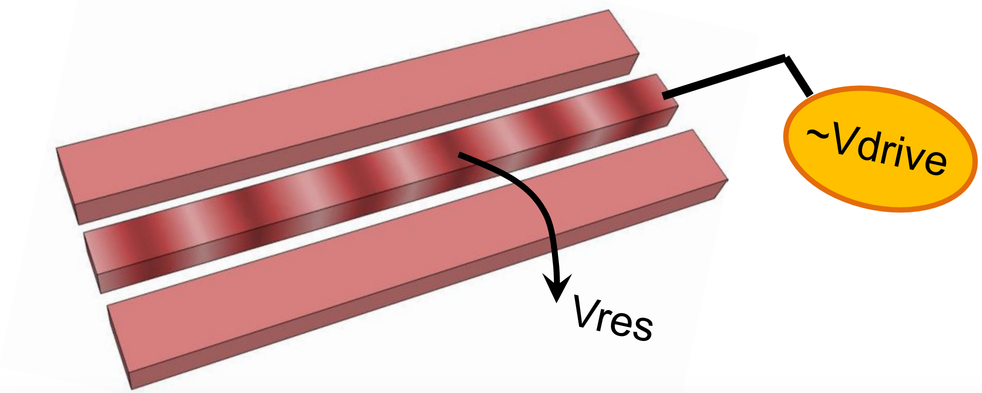






Coplanar Waveguide Resonator Accelerator

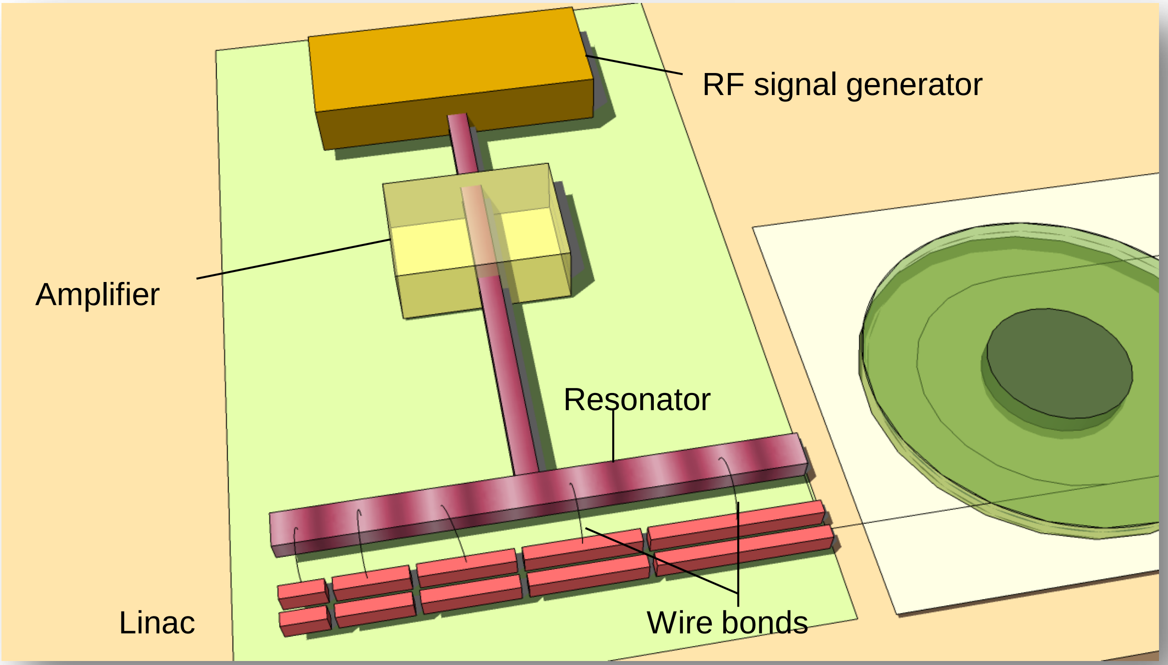




Use CPW resonator to drive LINAC segments…

- RF gen. power = 50W
- V_{drive} =10V (for 1000Ω)

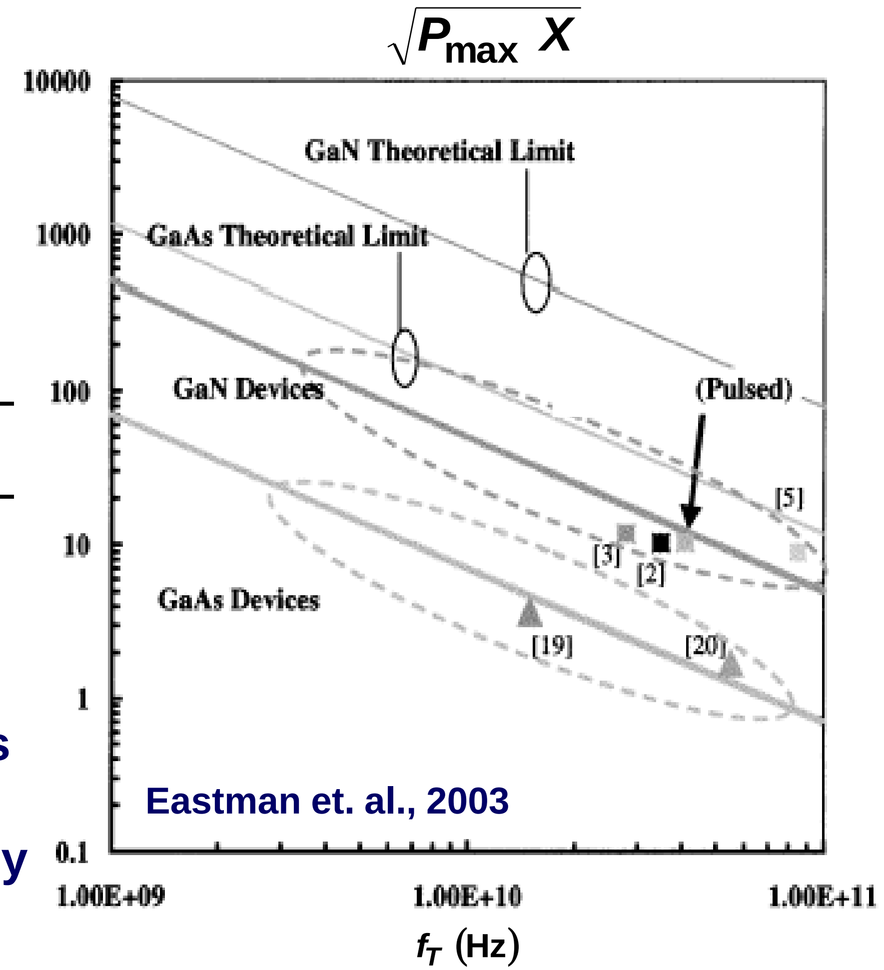
- Q can be high ~ 500
- V_a ~ 100kV



Wide Bandgap Semiconductors

$$P_{max} = I_{max} V_{max} = \left(\frac{E_{max} v_{sat}}{2\pi} \right)^2 \frac{1}{X} \left(\frac{1}{f_T^2} \right)$$

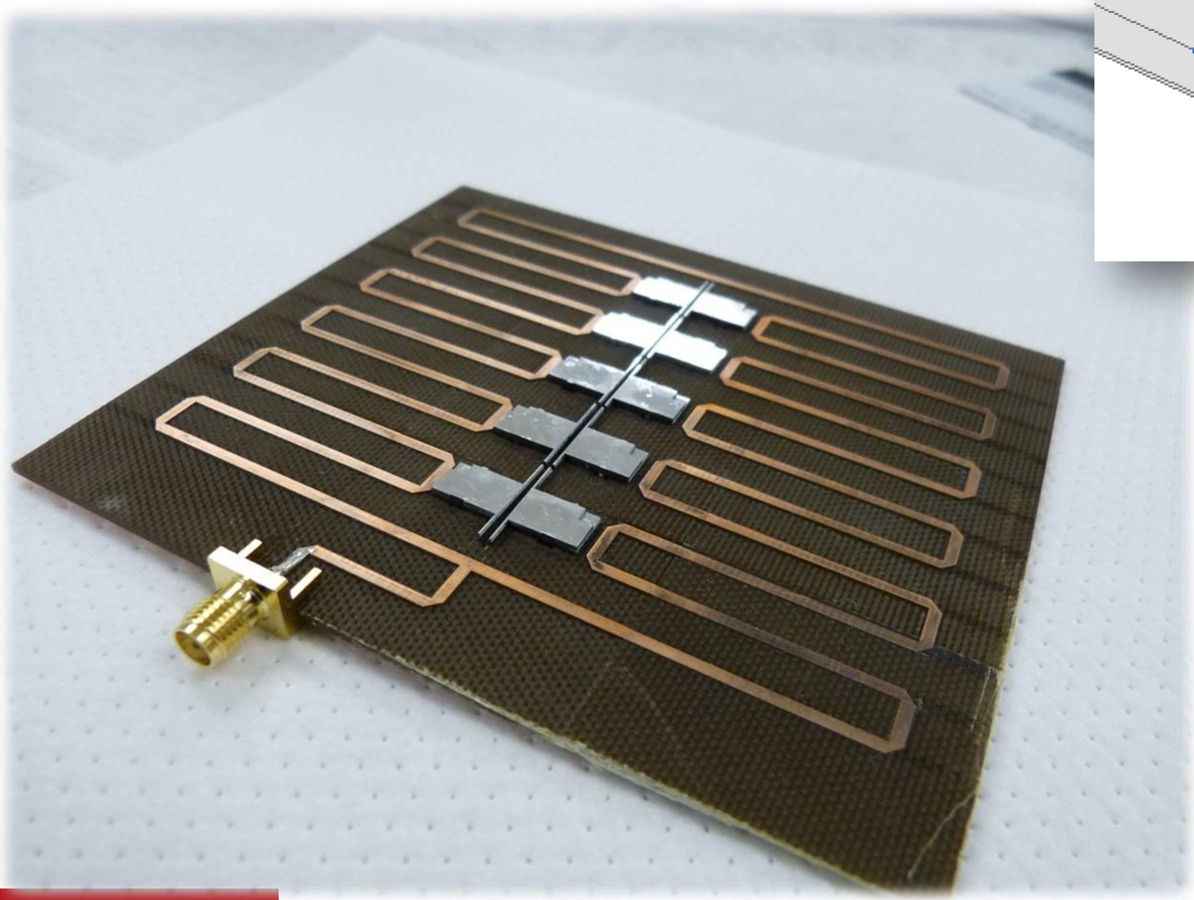
Material	E_g (eV)	E_{max} (MV/cm)	v_{sat} (cm/s)
GaAs	1.4	3.3	2×10^7
GaN	3.4	0.4	1.8×10^7

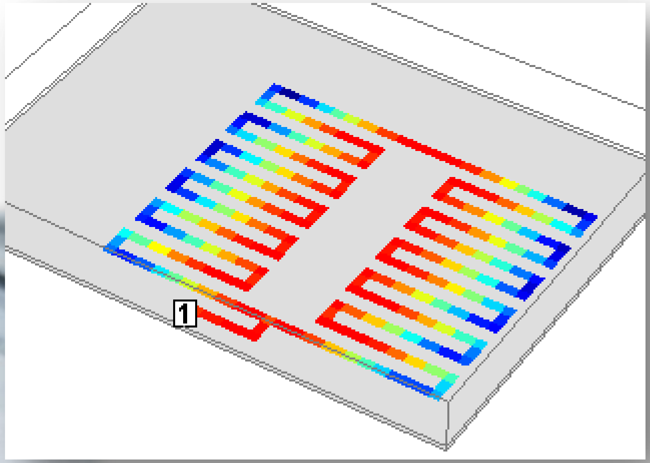


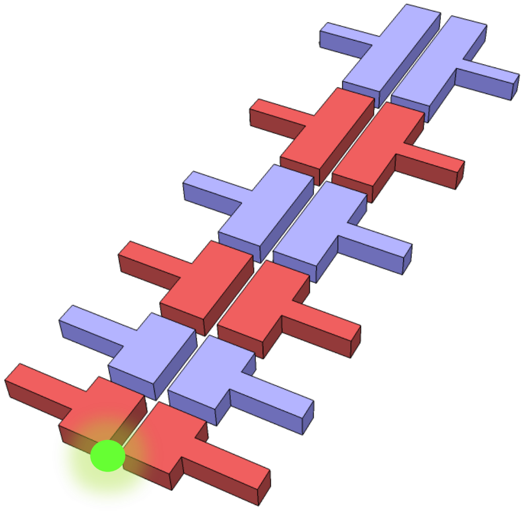
• Although, wide bandgap semiconductors can provide more power, device heating and parasitic elements limit high frequency performance

• Max power obtained at ~10 GHz is ~10 Watts/mm for GaN/AlGaN HEMTs ⇒ Less than 1 μW for a 10 μm wide device with f_T = 1 THz

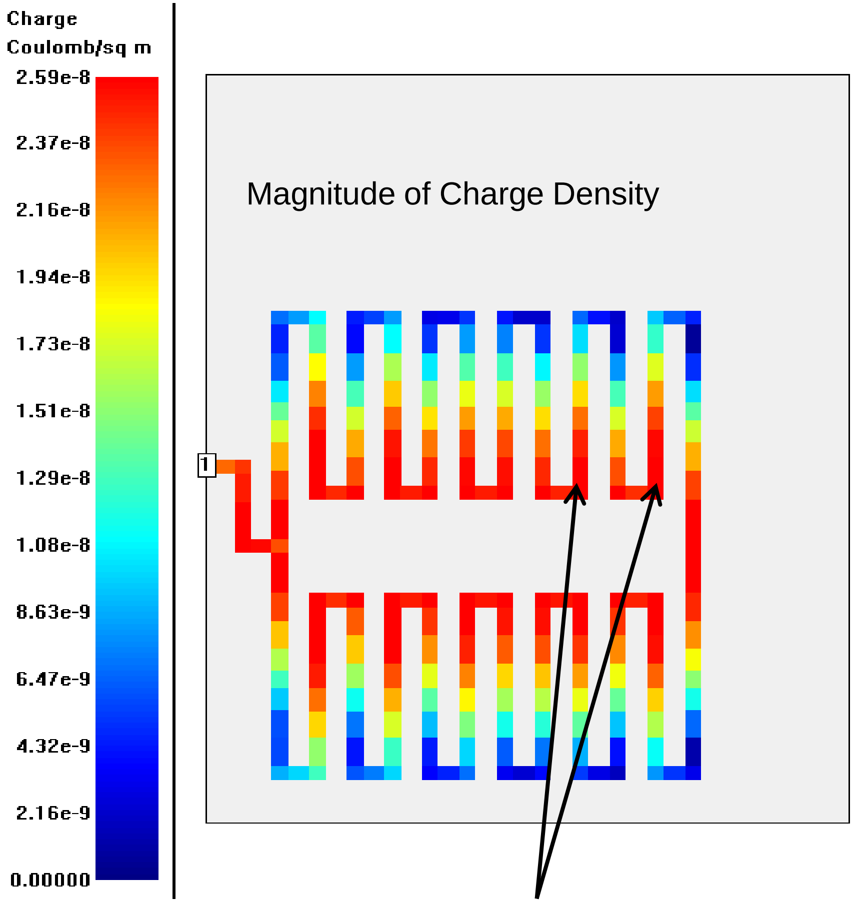
Design of Resonator Facilitated Linear Accelerator





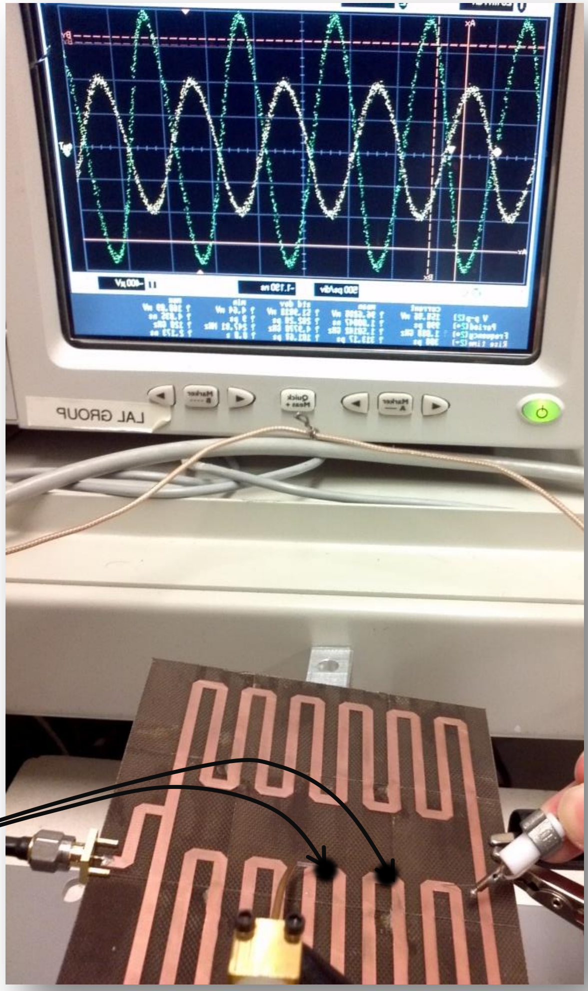


Measured Mode Shapes

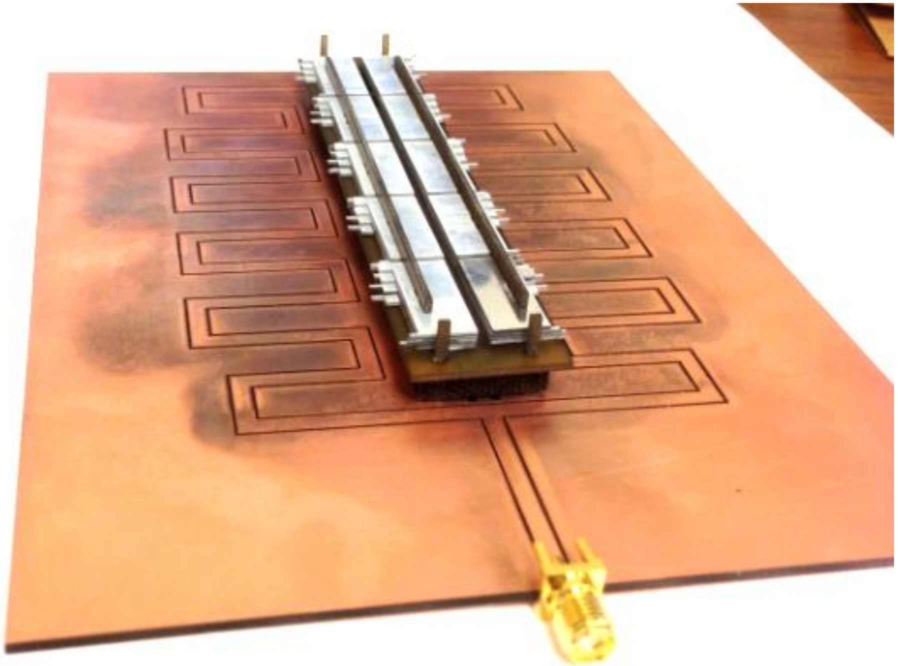


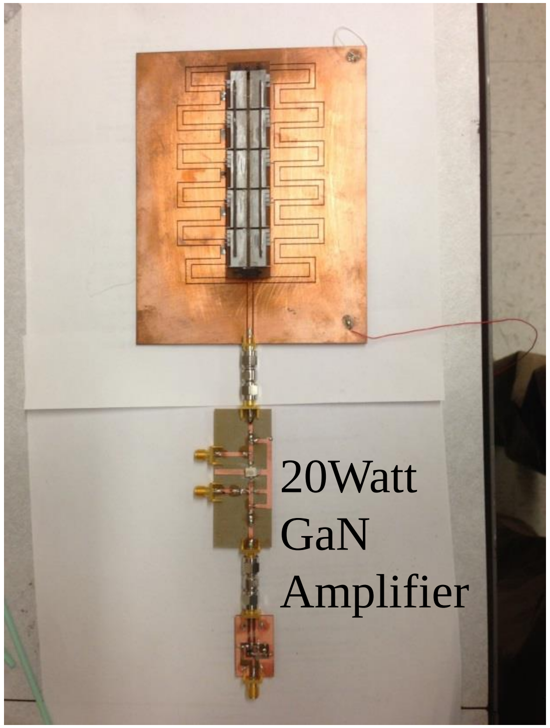
- Consecutive inner “fingers” π out of phase
- Exp. Confirmation of high inner finger p-p voltages

The phase of things…



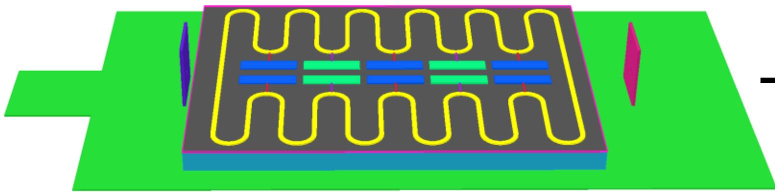
Raised LINAC + Driver + Oscillator

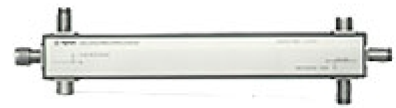




Linac Transmission Line Setup

Linac





Agilent Coupler
778D

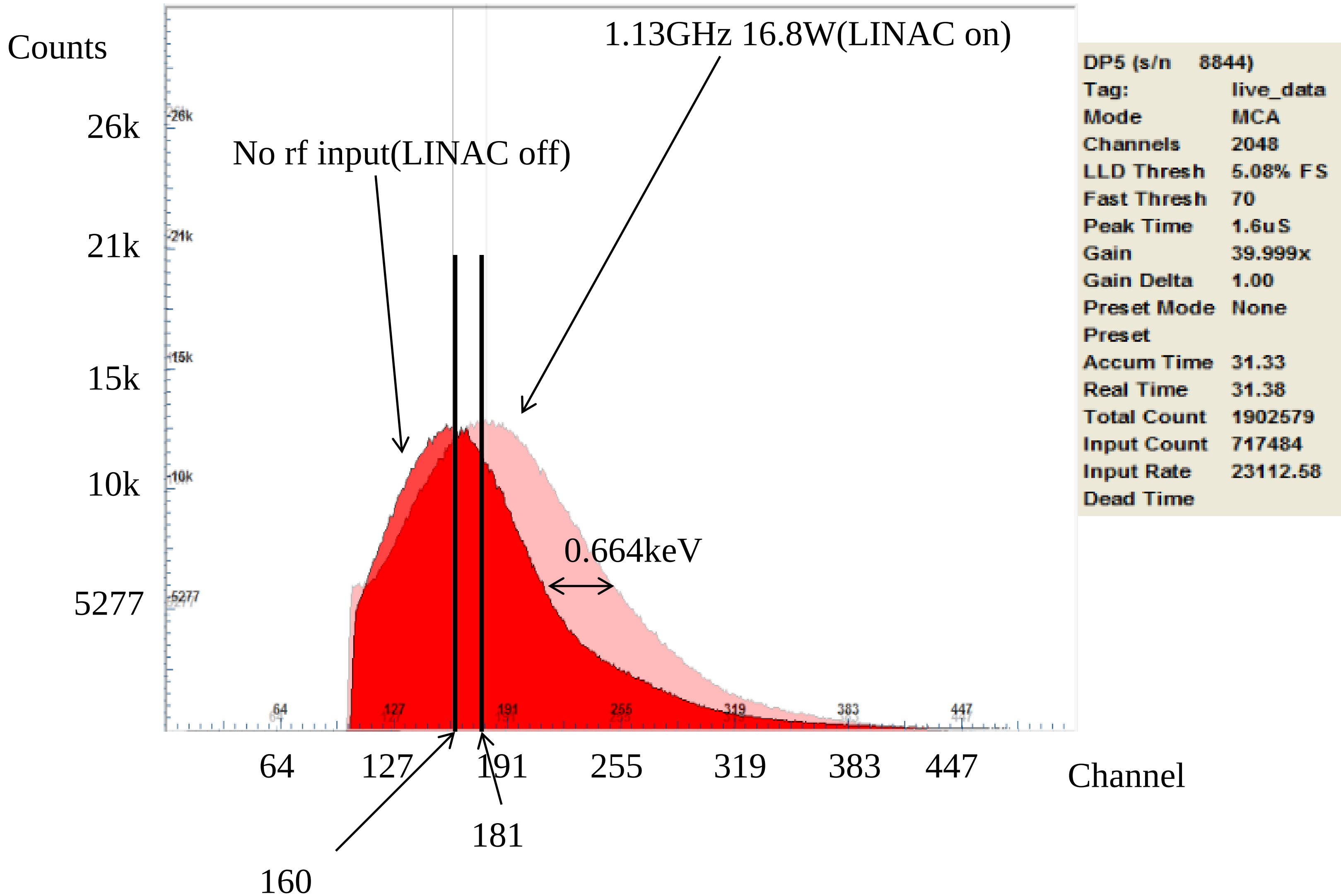
Ophir 5205

RF Power Amplifier
0.5~3.0 GHz 50Watts

Network Analyzer
Agilent 8753ES
30kHz – 6 GHz

Agilent N9310A
RF Signal Generator
9 kHz – 3.0 GHz

Amptek Detector(5keV LINAC)

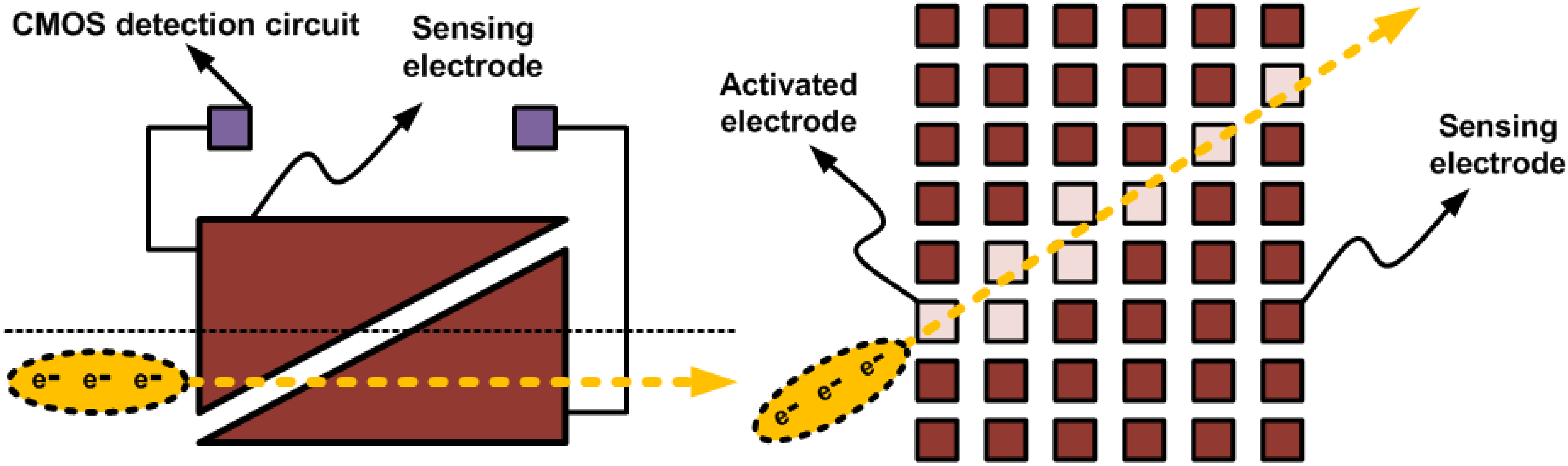


Outline

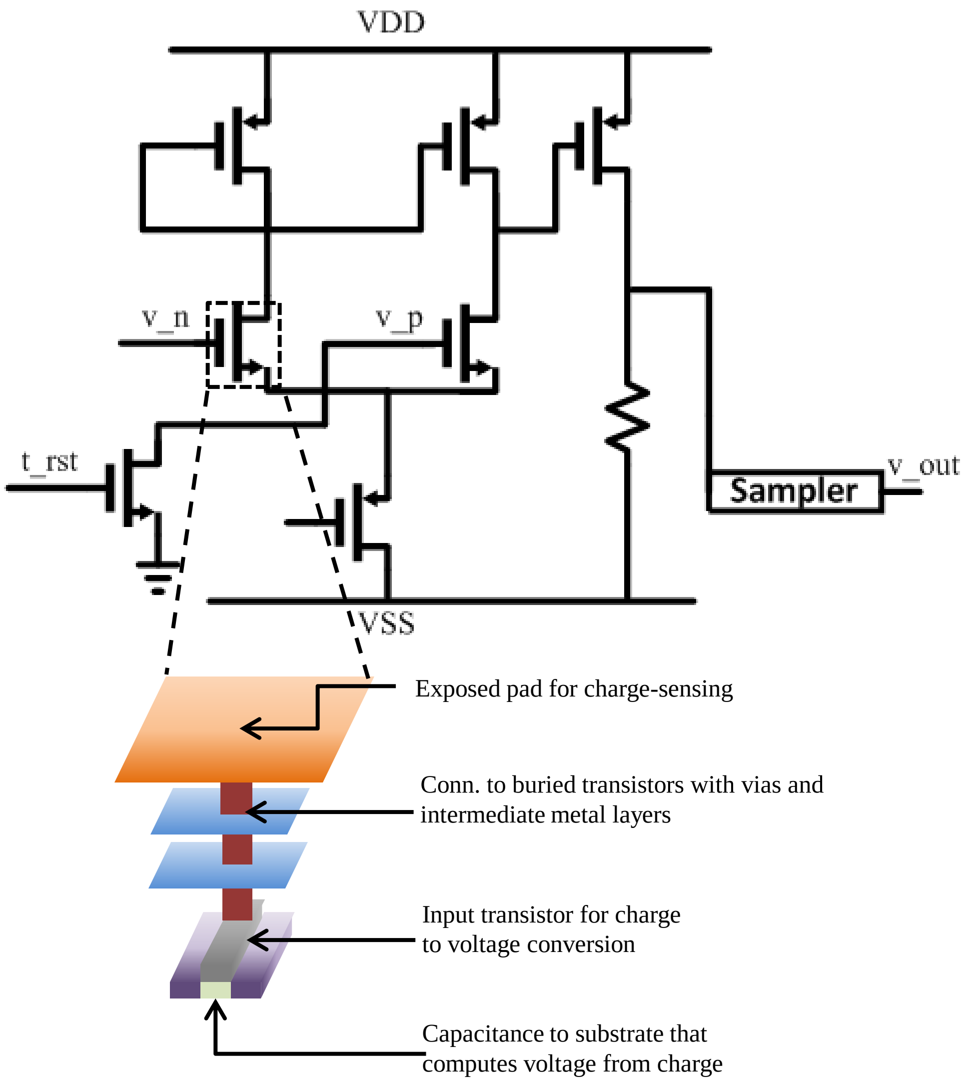
- Electric fields for Ion Manipulation
- Fabrication process flow for wafer-scale accelerators
- Einzel Lens, LINAC
- <u>CMOS Electronic Detection</u>
- Conclusions

Objective of electron bunch detection

- Electrons bunch alignment and diagnosis
- Mapping the electron bunch trajectory
- LINAC application



Sensor Electronics



- Ratio of sensed charge to capacitance i.e. measured voltage is fixed for given charge concentration
- Amplifier with large (~40 dB) gain used for measuring voltage generated by sensed charge
- Input-referred noise of amplifier competes with signal i.e. it must be suppressed to detect ion-charges. This is dominated by input transistor so can ignore vn2

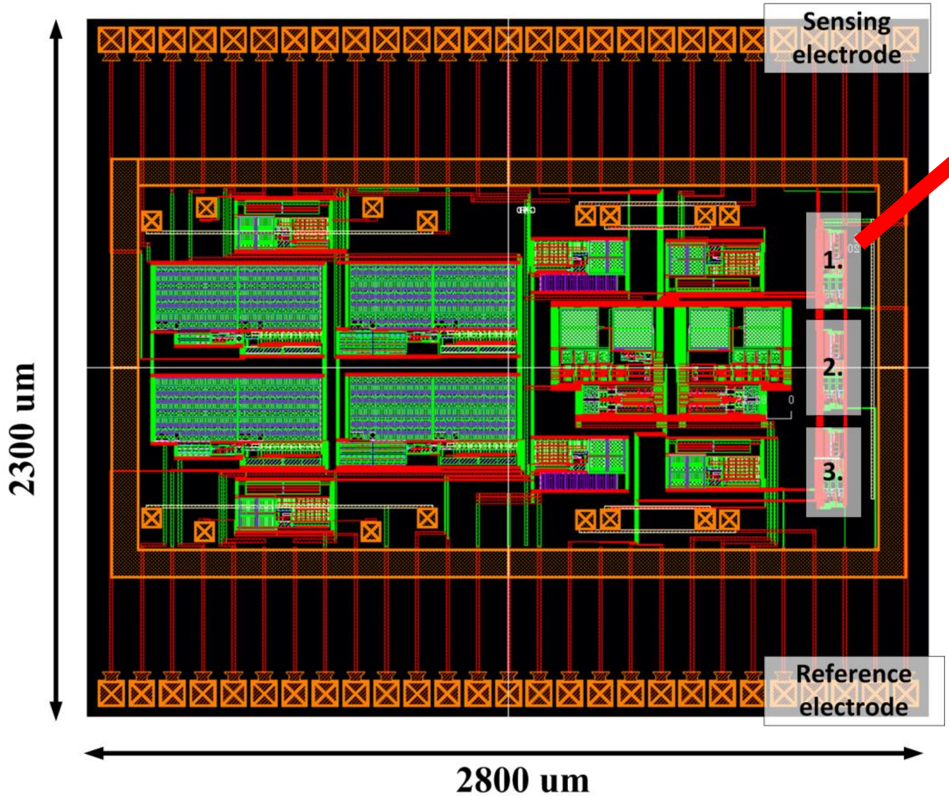
$$v_{out} = A_{v1}A_{v2}(v_{signal} + v_{n1}) + A_{v2}(v_{n2})$$

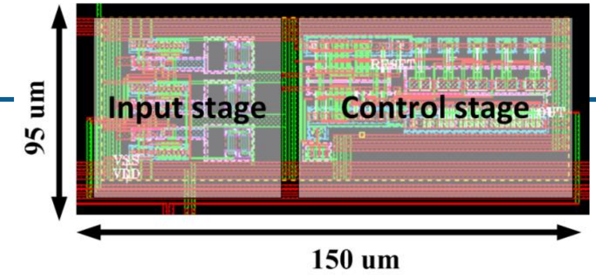
$$v_{signal} = \frac{q_{density}A}{C_{ox}A} = \frac{q_{density}}{C_{ox}}$$

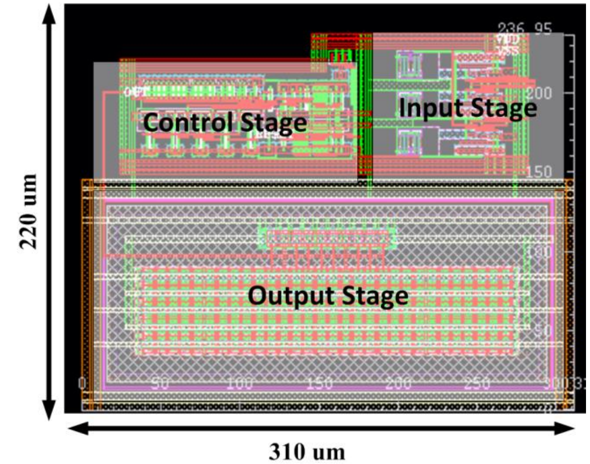
$$v_{n1} = \frac{4kT\gamma}{g_m} V^2 / \sqrt{Hz}$$

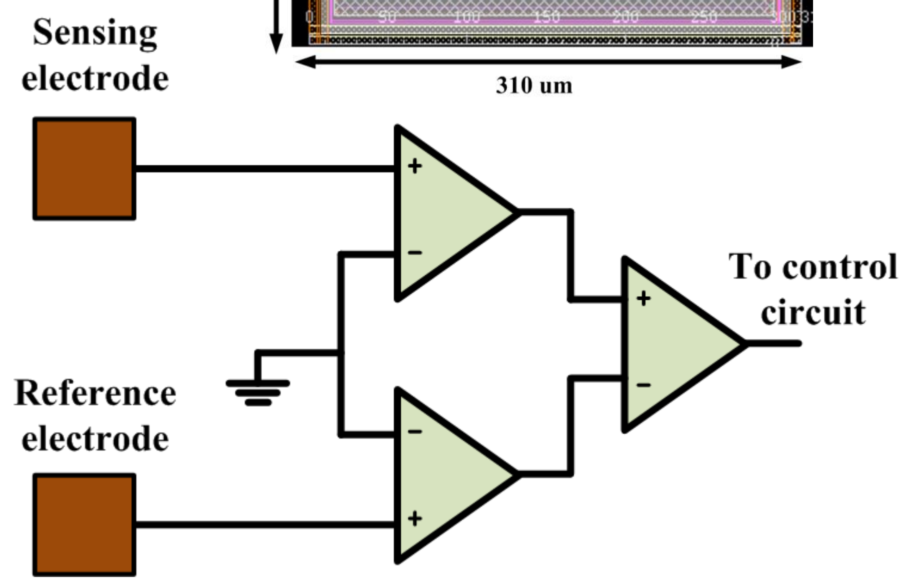
CMOS for Beam Detection

- **Invensense 0.35um HV CMOS process**
  - Differential input stage sensing
  - Tapeout date 05/31/2012.





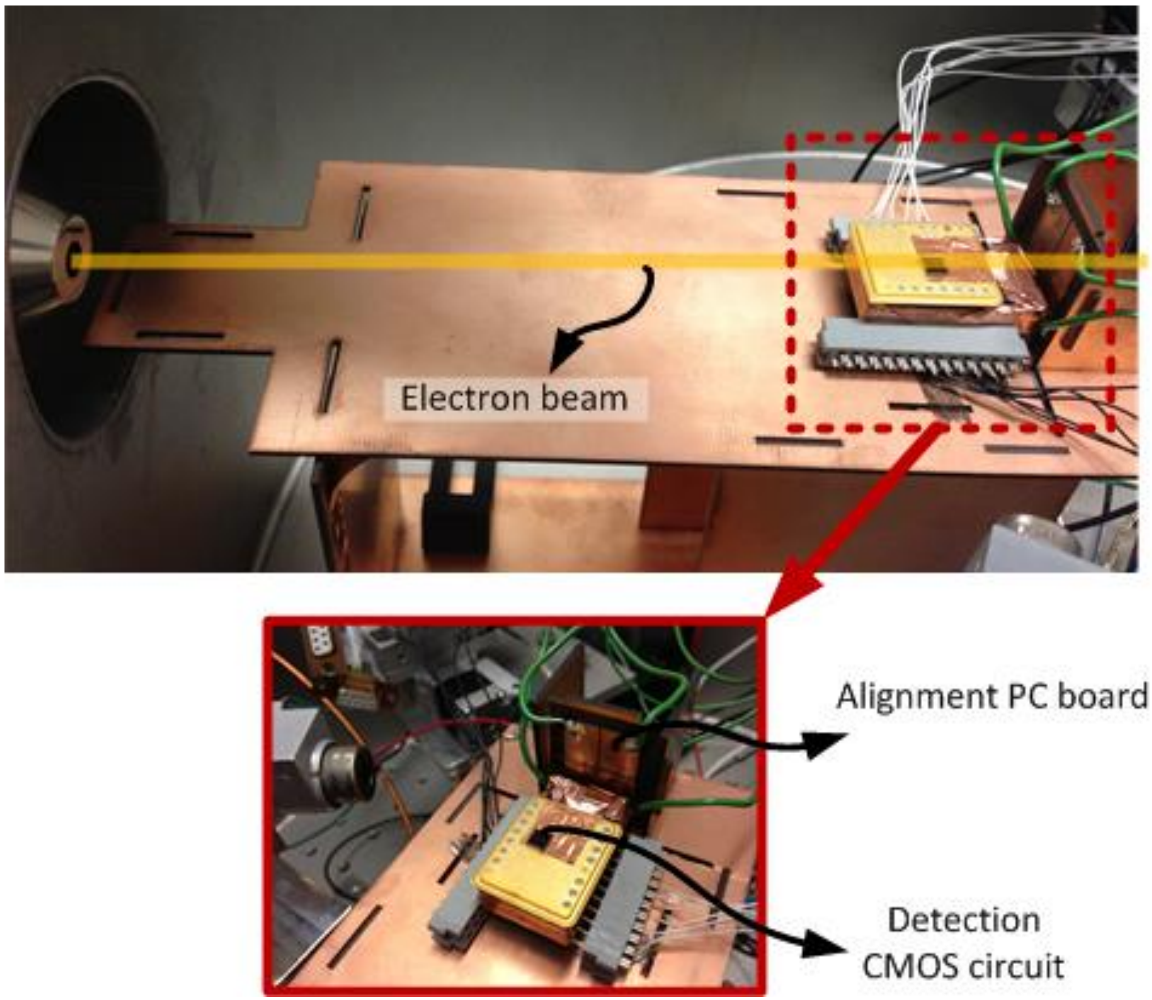




Latest electron gun experiment

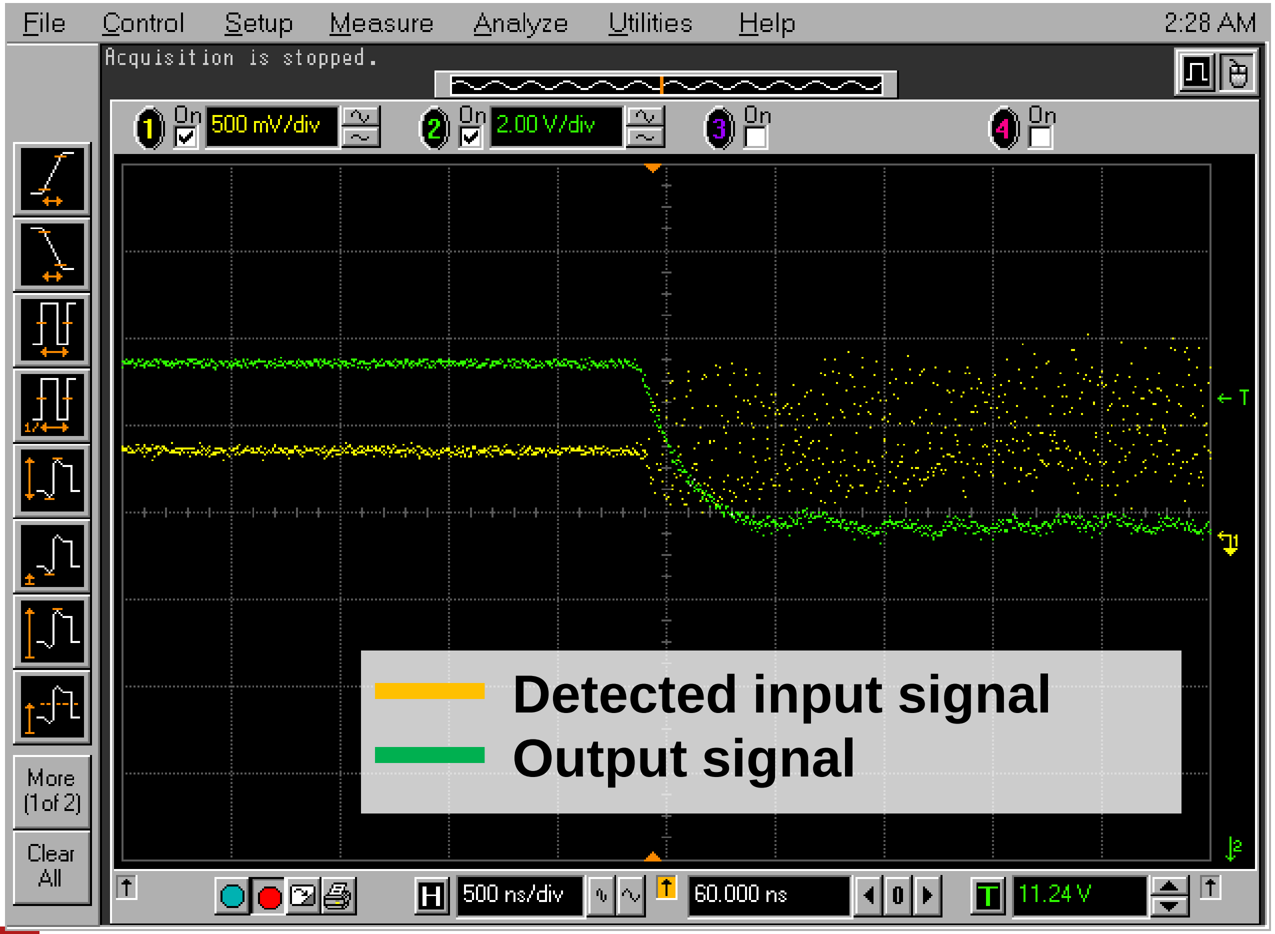
Better electron beam alignment technique

Perform the measurement with alignment PC board.



Latest electron gun experiment

The detection circuit will be triggered by constant electron beam, but need a discharge path to reset the status.

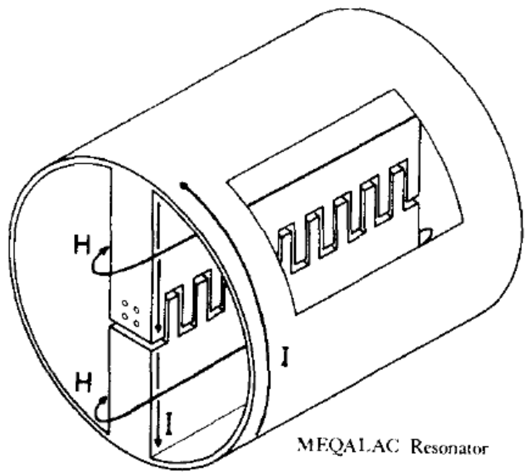


Fusion Ion Beam – Potential Design

Overall Goals of Fusion Drivers and MEQALAQ

- **Smaller LINAC dimensions →Higher frequencies**
- **Higher frequencies → smaller quadrupole dimensions**
- **Electrostatic quadrupoles are more efficient than magnetic at small scale**
- **MEQALAQ - Multiple-beam Electrostatic-Quadrupole Focusing Linear Accelerator – developed by Maschke (BNL)**
  - Consists of many small channels for beams
  - Use electrostatics at smaller dimensions for emittance with electrostatic quadrupoles
  - Divide and Conquer – Beat the space-charge limited current at low energies by breaking the beam into thousands of beams with less charge per beam to maintain emittance

MEQALAQ, 1984



MEQALAC Resonator

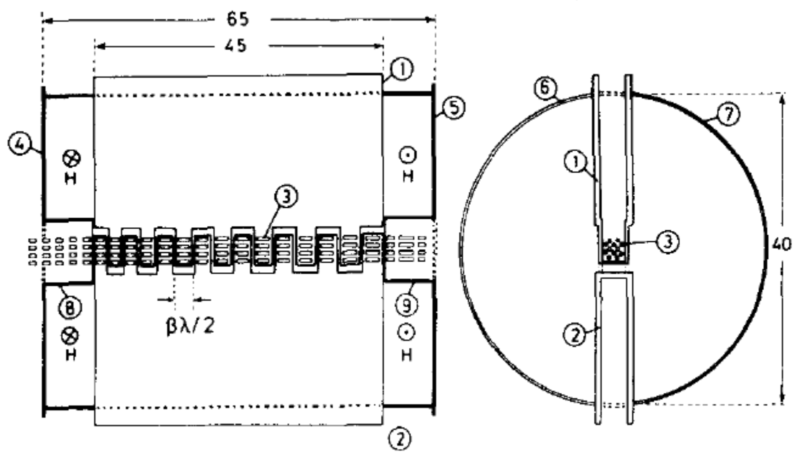


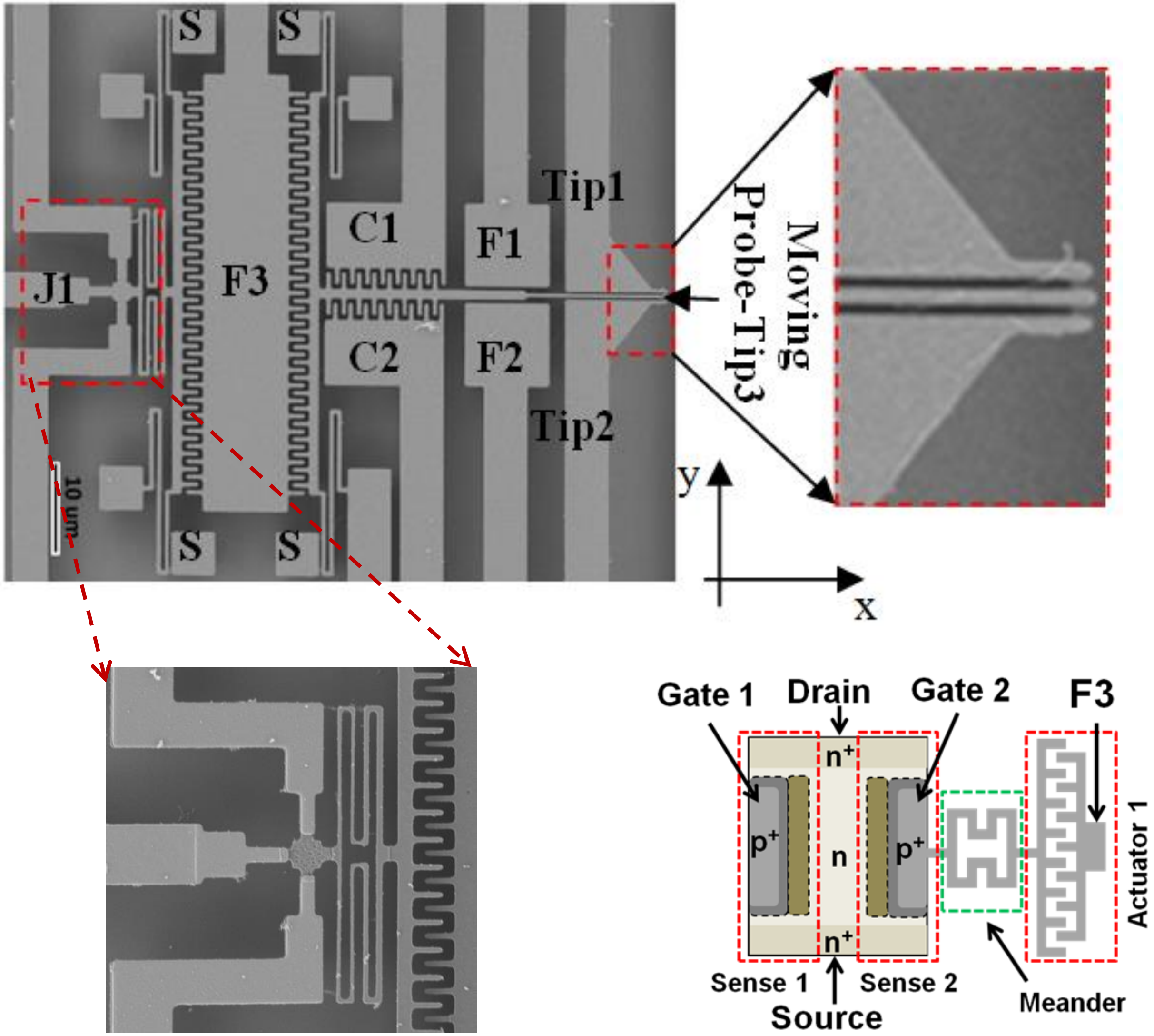
TABLE I

Parameter	Present exp.	Li accelerator stage 1	Li accelerator stage 2	Dim.
Particle	He^+	$^6Li^-$	$^6Li^-$	
Inj.energy	40	90	1210	keV
Exit energy	115	1210	6010	keV
RF frequency	40	40	80	MHz
Synchr.phase	-38	-33	-16	°
Trans.time factor	0.9	0.9	0.9	
Gap elec.field	2.6	9.3	8.0	MV/m
Av.acc.el.field	0.1	0.4	1.35	MV/m
Nr.of gaps	20	41	49	
Nr.of channels	4	16	16	
Overall beam dim.	4	25	25	cm²
Length resonator	65	260	355	cm
Diam.resonator	40	65	65	cm
Capacitive load (AV.)	7.0	2.6	0.7	pF/cm
Qual.factor Q_o	1800	2900	4100	
Shunt imped.Rp_o	16	44	120	MΩ
$Rp_{o,eff}$	9	26	91	MΩ
RF power losses	0.5	5.0	6.3	cm
(AV.)cell length	2.3	5.0	6.3	cm
Width RF gaps	0.2	0.4	1.3	cm
Quad.space/length	0.75	0.75	0.8	
Diam.quad.chan.	0.6	0.6	0.6	cm
Quad.voltage	±2.62	±4.09	±5.97	kV
Zero current μ_{oT}	60	80	20	°
Zero current μ_{oL}	20.0	34.5	10.6	°
Depressed μ_T	7.3	24.0	4.8	°
Depressed μ_L	8.0	10.4	6.7	°
Chan.acceptance α_T	108.π	83.π	26.π	mm.mrad
Chan.acceptance α_L	240.π	343.π	44.π	mm.mrad
$I_{T,MAX}$	24.1	59.8	151.0	mA
$I_{L,MAX}$	22.6	142.0	130.5	mA
$I_{T,AV}$	3.0	6.3	7.8	mA
$I_{L,AV}$	2.8	15.0	6.7	mA
Tot.current $I_{TOT,AV}$	11.2	101	101	mA
Acceler.efficiency	60	70	66	%

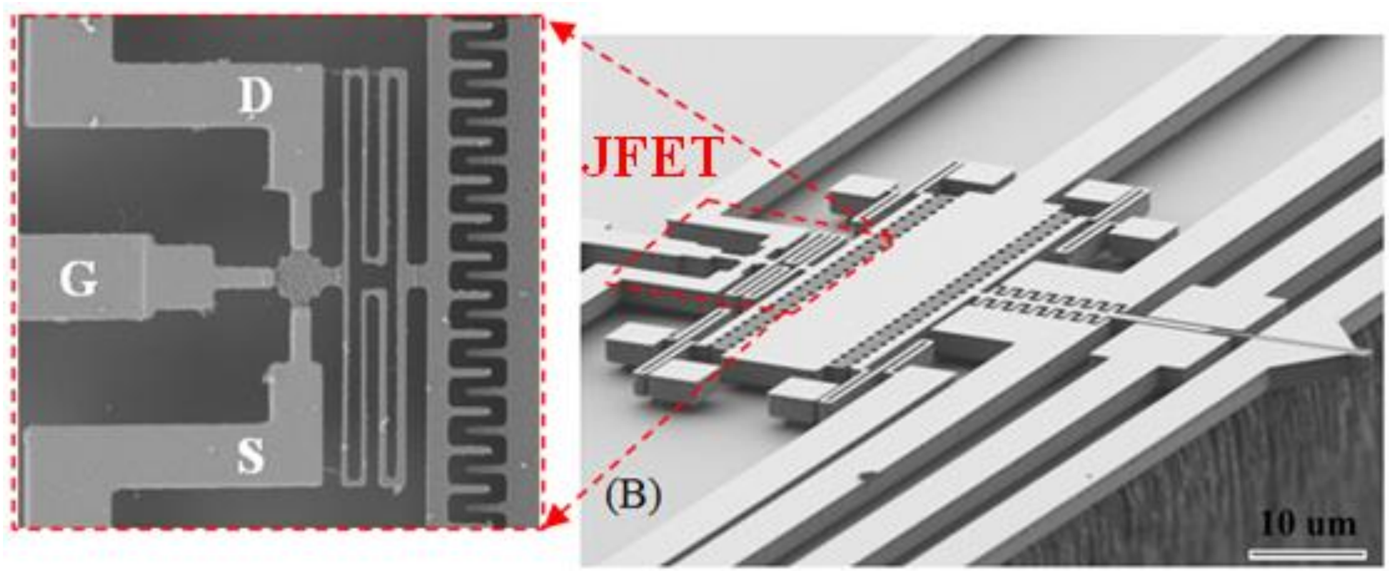
What does MEMS offer?

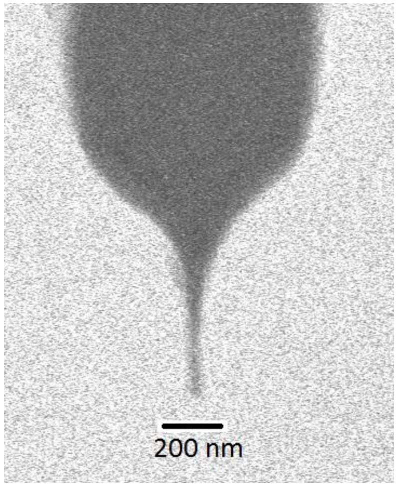
- Very high smoothness => minimize field emission (Silicon wafers are ~ 2-10nm surface roughness)
- Small drift-tubes can be made in arbitrary patterns using lithography and plasma etching
- Integrated electrostatic actuators to align beam alignment and change function of electrostatic beam manipulators

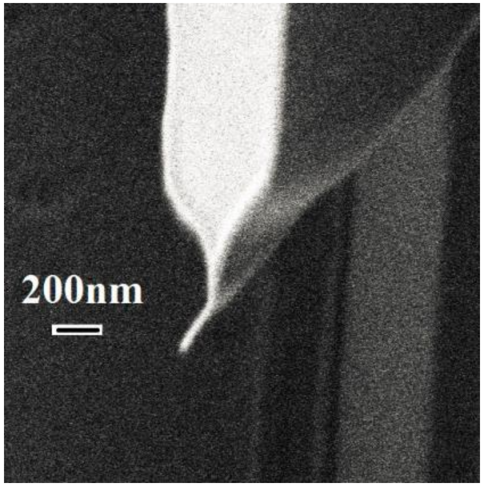
Integrated Actuators with JFET transistors

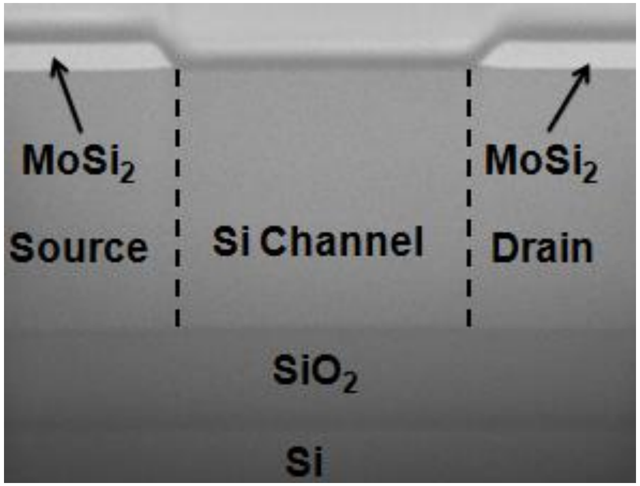


Movable Quadrupole Electrodes

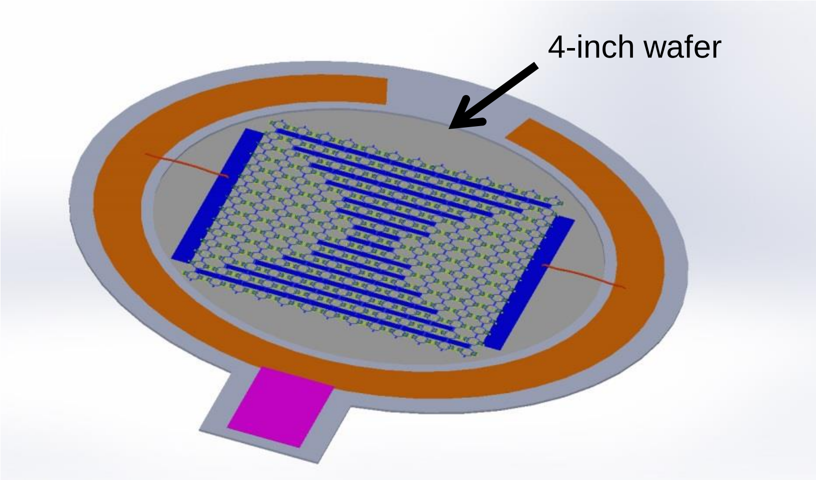


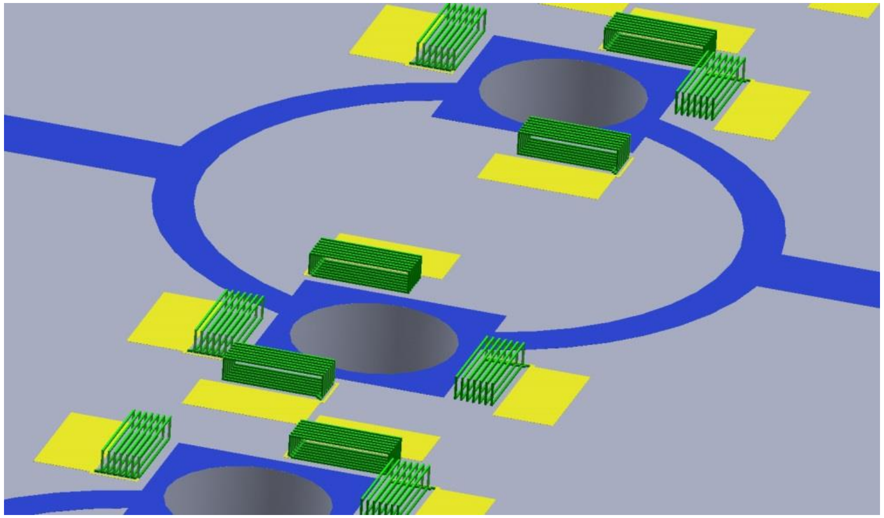






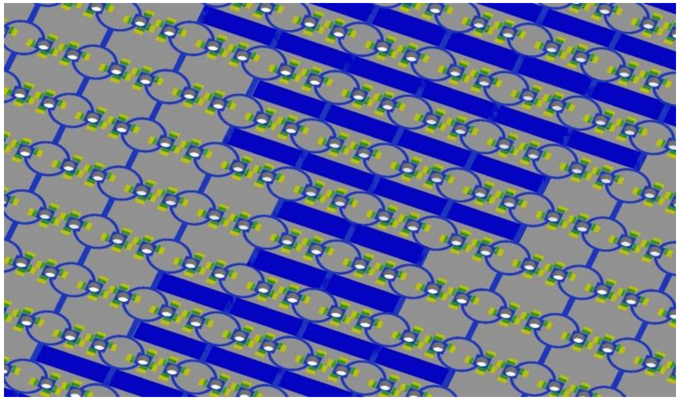
Silicon Wafer Held By CPW Resonator: MEMS MEQALAQ





GaN RF amplifier – 50W

Holder with RF CPW resonator



- Q ~ 700, Z0 = 200 Ohms, P = 50 W = > Peak voltage = 100kV
- Heat removal at $50W/5cm^2$
- RF design for equal phase at each beam channel
- Each wafer has its own resonator

Very Crude Cost Analysis

- **Per accelerator wafer**
  - Amplifier/Power Amplifier - $3
  - Wafer ~ $5
  - Processing ~$10
  - CPW Resonator ~ $1
  - Vacuum chamber ~$1
- **Total ~ $20/wafer in large quantities**
- **Assuming 8000 channels per wafer, and 20,000 wafers to get to 2 GeV 200 amu ions**
- **200 meter long**
- **$400K /accelerator at 400 Amps**
- **100kA => 250 accelerators => $100M**

Summary

- **Micromachining and MEMS enables electrostatic quadrupoles at massive densities and low cost due to economies of scale per wafer**
- **Distributed amplifiers may enable distributed heat dissipation**
- **Economies of scale of Moore's law maybe applied for low-cost fusion drivers**