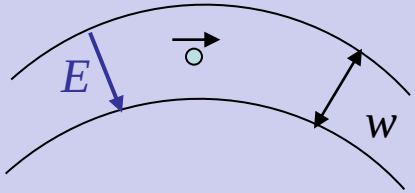
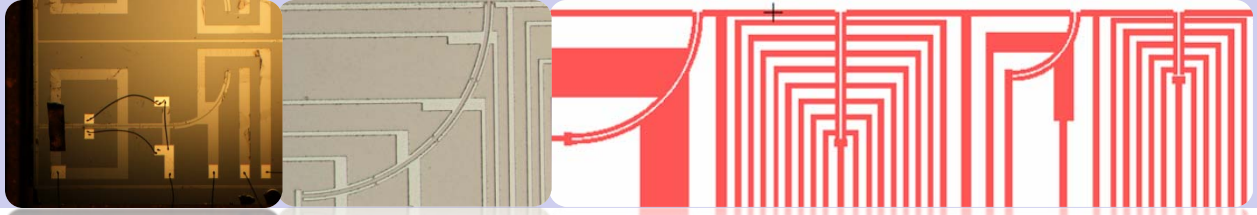




Towards Chip and Wafer Scale High Energy Charged Particle Sources

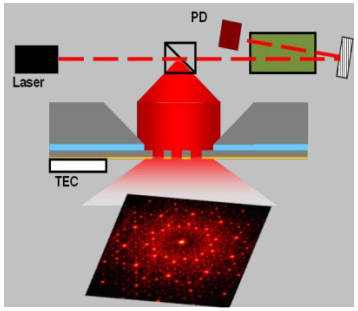
Amit Lal

amit.lal@cornell.edu

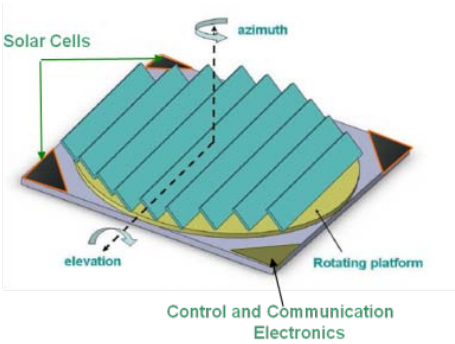
School Of Electrical and Computer Engineering
Cornell University

June 21, 2011

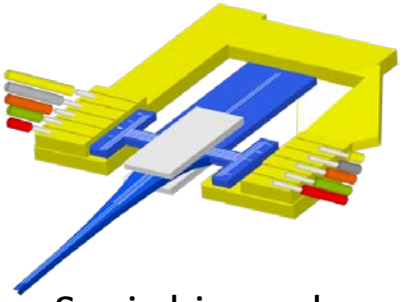
SonicMEMS Lab, Cornell University



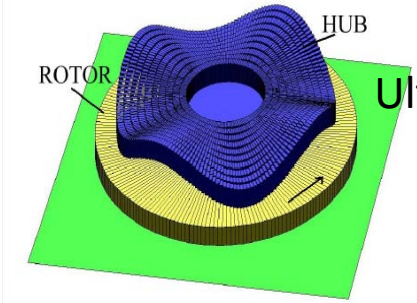
Atomic Metrology



Solar-Tiles

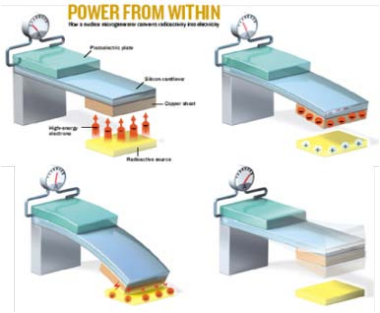


Sonic bio-probes

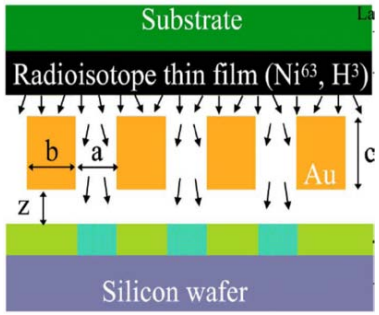


Ultrasonic Micromachine Actuation

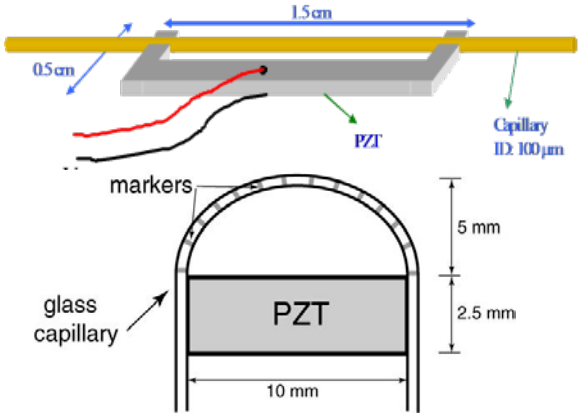
Insect Cyborgs



Radioisotope powered MEMS



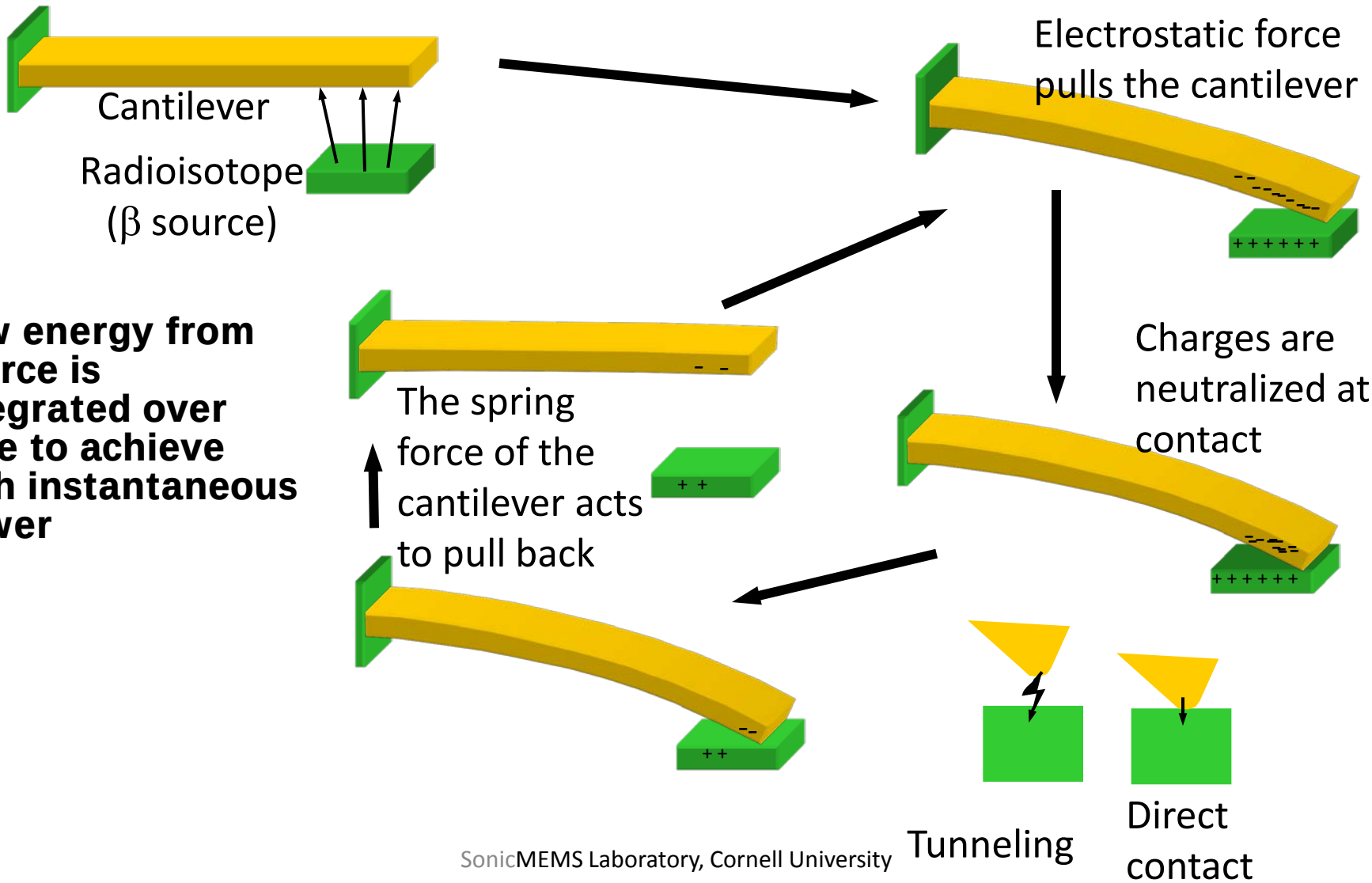
Radioisotope Lithography



Ultrasonic Microfluidics

Cornell University

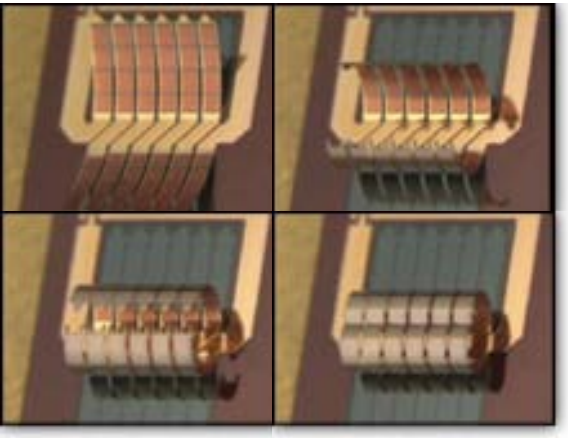
Direct conversion of emitted charges to mechanical motion

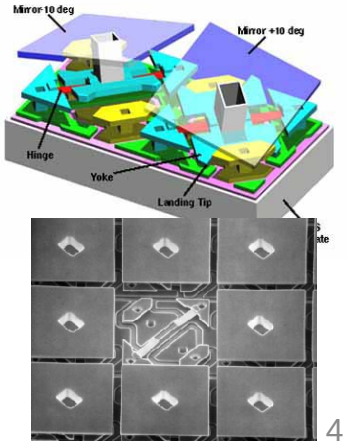


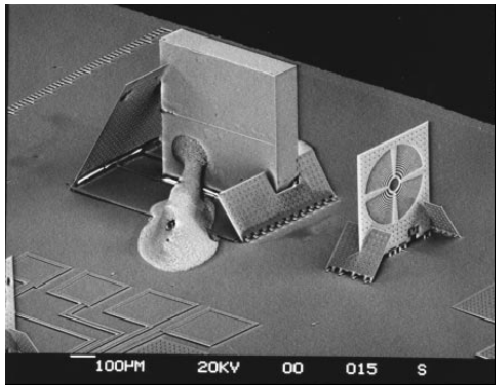
Low energy from source is integrated over time to achieve high instantaneous power

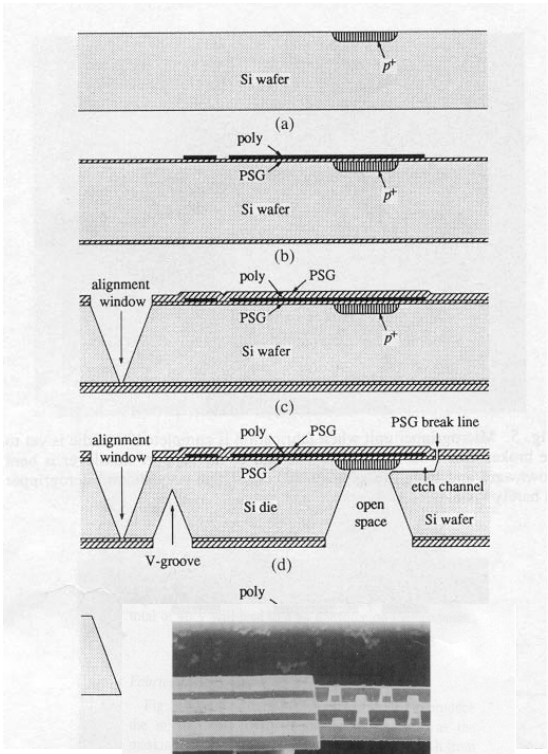
The New Paradigm Viewpoint

- Micromachining enables a new way of thinking about mechanical structures
- Parallel (huge) arrays of machines are possible
- Machines comparable to size of biological objects are possible
- Integration of electromechanical machines to individual small scale objects is possible
- Multi-physical systems









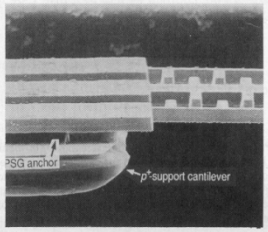


Fig. 6. SEM micrograph showing three conducting lines crossing the end of the support cantilever to the gripper arms. The remaining PSG insulating layer between the conducting lines and the support cantilever is marked.

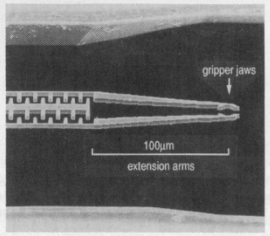
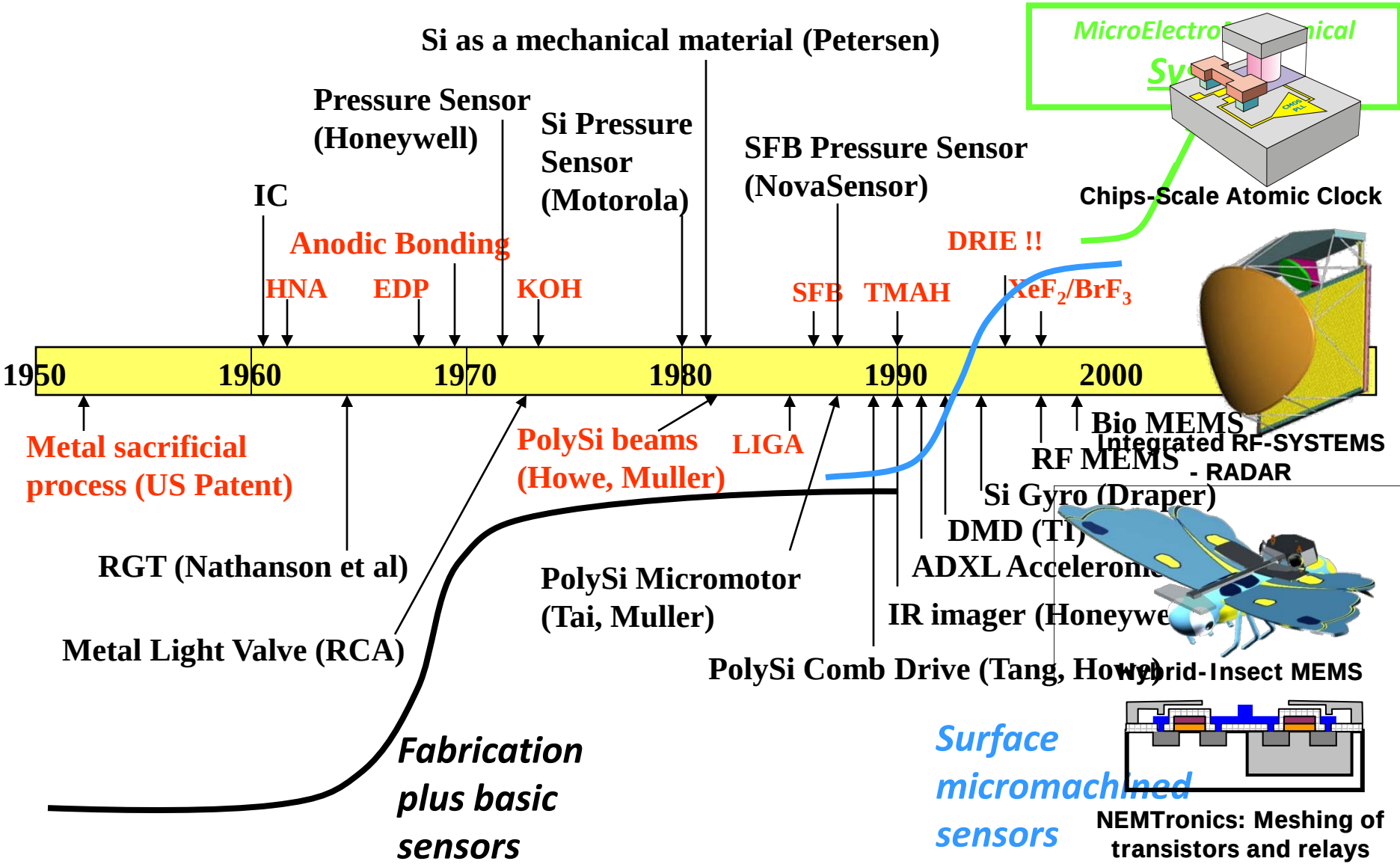


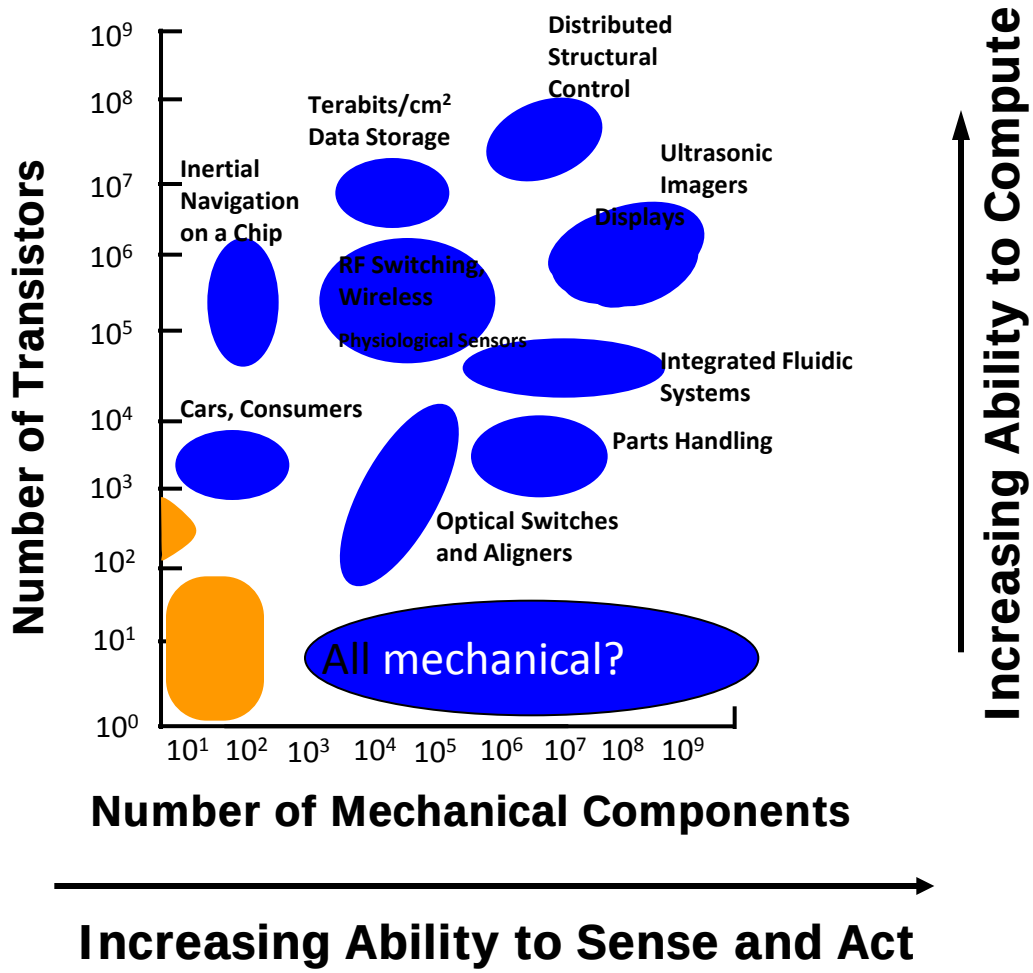
Fig. 7. SEM micrograph showing the flexible comb-drive structures, extension arms, and the gripper jaws.

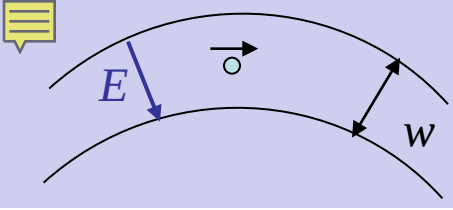
Progression of MEMS

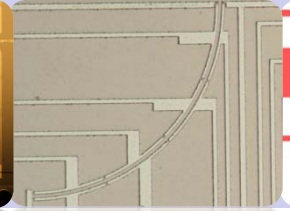


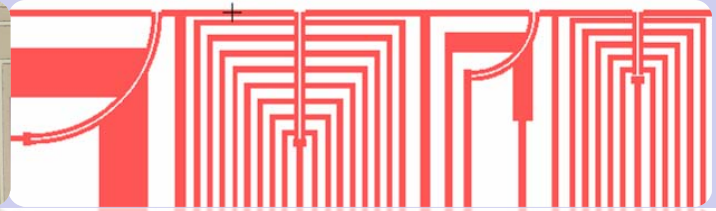
And others: On Chip Manufacturing, On-chip cooling, On-chip gas and liquid processing

Integration Space









I. Why are we doing this?

Make the smallest and lowest power MeV class Chip-scale accelerator

II. Beam guidance on chip

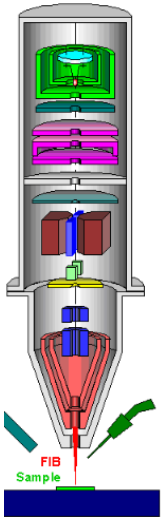
III. Particle acceleration

IV. Future

V. Summary

ION BEAM APPLICATIONS

Focused Ion Beam / SEM

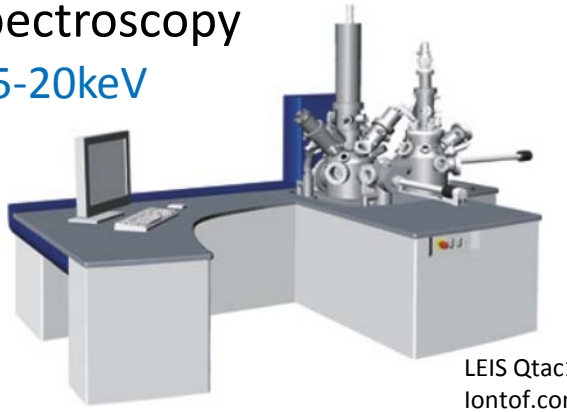


FIB:
5-50keV(Ga+)
SEM:
1-30keV

http://www.hzdr.de/db/

Low Energy Ion Scattering Spectroscopy

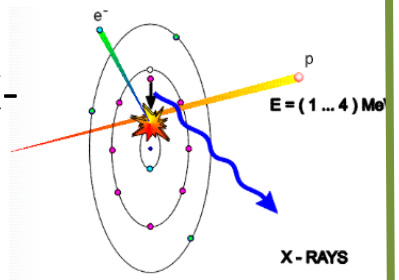
0.5-20keV



LEIS Qtac100
Iontof.com:

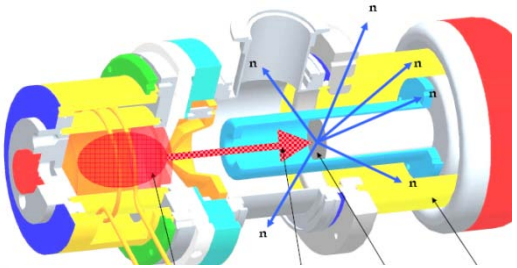
Particle – Induced X-ray Emission

1-2MeV



http://www.uni-leipzig.de/

Neutron Generators

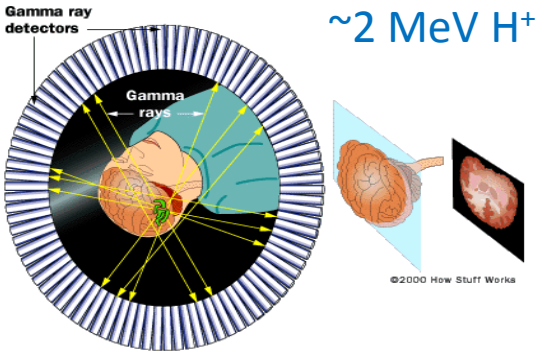


Reijonen, IAEA Technical Meeting on Neutron Generators, Vienna 2005

Deuterium →120keV, 2MeV

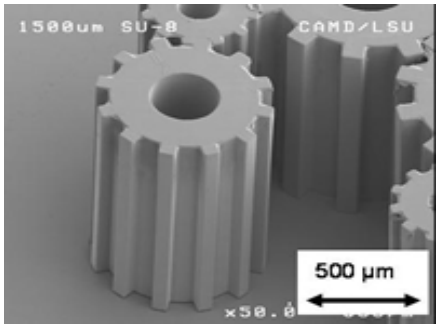
Positron Emission Tomography (PET)

~2 MeV H^+



LIGA: Lithography, Electroplating, Molding

(100keV e^{--})



CAMD
http://www.camd.lsu.edu/microfabrication

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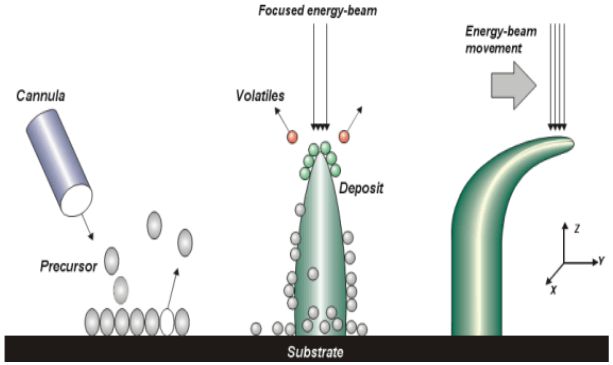

http://www.nanoss.de/en/
NanoScale Systems GmbH

~15-50keV (Ga+)

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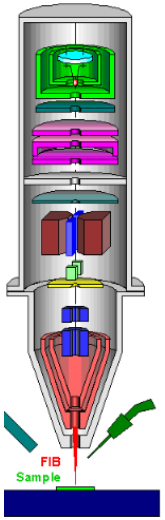
Focused Ion Beam / SEM



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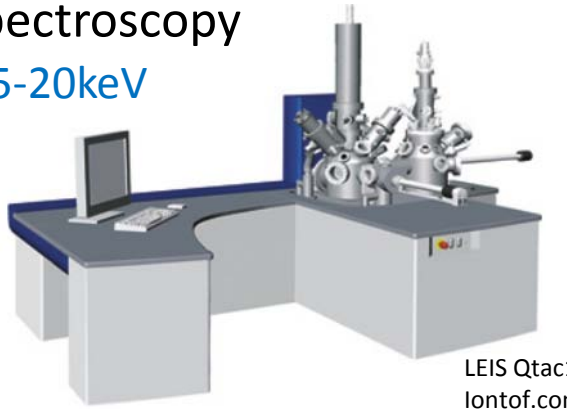

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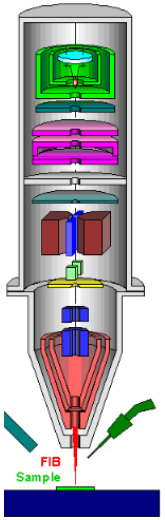

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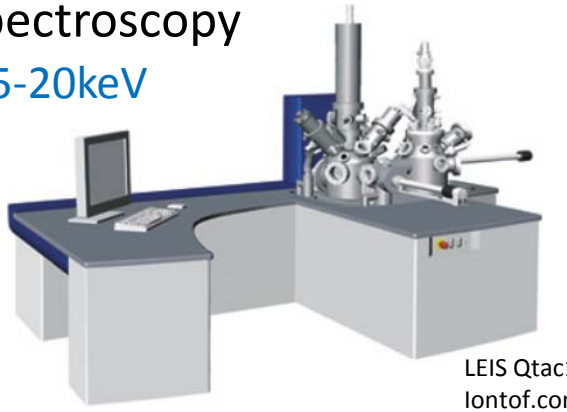

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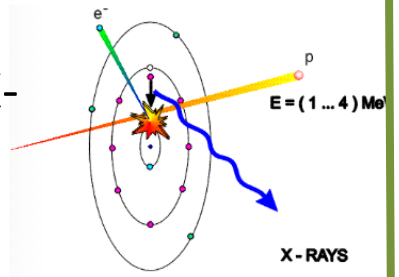

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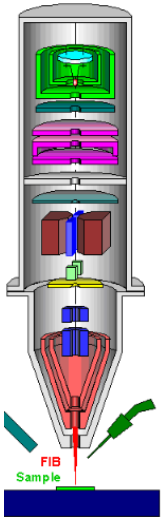

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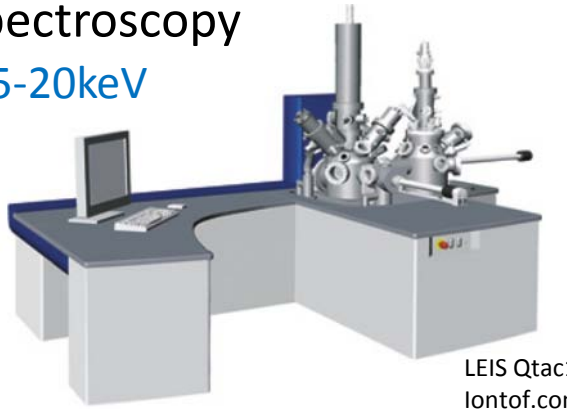

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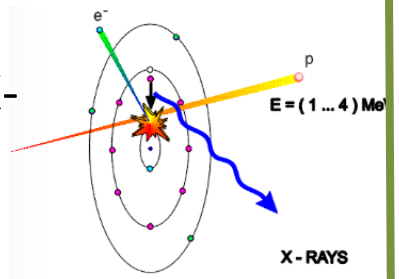

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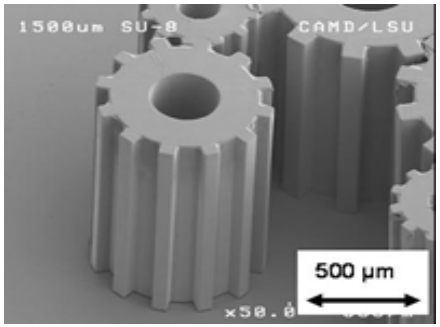

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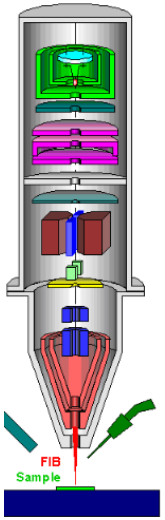

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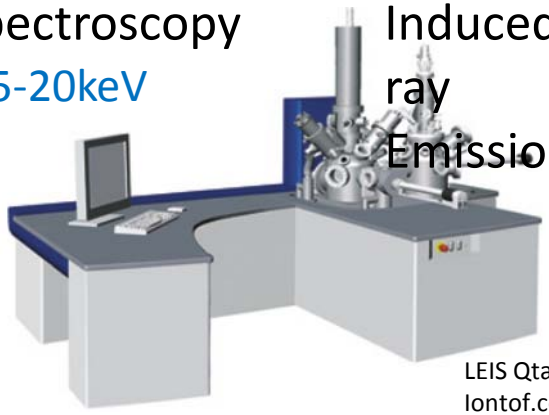

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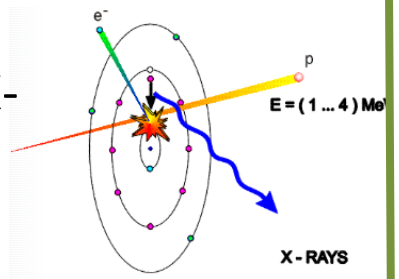

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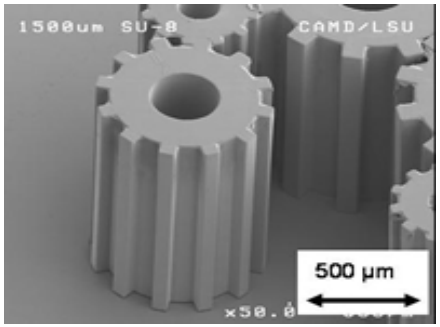

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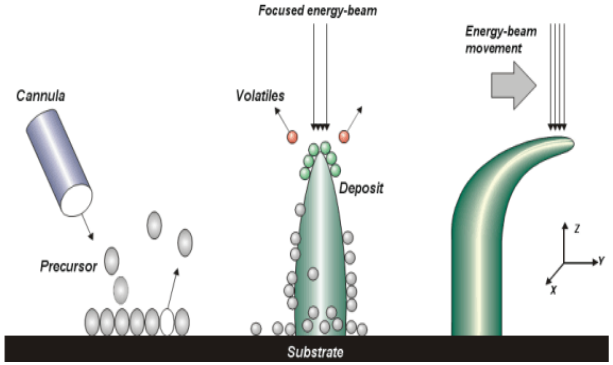

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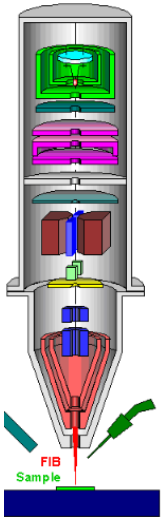
ION BEAM APPLICATIONS

Focused Ion Beam / SEM



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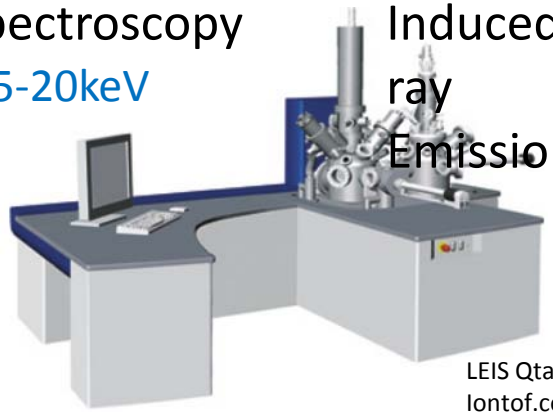

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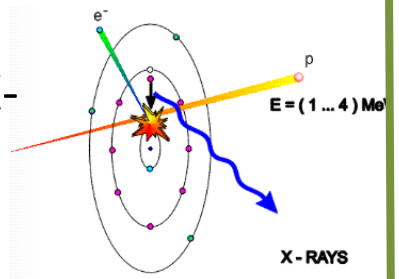

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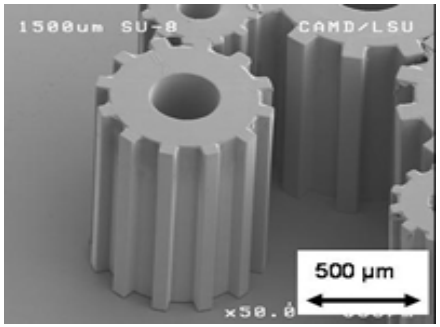

CAMD
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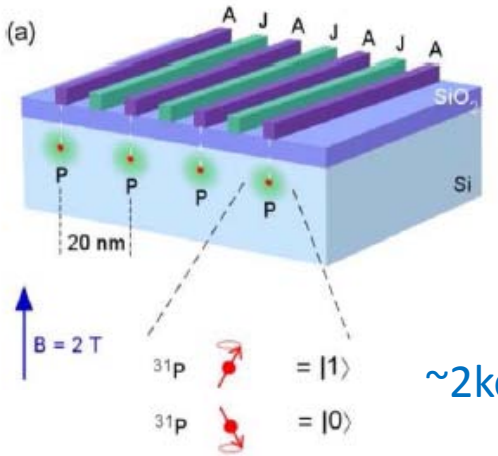
Single Ion Implantation

Photo Courtesy of Dzurak et. al.



~2keV

Neutron Generators

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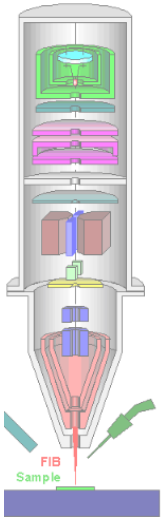
Common Theme: Energy range keV to MeV

Focused Ion Beam / SEM



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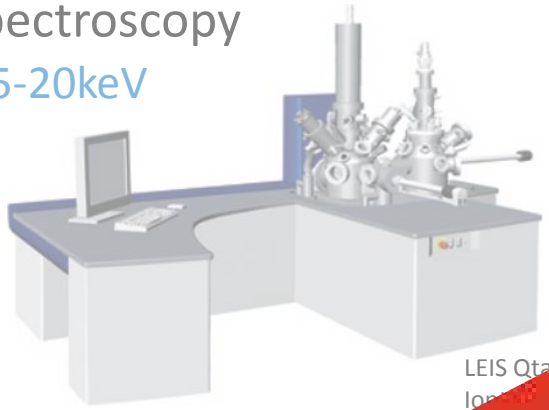
Low Energy Ion Scattering Spectroscopy

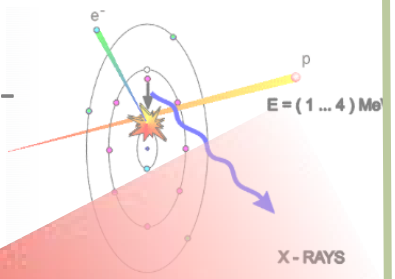
0.5-20keV



LEIS Qta
Ion

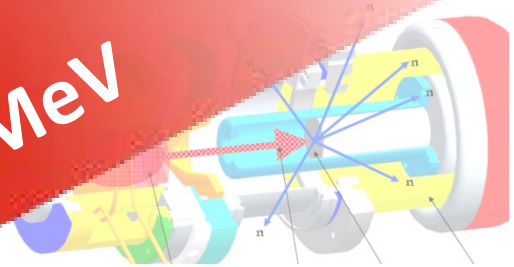
Particle – Induced X-ray Emission

1-2MeV



http://www.uni-leipzig.de/

Neutron Generators

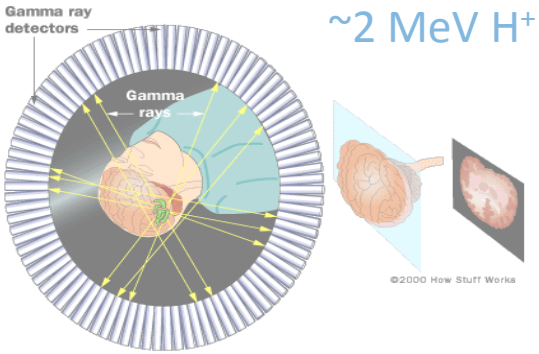


Reijonen, IAEA Technical Meeting on Neutron Generators, Vienna 2005

Deuterium →120keV, 2MeV

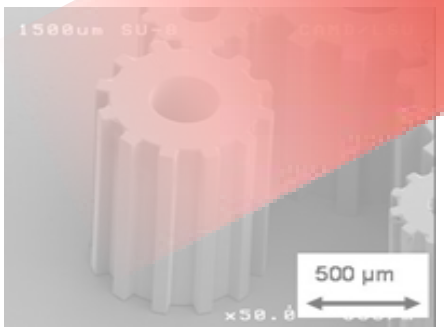
Positron Emission Tomography (PET)

~2 MeV H^+



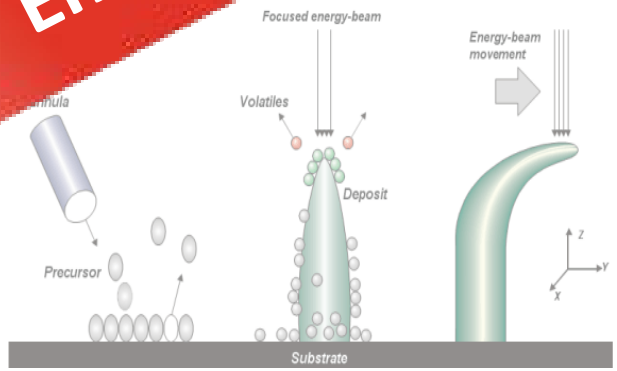
LIGA: Lithography, Electroplating, Molding

(100keV e^-)



CAMD
http://www.camd.lsu.edu/microfabrication

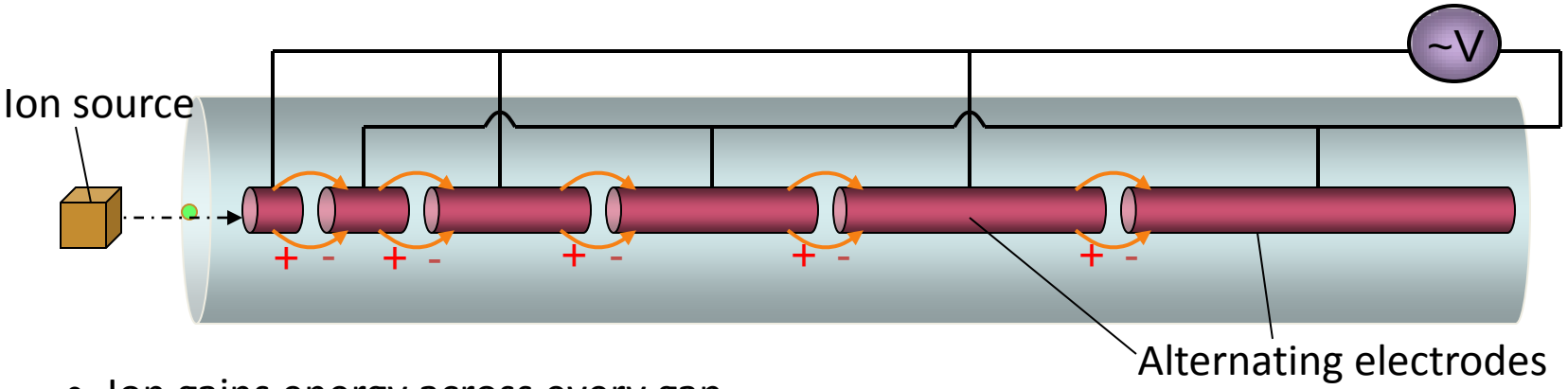
ION ced deposition



http://www.nanoss.de/en/
NanoScale Systems GmbH

~15-50keV (Ga+)

Linear Accelerator



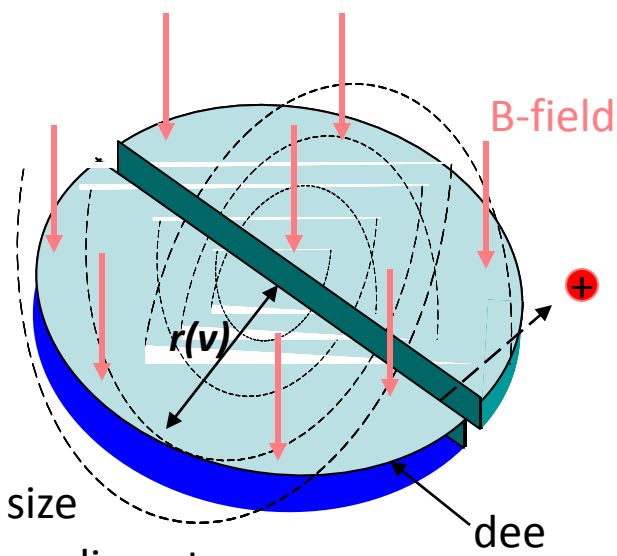
- Ion gains energy across every gap
- Electrodes driven at RF voltage (constant frequency)
- Subsequent electrode lengths greater due to increase in ion velocity → Very long
- For proton to reach 1MeV, need ~6 km (at 40MHz, V_{gap}=20V)

Cyclotron

→ Large & heavy

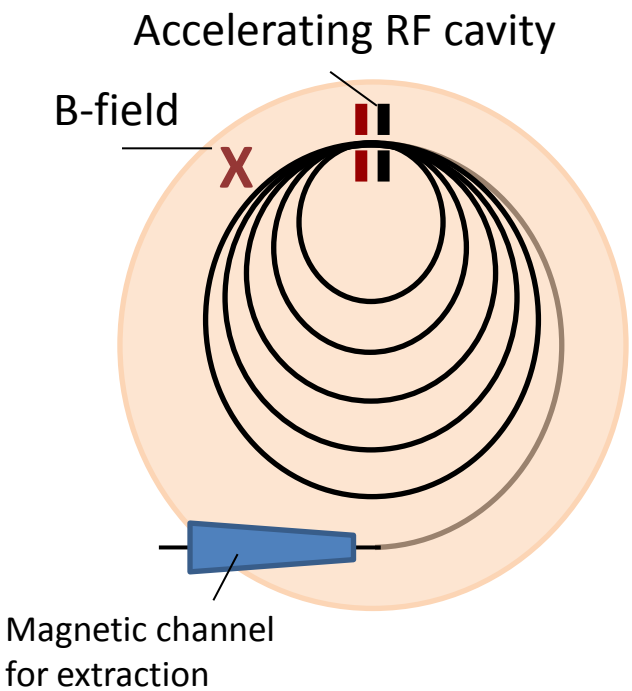
- Circular path of ion due to B-field:

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



- 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
- For 1MeV proton in 1T B-field, cyclotron size ~30cm diameter

Microtron [2]



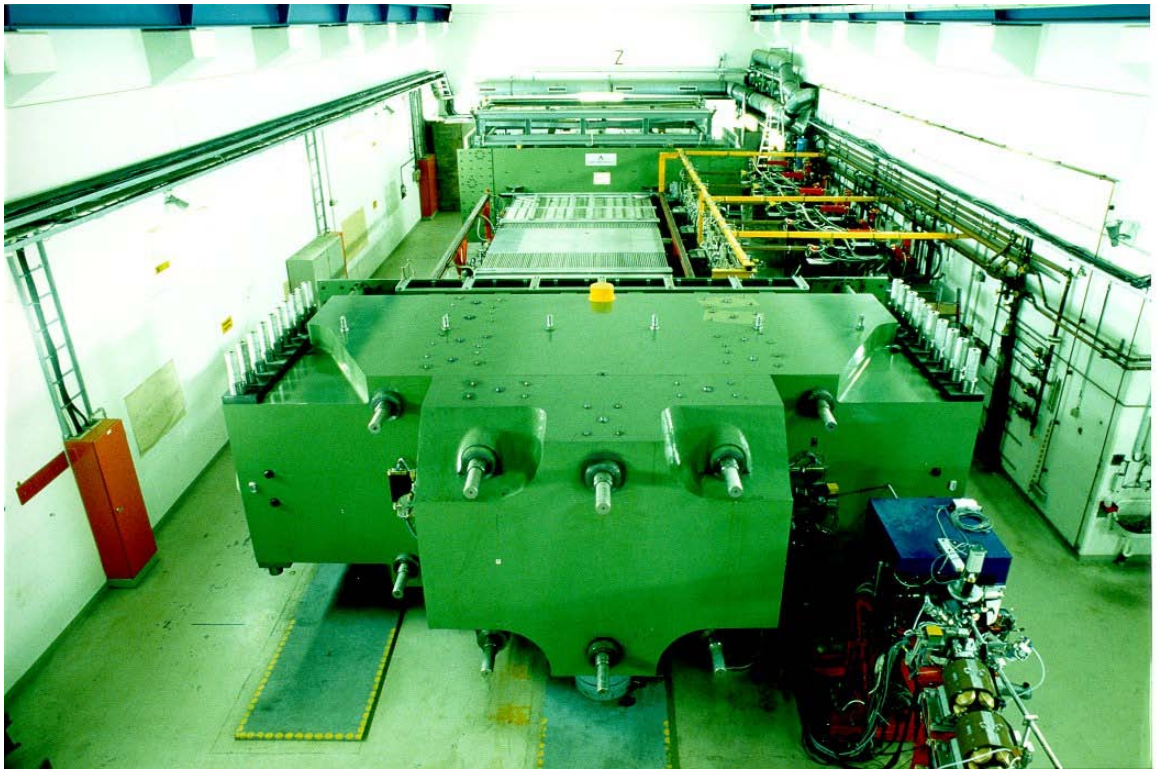
[1]

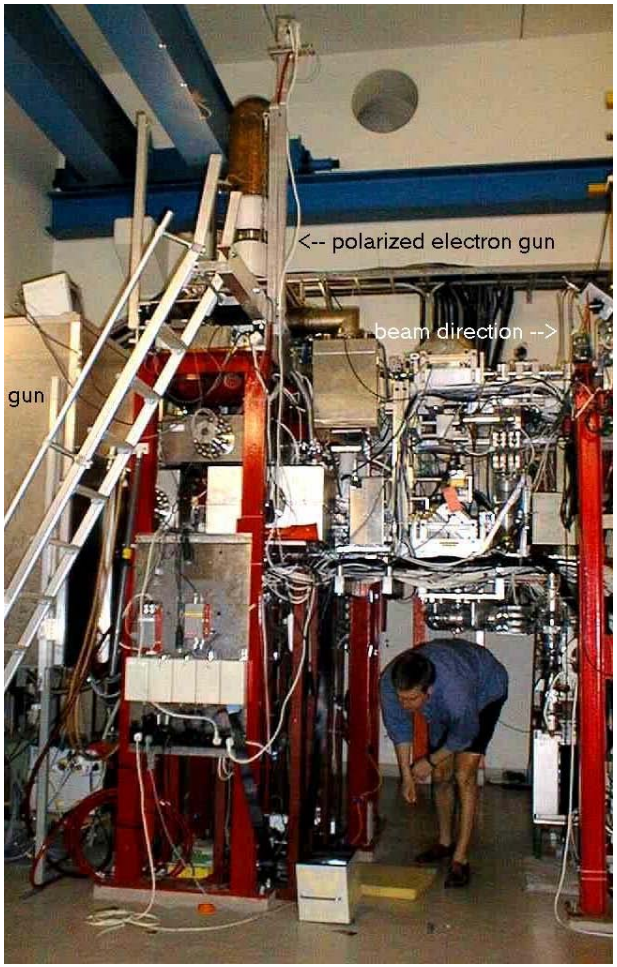
Institute	Pole Dia . [cm]	Energy [MeV]	No. of orbits	Pulse Current [mA]	Magnet Wei ght [tons]	Use
IPP, Russia	75	15	17	35	0.9	Nuclear physics
IPP, Russia	110	32	30	50	5	Radiation analysis
UINR, Russia	110	30	30	60	4.5	Neutron Fast reactor
PIASU, Russia	60	7	10	110	2	Positron accel.
Lunde Uni. Sweden	50	6.4	10	50	0.6	Synchrotr on injection
Western Ontario Uni. Canada	50	6.2	8	40	Split	Part. Dynamics, Rel.
London Uni. England	200	29	56	10^{-3}	20	
Uni. Winsconsin , USA	137	44	34	15	15	Storage ring injector

Microtron at Johannes Gutenberg University, Mainz [6]

100keV —Linac→ 3.5MeV —MAMI A1→ 14.86MeV —MAMI A2→ 180MeV —MAMI B→ 855MeV —MAMI C→ 1508MeV

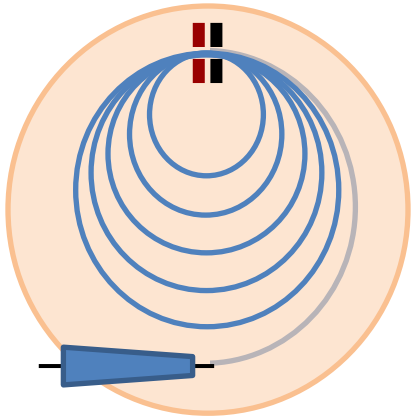
Linac: 22m total **Weight: 744 tons** **Frequency: 2.45GH**	**RF power diss. : ~280kW** **Current: 100uA**

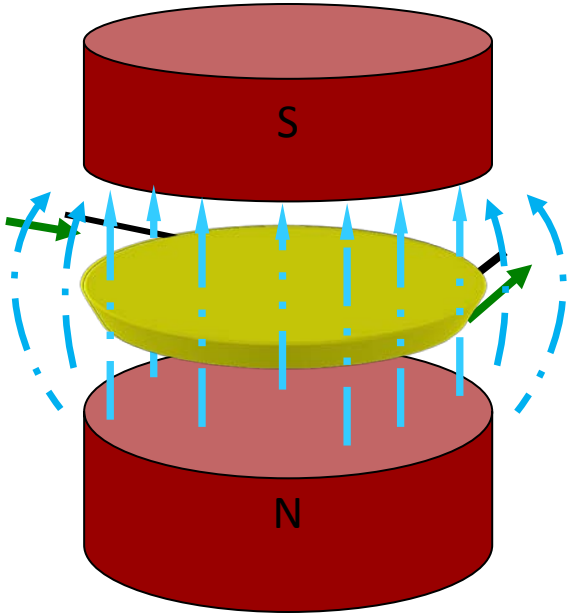


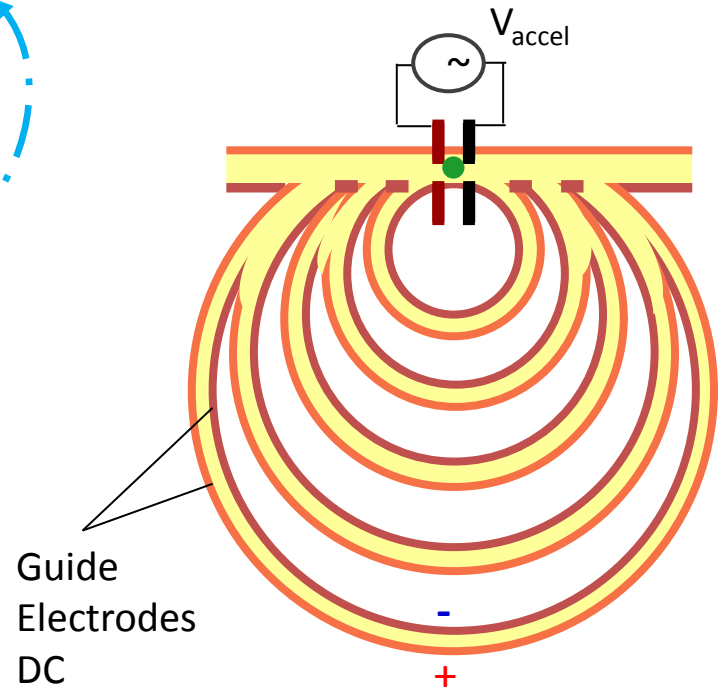


What if we use E-field only for guidance?

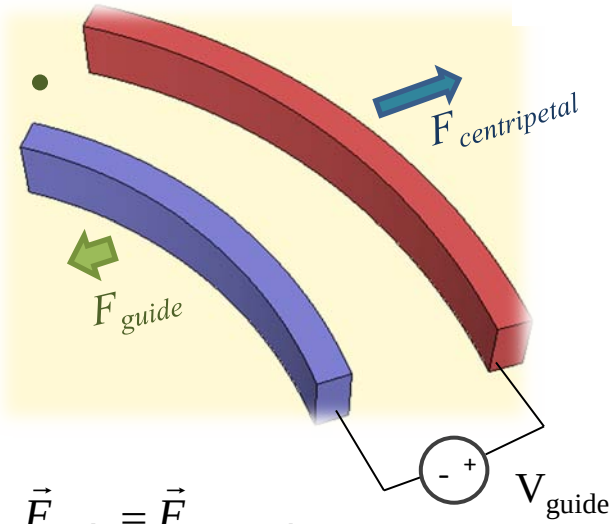
No B-field, no heavy magnets.







Basic Building Blocks

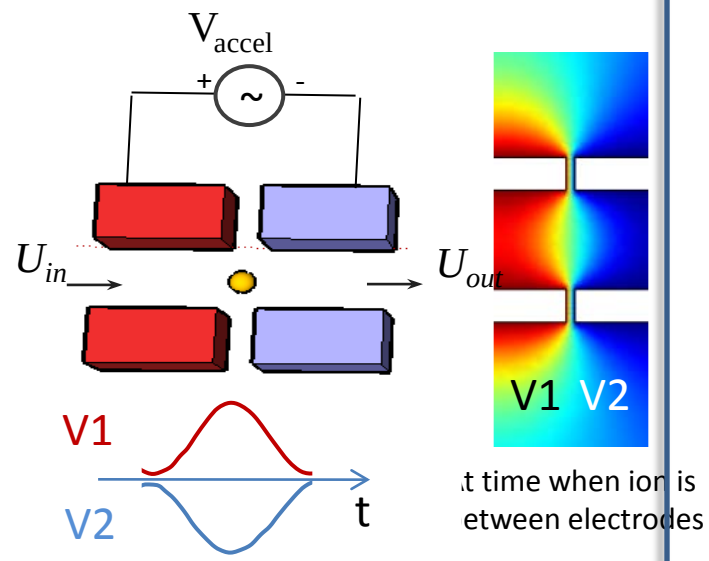


$$\vec{F}_{guide} = \vec{F}_{centripetal}$$

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

Ion Guidance

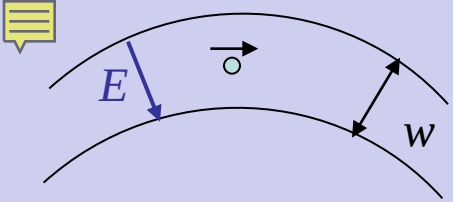
Positive charged ion with velocity *v* guided around radius curvature *r.*

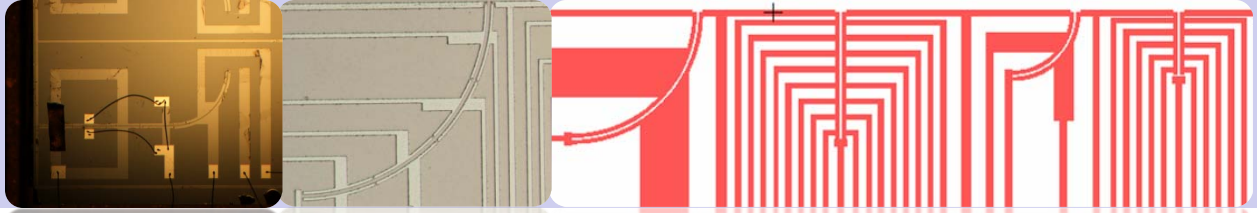


Ion Acceleration Component

Ion with initial energy U_{in} will be accelerated to

$$U_{out} = U_{in} + qV_{accel}$$





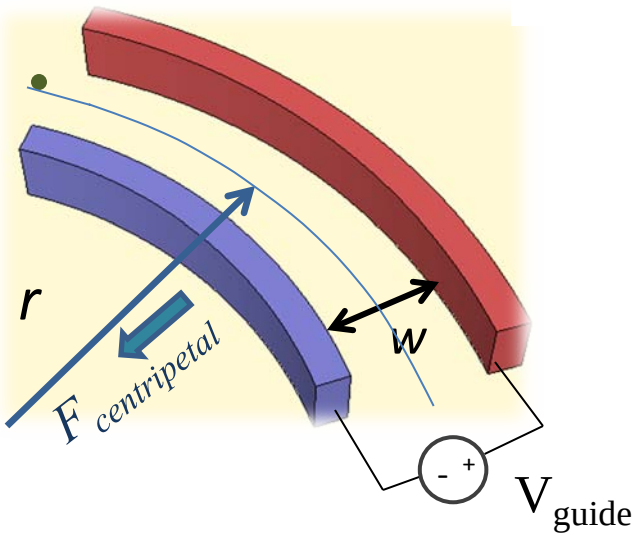
I. Why are we doing this?

II. Beam guidance on chip

III. Particle acceleration

IV. Summary

ION BEAM GUIDANCE



$$E_r = -\frac{d\phi}{dr} = -\frac{V_2 - V_1}{\ln(r_2/r_1)}\frac{1}{r}$$

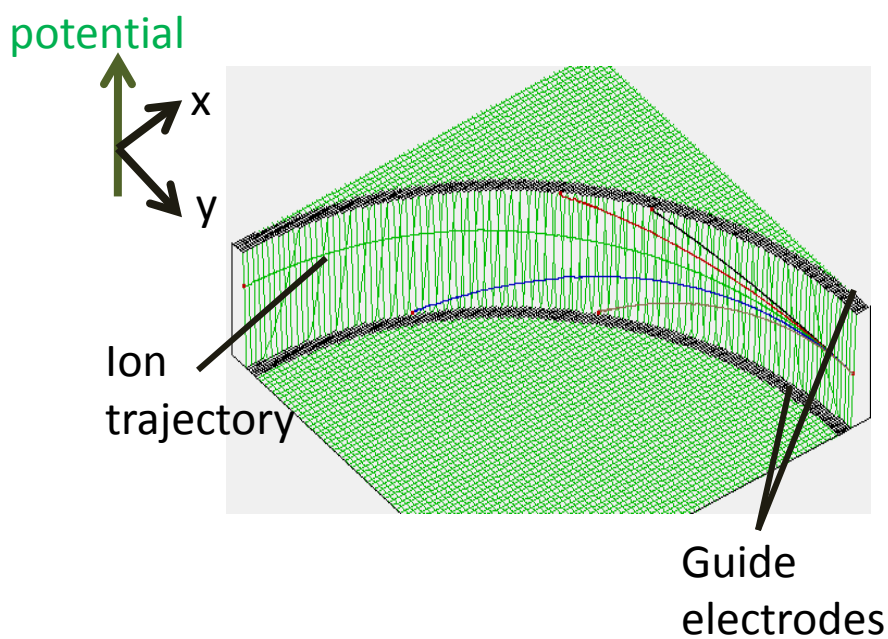
$$\frac{mv_0^{\ 2}}{r_e} = -qE_r(r_e) = rE_e$$

$$r_e = \frac{mv_0^{\ 2}}{qE_e}$$

$$V(r) = V_1 + k\ln\left(\frac{r}{R_1}\right)$$

$$k = \frac{V_2 - V_1}{\ln\left(\frac{R_2}{R_1}\right)}$$

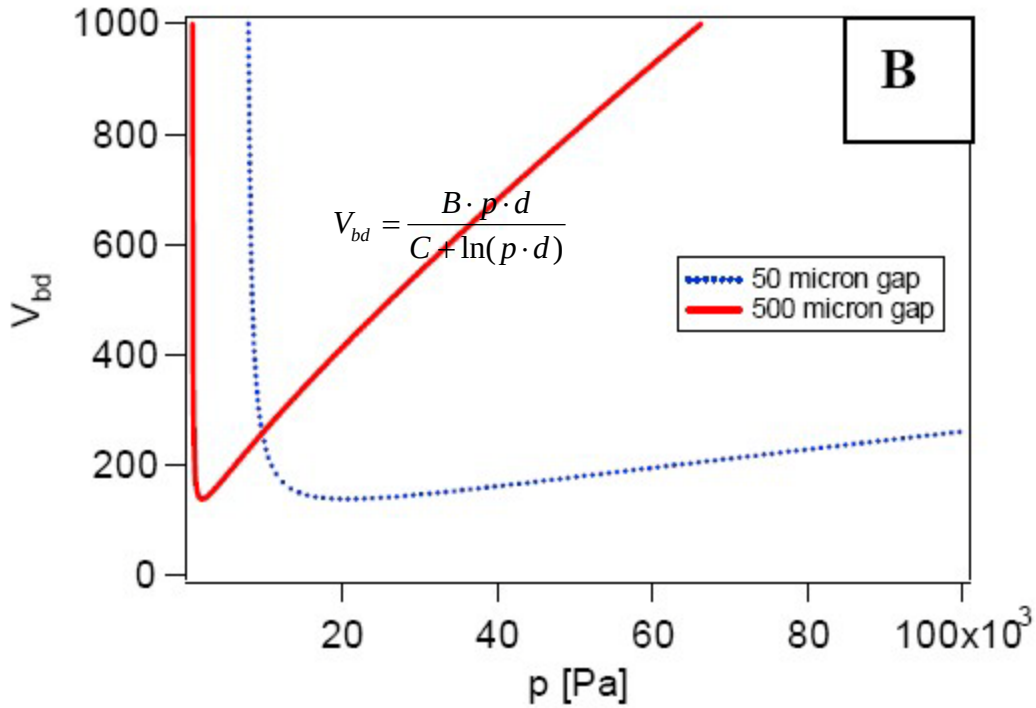
SIMION: potential landscape with particle trajectory for <u>ideal case</u>



Electrical breakdown – Paschen Breakdown

Gas	V_{bd} (min) [V]	Pd @ V_{bd} (min) [Torr-cm]
Ar	137	0.9
N_2	251	0.67
O_2	450	0.7
Air	327	0.567

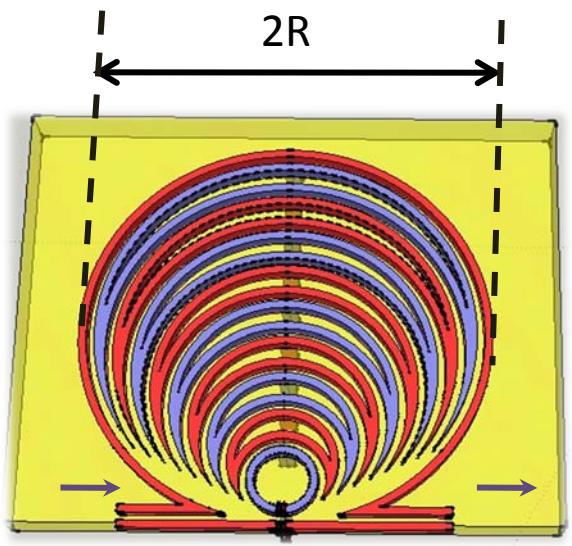
For 10um gap, need P<5uTorr
Safe to be at 1uTorr to accommodate for gaps in design

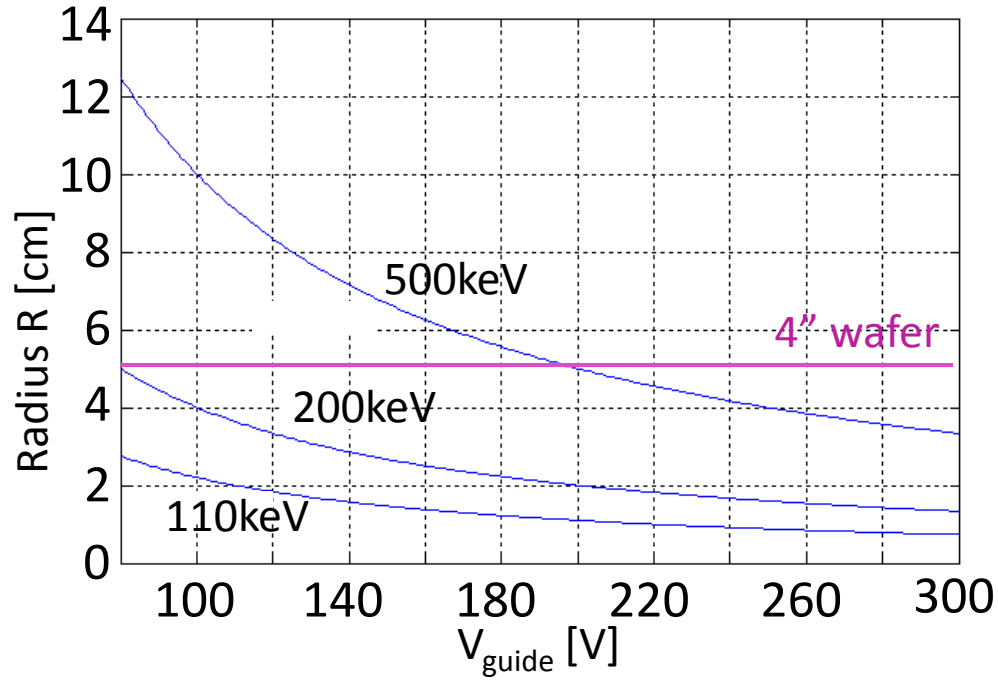


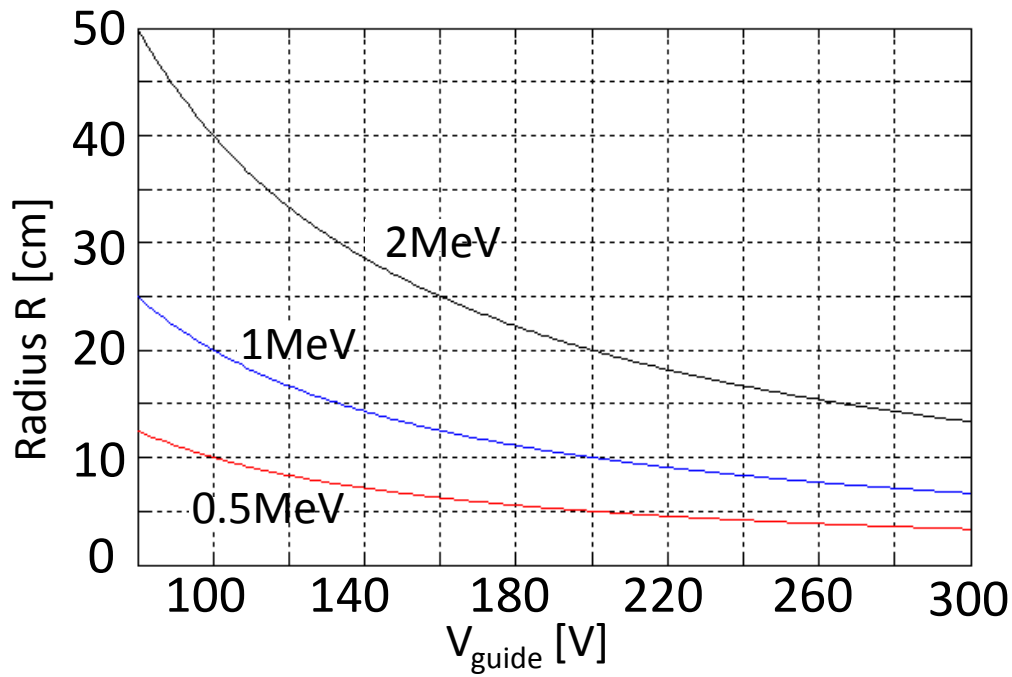
Carazzetti et. al., Proceedings of SPIE Vol 6884 (2008)

To Target KeV - MeV Energy (Protons)

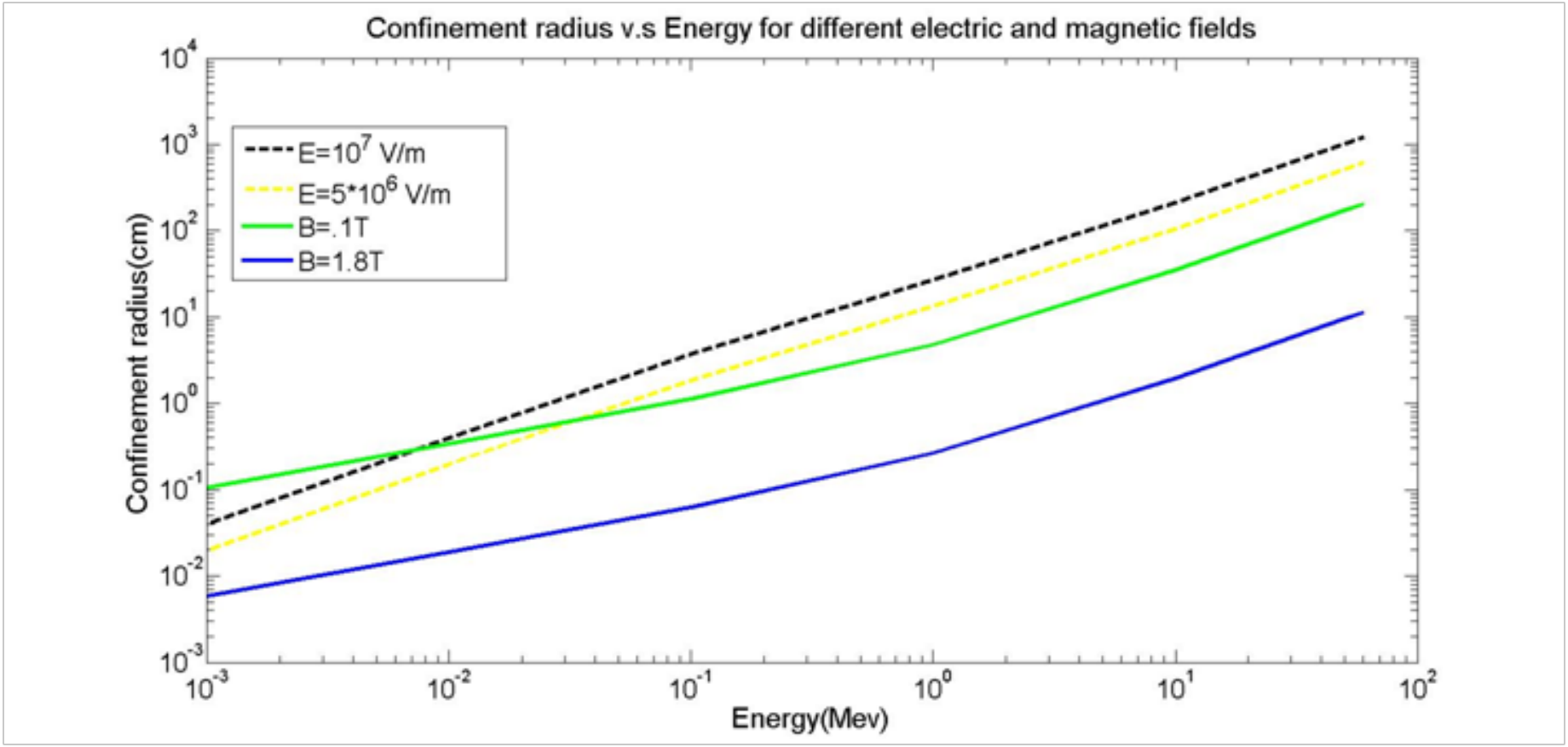
DESIGN SPACE







Confinement radius versus Electric and Magnetic Fields (Electrons)



Design Space for Proton Beams

Energy(keV)	velocity(m/s)	v/c	d (10-ns)(m)	radius of circle (cm)	voltage (10ns)(V)	TOF (100 micron distance)	Time (50v/stage)(10ns/cycle)(ns)	Frequency (Hz)(10uA beam)
1	4.37E+05	1.46E-03	4.37E-03	6.96E-02	2.87E+00	2.29E+02	200	5000000
10	1.38E+06	4.61E-03	1.38E-02	2.20E-01	9.08E+00	7.23E+01	2000	500000
100	4.37E+06	1.46E-02	4.37E-02	6.96E-01	2.87E+01	2.29E+01	20000	50000
1000	1.38E+07	4.61E-02	1.38E-01	2.20E+00	9.08E+01	7.23E+00	200000	5000
10000	4.37E+07	1.46E-01	4.37E-01	6.96E+00	2.87E+02	2.29E+00	2000000	500
100000	1.38E+08	4.61E-01	1.38E+00	2.20E+01	9.08E+02	7.23E-01	20000000	50

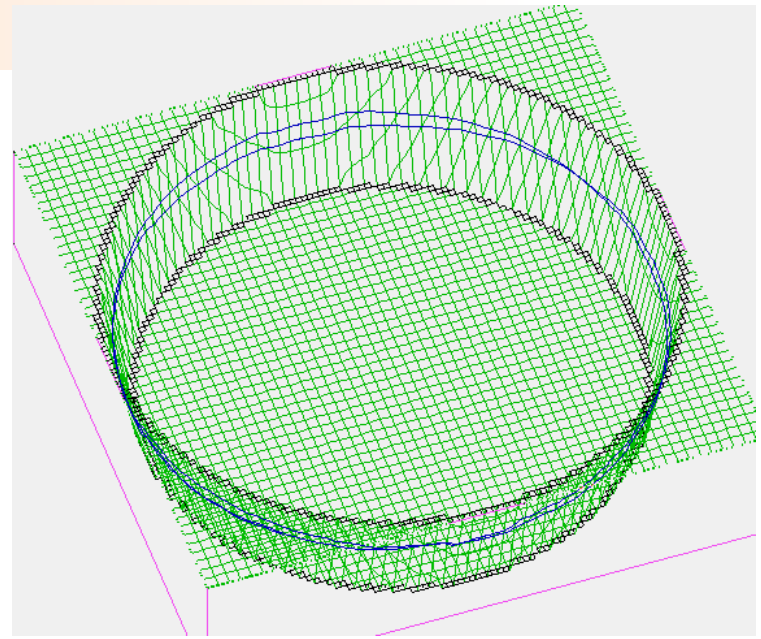
- **10ns transit time – 100MHz clocking**
- **50 Volt acceleration per stage**
- **100-micron accelerating stage**
- **10 uA beam output**

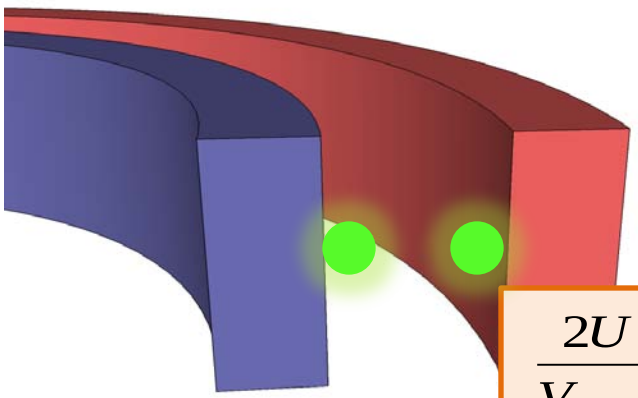
$$V = 2 * E_p \frac{g}{r}$$

ION BEAM GUIDANCE

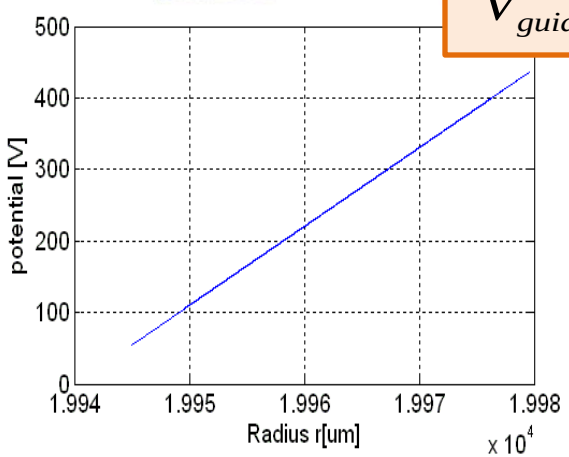
Balance between Kinetic & Potential Energies

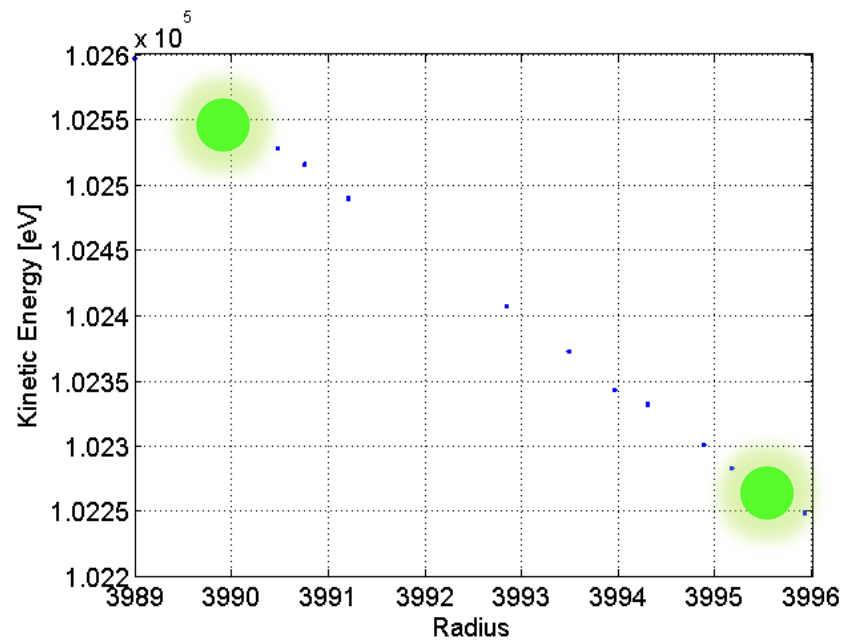
$$U_{tot} = \frac{1}{2} m v_0^2 + q\phi$$



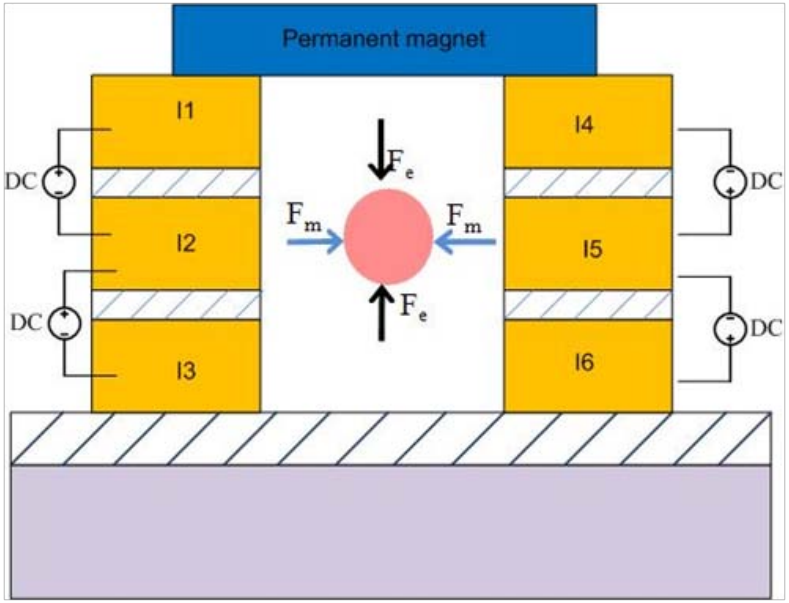


$$\frac{2U}{V_{guide}} \approx \frac{r}{w}$$

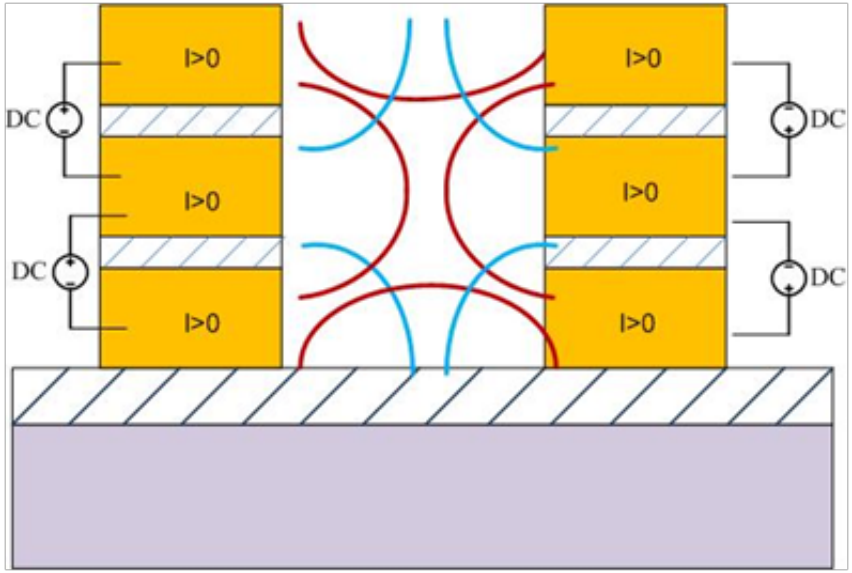




Confinement Techniques

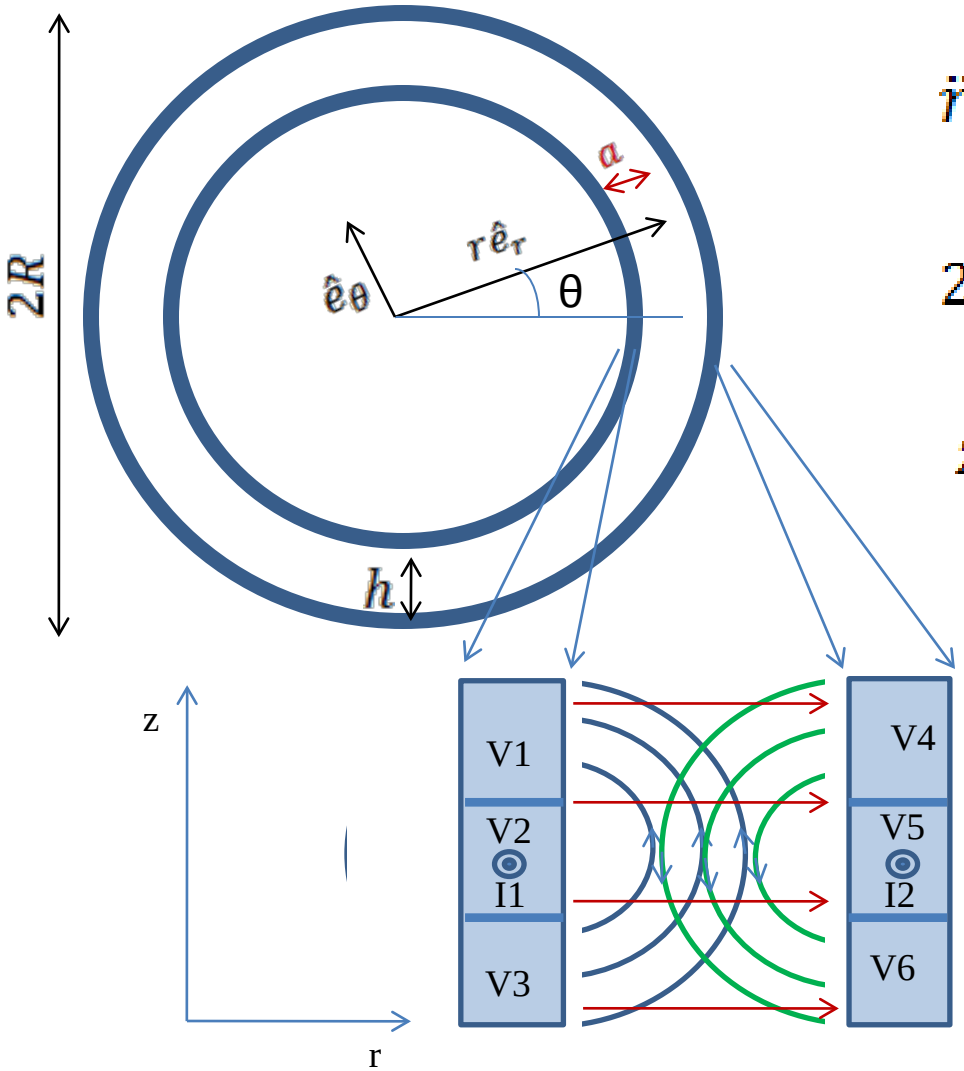


Electromagnetic forces on electron in the guiding channel in the guiding channel



Realization of electric and magnetic quadrupoles

Equations of motion for Radially Symmetric Ion=Electron Waveguide



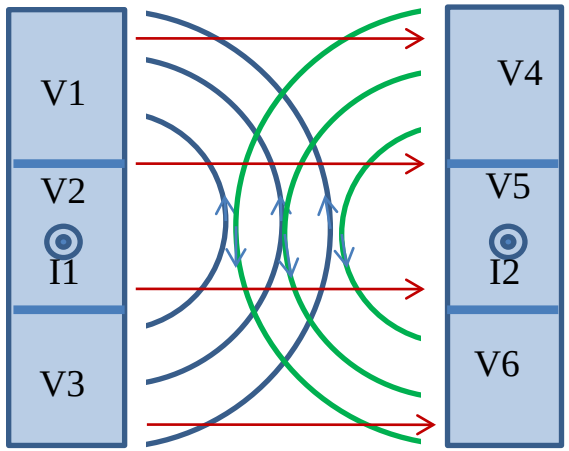
$$\ddot{r} - r\dot{\theta}^2 = \frac{q}{m}(E_r + r\dot{\theta}B_z)$$

$$2\dot{r}\dot{\theta} + r\ddot{\theta} = \frac{q}{m}(\dot{z}B_r - \dot{r}B_z)$$

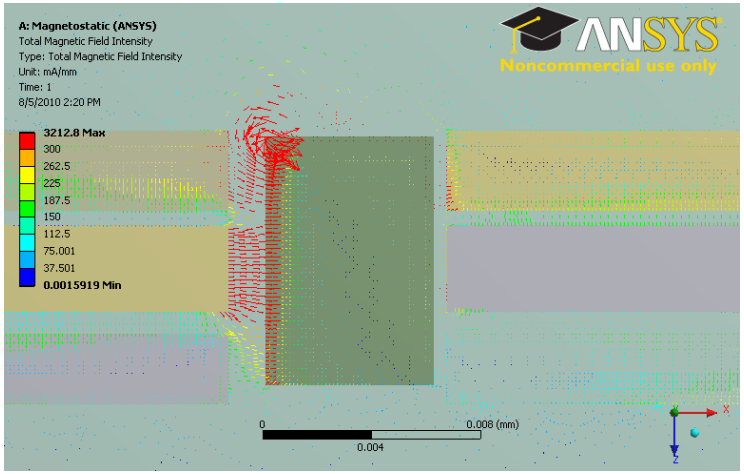
$$\ddot{z} = \frac{q}{m}(E_z - r\dot{\theta}B_r)$$

Real time code written in MATLAB for determination of ion track in presence of electrical and magnetic fields

Electrical and Magnetic Field Calculations

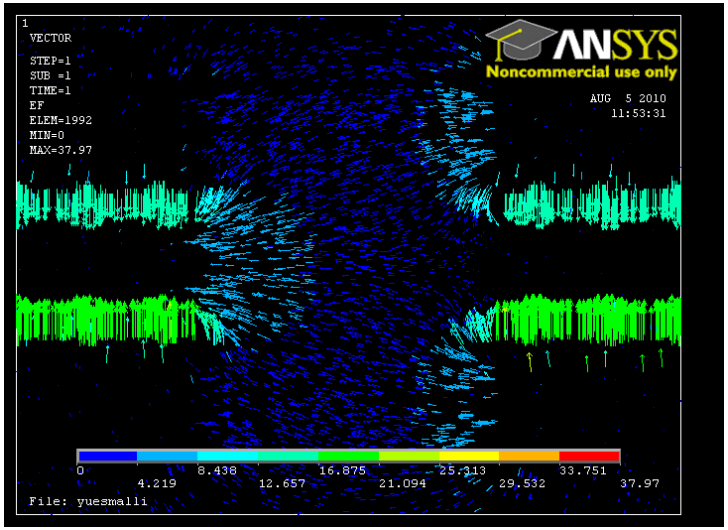


Electric and magnetic fields simulations

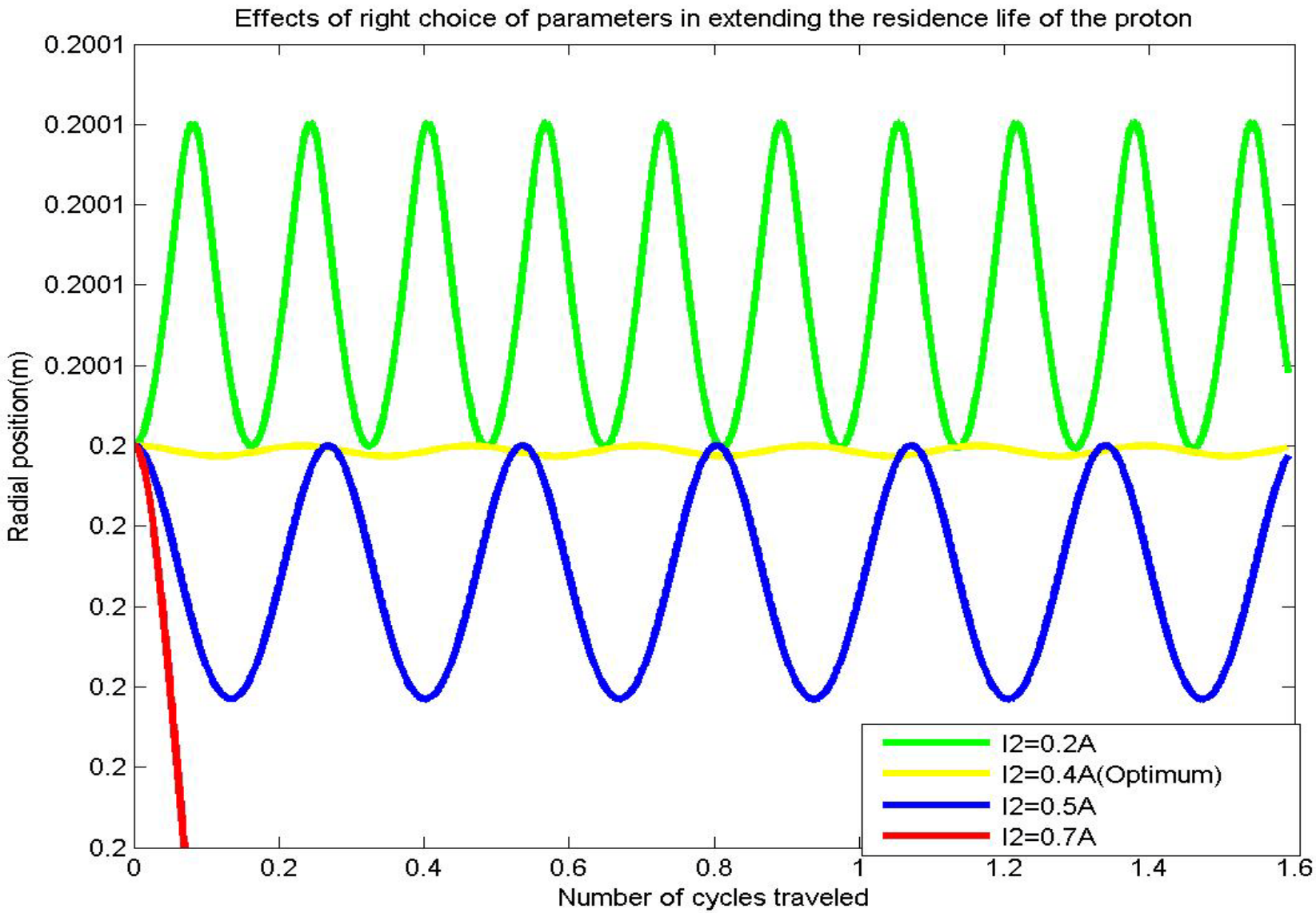


- Magnetic and Electrical fields can be extracted from ANSYS from any given voltages and currents on waveguides.

- Extracted fields can be used in MATLAB to calculate charged particle trajectories

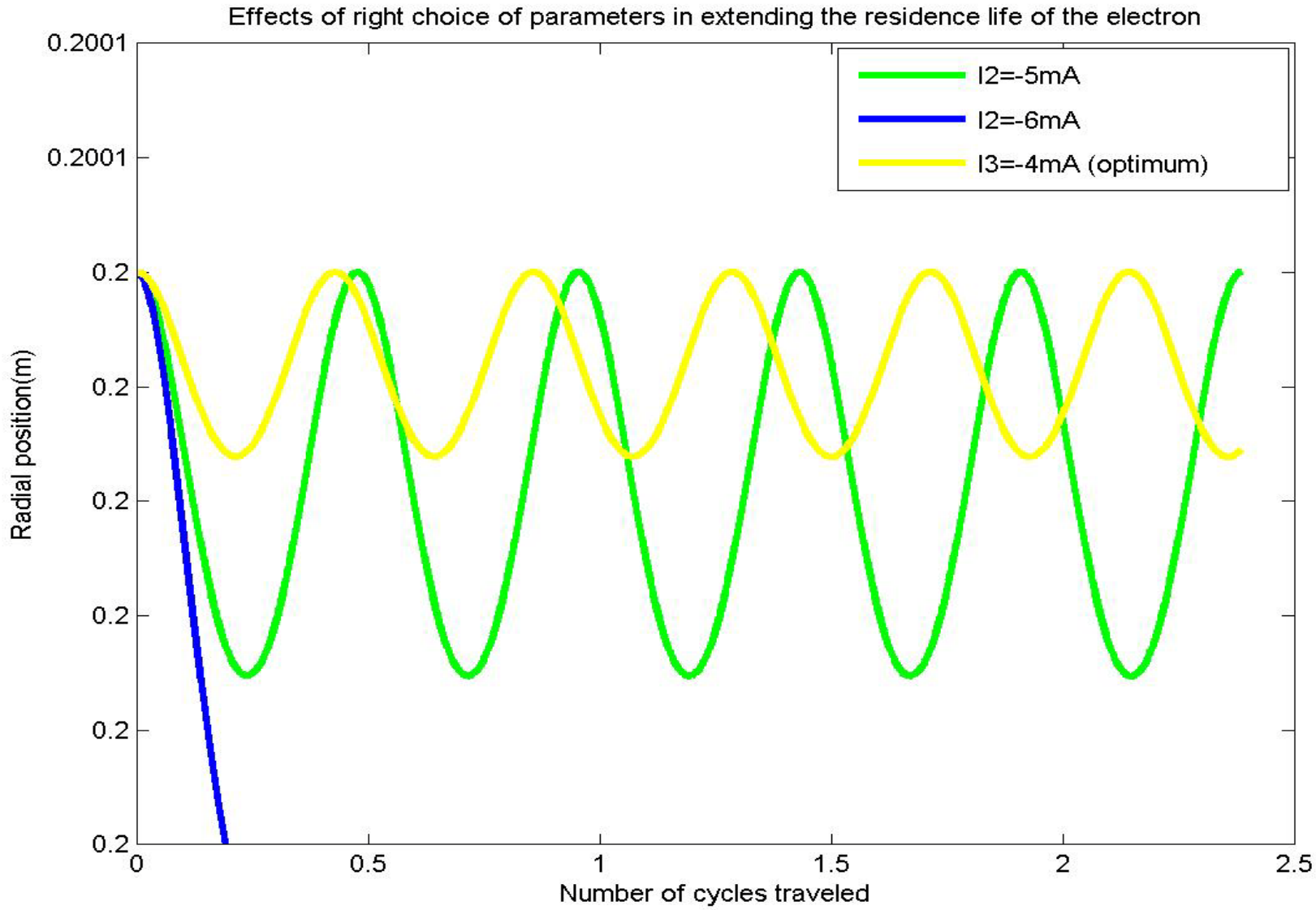


200 keV proton path: The right choice of design parameters can greatly increase the residence time of the particle



*Sonic*MEMS Laboratory, Cornell University

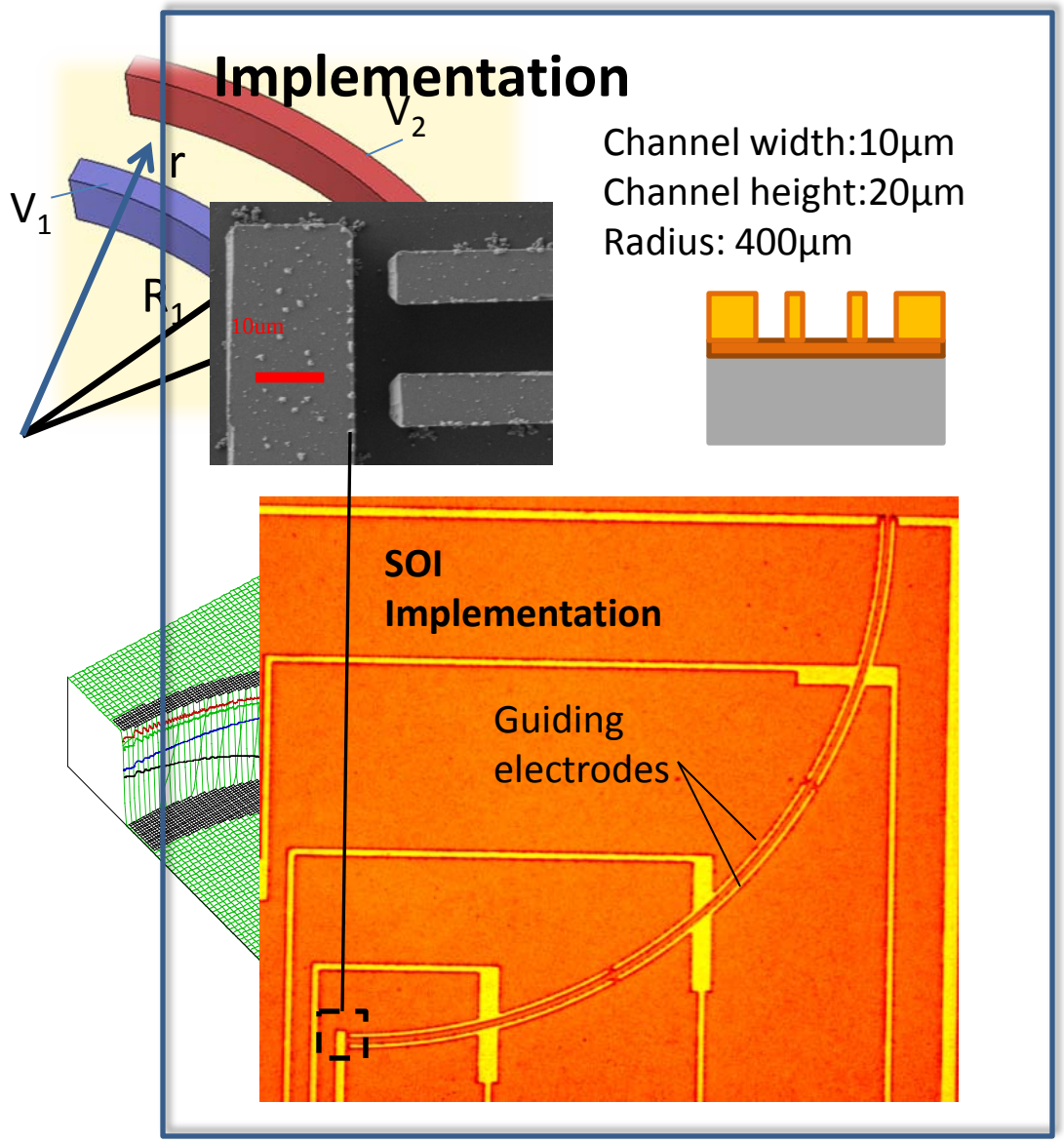
1 MeV electron path: The right choice of design parameters can greatly increase the residence time of the particle



*Sonic*MEMS Laboratory, Cornell University

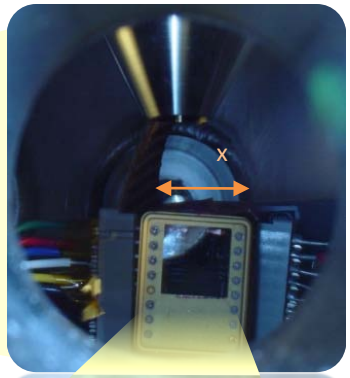
Argon Ion Guidance Experiments

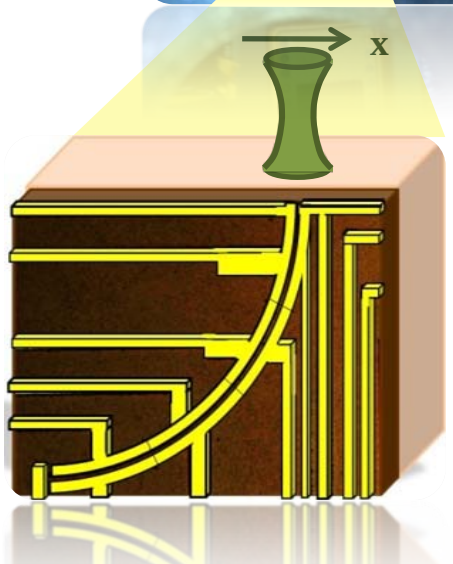
ION BEAM GUIDANCE



ORIGINAL SETUP

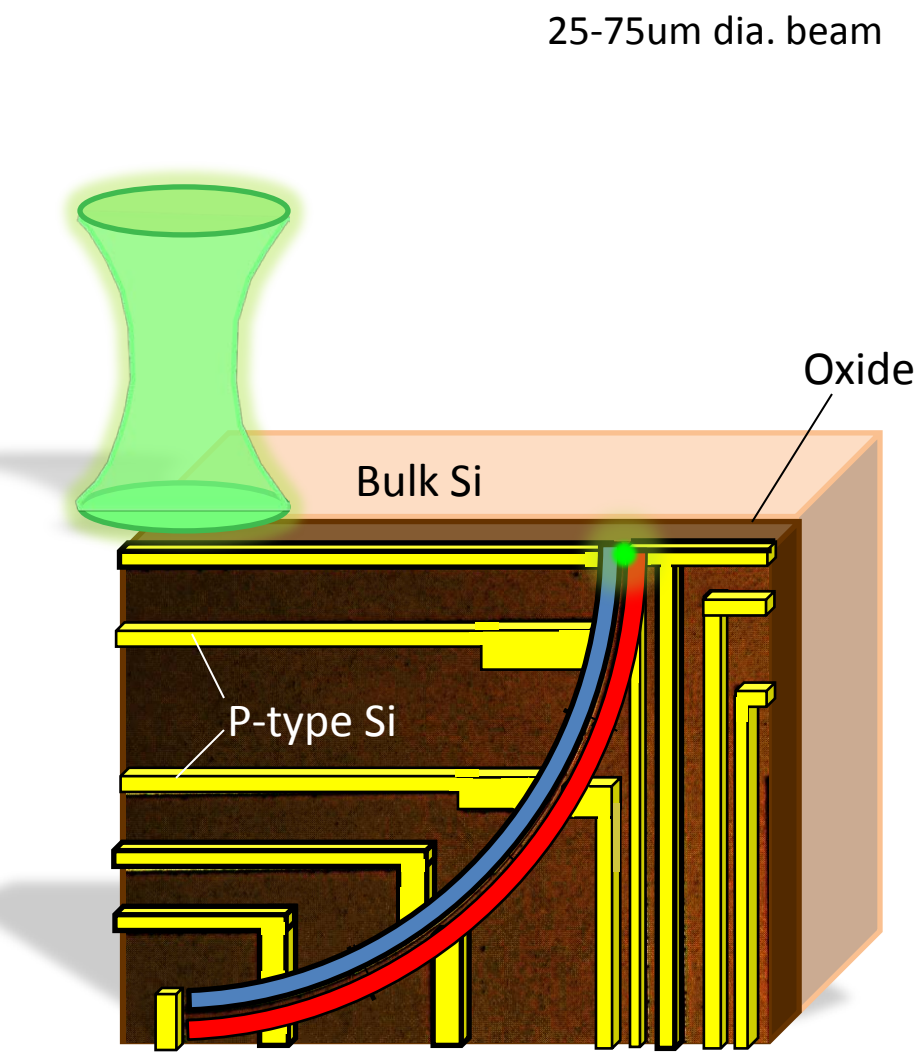
- Beam energy range 0.1keV – 5.0keV
- Working at 1.5keV
- Argon ion beam (2 – 5 uA)
- Other gases possible e.g. hydrogen, oxygen
- Pressure: ~10^{-6} Torr



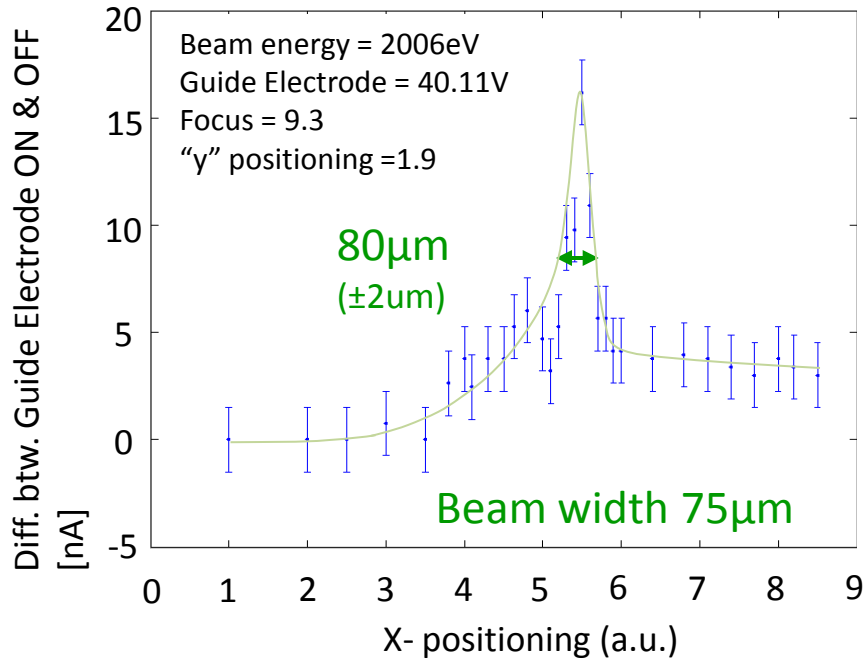


ION BEAM GUIDANCE

Alignment into chip



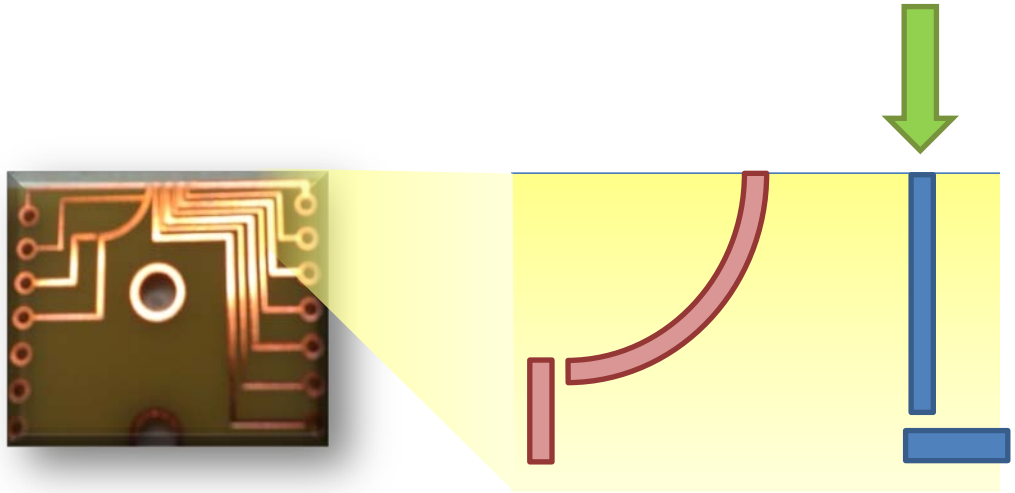
Result (SOI)

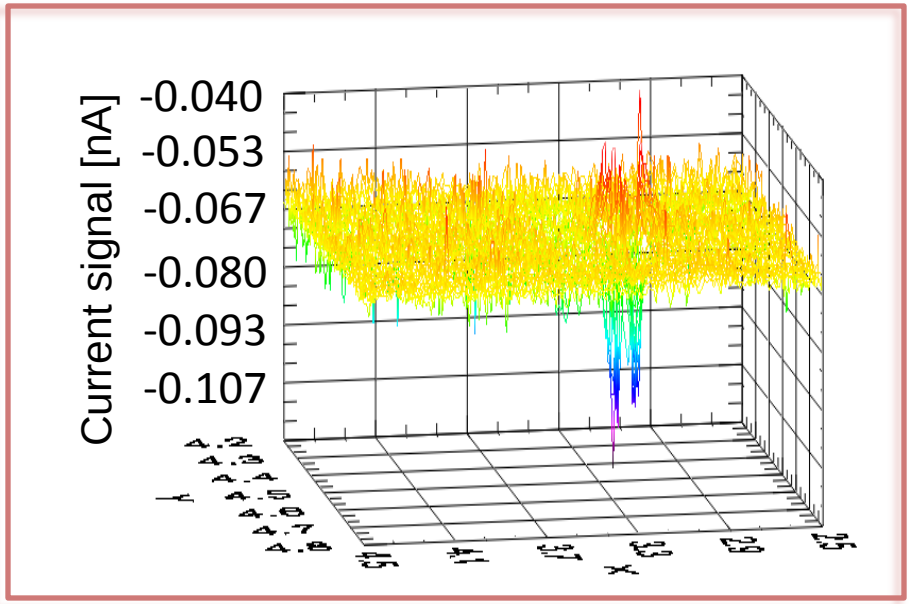


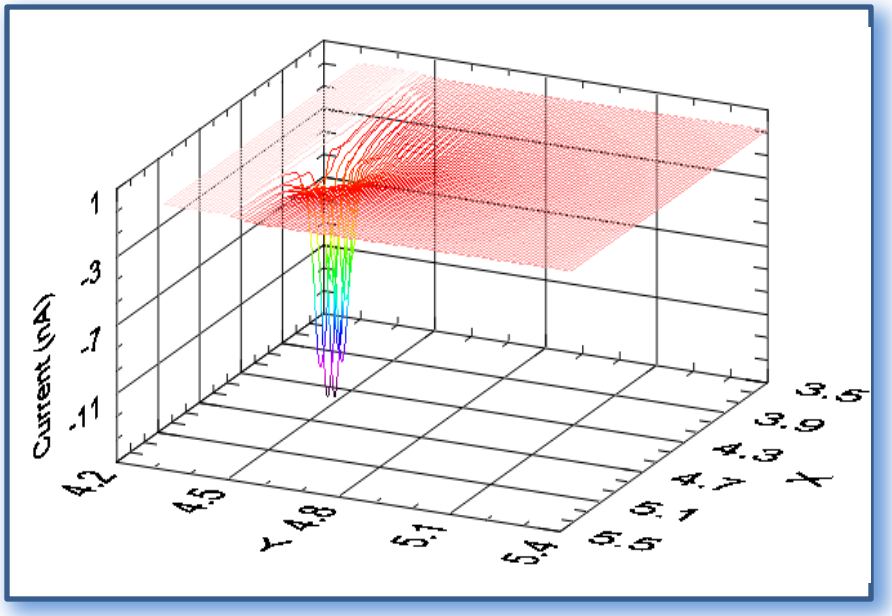
- SOI channel width 10µm.
- Signal current I_{on} : when V_{guide} is ON.
- Background I_{off} : V_{guide} is OFF.
- Plotted I_{on}-I_{off} shows ion beam is guided.

ION BEAM GUIDANCE

On Printed Circuit Board

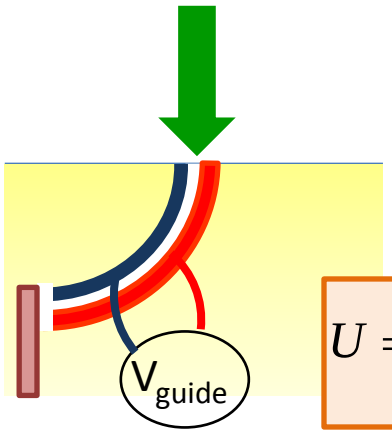




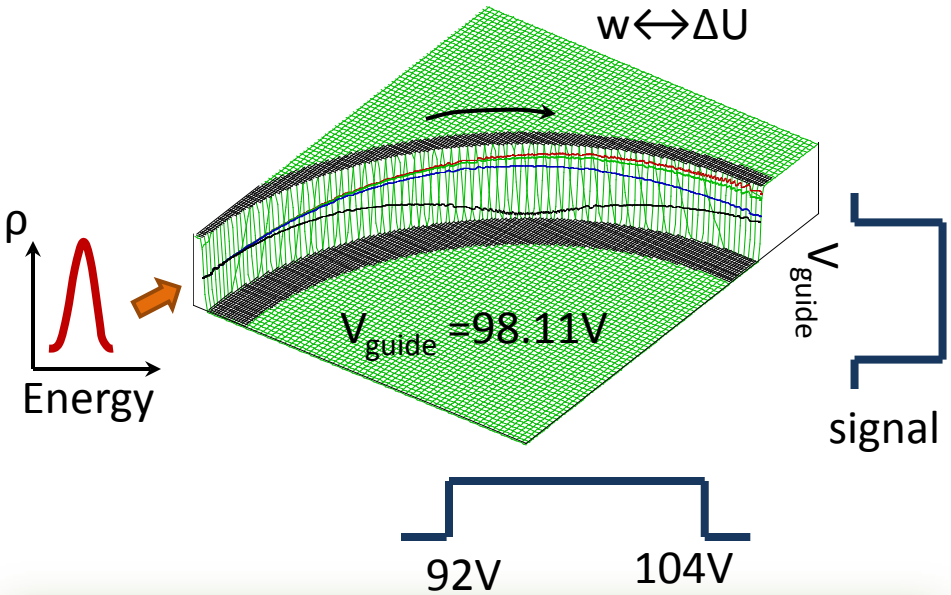


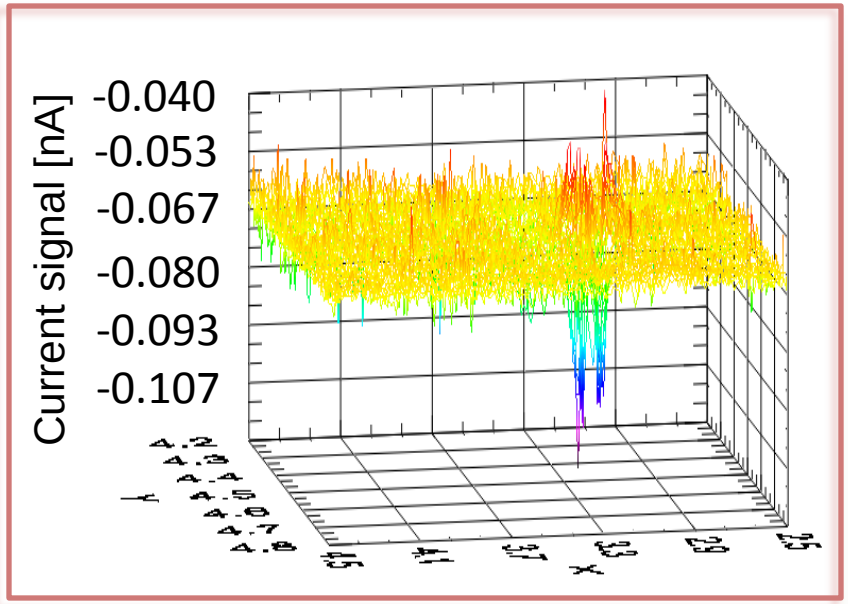
ION BEAM GUIDANCE

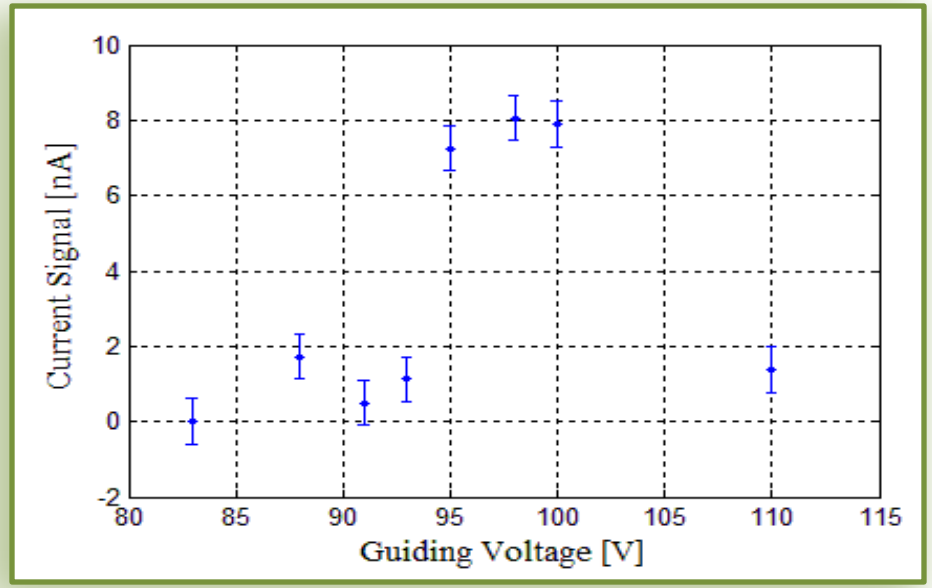
On PCB at Various Ion Energies



$$U = \frac{r}{2w} V_{guide}$$

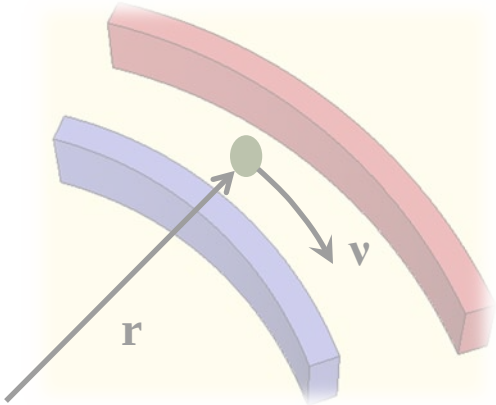




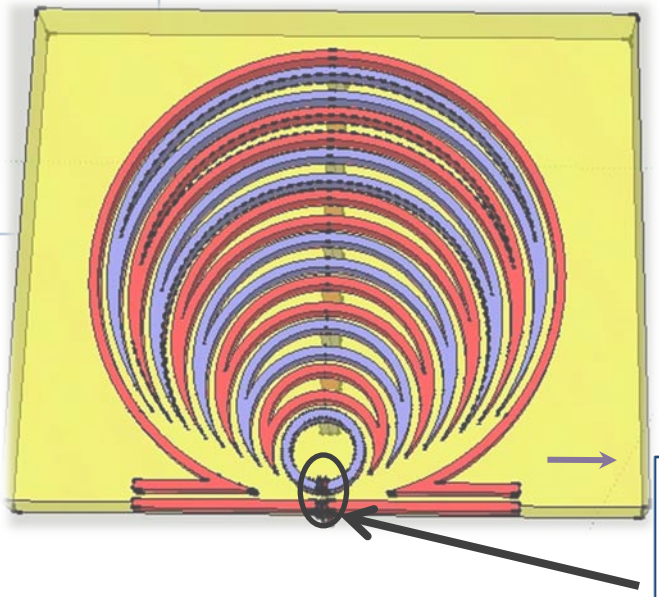


THE GOAL

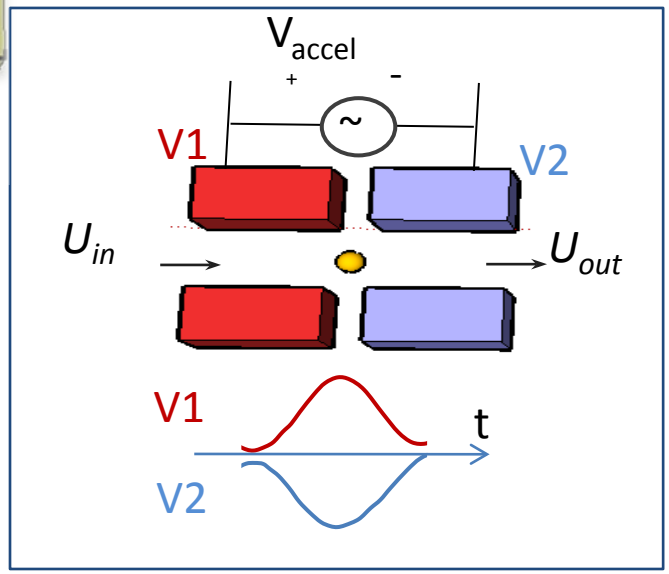
Guide Electrodes



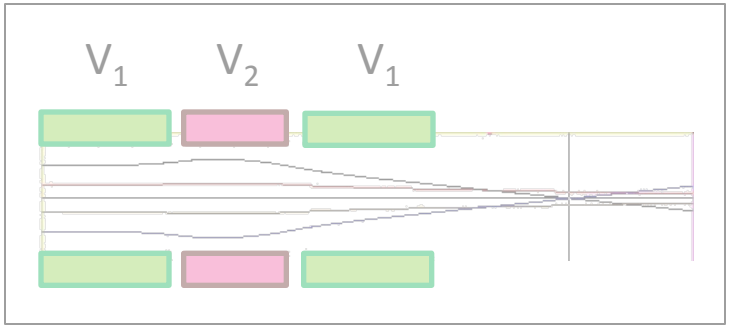
Ion Guidance

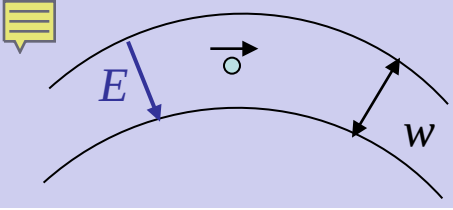


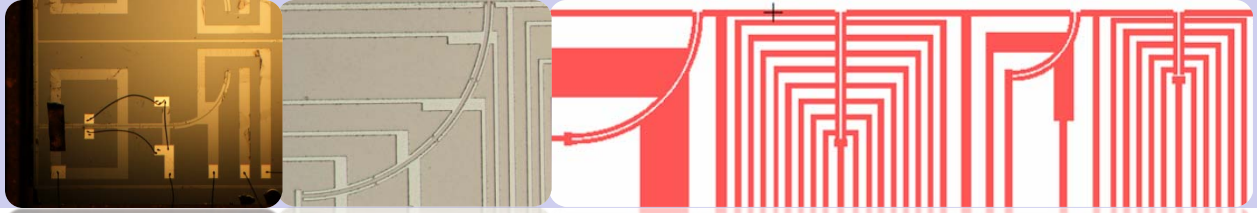
Ion Accelerator



Focusing







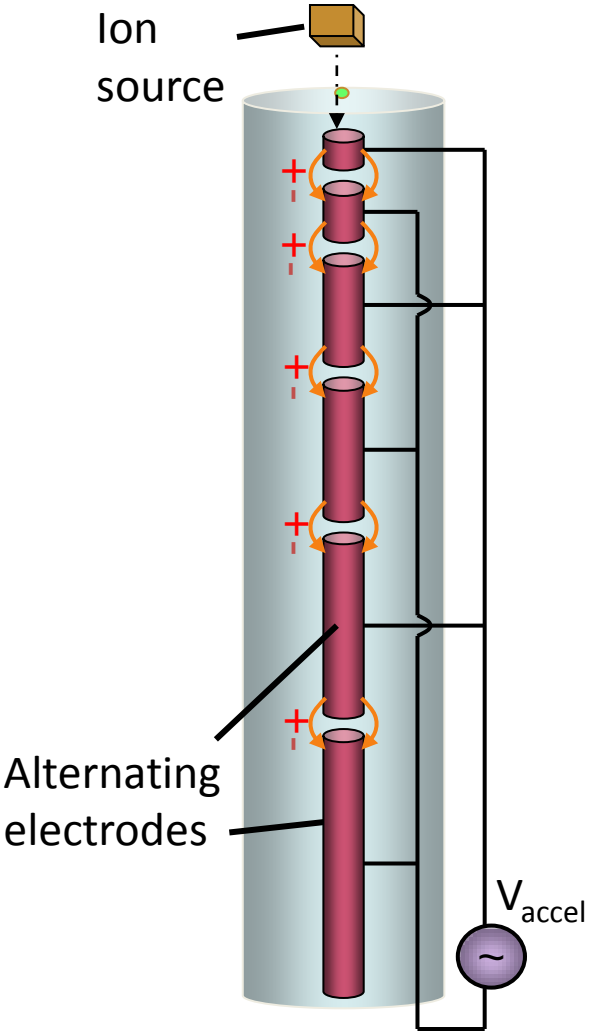
I. Why are we doing this?

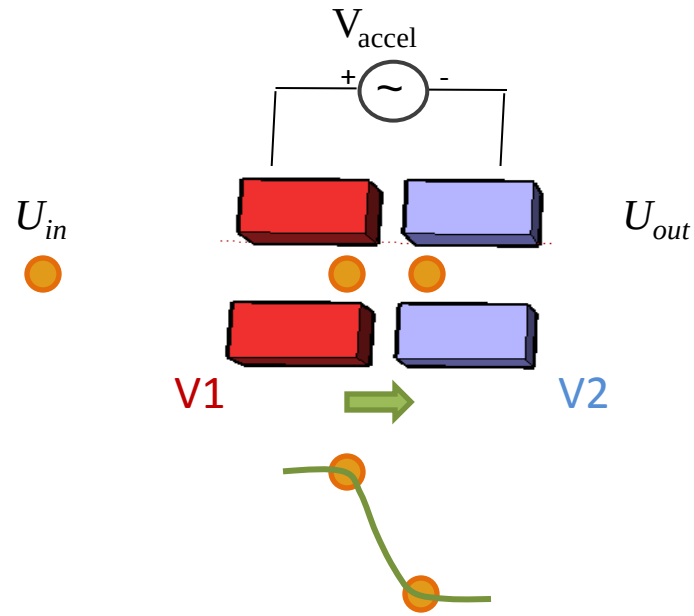
II. Beam guidance on chip

III. Particle acceleration

IV. Summary

ION ACCELERATION





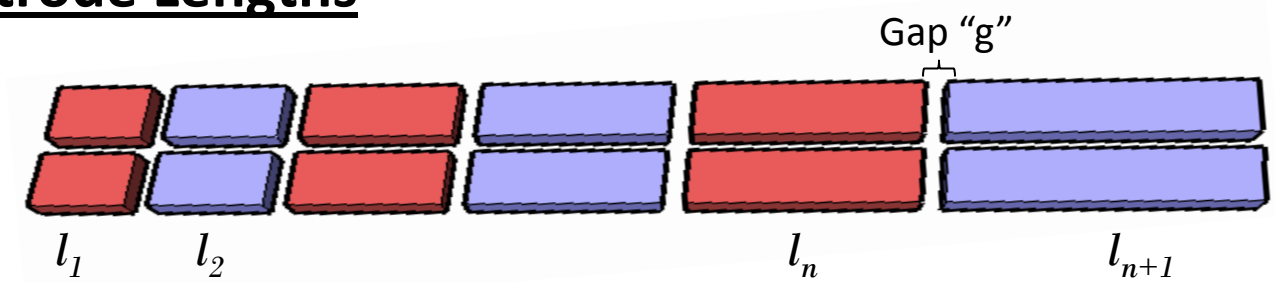
Ion Acceleration Component

Ion with initial energy U_{in} will be accelerated to

$$U_{out} = U_{in} + qV_{accel}$$

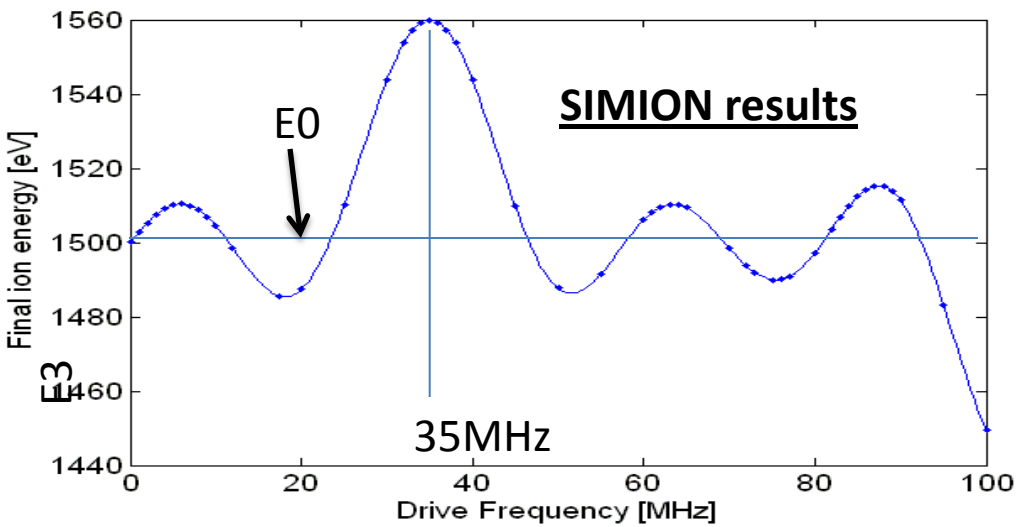
ION ACCELERATION ⇒ Design Factors

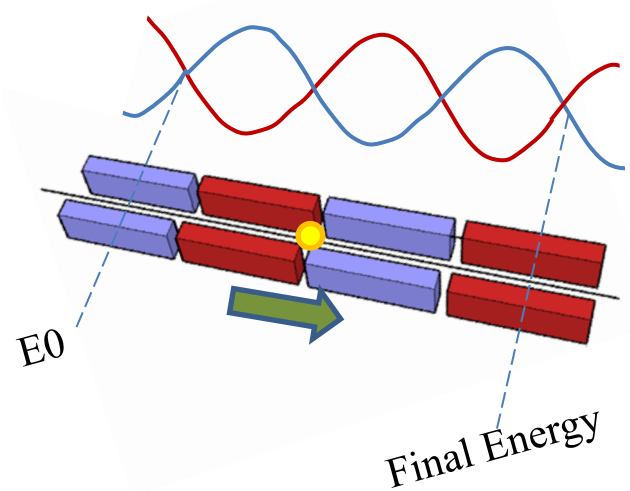
1. Electrode Lengths



$$l_{n+1} = \frac{v_n}{2f} = \frac{1}{2f}\sqrt{\frac{2q}{m}\left(V_0 + nV_{accel}\right)}$$

2. Frequency of RF-driven electrodes

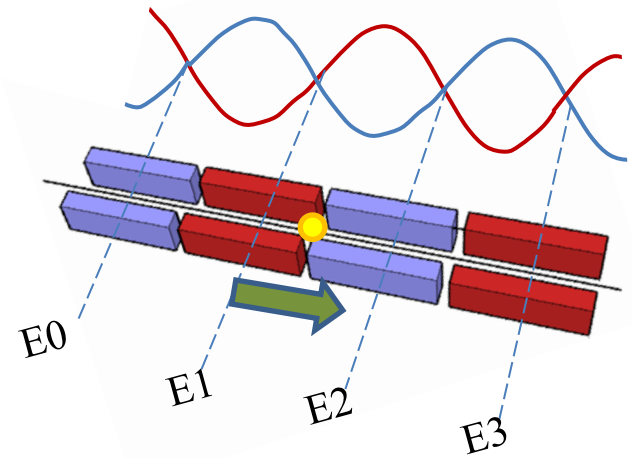


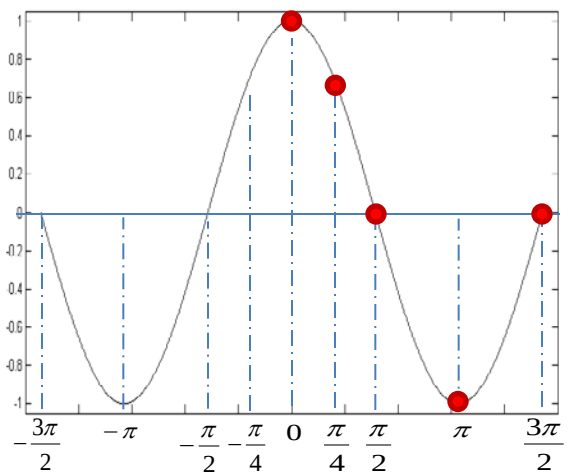


ION ACCELERATION → Design Factors

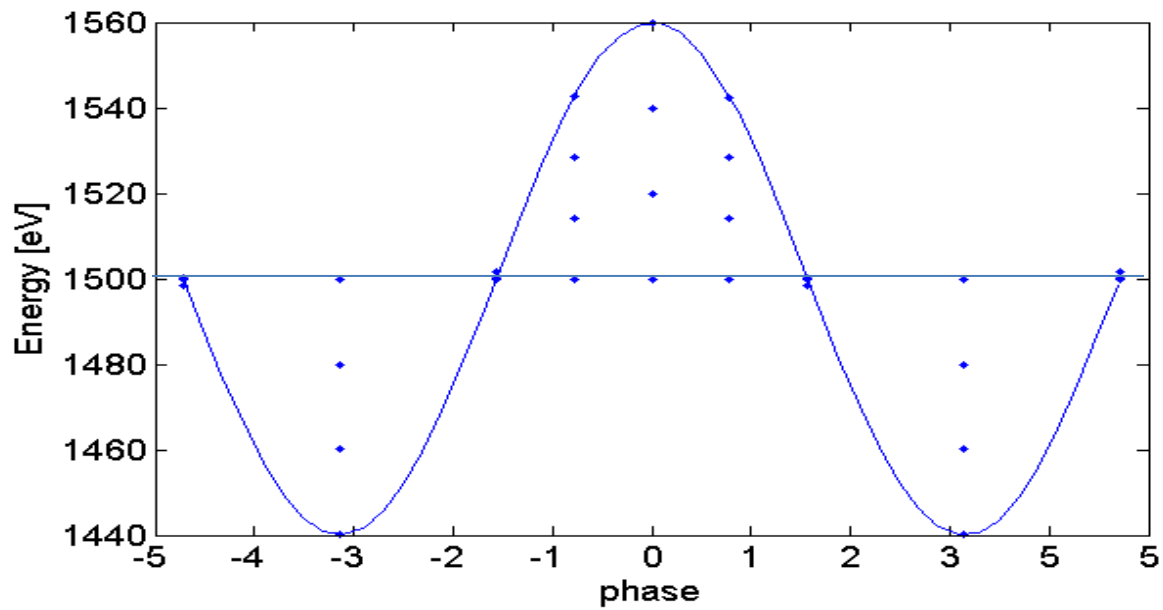
3. Particle Phase

- Ion needs to be in sync with RF E-field in gap for max. acceleration
- Particles π out of phase are decelerated
- **A spread in energy occurs**





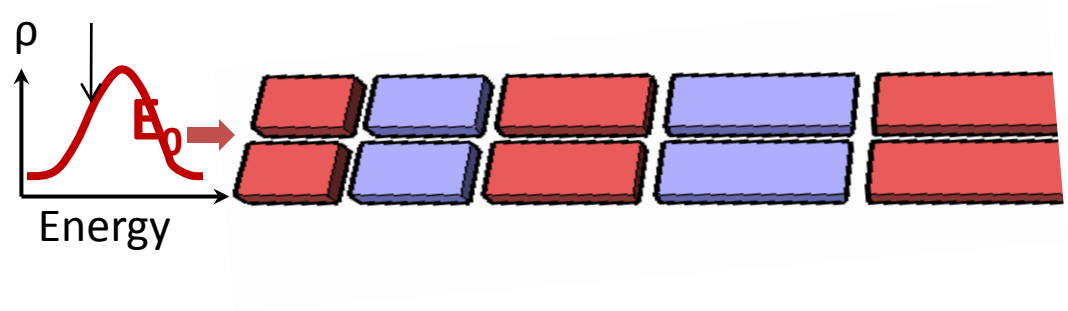
SIMION results

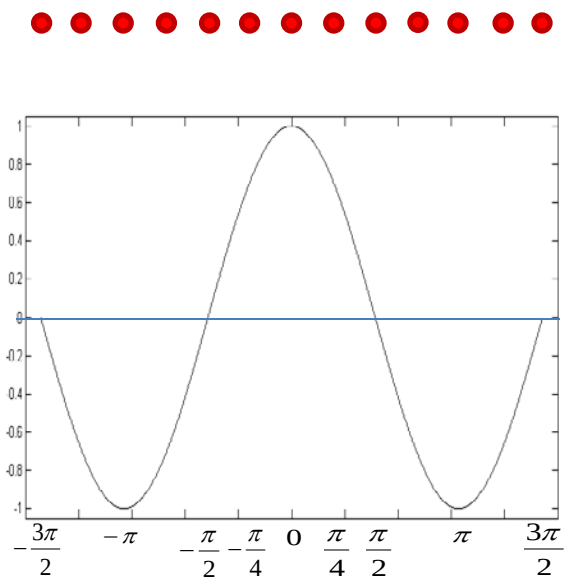


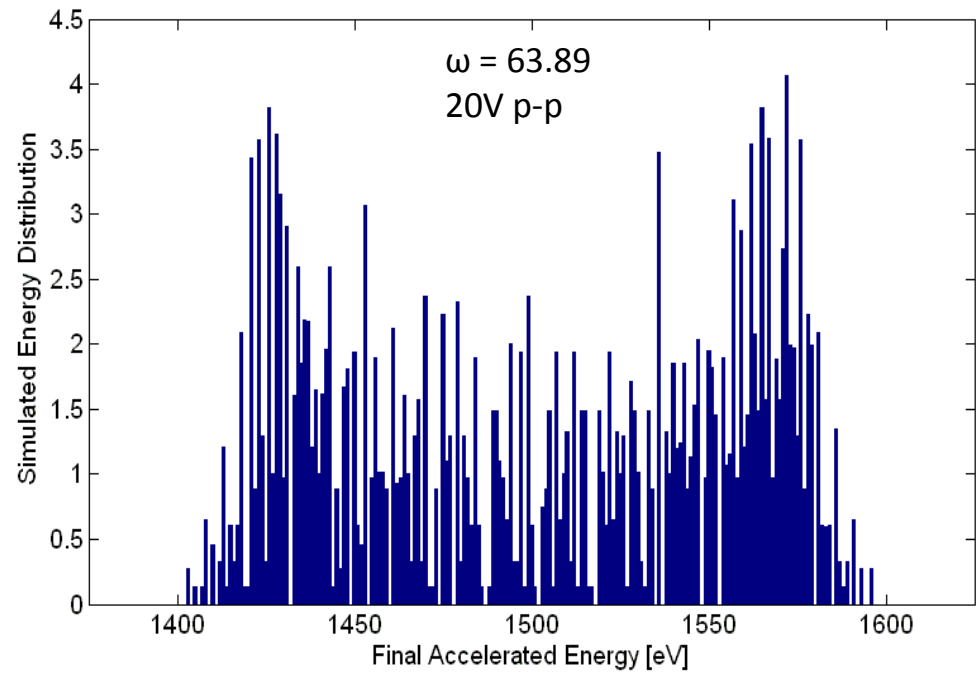
ION ACCELERATION → Design Factors

3. Particle Phase

- If assume particles enter channel in a line
- For a particle with given energy, it occupies an unique position in phase space
- Gaussian spread in energy





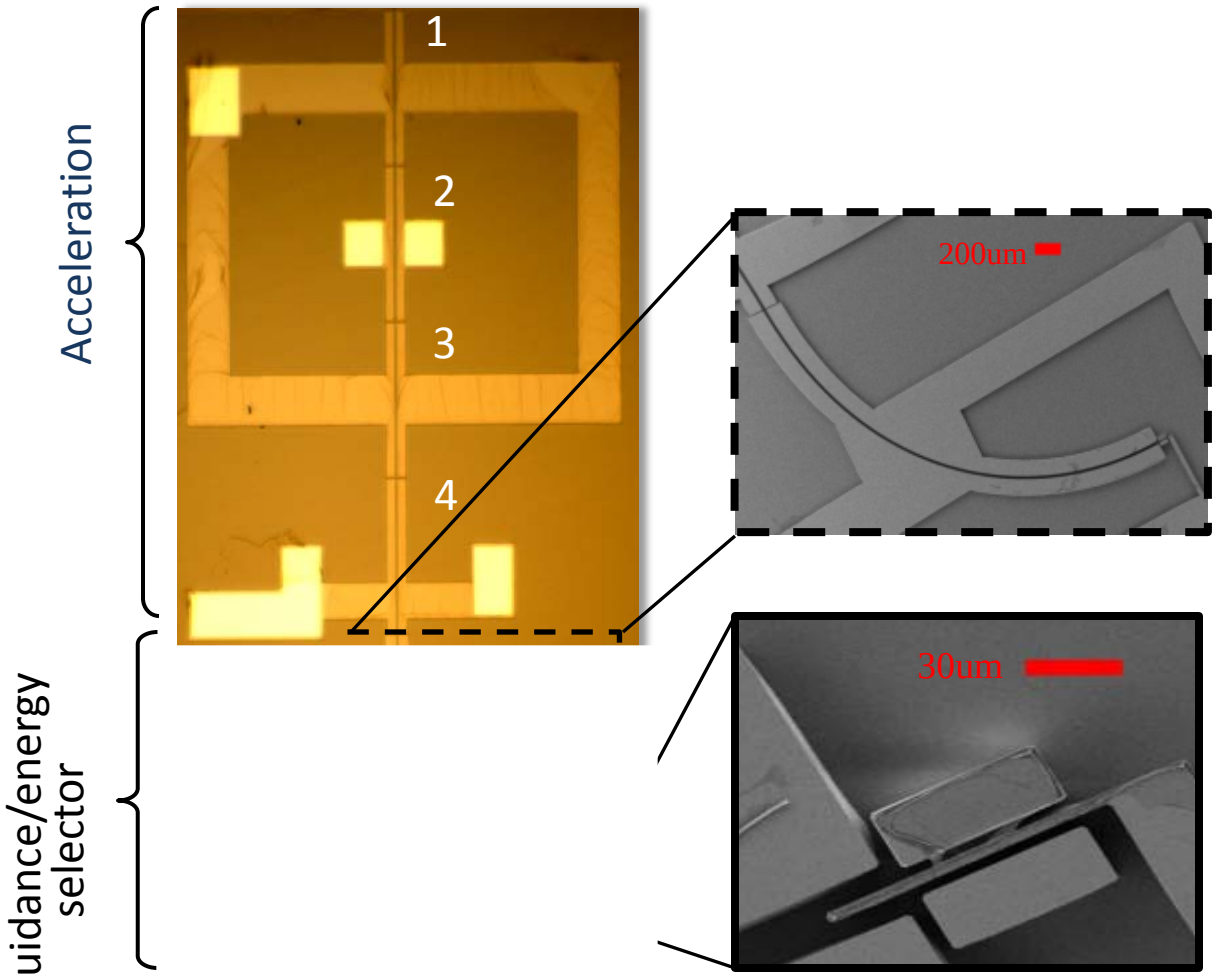


ION ACCELERATION → SOI Implementation

Driven at 35MHz

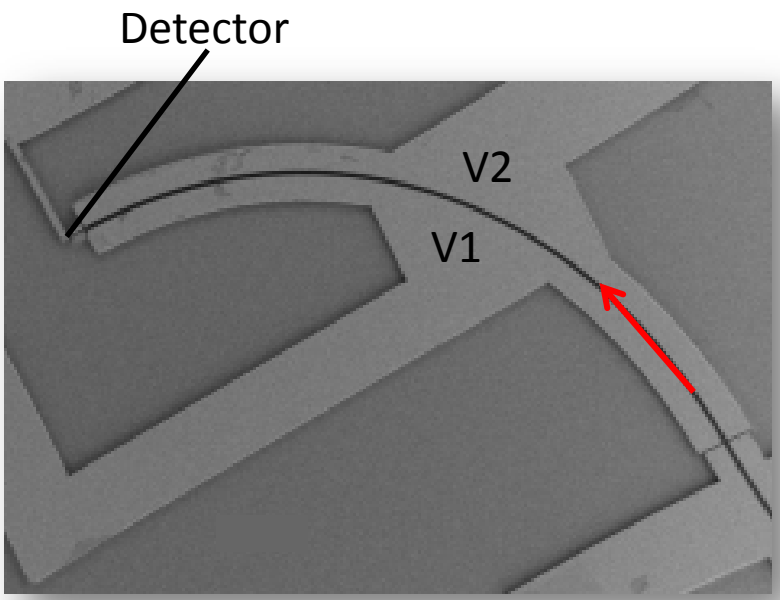
Gap gain:20eV

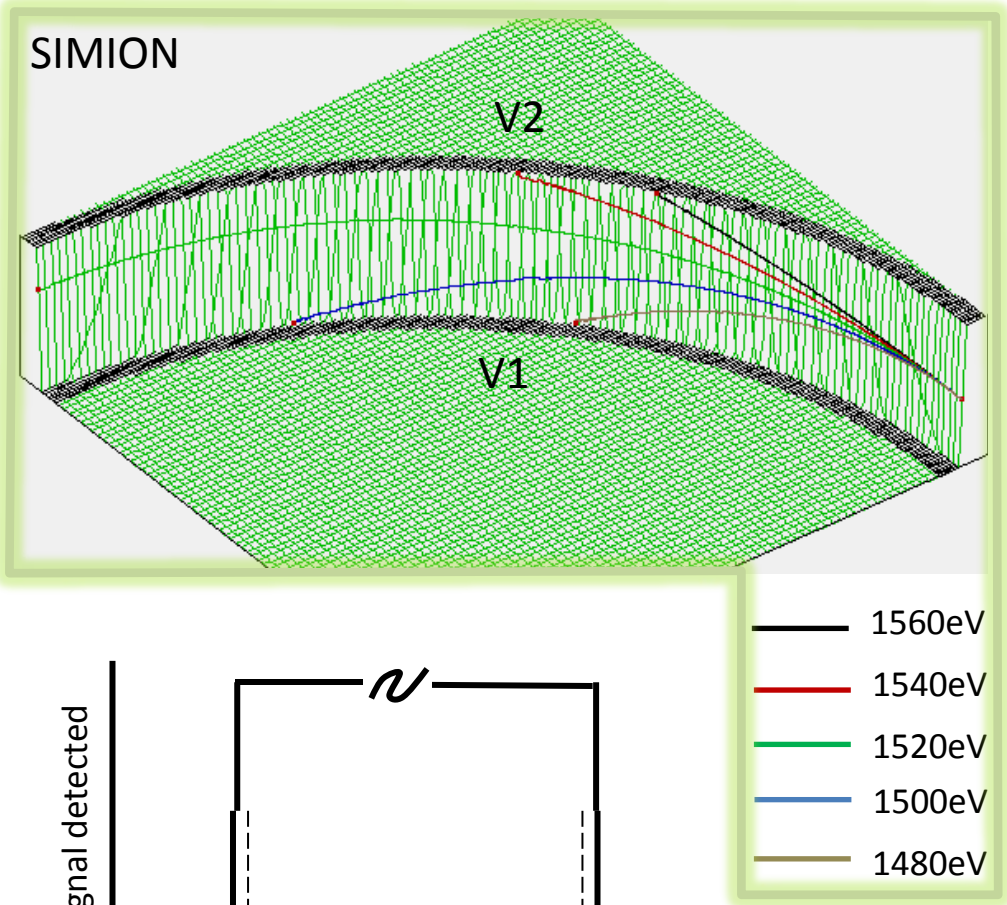
Total gain: 60eV



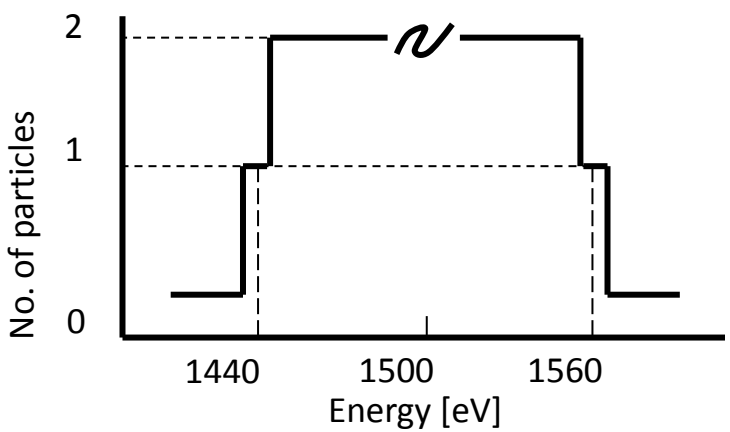
Sensor electrode

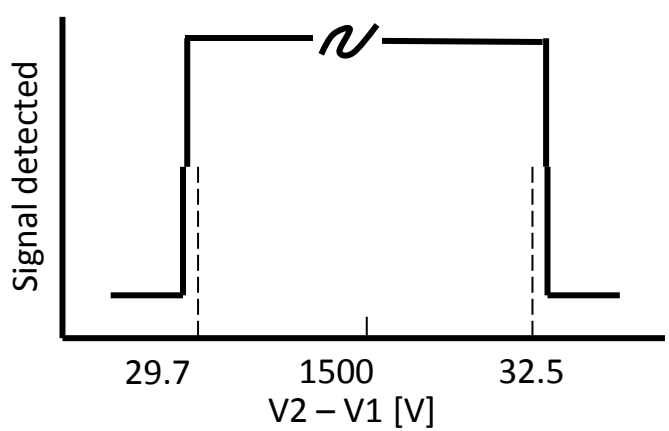
90^0 Guide as an Energy Selector



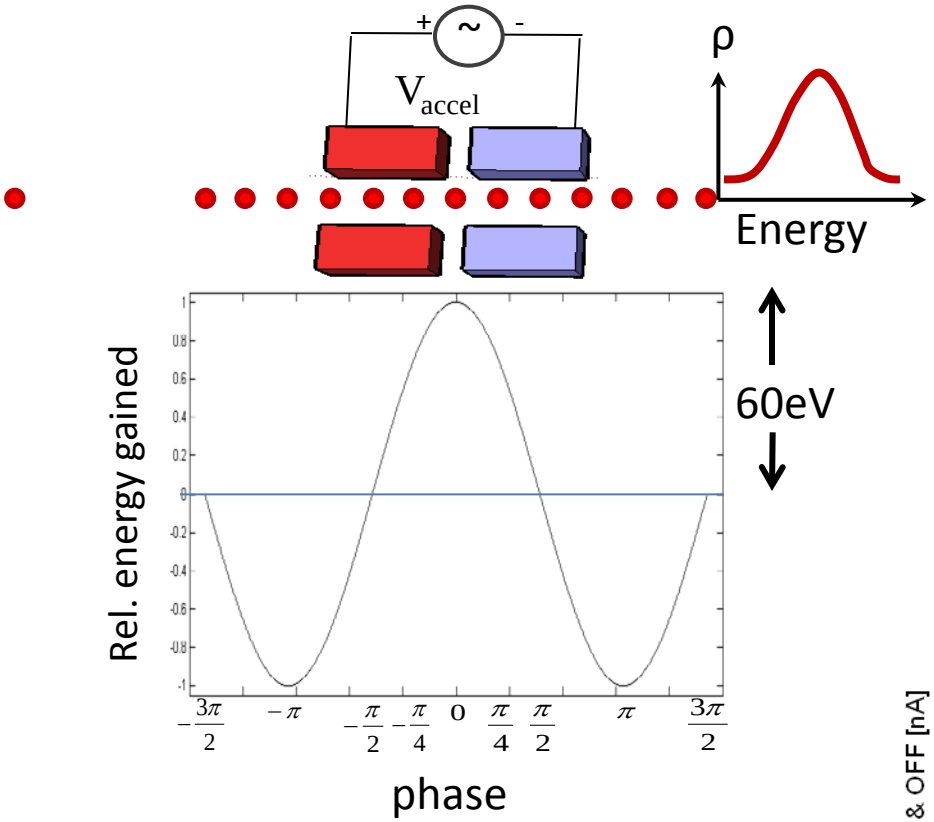


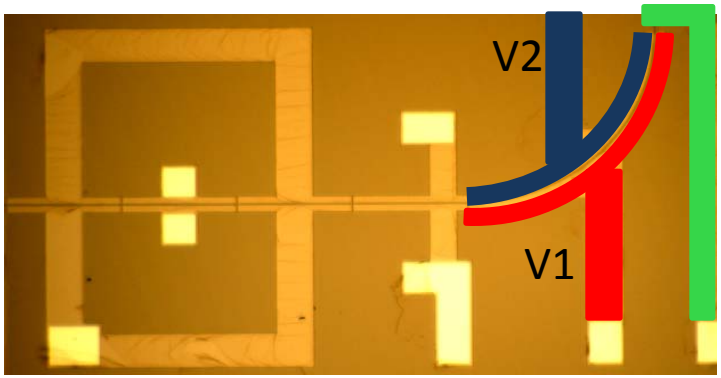
If one particle occupies each phase:

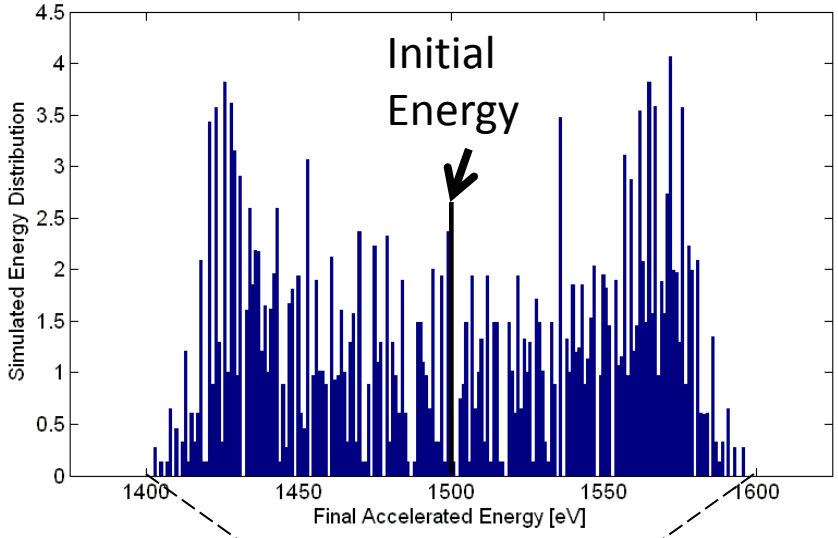


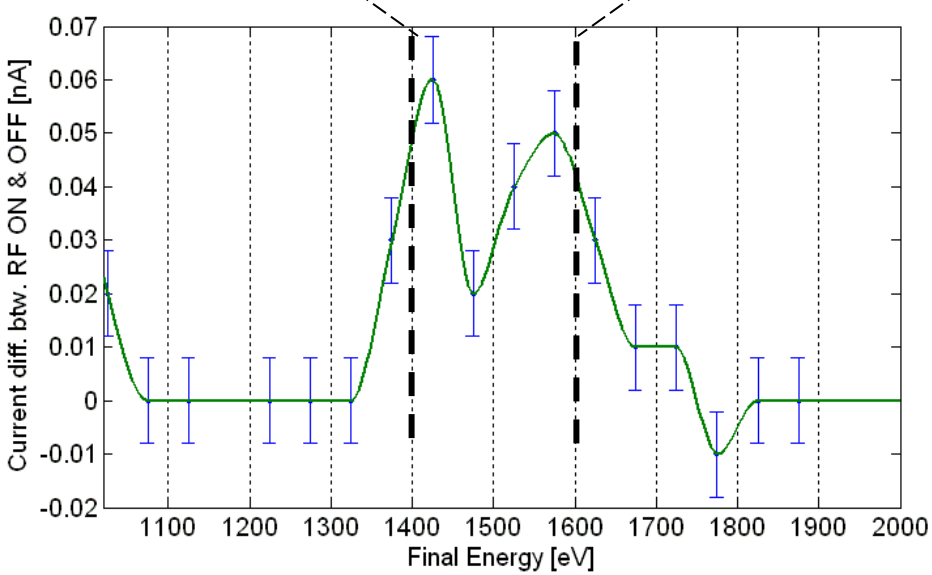


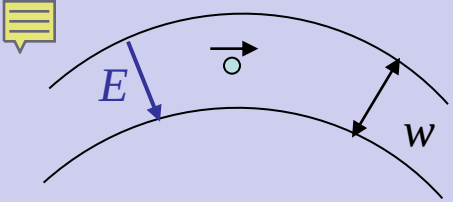
ION ACCELERATION → Preliminary Results

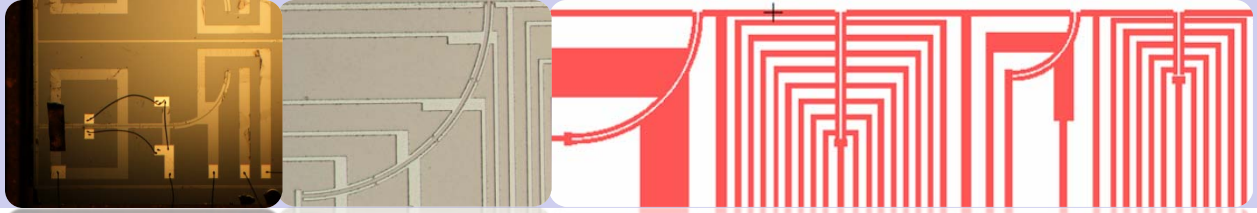












I. Why are we doing this?

II. Beam guidance on chip

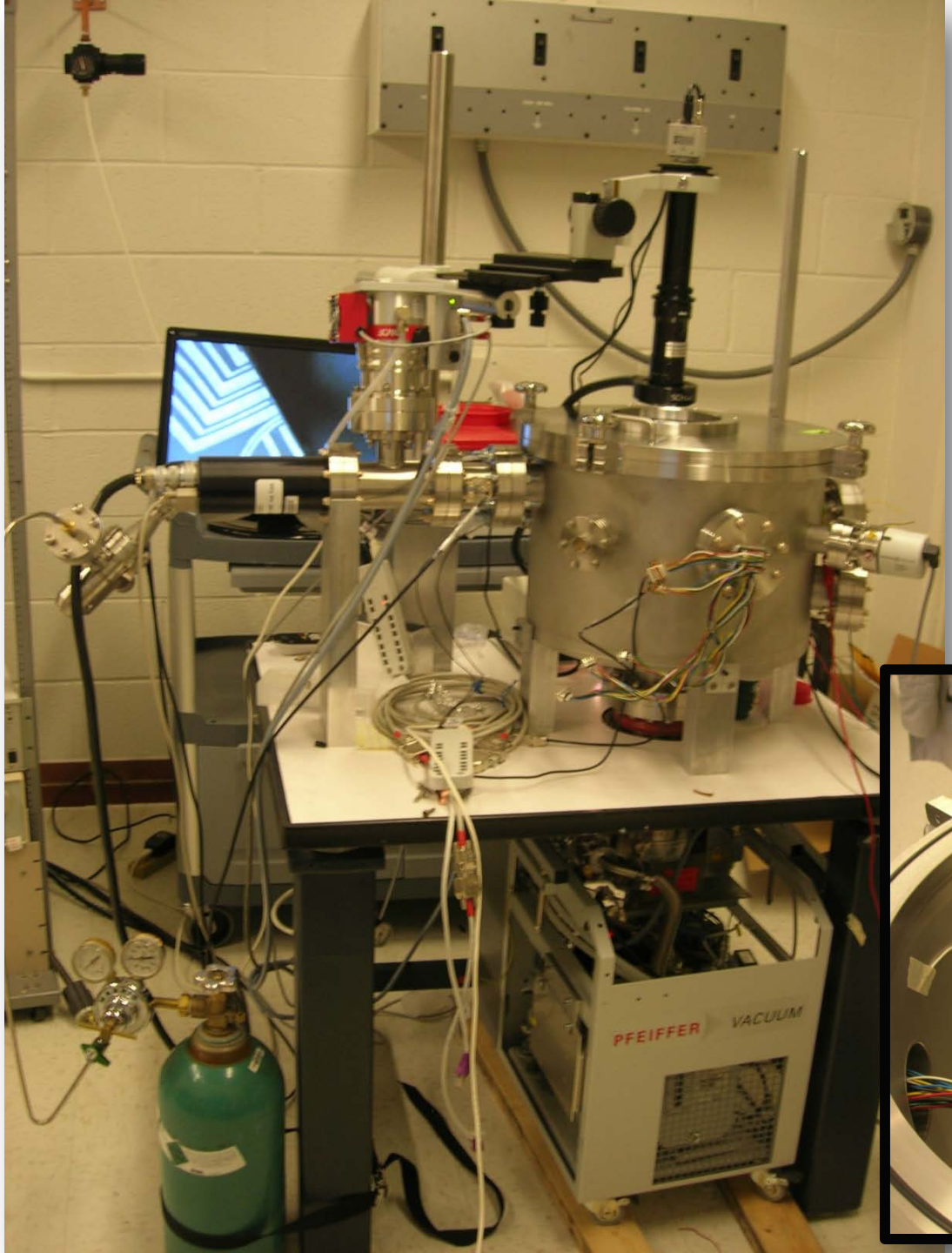
III. Particle acceleration

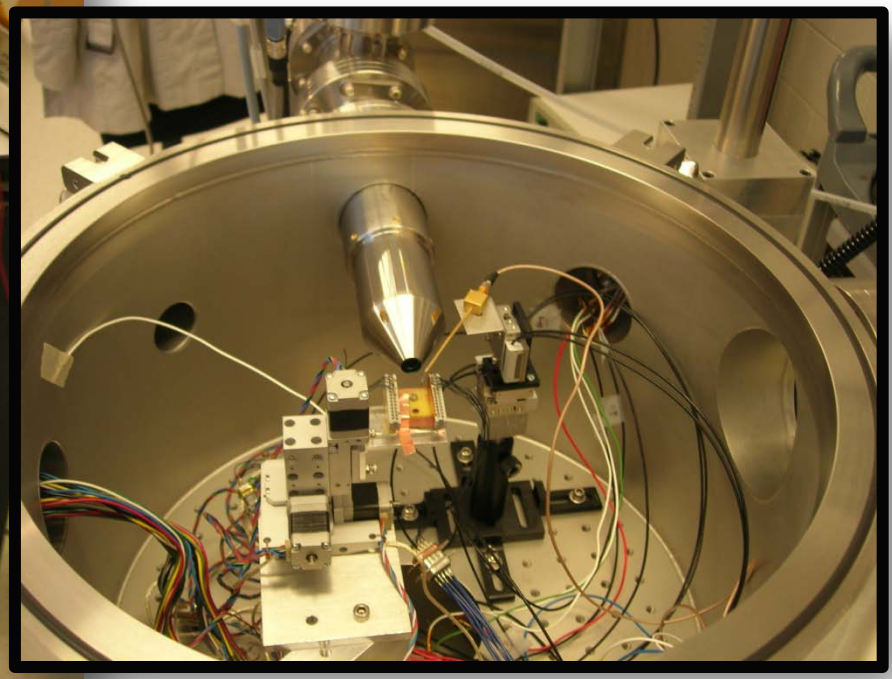
IV. Future

V. Summary

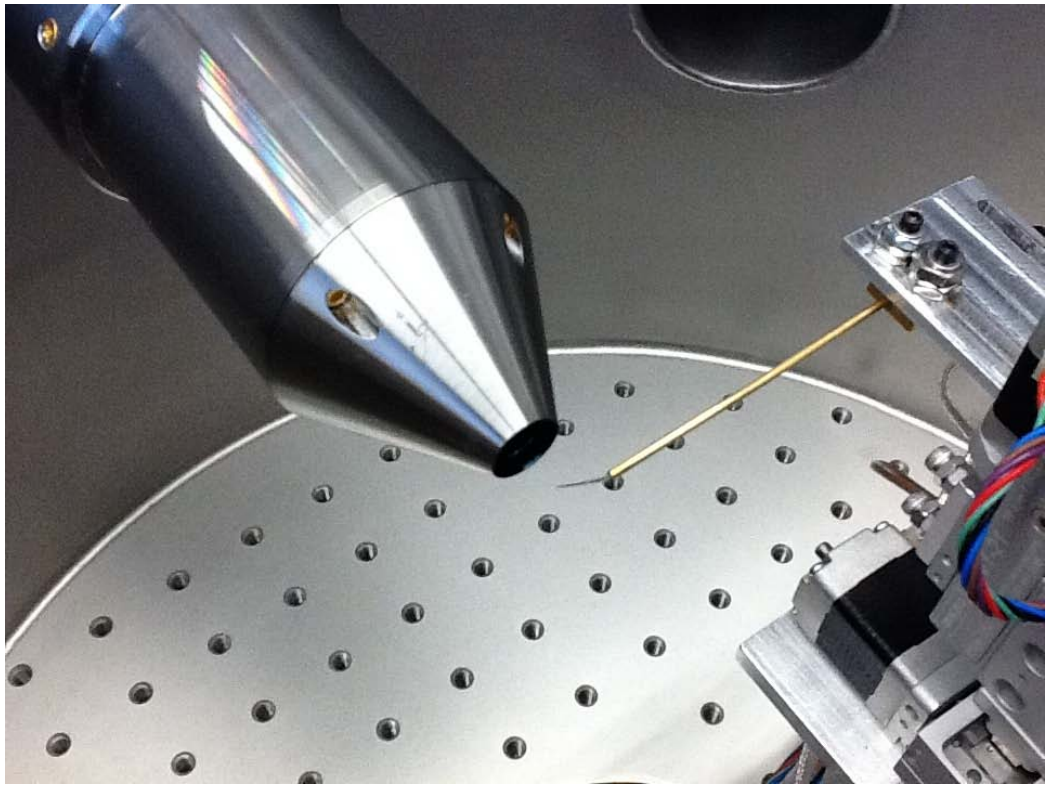
THE NEW SETUP

- Larger chamber
- Probe for beam detection
- Two x-y-z stages for probe and sample movement (50nm resolution)
- 2um resolution camera focused on chip
- Easier to open/close chamber

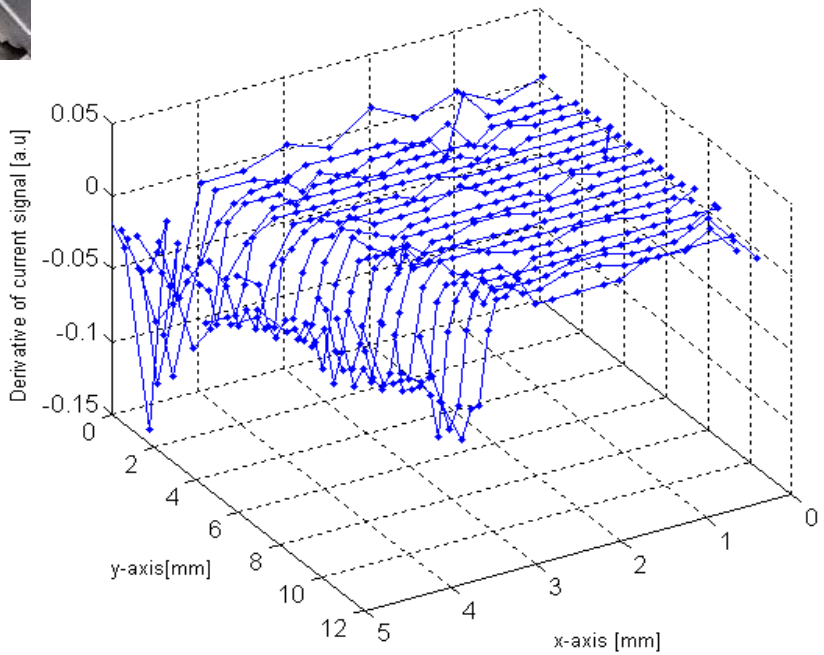


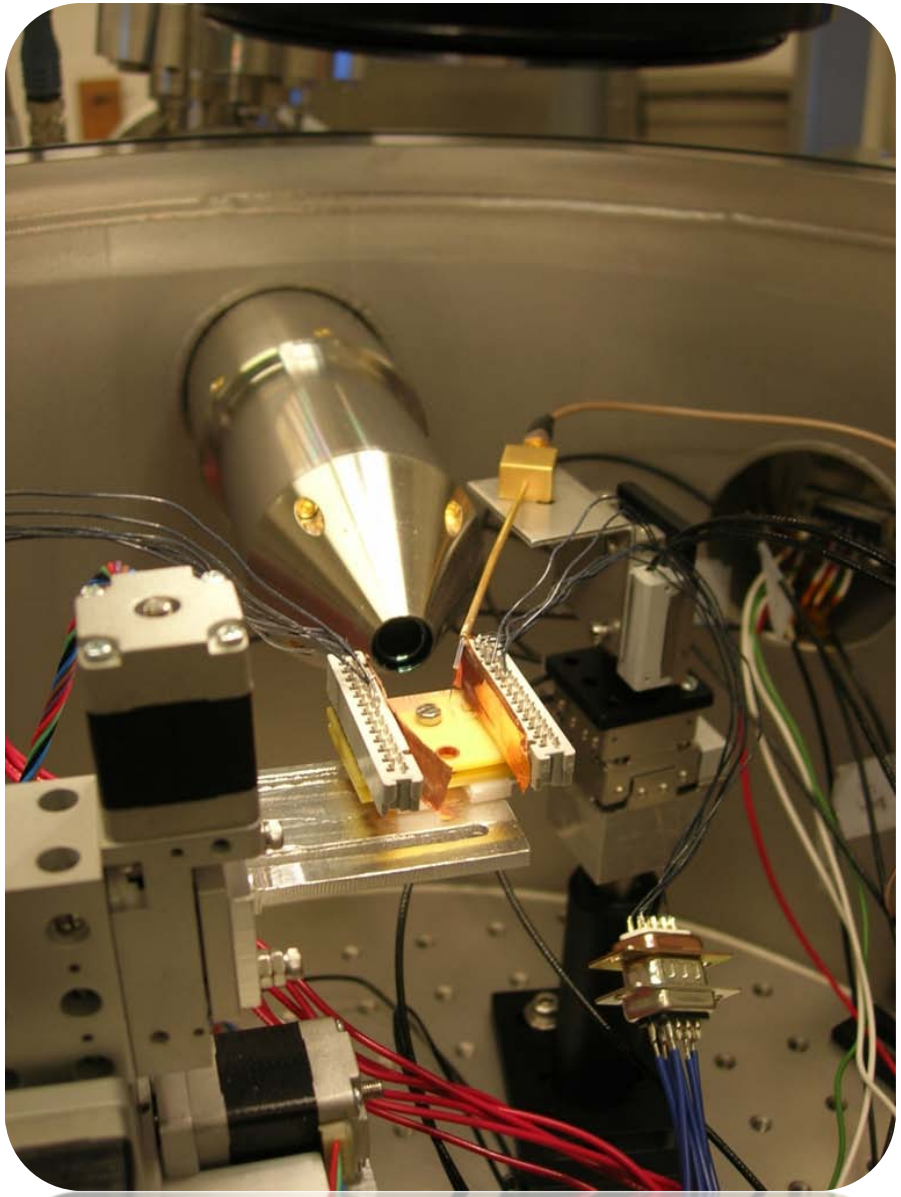


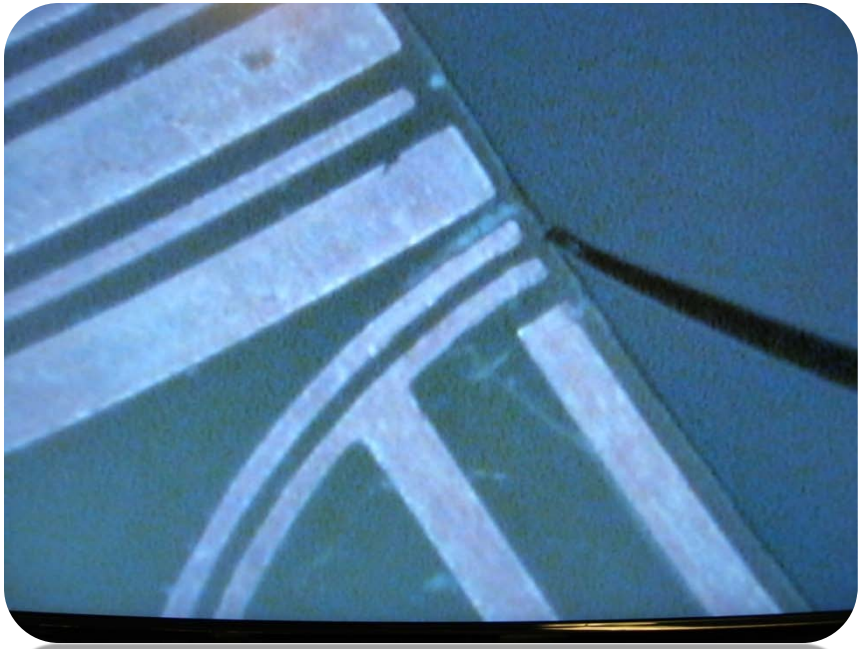
THE NEW SETUP

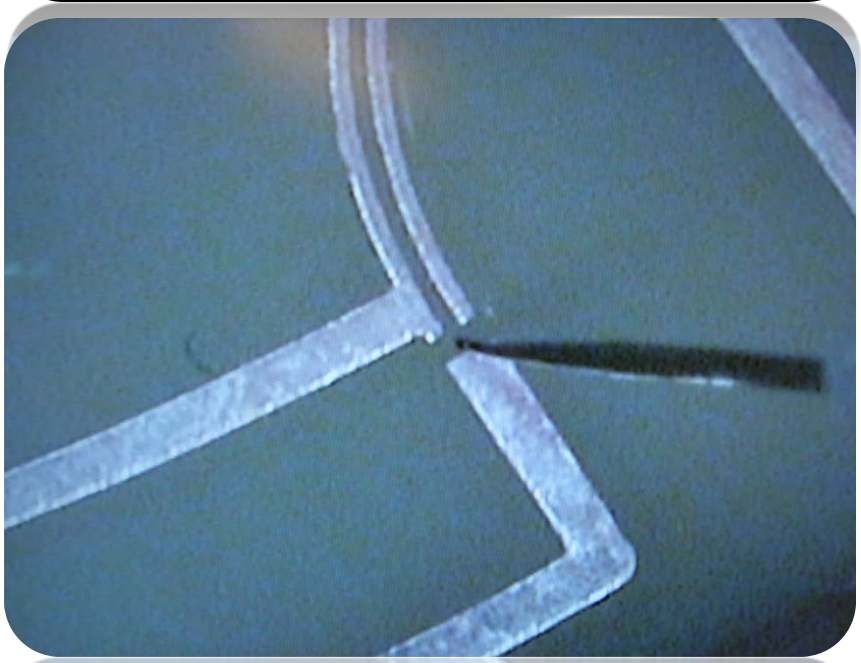


- Beam detected by probe
- Could be used for beam profiling









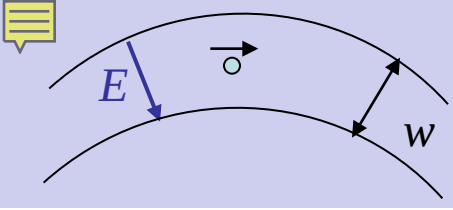
SUMMARY & PLAN

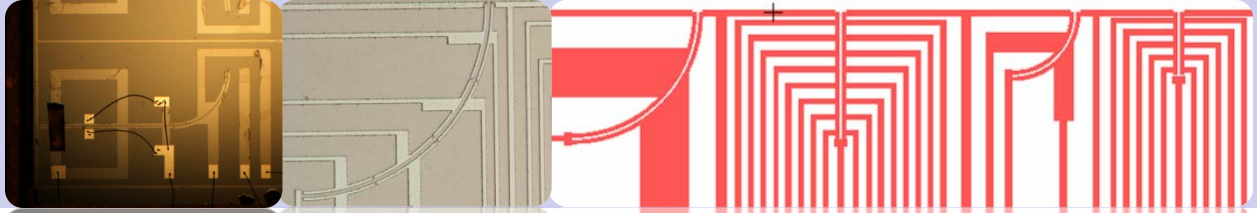
So far…

- Demonstration of guiding around 90° curve.
- Preliminary results of acceleration.
- Simulations of linear & 127.5 ° focusing.
- First design with simulation of accelerator that can scale up in size with energy.
- New setup with moving sample and probe stages for better alignment and optical visualization with scope.

Future work

- Continue fabrication process for Cu electroplating and SOI implementations of test devices for >90° curves and circular design (higher channel walls).
- Implement Einzel and 127.5 ° curve focusing.
- Test acceleration between two curved guide pairs.
- 3 layer structure for focusing out of plane.
- Implement accelerator from 2keV to 20keV





Thank You