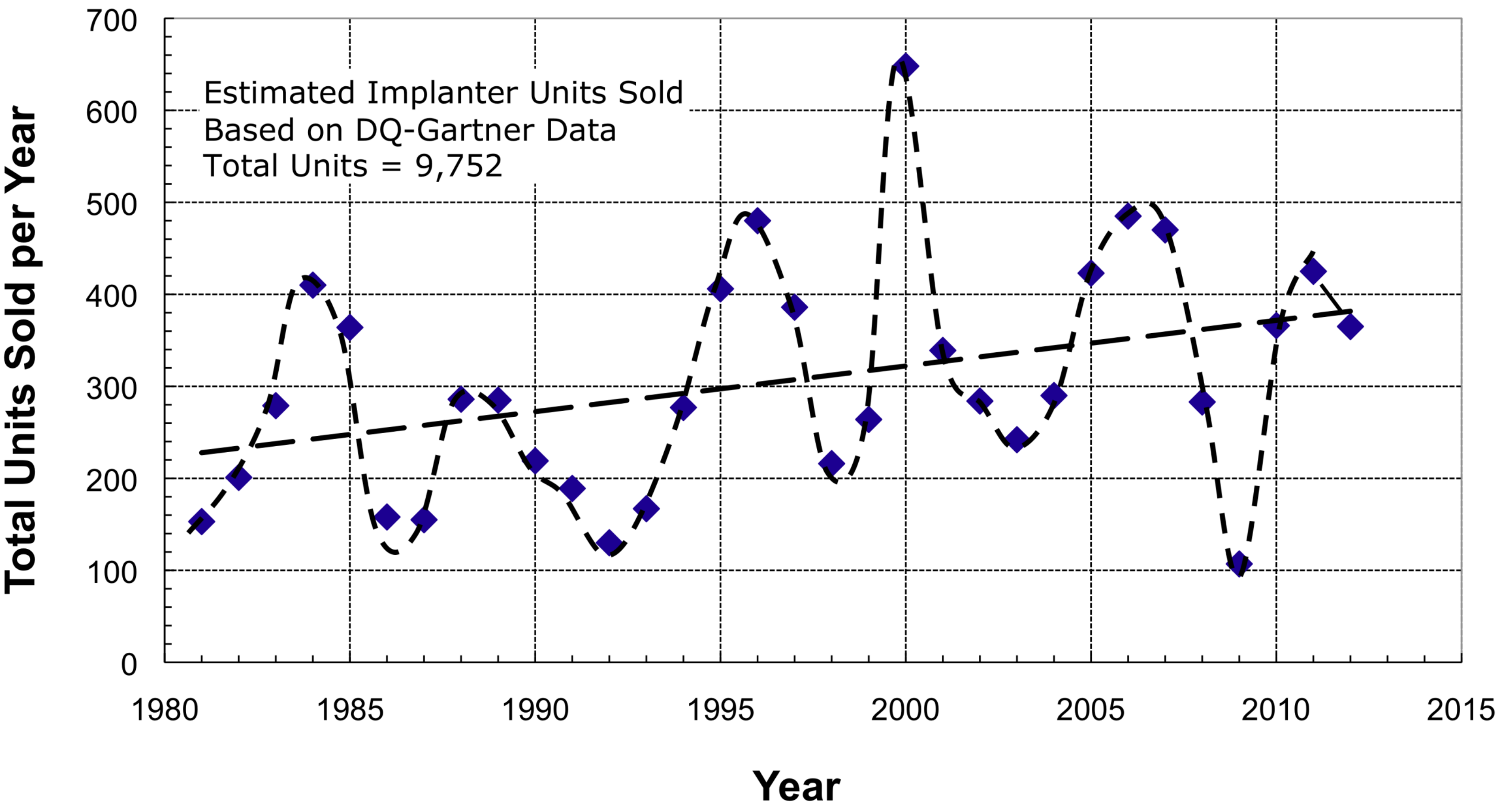
Ion Implantation for Semiconductor Devices: The Largest Use of Industrial Accelerators

Susan Felch, Michael Current,
and Mitchell Taylor

Outline

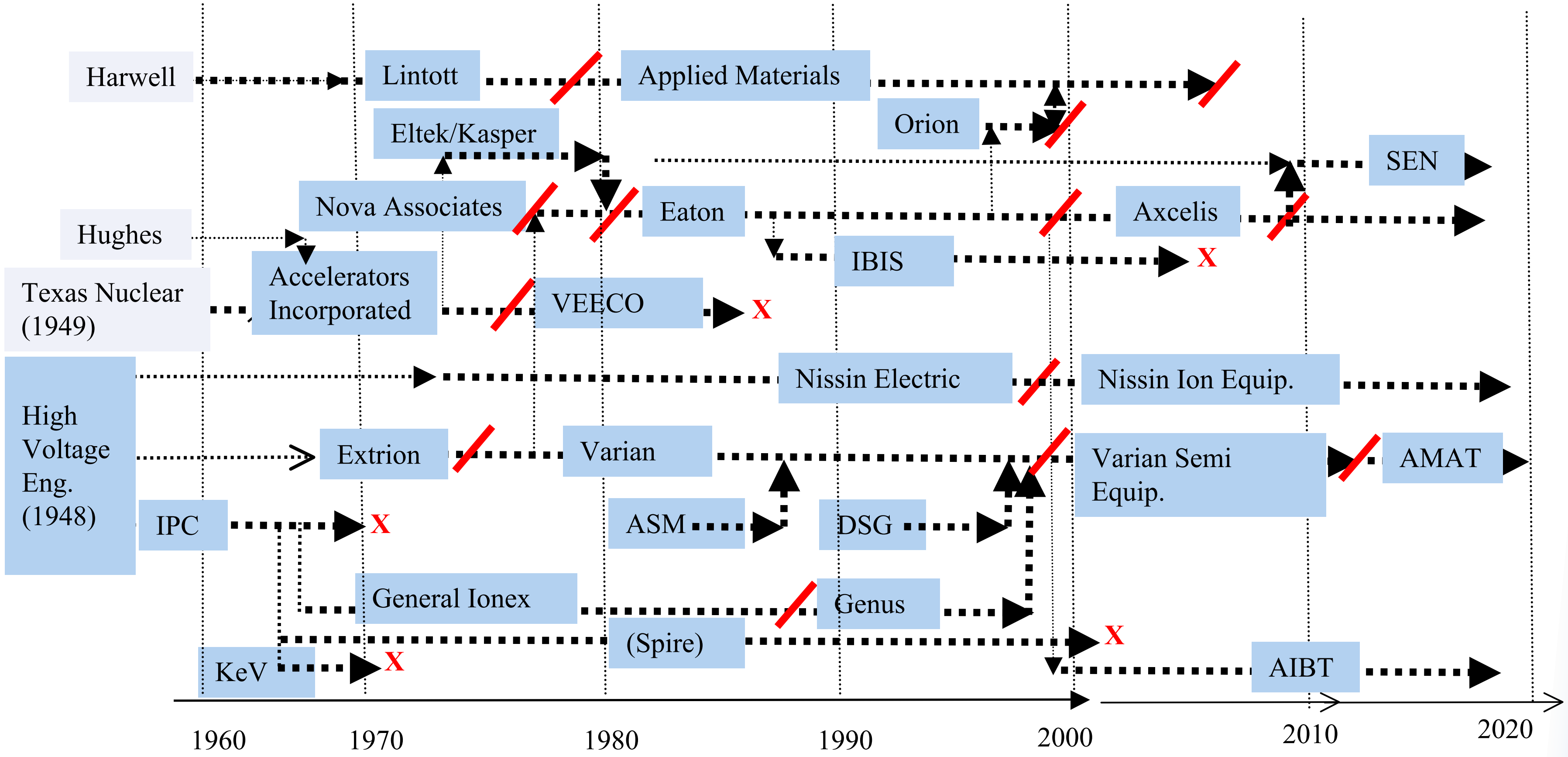
- Ion implantation business
- Semiconductor applications
- Ion implanter designs and accelerators
  - High-current implanters
  - Medium-current implanters
  - High-energy implanters
  - Specialty implanters
- Summary

Yearly Unit Sales of Ion Implanters



Major Implantation Tool Makers: 1960–2013

A long history of new ventures, failures & mergers.



Harwell

Lintott

Applied Materials

Orion

Eltek/Kasper

SEN

Nova Associates

Eaton

Axcelis

Hughes

IBIS

X

Texas Nuclear (1949)

Accelerators Incorporated

VEECO

X

Nissin Electric

Nissin Ion Equip.

High Voltage Eng. (1948)

Extrion

Varian

Varian Semi Equip.

AMAT

IPC

X

ASM

DSG

General Ionex

Genus

(Spire)

X

KeV

X

AIBT

1960

1970

1980

1990

2000

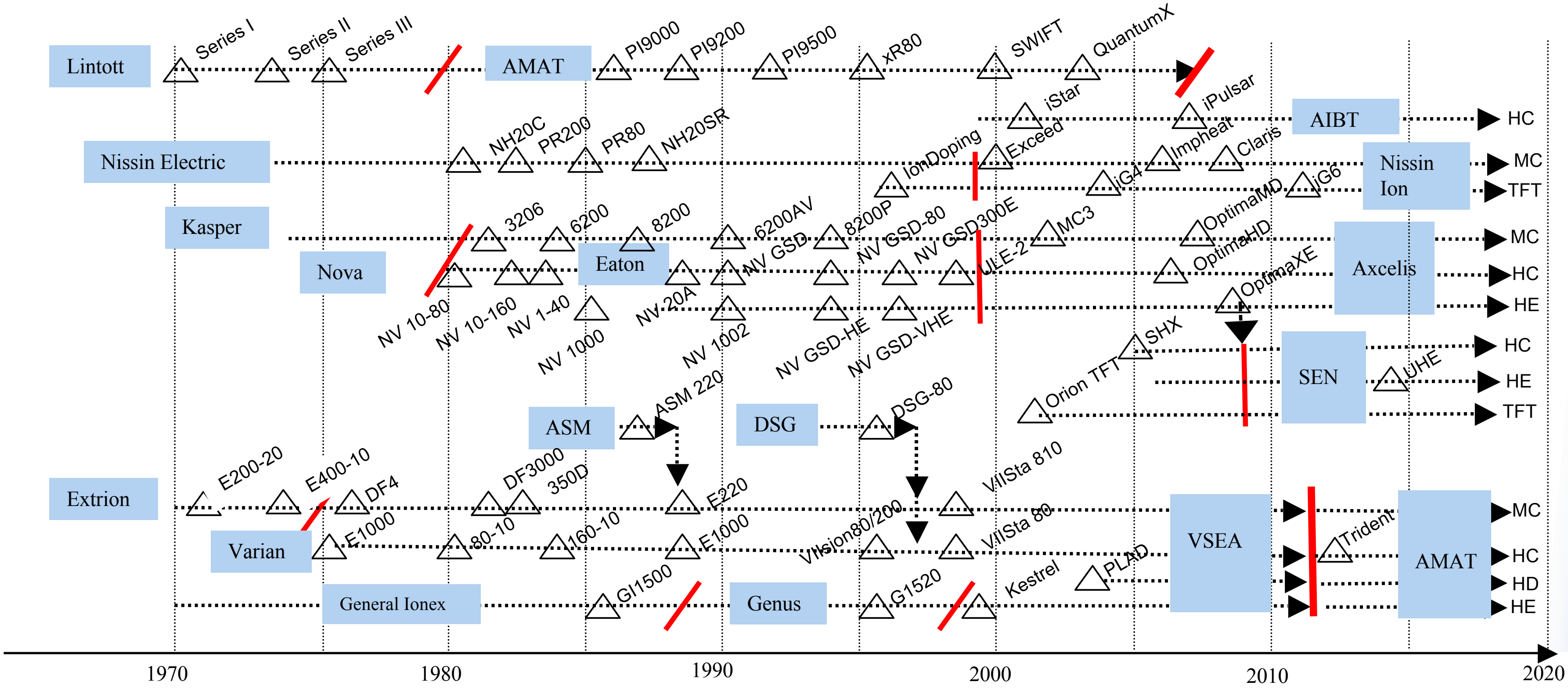
2010

2020

Other companies: mostly R&D and solar machines:
High Voltage Europa, Ulvac, National Electrostatics, Ion Beam Services, Intevac, Goldstone.

Major Implant Systems: 1970–2013

Many new designs & capabilities.

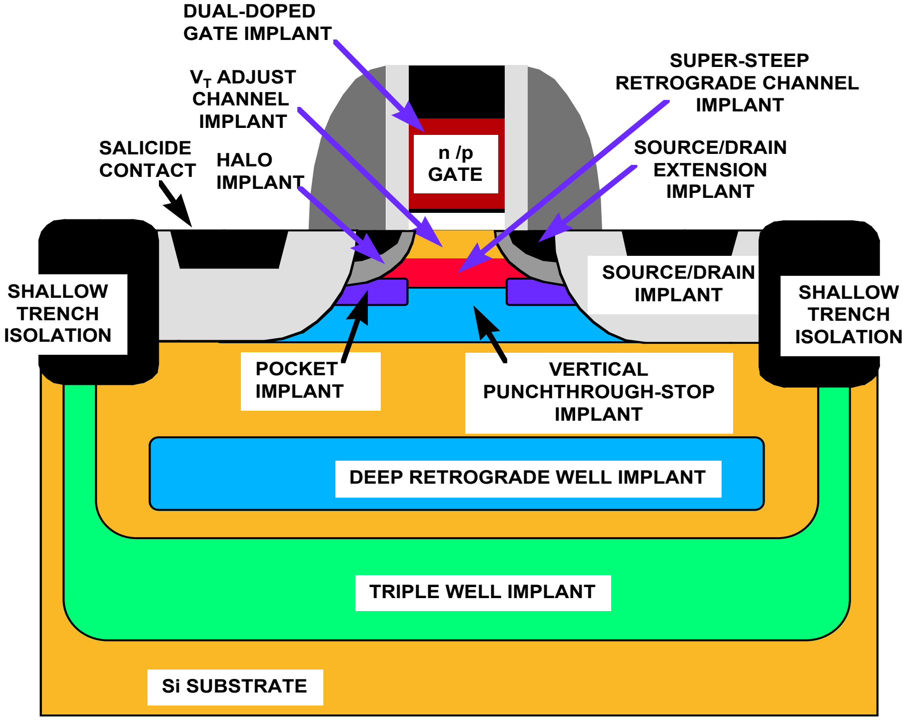


Gate Size (micron) - 5 — 2 — 0.8 — 0.18 — 0.09 — 0.065 - 0.032 0.022 — 0.014 →

Wafer Size (mm) — 75 — 100 — 125 — 150 — 200 — 300 — 450 →

Implants per Wafer — 2-3/PMOS — 4-6/NMOS — 8-12/CMOS — 15-25/Bi-CMOS — 30-50/Bi-CMOS — 40-60/bulk finFET →

“Classic” Planar-CMOS (on bulk-Si)

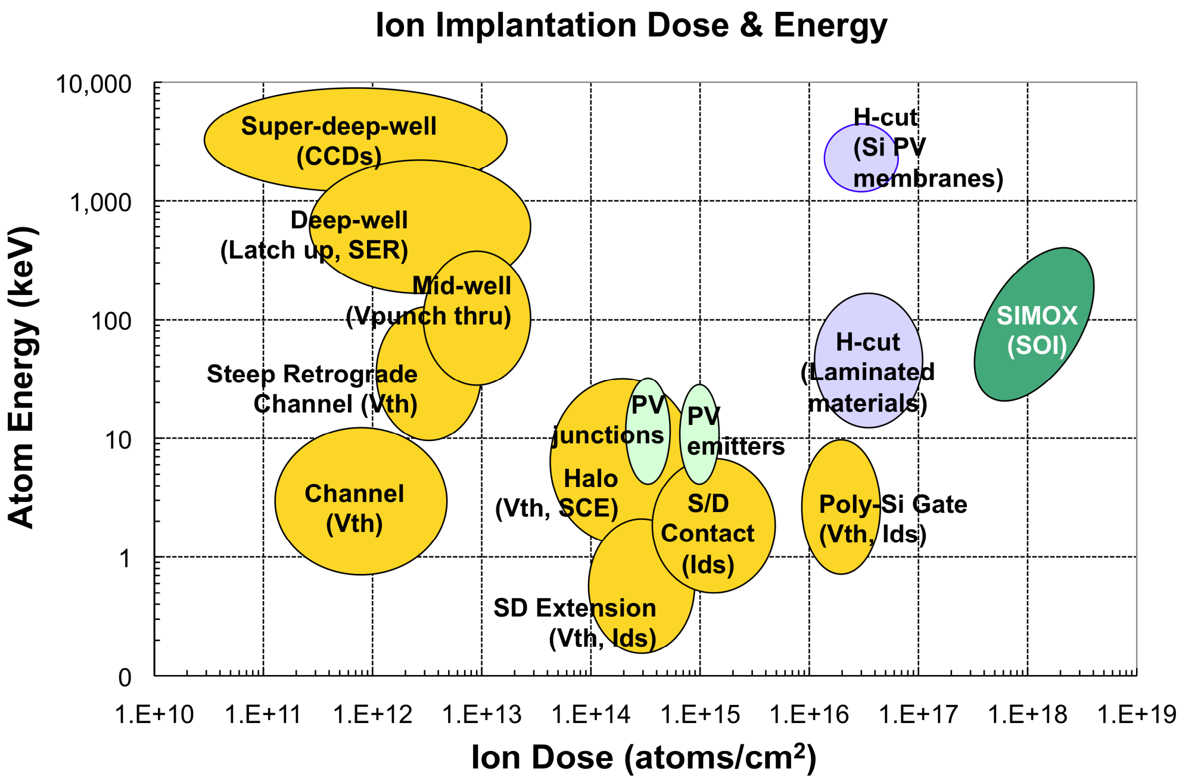


Source/Channel/Drain
50-200 nm deep
10^{17}-10^{20} atoms/cm^3

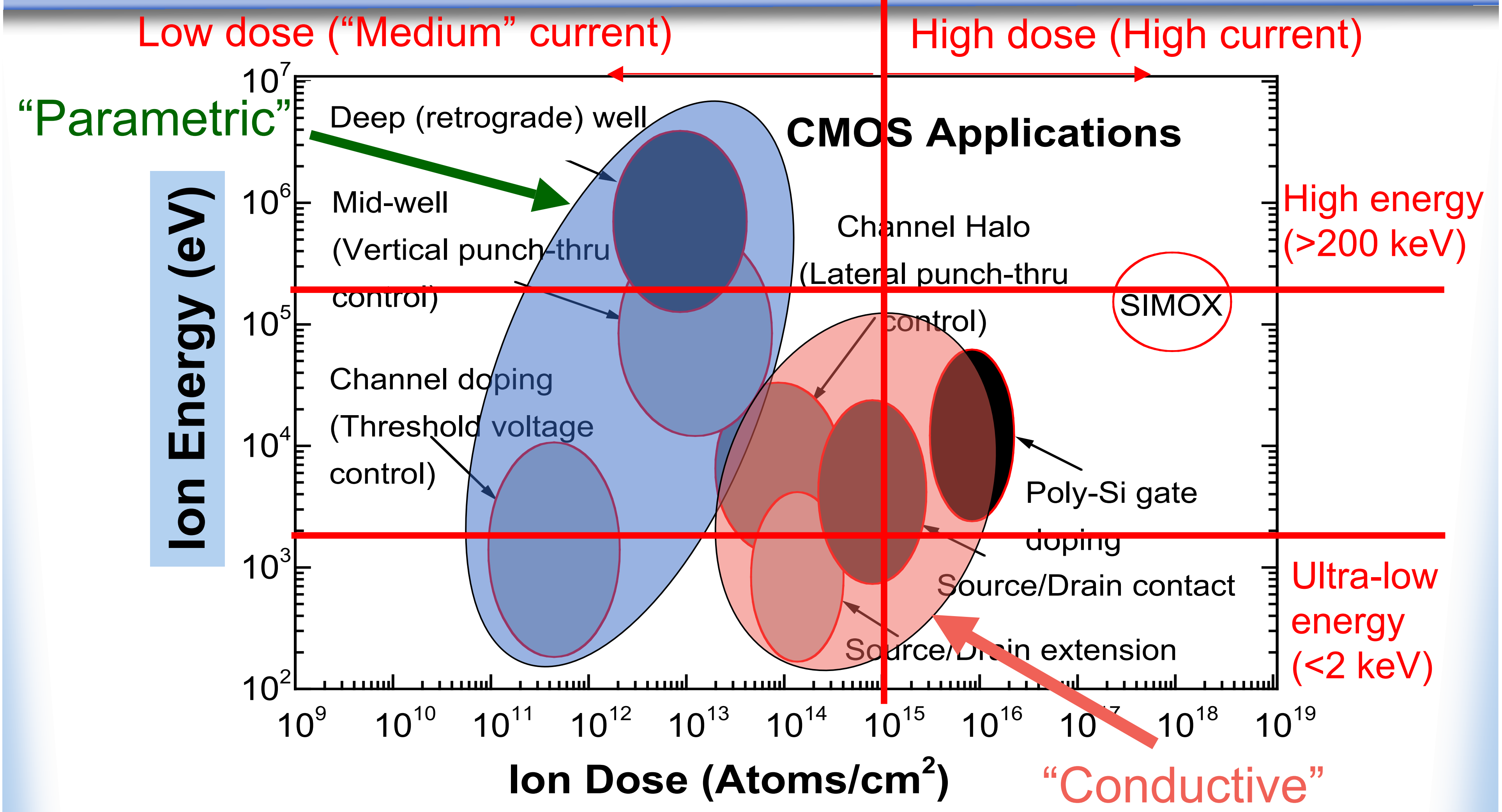
CMOS Well
500-3000 nm deep
10^{15}-10^{17} atoms/cm^3

[M.I. Current, L.A. Larson, “In-line Characterization of Doping Technologies for ULSI: Requirements and Capabilities”, in Characterization and Metrology for ULSI Technology, eds. D.G. Seiler et al., AIP Proc. 449, American Institute of Physics (1998).pp 143-151]

Dose-Energy Phase Space for CMOS

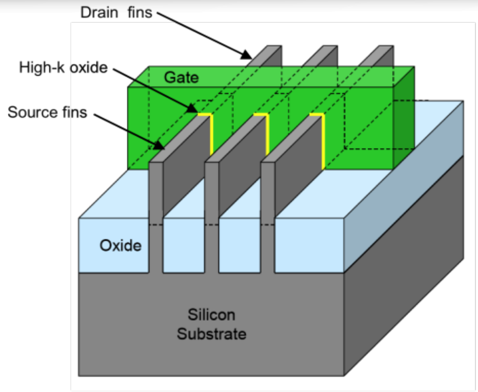


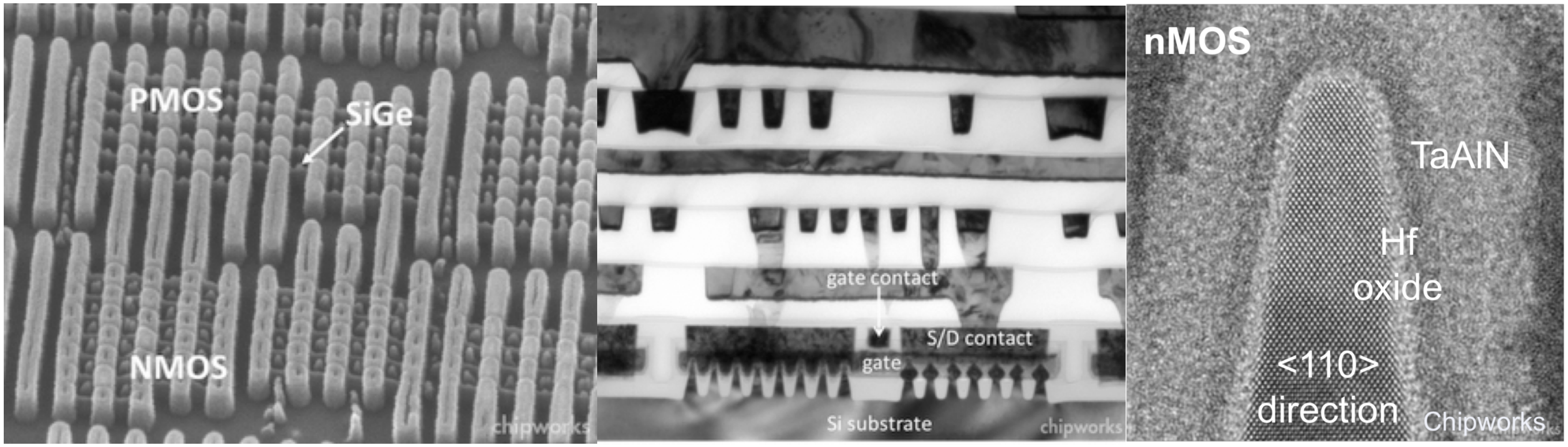
Implanter Types Reflect Dose/Energy Groups



Three-Dimensional (3D) Transistors

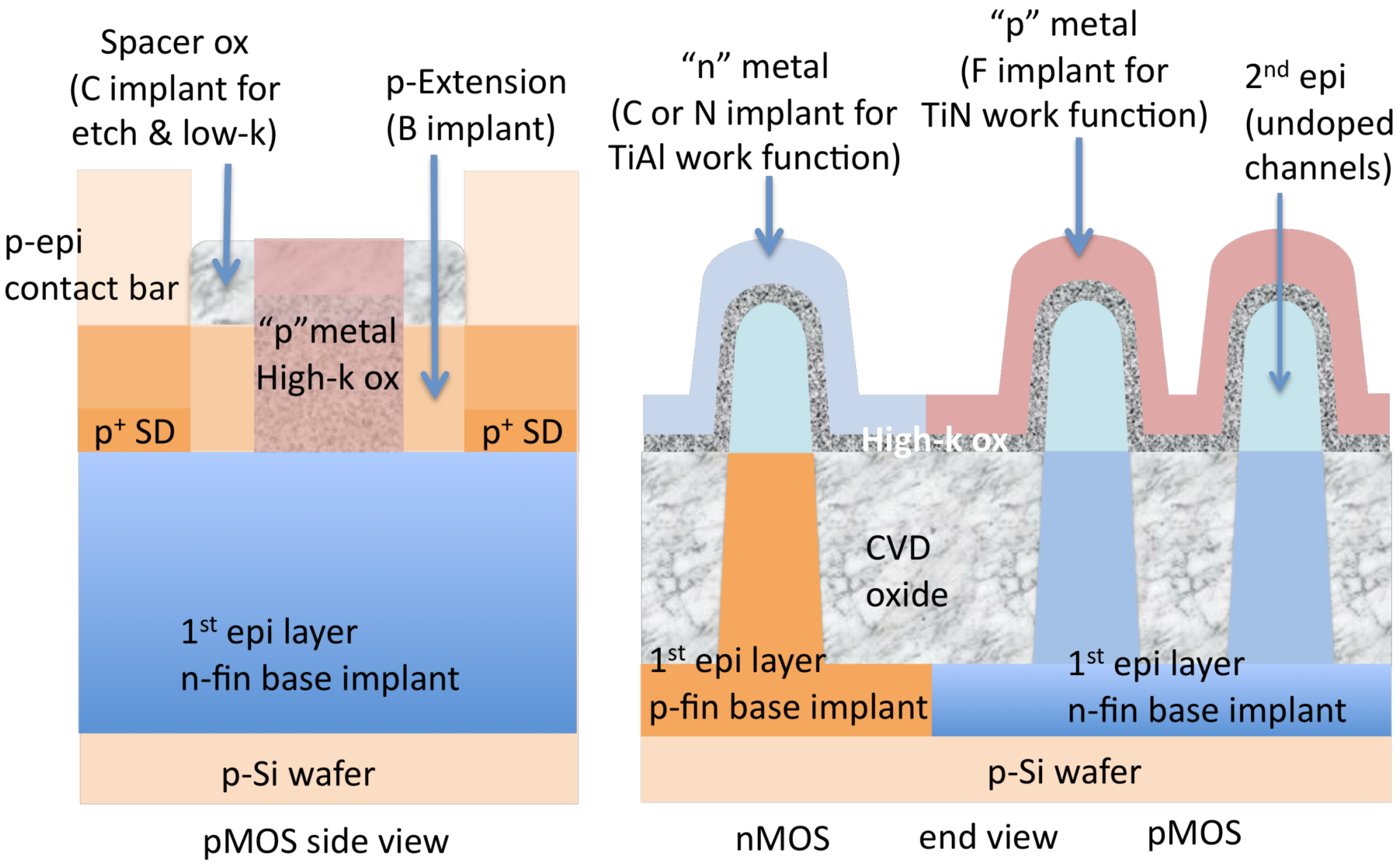
- FinFETs or tri-gate transistors
  - In production for Intel’s 22 nm technology
  - Scheduled for foundry production at Global Foundries, TSMC, UMC, etc.





Intel 22 nm FinFET: Images by Chipworks

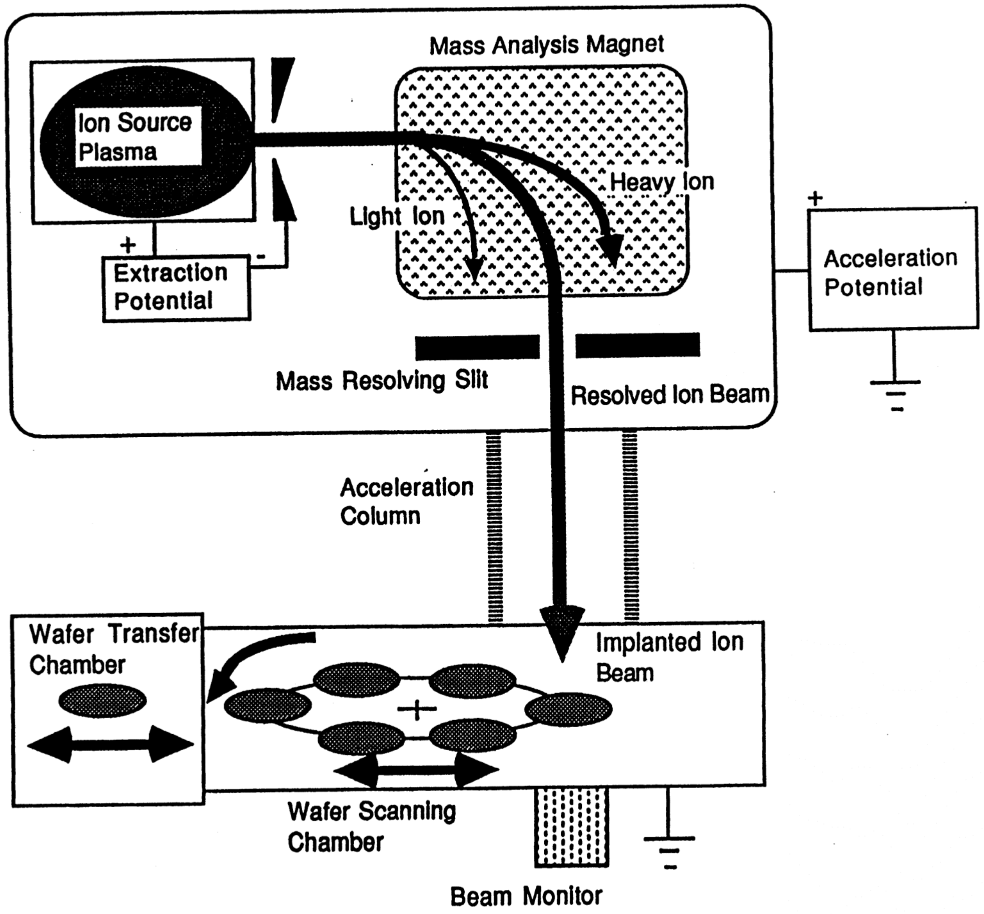
Potential Implants for Bulk FinFET Doping and Materials Modification



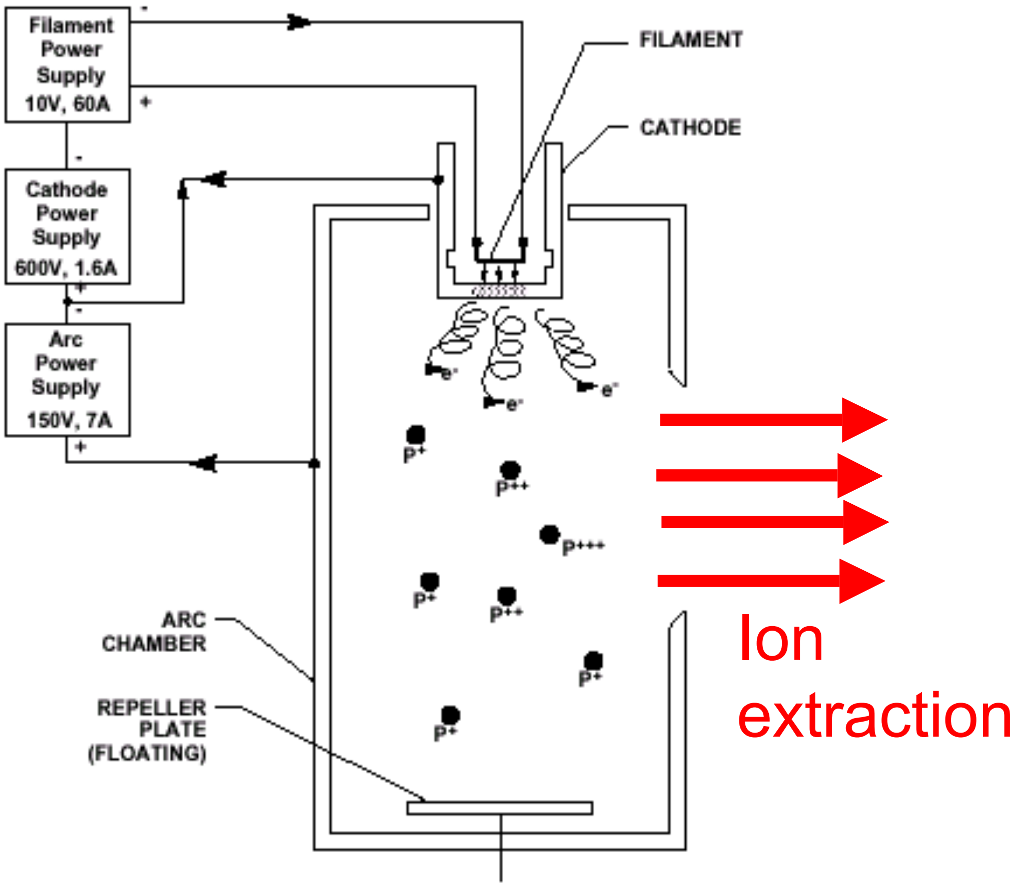
Implanter Requirements

- Dose uniformity: < 0.5 %, one sigma
- Dose repeatability: < 0.5 %, one sigma, wafer-to-wafer, day-to-day
- Energy Accuracy: <1.0%
  - <0.1% energy contamination
- Angular Accuracy: <1°
  - <0.1° for wells
- Particles
  - Frontside: ≤ 5 @ 0.042 µm
  - Backside: ≤ 500 @ 0.06 µm
- Contamination
  - Heavy / alkali metals: total ≤ 1E9 cm^{-2}
  - Al: ≤ 1E10 cm^{-2}
- Wafer temperature: ≤ 60C
- Throughput: >200 wafers/hour (for low doses)
- Ion Source Lifetime: >100-500 hours
- Tune Time (ion or energy change): <3 minutes
- Mean time before failure (MTBF): >200 hours
- Availability (“uptime”): >95 %

Beamline Implanter Design



Ion Source (Plasma)



Ion extraction

Source Materials

Solids (vapors)

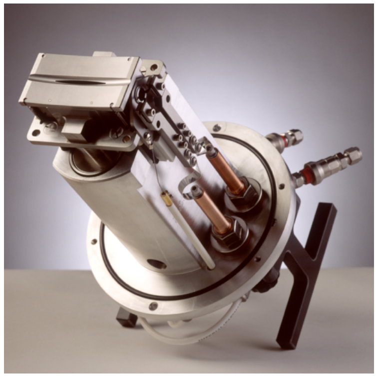
As, P, Sb_2O_3

Gases

BF_3, $B_{10}H_{14}$, AsH_3, PH_3

$InCl_3$, $In_2O_3+H_2$, SiF_4, GeF_4

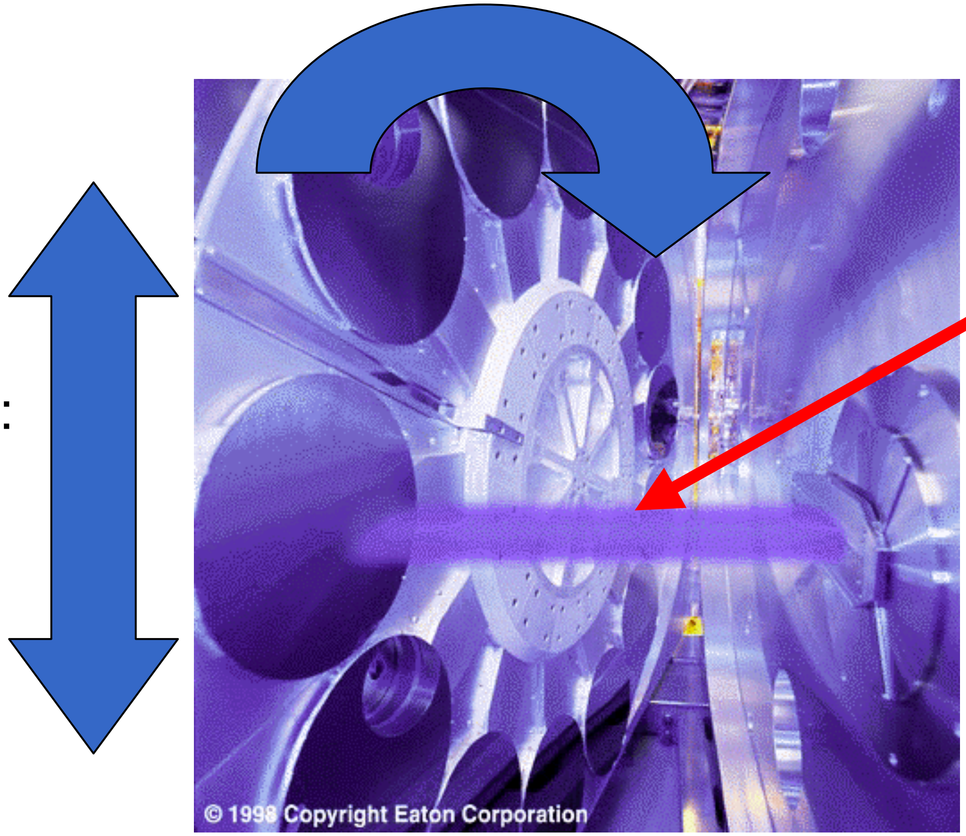
H_2, O_2, He, Ar



Axcelis GSD/200E^2
Enhanced Extended Life Source (ELS)

High-Current Implanters

Spinning Wheels to Hold Wafers



Radial speeds: 50-90 m/s

Scan speeds:
1-10 cm/s

Stationary ion beam

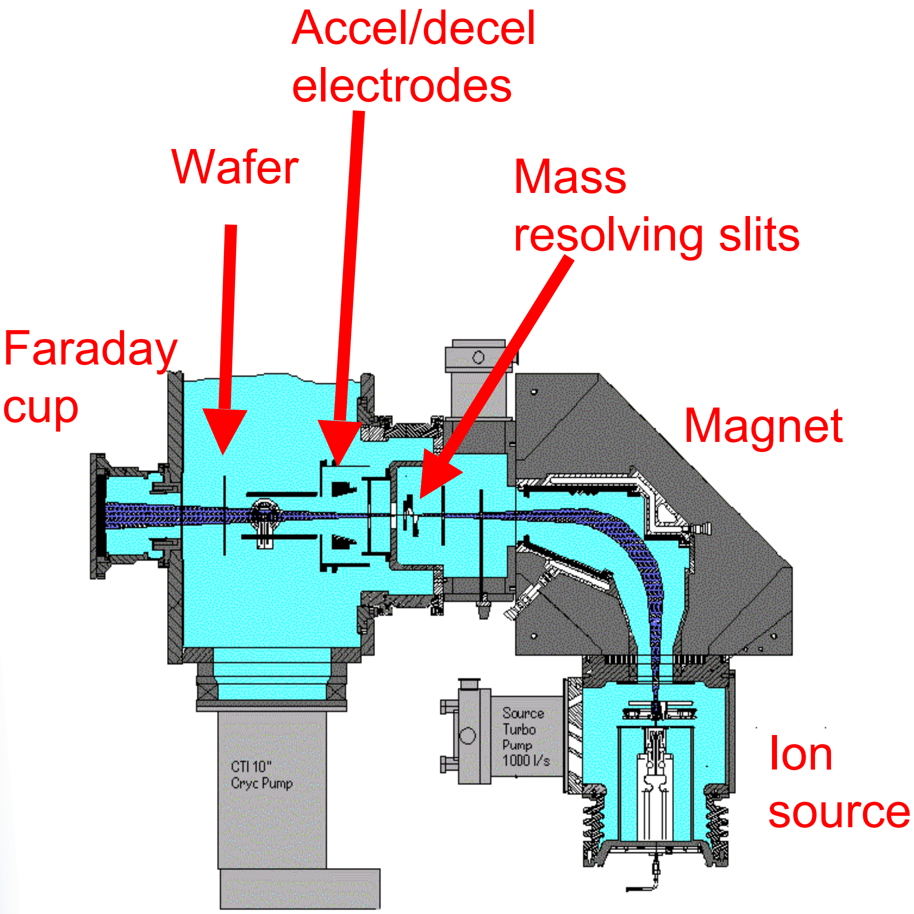
Spinning Wheels:

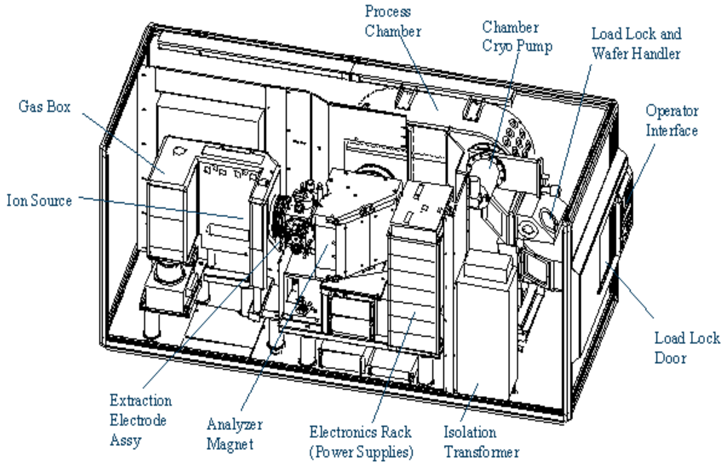
Lower Temperature

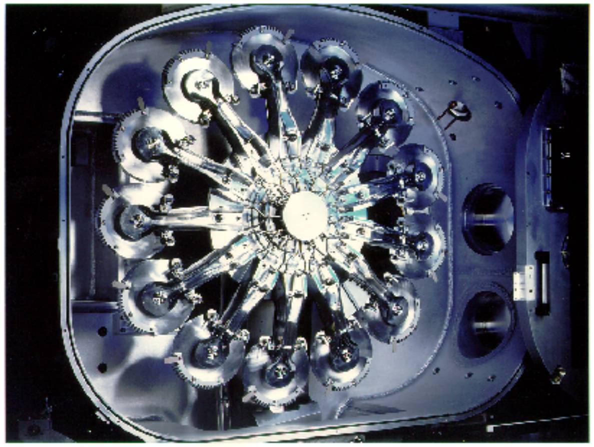
Lower Charging

Dose Scanning

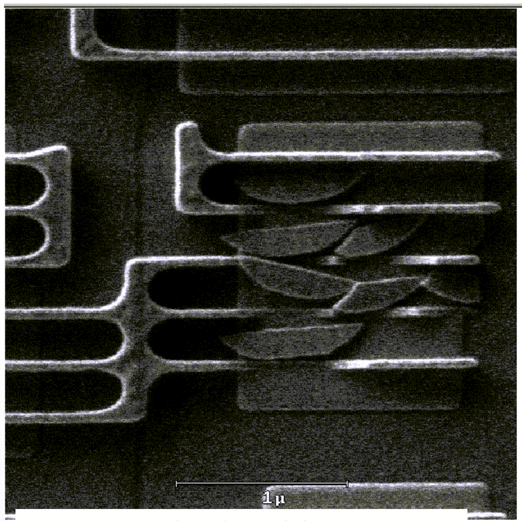
AMAT xR80

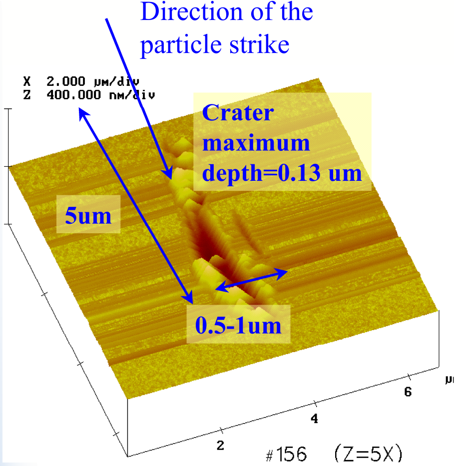

Accel/decel electrodes
Wafer
Mass resolving slits
Faraday cup
Magnet
Ion source
Source Turbo Pump 1000 l/s
CTI 10" Cryc Pump


Process Chamber
Chamber Cryo Pump
Load Lock and Wafer Handler
Gas Box
Operator Interface
Ion Source
Load Lock Door
Extraction Electrode Assy
Analyzer Magnet
Electronics Rack (Power Supplies)
Isolation Transformer

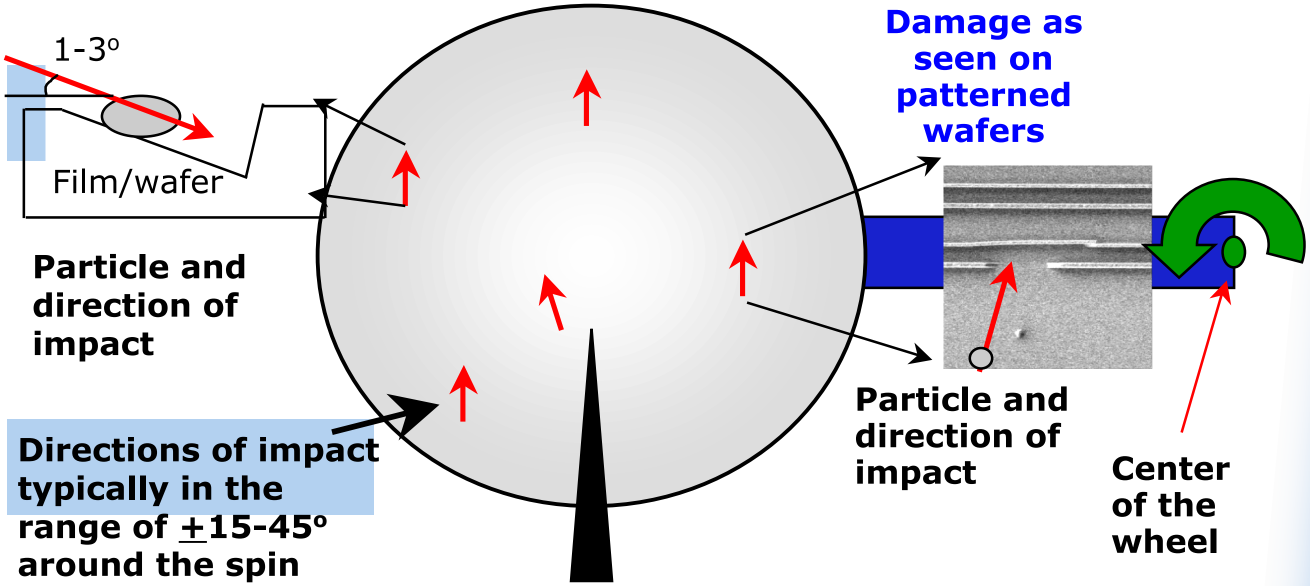


Broken Poly Gates: Particles and Spinning Wheels





Model describes collisions of poly-lines on wafers into particles.



Damage captured on blanket wafers
(Al and PR covered)

Particle and direction of impact

Directions of impact typically in the range of ±15-45° around the spin direction

Damage as seen on patterned wafers

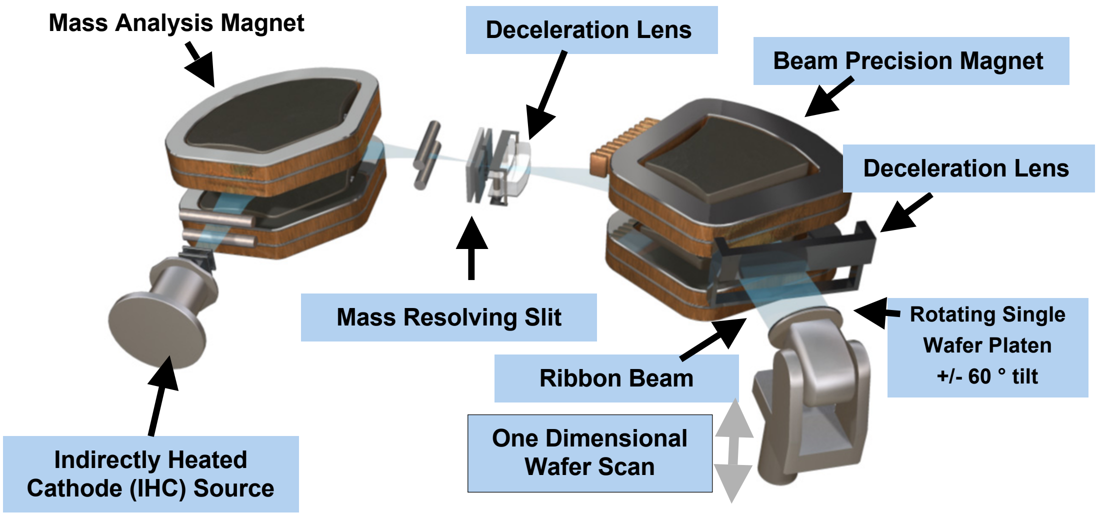
Particle and direction of impact

Center of the wheel

Damage is worse for thinner poly lines and fast spin speeds.

M.Taylor, IIT 2004

Varian VIISta HCP (circa 2000AD)

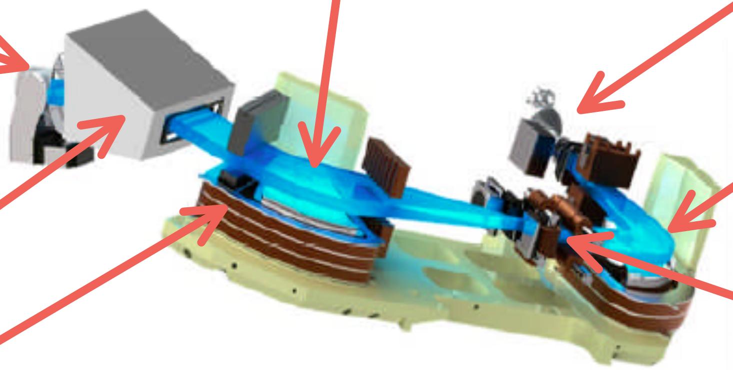


Energy Range	200eV–60keV
Dose Range	1E13 – 5E16
Max Throughput	350 WPH

- Key Features
  - Single Wafer
  - Common VIISta end station & control system
  - Static ribbon beam
  - 2 stage deceleration
  - 2nd Magnet
  - Closed loop dose/angle control
  - Simple 1D mechanical scan

AMAT/VSE VIISta Trident HC (2012)

- Inclined beamline; final energy & neutrals filter before wafer



Ribbon ion beam

Wafer chuck (vertical scan)

Ion source

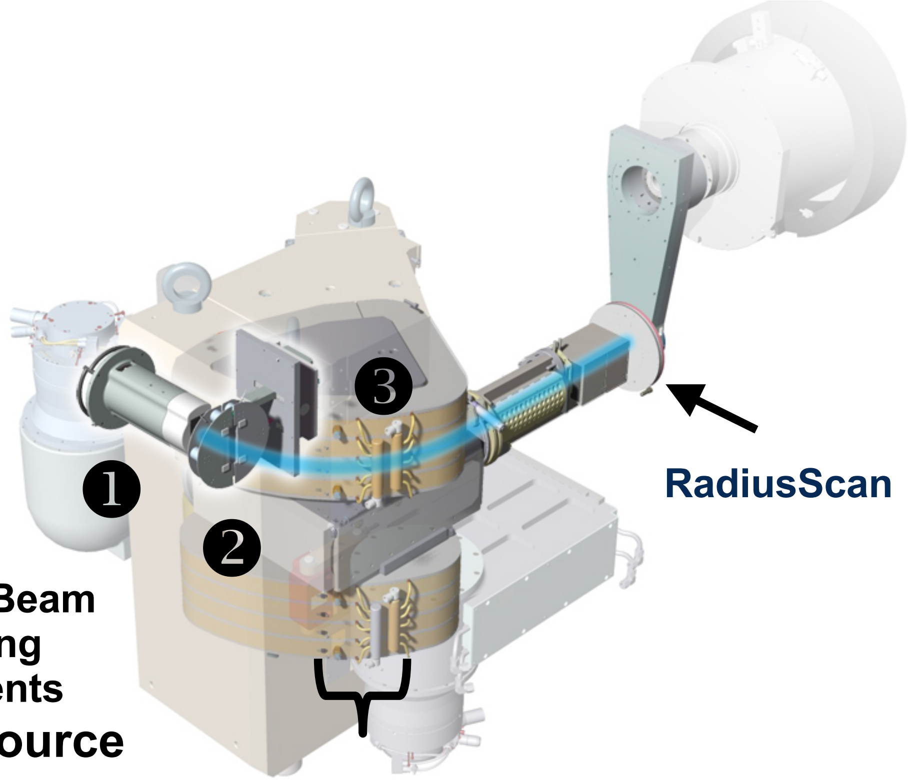
Ion selection magnet

Electrostatic neutrals & ion energy filter

Beam bending magnet

Ion selection aperture

Axcelis Optima HD



RadiusScan

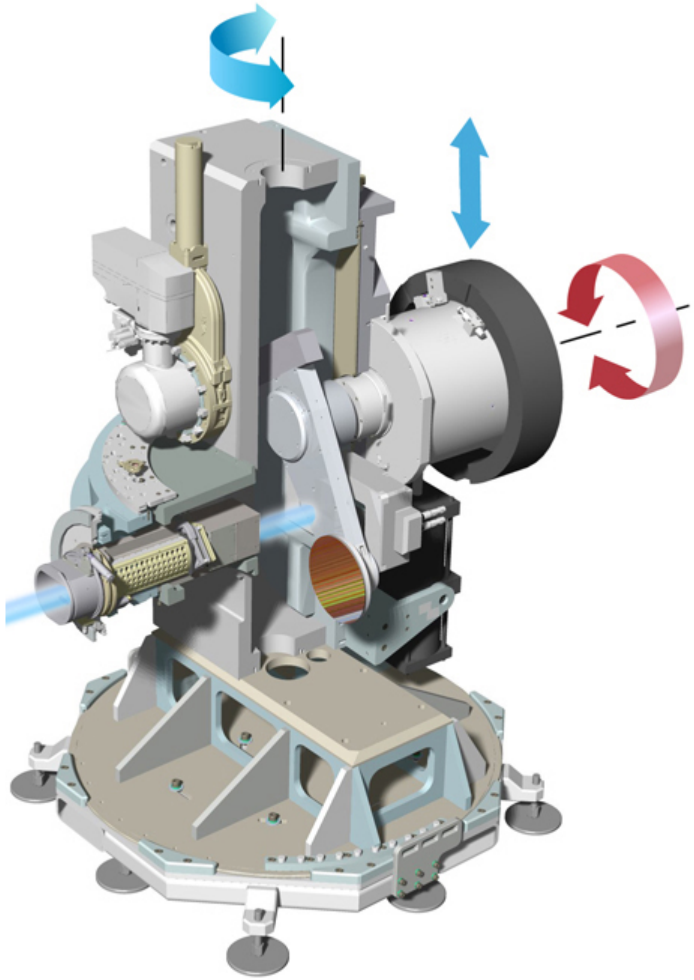
Only 3 Beam
Tuning
Elements

❶ Source

❷ Electrode

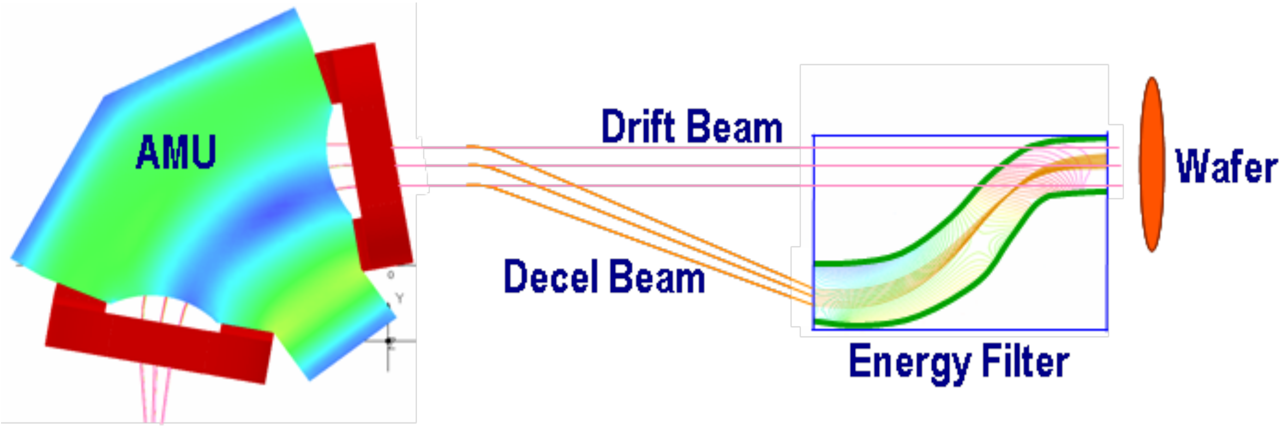
❸ Magnet

Beamline length
Only 1.8M



AIBT iPulsar

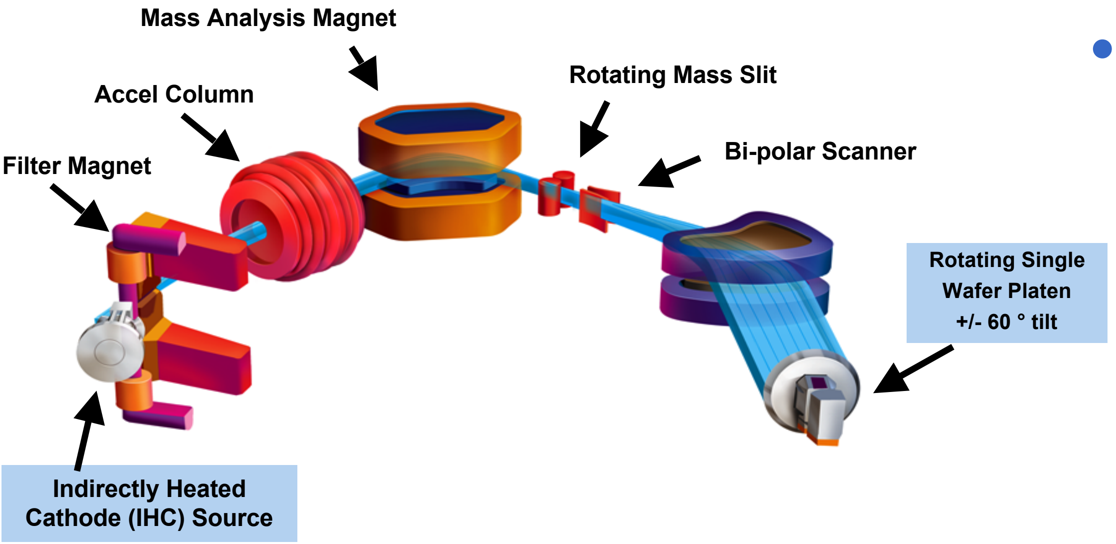
- Sub-keV Ultra Low Energy Implant
  - One Deceleration Stage with final Energy Filter
  - Off-energy neutrals are removed along the decel energy filter path – only ions traveling at the correct low velocity can make it through filter
  - Enables high purity, low energy beam with high beam currents (high decel ratio)



Dimension not to scale

Medium-Current Implanters

Varian VIISta 900XP

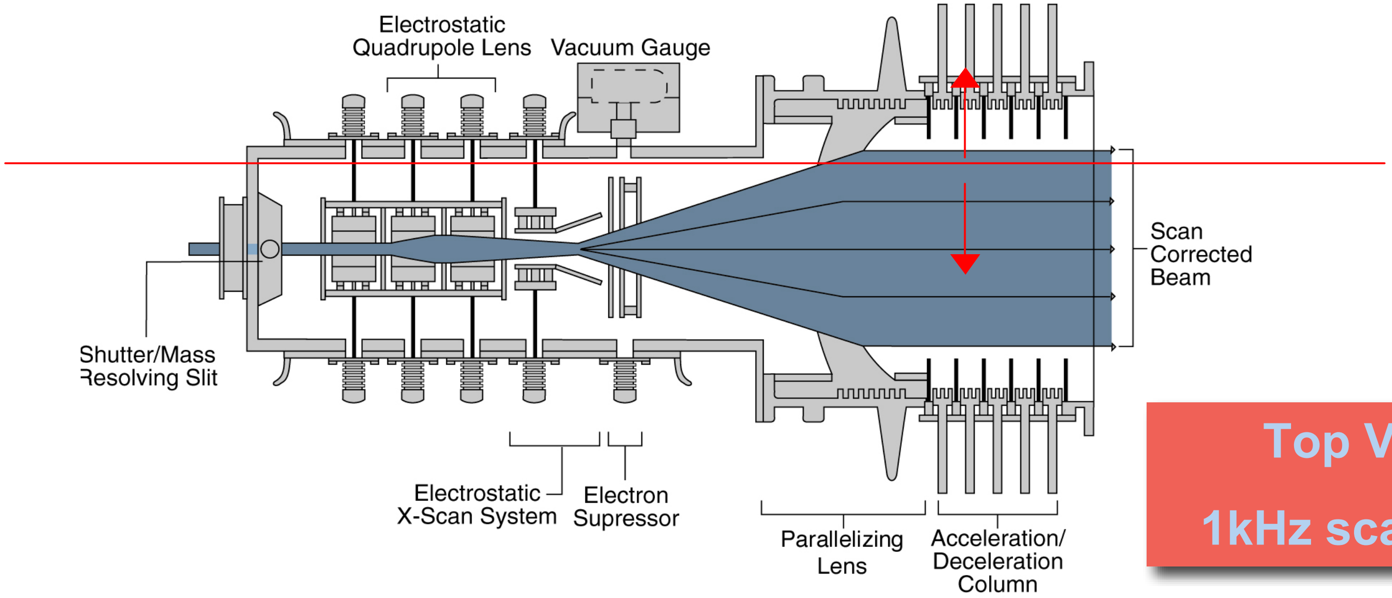


Energy Range	2keV–900keV
Dose Range	1E11–1E16/cm2
Max Throughput	500 WPH

- Key Features
  - Single Wafer
  - Common VIISta end station & control system
  - 500 wafer-per-hour throughput
  - Filter magnet at source
  - Closed loop dose/angle control
  - Simple 1D mechanical scan

Axcelis Optima MD$_{II}$: Repeatable Angle Control

- The Optima MD$_{II}$ scans the pencil beam electrostatically and symmetrically on a center axis
  - No magnetic correction or bend tuning needed
  - P-lens parallelizes beam to the central axis, which is normal to the wafer surface



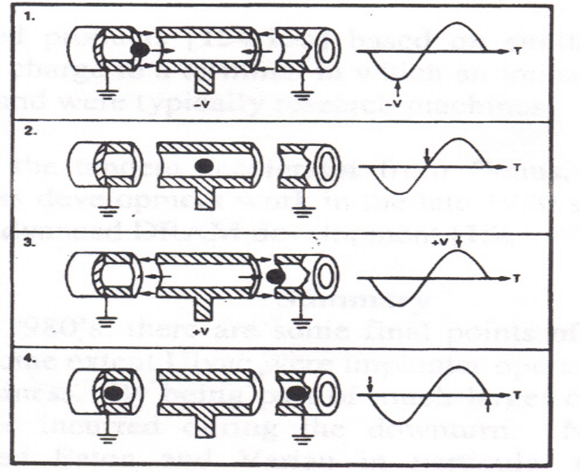
Top View

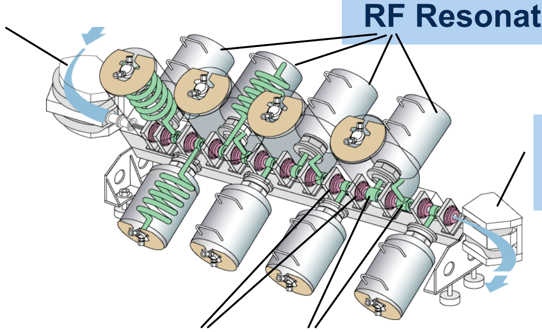
1kHz scanning

High-Energy Implanters

Axcelis' LINAC (LINear ACcelerator)

RF LINAC concept





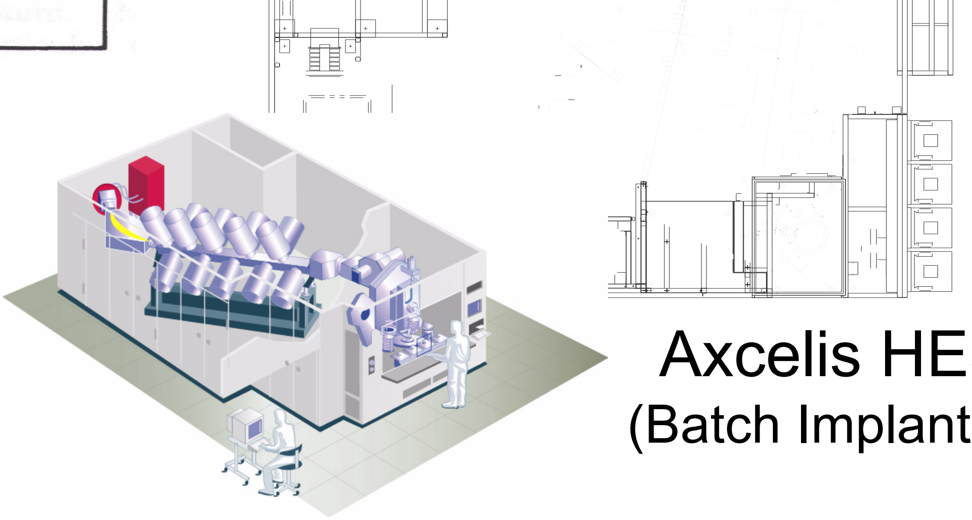
90° Mass Analyzing Magnet

RF Resonators

58.5° Final Energy Magnet

Quadrupole Lens

RF Electrode

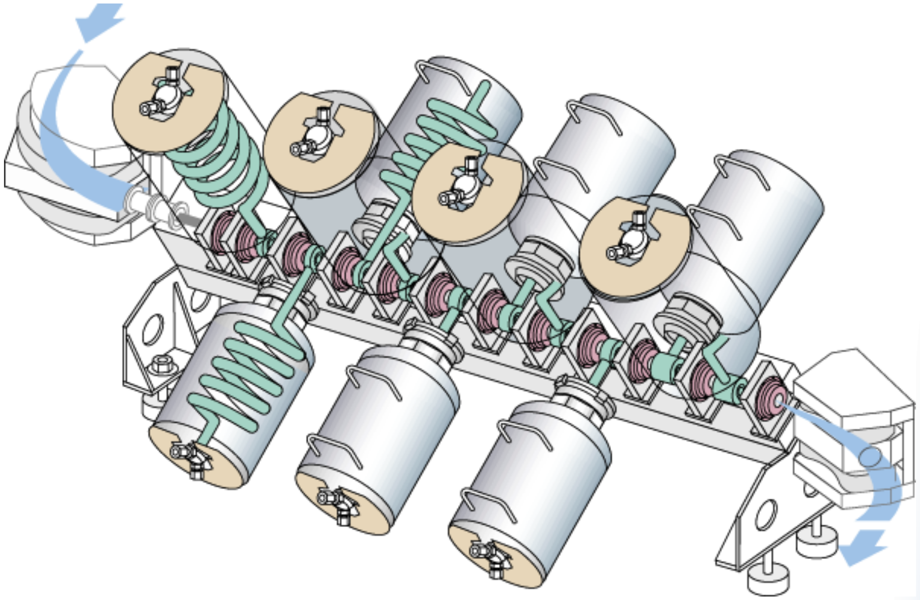


Axcelis HE3

(Batch Implanter)

Axcelis Purion XE

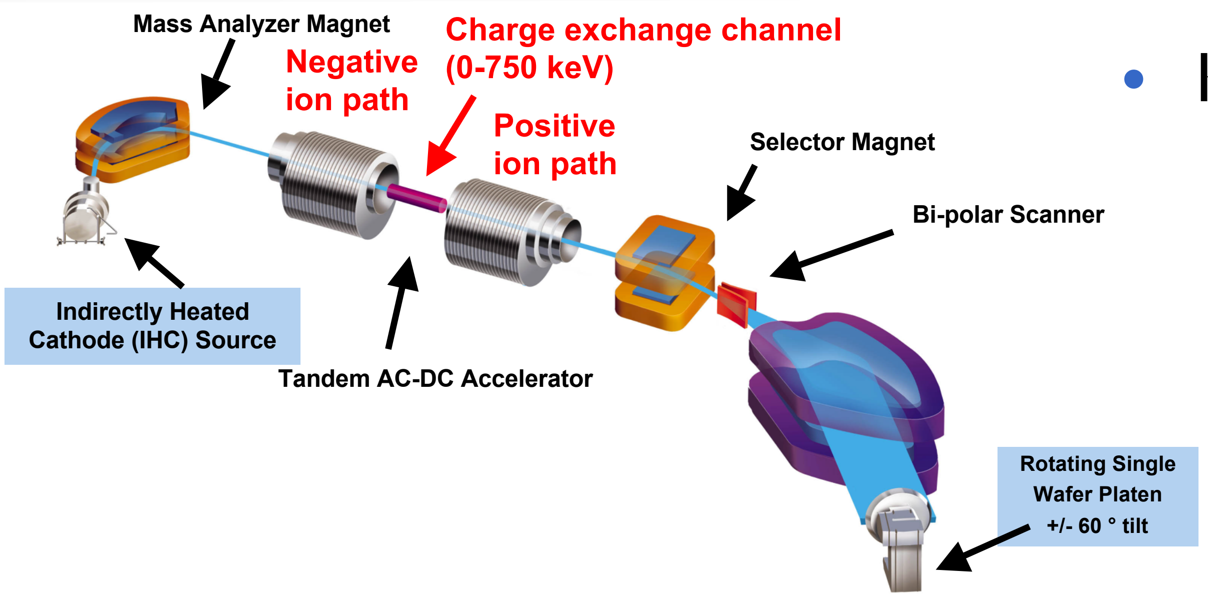
- Single-wafer implanter
- Unmatched beam purity through triple filtration



1) Triply indexed 70° mass analysis magnet
    - Mass filter – selects species and charge state
2) Patented RF Linear Accelerator (LINAC)
    - Velocity filter – selects velocity (mass and energy)
3) 58° Final Energy Magnet
    - Energy filter – selects final energy (rejection of off-energy ions and neutrals)

Energy Range	5keV–4.5MeV
Dose Range	1E11–1E16/cm2
Max Throughput	500 WPH

Varian VIISta 3000XP



Energy Range	5keV–3MeV
Dose Range	5E10–1E16/cm2
Max Throughput	400 WPH

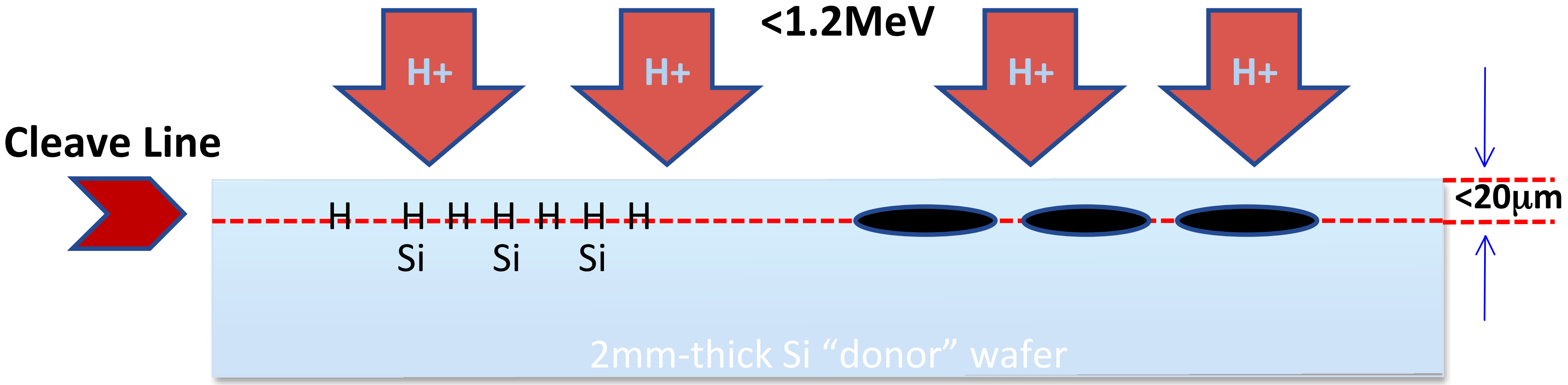
- Key Features
  - Single Wafer
  - Common VIISta end station, control system & software
  - Tandem HE-DC accelerator
  - Closed loop dose/angle control
  - Simple 1D mechanical scan

Specialty Implanters

1. MeV Proton Implanters
2. Plasma Immersion Ion Implanters

Proton Induced Exfoliation (PIE) for Solar Cell Membranes

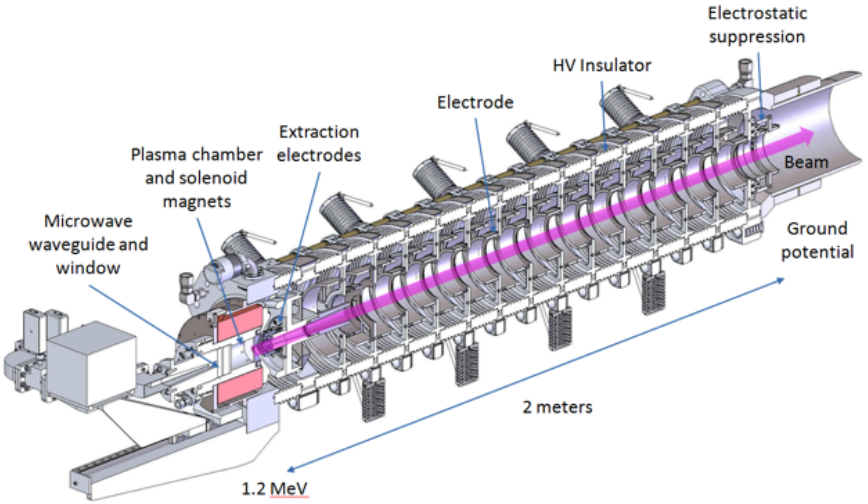
Protons are implanted into donor wafer

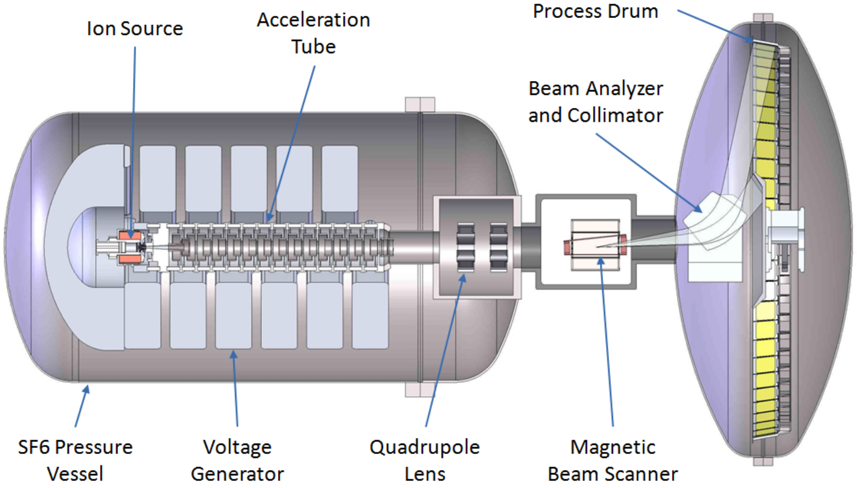


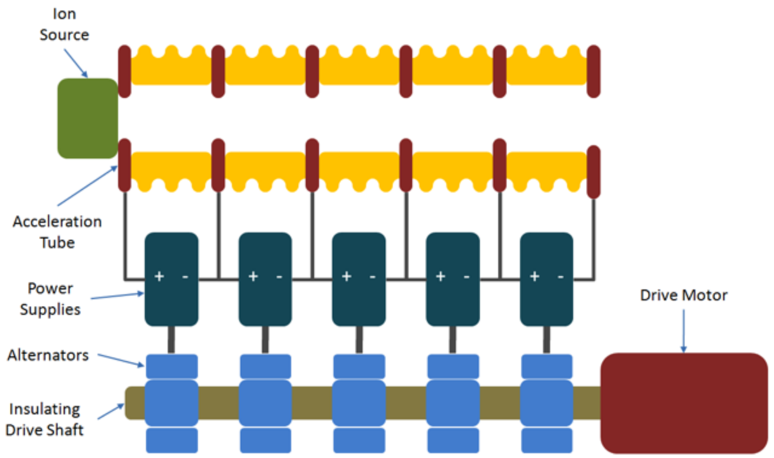
- When heated, the ultra–thin silicon wafer (lamina) cleaves from the donor wafer
  - The donor is reused
- Similar technology, with lower energy H^+ ions, is used for SOI wafer formation, diverse materials lamination, and 3D CMOS stacking

GT Advanced Technologies (GTAT) Hyperion: MeV H^+ Implanter for Solar Cells

- Single-ended DC acceleration
  - Commercial high voltage power supplies
  - Alternator provides electrically isolated source of power for its HV power supply
- 0.4–1.2 MeV (5–20 μm thick)
  - 3 generator assemblies, 15 independent HV power supplies



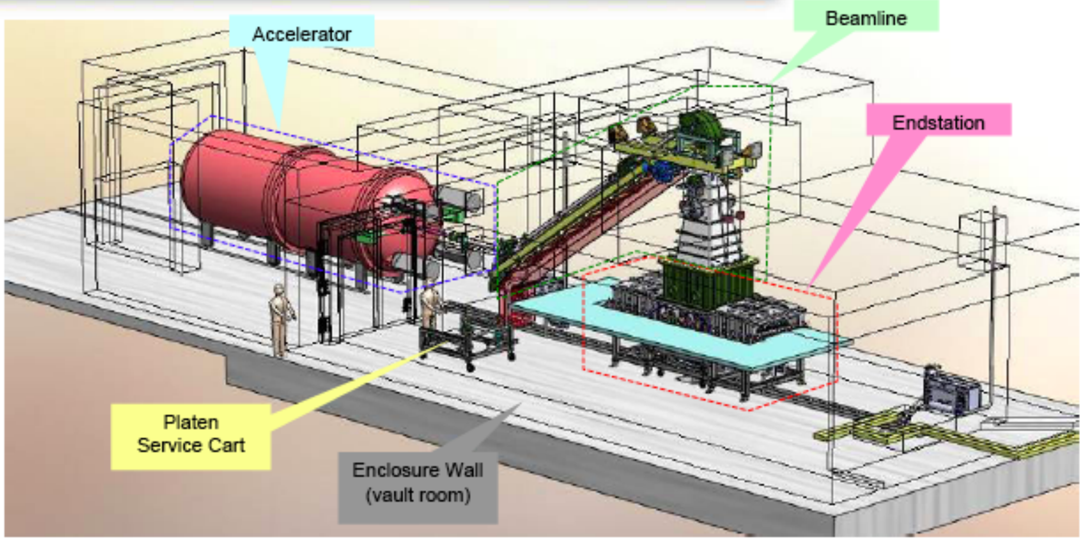


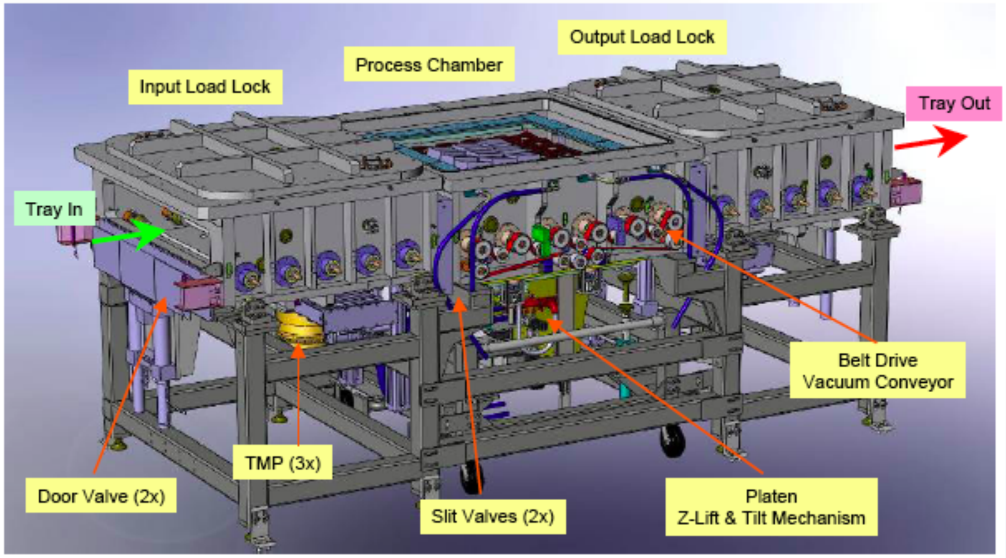


GTAT Hyperion MeV Protons

SiGen PolyMax:
MeV H^+ Implanter for Solar Cells

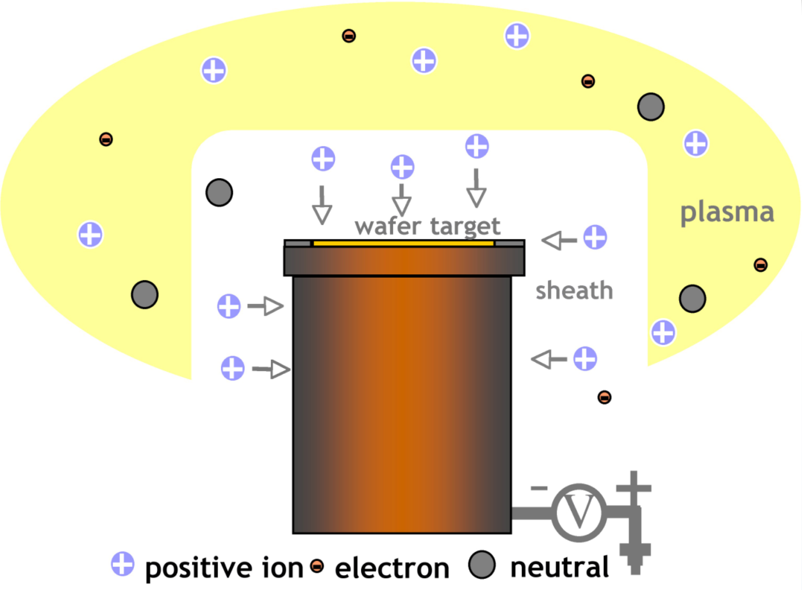
- 4 MeV maximum energy (150 µm Si depth)
- Pipe-lined, in-line system
- Enclosure (vault room) constructed of standard concrete

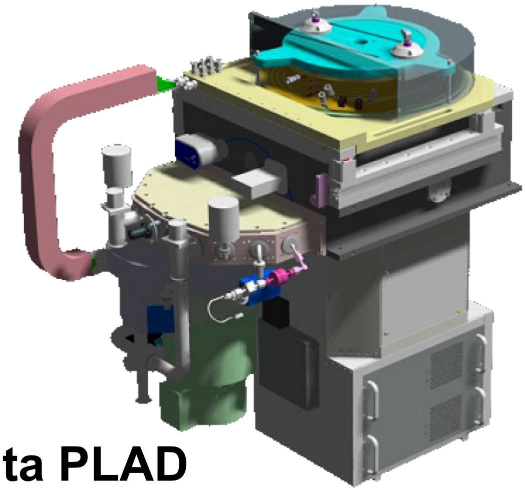




Plasma Immersion Ion Implantation:
High-Dose Doping & Materials Modification

- Negative voltage repels electrons and creates plasma sheath of positive ions
- Electric field accelerates positive ions and implants them into wafer
- Voltage determines implant depth
  - "Accelerator size" is sheath thickness
  - 100 V – 10 kV
- Simultaneous implantation of whole wafer
- Many doping and materials modification applications
  - Very high doses (> 10^{16} cm^{-2})
  - 2 applications used in production of almost all DRAM devices today





Varian VIISta PLAD

Summary: Ion Implantation Technology

- Technology built on >40 years of experience
  - Accelerators are key component of implant tools
- Doses span a range of 10^8
- Energies span a range of 10^4
- Implanter designs have evolved over time and will continue to evolve
  - >40 implant steps per device today for doping and materials modification applications
  - New applications bring new requirements
  - CMOS scaling brings more demanding requirements