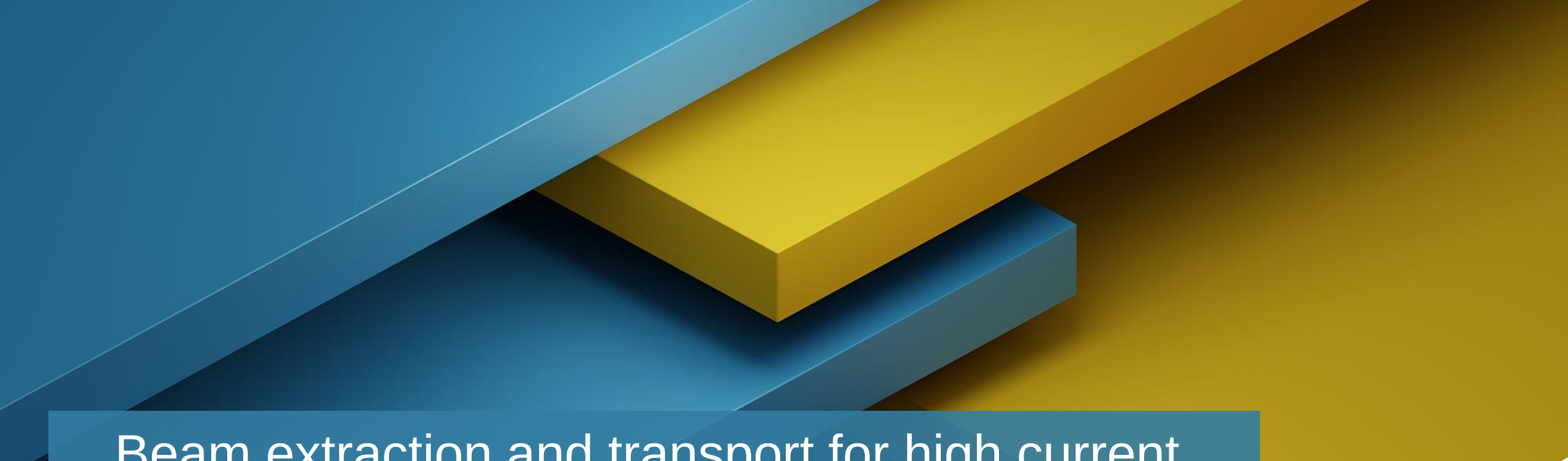


Beam extraction and transport for high current ribbon-beam ion implanters

Alex Perel, Applied Materials, Inc.

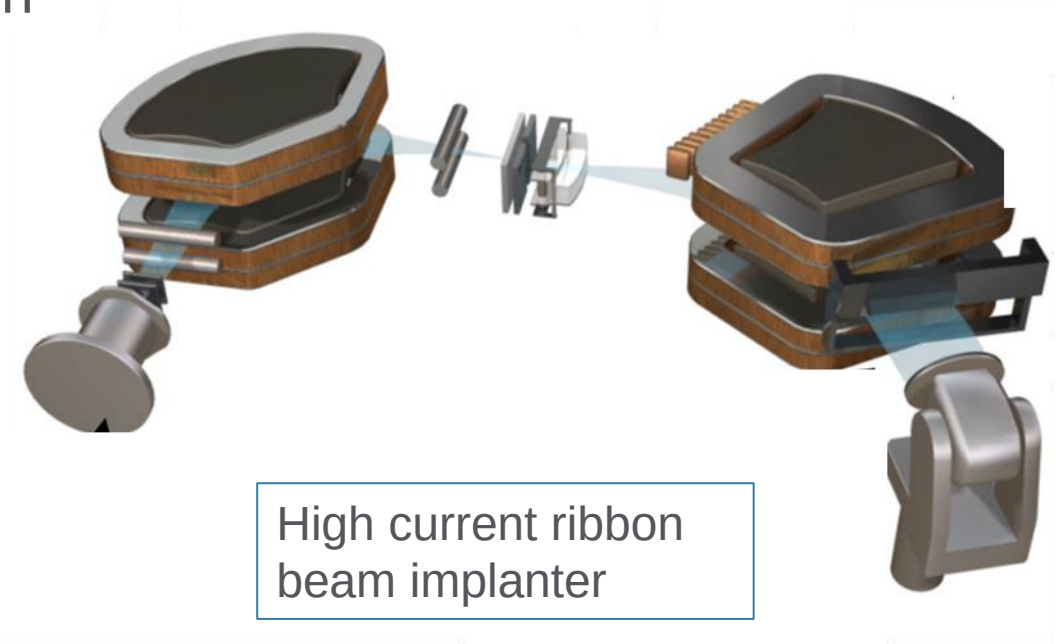
International Conference on Ion Sources, Oxford, UK

8 September 2025

APPLIED MATERIALS™

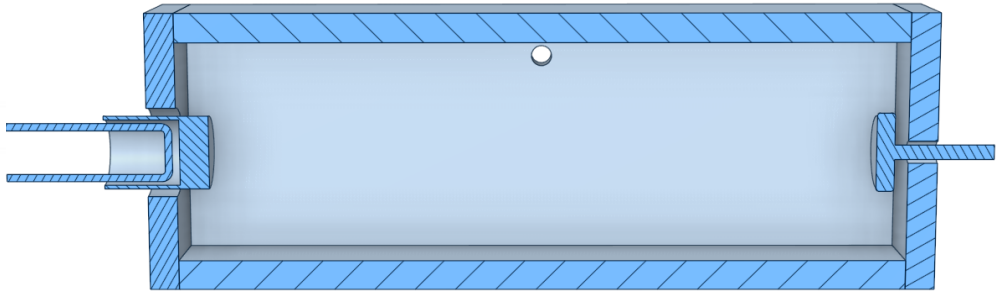
Beam extraction and transport for high current ribbon beam ion implanters

- Architecture – Spot beam and ribbon beam implanters
- Ion source requirements
- Extraction
- Beam noise
- Uniformity and charge control
- Digital Twin



High current ribbon beam implanter

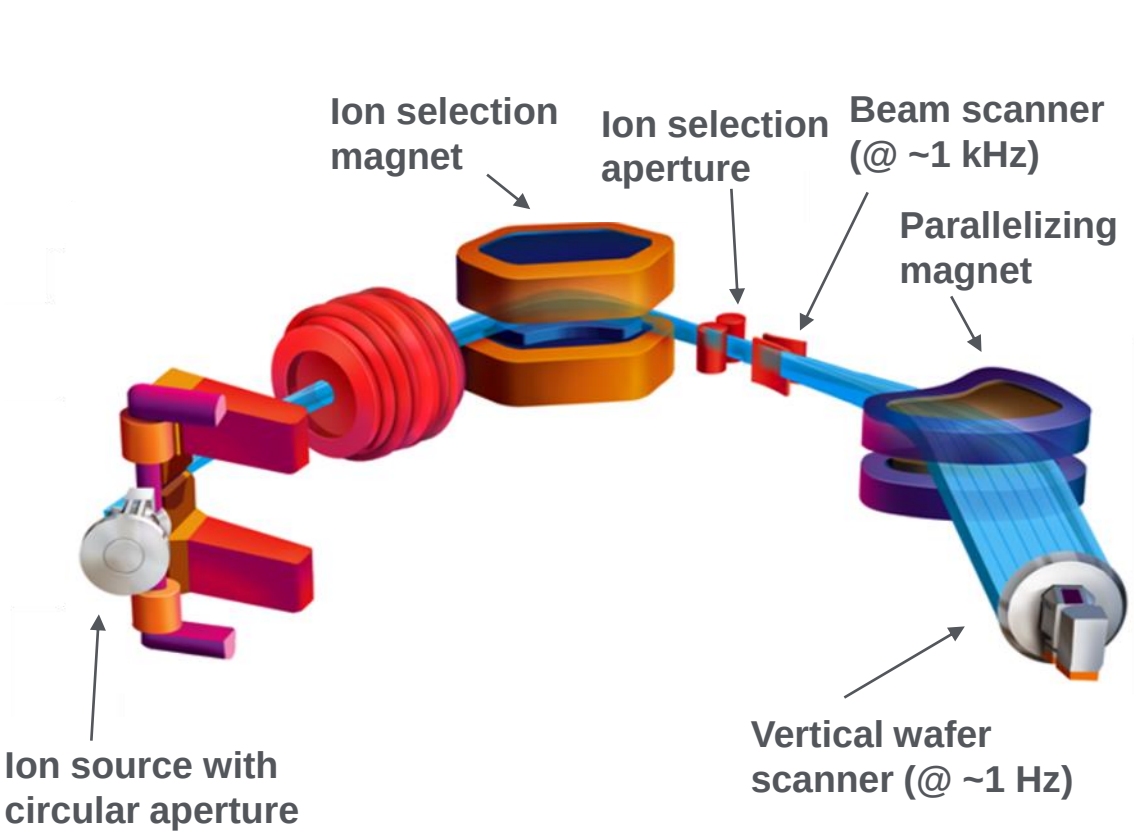
Indirectly Heated Cathode (IHC) ion source with extraction aperture



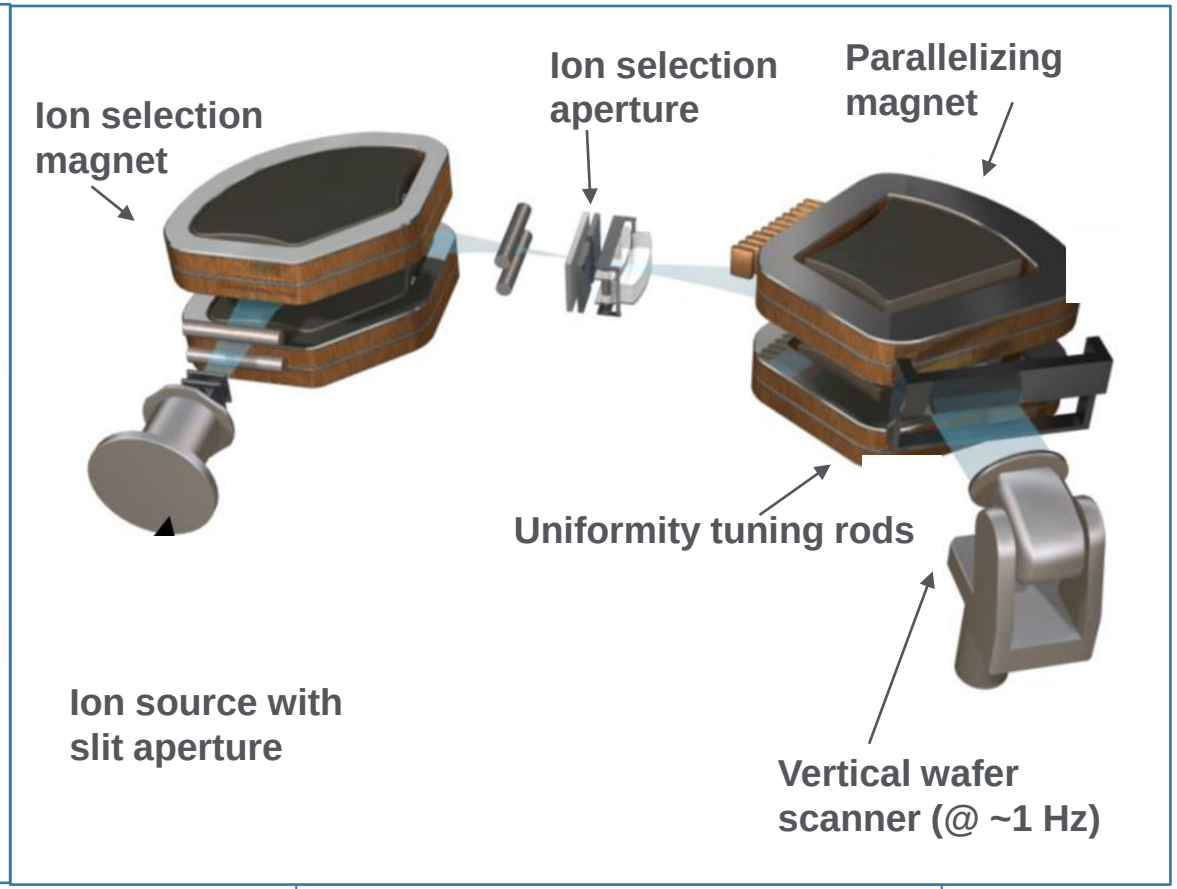
IHC ion source cross section

Spot beam vs. ribbon beam

Features	Spot beam	Ribbon beam
Ion source extraction aperture	Hole (5 to 20 mm in diameter)	Slot (40 to 100 mm in length)
Beam uniformity at wafer	Achieved with horizontal electrostatic scanning	Achieved with magnetic poles
Highlights	Better uniformity, smaller chamber, faster tune	Higher current density



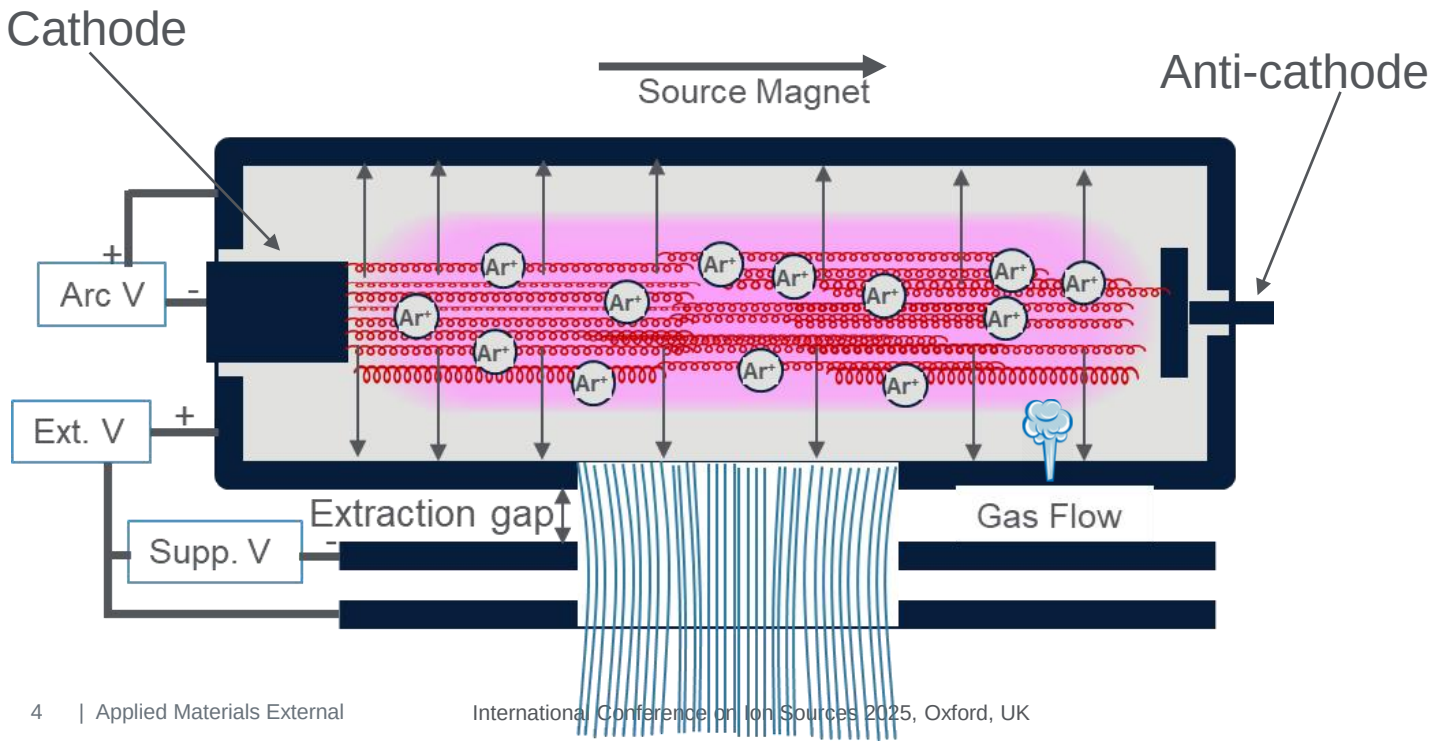
Spot Beam Implanter



Ribbon Beam Implanter

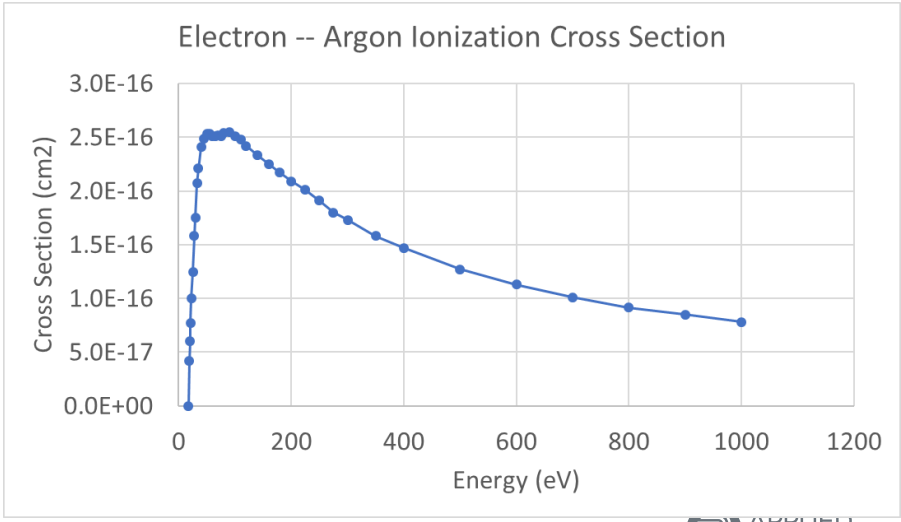
Ion source for a variety of species – Indirectly Heated Cathode (IHC)

- Typical atoms for device doping are B, As, P, In, Sb, Ga
- Typical materials modification atoms are H, He, C, O, F, Si, Ar, Ge, Xe
- A versatile ion source should be able to ionize all of these, typically in the form of a gaseous compound and have short transition times between species



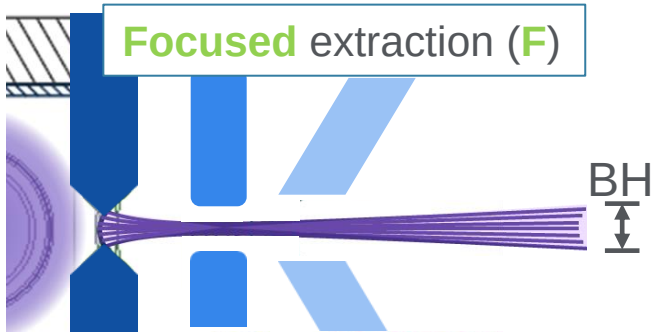
Adjustable Parameters

- Arc Voltage
  - » Ionization cross section, electron confinement
- Source magnet
  - » Electron confinement
- Gas flow
  - » Ionization production, electron diffusion
- Extraction Voltage and Current
  - » Implant depth and dose

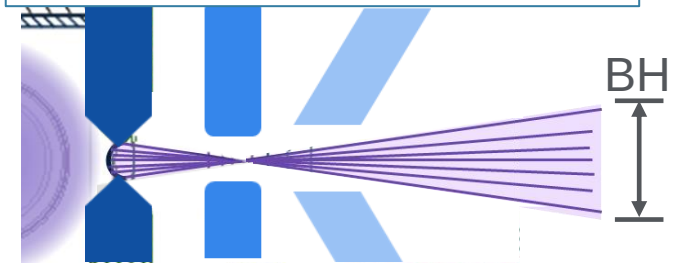


Extraction gap tuning of uniform and non-uniform beams

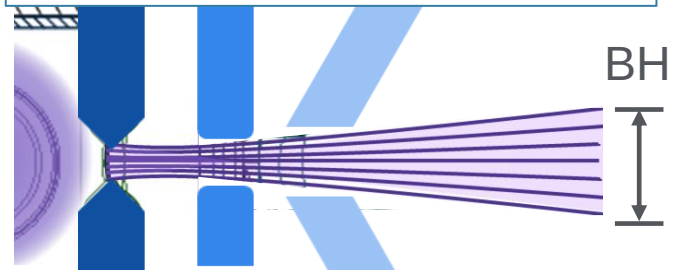
Focused extraction (**F**)



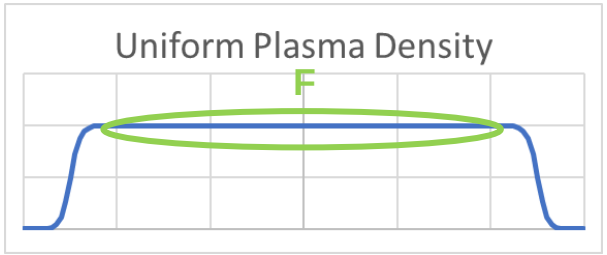
Over-Focused extraction (**OF**)

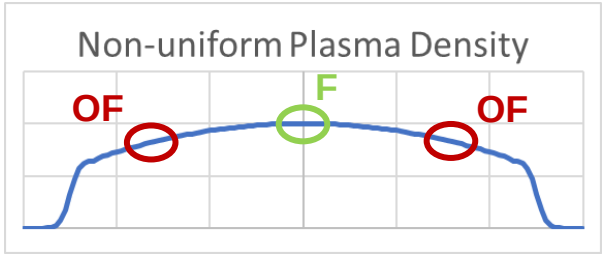


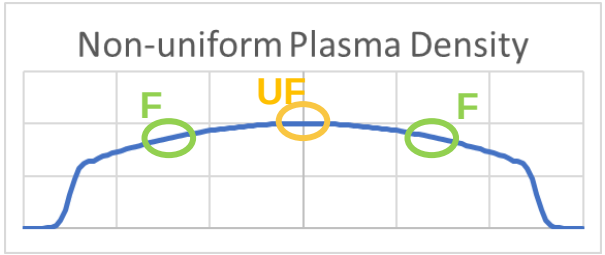
Under-Focused extraction (**UF**)



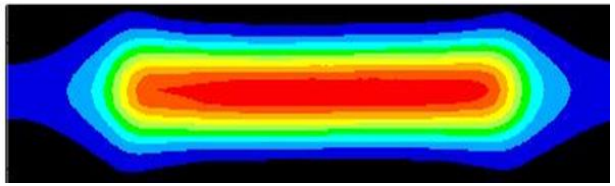
- Non-uniformities created at the source and extraction can cause beam height uniformity problems and angle control issues
- Model and experiments indicate that these are created by over- and under-focusing at extraction



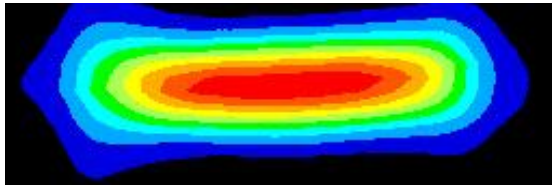




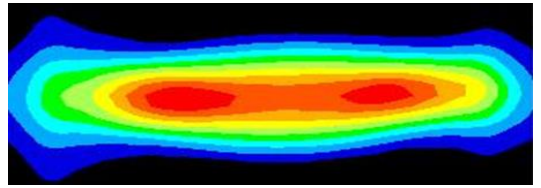
Tuned beam of uniform plasma



Beam tuned at aperture center



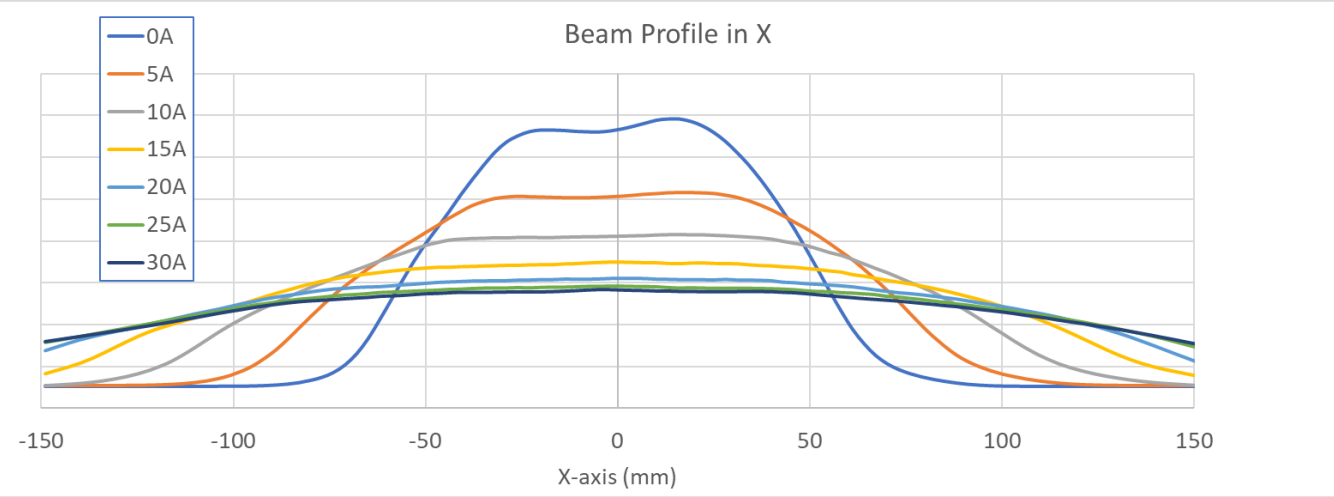
Averaged beam tune

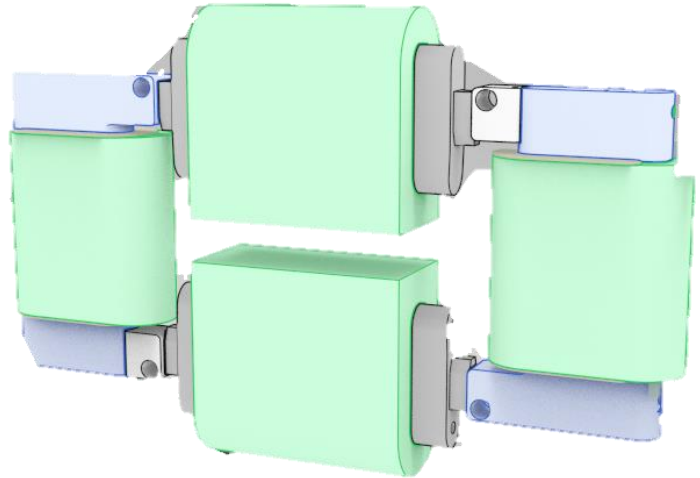


APPLIED MATERIALS

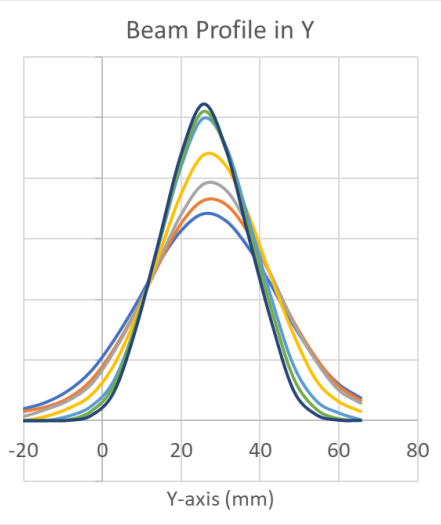
Control of beam spread horizontally and vertically with quadrupole lens

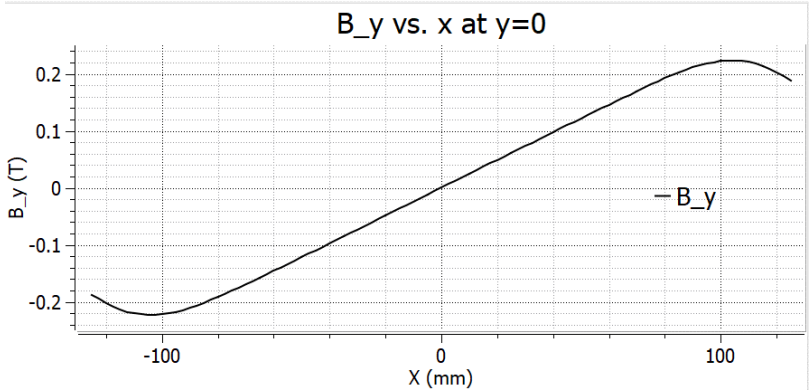
- Quadrupole magnet before the analyzer magnet spreads the beam horizontally to widen it
- This action also limits the vertical beam spread and thus helps improve beam transport

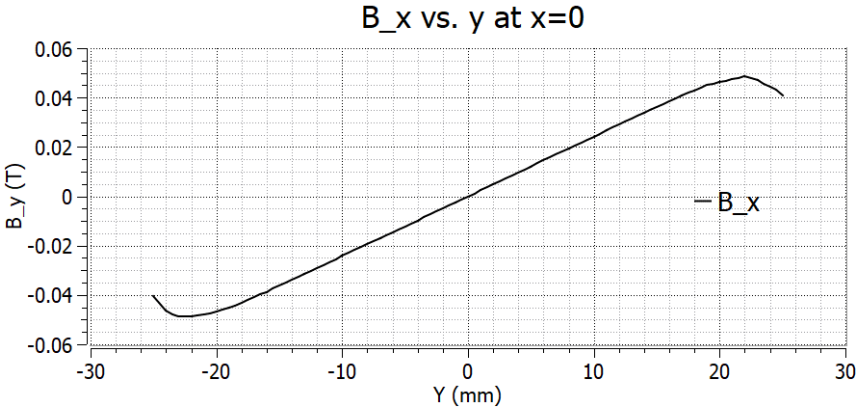




Quadrupole lens

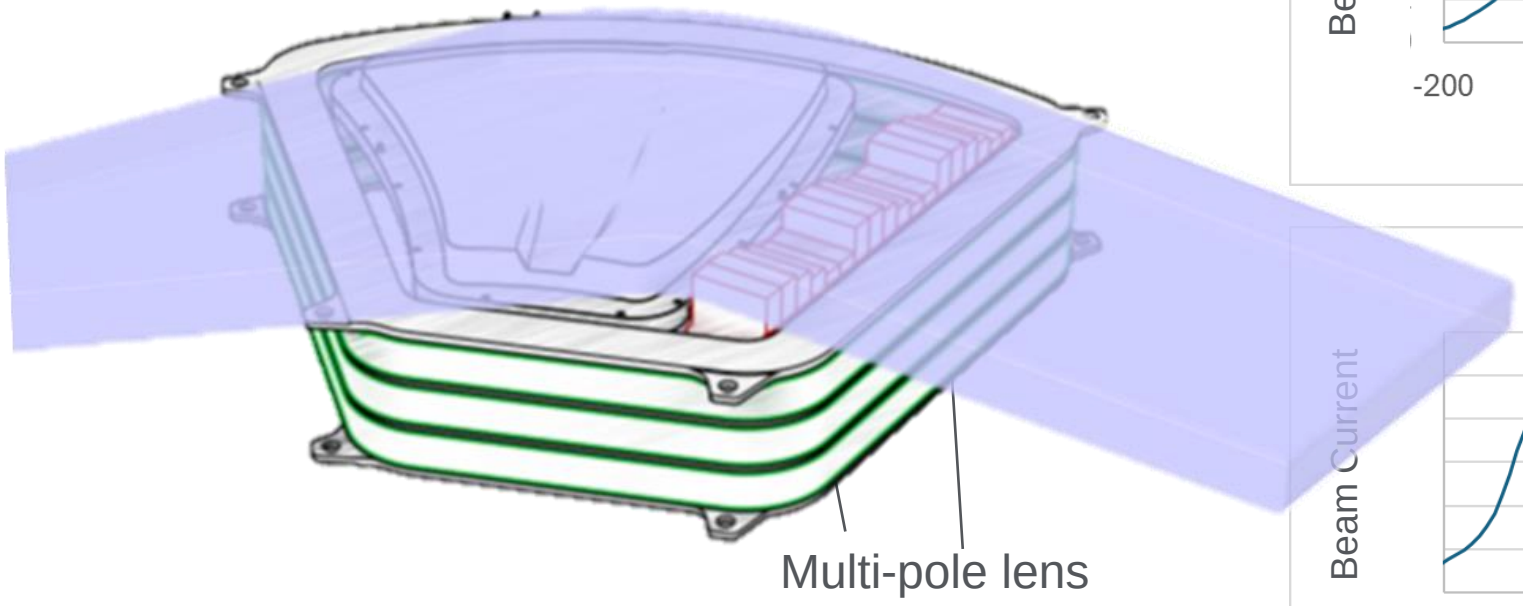




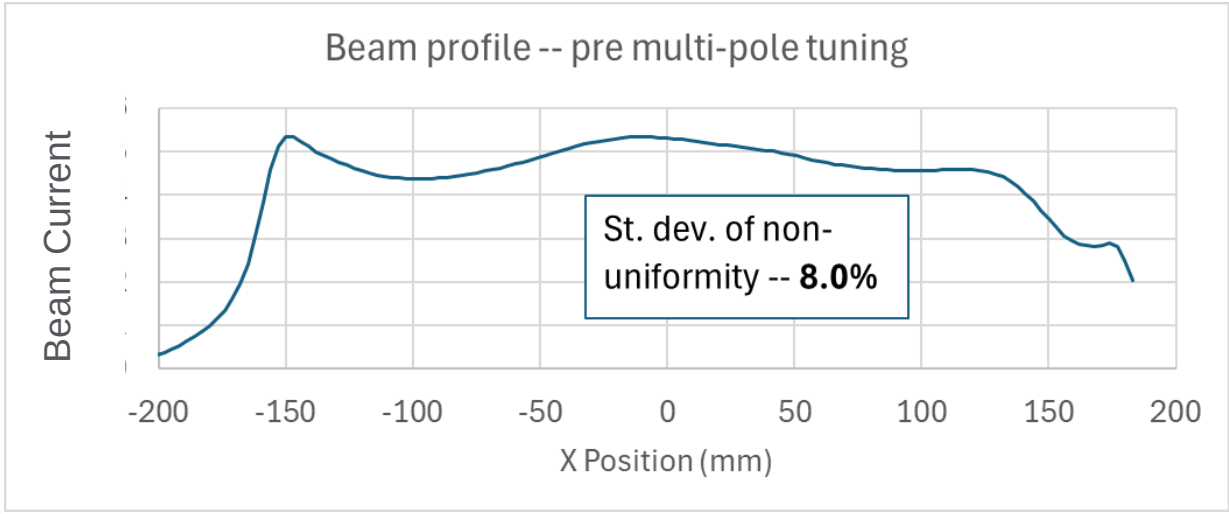


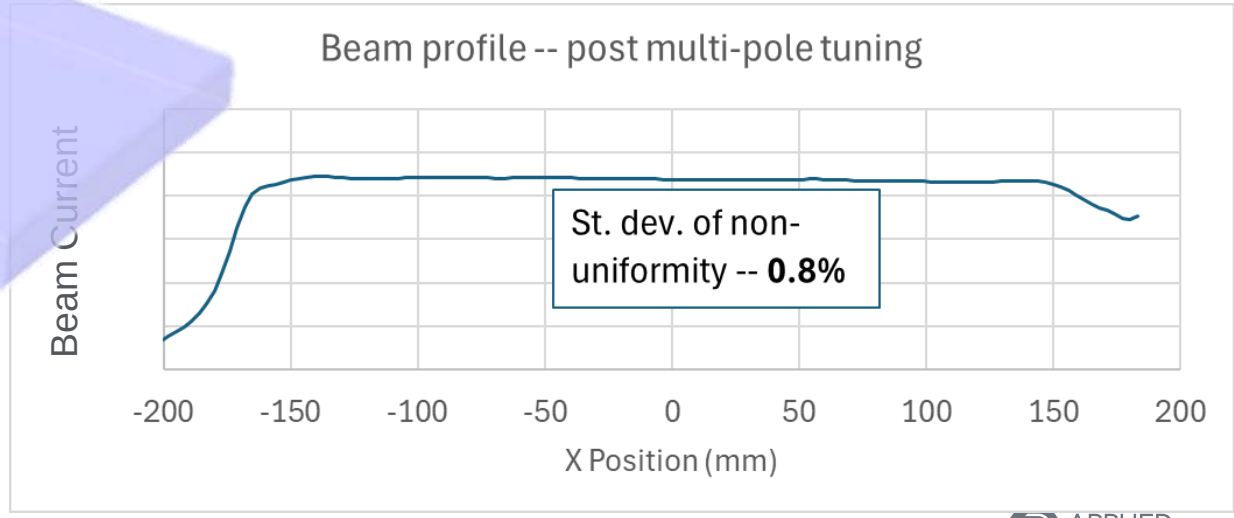
Multi-pole ion lens extends across the beam width

- Multi-poles are the key to reaching high uniformity across the beam and wafer
- Beam is regularly profiled in front of the wafer
- Beam current uniformity in X is measured across the central 320 mm for a 300 mm wafer



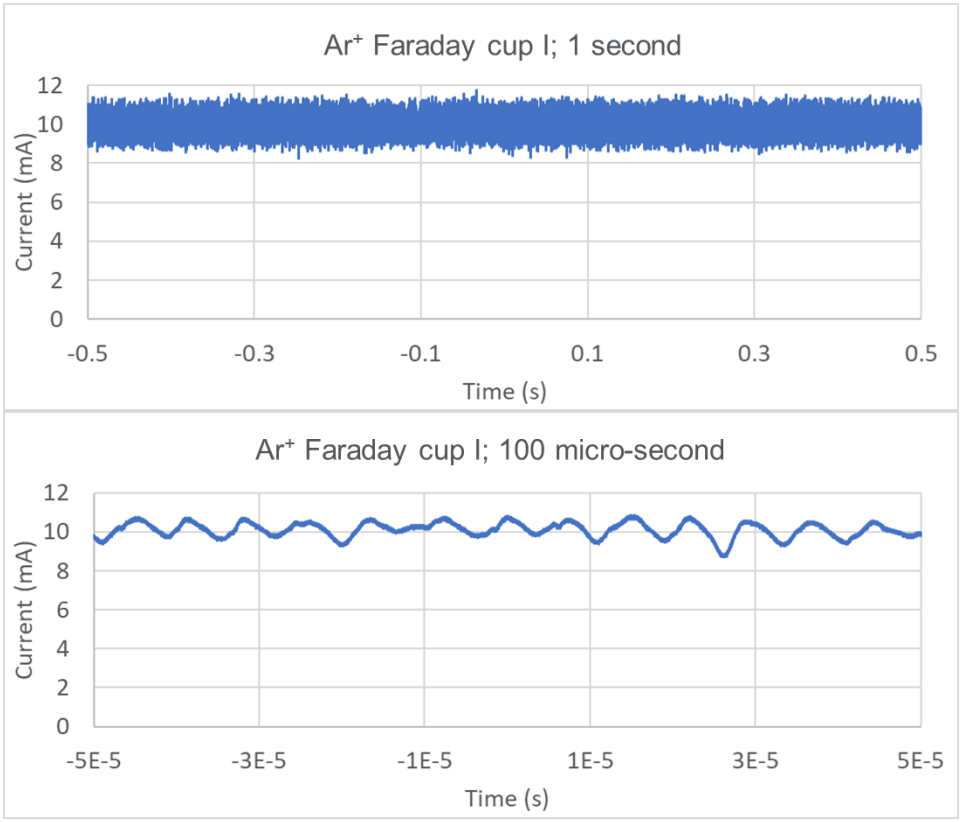
US Patent #: 5,834,786

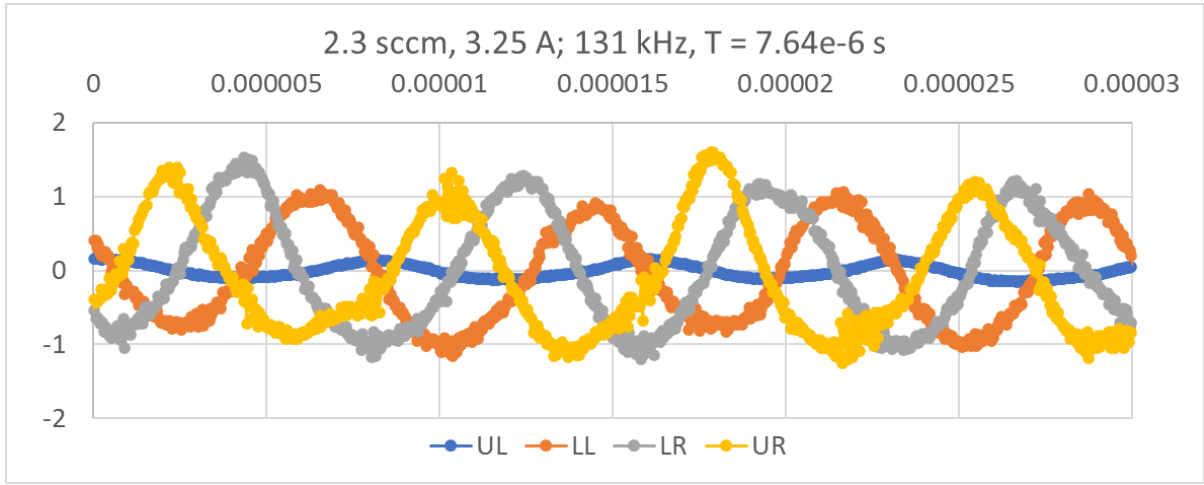




Cyclic Motion in a Magnetized Plasma

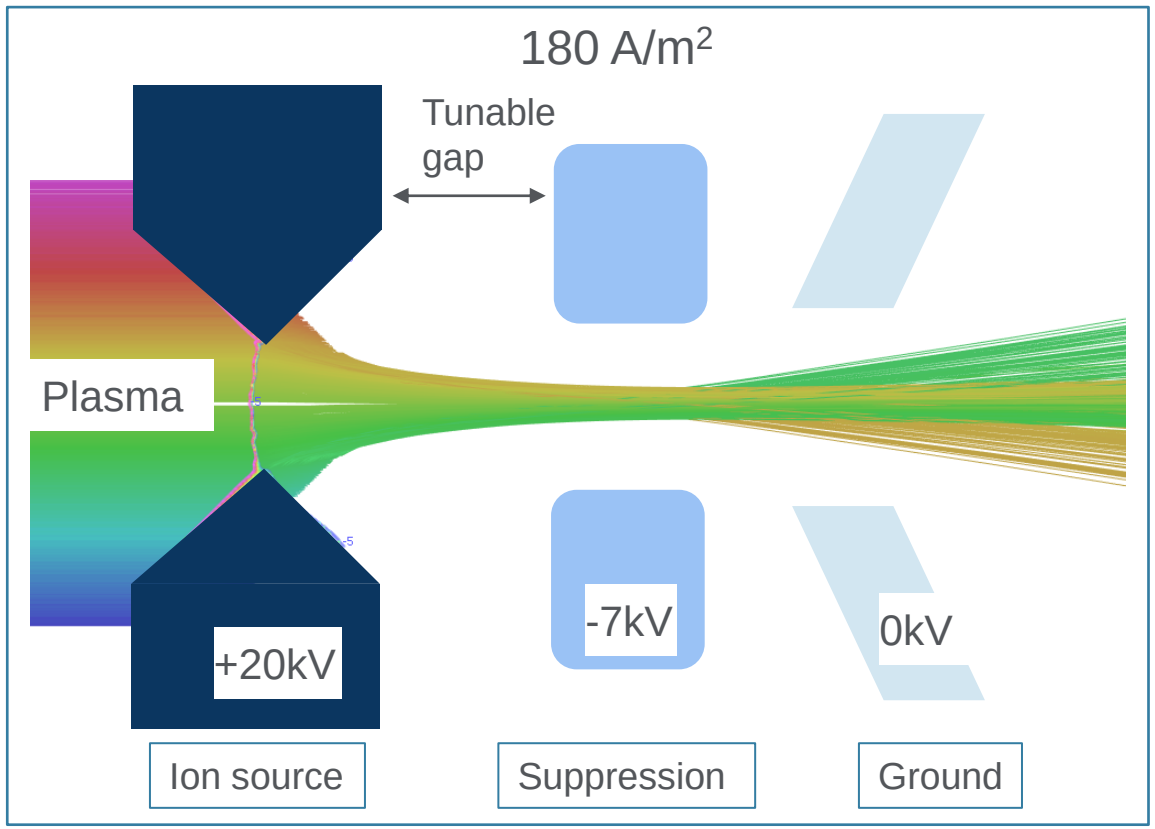
- Ion beams in ion implanters exhibit noise in the beam current amplitude
- Measurements in the ion source indicate an **E**x**B**-related rotary motion that causes this beam current noise
- Reduction of this noise from the ion source can improve beam transmission
- With a specially designed set of probes, we measured plasma vibrations at ~80 to 160 kHz and phase differences between 4 probes indicating a plasma rotation

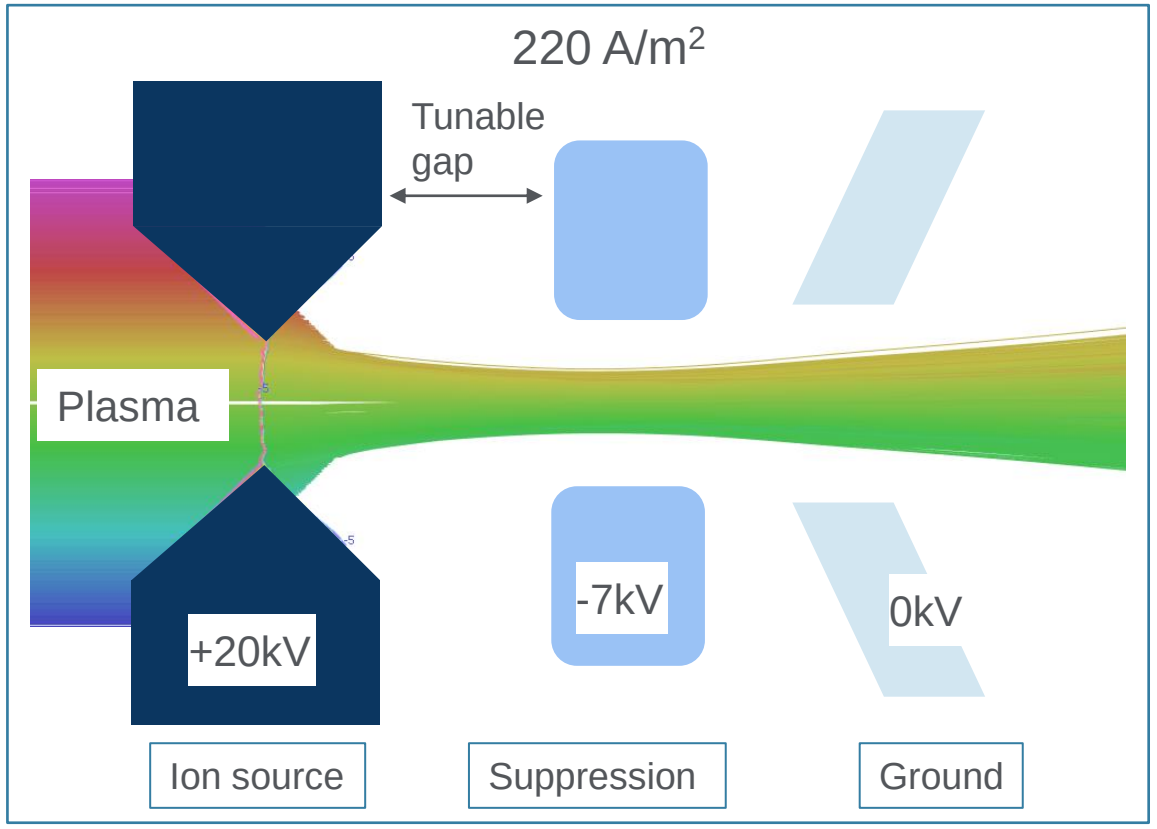




Effect of modulating plasma density on extracted ion beam

- Model of extracted beams with +/-10% difference in beam current density indicates difference in extraction meniscus and beam shape
- Oscillation of extracted current results in an oscillating beam shape



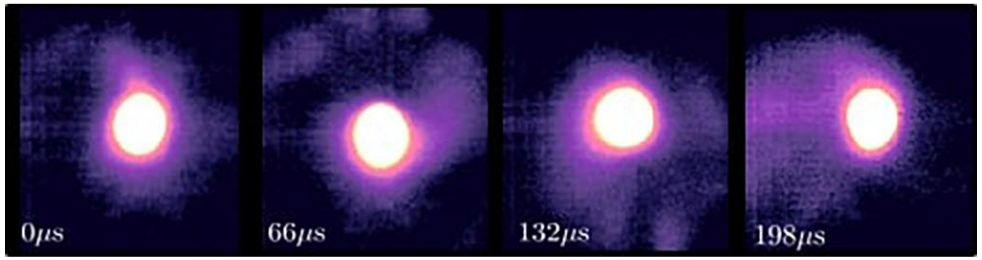


Plasma noise causes current density fluctuation that result in a tall beam height

Magnetized plasmas with ExB spokes

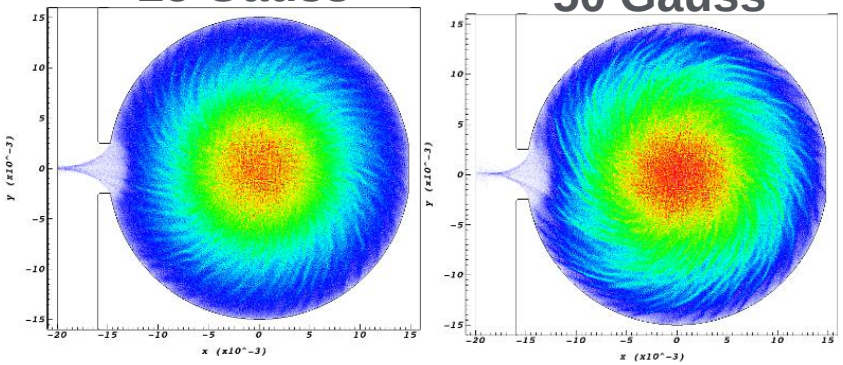
- IHC plasma
  - » Electron confinement results in high density at center with radial electric field
  - » Experiments and simulations indicate azimuthal density waves

80 Gauss

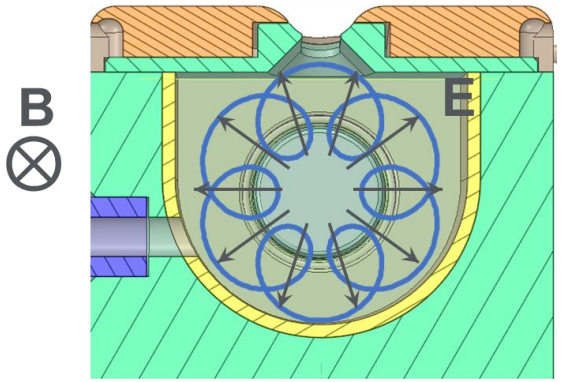


Modeled for Xe with arc voltage at 50 V and pressure at 0.2 mtorr; rotation frequency ~2-3 kHz

25 Gauss **50 Gauss**

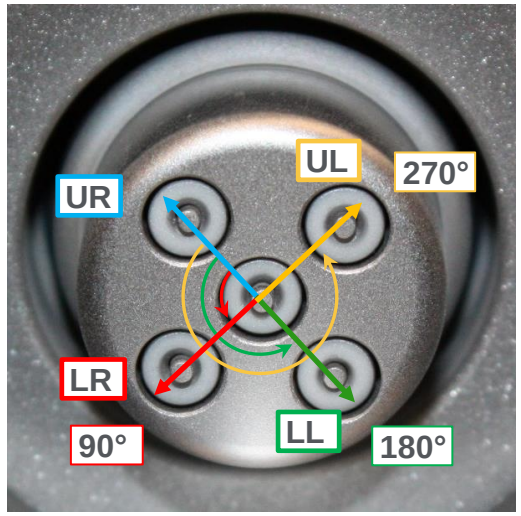


Modeled for Ar with arc voltage at 40 V and flow at 1 sccm; rotation frequency ~50 kHz

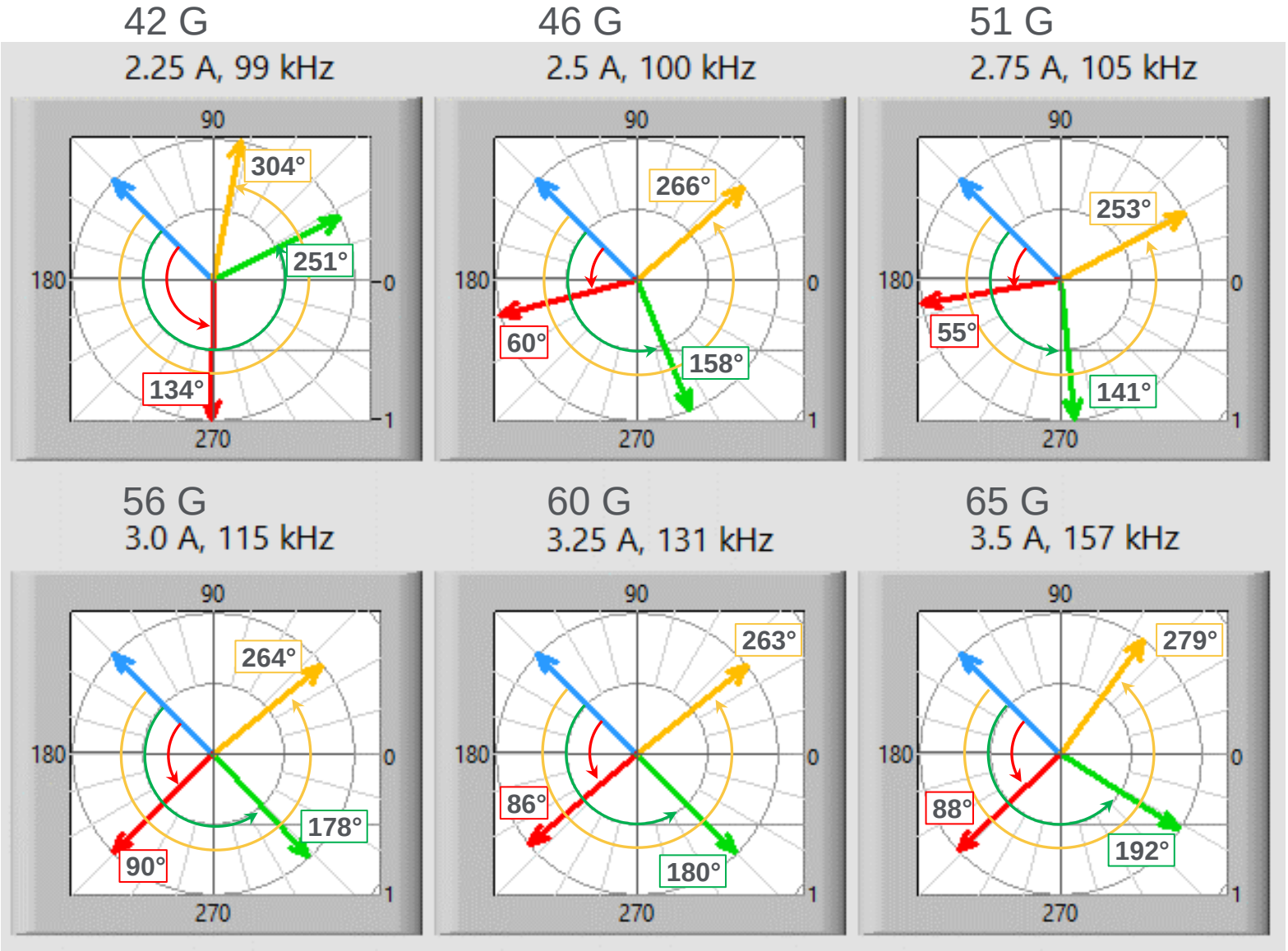


- Boundary-induced effect on the spoke-like activity in *ExB* plasma
  - » E. Rodrıguez, V. Skoutnev, Y. Raitses, A. Powis, I. Kaganovich, and A. Smolyakov, Princeton Plasma Physics Lab and University of Saskatchewan, Physics of Plasmas, **26**, 053503 (2019)
- Modeling of hot cathode DC magnetized plasma source
  - » A. Likhanskii, A. Perel, J. Koo, J. Scheuer, S. Rauf, Applied Materials, Inc., 71st Gaseous Electronics Conference, (2019)

Phase shift from Upper Left probe at 2.3 sccm

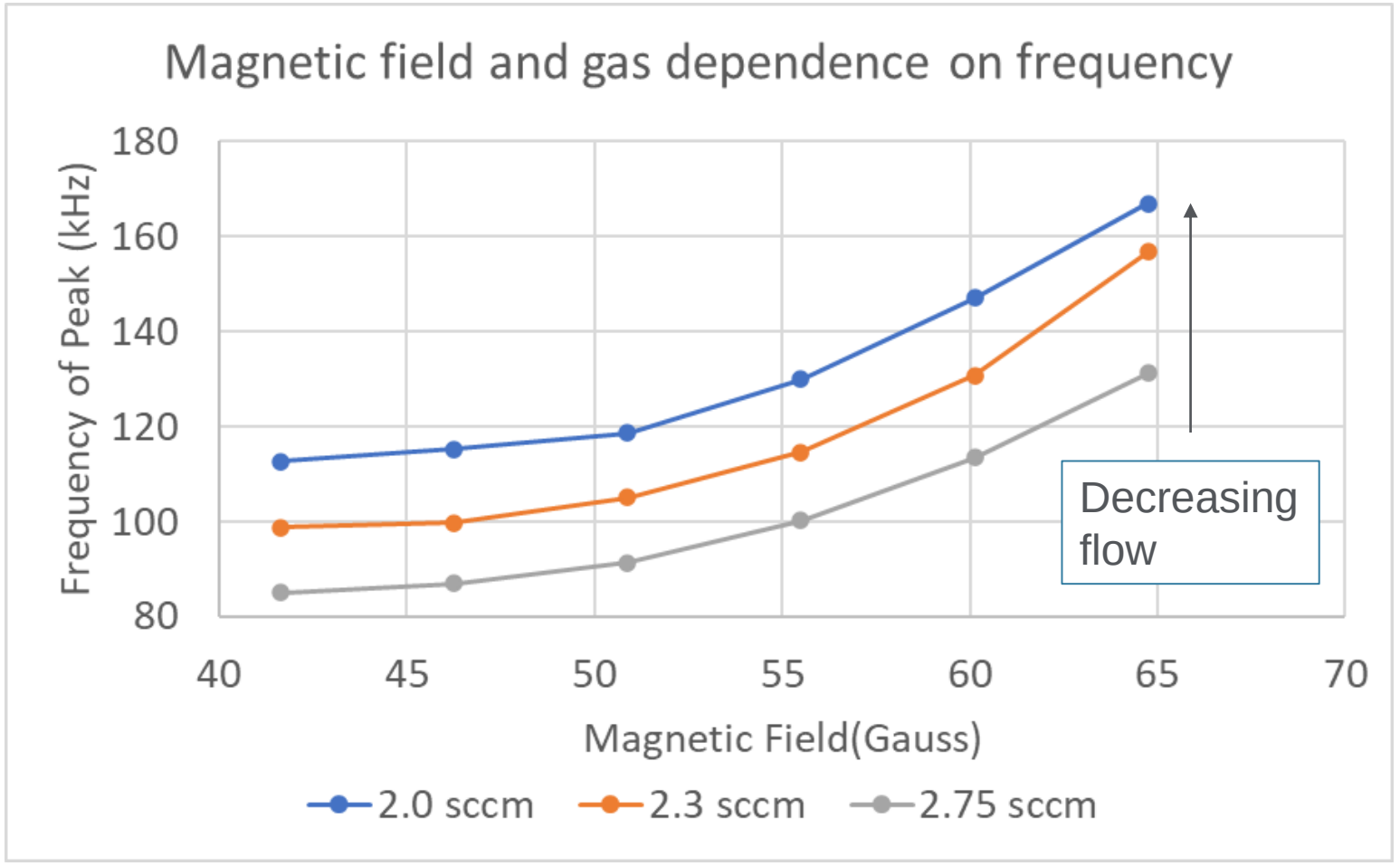


- All measured phases are in order of counter-clockwise positions
- At high magnetic fields excellent correlation with circular rotation
- ~90º phase relation implies single spoke rotation

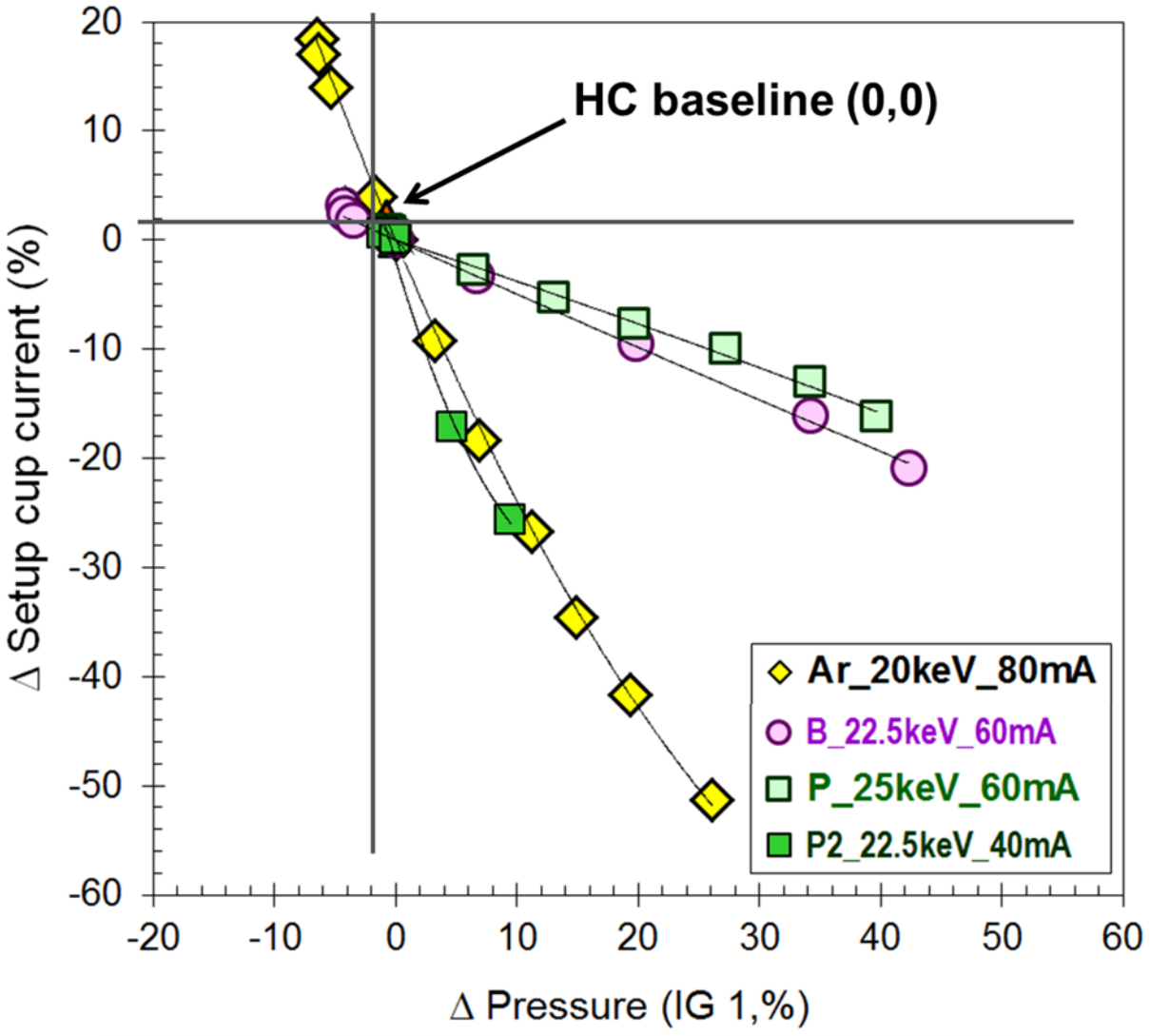


Oscillation frequency as a function of source magnet

- Frequency increases with magnetic field
- Frequency decreases with gas flow



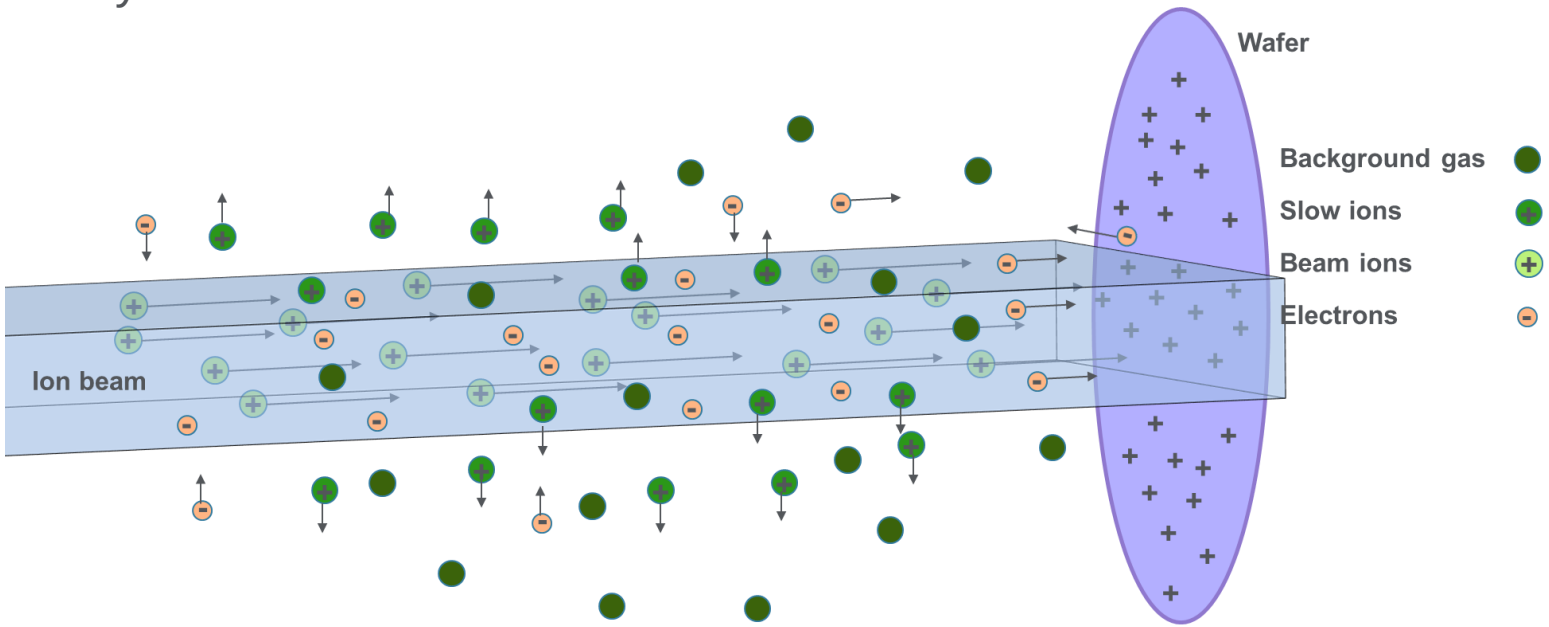
Gas flow: Higher beamline pressure → lower beam transmission



- Increase in gas flow to the source increases pressure in the beamline
- Ion beam current is reduced with high pressure due to neutralization

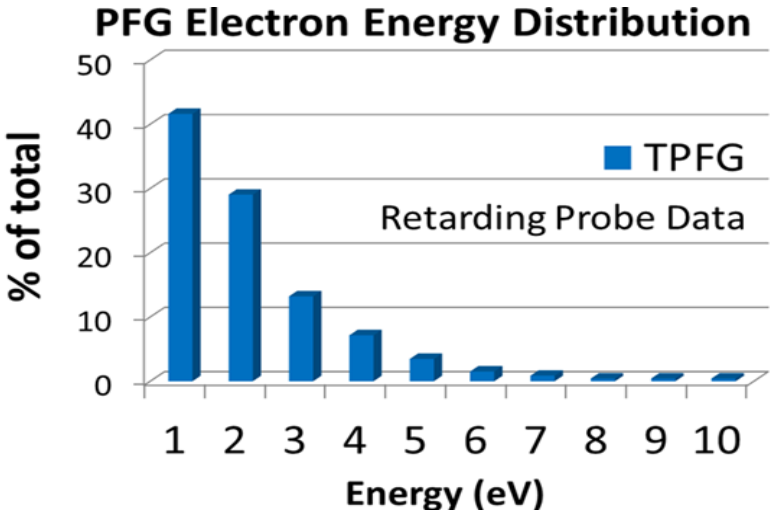
Wafer charge control and beam neutralization

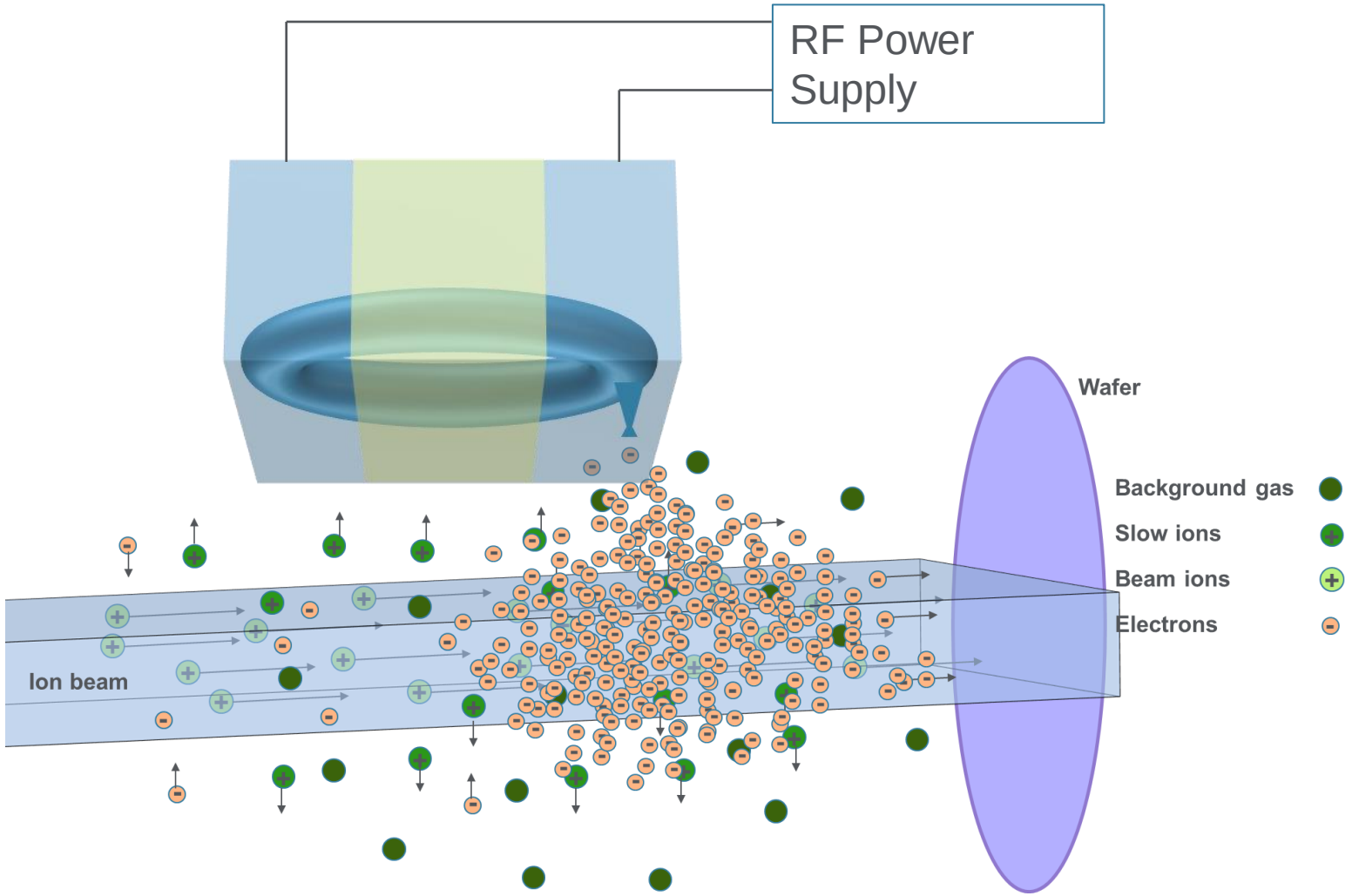
- Ion beam creates a positive space that attracts electrons from:
  - » Secondary emission of beam striking chamber surfaces
  - » Secondary emission of beam striking wafer
  - » Beam collisions with background gas
- Charge control on the wafer
  - » Helps protect devices on wafer
  - » Controls divergence of high density beams



Wafer charge control and beam neutralization

- Electrons from flood gun lower:
  - » Beam space charge
  - » Beam potential
  - » Charge on wafer
- Electron flood types:
  - » Plasma Flood Gun (PFG)
    - DC discharge with filament and **B** field
  - » Toroidal Plasma Flood Gun (TPFG)
    - RF toroid with central insulating block

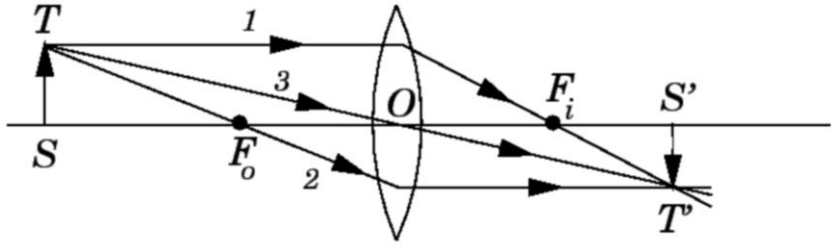


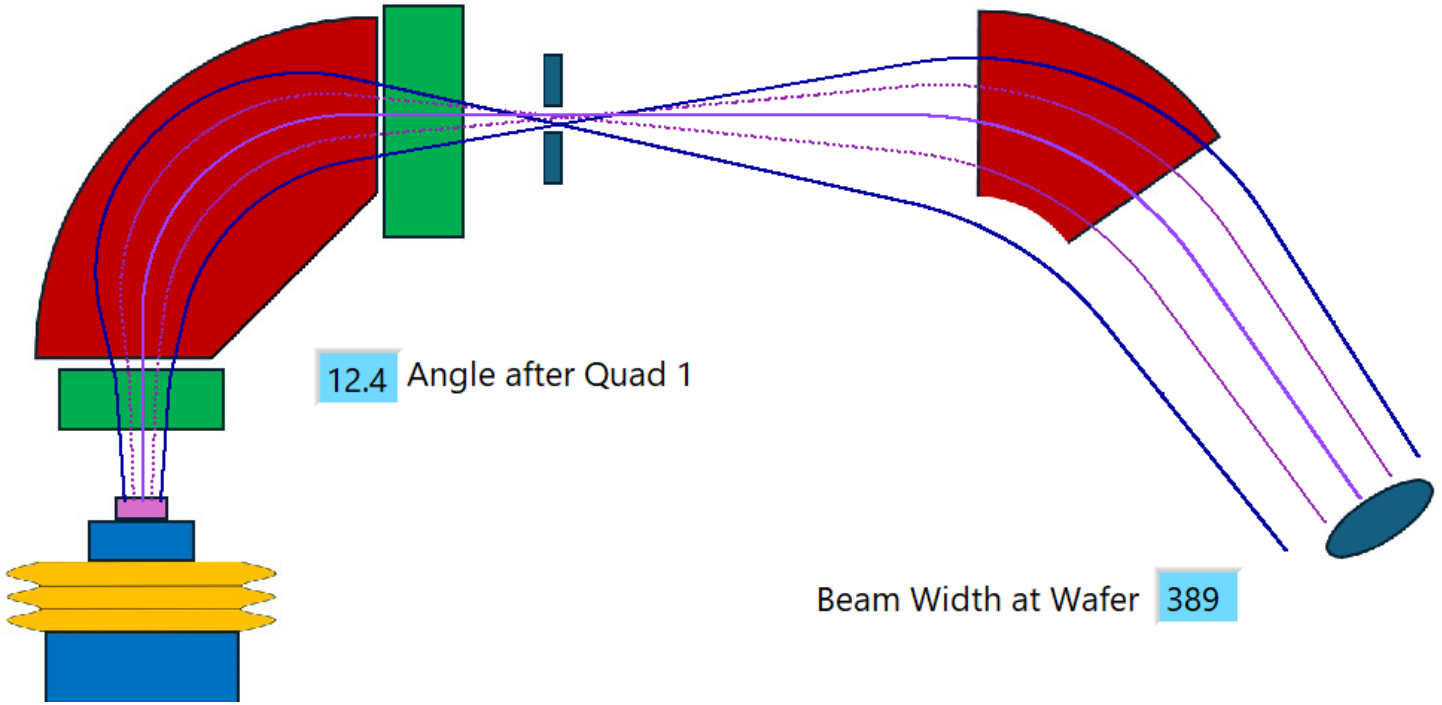


Digital twin for ribbon beam ion implanter

- What is a digital twin?
  - » A digital twin is a virtual representation of a real-world object or process. It uses data and simulations to mirror its physical counterpart, allowing for analysis, prediction, and optimization.
- Paraxial model simplifies implanter allowing for feedback

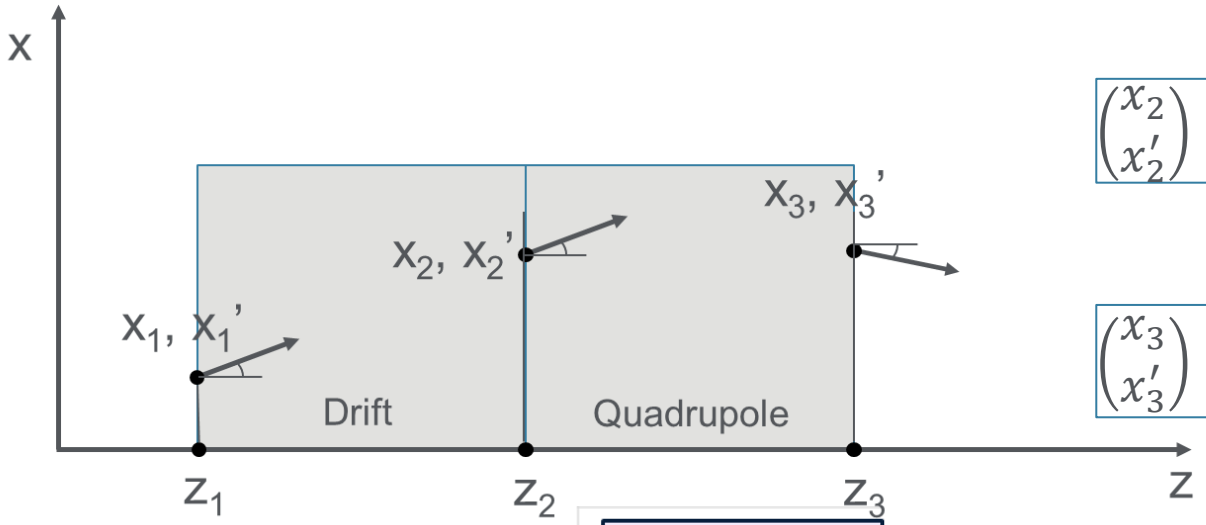
Paraxial model for a converging lens





Paraxial Model

- An ion beam has a central ray that is always parallel to the z-axis
- For any given z_1, a beamlet along x at position and angle x_1 and x_1', its position and angle x_2 and x_2' at z_2 can be determined with knowledge about the intervening elements
- Those elements may include quadrupoles, sector magnets, electrodes, and drift lengths

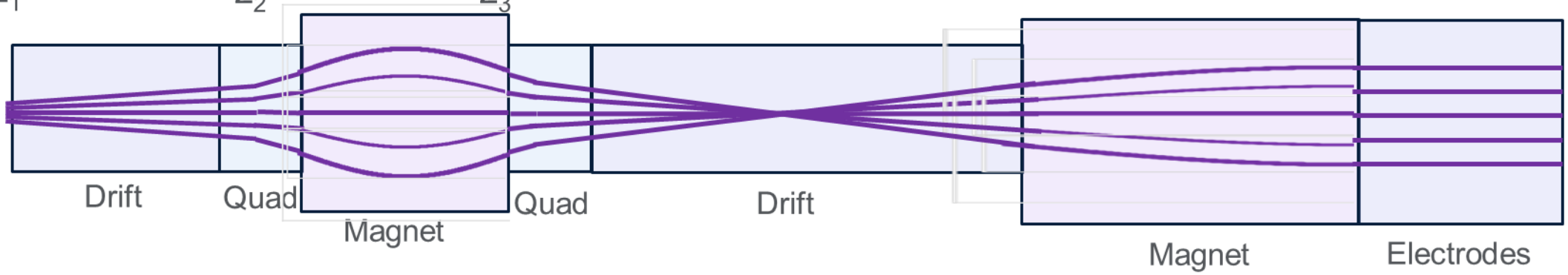


Drift Matrix

$$\begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = \begin{pmatrix} 1 & z_2 - z_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' \end{pmatrix}$$

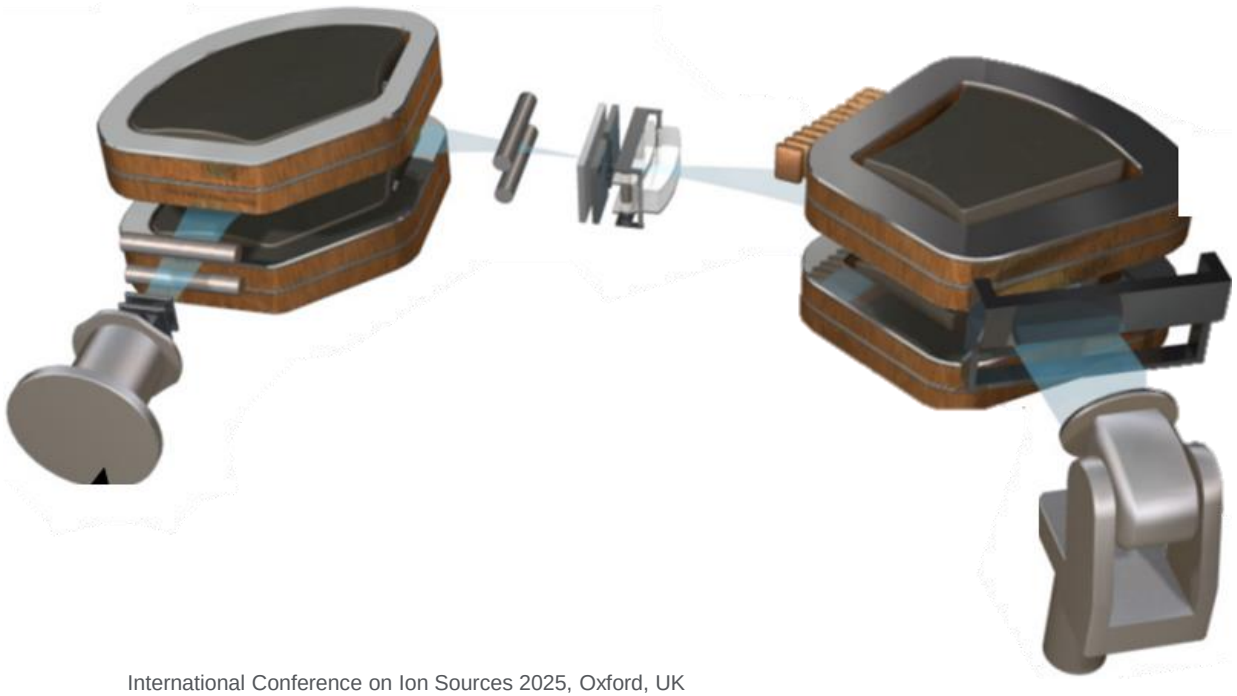
Quadrupole Matrix

$$\begin{pmatrix} x_3 \\ x_3' \end{pmatrix} = \begin{pmatrix} a_{11}(\alpha, z_3) & a_{12}(\alpha, z_3) \\ a_{21}(\alpha, z_3) & a_{22}(\alpha, z_3) \end{pmatrix} \begin{pmatrix} x_2 \\ x_2' \end{pmatrix}$$

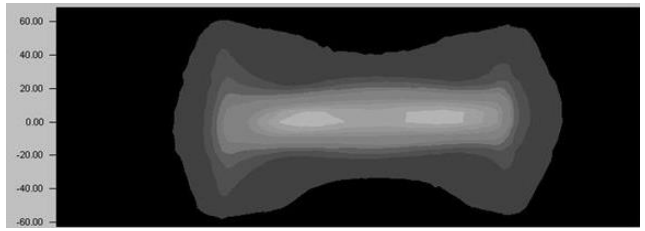


High current ribbon beam

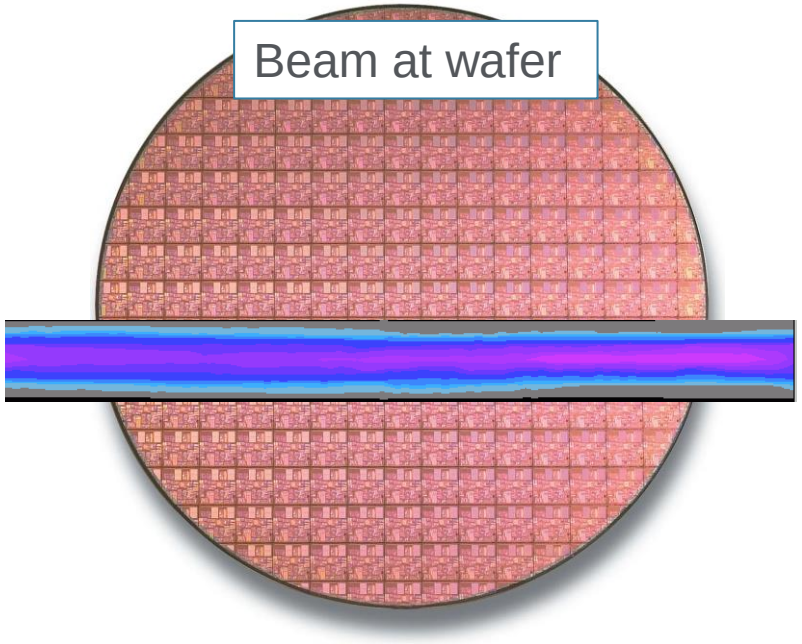
- Architecture – Spot beam and ribbon beam implanters
- Ion source requirements
- Extraction
- Beam noise
- Uniformity and charge control
- Digital Twin



Beam after extraction



Beam at wafer



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