DEVELOPMENT OF A BEAM ION VELOCITY DETECTOR FOR THE HEAVY ION BEAM PROBE

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ABSTRACT

The ability to measure the current density in a toroidal magnetic confinement plasma experiment with a spatial resolution of order 1 cm and a temporal resolution of 1 μs will be invaluable to stability and transport studies. In an axisymmetric plasma, canonical angular momentum conservation constrains heavy ion beam probe (HIBP) trajectories such that measurement of the toroidal velocity component of secondary ions provides a localized determination of the poloidal flux at the location where those ions originated. The poloidal flux can be used to determine the current density profile. We have developed a prototype detector which is designed to measure the beam angle in one dimension through measurement of currents landing on two planes of detecting elements. A set of front entrance apertures creates a pattern of beam current on wires in the first plane and solid metal plates behind them in the second plane; the relative amount detected by the wires and plates determines the angle which beam ions enter the detector, which is used to infer the toroidal velocity component. The design evolved from a series of simulations within which we modeled HIBP velocity changes due to equilibrium and fluctuating magnetic fields, the effect of the ion beam profile and velocity dispersion, and optimized the size of and spacing between wires within a grid and between the two grids. The model predicts the ion beam image and the currents measured by the detector elements. From these simulations, we have estimated the sensitivity of the velocity detector to the equilibrium and fluctuating poloidal flux of the plasma.

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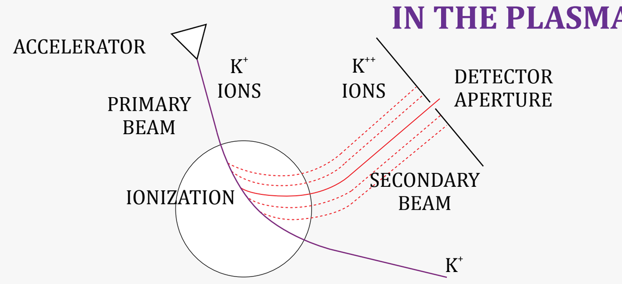
MOTIVATION

- Advance capabilities of the HIBP to
  - Measure the poloidal magnetic flux
  - Infer evolution of the current density profile
  - Characterize magnetic fluctuations
  - Constrain magnetic equilibrium reconstructions
- Develop a detector capable of measuring ion beam velocity without the use of an energy analyzer
  - Advantages include reduced size, cost, and complexity of diagnostic

HEAVY ION BEAM PROBE (HIBP) PRINCIPLES

ESTABLISHED MULTI-POINT, TIME-RESOLVED MEASUREMENTS IN THE PLASMA CORE



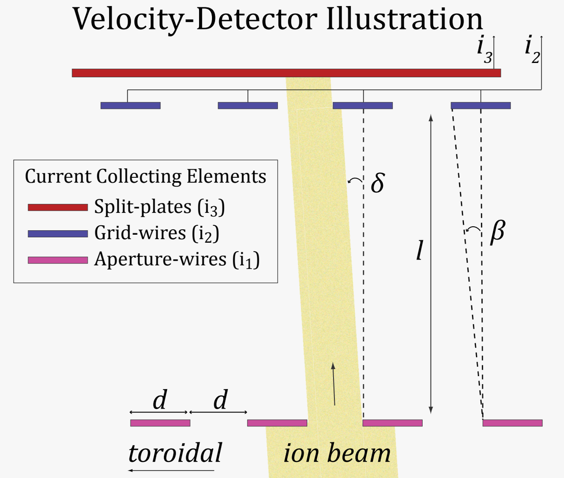
- HIBP typically measures φ, $\tilde{\varphi}$, $\tilde{n}/n$
- Inject primary (1+) ions
- Detect secondary (2+) ions
- Measurements spatially localized to ionization volume

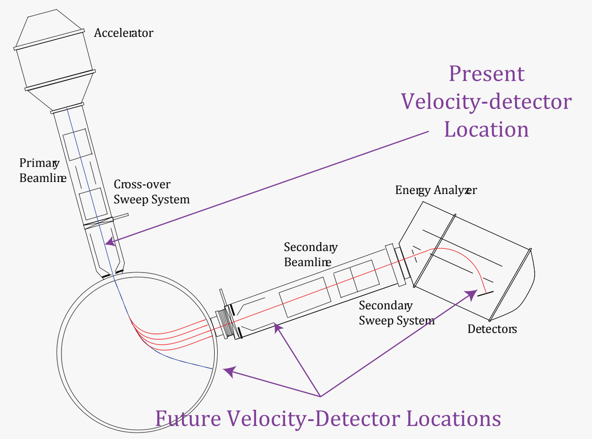
POLOIDAL FLUX MEASUREMENT

A TECHNIQUE AND DETECTOR ARE BEING DEVELOPED TO MEASURE ION BEAM VELOCITY (v_φ) TO DETERMINE ψ_p

- Measure v_{φ_d}
  - Currents measured by velocity-detector can
    - Be used to determine the toroidal beam angle δ
    - v_{φ_d} additionally requires total beam velocity v_0
  - $\tan(\delta) = (i_2 - i_3)/(i_2 + i_3) \cdot \tan(\beta)$
    - Currents on grid-wires (i_2) and split plates (i_3)
    - Currents on split-plates (i_3)
    - Detector geometry ($\beta = \mathrm{atan}(d/2l)$)
    - Detector geometry ($\beta = \mathrm{atan}(d/2l)$)
  - This relationship requires aperture and impact wire size and spacing to all be identical (d)
  - $v_{\varphi_d} = v_0 \sin(\delta)$

Velocity-Detector Illustration





- Determine ψ_p from v_{φ_d}
  - Toroidal (φ) component of canonical angular momentum (P_φ) is conserved in axisymmetric plasma
    - $P_\varphi = MRv_\varphi + q\psi$
    - At ionization point (p), electron carries away $-e\psi$
  - $\psi_p = (m/e)(R_d v_{\varphi_d} - R_i v_{\varphi_i}) + 2\psi_d - \psi_i$
    - $p \rightarrow$ ionization point
    - $d \rightarrow$ detector location
    - $i \rightarrow$ initial location
    - $p \rightarrow$ ionization point
  - Also need v_{φ_i} (initial beam velocity) and ψ_i, ψ_d

THE POLOIDAL MAGNETIC FLUX MAY BE USED TO INFER THE MAGNETIC VECTOR POTENTIAL, SAFETY FACTOR AND CURRENT DENSITY PROFILES

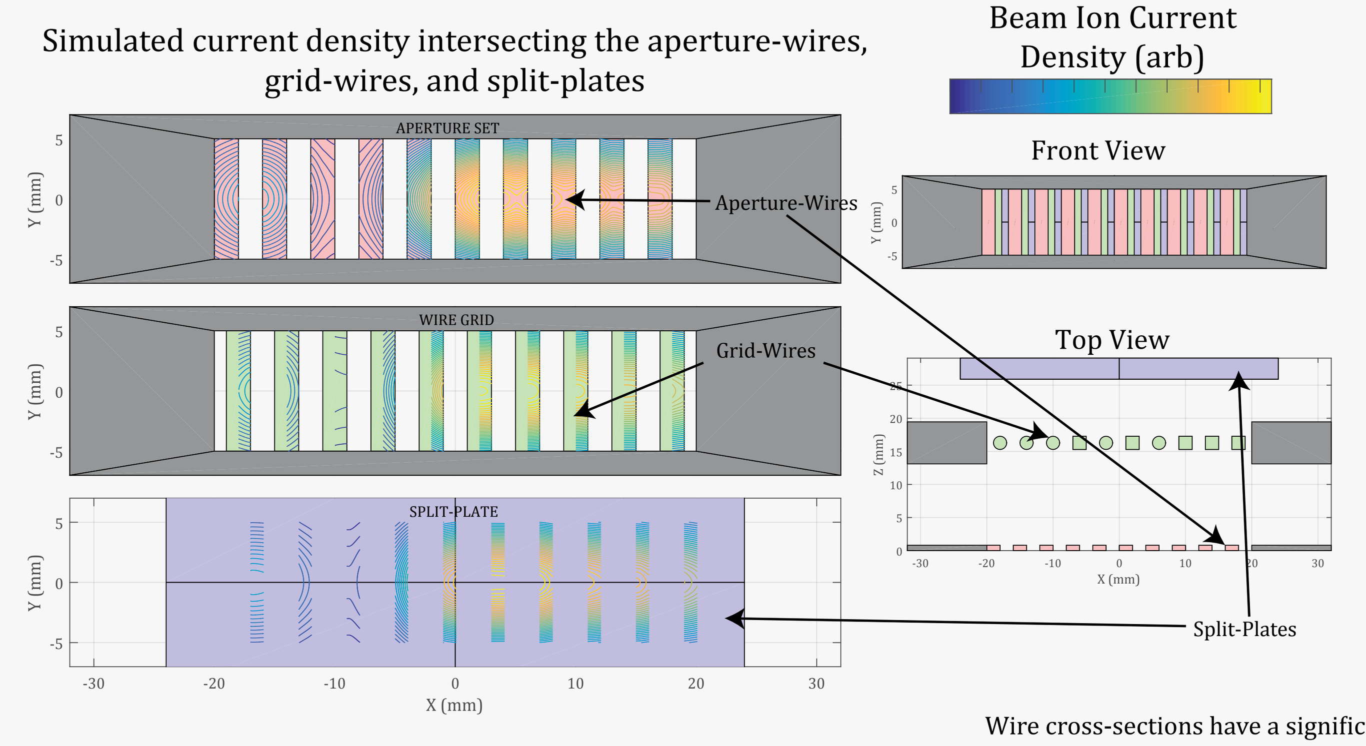
- Magnetic vector potential $A_\varphi(r) = \psi_\varphi(r)/R(r)$
- Safety factor $q(r) = d\psi_\varphi(r)/d\psi_\theta(r)$
- Current density $\mu_0 J_\varphi(r) = -\nabla^2 A_\varphi(r)$

MODELING OF THE VELOCITY-DETECTOR

CODES DEVELOPED TO DESIGN THE VELOCITY-DETECTOR ARE ALSO ENABLING ANALYSIS OF MEASUREMENTS

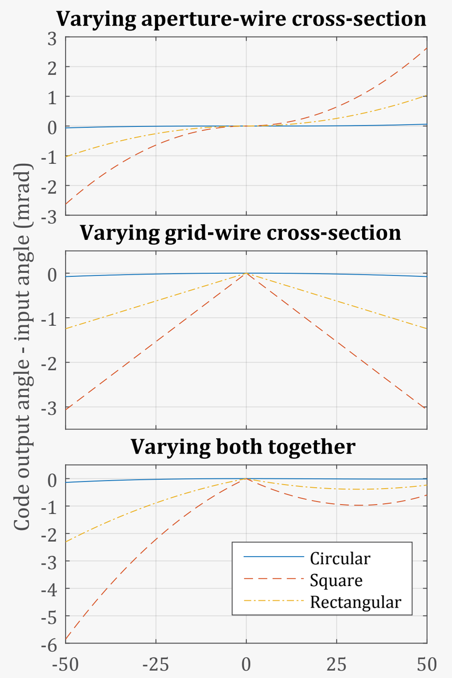
- Goals of velocity-detector modeling
  - Drive hardware design
  - Include physical effects of real components
  - Include effects due to a realistic beam current profile
  - Estimate sensitivity and dynamic range
  - Work as a virtual diagnostic that can be compared with measurements
- Key simulated components are
  - Velocity-detector
    - Aperture-wires and grid-wires
      - Size & spacing (d)
      - Displacement (l)
      - Cross-section
  - Incoming ions
    - Current density profile
    - Input beam angle (δ)
    - Incoming position
- Code outputs
  - Currents on
    - Aperture-wires
    - Grid-wires
    - Split-plates
  - These currents determine
    - Output beam angle
    - Weighted position of beam
      - $x_{eff} = \Sigma(x_{wire} i_{wire})/\Sigma(i_{wire})$

Simulated current density intersecting the aperture-wires, grid-wires, and split-plates

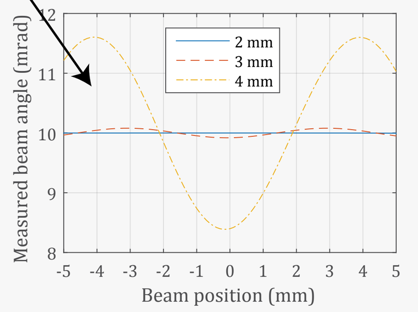


- Phenomenological Observations
  - Effective size of real wires depends on incoming angle (δ)
    - Must be accounted for when analyzing data
    - Square cross-section wires alter angle by >10% from ideal
    - Circular cross-section wires have small effect
  - Measurement must be insensitive to the toroidal position of the beam ion current at the velocity-detector
    - Smaller and more numerous wires result in summed grid-wire current which does not depend on position
    - 2 mm wires are sufficiently small for a 1 cm FWHM Gaussian ion beam current distribution
- The detector sensitivity to changes in angle
  - Depends strongly on the geometric factor
    - Estimated by $\Delta\delta = i_N/(i_2 + i_3) \cdot \tan(\beta)$
    - i_N is the noise current for a measurement
- The detector geometric factor
  - Is also referred to as the *dynamic range*
    - However, does not limit measurements
  - Measured or code output angles will always be between $\pm\beta$
    - Larger input beam angles can be inferred
- Results of modeling informed velocity-detector design
  - d = 2 mm, l = 16.3 mm
    - 61 mrad geometric factor (β)
    - 0.1 mrad sensitivity ($\Delta\delta$)
  - Ten aperture-slits and grid-wires
    - Width = 38 mm
    - Height of aperture-slits = 10 mm

Wire cross-sections have a significant impact on the code output beam angles

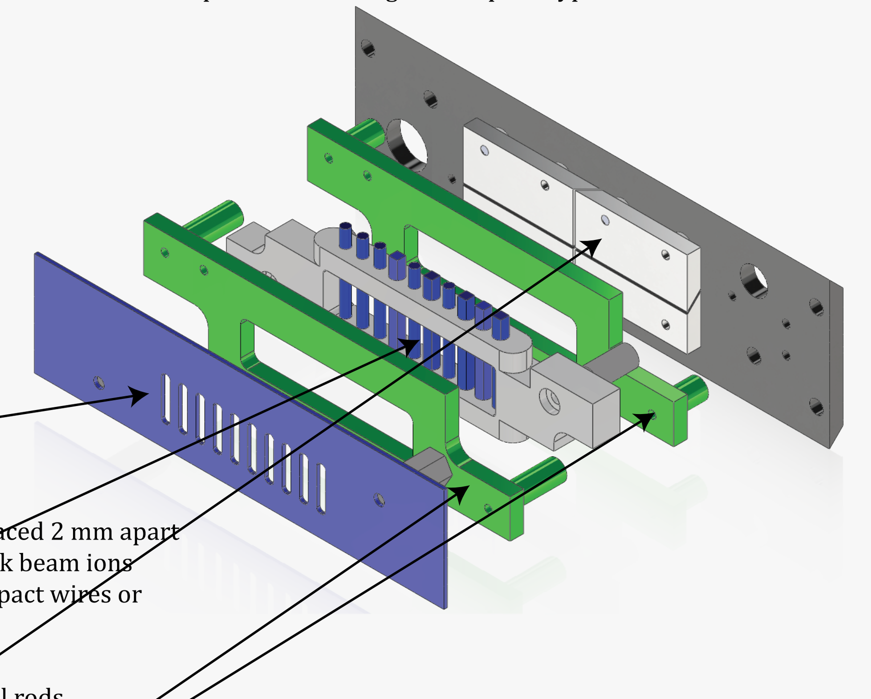


For a 1 cm FWHM ion beam, 2 mm wires are sufficiently small to ensure insensitivity to ion beam position



HIBP VELOCITY-DETECTOR PROTOTYPE

Exploded CAD design of the prototype



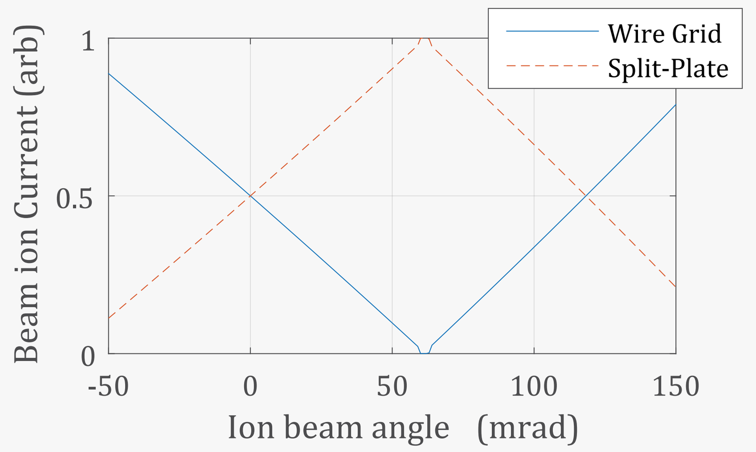
- Components are
  - Aperture-set
    - Stainless steel, thickness = 0.8 mm
    - Ten 2 mm wide, 10 mm long apertures, spaced 2 mm apart
    - Outer size of aperture-set designed to block beam ions passing above or below and impacting impact wires or detector plates
  - Impact wire grid
    - Ten 2 mm cross-section wire stainless steel rods
      - Held in Boron Nitride support structure
      - Five circular and five square cross-section wires
      - Spaced 16.3 mm from aperture-set
  - Split-plate detector
    - Four close-fit stainless steel detector plates
  - Two electrostatic bias plates
    - Stainless steel plates for secondary electron management
    - Measurements discussed here used a bias of +25V
    - See poster by T.P. Crowley (this session) for details

SIMULATIONS WERE USED TO IDENTIFY PROTOTYPE CHARACTERISTICS CAPABLE OF MEETING EXPERIMENTAL REQUIREMENTS

- To design a HIBP velocity-detector prototype
  - Used MST 380 kA improved confinement discharge as an example
  - Full plasma profile may require resolution of
    - Changes in toroidal velocity of 132 km/s
      - ~25% of beam velocity
    - Changes in angle
      - Depends on beam velocity
      - For a 45 keV ion beam it is ~17 degrees
    - A detector with a dynamic range this large is difficult to build
      - Spacing between aperture-set and impact-grid very tight
  - Velocity-detector should be capable of resolving magnetic fluctuations
    - Standard confinement amplitude
      - 10s of G → 10 mrad
    - Improved confinement amplitude
      - 1s of G → 1 mrad
    - Desire resolution of magnetic fluctuations
      - want sensitivity ~ 0.1 mrad
  - Unlikely to perform full profile measurement during single discharge
    - Suggested designing detector with smaller dynamic range and changing orientation as necessary

Simulations of the currents on the wire grid and the split-plates for the velocity detector prototype as a function of incoming ion beam angle.

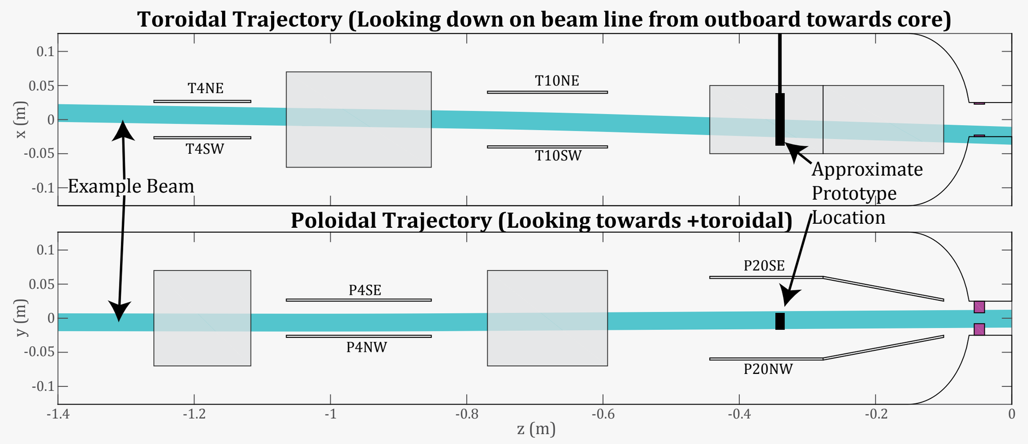
As the ion beam angle increases past the geometric factor of 61 mrad, the slopes of the currents swap.

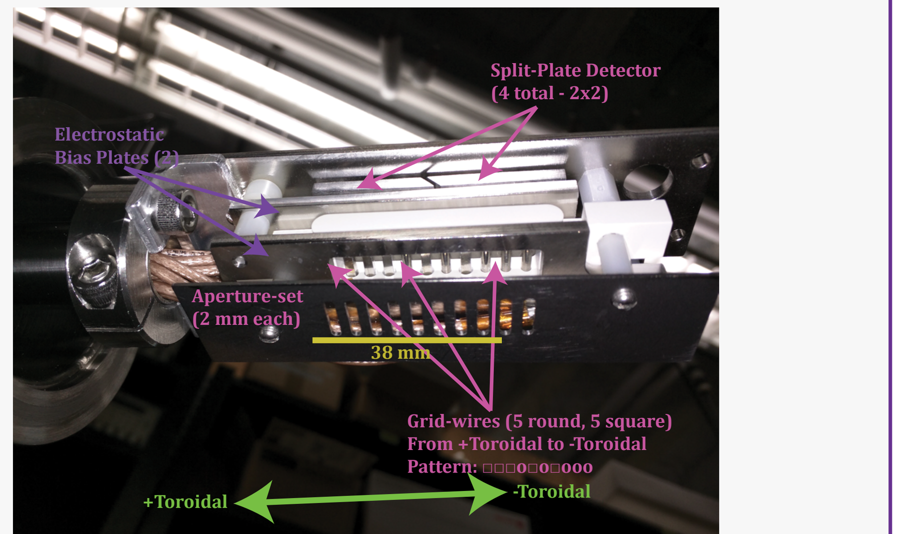


MEASUREMENTS OF ION BEAM VELOCITY

CONSTRUCTED AND INSTALLED ON THE MST-HIBP PRIMARY BEAM LINE

- The prototype was installed in the MST-HIBP primary beam line
  - Located approximately 31.5 cm from the outer surface of MST
    - Between the first set of poloidal steering plates
    - Allows use of toroidal cross-over steering system to change beam position and/or angle
  - Current measured by each impact grid wire and split-plate
    - Was independently converted to a voltage via a 10^7 trans-impedance amplifier
    - Was independently digitized at 1 MHz
    - Had a electronic noise level of approximately 0.25 nA RMS



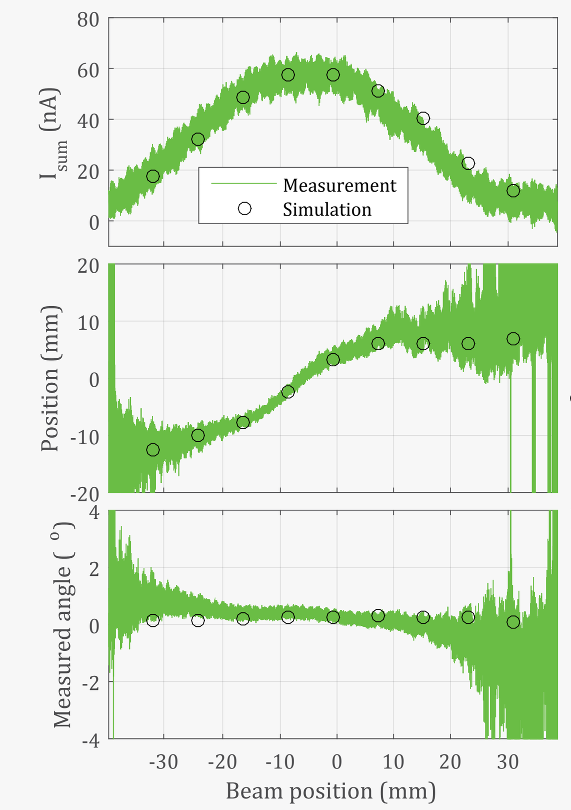


MEASUREMENTS OF ION BEAM ANGLE AND VELOCITY HAVE BEEN SUCCESSFULLY ACQUIRED

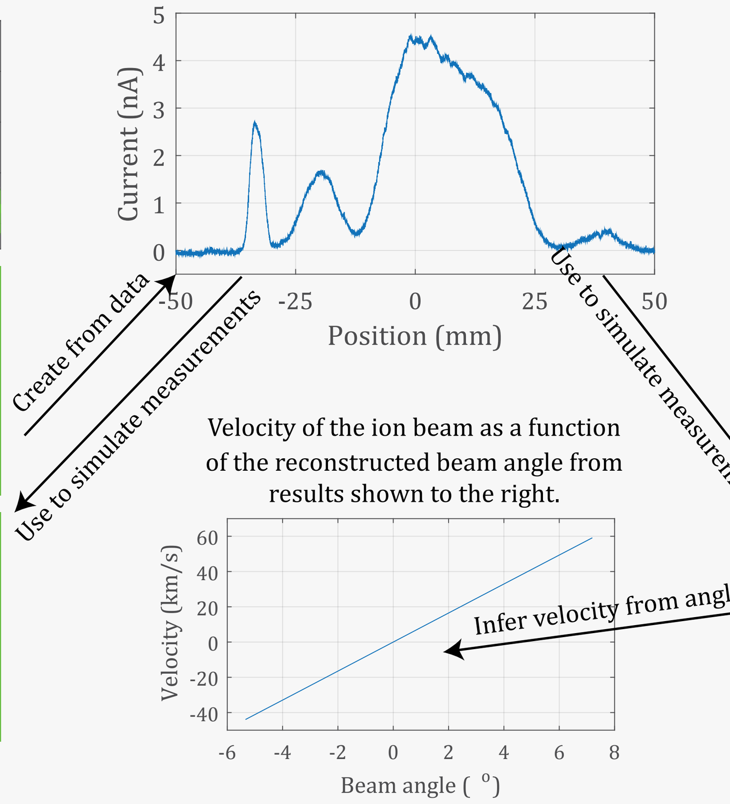
- Measurements being acquired in primary beam line
  - Provides low-noise measurement of beam current
  - Can use steering system to vary velocity
- Measurements are made by
  - Varying beam position
    - Determine ion beam current profile
  - Varying beam angle
    - Measure ion beam velocity

MEASUREMENTS AND SIMULATION RESULTS AGREE

Sum current ($i_2 + i_3$), x_{eff}, and δ from data (green) and simulations (black) as a function of beam position.

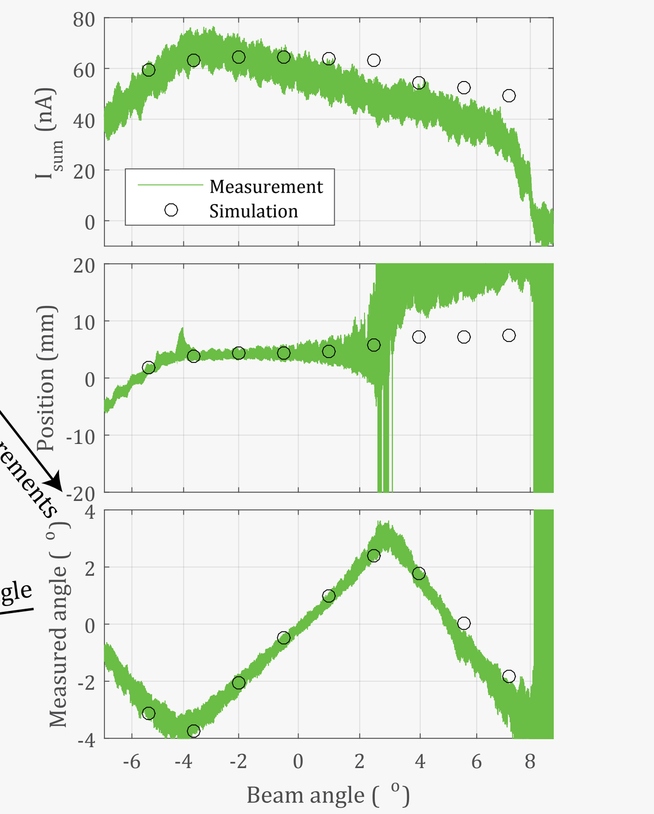


Reconstructed beam current profile created by using the measurements of a single 2 mm impact grid wire as the beam is swept across it.



Velocity of the ion beam as a function of the reconstructed beam angle from results shown to the right.

Sum current ($i_2 + i_3$), x_{eff}, and δ from data (green) and simulations (black) as a function of beam angle.



- Simulations are in excellent agreement with varying-position data
  - The simulated current, effective position (a weighted sum of the individual impact wires), and angle all agree with measurements
    - Simulations suggest a 0.2 degree initial angle of the ion beam and a 0.6 degree canting of the velocity-detector prototype
  - The current profile generated is similar on all wires
    - There are small differences which may be due to beam occlusion
    - There is some evidence of beam focusing between the accelerator and the velocity detector
- Simulations are in good agreement with varying-angle data
  - The angle measurement is in excellent agreement
  - Measurement of current and position are in agreement for angles less than about 2 degrees
    - Differences are likely due to part of the beam profile hitting one of the sweep plates
  - The toroidal component of velocity can be determined from the combination of measurement and simulation results

NEXT STEPS

- Measurement of beam ion velocity has been demonstrated
  - Next we will measure ion current from a beam traversing plasma
  - We will also study
    - The effect of wire cross section on UV
    - Environmental particle mitigation
    - Surface materials, textures, coatings
- Developed computer simulations have been successful predicting measured signals
  - Monte-Carlo electron trajectory simulations have been developed to investigate secondary electron behavior within the detector, they are advancing understanding of detector performance and interpretation of data
- Development of data analysis techniques to determine poloidal magnetic flux profiles from measurements
- Acquire velocity measurements in MST to
  - Map out equilibrium profiles of $\Psi(r)$, $J_\varphi(r)$, $q(r)$
  - Investigate localized magnetic fluctuations
  - Explore the differences between equilibrium conditions

SUMMARY

- A detector capable of measuring ψ, the poloidal magnetic flux, with a Heavy Ion Beam Probe is being developed
  - Requires detector capable of measuring v_φ, the toroidal velocity of the beam
  - Sequential goals include determination of $J(r)$ and $q(r)$
  - Sensitivity to equilibrium and fluctuating poloidal flux is possible
- A suite of simulation codes has been created to model the velocity-detector
  - Uncovered phenomenological details about the size, shape, and spacing of components
  - Simulations are being used both to drive design and analyze measurements
- A prototype velocity-detector has been constructed and installed on MST
- Measurements of ion beam velocity have been performed on MST
  - Used the HIBP primary beam to provide a low noise isolated beam current signal
  - Independently swept position and angle of the ion beam
    - Varying the ion beam position leads to beam ion current profile measurement
    - Varying the ion beam angle leads to velocity measurements
    - Simulations
      - Are revealing the details of the measurements
      - Using the measured ion beam profile are in agreement with data