NSTX

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

# Measurements and Modeling of Prompt Loss of Neutral Beam Ions from NSTX


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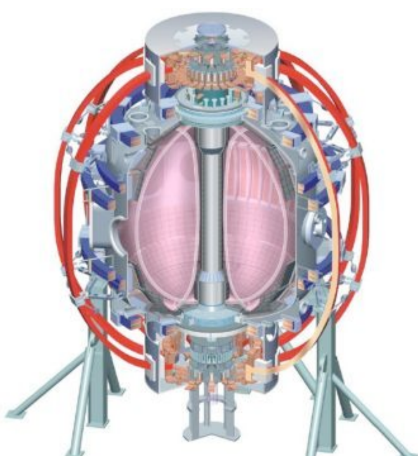
**American Physical Society, Division of Plasma Physics Meeting**

**Chicago**

**November 8-12, 2010**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# Abstract

Prompt loss of neutral beam ions in tokamaks can occur when the injected neutrals are ionized such that their orbits intersect solid objects near the plasma. Such losses are typically large at low plasma current, but diminish rapidly with increasing current. NSTX is equipped with a scintillator fast ion loss diagnostic that can detect prompt losses. Since other plasma phenomena, such as MHD activity, can also induce beam ion loss, it is useful to have a model that can predict the range of pitch angles that will experience prompt loss to the detector in a given plasma configuration. This then permits identification of which losses are prompt and which arise from other causes. A velocity space based prompt loss model has been developed for NSTX that predicts pitch angle distributions similar to those measured in NSTX plasmas. The model offers some possibility for extension to other fast ion diagnostics and to other loss mechanisms.

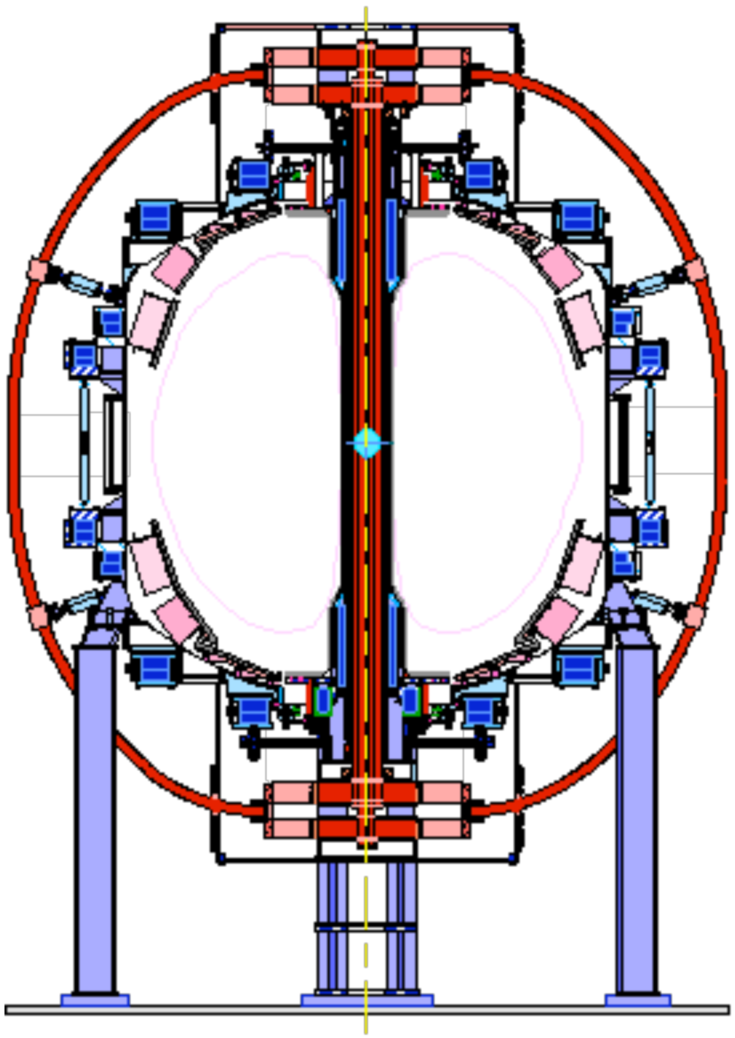
# Prompt orbit loss

- Prompt loss occurs when a beam ion is born on an orbit that intersects a plasma facing component within a few transits of the plasma
- The fraction of beam ions lost in a given plasma depends upon a number of factors, including:
  - Ip
  - Distance between plasma edge and wall (“outer gap”)
  - Beam injection angle
  - Ionization profile of the neutral beam in the plasma (depends on ne(r) and other profiles)
- Prompt loss is irreducible for a given plasma configuration
- MHD and other phenomena can cause additional losses beyond prompt loss

# Motivation

- Neutral beam ion loss is measured for all NBI shots on NSTX
- Important to determine whether any given loss feature is due to prompt loss or other phenomena
- Time history can give some clues about loss type, but modeling provides a more certain identification tool

# NBI parameters on NSTX

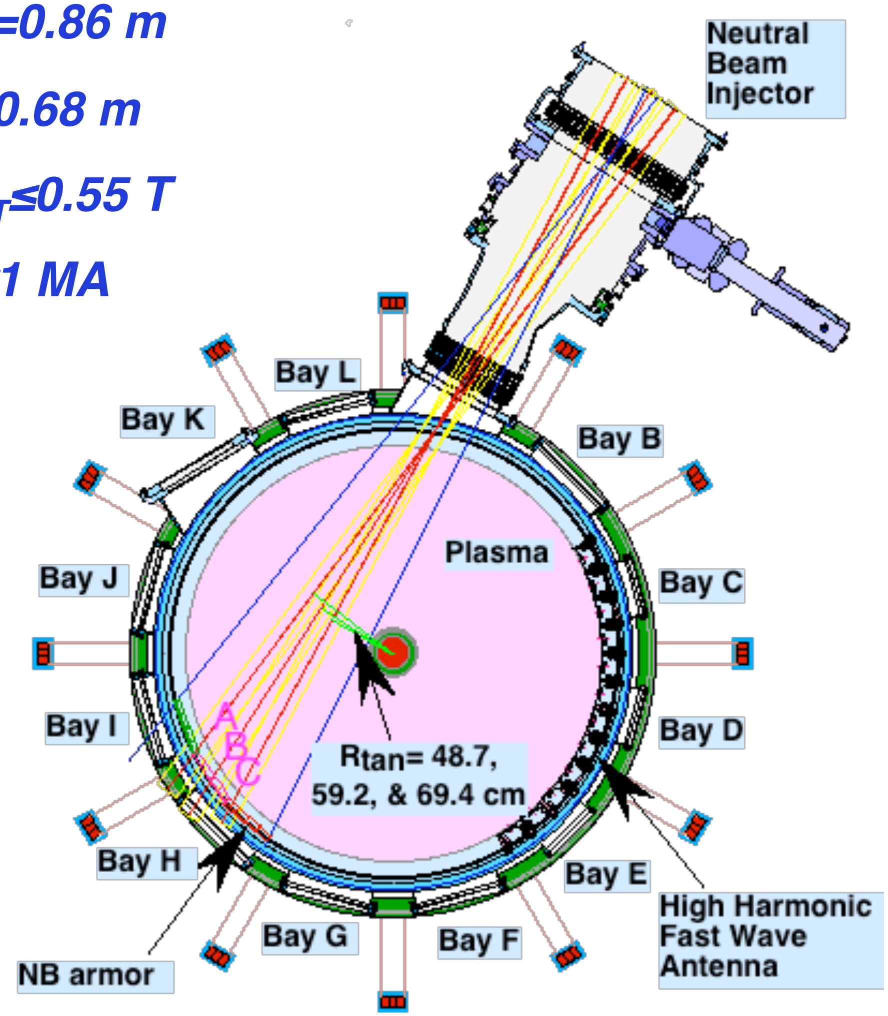


*$R_0$=0.86 m*

*a=0.68 m*

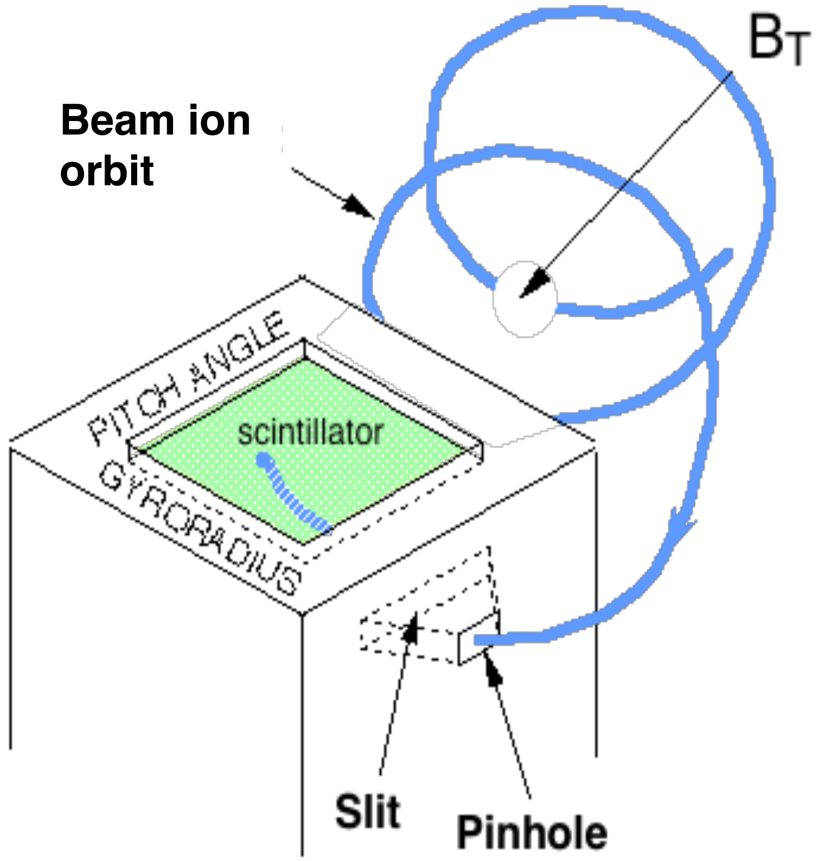
*$B_{0T}$≤0.55 T*

*$I_p$≤1 MA*




- 3 beam sources inject 80-90 kV D, ≤6 MW

# Scintillator probe measures prompt loss




Scintillator probe:

Combination of aperture geometry & **B** acts as magnetic spectrometer

Fast video camera captures luminosity pattern on scintillator as function of time

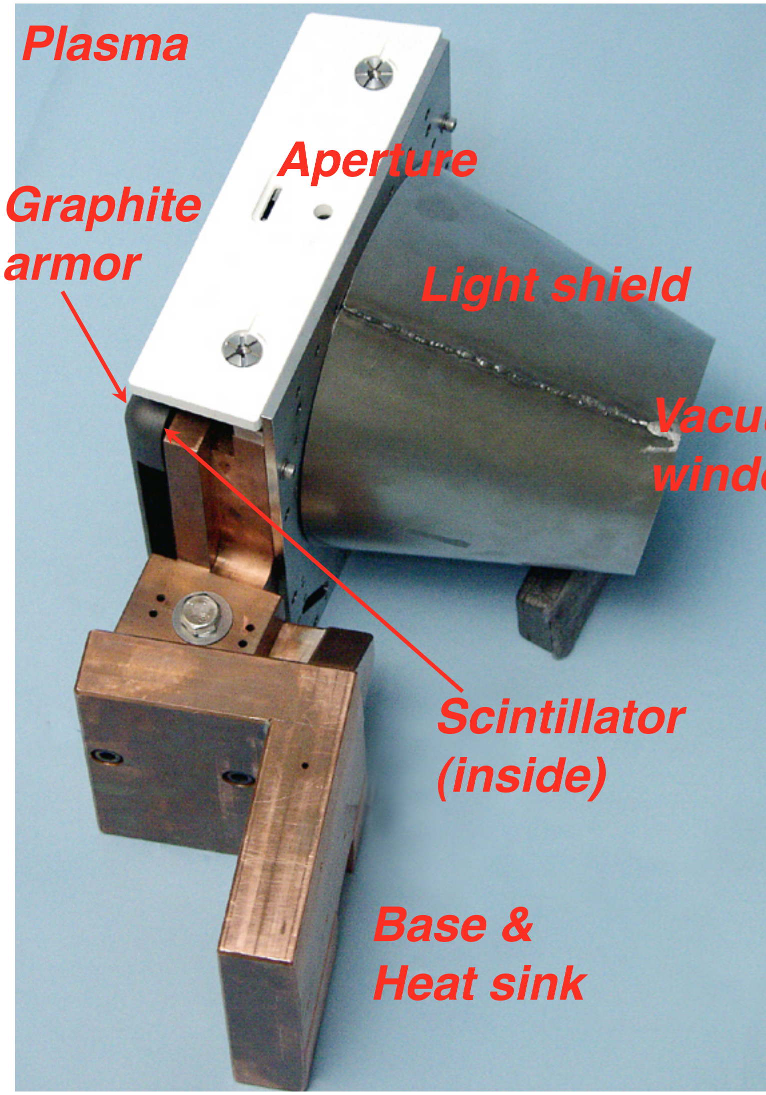
$\Gamma_{loss}(\rho, \chi, t)$

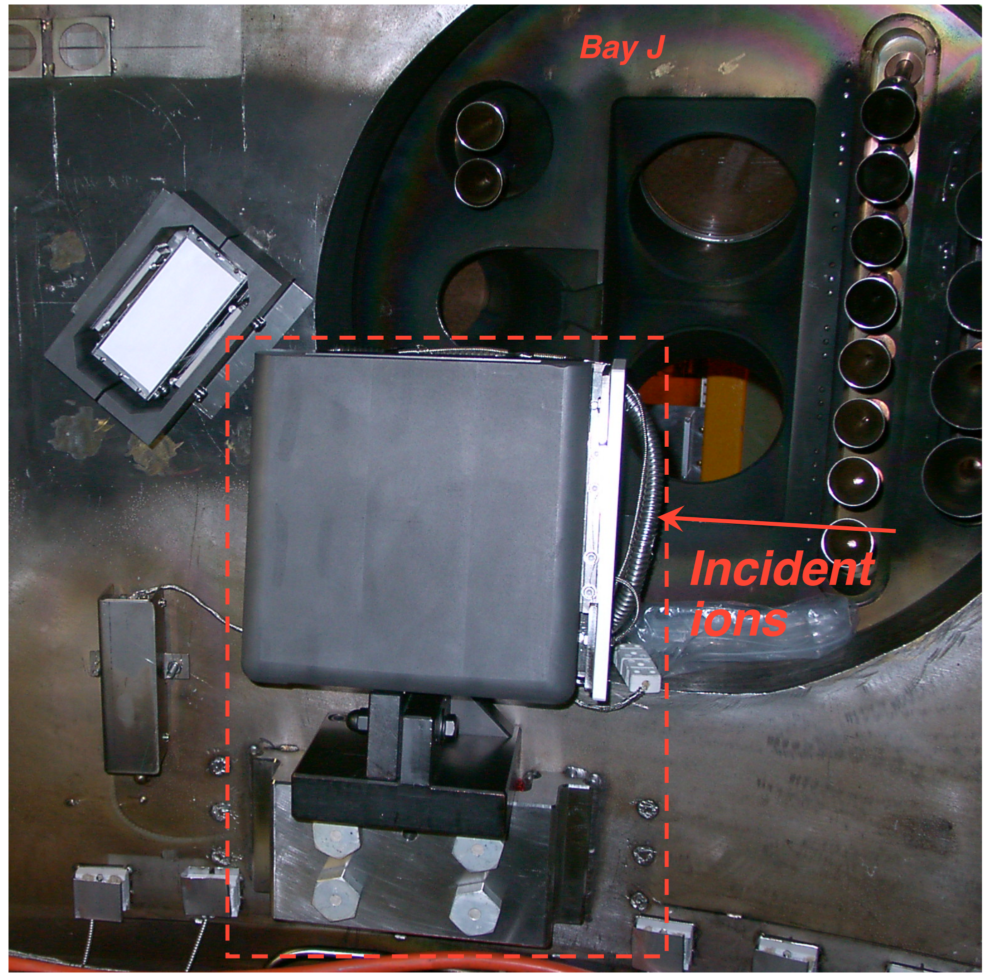
NSTX probe:

5 cm ≤ $\rho$ ≤60 cm

15° ≤ $\chi$ ≤ 80°

# Scintillator probe assembly

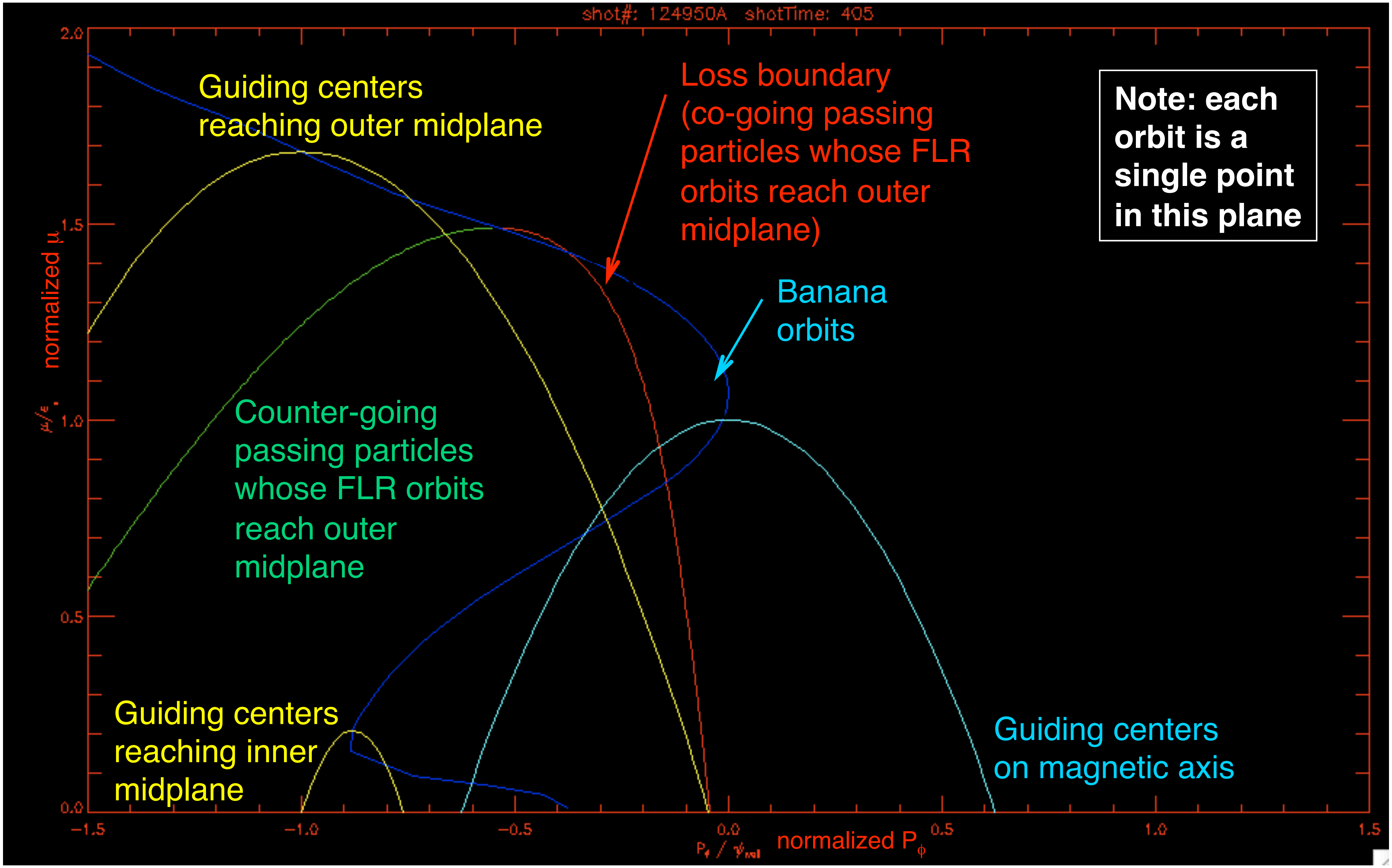


# Prompt loss model based upon constants of fast ion motion

- $E = \frac{1}{2} mv^2$ (kinetic energy)
  - Conserved on time scales short compared to collisional slowing down time
- $\mu = \frac{1}{2} mv_{perp}^2/B$ (magnetic moment)
  - Conserved in the absence of fields varying near the particle's cyclotron frequency or field gradients shorter than length $\rho_i$
- $P_\phi = mv_\phi R + q\psi_{pol}$ (canonical angular momentum)
  - Conserved in axisymmetry (i.e. in absence of nonaxisymmetric MHD or error field correction coil fields)
- Conservation conditions usually satisfied in NSTX
- Knowledge of these 3 parameters **fully determines orbit** (except toroidal position, $\phi$, and gyromotion, which are not used in this work)
- This approach equivalent to guiding center orbit following

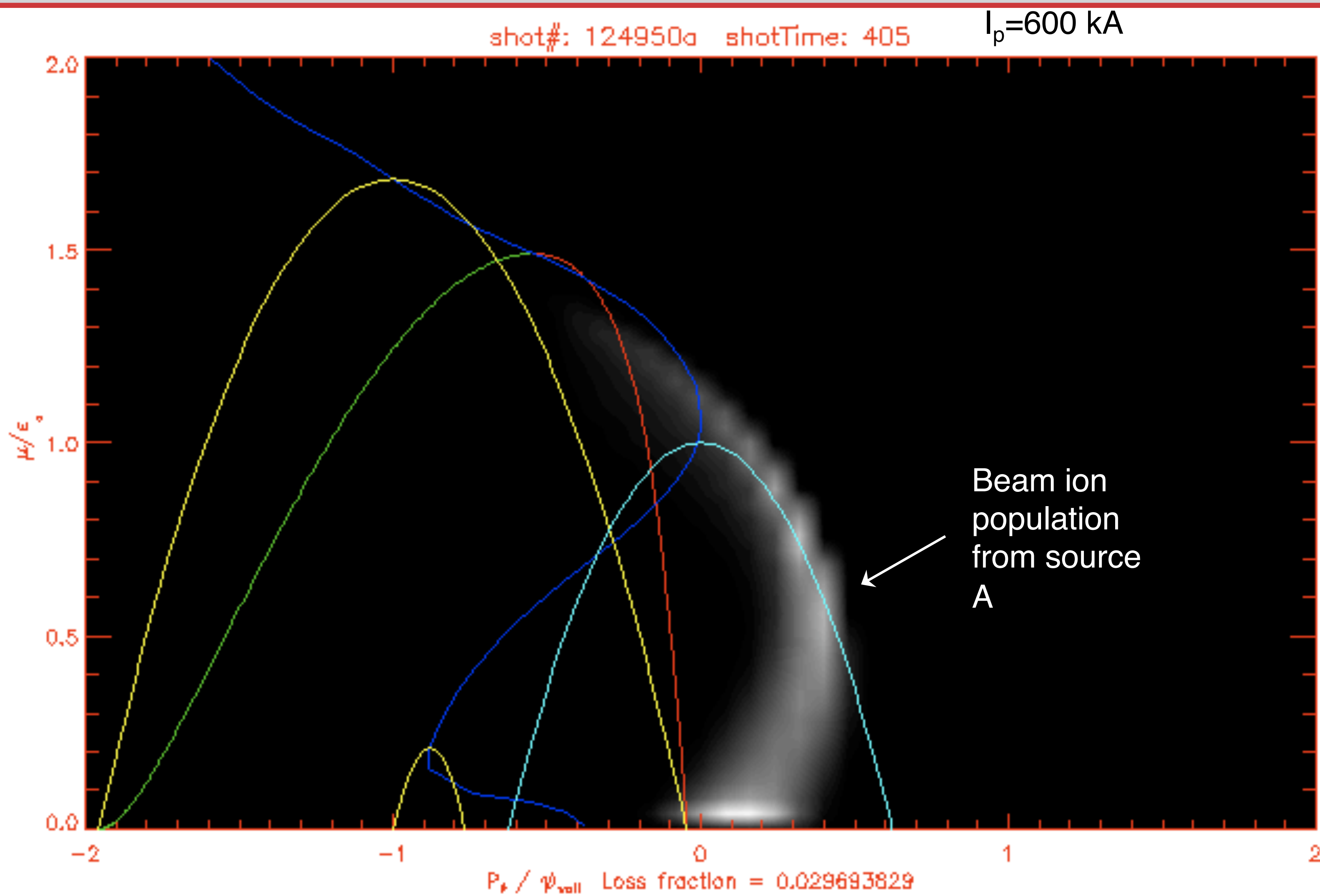
# Restricting attention to injection energy reduces phase space to 2 dimensions, greatly aiding visualization



# Deposition of beam can be simply modeled & mapped to ($P_\phi$, $\mu$) space

- Use known beam injection geometry and cross sectional profile, but neglect beam angular divergence
- Take EFIT equilibrium and measured $n_e$ profile for time of interest
- Assume electron impact ionization is dominant process
- Result is a beam deposition density in the 3D volume where beam intersects plasma
- For each deposited ion, $P_\phi$ & $\mu$ at guiding center easily computed (This formalism requires quantities at guiding center—90 kV D in NSTX can have $\rho_i$=25 cm, so this is an important factor to treat properly
- Summing over all deposited ions gives distribution function of injection energy ion guiding centers in ($P_\phi$, $\mu$) plane

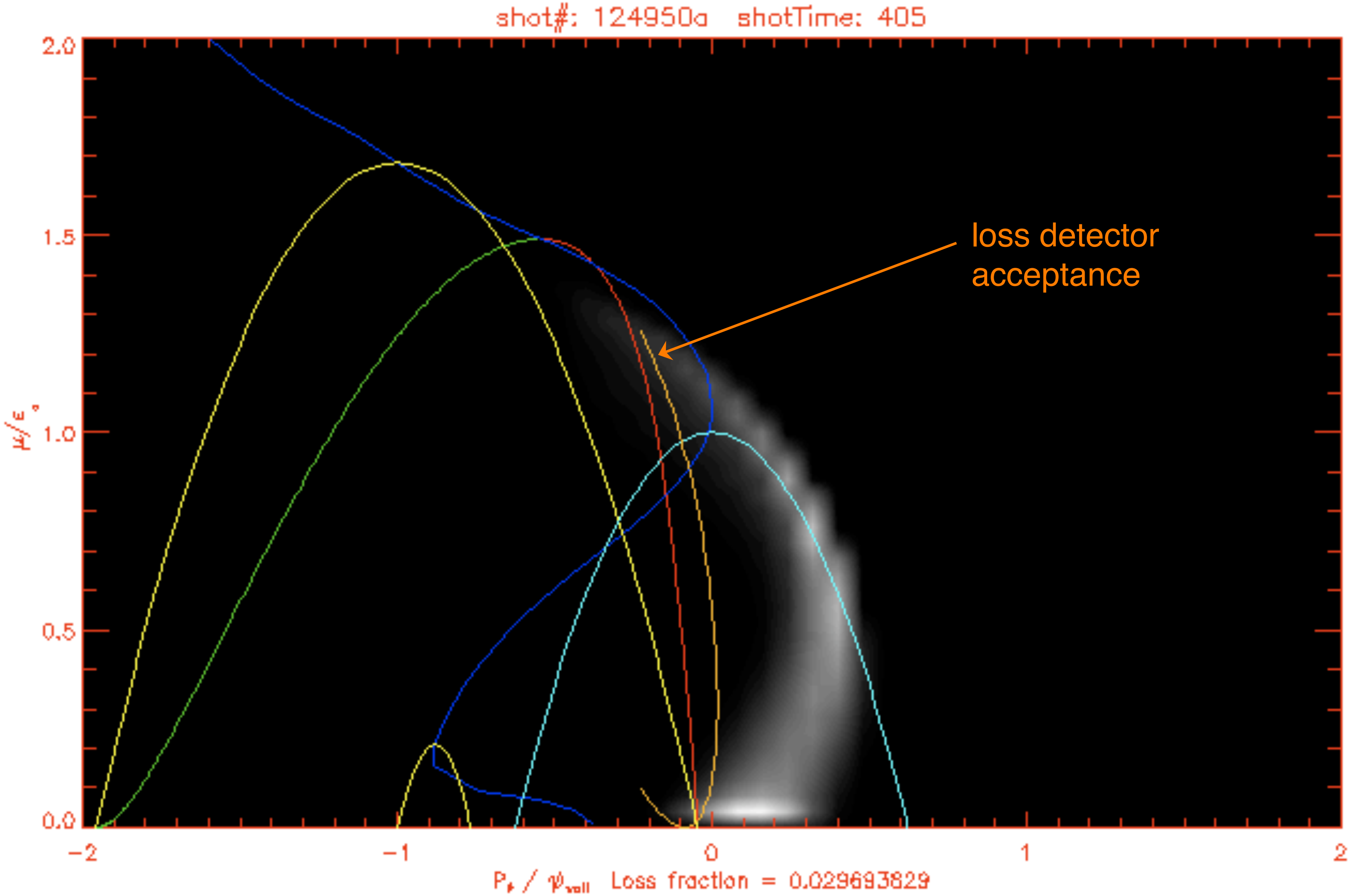
# Example deposited beam ion population represented in phase space



# Loss detector acceptance can also be represented in phase space

- Scintillator probe position, orientation, and angular acceptance of apertures can be used to formulate the set of injection energy beam ion velocity vectors that can be detected
- With data from equilibrium, this set can be converted to a curve in ($P_\phi$, $\mu$) space, including the FLR corrections

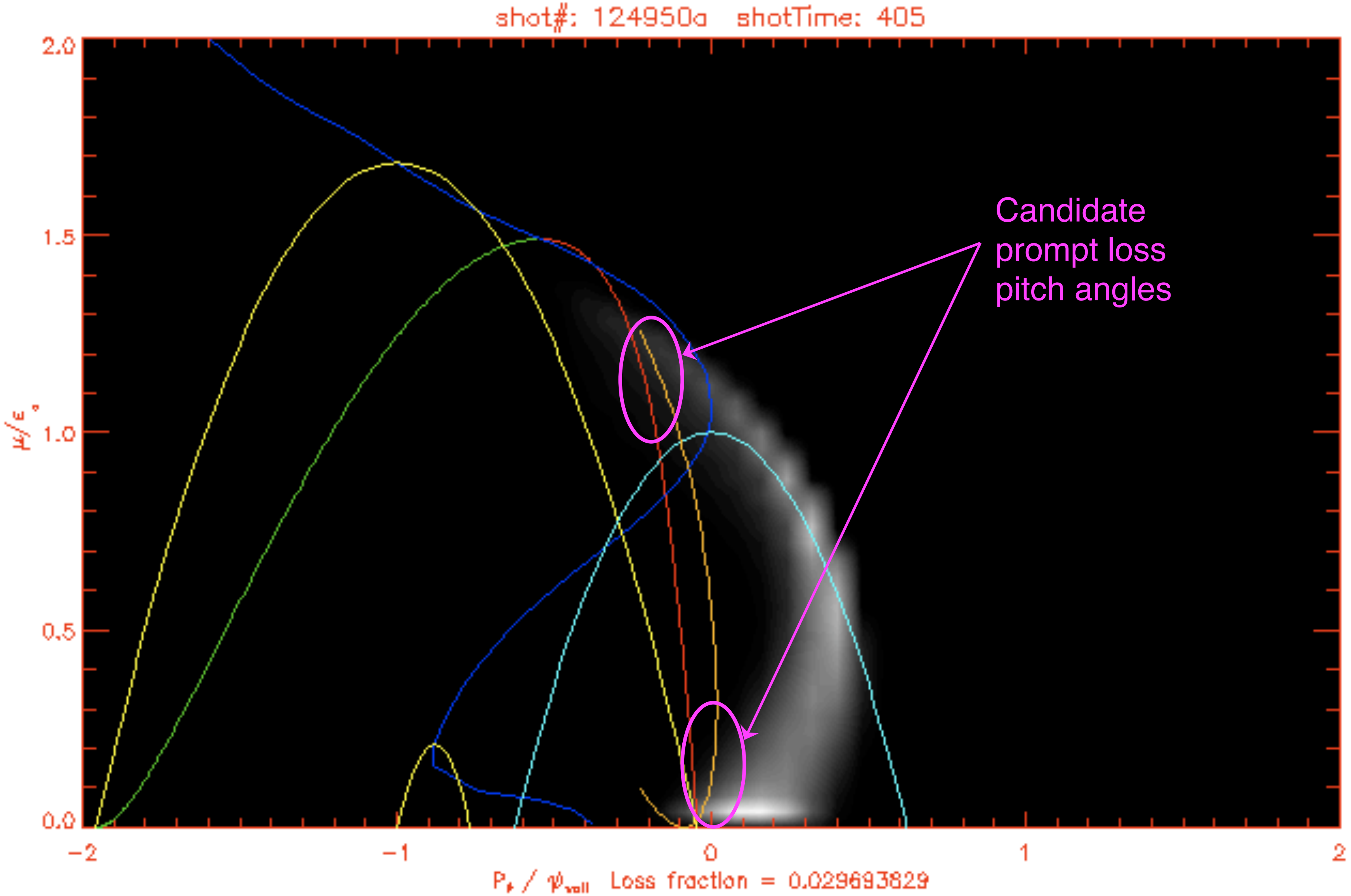
# Phase space with detector curve



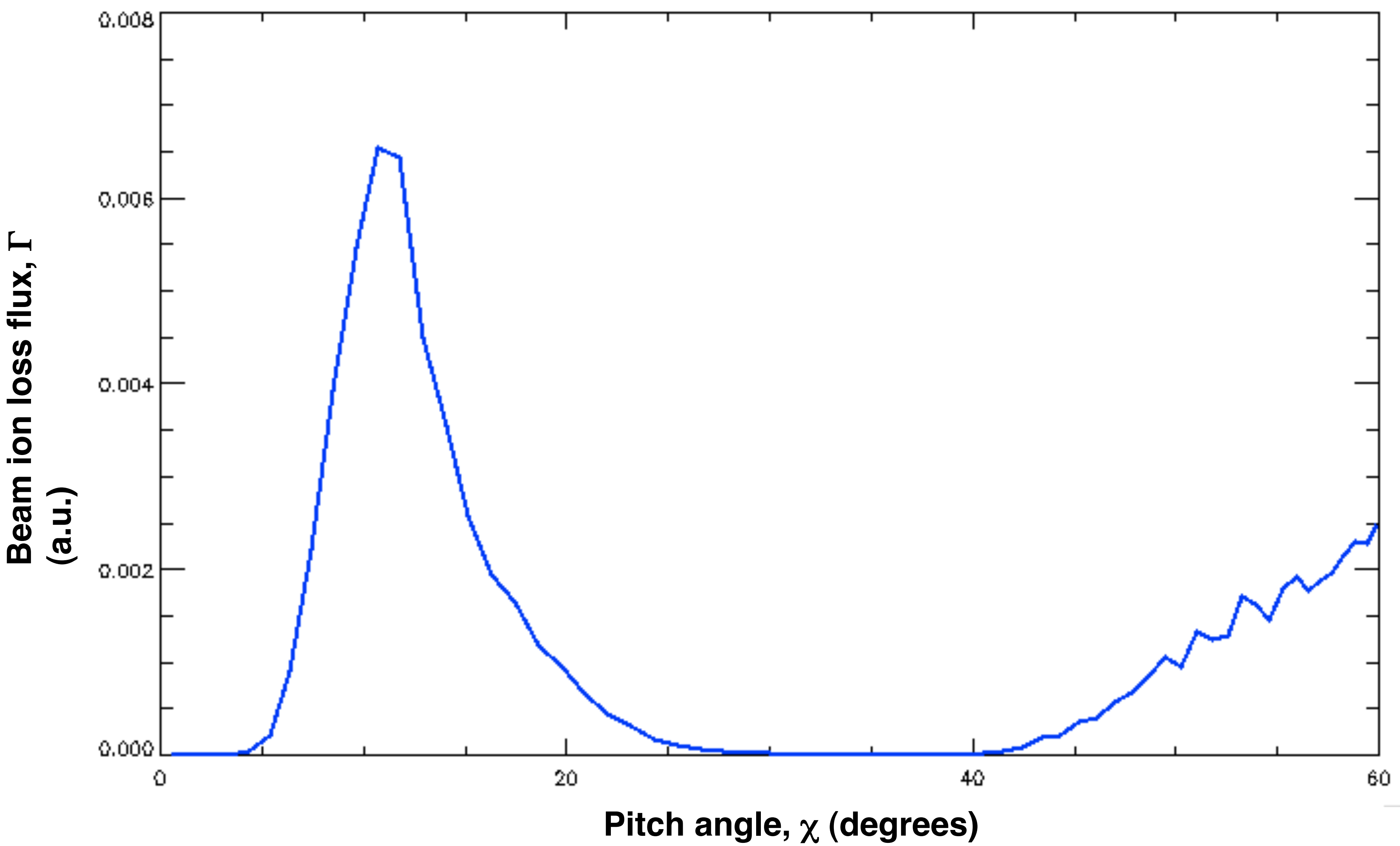
# Detector curve intersection with beam population gives pitch angles where prompt loss may be observed

- This is a necessary but not sufficient condition for observation of prompt loss at the detector, since the toroidal angle, $\phi$, is an ignorable coordinate in this formulation
  - Obstacles could block orbits to detector
  - Relative geometry of injection and detector might result in prompt loss orbits missing entrance aperture entirely due to mismatch in gyrophase of ions or mismatch of poloidal and toroidal advance of orbit as it approaches detector (D. Pace, *et al*., RSI 2010)
- Integration of beam density along detector line gives model flux, $\Gamma$, vs. pitch angle at detector ($\chi$=arccos($v_{||}$/v)
- Because $\phi$ structure of deposition & detector not retained, $\Gamma(\chi)$ is an envelope of the actual detected $\chi$ distribution

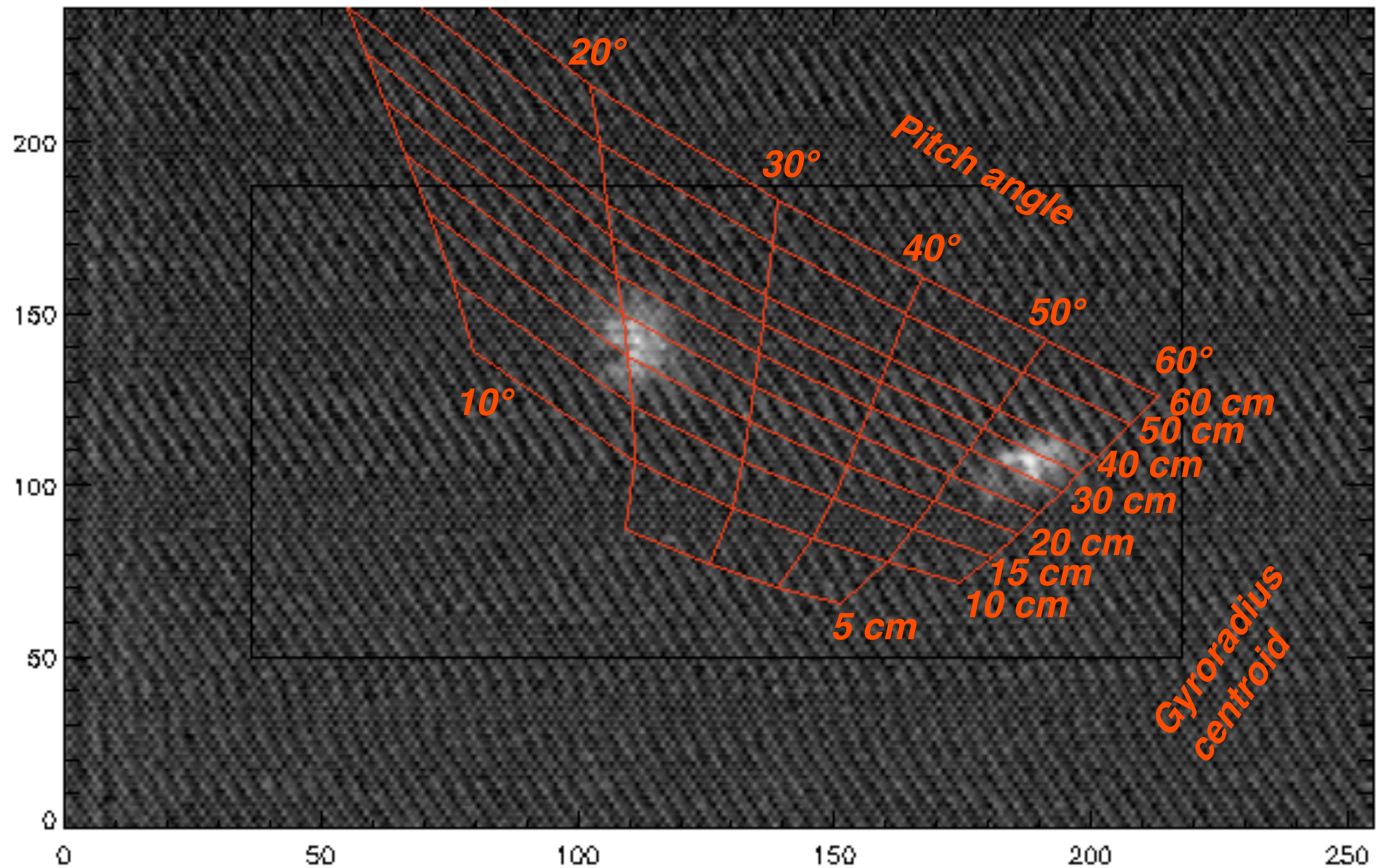
# For the discharge shown previously, 2 areas of intersection are found, indicating 2 pitch angles of prompt loss may occur



# Beam ion density along detector curve gives predicted pitch angle distribution at detector



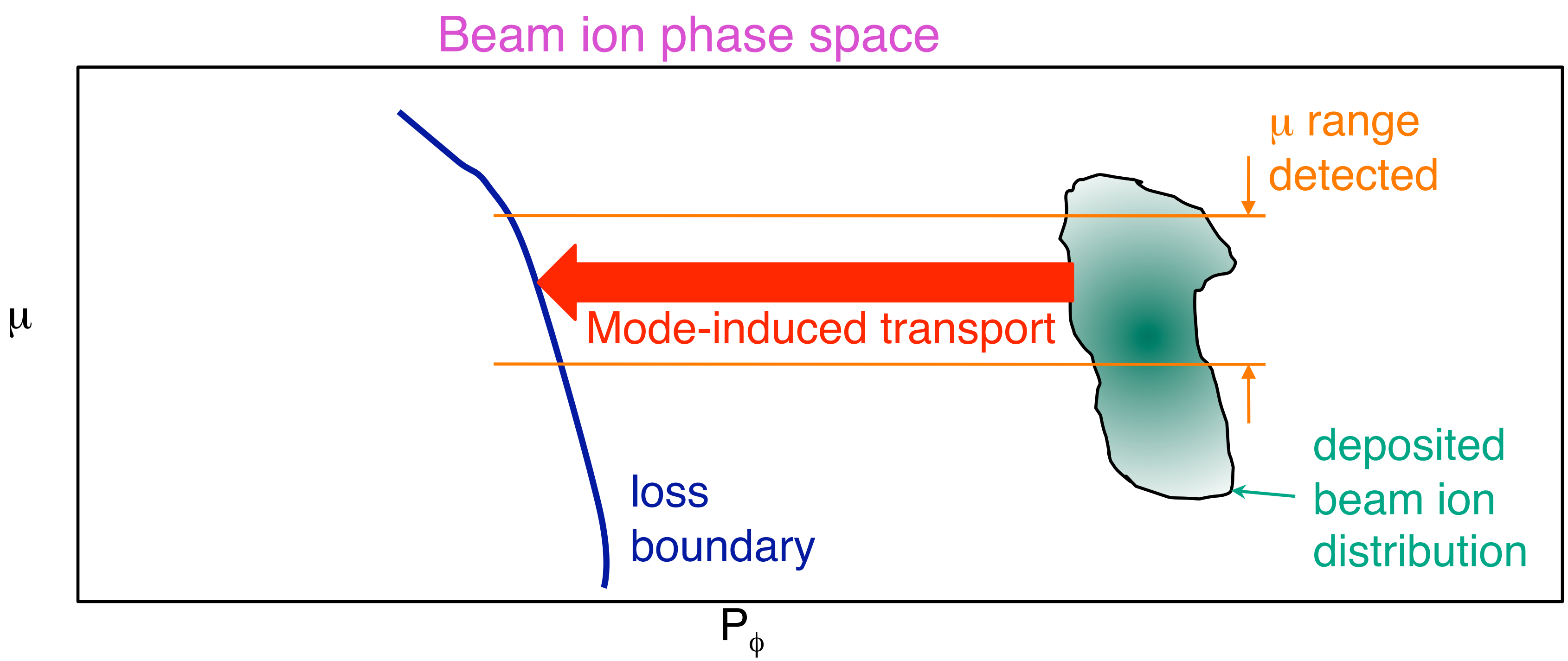
# Indeed, for this shot and time, 2 loss spots are seen



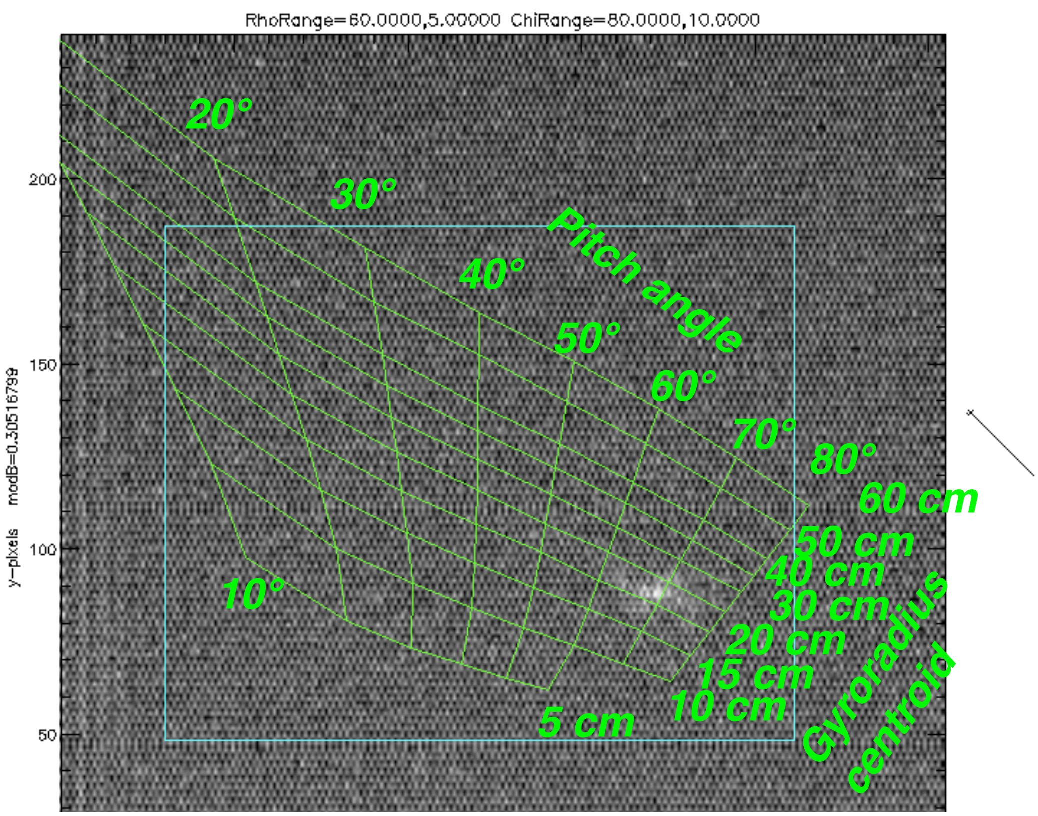

- Pitch angles close to those predicted

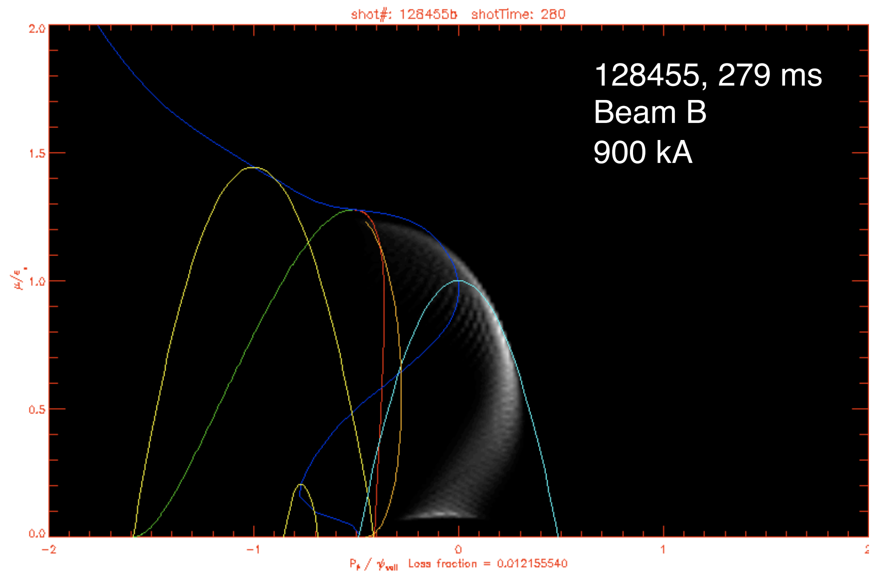
# Phase space model also helps understand MHD loss

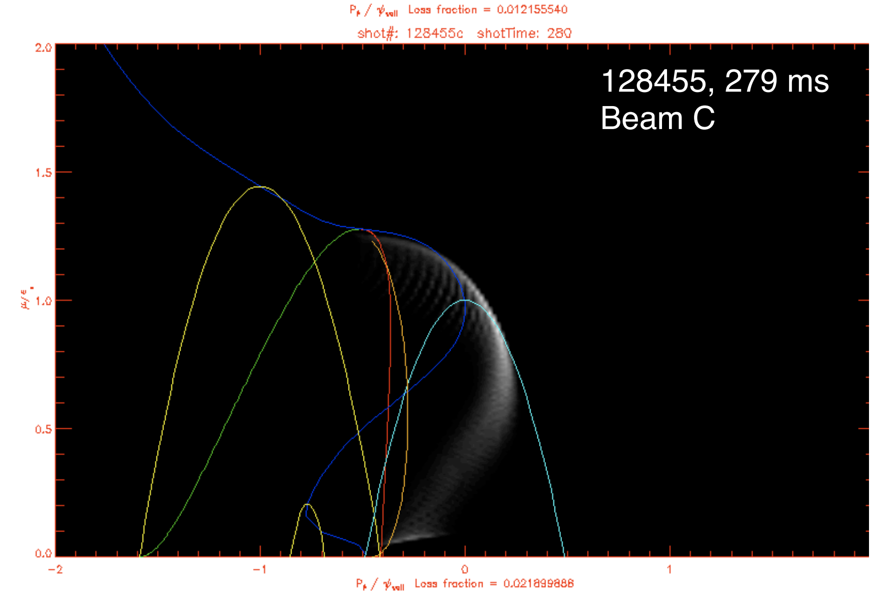
- Observed MHD frequencies $<<\Omega_{ci}$, so $\mu$ will be conserved
- Mode destroys toroidal symmetry, so $P_\phi$ no longer constant
- Often, $E_{loss} \approx E_{inj}$, so MHD convects ions at constant $\mu$ across loss boundary $\rightarrow$observed lost $\mu$ range defines affected set
- Distance displaced in $P_\phi$ indicates strength of transport



# Application to loss during TAE avalanche

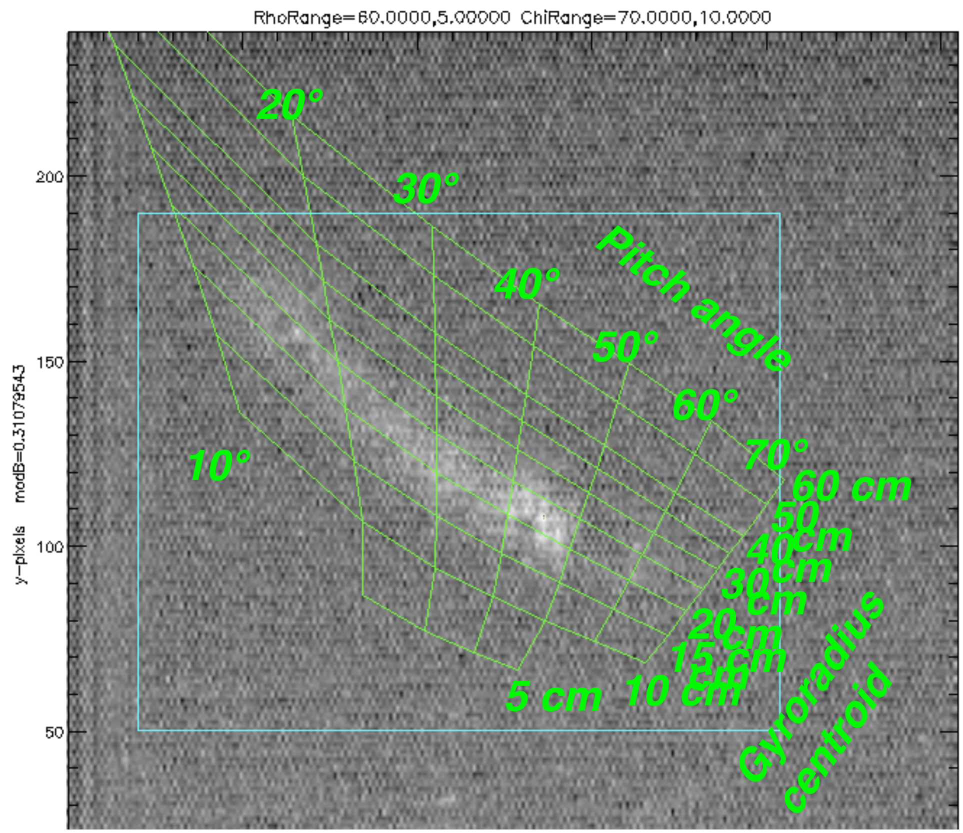


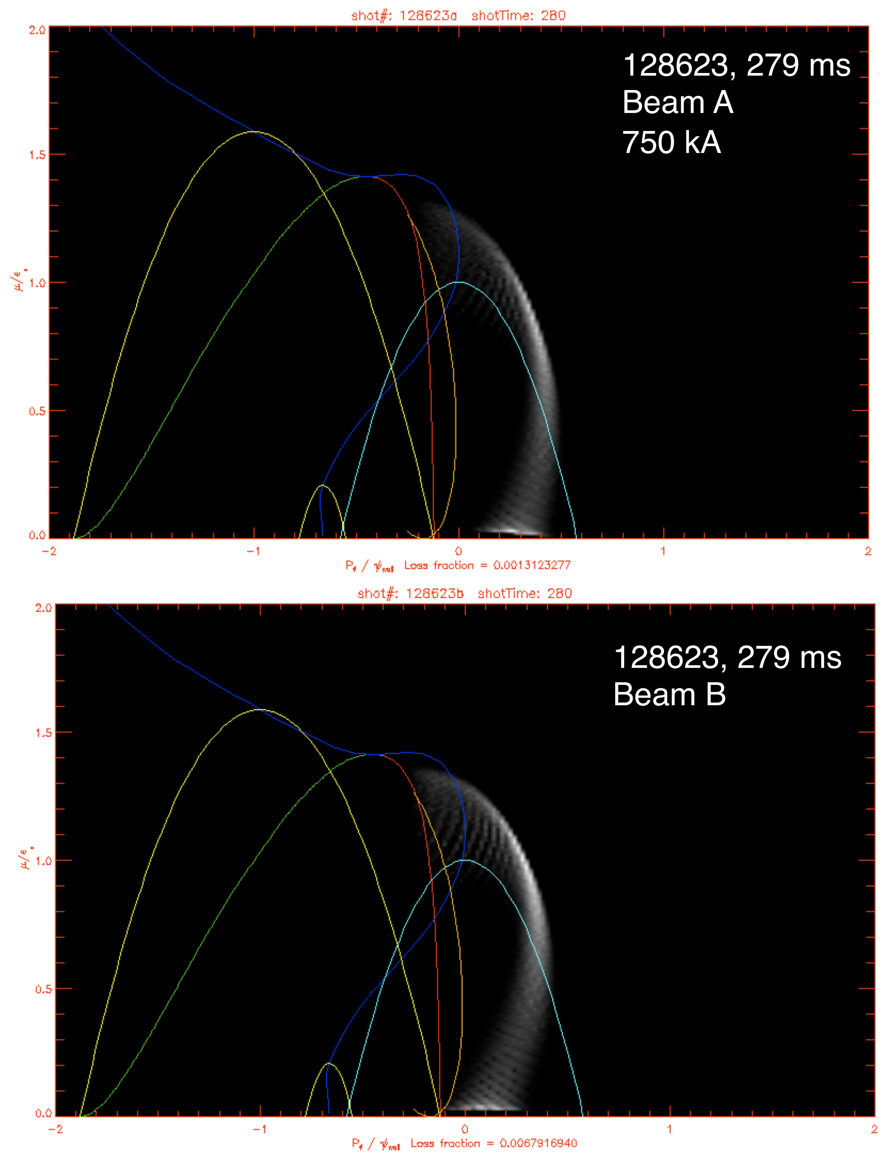




- Model distributions close or at detector only at highest $\chi$ ($\mu$)
- Small displacement causes loss at same $\chi$
- Low $\chi$ loss probably not detectable

# $\chi$ range in avalanche loss not elucidated by model




- At most $\chi$, ions must move large distance in $P_\phi$
- No clear reason for wide $\chi$ range lost

# Summary

- Prompt loss model constructed for neutral beam ions in NSTX using constants of motion approach
- At fixed energy, beam ion phase space reduces to 2D, allowing simple visualization of where beam ion population coincides with detector acceptance
- Method produces envelope of possible $\Gamma(\chi)$ curves at detector, but does not account for wall structures and spatial phase relationships between beam deposition region and detector, which are important in determining exact $\Gamma(\chi)$
- Phase space maps can aid in understanding MHD loss of beam ions

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