Off-axis Neutral Beam Current Drive Experiments in DIII-D

by

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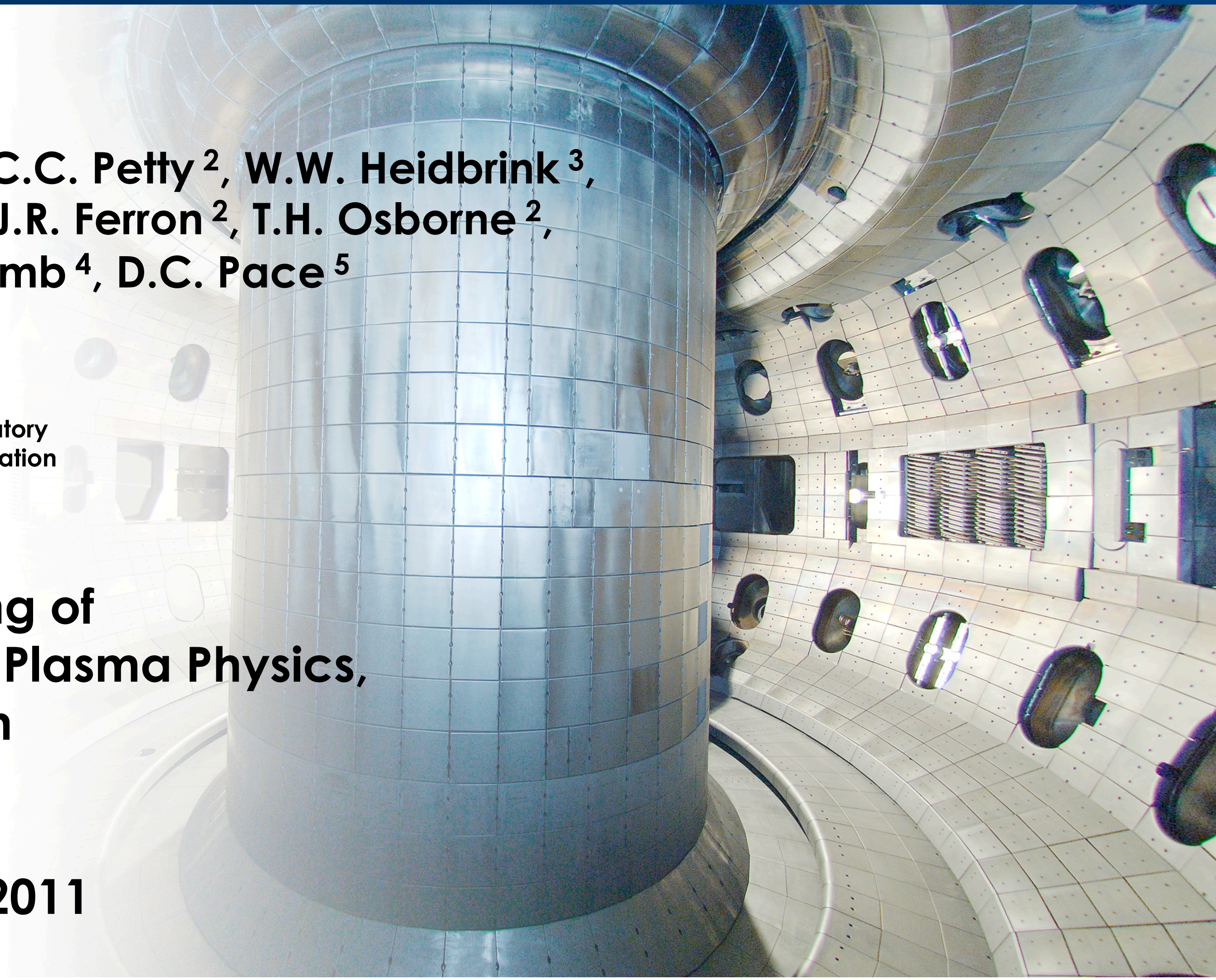

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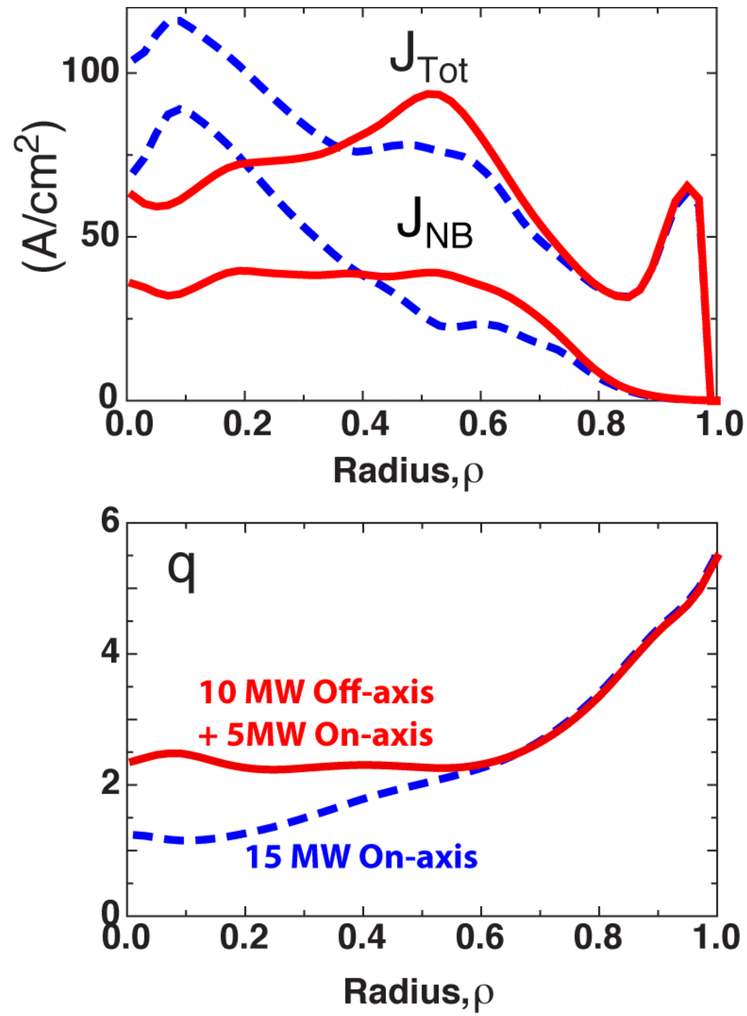
Off-axis NBCD Enables Advanced Scenario Development

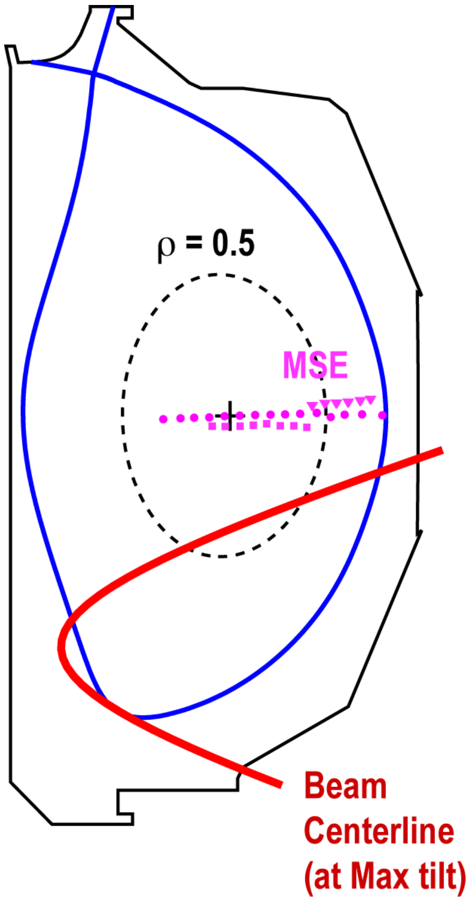
- Previous attempts to develop steady state, high performance scenario with high q_{min} at high β have been limited by overdrive of the central current from the NBI required for heating

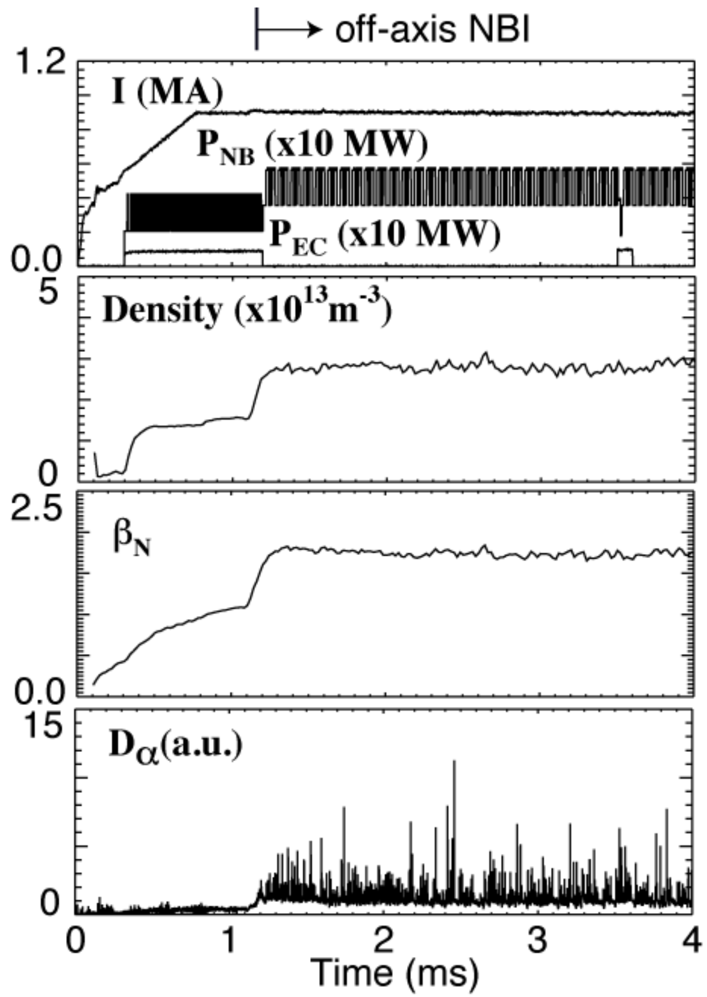
- Off-axis NBCD is expected to provide most of CD needed at half radius for noninductive high β scenario with flat q(ρ) > 2

- Focus of off-axis NBCD experiment
  - Confirm in experiments that new off-axis beams drive current as expected



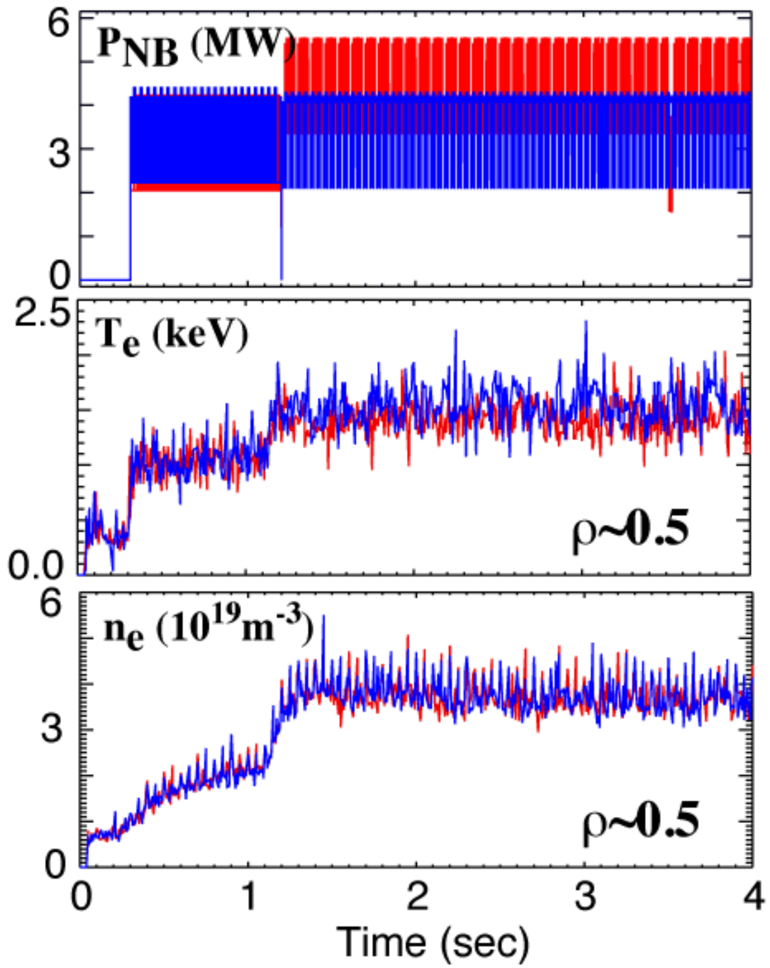
Off-axis NBCD Profile Measured in H-mode Discharge



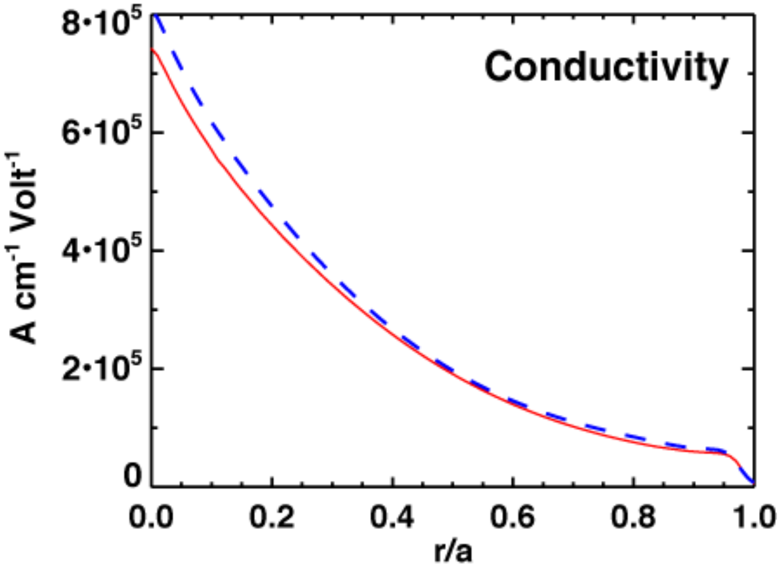


- **Use AT target configuration**
  - H-mode
  - DND plasma shape
  - $+B_T$ for good NBCD efficiency (Better alignment of NBI to local B)
- **Avoid significant core MHD**
- **Add balance NBI on top of off-axis NBCD beams**

Detailed NBCD Measurement Compares Two Discharges for On- and Off-axis NBI at Same Plasma Conductivity



On-axis Off-axis

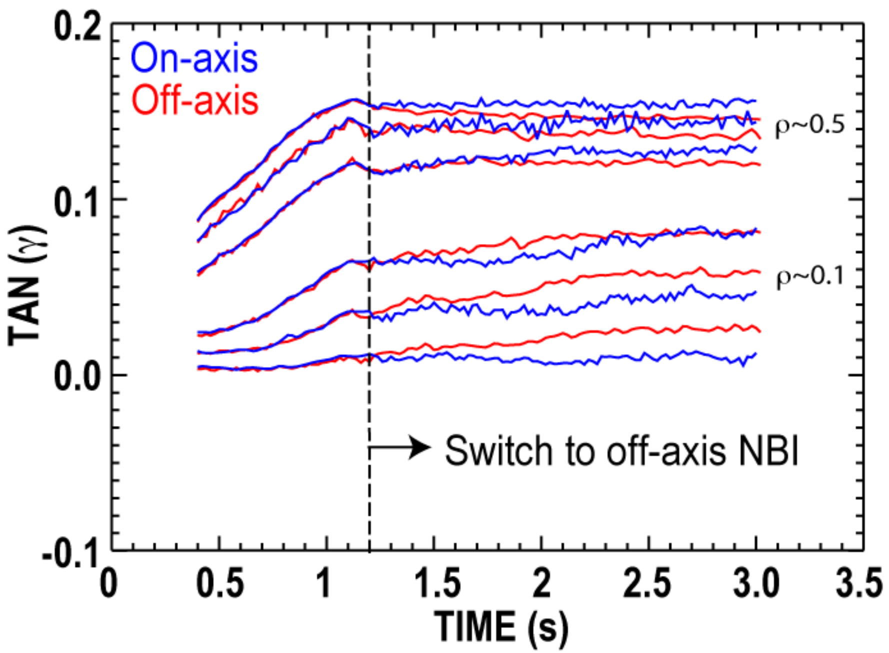


- Adjust on-axis beam power to match T_e and n_e

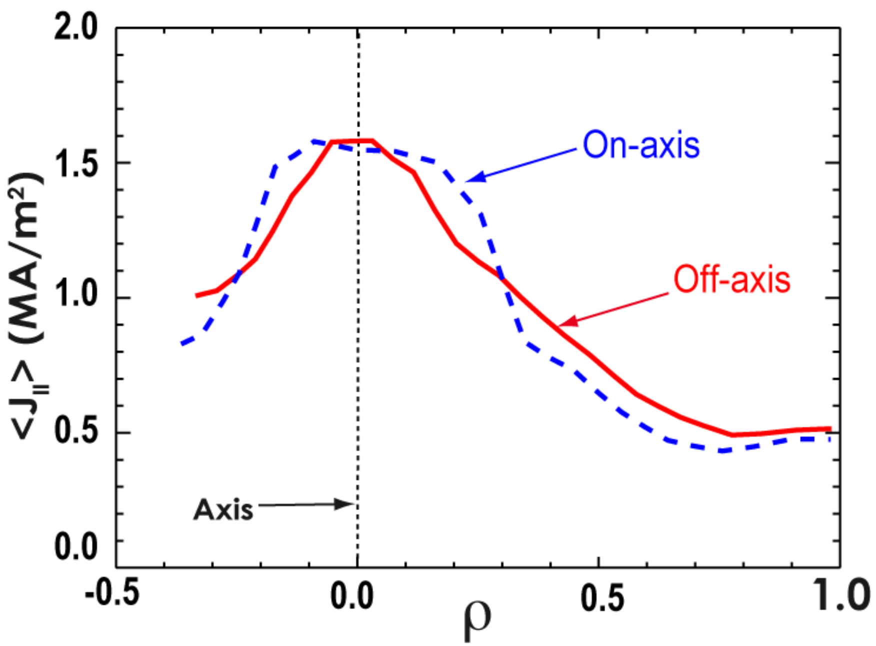
→ Difference in NBCD results in change of current profile evolution

Change Observed in Magnetic Pitch Angles for On- and Off-axis NBCD

- **Magnetic pitch angles**

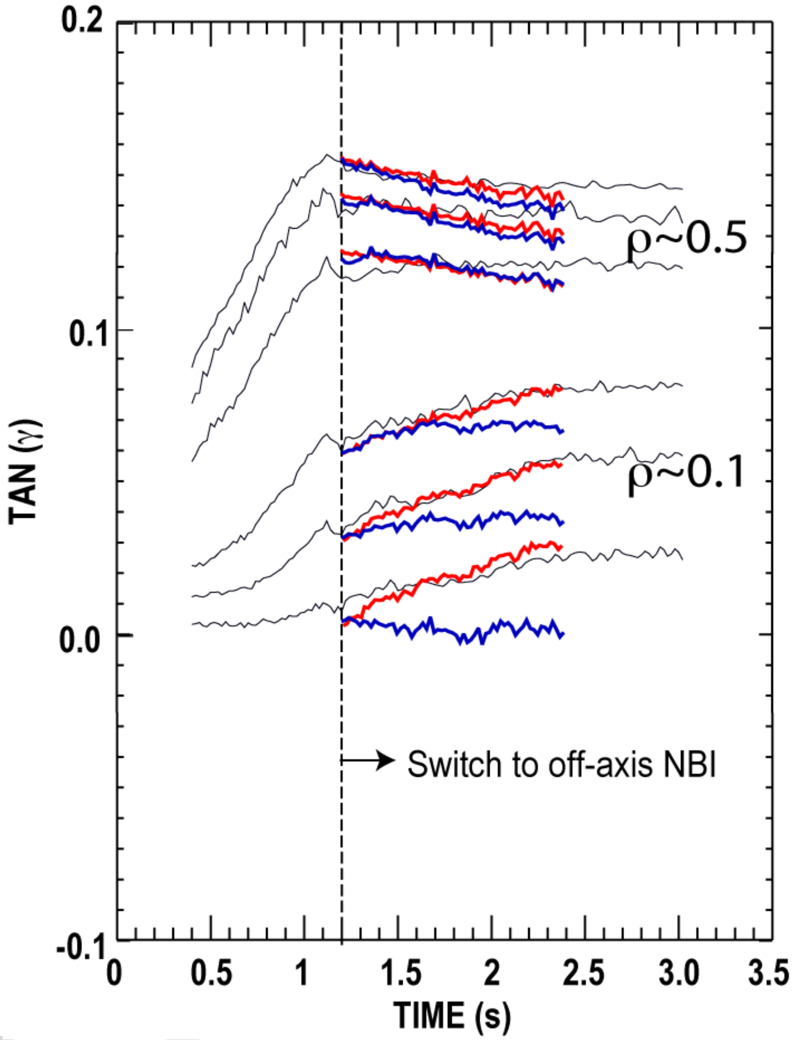


- **Direct MSE analysis**



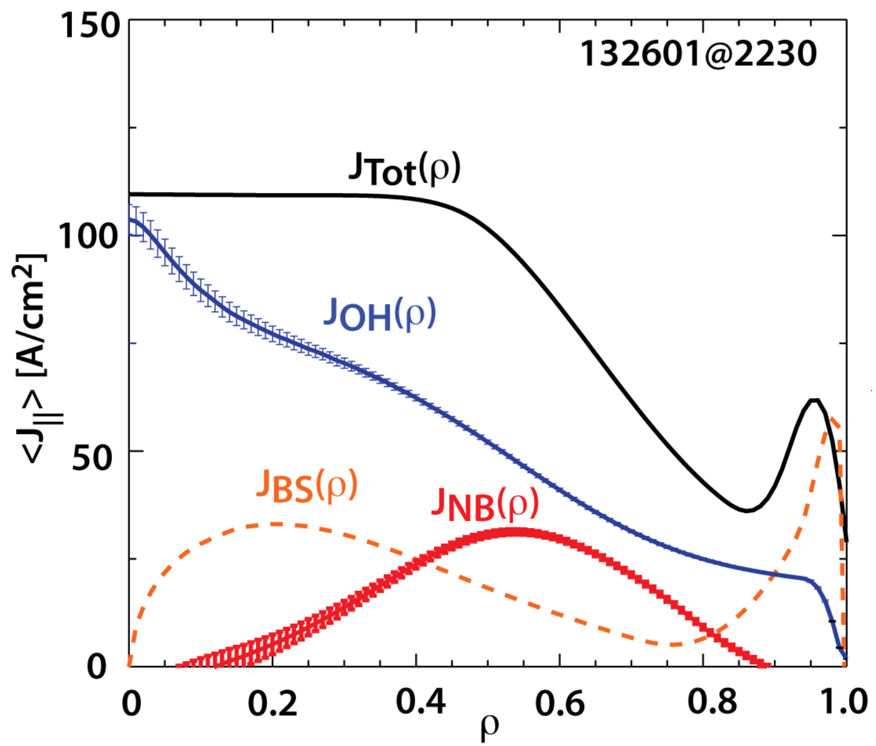
→ **Clear evidence of off-axis NBCD**

Time Evolution of MSE Signals is Consistent with Predicted Off-axis NBCD



- **MSE signals compared with transport simulation using realistic current drive sources**
  - ONETWO/EFIT/NUBEAM MSE simulator
- **Red: with NBCD**
- **Blue: without NBCD**

NBCD is Obtained Quantitatively from Evolution of the Equilibria

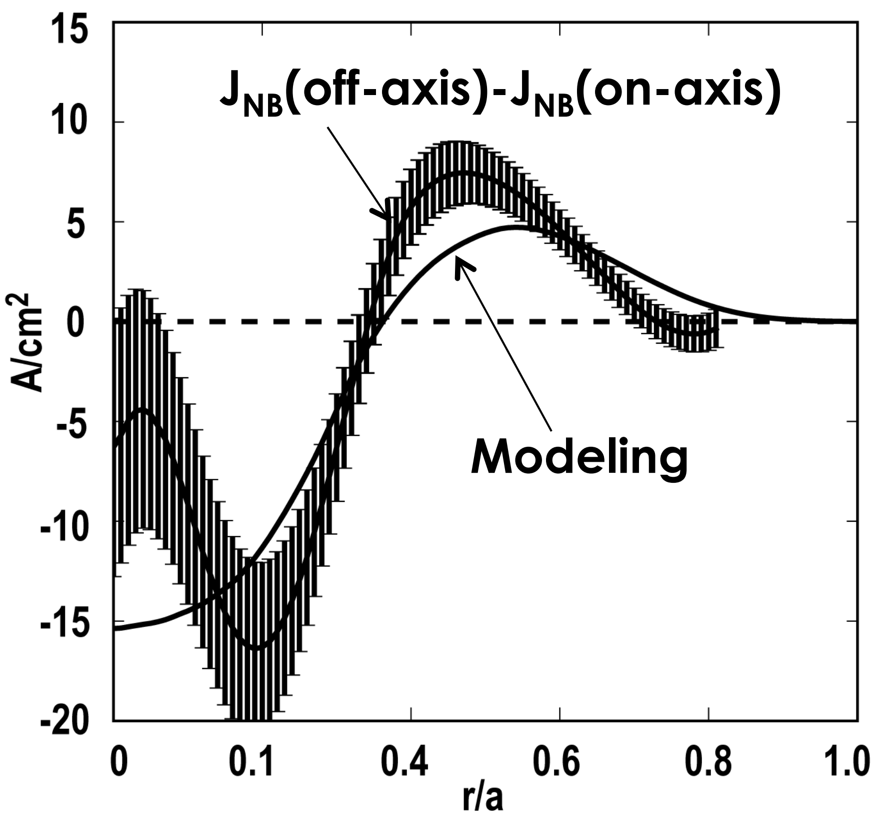


- **Kinetic equilibria reconstruction using magnetic pitch angles from MSE ⇒ J_{Tot}**
- **Internal loop voltage from time series of equilibria reconstruction ⇒ $J_{OH}=\sigma_{neo} \frac{\partial \psi}{\partial t}$**
- **Bootstrap current from neoclassical theory ⇒ J_{BS}**

$$J_{NB} = J_{Tot} - J_{OH} - J_{BS}$$

Experimental Difference between On- and Off-axis NBCD Profiles in Good Agreement with Classical Model

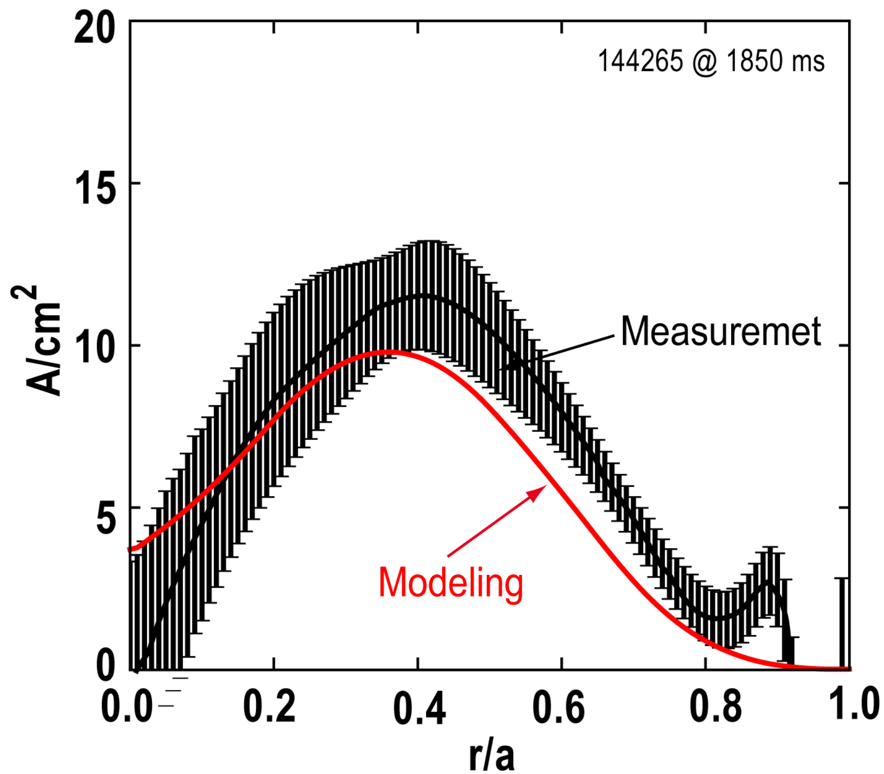
Measured NBCD Difference



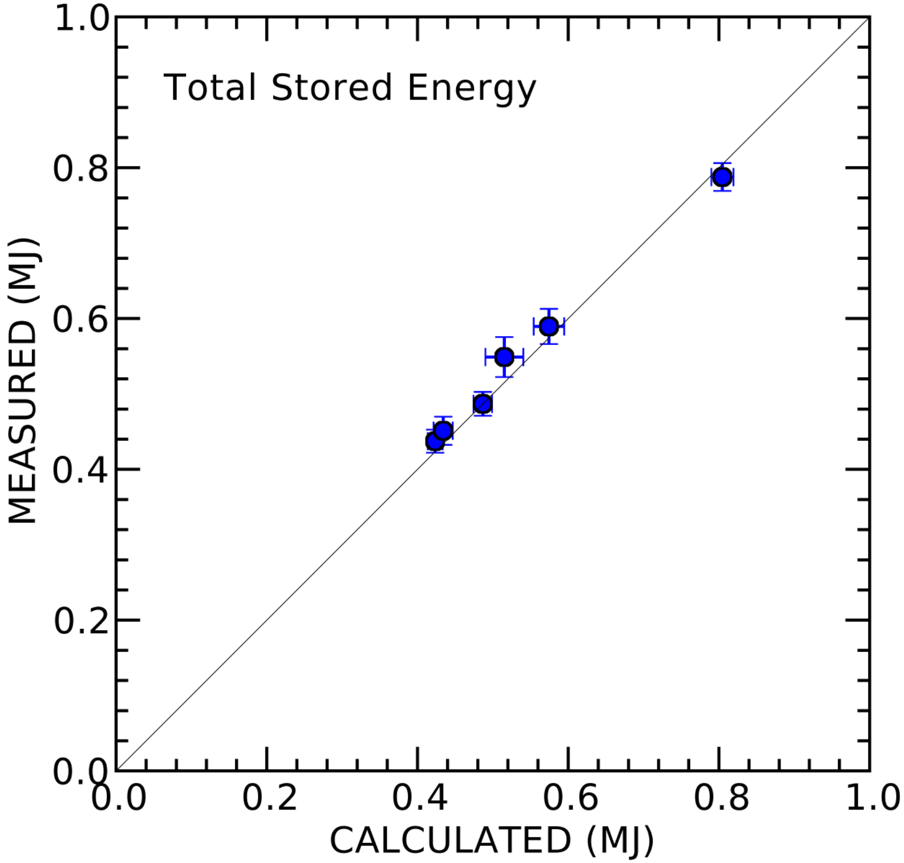
- **Differential CD analysis compares two discharges with on– and off–NBI at ~ same T_e and n_e**
  - ➔Reduce systematic sources of error (model dependency and uncertainties in measurement, e.g. Z_{eff})
- **Modeling comparison**
  - NUBEAM Monte-Carlo beam ion slowing down calculation
  - Assume no anomalous fast ion diffusion

Experiments Confirm that New Off-axis Beams Drive Current as Expected

- **Clear hollow NBCD profile**
- **Peak NBCD at ρ ~ 0.4**
- **Reasonable agreement with NUBEAM modeling**
- **Analysis is in progress for a range of beam injection and discharge conditions**
  - ± B_T, E_b, injection power, β, and T_e (E_b/T_e)



Beam Stored Energy Calculated by Classical Model Consistent with Equilibrium Reconstruction



- **Total stored energy = thermal + beam ion**
- **Beam stored energy calculated by NUBEAM without anomalous diffusion**

→ No large anomalous loss of fast ions

Summary

- Experiments on off-axis NBCD in DIII-D have clearly demonstrated off-axis NBCD using the new tilted beamline
- The MSE magnetic pitch angles show clear evidence of off-axis current drive when compared with the on-axis injection
- The beam-stored energy estimated by equilibrium reconstruction is consistent with the classical model calculation, indicating no large anomalous losses of NBCD and fast ions
- Good agreement of the local NBCD profile was found between experiment and modeling
- Off-axis NBCD is ready to use for AT scenario

  C. Holcomb, "High q_{min} Steady-State Scenario Development Using Off-Axis Neutral Beam Injection on DIII-D"