Validation of On- and Off-axis Neutral Beam Current Drive Against Experiment in DIII-D

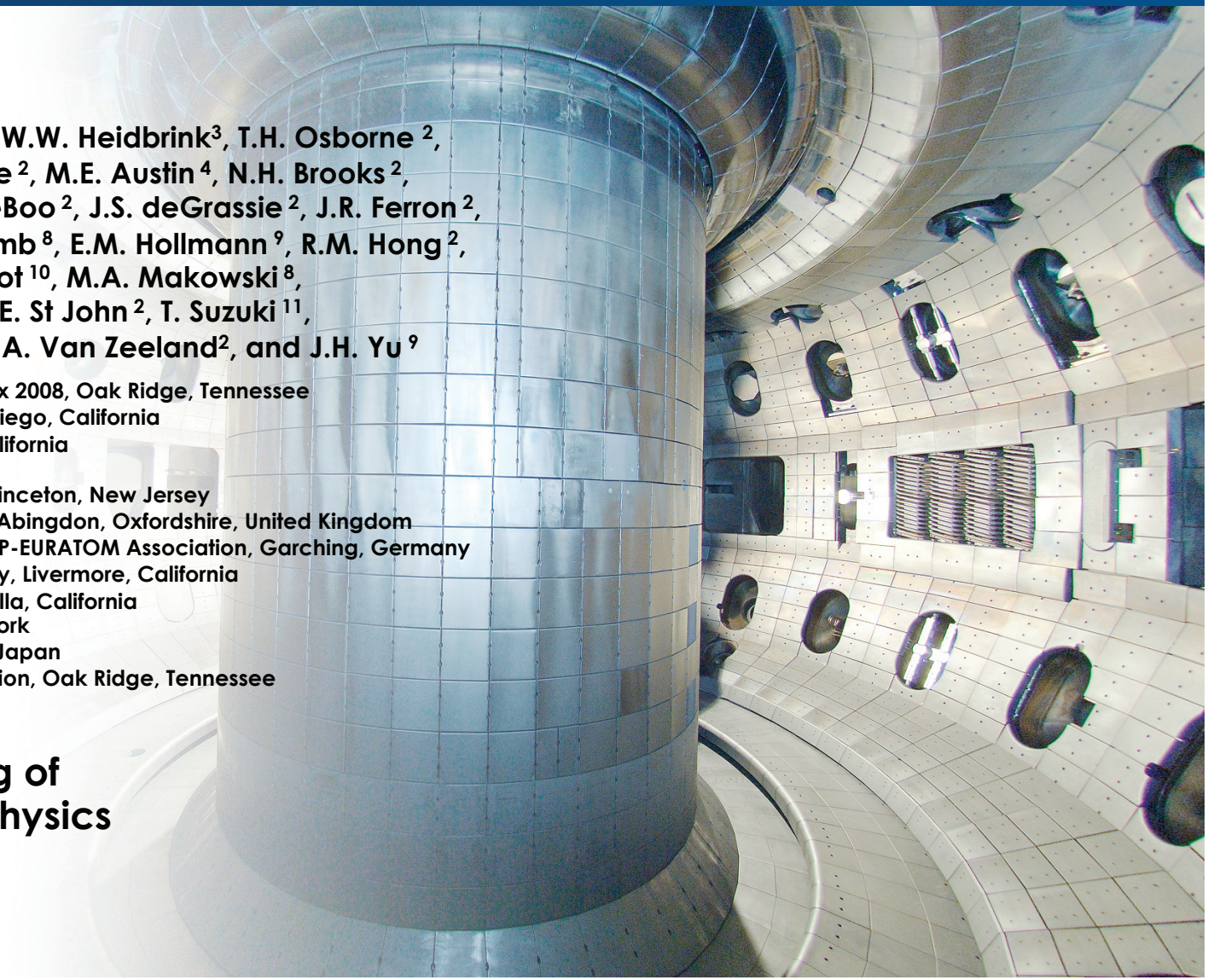
by
J.M. Park[1]

with M. Murakami[1], C.C. Petty[2], W.W. Heidbrink[3], T.H. Osborne[2], R. Prater[2], T.C. Luce[2], M.R. Wade[2], M.E. Austin[4], N.H. Brooks[2], R.V. Budny[5], C. Challis[6], J.C. DeBoo[2], J.S. deGrassie[2], J.R. Ferron[2], P. Gohil[2], J. Hobirk[7], C.T. Holcomb[8], E.M. Hollmann[9], R.M. Hong[2], A.W. Hyatt[2], J. Lohr[2], M.J. Lanctot[10], M.A. Makowski[8], D.C. McCune[5], P.A. Politzer[2], H.E. St John[2], T. Suzuki[11], W.P. West[2], E.A. Unterberg[12], M.A. Van Zeeland[2], and J.H. Yu[9]

1) Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee
2) General Atomics, P.O. Box 85608, San Diego, California
3) University of California, Irvine, Irvine, California
4) University of Texas-Austin, Austin, Texas
5) Princeton Plasma Physics Laboratory, Princeton, New Jersey
6) UKAEA Fusion Culham Science Centre, Abingdon, Oxfordshire, United Kingdom
7) Max-Planck-Institut fur Plasmaphysik, IPP-EURATOM Association, Garching, Germany
8) Lawrence Livermore National Laboratory, Livermore, California
9) University of California-San Diego, La Jolla, California
10) Columbia University, New York, New York
11) Japan Atomic Energy Agency, Naka, Japan
12) Oak Ridge Institute for Science Education, Oak Ridge, Tennessee

Presented at the
50th APS Annual Meeting of
The Division of Plasma Physics
Dallas, Texas

November 17–21, 2008

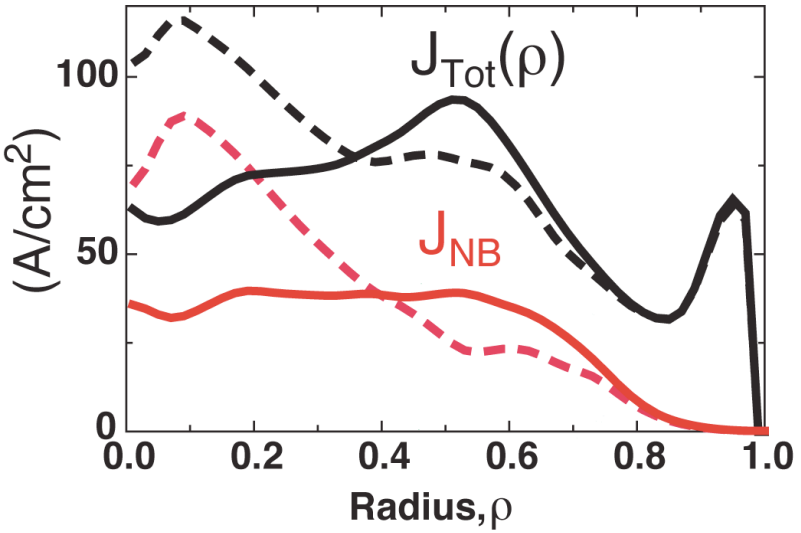


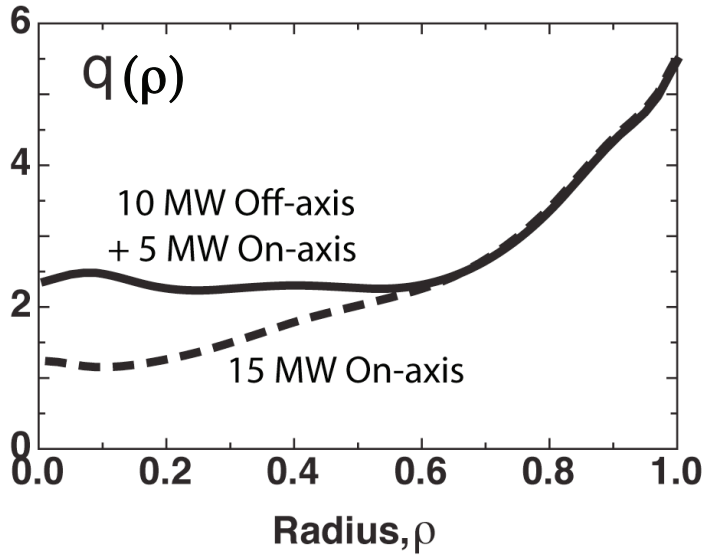
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

OAK RIDGE National Laboratory

Off-axis NBCD Enables Advanced Scenario Development

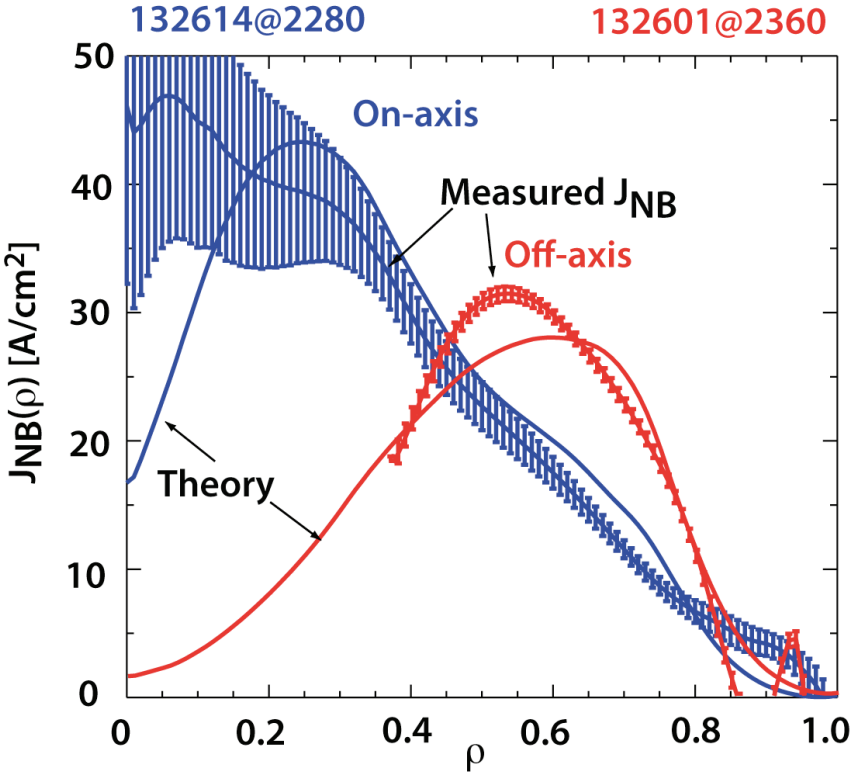
- Development of steady state, high performance scenario (high q_{min} at high β) for ITER and FDF is limited at present by overdrive of the central current by the NBI required for heating
- Off-axis NBCD provides most of CD needed at half radius for noninductive high β scenario with flat q(ρ) > 2
- Need to validate the off-axis NBCD model against experiment





Robust Off-Axis NBCD Found in DIII-D Experiments

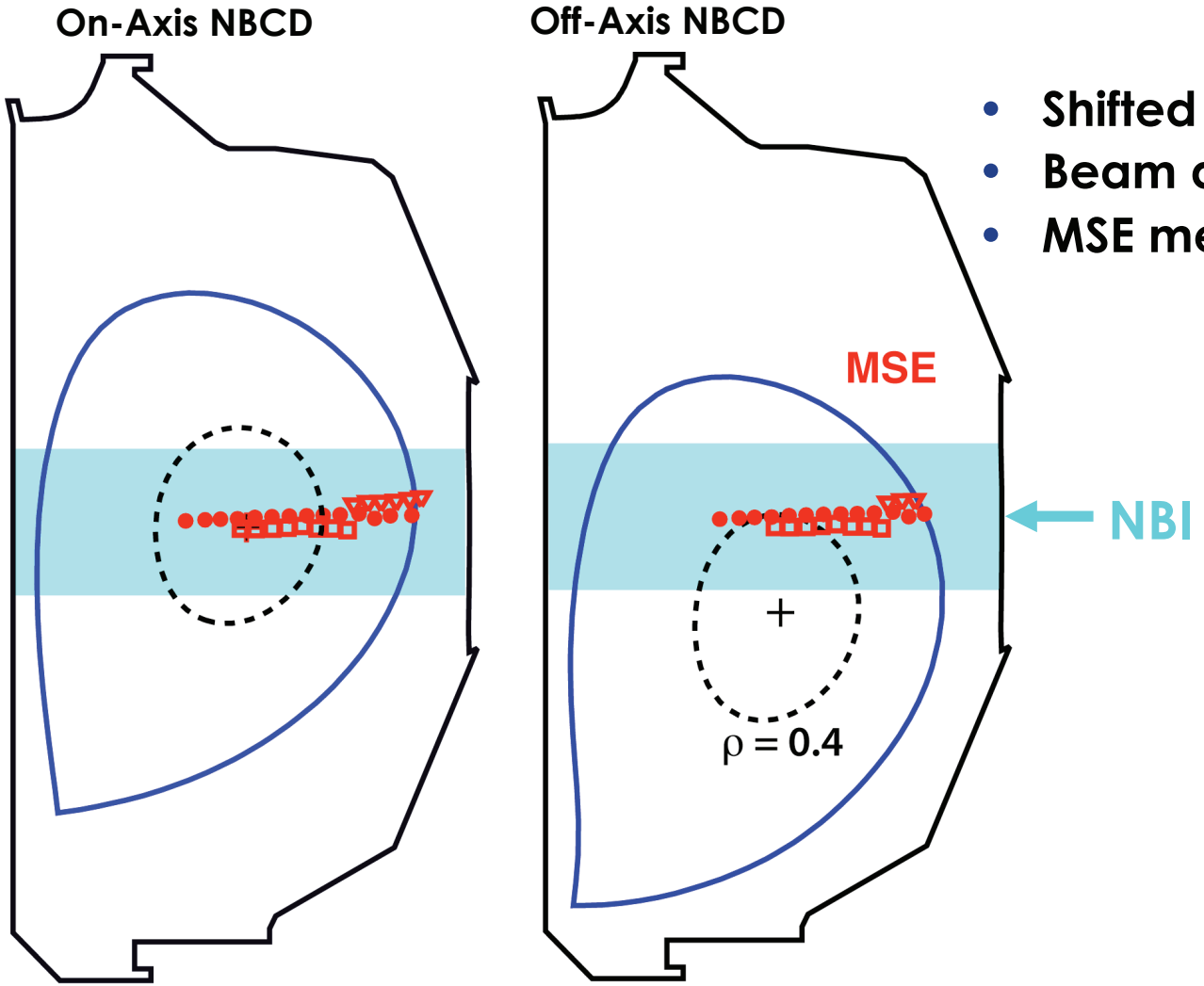
- Demonstration of robust off-axis NBCD in DIII-D
- Benefit of alignment of injection with magnetic pitch
- Small effect of anomalous transport of fast ions on off-axis NBCD profiles
- Prospect for ITER and DIII-D scenario development



Outline

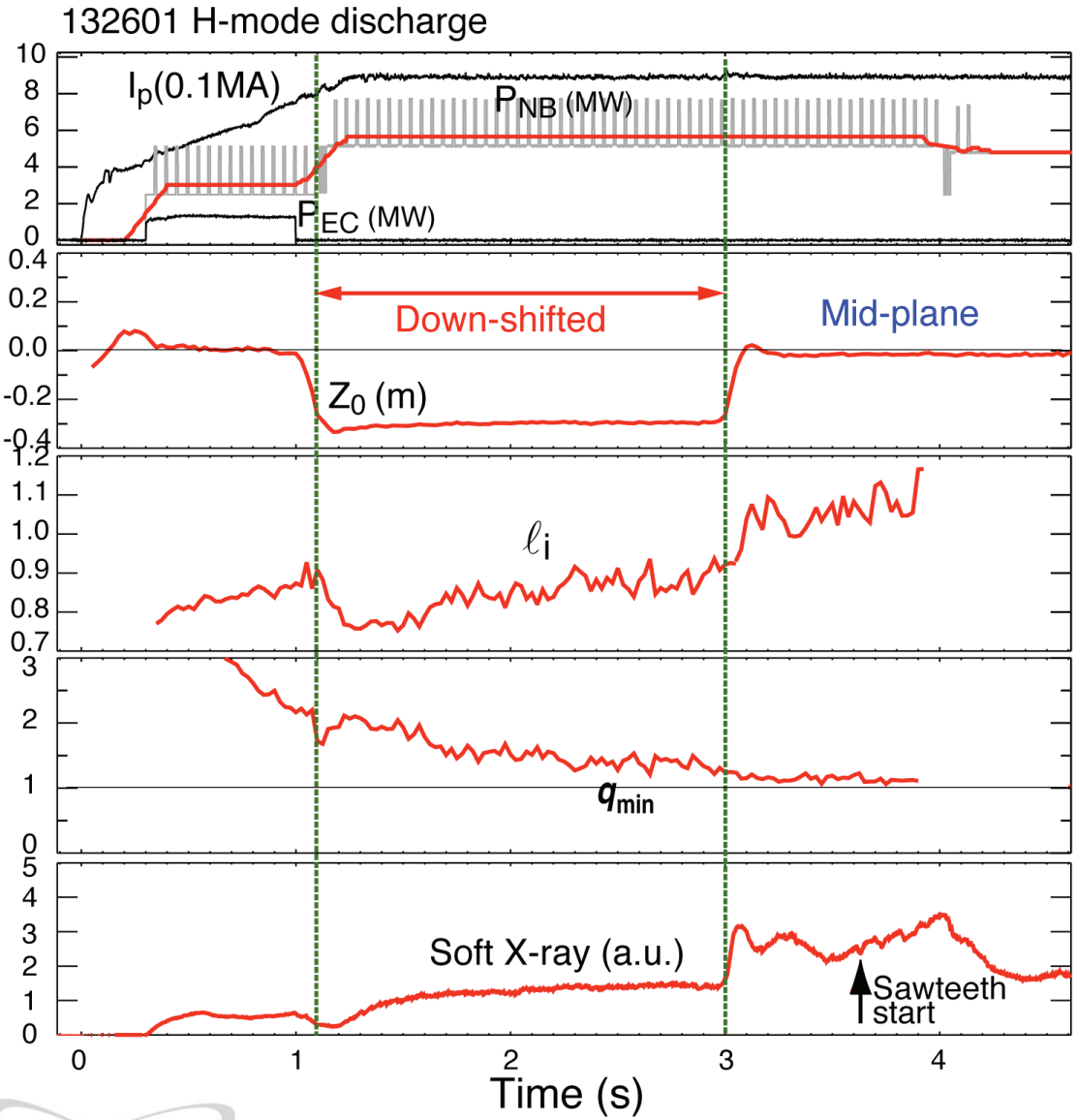
- **Demonstration of robust off-axis NBCD in DIII-D**
- **Benefit of alignment of injection with magnetic field**
- **Small effect of anomalous transport of fast ions on off-axis NBCD profiles**
- **Prospect for ITER and DIII-D scenario development**

Plasmas Were Shifted Vertically to Move NBCD Off-axis



- Shifted vertically ~30 cm
- Beam deposition at $\rho \approx 0.5$
- MSE measurement $\rho \geq 0.4$

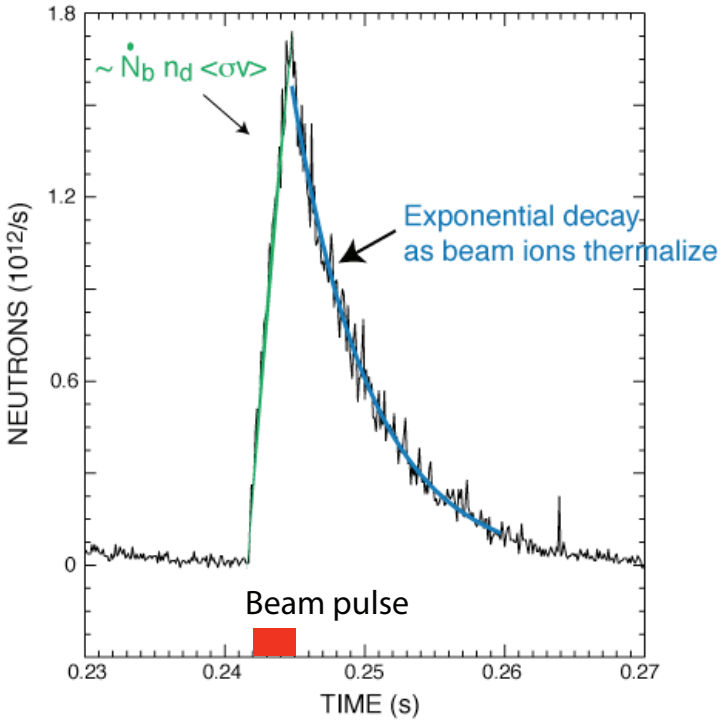
Global Behavior is Consistent with the Existence of Off-axis CD That Increases With Co-NB Power



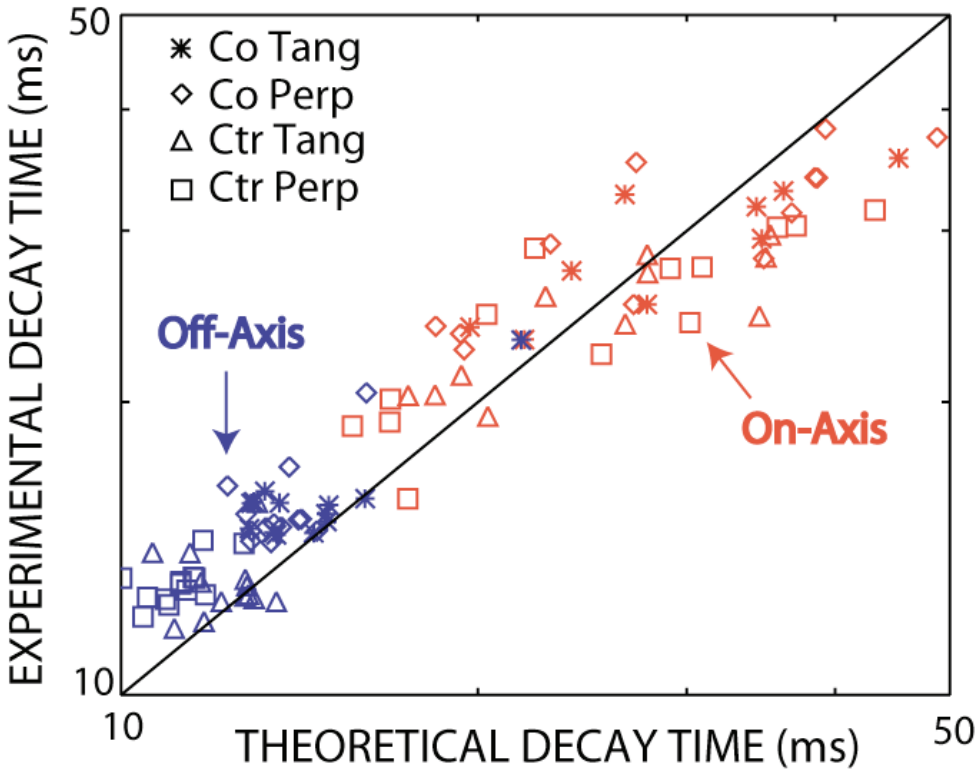
NBI while plasma is shifted causes off-axis NBCD that

- **reduces ℓ_i**
- **keeps $q_{min} > 1$**
- **avoids sawteeth**

Short Beam Pulses Show Fast Ions Confined as Expected for On- and Off-Axis Injection



W.W. Heidbrink JP6.93



- ***Neutron Rise*** ∝ on number of confined beam ions injected
- ***Decay*** ∝ slowing down & losses on τ_{th} timescale

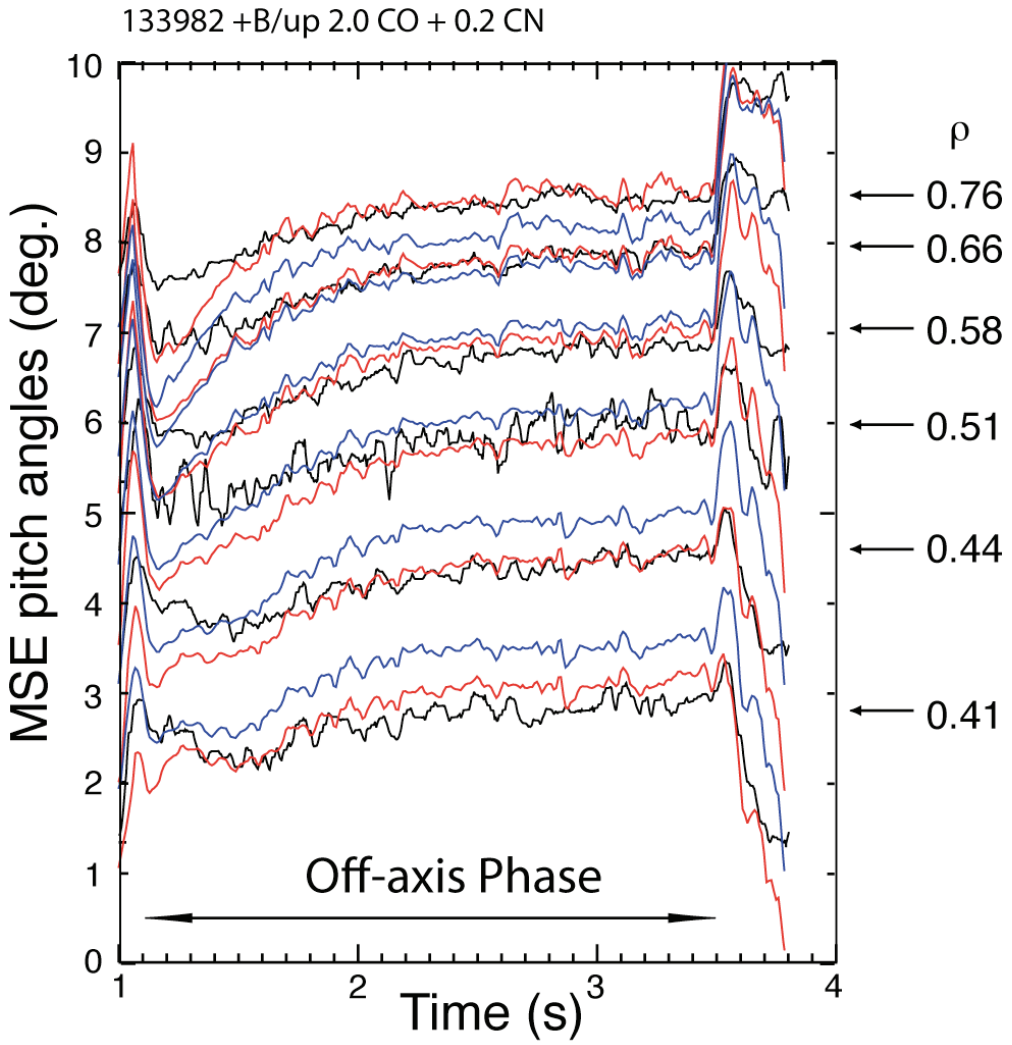
Time Evolution of MSE Signals is Consistent with the Existence of Off-axis NBCD

- **MSE signals compared with transport simulation using realistic current drive sources**
  - TRANSP/NUBEAM MSE simulator

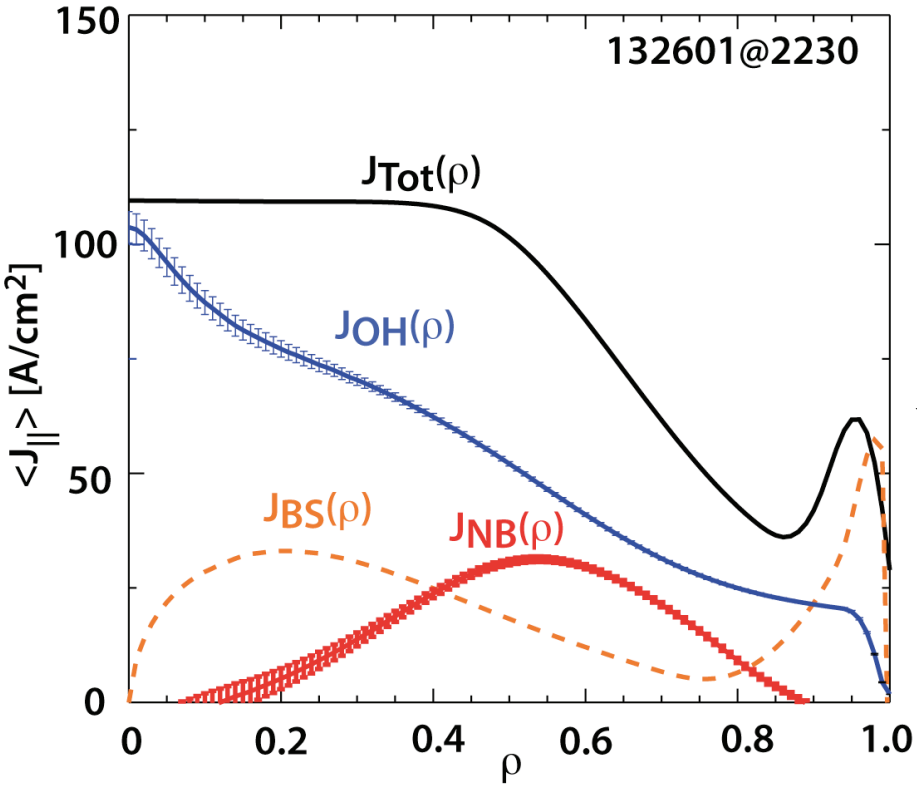
- **Black: MSE**

  Red: simulation with off-axis NBCD

  Blue: simulation without off-axis NBCD



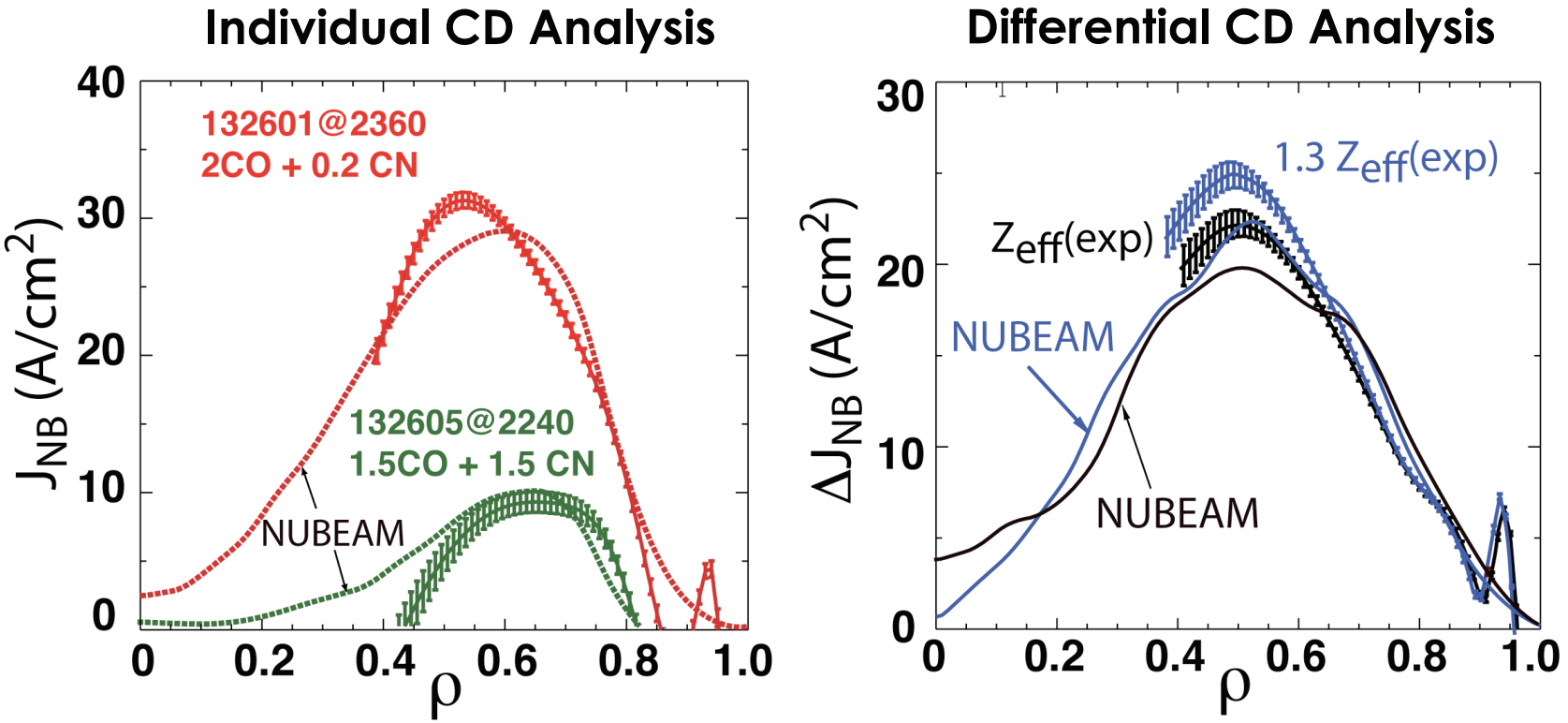
NBCD is Obtained Quantitatively from Evolution of the Equilibria



- **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}**

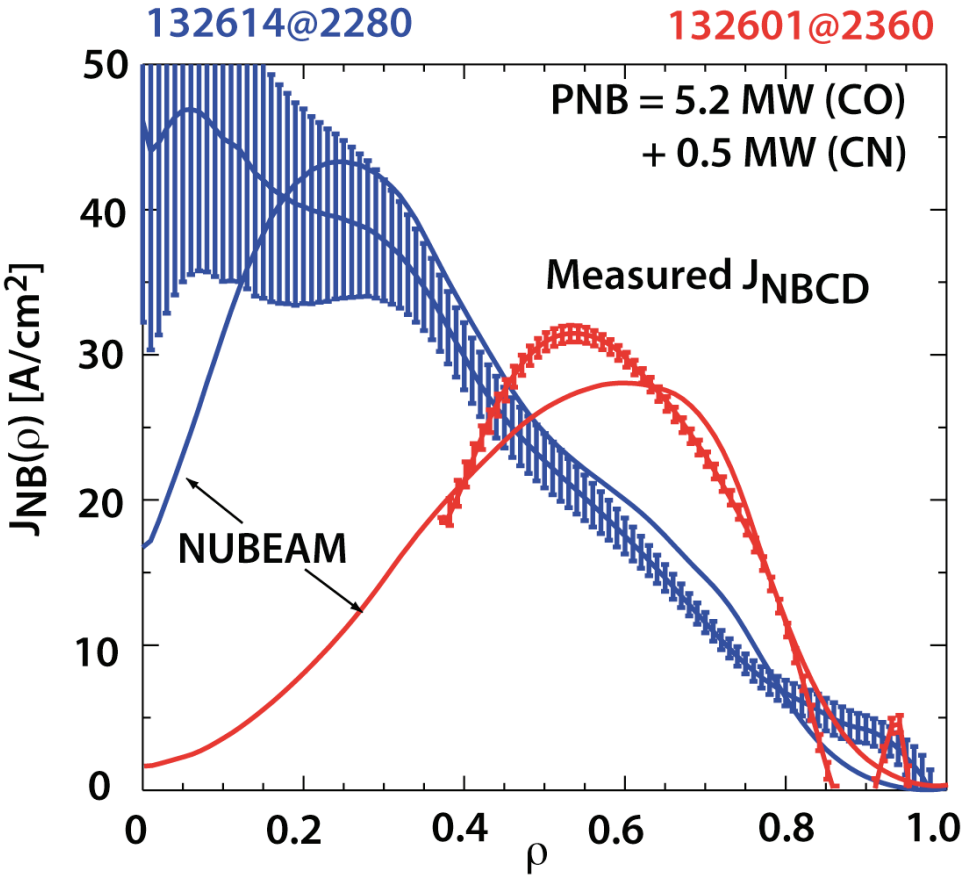
$$J_{NB} = J_{Tot} - J_{OH} - J_{BS}$$

Systematic Uncertainties in NBCD Analysis Reduced by Subtracting a Fiducial Case



- **Differential CD analysis compares two discharges with co and balanced – NBI at same n_e and T_e**
  ➔ Reduce systematic sources of error (e.g. Z_{eff})

Experimental On- and Off-axis NBCD Profiles in Good Agreement with NUBEAM Model

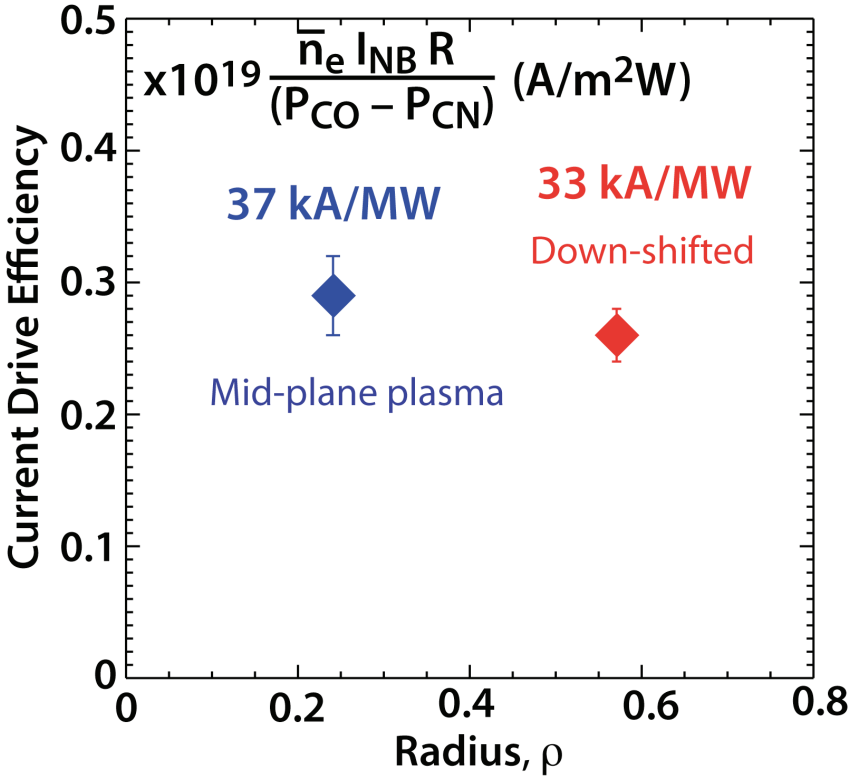


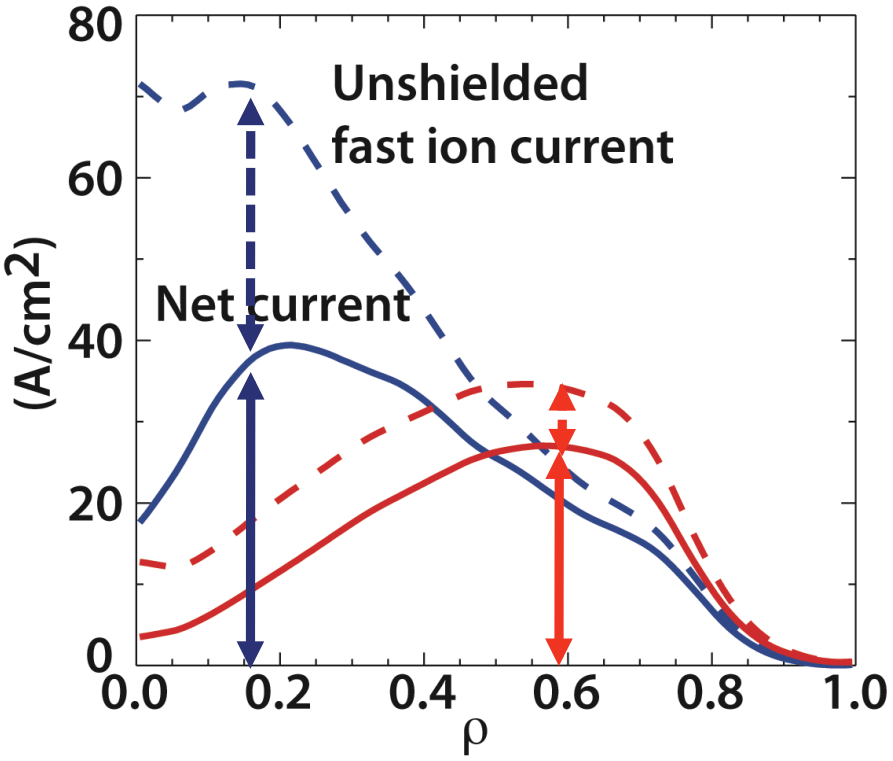
- **Theoretical model**
  - NUBEAM Monte-Carlo beam ion slowing down calculation
  - Assume no anomalous fast ion diffusion

- **Integrated current (kA)**

	Off-axis $I_{NB}(0.4\leq\rho\leq1)$	On-axis I_{NB}
Measured	167	170
NUBEAM	170	175

Off-axis NBCD Does not Lose CD Efficiency by Going to a Larger Radius

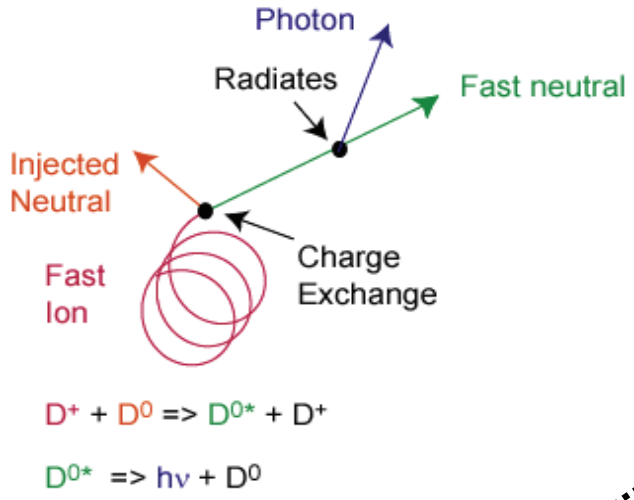




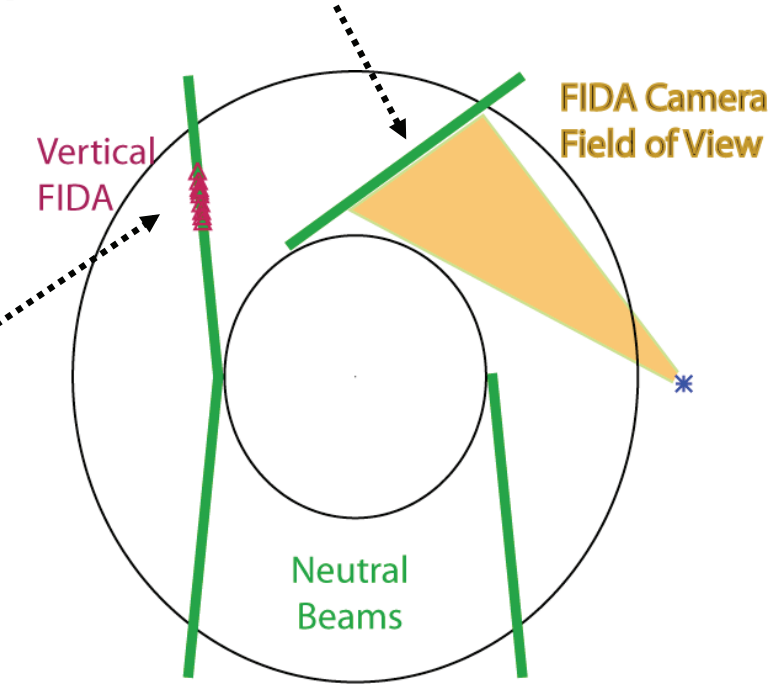
- Increase of trapped electron fraction with radius reduces the electron cancellation current, resulting in good off-axis CD efficiency
- Trapped electrons help off-axis NBCD, unlike off-axis ECCD

Fast-ion D_α (FIDA) Measures Radial Profile or 2-D Image of Beam Ion Density

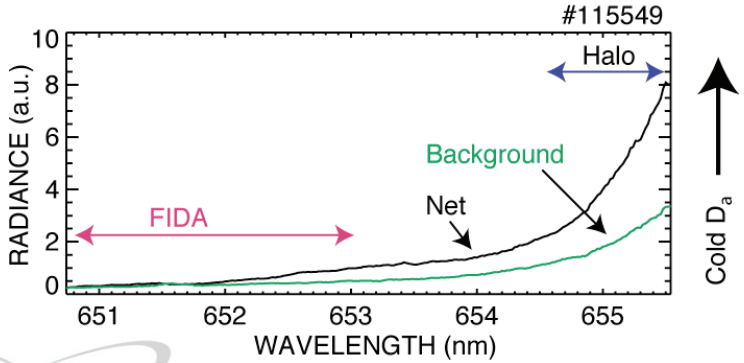
- **Doppler-shifted light from neutralized fast ions**



- **The camera images a 2-D plasma cross section.**

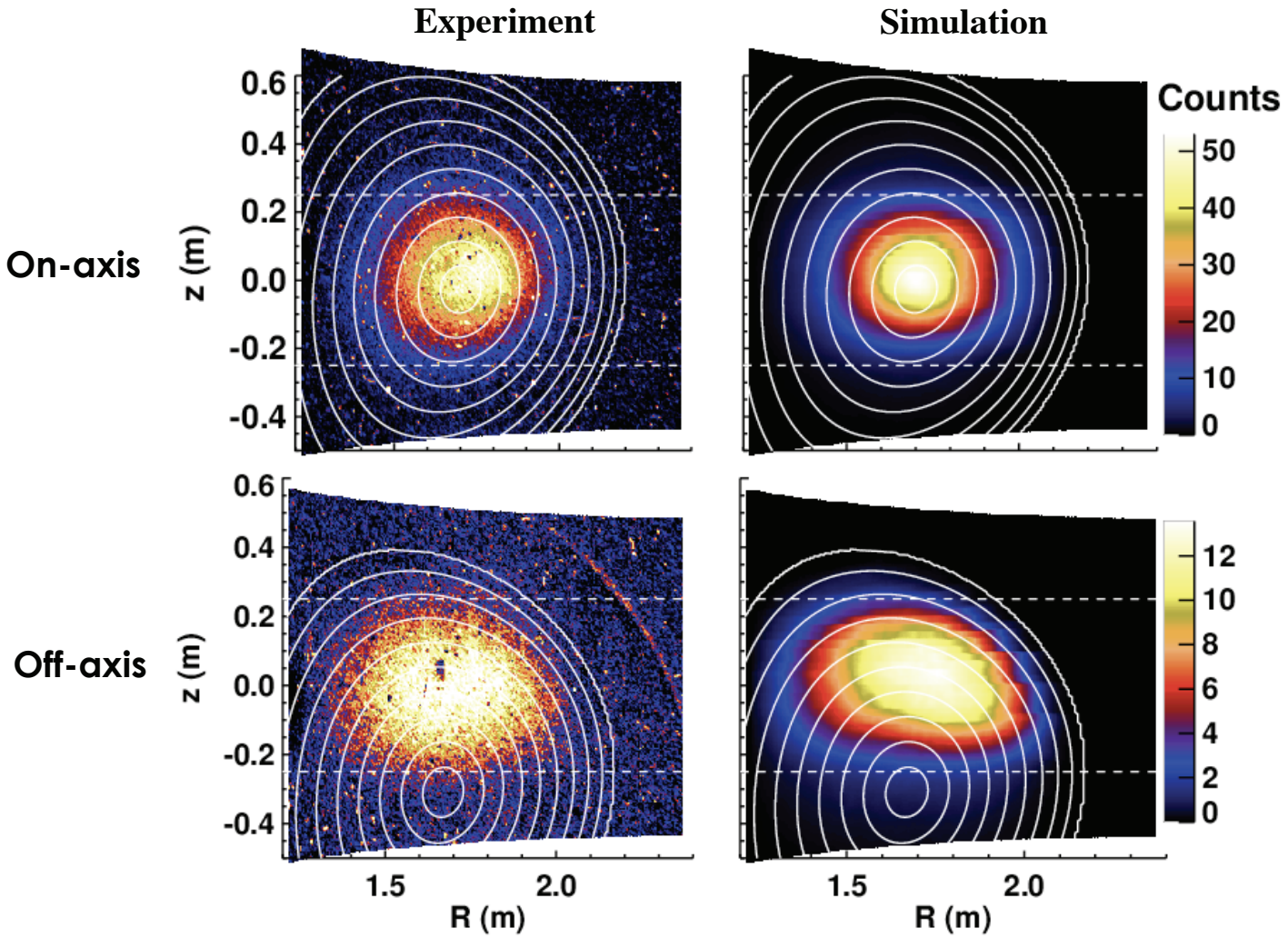


- **Vertical spectrometer measures profile and spectrum**



Heidbrink, PPCF 46 (2004)
Luo, Rev. Sci. Instrum. 78 (2007)

2-D FIDA Image Shows Clear Off-axis Beam Ion Profile Consistent with Theoretical Model



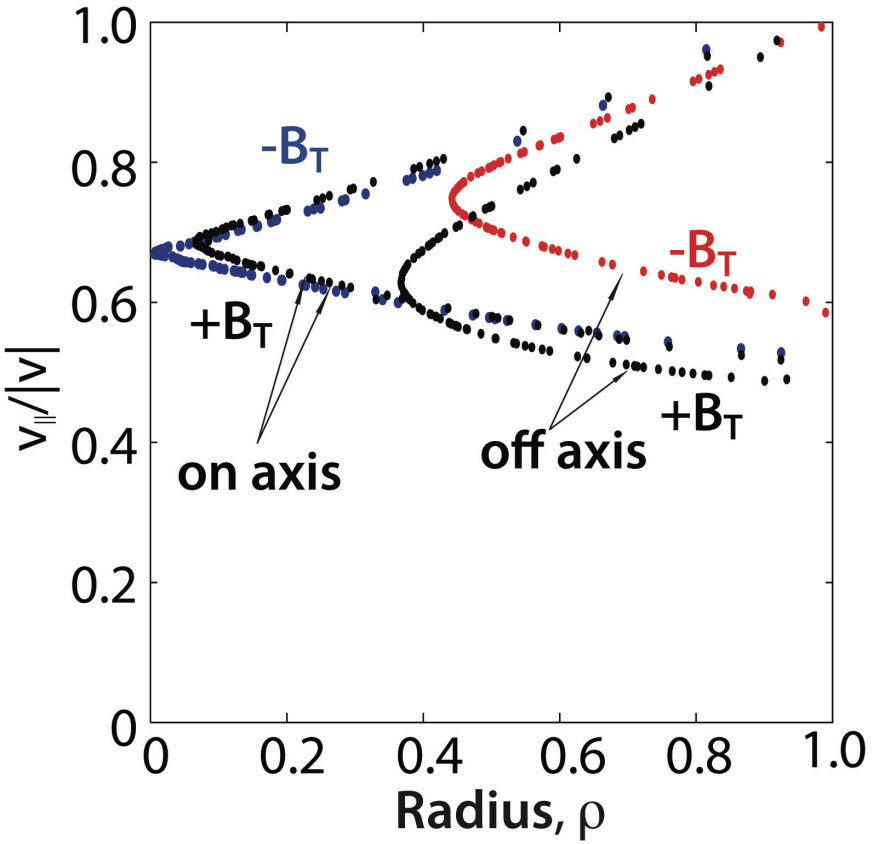
- Image convolves fast-ion profile with footprint of injected neutrals.

[Heidbrink, JP6.93]

Outline

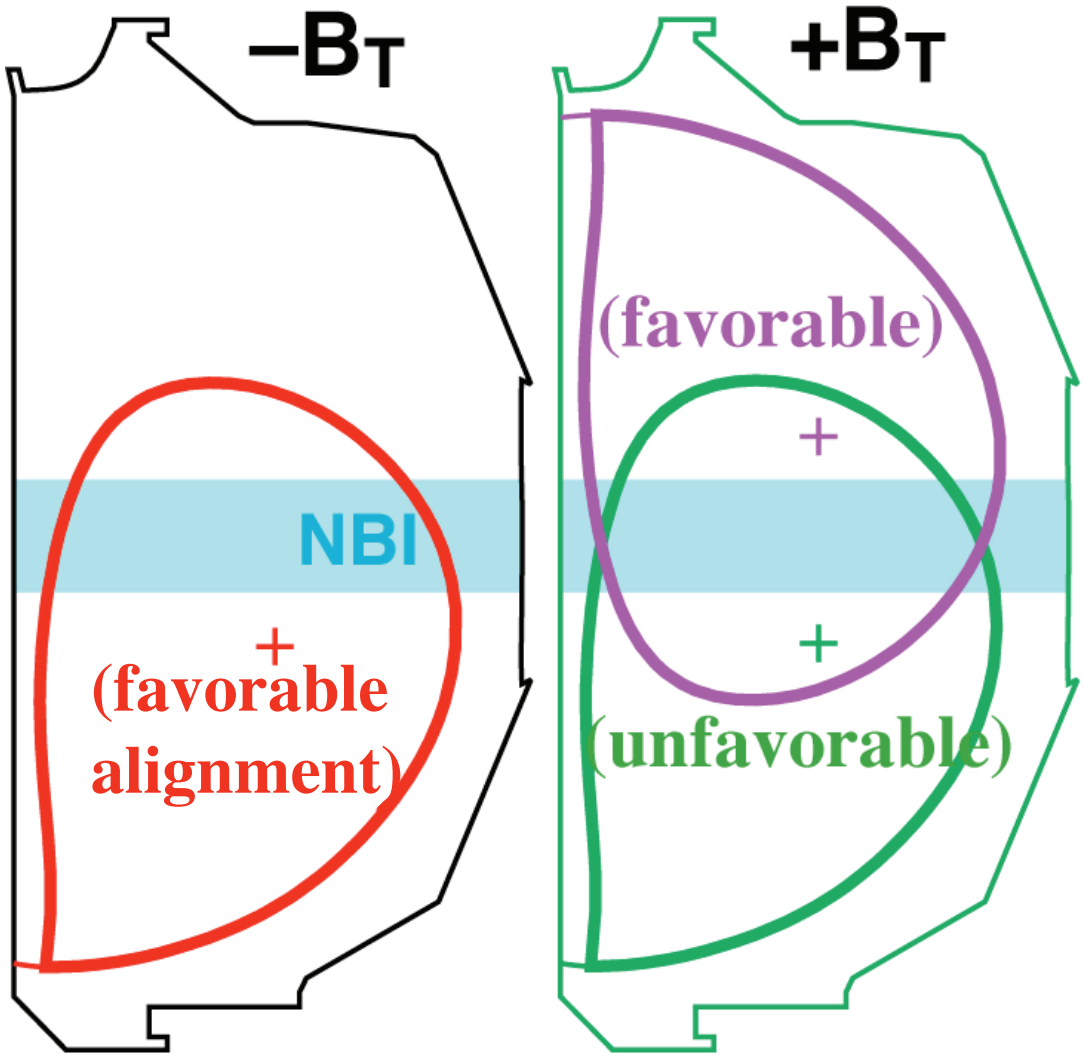
- Demonstration of robust off-axis NBCD in DIII-D
- **Benefit of alignment of injection with magnetic field**
- Small effect of anomalous transport of fast ions on off-axis NBCD profiles
- Prospect for ITER and DIII-D scenario development

Off-axis NBCD Is Sensitive to the B_T Direction Due to Alignment of NBI with Local Pitch of the Magnetic Field Lines

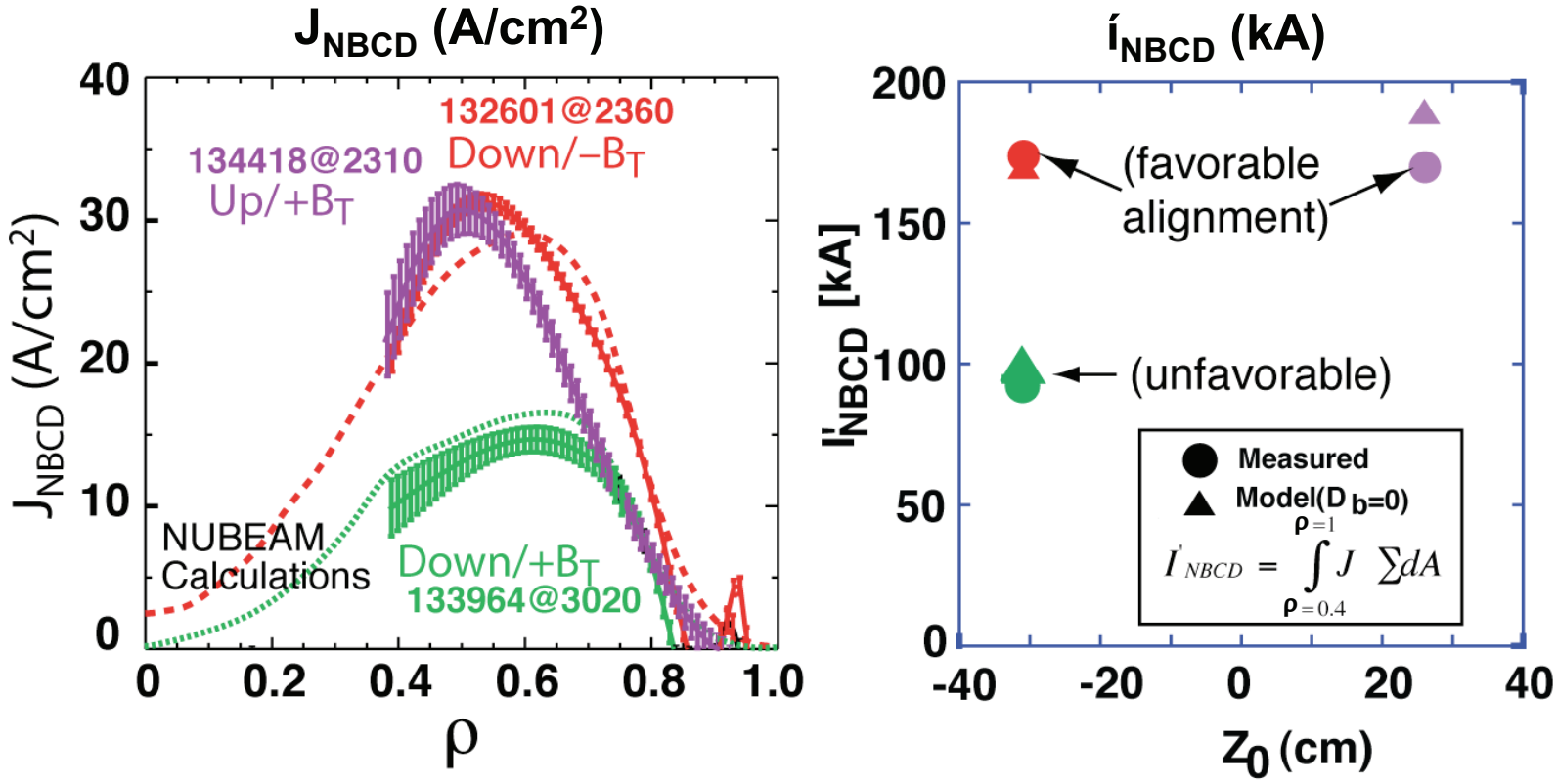


- Alignment of NBI with the local magnetic field (B_T / B_T+B_R) helicity is an important physics for on- and off-axis NBCD
- There MUST exist a favorable B_T direction for off-axis NBCD.

Magnetic Alignment Model Tested by Changing the Sign of B_T or, by Shifting Plasma Upward or Downward

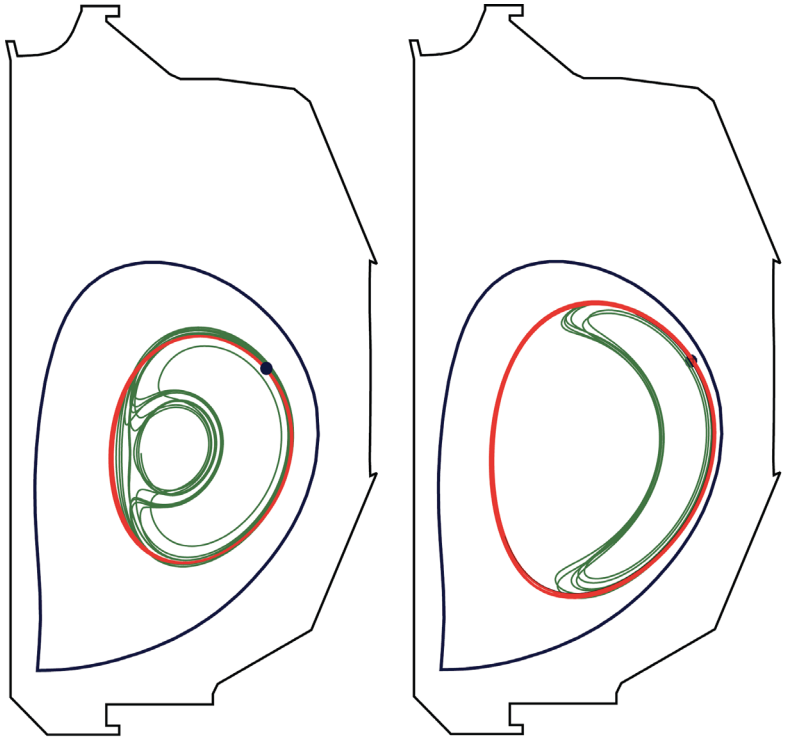


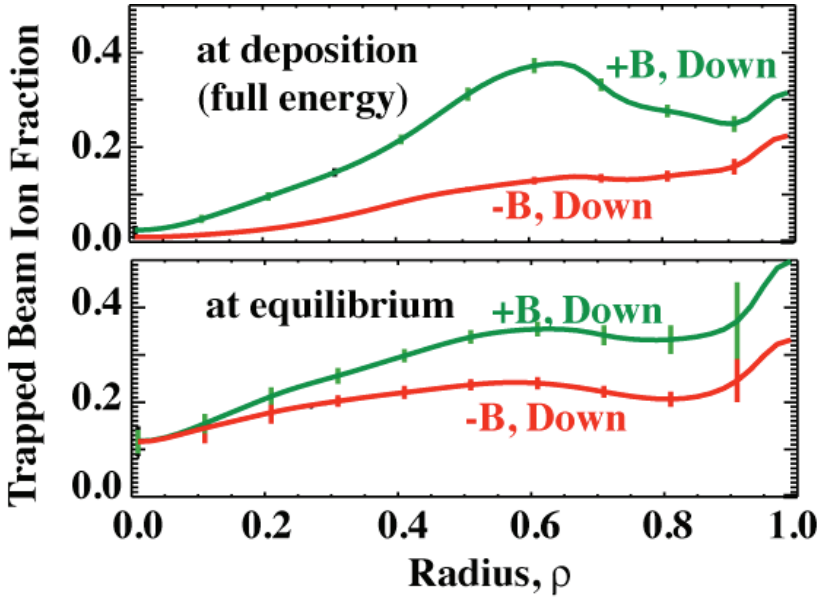
Experiments Confirmed Prediction that Off-axis NBCD Efficiency Depends on Magnetic Field Alignment



- I_{NB} (unfavorable alignment)/I_{NB} (favorable) ≈60 – 65% for both measurement and theory

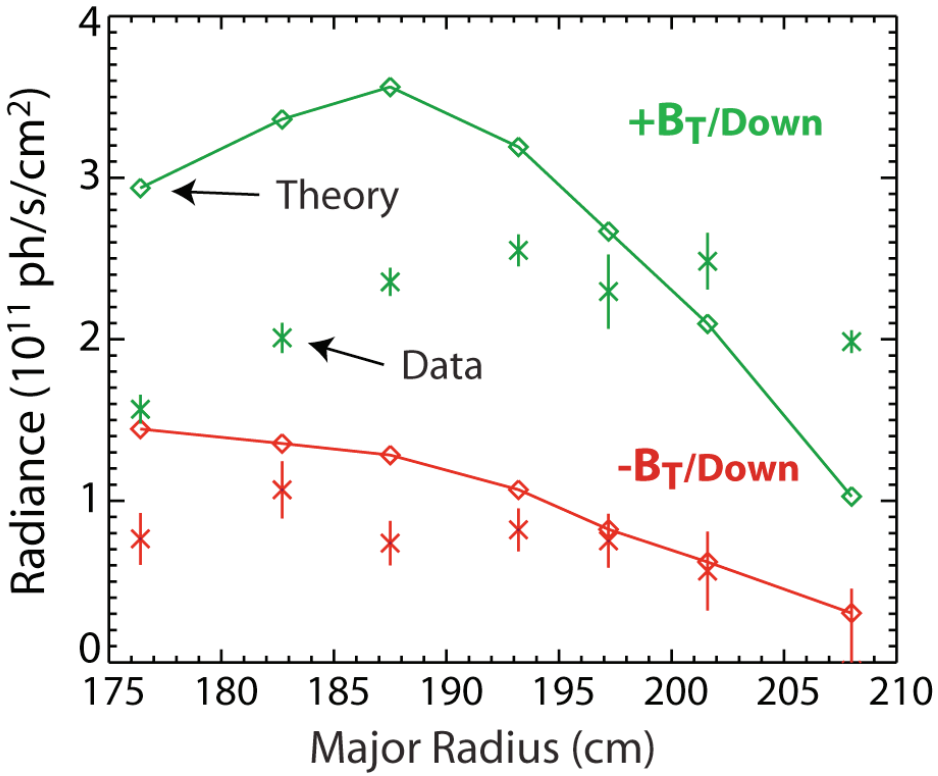
Unfavorable Alignment Leads to Increase in Fast Ion Trapping Fraction Resulting in Lower NBCD





- -BT direction : Passing orbits
  ⇒ well localized CD
- +BT direction :
  (1) Trapped orbits
  ⇒ Not contributing to fast ion current
  (2) Inward particle shift
  ⇒ place the particles where electron shielding is larger

Good Off-axis NBCD Does NOT Necessarily Mean Good Fast Ion Confinement



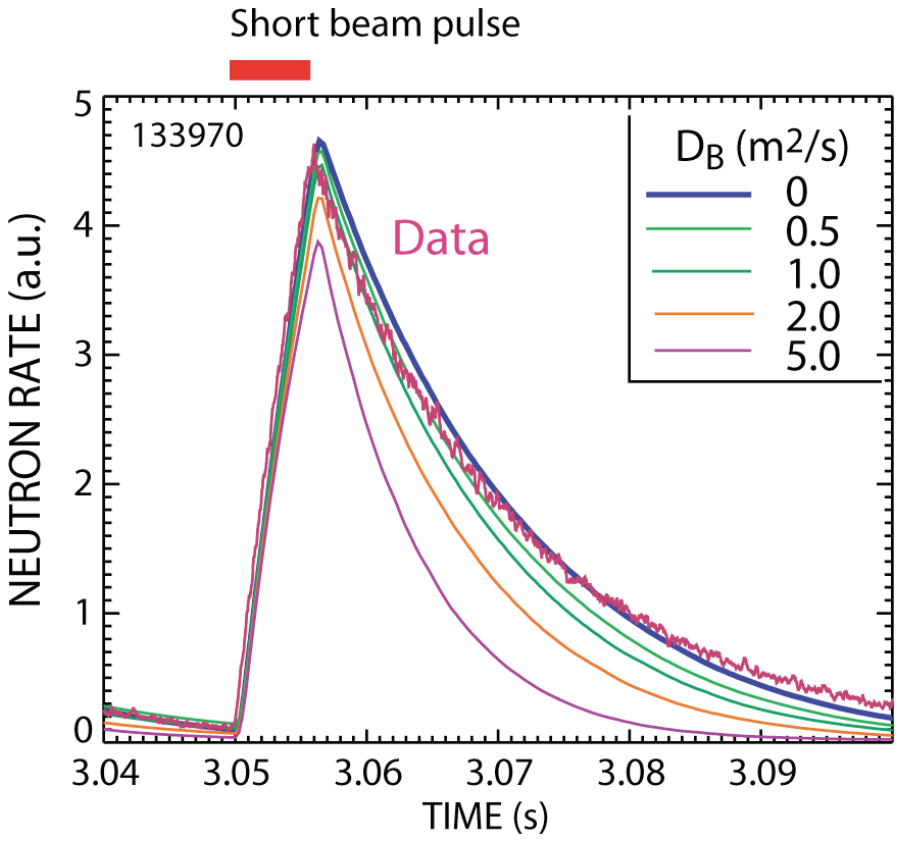
[Heidbrink, JP6.00093]

- **Fat banana orbits in unfavorable alignment results in more fast ion deposition near the axis, leading to better fast ion confinement**
- **Both vertical FIDA and neutron signals are higher with +B_T/down as predicted**
  - 28 % higher neutron rate (theory: 15 %)
- **Optimization of off-axis NBCD is different from optimization of fast ion confinement**

Outline

- Demonstration of robust off-axis NBCD in DIII-D
- Benefit of alignment of injection with magnetic field
- **Small effect of anomalous transport of fast ions on off-axis NBCD profiles**
- Prospect for ITER and DIII-D scenario development

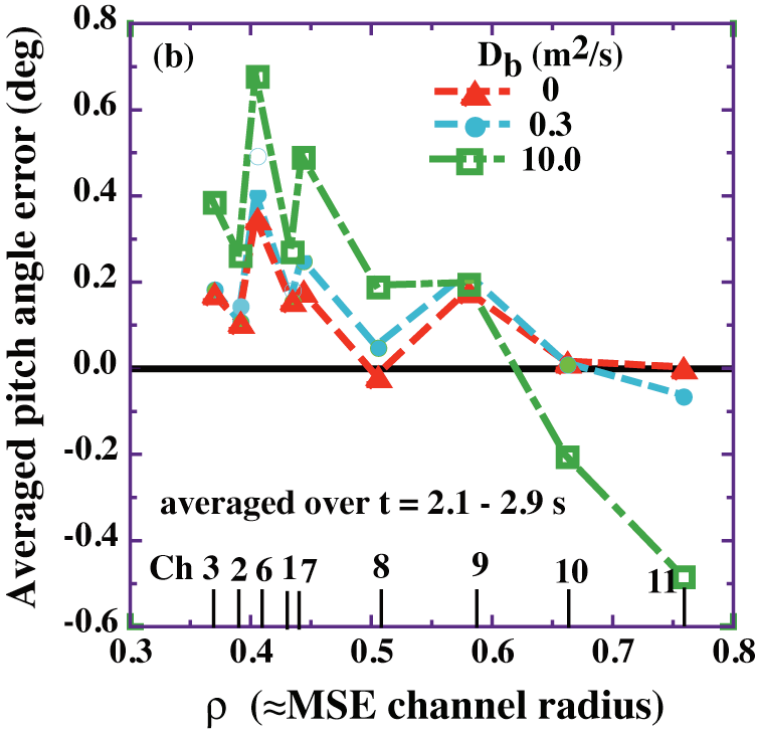
No Evidence for Anomalous Fast Ion Diffusion Observed at Low power

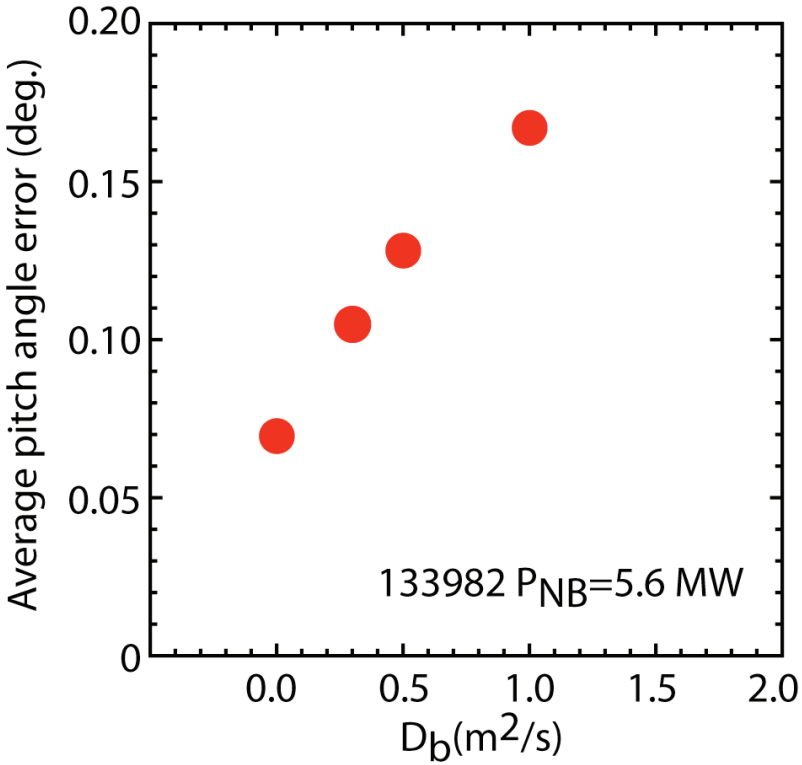


- **Beam-blip decay time agrees with classical prediction**

[Heidbrink, JP6.93]

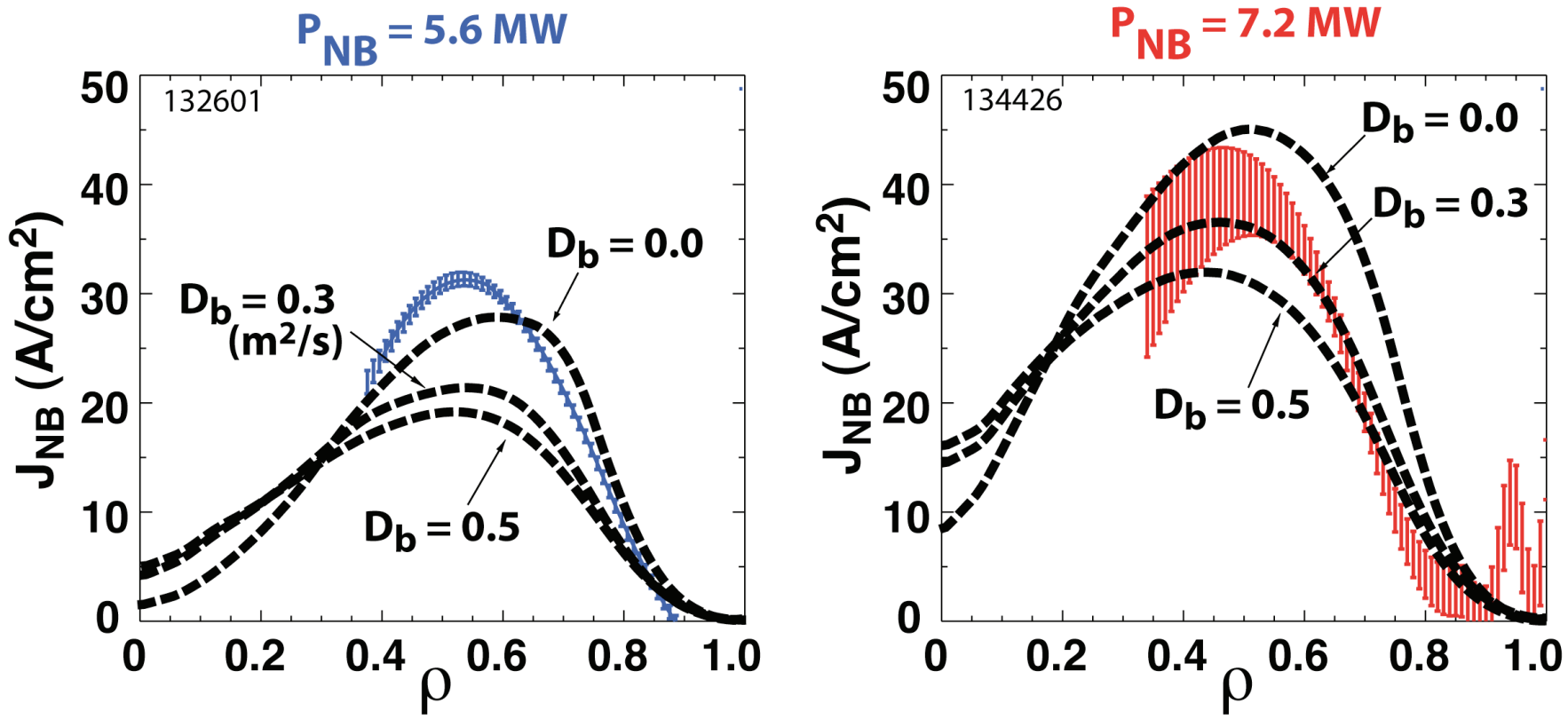
MSE Simulations With No Anomalous Fast Ion Diffusion Agree the Best With MSE Signals During Off-axis NBCD at $P_{CO} \leq 5$ MW





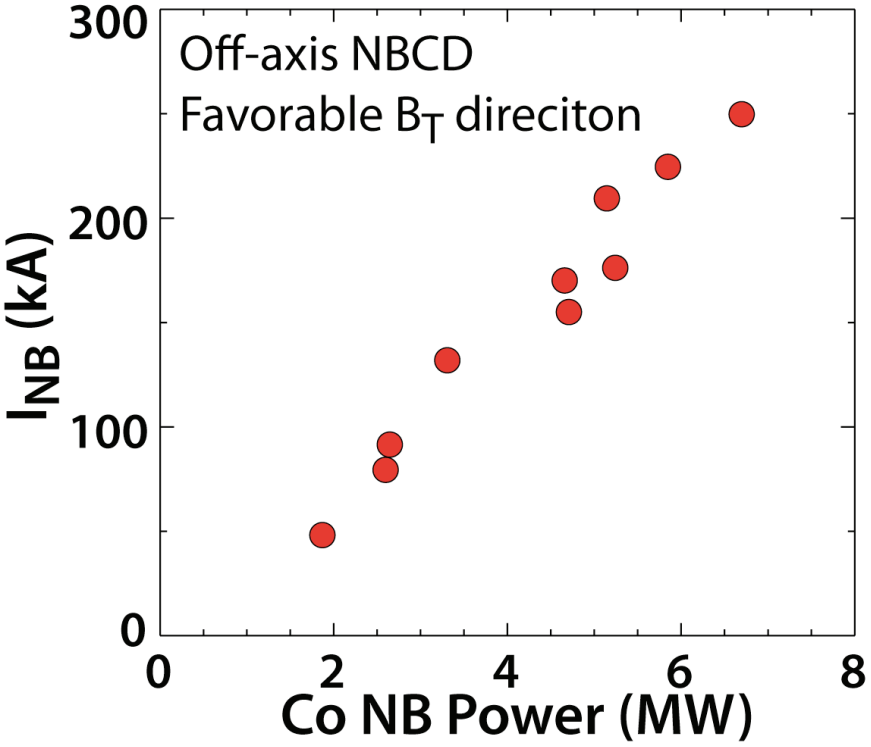
- MSE signals are less sensitive to D_b in vertically shifted plasmas

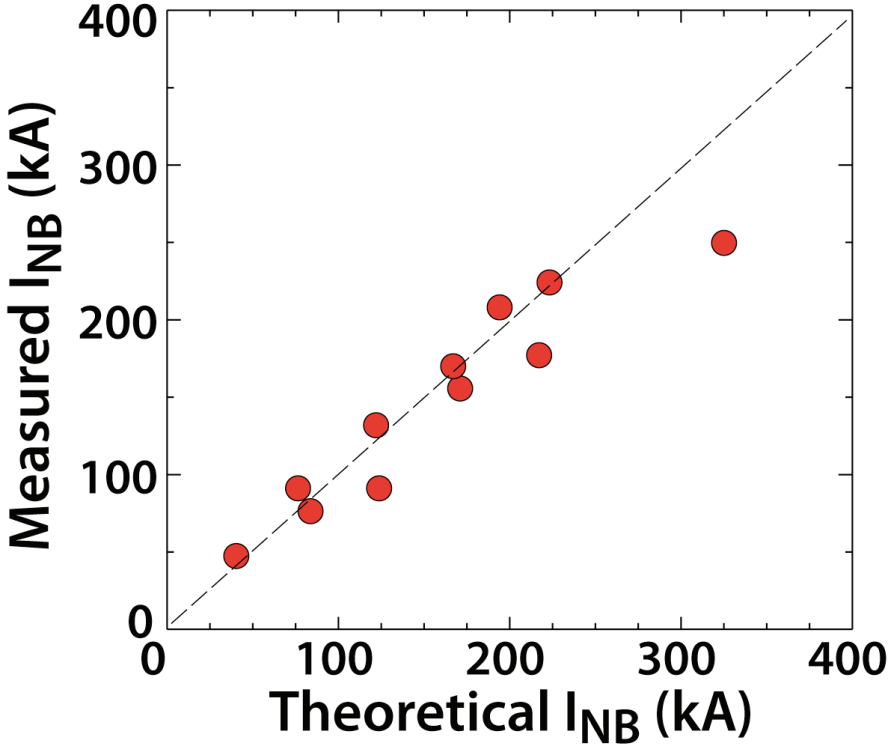
Modest Anomaly in NBCD Profile Observed for $P_{NB} \gtrsim 7$ MW



- **Fast ion diffusion places particles near the axis**
  - More diffused, inward shifted NBCD profile
  - Reduce net CD by ~20 % for P_{NB} = 7.2 MW
- **Anomaly appears to increase with NB power**

Measured I_{NB} Increases Approximately Linearly with NB power



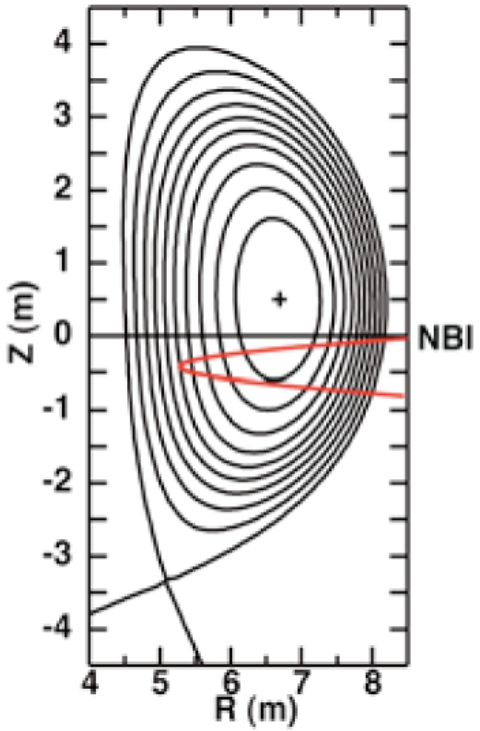


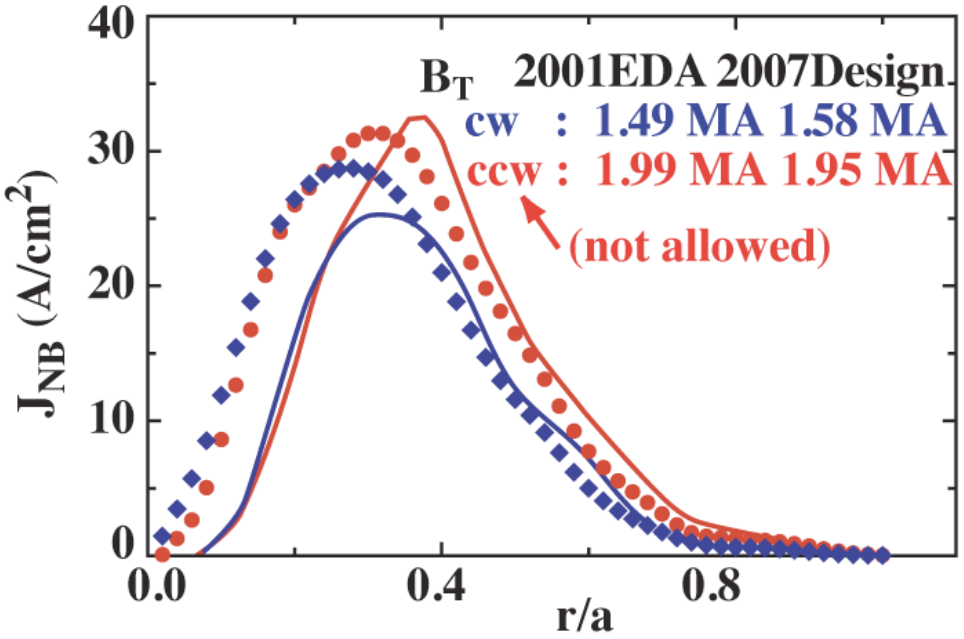
- **Off-axis NBCD is robust even with potential anomaly at high NB power**

Outline

- Demonstration of robust off-axis NBCD in DIII-D
- Benefit of alignment of injection with magnetic field
- Small effect of anomalous transport of fast ions on off-axis NBCD profiles
- **Prospect for ITER and DIII-D scenario development**

A ~20% Increase in Off-axis NBCD Expected, If ITER Is Operated the Reverse (CCW) B_T Direction

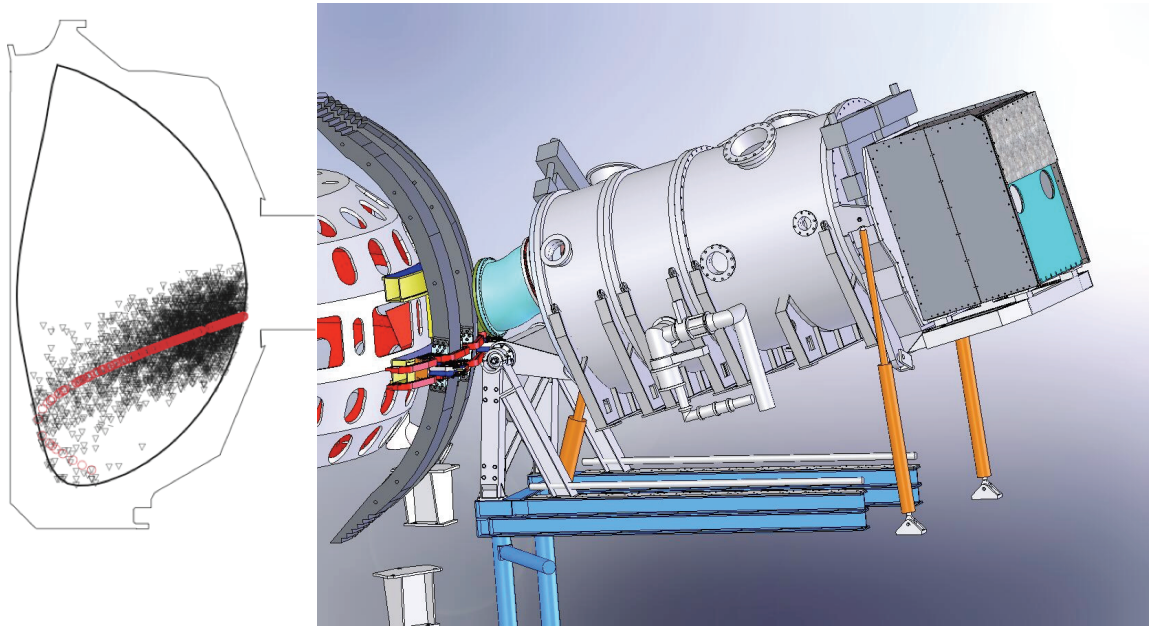


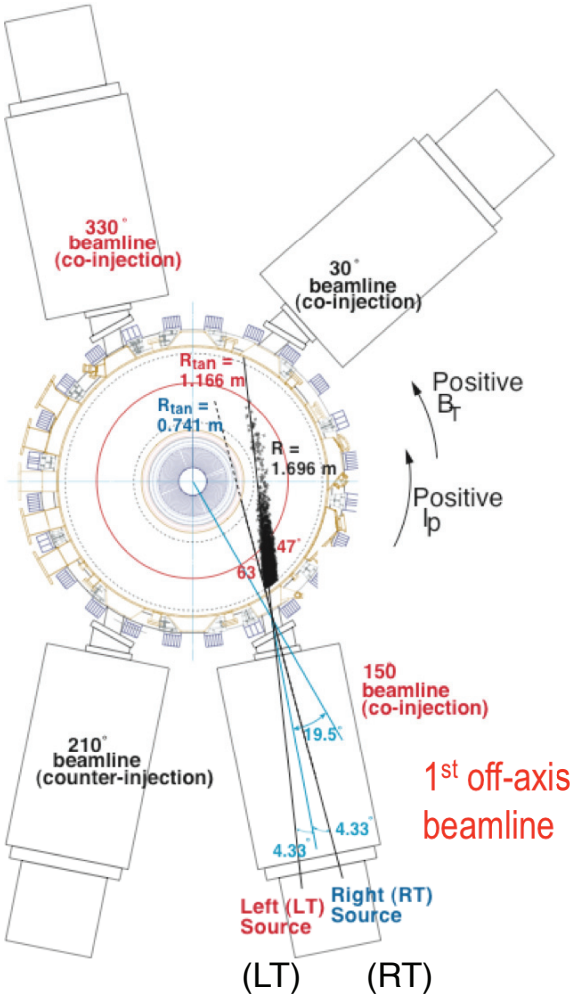


- **The ITER off-axis N-NBI for the hybrid scenario:**
  - Downward steered sources (with a substantial offset of NBI port)
  - More favorable with $-B_T$ direction (counter-clock-wise)
- **ITER decided to move toward a larger steering like the EDA design**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

The Planned Off-axis NBCD in DIII-D: Downward Steering of Two Beamlines by Raising the Source End by up to 1.5 m





[Murakami, TP6.2]

Conclusion

- Robust off-axis NBCD was found in DIII-D experiments
- Experiment confirmed prediction that off-axis NBCD efficiency depends on magnetic alignment
- There is no obvious observation that off-axis NBCD is more prone to anomalous fast ion transport than on-axis NBCD
- Off-axis NBCD can be increased by ~20 %, if ITER is operated in the reverse B_T direction
- Off-axis NBCD in DIII-D can supply substantial off-axis current drive needed for development of steady state, *AT* scenarios