New microwave diagnostics to measure internal magnetic fluctuations, intermediate-k density fluctuations, and flows on NSTX-U*

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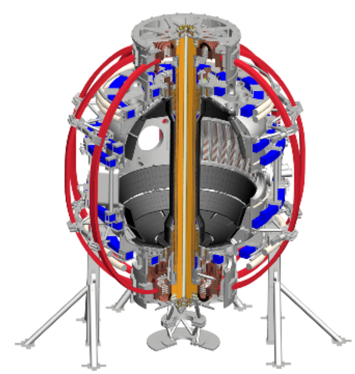


New microwave diagnostics are being installed on NSTX-U addressing range of important physics topics

- Addresses multi-scale turbulence and transport, energetic particles, and pedestal turbulence and flows:

- Doppler backscattering for int-k ñ levels, mean and fluctuating flow, sheared flows, GAMs, ELM and EHO activity, with $k_\theta\rho_s$=0.5–10, resolutions $\Delta r \leq 1$cm and $\Delta t \leq 1\mu s$.

- Cross-polarization scattering measurements of internal $\tilde{B}$ cover broader range ($k_\theta\rho_s$~0.2–17) with Δr~1cm, Δt=1μs. Addressing important instabilities including microtearing, ITG, TEM, KBM, lower-k ETG, and kinetic Alfvén waves.

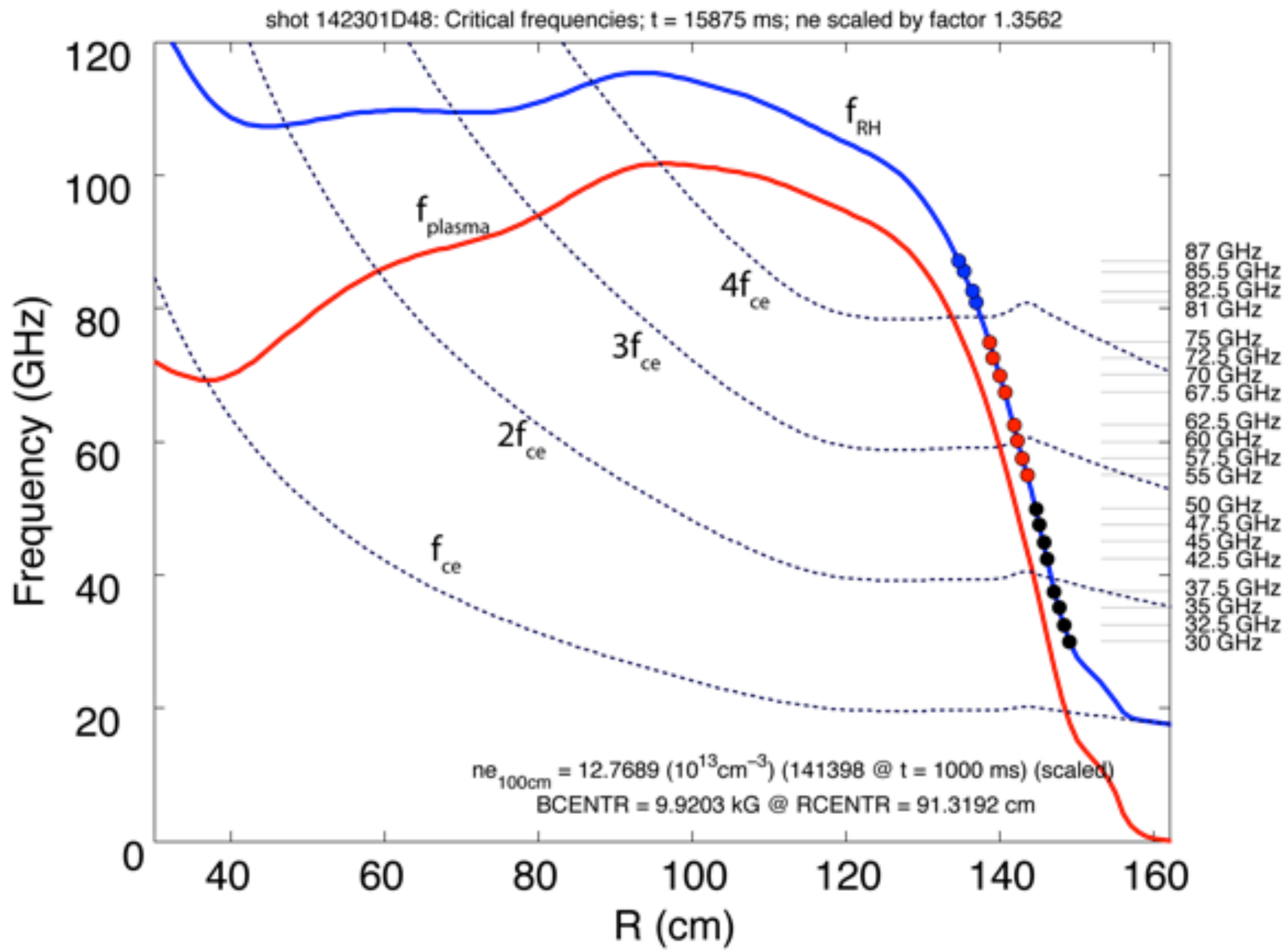
Work supported by USDOE Grant DE-FG02-99ER54527.

Overview of new diagnostics

New mm-wave diagnostics

Diagnostic	Measurement Importance	NSTX-U Topical Science Groups
Cross Polarization Scattering (CPS)	Measurement of magnetic fluctuations critically important in high beta NSTX-U • Currently <u>no</u> local B in core • Provides: four-channels of relative B (r), and frequency spectra	• Transport and Turbulence • Energetic particles
Core DBS Doppler Backscattering	Intermediate-k ñ, flows, GAMs, core • <u>Fills gap</u> in k-space between BES and high-k scattering • Provides: four-channels relative ñ(r), ExB <u>flows and sheared flows</u> (no NBI necessary), frequency spectra, wavenumber spectra	• Transport and Turbulence • Energetic particles
Edge DBS Doppler Backscattering **(future)**	Edge/pedestal int-k ñ, zonal flows, GAMs • <u>Fills gap</u> in k-space between BES and high-k scattering • Provides: 8-channels ñ(r), <u>flows and sheared flows,</u> GAM/zonal flows related to H-mode and L-H transition	• Pedestal Structure and Control • Transport and Turbulence
20 channel Reflectometer **4 New channels**	AE mode structure, surface displacement, 20-channels covering edge to high density core	• Energetic particles • Transport and Turbulence

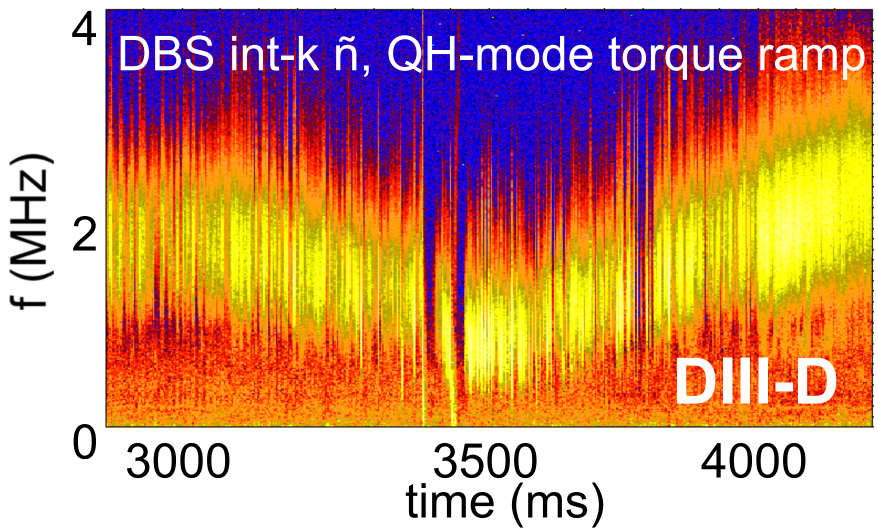
New four-channel high-frequency DBS/reflectometer/CPS system probes high densities on NSTX-U

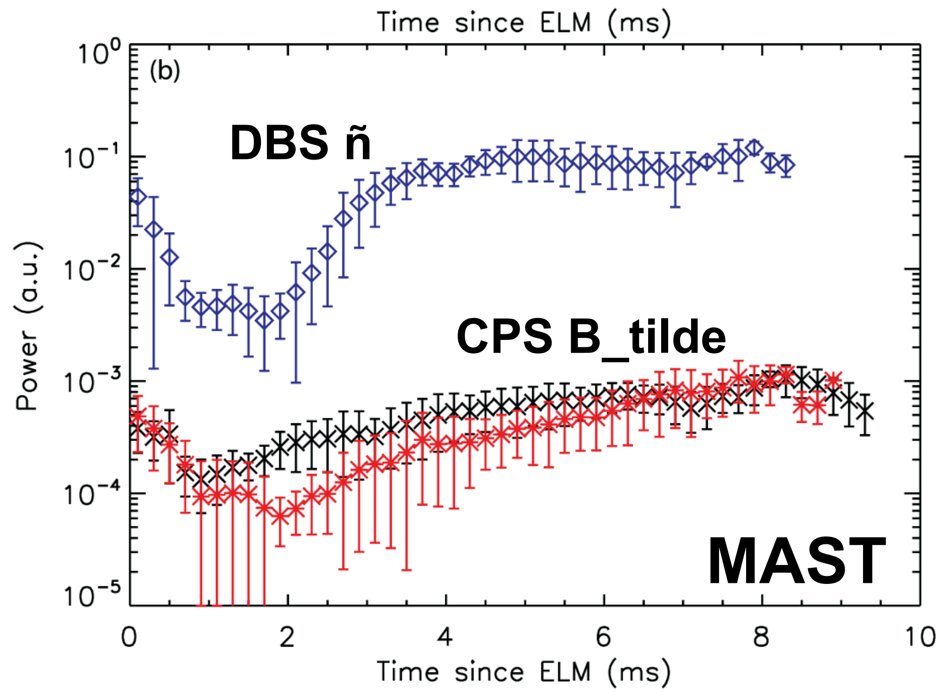


- Expands existing fluctuation reflectometer (from 16 to 20 channels)
- 81, 82.5, 85.5, and 87 GHz as shown

Example DBS and CPS results from other machines

Multi-channel DBS for int-k ñ, flow, and ExB velocity



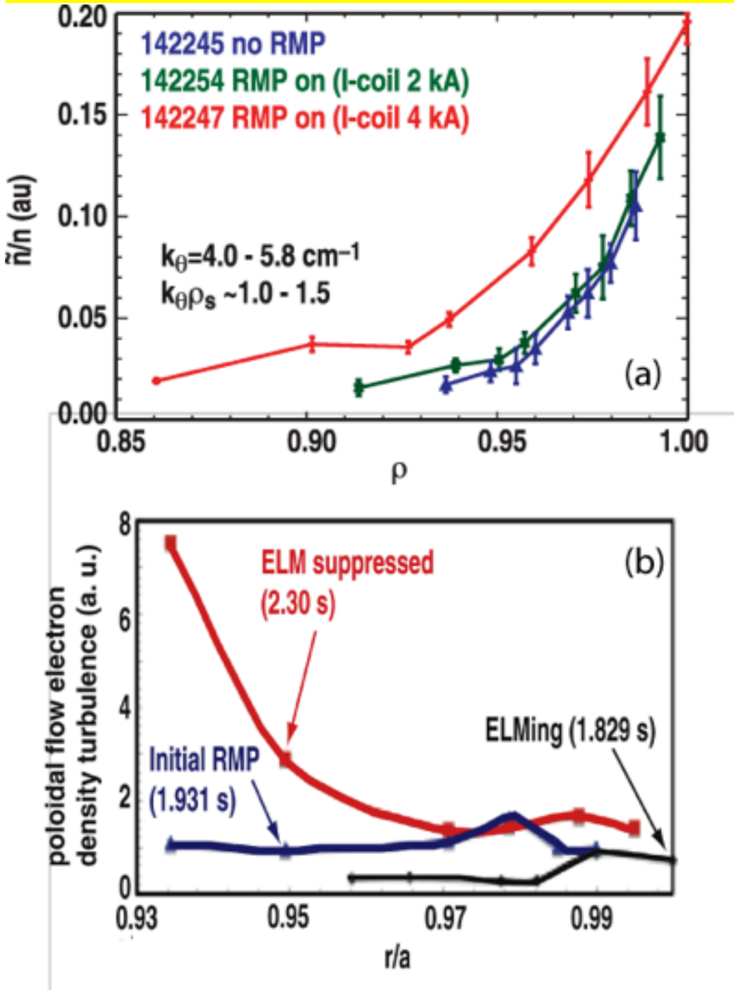


- $k_\theta \rho_s$ ~ 0.5–10, and typical spatial and temporal resolutions $\Delta r \lesssim 1$ cm and $\Delta t \lesssim 1 \mu s$
- Fills wavenumber gap between low-k BES and high-k forward scattering.
- Directly impacts testing and validation of codes/simulations

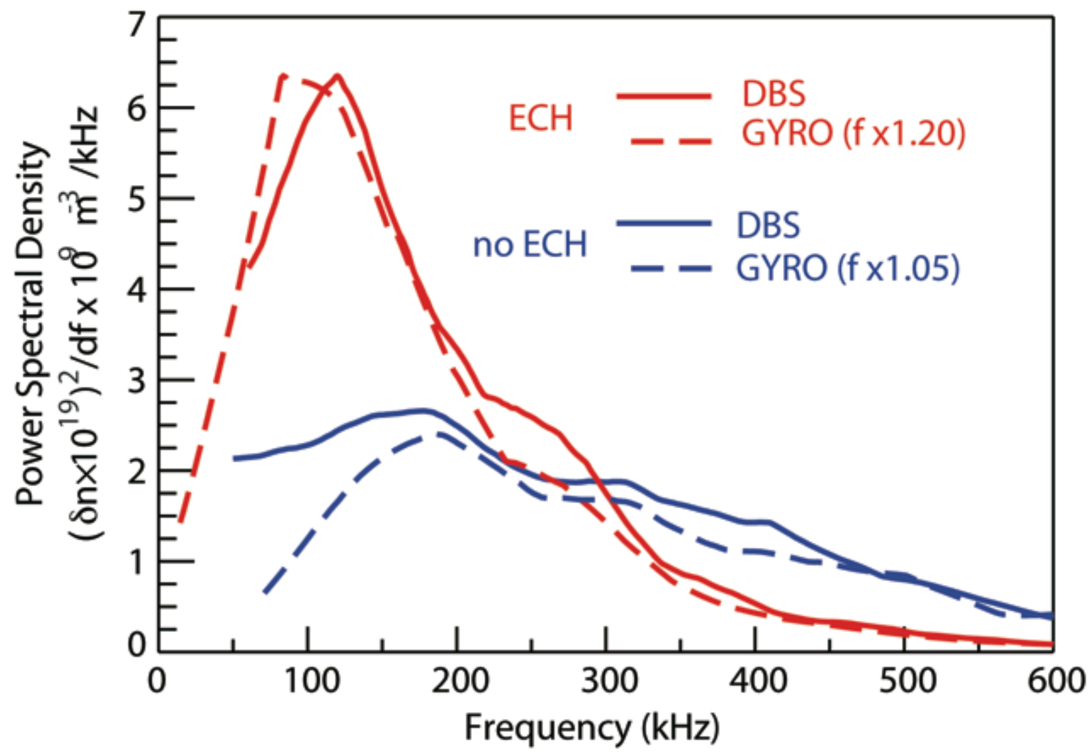
First CPS on spherical tokamak, DBS ñ in deep core. Inter-ELM ñ, B_tilde behavior consistent with EM ETG [Hillesheim NF15]

DBS can contribute significantly to discovery science and validating simulations/models

DBS ñ and flow, DIII-D RMP,[illegible]k[illegible], At this k-scale, ñ increases only when enough RMP-coil current is applied. [Mordjick NF12].

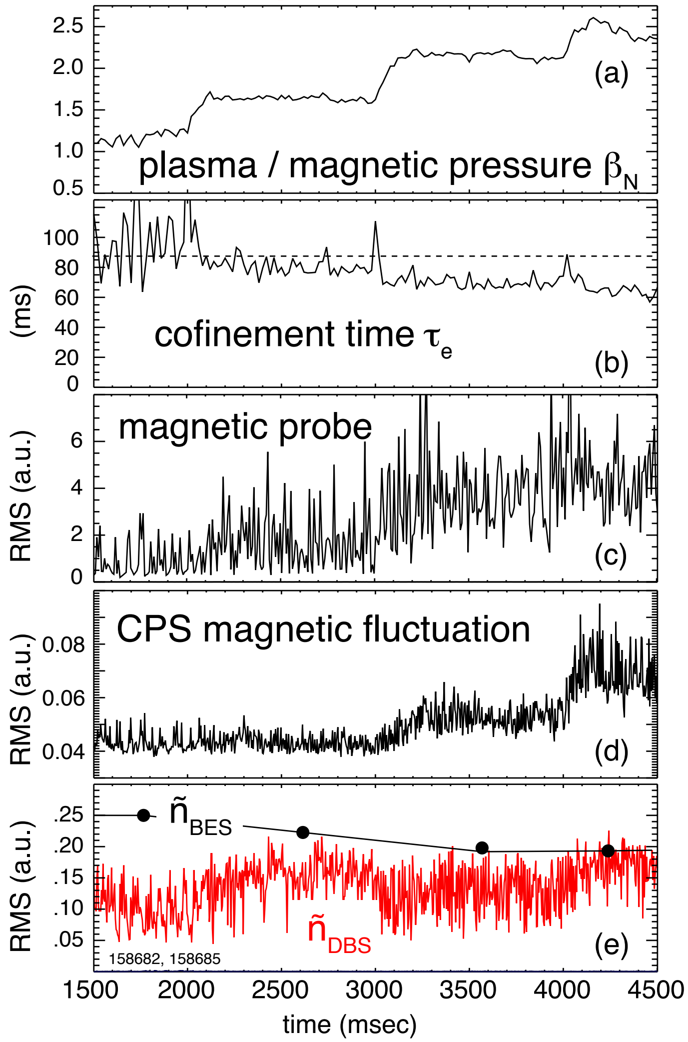


Core DBS ñ in DIII-D QH-mode – GYRO shows very good comparison to experiment identifying instability as density gradient driven TEM [Ernst PoP16]



Cross-polarization scattering (CPS) to measure internal magnetic fluctuations on NSTX-U

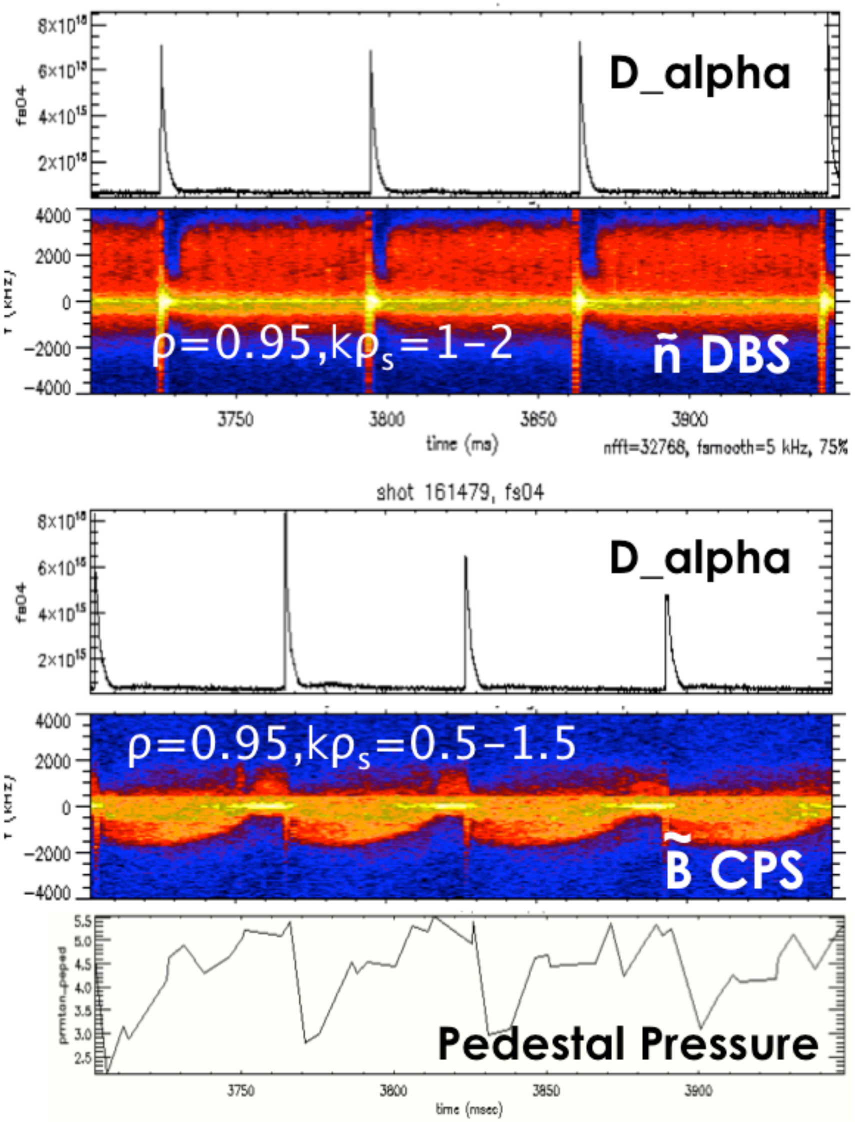
DIII-D, β scan, Hmode



Barada, et al., RSI, 2016

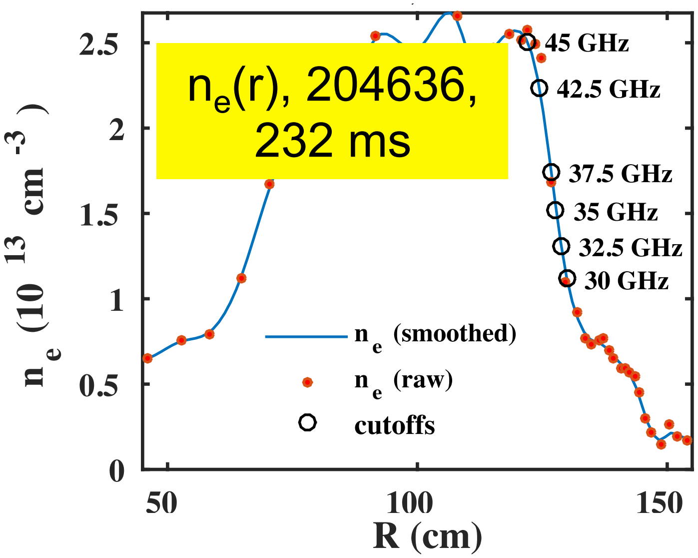
- Addresses key physics questions on existence and behavior of microtearing modes, KBM, EM ETG/DW behavior, etc. and possible affect on transport.
  - Especially important at higher β as EM effects are increasingly important.
- Measure internal B over broad wavenumber range $k_\theta \rho_s$ ~ 0.2–17; time, space resolutions (Δr≤1 cm, Δt≤1μs)
- Directly impacts testing and validation of codes/simulations

Inter-ELM $\tilde{B}$ and $\tilde{n}$ behavior very different on DIII-D

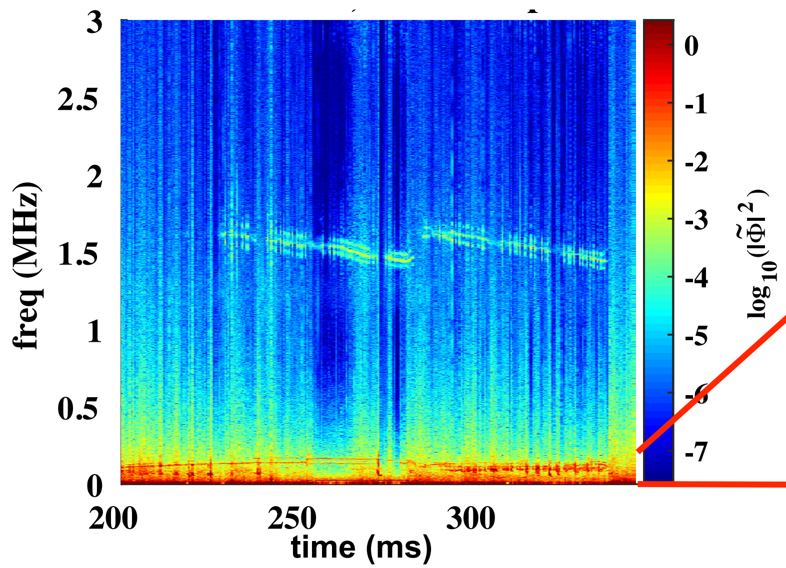


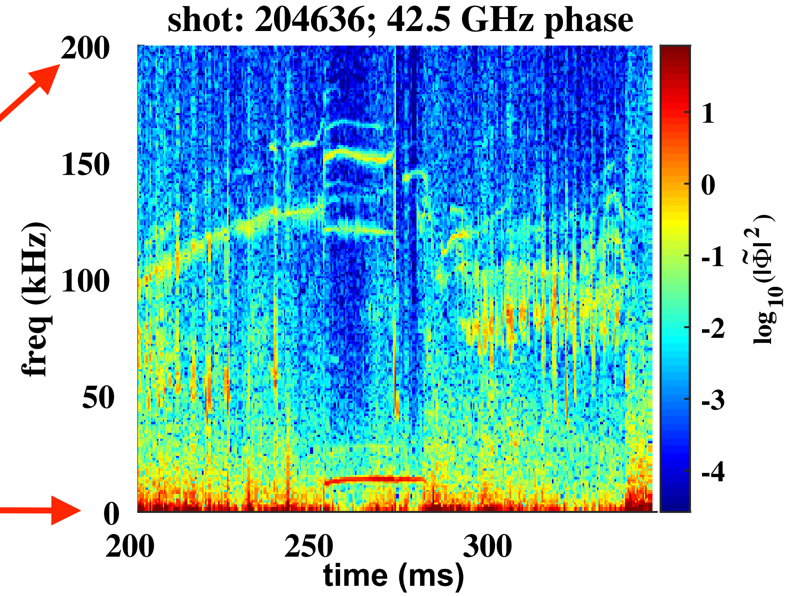
- Data from repeat shots
- Compare MAST data above, $\tilde{B}$ and $\tilde{n}$ behavior quite different from DIII-D

16-channel UCLA fluctuation reflectometer will be upgraded to twenty-channels



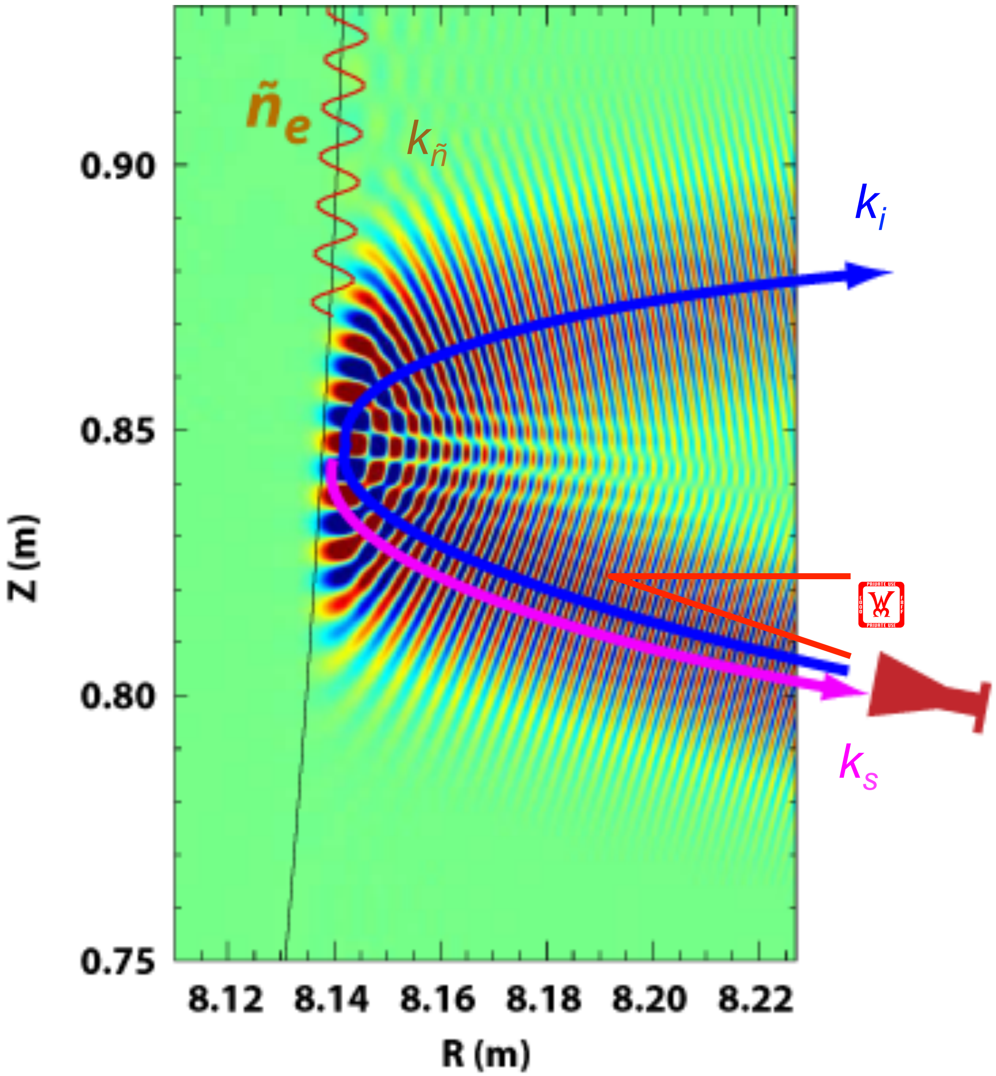
- Example data from this year showing higher frequency GAEs, and lower frequencies that are likely TAEs and other MHD
- Diagnostic addresses understanding of beam driven mode physics and code validation
- Cross-Machine studies - NSTX-U and DIII-D





Physics of DBS and CPS measurements

DBS technique first introduced on ASDEX-U (Hirsch, PPFC01) and is now a widely used technique



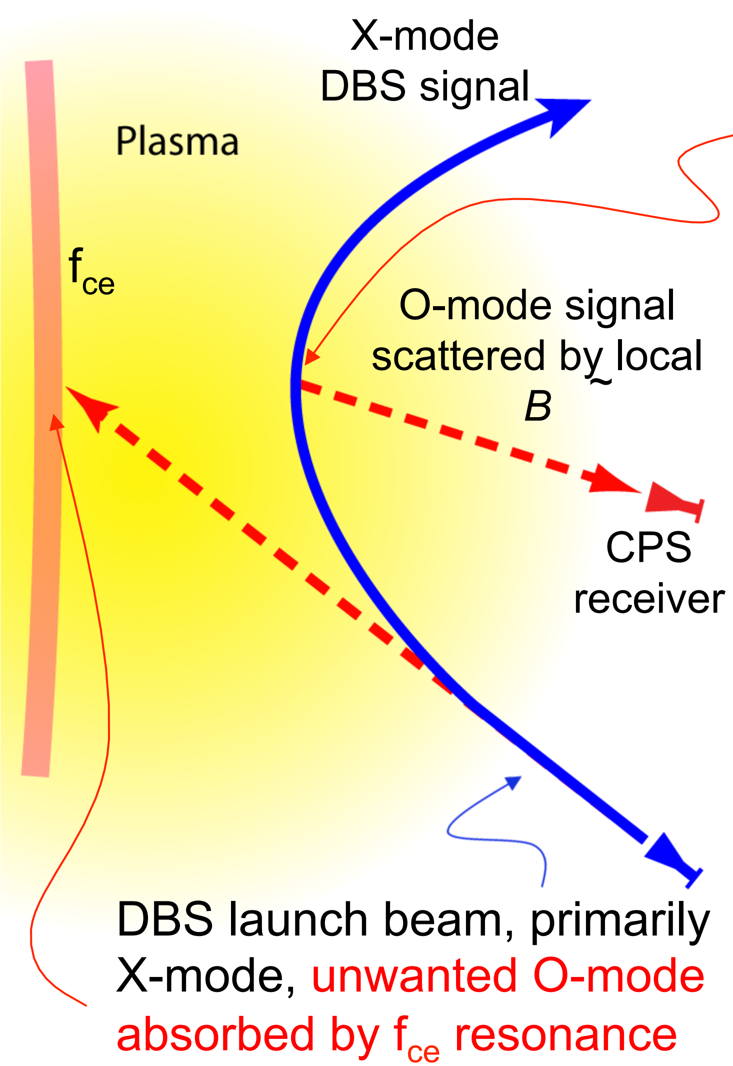
- Radiation injected at angle □, with wavenumber k_i
- Scattering at k_s occurs according to Bragg scattering relation:

  For $k_i \sim k_s$, can show that

  $k_{\tilde{n}} = 2k_i \sin(□/2)$, where □ is scattering angle
- Scattered signal is proportional to ñ at $k_{\tilde{n}}$ ±□*k* while Doppler shift is □□= $k_{\tilde{n}}V$
- Full wave calculation shows long wavelength propagating structure near cutoff
  - It is this structure that scatters from longer wavelength ñ.
  - Scattered k_s, spatial and k resolution □k determined by this structure.

Hirsch, PPCF 2001, Bulanin PPR 2000, Hennequin RSI 2004, Conway, PPCF 2008, Schmitz RSI 2008, Xiao PS&T 2008, Happel RSI 2009, Hillesheim NF 2015

CPS: Vector nature of magnetic fluctuations scatter electromagnetic probe beam into orthogonal polarization



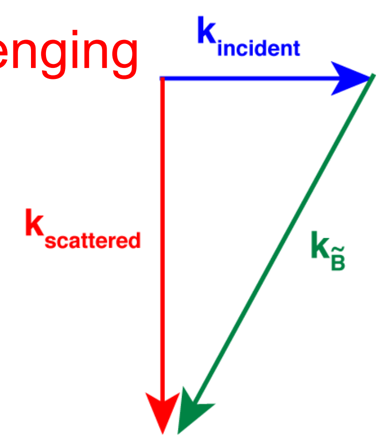
- Lehner '89, Vahala '92
- Interaction of incident electric field $\boldsymbol{E_i}$ with magnetic fluctuation $\tilde{\boldsymbol{B}}$ results in a perturbed current $\tilde{\boldsymbol{j}}$ which in turn generates a scattered electric field $\boldsymbol{E_s}$

$$\tilde{j} \sim \boldsymbol{E_i} \times \tilde{\boldsymbol{B}}$$

  – Scattered field $\boldsymbol{E_s}$ is then detected,
  – $\boldsymbol{E_s}$ follows Bragg scattering relation for wavevector and frequency

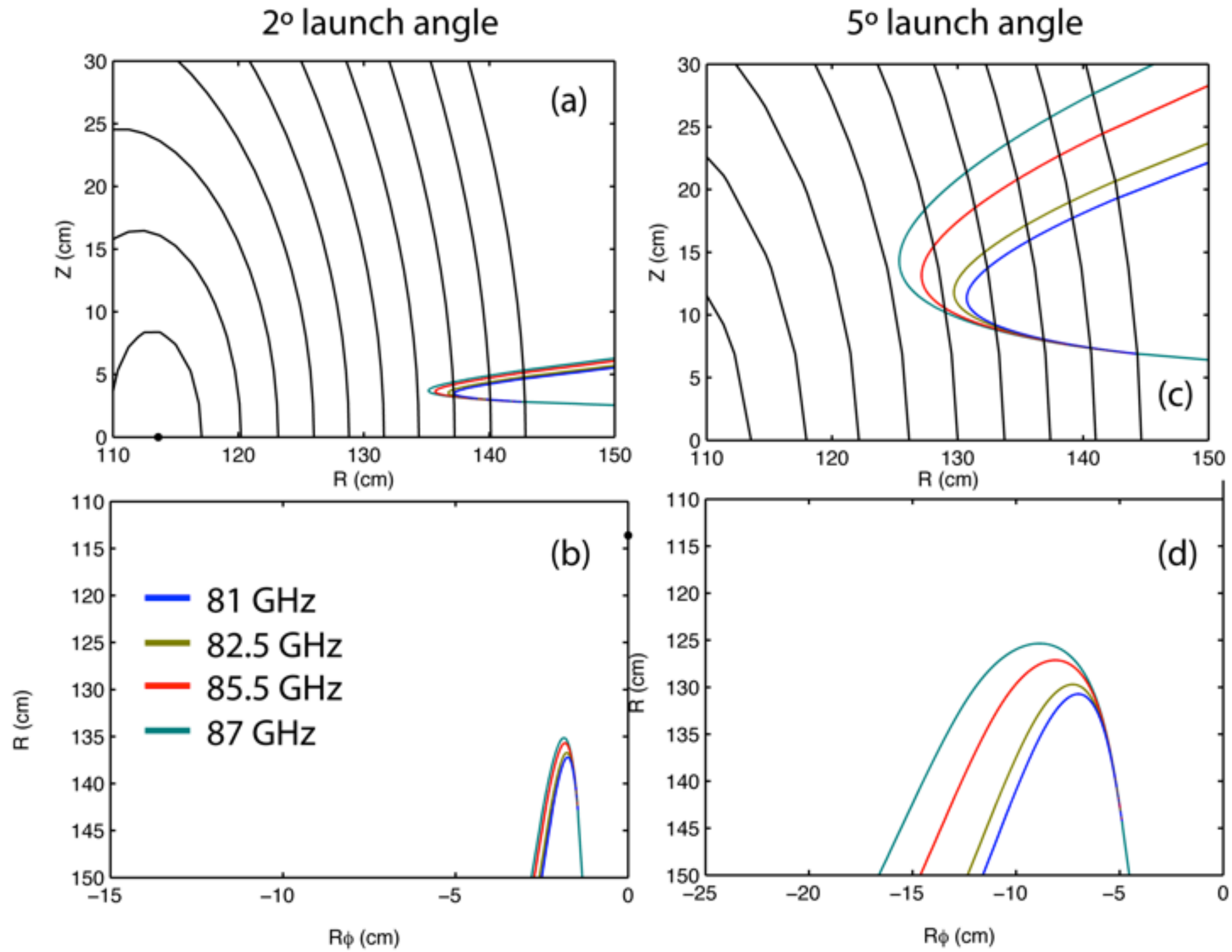
$$\boldsymbol{k_i} + \boldsymbol{k_B} = \boldsymbol{k_s} \text{ and } f_i + f_B = f_s$$

- CPS measurements are challenging
  – Small signal levels
  – Polarization purity
  – Aiming/crossed beams
  – Wavenumbers probed
  – Spatial localization



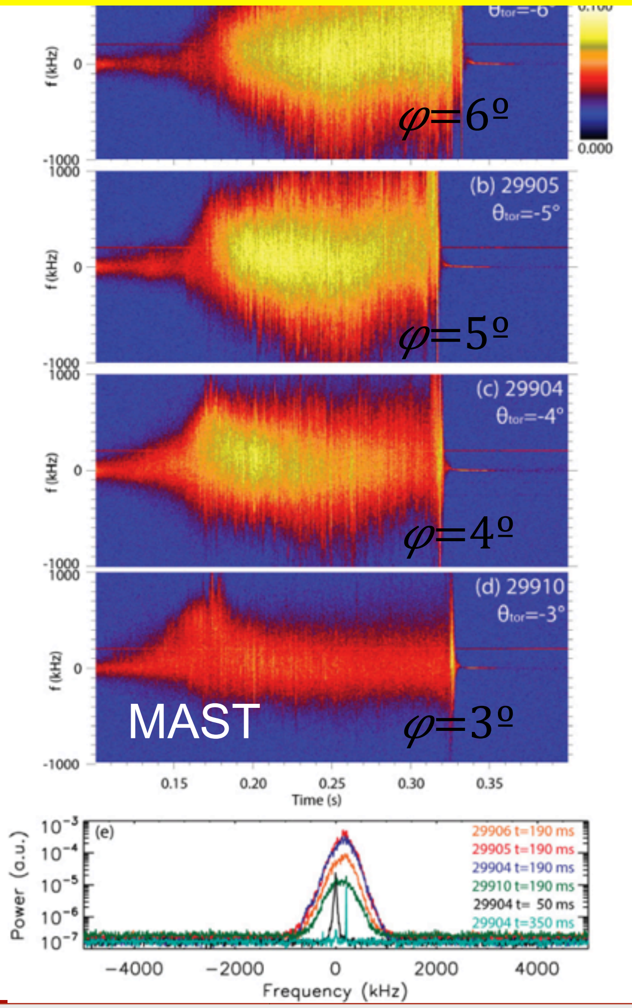
Design goals

DBS design provides for $k_\theta \rho_s$ range ~1–10

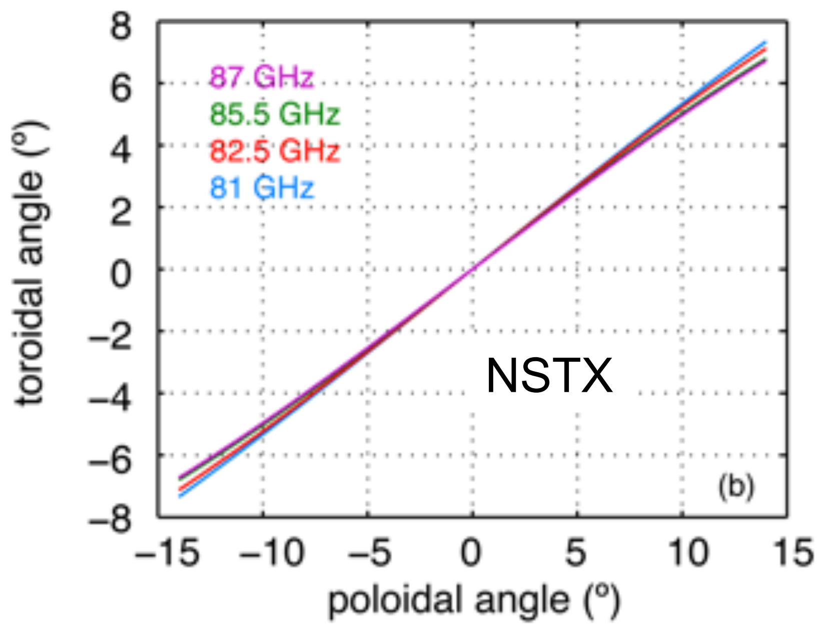


Important to match bi-normal k direction in plasma → optimum toroidal matching for each launch angle

DBS signal level depends on toroidal launch angle φ, MAST, Hillesheim, PPCF15

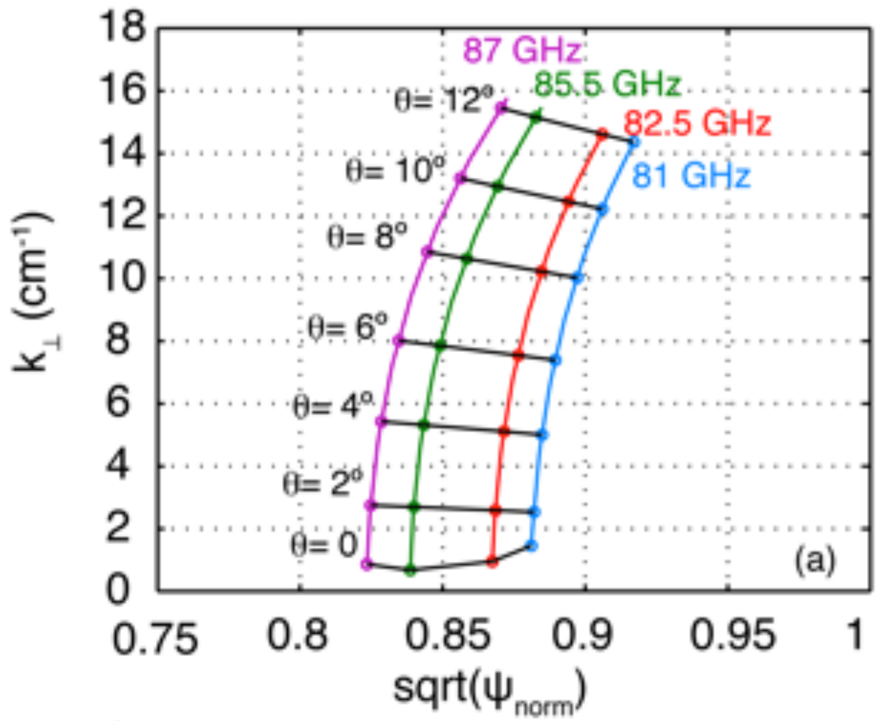


Optimum toroidal matching angle vs poloidal launch angle



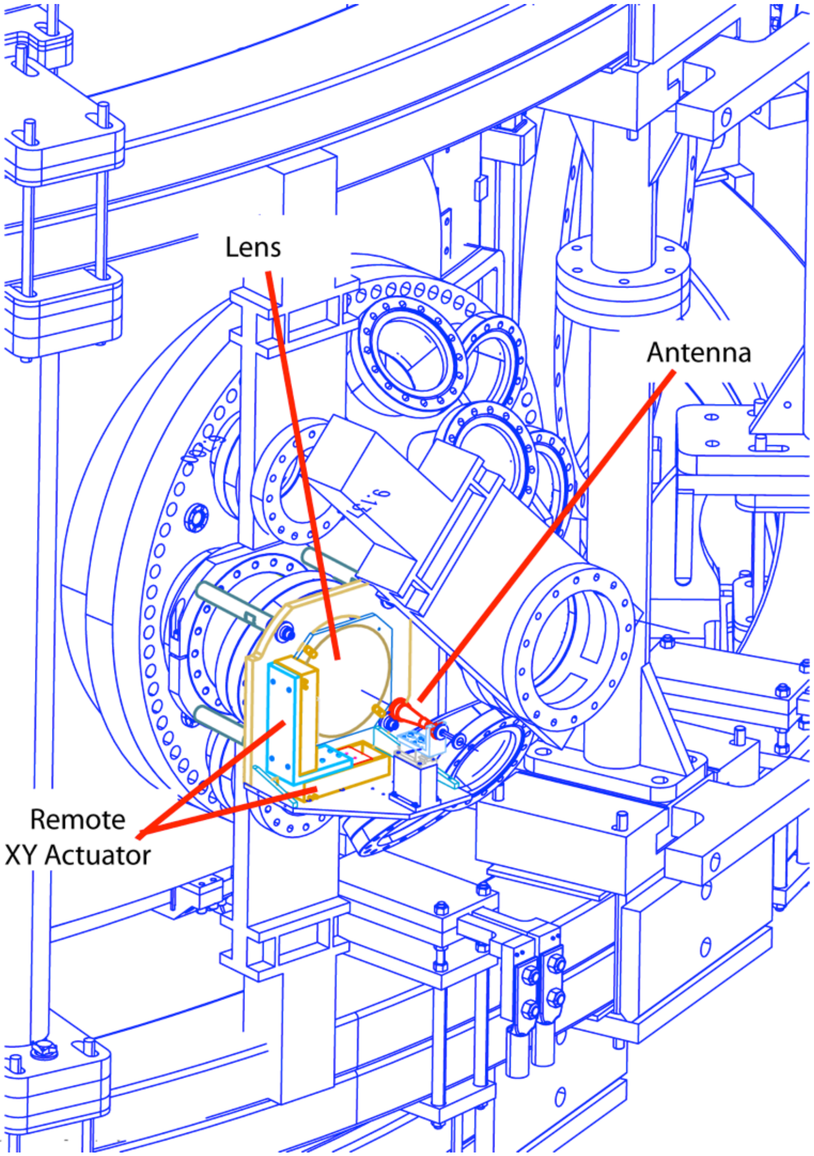
- Optimum toroidal matching angle depends on launch angle, plasma parameters and shape
- Optimum toroidal angle is nearly the same for all frequencies at a given poloidal angle.
- Using NSTX H-mode and 3D GENRAY raytracing code.

Accessible range of DBS wavenumbers varies from 0–7 cm^{-1}

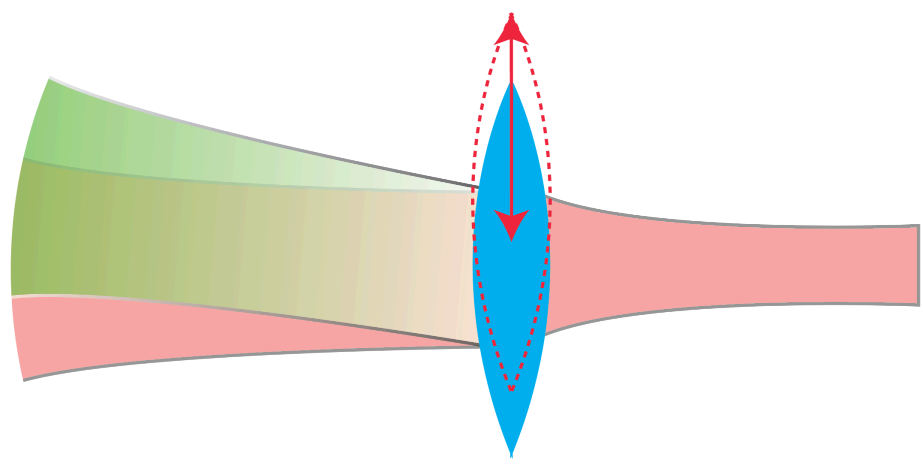


Design of DBS system and lab measurements

Quasi-optical design of DBS with remote control lens that changes launch angle

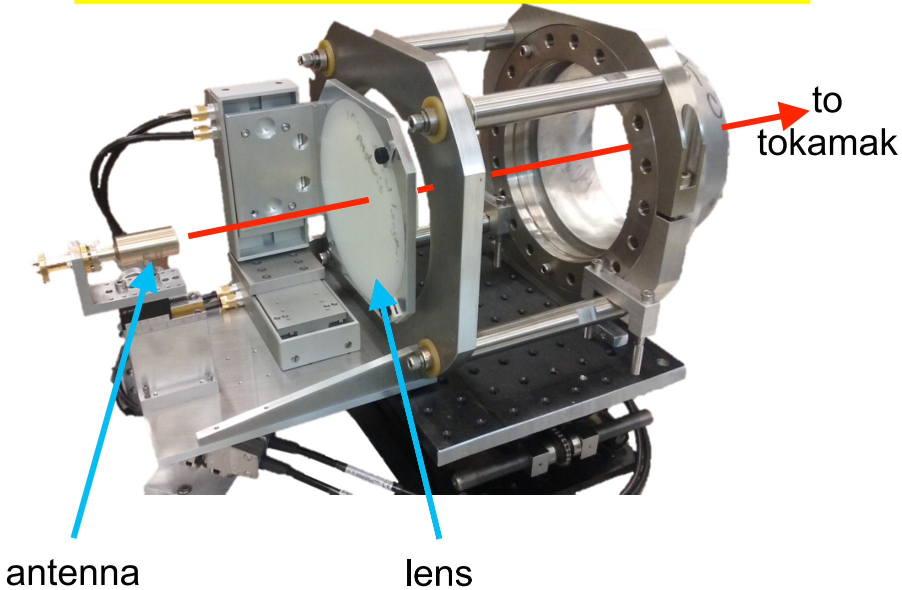


- X–Y displacement of lens induces independent angular displacements (poloidal and toroidal angles) of DBS probe beam

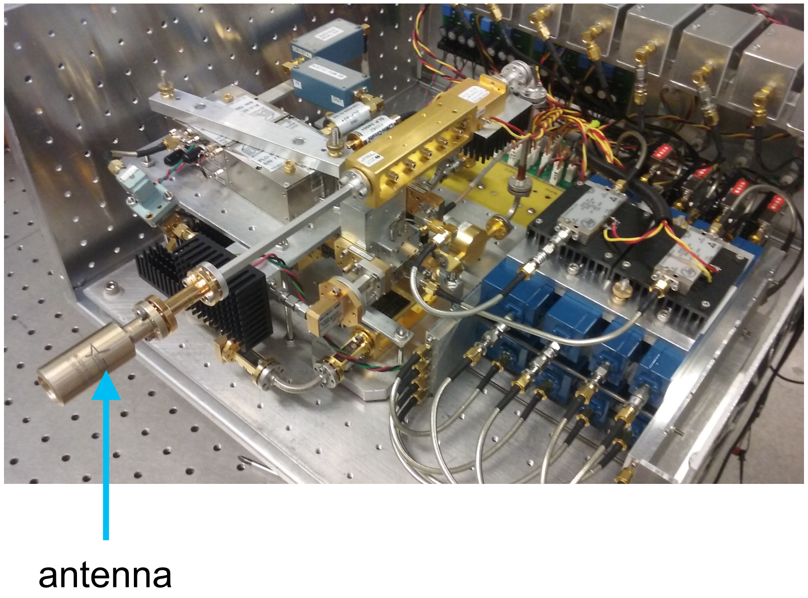


DBS quasi-optical system and electronics have been built and tested in laboratory

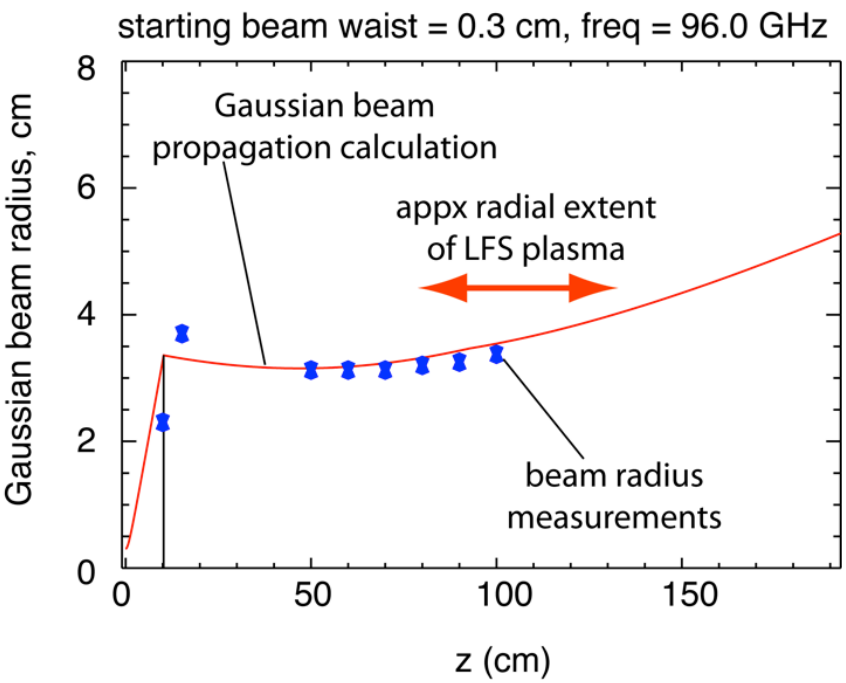
Launch antenna/optics, angle remote controlled



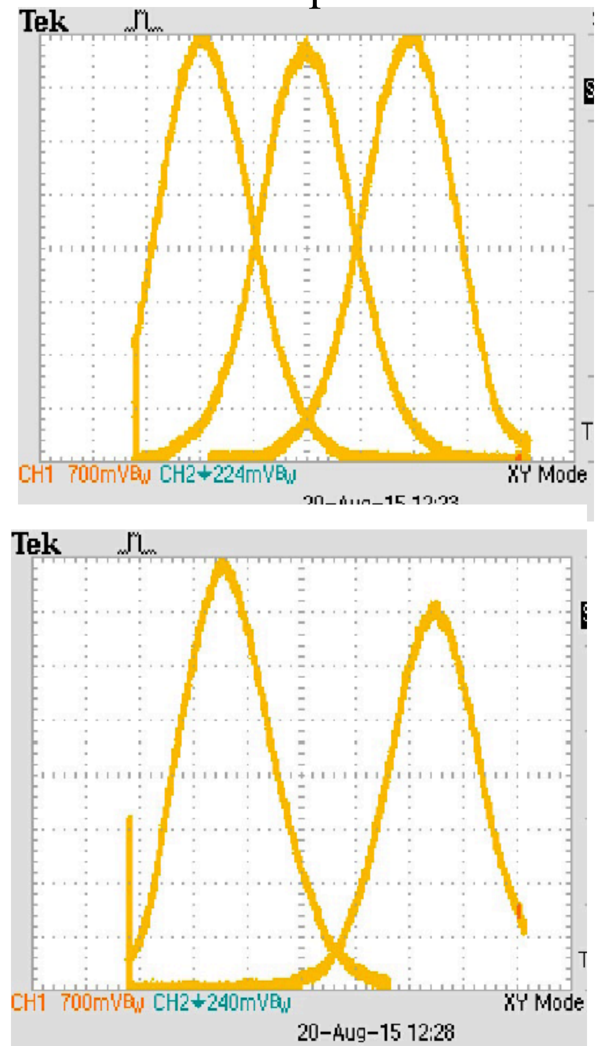
DBS source and receiver electronics



Probe beam measurements match desired Gaussian beam propagation code designs



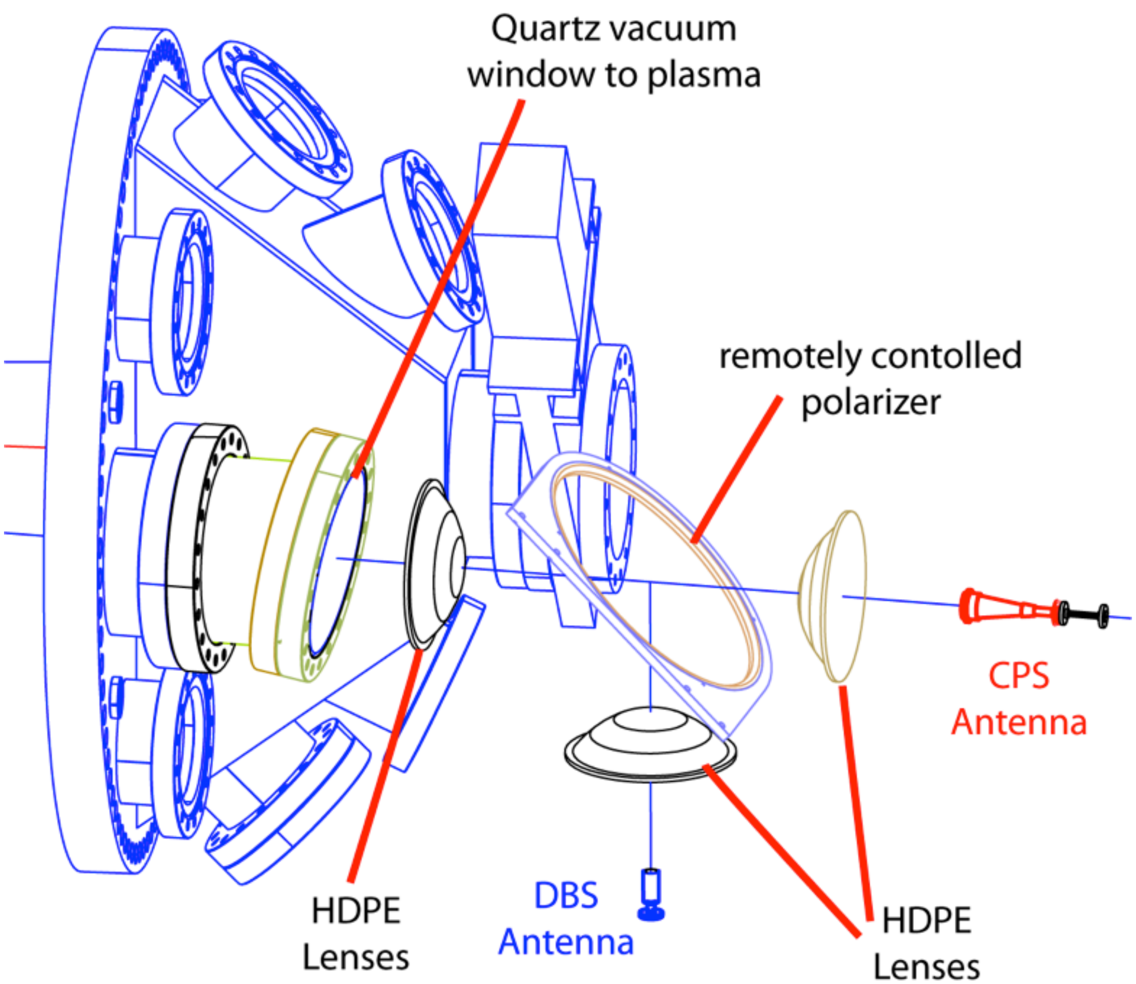
Beam profile measurements vs lens position



- ±5mm lens movement → beam steering of ±2.2º
- 10mm lens movement → beam steering of ~4.5º

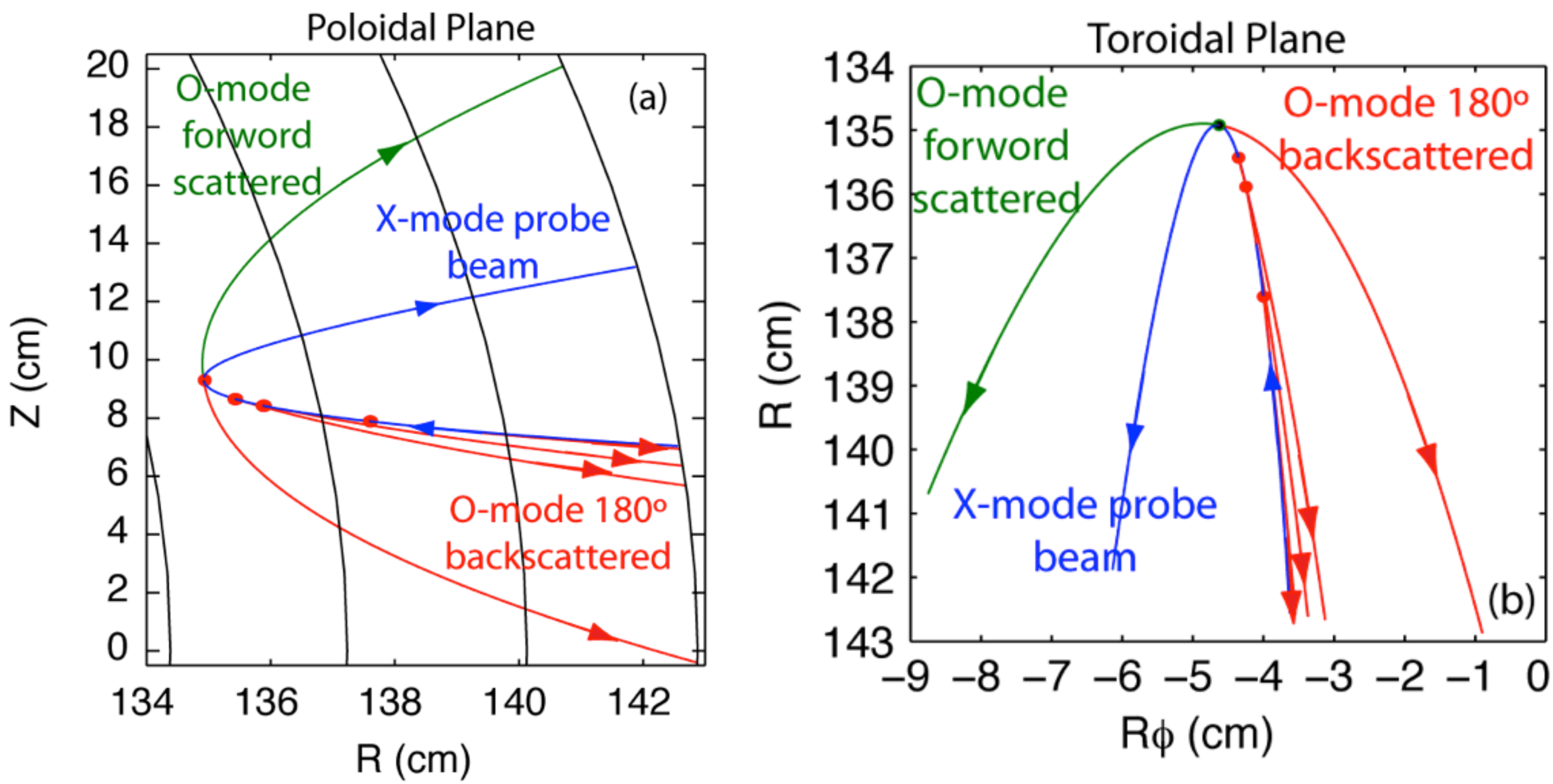
Design of CPS system

CPS quasi-optical design with DBS launch/receive antenna and CPS receive antenna



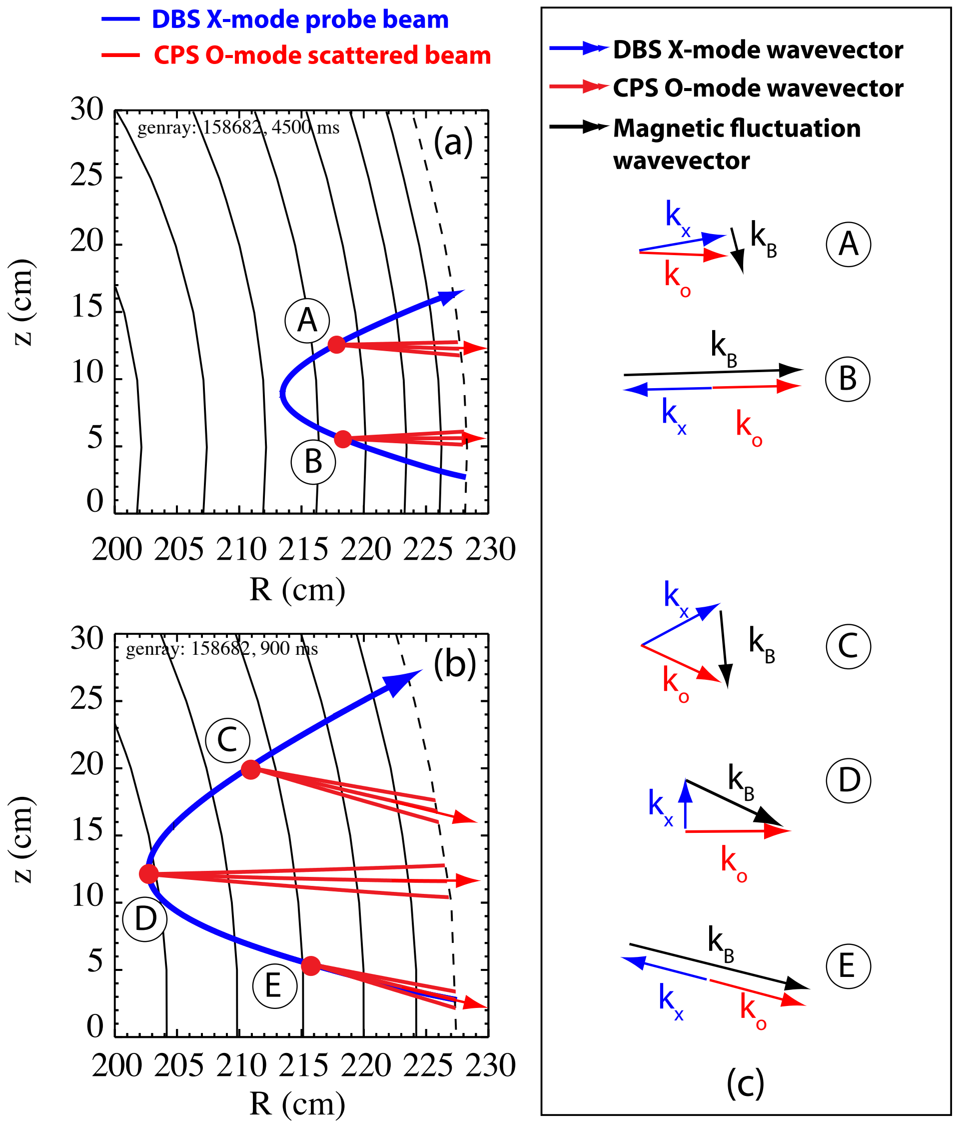
- remote controlled polarizer.
- Not shown is X–Y remote motion control of the last lens.

CPS scattering: O- and X-mode radiation propagate differently due to the different indices of refraction



- CPS scattering from 87 GHz DBS probe beam (NSTX-U H-mode plasma).
- Blue is DBS probe beam,
- Red is backscattering O-mode and green is ~0º forward O-mode scattering.
- Arrows show propagation directions and red disks show scattering centers.

Very different magnetic wavevectors can be measured using different CPS receive angles



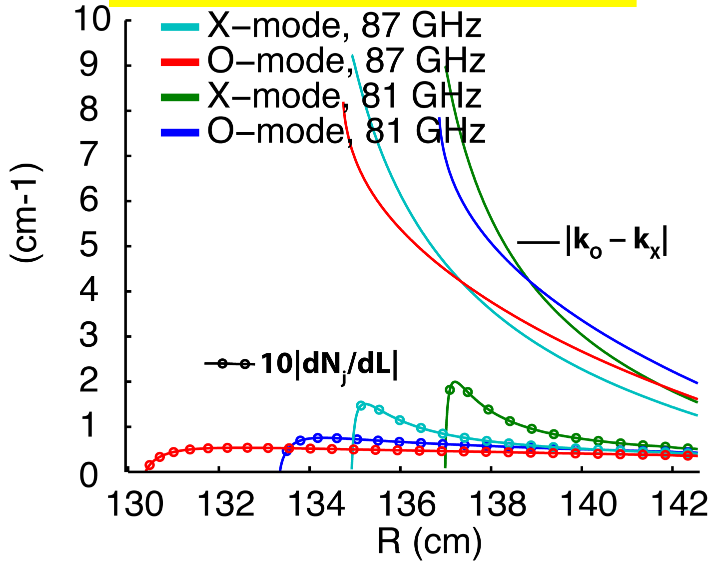
- The differences in magnitude of X and O-mode wavevectors illustrate differences in their respective indices of refraction.

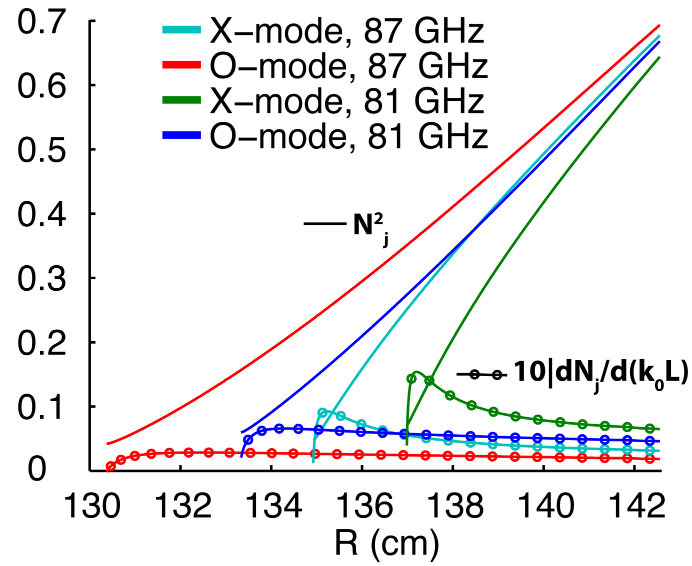
(For diagrammatic purposes only, not to scale.)

Sources of error in measurements and mitigation techniques

N = index of refraction,
k_0 = vacuum k

- Tests of non-WKB effects.
- Mode mixing is expected to be significant if $|k_O - k_X| << |dN_j/dL|$, Note x10 in $|dN_j/dL|$,
  - $|k_O - k_X| >> |dN_j/dL| \rightarrow$ non-WKB effects resulting in mode mixing are negligible for these frequencies.
- Testing WKB assumption via comparison of $|dN/dl|/k_0$ and N^2 Note x10 in $|dN_j/(dLk_0)|$ indicating that the WKB assumptions are satisfied for these frequencies.
- Using the NSTX-U H-mode plasma and 3D GENRAY raytracing
- Non-WKB effects and mode mixing not an issue for this plasma but must examine each condition individually





(continued) Sources of error in measurements and mitigation techniques

- Another potential error source in the CPS and DBS signals is due to probe beam having a non-zero wavevector component along the magnetic field B, ie $k_{||} \neq 0$ (Faraday effect).
  - If the probe wave is launched with linear polarization but couples to the plasma with non-vanishing $k_{||}$, then it is a superposition of the true X- and O-modes which are slightly elliptized again producing a source of contamination.
  - The necessity for toroidal steering discussed above in the context of optimal wavenumber or pitch angle matching will also serve to minimize this effect by reducing the $k_{||}$ component to near zero.
  - Also, if there is significant contamination due to this effect the CPS signal is expected to look very much like the DBS signal, again an indication of potential problems.
- In addition to the WKB testing above, each CPS/DBS dataset on NSTX-U will be compared to each other, magnitude and spectral shape, etc. to determine if there is a potential problem (DBS and CPS data on NSTX-U will be simultaneous).
  - While there is no reason, a priori, for B_tilde and ñ to be different, significant similarity is an indication to proceed cautiously.
  - experience has been that CPS is very different in its response to plasma parameters (e.g. response to beta), spectral shape, and magnitude as compared to the DBS data

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UCLA is excited about the scientific prospects on NSTX-U

- Multi-field diagnostics for turbulence and transport studies, beam driven modes, transients (ELMs, EHO, etc.)
- Testing and validation of simulations and theory
- Cross-device experiments are facilitated by similar diagnostics (e.g NSTX-U and DIII-D).

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