Strategy for Implementing an EBW Heating & Current Drive System on NSTX

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Presentation to Wave-Particle Science Focus Group

February 4, 2004

Outline

- Project Purpose & Scope
- Frequency Choice & Source Development
- Coupling, Deposition and CD Efficiency:
  Implications for launch frequency
- Estimated Project Cost & Schedule
- MAST EBW Launcher Collaboration
- Summary

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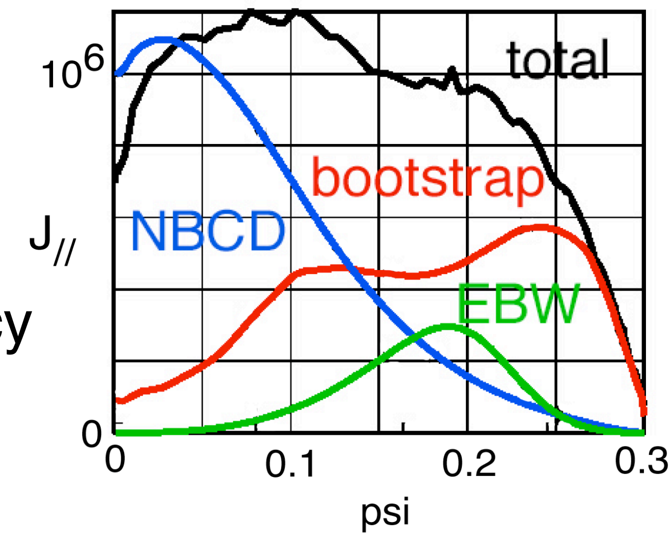
NSTX National Spherical Torus Experiment

EBW Can Provide Critical Off-Axis Current Drive in NSTX at High β

- ~ 100 kA of off-axis CD needed to sustain β ~ 40% in NSTX
- Ohkawa EBW CD can use the large off-axis electron trapping fraction in NSTX to achieve high CD efficiency
- EBW H&CD can also assist startup

NSTX, β = 40%



- Modulated EBW heating can enable electron transport studies
- NTM stabilization with EBWCD is more challenging than ECCD, due to lack of beam steering

EBW Project Scope Driven by the NSTX 5-Year Plan

- Fokker-Planck modeling predicts CD efficiencies ~ 40-50 kA/MW in projected high β NSTX plasma operating scenarios
- ~ 100 kA of EBW off-axis CD --> ~ 4 MW of RF source power
- RF source frequency choice driven by toroidal field, EBW coupling requirement & plasma accessibility at high β
- System designed to operate for RF pulse lengths of at least 2 s
- Optimum project schedule based on 2003 NSTX 5-year plan
- Flat FY05 & FY06 budget --> ~ 2 year delay in 1 MW install

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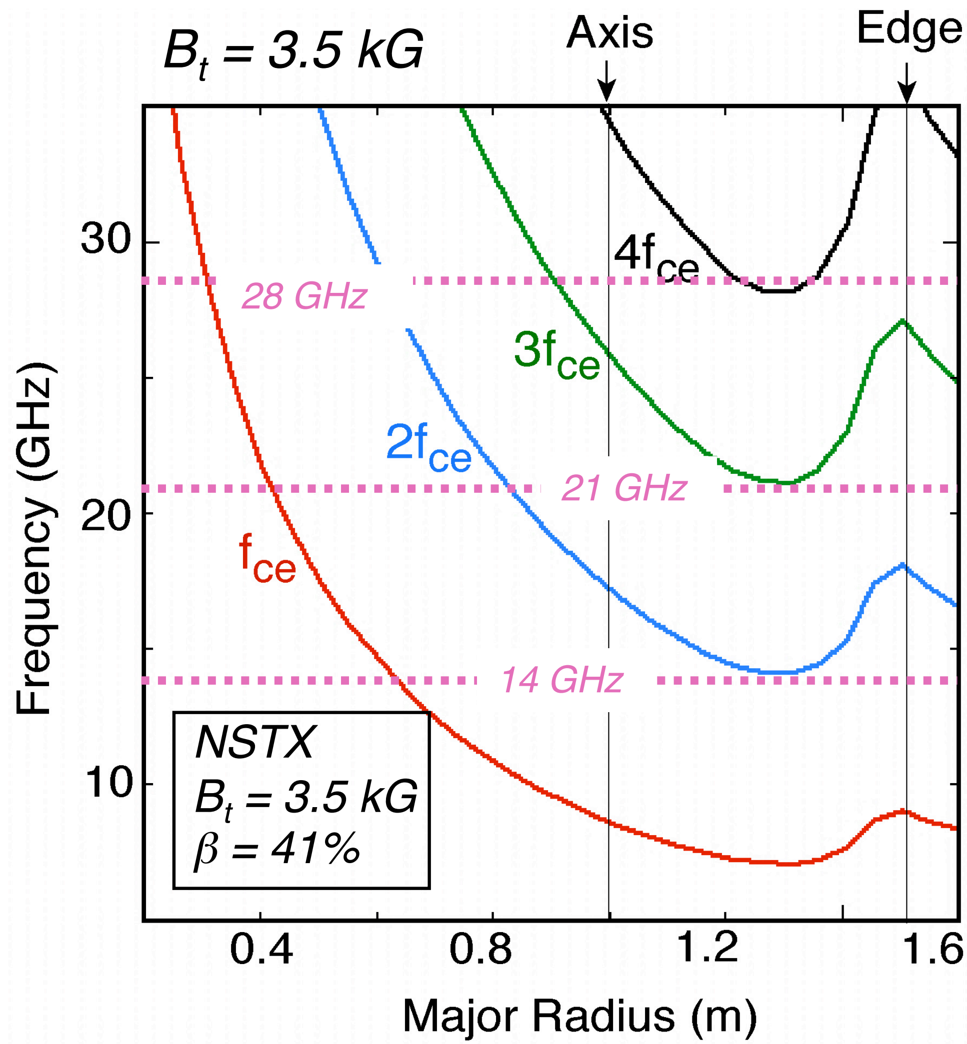
NSTX
NATIONAL SPHERICAL TORUS EXPERIMENT

Choice of RF Source Frequency Constrained by B_t, EBW Coupling and Accessibility

- For EBWCD need off-midplane launch to provide $n_{//}$ shift
- EBW damping is on Doppler-downshifted EC harmonics
- Launch at 14 & 21 GHz looks OK for plasma access
- Launch at 28 GHz may damp on both 3 f_{ce} & 4 f_{ce}:
  - *But small changes in B_t can help*

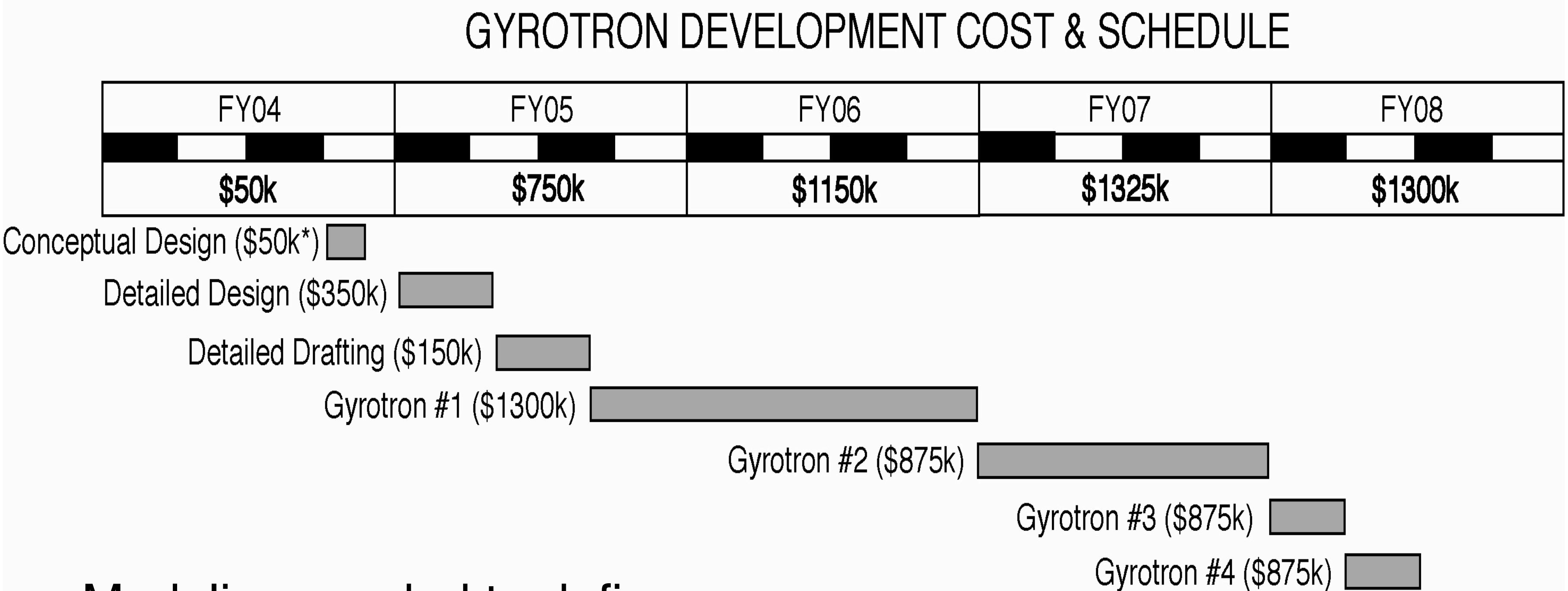


Choice of RF Source Frequency Also Driven by Available RF Technology and Future Applications

- No long pulse (~ 1 s) MW level, RF sources available at ~ 14 & ~ 21 GHz
- Gycom (Russia) makes 0.5 MW, 28 GHz gyrotron with 2 s pulse length (~ $500k/tube, including magnet, Gycom provided 110 GHz gyrotrons to DIII-D)
- ~14 GHz, ~21 GHz & 28 GHz tubes can be designed for 1 megawatt , 5 s operation (development ~ $1M + $875k/tube, 2 years to make first operational tube)
- 28 GHz could also be used on NCSX or future PPPL B_t ~ 1T ST

Source Frequency Decision Needs to Precede Start of Megawatt Level Gyrotron Development

- Internal tube design (mode converter etc.) will change significantly depending on choice of operating frequency



- Modeling needed to define optimum source frequency in FY04

TOTAL COST = $4575k

EBW Modeling has a Bigger Impact on Frequency Choice than EBW Emission Coupling Studies

- EBW emission measurements on NSTX this year provide a consistency check on theory, but:

  --> emission can be "polluted" due to multiple reflections & possible non-EBW sources

  --> does not test prototype EBW launcher geometry

- Model conceptual EBW launcher for proposed NSTX operating scenarios:

  --> need to agree on planned scenarios (B_t, β, etc..)

- Modeling EBW coupling already started for ~ 14 GHz:

  --> model coupling at 21 GHz & 28 GHz this year

  (Carter & Jaeger [ORNL]; collaboration with Preinahelter [Prague]?)

- EBW ray tracing, deposition and CD efficiency modeled with GENRAY & CQL3D for frequencies between 14 to 28 GHz

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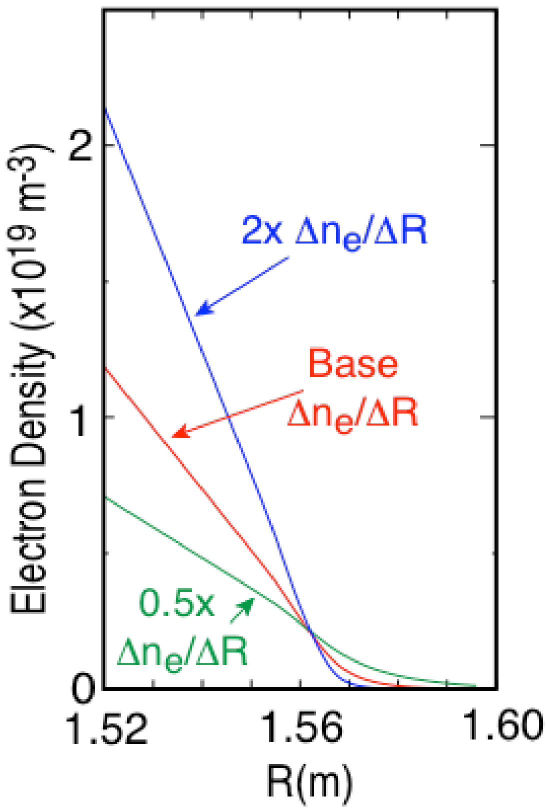
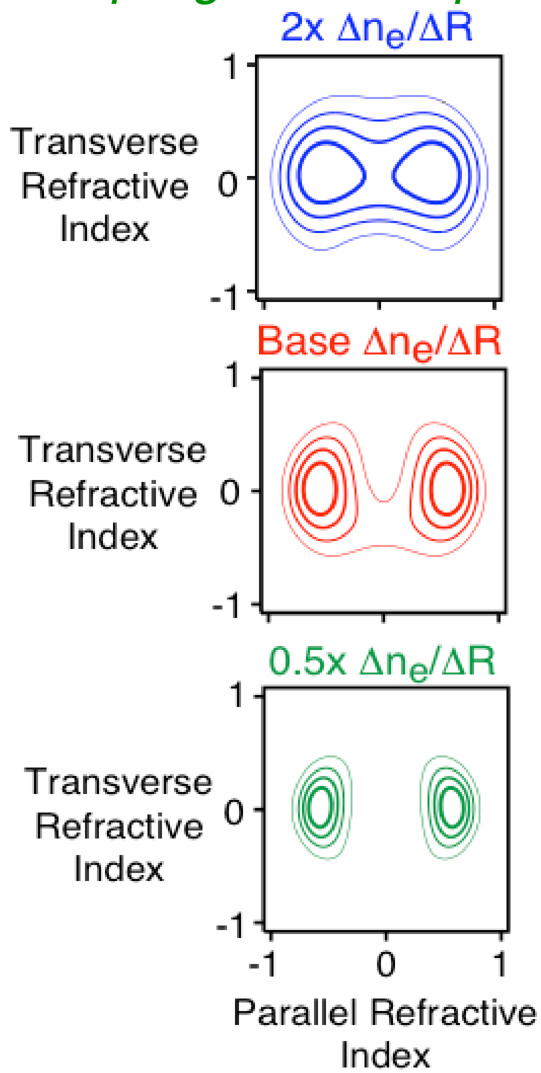
Oblique, "O-X-B", Launch Appears Resilient to Changes in Edge Density Gradient

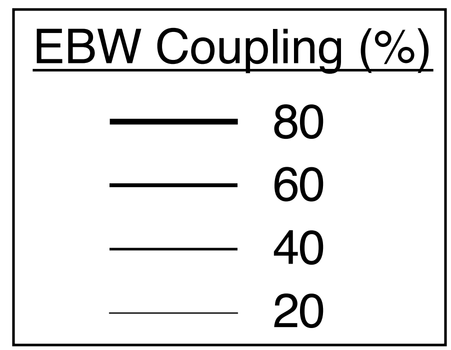
- *OPTIPOL surveys EBW coupling - uses impedance matrix from GLOSI*

Frequency = 14 GHz



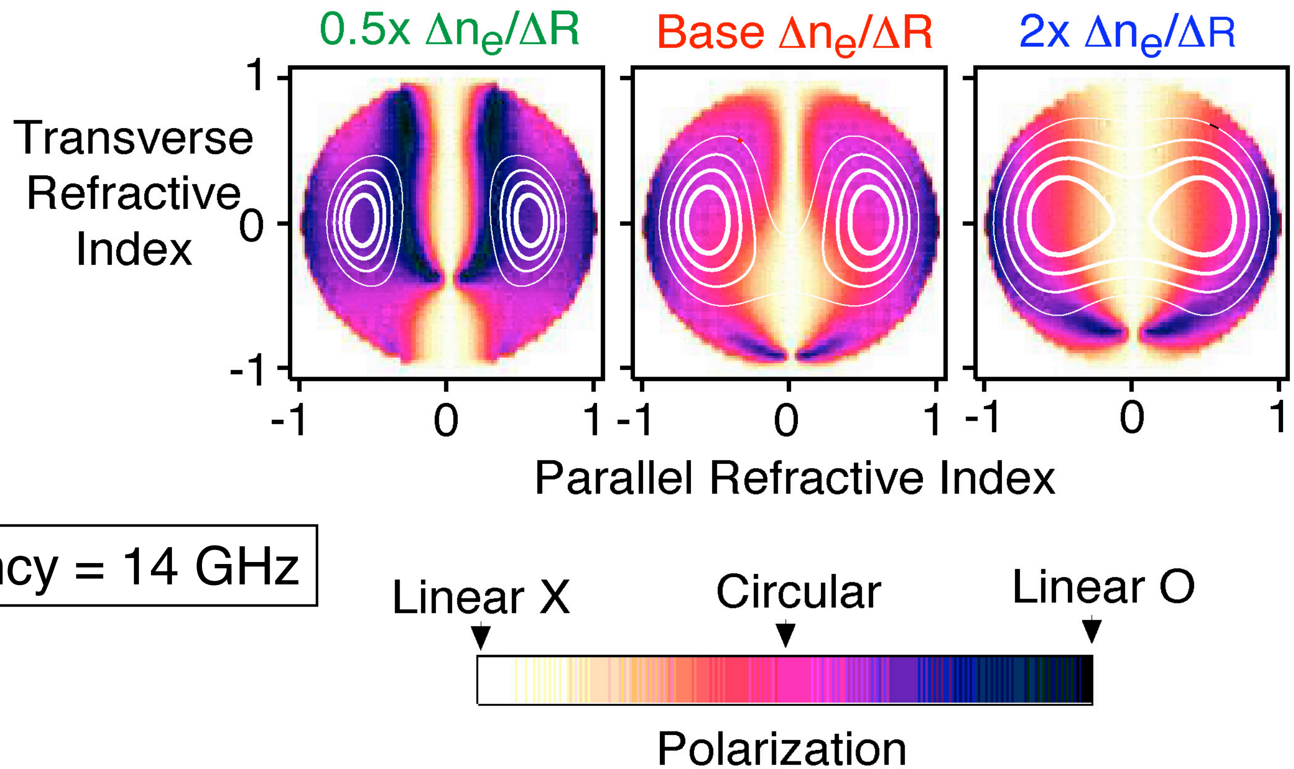


- Optimum $n_{//} = 0.55$; toroidal angle ~ 34° from normal to **B**
- > 75% coupling for O-X-B antenna with ± 5 degree beam spread



OPTPOL/GLOSI

Maximum EBW Coupling Efficiency Obtained for Near-Circularly Polarized Launch

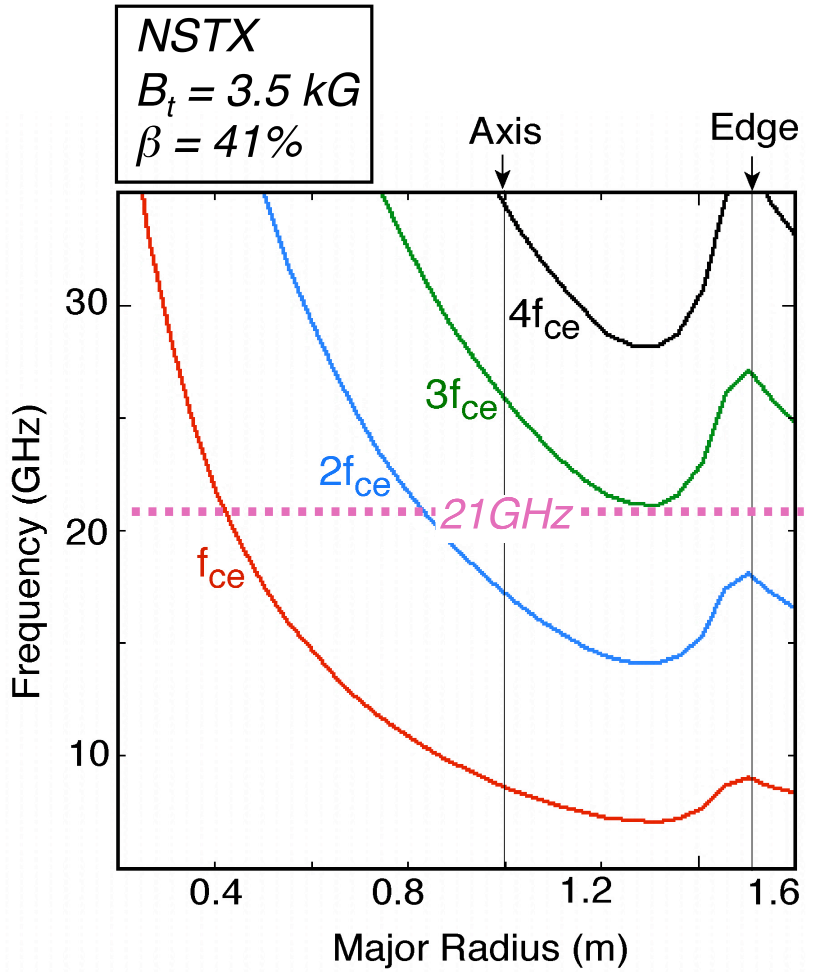


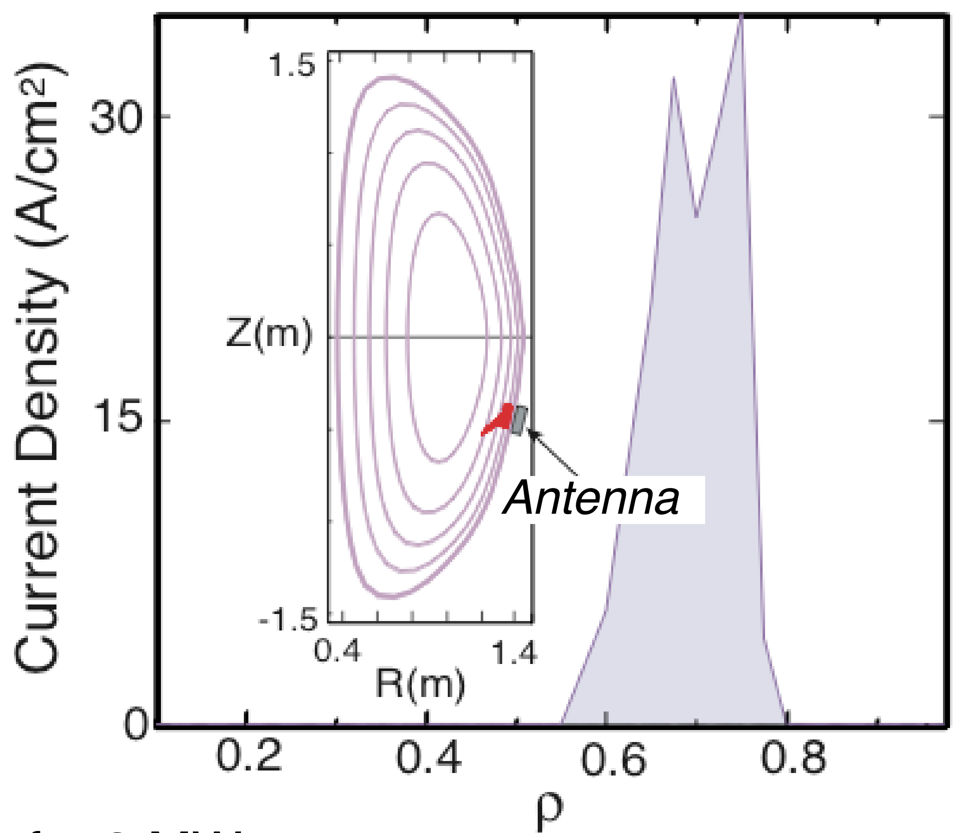
Frequency = 14 GHz

- Optimum polarization insensitive to edge field pitch variations of up to ± 15 degrees; but may need ellipticity control for startup
- About three man months needed to extend modeling to 28 GHz

ORNL Oak Ridge National Laboratory — OPTPOL/GLOSI — NSTX National Spherical Torus Experiment

Modeling Shows Efficient, Off-Axis, EBW CD at ~ 14 GHz & ~ 21 GHz in β = 41%, B_t = 3.5 kG NSTX Plasmas

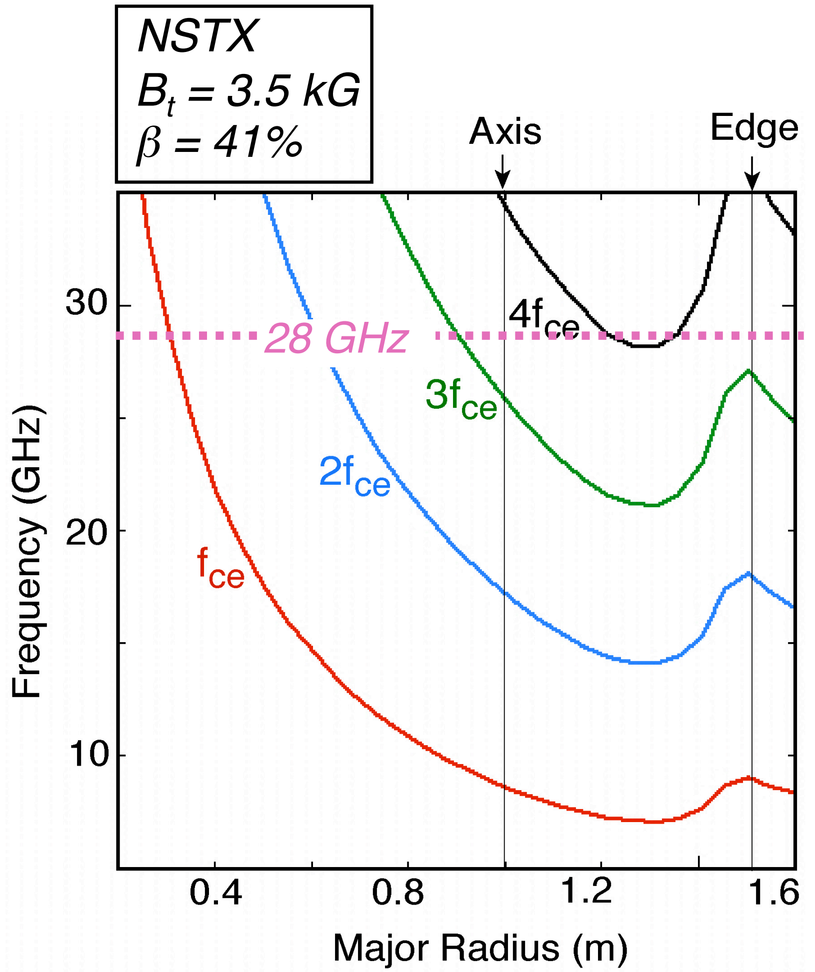


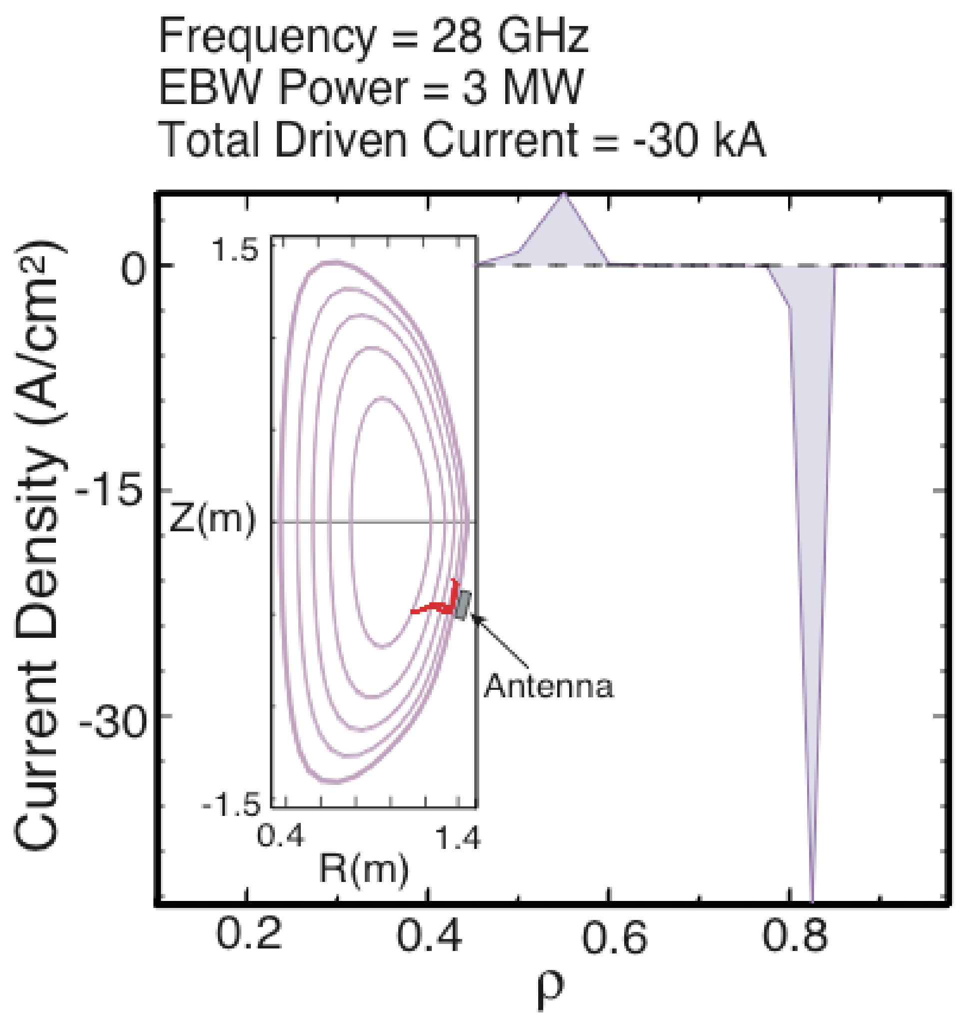


- At 14 GHz, EBWCD = 130 kA for 3 MW

CompX *GENRAY/CQL3D*

For β ~ 41% at B_t = 3.5 kG, 28 GHz Power Mostly Damps at Plasma Edge & Drives Fisch-Boozer Current

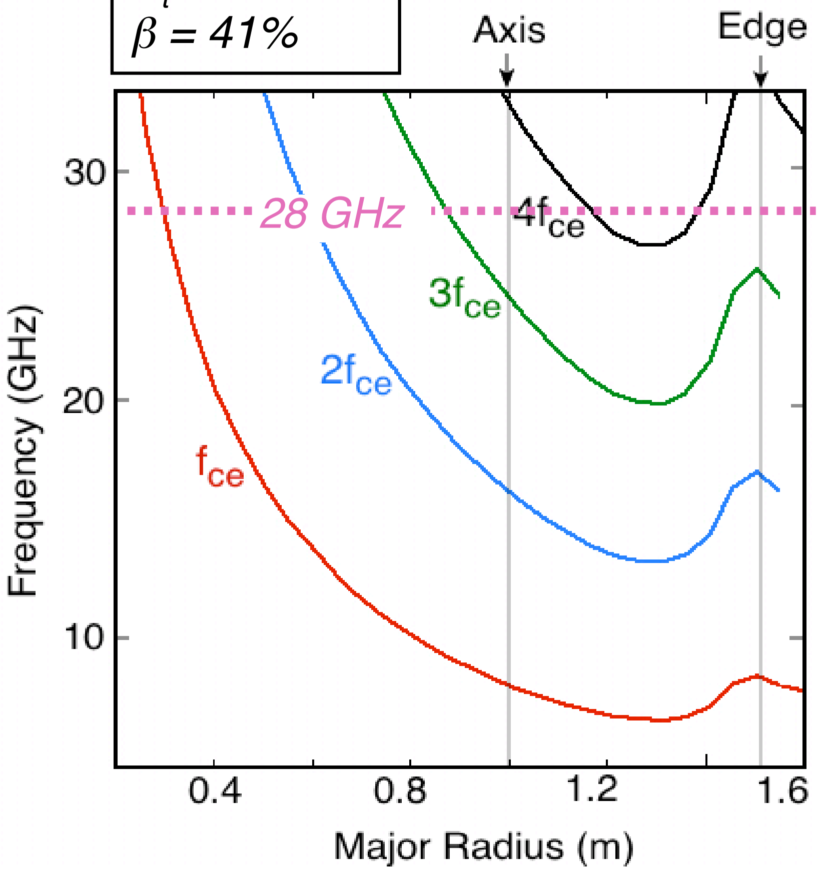




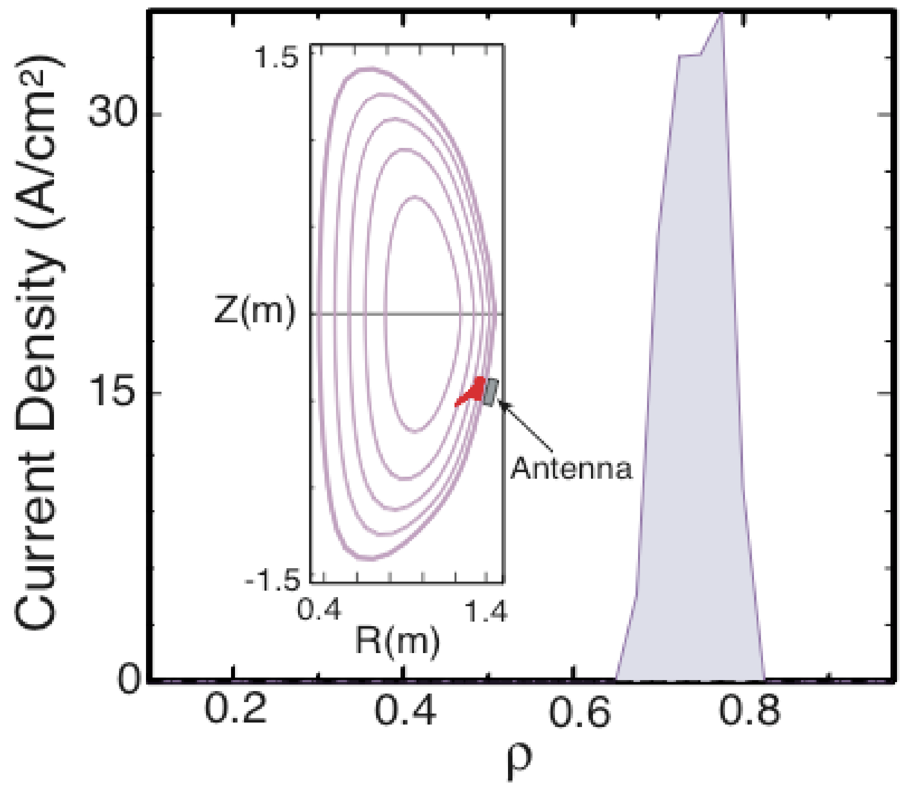
CompX *GENRAY/CQL3D*

Increasing B_t to 3.75 kG for β ~ 41% Plasma, Allows 28 GHz to Drive Efficient Off-Axis Current

NSTX
B_t = 3.75 kG
β = 41%

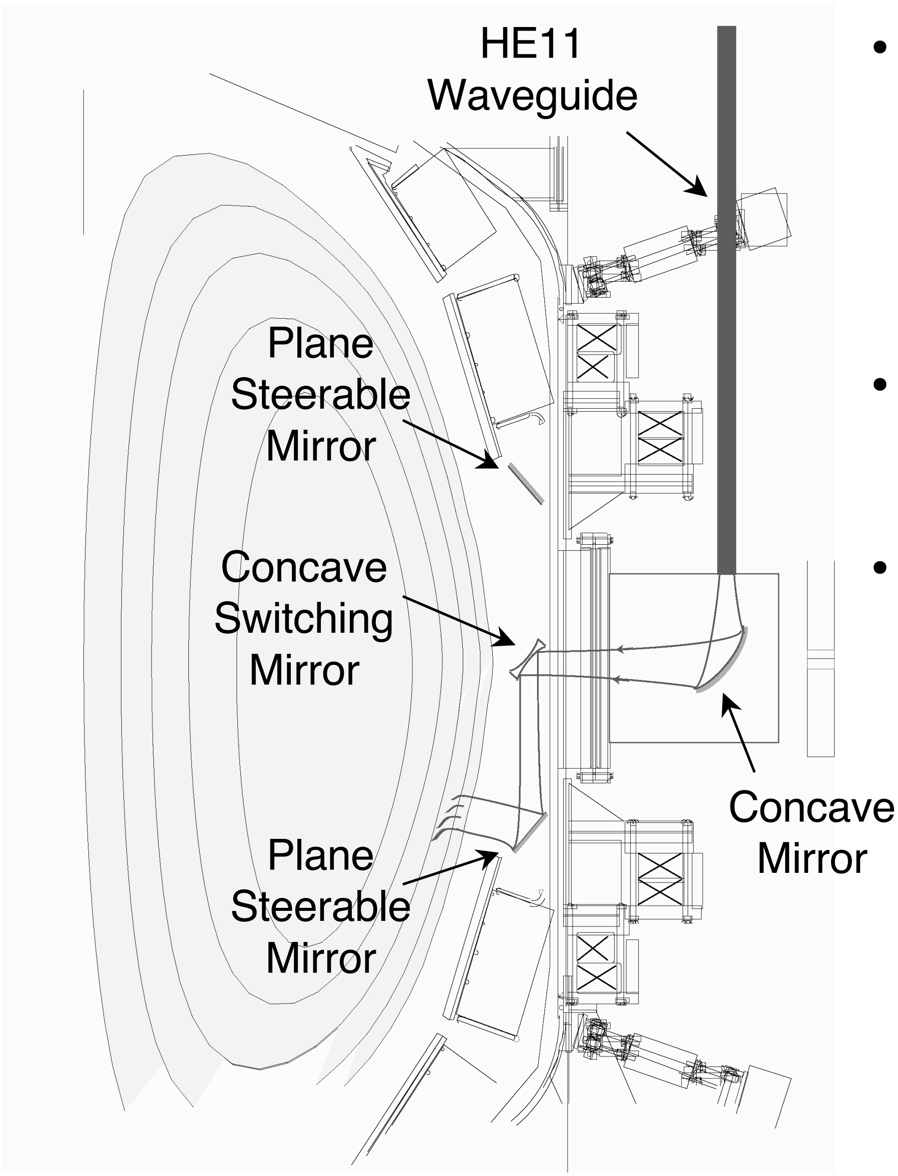


Frequency = 28 GHz
EBW Power = 3 MW
Total Driven Current = 135 kA



CompX *GENRAY/CQL3D*

Conceptual Designs for Steerable Mirror EBW Launchers being Considered for NSTX



- EBW mirror launcher design can benefit from PPPL experience developing DIII-D ECRH/ECCD antenna
- Propose collaboration with ORNL on EBW launcher development
- Switching between above and below midplane launch would allow flexibility for co- or counter-CD, and Ohkawa or Fisch-Boozer CD:

  --> *Significant diffraction at ~14 GHz is challenging*

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Estimated Project Cost* (Excluding Contingency) : $14.8 M
Assumes 1 MW installed in 2007, 4 MW in 2008

Title	FY04	FY05	FY06	FY07	FY08	Total
Site Preparation	20	170	360	120		**670**
Power Conversion	10	100	1625	1400	825	**3960**
Gyrotron Cooling	10	80	250	25	25	**390**
Gyrotron	50	750	1150	1325	1300	**4575**
RF Power Transmission	20	80	350	620	350	**1420**
Instrumentation and Control	10	190	50	50	50	**350**
EBW Launchers	50	500	650	900	900	**3000**
Proj. Management	10	120	150	100	50	**430**
Total	**180**	**1990**	**4585**	**4540**	**3500**	**14795**

* Funding levels are expressed in $k

- For flat FY05 & FY06 budget above schedule slips ~ 2yrs

Excluding Contingency, First MW Costs ~ $7M (Including Gyrotron Development) , ~ $2.6M for Each Addition MW

- Gyrotron development cost, excluding contingency, ~ $1M, should be budgeted through VLT
- 1 MW system would allow local heating for transport studies EBW-assisted startup, and possibly indications of EBWCD
- Level of contingency needs to be determined based on risk assessment
- Preliminary optimum funding profile developed to match original 5-year program plan (July 2003)
- Optimum funding has 1 MW of source power installed in Feb 2007, ramping to 4 MW (~ 3 MW EBW in NSTX) in Aug 2008

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Benefit of MAST 28 GHz EBW Launcher Collaboration is Questionable & May Waste Resources

- MAST planning < 200kW, 28 GHz EBW system with < 40 ms pulse length for plasma startup experiments late this year

- Should we design & build an EBW launcher for MAST's 28 GHz system?

  --> *Allows test of prototype NSTX EBW launcher on MAST in 2006*

- Available 28 GHz power on MAST in 2005-6 too low to directly observe local power deposition

- Development of a prototype EBW launcher for MAST would be costly, probably > $500k

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4 MW EBW Project Can Provide ~ 100kA Off-Axis Current Deemed Critical for Sustained High β NSTX Operation

- Frequency choice largely driven by modeling, not emission expts.
  - *--> polarization control appears critical*
  - *--> modeling allows frequency decision by late FY04*
  - *--> frequency decision must precede gyrotron development*
- Significant diffraction at 14 GHz challenges EBW launcher design
- Modeling needed to decide between 21 & 28 GHz
- 28 GHz looks promising:
  - *--> 0.5 MW, 2s sources available from Gycom (Russia)*
  - *--> could use 28 GHz on NCSX at B_t ~1T or on future PPPL ST*
- ~1 MW, long pulse (~5 s) source needs ~ $1M, 2 yr development
- 28 GHz MAST launcher expt. at < 200kW is too low a power to test EBW heating --> need ~ 1 MW