ECH/EBWH Research Plans and progress in the modeling of non-inductive ramp-up

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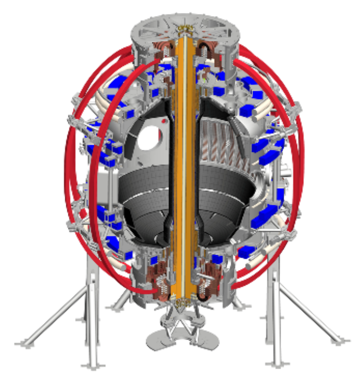
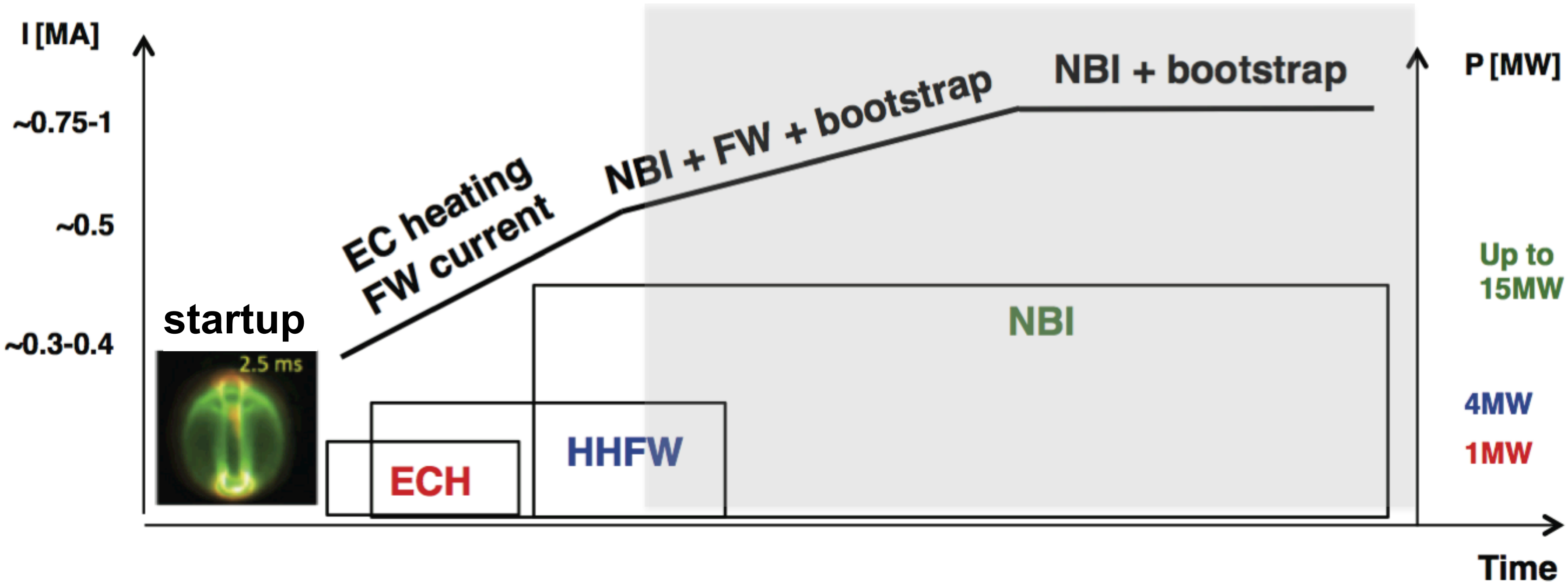
for the Integrated Scenarios science group

PAC37
Princeton, NJ
January 26, 2016



Strategy: combine integrated modeling and experiments to address rampup challenges



- Heat startup plasma with EC to maximize H/CD efficiency
- Combine RF and NBI for current profile optimization
- Optimize NBI source combination for CD and stability.
- Maintain control over position, current profile, MHD stability.

2^{nd} NB line can ramp current from HHFW-heated plasma and sustain 900kA

At the previous PAC meeting

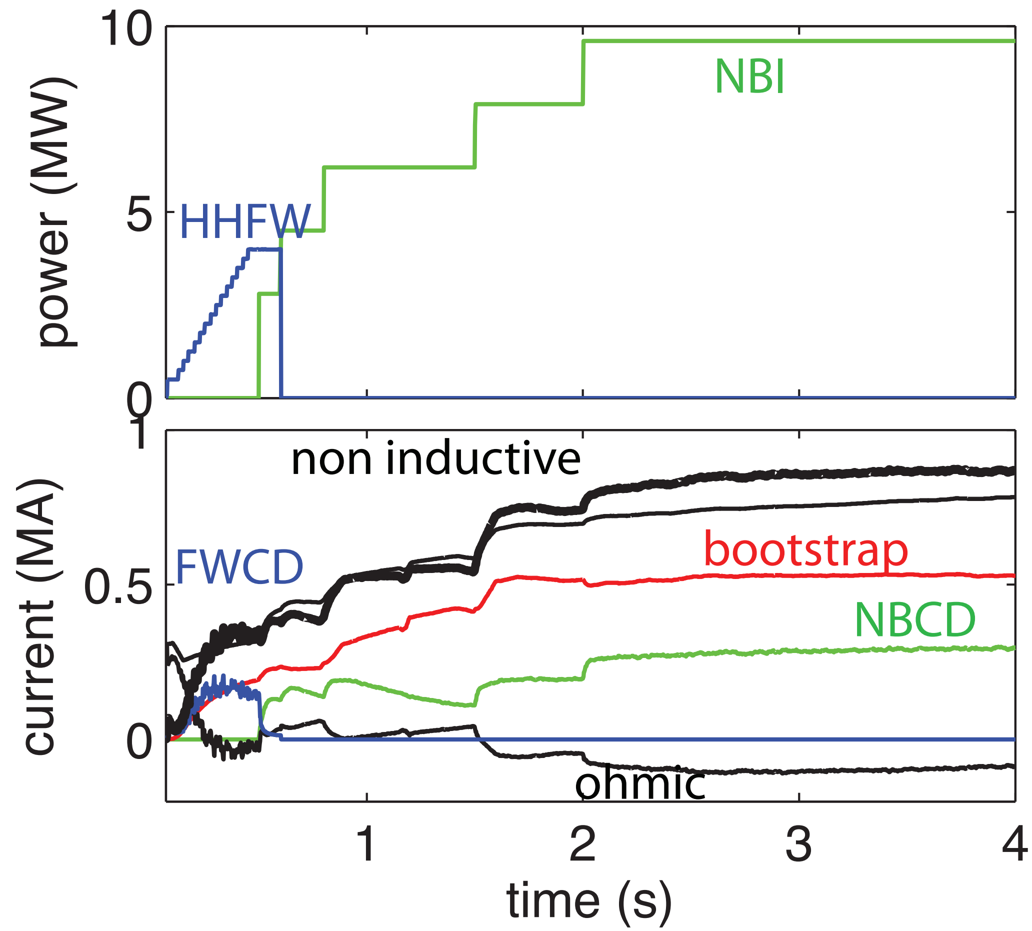
Focus was on ramp-up and

sustainment with NBI

HHFW @ t<0.5 ➔ ~400kA

$n_{e,lin}$ = 0.85 n_{GW} ➔~900kA non-inductive,

~60% bootstrap



Focus today is on start-up and early ramp-up

[F. Poli et al, Nucl. Fusion 55 (2015) 123011]

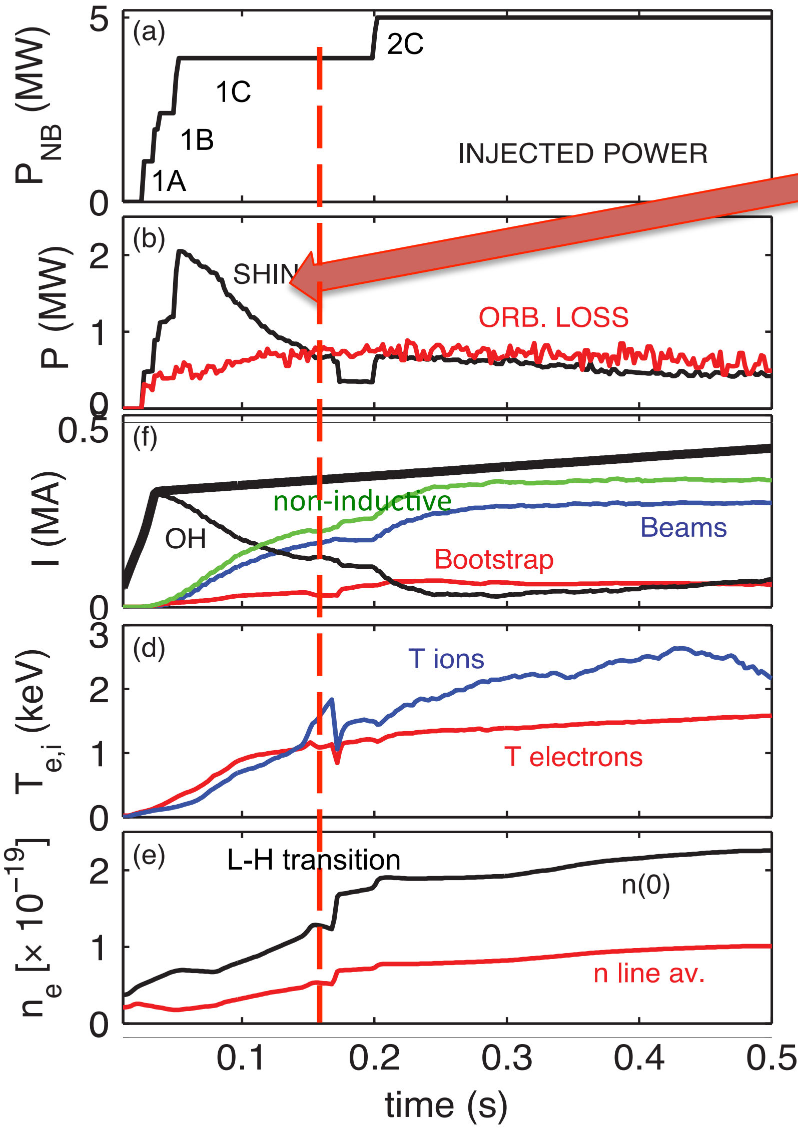
Assumptions in the simulations

- Select NSTX discharges, compare transport models on:
  - RF and NB at low, constant current
  - NB in the ramp-up and at high current flattop
- CAVEAT: Startup/rampup not the same as relaxed, flattop plasma.
- Transport assumptions will be updated using new NSTX-U data
  - pedestal structure, confinement, rotation, turbulence ...
- All simulations run with free-boundary TRANSP
  - ISOLVER for equilibrium evolution and coil currents
  - TORIC (full wave) for HHFW,
  - NUBEAM (Monte Carlo) for NBI,
  - GENRAY (ray-tracing) for ECH
  - Multi Mode Model for thermal transport [Lehigh univ.]
  - **Prescribe I_P waveform and maximize non-inductive current drive**

Identify challenges and needs towards non-inductive operation

- Optimizing non-inductive current at startup with NBI.
- Optimizing non-inductive current at startup with HHFW.
- Prepare a target plasma with EC Heating.
- Why is ECH a game changer?

NBI losses too large in low-density, low-current plasma target



~50% of NBI power lost due to low density shine-thru

Results in low current drive

Need: optimization of the first 200ms of discharge

Experiments: optimize NBI @low density:

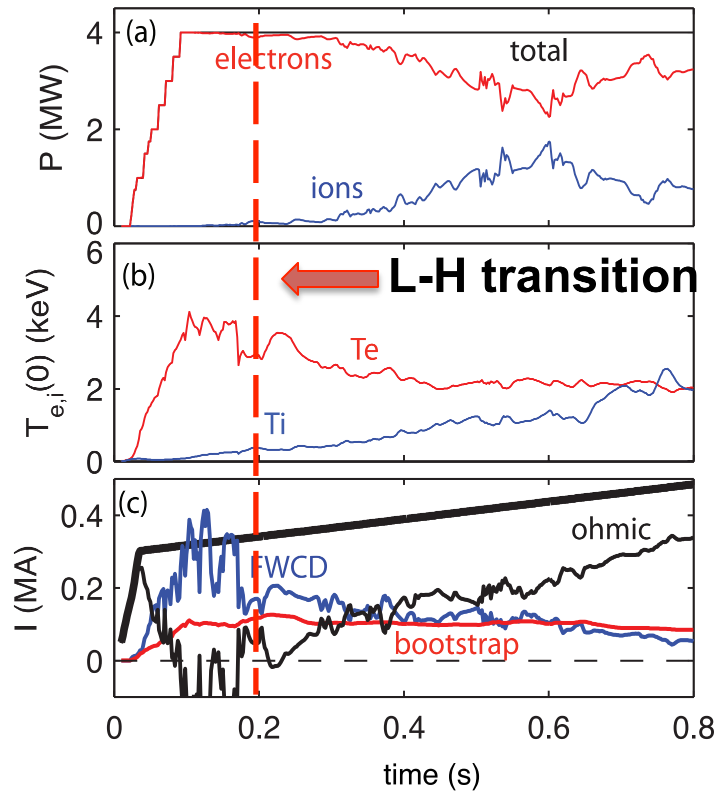
– minimize shine-thru and losses

– maximize non-inductive current

Modeling: current and q profile control

[W. Wehner, Lehigh univ., D. Boyer, PPPL]

HHFW can provide the needed current, but efficiency drops after L-H transition



dominant electron heating in the early ramp-up

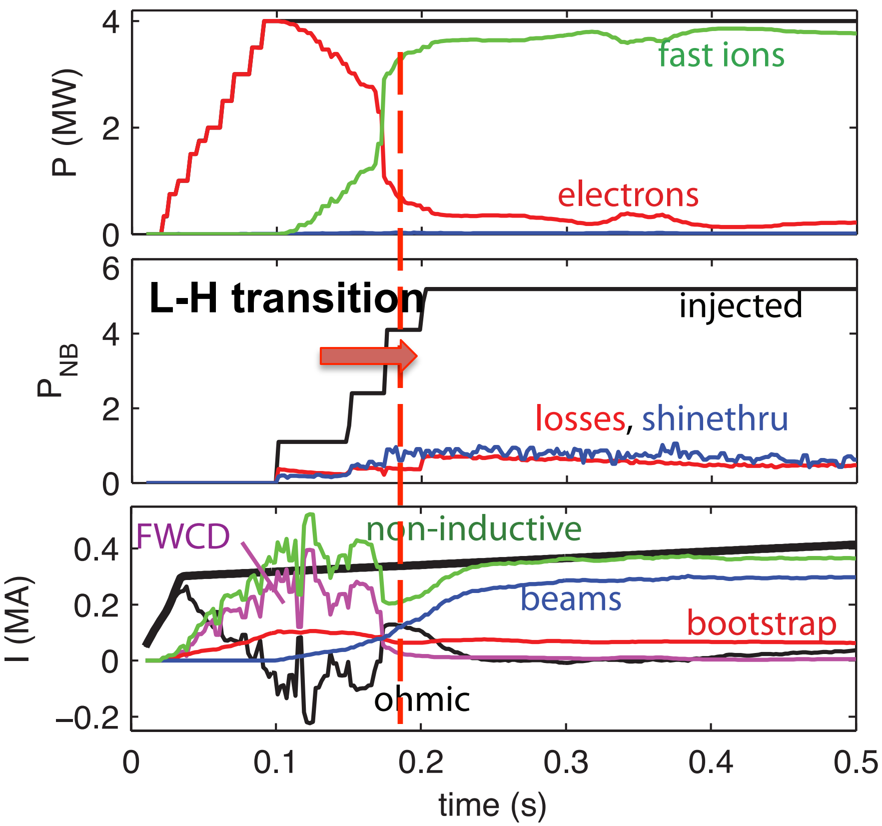
Issue: after L-H transition
- HHFW heating less efficiency
- current drive efficiency drops

Issue: expect peaked pressure and current profiles.
MHD stability to be assessed

Modeling: validation of wave absorption against experiments

Experiments: Wave coupling and FWCD at low density, low current [see presentation by Gerhardt]

Combine HHFW and NBI to drive current when HHFW becomes less efficient



Issue: large absorption to fast ions => reduces efficiency

Path: switch from HHFW to NBI and ramp-up to full current

delay NBI to minimize losses and maximize current drive

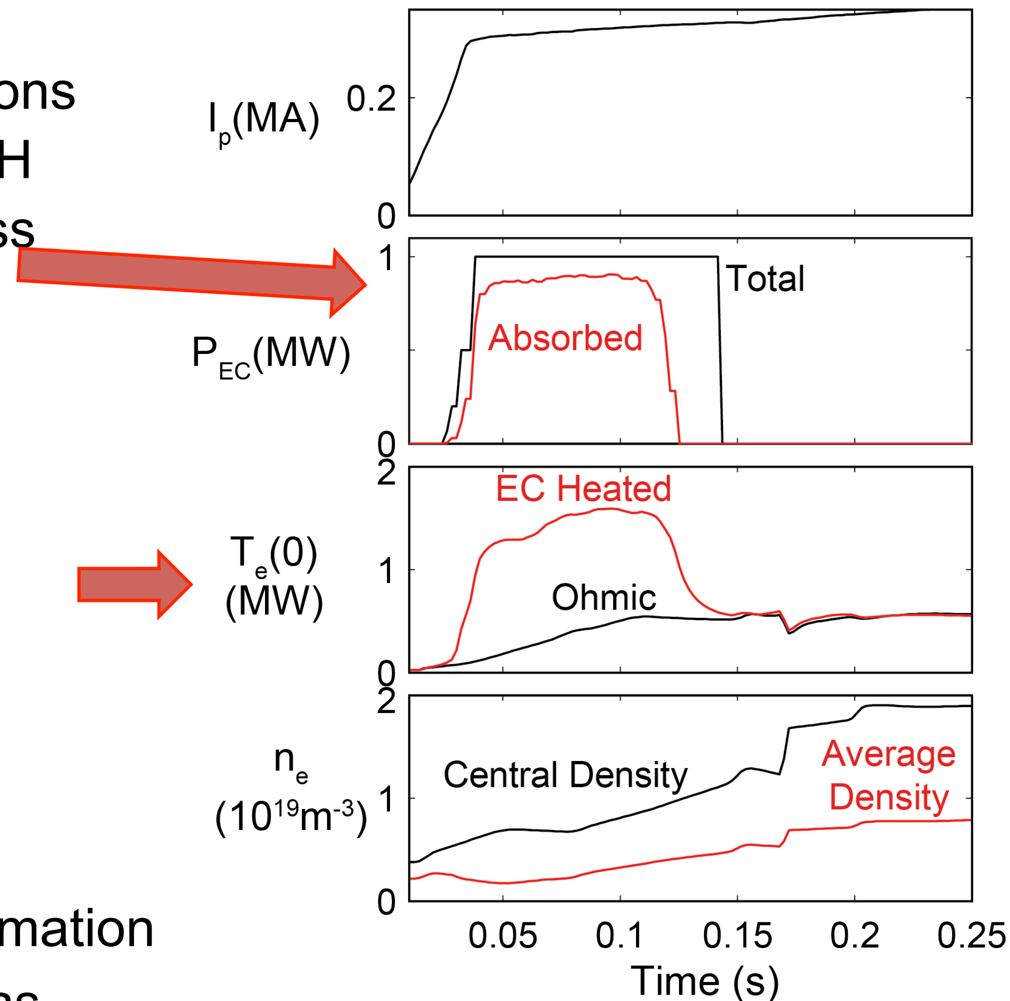
Need: optimization of the first 100ms of discharge

Experiments (future): HHFW+NBI at low current and density

Modeling: validation of fast ion absorption

Simulations predict that 28 GHz ECH is very effective at heating NSTX-U start-up plasmas

- TRANSP time-dependent simulations with 1 MW of 28 GHz O-mode ECH predict a rapid increase in first-pass absorption from 5% to 75% as $T_e(0)$ increases from 10 eV to 1 keV in ~10 ms
- **Issue:** ECH can be used for ~150 ms before the plasma $n_e > n_{cutoff}$



Experiments: get new density information from CHI and low-I_P RF target plasmas

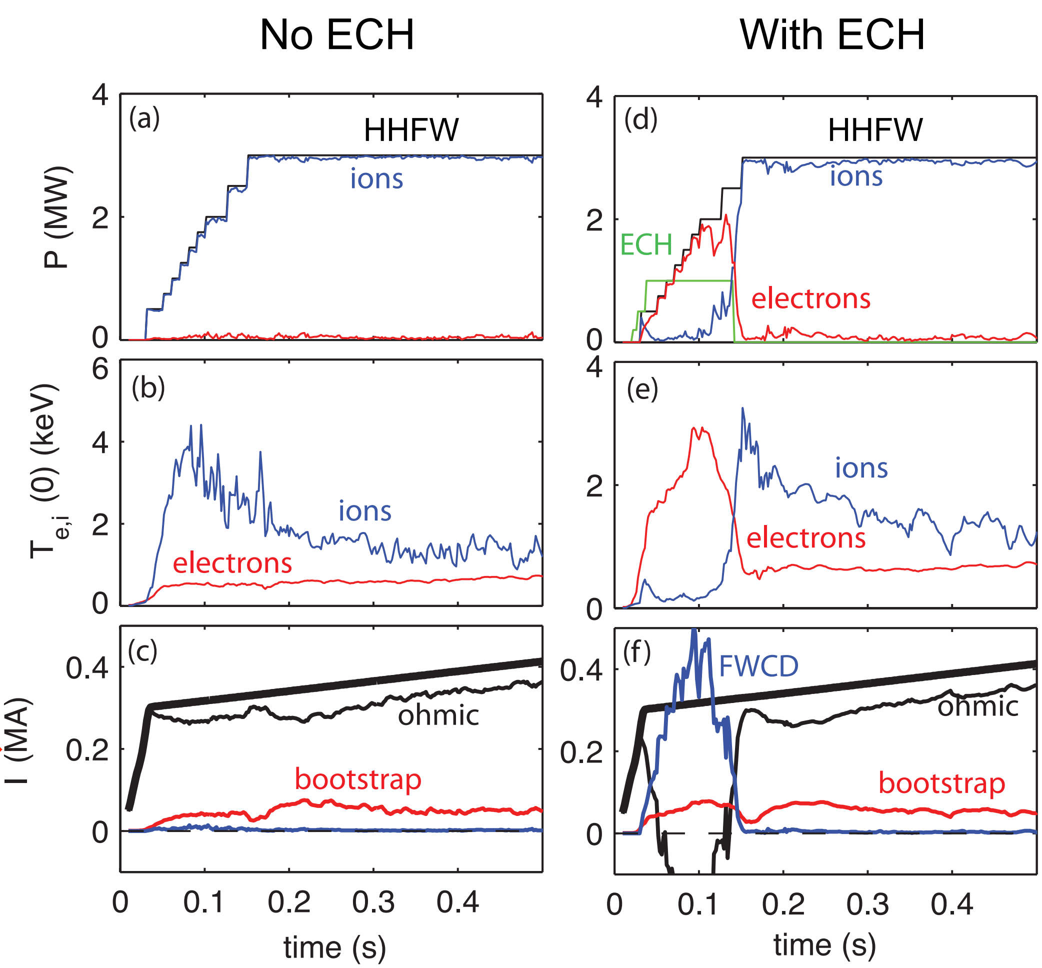
Modeling: assess EC heating against plasma parameter variations

ECH generates a high T_e start-up plasma that can significantly improve HHFW current drive

Even with unfavorable CD phasing ($k_{//}$=3 m^{-1})

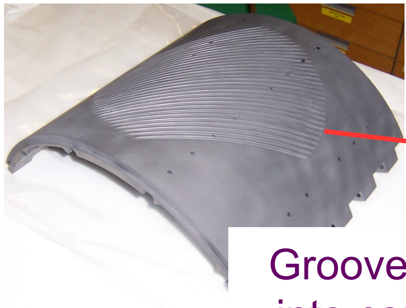
Strong synergy observed in simulations of NI plasma start-up that combine EC and HHFW heating

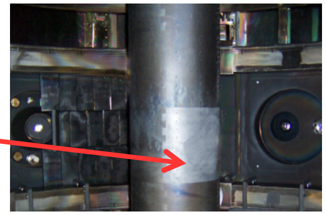
No FWCD w/o ECH
almost 400kA with 1MW of ECH



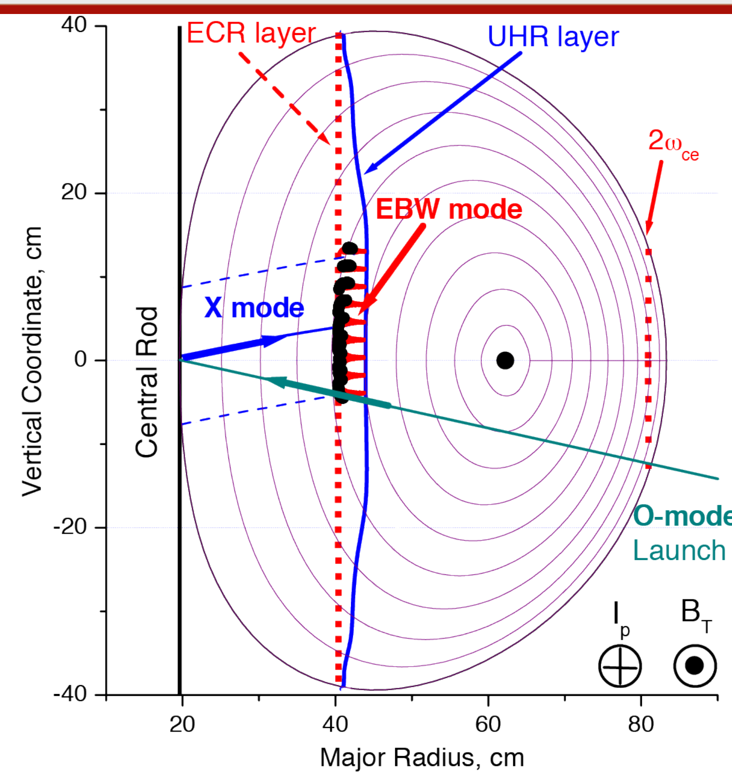
Modeling: assess EC+HHFW heating against plasma parameter variations and HHFW phasing [backup slide]

28 GHz EBW start-up on NSTX-U will test power scaling of MAST and QUEST results





Grooved reflecting polarizer machined into center column in MAST => 100% O-X-B conversion



- MAST achieved I_p~75 kA with ~75 kW power.
- EBW start-up on NSTX-U at megawatt level will test viability of technique at much higher RF power
- EBW current drive might scale much weaker than linearly with RF power

=> Pursuing modeling of EBW at startup and flattop using kinetic models

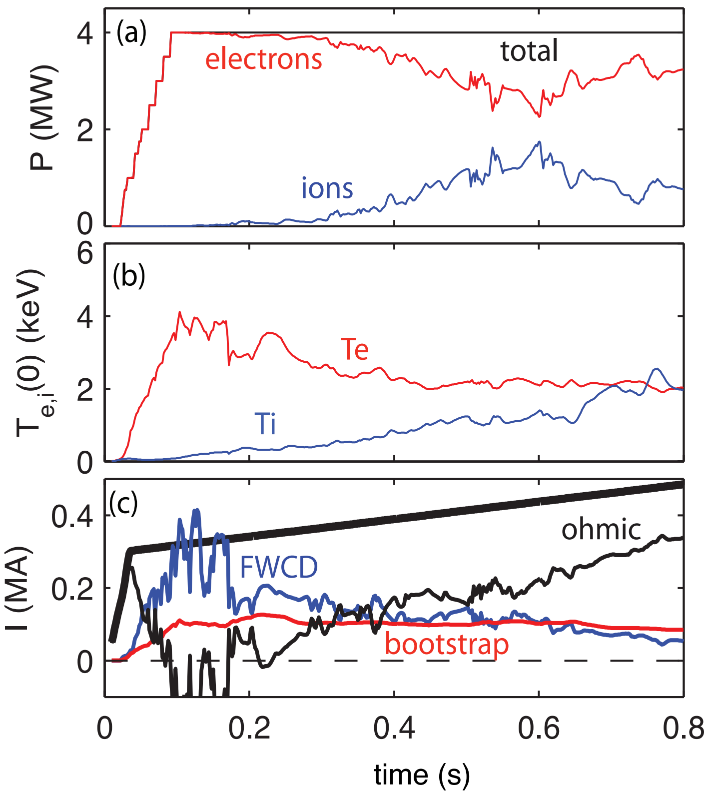
- future collaboration with QUEST on EBW startup modeling
- SAMI diagnostic on loan from University of York [see backup slide]

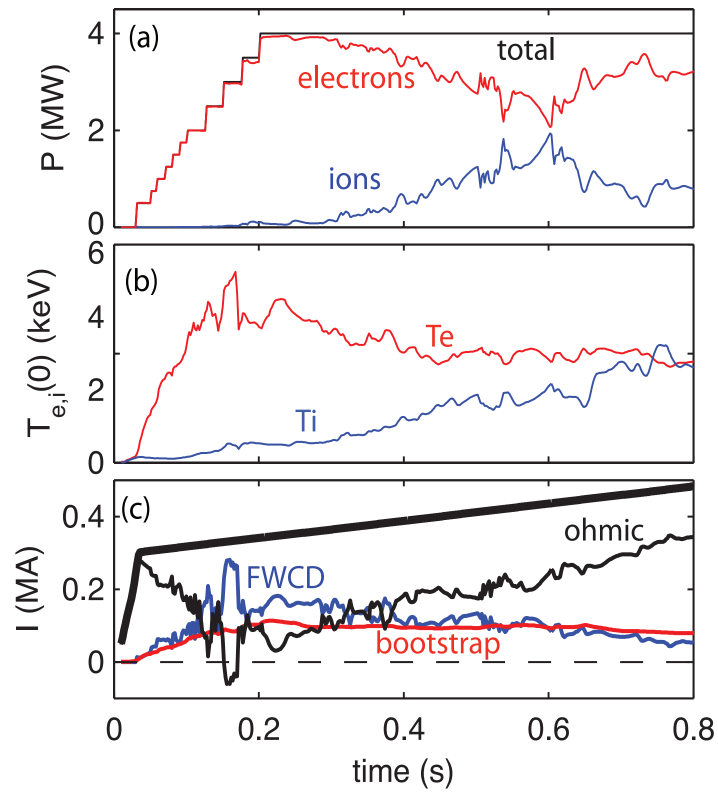
Summary and future work

- All sources needed for non-inductive current ramp-up
  - EC: game changer => reduces by 4 HHFW power needed to drive 300kA on CHI-like target.
  - HHFW: drives current where NBI losses are larger
- Close connection between integrated modeling and experiments is critical for development of this phase
- Longer term: EBW start-up may allow more time to control plasma position and discharge evolution than CHI start-up
  - In progress: EC/EBW startup simulations for direct transition to NBI phase [*N. Lopez, Princeton University*]

Backup slides

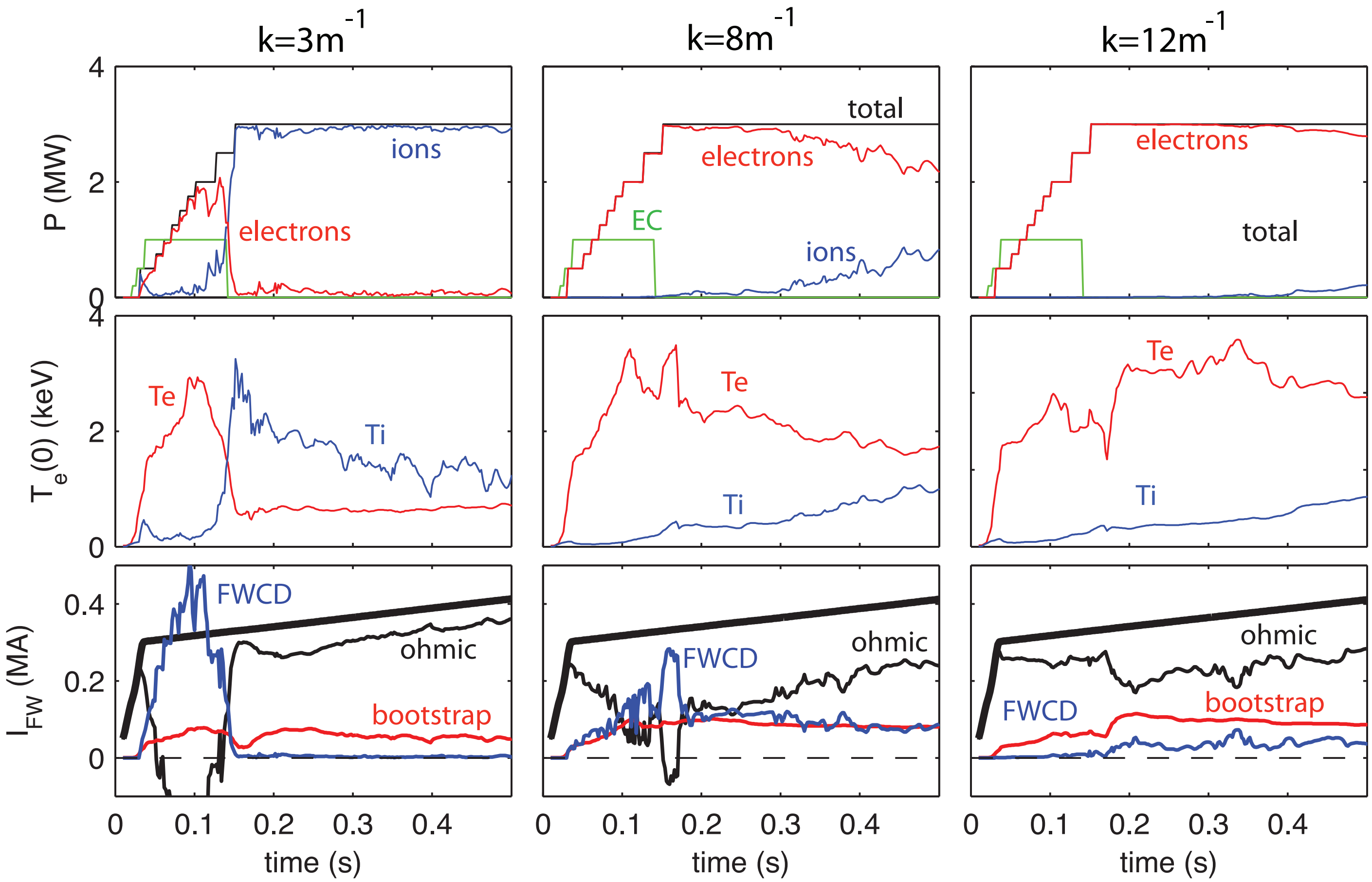
HHFW can provide the needed current, but good heating is critical





- Need 4 MW for ~350kA current (to be verified in exp.)
- FWCD drops after L-H: higher n_e, lower electron absorption.
- Current profiles peaked => challenge for control and MHD.

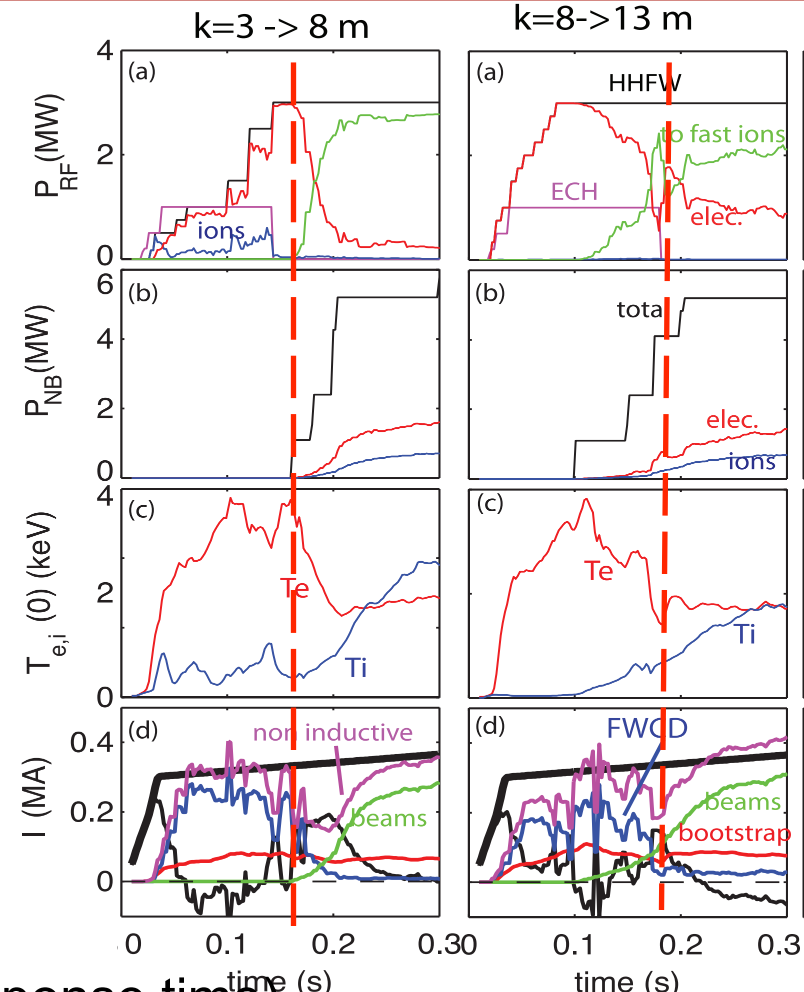
ECH improves HHFW efficiency



- when combined with EC, lowest phasing most favorable
- half power needed to drive 400kA compared to w/o EC

Dynamic phasing of HHFW antenna needed to maximize FWCD.

- High $k_{//}$ => lower fast ions absorption
- Low $k_{//}$ => higher CD efficiency
- **Synergy:** with 1 MW of EC heating, only 1 MW of absorbed HHFW power is predicted to drive 300 kA

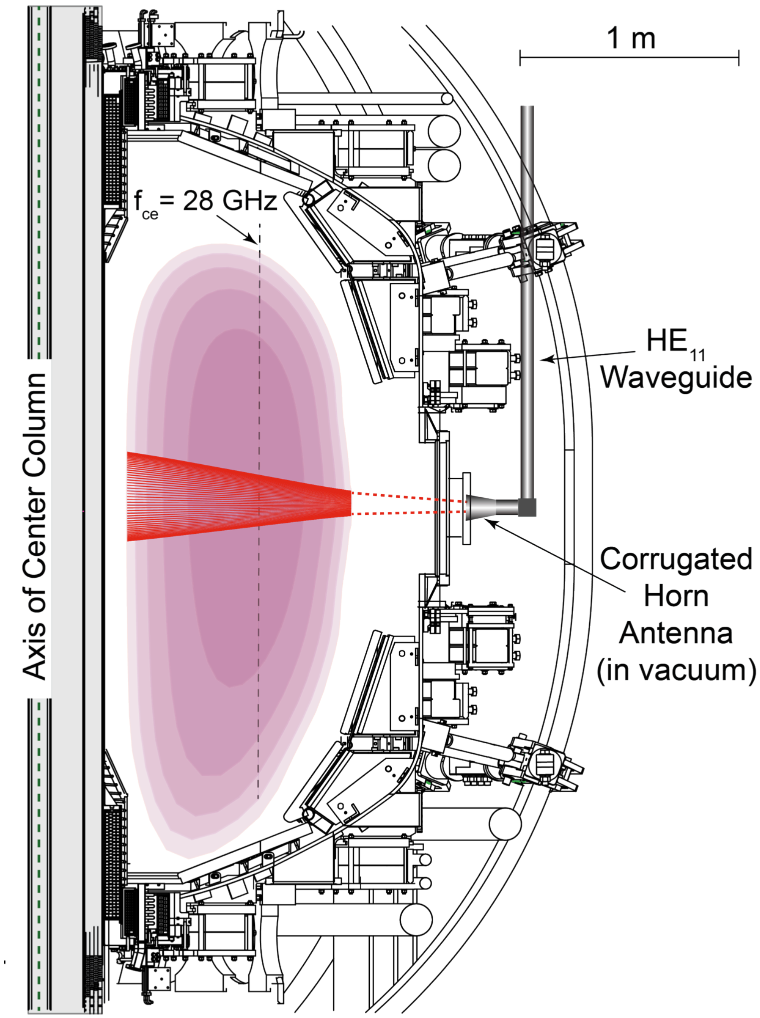


Experiments: assess phase changing (response time)

Modeling: optimize EC->HHFW->NBI transition based on experiments

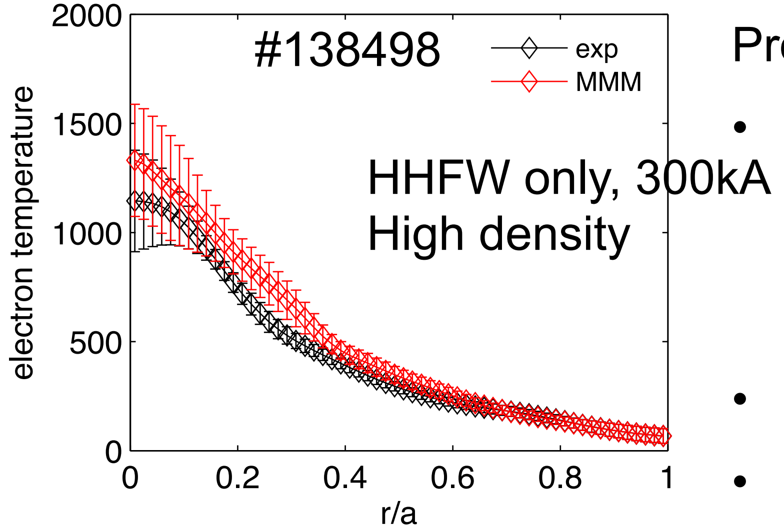
Design and implement 28 GHz EC/EBW heating system to support NI operation*

- Plan to use ~2 MW Gyrotron being developed by Tsukuba Univ.**
  - Fixed horn antenna & low-loss HE11 corrugated waveguide
  - Initially use 28 GHz system to heat CHI start-up plasmas
  - Later install grooved tile on center column to allow EBW plasma start-up
  - EBW start-up technique will be same as used successfully on MAST



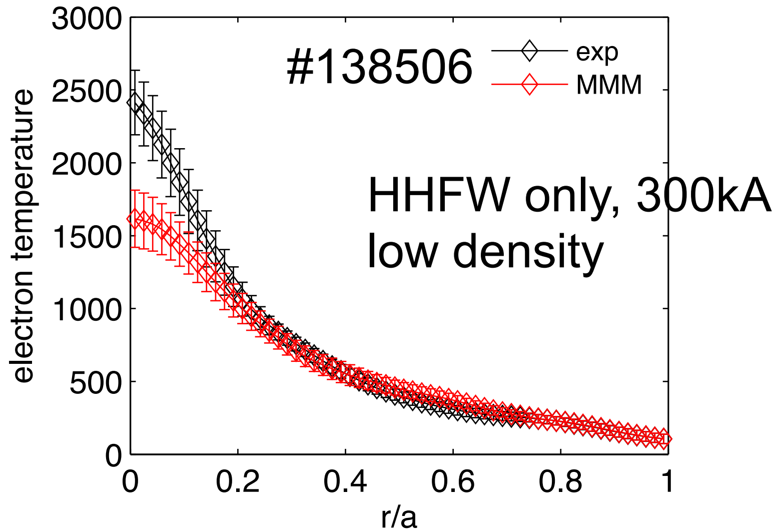
* G. Taylor et al., EPJ Web Conf. **87** (2015) 02013
** T. Kariya et al., Fusion Science and Technology **68** (2015) 147

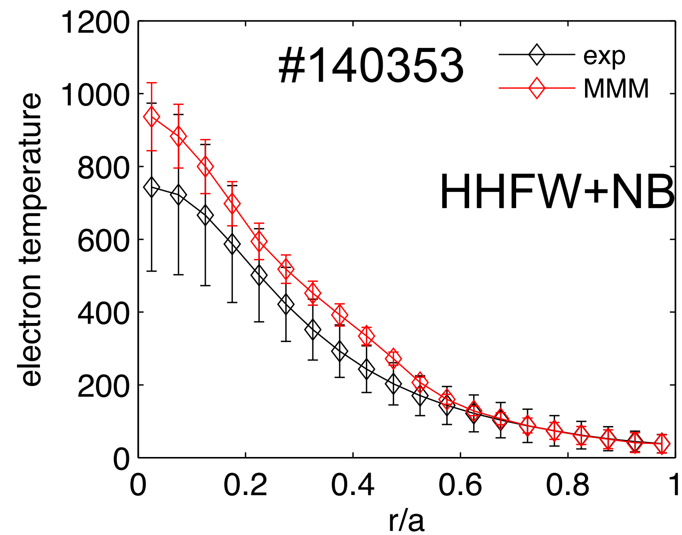
MMM95 reproduces amplitude and peaking of electron temperature during the HHFW phase



Profiles averaged over the heating phase

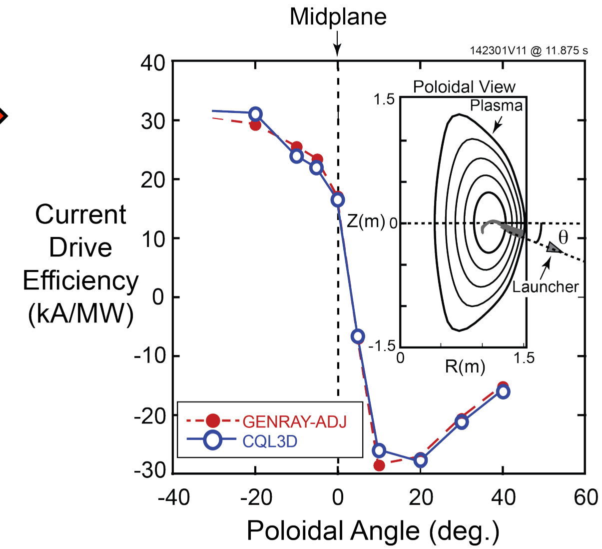
- MMM95 reproduces the average amplitude and peaking in HHFW discharges and in discharges with HHFW+NBI.
- Ion temperature overestimated in NBI discharges
- Electron temperature too peaked in NBI discharges





Develop 28 GHz EBW (O-X-B) heating and current drive system for NSTX-U H-modes

- EBW simulations for an NSTX-U H-mode predict η_{eff} ~ 25 kA/MW on axis for $n_e(0) = 9 \times 10^{19} m^{-3}$ and $T_e(0)$ = 1.2 keV:
  - Can generate significant EBWCD at r/a > 0.8, where NBICD is negligible
  - Extend simulations to include realistic SOL and edge fluctuations



- In FY16 measure O-X-B coupling on NSTX-U with synthetic aperture microwave imaging (SAMI)* [Collaboration with UK]
- Can test 28 GHz O-X-B heating with fixed horn antenna:
  - Use B-X-O emission data acquired by SAMI to guide antenna aiming

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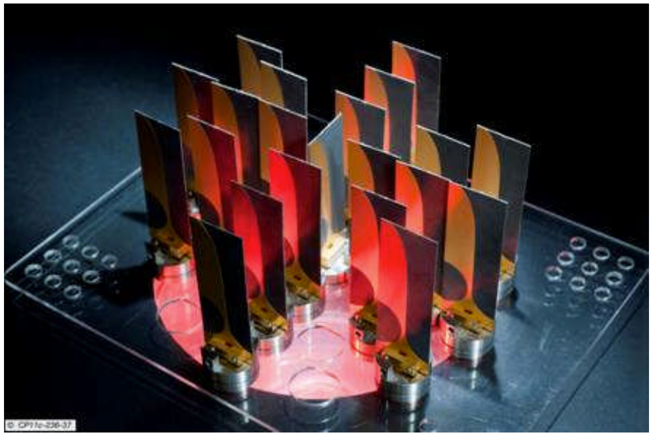

Synthetic aperture microwave imaging (SAMI) antenna array

* V.F. Shevchenko et al., AIP Conference Proceedings **1612** (2014) 53

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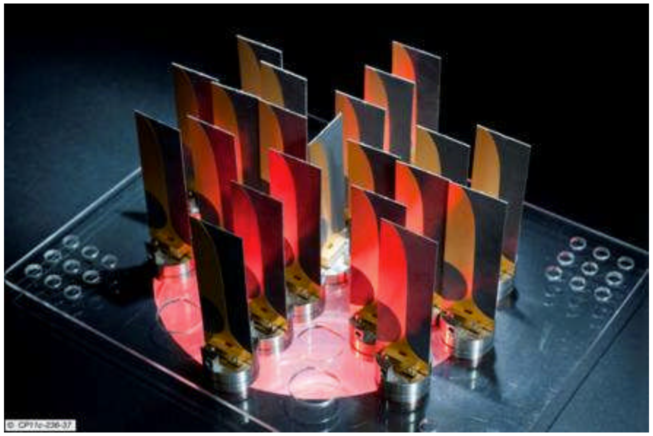

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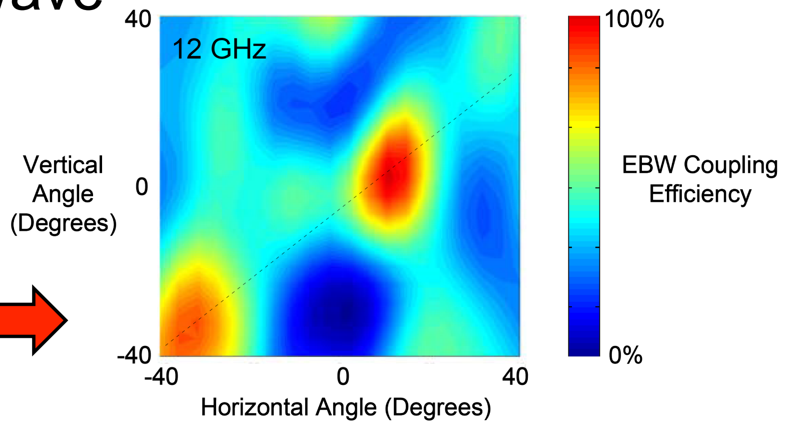

MAST SAMI EBW Emission Data

* V.F. Shevchenko et al., AIP Conference Proceedings **1612** 53 (2014)