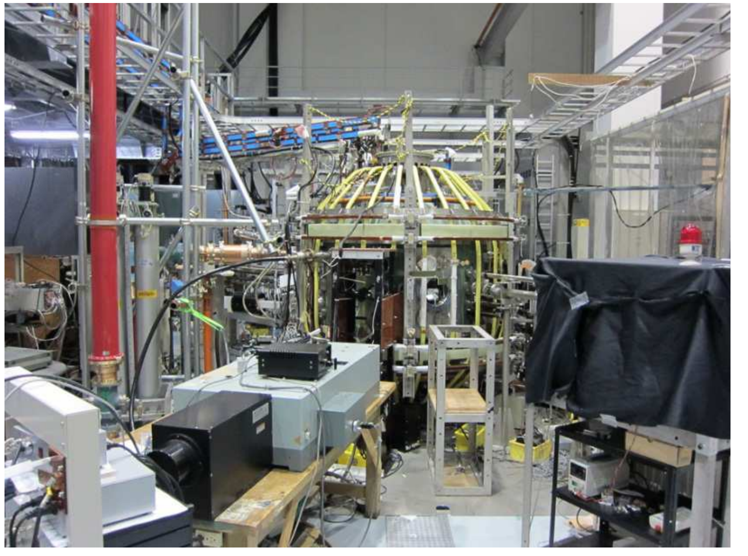
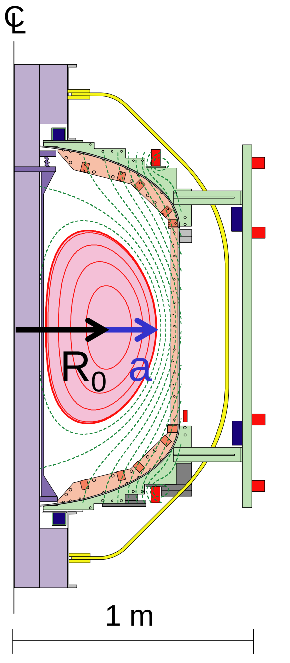
R_0 = 0.36 m
a = 0.23 m
$A = R_0/a > 1.5$
B_t = 0.3 T
I_p = 0.1 MA





Recent progress in the TST-2 RF start-up experiments

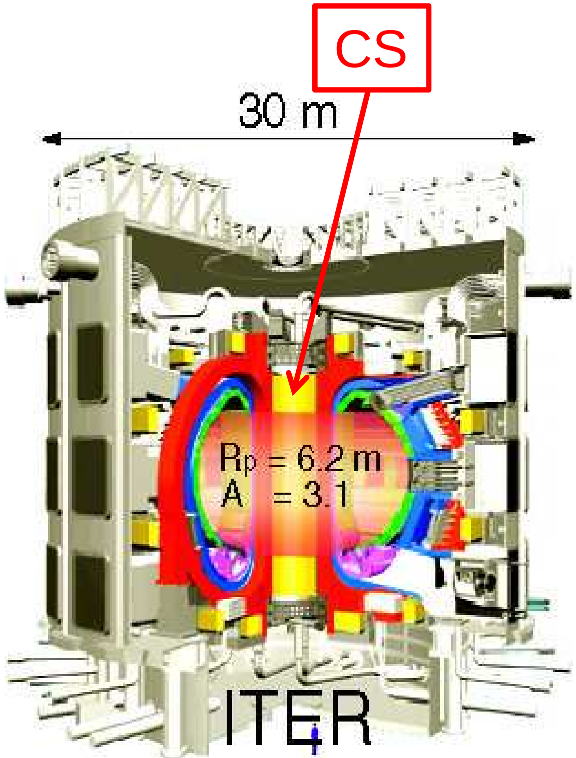
Y. Takase for the TST-2 Group

Graduate School of Frontier Sciences
The University of Tokyo

Third Kyushu Workshop on Solenoid-Free RF-Only ST Plasmas
RIAM, Kyushu University, Kasuga
25-26 March 2015

Motivation and Goal of Research

- Economically competitive tokamak reactor may be realized at low aspect ratio ($A = R_0/a$) by eliminating the central solenoid (CS)

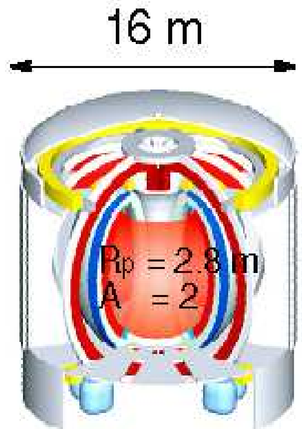


ITER
(18000 ton)
P_F=0.5 GW

$$P_{\text{fusion}} \propto \langle p^2 \rangle \propto \beta_t^{\,2} B_t^{\,4}$$

no CS

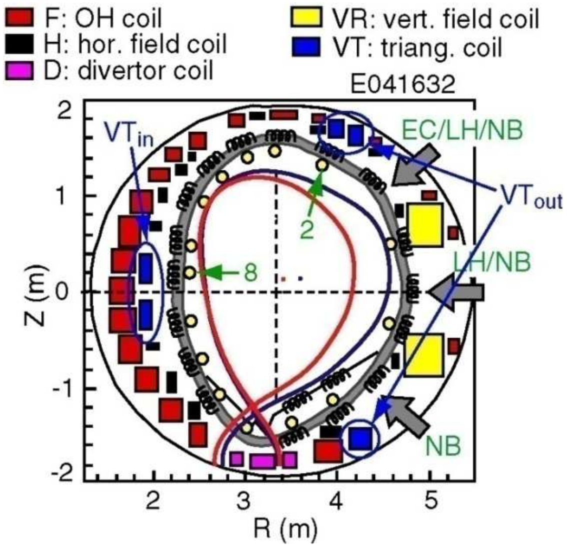
higher B_t
lower A → higher β_t

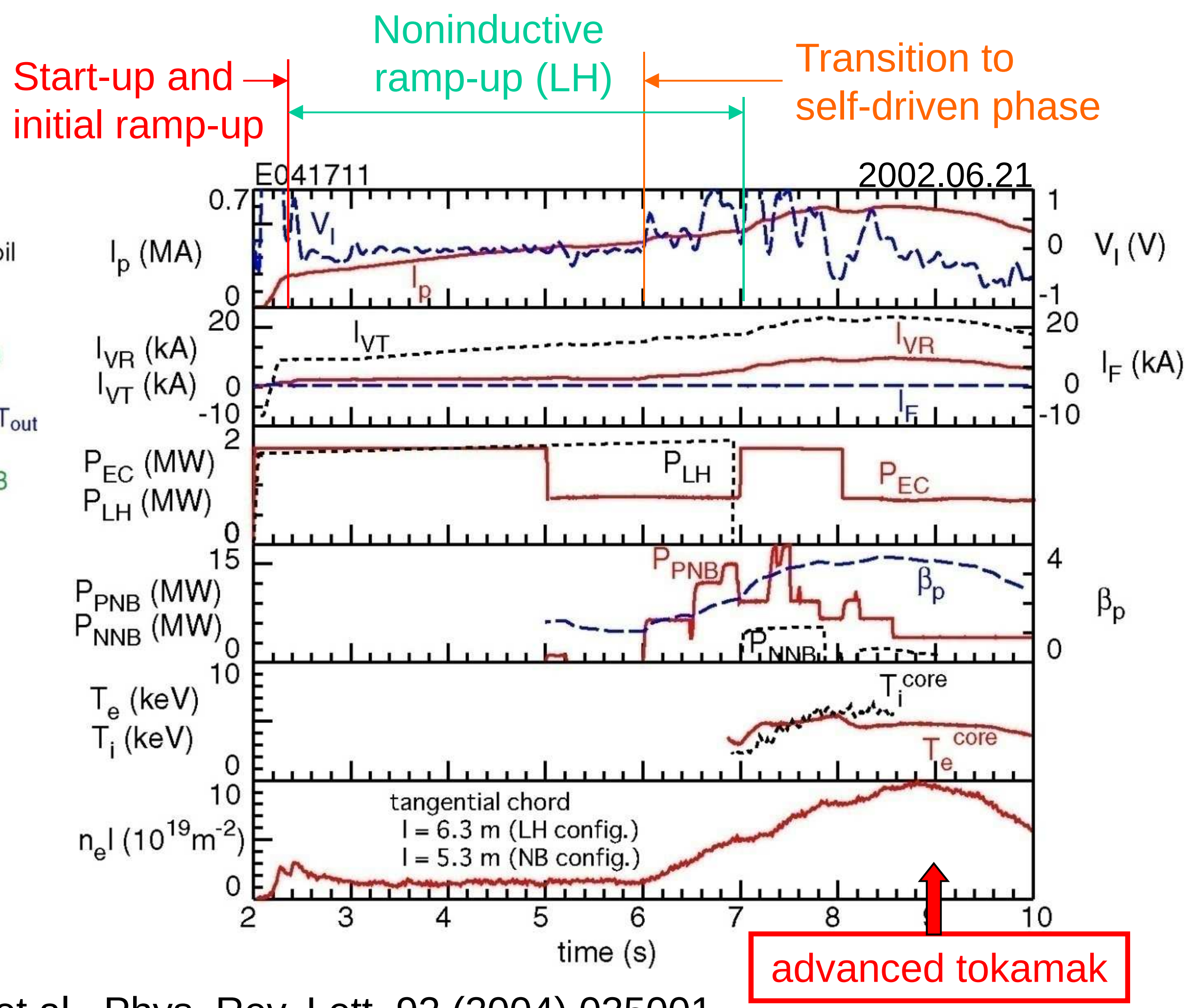


VECTOR
(~9000 ton)
P_F = 3.7 GW

S. Nishio, et al., in Proc. 20th IAEA Fusion Energy Conf., FT/P7-35 (Vilamoura , 2004).

- Formation of Advanced Tokamak Plasma without CS was Achieved on JT-60U





S. Shiraiwa, et al., Phys. Rev. Lett. 92 (2004) 035001.

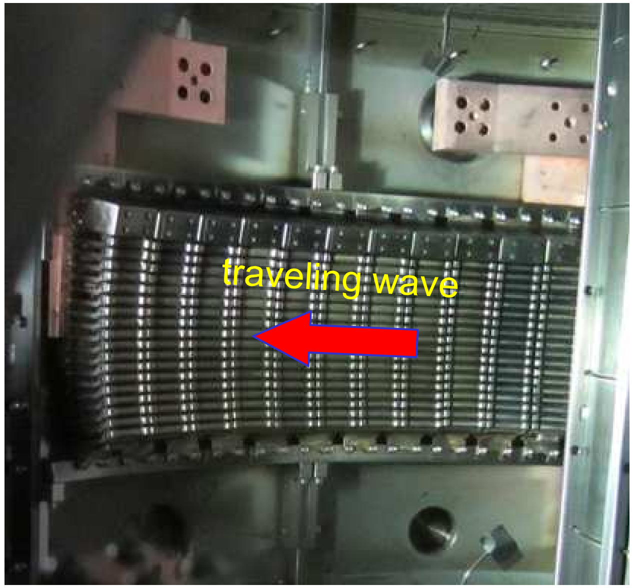
- Is plasma current (I_p) ramp-up by LHW possible in ST?

  $\rightarrow$ Demonstrate on TST-2

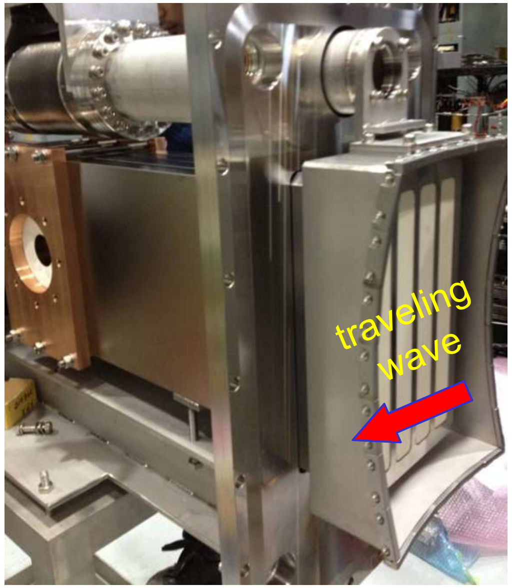
Y. Takase, IAEA FEC 2002

Three Antennas used on TST-2

(Inductively-Coupled) Combline Antenna



Grill Antenna



Capacitively-Coupled Combline (CCC) Antenna

- excites traveling FW
- I_p driven by SW (LHW)

requires mode conversion from FW to SW

- excites traveling SW

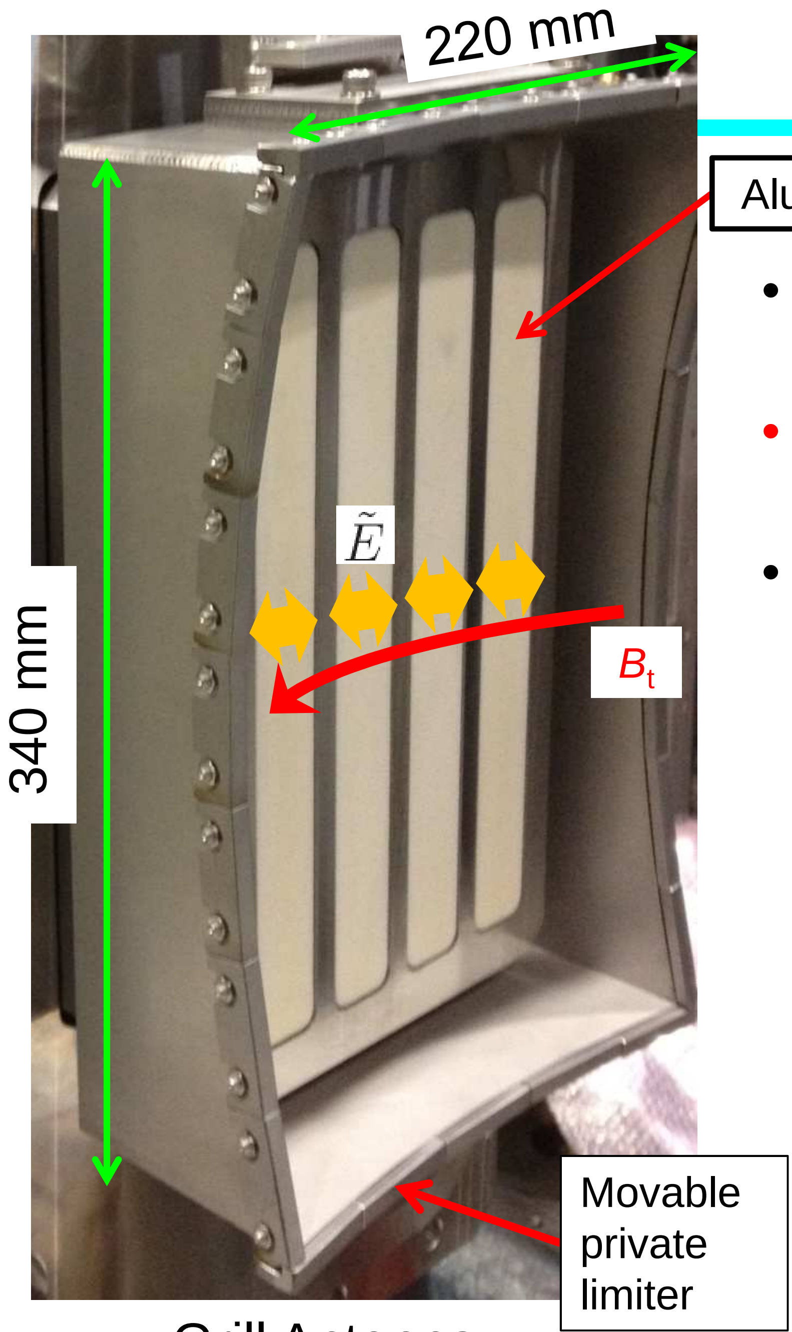
$n_{||} = ck_{||}/\omega$ can be varied

- excites traveling SW

sharper $n_{||}$ spectrum & higher directivity

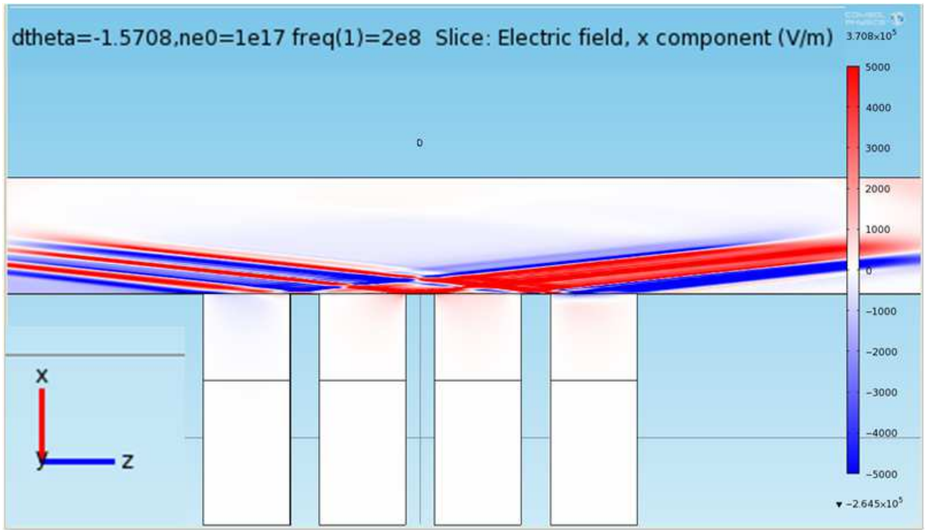
Developed in collaboration with C. P. Moeller (General Atomics, US)

Grill Antenna



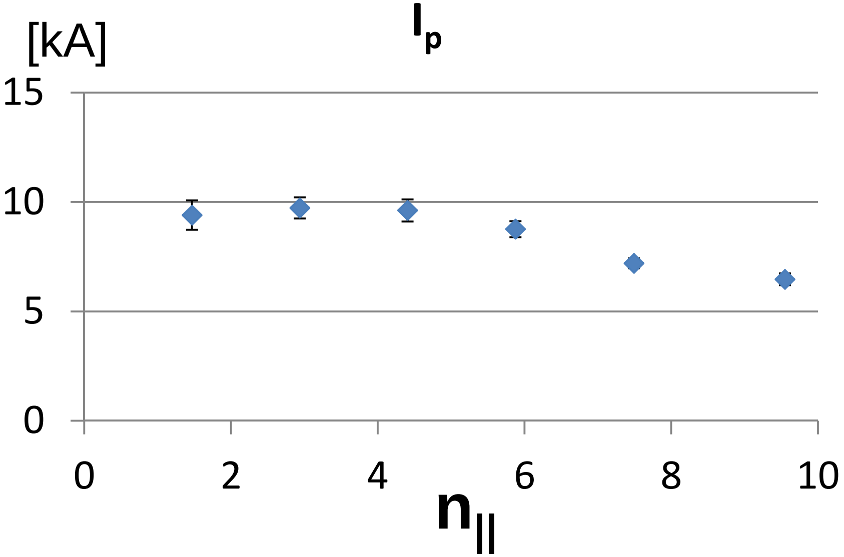
Grill Antenna

- A Ni-plated Alumina block was used as a dielectric-loaded waveguide
- LHW is excited directly by RF electric field in the toroidal direction
- $n_{||} = ck_{||}/\omega$ of the excited LHW can be varied by adjusting the phase difference between adjacent waveguides



T. Wakatsuki

$n_{\|}$ Dependence of I_p and HX Spectrum (Grill Antenna)

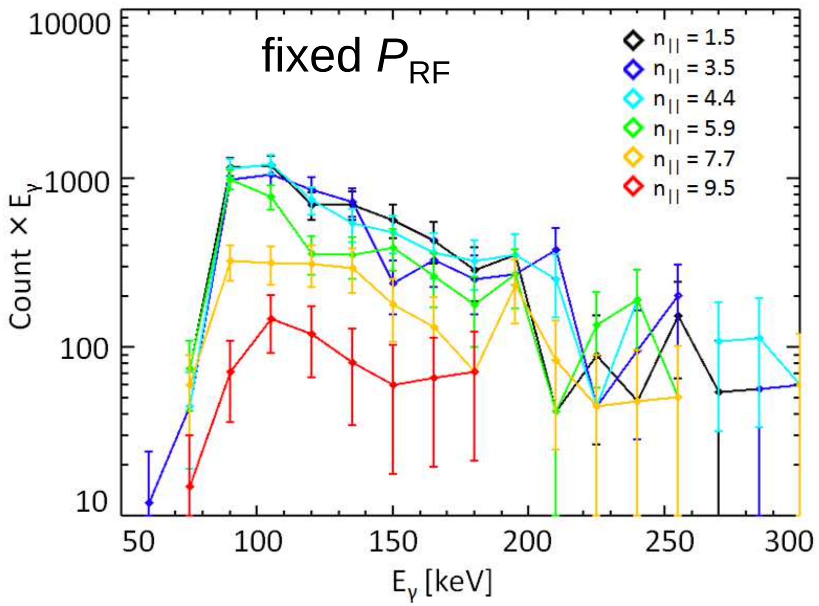


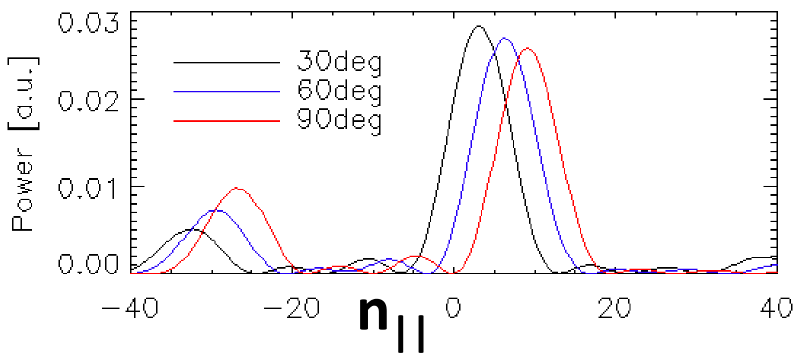
- Highest plasma current was obtained for

  $1.5 < n_{\|} < 4.5$

- Count rate of high energy photons was lower when

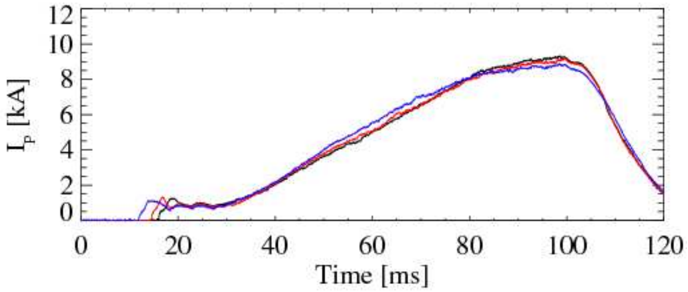
  $n_{\|} > 7.5$

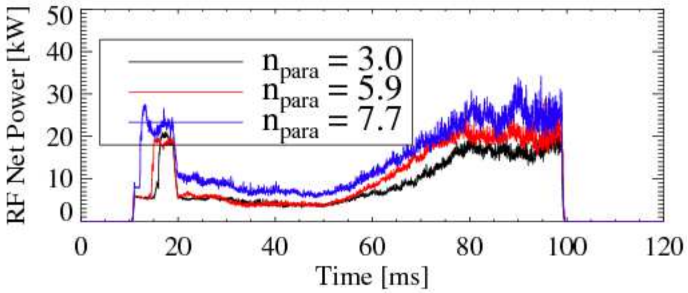


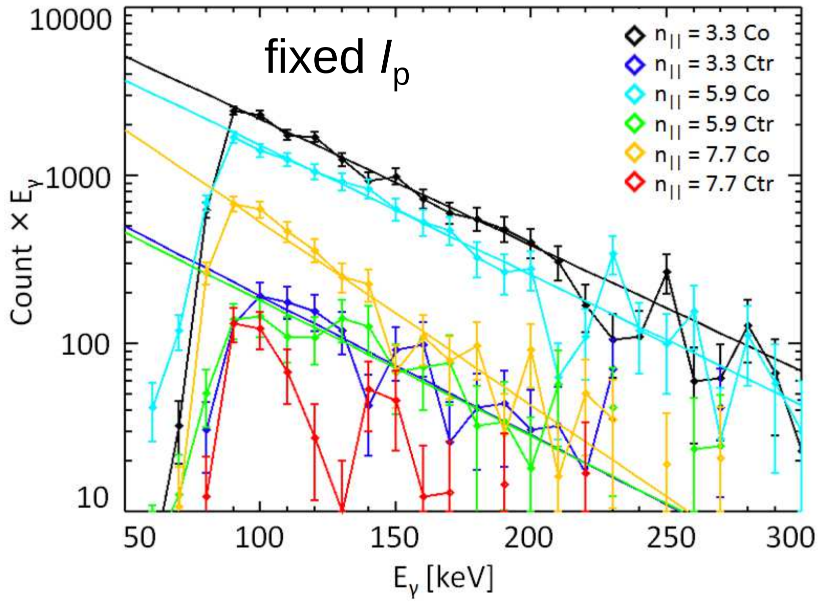


T. Wakatsuki

$n_{||}$ Dependence of I_p and HX Spectrum (Grill Antenna)







- HX spectra were compared with I_p held constant（but with different RF powers）.
- HX flux decreased for $n_{||}$ > 6 even with constant I_p.

  → $1.5 \leqq n_{||} \leqq 6$ are suitable for generating energetic electrons

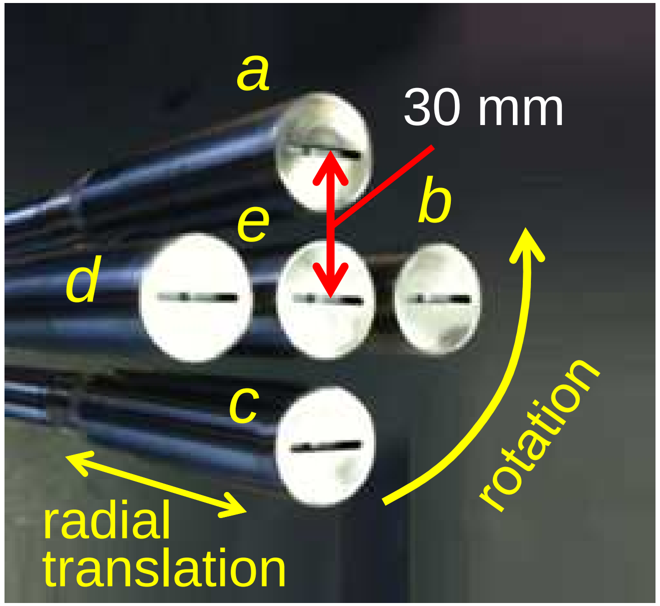
$n_{\|\|}$	3.3	5.9	7.7
T_{eff_co} [keV]	58±3	56±3	40±7

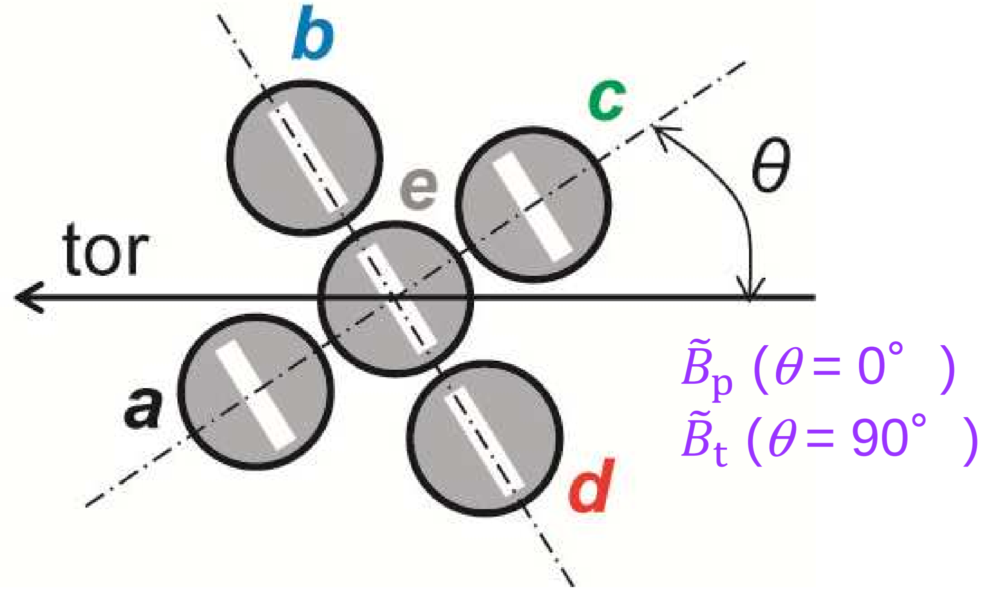
- HX flux is larger in the co-direction at any $n_{||}$

  → asymmetric velocity distribution is formed

T. Wakatsuki

RF Magnetic Probe Array for *k* Measurement (Grill Antenna, ~ 1kA)





- Array can be rotated about its axis
  - to distinguish RF $\tilde{B}$ polarization
  - to measure wavevector components
- Dominant *k* components excited by the antenna are $k_t \cong 50\ \mathrm{m}^{-1}$, $k_p \cong 10\ \mathrm{m}^{-1}$.
  - Measured $k_t \lesssim 10\ \mathrm{m}^{-1}$ is much smaller (higher k_t absorbed?)

	$\tilde{B}_\mathrm{p}$ (SW)	$\tilde{B}_\mathrm{t}$ (FW)
$\lvert k_t \rvert \cong \lvert k_\parallel \rvert$	< 10 m^{-1}	~ 10 m^{-1}
$\lvert k_p \rvert$	< 10 m^{-1}	< 5 m^{-1}
$\lvert k_R \rvert$	~ 35 m^{-1}	~ 10 m^{-1}
$\lvert k_\perp \rvert$	~ 35 m^{-1}	~ 10 m^{-1}

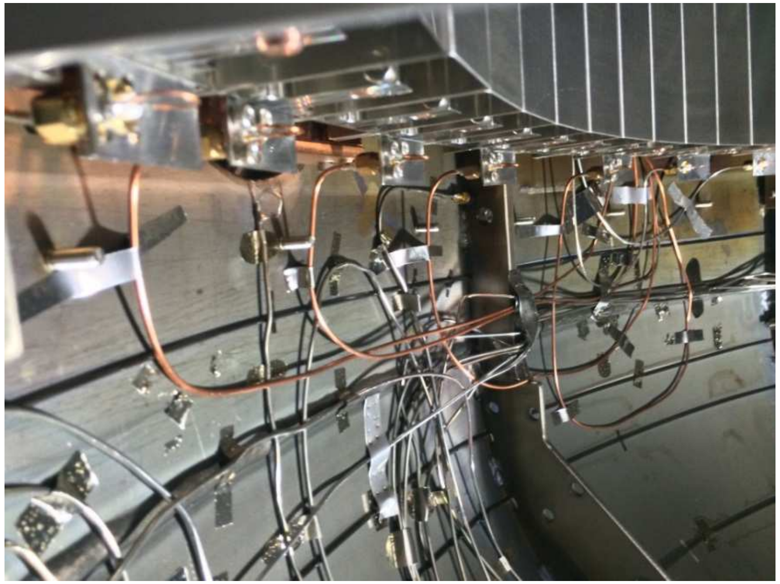
$k_\parallel = 10\ \mathrm{m}^{-1}$ corresponds to $n_\parallel = 2.4$

LH Traveling Wave Antenna Based on a New Concept

Capacitively-Coupled Combline (CCC) Antenna

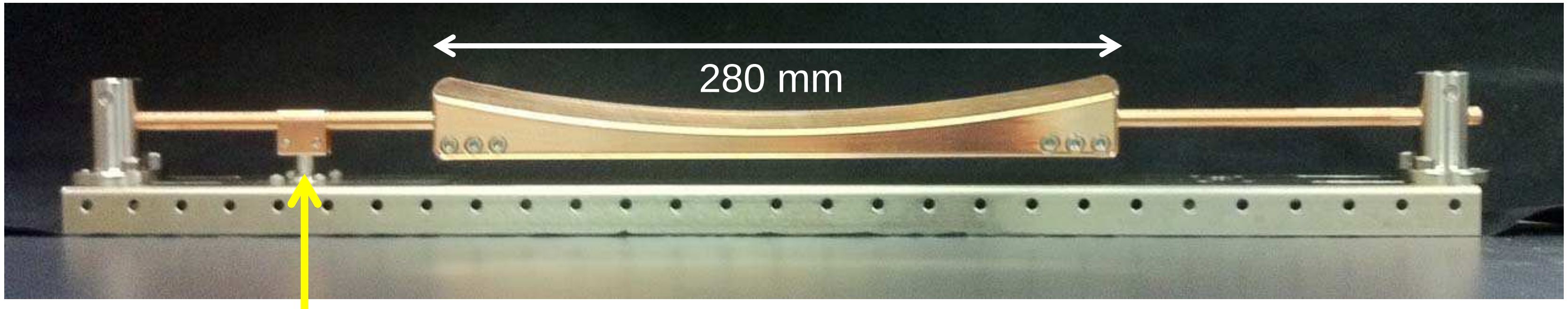
- sharper k spectrum
- higher wave directivity

Power and phase are monitored at 7 out of 13 elements

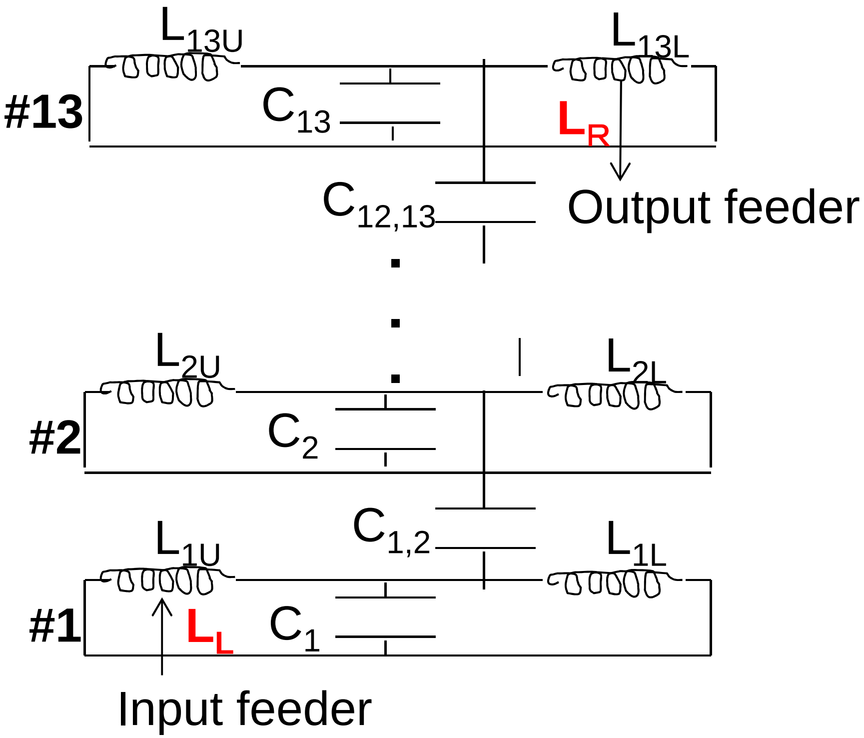


coil diameter: 8 mm
monitored elements:
1, 2, 4, 6, 9, 11, 13

CCC Antenna Element

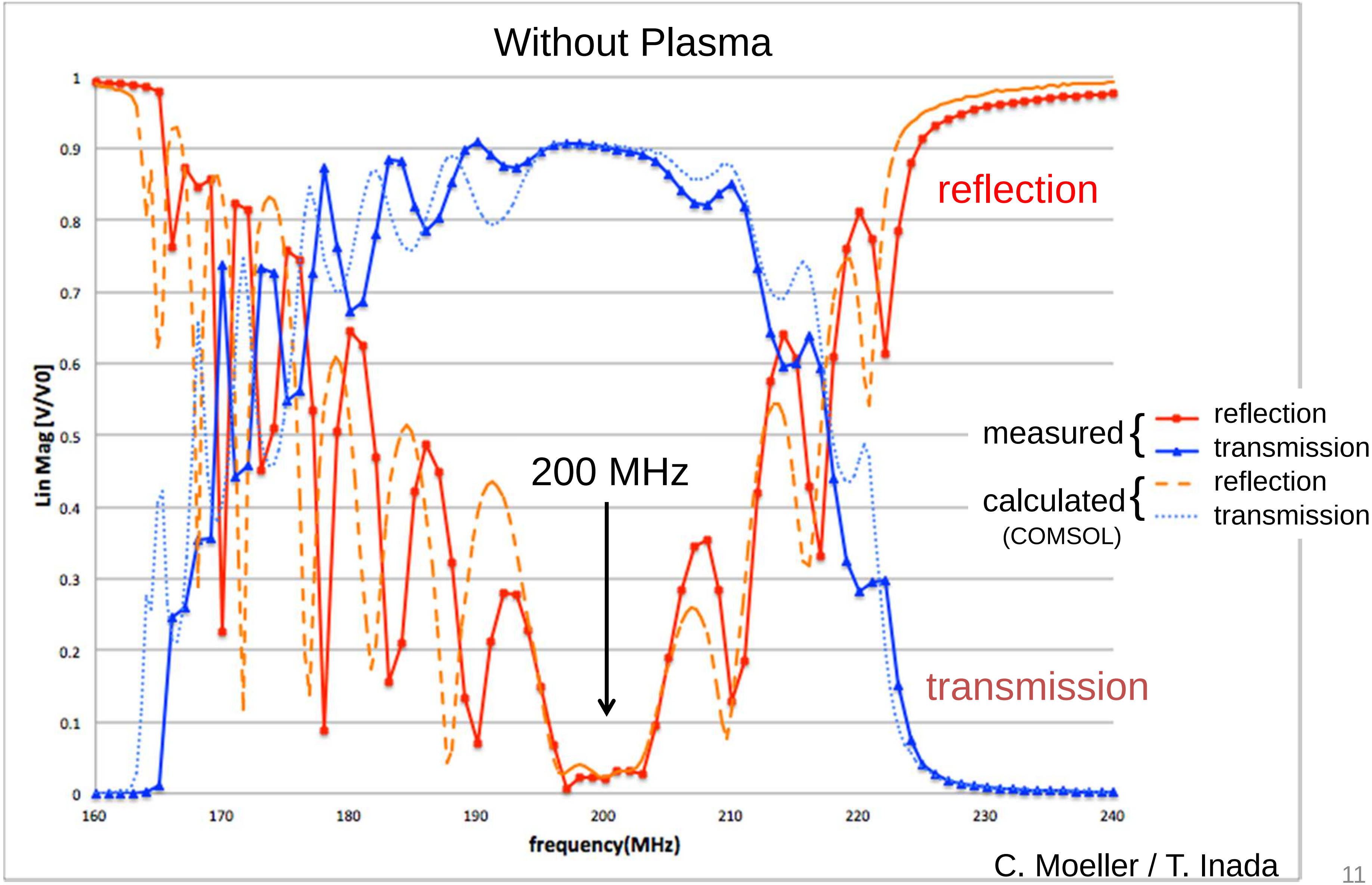


feeder at 50Ω input impedance

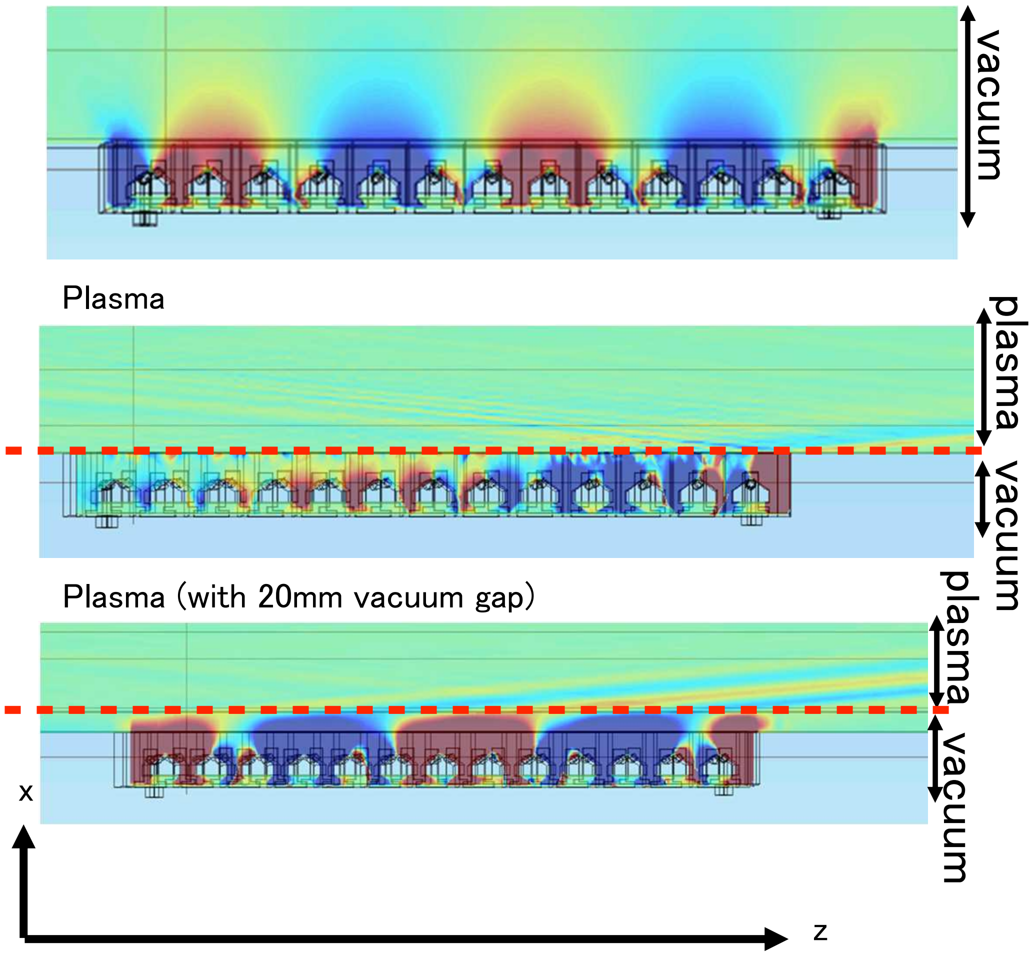


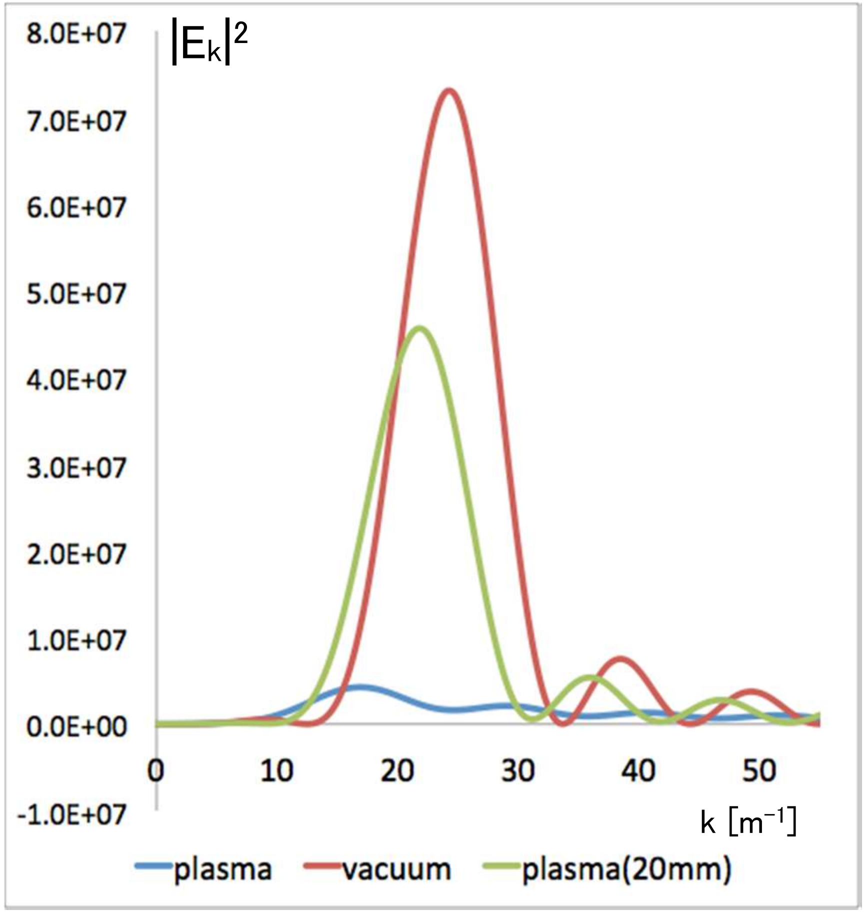
- Radiating element
  - house shaped cross section
  - chosen to reduce the stationary spatial harmonic field
- Inductive rods + rod supports
  - covered by shields to reduce inductive coupling and excitation of the fast wave
- Antenna consists of 13 elements
- Exhibits a band-pass filter characteristic

Measured and Calculated Pass-Band Characteristics



Numerical Simulation of LHW by COMSOL (CCC Antenna)





- Wavenumber spectrum deteriorates in the presence of plasma (depends on antenna–plasma distance)

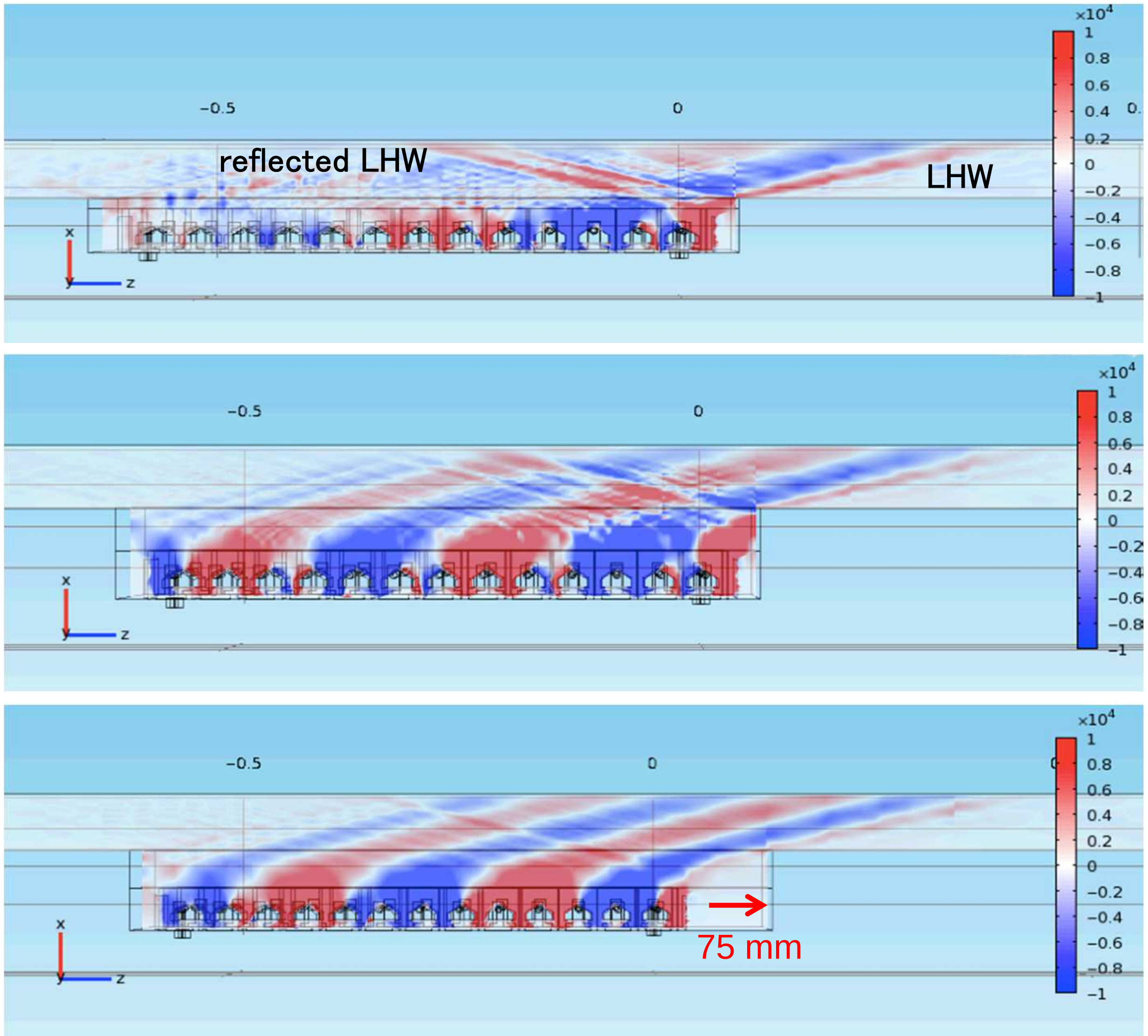
T. Inada

Reflection by the Limiter Must be Avoided

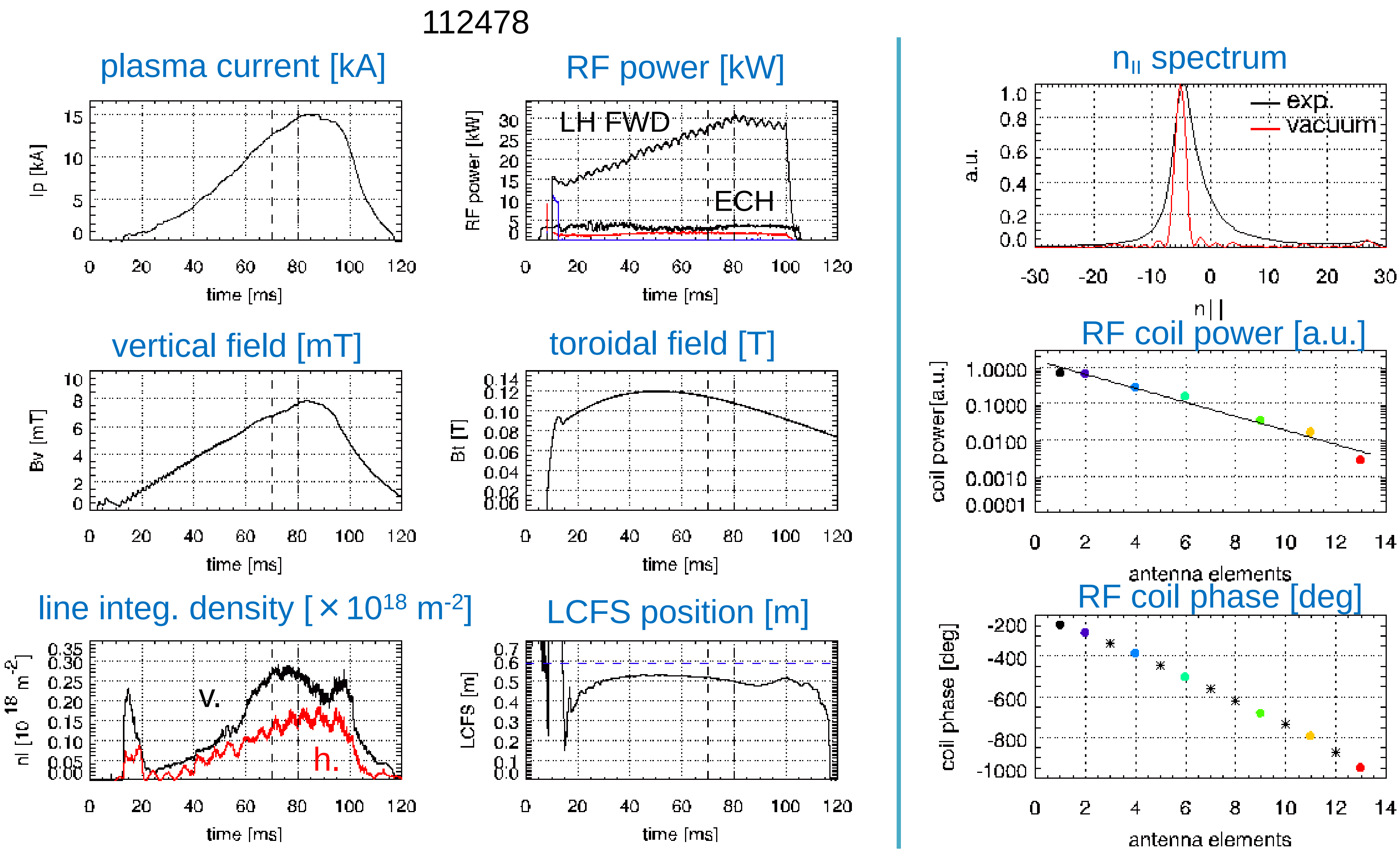
R = 585 mm
(present limiter position)

R = 550 mm

R = 550 mm
(limiter moved in z direction by 75 mm)



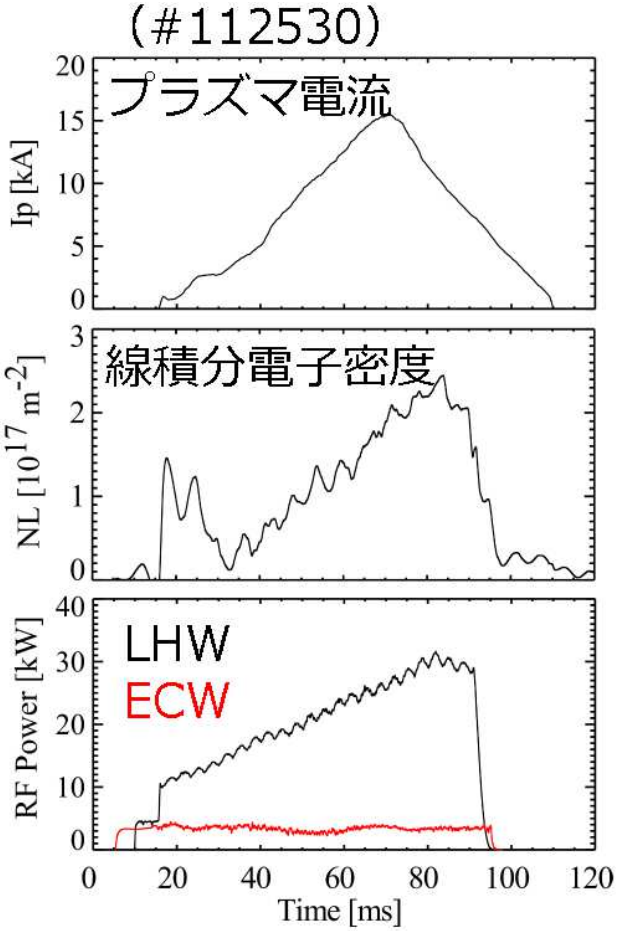
Typical I_p Ramp-up with LHW+ECH (CCC Antenna)

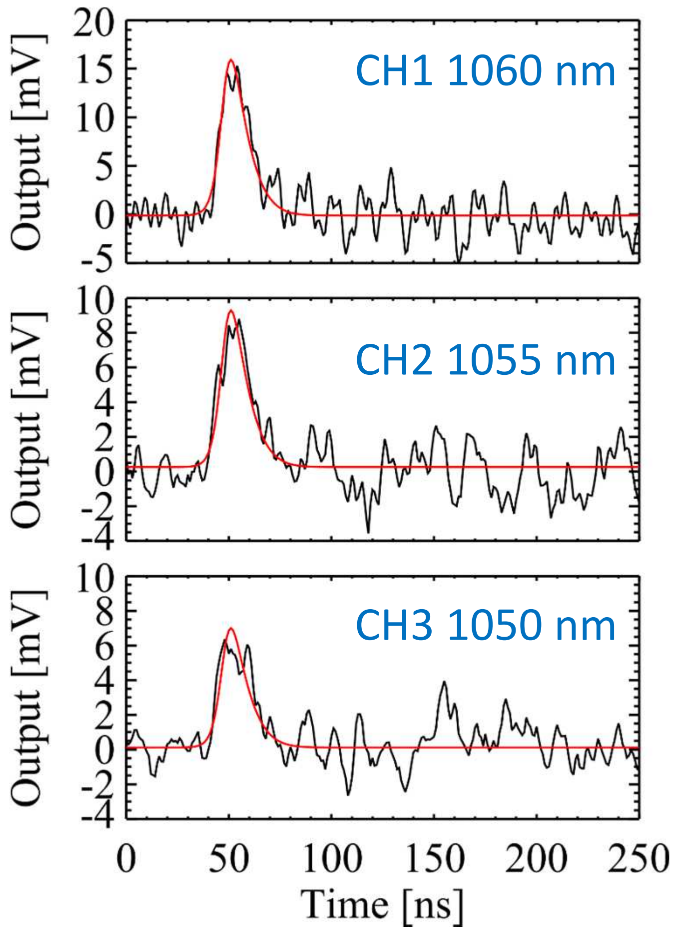


must maintain low density

T. Shinya

First Measurement of T_e in LHW Start-up Plasma (Single-Pass Thomson Scattering)





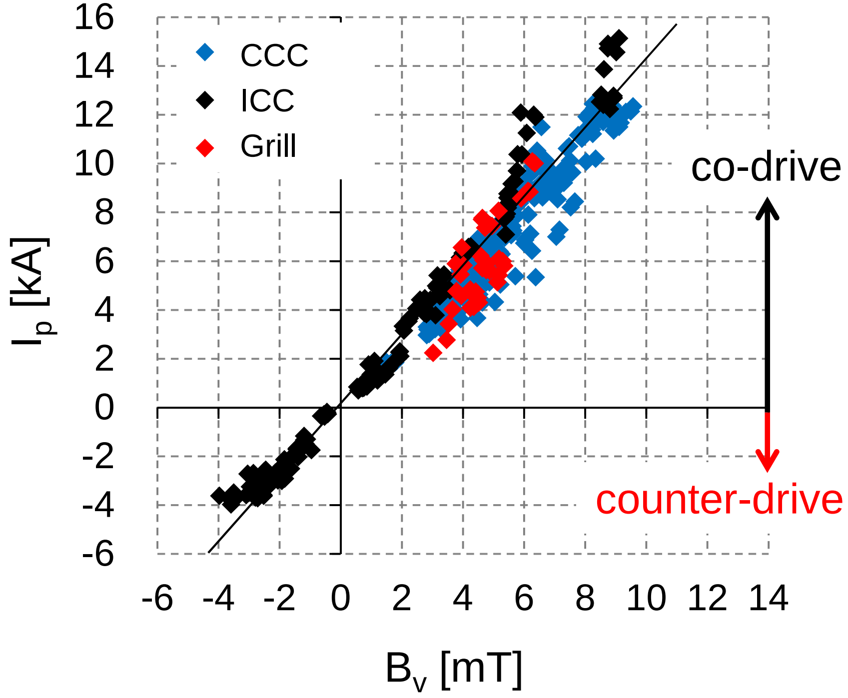
Measured T_e in plasmas ramped up to I_p > 10 kA by LHW with $n_e l$ ~ 10^{17} m^{-2}

Averaged scattered signals over 4 spatial channels and 26 reproducible discharges
→ T_e ~ 10 eV (<±1 eV)

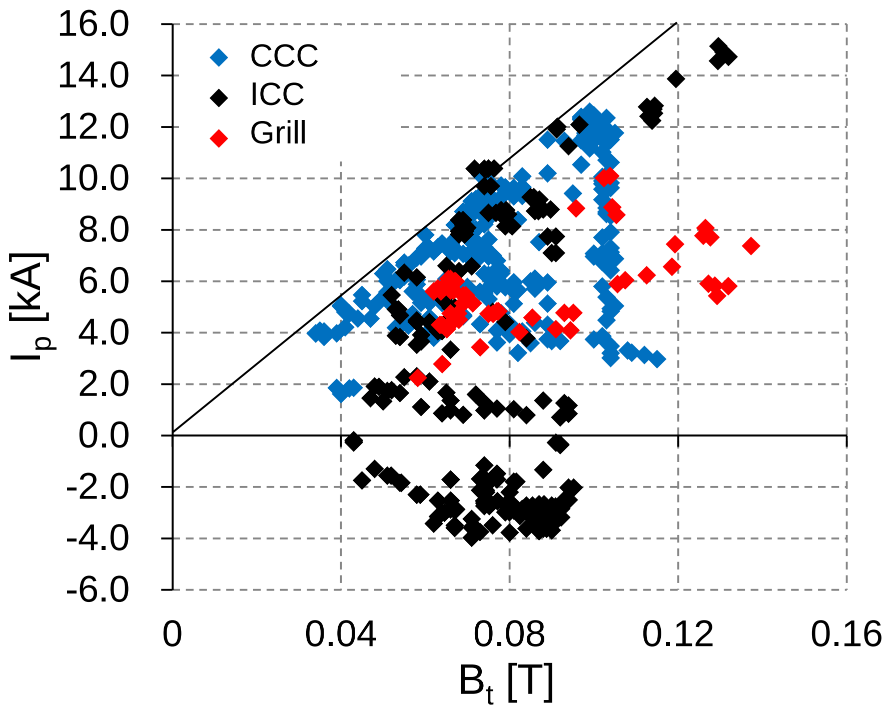
H. Togashi

Scaling of I_p with B_v and B_t

$I_p \propto B_v$



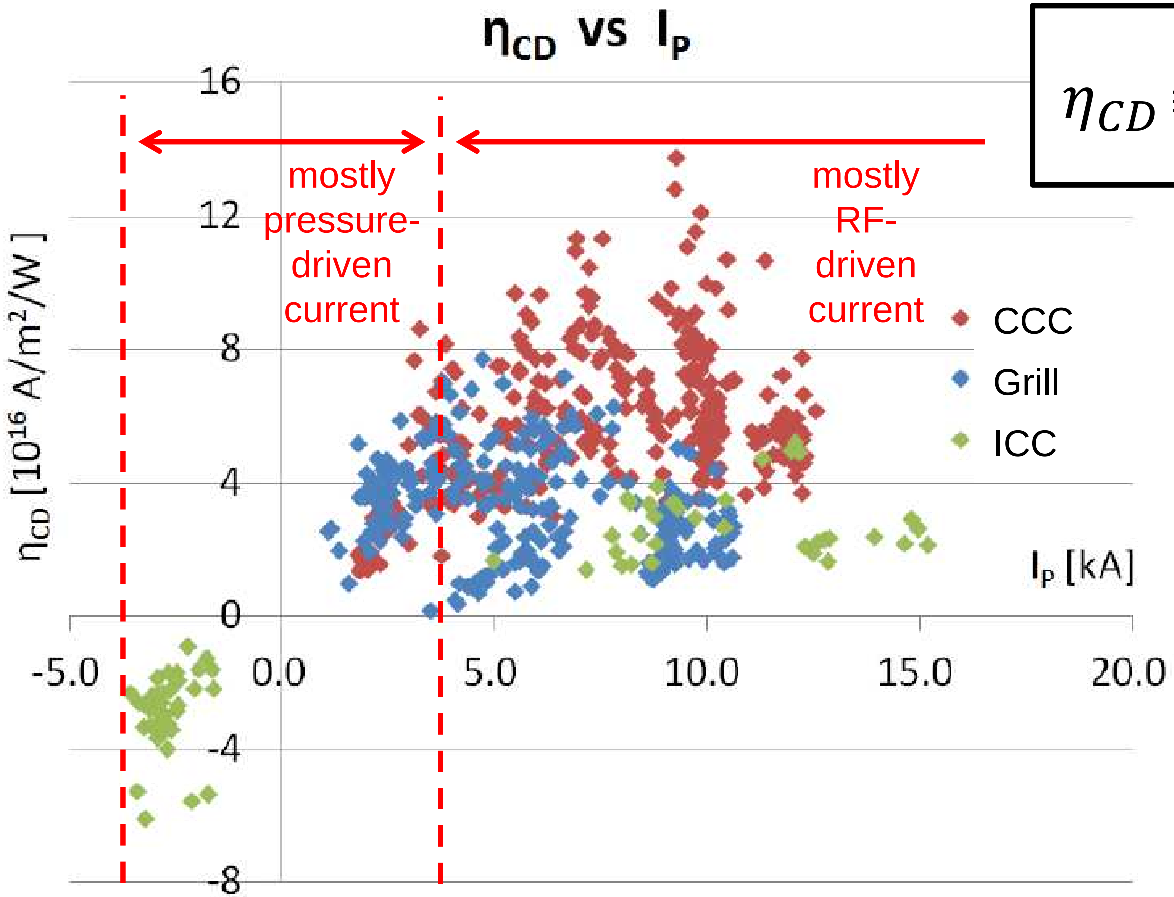
$I_p^{max} \propto B_t$



- I_p increases with B_v (equilibrium).
- Upper bound of I_p increases with B_t (wave accessibility).

T. Shinya

Comparison of the Current Drive Figure of Merit

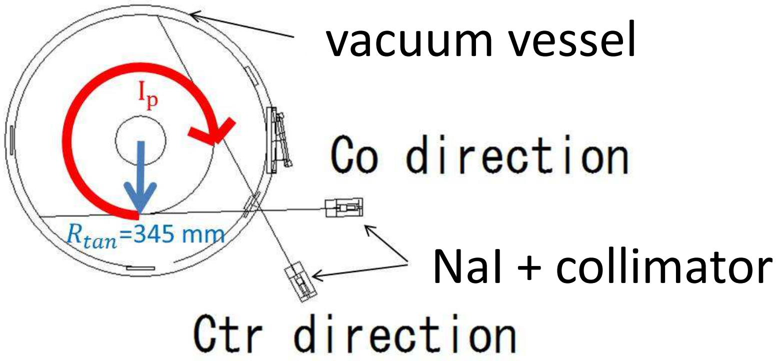


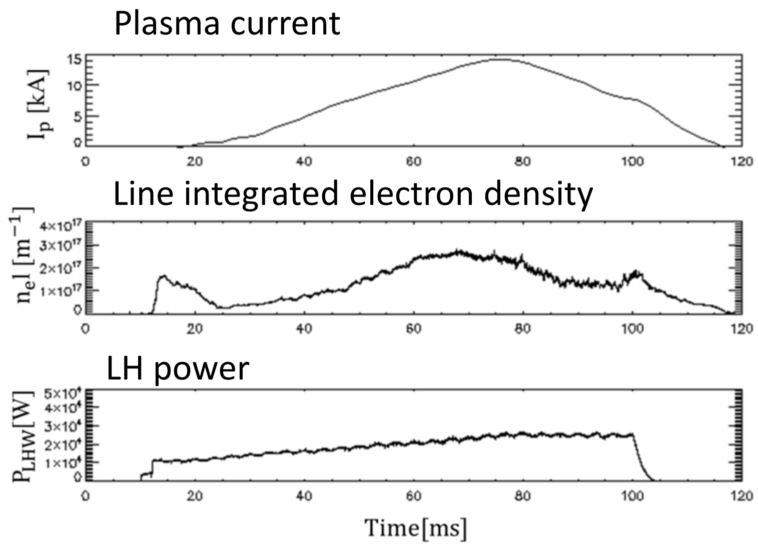
$$\eta_{CD} \equiv \frac{I_p n_e R}{P_{RF}}$$

- Highest η_{CD} is obtained with the CCC antenna.
- An order of magnitude improvement in η_{CD} may be possible by suppression of edge wave power loss and fast electron loss
  $\rightarrow$ operation at higher B_t, n_e, I_p , P_{RF}, T_e

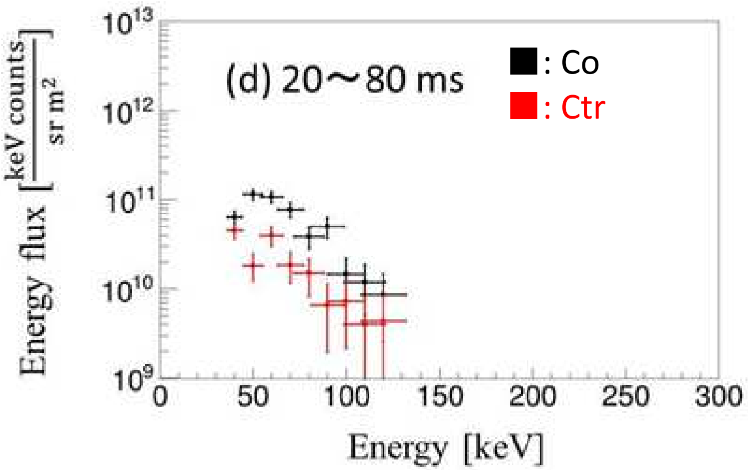
T. Wakatsuki

Co/Ctr X-ray Spectra for Grill/CCC Antenna

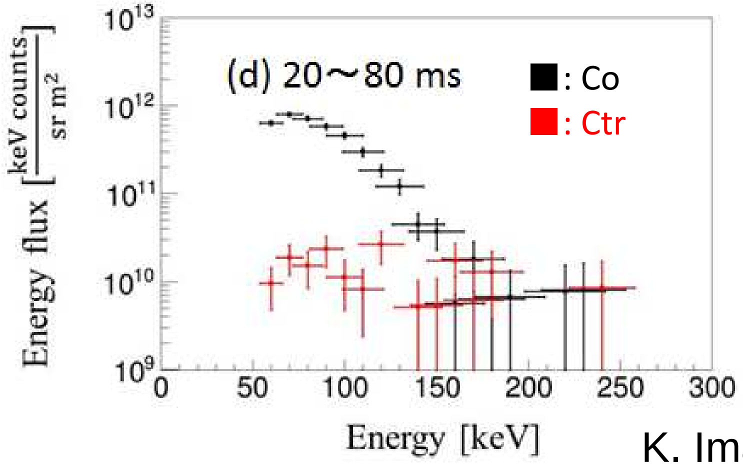




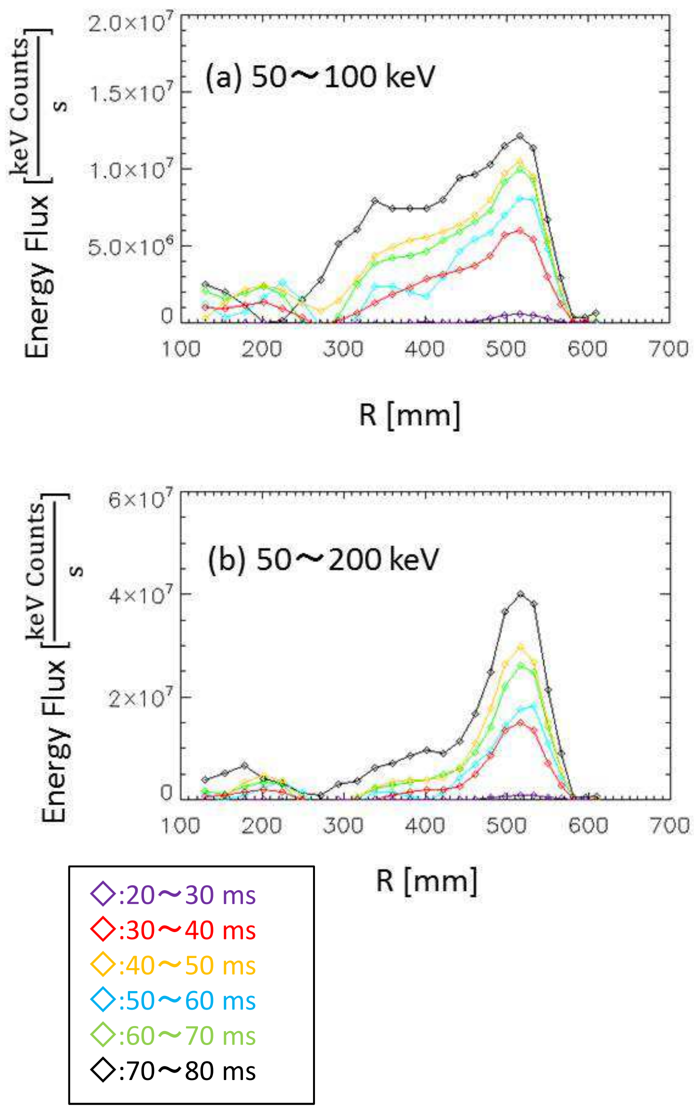
Grill Antenna



CCC Antenna

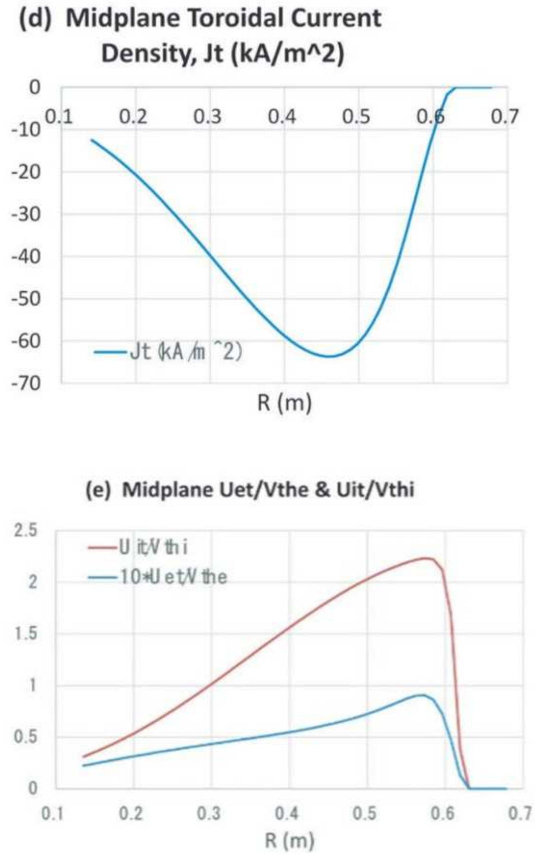


Spatial X-ray Profiles (CCC Antenna)



Higher energy X-ray profile is peaked on the outboard side.

Example of two-fluid equilibrium

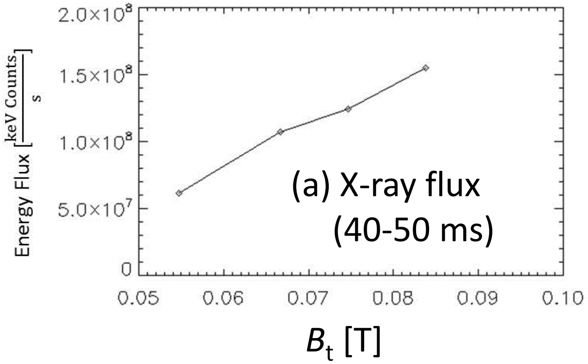


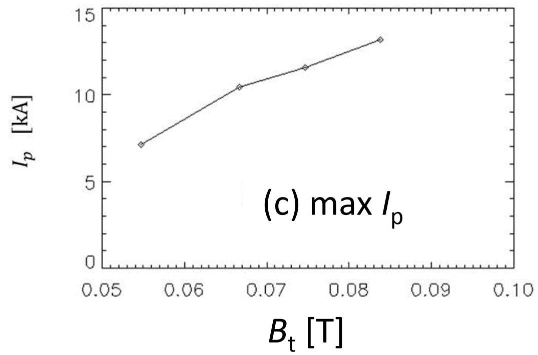
Yueng-Kay Martin PENG, et al., Plasma and Fusion Research 9 3403146 (2014)

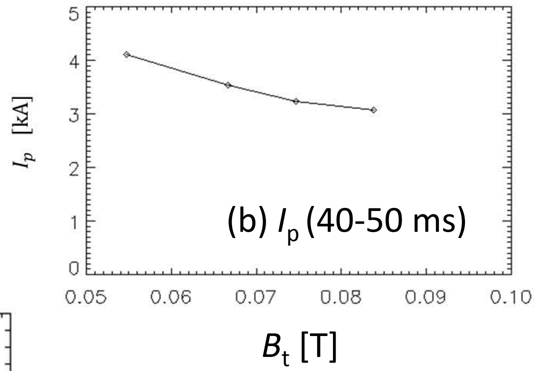
Toroidal Field Dependence of X-ray Profile (CCC Antenna)

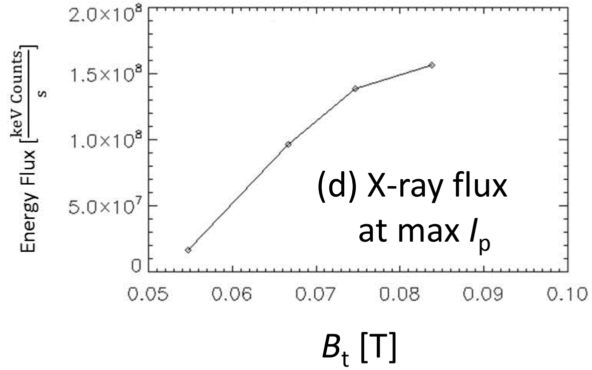
Wave propagation improves at high B_t.

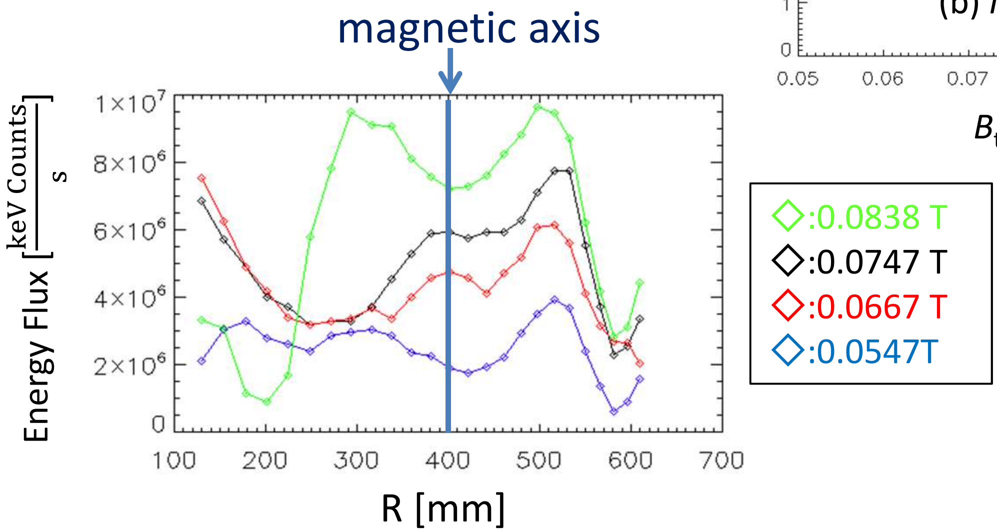
Fast electron population and I_p increase at high B_t.









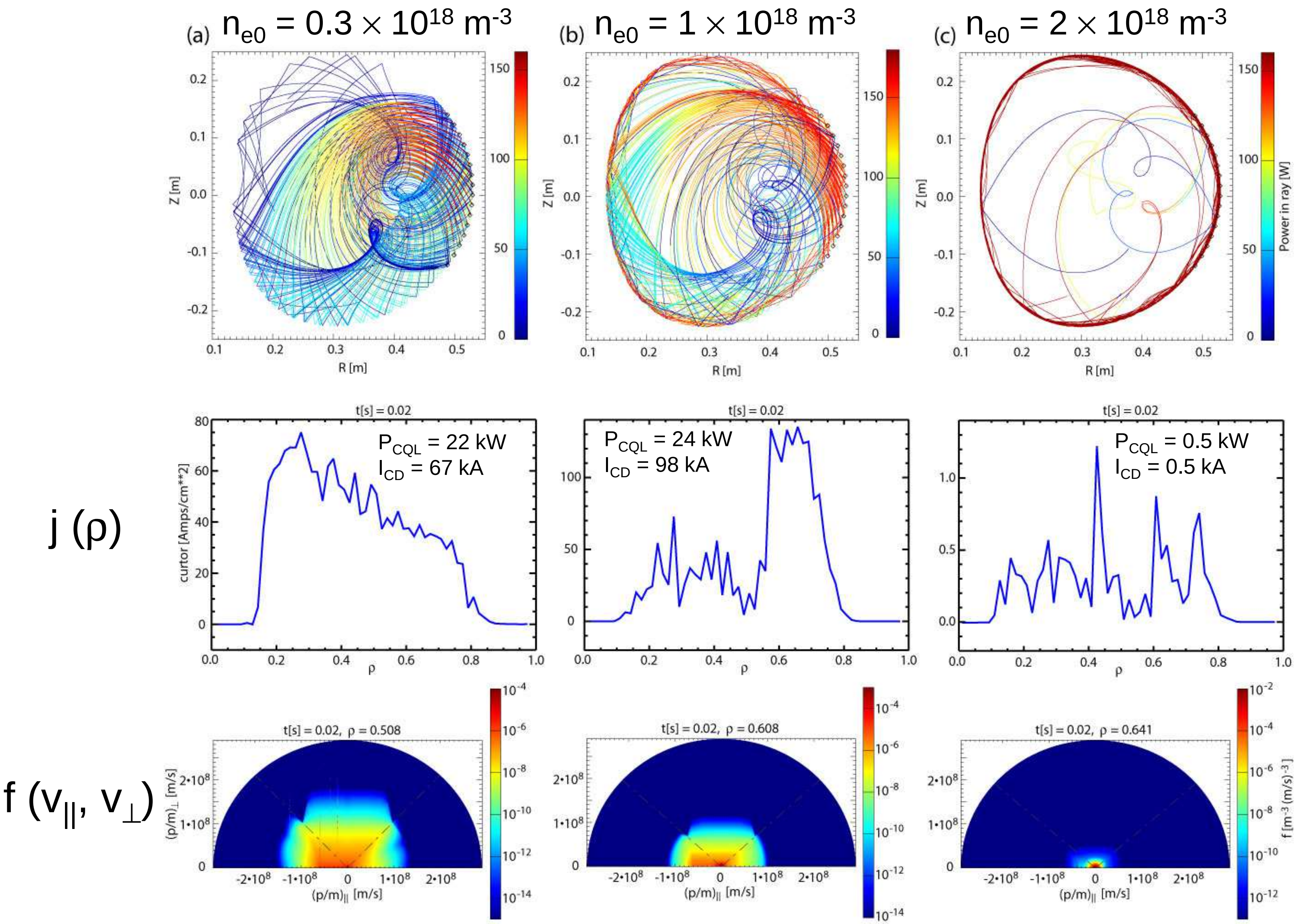


Radial profile shows stronger radiation from the plasma core at high B_t.

LHW propagates to the core and accelerate electrons.

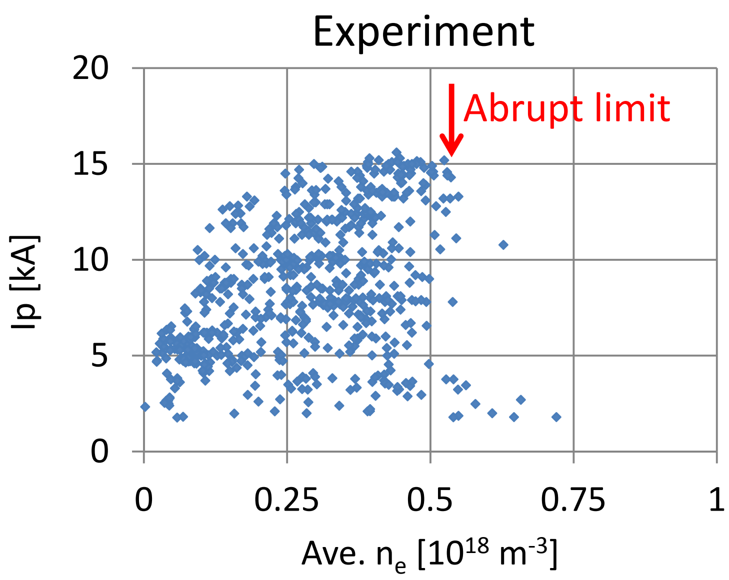
GENRAY/CQL3D Calculation

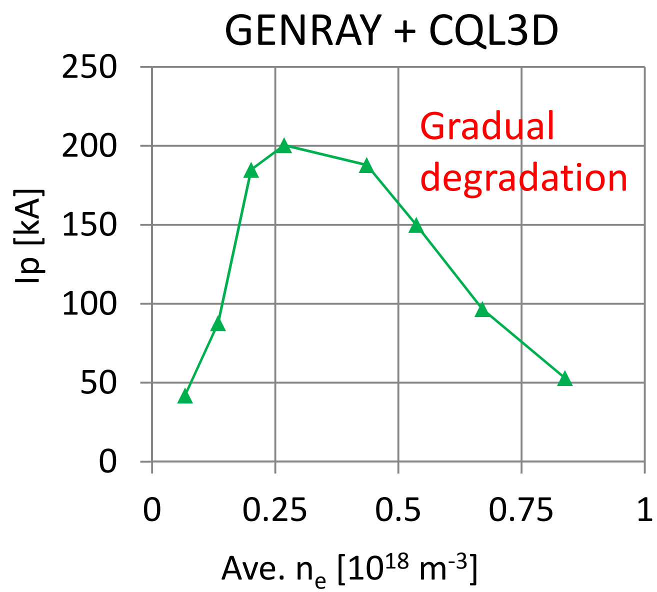
B_t = 0.1 T; I_p = 12 kA; f_{RF} = 200 MHz; P_{RF} = 25 kW; T_{e0} = 0.1 keV



Y. Takase / J. Wright

Is Density Limit Due to Accessibility?

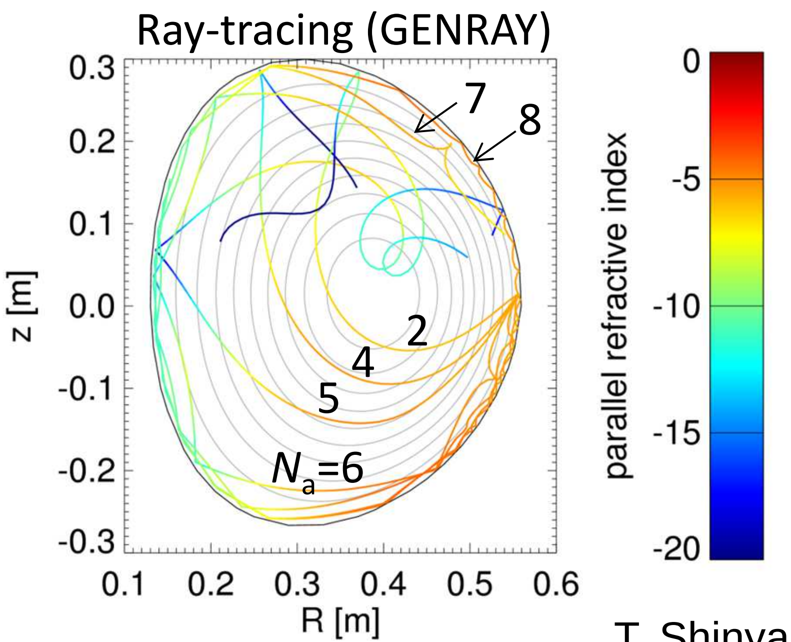




Ave. n_e = $n_e l$ (R = 390 mm) / 0.5

Accessibility: $N_{||} > N_a$

$$N_a = \omega_{pe}/\omega_{ce} + \sqrt{\epsilon_\perp}$$
$$\epsilon_\perp = 1 + (\omega_{pe}/\omega_{ce})^2 - (\omega_{pi}/\omega)^2,$$
$$\omega_{pe}^2 = \tilde{n}_e q^2/\epsilon_0 m_e \, , \omega_{ce} = qB/m_e$$



Fixed: B_t = 0.08 [T], $N_{||}$ = 5.5, shot=111821

Density scan:

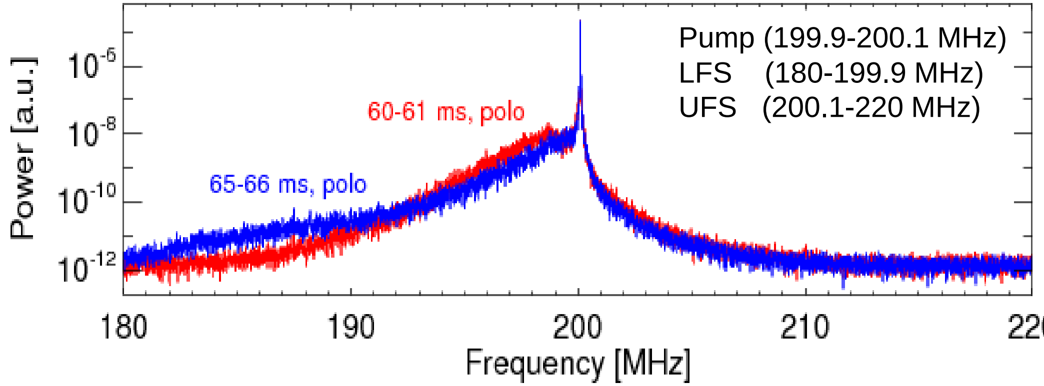
N_a = 2, 4, 5, 6, 7, 8

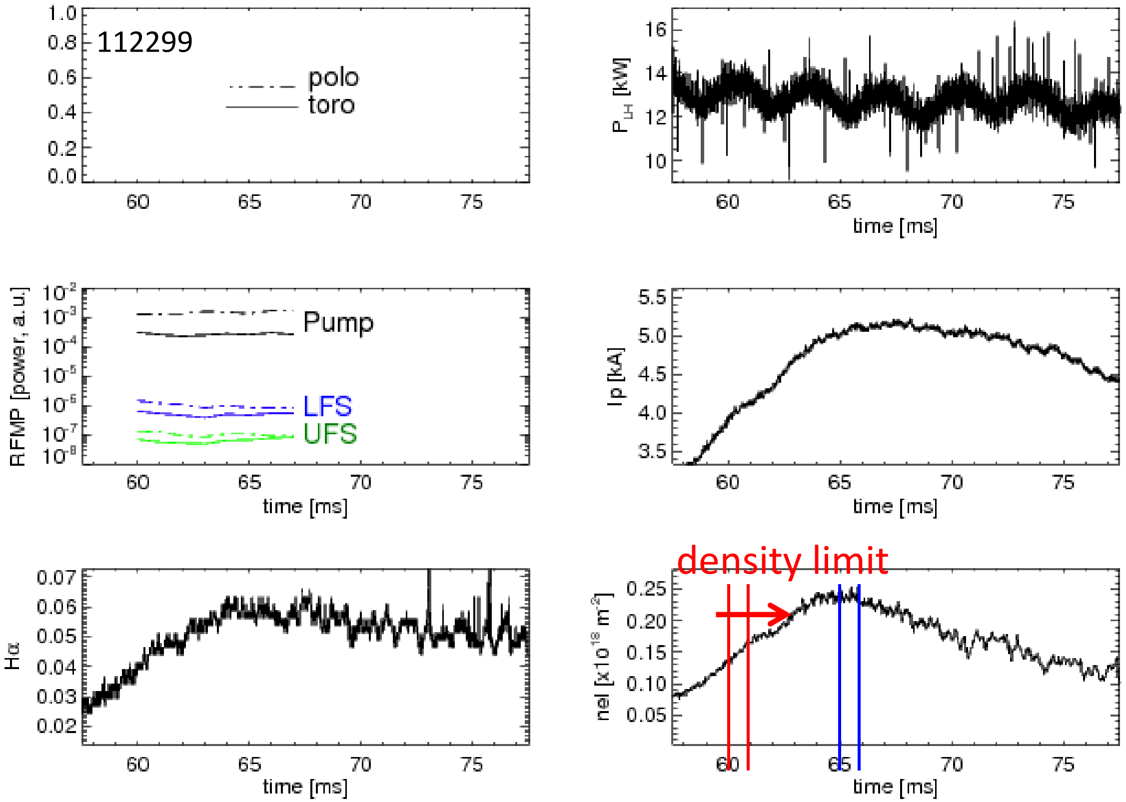
Ave. n_e = 0.034, 0.24, 0.38, 0.56, 0.77, 1.0 x 10^{18} m^{-3}

T. Shinya

Is Density Limit Due to Parametric Decay?

2-channel RF mag. probe
(R, z) = (580 mm, 250 mm)





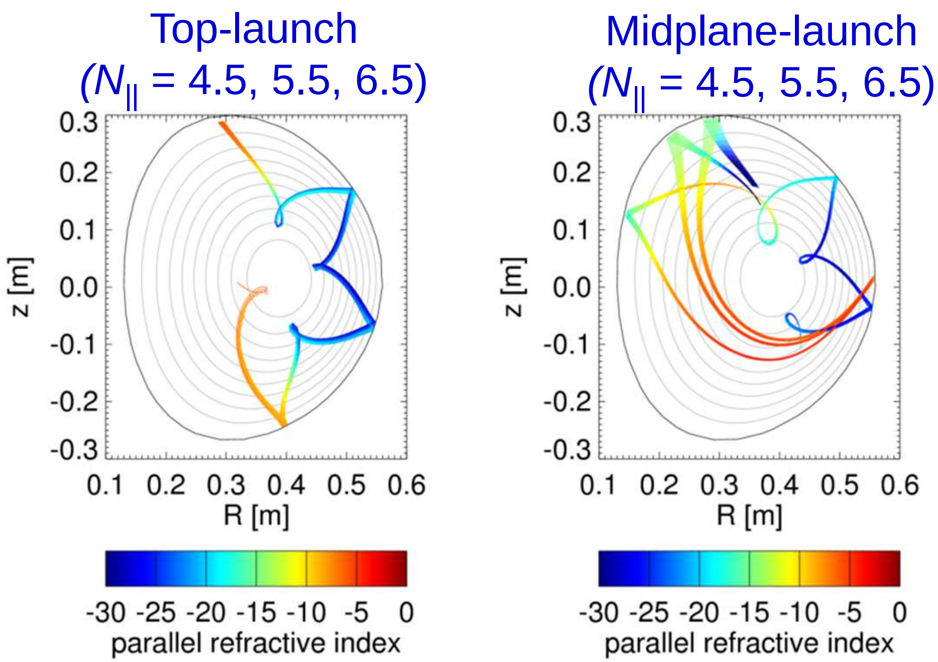
LH resonance frequency for TST-2 RF plasma

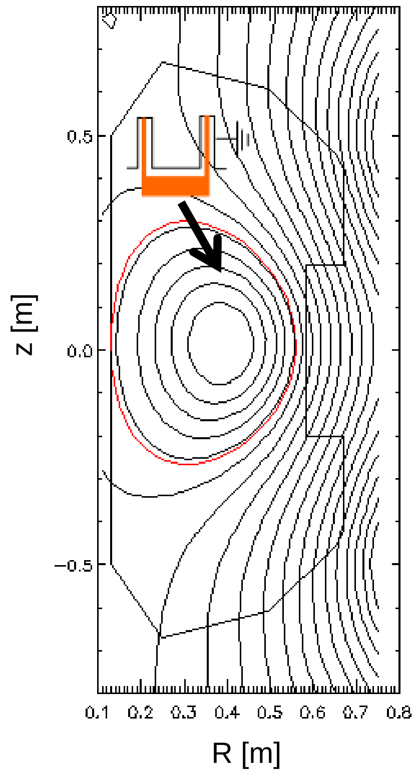
$$f_{\mathrm{LH}} \approx \frac{\omega_{pi}}{2\pi\sqrt{1+\omega_{pe}^2/\Omega_e^2}}$$

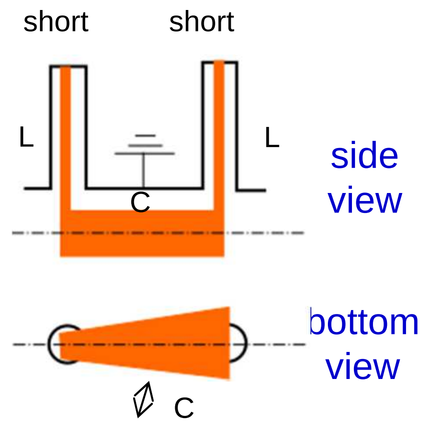
$$\approx 30 \sim 40\ \mathrm{MHz} < 200\ \mathrm{MHz}$$

T. Shinya

Preparation of a Top-Launch Antenna



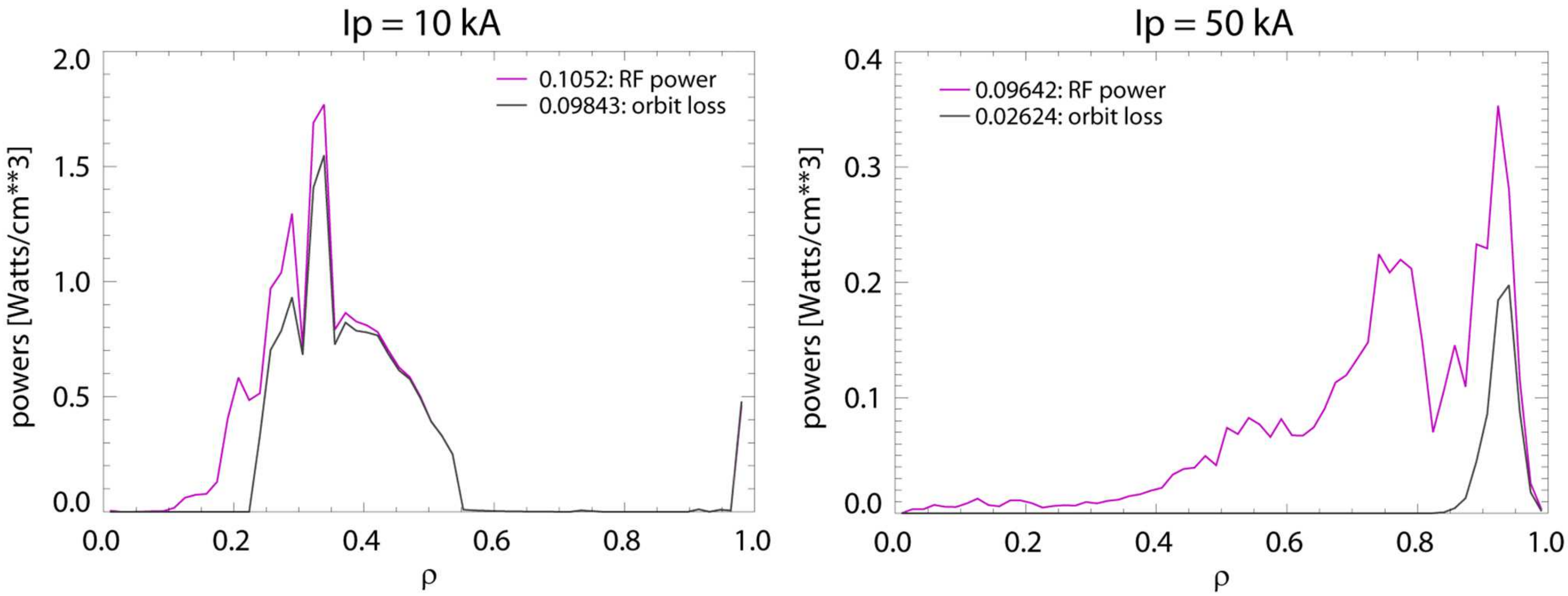




Improved wave propagation and damping are expected by launching the LHW from the top of the plasma.

Collaboration with C. P. Moeller (GA)

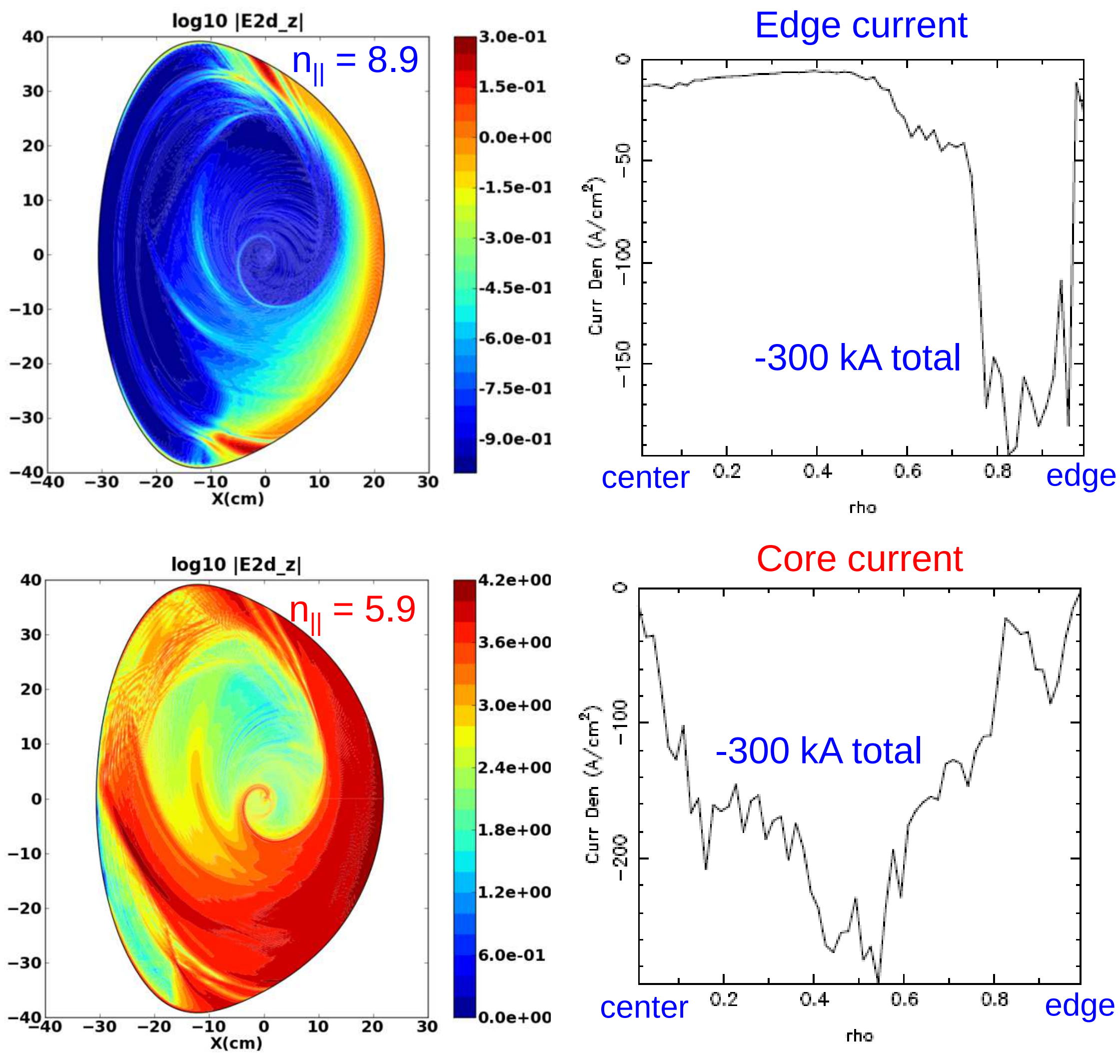
Orbit Loss is Important at Low I_p



- CQL3D Fokker-Planck code calculation shows that the orbit loss is the dominant loss for $\rho \geq 0.2$ at I_p = 10kA.
- Orbit loss from the core is greatly reduced at I_p = 50kA.

Calculated Wave Field and Driven Current Profiles

full wave code ⟷ iteration ⟷ Fokker-Planck code



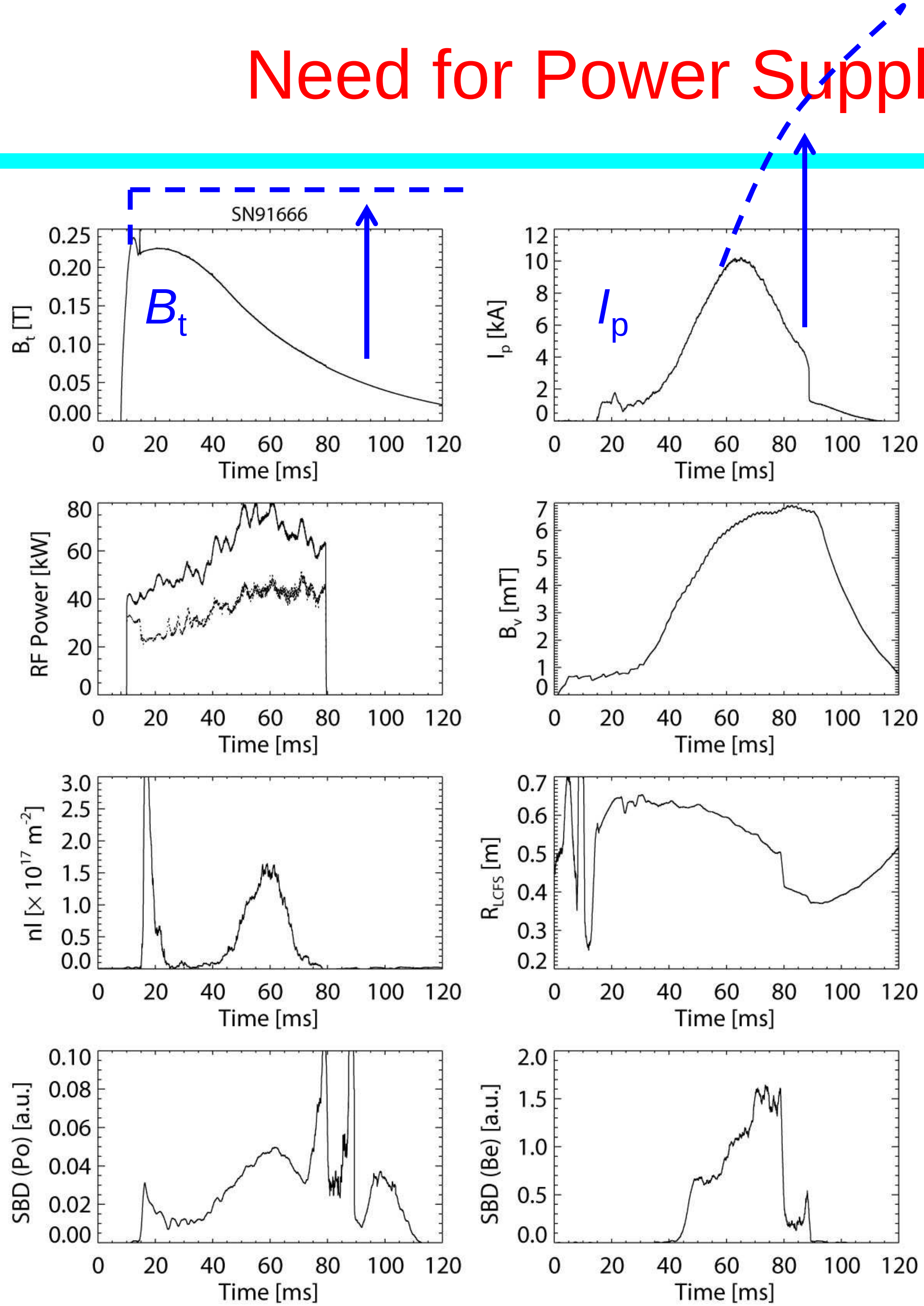
$n_e = 10^{18}$ m^{-3}
B_t = 0.3 T
T_e = 200 eV
P_{RF} = 100 kW

- B_t must be higher to ensure LHW accessibility to the plasma core.
- $n_{||} = ck_{||}/\omega$ must be lower to avoid edge absorption of LHW.

collaboration with
Bonoli, Wright (MIT, US)

T. Wakatsuki

Need for Power Supply Upgrade



In order to demonstrate ramp-up to higher I_p, power supply upgrade is needed to sustain higher B_t (~ 0.3 T) for longer duration (> 0.1 s).

Conclusions

- ST plasma initiation and I_p ramp-up by waves in the LH frequency range were demonstrated on TST-2.
  - Inductively-coupled combline antenna (FW launch), dielectric-loaded waveguide array ("grill") antenna (LHW launch), and capacitively-coupled combline antenna (LHW launch) were used.
  - Similar I_p was obtained with different antennas for similar B_v and P_{RF}, but η_{CD} is higher with the CCC antenna because of higher n_e.
  - At low I_p (< 2 kA in TST-2), I_p is dominantly pressure-driven, and is proportional to B_v. In this regime, I_p is independent of the wave type. At higher I_p (> 5 kA in TST-2), I_p becomes mainly wave-driven. In this regime, control of the current density profile by externally excited waves should become possible.
- Various diagnostics and analysis tools are being developed to study these plasmas.

Near-Future Plans

- Coil Power Supply Upgrade
  - Sustained high field (B_t = 0.3 T for > 0.1 s) for further I_p ramp-up.
- Antenna Upgrade
  - Top-launch combline antenna.
- Wave/Turbulence Diagnostics
  - Electrostatic probe array
  - Reflectometer / interferometer-polarimeter
- Plasma diagnostics
  - Multi-pass Thomson scattering
  - EBW emission
  - Current profile measurement by Rogowski probe / magnetic probe
  - Ion flow measurement (see presentation by A. Ejiri)