The Joint Meeting of 5th IAEA Technical Meeting on Spherical Tori, 16th International Workshop on Spherical Torus (ISTW2011), and 2011 US-Japan Workshop on ST Plasma
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Recent Progress in the SUNIST Spherical Tokamak

Yi Tan[1], Zhe Gao[1], Wenhao Wang[1], Lifeng Xie[1], Long Zeng[1], Huiqiao Xie[1], Ou Zhao[1], Yangqing Liu[1], Yanzheng Jiang[1], Song Chai[1], Xiaowei Peng[1], Kun Yao[1], Aihui Zhao[1]
Chunhuan Feng[2], Long Wang[2], Xuanzong Yang[2]
Guixiang Yang[3]
Email: tanyi@sunist.org

1) Department of Engineering Physics, Tsinghua University, Beijing, China
2) Institute of Physics, Chinese Academic of Science, Beijing, China
3) College of Nuclear Physics and Technology, Nanhua University, Hengyang, China

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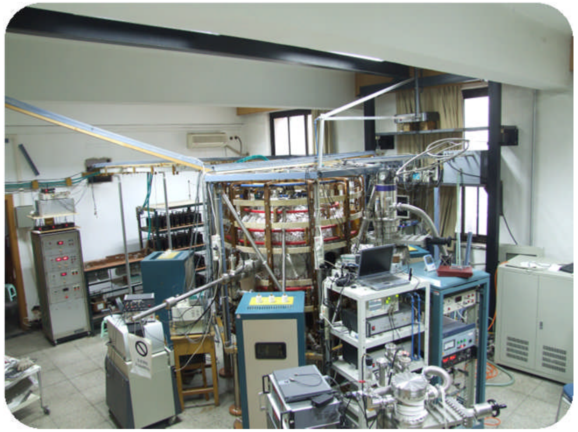
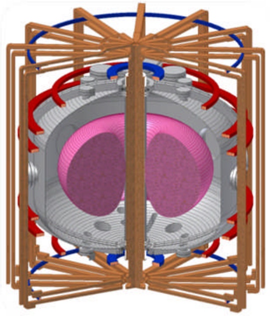
Introduction to SUNIST

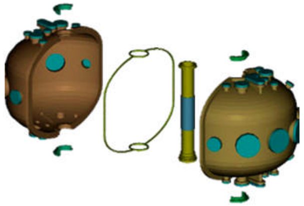
- **SUNIST: Sino *UNIted* Spherical Tokamak**
  - What are united?
    - Department of Engineering Physics, Tsinghua University
    - Institute of Physics, Chinese Academy of Sciences
  - Major parameters
    - R_0/a: 0.3 / 0.23 m ~ 1.3
    - B_{T0}: <0.15 T
    - I_P: ~ 50 kA
    - n_e: ~ 1×10^{19} m^{-3}
  - Major diagnostics
    - Langmuir probes
    - Normal (<100 kHz) / High frequency (~1 MHz) magnetic probes
    - Visible Spectrometers (250~ 750 nm)
    - 94 GHz interferometer
    - 8 mm reflectometer
    - Fast visible camera
    - H_α diode array

Overview of the SUNIST device





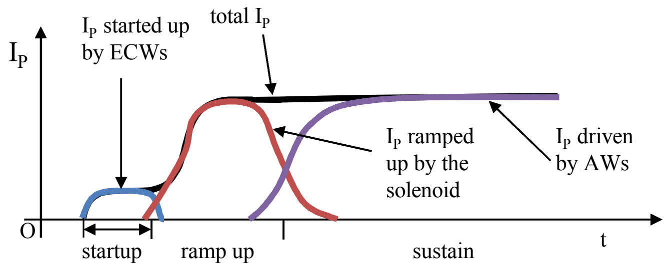
Section view of the SUNIST device



The vacuum vessel of SUNIST

Major Research Interests of SUNIST

- **Non-inductive current startup and drive**
  - Startup: by electron cyclotron waves (ECW)
    - Breakdown the neutral gas and initiate a small plasma current
  - Drive: by Alfven waves (AW)
    - Maintain the ohmic plasma current



An idealized running scheme for SUNIST

- **Properties of ST plasmas**
  - Edge plasmas
    - Electrostatic/magnetic fluctuation and anomalous transport characteristics
  - MHD characters
    - MHD behaviors and methods to affect or control MHD activities

Outline

- **Recent research progress**
  - Analysis of the startup by ECWs
  - Preliminary results of AW experiments
  - MHD studies
- **Recent engineering progress**
  - Upgrade of the field power supplies
  - Other upgrades
- **Future plans**
- **Summary**

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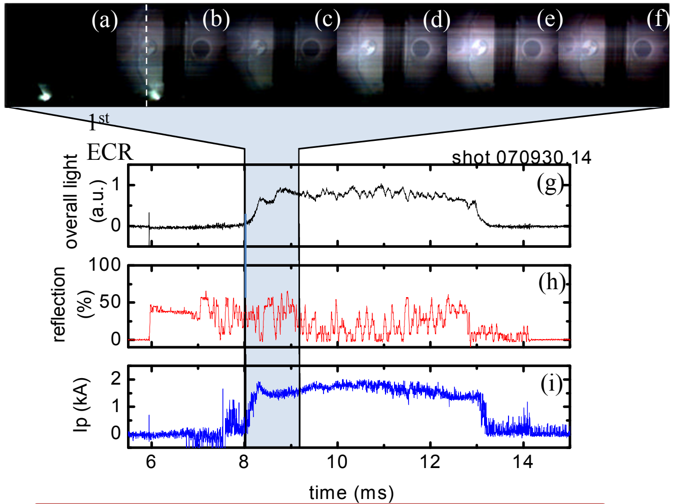
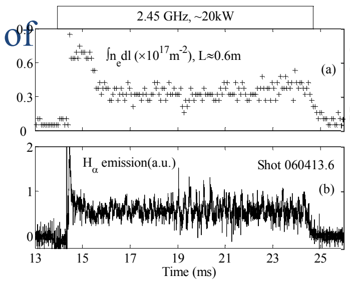
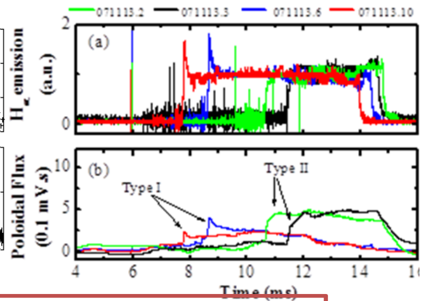
Analysis of ECW startup

- **Brief experimental results of ECW startup**
  - 2.45 GHz/100 kW/10 ms (limited)
  - O mode outboard injection
  - ~2 kA I_P last for several ms
  - I_P is inversely proportional to B_V
  - Closed flux surface may formed but no current jump observed
- **What we focused on**
  - The spikes at the beginning of discharges (I_P, H_α and n_e)
  - → The time and spatial evolution of n_e is essential to understand the physics of startup
  - → **<u>Investigate the transient process of the plasmas during startup !</u>**
  - PS: spikes are widely found on STs



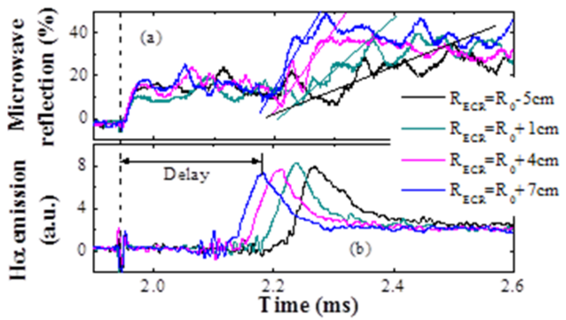
Typical waveforms of ECW startup on SUNIST



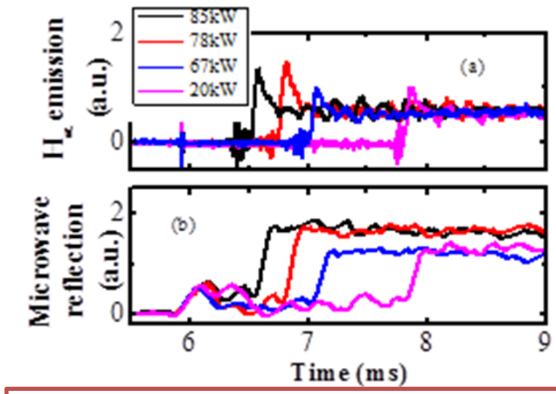


Spikes are found at the beginning of discharges

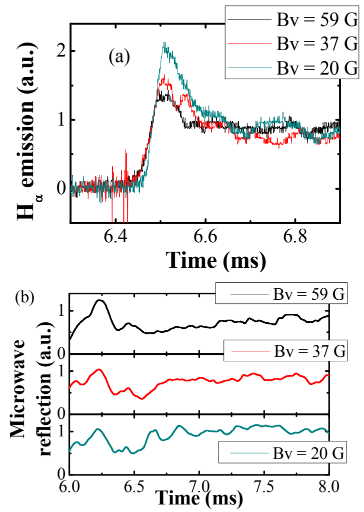
Effects of B_V, B_T and P_{rf} on the spikes



B_T scanning results



P_{rf} scanning results



B_V scanning results

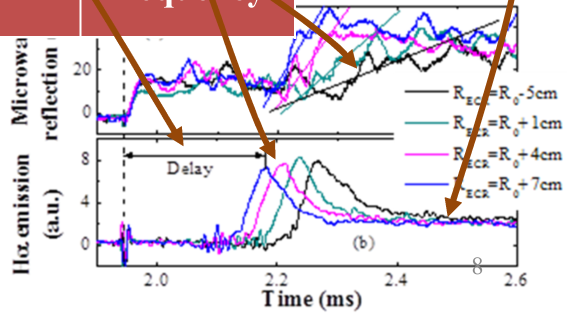
- **H_α and the reflected microwave are found to have connections with these scanning parameters**
  - These two signals are fast enough to be able to catch the details of changes

Conjectures from the scanning results

Summary of the scanning results

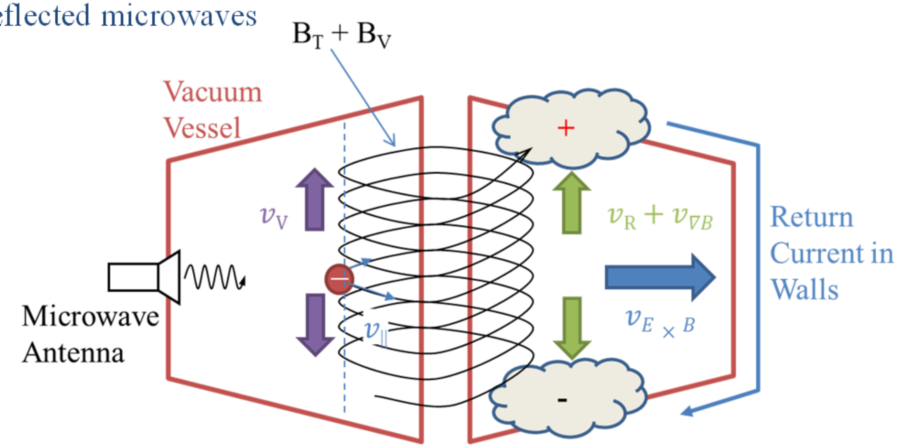
+: positive effects, -: negative effects; 0: no effects

	Slew rate of the reflected rf power	Delay of H_α peaks	Maximum amplitude of H_α	Amplitude of the flat top of H_α
B_T	+	-	0	0
B_V	-	0	-	0
P_{rf}	0	-	+	0
Conjectured explanations	Drift/Formation time of the cut off layer	Power density @ ECR	Ionization rate and loss rate	Microwave frequency



The physical image of the initial stage of ECW startup

- **Main processes**
  - Ionization by microwaves
  - Reflection of microwaves
  - The motion of particles: (1) drift and diffusion across the field lines, (2) parallel motion along field lines
- **Features of our experimental arrangements**
  - Perpendicular installation of the horn antenna
    - The antenna acts not only as a launcher of power microwaves but also a receiver of reflected microwaves



Tan Y, et al. Nuclear Fusion. 2011;51(6):063021.

Estimation of the speeds

- **For electrons (100 eV)**
  - Lamor Radius: ~ 0.4 mm ($v_{//} = 0$, B = 875 G)
  - $v_{//}$: ~6E6 m/s ($v_{\perp} = 0$)
- **For hydrogen gas (300 K, 1E-3 Pa)**
  - $\nu_{\rm en}$: ~3E4 1/s (3E9 1/s for 1 torr)
  - $\nu_{\rm ionization}$: ~2E4 1/s (2E9 1/s for 1 torr)
  - $\nu_{\rm ei}$: ~ 1E3 1/s (n_e ~ 1E17)
- **For SUNIST (R_0 = 0.3 m, B = 875 G)**
  - $< v_{\rm R} + v_{\nabla B} > = \frac{2T}{q}\frac{1}{R_C B}$: ~ 7.6E3 m/s (vertical)
  - $v_{E\times B} = \frac{\rm E}{\rm B}$: ~1.1E3 m/s (E = 100 V/m) (radial)
  - $v_{\rm V} = v_{\parallel}\frac{B_z}{B_T}$: ~ 1.4E5 m/s ($B_z$ = 20 G) (vertical)

Modeling

$$P_{k_{\mathrm{ECR}}} = P_{inj} \cdot \frac{W}{2d'\tan\frac{\alpha}{2}+W}\frac{L}{2d'\tan\frac{\beta}{2}+L} \cdot \prod_{k=k_{ANT}}^{k_{ECR}} \left| e^{i2k\delta\sqrt{1-\frac{n_k}{n_c}}} \right| \qquad (5)$$

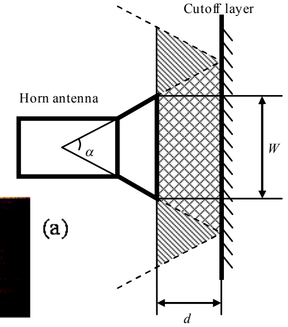
$$r_{\mathrm{REF}} = \frac{W}{4d\tan\frac{\alpha}{2}+W}\frac{L}{4d\tan\frac{\beta}{2}+L} \qquad (4)$$

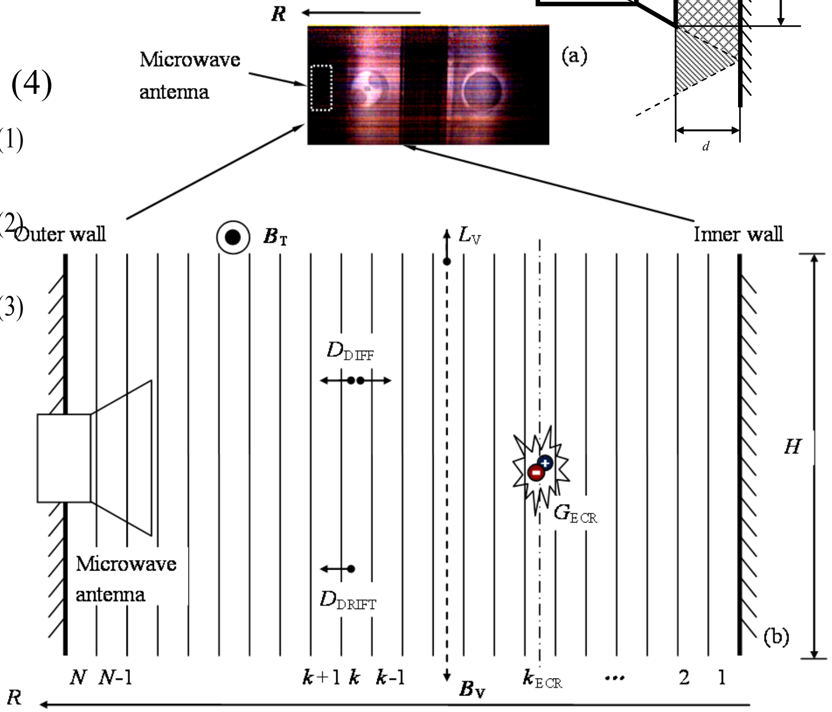
$$\frac{\partial n_{\mathrm{k}}}{\partial t} = D_{\mathrm{DIFF}}\nabla^2 n_{\mathrm{k}} - D_{\mathrm{DRIFT}}\nabla n_{\mathrm{k}} - L_{\mathrm{B_V}} n_{\mathrm{k}} + G_{\mathrm{ECR}} n_{\mathrm{k}} n_{\mathrm{NP}} \qquad (k = k_{\mathrm{ECR}}) \qquad (1)$$

$$\frac{\partial n_{\mathrm{k}}}{\partial t} = D_{\mathrm{DIFF}}\nabla^2 n_{\mathrm{k}} - D_{\mathrm{DRIFT}}\nabla n_{\mathrm{k}} - L_{\mathrm{V}} n_{\mathrm{k}} \qquad (k \neq k_{\mathrm{ECR}}) \qquad (2)$$

$$\frac{\partial n_{\mathrm{NP}}}{\partial t} = -\frac{\partial \Sigma n_{\mathrm{k}}}{\partial t}\frac{1}{N} \qquad (3)$$

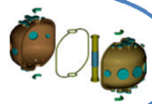
- **A 1.5 dimension model**
  - To describe the main processes
  - To simulate the time and spatial evolution of ne, the characters of microwave reflections
  - Approximations: optical launch and receive, WKB et al.





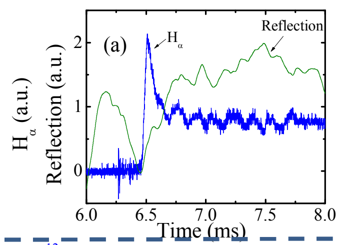
Compare the simulations and the experiments

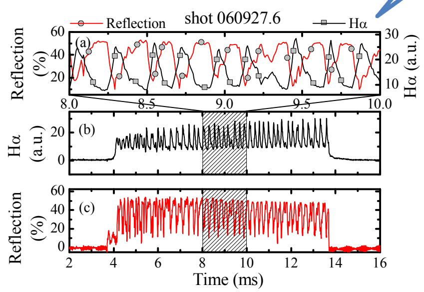
Due to:

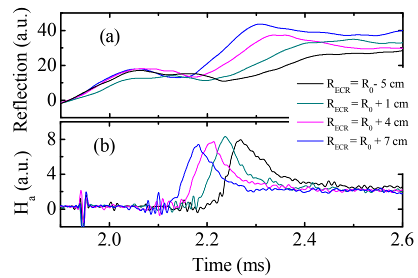


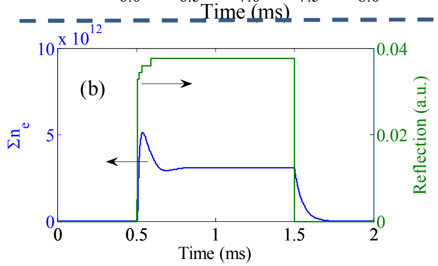
Experimental results:

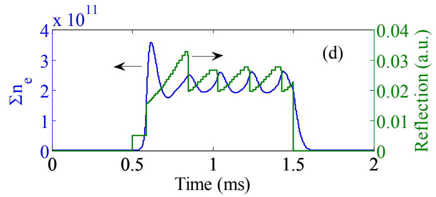
One spike | Oscillating | B_T scanning

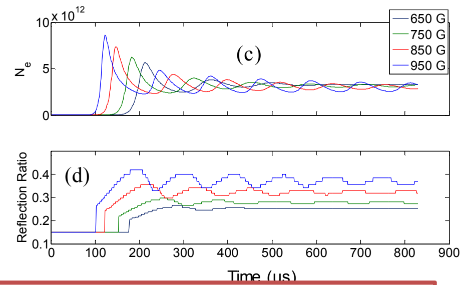












Simulation results

Tan Y, et al. Plasma Sci. Tech. 2011;13(1):30.

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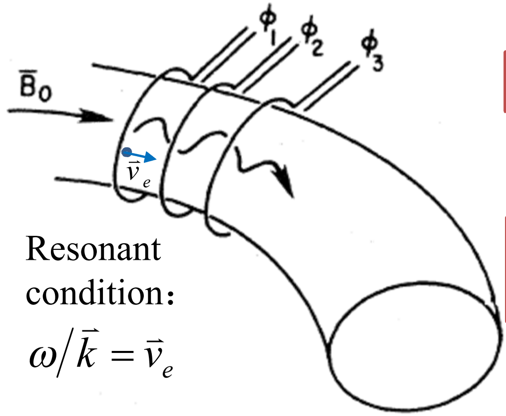
Principle of Alfven wave current drive

- **Diagram of Alfven wave current drive (AWCD)**
  - The peristaltic Tokamak (Wort, 1971)

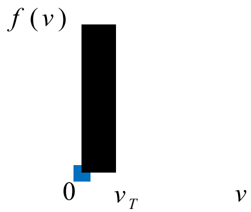


Resonant condition: $\omega/\vec{k} = \vec{v}_e$

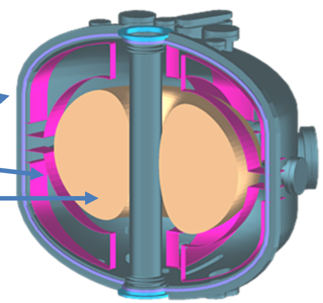
N J Fisch and C F F Karney, 1987

The driving force: $m\dfrac{dv_z}{dt} = -eE_z - \mu\dfrac{\partial B_z}{\partial z}$

V_{ph} is slow thus thermal electrons are driven:



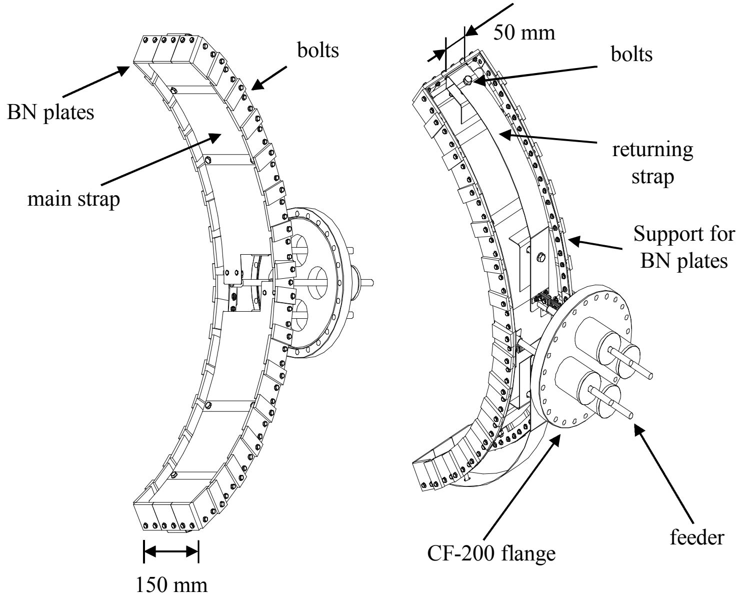
The schema:
Vacuum Vessel
Antennas
Plasmas



- **Apply AWCD to SUNIST**
  - 4 pairs of strap antennas
  - 0.15 T / 1E19 m^{-3}, resonant frequency: 0.4 ~ 1 MHz

Alfven wave antenna design for SUNIST

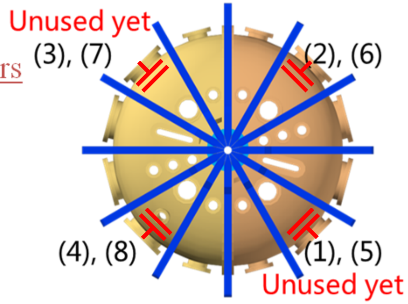
- **Simple design, simple manufacture**
  - Extends in the poloidal direction as much as possible

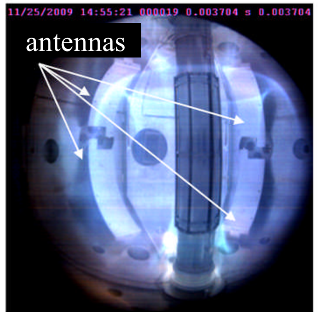


Tan Y, Gao Z, He Y. Fusion Eng. Des. 2009;84(12):2064-71.

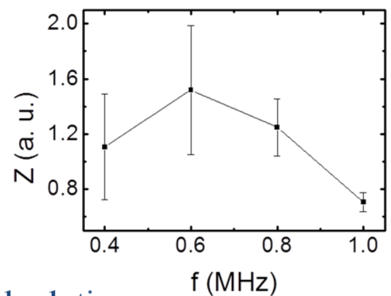
Preliminary results of AW experiments

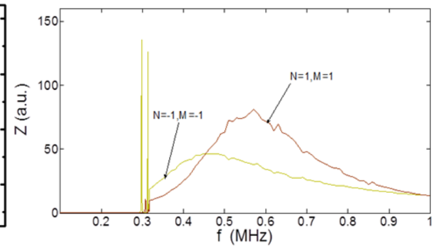
- **Antennas**
  - Currently no shielding, no limiters
  - Two of four pairs used
  - π phasing
  - |N|=1 ~ 60%, |M|=1 ~ 15%
- **The RF generator**
  - Four phases outputs
    - But only two phases are stable
  - 20 ~ 50 kW, 0.4 ~ 1 MHz (non-continuous)
- **Experimental parameters**
  - I_P: 30~50 kA
  - n_e: 0.5 ~ 3×19 m^{-3}
  - B_T: 800~1200 G
- **Antenna impedances**
  - Have similar trends as 1-d calculations





Toroidal arrangement of the antennas(left) and a picture of the antennas along with plasmas (right)

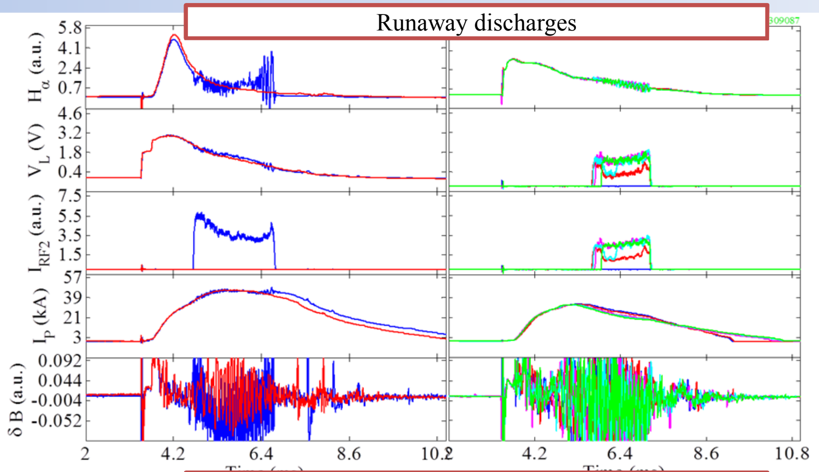


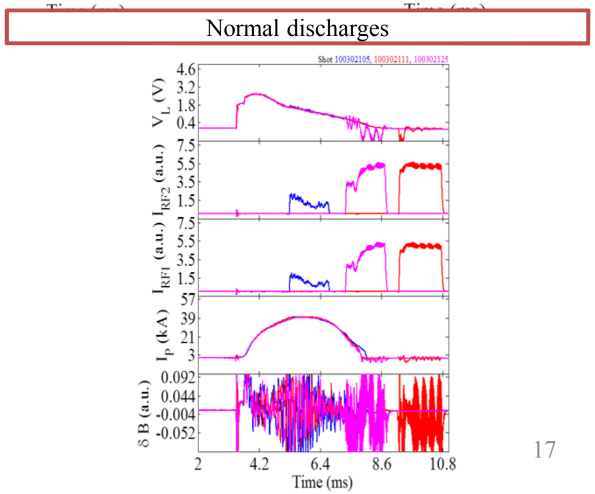


Experimental results (left) and theoretical results (right) of the impedances of antennas

The effects of RF waves on I_P

- **Runaway discharges are enhanced when:**
  - Low I_P (~30 kA), low n_e (<1E19 m^{-3})
  - Hard to understand
    - The speed of rf phases and the runaway electrons differ by one order of magnitude
    - $V_c \sim 1.5*10^{-2} (2\pi Rn/V)/2 \sim 2*10^7$m/s (for $n_e \sim 10^{18} m^{-3}$)
    - Vph～f2 π R ～ $1.5*10^6$ m/s
- **Normal discharges**
  - 50 kA，>1E19 m^{-3}
  - No effects observed





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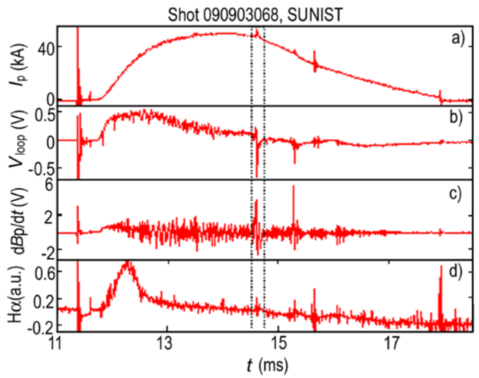
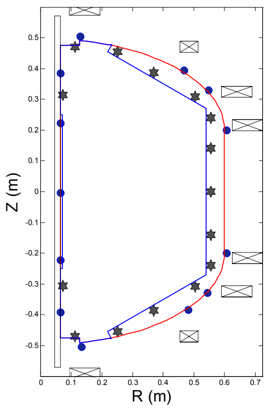
Internal reconnection events on SUNIST

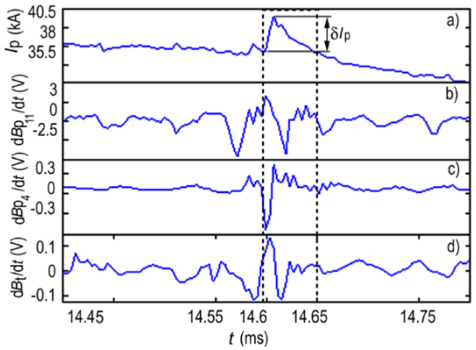
- **Motivations**
  - Internal reconnection events (IREs) are widely found on STs
  - What mode structures do IREs have?
  - The evolution of equilibrium parameters during an IRE
- **Methods**
  - Magnetic measurements
  - EFIT
  - SVD analysis



A typical discharge with IREs of SUNIST



Magnetic probes (*) and flux loops (.) used to study MHD activities on SUNIST

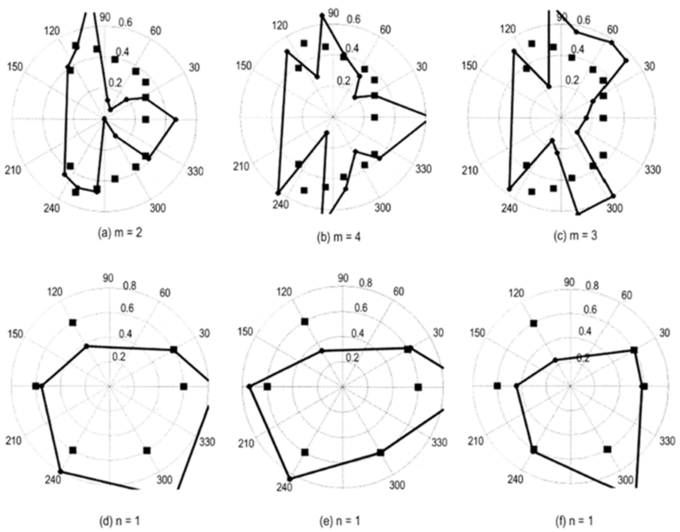


Zoomed in waveforms of I_P and magnetic perturbations of an IRE

Zeng L, et al. Plasma Sci. Tech. 2011;13(4):420.

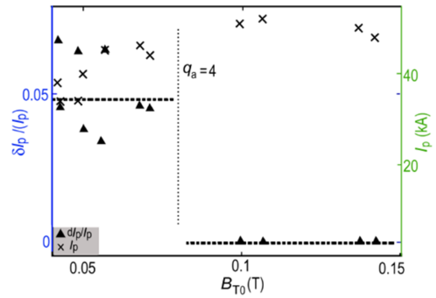
IRE analysis

- **Mode structures and the evolutions of parameters**

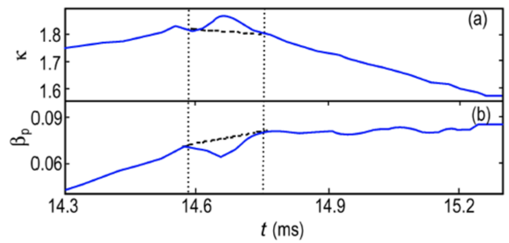


before during after

The poloidal (upper) and toroidal (lower) modes before, during and after an IRE on SUNIST



IREs have a strong dependence on the strength of toroidal field

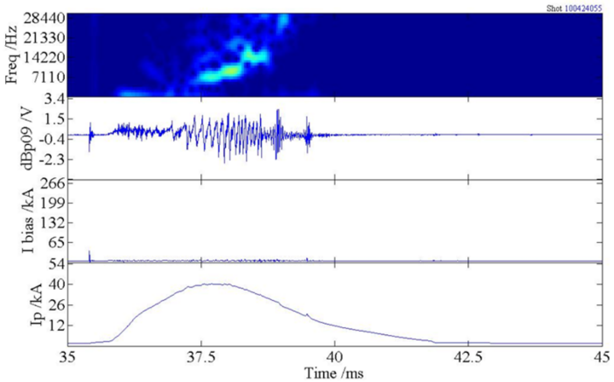


The evolution of elongation ratio (upper) and poloidal beta (lower) in an IRE on SUNIST

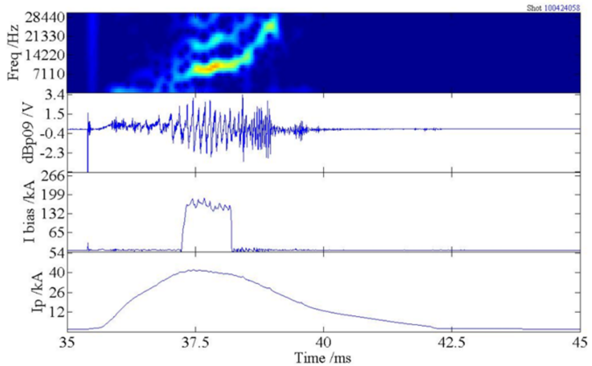
The effects of biased electrical field on MHD

- **Apparatus**
  - A biased DC voltage is applied to an electrode located at the equatorial plane
  - Diameter: 3 cm; voltage applied: 200 V
- **Effects**
  - The biased voltage excites the harmonics of MHD perturbations !!!???
  - Expected: to suppress MHD (since the E_r cross B_T shearing effects)

The electrode



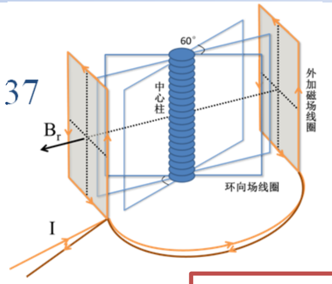
The discharge without biased voltage

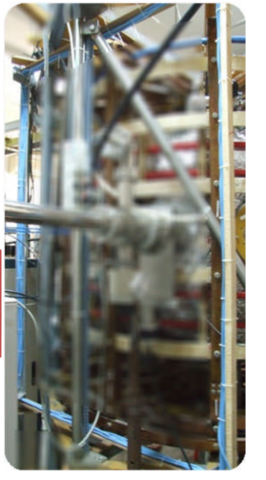


The discharge with biased voltage

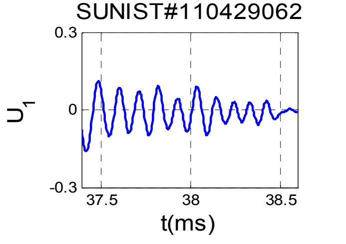
The effects of biased magnetic field on MHD

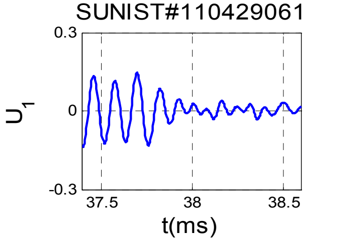
- **Biased radial magnetic field**
  - 5 turns, L: 210 uH, I: 1 kA, B_R max: 37 Gauss
  - Suppress the MHD oscillations
  - Change the spatial structures
  - Slightly increase electron density

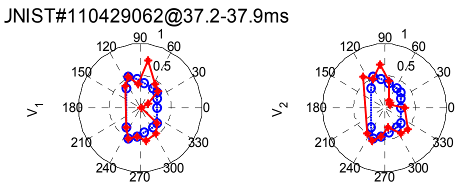


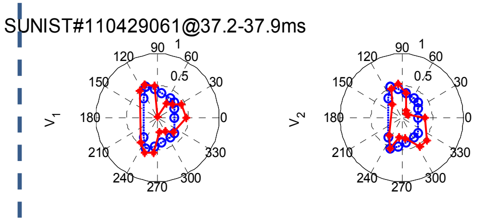


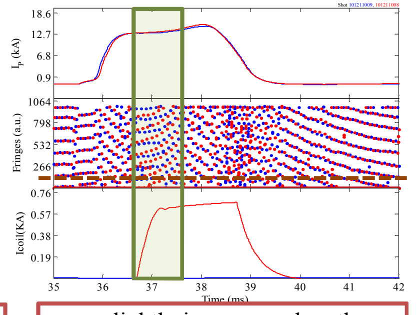
The coils to produce a biased magnetic field.











The discharge without biased magnetic field

The discharge with biased magnetic field

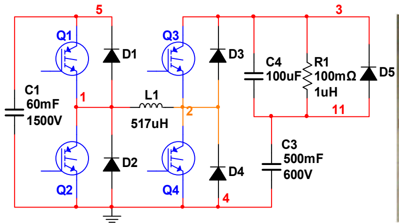
n_e slightly increases when the radial magnetic field is applied

Outline

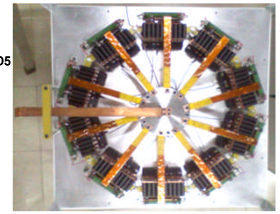
- **Recent research progress**
  - Analysis of the startup by ECWs
  - Preliminary results of AW experiments
  - MHD studies
- **Recent engineering progress**
  - Upgrade of the field power supplies
  - Other upgrades
- **Future plans**
- **Summary**

Upgrade of field power supplies

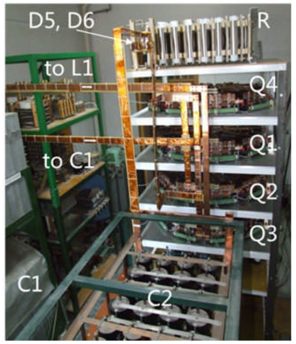
- **Pulse length limits SUNIST's ability**
- **Ohmic field power supply: double swing operation**
  - IGBT switches enable +10 kA →-5 kA swing (+13 kA → -13 kA further)
  - Pulse length of ohmic discharge has been extended to >10 ms (20 ms expected further)
- **Vertical field power supply: arbitrarily programmable**
  - DSP + IGBT (1.5 kA) solution
  - Adjustments are on going



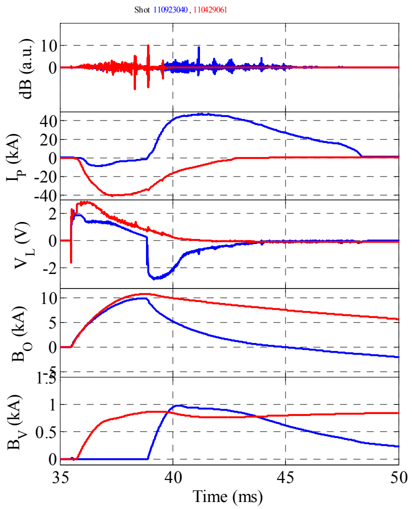
The circuit for double swing discharge



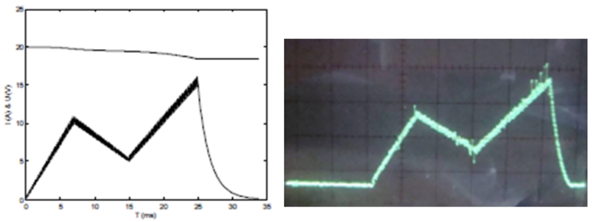
The 13 kA IGBT switch



The assembled circuit



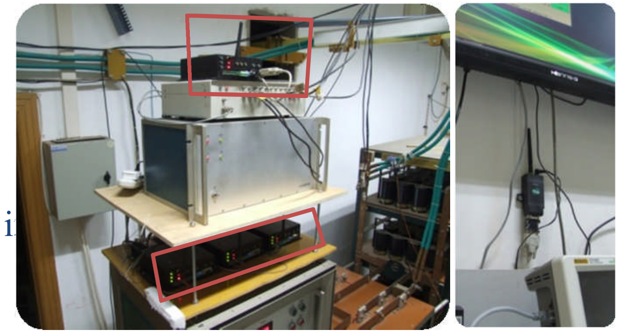
The waveforms of a double swing discharge (blue) and single swing discharge (red)



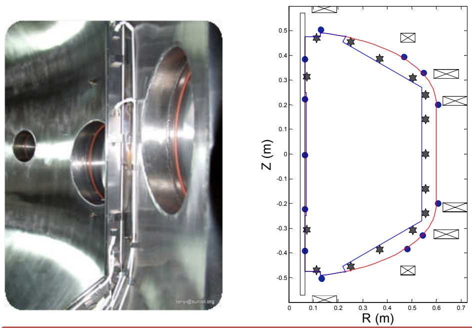
The defined waveform (left) and the waveform actually obtained (right)

Other upgrades

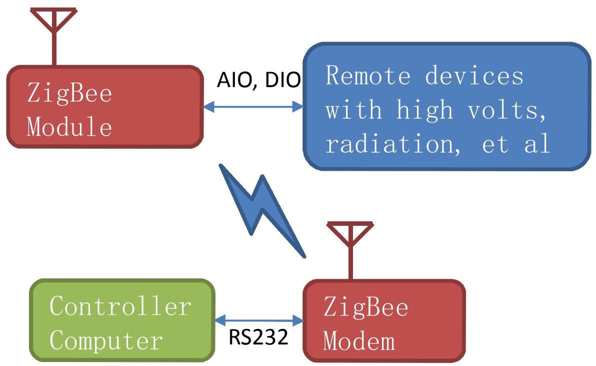
- **SUNIST is wirelessly controlled and monitored**
  - The feasibility of wireless monitoring and control of a tokamak has been verified
  - Using Zigbee technology (now very popular i the *Internet of Things*)
  - Good flexibilities and reliabilities
- **A new magnetic diagnostic system**
  - 13 flux loops / 15 poloidal probes / 6 toroidal probes
  - Plasma equilibrium reconstruction and MHD analysis can be done based on this system



(left) 4 wireless modules installed in the power supply and the timer; (right) The wireless modem attached on the remote computer.



The magnetic probes and flux loops



The diagram of the wireless infrastructure for control and monitoring

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Future plans

- **Continue to startup by ECW**
  - The old 2.45 GHz magnetron source is damaged
  - A 5 GHz/200 kW/50 ms microwave system is under construction (Institute of Electronics, CAS)
- **Re-try AWCD experiments**
  - Based on ohmic discharges with longer flat top
  - With BN limiters installed (design completed)
- **Continue MHD studies**
  - With better abilities of equilibrium control
- **Alfven eigenmodes investigation**
  - Use the AWCD antenna systems

Summary

- The transient of process of ECW startup is analyzed. The process involves particle drifts and microwave reflections. The simulation results of a simple model can reappear the experimental results.
- Preliminary results of Alfven wave experiments show that runaway discharges can be enhanced by the low phase speed waves. This is difficult to understood.
- Both biased electrical and magnetic field have observable effects on MHD activities.
- The ohmic field of SUNIST is now operated in double swing mode. The vertical field can be arbitrarily programmed.
- The SUNIST machine is wirelessly controlled and monitored. This brings a lot of flexibilities to us.
- Future plans of SUNIST are also presented.

Questions, comments and suggestions are warmly welcome!