# Wave-Particle Interaction Analyzer: Direct Measurements of Wave-Particle Interactions in Planetary Magnetospheres

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*Abstract:*

We present a new instrumentation "Wave Particle Interaction Analyzer (WPIA)" for measurement of the energy transfer process between energetic electrons and plasma waves in the magnetosphere [*Fukuhara et al.*, 2009; *Katoh et al.*, 2013]. The WPIA measures a relative phase angle between the wave vector and velocity vector of each particle and computes an inner product W(t), while W(t) is equivalent to the variation of the kinetic energy of energetic electrons interacting with plasma waves. The WPIA will be firstly realized by the Software-type WPIA in the ERG satellite mission to measure interactions between energetic electrons and whistler-mode chorus in the Earth's inner magnetosphere. In this talk we discuss scientific objectives and implementation of the WPIA on board ERG.

*References:*

Fukuhara, H., H. Kojima, Y. Ueda, Y. Omura, Y. Katoh and H. Yamakawa, A new instrument for the study of wave-particle interactions in space: One-chip Wave-Particle Interaction Analyzer, *Earth Planets Space*, **61**, 765-778, 2009.

Katoh, Y., M. Kitahara, H. Kojima, Y. Omura, S. Kasahara, M. Hirahara, Y. Miyoshi, K. Seki, K. Asamura, T. Takashima, and T. Ono, Significance of Wave-Particle Interaction Analyzer for direct measurements of nonlinear wave-particle interactions, *Ann. Geophys.*, **31**, 503-512, doi:10.5194/angeo-31-503-2013, 2013.

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## Outline





## Breakthrough driven by the WPIA

[*Fukuhara et al.*, EPS 2009]

In Wave-Particle Interactions, the phase relation of waves and particle velocity vectors determines the energy flow direction

$$\frac{d}{dt}\left(\frac{1}{2}mV^2\right) = \boldsymbol{E} \bullet \boldsymbol{V} = q|\boldsymbol{E}||\boldsymbol{V}|\cos\theta \qquad \begin{cases} C(t) = \frac{dK}{dt} = q\mathbf{E}(t)\cdot\mathbf{v}(t) \\ K = m_0c^2(\gamma - 1) \end{cases}$$

Energy flow balance

Particle ⇨ Waves
Waves ⇨ Particle

We need the time resolution enough to detect the above phase relation.

Plasma waves: **Success of the Wave-Form capture in Geotail**
Particle: **a particle pulse detection with a few usec accuracy will be achieved in the ERG mission**

⇨ New attempt for identifying the phase relation of waves and particles





## Difference of the WPIA and conventional observations

**Conventional**

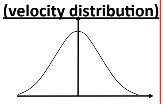
$$\frac{d}{dt}\left(\frac{1}{2}mV^2\right) = q|\mathbf{E}||\mathbf{V}|\cos\theta \;?$$

Plasma waves (waveform)

?

Energy flow

particles (velocity distribution)



No phase information = No energy flow information

**WPIA**

$$\frac{d}{dt}\left(\frac{1}{2}mV^2\right) = q|\mathbf{E}||\mathbf{V}|\cos\theta$$

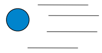
Plasma waves (waveform)

$\cos\theta > 0$

Energy flow

$\cos\theta < 0$

particle (in each particle)



Detection of phase relation = Detection of energy flow

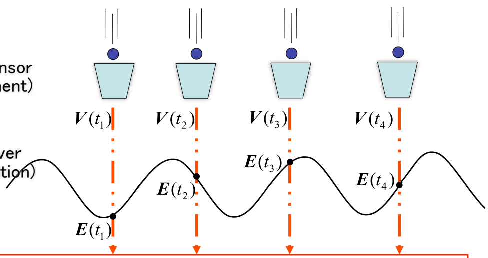


## New measurement method – WPIA



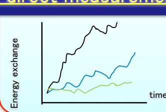
Plasma particle sensor (Plasma measurement)

Plasma wave receiver (Waveform observation)




Record of the instantaneous wave vectors and velocity vector of each particle

Possible direct measurement of energy transfer

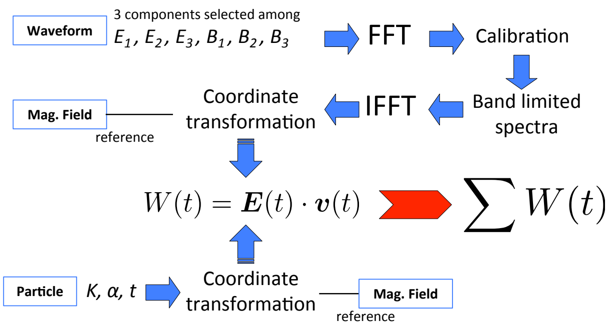



$$\frac{d}{dt}\left(\frac{1}{2}mV^2\right) = q\boldsymbol{E}(t) \bullet \boldsymbol{V}(t)$$

Physical quantity no one has seen before in space



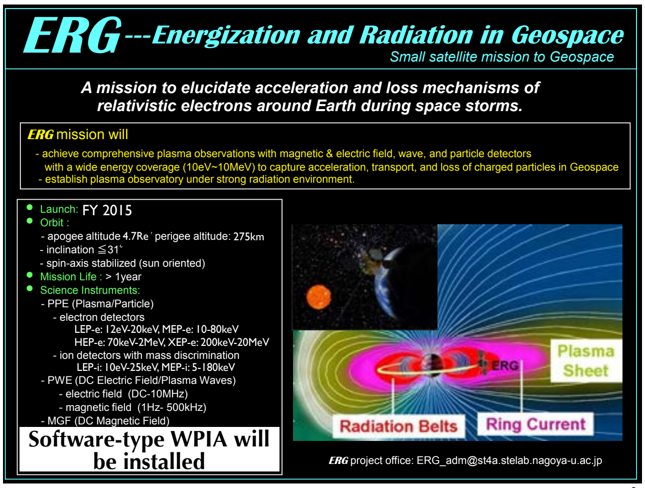
## Representative algorithm of the S-WPIA



## Wave-Particle Interaction Analyzer (WPIA)

- One-chip type WPIA (O-WPIA)
  - ✓ The algorithm is implemented inside the FPGA
  - ✓ The real time processing is realized.
- Software type WPIA (S-WPIA)
  - ✓ The algorithm is realized by the onboard software.
  - ✓ Difficulty in the real time processing
  - ✓ High flexibility in the data processing
  - ✓ Onboard the ERG satellite mission








## Whistler-mode chorus

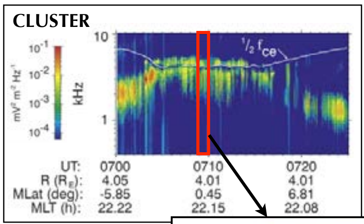
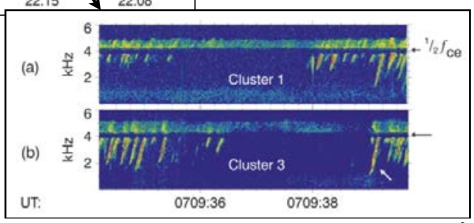



Fig: Chorus emissions observed by CLUSTER in the equatorial region of the inner magnetosphere [*Santolik et al.*, 2004]

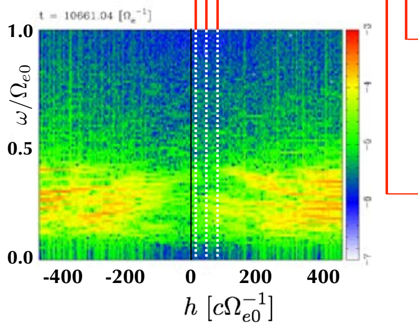


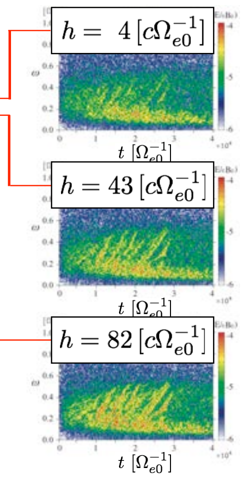



## Chorus generation near the magnetic equator

[*Katoh and Omura*, 2007, 2011; *Omura et al.*, 2008]

fp/fc=4

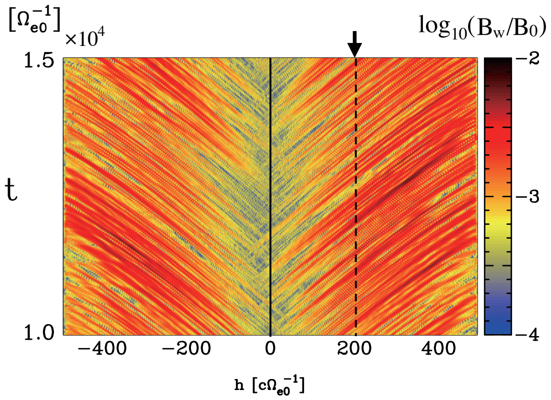


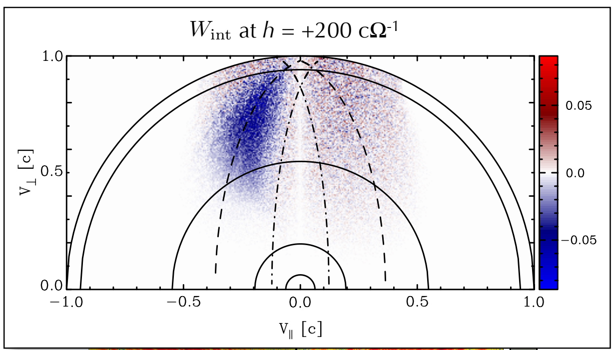



## Pseudo-measurement of WPIA in the simulation results

[*Katoh et al.*, Ann. Geophys., 2013]



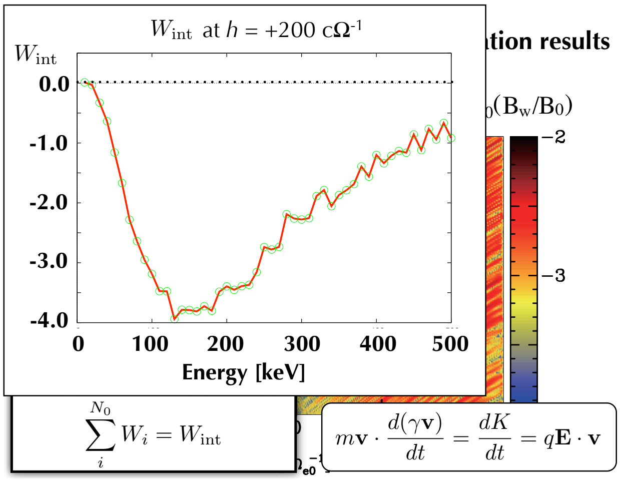



$$W(t) = q\mathbf{E}_W(t) \cdot \mathbf{v}(t)$$

$$\sum_i^{N_0} W_i = W_{int}$$

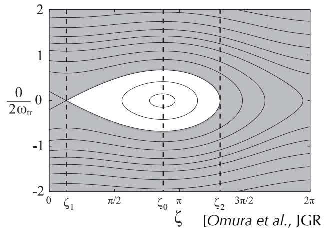
$$m\mathbf{v} \cdot \frac{d(\gamma \mathbf{v})}{dt} = \frac{dK}{dt} = q\mathbf{E} \cdot \mathbf{v}$$




$$\sum_{i}^{N_0} W_i = W_{\rm int}$$

$$m\mathbf{v} \cdot \frac{d(\gamma \mathbf{v})}{dt} = \frac{dK}{dt} = q\mathbf{E} \cdot \mathbf{v}$$



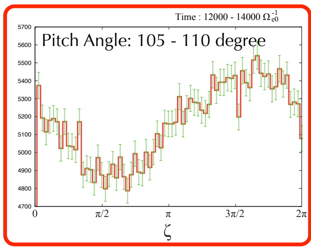



[*Omura et al.*, JGR 2009]

**Signature of the electromagnetic electron hole with the statistical significance**

The standard deviation of the statistical noise:

$$\sigma(\zeta) = \sqrt{N(\zeta)}$$





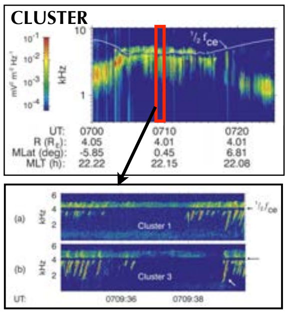

## Science objectives of WPIA on JUICE

- **Jovian chorus generation and relativistic electron acceleration**
- **Ion cyclotron waves around satellites: wave excitation and ion heating**
- **Interactions between Ion cyclotron waves and relativistic electrons**

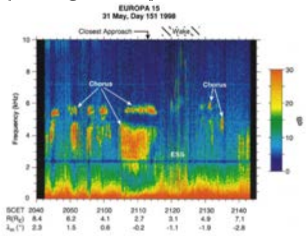


## Objective 1: Chorus and relativistic electron acceleration

### Chorus in planetary magnetospheres




Chorus emissions observed by CLUSTER in the equatorial region of the Earth's inner magnetosphere
[*Santolik et al.*, GRL 2004]



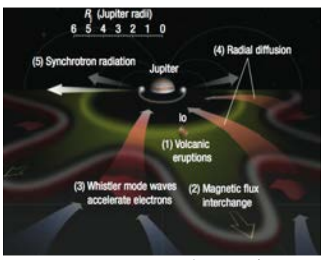

Chorus emissions observed by Galileo in the equatorial region of the Jovian inner magnetosphere

[*Kurth et al.*, PSS 2001]

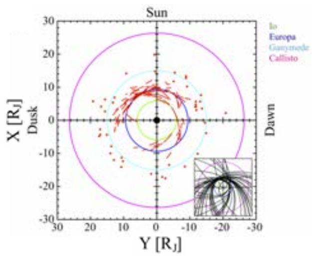


## Objective 1: Chorus and relativistic electron acceleration

### Acceleration of relativistic electrons by chorus in the Jovian inner magnetosphere




[*Horne et al.*, Nature Phys. 2008]



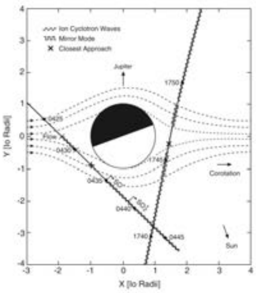

**distribution of Jovian chorus**

[*Katoh et al.*, JGR 2011]



## Objective 2: Ion cyclotron waves around satellites

### Excitation of Ion cyclotron waves



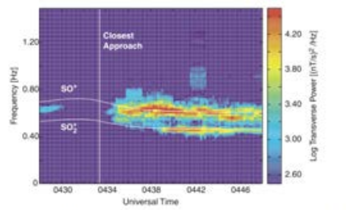
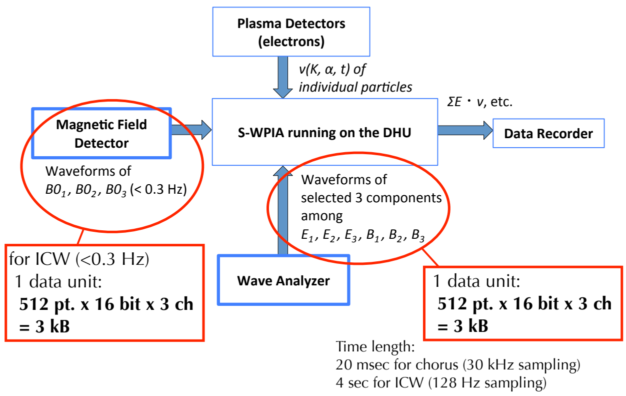




**Fig. 1 (left).** The trajectories of Galileo relative to Io and the inferred plasma flow on 7 December 1995 (labeled 1740 to 1750) and on 11 October 1999 (labeled 0425 to 0445). Sinusoids mark the presence of ion cyclotron waves, and square waves mark the presence of mirror mode waves (*14*). One Io radius is 1818 km. **Fig. 2 (right).** A dynamic spectrum showing the power spectral density of waves during the October 1999 Io flyby. Shown is the power in the derivative of the magnetic field in the direction transverse to the magnetic field. The analysis interval was 85.2 s in duration, and successive spectra are separated by 10.66 s. Spectral estimates have been averaged in bands of three frequencies to enhance statistical accuracy. The white lines are the gyrofrequencies of singly ionized SO and $SO_2^+$. The spectrum begins at the end of a 1-min data gap. There were no waves before this time.

[*Russell et al.*, Science 2000]

## Necessary data interface of the S-WPIA on JUICE



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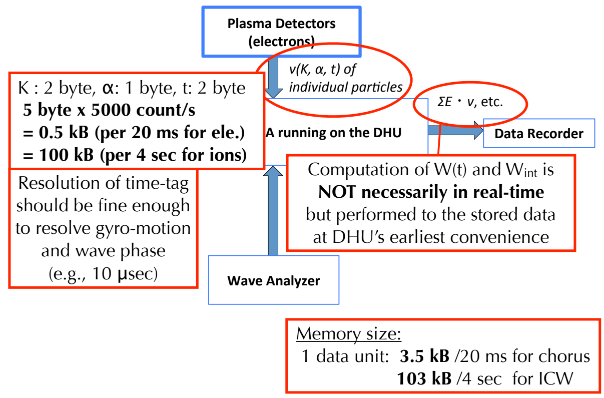
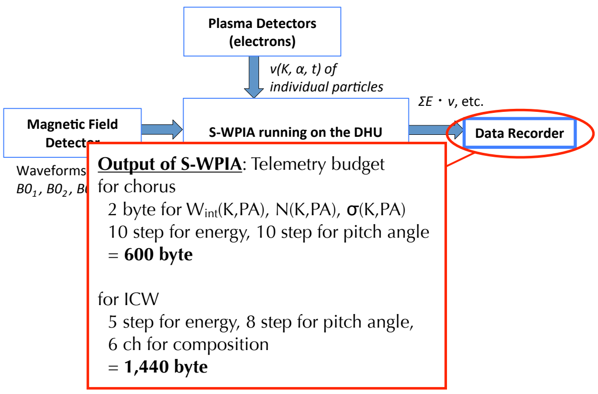





## Necessary data interface of the S-WPIA on JUICE






## Summary

- We studied the feasibility of the Wave-Particle Interaction Analyzer (WPIA) by using the simulation results reproducing chorus emissions
  - The present study clarified that the method of WPIA is useful to evaluate the energy exchange between waves and particles directly and quantitatively
  - Necessary time resolutions studied by the present study can be achieved by the state-of-the-art system of plasma instruments
- The WPIA measurements should be realized in the forthcoming missions.



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