Simulation needs for EJSM/JGO in the light of Cassini experiences

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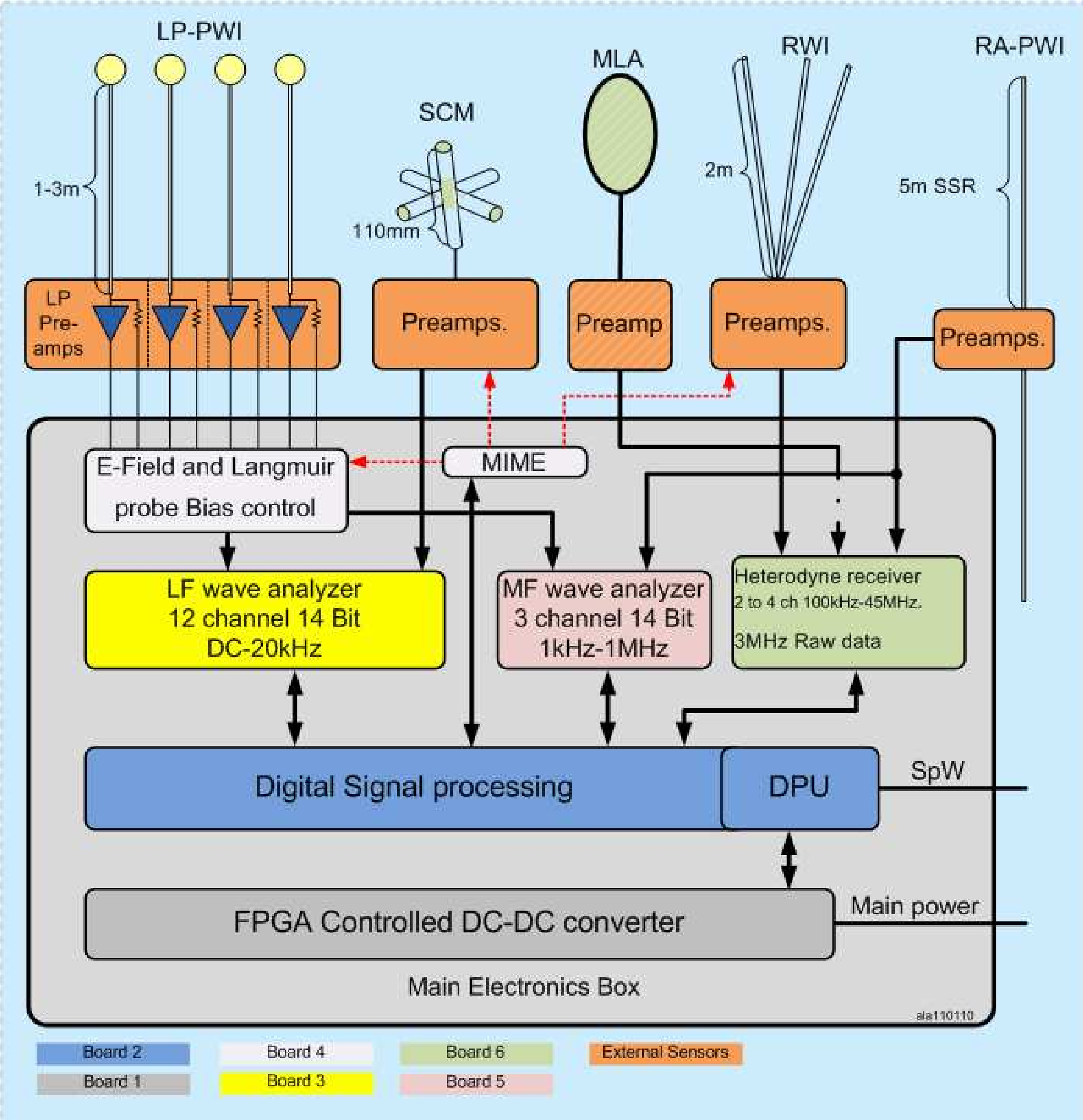
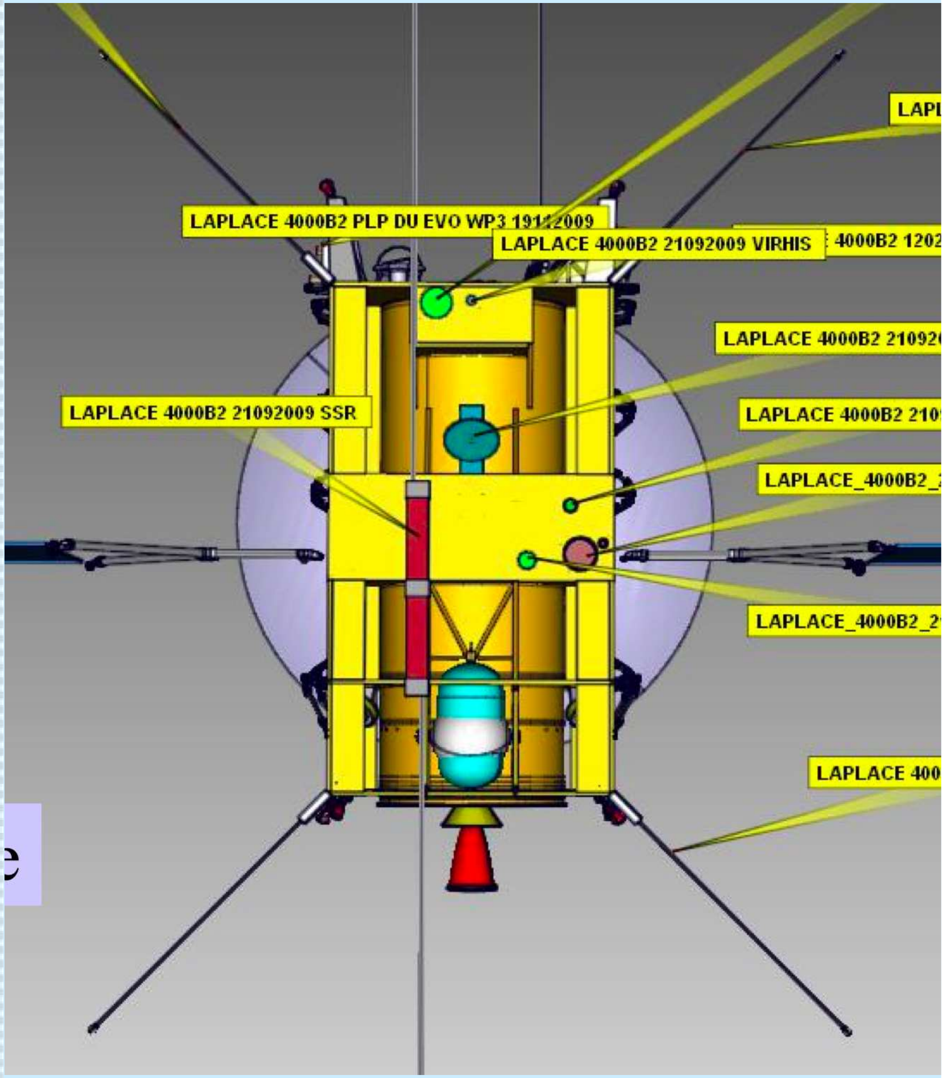
- EJSM/JGO & RPWI consortia
  - LP capability
  - Near DC **E**-field capability
- Cassini RPWS/LP experience
  - Several electron "populations"!? Anisotropy?
  - Secondary electrons from energetic particle impacts
  - Secondaries from dust impacts
  - Dust-plasma effects (charged dust, sheath effects, …)
- Guidelines for SPIS development

SPINE WS, Uppsala, 2011

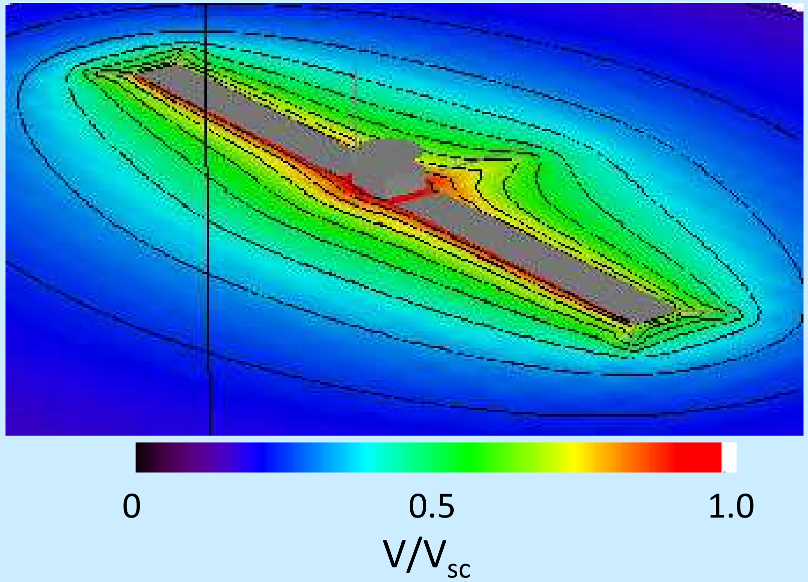
Radio & Plasma Wave Investigation (RPWI)





S/C Modelling support for RPWI Sensor accommodation

- Potential patterns
  - fr. C. Cully code
- Wake & S/C photo-e$^-$ patterns
  - fr. SPIS applied to ROSETTA
  - Only SW conditions



Wake pattern in Solar wind

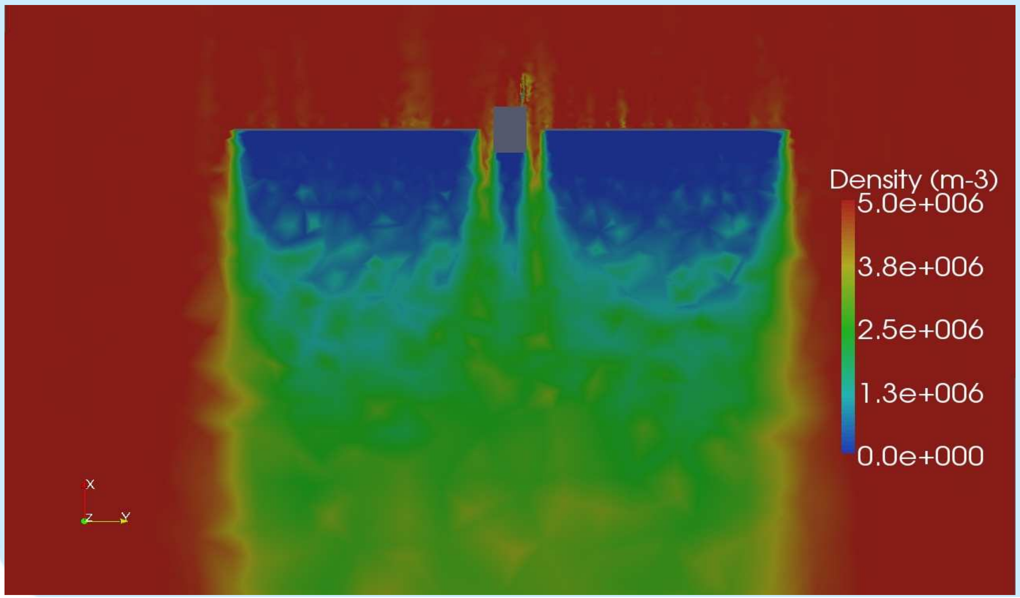
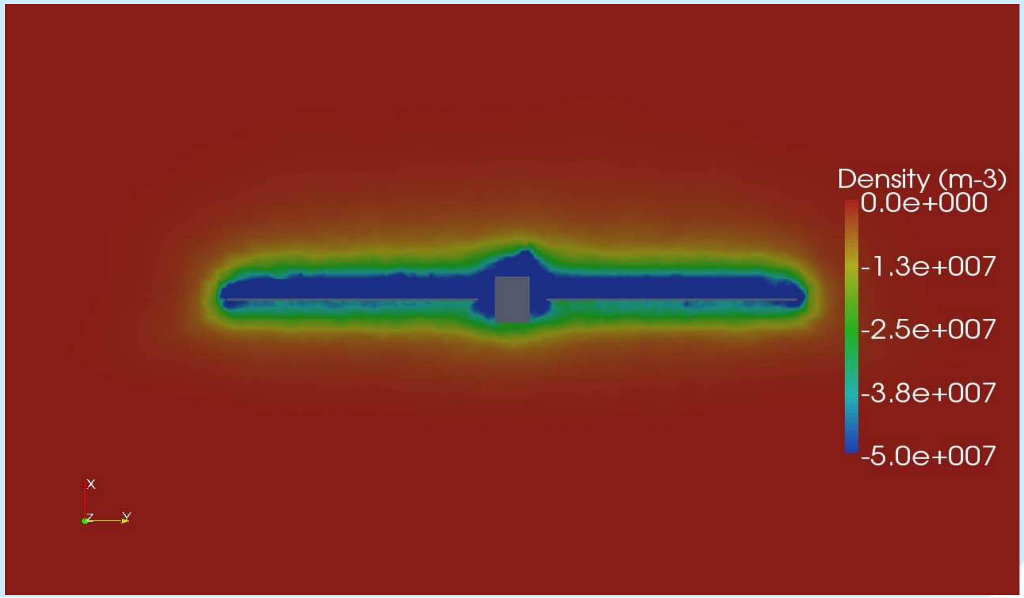
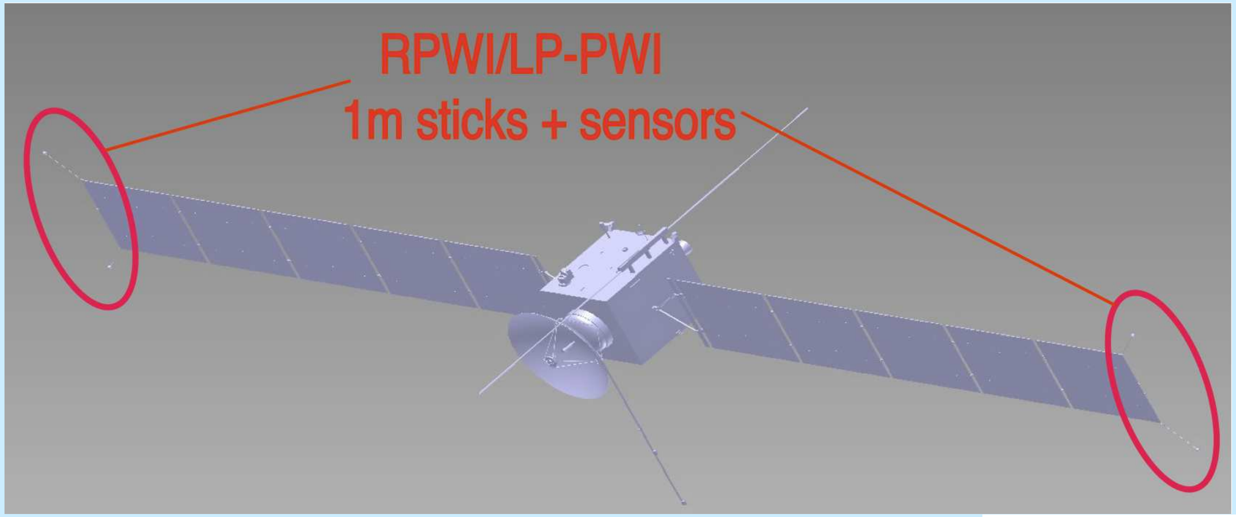


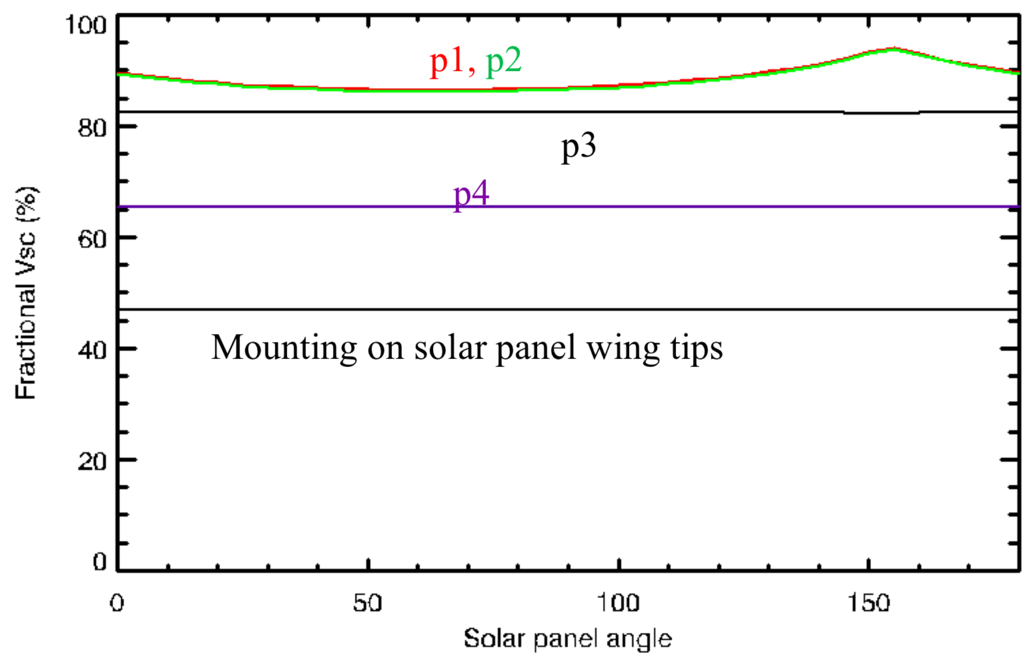
Photo-electron density in solar wind



- Baseline: Four 3m booms on S/C body
- Preferred (Sci. performance) option: Four 1m sticks at tip of solar panels



Calculations by C. Cully

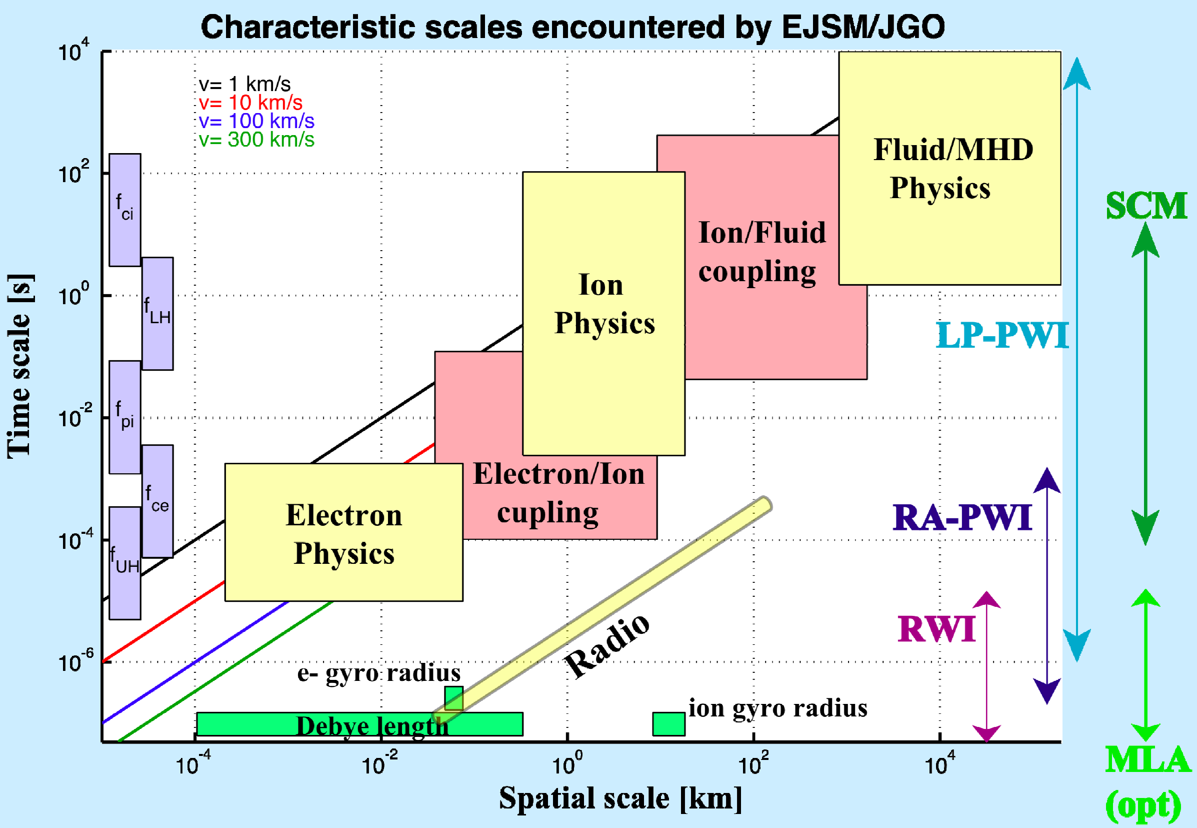


SPIS development request 1

- (Include photo electrons)
- Include mobile & time variable S/C structures

RPWI Science Performance

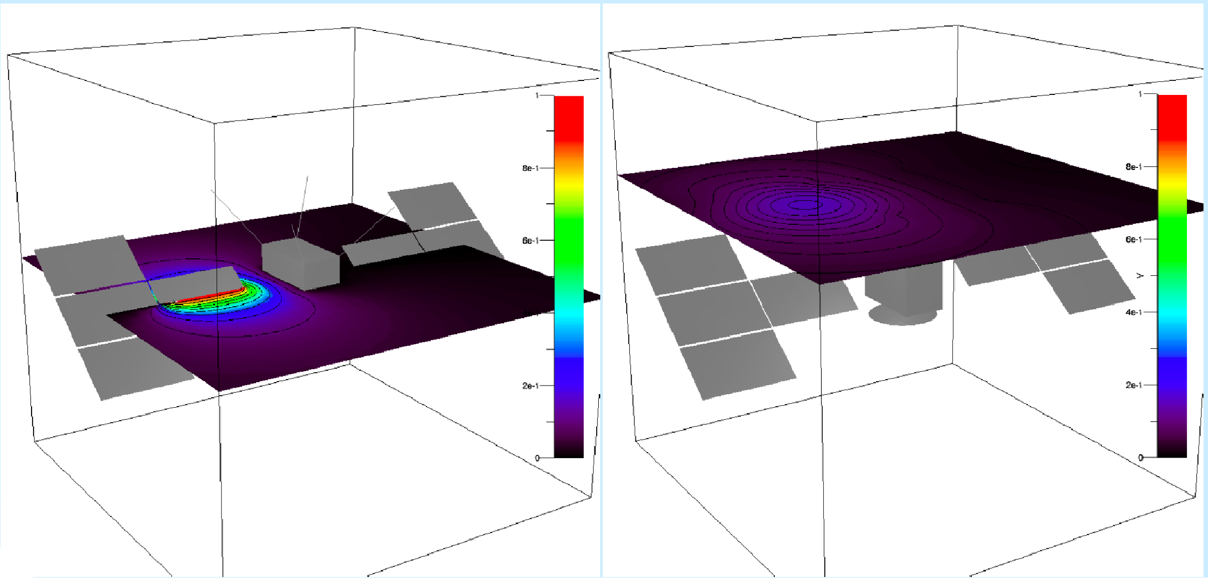
Measured Quantity	Range
LP-PWI	
Electron density (n_e, $\delta n/n$)	10^{-4} – 10^{5} cm^{-3}, 0(DC)-20 kHz
Ion density (n_i)	1–10^{5} cm^{-3}, <1 Hz
Electron temperature (T_e)	0.01 – 20 eV, <1 Hz
Ion drift speed	0.1–200 km/s, <1 Hz
Ion temperature upper limits	0.01 – 20 eV, <1 Hz
Spacecraft potential	±100 V, <1 Hz
Electric field vector, δ**E**(f)	DC – 1 MHz (waveform), ±1 V/m Bit resolution: 0.015 mV/m Expected error at DC: 1 mV/m
Integrated solar EUV flux	Resolution 0.05 Gphotons/cm^2/s
MIME	
Electron density (n_e)	0.01 – 1.5·10^{5} cm^{-3}
Electron temperature	0.01 – 100 eV
Electric sensor calibration	
Effective antenna length of sensors	
Deployment length of sensors	
RWI	
Electric field vector, δ**E**(f)	100 kHz – 45 MHz
SCM	
Magnetic field vector, δ**B**(f)	0.1 Hz – 20 kHz Sensitivity at 1 Hz: 8 pT/√Hz Sensitivity at 10 Hz: 0.6 pT/√Hz Sensitivity at 100 Hz: 0.06 pT/√Hz Sensitivity at 1 kHz: 10 fT/√Hz Sensitivity at 10 kHz: 4.5 fT/√Hz
RA-PWI	
Electric field, δE(f)	1 kHz – 45 MHz
MLA (opt)	
Magnetic field component, δB(f)	100 kHz – 45 MHz Sensitivity at 1 MHz: 0.3 fT/√Hz

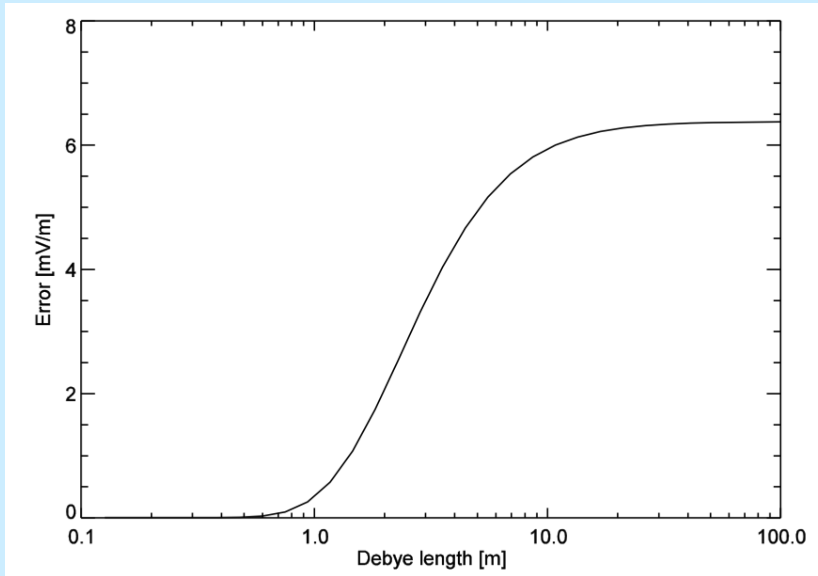


Wide range of plasma conditions!

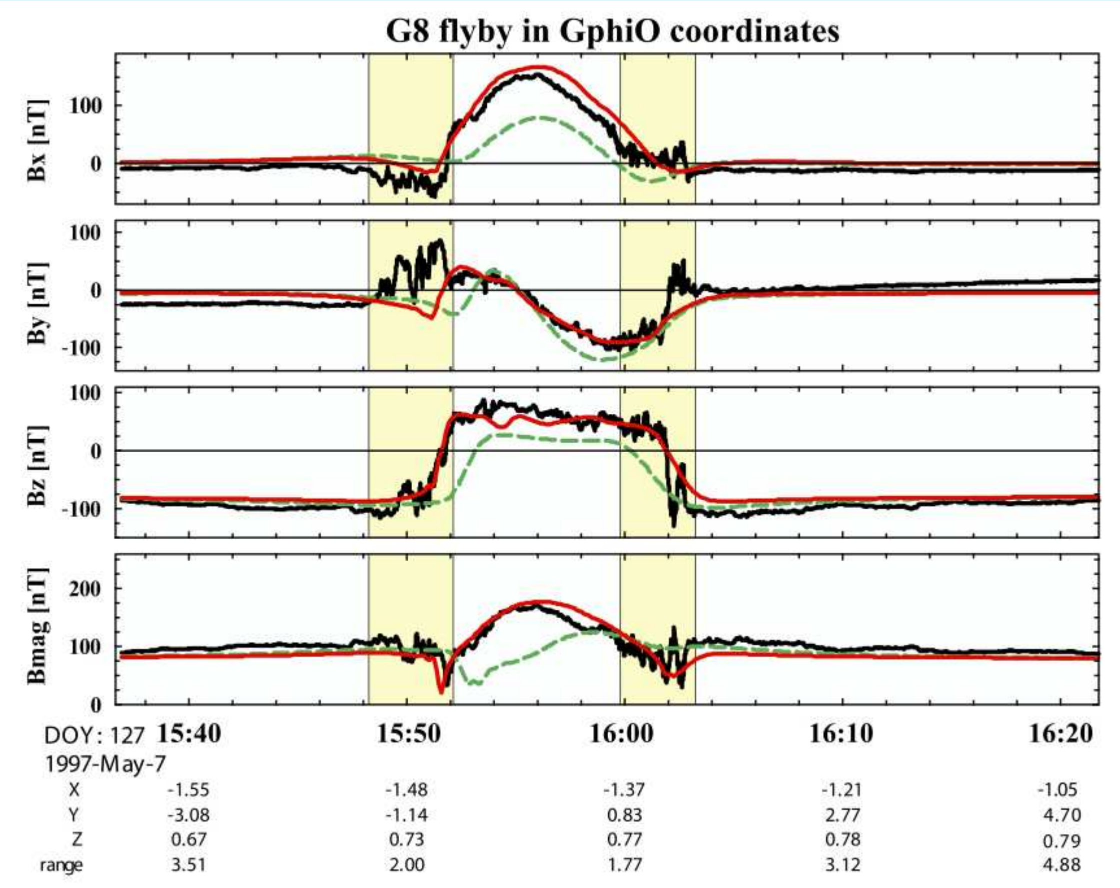
Near DC (sub Hz) **E**-field capability

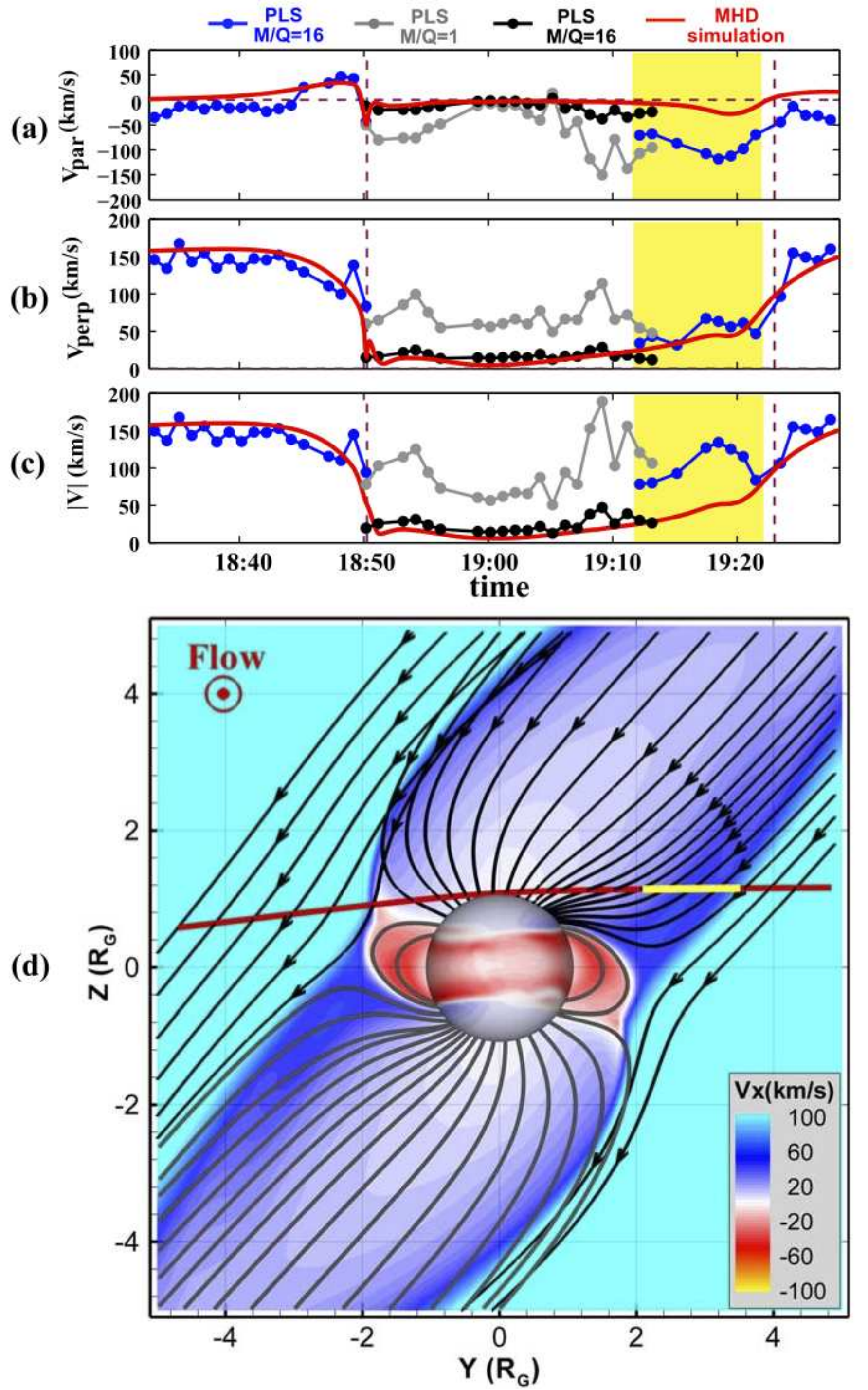
- “EJSM Electrostatic cleanliness”
  - ***The potential difference between any two surfaces on the S/C shall not exceed 1 V, assuming an ambient current density to the surface of 2 nA/cm^2.***
  - Max error: 6-7 mV/m for long Debye lengths
    - Jupiter convection field near Ganymede = 10-20 mV/m (< 1 V over S/C)
    - The ability of LP-PWI to measure magnetospheric convection fields requires a **conductive S/C surface**
    - Denser plasma near Ganymede ➔ short λ_D (30 cm – 1m) ➔ better than 1 mV/m accuracy
    - Solar panel mounted sticks + sensors improve by at least a factor 5 (longer separation distance & less photoelectrons from S/C & more symmetric configuration)





Alfvén Waves & Plasma flows





$\delta E = V_A \cdot \delta B \approx$ few mV/m

Fraction of a Volt over the S/C!

$V_i \approx$ 10-150 km/s

SPIS development request 2

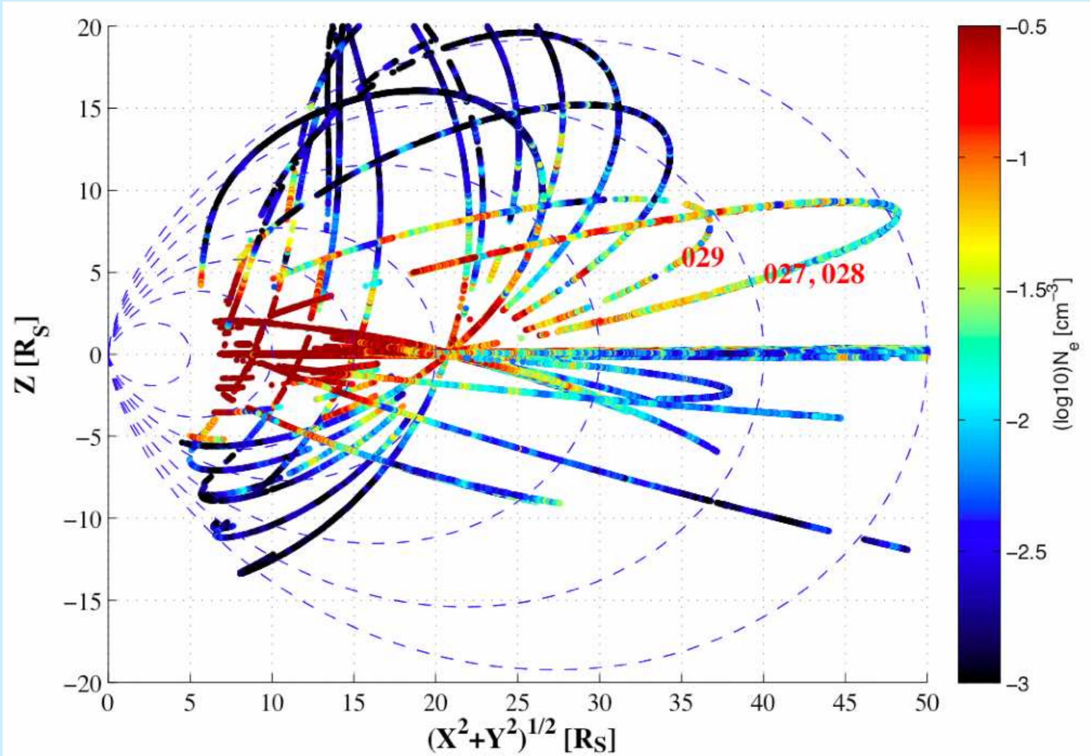
- S/C simulations for a wide range of external plasma conditions
- Include **v×B** and other large scale electric fields

  (for non-conductive S/C surface)

RPWI Thermal plasma capabilities

- Electron/Ion number densities
  - LP bias voltage sweeps (both electrons & ions)
  - Monitor f_{UH}
  - Monitor U_{float} (proxy method)
  - Continuous sampling of probe current (incl. $\delta n/n$)
  - Active mutual impedance
- Electron temperature
  - LP bias voltage sweeps
  - Active mutual impedance
- Ion drift speed
  - LP bias voltage sweeps
  - Near DC **E**–field (convection **E×B**)

[Morooka et al., Ann. Geophys., 2009]

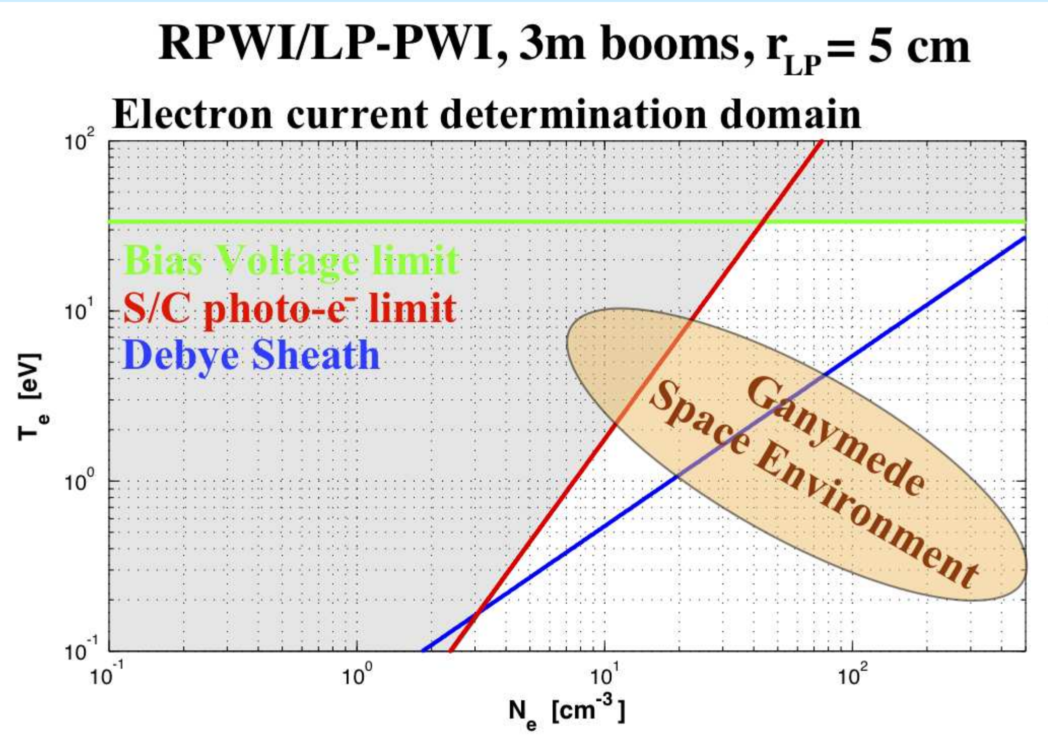


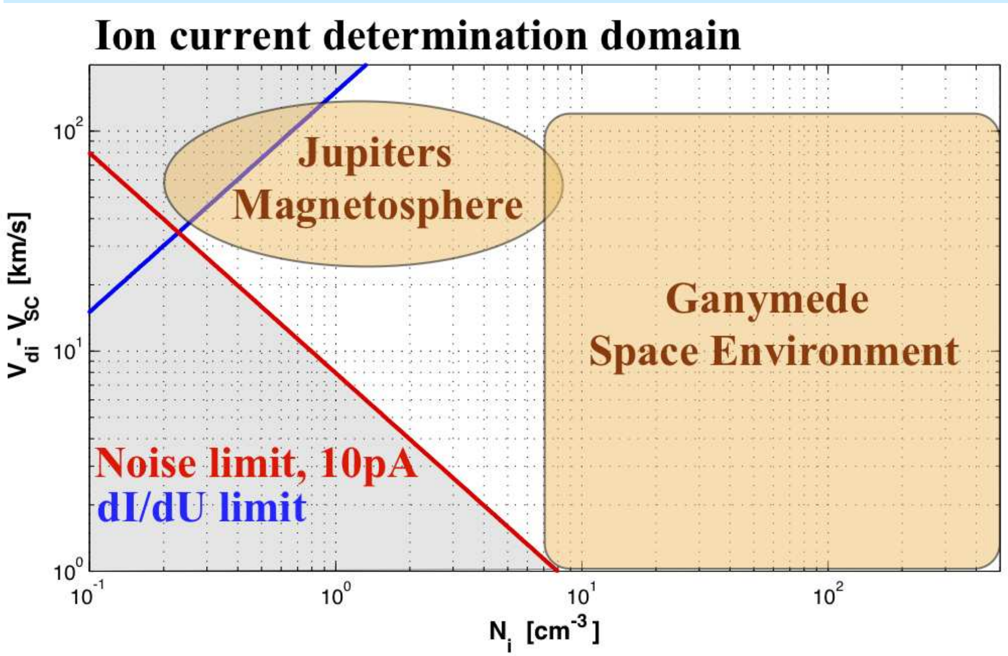
LP capability to measure thermal plasma

- S/C photoelectrons (fr. ESA SPIS)
  - Worst problem for $U_{SC} > 0$, less for U_{SC} negative

Assumed:
±100 V sweeps
10 pA noise level

Situation will improve if
• LP-PWI sensors on tips of solar panels
• 1 pA noise level reached

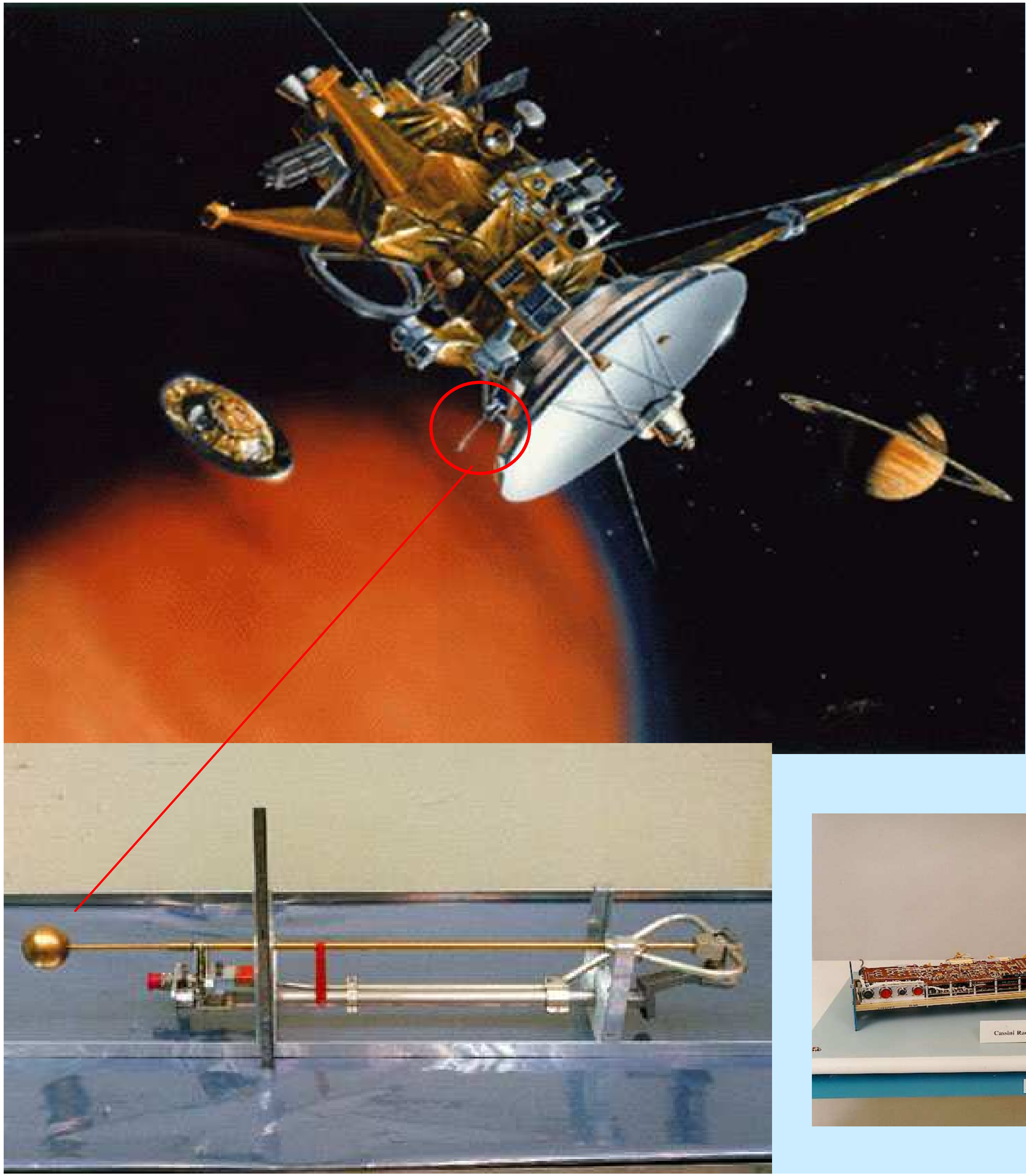




SPIS development request 2b

- Include (ion) ram component
  - $m_i V_{ram}^2/2 >> k_B T_i$
  - V_{SC} large
  - Especially in eclipse cases
- Include wake effects

Cassini RPWS LP



5 cm diameter probe

Obvious notes:
- Very close to S/C (1.5 m)
- Many asymmetric structures nearby

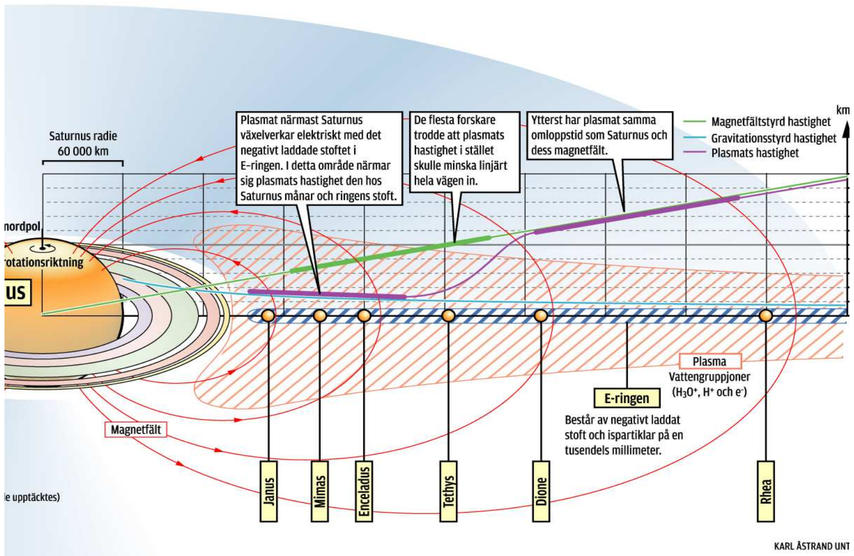
- Will be within S/C sheath except for very dense plasma conditions

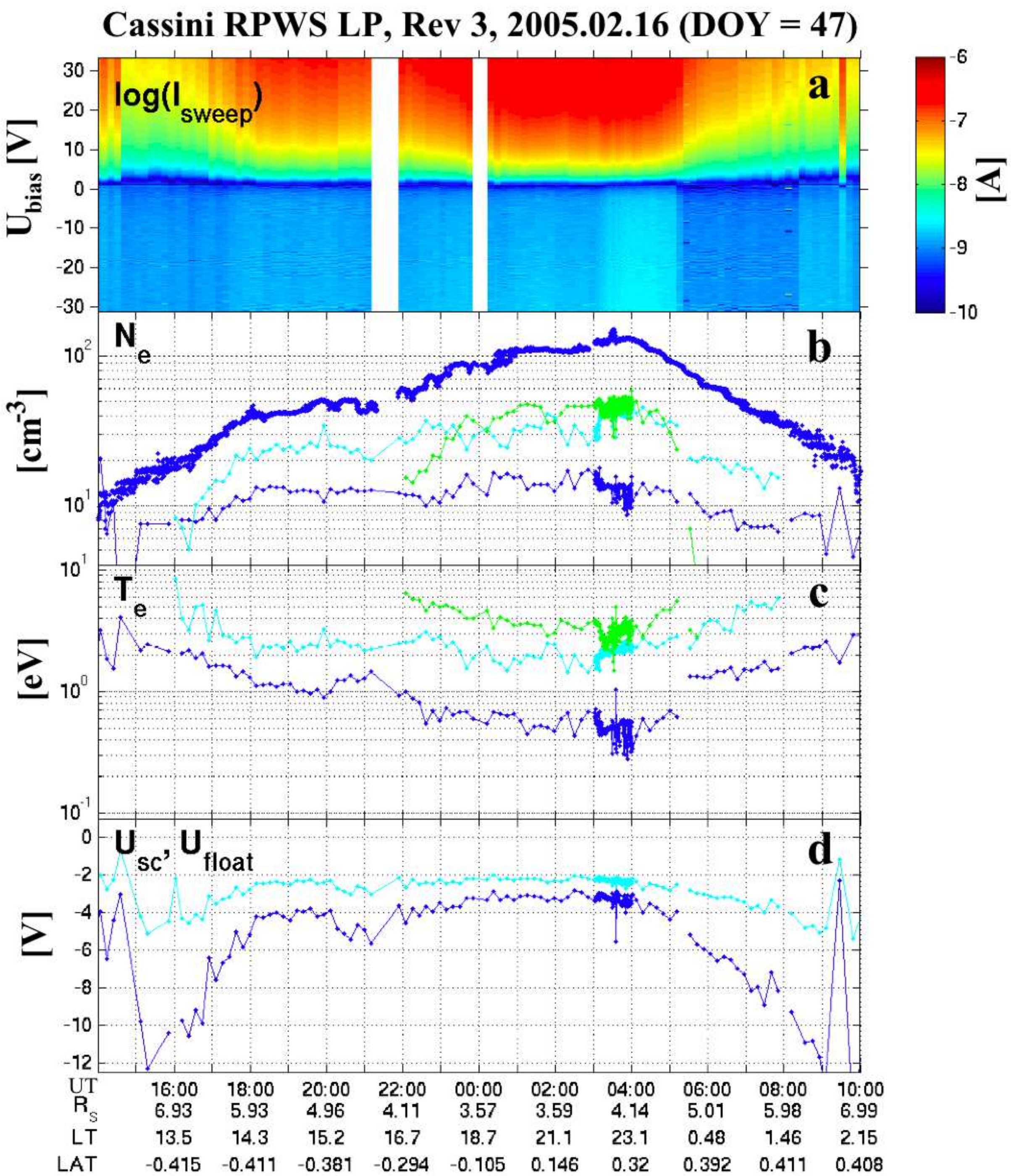
- Designed for Titan's ionosphere
- Turned out it could do much more

Saturn Plasma Disc measurements

N_e = 5 – 150 cm^{-3}
T_e = 0.5 – 8 eV

E-ring dust
Effects of energetic particle impacts
(few 100 eV electrons)





Ex: Sweep from Saturn Plasma Disc

$$I_{tot} = I_i + I_e + I_{ph} + I_{e*,i*} + I_{dust} + I_{\sec}$$

$I_{ph} = 0.4 - 0.6nA$

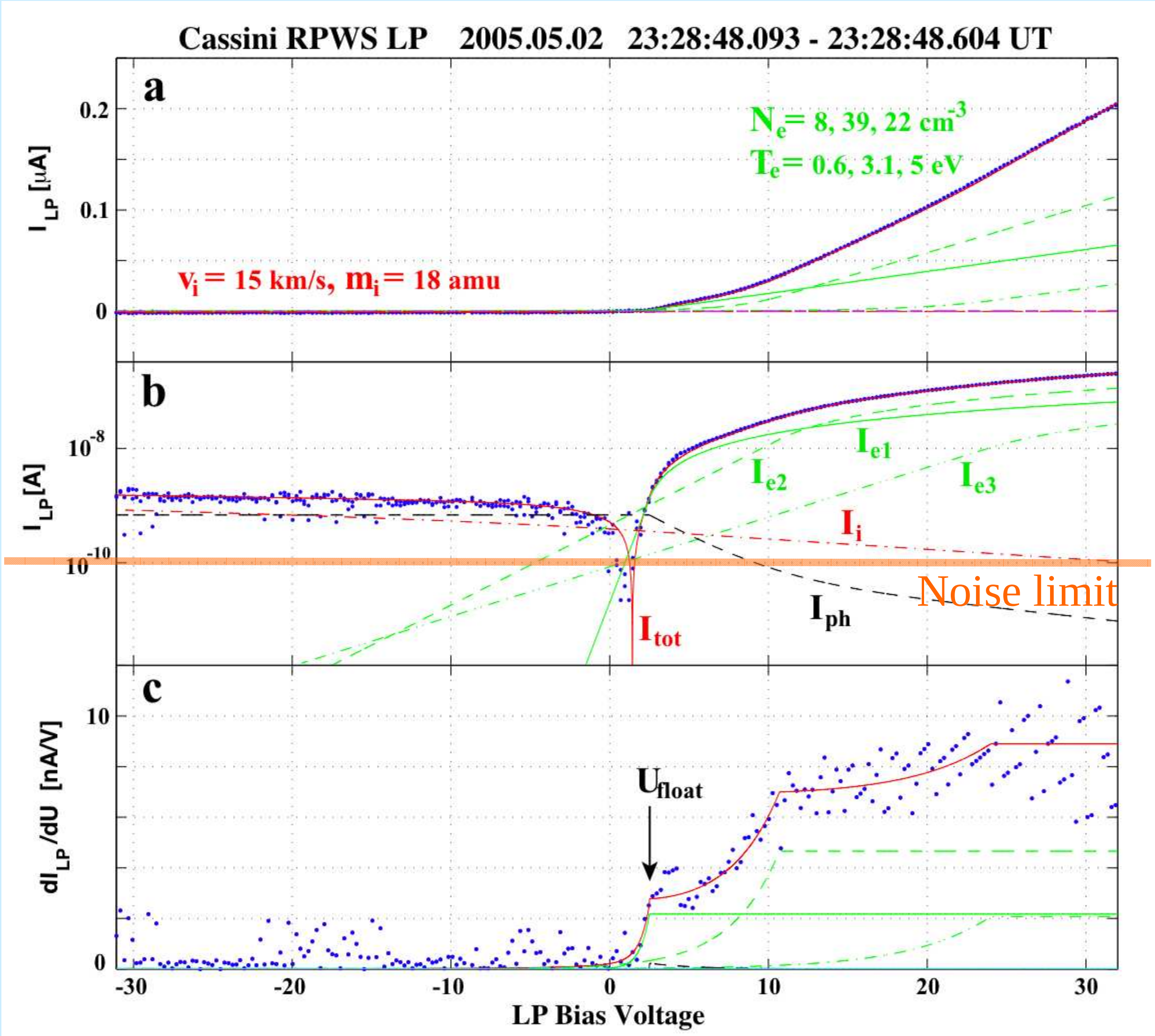
$I_e <<$

$I_i = I_{i0}(1 - \chi_i)$

where

$$I_{i0} = A_{LP} n_i q_i \sqrt{\frac{v_i^2}{16} + \frac{k_B T_i}{2\pi m_i}}$$

$$\chi_i = \frac{e(U_{bias} + U_{SC})}{\frac{m_i v_i^2}{2} + k_B T_i}$$



RPWS/LP ±32 V sweeps

$I_{ph,S/C}$

$I_e = I_{e0}(1 - \chi_e)$

$I_i <<$

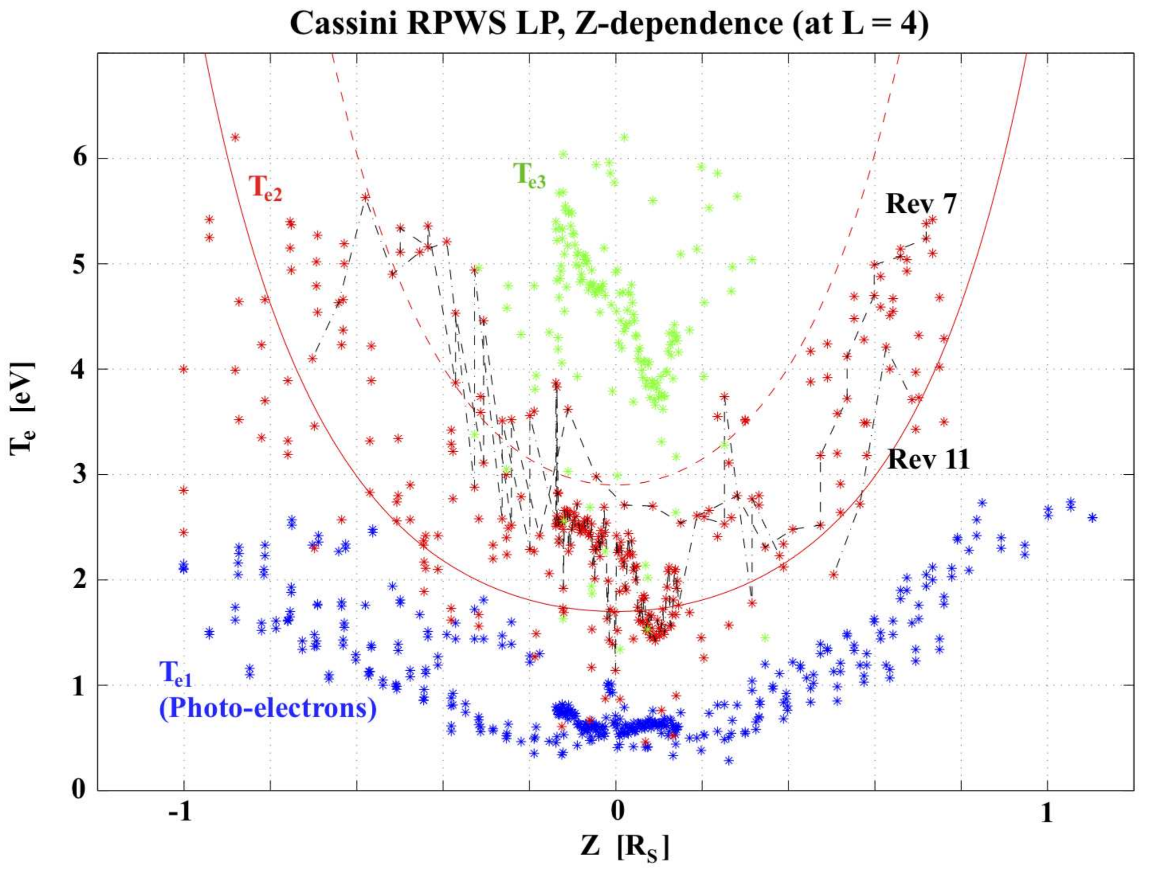
where

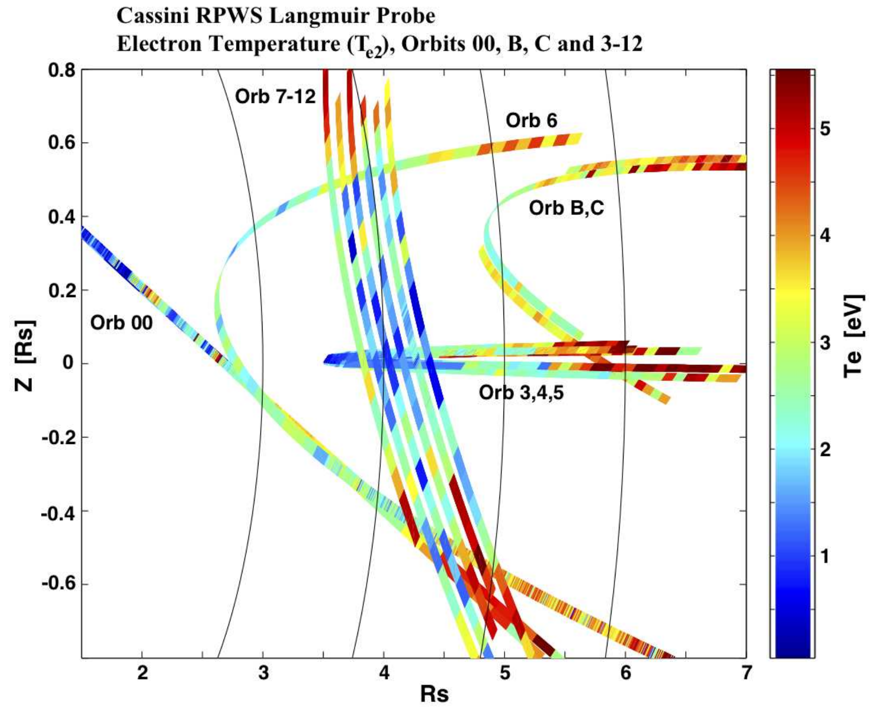
$$I_{e0} = A_{LP} n_e q_e \sqrt{\frac{k_B T_e}{2\pi m_e}}$$

$$\chi_e = \frac{e(U_{bias} + U_{SC})}{k_B T_e}$$

Plasma Disc T_e

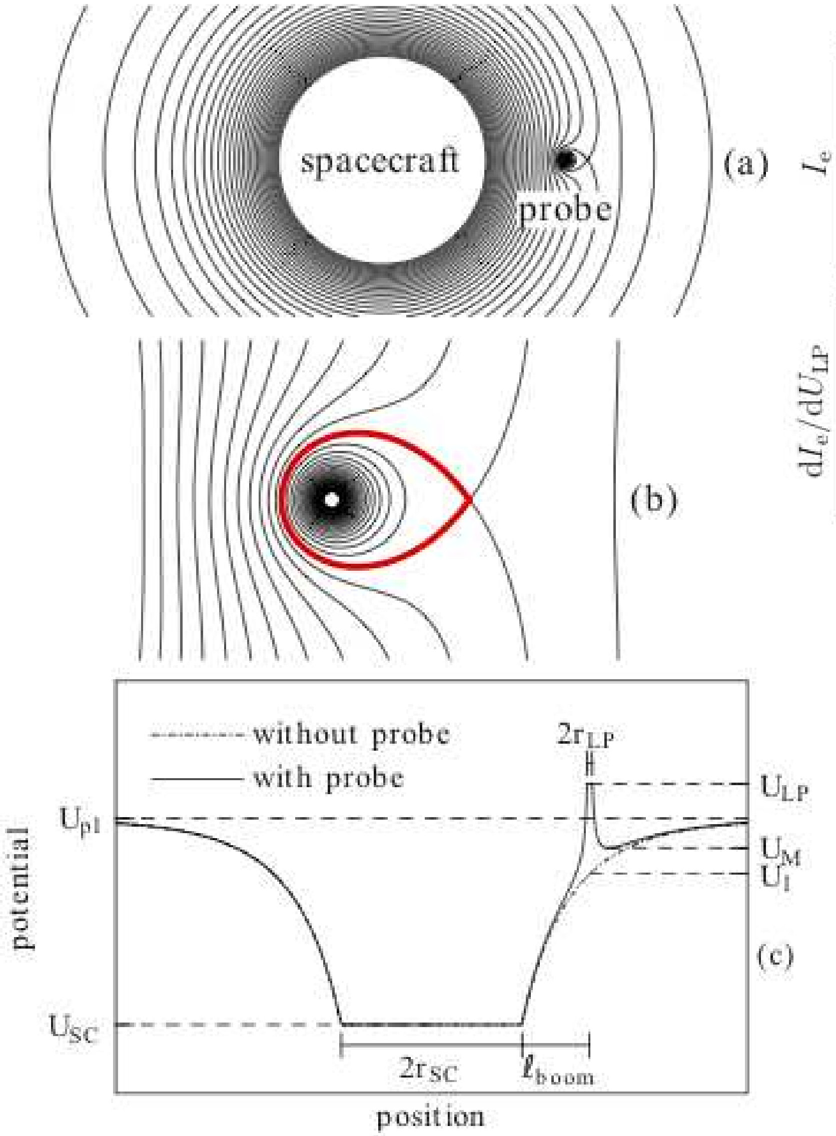
Gustafsson & Wahlund, PSS, 2010

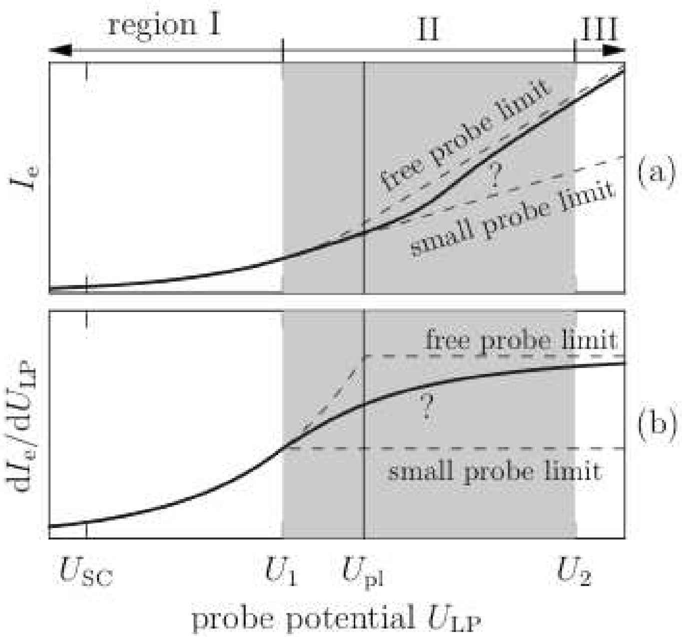


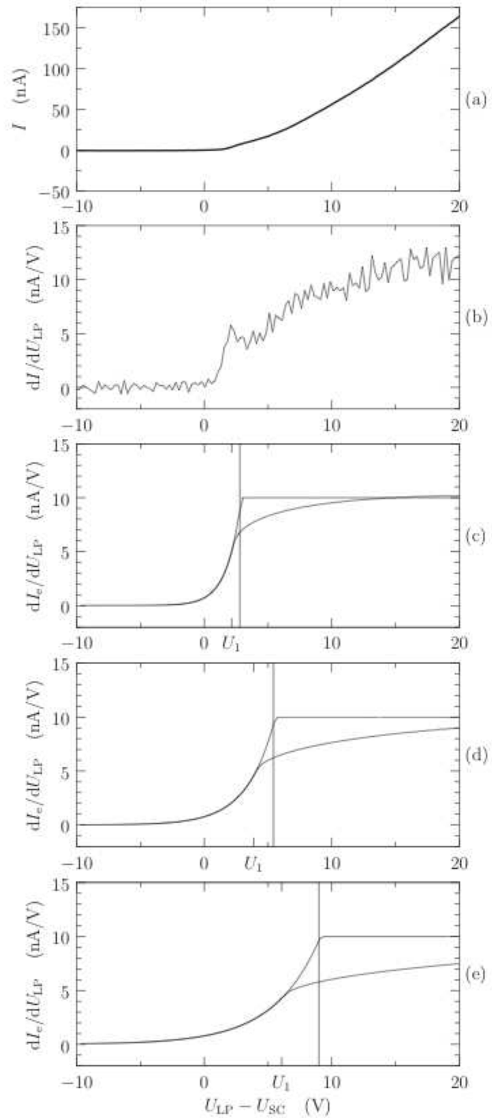


Probe in S/C Sheath Effect?

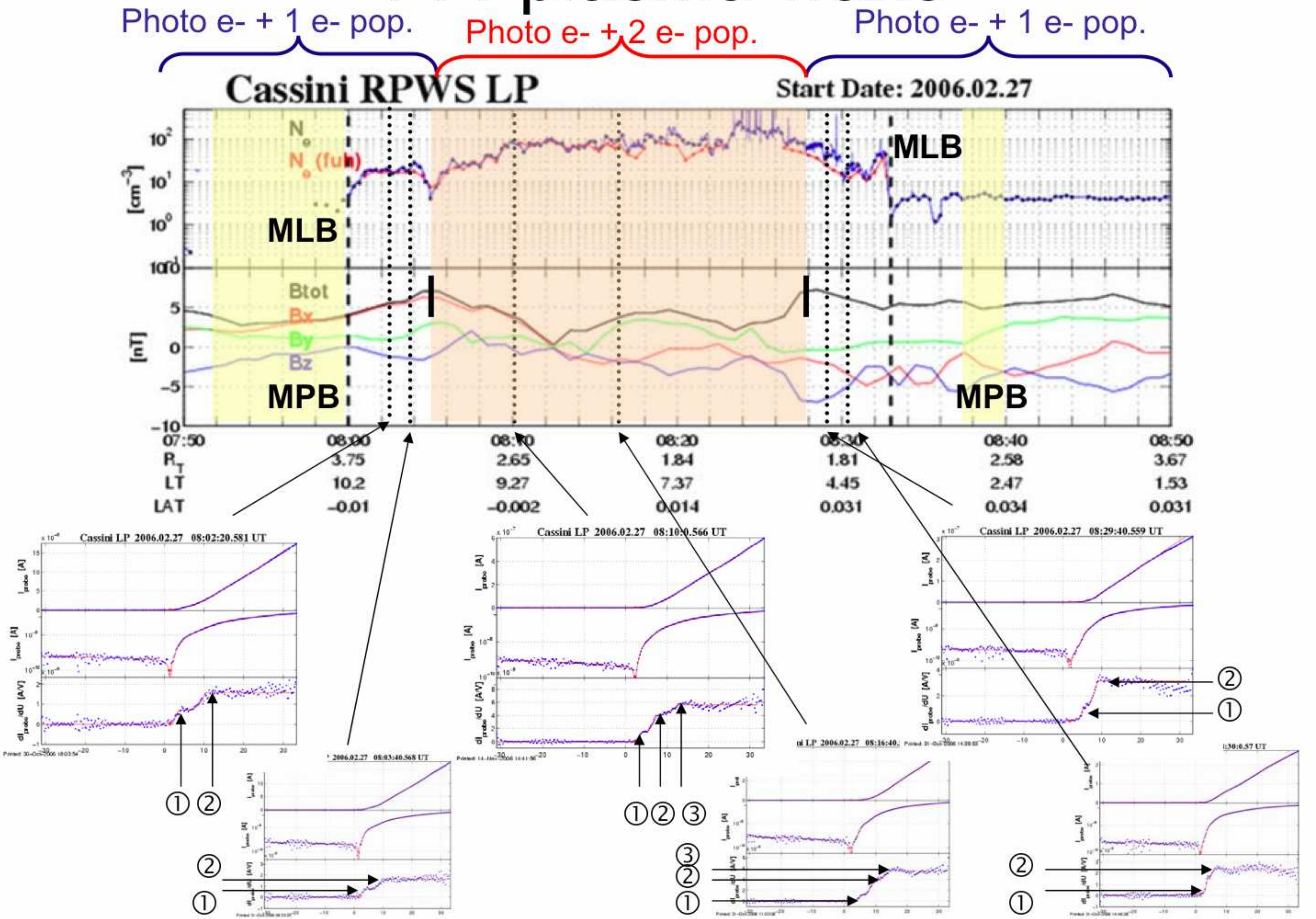
[Olson et al., 2010]



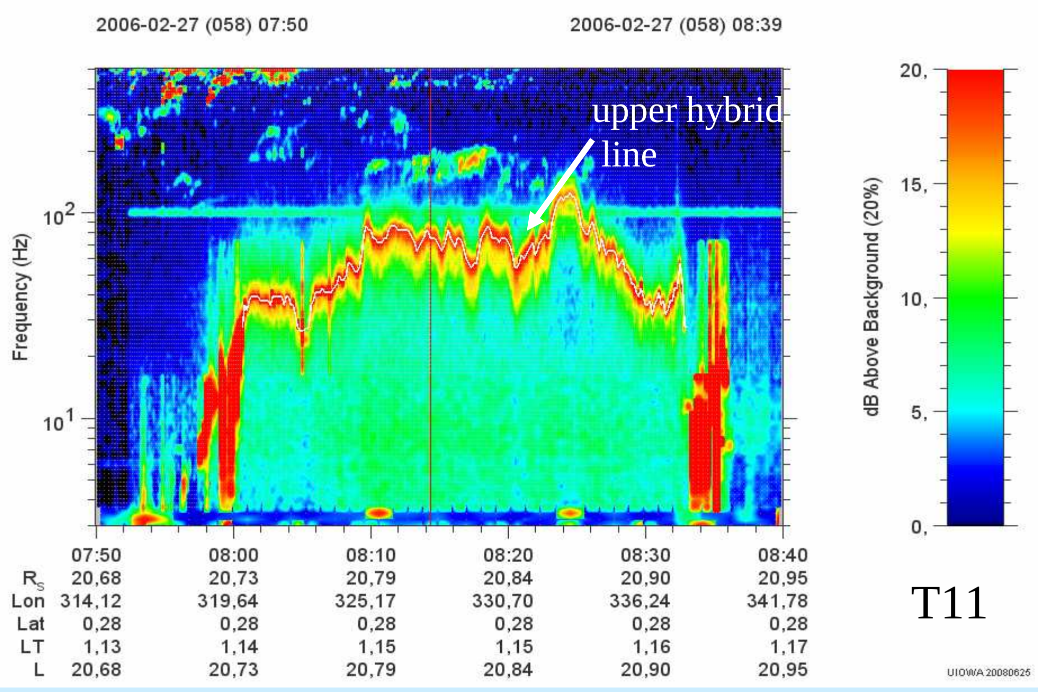


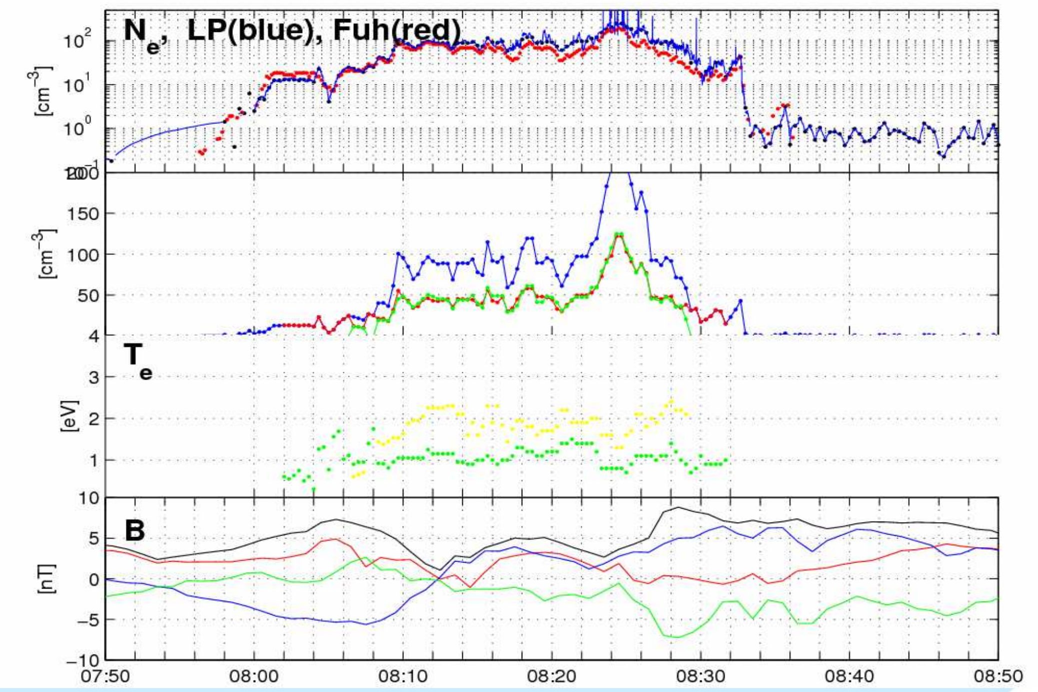


T11 plasma wake



- Titan plasma wake
  - Extend several R_{Titan}
  - Cold plasma of ionospheric origin
  - Anisotropic T_e in Titan's plasma wake/exo-ionosphere?
  - Small Debye lengths





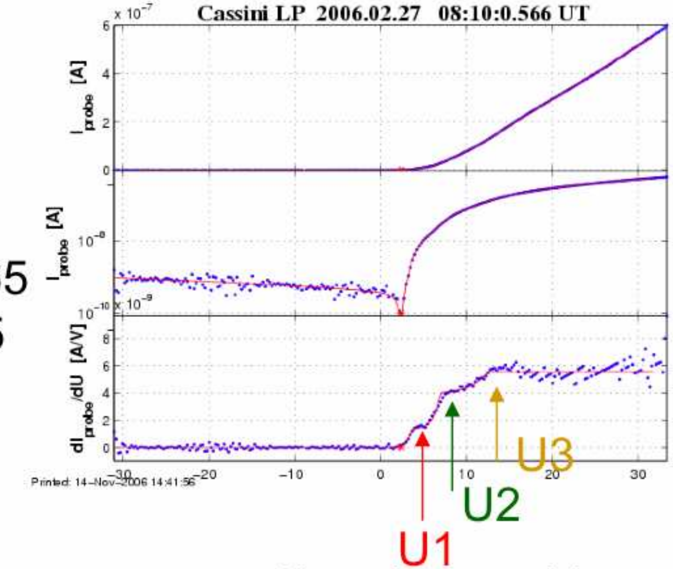
Interpretation of the sheath effect

- ☐ $\lambda_D \sim r_p \Rightarrow$ sheath effect important
- ☐ potential from charged object shielded by a cloud of particle with an opposite charge $\Rightarrow$ *sheath*

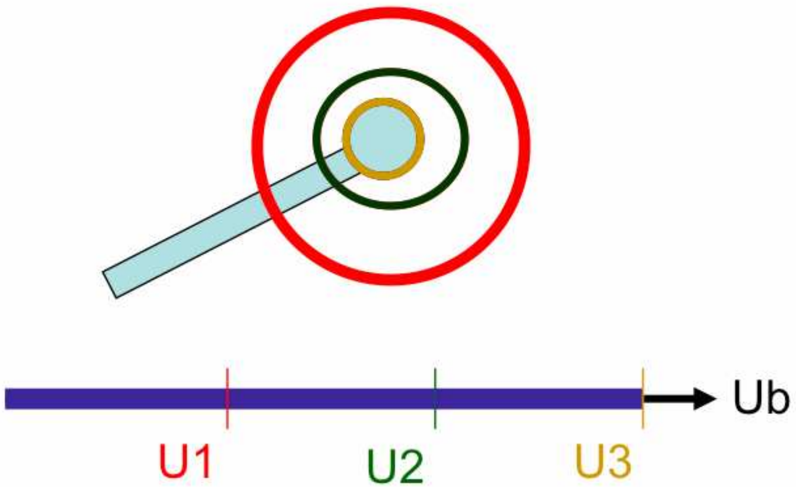
$$s = 0.83\lambda_D \left(\frac{r_{LP}}{\lambda_D}\right)^{1/3}\left(\frac{qU}{kT}\right)^{1/2}$$

Whipple, 1965
Walker, 1965

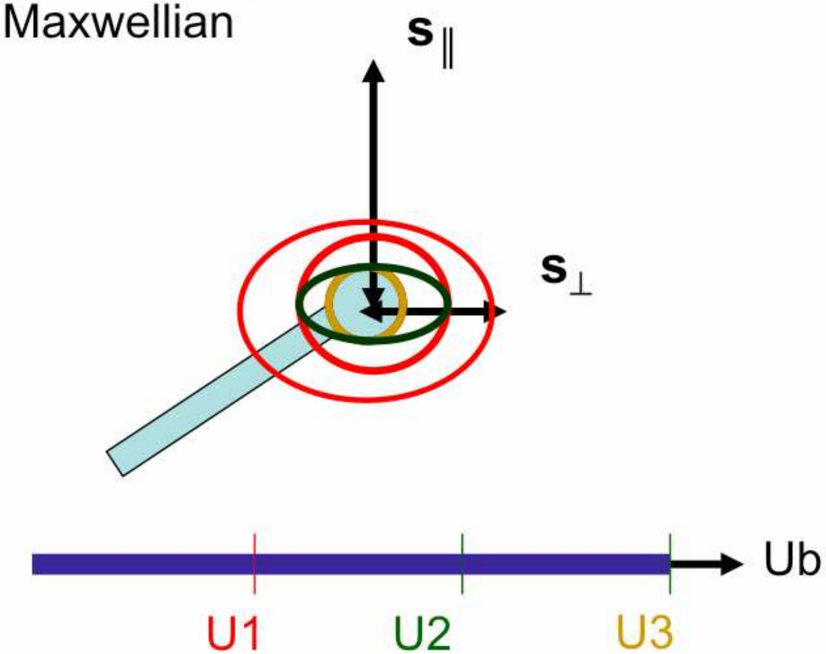
$$\lambda_D \sqrt{\frac{\varepsilon_0 kT}{n_e q^2}}$$



In the analysis : each e- population have a Maxwellian distribution function



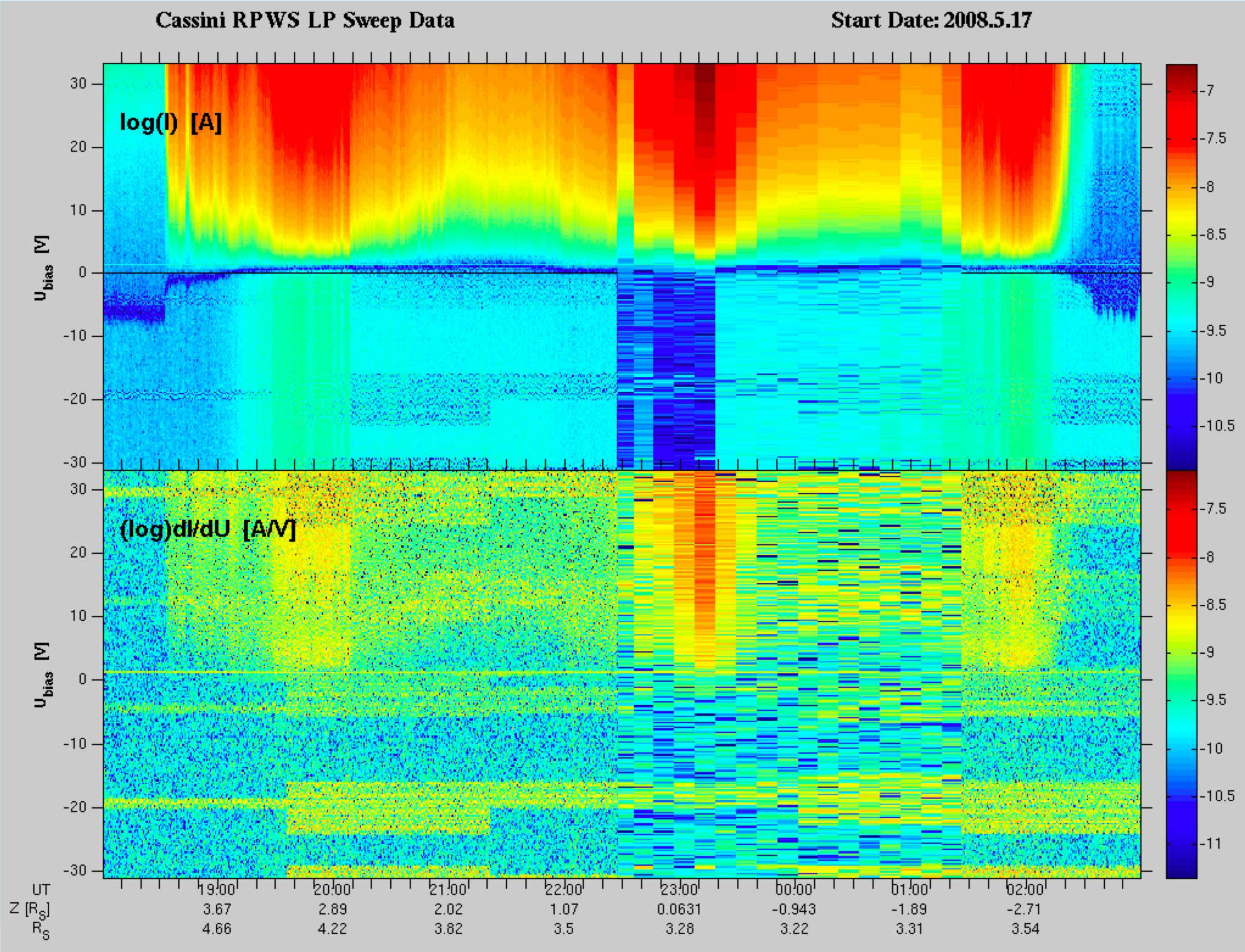
What we expect if we have a bi-Maxwellian



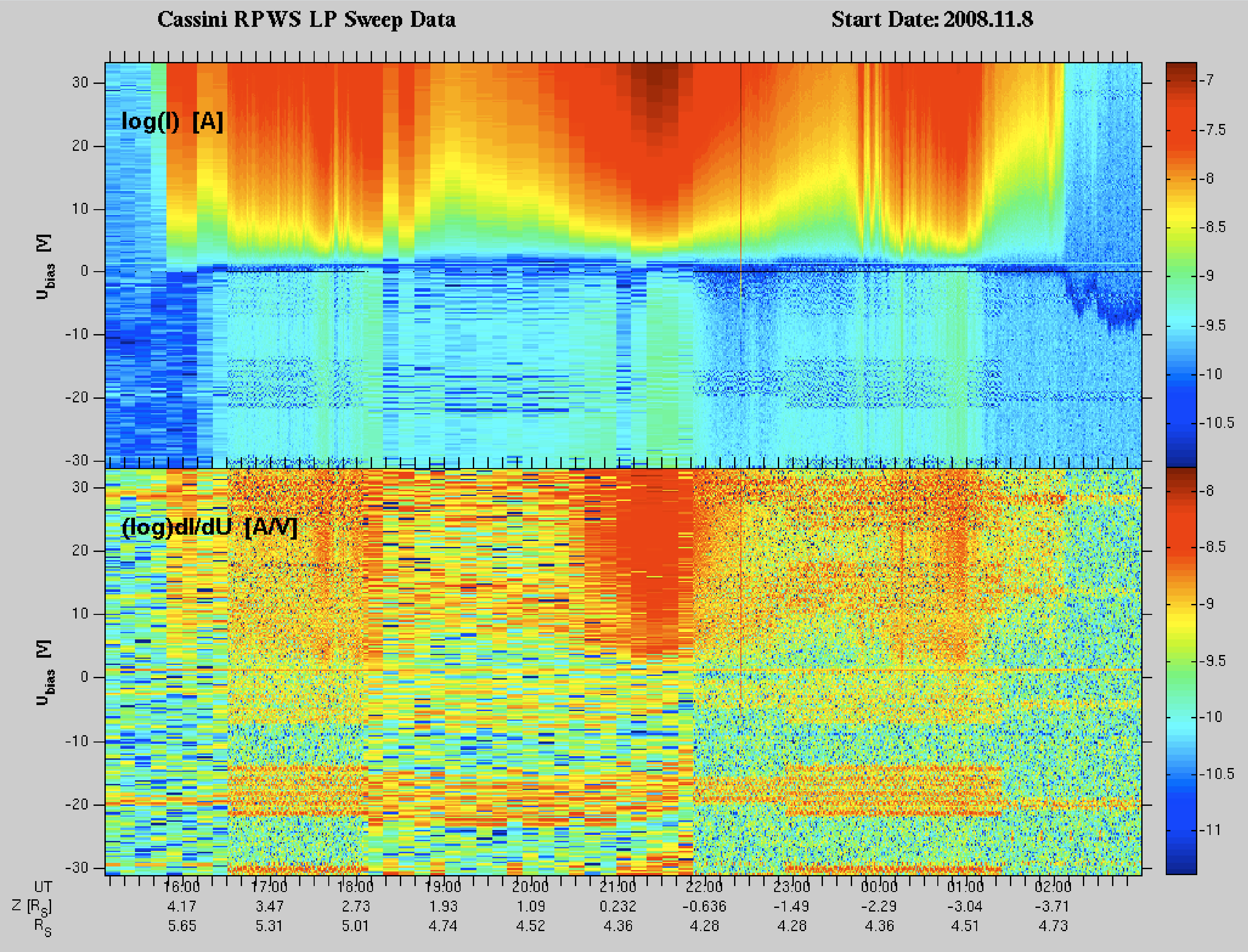
SPIS development request 3

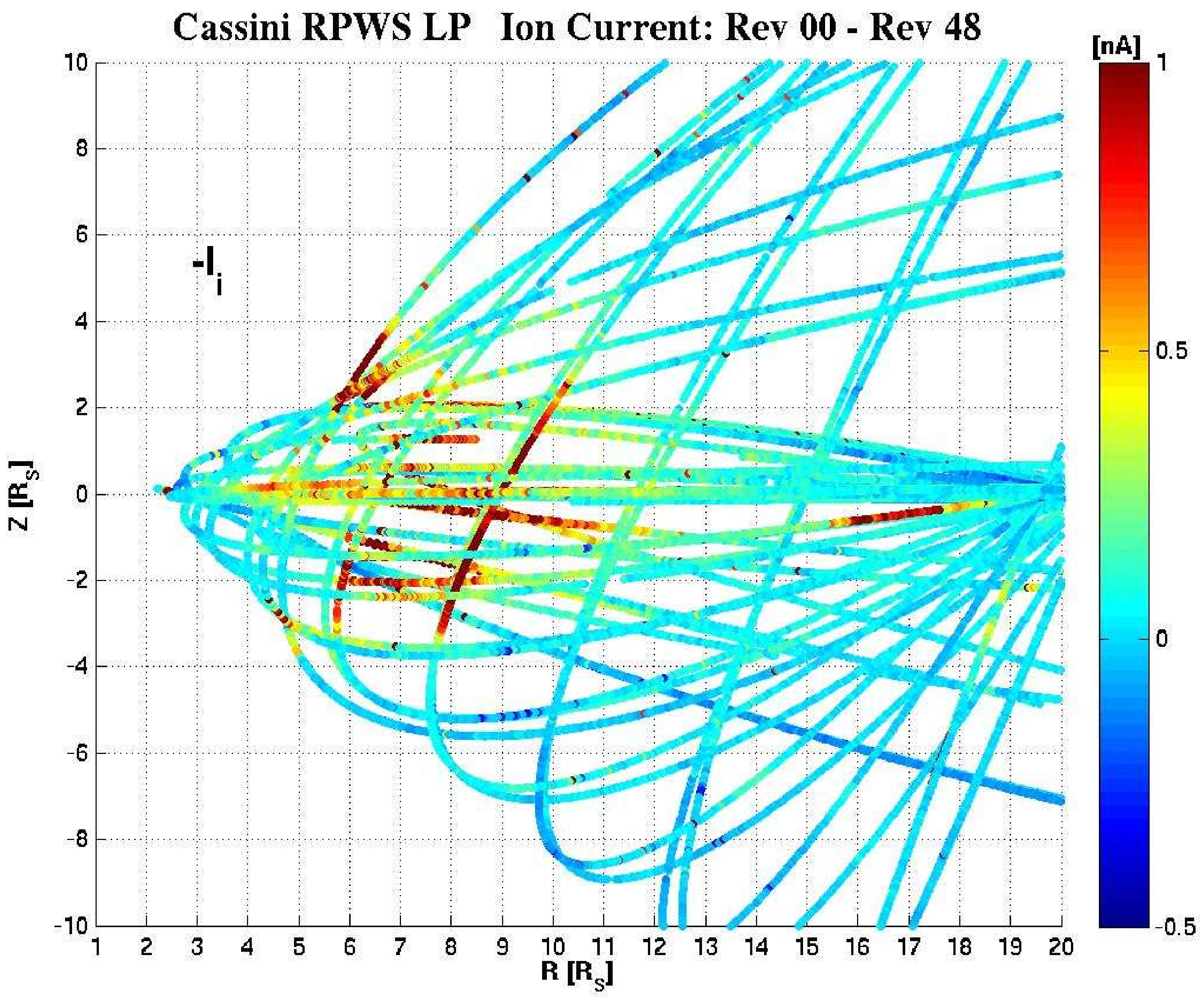
- Include magnetic field (**B**)
- Include anisotropic T_e
- Include case with LP within S/C sheath
- Include “weird” S/C configurations giving anisotropic potential patterns (e.g., booms, landers, antenna, thrusters … etc)

Effects of energetic particles



- Secondary e^-:s fr.
  - S/C
  - Probe


Cassini RPWS LP Sweep Data
Start Date: 2008.11.8
log(I) [A]
(log)dI/dU [A/V]
U_{bias} [V]
30
20
10
0
-10
-20
-30
-7
-7.5
-8
-8.5
-9
-9.5
-10
-10.5
-11
UT
Z [R_S]
R_S
16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00 00:00 01:00 02:00
4.17 3.47 2.73 1.93 1.09 0.232 -0.636 -1.49 -2.29 -3.04 -3.71
5.65 5.31 5.01 4.74 4.52 4.36 4.28 4.28 4.36 4.51 4.73

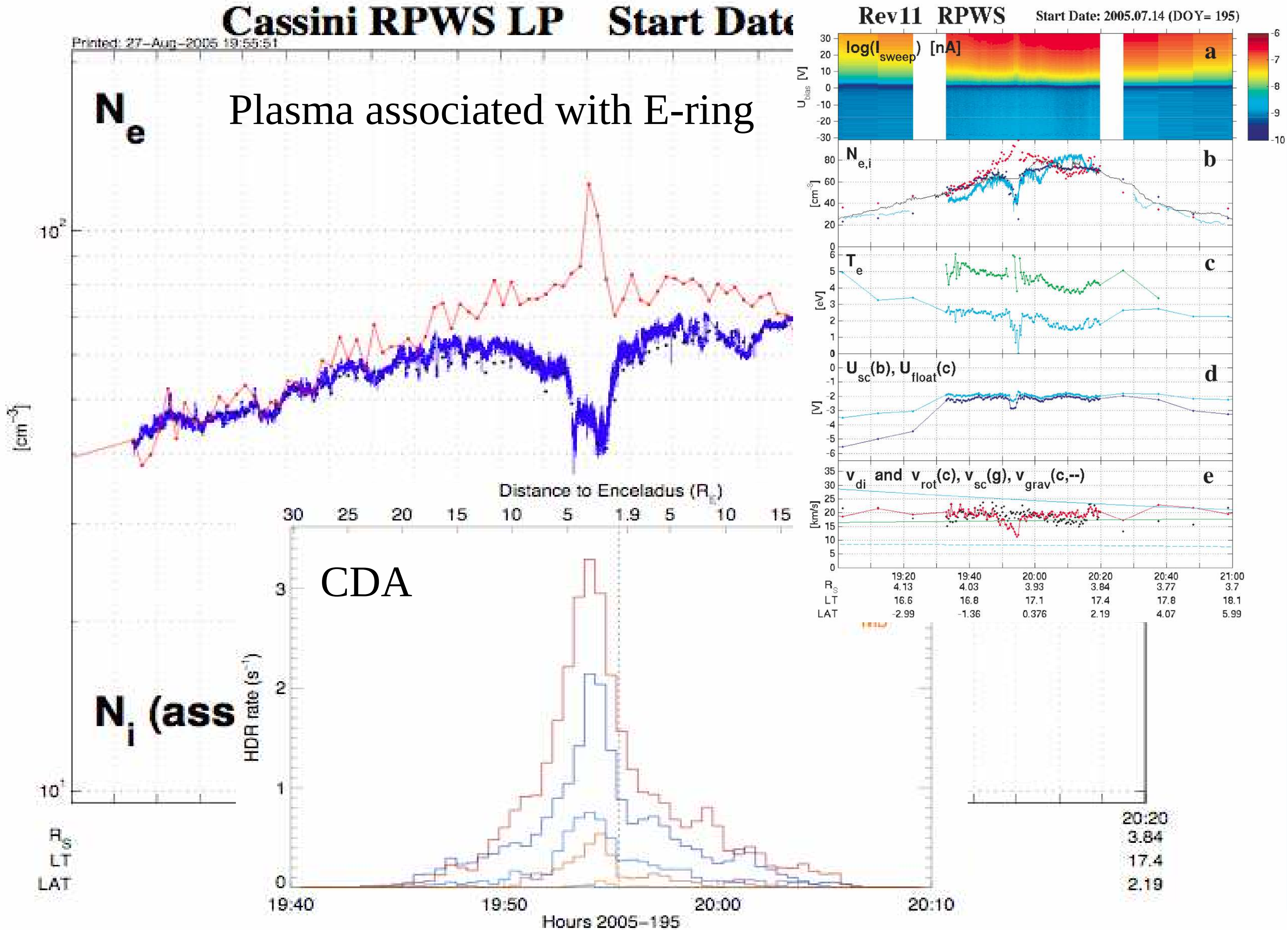


Cassini RPWS LP Ion Current: Rev 00 - Rev 48
-I_i
Z [R_S]
R [R_S]
[nA]
1
0.5
0
-0.5
10
8
6
4
2
0
-2
-4
-6
-8
-10
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

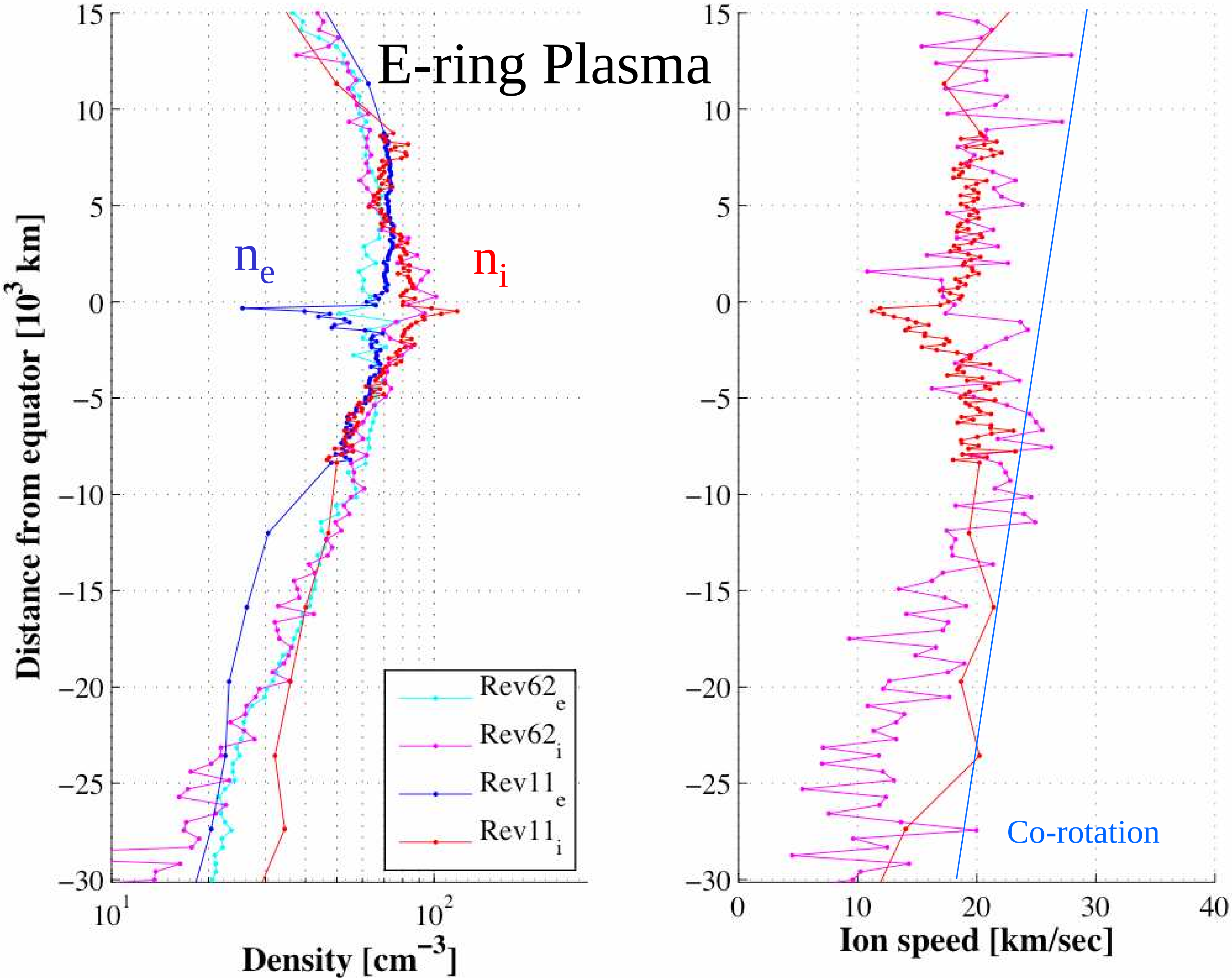
SPIS development request 4

- Include secondary electron (& ion) emissions due to energetic particle radiation
  - Fr. S/C
  - Fr. LP
- Include different energetic particle distribution functions (energy & pitch-angle)
- Include different surface material possibilities

Wahlund et al., PSS, 2009



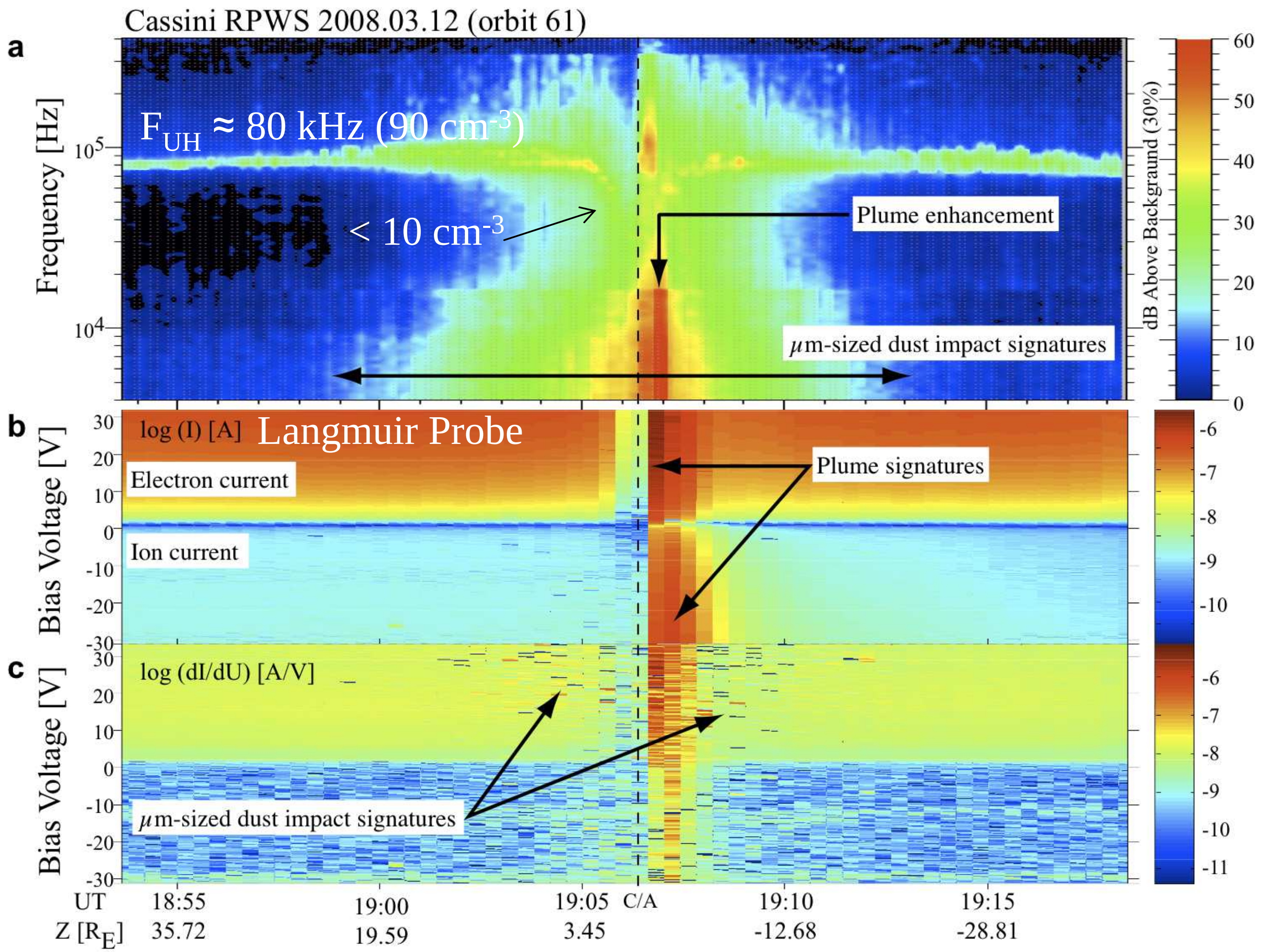
E-ring Plasma



SPIS development request 5

- Include dust-plasma with significant charge partition on the negative dust
  - $N_e + Z_d N_d = N_i$
  - Effect on S/C sheath
- Include collisions (effect on sheath)
  - With neutrals
  - With charged dust
  - Between electrons & ions

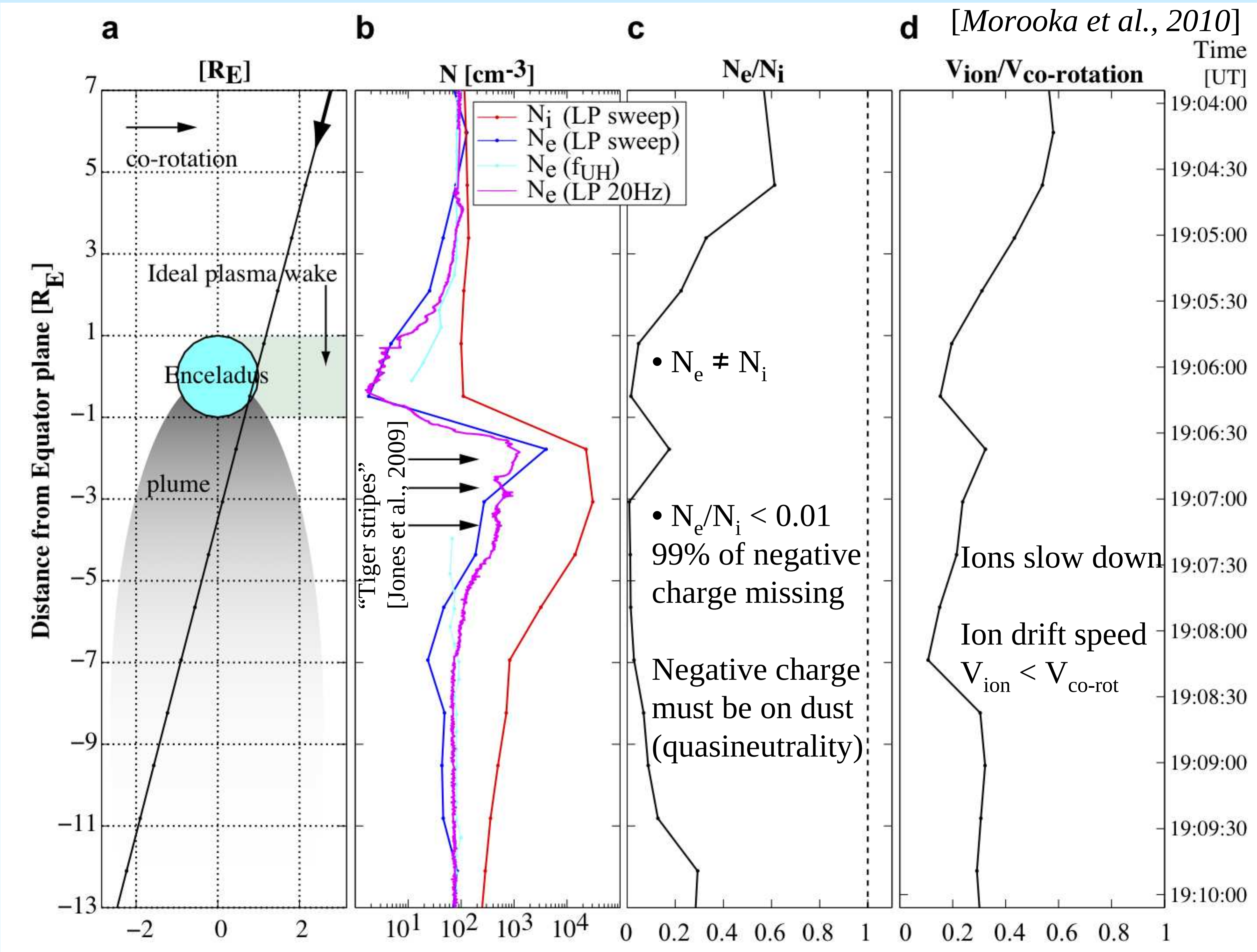
Overview: Enceladus E03 Encounter



- Electron depletion w/i the ideal co-rotation wake
- No corresponding ion depletion signature
- E-ring μm-sized dust
- Enceladus plume
    - dust + plasma

[*Farrell et al., 2009; Morooka et al., 2010*]

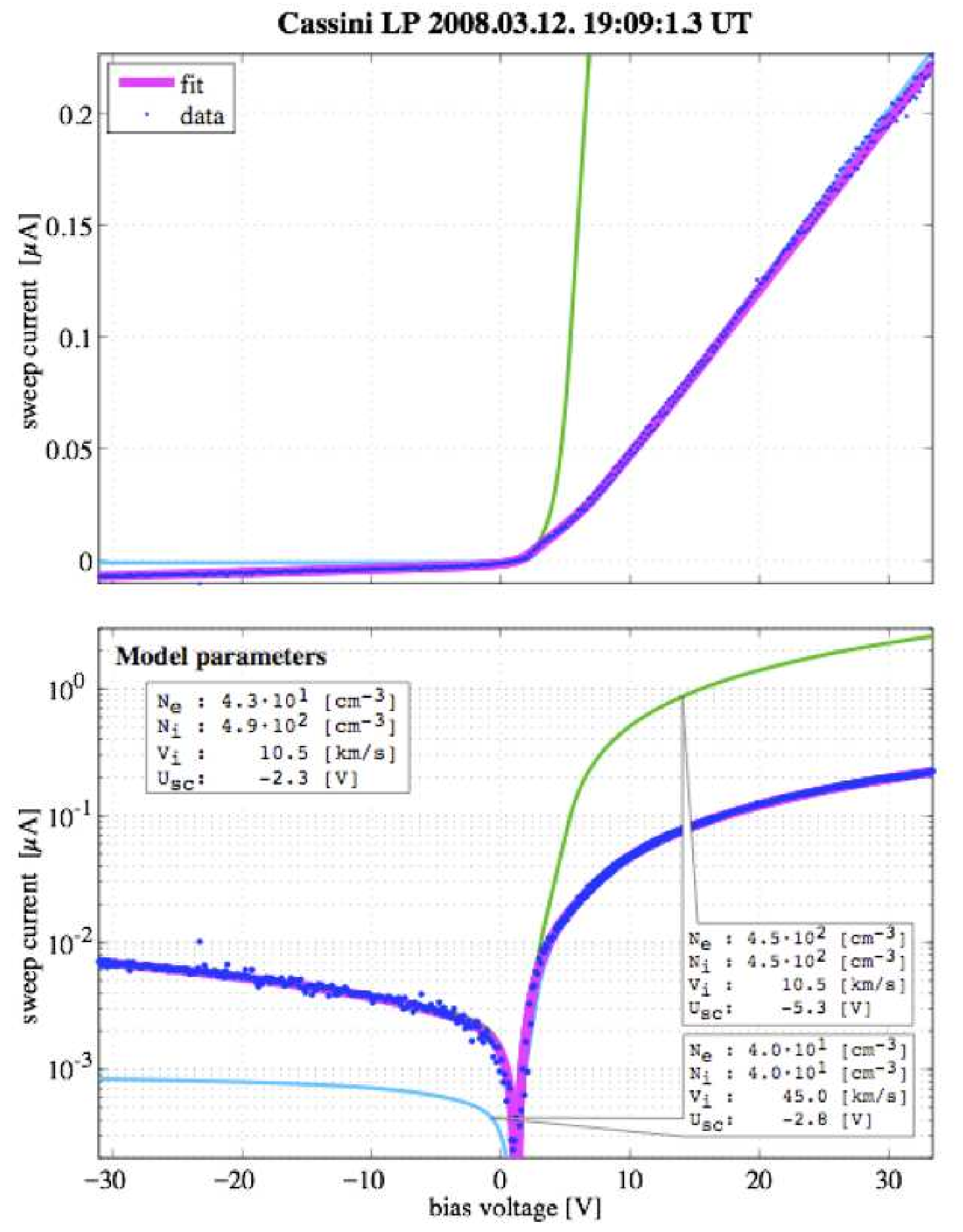
RPWS/LP sensitive to electrons < 8-10 eV


[Morooka et al., 2010]
a
b
c
d
[R_E]
N [cm-3]
Ne/Ni
Vion/Vco-rotation
Time [UT]
Distance from Equator plane [R_E]
co-rotation
Ideal plasma wake
Enceladus
plume
Ni (LP sweep)
Ne (LP sweep)
Ne (fUH)
Ne (LP 20Hz)
"Tiger stripes" [Jones et al., 2009]
• Ne ≠ Ni
• Ne/Ni < 0.01
99% of negative charge missing
Negative charge must be on dust (quasineutrality)
Ions slow down
Ion drift speed
Vion < Vco-rot
19:04:00
19:04:30
19:05:00
19:05:30
19:06:00
19:06:30
19:07:00
19:07:30
19:08:00
19:08:30
19:09:00
19:09:30
19:10:00
7
5
3
1
−1
−3
−5
−7
−9
−11
−13
−2
0
2
10^1
10^2
10^3
10^4
0
0.2
0.4
0.6
0.8
1

Enceladus far plume

- Optimum fit (magenta):
  - N_e = 43 cm^{-3}, N_i = 490 cm^{-3}
  - Assuming ion density correct (green)
  - Assuming electron density correct (cyan)
  - Hardly reach I_{ph} levels
  - $I_{sec} \approx 10$ nA = const
  - can not explain shape of characteristic

- LP characteristic must be due to thermal ion population

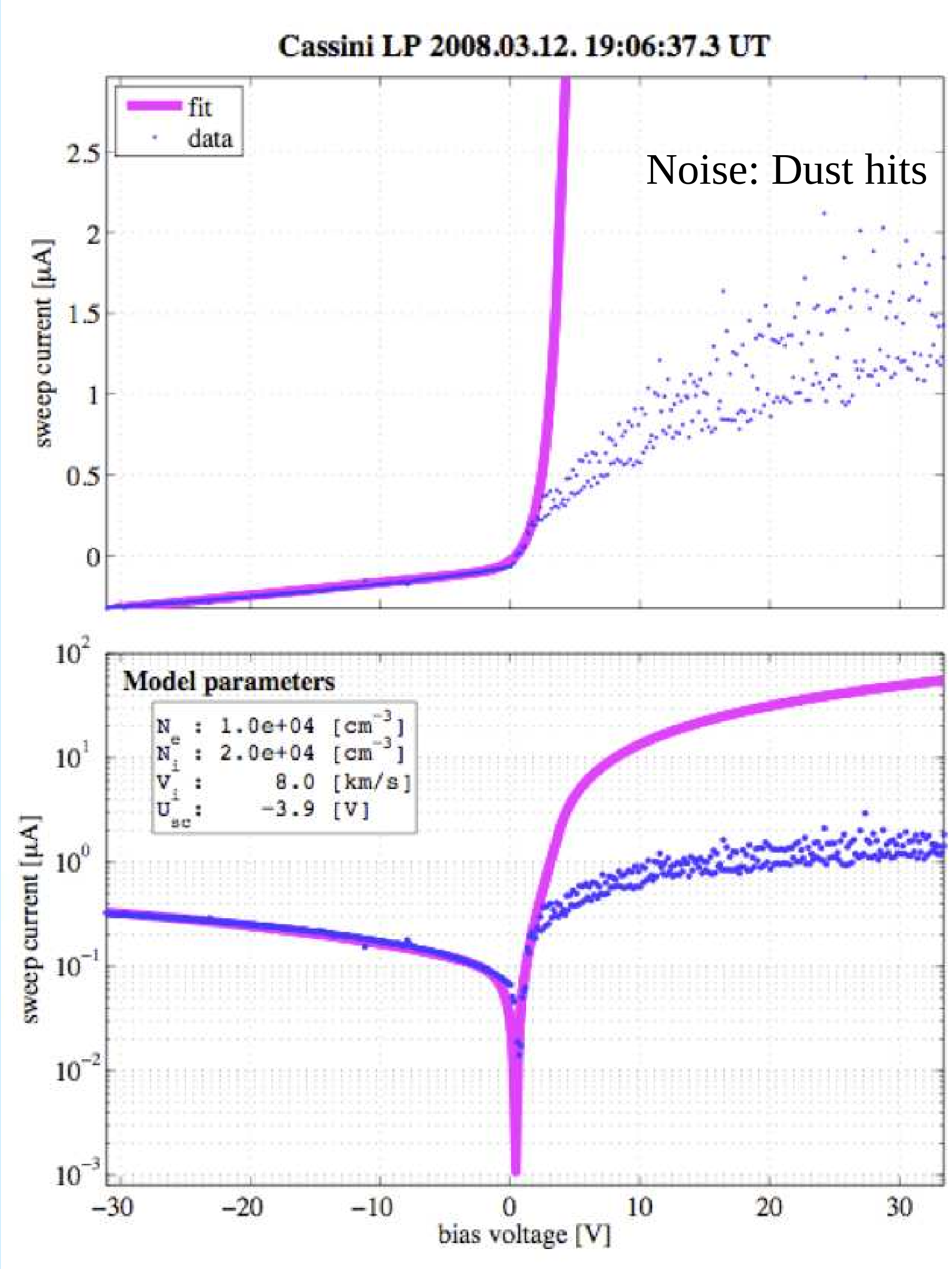


Enceladus central plume

- Electron current saturates!
  - 0.5 – 2 μA (!)
  - No question about that a very dense plasma exist here

$$I_{e0} = A_{LP} n_e q_e \sqrt{\frac{k_B T_e}{2\pi m_e}}$$

  - $N_e[cm^{-3}]\sqrt{T_e[eV]} \approx 5000\text{-}10000$
- Ion current huge (0.1-0.3 μA)
  - I_{sec} <<
- Saturation occurs near $U_{float} \approx +1$ V
  - Short Debye length necessary
  - Collective effects



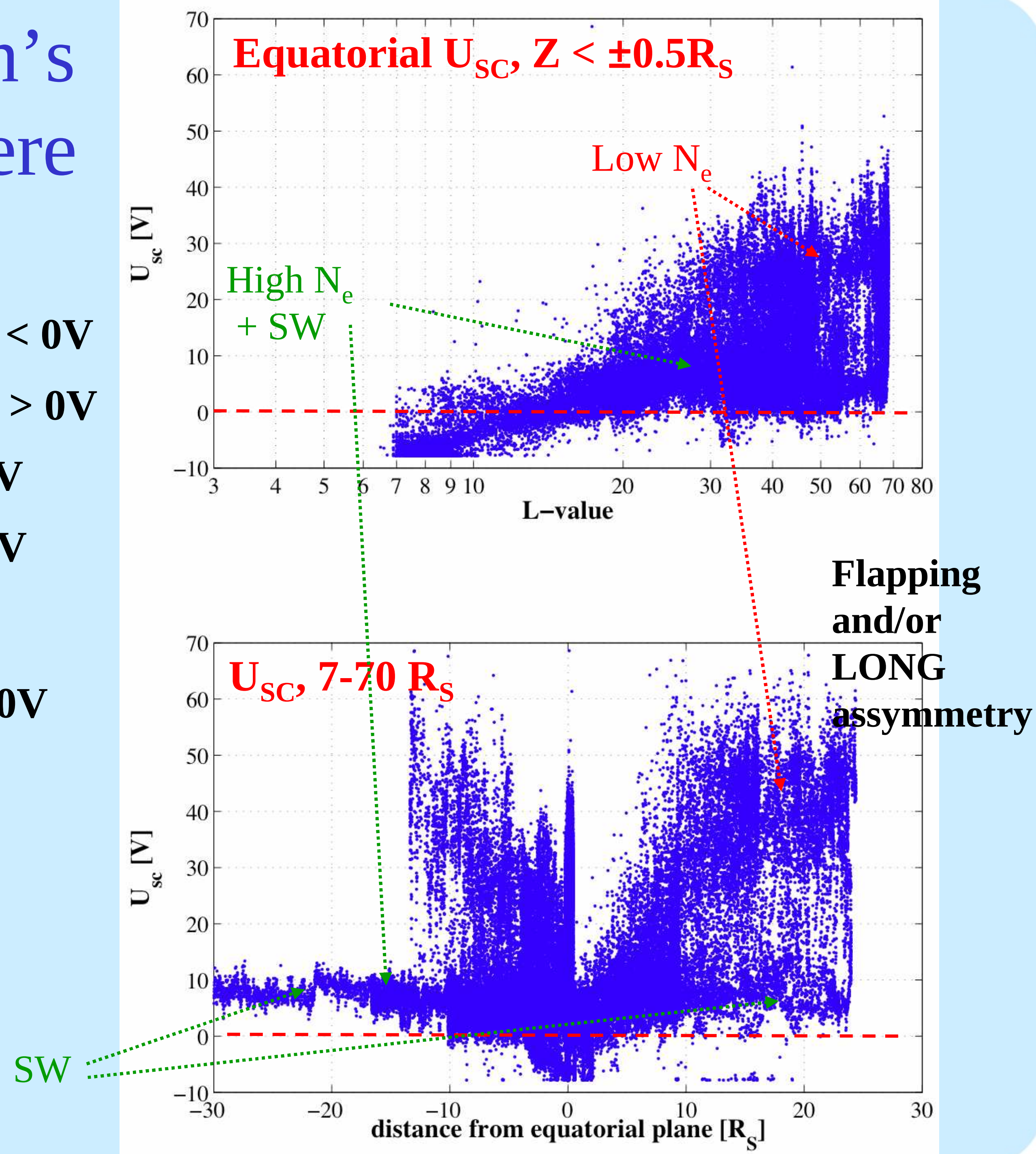
SPIS development request 6

- Include secondary e^- (& ions) from impacting dust
  - On S/C
  - On LP
- Include case where major part of negative charge is situated on dust (dust-ion plasma)

Thank You!

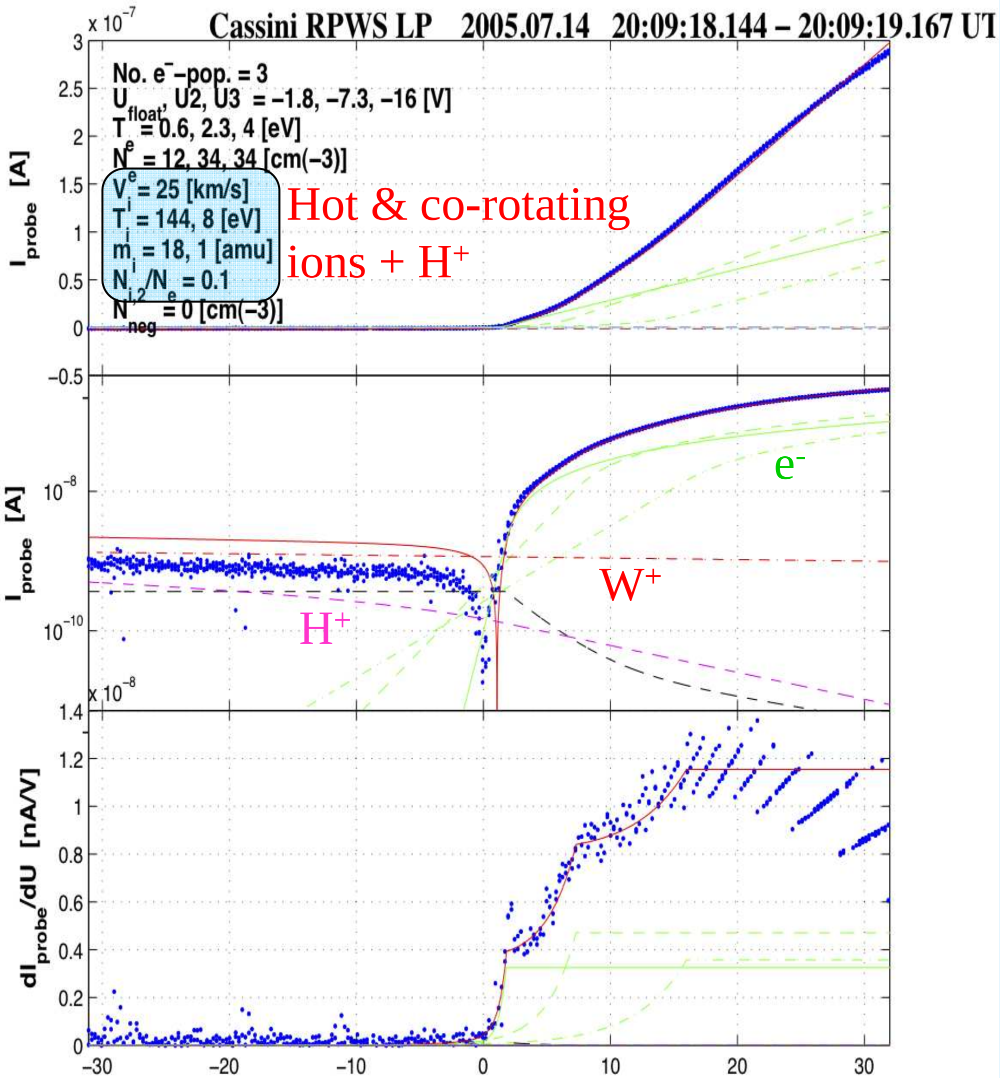
U_{SC} in Saturn's Magnetosphere

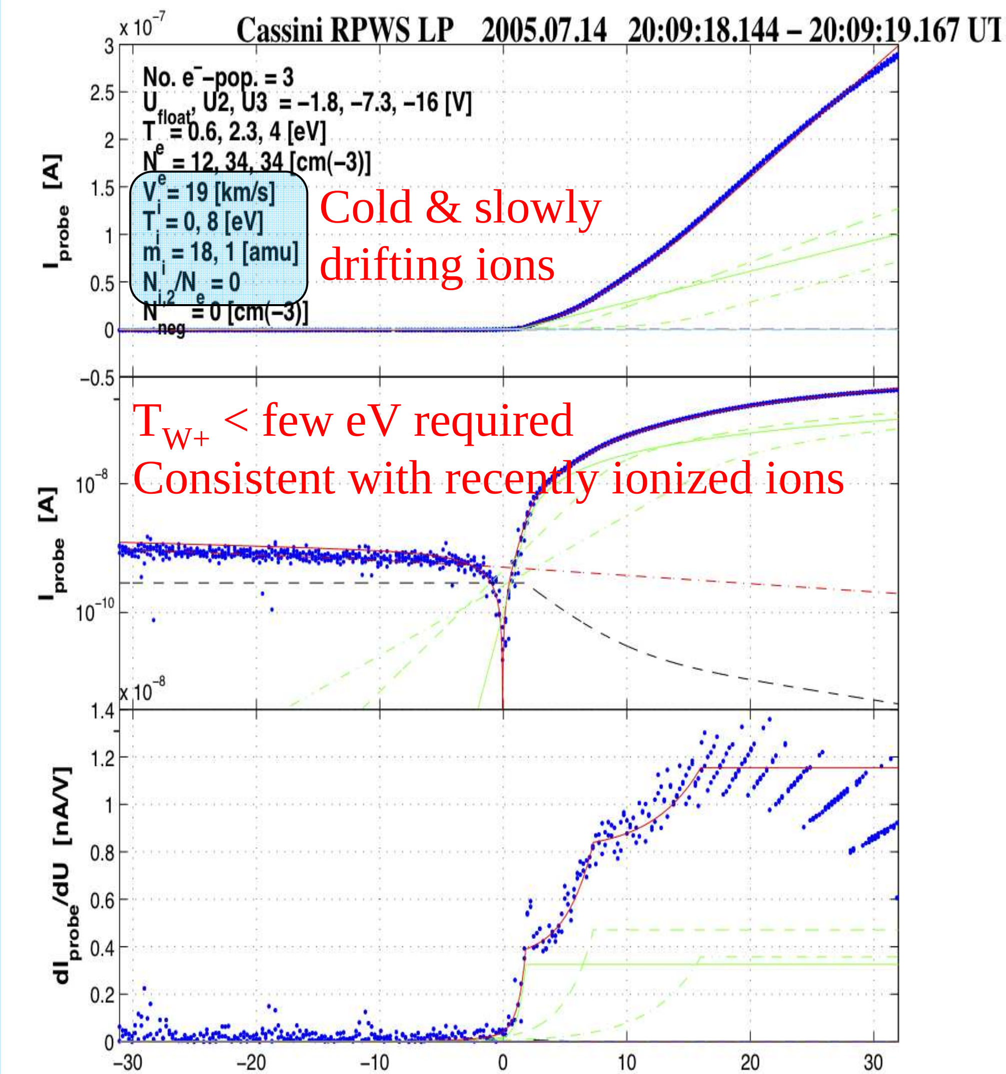
- **Equatorial U_{SC}**
  - **Plasma Disk (<11-14 R_S) : < 0V**
  - **Beyond 11-14 R_S: > 0V**
  - **High N_e: + few V**
  - **Low N_e: +15-40V**
- **Z-dependence:**
  - **Lobe regions: +25V to +60V**
  - **SW: + few V**



Enceladus far plume

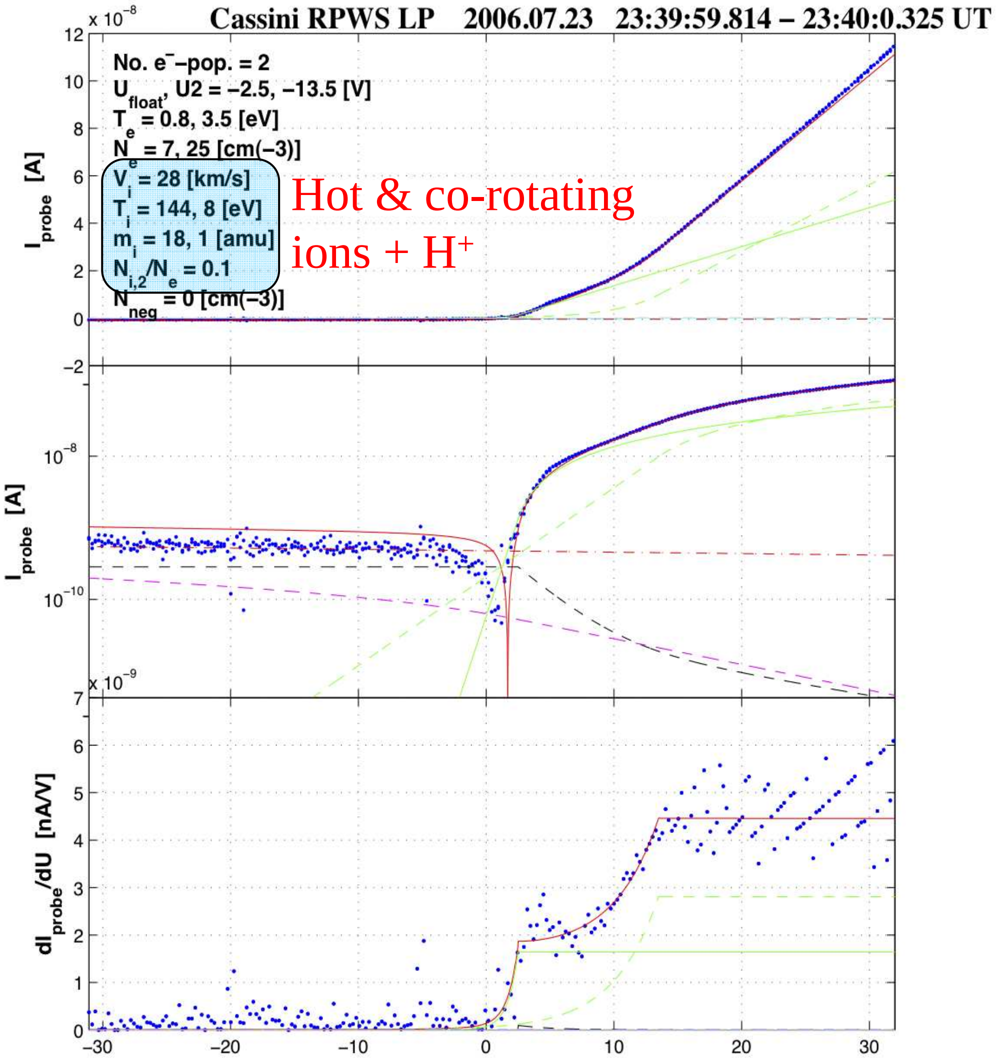
Contribution from secondary electrons will make ions colder & slower !
[see also *Jacobsen et al., 2009*]

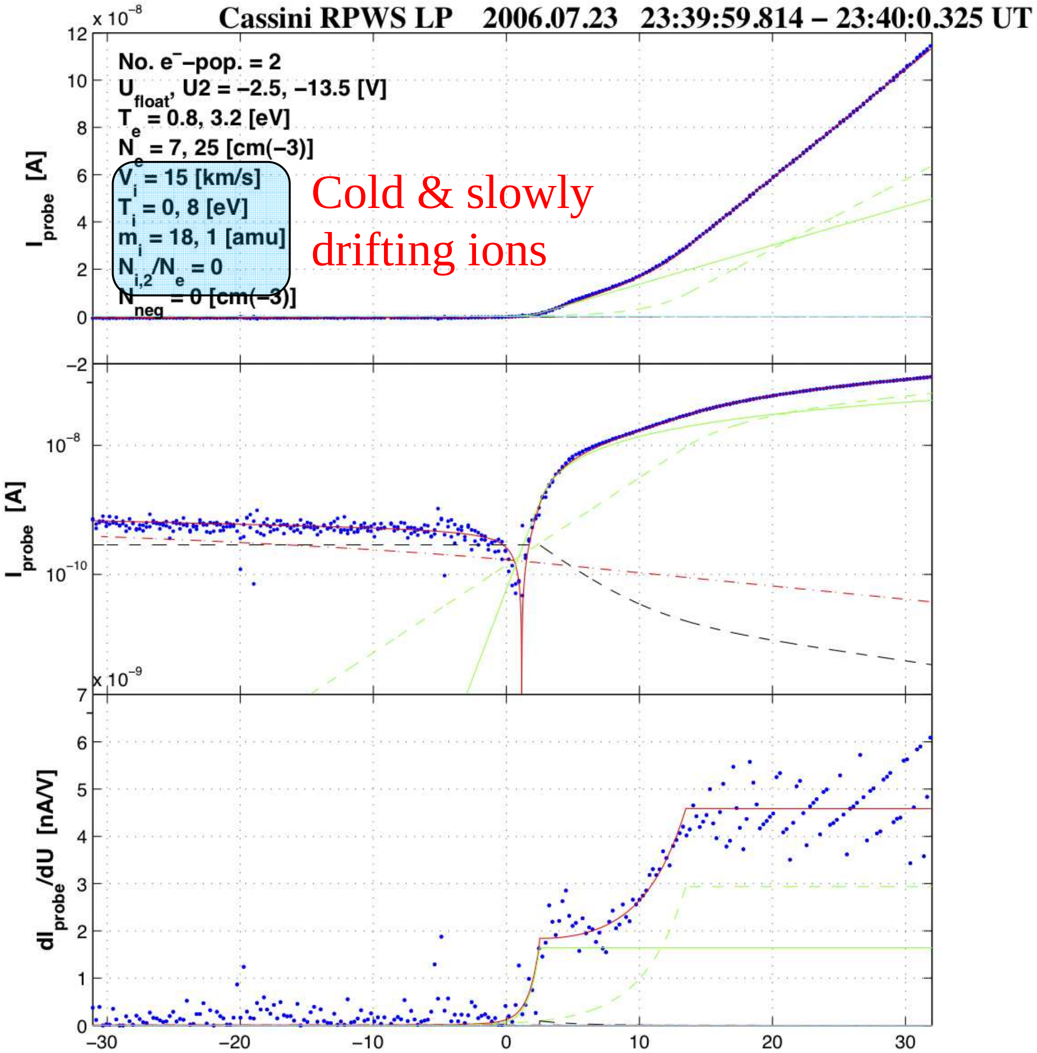




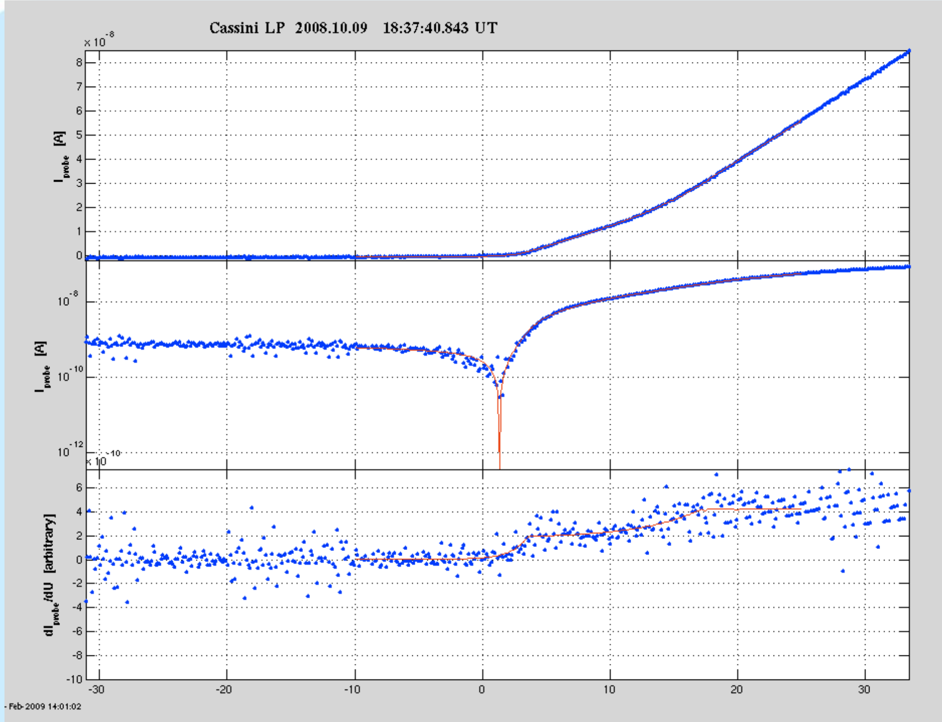
U_{bias} [V]

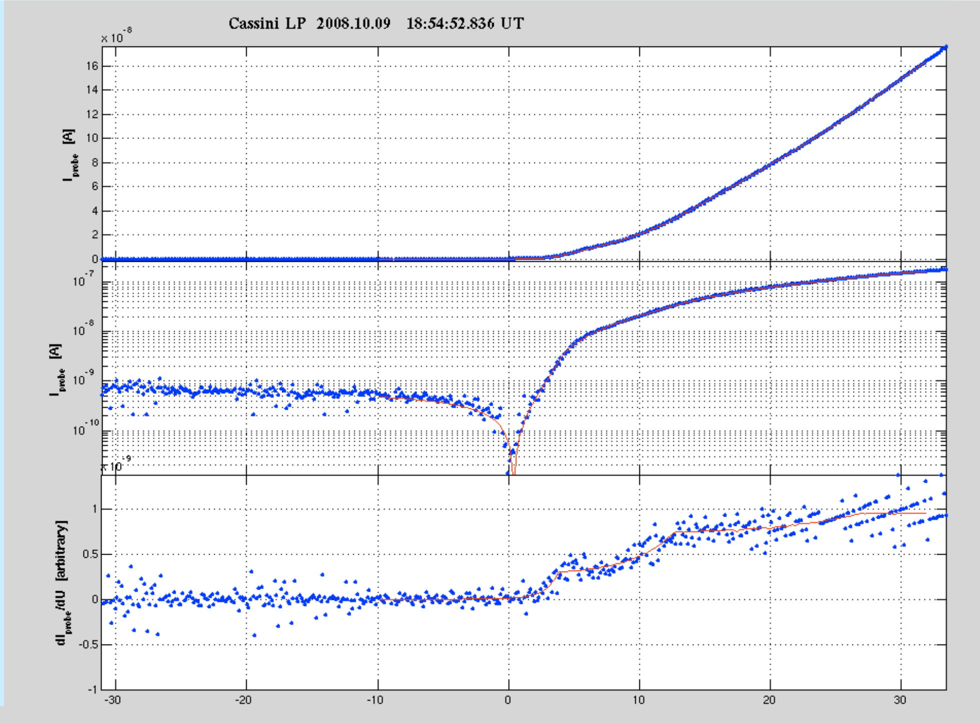
E-ring plasma



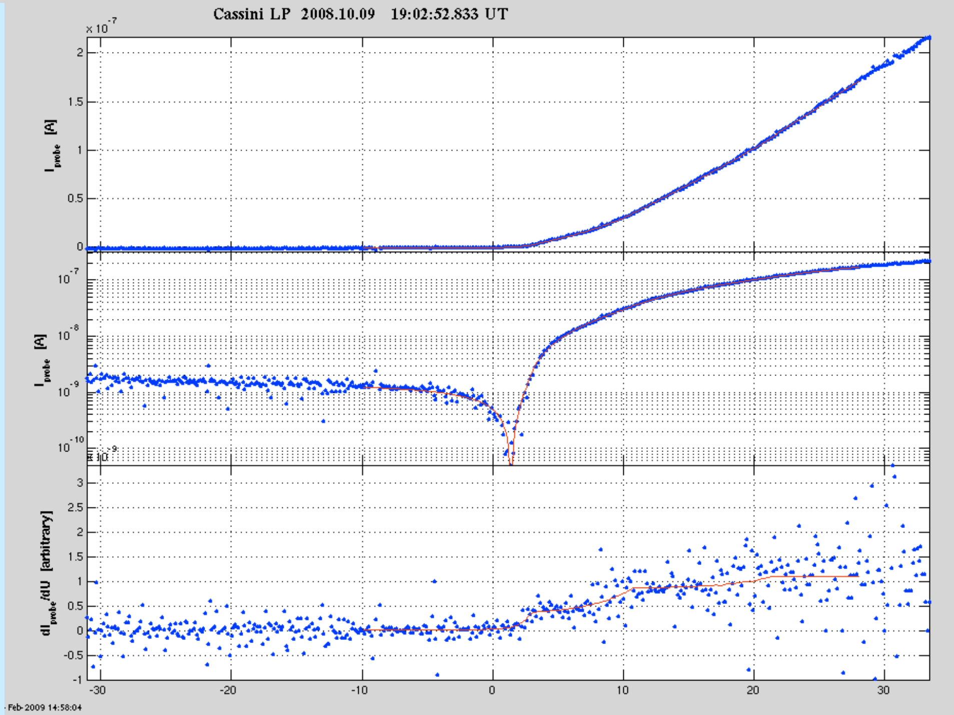


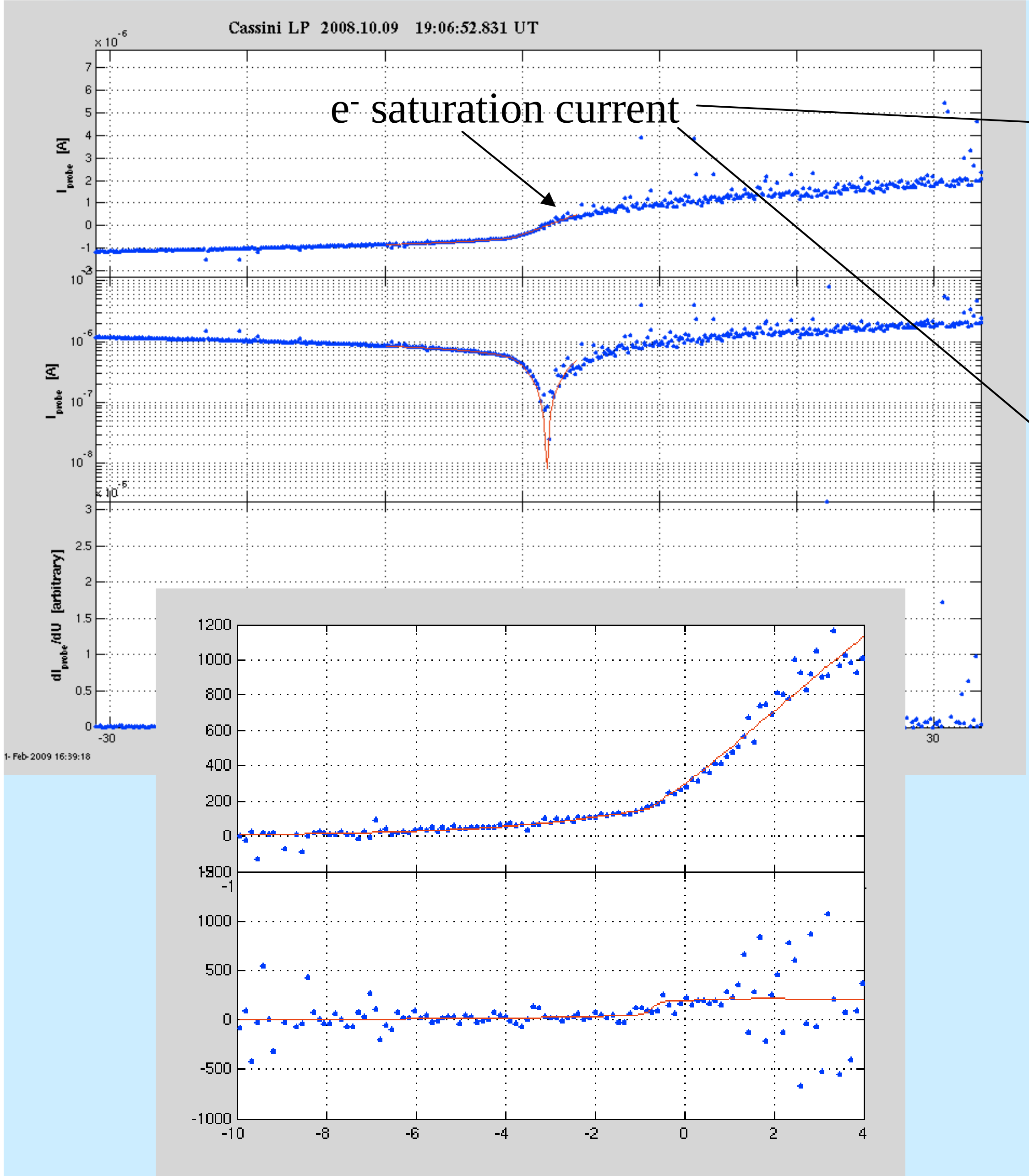
U_{bias} [V]

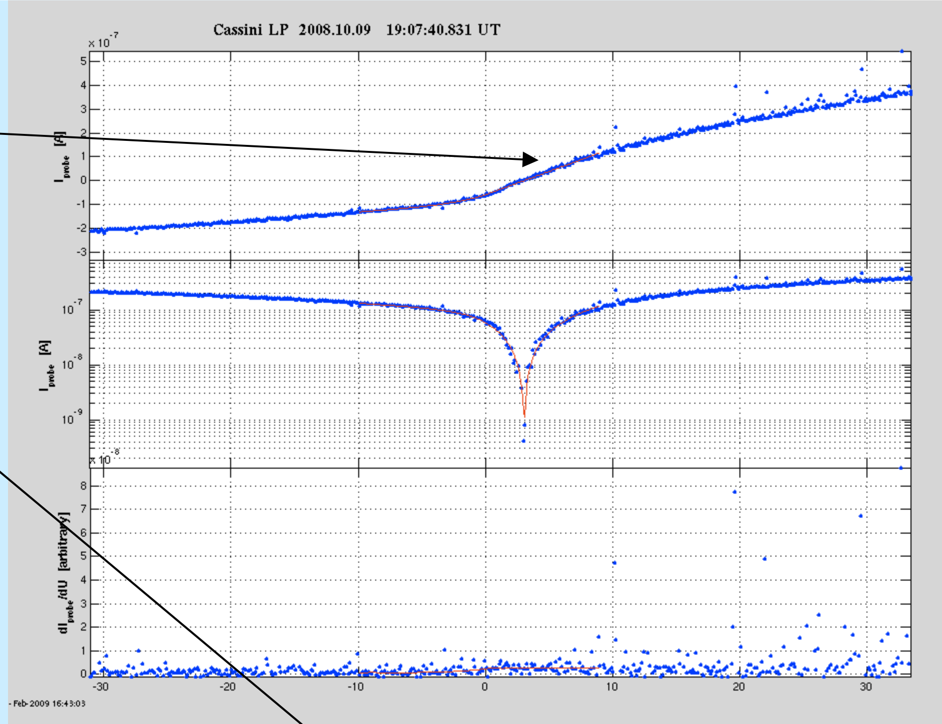


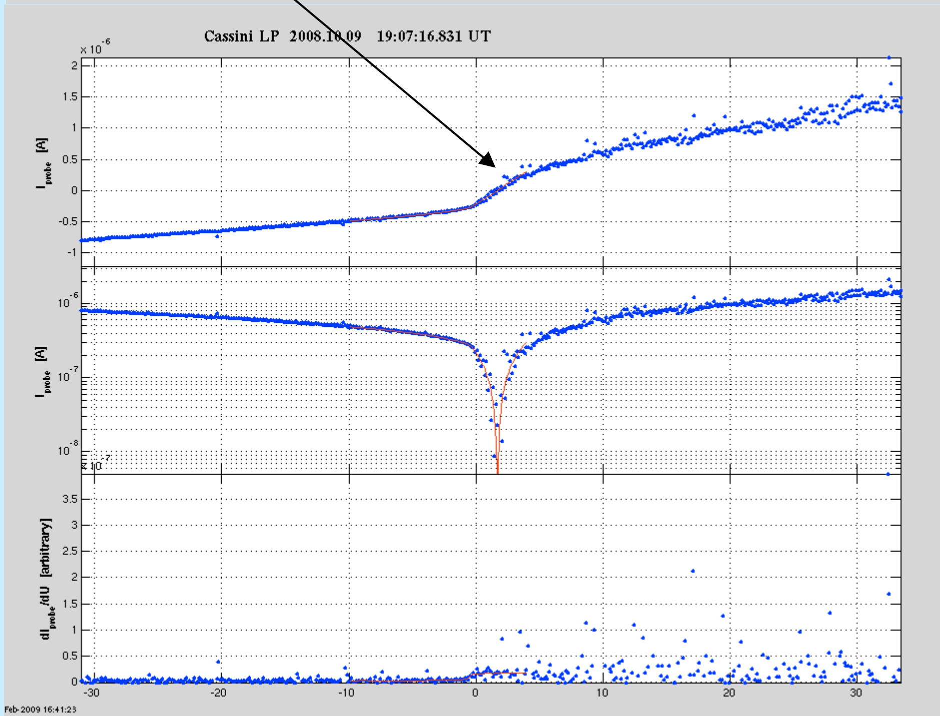


Before Plume



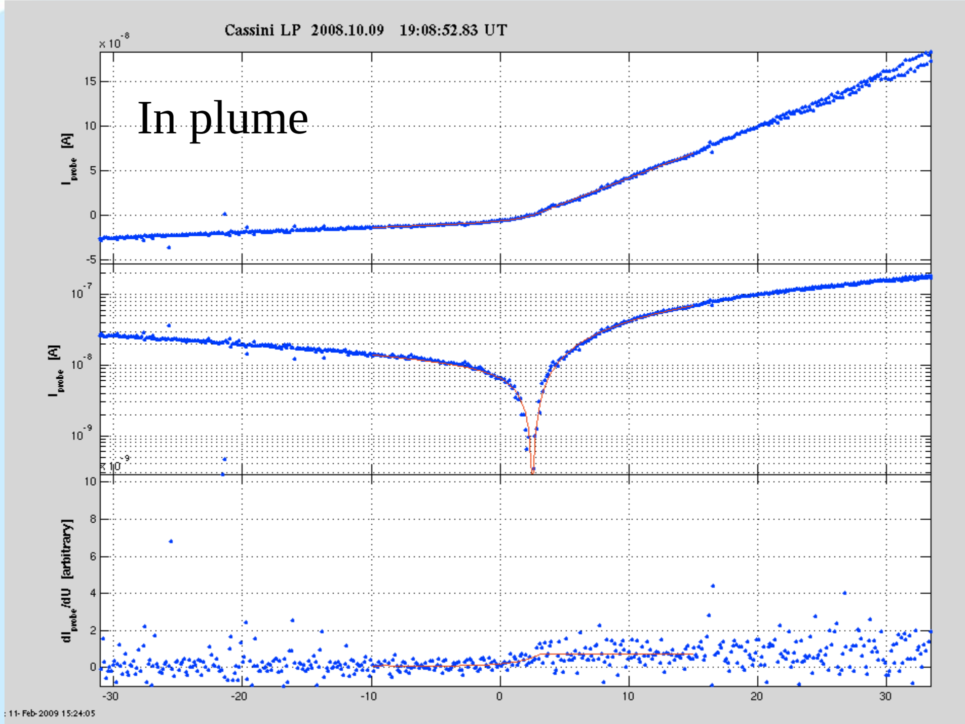


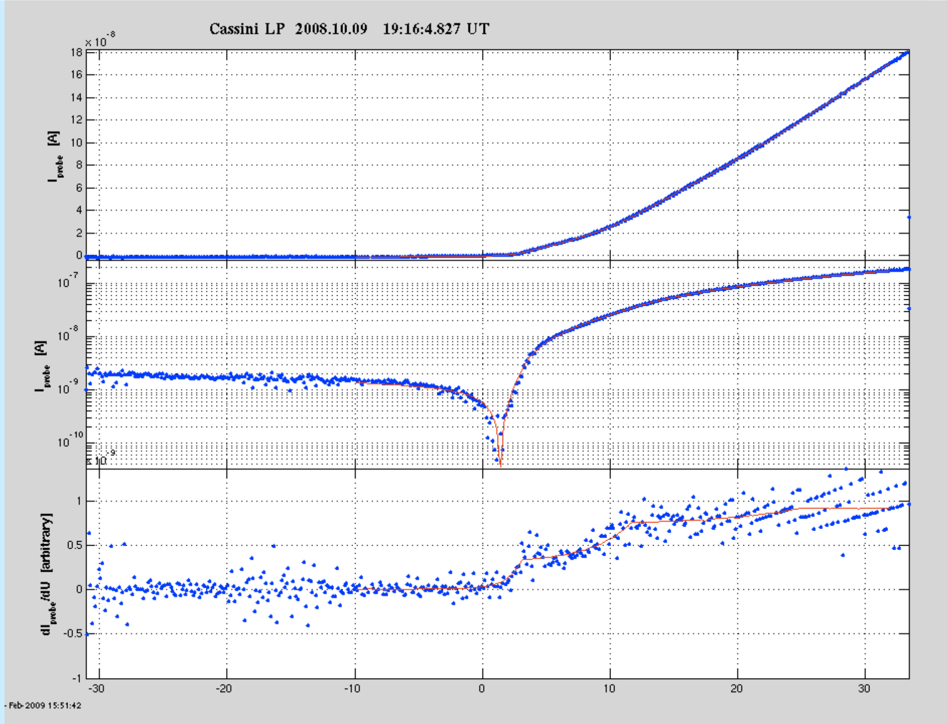


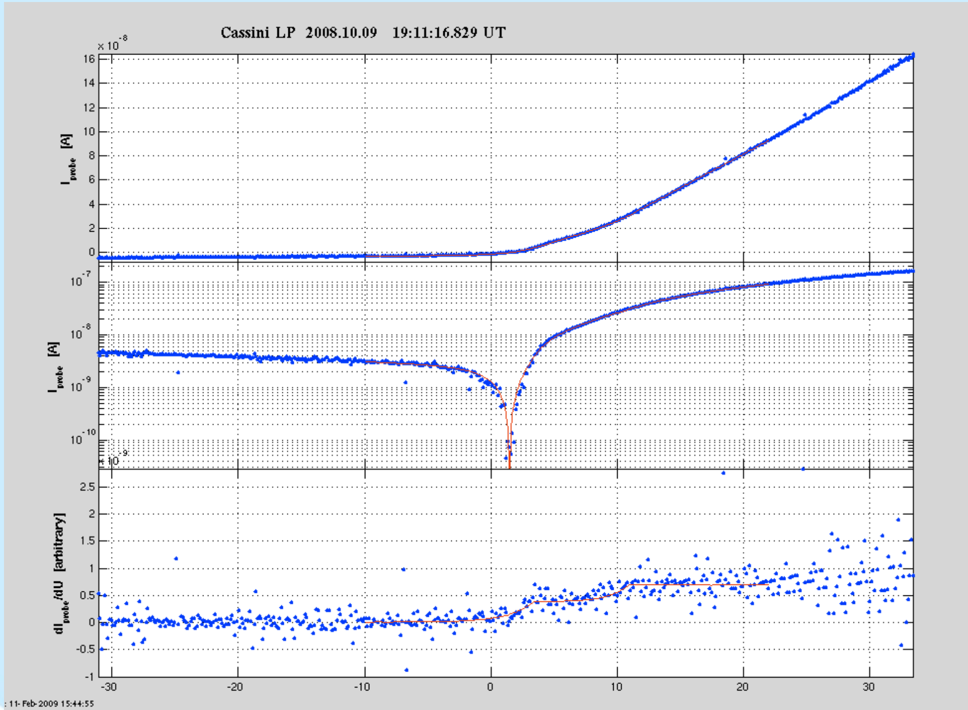


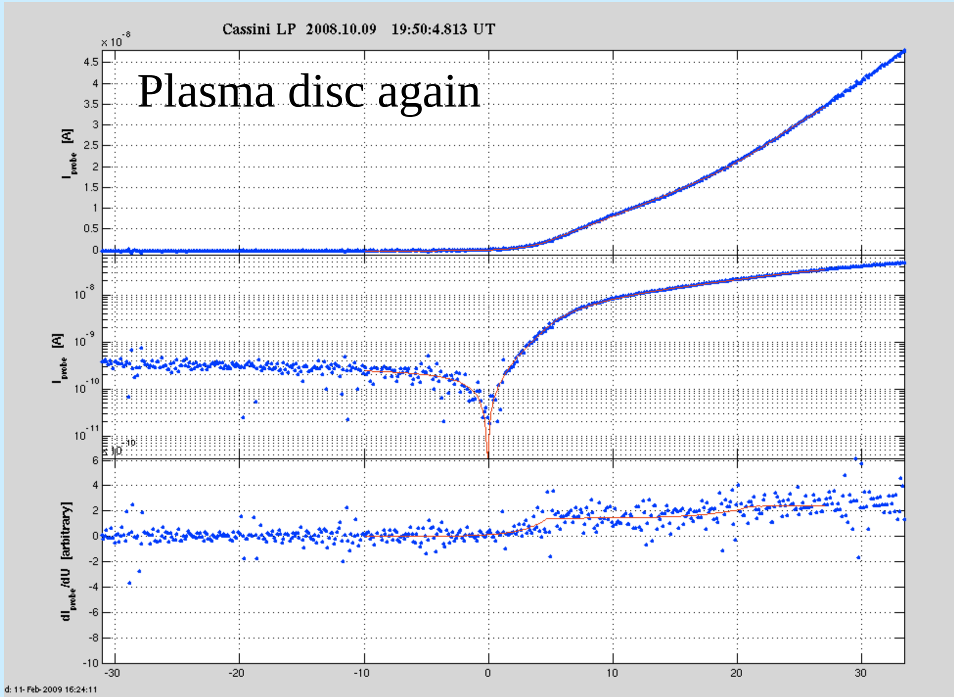
In densest part of plume

$I_{e,sat} \approx 0.5\text{-}2\ \mu A \Rightarrow n_e[cm^{-3}]\sqrt{T_e}[eV] \approx 2500\text{-}10000$


Cassini LP 2008.10.09 19:08:52.83 UT
In plume
I probe [A]
I probe [A]
dI probe/dU [arbitrary]


Cassini LP 2008.10.09 19:16:4.827 UT
I probe [A]
I probe [A]
dI probe/dU [arbitrary]


Cassini LP 2008.10.09 19:11:16.829 UT
I probe [A]
I probe [A]
dI probe/dU [arbitrary]


Cassini LP 2008.10.09 19:50:4.813 UT
Plasma disc again
I probe [A]
I probe [A]
dI probe/dU [arbitrary]