Plasmas radiofréquence à couplage capacitive: effet de la fréquence, les mélanges de fréquences et la forme d'onde

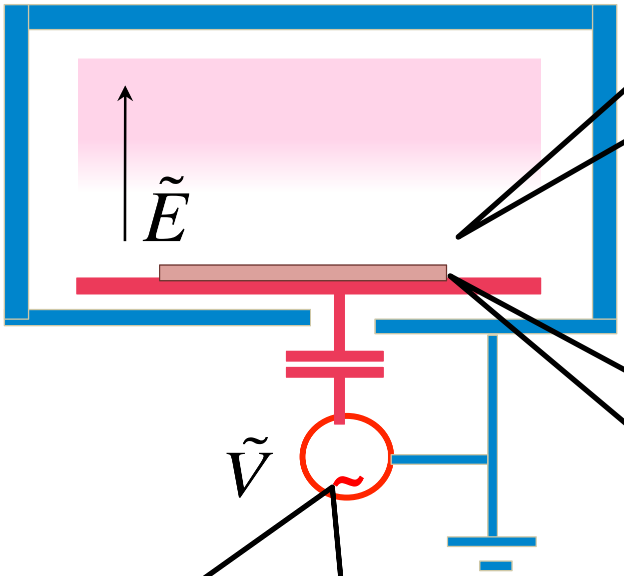
Laboratoire de Physique des Plasmas

Jean-Paul Booth

Radiofrequency capacitively-coupled plasmas

Low-pressure:

$\omega_{RF} >> \omega_{\text{collision e-neutral}}$



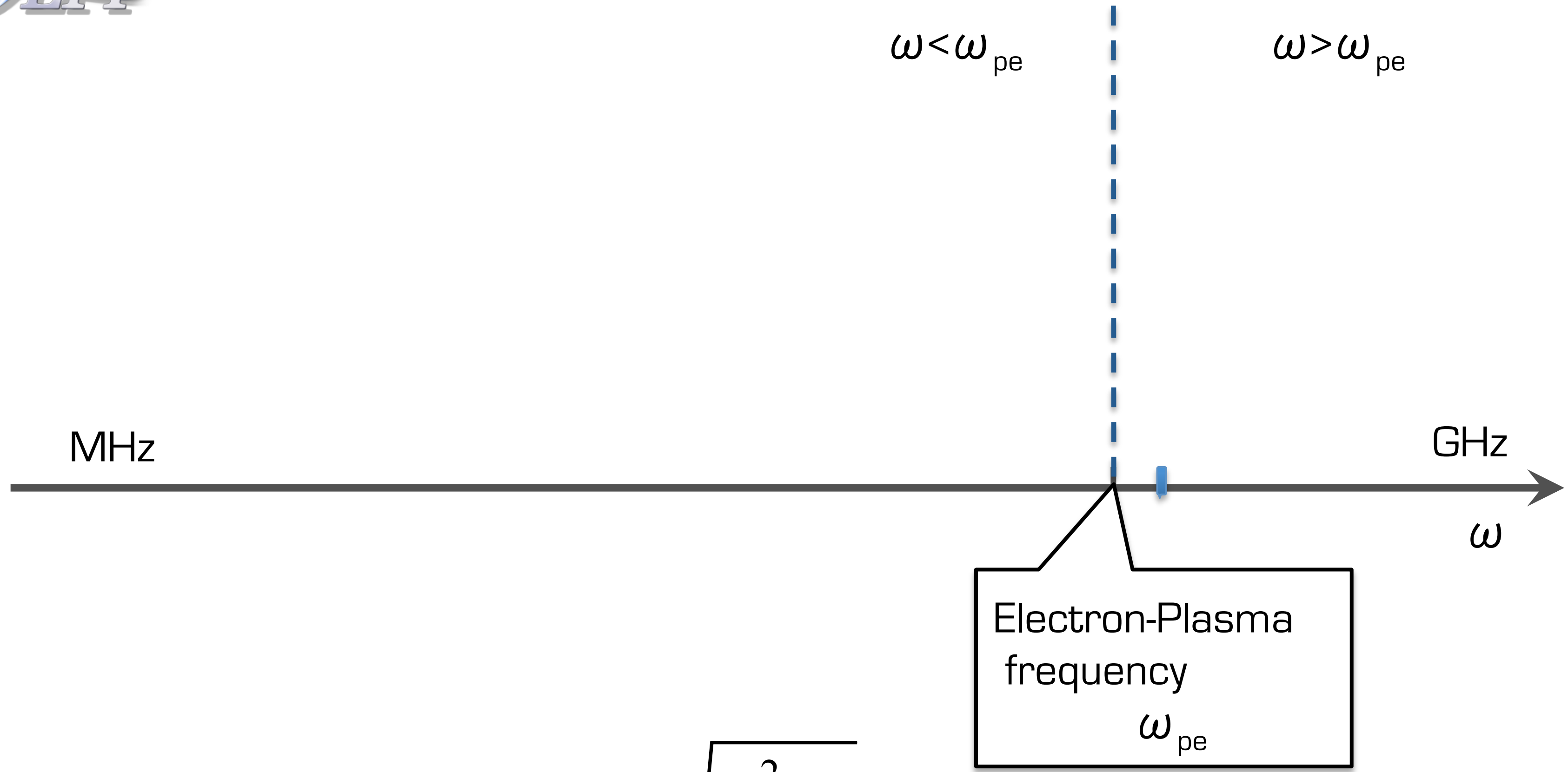
Processing by ions:
-flux
-energy
-composition
(+ reactive neutrals)

Substrate:
-Often insulating
-damaged by DC current
DC discharge not suitable!

RF generator:
1 MHz < ω_{RF} < 100MHz
Often 13.56 MHz

Why?

Plasma response to RF fields



$\omega < \omega_{pe}$

$\omega > \omega_{pe}$

MHz

GHz

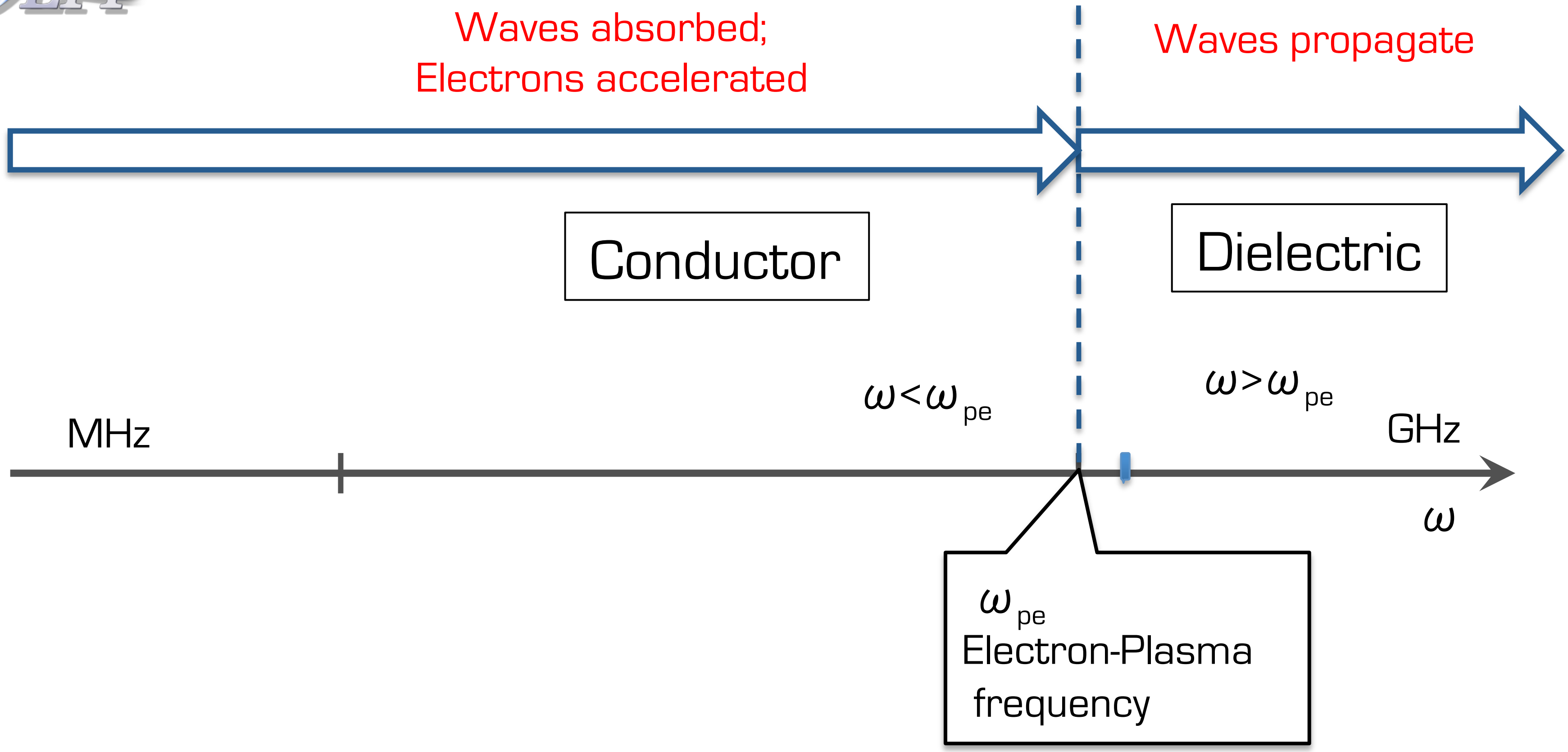
ω

Electron-Plasma frequency ω_{pe}

$$\omega_{pe} = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}}$$

$f_{pe} \approx 1$ GHz @ 10^{10}cm^{-3}

Plasma response to RF fields



Waves absorbed;
Electrons accelerated

Waves propagate

Conductor

Dielectric

$\omega < \omega_{pe}$

$\omega > \omega_{pe}$

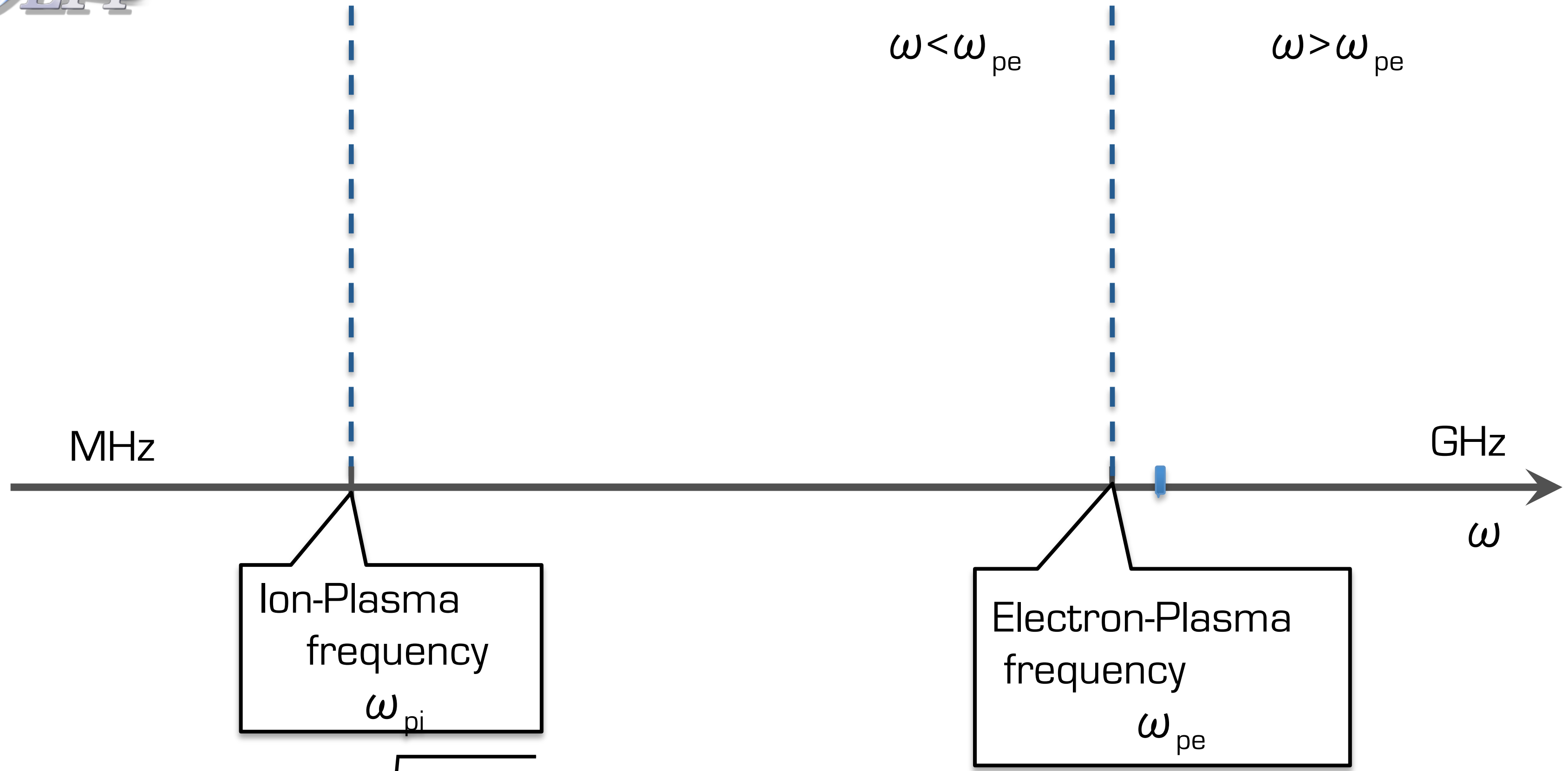
MHz

GHz

ω

ω_{pe}
Electron-Plasma frequency

Plasma response to RF fields



$\omega<\omega_{pe}$

$\omega>\omega_{pe}$

MHz

GHz

ω

Ion-Plasma frequency ω_{pi}

Electron-Plasma frequency ω_{pe}

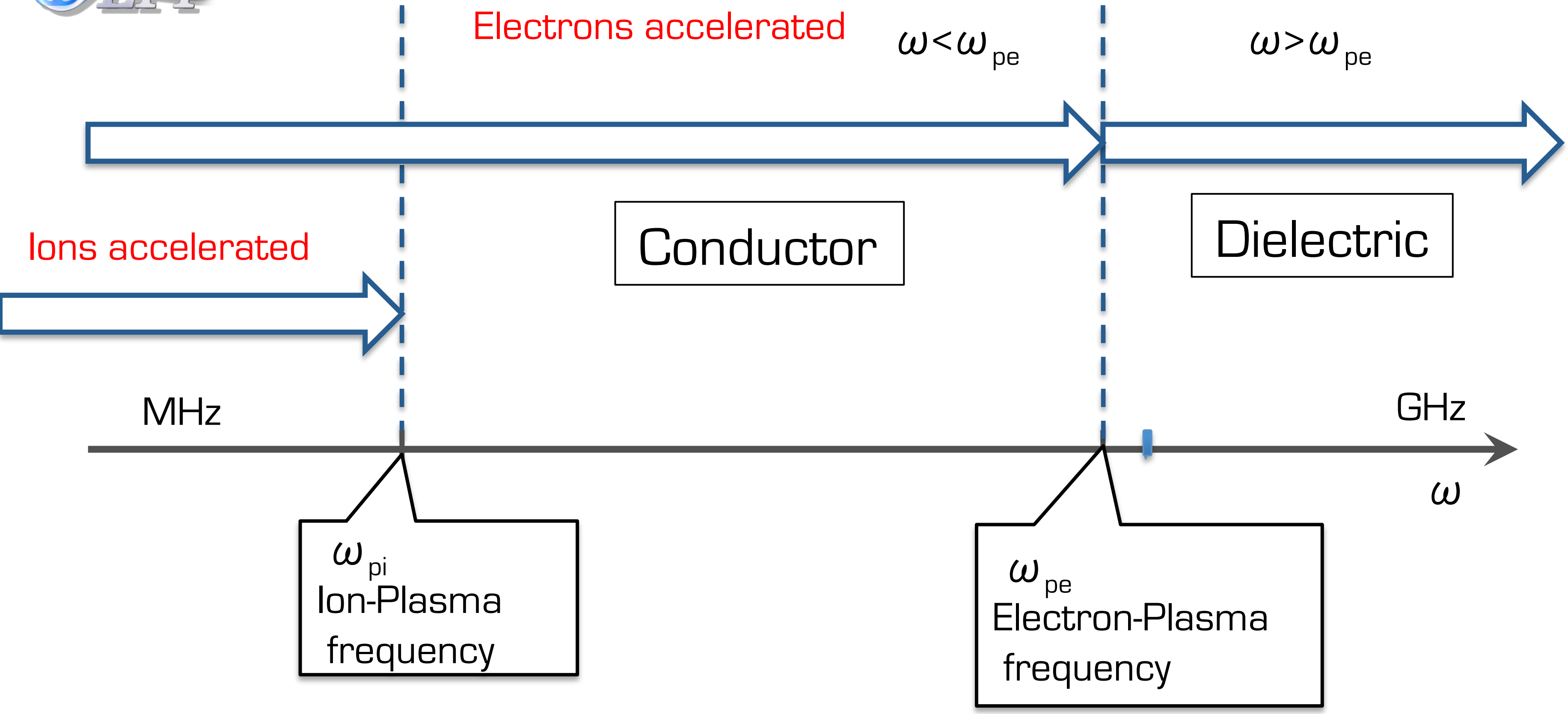
$$\omega_{pi}=\sqrt{\frac{e^2 n_e}{\varepsilon_0 m_i}}$$

$f_{pi} \approx 3$ MHz for Ar @ 10^{10}cm^{-3}

$$\omega_{pe}=\sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}}$$

$f_{pe} \approx 1$ GHz @ 10^{10}cm^{-3}

Plasma response to RF fields



Electrons accelerated

$\omega < \omega_{pe}$

$\omega > \omega_{pe}$

Ions accelerated

Conductor

Dielectric

MHz

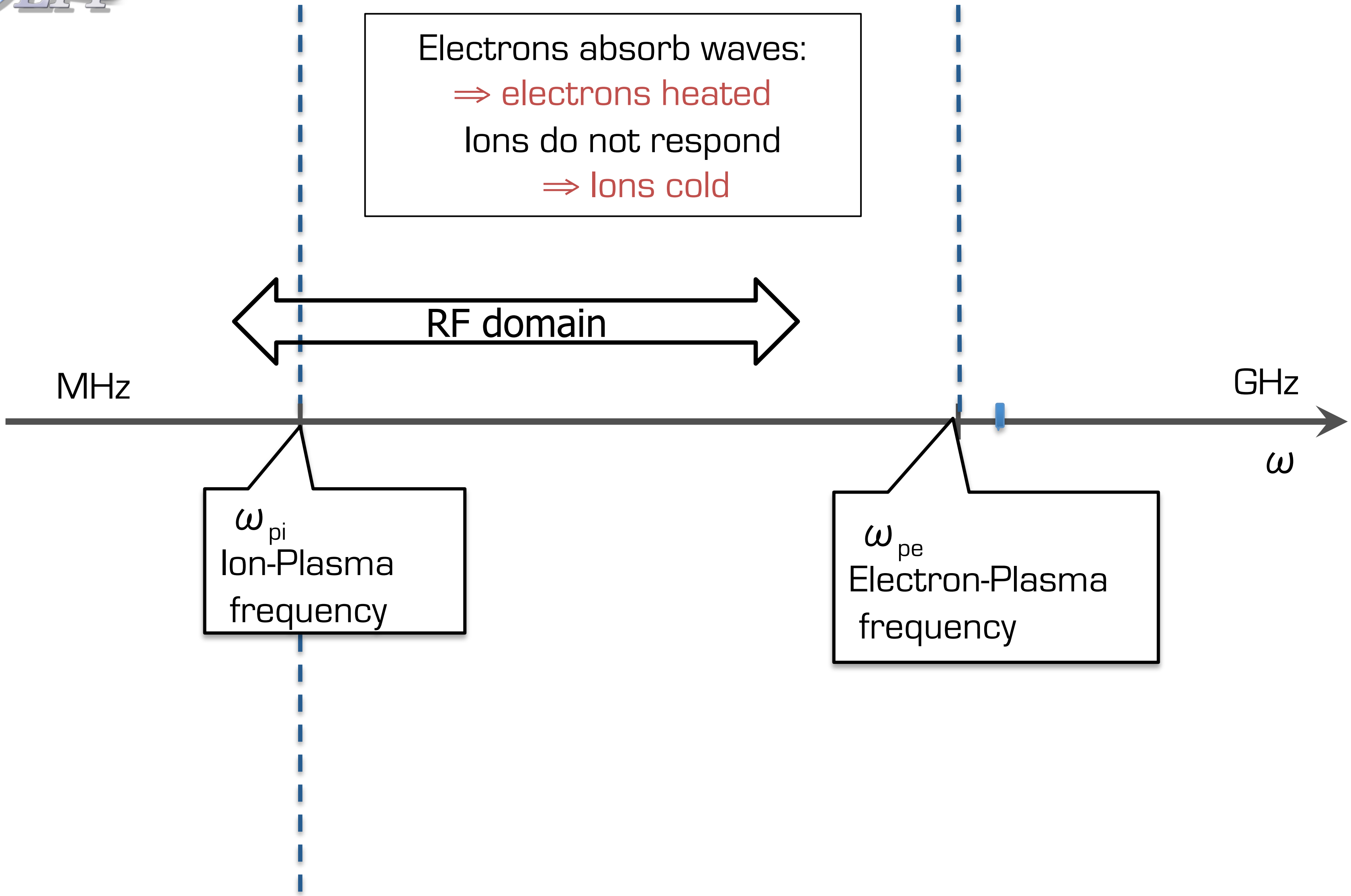
GHz

ω

ω_{pi}
Ion-Plasma frequency

ω_{pe}
Electron-Plasma frequency

Plasma response to RF fields



Electrons absorb waves:

⇒ electrons heated

Ions do not respond

⇒ Ions cold

Why Radiofrequency excitation?

- Substrates are often insulating
- Drawing current through a device causes damage

DC discharges not suitable!

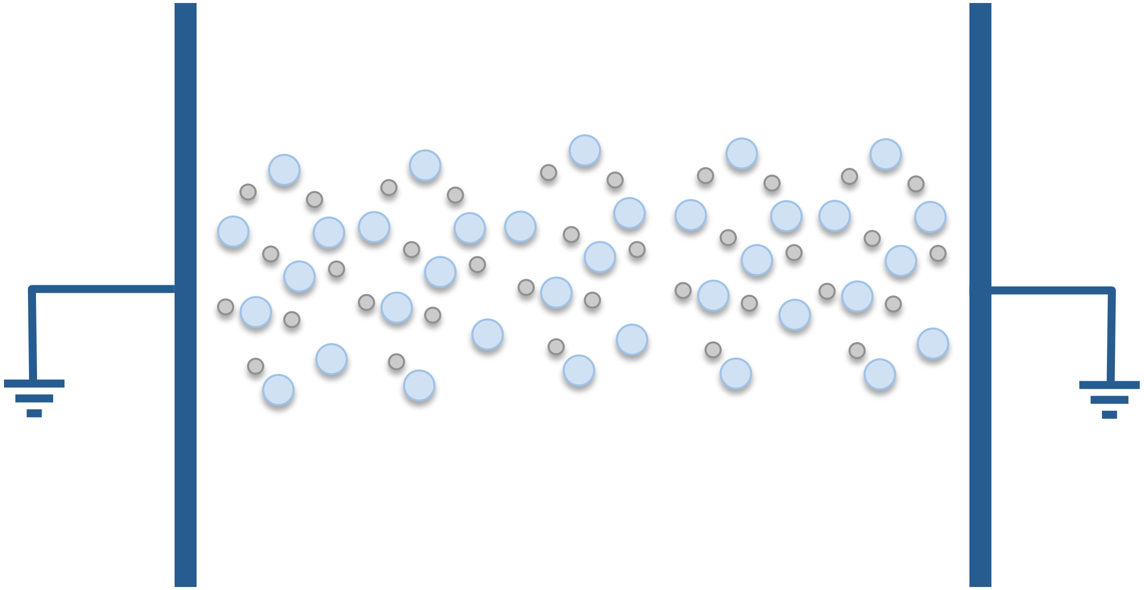
- Heat electrons not ions – $\omega_{pion} < \omega_{RF} < \omega_{pe}$
  - However, ions accelerated by DC fields at boundaries

- Uniform over large areas : $\lambda_{RF} >>$ substrate (not microwave!)

- In practice, 1 – 100 MHz, often 13.56 MHz

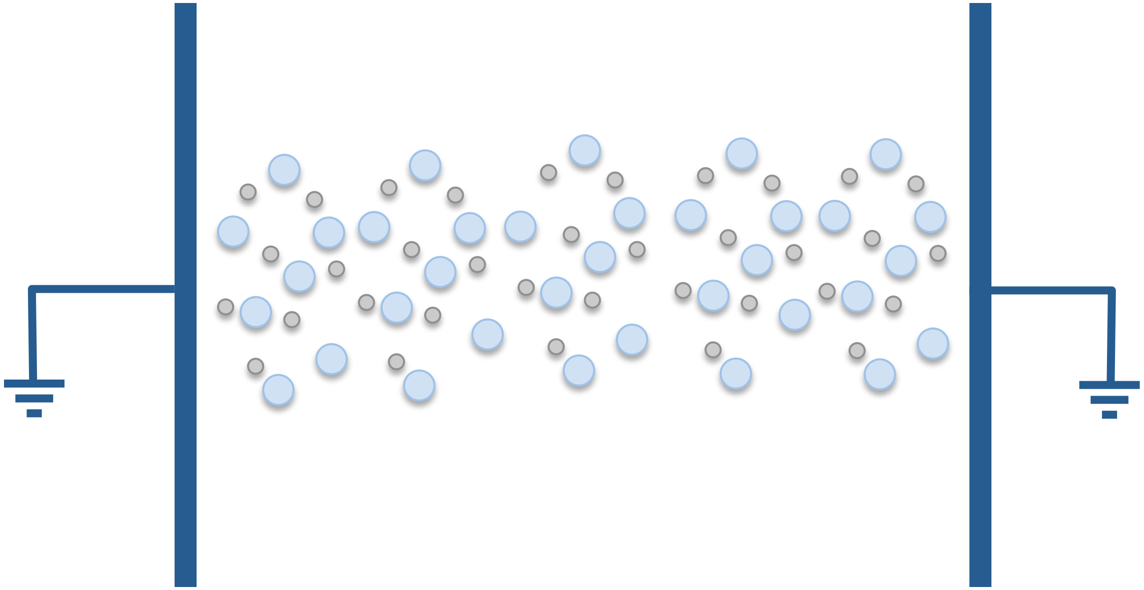
Sheaths and Plasma potential

Imagine a uniform plasma created between two electrodes:



Electron velocity (Te = 3eV) ?

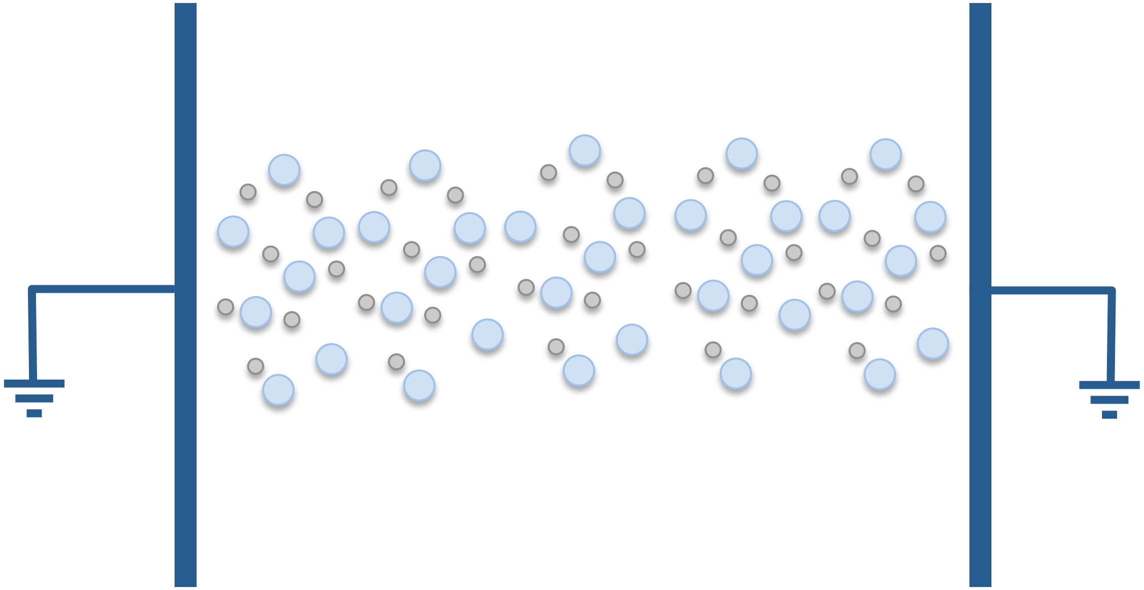
Sheaths and Plasma potential



Electron velocity

$$v_{th,e} = \sqrt{\frac{8kT_e}{\pi m_e}} \approx 10^6 ms^{-1}$$

Sheaths and Plasma potential



Electron velocity

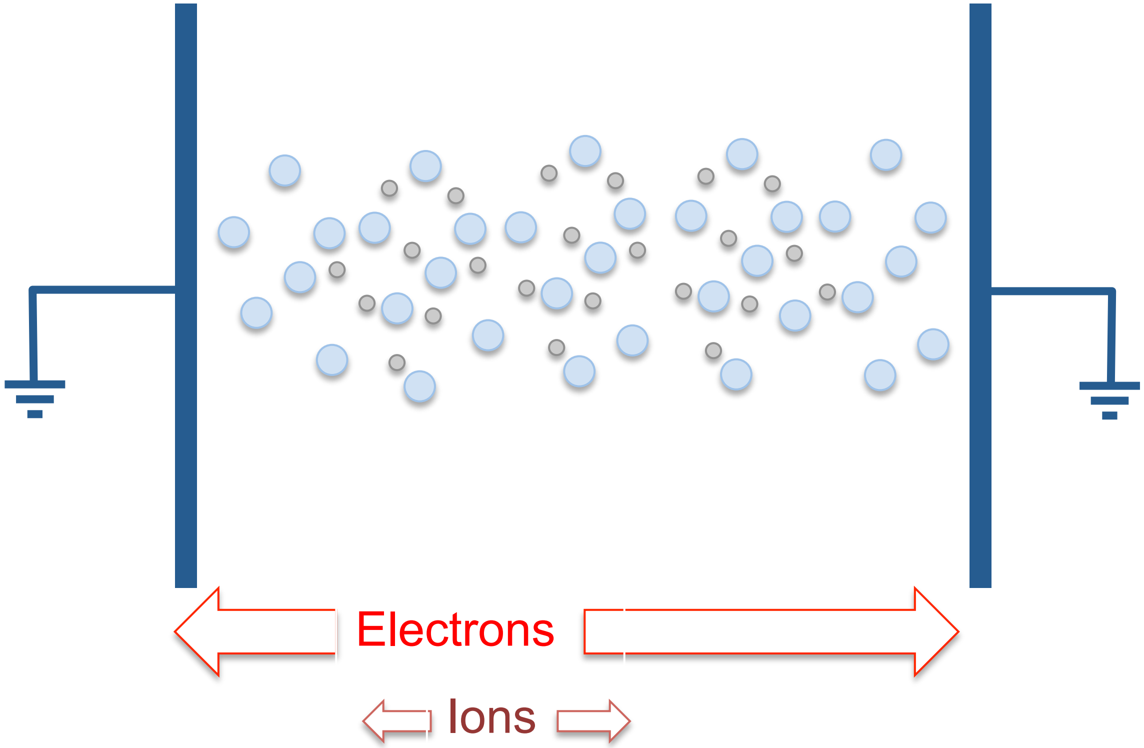
$$v_{th,e} = \sqrt{\frac{8kT_e}{\pi m_e}} \approx 10^6 ms^{-1}$$

Ion velocity

$$v_{th,i} = \sqrt{\frac{8kT_i}{\pi m_i}} \approx 10^4 ms^{-1}$$

What is the flux of particles to the surfaces?
What effect will this have?

Sheaths and Plasma potential

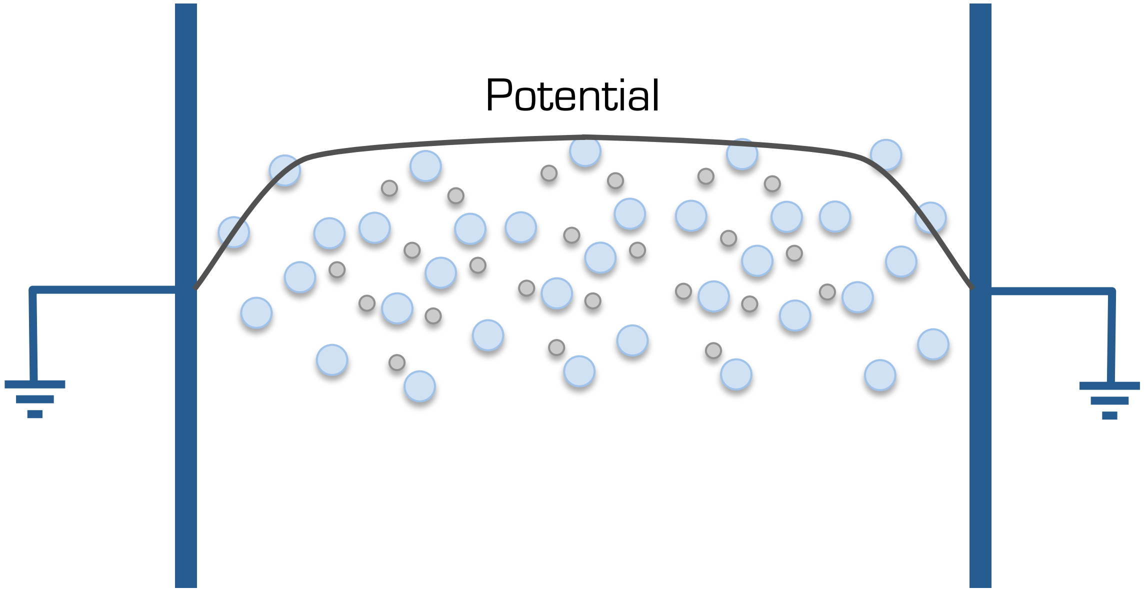


Electrons

Ions

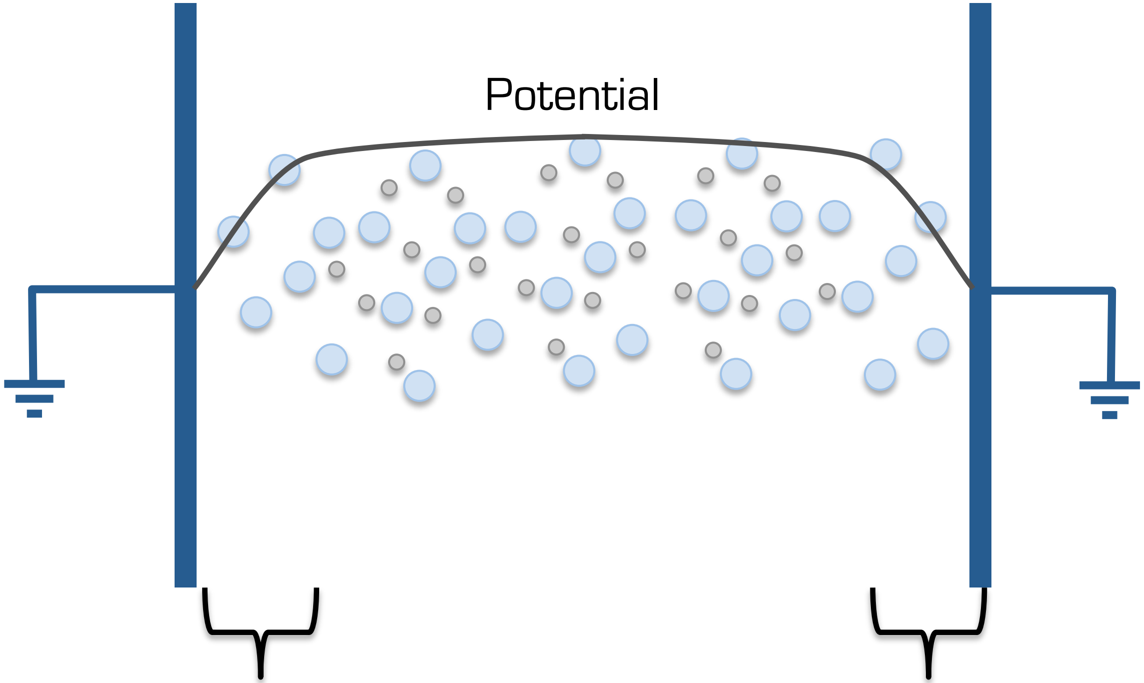
More electrons leave than ions:
Space Potential?

Sheaths and Plasma potential



Loss of electrons causes the plasma space potential to increase until electron flux = ion flux

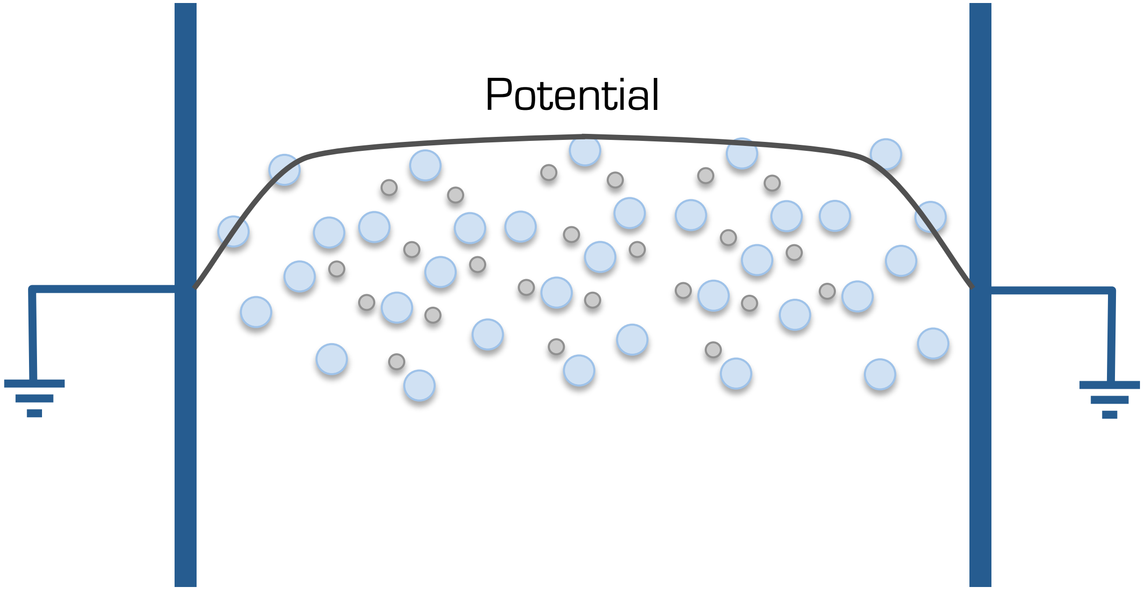
Sheaths and Plasma potential



High field boundary regions created near walls :

Space-charge SHEATHS

Sheaths and Plasma potential



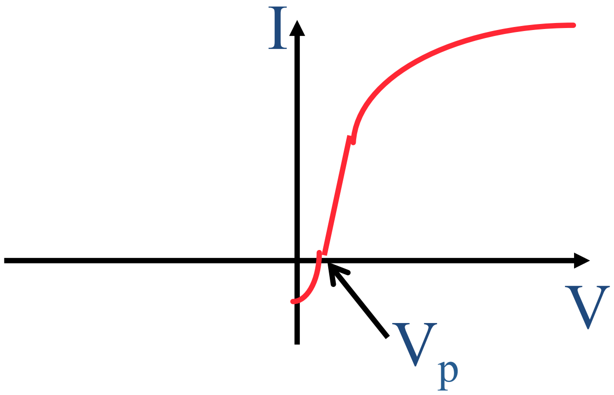
Electrons pushed towards the centre:
Ions accelerated towards surfaces

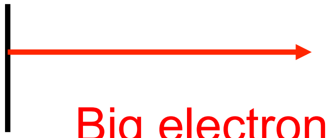
At steady state,
Ion flux= electron flux

Ion velocity out of bulk plasma = sound speed (Bohm velocity)
- Limits ion flux

$$v_{Bohm} = \sqrt{\frac{kT_e}{m_{ion}}}$$

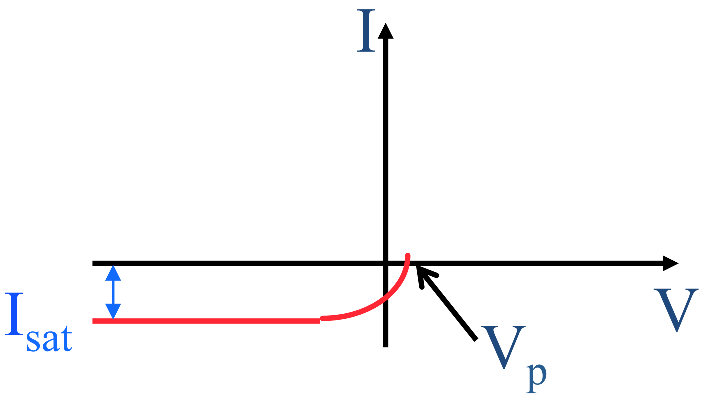
Radiofrequency Sheaths

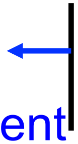




Big electron current

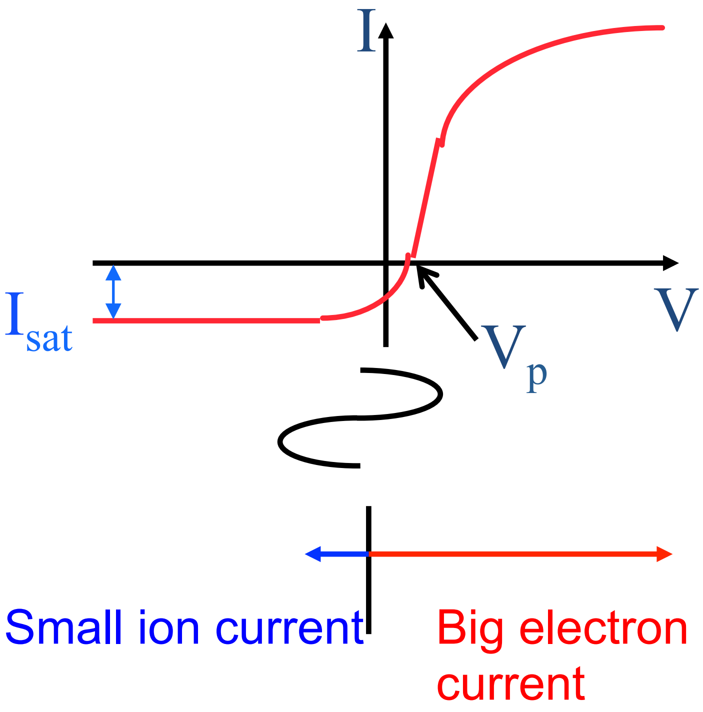
Radiofrequency Sheaths





Small ion current

Radiofrequency Sheaths

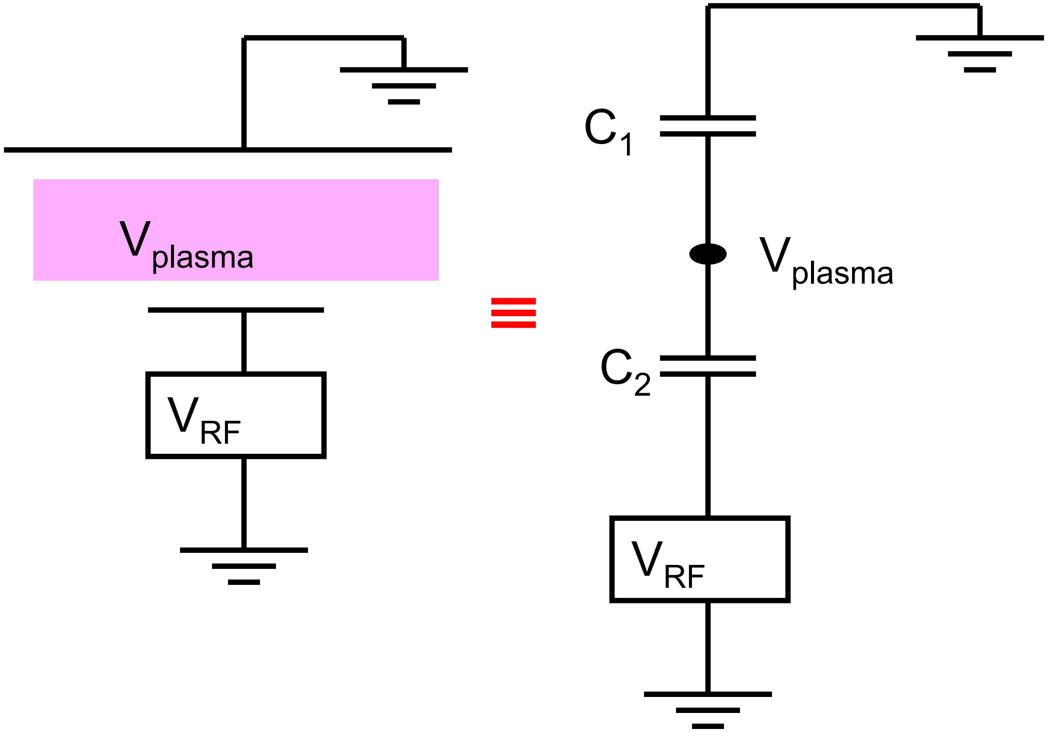


Radiofrequency field is rectified by the sheath non-linearity:

-DC sheath voltage must increase to balance fluxes

Distribution de potentiels RF

Quand la surface polarisée en RF est de taille non-négligeable,
le potentiel plasma est perturbé par le RF.
La tension RF est repartie selon les capacités respectives des gaines:



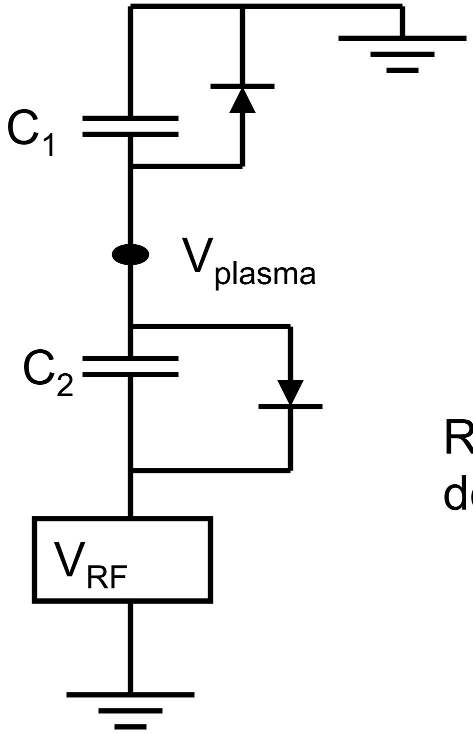
$$\boxed{V_{plasma} = \overline{V}_{plasma} + V'_{plasma} \cos \omega t}$$

Pont diviseur capacitif:

$$V'_{plasma} = \frac{C_2}{C_1 + C_2} . V_{RF}$$

$$C \propto surface$$

Distribution de potentiels continus



Mais la gaine est non-linéaire:
courant d'électrons >> courant d'ions
⇒ se comporte comme une diode
⇒ rectification de la tension
(autopolarisation)

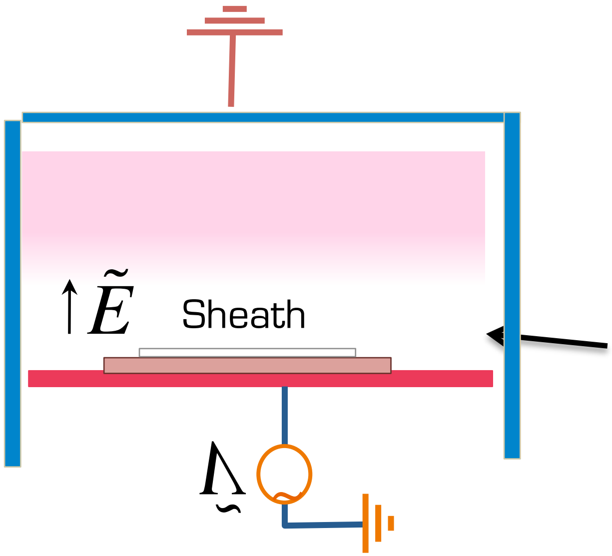
Repartition des tensions depend de l’inverse du rapport des surfaces des electrodes :

$$\frac{V_1'}{V_2'} = \left(\frac{S_2}{S_1}\right)^n$$

$n \approx 2.5$ (selon theorie)

Ion Energy Control : RF biased substrates

Capacitive coupling
(E-mode)



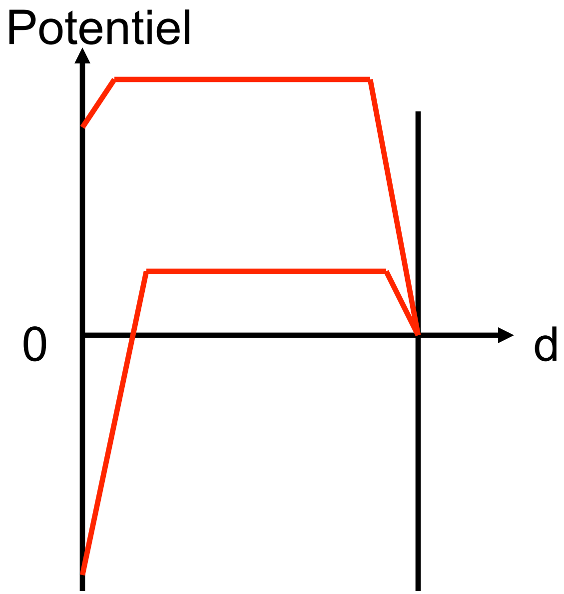
Substrate on small electrode:
High energy ion bombardment

Reacteurs grand surface: Plasma symétrique

Surfaces égales: $C_1 = C_2$

$V'_{plasma} = V_{RF}/2$:

-potentiel plasma fortement modulé



Effects of frequency

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Effect of RF frequency

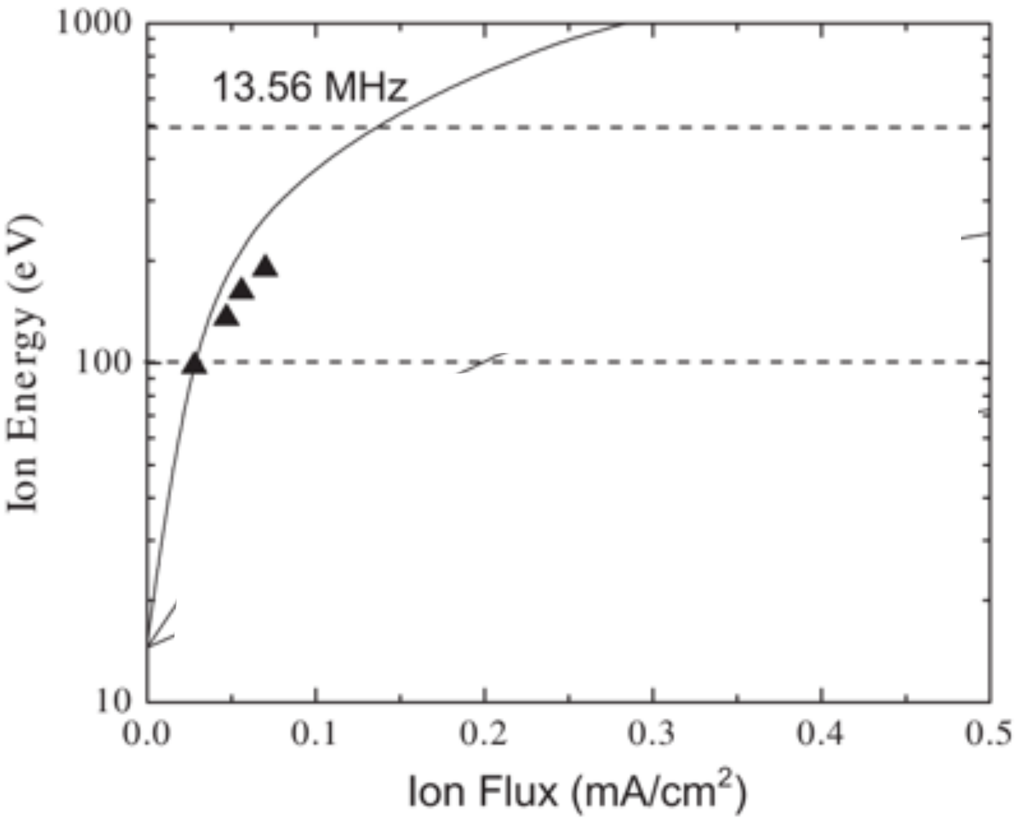
13,56 MHz :

Low ion flux

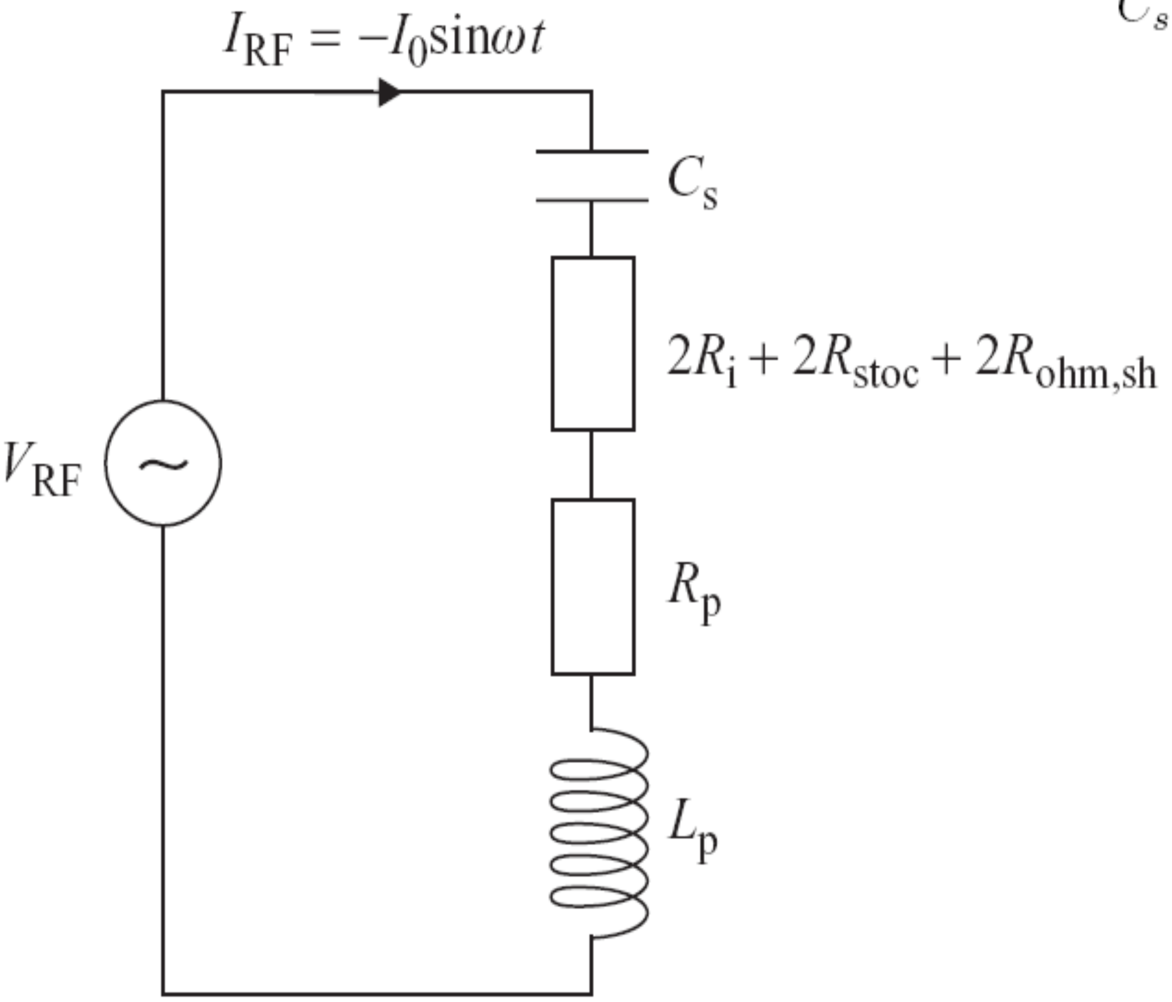
High Ion energy

Increasing voltage increases energy and flux simultaneously

How to get high flux at low energy?



Equivalent circuit for the capacitive discharge



$$C_s = \frac{\varepsilon_0 A}{2 s_0} = \frac{\varepsilon_0 A}{s_m} \approx \frac{e n \omega \varepsilon_0 A^2}{2 I_0}$$

$$R_i = \frac{3 u_B}{2 \varepsilon_0 \omega^2 A}$$

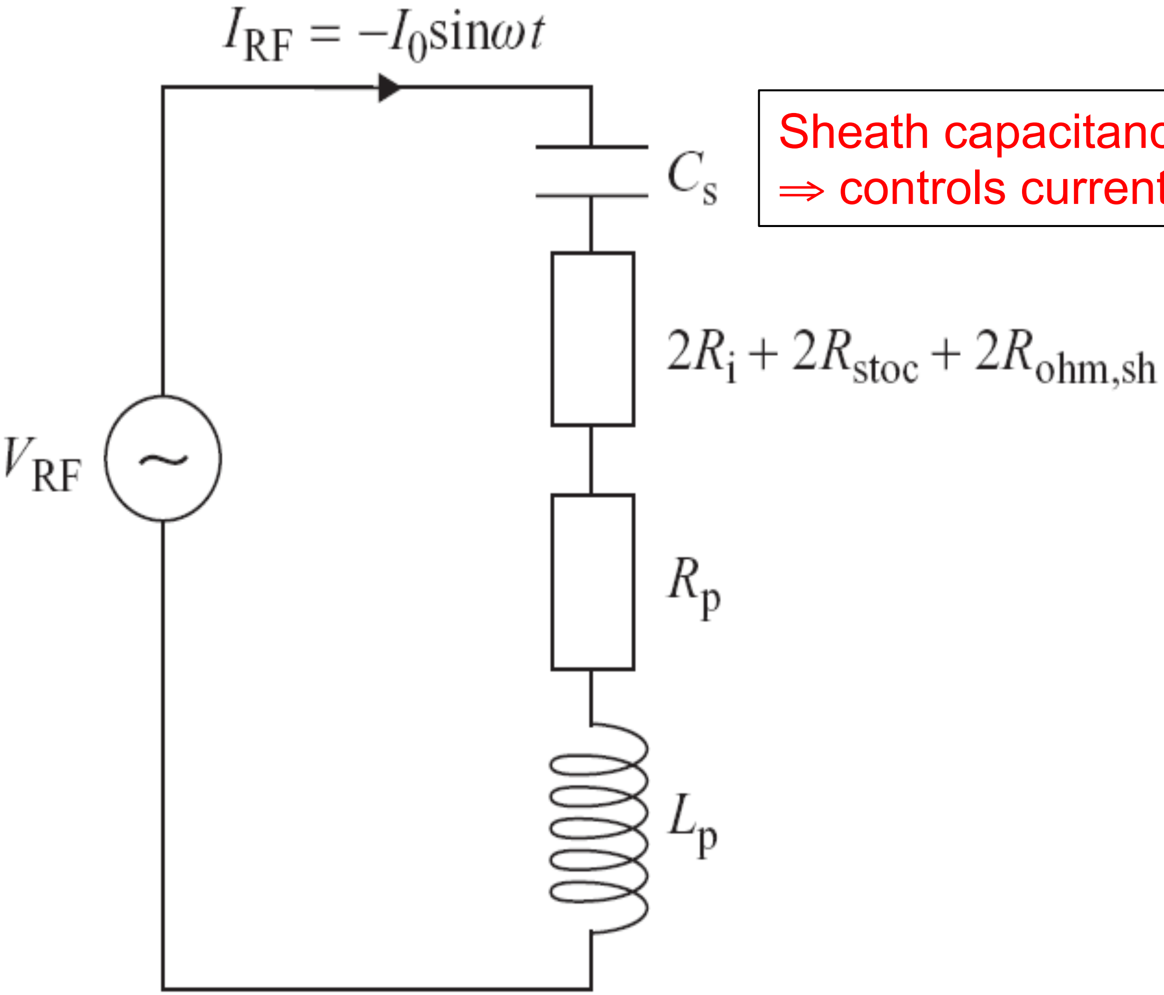
$$R_{stoc} = \frac{m \overline{v}_e}{n e^2} \frac{1}{A}$$

$$R_{ohm,sh} = \frac{1}{3} \frac{m \nu_m}{n_0 e^2} \frac{s_m}{A}$$

$$R_p = \frac{m \nu_m}{n e^2} \frac{d}{A}$$

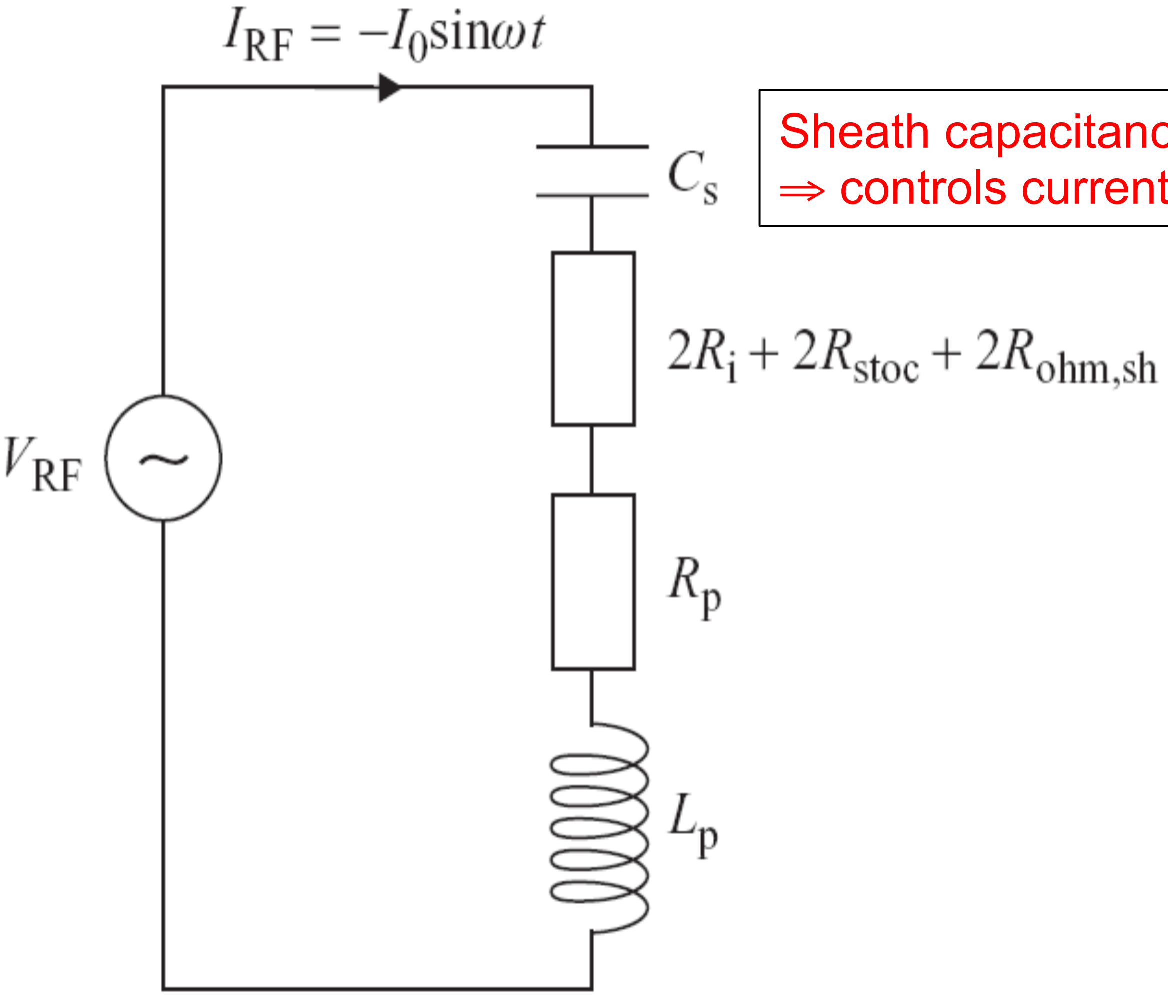
$$L_p = \frac{d}{\omega_p^2 \varepsilon_0 A} = \frac{m}{n e^2} \frac{d}{A}$$

Equivalent circuit for the capacitive discharge



Sheath capacitance : highest impedance
⇒ controls current

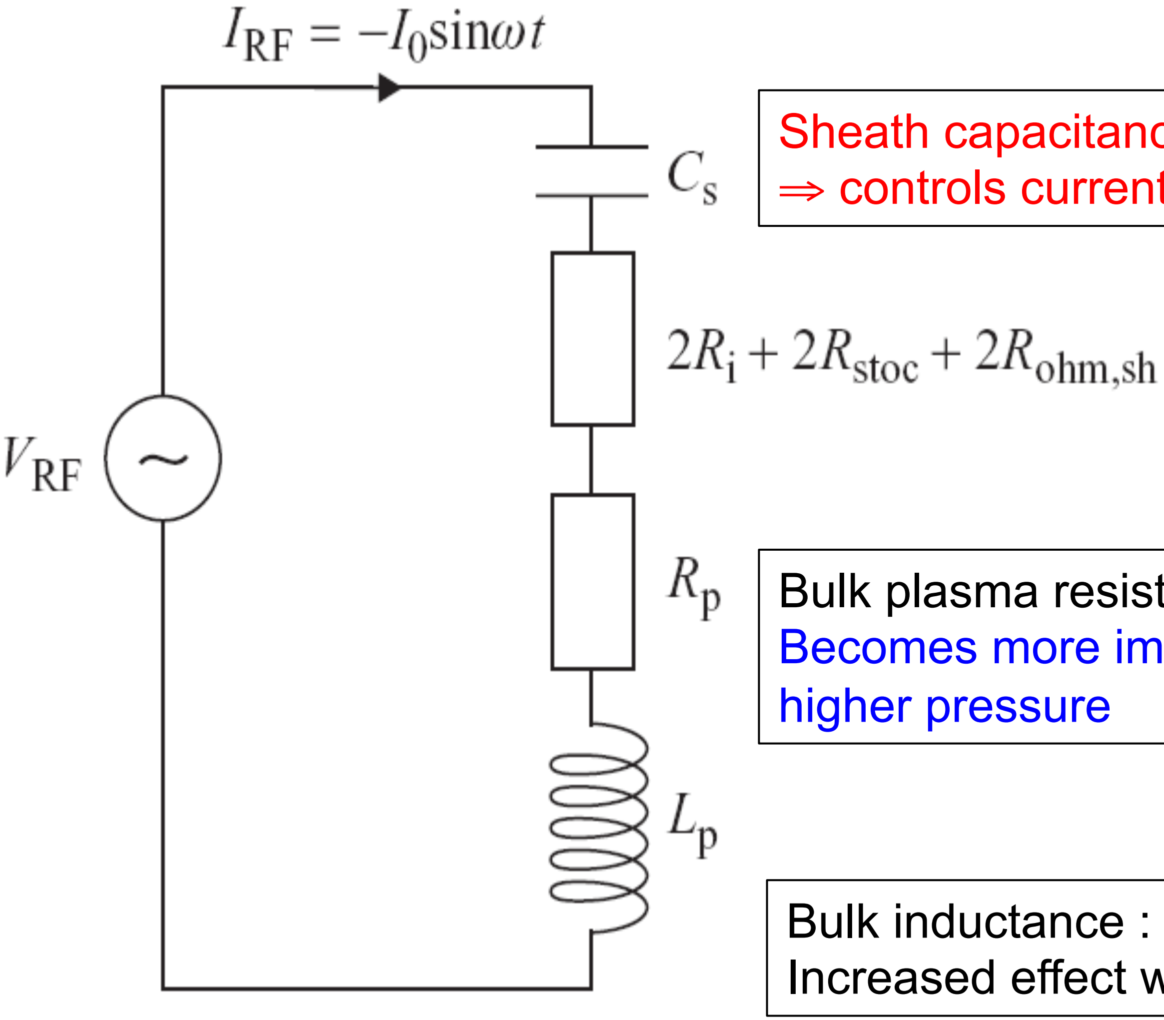
Equivalent circuit for the capacitive discharge



Sheath capacitance : highest impedance
⇒ controls current

Sheath resistance :
most power absorbed here:
Ion acceleration
Electron heating ⇒ **density**

Equivalent circuit for the capacitive discharge



Sheath capacitance : highest impedance
⇒ controls current

Sheath resistance :
most power absorbed here:
Ion acceleration
Electron heating⇒density

Bulk plasma resistance :
Becomes more important at higher pressure

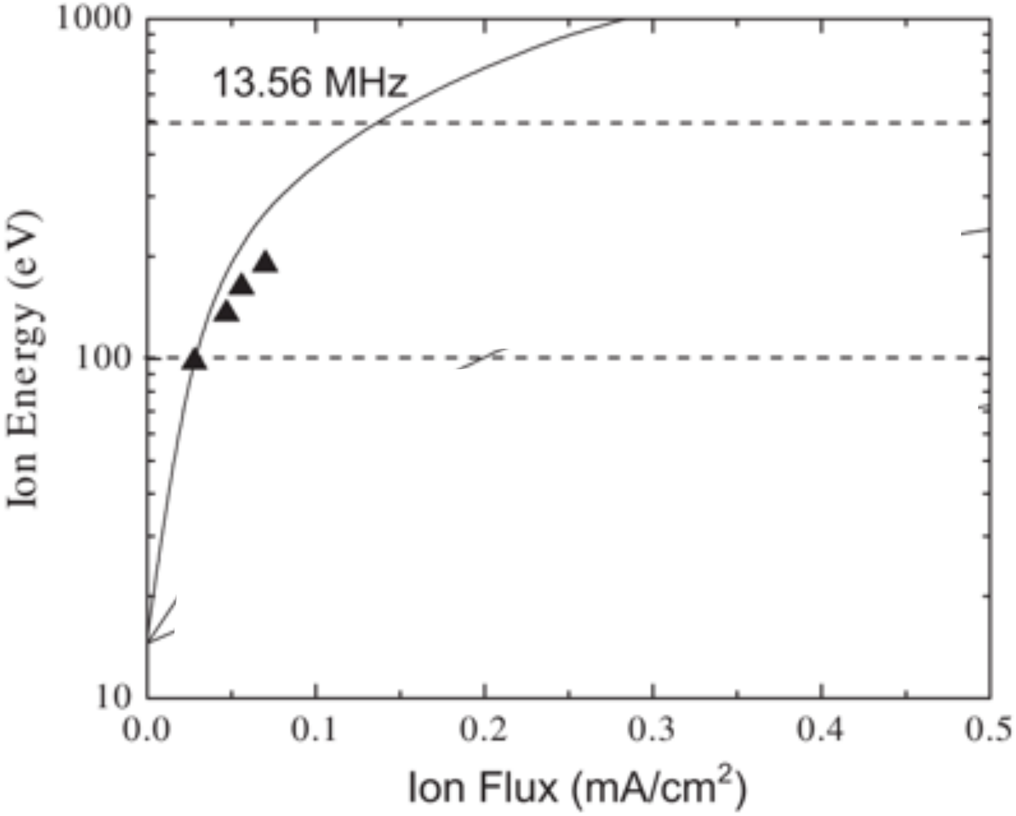
Bulk inductance : Electron inertia
Increased effect with frequency

Effect of RF frequency

13,56 MHz :
- Low ion flux
- High Ion energy

Increasing voltage increases energy and flux simultaneously

How to get high flux at low energy?

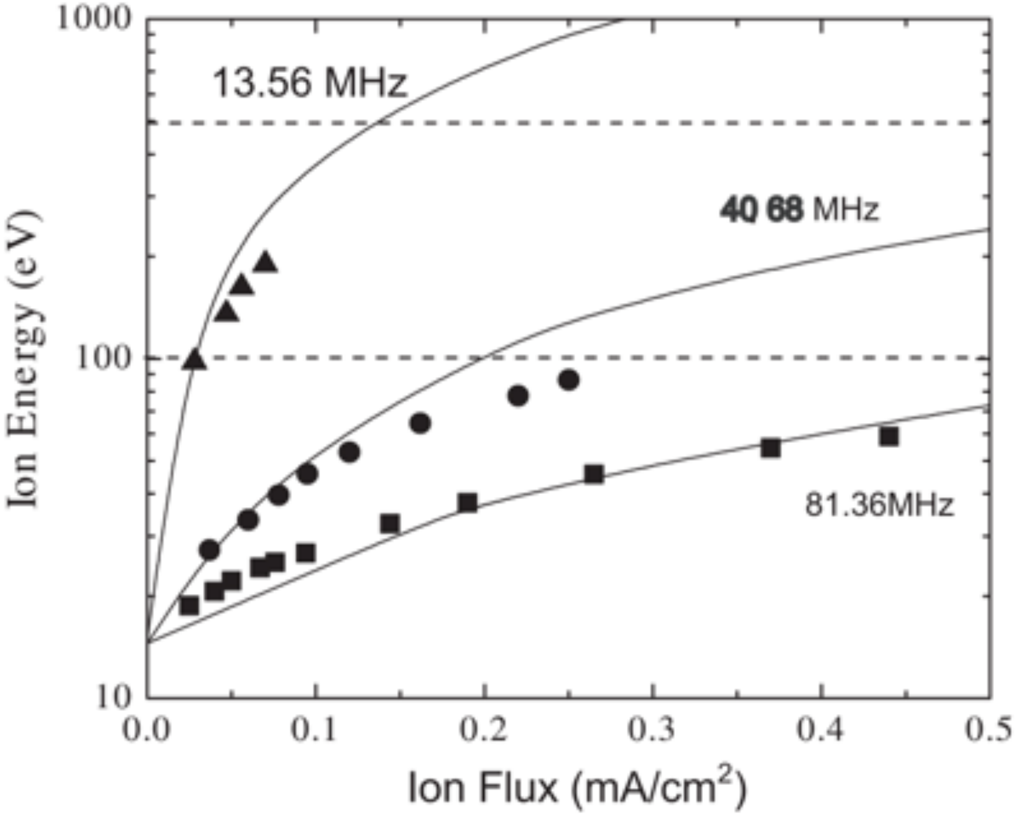


Effect of RF frequency

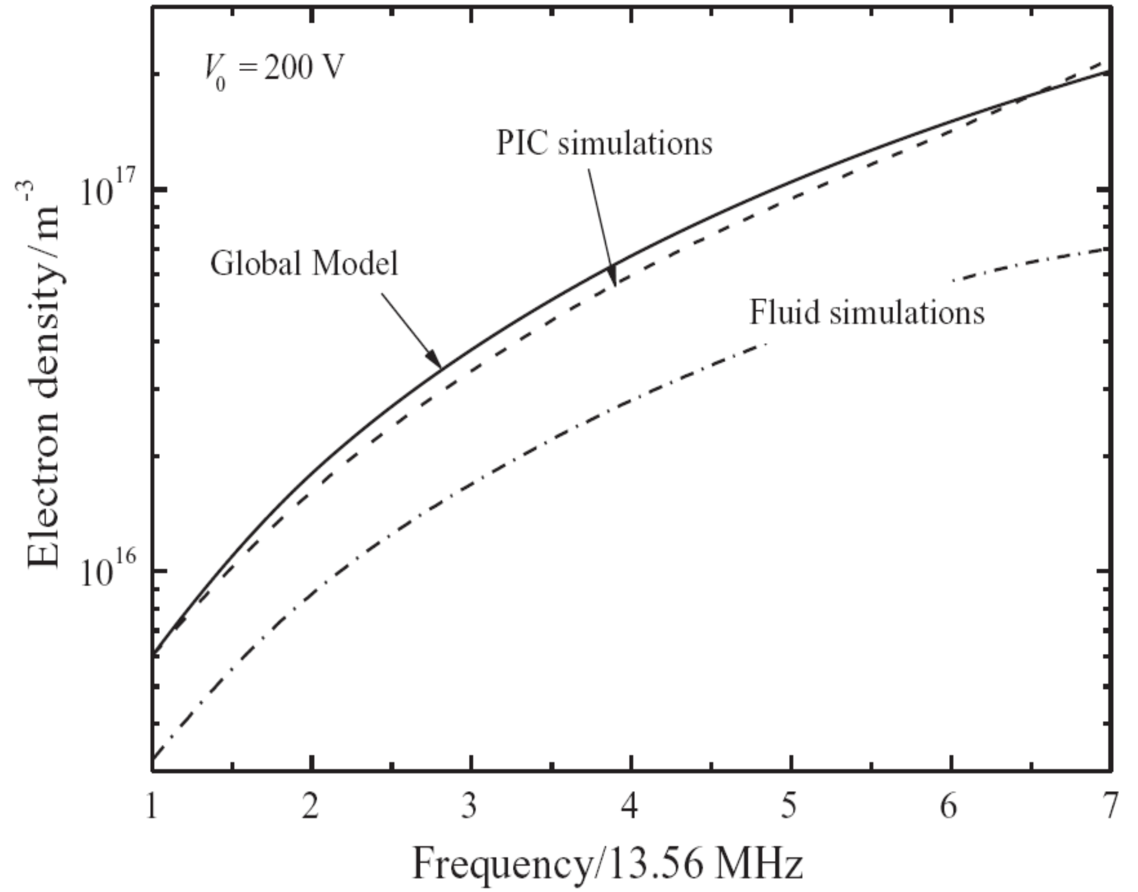
Electrons heated by expanding sheath front

Increasing frequency heats electrons more efficiently than ions:

Allows high ion flux at low energy



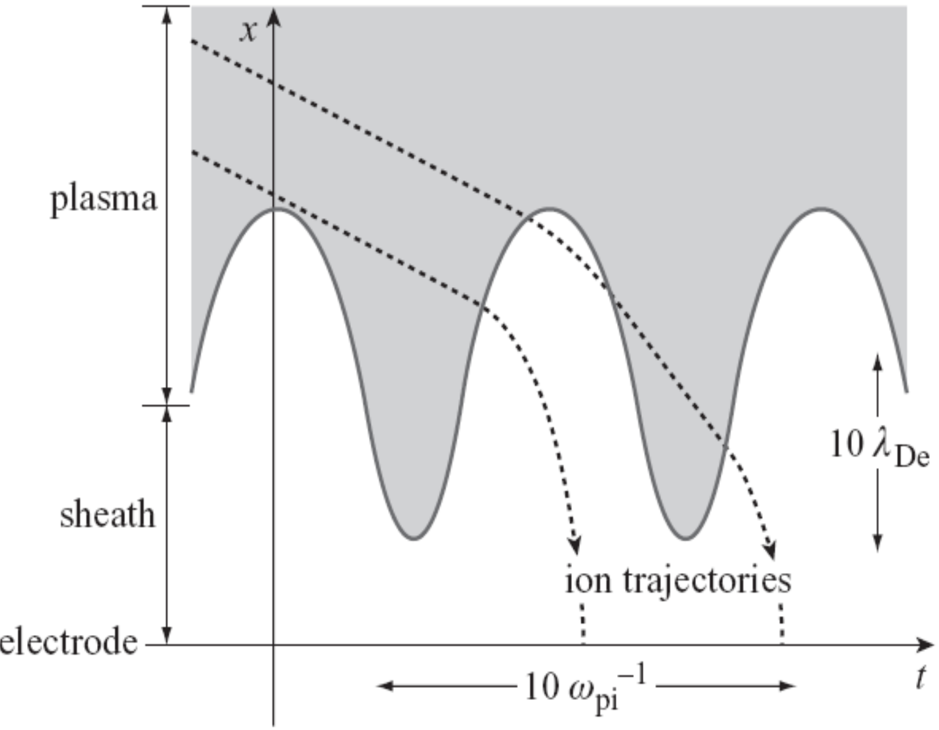
Theory: Effect of frequency



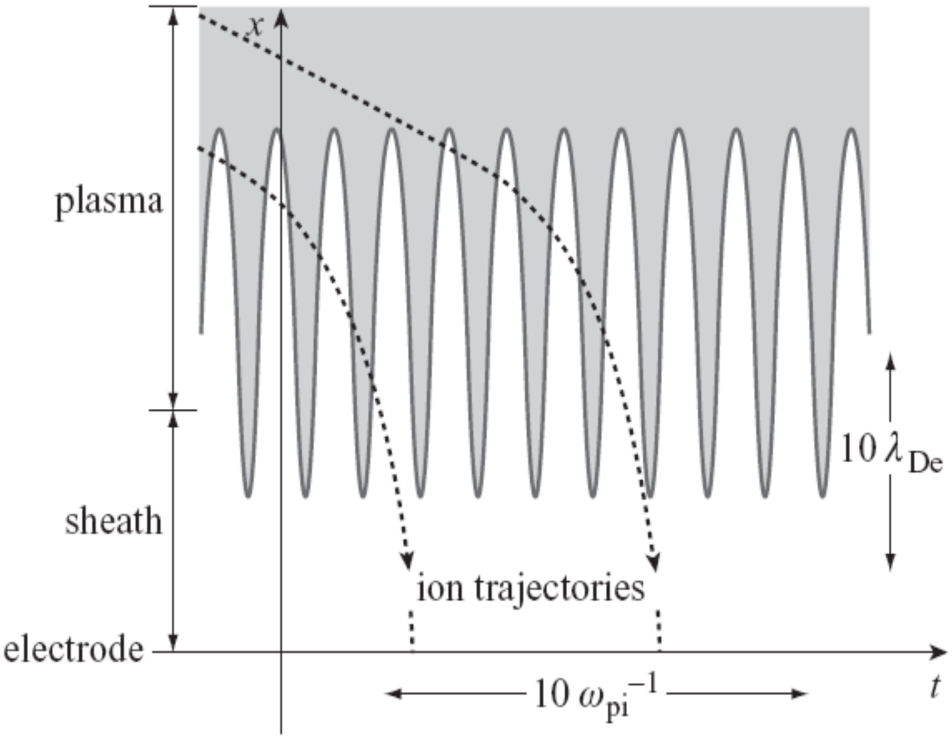
$$n_e \propto V_0\omega^2$$

Increase the frequency to increase the plasma density

Ion acceleration in an oscillating (RF) sheath



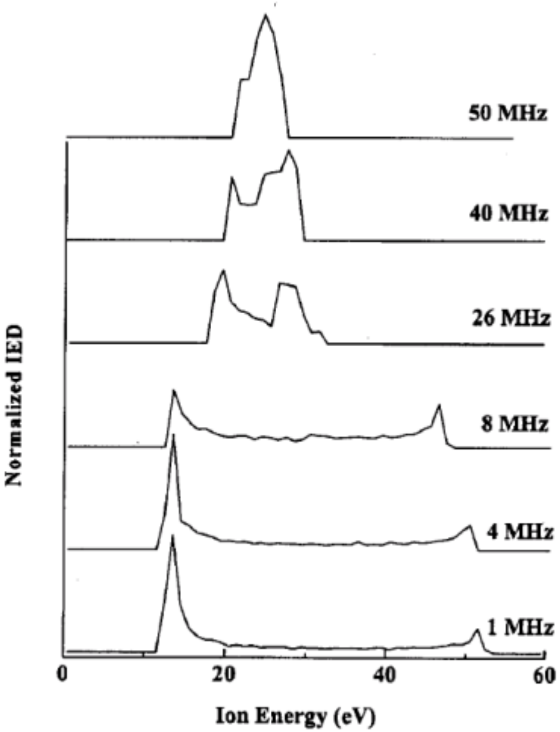
Low frequency
-Ions see time-varying field



High frequency
Ions only see time-averaged field

Énergie des ions

Les ions sont donc accélères dans la gaine et bombardent la surface avec une grande énergie. Cependant, selon la fréquence appliqué, les ions ne sont pas mono-énergétiques:



Haute fréquence - les ions ne voient que le champ électrique moyenne

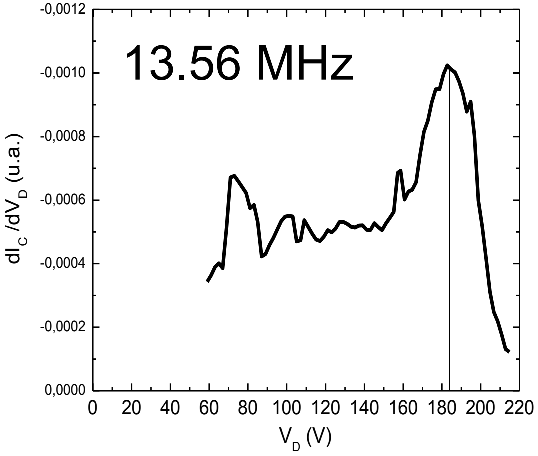
Basse fréquence - L ’énergie dépend de la phase RF quand l ’ion est rentré dans la gaine

Temps de transit: $t = d\sqrt{\frac{2m_+}{Ve}}$

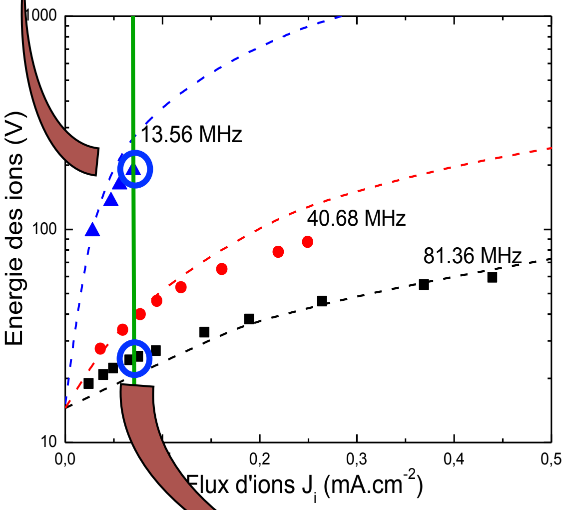
(100 ns pour Ar^+/100V/1mm)

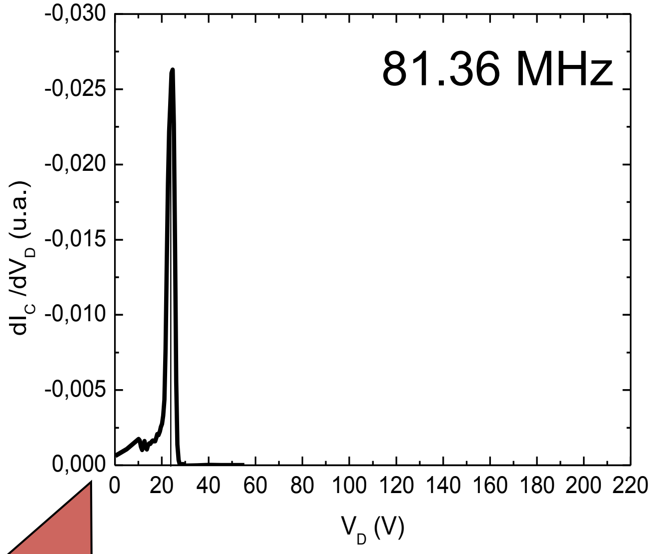
Frequency:
Ion energy vs Ion flux

Ion flux = 0.06mA/cm2
15 mTorr



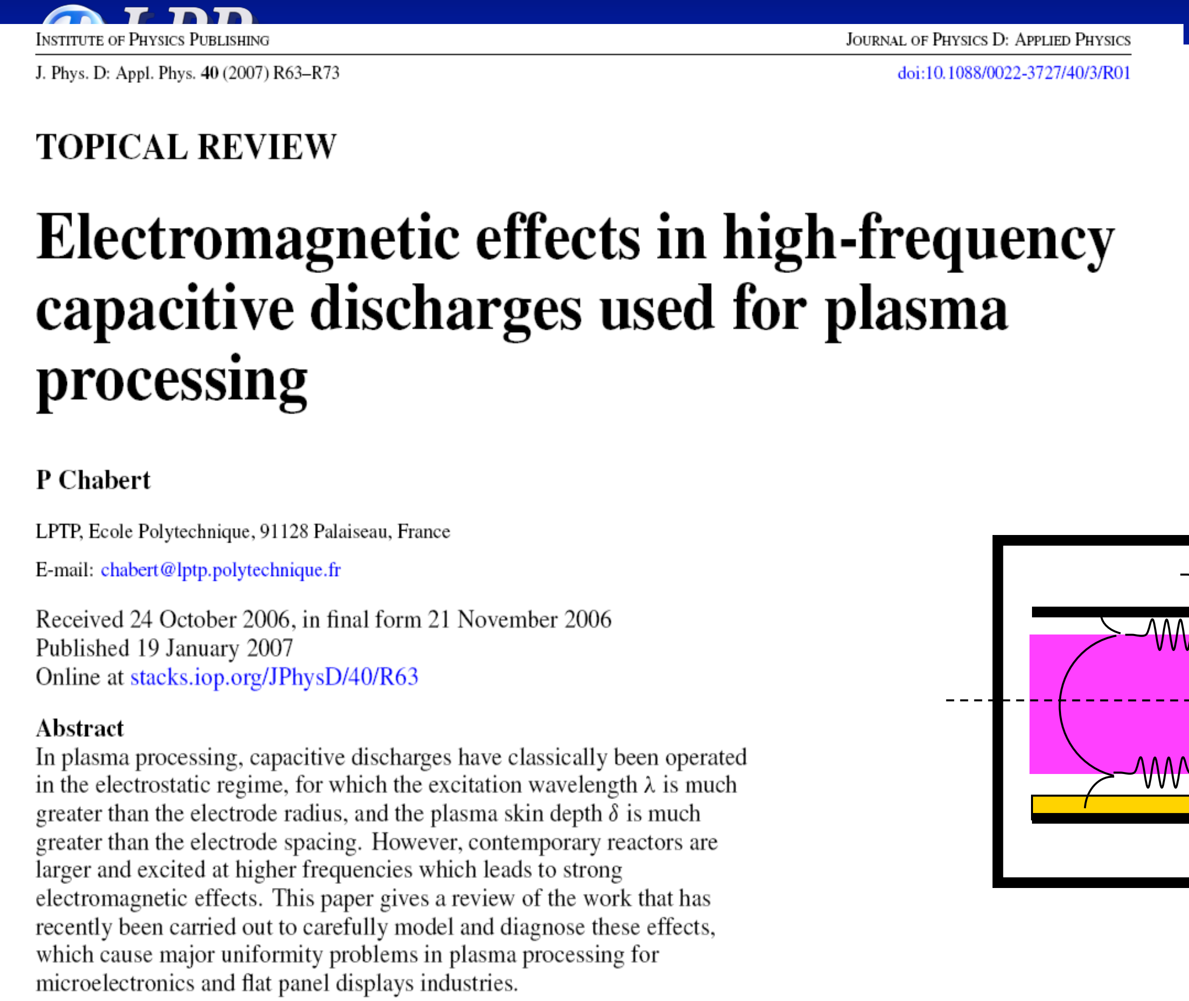
s_m = 7 mm





s_m = 1.2 mm

Electromagnetic effects at high frequency



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TOPICAL REVIEW

Electromagnetic effects in high-frequency capacitive discharges used for plasma processing

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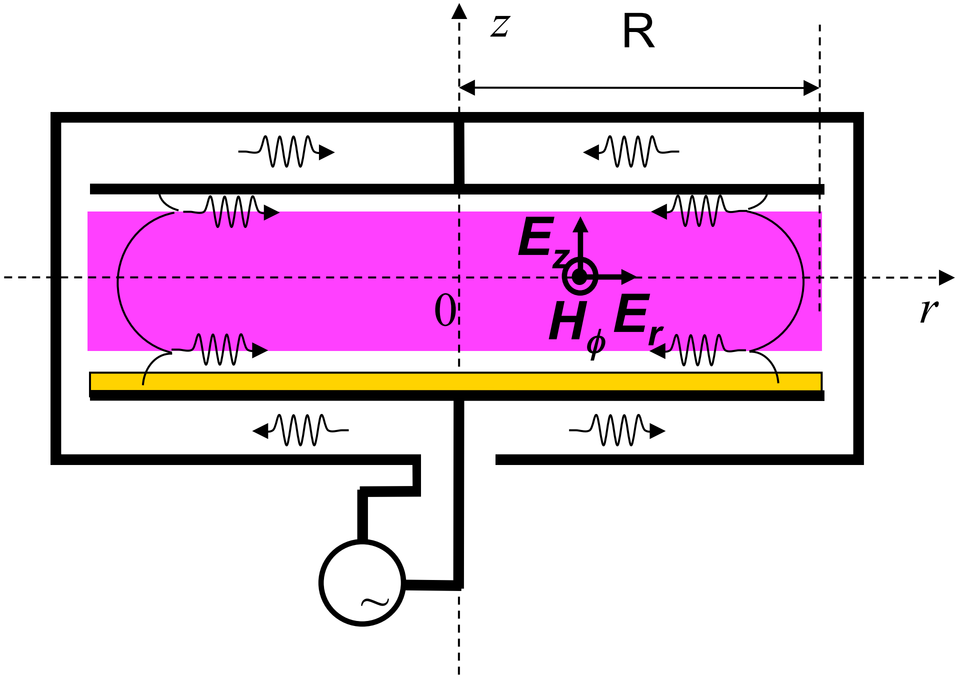
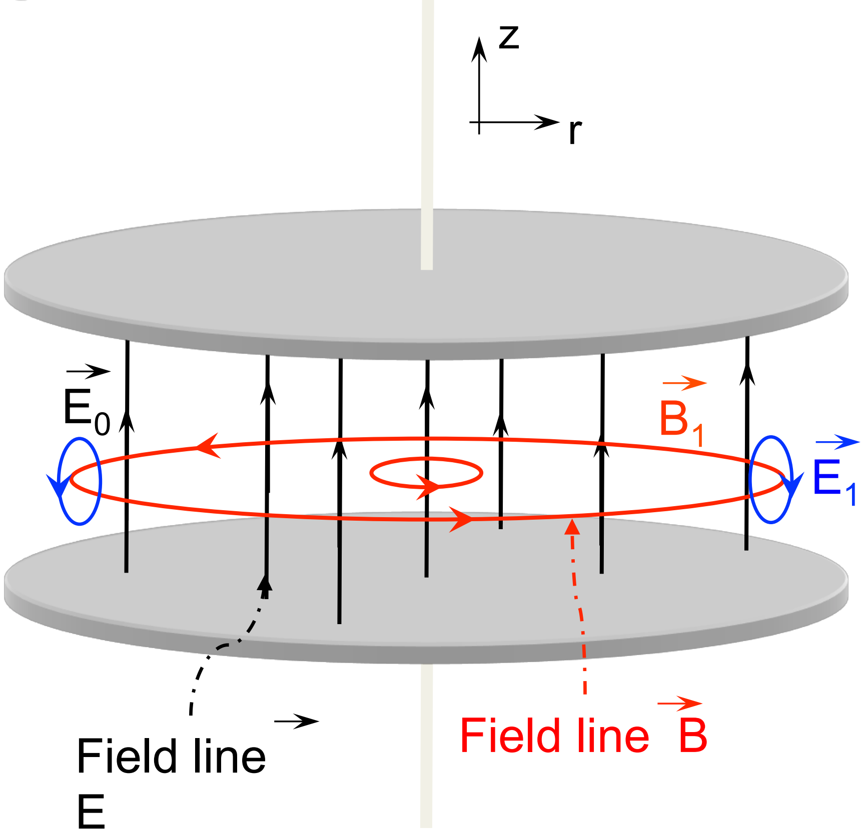
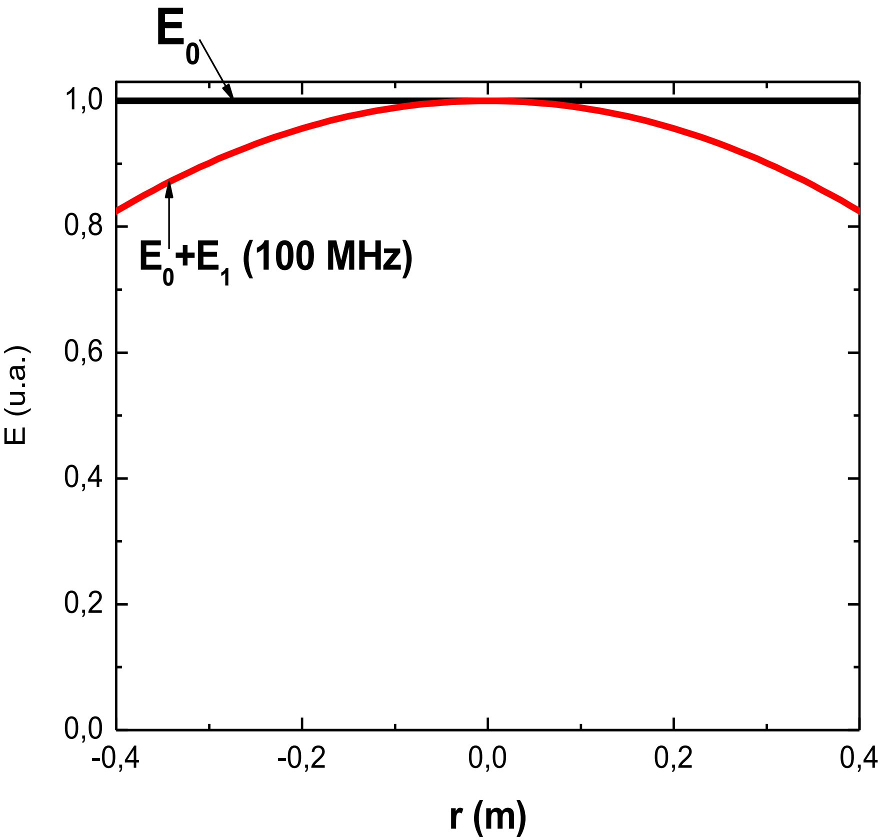
Abstract

In plasma processing, capacitive discharges have classically been operated in the electrostatic regime, for which the excitation wavelength λ is much greater than the electrode radius, and the plasma skin depth δ is much greater than the electrode spacing. However, contemporary reactors are larger and excited at higher frequencies which leads to strong electromagnetic effects. This paper gives a review of the work that has recently been carried out to carefully model and diagnose these effects, which cause major uniformity problems in plasma processing for microelectronics and flat panel displays industries.



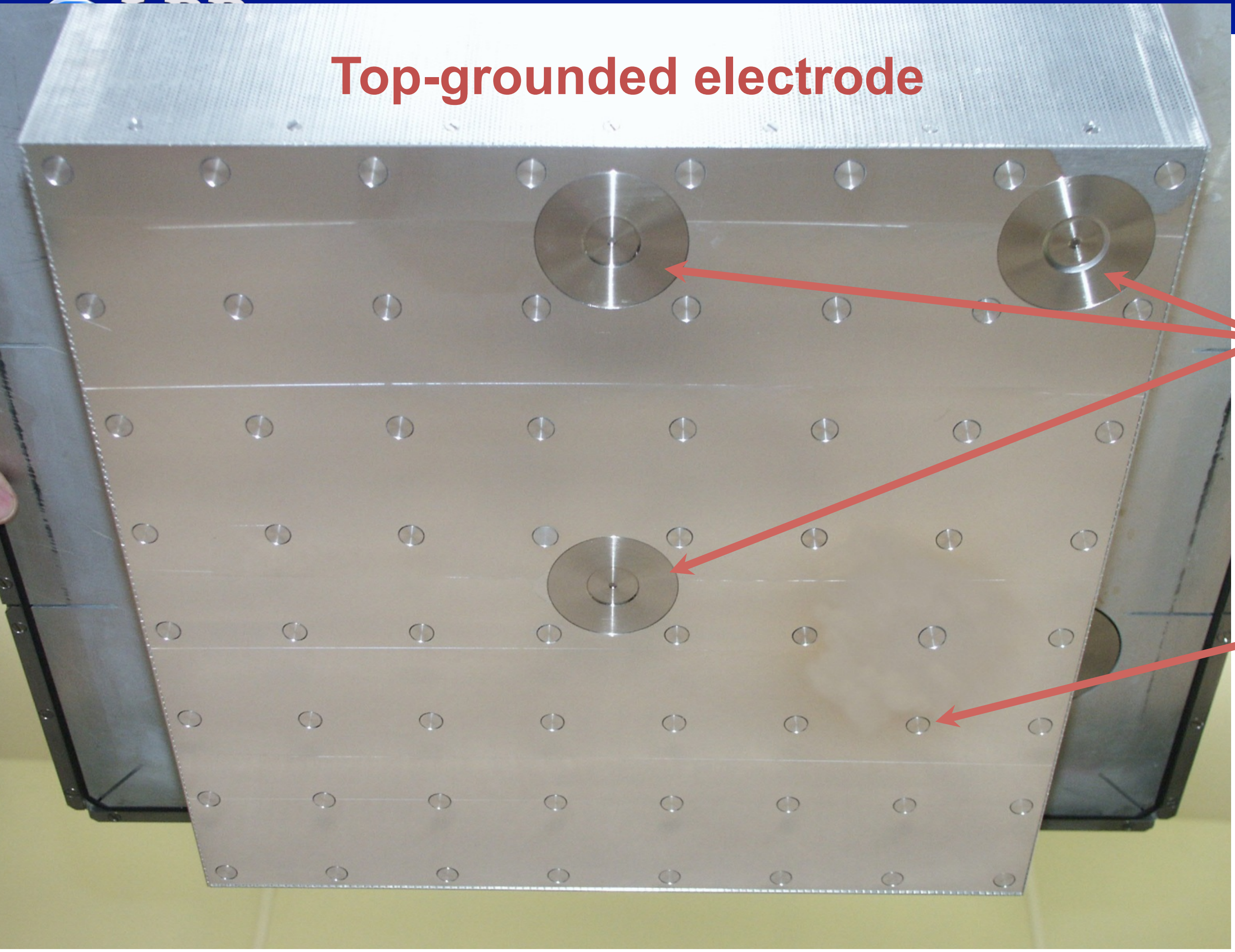
The capacitor at high frequency
(Feynman “Lectures on Physics”, chapter 23-2)





- Standing wave profile
- The electric field is not radially uniform

Experimental evidence of EM effects

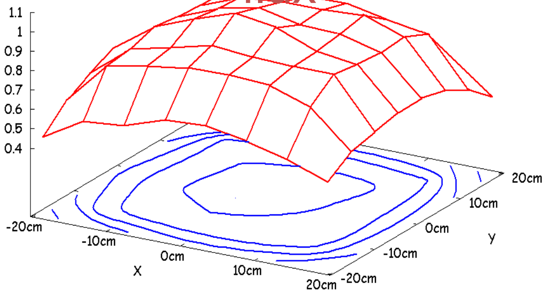


Top-grounded electrode

3 RFEA
Retarding Field Energy Analyser
Ion energy uniformity

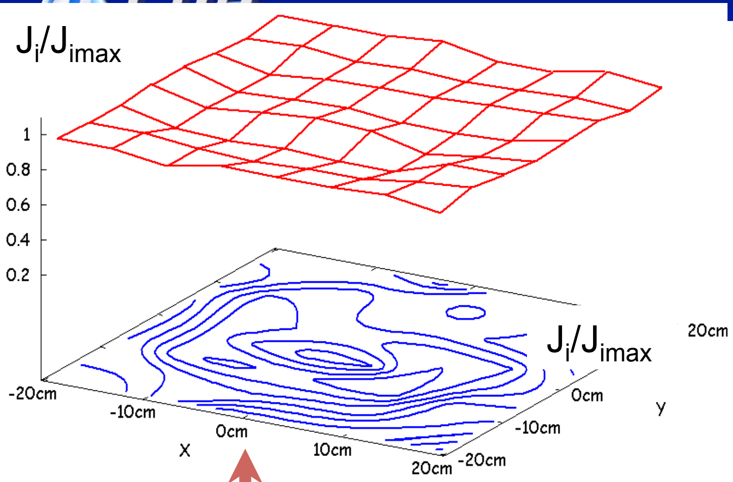
64 planar probes

Cartography of the ion flux



Standing wave effect

50 W, 200 mTorr



13.56 MHz

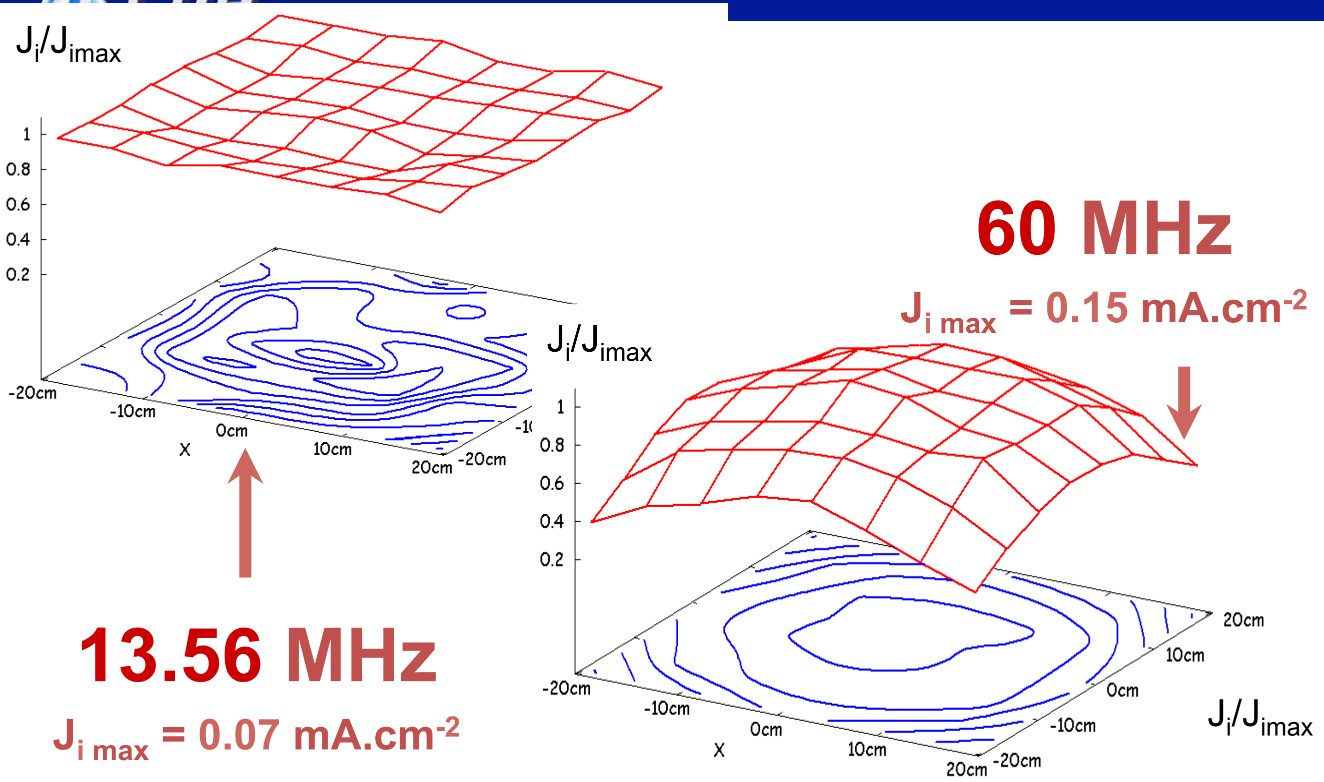
$J_{i\ max}$ = 0.07 mA.cm^{-2}

Good uniformity

*A. Perret et al., Appl. Phys. Lett **83** (2003) 243*

Standing wave effect

50 W, 200 mTorr



60 MHz

$J_{i\,max}$ = 0.15 mA.cm^{-2}

13.56 MHz

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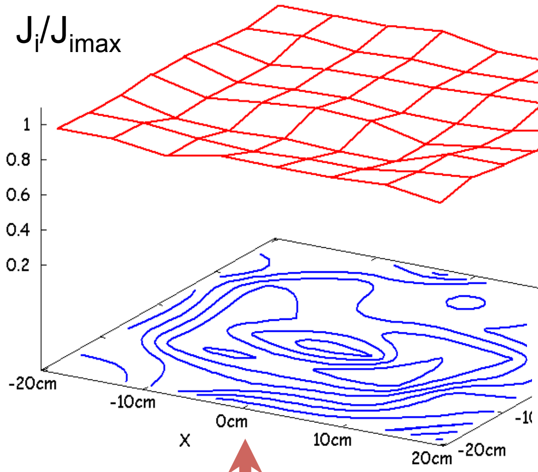
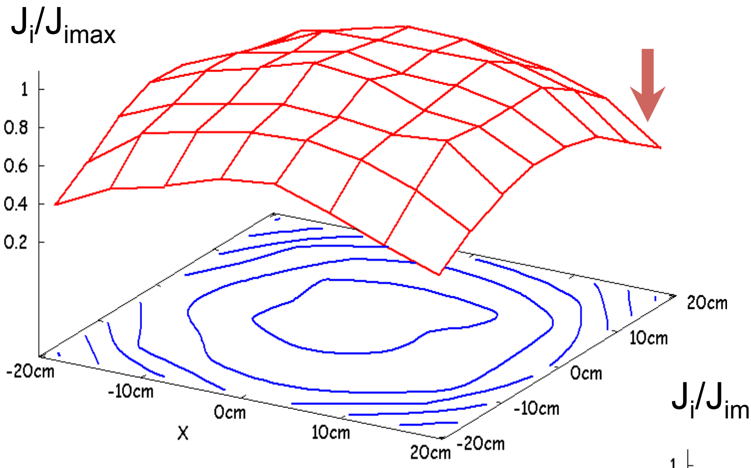


13.56 MHz

$J_{i\ max}$ = 0.07 mA.cm^{-2}



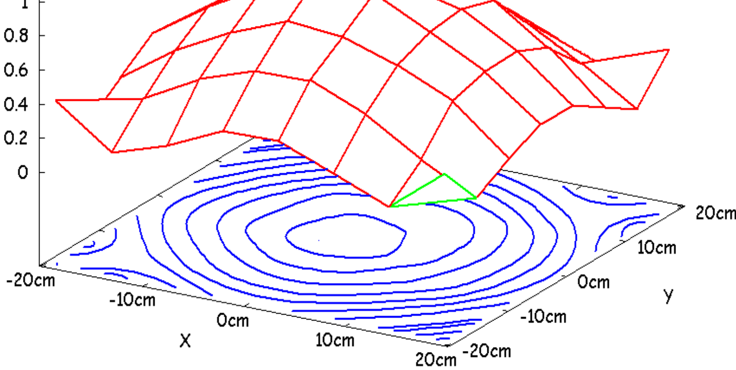
60 MHz

$J_{i\ max}$ = 0.15 mA.cm^{-2}

Significant standing wave
+ edge heating
(inductive effect)

81.36 MHz

$J_{i\ max}$ = 0.17 mA.cm^{-2}



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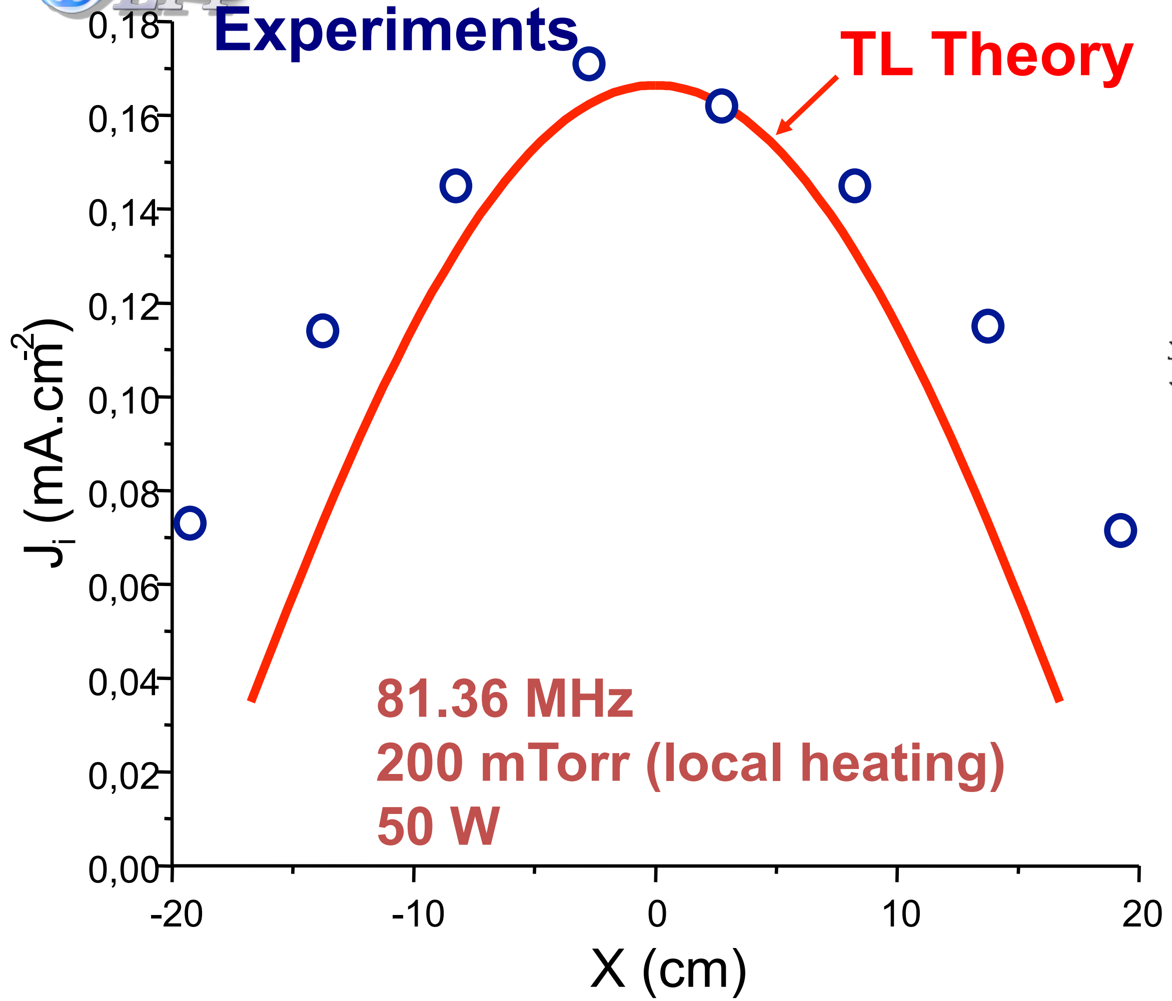
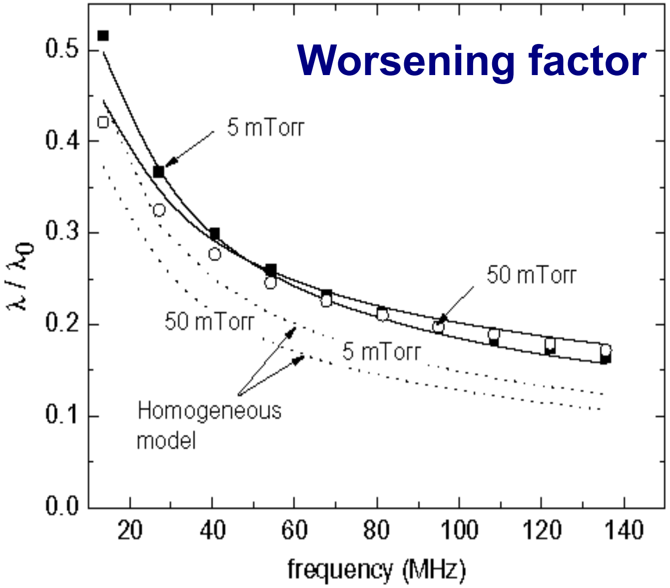
Standing wave effect



81.36 MHz
200 mTorr (local heating)
50 W



Worsening factor

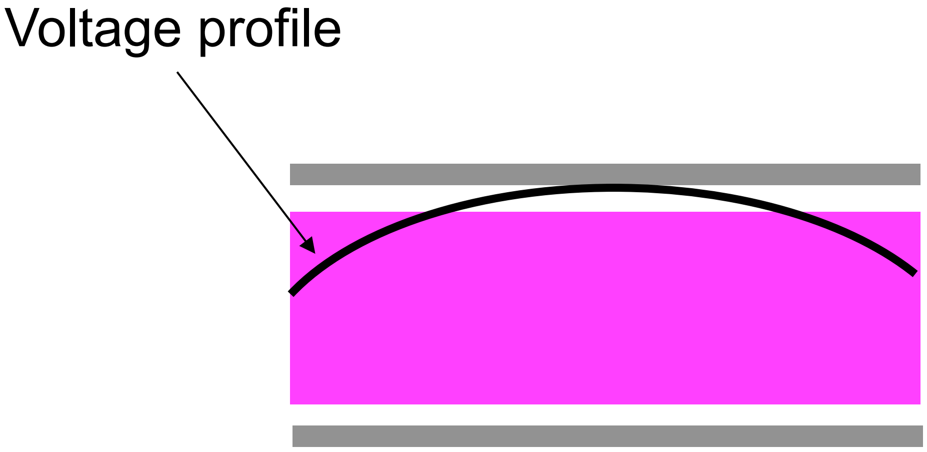
$$\frac{\lambda}{\lambda_0} \approx 40\ V_0^{1/10} l^{-1/2} f^{-2/5}$$

Fairly insensitive to the gas composition

P. Chabert et al., Physics of Plasmas **11** (2004) 1775

Ion energy uniformity

81.36 MHz, 10 mTorr

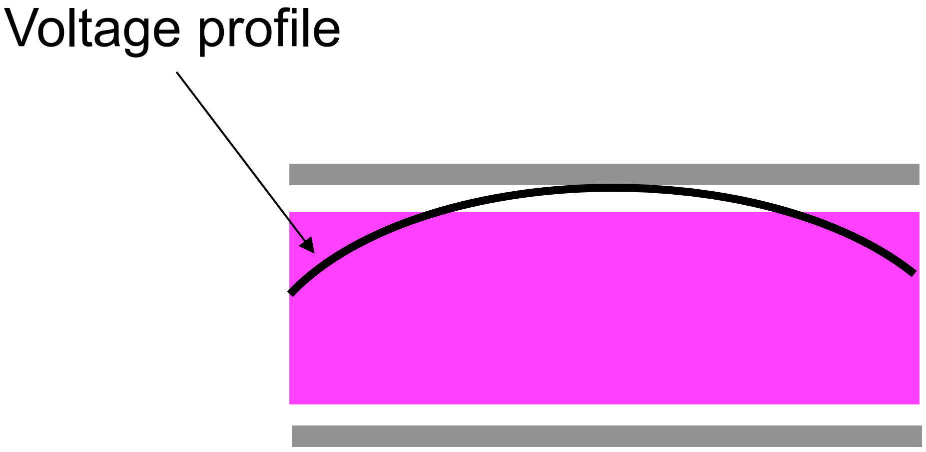


From simple usual theory:

$$V_p \cong V_{rf} / 2 + 5T_e$$

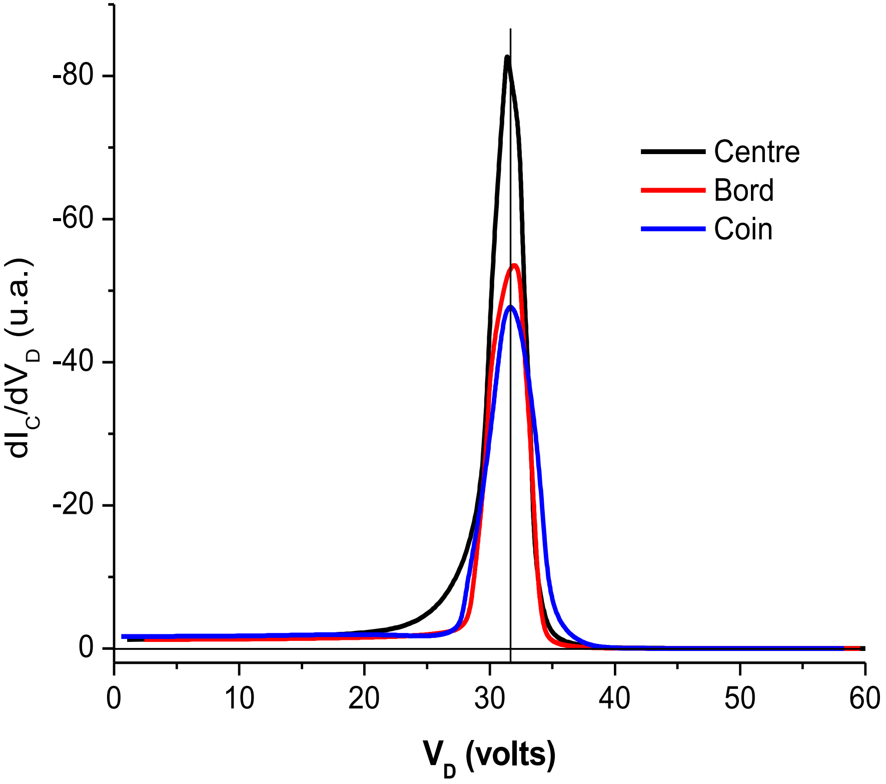
Ion energy uniformity

81.36 MHz, 10 mTorr



From simple usual theory:
$V_p \cong V_{rf} / 2 + 5T_e$

V_p = 32 V

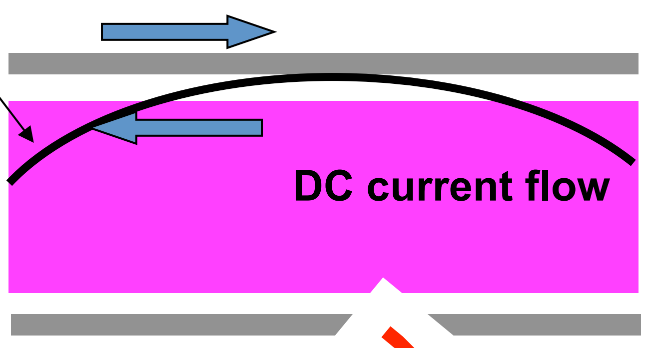


Ion energy is uniform although V_{rf} is not!

Ion energy uniformity

81.36 MHz, 10 mTorr

Voltage profile

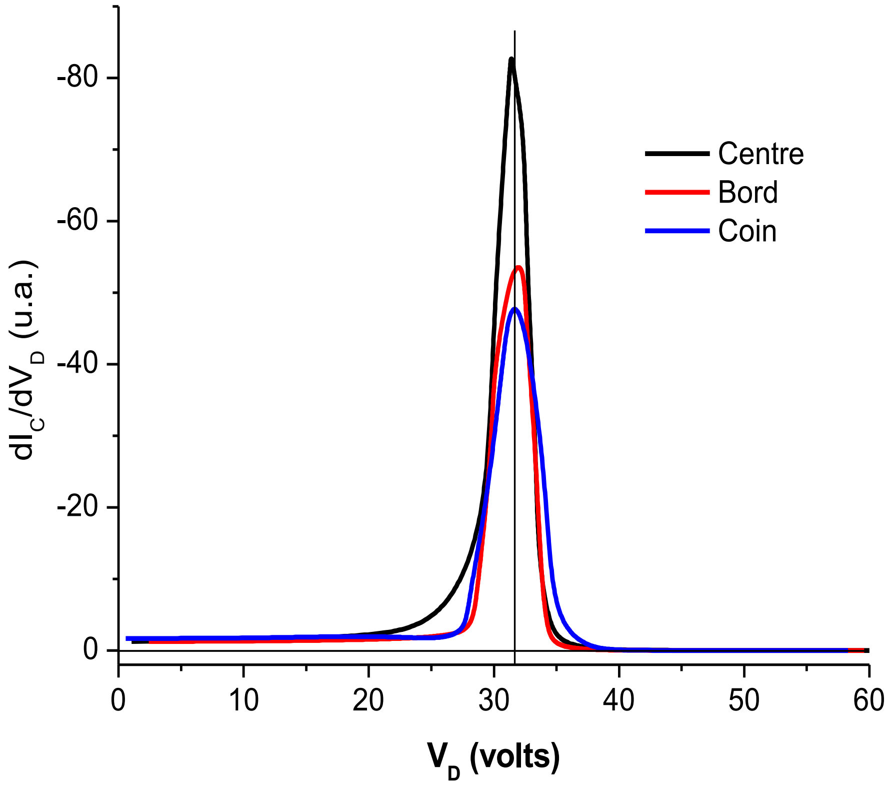


From simpl l theory:

V_p $5T_e$

Not true !

V_p = 32 V



Ion energy is uniform although V_{rf} is not!

L’excitation multifréquence: non-synchronisée

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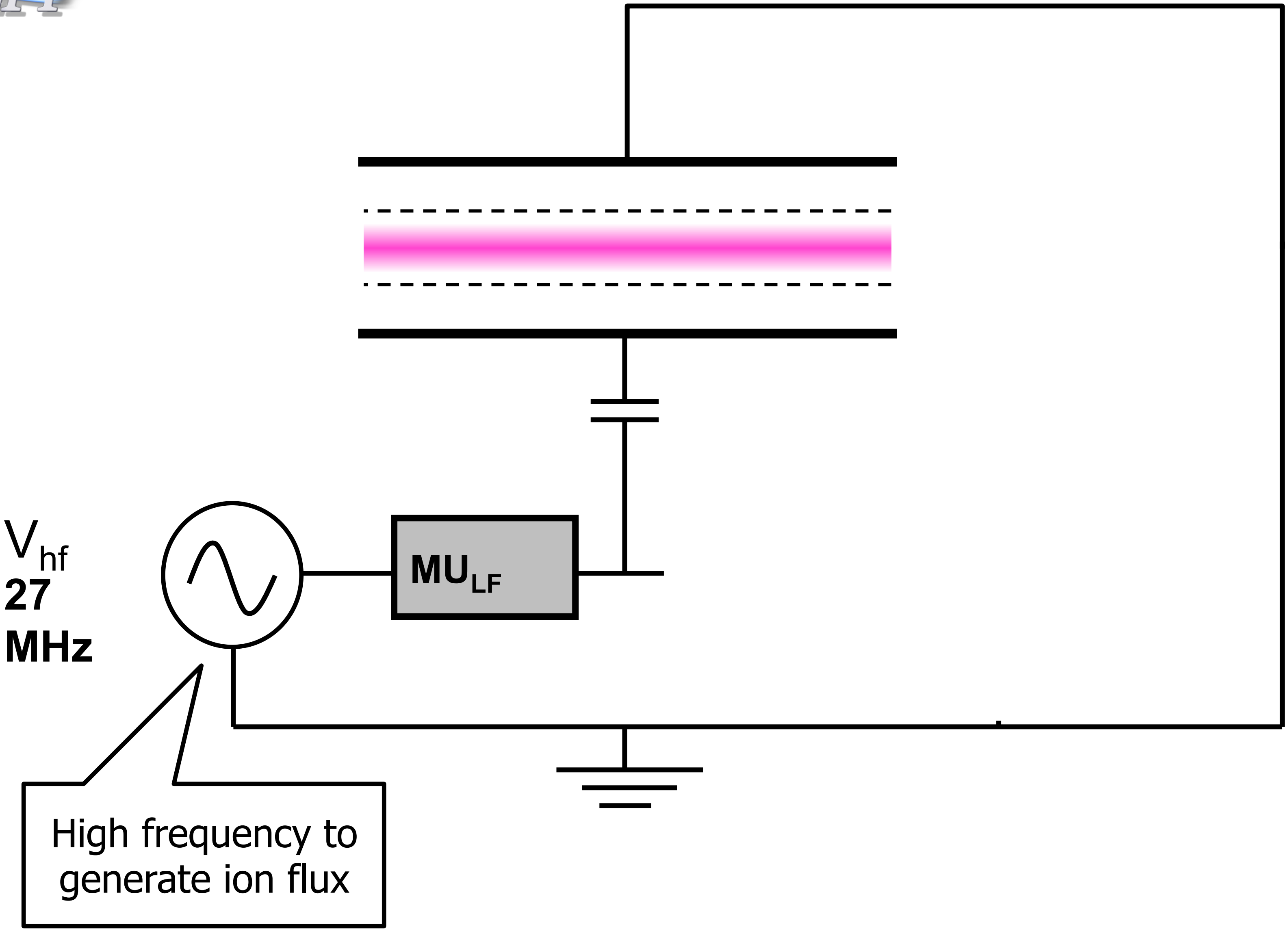
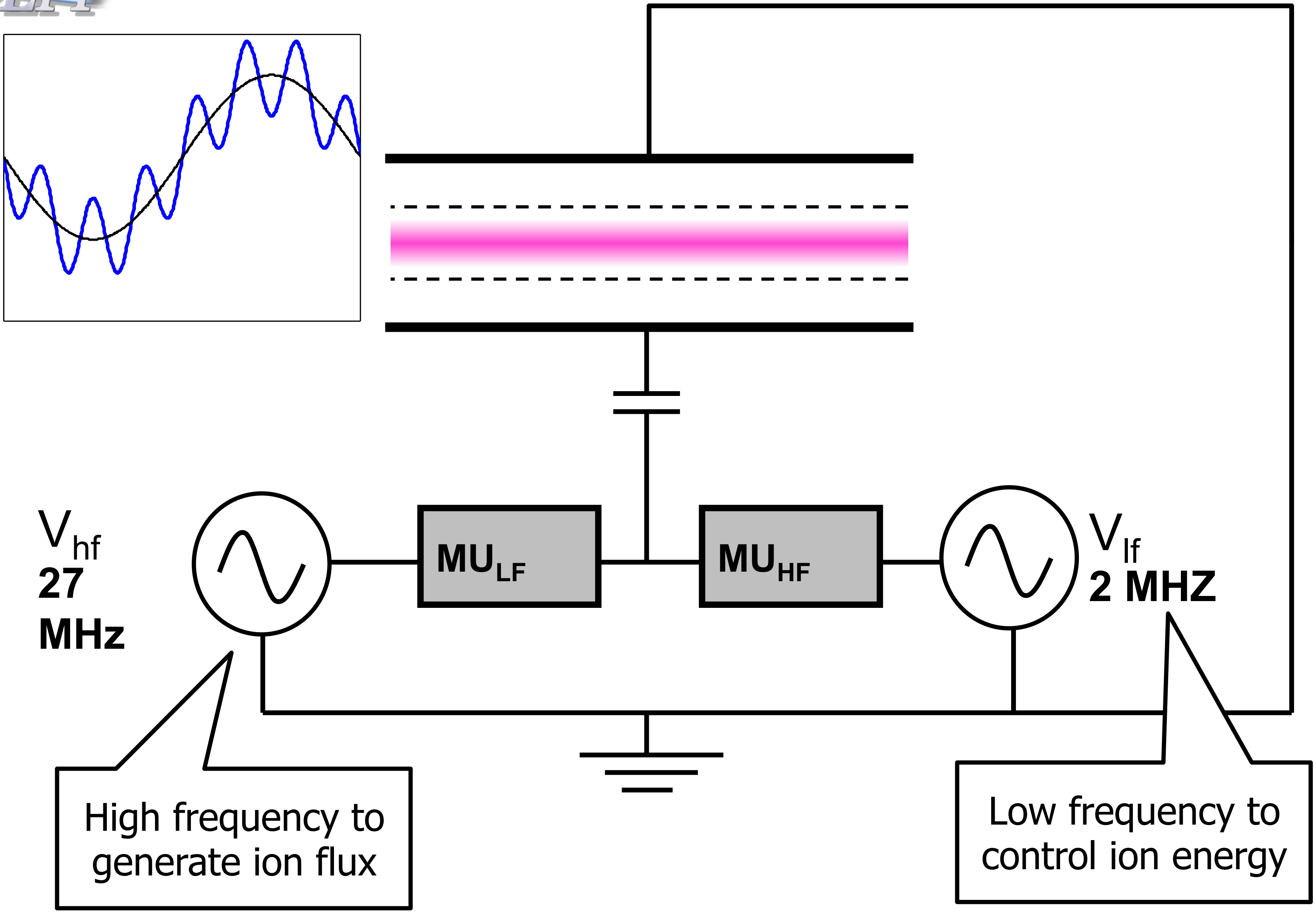
Comment contrôler indépendamment
le flux et l’énergie des ions?

Dual Frequency Capacitively Coupled Plasma Separate control of Ion flux and energy?



High frequency to generate ion flux

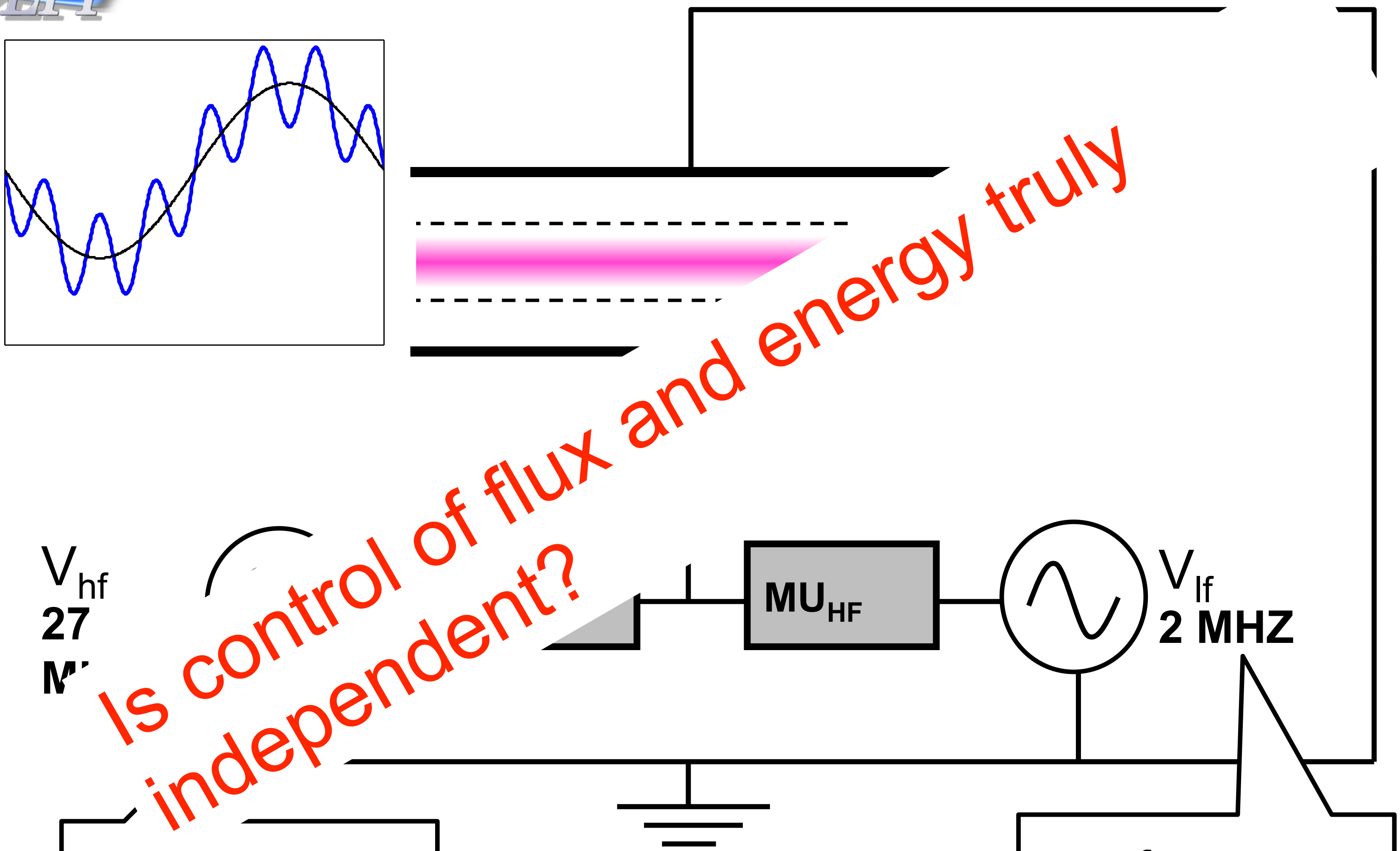
Dual Frequency Capacitively Coupled Plasma
Separate control of Ion flux and energy?



High frequency to generate ion flux

Low frequency to control ion energy

Dual Frequency Capacitively Coupled Plasma
Separate control of Ion flux and energy?



Is control of flux and energy truly independent?

High frequency to generate ion flux

Low frequency to control ion energy

Electron density and ion flux in a Dual-Frequency CCP

- Based on an industrial 200 mm dielectric etch tool

-Confinement assembly home-made

-HARC etch recipe:

Ar/O_2 (+C_4F_8)

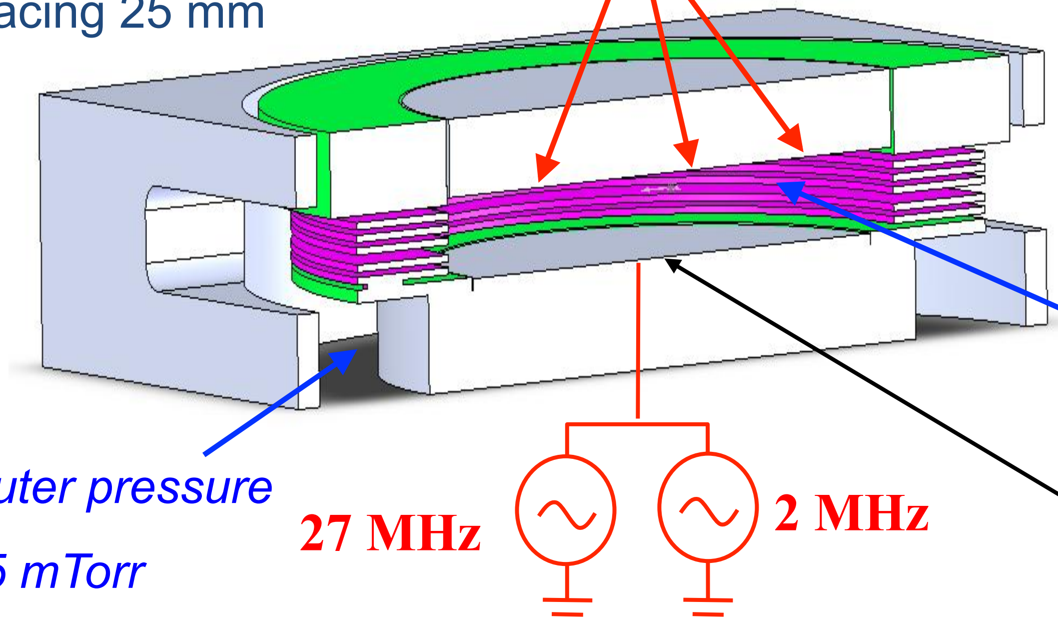
Silicon Electrodes,

Spacing 25 mm

27 MHz: ≤ 750 W

2 MHz : ≤ 750 W

Ion energies up to 2 keV



Inner Pressure :

50 mTorr

Outer pressure

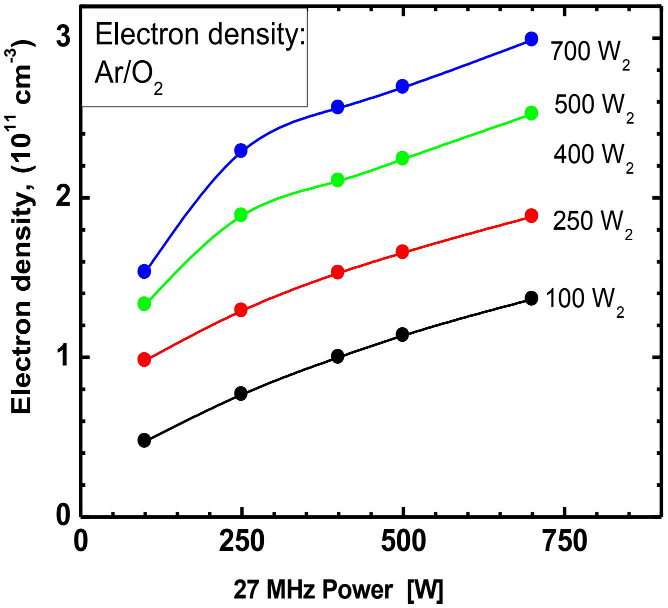
≈5 mTorr

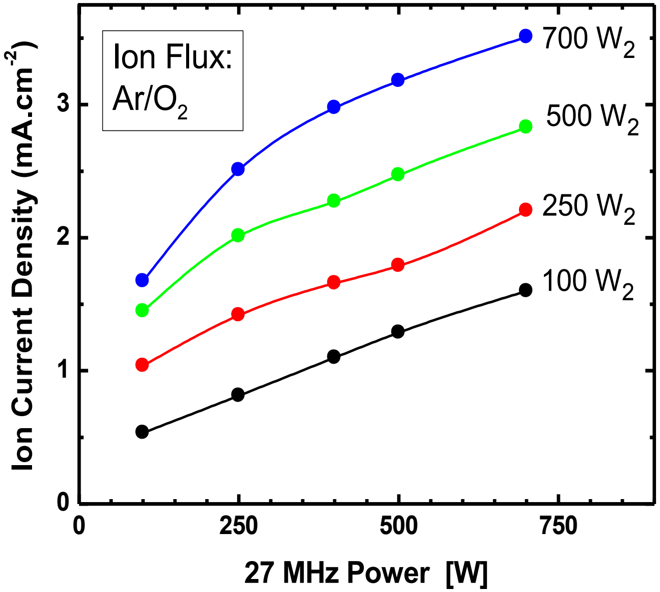
27 MHz

2 MHz

200 mm Silicon wafer

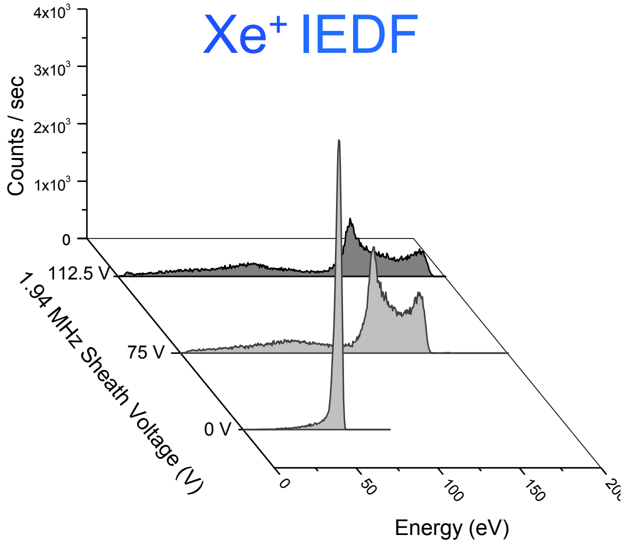
Electron density & Ion flux vs 27 and 2 MHz (Ar/O_2)





- both **W_{27} and W_2** increase **Electron Density** and **Ion Flux**
- 2 MHz increases sheath width, enhances 27 MHz heating
- Secondary electrons play a major role

Control of ion energy in 2f – CCRF discharge (O'Connell/Gans, QUB)

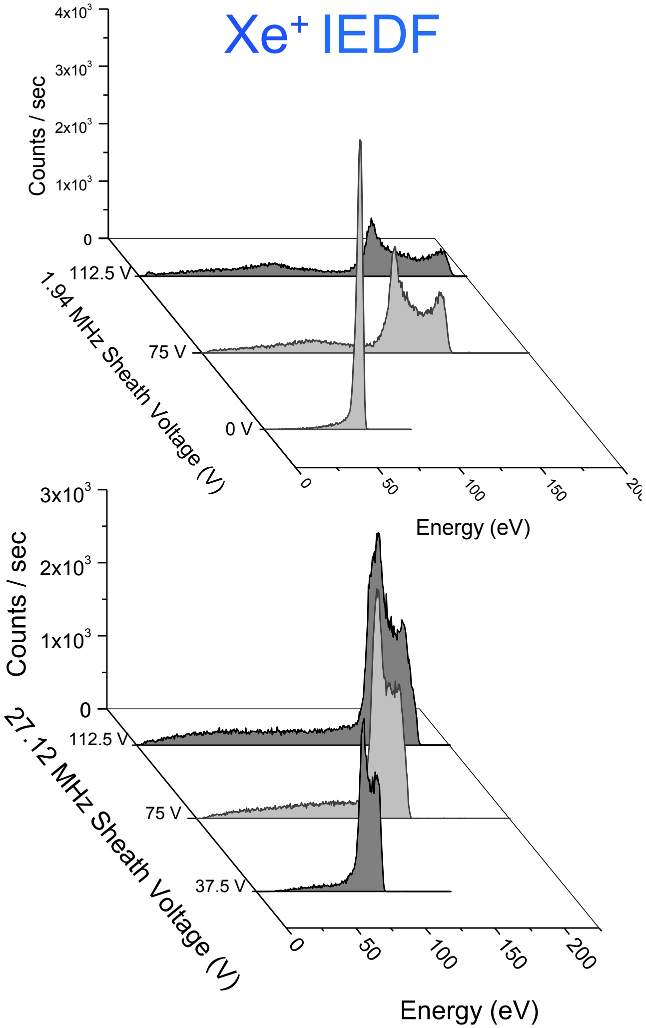


Xe^+ IEDF

Increasing 2 MHz voltage (27 MHz constant)
→ increases ion energy (& spread)

Xe admixture H_2 discharge, p = 5 Pa, $V_{1.94\ \mathrm{MHz}} = 37.5$ V, $V_{27.12\ \mathrm{MHz}} = 37.5$ V

Control of ion energy in 2f - CCRF discharge (O'Connell/Gans, QUB)



Increasing 2 MHz voltage (27 MHz constant)
→ increases ion energy (& spread)

Increasing 27 MHz voltage (2 MHz constant)
→ Also increases ion energy

Xe admixture H_2 discharge, p = 5 Pa, $V_{1.94\ \mathrm{MHz}}$ = 37.5 V, $V_{27.12\ \mathrm{MHz}}$ = 37.5 V

DF-CCP Summary

- Use of dual (or even triple) frequency allows access to a wide range of ion flux/ energy not available with single frequency

- Ion energy distribution functions : wide, complex (But may be useful for processing..)

- Low frequency power nevertheless also increases flux

- High frequency power also increases ion energy

L'excitation multifréquence synchronisée: les formes d'onde « sur-mesure »

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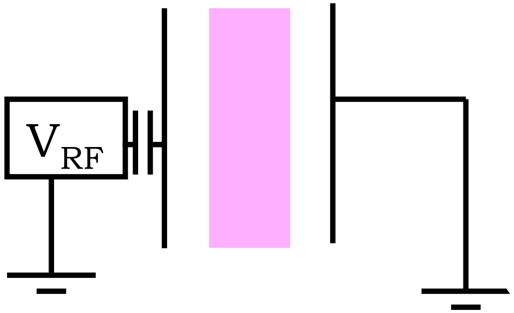
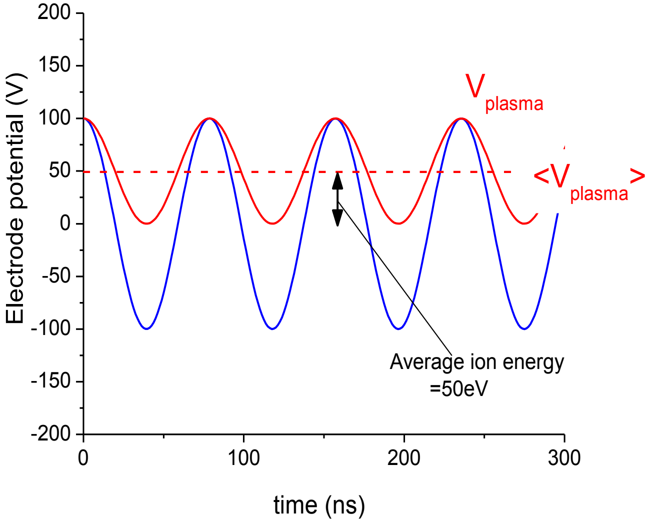
Large area CCP:
equal area electrodes - equal sheaths



Sheath rectifies RF voltage
Same RF current flows through each sheath (180° phase)
Plasma potential high and strongly modulated
    Same large DC potential drop

Both sides recieve high ion bombardment

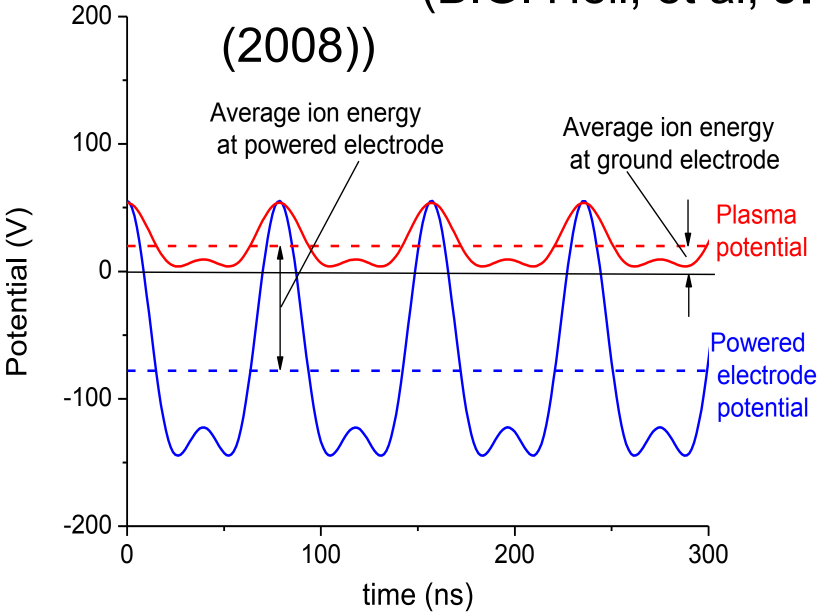


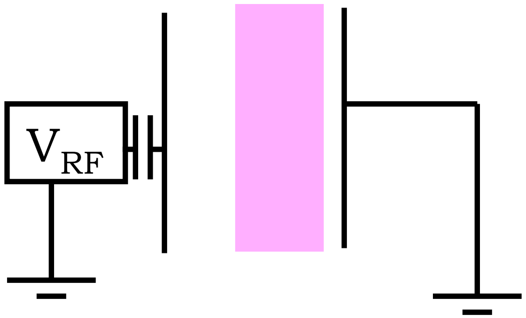
Can we break this symmetry?
⇒low energy and high energy sides ?

Non-sinusoidal waveforms in a symmetric reactor

f + 2f excitation : **Electrical Asymmetry Effect (EAE)**

(B.G. Heil, et al, **J. Phys. D: Appl. Phys. 41**, 165202 (2008))





The same current must flow through both sheaths,
polarity is inverted:
voltage is no longer divided equally between the two:

High energy and low energy sides : adjust division by changing the relative phase:
-allows ion energy control at constant flux

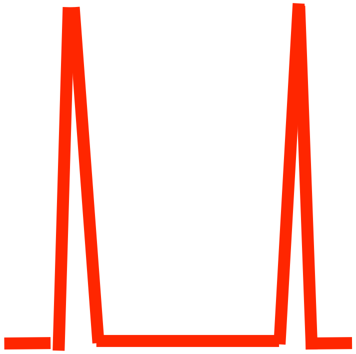
What is the optimum waveform for high density/low energy ?

- Highly asymmetric waveform
  - Minimise sheath voltage at substrate

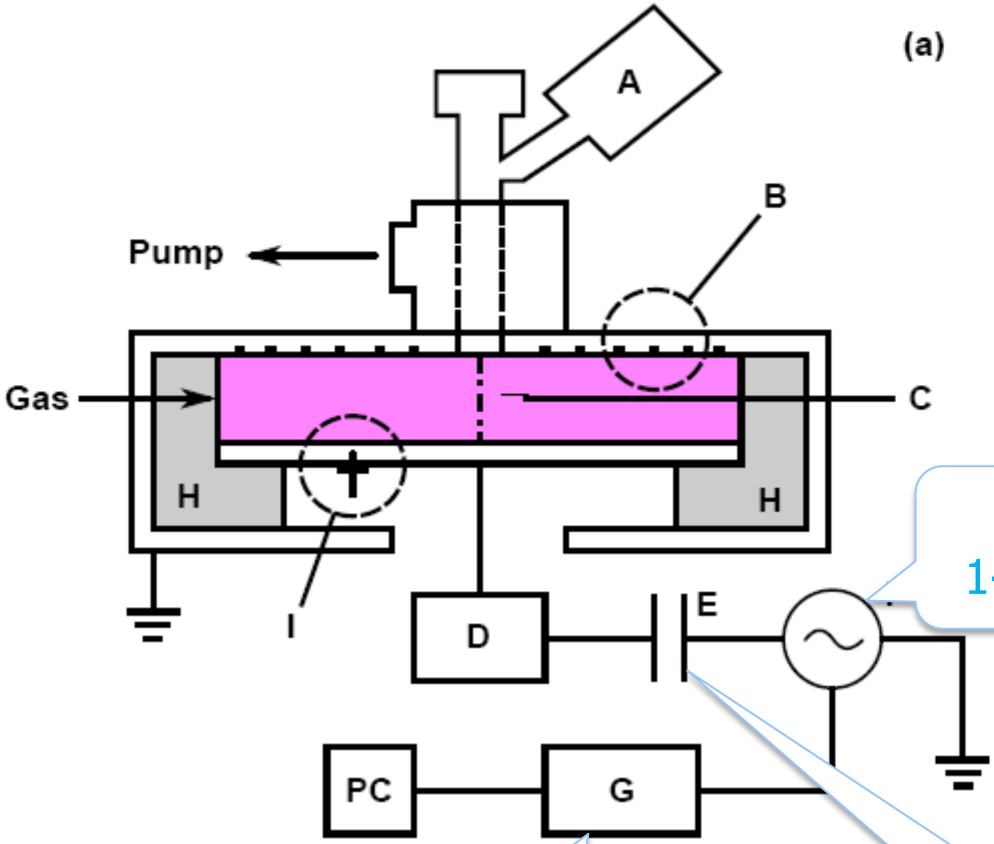
- Fast rise-time / slew rate
  - Efficient electron heating (c.f. VHF)
    - Ohmic :High peak current through sheaths + bulk plasma
    - Stochastic : high sheath velocity
  - High density for high deposition rate/high H atom density

- High repetition rate
    - High average power

⇒ Fast positive spikes (ns rise)
on a flat background,
>10 MHz repetition frequency



DRACULA reactor: Waveform generation



Power amplifier
1-200 MHz 1kW class A

NB no impedance matching!

Arbitrary function generator

Blocking capacitor

Waveforms used

- Gaussian pulses difficult to make
  - -finite bandwidth of the amplifier

- Use sums of sine wave harmonics

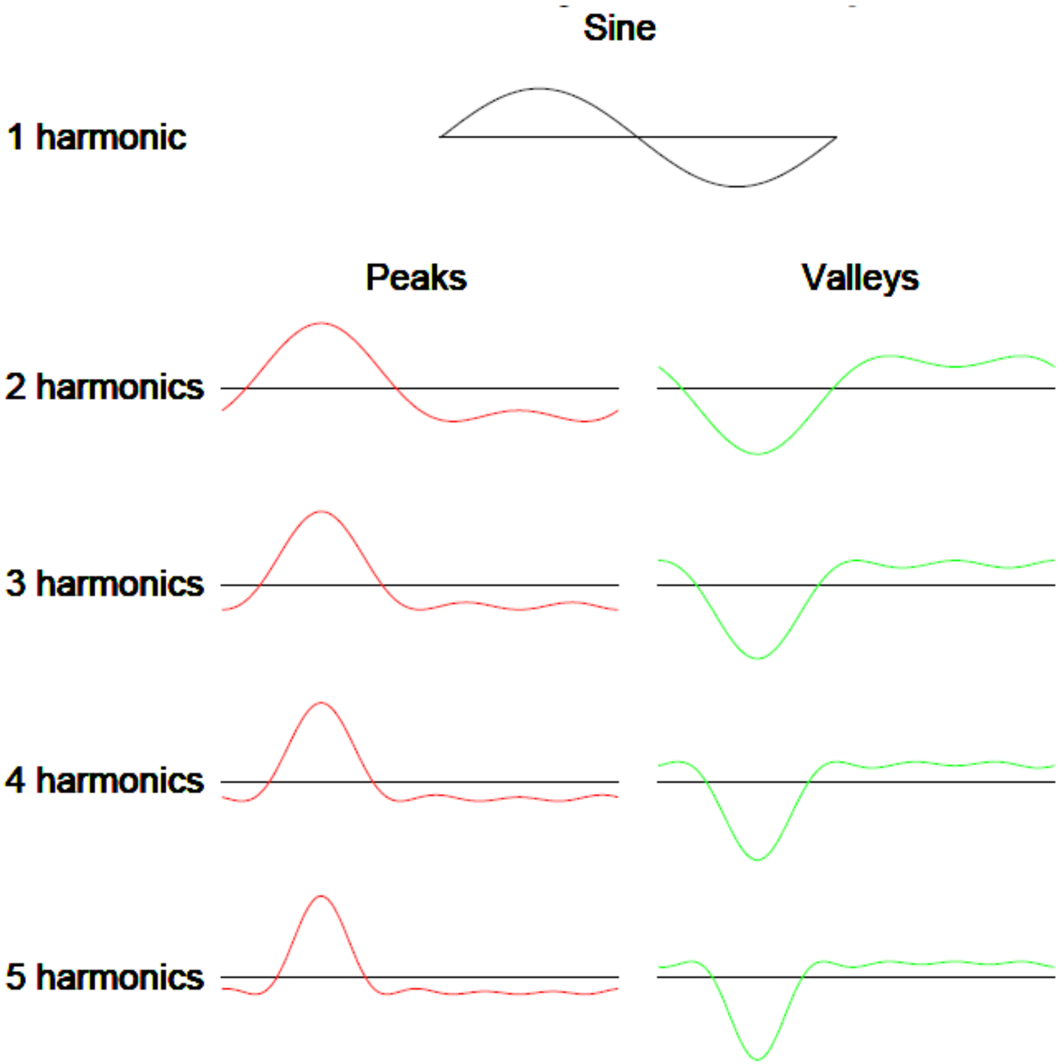
$$V^k = V_0 \sum_{n=1}^{k} C_n^k \cos(n\omega t)$$

With $C_n^k = \frac{k-n+1}{(1+k)^2}$

(constant total amplitude)

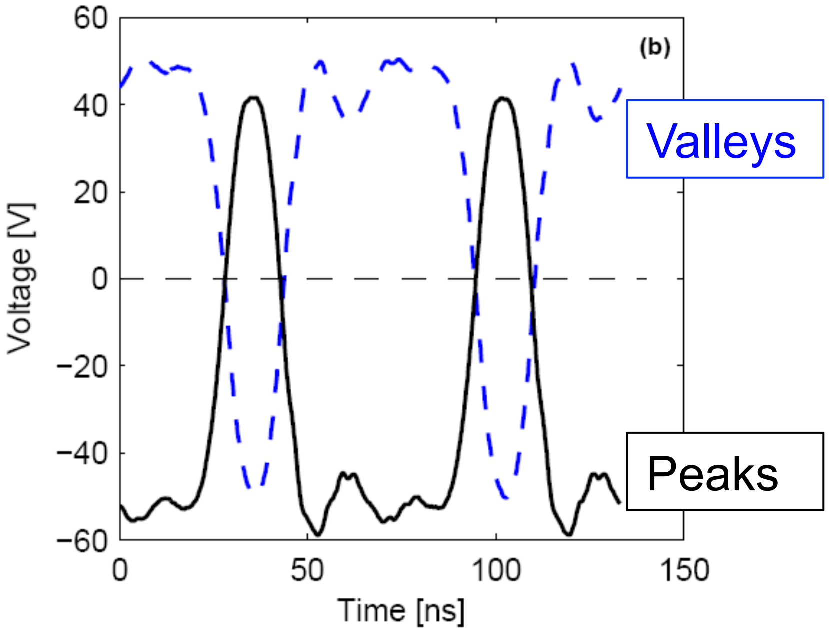
Relative phase = 0^0

(similar to Schulze PSST 2011)



Voltage waveforms and DC bias

(Ar 50mTorr 100Vpp unless stated)

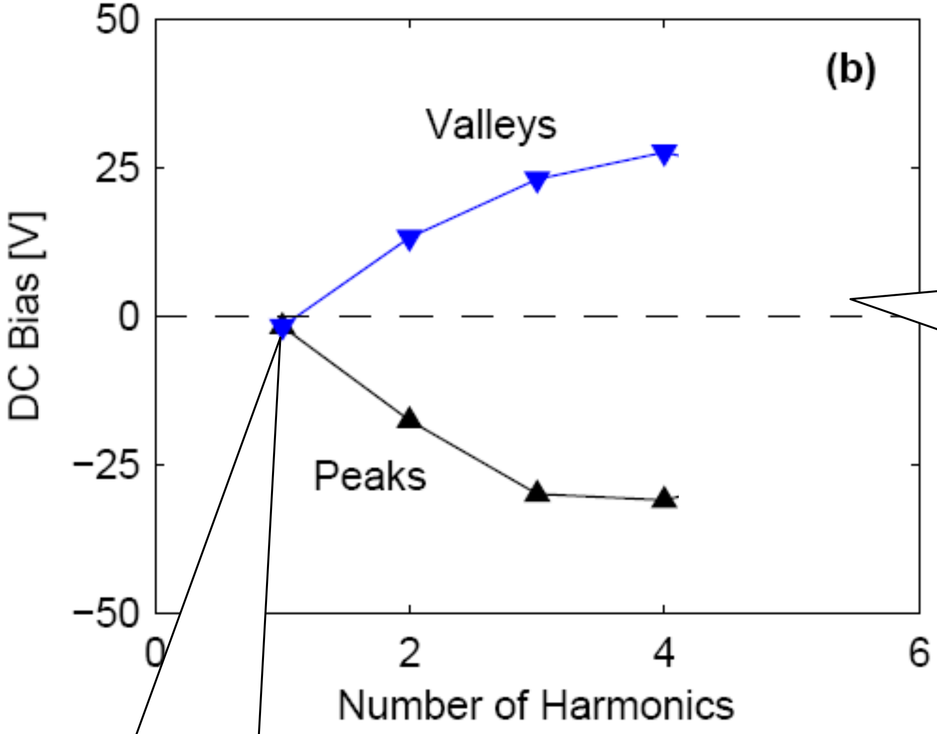


Establishment of positive or negative self-bias depending on the polarity of the pulses:

We can probe either the high or low energy sheath simply by inverting the waveform

Voltage waveforms and DC bias

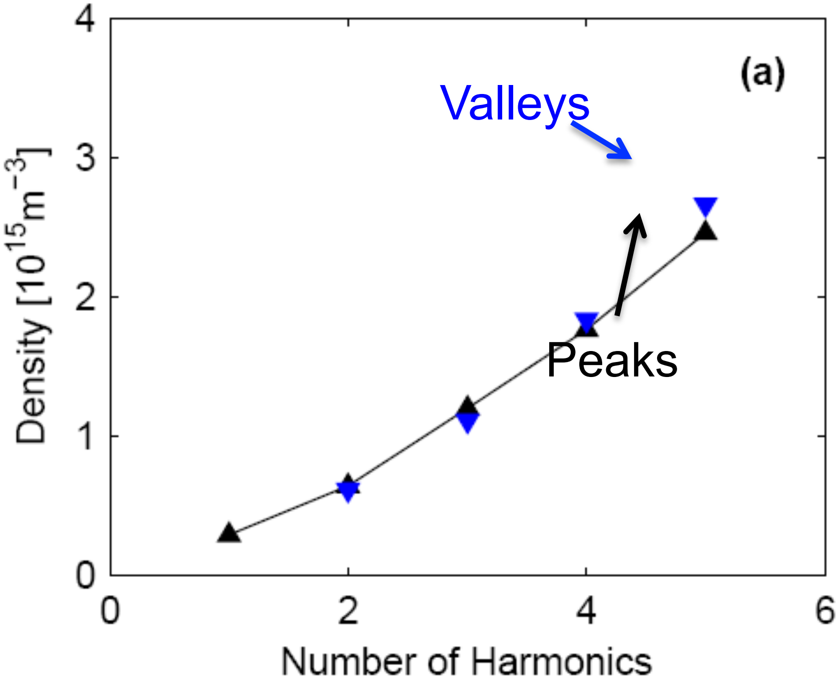
(Ar 50mTorr 100Vpp unless stated)



Increasing
(positive or negative)
DC bias for increasing
number of harmonics

Sinusoidal:
-Near-zero bias
Near perfect
geometrical symmetry

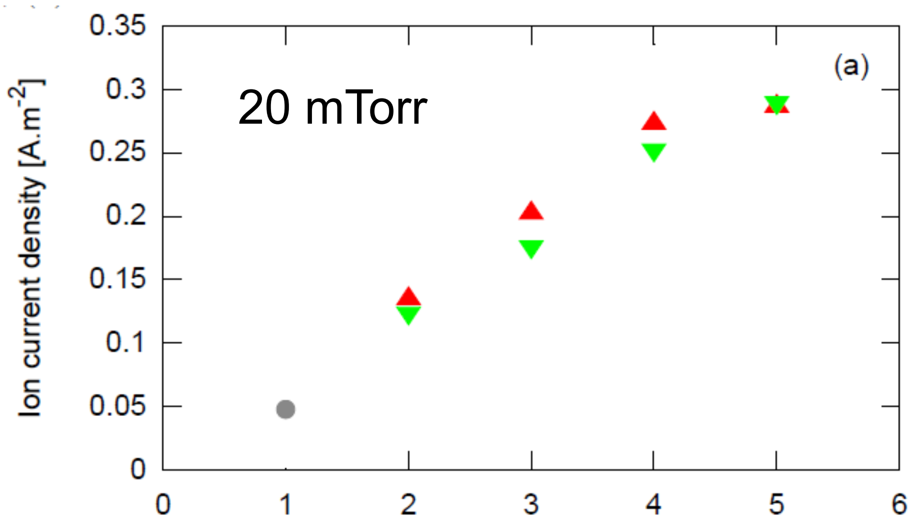
Electron density (Microwave resonator probe)



Electron density increases strongly (as predicted by PIC model)

Peaks and valleys very similar (good geometrical symmetry of reactor)

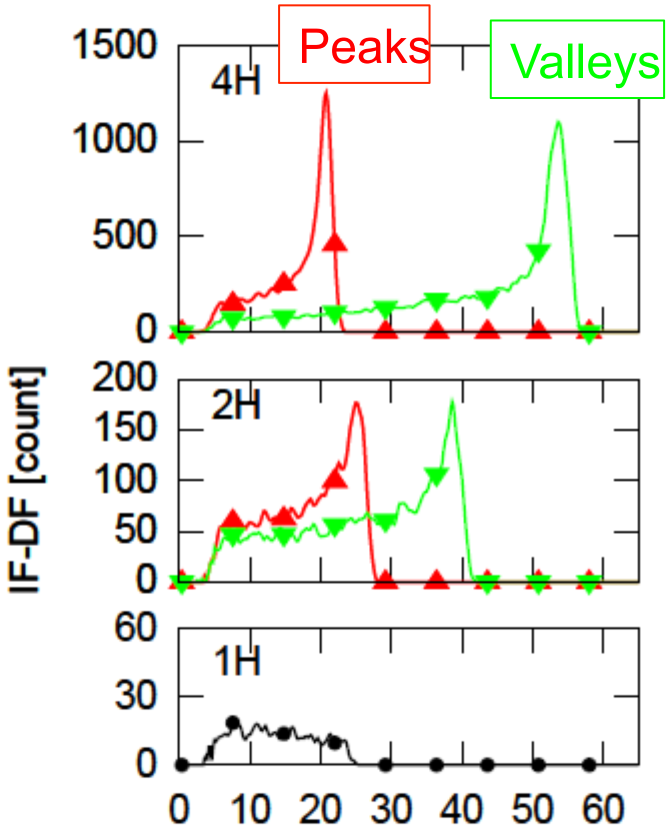
Ion Flux



Linear increase in ion flux with number of harmonics

Ion energy distribution at ground side : 20 mTorr

Measured :

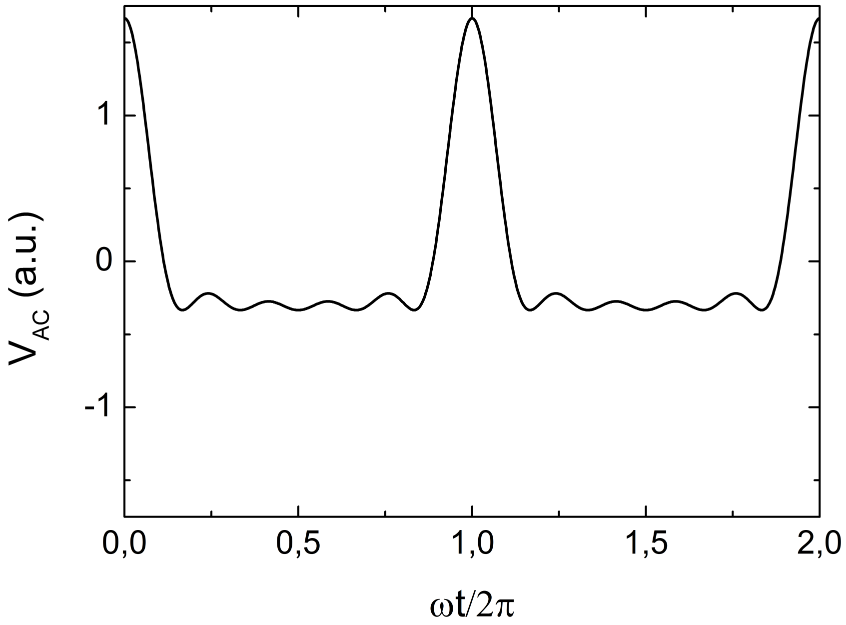


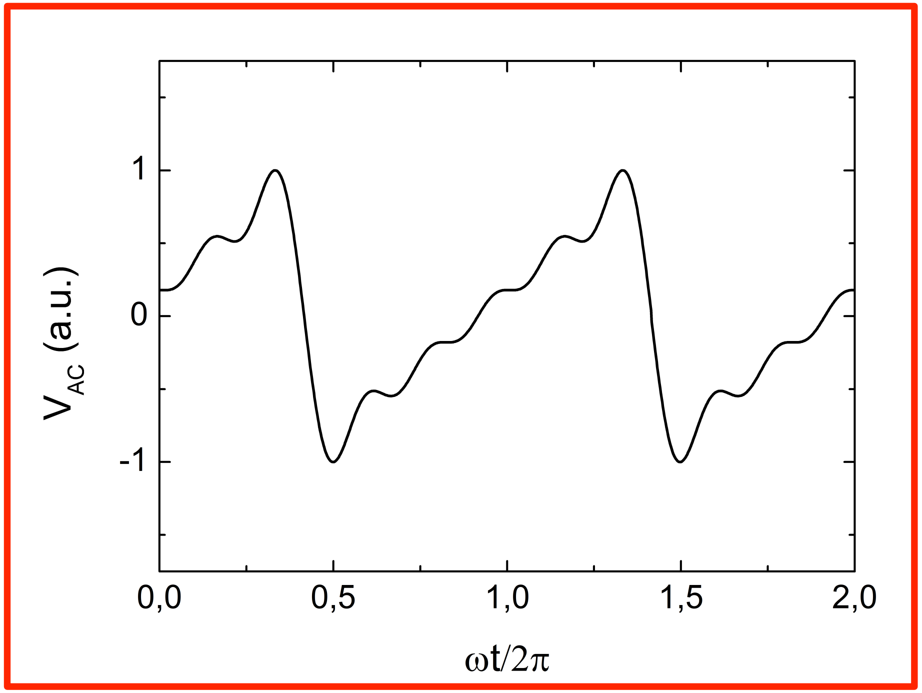
Ion energy at a substrate can be switched from low to high by inverting the waveform

Increased control as number of harmonics is increased

Can we break the ion FLUX symmetry?

Amplitude or temporal asymmetry



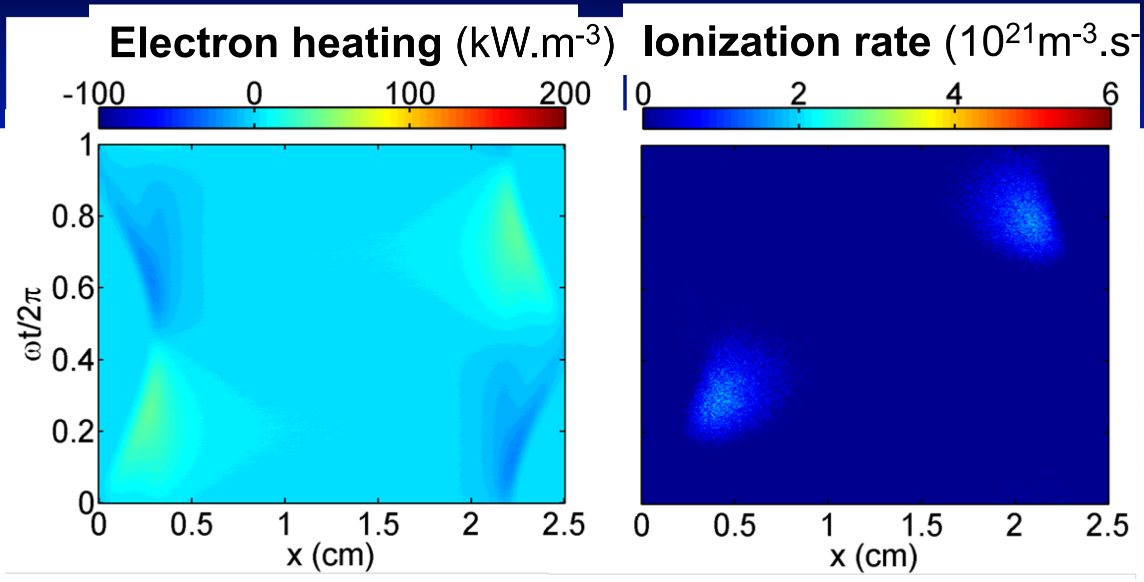


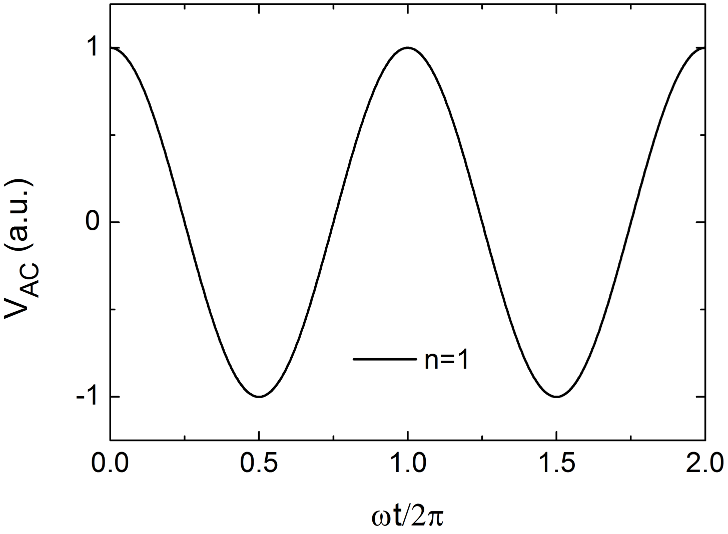
WHAT IS THE EFFECT OF SAWTOOTH WAVEFORMS?

B. Bruneau et al., *Plasma Sources Sci. Technol.*, vol. 23, no. 6, p. 065010, Aug. 2014.

Asymetric electron heating and ionization

P=400 mTorr, V_{PP}=200 V, n=1





Asymetric electron heating and ionization

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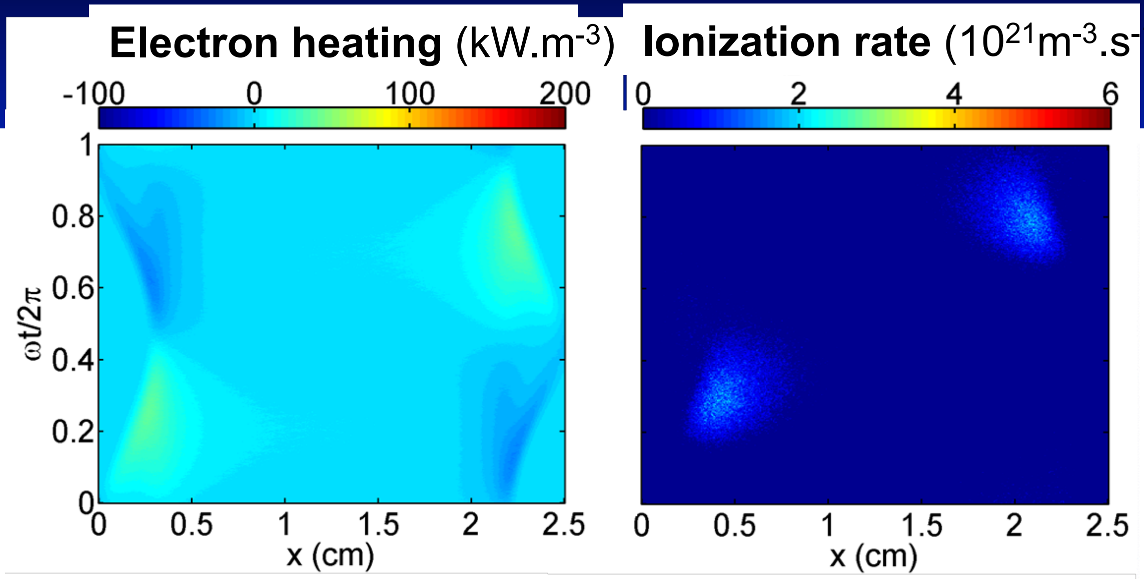

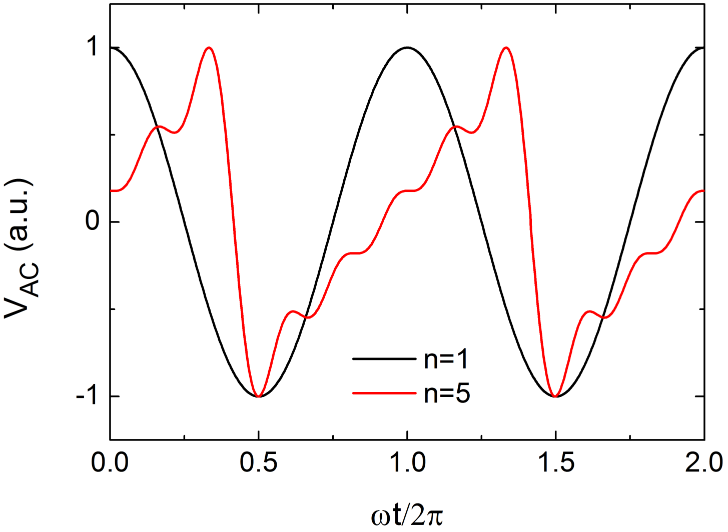

Asymetric electron heating and ionization

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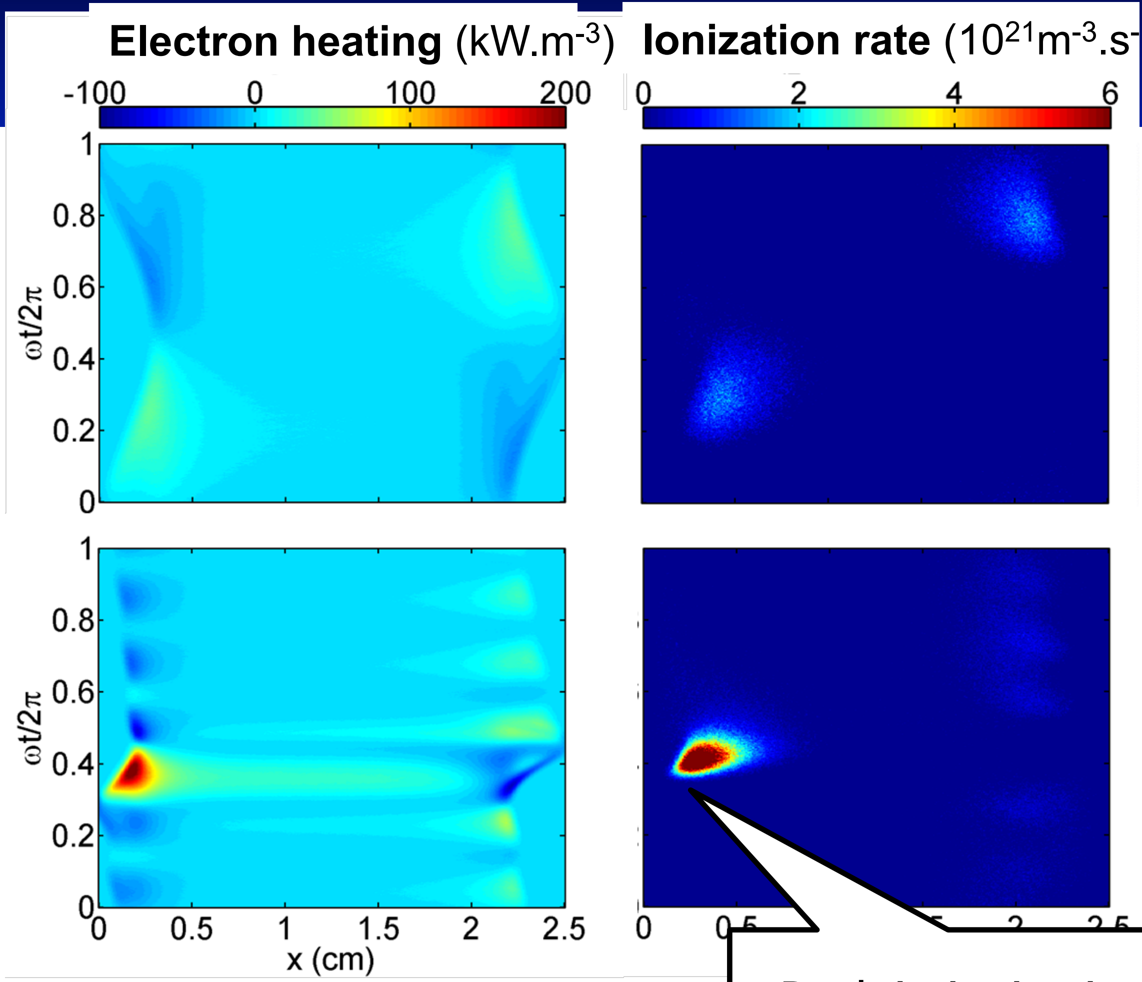
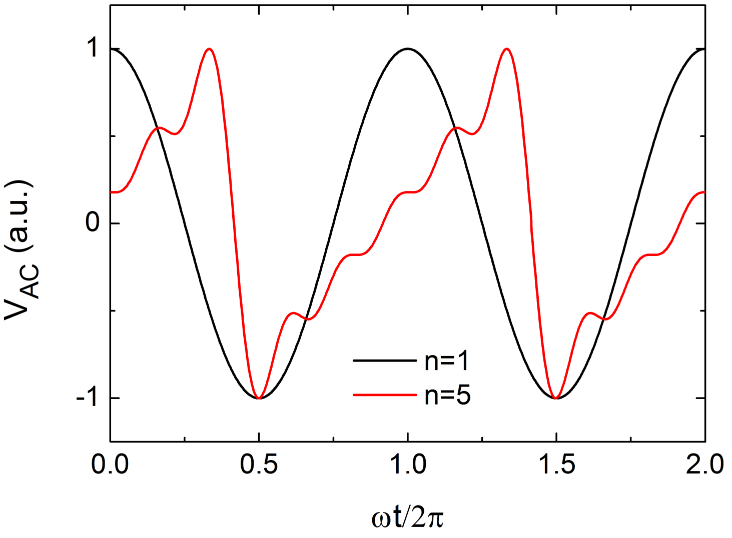
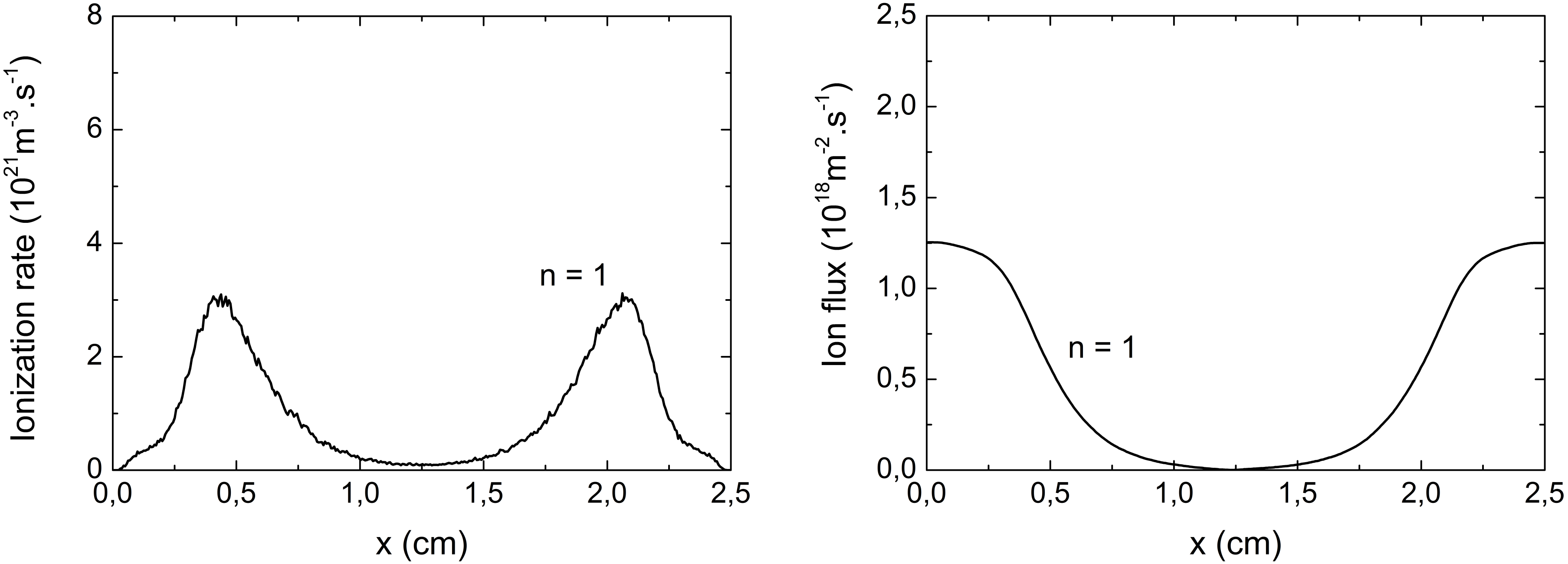




Peak in ionisation at fast expanding sheath only

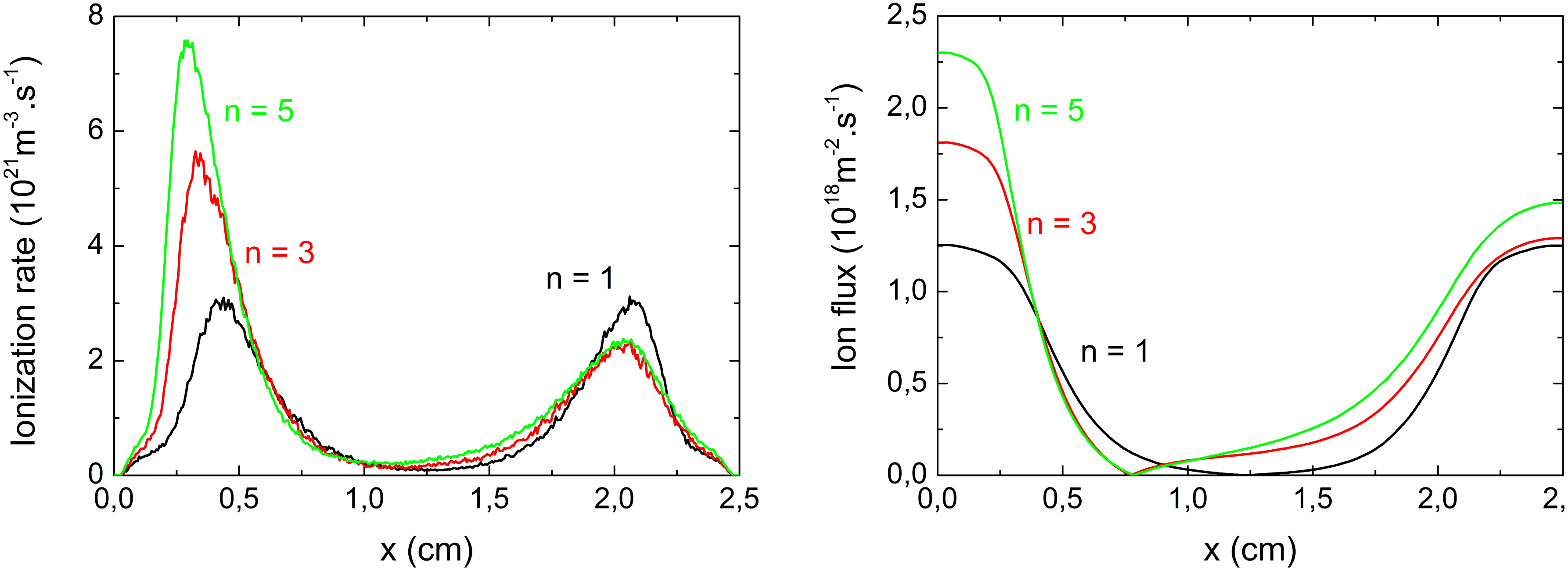
Bastien Bruneau –
12/11/2014

Ionization rate asymmetry = ion flux asymmetry



P=400 mTorr, V_{PP}=200 V, n=1-5

Ionization rate asymmetry = ion flux asymmetry



The asymmetry in the ionization rate…

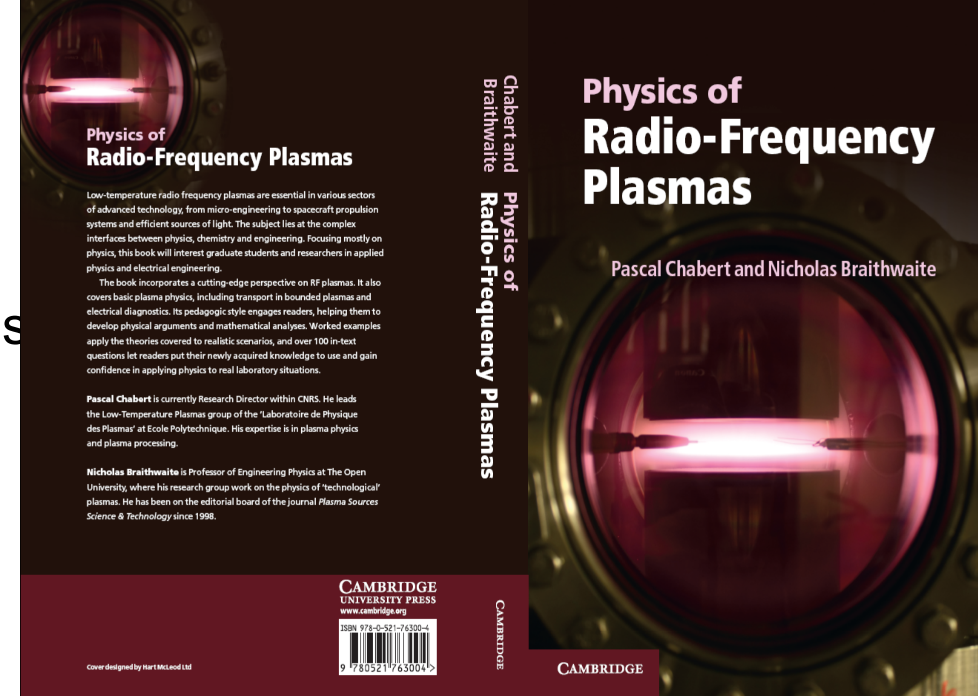
…is translated in an asymmetry of the ion flux

P=400 mTorr, V_{PP}=200 V, n=1-5

Bibliography

- Physics of Radiofrequency Plasmas

P. Chabert and N. Braithwaite,
Cambridge University Press, 2011



Physics of
Radio-Frequency Plasmas

Low-temperature radio frequency plasmas are essential in various sectors of advanced technology, from micro-engineering to spacecraft propulsion systems and efficient sources of light. The subject lies at the complex interfaces between physics, chemistry and engineering. Focusing mostly on physics, this book will interest graduate students and researchers in applied physics and electrical engineering.

The book incorporates a cutting-edge perspective on RF plasmas. It also covers basic plasma physics, including transport in bounded plasmas and electrical diagnostics. Its pedagogic style engages readers, helping them to develop physical arguments and mathematical analyses. Worked examples apply the theories covered to realistic scenarios, and over 100 in-text questions let readers put their newly acquired knowledge to use and gain confidence in applying physics to real laboratory situations.

Pascal Chabert is currently Research Director within CNRS. He leads the Low-Temperature Plasmas group of the 'Laboratoire de Physique des Plasmas' at Ecole Polytechnique. His expertise is in plasma physics and plasma processing.

Nicholas Braithwaite is Professor of Engineering Physics at The Open University, where his research group work on the physics of 'technological' plasmas. He has been on the editorial board of the journal *Plasma Sources Science & Technology* since 1998.

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Pascal Chabert and Nicholas Braithwaite

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M.A.Lieberman and A.J.Lichtenberg, 2nd Edition, John Wiley and Sons Inc.,

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