Ion Energy Distributions in Pulsed Plasmas with Synchronous DC Bias: Effect of Noble Gas

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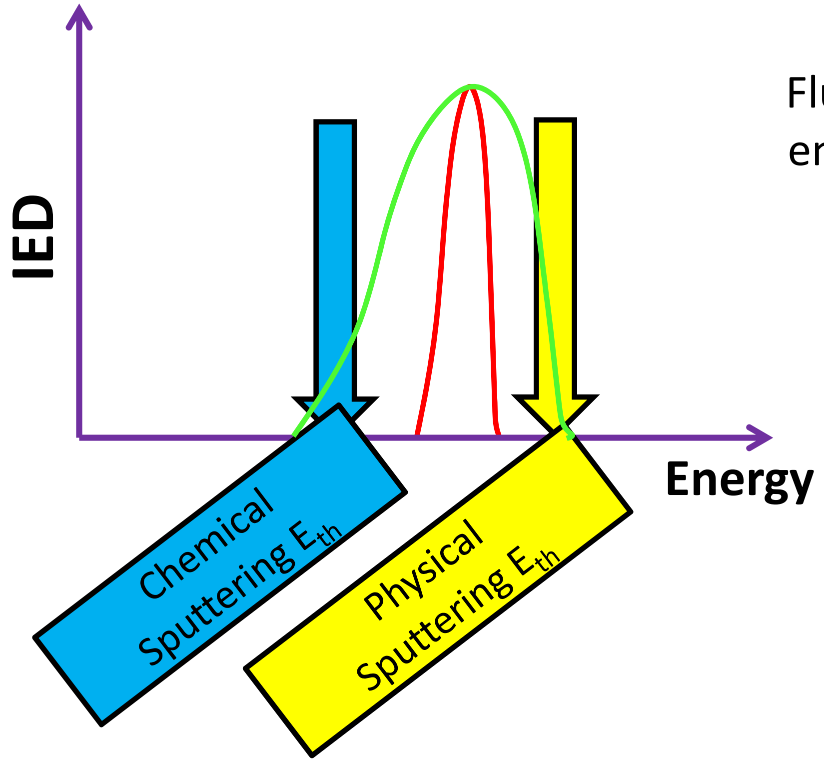
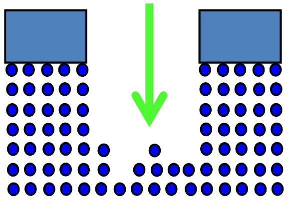
Outline

- Motivation
- Experimental Apparatus
- Results and Discussion
  - Ion energy distribution (IED) control
  - Effect of noble gas (Ar, Kr, Xe)
- Summary and Conclusions

Motivation: control of IED

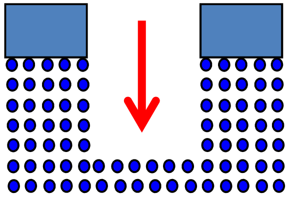


Flux with broad ion energy distribution



- ➢ Wide range of ion energies results in surface roughness and damage
  - $E_i<E_{chemical\ sputtering}$
  - $E_i> E_{physical\ sputtering}$

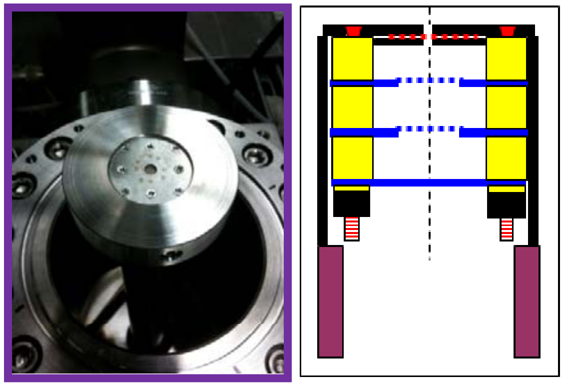
Monoenergetic ion flux



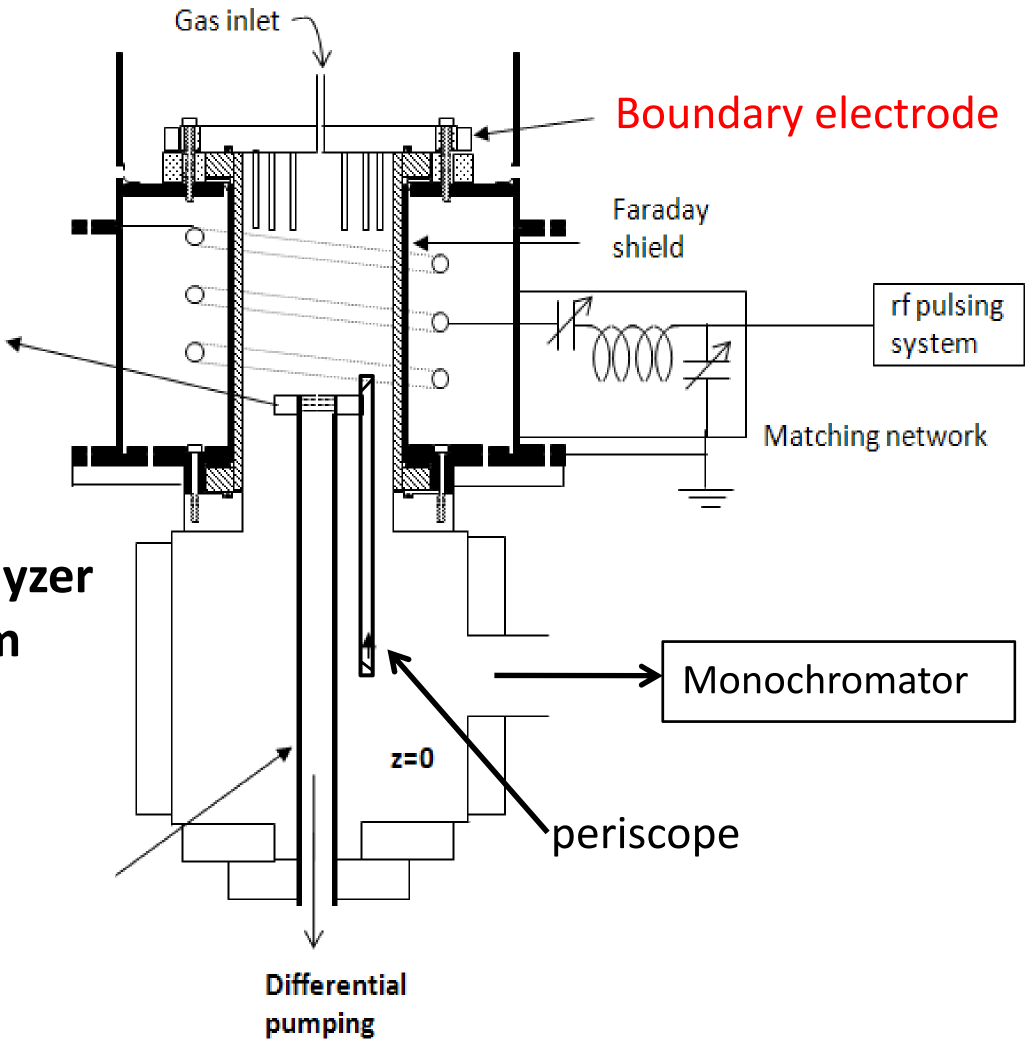
- ➢ Nearly monoenergetic ion bombardment results in higher level of control
  - ❖Low surface damage
  - ❖Accurate thickness control
  - ❖High selectivity

- **Control of IED:**
  - **Accurate control of ion energy peak position**
  - **Narrow width of ion energy distribution**

Experimental apparatus



Ion energy analyzer at Z= 170mm



Boundary electrode

Monochromator

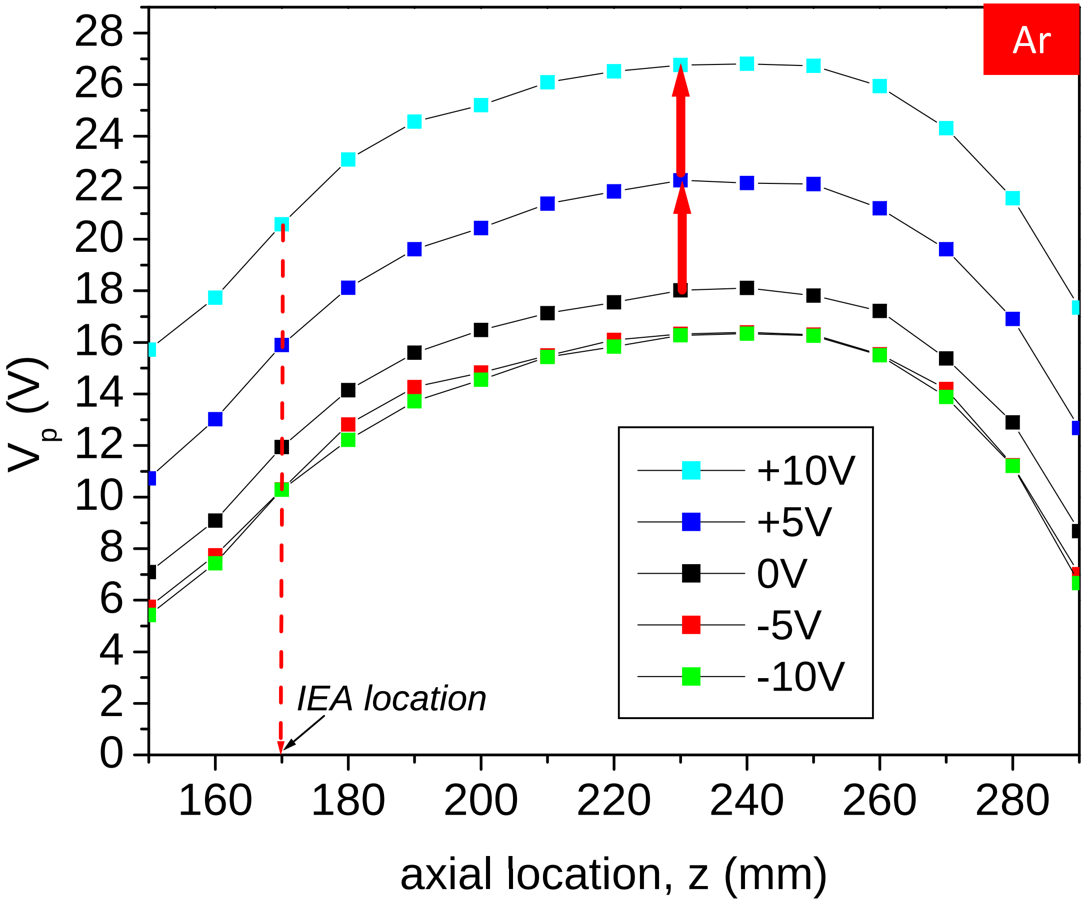
periscope

- ☐ **Differentially pumped ion energy analyzer (IEA)**
- ☐ **Movable Langmuir probe (LP)**

Ion energy can be manipulated by applying DC bias to *Boundary Electrode*.

Control of V_p using DC boundary voltage

- ❑ Continuous DC bias on the boundary electrode in cw plasma

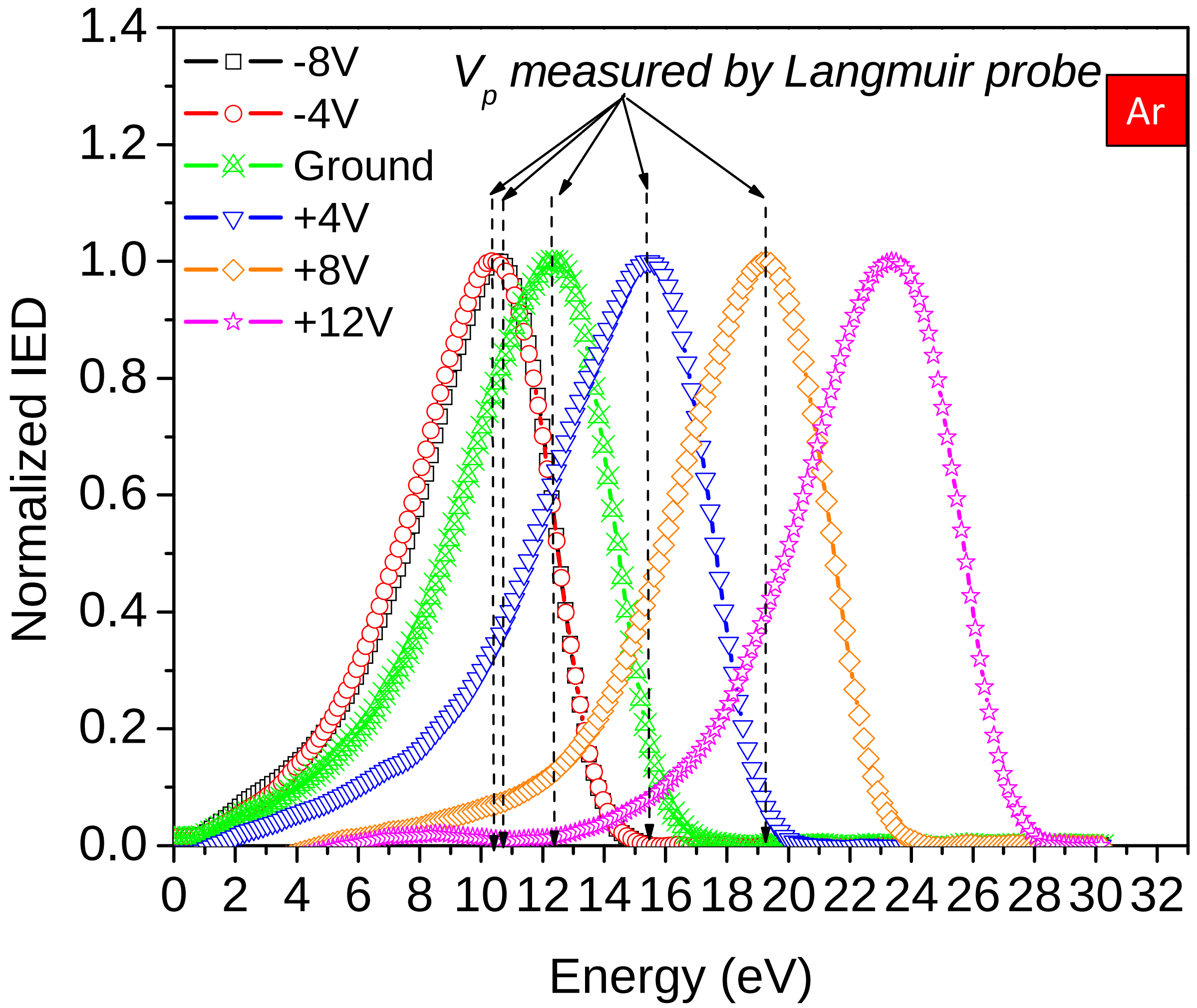


❑The DC bias on the boundary electrode is superimposed to the plasma potential.

❑With positive DC bias, V_p is shifted by corresponding boundary bias voltage.

❑Negative DC bias barely changed V_p since ion flux to the wall is limited.

IEDs in CW plasma with *continuous* DC boundary voltage



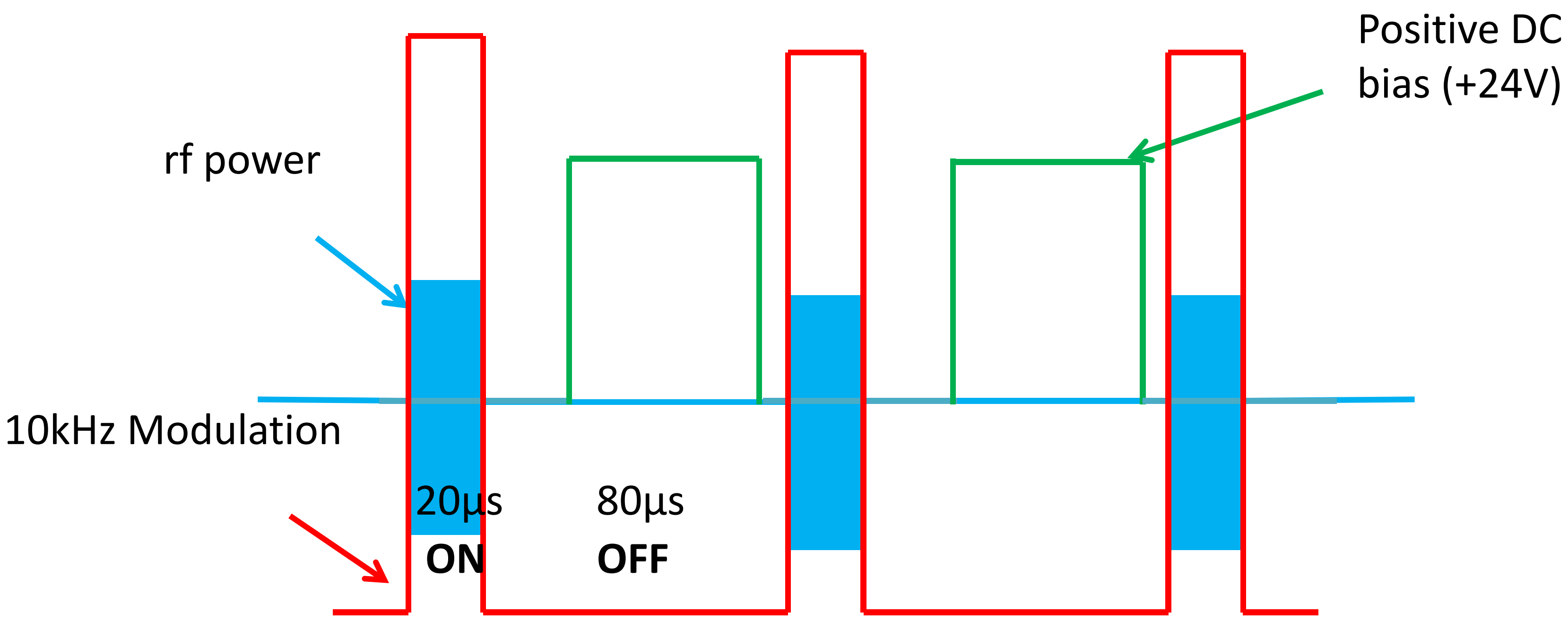
- ❑ **Ion energy peaks indicate plasma potential because the IEA entrance is ground (V_p=V_{sh}).**

- ❑ **V_p is in excellent agreement with Langmuir probe measurement at the same location.**

- ❑ **Positive DC bias on boundary electrode shifts plasma potential**

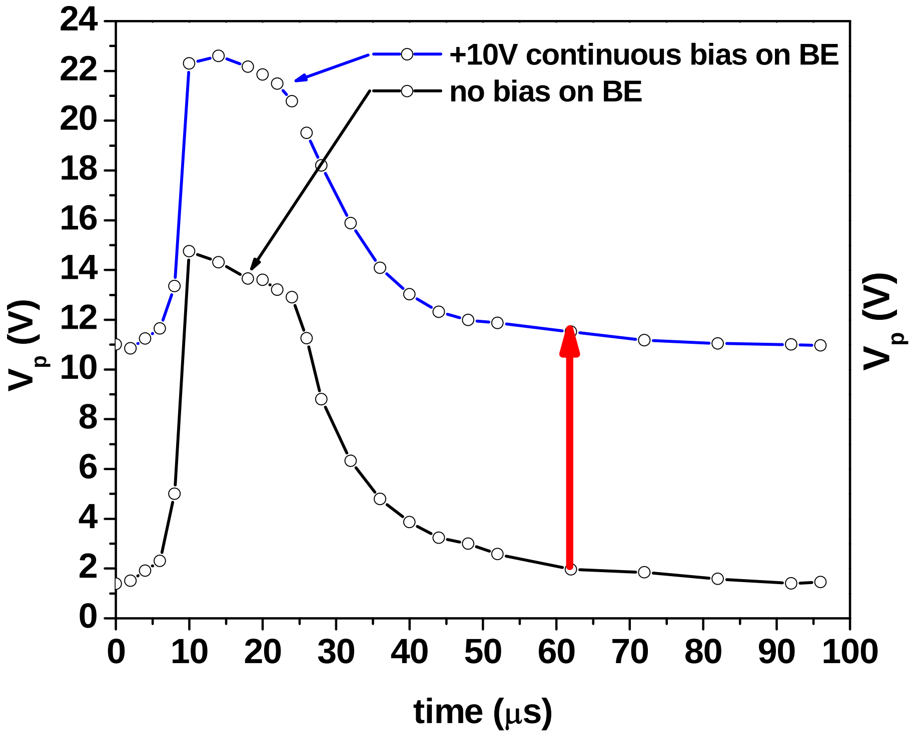
- ❑ **IEDs from continuous wave plasma are broad**

Timing scheme for pulsed plasma with synchronous DC boundary voltage in afterglow

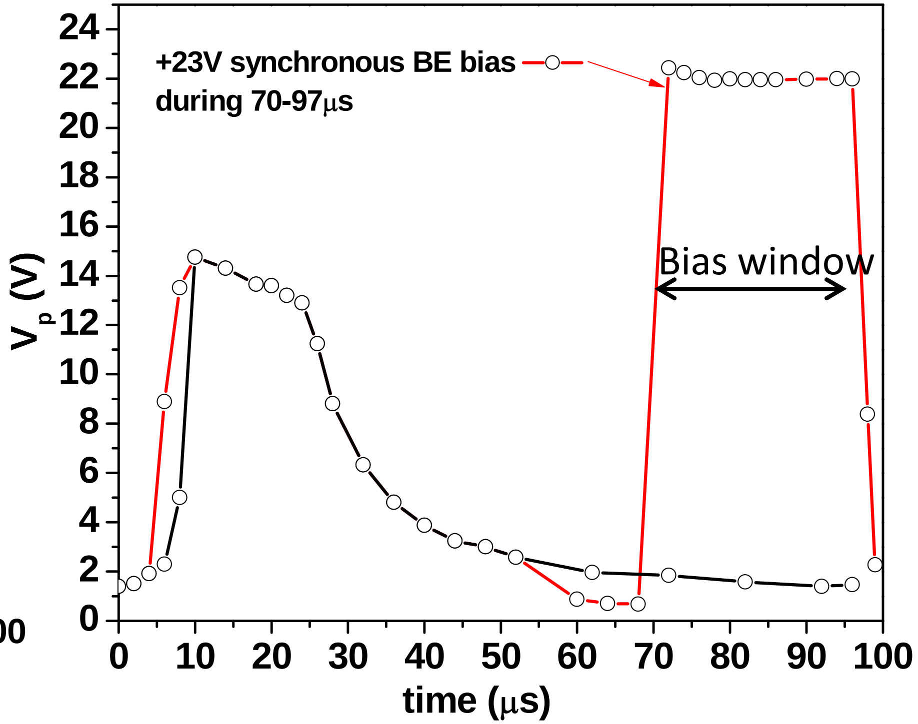


Control of V_p using DC boundary voltage

❑ Time-resolved LP measurements in pulsed plasma



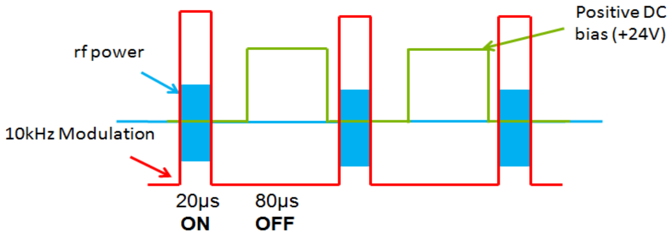
Continuous **bias**

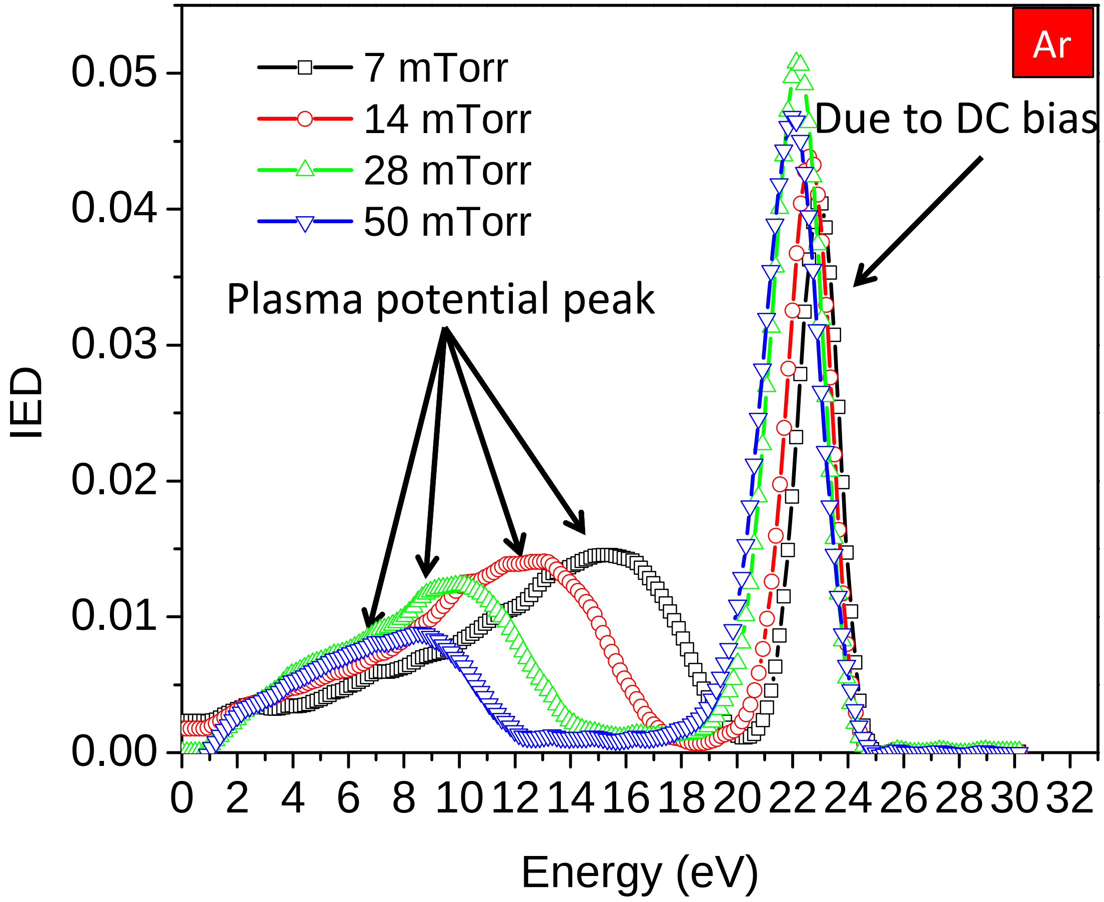


Synchronous **bias**

Synchronous DC bias on the boundary electrode can shift plasma potential only during biasing window

IEDs of pulsed plasma with synchronous DC boundary voltage

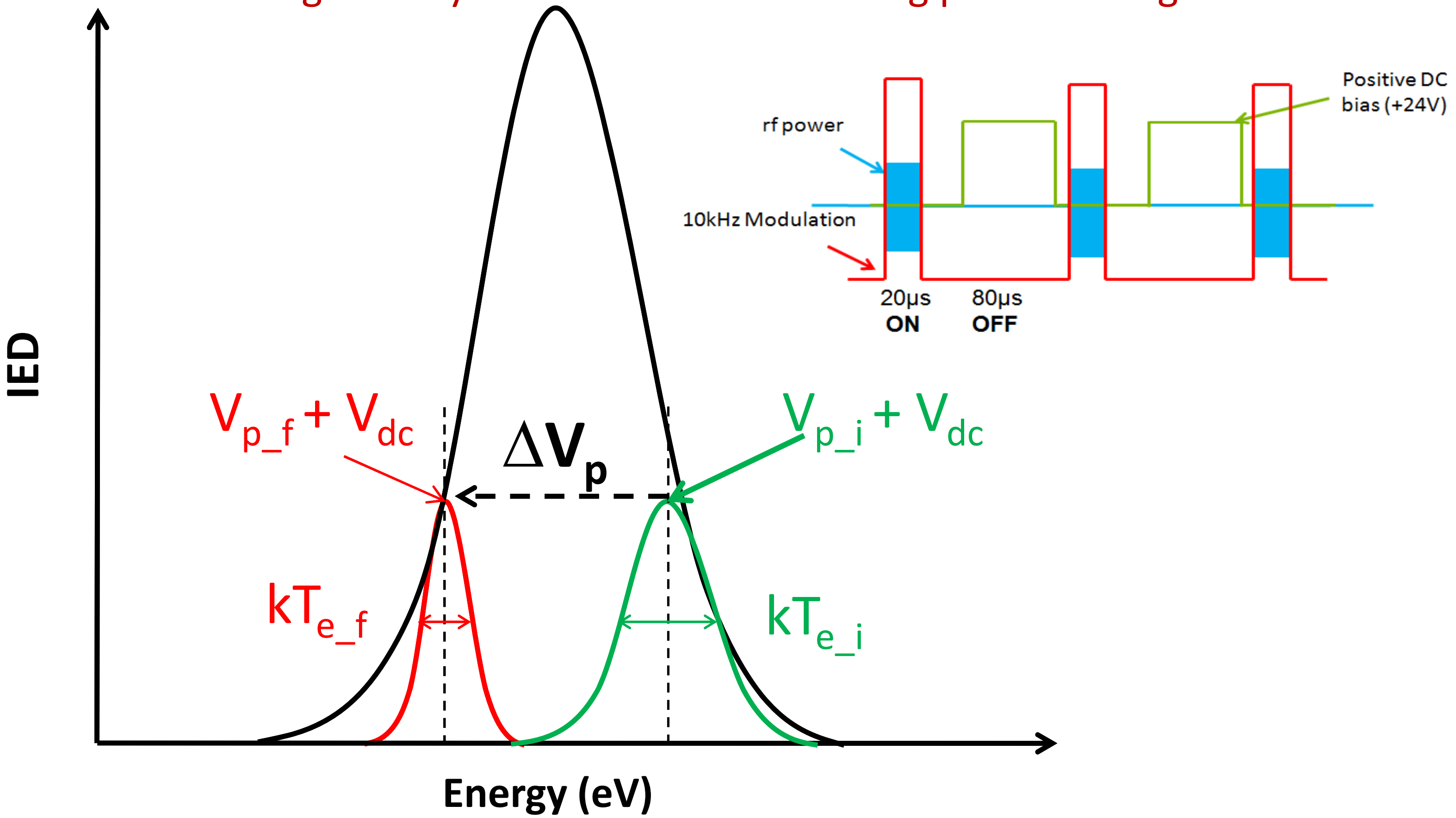




- **Low energy broad peaks are due to active glow; High energy sharp peaks are due to DC bias in the afterglow.**
- **Separation of the peaks can be tuned by DC bias value and pressure**
- **Narrow IED can be achieved in the afterglow.**
- **Full width at half maximum (FWHM) of the IED ranges from 1.7 to 2.4 eV and scales with T_e.**

Broadening of IED

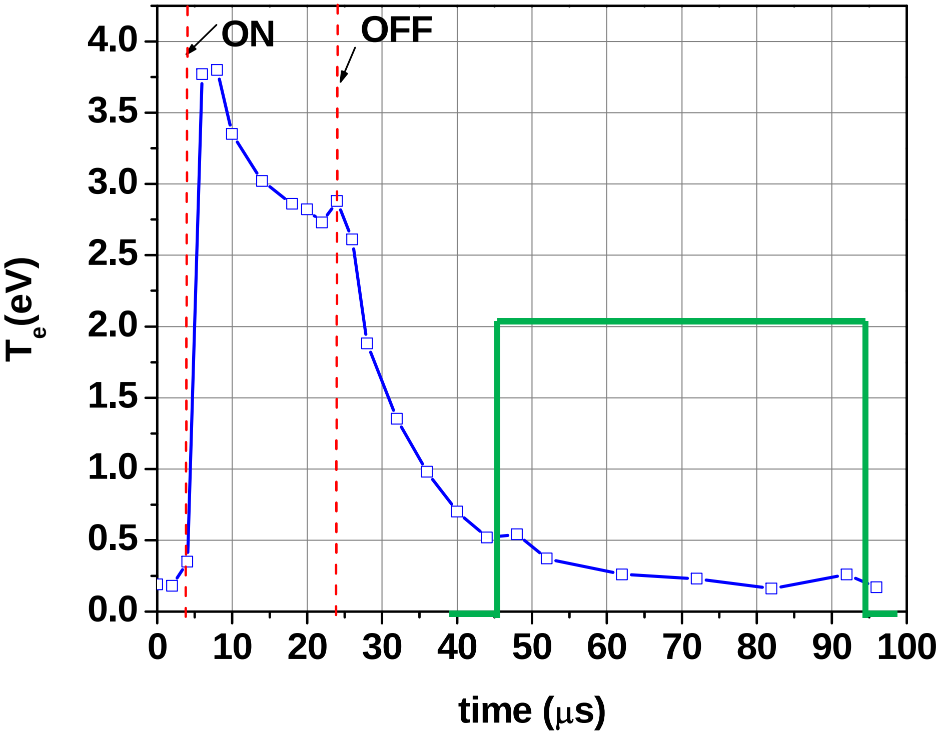
☐ Qualitative IEDs resulting from synchronous DC bias during part of afterglow.

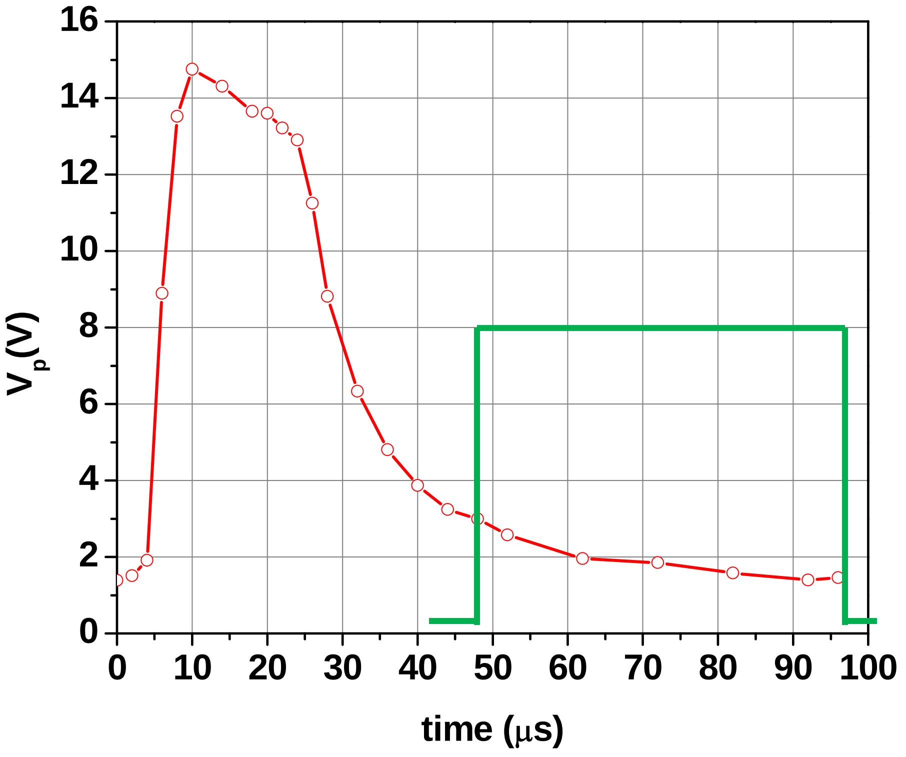


- **The IED shifts to lower energies and becomes sharper with time.**
- **The measured IED in the afterglow is a time-averaged distribution.**
- **Width of IED correlates with T_e and variation of V_p during bias window.**

T_e and V_p change during bias

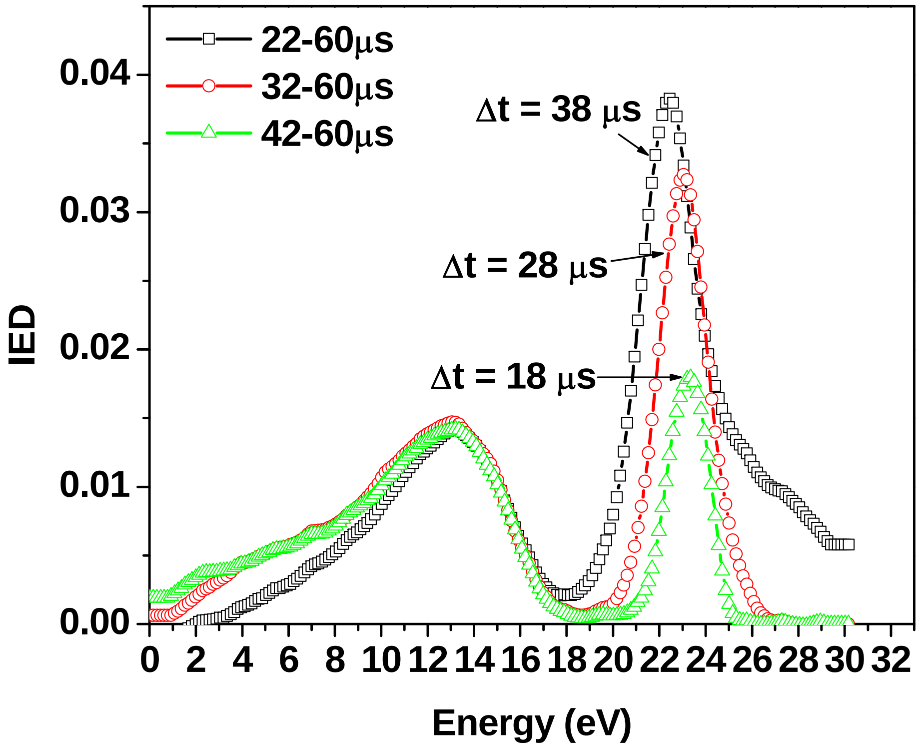
❑ **Time-resolved Langmuir probe measurements**

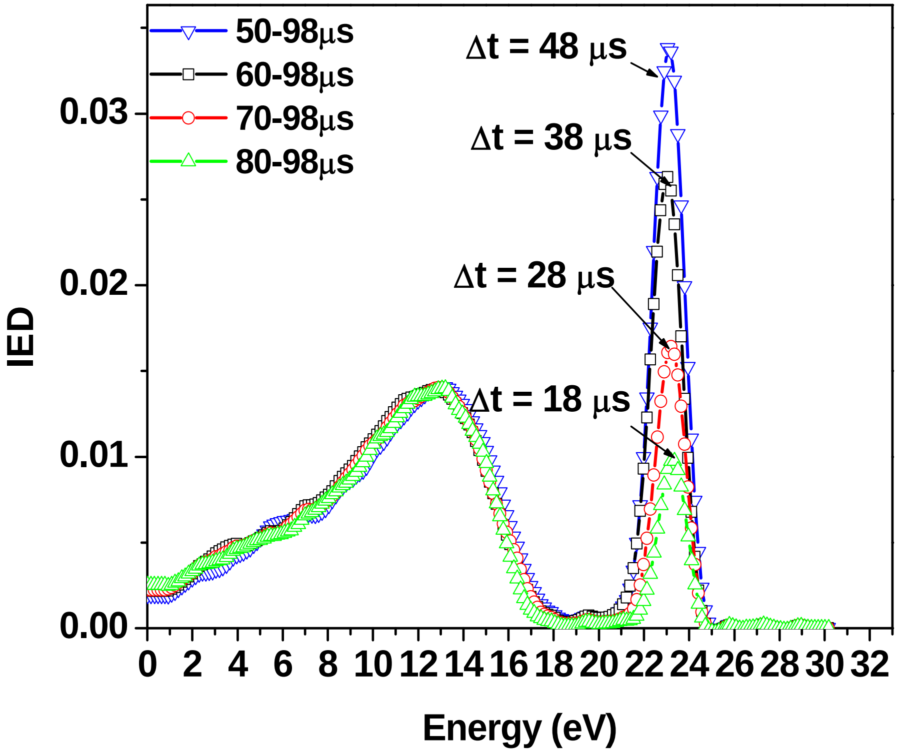




The smaller the electron temperature and the variation of plasma potential during the biasing window, the sharper the ion energy distribution.

Early vs. late afterglow bias





- **Early afterglow biasing (V_p changes considerably and T_e is high) vs. late afterglow biasing (V_p and T_e have decayed to low values).**
- **IED width is smaller with late afterglow biasing.**

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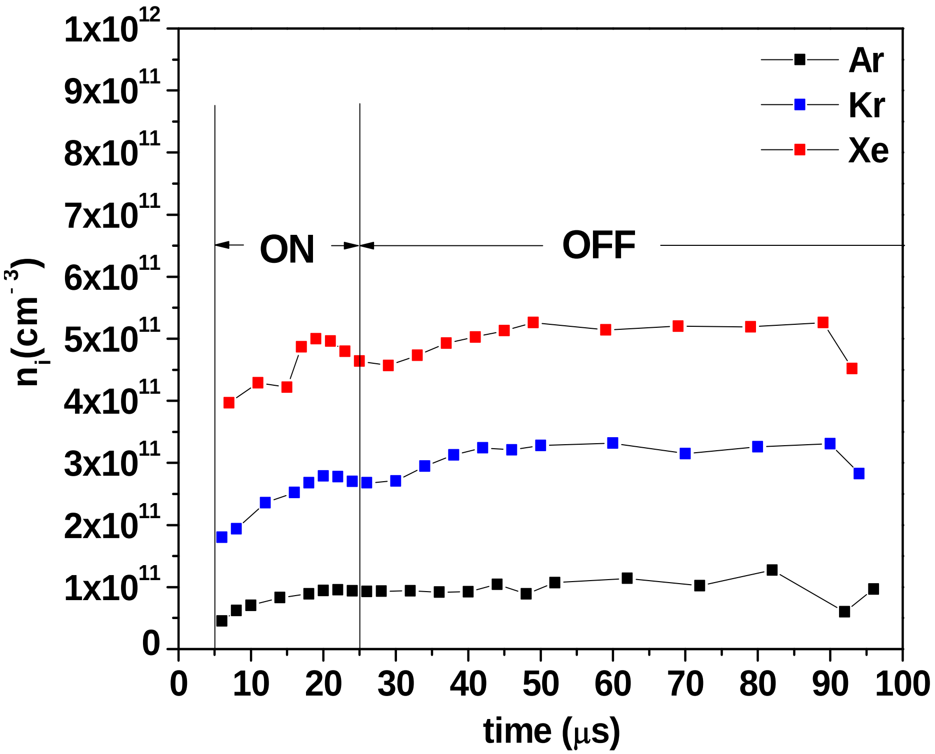
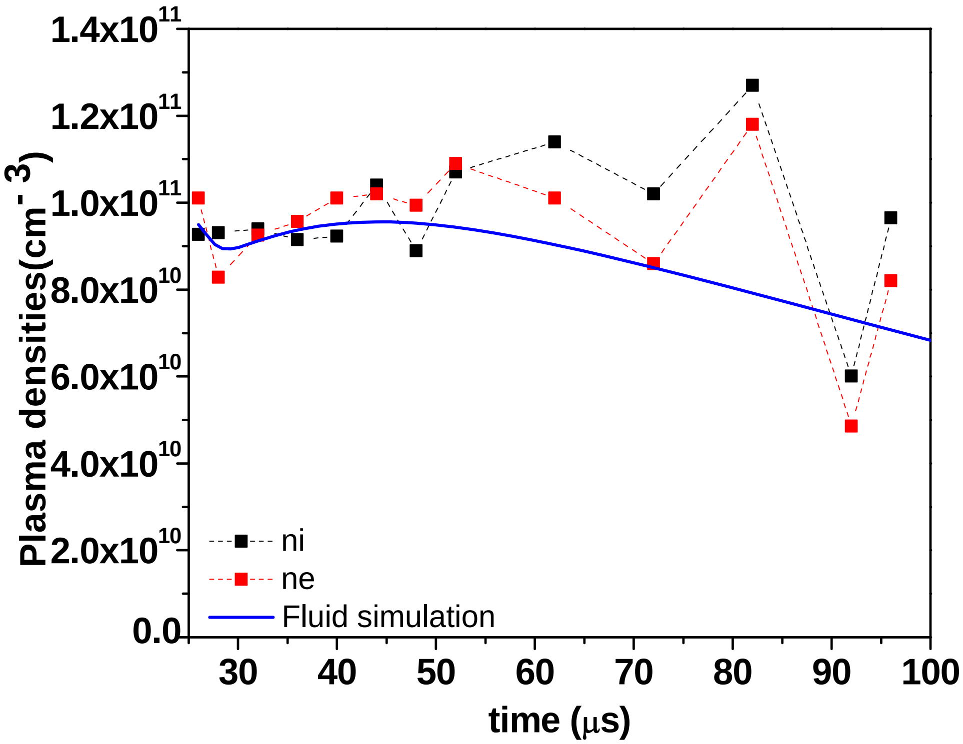
- Summary

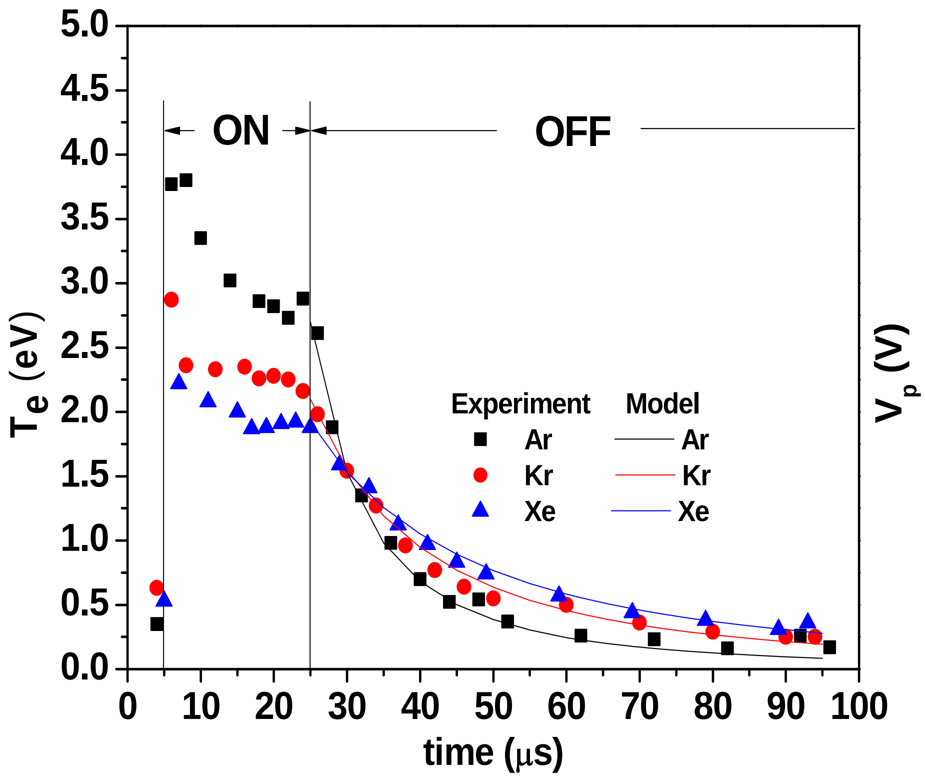
Temporal evolution of plasma density for different gases

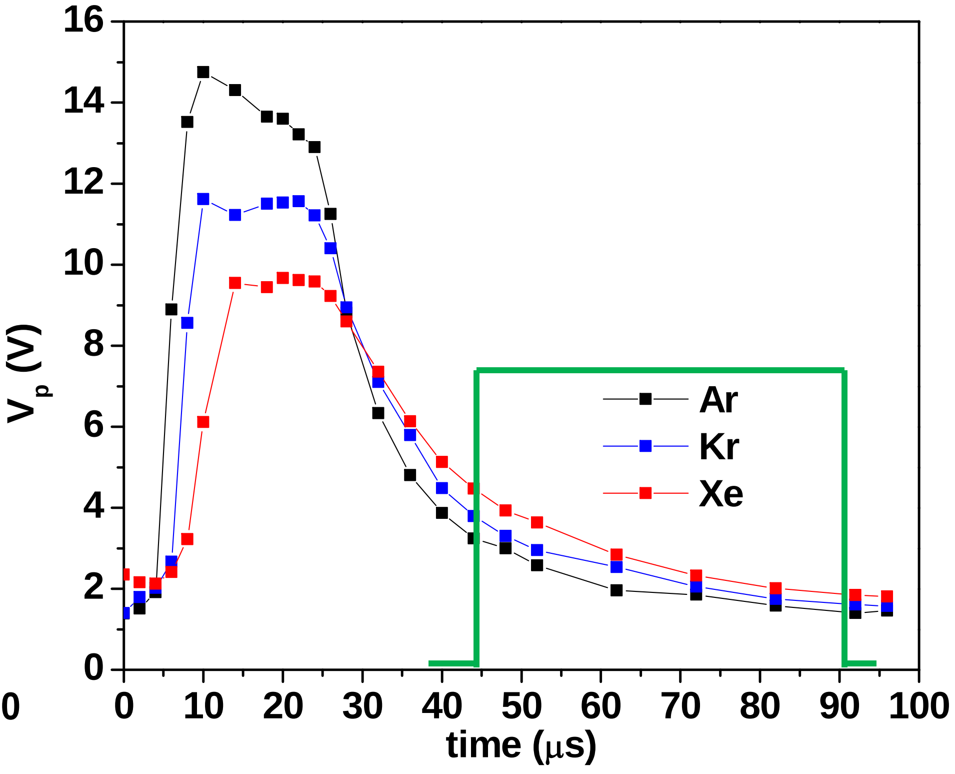




- At the edge of the plasma, the plasma density is nearly constant, even over a long afterglow duration of 80 µs.
- Transport of electrons from the higher density central region of the plasma to the edge region, is balancing the loss of plasma due to diffusion.
- Maintaining a nearly constant ion (and electron) density during the afterglow may be useful in processes employing pulsed plasmas.

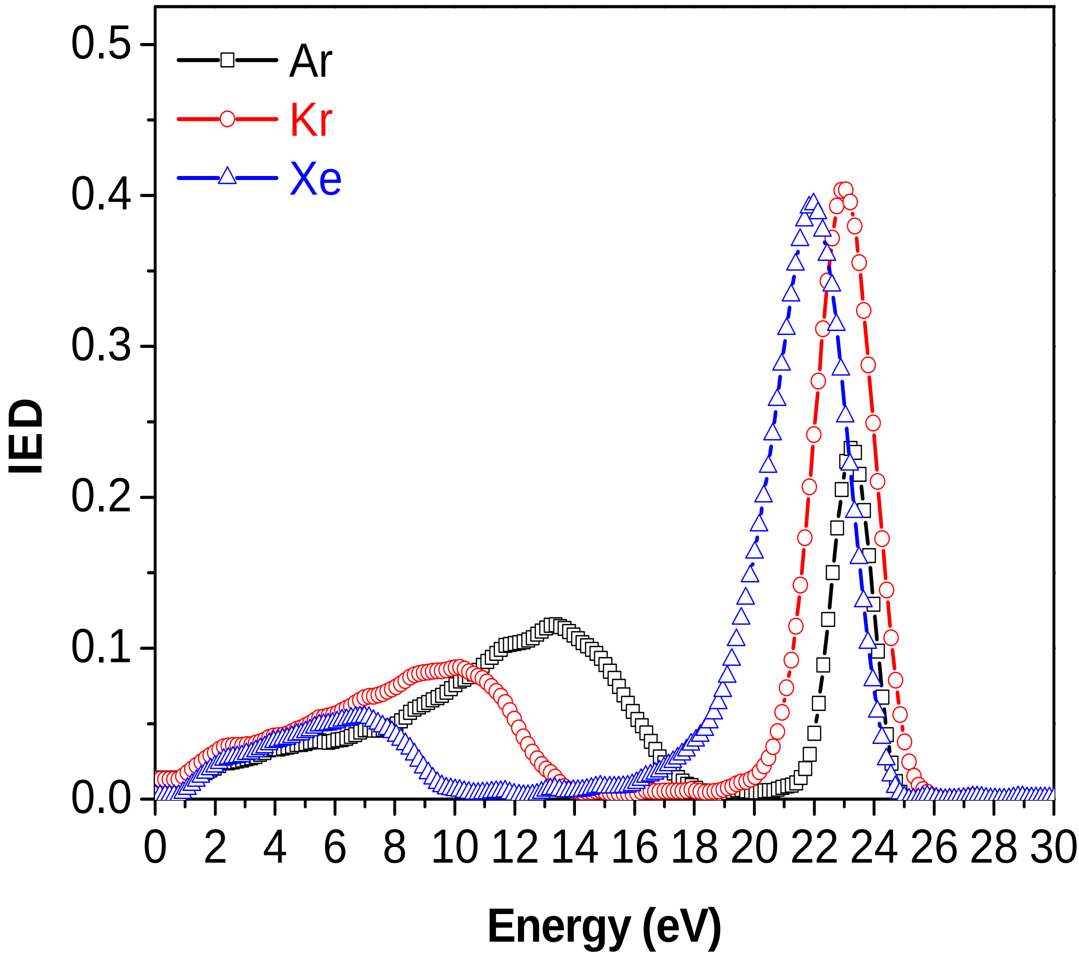
Temporal evolution of T_e and V_p for different noble gases





- T_e and ΔV_p are in the order of Ar < Kr < Xe
- T_e and V_p decay slower in Xe plasma (slower diffusion cooling).
- Experimental data of T_e are consistent with predictions from global model.

IEDs for different carrier gases



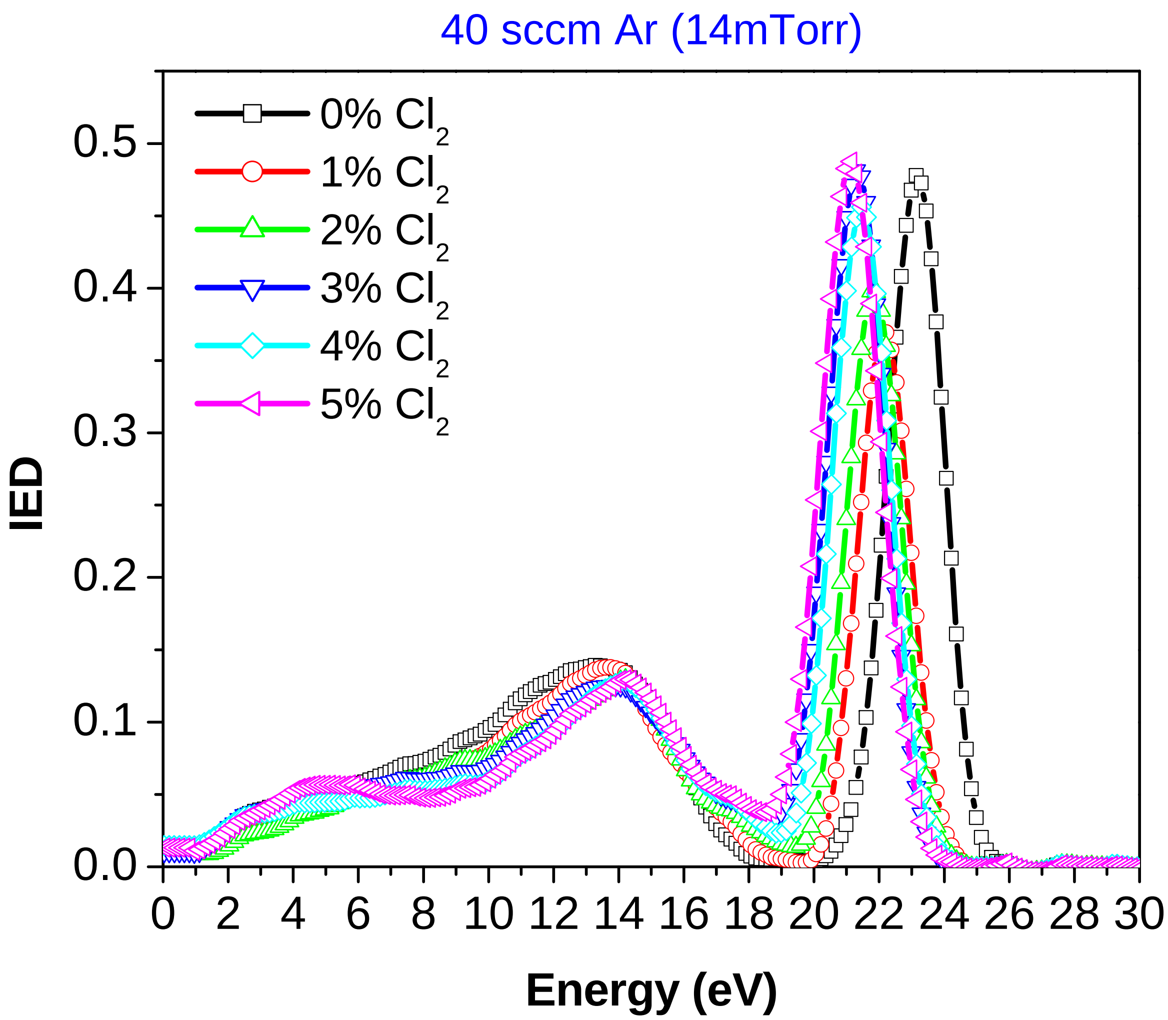
- ☐ **IED shows the same order of T_e and ΔV_p during bias window :**

  Ar < Kr < Xe

- ☐ **FWHM of the narrow peak is 1.6, 2.4, and 3.0 eV for Ar, Kr and Xe**

- ☐ **The area under the IED peak resulting from afterglow biasing is proportional to the ion flux**

IEDs for different Cl_2 additions



- ❑Similar IEDs were found with trace amount of Cl_2 addition (<5%)
- ❑Peak ion energy was lower by a few eV, possibly due to lower V_p and T_e from Cl_2 plasma.
- ❑Such control of IED can be applied to plasma etching with high precision.

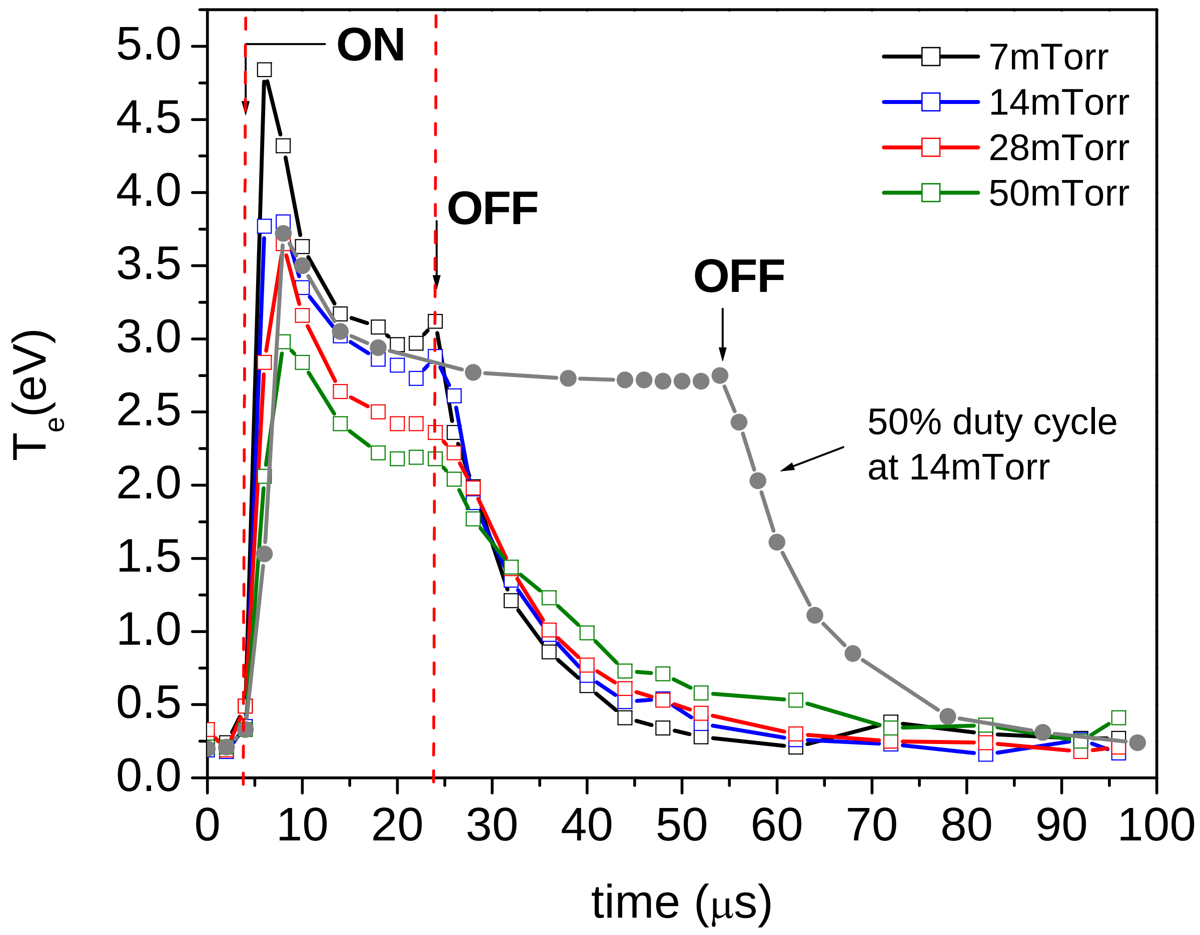
Summary and Conclusions

1. Nearly monoenergetic IEDs can be achieved using synchronous DC bias in the afterglow of a pulsed plasma.
2. The peak values and the FWHM of the IED can be controlled by varying DC bias and the time window it is applied, operating pressure, and carrier gas.
3. FWHM depends on the electron temperature and plasma potential variation during the time of biasing.
4. Maintaining a nearly constant ion (and electron) density during the afterglow may be useful in processes employing pulsed plasmas.
5. By adding small amounts of chlorine to an argon plasma the IEDs are shifted to slightly smaller energies.

Questions?

Backup slides

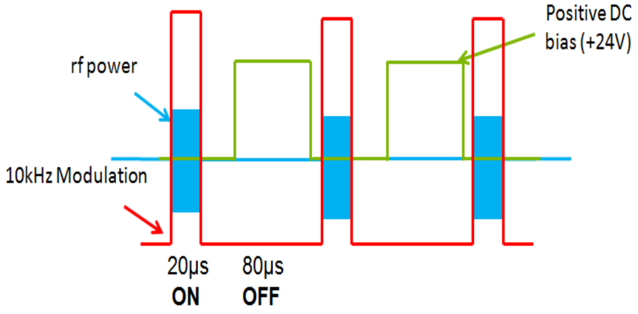
Time-resolved T_e in pulsed plasma



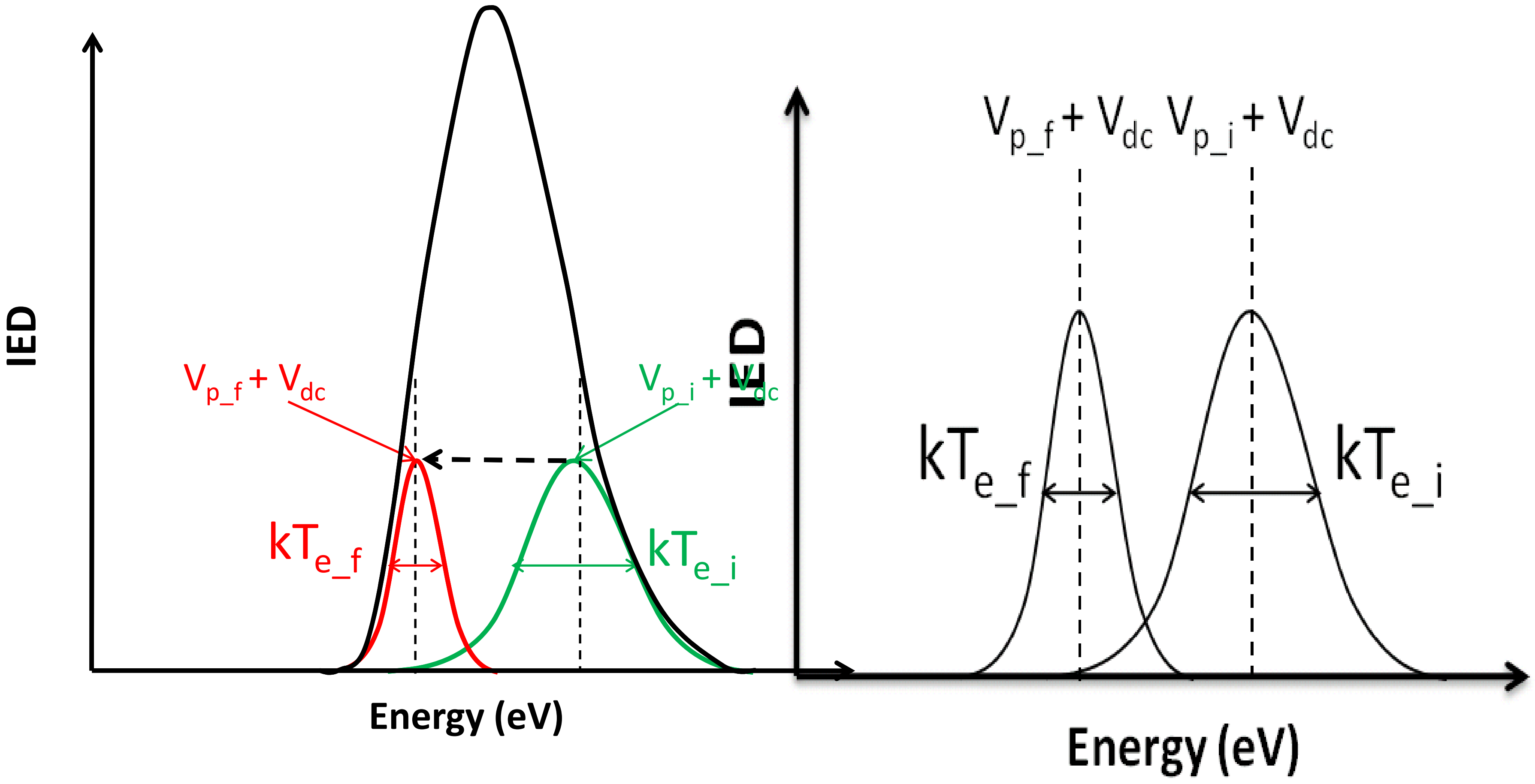
❑ **At higher pressure, T_e is lower during active glow, but higher during afterglow.**

❑ **T_e decays to low values in 15 – 20 ms after plasma is turned off.**

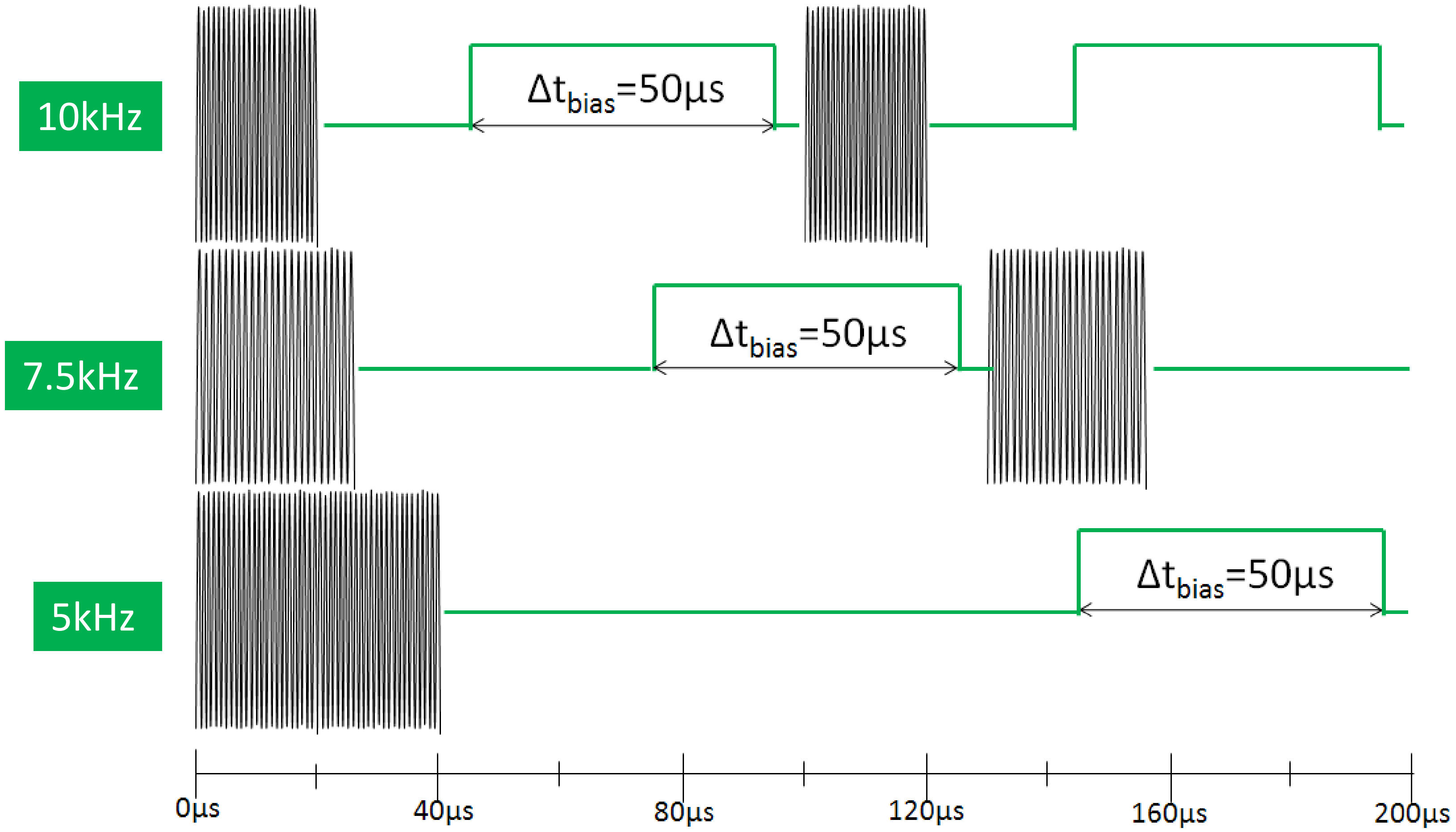
❑ **Duty cycle has no effect on the T_e decay.**



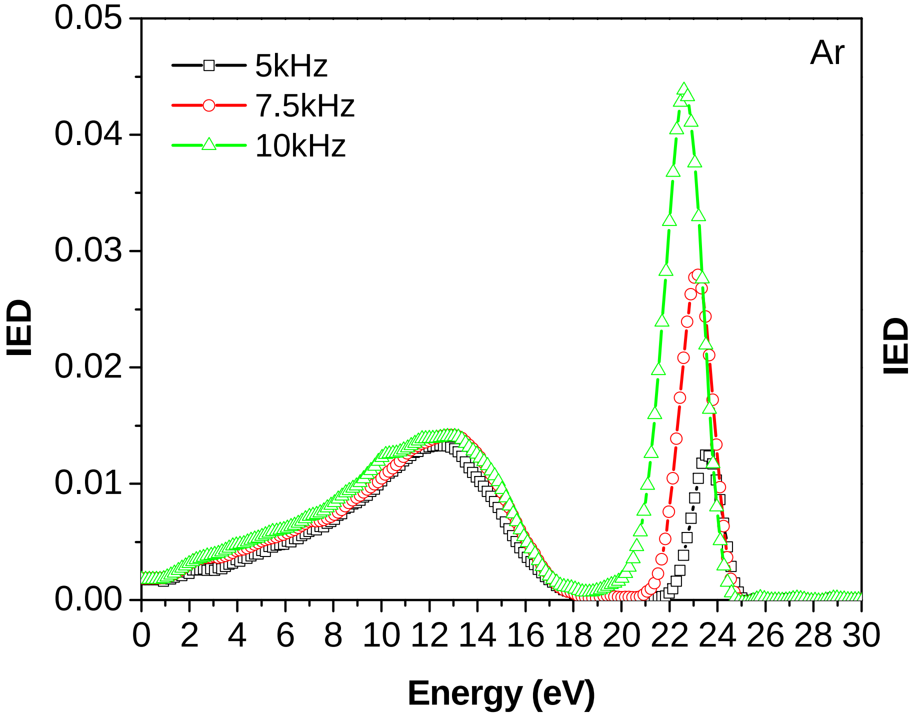
V_p variation during bias window

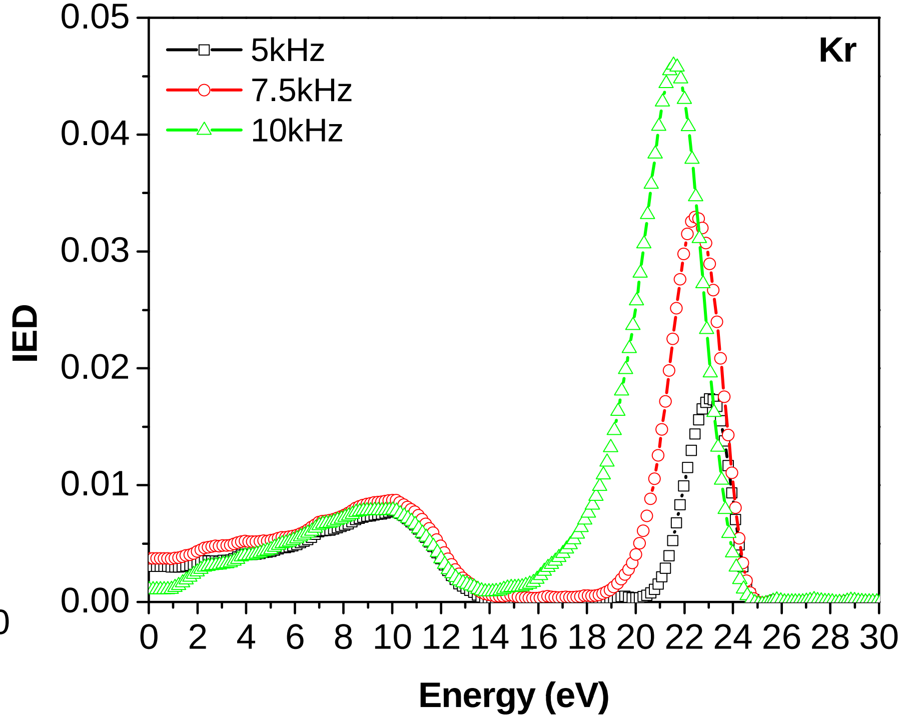


Time scheme for different mod. frequency



IED with different mod. frequency

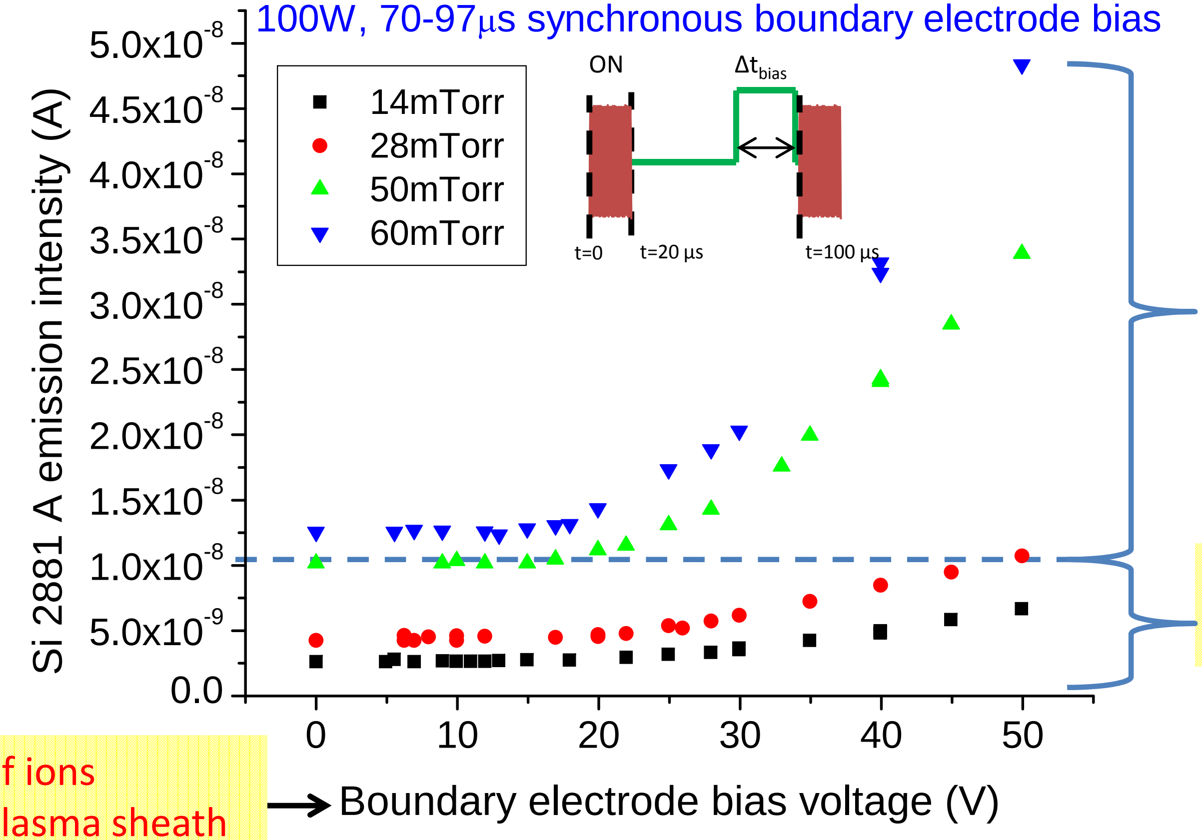




❑Decreasing area of high energy peaks is due to lower T_e and ion density
❑Overall, pulsed Ar plasma shows best FWHM in the afterglow

Etching process monitoring

20% pulsed 1% Cl_2, 5% TRG, 94% Ar plasma, 10kHz
100W, 70-97μs synchronous boundary electrode bias



Si removal by synchronous biasing in the afterglow.

Si removal during activeglow .

kinetic energy of ions accelerated in plasma sheath = boundary electrode bias voltage

❑Afterglow etching threshold was found ~16V

❑Activeglow p-type Si etching with sub-threshold ion energy

❑The sub-threshold etch rate is significant, compared to ion-assisted etching, for process such as atomic layer etching.