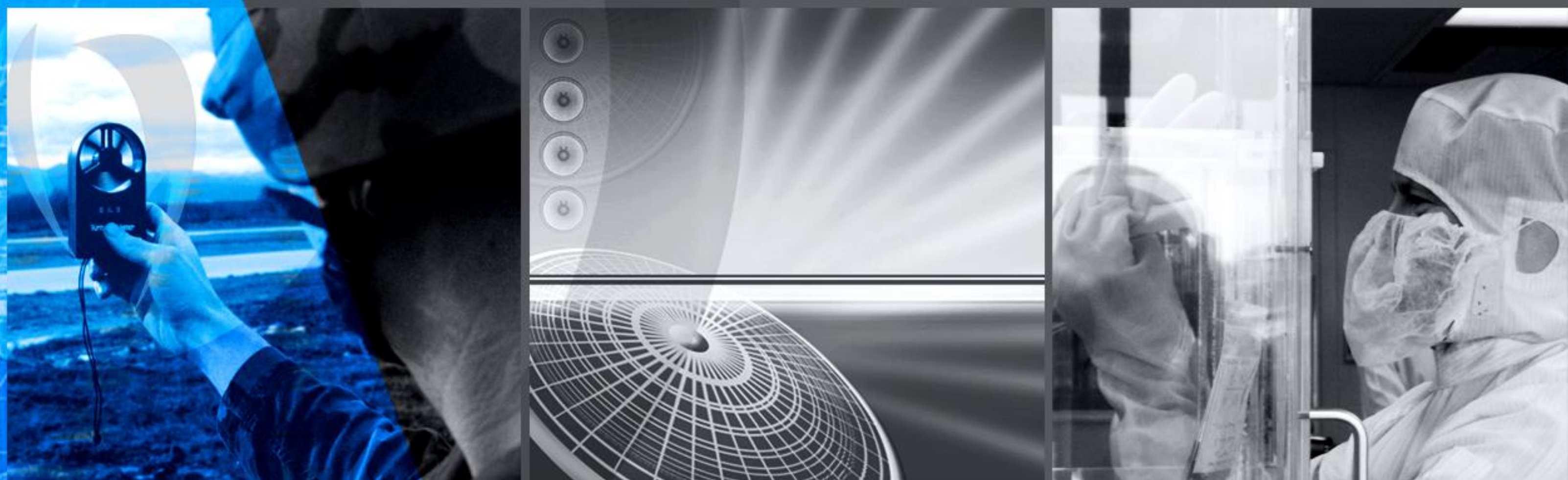
Optimizing Ion Separators for DMS/FAIMS at Ultra-High-Fields

Ashley Wilks, Danielle Toutoungi & Billy Boyle

OWLSTONE



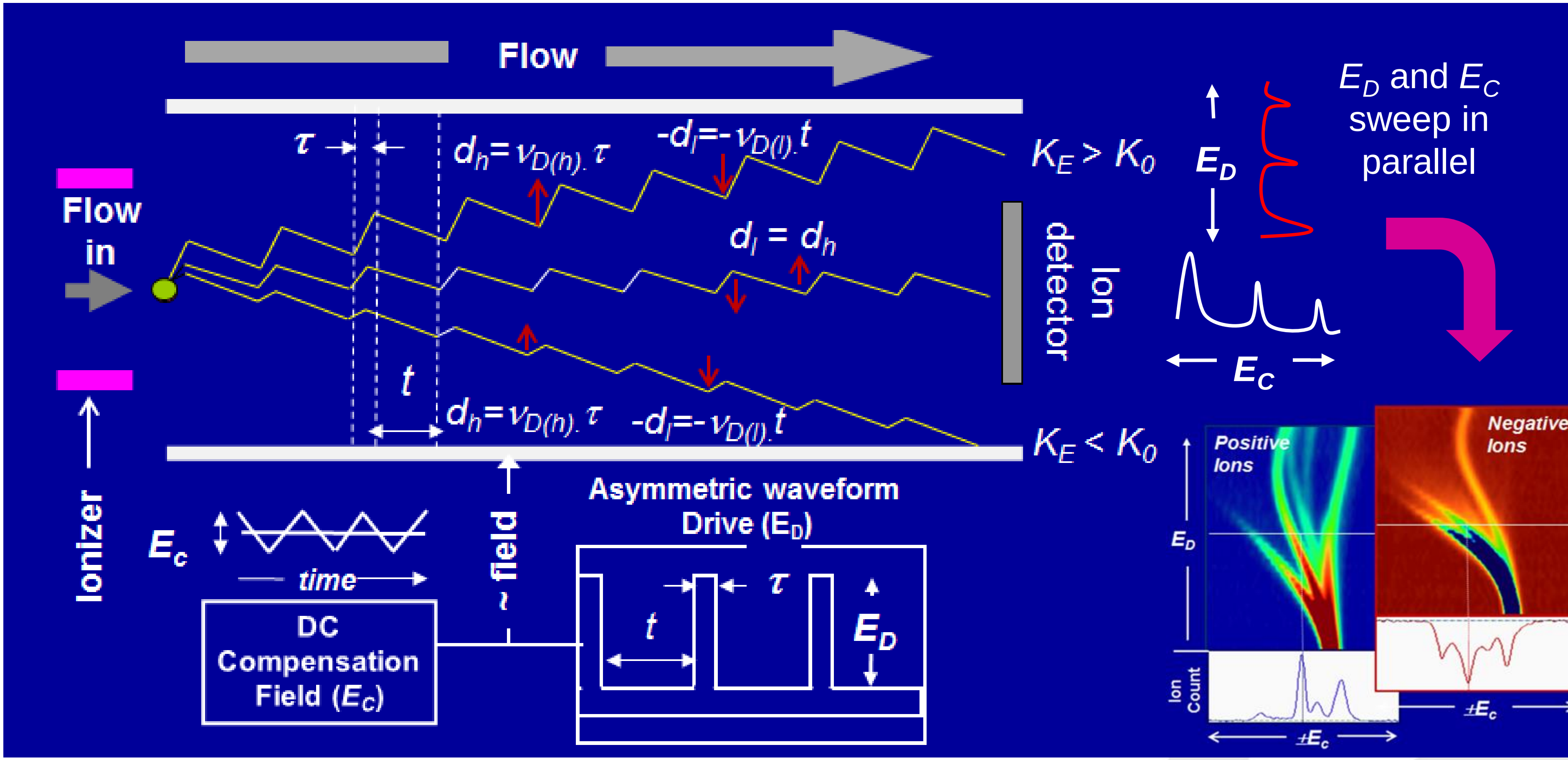
American Chemical Society

Fall Meeting – Analytical Division

Conventional and Differential Ion Mobility Spectrometry - AM Session

Philadelphia, PA. August 20 2012

DMS / FAIMS 101



$$\upsilon_{D(h)} = K_E \mathrm{E}(\tau)$$

$$\upsilon_{D(l)} = K_0 \mathrm{E}(t)$$

$$\frac{K_E}{K_0} = 1 + a_1 {E_D}^2 + a_2 {E_D}^4 + \cdots + a_n {E_D}^{2n}$$

$a_1, a_2 \dots . a_n$ are separtion coefficents

Why Ultra-High Field Operation?

Increase analytical space

$$R = \frac{E_C}{w_{1/2}} = \frac{E_C K_0 N_0}{4N}\left(\frac{t_{res}}{D_{II}\ln 2}\right)^{1/2}$$

Shvartsburg 2009

$$\frac{E_C}{N} = -\sum_{n=1}^{\infty} \kappa_n \left(\frac{E_D}{N}\right)^{2n+1}$$

κ relates property of waveform moments $\langle f_n \rangle$ and alpha coefficents a_n

$$\kappa_1 = -a_1\langle f_3\rangle \qquad \kappa_2 = (a_2\langle f_5\rangle) - (3\kappa_1\alpha_1\langle f_2\rangle) \qquad \ldots.\kappa_n$$

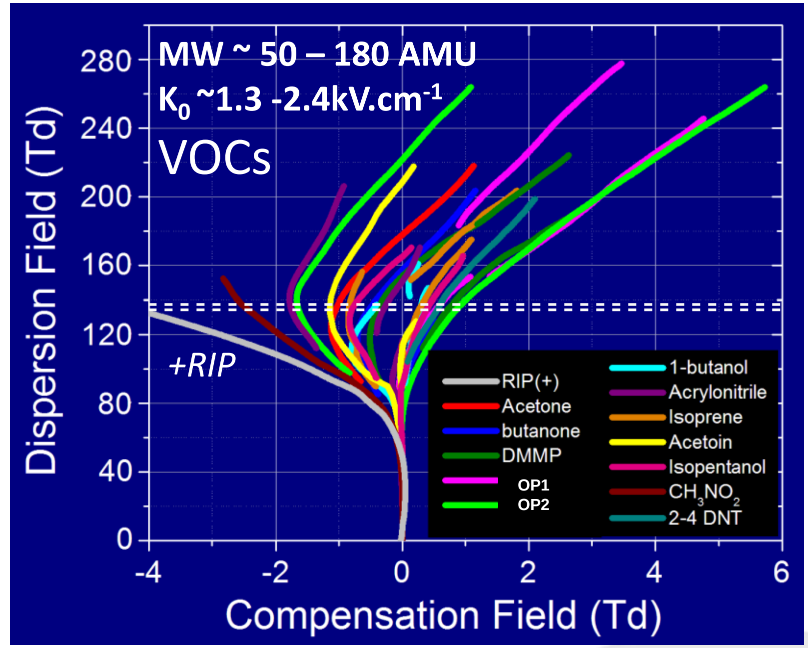
Truncating to only n = 1 and n =2 terms (a_1 & a_2)….

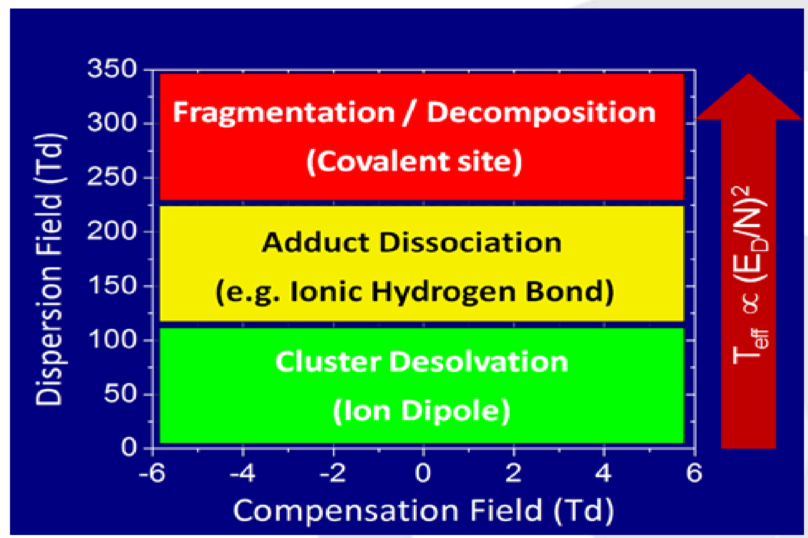
$$E_C \propto E_D{}^2$$

Take advantage of high effective ion temperature (T_{eff}) …

$$T_{eff} = T + \zeta.M.K_0{}^2.N_0{}^2(E_D/N)^2/(3k_b)$$

$$T_{eff} \propto E_D{}^2$$





Challenges of Ultra-High-Field Operation

- Fabrication of High V asymmetric waveform drivers in a small form factor is challenging
- To relax the demand on the electronic drivers we want to narrow the gap size (*g*) (*so higher fields may be generated with lower drive voltages)*

  → at **35 µm**, V = **270V** yields $E_D \approx$ 80kV.cm^{-1} (320Td at 1atm)

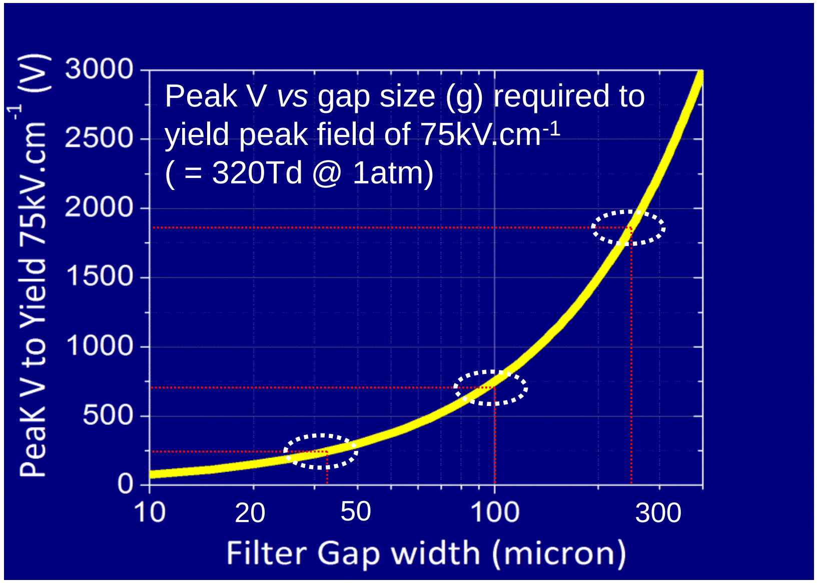
  → at **250 µm** V ≈ **2000V** is required

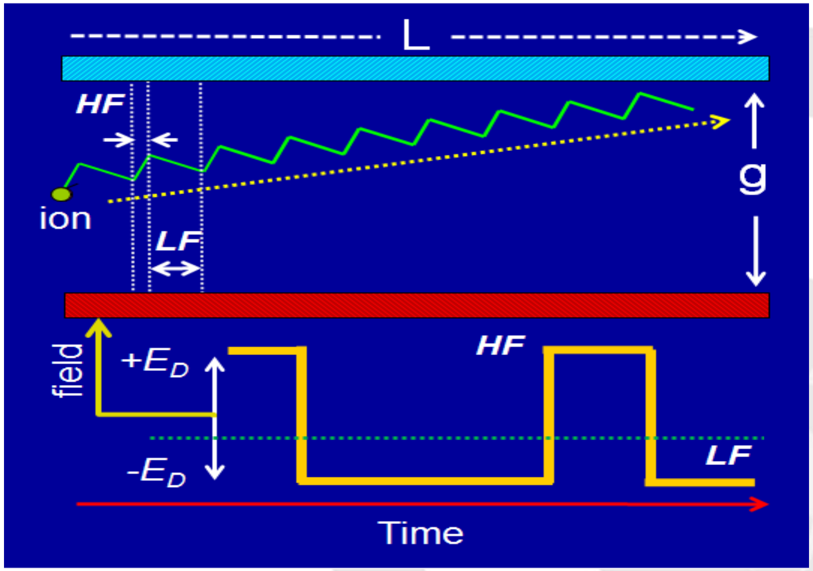
- **However –**

  → *A narrow gap requires high flow to support ion transmission (and sensitive detection)*

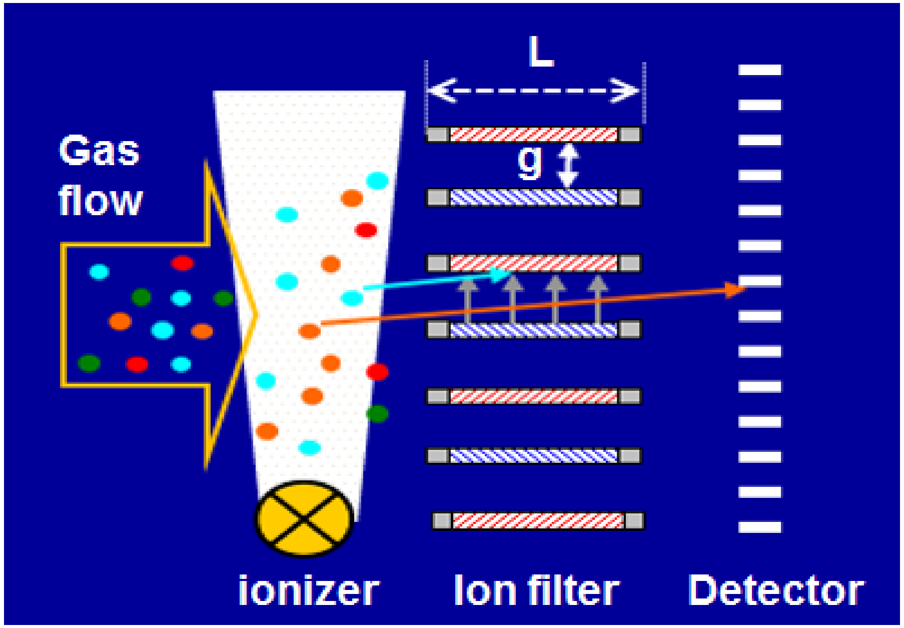
  → *But this leads to peak broadening*

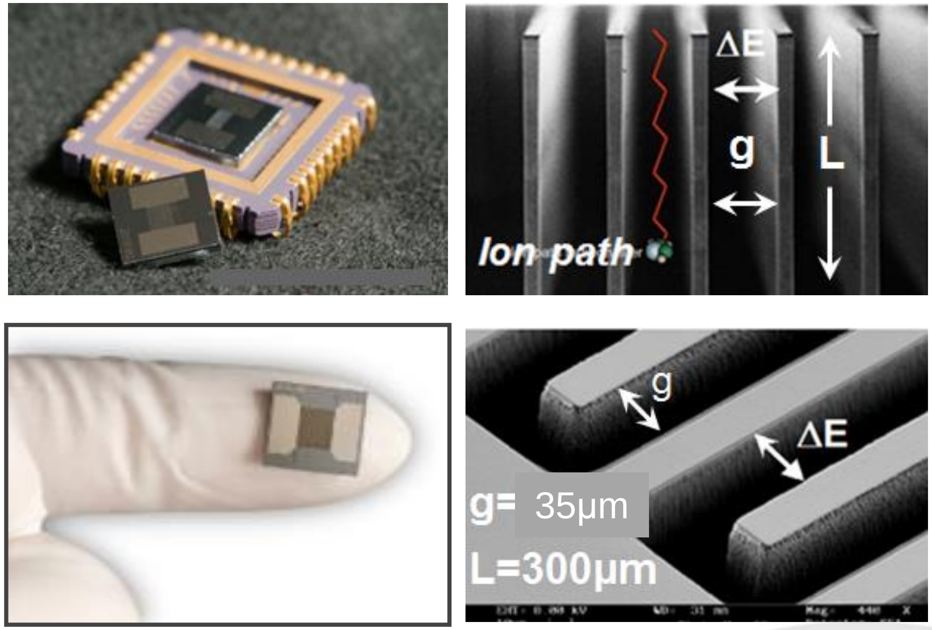
  → *Cannot therefore rely on a separation single gap*

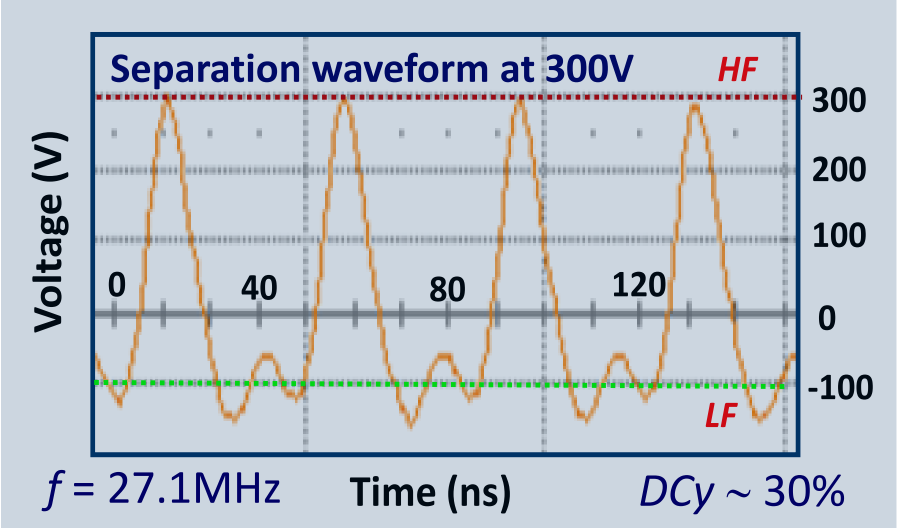


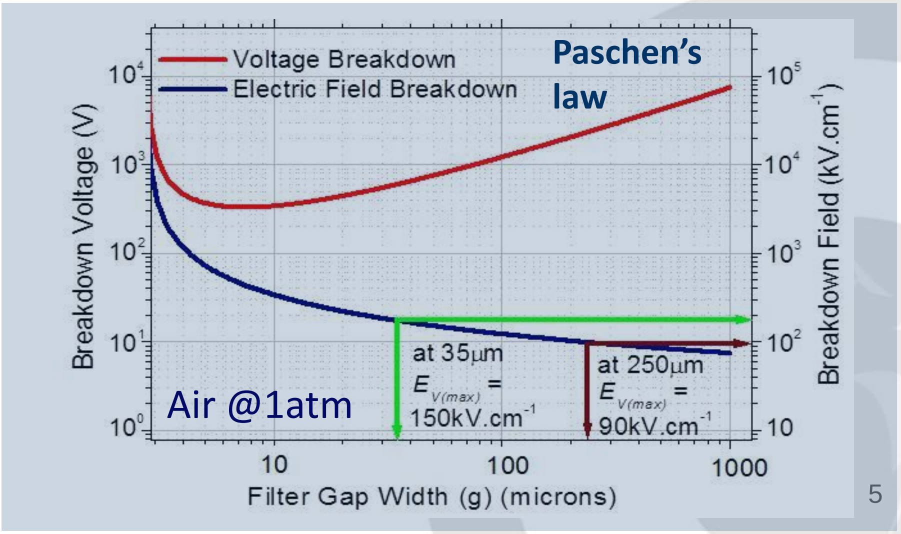


Enabling Ultra-High-Field Operation









Performance Parameters

Narrow gaps have been used to *push* the operational field limits in DMS / FAIMS but with penalties…

- *Ion channels must be kept short to sustain acceptable ion transmission (sensitivity)*
- *Fast ion separation time is achieved t_{res} ~ 35µs (allowing very fast E_C:E_D scanning) but peaks are broadened by the t_{res} term in the equation defining peak capacity*
- *Also, the D_{II} leads to significant transmission loss at high fields (esp. for smaller, high K_0 analytes)*
- *Consequence is moderate resolution & reduced data rate (necessary to sample ion current on a timescale >> t_{res})*
- *Conclusion is separation device is not fully optimal*

Resolution

$$R = \frac{E_C}{w_{1/2}} = \frac{E_C K_0 N_0}{4N} \left(\frac{t_{res}}{D_{II} ln2} \right)^{1/2}$$

Transmission

$$\frac{I_{out}}{I_{in}} = A_{I(in)}.\, Q.\exp\left(\frac{-t_{res}.\, \pi^2.\, D_{II}}{g_{eff}{}^2} \right)$$

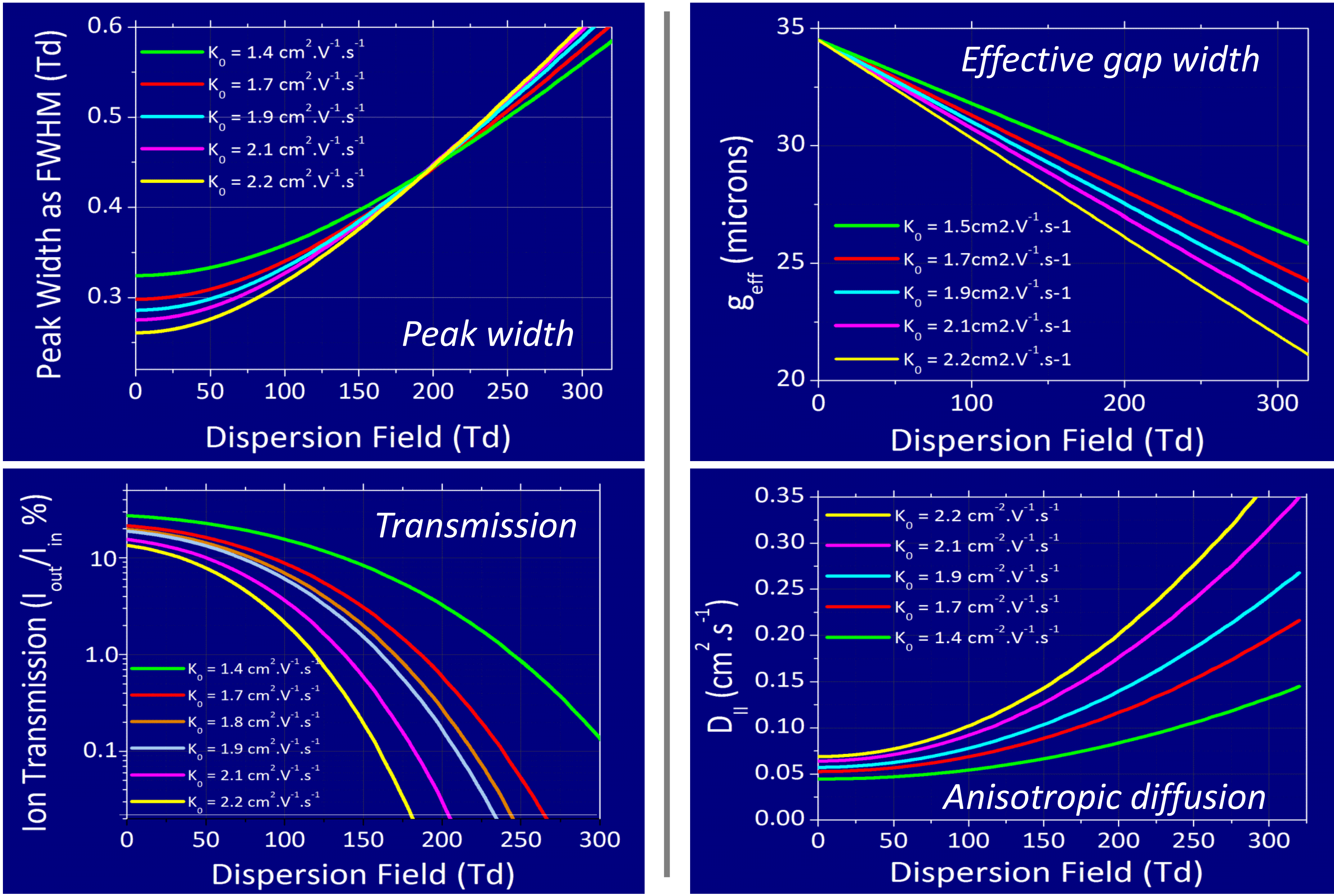
Effective gap width

$$g_{eff} = g - (K_{(0)}.\, E_{min}.\, t)$$

Anisotropic diffusion

$$D_{II} = D\left[1 + \frac{\langle f_2 \rangle F_{II} M K_0{}^2 N_0{}^2 (E_D/N)^2}{3k_b T} \right]$$

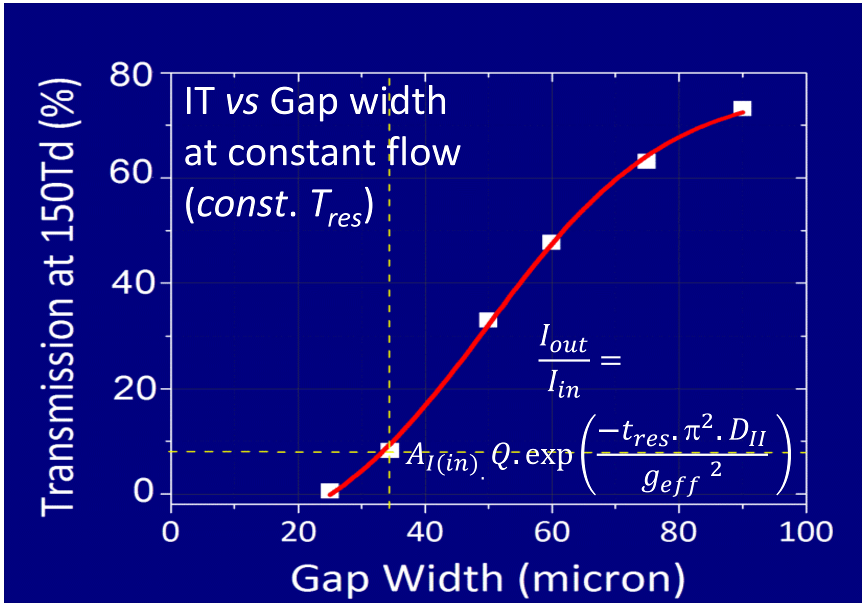
Some Quantification…

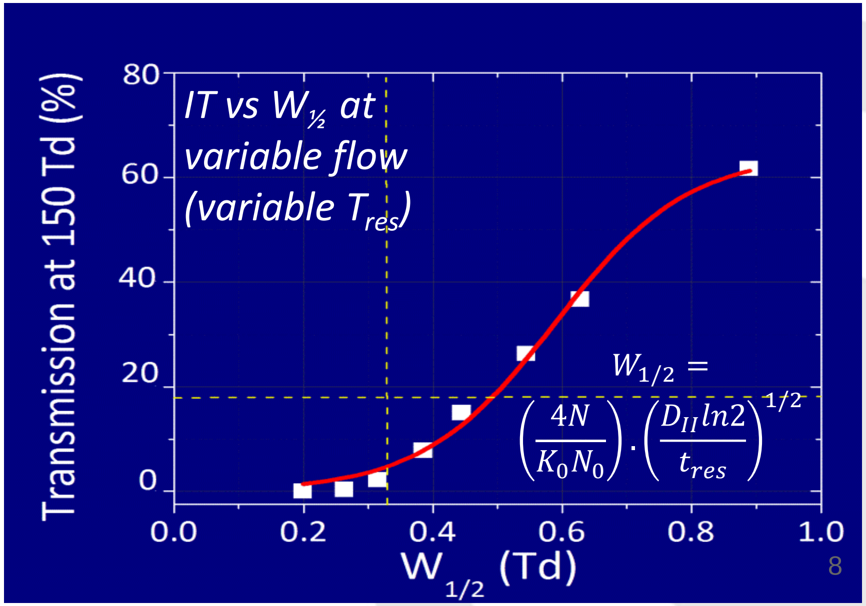


Simply…

Comparing planar gaps

- Narrow gap hits transmission
- High flow (short residence time) hits resolution (peak width)
  - At g_{eff} = 35µm and flow = 375cm^3.min^{-1}, $w_{1/2}$ ~ 0.3Td (at 1atm) and *T* ~ 7%
  - This puts us close to the bottom end of the $W_{1/2}$ curve which is *good*, but the ion transmission here is rather poor - there is *sensitivity* penalty for *resolution*





Clear Solution

Wider Gaps

- Higher flow
- Greater ion transmission without resolution penalty

Longer channel

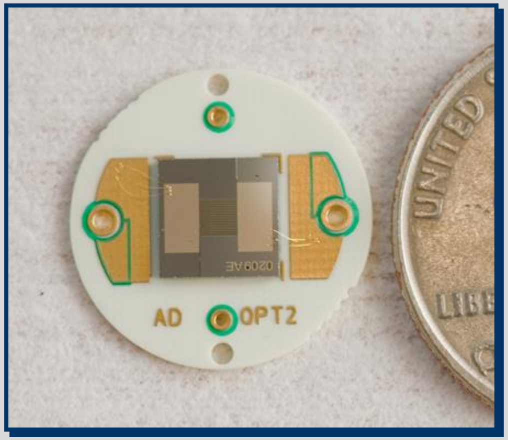
- Increased residence time
- Narrower peak without transmission penalty

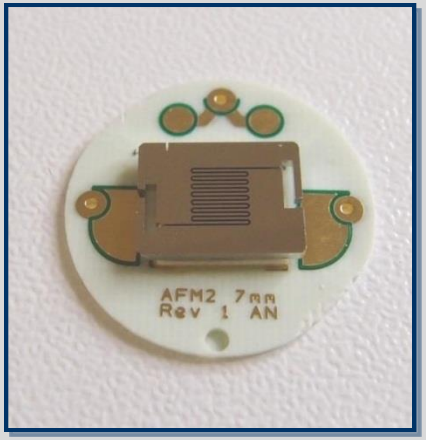
But…

- Need much **higher voltage** field drivers….

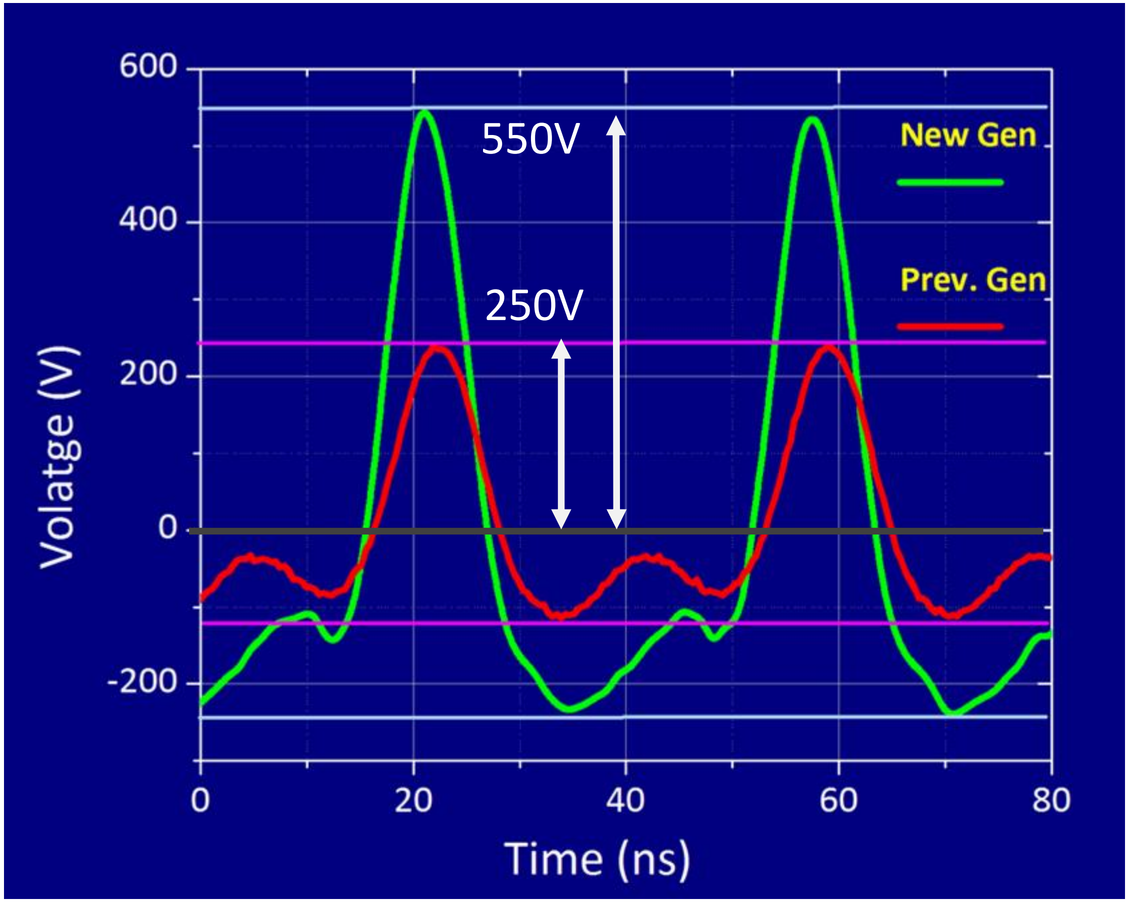
Gap width (g)	35 *vs.* 100µm
Length (l)	300 *vs.* 700µm
Area (A)	15 *vs.* 20mm^2
DF range (*E_D/N*)	350Td *vs.* 320Td
Res. time **(*t_{res}*)**	~40µs *vs.* ~120µs

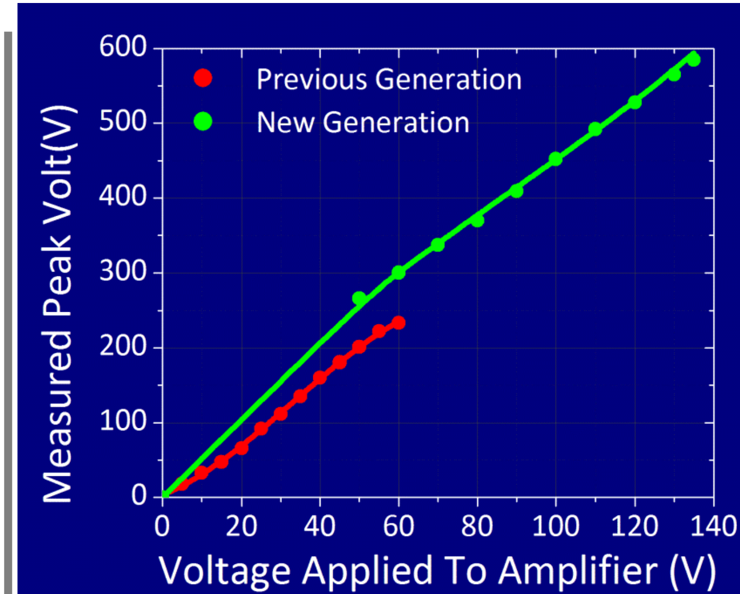
Narrow gap **Wide gap**

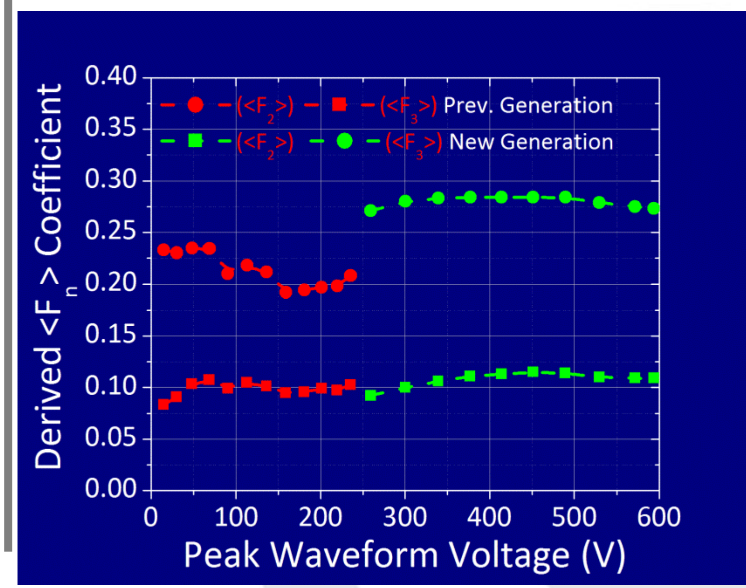




Waveform Analysis & Comparisons





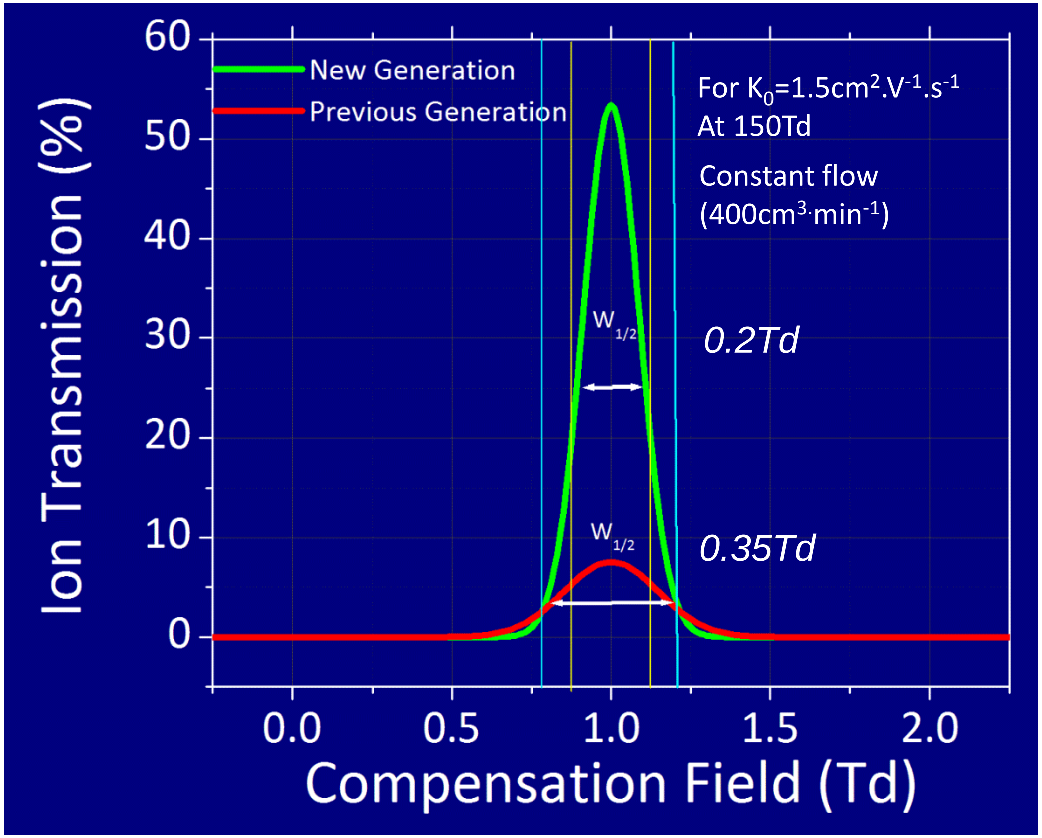


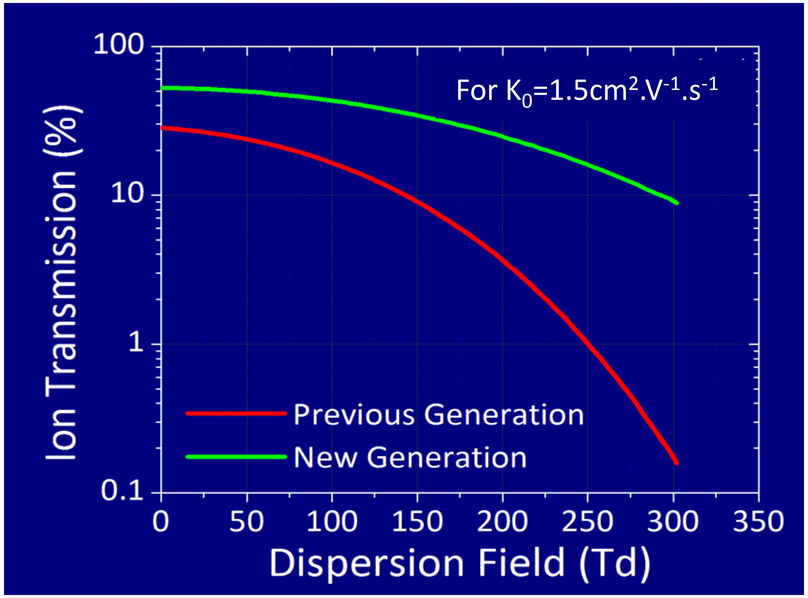
550V on 75µm gap = 78kV.cm^{-1} (> 320Td at 1 atm)

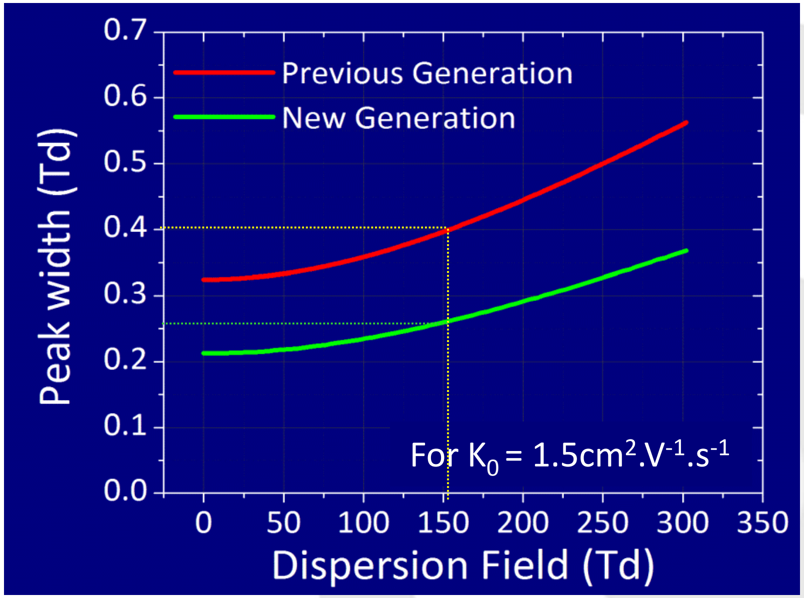
$\langle f_n \rangle$ nearer “optimums” for *2-harmonic* waveform and stable at high drive voltages

(*Shvartsburg 2009)*

Transmission & Resolution Comparison





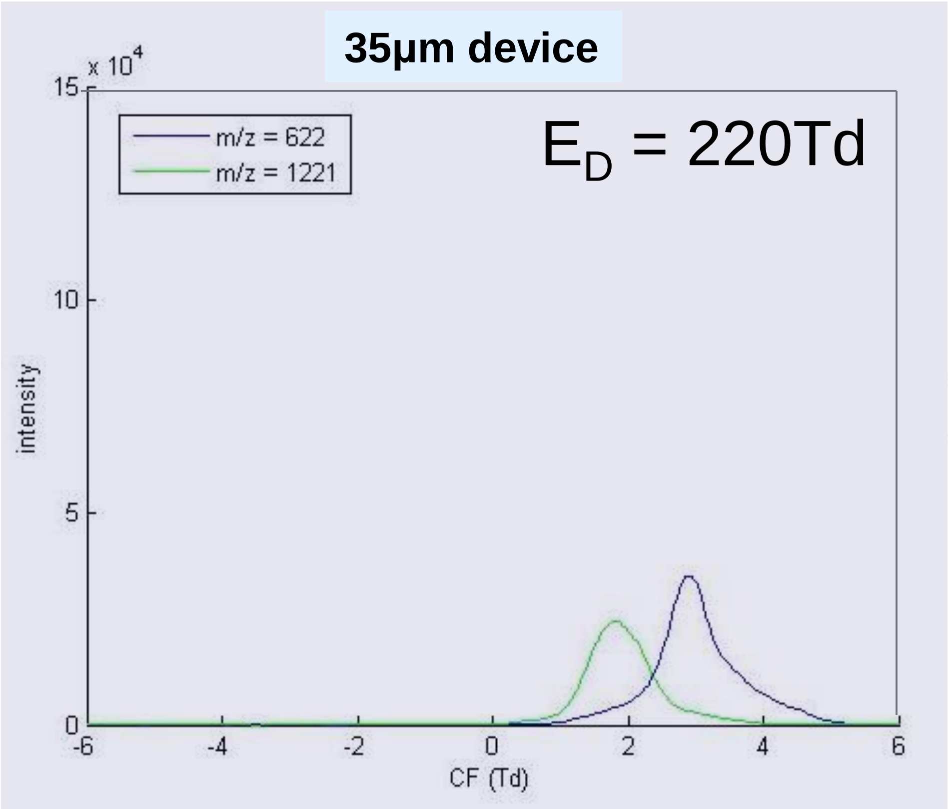


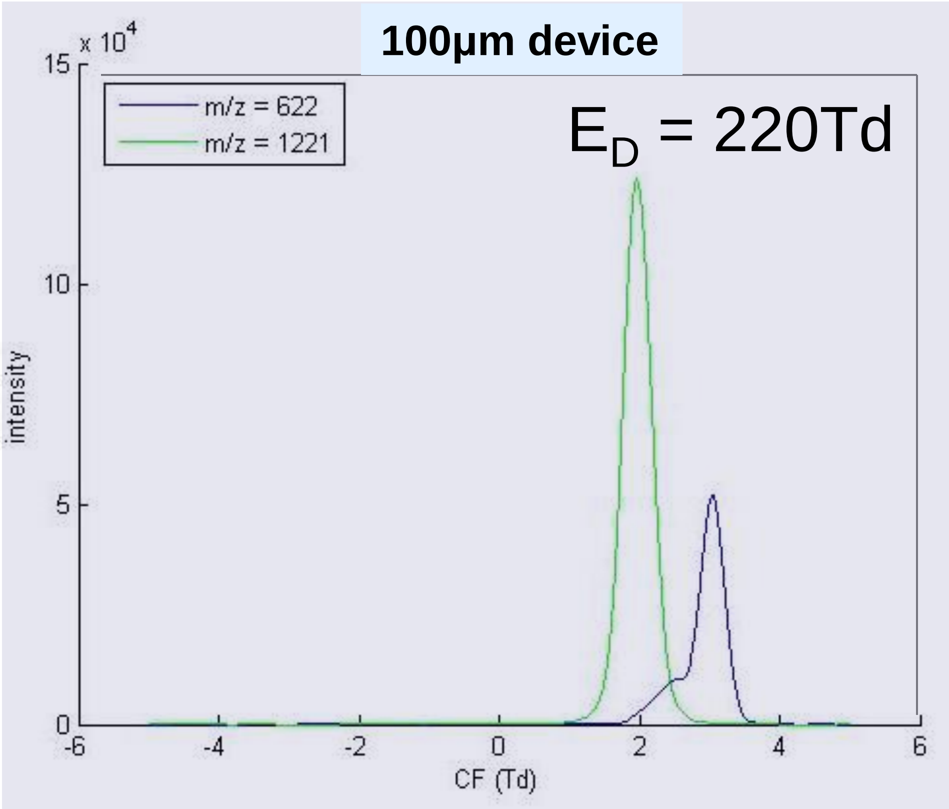
Peak width reduced by factor ~ 2 (and better at reduced flow)

Transmission increased by factor > 10 at very high fields

Experimental (Large ions up to 1.5kDalton)

m/z	35µm 0Td	100µm 0Td	35µm 220Td	35µm 220Td	35µm 300Td	100µm 300Td
118	10	35	1.5	7	<1	1
322	15	50	4.5	20	1.5	8
622	60	60	35	50	5	15
922	70	80	60	70	15	45
1522	80	100	35	95	20	90

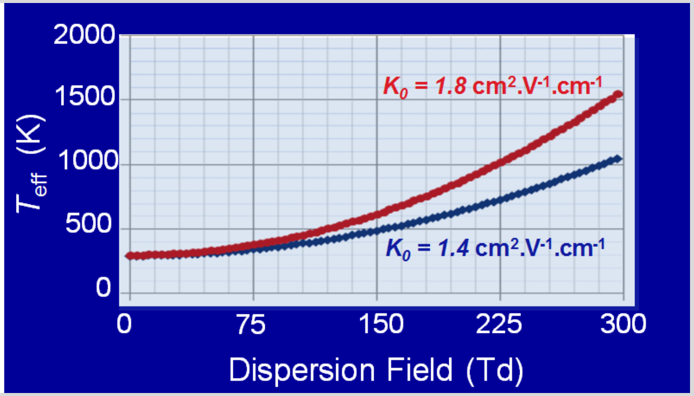


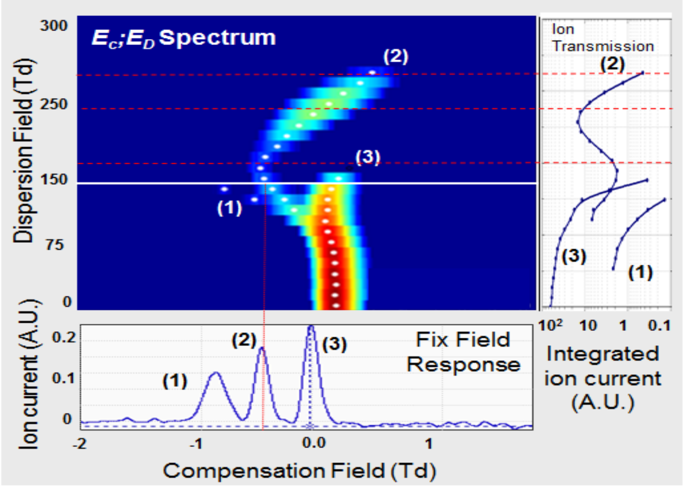


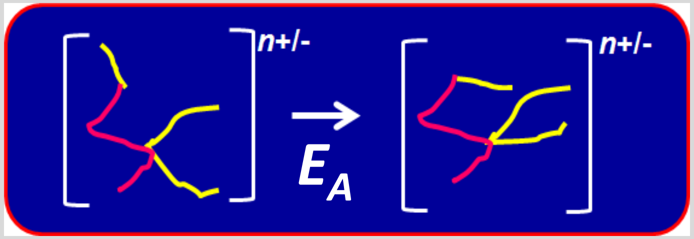
What to do with it?

Ultimately we wish to explore the high field region more rigorously

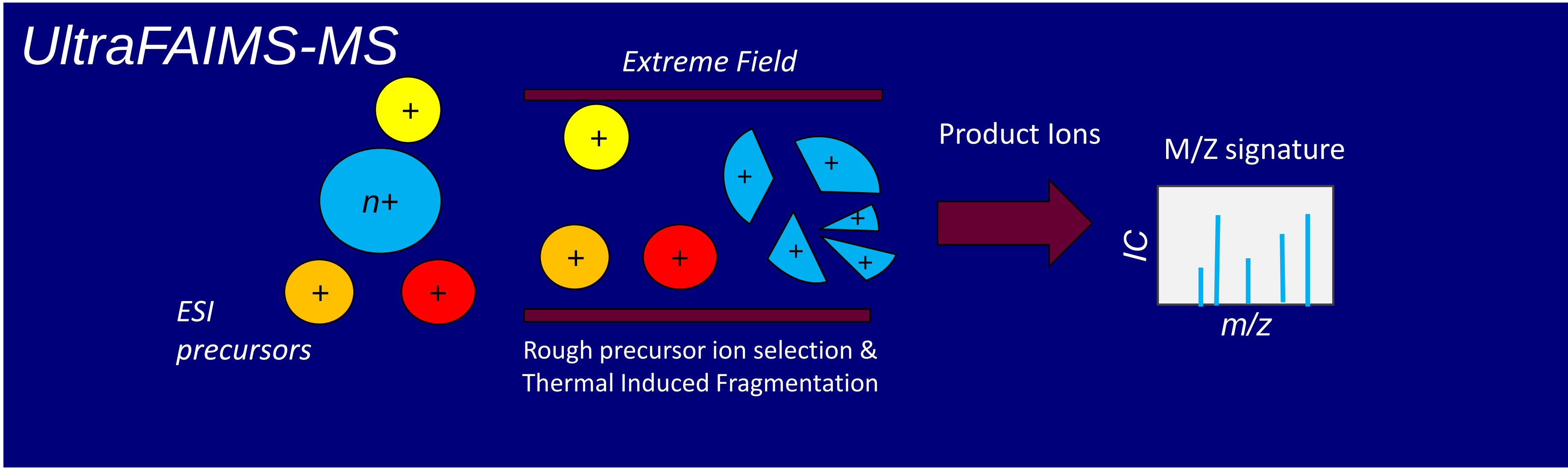
- *Effective Ion Temperature (T_{eff})* $\propto (E_D/N)^2$
- High field ion chemistry in both small and large molecules is of interest
- In small molecules (*e.g.* VOC sensing applications) the ion transmission spectrum holds valuable analyte classification information – *ions fragment at high field*
- For large molecules (in MS-hyphenated solutions) it is possible to exploit other T_{eff} dependent processes (*e.g.* ion conformational changes) to promote MS-prefiltering

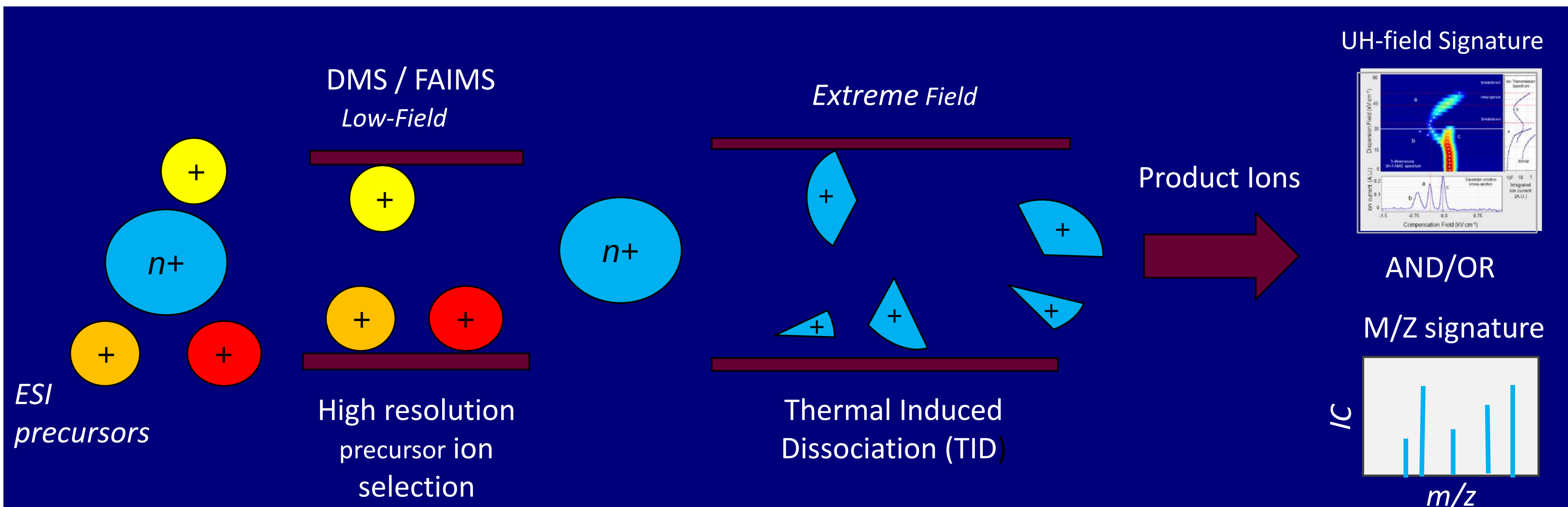






Interesting avenues?





Acknowledgements

Owlstone Team

Agilent Technologies

Michael Ugarov

Yuqin Dai

Harry Bunting

William Frazer

Owlstone Inc
761 Main Avenue
Norwalk, CT
USA
(+ 1) 203 908 4848

Owlstone Ltd
127 Cambridge Science Park
Milton Road
Cambridge, UK
(+ 44) 1223 428 200

Useful References

E. V. Krylov , E. G. Nazarov, R. A. Miller (2007) Differential mobility spectrometer: Model of operation. Int J Mass Spectrom 266:76–85

A. A. Shvartsburg (2009) Differential Ion Mobility Spectrometry. CRC Press, Boca Raton

15