Very Long Path Length Ion Mobility Separations using Structures for Lossless Ion Manipulations

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Some approaches for achieving higher resolution ion mobility separations; there's typically a catch…..

- Separation at very low temperature; challenges: design complexity, maintaining uniform temperature over useful volume
- Extended residence time Differential Mobility separations (e.g. FAIMS); challenges: large ion losses, slow scan speed
- Separation in flowing (or expanding) gas; challenges: limited separation space, performance trade-offs
- Separation in multi-pass (i.e. cyclic) devices; challenges: increasingly limited mobility range and compounded losses with each pass
- **Drift separation over extended path length; challenges: space and cost of long path designs, large voltage drop for long path**

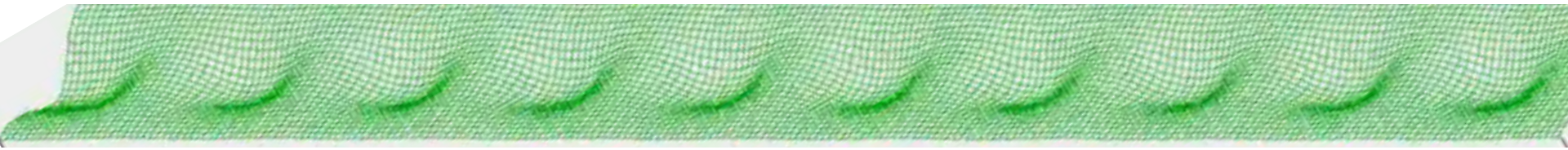
Questions to be addressed

- Is very long path length (L) IMS feasible?
- Can efficient ion utilization be achieved?
- Does resolution (R) increase significantly?
- If achieved, is increased IMS resolution really useful?
- Can peak broadening with greatly extended path IMS be avoided?
- What are the limits on IMS path length?

Use of traveling waves (TW) in Structures for Lossless Ion Manipulations (SLIM)

- Initial work with short path TW SLIM IMS showed good performance*; theory** indicates R achievable $\propto (L)^{1/2}$
- TW use reduces SLIM complexity (e.g. no need for 'on-board' components)
- Voltages needed independent of L; large voltage drops avoided
- Enables new (and more easily implemented) ion manipulations

Simion 8.1 representation of field at mid-point of gap (1.5 mm from surface for 3 mm gap between two surfaces)

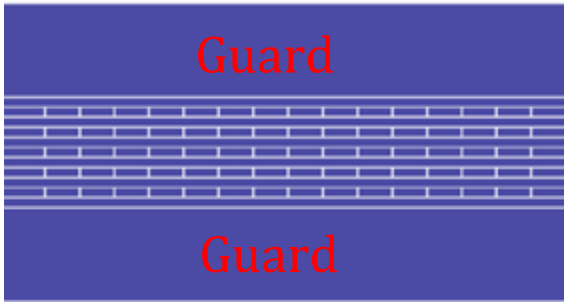


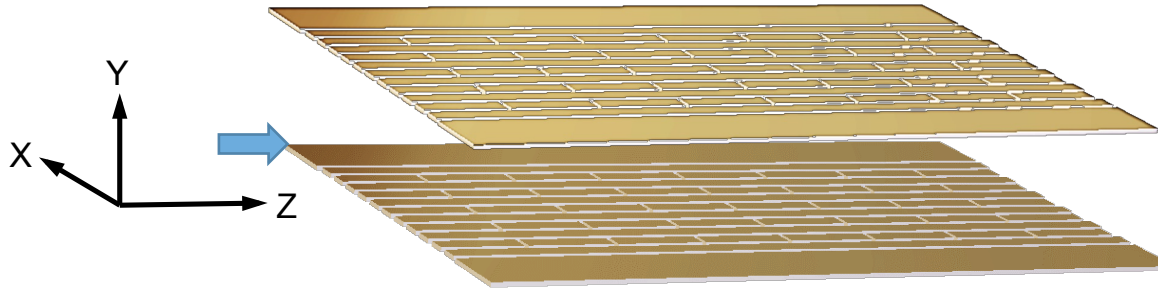
*Hamid et al., Anal. Chem., *87*, 11301 (2015)
**Shvartsburg and Smith, Anal. Chem., *80*, 9689 (2008)

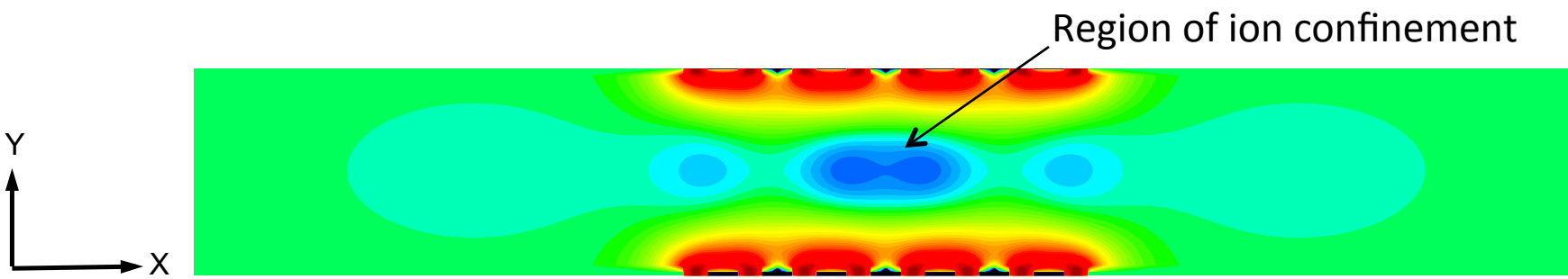
Ion confinement in TW SLIM 2.0 designs

- Ions confined by pseudopotential to gap between surfaces
- Guard bias prevents lateral losses
- Simulations and experiment show lossless operation feasible from ~0.01 to ~50 torr

6,5 electrode arrangement
(6 RF electrodes separating 5 TW electrode arrays)





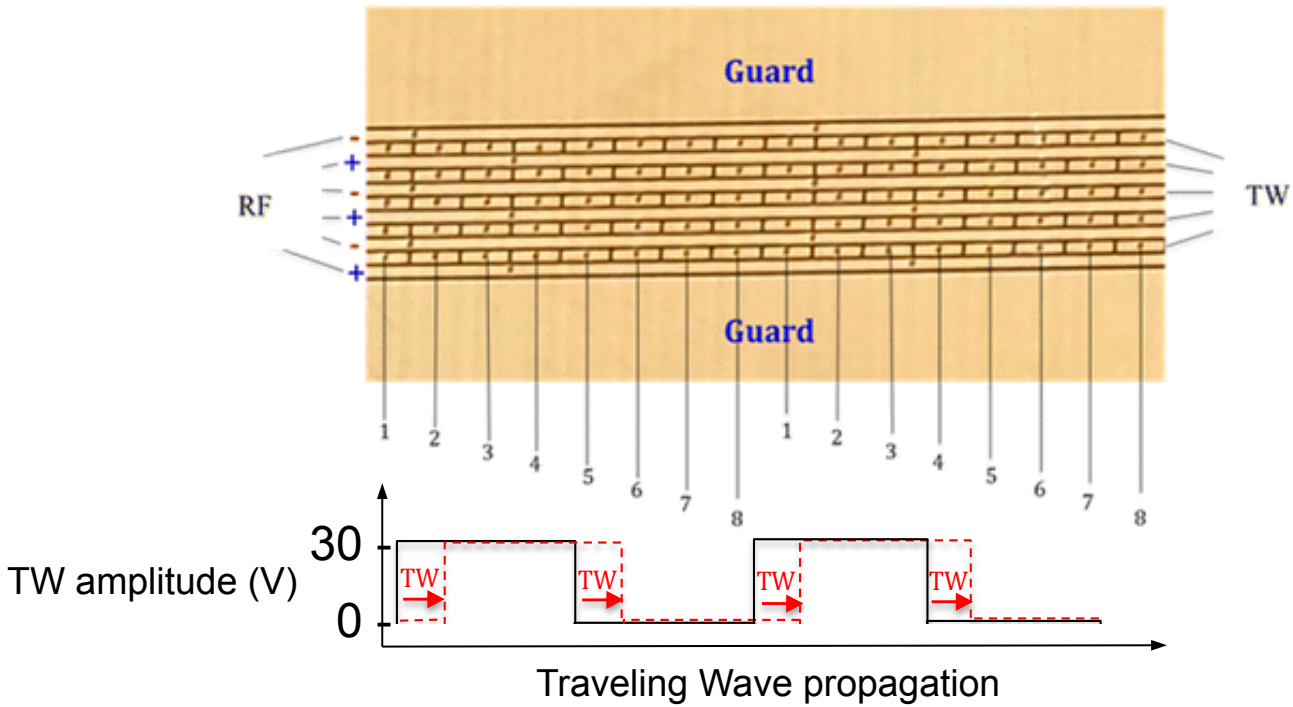


Gap 3 mm; 4,3 electrode arrangement
TW amplitude 30 V; Guard 32 V; RF 750 kHz, 300 $V_{p\text{-}p}$

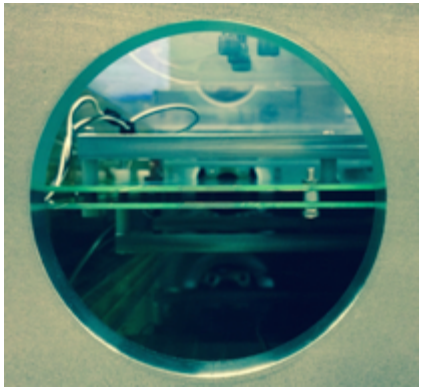
See Wednesday presentation by Sandilya Garimella; WOH 2:30 pm

SLIM 2.0 traveling wave IMS (6,5 electrode arrangement)

One of two SLIM surfaces with 6 RF electrodes separating 5 TW electrode arrays



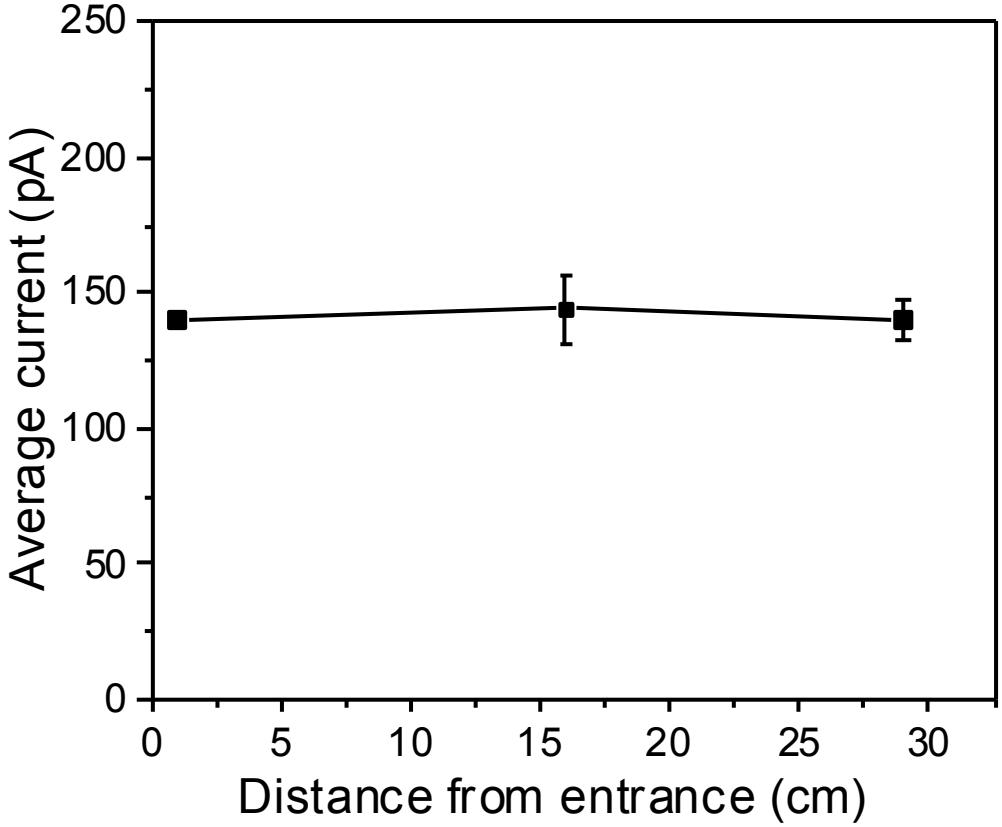
~3 mm gap between surfaces



Hamid et al., Anal. Chem., *87*, 11301 (2015)

Ion current transmitted through 30-cm TW SLIM module

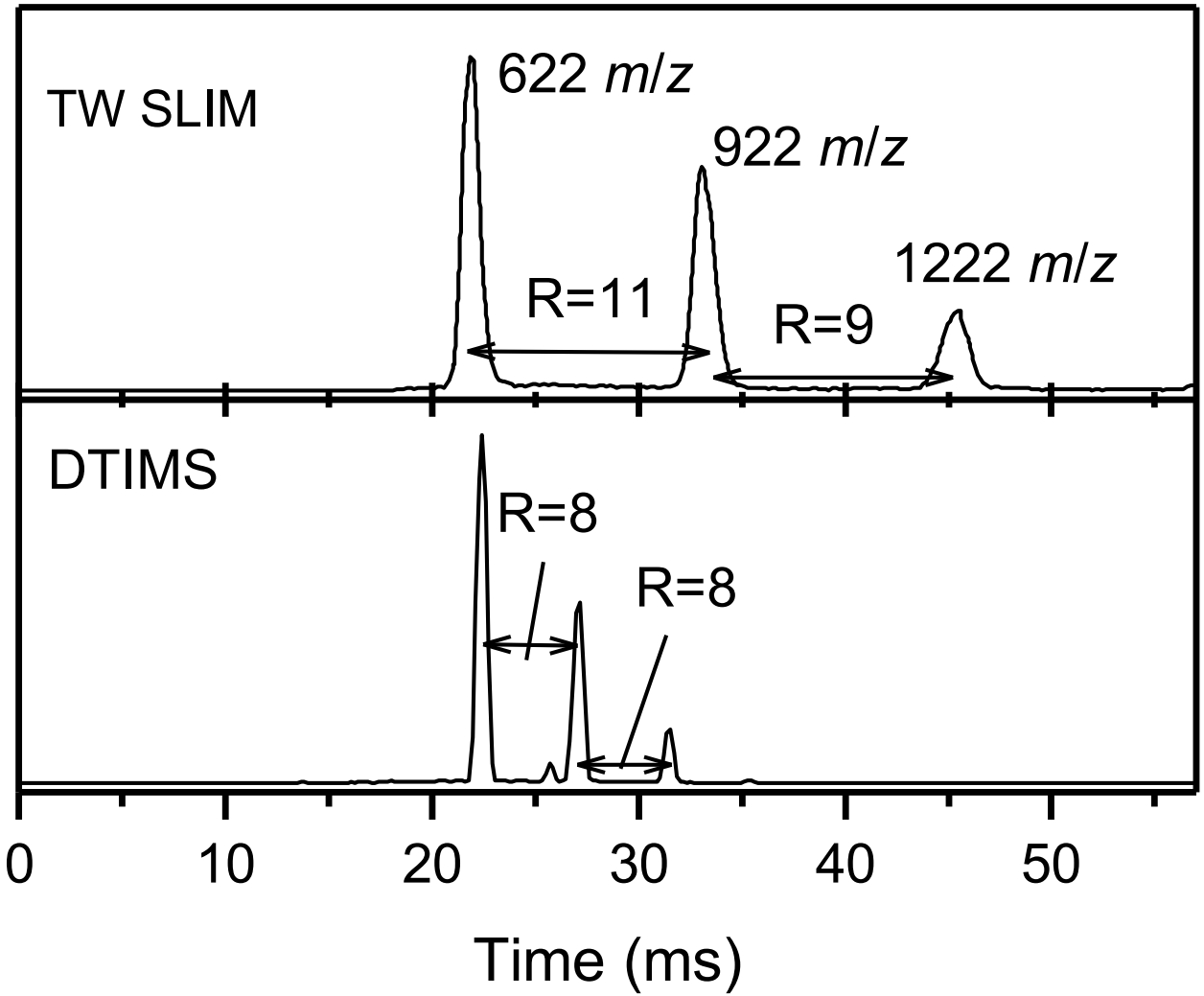
Gap 5 mm; guard bias 15 V; TW amplitude 30 V, speed 84 m/s; RF ~800 kHz, 200 V_{P-P}



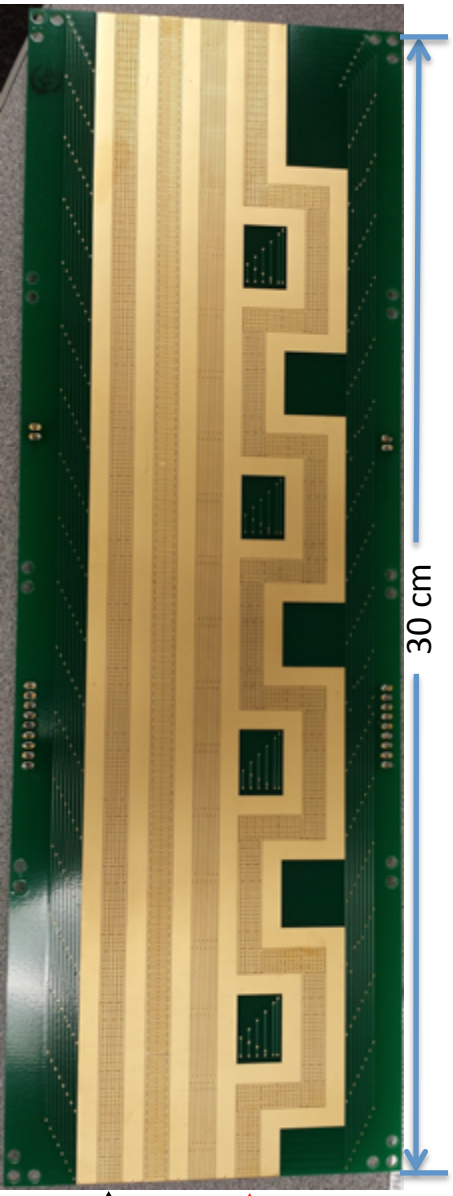
Hamid et al., Anal. Chem., *87*, 11301 (2015)

TW SLIM IMS vs. drift tube IMS resolution

30-cm TW SLIM module vs. 0.9-m conventional drift tube (DTIMS)

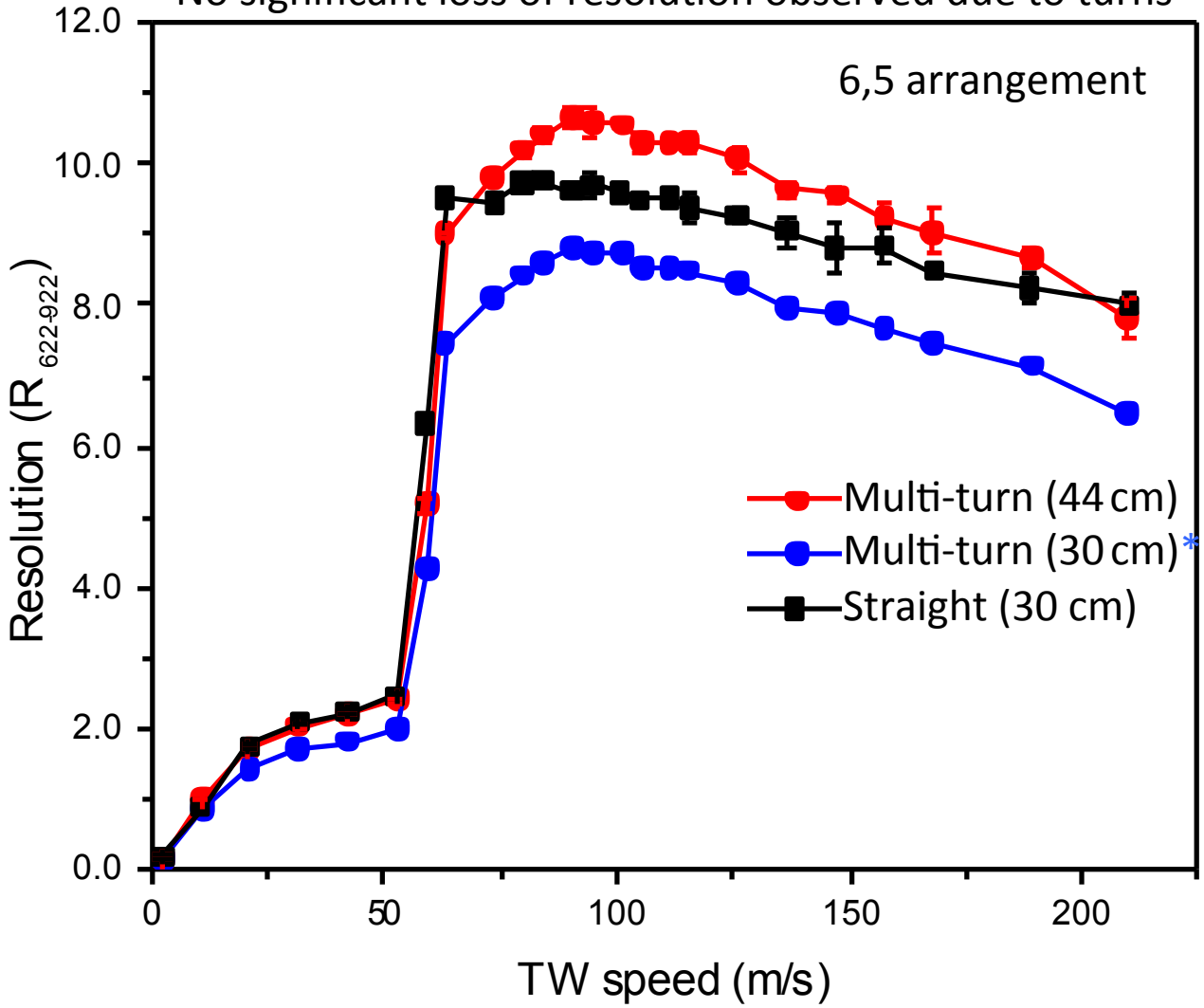


The cost of changing direction?



Straight Multi-turn (16)

No significant loss of resolution observed due to turns



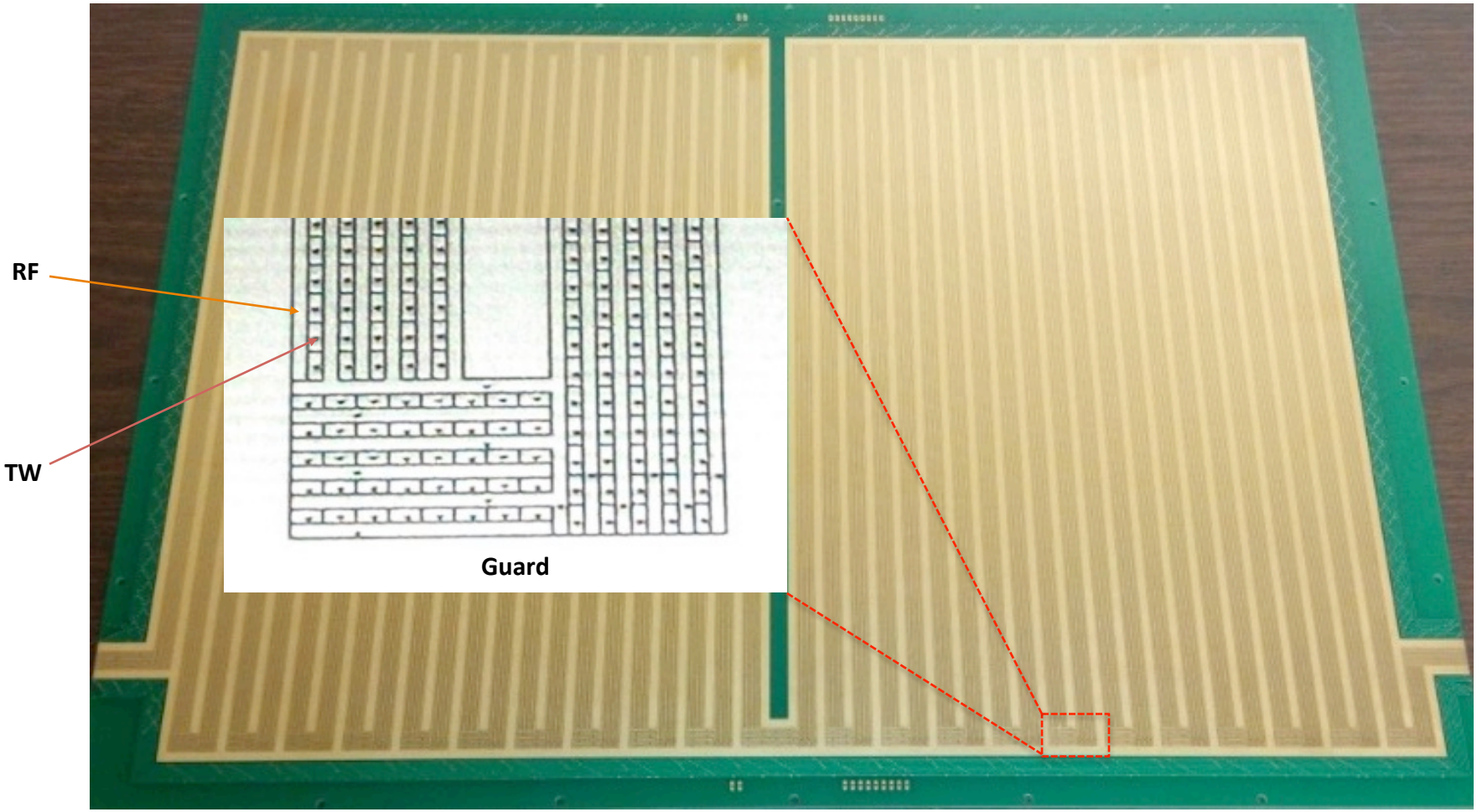
* 30-cm multi-turn path scaled from 44 cm path experimental measurements

Hamid et al; submitted for publication

Long path (13-m; 6,5) SLIM IMS module

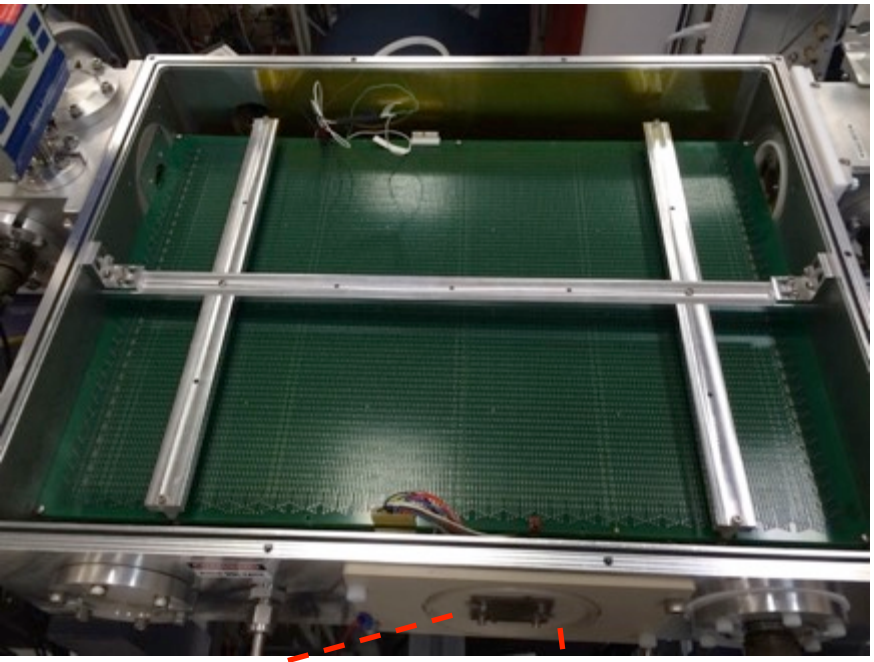
Long path IMS module consists of two 14” x 18” surfaces with mirror image electrode arrays

TW electrode dimensions: 0.43 mm width x 0.91 mm length; 0.13 mm electrode gaps

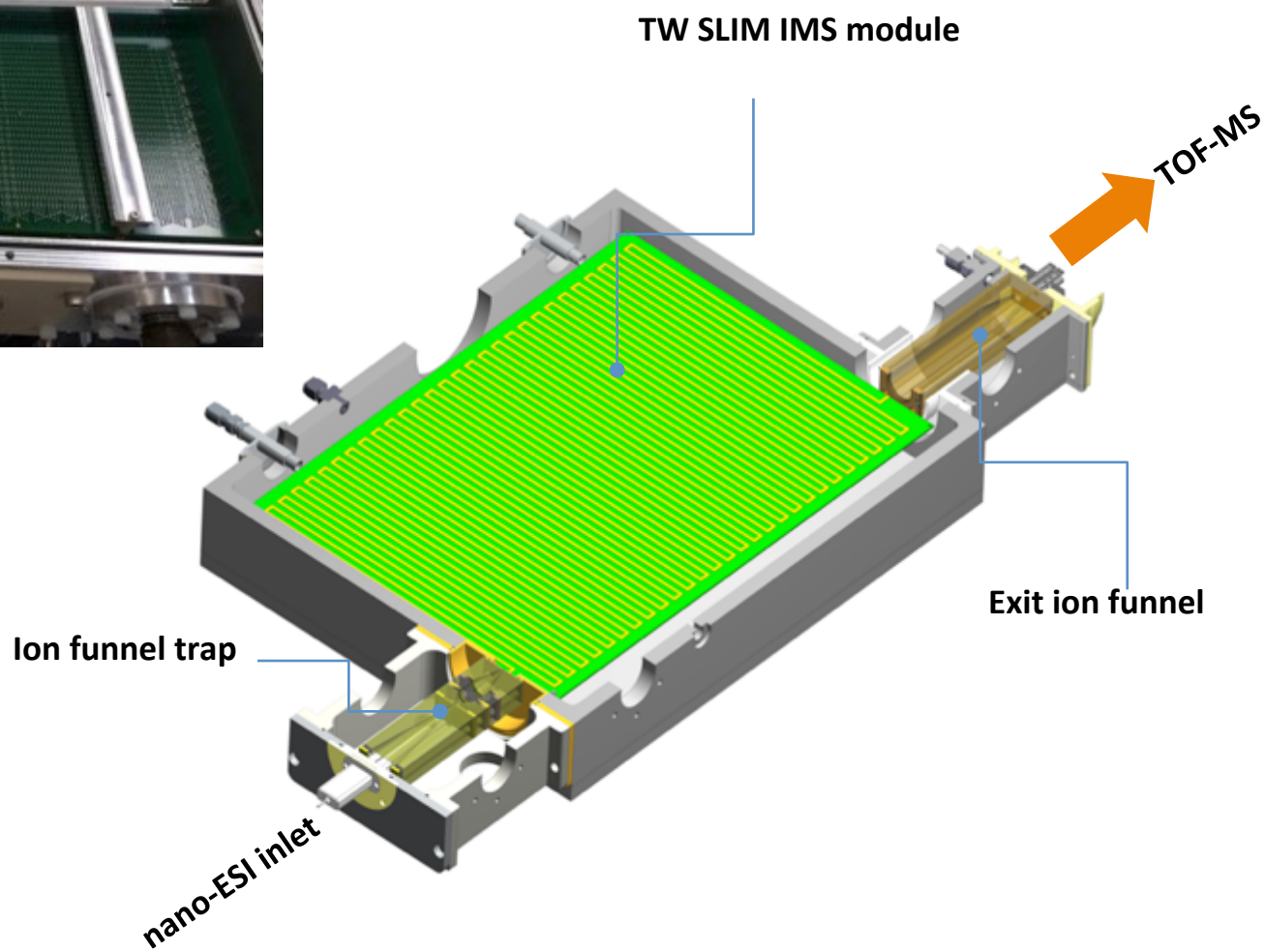


See Wednesday poster by Liulin Deng et al; WP 453

Arrangement for initial long path SLIM IMS studies



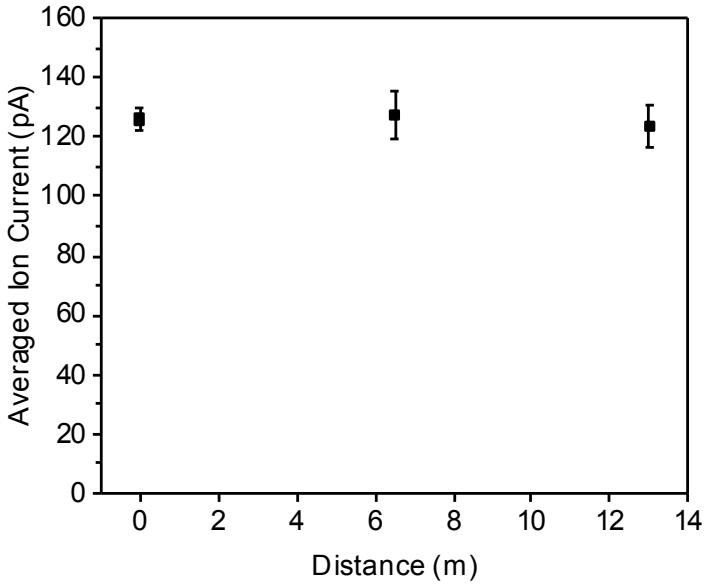
- Ion funnel trap used for ion packet injection
- Long path SLIM module replaces DTIMS
- Exiting ions transmitted to TOF-MS



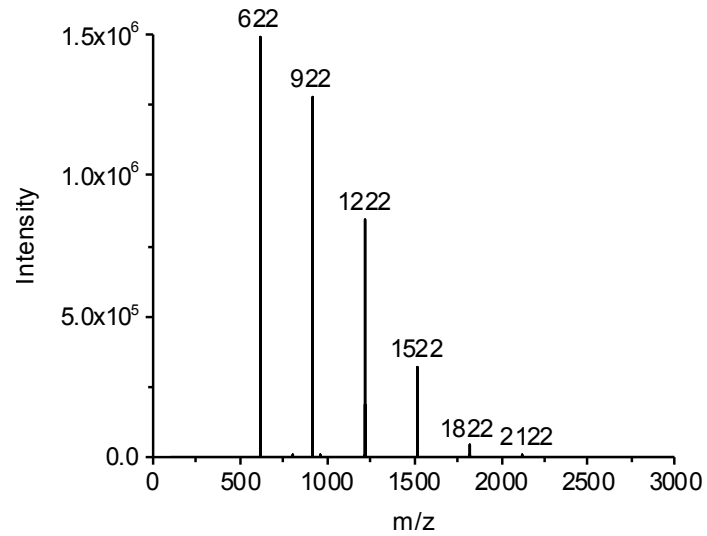
Robust long path SLIM IMS performance

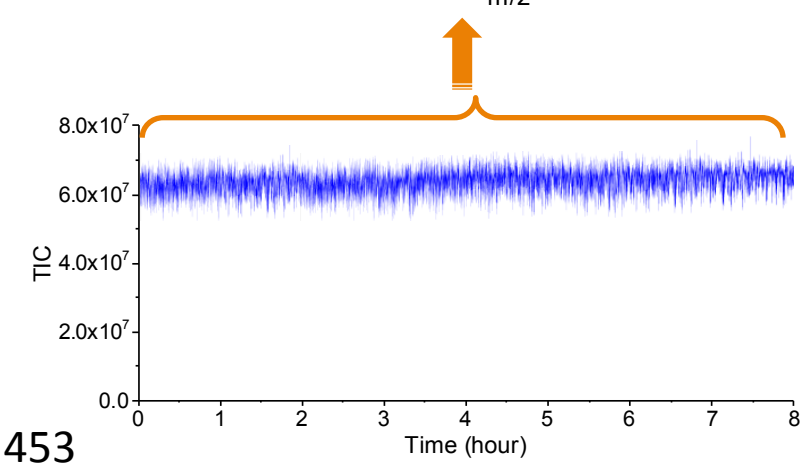
13-m path length, 6,5 electrode arrangement

Essentially lossless ion transmission



Stable extended ion transmission



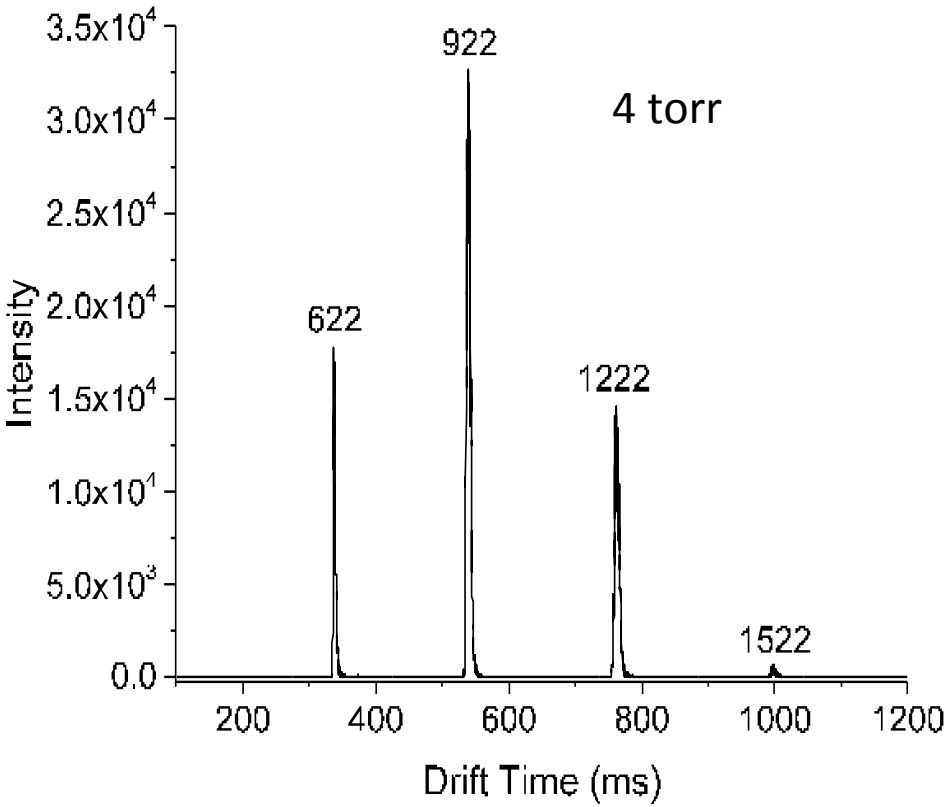


TW speed 124 m/s, amplitude 30 V; guard bias 5 V
RF 220 V_{p-p} 650 kHz; gap 2.75 mm ; 4.0 Torr N_2

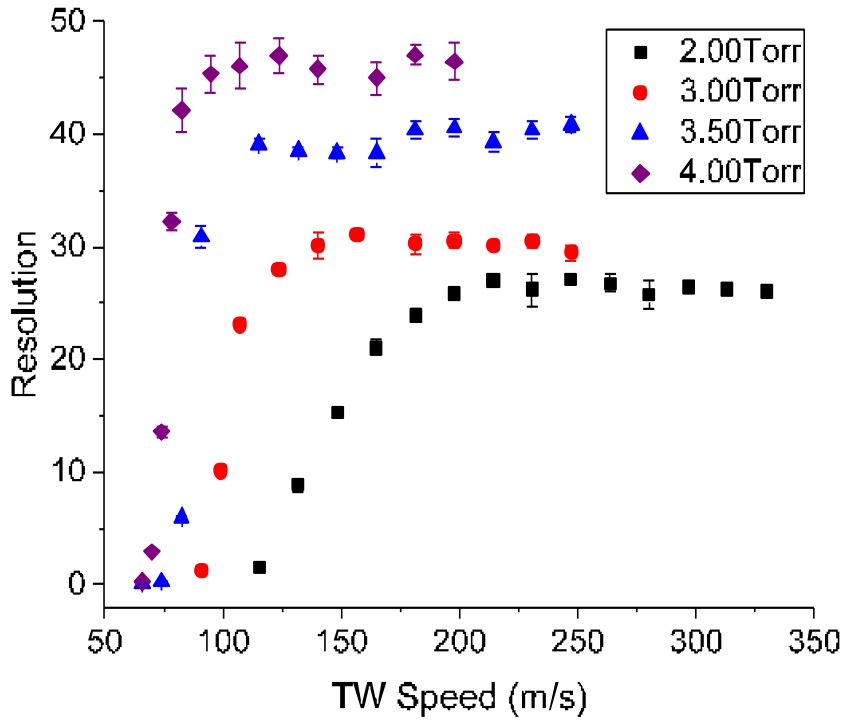
See Wednesday poster by Liulin Deng et al; WP 453

Robust long path SLIM IMS performance

13-m path length, 6,5 electrode arrangement

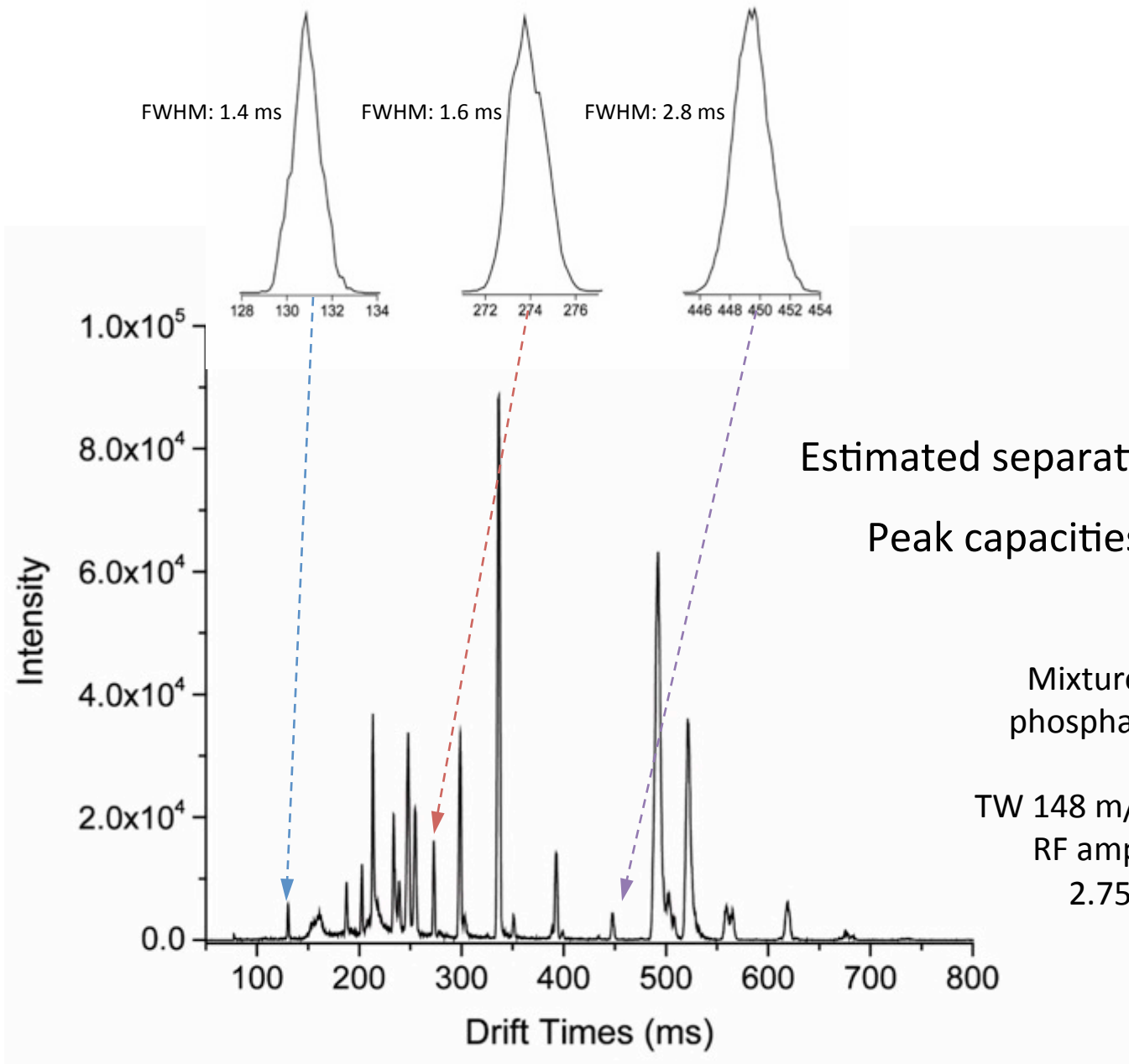


Resolution for m/z 622 and 922 peaks



TW speed =124 m/s; TW amplitude 30 V; guard 5 V
RF amplitude = 220 $V_{p\text{-}p}$ 650 kHz; 2.75 mm gap

13-m path TW SLIM separation



Estimated separation peak capacity ~ 300

Peak capacities achieved rival LC

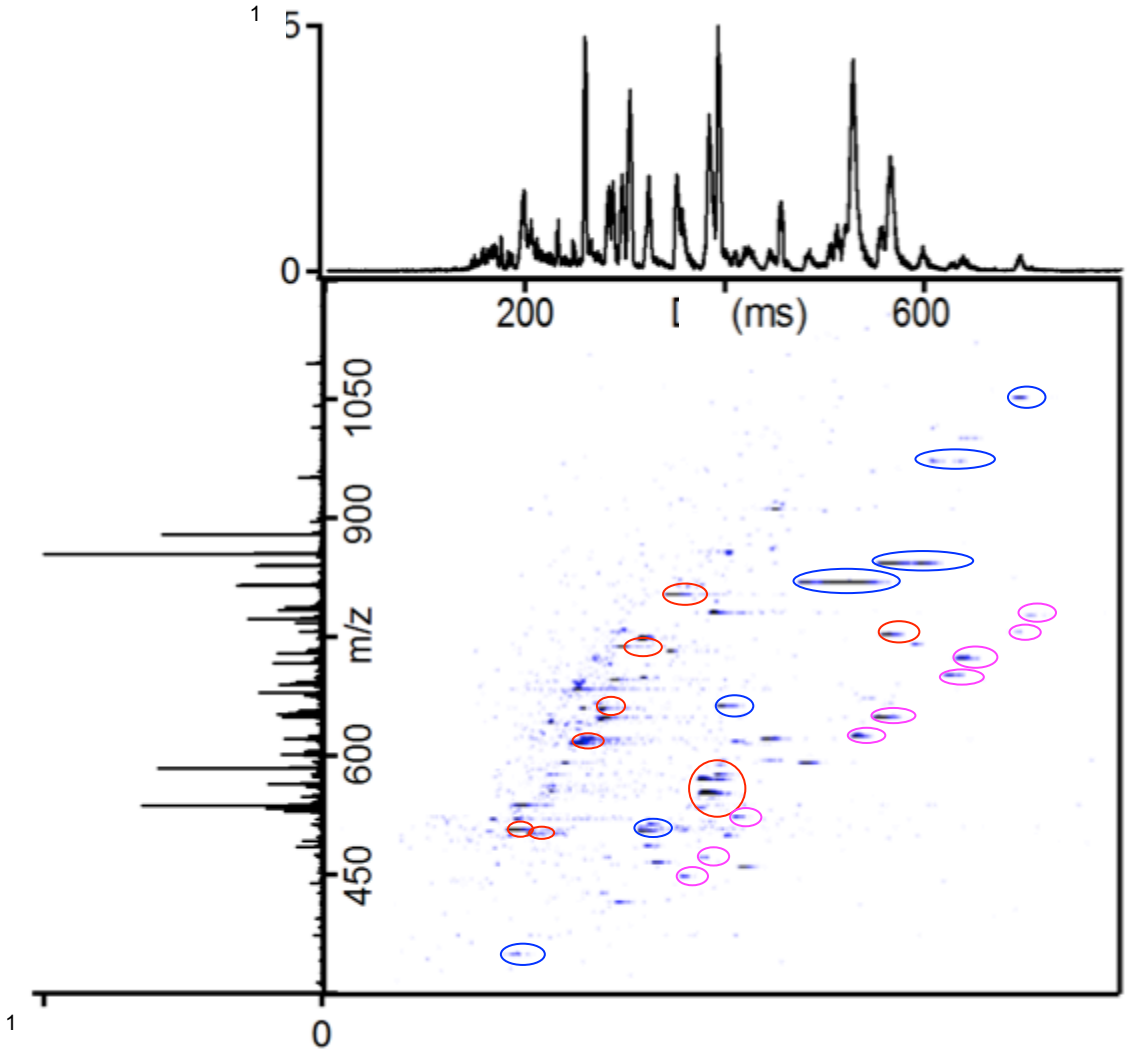
Mixture of peptides, fluorinated phosphazines, and isomeric sugars

TW 148 m/s; amplitude 30 V, guard 5 V
RF amplitude 220 $V_{p\text{-}p}$,650 kHz;
2.75 mm gap; 3.00 Torr N_2

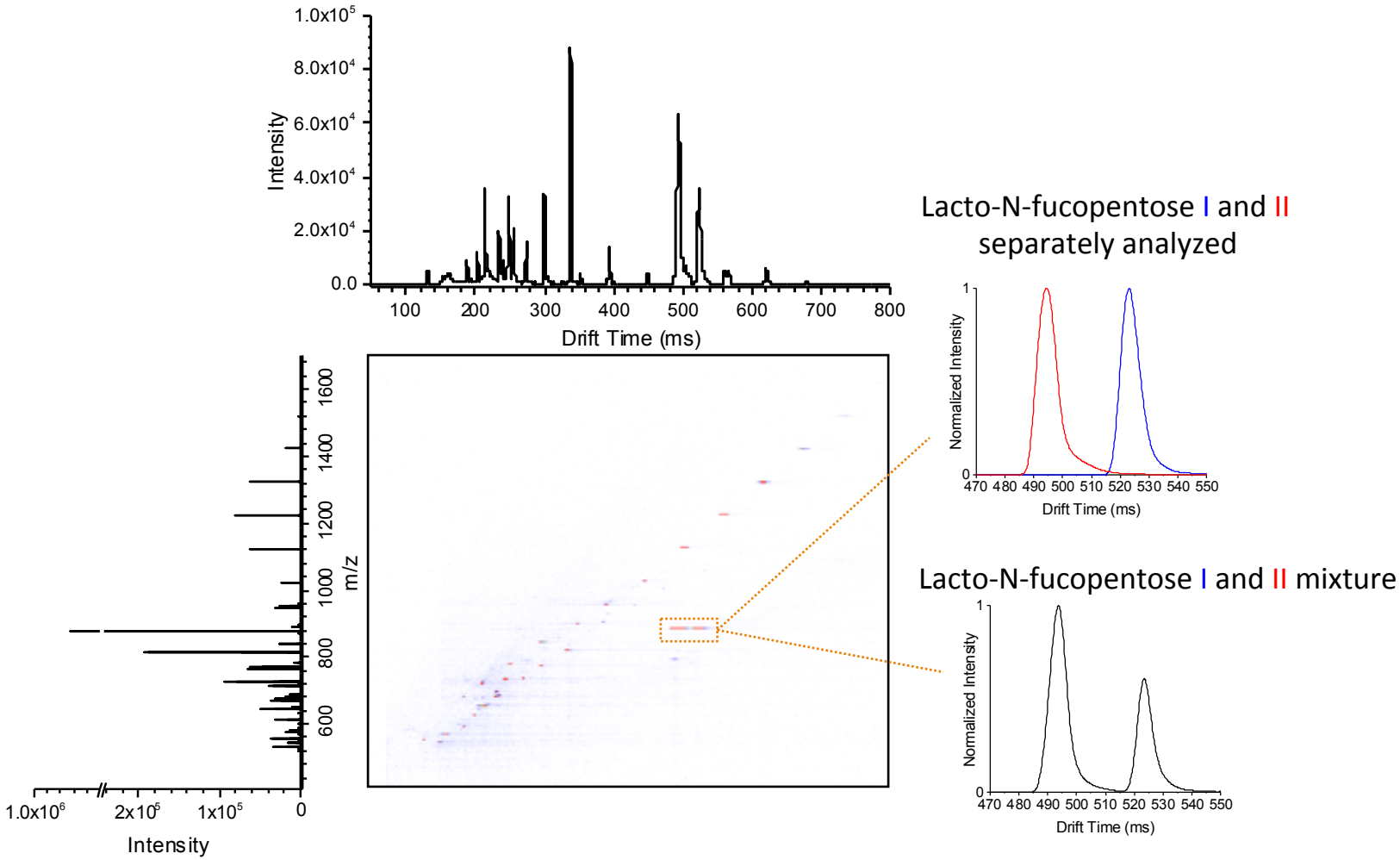
Liulin Deng

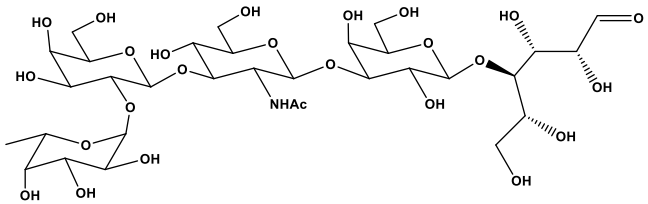
Long path SLIM IMS-MS of a peptide/carbohydrate/lipid mixture

13-m path length TW SLIM IMS

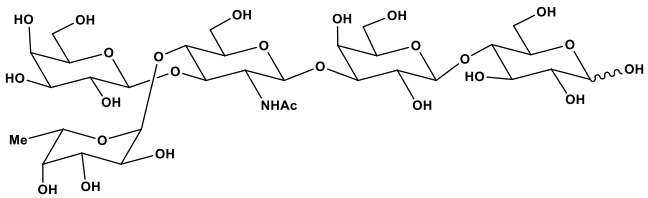


SLIM IMS-MS of a mixture containing Lacto-N-fucopentose I and II isomers



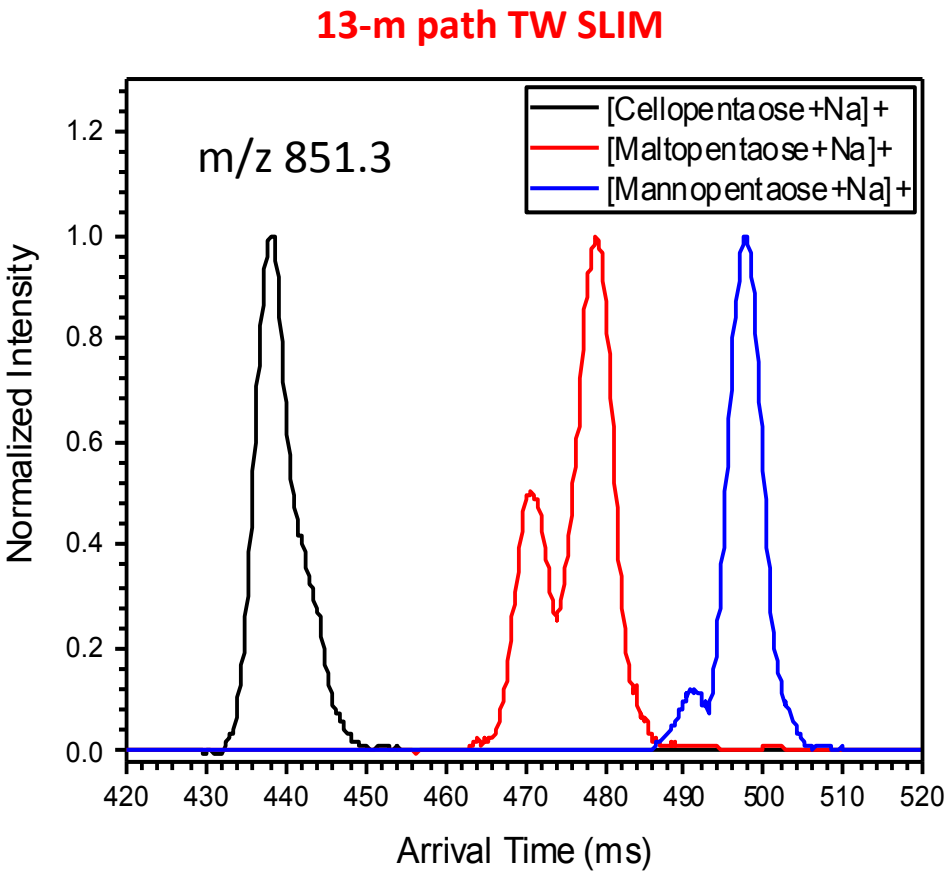


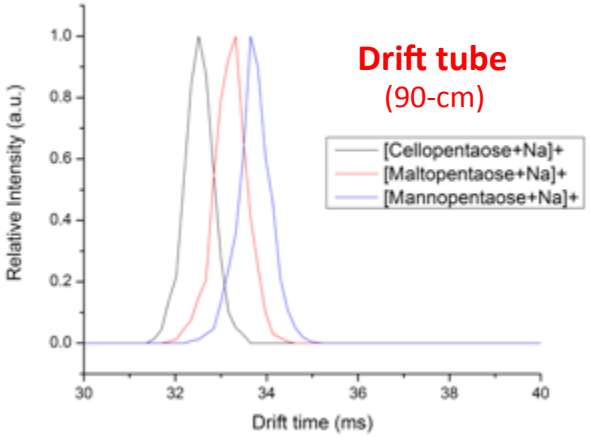
Lacto-N-fucopentaose I

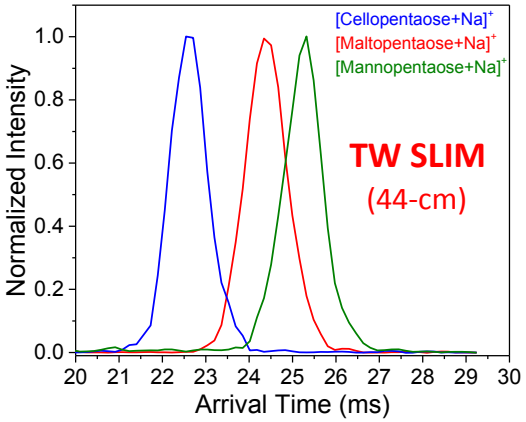


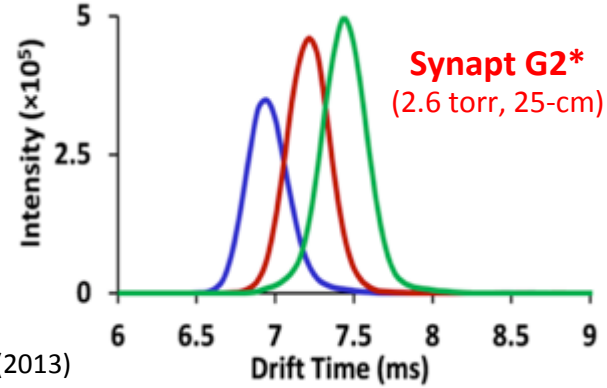
Lacto-N-fucopentaose II

Comparison of IMS MS performance for 3 pentasaccharides using long path SLIM, drift tube, short SLIM and Waters Synapt G2 IMS-MS





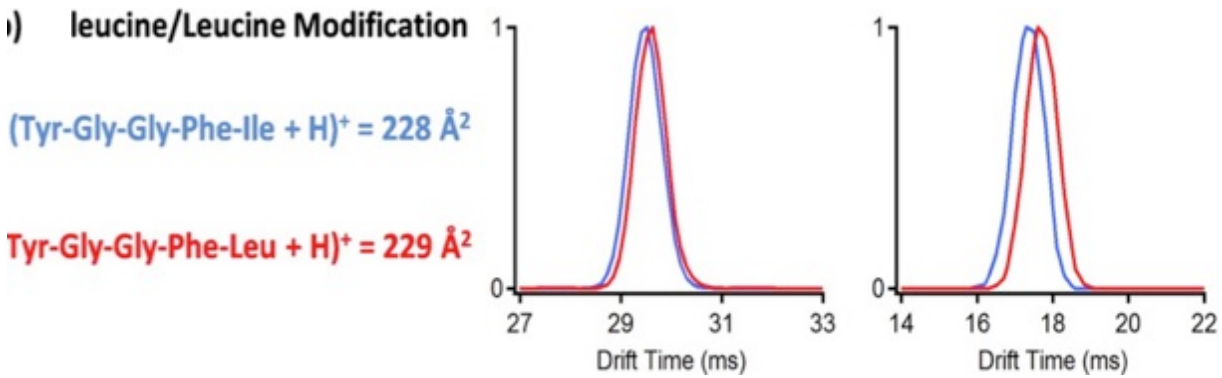


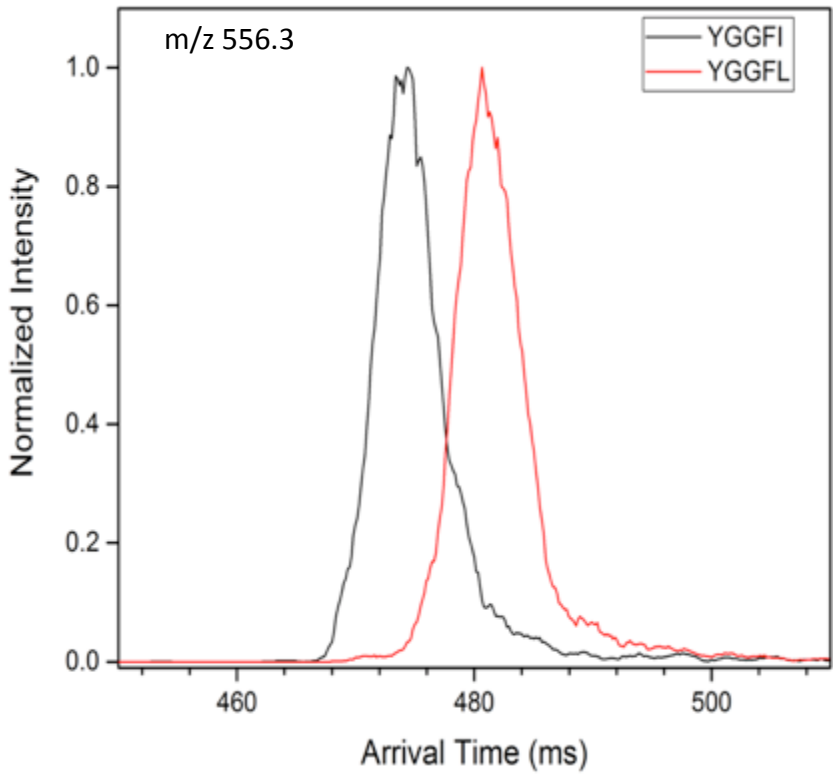


*Li, H.; Bendiak, B.; Siems, W. F.; Gang, D. R.; Hill Jr, H. H. Anal. Chem., *85*, 2760 (2013)

IMS separations of pentapeptides differing by luecine vs. isoluecine

90-cm drift tube 44-cm TW SLIM

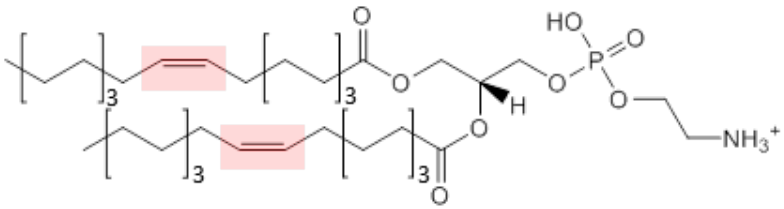




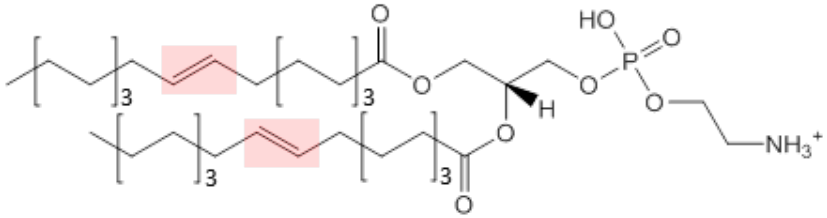
13-m path TW SLIM

Distinguishing Cis/Trans Double Bonded Lipids

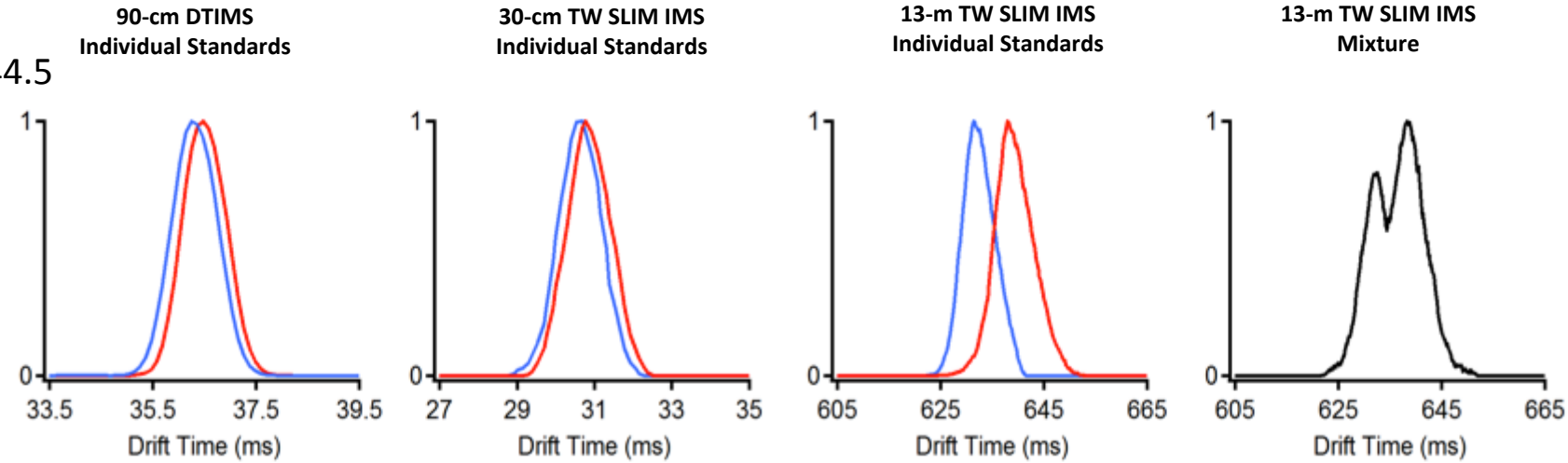
(PE(18:1(9Z)/18:1(9Z)) + H)$^+$



(PE(18:1(9E)/18:1(9E)) + H)$^+$



m/z 744.5



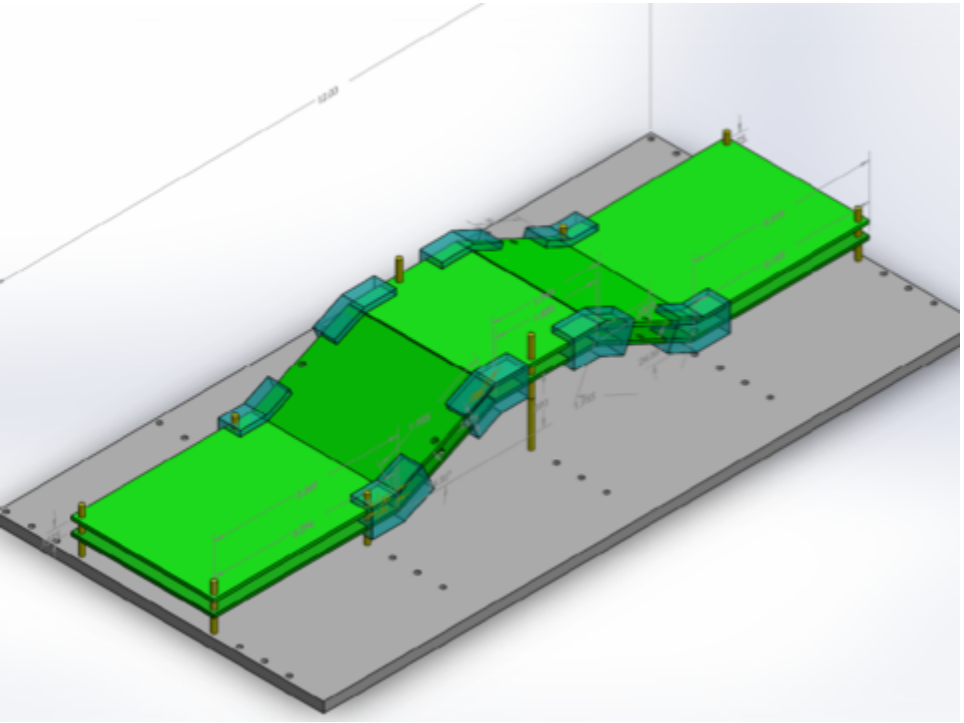
Liulin Deng and Erin Baker

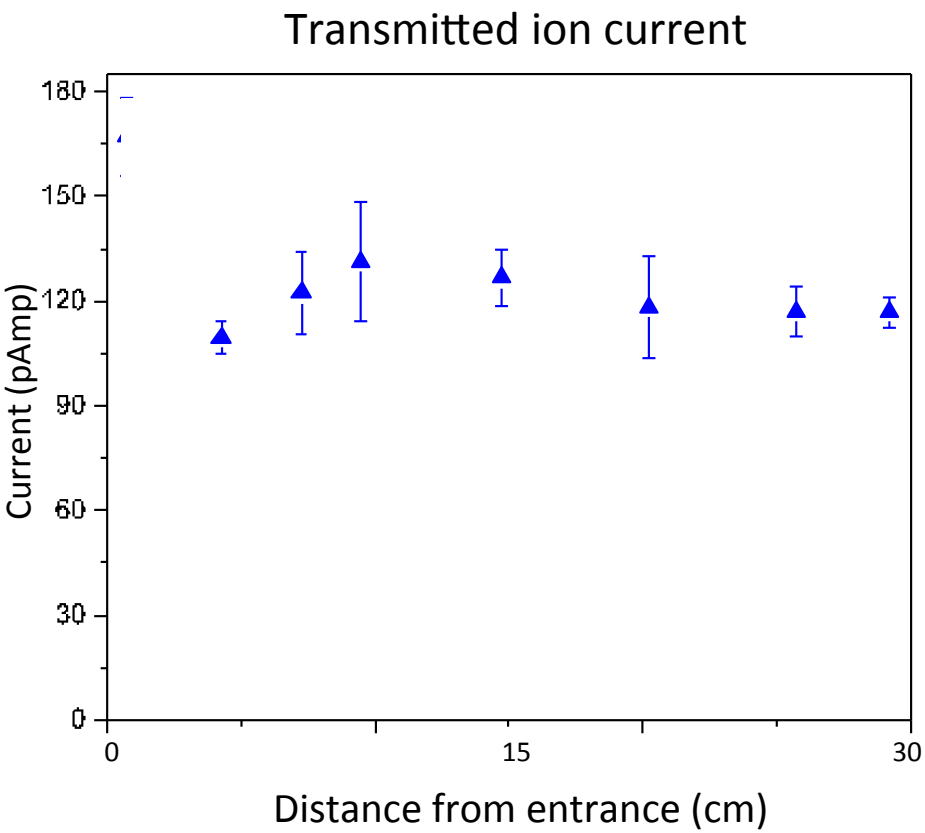
Multiple SLIM paths to yet higher resolution ion mobility separations

- Optimization of SLIM design and operating conditions
- Much longer path SLIM (e.g. multilevel designs)

Evaluation of an ion escalator for moving ions between SLIM levels

Escalator evaluated using short 30-cm TW SLIM IMS module

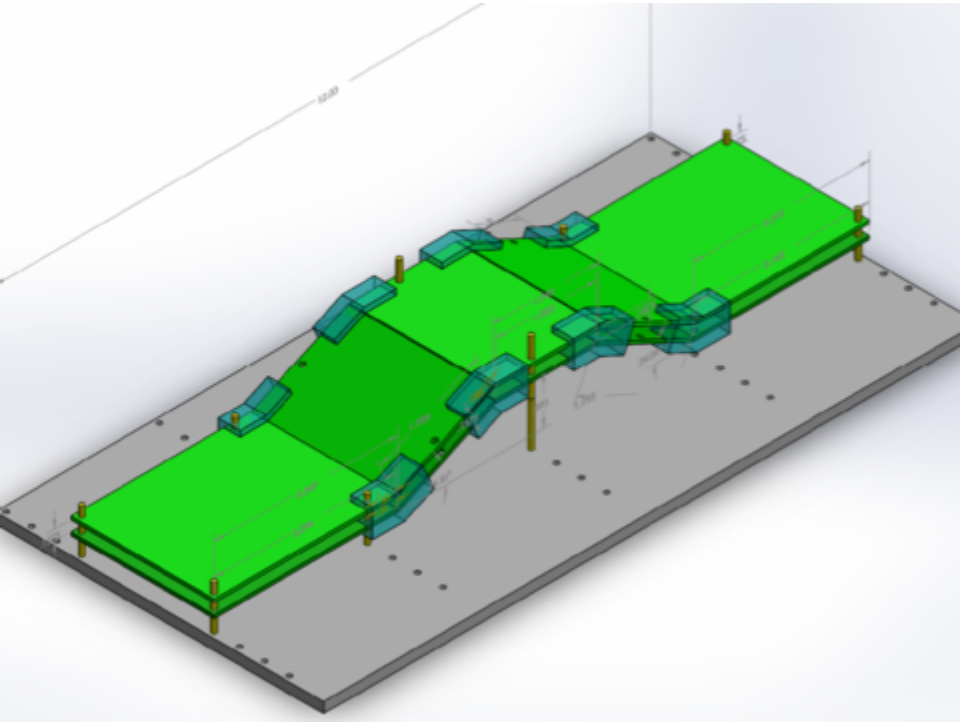




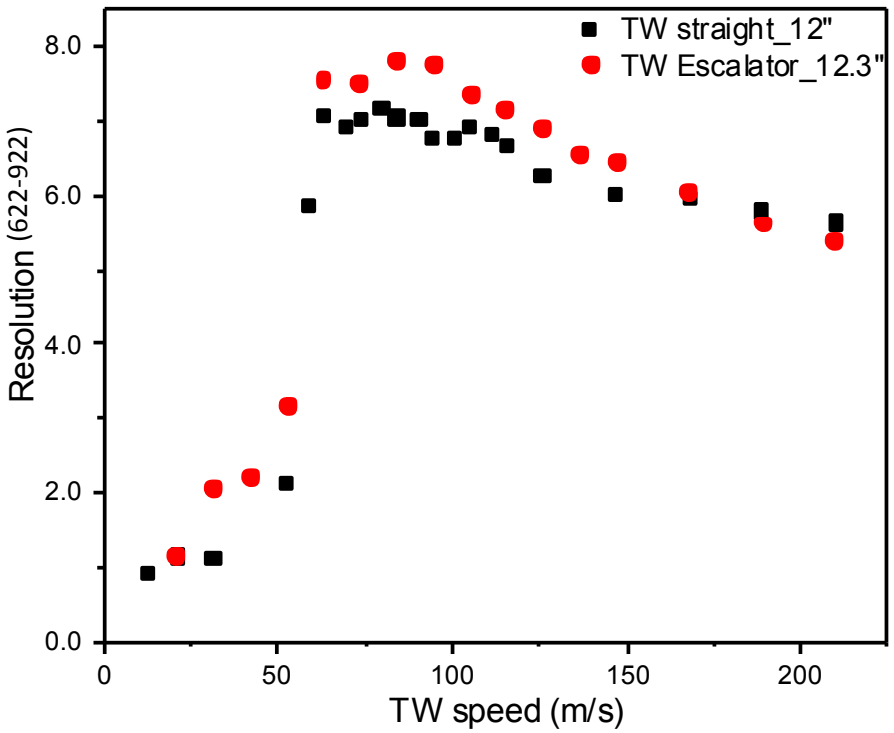
See Wednesday poster by Ahmed Hamid et al; WP452

Evaluation of an ion escalator for moving ions between SLIM levels

Escalator evaluated using short 30-cm TW SLIM IMS module

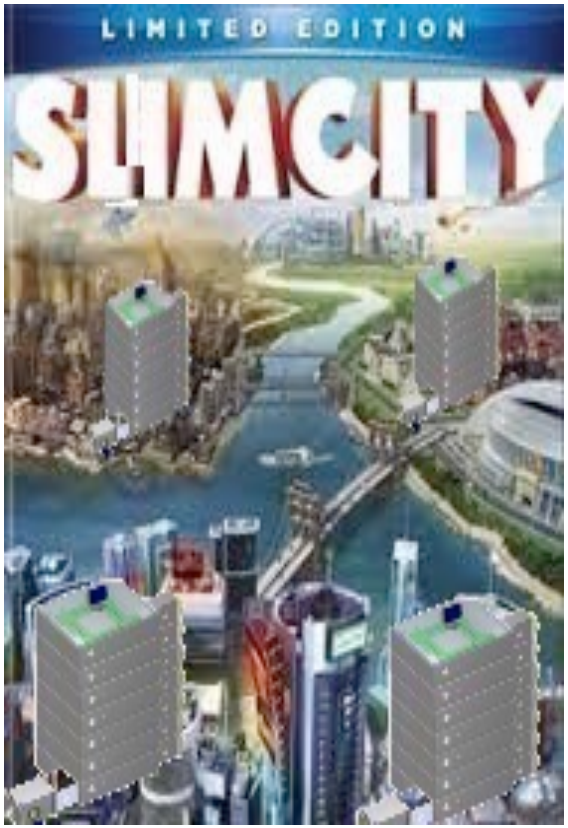


No degradation of IMS performance



See Wednesday poster by Ahmed Hamid et al; WP452

Building up in SLIM city; multi-level devices



Multi-level SLIM with ion escalators between levels

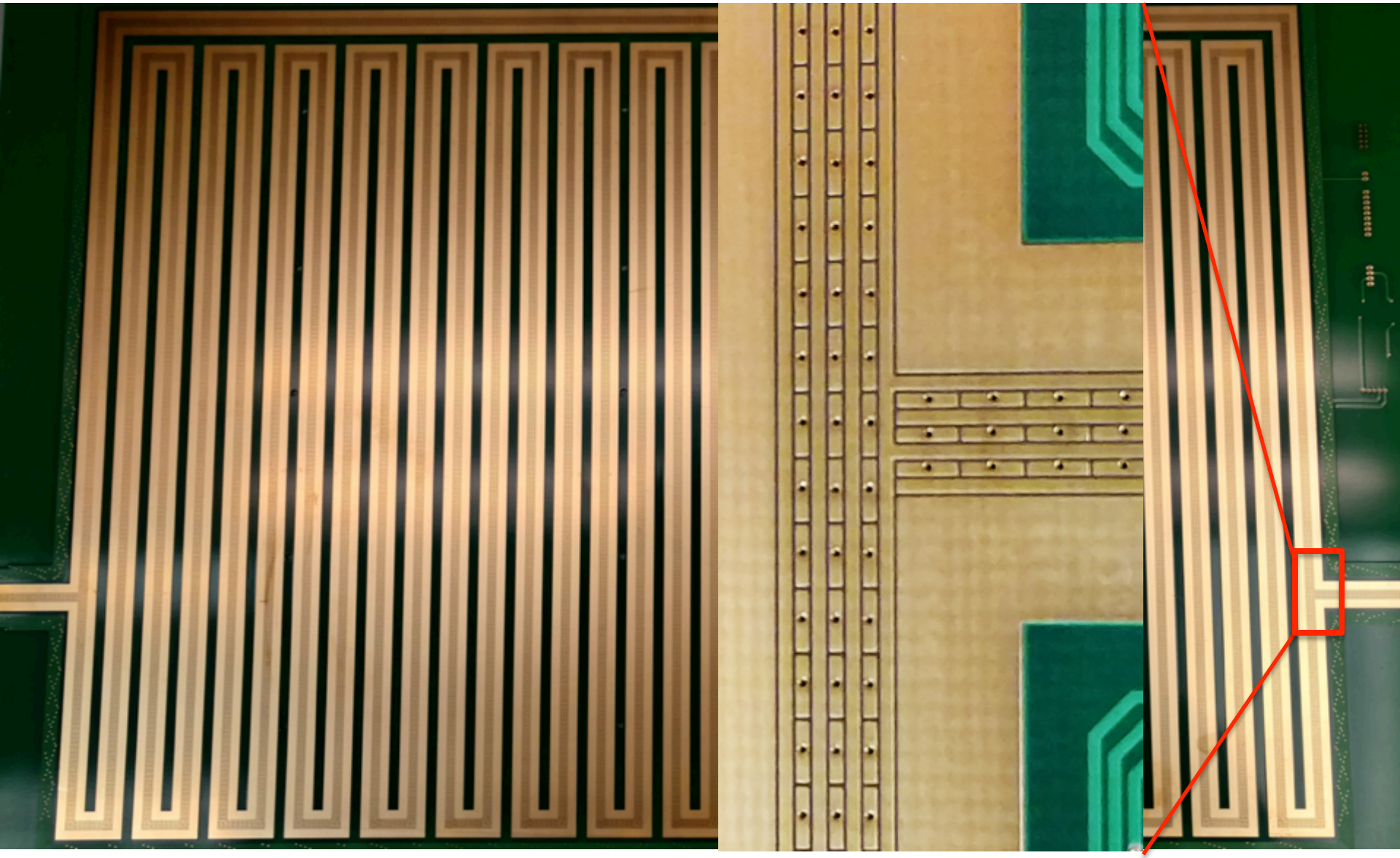
Multiple SLIM paths to higher resolution ion mobility separations

- Optimization of SLIM design and operating conditions
- Much longer path SLIM (e.g. multilevel designs)
- Multi-pass capability in conjunction with long path lengths

Multi-pass long path SLIM IMS implementation

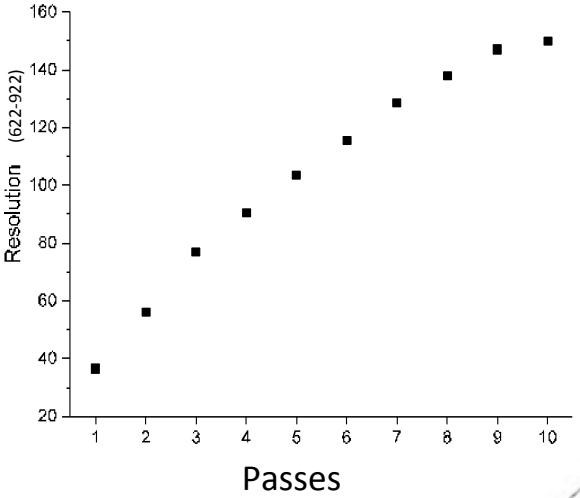
When one good turn deserves another (and another….)

Detail of switch

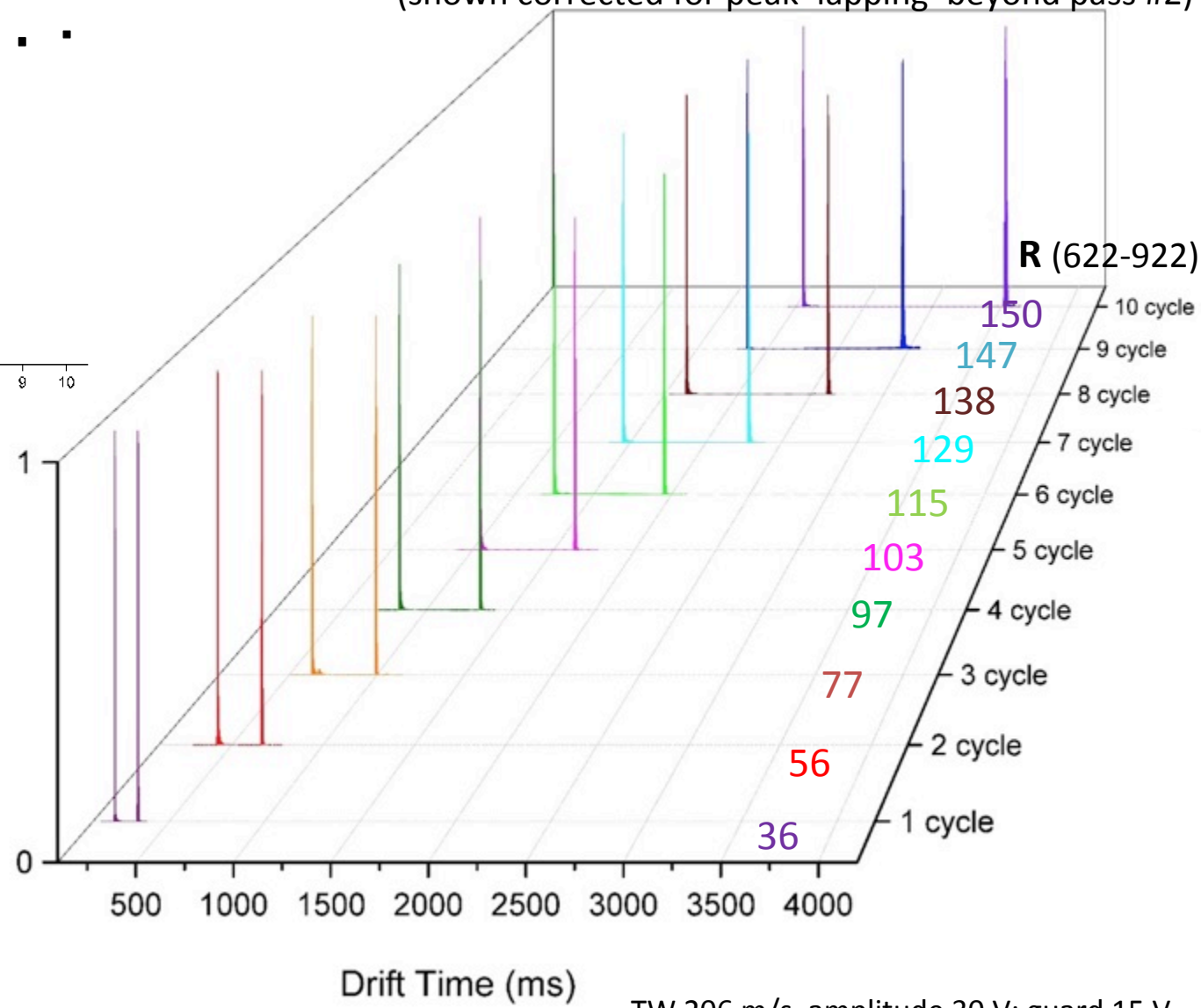


See Thursday oral presentation by Ian Webb; ThOH 8:50 AM

Separations in a multi-pass long path TW SLIM IMS module



Resolution for m/z 622 and 922
(shown corrected for peak 'lapping' beyond pass #2)



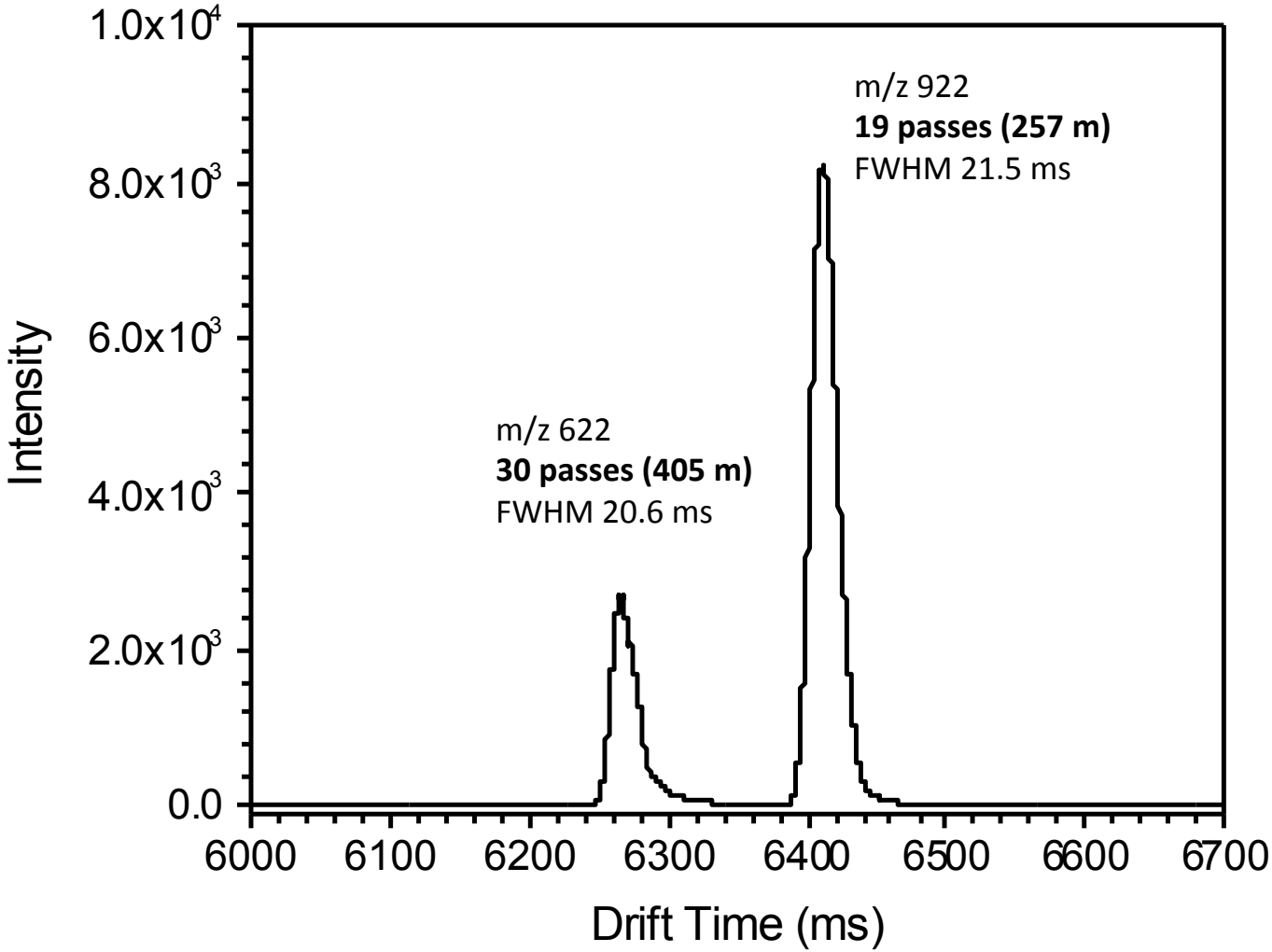
Liulin Deng

TW 206 m/s, amplitude 30 V; guard 15 V
RF 822 kHz, 340 V_{p-p}; 2.5 torr N_2; gap 2.75 mm

Multiple SLIM paths to higher resolution ion mobility separations

- Optimization of SLIM design and operating conditions
- Much longer path SLIM (e.g. multilevel designs)
- Multi-pass capability in conjunction with long path lengths
- Multi-level SLIM with multi-pass capability
- Better use of available path length using peak compression

Limitations due to increasing peak widths in long path TW SLIM IMS

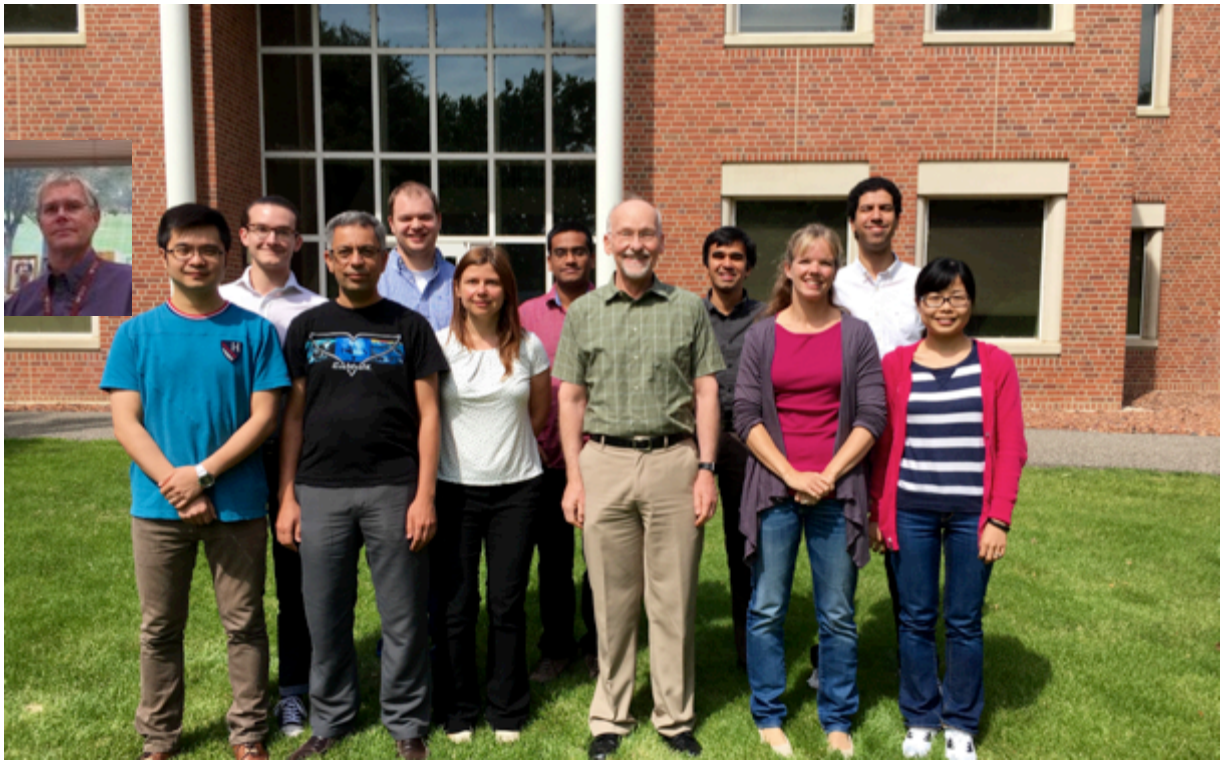


In Summary, sometimes there is not a catch….

- Very long path lengths in SLIM allow achieving significantly higher IMS resolution with MS demonstrated
- High resolution IMS separations achieved with efficient ion utilization
- Much longer path IMS feasible with multi-level designs (>200-m in compact designs); km paths with multi-pass separations and periodic peak compression
- Ion manipulations feasible with TW SLIM can be interfaced with essentially any MS platform type (e.g. FTICR or orbitraps)

Acknowledgements

PNNL SLIM Team



$upport

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Biomedical Technology Research Resource at PNNL

DOE Office of Biological and Environmental Research