Rapid Analysis of Synthetic Polymers and Polymer Additives Using Multi-Sample Solvent-free MALDI Target Preparation and ASAP Mass Spectrometric Approaches

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Polymers

Are complex mixtures for which physical properties such as:

- **tensile strength**
- **elasticity**
- **thermal and oxidative stability**

as well as molecular properties such as:

- **repeat unit**
- **end group or pendant group compositions**
- **branching**
- **molecular weight distribution**
- **additives composition**

are required for complete characterization.

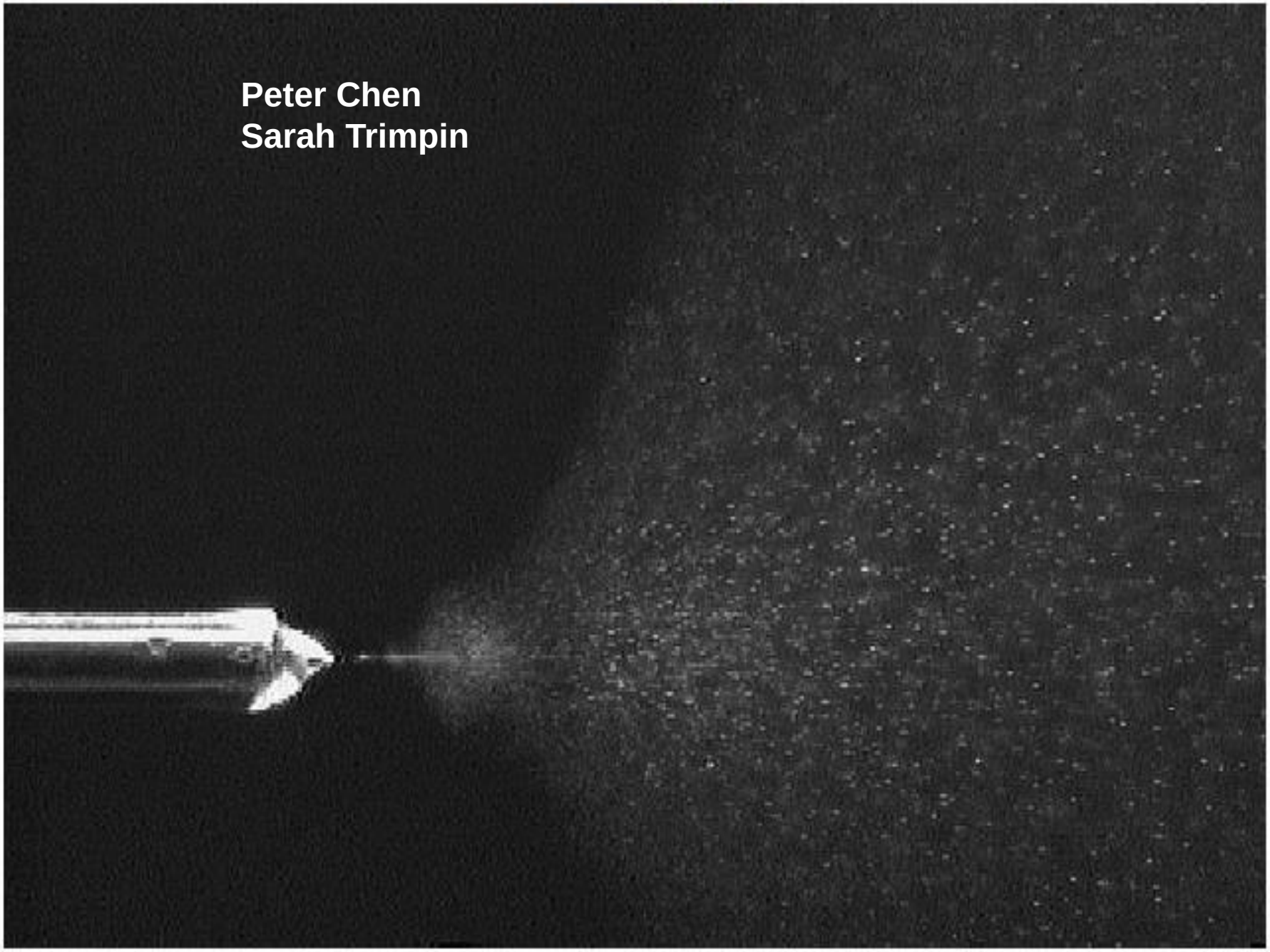
Mass Spectrometry Tools

- **MALDI**
- **LD**
- **ESI**
- **FD**
- **SIMS**
- **GC/MS**
- **LC/MS**
- **KIDS**
- **Pyrolysis (EI or CI)**
- **ESI-IMS/MS**

Challenges for Mass Spectrometry

- **Molar mass distribution (e.g. wide PD polymers)**
- **Ionization (e.g. non-polar, polyanion, insoluble polymers)**
- **Chemical composition (e.g. high-mass homopolymers, and lower mass co- and ter-polymers, especially with multiple end groups)**
- **Secondary structure (random, block, branched)**
- **Tertiary structure (e.g. elastomers)**
- **Quantitation (e.g. ends, additives, blends)**
- **Fast, cheap and accurate**

Electrospray



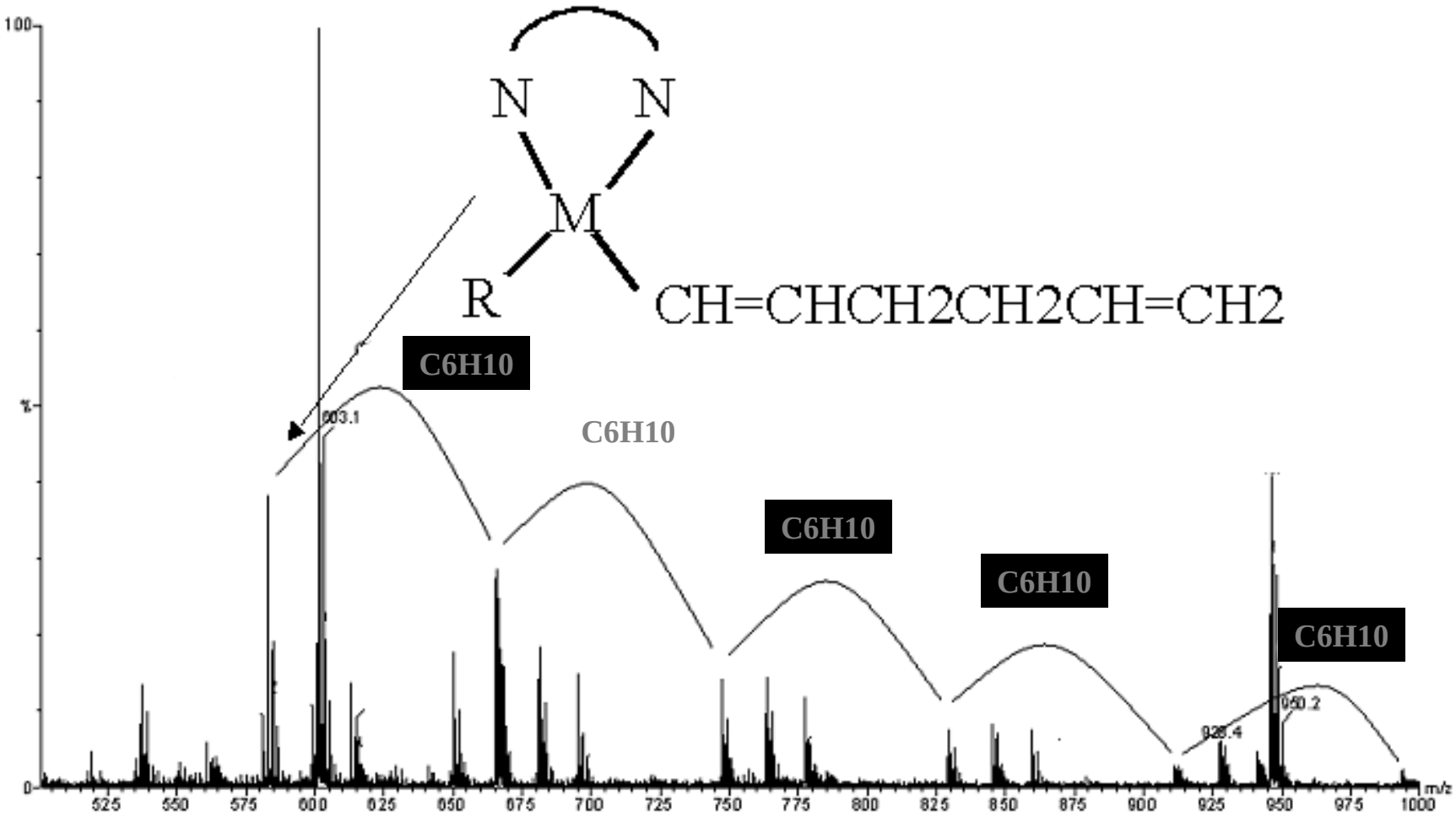
ESI MS for Studying Polymerization Catalysis

- Ethylene oligomers attached to homogeneous Ziegler-Natta Pd catalysts.
- Distributions were observed for the catalytic centers before and after chain transfer
- Obtained absolute rates of initiation, propagation, and chain transfer

- **Hinderling, C.; Chen, P. *Int J Mass Spectrom*, 2000, *195/196*, 377-383.**

Identification of Inactive Catalyst Species and Active Polymer/Catalyst Complexes

ESI of Versipol Catalysts with Growing Polymer Chain



Anal. Chem. **2007**, *79*, 7965−7974

Accelerated Articles

Resolving Oligomers from Fully Grown Polymers with IMS−MS

Sarah Trimpin, Manolo Plasencia, Dragan Isailovic, and David E. Clemmer*

Department of Chemistry, Indiana University, Bloomington, Indiana 47405

Ion mobility and mass spectrometry techniques, combined with electrospray ionization, have been used to examine distributions of poly(ethylene glycols) (PEG) with average molecular masses of 6550 and 17900 Da. The analysis provides information about the polymer size distributions as well as smaller oligomers existing over a wide range of charge states and sizes (i.e., $[HO(CH_2CH_2O)_xH + nCs]^{n+}$, where x ranges from 21 to 151 and n = 2 to 11 for the 6550 Da sample; and, x ranges from 21 to 362 and n = 2 to 23 for the 17 900 Da sample). The present data show that oligomer distributions also fall into families, corresponding to much narrower size distributions for individual charge states; this dramatically simplifies data analysis. For example, we show evidence for baseline resolution of the +10 charge state of polymers. Unlike the charge-state trends reported previously

and are, therefore, of significant interest.[1−3] Such compounds are described by indication of the monomer unit composition and a value that represents the average size or molecular weight [e.g., poly(ethylene glycol) (PEG) 6550, which corresponds to a polymeric ethylene oxide chain containing ~150 monomer units]. Historically, methods aimed at characterizing polymers (e.g., light scattering or size exclusion chromatography)[4] only provide information about the bulk material. However, it is generally understood that even simple polymers created from well-characterized reactions may exist as a mixture of sizes commonly defined by the polydispersity index (PDI).[4] If more complex chemistries are employed, significant chemical heterogeneity may also be present, such as variations in end-groups or within the polymer chain (e.g., copolymers).

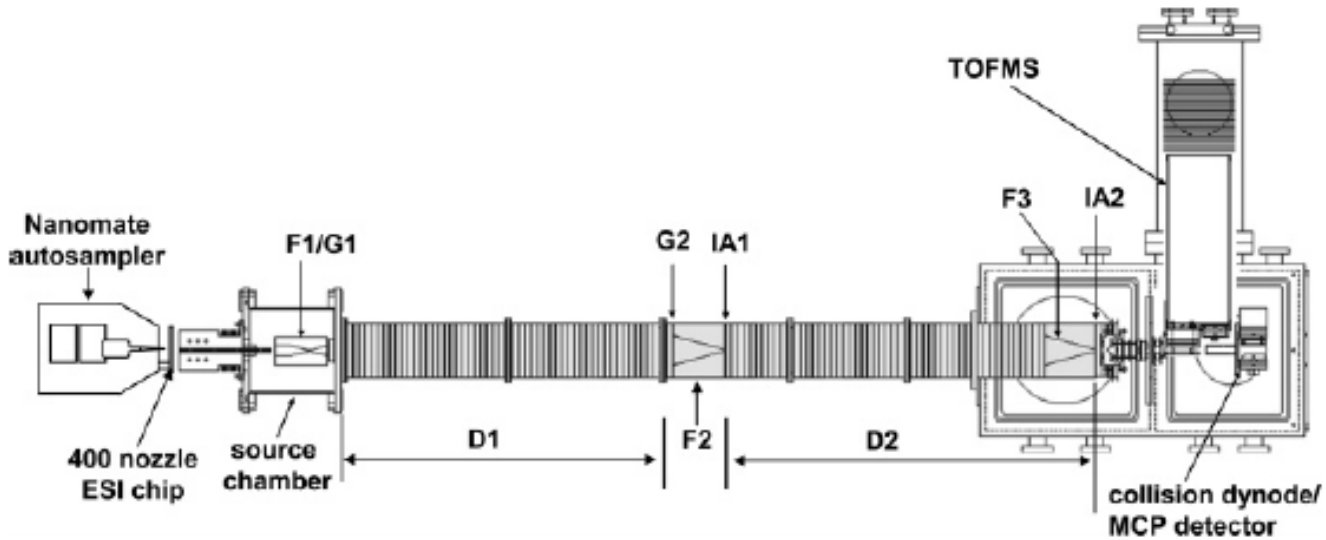


Figure 1. Schematic diagram of the ESI-IMS−IMS−MS instrument. Ions accumulated in the source funnel (F1) are gated through ion gate G1, where they undergo mobility separation in consecutive drift regions (D1, D2). Ions can be selected on the basis of mobility at G2 and used to determine cross sections. Samples are infused into the source region by means of a Nanomate autosampler mounted at the ESI source. For more detail on ion selection and cross section determination, refer to the text.

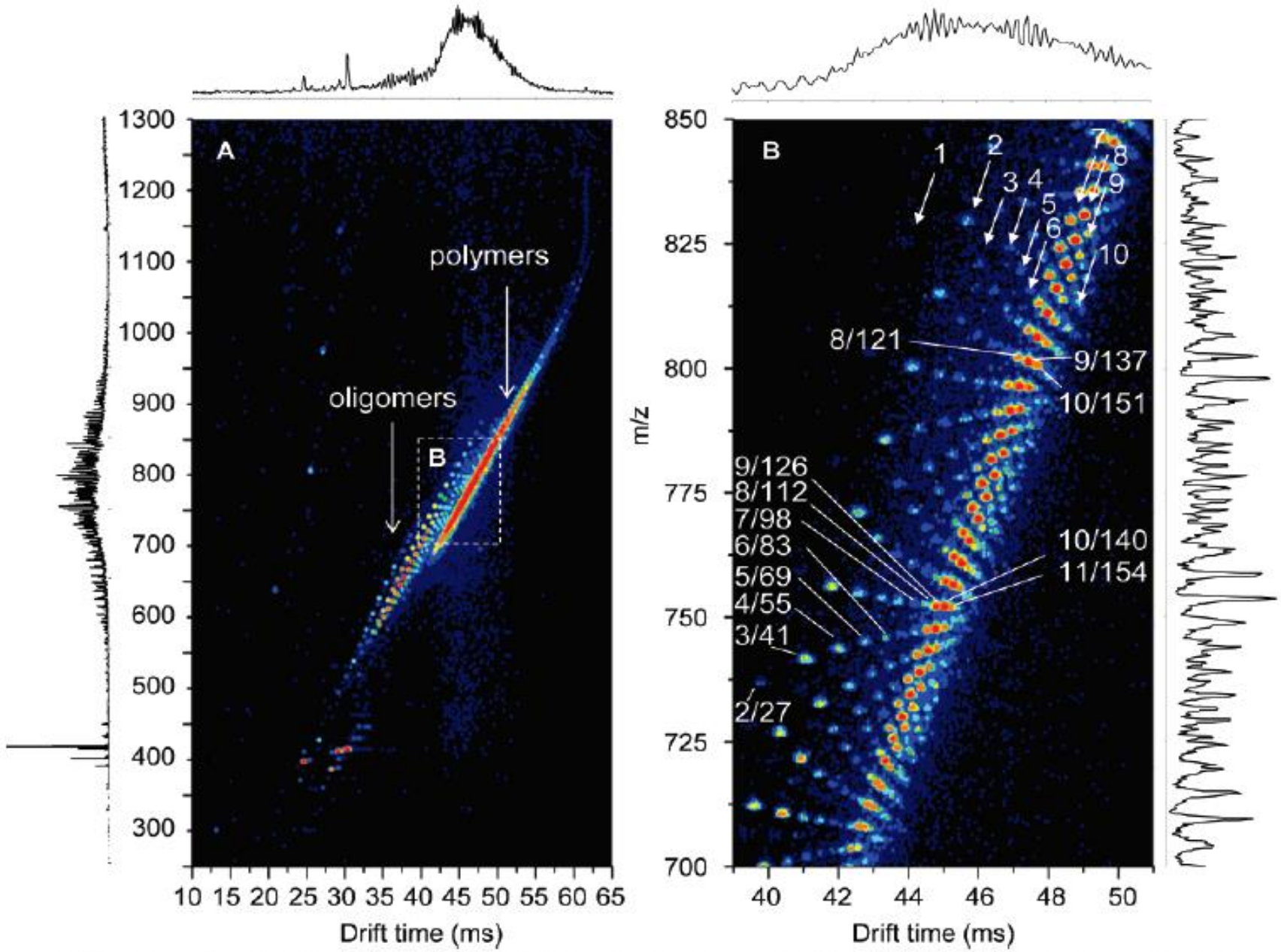
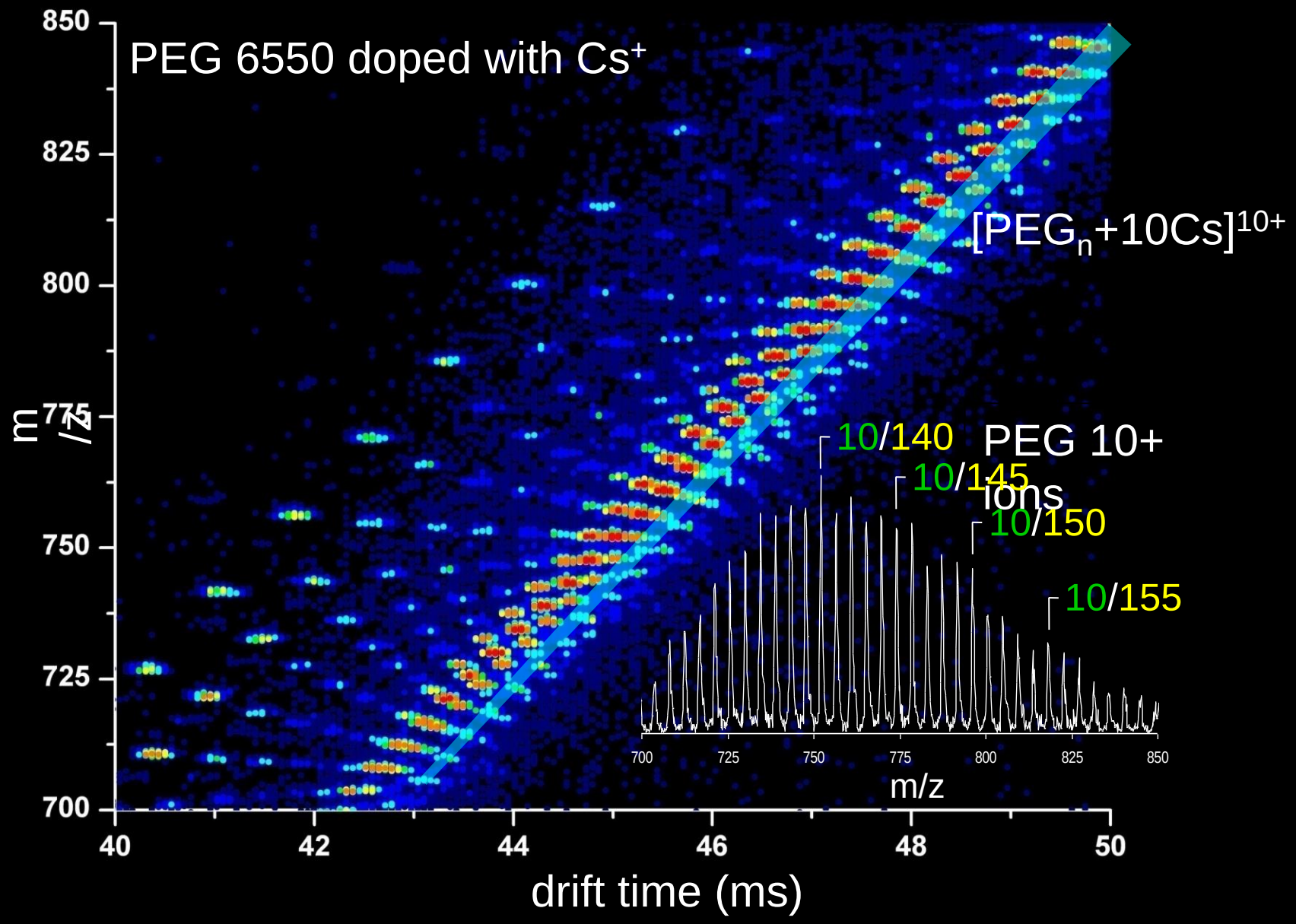
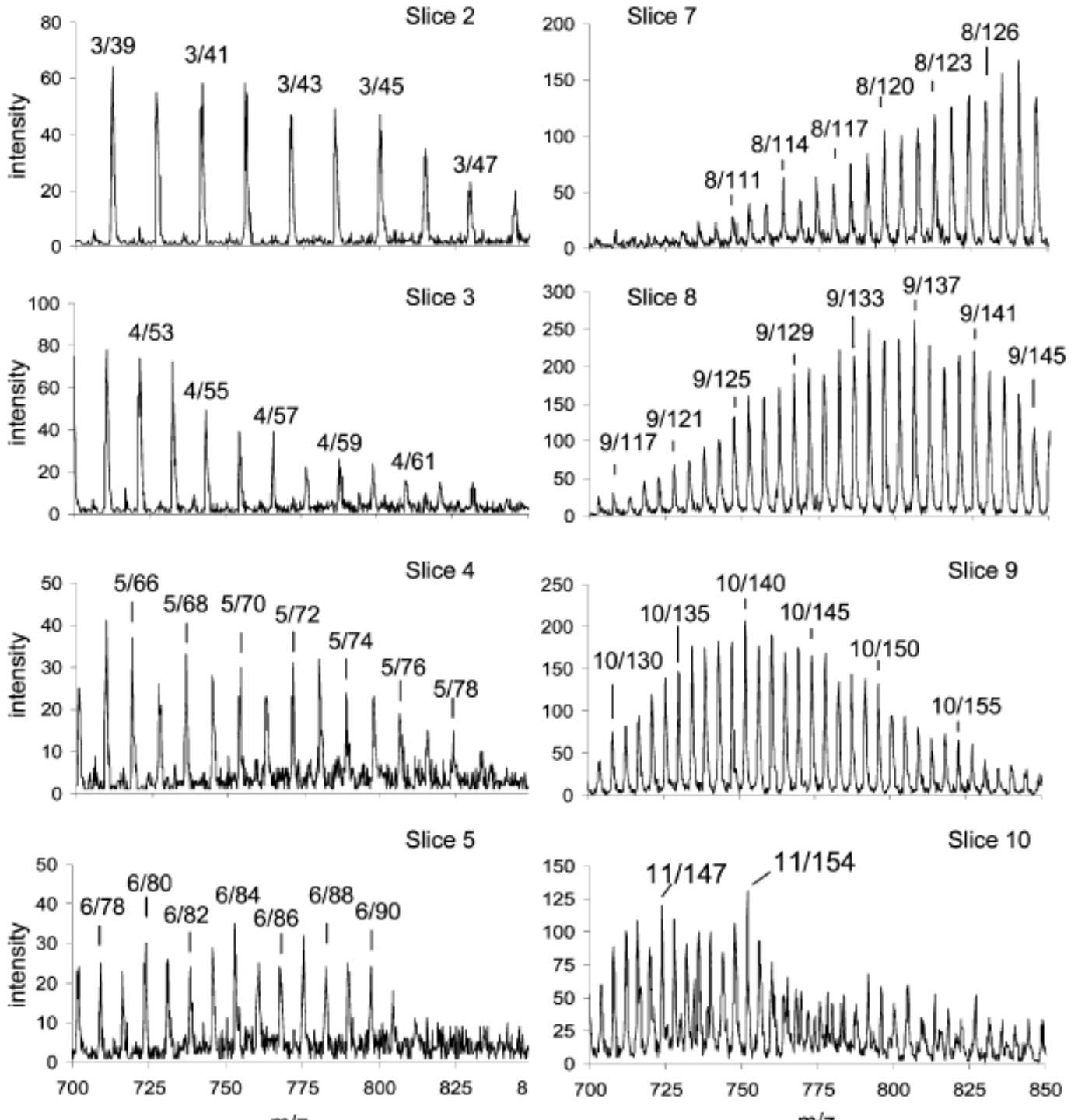


Figure 2. Two-dimensional $t_D(m/z)$ distribution of PEG 6550 doped with cesium acetate. The $t_D(m/z)$ distribution is shown on the left (inset A) with the integrated mass spectrum (trace on left of inset A) and integrated drift time distribution (top trace on inset A). The groups in the distribution corresponding to oligomers and polymers are labeled. Inset B (right panel) shows an expanded view of the $t_D(m/z)$ region of the most intense polymer features with representative integrated drift time distribution and mass spectrum. The charge-state resolved components are labeled by charge-state families ranging from low-intensity +2 oligomers to the more intense +10 and +11 polymers (white arrows).


PEG 6550 doped with Cs+
[PEGn+10Cs]10+
10/140
10/145
10/150
10/155
PEG 10+ ions
m/z
drift time (ms)
850
825
800
775
750
725
700
40
42
44
46
48
50


Slice 2
3/39
3/41
3/43
3/45
3/47
intensity
Slice 7
8/111
8/114
8/117
8/120
8/123
8/126
Slice 3
4/53
4/55
4/57
4/59
4/61
intensity
Slice 8
9/117
9/121
9/125
9/129
9/133
9/137
9/141
9/145
Slice 4
5/66
5/68
5/70
5/72
5/74
5/76
5/78
intensity
Slice 9
10/130
10/135
10/140
10/145
10/150
10/155
Slice 5
6/78
6/80
6/82
6/84
6/86
6/88
6/90
intensity
Slice 10
11/147
11/154
700
725
750
775
800
825
850

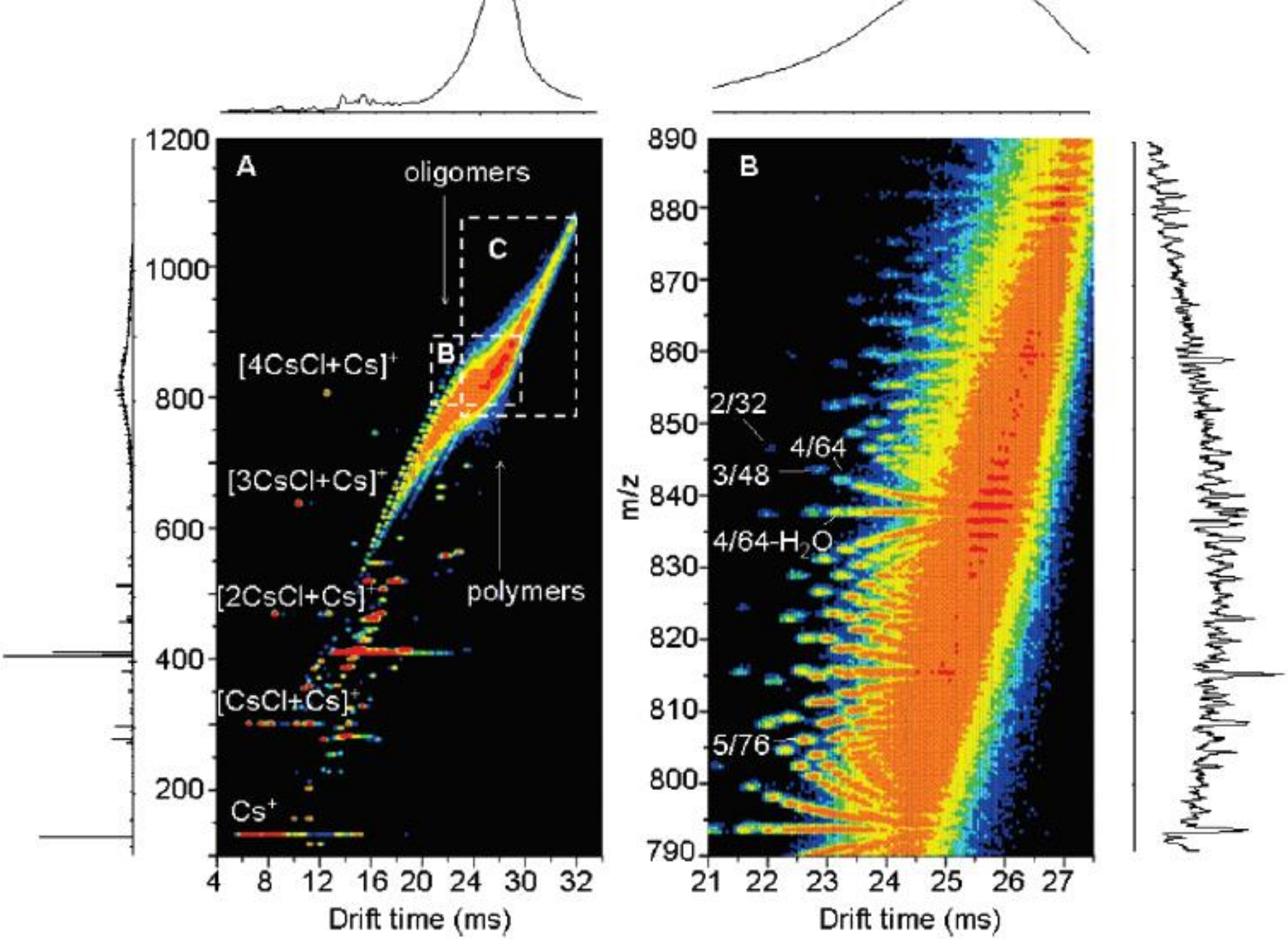
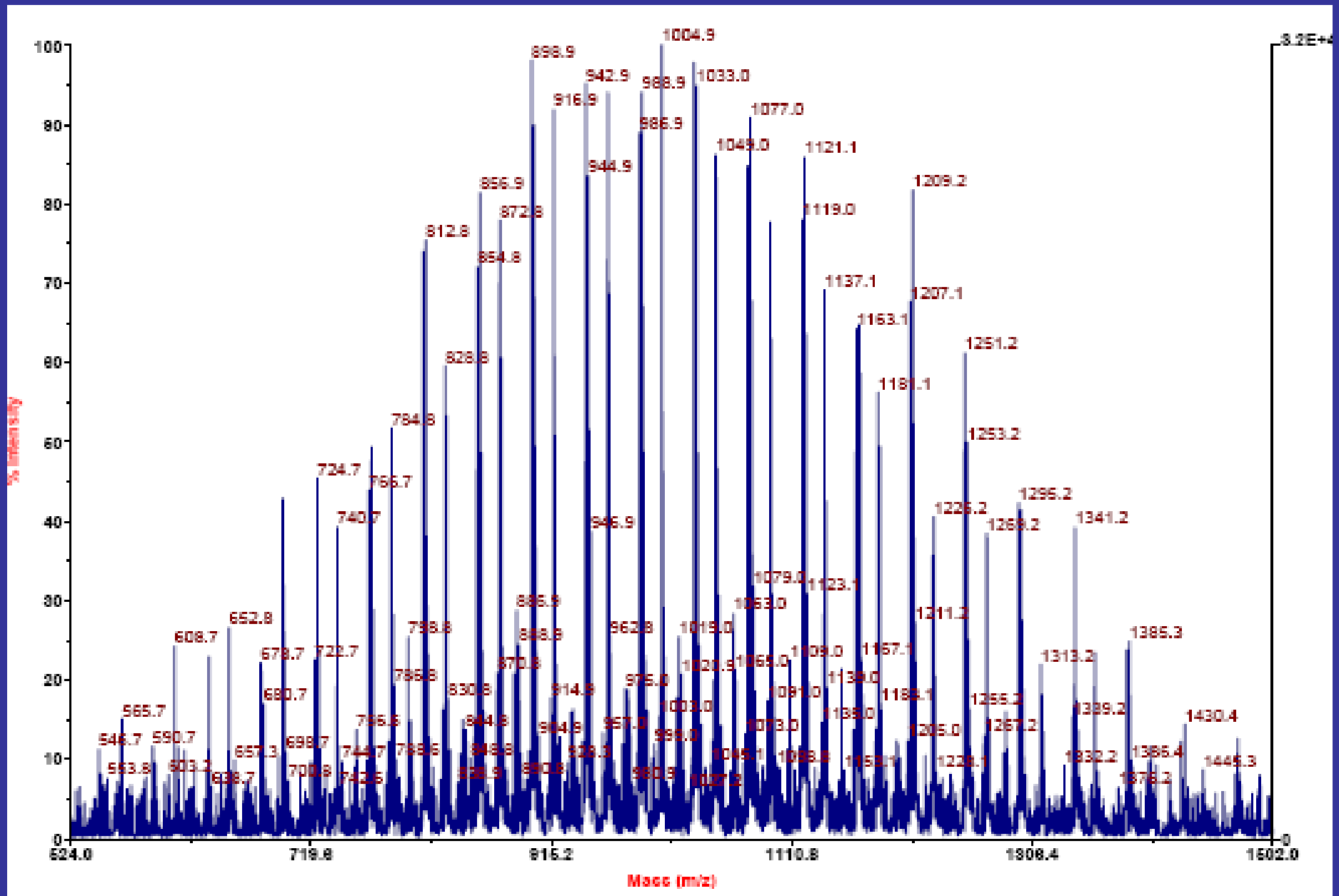


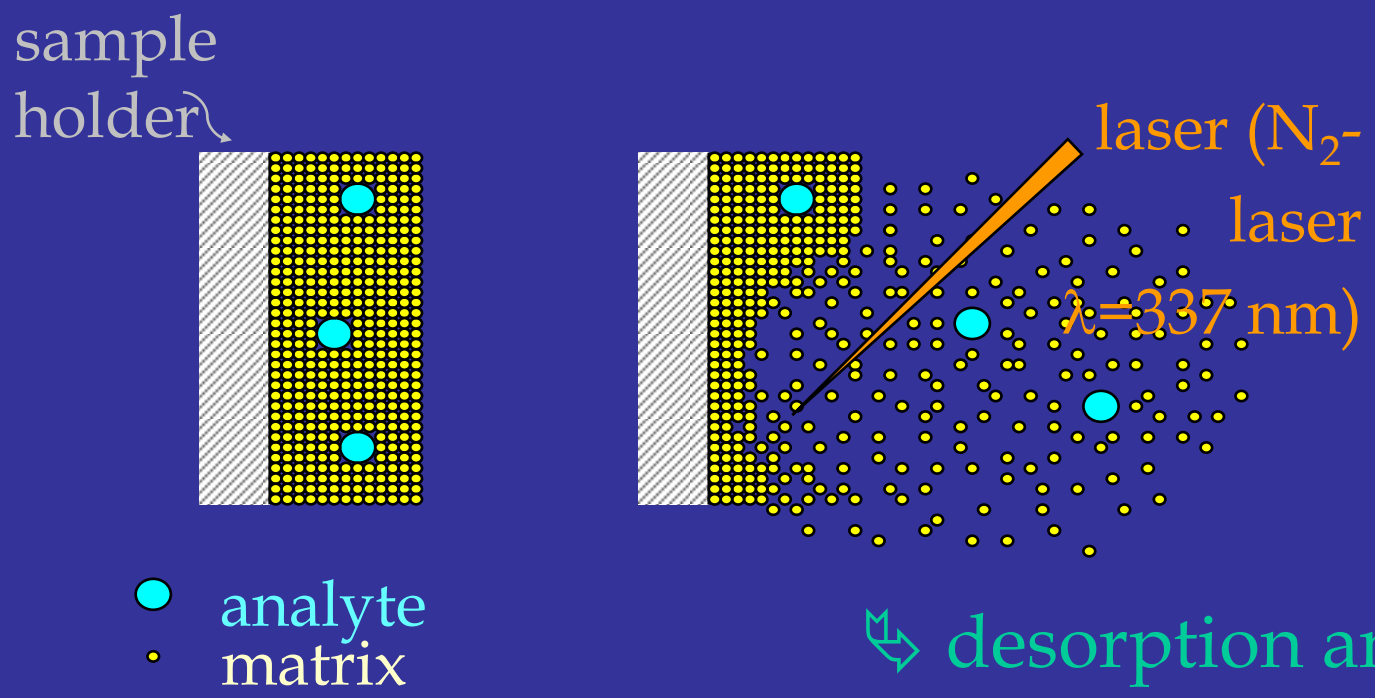
Figure 4. Two-dimensional $t_D(m/z)$ distribution of PEG 17 900 doped with cesium chloride. The $t_D(m/z)$ distribution is shown on the left (inset A) with corresponding total drift time distributions and integrated mass spectrum (top and leftmost trace, respectively). Prominent features in the distribution include cesium chloride clusters and regions dominated by oligomers and polymers (C, see Figure 5). Inset B shows an expanded view of the $t_D(m/z)$ region where the representative polymer (high charge-state) family is separated from smaller species (oligomers).

MALDI MS of a Random Copolymer



clemmer@indiana.edu

Matrix-Assisted Laser Desorption/Ionization (MALDI)



↳ desorption and ionization of the macromolecules

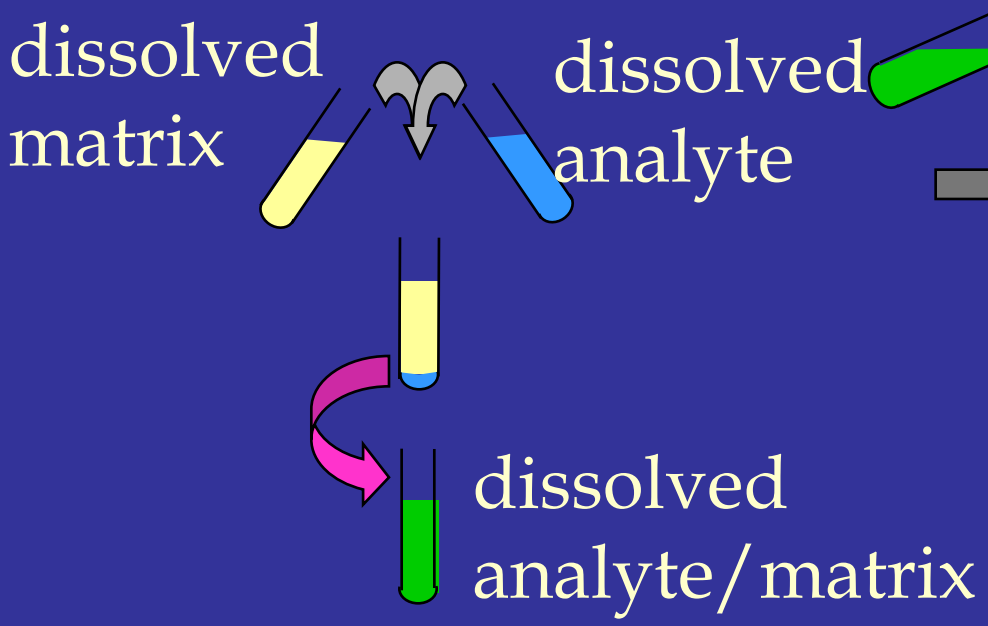
Properties and Significance of MALDI

- Mild desorption/ionization: often fragment-free
- Nearly unlimited mass range
- Broad applicability to macromolecule characterization:
  - Low sample amounts required
    → important for biological applications
  - Singly charged molecule ions
    → important for synthetic polymers and mixtures

⇒ MALDI and ESI complementary

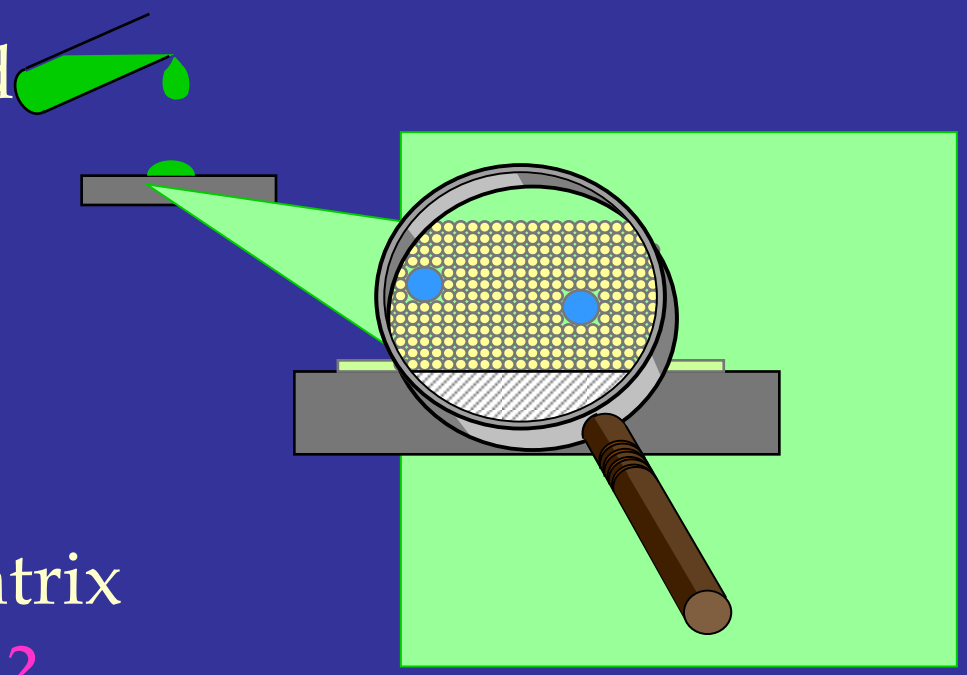
Solvent-based Sample Preparation

homogenization



homogenous solution!?

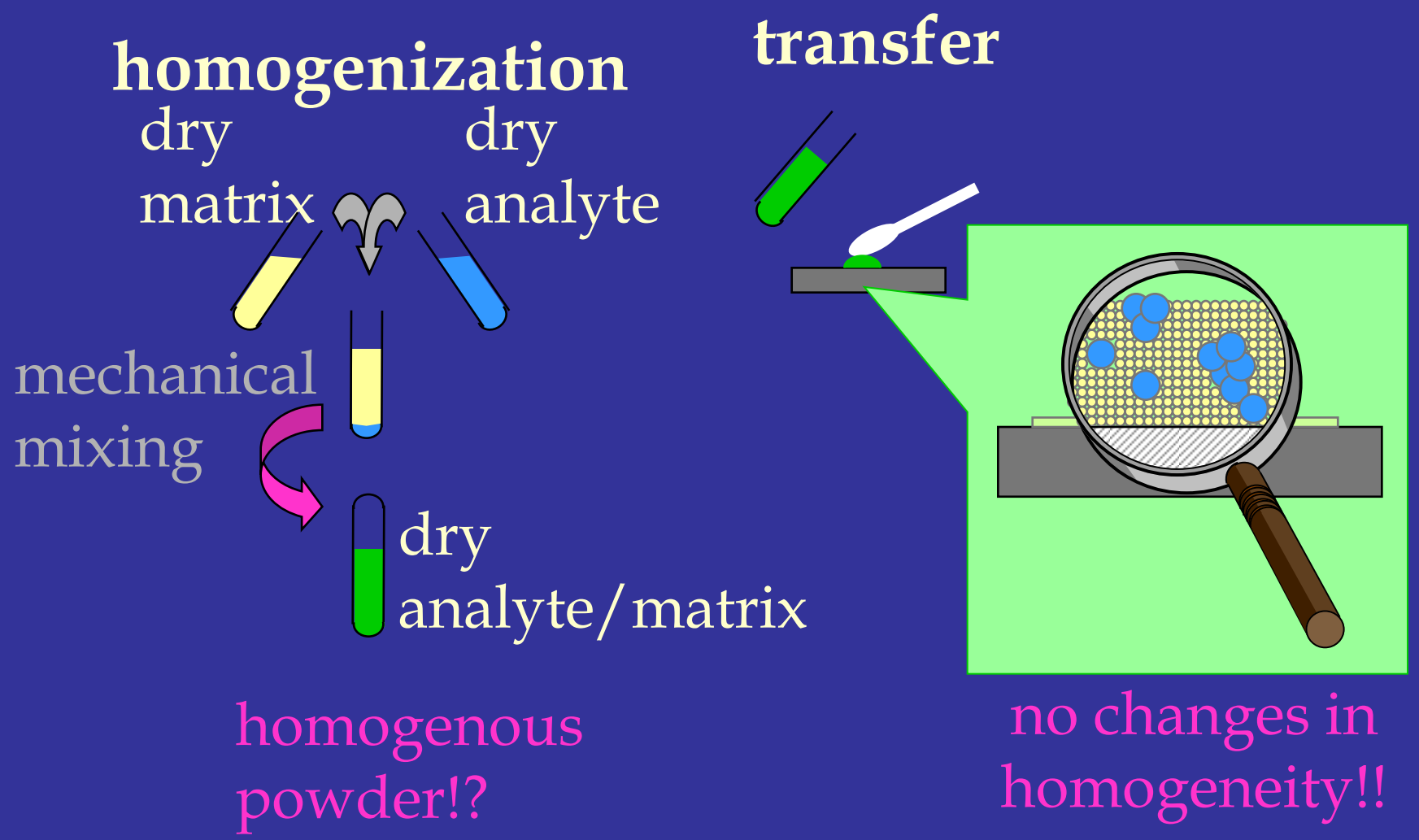
transfer



homogenous crystal formation!

Karas, M., Bahr, U., Bachmann, D., Hillenkamp, F. *Int. J. Mass Spectrom. Ion Processes* 1989, *92*, 231-242.

Solvent-free Sample Preparation



Trimpin, S., Rouhanipour, A., Az, R., Räder, H.J. and Müllen, K. *Rapid Commun. Mass Spectrom.* 15: 1364-1373, 2001.

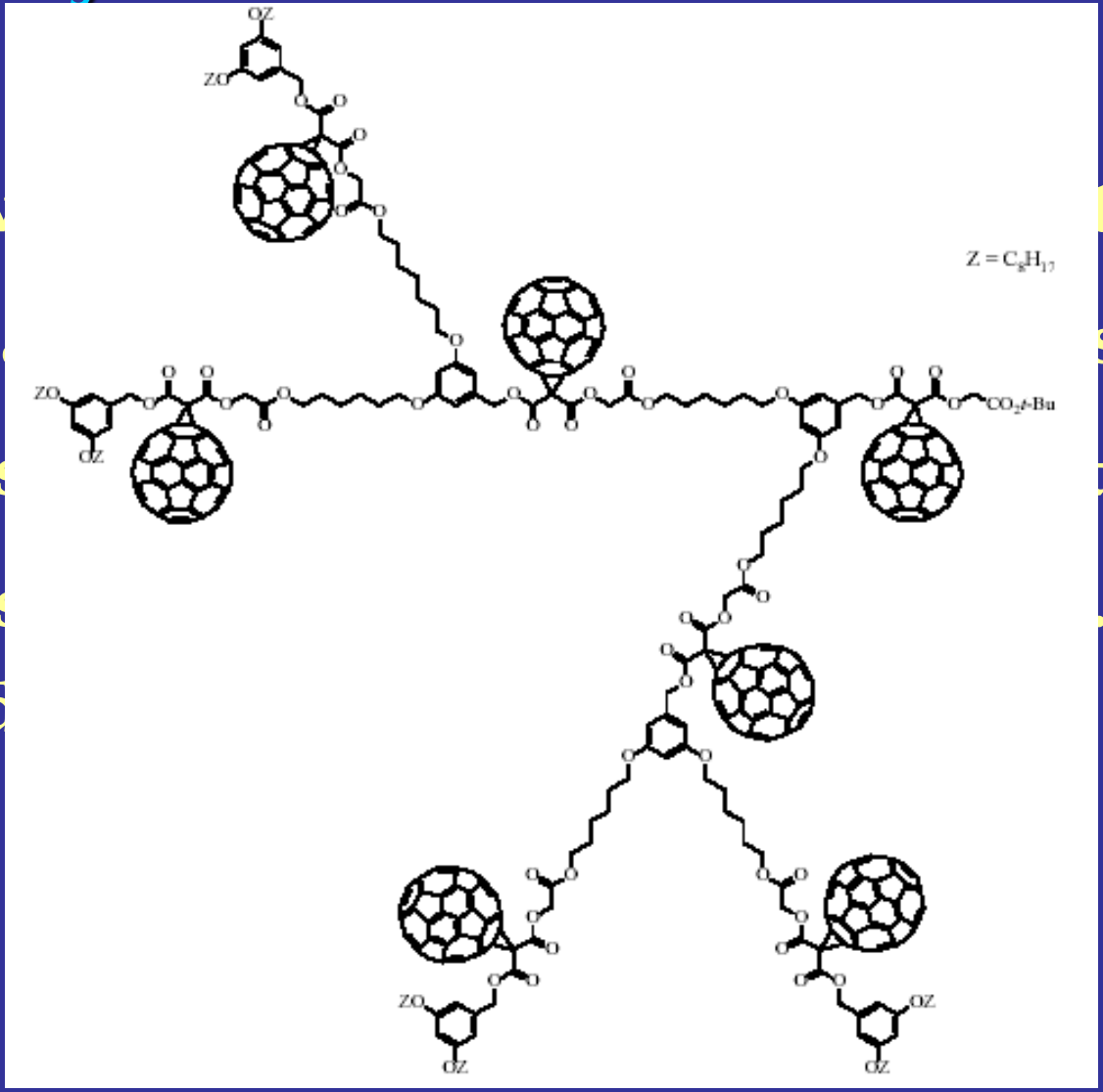
Analyte/matrix homogenization

Mortar and pestle

Ball Mill (mini ball mill)

Vortex devices

Advantages Beyond Solubility of Synthetic Macromolecules



- Low tation)
- Gre s)
- No s trials)
- No s g. oxid

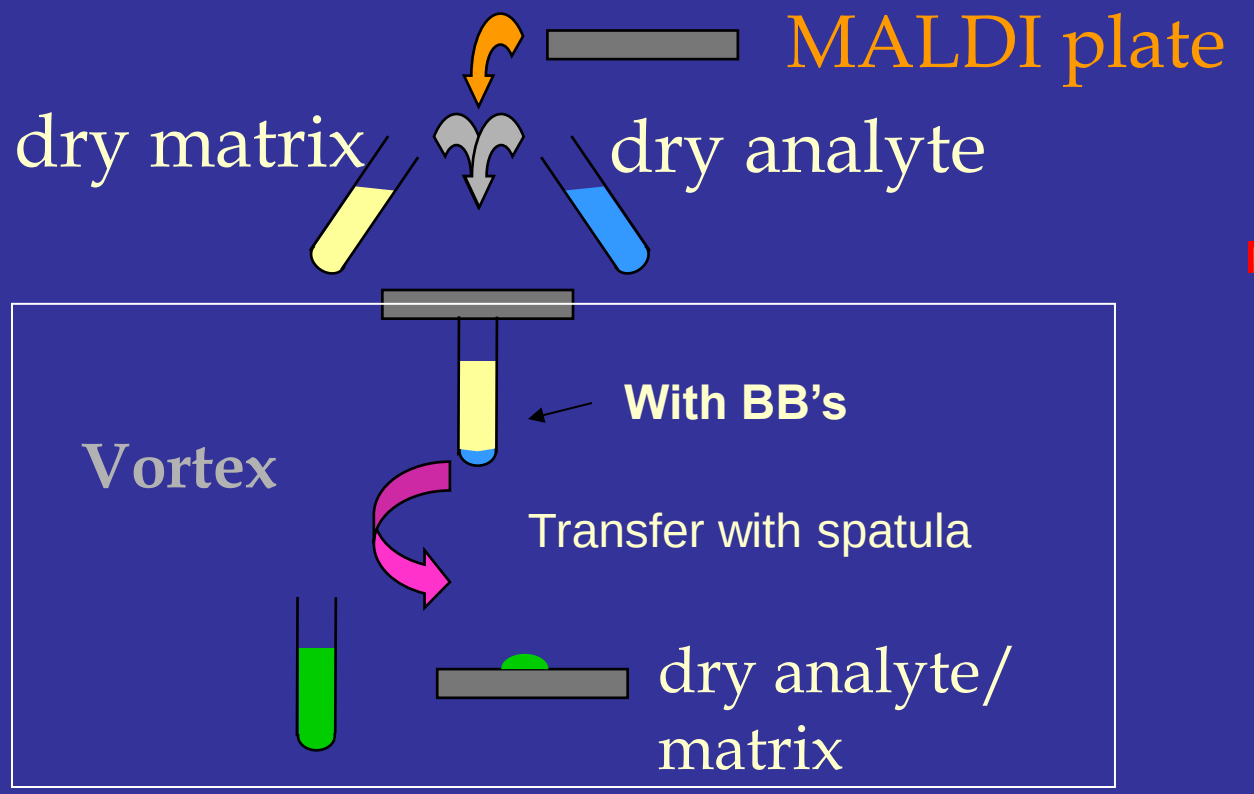
Advantages Beyond Solubility of Synthetic Macromolecules

- Less laser power (fragmentation intense analytes)
- No segregation (fewer optimization trials)
- No alteration of sample during sample prep

Trimpin, S., Keune, S., Räder, H.J., Müllen, K. *J. Amer. Mass Spectrom.* 17: 661-671, 2006.

Solvent-free single sample preparation

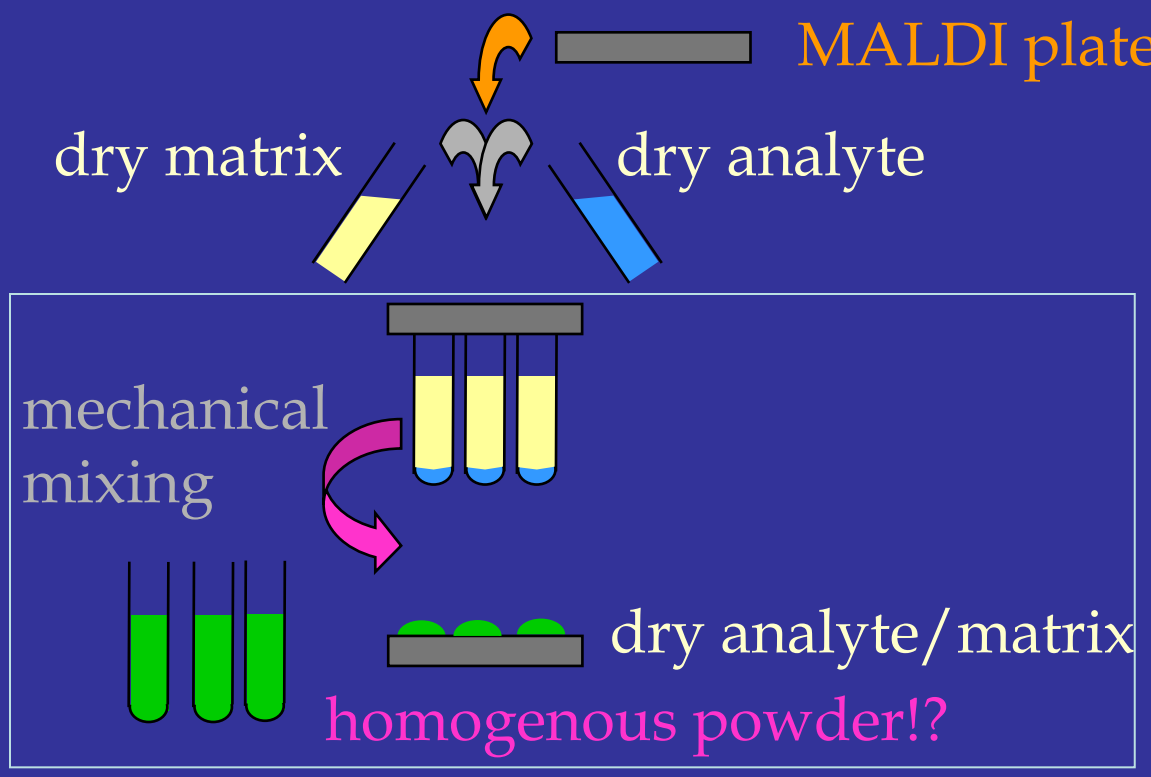
Homogenization + transfer



Hanton, S.D.: Parees, D.M. J.Am. Soc. Mass Spectrom., 2005, 16, 90-93.

Solvent-free multisample preparation

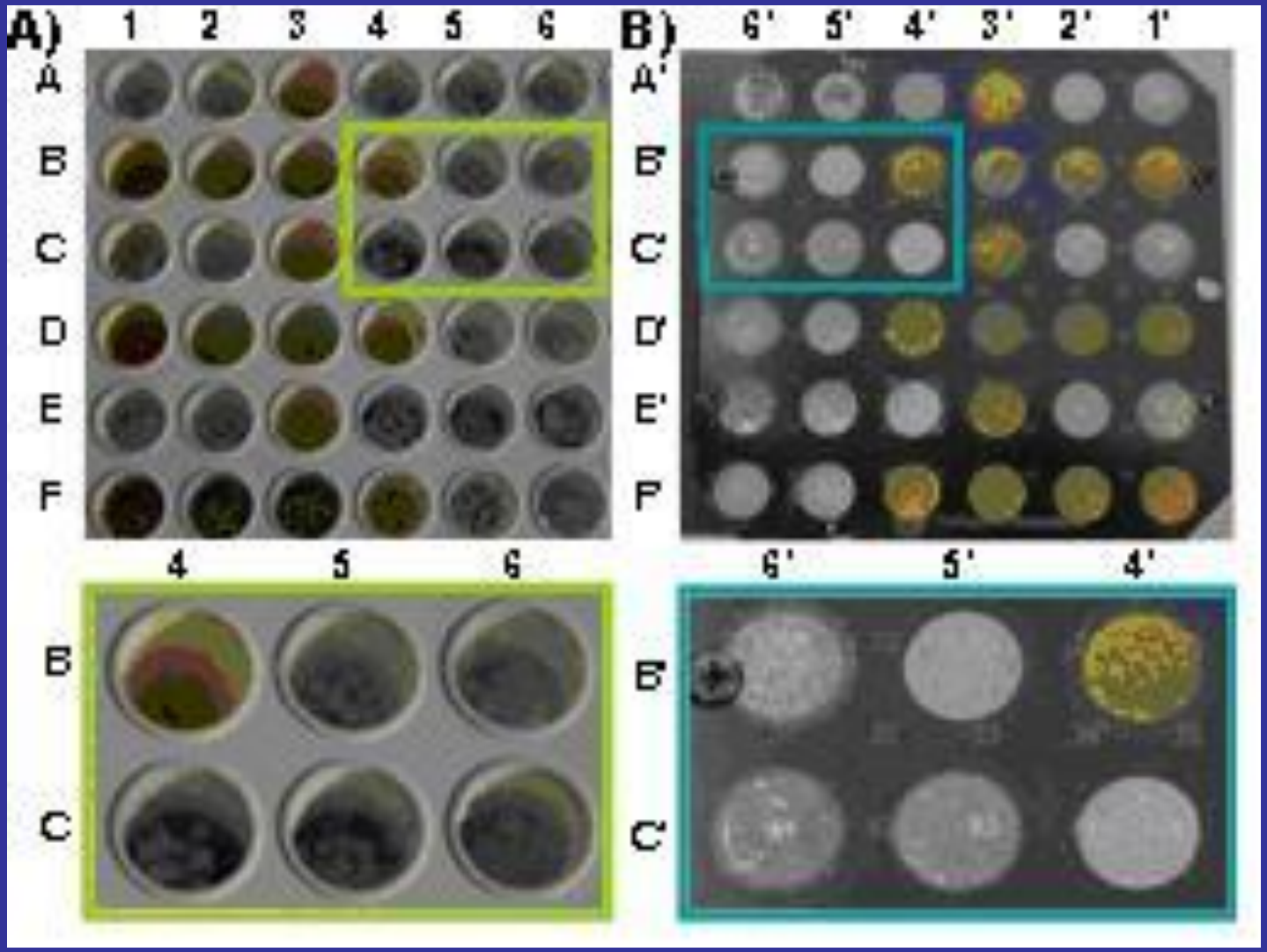
homogenization/transfer simultaneously



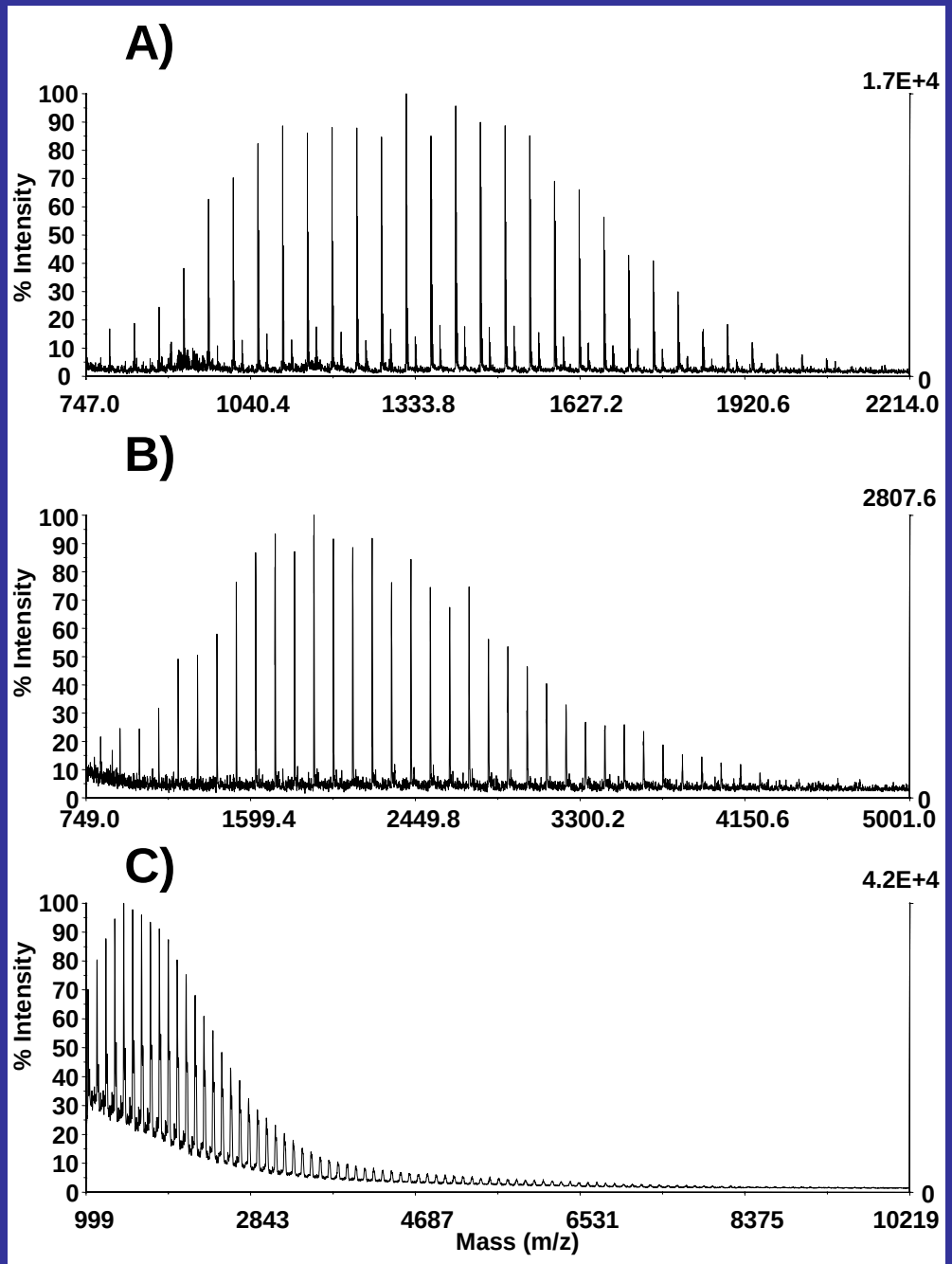
- Sample preparation reduced to a single step.
- Time savings
- Multiplexed sample preparation gives prospect for high throughput

Trimpin, S., McEwen, C.N. *JASMS* , 2007, 18, 377-381.

Bactiplate (A) and Mirror Image MALDI Plate (B) Employing 5 min. Vortexing



Multisample Solvent free MALDI Preparation

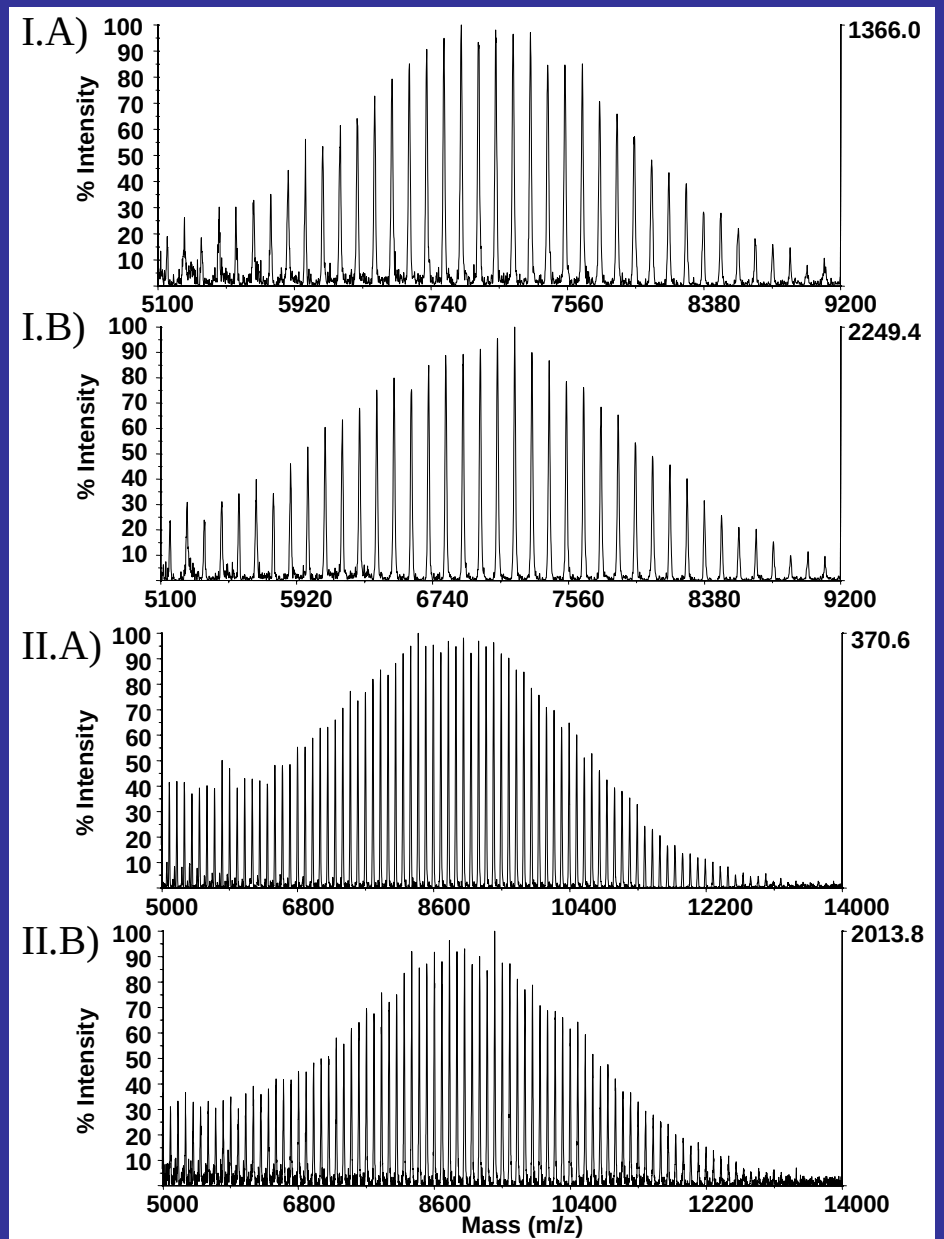


PEG 1400

PMMA 1830

PMMA 1830, 2400, 2990, 3800, 5270, 6950, 10300
Equi-weight

Multisample Solvent-free MALDI Preparation: IA and IB comparing reproducibilityIIA and IIB comparing solvent-free vs. solvent-based



PS 7200
Solvent-free

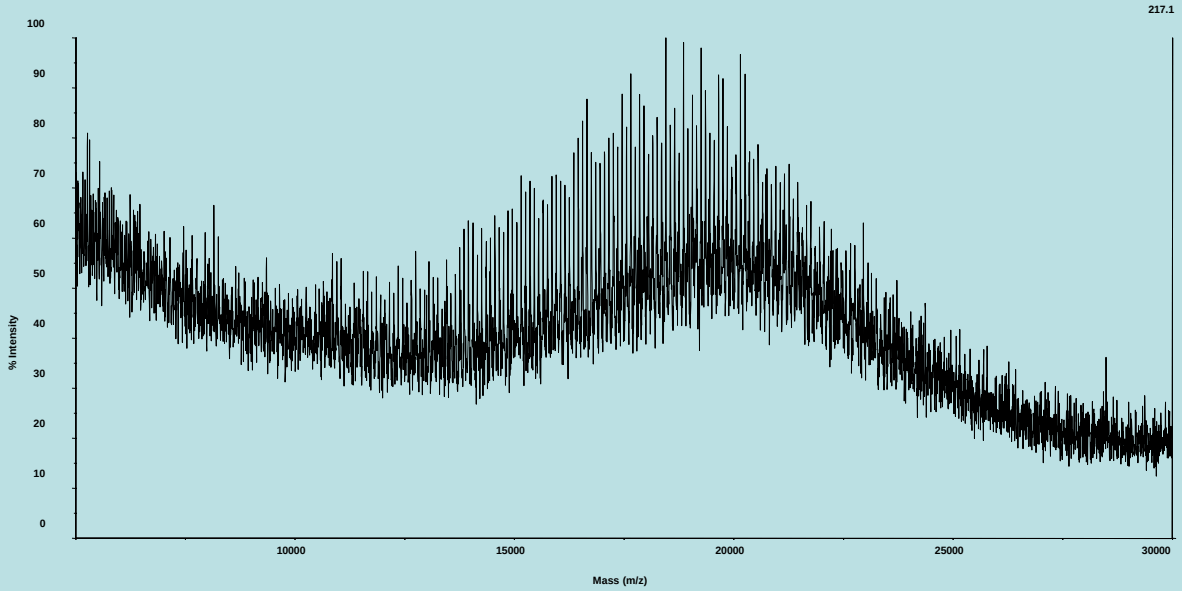
PS 7200
Solvent-based

PMMA 10300
Solvent free

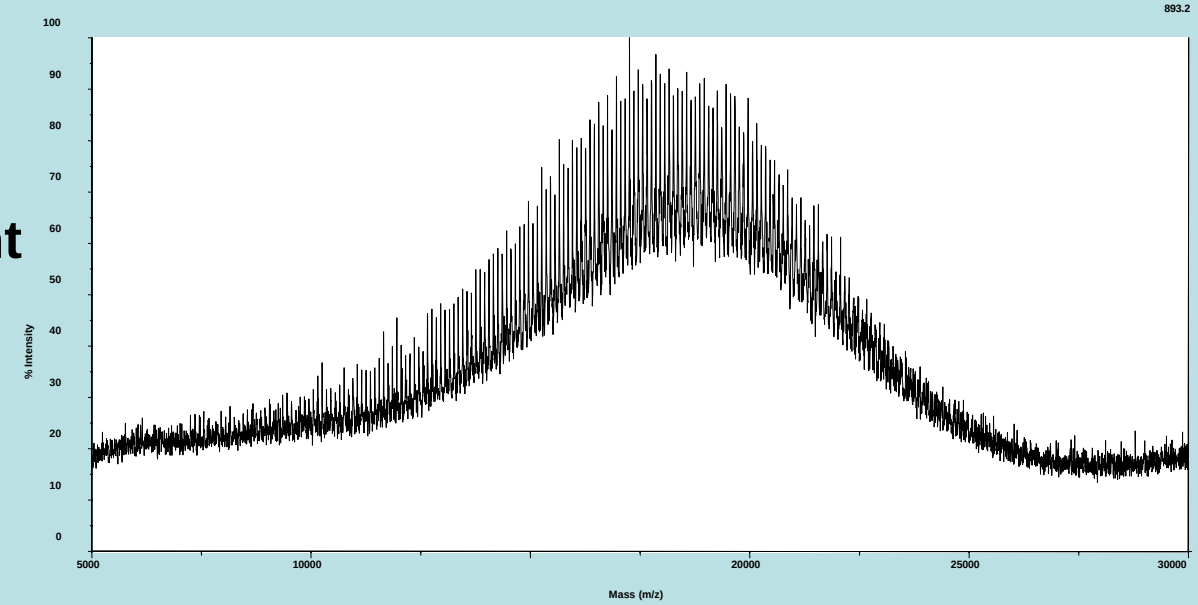
PMMA 10300
Solvent based

PMMA 21000

5 min Solvent free

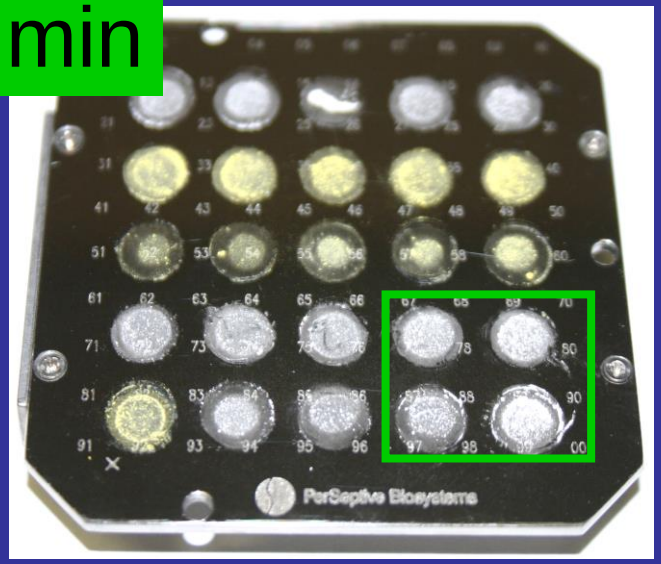


Solvent based

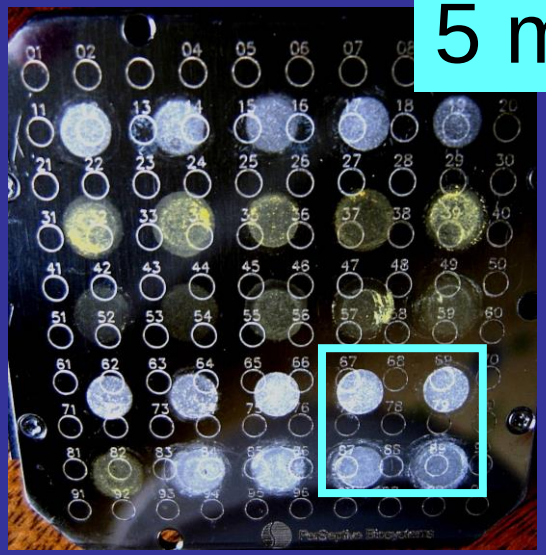


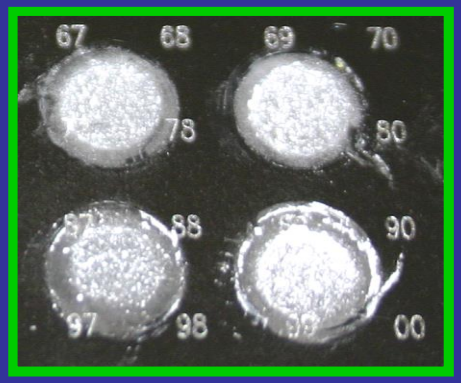
Multisample(25) Solvent-free MALDI Analysis

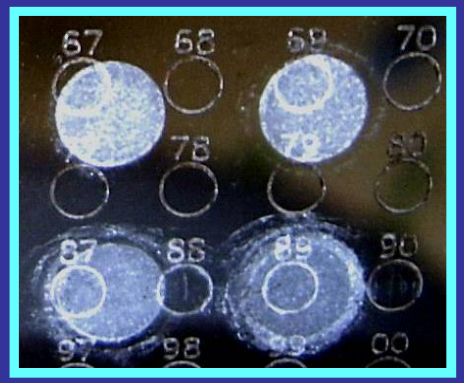
2 min



5 min



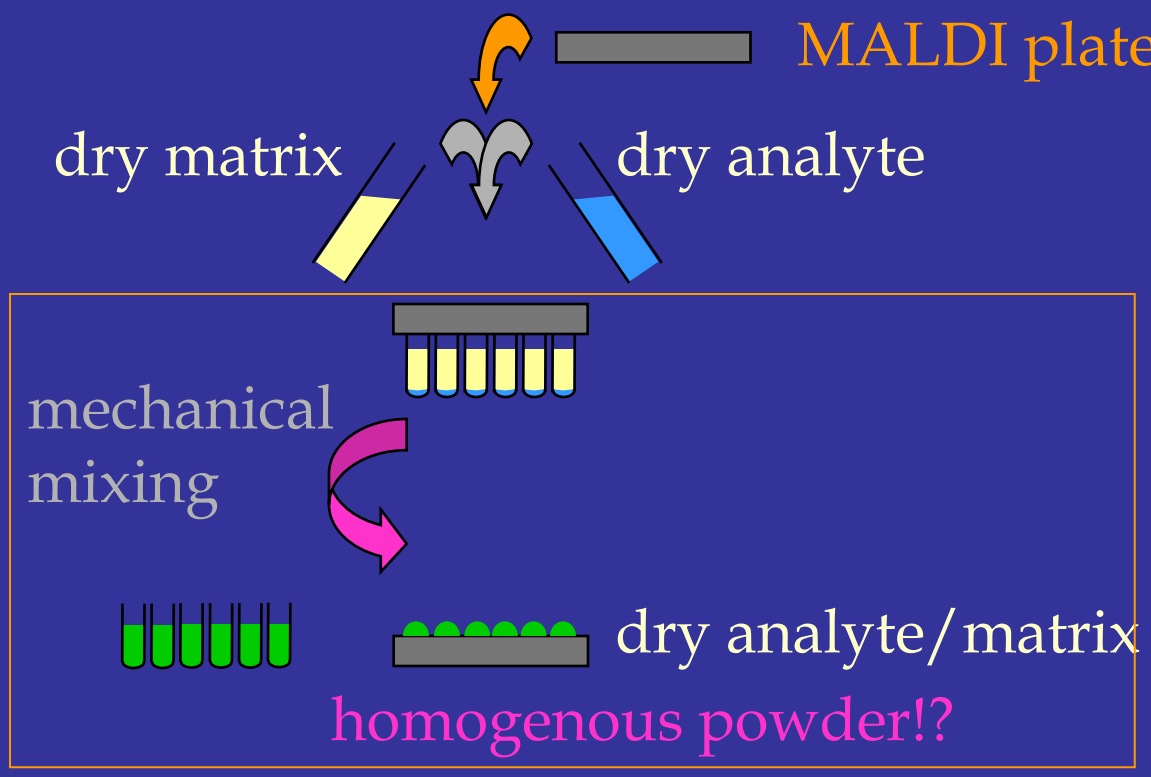




Homogeneous Surface Important for Quantitation

Solvent-free multisample preparation

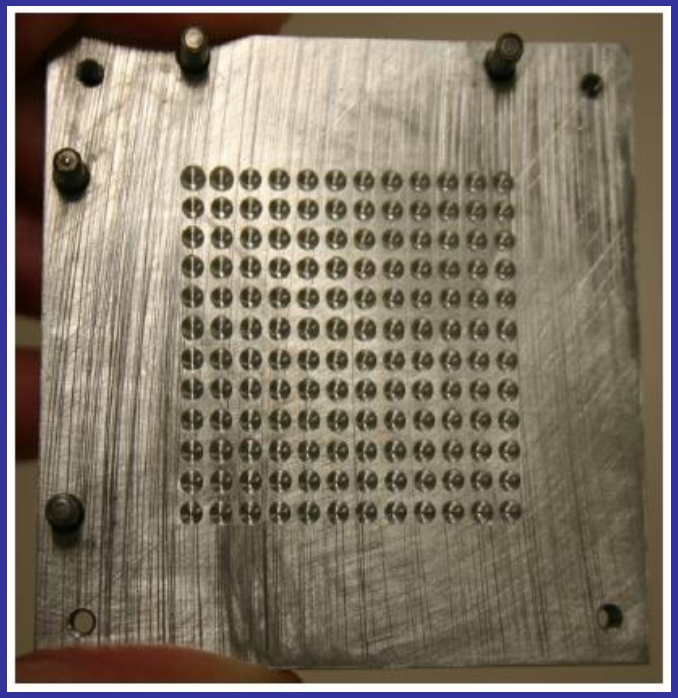
homogenization/transfer simultaneously



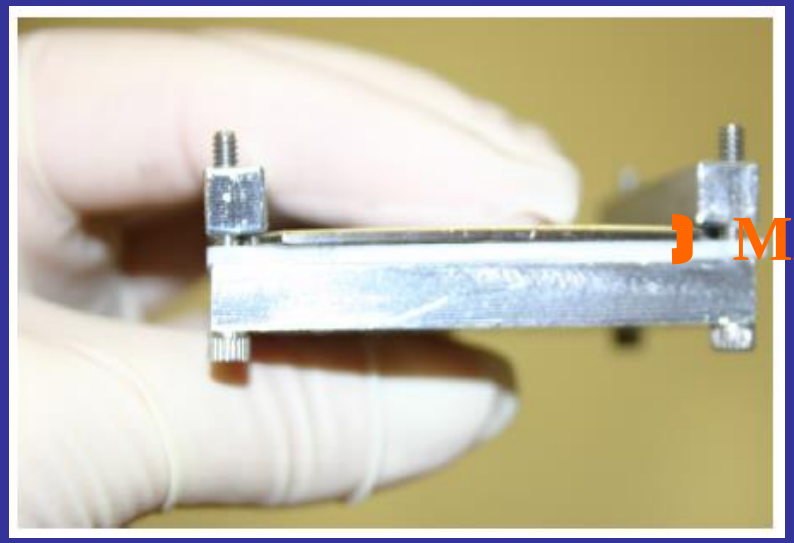
- Sample preparation reduced to a single step.
- Time savings
- Multiplexed sample preparation gives prospect for high throughput
- Miniaturization aiding sensitivity increase

Trimpin, S., McEwen, C.N. *JASMS, 2007, 18, 377-381*

Multisample Solvent-free MALDI Analysis



custom-made sample holder



MALDI plate

Precise transfer

LC 100-Sample Solvent-free MALDI Analysis

Model Polymer Mixture of 5 PEG samples

Dr. Jana Falkenhagen, Dr. Steffen M. Weidner; BAM, Berlin, Germany.

LC fractionation of PEG samples

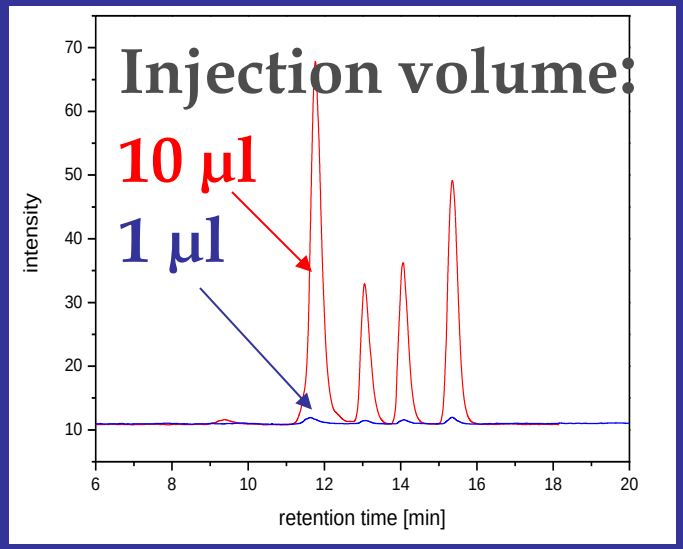
Dr. Sarah Trimpin, OSU, Corvallis, OR.

100-sample solvent-free MALDI sample preparation

Dr. Charles N. McEwen, DuPont, Wilmington, DE.

Mass Analysis

Liquid Adsorption Chromatography at "Critical' Conditions of Adsorption (LACCC)-Fractionation of PEG samples [1]



System:

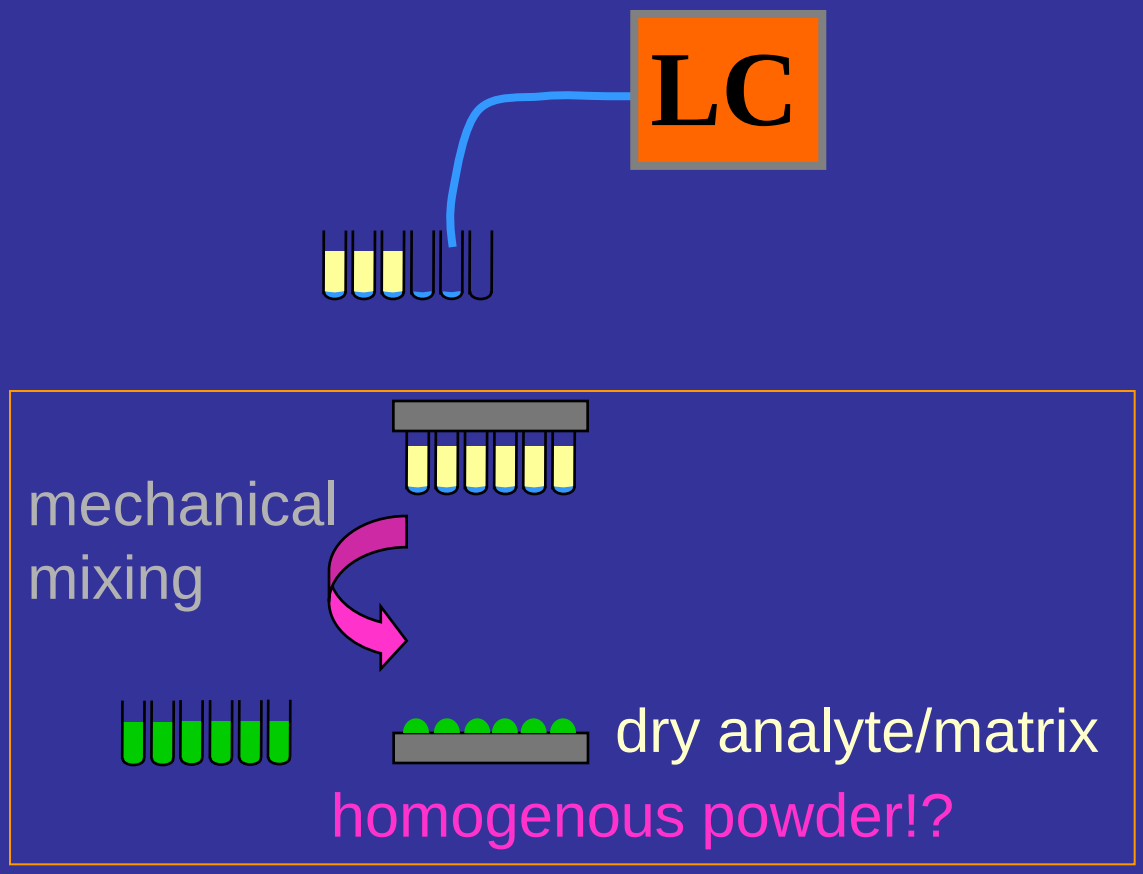
Column: 2 X YMC RP 18 (150, 300 Å)
Solvent: Methanol / Water; 83/17, v/v
Detection: ELSD, SEDEX 45 (Sedere, ERC)
Temperature: 45°C
Flow: 0.5 ml/min
Concentration: 5 samples, total amount: **5.41 mg/mL**
Injection amount: **10 µl** and **1 µl**
1 fraction (25 µL) per 3 seconds

➡ **2 x 43 fractions collected in 200 µL vials with 3 beads present**, dried to completeness, sent out for solvent-free multi-sample analysis

[1] Falkenhagen, J., Weidner, S.M. *Rapid Commun. Mass Spectrom.* 19: 3724-3730, 2005.

Solvent-free Multisample Loading

Automated loading

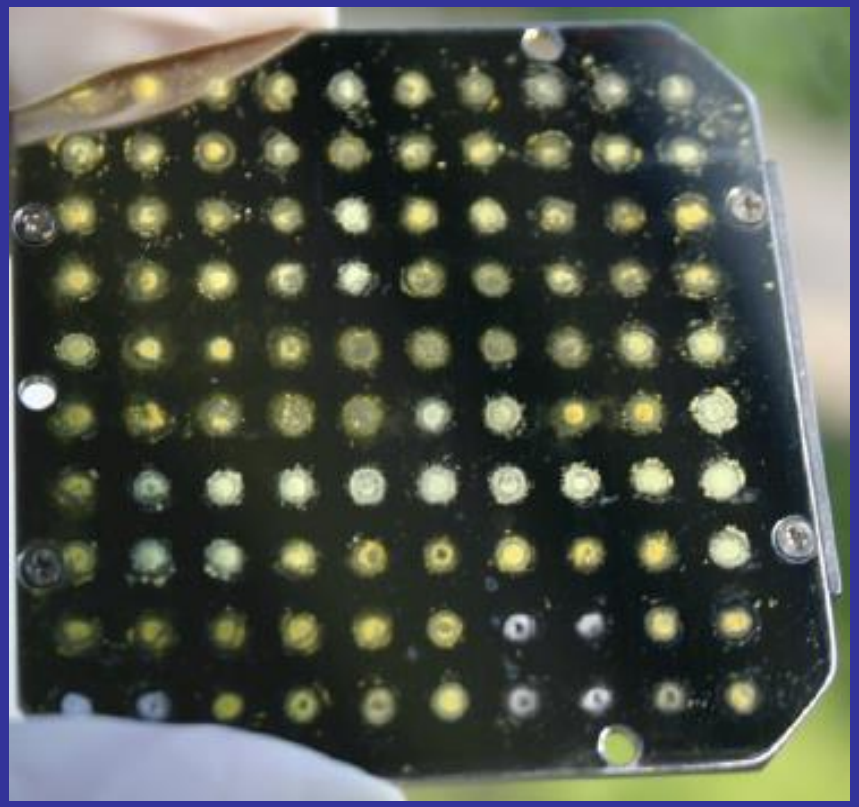


- Simplifies and automates sample loading
- Time savings
- Non ESI-sprayable LC conditions possible
- Non traditional solvent systems may aid improved separation
- Ionization of molecules inaccessible by traditional MALDI

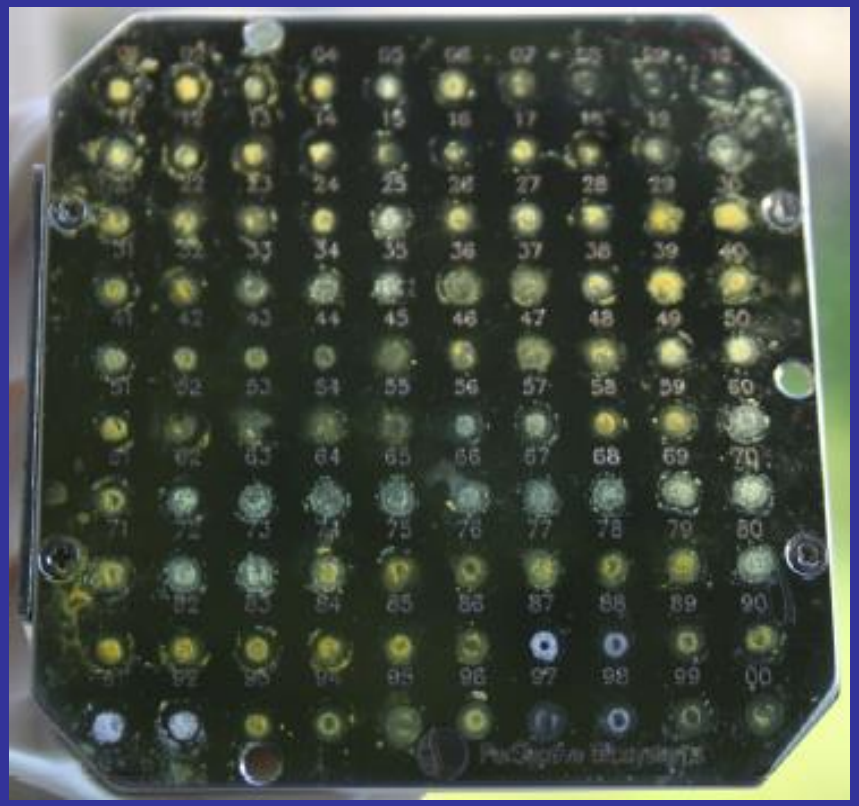
S. Trimpin, S. M. Weidner, J. Falkenhagen, C. N. McEwen, *Anal. Chem.* 79, 7565-7570 (2007).

Multiple MALDI plates prepared from the same assembly using the 100-sample homogenization/transfer method (vortex-based)

MALDI plate 1: 10 minutes

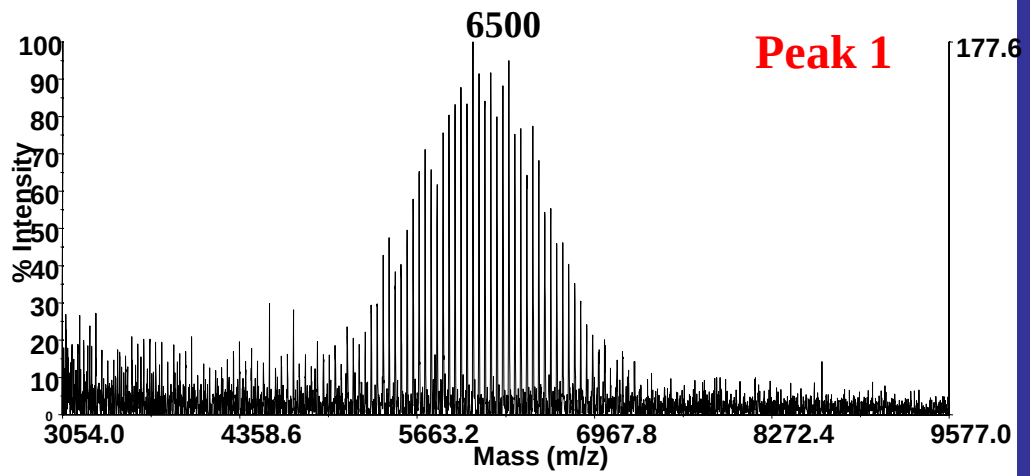


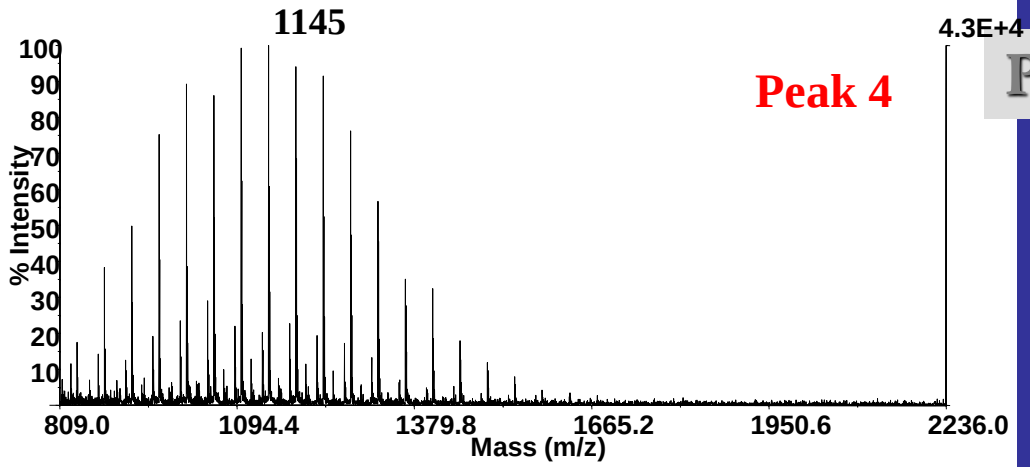
MALDI plate 2: 1 minute



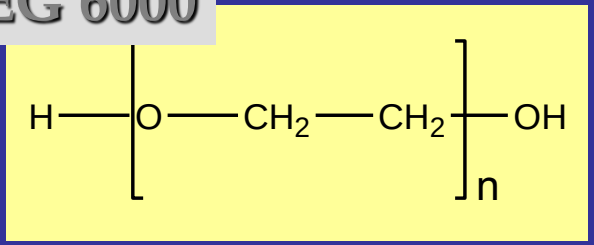
Mass spectra of the MALDI plate 2 (1 minute transfer)

10 µL injection

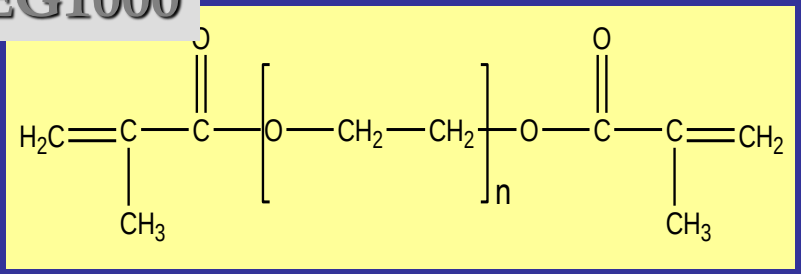




PEG 6000

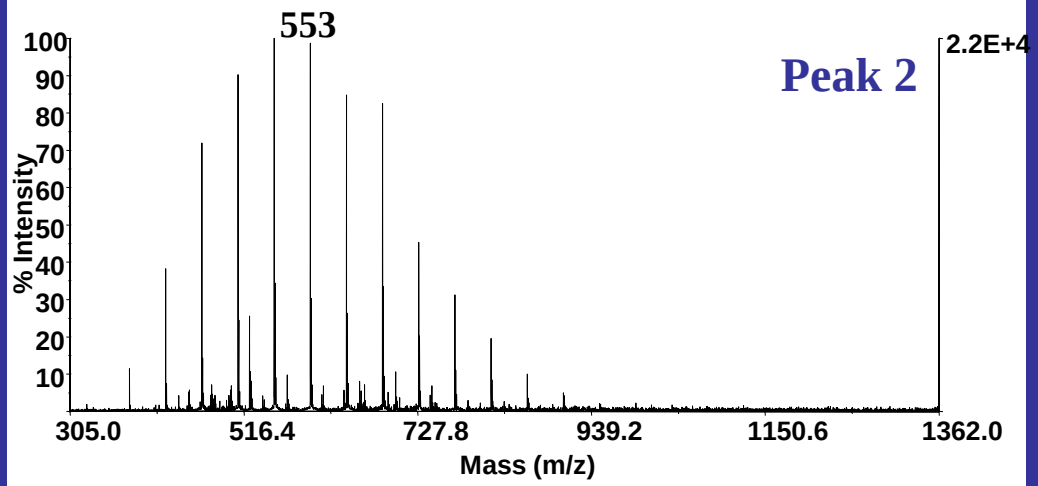


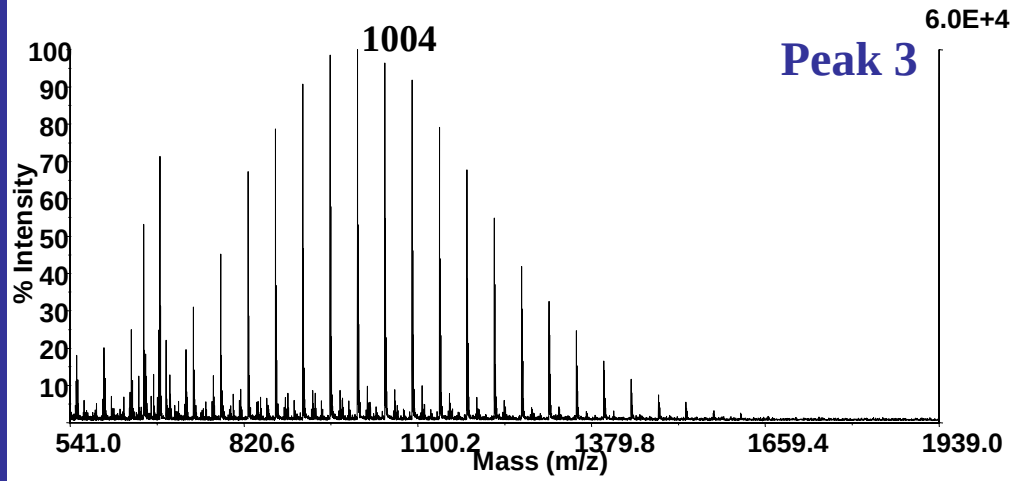
PEG1000



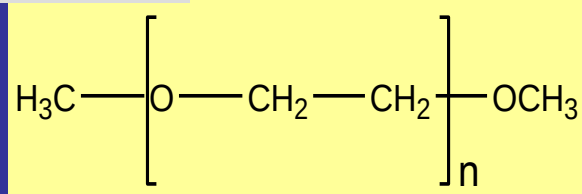
Mass spectra of the MALDI plate 2 (1 minute transfer)

1 µL injection

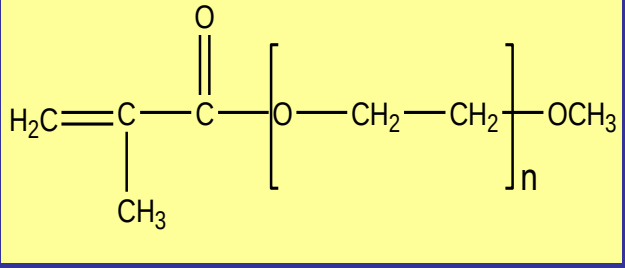




PEG 500



PEG 1000



Conclusion: Multisample solvent-free preparation and transfer

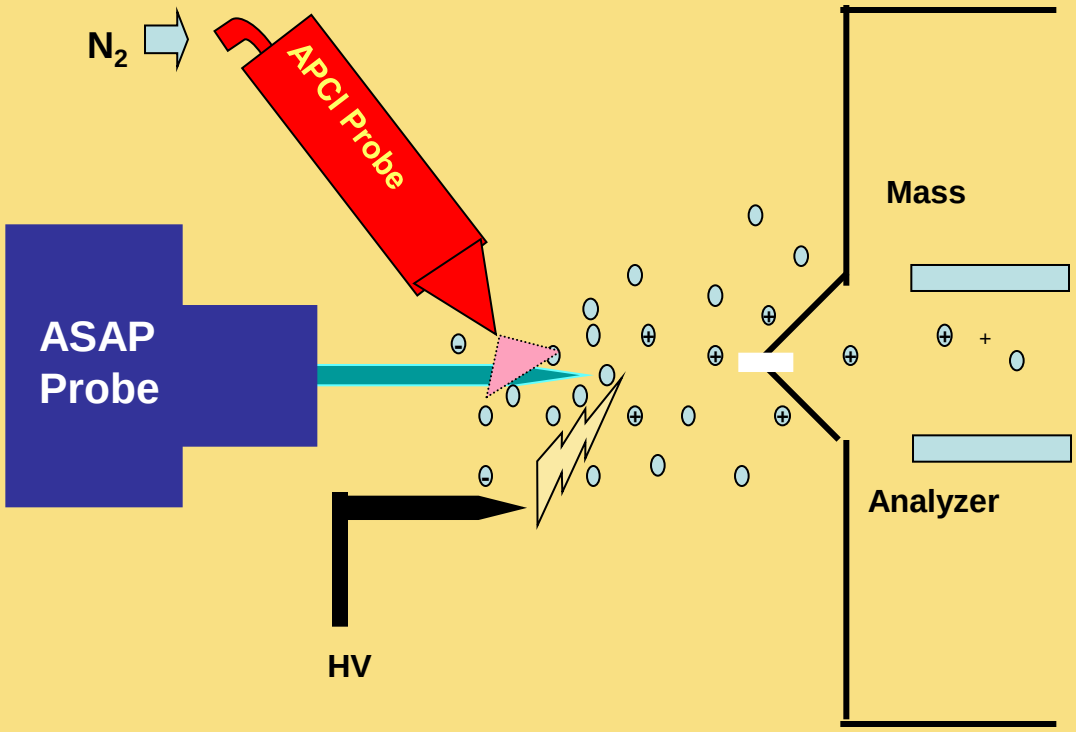
- Total time per sample is < 1 min.
- Eliminates need to dissolve analyte
- Best for polymers with M_n < 10 kDa
- Use with multiple samples or for optimization
- Prepare >100 samples simultaneous
- Smaller mixing volume translates to lower sample requirement
- All the advantages of the solvent-free method

Polymer Identification and Analysis of Additives

Atmospheric **S**olids **A**nalysis **P**robe Mass Spectrometry

(Fast/inexpensive)

ASAP-MS



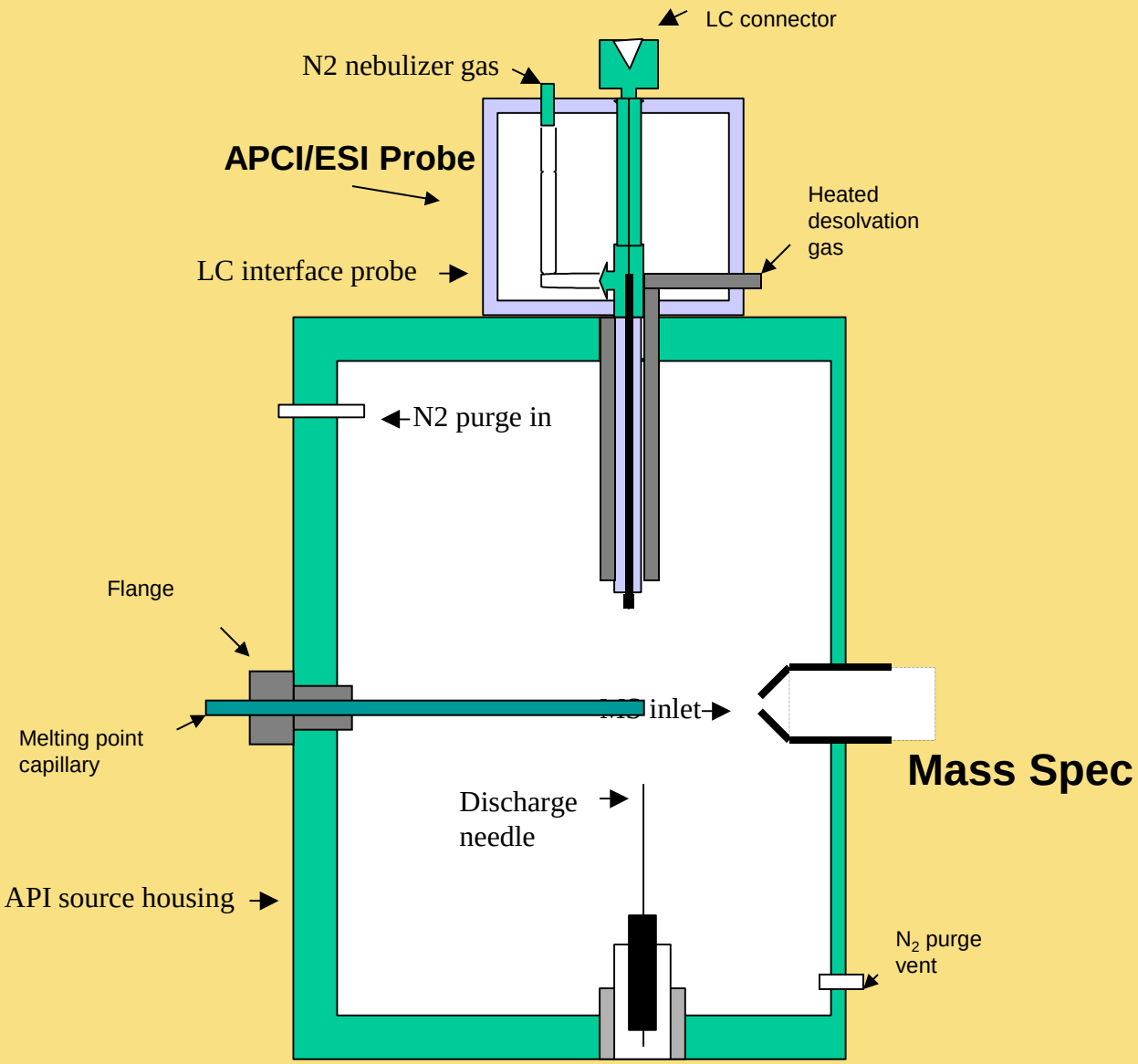
Direct Analysis using ASAP

- Rapid analysis of
  - Solids
  - Liquids
  - Polymers
  - Biological tissue
- Sensitive, ease of use, broad applications
- No interference with standard ion source operations
- Enclosed ion source for safety

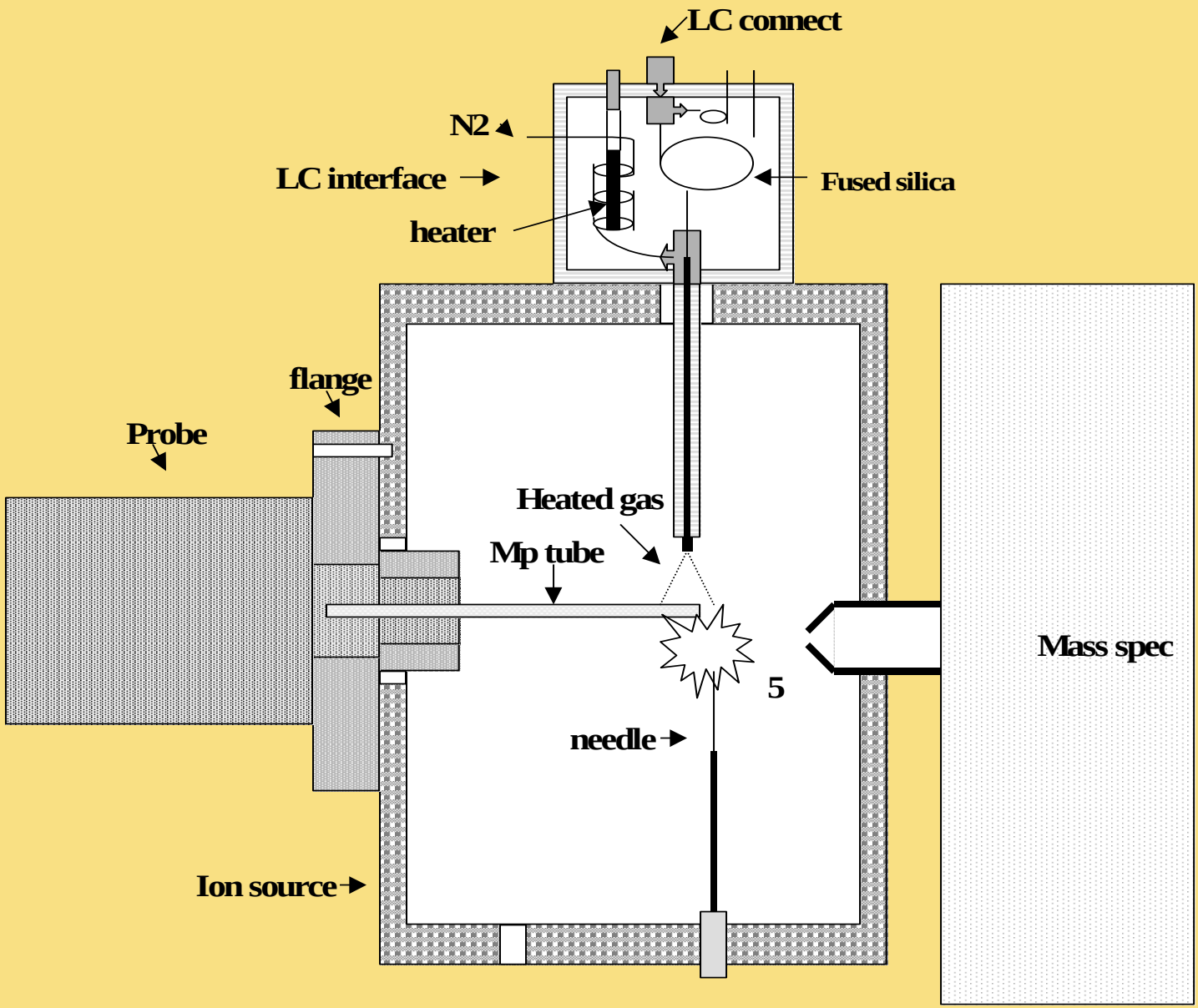
ASAP for Polymer Additive and Volatile Oligomer Analysis

- Obtain mass of additives in seconds
- No sample extraction or preparation required
- No vacuum lock
- Accurate mass or MS/MS for confirmation
- Molecular distribution can be obtained for volatile polymers
- No interference with ESI/APCI operation

ASAP Ion Source



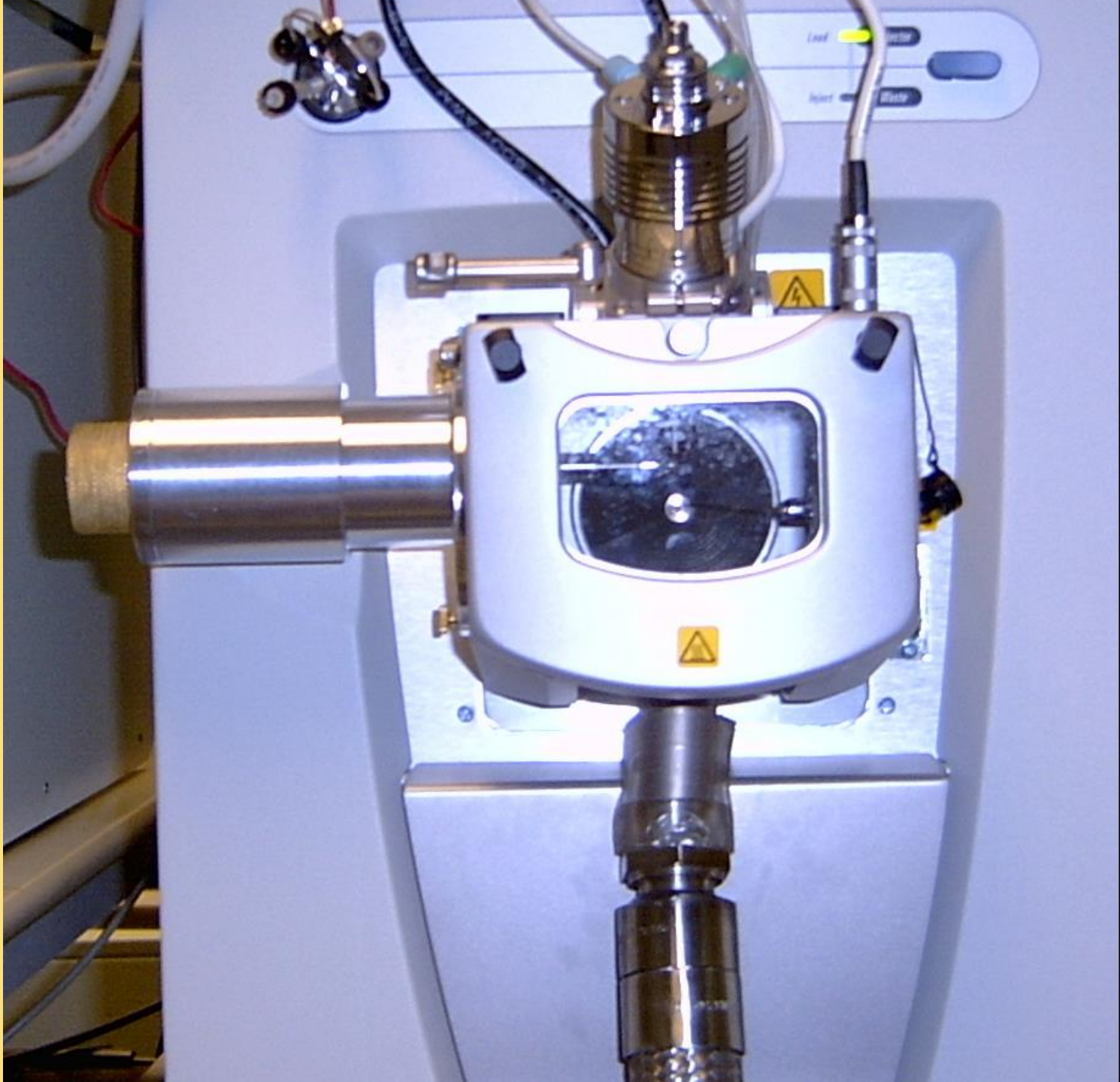
Commercial ASAP Probe



ASAP-MS.COM

ASAP Waters Fishbowl Probe

Thermo-Fisher Ion-Max Source With ASAP Probe



Nitrogen Purge Ion Molecule Reactions

$$N_2 + e^- \rightarrow N_2^+ + 2e^- \quad (1)$$

$$N_2^+ + 2N_2 \rightarrow N_4^+ + N_2 \quad (2)$$

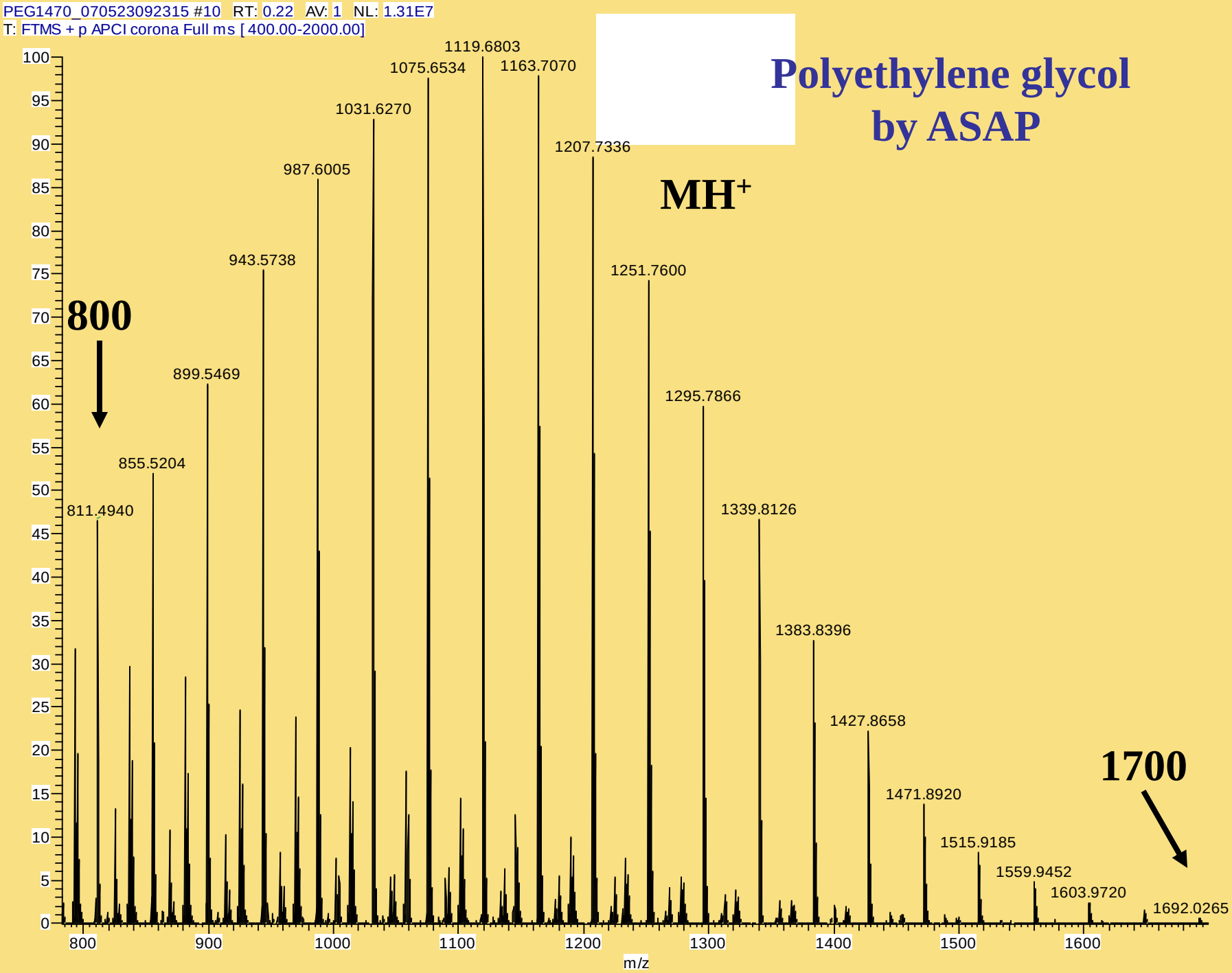
$$N_4^+ + H_2O \rightarrow H_2O^+ + 2N_2 \quad (3)$$

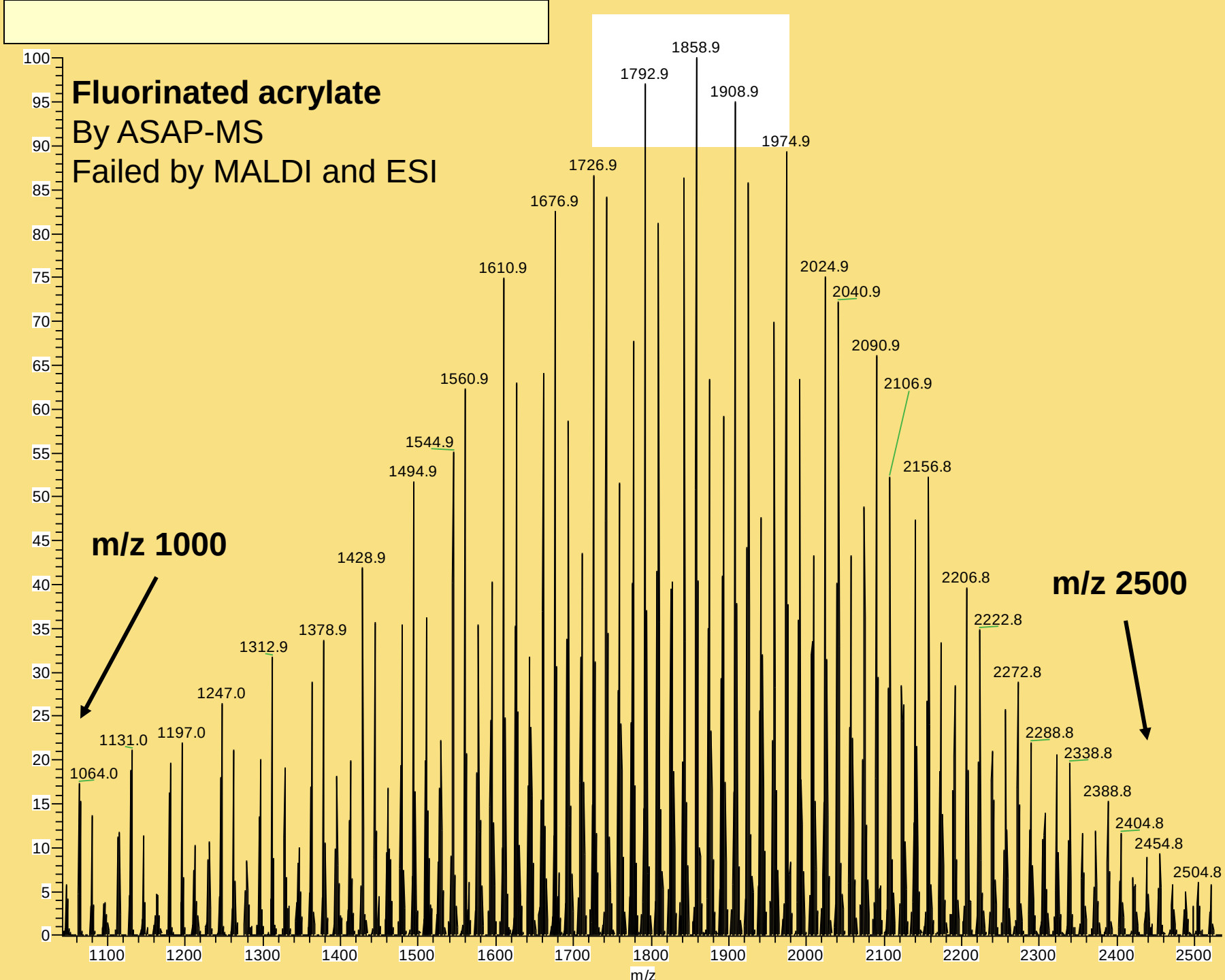
$$H_2O^+ + H_2O \rightarrow H_3O^+ + OH \quad (4)$$

$$H_3O^+ + (H_2O)_n + N_2 \rightarrow H^+(H_2O)_n + N_2 \quad (5)$$

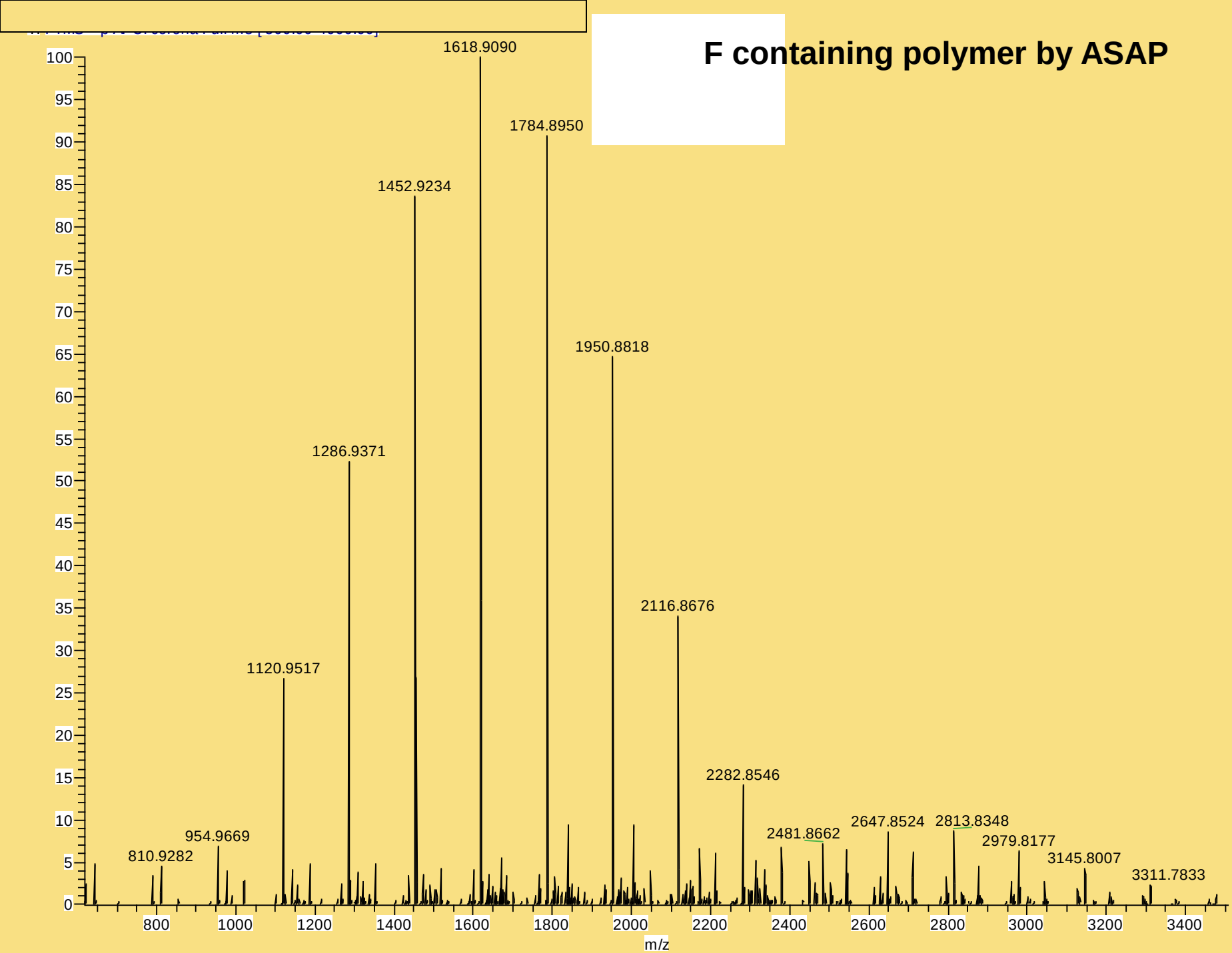
$$H^+(H_2O)_n + A \rightarrow AH^+ + nH_2O \text{ (Analyte)} \quad (6)$$

Polyethylene glycol by ASAP




Fluorinated acrylate
By ASAP-MS
Failed by MALDI and ESI
m/z 1000
m/z 2500
1858.9
1792.9
1908.9
1974.9
1726.9
1676.9
1610.9
2024.9
2040.9
2090.9
2106.9
1560.9
1544.9
1494.9
2156.8
1428.9
2206.8
2222.8
1378.9
1312.9
2272.8
1247.0
2288.8
1197.0
1131.0
2338.8
1064.0
2388.8
2404.8
2454.8
2504.8
m/z

F containing polymer by ASAP



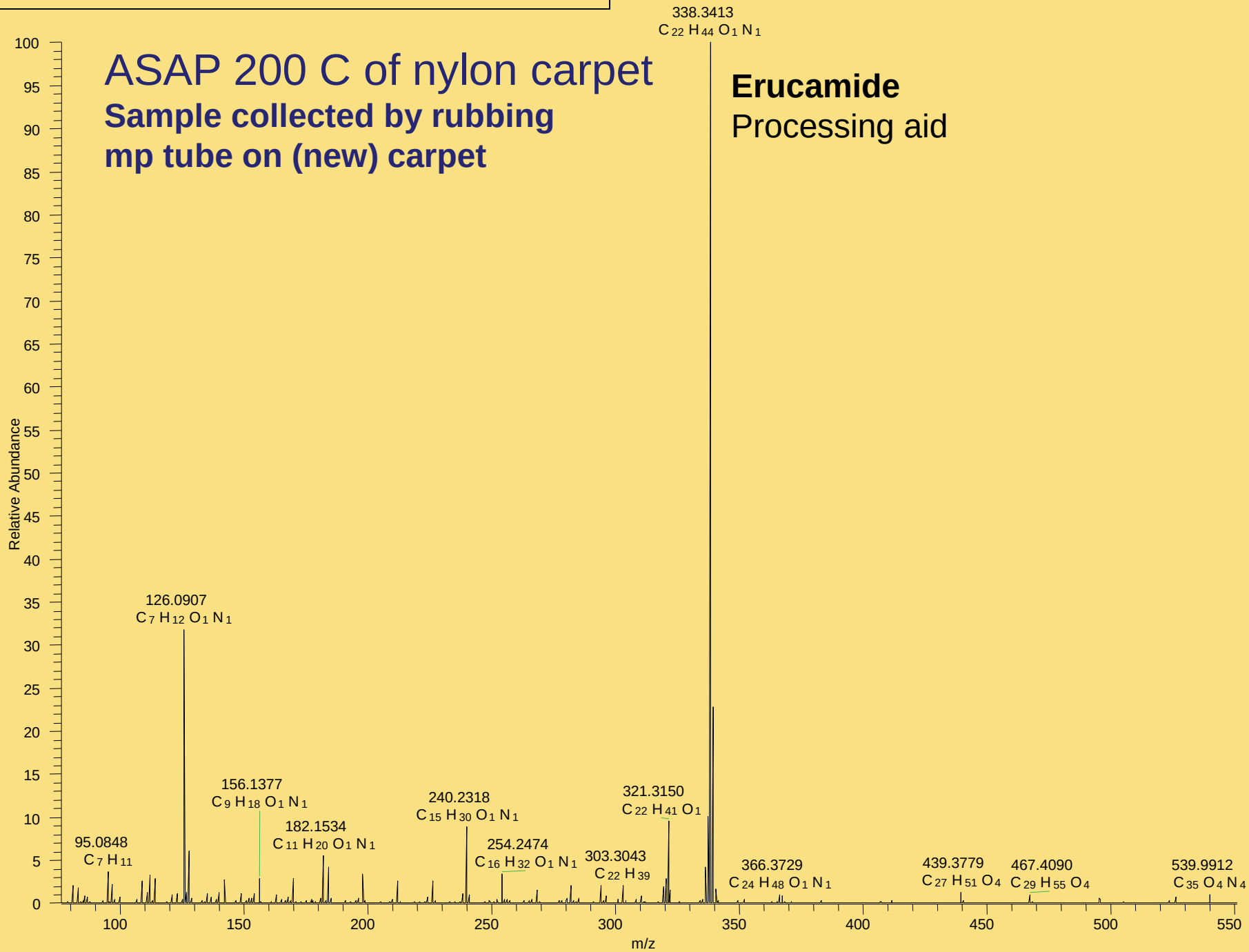
Polymer Additive Analysis

- **Obtain mass of additives in seconds**
- **No sample extraction or preparation required**
- **Accurate mass or MS/MS for confirmation**

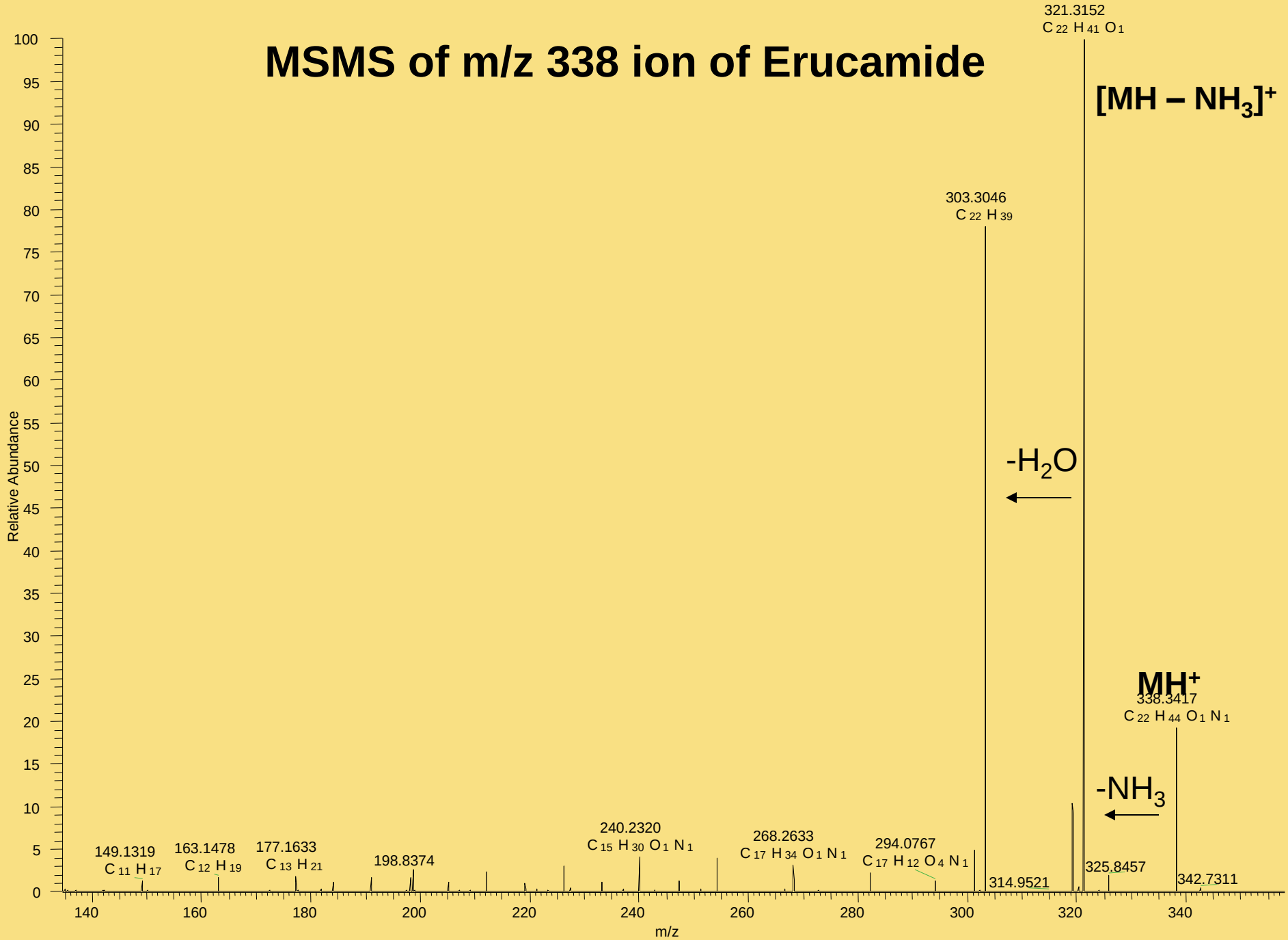
ASAP 200 C of nylon carpet

Sample collected by rubbing mp tube on (new) carpet

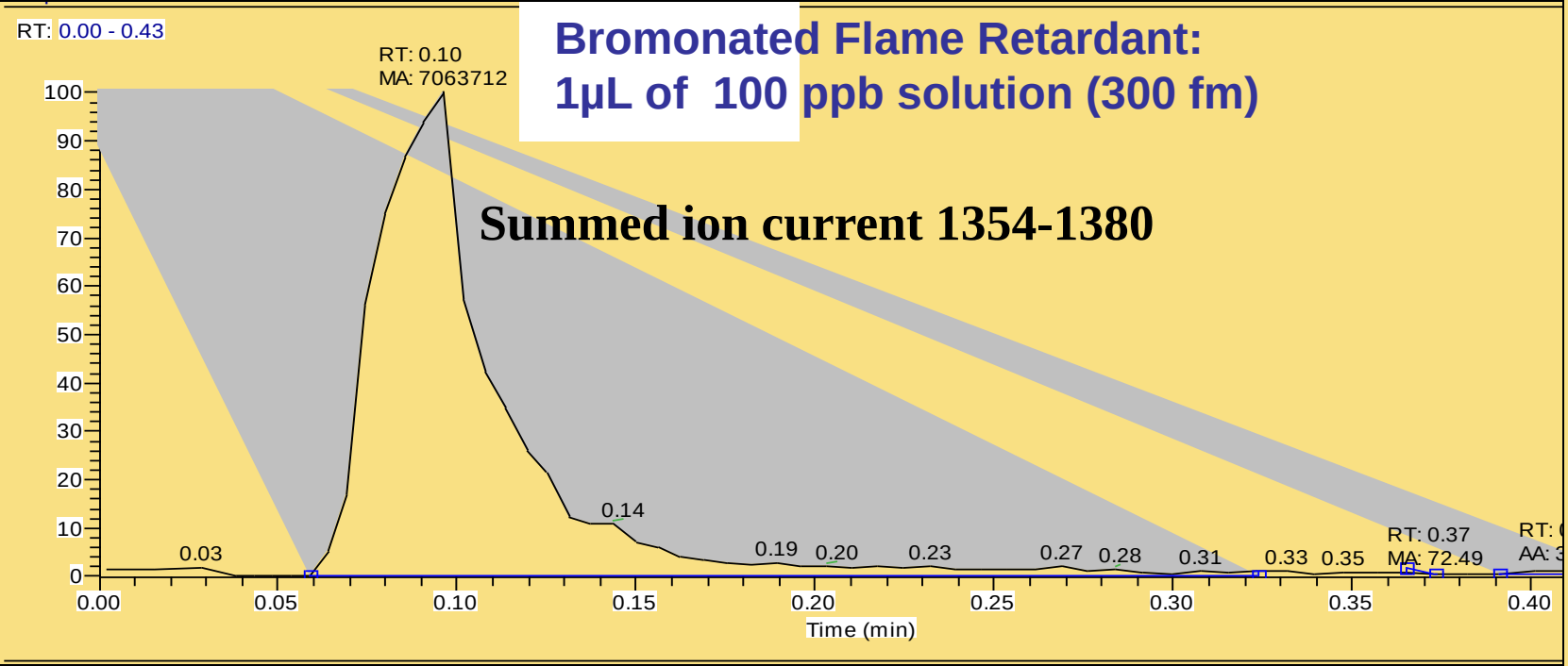
Erucamide
Processing aid

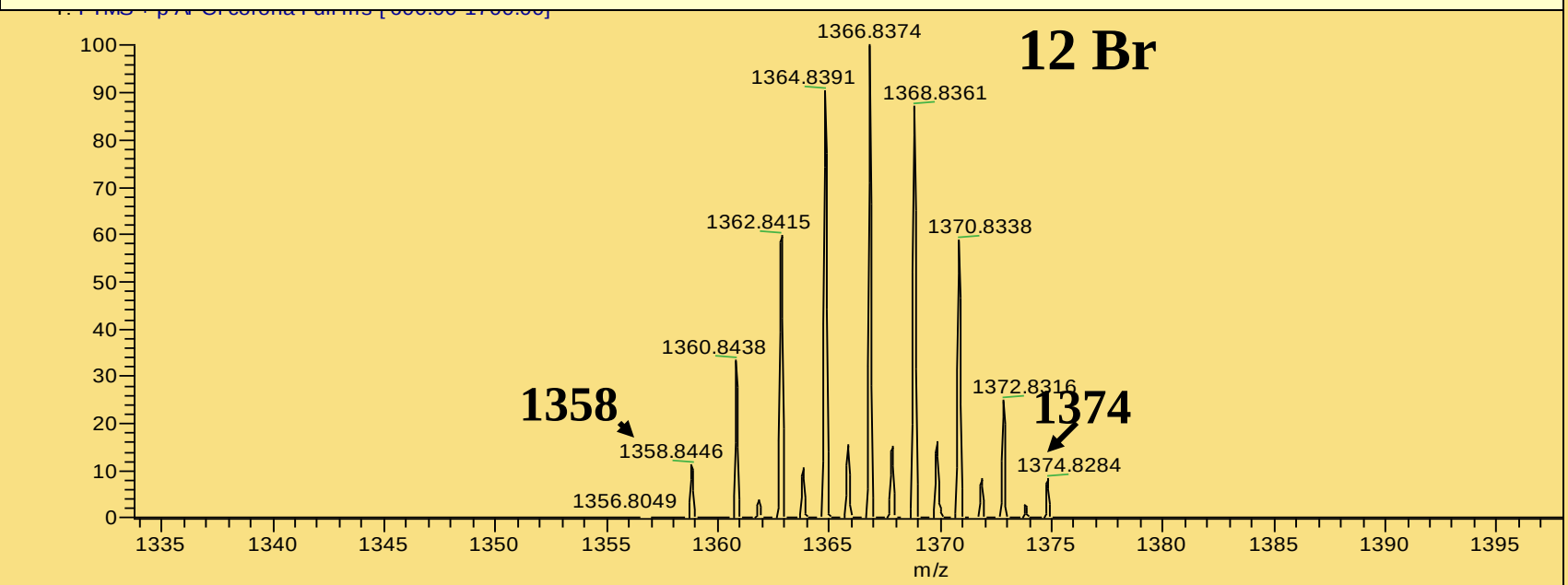


MSMS of m/z 338 ion of Erucamide

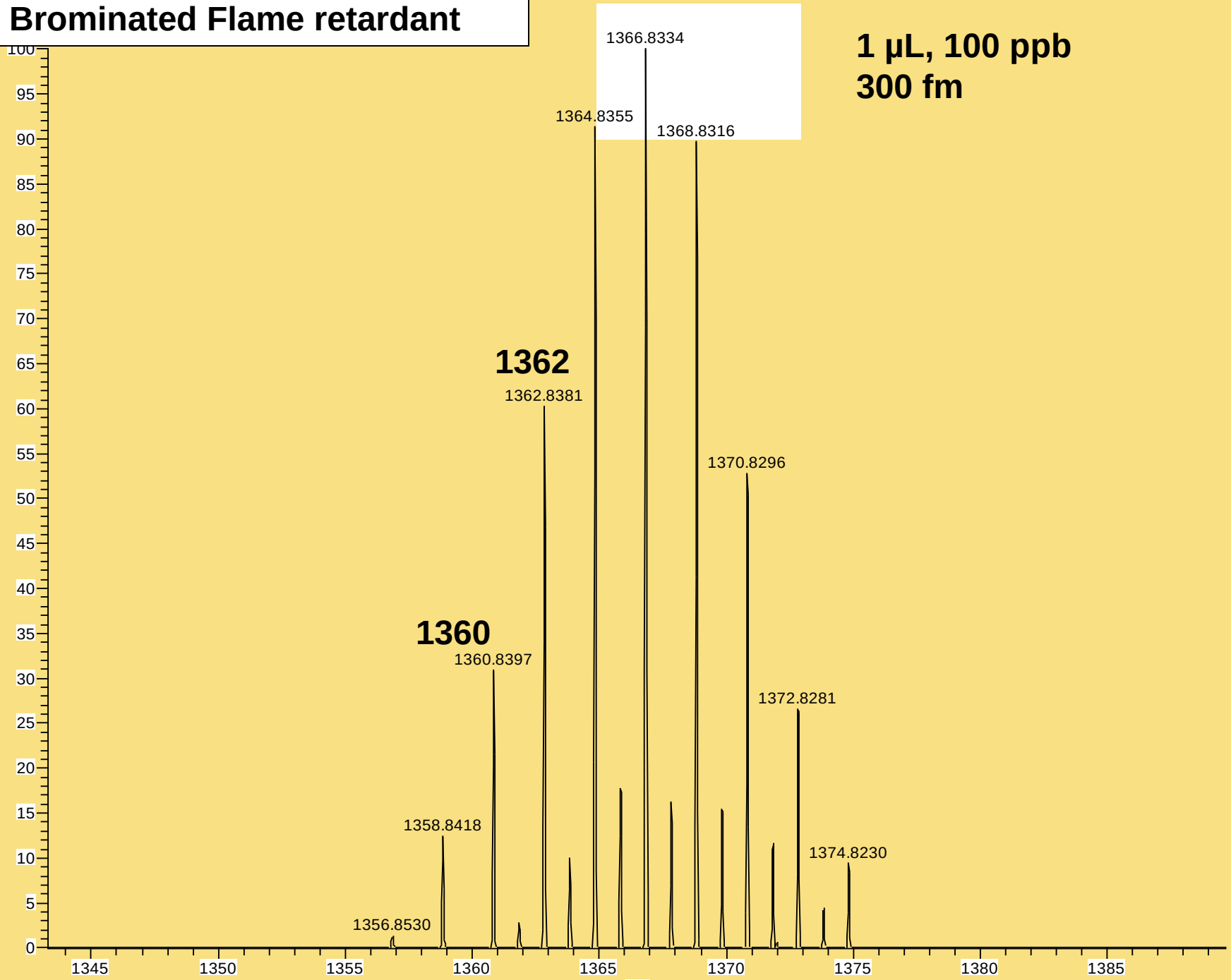


Bromonated Flame Retardant: 1µL of 100 ppb solution (300 fm)



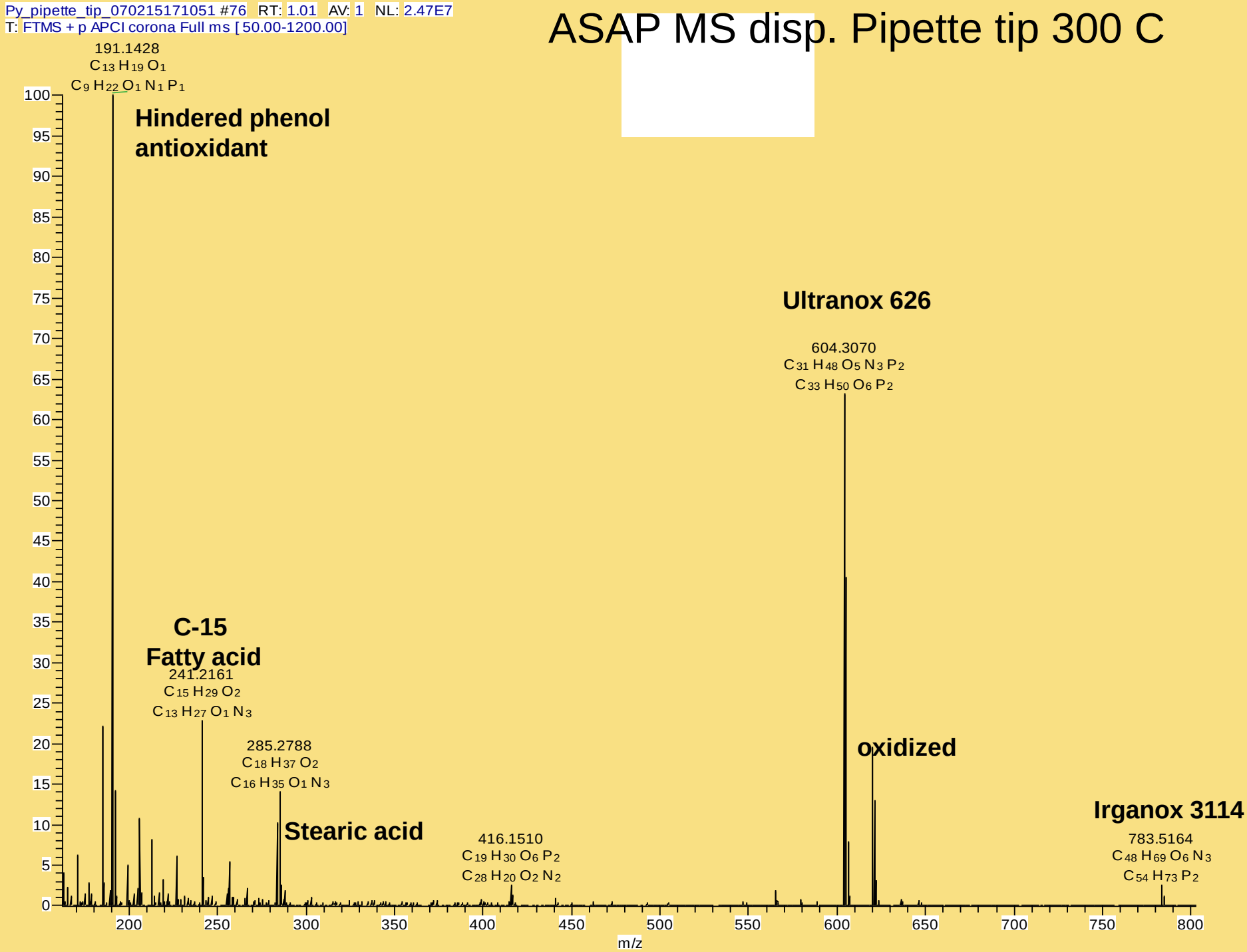


Brominated Flame retardant

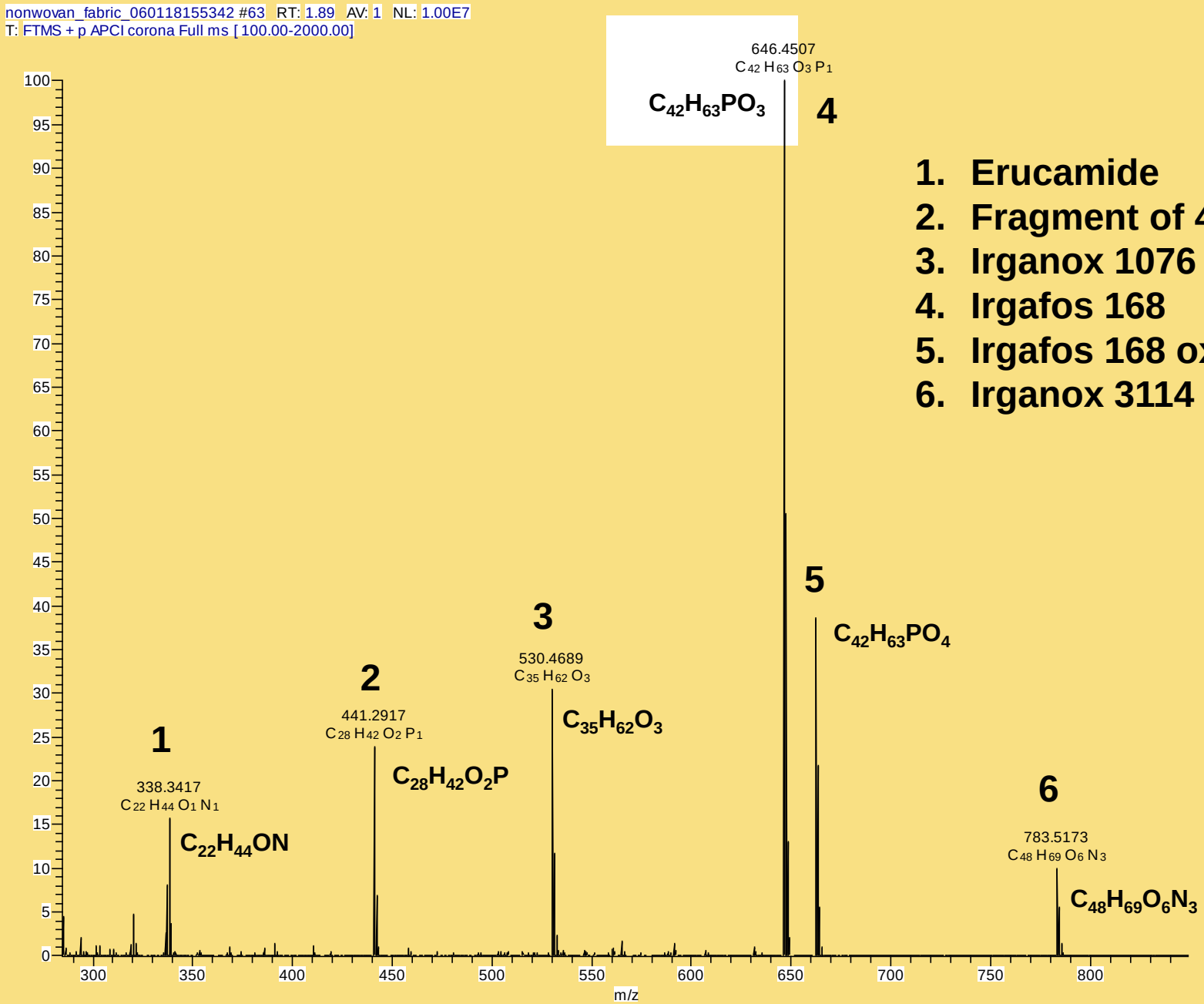


1 µL, 100 ppb
300 fm

ASAP MS disp. Pipette tip 300 C



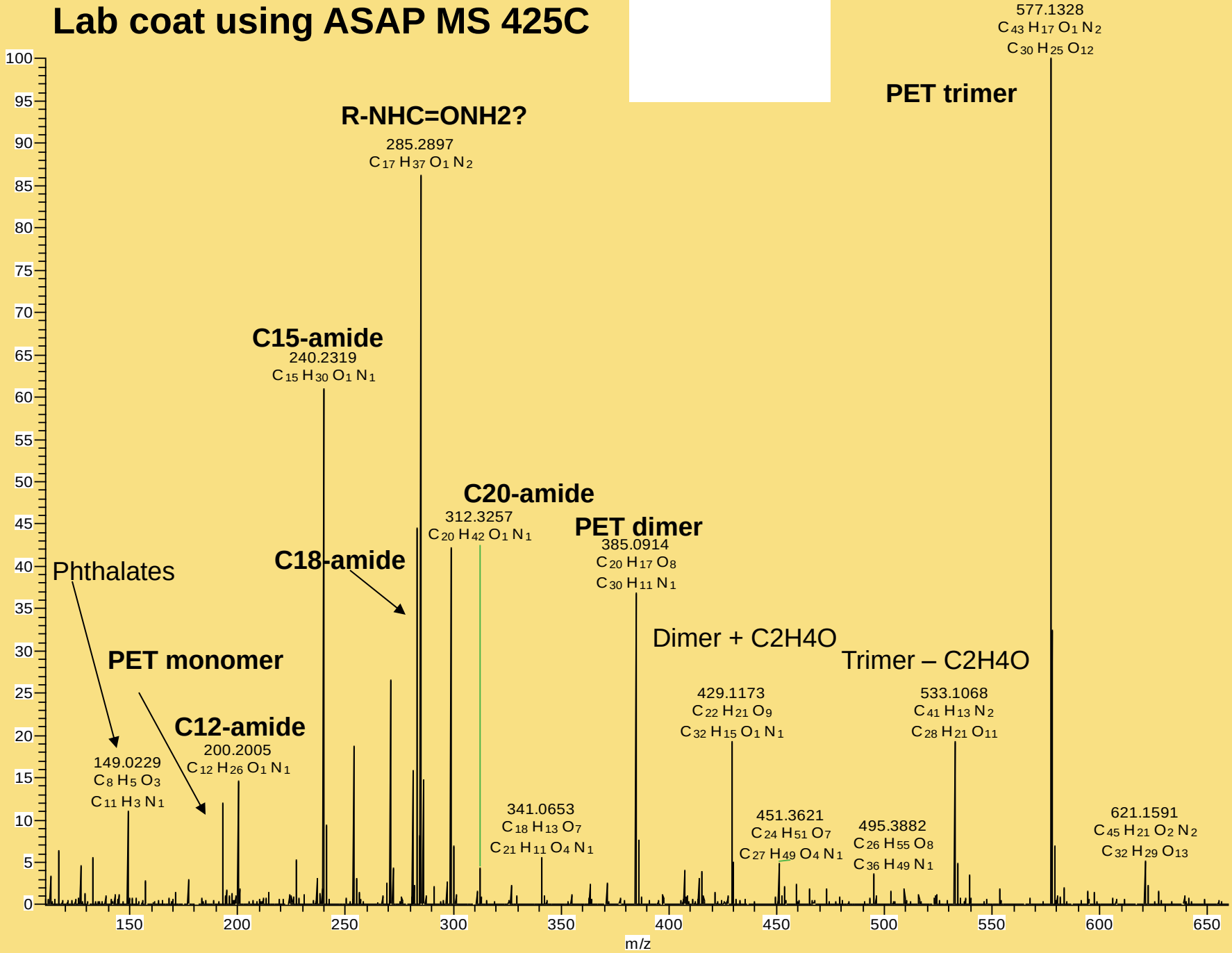
ASAP of Nonwoven Fiber (250 C)



1. Erucamide
2. Fragment of 4
3. Irganox 1076
4. Irgafos 168
5. Irgafos 168 oxidized
6. Irganox 3114

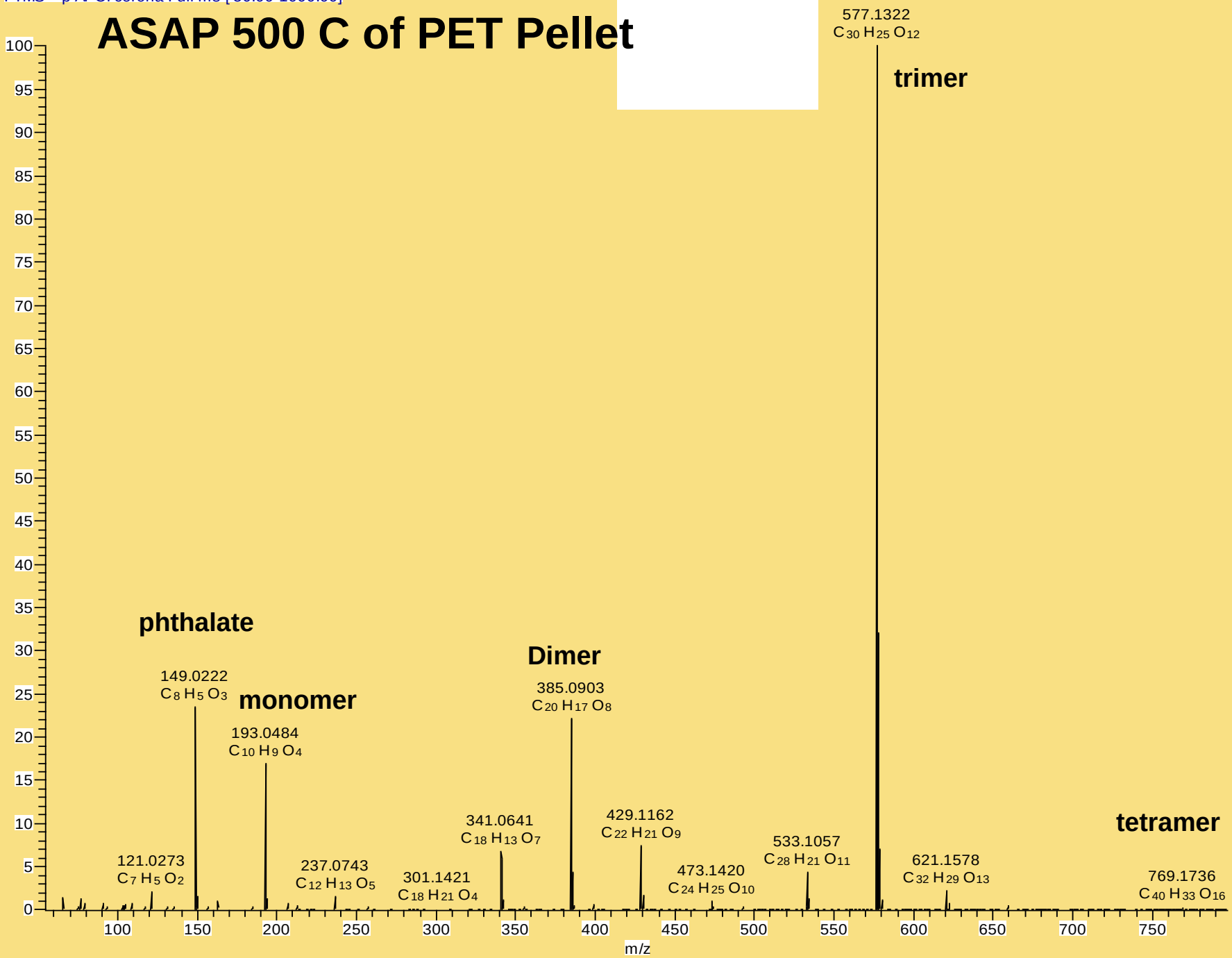
Py_lab_coat_070215171051 #52 RT: 0.54 AV: 1 NL: 6.13E7
T: FTMS + p APCI corona Full ms [50.00-1200.00]

Lab coat using ASAP MS 425C



PET_060824093317 #30-47 RT: 0.28-0.43 AV: 18 NL: 5.13E8
T: FTMS + p APCI corona Full ms [50.00-1000.00]

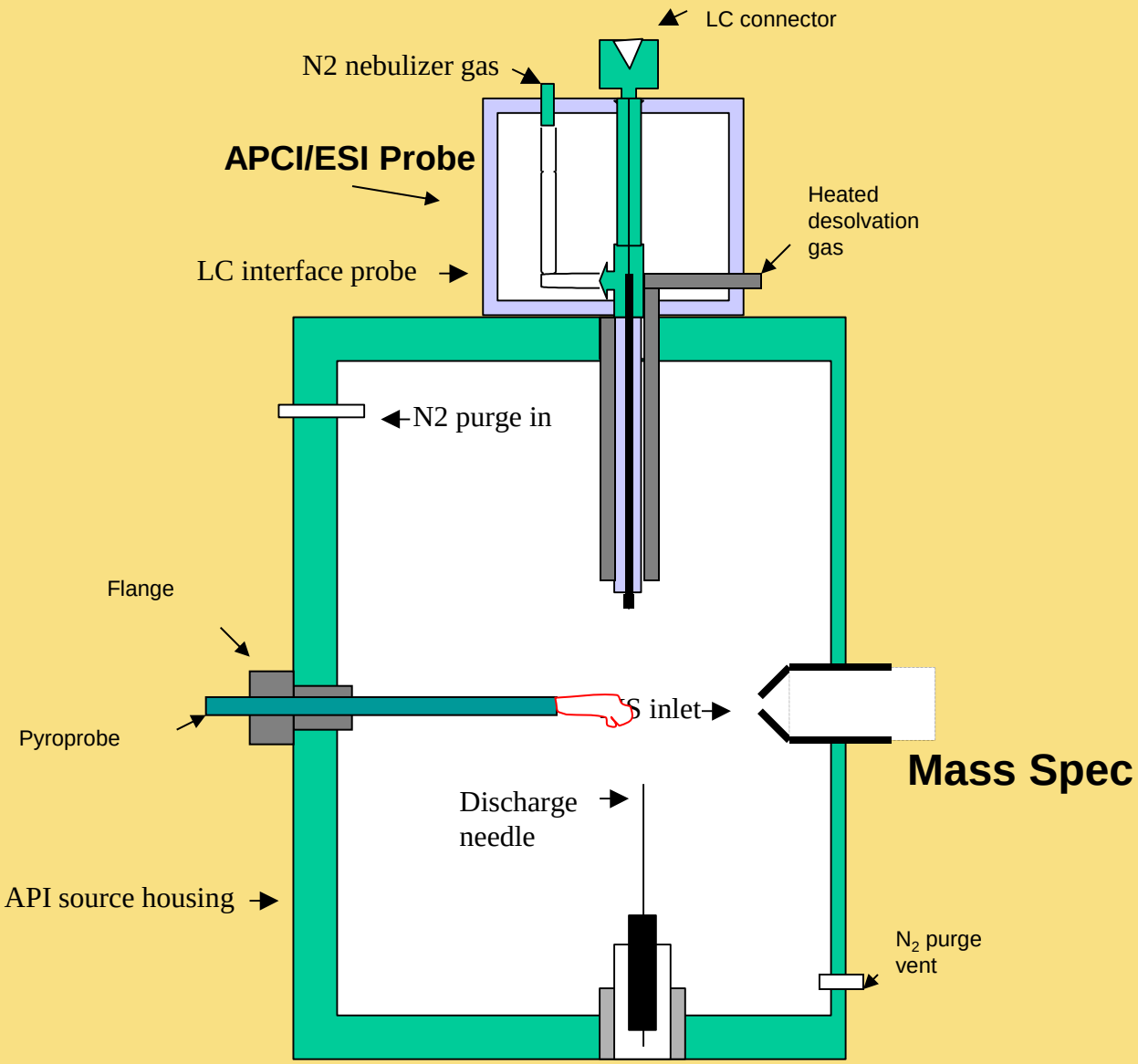
ASAP 500 C of PET Pellet



Atmospheric Pressure Pyrolysis Ionization

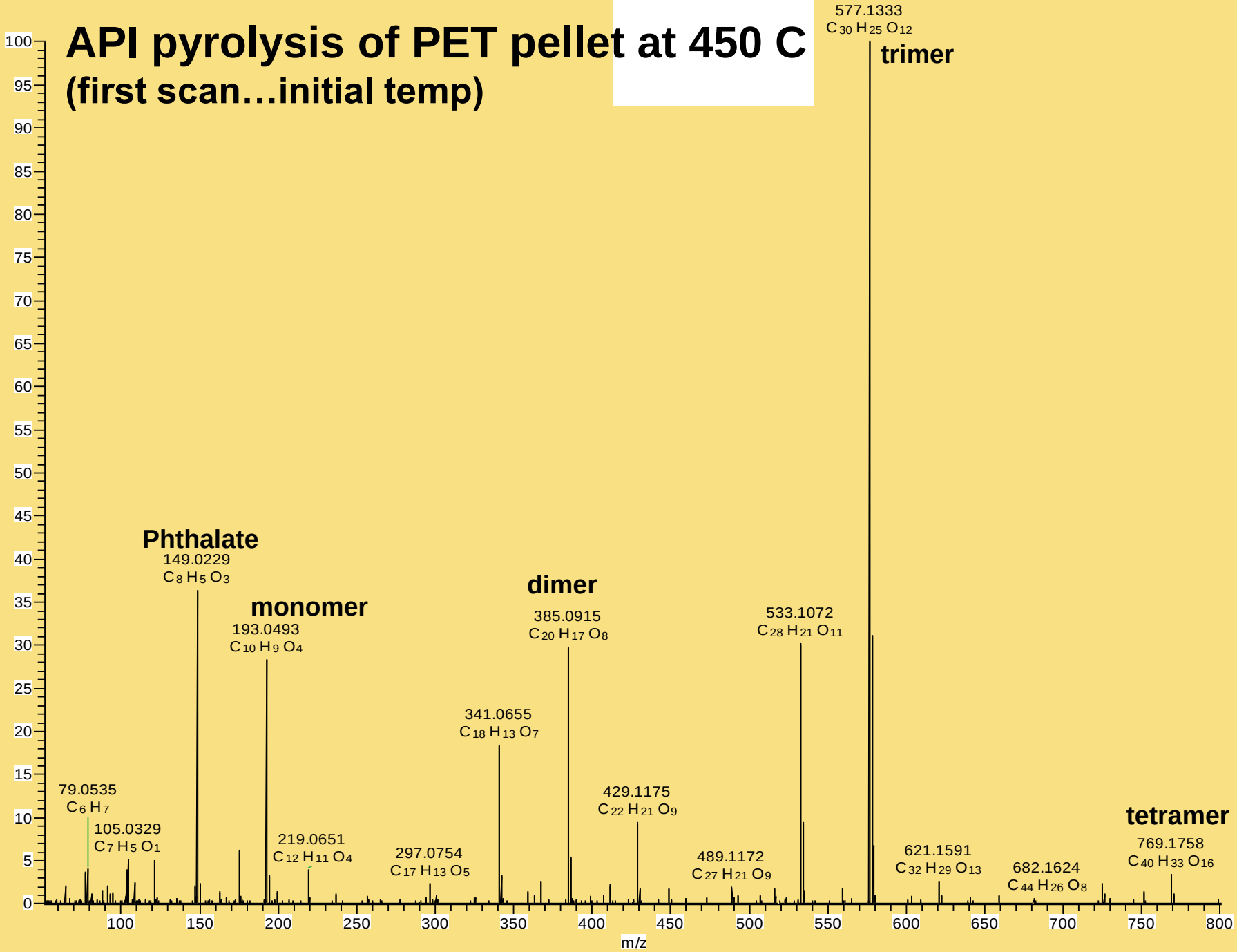
ASAP on steroids

ASAP Ion Source



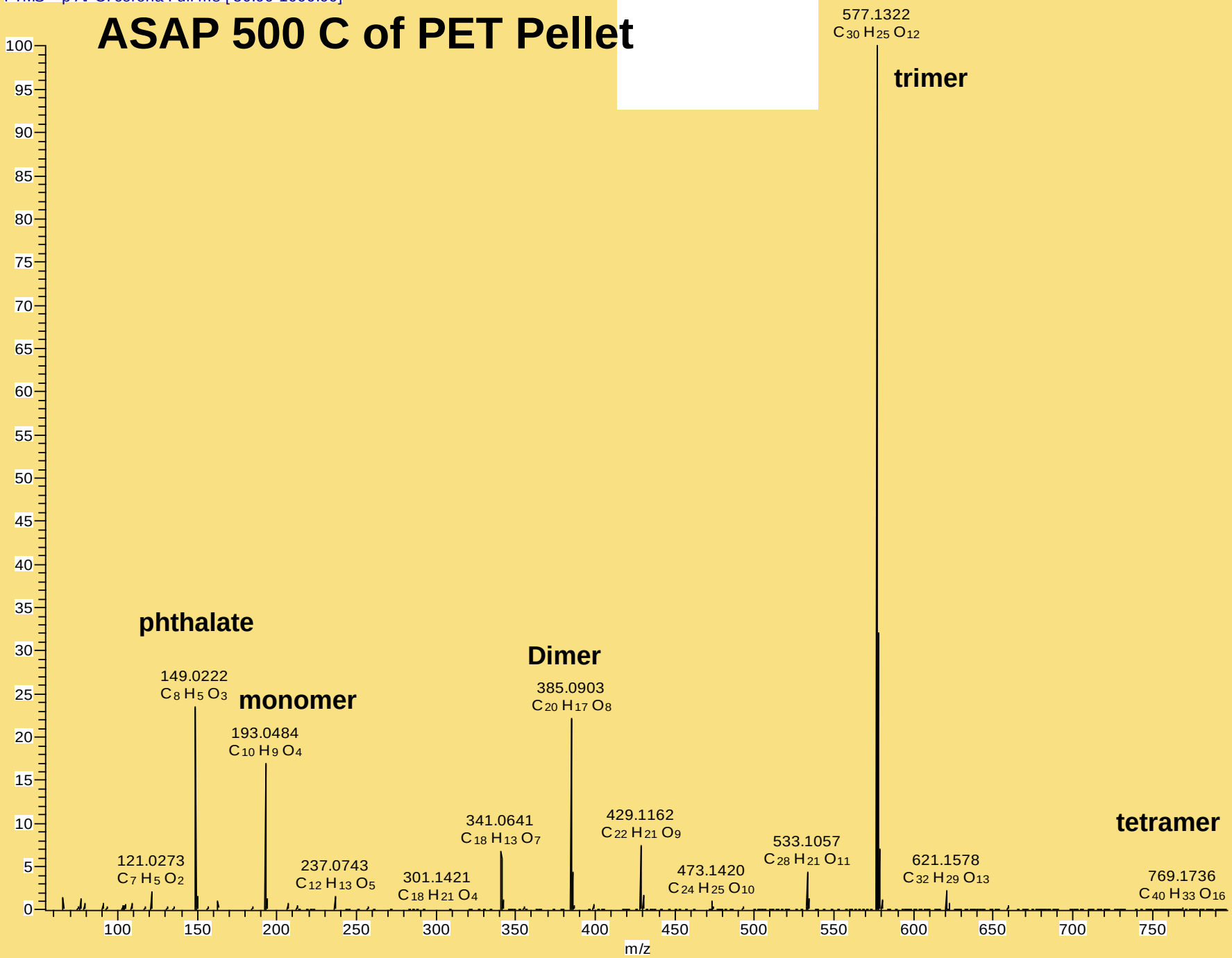
Nui_polymer_pet_061011134824 #110 RT: 0.96 AV: 1 NL: 6.69E6
T: FTMS + p APCI corona Full ms [50.00-1000.00]

API pyrolysis of PET pellet at 450 C
(first scan…initial temp)

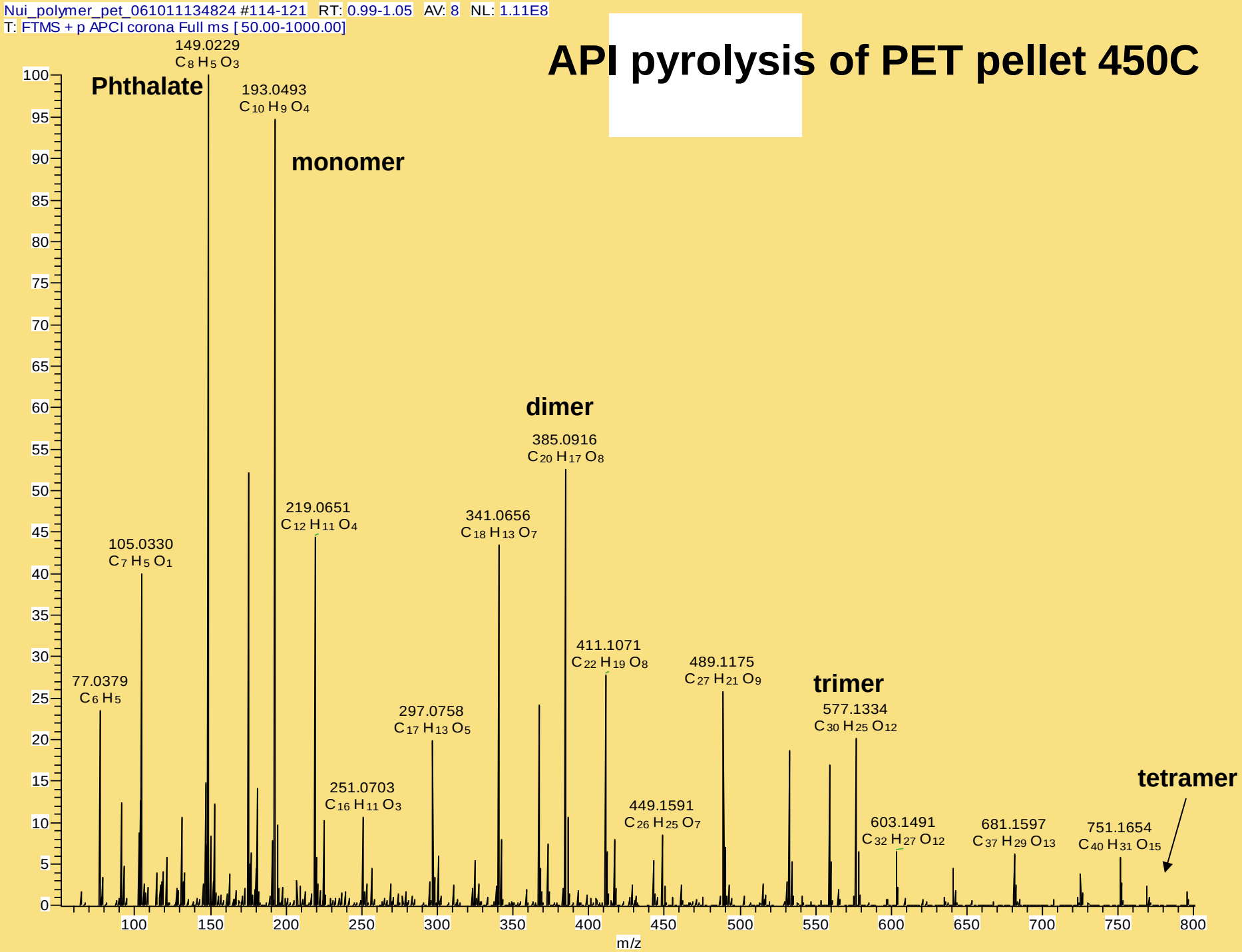


PET_060824093317 #30-47 RT: 0.28-0.43 AV: 18 NL: 5.13E8
T: FTMS + p APCI corona Full ms [50.00-1000.00]

ASAP 500 C of PET Pellet

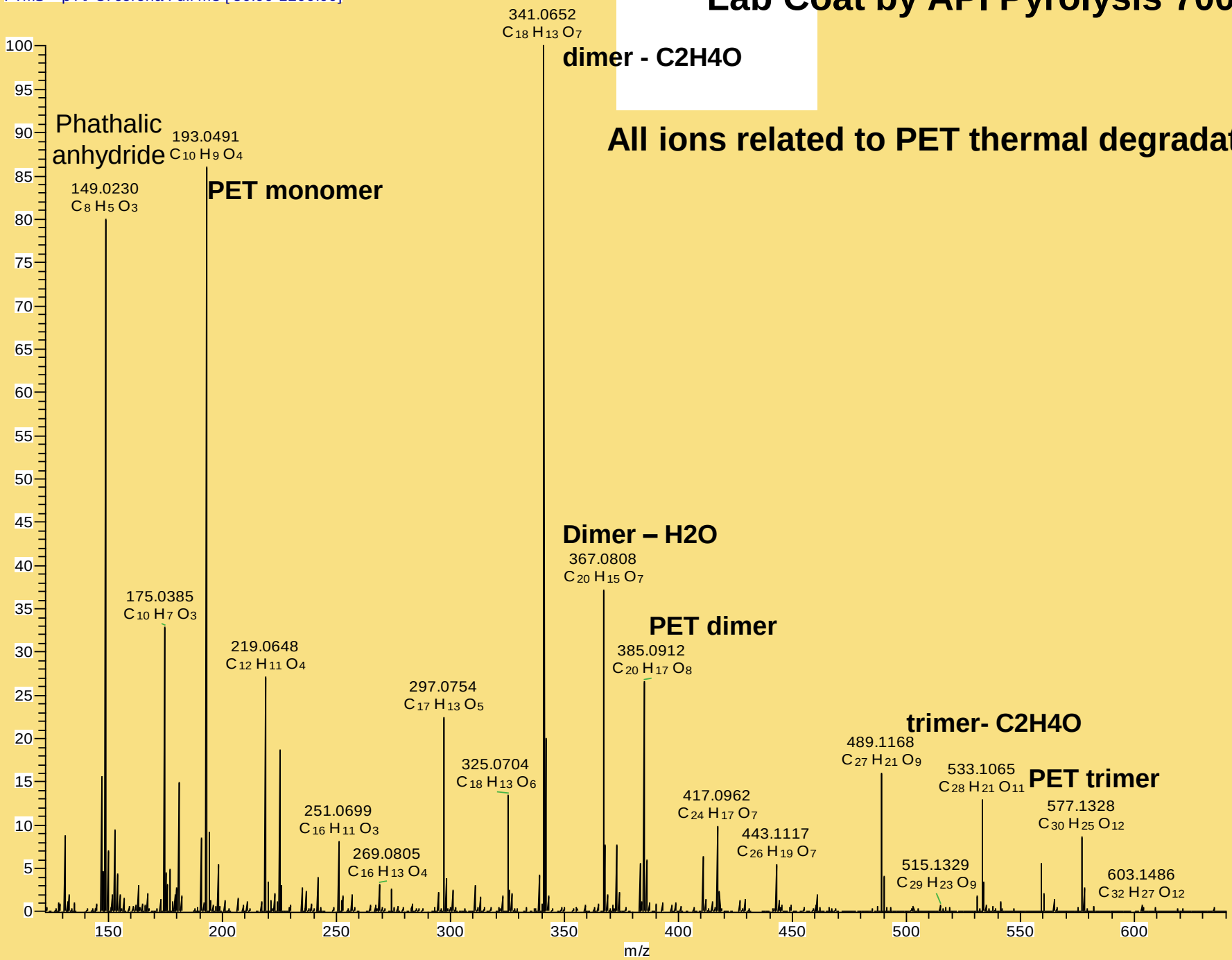


API pyrolysis of PET pellet 450C



Py_lab_coat_py_070216112244 #18 RT: 0.25 AV: 1 SB: 5 0.04-0.11 NL: 5.41E7
T: FTMS + p APCI corona Full ms [50.00-1200.00]

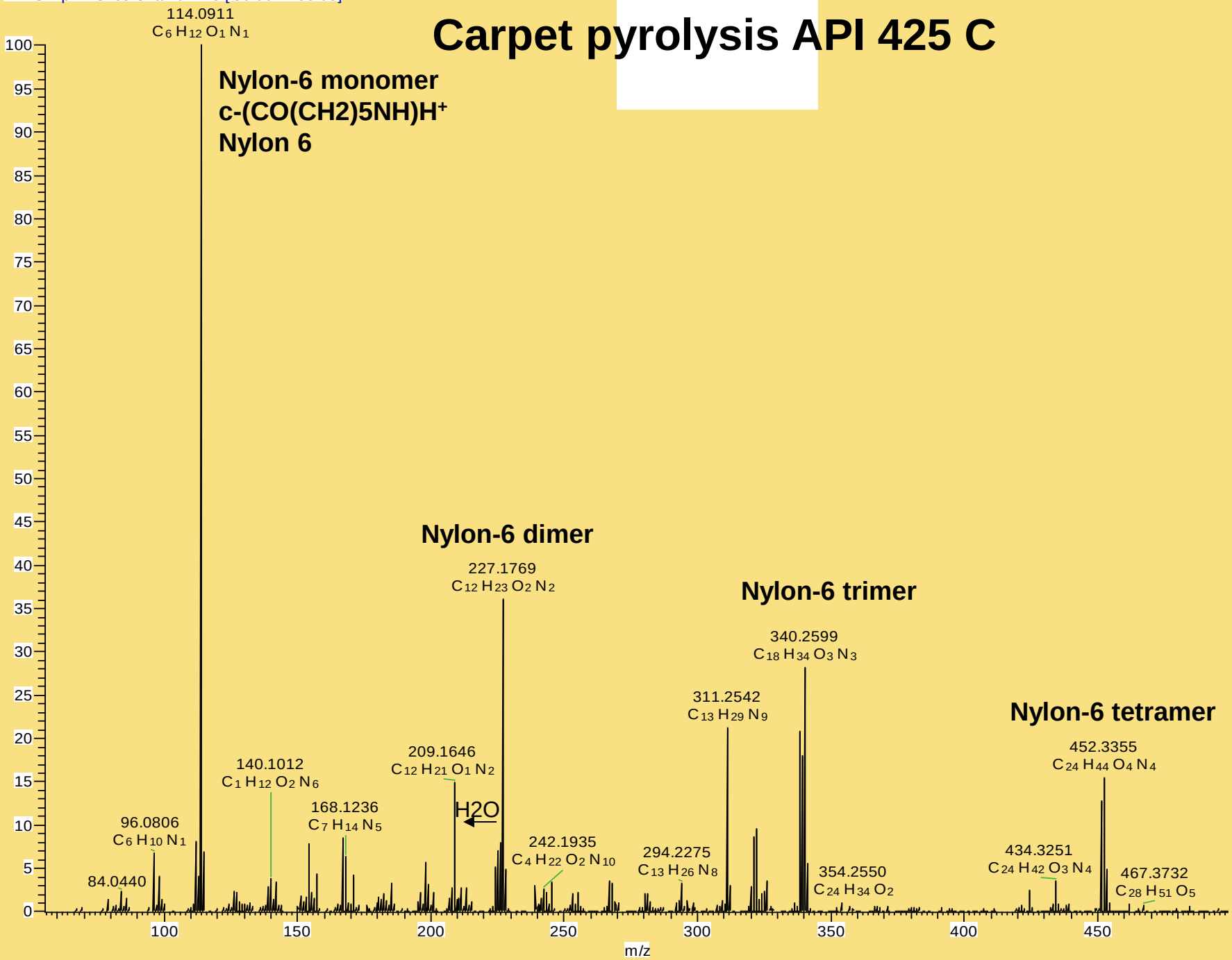
Lab Coat by API Pyrolysis 700C



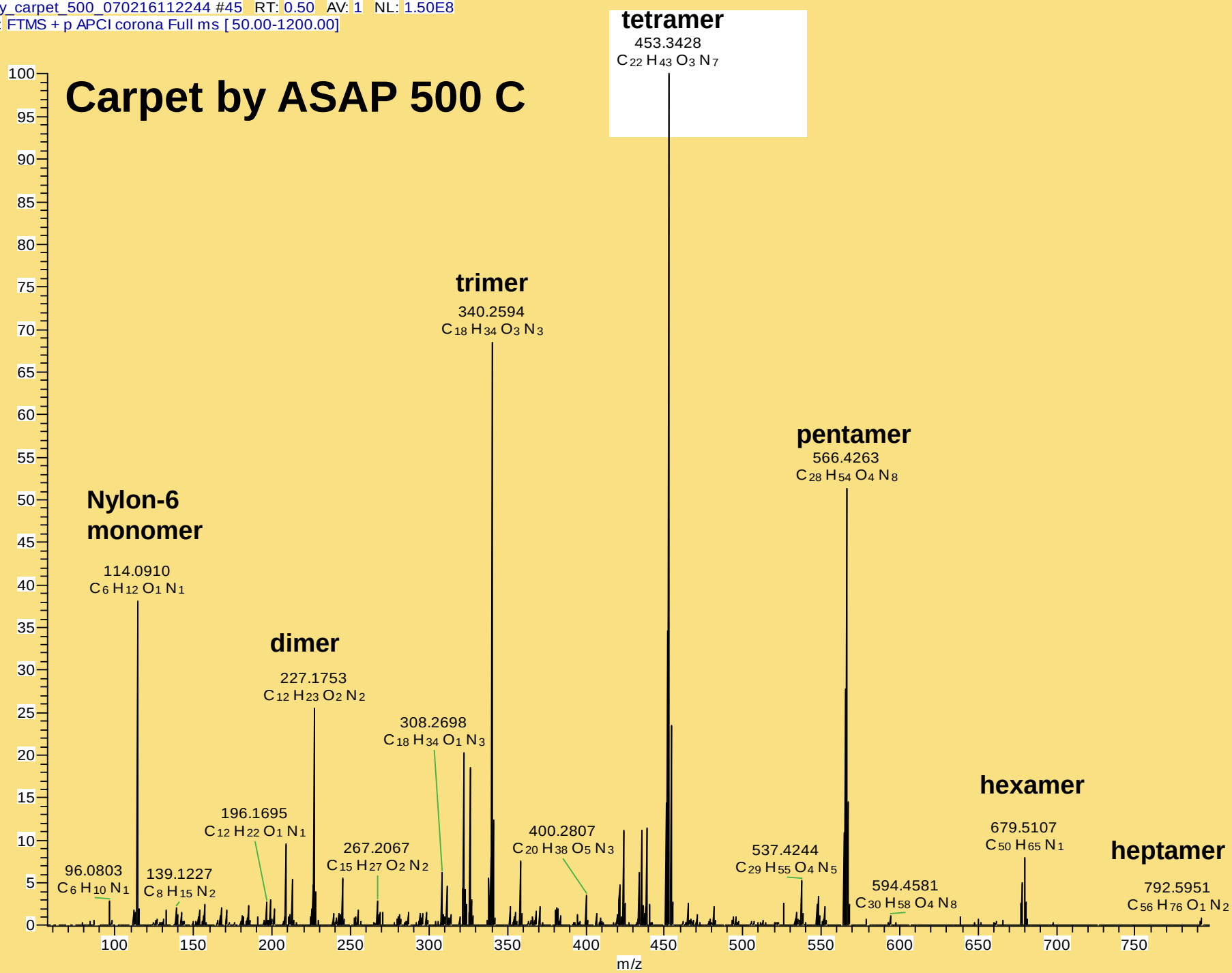
All ions related to PET thermal degradation

Py_carpet_py425_070216112244 #12-16 RT: 0.19-0.24 AV: 5 SB: 5 0.04-0.11 NL: 2.09E6
T: FTMS + p APCI corona Full ms [50.00-1200.00]

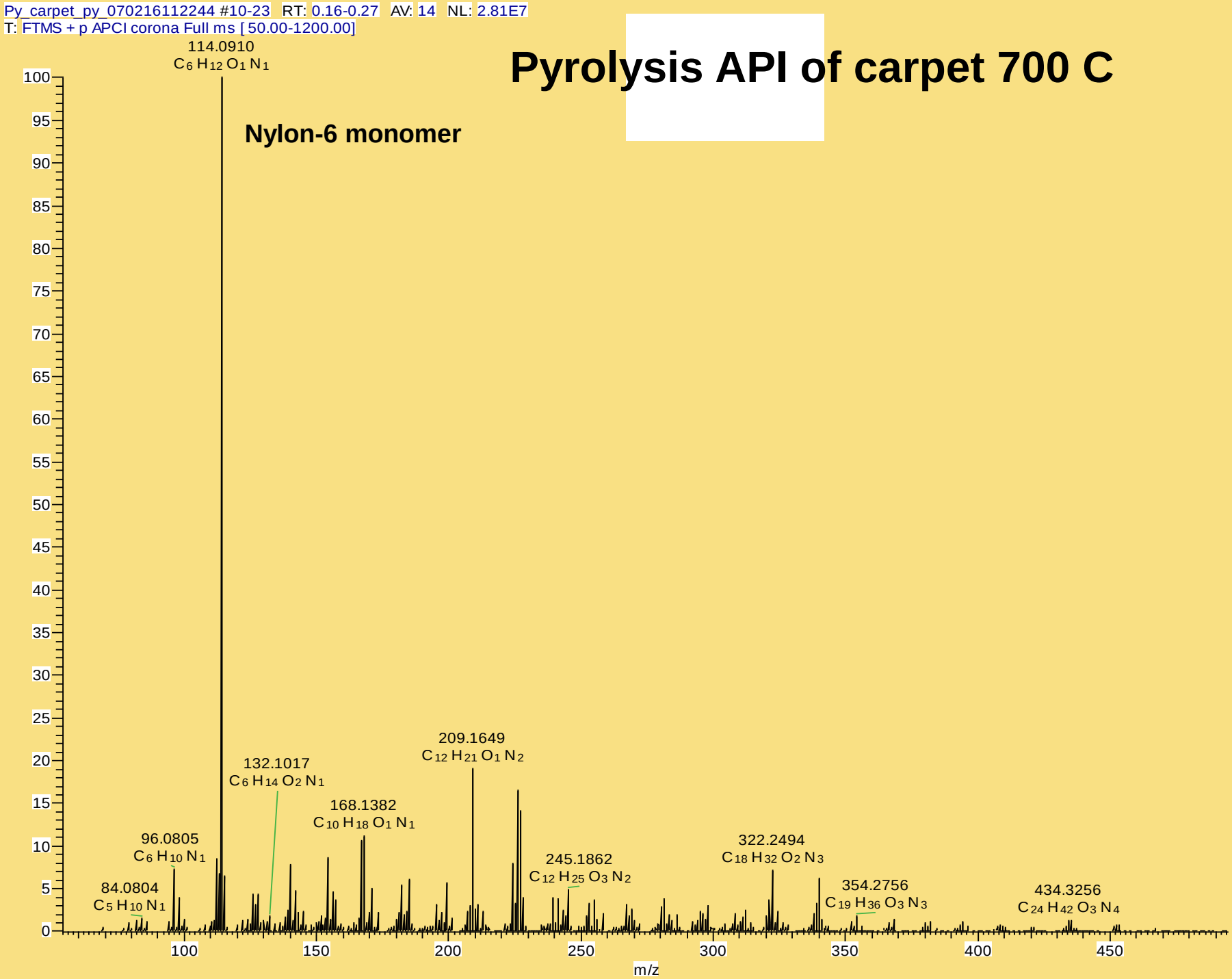
Carpet pyrolysis API 425 C



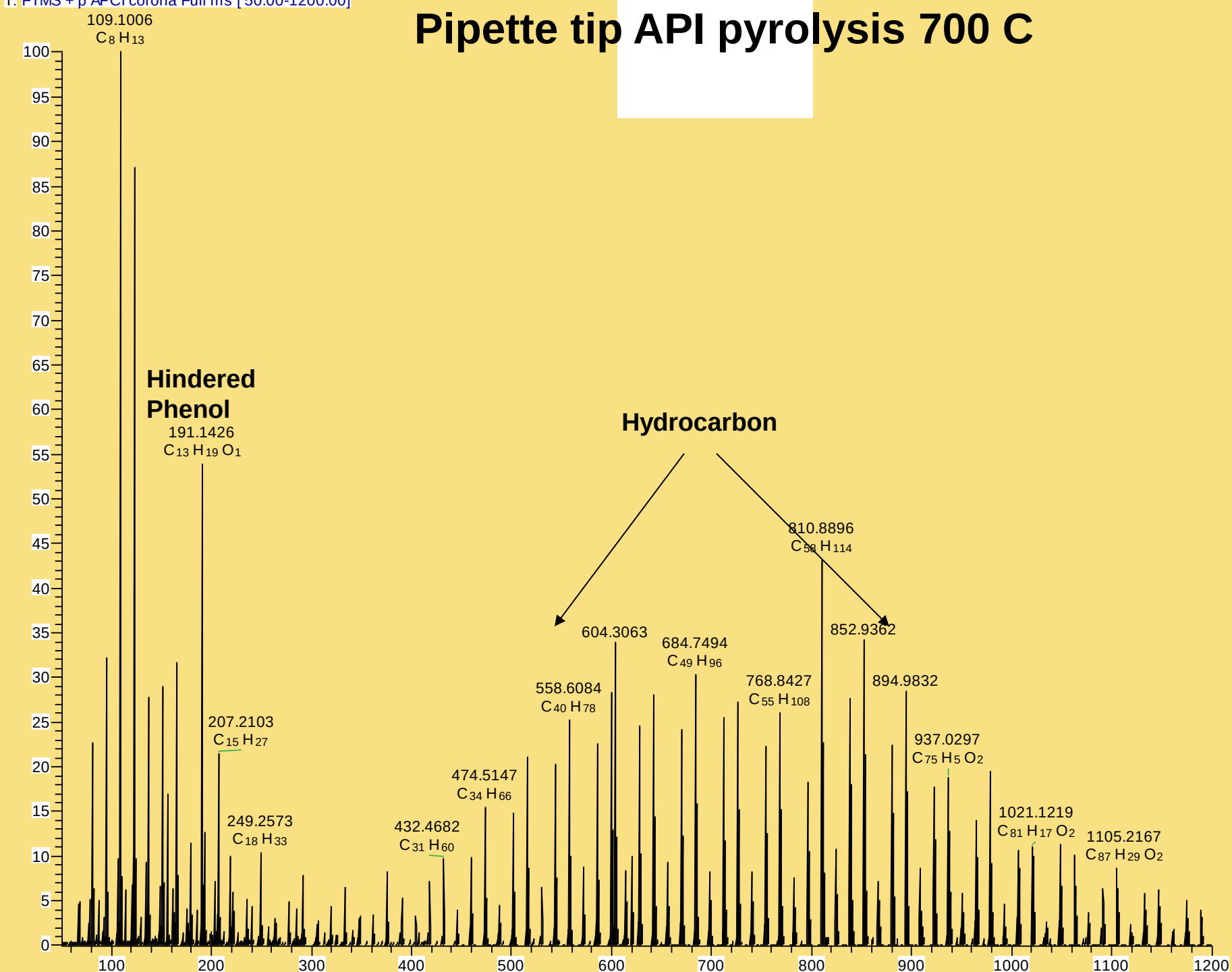
Py_carpet_500_070216112244 #45 RT: 0.50 AV: 1 NL: 1.50E8
T: FTMS + p APCI corona Full ms [50.00-1200.00]



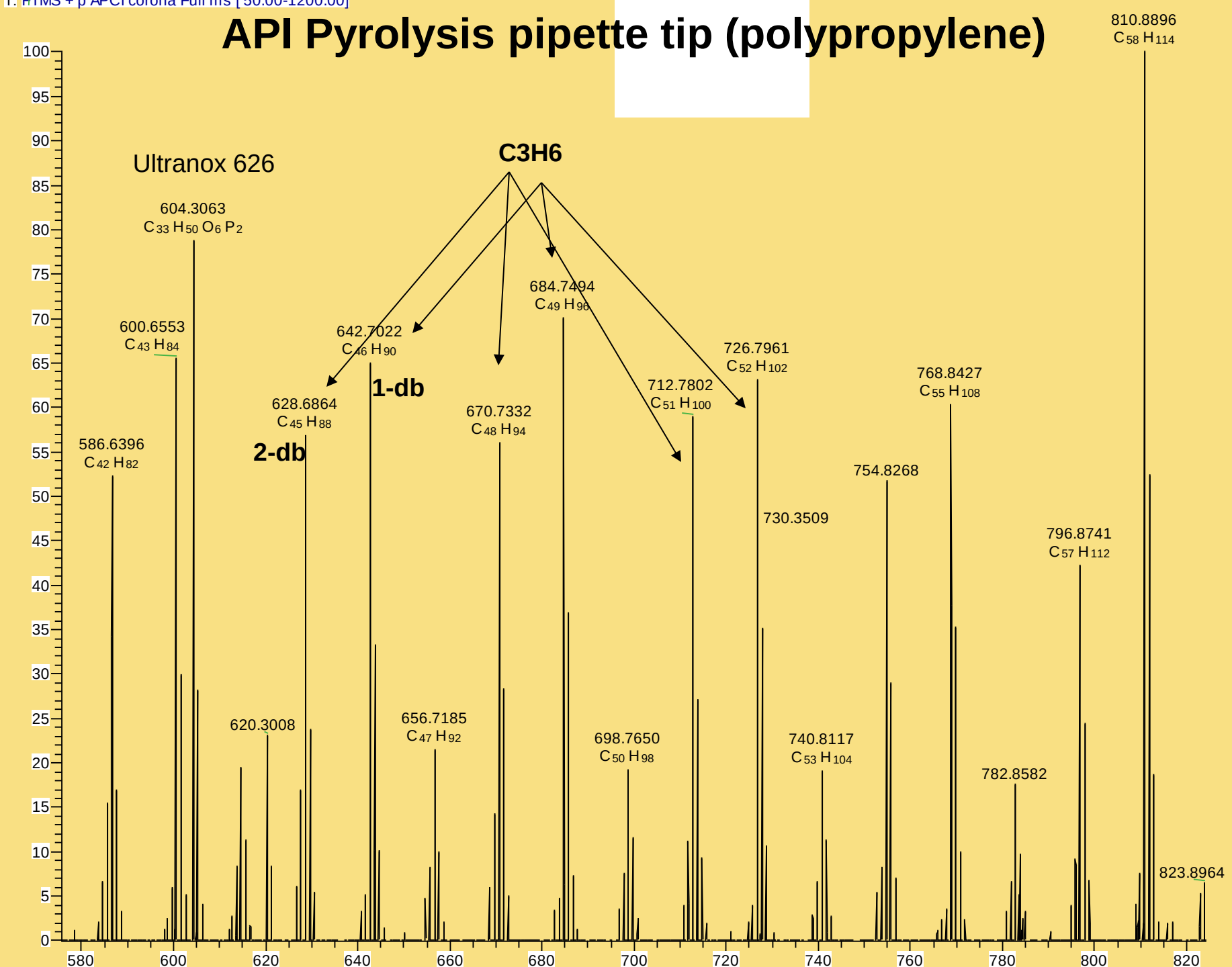
Pyrolysis API of carpet 700 C



Pipette tip API pyrolysis 700 C

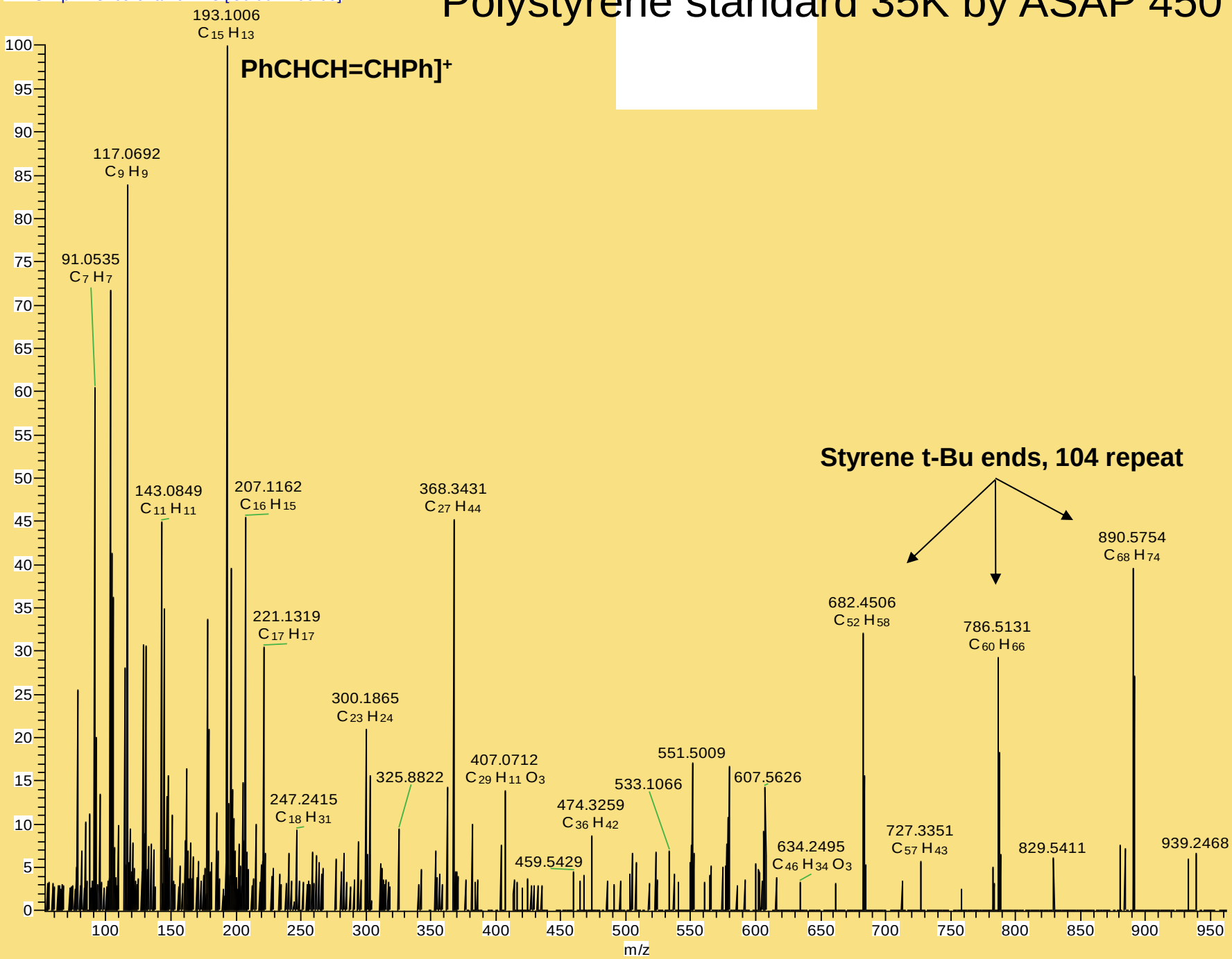


API Pyrolysis pipette tip (polypropylene)

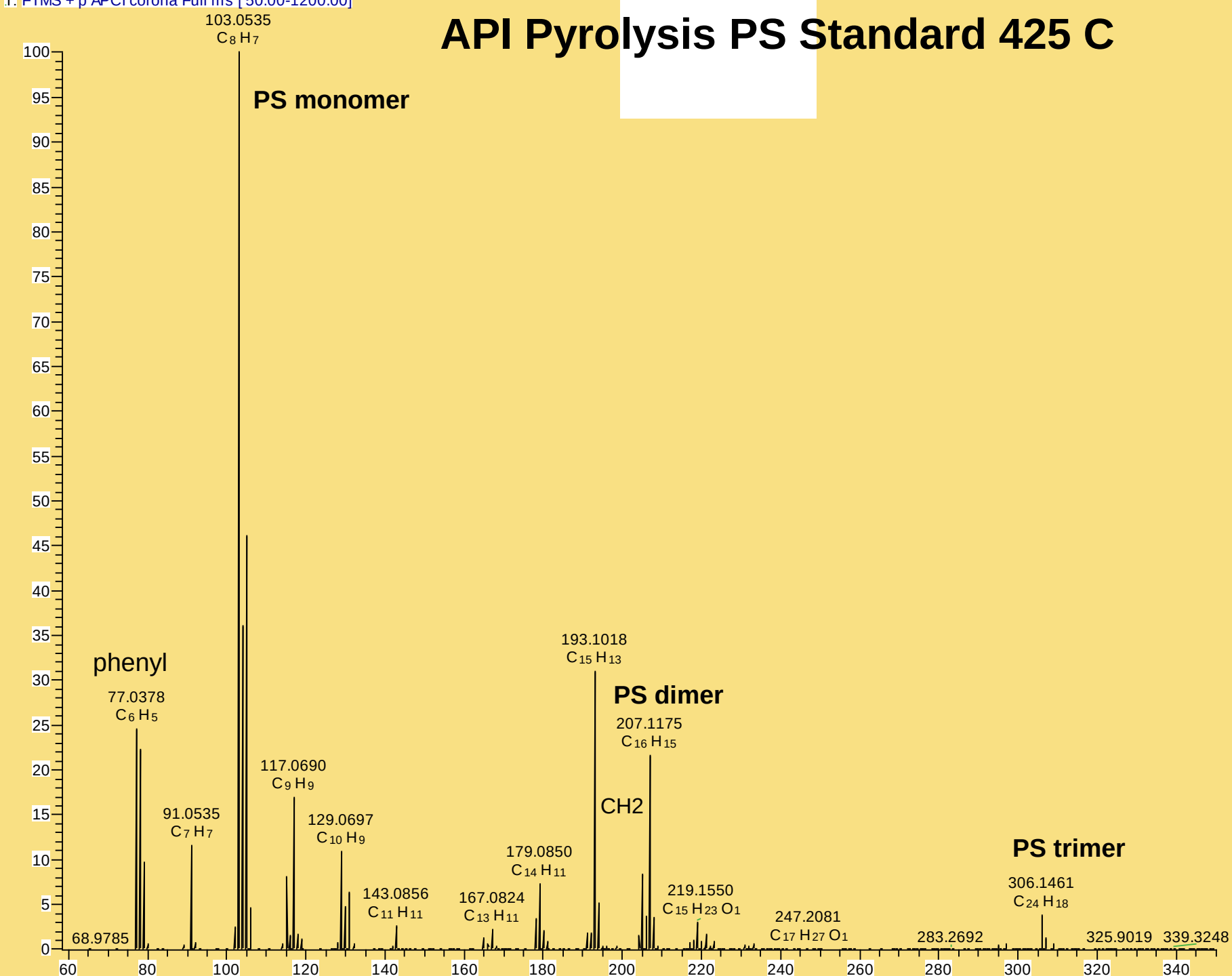


Py_lpolystyrene_070216112244 #92 RT: 0.99 AV: 1 SB: 7 0.01-0.11 NL: 1.75E5
T: FTMS + p APCI corona Full ms [50.00-1200.00]

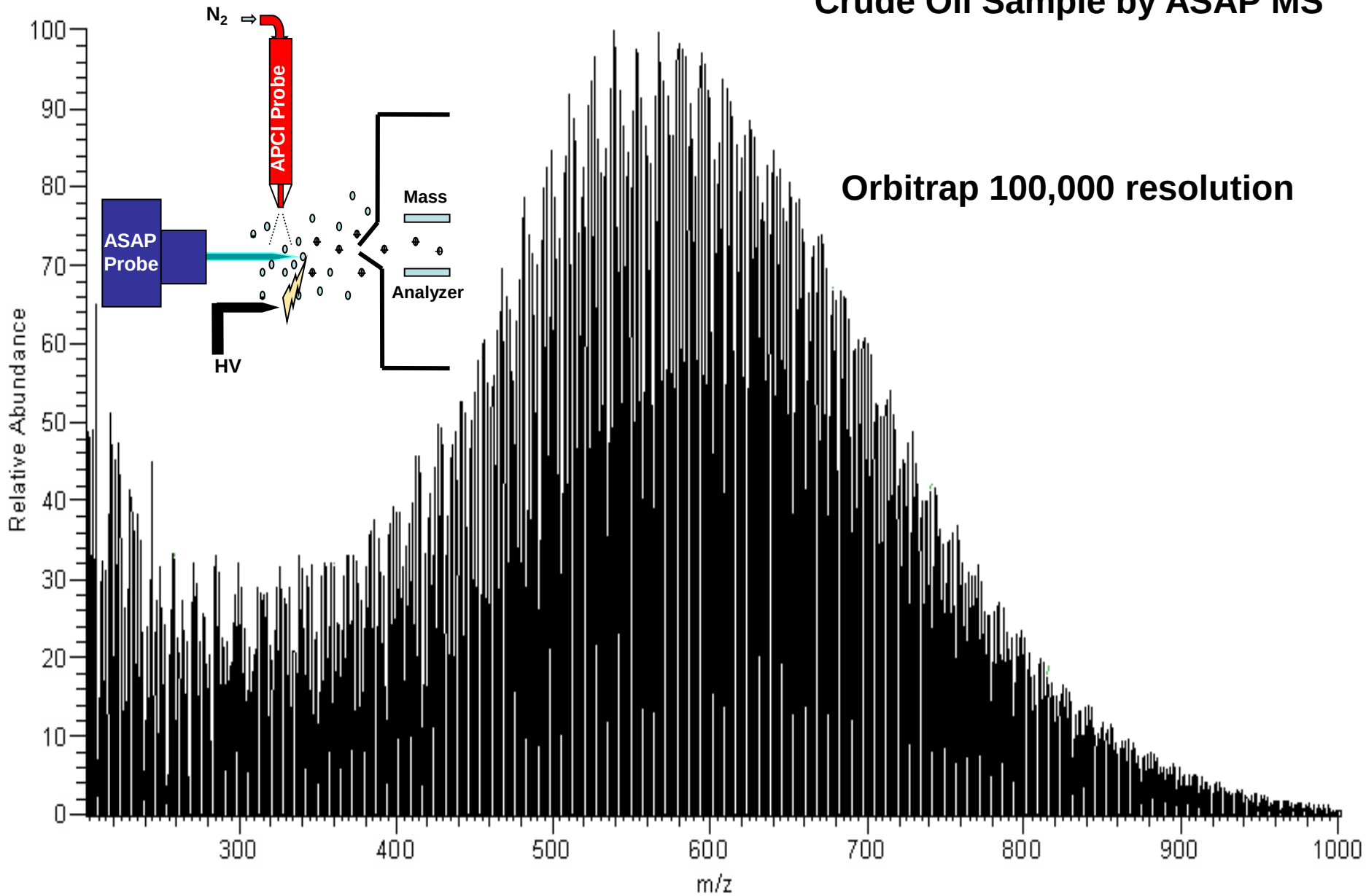
Polystyrene standard 35K by ASAP 450 C



API Pyrolysis PS Standard 425 C



Crude Oil Sample by ASAP MS



Conclusion: ASAP and Py-ASAP MS of Polymers

- **Rapid methods for analysis of additives**
- **and identifying polymers**
- **AP pyrolysis gives better representation of high mass species than traditional pyrolysis methods**
- **Useful in combination with TGA analyses**
- **Unknown: What ions will be observed below m/z 50**

ASAP for Polymer Additive and Volatile Oligomer Analysis

- **Obtain mass of additives in seconds**
- **No sample extraction or preparation required**
- **No vacuum lock**
- **Accurate mass or MS/MS for confirmation**
- **Molecular distribution can be obtained for volatile polymers**

Acknowledgements

Richard G. McKay
Barbara S. Larsen
Patricia M. Peacock

DuPont Corporate Center for Analytical Sciences