

Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

Debjani Banerjee

Department of Chemical Engineering
IIT Kanpur



Introduction

What is ICP-MS ?

Inductively Coupled Plasma Mass Spectrometry

Mass spectrometry (MS) is an analytical technique that ionizes chemical species and sorts the ions based on their mass-to-charge ratio.

Inductively coupled plasma mass spectrometry (ICP-MS) is a type of mass spectrometry which is capable of detecting metals and several non-metals at concentrations as low as parts per billion on non-interfered low-background isotopes.

Elemental Analysis with

Wide Elemental Coverage

Fast Analysis times (all elements at once)

High Throughput & Productivity

Extremely Low Detection Limits (ppt/ppm) or (ng/L to mg/L)

Simple Spectra

Isotopic Information

Principle of Atomic Spectroscopy

Atomic Absorption Spectroscopy

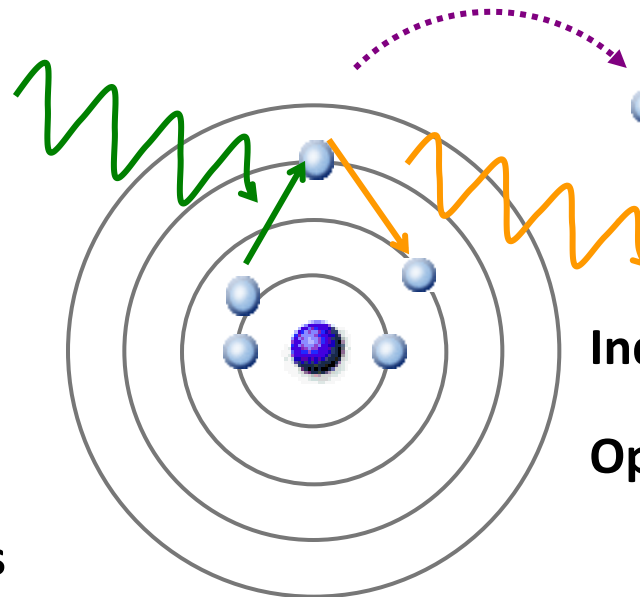
(FAAS)

Graphite Furnace AAS

(GFAAS)

 **Nucleus**

 **Electron**



 **ICP-Mass Spectroscopy**

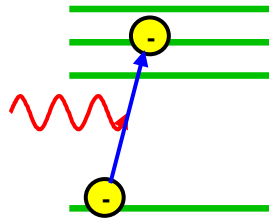
Inductively Coupled Plasma -

Optical Emission Spectroscopy

Atomic spectrometry

Atomic Absorption

Light of specific wavelength from Hollow Cathode Lamp (HCL)

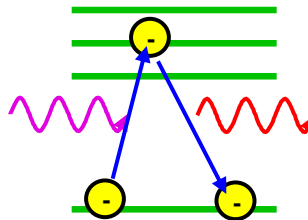


Light of specific characteristic wavelength is absorbed thereby promoting an electron to a higher energy level.

Light absorption is proportional to elemental concentration

Atomic Emission

Light and heat energy from high intensity source (flame or plasma)

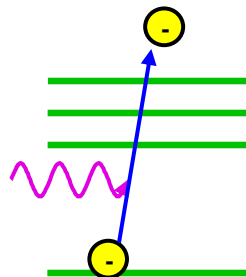


High energy (light and heat) promotes an electron to a higher energy level (excitation). Electron falls back and emits light at characteristic wavelength

Light emission is proportional to elemental concentration

Mass Spectrometry

Light and heat energy from high intensity source (plasma)

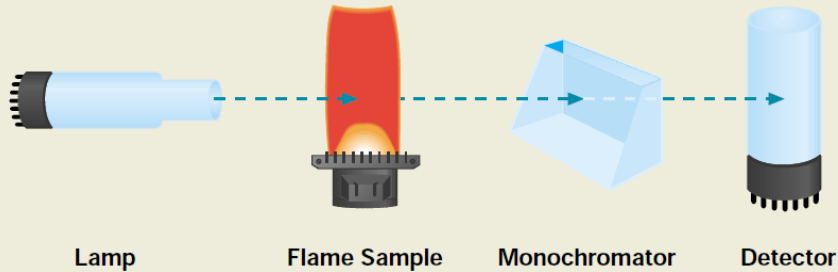


High energy (light and heat) ejects electron from shell (ionization). Result is free electron and atom with positive charge (ion)
Ions are extracted and measured directly in mass spectrometer

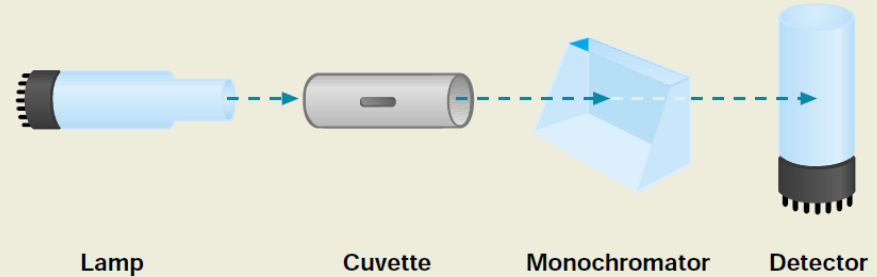
An atom can only absorb the radiations that it is able to emit

Types of Atomic Spectroscopy

Flame Atomic Absorption Spectrometry (FAAS)

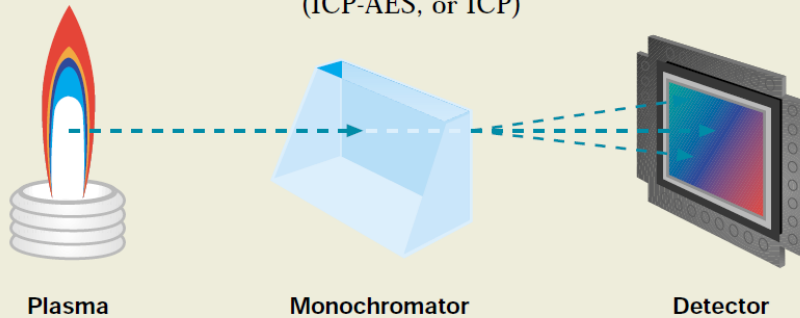


Graphite Furnace Atomic Absorption Spectrometry (GFAAS)

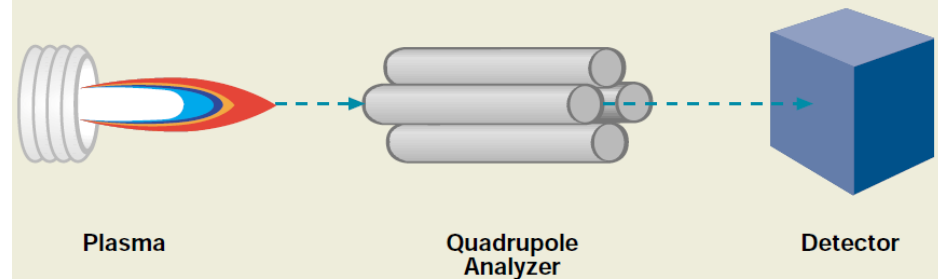


Air/acetylene flame or an electrically heated Graphite tube is used to evaporate the solvent and dissociate the sample into its component atoms. When light from a hollow cathode lamp passes through the cloud of atoms, the atoms of interest absorb the light from the lamp. This is measured by a detector, and used to calculate the concentration of that element in the original sample

Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES, or ICP)



Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

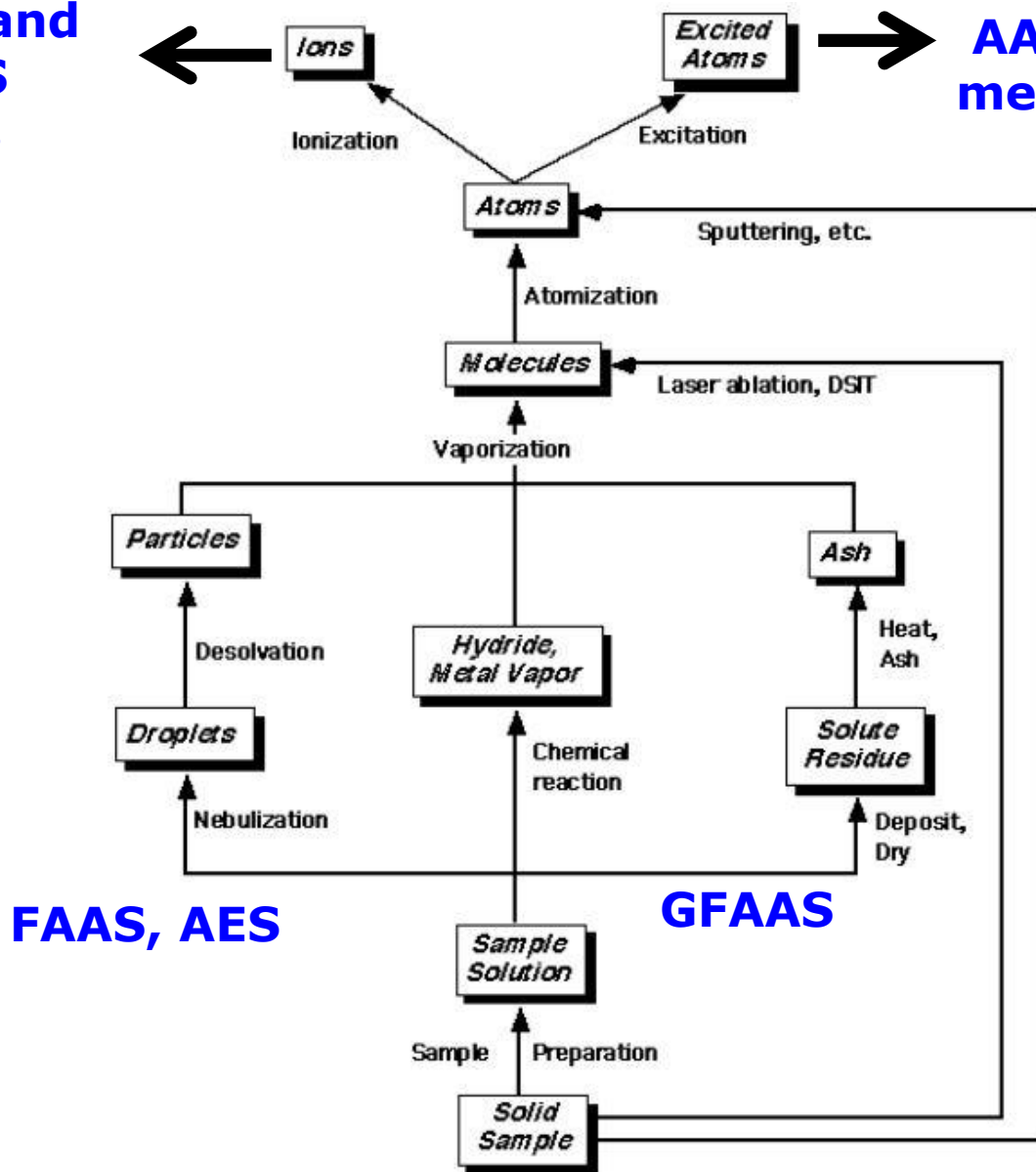


ICP-AES is a multi-element analysis technique that uses an inductively coupled plasma source to dissociate the sample into its constituent atoms or ions, exciting them to a level where they emit light of a characteristic wavelength. A detector measures the intensity of the emitted light, and calculates the concentration of that particular element in the sample

Crucial steps in atomic spectroscopies and other methods

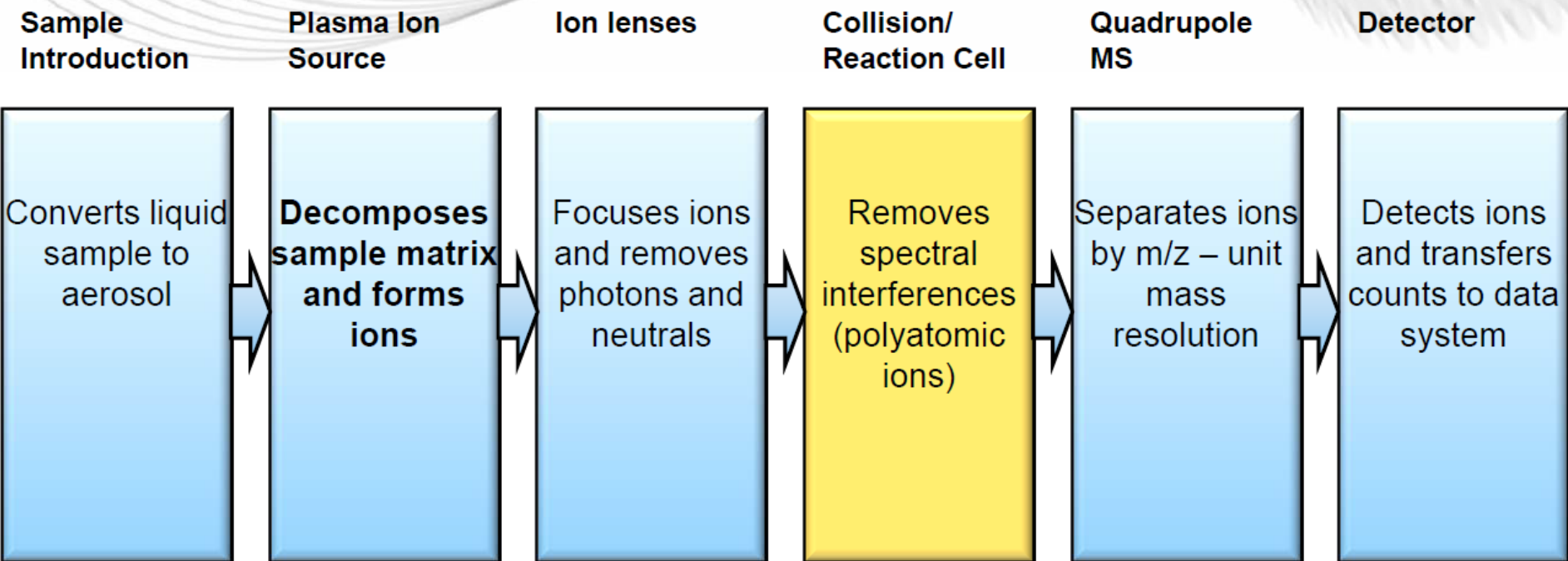
ICP-MS and other MS methods

AAS and AES, X-ray methods



Basic Instrumental Components of ICP-MS

Simplified Schematic – the functional components

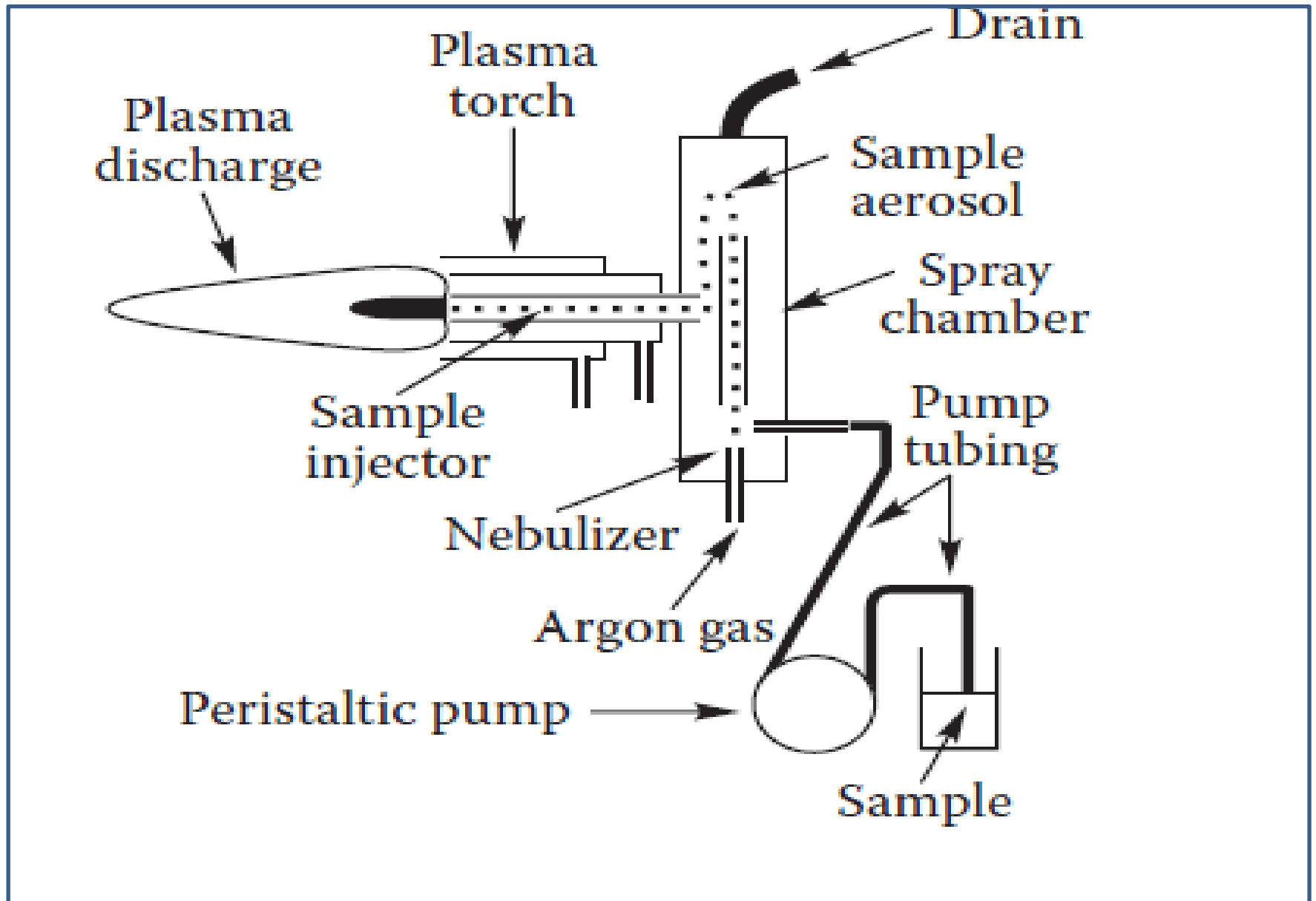


Interface: Links the atmospheric pressure ICP ion source to the high vacuum MS

Vacuum System: Provides high vacuum for Ion Optics, Quadrupole and Detector

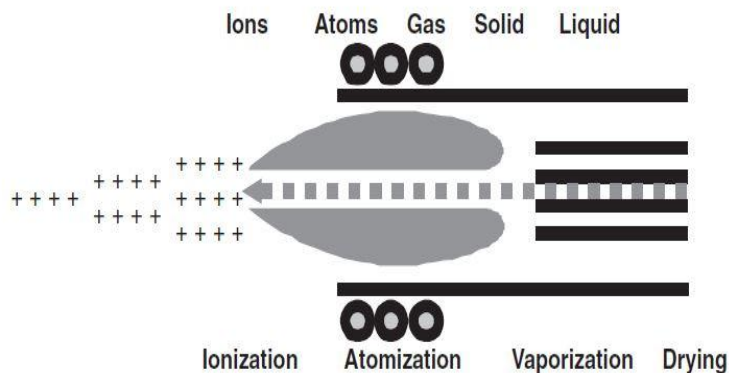
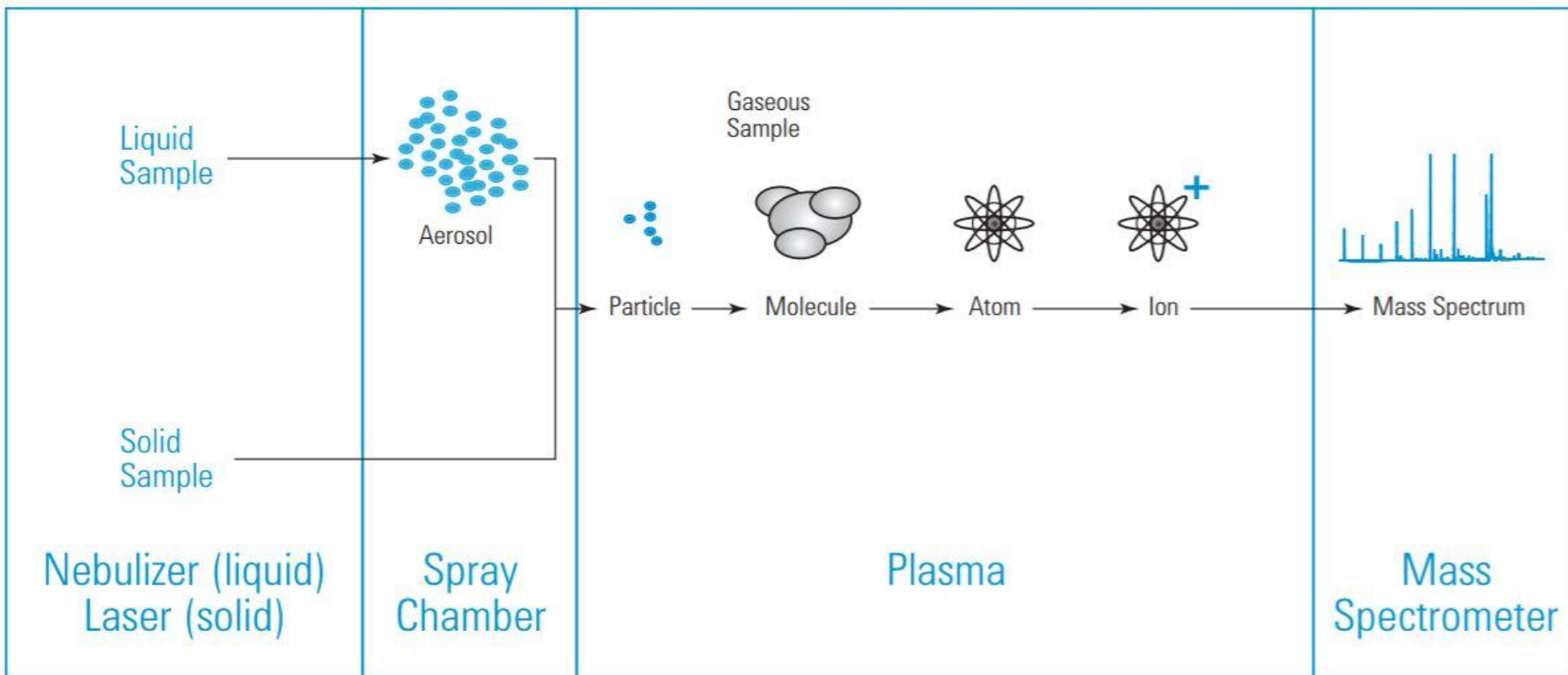
Data Handling & System Controller: Controls all aspects of instrument control and data handling to obtain final concentration results

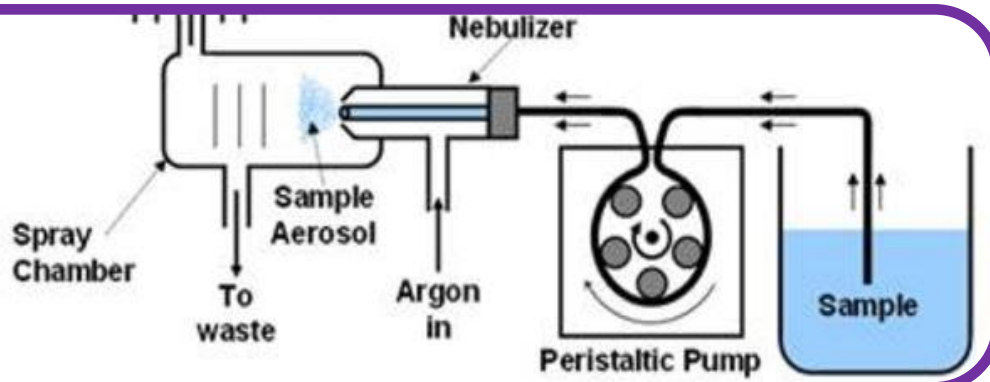
ICP-MS Sample Introduction Area



Generation of Positively Charged Ions in Plasma

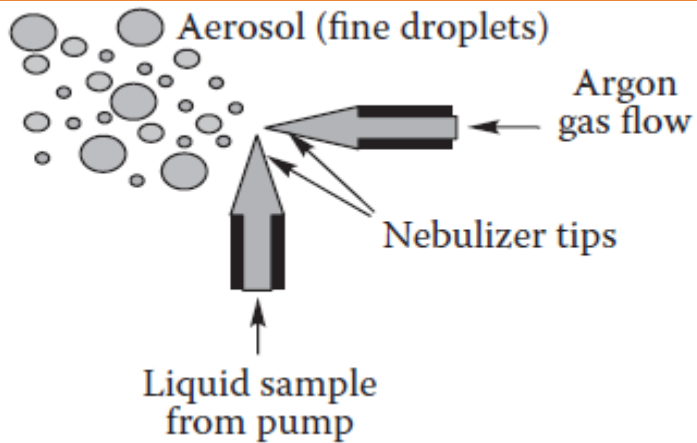
NEBULIZATION DESOLVATION VAPORIZATION ATOMIZATION IONIZATION MASS ANALYSIS





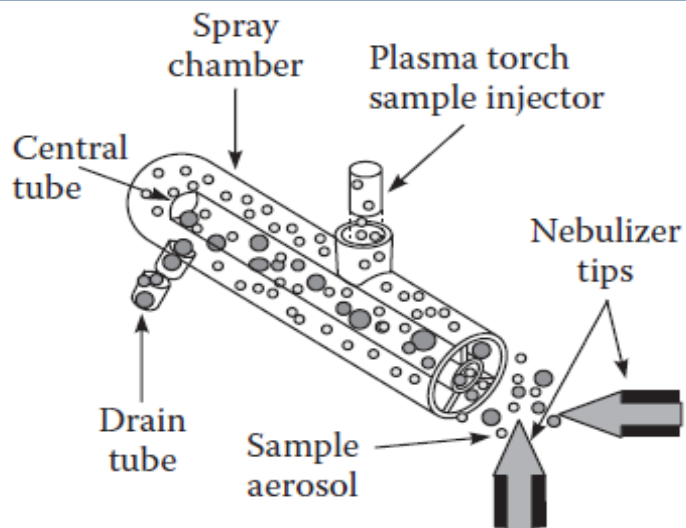
Peristaltic Pump:

Ensures constant flow of liquid irrespective of differences in viscosity between samples, standards and blanks. Sample pumped at 1ml/min



Micromist Nebulizer:

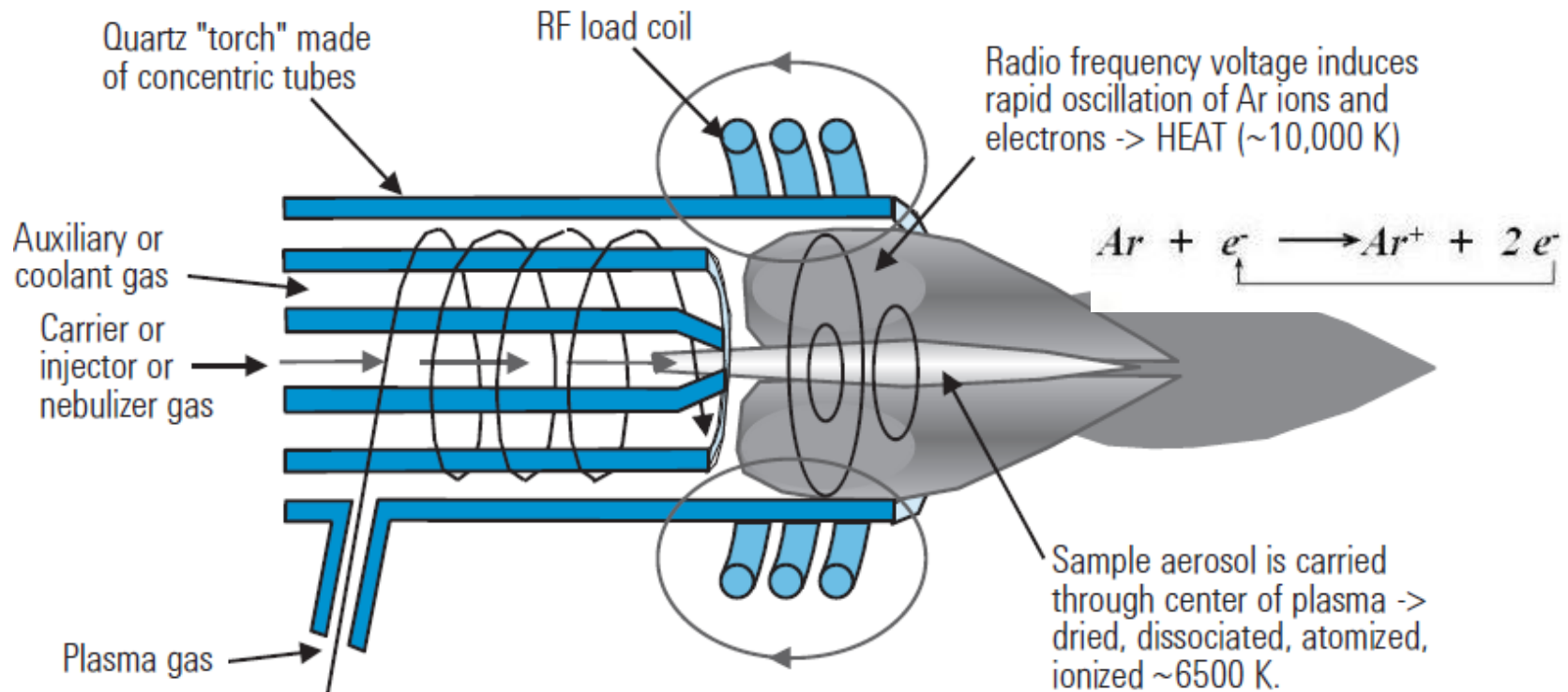
Liquid is converted into a fine aerosol by pneumatic action of a flow of argon gas (~1L/min) smashing the liquid into tiny droplets



Double Pass Spray Chamber:

Spray Chamber only allows small droplets (<math><10\mu\text{m}</math>) to enter the plasma. Larger droplets having higher momentum collide with wall of spray chamber, get condensed & eventually fall out by gravity through the drain

ICP Plasma Ionization Source

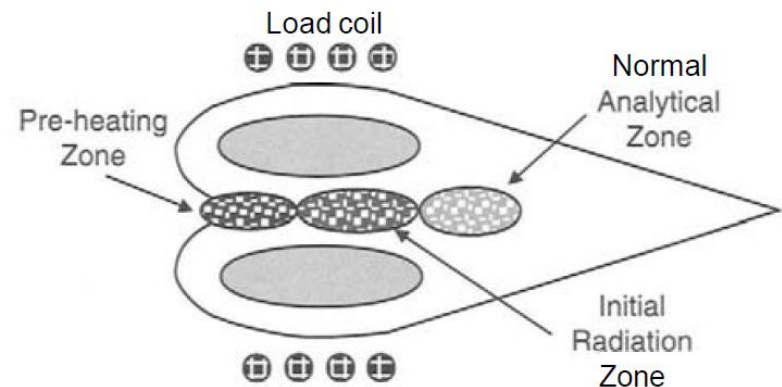


Inductively coupled plasmas are formed by coupling energy produced by a RF generator to the plasma support gas with an electromagnetic field. The field is produced by applying an RF power (typically 700-1500 W) to a load coil.

PHZ: Sample desolvation

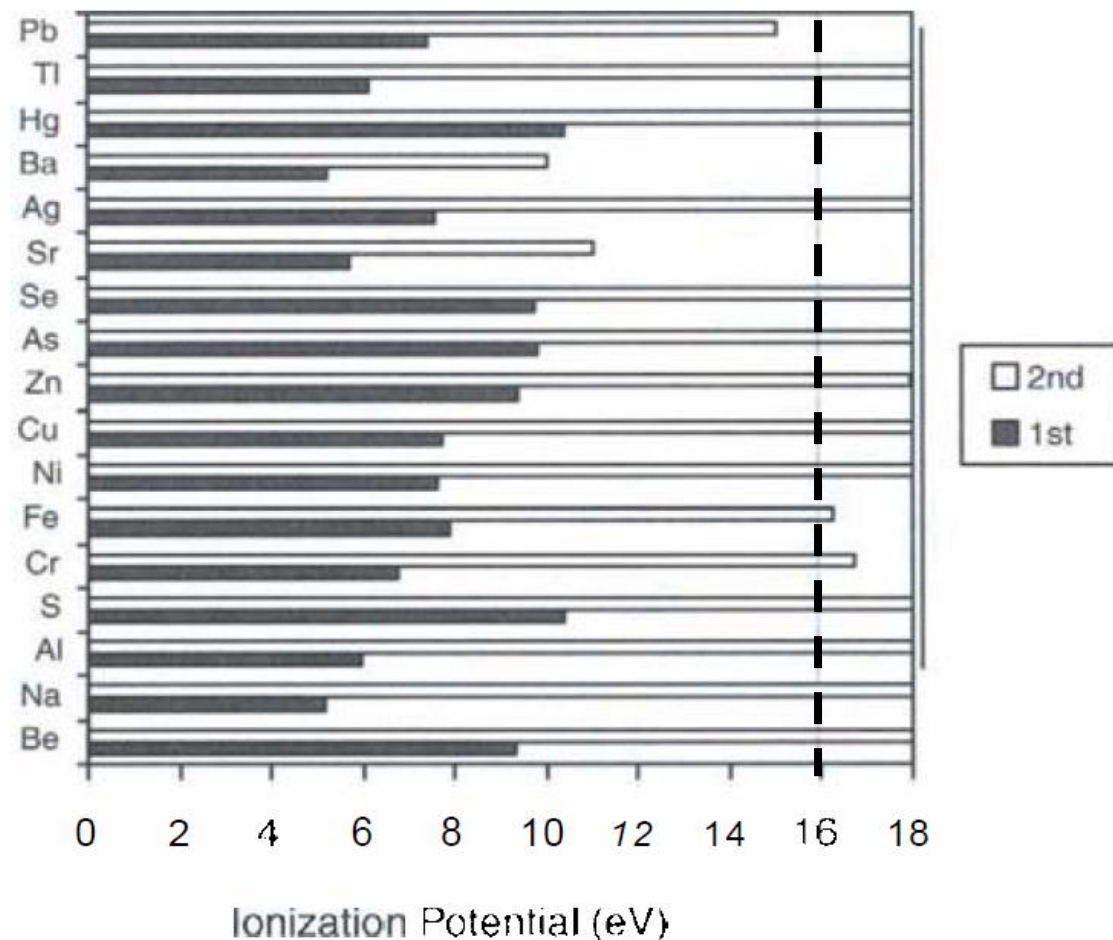
IRZ: Atomization

NAZ: Ionization



Degree of Ionization, First & Second Ionization potentials of selected elements

Element	Degree of ionization (%)
Ar	0.04
As	52
Br	5
Cd	65
Co	93
Cr	98
Cu	90
Fe	96
La	90
Mn	95
Na	100
P	33
Pb	97
Rb	100
Se	33
Sr	96
Tl	100
V	99
Zn	75

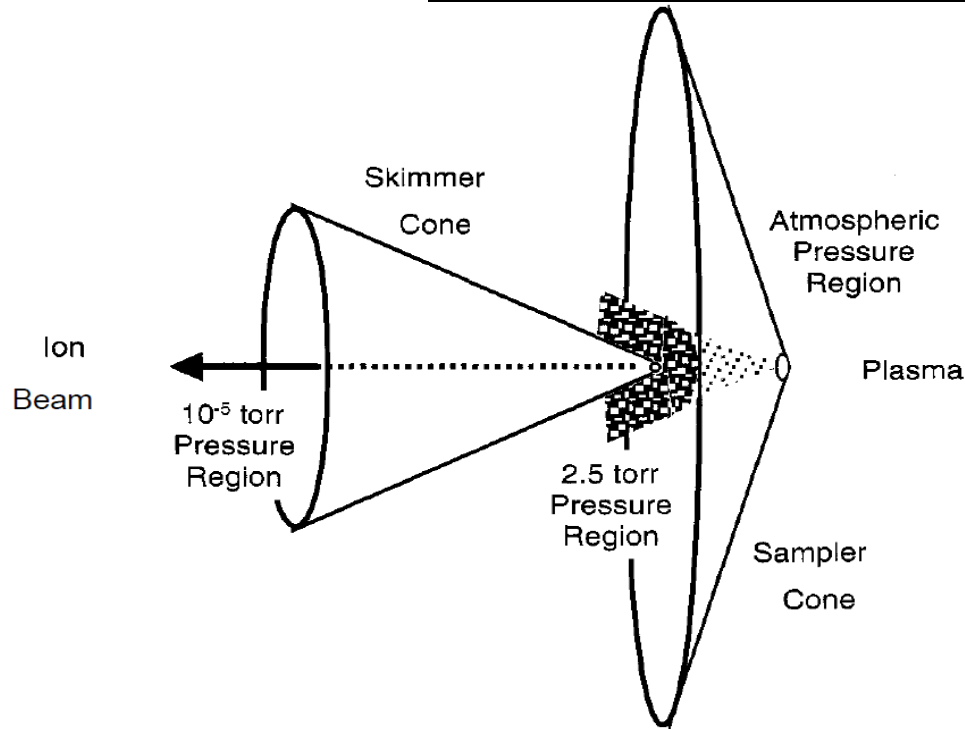


✓ Argon first ionization potential ~ 15 eV

✓ Most elements have first ionization potentials below 10 eV, hence >50% ionization

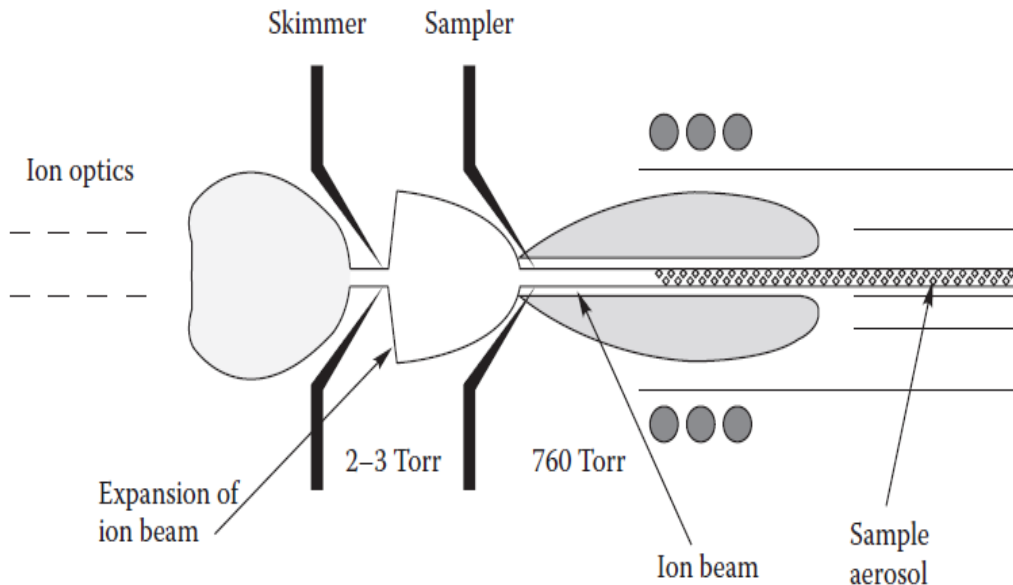
✓ Very few elements have second ionization potential below 10 eV, less doubly charged species

ICP Interface Region



✓ A section that connects the ionizing section at ambient pressure to the mass spectrometer at high vacuum (~10⁻⁶ torr).

✓ Function is to export the ions produced in argon plasma and transport them to the mass spectrometer

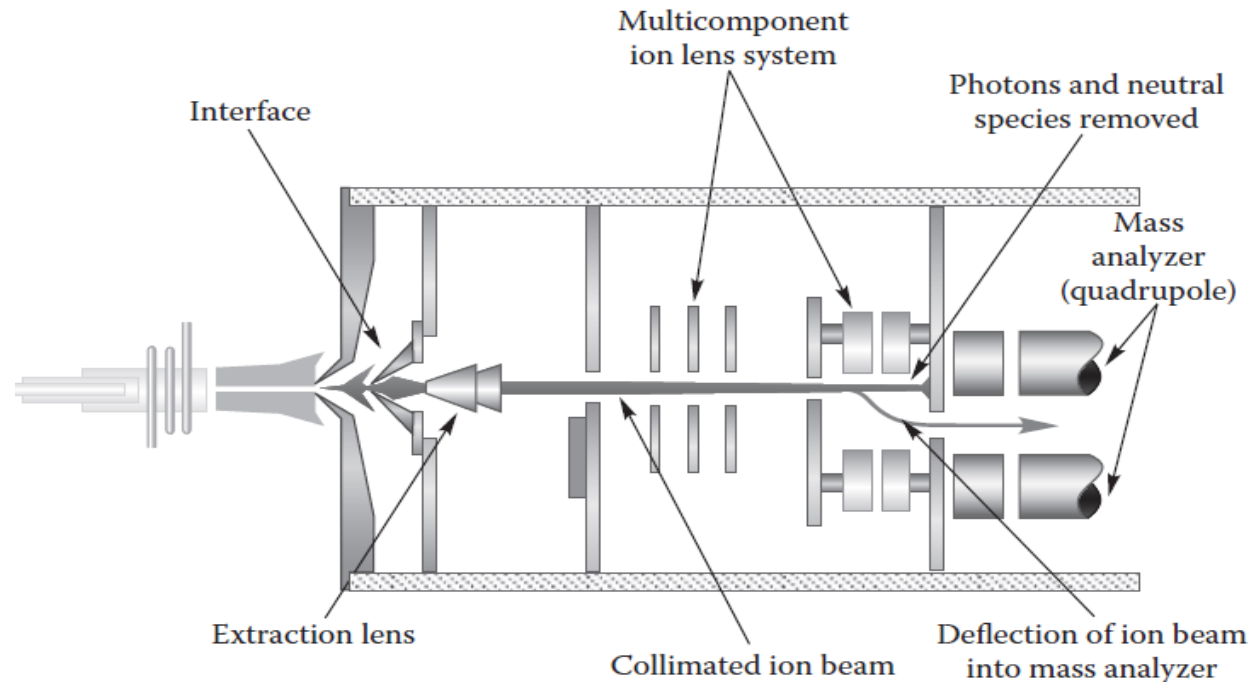


✓ Two metallic (Ni or Pt) cones with small orifices (1mm)- Sampler and Skimmer Cones directs the expanded gas jet of ions into the MS

ICP Ion Focussing Region

One or more electrostatically controlled lens component made up of series of metallic plates or cylinders having a voltage placed on them

Ions are separated from Photons & Neutrals by positioning MS off-axis to the ion beam or using a Physical barrier

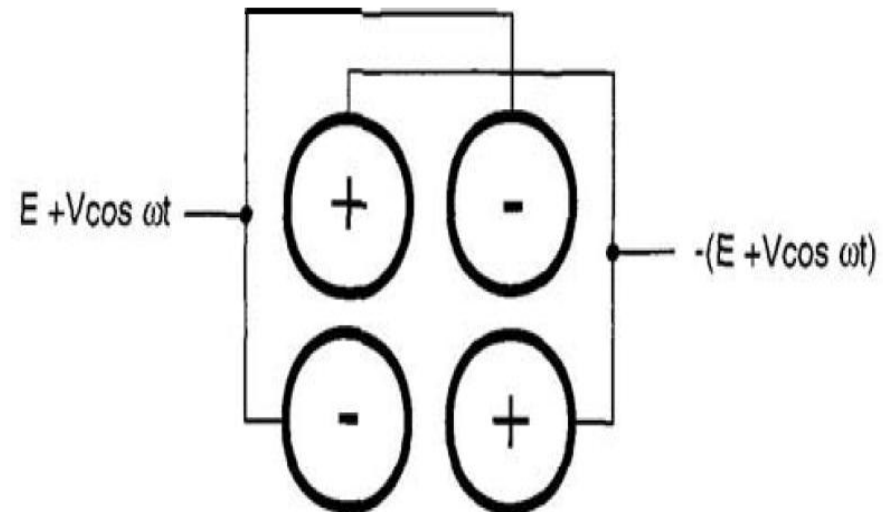
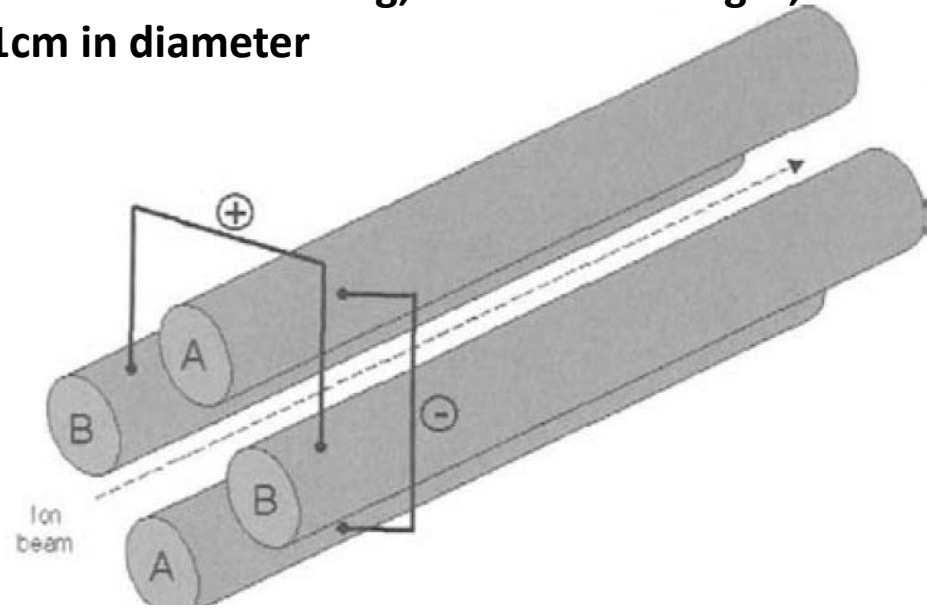


- ✓ Out of a million ions generated in the plasma, only one actually reaches the detector due to higher concentration of matrix elements than analyte.
- ✓ Role of ion focussing is to transport maximum number of analyte ions from the hostile environment of plasma to the MS via the interface.
- ✓ Photons & Neutrals cause signal instability & contribute to background noise.
- ✓ Voltages on the ions lens components electrostatically steer the ions of interest into the MS.

Mass Analyzer- Quadrupole

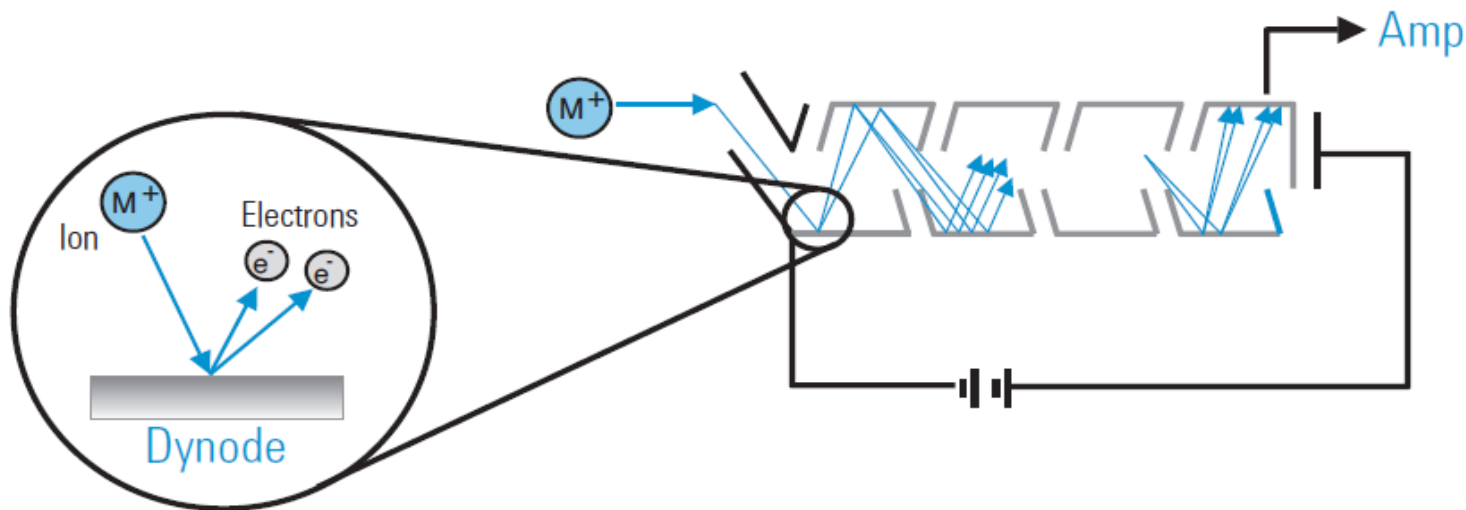
- Quadrupole is a sequential mass filter, which separates ions based on their m/z .
- Measurement of the m/z of the ion allows qualitative identification of the isotope or molecule. Magnitude of the ion current is used to provide quantitation of the amount of the analyte in the original sample.
- Two pairs of parallel cylindrical rods to which a varying AC voltage plus a DC voltage is applied.
- Any ion above or below the set mass of the quadrupole enters an unstable trajectory and gets lost from the ion beam.
- Varying the AC and DC voltages, different masses can be selectively allowed to pass through.

Made of stainless steel or molybdenum with ceramic coating, 15-25 cm in length, 1cm in diameter



Ion Detectors

Detector in ICPMS ensures high sensitivity and low background noise.



- ✓ Detector is an Electron Multiplier Device which can generate a measurable signal pulse from the impact of a single ion.
- ✓ A positive ion arrives at the mouth of the detector, it is deflected onto the first dynode, held at a high negative voltage.
- ✓ The impact of the ion releases several free electrons from the dynode surface, which are repelled from the high negative voltage at the front and strike the next dynode.
- ✓ Each electron which strikes a dynode releases several electrons from that surface and hence the device is called "electron multiplier". The multiplication factor builds up a pulse large enough to be measured reliably as an ion "count".

Spectral Interferences

✓ Polyatomic or molecular Spectral Interferences severely compromise detection capability of certain elements by ICP-MS using the Quadrupole mass analyzer technology. Generated by combination of Plasma/nebulizer Gas, solvent and matrix derived ions.

EXAMPLES OF SPECTRAL INTERFERENCES

Plasma Gas Interference:

✓ Most abundant isotope of Ar is at mass 40 which dramatically interferes with the most abundant isotope of Ca at mass 40.

✓ Combination of argon and oxygen in an aqueous sample generates the $^{40}\text{Ar}^{16}\text{O}^+$ interference, which has a significant impact on the major isotope of Fe at mass 56.

- $^{40}\text{Ar}^{16}\text{O}^+$ in the determination of $^{56}\text{Fe}^+$
- $^{38}\text{ArH}^+$ in the determination of $^{39}\text{K}^+$
- $^{40}\text{Ar}^+$ in the determination of $^{40}\text{Ca}^+$
- $^{40}\text{Ar}^{40}\text{Ar}^+$ in the determination of $^{80}\text{Se}^+$
- $^{40}\text{Ar}^{35}\text{Cl}^+$ in the determination of $^{75}\text{As}^+$
- $^{40}\text{Ar}^{12}\text{C}^+$ in the determination of $^{52}\text{Cr}^+$
- $^{35}\text{Cl}^{16}\text{O}^+$ in the determination of $^{51}\text{V}^+$

Solvent Based Interferences: In a HCl acid medium, $^{40}\text{Ar}^+$ combines with the most abundant chlorine isotope at 35 amu to form $^{40}\text{Ar}^{35}\text{Cl}^+$, which interferes with the only isotope of As at mass 75.

Isobaric Interferences: Direct overlap from a different element with an isotope at the same nominal mass known as an isobaric interference, e.g. ^{114}Sn overlap on ^{114}Cd

****Doubly-charged species resulting from ions created by the loss of two electrons instead of just one. Because the quadrupole separates ions based on m/z (mass over charge ratio), a doubly-charged ion (M^{2+}) will appear at mass M/2. An example of a doubly-charged interference would be the $^{136}\text{Ba}^{2+}$ overlap on $^{68}\text{Zn}^+$**

Collision Reaction Cell (CRC)-Removal of Spectral Interferences

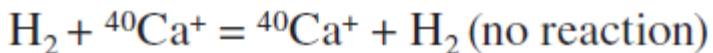
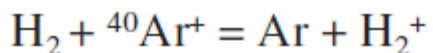
The CRC devices in commercial ICP-MS instruments have been designed to remove polyatomic species

Modes of Operation:

No-gas mode - no gas in the cell - the instrument performs like a standard ICP-MS. High sensitivity is achieved for all elements. This mode is typically used for uninterfered elements such as Be, Hg, Pb.

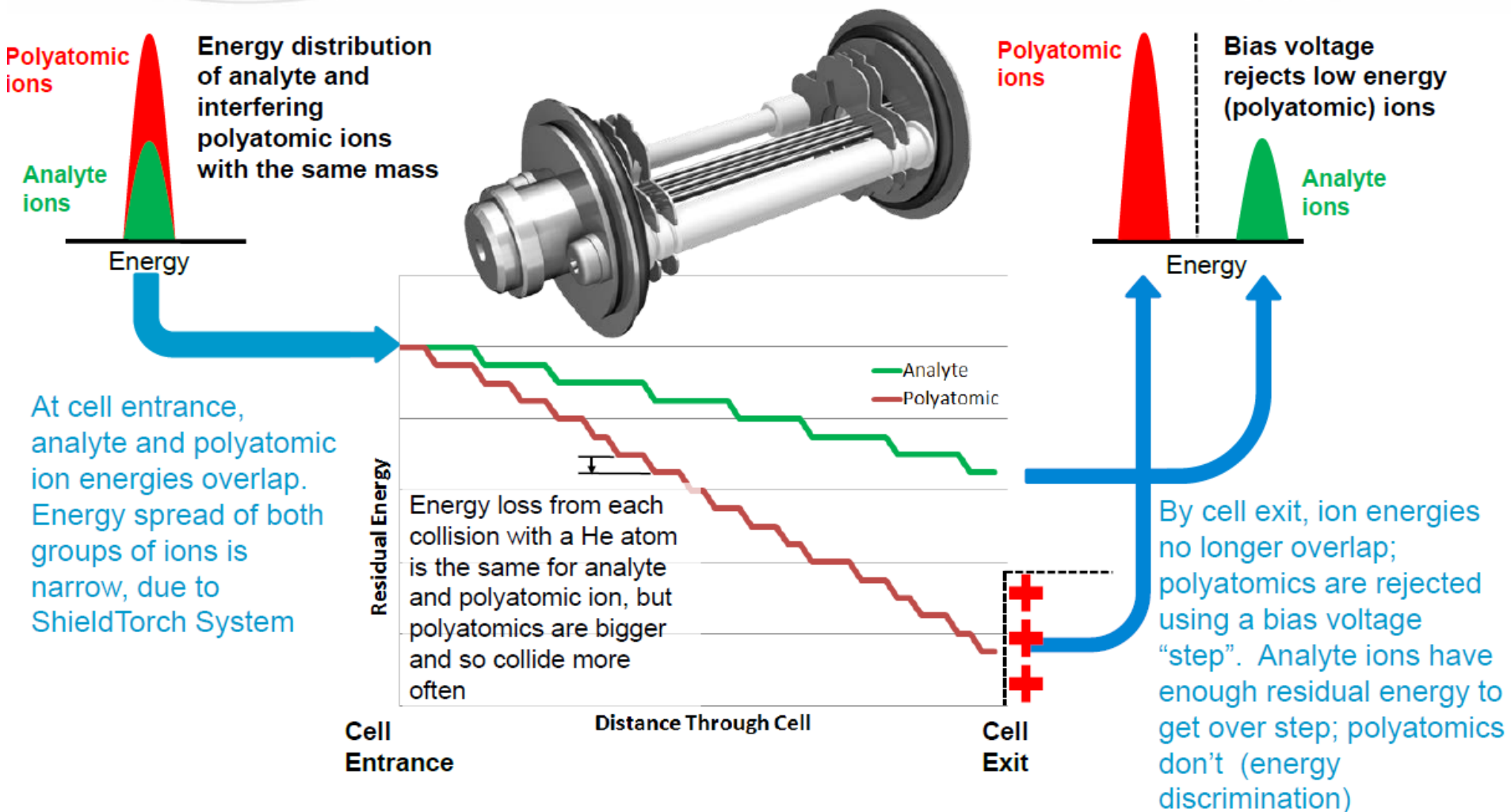
Helium (Collision) mode - used for all analytes that suffer matrix-based Interferences are removed based on their physical size. Since all polyatomic interferences are larger than the analytes they interfere with, they will collide with the He cell gas atoms more frequently than will the smaller analyte ions. The polyatomic ions will therefore lose more energy and will be prevented from entering the mass analyzer by a positive discrimination voltage. This is known as Kinetic Energy Discrimination (KED).

Hydrogen (Reaction) mode - used only for the very few situations where He collision mode is not efficient enough, which is only for intense plasma-based interferences.



Collision Mode:

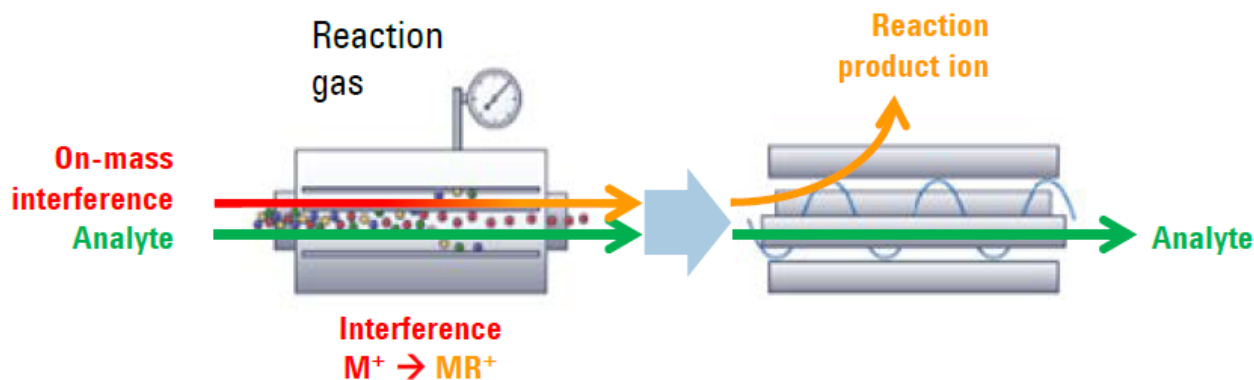
Principle of for removing polyatomic interferences *He Mode and KED (Kinetic Energy Discrimination)*



Reaction Mode:

Another tool for removing interferences

1. On-Mass Measurement: **Unreactive analyte** does not react with chosen cell gas, remains at original m/z and so can be separated from reactive interferences



Analyte and interfering ions enter reaction cell

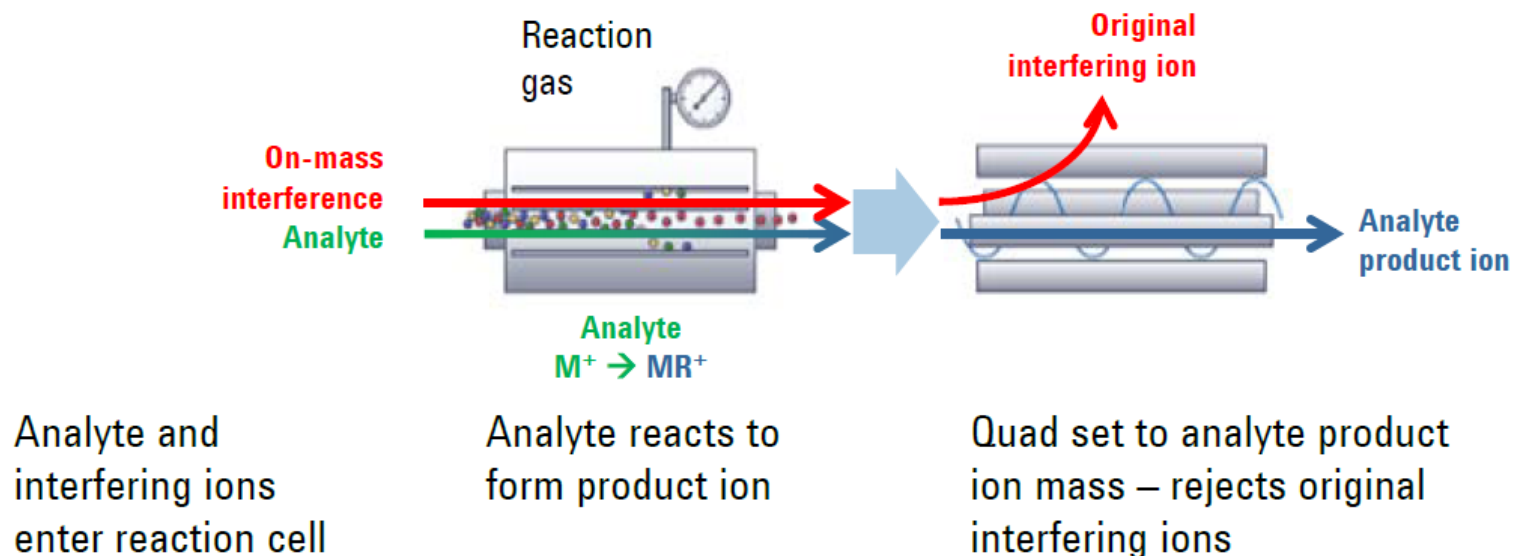
Interference reacts to form product ion

Quad set to original analyte mass – rejects interference product ion(s)

Reactive interferences are converted to product ions at a new mass – can be rejected by analyzer quad, which is set to original analyte mass

Reaction Mode:

2. Mass-Shift Measurement: Reactive analyte reacts with chosen cell gas, is moved to a new product ion mass and can be separated from unreactive interferences



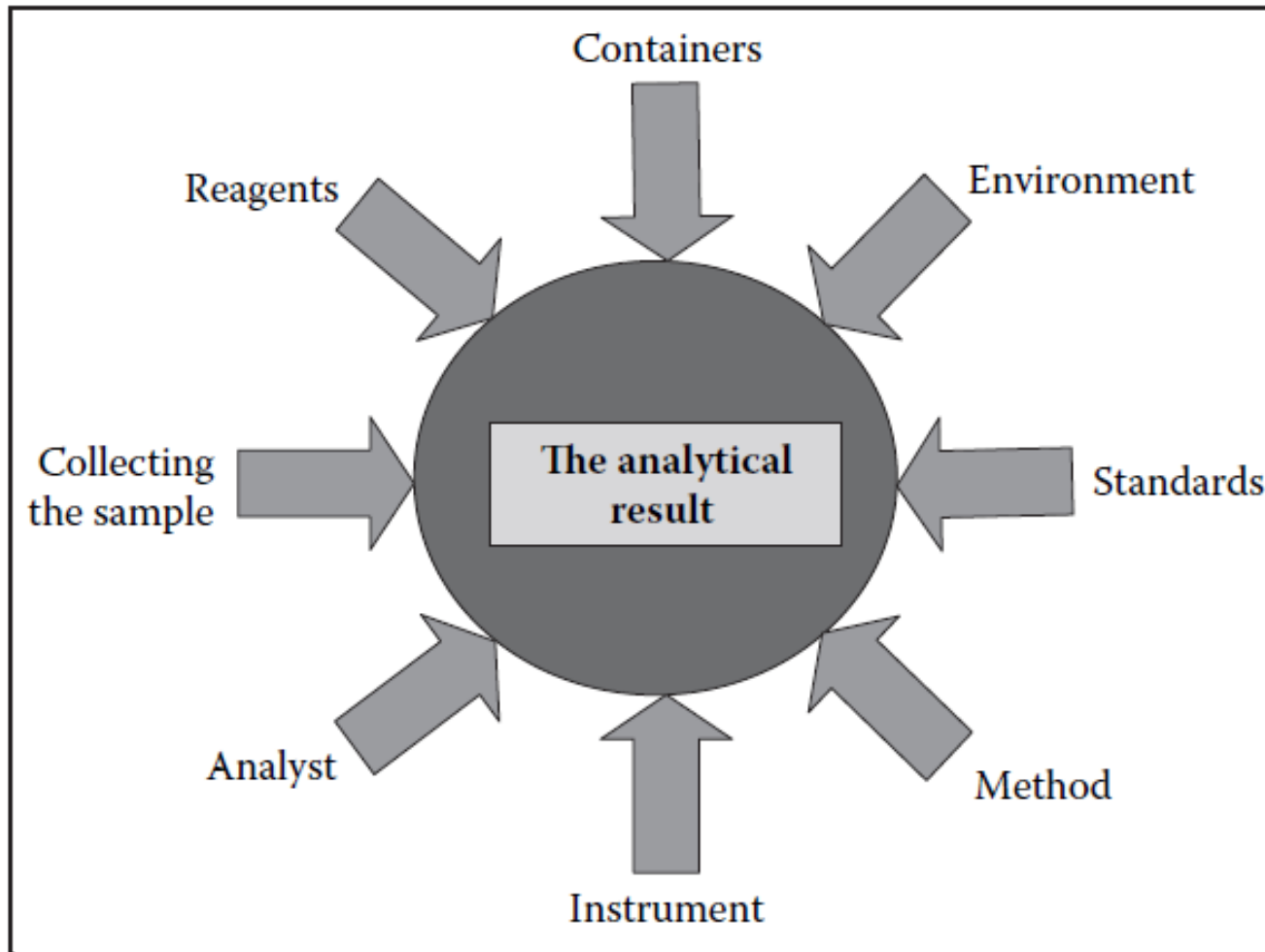
Reactive analyte is converted to product ions at a new mass – interferences remain at original mass and are rejected by analyzer quad

Standard Preparation

- ✓ Standards can be prepared directly by dissolution of the metal or metal salt. Prepared solutions are also commercially available.
- ✓ If similar multi-elemental analyses are being performed on a routine basis, pre-prepared multi-element solutions are commercially available from a number of suppliers.
- ✓ Typical concentrations in the prepared stock solutions would be 1000 mg/L or 1000 ppm
- ✓ Pipette 1 ml of Analyte from a stock solution of 1000 ppm to a volumetric flask (100 ml). Make the solution up to volume with water. The concentration in this intermediate solution is: 10 ppm for Analyte. Transfer 1 ml of the above solution to a volumetric flask (100 ml) and make up to volume using dilute trace metal grade nitric acid. The resulting concentration of Analyte will be 0.1 ppm or 100 ppb. Prepare 5 Standards in accordance with concentrations that you expect in your sample but less than 500 ppb.
- ✓ Each standard sample (10 ml) should be prepared in millipore water and 2% trace metal grade HNO₃.
- ✓ Total dissolved solids must not exceed 0.1 wt %.(e.g. 0.1 g per 100 ml of solution). There must be no suspended solids (if in doubt filter a portion with 0.2 micron cellulose nitrate syringe filter).
- ✓ Sulphuric acid is to be avoided because it forms polyatomic species and causes rapid damage to the Ni interface cones. HF can harm plasma torch and spray chamber.

Contamination issues

Various factors influence the ability to get the correct result with any trace element technique. Potential Sources of contamination must be addressed



ICPMS is mainly for liquid samples. Laser Ablation and other methods for Solid Samples.

Total Dissolved Solids (TDS) must be kept below 0.2%

Common dissolution agents are nitric acid, perchloric acid, hydrofluoric acid, aqua regia, hydrogen peroxide, or various mixtures of these—typically used for metals, soils or sediments, minerals and biological samples. The acid concentration in the final solution being presented to the instrument should ideally be 2–3% maximum. Appropriate corrosion-resistant sample introduction components should be used for HF. Hydrochloric, sulfuric, and phosphoric acids should be avoided due to matrix interferences. Nitric acid should be the preferred choice

Ultrapure reagents & millipore water & Argon should be used for preparation and dilution. Reagents should not contaminate or interfere with the analysis. Manufacturers of laboratory chemicals now offer ultra-high purity grades of chemicals, acids specifically for use with ICP-MS. Shelf life of all chemicals should be noted.

Liquid Samples should be stored in clean containers. Potential Contaminants can be your glasswares. Contamination during preparation, dilution, storage & sample introduction affect reagent blank levels and negatively impact instrument and method detection limits. PTFE or PFA, although costly are considered the cleanest materials. Analyst must be careful about some common trace element contaminants found in human body.

ICP-MS is a technique capable of quantifying up to 75 different elements. It is therefore absolutely critical to use calibration standards that have been specifically made for a multi-element technique such as ICP-MS. Calibration standards made from high purity metal salts must be evaluated for potential interferents.

Methods of Quantitation

Semi Quantitative Analysis:

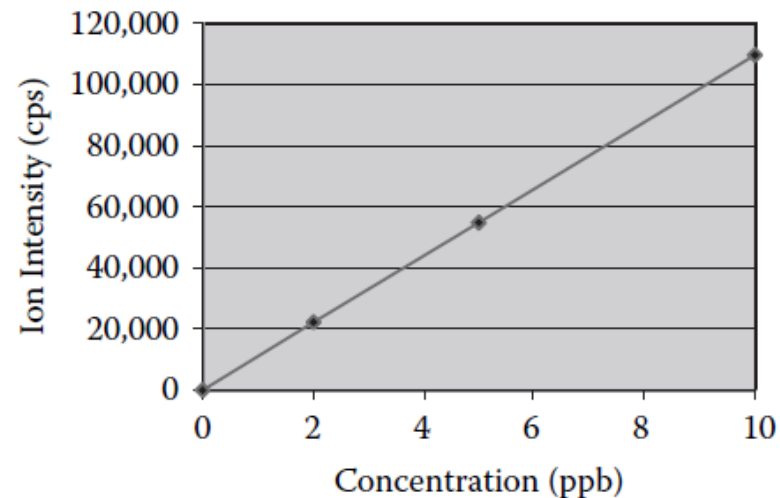
- ✓ If data quality objectives for accuracy and precision are less stringent, ICP-MS offers a very rapid semiquantitative mode of analysis. This technique enables you to automatically determine the concentrations of up to 75 elements in an unknown sample, without the need for calibration standards.
- ✓ General principle is to measure the entire mass spectrum, without specifying individual elements or masses.
- ✓ A positive or negative confirmation can be made for each element present in the sample.
- ✓ Semiquant, as it is often called, is an excellent approach to rapidly characterize unknown samples.

Methods of Quantitation

Quantitative Analysis:

- ✓ Quantitative analysis in ICP-MS is the fundamental tool used to determine analyte concentrations in unknown samples.
- ✓ The instrument is calibrated by measuring the intensity for all elements of interest in a number of known calibration standards that represent a range of concentrations likely to be encountered in your unknown samples.
- ✓ Software creates a calibration curve of the measured intensity versus concentration for each element in the standard solutions
- ✓ Once calibration data are acquired, the unknown samples are analyzed by plotting the intensity of the elements of interest against the respective calibration curves. The software then calculates the concentrations for the analytes in the unknown samples.
- ✓ This type of calibration is often called external standardization and is usually used when there is very little difference between the matrix components in the standards and the samples

1. Blank >
2. Std. 1 >
3. Std. 2 >
4. Std. 3 >
5. Sample 1 >
6. Sample 2 >
7. Sample...*n*
8. Recalibrate
9. Sample *n* + 1, etc.



Quantitative Analysis

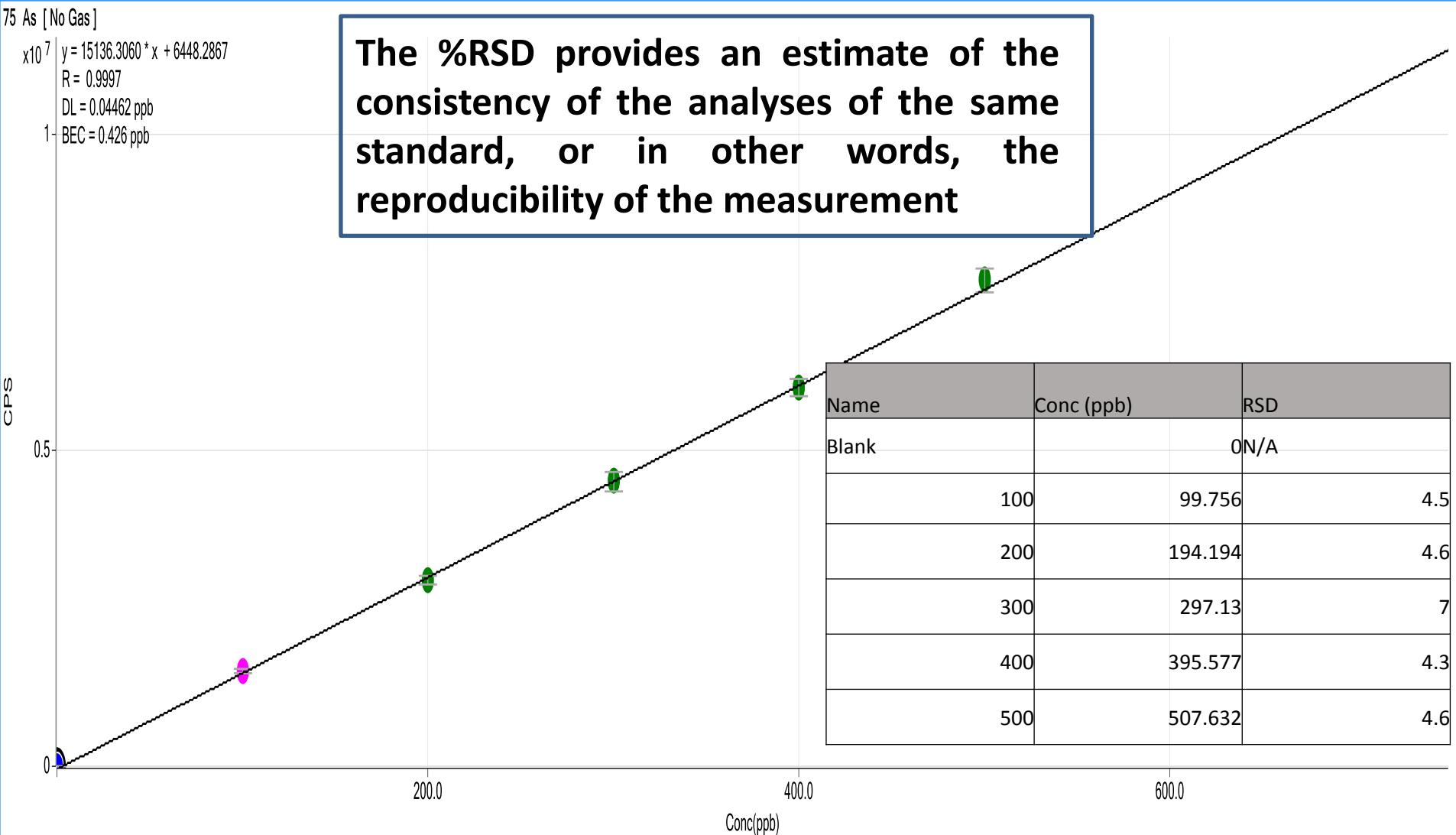
A statistical least squares regression fit of the data is obtained. The "goodness of fit" of the regression is used as a measure of the reliability of the calibration. The correlation coefficient (R^2) should be computed at 0.999 or better. Precision of measurement is reported at % RSD.

75 As [No Gas]

$y = 15136.3060 * x + 6448.2867$
 $R = 0.9997$
DL = 0.04462 ppb
BEC = 0.426 ppb

The %RSD provides an estimate of the consistency of the analyses of the same standard, or in other words, the reproducibility of the measurement

CPS



Name	Conc (ppb)	RSD
Blank		ON/A
	100	99.756 4.5
	200	194.194 4.6
	300	297.13 7
	400	395.577 4.3
	500	507.632 4.6

Figures of Merit

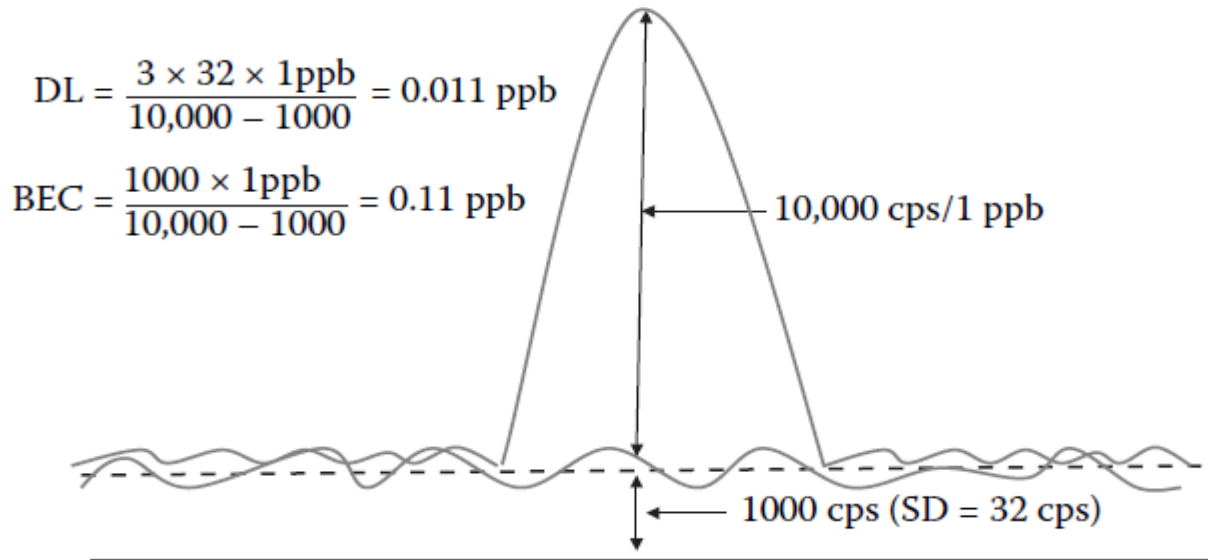
instrument detection limit (IDL)

$$\text{IDL} = \frac{3 \times \text{Standard deviation of background signal}}{\text{Analyte intensity} - \text{background signal}} \times \text{analyte concentration}$$

background equivalent concentration (BEC).

$$\text{BEC} = \frac{\text{Intensity of background signal}}{\text{Analyte intensity} - \text{background intensity}} \times \text{analyte concentration}$$

1 ppb of an analyte produces a signal of 10,000 cps and a background of 1000 cps. Based on the calculations defined earlier, the BEC is equal to 0.11 ppb because it is expressing the background intensity as a concentration value. On the other hand, the DL is 10 times lower because it is using the SD of the background (i.e., the noise)



The sample introduction system, comprising the peristaltic pump, nebulizer, spray chamber, and drain system, takes the initial abuse from the sample matrix, and as a result, is an area of the ICPMS that requires a great deal of attention

Constant motion and pressure of the pump rollers on the pump tubing, made from a polymer-based material, ensure a continuous flow of liquid to the nebulizer. Pump tubing has the tendency to stretch, which changes the amount of sample being delivered to the nebulizer

Tip of the nebulizer should not get blocked. Microscopic particles can build up on the tip of the nebulizer without the operator noticing, which, over time, can cause a loss of sensitivity, imprecision, and poor long-term stability.

Routine Maintenance

Staining and discoloration of the outer tube of the quartz torch because of heat and the corrosiveness of the liquid sample can cause electrical arcing

Drain of spray chamber must function properly. Malfunctioning or leaking drain can produce changes in the spray chamber backpressure, producing fluctuations in the analyte signal, resulting in erratic and imprecise data

The most common types of problems associated with the interface are blocking or corrosion of the sampler cone & skimmer cone

Important Criteria

Selecting a technique requires the consideration of a variety of important criteria, including:

- **Detection limits**
- **Analytical working range**
- **Sample throughput**
- **Data quality**
- **Cost**
- **Interferences**
- **Ease-of-use**
- **Availability of proven methodology**



Comparison of ICP-MS & other techniques

	ICP-MS	ICP-AES	GFAAS	FAAS
Detection Limits	Excellent	Good	Excellent	Good
Productivity	Excellent	Excellent	Low	Good
Precision	1-3%	0.3 – 2 %	1 – 5 %	0.1 – 1 %
Chemical Interferences	Moderate	Few	Many	Many
Dissolved solids	0.1 – 0.4 %	2 – 25 %	Up to 20 %	0.5 – 3 %
# Elements	75	73	50	68
Sample Usage	Low	Medium	Very Low	High
Isotope Analysis	Yes	No	No	No
Method Development	Skill required	Skill required	Skill required	Easy
Running Costs	High	High	Medium	Low
Capital Costs	Very high	High	Medium	Low

ICP-MS Applications

Environmental

Drinking Water, Ambient Water, Sea Water

Soils, Sludges, Solid Waste

Plant material/agriculture

Speciation of Hg, As, Pb, and Sn

Clinical

Blood, Urine, Serum

Hair, Tissues

Toxicology

Nutrition/deficiency/vitamins

Food Analysis

Nutrition

Toxic element and species monitoring

QA/QC

Pharmaceutical

Routine heavy metal contamination

Drug discovery

Clinical trials

Nuclear

Fuel production

Measurement of Radioisotopes

Primary Cooling Water

Geological

Soil, Rocks, Sediments

Hydrology

Isotope Ratio Studies

Archaeological

Artifact analysis, proof of origin

Tooth, bone, tusk, shell, coral analysis

Forensics

Gun Shot Residue

Materials Characterization

Point of Origin

Poisoning

References

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- 7) Agilent ICPMS 7900 Manual and Videos
- 8) The 30 minute guide to ICP-MS by Perkin Elmer
- 9) Inductively Coupled Plasma– Mass Spectrometry (ICP-MS) for Quantitative Analysis in Environmental and Life Sciences: A Review of Challenges, Solutions, and Trends.

Thank you for your attention!!

1 H Hydrogen											2 He Helium						
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium											13 Al Aluminium	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	57 La Lanthanum	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89 Ac Actinium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110	111	112	113	114				



Metals



Metalloids

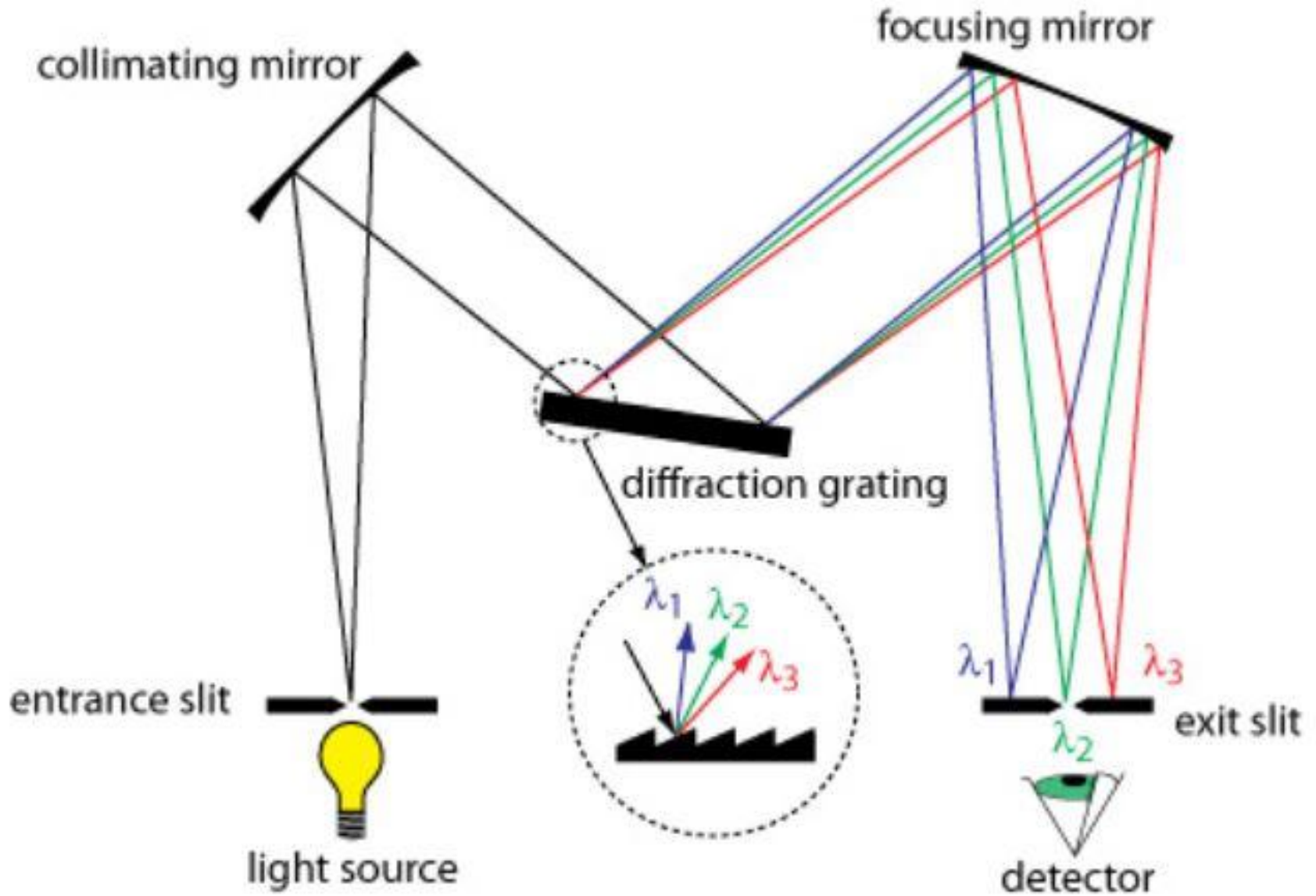


Non-Metals

Transition Metals

	ICP-MS	ICP-OES	Flame AAS	GF-AAS
Detection limits	Excellent for most elements	Very good for most elements	Very good for some elements	Excellent for some elements
Sample throughput	all elements 2-6 min	5-30 elements /min	15 seconds/ element	4 min/element
Linear dynamic range	10^5 (10^8 with range extension)	10^4 to 10^8	10^3	10^2
Precision:				
Short term (in-run)	1-3%	0.3-1%	0.1-1%	1-5%
Long term (4hrs)	<5% *	<3% *		
Isotopes	yes	no	no	no
Dissolved solids max. concentration	0.1-0.4	1-30	0.5-3	> 30
No. of elements	> 75	> 75	> 68	> 50
Sample usage	low	low	very high	very low
Semi-quant analysis	yes	yes	no	no
Isotope analysis	yes	no	no	no
Routine operation	easy	easy	easy	easy
Method development	skill required	skill required	easy	skill required
Unattended operation	yes	yes	no	yes
Combustible gases	no	no	yes	no
Operating cost	high	high	low	medium
Capital cost	very high	high	low	medium/high

Monochromator



Comparison of ICP-MS & other techniques

	Flame AAS	GFAAS	ICP-AES	ICP-MS
Detection limits	Very good for some elements	Excellent for some elements	Very good for most elements	Excellent for most elements
Sample throughput	10-15 secs per element	3-4 mins per element	1-60 elements/minute	All elements in <1 minute
Dynamic range	10 ³	10 ²	10 ⁶	10 ⁸
Precision short term long term	0.1-1.0% 2-beam 1-2% 1-beam < 10%	0.5-5% 1-10% (tube lifetime)	0.1-2% 1-5%	0.5-2% 2-4%
Interferences Spectral Chemical (matrix) Physical (matrix)	Very few Many Some	Very few Very many Very few	Many Very few Very few	Few Some Some
Dissolved solids in solution	0.5-5%	> 20% (slurries)	0-20%	0.1-0.4%
Elements applicable to	68+	50+	73	82
Sample volumes required	Large	Very small	Medium	Very small to medium
Semiquantitative analysis	No	No	Yes	Yes
Isotopic analysis	No	No	No	Yes
Ease of use	Very easy	Moderately easy	Easy	Moderately easy
Method development	Easy	Difficult	Moderately easy	Difficult
Unattended operation	No	Yes	Yes	Yes
Capital costs	Low	Medium to high	High	Very high
Running costs	Low	Medium	High	High

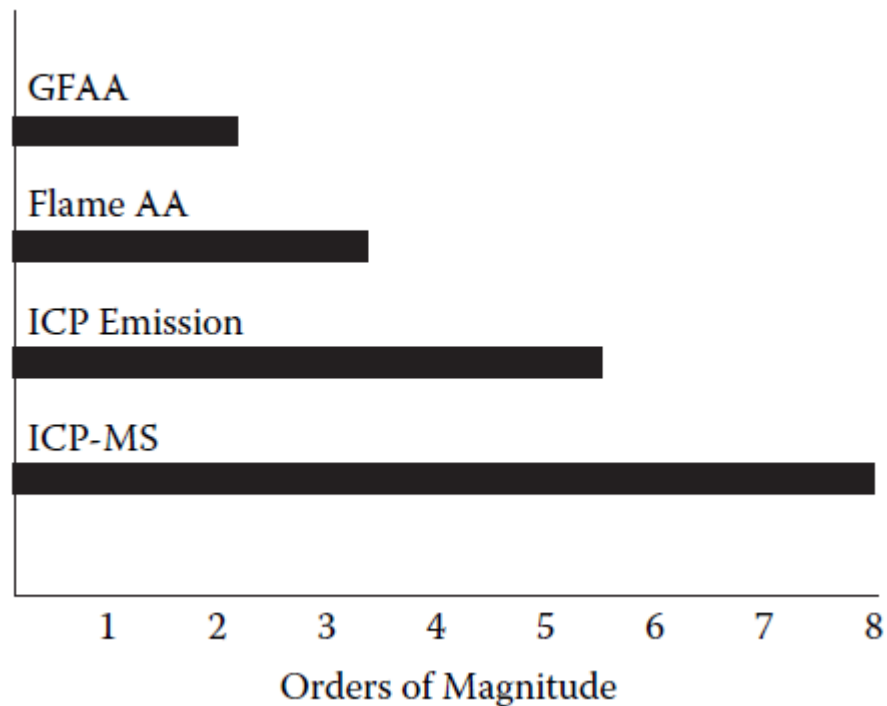
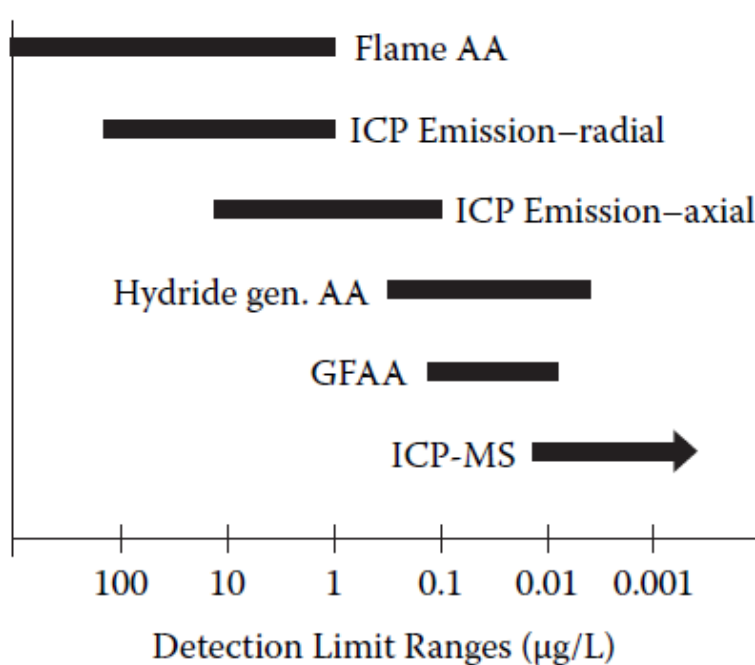


TABLE 20.2
Comparison of Sample Throughput of the Four AS Techniques

Technique	Elements at a Time	Duplicate Analysis (min)	Samples per Hour (1 element)	Samples per Hour (5 elements)	Samples per Hour (20 elements)
FAA	1	0.3	180	36	9
ETA (single)	1	5	12	2-3	1
ETA (multi)	2-6	5	12	12	3
ICP-OES	Up to 70	3	20	20	20
ICP-MS	Up to 70	3	20	20	20

