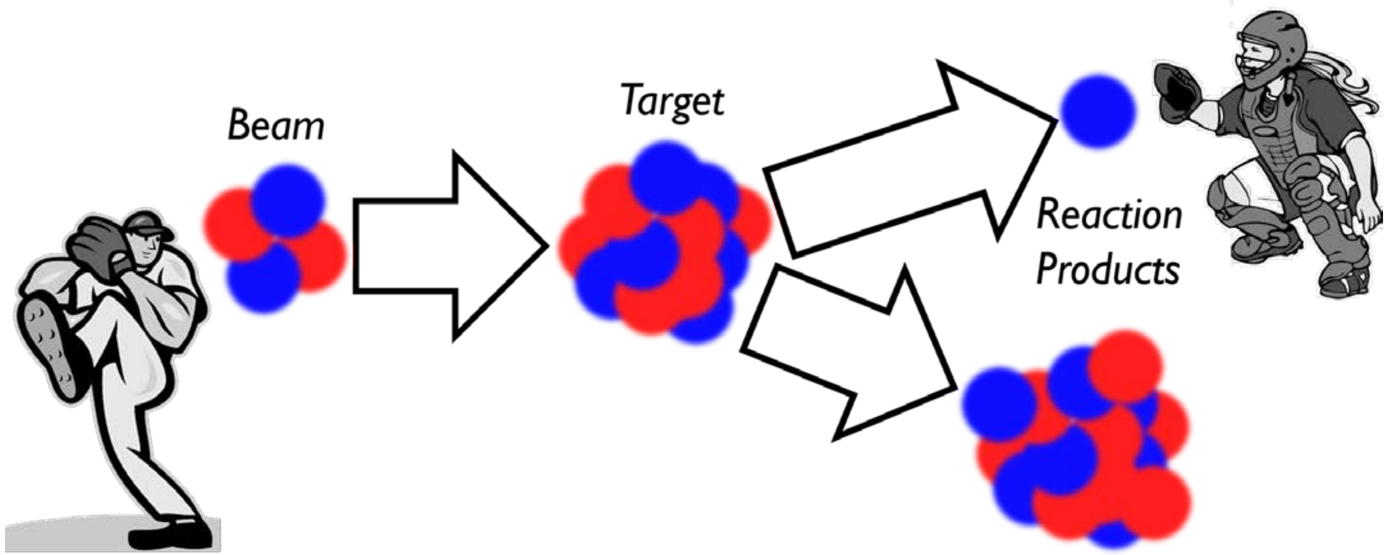
Lecture 22: Experimental Techniques

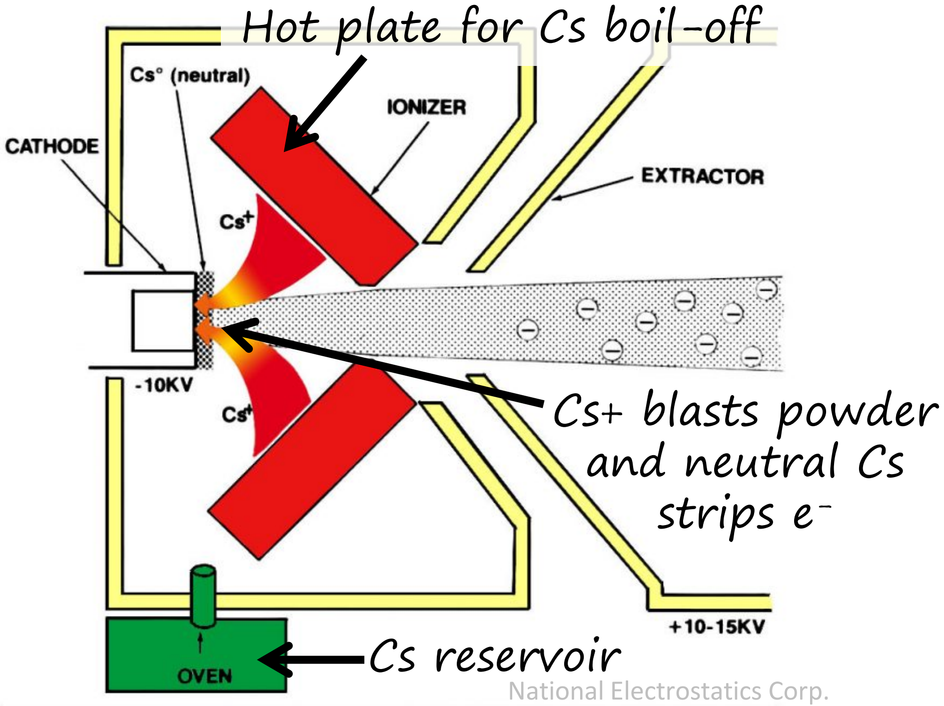
- Beam production
- Beam transport
- Targets
- Ion detection
- Charged particle detection
- Neutron detection
- Gamma detection



Ion Sources *(selected examples)*

- Nuclear physics experiments require an ion beam to be produced which is then studied directly or, more likely, impinged on some target
- Ion sources do the magic of taking a sample (solid or gaseous) of an uncharged element and turning it into a stream of ions that can be manipulated with electric and magnetic fields
- Type depends on whether you want positive or negative ions and the element, e.g.

Source of Negative Ions by Cesium Sputtering (SNICS)



Hot plate for Cs boil-off

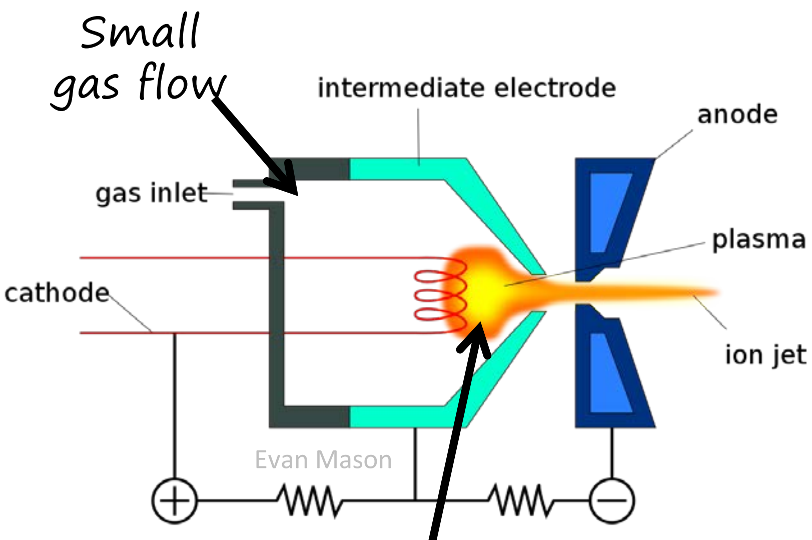
Cs+ blasts powder and neutral Cs strips e⁻

Cs reservoir

National Electrostatics Corp.

Duoplasmatron

(positive or negative ions, typically of noble gases)

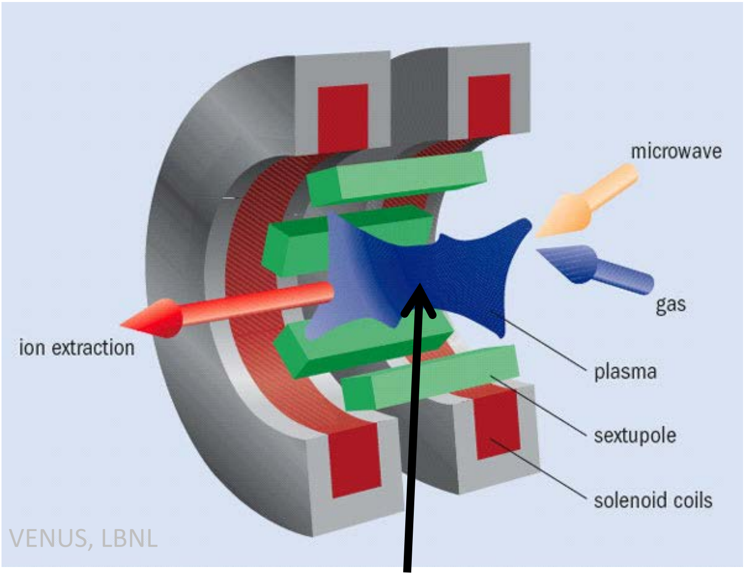


Small gas flow

Evan Mason

Positive or negative plasma (created by e- from cathode) confined with mag. field

Electron Cyclotron Resonance (ECR) *(positive ions)*

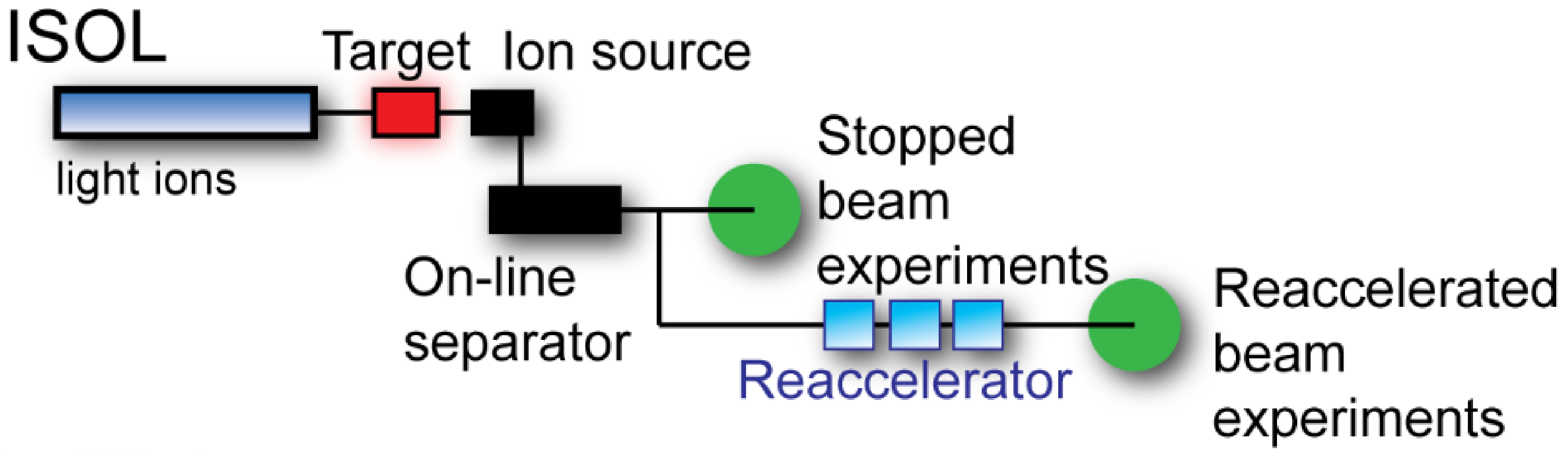


VENUS, LBNL

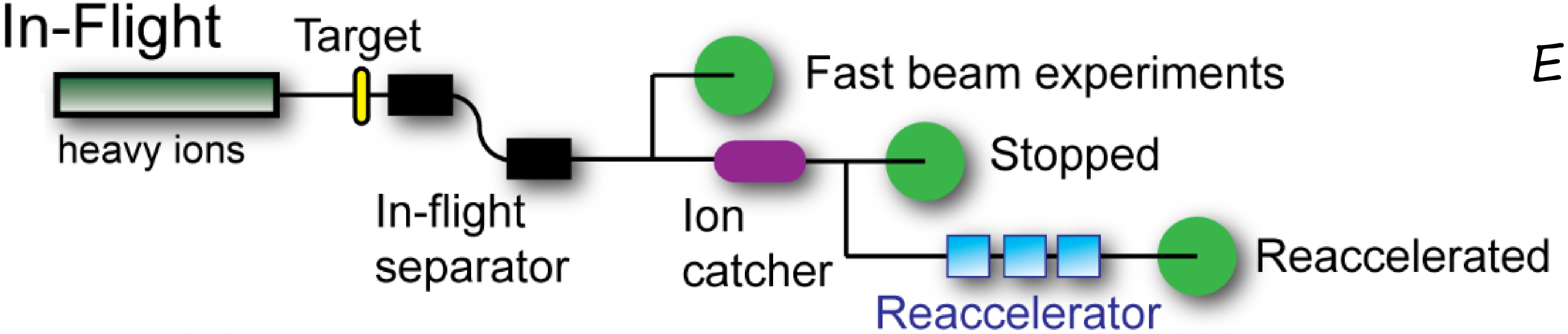
Electrons in a cyclotron resonance (at the microwave frequency) maintain a plasma

Radioactive Ion Beams (RIBs)

- For a long enough lived isotope, e.g. ^{7}Be, it's possible to directly produce an ion beam using a traditional ion source, like we just discussed. However, this only works for special cases.
- RIB production is typically done either *in-flight*, with isotope separation online (*ISOL*), or by capturing and re-accelerating fission fragments (e.g. CARIBU @ Argonne National Lab)



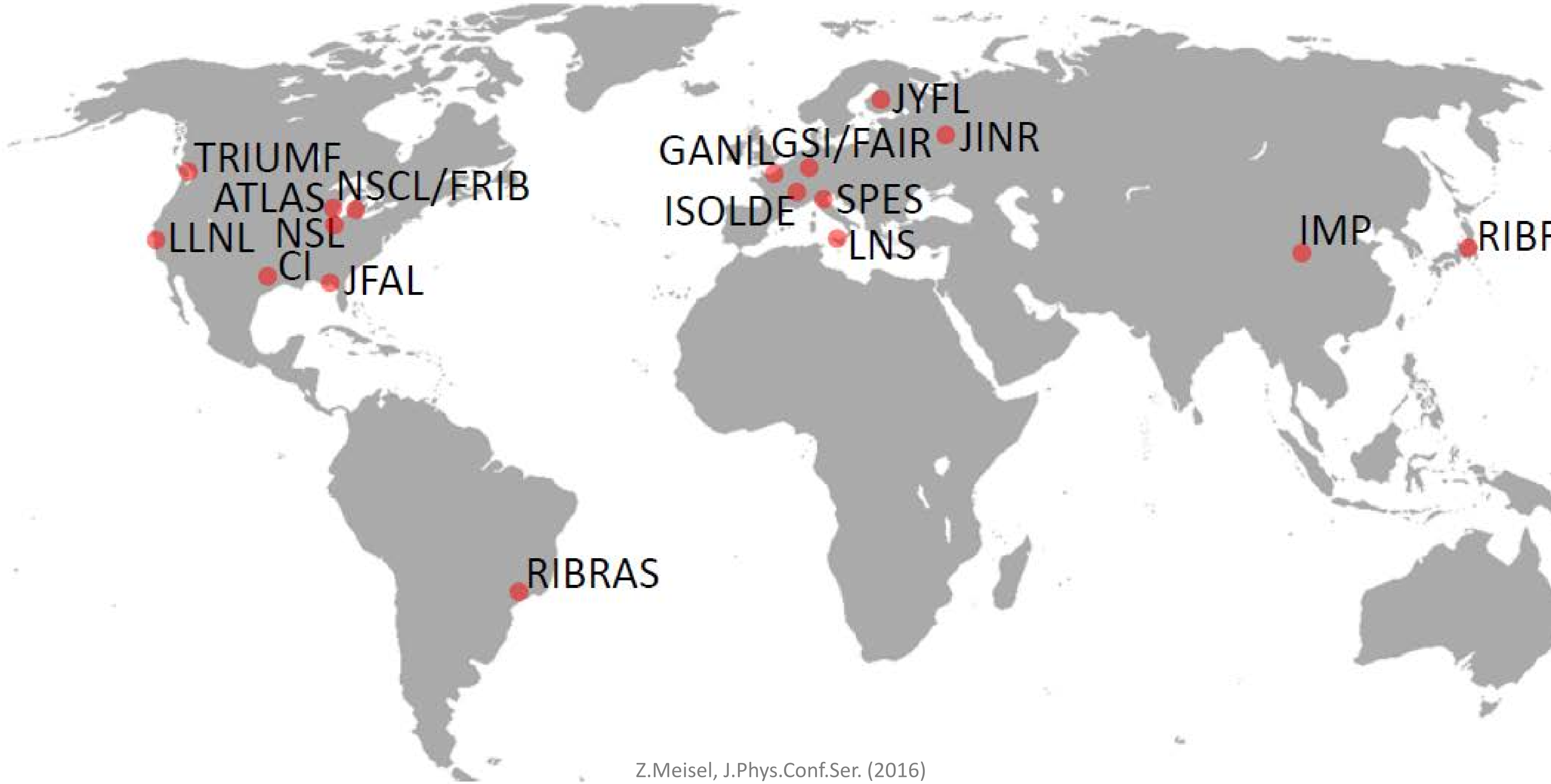
E.g. SPIRAL@GANIL,
ISOLDE@CERN,
ISAC@TRIUMF



E.g. GSI/FAIR,
NSCL/FRIB,
RIBF@Riken,
GANIL

O. Tarasov, Euroschool on Exotic Beams 2013

Radioactive Ion Beam Facilities (2017)

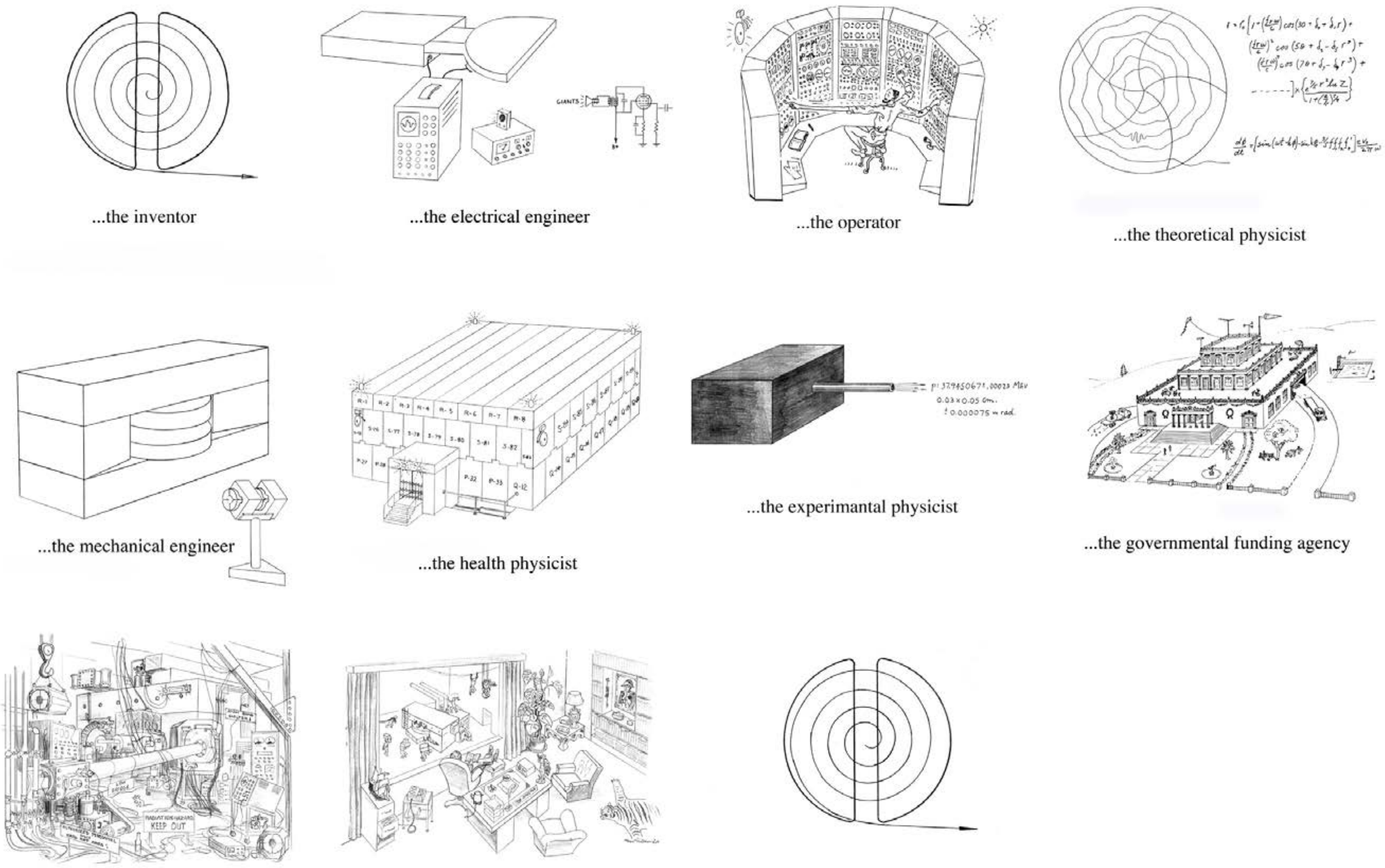


Z.Meisel, J.Phys.Conf.Ser. (2016)

Accelerators

- Accelerators attract and/or repel ions with electric fields that are stationary or time-varying, possibly employing magnetic fields for confinement
- Common electrostatic types are the Cockcroft-Walton and the Van de Graaff
- Common electrodynamic types are the Linear Accelerator (LINAC), Cyclotron, and Synchrotron, where the latter two include confinement from magnetic fields

THE CYCLOTRON as seen by...



...the inventor

...the electrical engineer

...the operator

...the theoretical physicist

...the mechanical engineer

...the health physicist

...the experimantal physicist

...the governmental funding agency

...the visitor

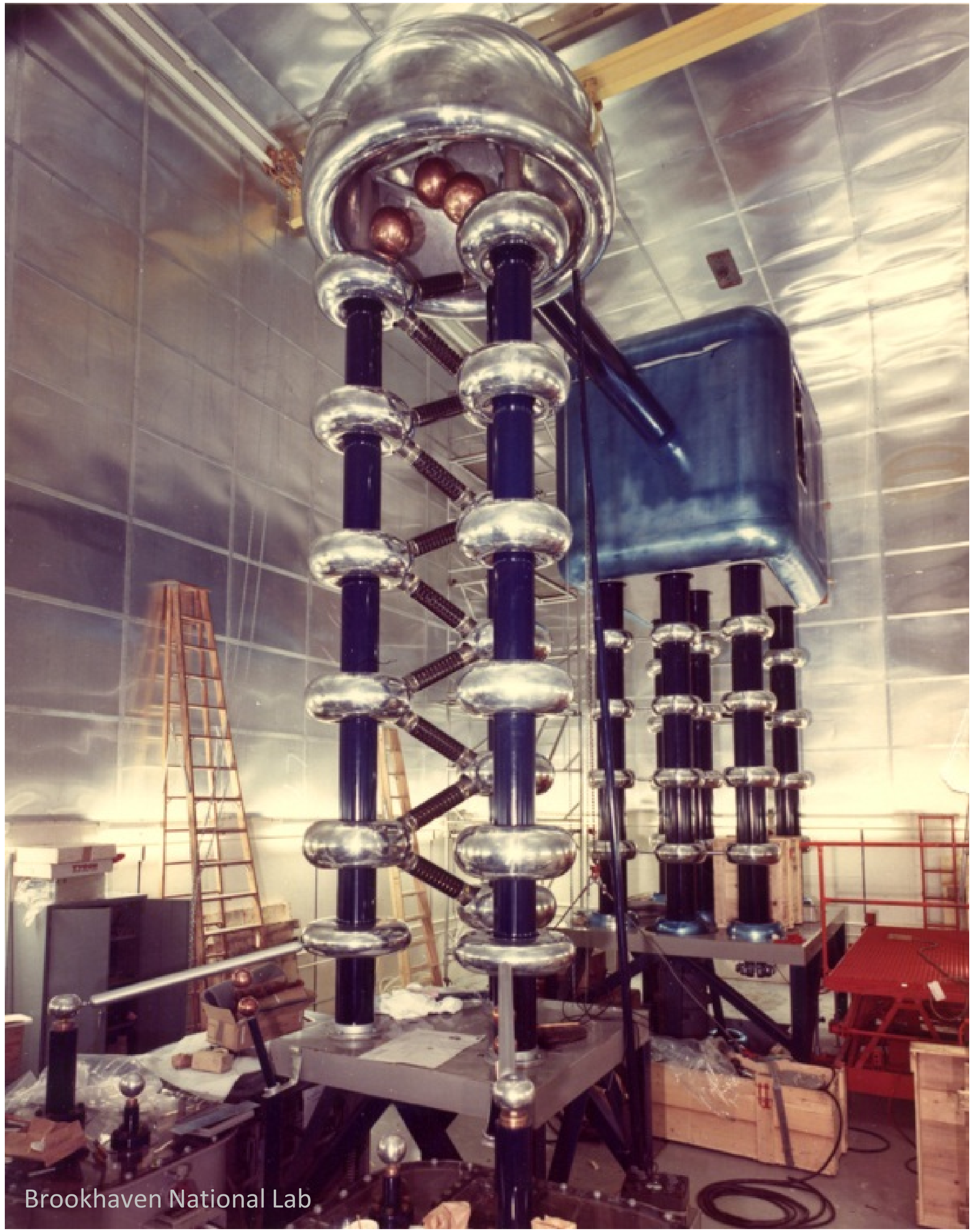
...the director

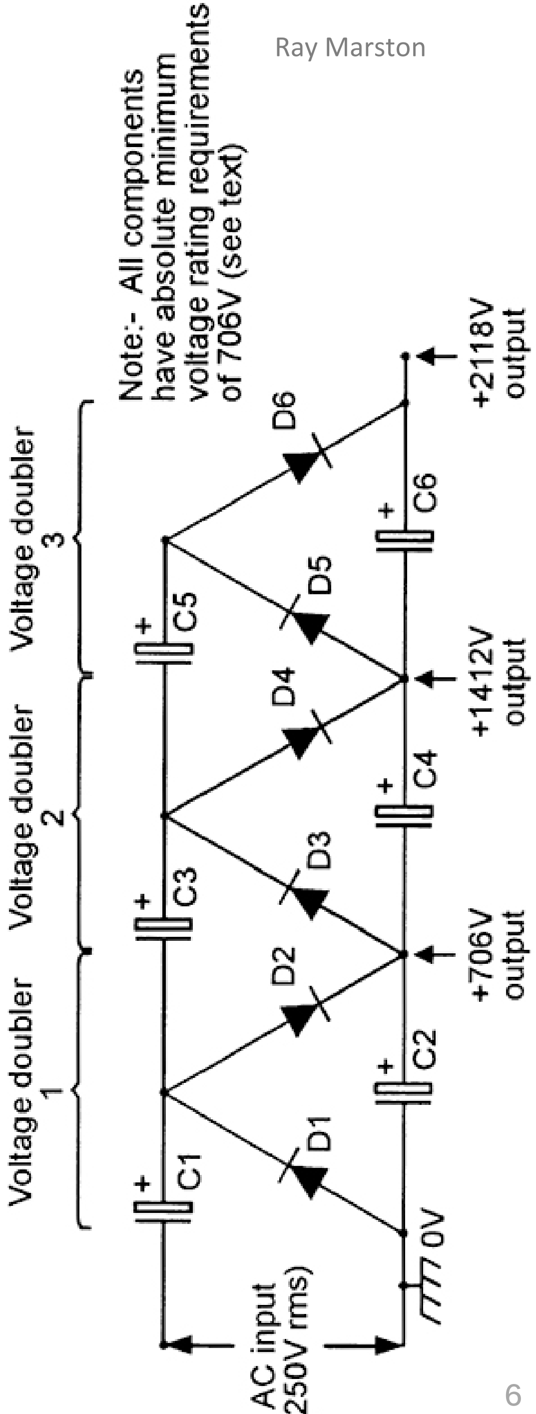
...the student

Dave Judd, LBL Photo Archive

Electrostatic Accelerators: *Cockcroft-Walton*

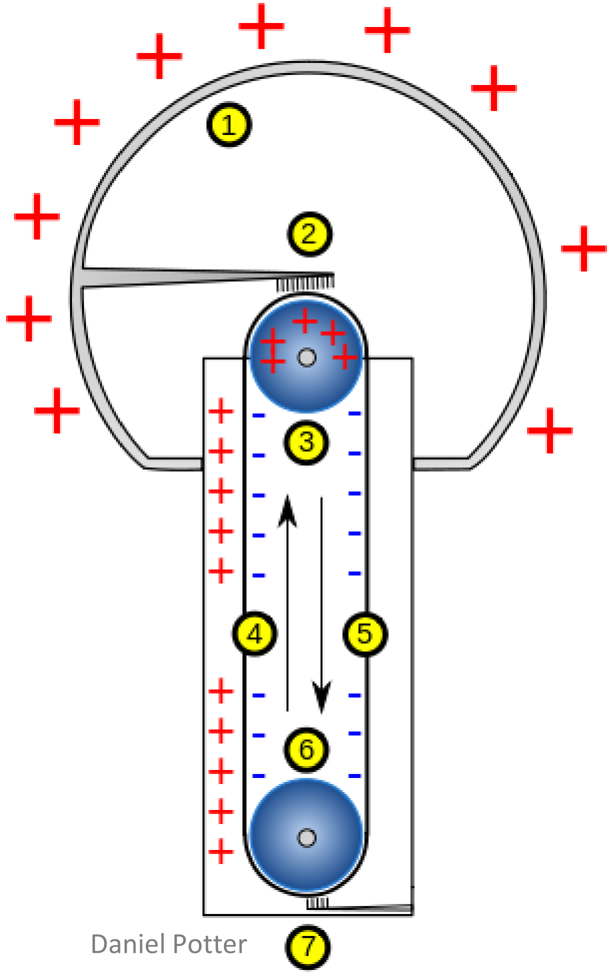
- A fancy circuit is used to convert AC to DC and achieve a large voltage multiplication
- Ions are introduced near the charged terminal (or in a cavity electrically connected to it) and are then repelled by the large voltage
- Electrical discharges in air limit the practically achievable voltages to ~MV, i.e. ~MeV ion energies for ions coming from typical ion sources


Brookhaven National Lab

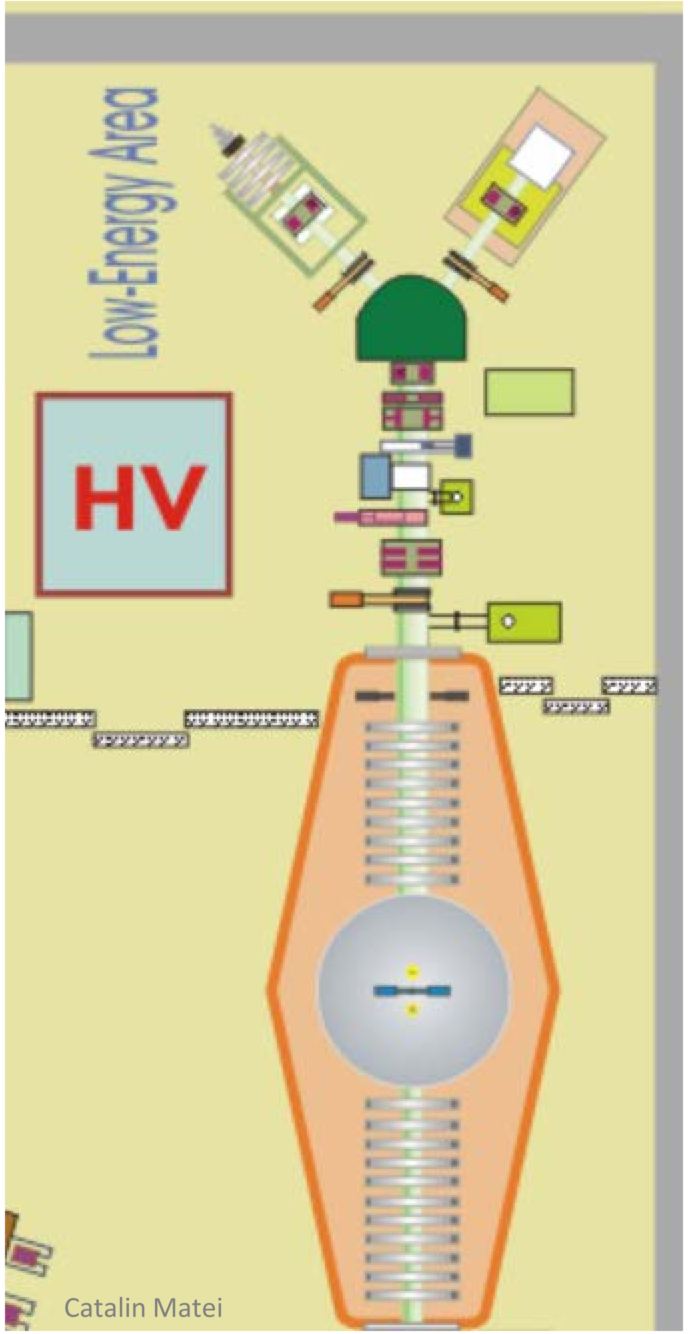

Ray Marston

Electrostatic Accelerators: *Van de Graff*

- Like the Cockcroft-Walton, a Van de Graff accelerator uses a large potential to attract/repel ions
- In this case, charge is delivered to a terminal system on a pully, where a belt picks-up charge from a brush and then deposits charge onto a brush near the terminal
- An alternative option is to induce charge on pellets using capacitors, which is called a Pelletron (like the Edwards Lab Accelerator)
- This is typically done under vacuum to avoid electrical breakdowns and, for negative ion sources, is done in the middle of the accelerator, so there's an attraction and then repulsion (after charge stripping)



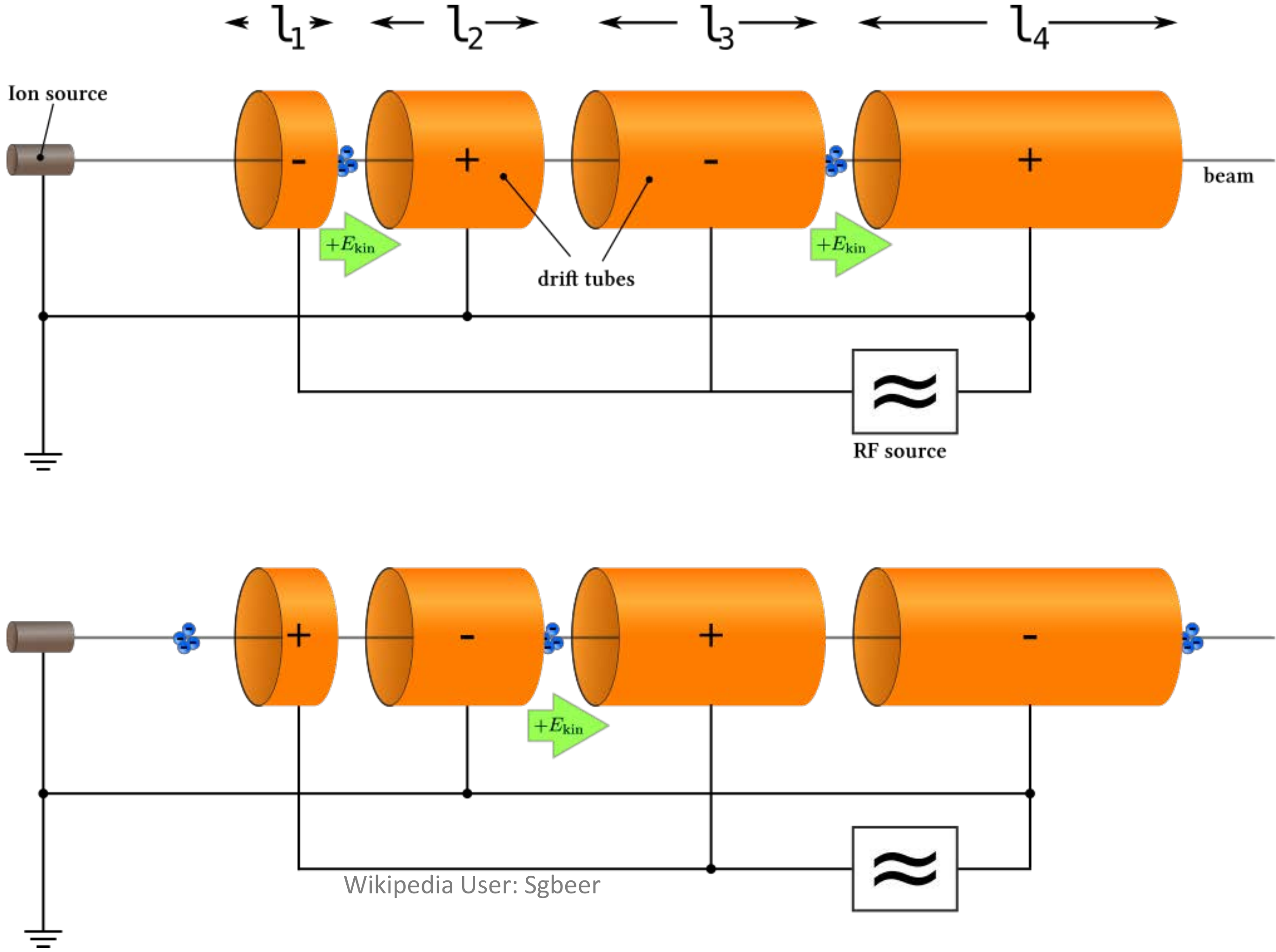
Daniel Potter



Catalin Matei

Electrodynamic Accelerators: *LINAC*

- A linear accelerator (LINAC) uses time-varying electric fields to alternately attract and repel ions in between “drift tubes”
- As the ion velocity increases along the LINAC, the drift tube lengths increase so that all tubes can be alternated at the same frequency
- The largest beam energies can be achieved for these types of accelerators …but you need a lot of space for a long path and the RF cavities typically require cooling to be superconducting and must be extremely clean (dust free)

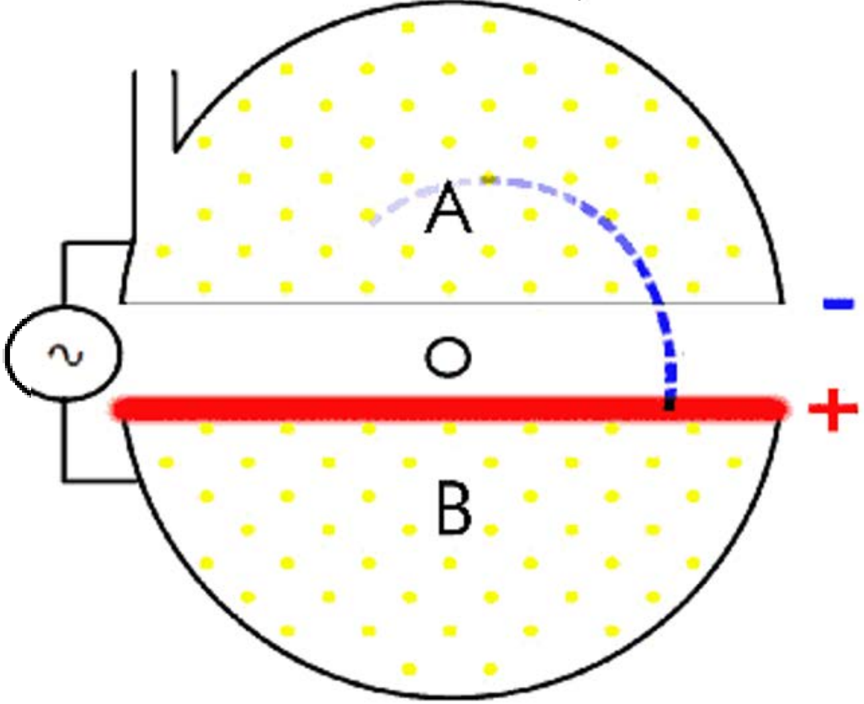


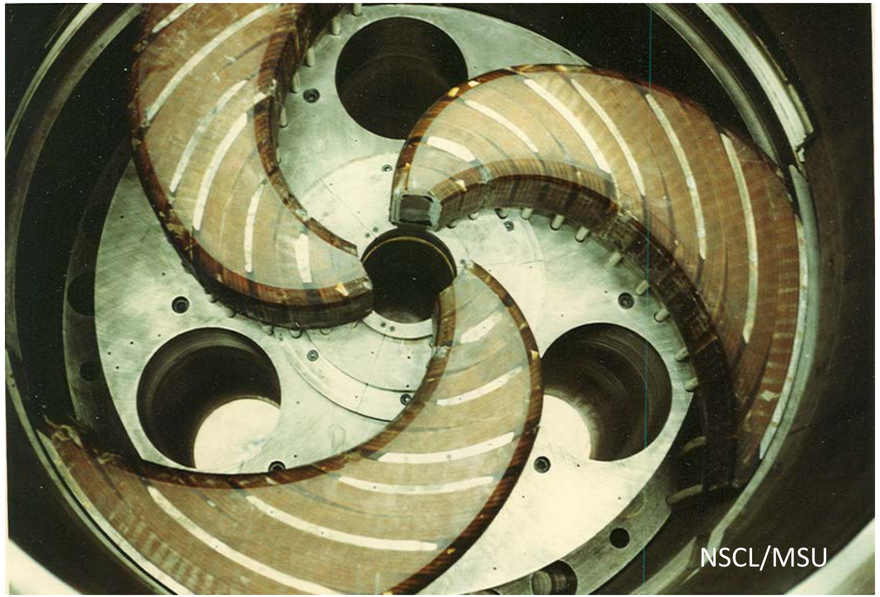
Wikipedia User: Sgbeer

Electrodynamic Accelerators: *Cyclotron*

- The cyclotron employs time-varying fields to alternate the voltage on “dees”, which may or may not be D-shaped
- Ions are injected in bunches into the center of the cyclotron and attracted by one dee and repelled by the other
- The dees are situated within a large magnetic field, causing ions to follow a spiral trajectory as they accelerate
- An electrostatic extractor near the cyclotron radius deflects ions out of the cyclotron
- Cyclotrons offer the most compact way to achieve useful energies for heavy ions
  (typical energies are 10’s to 100’s of MeV/u)
- The K-factor refers to the maximum kinetic energy for a proton. The achievable energy per nucleon for heavier ions is $\frac{KE}{A} = K\left(\frac{Q}{A}\right)^2$

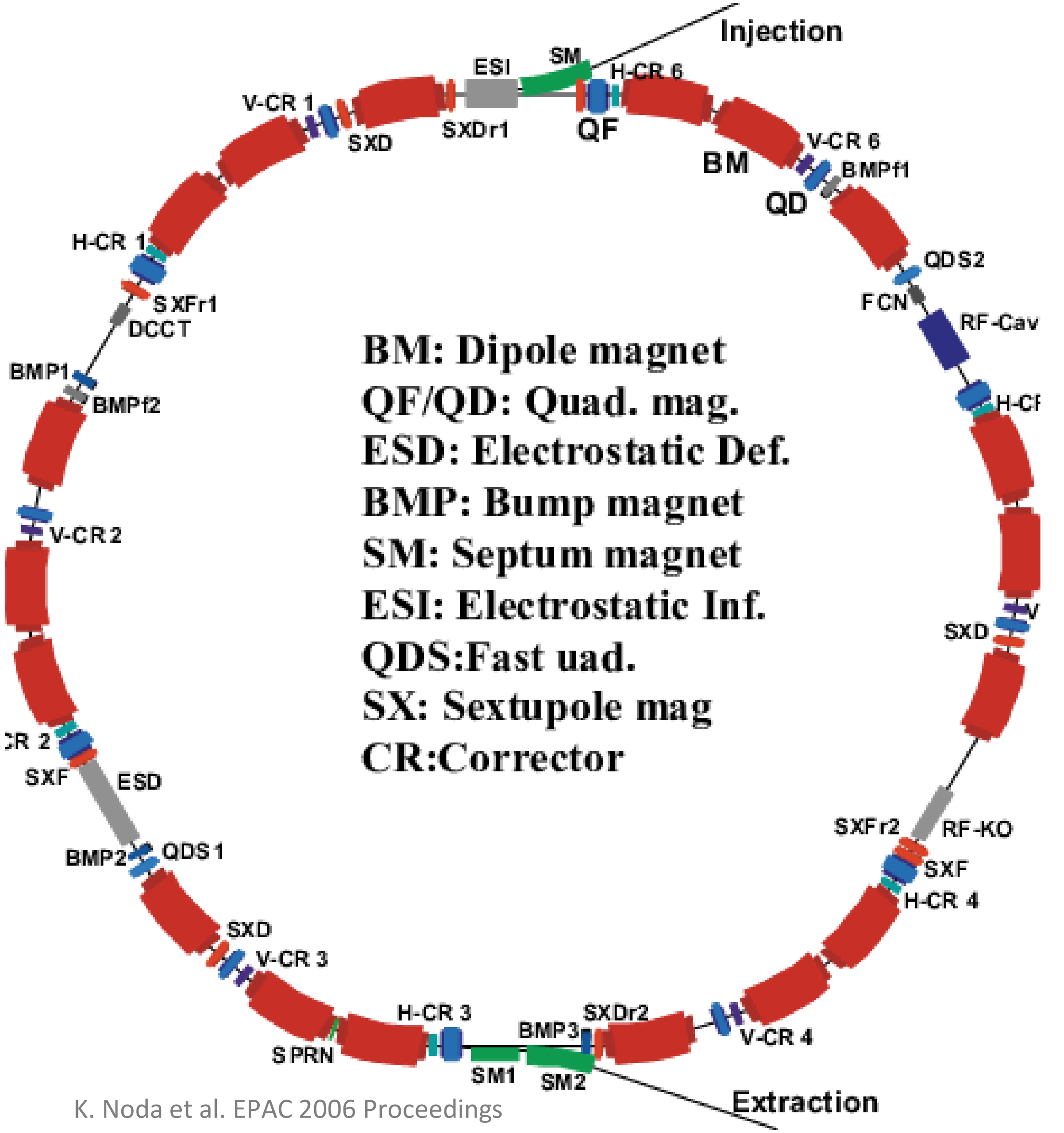
American Institute of Physics




NSCL/MSU

Electrodynamic Accelerators: *Synchrotron*

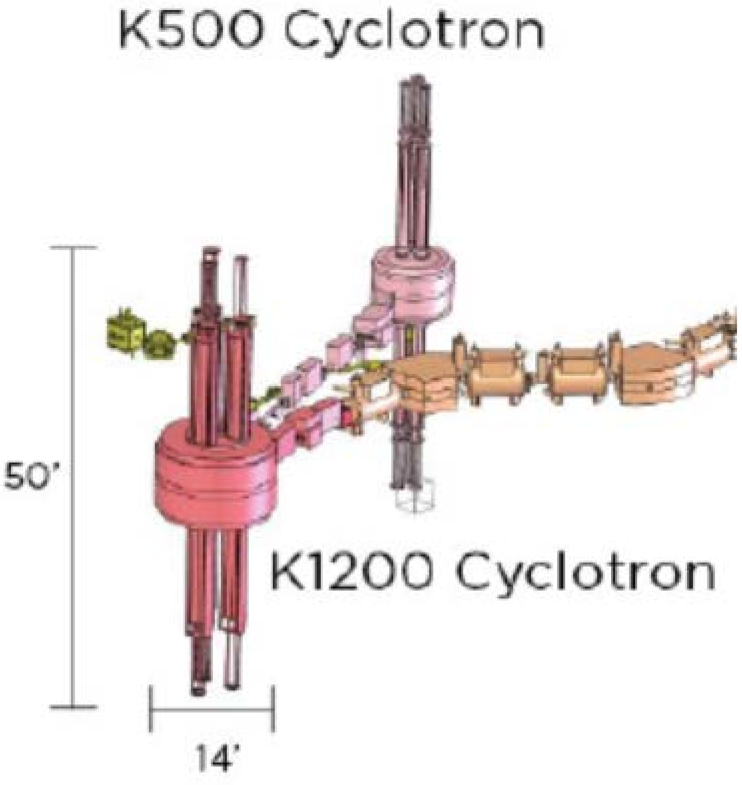
- Synchrotrons accelerate ions using a time-varying electric field on one or more accelerator cavities located in a ring
- To stay in the ring, the magnetic fields must also vary so that the ions stay within the ring as their energy increases
- Practical limitations necessitate that multiple synchrotrons may be needed in series to achieve high energies, e.g. GSI/FAIR



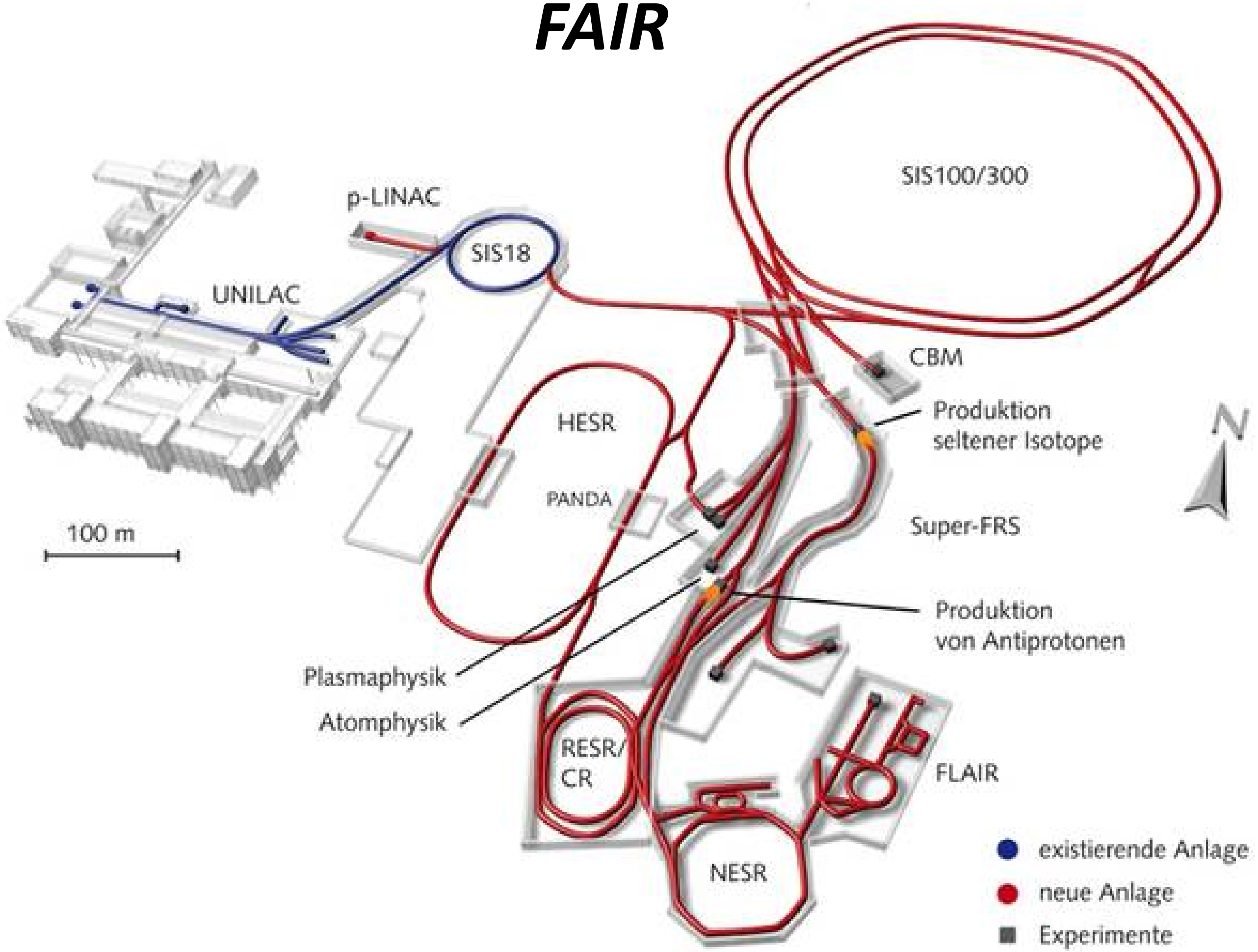
K. Noda et al. EPAC 2006 Proceedings

Accelerators are often used in series to get the desired energies & intensities

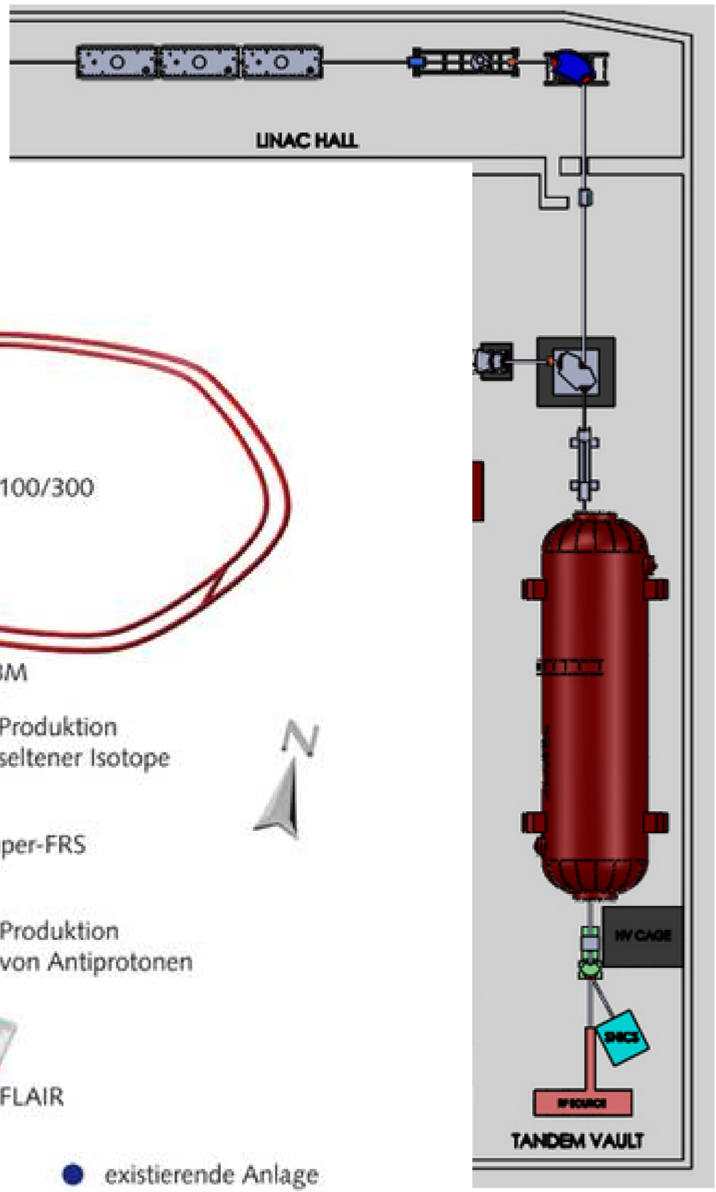
NSCL



FAIR



John Fox Lab



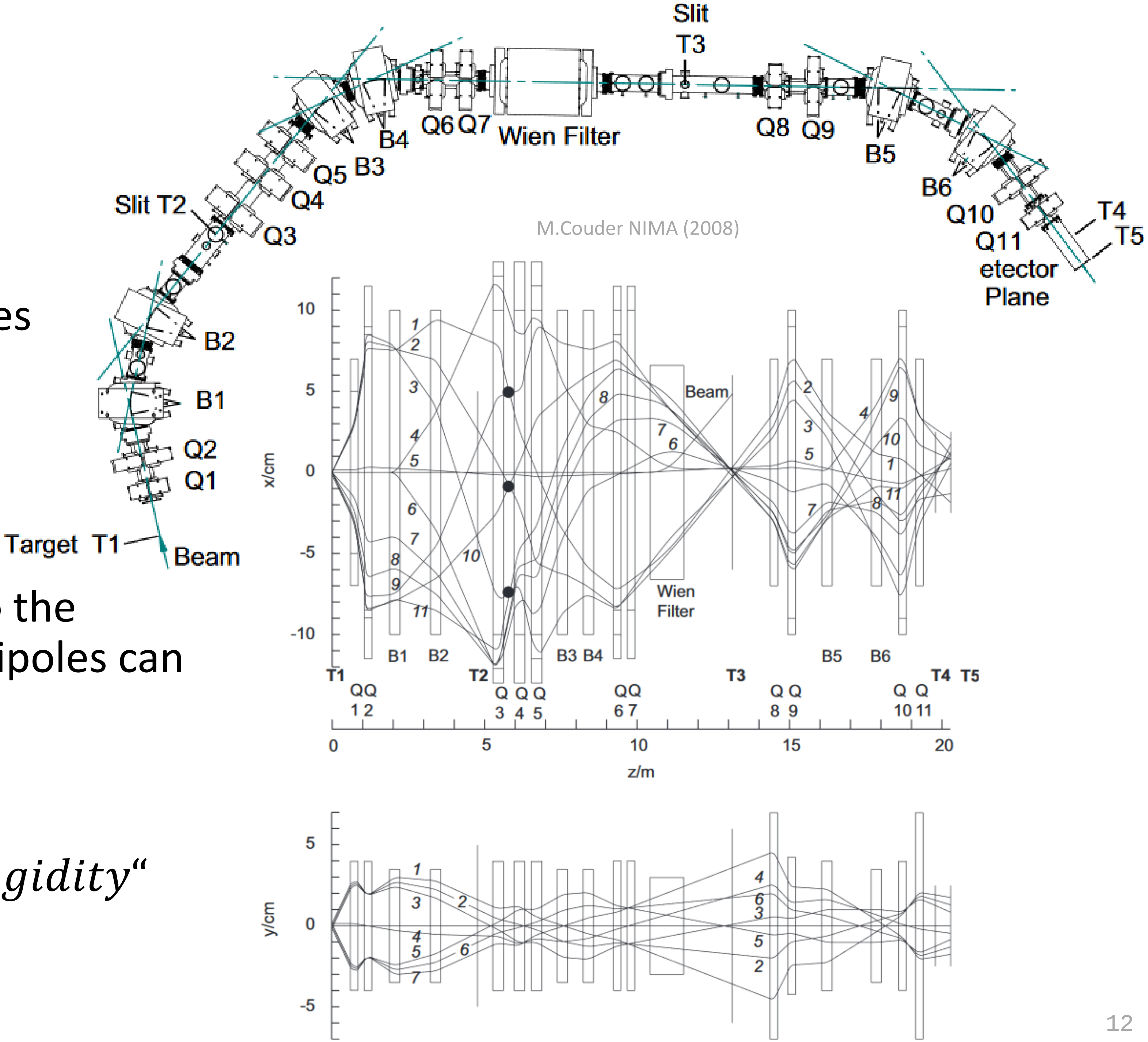
Beam Transport

- Ion transport consists of steering charged ions with dipoles and focusing with higher-order multipoles
- For low energies (10’s of keV/nucleon), electrostatic elements are used, so magnetic steering/focusing elements are far more prevalent
- By setting the Lorentz force equal to the centrifugal force, it becomes clear dipoles can be used for ion separation:

$$F_c = F_L$$

$$\frac{mv^2}{r} = qvB$$

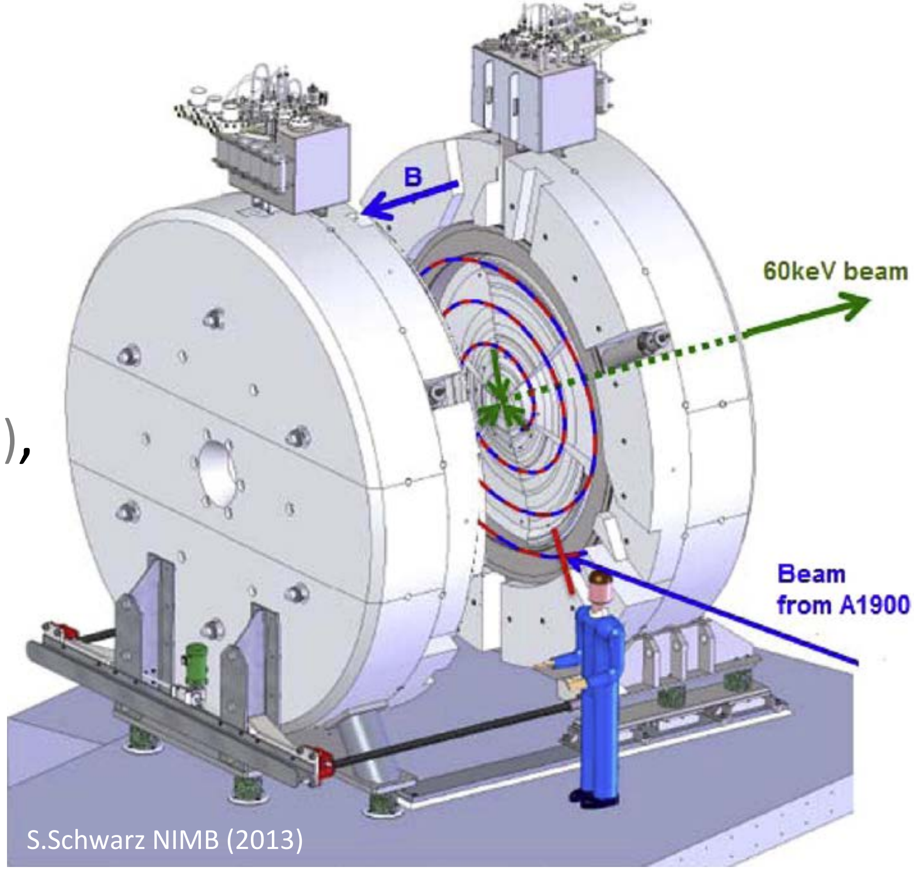
$$\frac{mv}{r} = \frac{p}{q} = Br \equiv B\rho = \text{"}\textit{magnetic rigidity}\text{“}$$



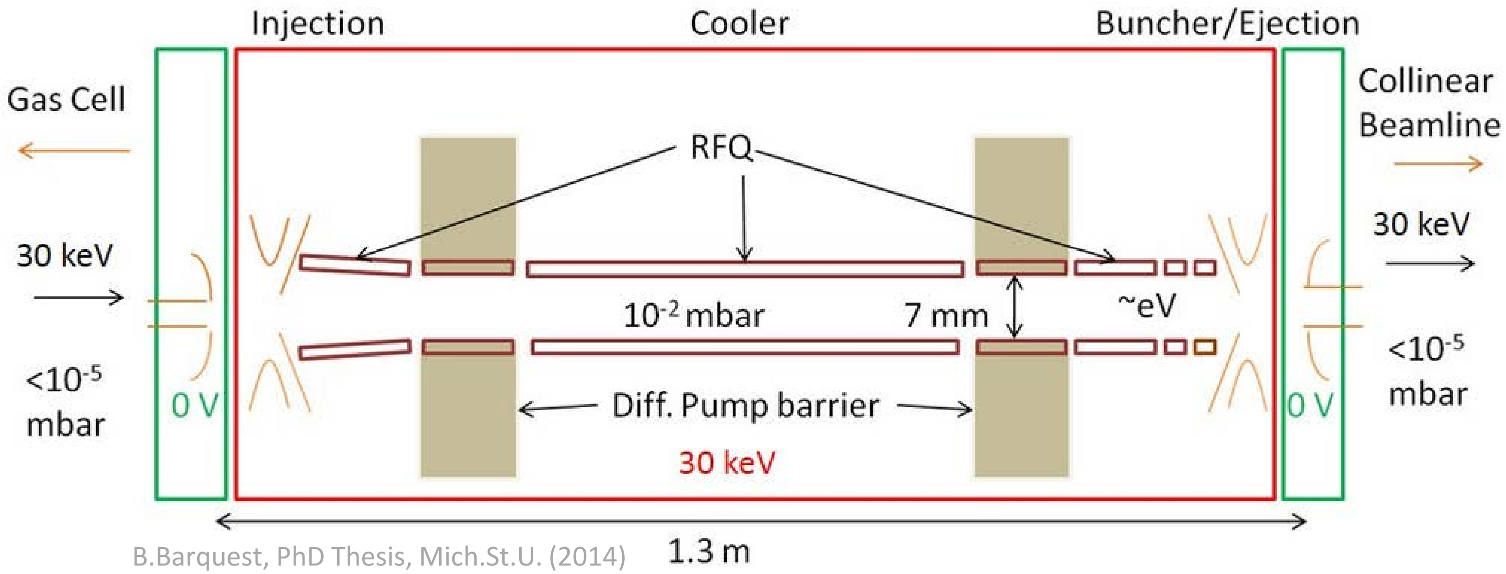
M.Couder NIMA (2008)

Beam Stopping and Bunching

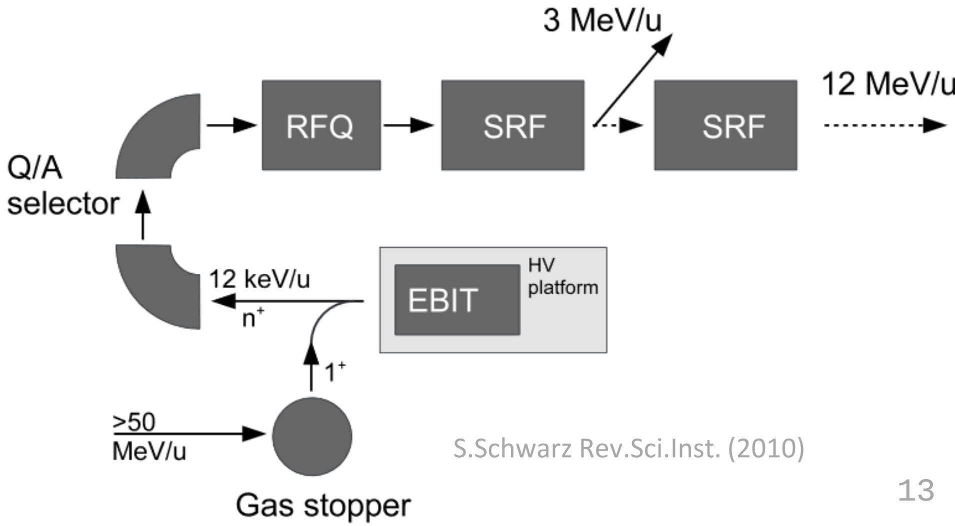
- Often times we would like our ions of interest to be at much lower energies than they were produced at, or even stopped
- Gas stopping achieves this by ions undergoing multiple collisions with atoms of a light inert gas (*cough* helium *cough*), followed by re-ionization so the ions can be controlled and usually some form of bunching
- Bunching uses electrostatic traps, where segments of varying electric potentials create a potential well



S.Schwarz NIMB (2013)



B.Barquest, PhD Thesis, Mich.St.U. (2014)



S.Schwarz Rev.Sci.Inst. (2010)

Targets

- Nuclear physics experiments typically involve a beam impinging on a fixed target
- Two separate classification types exist:
  - Thick *or* Thin (in relative to the beam energy loss)
  - Stopping *or* Transmission (i.e. does the beam go through or not)

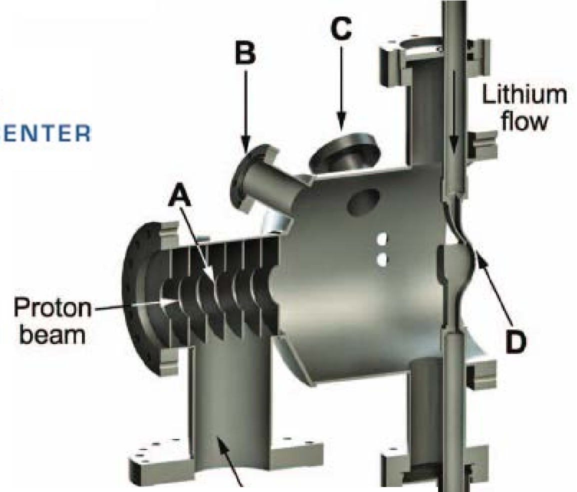
A stopping target doesn't have to be thick. Often times thin targets are stuck to a thick backing.

- When possible, a solid target is used, but high intensities or pure targets for gaseous elements may require liquid or gas targets

Solid

Solid target fabrication requires chemistry & black magic. Recipes are available from the International Nuclear Target Development Society ..or you an buy them from the National Isotope Development Center

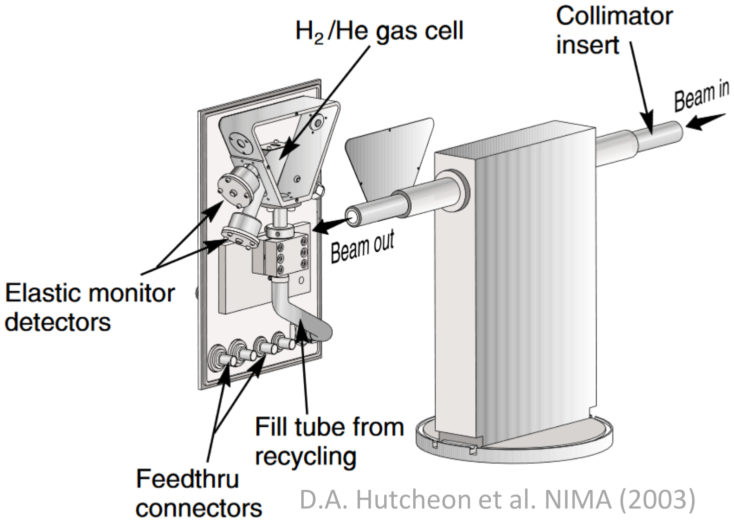
Liquid



S.Halfon et al. Rev.Sci.Inst. (2013)

~cm-thick H within a container is most common, but the LiLit Li waterfall is awesome

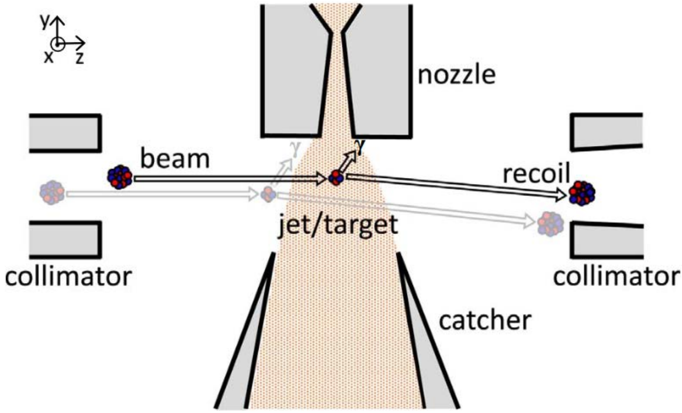
Gas Cells



D.A. Hutcheon et al. NIMA (2003)

several cm-long at ~10 torr (windowless) to ~500 torr (windows)

Gas Jets

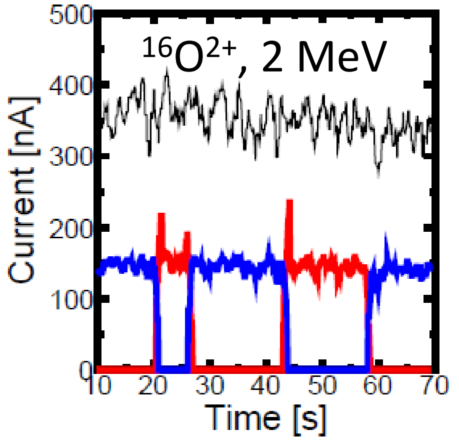


Z.Meisel et al. NIMA (2016)

~cm^3 size cylinder with ~10$^{17-19}$ atoms/cm^2

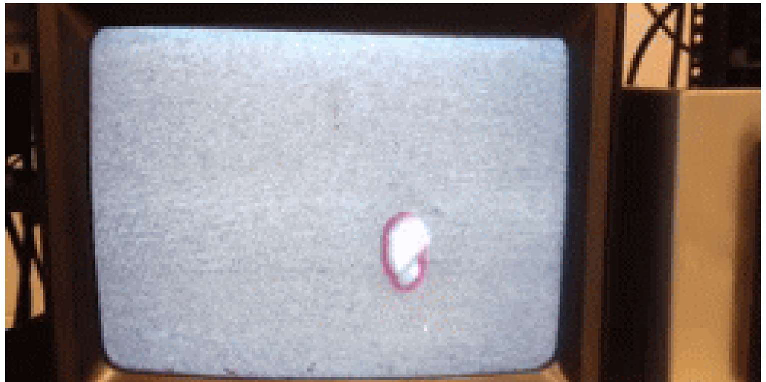
Beam detection: *Simplest techniques (cups & viewers)*

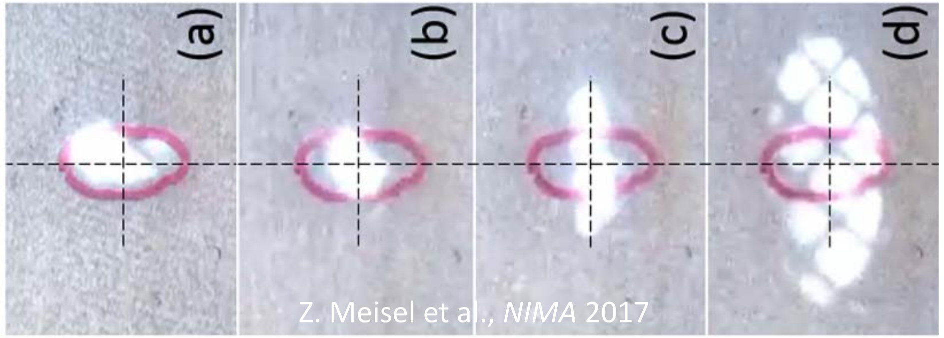
- Since ions are charged particles, these can be collected, resulting in an electric current
- Beam currents are typically recorded using a Faraday Cup
  - The cup is electrically isolated, so deposited charges can be read out
  - Suppression electrodes are located upstream of the back of the cup to prevent escaping electrons from altering current readings
  - These only work for relatively large beam intensities, since $1e = 1.602 \times 10^{-19} C$ means $1pA$ requires $\sim 6x10^6 pps$



Z. Meisel et al., *NIMA* 2017

- Other relatively high-intensity beam detecting devices include beam viewers, which typically rely on fluorescence or phosphorescence of a material
  - These are also limited to the $\sim pA$ to $\sim nA$ regime



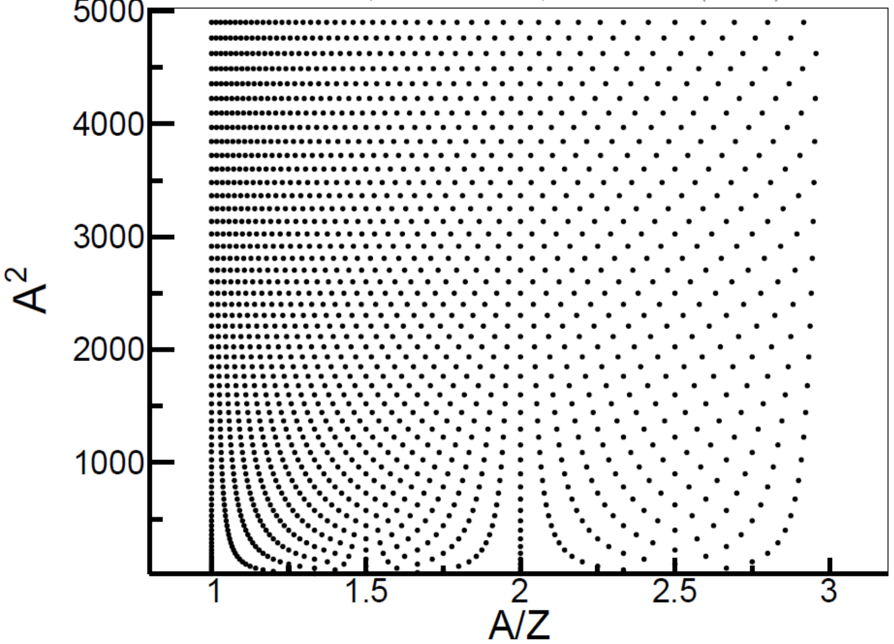


Z. Meisel et al., *NIMA* 2017

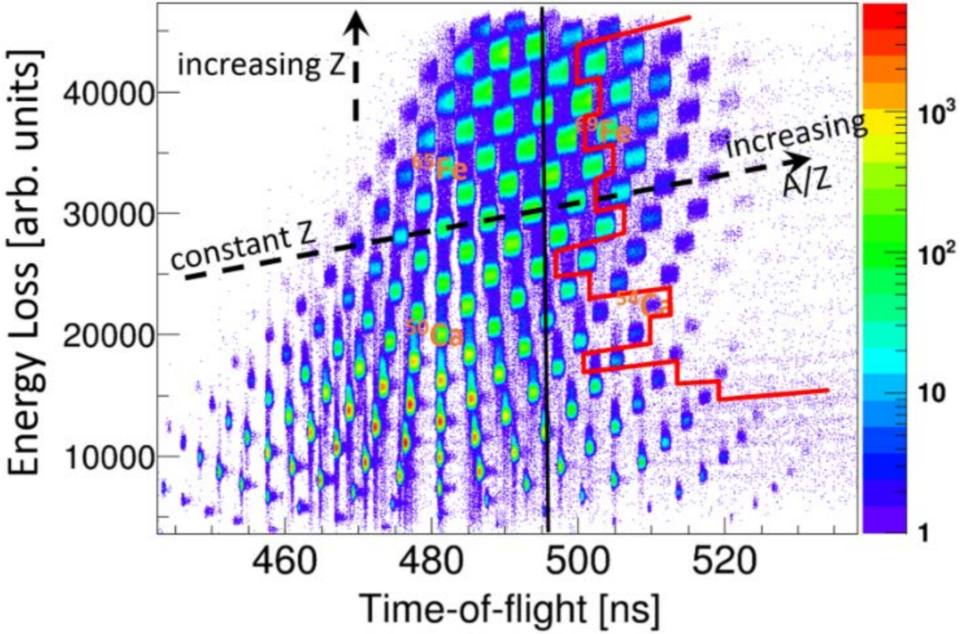
Beam detection: *Particle identification using energy loss*

- Charged particle detection generally relies on energy deposition within a detector
  (we'll discuss how that energy is deposited in a moment)
- From the Bethe formula, energy loss goes as $\Delta E \propto \frac{Z^2}{v^2}$. Since $v^2=\frac{p^2}{m^2}=\frac{q^2(B\rho)^2}{m^2}=\frac{Z^2(B\rho)^2}{A^2}$ for fully-stripped nuclei, then $\Delta E \propto \frac{Z^2A^2}{Z^2(B\rho)^2}$ …and for $B\rho \sim constant$, $\Delta E \propto A^2$
- For ions in a magnetic system, $F_c=F_L$ means $\frac{mv^2}{r}=qvB$. Since $v=\frac{L_{path}}{TOF}$ and $m=A$, $TOF \propto \frac{A}{Z}$
- Therefore ΔE vs TOF results in a matrix uniquely identifying nuclei. (ΔE vs E can be used as well)

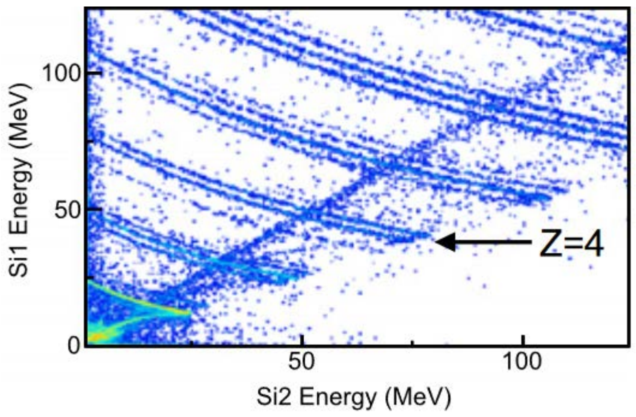
Z. Meisel, Ph.D. Thesis, Mich.St.U. (2015)



Z. Meisel et al., *Phys.Rev.C* (2016)

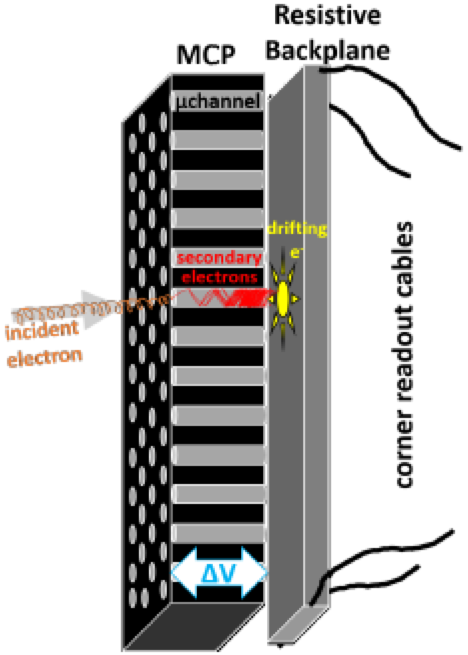


S.Carboni et al. NIMA (2012)

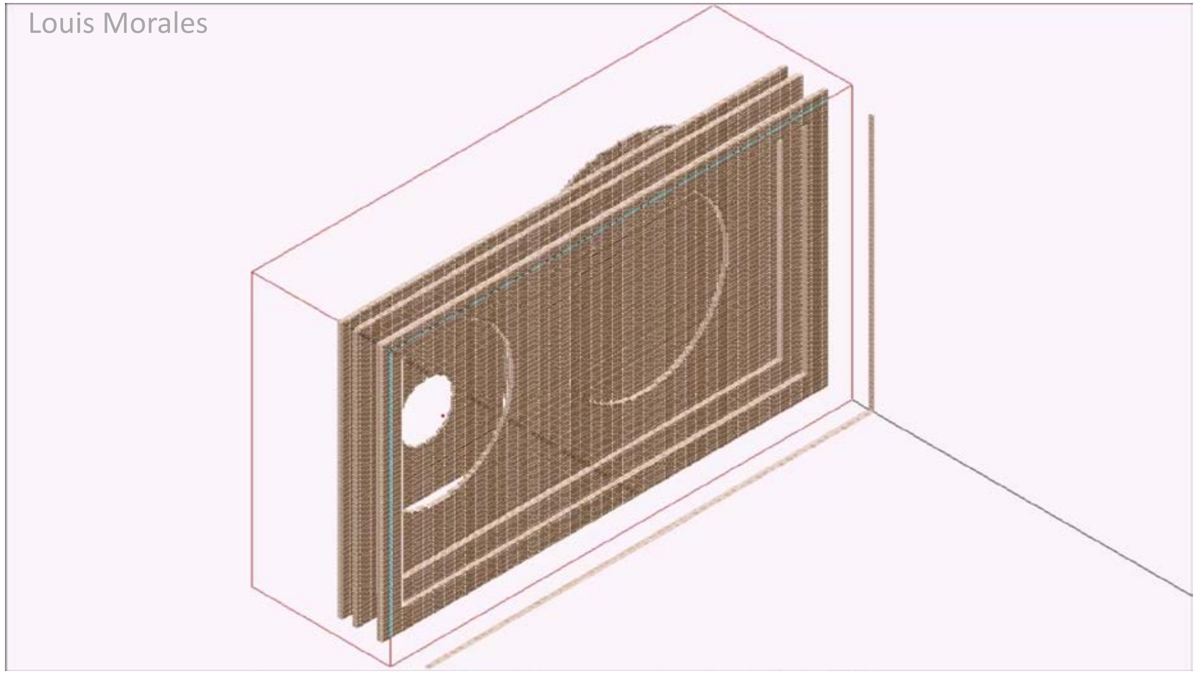


Beam detection: *Microchannel plate detectors*

- A neat and notable option for detecting ions directly or indirectly is the microchannel plate detector. As the name implies, it's a plate (or plates) with micron-size channels.
- The plates are made of resistive material and there's a large voltage gradient across the planes
- This means an incident photon or charged particle causes one or a few electrons to be emitted, those electrons are accelerated by the voltage difference, they collide with the channel wall and release more electrons, resulting in an electron avalanche
- For indirect detection, secondary electrons are collected using one of various schemes and used to obtain sub-millimeter resolution position and ~ns-resolution timing information



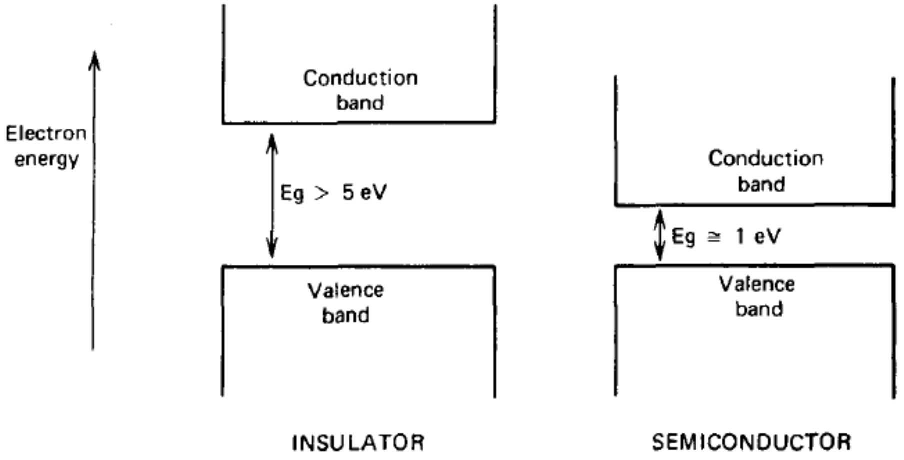
Z. Meisel, Ph.D. Thesis, Mich.St.U. (2015)

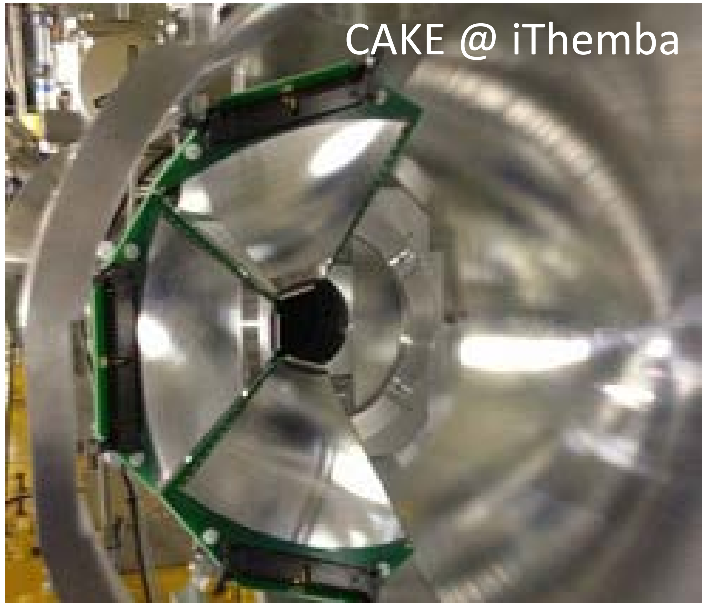

Louis Morales

Charged particle detection: *Silicon detectors*

- Silicon detectors are by far the most common way to detect charged particles
- They are semiconductors, meaning there's a small energy gap between their valence and conduction electron bands
- Coulomb interactions between an incident charged particle and atoms in the semiconductor result in energy transfer, which enables electrons to be excited across the band-gap
- If a voltage (usually 10's of V) is applied across the detector (typically silicon) then the freed electrons and the holes they leave behind can be collected on detector electrodes, resulting in 10's of keV energy resolution
- Segmentation into strips enables simultaneous position determination, where the strip width (typically mm) sets the position resolution.
- Many fancy geometries can be created, but the practical thickness is limited to ~1mm thick
- Particle intensities are limited to $\lesssim 10kHz$ to prevent excessive charge build-up, though this is dependent on the detector type and footprint on the detector

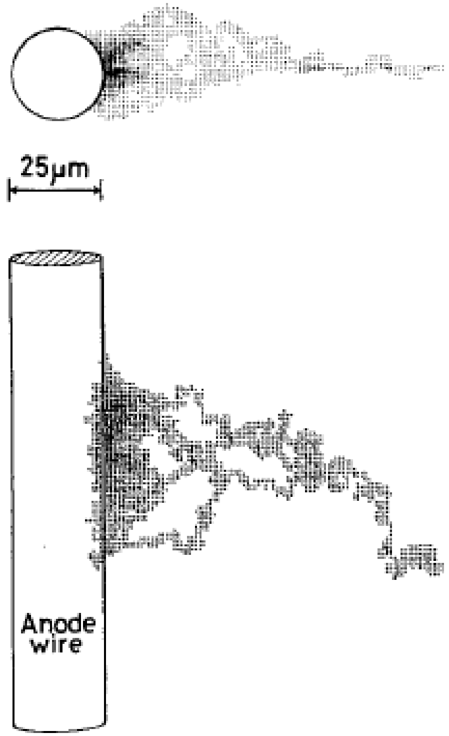
G.F.Knoll, Radiation Detection and Measurement (2000)



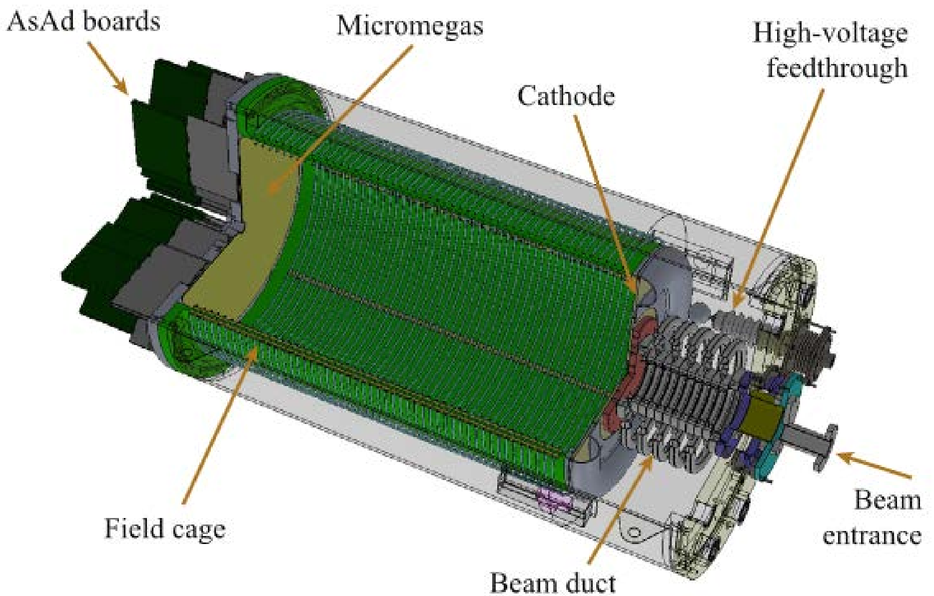


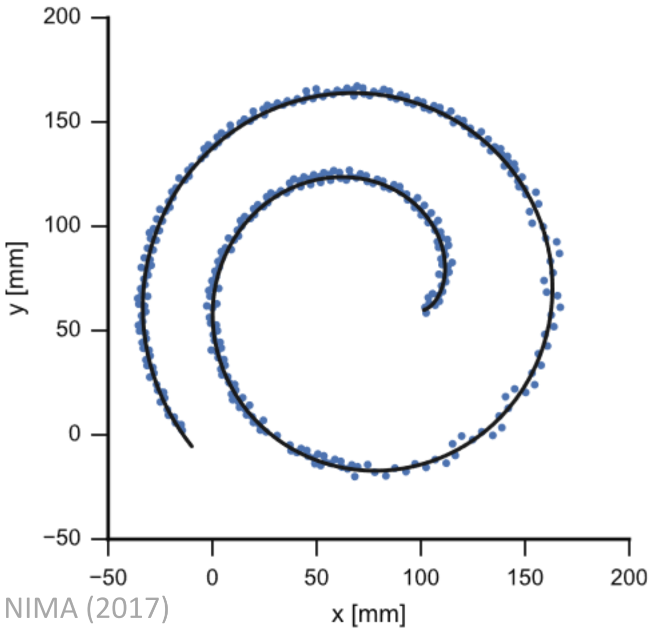
Charged particle detection: *Gaseous detectors*

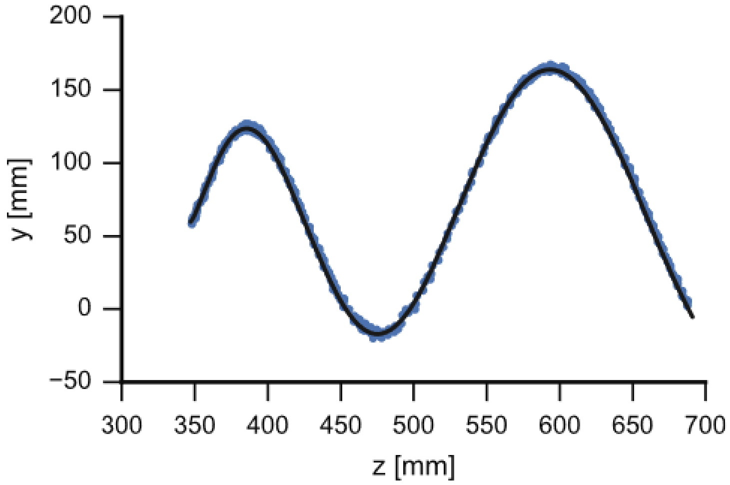
- When traveling through a gas, charged particles can deposit energy via Coulomb interactions with atomic electrons, resulting in ionization of atoms in the gas
- Electrons can be accelerated towards and collected on high-voltage wires or pad planes
- Accelerated electrons ionize other gas atoms, leaving a track and/or generating an electron avalanche
- Additional position information is obtained by recording e^- collection times



M. Matoba et al., *ITNS* (1985)





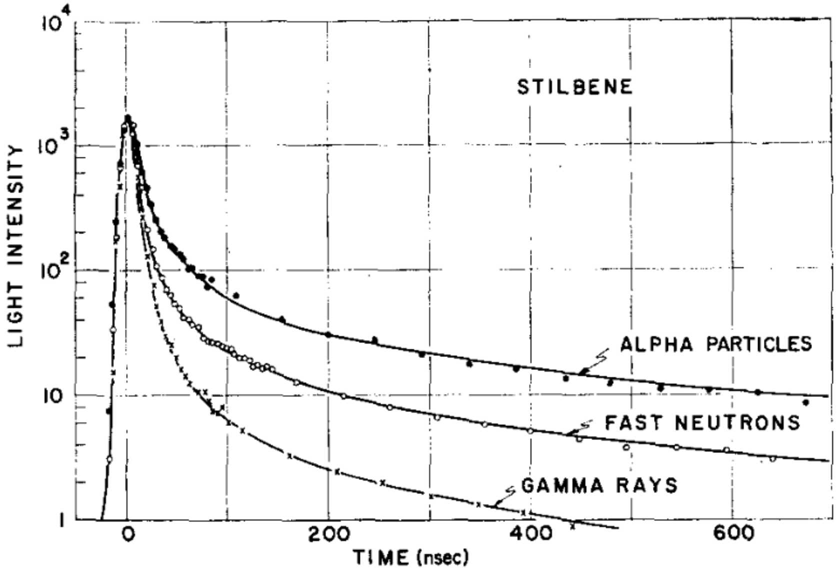


J.Bradt et al. NIMA (2017)

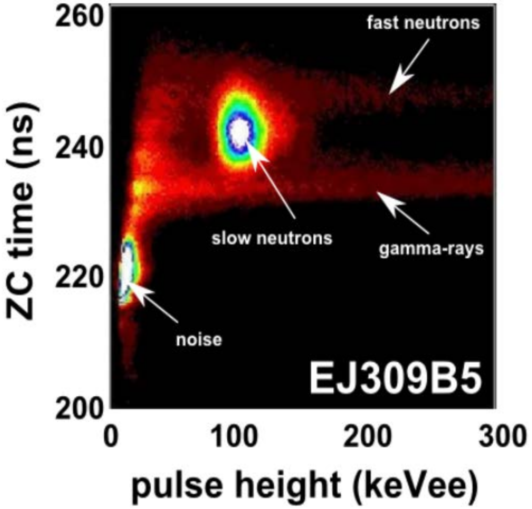
Neutron detection: *Scintillators*

- Neutron detection typically works by *either* measuring light emitted within a scintillator from a neutron recoiling off of a scintillator nucleus *or* measuring a charged particle emitted in a neutron-capture reaction.
- Organic scintillators convert collision energy to molecular excitations, which emit light upon deexcitation
    - Light output and duration depend on the characteristics of the material.
    - Scintillators are sensitive to charged particles, light, and neutrons, where particular types are better suited for particular applications.
    - The light-output vs time (pulse shape) enables radiation types to be discriminated
- When placed at a distance, the time difference between neutron detection and neutron creation can be used to determine the energy of the emitted neutron, enabling spectroscopy

Bollinger & Thomas, Rev.Sci.Inst. (1961)



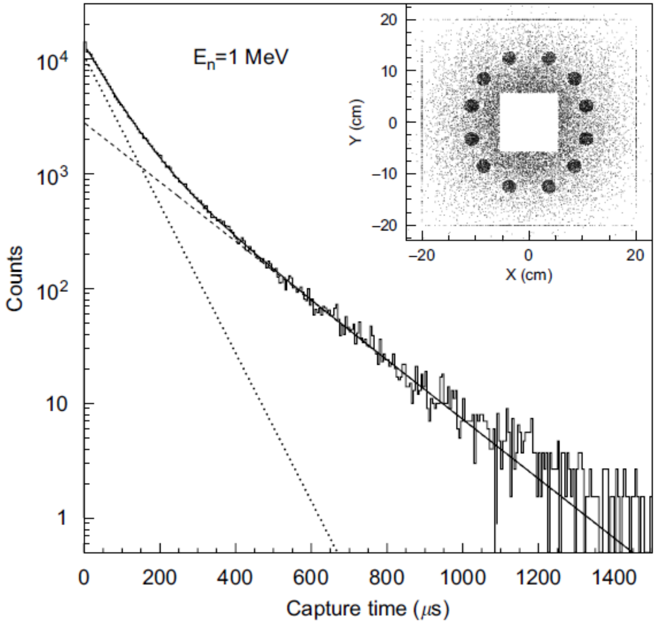
Iwanowska, Swiderski & Moszynsk, J.Inst. (2011)

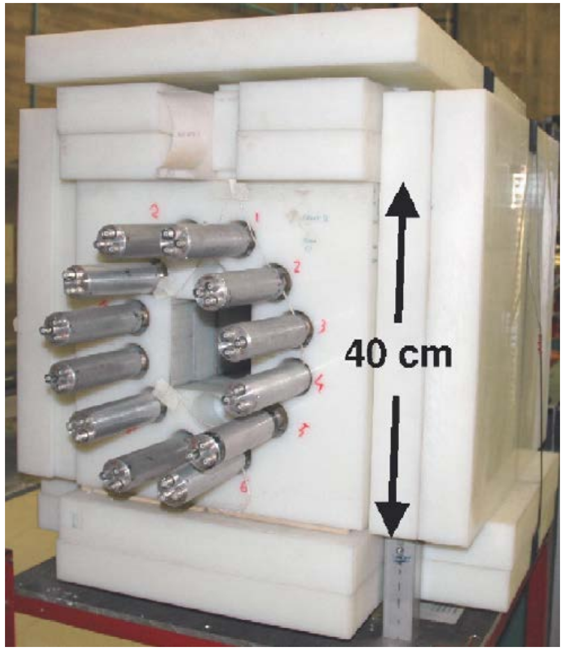


Neutron detection: *Long counters (a.k.a 4π detectors)*

- Neutron detection typically works by *either* measuring light emitted within a scintillator from a neutron recoiling off of a scintillator nucleus *or* measuring a charged particle emitted in a neutron-capture reaction.

- Long-counters work by first slowing neutrons down via many inelastic collisions and then taking advantage of the large cross sections at thermal energies (due to $\sigma_{ncap} \sim \frac{1}{v}$)
  - These devices typically have several neutron-sensitive proportional counters (either BF_3 or ^3He) embedded within a polyethylene (or other high H-density material) matrix
  - Since most information is lost about the initially ejected neutrons, these devices are typically just used for counting

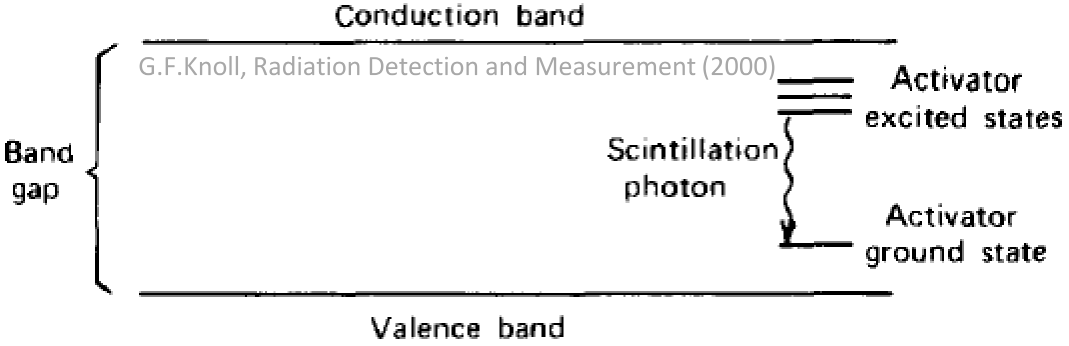




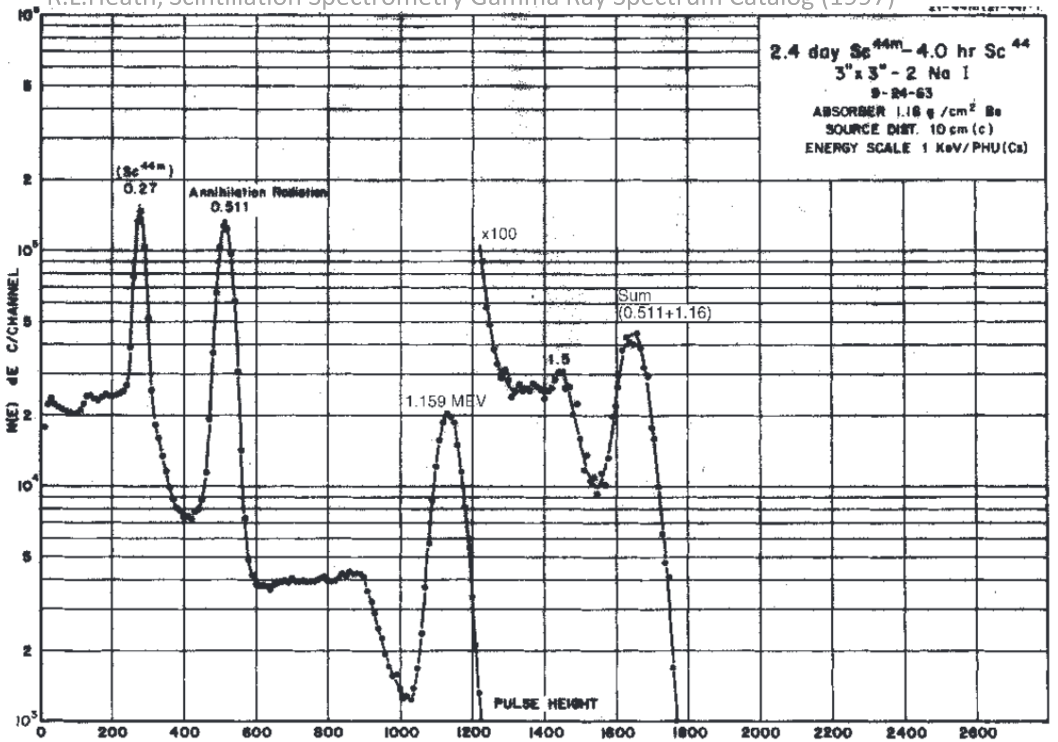
A. del Zoppo et al. NIMA (2007)

Gamma detection: *High Efficiency (NaI)*

- Photons can be detected using either scintillators or semiconductors. Scintillators, in particular NaI, generally provide the highest efficiencies
  (NaI(Tl) has high-Z materials, which interact strongly with photons, and a beastly light output)
- An inorganic crystal scintillator like NaI(Tl), energy deposited results in an excitation of an electron into the conduction band, which then de-excites through impurity states in the forbidden region. De-excitation results in the emission of a photon, which can be collected and converted into an electric current via the photoelectric effect
- The large number of options in which excitation and de-excitation can proceed results in a relatively poor energy resolution


G.F.Knoll, Radiation Detection and Measurement (2000)

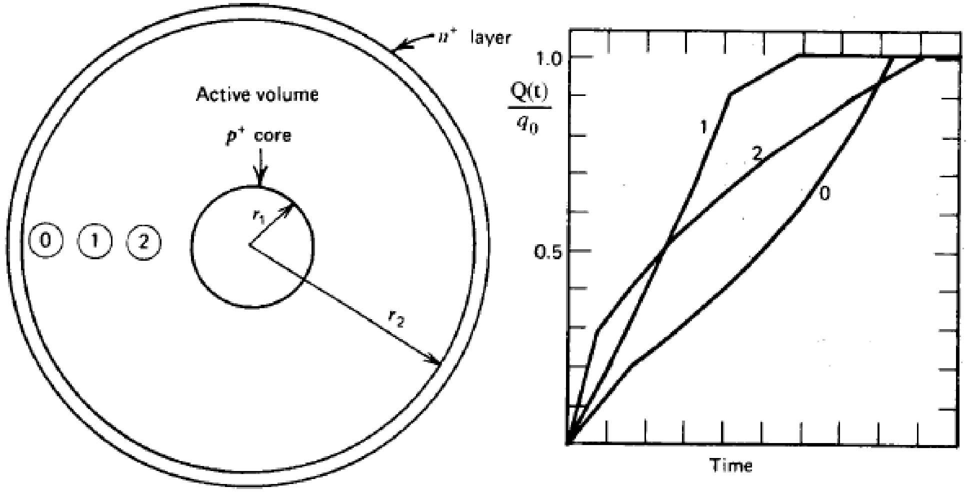
R.L.Heath, Scintillation Spectrometry Gamma Ray Spectrum Catalog (1997)



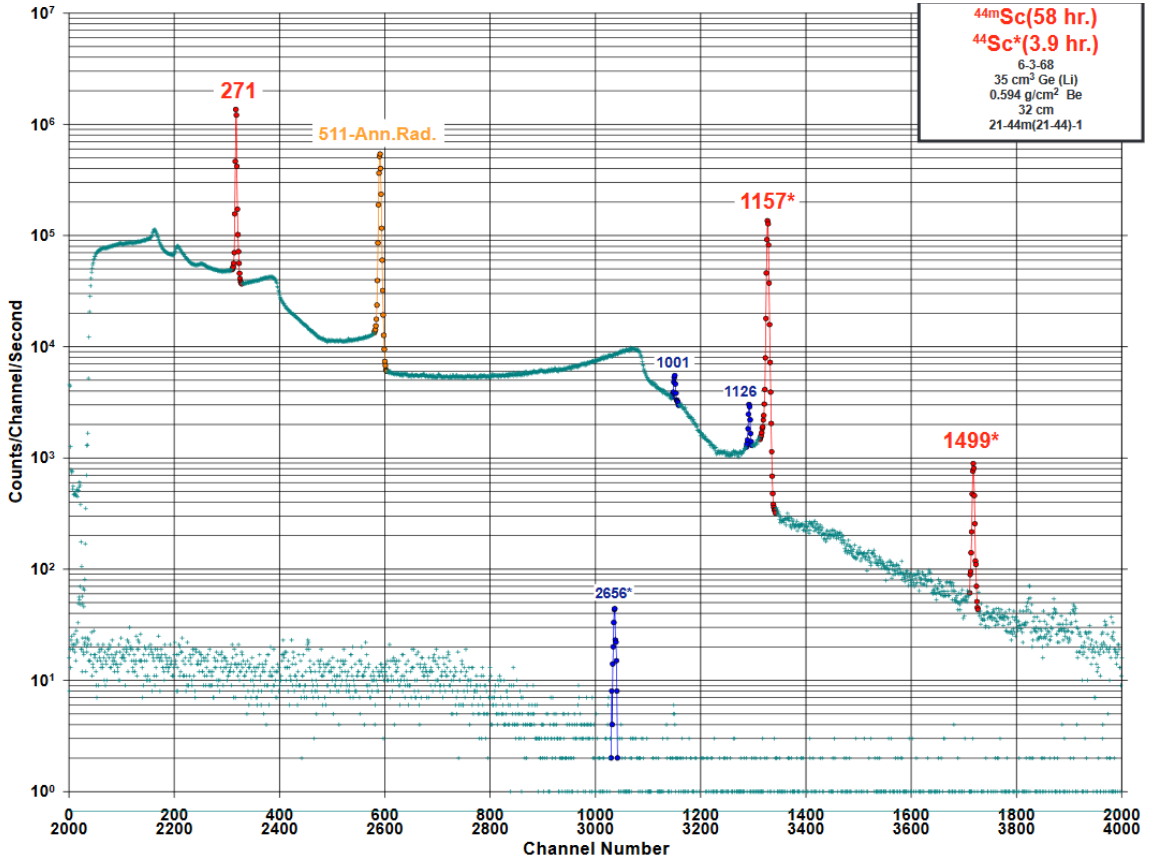
Gamma detection: *High Resolution (HPGe)*

- Photons can be detected using either scintillators or semiconductors. Germanium is the semiconductor of choice for gamma-rays.
  (The tiny band-gap provides a large number of electron-hole pairs, but requires cooling during operation)
- The underlying mechanism is the same as for Si, but much thicker crystals can be grown
- The small band-gap (~3eV) and efficient charge collection results in extremely narrow energy resolutions
- Clever signal timing analyses enable the interaction point to be determined, resulting in tracking capabilities

G.F.Knoll, Radiation Detection and Measurement (2000)

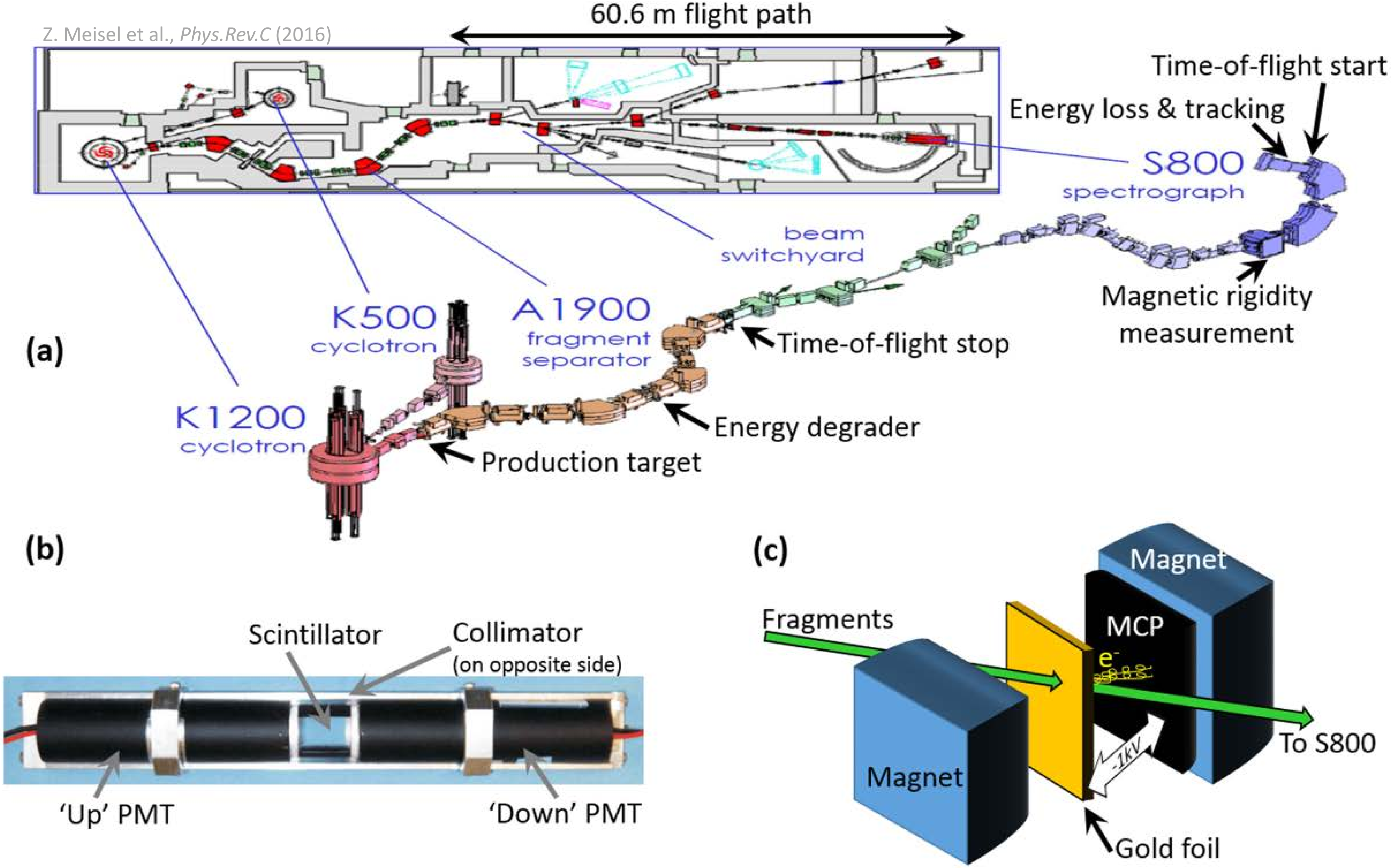


INEEL Gamma Ray Spectrum Catalog: Ge and Si detector spectra (1998)



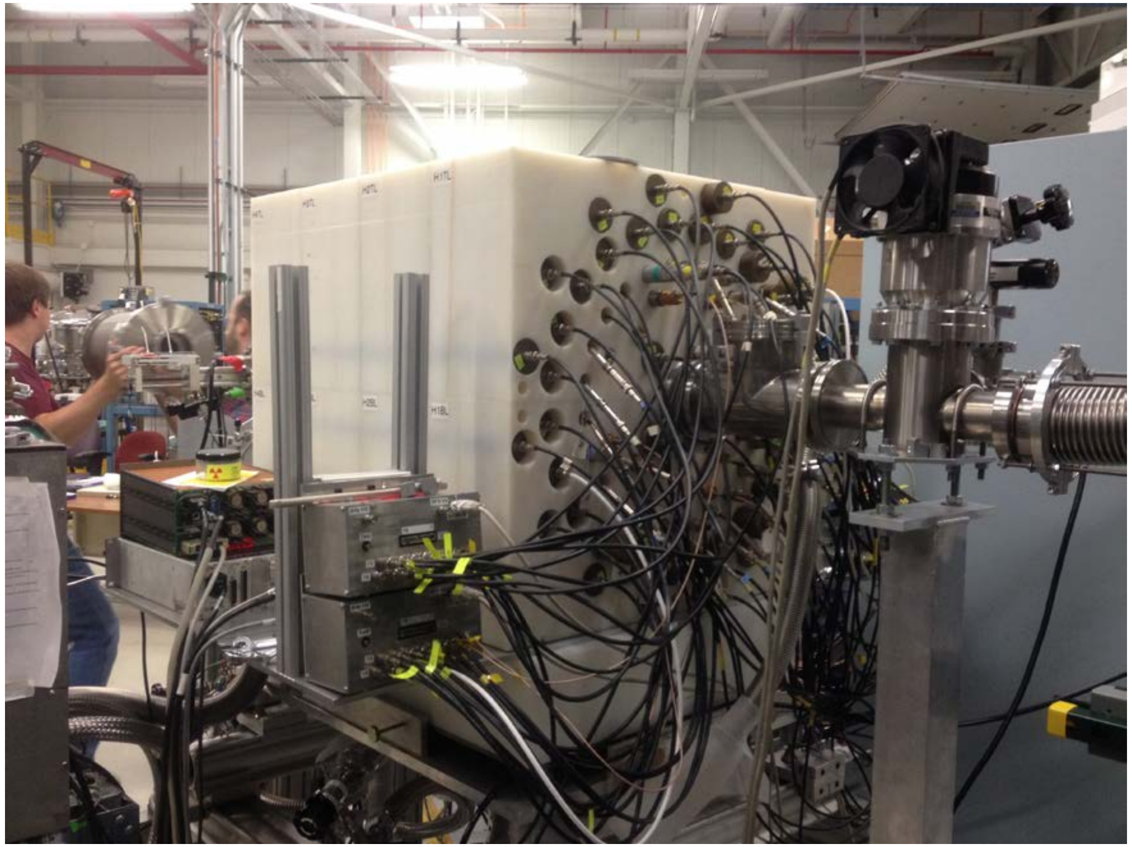
Putting it all together for a modern experiment (example 1)

Z. Meisel et al., *Phys.Rev.C* (2016)

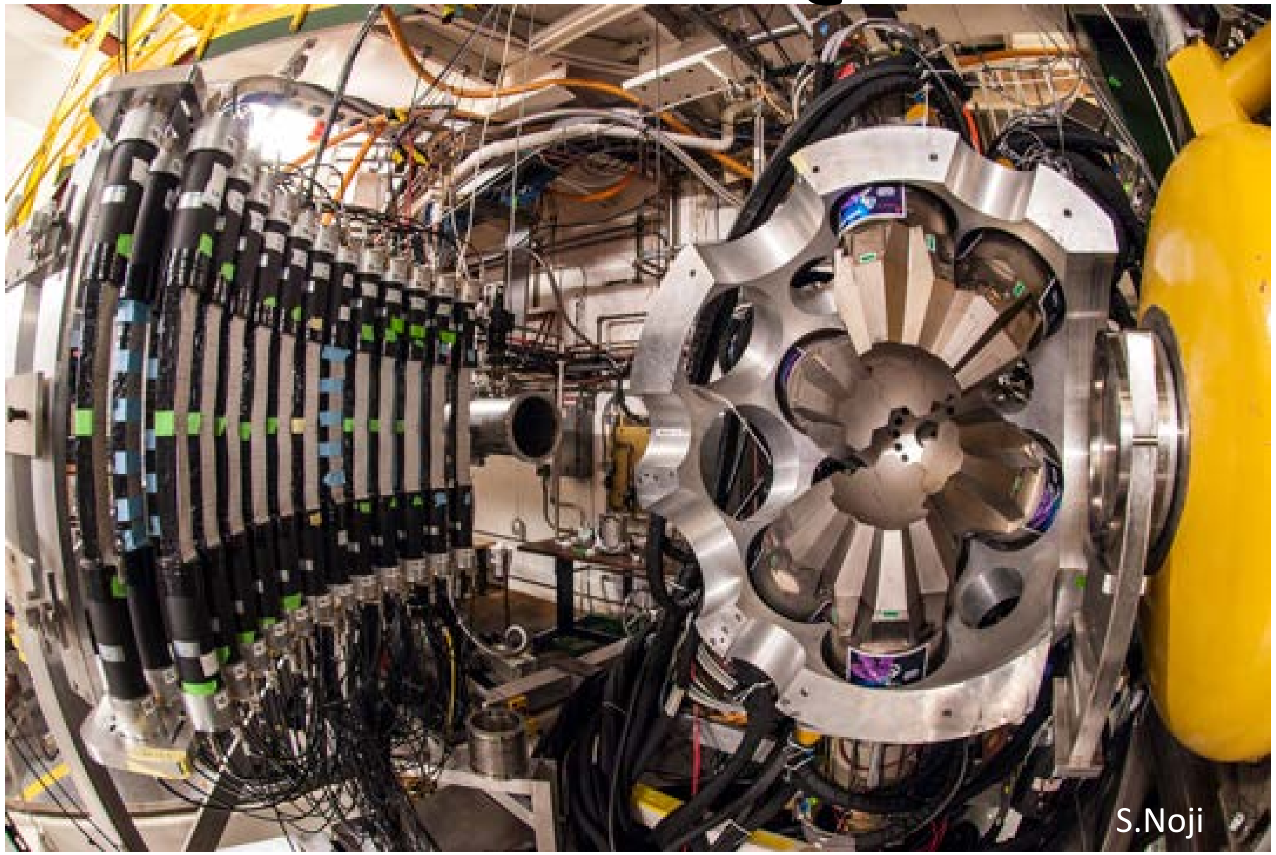


Putting it all together for a modern experiment (examples 2 & 3)

HABANERO + Ion Chamber



GRETINA + LENDA @ S800



Further Reading

- Chapters 14,17,18: Modern Nuclear Chemistry (Loveland, Morrissey, & Seaborg)
- Chapter 4: Nuclear Physics of Stars (C. Iliadis)
- Chapter 5: Cauldrons in the Cosmos (C. Rolfs & W. Rodney)
- Radiation Detection & Measurement (G.F. Knoll)
- Lecture Notes, Euroschool on Exotic Beams