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LAWRENCE BERKELEY NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

1./2. Fundamentals of Ion Sources

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Damon Todd (LBNL),

Daniel Winklehner (MIT)

Massachusetts Institute of Technology

Course Organization

3 Lecturers, AM+PM lectures, PM lab, daily homework

Selected topics for ion source development and low energy beam transport for injector systems

Monday	Tuesday	Wednesday	Thursday	Friday
Introduction	Multicusp Ion Sources	Low Energy Beam Transport	Space Charge	Finals with open notes
Plasma Physics for Ion Sources				
Beam Quality Parameters	ECRIS	Diagnostics	Vacuum	
Ion Extraction		LEBT	EBIT	Close out session
Homework				
Computer Labs				

Homework/Computer Labs/Finals

Grading:

40% participation and computer lab work

40% Homework

- Teamwork is encouraged for the computer lab and the homework!! Homework is given daily. Solutions will be distributed the next day.
- We are here to help!! Don't hesitate to ask for assistance with homework problems! The grading is more focused on the effort to solve a problem than submitting the perfectly worked out solution
- Use the internet as resource

20% Finals: Open book – we should discuss the use of internet

- .

There are a large variety of ion sources- tailored to the need of the experiments

- *Bayard-Alpert type ion source*
- *Electron Bombardment ion source*
- *Hollow Cathode ion source*
- *Reflex Discharge Multicusp source*
- *Cold- & Hot-Cathode PIG*
- *Electron Cyclotron Resonance ion source (ECR)*
- *Electron Beam Ion Source (EBIS)*
- *Surface Contact ion source*
- *Cryogenic Anode ion source*
- *Metal Vapor Vacuum Arc ion source (MEVVA)*
- *Sputtering-type negative ion source*
- *Plasma Surface Conversion negative ion source*
- *Electron Heated Vaporization ion source*
- *Hollow Cathode von Ardenne ion source*
- *Forrester Porus Plate ion source*
- *Multipole Confinement ion source*
- *EHD-driven Liquid ion source*
- *Surface Ionization ion source*
- *Charge Exchange ion source*
- *Inverse Magnetron ion source*
- *FEBIAD ion source*
- *Microwave ion source*
- *XUV-driven ion source*
- *Arc Plasma ion source*
- *Capillary Arc ion source*
- *Von Ardenne ion source*
- *Capillaritron ion source*
- *Canal Ray ion source*
- *Pulsed Spark ion source*
- *Field Emission ion source*
- *Atomic Beam ion source*
- *Field Ionization ion source*
- *Arc Discharge ion source*
- *Multifilament ion source*
- *RF plasma ion source*
- *Freeman ion source*
- *Liquid Metal ion source*
- *Beam Plasma ion source*
- *Magnetron ion source*
- *Resonance laser ion source*
- *Nier ion source*
- *Bernas ion source*
- *Nielsen ion source*
- *Wilson ion source*
- *Recoil ion source*
- *Zinn ion source*
- *Plasmatron*
- *Duoplasmatron*
- *Duopigatron*
- *Laser ion source*
- *Penning ion source*
- *Monocusp ion source*
- *Bucket ion source*
- *Metal ion source*
- *Multicusp ion source*
- *Kaufman ion source*
- *Flashover ion source*
- *Calutron ion source*
- *CHORDIS*

Courtesy, Martin P. Stockli

There are a large variety of ion sources- tailored to the need of the experiments

- *Bayard-Alpert type ion source*
- *Electron Bombardment ion source*
- *Hollow Catho*
- *Reflex Discha*
- *Cold- & Hot-C*
- *Electron Cyclo*
- *Electron Bean*
- *Surface Conta*
- *Cryogenic An*
- *Metal Vapor V*
- *Sputtering-ty*
- *Plasma Surfa*
- *Electron Heat*
- *Hollow Catho*
- *Forrester Por*
- *Multipole Confinement ion source*
- *EHD-driven Liquid ion source*
- *Surface Ionization ion source*
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- *Nier ion source*
- *Bernas ion source*
- *Multicusp ion source*
- *Kaufman ion source*
- *Flashover ion source*
- *Calutron ion source*
- *CHORDIS*

Student body is equally scattered –
Negative ion sources
PIG, Duaplasmatron, …
High charge state ion source (ECR, EBIT)
Laser acceleration
Beam transport systems for injectors…

we will not be able to cover all topics – so we selected a few

Courtesy, Martin P. Stockli

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Suggested Literature - Books

- We have added references through-out the presentations- the presentations will be posted on the USPAS web

Additional resources for ion source literature

- Ion Sources, Huashun S. Zhang, Jianrong Zhang, Springer-Verlag, 2000
- Handbook of Ion Sources, Bernhard H. Wolf, CRC Press, 1995
- Electron Cyclotron Resonance Ion Sources, R. Geller, IOP Pub, 1996
- Electron Beam Ion Sources and Traps and Their Applications, Krsto Prelec, Springer-Verlag, 2001
- CERN Accelerator School – *CAS* (2013), CERN-2013-007

Suggested Literature - Conferences

- We have added references through-out the presentations- the presentations will be posted on the USPAS web
- JACOW website: PACs, CYCLOTRONS, ….
- Every 2 year – ICIS conference (all ion sources)
  - Proceedings of the International Conferences on Ion Sources, in Rev. of Sci. Instrumentation. early in all odd years, 2017 next one
- Every 2 years ECR workshops (early ones are not available on the web)
  - Proceedings of the Workshops on ECRIS, JACOW website, next one 2016
- Every 2 years EBIS workshop
  - Proceedings on the International Symposium on Electron Ion Beam Sources and Their Applications, American Institute of Physics, 2016 next
- International Symposium on Negative Ions, Beams and Sources
  - Proceedings are published by AIP, in their conference proceedings series, since 2009 , next one 2016

Content

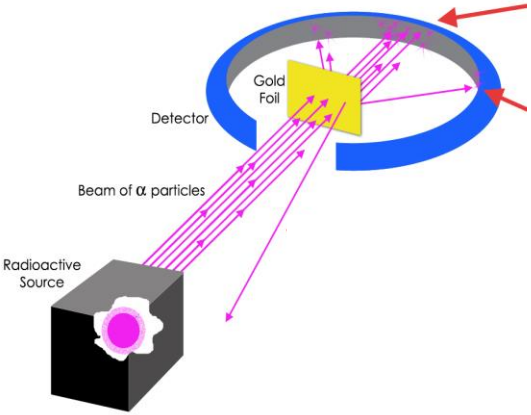
- A little bit of history
- Sources General – Overview
- Front Ends - Injectors
- Simple Sources
- Plasma Physics Fundamentals
- Homework for the day

Ion sources – Brief History

- 1857: experiments with electrical glow discharge – Geissler tube (neon lights): Weakly ionized plasma in glass tubes!
- 1889: Friedrich Paschen: Breakdown in gas discharges
- 1900: Townsend discharge
- 1908-1911: Discovery of the structure of the atom: Rutherford, Geiger, Marsden– start of modern nuclear physics and accelerator applications
- Need was established to develop accelerators as a source for charged particles to replace radioactive sources and produce particles at controlled energies

Rare 1890 German multi-bulb with Rhodanine, Eosine, Fluorecine, and Authacein.

Rutherford's Gold Foil Experiment



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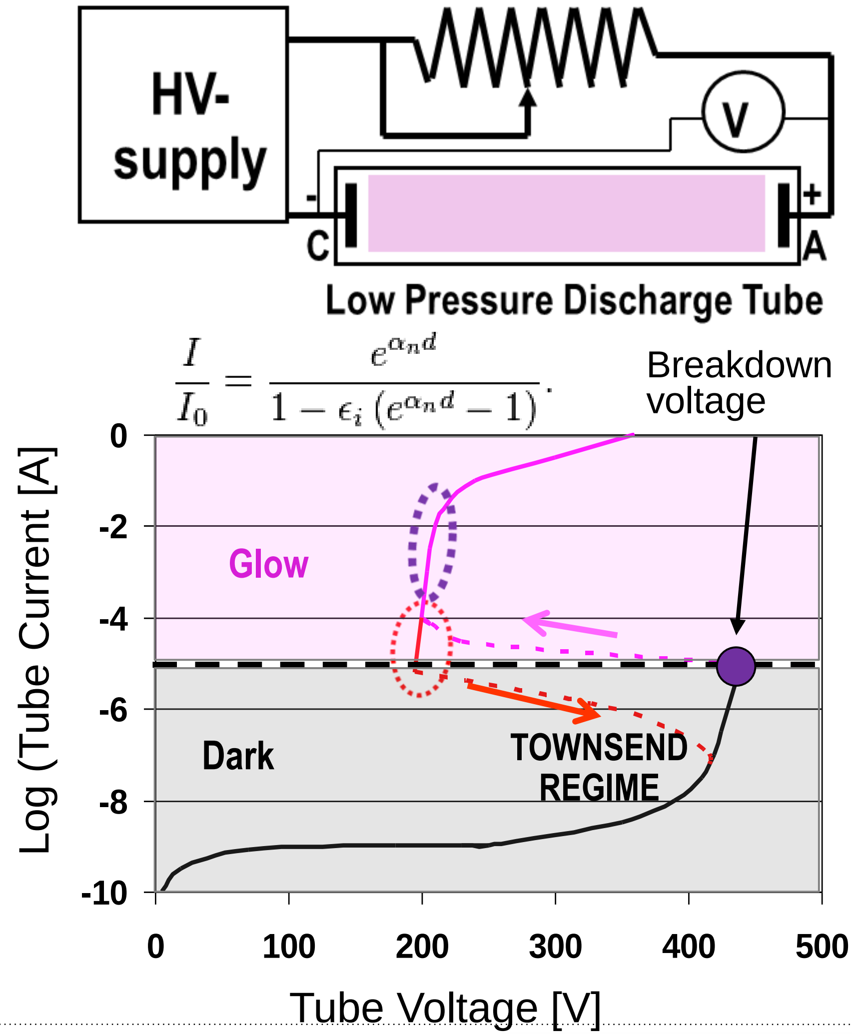
The Evolution of Low Pressure Gas Discharges

- 1900: Townsend studies gas discharges in partially evacuated tubes with two electrodes
- Small voltages yields nA currents by collecting electron–ion pairs produced by background radiation
- Raising the voltage starts the Townsend multiplication, yielding many µA (corona – avalanche event)
- Increasing the voltage, suddenly the gas starts to glow and the current grows up to many mA at a much reduced voltage



$$\frac{I}{I_0} = \frac{e^{\alpha_n d}}{1 - \epsilon_i \left(e^{\alpha_n d} - 1\right)}.$$

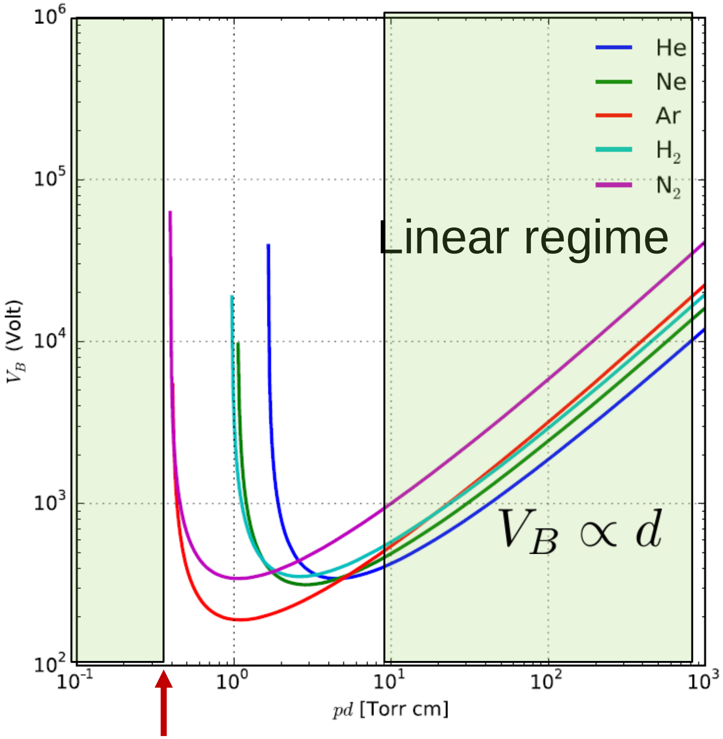
Courtesy, Martin P. Stockli, ORNL

The Breakdown Voltage (Paschen's Law)

- 1889 Friedrich Paschen described a breakdown voltage function V(p,d) with pressure *p*, electrode gap *d*, and experimental determined coefficients :*A* & *B, which* depend on the gas and the electrodes
- γ_{se} is the secondary electron coefficient

$$V_B = \frac{Bpd}{\ln(Apd) - ln[ln(1 + \frac{1}{\gamma_{se}})]}$$

- Decreasing the pressure increases the mean path between collisions (λ_i), which is compensated by proportionally increasing d
- The minimum represents the minimum energy spent on producing enough ions for one secondary electron from the cathode.
- At high $p \cdot d$, the voltage increases linearly with the gap between the electrodes



Energy gained by the electrons between collisions is too small

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Constants as References

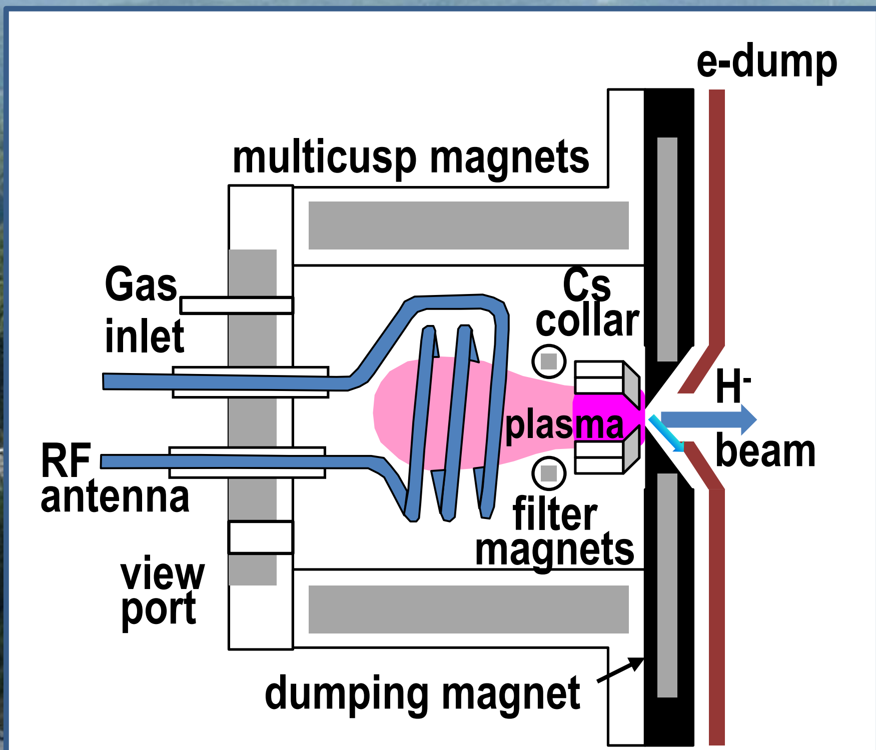
Gas	A	B	Range of E/p (V/cm-Torr)
Air	14.6	365	150–600
Ar	13.6	235	100–600
CO_2	20.0	466	500–1000
H_2	5.0	130	150–400
H_2O	12.9	289	150–1000
He	2.8	34	20–150

Source. Cobine (1958).

- Constants A, B for various gases and pressure regimes
- Secondary electron coefficients: 1 to 2 (depending on the material)

The Spallation Neutron Source

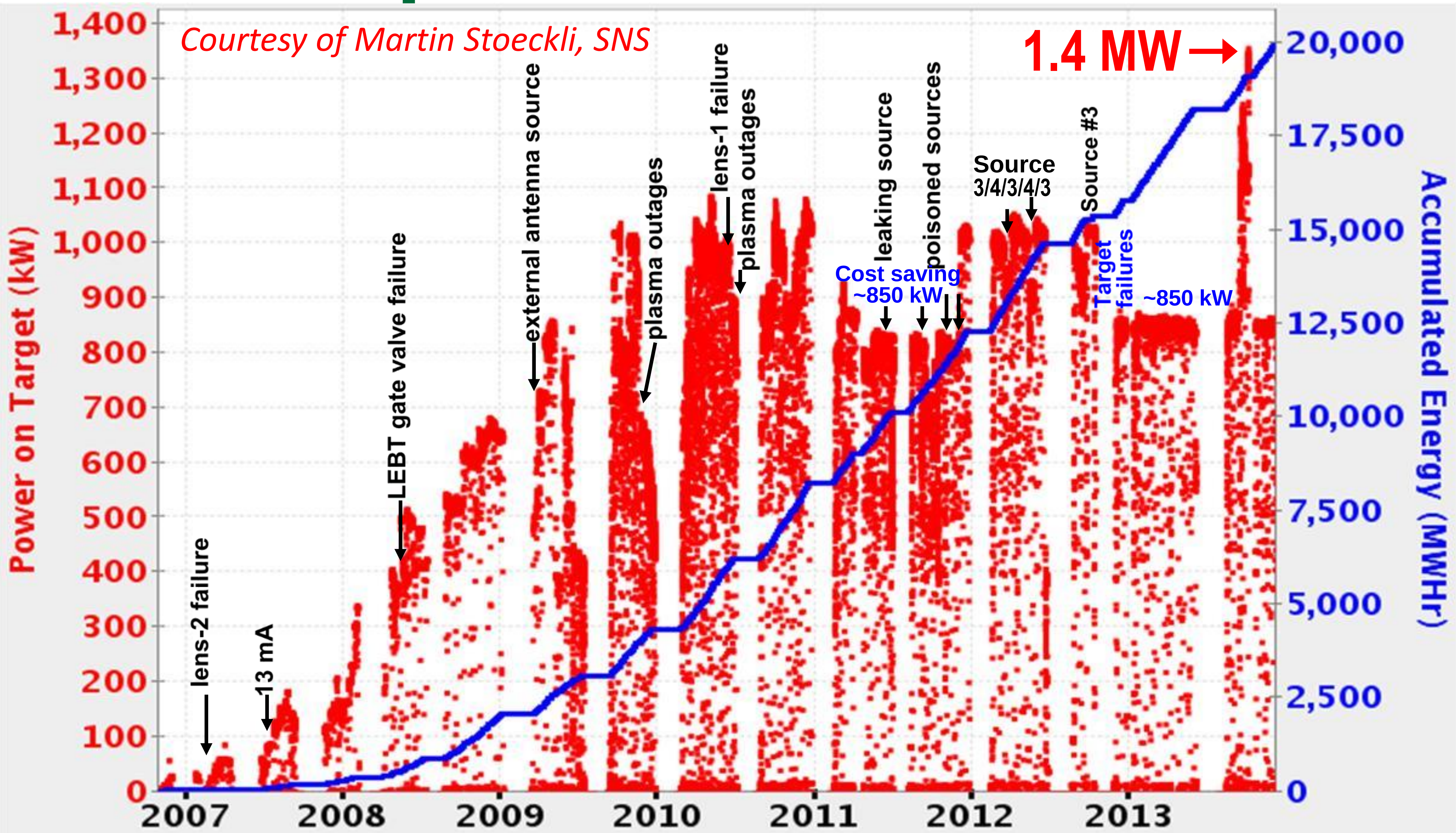
smashes a pulsed, 1 MW proton beam on to a Hg target to produce ~$2 \cdot 10^{17}$ neutrons 60 times per second!



SNS was constructed by a collaboration of
Lawrence Berkeley National Laboratory
Los Alamos National Laboratory
Jefferson National Laboratory
Brookhaven National Laboratory
Argonne National Laboratory and
Oak Ridge National Laboratory

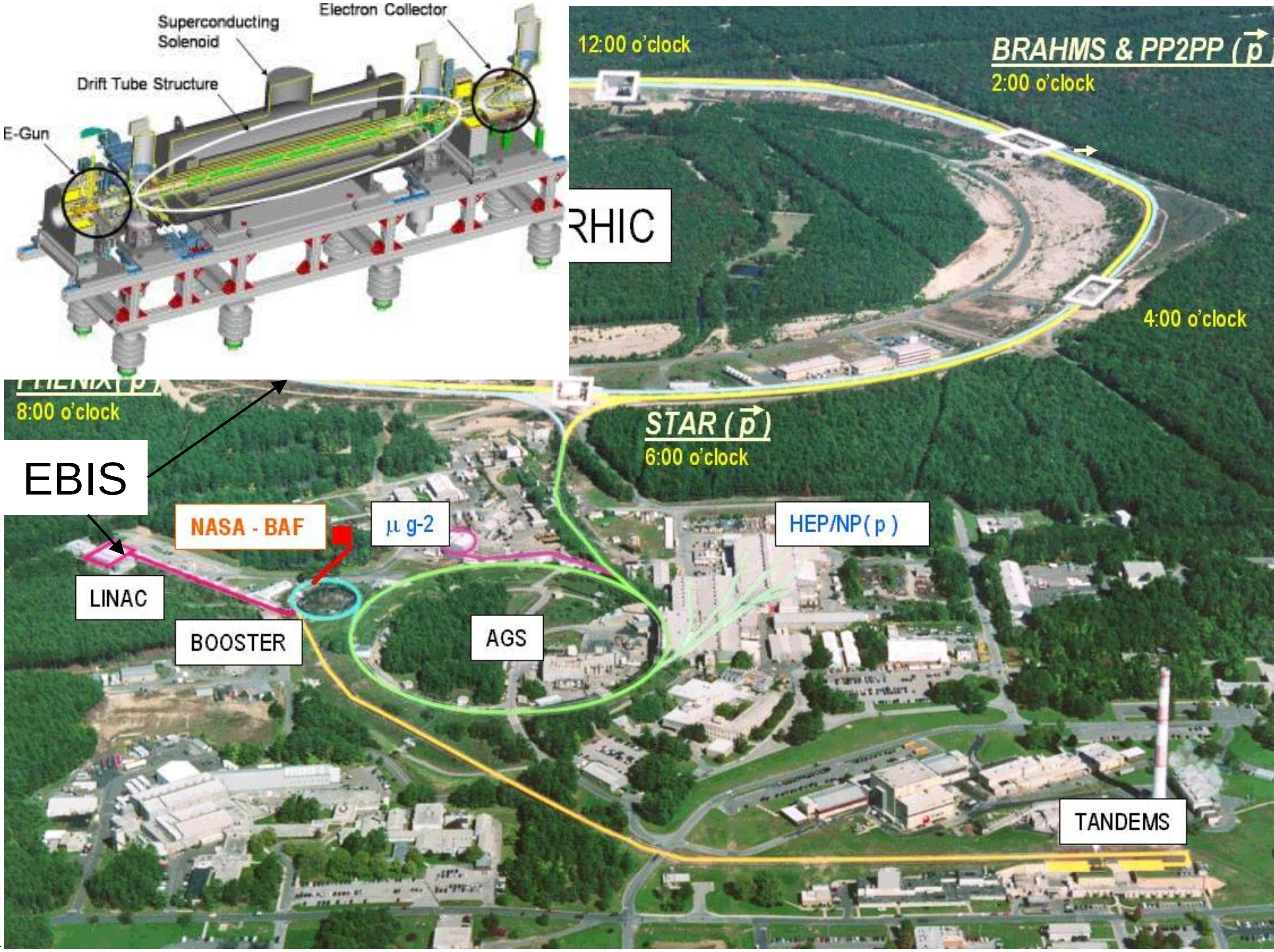
Courtesy of Martin Stoeckli, SNS

The Spallation Neutron Source



After a 3-year ramp up, SNS is running ~1 MW except for cost- and target-issues!
These unprecedented power levels uncovered many source and LEBT issues!
Much had to be learned to support ~1 MW operations with high availability!

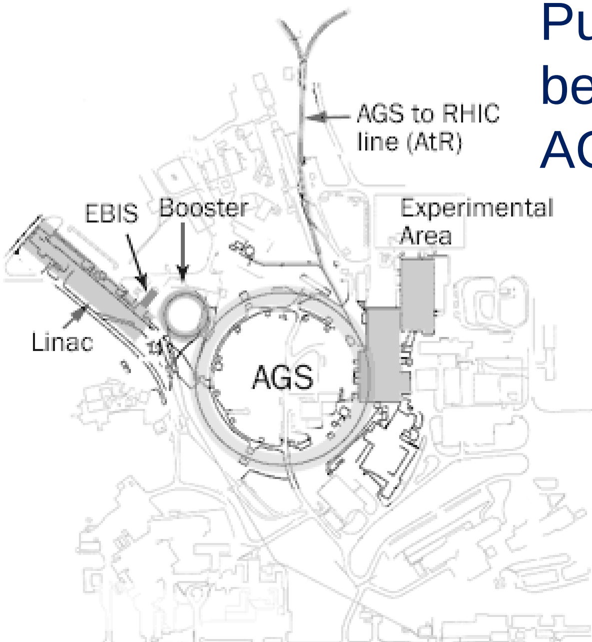
Heavy Ion Collider at Brookhaven National Laboratory – RHIC Accelerator Complex

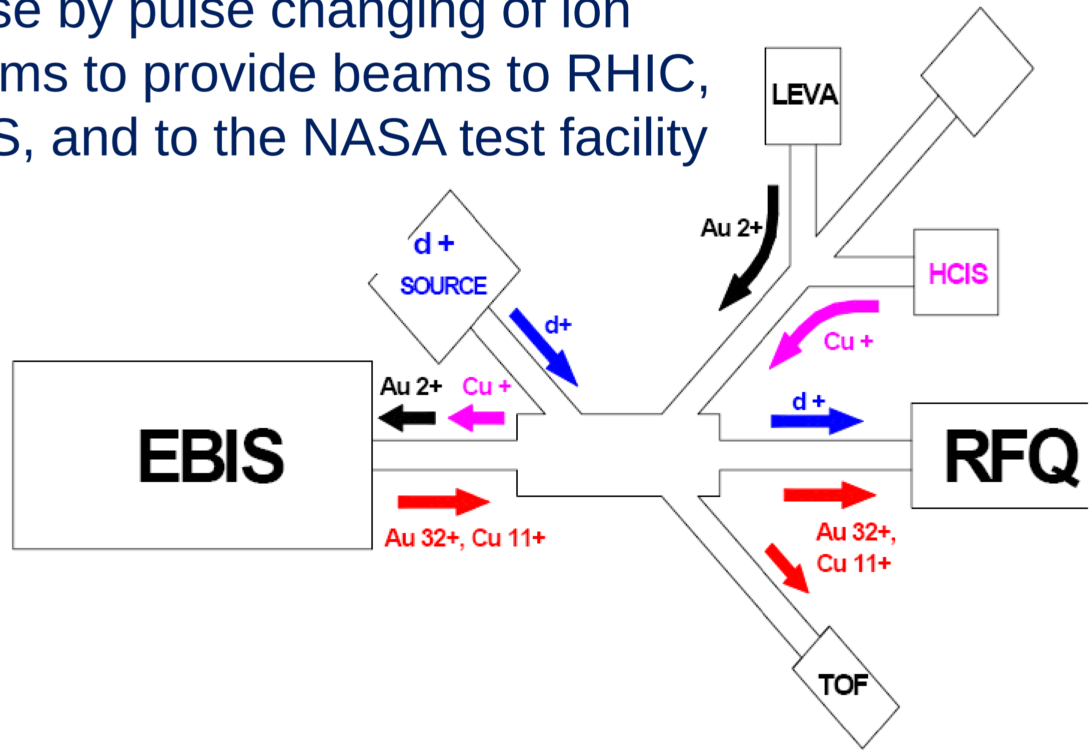


Alexander Pikin

Injection and extraction scheme for the BNL EBIS source

Pulse by pulse changing of ion beams to provide beams to RHIC, AGS, and to the NASA test facility





- **EBIS – Electron Beam Ion Source**
- **RFQ – Radio Frequency Quadrupole Ion Accelerator**
- **TOF – Time-of-Flight Spectrometer**
- **LEVA – Low Energy Metal Vapor Vacuum Arc Ion Source**
- **HCIS – Hollow Cathode Ion Source**

Courtesy of E. Beebe, BNL

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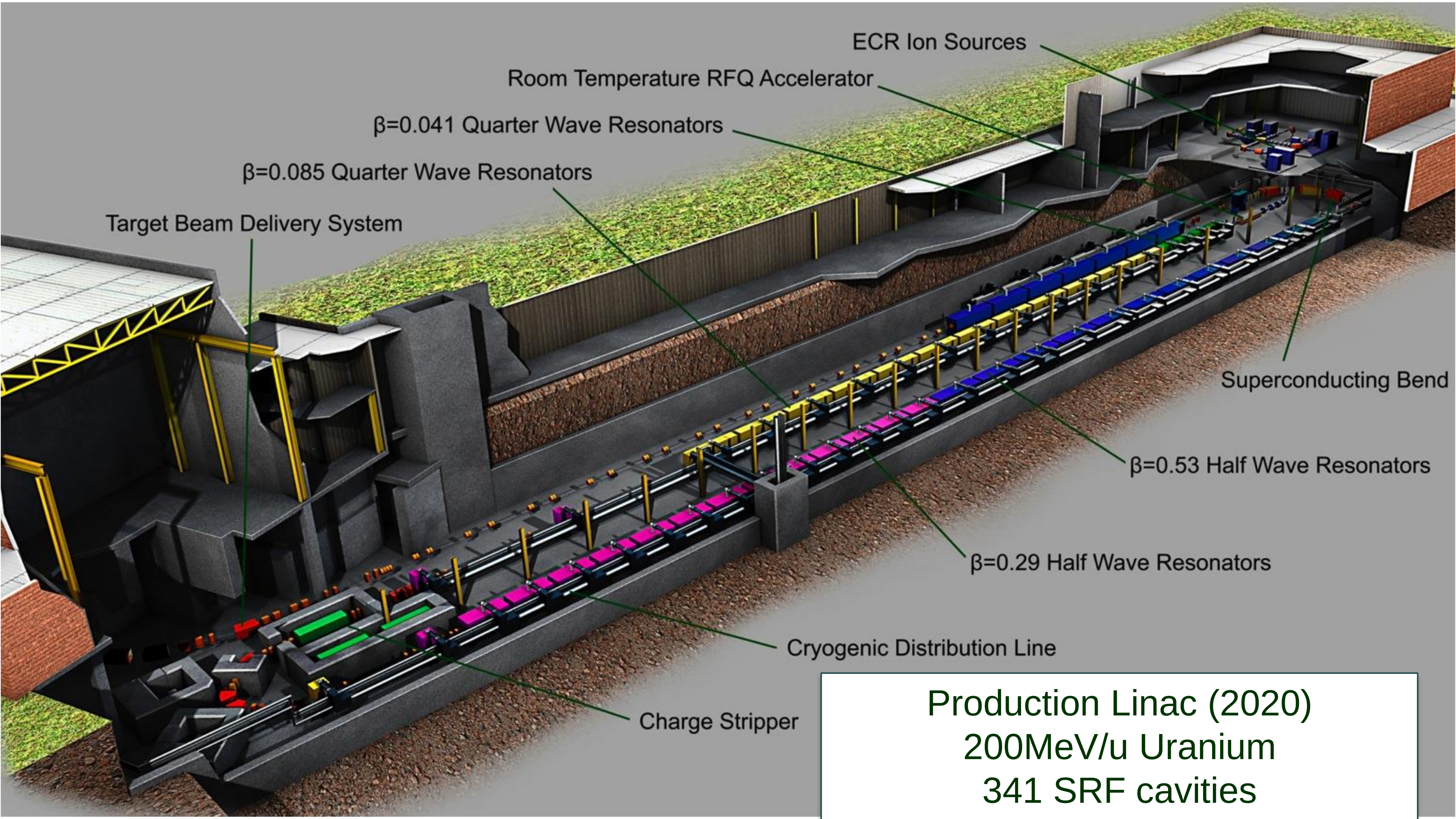
FRIB Rare Isotope Driver LINAC



Production Linac (2020)
200MeV/u Uranium
341 SRF cavities
ß=0.041, 0.085,0.29,0.53

Figure: Courtesy of M. Leitner, LBNL

https:// www.FRIB.msu.edu

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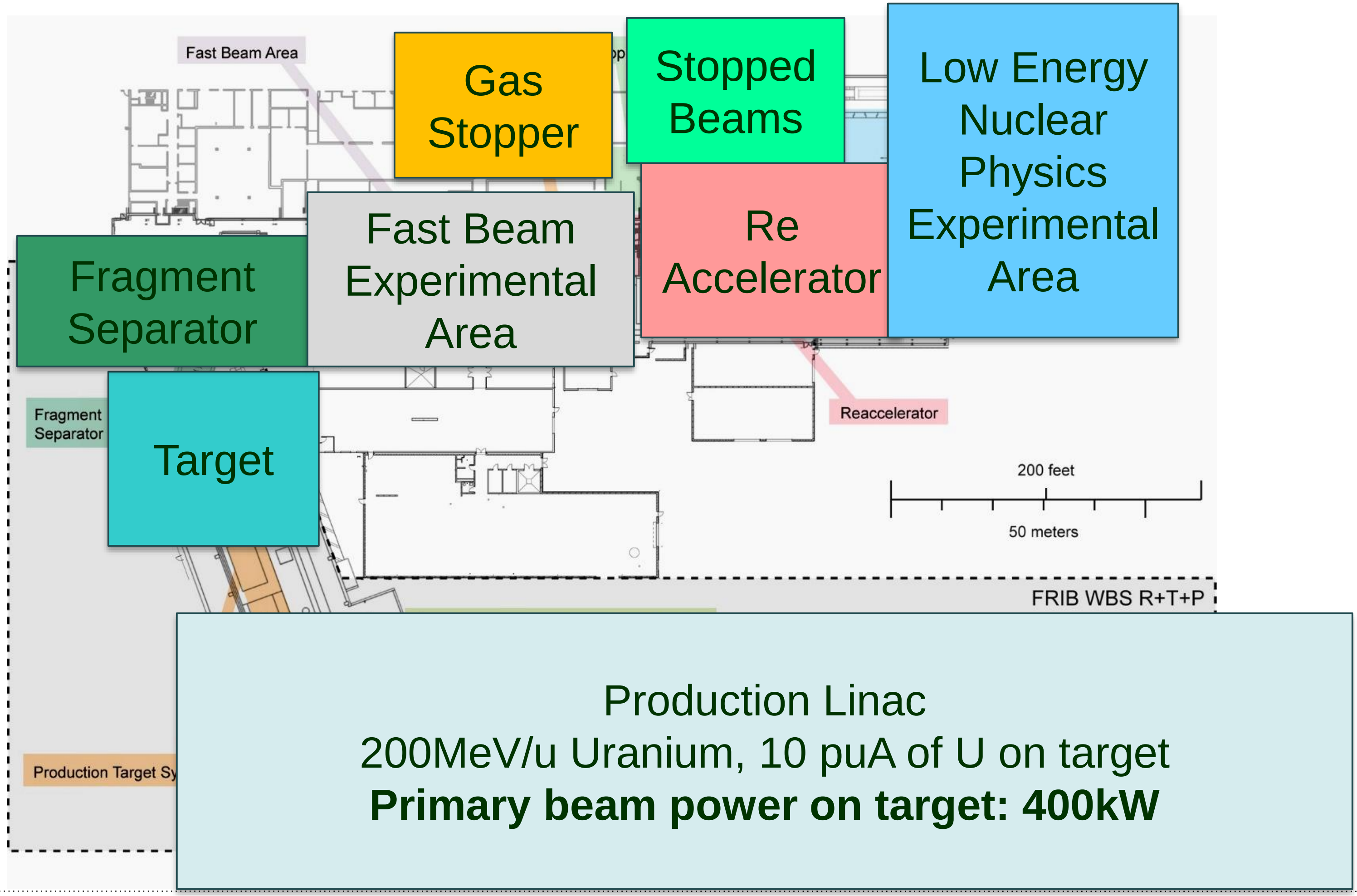
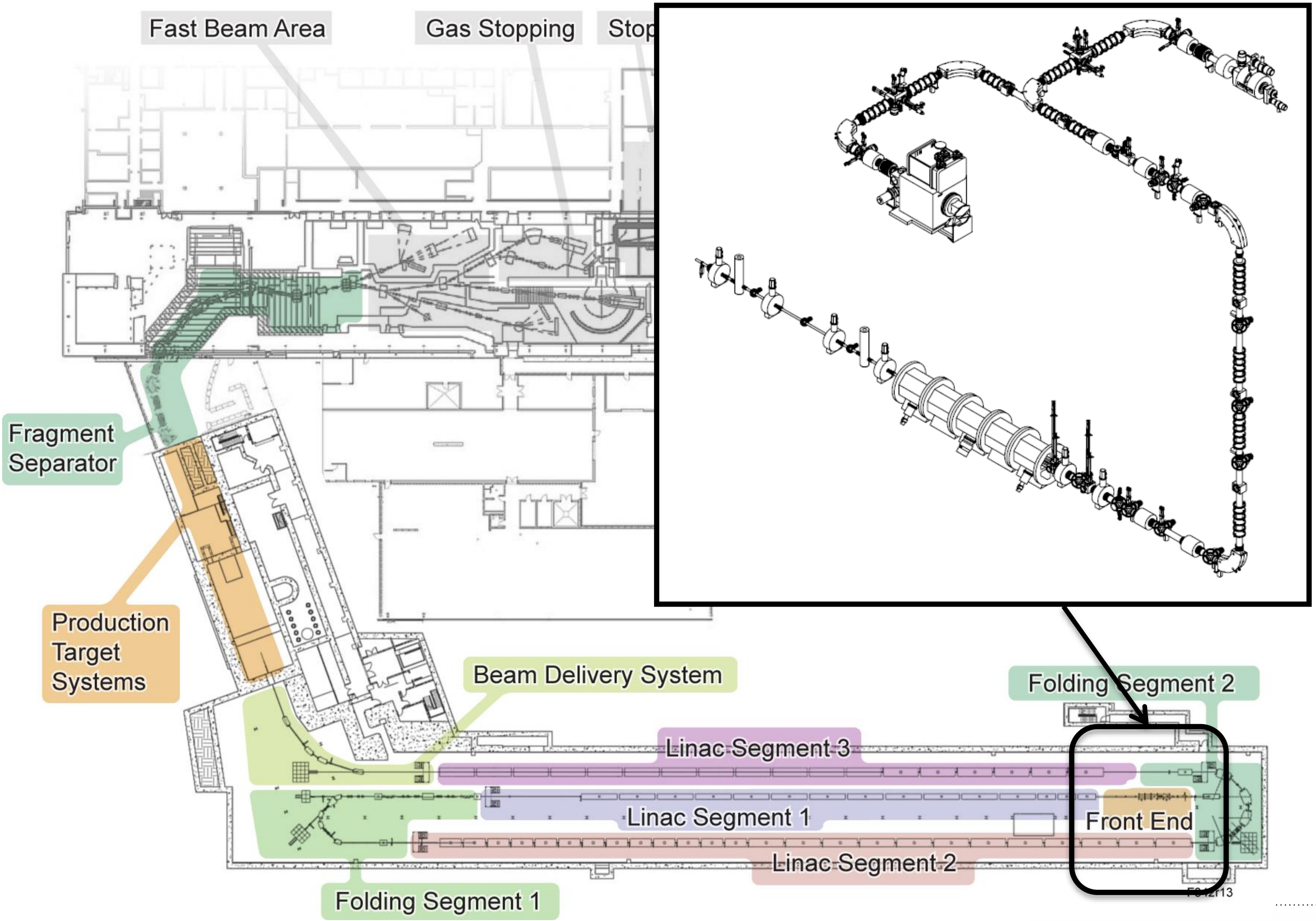
Rare isotope production at NSCL in the future: Facility for Rare Isotope Production at MSU



FRIB Front End



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Front End optics design is different from the regular lattice. It needs to do adapt to different beam parameters from the source and it has several matching points

Beam is very slow 12 keV/u (required injection energy for the RFQ)

Electrostatic focusing elements

Focusing is independent of ion/charge ratio for electrostatic elements

Possible in the low energy section, (because the ions are slow)

not a good choice in the high energy sections.

Force is independent of velocity

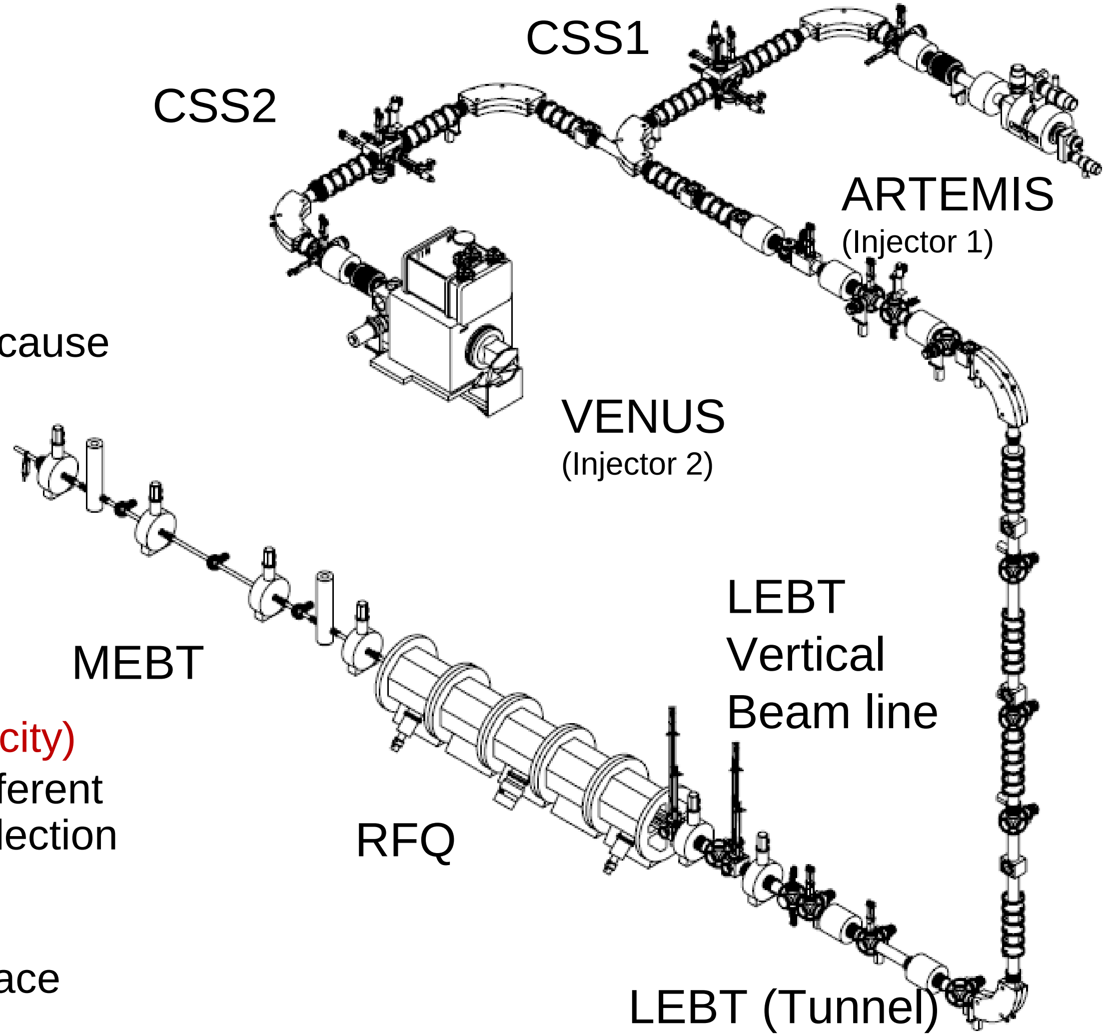
F=e*Q*E

Magnetic elements:

F=e*Q*v x B (force increases with velocity)

Magnetic elements will separate for different momenta, dipoles are in the charge selection section

Solenoids are used because they are convenient (round beam) and allow space charge compensation



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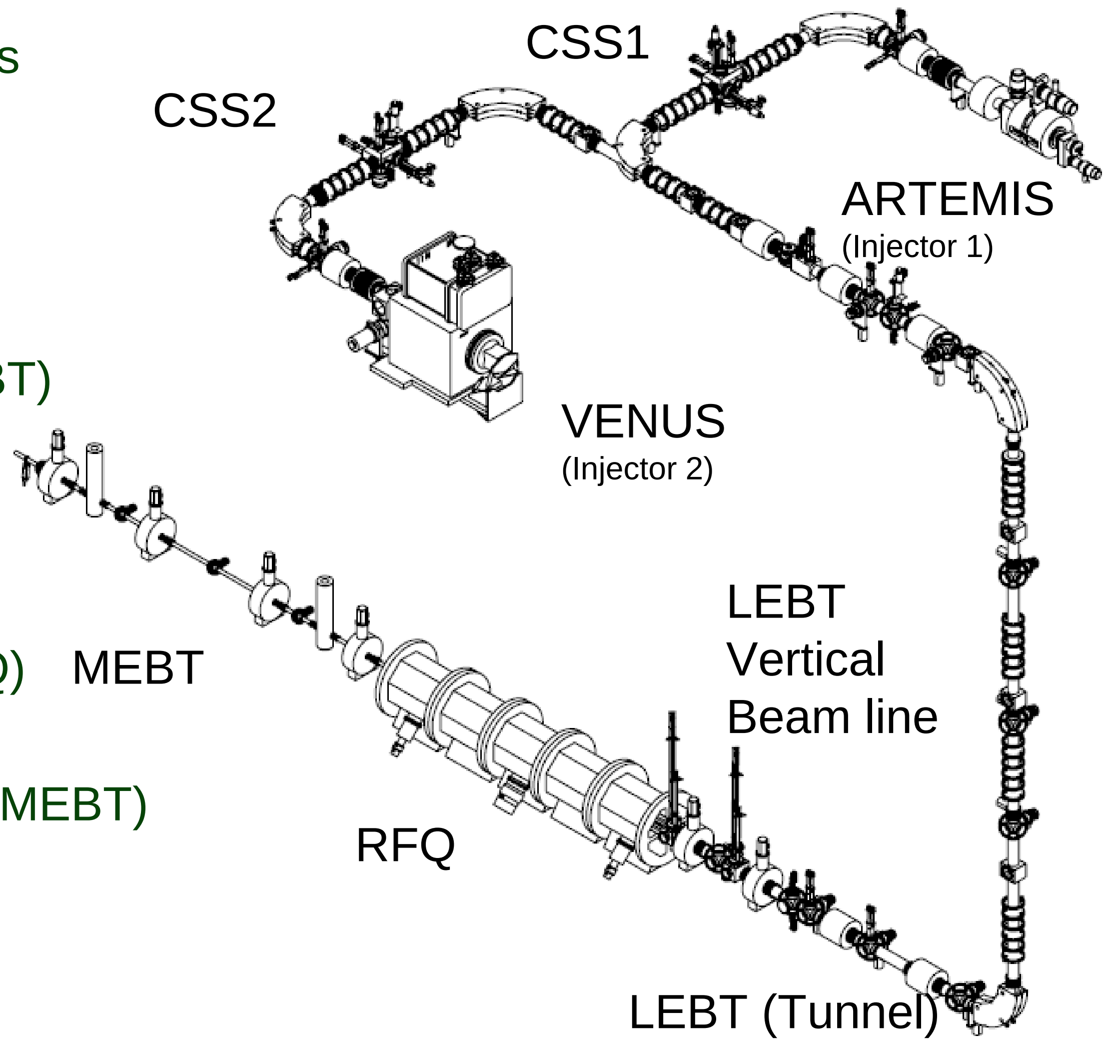
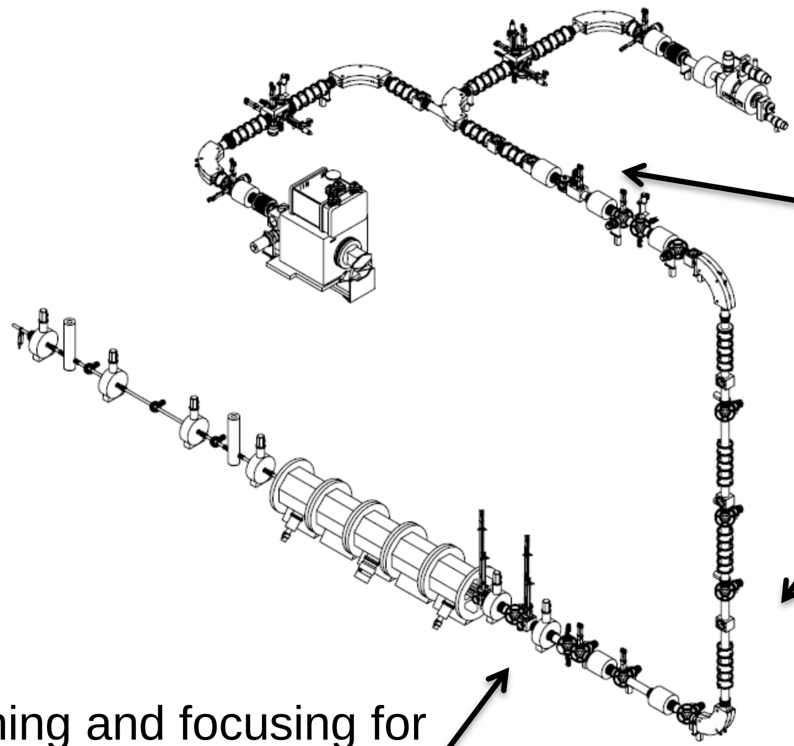
Front End Elements

- Two ECR sources on HV platforms
  - ARTEMIS - commissioning
  - VENUS – high performance
- Two charge selection systems (CSS1, CSS2)
- Low Energy Beam Transport (LEBT)
  - Chopper
  - Collimation system
  - Vertical transport line
  - Buncher and velocity equalizer
- RadioFrequencyQuadrupole (RFQ)
  - E=500 keV/u
- Medium Energy Beam Transport (MEBT)
  - Two bunchers, solenoids
- Instrumentation



Transport to the RFQ LEBT electrostatic (to separation of the charge states in the bends)



Transport to the RFQ LEBT electrostatic (to avoid separation of the charge states in the bends)

Bunching and focusing for injection in the RFQ

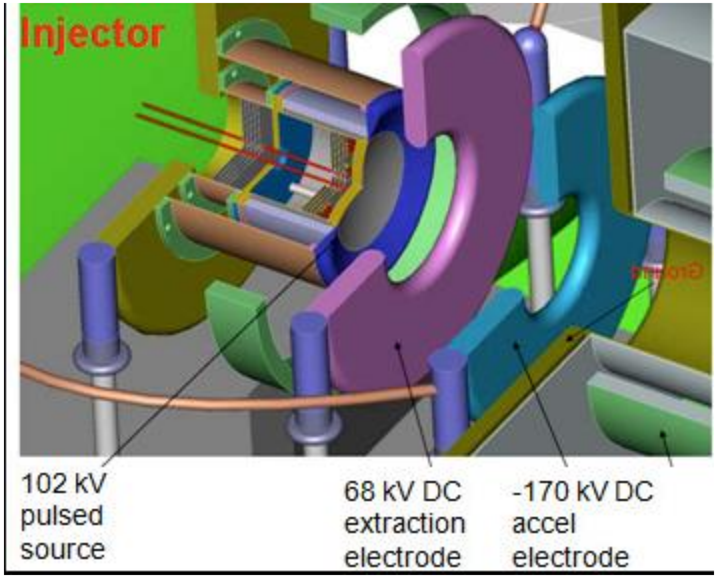
Plasma Physics

Selected Ion Source Types
(not covered in detail in the next couple of days)

Surface Ionization Source: Ideal Accelerator Ion Source

Basic Principle:

Metals with low ionization potential (e.g. alkali) can get ionized when they come in contact with a hot surface: For example Tungsten coated with aluminosilicate compound of a metal: $Li_2O*Al_2O_3*2SiO_2$



Single charged ions only

Advantages:

<u>the emitting surface is fixed, initial conditions are defined</u>

Ion temperature is very low (<.2eV)

(Surface ion source are heated to 1200-2000C, 1eV = 11600K)

<u>Emittance of the ion beam produced is small</u>

Li Ion source at LBNL for the high density physics experiments

Injector for diagnostic beams for fusion reactors

Surface Ionization Source: Ideal Accelerator Ion Source

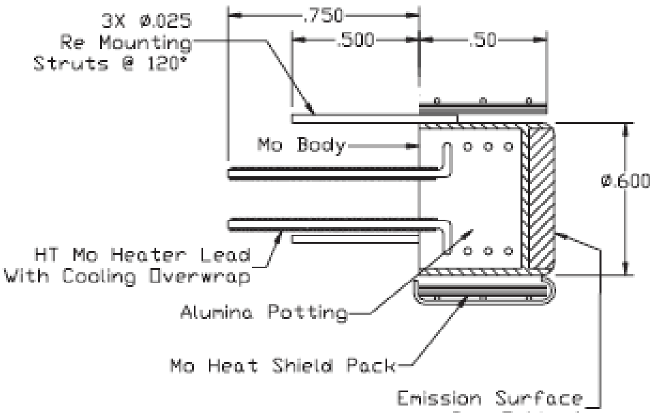


Figure 1
Model 101142 Ø.600 Ion Source
(Includes Shield Assembly)

Commercial available Surface Ion Source

I typical pA to nA

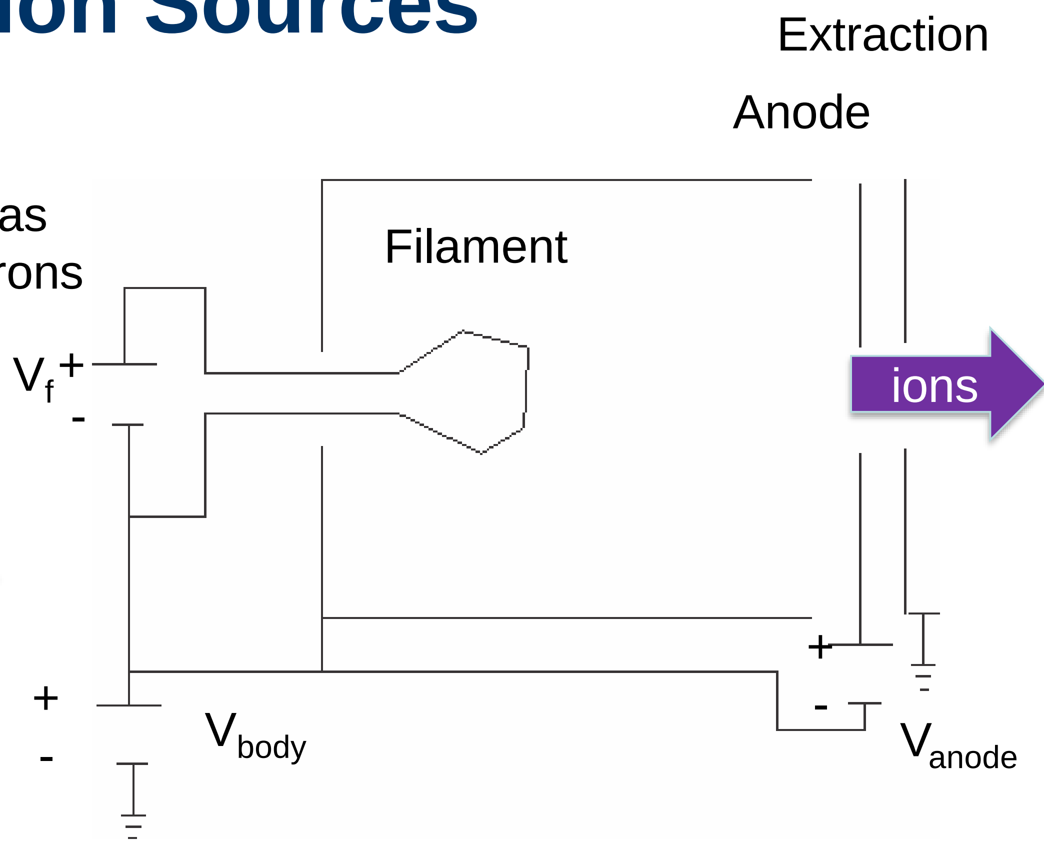
Typically used as external source for testing or charge breeding experiments

Disadvantage:
Current density limited to <1.5mA/cm^2
Large emitters (>10cm diameter) are needed for high current (HIF 100mA)
Life time is limited, amount of charge is given by the coating
Limited to alkali and alkaline metals

Parts of a simple Ion Sources

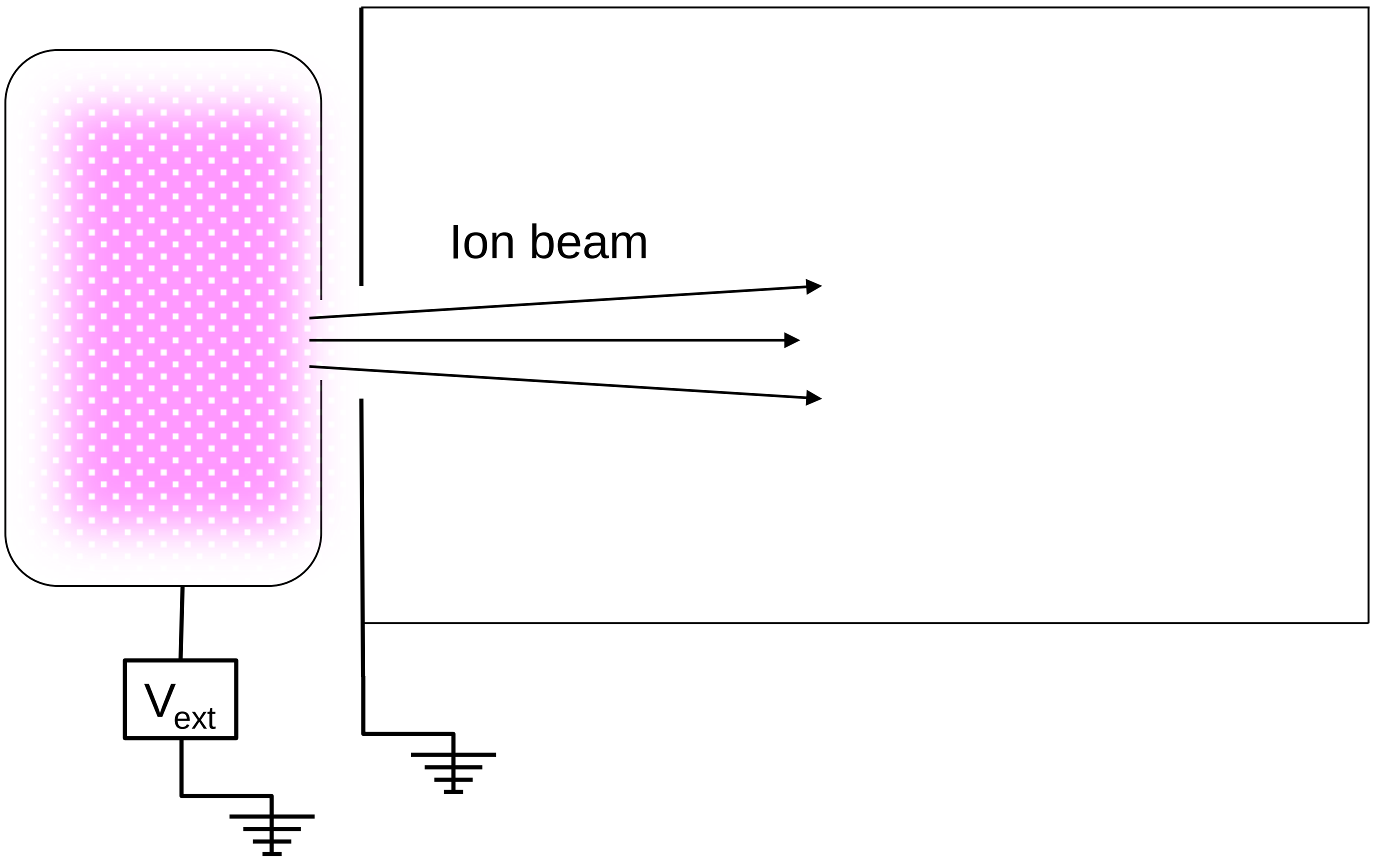
Ion source input:
free electrons (E> Ionization Potential)=discharge voltage, neutral gas
Means of providing energy to the electrons
Keep ions cold !

- Cathode +Anode
- Filament
- RF discharge
- Microwave discharge

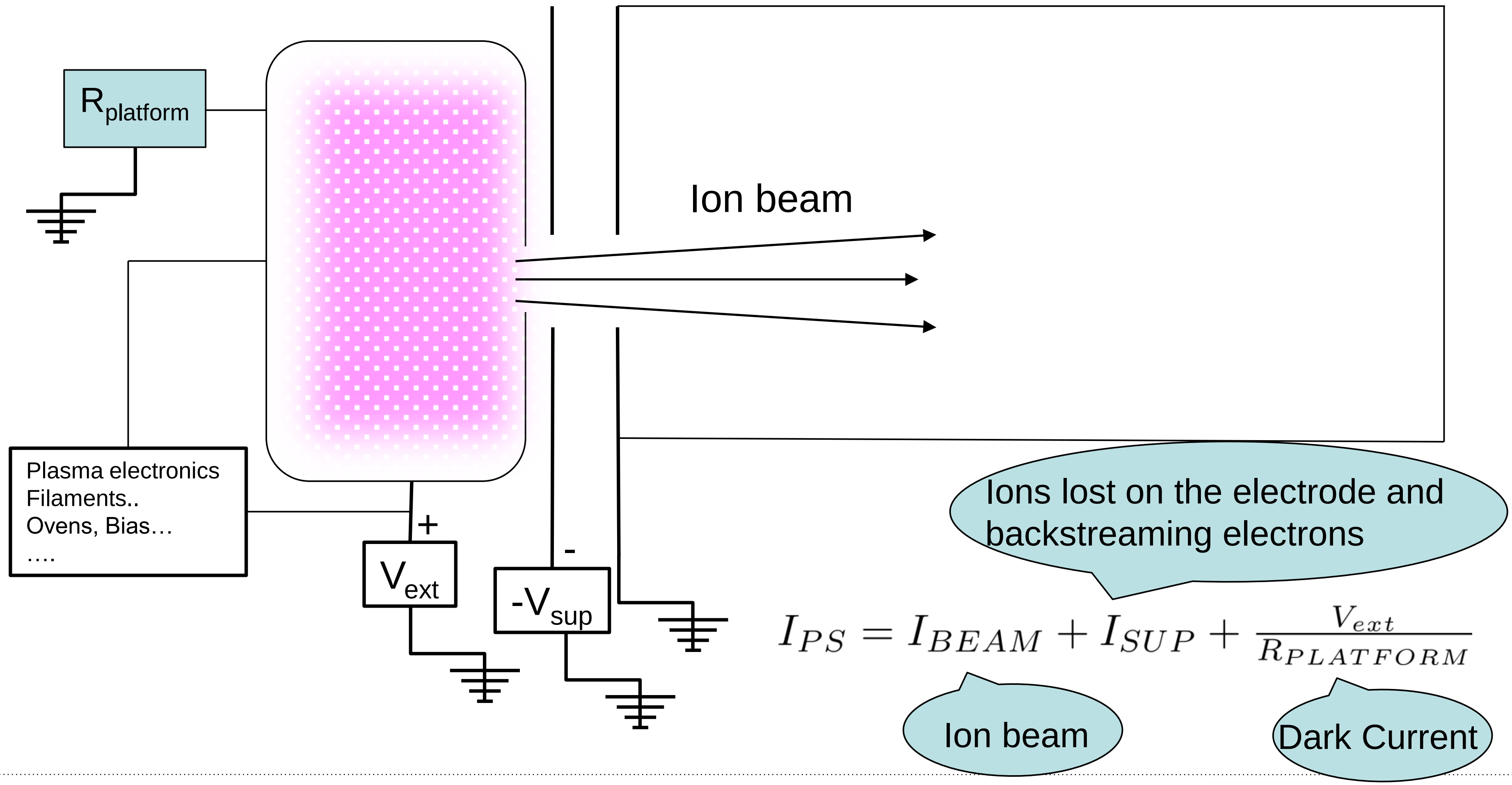


Ion source has no confinement, ion confinement time is short, only singly charged ions – confinement time is very short, not efficient, but ion temperature low (good emittance)
Require a high gas pressure to run, many different types developed

Basic elements of an ion source



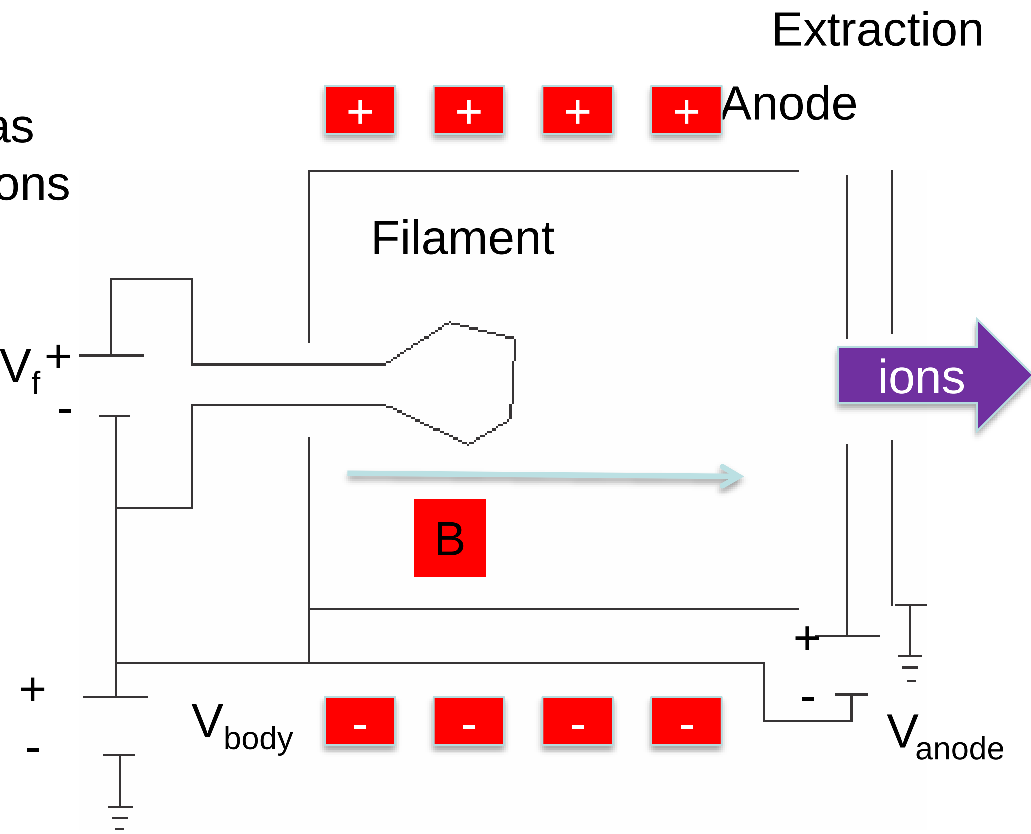
Basic elements of an ion source



Add confinement with external B-Field

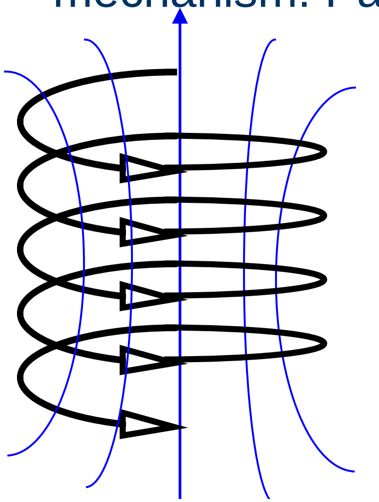
Ion source input:
free electrons (E> Ionization Potential)=discharge voltage, neutral gas
Means of providing energy to the electrons
Keep ions cold !

- Cathode +Anode
- Filament
- RF discharge
- Microwave discharge

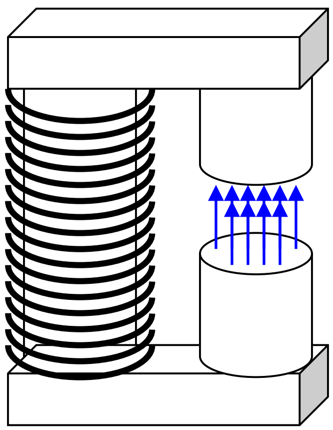


Confining charged particles

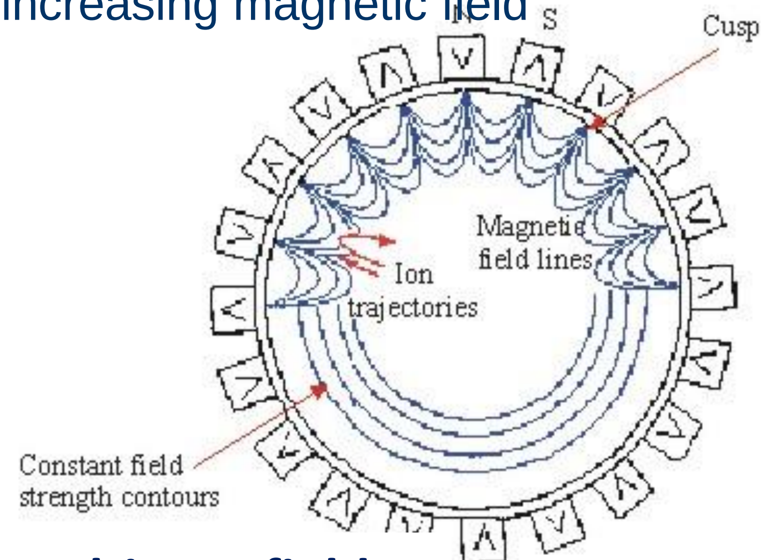
- In the direction of the fields there is no force, transverse the particles are bend into the circular motion $F = q\vec{v} \times \vec{B}$
- Helical motion increases the time the electron send in the discharge chamber- field lines can only be crossed through collisions – wall losses are reduced
- Add strongly increasing magnetic field as the confinement mechanism: Particles get reflected by an increasing magnetic field



Solenoidal field



Dipole field



Multicusp field

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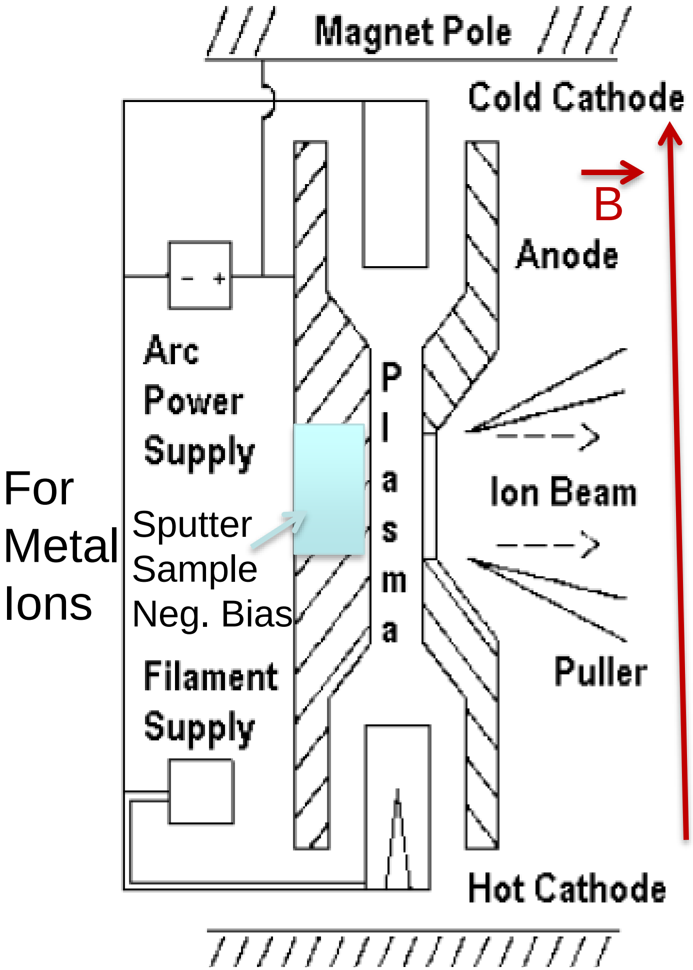
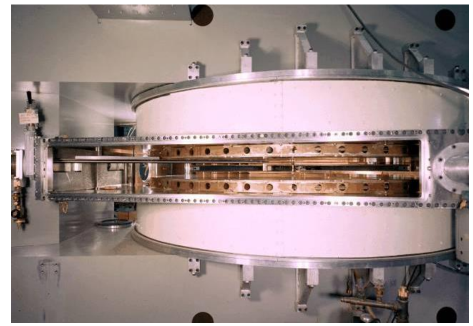
Important Ion Source Type: PIG Source
Can produce some highly charged ions



F.M. Penning, Physica, 4, 71, (1937)

Internal Ion source for early cyclotrons



B $$\frac{E}{M} = \left(\frac{Q}{M}\right)^2 \cdot K$$

K ~ $B^2 \cdot R^2$

Cyclotron magnetic Field adds confinement

Performance is determined by
Product of n_e* τ_i
Confinement time : $\tau_i = 10 * r^2 * B/T_e$
(diffusion across B field)

r=0.3cm, B=3kG, Te=10eV, τ_i~10 μsec

Source lifetime is an issue, need different source to get reliable high charge states

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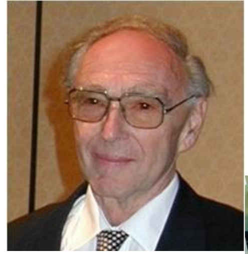
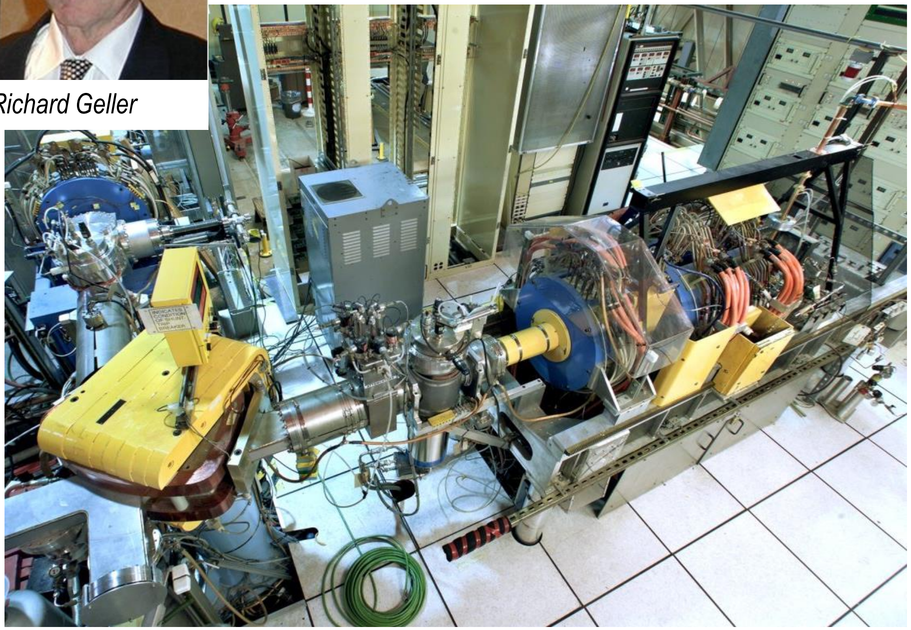
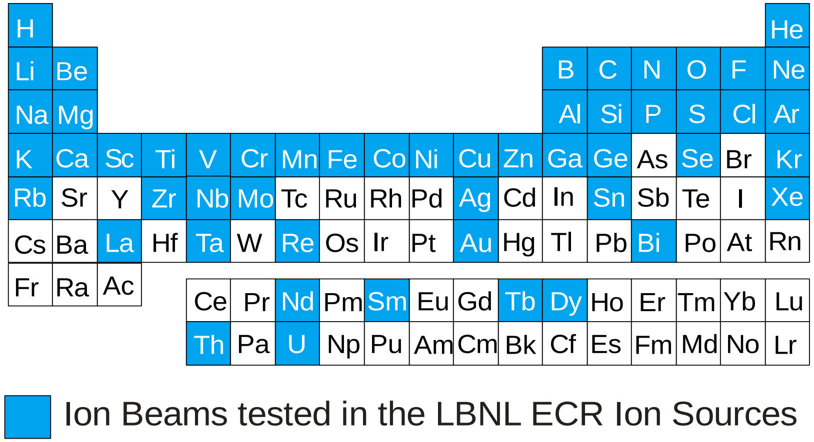
ECR Ion Sources largely replaced PIG sources for cyclotrons



Richard Geller

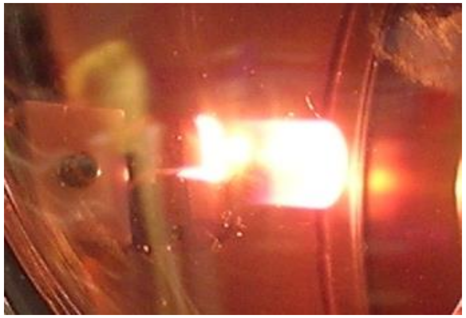




- Any element can be ionized provided it can be vaporized

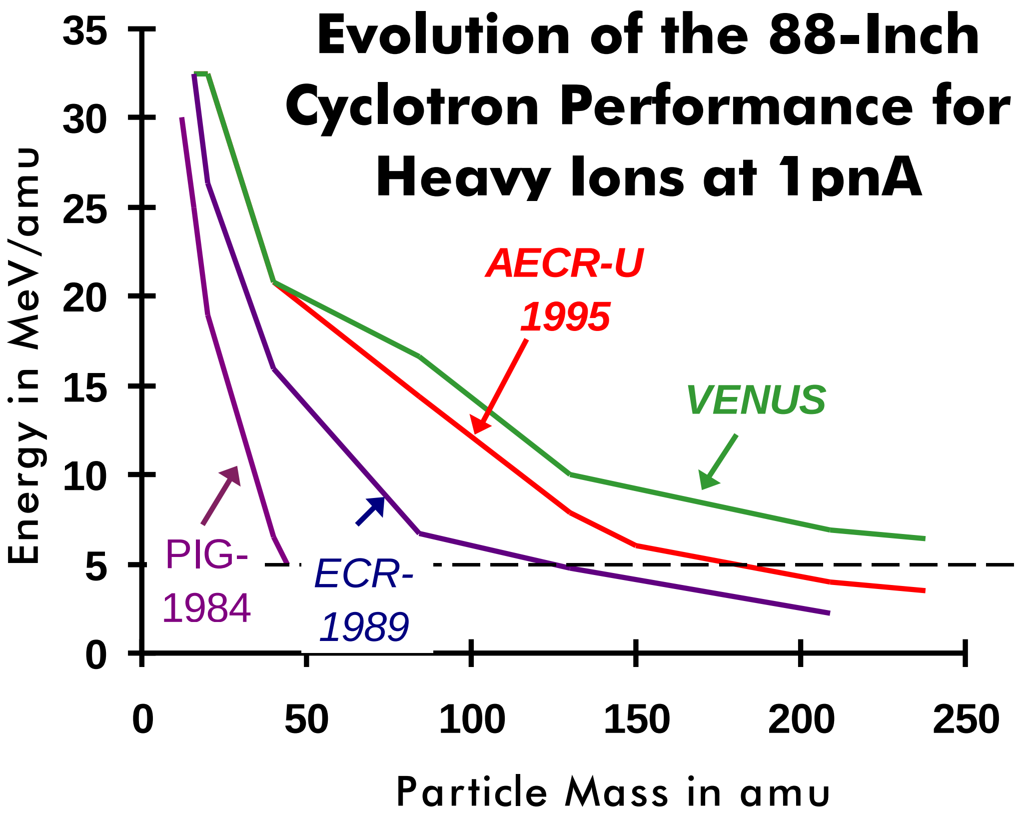
AECR-U Injector, 88-Inch Cyclotron LBNL

- Runs 24 hours/day,
  7 days/ week with minimum intervention
- Minimum maintenance (typically not required for years)
- Good beam stability and quality
- High intensities (μA to mA of beams are available)
- Can produce ion beams from every element



VENUS oven at the required uranium temperature of 2100 C

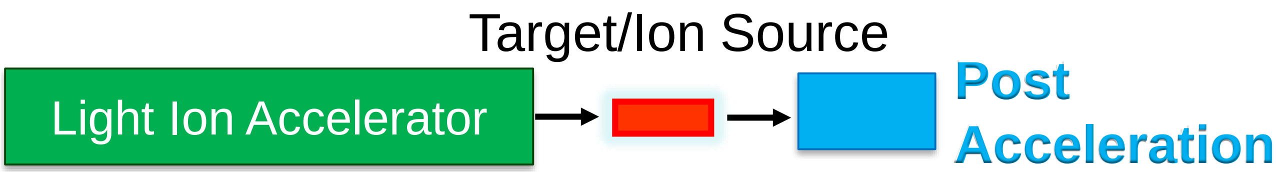
Impact of ECR ions on accelerators



Specialized Sources for Rare Isotope Facilities

ISOL – Isotope Separator On-line

Light Ion-induced "Spallation" Or Fission Of Heavy Targets



- Isotopes must diffuse from hot targets and effuse to an ion source
- Typical beams ~100-1000 MeV protons; typical targets Ta & UC
- Photofission using high power electron linac

- Very intense beams of many elements (e.g. noble gases and alkalis)
- Weak beams of refractory and chemically active elements

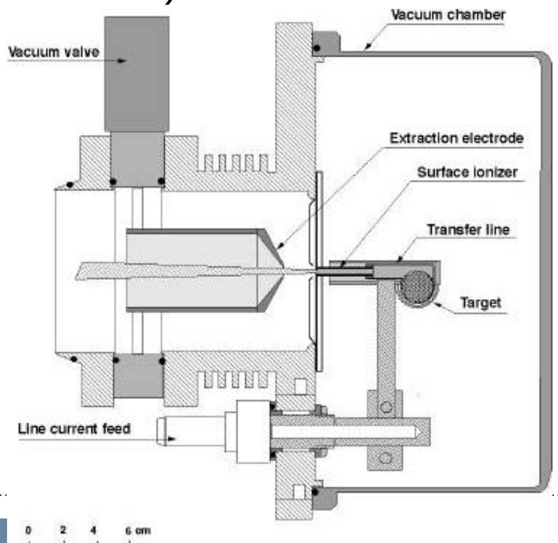
Several facilities around the world:
Rex-Isolde, GANIL-Spiral, ISAC, EXYPT, SPES, EURISOL …

Ion Sources for Rare Isotope (radioactive ion beam) acceleration

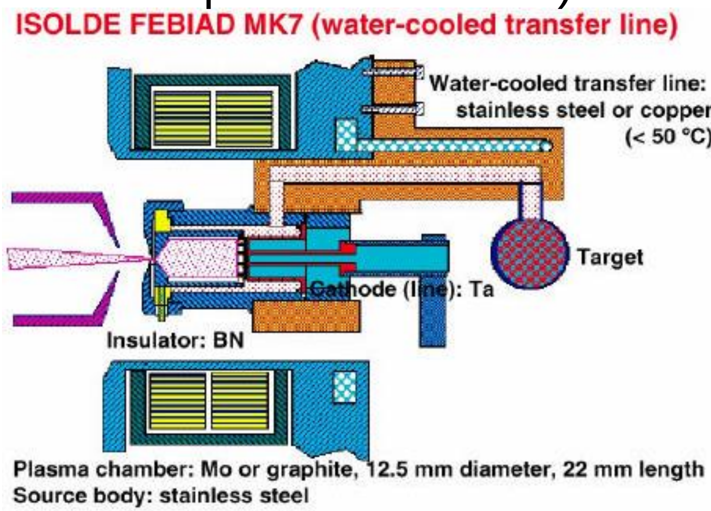
Specialist field: ISOL facilities

- The ion source is often combined with the target and optimized for each ion species, Issues:
  - Release time of the ions from the target
  - Chemistry of the ion in the target and the ion source
  - The impurity of the beam

Surface Ionization Source (Alkali metals)



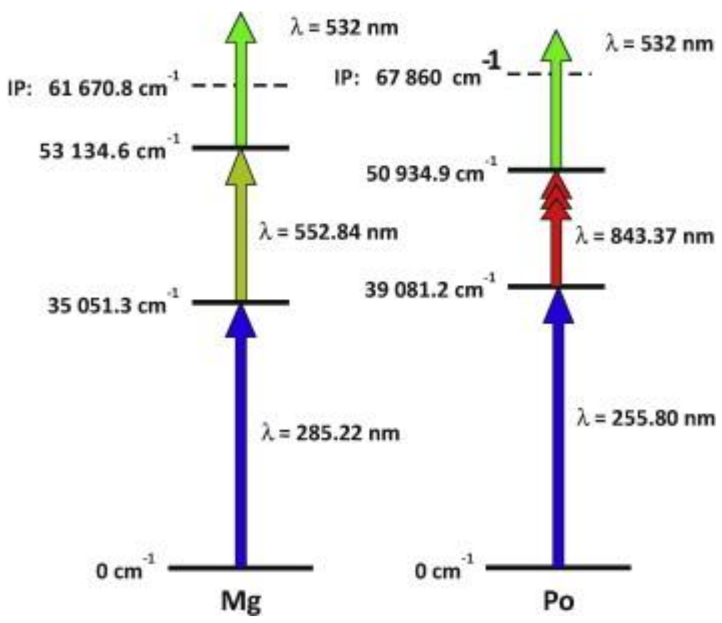
FEBIAD (plasma with heated plasma chamber)



ECRIS (gases)

Resonant Laser ion sources – example for selective photoionization

http://rilis.web.cern.ch/



Resonance Laser Ion Source
-> element selective
-> isobar free beams

Laser must be matched to the element

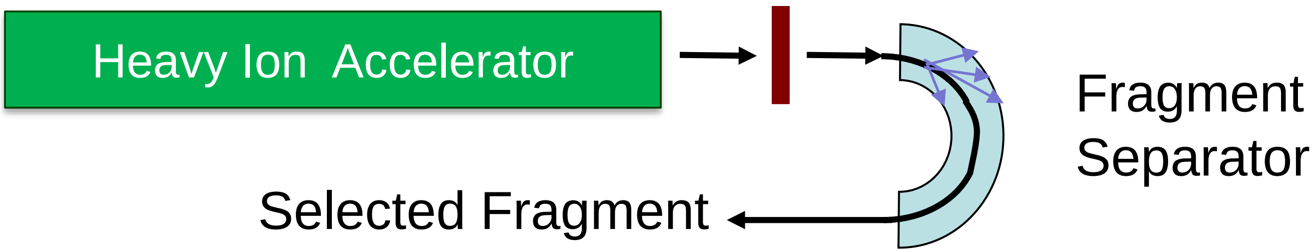
High repetition rate is required to ensure ionization as the rare isotope in the transfer tube

2-3 steps for ionization to ensure selectivity

First application of the Laser Ion Source and Trap (LIST) for on-line experiments at ISOLDE
D A Fink, et. al, *Nucl. Instr. and Meth. in Phys. Res. B*, DOI: http://dx.doi.org/10.1016/j.nimb.2013.06.039(link is external) (2013)

In-Flight Heavy-Ion Fragmentation or Fission on a Light Target

Rare Isotopes are Separated Physically; No Chemical Dependence



Less chemistry involved; beams at high energy

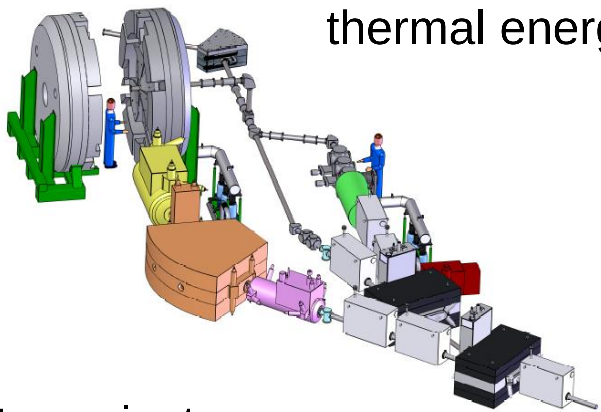
- Fragments of the beam are kinematically forward directed at ~beam velocity
- Typical heavy ion beams are ^{18}O-^{238}U at 200-2000 MeV/u; typical targets Be or C

- Separated **beams of any species** including refractory and chemically active elements and isotopes with very short half-lives, even isomers
- Needs gas catcher or solid stopper for post acceleration, ion cooler
- Charge breeder ion sources for reacceleration

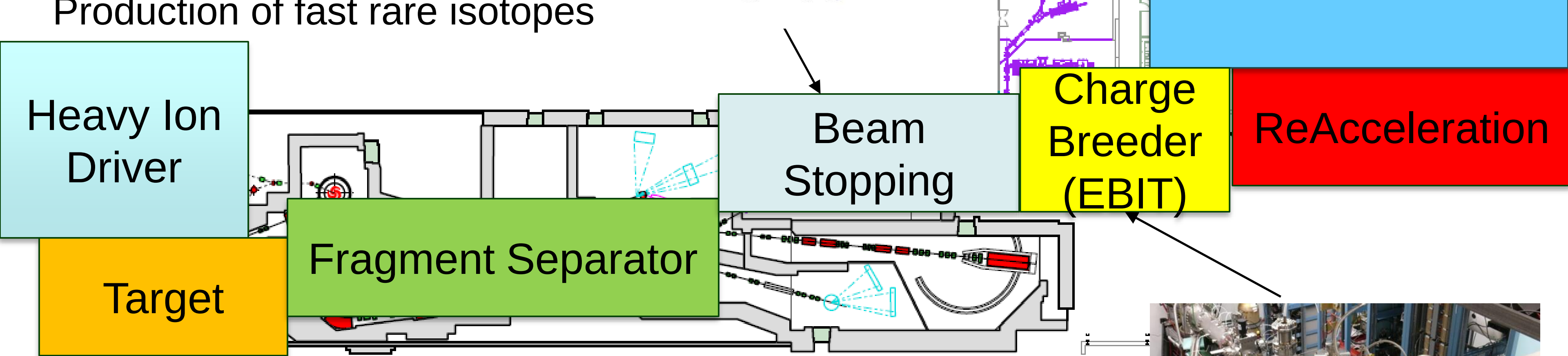
CCF-MSU, RIKEN, GANIL, FAIR, FRIB..

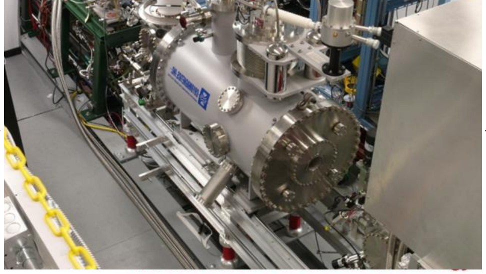
Fragmentation Facility Ion sources

Gas Stoppers to slow down ions to thermal energies



Production of fast rare isotopes





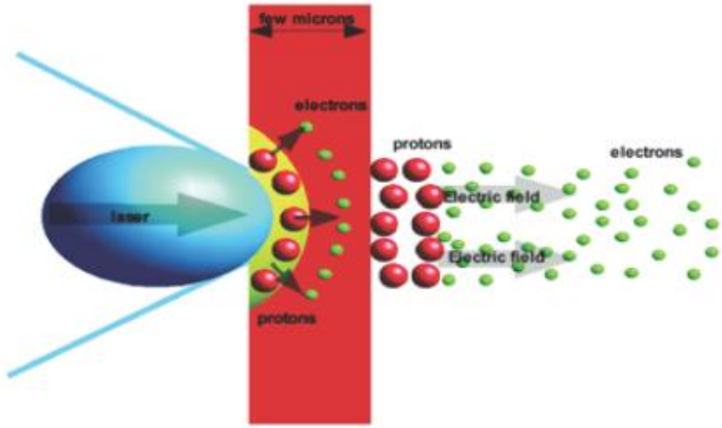
More on Thursday

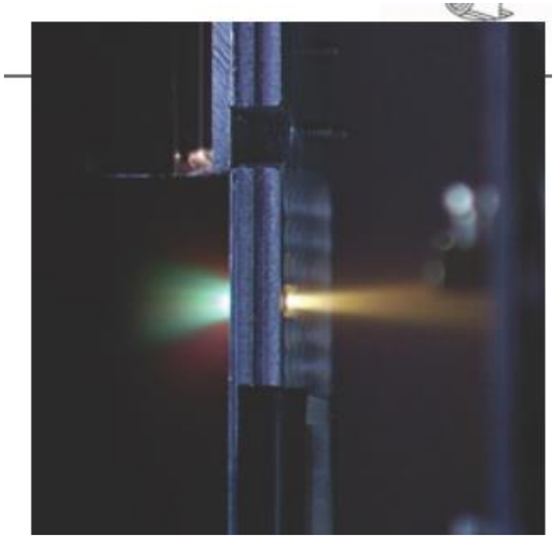
BERKELEY LAB

Laser Plasma Accelerator
Ion source and accelerator combined

Laser Plasma Ion Accelerator

- Accelerator and ion source are combined!
- A high power laser (10^{20} to 10^{22}/cm^2) is focused on a thin foil target or gas jet, the ions are accelerated through charge separation (several mechanism, e.g Target Normal Sheath Acceleration)
- Ions are formed in the expanding plasma and accelerated to 10s to 100s of MeV energies directly





BERKELEY LAB

Massachusetts Institute of Technology

Laser Plasma Ion Accelerator

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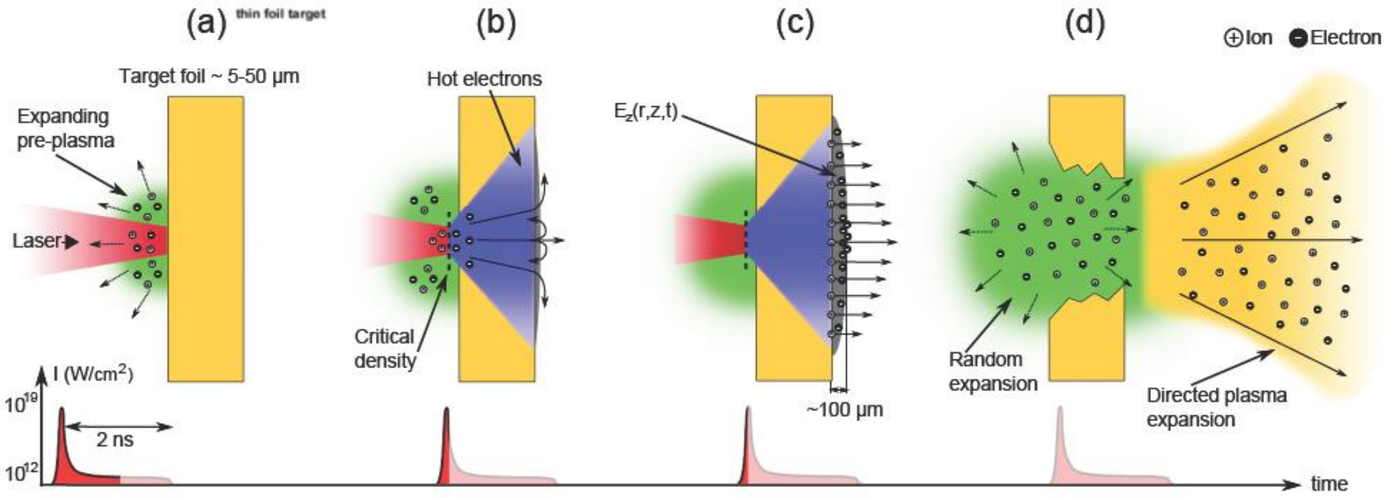

Berkeley Lab Laser Accelerator (BELLA) - Center

- Currently Electron Laser Acceleration research facility
- New initiative at LBNL to build an laser ion accelerator facility