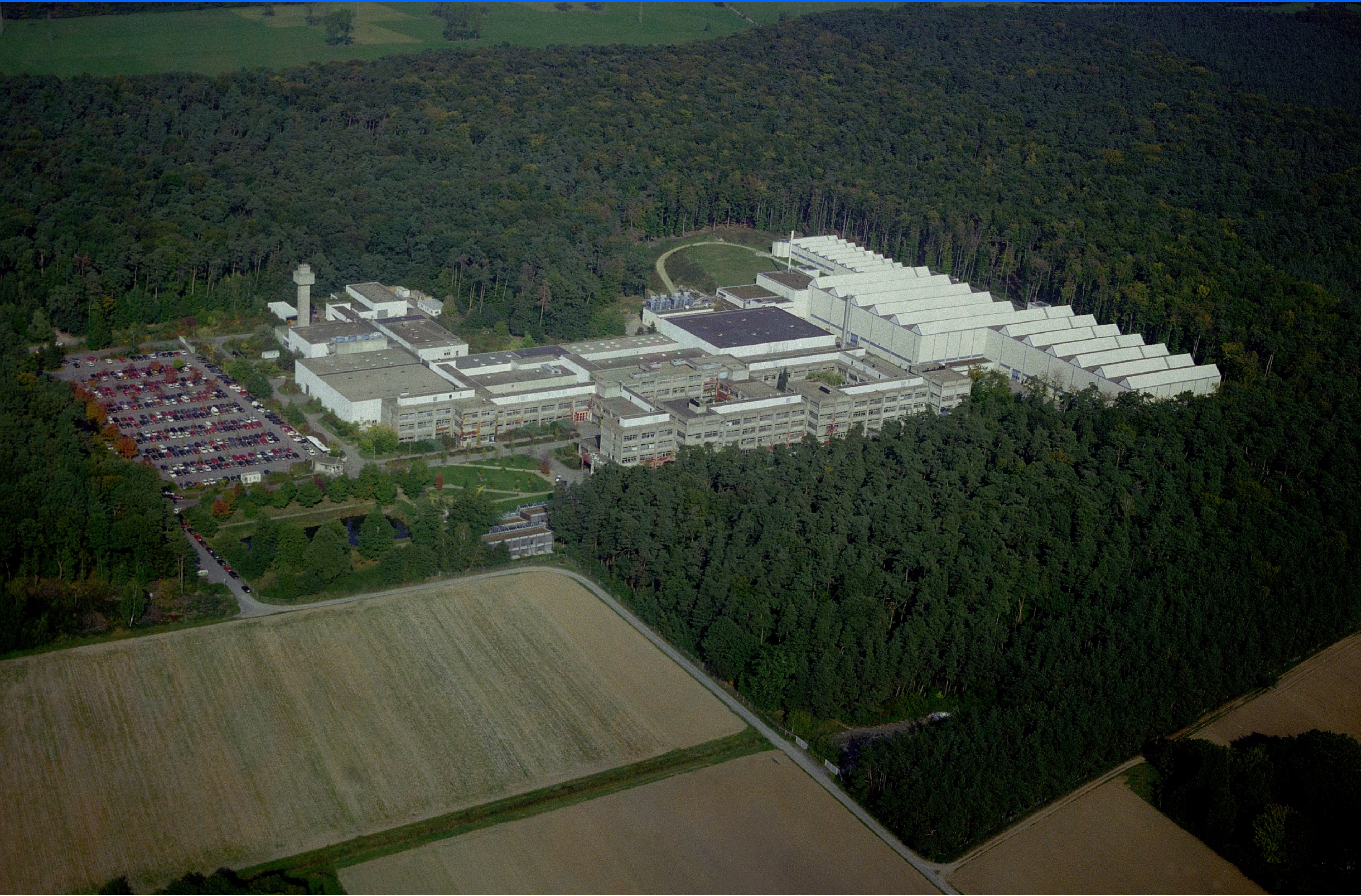
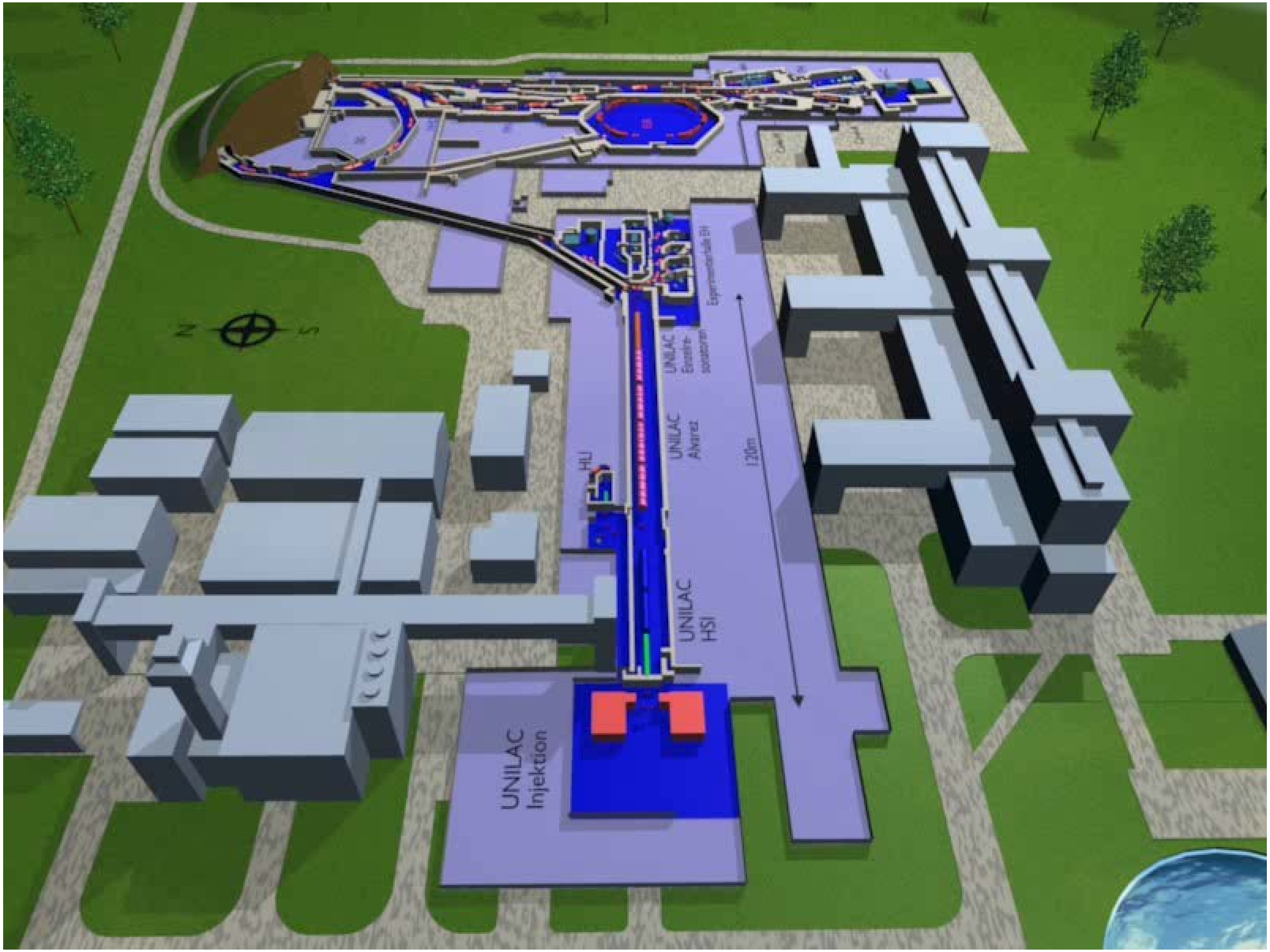
GSI Helmholtz Centre for Heavy Ion Research



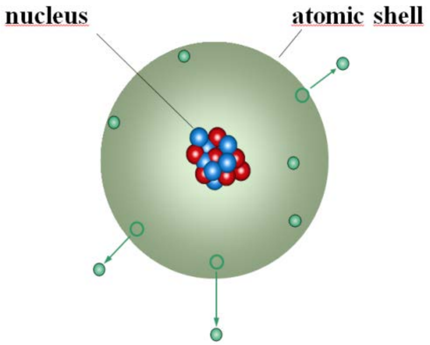
Accelerator facility

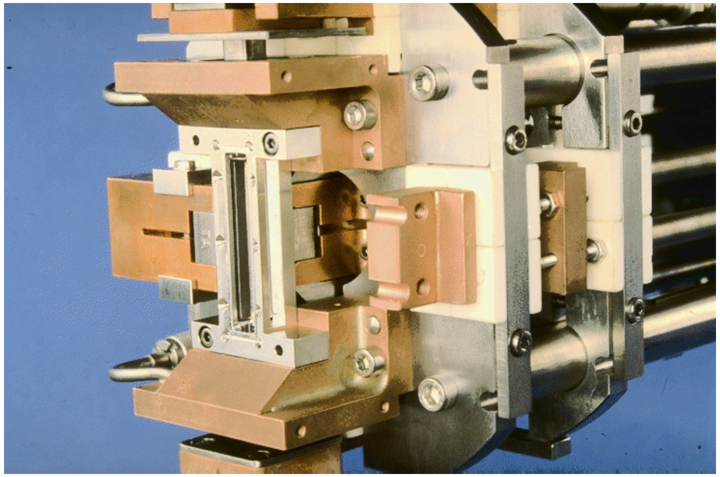


Ion source

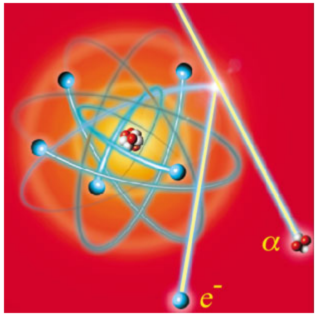
To create ions one needs:

1. electrons
2. noble gases
3. element material (e.g. Fe, Sn, Pb, U)

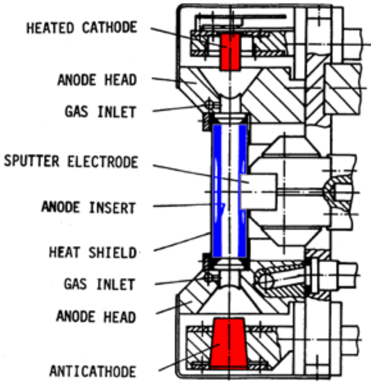




Penning ion source



Ionization



Discharge voltage	0.3...1.3 kV
Discharge current	5...20 A
Magnetic flux	0,2...2 T
Filament heating	0.5 kW
Power consumption	up to 20 kW
T_e in the order of	1 eV
Current density	10 mA/cm^2

Ionization for positive ions

collisions with **electrons**

Impact Ionization — Three-Body-Recombination (TBR)

$$A^{Z+} + e \leftrightarrow A^{(Z+1)+} + e' + e''$$

A^{Z+}: Atom of species A with charge state Z

e' : electron changed energy

Impact excitation — Impact disexcitation

$$A^{Z+} + e \leftrightarrow \left(A^{Z+}\right)^{*} + e' \Rightarrow$$

Non-radiative transition

collisions with **photons**

Photo ionization — Radiative Recombination (RR)

$$A^{Z+} + h\upsilon \leftrightarrow A^{(Z+1)+} + e \Rightarrow$$

Line spectrum

Excitation — Spontaneous emission

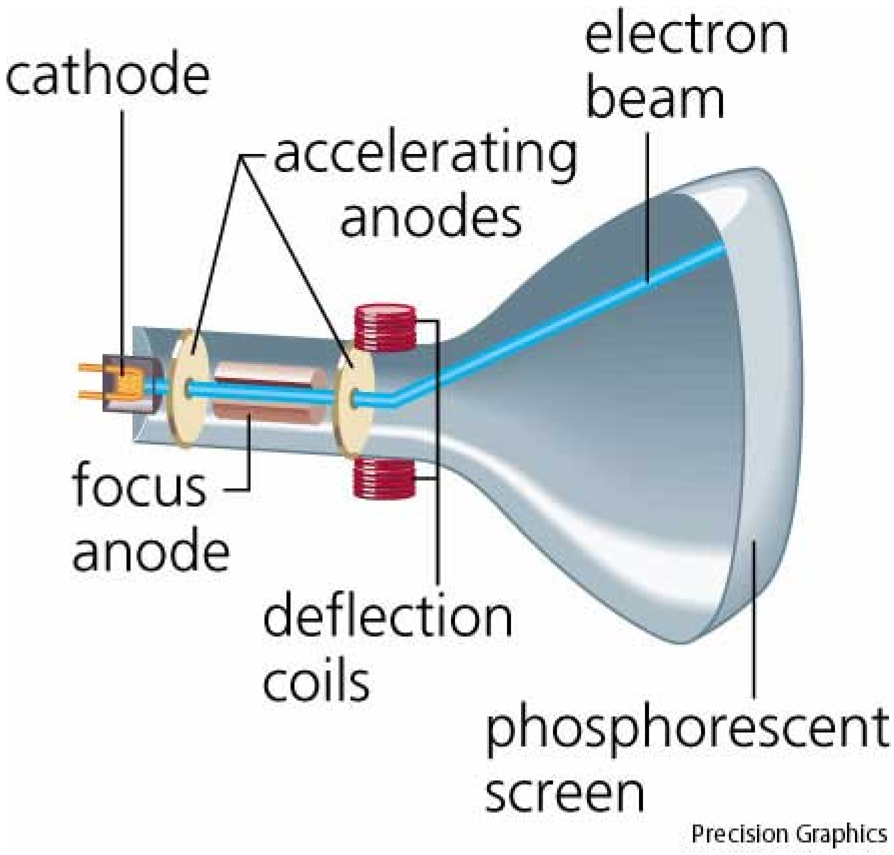
$$A^{Z+} + h\upsilon \leftrightarrow \left(A^{Z+}\right)^{*}$$

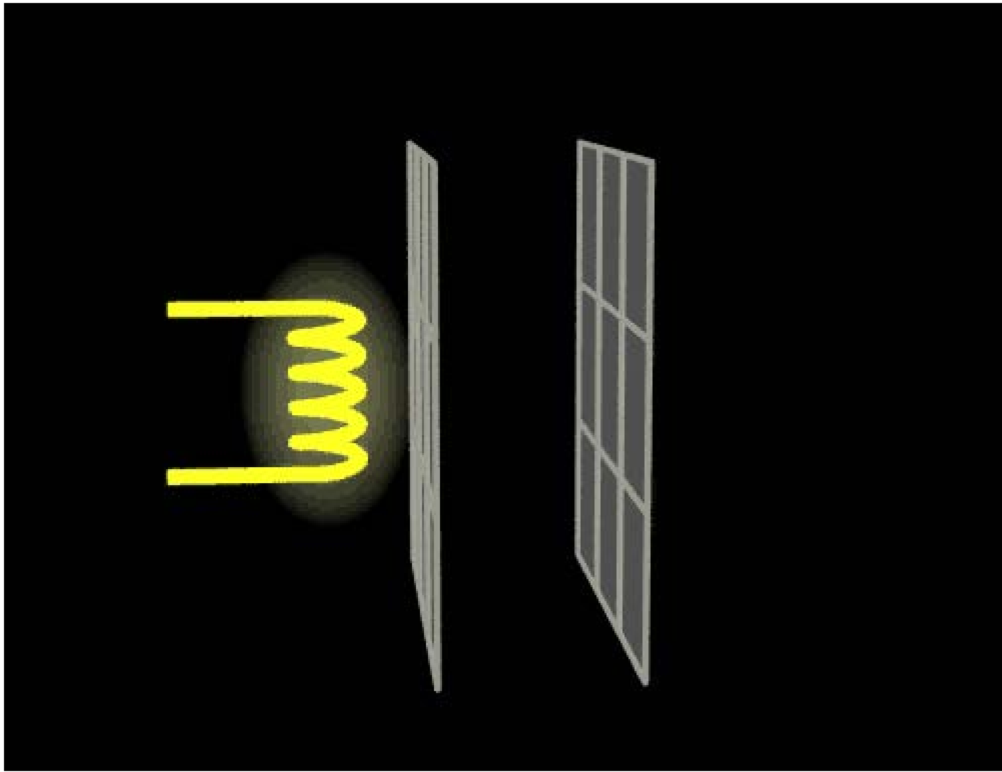
Photo absorption — Bremsstrahlung

$$A^{Z+} + h\upsilon + e \leftrightarrow A^{Z+} + e' \Rightarrow$$

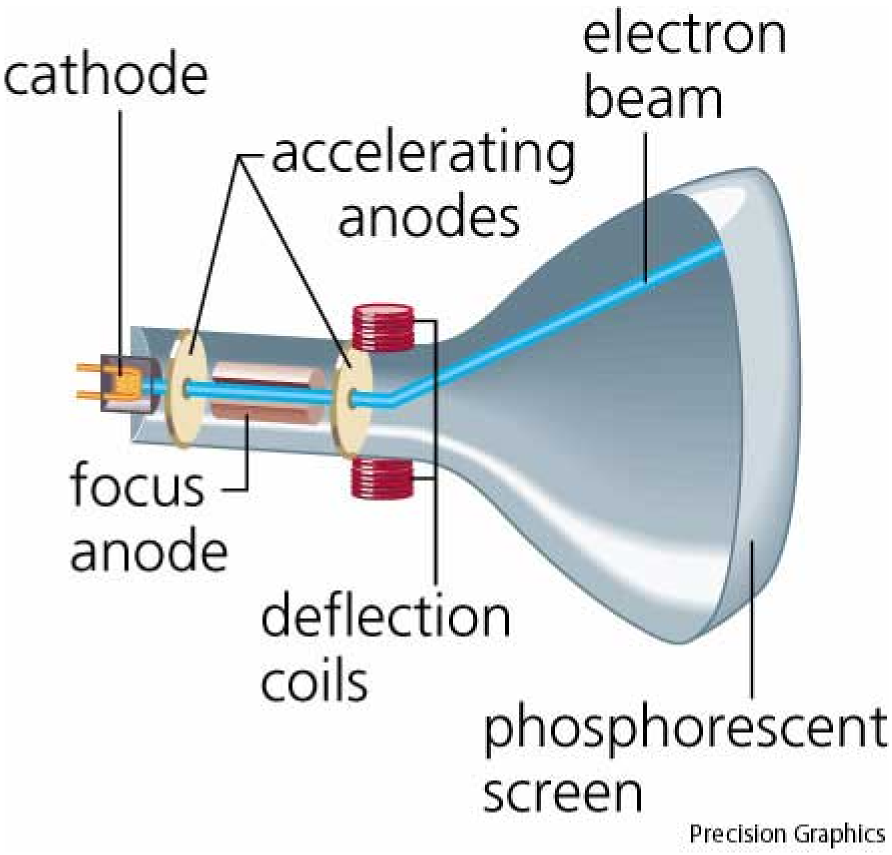
Continuous spectrum

Cathode Ray Tube

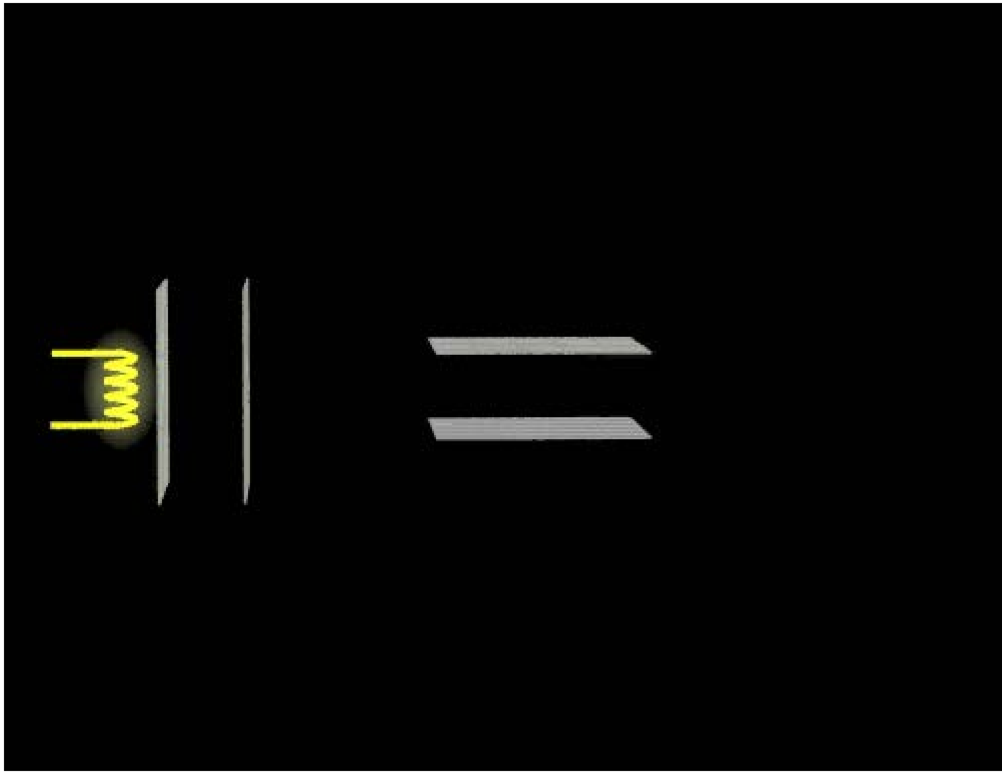




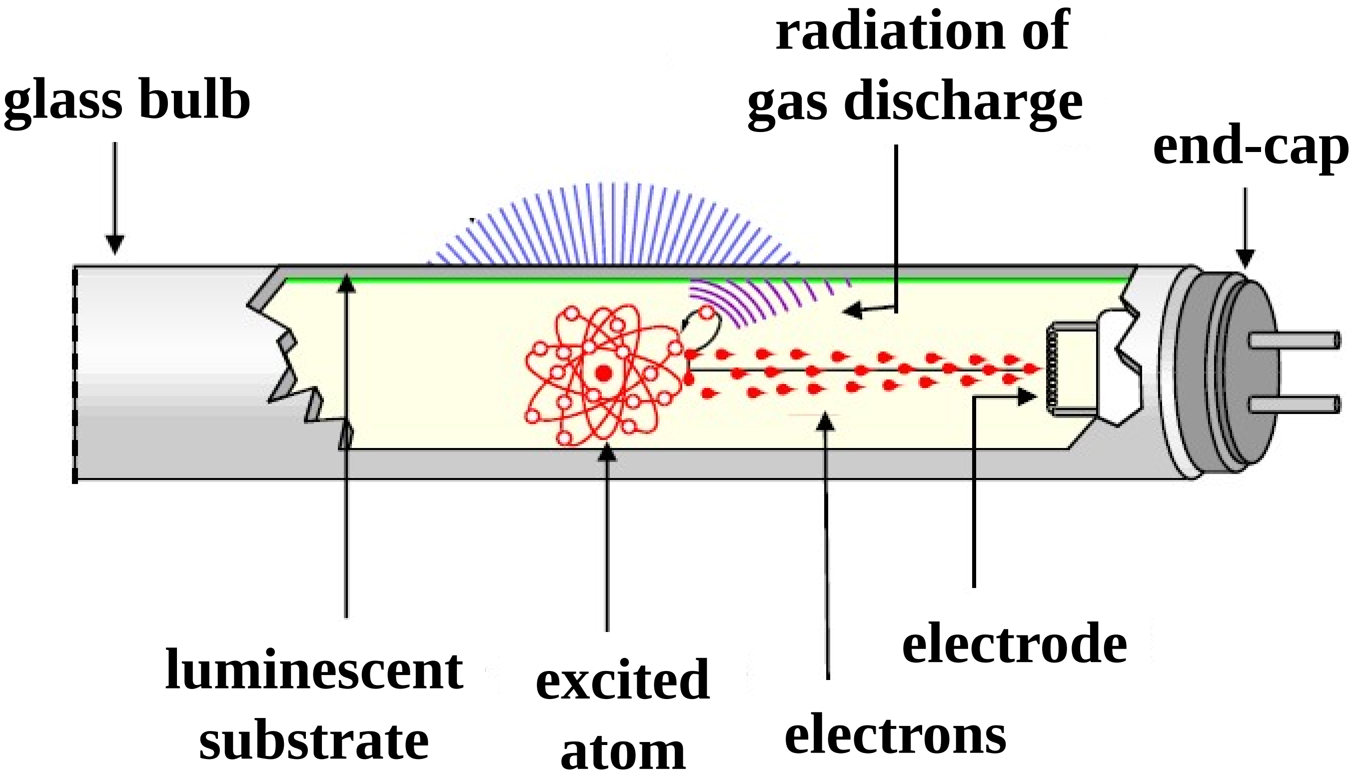
Cathode Ray Tube

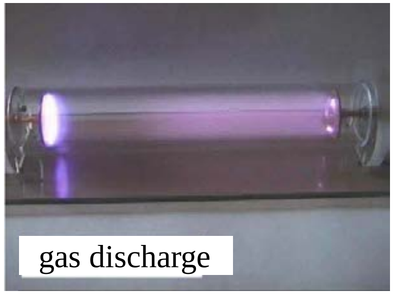


Precision Graphics



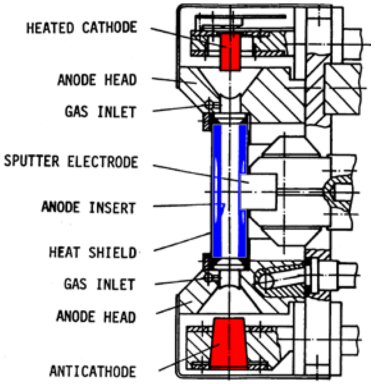
How to create ions?

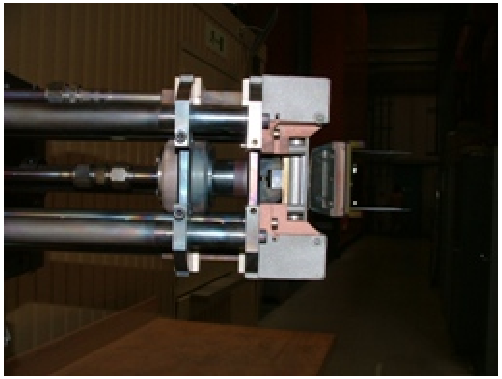




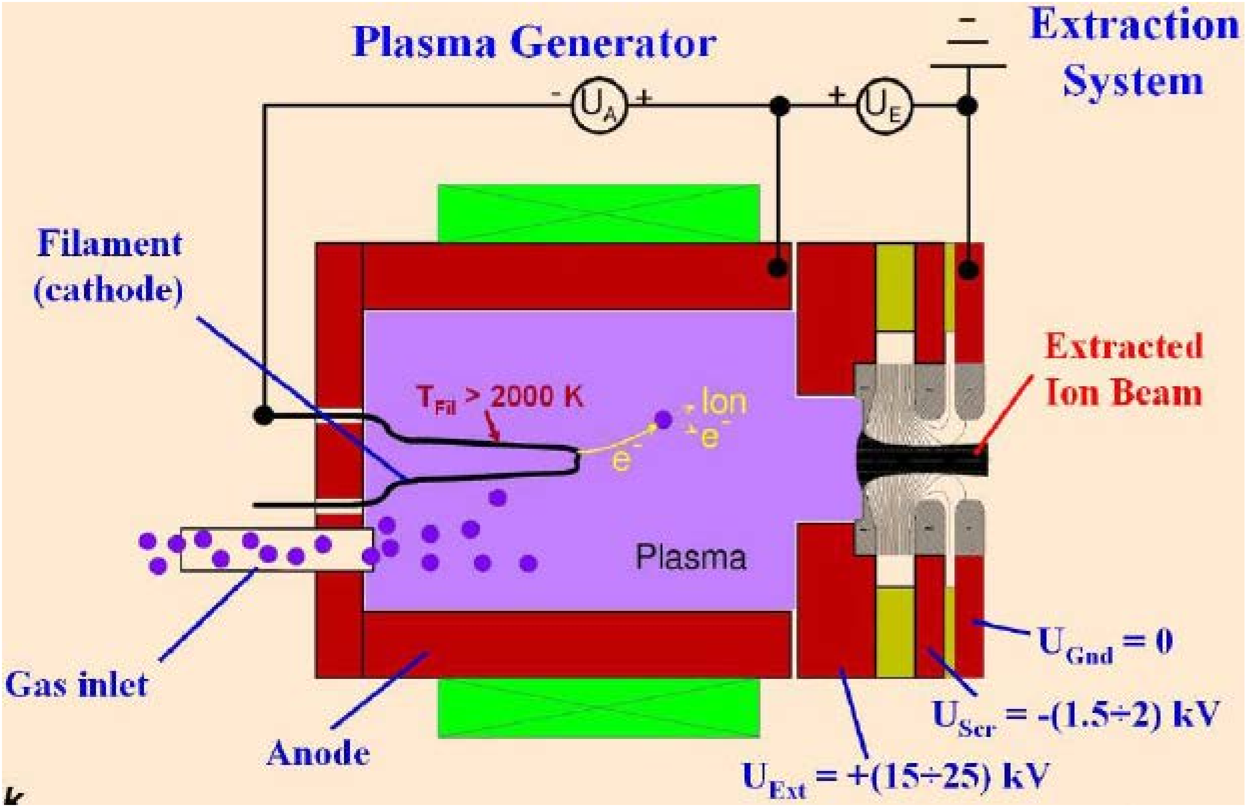
To create ions one needs:

1. electrons
2. noble gases
3. element material (e.g. Fe, Sn, Pb, U)





Volume ion source with filament



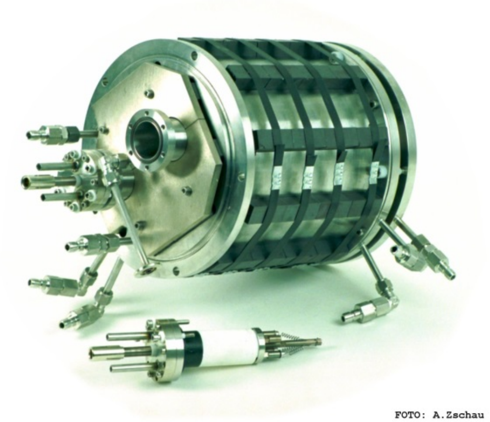
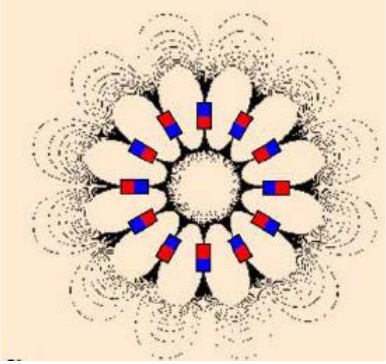


FOTO: A.Zschau

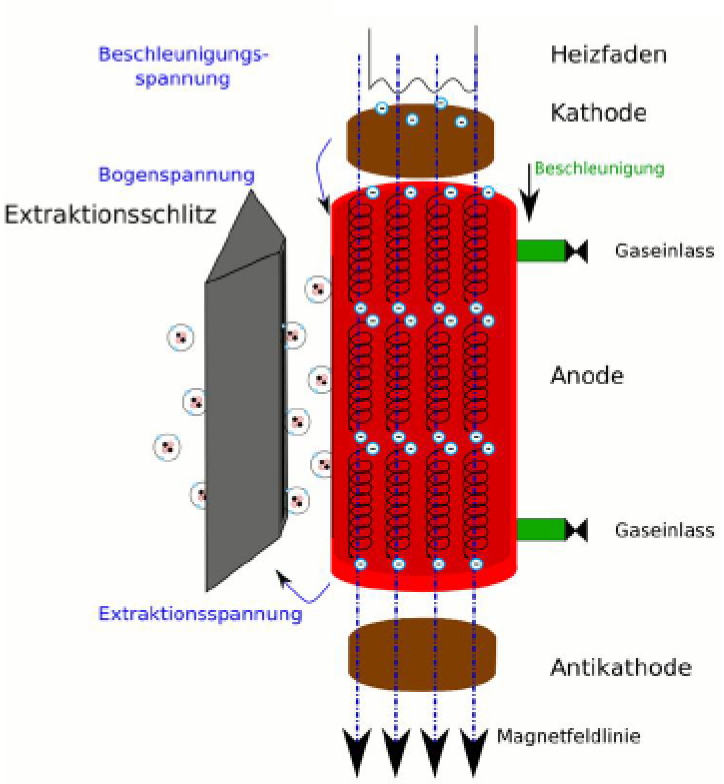
Multi **C**usp **I**on **S**ource with permanent magnets



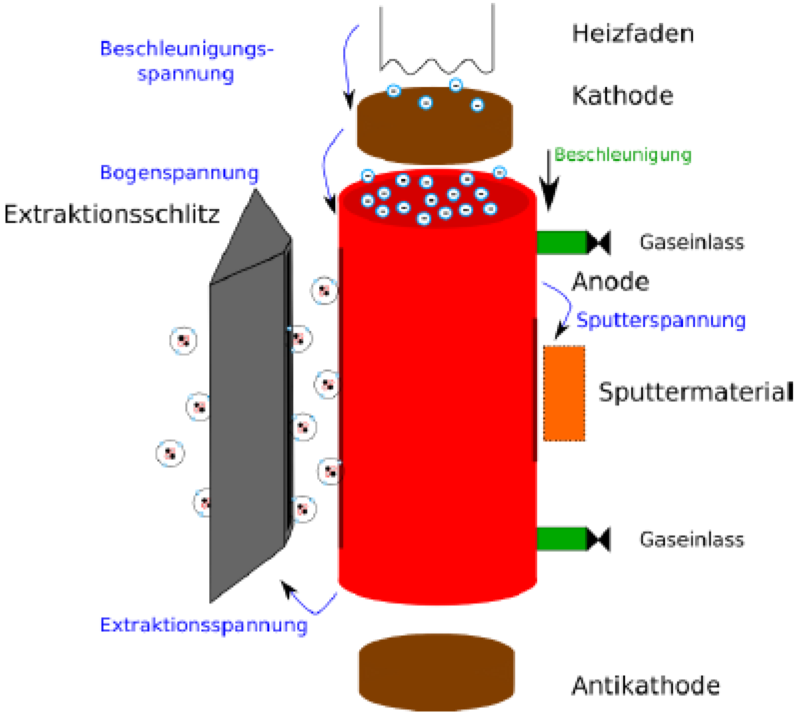
Electrons generated from a filament and used for ionization within a gas volume. Magnetic field guides electrons towards the plasma chamber.

Penning ion source for gases and metals

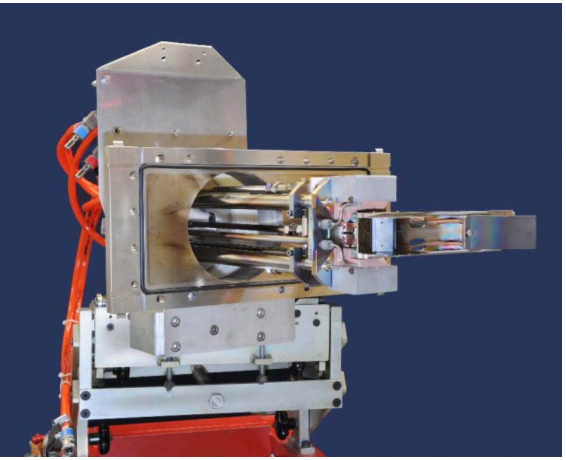
Penning source for gas ions



Penning source for metal ions



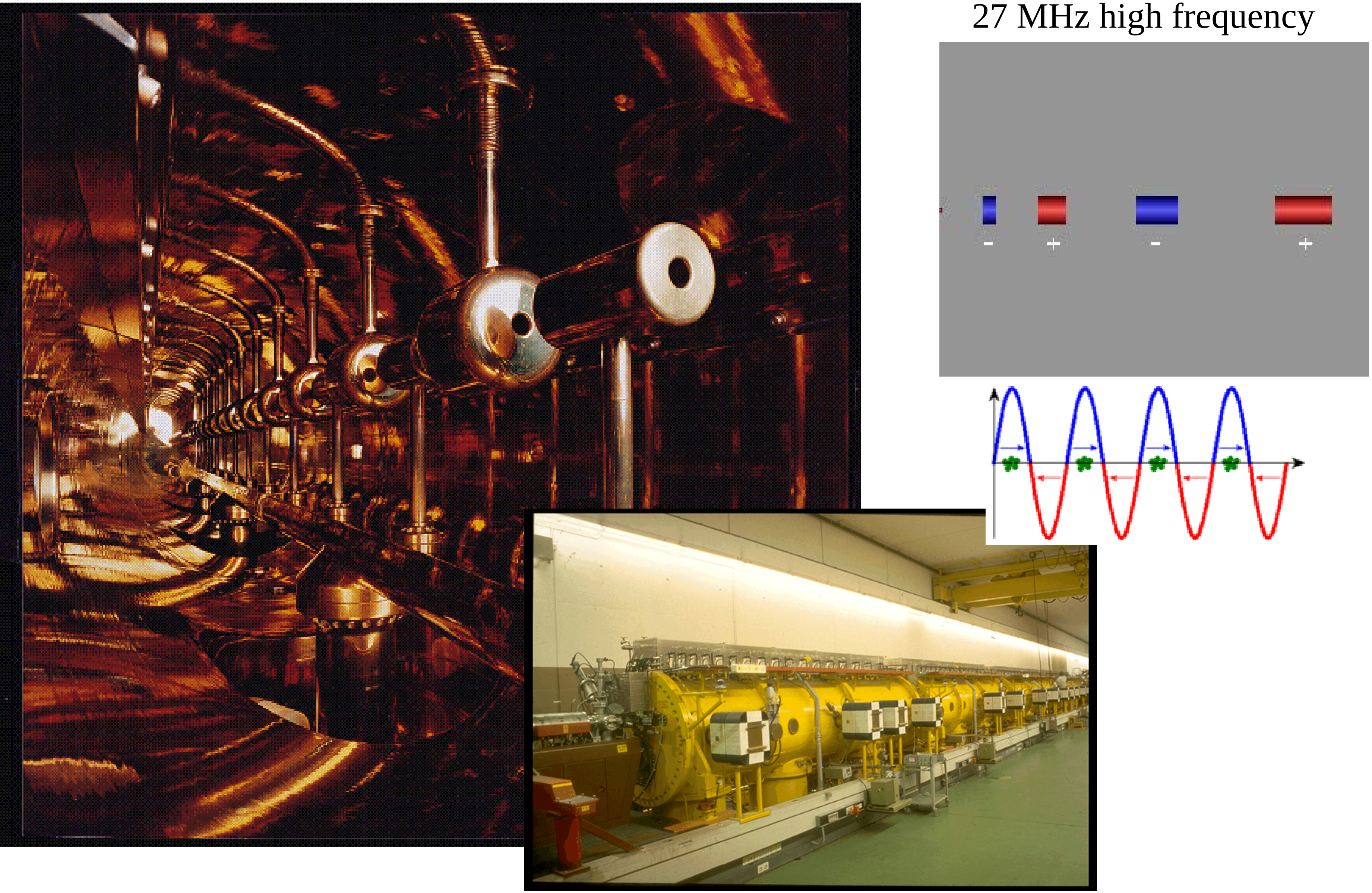
UNIversal Linear ACcelerator



- From zero to 2,000,000 km/h

with a voltage of 20,000 V to 130,000 V
ions will be accelerated to v/c = 0.002

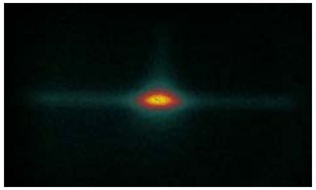
UNILAC Wideroe - Accelerator



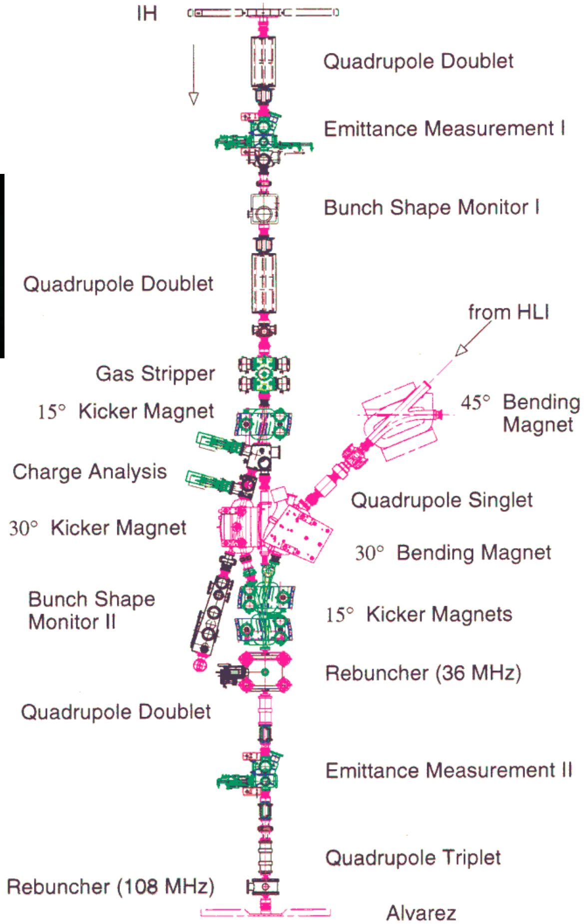
27 MHz high frequency

Gas-stripper to increase acceleration efficiency

$N \cdot {}^{238}U^{4+}$



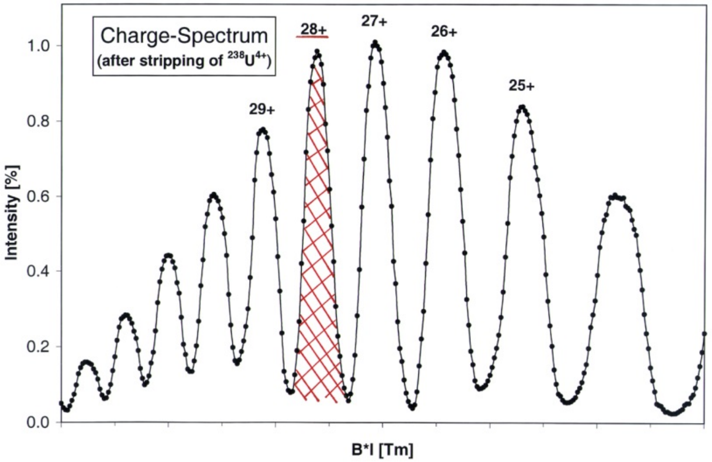
noble gas (Xe)

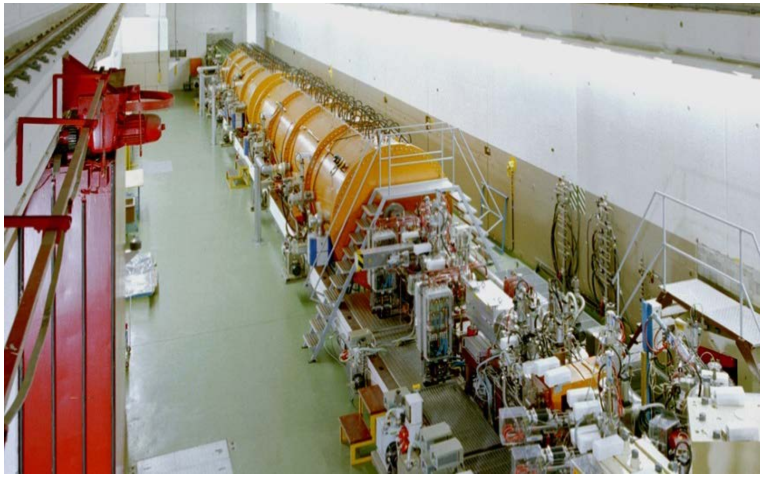


$0.13 \cdot N \cdot {}^{238}U^{28+}$

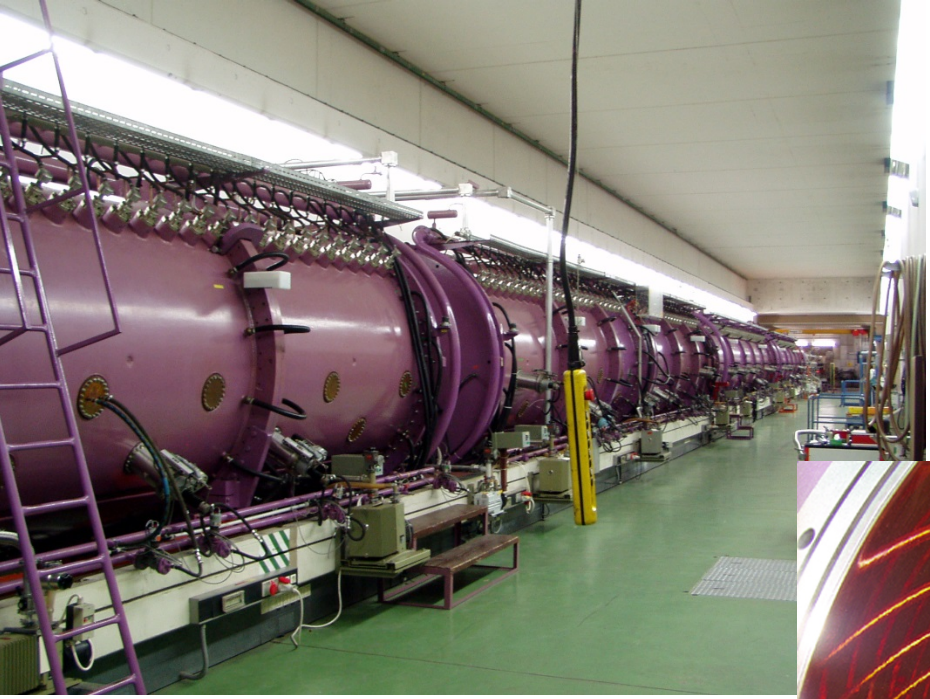
v/c = 5.4% or 1.4 MeV/u

increase of accel. efficiency by a **factor** of 28/4 = **7**
but ≈ 87% of ions get lost (q ≠ 28)

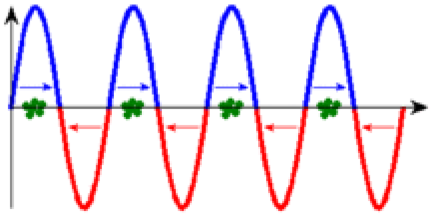


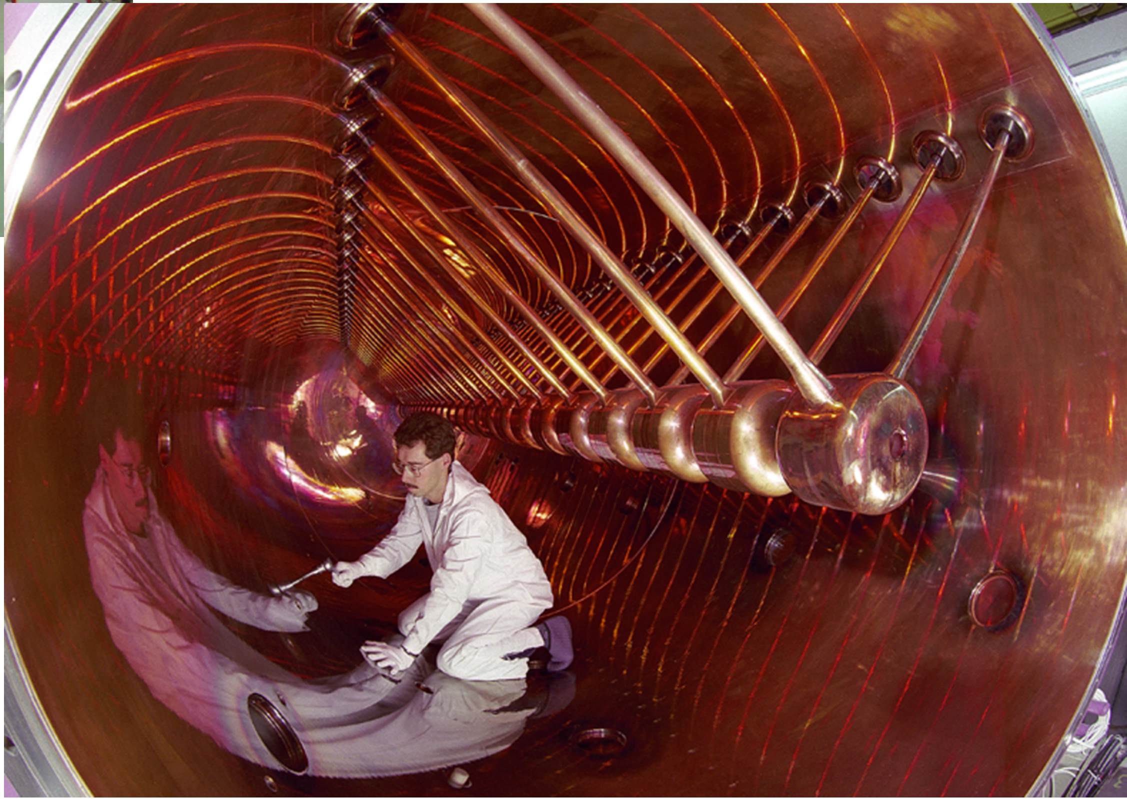


UNILAC Alvarez Accelerator



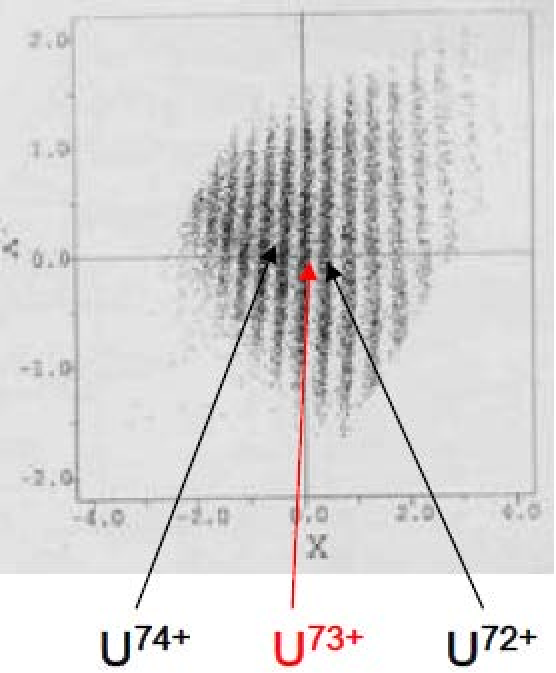
108 MHz high frequency standing wave





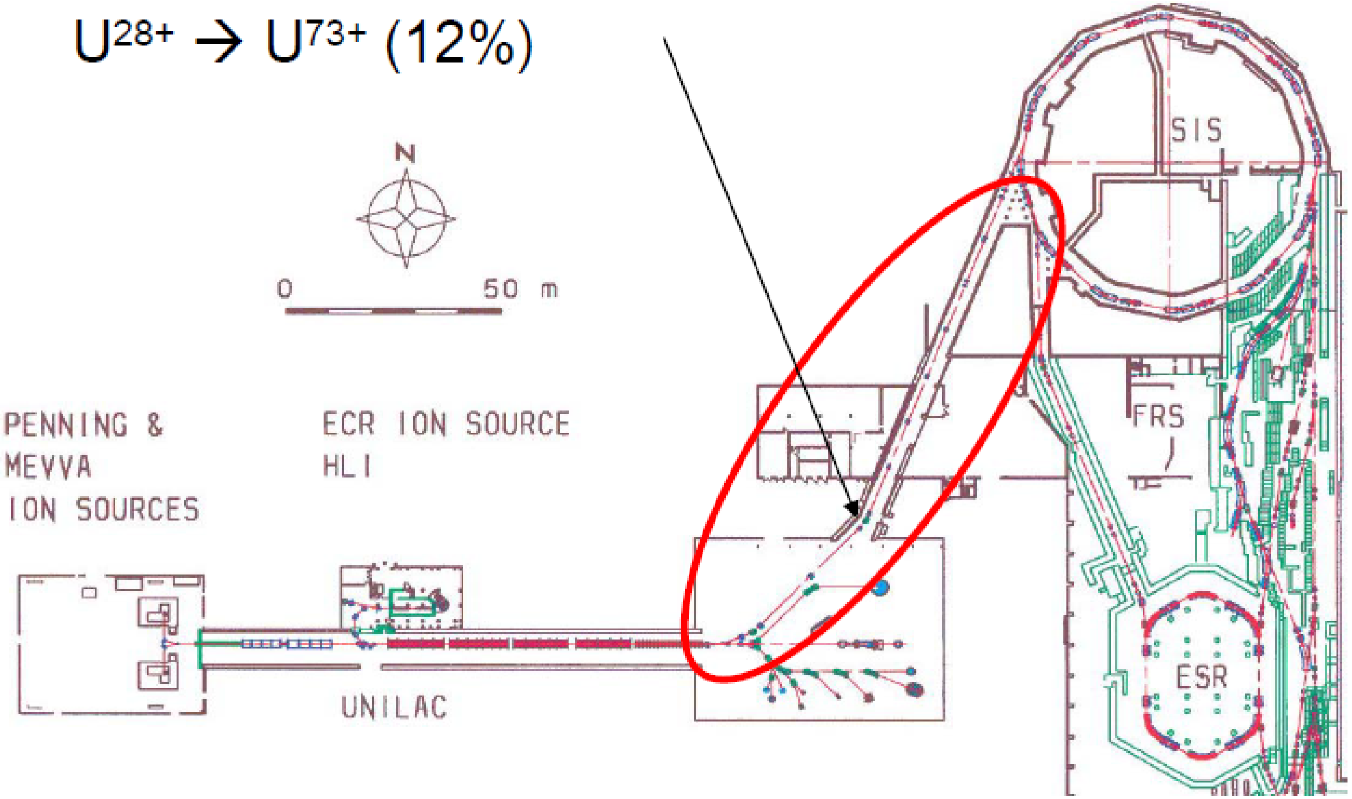
v/c = 16% or 11.4 MeV/u

UNILAC: Beam transfer to synchrotron SIS-18



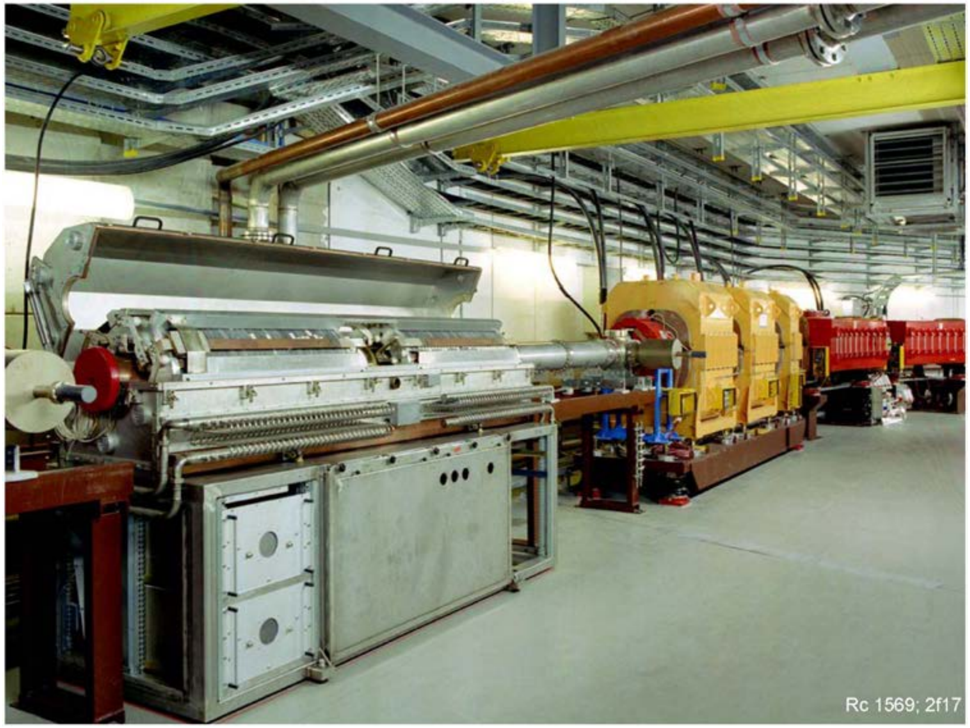
Foil Stripper and Charge State Separation

$U^{28+} \rightarrow U^{73+}$ (12%)

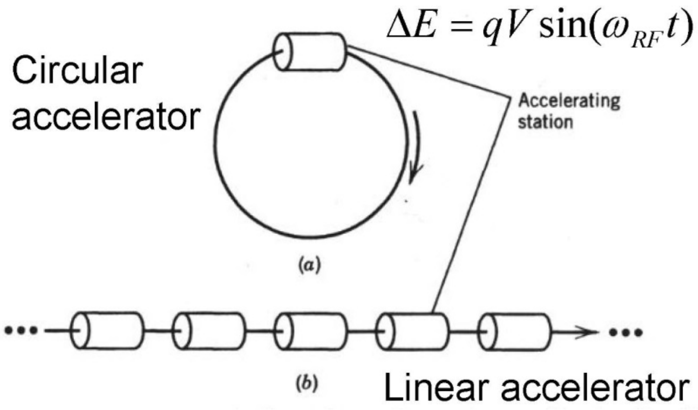


GSI Synchrotron SIS-18

As linacs are dominated by cavities, circular maschines are dominated by magnets



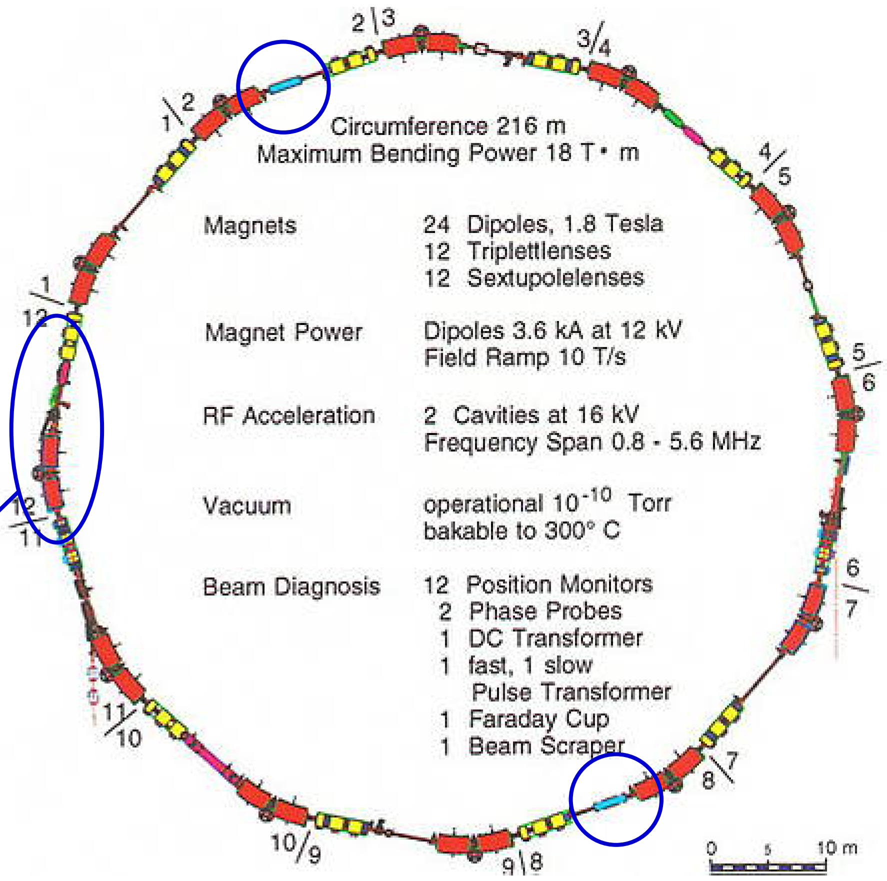
SIS-18 accelerating cavity



GSI Synchrotron SIS-18

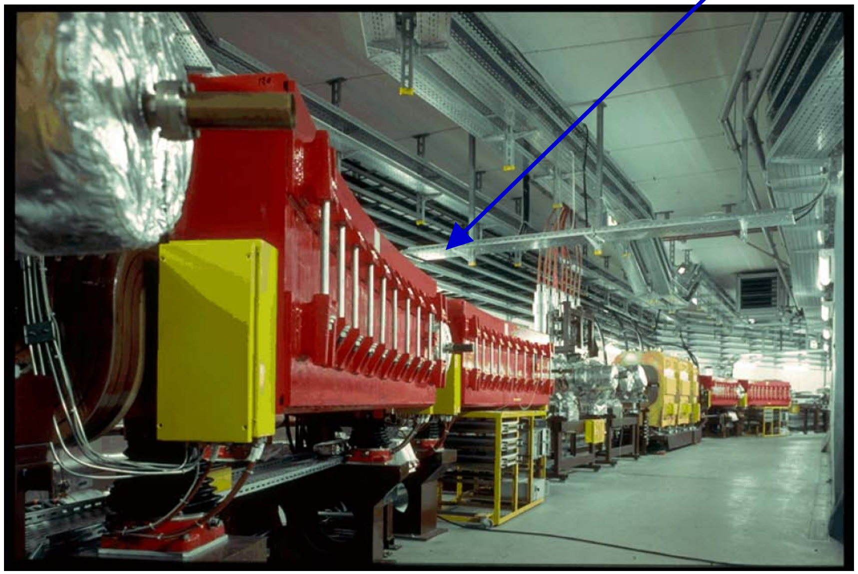
SIS: Schwere Ionen Synchrotron
Heavy Ion Synchrotron

- accelerates ions from p to U
- energy: 4 GeV (p), 2 GeV/u (Ne), 1 GeV/u (U)
- $\beta = 0.98$ (p), 0.95 (Ne), 0.88 (U)
- bending radius: 10 m
- max mag. field 18 T
- rf frequency: 0.85 – 6 MHz



Circumference 216 m
Maximum Bending Power 18 T • m

Magnets	24 Dipoles, 1.8 Tesla 12 Triplettlenses 12 Sextupolelenses
Magnet Power	Dipoles 3.6 kA at 12 kV Field Ramp 10 T/s
RF Acceleration	2 Cavities at 16 kV Frequency Span 0.8 - 5.6 MHz
Vacuum	operational 10^{-10} Torr bakable to 300° C
Beam Diagnosis	12 Position Monitors 2 Phase Probes 1 DC Transformer 1 fast, 1 slow Pulse Transformer 1 Faraday Cup 1 Beam Scraper



GSI Synchrotron SIS-18

SIS: Schwere Ionen Synchrotron
Heavy Ion Synchrotron

- SIS 18 has a circumference of 216 m
- 92 elements will be accelerated from p to U
- max. ion velocity up to 270 000 km/s (β = 90%)
- ions are accelerated by 80 000 V in the accelerator structures during every circulation
- ions are accelerated in one second cover a distance of 90 000 km, that corresponds to 416 000 cycles in the ring
- 32 billion medium-charged uranium ions can be accelerated at SIS 18
- one billionth Pascal: an ultra-high vacuum is a prerequisite for acceleration.

Nuclear reaction rate

Reaction rate (**thick target**):

$$R\left[s^{-1}\right] = \phi_p\left[s^{-1}\right] - \phi\left[s^{-1}\right] = \phi_p\left[s^{-1}\right] - \phi_p\left[s^{-1}\right] \cdot e^{-N_t\left[cm^{-2}\right] \cdot \sigma\left[cm^2\right]}$$

$$\phi\left[s^{-1}\right] = \phi_p\left[s^{-1}\right] \cdot e^{-\frac{x\left[g/cm^2\right] \cdot 6.02 \cdot 10^{23}\,\sigma\left[cm^2\right]}{A\left[g\right]}}$$

Reaction rate (**thin target**):

$$R\left[s^{-1}\right] \cong \phi_p\left[s^{-1}\right] \cdot N_t\left[cm^{-2}\right] \cdot \sigma\left[cm^2\right]$$

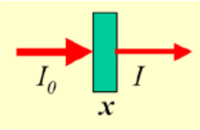
$$R\left[s^{-1}\right] \cong \phi_p\left[s^{-1}\right] \cdot \frac{x\left[g/cm^2\right] \cdot 6.02 \cdot 10^{23}}{A\left[g\right]} \cdot \sigma\left[cm^2\right]$$

Example: $^{238}U\left[1 \cdot 10^9\ s^{-1}\right] on\ \ ^{208}Pb\ \ x = 1.3\left[g/cm^2\right] \rightarrow {}^{132}Sn\ (\sigma = 15.4[mb])$

Reaction rate: 57941[s^{-1}] transmission (SIS/FRS)=70%, transmission (FRS) 1.9%

$$\boxed{1 - e^{-y} \cong y \qquad for\ \ y = 0.02}$$

Nuclear reaction rate



Primary reaction rate:

$$\phi_f\left[s^{-1}\right] \cong \phi_p\left[s^{-1}\right]\cdot\frac{x\left[g/cm^2\right]\cdot 6.02\cdot 10^{23}}{A_t[g]}\cdot\sigma_f\left[cm^2\right]$$

Example: ^{238}U ($10^9 s^{-1}$) on ^{208}Pb ($x=1g/cm^2$) ⟶ ^{132}Sn ($\sigma_f=15.4mb$) reaction rate: $44571[s^{-1}]$

Example: ^{124}Xe ($10^9 s^{-1}$) on ^{9}Be ($x=1g/cm^2$) ⟶ ^{104}Sn ($\sigma_f=5.6\mu b$) reaction rate: $375[s^{-1}]$

The ***optimum thickness*** of the production target is limited by the loss of fragments due to secondary reactions

Primary + secondary reaction rate:

$$\phi_f\left[s^{-1}\right] \cong \phi_p\left[s^{-1}\right]\cdot\frac{6.02\cdot 10^{23}\cdot\sigma_f\left[cm^2\right]}{A_t[g]}\cdot\frac{1}{\mu_f-\mu_p}\cdot\left(e^{-\mu_p\cdot x\left[g/cm^2\right]}-e^{-\mu_f\cdot x\left[g/cm^2\right]}\right)$$

$$\textit{with}\quad \mu=\frac{6.02\cdot 10^{23}}{A_2[g]}\cdot\sigma_{reaction}\left[cm^2\right]$$

$x\left[g/cm^2\right]$	$\frac{1}{\mu_f-\mu_p}\left[e^{-\mu_p\cdot x}-e^{-\mu_f\cdot x}\right]$
1	0.79
2	1.25
3	1.47
4	1.55
5	1.53
6	1.45

Example: $^{124}Xe\ \ on\ \ ^{9}Be\rightarrow{}^{104}Sn,\quad \sigma(^{124}Xe+{}^{9}Be)=3.65[b]\ \rightarrow\ \mu_p=0.244\left[cm^2/g\right]$

$\sigma(^{104}Sn+{}^{9}Be)=3.44[b]\ \rightarrow\ \mu_f=0.230\left[cm^2/g\right]$