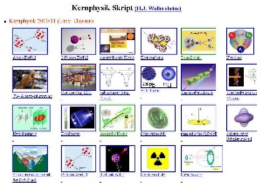
Outline: GSI accelerator facility

Lecturer: Hans-Jürgen Wollersheim

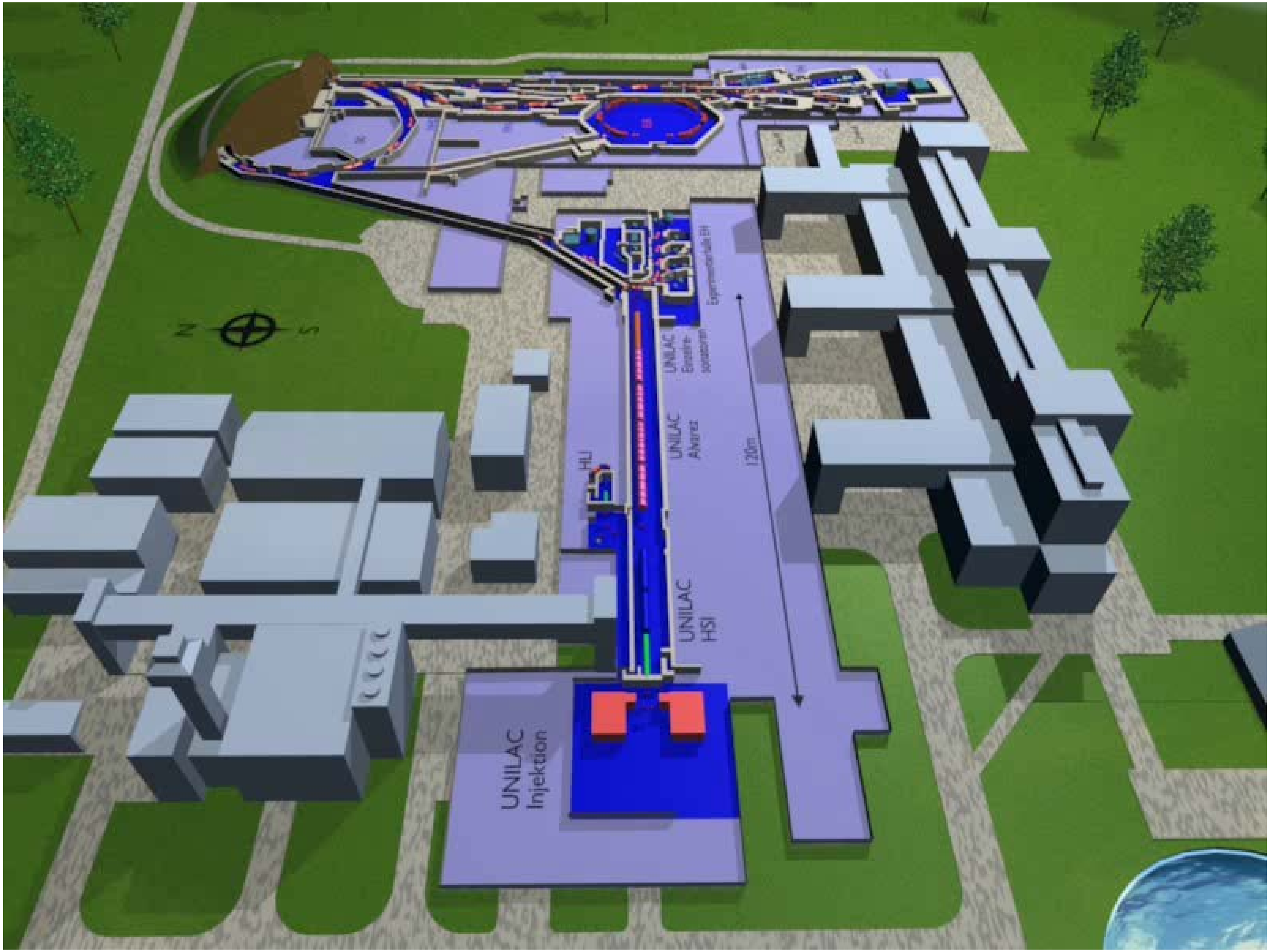
e-mail: h.j.wollersheim@gsi.de

web-page: https://web-docs.gsi.de/~wolle/ and click on 

1. heavy ion source
2. universal linear accelerator UNILAC
3. synchrotron SIS-18
4. nuclear reaction rate

GSI Helmholtz Centre for Heavy Ion Research

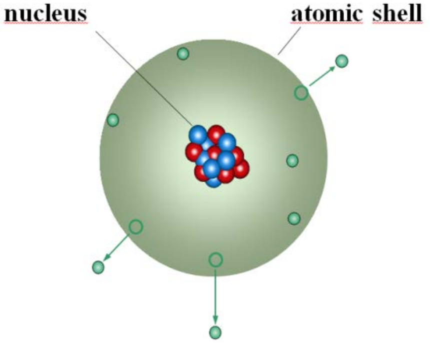
Accelerator facility

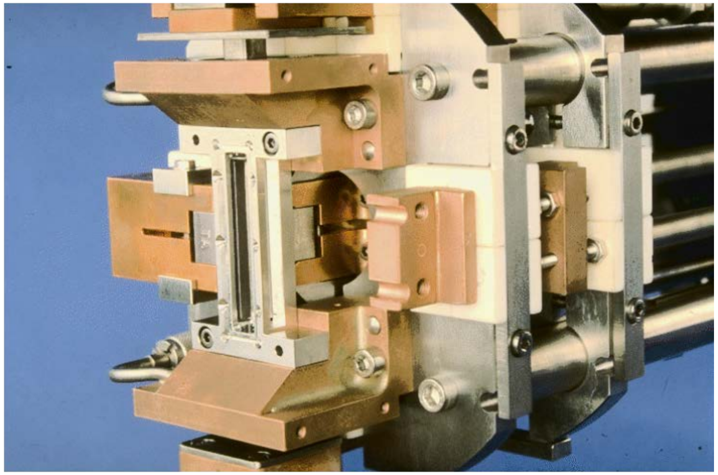


Ion source

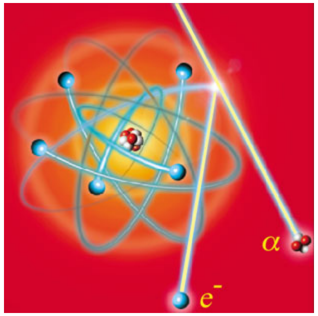
To create ions one needs:

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

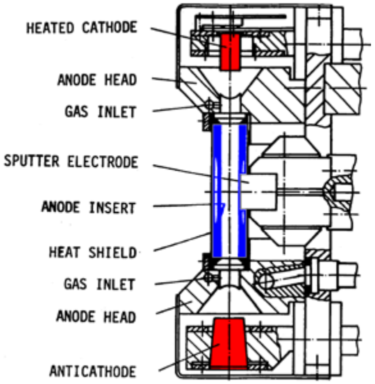




Penning ion source



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/cm²

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

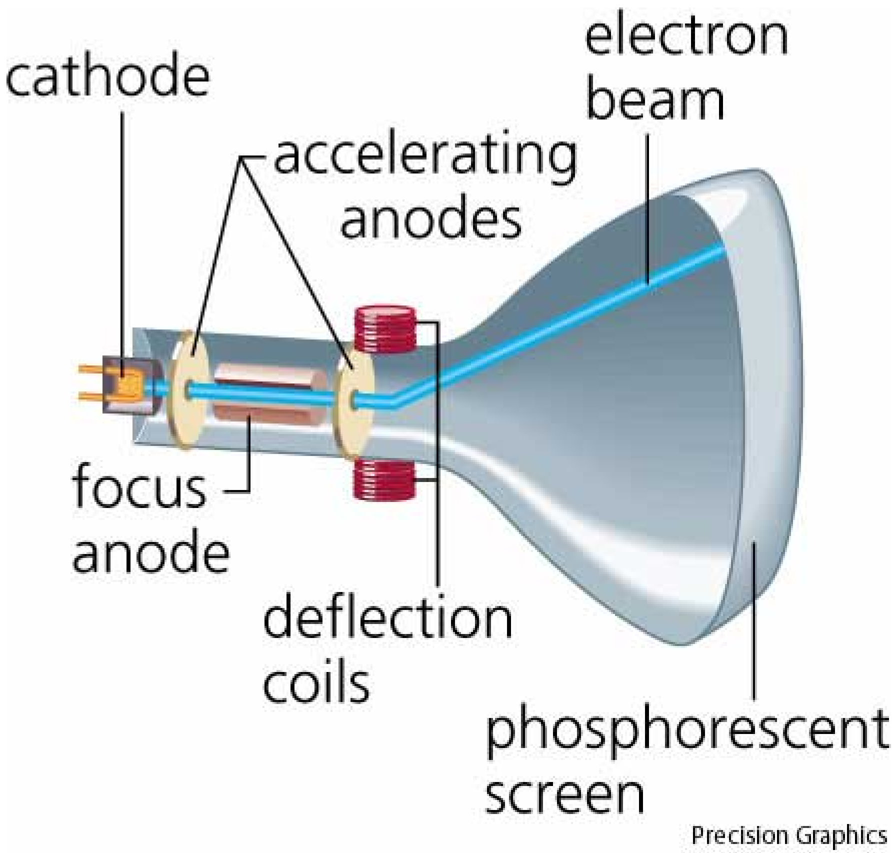
Excitation — Spontaneous emission

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

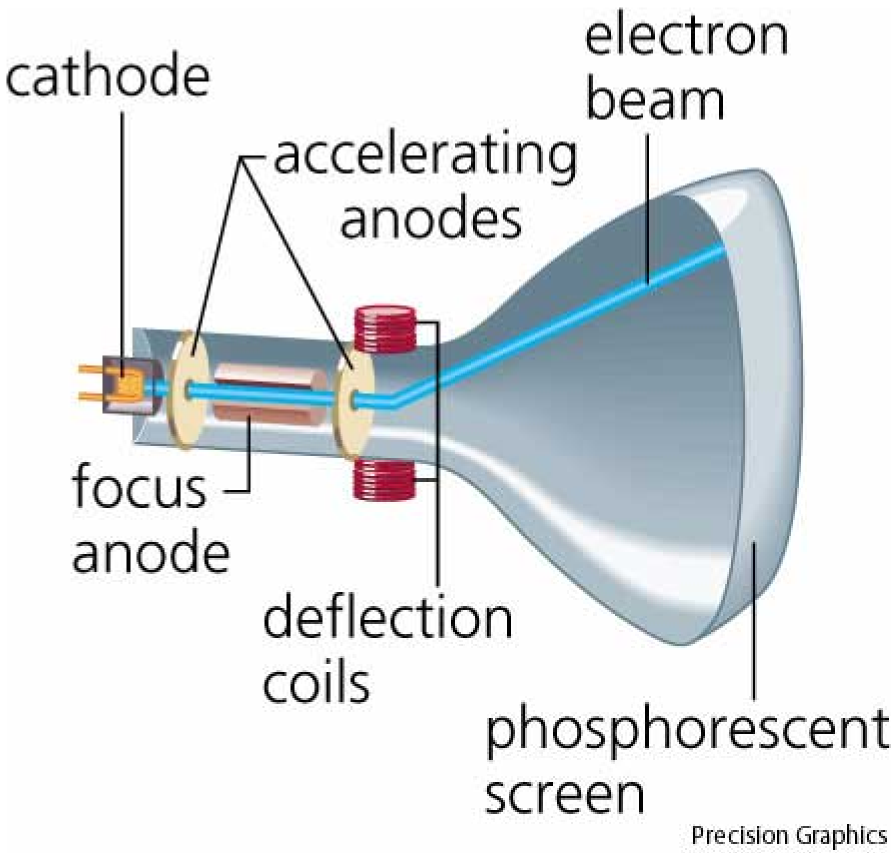
Photo absorption — Bremsstrahlung

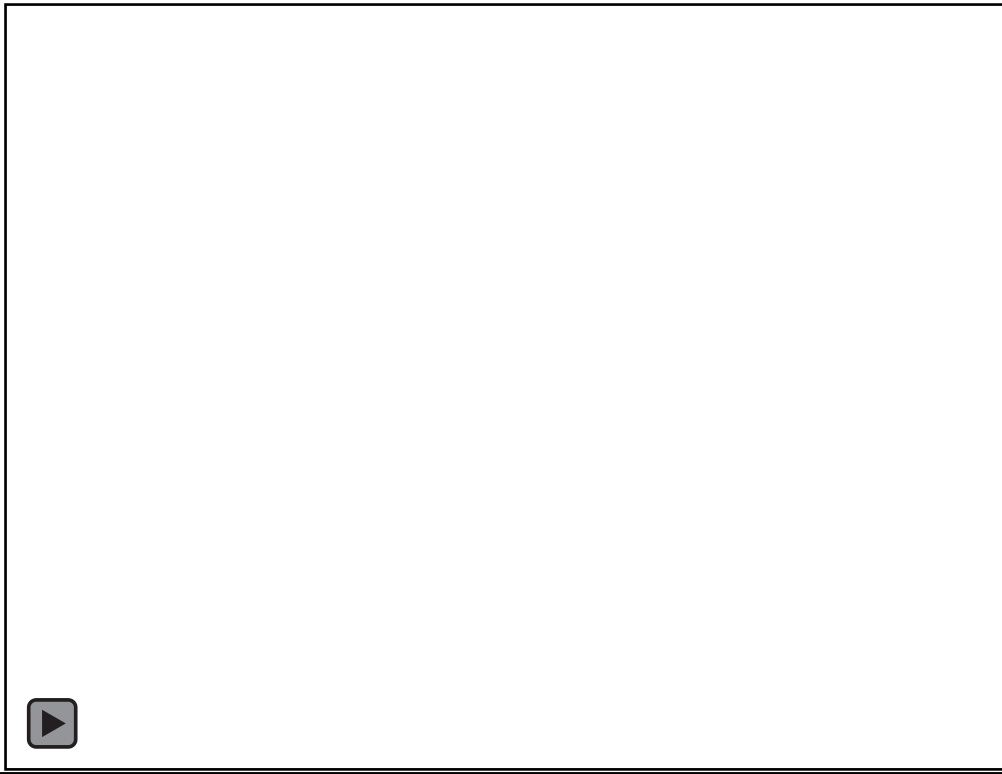
$$A^{Z+} + h\upsilon + e \leftrightarrow A^{Z+} + e' \Rightarrow$$ Continuous spectrum

Cathode Ray Tube

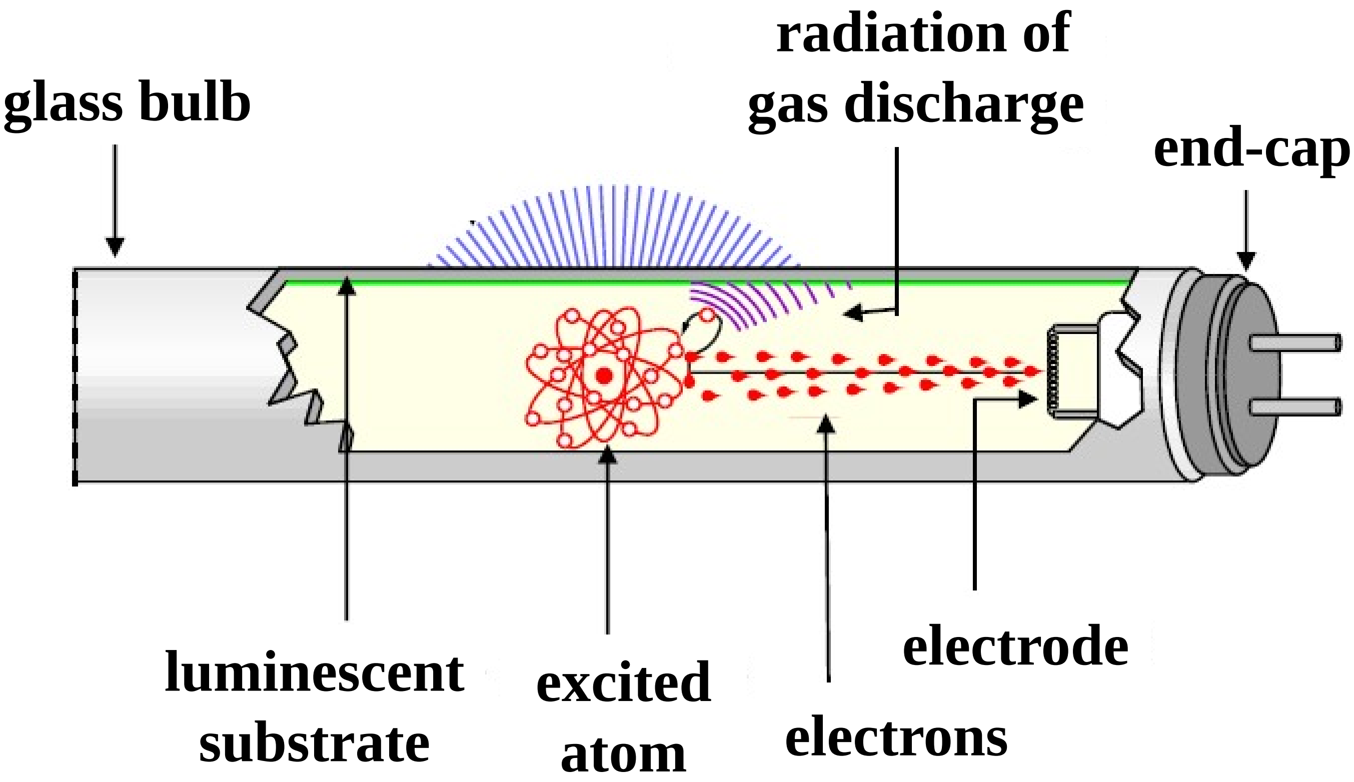


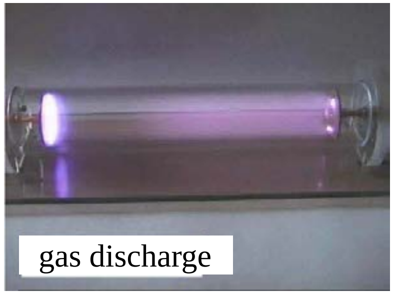
Cathode Ray Tube





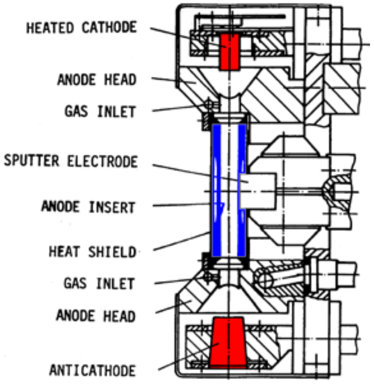
How to create ions?

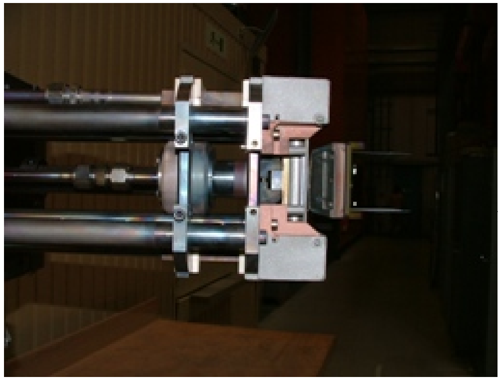




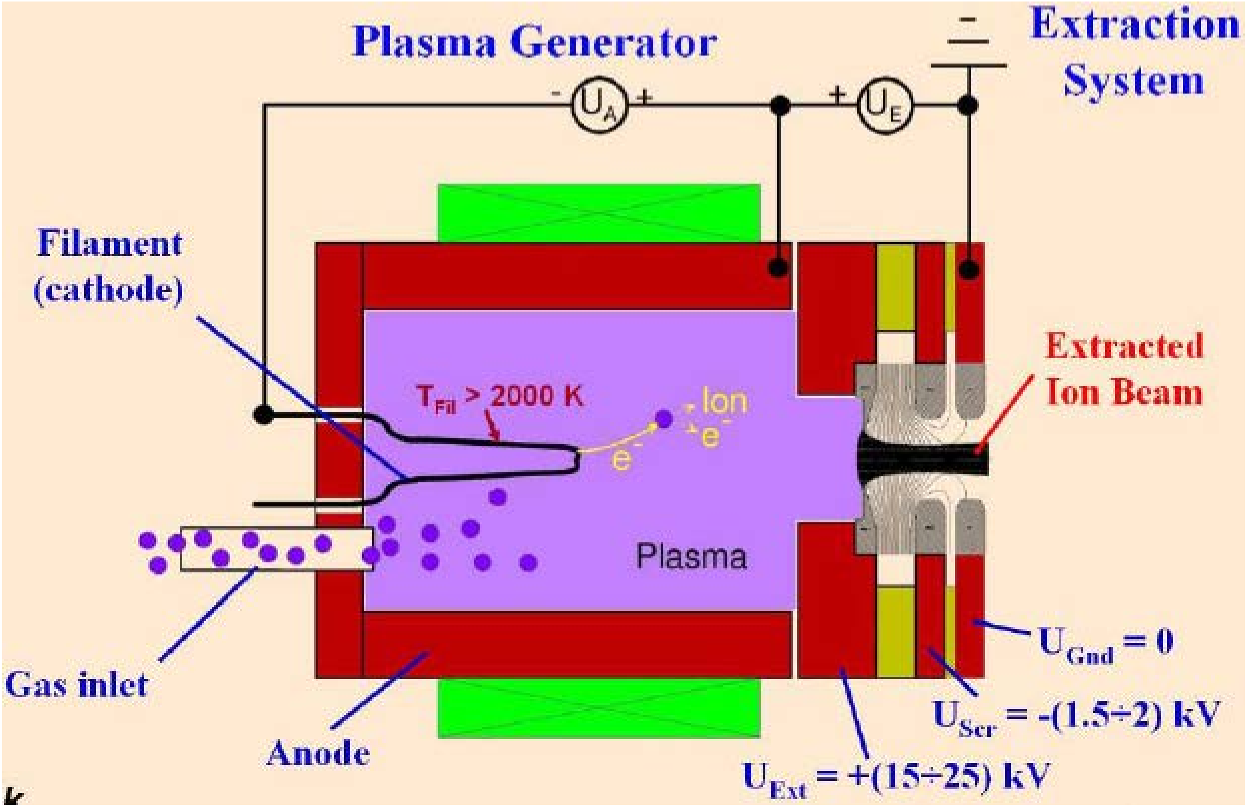
To create ions one needs:

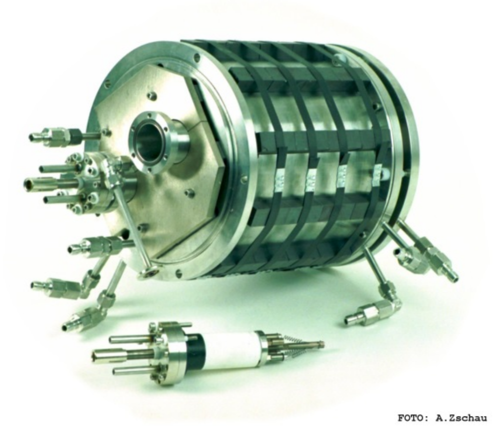
1. electrons
2. noble gases
3. element material (e.g. Fe, Sn, Pb, U)



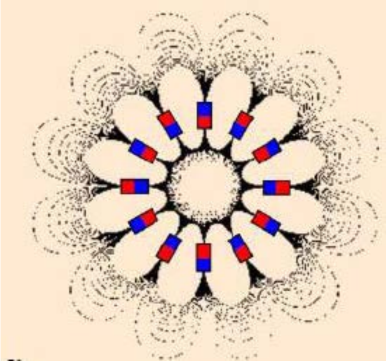


Volume ion source with filament





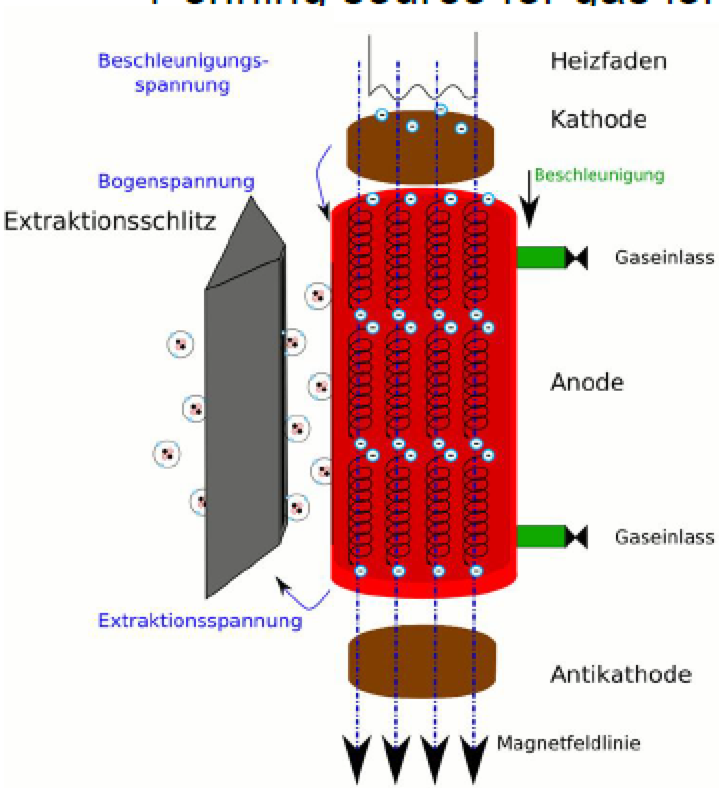
Multi **C**usp **I**on **S**ource
with permanent magnets



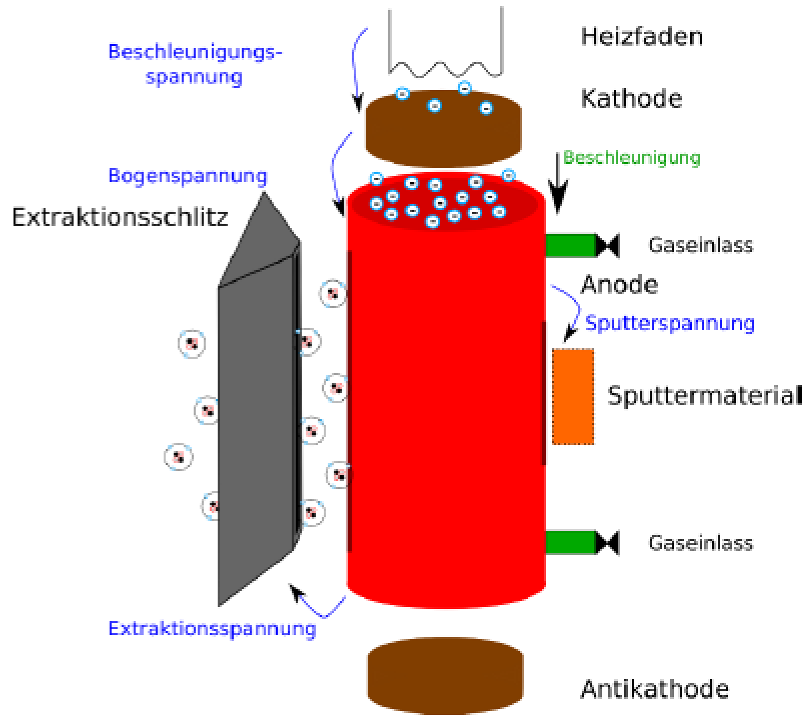
Electrons generated from a filament and used for ionization within a gas volume.
Magnetic field guides electrons towards the plasma chamber.

Penning ion source for gases and metals

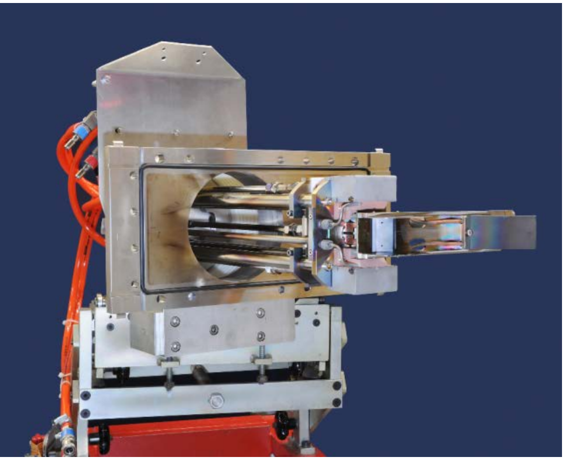
Penning source for gas ions



Penning source for metal ions



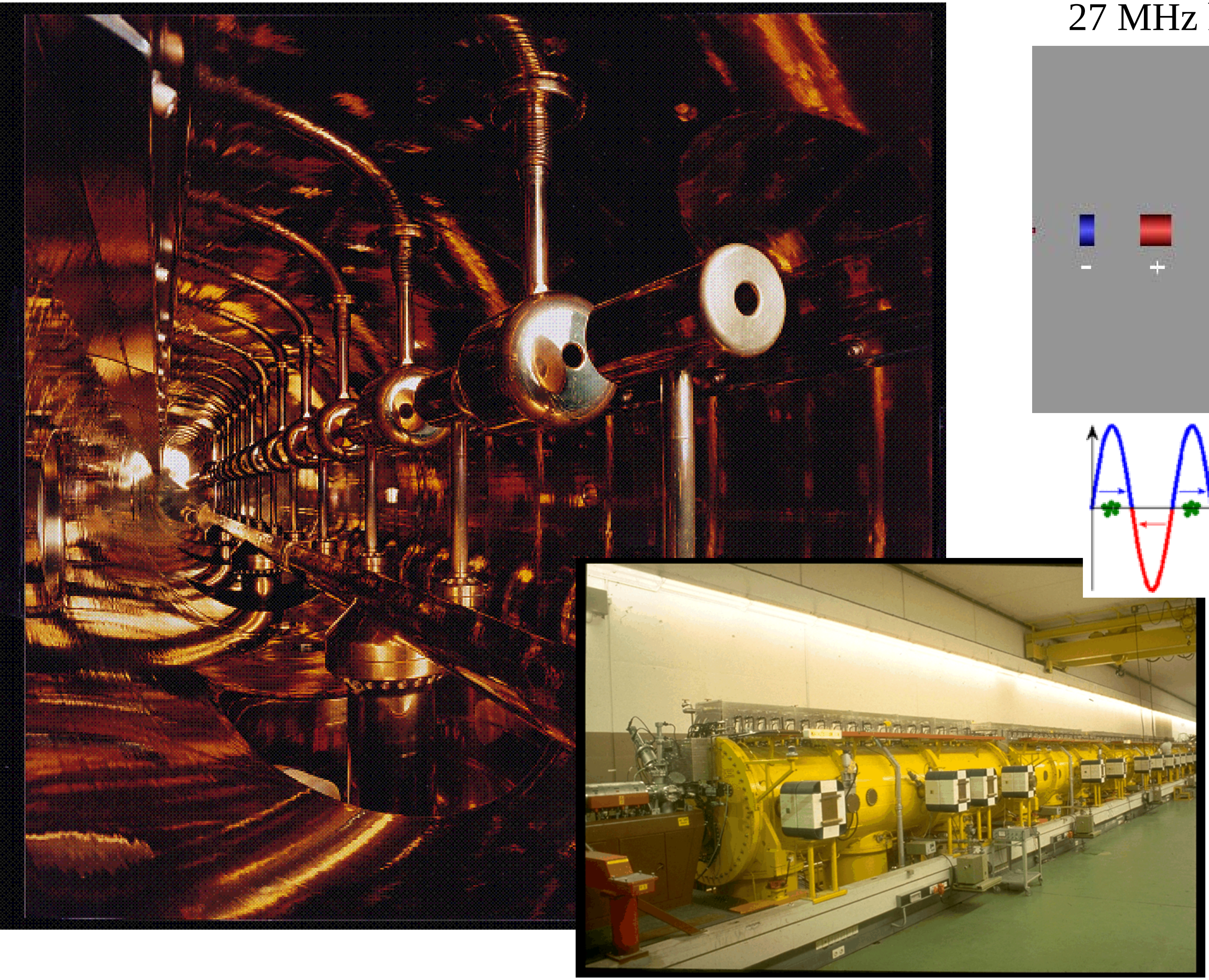
UNIversal Linear ACcelerator



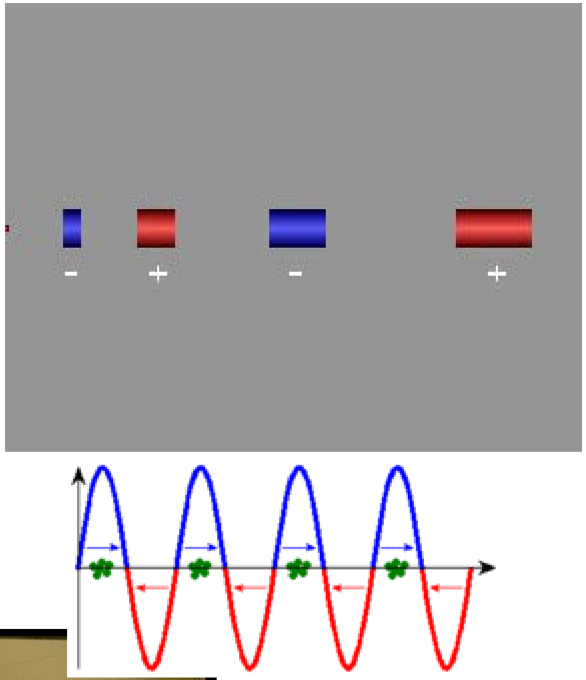
- From zero to 2,000,000 km/h

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

UNILAC Wideroe - Accelerator



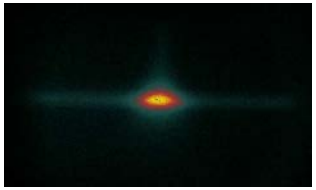
27 MHz high frequency



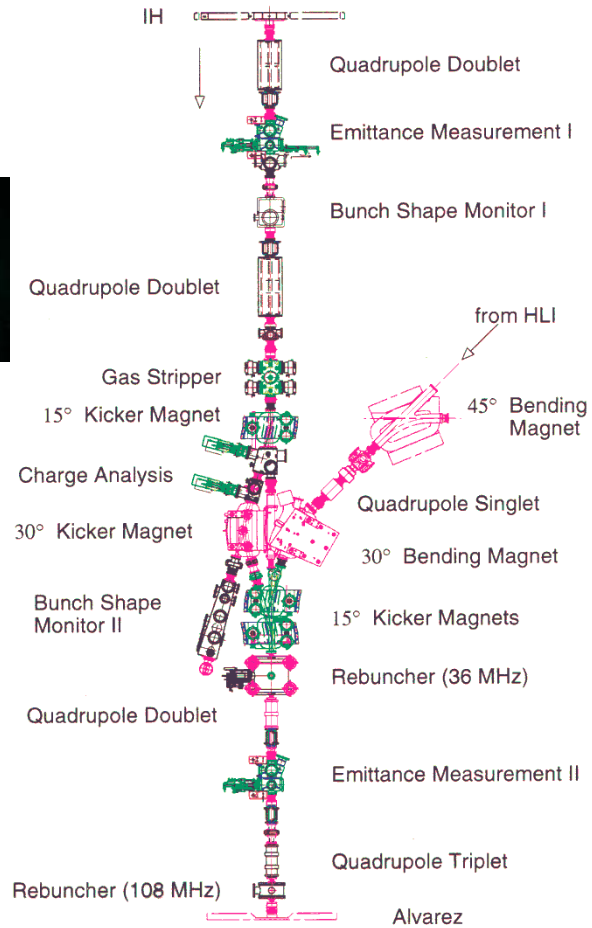
Gas-stripper to increase acceleration efficiency

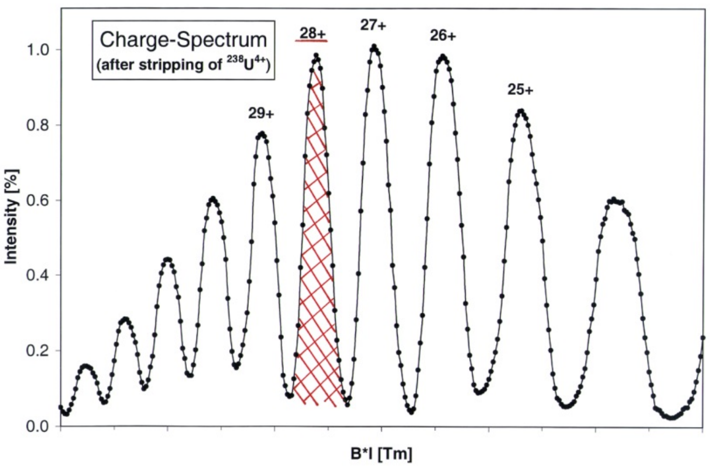
$N \cdot {}^{238}U^{4+}$

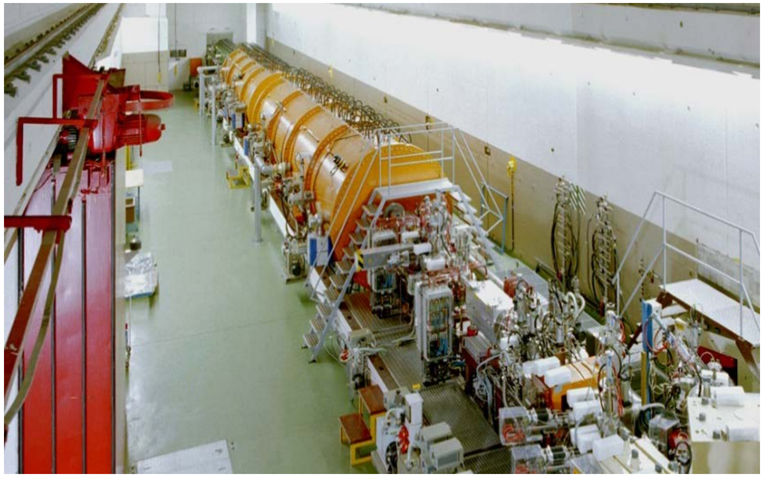
increase of accel. efficiency by a **factor** of 28/4 = **7**
but ≈ 87% of ions get lost (q ≠ 28)



noble gas (Xe)



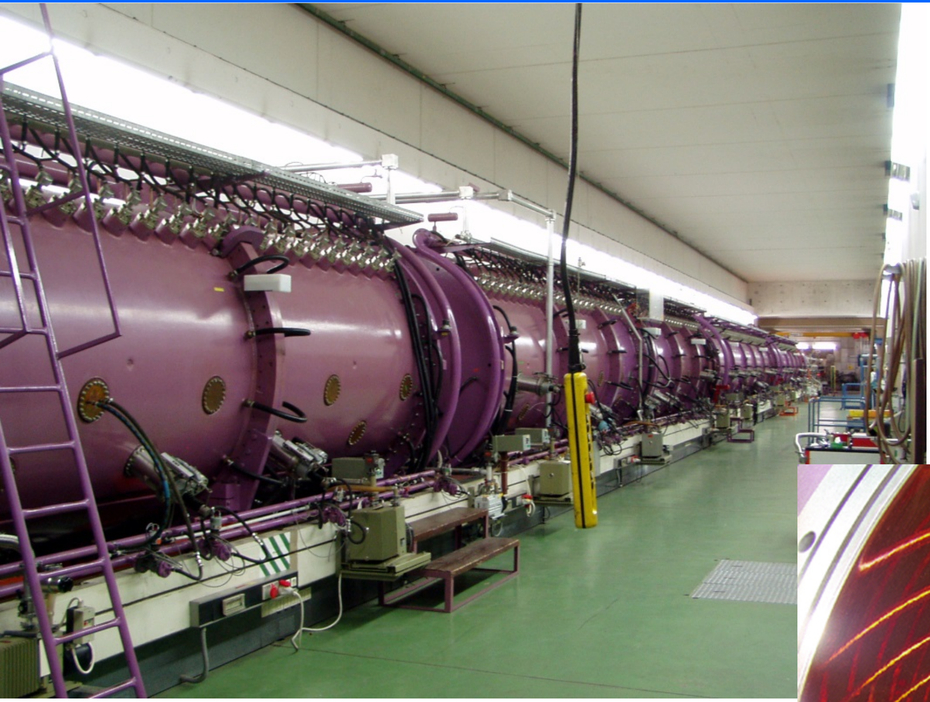




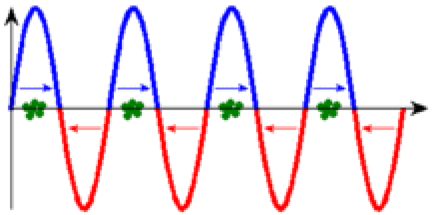
$0.13 \cdot N \cdot {}^{238}U^{28+}$

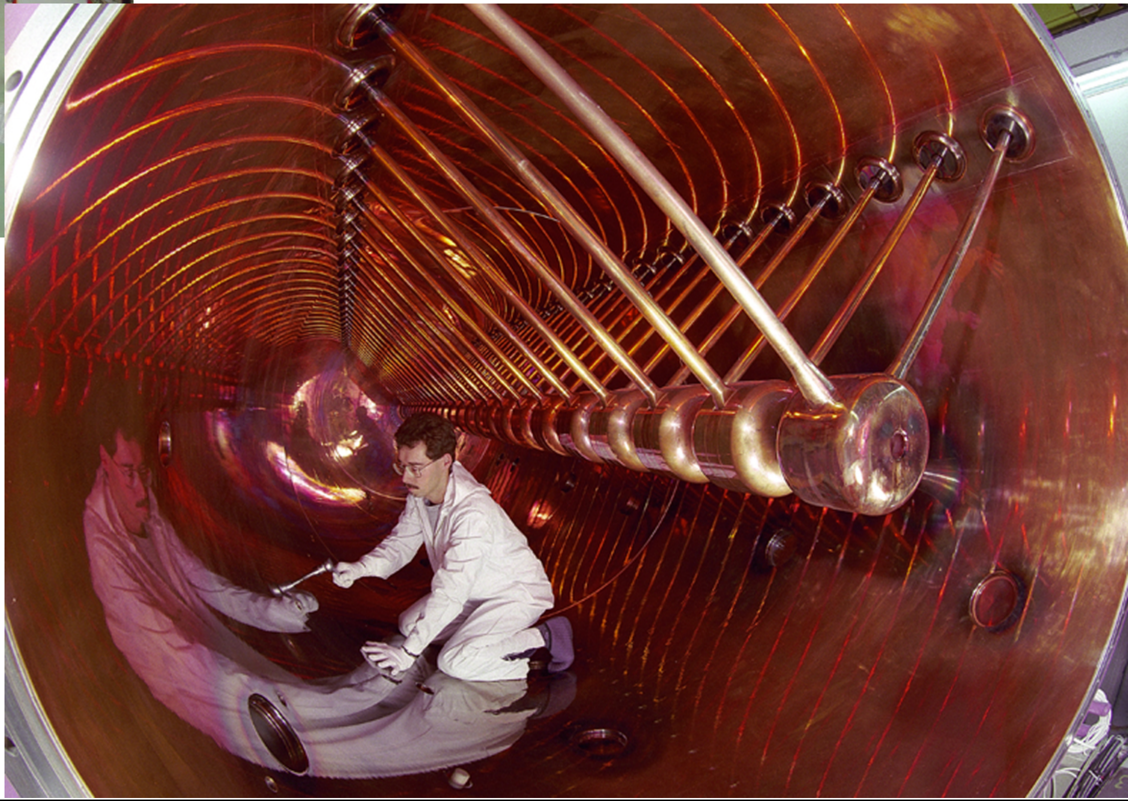
v/c = 5.4% or 1.4 MeV/u

UNILAC Alvarez Accelerator



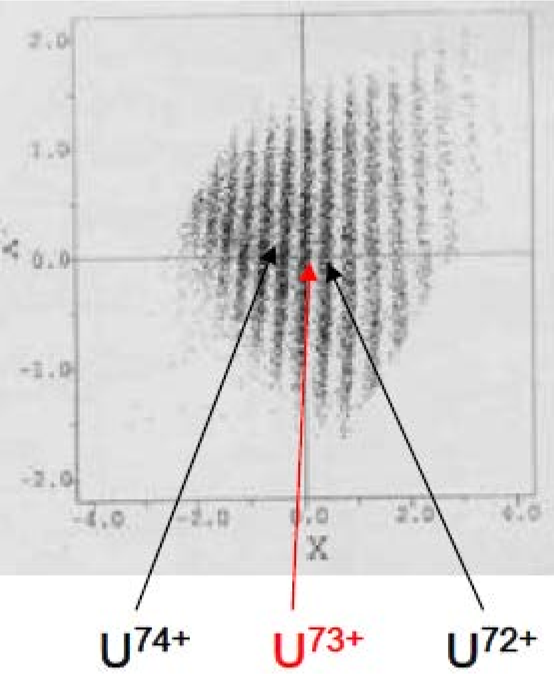
108 MHz high frequency
standing wave





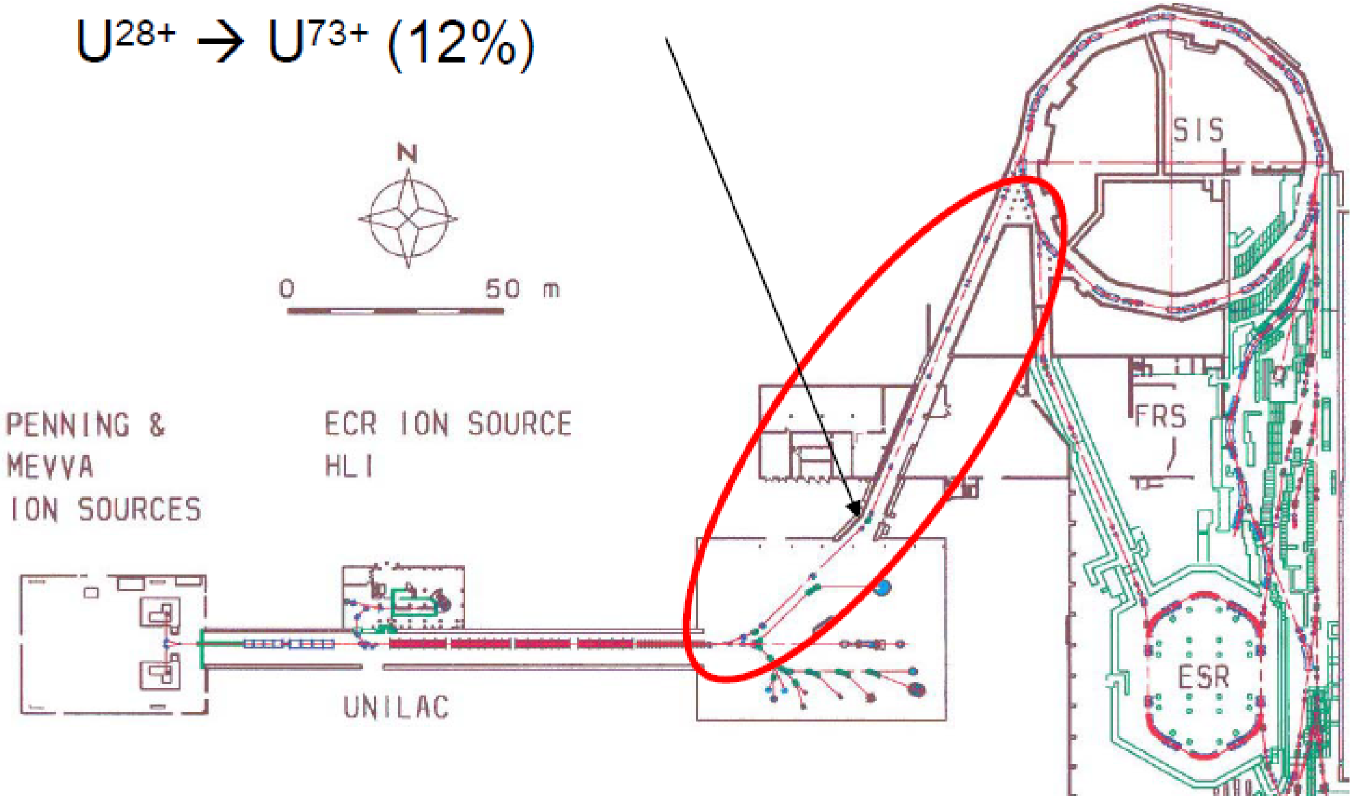
v/c = 16% or 11.4 MeV/u

UNILAC: Beam transfer to synchrotron SIS-18



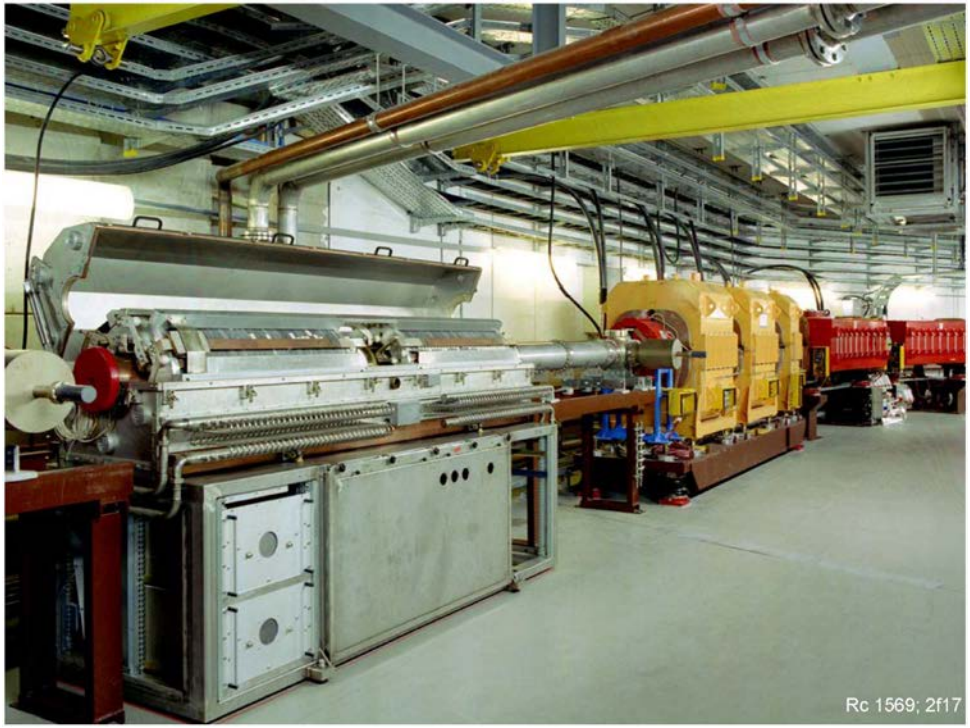
Foil Stripper and Charge State Separation

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

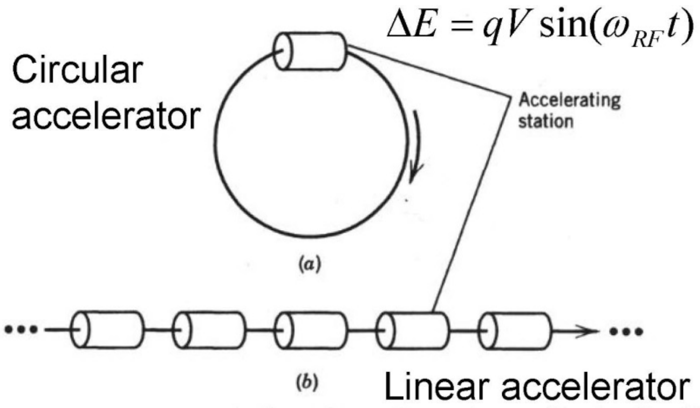


GSI Synchrotron SIS-18

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



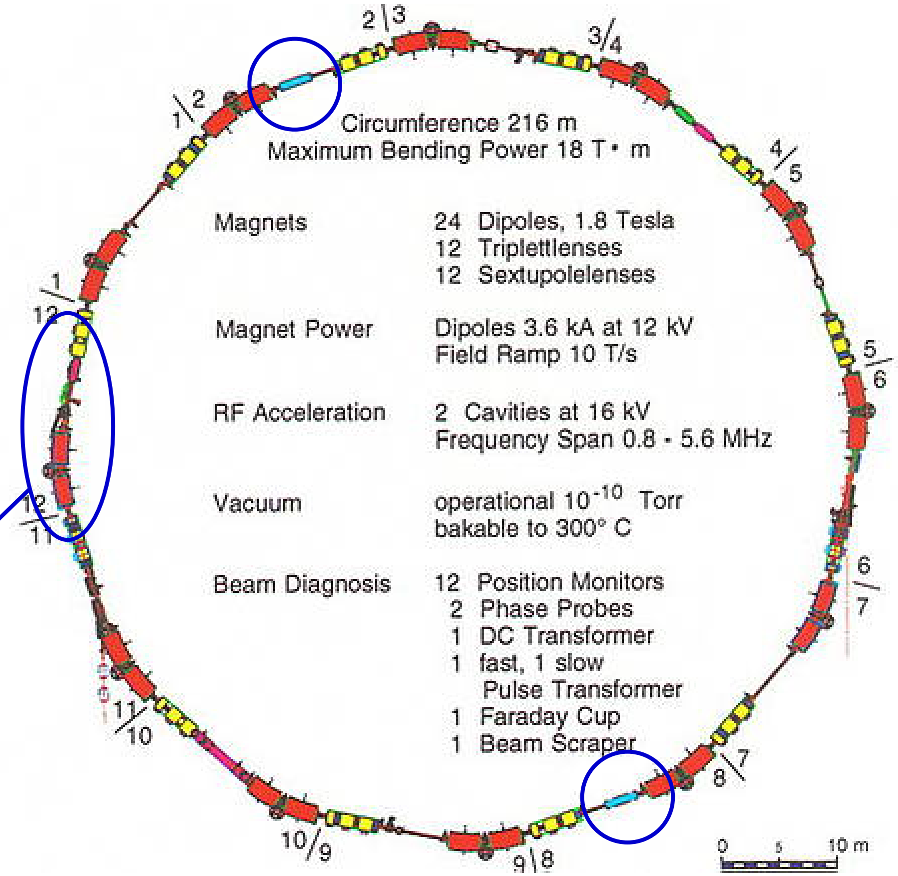
SIS-18 accelerating cavity

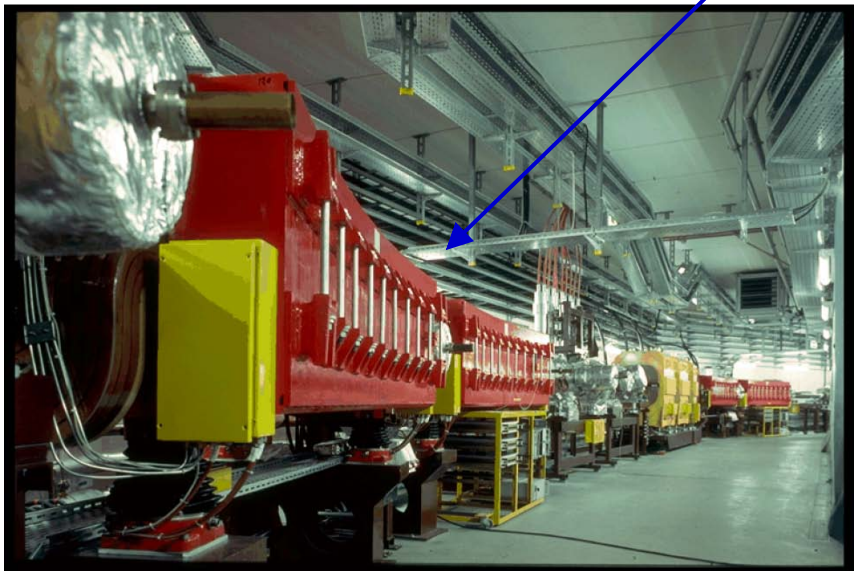


GSI Synchrotron SIS-18

SIS: Schwere Ionen Synchrotron
Heavy Ion Synchrotron

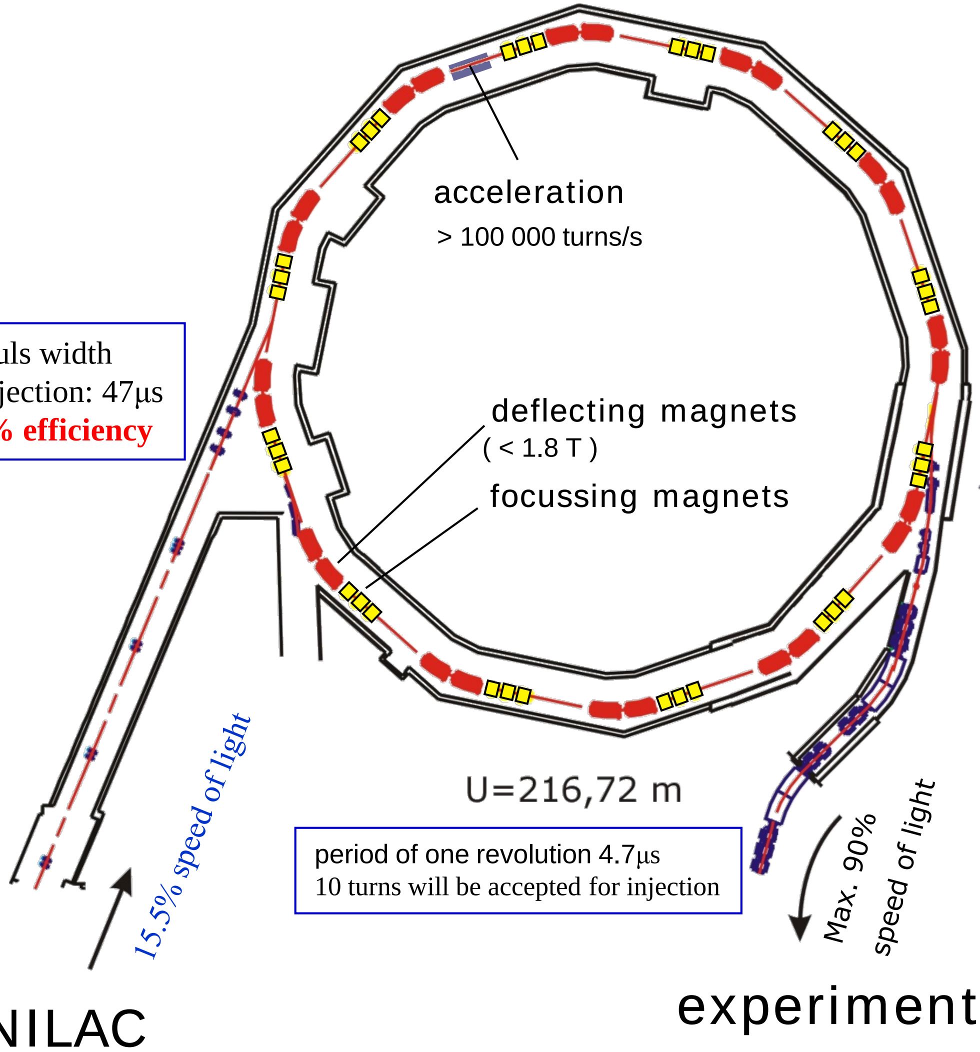
- accelerates ions from p to U
- energy: 4 GeV (p), 2 GeV/u (Ne), 1 GeV/u (U)
- β = 0.98 (p), 0.95 (Ne), 0.88 (U)
- bending radius: 10 m
- max mag. field 18 T
- rf frequency: 0.85 – 6 MHz



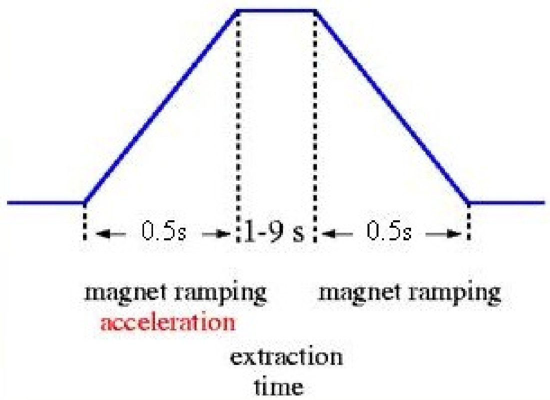


SIS – Schwere Ionen Synchrotron

eff. puls width
for injection: 47µs
36.2% efficiency

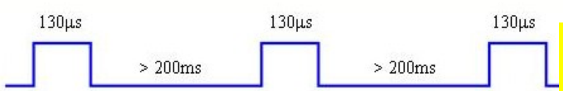


period of one revolution 4.7µs
10 turns will be accepted for injection



$$1.0 \cdot 10^{10} \cdot \frac{0.362}{2} = 1.8 \cdot 10^{9} \text{ particles/s}$$

Ion	Number of injections	Intensity [spill^{-1}] at FRS	Ion source	Date
^{58}Ni	1	$6*10^{9}$	MEVVA	3.2006
^{107}Ag	1	$3*10^{9}$	MEVVA	2.2006
^{124}Xe	1	$5*10^{9}$	MUCIS	3.2008
^{136}Xe	4	$5*10^{9}$	MEVVA	7.2006
^{208}Pb	30	$1.3*10^{9}$	PIG	3.2006
^{238}U	1	$2.0*10^{9}$	PIG	9.2009



$$900\mu A = \frac{900 \cdot 10^{-6}[A] \cdot 130 \cdot 10^{-6}}{73[U-charge] \cdot 1.6 \cdot 10^{-19}[C]} = 1.0 \cdot 10^{10}\ particles/s$$

intensity[s^{-1}]=0.5*intensity[spill^{-1}]

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**):

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

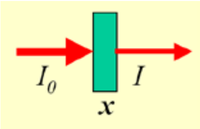
$$R\left[s^{-1}\right]\cong\phi_p\left[s^{-1}\right]\cdot\frac{x\left[g/cm^2\right]\cdot 6.02\cdot 10^{23}}{A\left[g\right]}\cdot\sigma\left[cm^2\right]$$

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%

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

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 ($x=1g/cm^2$) $\longrightarrow$ ^{132}Sn ($\sigma_f=15.4mb$) reaction rate: $44571[s^{-1}]$

Example: ^{124}Xe ($10^9 s^{-1}$) on ^{9}Be ($x=1g/cm^2$) $\longrightarrow$ ^{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:

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

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

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

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

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