Introduction to Accelerator Physics

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Physikalisches Institut der Universität Heidelberg

Lecture 3

Lecture Dates

https://uebungen.physik.uni-heidelberg.de/vorlesung/20222/1611/lecture

Date	Topic
19.10.2022	Introduction and basic definitions
26.10.2022	Accelerating structures
02.11.2022	Accelerator Components
09.11.2022	Optics with magnets (1)
16.11.2022	Optics with magnets (2)
23.11.2022	Equations of motion
30.11.2022	Phase ellipses and magneto-optical system / Transverse beam dynamics
07.12.2022	Transverse beam dynamics, beam stability / Longitudinal beam dynamics
14.12.2023	Phase space and beam cooling (Invitation)
11.01.2023	Space charge and beam-beam dynamics
18.01.2023	Physics at Storage Rings
25.01.2023	Physics at Colliders
01.02.2023	New accelerator technologies
08.02.2023	Student seminar
15.02.2023	reserve
22.02.2023	reserve

Wednesdays, 14:15-16:00

„Leistungskontrolle“

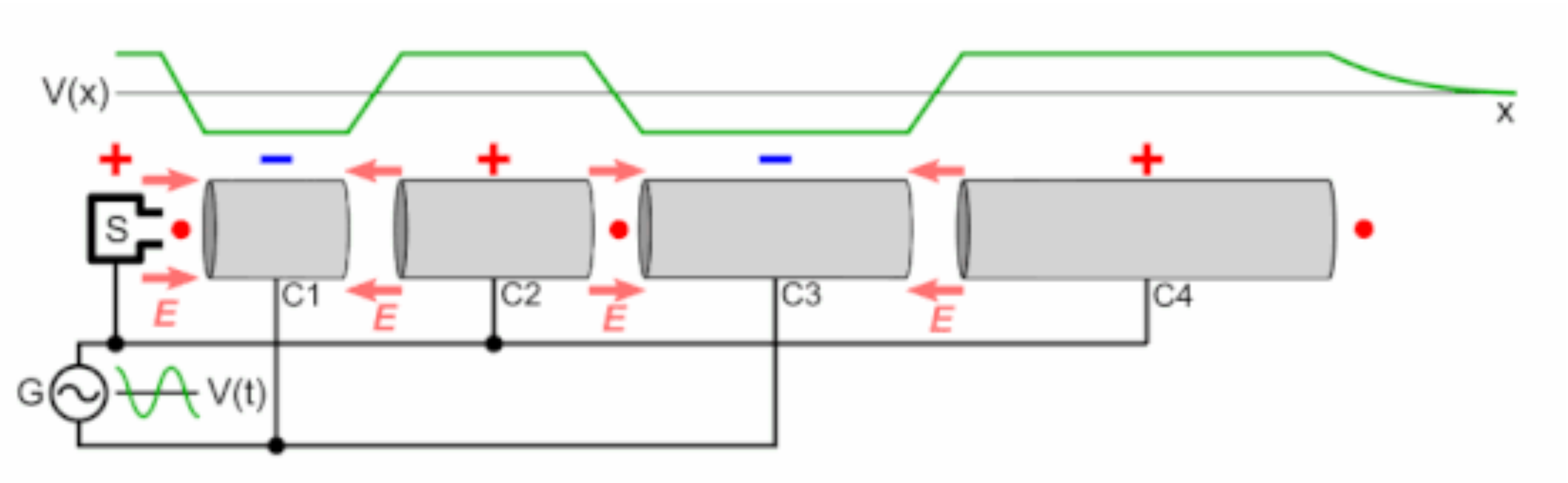
Accelerator Physics Related Applications

- *Particle cancer therapie*
- *Cosmic rays*
- *Accelerator Mass Spectrometry*
- *Accelerator Driven System*
- *Energy recovery accelerator*
- *Superheavy elements*
- *Strongest magnetic field*
- *Tokamak*
- *Photon facility*
- *Isotopes for medicine*
- *Crystalline beams*

2 Accelerator Types

Photo: GSI Darmstadt

Wideröe structure



Wideröe structure

Non-relativistically:

Charge

Phase difference to $\psi = 0$
(no energy gain)

$$d_i = \frac{1}{f_{HF}} \sqrt{\frac{iQU_0 Sin(\psi_S)}{2m}}$$

Particle rest mass

Properties:

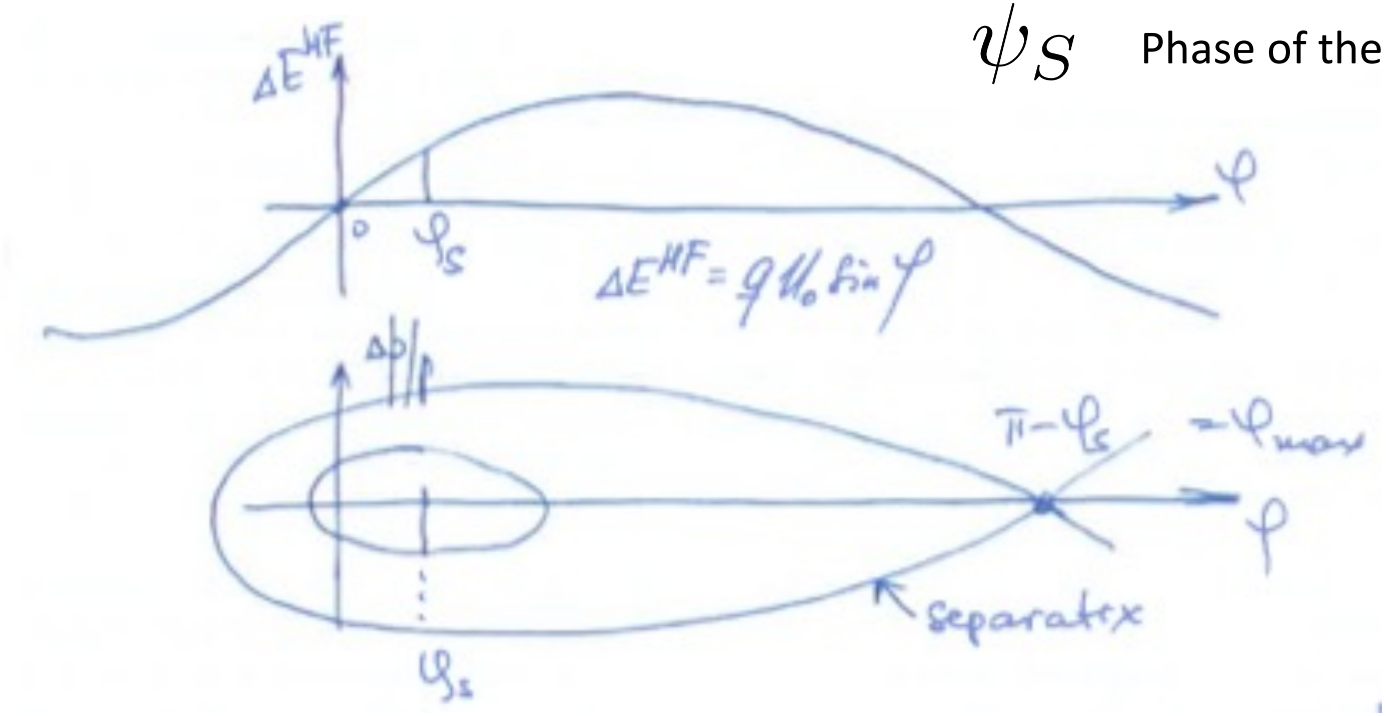
Transverse plane – defocusing >> need for extra focusing magnets (quadrupoles) later

Longitudinal plane – phase focusing Later (discovered during design of synchrotron 1944/45)

Wideröe structure

ψ_S Phase of the synchronous particle

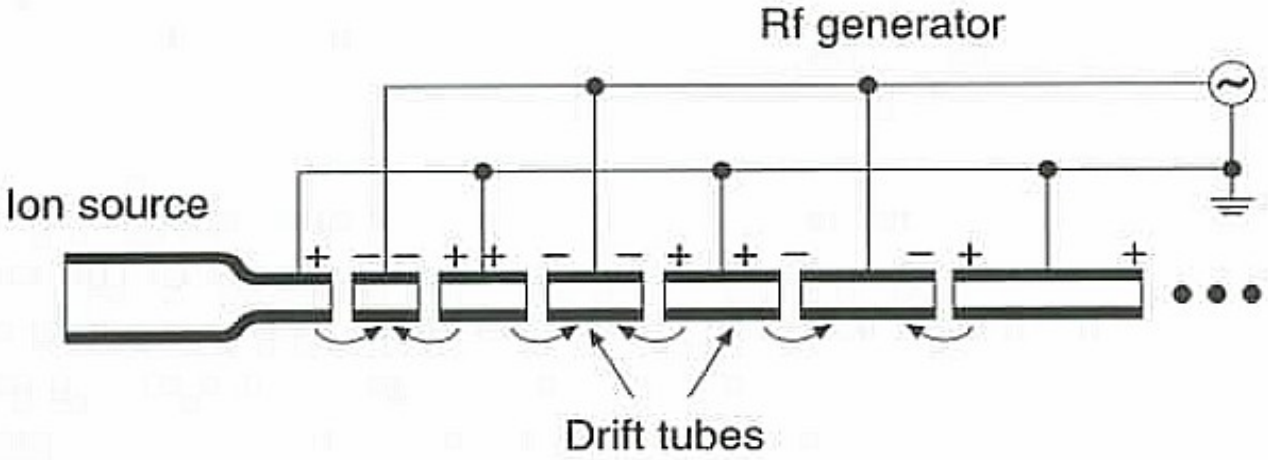
Separatix



$$\Delta E_S^{HF} = QU_0 \sin(\psi_S)$$ Average energy gain of the bunch

ψ_{min} can be obtained from $$\int_{\psi_{min}}^{\psi_{max}} (\sin(\psi) - \sin(\psi_S))d\psi = 0$$

Drift tubes (Wideröe structure):

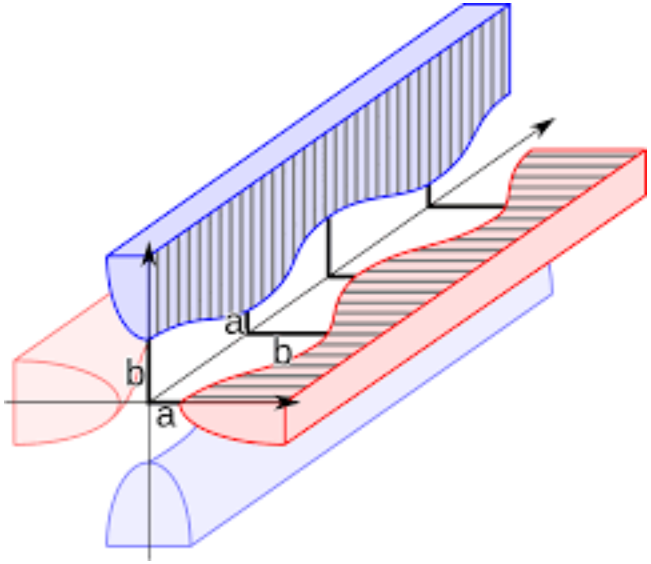


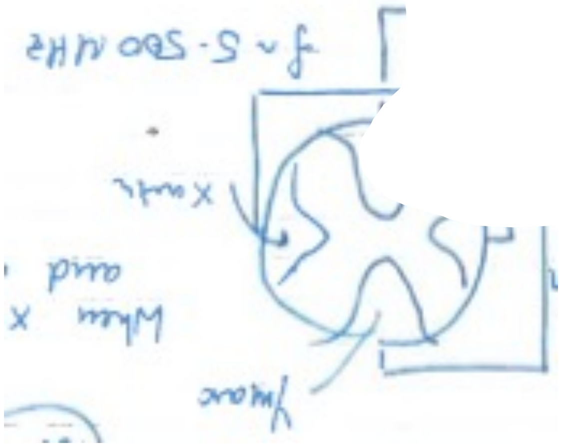
Radio-Frequency Quadrupole (RFQ)

1970 Kapinskiy & Teplyakov

Length $l = 1 - 3\ \mathrm{m}$

Sine-like shaped electrodes in z-direction



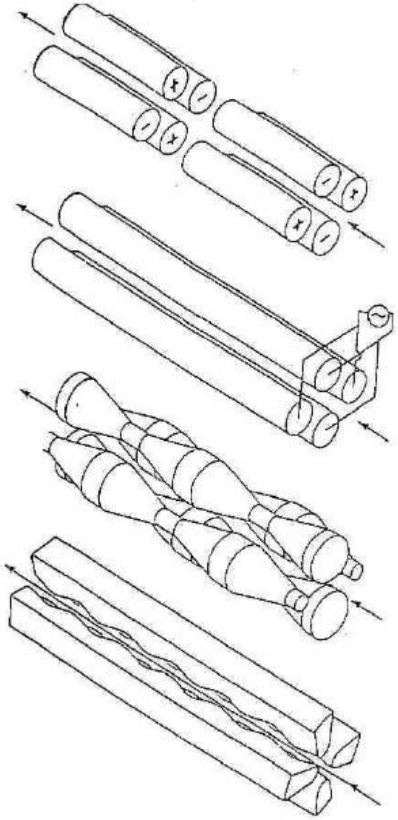


When x-min : y = max and
the other way around

$$\Downarrow$$

Field gradient in longitudinal z-direction

RFQ (2)

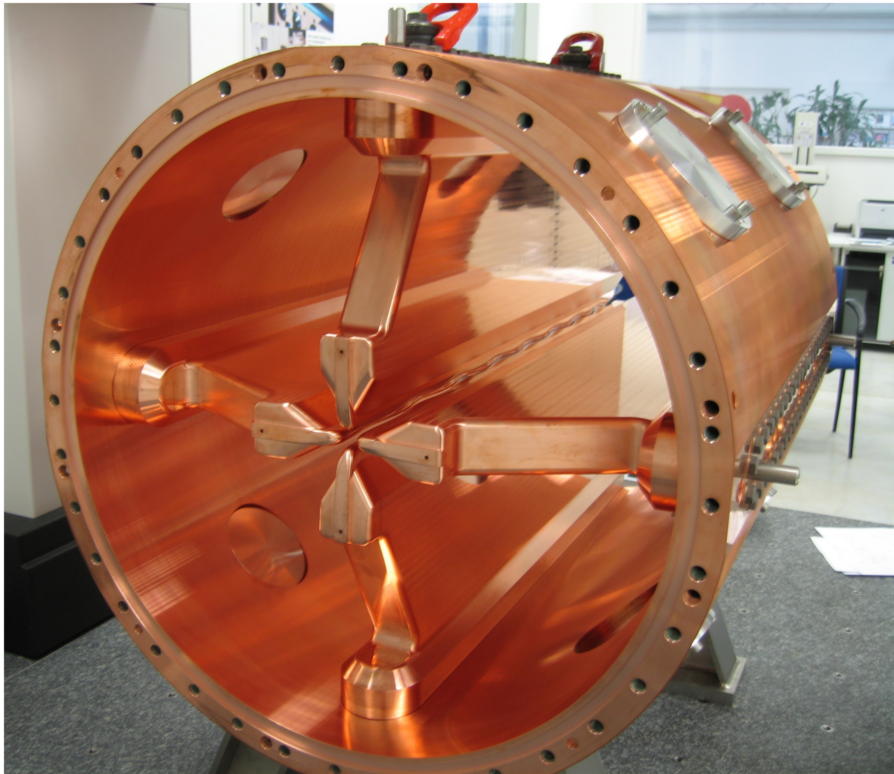


Magnetische Quadrupole
J. Blewett, PR 88 (1952) 1197
Elektrische Quadrupole
L. Teng, RSI 25 (1954) 264

HF-Quadrupol
W. Paul et. Al., Z. Physik 140 (1955)

RFQ
I. Kapchinski, V. Teplyakov
Prib. Tekh. Eksp. 4 (1979) 17

RFQ mit Vane-Elektroden
(aktuelle Bauweise)



RFQ (3)

Properties:

- Transverse focusing
- Adiabatic longitudinal focusing
- About 100% effciency (!)

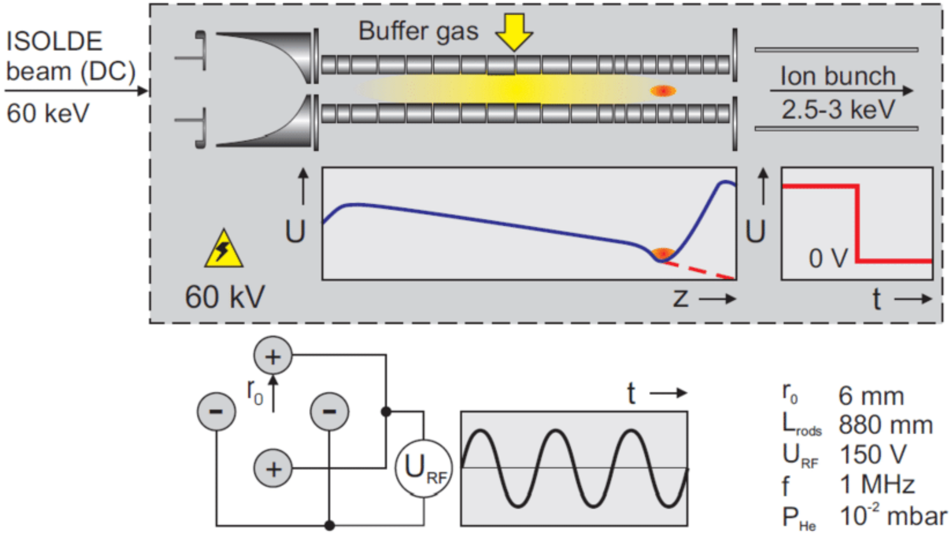
Typical operation regime

$$E_{p,HI} \approx 10 \text{ keV/u} \rightarrow 0.5 - 2 \text{ MeV/u}$$

Continuous or pulsed operation

Numerous applications. Most frequently used as first-stage low-energy accelerations structure

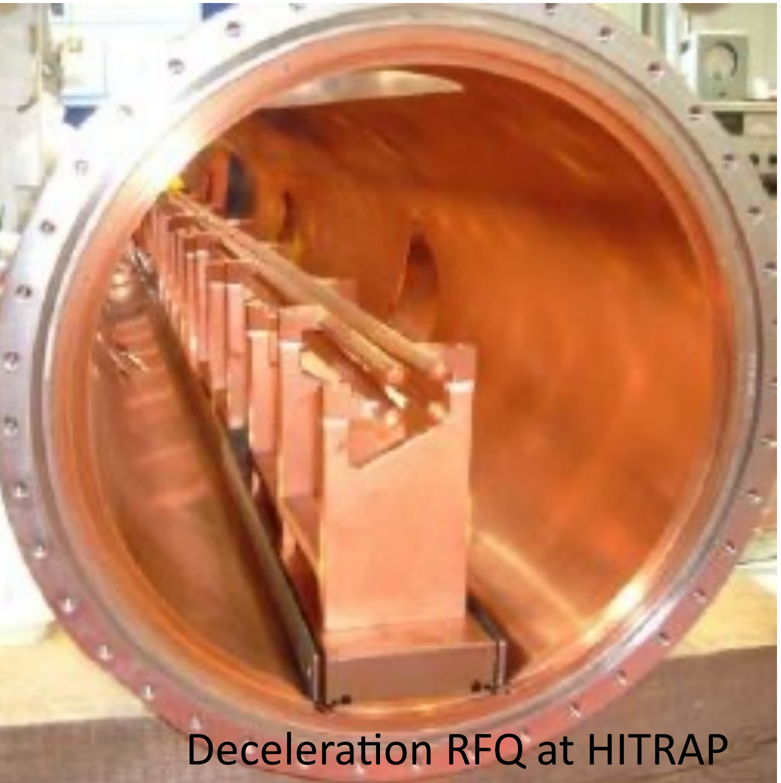
RFQ (4)



r_0	6 mm
L_{rods}	880 mm
U_{RF}	150 V
f	1 MHz
P_{He}	10^{-2} mbar

RFQ cooler & buncher at ISOLTRAP

RFQ for high-current beams



Deceleration RFQ at HITRAP

Summary from the last lecture

Acceleration of ions and electrons

Force $\vec{F} = \dot{\vec{p}} = q \cdot \vec{E}$

$\vec{E} = -\vec{\nabla} V$ **Potential difference**

How to produce large potentials?

Separatix
~~Cavity and TM/TE Modes~~

$$p = QRB$$

~~Strong Focusing~~

SLAC
S-DALINAC
MAMI
UNILAC
RIKEN

electrostatic

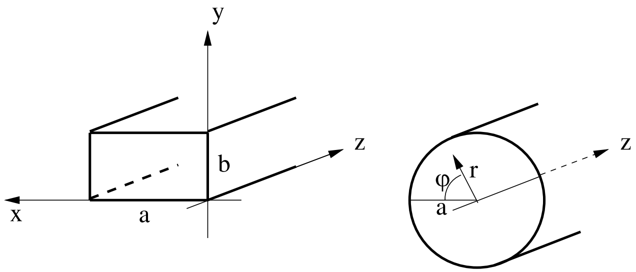
- *Cockroft and Walton Generator*
- *Dynamitron®*
- *Marx Generator*
- *Van de Graaf Accelerator*
- *Tandem Accelerator* $\frac{\Delta E}{E}(\text{beam}) \sim 10^{-4}$

High-frequency

- **Linear**
  - *Wideröe Structure*
  - *Alvarez Structure*
  - *Single resonators*
  - *Radio-Frequency Quadrupole*
  - *Waveguide / Wellenleiter*
- **Circular**
  - *Cyclotron / Microtron* $\frac{\Delta E}{E}(\text{beam}) \sim 10^{-3}$
  - *~~Synchrotron~~ / Betatron*

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Cavities/Waveguides



Rectangular and circular waveguides

From Maxwell equations:

$$\vec{\nabla}^2 \vec{E} = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \vec{E} \qquad \vec{\nabla}^2 \vec{H} = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \vec{H}$$

Assuming periodic dependency

$$\vec{E} = \vec{E}(\vec{r}) e^{i(\omega t - k_z z)} \qquad \vec{H} = \vec{H}(\vec{r}) e^{i(\omega t - k_z z)}$$

Wave number $\boxed{k_z = \frac{\omega_z}{c}}$

Cavities/Waveguides

$$\left(\vec{\nabla}^2 - \frac{\partial^2}{\partial z^2}\right)\vec{E} + \left(\frac{\omega^2}{c^2} - k_z^2\right)\vec{E} = 0$$

$$\left(\vec{\nabla}^2 - \frac{\partial^2}{\partial z^2}\right)\vec{H} + \left(\frac{\omega^2}{c^2} - k_z^2\right)\vec{H} = 0$$

Solution from boundary conditions:

$\vec{E}_{||} = 0$ parallel to conduction walls

$\vec{H}_{\perp} = 0$ orthogonal to conduction walls

- small-field components producing Eddy currents
- Field components in z-direction

E-waves	$E_z \neq 0$	$H_z = 0$	TM (Transverse H)
H-waves	$E_z = 0$	$H_z \neq 0$	TE (Transverse E)

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Cavities/Waveguides

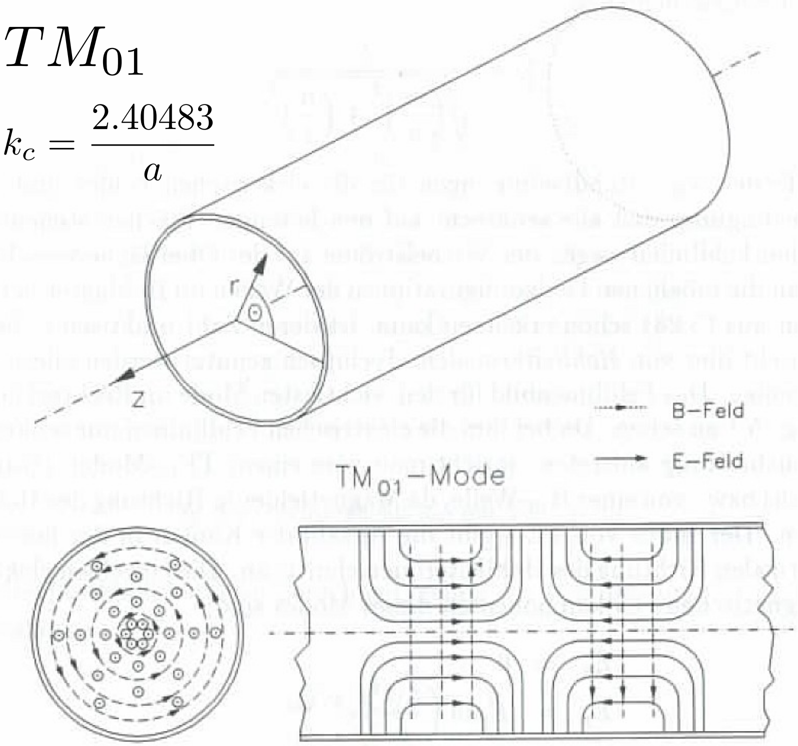
$$TE_{mn}\,(TM_{mn})$$

where

m – number of zero-crossings in x/r direction
n – number of zero crossings in y/ϕ direction

TM_{01}

$$k_c = \frac{2.40483}{a}$$



Repeat from PEP3

k_z is smaller than $k=\omega/c$ (free EM wave)
k_c – critical wave number

$$k_c^2 + k_z^2 = k^2 = \omega^2/c^2$$

Brioullin (Dispersion) diagram

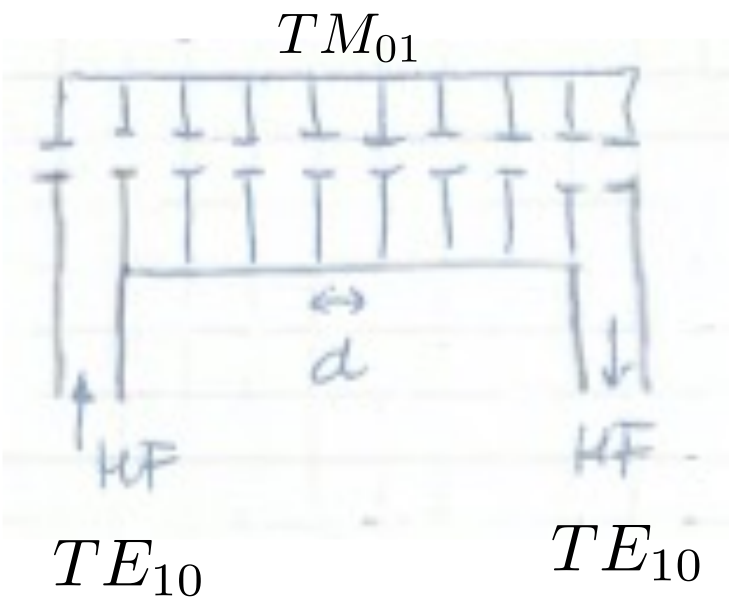
if $\omega/c < k_c$ >> k_z - Im

-phase velocity: $v_{ph} = \dfrac{\omega}{k_z} = c\dfrac{1}{\sqrt{1-k_c^2/k^2}} > c$

-group velocity:

$$v_g = \frac{d\omega}{dk_z} = \frac{c^2 k_z}{\omega} = c\sqrt{1-k_c^2/k^2} << c$$

Waveguide with Iris-holes



To cope with $v_{ph}>c$ iris holes can be used (interference filter)

Example, SLAC structure

$$v_{ph} \approx c \qquad k_z = \frac{2\pi}{3d} \qquad \lambda_z = 3d$$

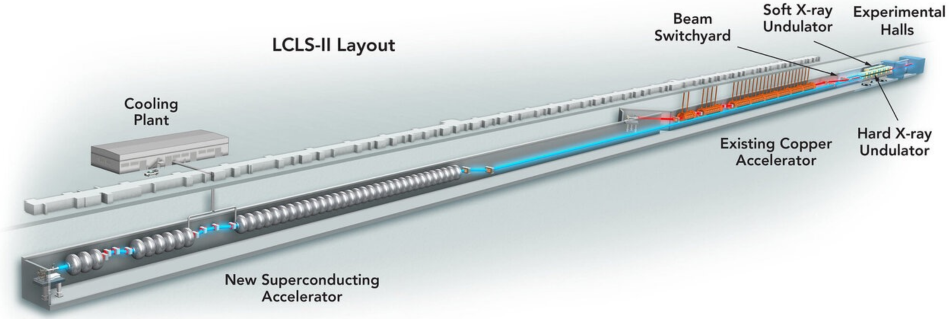
For P=10 MW >> E~10 MV/m

Acceleration of electrons

Stanford Linear Accelerator Center
2009 Linac Coherent Light Source

Waveguide with Iris-holes

Stanford Linear Accelerator Center



Linac Coherent Light Source I & II

Resonator Cavities

Standing wave – superposition of direct and reflected waves

Resonance condition:

$$L = q\frac{\lambda_z}{2} \Rightarrow k_z = \frac{q\pi}{L}$$

length

with q=0, 1, 2, ...

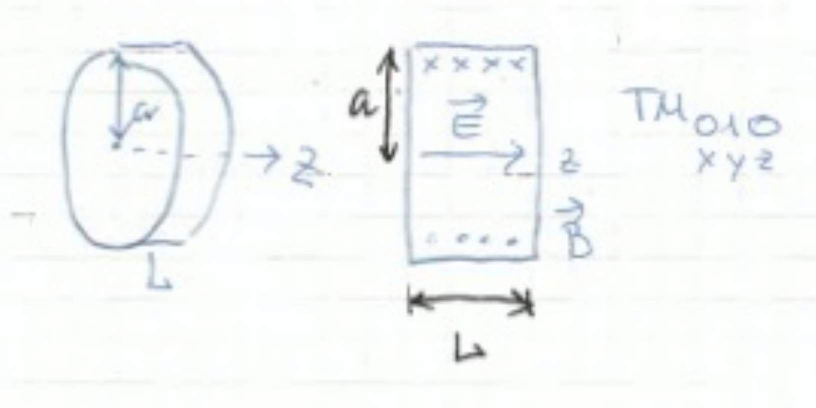
only for TM mode

q=0 (TM mode only) $\Rightarrow \lambda_z = \infty,\ k_z = 0$ field is independent of z

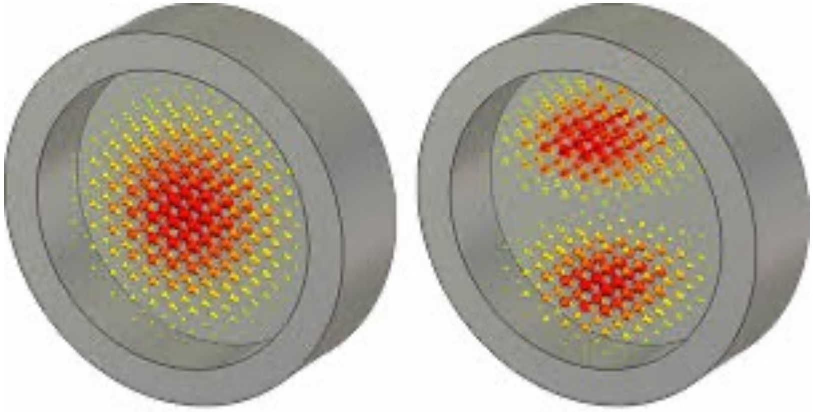
Resonator Cavities

Resonant frequency for a given q: $\omega = c\sqrt{k_z^2 + k_c^2}$

The simplest cavity – pill-box cavity

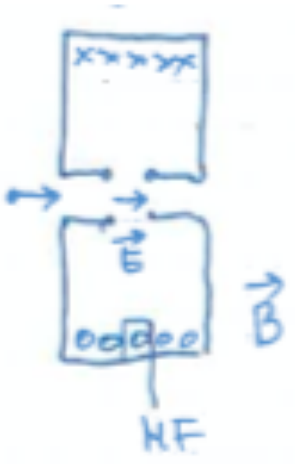


Resonance frequency: $\nu = \dfrac{2.40483c}{2\pi a}$



(a)TM_{010}. (b)TM_{110}.

Single resonator / Einzelresonator



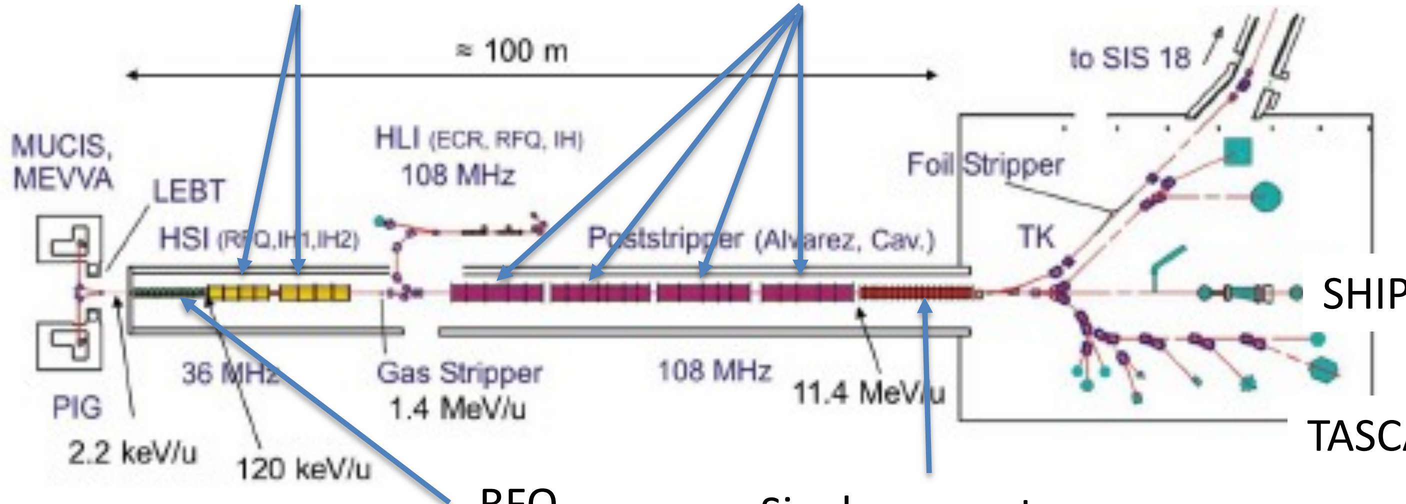
Inductive coupling

- Flexibility: synchronization between individual single resonators can specially be tuned
- A sequence of songle resonators allows for accurate and simple energy tuning

Topic:
Superheavy Elements

Wideröe structures

Alvarez structures



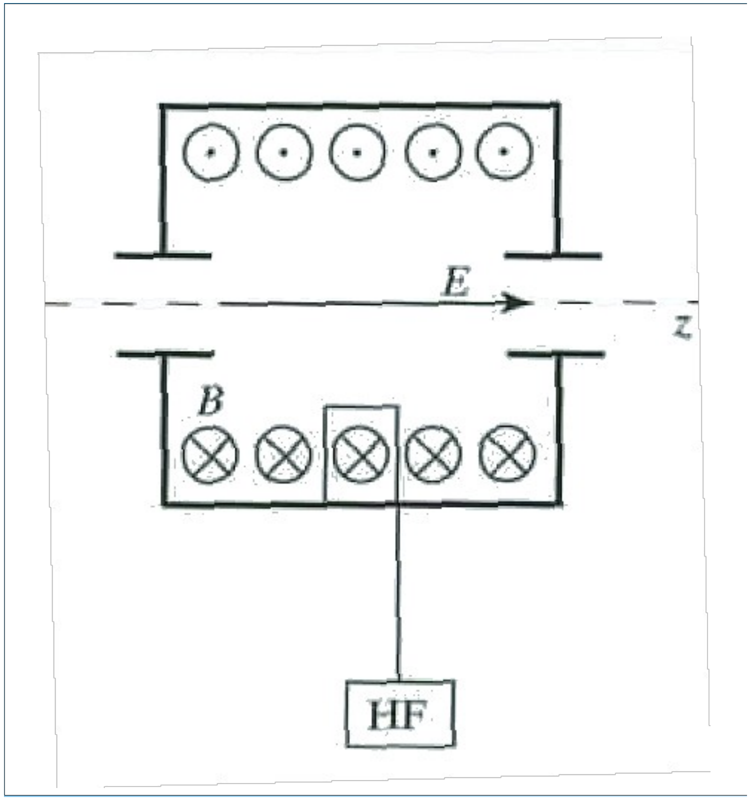
SHIP

TASCA

RFQ

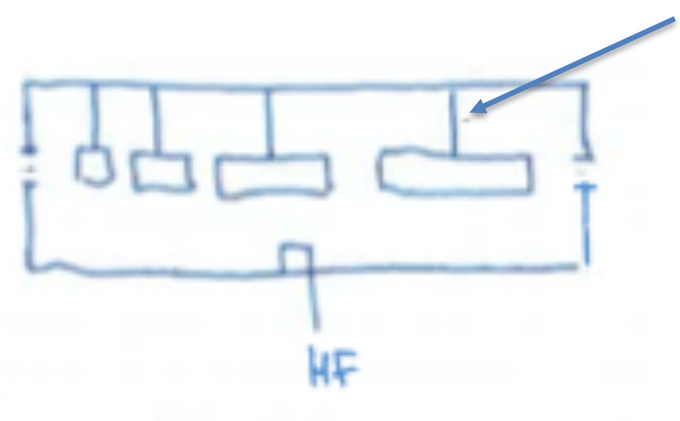
Single resonators

Single resonator



Alvarez Structure

A series of single resonators without separation walls

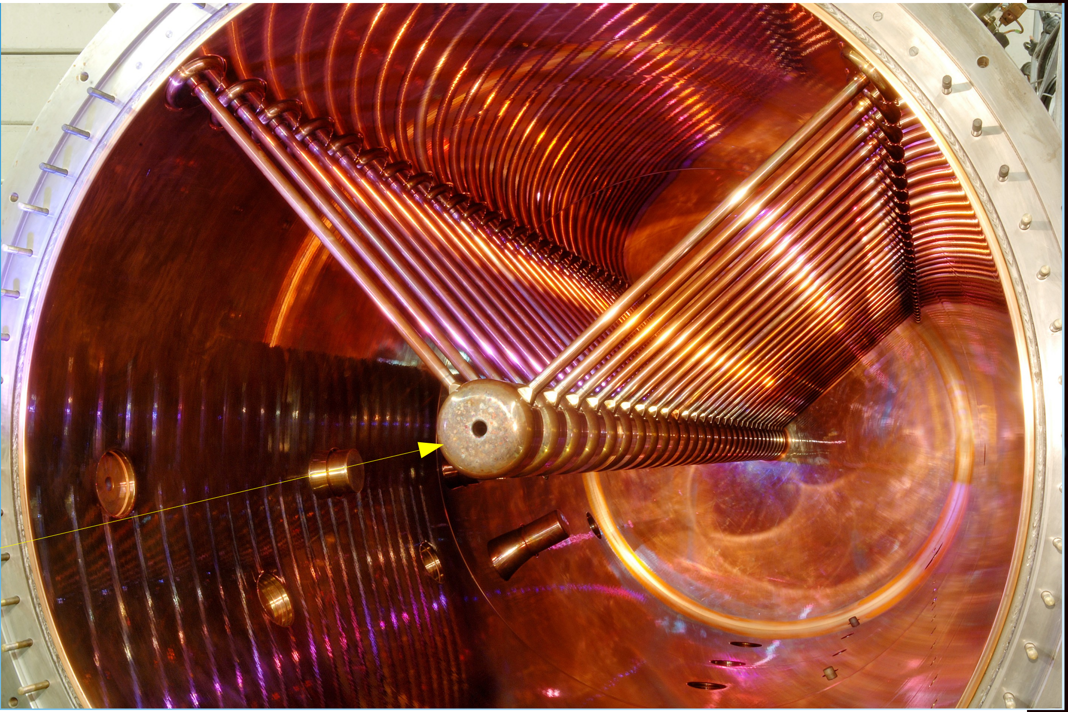


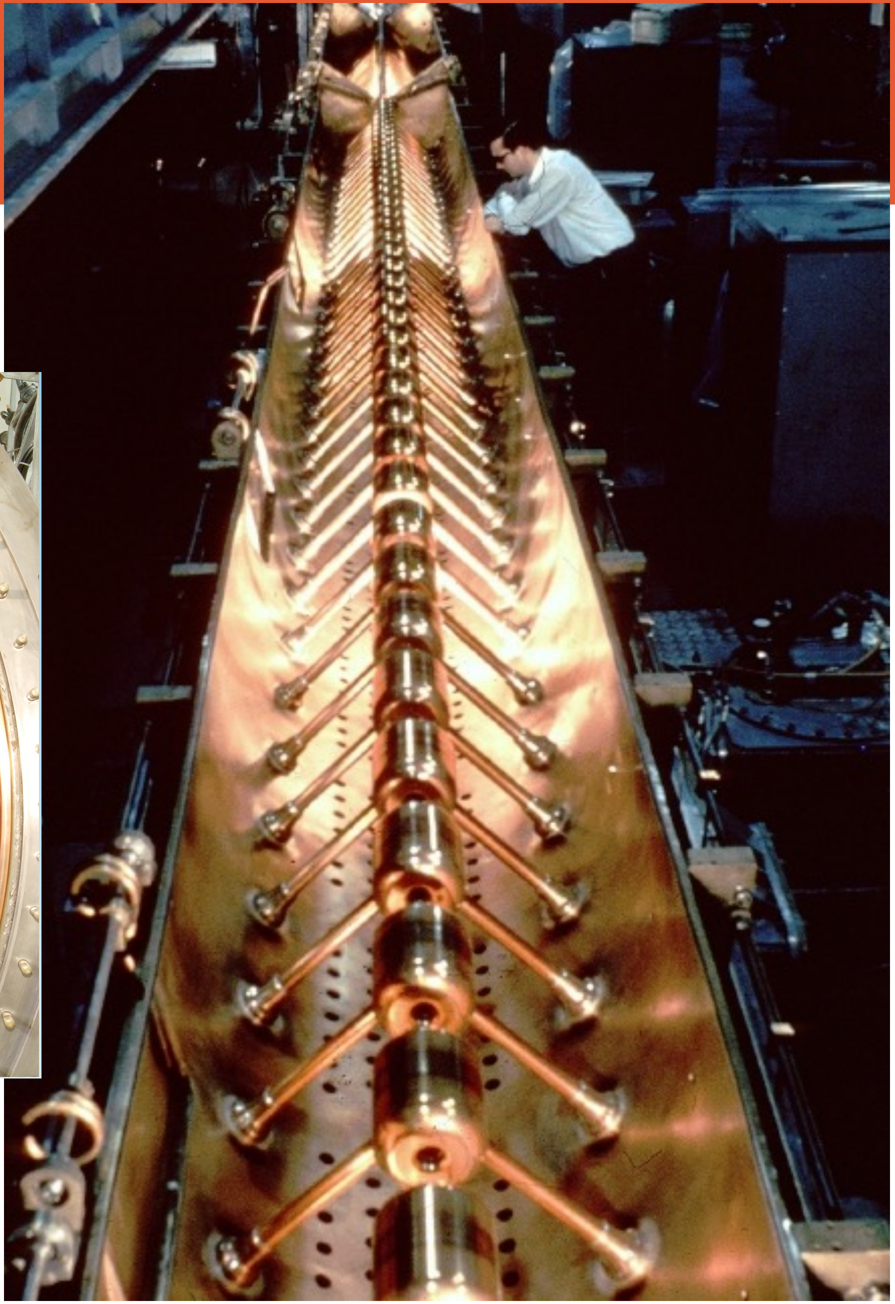
Thin holders (also cooling water)

Each drift tube is aligned separately

Typical resonance frequencies 100-200 MHz

Alvarez Structure





Ring Accelerators

Most efficient use of cavities

Problem:

$$p = \underset{\text{charge}}{Q}\,\overset{\text{radius}}{R}\,\underset{\text{Magnetic flux density}}{B}$$

If B-fixed $\Rightarrow \quad p \propto R$ cyclotron / microtron (electrons)

If R-fixed $\Rightarrow \quad p \propto B$ synchrotron / betatron (electrons)

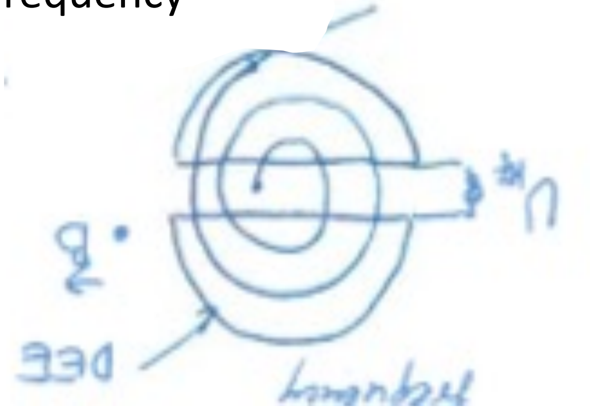
Cyclotron (Classic)

$$\omega = \frac{Q}{\gamma m} B = const$$

Revolution frequency

If $\gamma \approx 1$ non-relativistic approximation

D-shaped electrodes



$$\nu_c = \frac{1}{2\pi} \frac{Q}{m} B$$

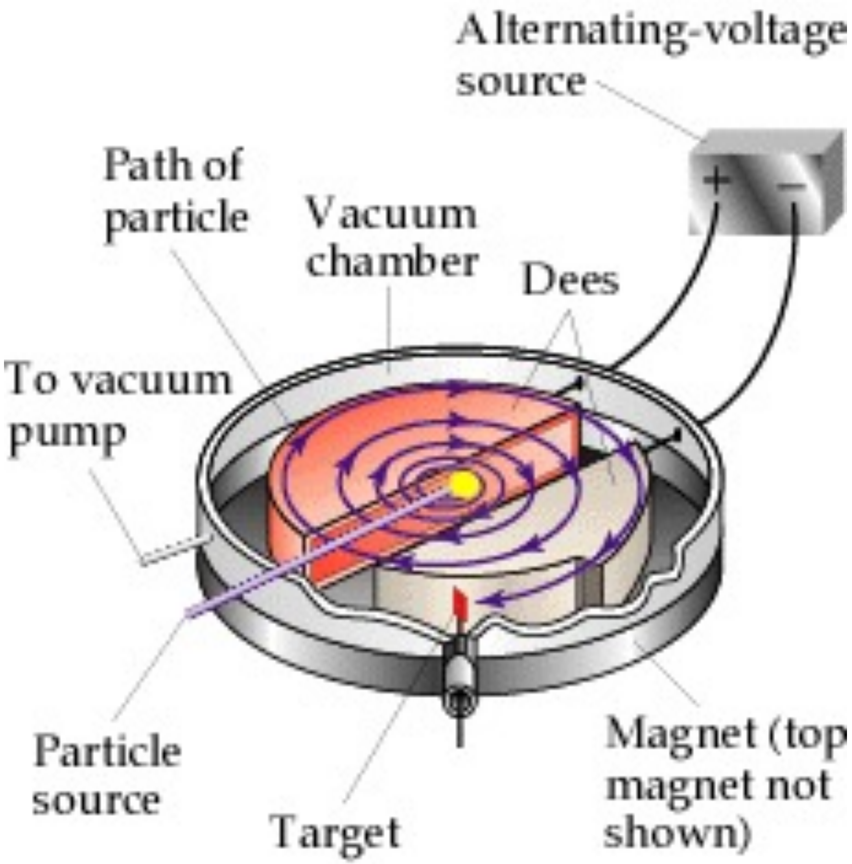
ν_c ~ 5-20 MHz

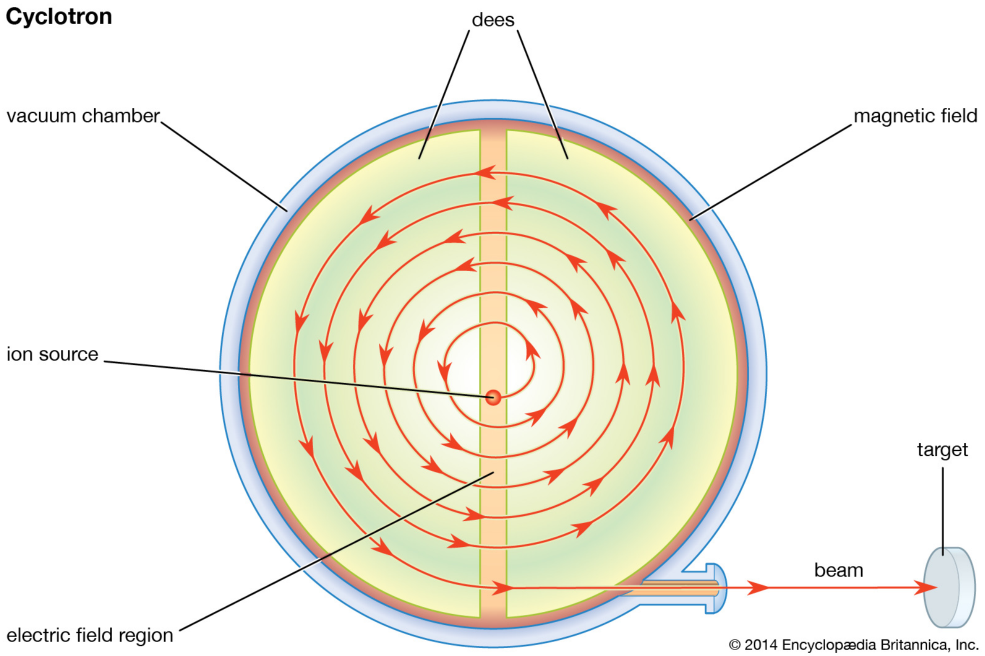
Example: *B*=1 T ν_c(p) = 15.2 MHz
ν_c(d) = 7.6 MHz

Energy gain $\Delta E = Q U_0 Cos(\psi)$

($\psi = 0$ is for $\Delta E = max$)

Cyclotron




Cyclotron

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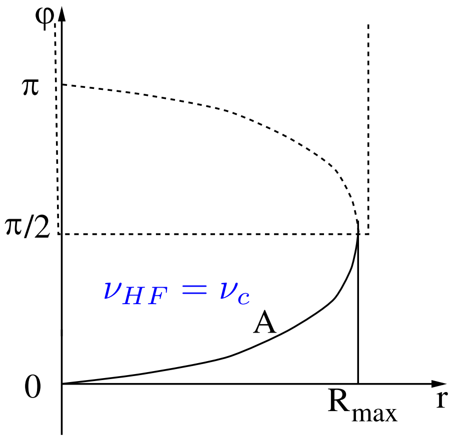
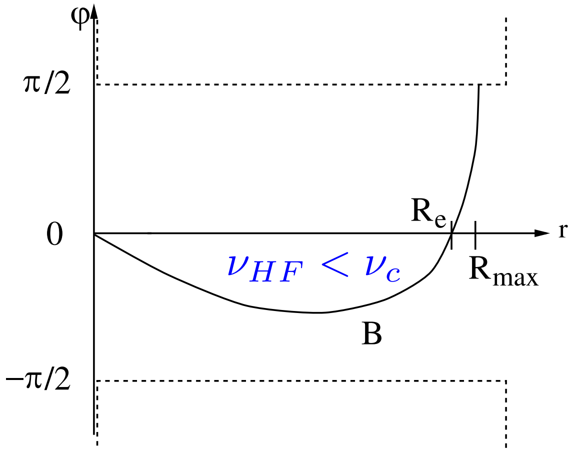
Cyclotron (Classic)

Problem: ω is not constant and gets smaller with larger radius

- Relativistic mass
- Reduction of magnetic field B away from center





R_e – radius at extraction

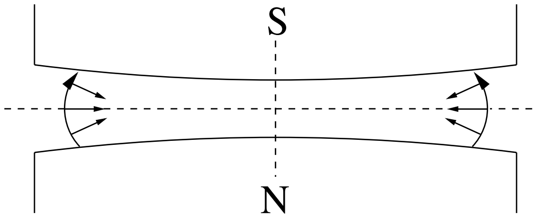
Maximal separation in energy

Maximal intensity: R_e~R_{max}

Properties: Relatively high U_0 up to several 100 kV

Acceleration within a few 10 revolutions

Stability:



Lorentz force acts to keep particles in the plane

Cyclotron

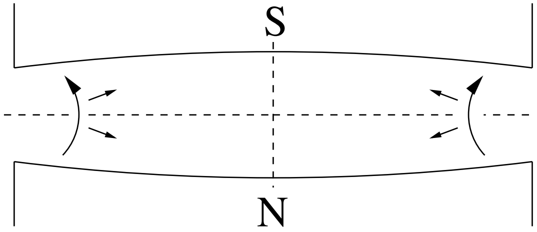
Synchrocyclotron – modulated frequency of the HF

$$\nu_{HF} = \frac{1}{2}\frac{Q}{m}\frac{B(R)}{\gamma(R)}$$

Higher energies

Low „duty cycle“

Isochronous cyclotron



Increase magnetic field with increasing radius

Challenge – defocusing force

Strong Focusing Principle

1938 Thomas
1950 Christophilos
1952 Courant, Livingston and Snyder

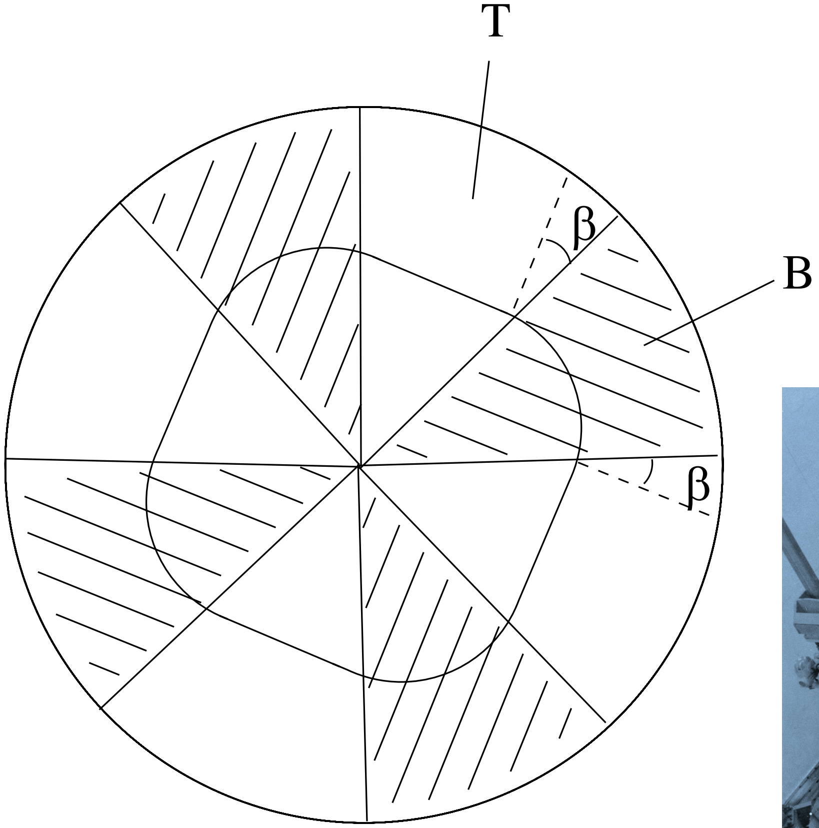
Revolutionary discovery!

The combination of a focusing and defocusing lenses of same size and same refractive index $1/f_1=-1/f_2$ have an overall focusing effect

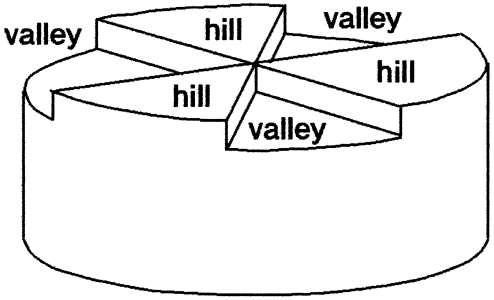
$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{D}{f_1 f_2} = \frac{D}{f_1^2}$$

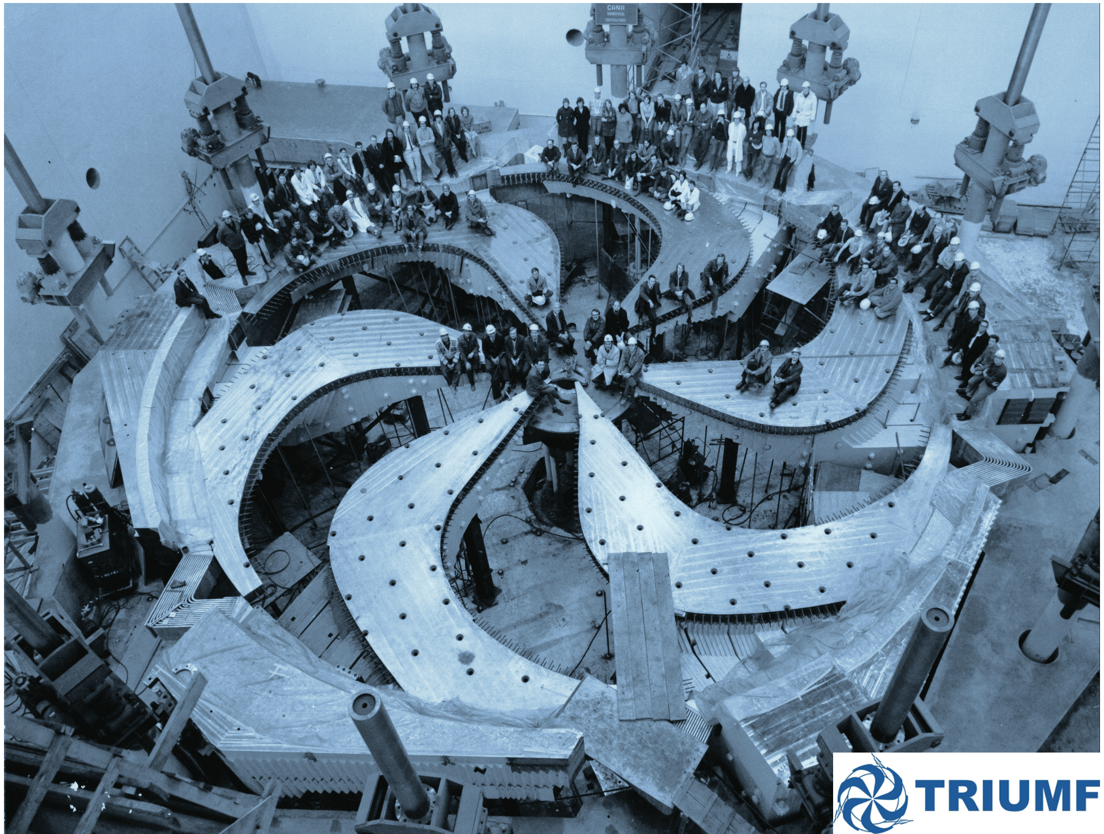
Distance
between lenses

Isochron-Cyclotron



T - Tall (valley)
B – Berg (hill)





Cyclotron

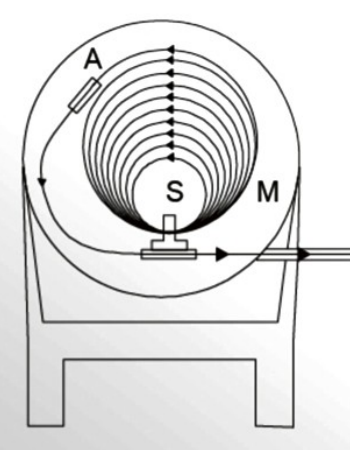
Lawrence cyclotron

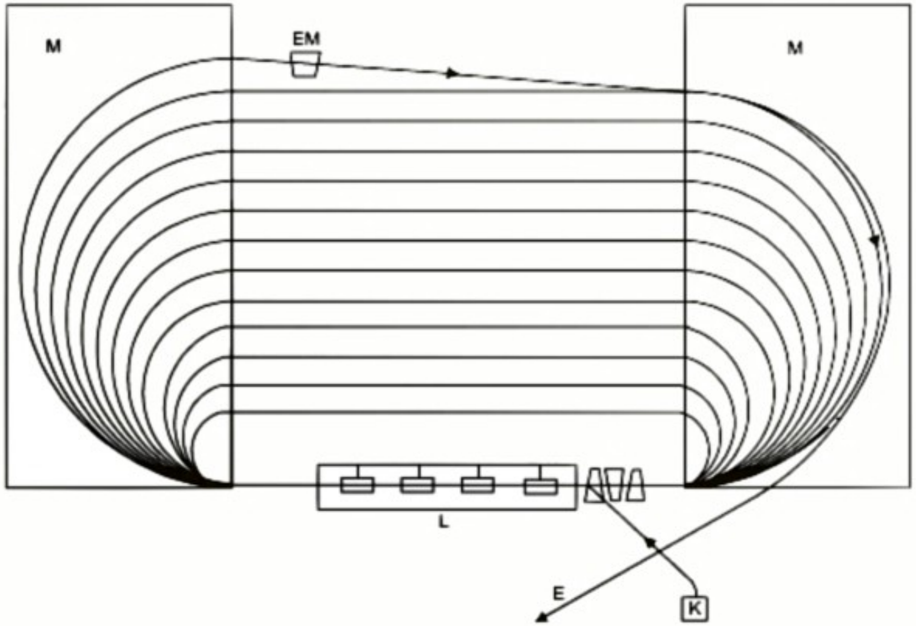
Medical purpose cyclotron

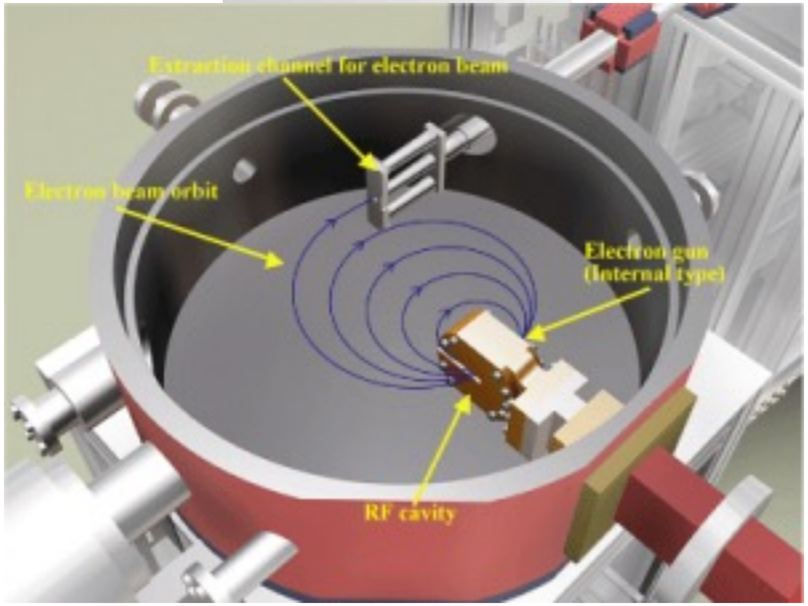
Cyclotron

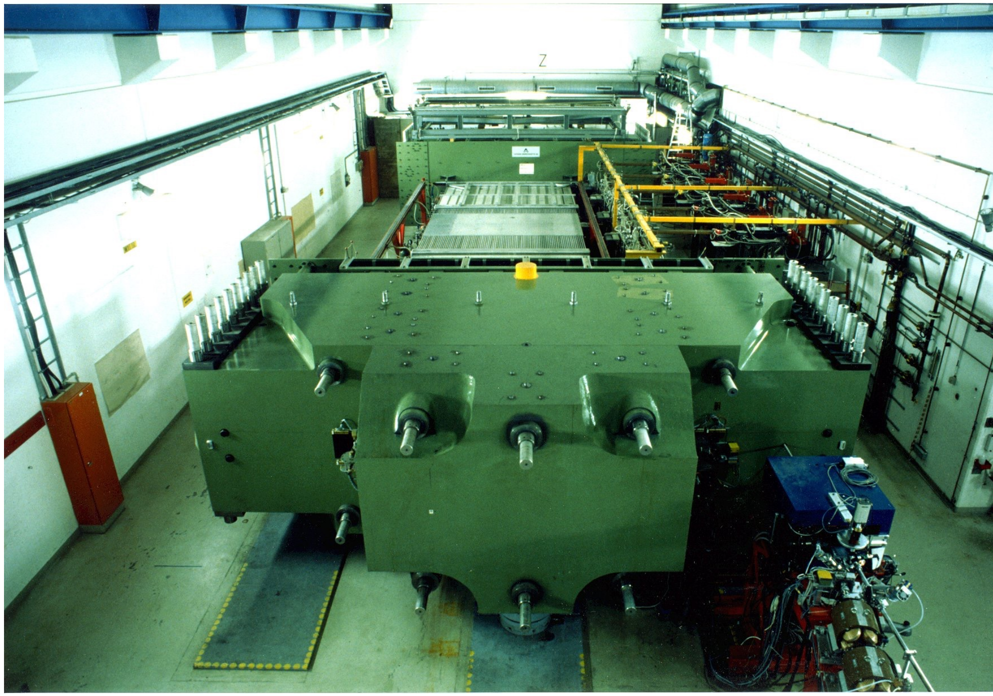
RIKEN

Microtron


A
S
M

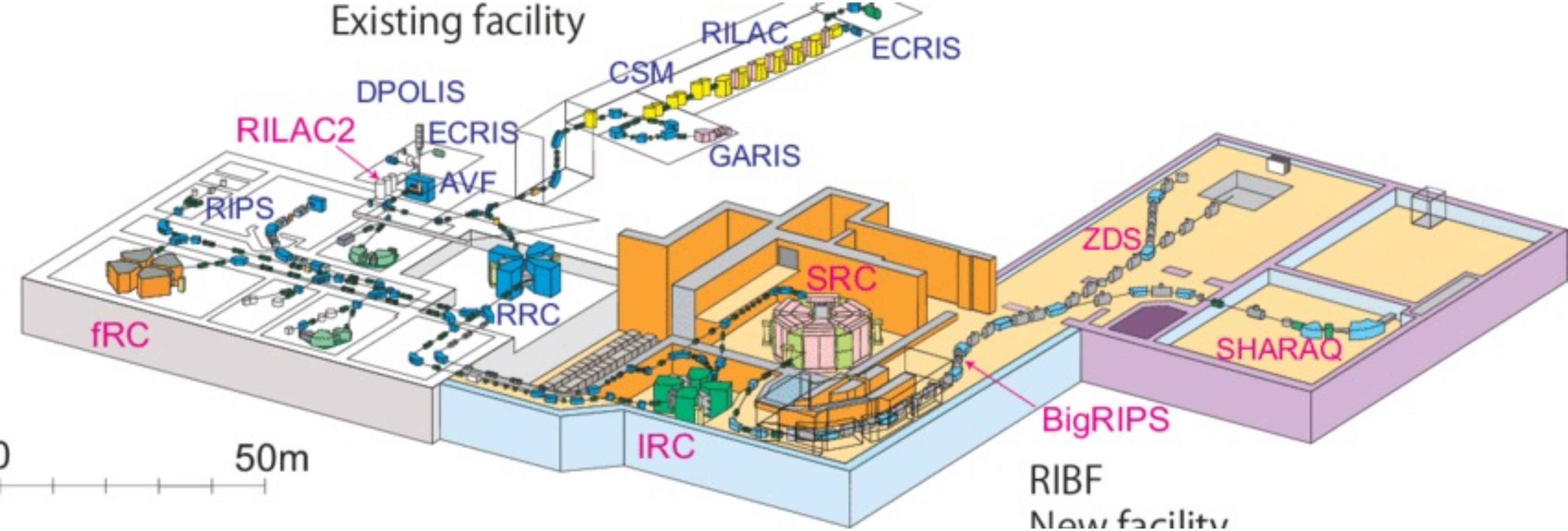

M
EM
M
L
E
K


Extraction channel for electron beam
Electron beam orbit
Electron gun (Internal type)
RF cavity



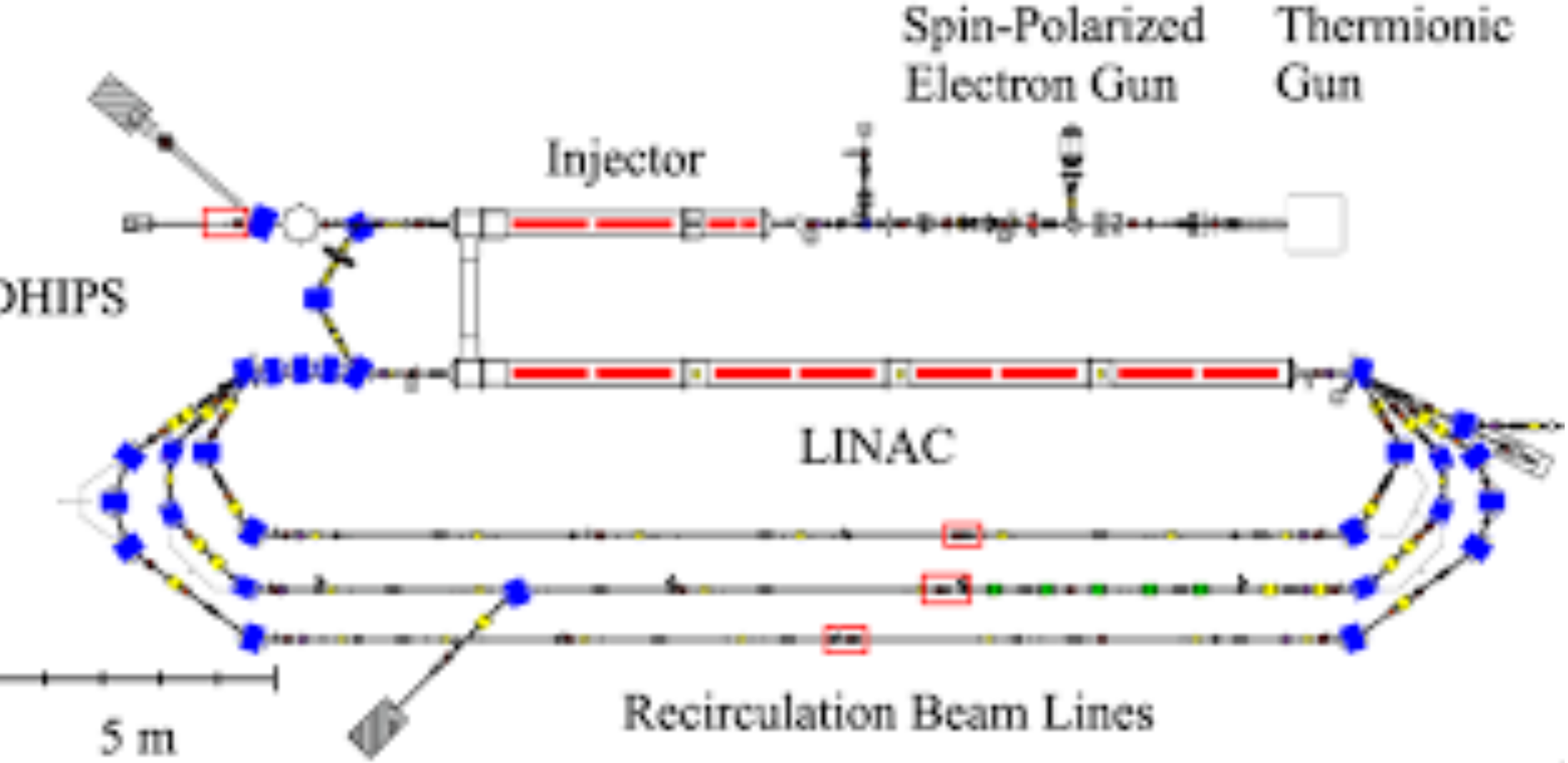
Additional slide 1: Facility at RIKEN

Multiple cyclotrons in sequence



Additional slide 2: S-DALLINAC

Electron accelerator in TU Darmstadt



Synchrotron

$$p = QRB$$

If R-fixed $\Rightarrow \ p \propto B$ synchrotron

Motion is desribed relative to the ***reference particle***

Oscillations in transverse direction – ***betatron oscillations***
Oscillations in logitudinal direction – ***synchrotron oscillations***

Field Index

For a particle deviating from a reference orbit:

$$F_c = \gamma m \frac{v^2}{R} - \frac{e}{c} v B_y(R)$$

If a small deviation *x*:

$$r = R + x = R\left(1 + \frac{x}{R}\right)$$

Taylor expansion:

$$\frac{1}{r} \approx \frac{1}{R}\left(1 - \frac{x}{R}\right)$$

$$B_y(r) \approx B_y(R) + \frac{\partial B_y(R)}{\partial x} \cdot x \equiv B_y(R) \cdot \left(1 - n \cdot \frac{x}{R}\right)$$

Field Index:

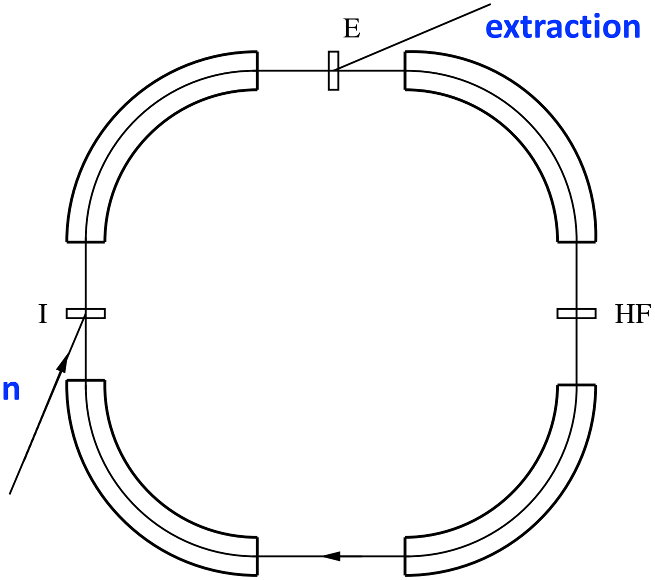
$$\boxed{n \equiv -\frac{R}{B_y(R)} \frac{\partial B_y(R)}{\partial x}}$$

Synchrotron (1)

Before discovery of the ***strong focusing principle***

Constant gradient synchrotron (CG-Synchrotron) or ***weak focusing synchrotron***

$0 < n < 1$ (Weak focusing pronciple)



Up to 1991 Synchro-phasotron in Dubna

Magnets were huge due to huge apertures needed

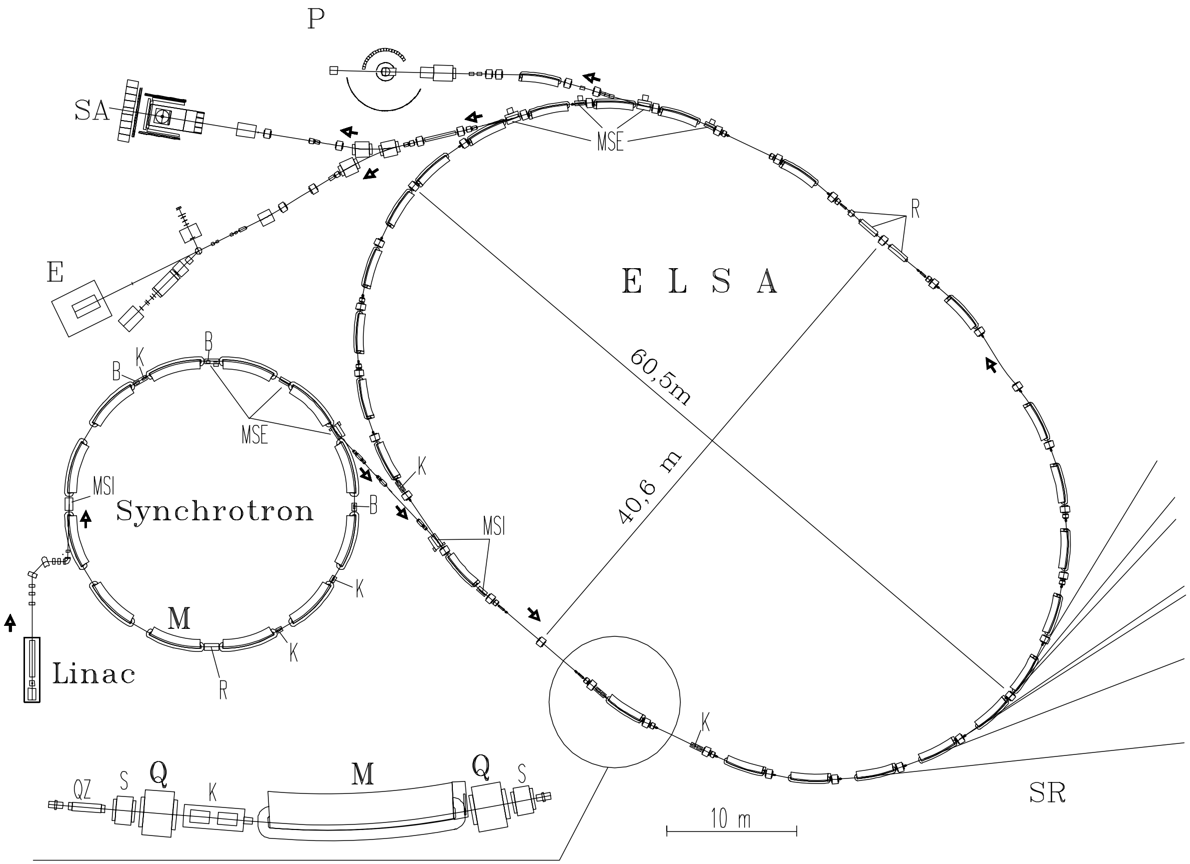
Synchrotron (2)

1952 Courant, Livingston and Snyder

$$n >> 1$$

alternating gradient synchrotron or ***strongly focusing synchrotron***

Example from Hinterberger



Combined-function synchrotron

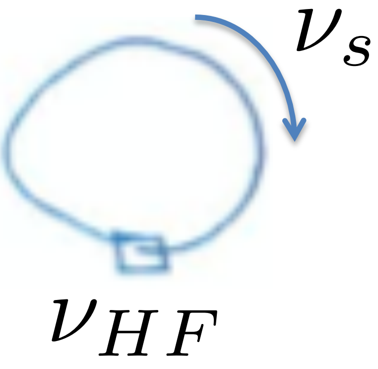
M= 1 focusing magnet, n=-22.26
1 defocusing magnet, n=+23.26

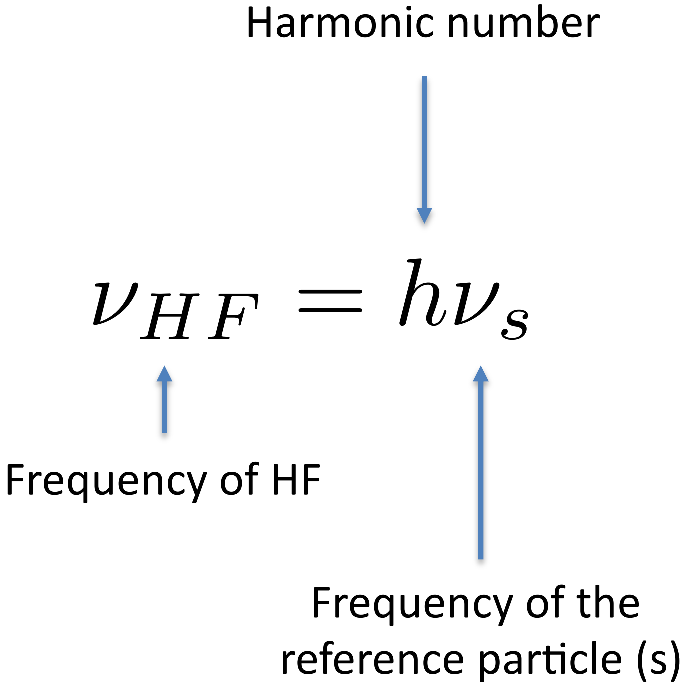
Separated-function synchrotron

M – dipole magnets
Q – quadrupole magnets
S – sextupole magnets ...

Synchrotron (3)

Acceleration





Harmonic number

$$\nu_{HF} = h\nu_s$$

Frequency of HF

Frequency of the reference particle (s)

Synchronous **ramping** of the magnetic field

Synchrotron (4)

Acceleration

Cirumference

$$\Delta E_s = C\frac{\Delta P_s}{\Delta t}$$

Energy gain
per revolution

Momentum
change in time

$$\Delta E_s = qU_0 Sin(\phi_s) + \Delta E_{bet} - \Delta E_{rad} - \Delta E_{loss}$$

betatron
acceleration

Radiation
losses

Interaction
with rest gas

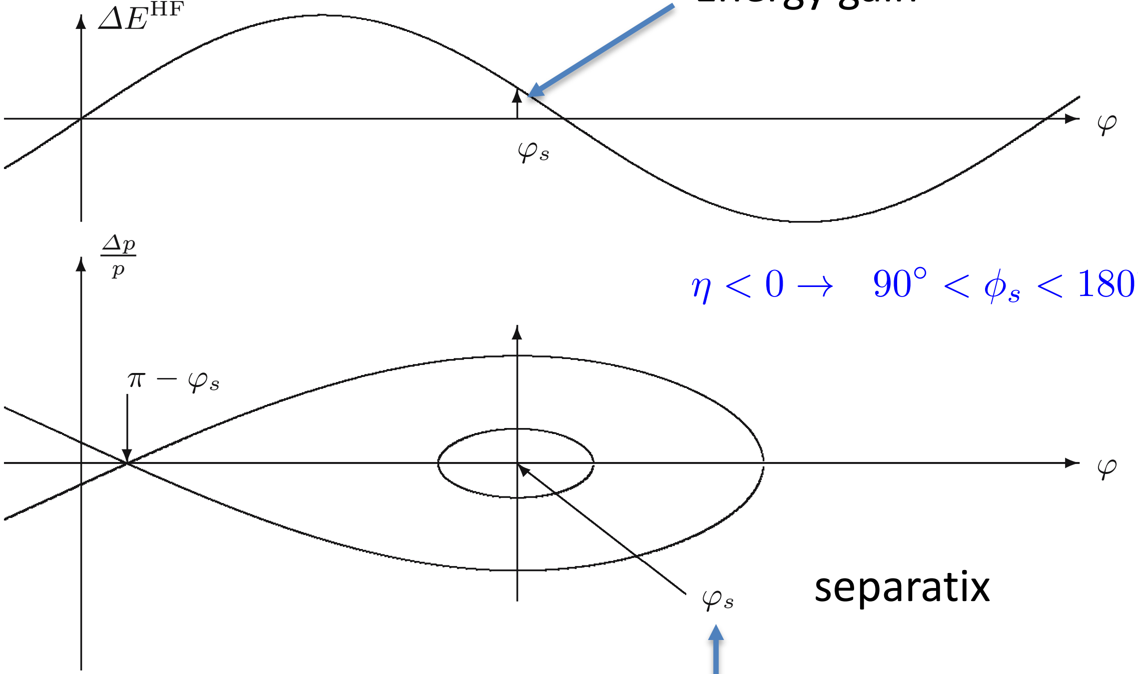
Synchrotron (5): Phase Focusing

Synchrotron principle:

$$\frac{\Delta\omega}{\omega} = \eta \frac{\Delta p}{p}$$

Dispersion of angular frequencies

η Accounts for change in velocity and in orbit length



Energy gain

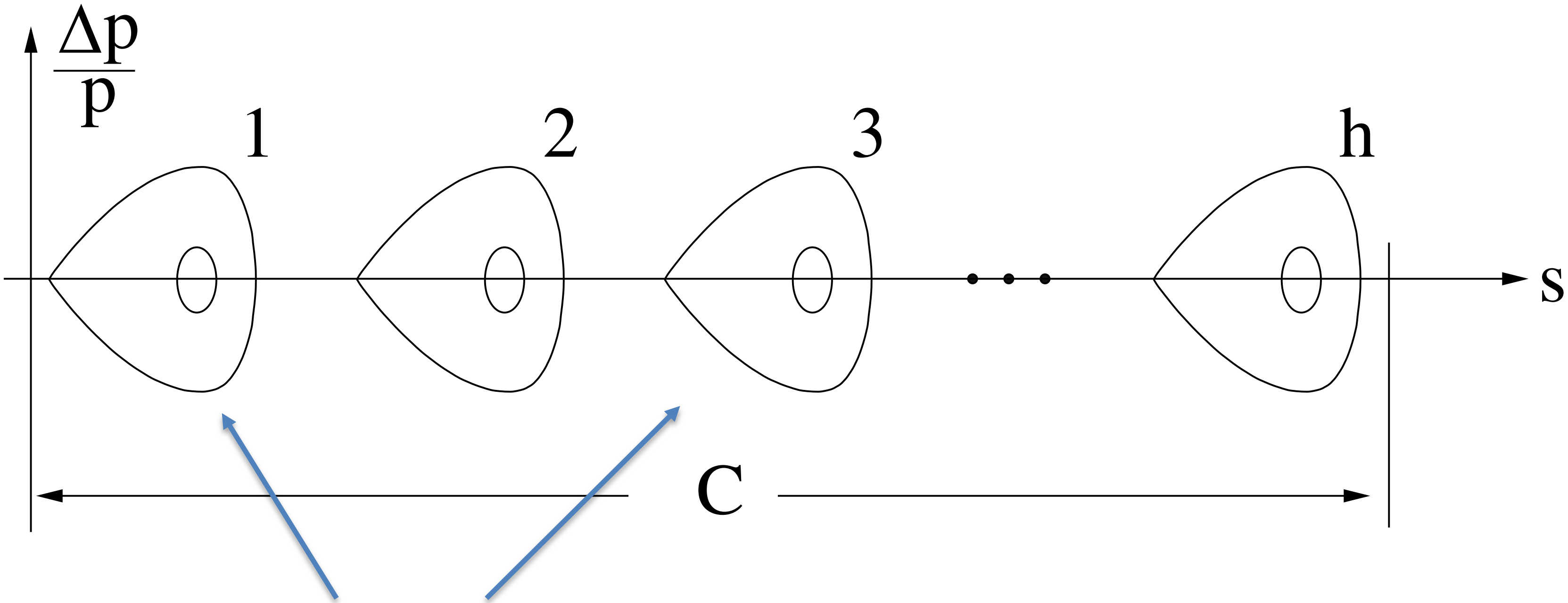
$\eta < 0 \rightarrow \quad 90^\circ < \phi_s < 180^\circ$

separatix

phase of the reference particle (s)

Phase $\varphi = 0$ corresponds to $\Delta E = 0$

Synchrotron (6): Phase Focusing



„Buckets“

$$\omega_{HF} = h\omega_s$$

h – stable regions along the circumference

Betatron

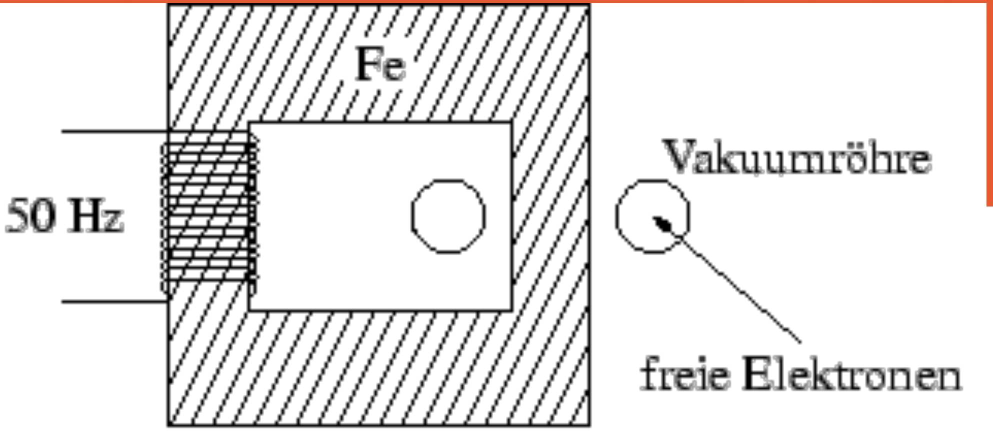
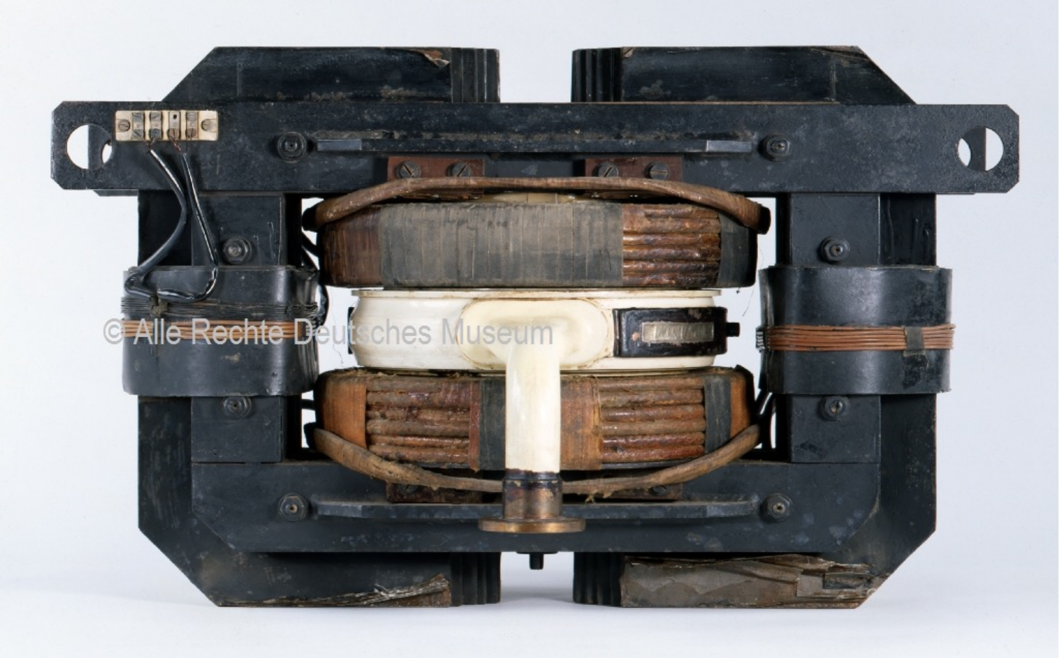


Abb. 2.7: Schematische Darstellung eines Betatrons

Faraday law

$$U_{ind} = \oint \mathbf{E} d\mathbf{s} = -\frac{d}{dt}\int \mathbf{B} d\mathbf{A}$$

$$0 < n < 1$$



6 MeV Betatron

Acceleration field $\mathbf{B_a}$
Guiding field $\mathbf{B_g}$

$$p(t) = qB_g(t)r$$

Electrons have initial momentum

Summary from the last lecture

Acceleration of ions and electrons

Force $\vec{F} = \dot{\vec{p}} = q \cdot \vec{E}$

$\vec{E} = -\vec{\nabla} V$ **Potential difference**

How to produce large potentials?

Separatix
Cavity and TM/TE Modes

$$p = QRB$$

Strong Focusing

SLAC
S-DALINAC
MAMI
UNILAC
RIKEN

electrostatic

- *Cockroft and Walton Generator*
- *Dynamitron®*
- *Marx Generator*
- *Van de Graaf Accelerator*
- *Tandem Accelerator* $\frac{\Delta E}{E}(\text{beam}) \sim 10^{-4}$

High-frequency

Linear

- *Wideröe Structure*
- *Alvarez Structure*
- *Single resonators*
- *Radio-Frequency Quadrupole*
- *Waveguide / Wellenleiter*

Circular

- *Cyclotron / Microtron* $\frac{\Delta E}{E}(\text{beam}) \sim 10^{-3}$
- *Synchrotron / Betatron*

3 Ion sources

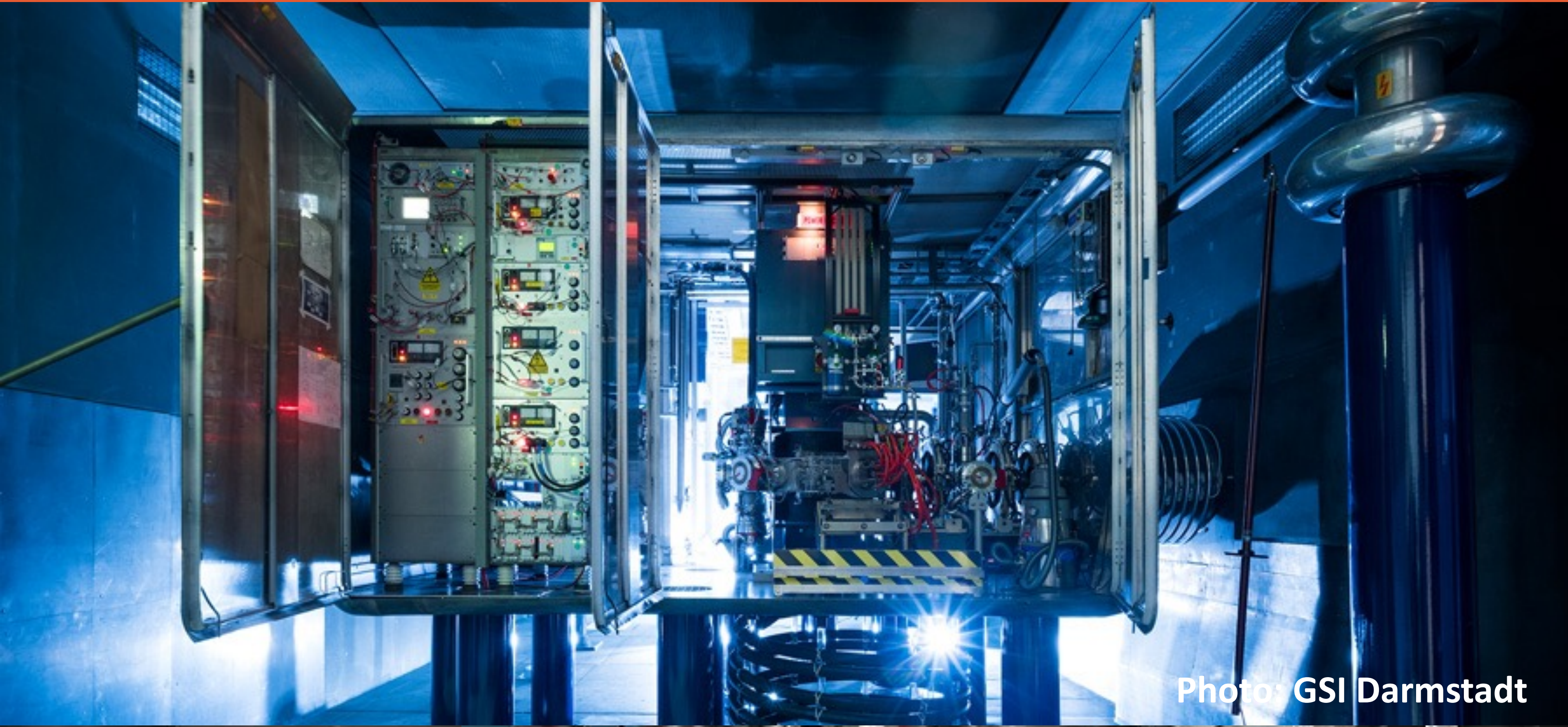
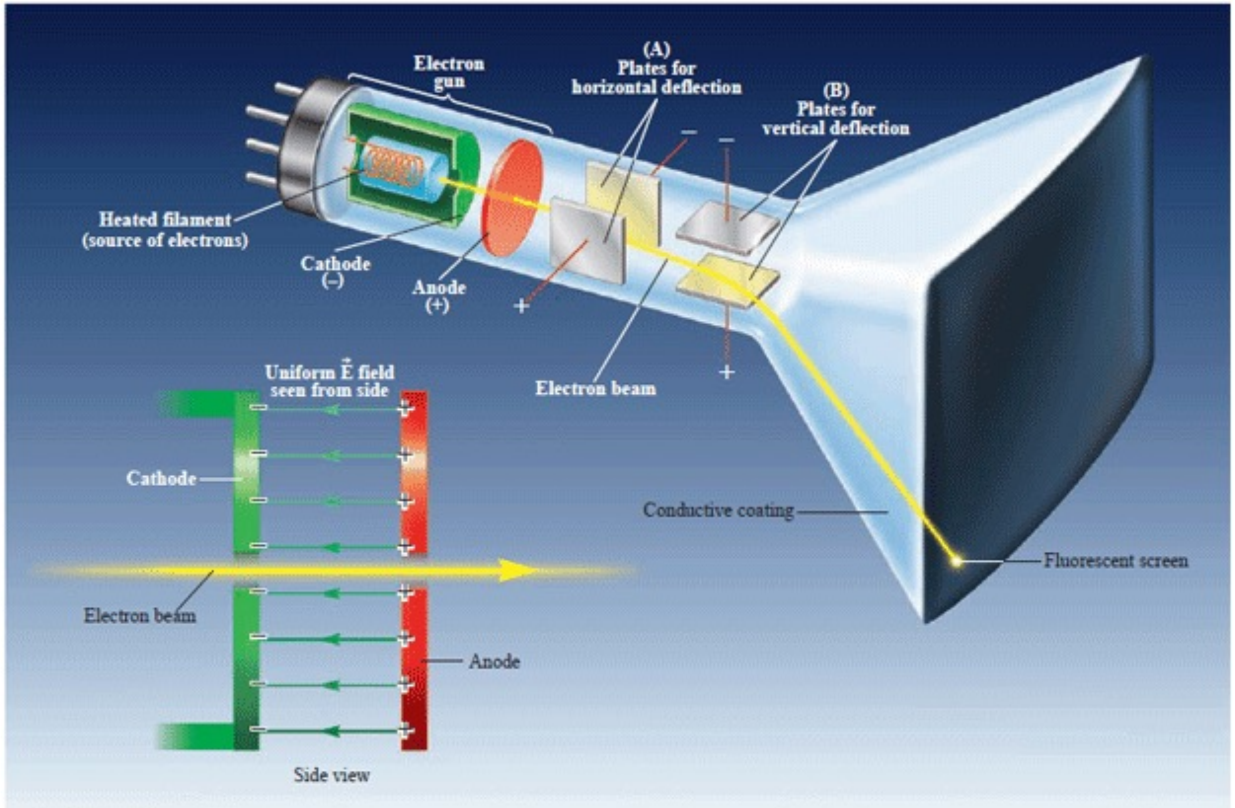


Photo: GSI Darmstadt

Production of electrons

Photos: Wikipedia

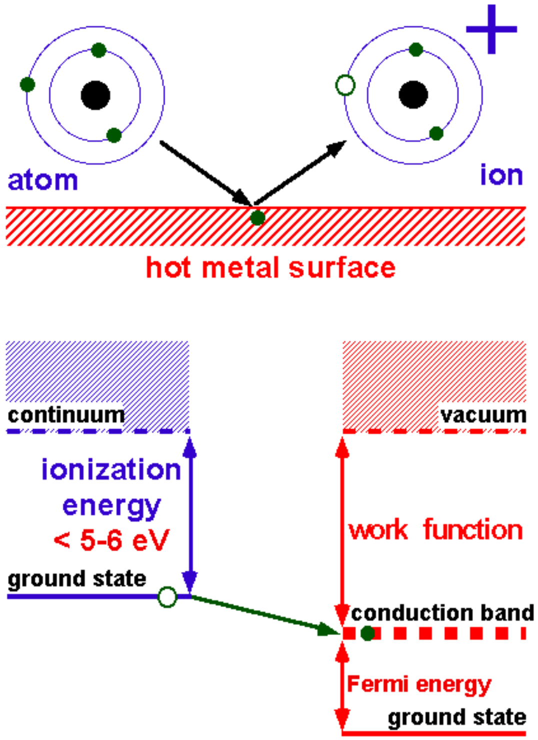


Edison emission (thermal)
Field emission – microscopes
Photo-emission

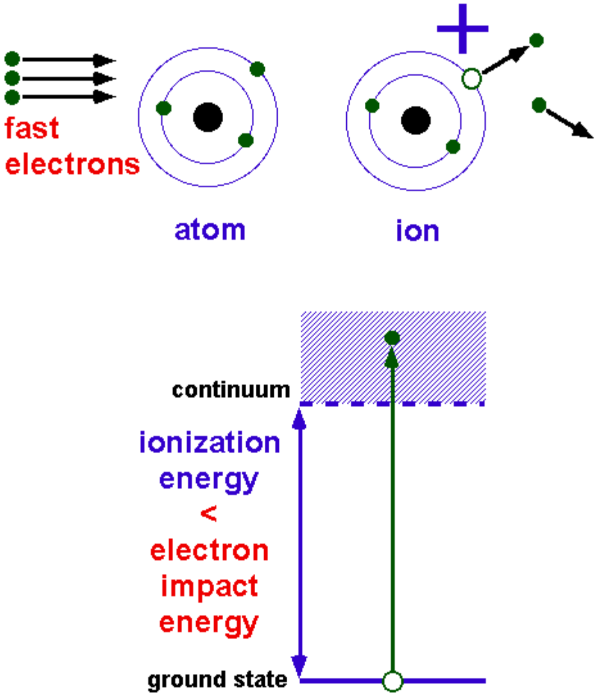
©2001 HowStuffWorks

Ionization possibilities

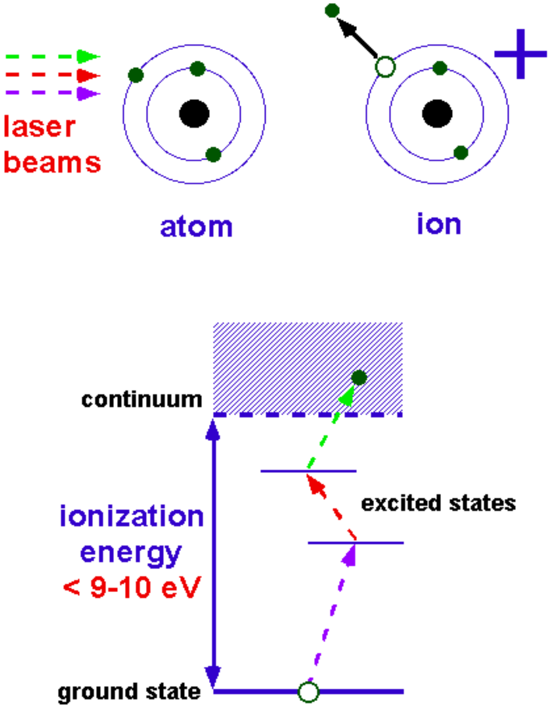
Surface ionization



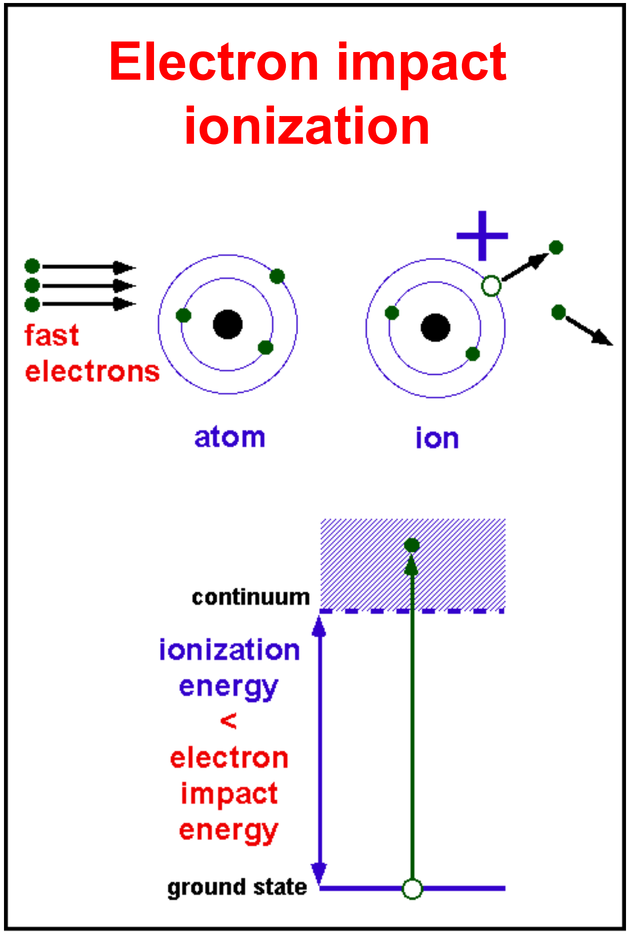
Electron impact ionization



Laser ionization

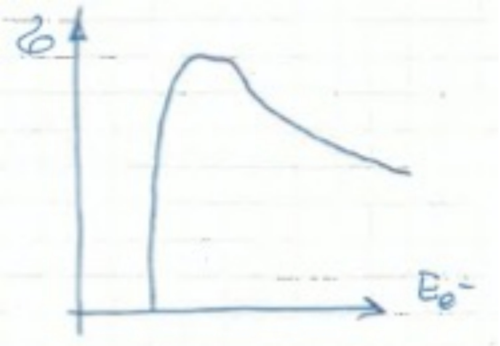


Ionization possibilities



Electron-impact ionization

$$e^- + A \rightarrow 2e^- + I^+$$



$$E_i \geq \text{Ionization energy of A}$$

Simple scheme of a source

$$\sigma_i = N\pi\rho^2 = N\pi\frac{e^4}{E_i^2}f\left(\frac{E}{E_B}\right)$$

Ionization Cross-section

Collision parameter

Energy transfer

Energy of bound electron

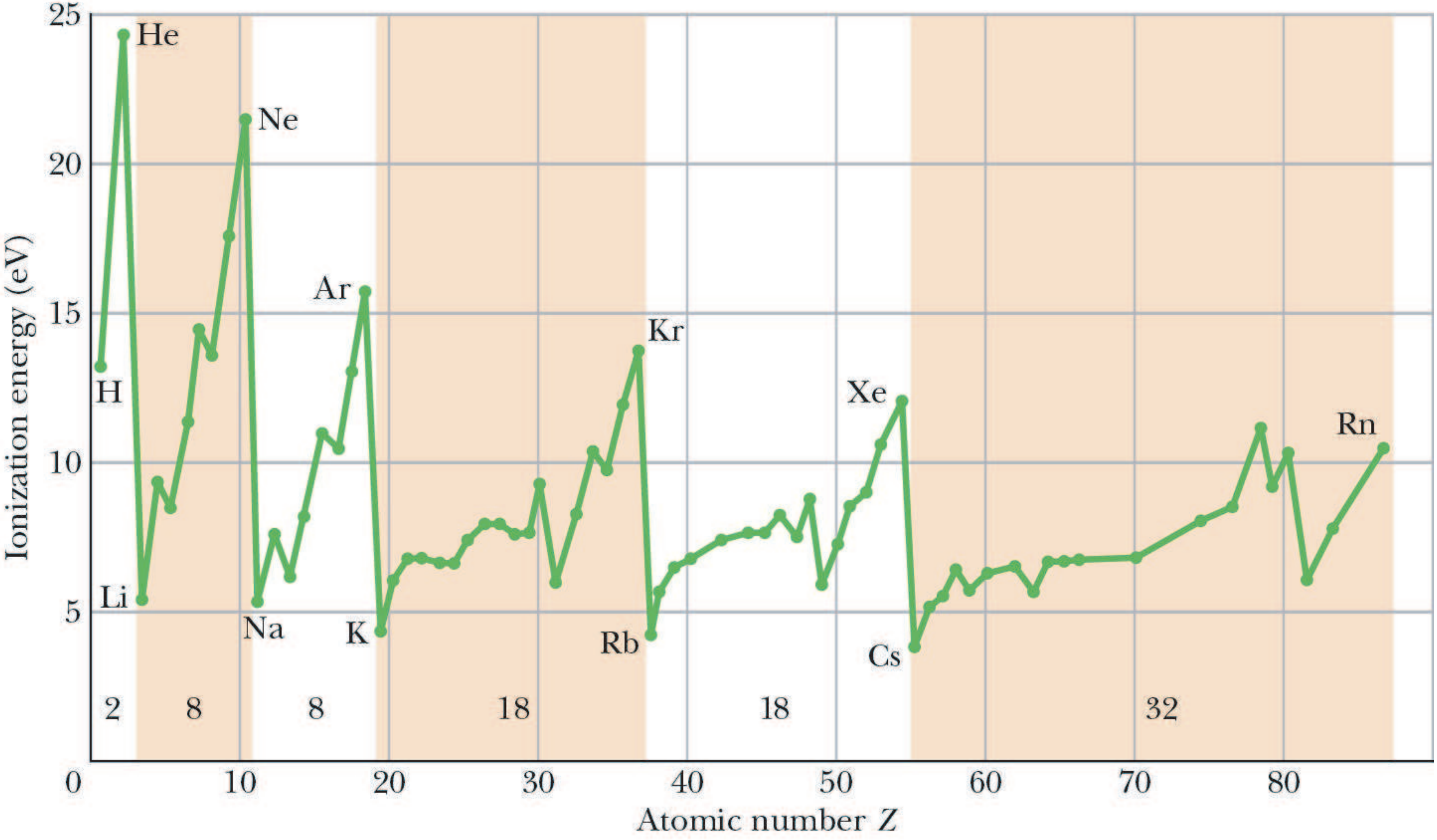
Number of electrons In the outter shell

Ionization energy

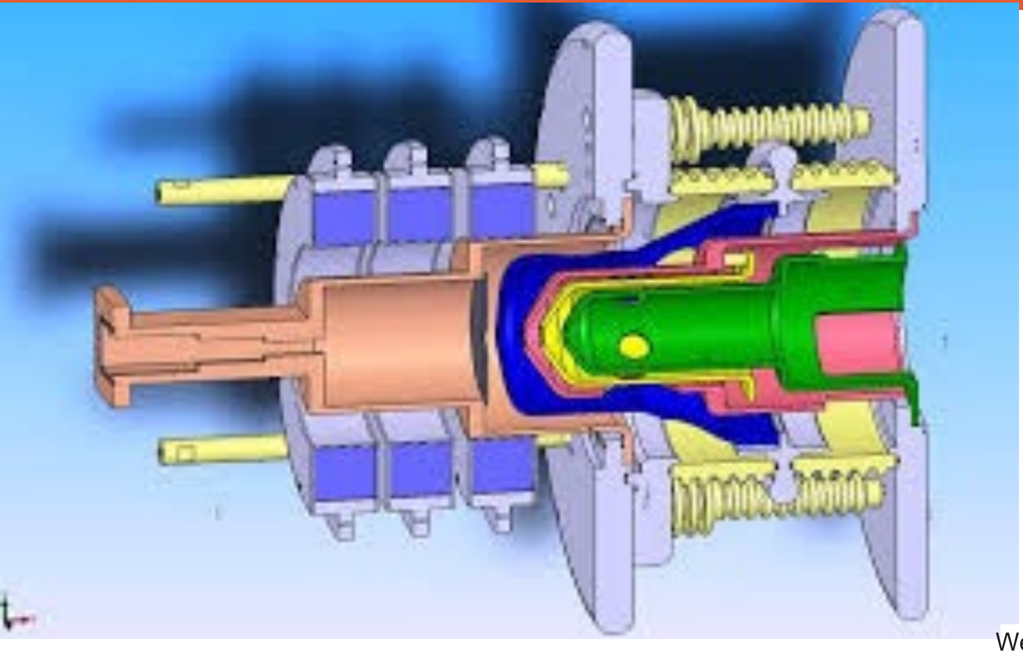
If energy is increased $E_{e^-} \Rightarrow$ higher ionization degree $\Rightarrow$ highly charged ions (HCI)

Ionization Energies

D. Halliday, R. Resnick, and J. Walker, Physik, WILEY-VCH, Weinheim (2003).

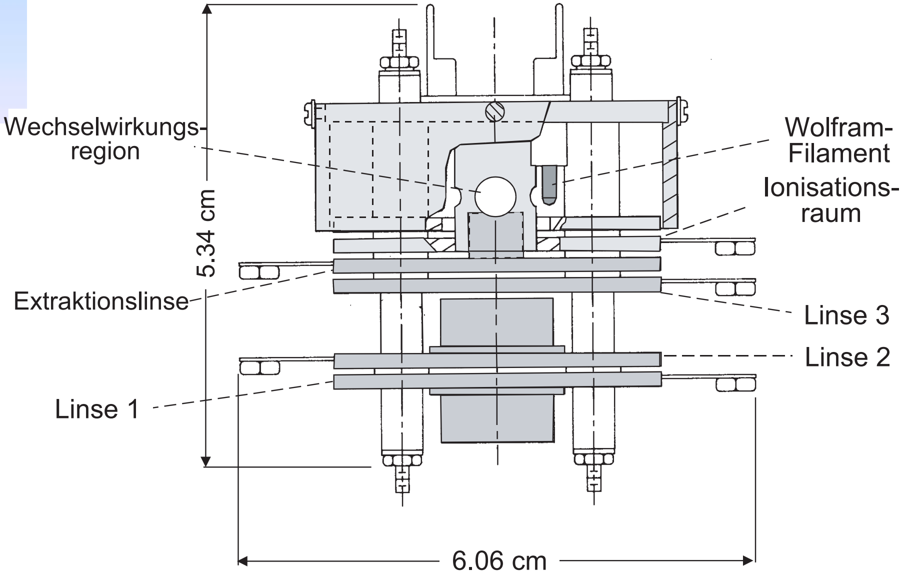


Source Examples

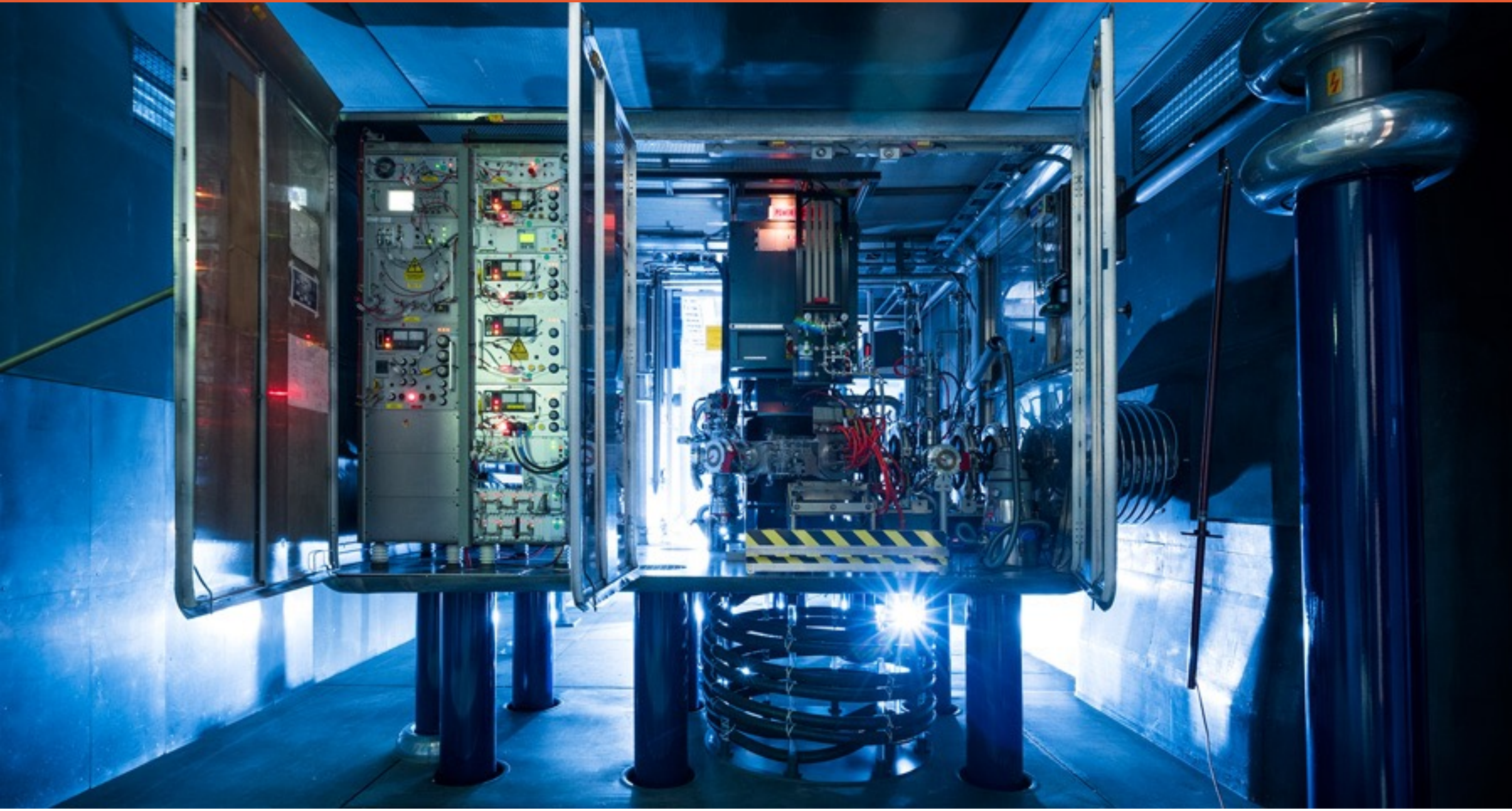


ECR Source

Cross-Beam Source

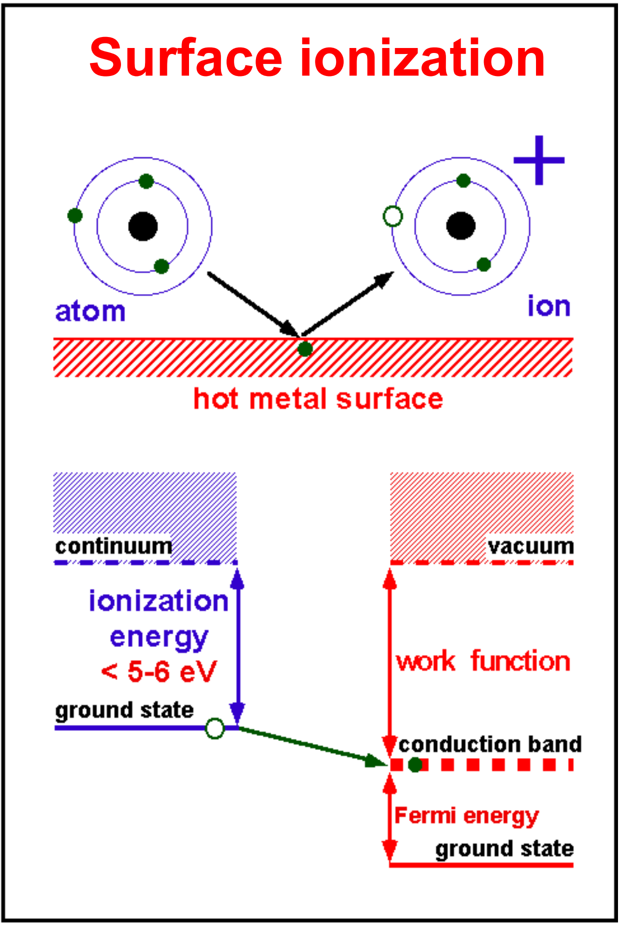


Source Examples



High-voltage ion sources platform

Surface Ionization / Contact Ionization



Surface Ionization / Contact Ionization

E_i – small (alkali $E_i < 5$ eV)

E_a – electron affinity (halogens)

Material with large work function (W, Re, ….)

Contact – long enough $t \sim 10^{-5} - 10^{-3}$ s

Surface – high temperature (up to 2000 degrees Celsius)

$$P_i = \frac{N_i}{N_0 + N_i} = \left(1 + \frac{g_0}{g_i} e^{e(\phi_i - \phi_s)/kT}\right)^{-1}$$

Ionization probability

Number of atoms (0); ions (i)

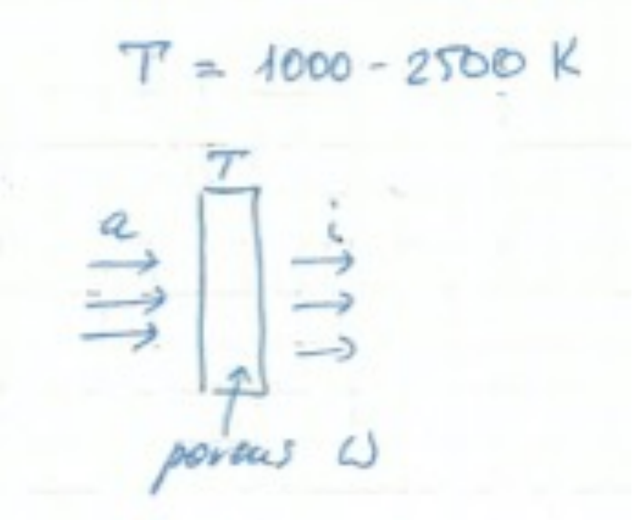
Statistical factors

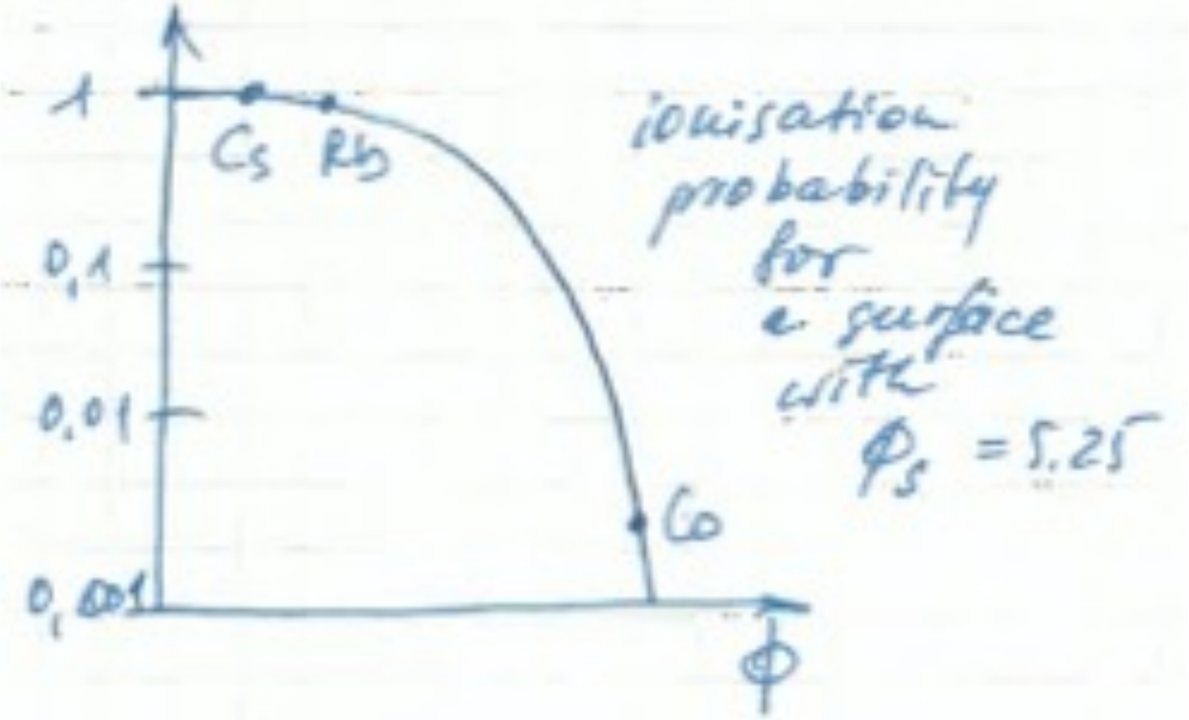
Ionization potential

Work function

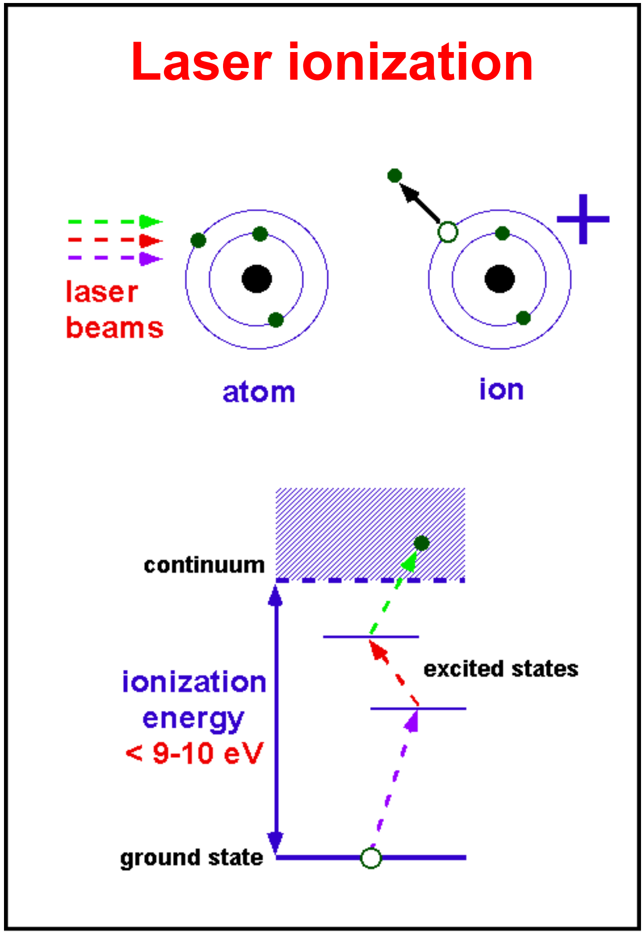
Statistical, Saha-like, equation

Surface Ionization / Contact Ionization

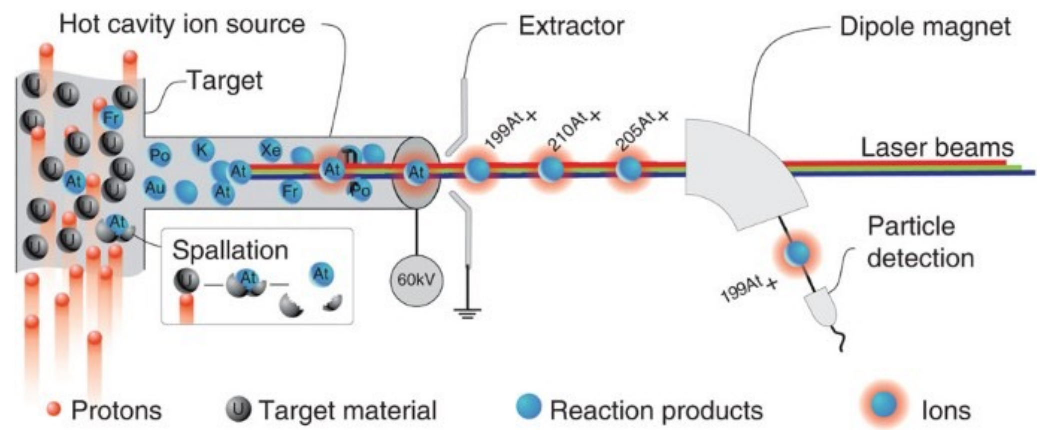


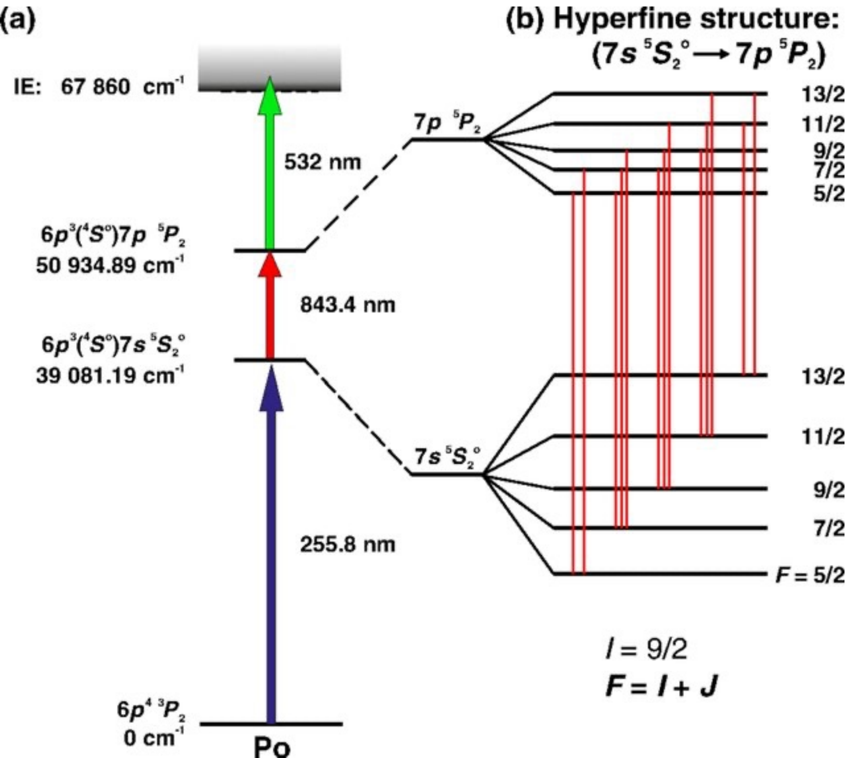


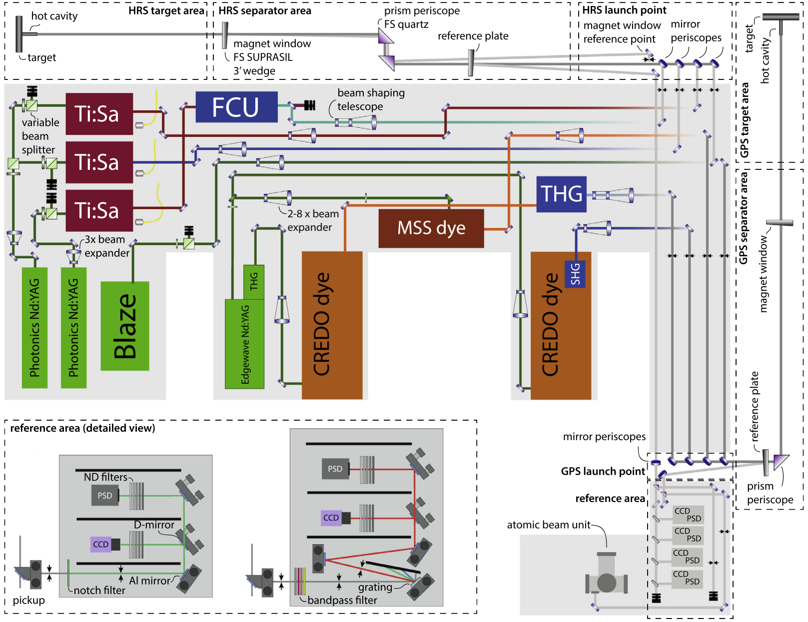
Laser Ionization / Resonant Ionization



Laser Ionization / Resonant Ionization







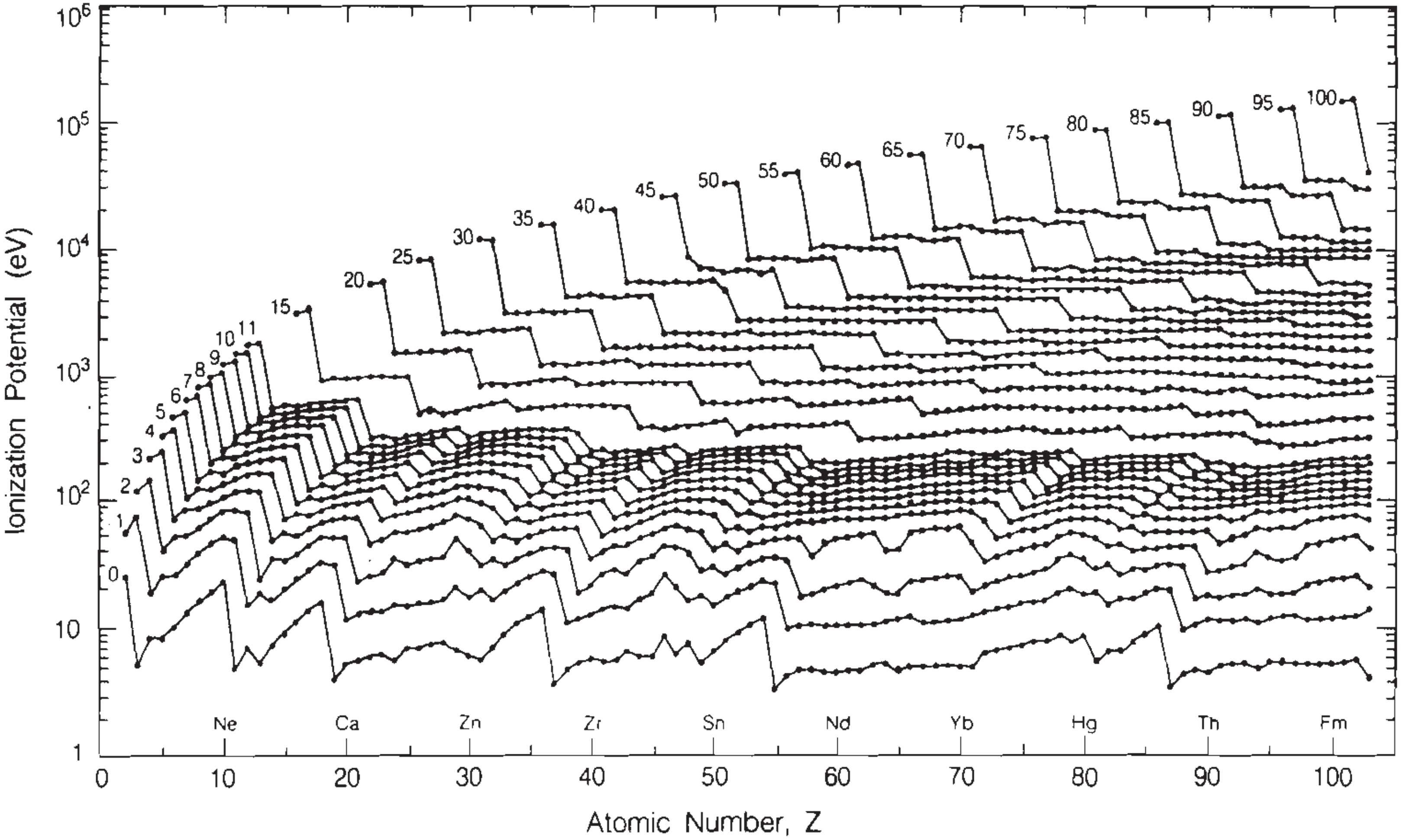
Scheme of RILIS / ISOLDE

Knowledge of atomic levels
(Isotope shifts)

D. Fink, et al., Phys. Rev. X5 (2015) 011018

Production of highly charged ions

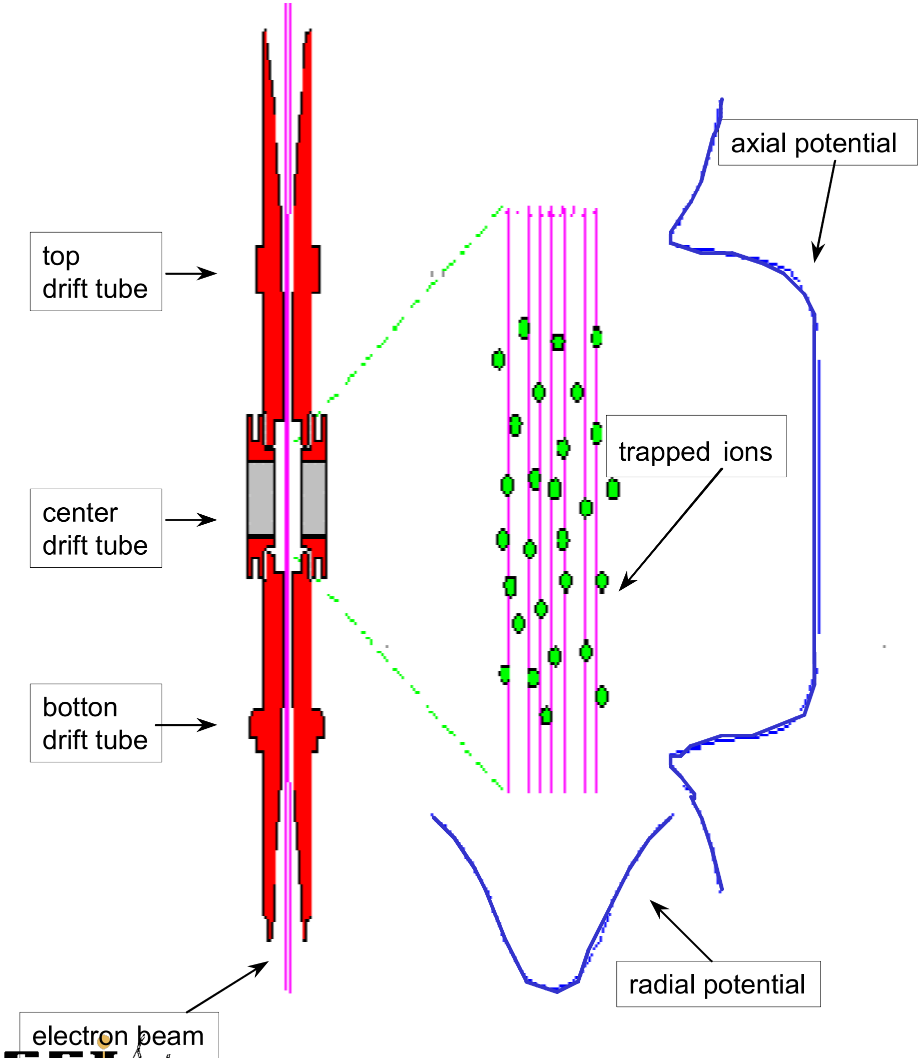
Calculated ionization potentials for all charge states

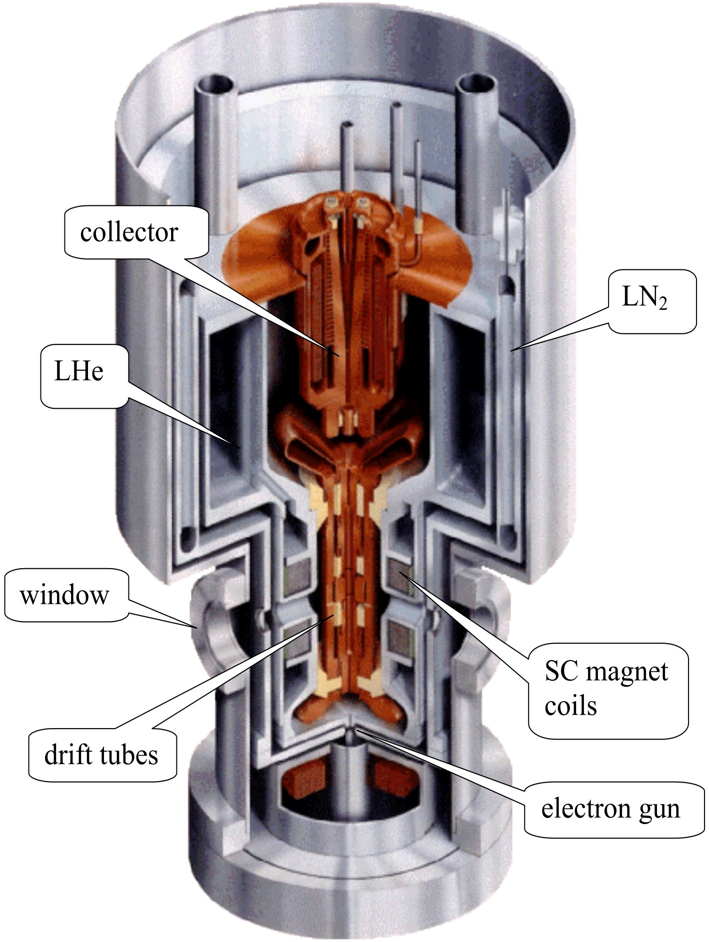


B. Wolf, Ion Sources, CRC Press, New York, 1995

EBIT/S (electron beam ion trap/source)

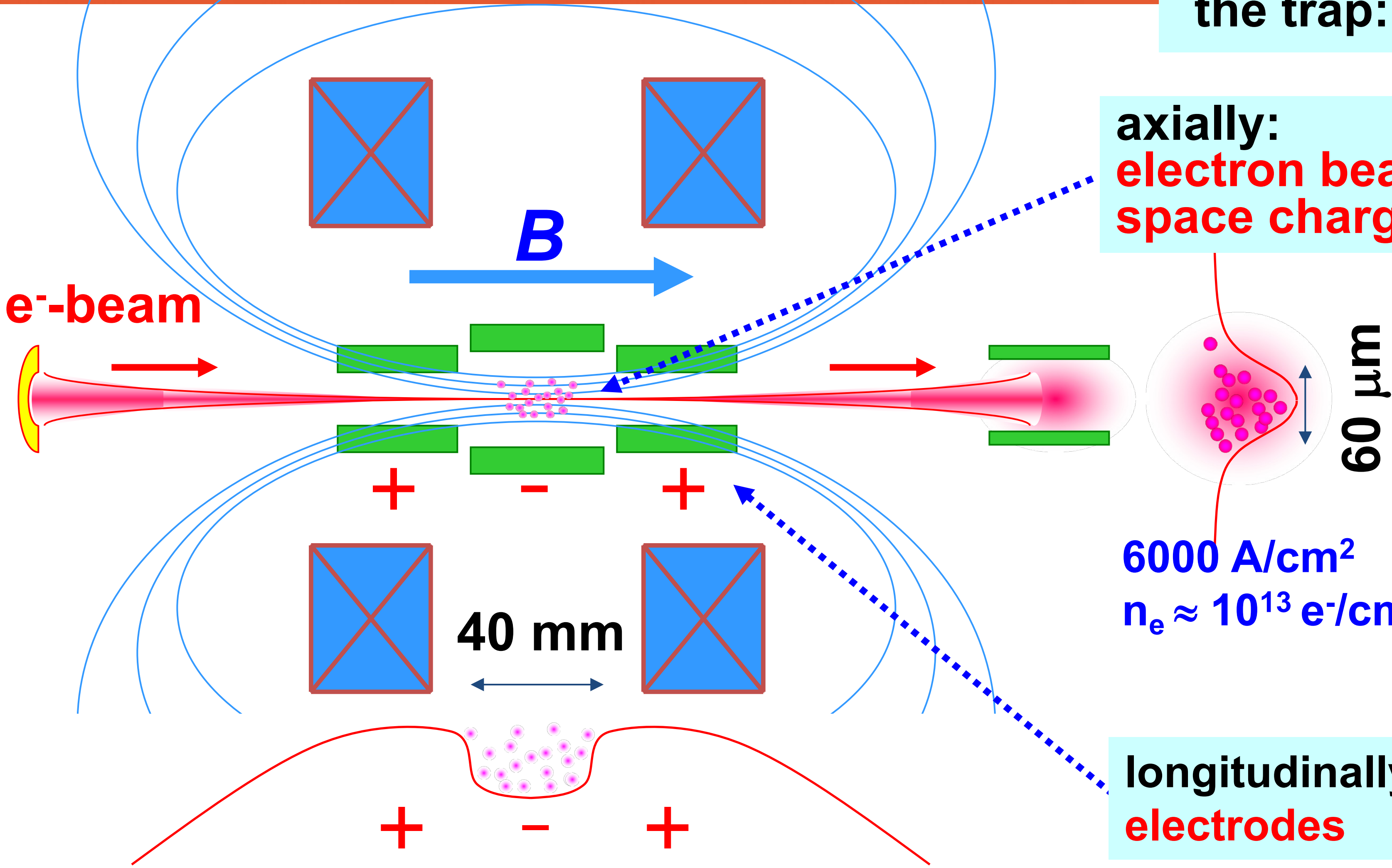
1980s R. Marrs and M. Levine Lawrence Livermore National Laboratory (LLNL)





EBIT II

EBIT/S (electron beam ion trap/source)



the trap:

axially:
electron beam space charge

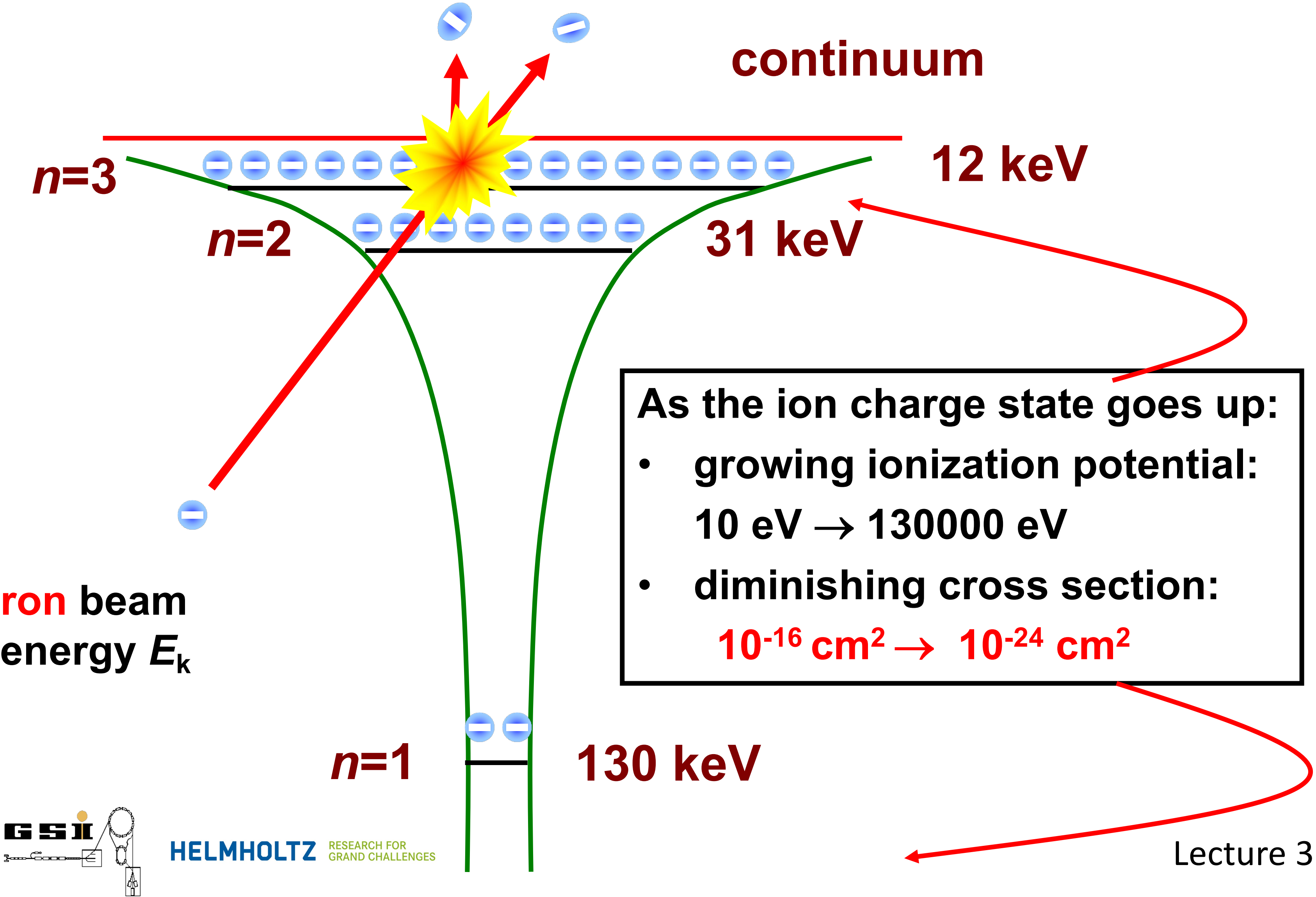
longitudinally:
electrodes

6000 A/cm^2
$n_e \approx 10^{13}$ e$^-$/cm^3

trap potential $U_t \approx$ 100 V
($U_t \times$ ion charge) $\approx$ 5000 eV

The ionization process

Sequential electron impact ionization in an electron beam ion trap



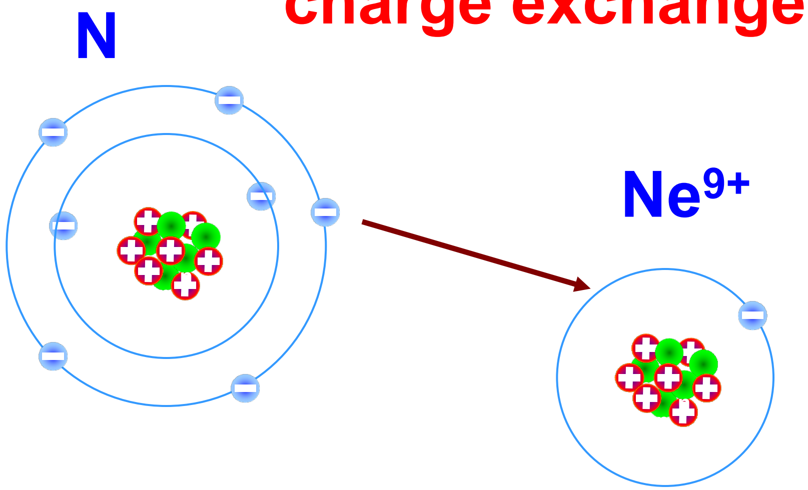
electron beam with energy E_k

As the ion charge state goes up:

- **growing ionization potential: 10 eV → 130000 eV**
- **diminishing cross section: 10^{-16} cm^2 → 10^{-24} cm^2**

Competing processes: recombination

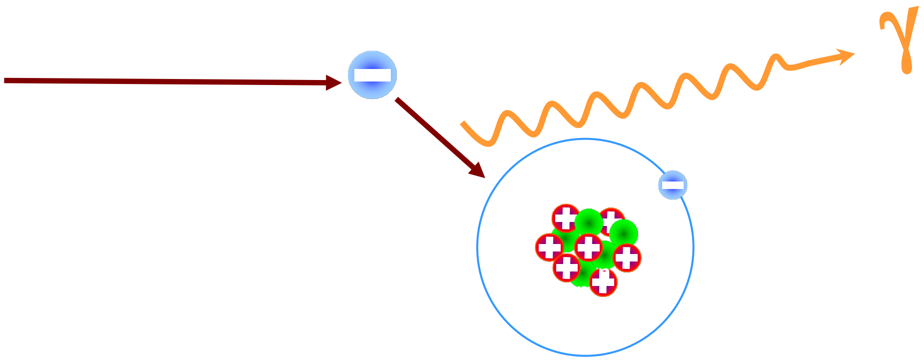
charge exchange with restgas neutral atoms



solution: vacuum 10^{-13} Torr

(1000 atoms/cm^3)

capture of free electrons

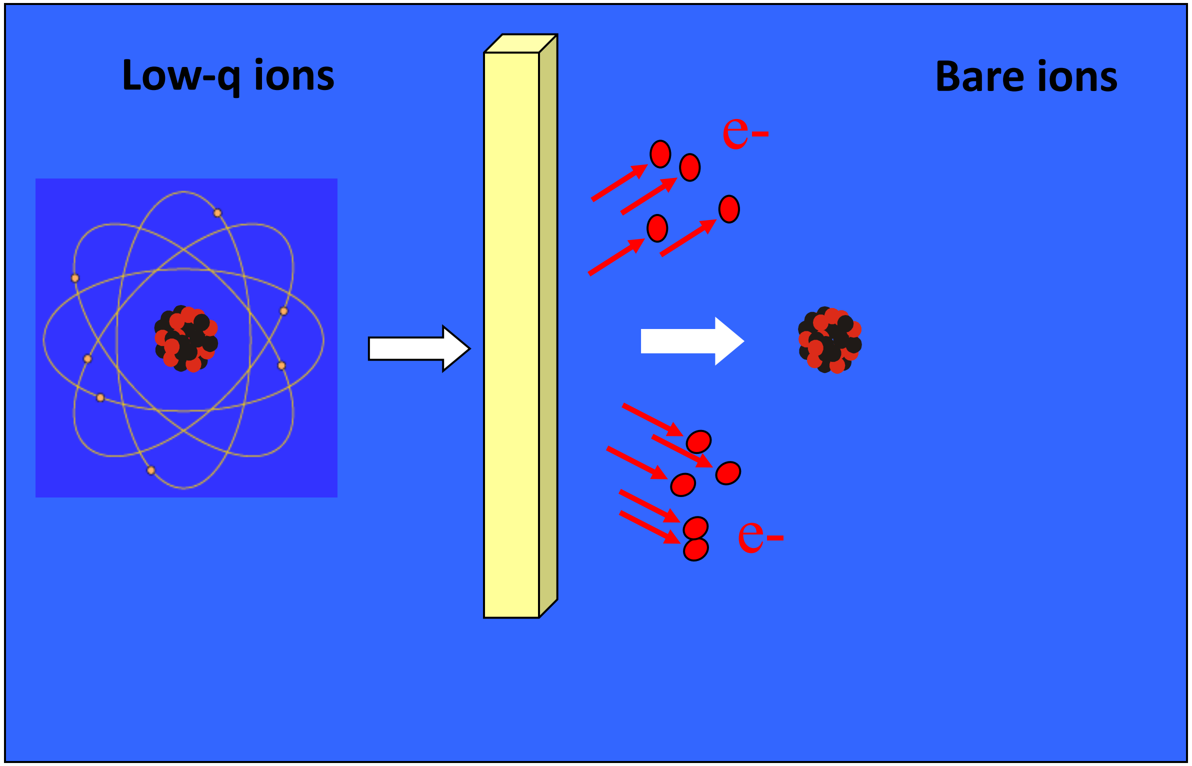


radiative recombination (RR)

solution: raising electron beam energy

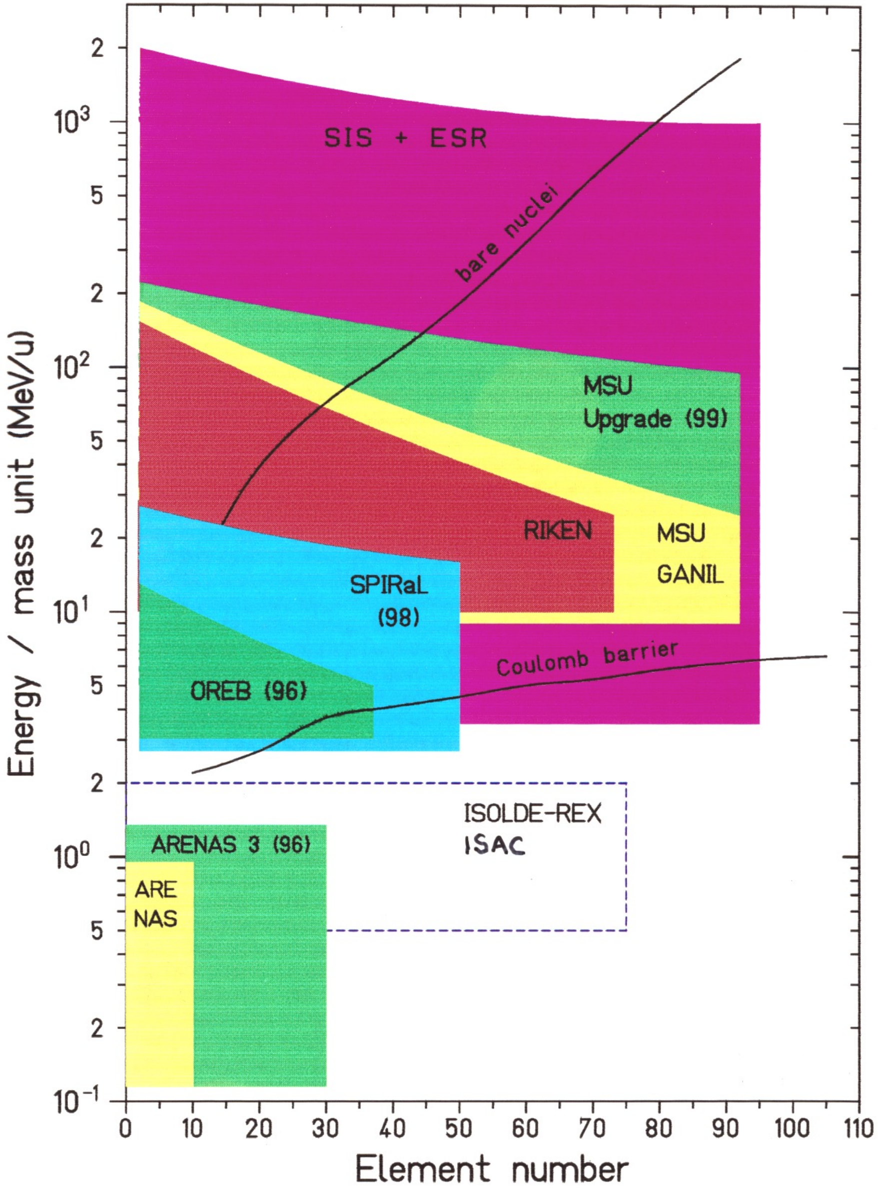
Production of highly charged ions

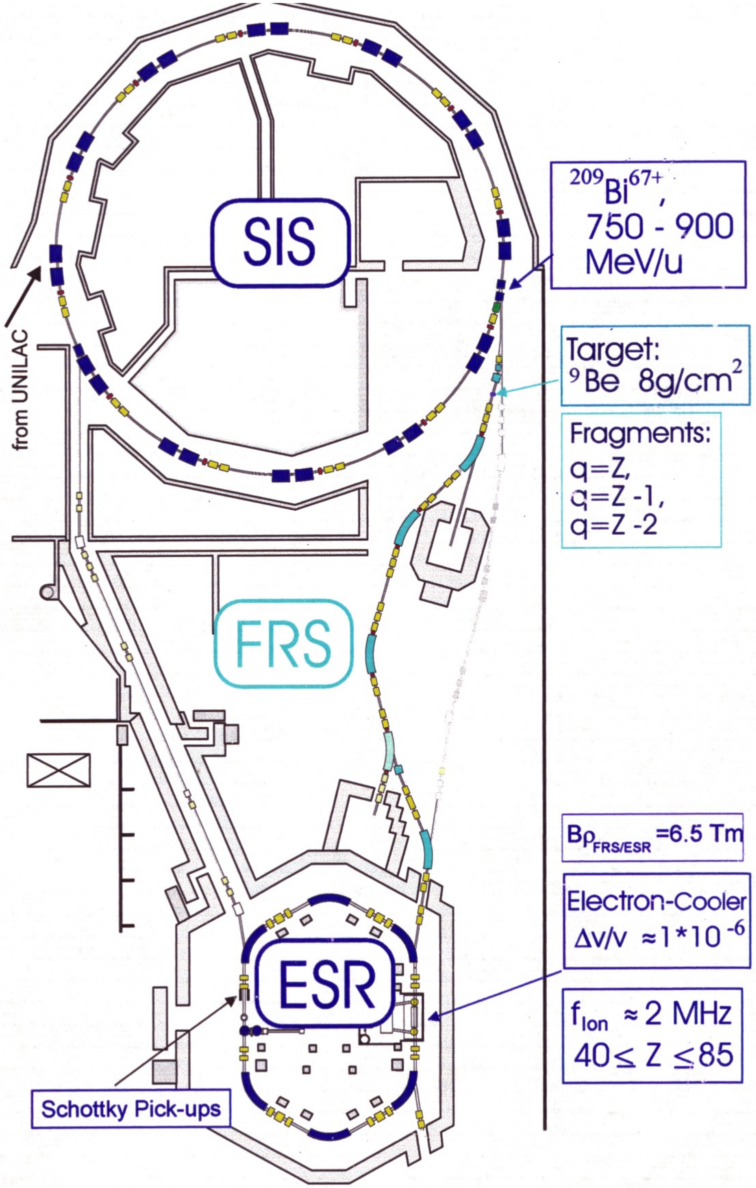
Bohr criterion: Largest ionization cross section at $v/c \approx v_K/c = \alpha Z$



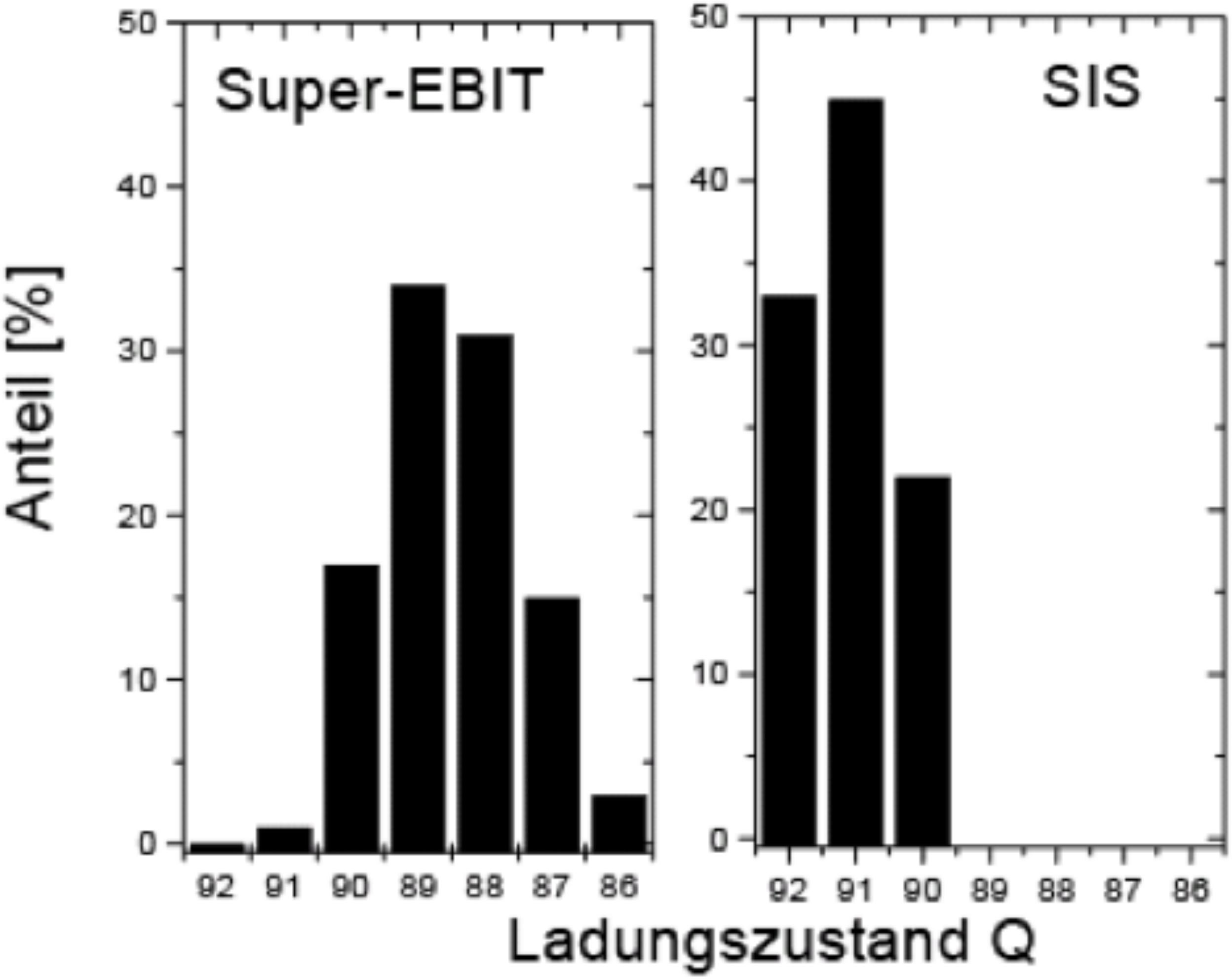
Uranium: $v_K/c \approx 0.67$ - **$E_{KIN} \approx$ 330 MeV/u**

Production of highly-charged ions at GSI





Production of highly charged ions



Super-EBIT

$I_{e^-} = 200\ \mathrm{mA}$

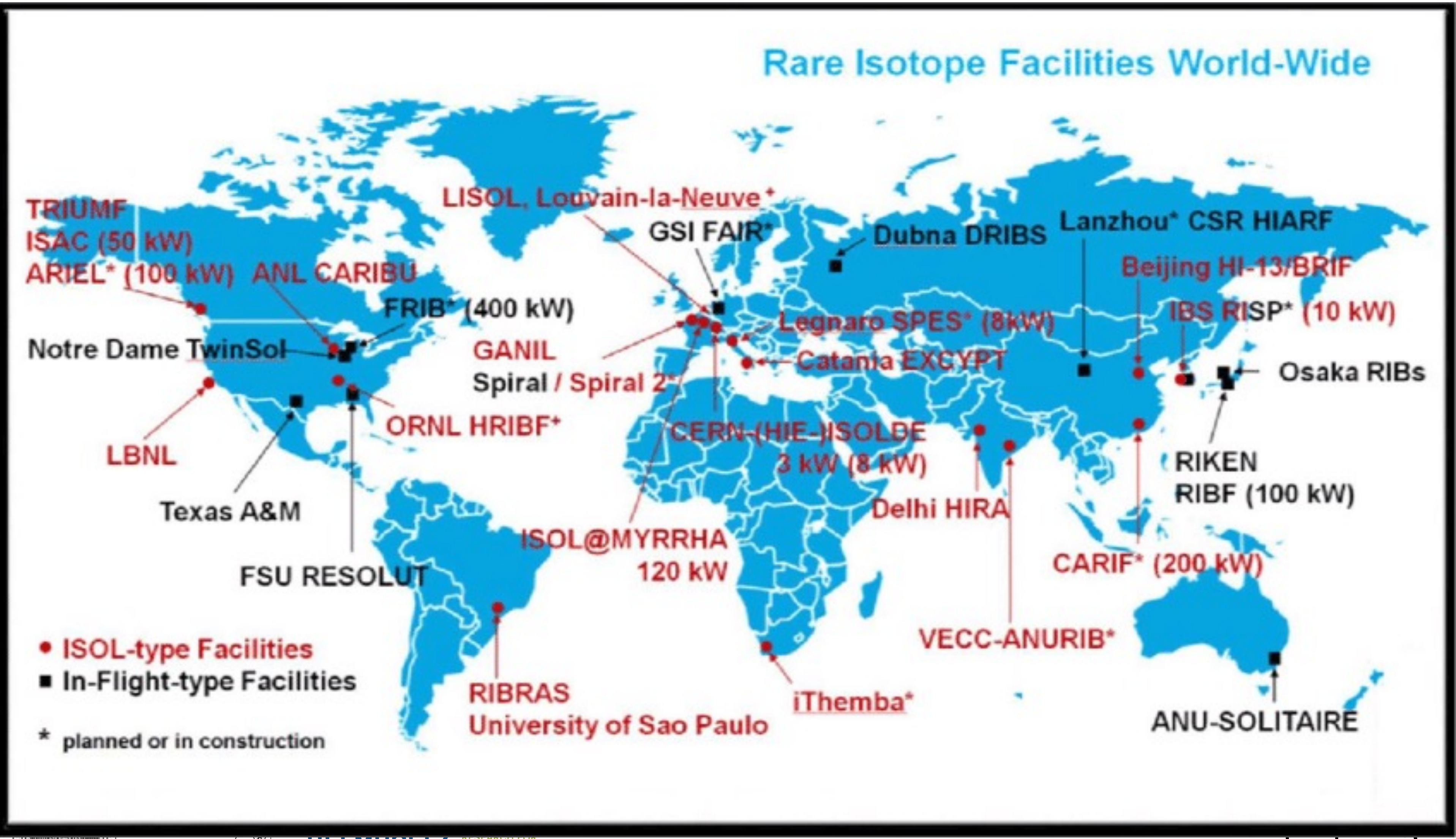
$E_{e^-} = 198\ \mathrm{keV}$

SIS

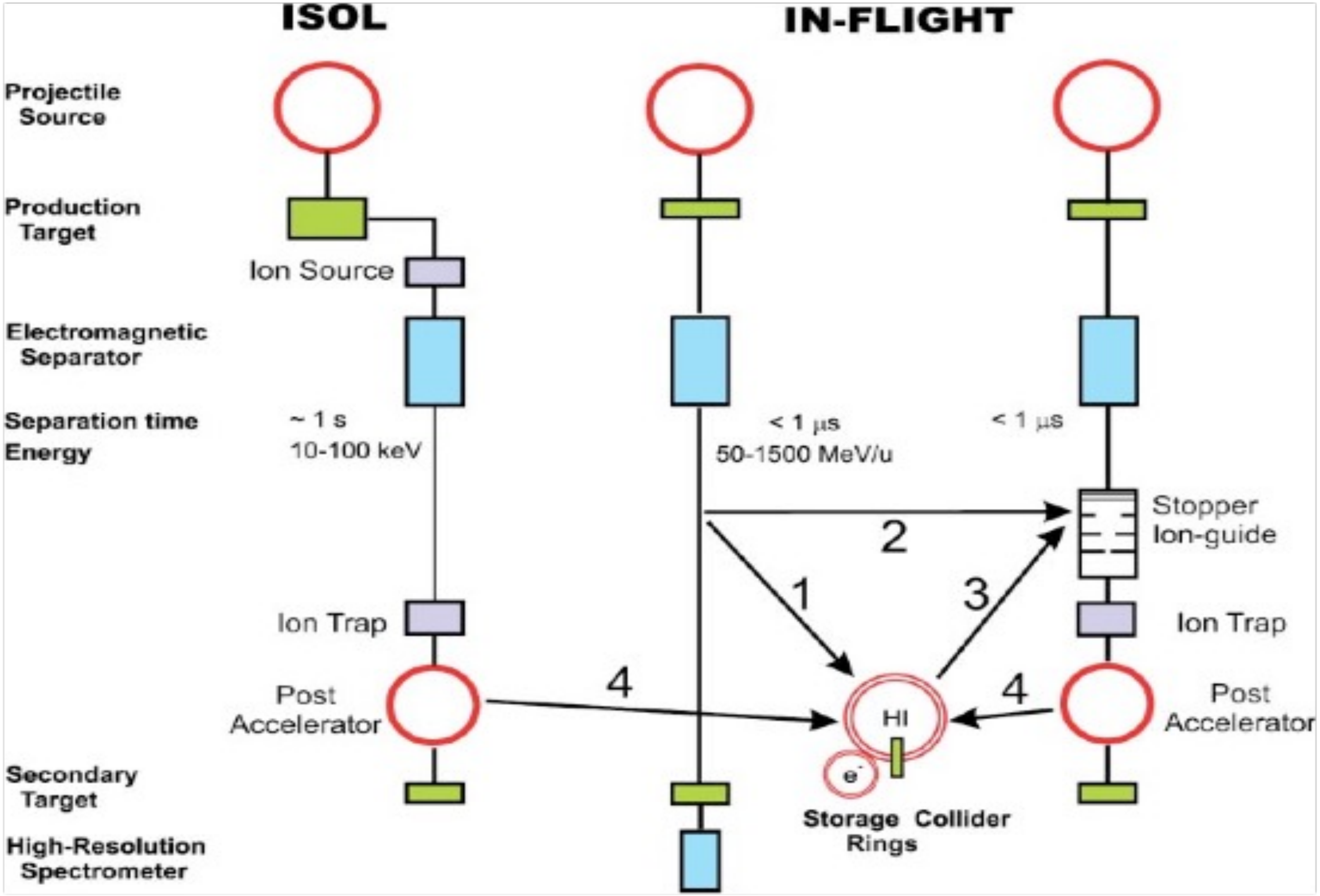
$E_U = 360\ \mathrm{MeV/u}$

Cu-stripper foil

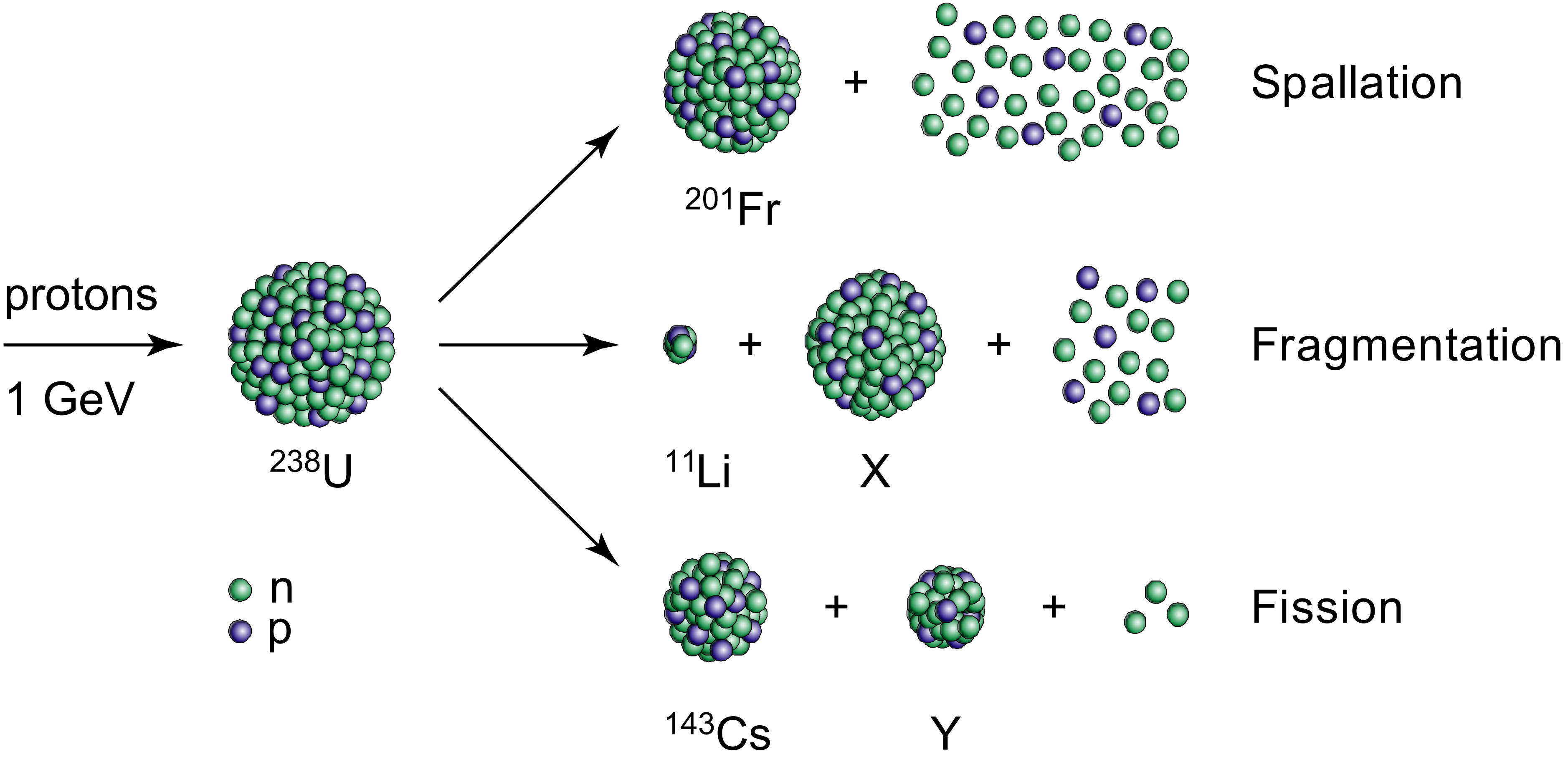
Radioacive Ion Beam Facilities



Production and separation of radionuclides



Proton-induced reactions (e.g. ISOLDE, ISAC)



Production Yields of ISOL Produced Radionuclides

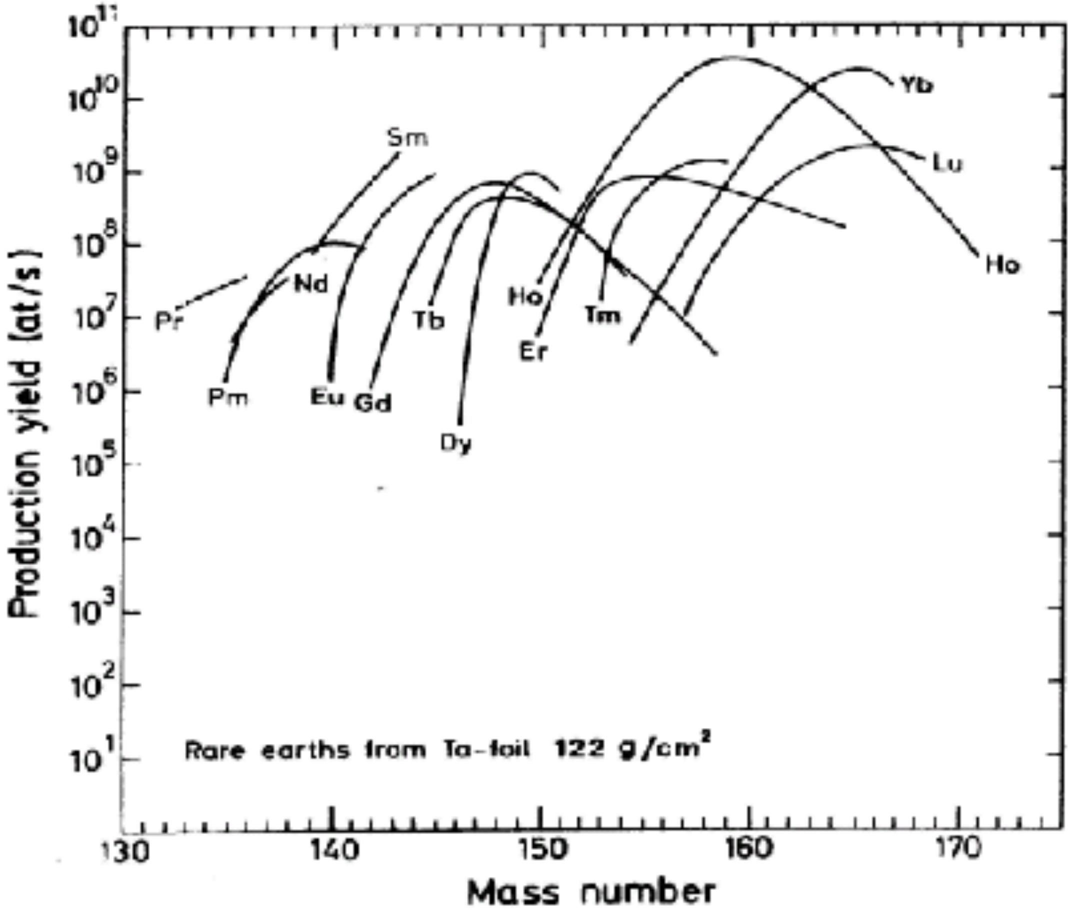
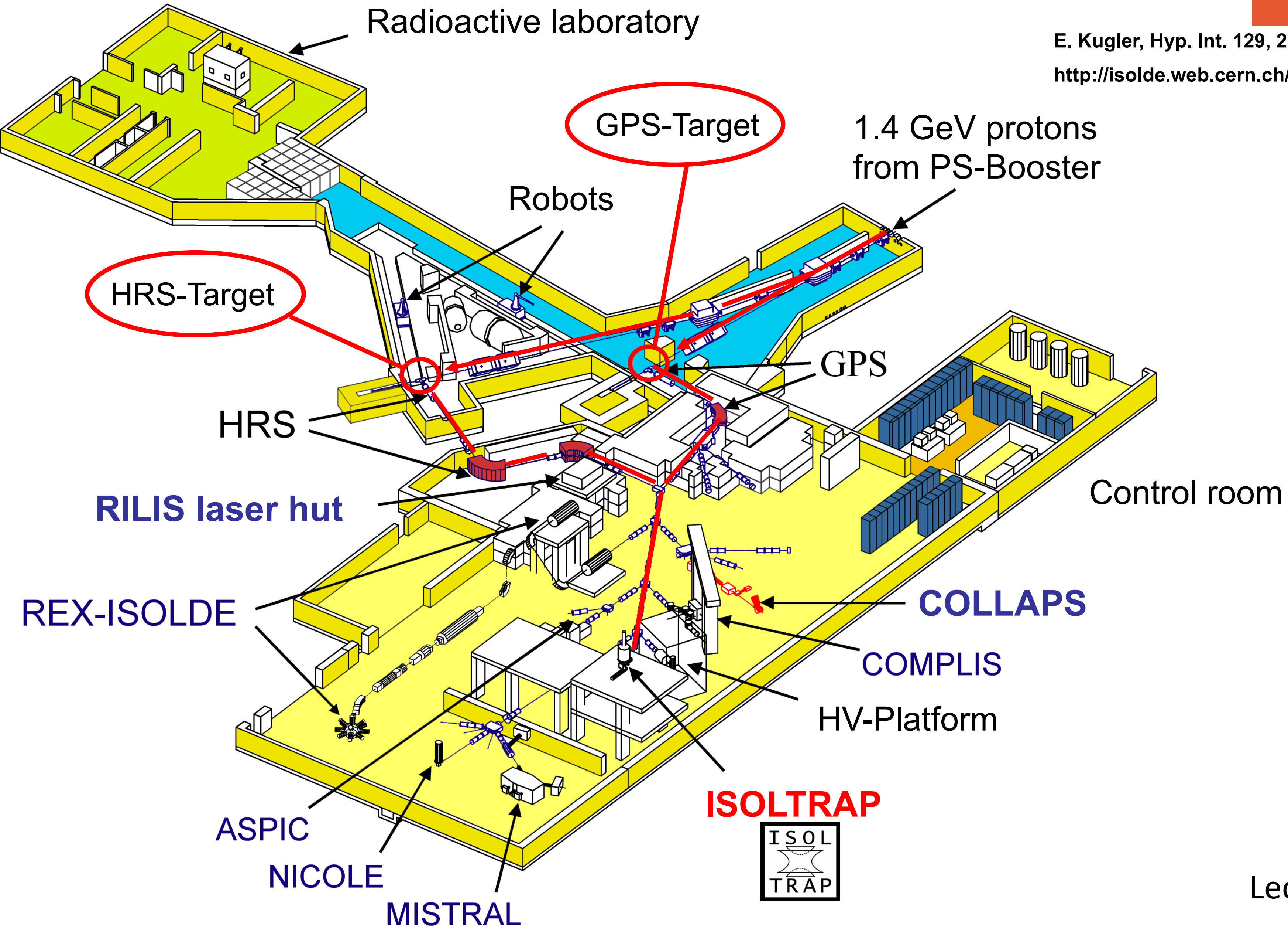


Figure 2.6: The production yields of di?erent radioactive nuclides in the rare earth element region produced by a 1 GeV proton beam impinging on a tantalum foil target [Bjø1986].

The ISOLDE facility at CERN

E. Kugler, Hyp. Int. 129, 23-42 (2000).

http://isolde.web.cern.ch/isolde

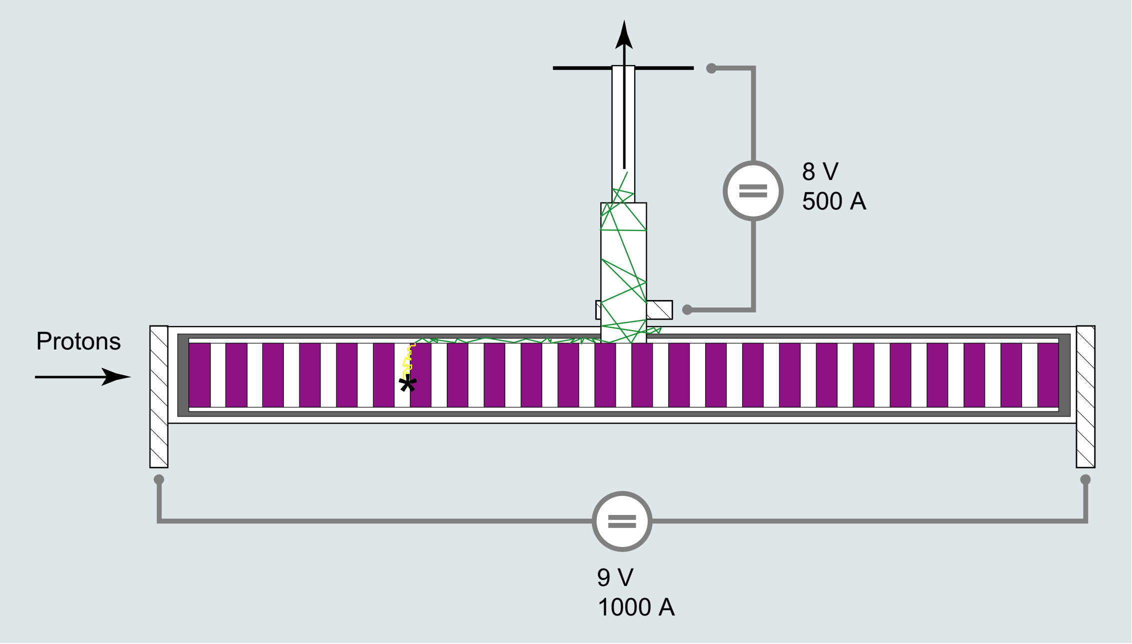


The ISOLDE targets

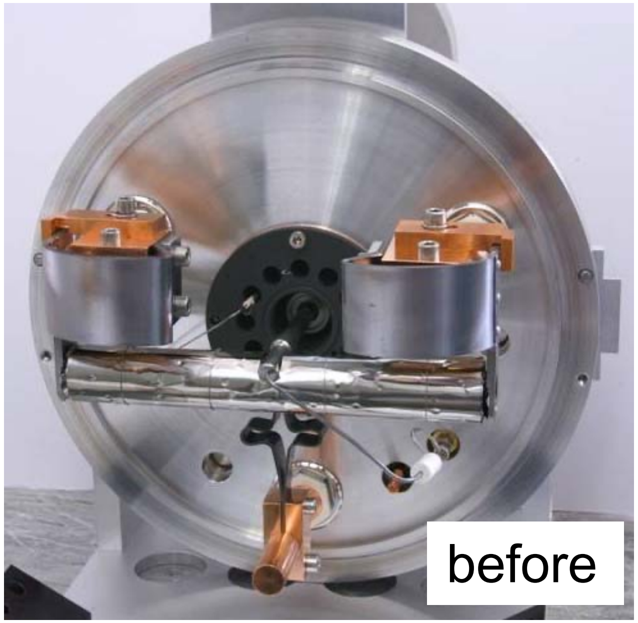
E. Kugler, Hyp. Int. 129, 23-42 (2000).

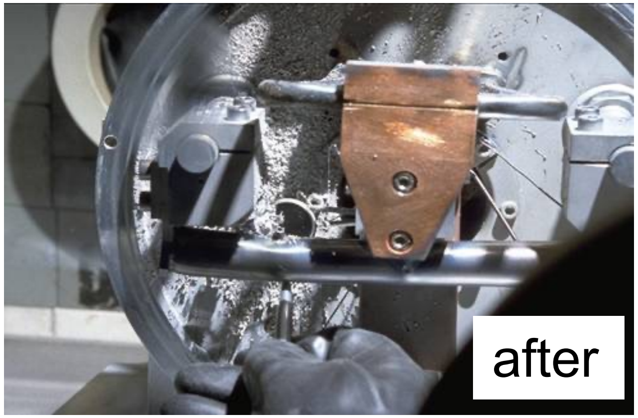
Ionization techniques:

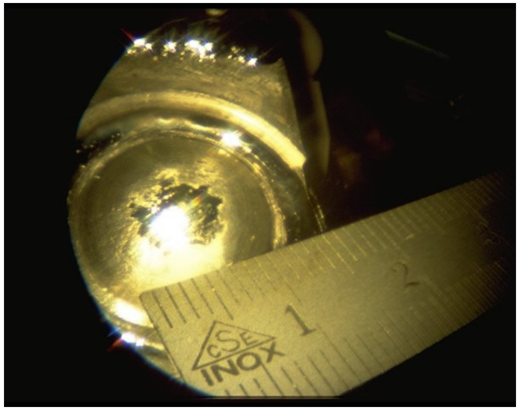
- Surface ionization
- Plasma ionization
- Resonant laser ionization



http://isolde.web.cern.ch/isolde



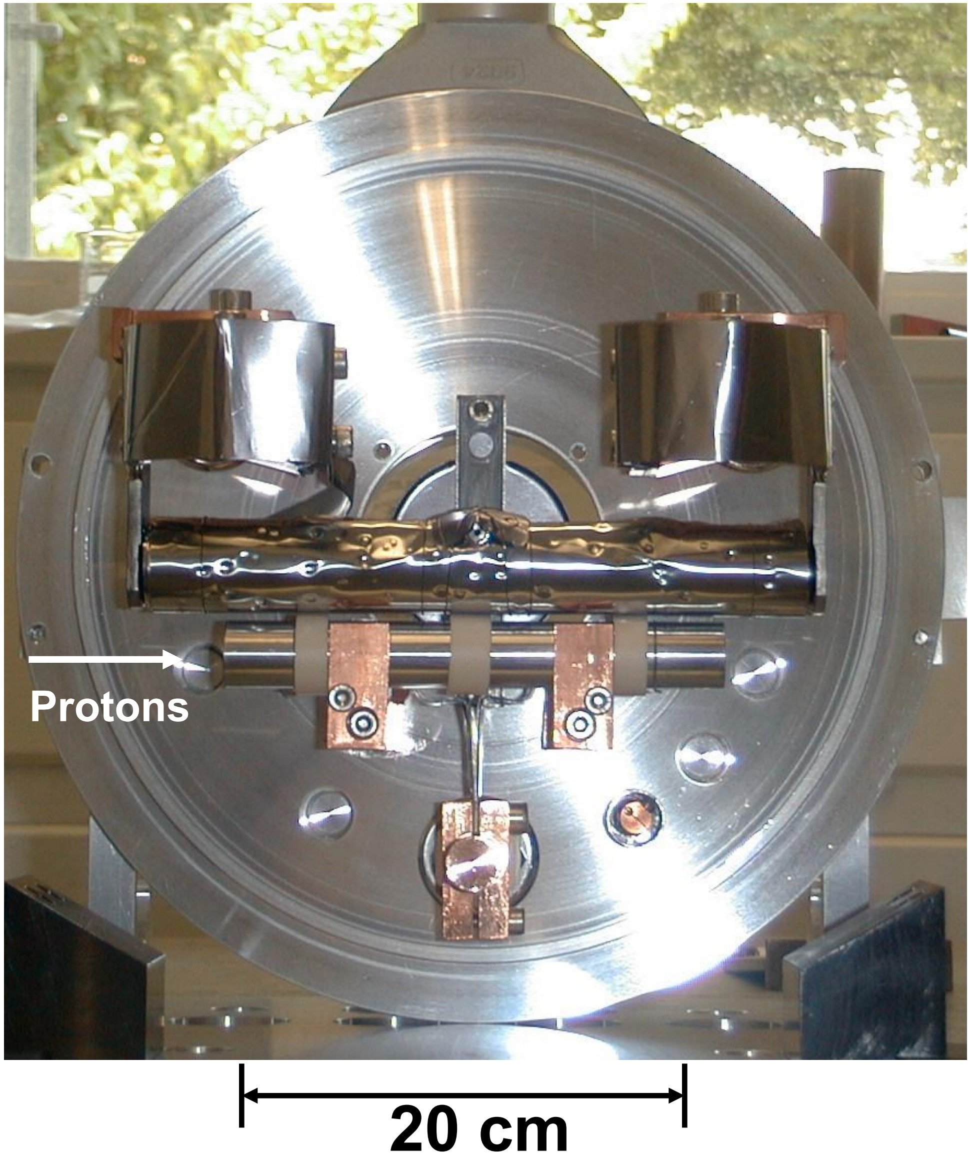


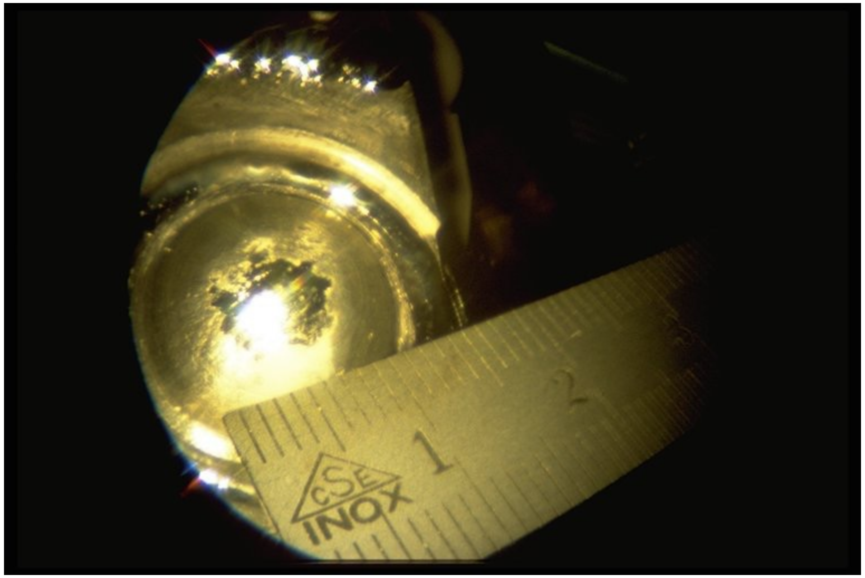


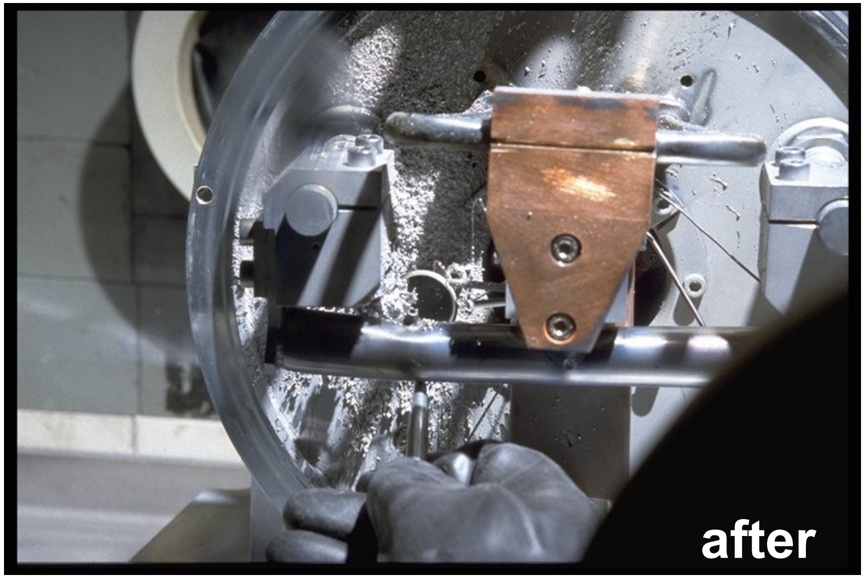
The ISOLDE targets

before

Kosten: ~ 20000 €

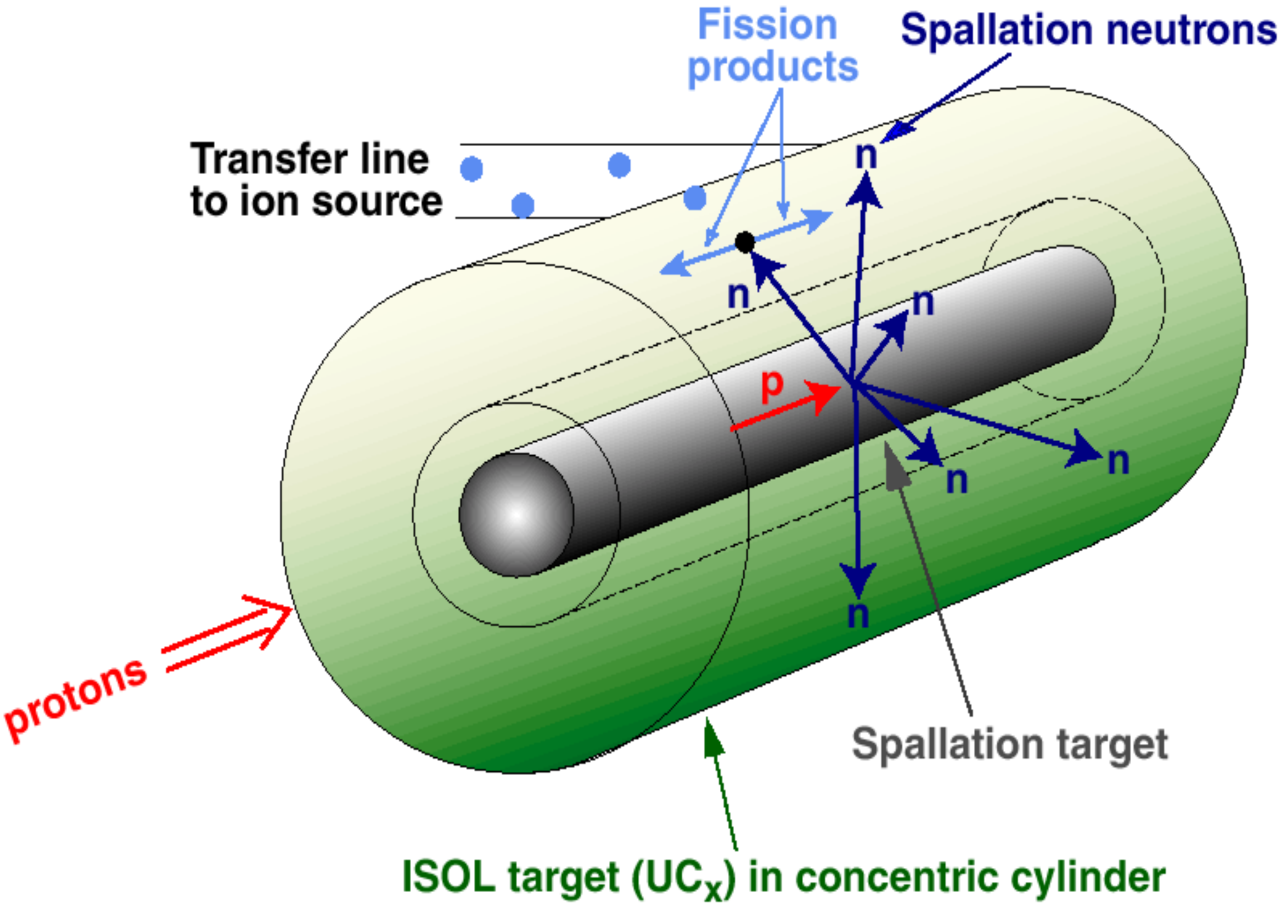




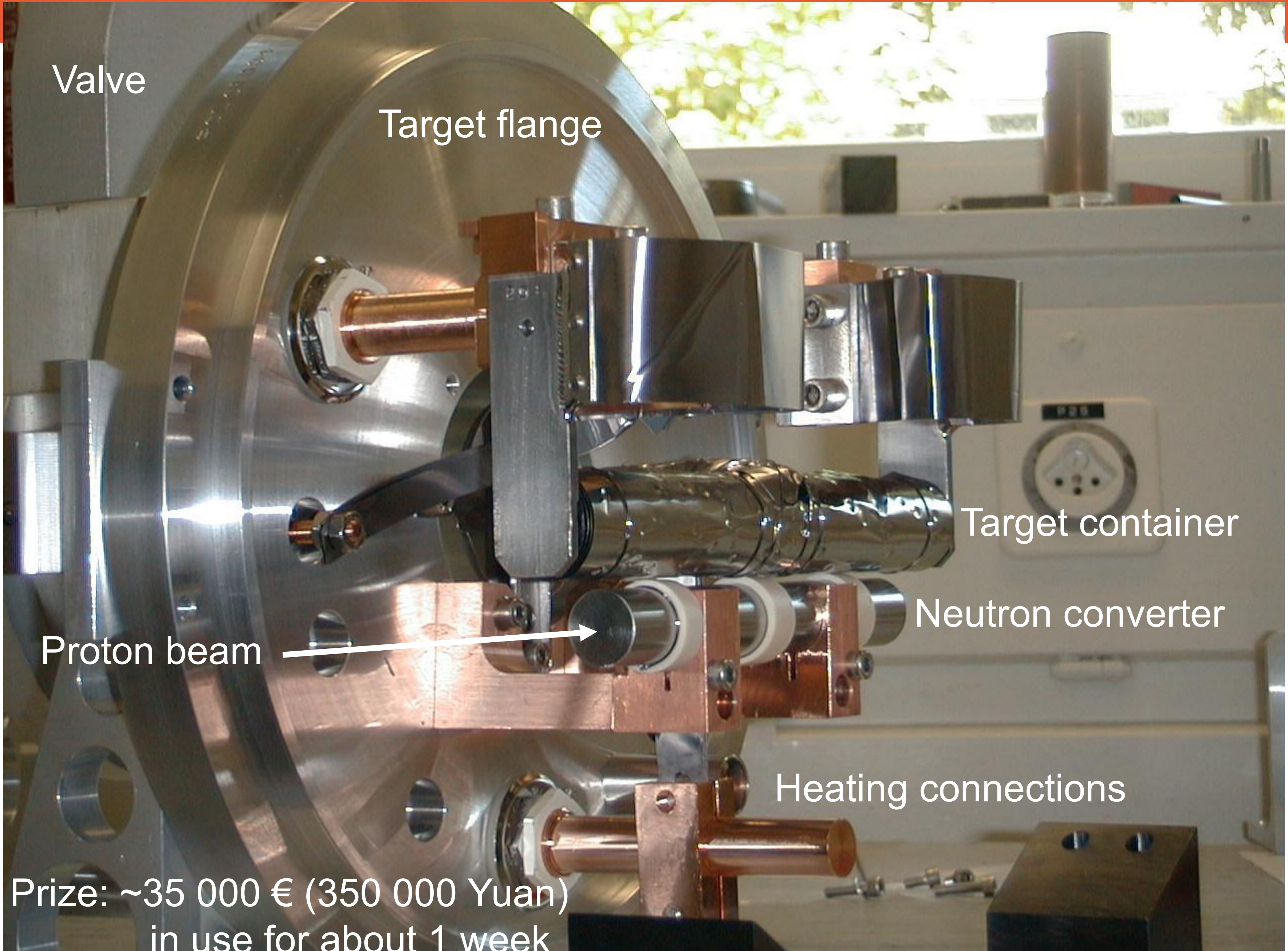


The ISOLDE neutron converter target

Converter target for high-energy-proton driven ISOL facility

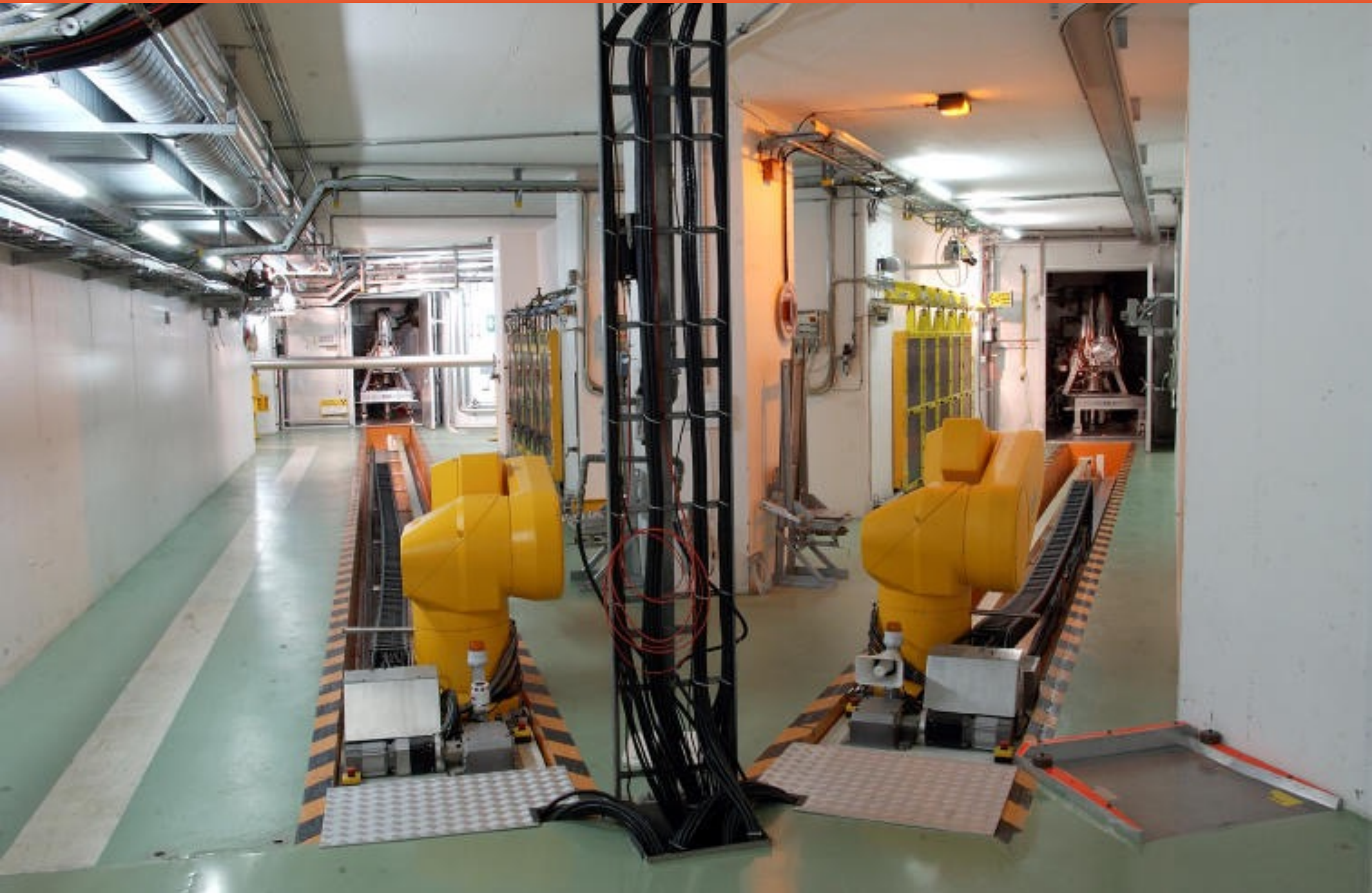


The ISOLDE neutron converter target

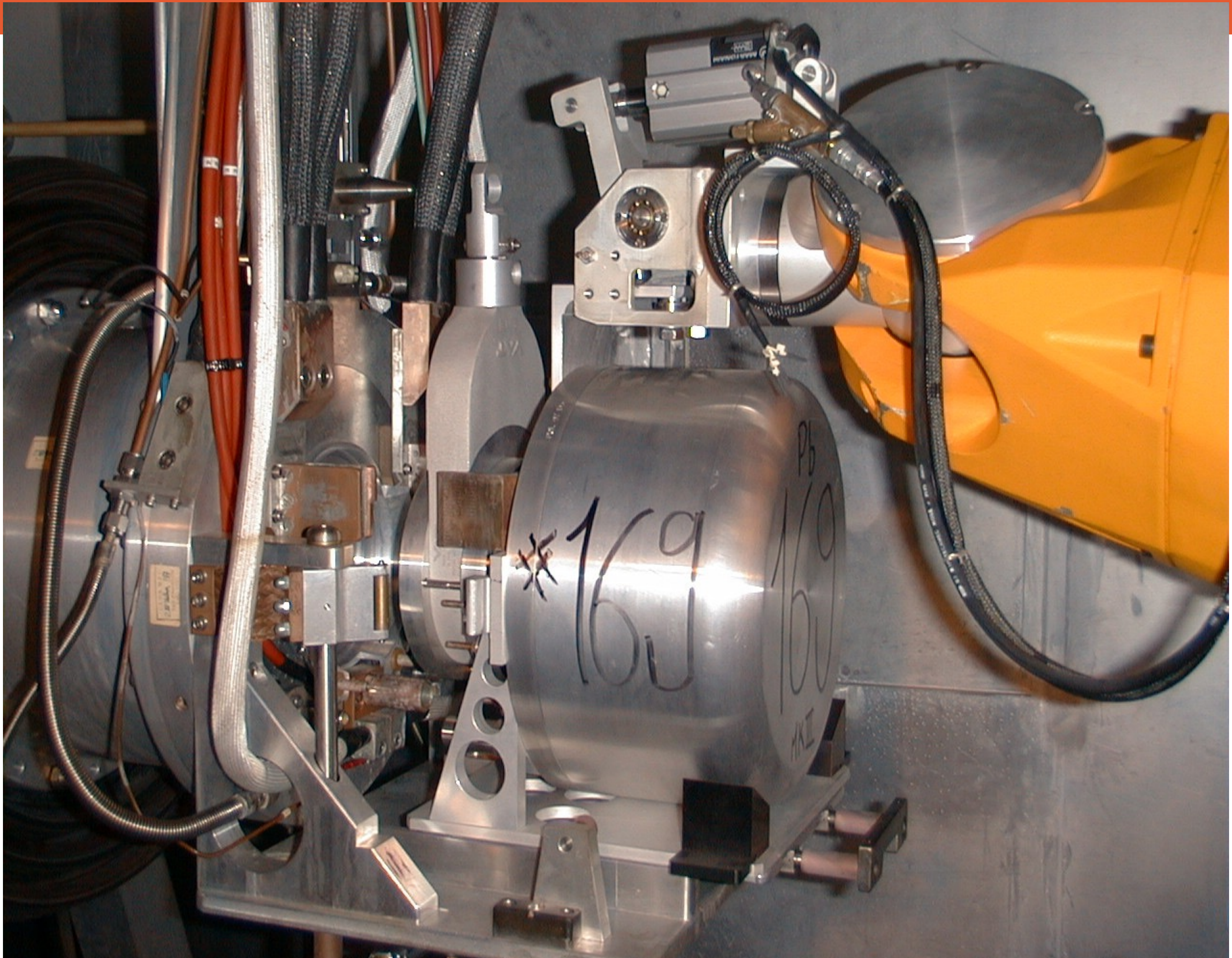


Prize: ~35 000 € (350 000 Yuan)
in use for about 1 week

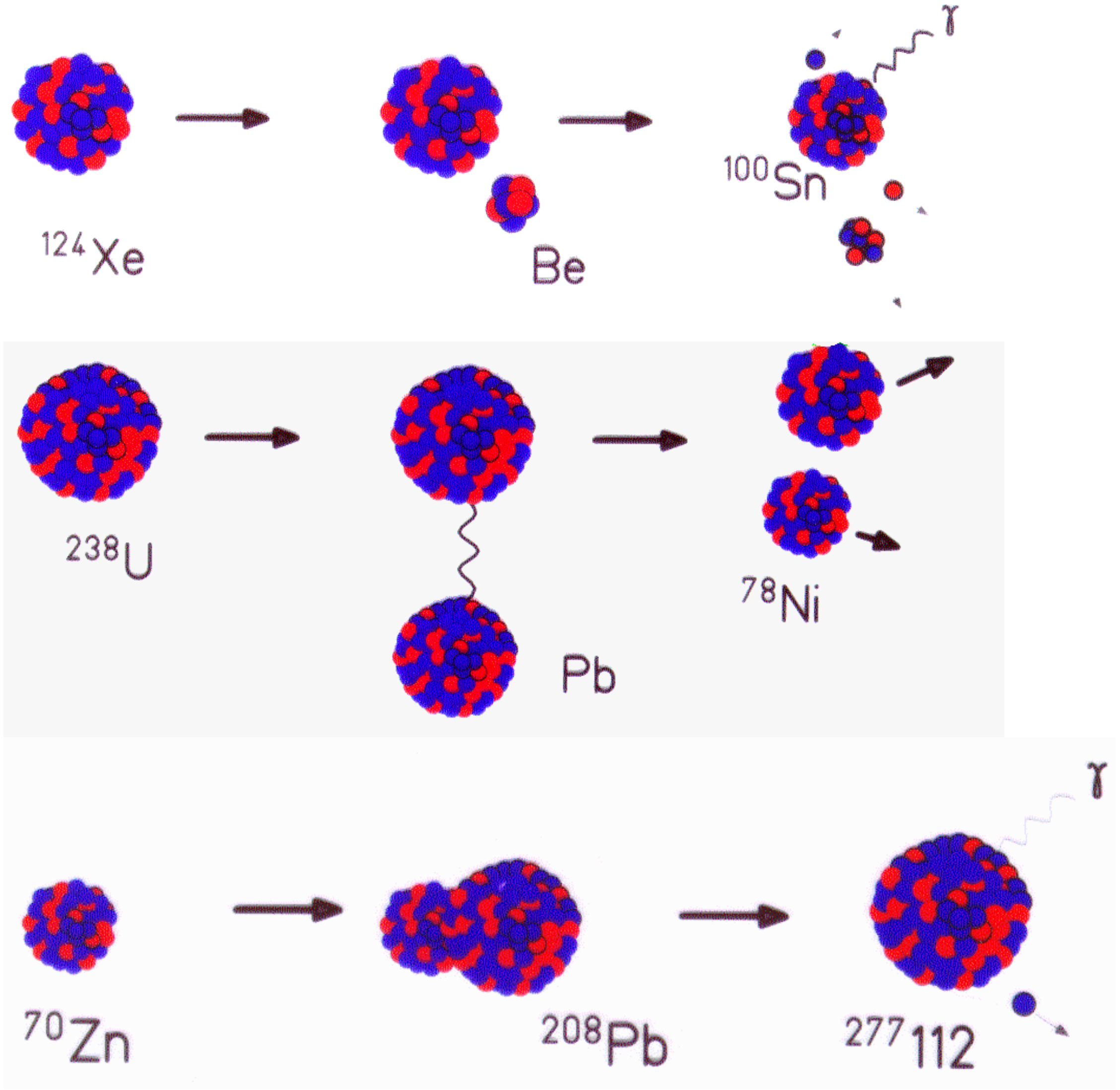
The ISOLDE target handling



The ISOLDE target handling



In-flight production of radionuclides

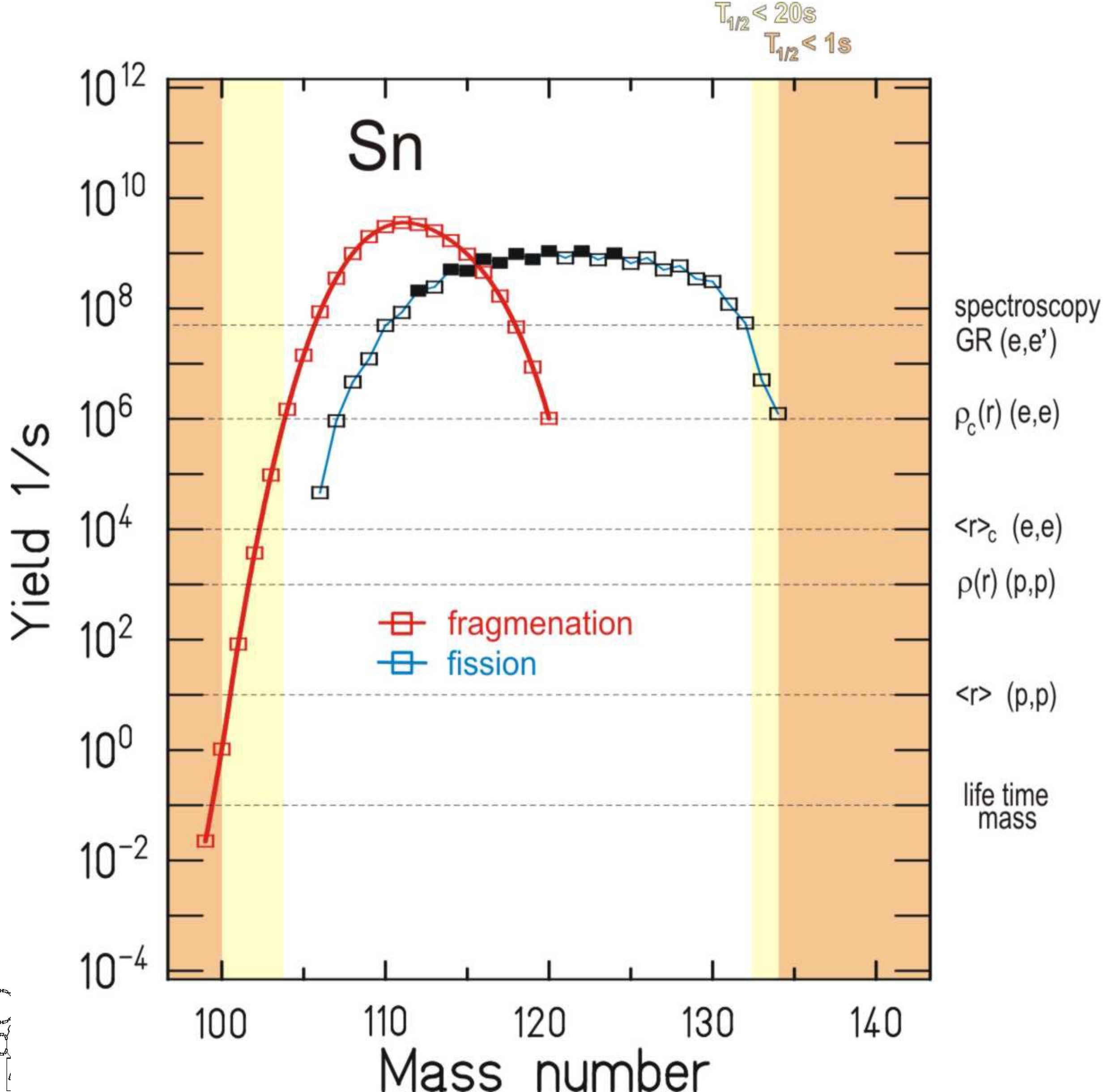


Fragmentation

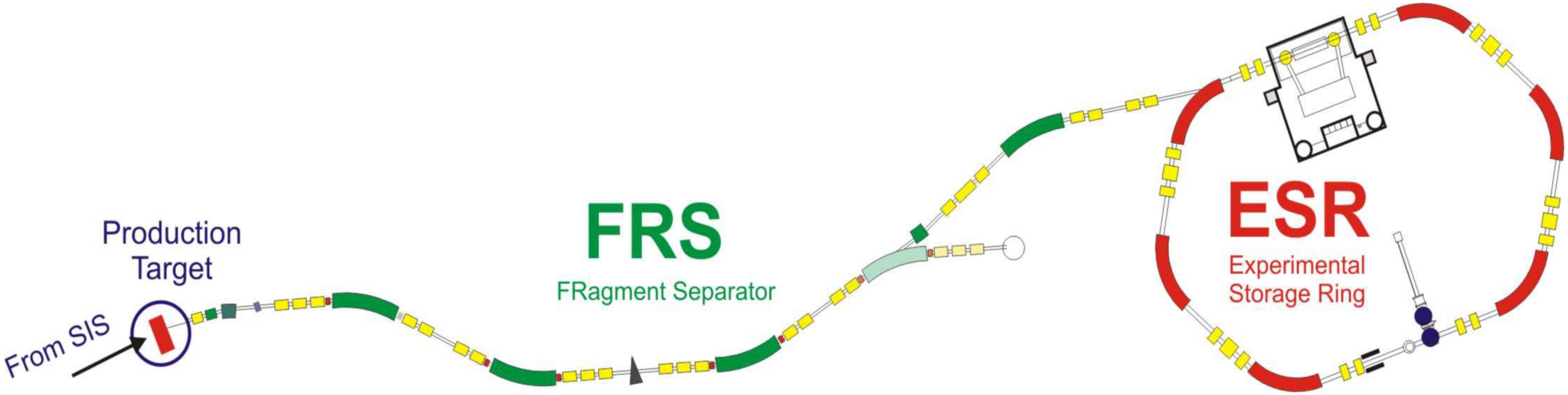
Coulomb dissociation

Fusion

Production Cross-Sections for Tin-Isotopes



Production & Separation of Exotic Nuclei



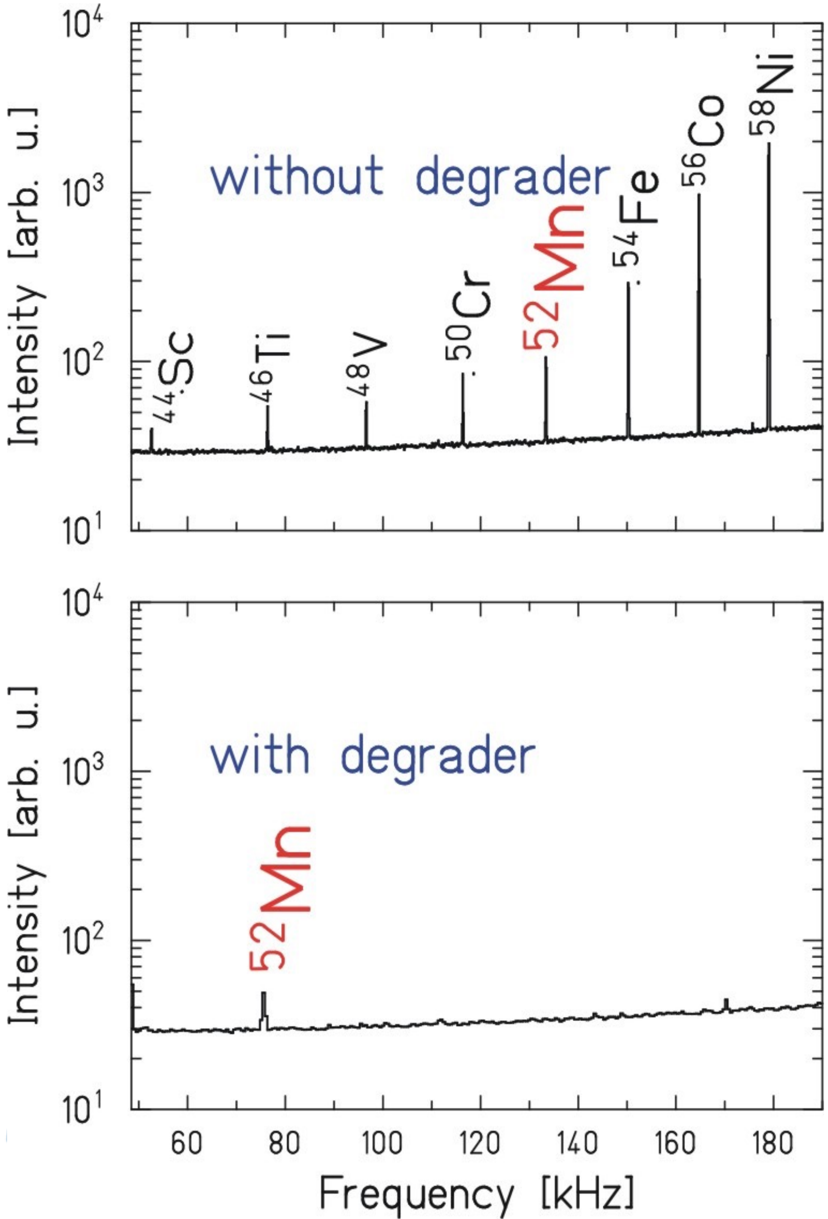
Primary beams @ 400-1000 MeV/u

Highly-Charged Ions (0, 1, 2 … bound electrons)

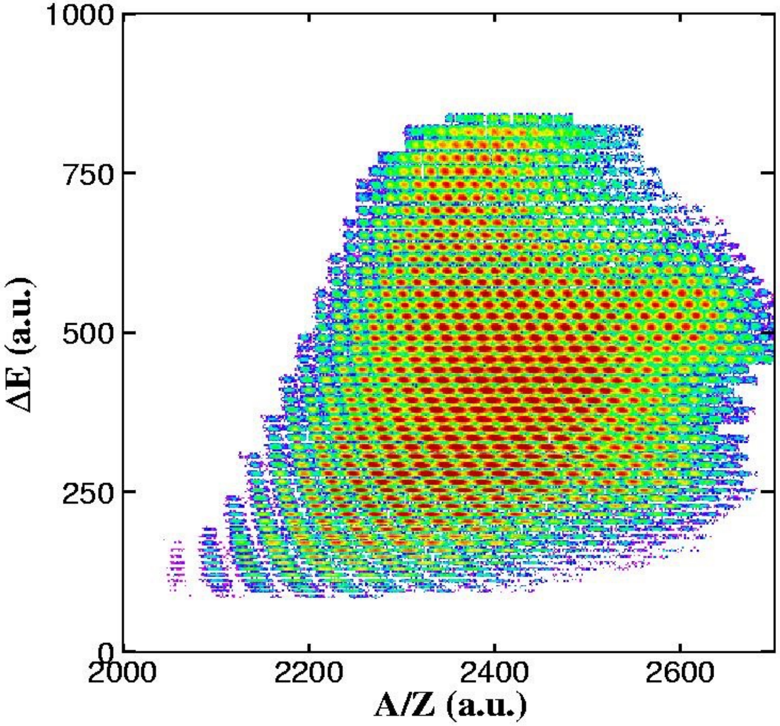
In-Flight separation within ~ 150 ns

Cocktail or mono-isotopic beams

Production & Separation of Exotic Nuclei



About 1000 nuclear residues identified



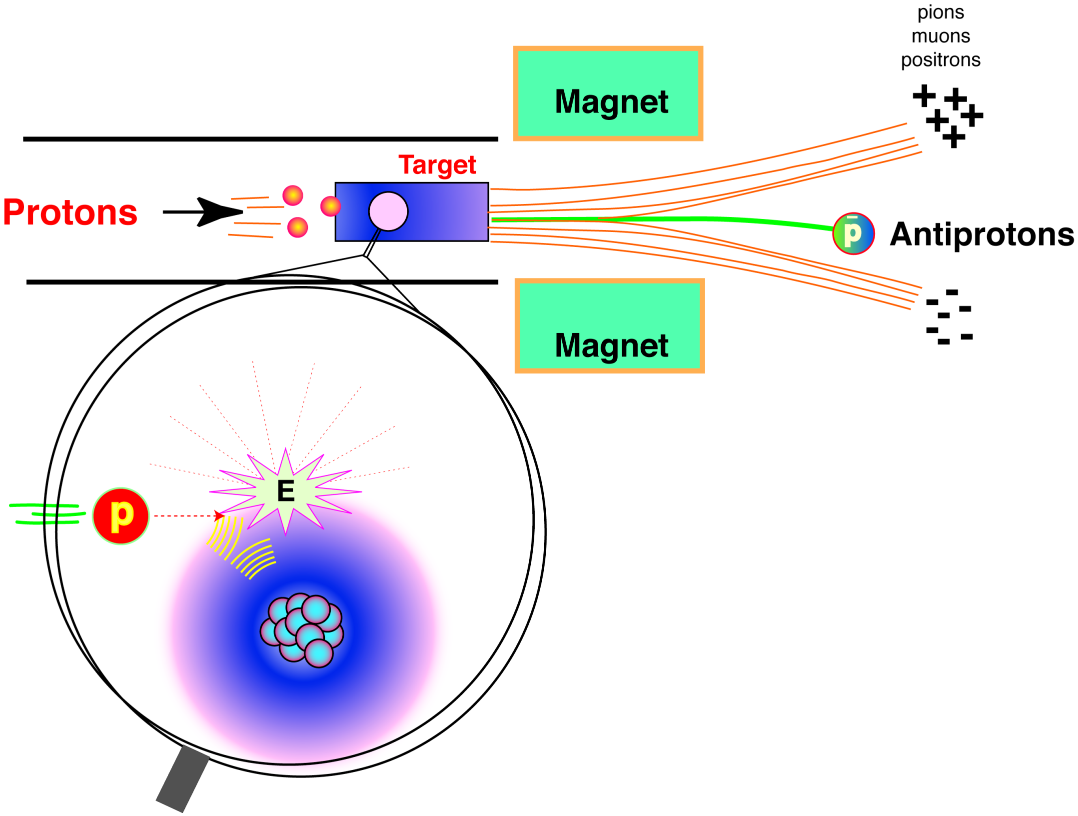
A/Z-resolution ~10^{-3}

J. Pereira et al., PRC (2007)

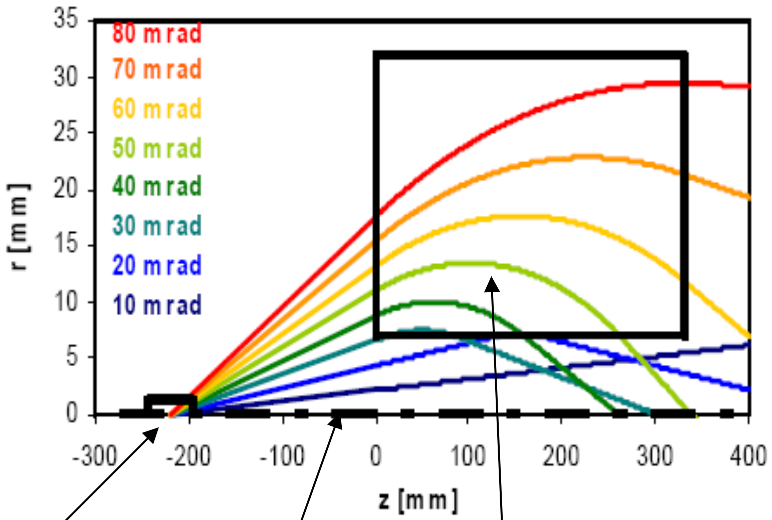
Production of Antiprotons

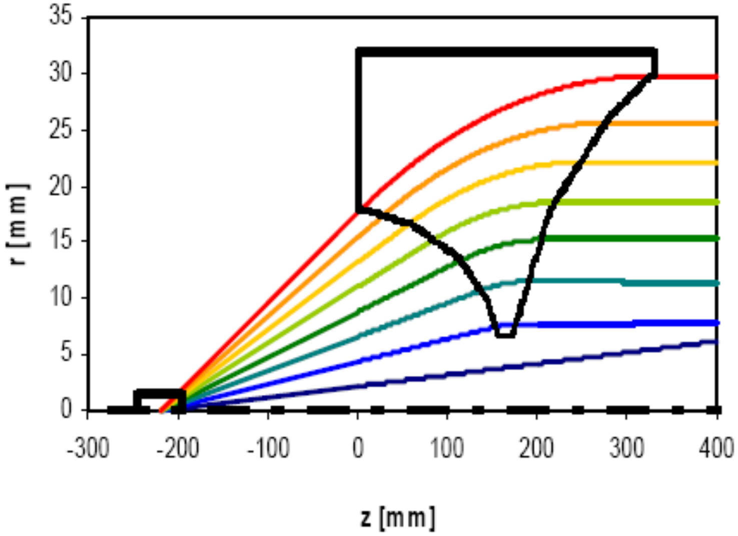
p beam
p target at rest

$$T_p > 6m_p$$



Collection of Antiprotons

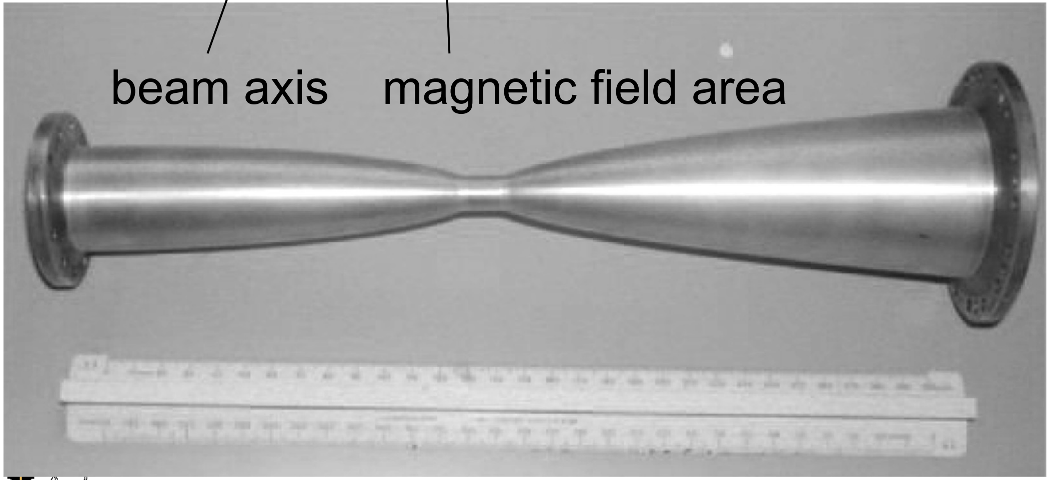




target

beam axis

magnetic field area

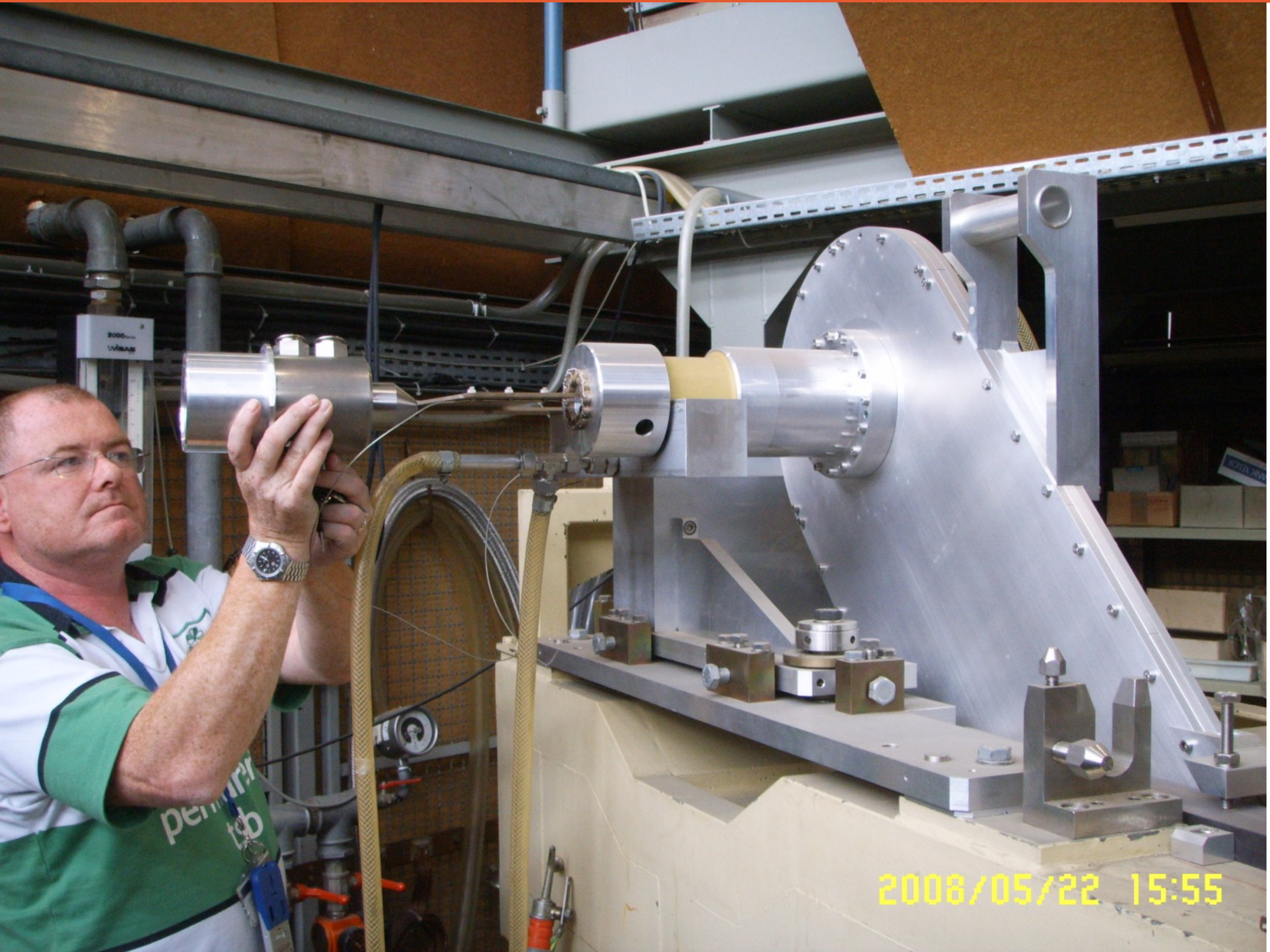


CERN ACOL Horn,

I = 400 kA

Courtesy V. Gostishchev

Collection of Antiprotons



Summary of the lecture

1) Synchroton and Betatron

2) Production of ion and electron beams
- electron sources
- ionization processes
  - electron-impact ionization
  - surface ionization
  - resonant laser ionization
- production of highly charged ions
- production of radionuclides
- production of antiprotons

3) Magents
- dipole magnets
- quadrupole magnets (QP)
- sextupole magnets

- superconducting magnets