Scuola Raimondo Anni

Electro-weak probes in Nuclear Physics

Electron scattering

(a general introduction)

Antonio M. Lallena

Universidad de Granada

Otranto, 2013

Outline

i. A very short history of electron scattering
ii. General properties of electron scattering
iii. A rough description of an experiment

A very short history of electron scattering

The discovering of the electron

-in 1897, J.J. Thomson discovered “electrons”, the corpuscles forming the cathode rays

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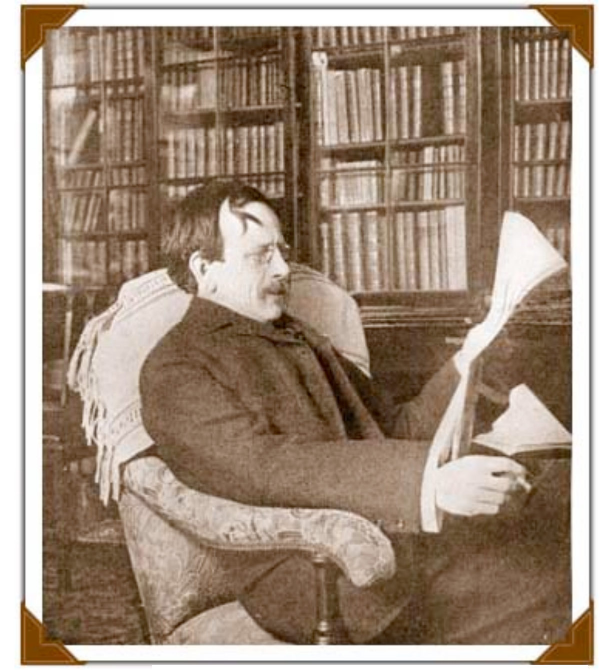
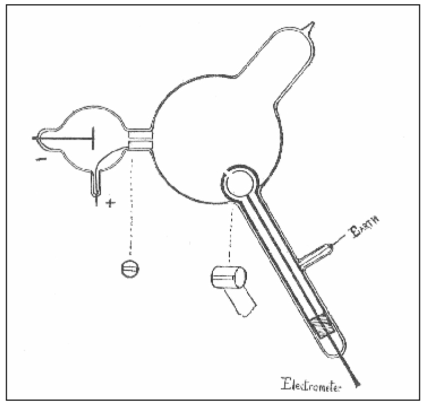
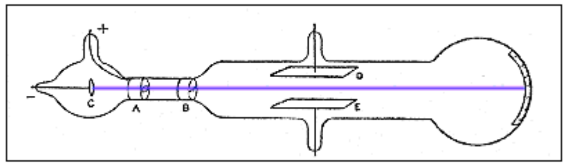
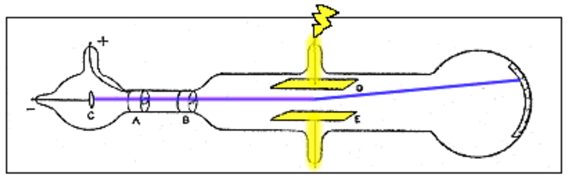


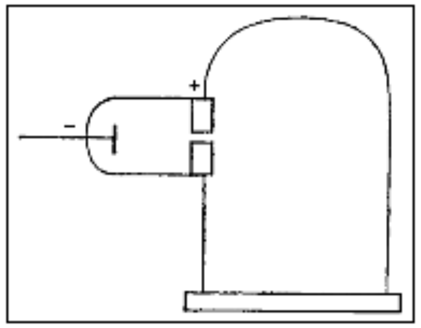
At first there were very few who believed in the existence of these bodies smaller than atoms.







Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen?



We have in the cathode rays matter in a new state.

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-in 1897, J.J. Thomson discovered "electrons", the corpuscles forming the cathode rays

The properties of the electron

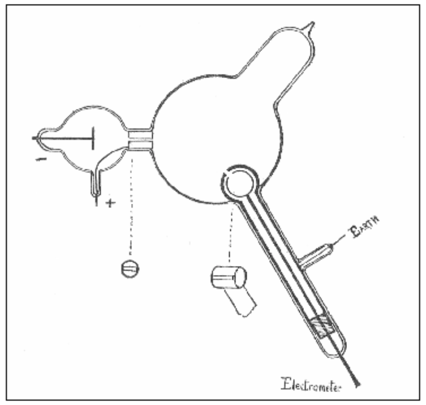
-charge: -1.609×10^{-19} C

-mass: 9.109×10^{-31} kg $= 0.511$ MeV/c^2

-spin: $\frac{1}{2}\hbar$ -magnetic moment: $\sim 1\mu_B$

-stable particle: $\tau \geq 4.6 \times 10^{26}$ y

-involved in: electroweak interactions



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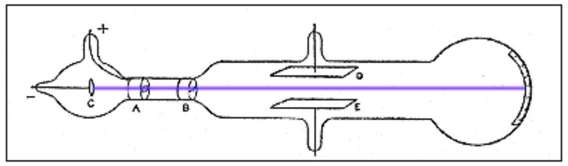

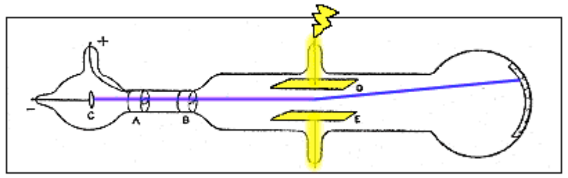

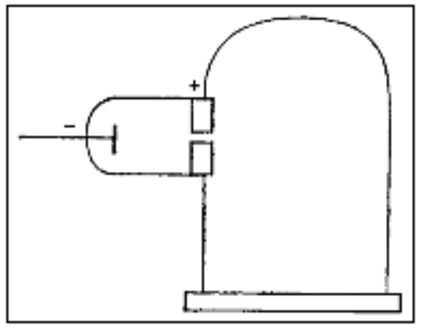

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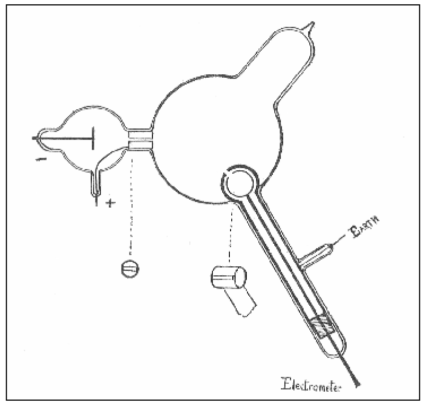

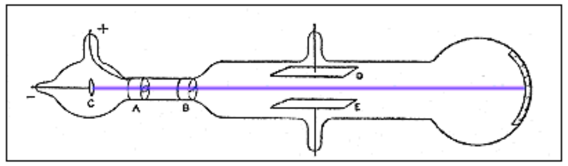

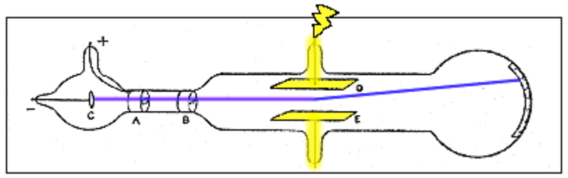

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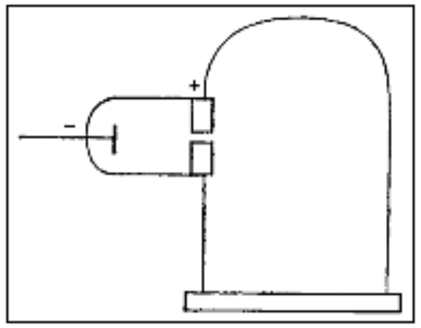

-J.J. Thomson won the Nobel prize in 1906

-"electron": name coined by G. Johnstone Stoney in 1891

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A very short history of electron scattering

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Proc. R. Soc London 124 (1929) 425

-he used Dirac equation, point-like nucleus: Mott cross section

$$\sigma_{\mathrm{Mott}} = \left(\frac{\alpha \cos\theta/2}{2\,\epsilon_{\mathrm{i}} \sin^2\theta/2} \right)^2$$

The Scattering of Fast Electrons by Atomic Nuclei.

By N. F. Mott, B.A., St. John's College, Cambridge.

(Communicated by N. Bohr, For. Mem. R.S.—Received April 25, 1929.)

Section 1.—The hypothesis that the electron has a magnetic moment was, as is well known, first introduced to account for the duplexity phenomena of atomic spectra. More recently, however, Dirac has succeeded in accounting for these same phenomena by the introduction of a modified wave equation, which conforms both to the principle of relativity and to the general transformation theory. Formally, at least, on the new theory also, the electron has a magnetic moment of $\varepsilon h/mc$, but when the electron is in an atom we cannot observe this magnetic moment directly; we can only observe the moment of the whole atom, or, of course, the splitting of the spectral lines, which we may say is "caused" by this moment. The question arises, has the *free* electron "really" got a magnetic moment, a magnetic moment that we can by any conceivable experiment observe? The question is not so simple as it might seem, because a magnetic moment $\varepsilon h/mc$ can never be observed directly, *e.g.*, with a magnetometer; there is always an uncertainty in the external electromagnetic field, due to the uncertainty in the position and

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- H.S.W. Massey. Proc. R. Soc London 127 (1930) 666

-magnetic cross section much smaller than charge cross section

Scattering of Fast Electrons and Nuclear Magnetic Moments.

By H. S. W. Massey, B.A., M.Sc., Trinity College, Cambridge; Aitchison Scholar, University of Melbourne.

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Scattering of Fast Electrons and Nuclear Magnetic Moments.

Summary.—The problem of the nuclear scattering of fast electrons has been considered by Mott.* His method consists in using the wave equation of Dirac† and applying the usual theory of collisions thereto. The result obtained is not in good agreement with experiment and it is thus of interest to consider the possibilities of other effects. In this note the effect of a nuclear magnetic moment is considered and shown to be negligible. Thus the only explanation of the disagreement between theory and experiment seems to be the effect of radiation as suggested by Mott.*

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➡more energetic electrons are needed to probe the nuclear interior:

electron wavelength ~ nuclear size

➡lack of experimental electron facilities:

electron scattering↓↓ hadron scattering↑↑

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-De Broglie wavelength: $$\lambda = \frac{h}{mv}$$

$$\frac{\lambda_p}{\lambda_e} = \frac{m_e}{m_p} \sim \frac{1}{2000}$$ (for the same velocity)

smaller wavelengths can be achieved with relatively low energies in case of hadrons

•H.

-ma

Scat

By H. S

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-use of electron scattering to investigate nuclear structure.

-Dirac theory + PWBA: Fourier transform of the nuclear electrostatic potential ⟶ to measure nuclear sizes!!!

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•E.M. Lyman, A.O. Hanson, M.B. Scott.

PHYSICAL REVIEW VOLUME 84, NUMBER 4 NOVEMBER 15, 1951

Scattering of 15.7-Mev Electrons by Nuclei*

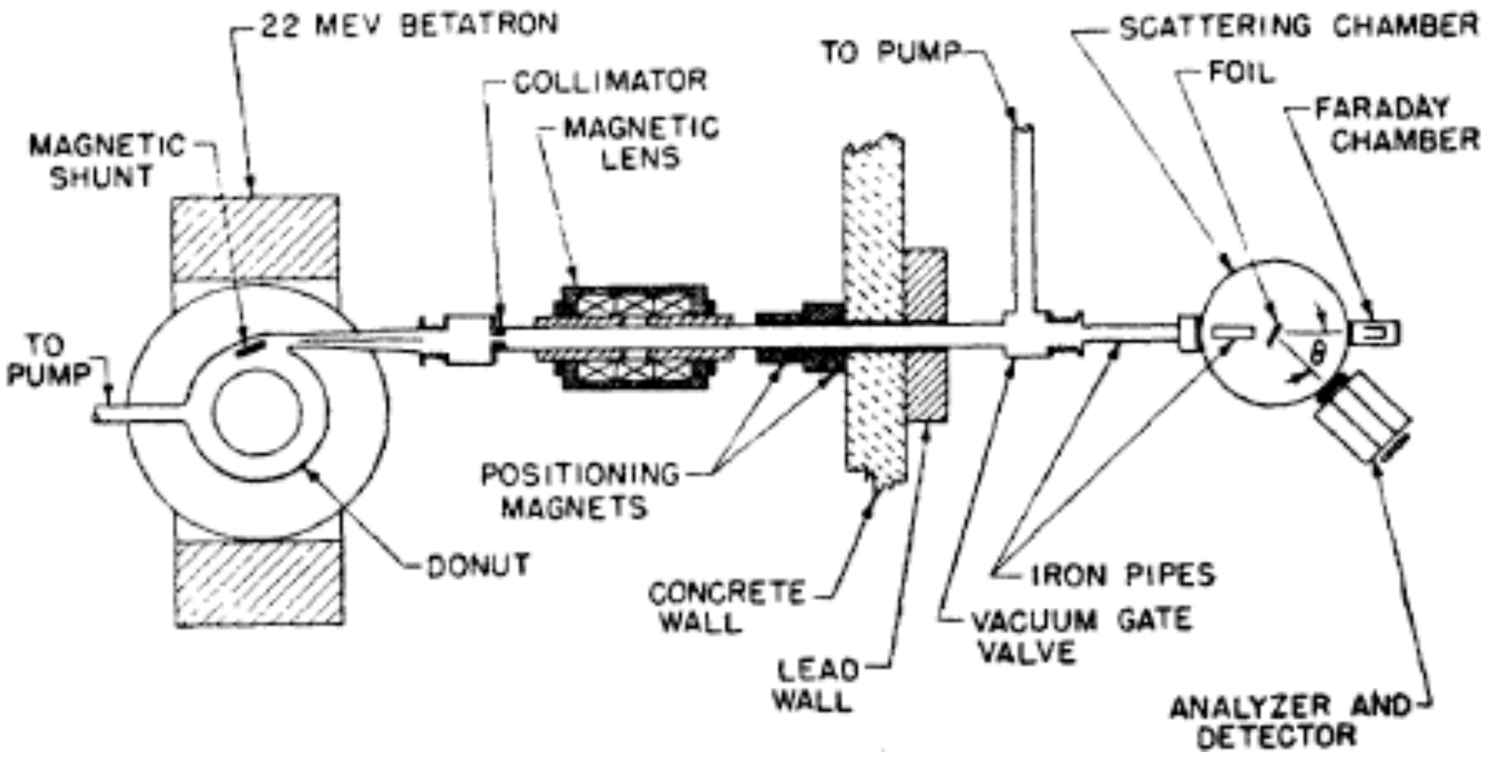
E. M. LYMAN, A. O. HANSON, AND M. B. SCOTT†
Department of Physics, University of Illinois, Urbana, Illinois
(Received July 3, 1951)

Electrons removed from the 20-Mev betatron are focused to a 0.08-inch spot about 10 feet from the betatron by a magnetic lens. The electrons impinge on thin foils at the center of a highly evacuated scattering chamber having a diameter of 20 inches. Elastically scattered electrons, selected by a $\frac{3}{8}$ inch×2 inch aperture, are focused by means of a 75° magnetic analyzer with 3 percent energy resolution and are detected by coincidence Geiger counters. Corrections are applied for multiple scattering and for energy losses which remove the electrons from the range of energies accepted by the detector arrangement. The scattering cross section for gold at 150° is found to be about 2.6 times that given by Mott's formula in the Born approximation and about one-half of that expected for the scattering by a point nucleus. This result is in good agreement with the calculations for electrons of this energy if the nuclear charge is assumed to be distributed uniformly throughout the nuclear volume.

The results for the scattering from C, Al, Cu, and Ag are also in agreement with the assumption of a uniformly distributed nuclear charge within the uncertainties involved in the theory and the experimental results.

-first experiment confirming Guth predictions.

Lyman, Hanson & Scott experiment



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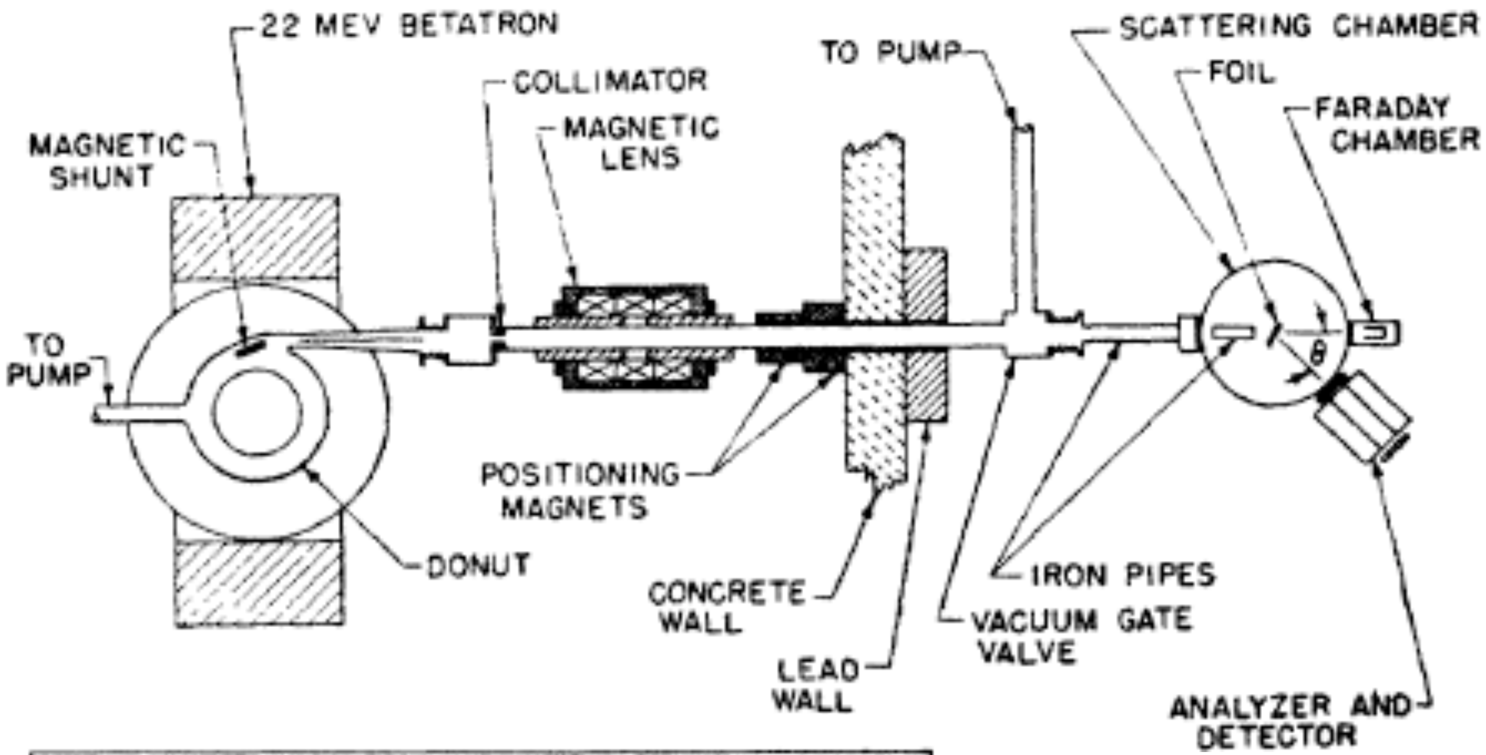

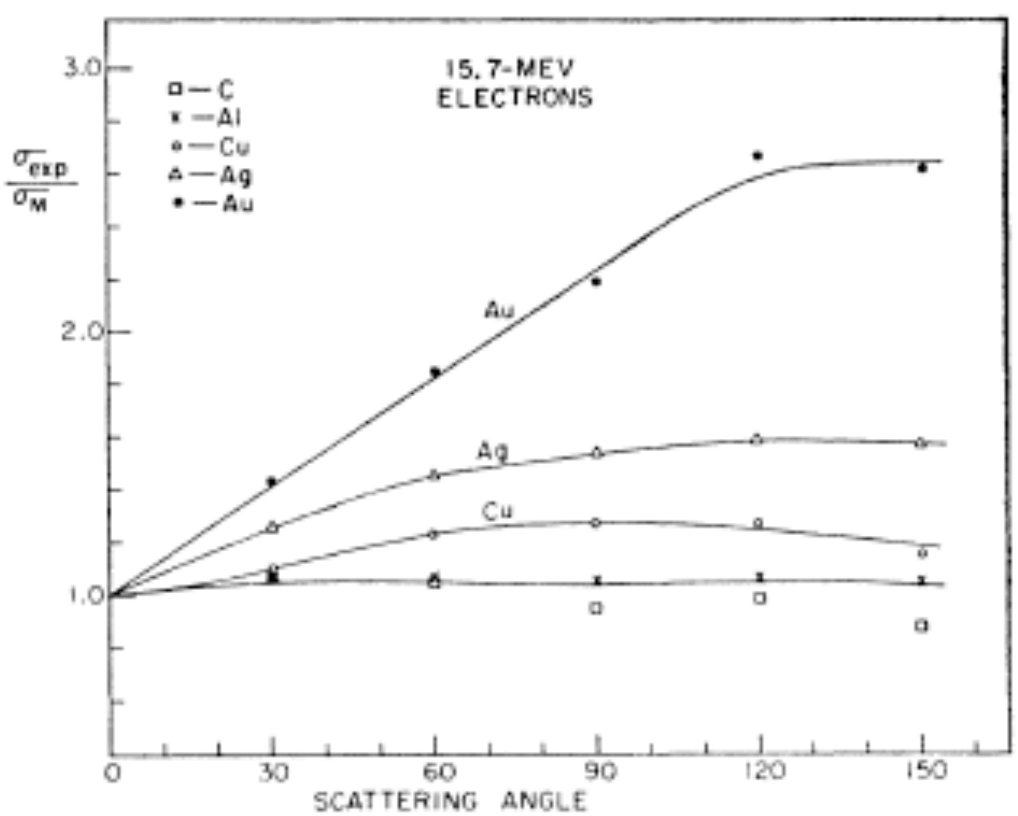

deviations with respect to Mott cross sections

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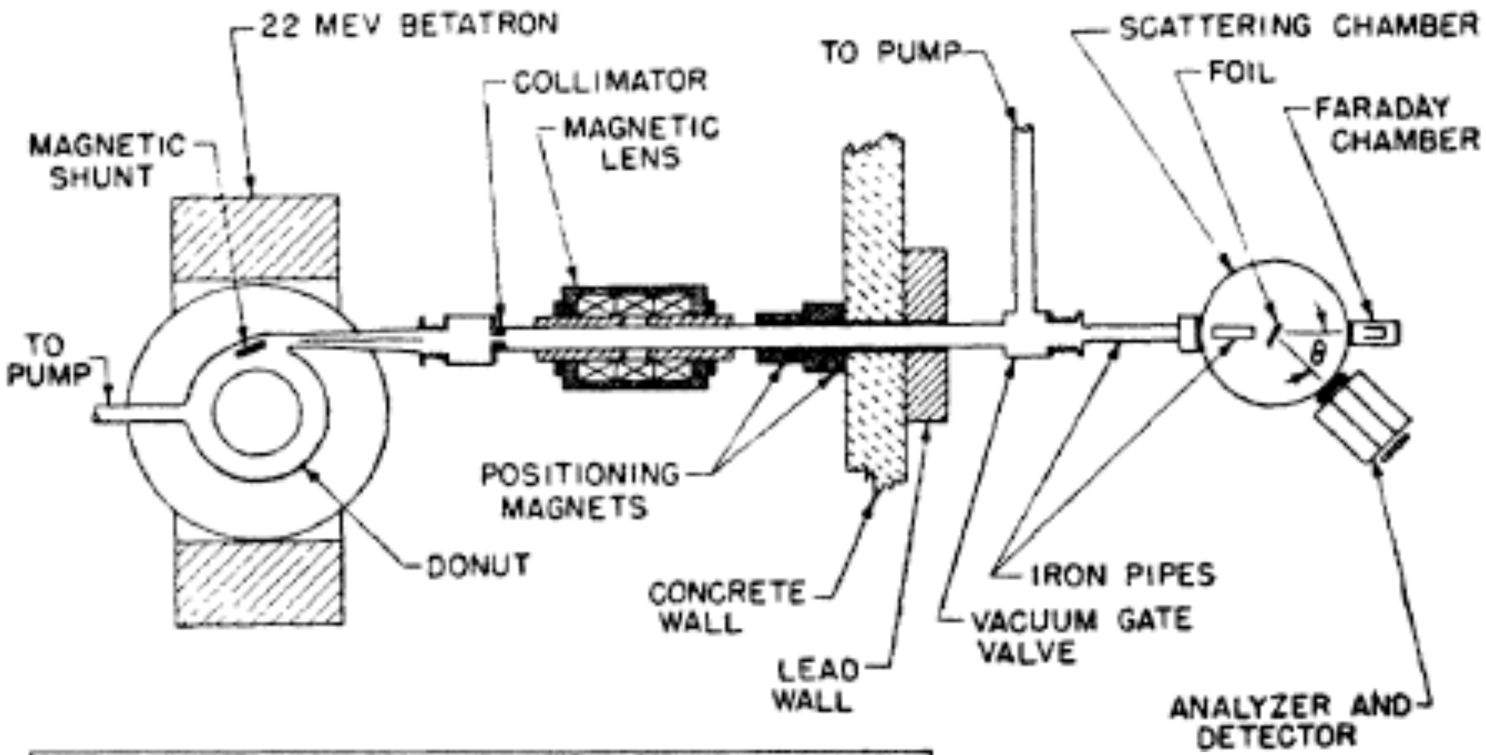
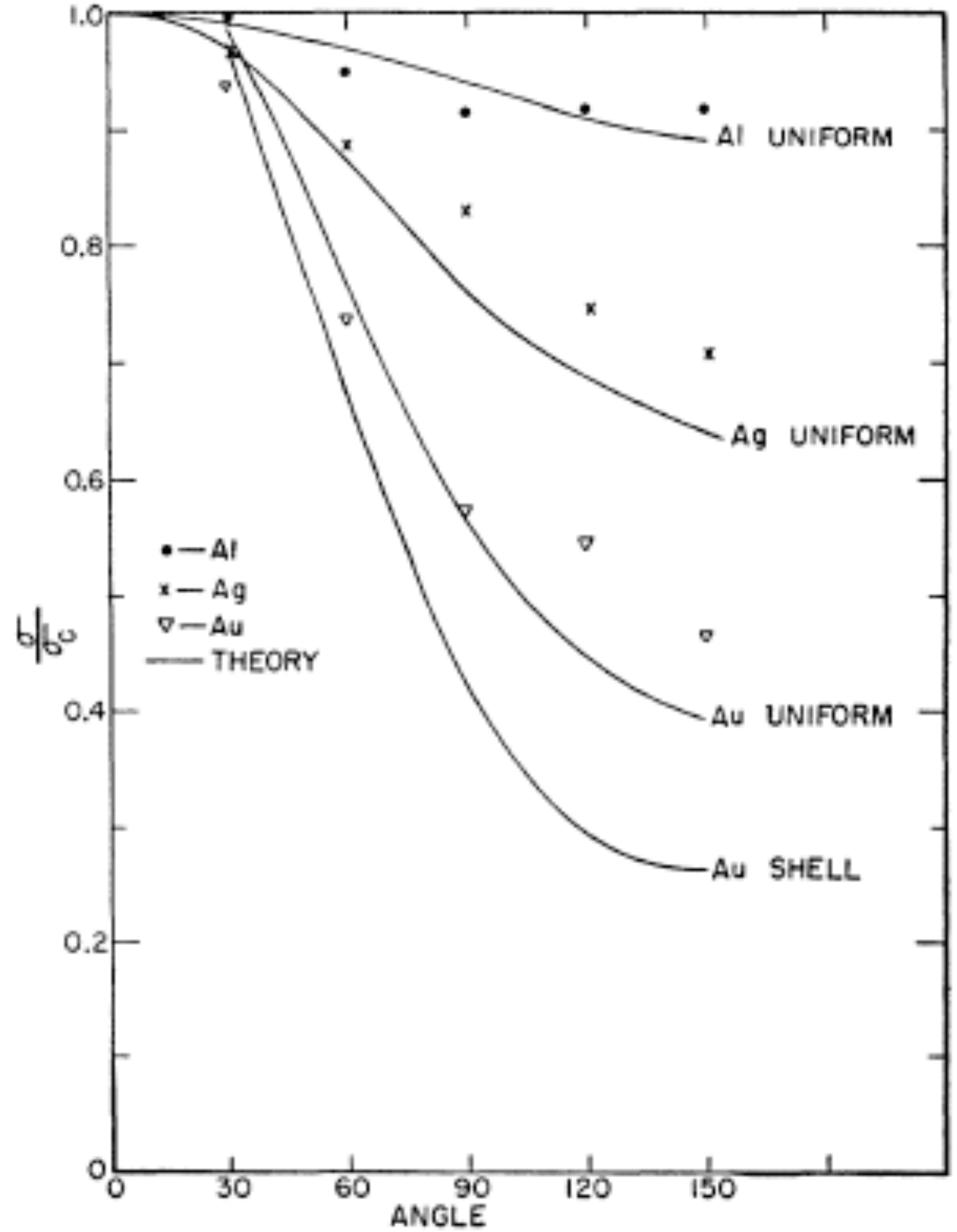
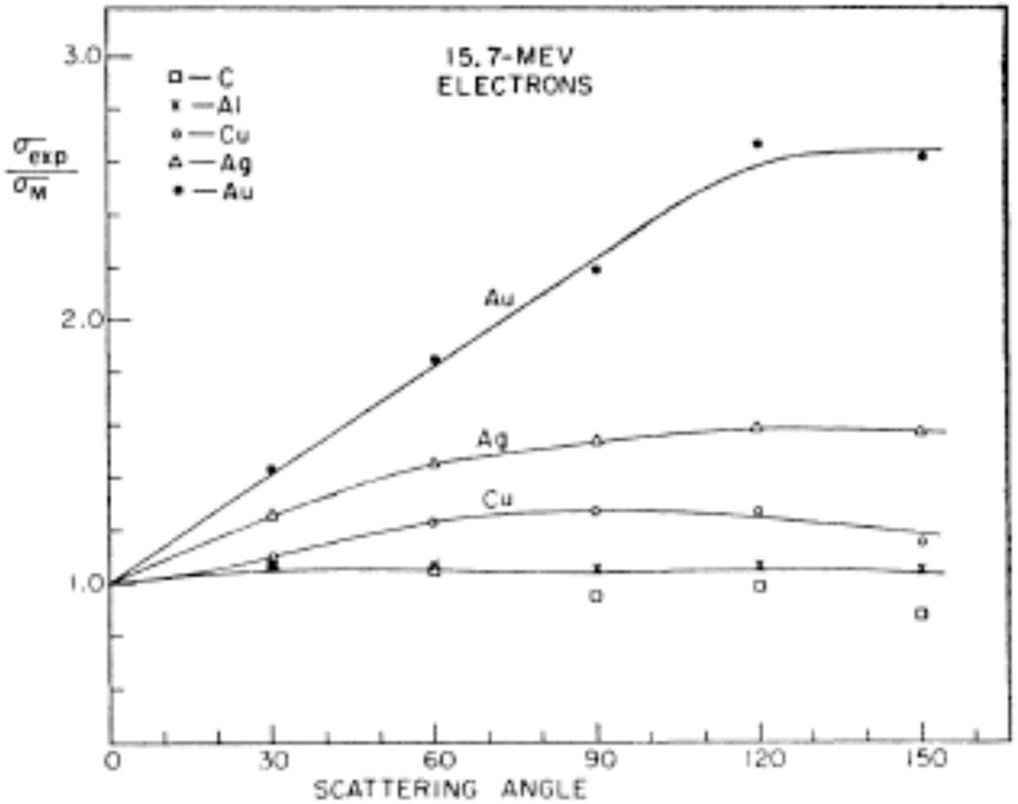






nuclear radius 20% smaller than the commonly accepted obtained with hadronic probes $(1.45 \cdot A^{1/3})$

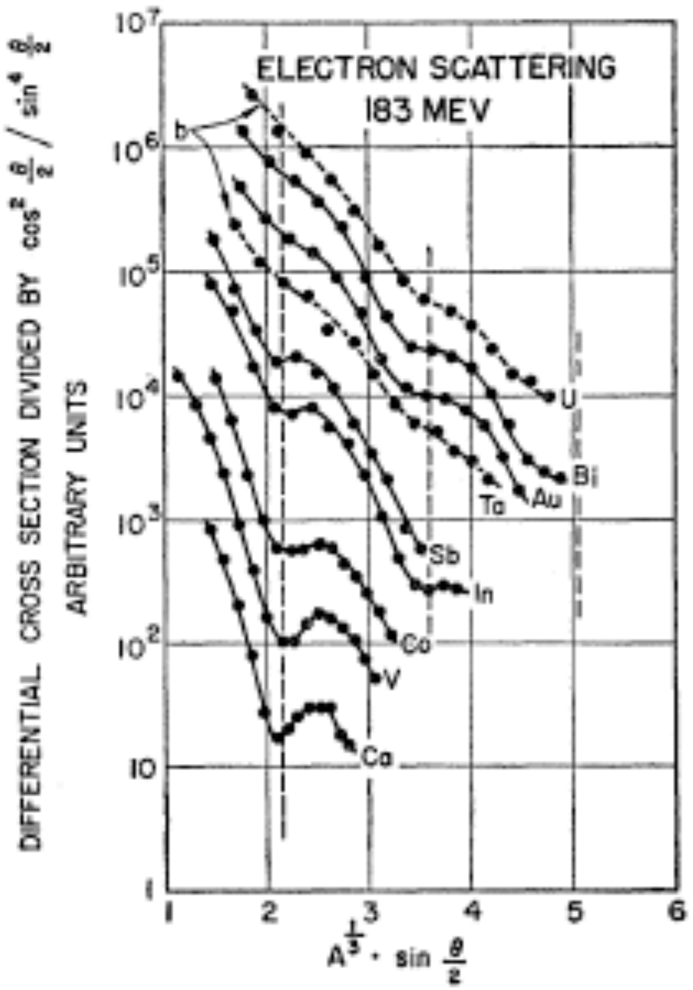
deviations with respect to Mott cross sections

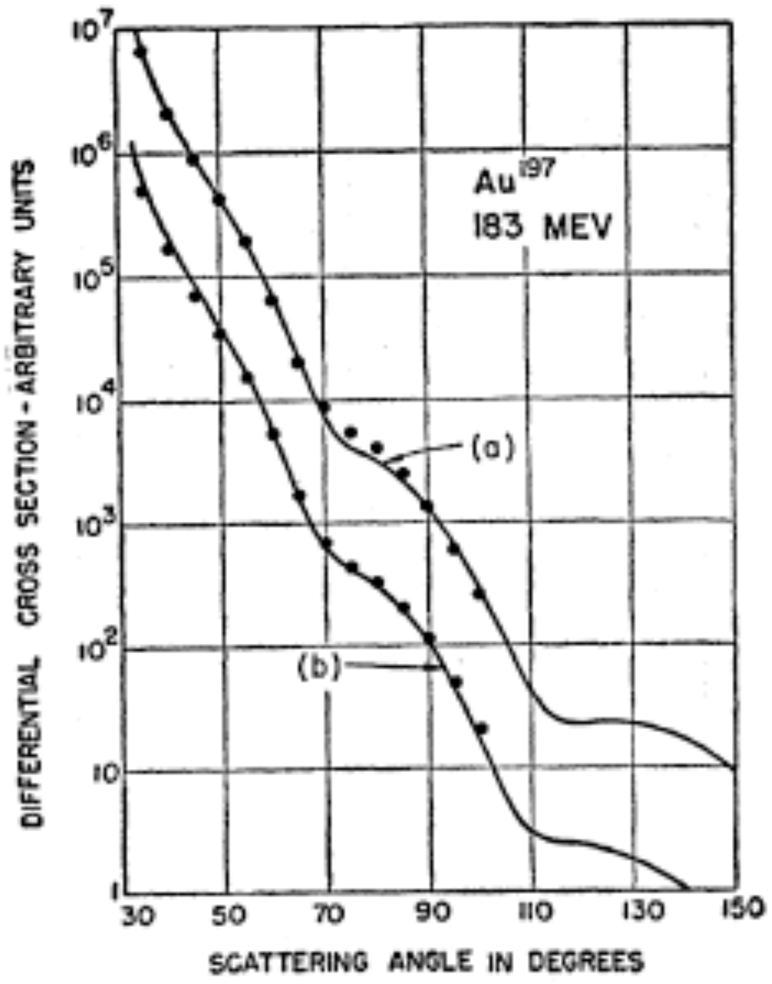
A very short history of electron scattering

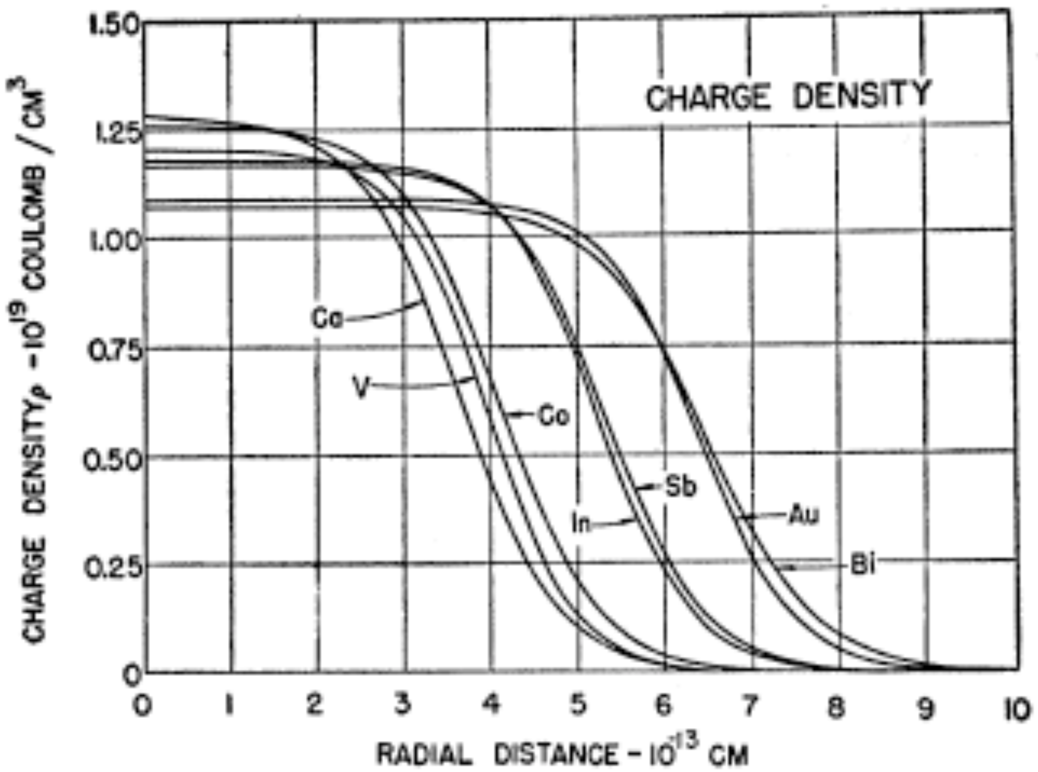
- R. Hofstadter and collaborators. [Rev. Mod. Phys. 28 (1956) 214]

-Stanford electron accelerator

-elastic electron scattering from nuclear charge







Hofstadter:
Nobel Prize in 1961

A very short history of electron scattering

Magnetic electron scattering: very small cross sections!!

• M.N. Rosenbluth.

Phys. Rev. 79 (1950) 615

-derived electron-proton cross section taking into account charge and normal and anomalous magnetic moments

High Energy Elastic Scattering of Electrons on Protons

M. N. Rosenbluth
Stanford University, Stanford, California

(Received March 28, 1950)

The theory of the elastic scattering of electrons on protons at very high energies is discussed in detail. A formula is given for the cross section. This formula contains certain parameters which depend on the action of the virtual photon and meson fields. In particular, curves have been calculated on the assumption of scalar and pseudoscalar meson theory. While these perturbation theory calculations are not very trustworthy, and the results depend on the choice of coupling constants, it is felt that qualitative features can be checked with experiment. It is concluded that at low relativistic energies ($E<50$ Mev) the experiment provides a valuable check on quantum electrodynamics. At higher energies it should yield data on the nature of the meson cloud of the proton.

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- R. Hofstadter and R.W. McAllister.

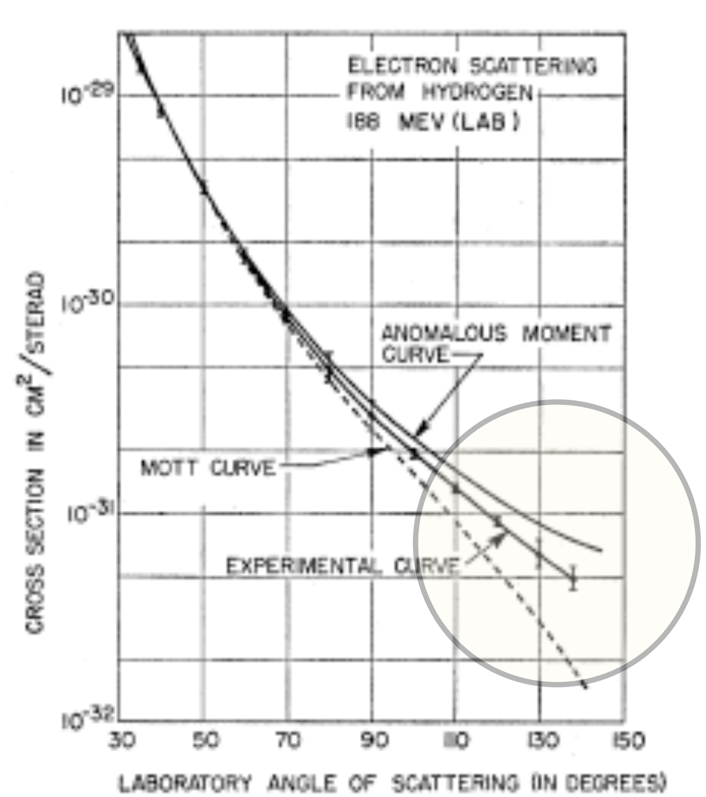
Phys. Rev. 98 (1955) 217

-deviations with respect to the Mott cross section:

due to proton magnetic moment

-rms proton radius:

$$(7.4 \pm 2.4) \cdot 10^{-14}\ \text{cm}$$



Electron Scattering from the Proton*†‡

Robert Hofstadter and Robert W. McAllister
Department of Physics and High-Energy Physics Laboratory, Stanford University, Stanford, California
(Received January 24, 1955)

With apparatus previously described,[1,2] we have studied the elastic scattering of electrons of energies 100, 188, and 236 Mev from protons initially at rest. At 100 Mev and 188 Mev, the angular distributions of scattered electrons have been examined in the ranges 60°–138° and 35°–138°, respectively, in the laboratory frame. At 236 Mev, because of an inability of the analyzing magnet to bend electrons of energies larger than 192 Mev, we have studied the angular distribution between 90° and 138° in the laboratory frame. In all cases a gaseous hydrogen target was used.

A very short history of electron scattering

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INNER-SHELL PROTON BINDING ENERGIES IN C^{12} AND Al^{27} FROM THE $(e, e'p)$REACTION USING 550-MeV ELECTRONS*†

U. Amaldi, Jr., G. Campos Venuti, G. Cortellessa, C. Fronterotta, A. Reale, and P. Salvadori
Physics Laboratory, Istituto Superiore di Sanità, Rome, Italy

and

P. Hillman‡
Laboratori Nazionali di Frascati, Rome, Italy
(Received 3 August 1964)

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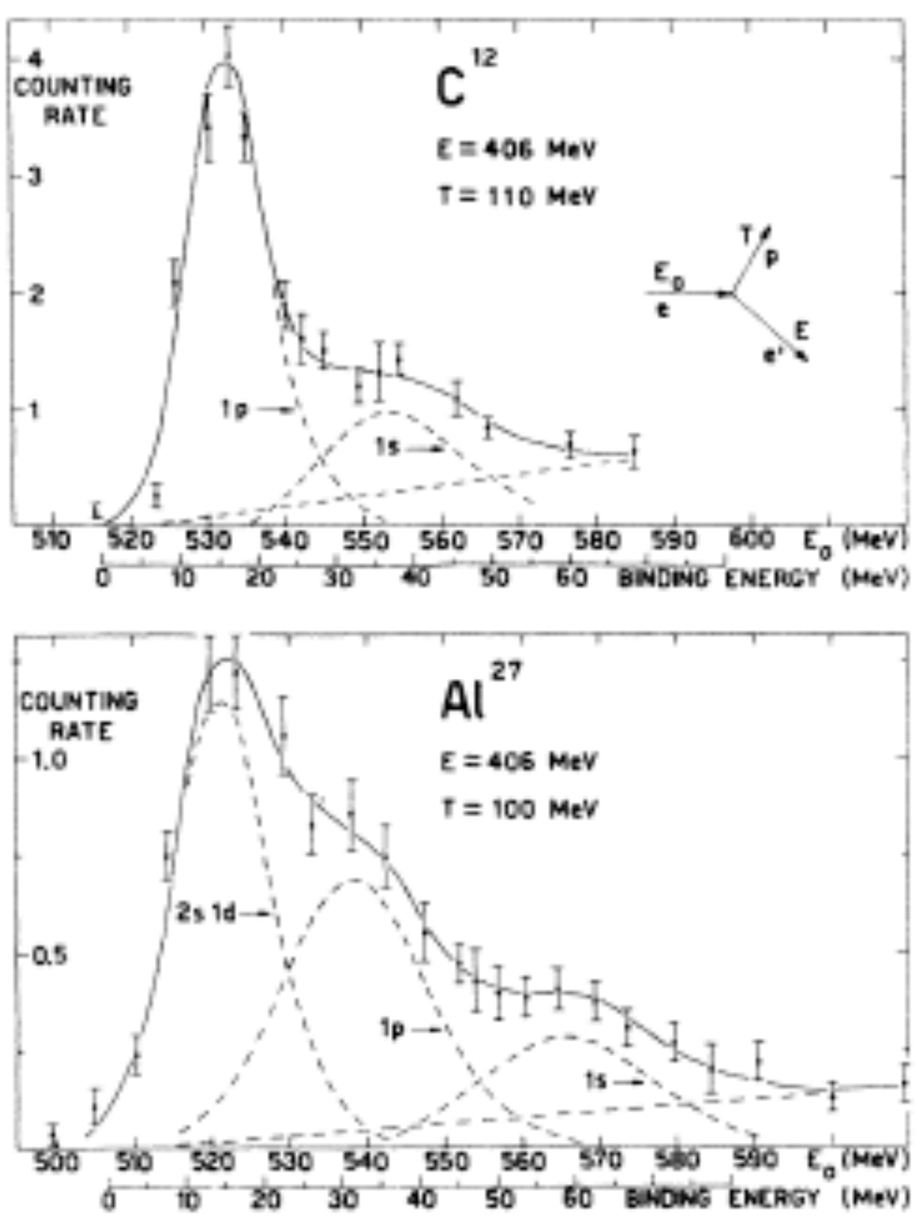
Phys. Rev. Lett. 13 (1964) 341

-first coincidence experiment: the scattered electron is observed in coincidence with other particles emitted after the collision



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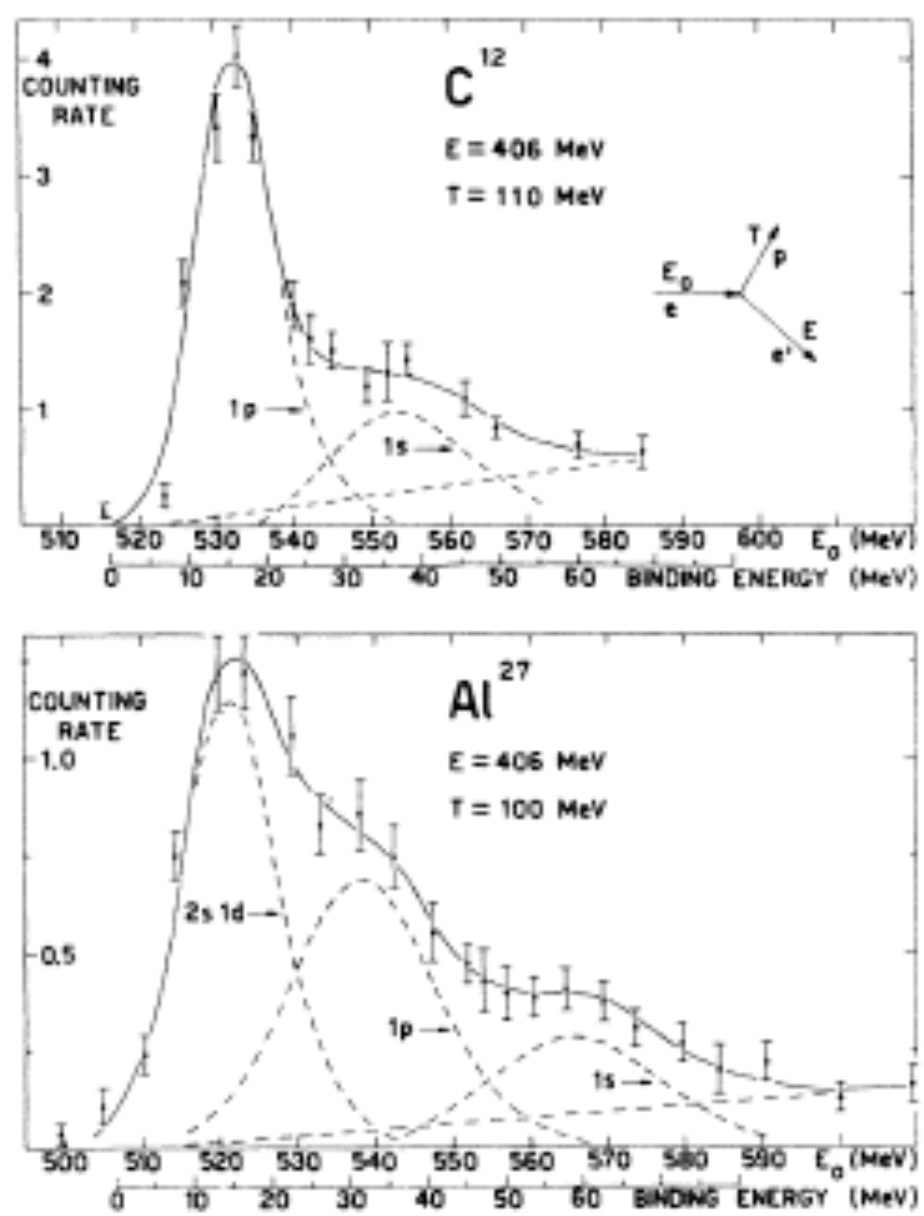

performed in the synchrotron facility at Frascati

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Meson exchange currents

- H. Collard et al. Phys. Rev. 138 (1965) B57

Elastic Electron Scattering from Tritium and Helium-3*

H. Collard, R. Hofstadter, E. B. Hughes, A. Johansson,† and M. R. Yearian
Department of Physics and High-Energy Physics Laboratory, Stanford University, Stanford, California

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R. B. Day and R. T. Wagner‡
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received 23 November 1964)

- R.E. Rand et al.

Phys. Rev. Lett. 18 (1967) 469

ELECTRON SCATTERING FROM THE DEUTERON AT $\theta = 180°$*

R. E. Rand,† R. F. Frosch, C. E. Littig, and M. R. Yearian
High Energy Physics Laboratory and Department of Physics, Stanford University, Stanford, California
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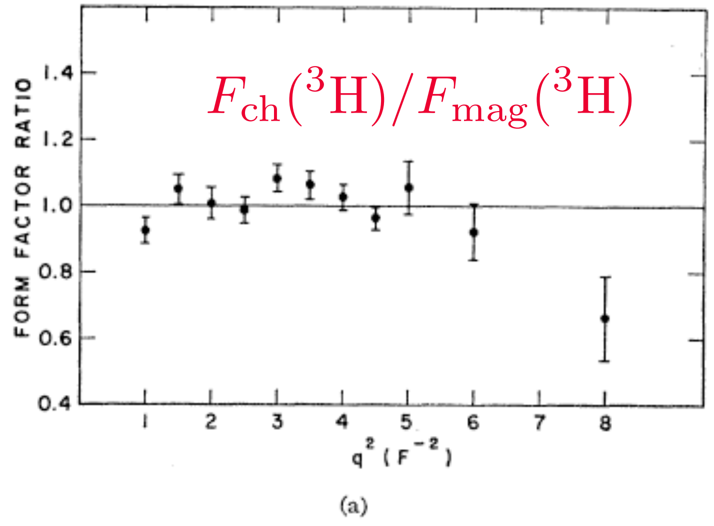

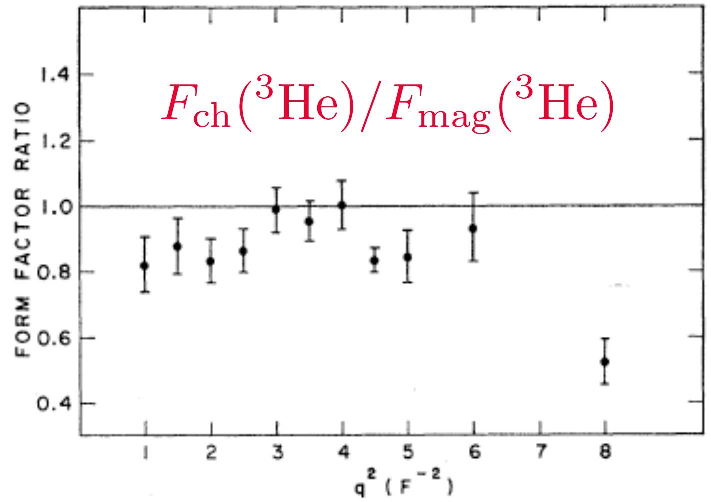

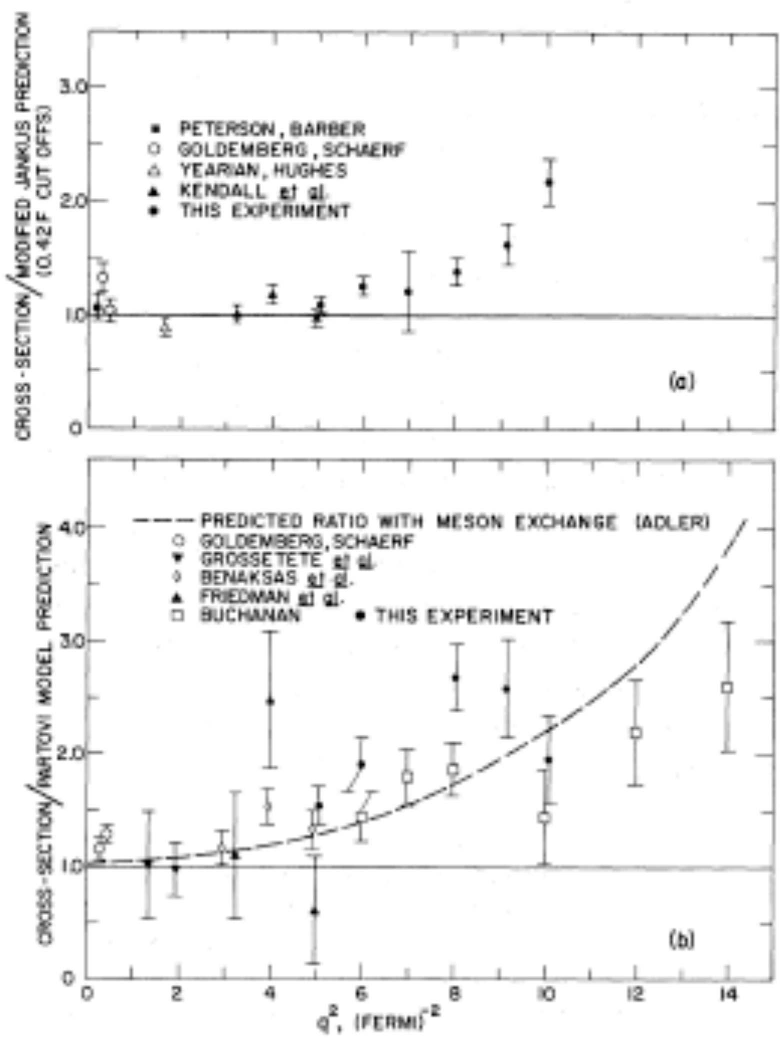

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Facilities

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-Frascati (Italy)
-NIKHEF, Amsterdam (Netherlands)
-Bates, MIT (USA)
-MAMI, Mainz (Germany)
-Senadi (Japan)
-DESY, Hamburg (Germany)
-DALINAC, Darmstadt (Germany)
-Saclay (France)
-TJNL, Newport News (USA)

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-Bates, MIT (USA)

-MAMI, Mainz (Germany)

-Senadi (Japan)

-DESY, Hamburg (Germany)

-DALINAC, Darmstadt (Germany)

-Saclay (France)

-TJNL, Newport News (USA)

Future facilities: exotic nuclei!!

-SCRIT, Sendai (Japan)

-Elise@FAIR, Darmstadt (Germany)

A very short history of electron s

Facilities

- -SLAC, Stanford (USA)
- -Frascati (Italy)
- -NIKHEF, Amsterdam (Nether
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- -MAMI, Mainz (Germany)
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PTEP

Prog. Theor. Exp. Phys. **2012**, 03C008 (11 pages)
DOI: 10.1093/ptep/pts043

Nuclear physics at the SCRIT electron scattering facility

Toshimi Suda[1,*], Tatsuya Adachi[1], Tatsuya Amagai[1], Akitomo Enokizono[2], Masahiro Hara[3], Toshitada Hori[3], Shin'ichi Ichikawa[3], Kazuyoshi Kurita[2], Takaya Miyamoto[1], Ryo Ogawara[2], Tetsuya Ohnishi[3], Yuuto Shimakura[2], Tadaaki Tamae[1], Mamoru Togasaki[2], Masanori Wakasugi[3], Shuo Wang[1], and Kayoko Yanagi[1]

[1]*Research Center for Electron Photon Science, Tohoku University, 1-2-1 Mikamine, Sendai 982-0826*
[2]*Department of Physics, Rikkyo University, Nishiikebukuro, Toshima, Tokyo 171-8501*
[3]*Nishina Center for Accelerator-Based Science, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198*
*E-mail: suda@lns.tohoku.ac.jp

Received August 15, 2012; Accepted August 27, 2012; Published December 17, 2012

The SCRIT electron scattering facility is under construction at the RIKEN RI Beam Factory. This is the world's first facility dedicated to the study of the structure of short-lived nuclei by electron scattering, which has been a long-standing dream for nuclear physics. A novel Self-Confining RI Target (SCRIT) technique makes this challenging research possible. A series of test experiments using stable nuclei performed at this partially completed facility show that the collision luminosity between electron beam and target nucleus reaches 10^{27} cm^{-2} s^{-1}, which is required for an elastic electron scattering measurement to determine the charge density distribution of the target nucleus. The first electron scattering for unstable Sn isotopes will take place in the year 2014.

Future facilities: exotic nuclei!!

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Facilities

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Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

The electron–ion scattering experiment ELISe at the International Facility for Antiproton and Ion Research (FAIR)—A conceptual design study

A.N. Antonov [a], M.K. Gaidarov [a], M.V. Ivanov [y], D.N. Kadrev [a], M. Aïche [b], G. Barreau [b], S. Czajkowski [b], B. Jurado [b], G. Belier [c], A. Chatillon [c], T. Granier [c], J. Taieb [c], D. Doré [d], A. Letourneau [d], D. Ridikas [d], E. Dupont [d], E. Berthoumieux [d], S. Panebianco [d], F. Farget [e], C. Schmitt [e], L. Audouin [f], E. Khan [f],

A B S T R A C T

The electron–ion scattering experiment ELISe is part of the installations envisaged at the new experimental storage ring at the International Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany. It offers an unique opportunity to use electrons as probe in investigations of the structure of exotic nuclei. The conceptual design and the scientific challenges of ELISe are presented.

Future facilities: exotic nuclei!!

-SCRIT, Sendai (Japan)

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Why to use electron scattering?

Why to use electron scattering?

electron-nucleus scattering is an excellent tool for studying the structure of the nuclei and their electromagnetic properties.

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electron-nucleus scattering is an excellent tool for studying the structure of the nuclei and their electromagnetic properties.

Reason #1: electrons and nuclei interact via the electromagnetic force

- coupling constant: $\alpha = 1/137.04$
- much smaller than the intensity of the strong interaction that governs most of the nuclear properties
- experiments do not greatly disturb the target nucleus structure
- advantage respect to hadron-nucleus scattering (difficulties in separating reaction mechanisms and nuclear structure)

Why to use electron scattering?

electron-nucleus scattering is an excellent tool for studying the structure of the nuclei and their electromagnetic properties.

Reason #1: electrons and nuclei interact via the electromagnetic force

Reason #2: very good knowledge of the electromagnetic interaction

- quantum electrodynamics describes the interaction in an almost "exact" manner
- quantitative information about nuclear properties can be extracted

Why to use electron scattering?

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but: electroweak interactions share these two characteristics!
what about neutrino-nucleus and photon-nucleus scattering?

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Reason #3: neutrino-nucleus coupling constant much smaller than α

- cross sections several order of magnitude smaller than for electron-nucleus scattering

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Why to use electron scattering?

Reason #1: electrons and nuclei interact via the electromagnetic force

Reason #2: very good knowledge of the electromagnetic interaction

Reason #3: neutrino-nucleus coupling constant much smaller than α

Reason #4: electron-nucleus interactions mediated by virtual photons

- in "real" photon scattering the momentum transferred to the nucleus in unequivocally determined: $q_\mu^2 = \omega^2 - \mathbf{q}^2 = 0$
- in electron scattering, the four-momentum must be space-like, that is: $q_\mu^2 = \omega^2 - \mathbf{q}^2 \leq 0$
- one can vary the momentum transferred to the nucleus for a fixed energy ω: we can study the behavior of the nucleus with the momentum $\mathbf{q}$

General pro

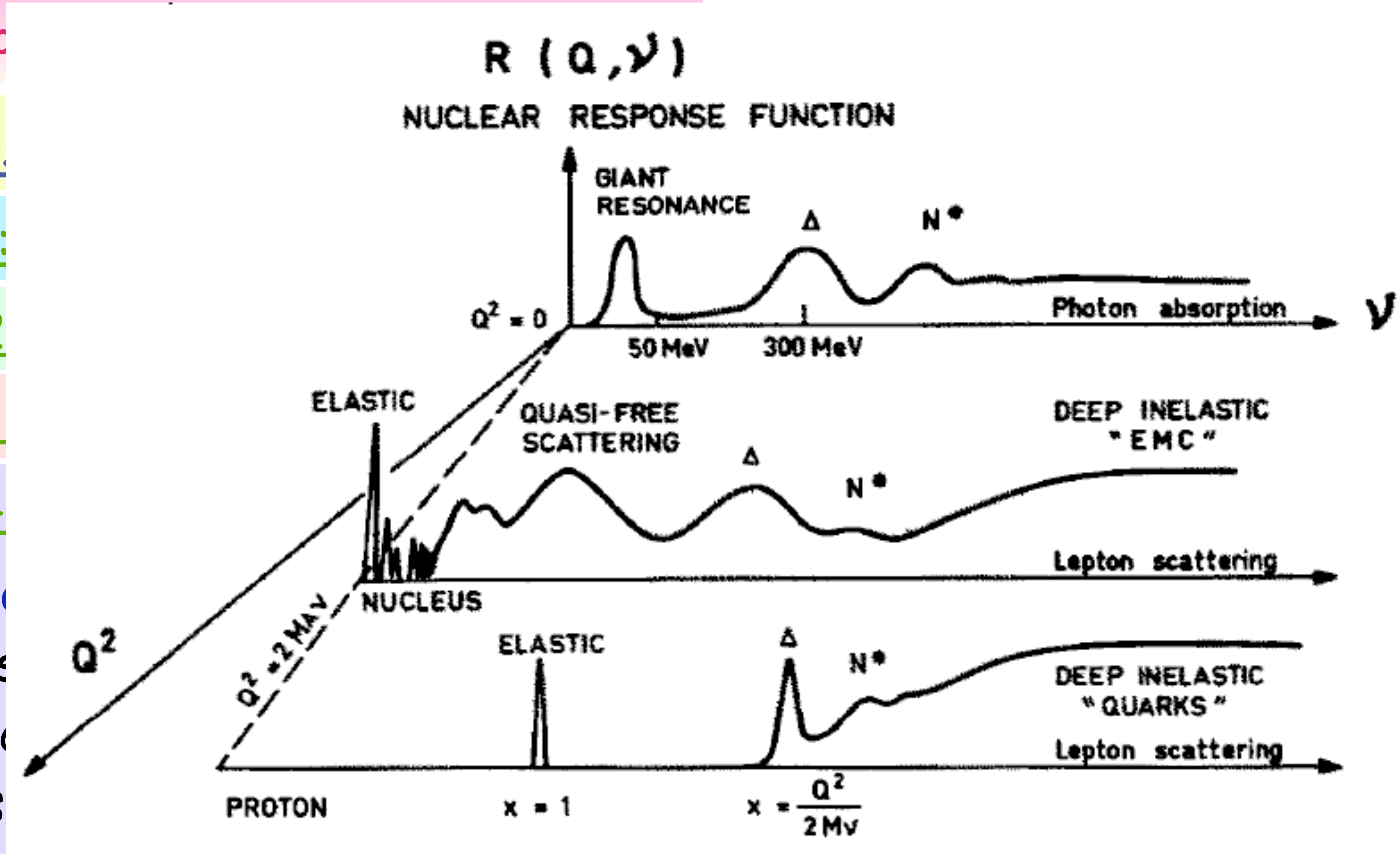
Why to us

Reason #1:

Reason #2

Reason #3

Reason #4



•in "re

nucleus

•in elec

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General properties of electron scattering

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Consequences:

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Reason #4: electron-nucleus interactions mediated by virtual photons

Consequences:

-as α is small, lowest order processes (one photon exchange) are enough to obtain accurate results of easy interpretation

-excitation energy and momentum transfer can be varied independently and one can obtain:

- nuclear excitation profiles, observing not only the electric dipole transition (dominating at low momentum transfer) but also higher multipolarities (that appear at higher momenta)
- Fourier transforms of charge and current nuclear densities

experimental facilities for electron scattering:

-an electron accelerator

-a system to transport the beam to the to the target

-a setup to detect and analyze
the products

A rough description of an experiment

experimental facilities for electron scattering:

Stanford

-an electron accelerator

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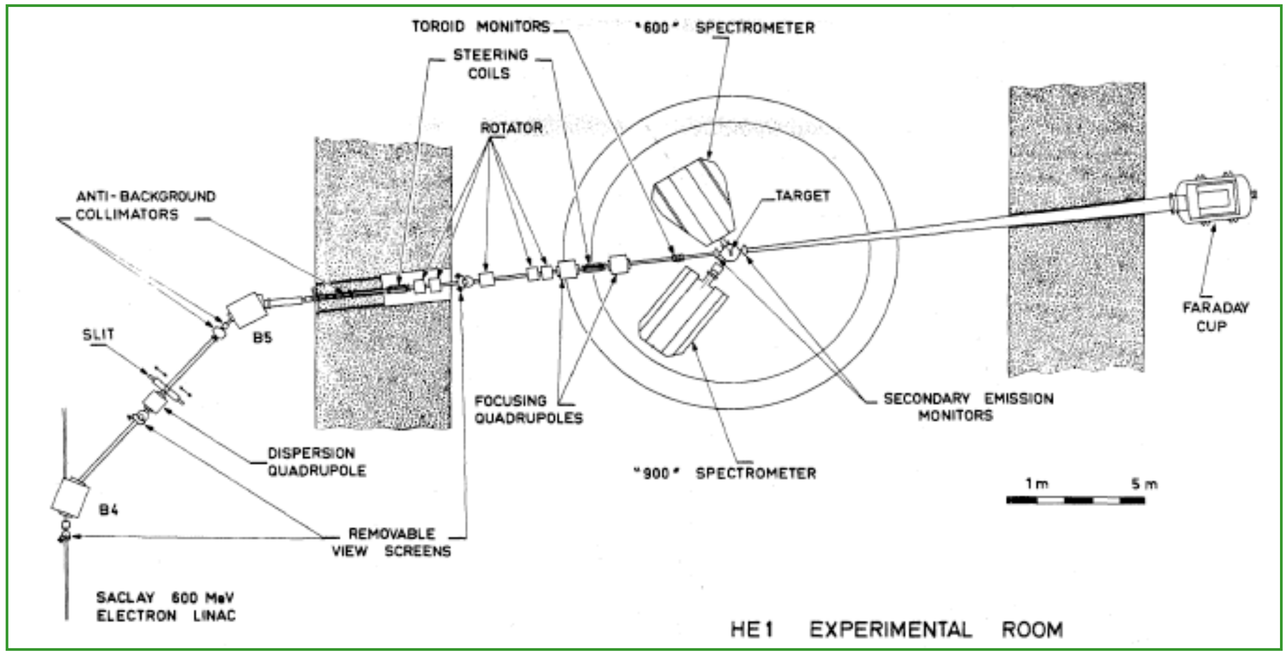

Saclay

A rough description of an experiment

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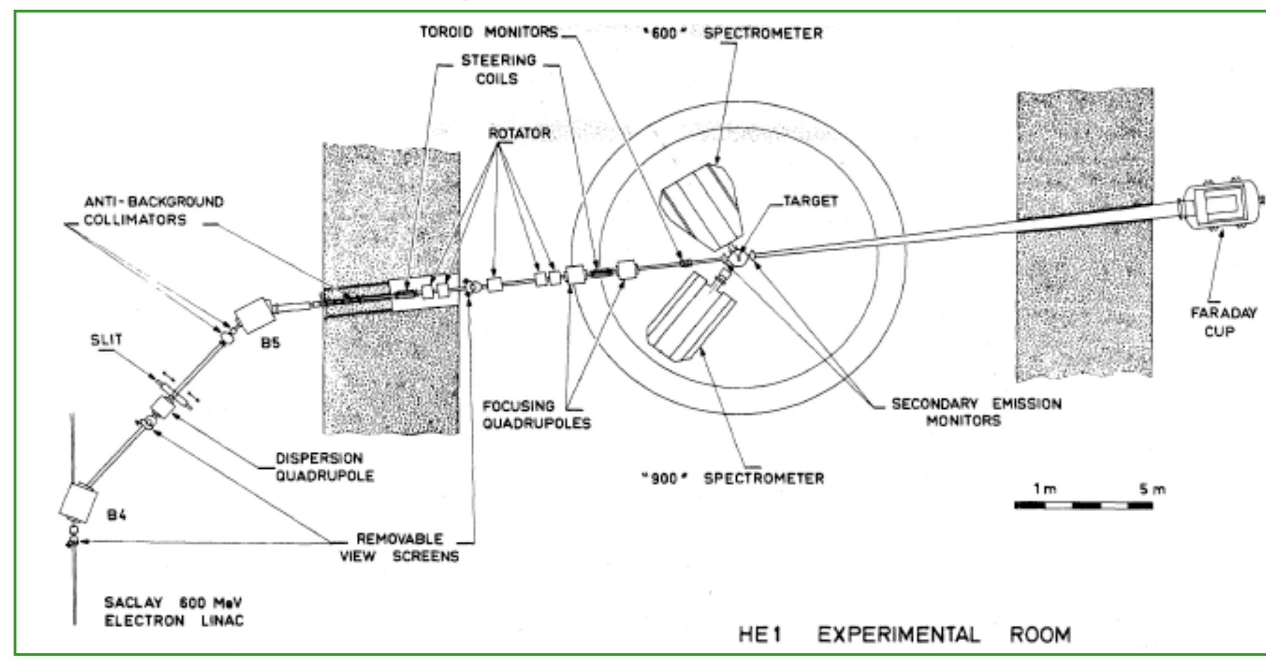

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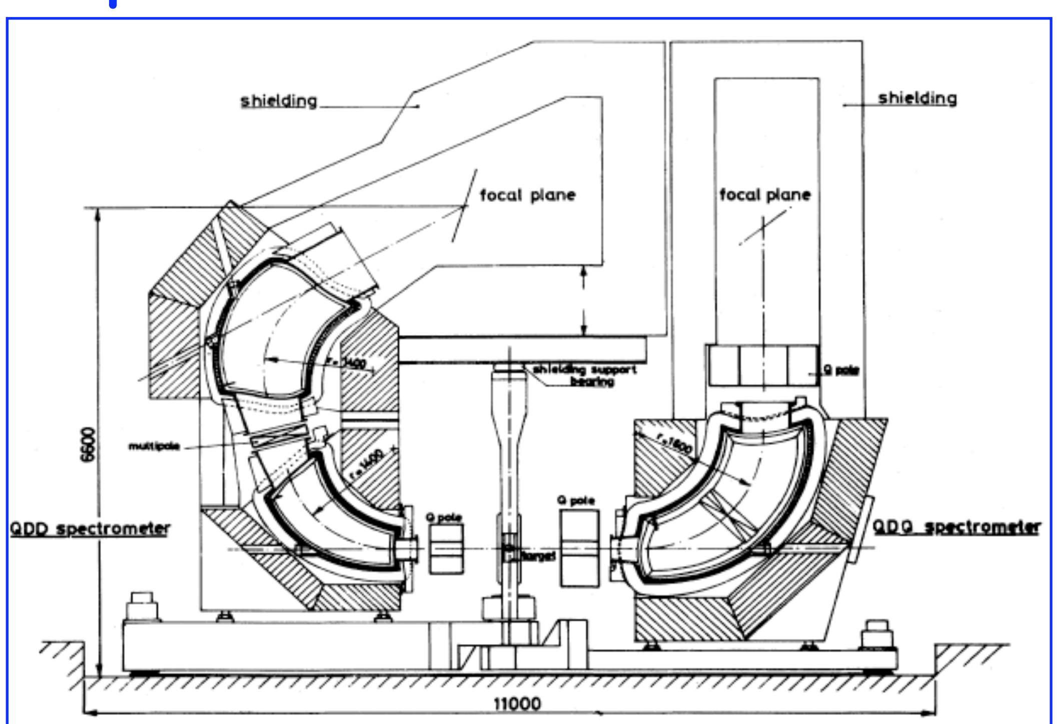

NIKHEF

Saclay

A rough description of an experiment

A rough description of an experiment

positive for nuclear structure investigations

Some previous considerations:

-weakness of the electromagnetic interaction:

small cross sections - α^2 smaller than hadronic ones!!!

- use of thick targets: this complicates data interpretation
- increase the detection solid angle: complicates experimental setup
- maximum beam intensity on the target: target could melt
- improve the detection system (with respect to hadronic case)
- need of much more beam time for measurements

A rough description of an experiment

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-electron energy and relative energy resolution: related to the nuclear structure details to be investigated

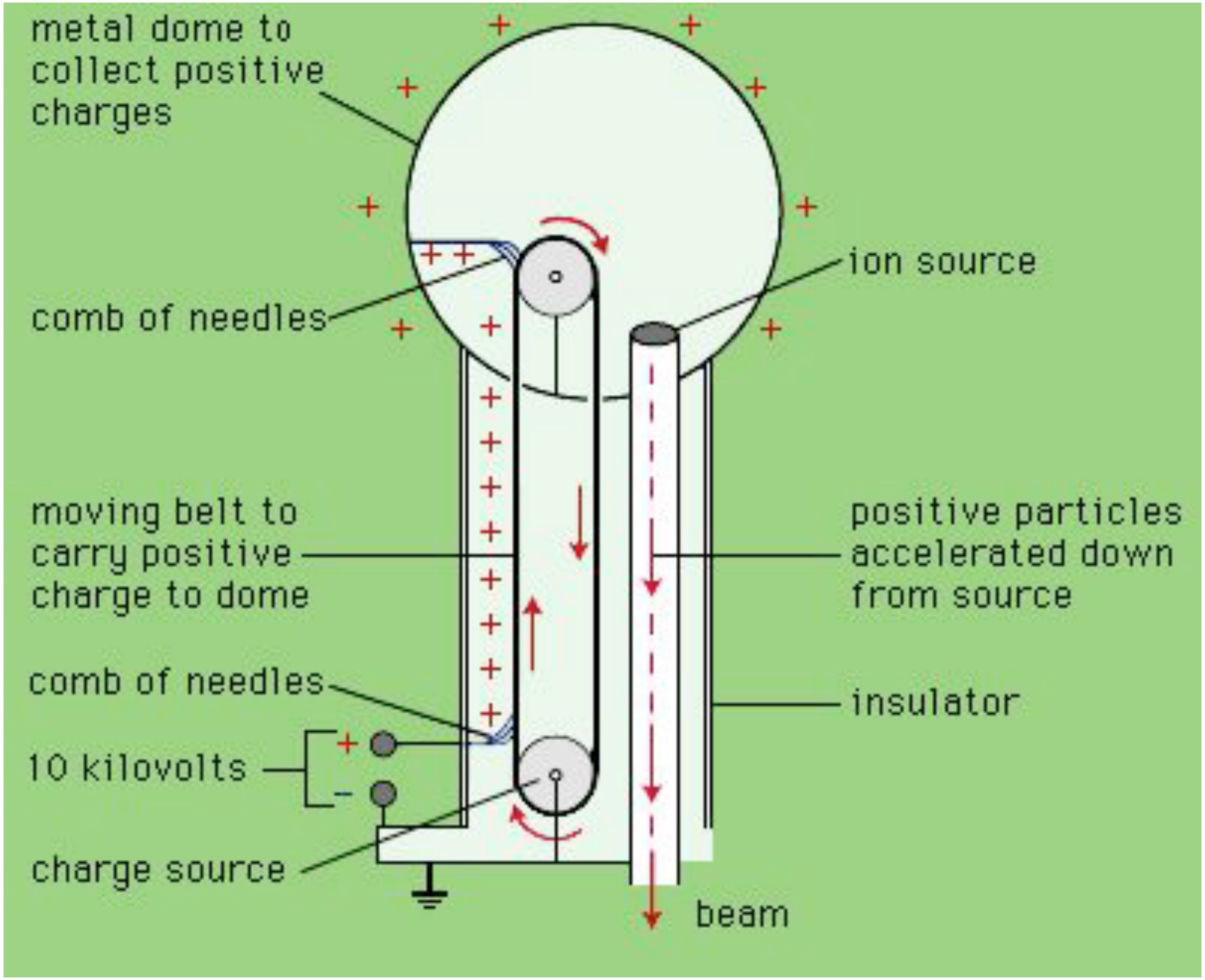
- nuclear wave functions details (~ a few fm) require to transfer to the nucleus a momentum ~ a few fm^{-1} and energies of ~ 10^2 - 10^3 MeV are needed
- nuclear level separation (~ a few tenths of keV) requires a relative energy resolution of 10^4 or better

A rough description of an experiment

Accelerators

- Van de Graaff

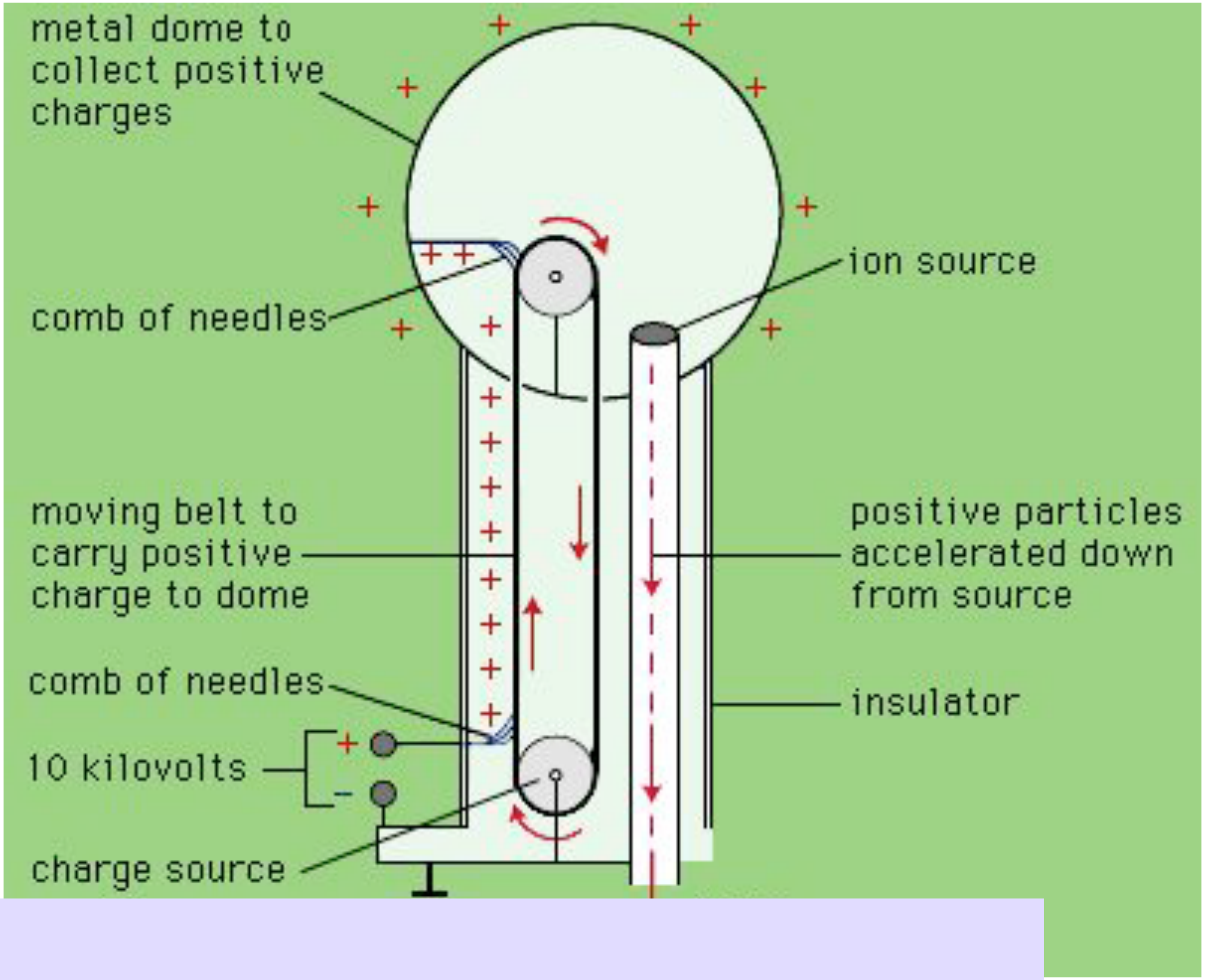
-energies ~ 10 MeV



A rough description of an experiment

Accelerators

- Van de Graaff



-energies ~ 10 MeV

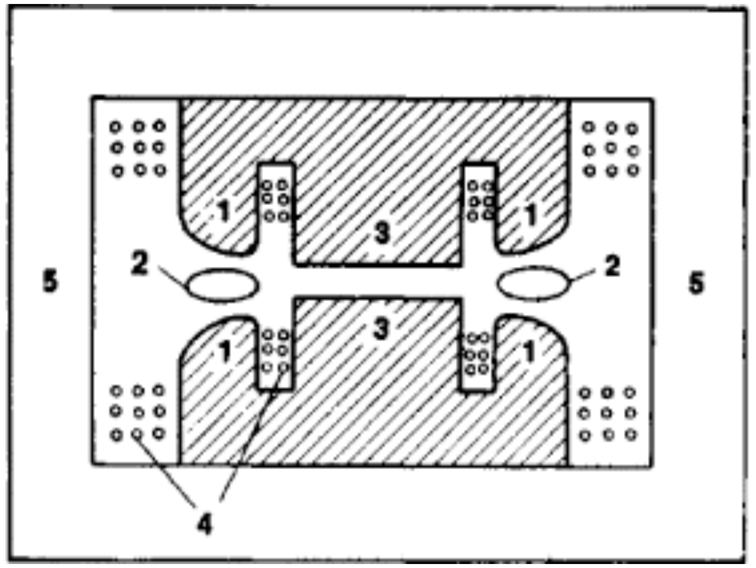
Reason #5:

electrons are charged particles (photons and neutrinos are not)

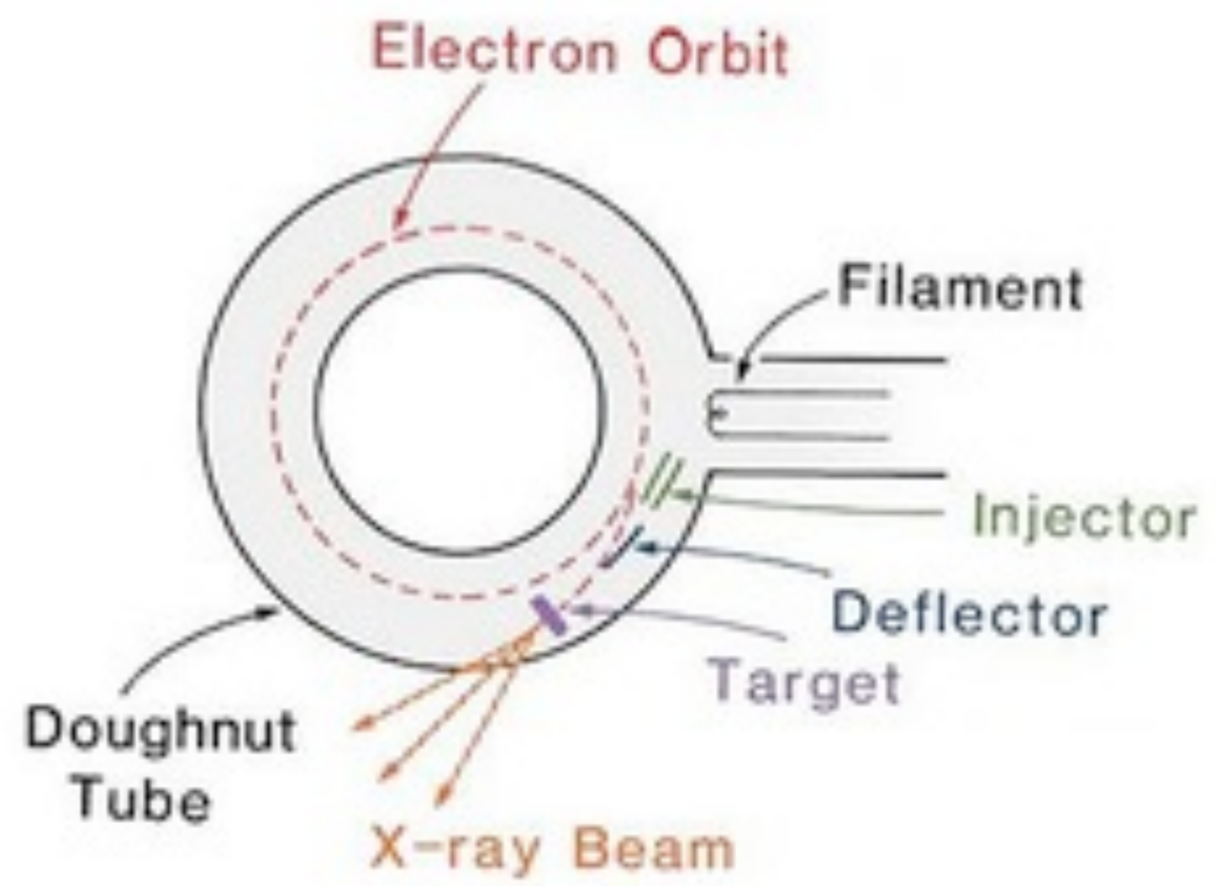
A rough description of an experiment

Accelerators

- betatron



(1) magnet poles, (2) cross section of annular vacuum chamber, (3) central core, (4) electromagnet windings, (5) magnet yoke



-uses a varying magnetic field

-electrons are fed into a doughnut-shaped ring placed between the poles of an alternating-current electromagnet and follow a circular trajectory of fixed radius

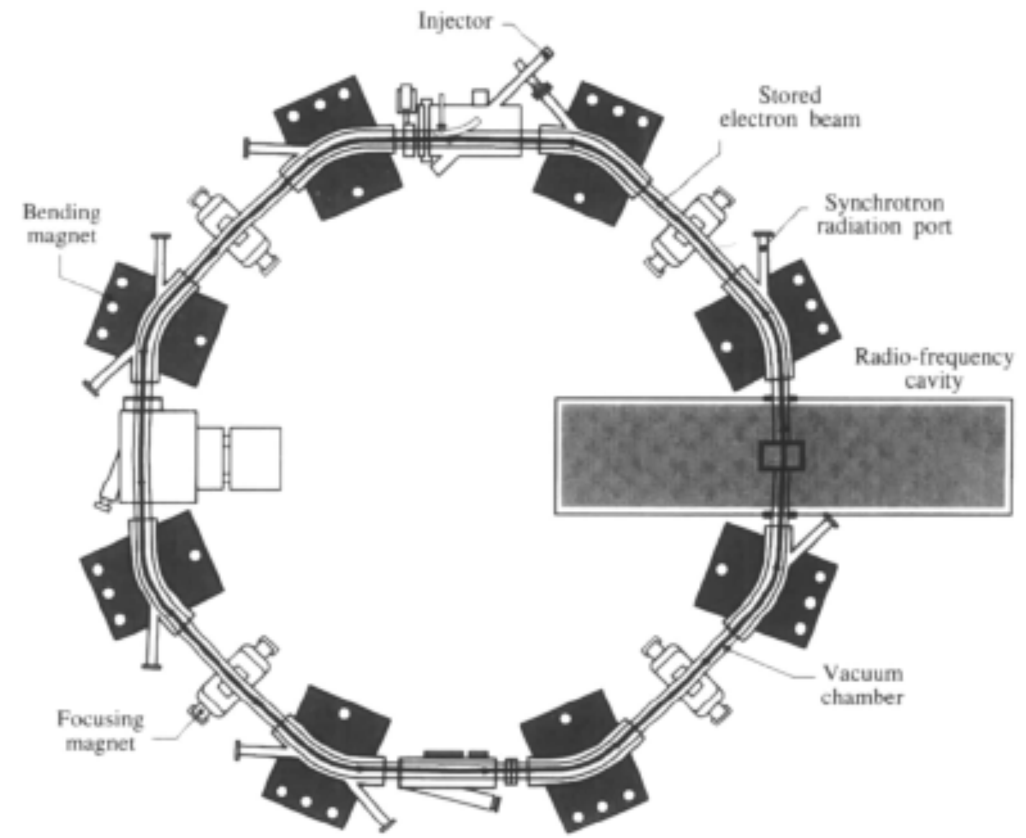
-the variation of the magnetic field makes the electron energy to increase by a few hundred eV in each turn

-maximum energies: ~ 300 MeV

A rough description of an experiment

Accelerators

- synchrotron



-consists of a tube in the shape of a large ring through which the particles travel

-the tube is surrounded by magnets to maintain particle trajectory

-particles are accelerated at one or more points on the ring each time they complete a circle around the accelerator

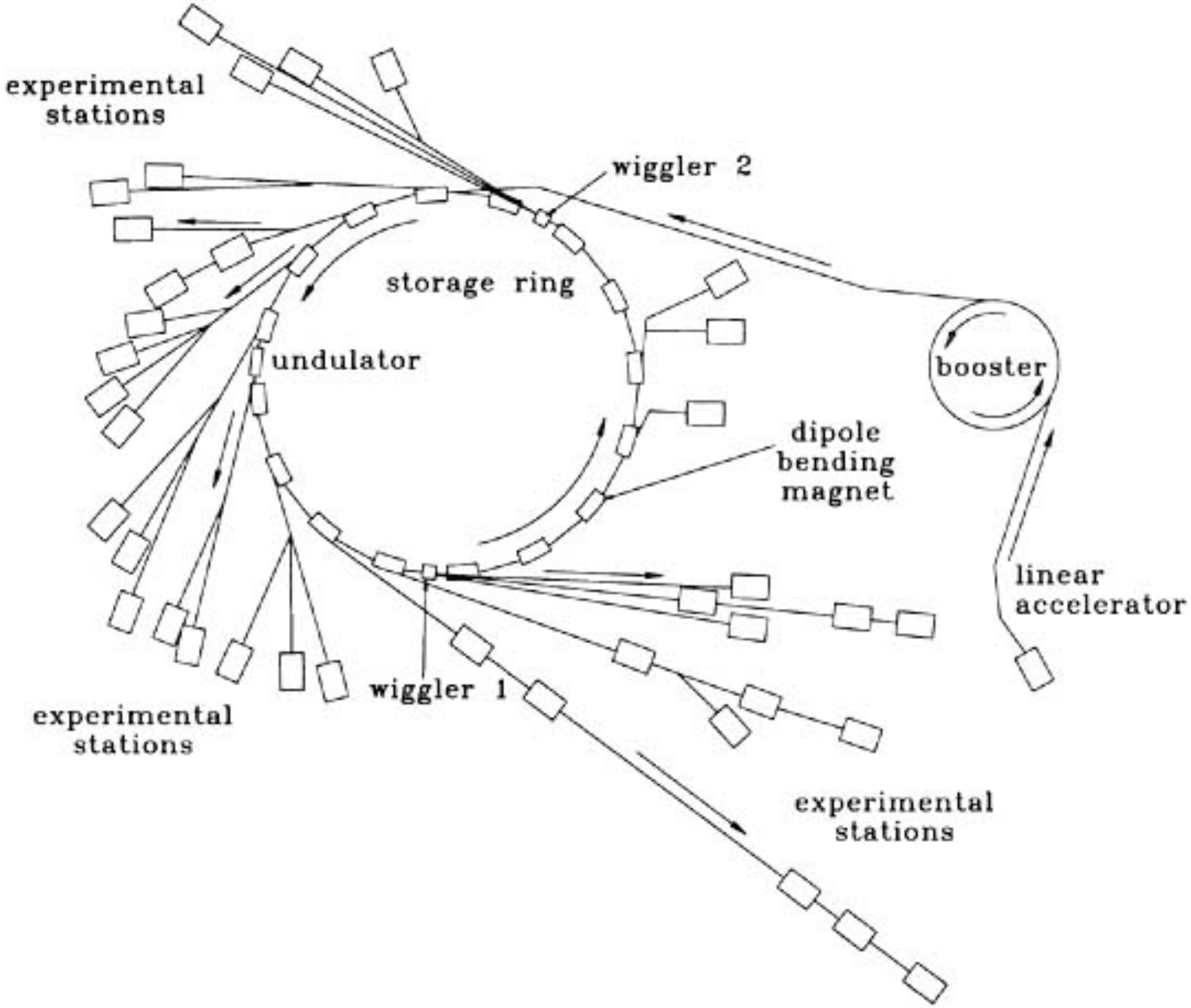
-particles are kept in a rigid orbit by increasing the magnetic fields as particles gain energy

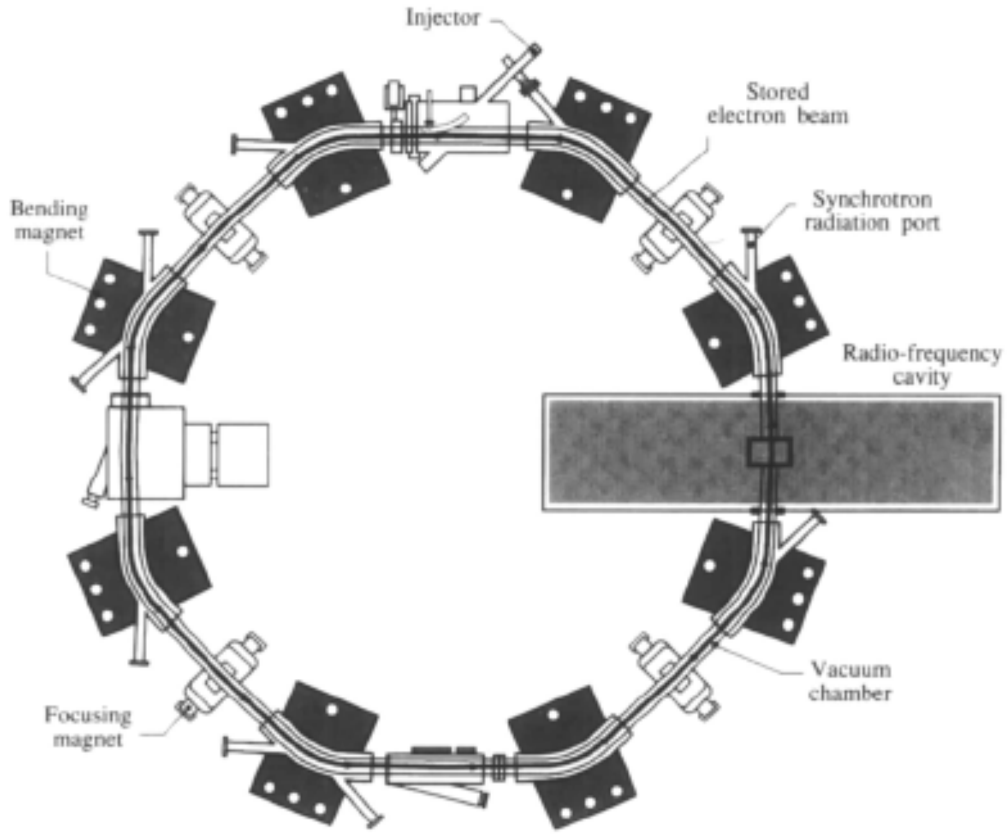
-energies up to ~ 1 GeV

A rough description of an experiment

Accelerators

- synchrotron





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A rough description of an experiment

Accelerators

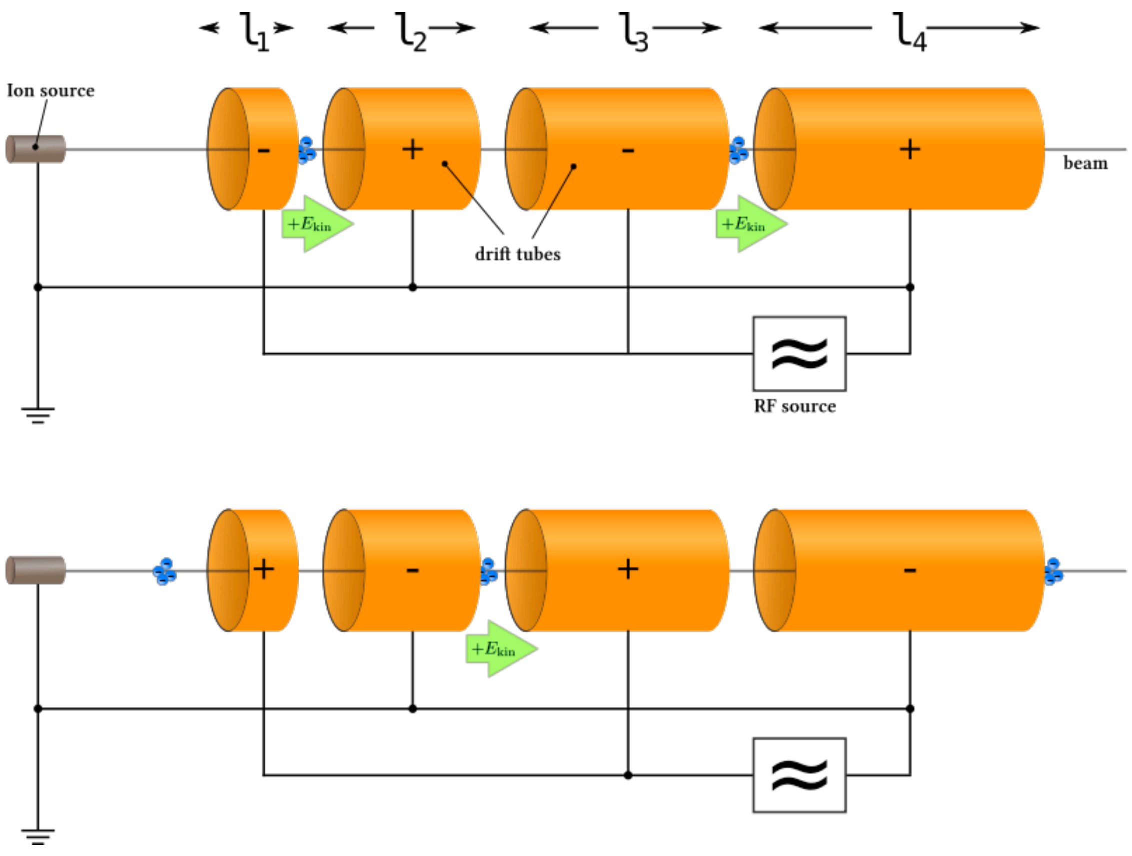
- linear accelerator

A rough description of an experiment

original design

Accelerators

- linear accelerator



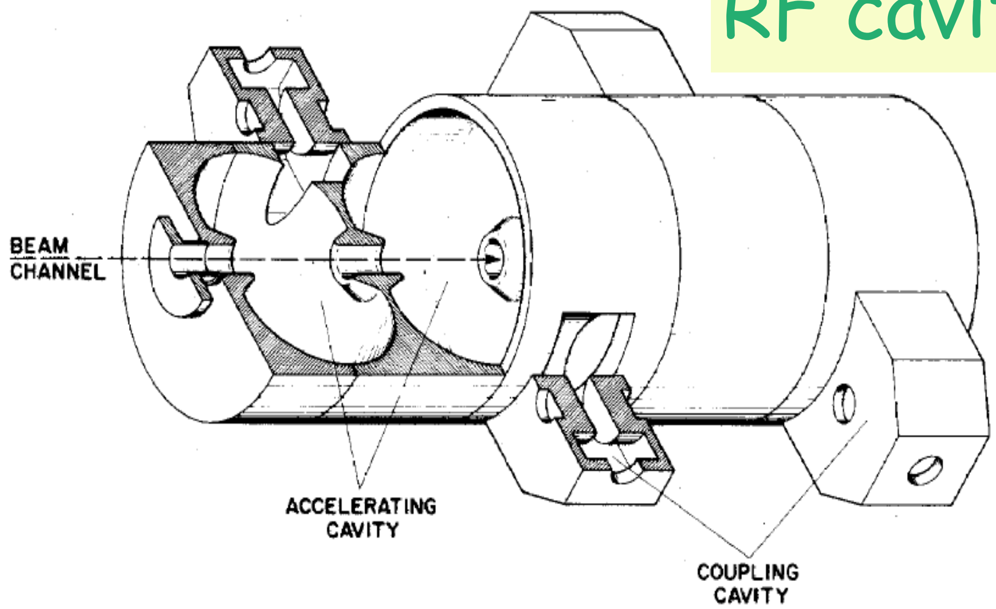
A rough description of an experiment

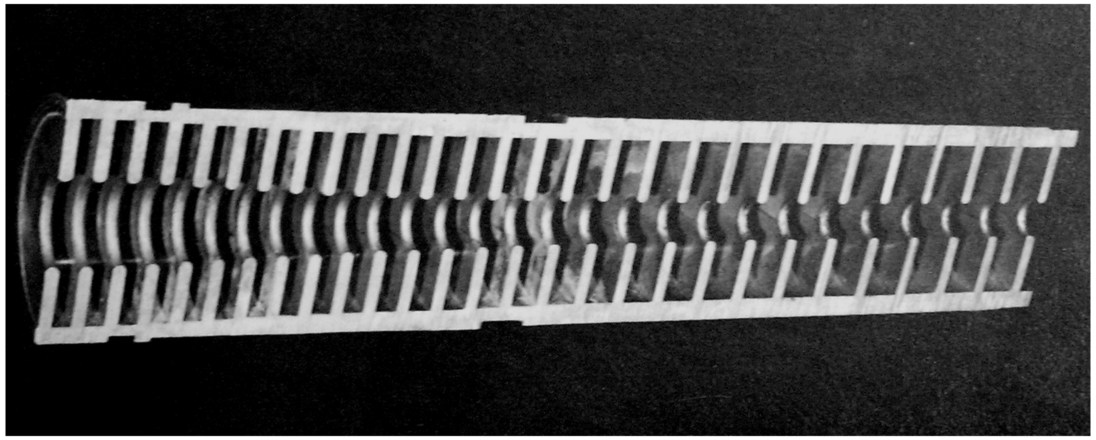
original design

Accelerators

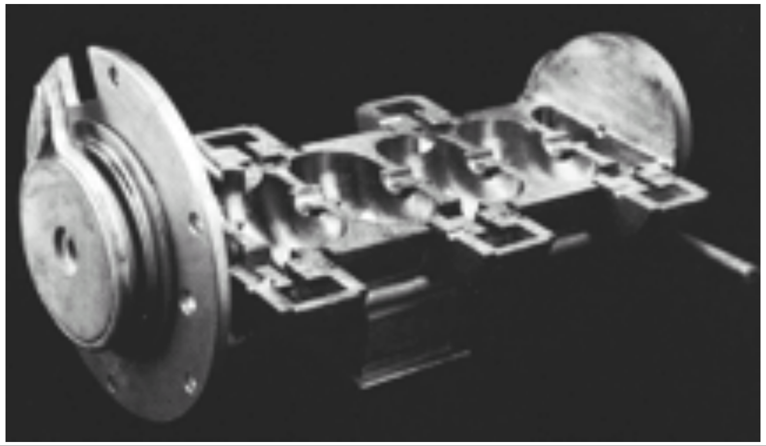
- linear accelerator

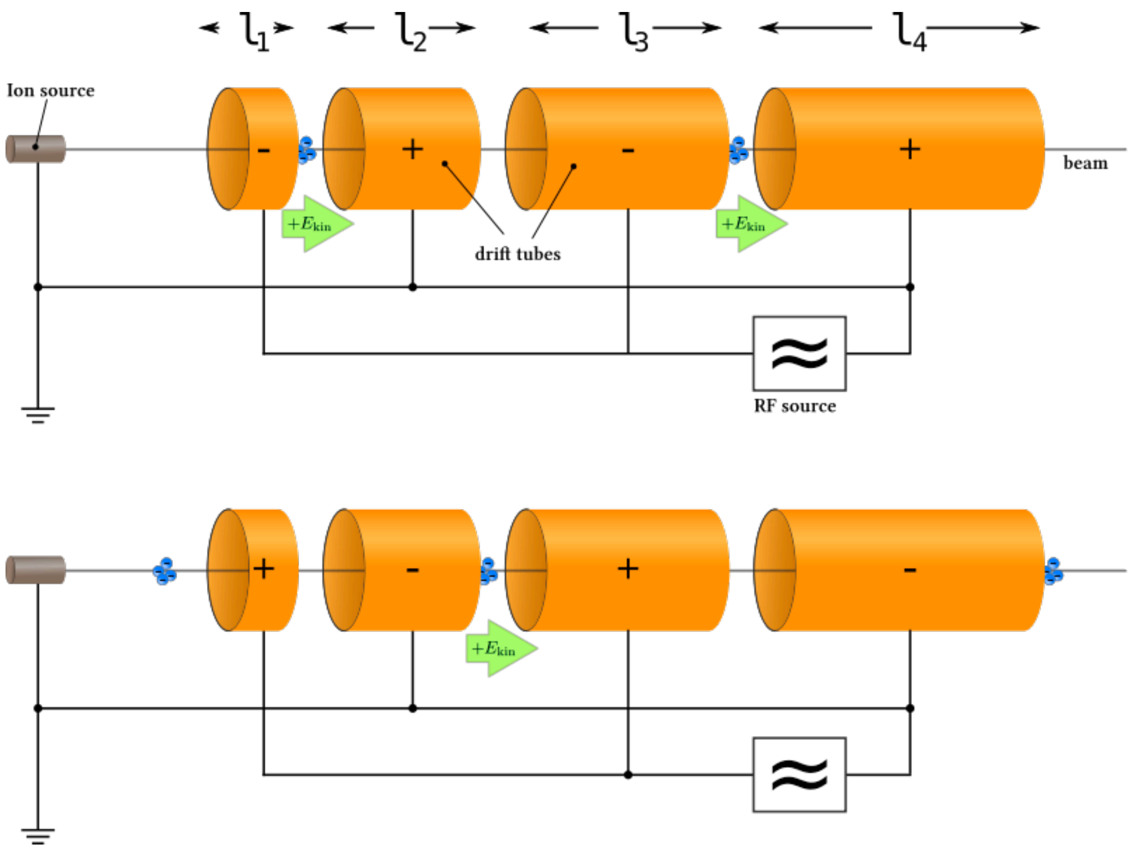
RF cavities





TW vs. SW





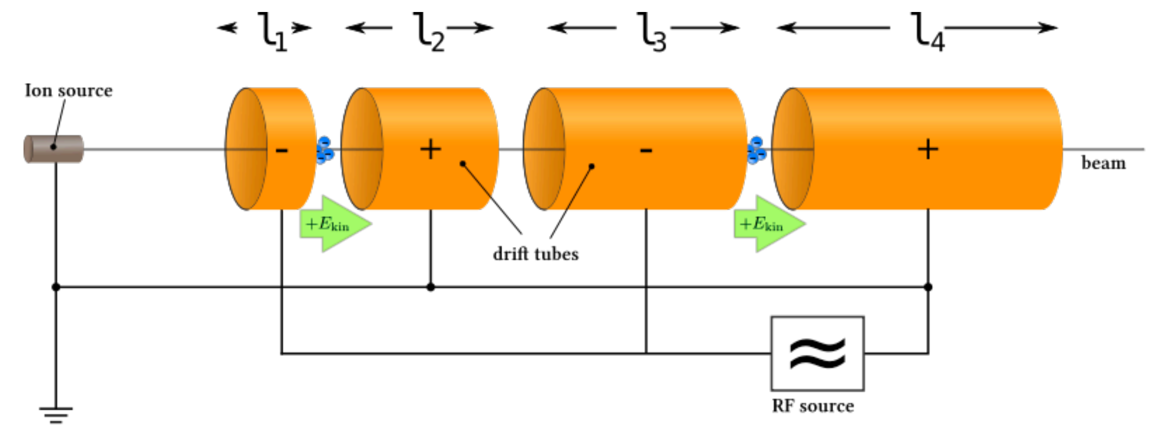
A rough description of an experiment

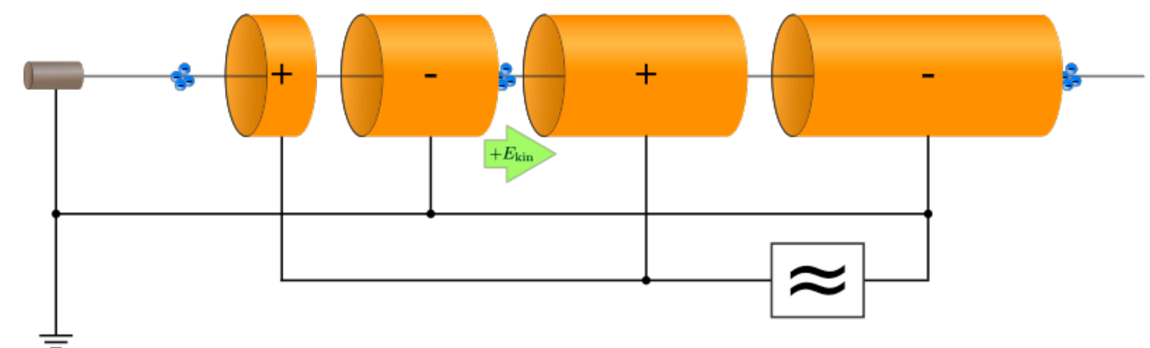
original design

Accelerators

- linear accelerator

~ GeV energies





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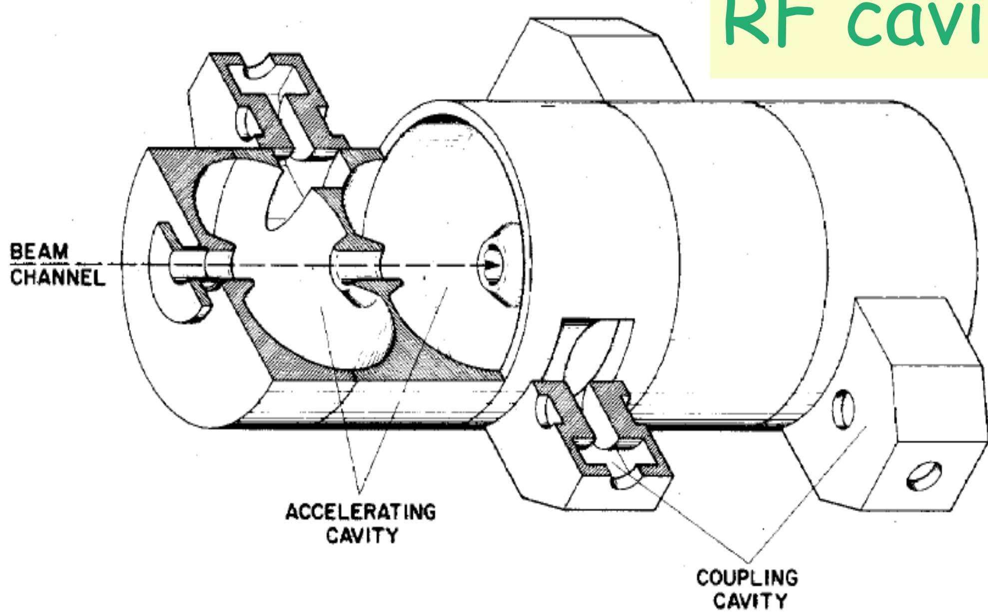
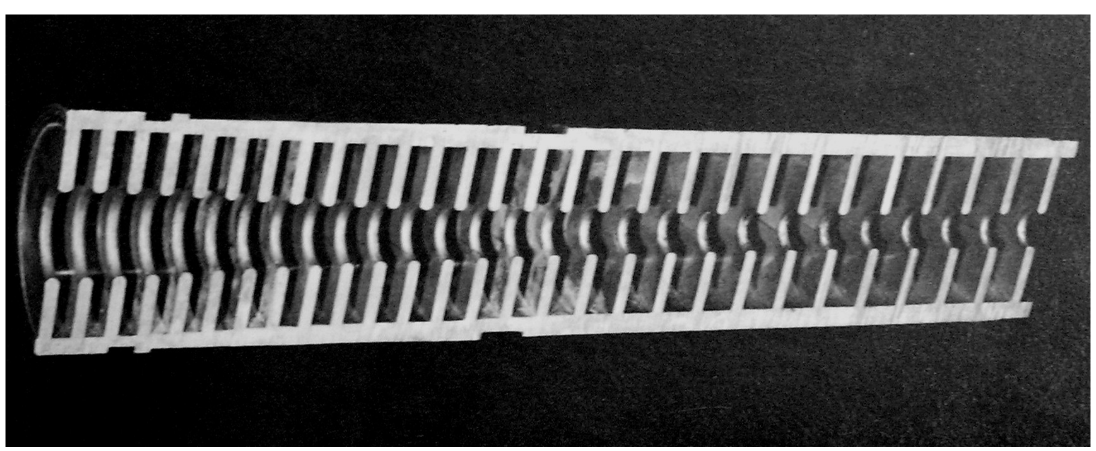
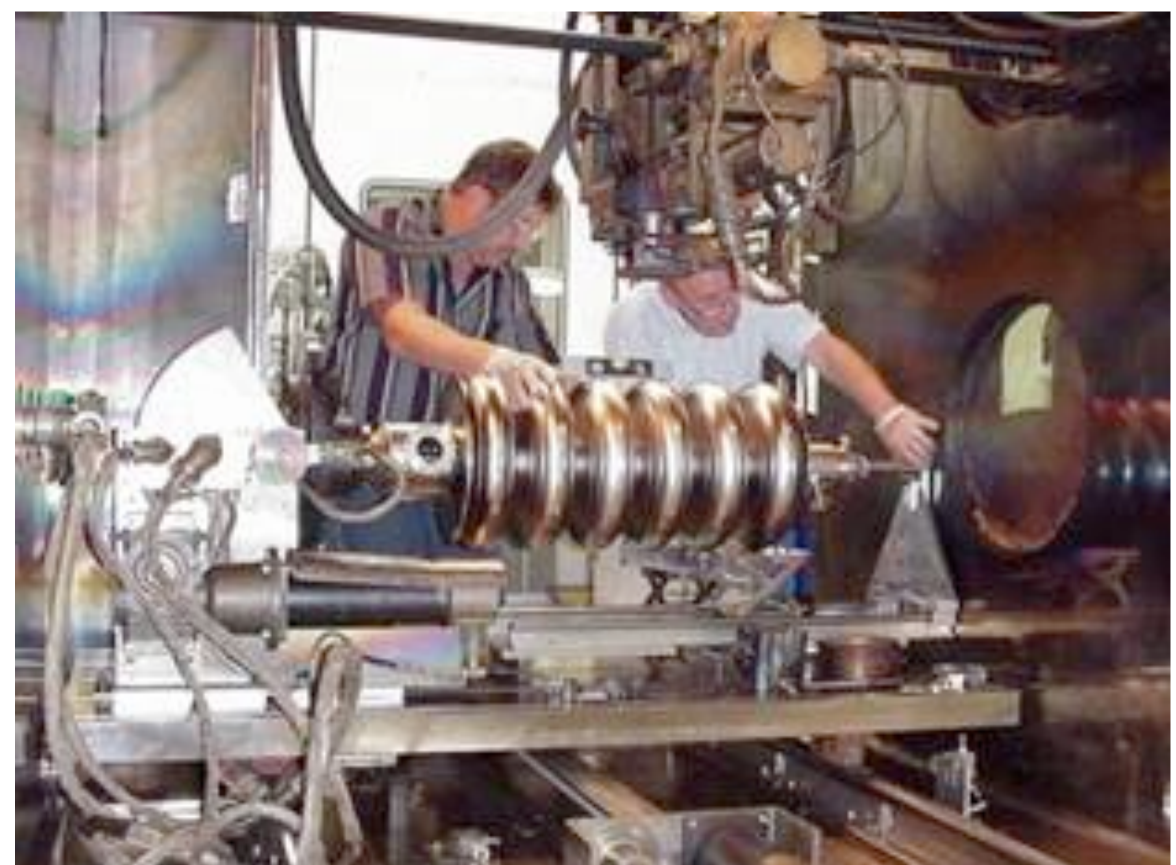




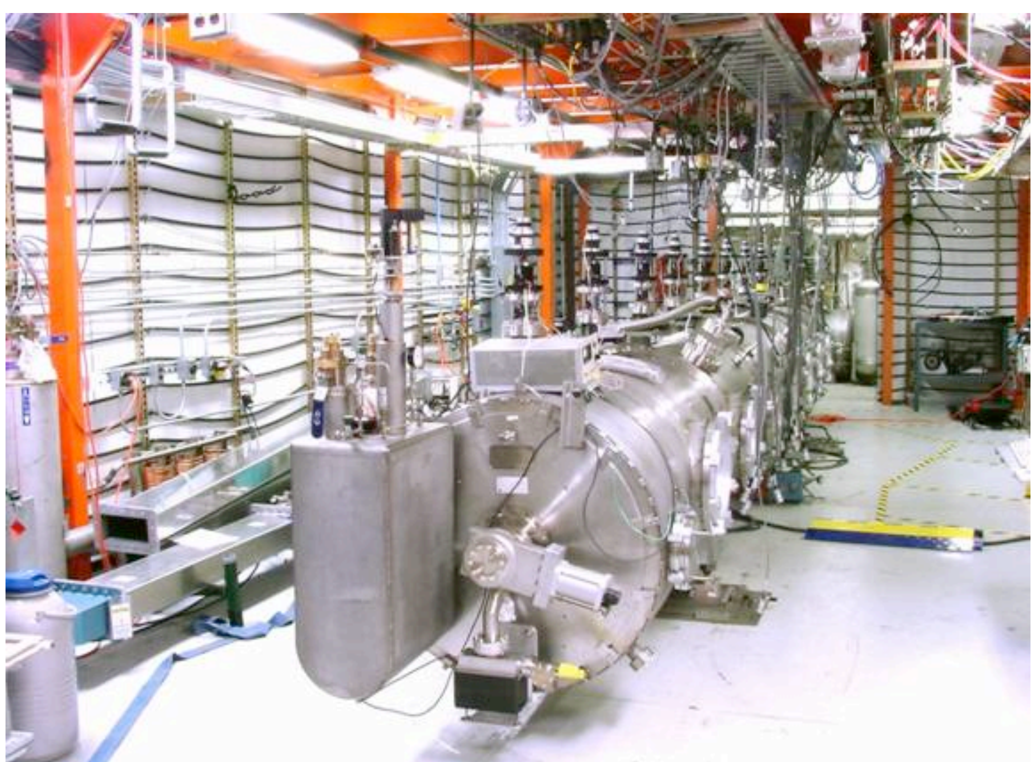


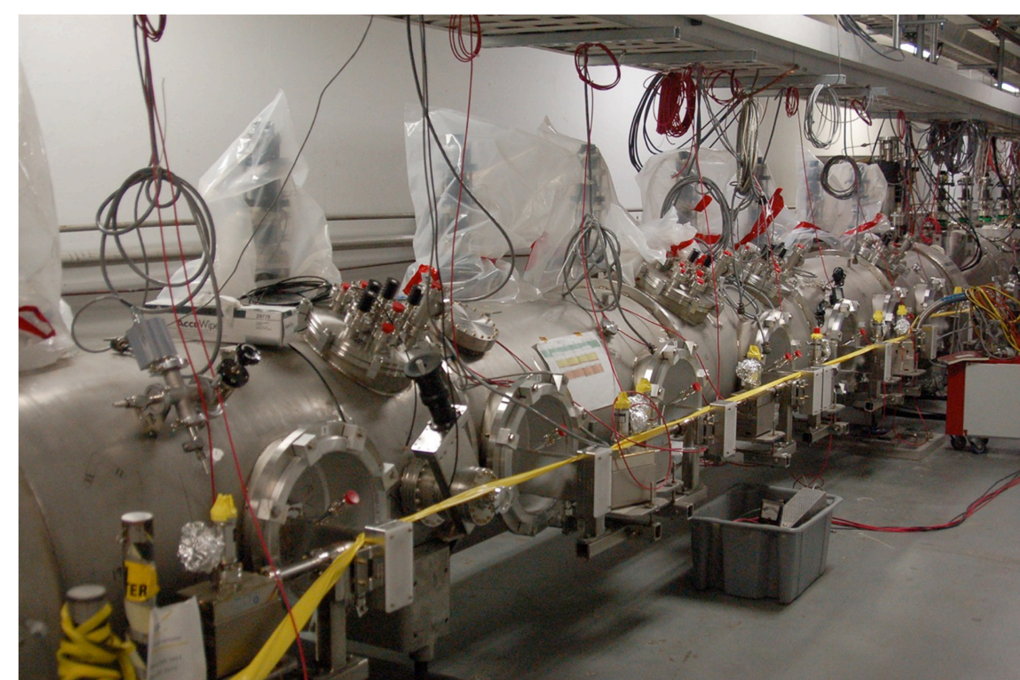
TW vs. SW

A rough description of an experiment

TJNAF linac

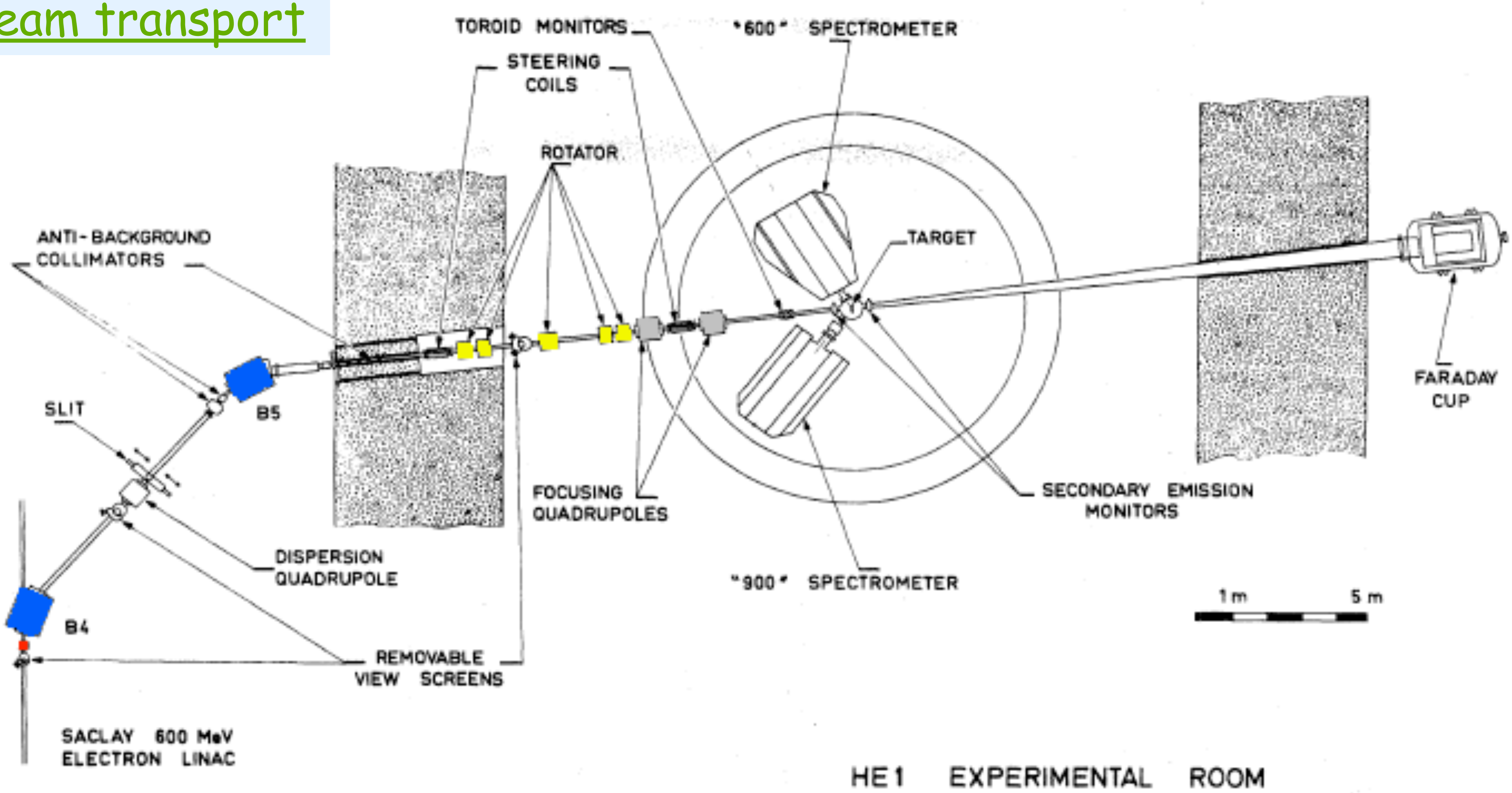
clinical linac





A rough description of an experiment

Beam transport



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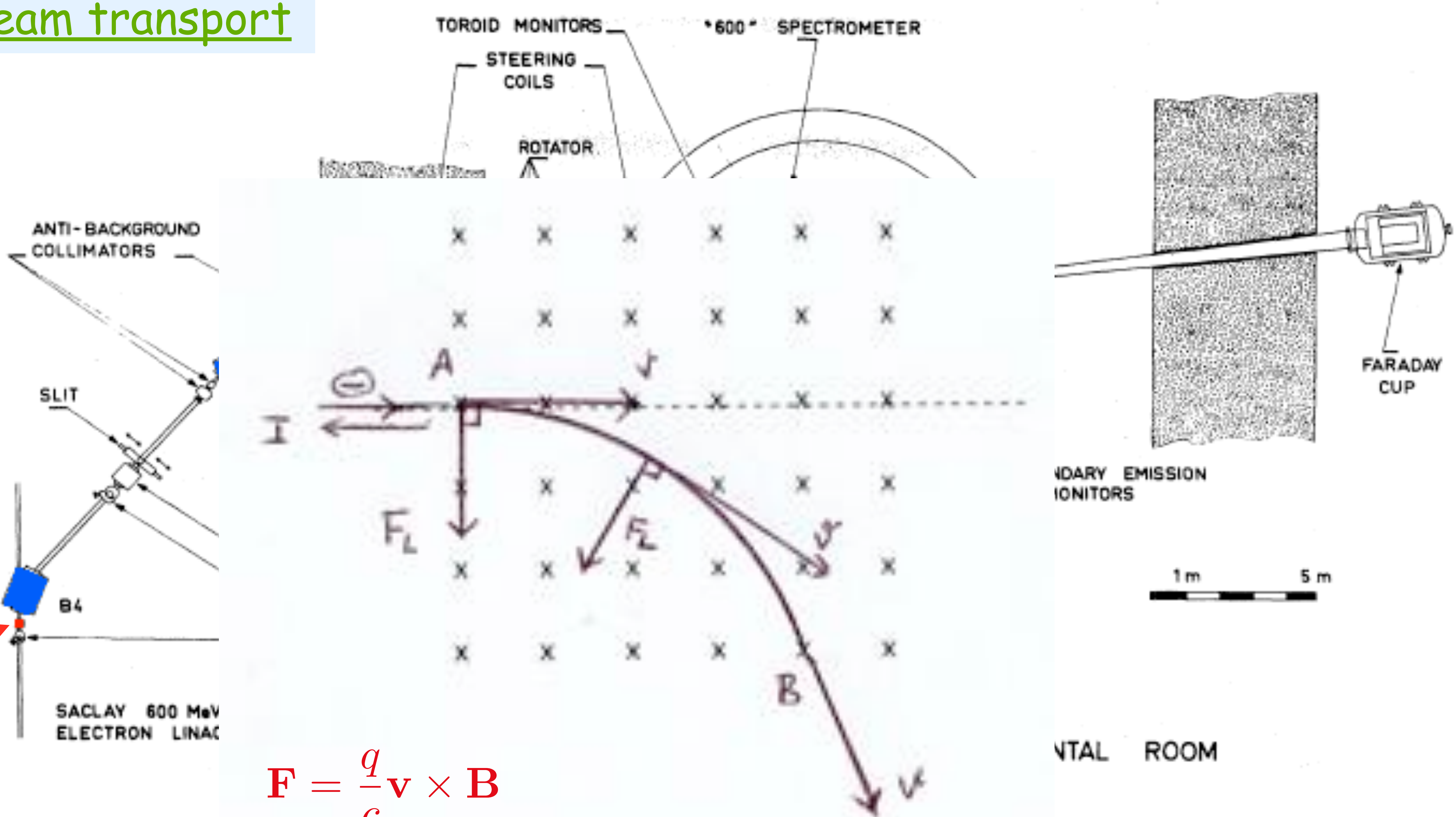

$$\mathbf{F} = \frac{q}{c}\mathbf{v} \times \mathbf{B}$$

$$\rho = \frac{mcv}{qB}$$

extracting magnet

A rough description of an experiment

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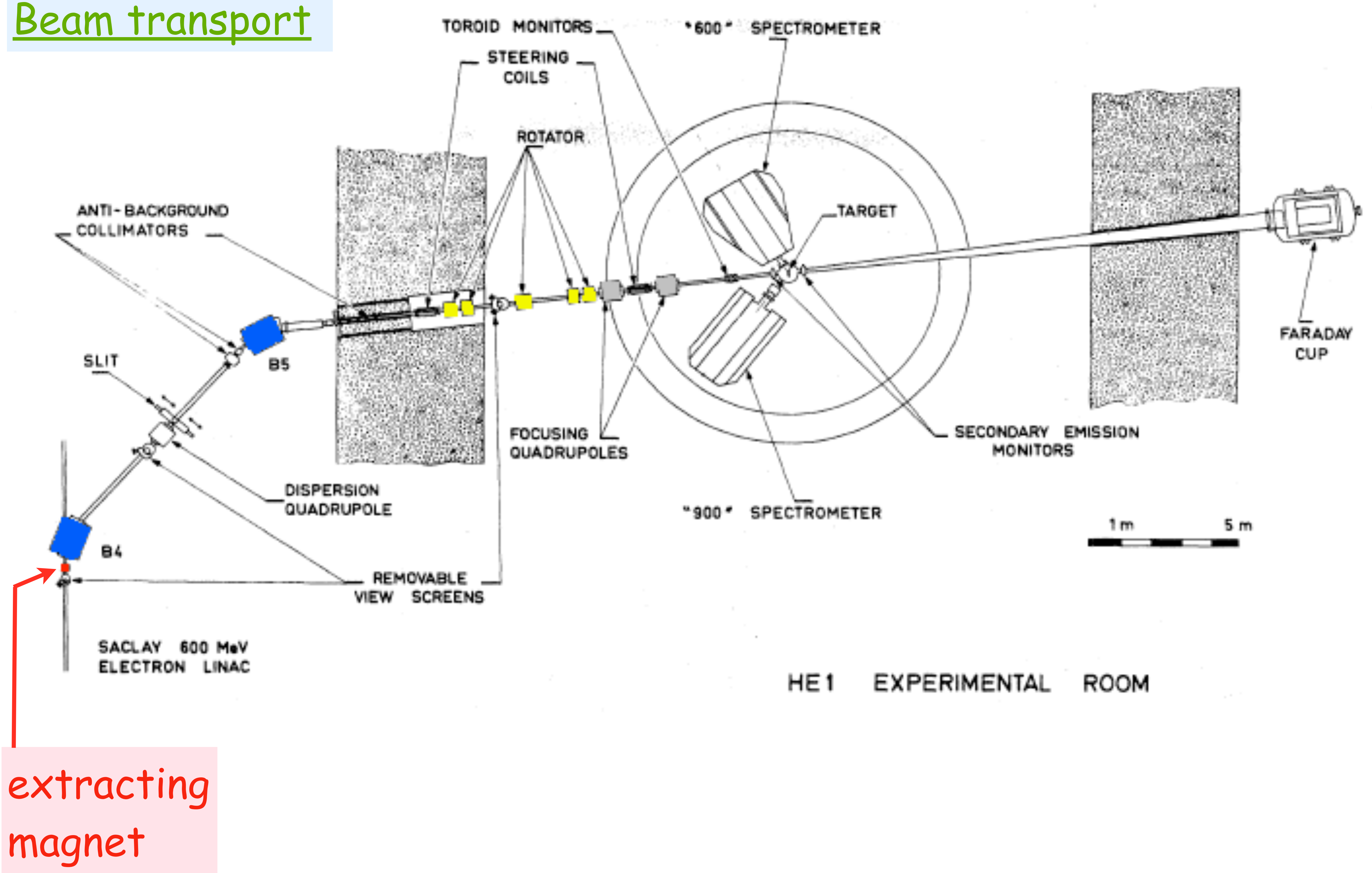

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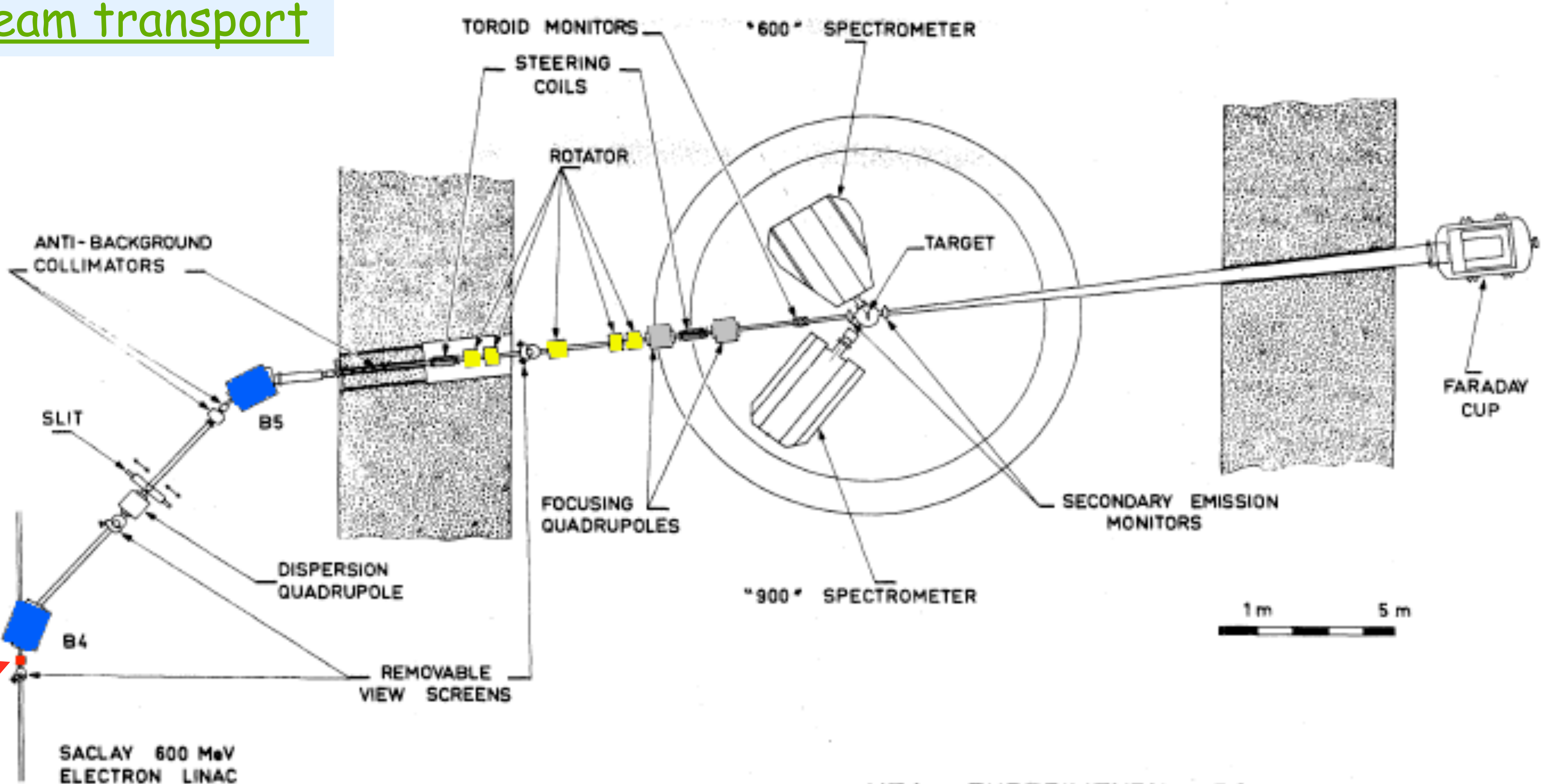

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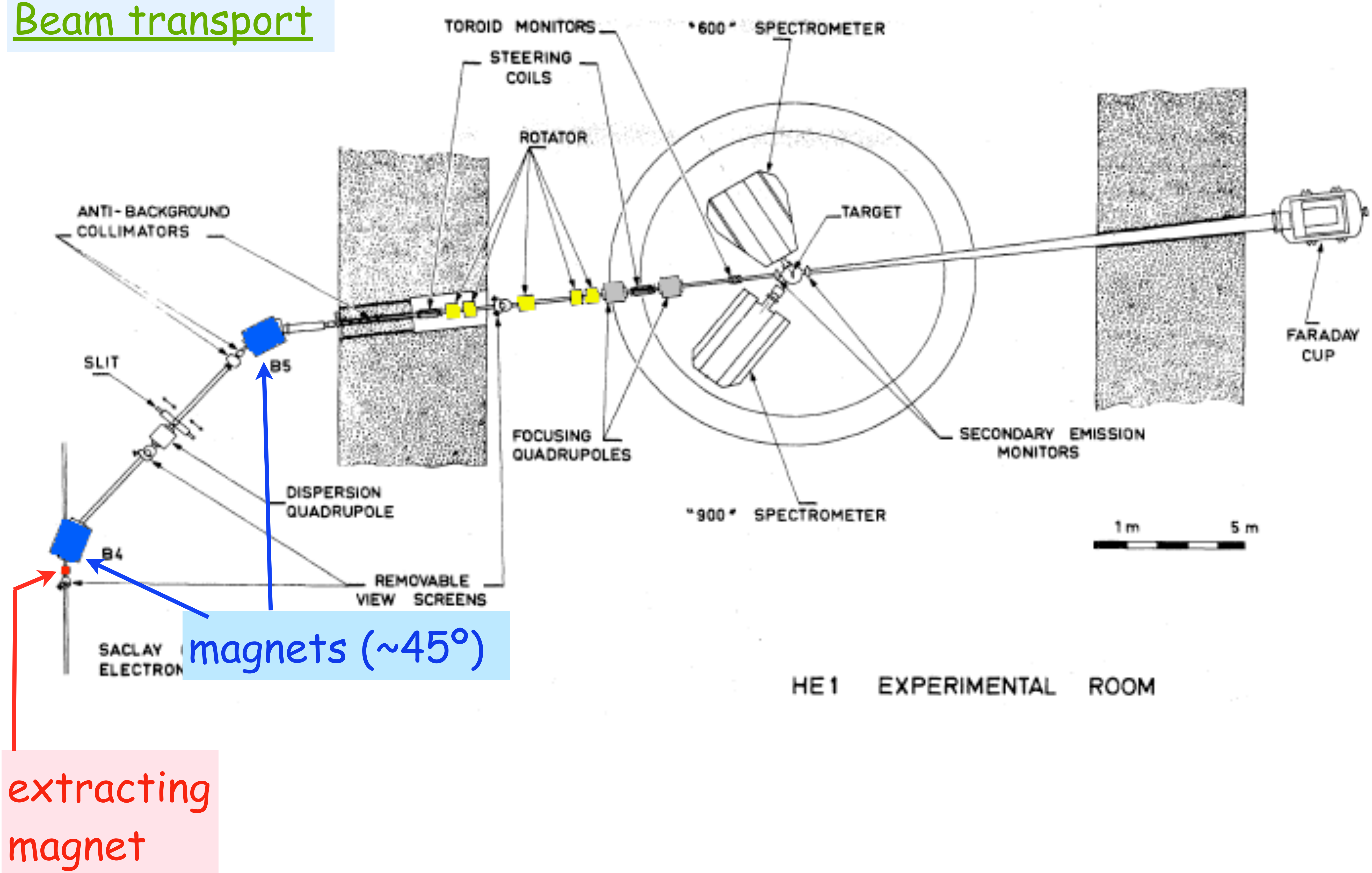

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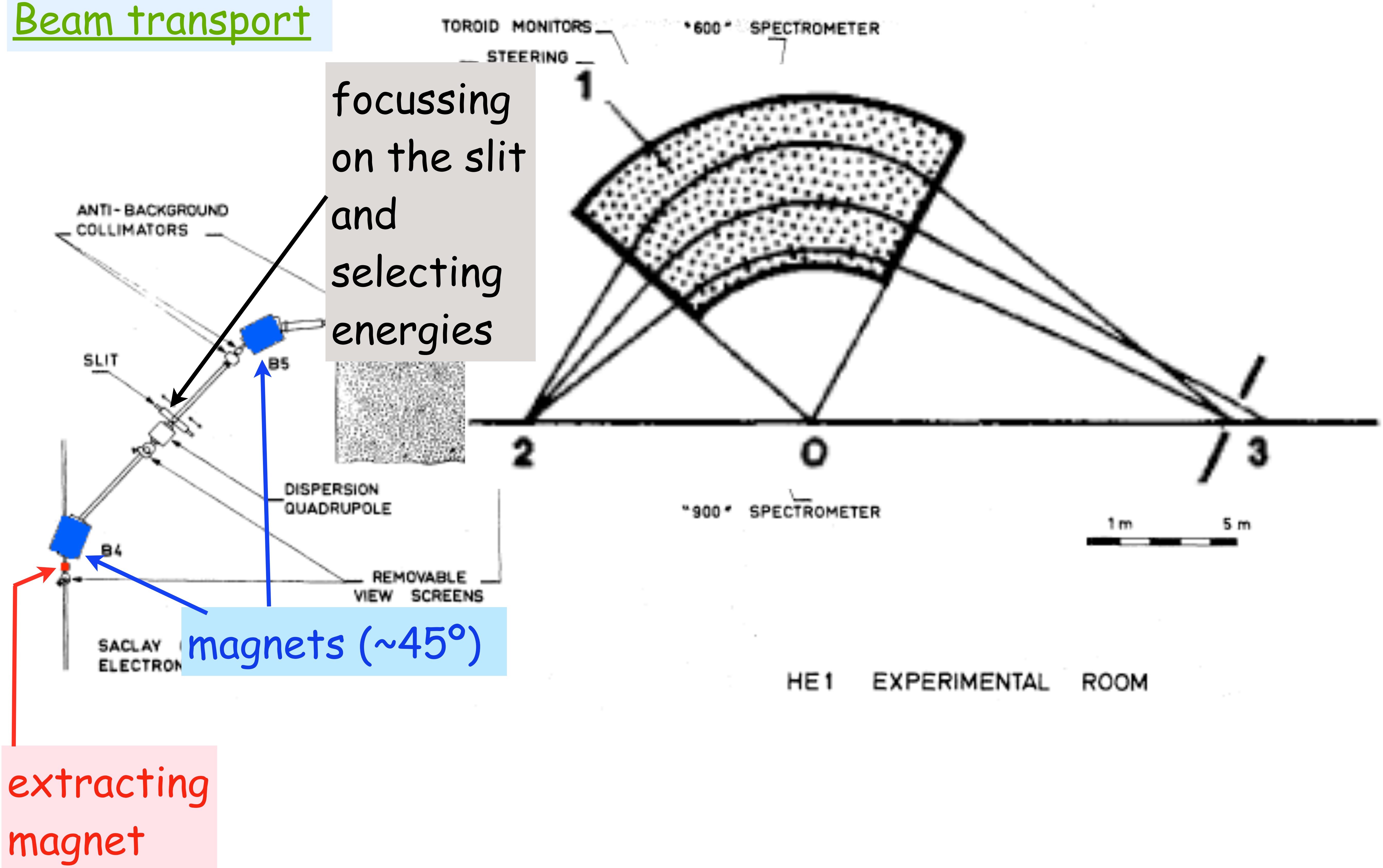

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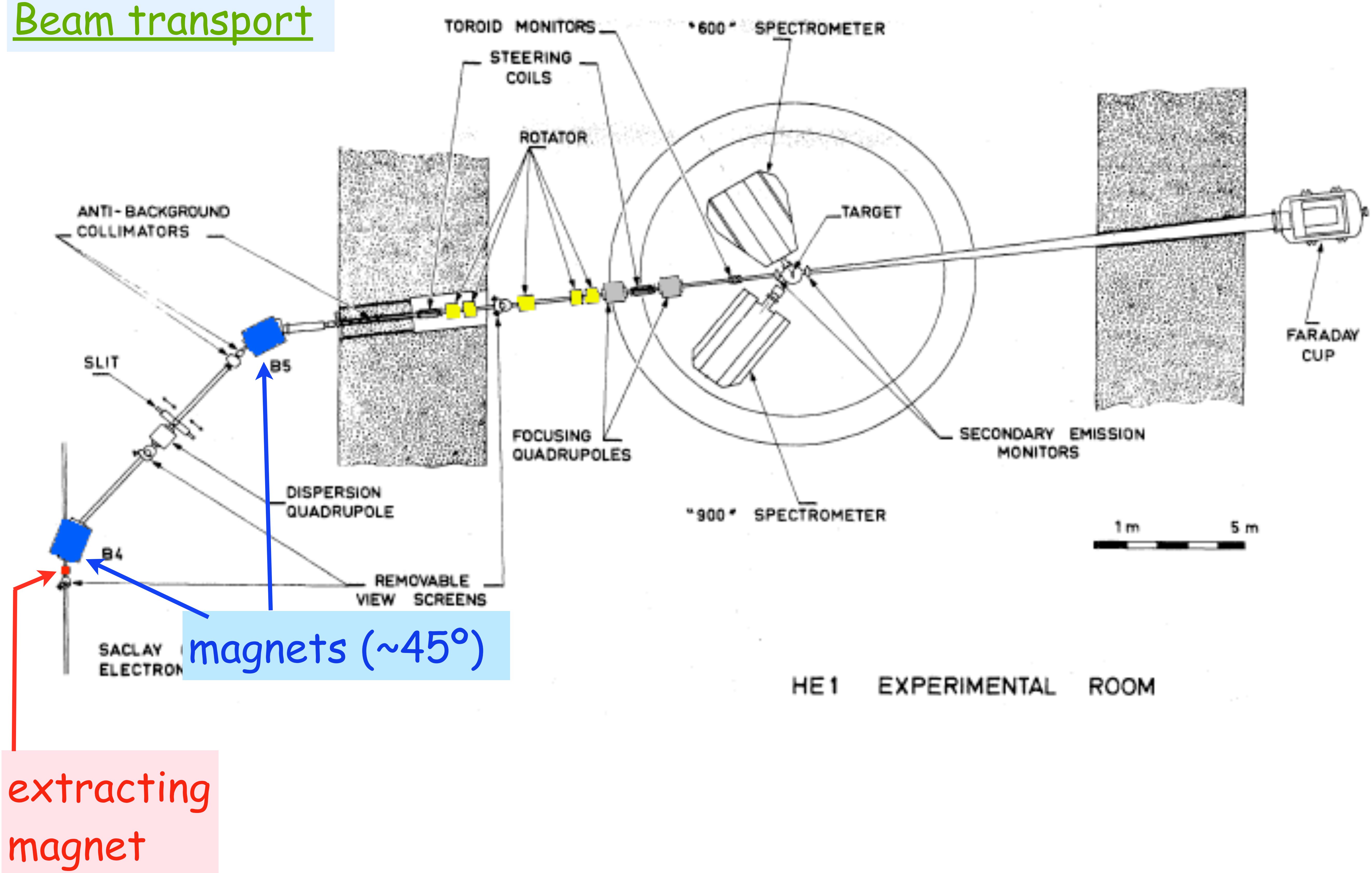

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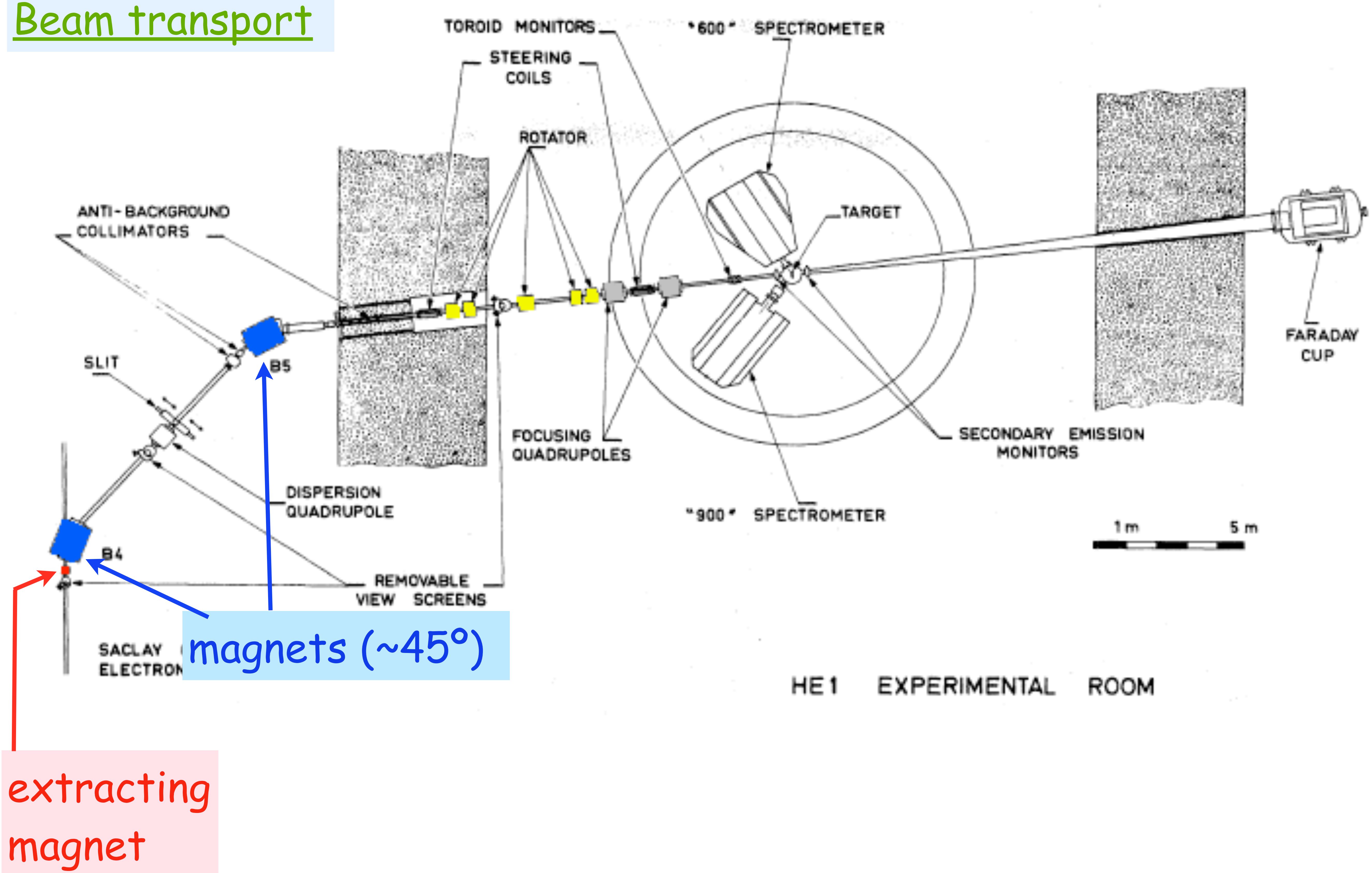

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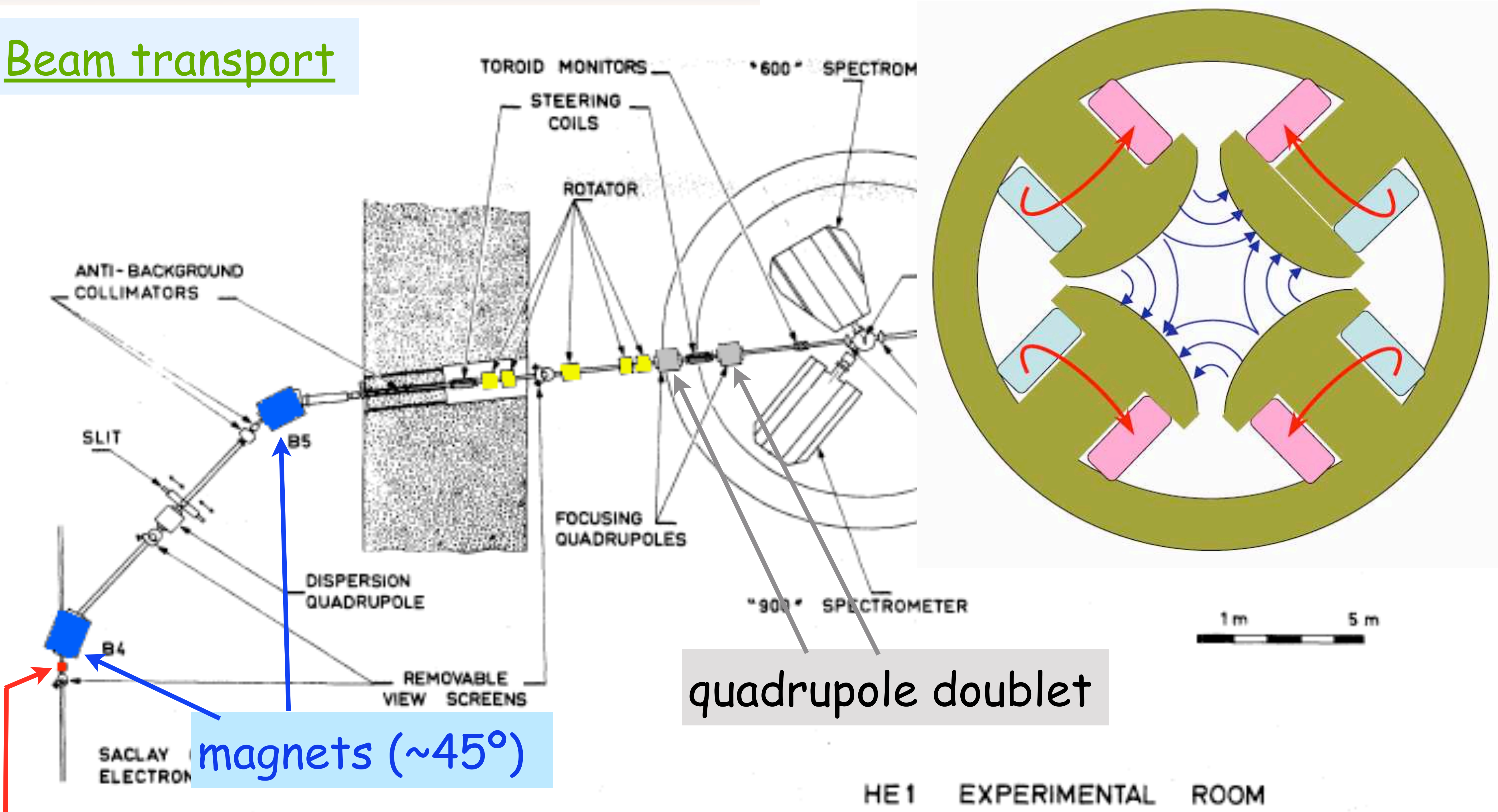

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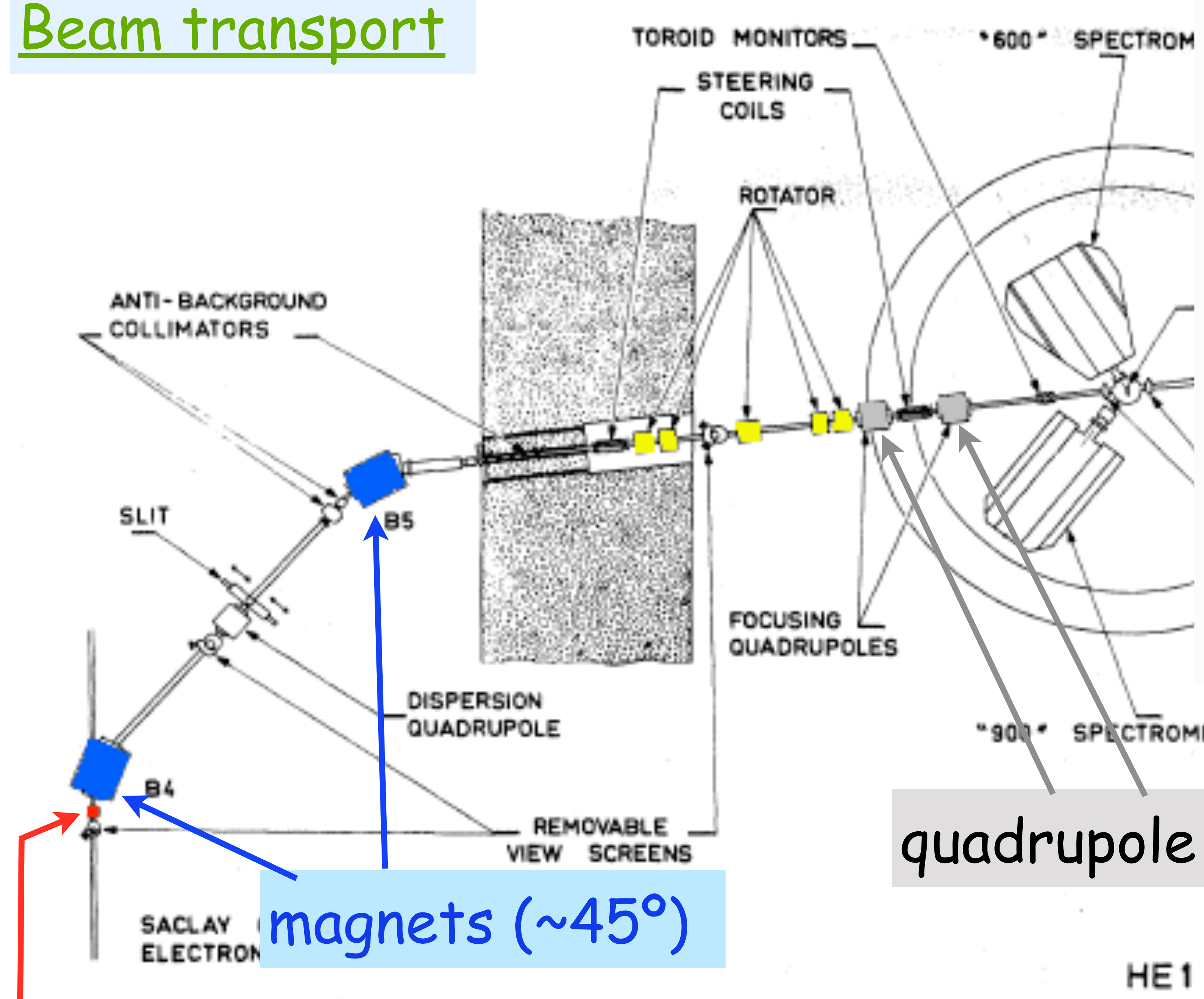

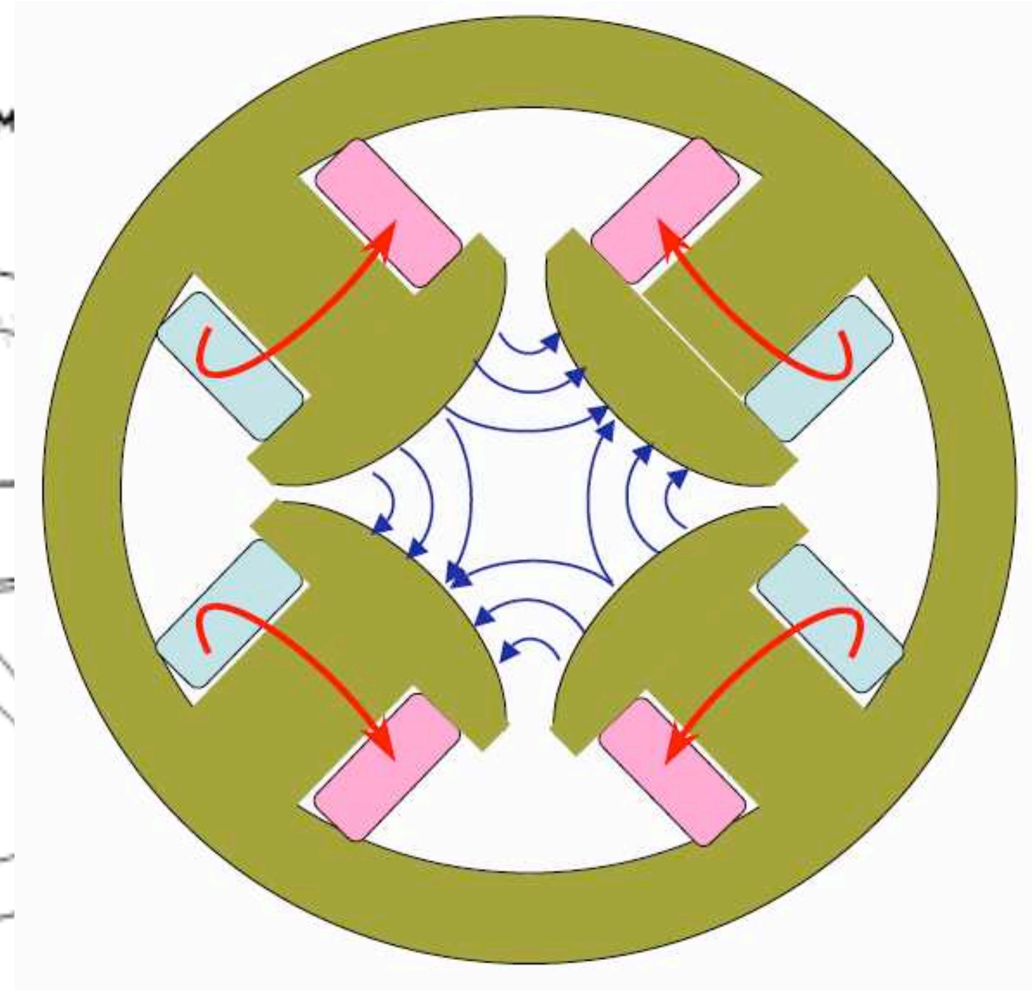

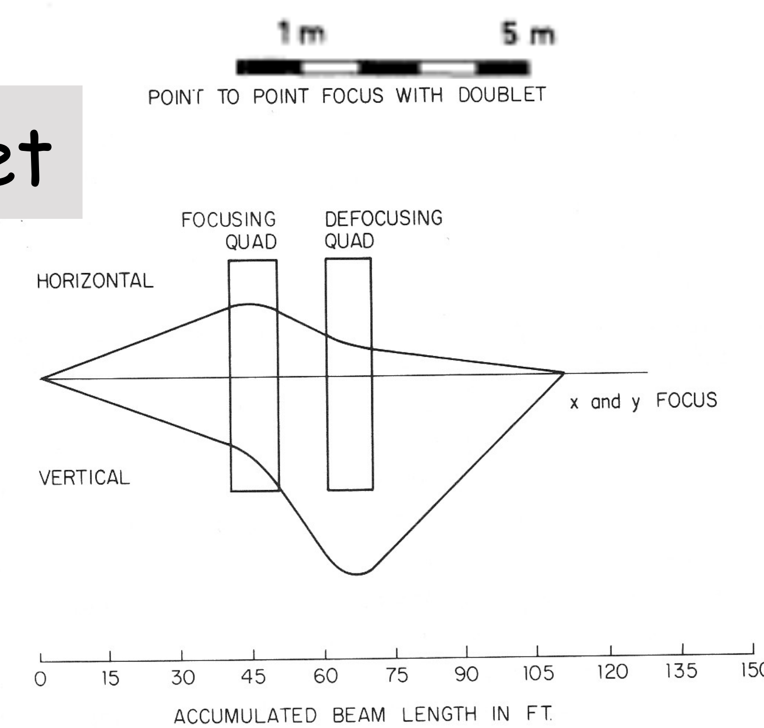

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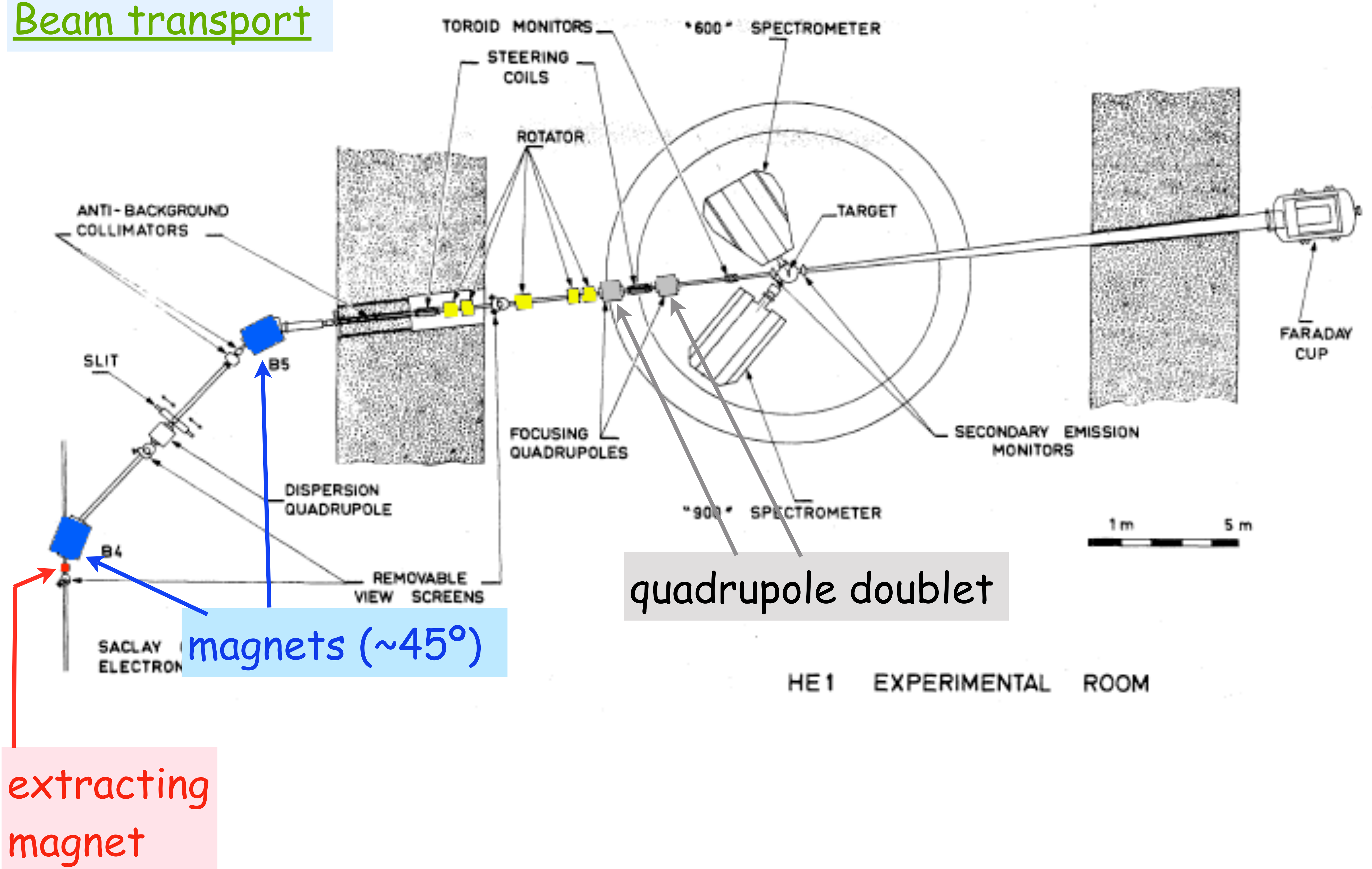

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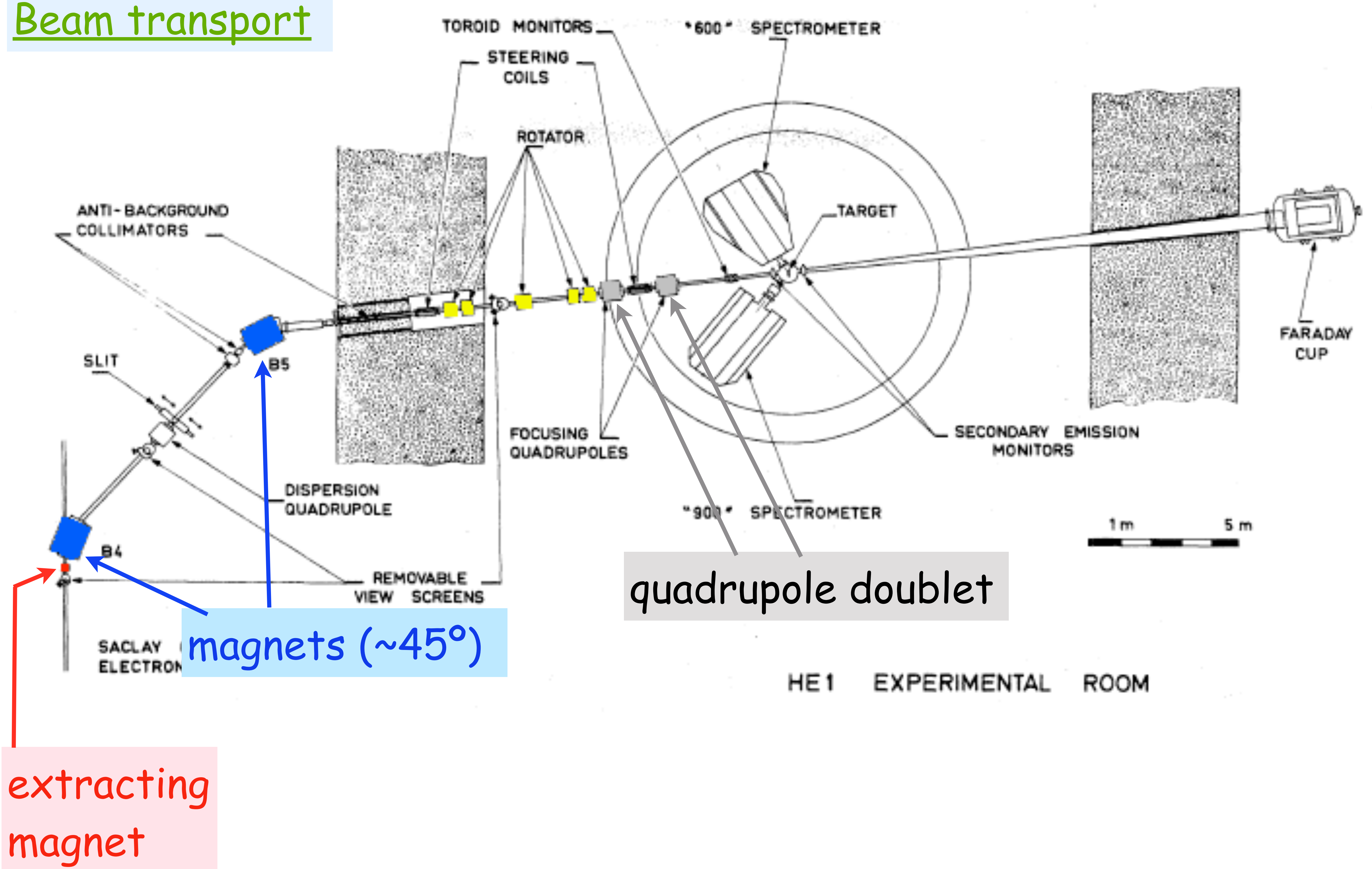

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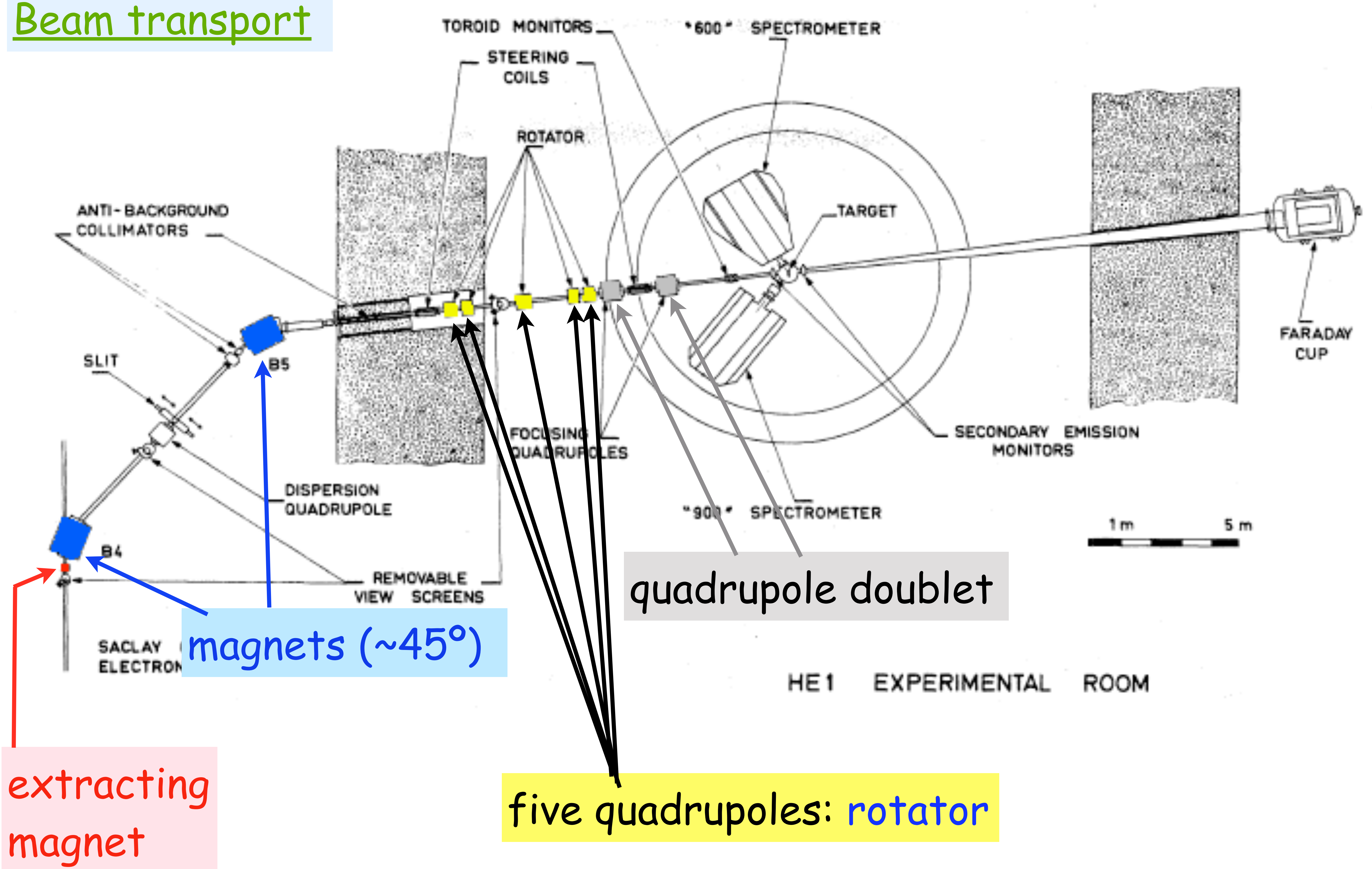

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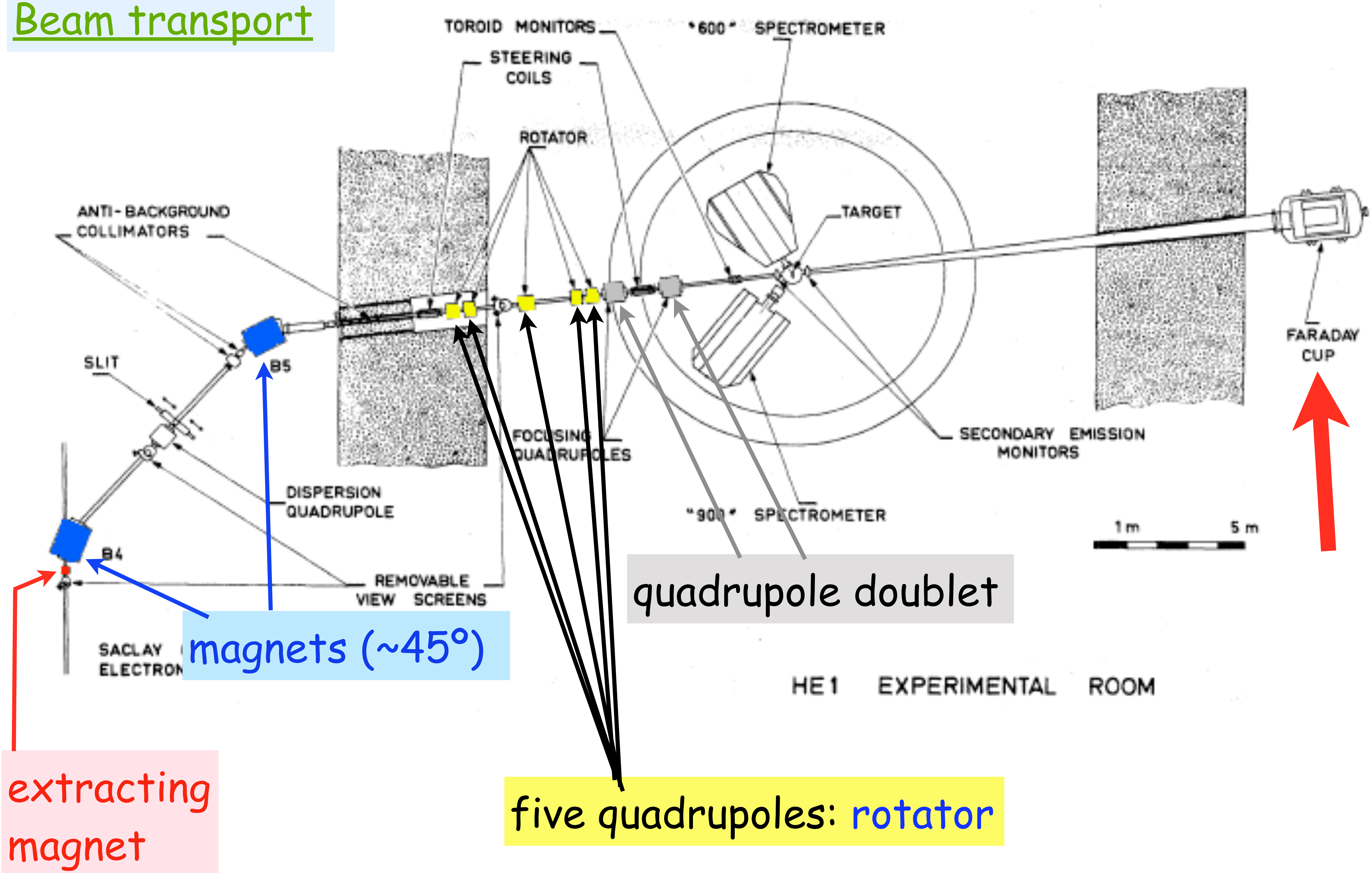

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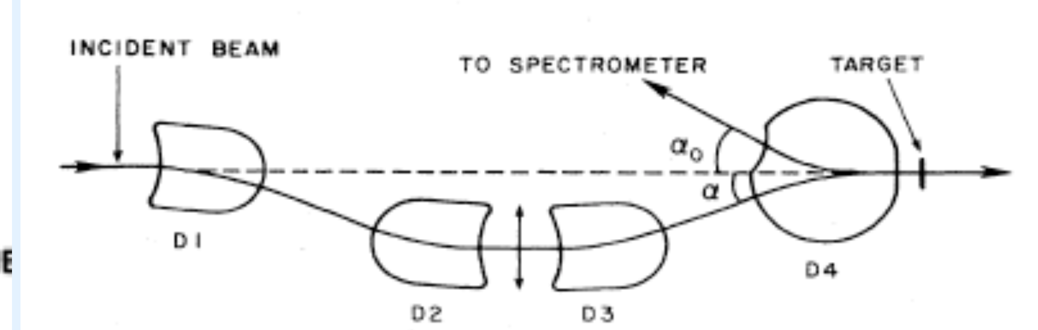
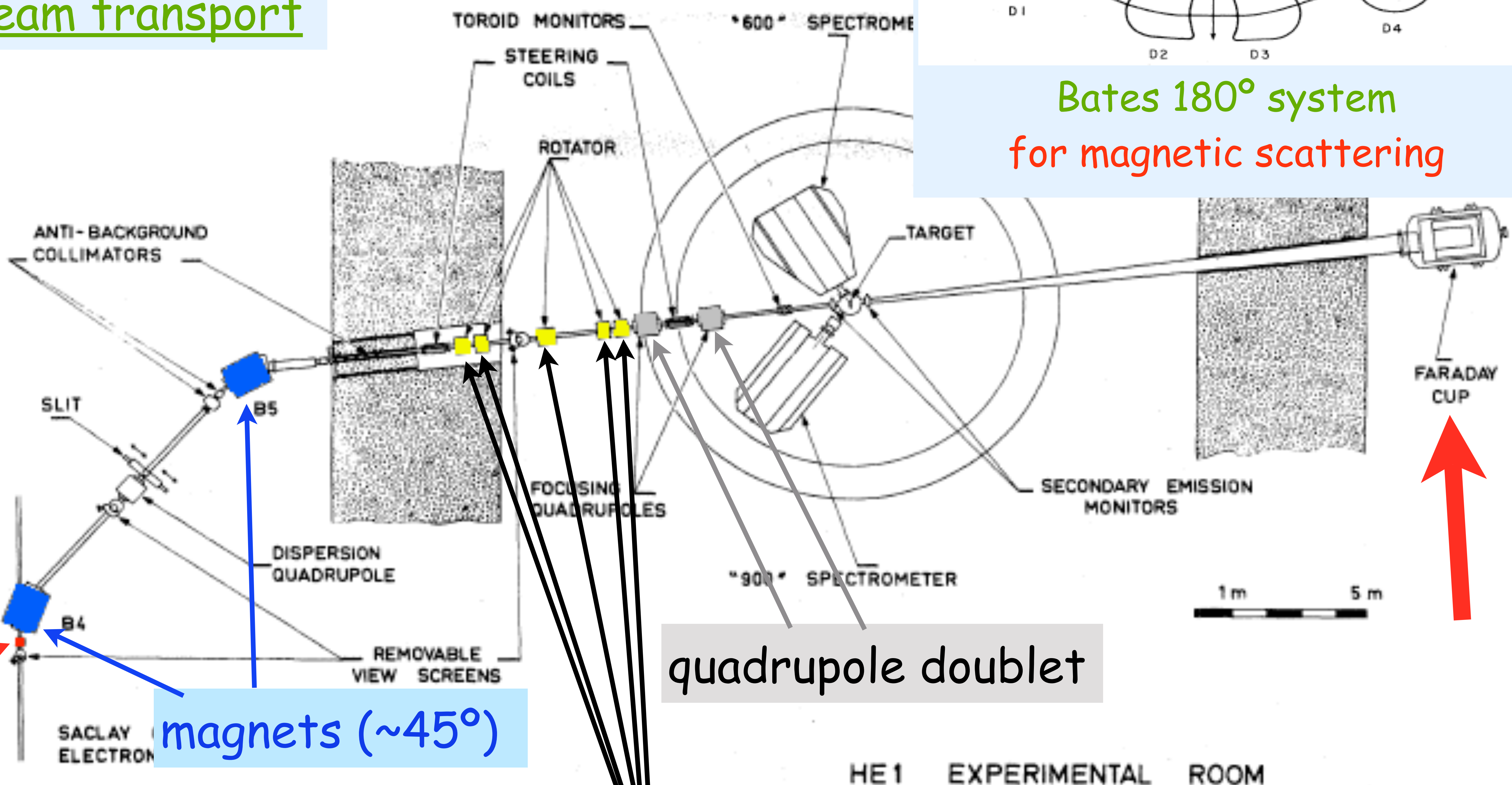


Bates 180° system
for magnetic scattering



quadrupole doublet

magnets (~45°)

extracting magnet

five quadrupoles: rotator

A rough description of an experiment

Targets

• solid, liquid or gas:
depending on the characteristics of the isotopes to be investigated

• target thickness:
imposed by energy resolution desired (energy straggling: 0.4 keV/mg cm^2)
and required to obtain cross section data

• thickness for the area covered by the beam: obtained with an accuracy <1%
-relative density profile (measured in beta or gamma absorption experiments)
+ average area density (calculated from the weight and area of the target)

• removal of the heat deposited in the target by the beam:
-essential in experiments with small cross sections
-circulate pressurized H_2 gas

A rough description of an experiment

Spectrometers

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-determine the momenta of the scattered particles

-intrinsic resolution:

$\Delta E/E \sim 10^4$ or better

-electron energy: determined from the applied field, the radius of the trajectory of the detected particle and its momentum

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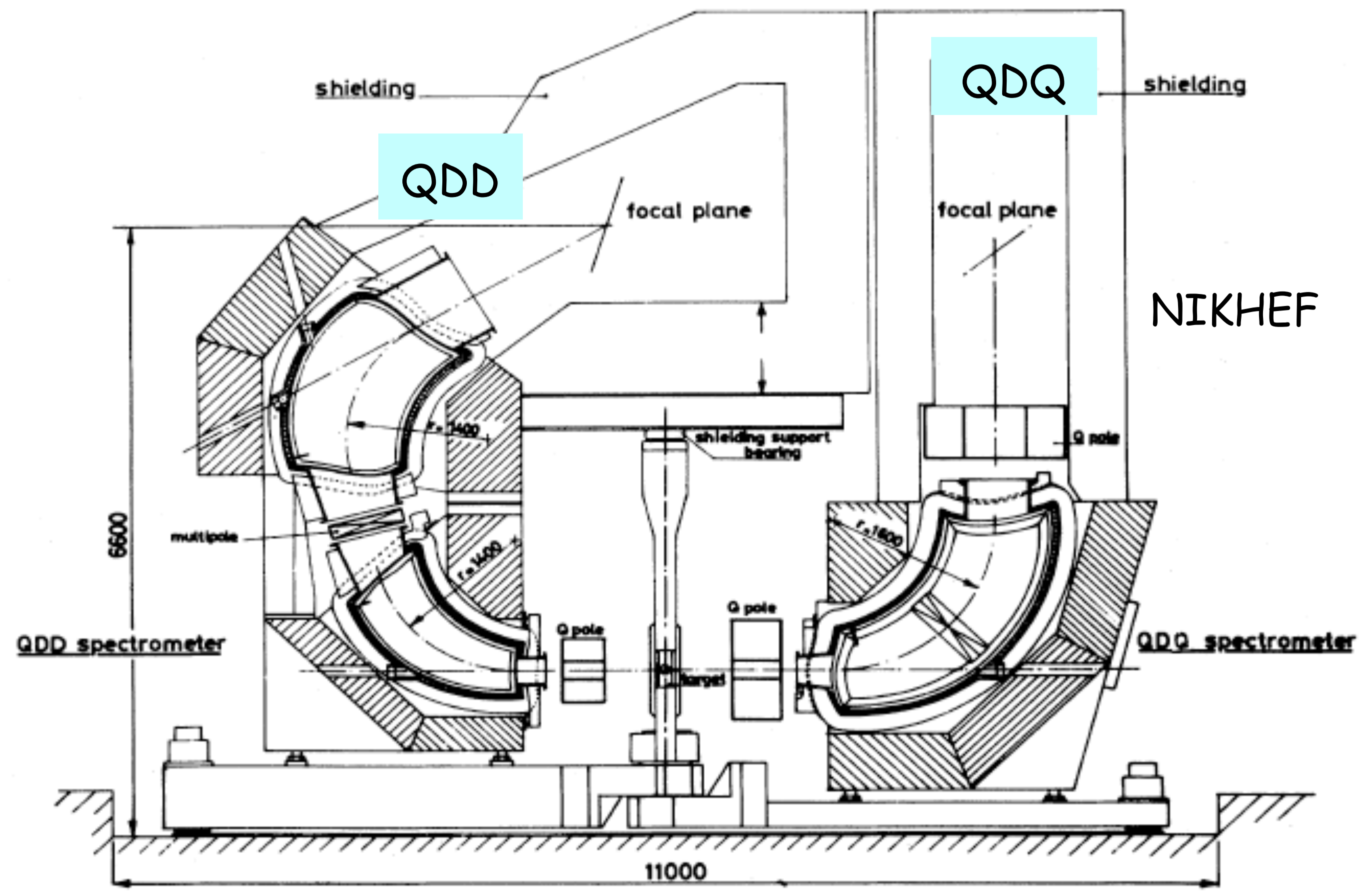

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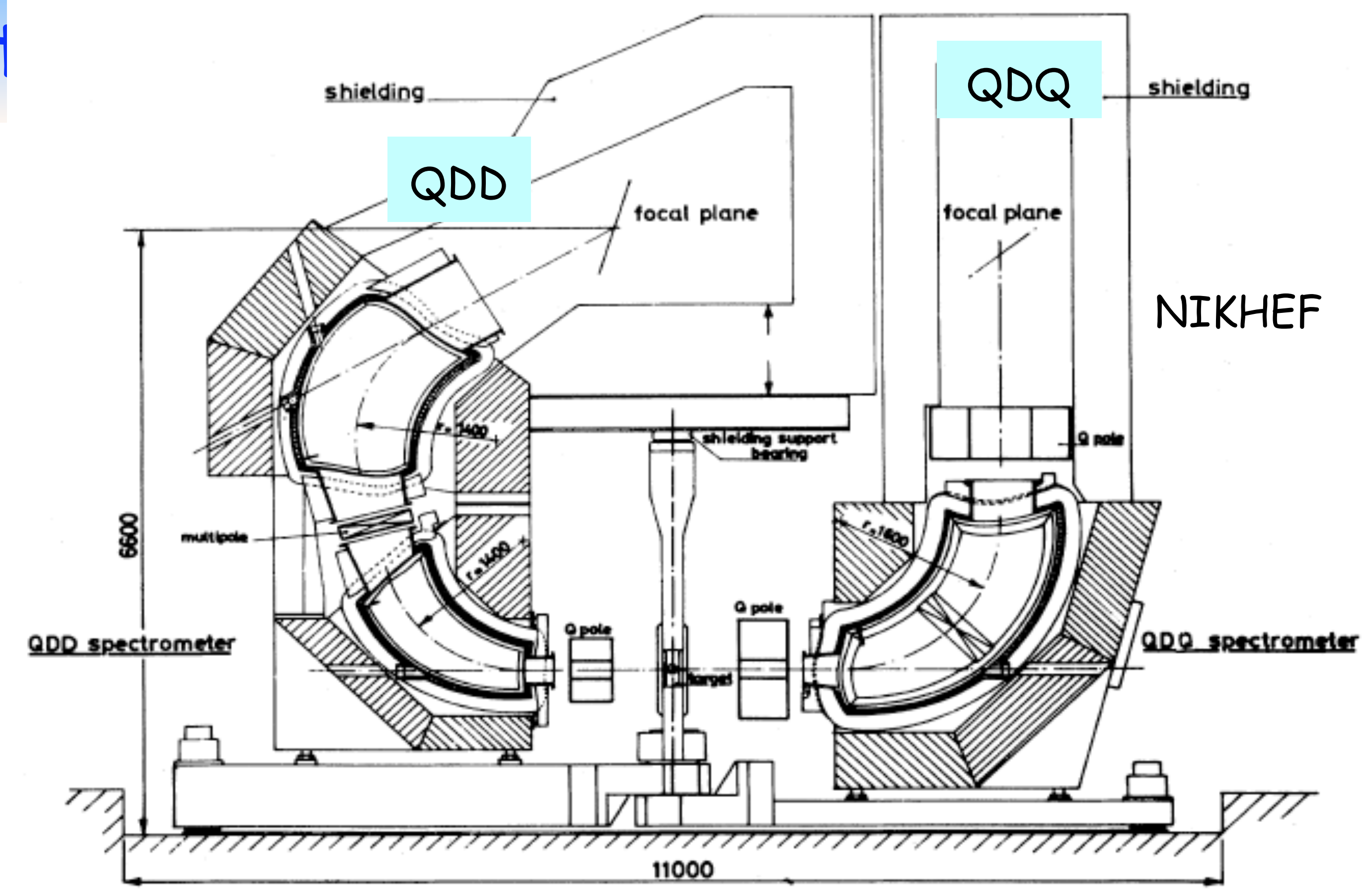
-depends upon matching between energy dispersion at the end of the beam transport system and the energy dispersion admittance of the spectrometer



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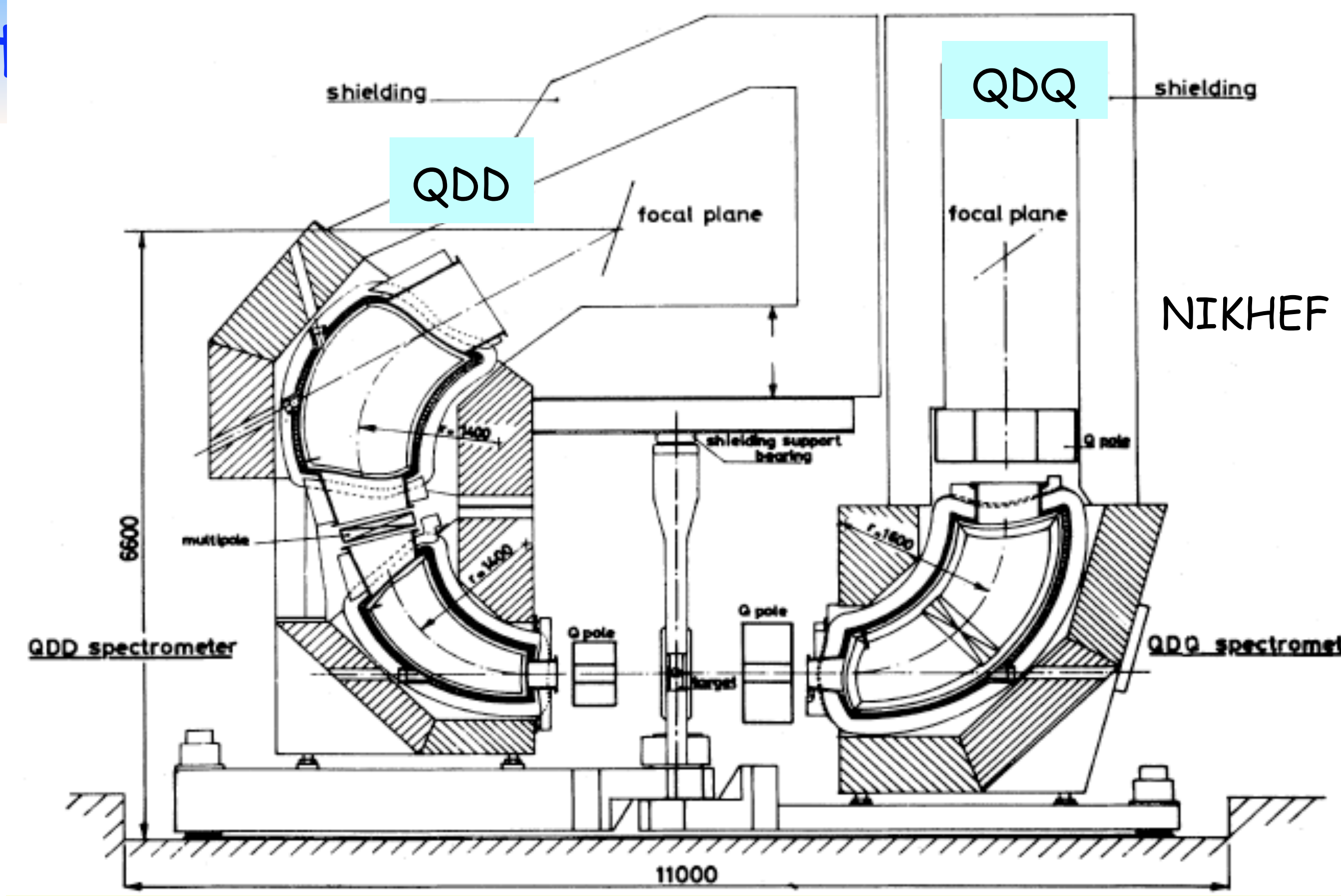

Detectors

-situated in the focal planes

-determine the particle type, its trajectory (proportional mutiwire chambers), ...

-efficiency: fundamental to obtain cross sections

- measure ^1H or ^{12}C cross sections

A rough description of an experiment

Types of experiments

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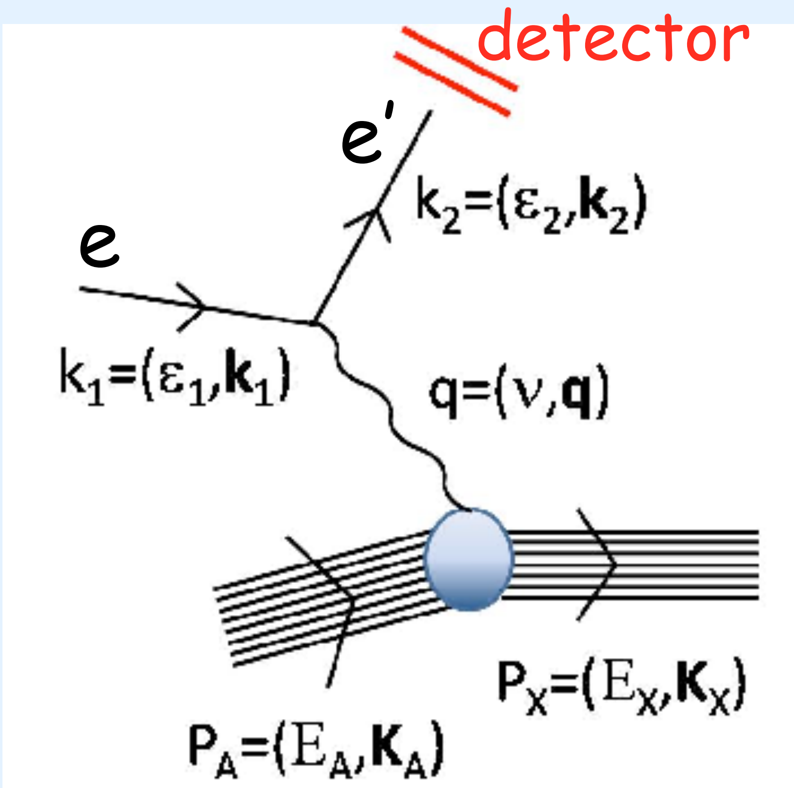

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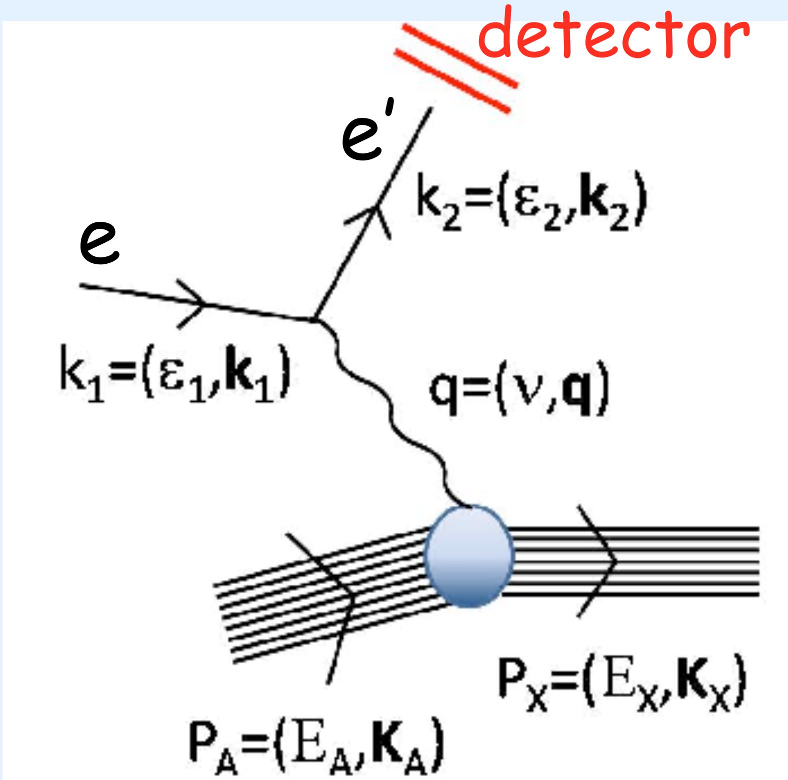
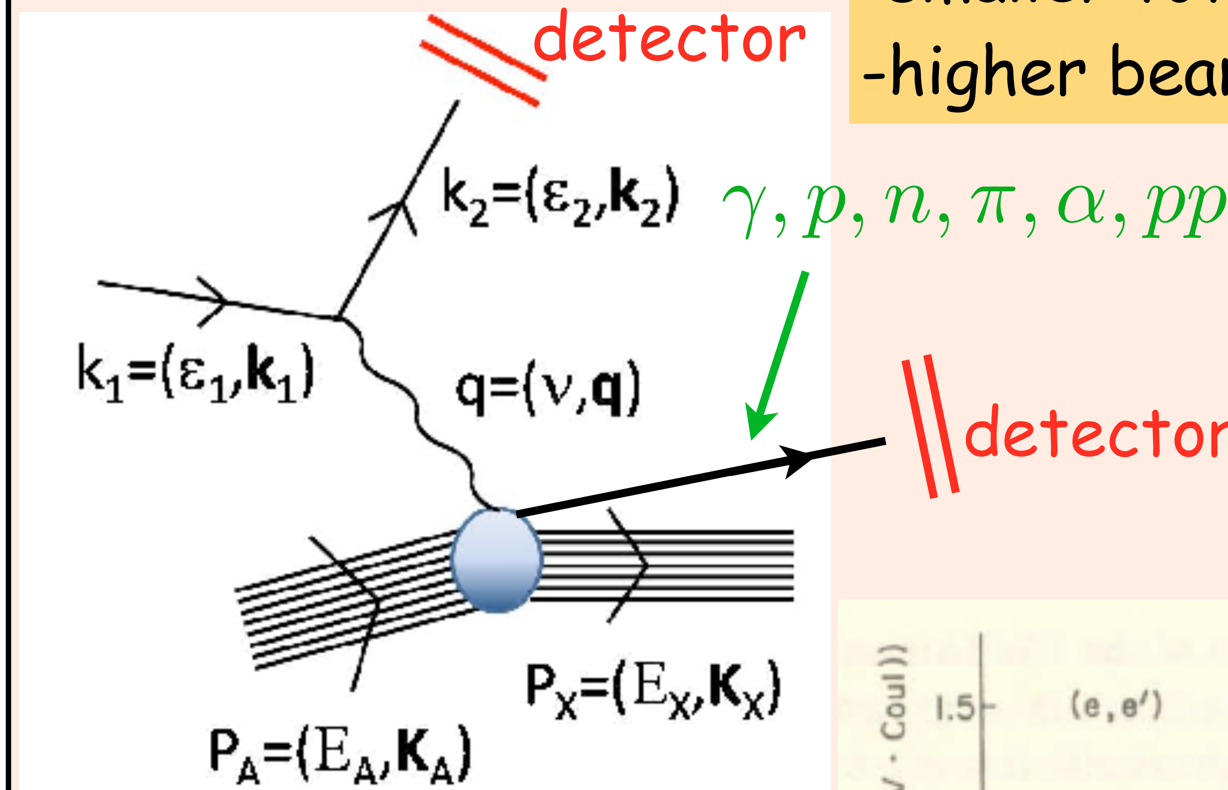


inclusive experiment

- -smaller cross sections
- -smaller total efficiency
- -higher beam intensity



$\gamma, p, n, \pi, \alpha, pp, pn, nn, \ldots$

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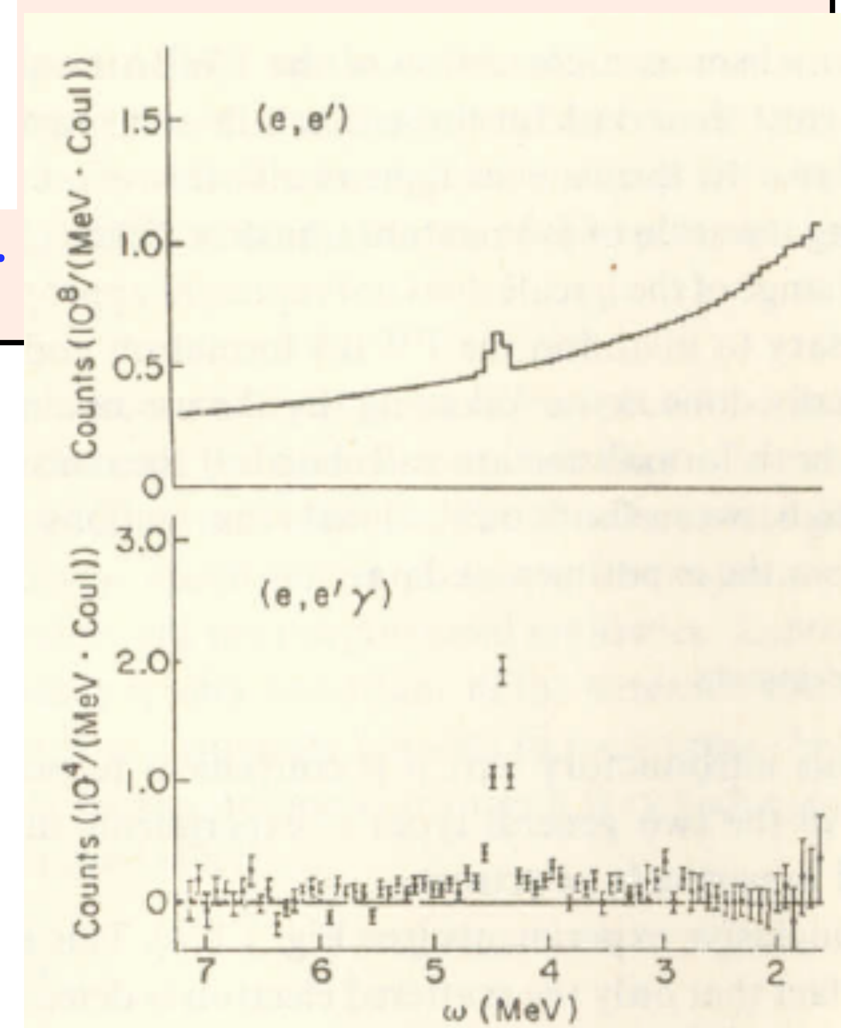

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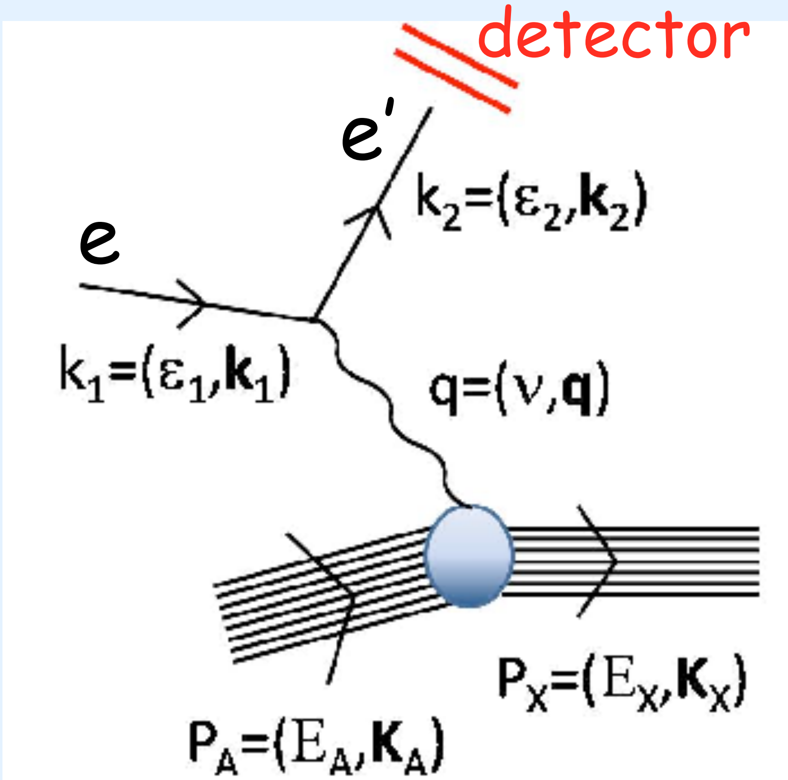

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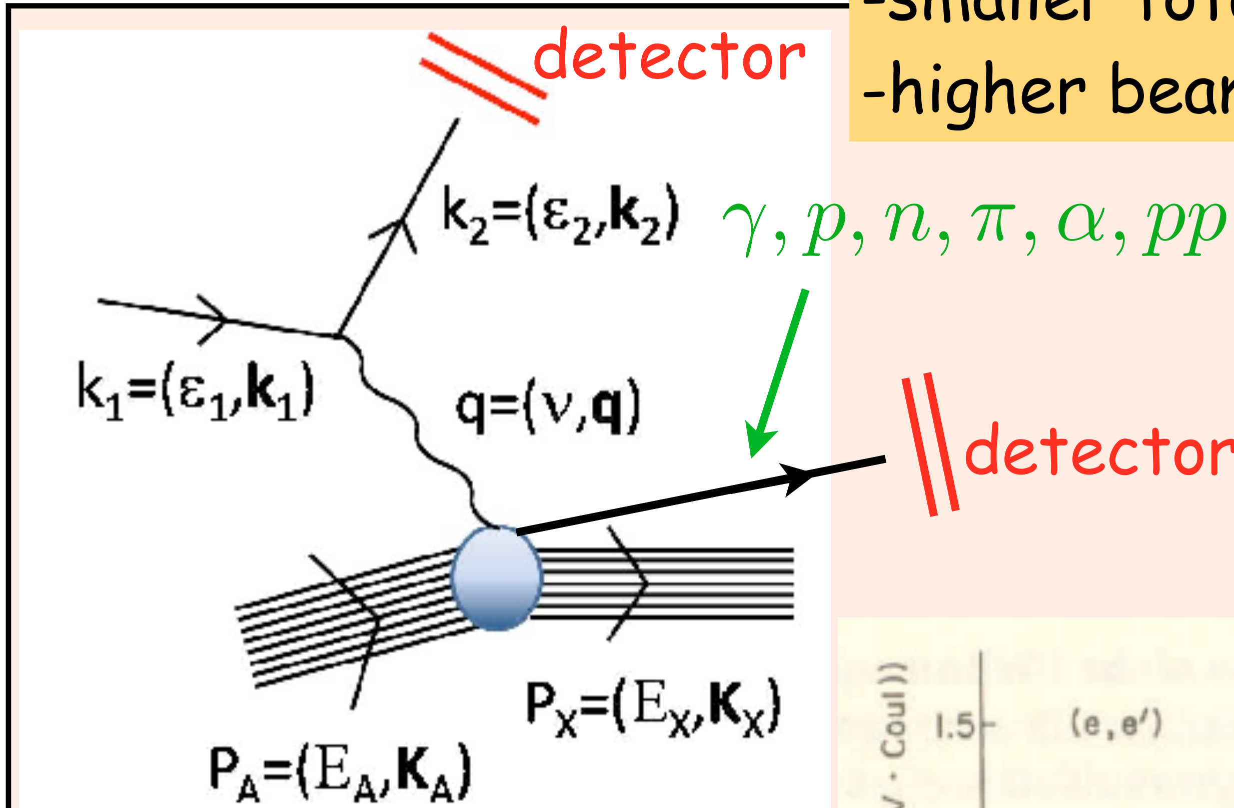

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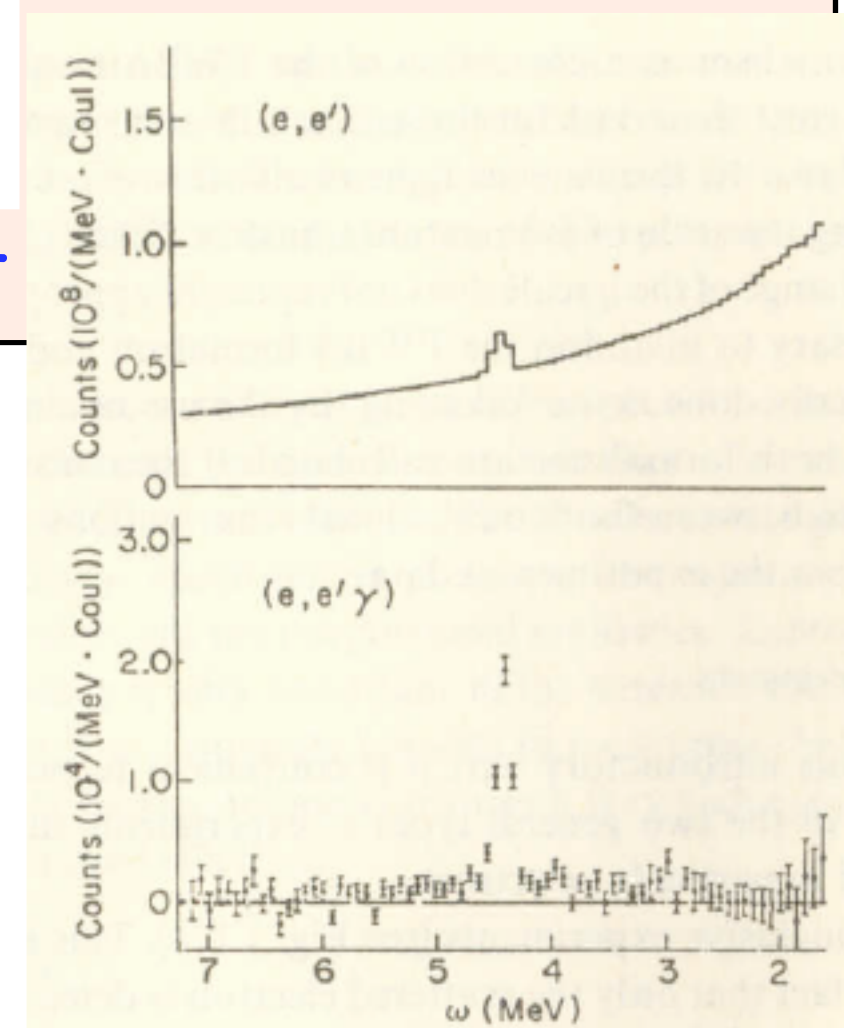

-accidental coincidences:
pulsed vs. CW beams

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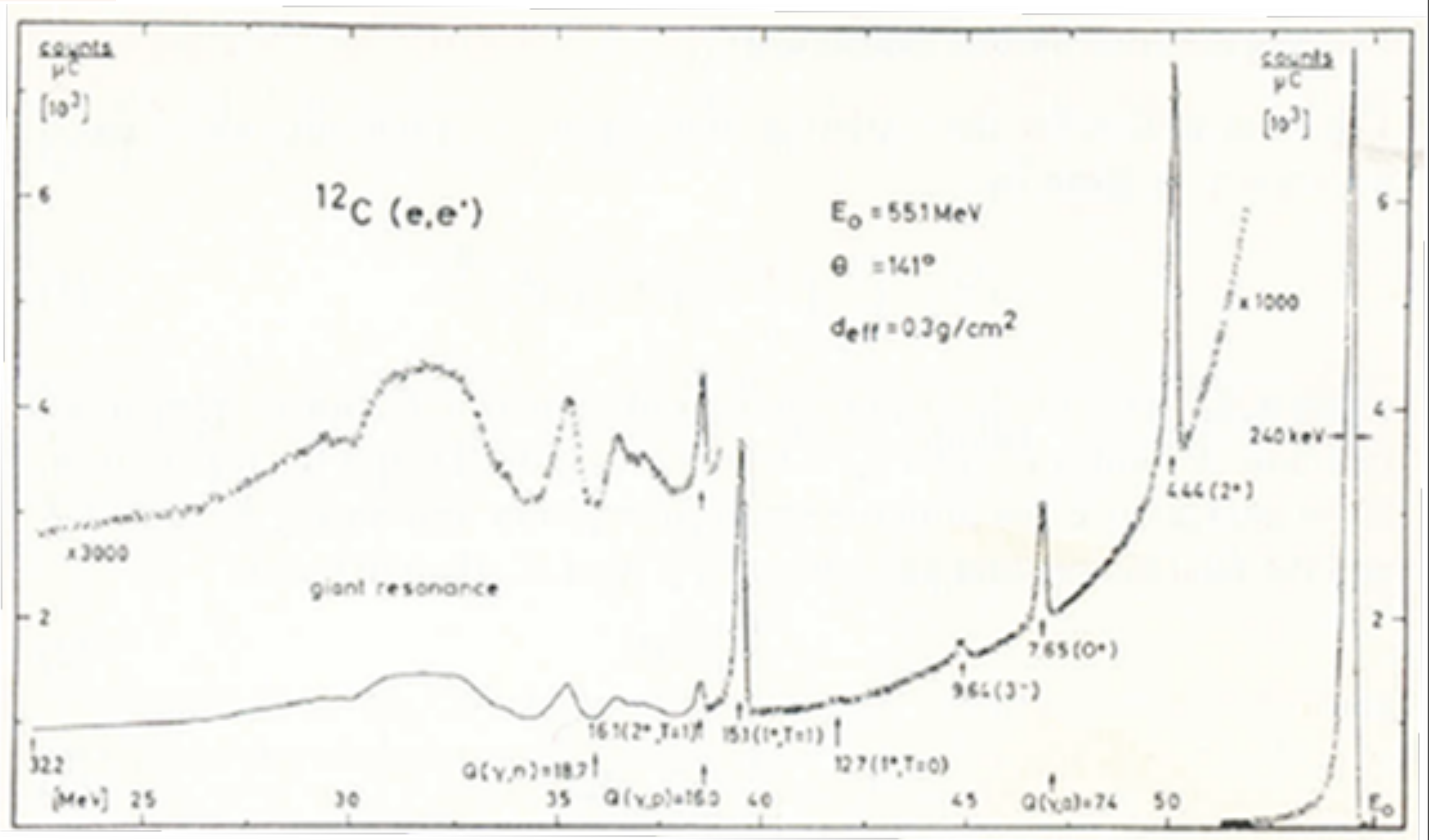

Radiative tail: must be eliminated

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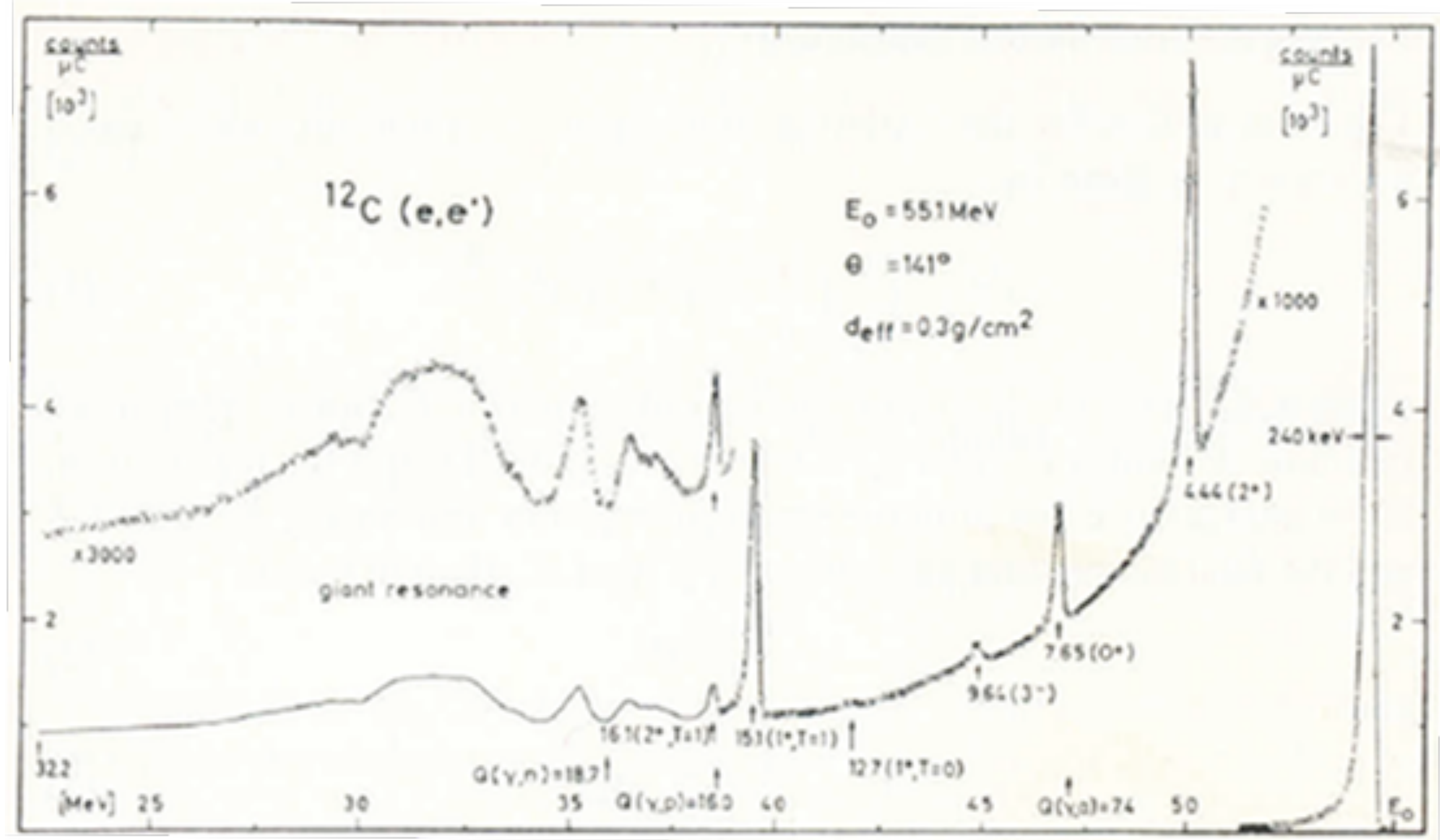

Radiative tail: must be eliminated

Distortion of the electron wave functions

-provoked by the Coulomb interaction e-nucleus

-experimental data are corrected to be compared to PWBA calculations that are simpler (change q scale for light nuclei)

-DWBA required in case of heavy nuclei