

Experimente mit Antimaterie

- Elementarteilchen heute
- Antimaterie in der Natur
- Antimaterie (Positronen) in der Medizin (PET)
- Beschleunigung von Elementarteilchen
- Reaktionen zwischen Elementarteilchen und ihr Nachweis
- Antiprotonen
 - Erzeugung von Antiprotonen
 - Experimente mit Positronen und Antiprotonen
 - Effiziente Erzeugung von kurzlebigen Elementarteilchen (W^\pm , Z^0 , J/ψ , t-Quark, Glueballs, ...)
- Antiwasserstoff
- Antiprotonen in Deutschland (GSI/Darmstadt)

Tab. 1.1 Die Bausteine der Materie

Teilchen	Spin	Ladung (in Einheiten der Elementarladung)	Masse *) MeV/c ²	Art der Wechselwirkung		
				stark	elektromagnetisch	schwach
d-Quark (down)	1/2	-1/3	<100	ja	ja	ja
u-Quark (up)	1/2	2/3	<100	ja	ja	ja
s-Quark (seltsam)	1/2	-1/3	~400	ja	ja	ja
c-Quark (charm)	1/2	2/3	~1500	ja	ja	ja
b-Quark (bottom)	1/2	-1/3	~5000	ja	ja	ja
t-Quark (top)	1/2	2/3	~174300			
Elektron-Neutrino ν_e	1/2	0	<17 eV/c ²	nein	nein	ja
Elektron e^-	1/2	-1	0.511	nein	ja	ja
Myon-Neutrino ν_μ	1/2	0	<0.25	nein	nein	ja
Myon μ^-	1/2	-1	105.66	nein	ja	ja
τ -Neutrino ν_τ	1/2	0	<35	nein	nein	ja
τ -Lepton τ^-	1/2	-1	1784	nein	ja	ja

*) Da die Quarks nicht als freie Teilchen vorkommen, sind ihre Massen nur im Zusammenhang mit Modellvorstellungen angebbbar.

Zusätzlich Boten-Teilchen: Photonen (γ), Intermediäre Bosonen (W^\pm, Z^0), Gluonen (g), Gravitonen

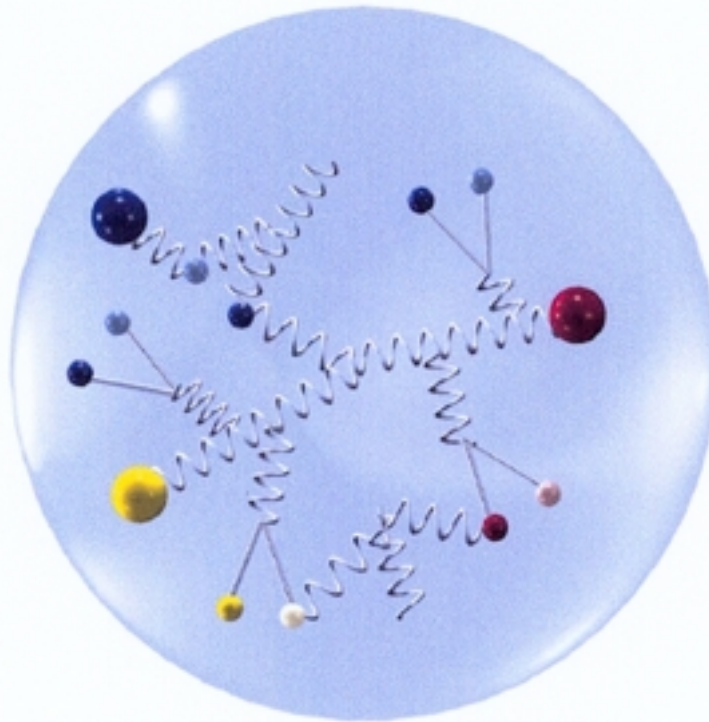


Figure 2.2. Schematic view into the nucleon, illustrating its complex structure. The three valence quarks of the nucleon are held together by exchanging gluons (symbolized by springs) which for tiny moments split into pairs of so called virtual quarks and antiquarks.

Dirac-Gleichung

Dirac-Gleichung = Relativistisches Analogon zur Schrödinger-Gleichung

$$i\hbar \frac{\partial \psi(\mathbf{r}, t)}{\partial t} = c \left(\frac{\hbar}{i} \boldsymbol{\alpha} \cdot \nabla + \beta \mu c \right) \psi(\mathbf{r}, t)$$
$$\vec{\alpha} = \begin{pmatrix} 0 & \vec{\sigma} \\ \vec{\sigma} & 0 \end{pmatrix}, \text{ z.B. } \alpha_1 = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$$
$$\beta = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Lösungen der Dirac-Gleichung:

$$\psi^{(+)}(\mathbf{r}, t) = \frac{1}{(2\pi\hbar)^{3/2}} \int [u^{(R)}(\mathbf{p})a_R(\mathbf{p}) + u^{(L)}(\mathbf{p})a_L(\mathbf{p})] e^{(i/\hbar)(\mathbf{p}\cdot\mathbf{r} - E_p t)} d^3 p$$

$$\psi^{(-)}(\mathbf{r}, t) = \frac{1}{(2\pi\hbar)^{3/2}} \int [v^{(R)}(\mathbf{p})b_R^\dagger(-\mathbf{p}) + v^{(L)}(\mathbf{p})b_L^\dagger(-\mathbf{p})] e^{(i/\hbar)(\mathbf{p}\cdot\mathbf{r} + E_p t)} d^3 p$$

Positronen-Emissions-Tomographie (PET)

Herstellung von kurzlebigen β^+ -Strahlen, z.B. ^{15}O

Beschleuniger : $^{14}\text{N} (d, n)^{15}\text{O}$ $t_{1/2} (^{15}\text{O}) = 2.03 \text{ min}$

Im Körper : $\beta^+ (e^+) + e^- (\text{Körper}) \rightarrow \underbrace{\gamma (0.5 \text{ MeV}) + \gamma (0.5 \text{ MeV})}_{\text{Gemessen von Detektoren}}$

Gemessen von Detektoren

↳ Rekonstruktion des Zerfallortes des ^{15}O

Wenig radioaktive Belastung des Körpers

Diagnose bei Krebs-, Herz- und Hirnerkrankungen

Nuklid-Karte

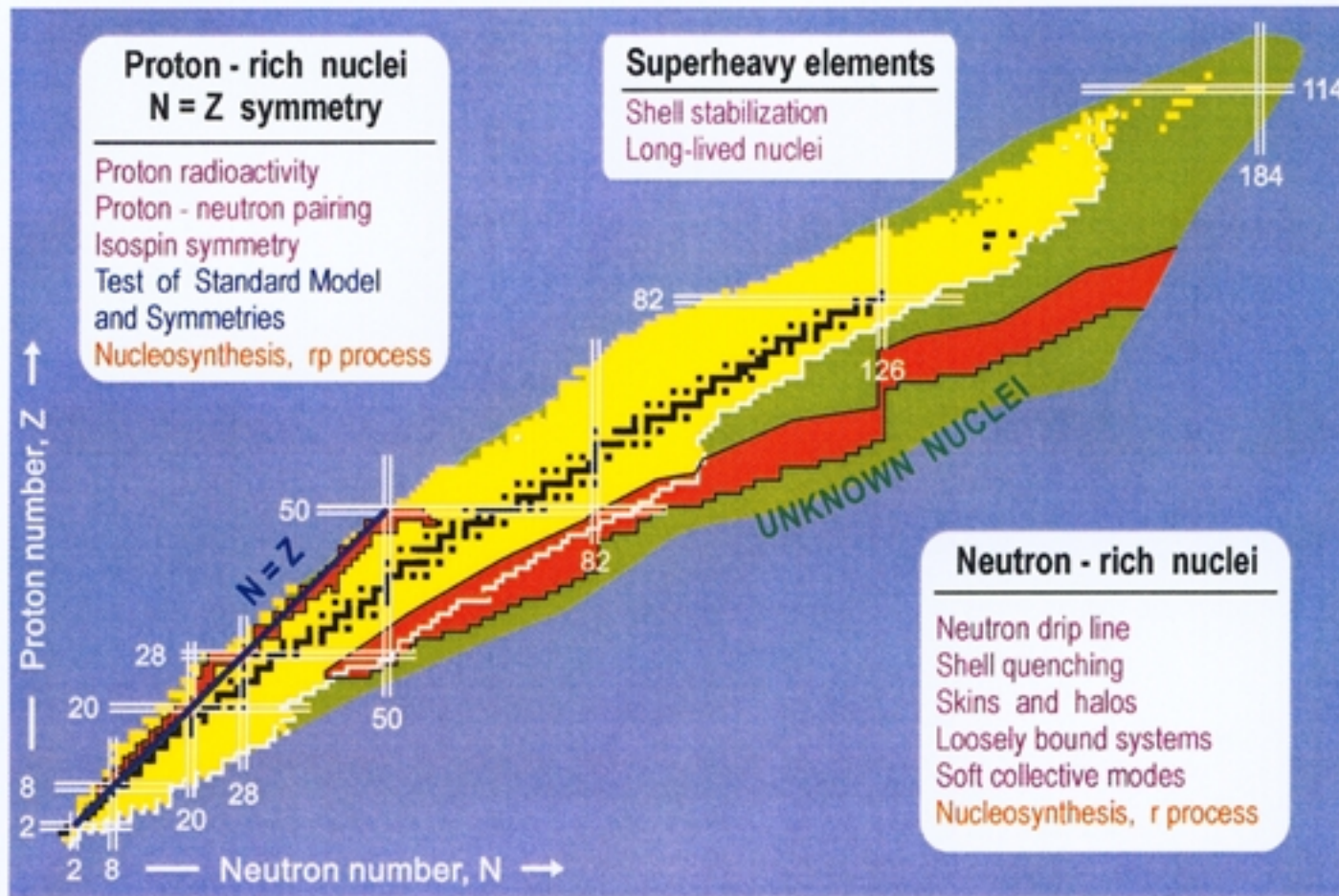
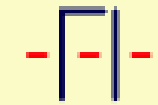
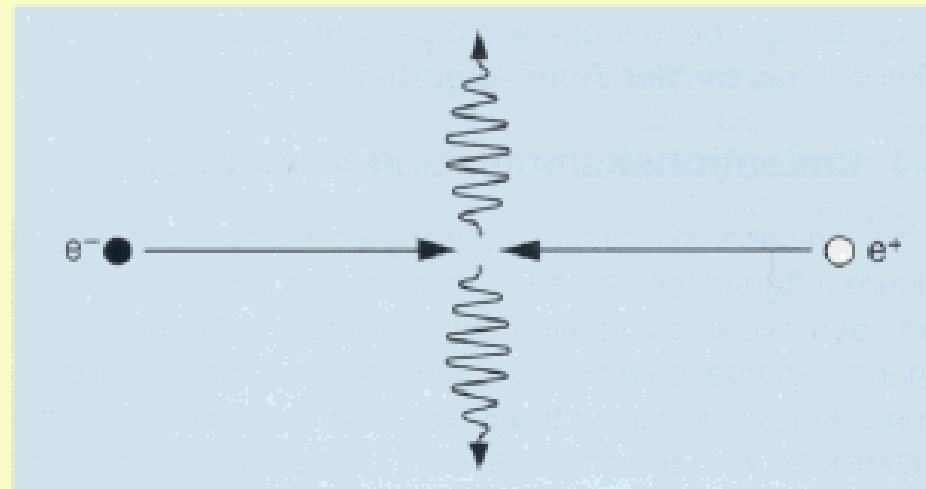


Figure 1.1: Chart of nuclei. Stable nuclei, as found on earth, are marked by black symbols. The yellow area covers unstable nuclei already produced in laboratories. Many more unstable, but bound nuclei may exist, the region of these *exotic nuclei* is given in green. Red areas cover specific stellar nucleosynthesis pathways, the r - and rp -processes. Magic proton and neutron numbers are indicated. The insets itemize some of the key questions to be addressed at next-generation exotic-beam facilities.

Positronen-Emissions- Tomographie (PET)



- **Positronenvernichtung** (Zerstrahlung von Materie und Antimaterie) erzeugt kollineares Photonenpaar.



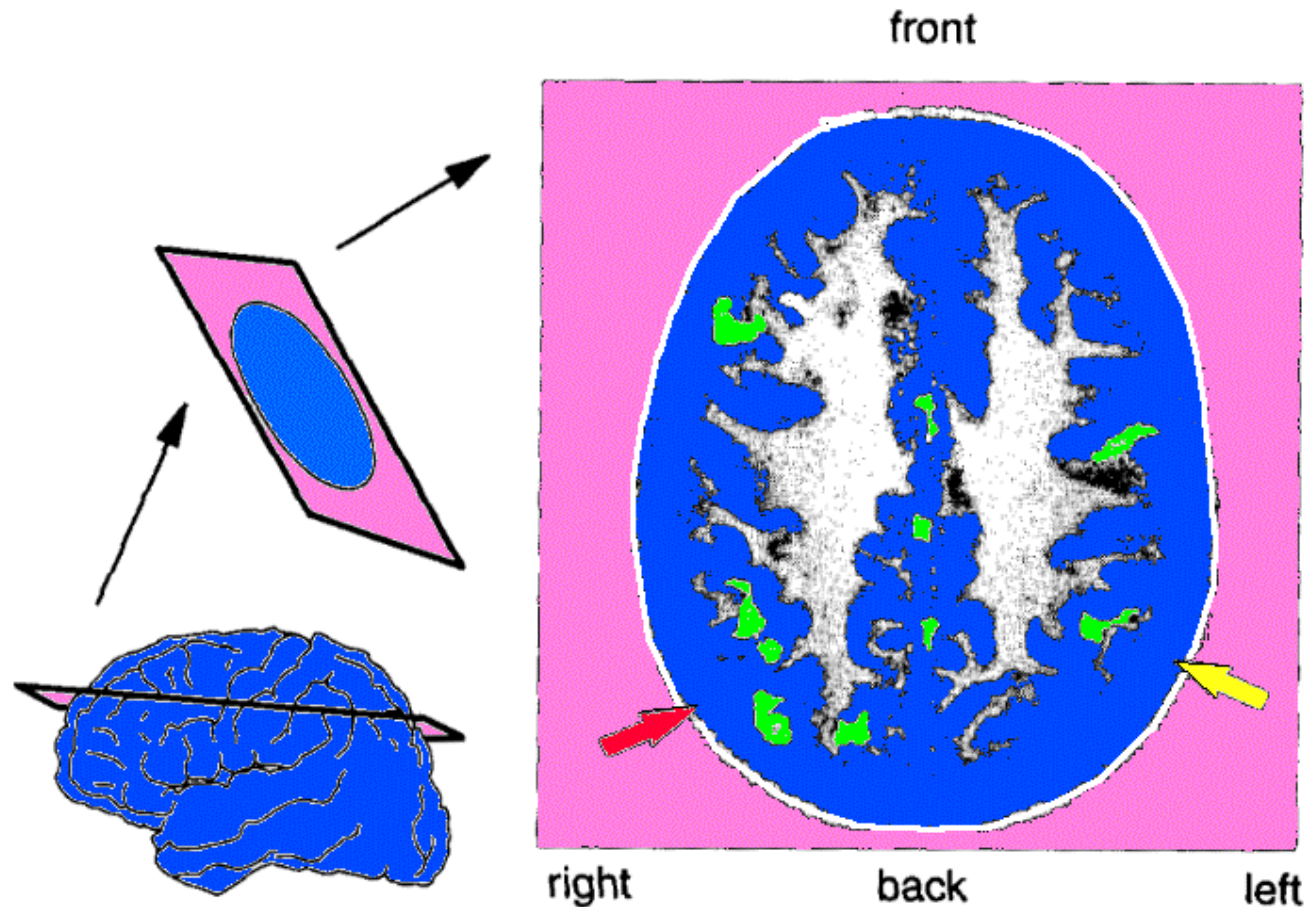
20.03.2002

Isotopentechnik von U. J. Schrewe

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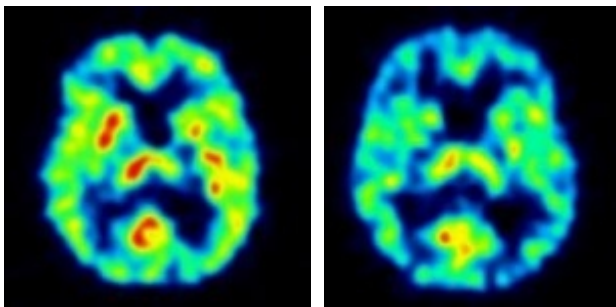
Positronen-Emissions-Tomographie (PET) und Hirnaktivität

Neuronale Aktivitäten bei der Wahrnehmung, kann die PET mit Hilfe radioaktiver Substanzen messen, die entweder die Zunahme von Stoffwechselaktivitäten im Blut zeigen oder die den verstärkten Blutfluss in den gerade aktiven Gehirnregionen anzeigen.





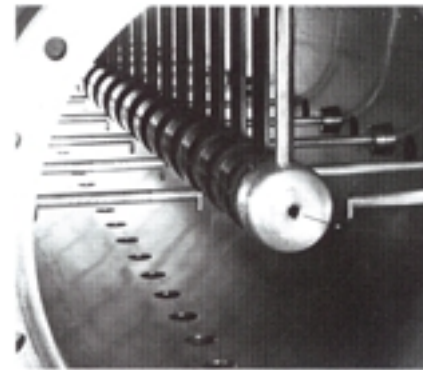
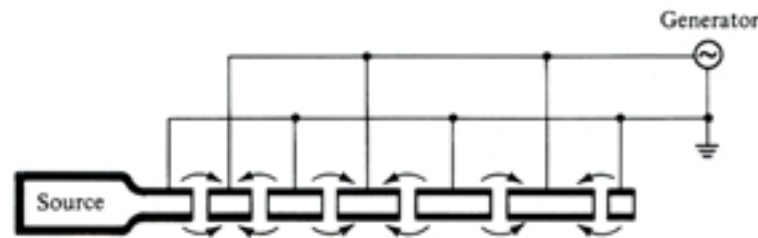
Die Positronen-Emissions-Tomographie (PET) ist ein nuklearmedizinisches Schnittbildverfahren, mit dem Stoffwechselvorgänge im Körper untersucht werden können. Nach Injektion einer geringen Menge radioaktiv markierter Substanz wird die aus dem Körper austretende Strahlung mit Detektoren gemessen. Substanzen, die in den Stoffwechsel eingeschleust werden, können u. a. Zucker, Eiweißbausteine oder auch Wasser sein. Solche markierten Substanzen werden im Körper weitgehend normal umgesetzt, deshalb ist mit der PET eine Darstellung der natürlichen Zellfunktion möglich. PET kann in der onkologischen, neurologischen und kardiologischen Diagnostik eingesetzt werden.



Die Schnittbilder des Hirns eines Schlaganfall-Patienten zeigen die Durchblutung vor (Bild links) und nach (Bild rechts) einer Therapie.

Beschleunigung von Elementarteilchen

Linearbeschleuniger

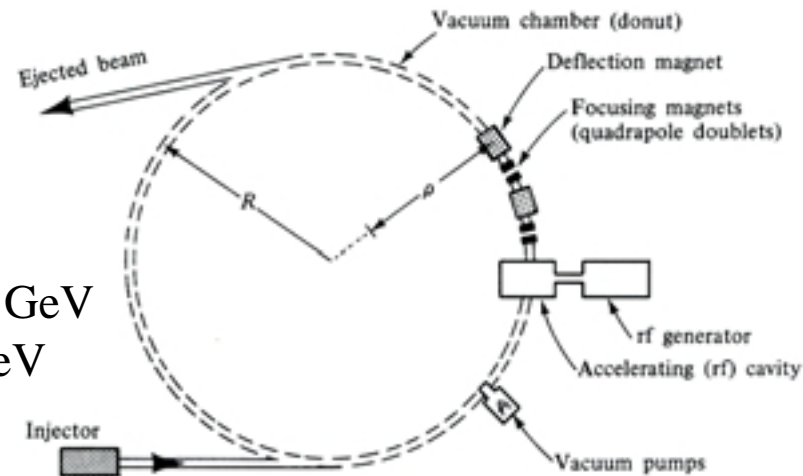


SLAC: 2 miles accelerator : e^+ , e^- bis 40 GeV

Synchrotronbeschleuniger

Fermilab/Chicago : p , \bar{p} bis 1000 GeV

CERN/Genf : p bis 7000 GeV



Experimente mit festem Target

Hohe Reaktionsraten

Kleine Schwerpunktsenergien

Experimente im Kollisions-Mode

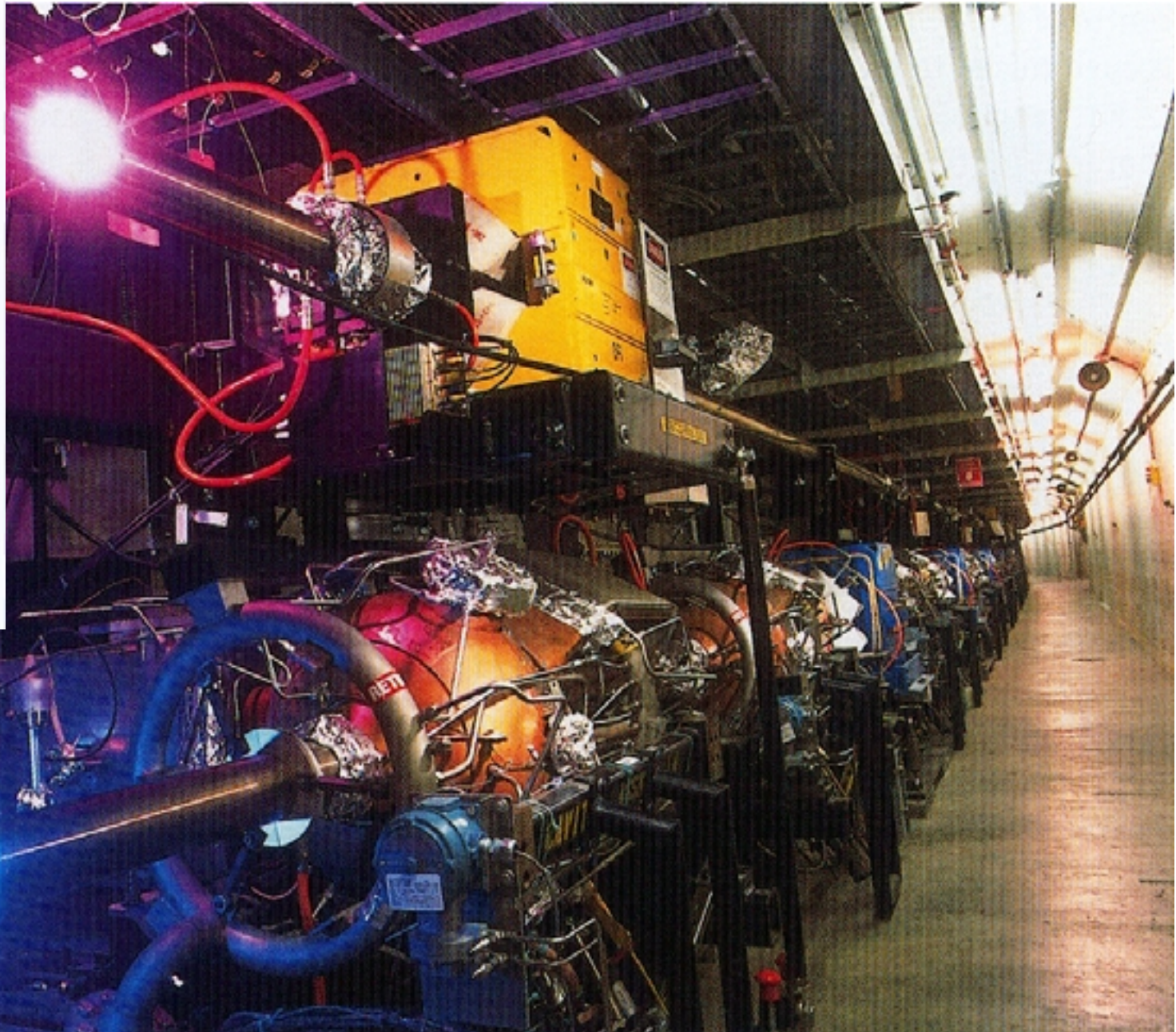
Kleine Reaktionsraten

Große Schwerpunktsenergien



Fig. 6.37 The 3 km (2 mile) long linear accelerator at the Stanford Linear Accelerator Center (SLAC). The electrons start off from an electron 'gun' where they are released from a heated filament, at the end of the machine near the bottom left of the picture. The electrons in effect surf along radio waves set up in a chain of 100 000 cylindrical copper 'cavities', about 12 cm in diameter. The machine is aligned to 0.5 mm along its complete length and is situated in a tunnel 8 m below ground. The surface buildings that mark out the line of the linac contain the klystrons (see Fig. 6.40, p. 104), which provide the radio waves.

Fig. 11.6 The PEP-II machine at SLAC contains counter-rotating electron and positron beams which are accelerated separately in two rings. The upper ring here contains the positron beam, the lower ring the electron beam. With two rings, the particle beams can be accelerated to different energies before being brought to collide head on. The electrons and positrons annihilate at the correct total energy to rematerialize as a bottom quark and antiquark, bound together as an excited upsilon particle (see p. 164). However, as the initial particles have different energies, the quark-antiquark pair is born in motion, and the B mesons they form travel onwards in the direction of the highest energy beam (the electron beam). This gives the B mesons extended lifetimes due to 'time dilation', an effect of special relativity. (The bright pink and blue spots simulate the passage of bunches of positrons and electrons.)



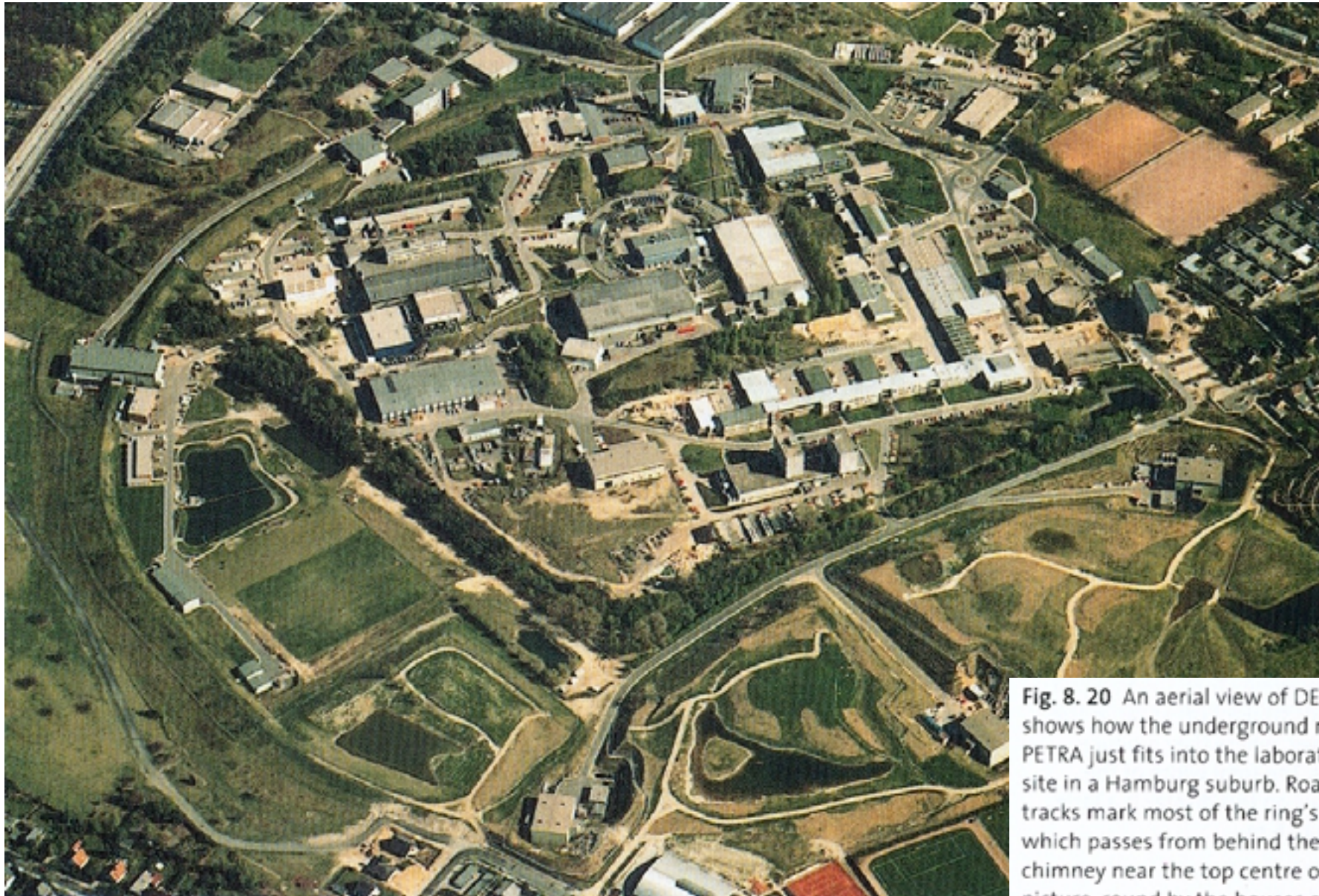


Fig. 8. 20 An aerial view of DESY shows how the underground ring for PETRA just fits into the laboratory's site in a Hamburg suburb. Roads and tracks mark most of the ring's path, which passes from behind the chimney near the top centre of the picture, round by the houses at the right, close to the sports field at the bottom, and back up across the fields at the left.





Fig. 6.36 The tunnel of the Super Proton Synchrotron (the SPS), in the weeks before the machine accelerated its first protons in 1976. The SPS became the world's first proton-antiproton collider in 1981, and remains in use to this day as part of CERN's network of accelerators.

Reaktionen zwischen Elementarteilchen und ihr Nachweis

Umwandlung von Energie in Masse ($E = mc^2$)

Beispiele (Kollisions-Experimente):

$$e^+ \left\{ \begin{array}{l} \text{Kin. En.:} \\ 1.55 \text{ GeV} \\ \text{Masse:} \\ 0.0005 \text{ GeV} \end{array} \right\} + e^- \left\{ \begin{array}{l} \text{Kin. En.:} \\ 1.55 \text{ GeV} \\ \text{Masse:} \\ 0.0005 \text{ GeV} \end{array} \right\} \rightarrow J/\psi \left\{ \begin{array}{l} \text{Kin. En.:} \\ 0 \text{ GeV} \\ \text{Masse:} \\ 3.1 \text{ GeV} \end{array} \right\} \{ \rightarrow \mu^+ \mu^- \}$$

$$\bar{p} \left\{ \begin{array}{l} \text{Kin. En.:} \\ 500 \text{ GeV} \\ \text{Masse:} \\ 1 \text{ GeV} \end{array} \right\} + p \left\{ \begin{array}{l} \text{Kin. En.:} \\ 500 \text{ GeV} \\ \text{Masse:} \\ 1 \text{ GeV} \end{array} \right\} \rightarrow t\text{-Quark} \left\{ \begin{array}{l} \text{Kin. En.:} \\ \approx 100 \text{ GeV} \\ \text{Masse:} \\ 173 \text{ GeV} \end{array} \right\} + \bar{t}\text{-Quark} \left\{ \begin{array}{l} \text{Kin. En.:} \\ \approx 100 \text{ GeV} \\ \text{Masse:} \\ 173 \text{ GeV} \end{array} \right\} + X$$

Beispiel (Fixed Target Experiment):

$$\bar{p} \left\{ \begin{array}{l} \text{Kin. En.:} \\ 15 \text{ GeV} \\ \text{Masse:} \\ 1 \text{ GeV} \end{array} \right\} + p \left\{ \begin{array}{l} \text{Kin. En.:} \\ 0 \text{ GeV} \\ \text{Masse:} \\ 1 \text{ GeV} \end{array} \right\} \rightarrow 4\pi^+ + 4\pi^-, \gamma\gamma, \dots \text{ (Annihilation)}$$

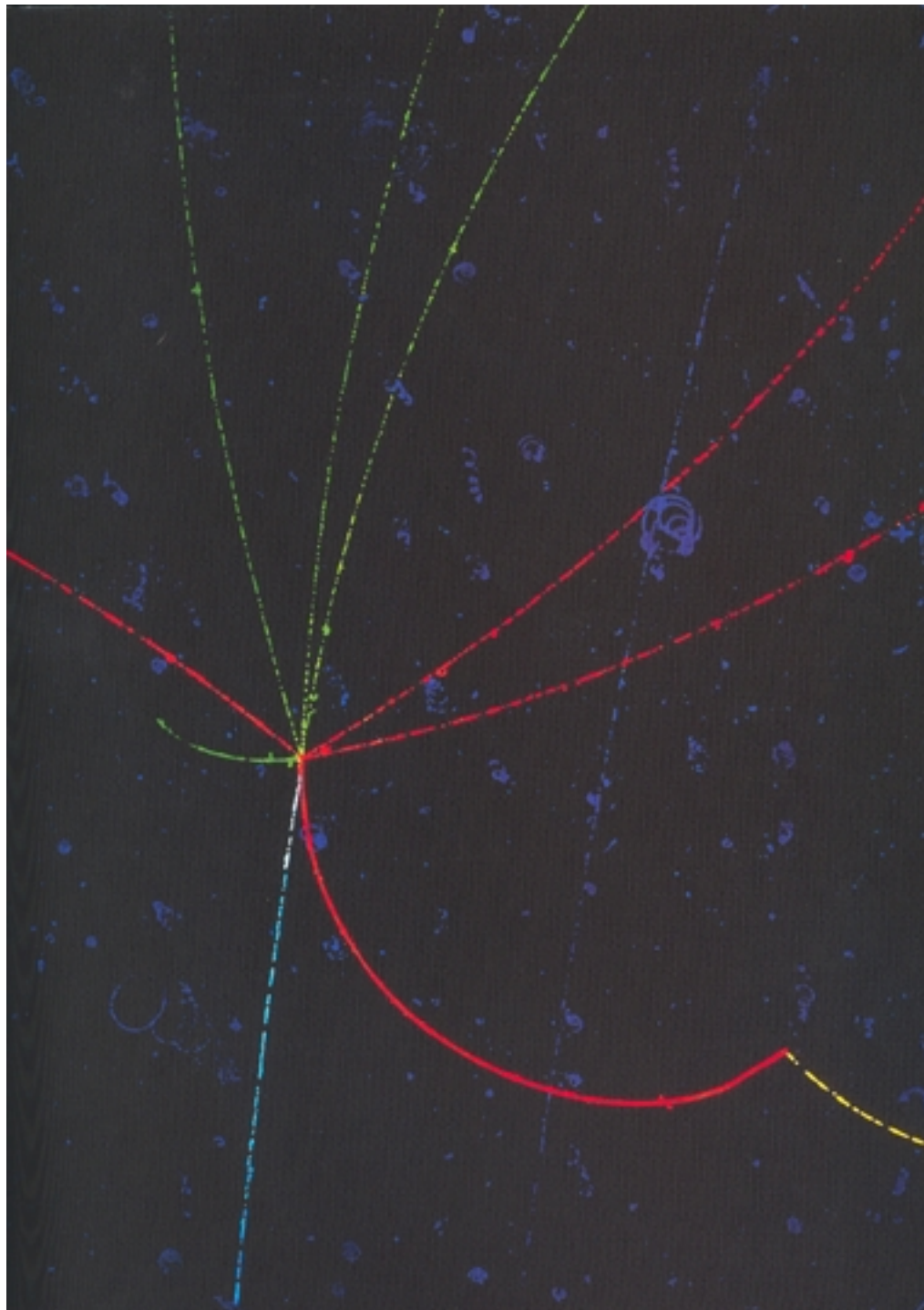


Fig. 7.7 (OPPOSITE) An antiproton (pale blue) strikes a proton in a bubble chamber at Berkeley. In the resulting annihilation, the energy released rematerializes as four positive pions (red) and four negative pions (green). In the bubble chamber's magnetic field, the negative pions and the negative antiproton curve in a clockwise direction, the positive particles anticlockwise. The two lower pions have less energy than the others and therefore curve more and leave thicker tracks. The one on the left travels only a short distance and stops when it is captured by a proton. The one on the right ends by decaying into a muon (yellow) and an invisible neutrino. Tracks not involved in the interaction, including the characteristic curlicues of low-energy electrons knocked from atoms, are coloured dark blue.

Reaktionen zwischen Elementarteilchen und ihr Nachweis

Detektoren

Emulsions-Schichten im Magnetfeld

Blasenkammern

Elektronische Detektoren (Geiger-Müller Nachfahren, ...)

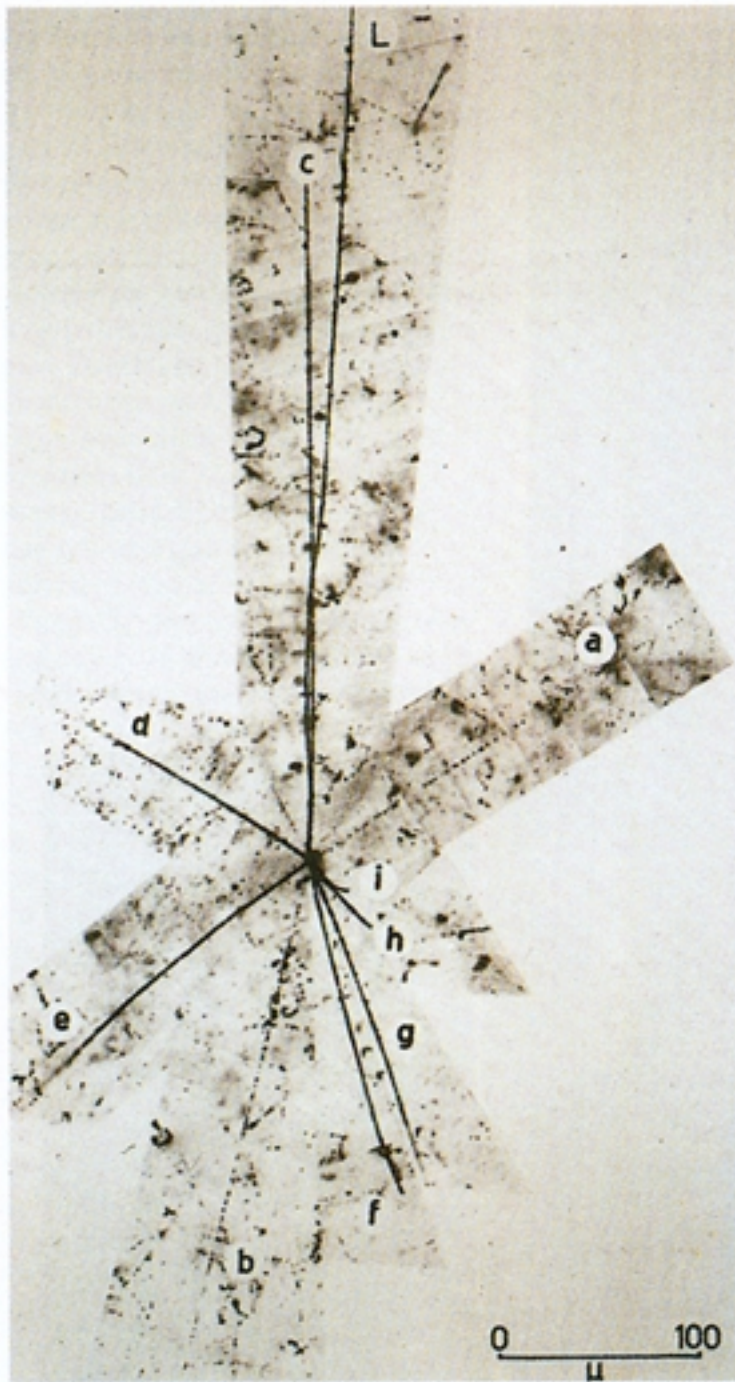
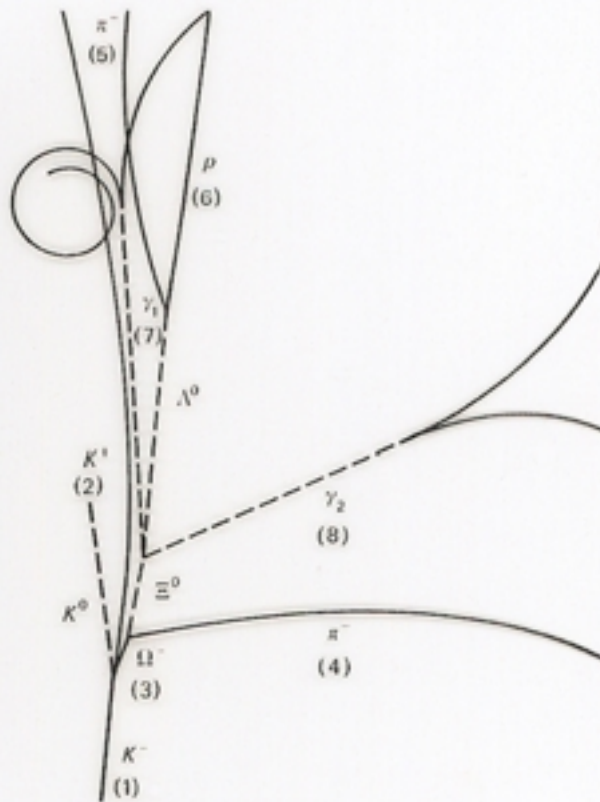


Fig. 7.6 The first image of an antiproton annihilation 'star', found in emulsion exposed to antiprotons at the Bevatron in 1955. The antiproton enters the picture at the top (the track marked L) and travels about 430 micrometres before ending its life in an explosive act of mutual destruction with a proton. Nine charged particles emerge from the point of annihilation and move outwards, their tracks forming a characteristic star-like pattern. The tracks marked *a* and *b* are probably pions, the others probably protons.



The first Ω^- event (Barnes *et al.*, 1964). (Courtesy, Brookhaven National Laboratory.)

It depicts the following chain of events:

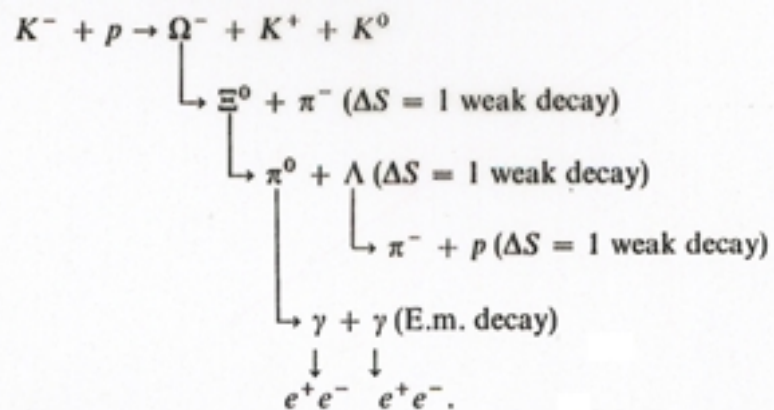


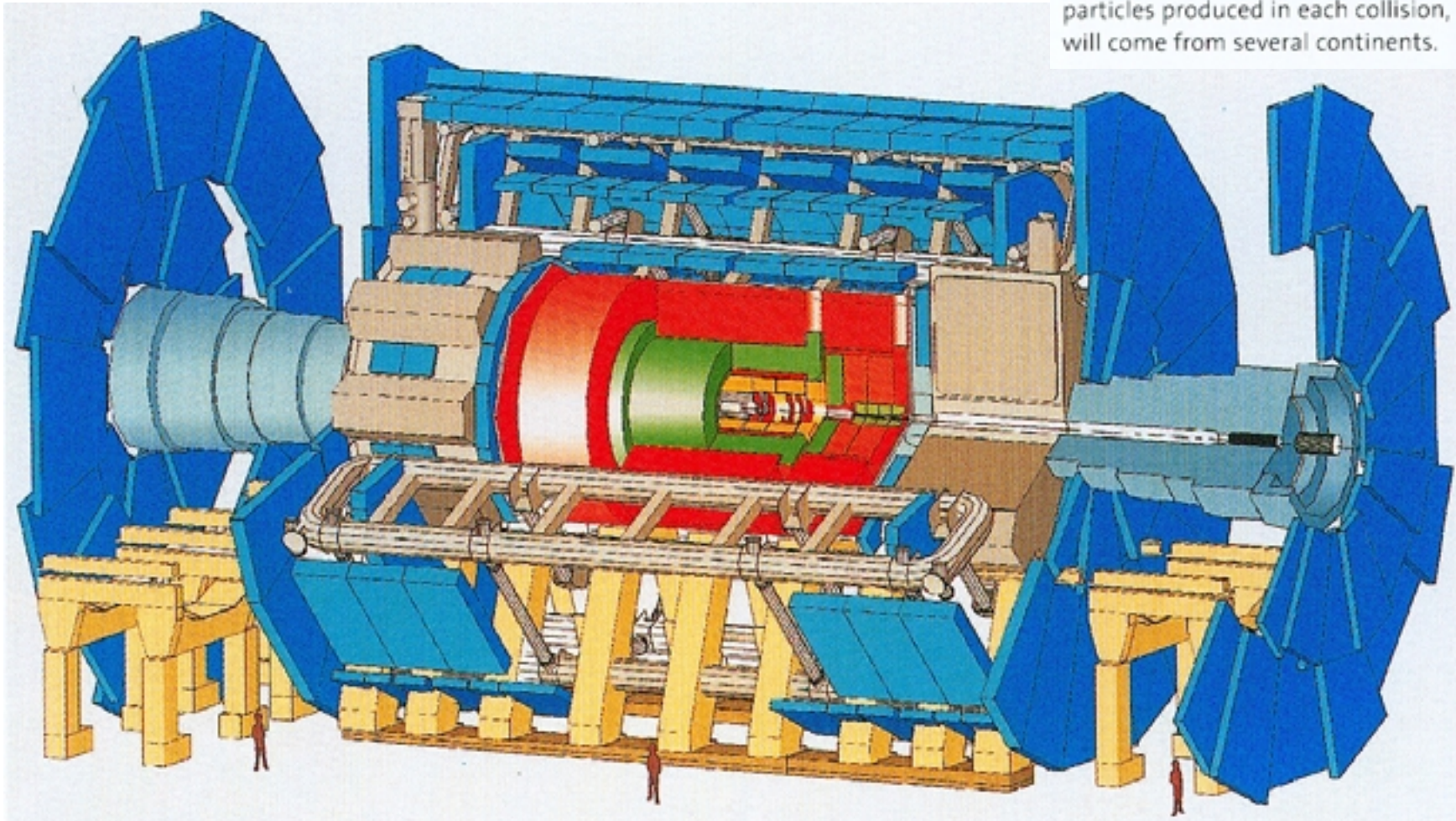


Fig. 6.26 A scanner at Fermilab works on a photograph taken at the laboratory's 4.6 m (15 ft) bubble chamber. A spray of particles appears as if from nowhere, produced by the violent interaction of a neutrino which, being neutral, leaves no track. The photograph is projected onto a table to enable the scanner to make accurate measurements of the positions, lengths, angles, and curvature of the particle tracks. From these measurements physicists can identify the various types of particles involved in the event.

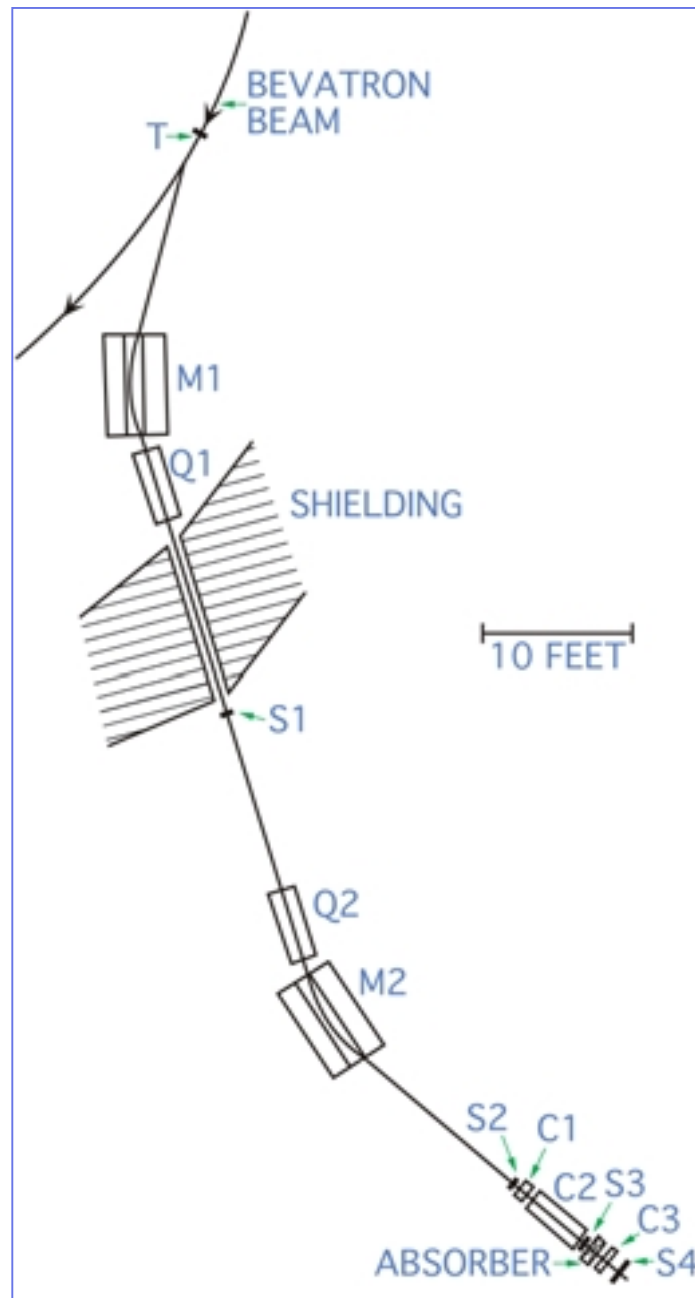


Fig. 1.17 This view of one end of the H1 experiment at the DESY laboratory in Hamburg shows the complexity of modern particle physics detection. H1 is like a huge Swiss roll – a cylinder of layers of different particle detectors, each with a specific task. Each of these detectors produces electrical signals that contain information about the path of a particle, the energy it deposited, and the time it passed through. And each of these signals must pass through cables to the electronics and computer processors (see Fig. 12.14, p. 228) that piece together the information, ultimately to reveal the particles created in the high-energy collision of an electron with a proton at the heart of the apparatus.

Fig. 11.3 A cut-away diagram of the ATLAS detector being constructed to record proton-proton collisions in the LHC at CERN. The mammoth detector will have an overall diameter of 22 m – the height of a five-storey building – and will weigh 7000 tonnes. Its various component layers, designed to provide as much information as possible to identify the hundreds of particles produced in each collision, will come from several continents.



Erzeugung von Antiprotonen



Antiproton beam at the Berkeley Bevatron. The antiprotons were produced in a *Cu*-target (T). The momentum of the produced negative charged particles (π^- , \bar{p}) was 1.19 GeV/c determined by two dipole magnets (M1, M2). The velocities of the particles were measured via TOF- (S1, S2, S3, S4)- and Cerenkov-counters (C1, C2, C3).

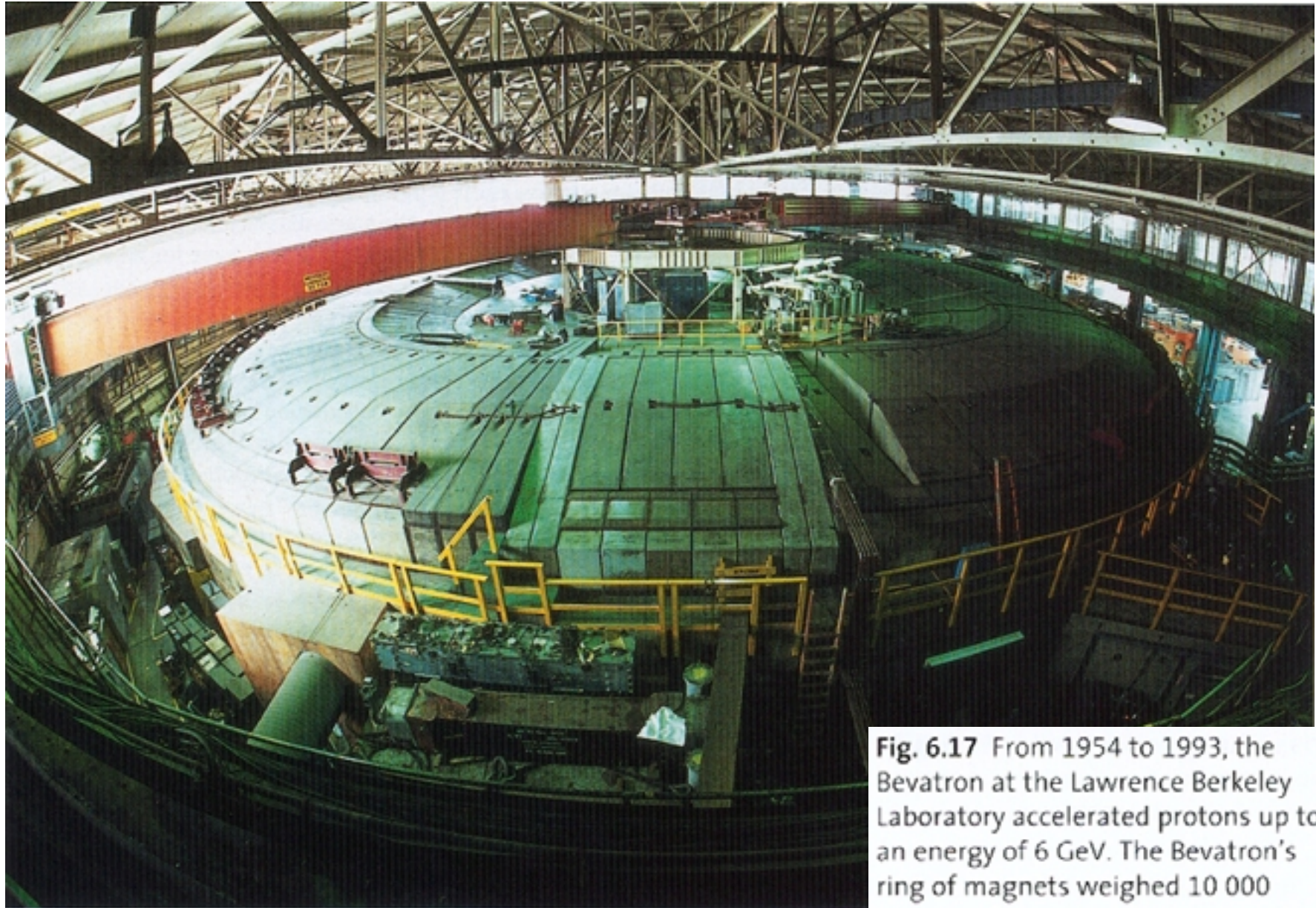
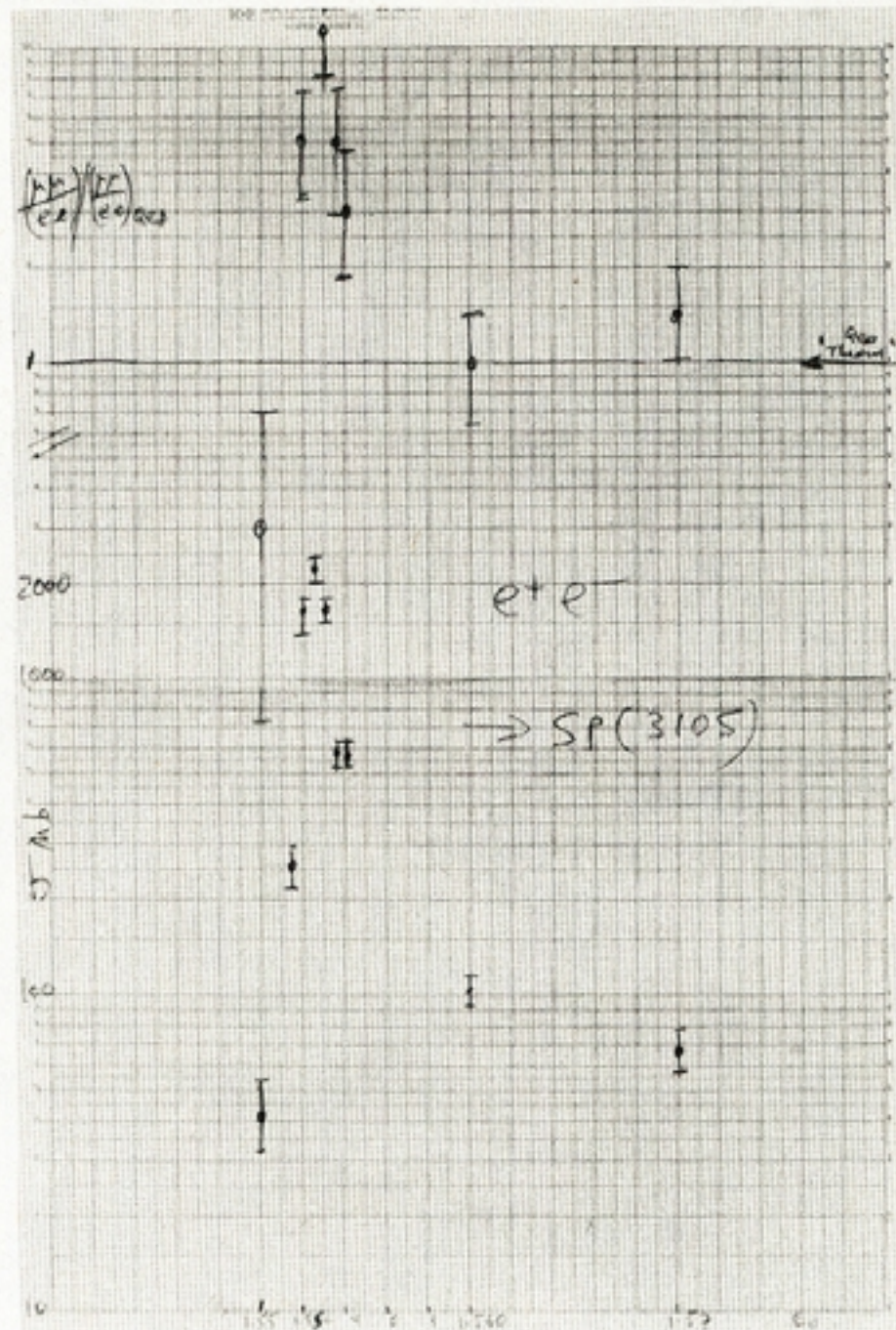


Fig. 6.17 From 1954 to 1993, the Bevatron at the Lawrence Berkeley Laboratory accelerated protons up to an energy of 6 GeV. The Bevatron's ring of magnets weighed 10 000 tonnes – five times greater than the magnet ring in the Cosmotron.

Fig. 6.

Semilog plot of the cross section for $e^+ e^- \rightarrow \text{hadrons}$; the ψ (3100) stands out clearly. The radiative tail can also be seen extending to the high-energy side. At the top of the figure is the experimental muon pair to electron pair ratio compared to the same ratio calculated from quantum electrodynamics. This shows the rise in the muon pair cross section at the ψ (3100). [From SLAC-LBL logbook sketch by Gerson Goldhaber, November 10, 1974.]



Asymmetrie zwischen Materie/Antimaterie im Universum

Experiment (Sichtbares Universum):

$$n_b - n_{\bar{b}} \approx n_b ; n_b/n_\gamma \approx 10^{-10}$$

- ↳ Materie und Antimaterie (nach Big Bang) haben annihiliert, aber:
Ein wenig Materie ist übrig geblieben (**Asymmetrie !**)

Voraussetzungen für Entstehung von Asymmetrie (Sakharov)

- Verletzung der Baryonen-Zahl Erhaltung
- C- und CP- Verletzung
- Abweichung vom thermischen Gleichgewicht

Neuere Messungen (K^0/\bar{K}^0 , B^0/\bar{B}^0 -System)

CP-Verletzung existiert, aber bei weitem zu klein um beobachtete Asymmetrie zu erklären

Neuestes Resultat (BaBar/SLAC/Stanford):

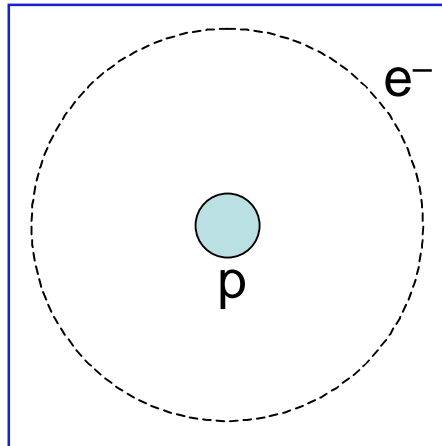
BaBar-Daten:

$$\begin{array}{l} B^0 \rightarrow K^+\pi^- \quad (u\bar{s} + \bar{u}d) \quad (910) \\ \bar{B}^0 \rightarrow K^-\pi^+ \quad (\bar{u}s + u\bar{d}) \quad (696) \end{array} \left. \vphantom{\begin{array}{l} B^0 \\ \bar{B}^0 \end{array}} \right\} \text{Zahlen sollten gleich sein bei CP-Erhaltung}$$

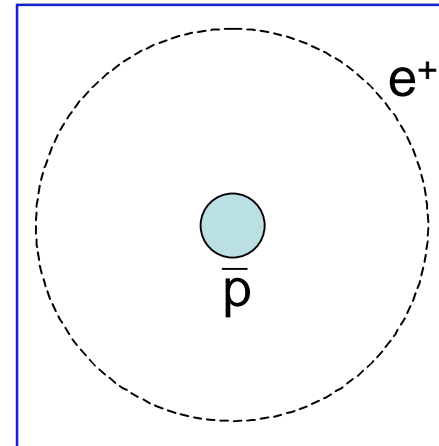
CP - Asymmetrie !!

Anti-Wasserstoff

H-Atom:



$\bar{\text{H}}$ -Atom:

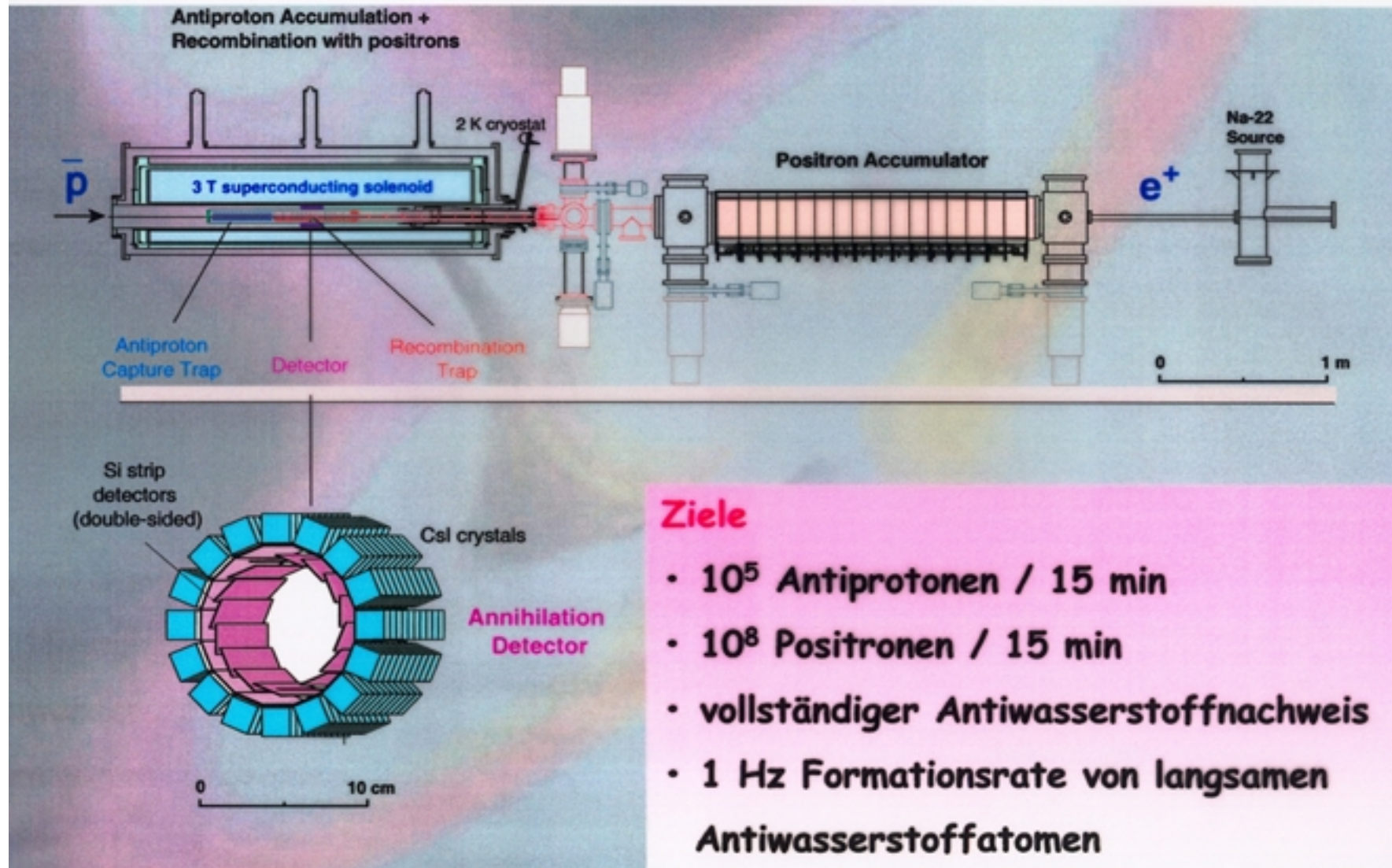


Erstmals bei CERN gefunden
Elektromagnetische Falle

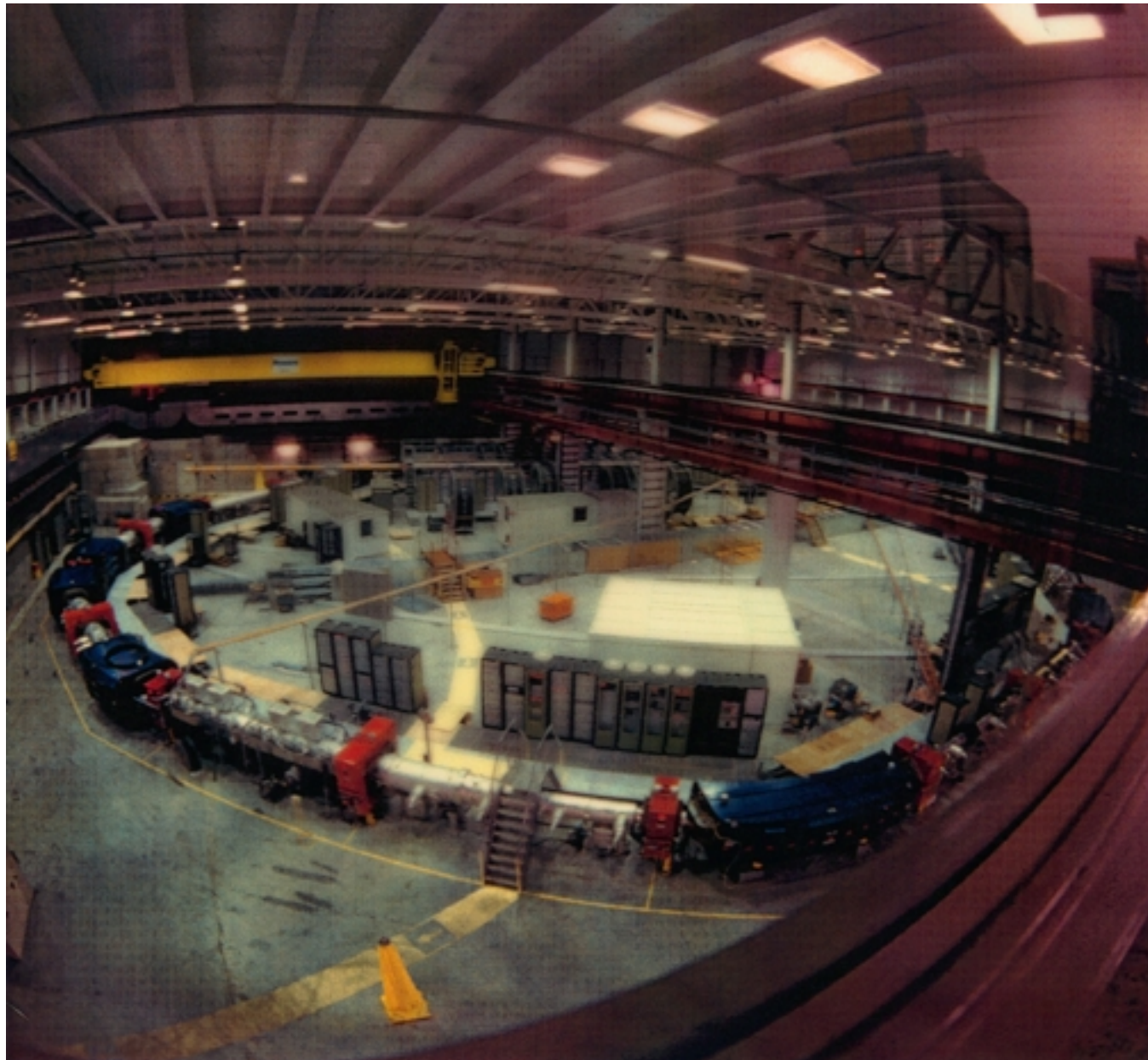
Zukunft: Test der CPT-Symmetrie

ATHENA Apparatur

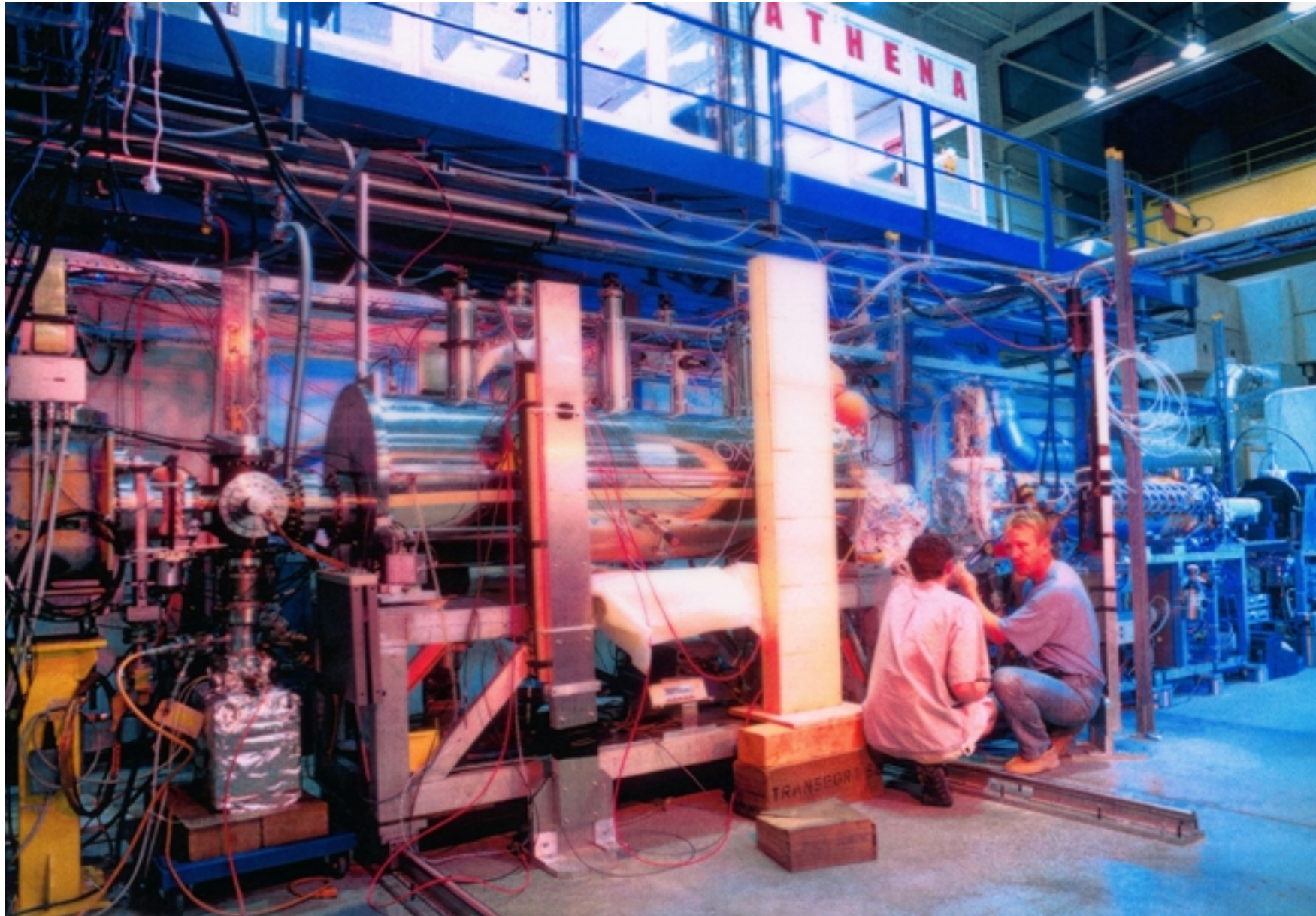
ATHENA/AD-1: Antiwasserstoff Produktion und Spektroskopie



Der AD am CERN



ATHENA Apparatur



Antiprotonen in Deutschland: Hadronenprojekt bei der GSI/Darmstadt



Figure 3.1: Location of the projected new international facility

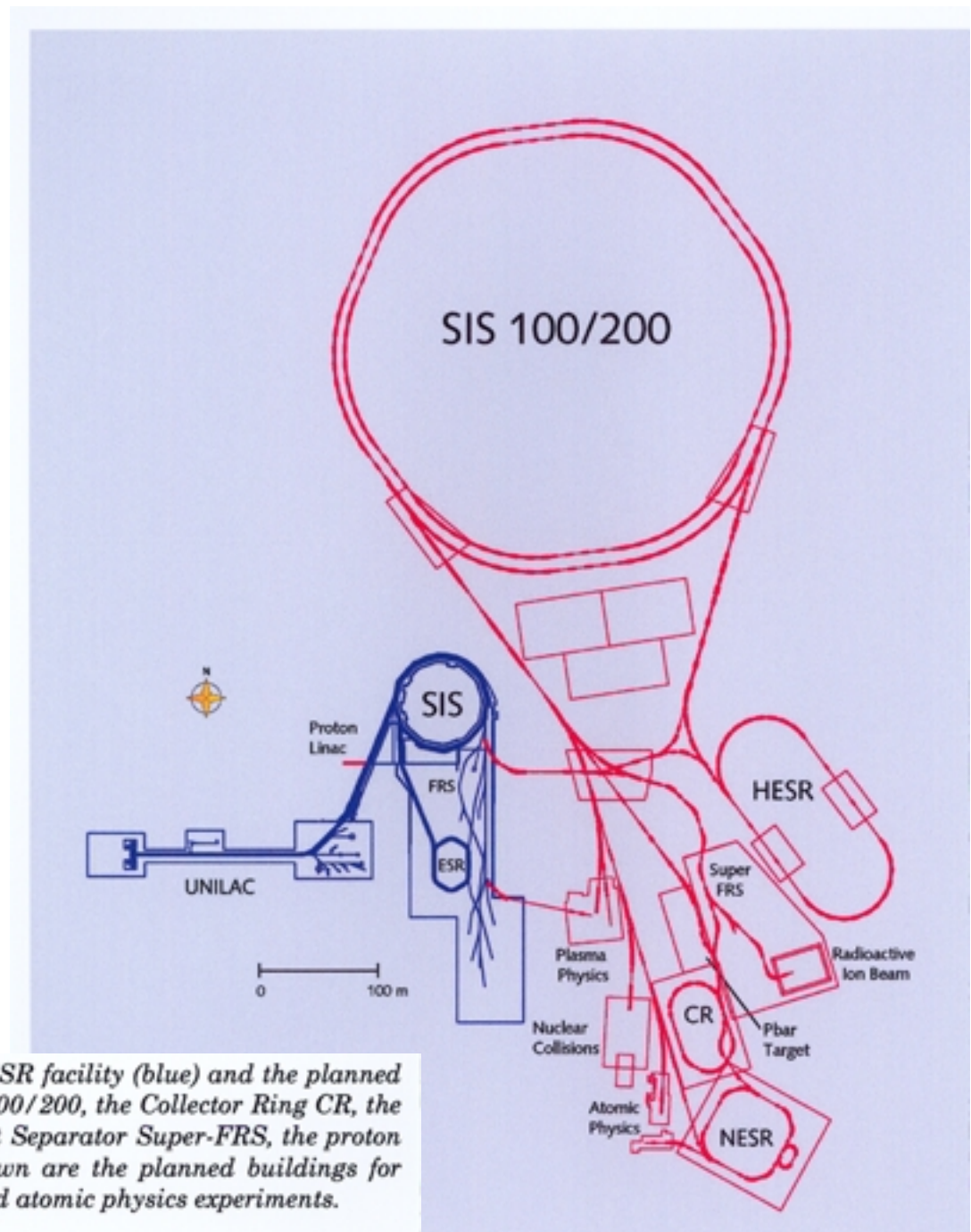


Figure 2.1: Present layout of the existing UNILAC/SIS18/ESR facility (blue) and the planned new facilities (red): the Super-conducting Synchrotrons SIS100/200, the Collector Ring CR, the New Experimental Storage Ring NESR, the Super Fragment Separator Super-FRS, the proton linac, and the High-Energy Storage Ring HESR. Also shown are the planned buildings for plasma physics, nuclear collisions, radioactive ion beams, and atomic physics experiments.

Antiprotonen in Deutschland

Ausbau des GSI (Gesellschaft für Schwerionenforschung) - Beschleunigers in Darmstadt

Werdegang des Projektes

- Push durch eine kleine Gruppe
- Überzeugung der Kollegen
- Letter of Intent (50 Wiss.)
- Vorlage eines Proposals (600 Seiten)
- Begutachtung durch den Wissenschaftsrat (Internat. Gremium)
- Finanzierungszusage durch das bmb+f (25% auswärtige Beteiligung)
- Ausarbeitung eines Detektorkonzepts (>300 Wiss. aus der ganzen Welt): PANDA-Projekt
- Hardware Arbeiten/Simulationen
- Technisches Proposal (Jan. 2005)
- Begutachtung (Peer Review)
- Baubeginn: 2006
- Fertigstellung: 2011/12

Zusammenfassung

- Antimaterie ist nicht so exotisch wie man oft denkt
- Antimaterie lässt sich in mikroskopischen Dosen heute routinemäßig erzeugen
- Antimaterie ist von großem Nutzen in Studien von Teilchenreaktionen und der dabei erwarteten neuen Phänomene