Lehrerfortbildung Elementarteilchenphysik

Physikalisches Institut, Bonn, 05. – 09. Oktober 2015

Teilchenbeschleuniger…

… für die Hochenergiephysik

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Elektronen-Stretcher-Anlage

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Bonn, 05.10.2015

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Teilchenbeschleuniger…

… für die Hochenergiephysik

Inhalt:

- **Einführung:** Beschleunigung: warum und wie
- **Kreisbeschleuniger:** Magnete, Magnete, Magnete, …
- **Strahldynamik:** Erwünschtes und Unerwünschtes
- **Luminosität:** Raumladung, Strahl-Strahl, …
- **Elektronen>100GeV:** Synchrotronstrahlung, LINACs
- **Zukunftsträume:** CLIC, FCC, PWA, …

Warum Beschleuniger?

Fragen der Elementarteilchenphysik:

a. **Was sind die elementaren Bausteine der Materie?**

→ Auflösung kleinster Strukturen:

Photonen: $E = \hbar\omega = hc/\lambda$

Faustformel: **1Å ≈ 12345 eV** ↔

$$\Delta x \geq \lambda$$

$$\Delta x[\mathrm{fm}] \approx \frac{1{,}2}{E[\mathrm{GeV}]}$$

b. **Wie wechselwirken sie miteinander?**

Eichbosonen und Higgs:

W ≈ 80,4 GeV

Z ≈ 91,2 GeV

H ≈ 125 GeV

Schwere Quarks:

c ≈ 1,3 GeV

b ≈ 4,2 GeV

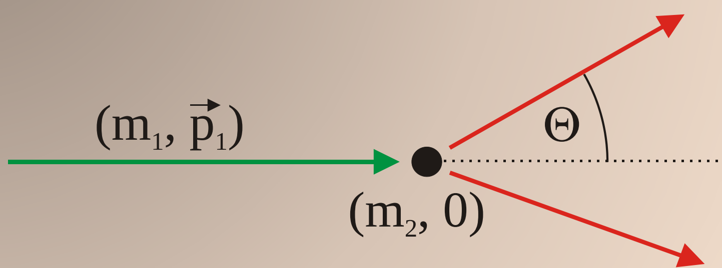
t ≈ 173,5 GeV

$E > 1$ TeV ↔ Terascale ↔ „sub"-Attoscale

Collider

(Hochenergie-Einheiten: $\hbar = c = 1$)

Fixed-Target-Experiment

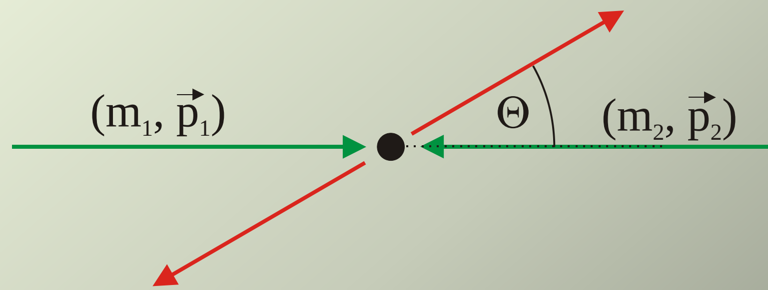


$$S = P_1 + P_2 = (E_1 + m_2, \vec{p}_1 + \vec{p}_2)$$

$$\vec{\beta}_{CMS} = \frac{\vec{p}_1}{E_1 + m_2}$$

$$M_{inv}{}^2 = S^2 = 2E_1 m_2 + m_1{}^2 + m_2{}^2$$

Kollidierende Strahlen



$$S = P_1 + P_2 = (E_1 + E_2, \vec{p}_1 + \vec{p}_2)$$

$$\vec{\beta}_{CMS} = \frac{\vec{p}_1 + \vec{p}_2}{E_1 + E_2} = 0$$

$$M_{inv}{}^2 = S^2 = (E_1 + E_2)^2$$

Beispiel: p-p Kollisionen, wollen *S* = 1 TeV

benötigen:

***E* = 500 TeV** | ***E* = 0,5 TeV**

Beschleunigung:

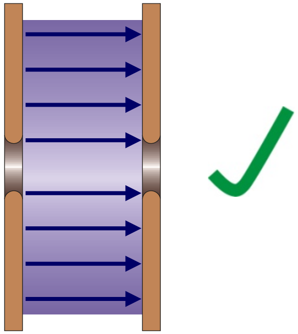
Beeinflussung geladener Teilchen durch die Lorentz-Kraft:

$$\vec{F} = e \cdot \vec{E} + e \cdot \left(\vec{v} \times \vec{B} \right)$$

Energiegewinn: $\Delta W_{kin} = \int \vec{F} \cdot d\vec{s} = e \cdot \int E_{\parallel} \cdot ds = e \cdot U$

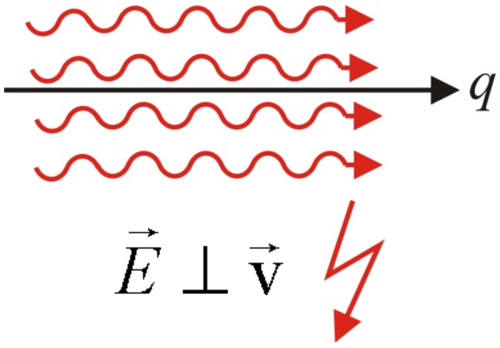
→ brauchen ein longitudinales elektrisches Feld $E_{\parallel}$!

Kondensator:



Lichtstrahl:

(TEM)

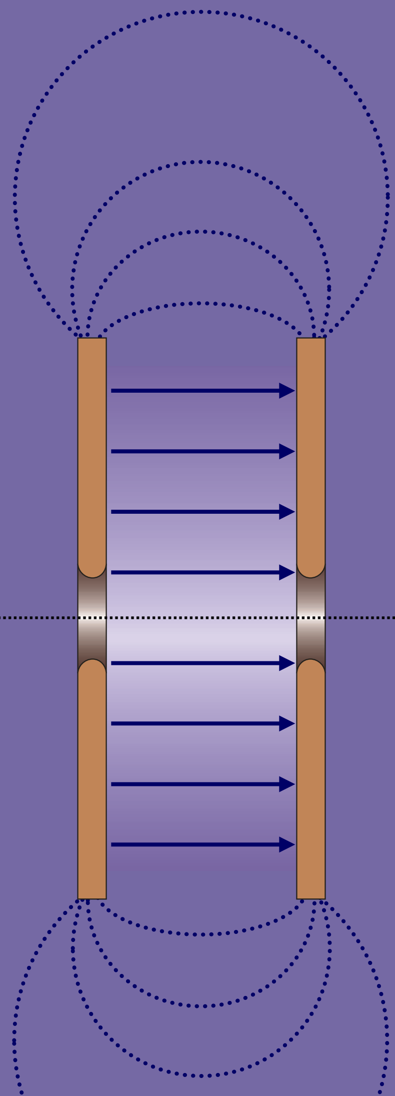


$\vec{E} \perp \vec{v}$

Statische Felder

$\Delta W = e \cdot U$

Einheit eV



Wir brauchen

$E \geq 1\ \text{TeV} = 10^{12}\ \text{eV}$

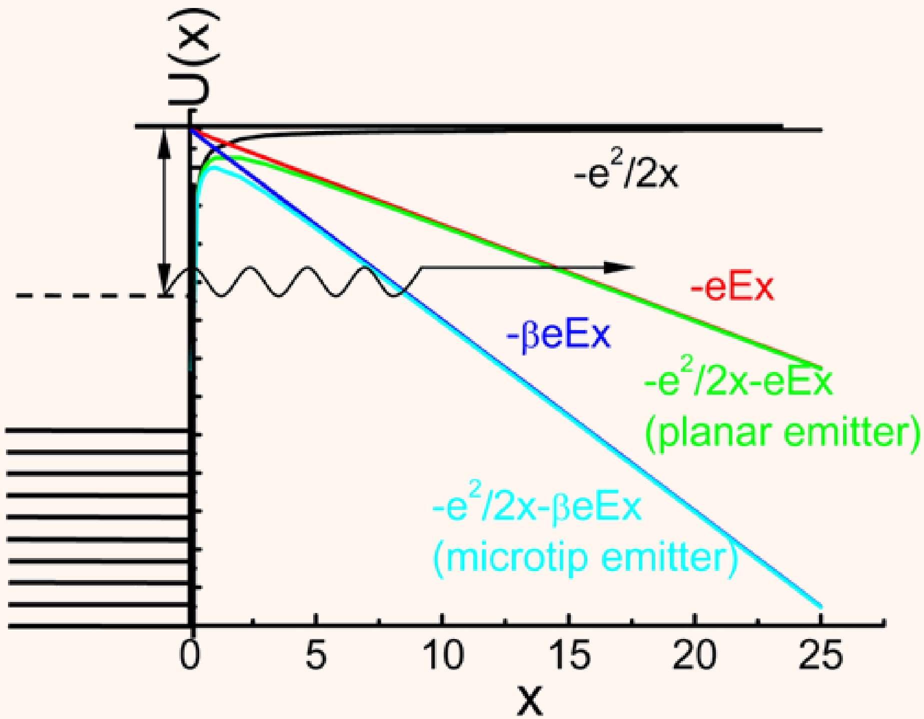
Feldemission:

Coulomb-Potential:

$$U = \int \vec{F} \bullet d\vec{s} = \frac{q^2}{4\pi\varepsilon_0} \int \frac{ds}{r^2} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{-q^2}{2r}$$

homogenes E-Feld:

$$U = \int \vec{F} \bullet d\vec{s} = \int q\vec{E} \bullet d\vec{s} = -qEr$$

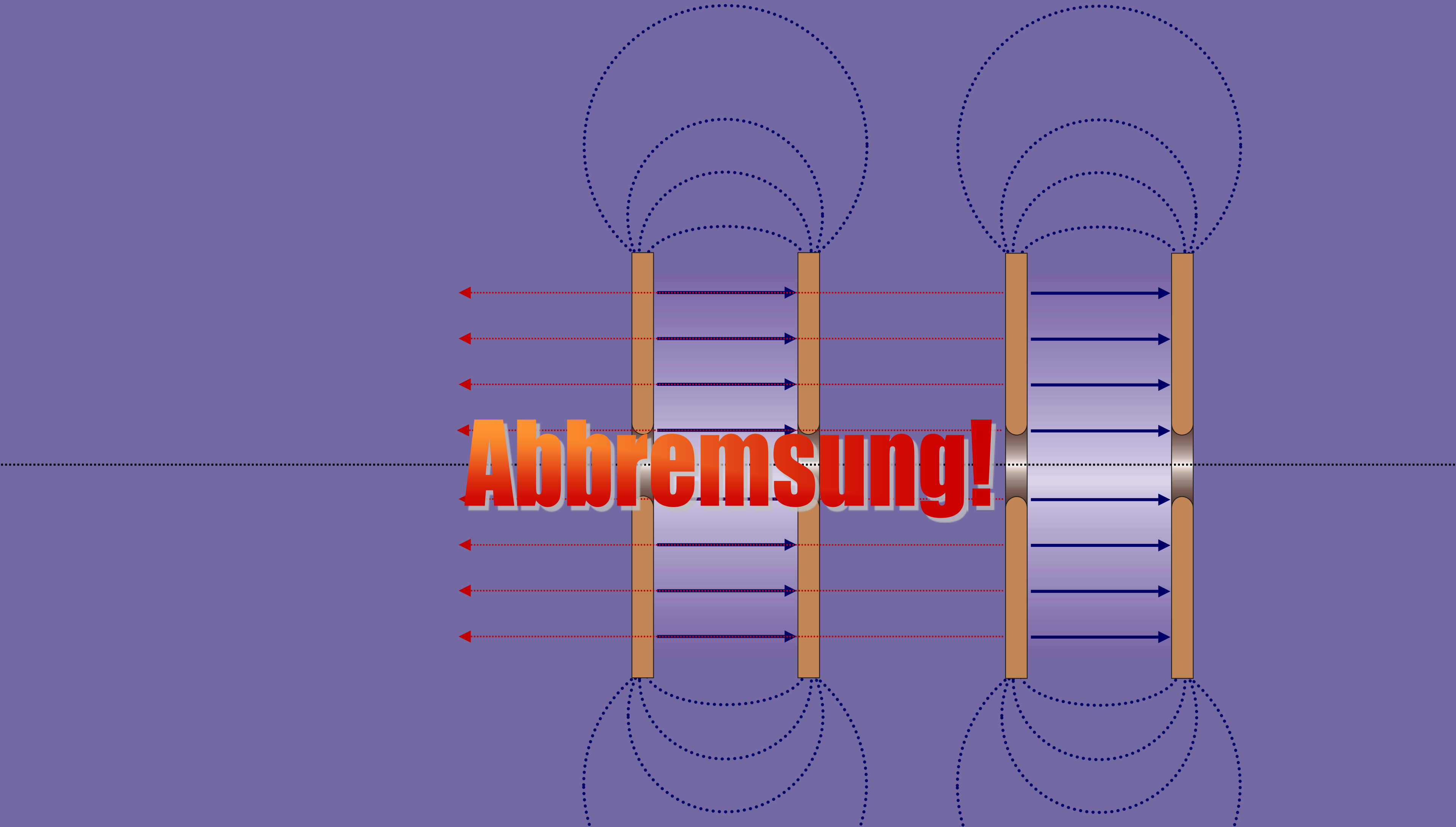


Tunneleffekt!

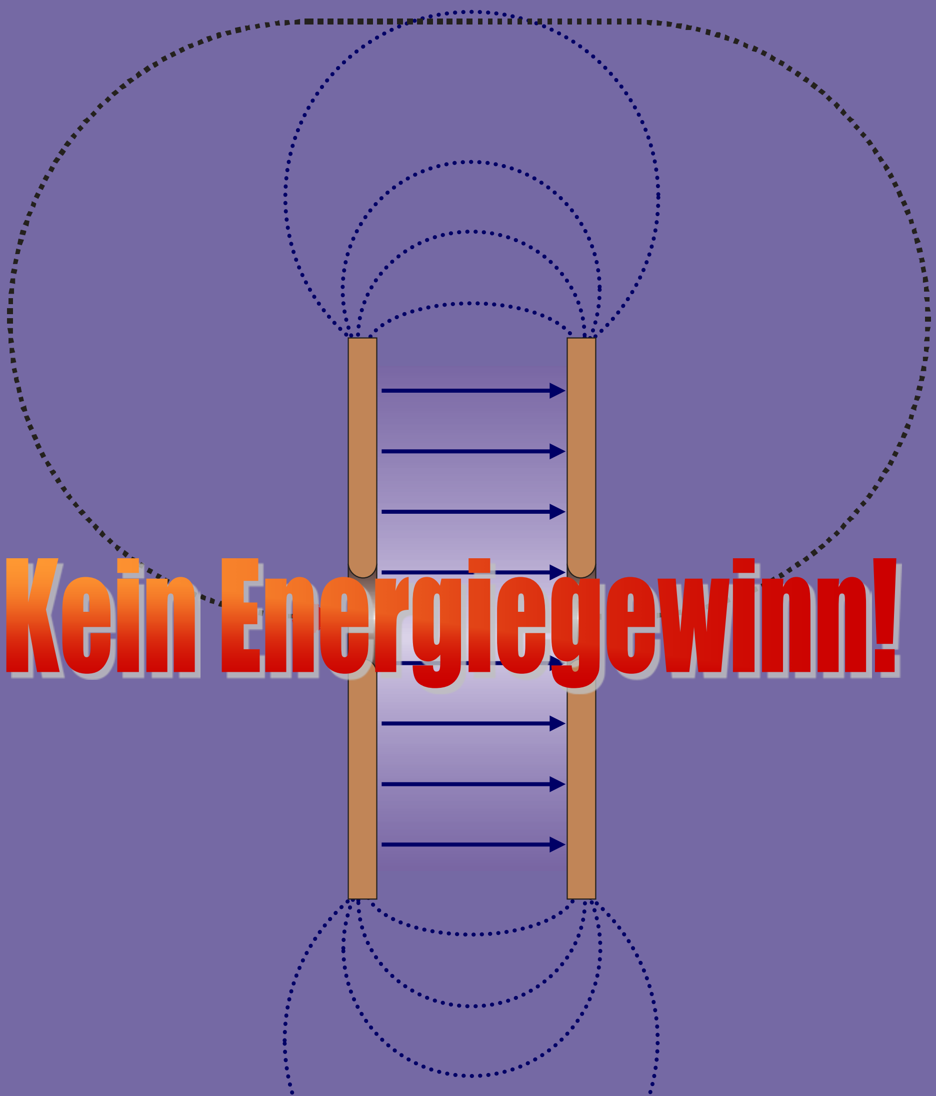
Überhöhungs-faktor β!

$E \leq$ **10 - 100 MV/m**

Statische Felder

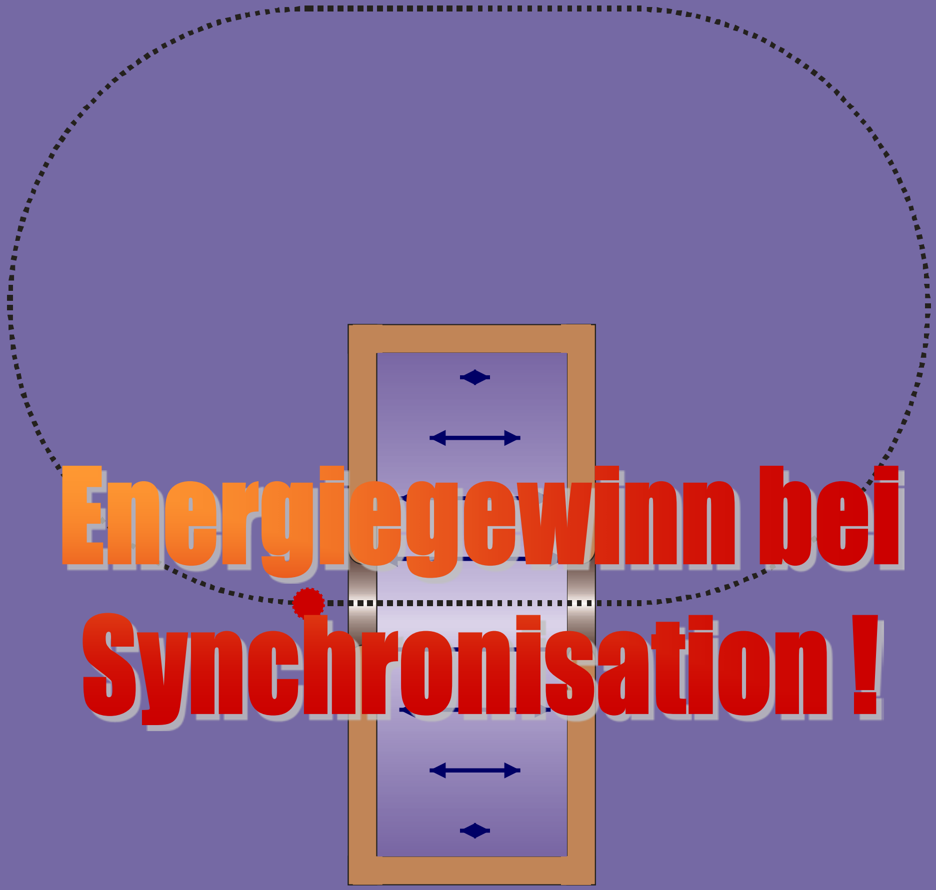


Statische Felder



$$\oint \vec{E} \bullet d\vec{s} = 0$$

HF – Wechselfelder

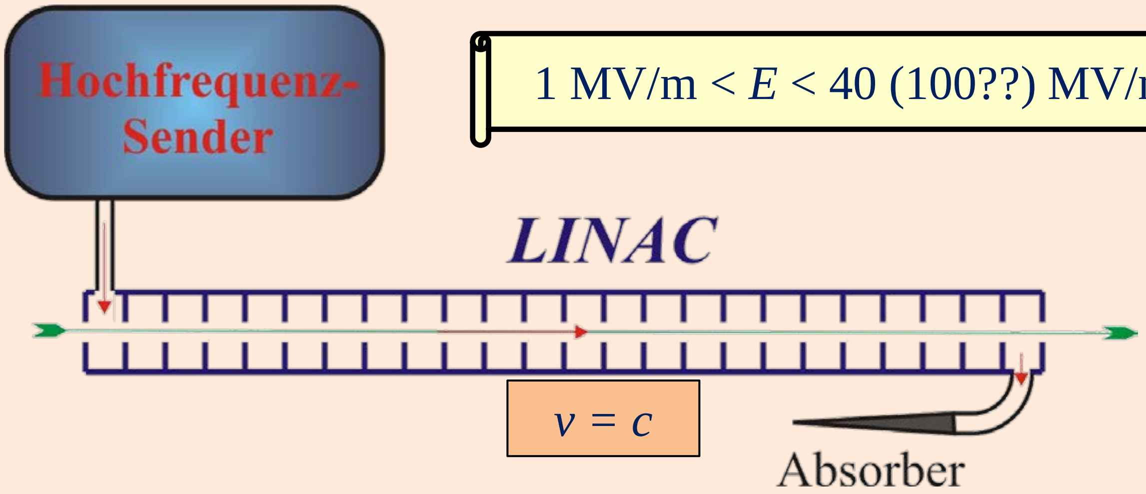


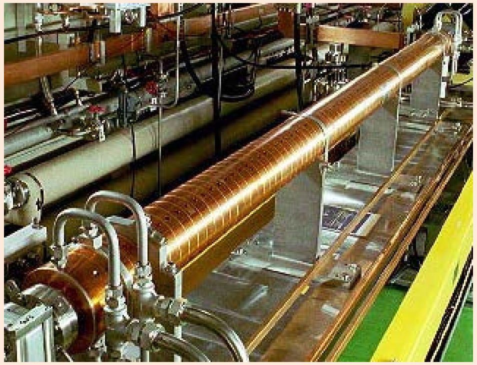
Energiegewinn bei Synchronisation !

Geradeaus?

Elektronen:

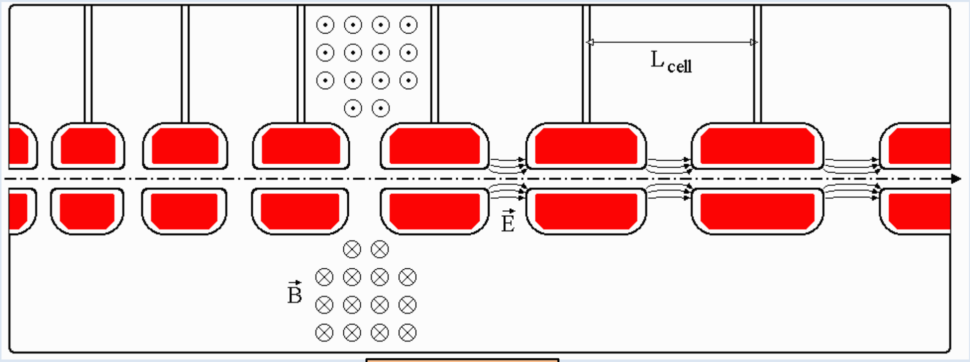
1 MV/m < E < 40 (100??) MV/m





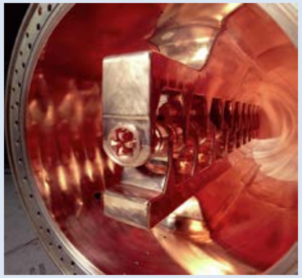
1 TeV ↔ L > 50 km

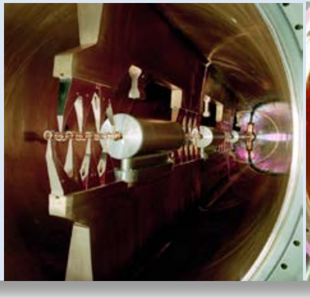
Protonen / Ionen:

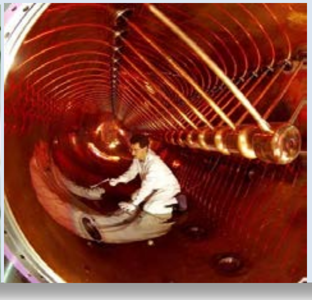


$v << c$

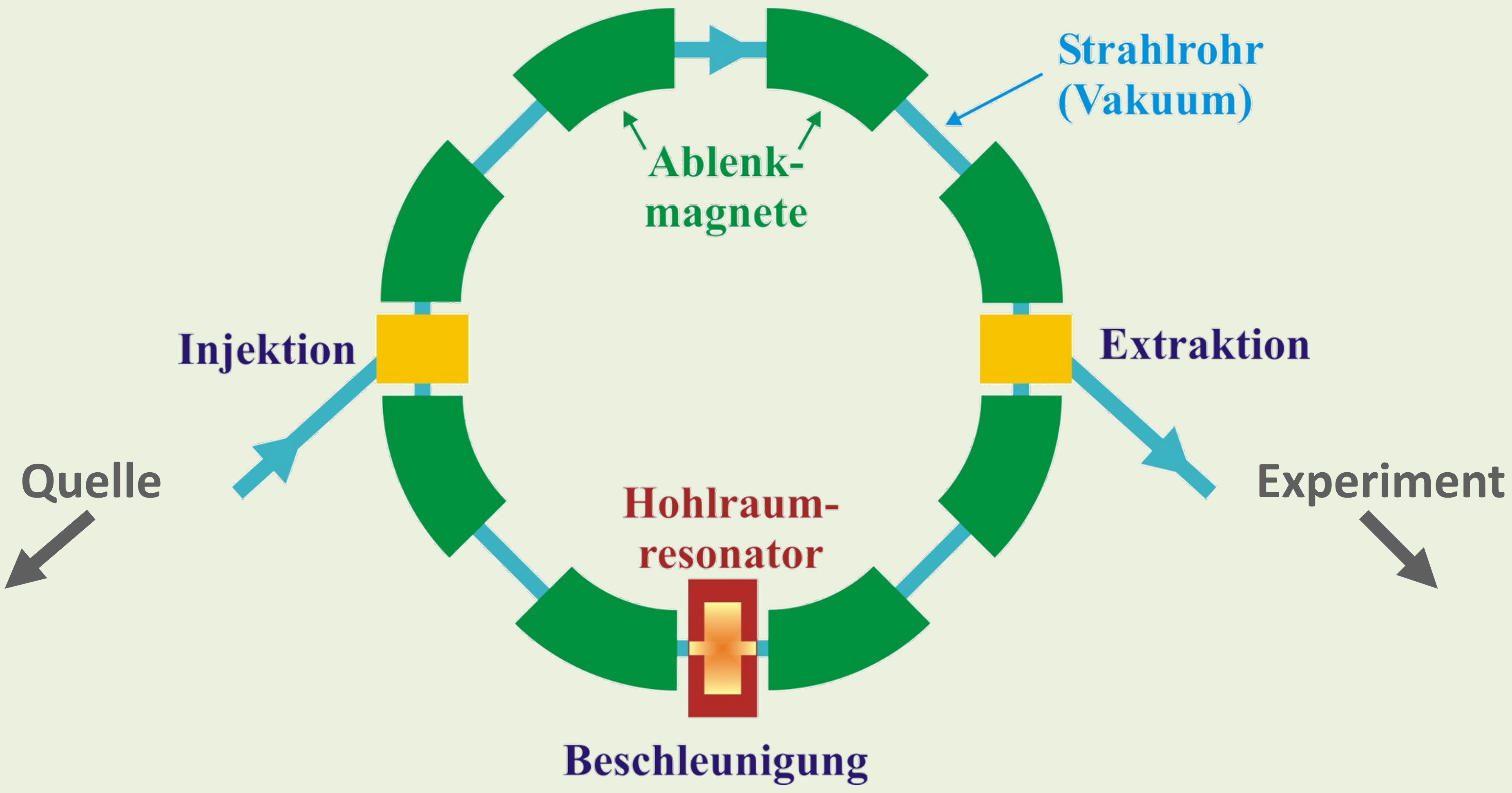
E_{avg} < 25 MV/m







Kreisbeschleuniger

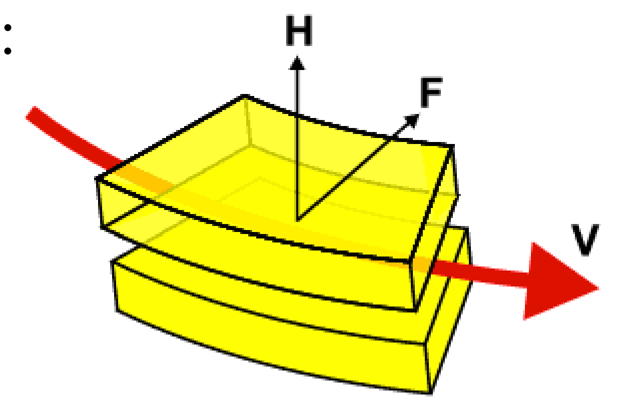


Strahlablenkung

Lorentzkraft: $\vec{F} = e \cdot \left(\vec{E} + \underline{\underline{\vec{\mathrm{v}}}} \times \vec{B} \right)$ $\longrightarrow$ **Magnetfelder**

Kreisbahn $\leftrightarrow$ homogenes Magnetfeld:

$$\frac{m\mathrm{v}^2}{R} = e \cdot \mathrm{v} \cdot B_z \quad \Rightarrow \quad \frac{1}{R} = \frac{e}{p} \cdot B_z$$

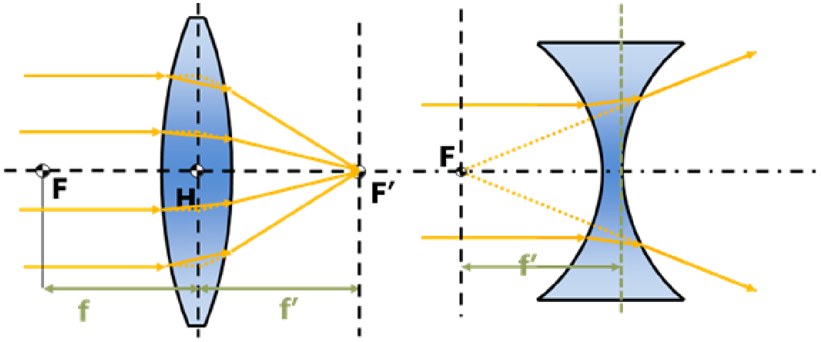


Wichtige Größen:

- Dipolstärke: $\boldsymbol{\kappa = 1/R}$, $[\kappa] = \mathrm{m}^{-1}$ (Krümmung)
- Magn. Steifigkeit: $\boldsymbol{BR = p/e \approx E/c}$ (ultrarelativistisch!)
- Strahlenergie: $p = \frac{e}{2\pi} \cdot \oint B_z \cdot dl$

Strahlfokussierung

Linse (Lichtoptik):

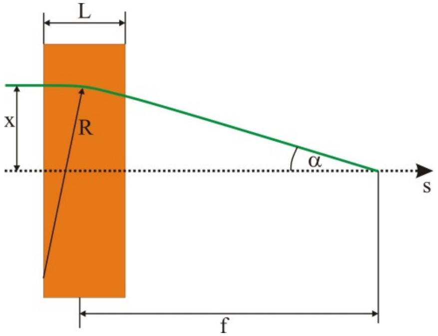


Ablenkung nimmt linear mit Abstand von der optischen Achse zu!

$$\vec{F} = e \cdot \vec{v} \times \vec{B} \quad \Rightarrow \quad B_z = g \cdot x, \quad B_x = g \cdot z, \quad g = \frac{\partial B_z}{\partial x}$$

<u>Wichtige Größen:</u>

- Quadrupolstärke: $\boldsymbol{k = e/p \cdot g}$, $[k] = \mathrm{m}^{-2}$
- Brennweite: $\boldsymbol{1/f \approx k \cdot L}$



$$\frac{x}{f} = \tan\alpha = \frac{L}{R} = L \cdot \frac{e}{p} B_z = \frac{e}{p} g\, x L = x k L$$

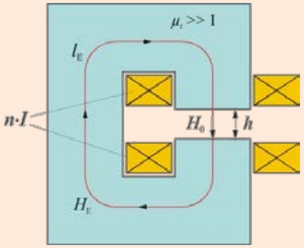
Höhere Ordnungen:

Taylorentwicklung des Magnetfeldes:

$$B_z(x) = \underbrace{B_0}_{\text{Dipol}} + \underbrace{\frac{\partial B_z}{\partial x}}_{\text{Quadrupol}} \cdot x + \frac{1}{2}\underbrace{\frac{\partial^2 B_z}{\partial x^2}}_{\text{Sextupol}} \cdot x^2 + \frac{1}{6}\underbrace{\frac{\partial^3 B_z}{\partial x^3}}_{\text{Oktupol}} \cdot x^3 + \ldots$$

Definition eines skalaren magnetischen Potentials:

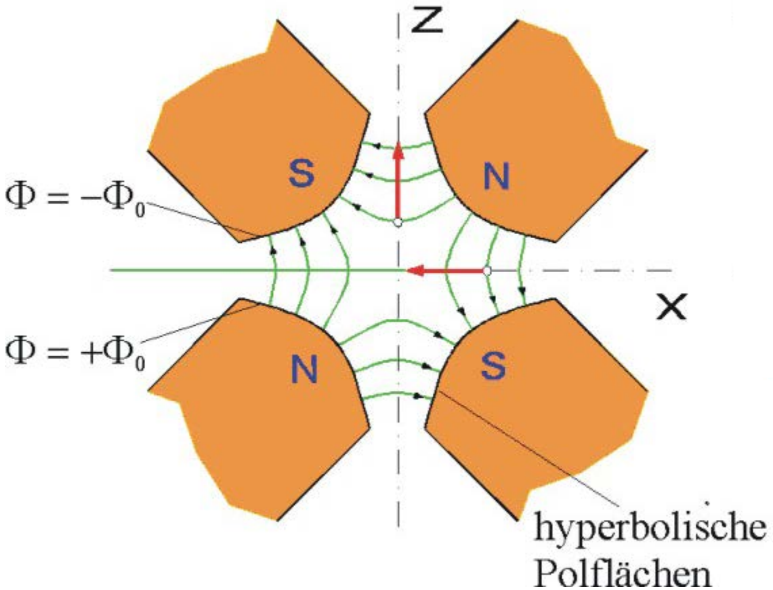
$$\vec{\nabla} \times \vec{B} = \mu_0 \cdot \vec{j} = 0 \quad \Rightarrow \quad \vec{B} = \vec{\nabla}\Phi$$



- Dipol: $-\frac{e}{p} \cdot \Phi_1 = \kappa_z x - \kappa_x z$
- Quadrupol: $-\frac{e}{p} \cdot \Phi_2 = -1/2\, \underline{k}\left(x^2 - z^2\right) + k\, x\, z$
- Sextupol: $-\frac{e}{p} \cdot \Phi_3 = -1/6\, \underline{m}\left(x^3 - 3\, x\, z^2\right) + 1/6\, m\left(3\, x^2\, z - z^3\right)$
- …

Strahlfokussierung

Quadrupolmagnet:



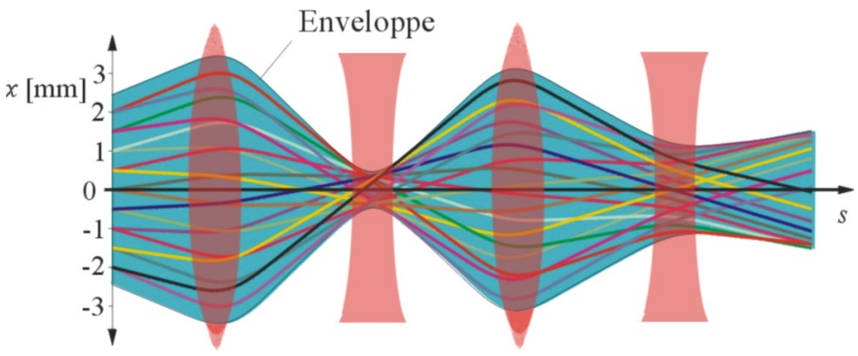
$$\Phi = -g \cdot x \cdot z$$

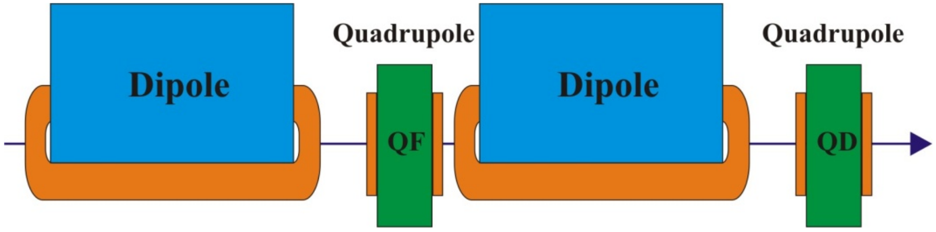
$$\vec{B} = g \cdot \left(x\hat{e}_z + z\hat{e}_x \right)$$

$$\vec{F} = e \cdot \left(\vec{v} \times \vec{B} \right) = e v g \cdot \left(x\hat{e}_x - z\hat{e}_z \right)$$

Starke Fokussierung:

(Courant, Livingston und Snyder, 1952)

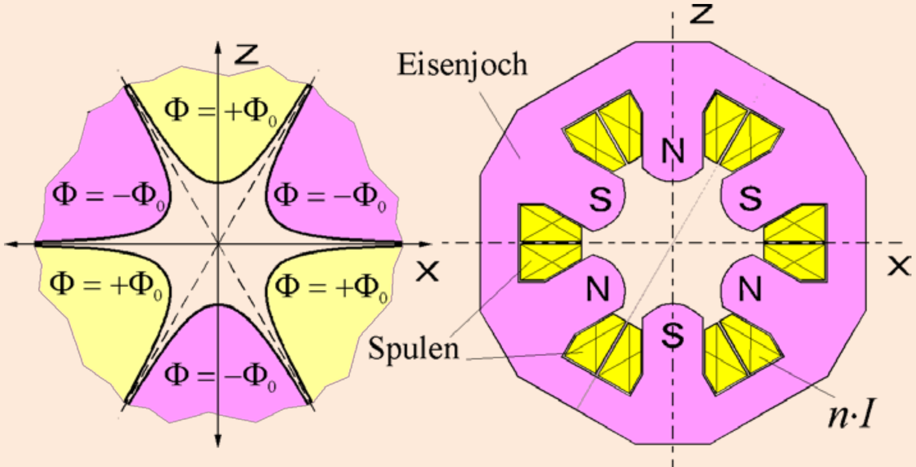




Einfachste Anordnung: FODO

Farbkorrektur

Sextupolmagnet:

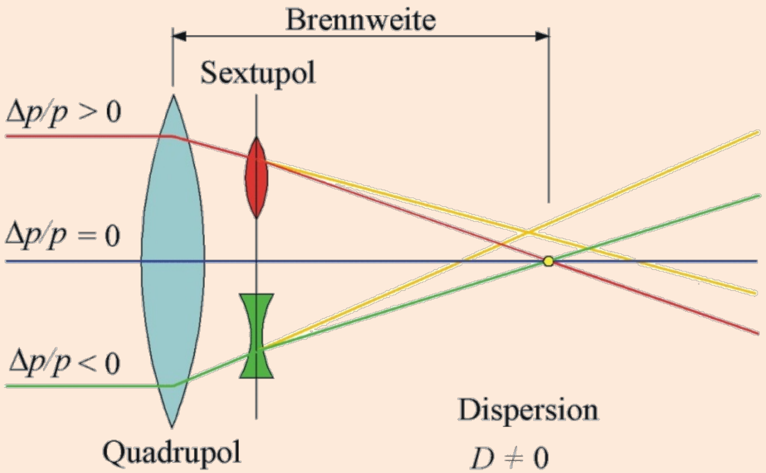


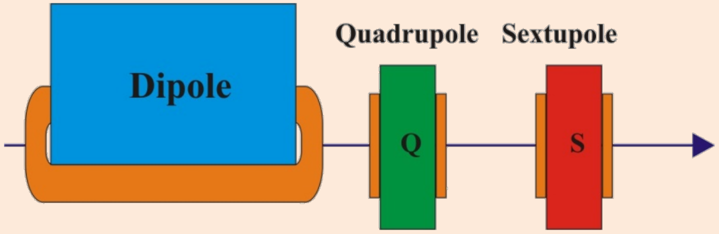
$$\Phi(x,z) = -\frac{1}{6} g'\left(z^3 - 3x^2 z\right)$$

$$\vec{B} = g'\left\{x z \cdot \hat{e}_x + \frac{1}{2}\left(x^2 - z^2\right) \cdot \hat{e}_z\right\}$$

$$\vec{F} = evg'\left\{\frac{1}{2}\left(x^2 - z^2\right) \cdot \hat{e}_x - x z \cdot \hat{e}_z\right\}$$

Brennweitenkorrektur:



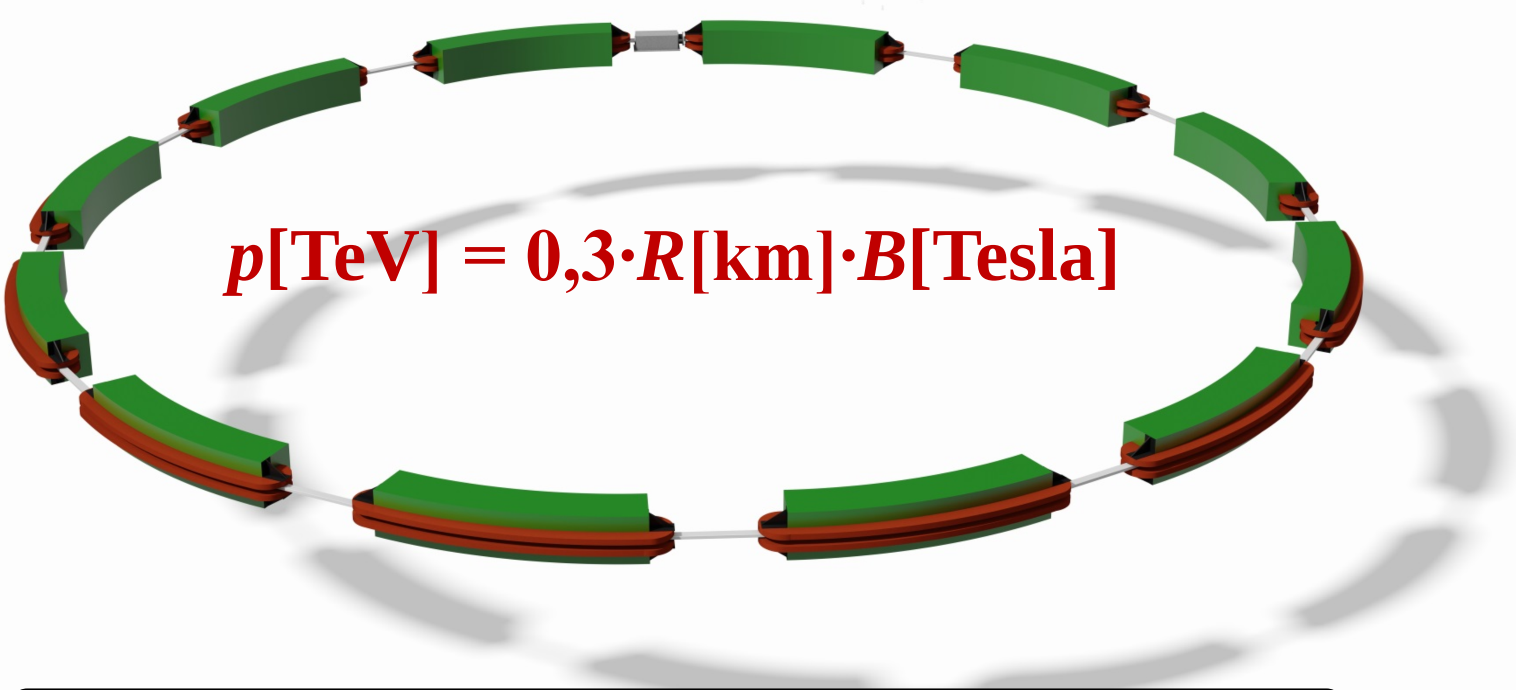


Eisen-Magnete

Ablenkung	**Fokussierung**	**Farbkorrektur**
Dipolmagnete	Quadrupolmagnete	Sextupolmagnete

Eigenschaften definiert durch Polschuhe!
Maximal erreichbare Felder: B < 2,5 Tesla

Protonen-Beschleuniger

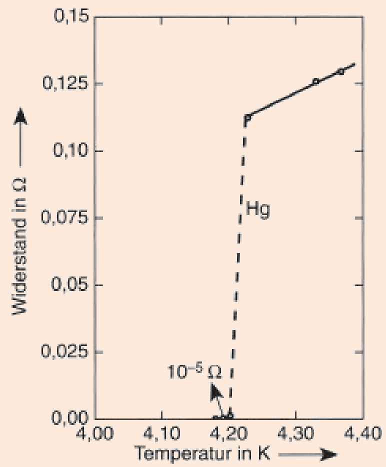


$$p[\text{TeV}] = 0{,}3 \cdot R[\text{km}] \cdot B[\text{Tesla}]$$

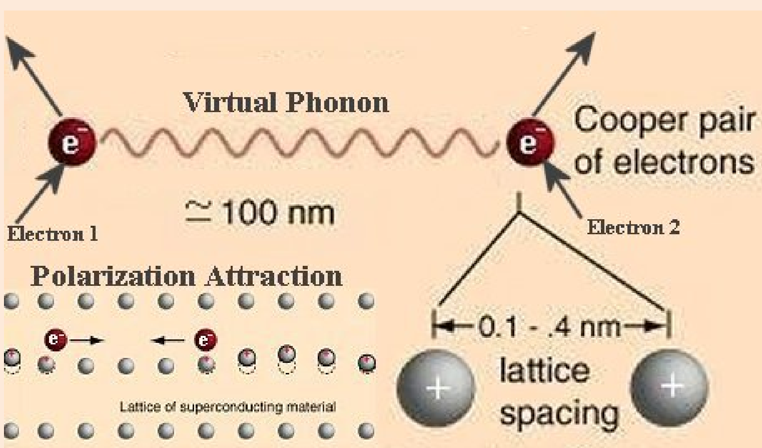
7 TeV @ 2 Tesla $\rightarrow$ R = 11,6 km $\leftrightarrow$ L > 80 km

Supraleitung

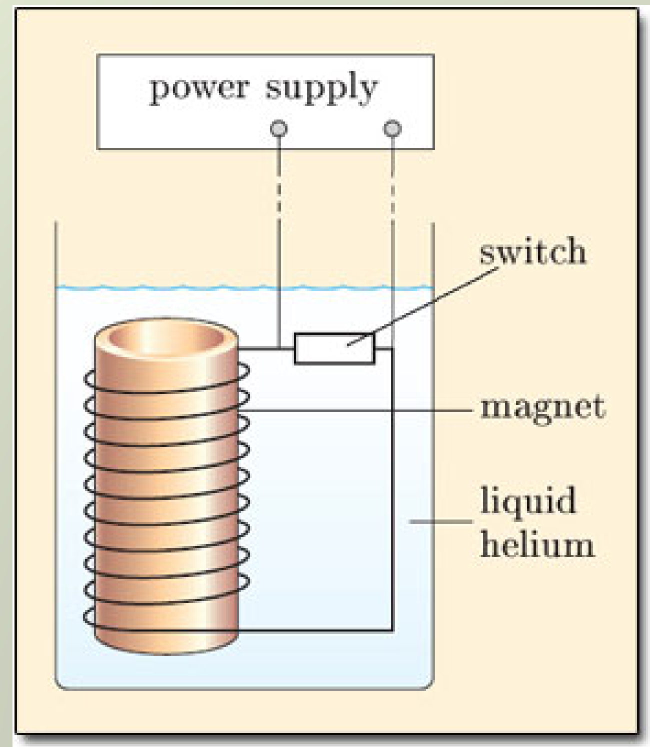
8. April 1911: Entdeckung der Supraleitung durch Heike Kamerlingh Onnes



Unterhalb von T_C kein DC-Widerstand
Grund: Bildung von Cooper-Paaren:

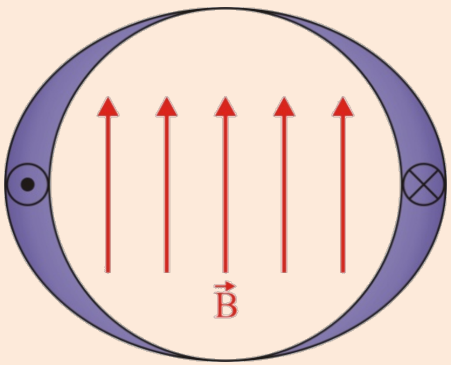


→ **<u>„Verlustfreie“ Magnete:</u>**



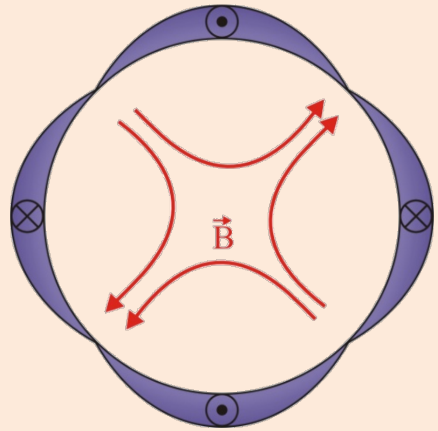
Supraleitende Magnete

Dipol



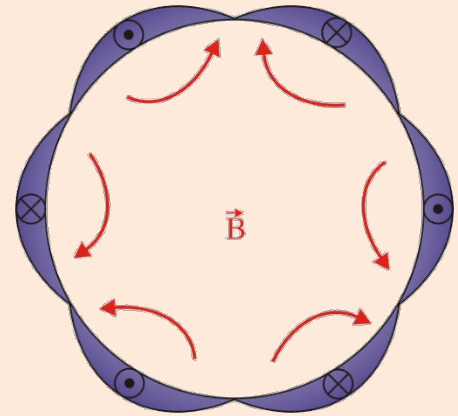
$$I(\varphi) = I_0 \cdot \cos\varphi$$

Quadrupol



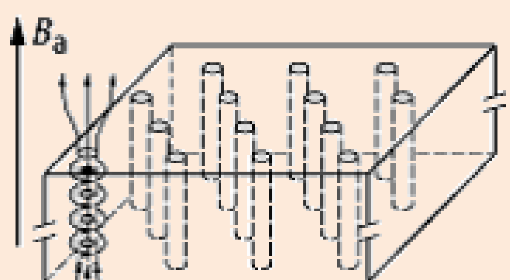
$$I(\varphi) = I_0 \cdot \cos 2\varphi$$

Sextupol



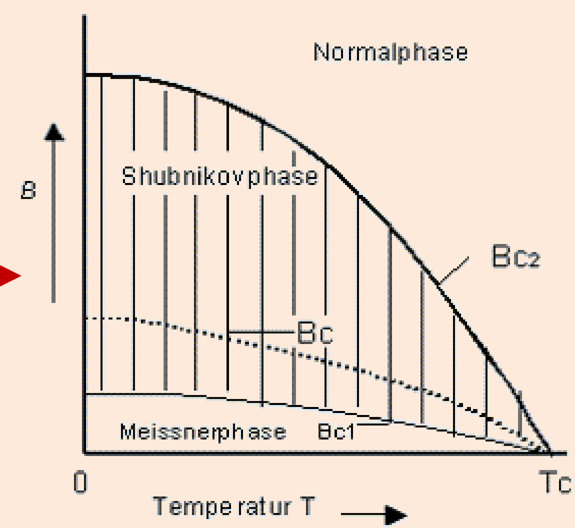
$$I(\varphi) = I_0 \cdot \cos 3\varphi$$

Typ II Supraleiter e.g. Nb_3Sn →

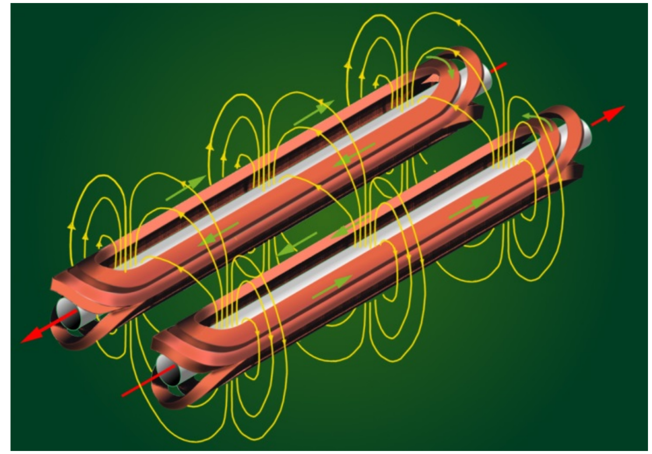


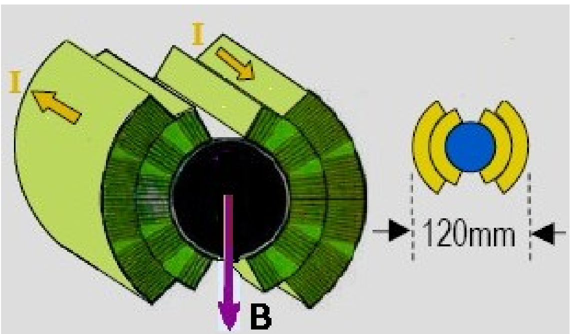
"flux pinning"

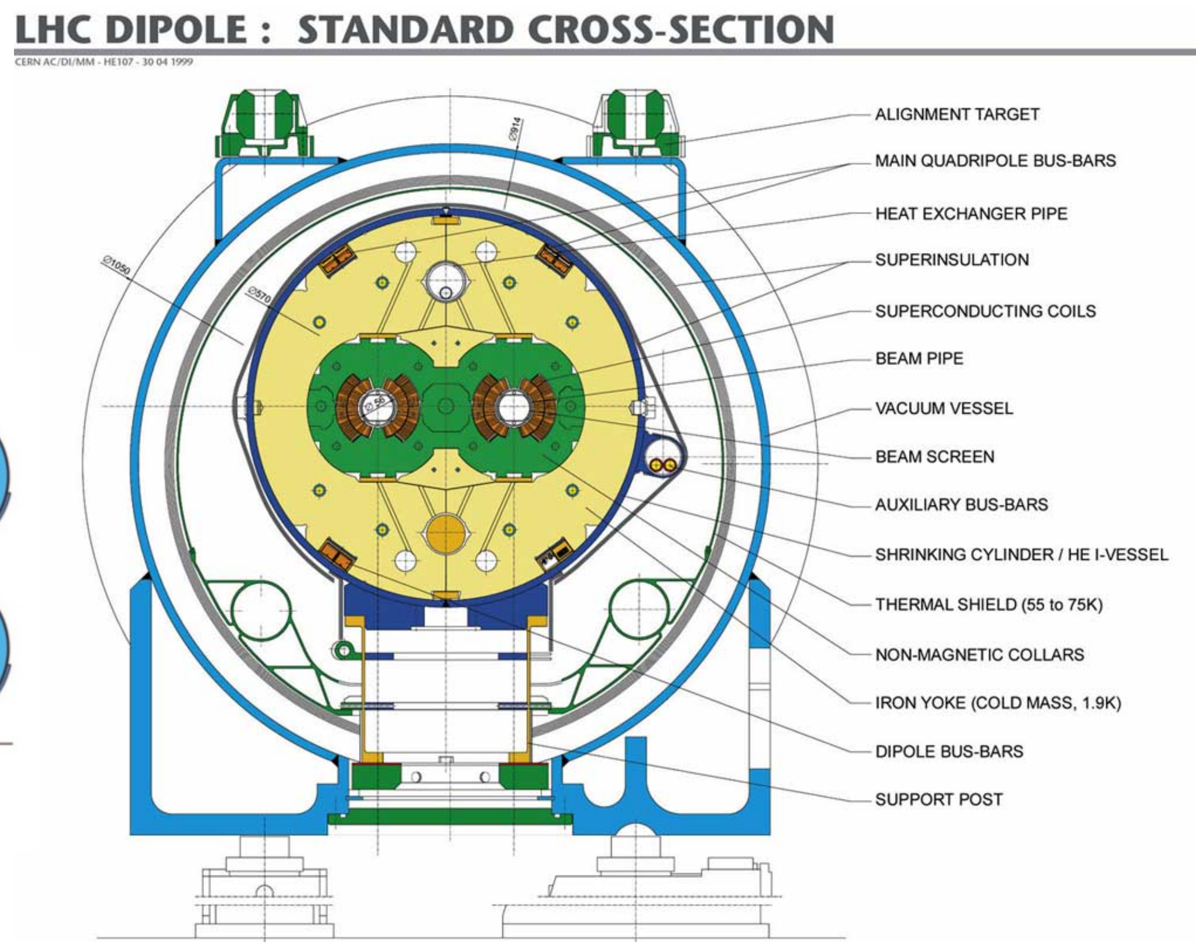
→

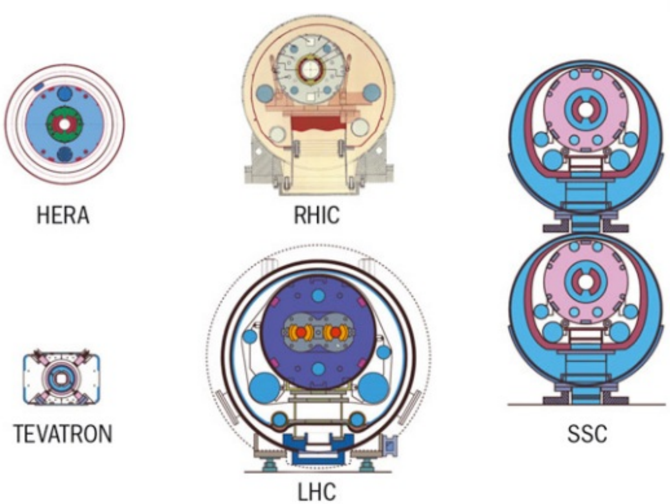


SC Dipolmagnete









LHC Dipolmagnete:

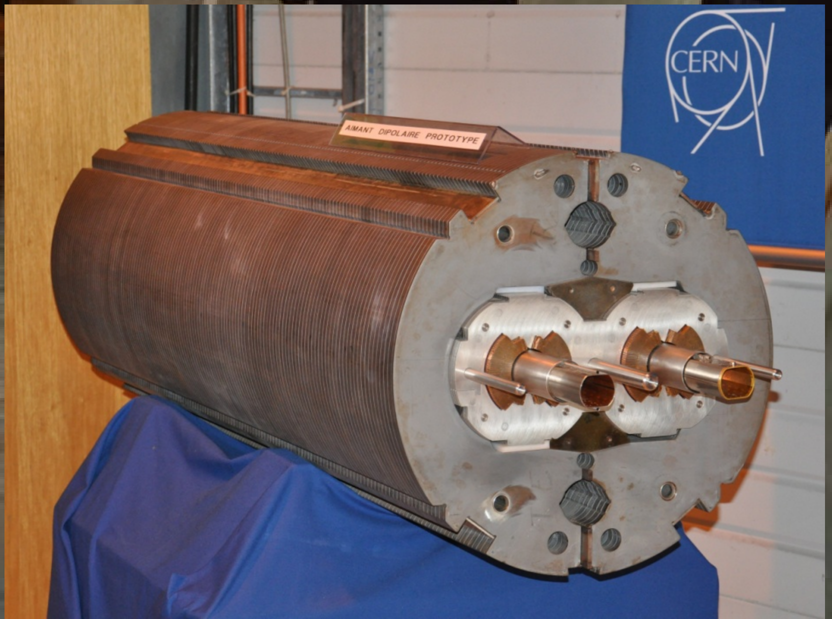
E_{max} = 7 TeV ↔ B_{max} = 8.33 T

He-Temperatur: T = 1.9 K

nom. Strom: I = 11850A @ 8.33T

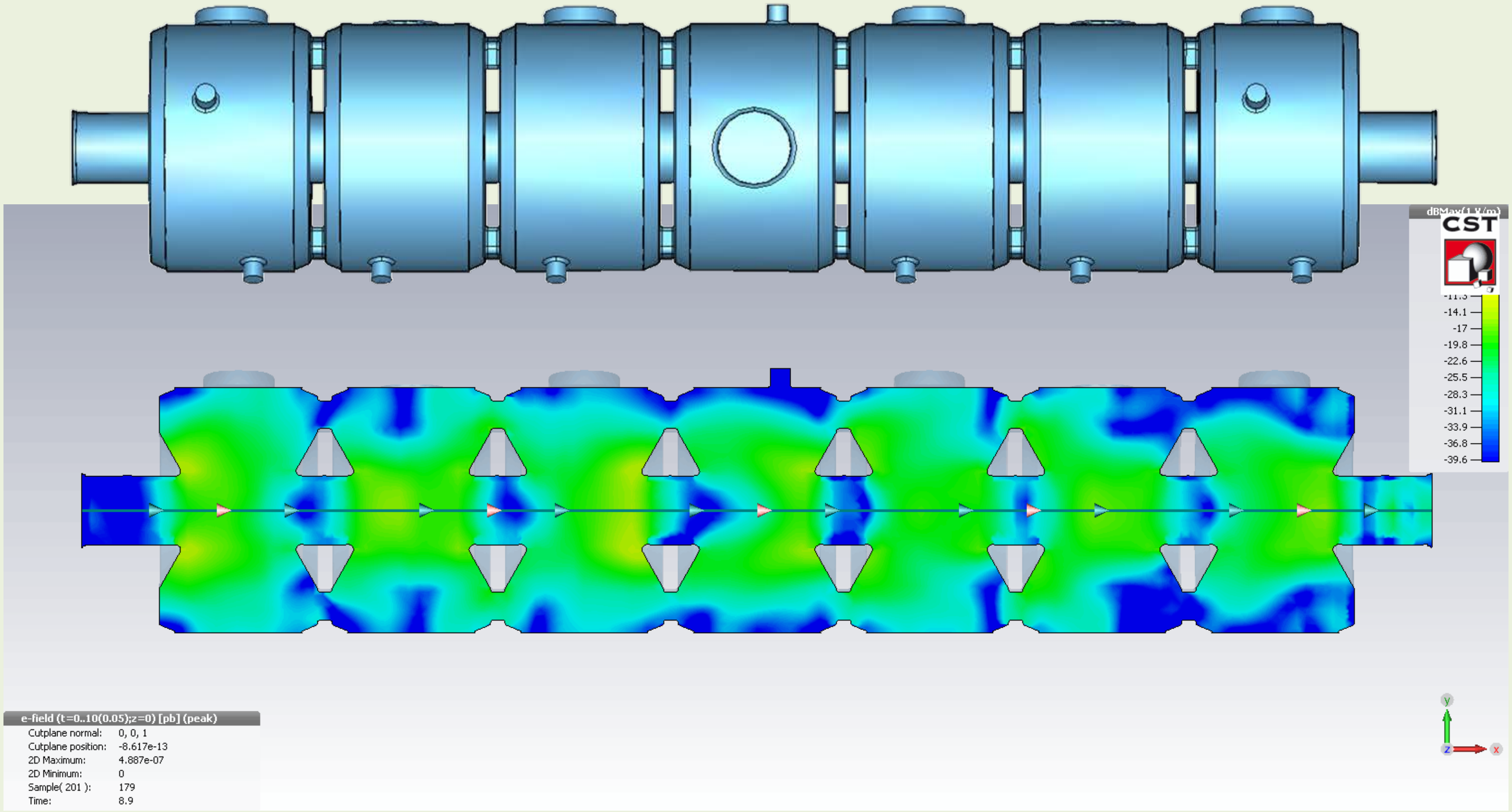
krit. Strom: I = 13750A @ 1.9 K

gespeicherte Energie: W = 11 GJ

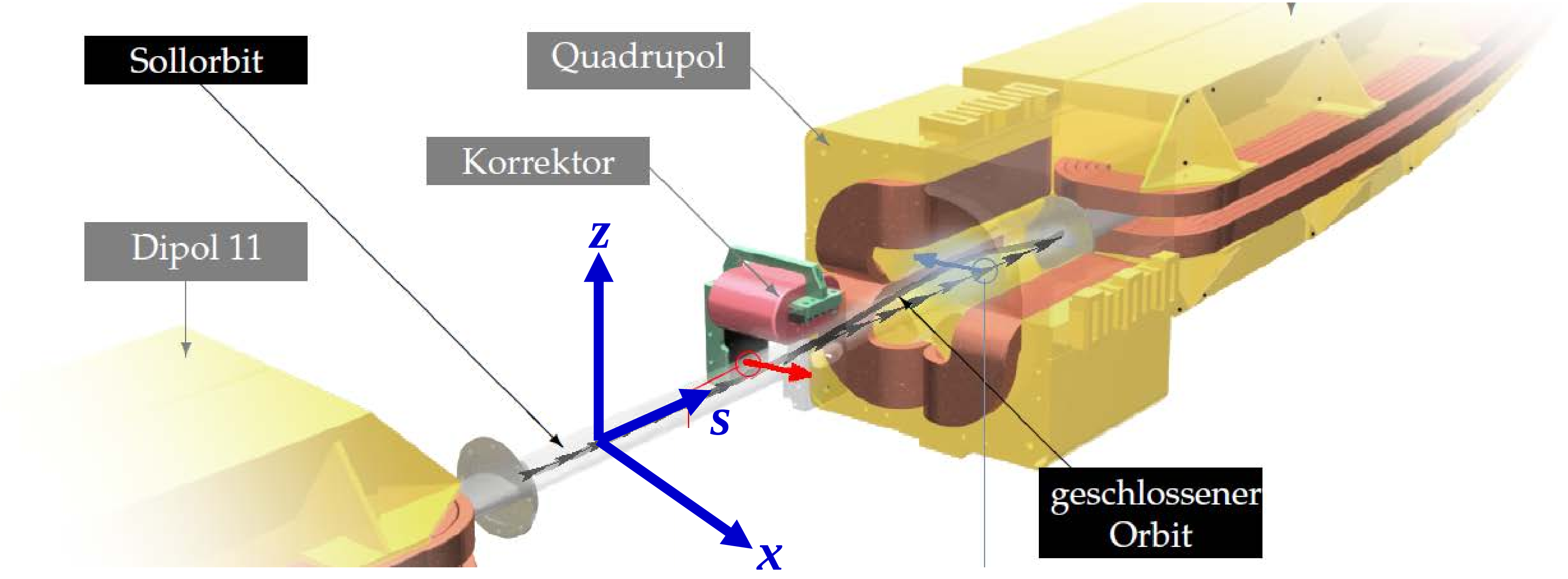


Strahldynamik

Bsp.: Teilchenpaket im PETRA Beschleunigungsresonator:



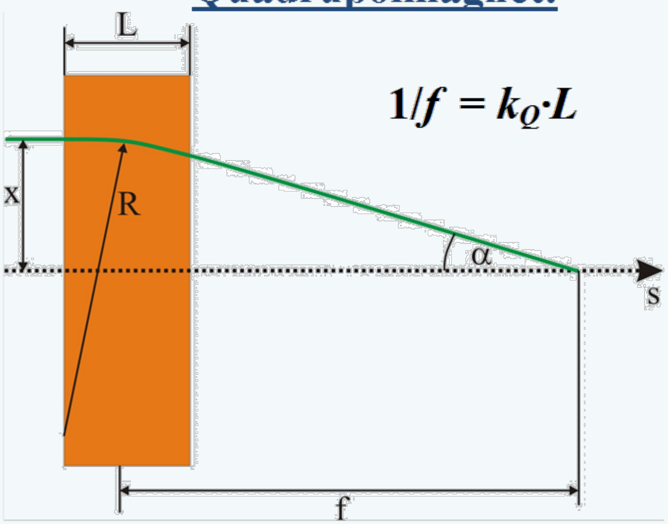
Teilchenbahnen



Mitbewegtes Koordinatensystem, an Sollteilchen angeheftet

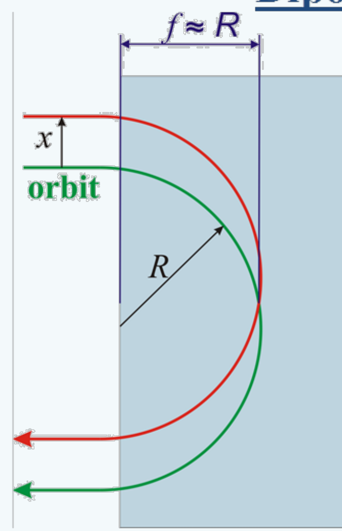
Bewegungsgleichung

Quadrupolmagnet:



$$\vec{F}_{mag} = m \cdot (\beta c)^2 \cdot k \cdot (x\hat{e}_x - z\hat{e}_z)$$

Dipolmagnet:



Fokussierung analog zum Quadrupol:

$1/f = k_D \cdot L$

$k_D = 1/R^2$

$$\vec{F}_{mag} = -m \cdot (\beta c)^2 \cdot \frac{1}{R^2} x\hat{e}_x$$

⇓

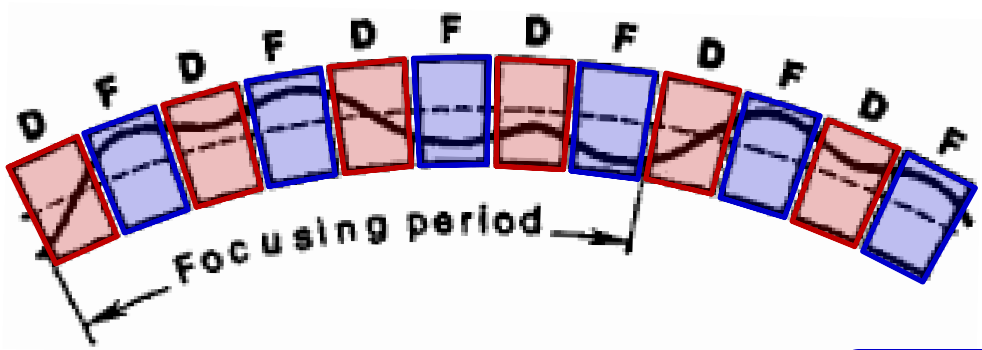
$$m \cdot \ddot{\vec{x}}(t) = m \cdot (\beta c)^2 \cdot \vec{x}''(s) = \vec{F}_{mag}$$

⇒ **Hillsche Differentialgleichung**

$$x''(s) + \left(\frac{1}{R^2(s)} - k(s)\right) \cdot x(s) = \frac{1}{R(s)} \frac{\Delta p}{p}$$

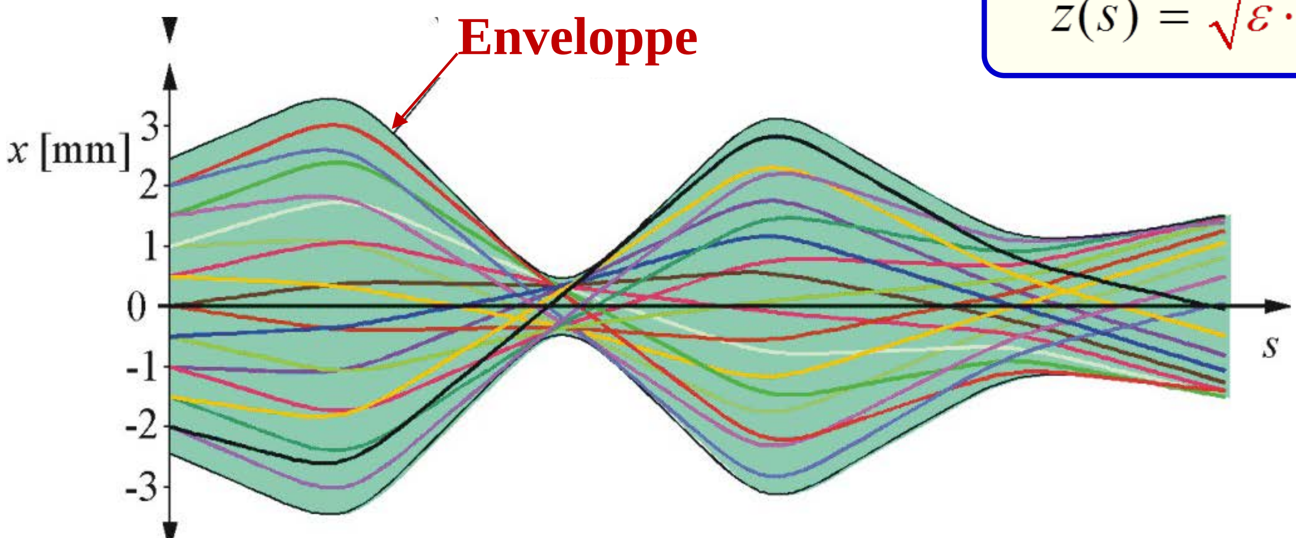
$$z''(s) + k(s) \cdot z(s) = 0$$

Betatron-Oszillationen



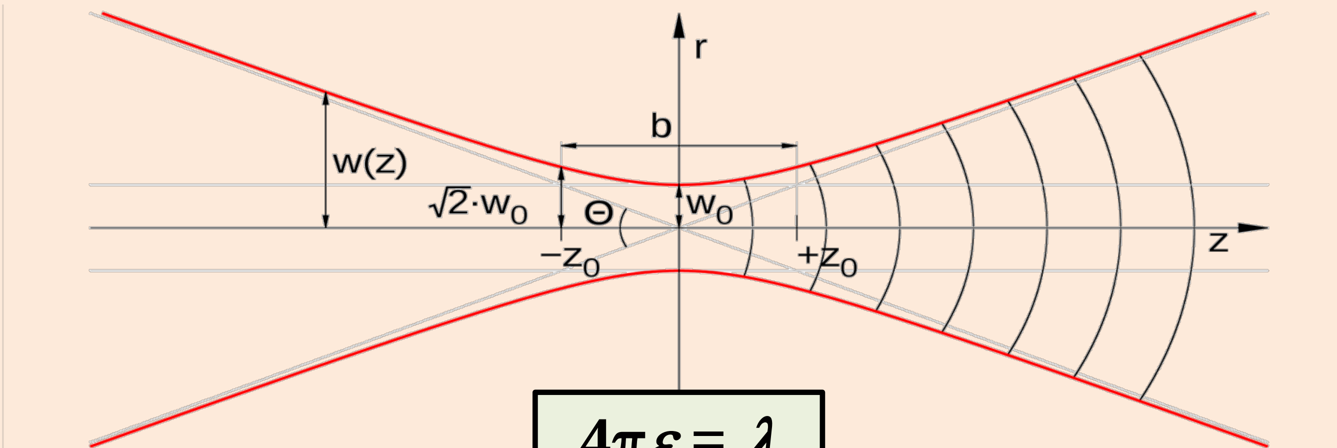
$$z''(s) + k(s) \cdot z(s) = 0$$

$$z(s) = \sqrt{\varepsilon \cdot \beta_z(s)} \cdot \cos\left(\phi(s) + \varphi_0\right)$$

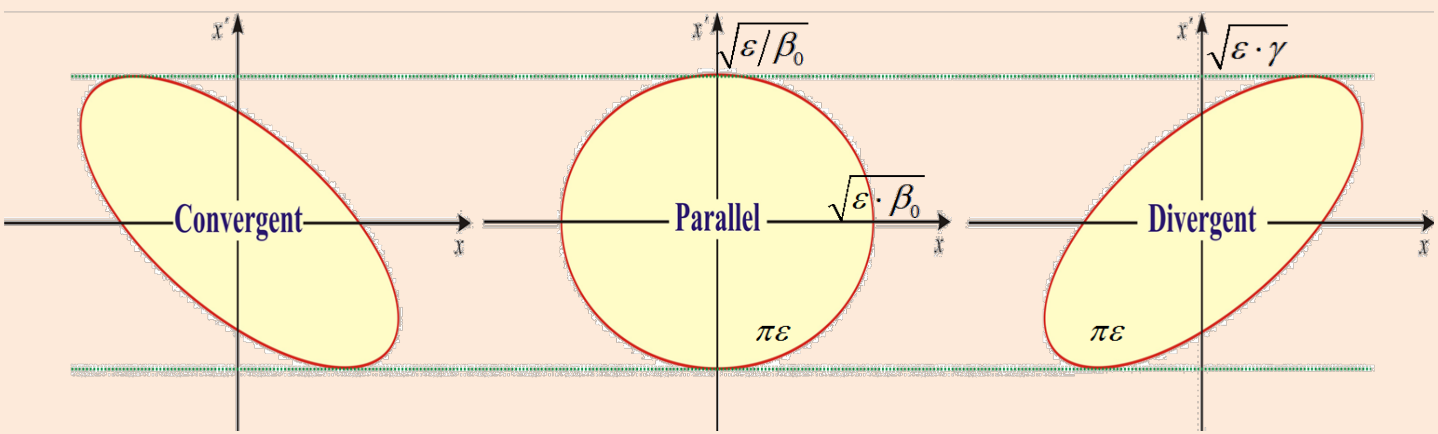


 # Schwingungen pro Umlauf: Arbeitspunkt $Q_{x,z} = \frac{1}{2\pi} \oint \frac{ds}{\beta_{x,z}(s)}$

TWISS und Emittanz

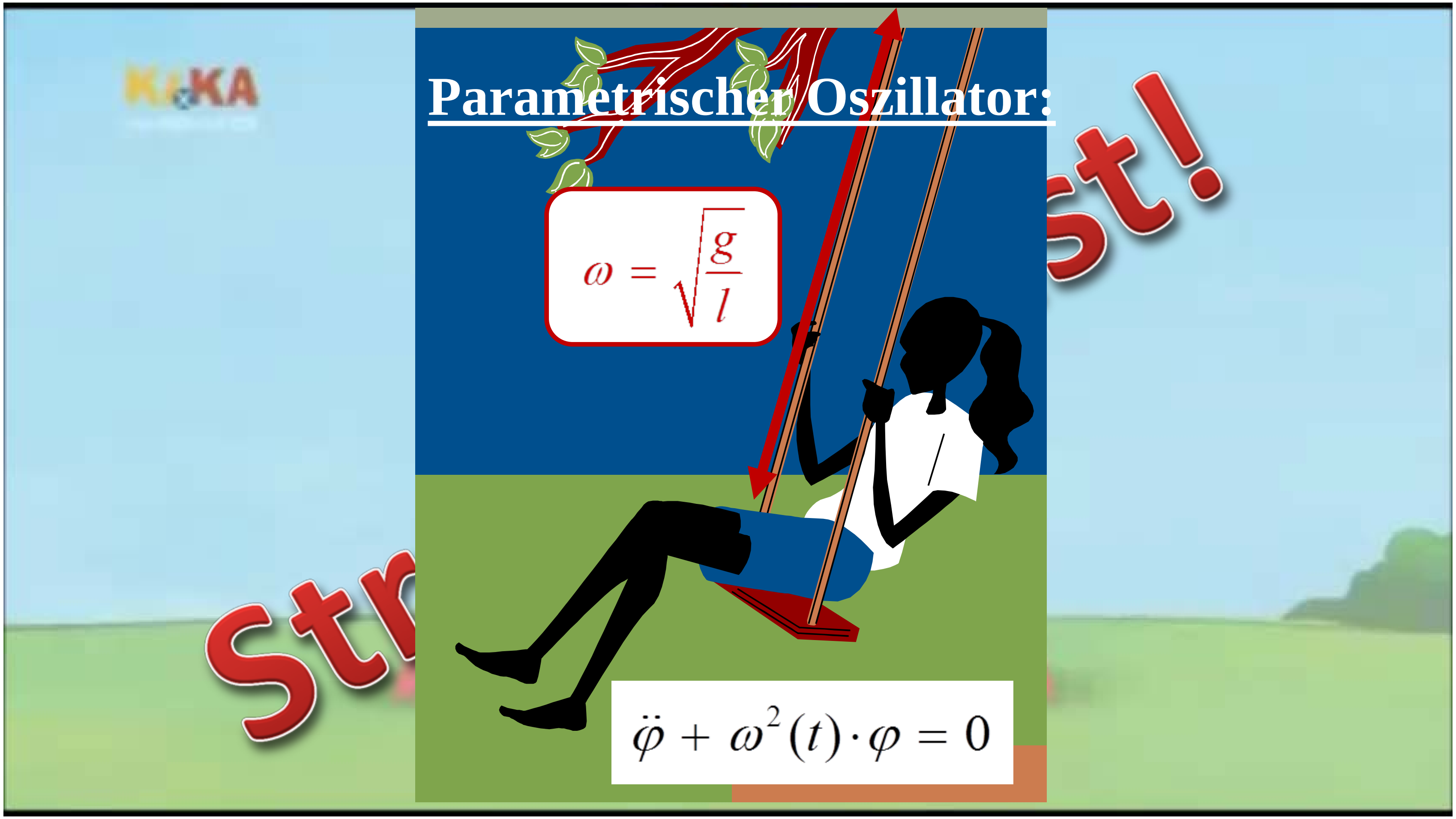


$$4\pi\varepsilon = \lambda$$



$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon, \qquad \text{wobei} \quad \alpha = -\frac{\beta'}{2} \quad \text{und} \quad \gamma = \frac{1+\alpha^2}{\beta}$$

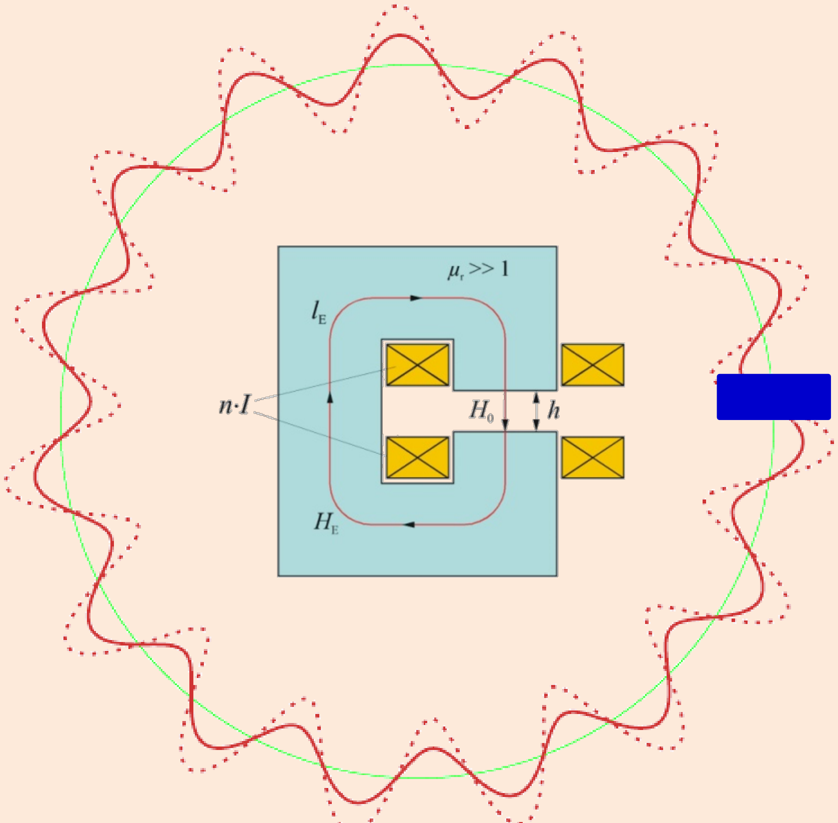
Lösen der Hillschen DGL



Feldfehler

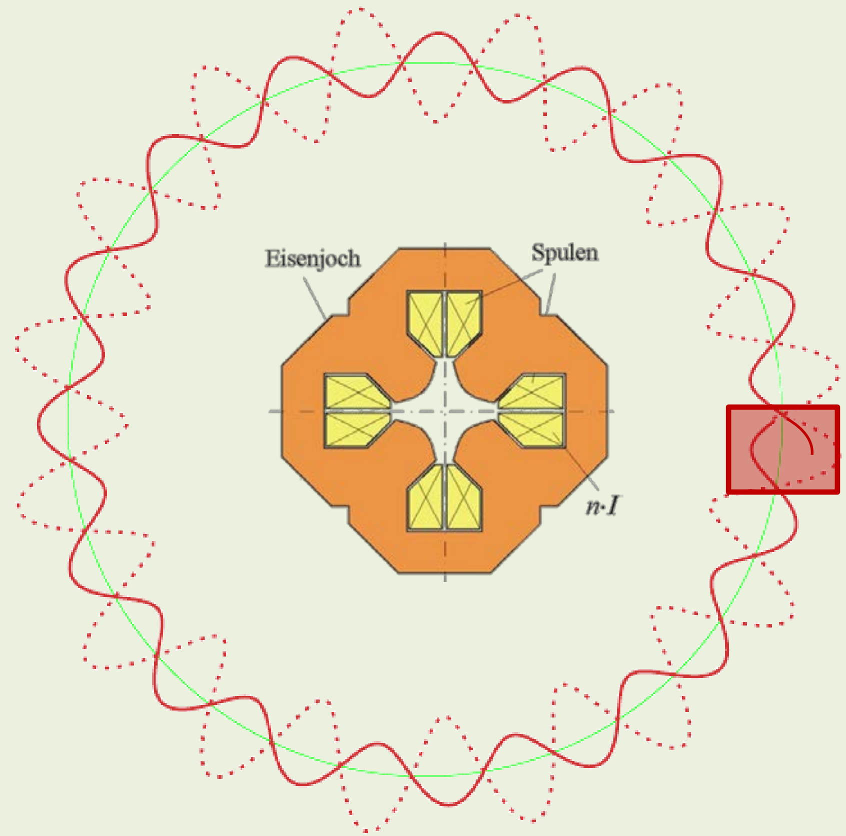
Dipolmagnet

$Q = n$

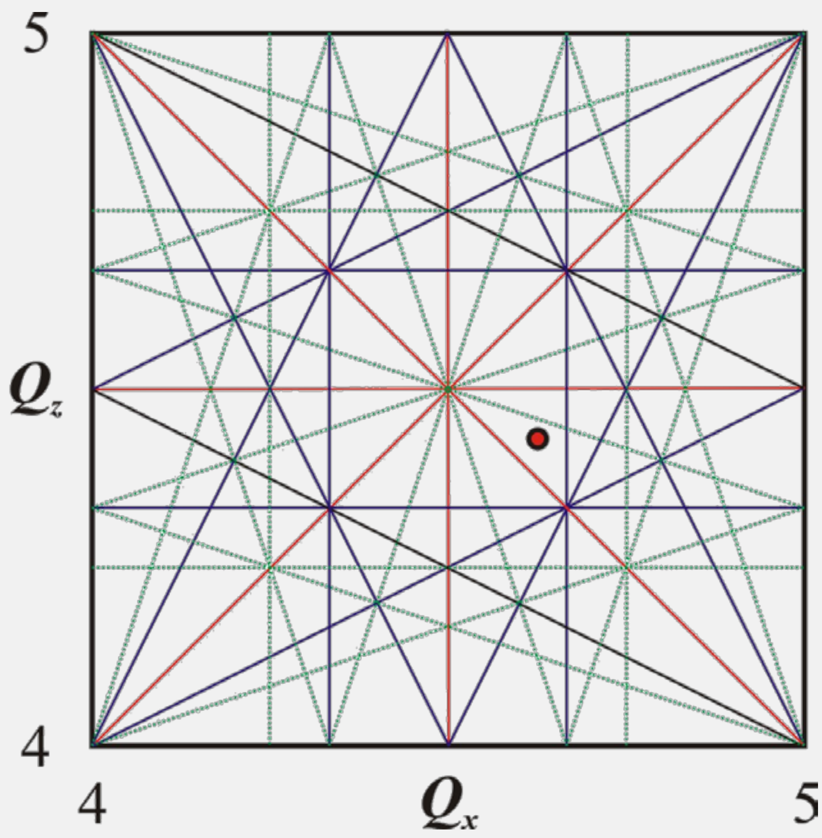


Quadrupolmagnet

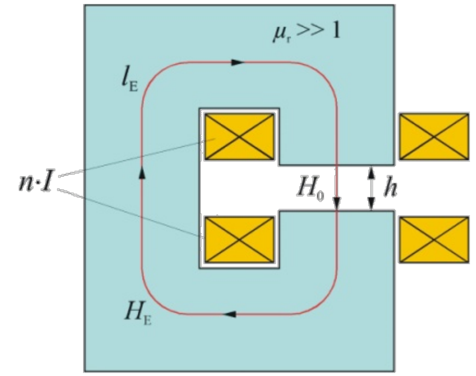
$Q = m/2$

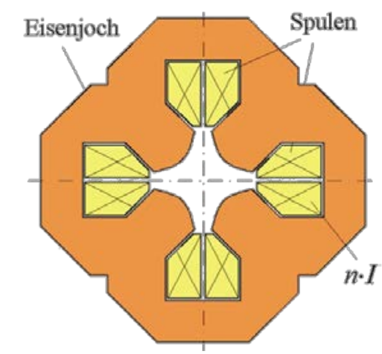


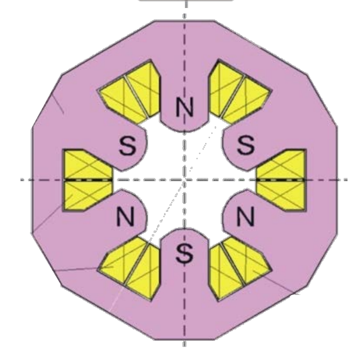
Optische Resonanzen



$$j \cdot Q_x + k \cdot Q_z = N$$

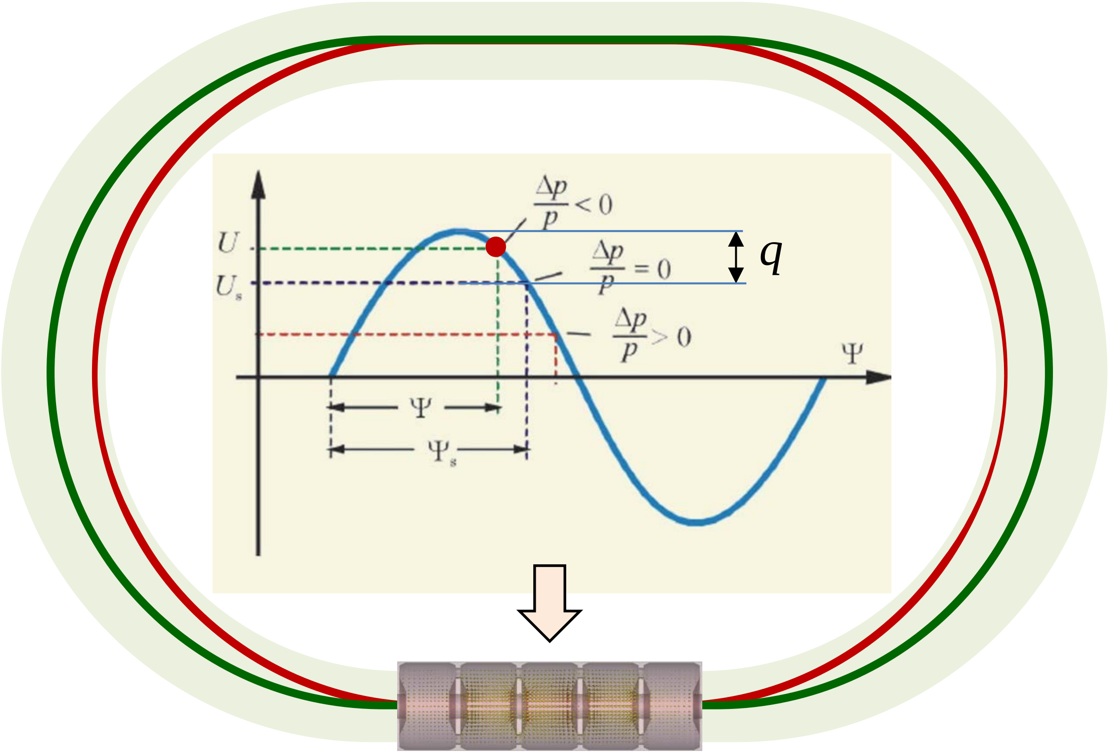




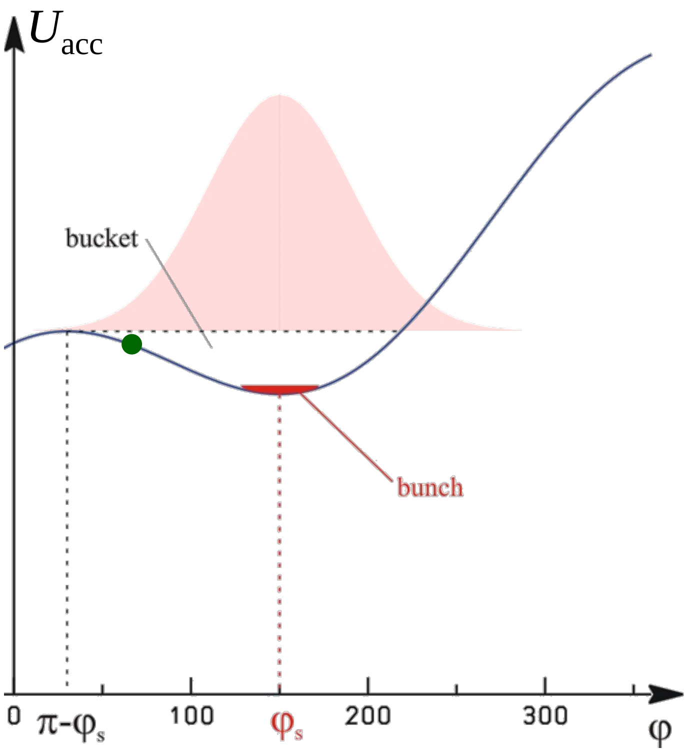


Longitudinale Fokussierung

Phasenschwingung:



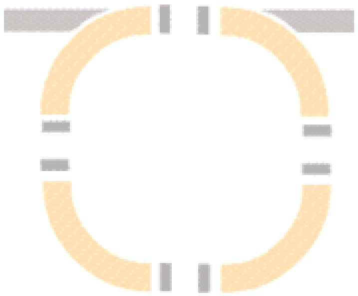
Energieschwingung:



Überspannungsfaktor: $q = U_0/U_s$

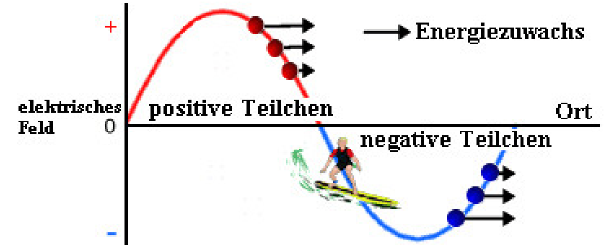
Synchronisation

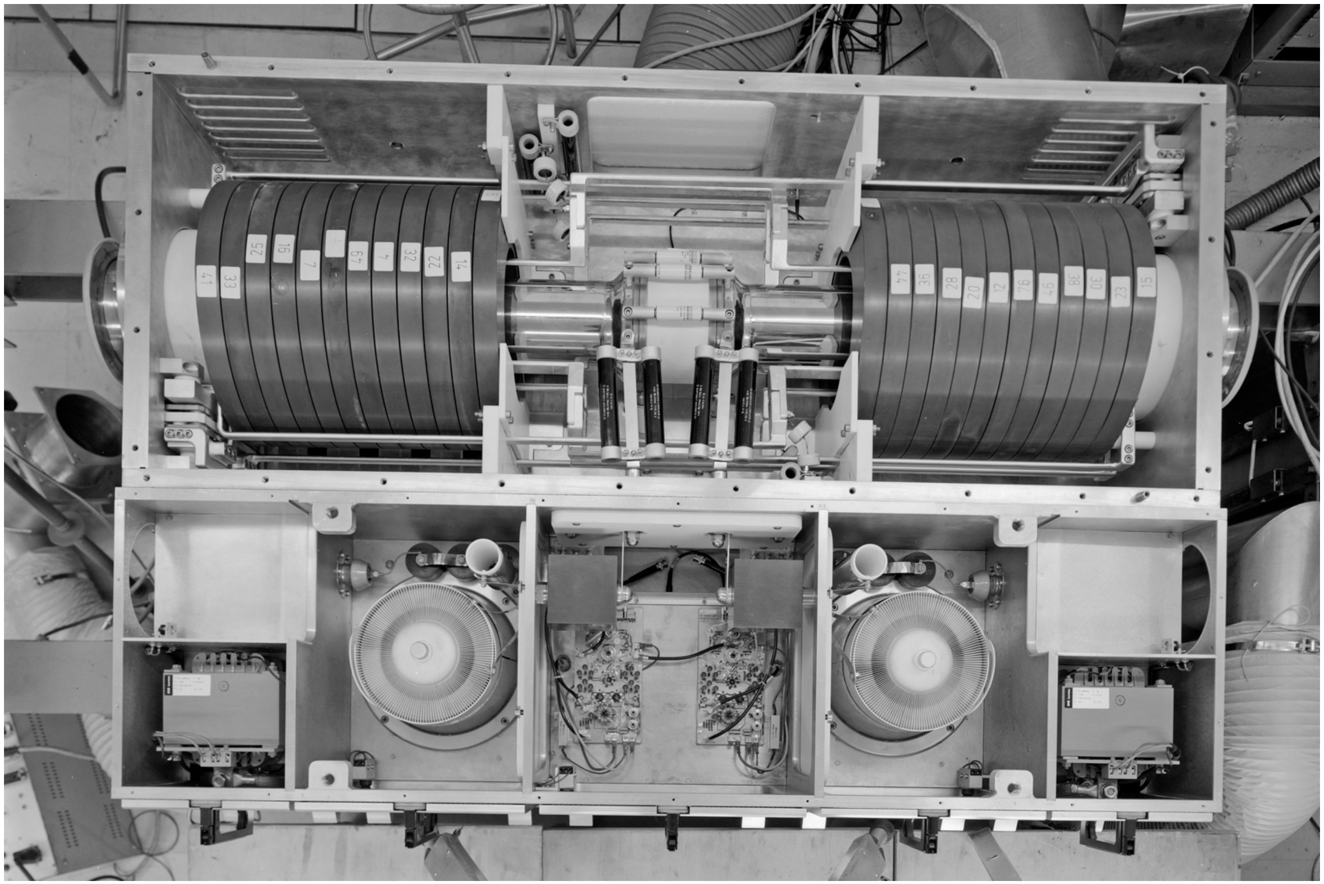
$$B \leftrightarrow \omega_{HF}$$



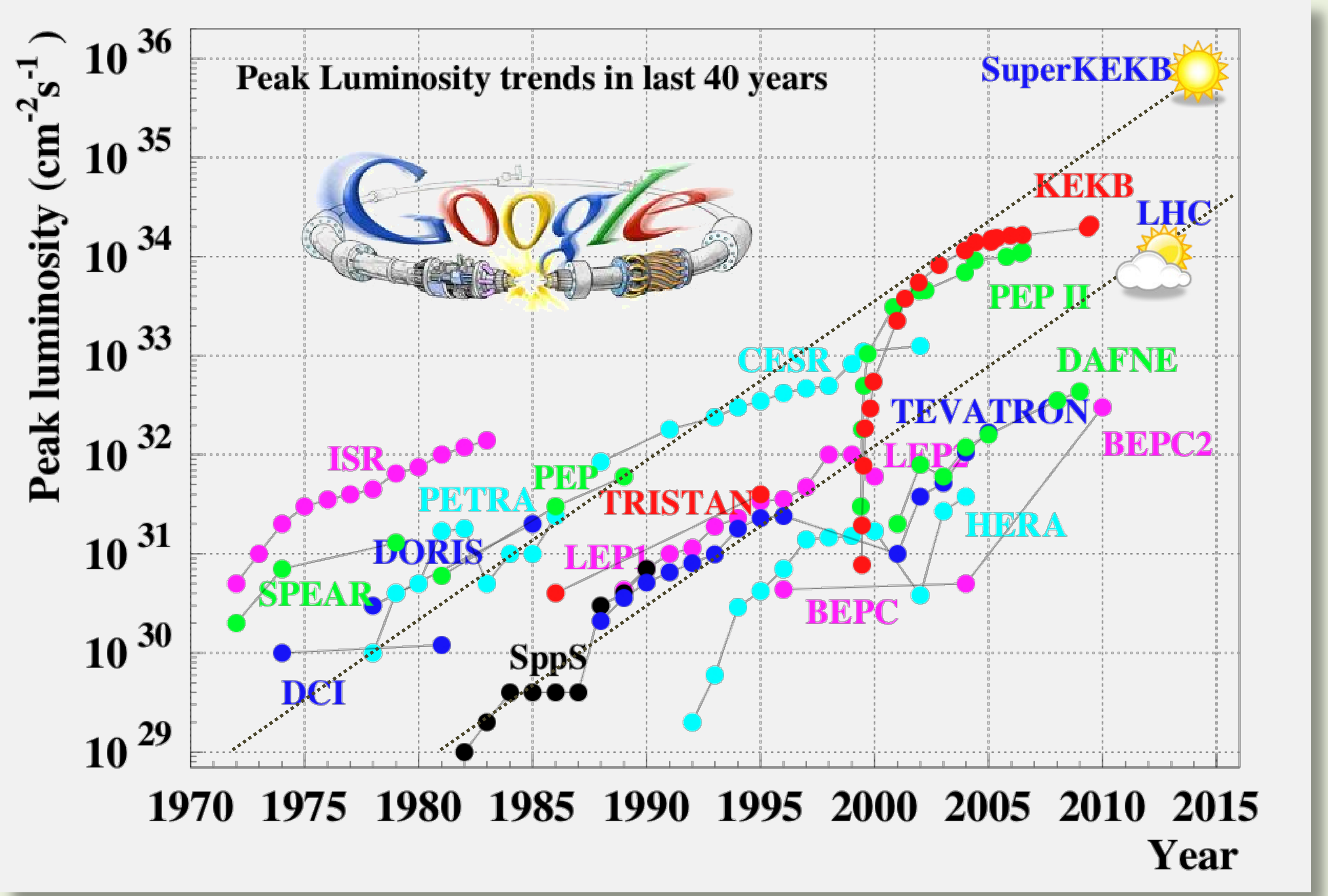
Teilchen werden schneller: $h \cdot \omega_0 = \omega_{HF}$

Bahnlänge bleibt konstant: $L = h \cdot \beta \cdot \lambda_{HF}$





Luminosität



Luminosität

… das unbekannte Wesen …

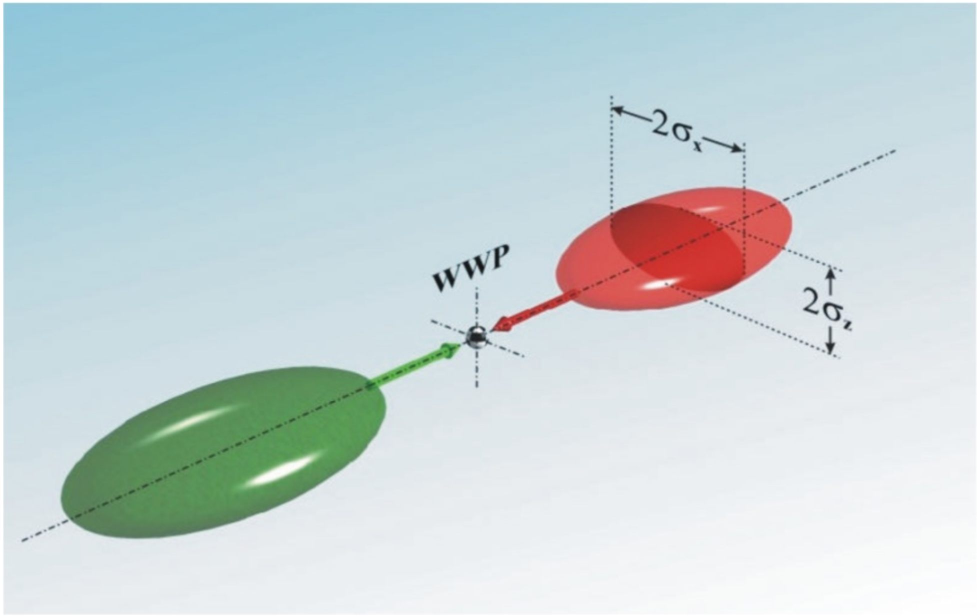
Was interessiert den Teilchenphysiker an Beschleunigern?

- **Luminosität** $\dot{N} = \sigma \cdot \mathfrak{L}$
- **Integrierte Luminosität:** $N = \sigma \cdot \int_{\text{Messzeit}} \mathfrak{L} \cdot dt = \sigma \cdot \mathfrak{J}$

e⁺-e⁻, p-p Collider:

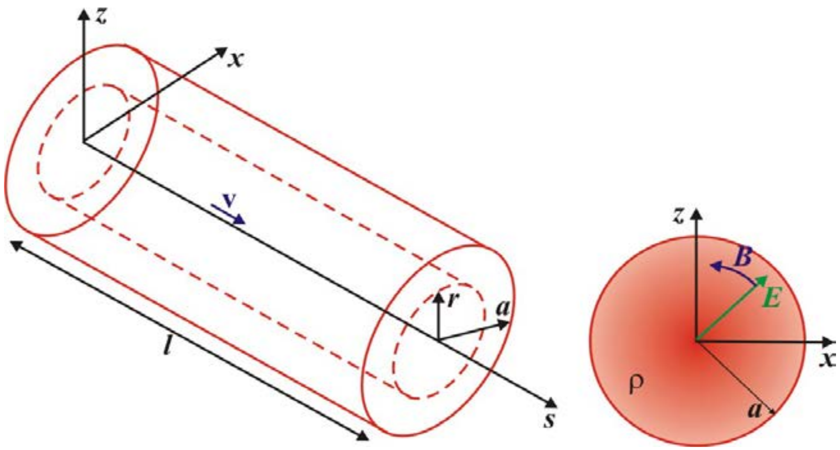
$$\mathfrak{L} = \frac{1}{2 e^2 \omega_0 n} \cdot \frac{I_1 \cdot I_2}{\sigma_x \cdot \sigma_z}$$

$1\,\mathrm{ab}^{-1}/\mathrm{Jahr} \leftrightarrow \mathfrak{L} = 3 \cdot 10^{35} \frac{1}{\mathrm{cm}^2 \mathrm{s}}$



Direkte Raumladung

Abstoßung im Feld der Nachbarteilchen:



$$\oiint_{\partial V} \vec{E} \cdot d\vec{A} = \frac{1}{\varepsilon_0} \iiint_V \rho \cdot d^3 r$$

$$\Rightarrow E_r(r) = \frac{\rho}{2\varepsilon_0} \cdot r$$

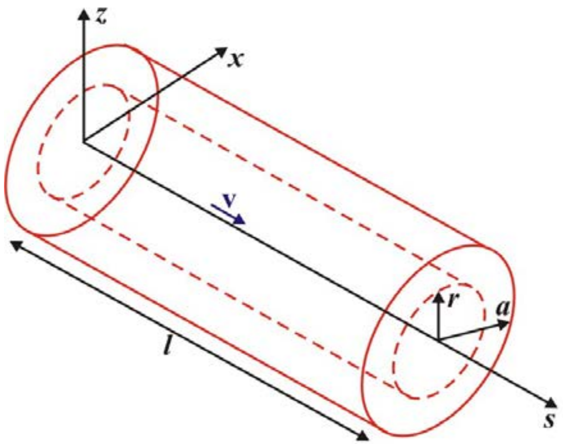
$$F^*(r) = \frac{e\rho}{2\varepsilon_0} \cdot r$$

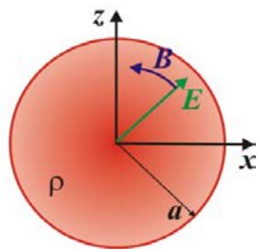
Transformation ins Laborsystem:

- Lorentzkontraktion → Faktor γ

Direkte Raumladung

Abstoßung im Feld der Nachbarteilchen:





$$\oiint_{\partial V} \vec{E} \cdot d\vec{A} = \frac{1}{\varepsilon_0} \iiint_V \rho \cdot d^3 r$$

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Direkte Raumladung

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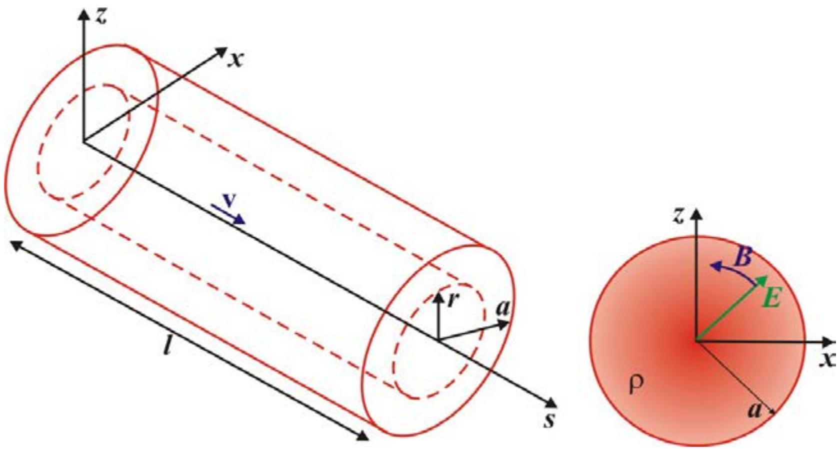

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$$\Rightarrow E_r(r) = \frac{\rho}{2\varepsilon_0} \cdot r$$

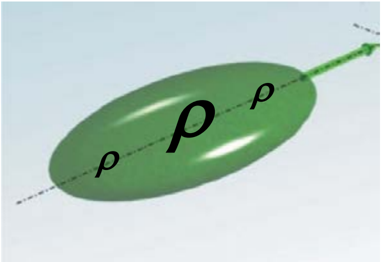
$$F^*(r) = \frac{e\rho}{2\varepsilon_0} \cdot r$$

Transformation ins Laborsystem:

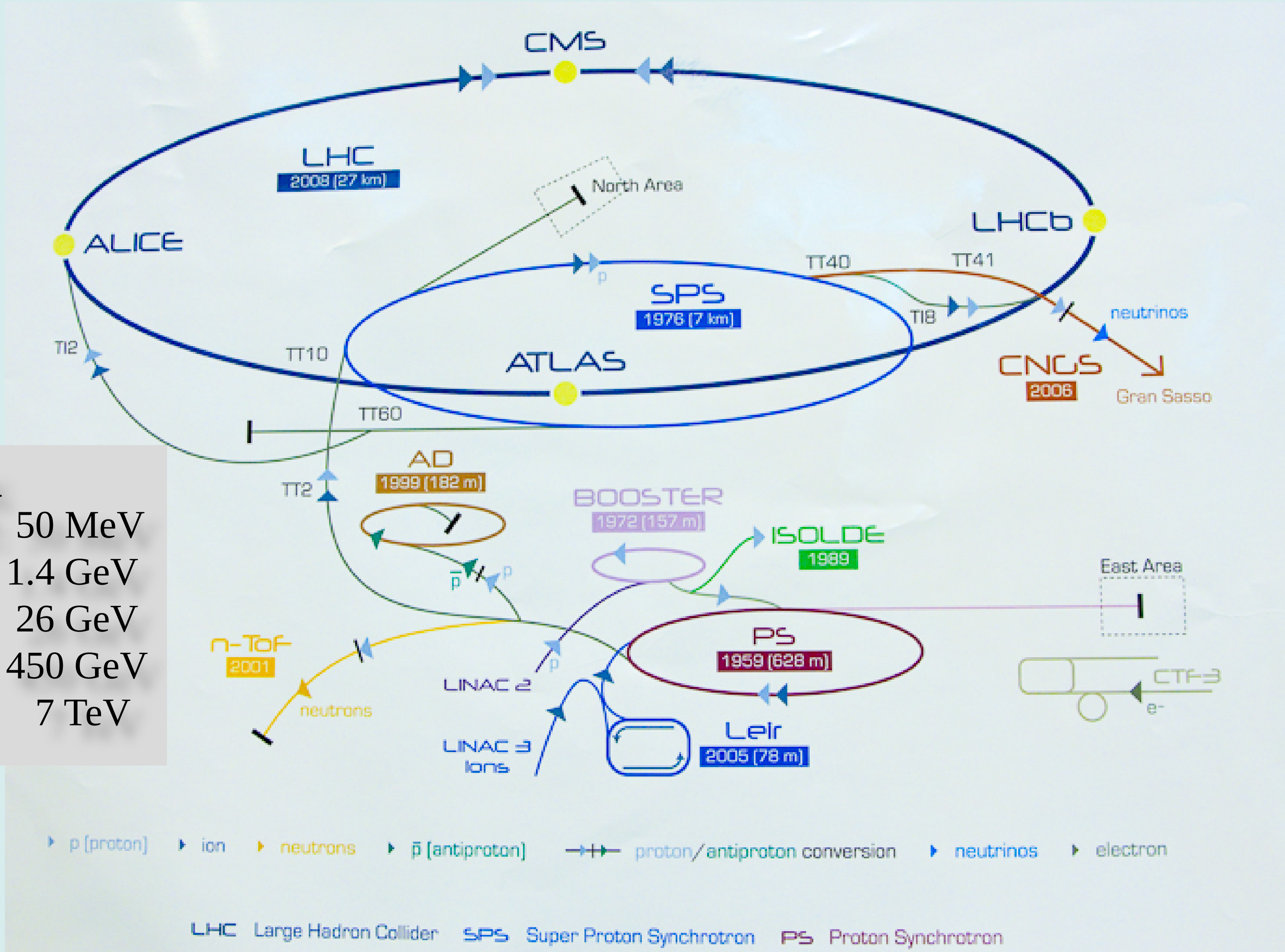
- Lorentzkontraktion → Faktor γ
- Ladungsdichteverdünnung → Faktor γ

$$\gamma m_0 \ddot{x} = F_x = \frac{F_x^*}{\gamma^2}$$

$$\Delta Q_{x,z} = -\frac{e}{8\pi^2 \varepsilon_0 m_0 (\beta c)^3 \gamma^3} \cdot \frac{I}{\varepsilon_{x,z}} \cdot L$$



Beschleunigerkette @ CERN



<u>Protonen:</u>

LINAC2: 50 MeV

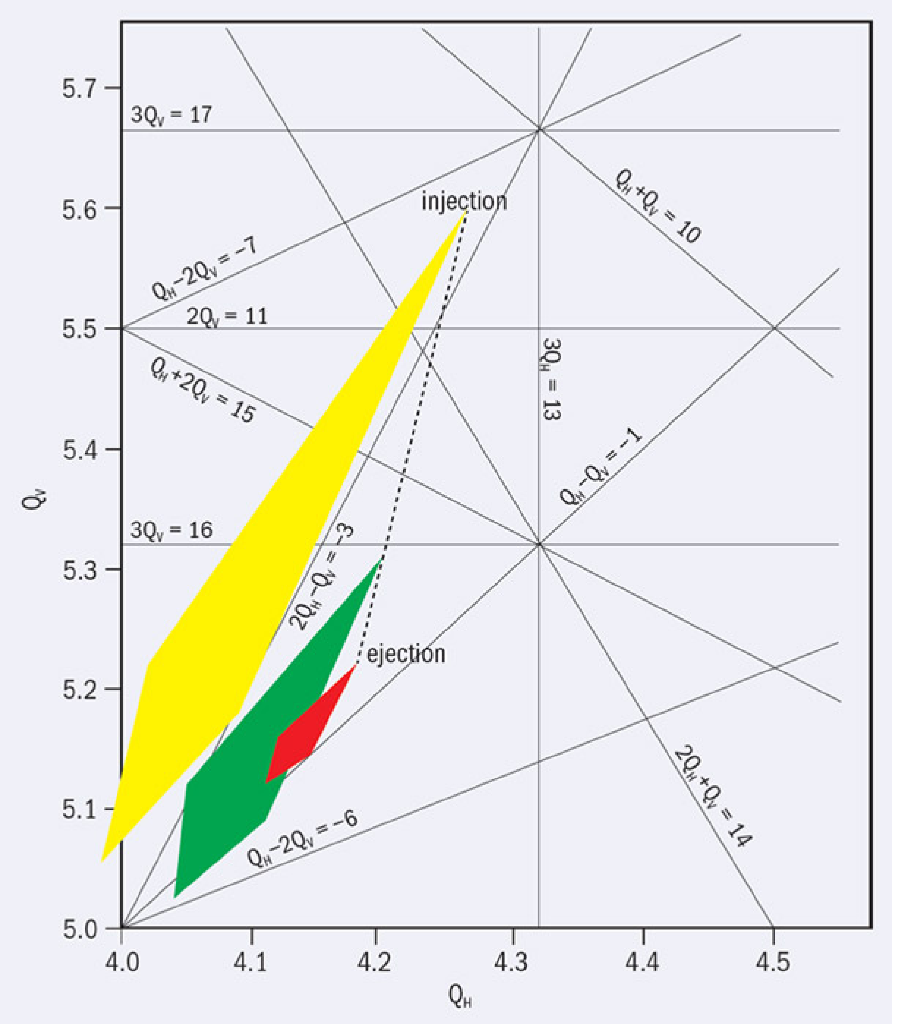
PSB: 1.4 GeV

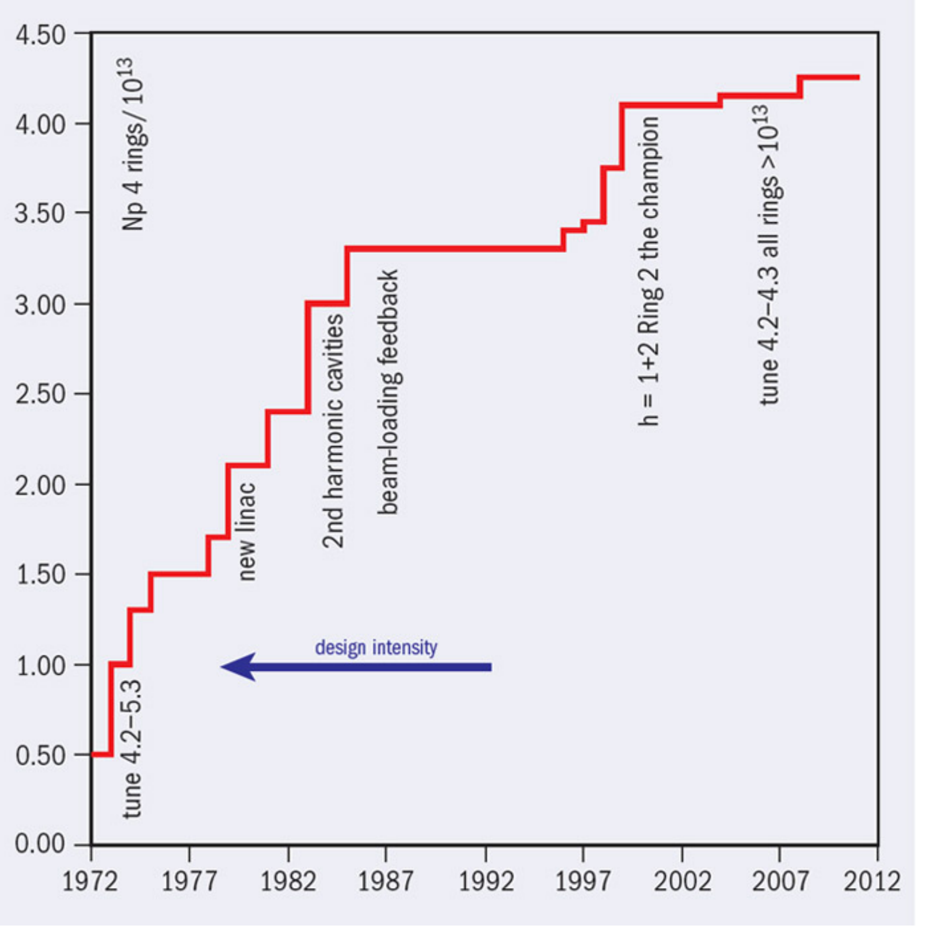
PS: 26 GeV

SPS: 450 GeV

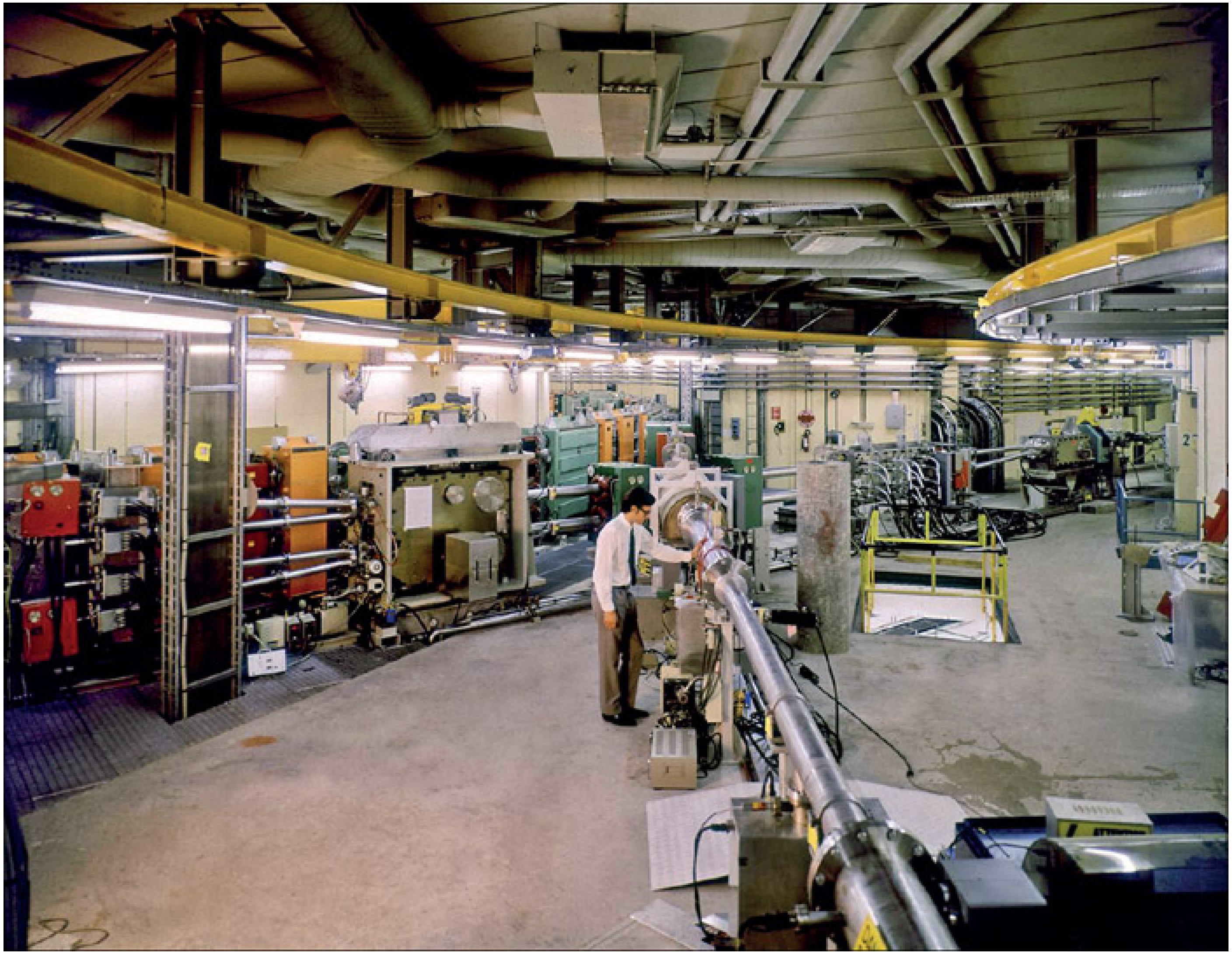
LHC: 7 TeV

PS Booster @ CERN



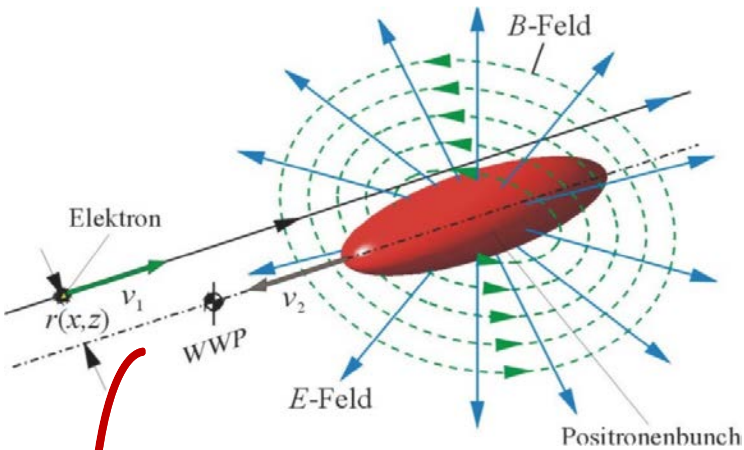


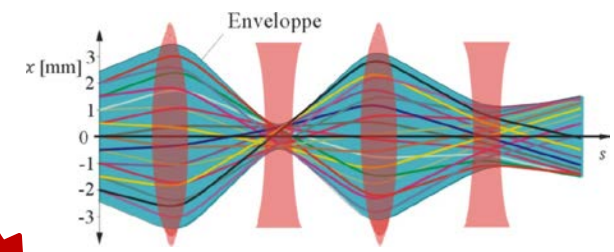
PS Booster @ CERN

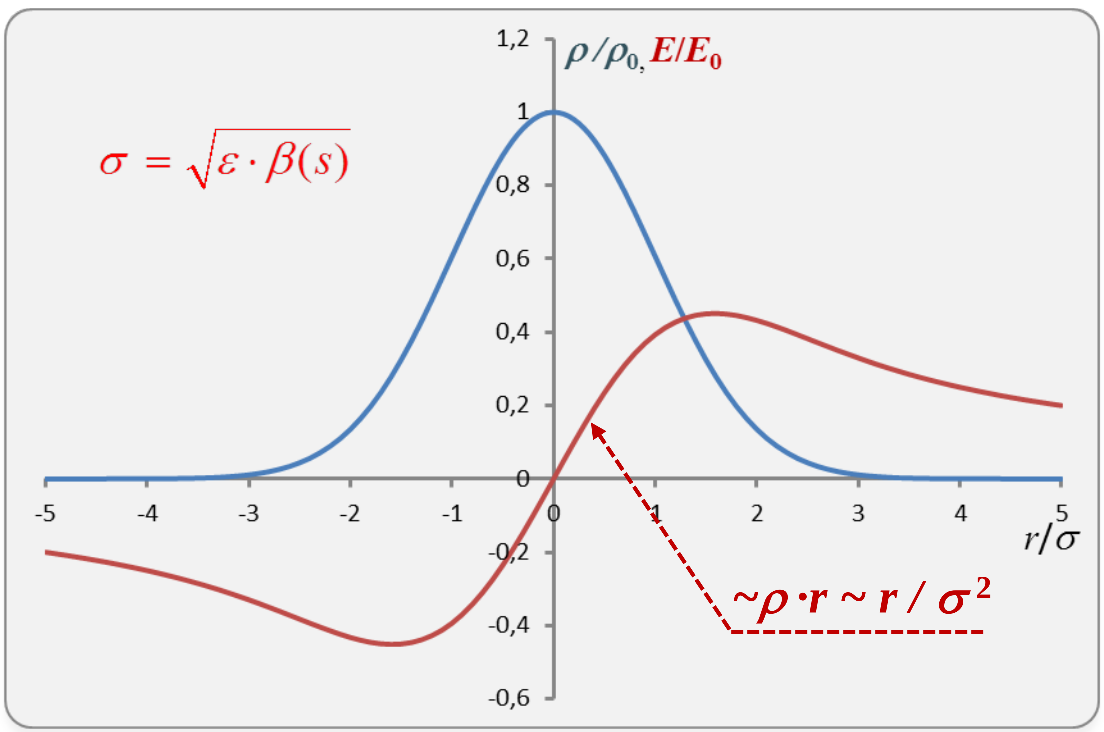


Strahl-Strahl-WW

Zusätzliche Fokussierung bzw. Defokussierung bei der Strahlkreuzung







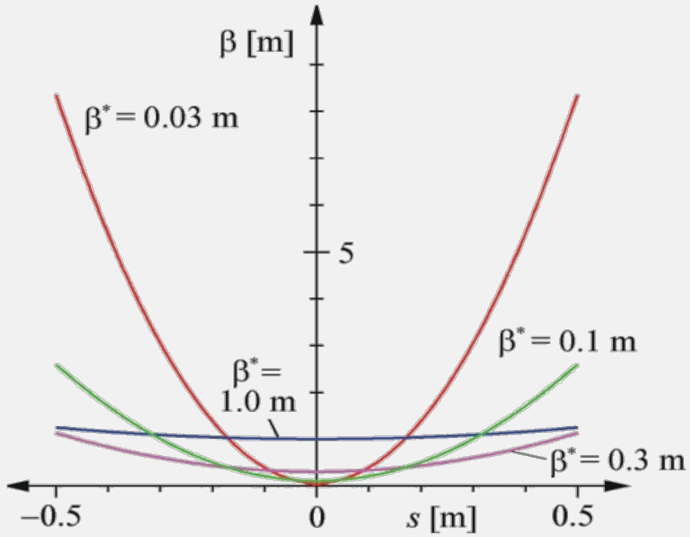
Strahl-Strahl-Parameter:

$$\Delta Q_x = -\frac{N r_e}{2\pi} \cdot \frac{1}{\gamma} \cdot \frac{\beta_x^*}{(\sigma_x + \sigma_z)\sigma_x}$$

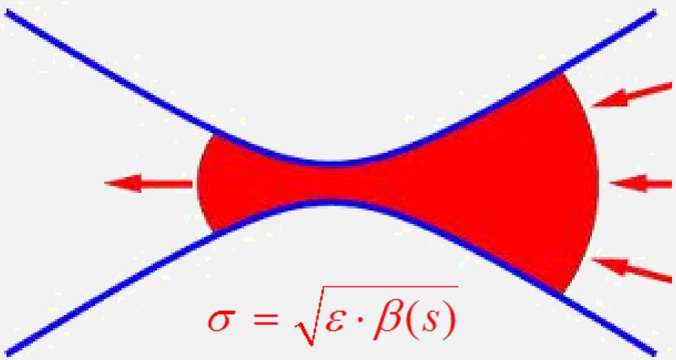
$$\Delta Q_z = -\frac{N r_e}{2\pi} \cdot \frac{1}{\gamma} \cdot \frac{\beta_z^*}{(\sigma_x + \sigma_z)\sigma_z}$$

Strahlbreitenreduktion

Strahlaufweitung:



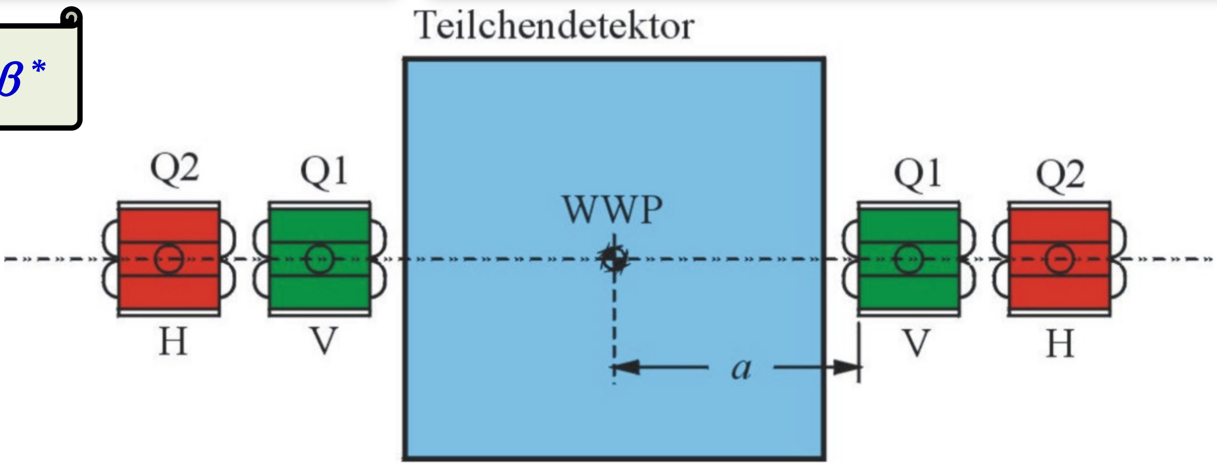
Hourglass-Effekt:



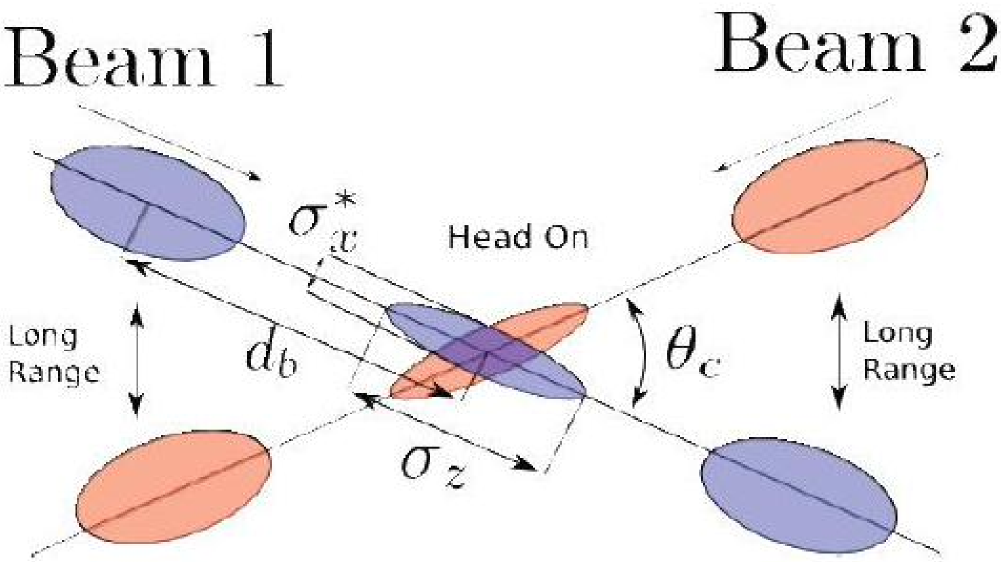
kleine Paketlänge!

$\sigma < 1{,}7 \cdot \beta^*$

$$\mathfrak{L} = \frac{1}{2\, e^2\, \omega_0\, n} \cdot \frac{I_1 \cdot I_2}{\sigma_x \cdot \sigma_z}$$



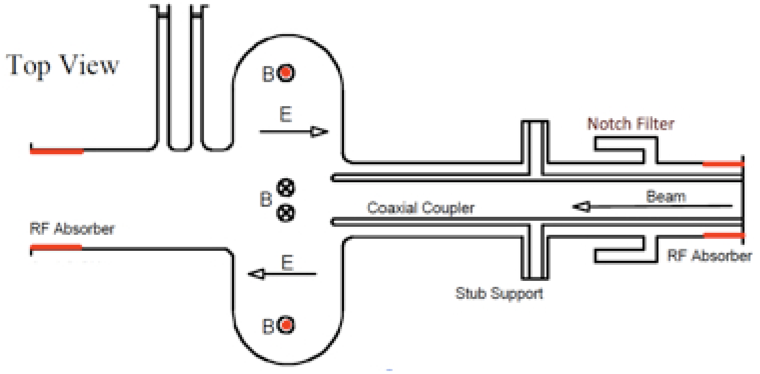
Strahlkreuzung

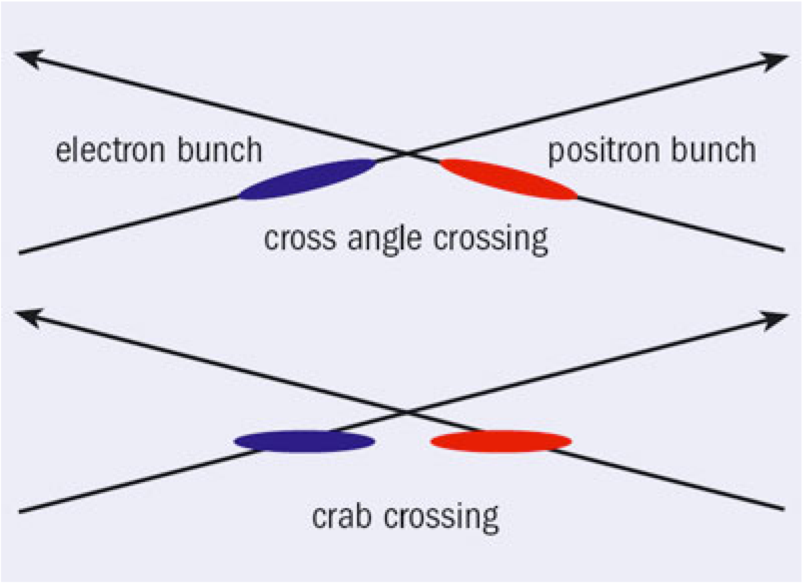


- ausreichende Strahlseparation
- kleiner Kreuzungswinkel
- hinreichende Paketabstände
- …

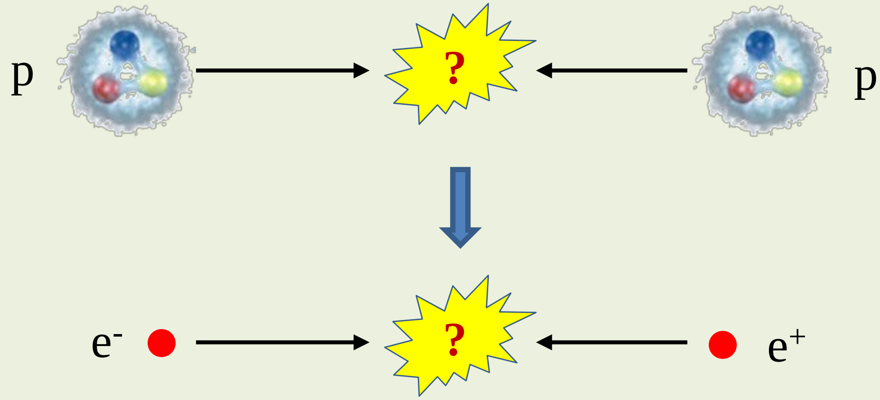
$$\mathfrak{L} = \frac{1}{2\, e^2\, \omega_0\, n} \cdot \frac{I_1 \cdot I_2}{\sigma_x \cdot \sigma_z}$$

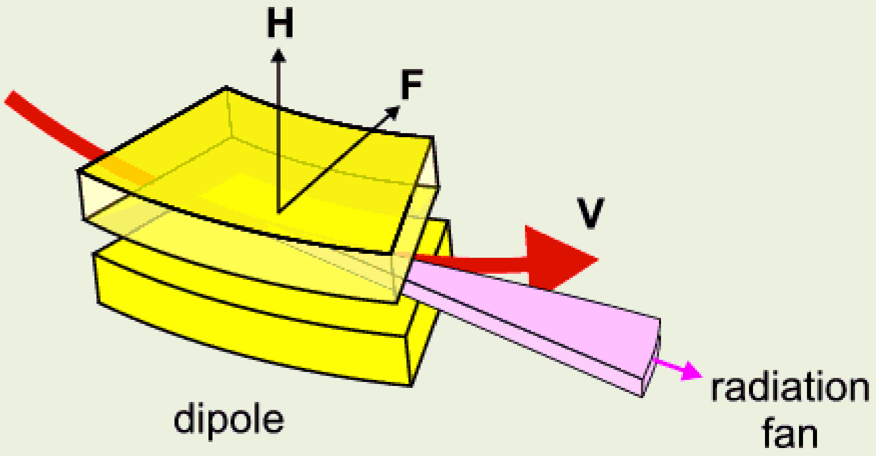
Crab-Cavities:

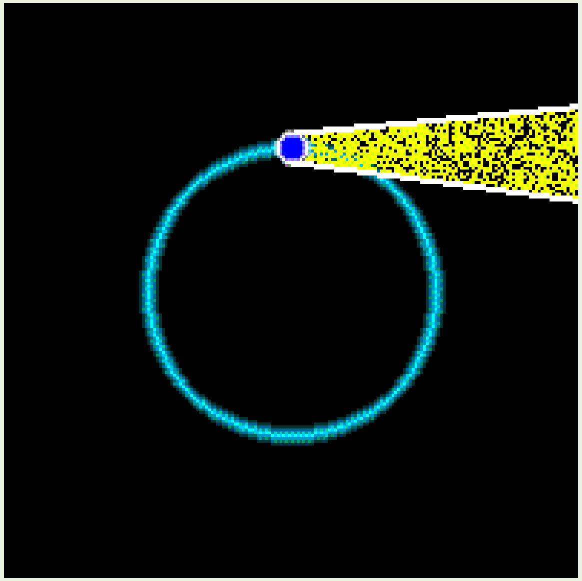




Elektronen / Positronen

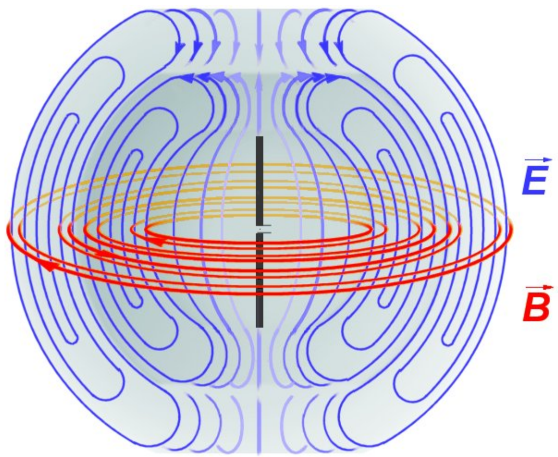






Synchrotronstrahlung

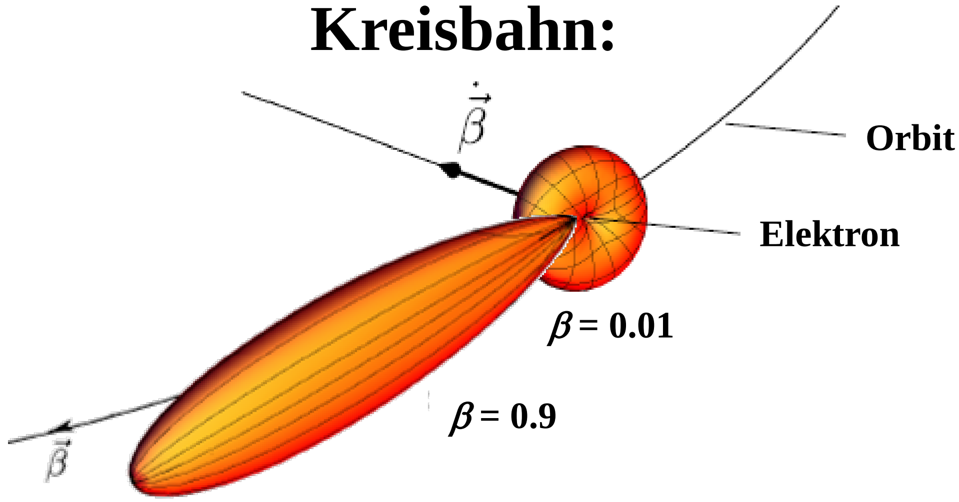
Hertzscher Dipol:



$$P = \frac{e^2}{12\pi\varepsilon_0 c^3}\cdot\omega^4 d^2$$

$\longrightarrow$

Kreisbahn:

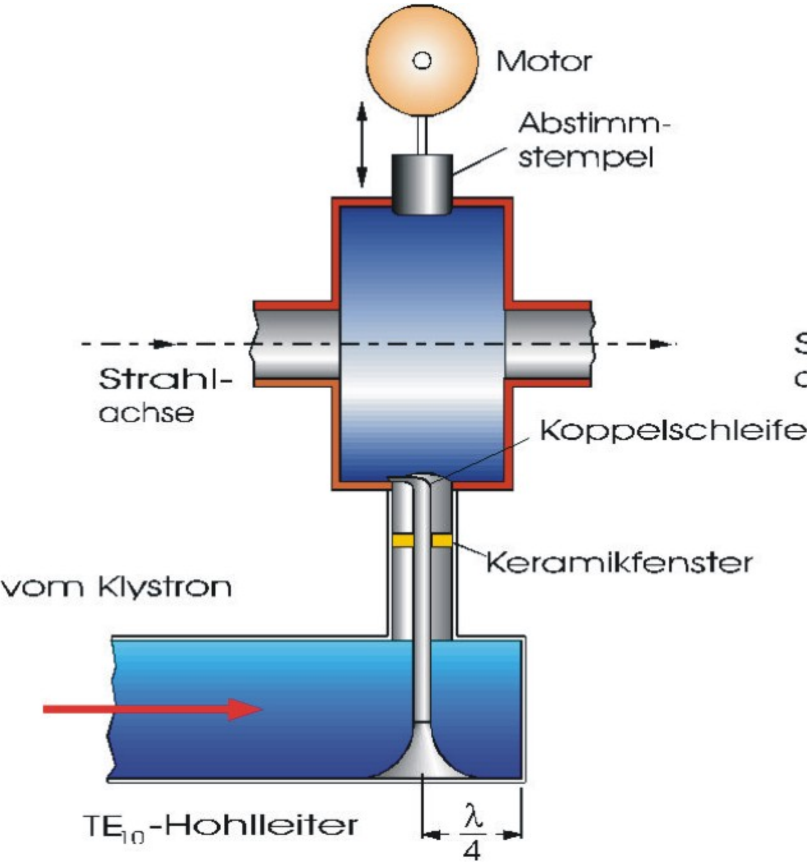


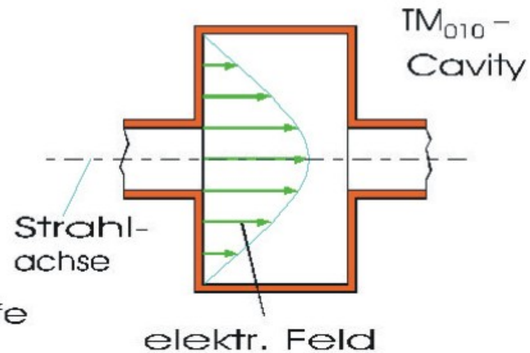
$$P = \frac{e^2 c}{6\pi\varepsilon_0}\cdot\frac{\gamma^4}{R^2}$$

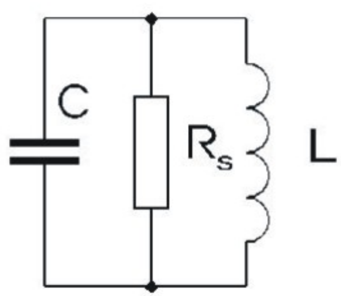
$$U[\mathrm{kV}] = 88,5\cdot\frac{E^4\left[\mathrm{GeV}^4\right]}{R[\mathrm{m}]} \Rightarrow U\Big|_{E=104,5\,\mathrm{GeV}} = \underline{\underline{3,4\,GeV}}$$

$$P_{rad}(6\,mA\ @\ 104,5\,GeV) = 18\,\mathrm{MW}$$

Resonatoren I







Kenngrößen:

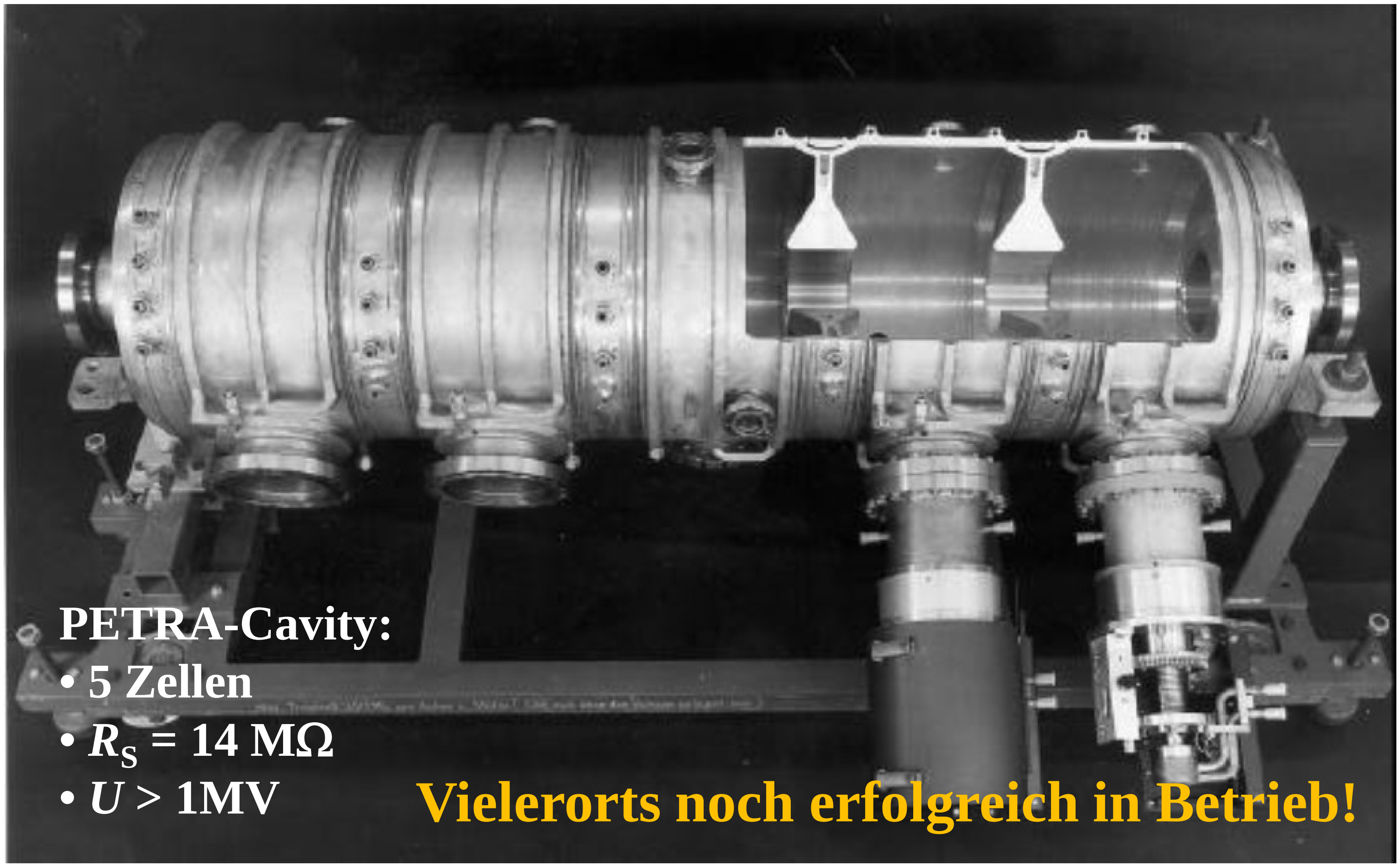
- Shuntimpedanz R_S
  nc: $\boldsymbol{R_S \approx}$ **MΩ**
- Kreisgüte Q
  nc: $\boldsymbol{Q \approx 10^4}$
- Geometriefaktor R_S/Q

Für Spannung ***U*** benötigte HF-Leistung:

$$P = \frac{U^2}{2\,R_S}$$

$\boldsymbol{U = 1\text{MV} \leftrightarrow P = 100\ \text{kW}}$

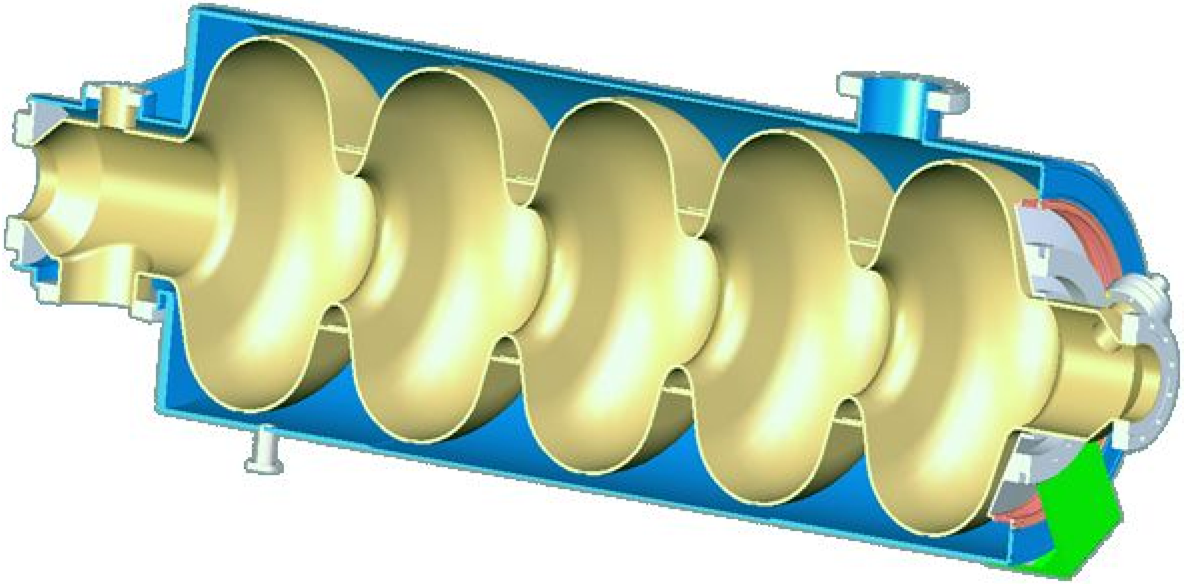
Immerhin:



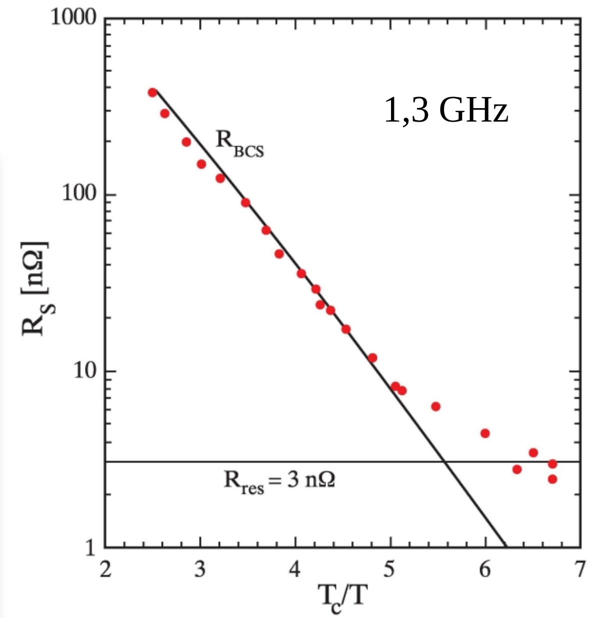
PETRA-Cavity:
- 5 Zellen
- R_S = 14 MΩ
- U > 1MV

Vielerorts noch erfolgreich in Betrieb!

Resonatoren II



Frequenz begrenzt
durch ansteigenden
Oberflächenwiderstand



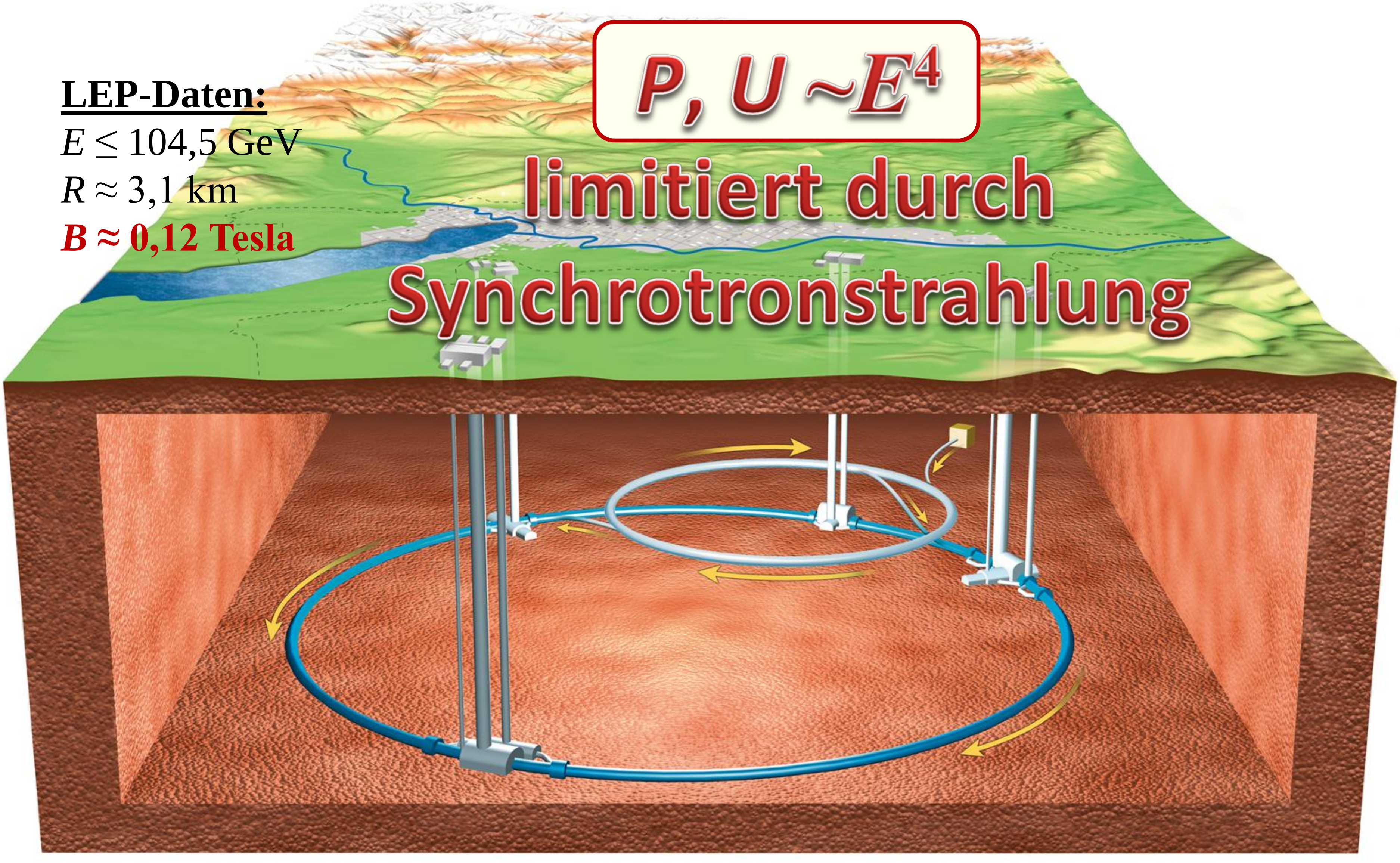
<u>Supraleitende Resonatoren aus Niob:</u>

→ Reduktion der Verluste um Faktor > 10^5 !

… hervorgerufen durch nc Elektronen …

aber: E_{max} < 50 MV/m

Large Electron Positron Collider



LEP-Daten:

$E \leq 104{,}5$ GeV

$R \approx 3{,}1$ km

$\boldsymbol{B \approx 0{,}12}$ **Tesla**

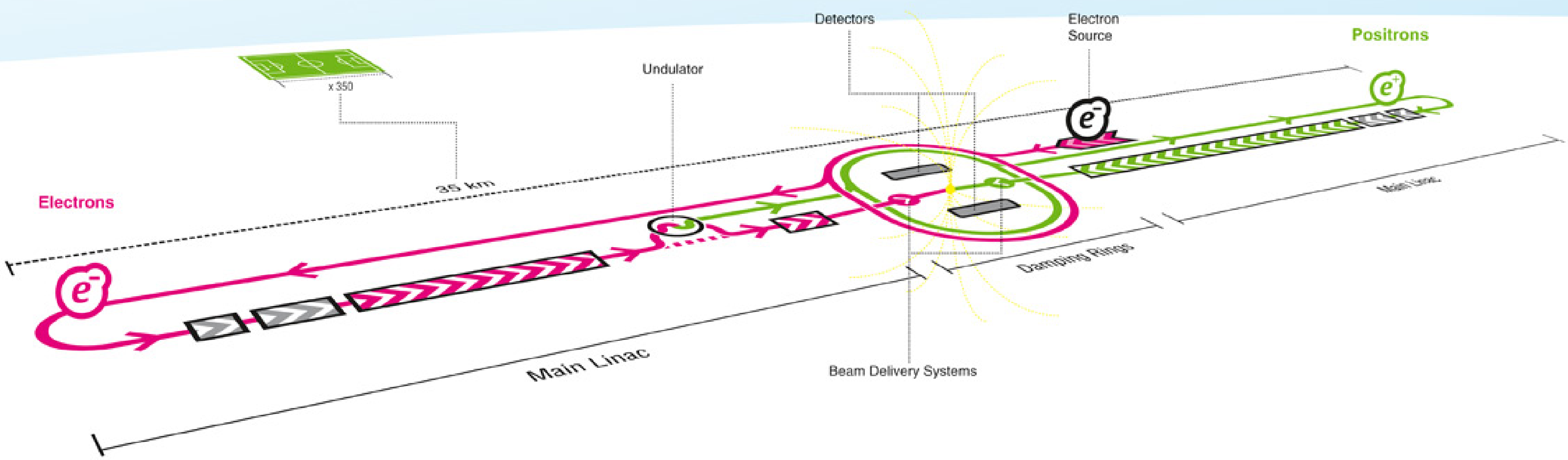
$P, U \sim E^4$

limitiert durch Synchrotronstrahlung

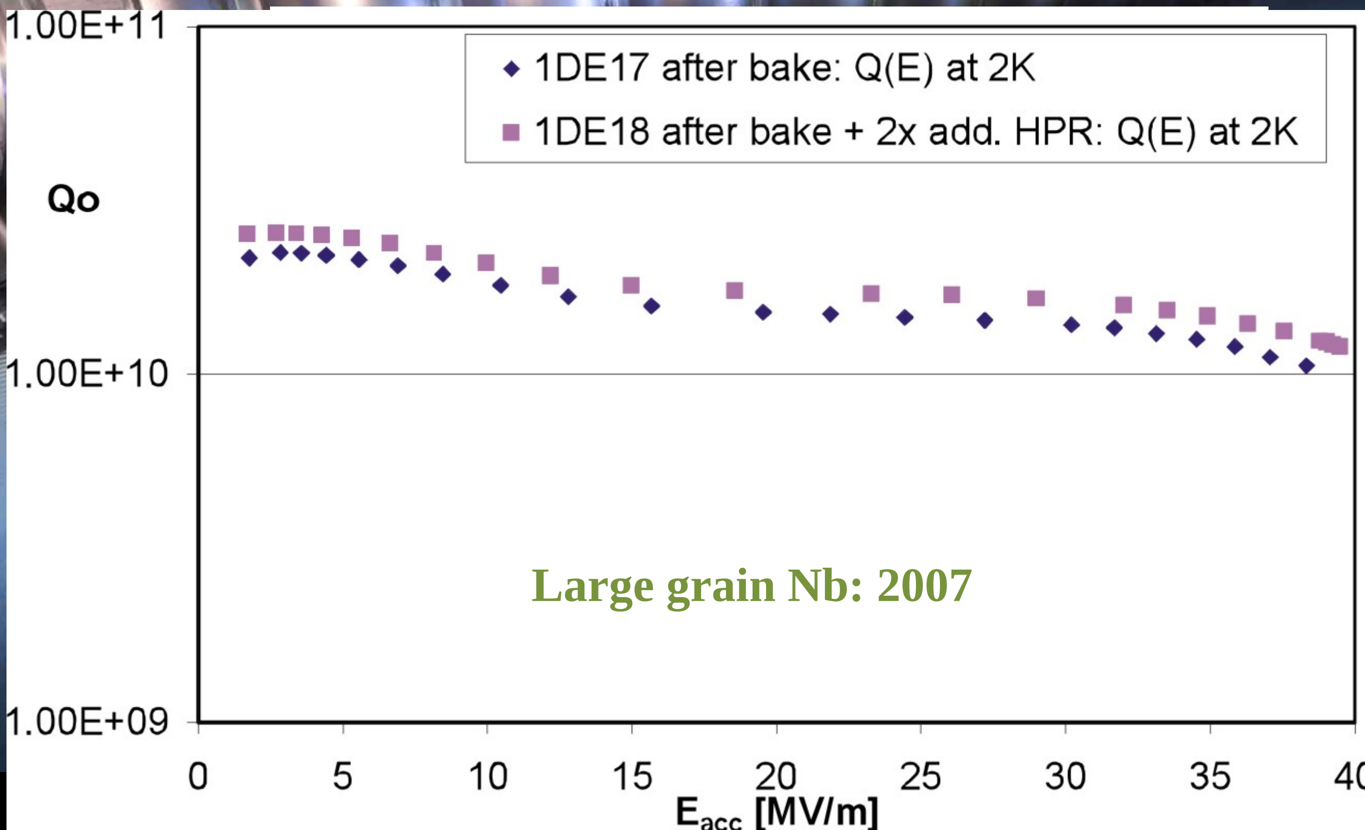
e^- / e^+ @ 500 GeV

ILC:
International
Linear
Collider

sc linear accelerator
ν = 1.3 GHz
$E \geq$ 25 MV/m

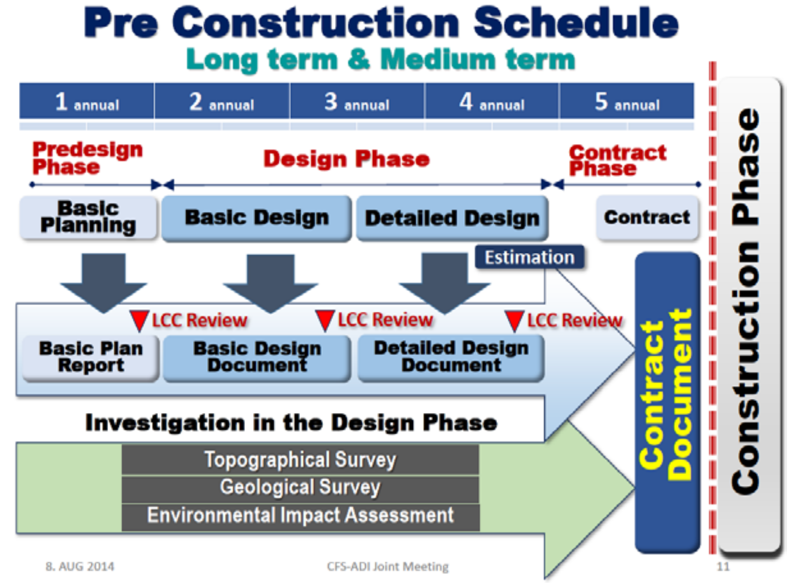


Erreichen hoher Gradienten:



Preparation Steps:

- 80μm chemical etching (BCP)
- 800°C firing
- 100μm electropolishing (EP)
- high pressure water rinsing (HPR)
- baking (under Ar) atmosphere
- additional HPR
- assembly in cleanroom



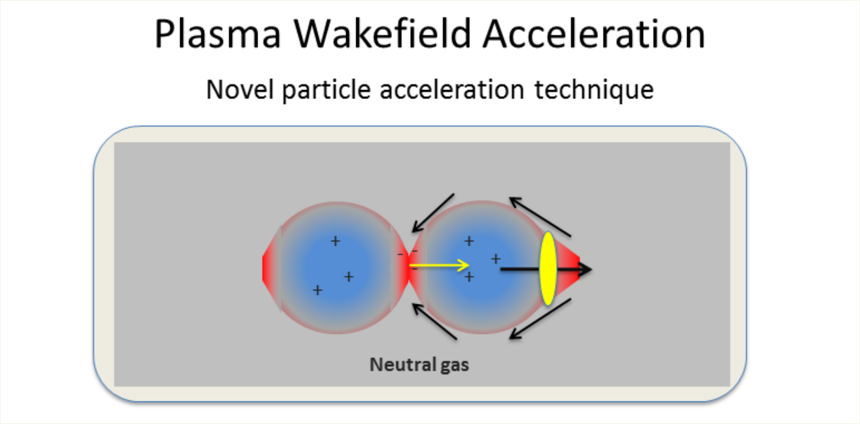
… es geht voran …

Inbetriebnahme 2030?

Zukunftsträume

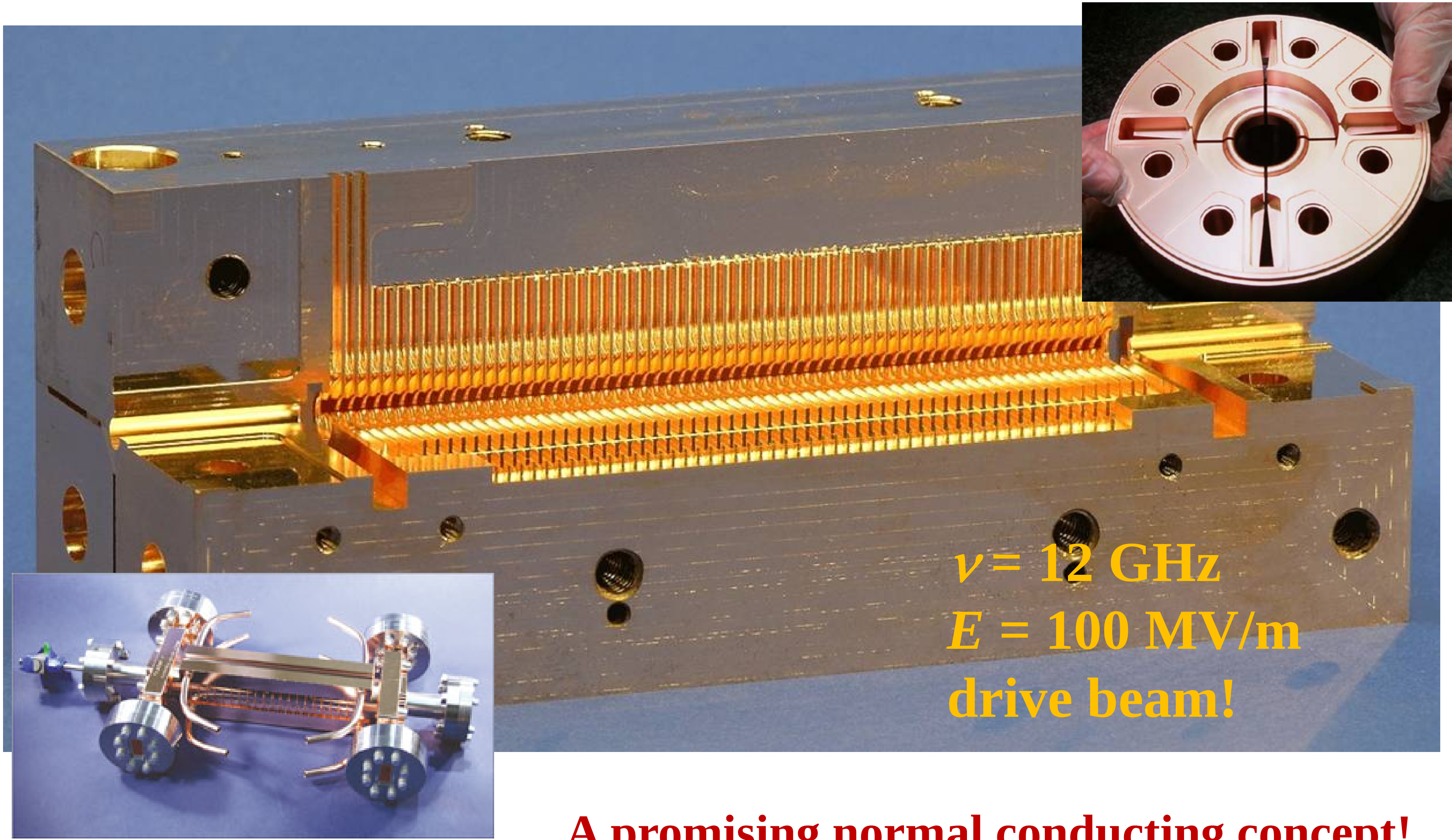
CLIC

FCC
hh ee he



…

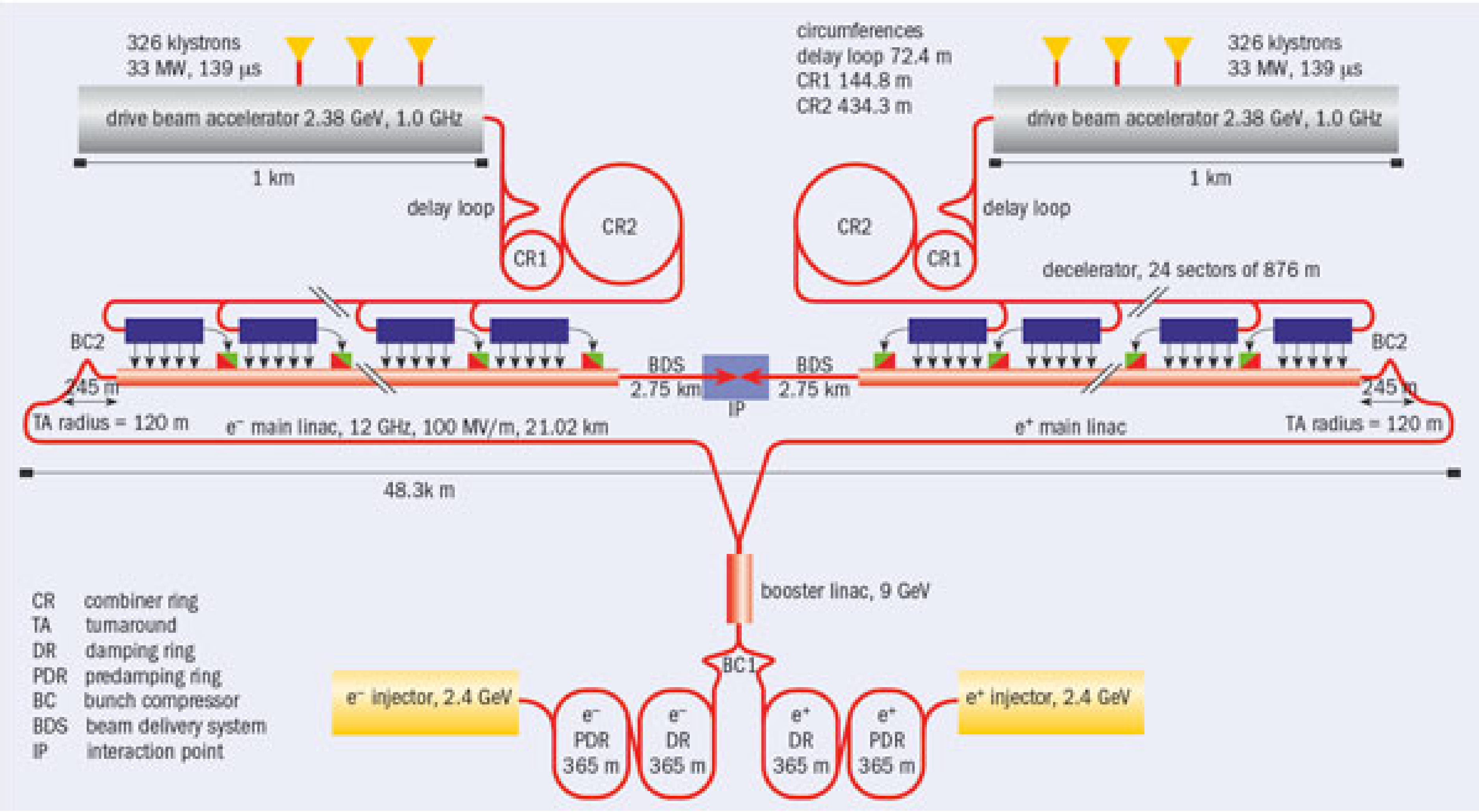
Compact Linear Collider (CLIC)



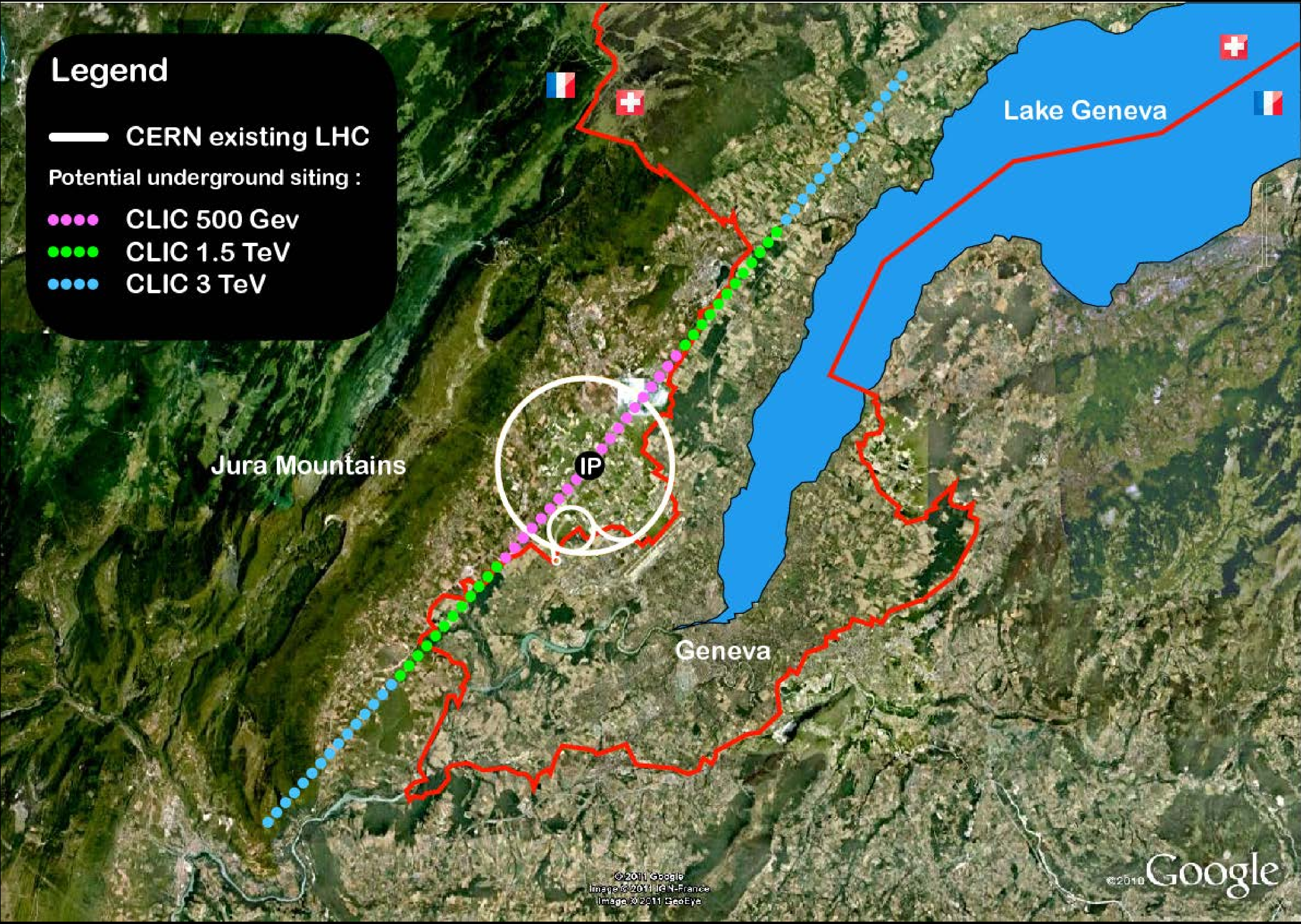
ν = 12 GHz
E = 100 MV/m
drive beam!

A promising normal conducting concept!

CLIC set-up



326 klystrons
33 MW, 139 μs
drive beam accelerator 2.38 GeV, 1.0 GHz
1 km
circumferences
delay loop 72.4 m
CR1 144.8 m
CR2 434.3 m
326 klystrons
33 MW, 139 μs
drive beam accelerator 2.38 GeV, 1.0 GHz
1 km
delay loop
CR2
CR1
CR2
delay loop
CR1
decelerator, 24 sectors of 876 m
BC2
BC2
BDS
2.75 km
IP
BDS
2.75 km
245 m
245 m
TA radius = 120 m
e⁻ main linac, 12 GHz, 100 MV/m, 21.02 km
e⁺ main linac
TA radius = 120 m
48.3k m
booster linac, 9 GeV
BC1
CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
e⁻ injector, 2.4 GeV
e⁻ PDR 365 m
e⁻ DR 365 m
e⁺ DR 365 m
e⁺ PDR 365 m
e⁺ injector, 2.4 GeV


Legend
CERN existing LHC
Potential underground siting :
CLIC 500 Gev
CLIC 1.5 TeV
CLIC 3 TeV
Lake Geneva
Jura Mountains
IP
Geneva
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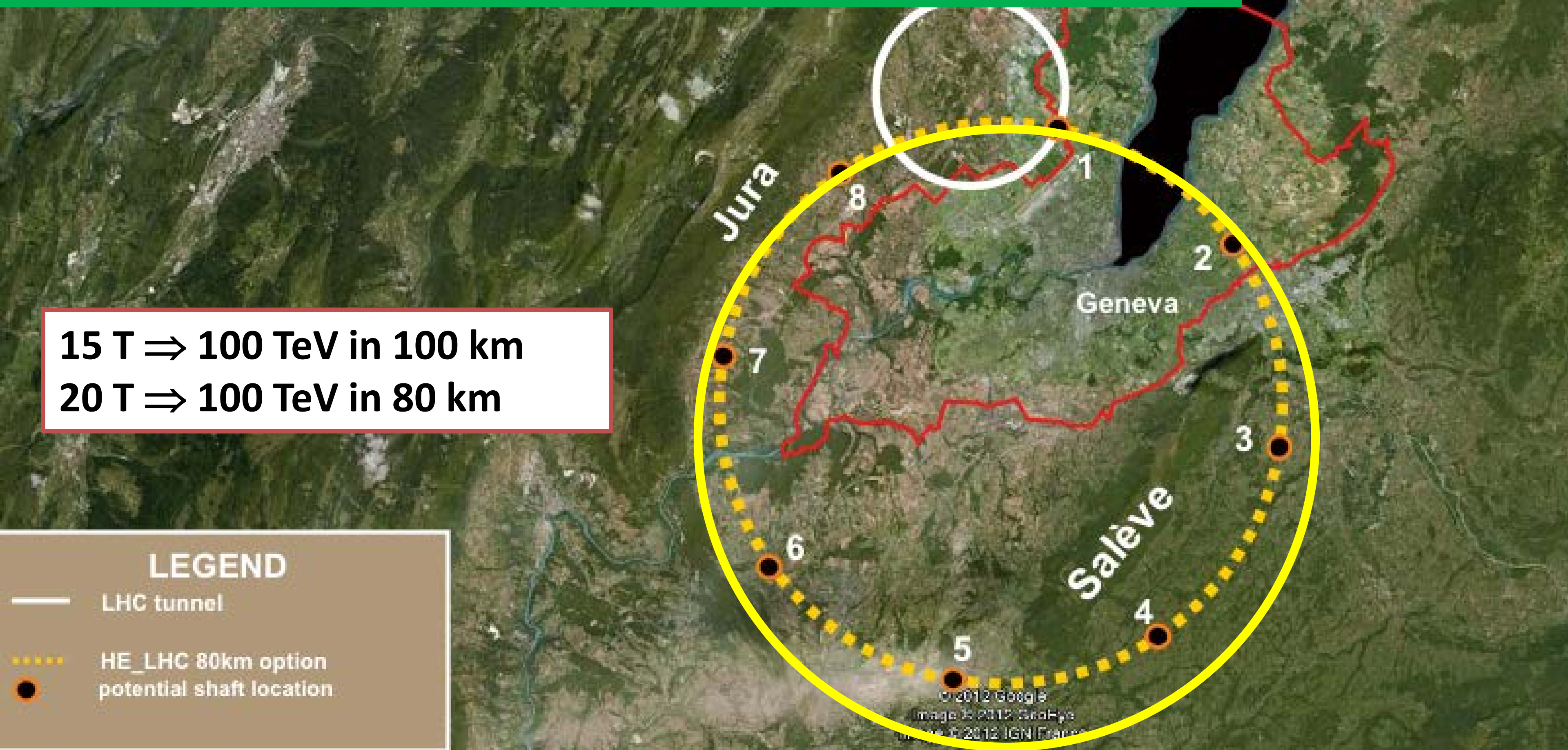
FCC Study (Future Circular Colliders)

CDR and cost review for the next ESU (2018)

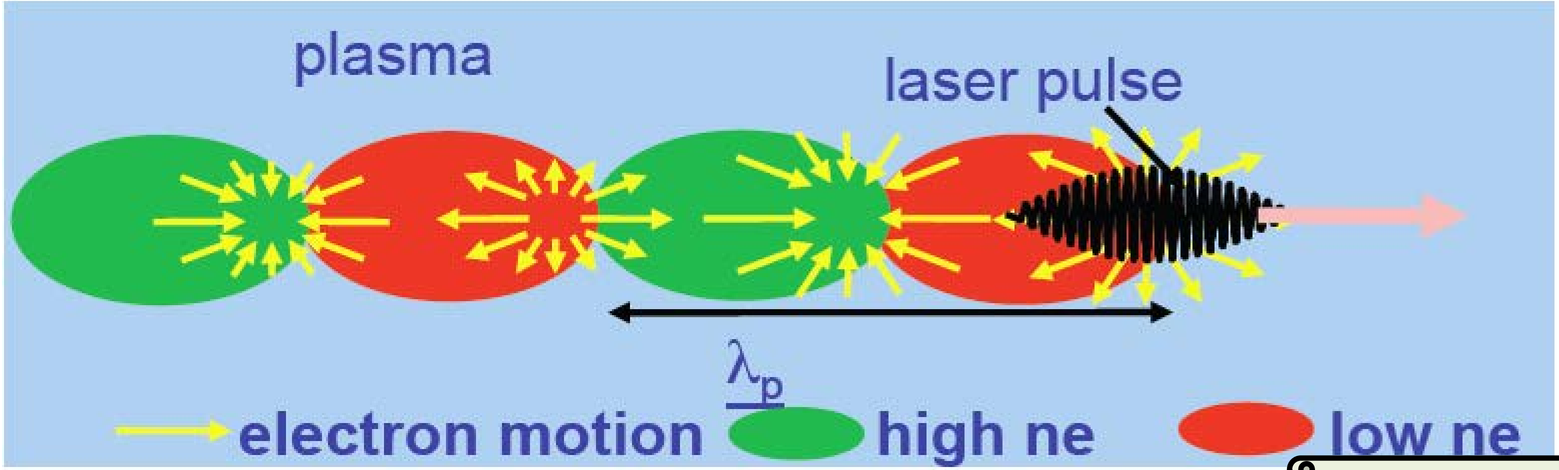
- 80-100 km tunnel infrastructure in Geneva area
- design driven by pp-collider requirements
- with possibility of e+-e- (TLEP) and p-e (VLHeC)
- CERN-hosted study performed in international collaboration

15 T $\Rightarrow$ 100 TeV in 100 km
20 T $\Rightarrow$ 100 TeV in 80 km



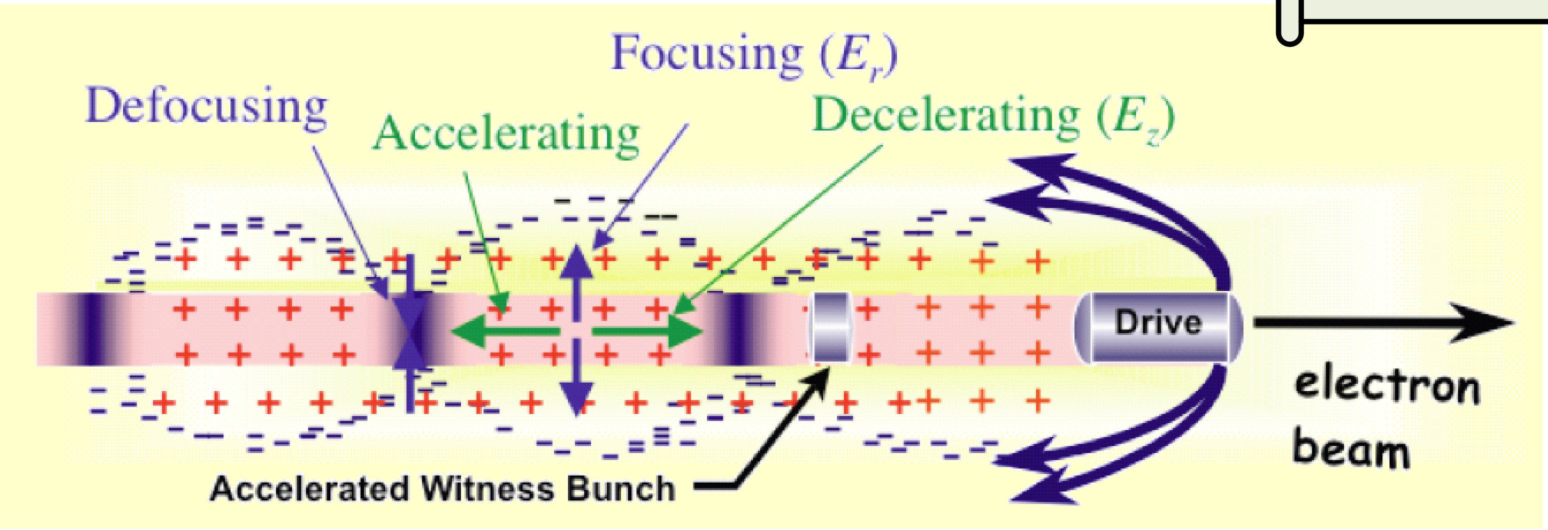
Plasma Wakefield Acceleration

Laser-getrieben:



$E \geq 10$ GV/m

Strahl-getrieben:



Resümee:

Wunsch nach höchsten Energien führt zu unterschiedlichen Konzepten für Collider:

- **Hadronen:** limitiert durch Ablenkung:
  Magnetfelder B < 10 Tesla…
- **Elektronen:** limitiert durch Beschleunigung:
  AC-E-Felder ≤ 40 MV/m

Luminositäten $\geq 10^{34}$ $cm^{-2}s^{-1}$ bilden eine zusätzliche Herausforderung!