

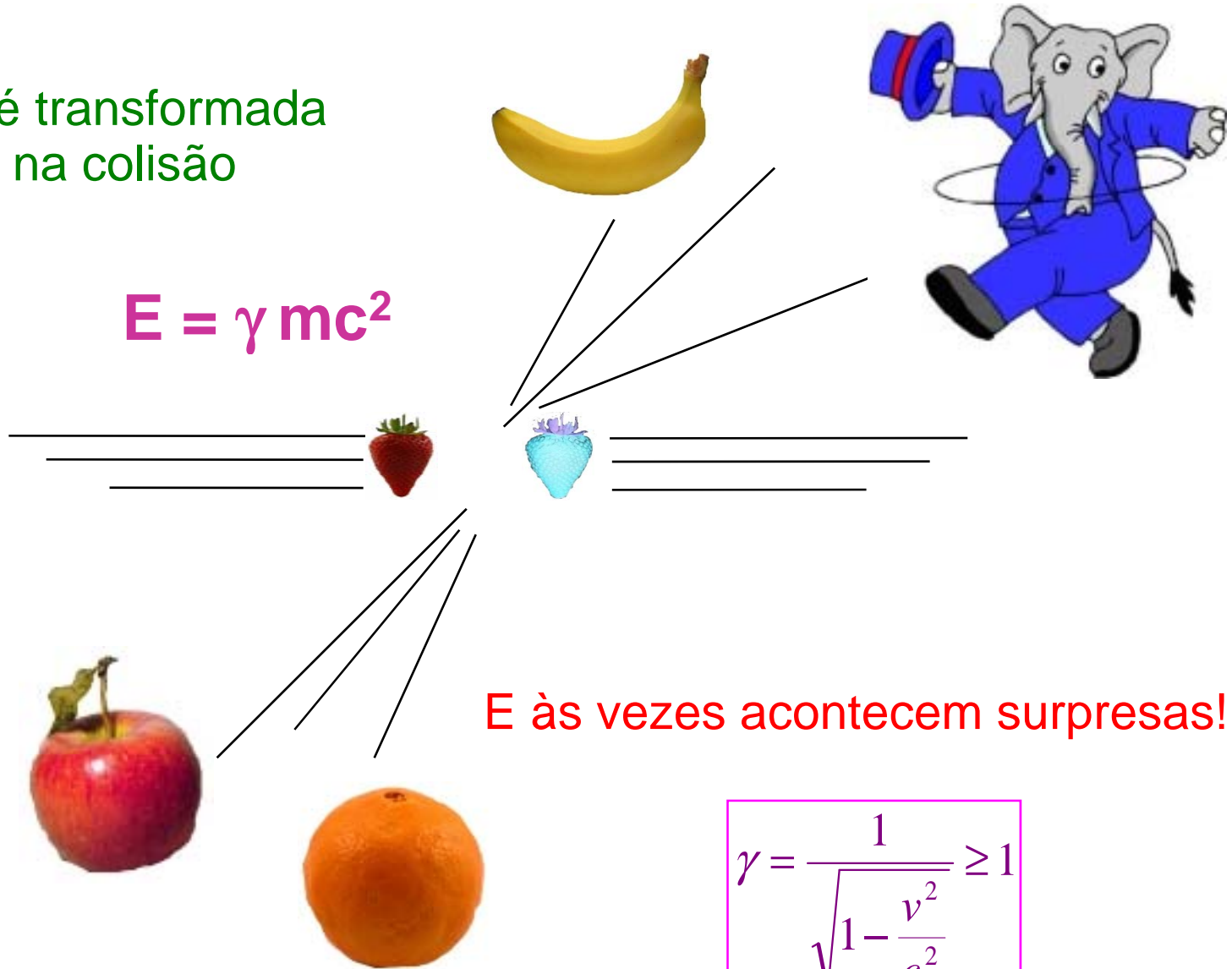


Aceleradores em Física de Partículas

Luis Peralta
FCUL e LIP

A energia é transformada em massa na colisão

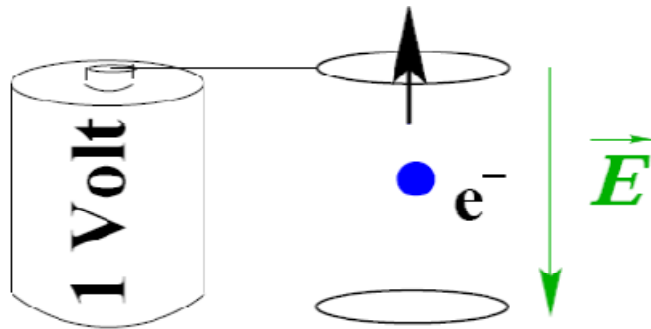
$$E = \gamma mc^2$$



E às vezes acontecem surpresas!

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \geq 1$$

Unidade de Energia – electrão-volt (eV)



$$1 \text{ eV} = 1,602 \times 10^{-19} \text{ joule}$$

Múltiplos mais usados em Altas Energias

keV	MeV	GeV	TeV
(10^3)	(10^6)	(10^9)	(10^{12})

Massa protão $\sim 1 \text{ GeV}/c^2$

Feixe de protões LHC

$E \sim 7 \text{ TeV}$

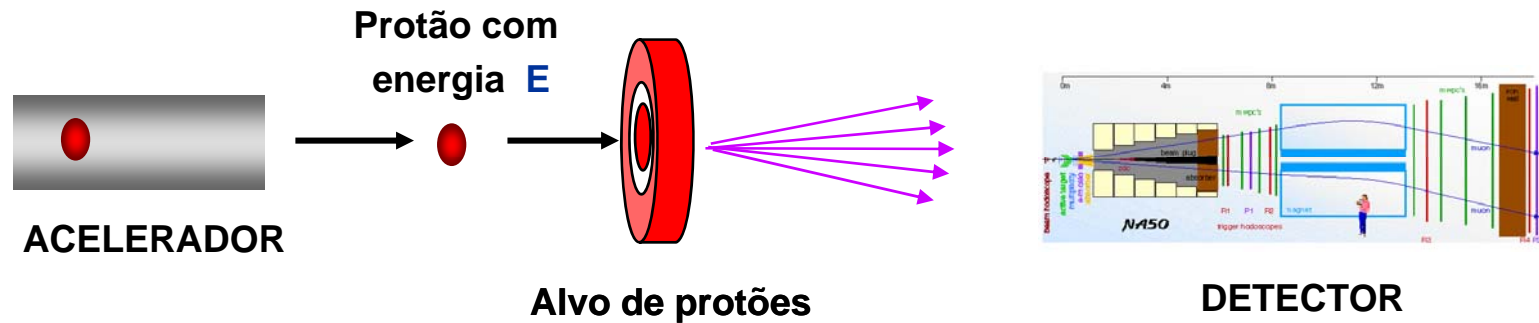
Um mosquito:

$m \sim 2,5 \text{ mg}$



$v \sim 0,5 \text{ m/s} \Rightarrow E_c \sim 6,3 \times 10^{-7} \text{ J} = 4 \text{ TeV}$

Energía útil = Energía no centro de massa



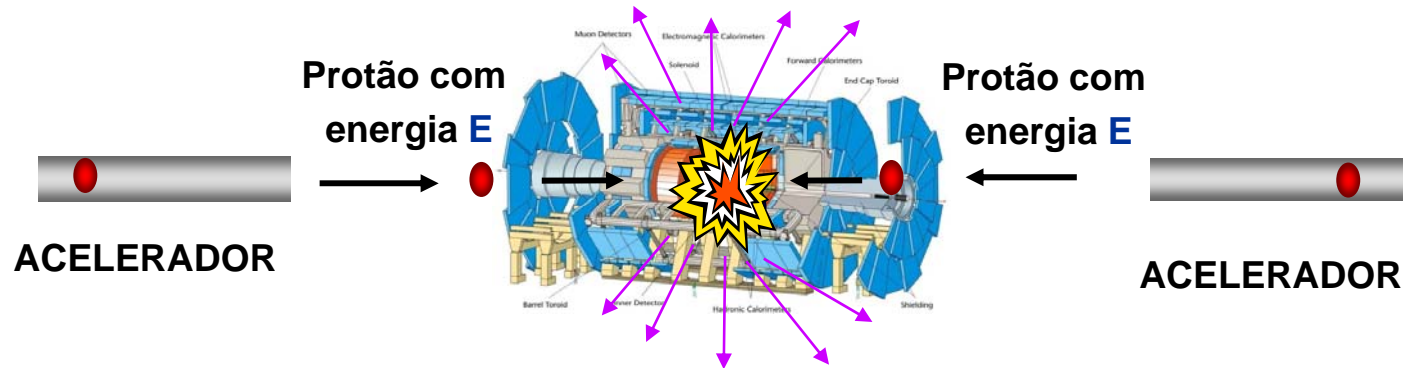
$$E_{cm} \approx \sqrt{2m_p c^2 E}$$

Feixes com alta intensidade

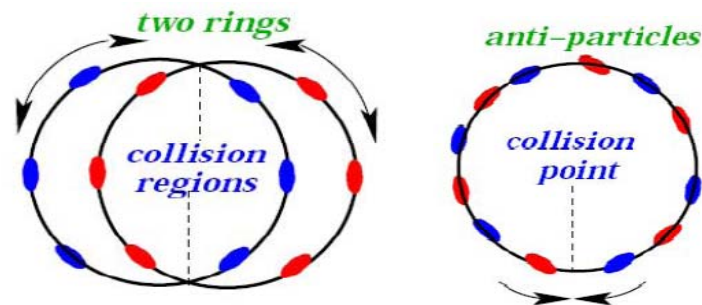
Alvo pode ser escolhido

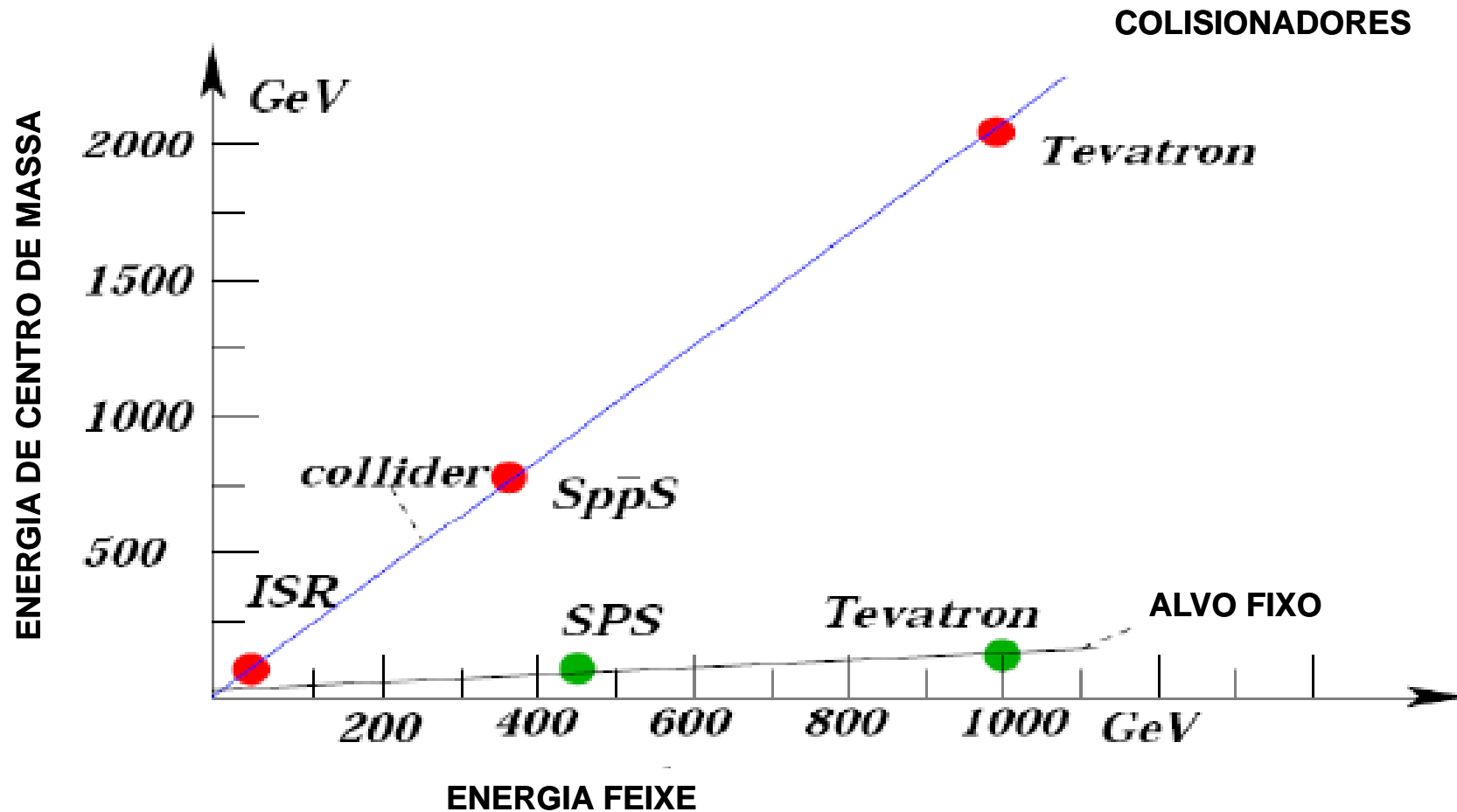
Mau aproveitamento da energia do feixe (menos de 10%)

Energia útil = Energia no centro de massa

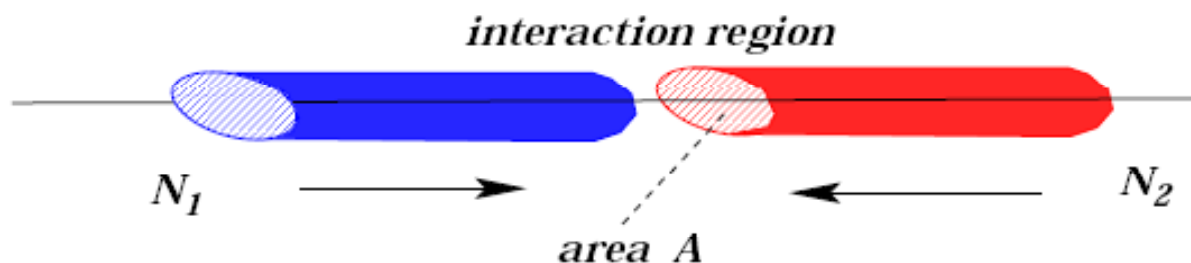


$$E_{cm} = 2 \cdot E$$





Luminosidade: medida da intensidade do feixe



Eventos Luminosidade Secção Eficaz

$$\frac{N}{\Delta t} = L \cdot \sigma$$

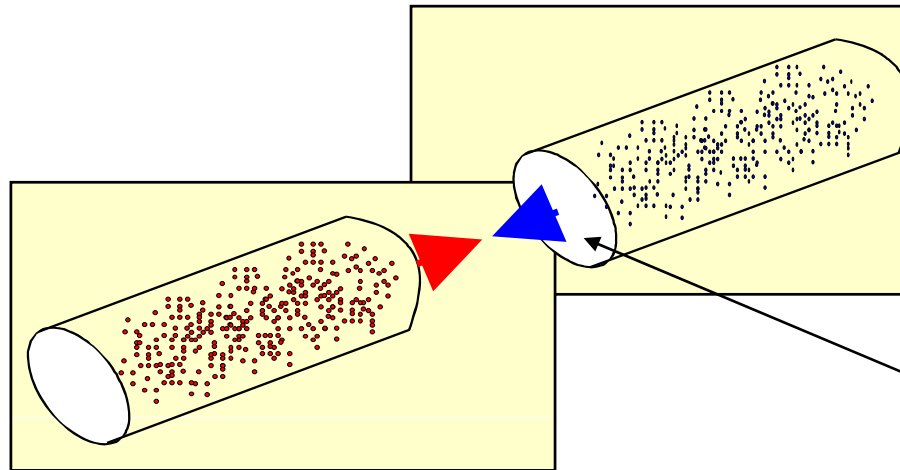
Luminosidade para LHC

10^9 eventos/s

$10^{34} \text{ cm}^{-2}\text{s}^{-1}$

10^{-25} cm^2

Alta Luminosidade Implica:



Partículas por pacote

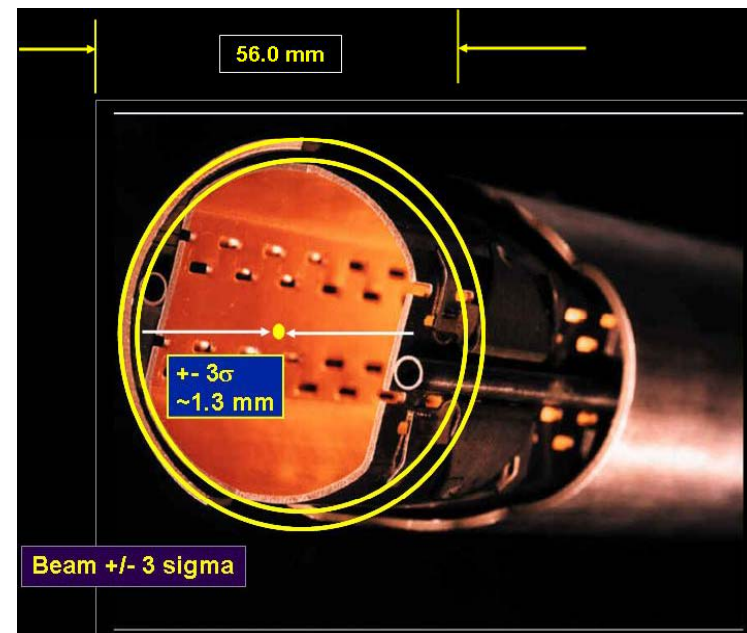
No. Pacotes

$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{A}$$

Área do feixe

Frequência

1. Alta corrente no feixe
2. Muitos pacotes de partículas
3. Tamanho pequeno do feixe



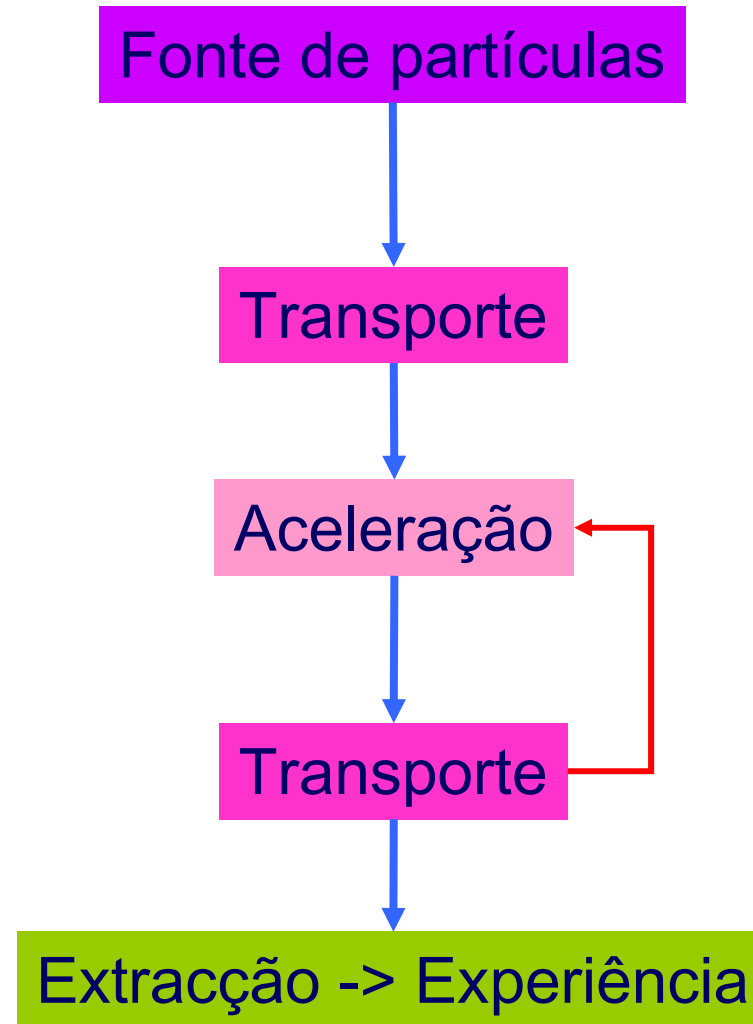
Nº pacotes = 2808

Protões / pacote = 10^{11}

$E = 2 \times 2808 \times 10^{11} \times 7 \text{ TeV} \sim 4 \times 10^{15} \text{ TeV} \sim \mathbf{0,6 \text{ GJ}}$



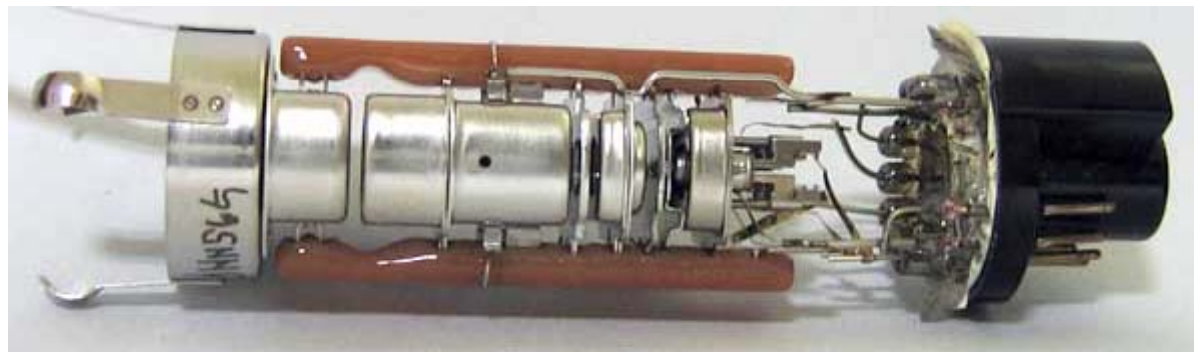
0,6 GJ é a energia cinética de um TGV à velocidade de **200 km/h** !



Só conseguimos acelerar partículas
com carga eléctrica $F=qE$

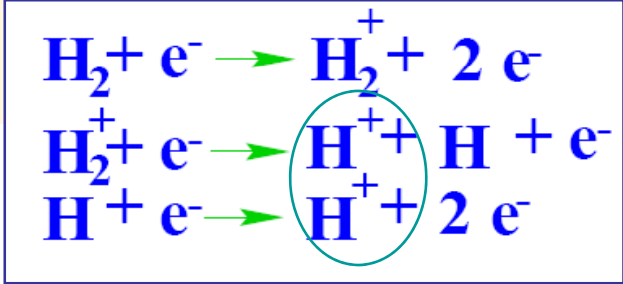
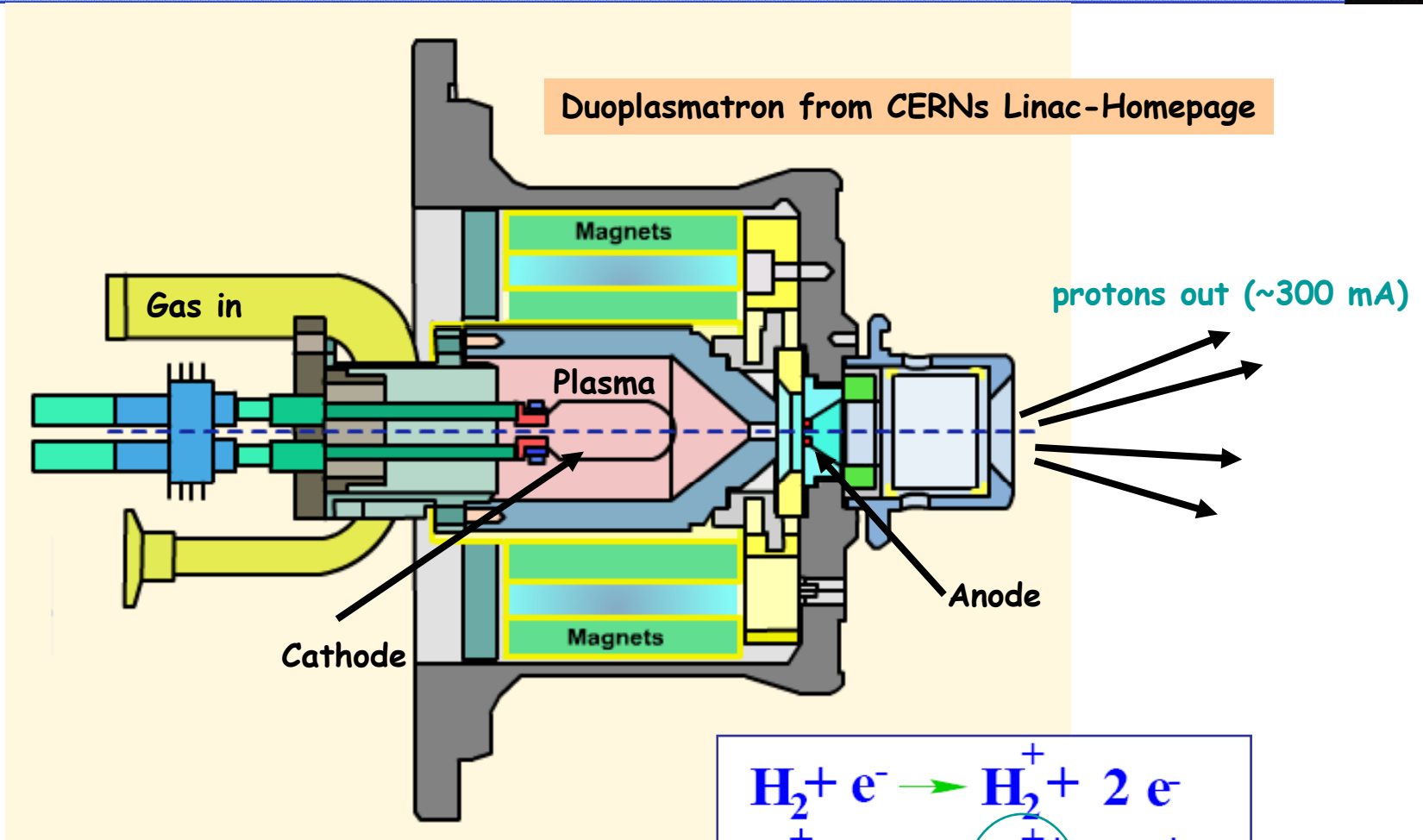


Por efeito termo-
iónico podemos
obter electrões
livres



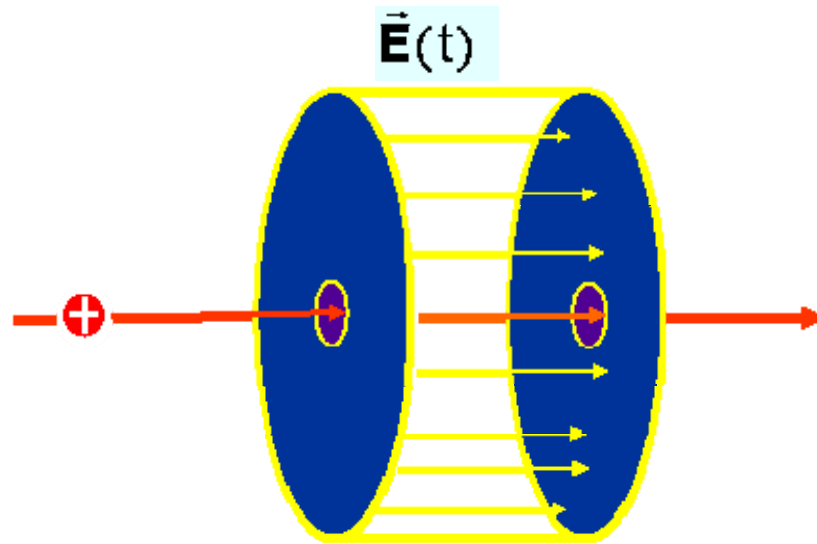
Canhão de electrões do cinescópio de um televisor

Duoplasmatron from CERNs Linac-Homepage

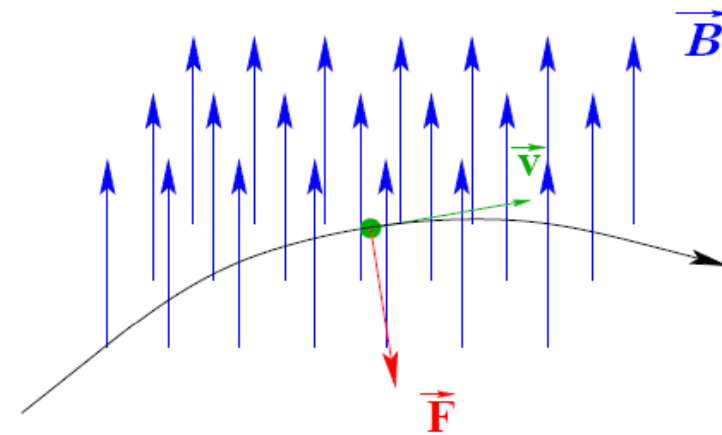


Força de Lorentz

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

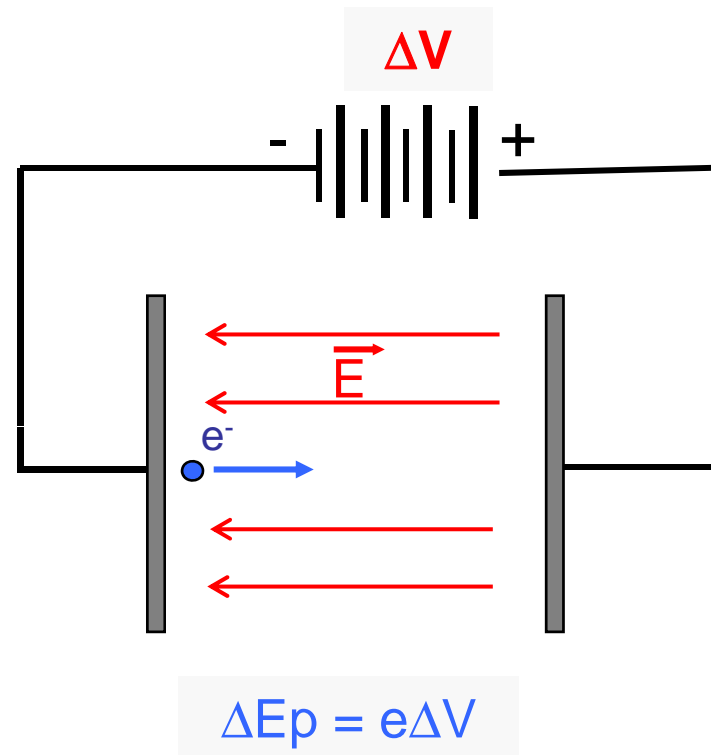


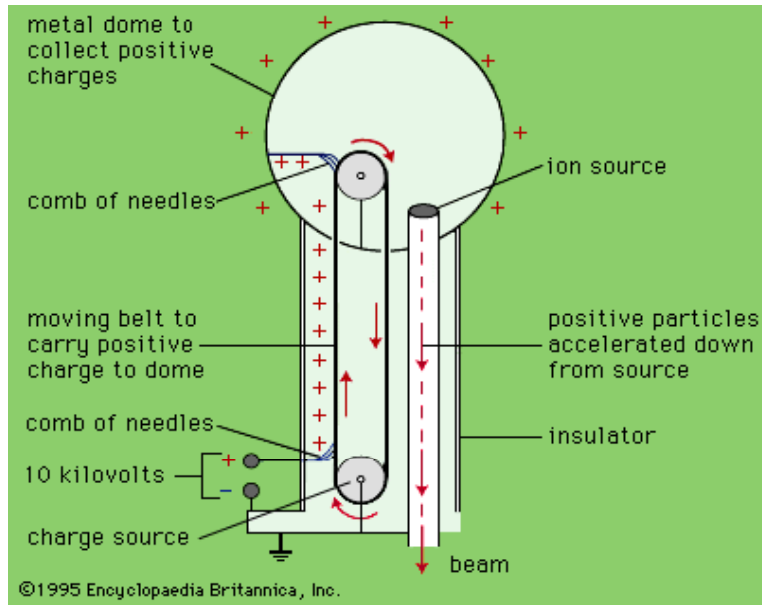
$E(t)$ aumenta a energia



$B(t)$ modifica a trajetória

A ideia é criar uma diferença de potencial suficientemente elevada para acelerar as cargas eléctricas até energias elevadas





Interior do primitivo Van de Graaff do Laboratório de Sacavém

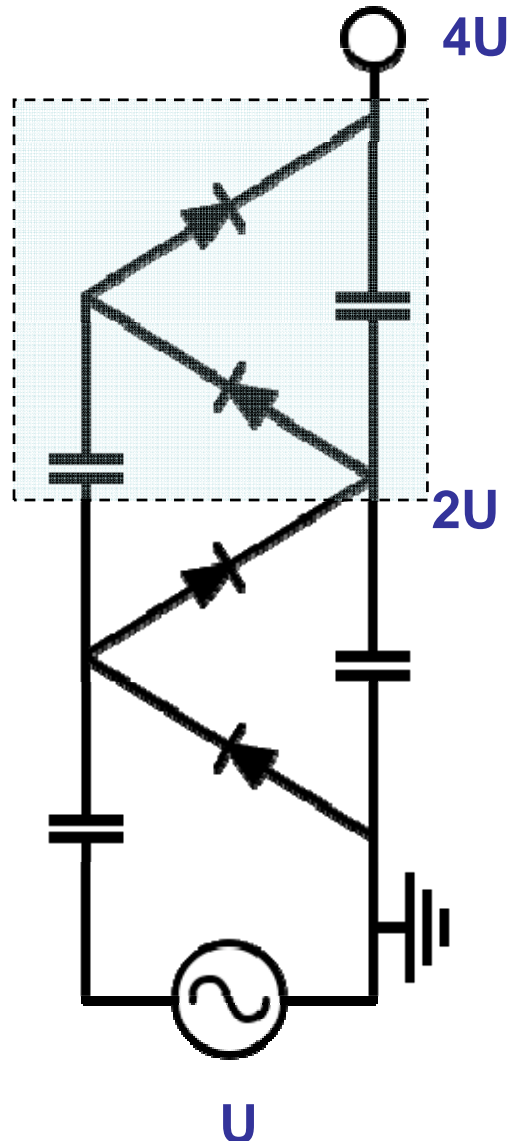
$E < 10 \text{ MeV}$



Van de Graaff do campus Jussieu em Paris

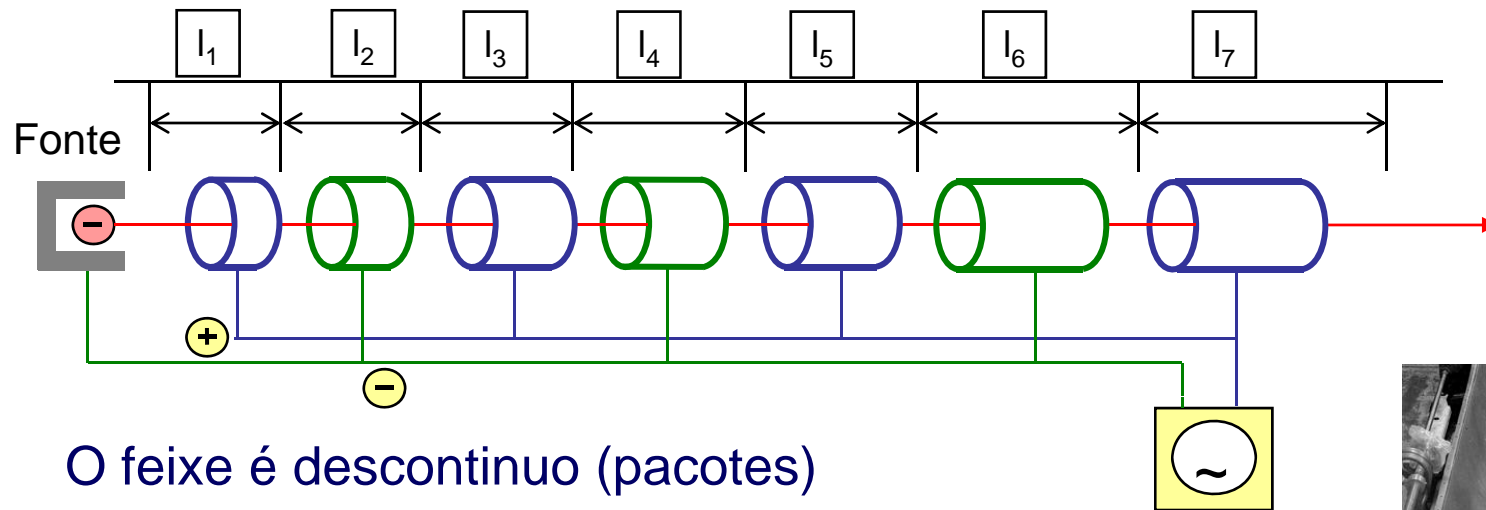
Escada de multiplicação de tensão

$$V_{\text{out}} = 2n U$$



Pré-injector do LINAC2 (750 keV) no CERN. Foi substituído em 1993

Wideroe - 1928

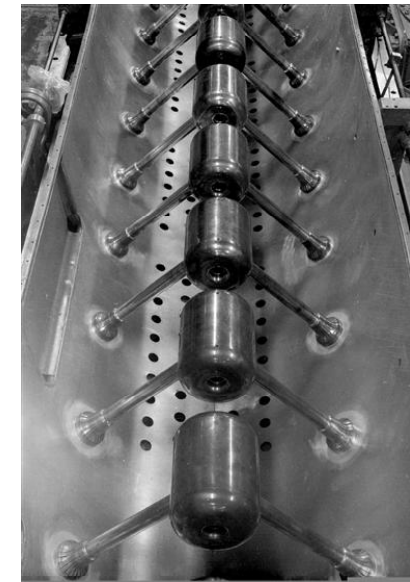
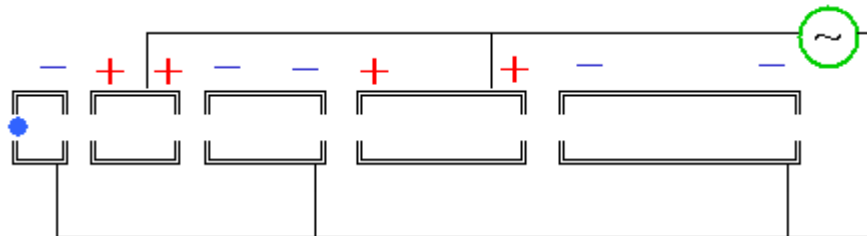


O feixe é descontínuo (pacotes)

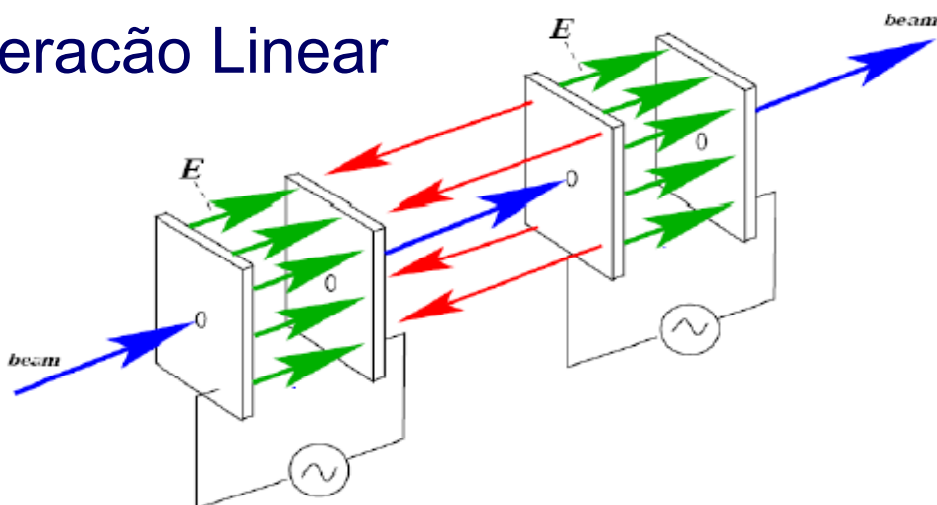
$L_1 < L_2 < L_3 \dots$

Para se obter uma energia elevada são necessário grandes comprimentos

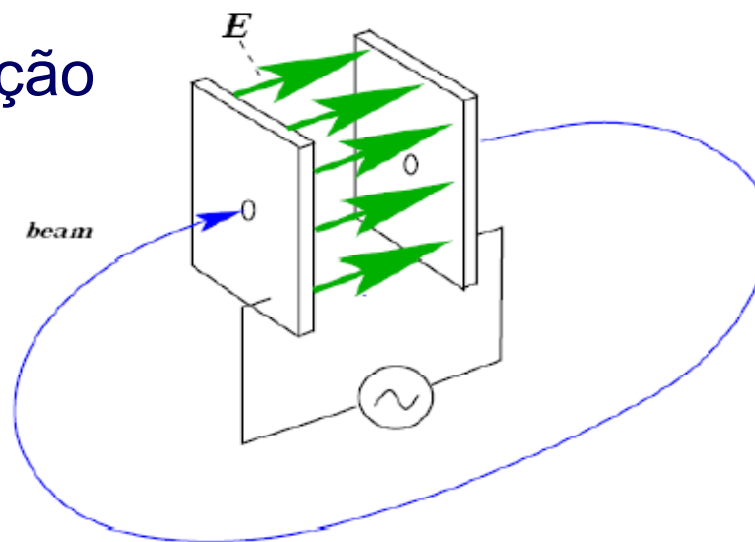
Fonte RF



Aceleração Linear

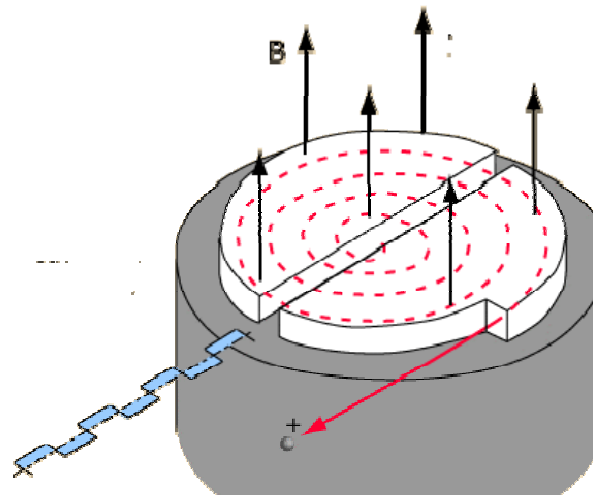
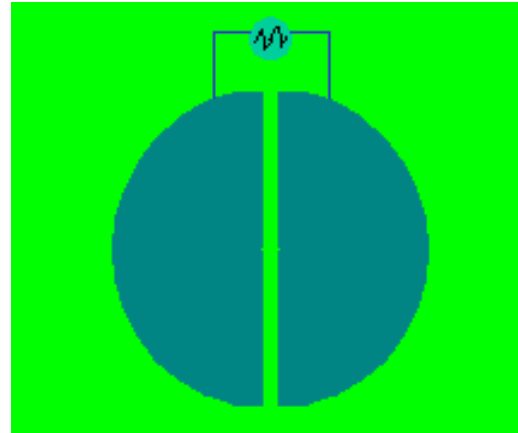


Aceleração Circular





E. Lawrence 1929



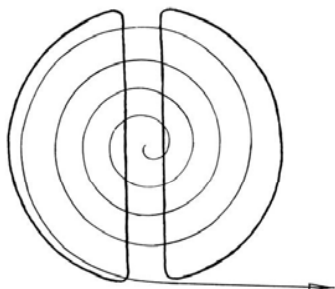
$$\frac{mv^2}{r} = vqB$$

força centrípeta = força Lorentz

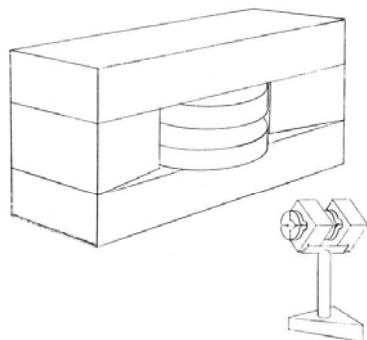
$$\omega = \frac{v}{r}$$

$$f = \frac{qB}{2\pi \cdot m} \quad \text{frequência do ciclotrão}$$

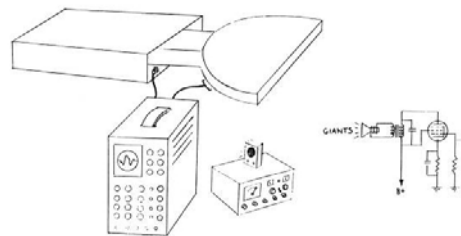
O ciclotrão visto por...



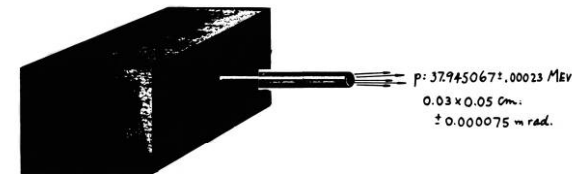
... the inventor



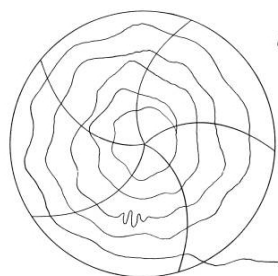
... the mechanical engineer



... the electrical engineer



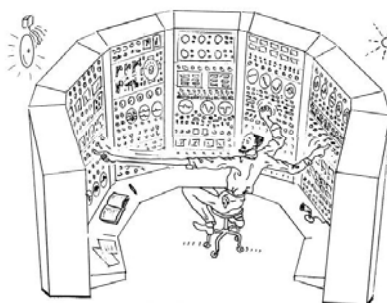
... the experimental physicist



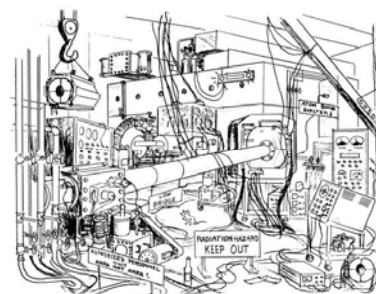
... the theoretical physicist

$$r = r_0 \left[1 + \left(\frac{t r \omega}{r_0} \right) \cos(3\theta + \delta_0 + \delta_1 r) + \left(\frac{t r \omega}{r_0} \right)^2 \cos(5\theta + \delta_2 - \delta_2 r^2) + \left(\frac{t r \omega}{r_0} \right)^3 \cos(7\theta + \delta_3 - \delta_3 r^3) + \dots \right] \times \left\{ \frac{e^{2\pi i k r Z}}{1 + \left(\frac{t r \omega}{r_0} \right)^2} \right\}$$

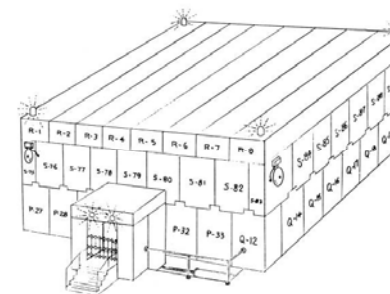
$$\frac{d\theta}{dt} = \left[\sin(\omega t - k\theta) - i \sin k\theta - \frac{3}{2} \frac{t r \omega}{r_0} \cos k\theta - \frac{5}{8} \left(\frac{t r \omega}{r_0} \right)^2 \frac{e^{2\pi i k r Z}}{1 + \left(\frac{t r \omega}{r_0} \right)^2} \right] \frac{e^{2\pi i k r Z}}{2\pi r \omega}$$



... the operator



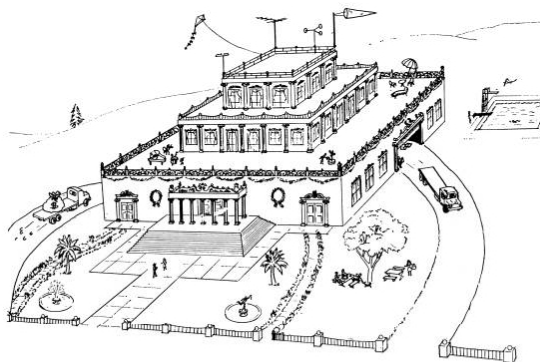
... the visitor



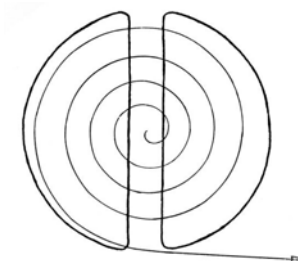
... the health physicist



... the laboratory director



... the governmental funding agency



... the student

desenhos de Dave Judd e
Ronn MacKenzie



Sincrociclotão e ciclotrão isócrono



$$f = \frac{qB}{2\pi \cdot \gamma m}$$

Para partículas relativistas a frequência de ciclotrão varia com a velocidade $\gamma > 1$

Para manter as partículas em fase com o potencial acelerador no hiato dos D com o aumento da energia das partículas é necessário:

Variar B com o raio :ciclotrão isócrono

Variar a frequência f do gerador de RF:sincrociclotrão

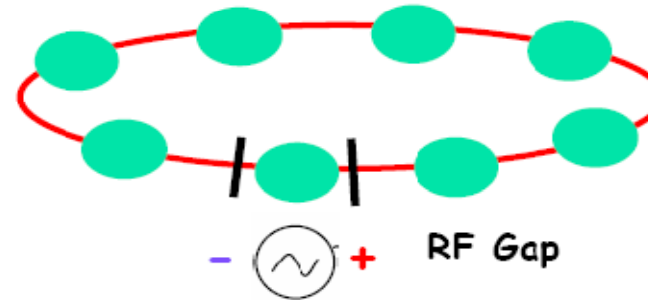
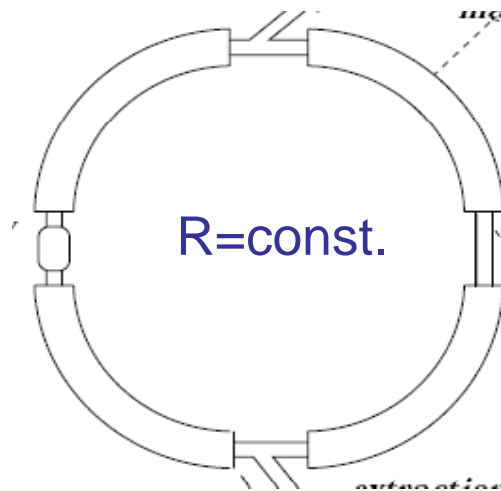
$$\frac{mv^2}{r} = vqB$$



$$B = \frac{\gamma mv}{qr}$$

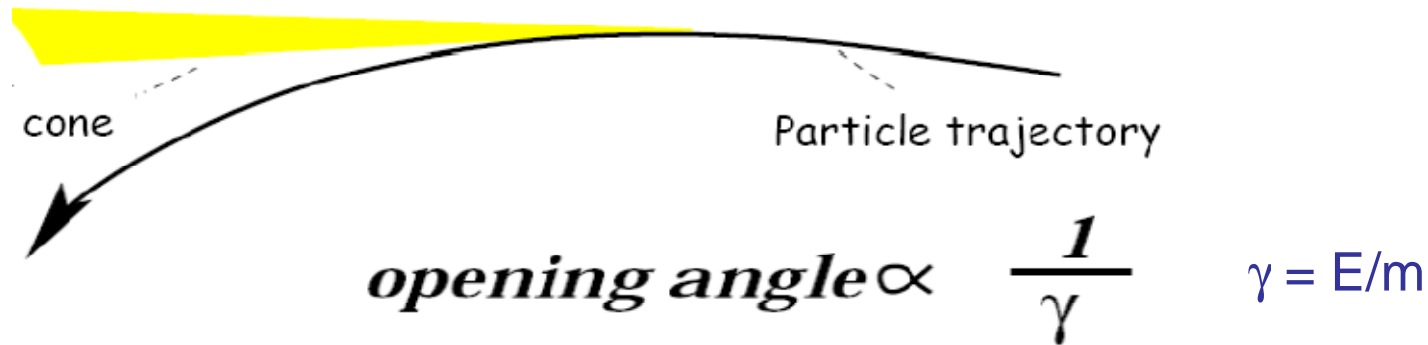
relativista

$$B[T] = \frac{p[\text{GeV}/c]}{0,3 r[m]}$$



- O feixe ganha energia em cada volta
- São necessários imanes dipolares para curvar o feixe
- O campo B e a energia do feixe variam sincronizadamente.
- Os elementos aceleradores (cavidades de RF) podem estar distribuídos por todo o anel (LEP) ou localizados num ponto (LHC)

A radiação emitida pelas partículas sujeitas à aceleração centripeta limita a energia que é possível alcançar



$$\langle E_{\gamma} \rangle \propto \frac{\gamma^3}{r}$$

LEP Electrões $E=90$ GeV $\Rightarrow \gamma=180000$

LHC Protões $E=7$ TeV $\Rightarrow \gamma=7000$

- Em LEP (90 GeV), os electrões/positrões perdiam quase 1 MeV em cada volta em forma de raios gama.
- Os protões de LHC (7000 GeV) perderão só 0.04 keV por volta

□ Leptões: (e^- / e^+)

Partículas Elementares

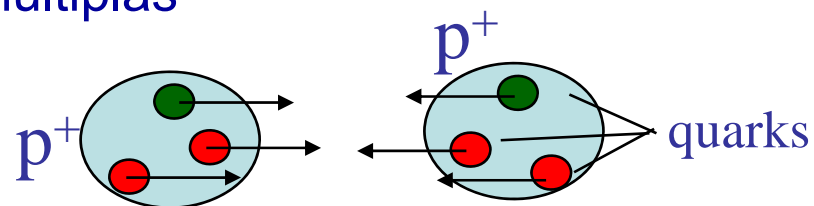


→ Energia muito bem definida

→ Experiências de precisão

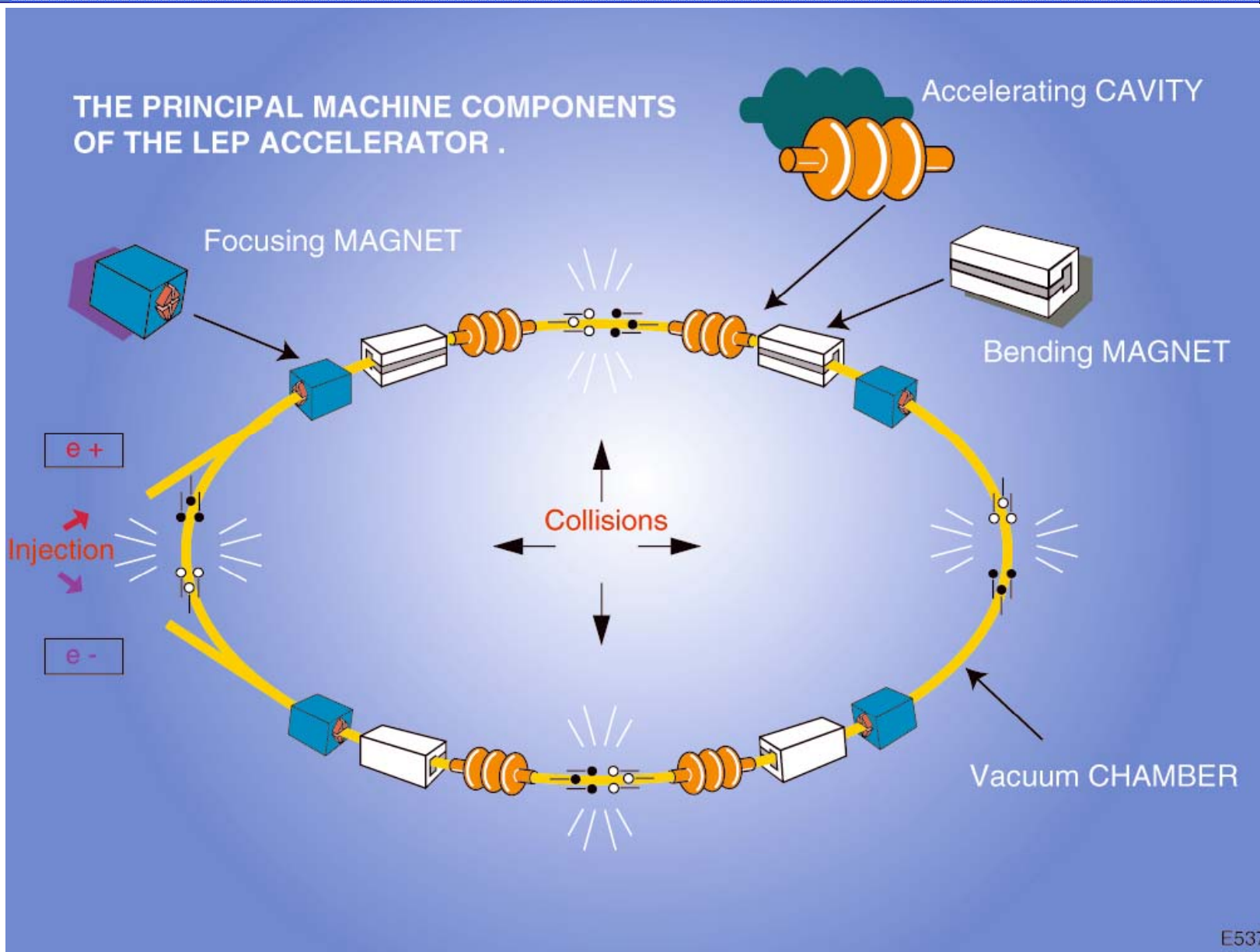
□ Hadrões: (p^- / p^+)

Colisões múltiplas



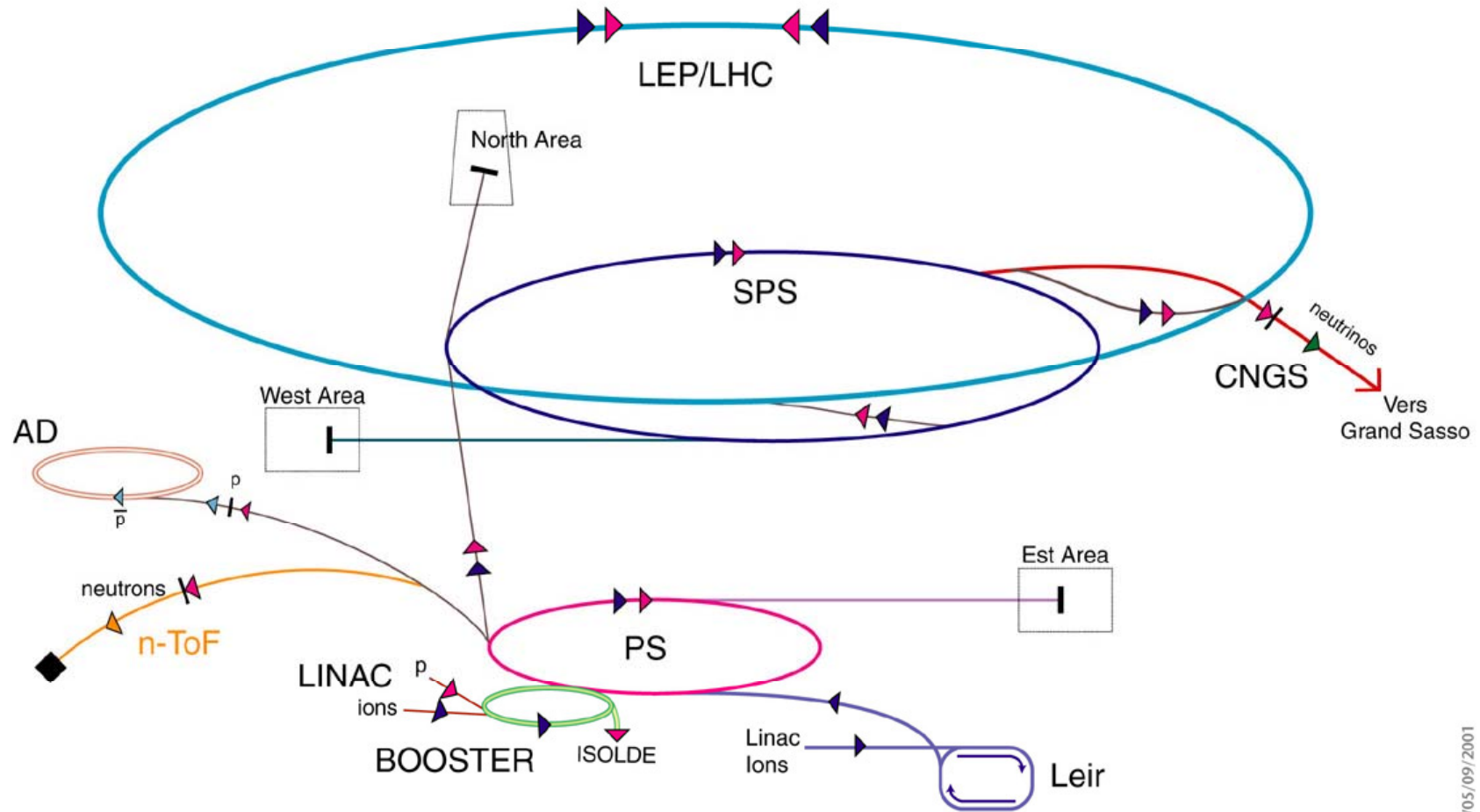
→ Dispersão de Energia

→ Experiências com grande potencial de descoberta

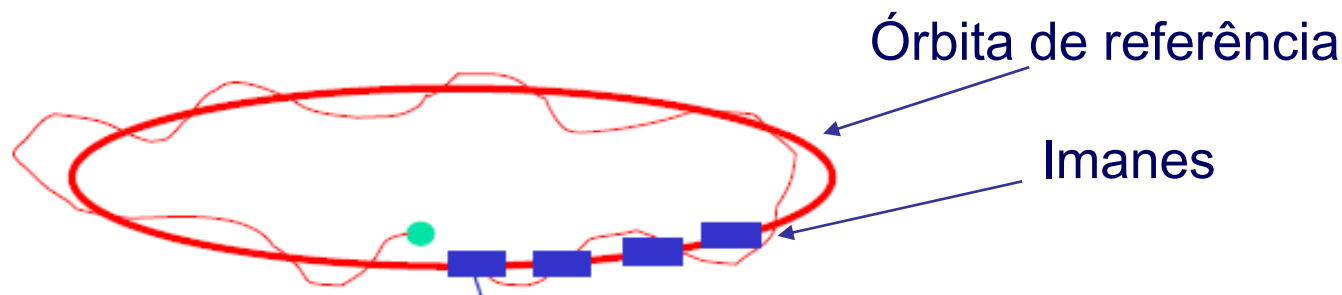


E537

Cadeia de injeção do LHC no CERN

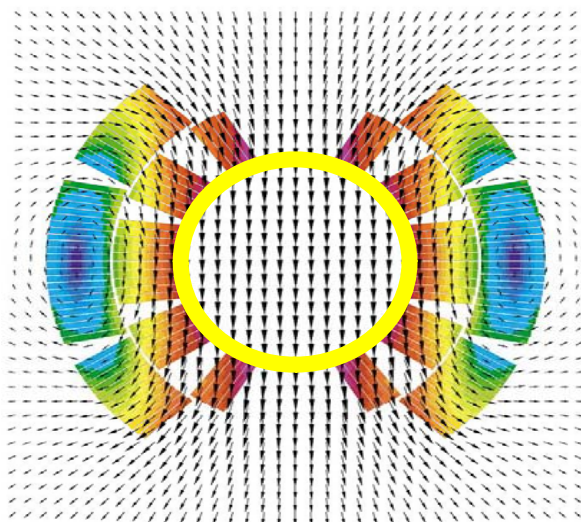


- | | | | |
|--------------|--------------------------------|------------------------------|---------------------------------|
| ▶ p (proton) | ▶ \bar{p} (antiproton) | AD Antiproton Decelerator | LHC Large Hadron Collider |
| ▶ ion | ▶ proton/antiproton conversion | PS Proton Synchrotron | n-ToF Neutrons Time of Flight |
| ▶ neutrons | ▶ neutrinos | SPS Super Proton Synchrotron | CNGS Cern Neutrinos Grand Sasso |



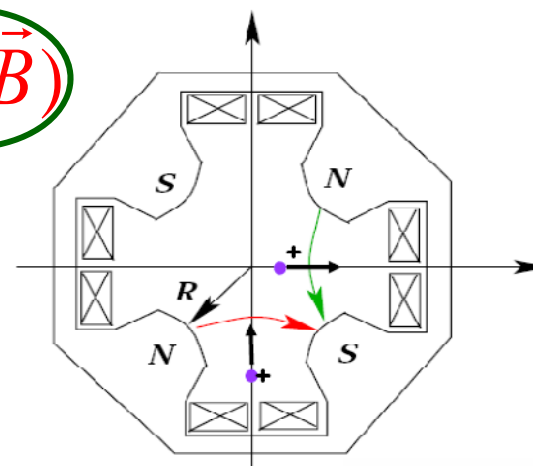
Curvatura: **Dipólos**

Focalização: **Quadrupólos**

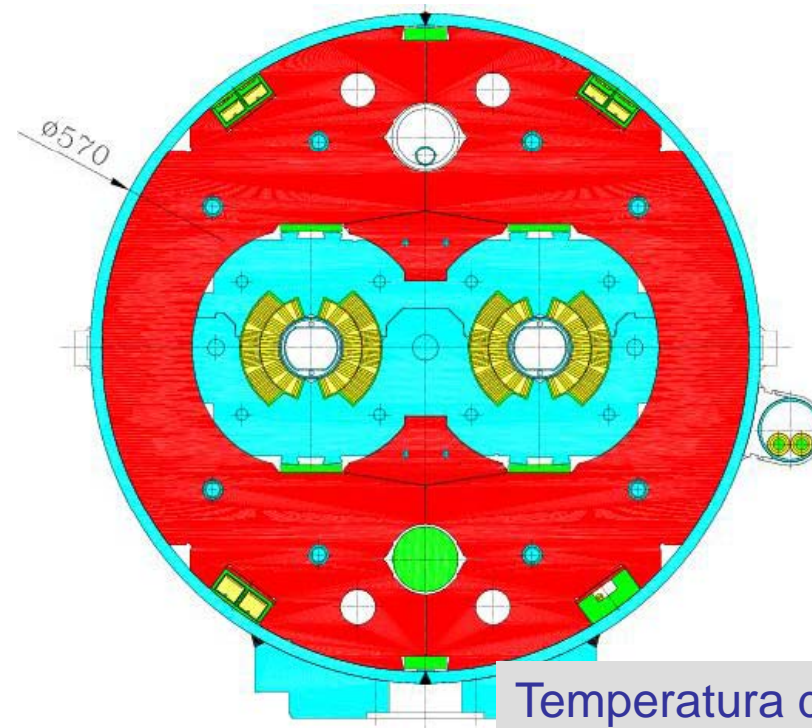
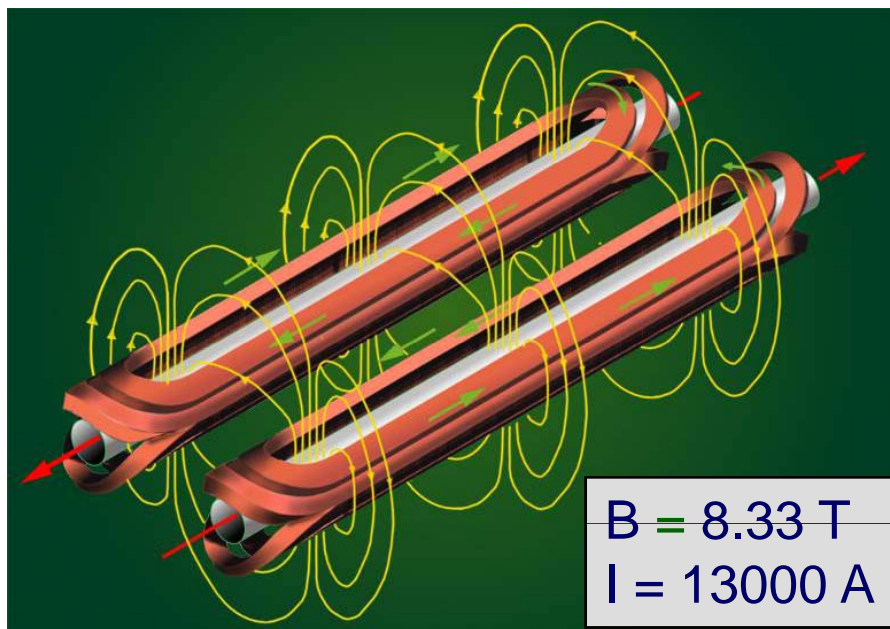


Uma partícula carregada circulando no tubo de feixe (perpendicular ao plano do slide) será desviada para a esquerda ou direita conforme o sinal da sua carga.

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$



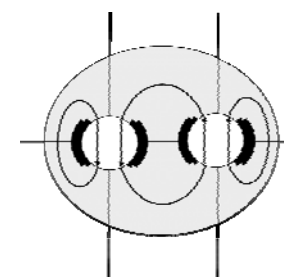
Uma partícula positiva dirigida para fora do plano do slide focaliza no plano vertical e desfocaliza no plano horizontal. A força é proporcional à distância ao centro.



Temperatura de trabalho ~1.9 K



1232 criodipolos de 15 m de comprimento



Construção 2 em 1

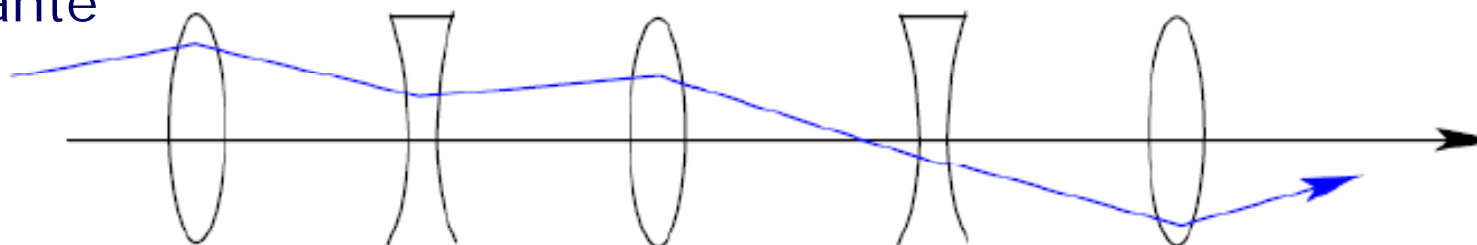


A energia armazenada no dipolos e quadrupolos principais do LHC é análoga à energia cinética do porta-aviões **USS Kitty Hawk** quando se desloca a **55 km/h**

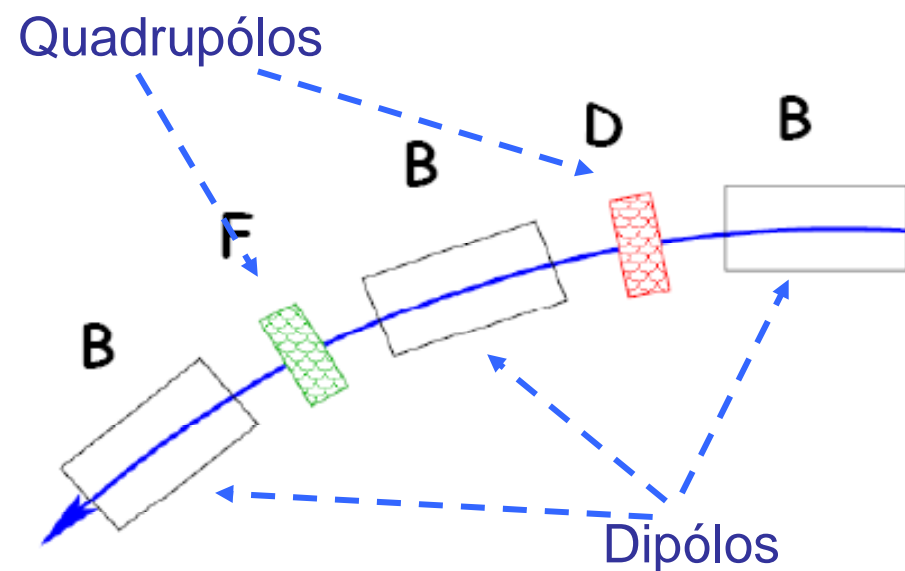
Quando as coisas não funcionam...!

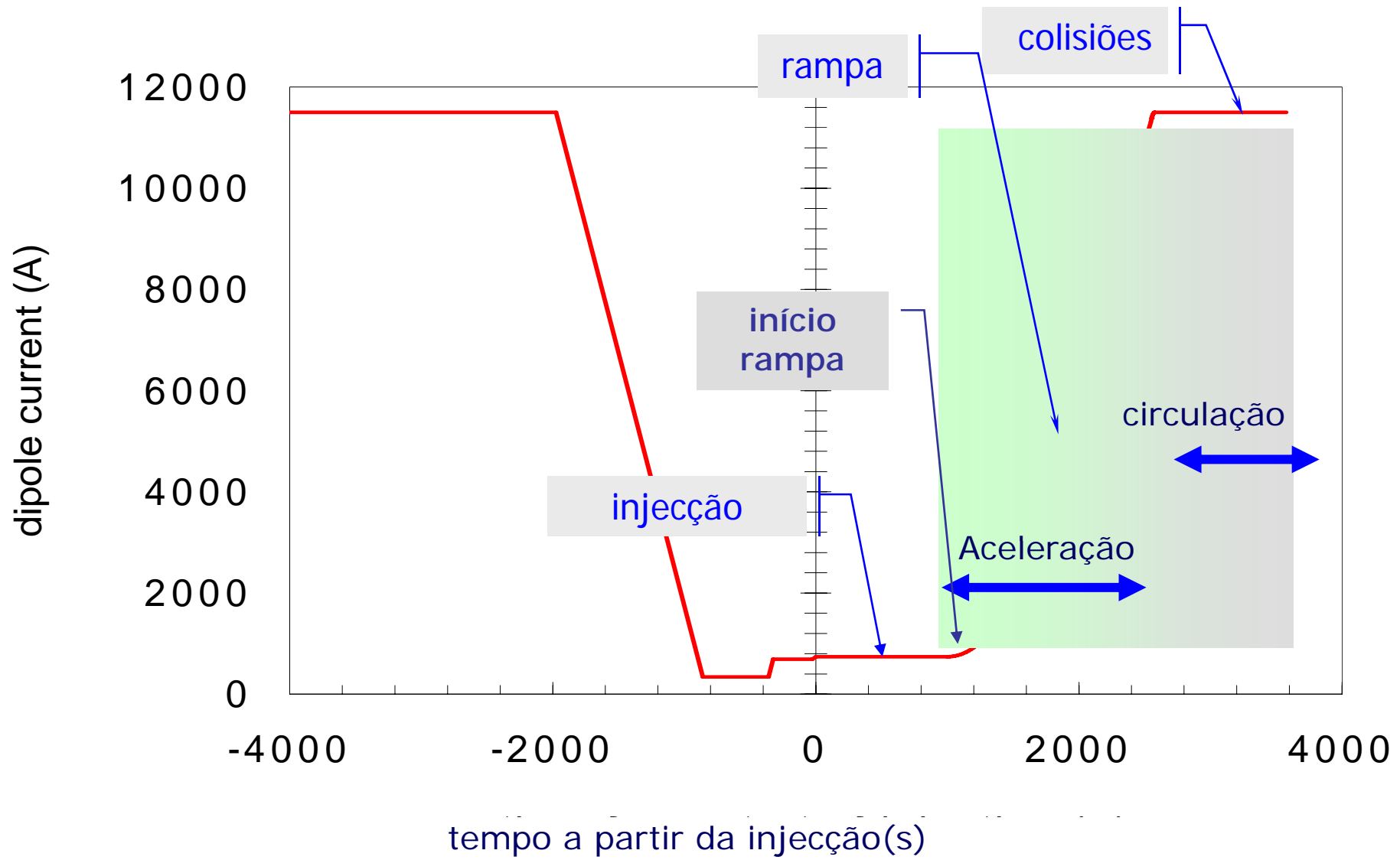


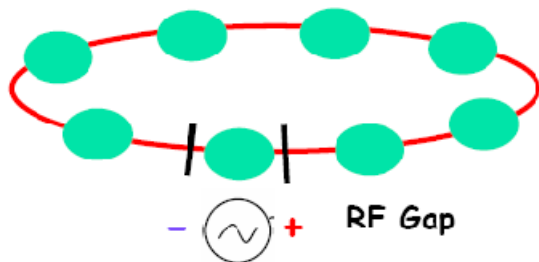
Um gradiente de focalização alternado (focalização-desfocalização no plano horizontal-vertical) dá um efeito global focalizante



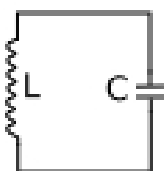
No quadrupólo quanto maior é a distância ao centro maior é o desvio sofrido pela partícula



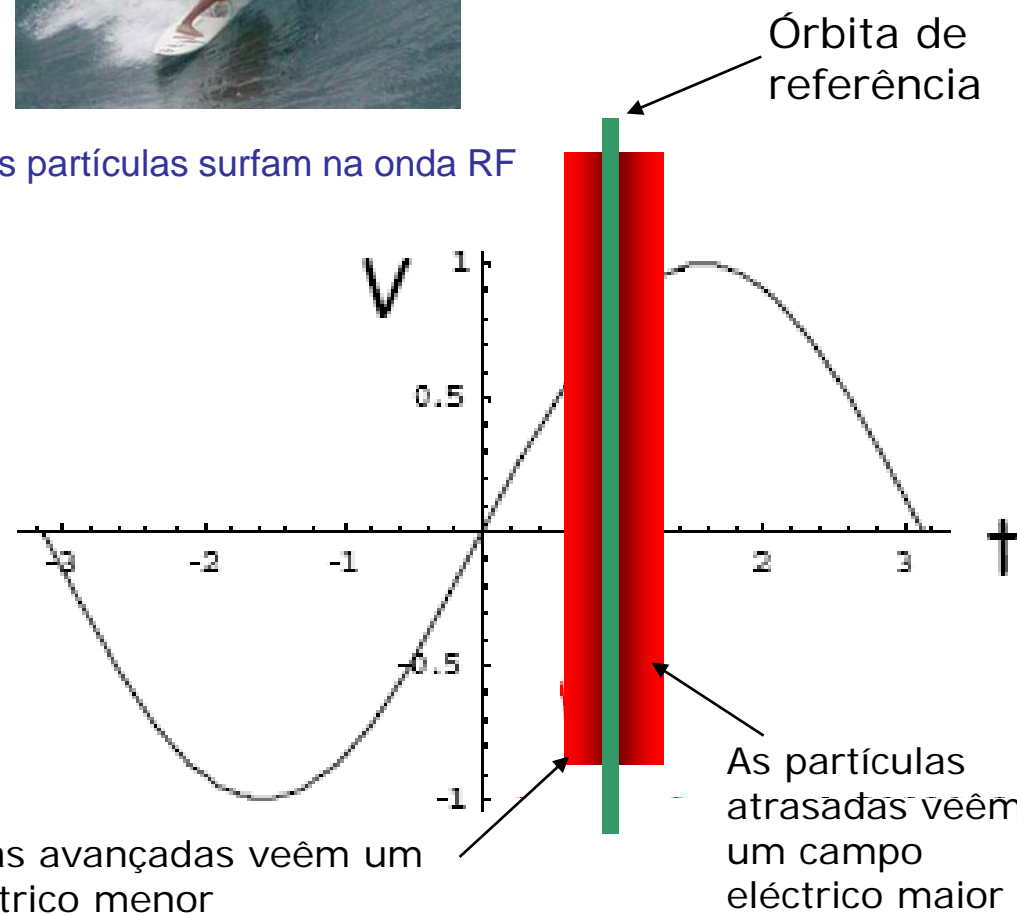
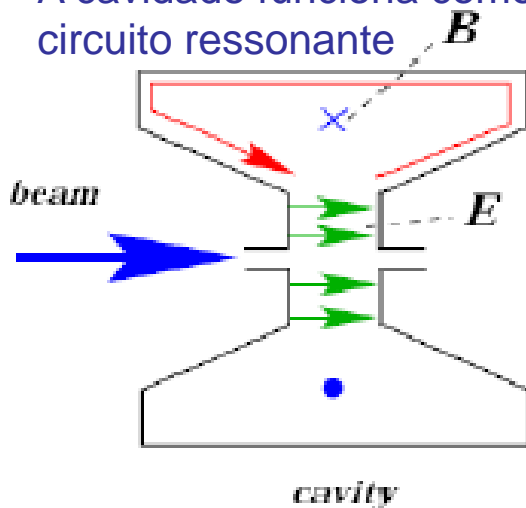


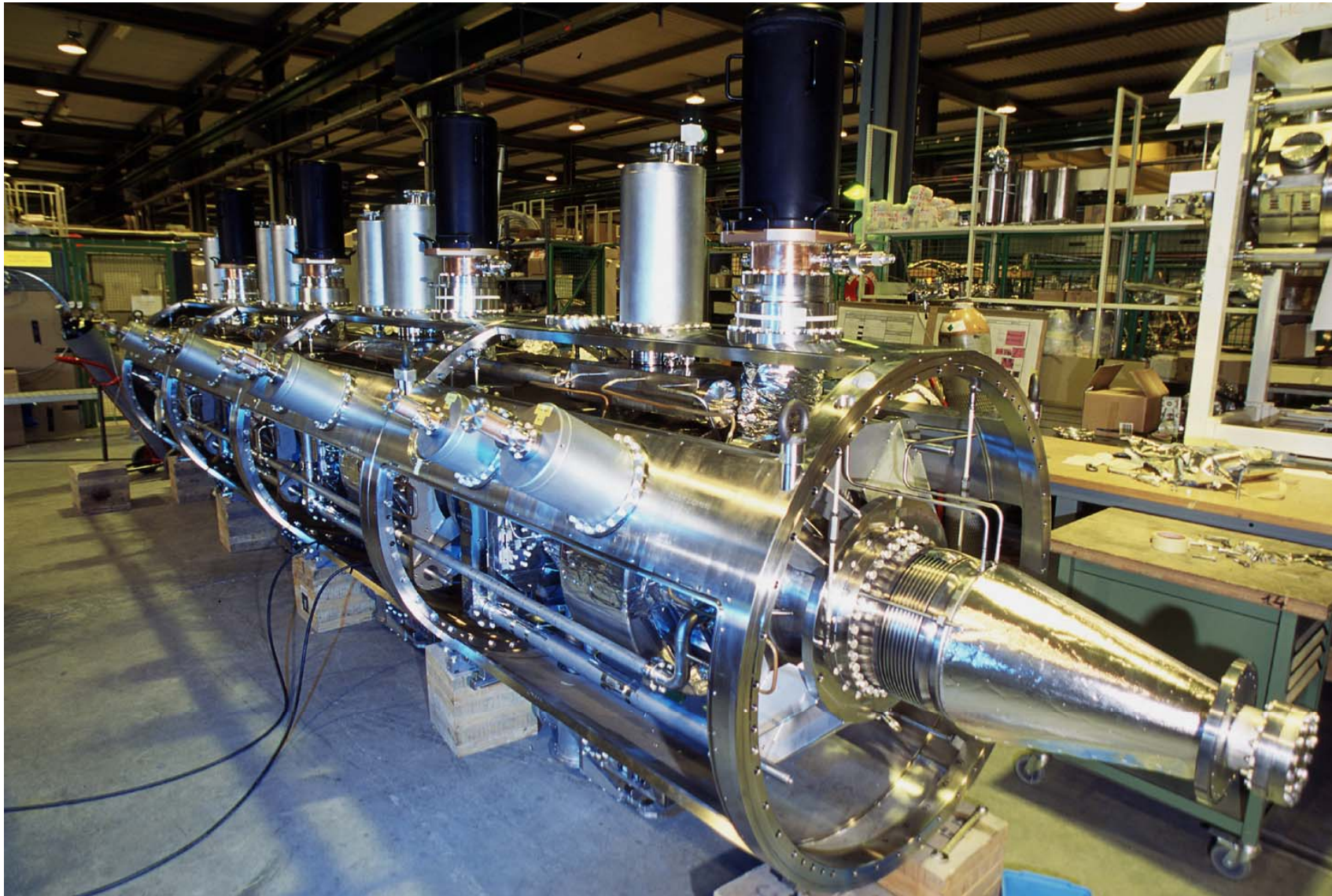


As partículas surfam na onda RF

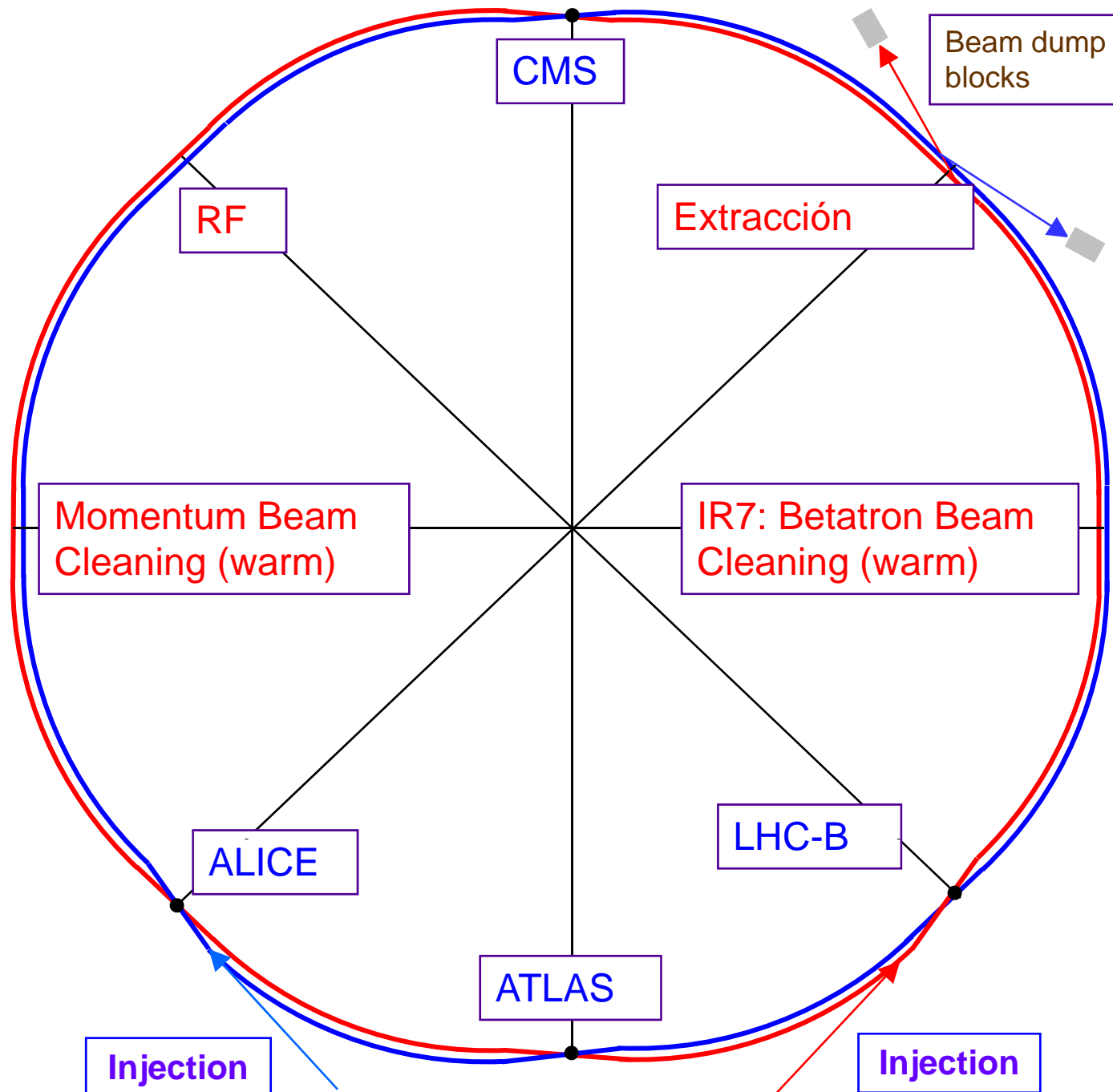


A cavidade funciona como um circuito ressonante











Agradecimentos



Vários slides / figuras foram retirados das apresentações de:

Antonio Vergara (CERN – CIEMAT) “Introducción a los Aceleradores de Partículas”, 2007

Elena Wildner (AT/MCS) “Introduction to Accelerators”, 2007