High Power Proton LINACs
PART 2

JOINT UNIVERSITIES
ACCELERATOR SCHOOL

Sébastien BOUSSON
CNRS/IN2P3
Pôle Accélérateurs
IJCLab
bousson@ipno.in2p3.fr

IJCLab
Irène Joliot-Curie
Laboratoire de Physique
des 2 Infinis

(New Laboratory in Orsay issued from the merging of IPNO, LAL, CSNSM, IMNC and LPT)

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Superconducting cavities

- « **CAVITY** » = Electromagnetic resonant cavity

  ⇒ RF fields (electric and magnetic)

  ⇒ To accelerate charged particles

- « **SUPERCONDUCTING** » : very low operating temperature (Liquid Helium)

  ⇒ Superconducting state of the matter

Frequency f

50 MHz to 3 GHz

Size

Proportional to 1/f

Temperature T

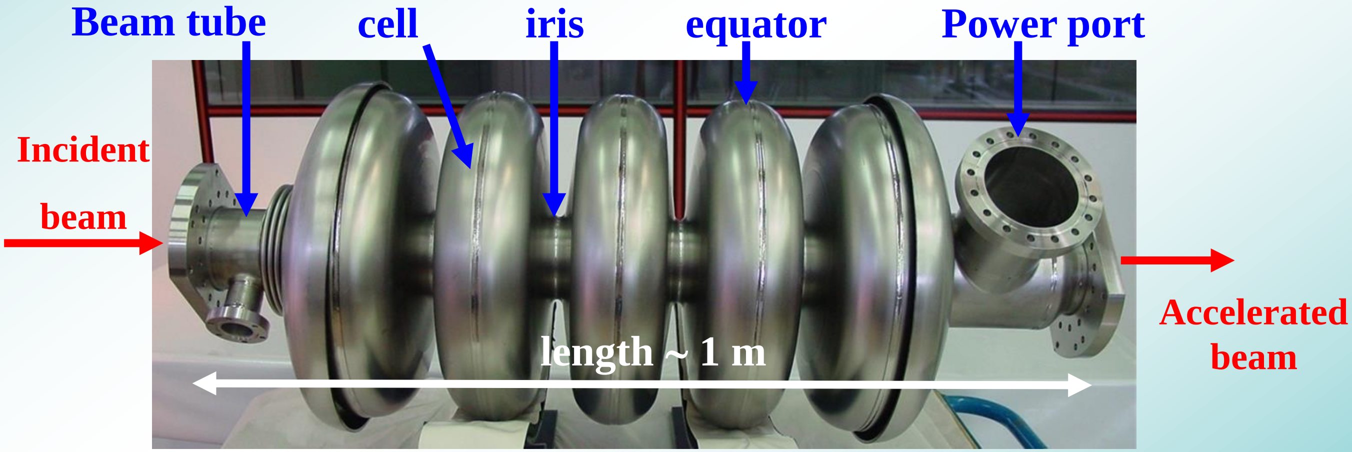
1,5 K to 4,5 K

Accelerated particle velocity

β=v/c from 0,01 to 1

0 K ≈ - 273,15 °C

$c \approx 2{,}998 \cdot 10^8$ m/s



Superconducting cavity (IPN Orsay) – 5 cells, 700 MHz, β=0,65

Why using superconducting cavities ?

<u>Intrinsic advantage of cold cavities</u>

Almost no losses on the cavity wall (thanks to superconductivity)

⇒ ~100% of the injected RF power goes to the beam : very high efficiency !!!

- **<u>Operating cost gain</u>** as compared to warm structures (which dissipate ~10^5 times higher)

- **Possibility to accelerate CW beams or beams with a high duty cycle (> 1 %) with high accelerating gradients** (impossible with warm structures)

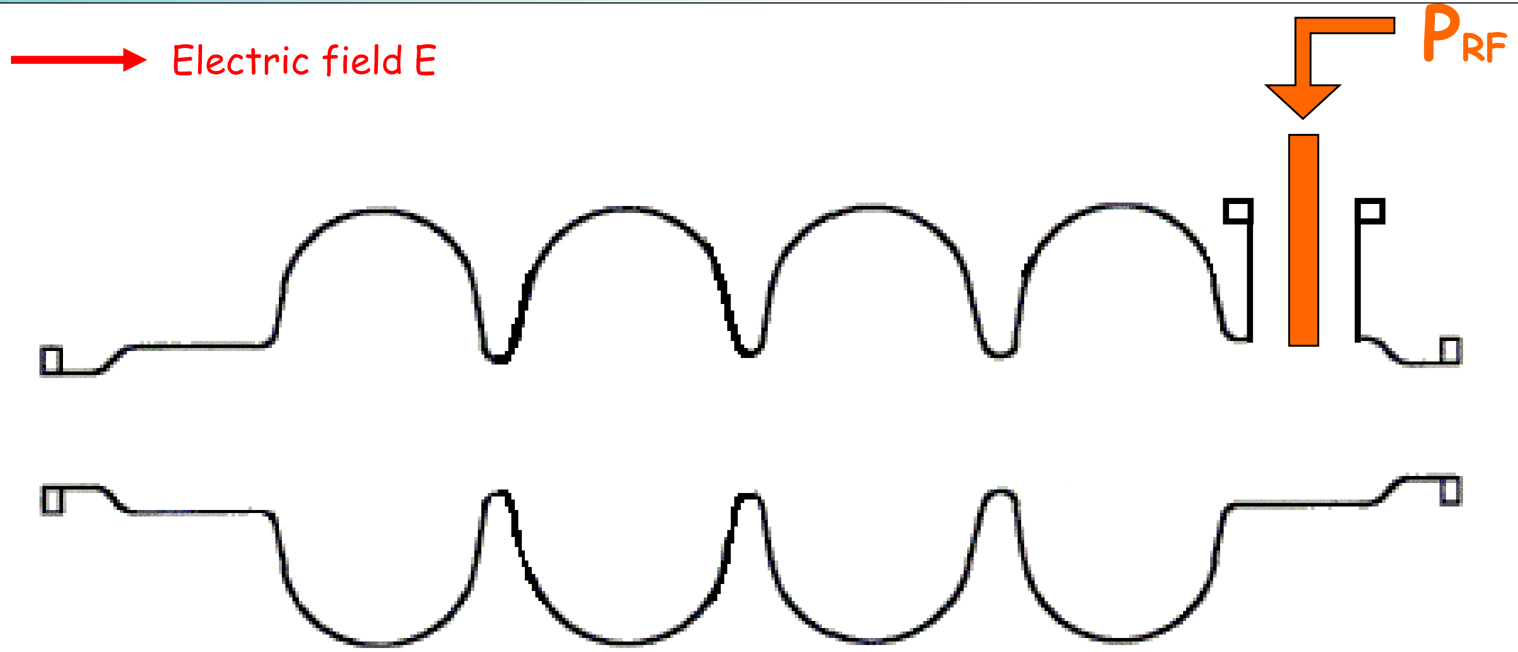
- Possibility to relax the constraints on the cavity RF design: choosing larger beam port aperture is possible ⇒ reduction of the activation hazard = <u>security gain</u>

- High potential for **reliability and flexibility**

- **Main drawback** : need to be operated at cryogenic temperature

SC Cavity : basis

(1) **An electric field is created on the beam axis , and is available to accelerate charged particles**



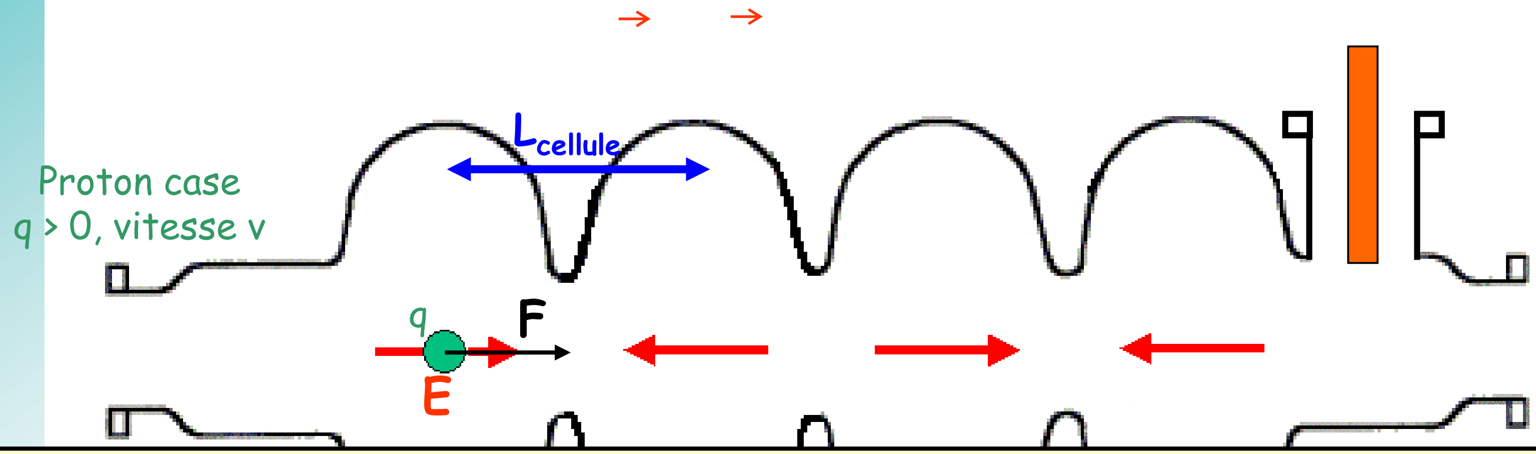
This E field is time and space dependant

With f the cavity frequency, $T = 1 / f$

Ex : $f = 700$ MHz → $T = 1{,}43$ ns

SC cavity : basis

(2) The charged particle enter the : for an efficient acceleration, the particle should be synchronized with the RF wave



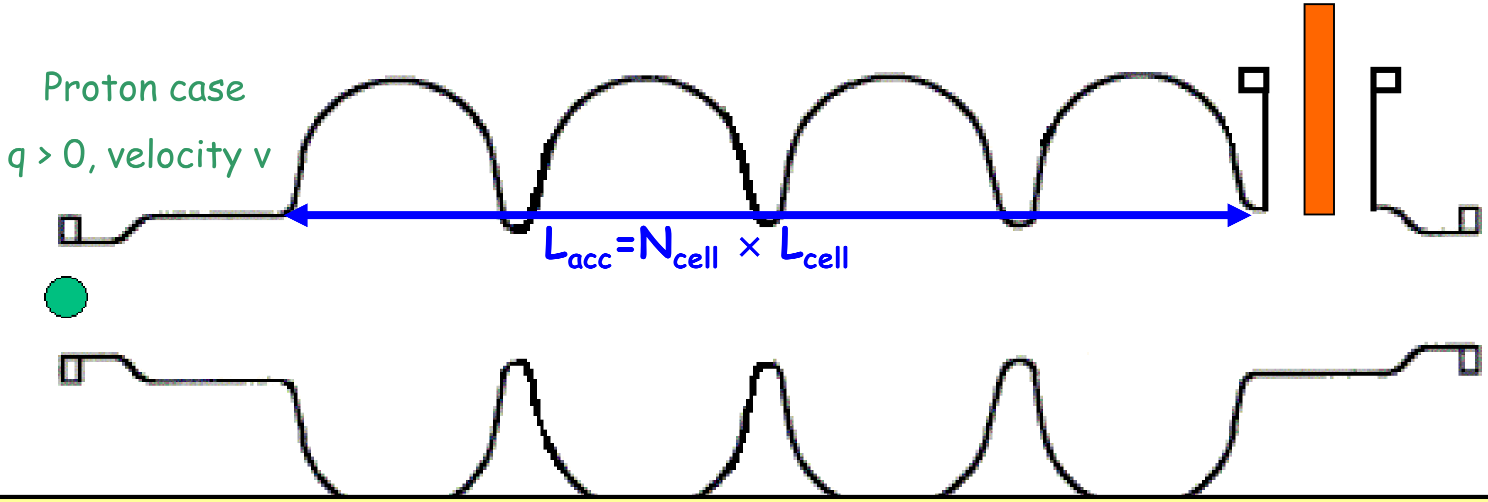
Synchronism condition :

The time for the particle to cross one cell should be $T_{RF}/2$ ⇔ $\frac{L_{cell}}{v}=\frac{1}{2f}$

The cell length should verify: $\boxed{L_{cell}=\frac{v}{2f}=\frac{\beta c}{2f}}$ or $L_{cell}=\frac{\beta\lambda}{2}$

The cell length should be adjusted to the particle velocity

SC cavity : basis



Energy gain :

$$\Delta U = q \times \int_{t_{entrée}}^{t_{sortie}} \vec{E}.\vec{v}\,dt \quad \text{or} \quad \boxed{\Delta U = q \times E_{acc} \times L_{acc} \times \cos(\varphi)}$$

E_{acc}: accelerating field of the cavity (for a given particle velocity)

L_{acc}: cavity accelerating length

φ : particule phase with respect to the RF wave

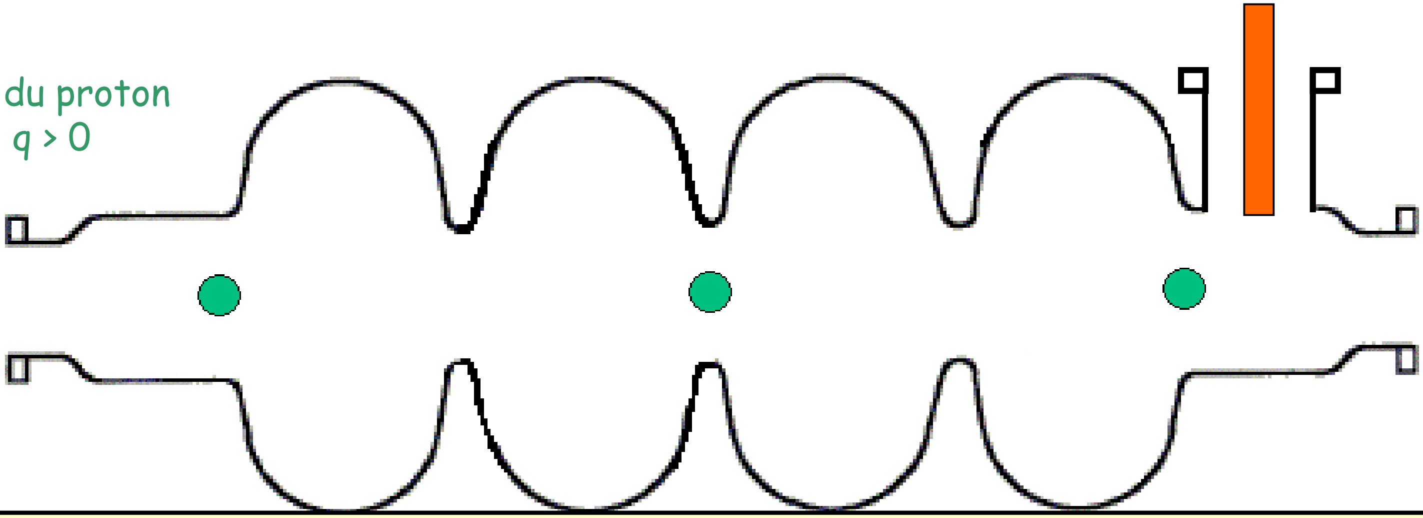
Ex : f = 700MHz ; 5-cell proton cavity β = 0,65 (L_{acc}=5×14cm); E_{acc}= 10MV/m ; φ = 0°

$\Rightarrow$ *Energy gain : ΔU =*

SC Cavity : basis

(3) Beam acceleration : particles should be bunched and synchronized with the electromagnetic wave

Cas du proton
q > 0



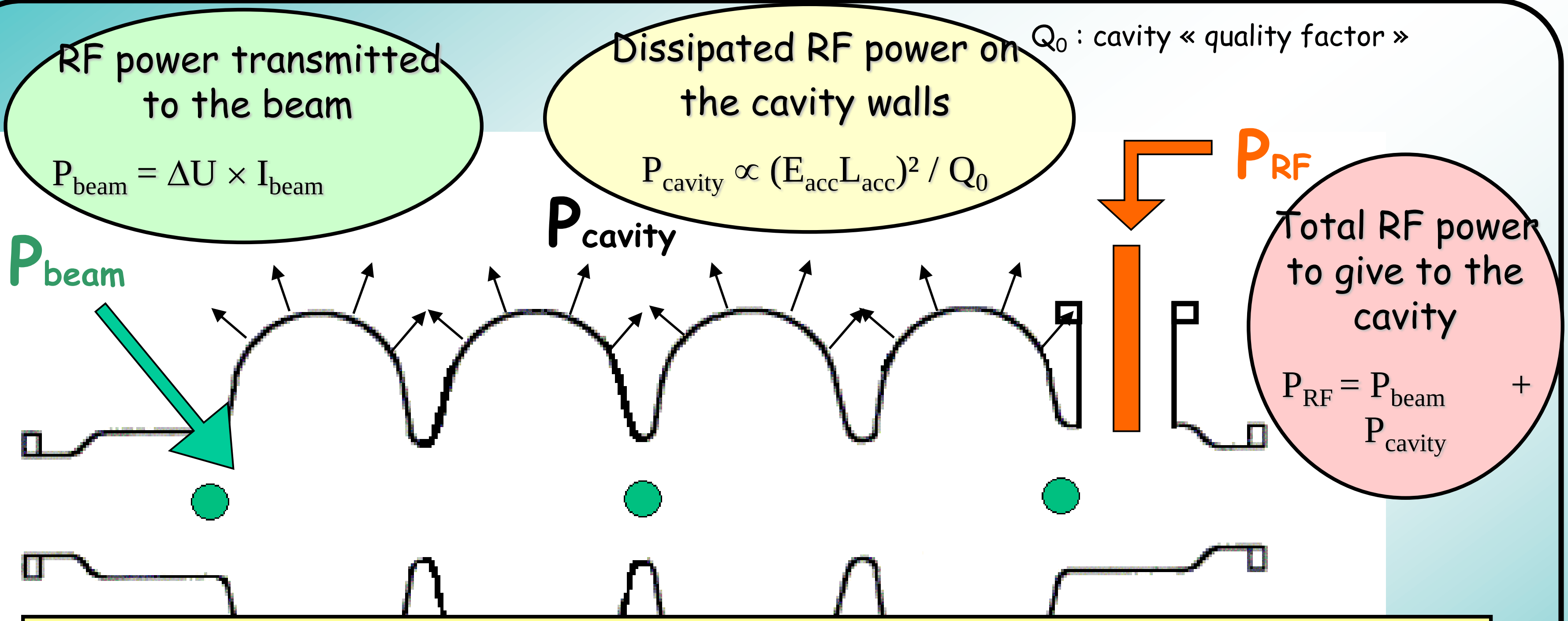
$$T_{beam} = n\,T_{RF} \qquad (n=1,2,3\ldots)$$

« the cavity resonant frequency should be a multiple of the beam frequency that it wants to accelerate»

Ex: if f_{beam}=350 MHz (T_{beam}=2,86ns), then the cavity should resonate at :

f = 350 MHz (T_{RF}=2,86ns), or f = 700 MHz (T_{RF}=1,43ns), or f = 1050 MHz (T_{RF}=0,95ns), etc.

SC cavity : basis



RF power transmitted to the beam

$P_{beam} = \Delta U \times I_{beam}$

Dissipated RF power on the cavity walls

$P_{cavity} \propto (E_{acc}L_{acc})^2 / Q_0$

Q_0 : cavity « quality factor »

Total RF power to give to the cavity

$P_{RF} = P_{beam} + P_{cavity}$

Order of magnitude *(700 MHz cavity - β = 0,65 - 5 cells- 10MV/m - φ=-30° - protons beam 10 mA)*

SC cavity (Q_0 ~ 10^{10}) : P_{beam} = 6 MeV × 10 mA = **60 kW**

P_{cavity} ≈ **16 W**

"Warm" cavity (Q_0 ~ 3.10^4) : P_{beam} = 60 kW also

P_{cavity} ≈ **5,5 MW !!!** ← *not possible in CW !*

SC cavity : basis

Material choice → **niobium** = compromise between :

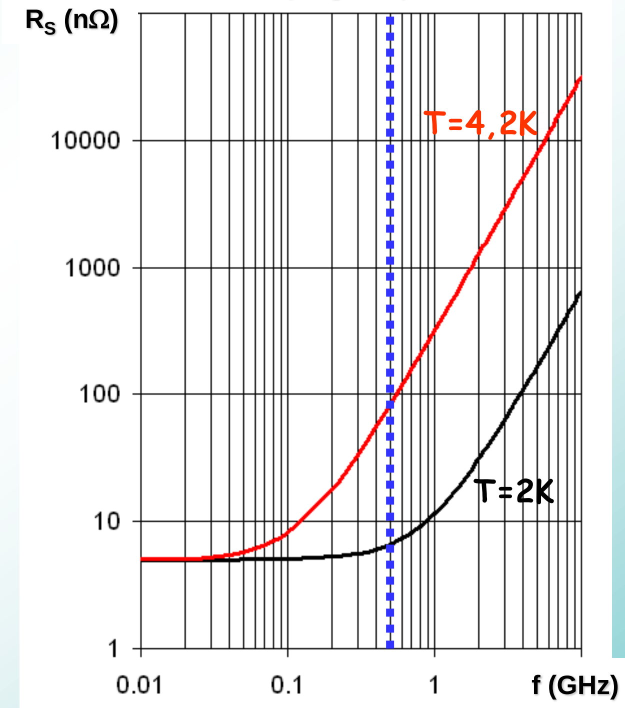
- High Tc and Bc
- Low surface resistance (in order to minimize the losses)
- Quite good mechanical (easy to shape) and thermal properties

Operating temperature → compromise between :

- Low surface resistance (means T not to high)
- Cooling system not too expensive (means T not too low)

Conclusion : if f < 500 MHz → T ~ 4,2 K (Liquid Helium)
if f > 500 MHz → T ~ 2 K (Superfluid Helium)

Surface resistance as a function of frequency



Niobium characteristics

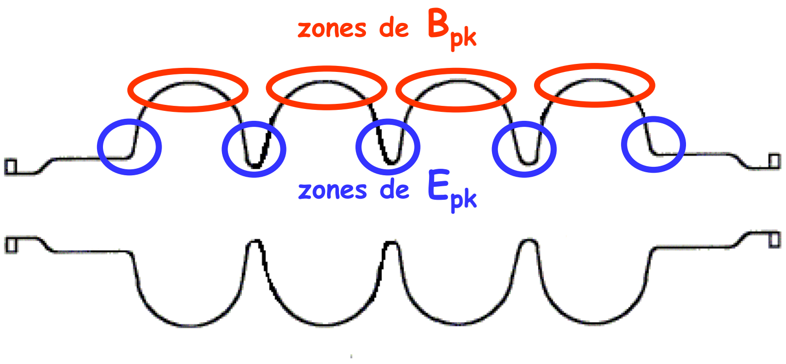
$$\left\{\begin{array}{l} T_c = 9{,}2\ \mathrm{K} \\ R_S(\Omega) \approx 2\times10^{-4}\,\frac{1}{T}\left(\frac{f(\mathrm{GHz})}{1{,}5}\right)^2 e^{-17{,}67/T} + R_{res} \end{array}\right.$$

SC cavity : basis

→ What achievable accelerating field ?

When creating E_{acc} inside the cavity, surface electromagnetic fields are also created, with maximum values refered as B_{pk} et E_{pk}

In order to stay in the superconducting state, the niobium should not see a field $\mathbf{B_{pk} < Bc_{RF}}$



The ratio B_{pk}/E_{acc} (and also E_{pk}/E_{acc}) only depends on the cavity geometrical shape

For elliptical cavities $\underline{\beta = 1}$, we have

$B_{pk}/E_{acc} \approx$ 4 mT / (MV/m)

$\Rightarrow$ @ T = 2 K, $\mathbf{E_{accMAX}}$ = 220 mT / 4 = **55 MV/m**

This theoretical maximum Eacc varies with the cavity β:

- cavity $\beta = 0.65$, $B_{pk}/E_{acc} \approx$ 5 mT/(MV/m)

i.e. $\mathbf{E_{accMAX}}$ = **44 MV/m** @ 2K

- cavity $\beta = 0.5$, $B_{pk}/E_{acc} \approx$ 6 mT/(MV/m)

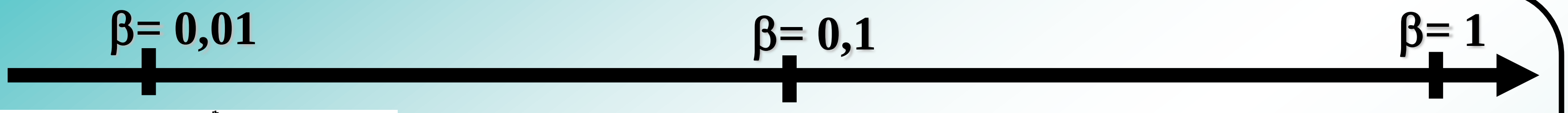
i.e. $\mathbf{E_{accMAX}}$ = **37 MV/m** @ 2K

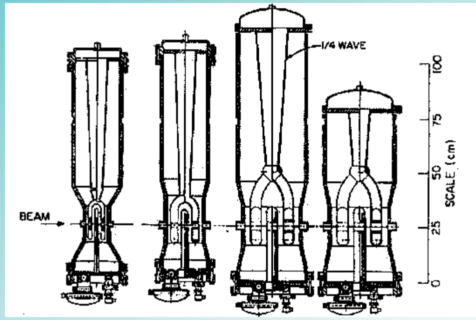
SC cavity : basis

Comparison between a "warm" and "cold" solution for a high intensity proton linac

 ***Cavity: 700 MHz β=0,65*** ***5 cells (protons 10mA)***	SC cavity (2K)	« Warm » cavity (300K)
Surface resistance R_S *(ideal)*	20 nΩ *(3,2 nΩ)*	7 mΩ
Quality factor Q_0 *(ideal)*	10^{10} *(6.10^{10})*	3.10^4
E_{acc} *(theoretical)*	10 MV/m *(44 MV/m)*	2 MV/m
Beam power P_{beam}	60 kW	12 kW
Dissipated power / cavity P_{cav}	16 W @ 2K	218 kW @ 300K
RF power / cavity $P_{RF} = P_{beam} + P_{cav}$	60 kW	230 kW
Power taken to the grid P_{AC}	125 kW	400 kW
Accelerator efficiency P_{beam} / P_{AC}	48 %	3 %
Number of cavity to gain 100 MeV	17 (about 30m)	85 (about 80m)

Various SC cavities for different particle velocity





Structures inter-digitales (ATLAS, Argonne)

48 et 72 MHz - β = 0,009 à 0,037

Résonateurs quart d'onde (ALPI, Legnaro)

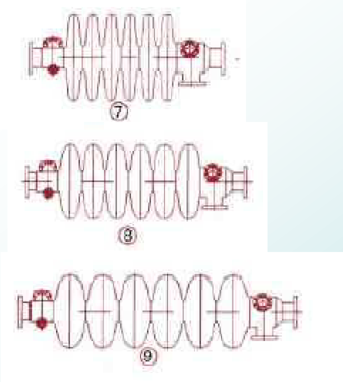
80 à 352 MHz - β = 0,047 à 0,25

Cavité ré-entrante (Legnaro)

352 MHz - β ≥ 0,1

Cavités elliptiques

350 MHz à 3 GHz - β = 0,47 à 1



Cavité TTF

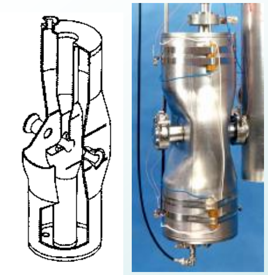
1,3 GHz - β = 1

RFQs supra (Legnaro)

80 MHz - β = 0,009 à 0,035

Résonateurs split-ring (ATLAS, Argonne)

97 et 145 MHz - β = 0,06 à 0,16



Résonateur demi-onde (Argonne)

355 MHz - β = 0,12

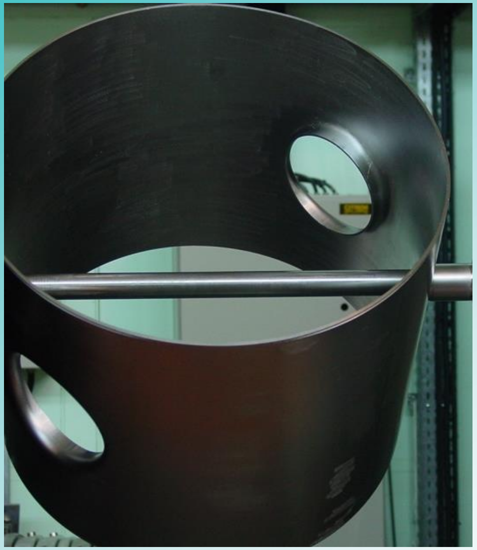
Cavités spoke (CNRS Orsay)

352 MHz - β = 0,15 et 0,35

Cavité APT (Los Alamos)

700 MHz - β = 0,64

SC cavity : fabrication

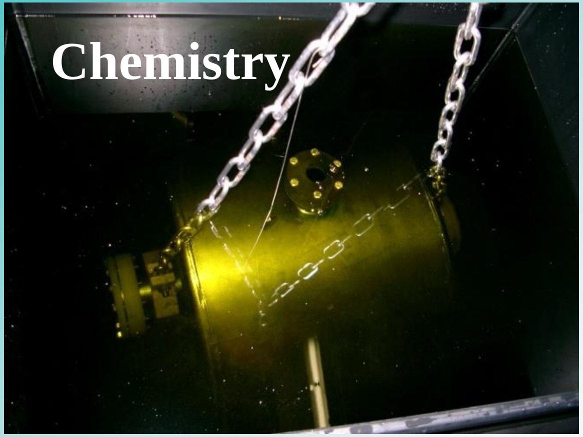


Niobium sheets 3 mm thick
Welding by electron beams

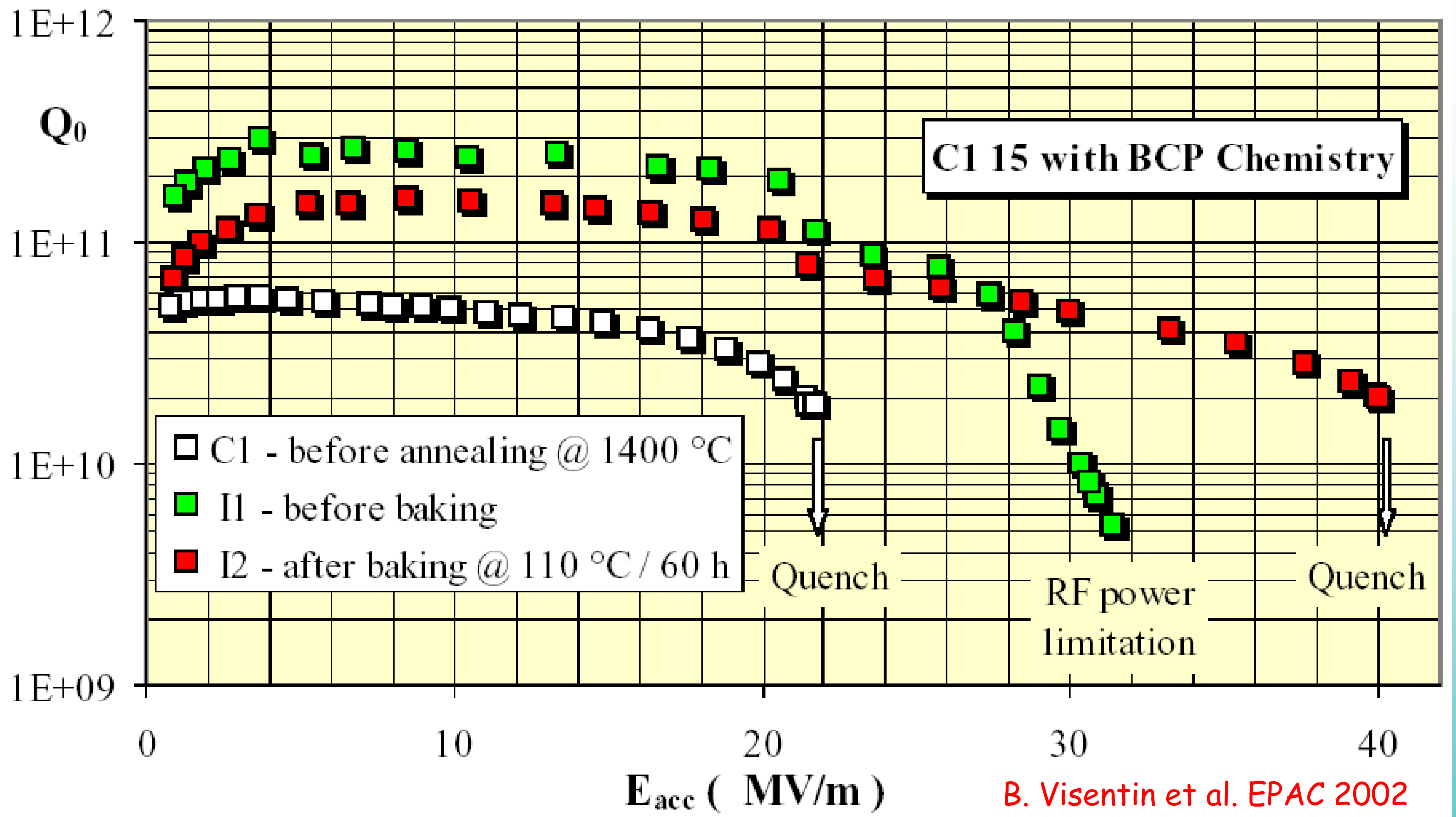
[Spoke cavity]()

$\beta = 0.35$
f = 352.2 MHz

SC cavity : preparation and test



Another example : Performances of TESLA cavity



B. Visentin et al. EPAC 2002

Spiral-2 cavities : all cavities results in VC (beta = 0.12)