# High Power Proton LINACs
# PART 2

JOINT UNIVERSITIES ACCELERATOR SCHOOL

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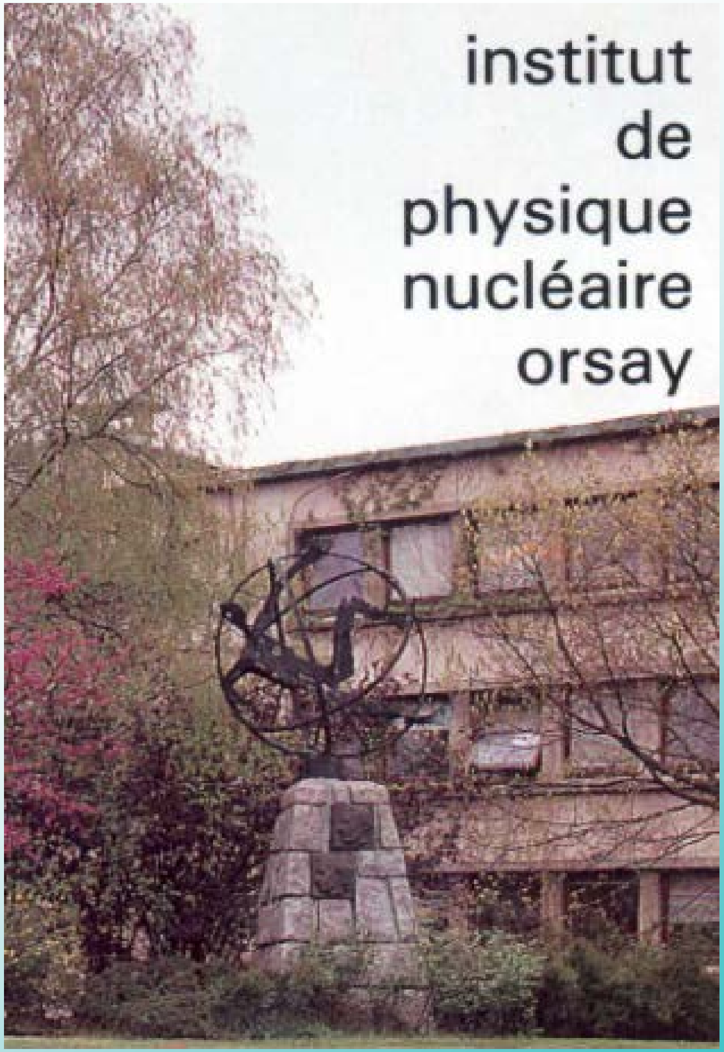


# Superconducting cavities

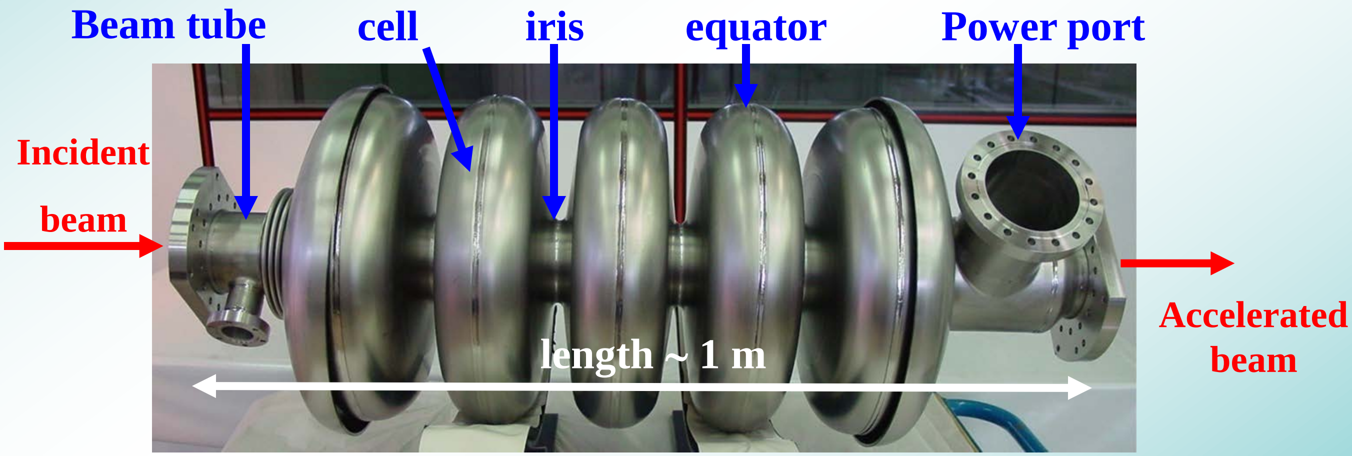
- « **CAVITY** » = Electromagnetic resonant cavity

  ⇒ RF fields (electric and magnetic)

  ⇒ To accelerate charged particles

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

  ⇒ Superconducting state of the matter



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

**Frequency f**

50 MHz to 3 GHz

**Size**

Proportional to 1/f

**Temperature T**

1,5 K to 4,5 K

**Accelerated particle velocity**

$\beta = v/c$ from 0,01 to 1

*0 K ≈ - 273,15 °C*

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

# Why using superconducting cavities ?

Intrinsic advantage of cold cavities

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

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

- **Operating cost gain** 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)

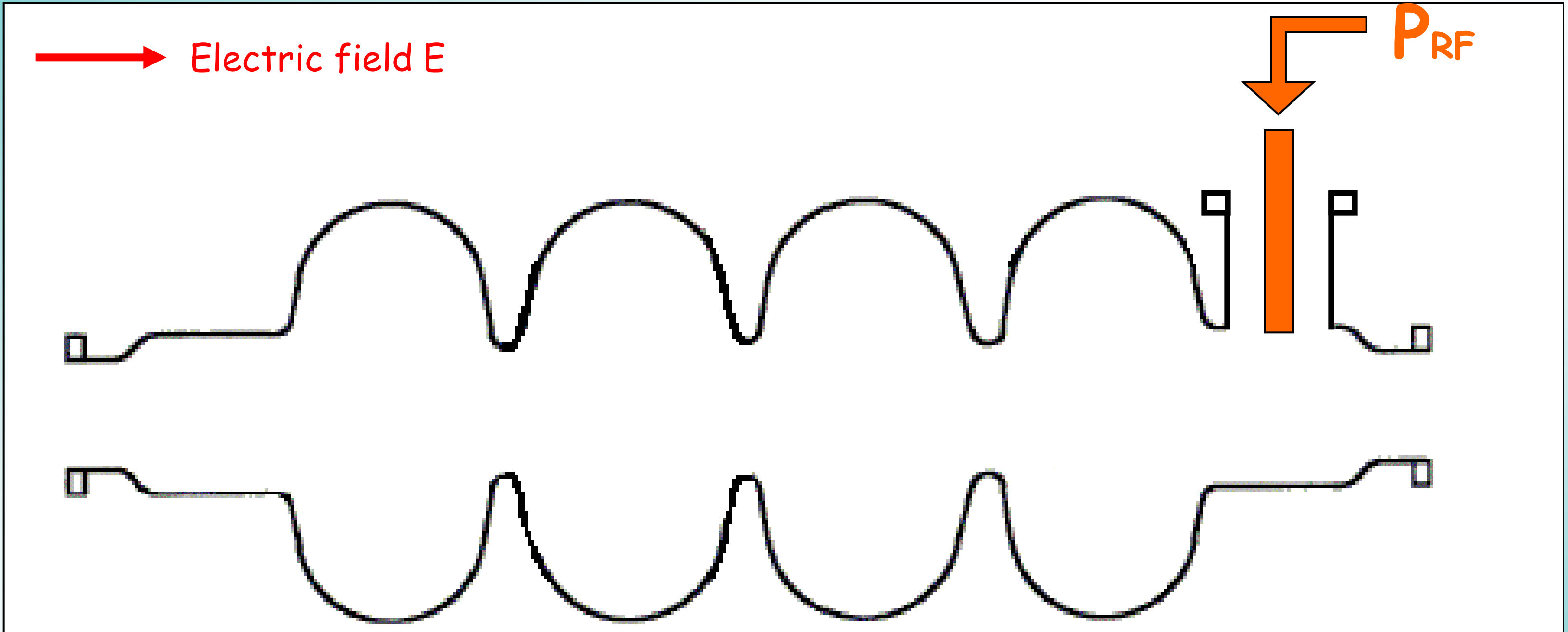
- Possibility to relax the constraints on the cavity RF design: choosing larger beam port aperture is possible ⇒ reduction of the activation hazard = security gain

- High potential for **reliability and flexibility**

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

# SC Cavity : basis

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



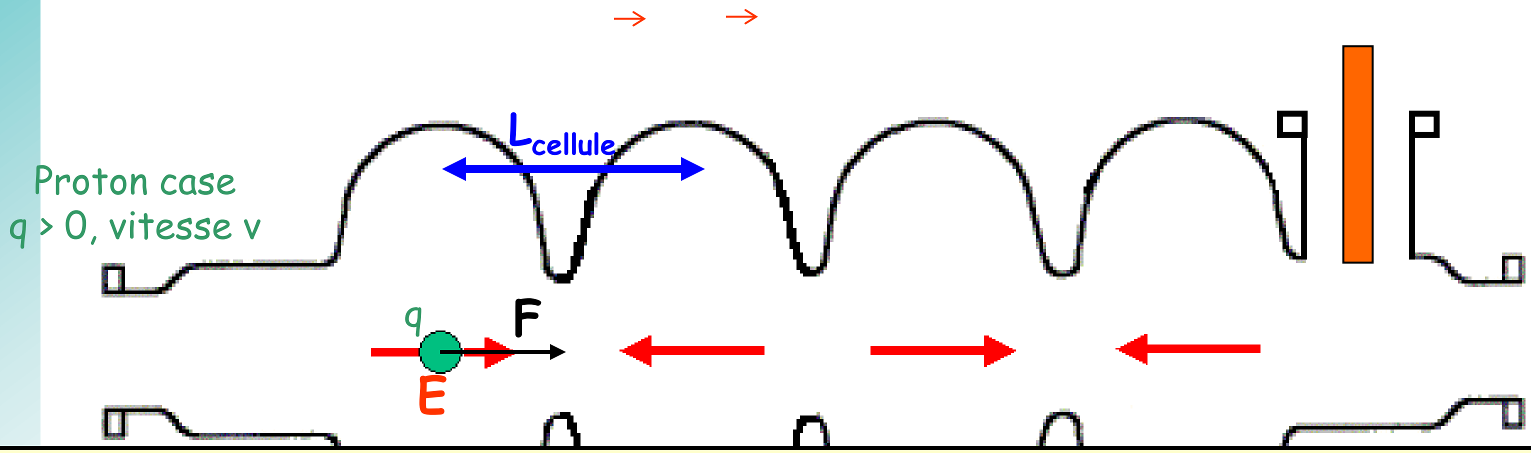
This E field is time and space dependant

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**



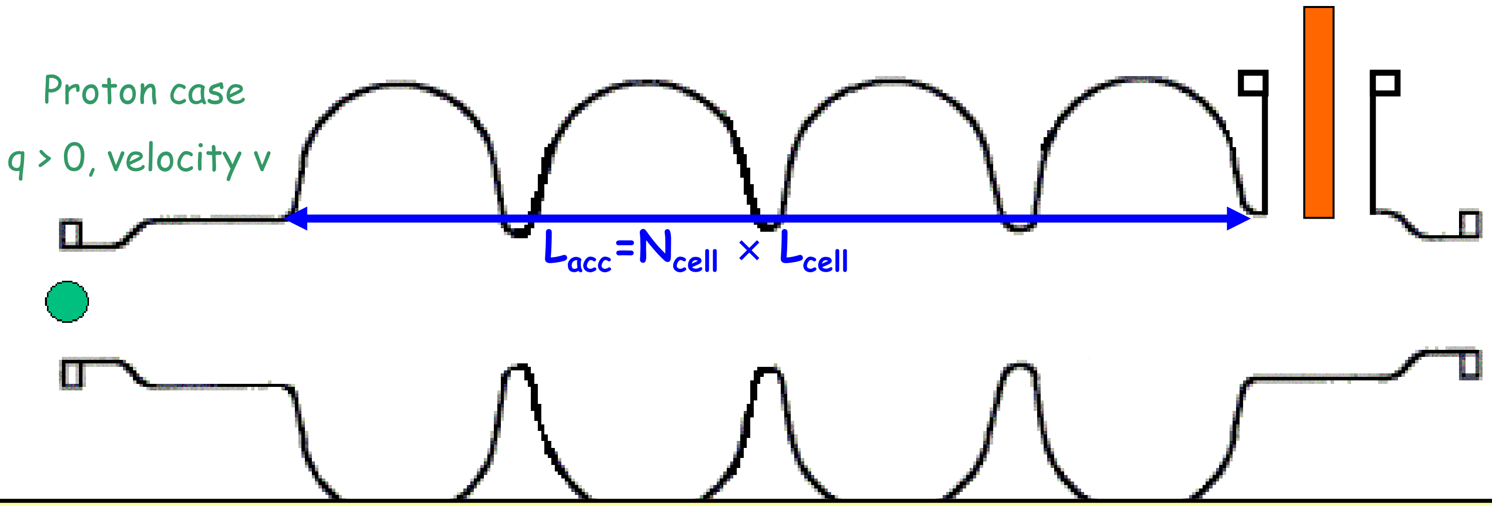
Synchronism condition :

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

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



Proton case

q > 0, velocity v

$L_{acc} = N_{cell} \times L_{cell}$

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

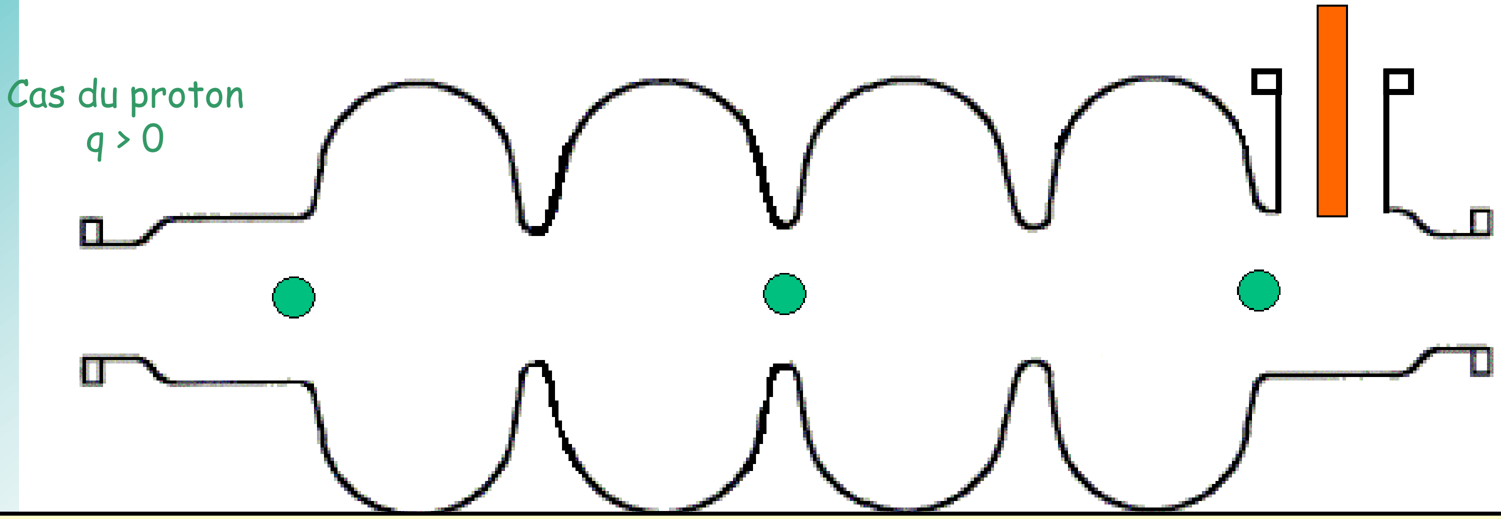
$\varphi$ : particule phase with respect to the RF wave

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

⇒ *Energy gain : ΔU =*

# SC Cavity : basis

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



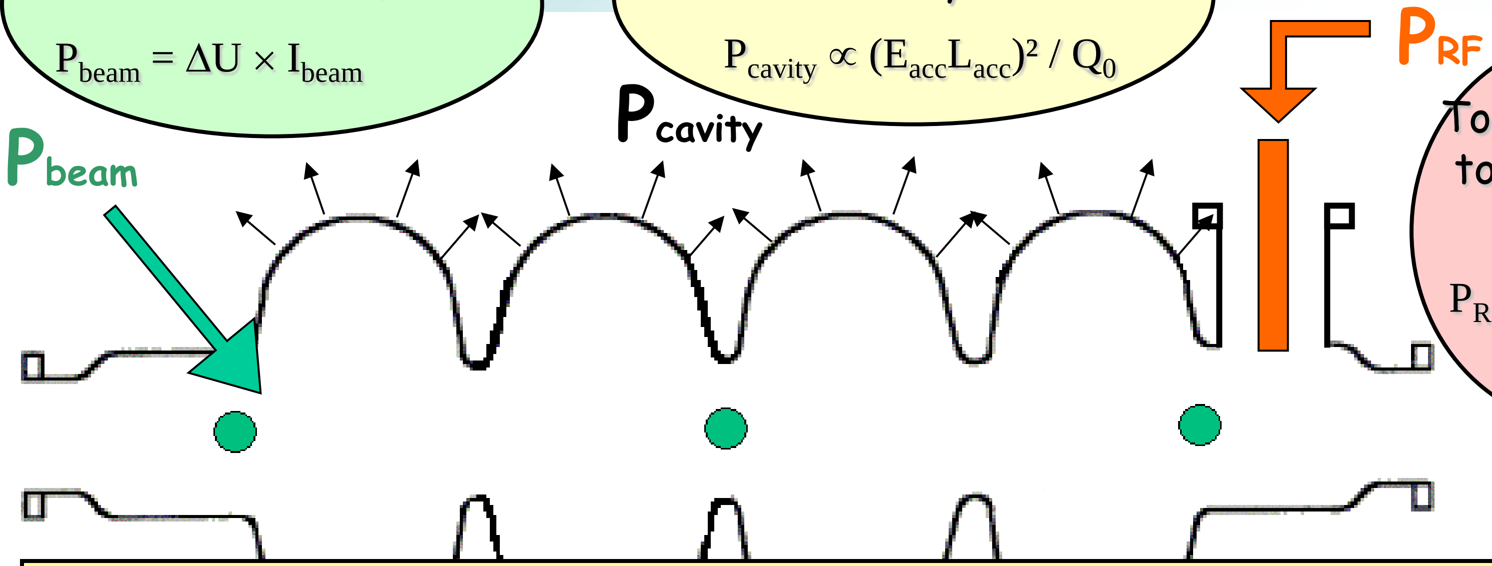
$T_{beam} = n\ T_{RF}$ (n=1,2,3…)

**« 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

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

<u>Order of magnitude</u> *(700 MHz cavity - $\beta$ = 0,65 - 5 cells- 10MV/m - $\varphi$=-30° - protons beam 10 mA)*

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

**$P_{cavity} \approx$ 16 W**

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

**$P_{cavity} \approx$ 5,5 MW !!!** ← *not possible in CW !*

# SC cavity : basis

**<u>Material choice</u>** → **niobium** = compromise between :

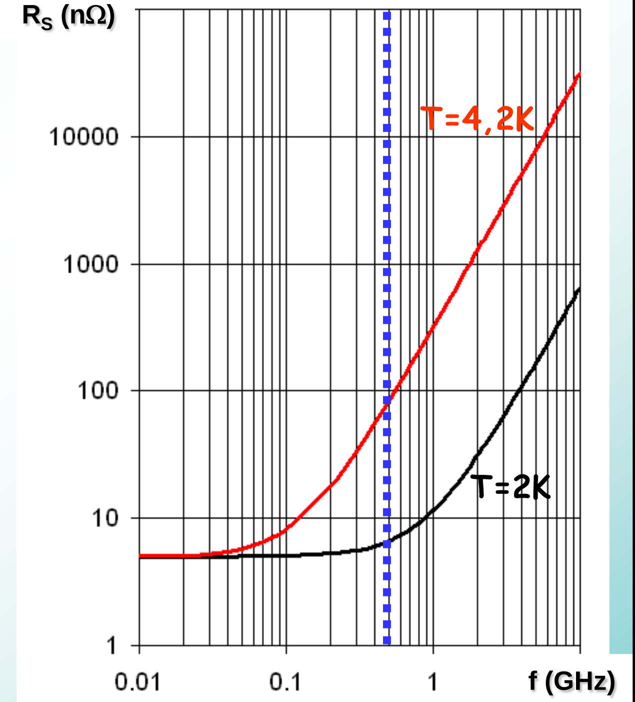
- High Tc and Bc
- Low surface resistance (in order to minimize the losses)
- Quite good mechanical (easy to shape) and thermal properties

**<u>Operating temperature</u>** → 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**

**Tc = 9,2 K**

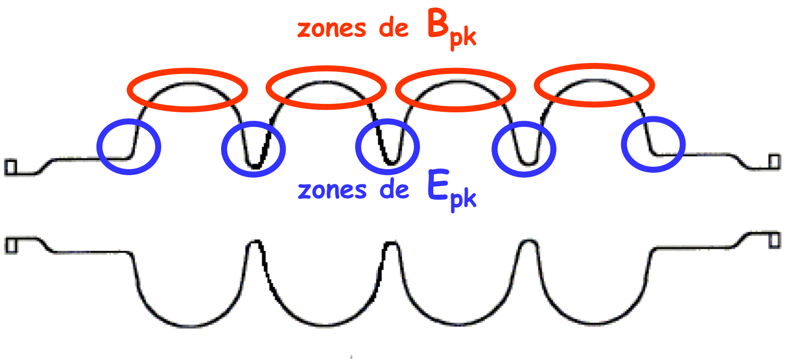
$$R_S(\Omega) \approx 2\times10^{-4}\,\frac{1}{T}\left(\frac{f(\mathrm{GHz})}{1,5}\right)^2 e^{-17,67/T} + R_{res}$$

# 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 = **<u>55 MV/m</u>**

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

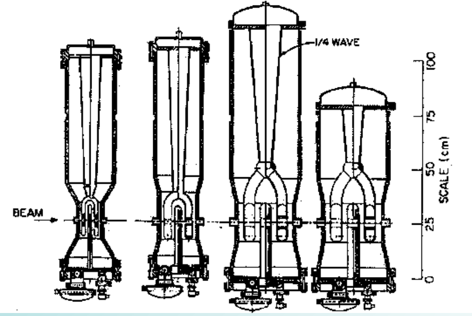
# SC cavity : basis

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

|  ***Cavity: 700 MHz $\beta$=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

β= 0,01 β= 0,1 β= 1



**Structures inter-digitales (ATLAS, Argonne)**

**48 et 72 MHz - β = 0,009 à 0,037**

**Résonateurs quart d'onde (ALPI, Legnaro)**

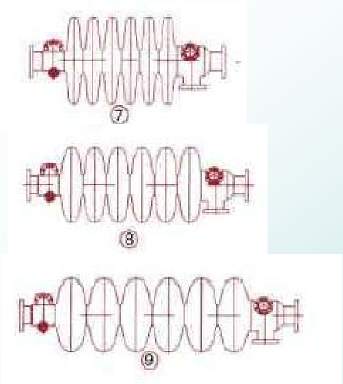
**80 à 352 MHz - β = 0,047 à 0,25**

**Cavité ré-entrante (Legnaro)**

**352 MHz - β ≥ 0,1**

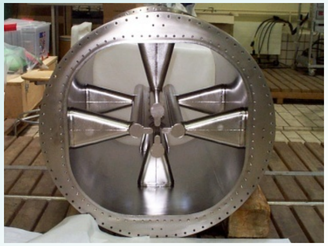
**Cavités elliptiques**

**350 MHz à 3 GHz - β = 0,47 à 1**



**Cavité TTF**

**1,3 GHz - β = 1**

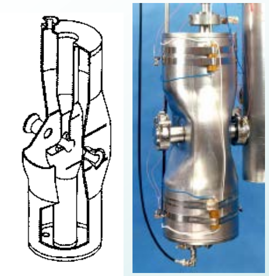


**RFQs supra (Legnaro)**

**80 MHz - β = 0,009 à 0,035**

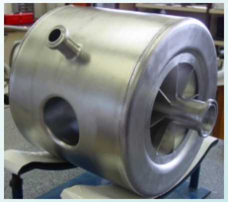
**Résonateurs split-ring (ATLAS, Argonne)**

**97 et 145 MHz - β = 0,06 à 0,16**



**Résonateur demi-onde (Argonne)**

**355 MHz - β = 0,12**



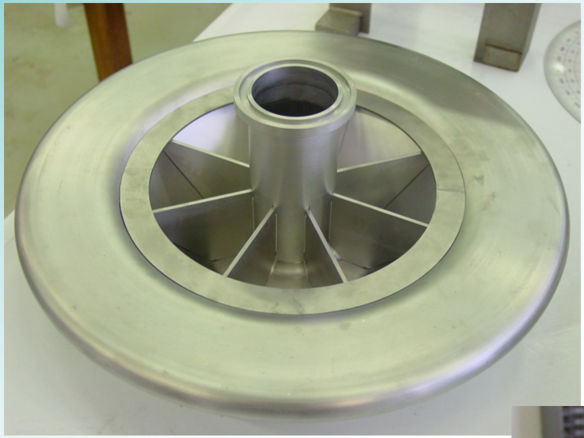
**Cavités spoke (CNRS Orsay)**

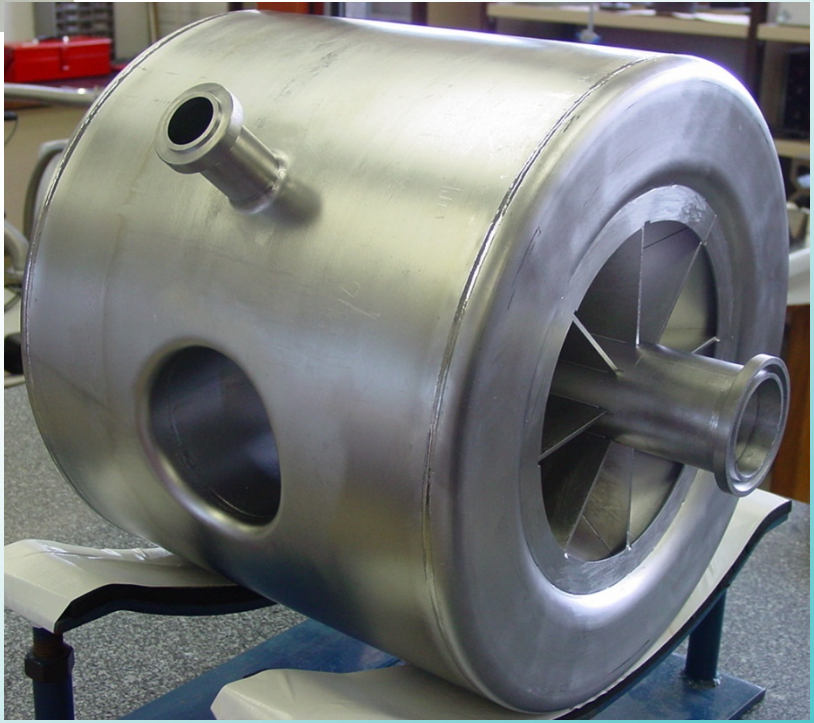
**352 MHz - β = 0,15 et 0,35**

**Cavité APT (Los Alamos)**

**700 MHz - β = 0,64**

# SC cavity : fabrication



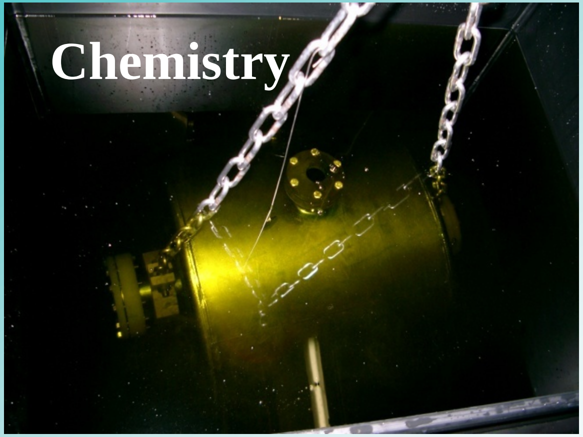


Niobium sheets 3 mm thick
Welding by electron beams

Spoke cavity

$\beta = 0.35$
$f = 352.2$ MHz

# SC cavity : preparation and test

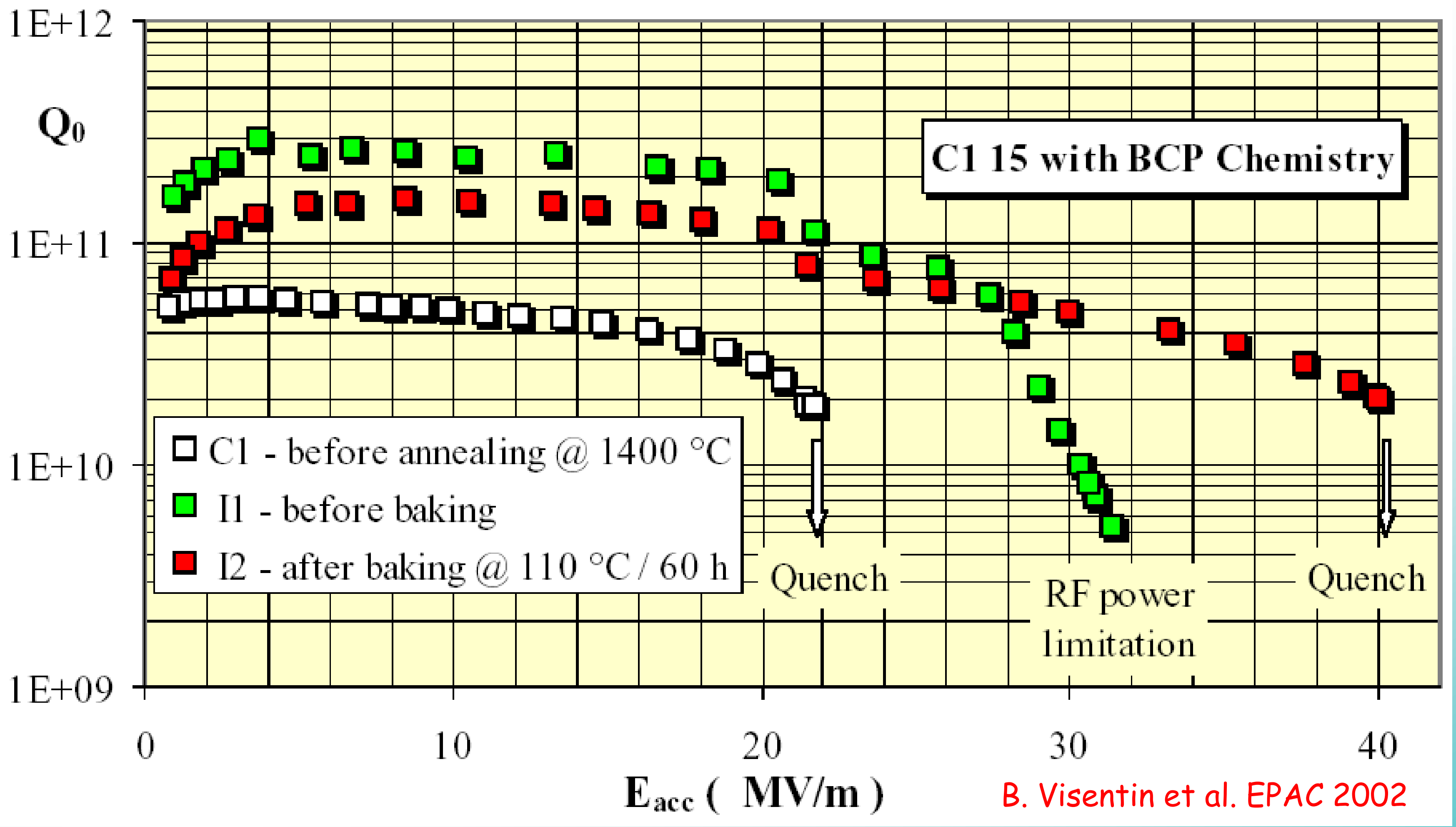

Chemistry


High pressure rinsing


Assembly in clean room


CryHoLab

# Another example : Performances of TESLA cavity



B. Visentin et al. EPAC 2002

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