

# High Power Proton LINACs PART 2



JOINT UNIVERSITIES  
ACCELERATOR SCHOOL

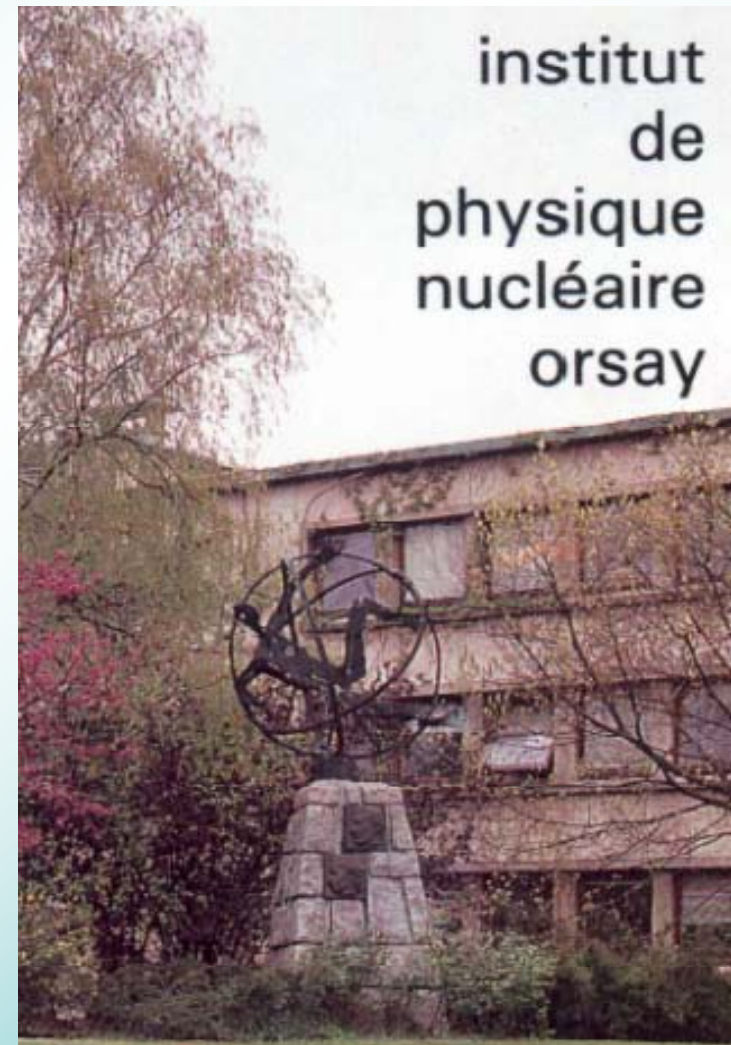
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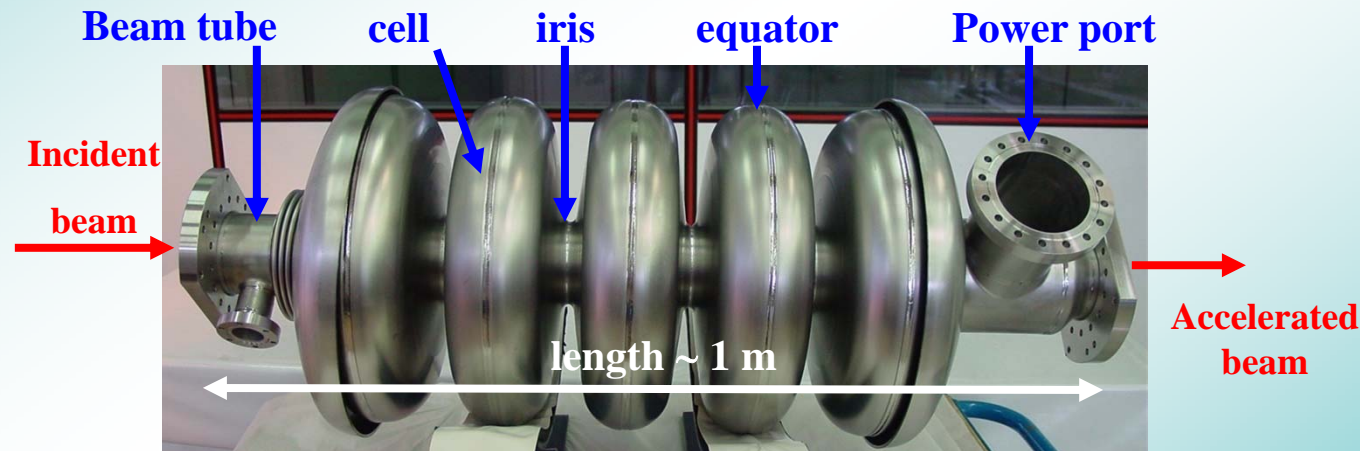
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## Superconducting cavities

- « **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,  $\beta=0,65$

### 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

$0\text{ K} \approx -273,15\text{ }^{\circ}\text{C}$   
 $c \approx 2,998 \cdot 10^8\text{ m/s}$



# 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 !!!

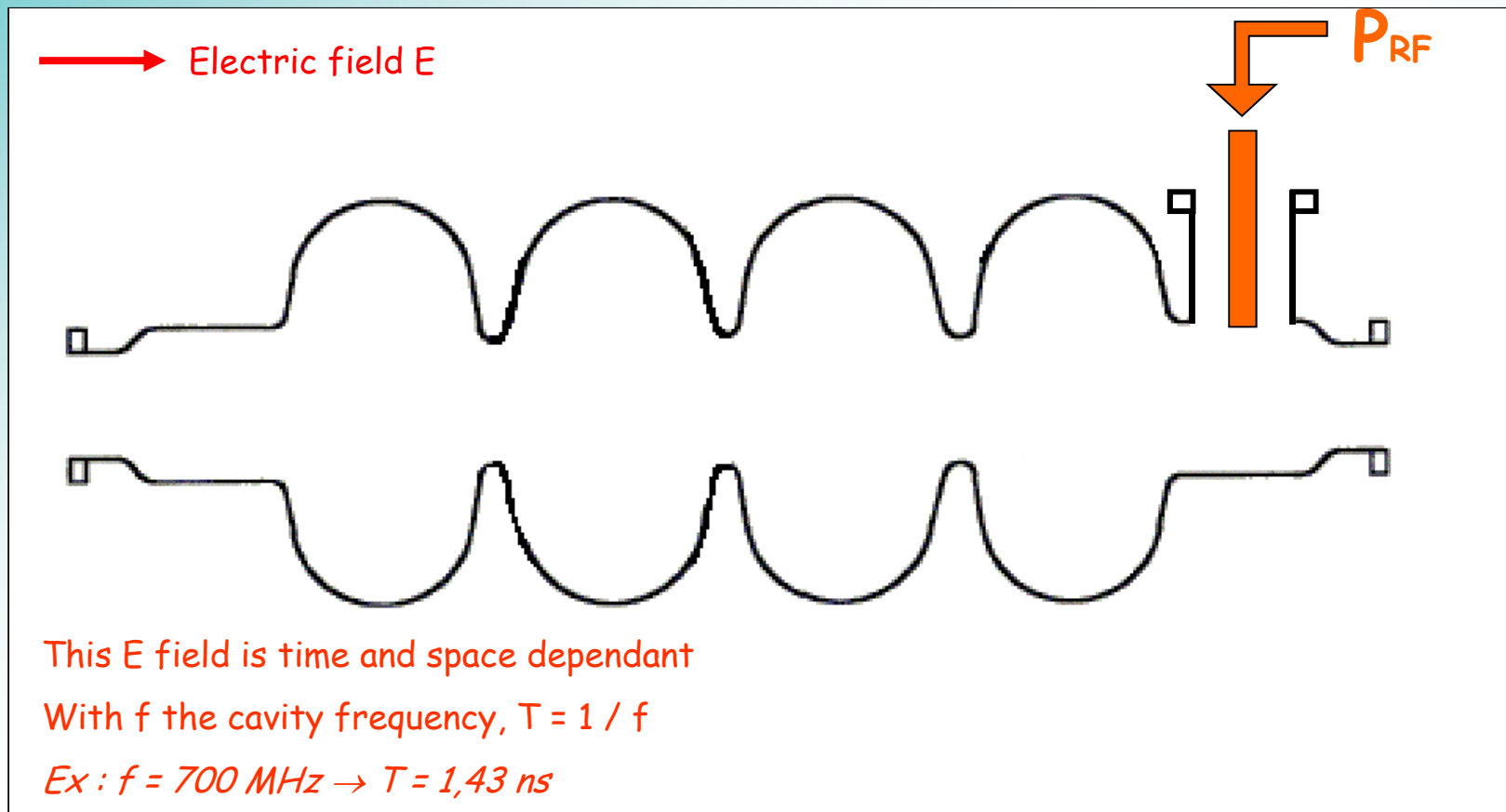
- ➡ **Operating cost gain** as compared to warm structures (which dissipate  $\sim 10^5$  times higher)
- ➡ **Possibility to accelerate CW beams or beams with a high duty cycle ( $> 1\%$ ) with high accelerating gradients** (impossible with warm structures)
- ➡ Possibility to relax the constraints on 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

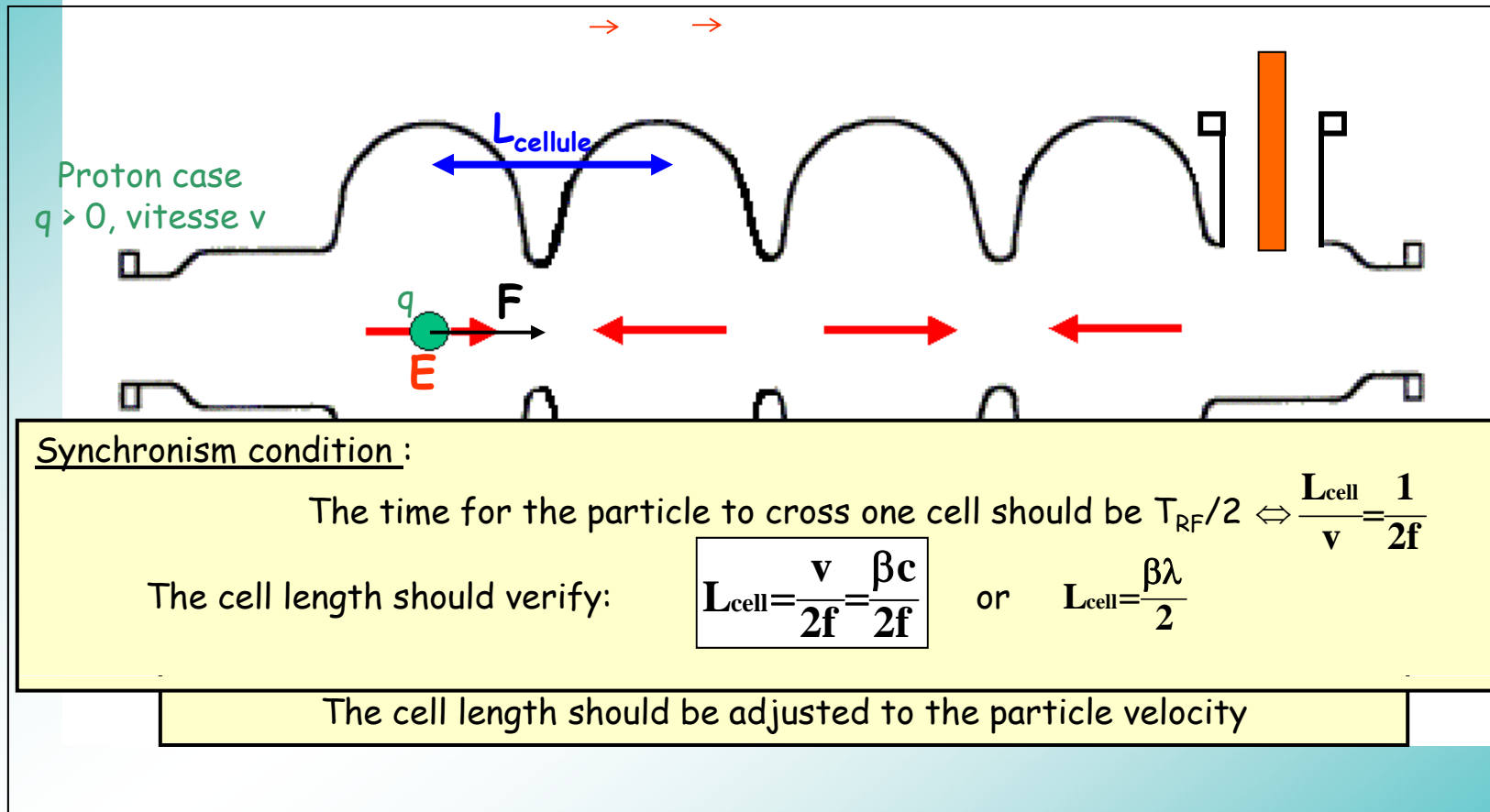
- (1) An electric field is created on the beam axis , and is available to accelerate charged particles





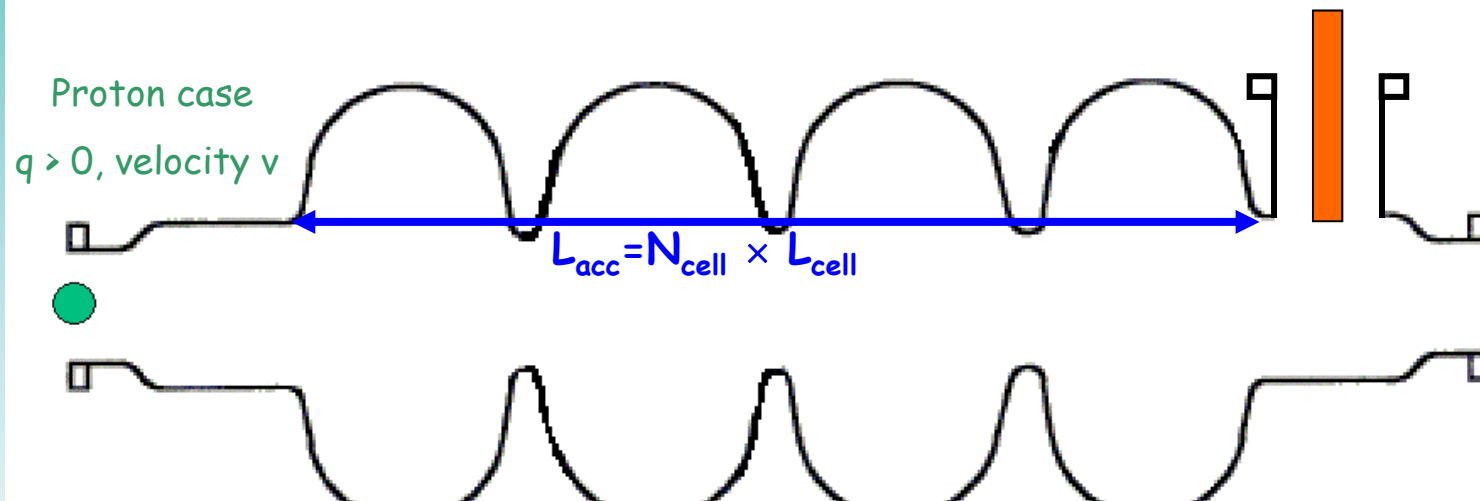
## SC cavity : basis

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





# SC cavity : basis



Energy gain :

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

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

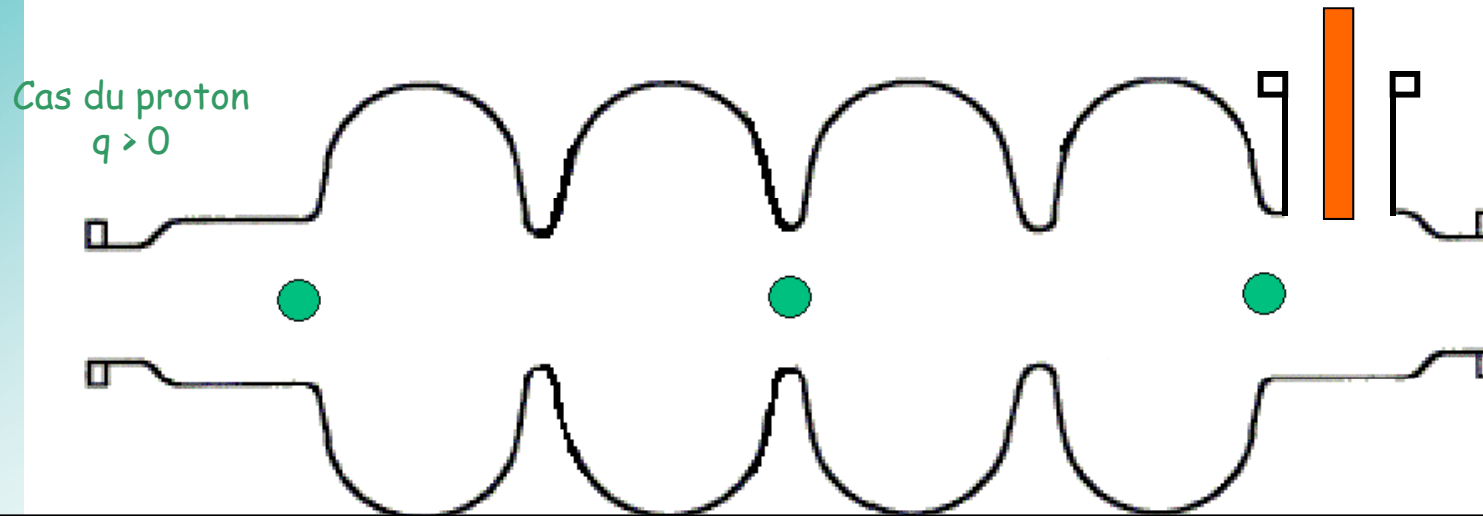
*$\Rightarrow$  Energy gain :  $\Delta U =$*





## SC Cavity : basis

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



$$T_{\text{beam}} = n T_{\text{RF}} \quad (n=1,2,3\dots)$$

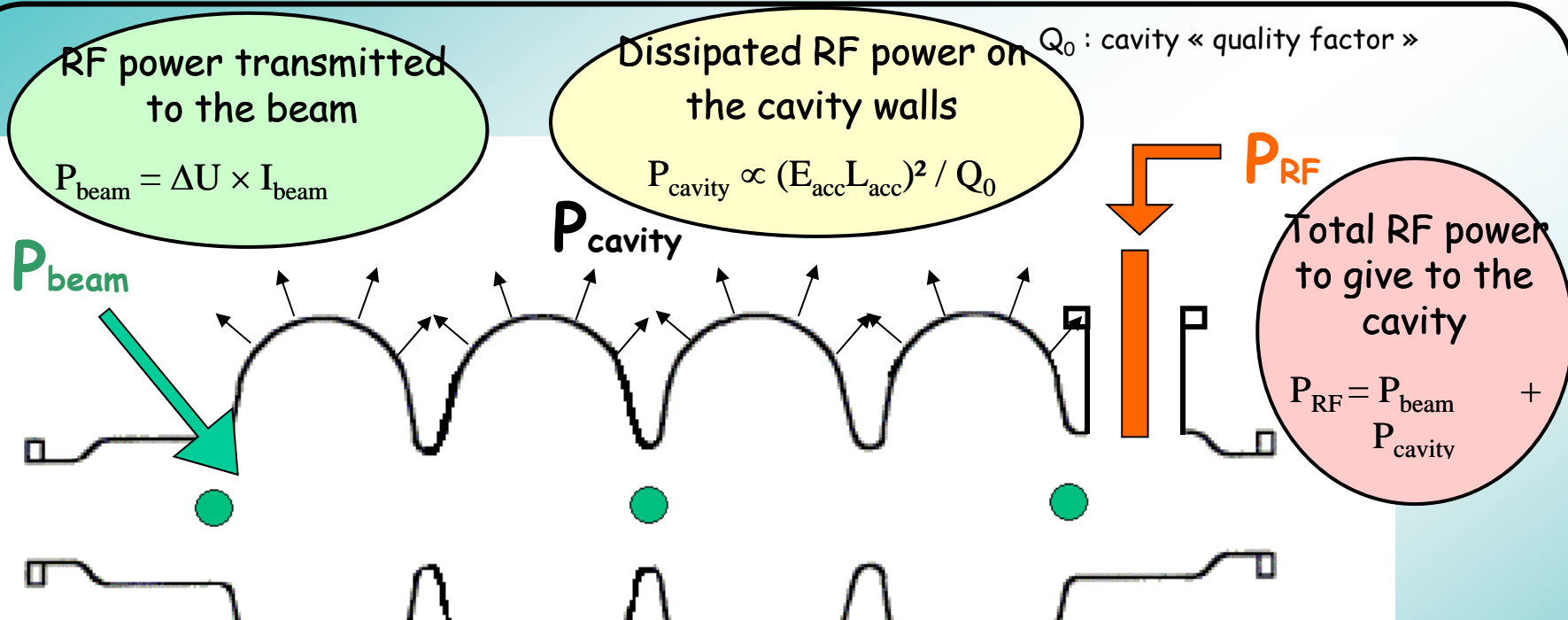
« the cavity resonant frequency should be a multiple of the beam frequency that it wants to accelerate »

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

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



# SC cavity : basis



Order of magnitude (700 MHz cavity -  $\beta = 0,65$  - 5 cells- 10MV/m -  $\phi = -30^\circ$  - protons beam 10 mA)

SC cavity ( $Q_0 \sim 10^{10}$ ) :  $P_{\text{beam}} = 6 \text{ MeV} \times 10 \text{ mA} = 60 \text{ kW}$

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

"Warm" cavity ( $Q_0 \sim 3 \cdot 10^4$ ) :

$P_{\text{beam}} = 60 \text{ kW}$  also

$P_{\text{cavity}} \approx 5,5 \text{ MW} !!! \leftarrow \text{not possible in CW!}$





## SC cavity : basis

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

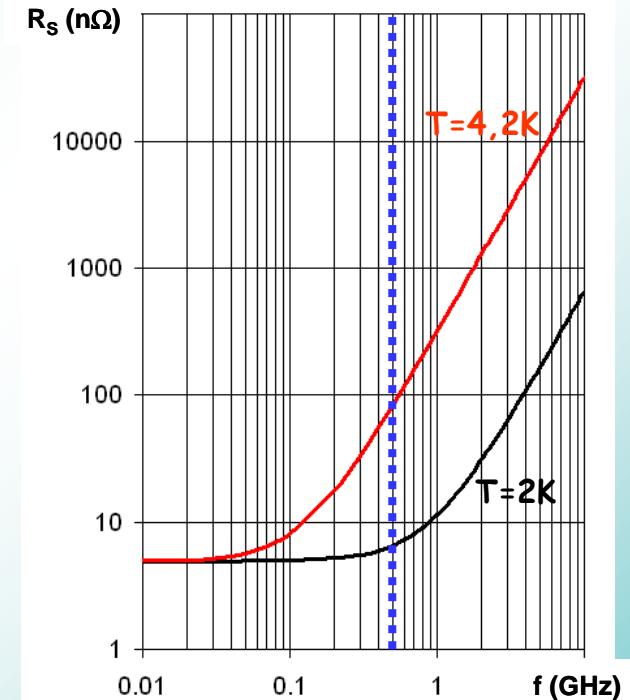
- High  $T_c$  and  $B_c$
- Low surface resistance (in order to minimize the losses)
- Quite good mechanical (easy to shape) and thermal properties

**Operating temperature** → compromise between :

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

Conclusion { if  $f < 500$  MHz →  $T \sim 4,2$  K (Liquid Helium)  
 if  $f > 500$  MHz →  $T \sim 2$  K (Superfluid Helium)

Surface resistance as a function of frequency



**Niobium characteristics**

$T_c = 9,2$  K

$$R_s(\Omega) \approx 2 \times 10^{-4} \frac{1}{T} \left( \frac{f(\text{GHz})}{1,5} \right)^2 e^{-17,67/T} + R_{\text{res}}$$

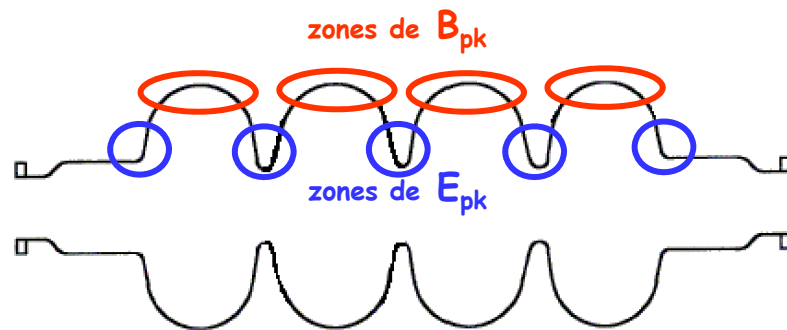


## SC cavity : basis

### → What achievable accelerating field ?

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

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



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

For elliptical cavities  $\beta = 1$ , we have

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

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

This theoretical maximum  $E_{acc}$  varies with the cavity  $\beta$ :

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

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

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

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



## 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 $R_s$ ( <i>ideal</i> )	20 n $\Omega$ (3,2 n $\Omega$ )	7 m $\Omega$
Quality factor $Q_0$ ( <i>ideal</i> )	$10^{10}$ (6.10 <sup>10</sup> )	$3 \cdot 10^4$
$E_{acc}$ ( <i>theoretical</i> )	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)

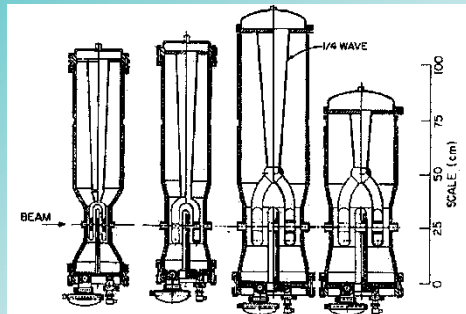


# Various SC cavities for different particle velocity

$\beta = 0,01$

$\beta = 0,1$

$\beta = 1$



Structures inter-digitales (ATLAS, Argonne)

48 et 72 MHz -  $\beta = 0,009$  à  $0,037$



RFQs supra (Legnaro)

80 MHz -  $\beta = 0,009$  à  $0,035$



Résonateurs split-ring (ATLAS, Argonne)

97 et 145 MHz -  $\beta = 0,06$  à  $0,16$



Résonateurs quart d'onde (ALPI, Legnaro)

80 à 352 MHz -  $\beta = 0,047$  à  $0,25$



Résonateur demi-onde (Argonne)

355 MHz -  $\beta = 0,12$

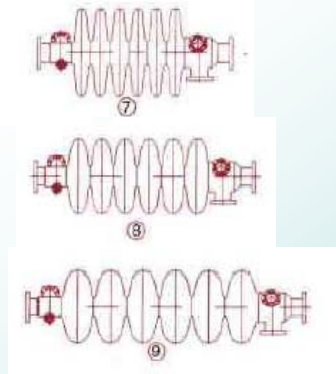
Cavité ré-entrante (Legnaro)

352 MHz -  $\beta \geq 0,1$



Cavités elliptiques

350 MHz à 3 GHz -  $\beta = 0,47$  à  $1$



Cavité TTF

1,3 GHz -  $\beta = 1$

Cavités spoke (CNRS Orsay)

352 MHz -  $\beta = 0,15$  et  $0,35$



Cavité APT (Los Alamos)

700 MHz -  $\beta = 0,64$





## SC cavity : fabrication



Niobium sheets 3 mm thick  
Welding by electron beams

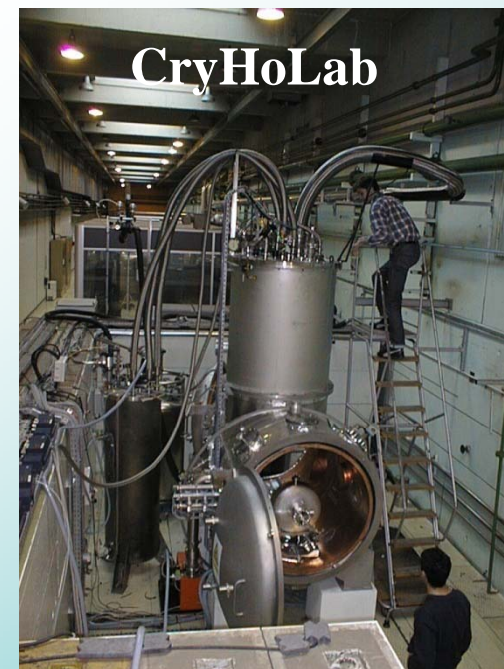
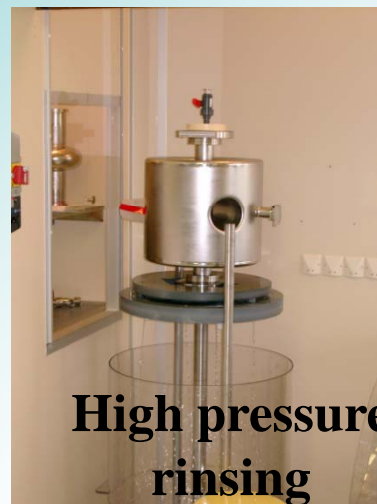
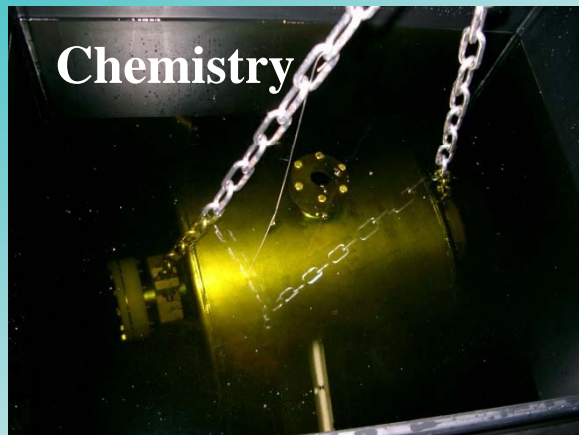
### Spoke cavity

$$\beta = 0.35$$
$$f = 352.2 \text{ MHz}$$





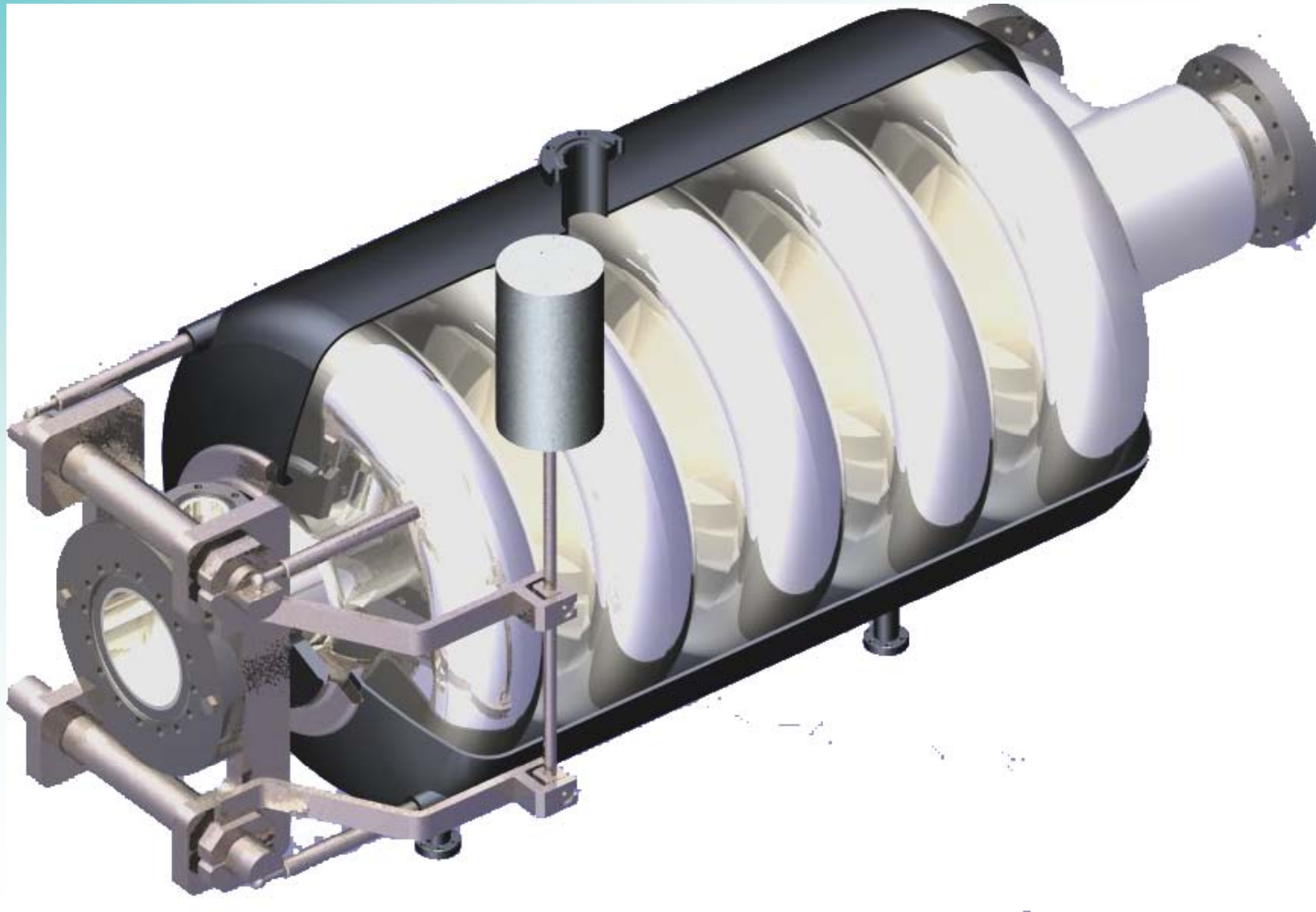
## SC cavity : preparation and test





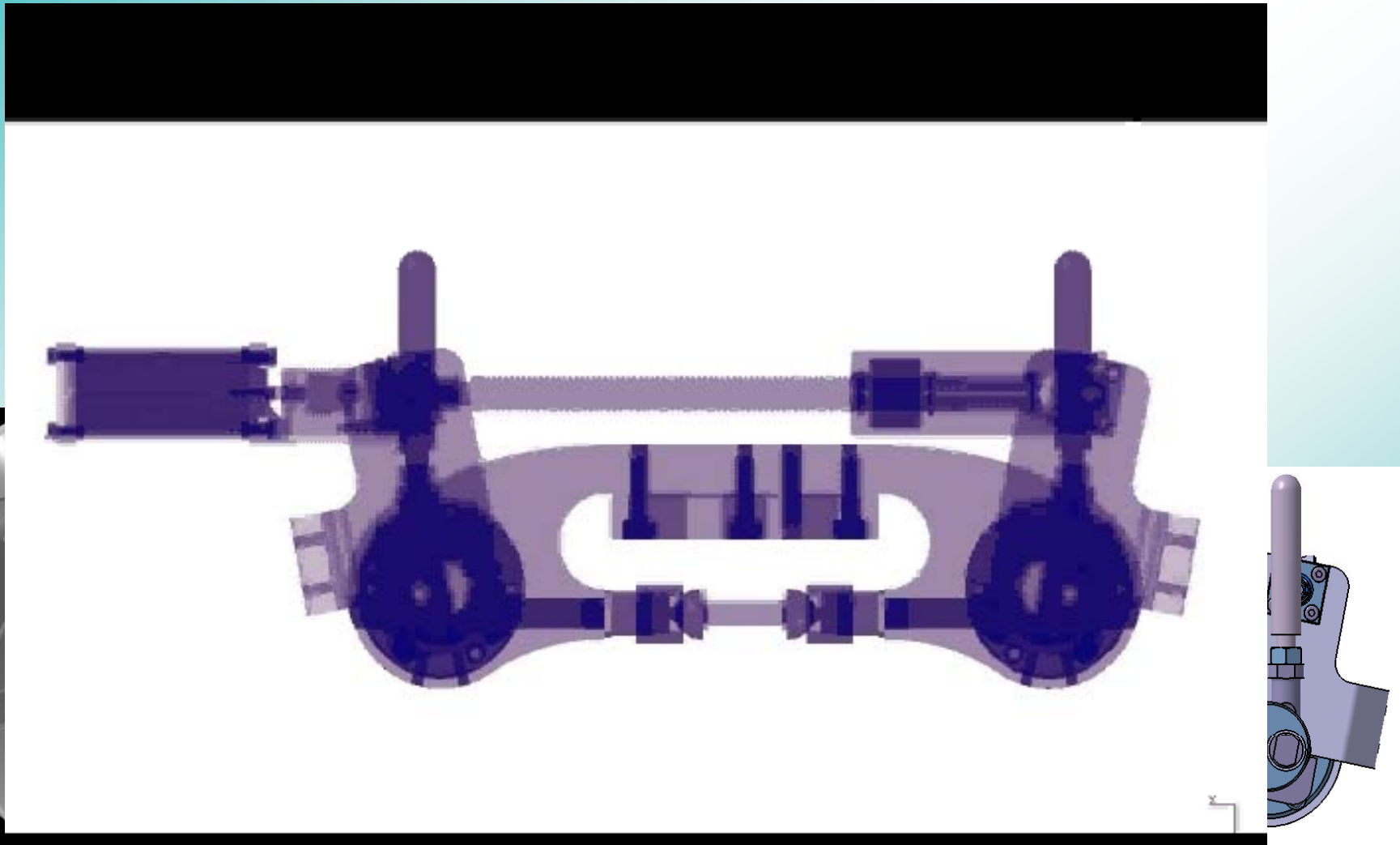


## SC Cavity : cold tuning system (1)





## Cold tuning system for spoke cavities

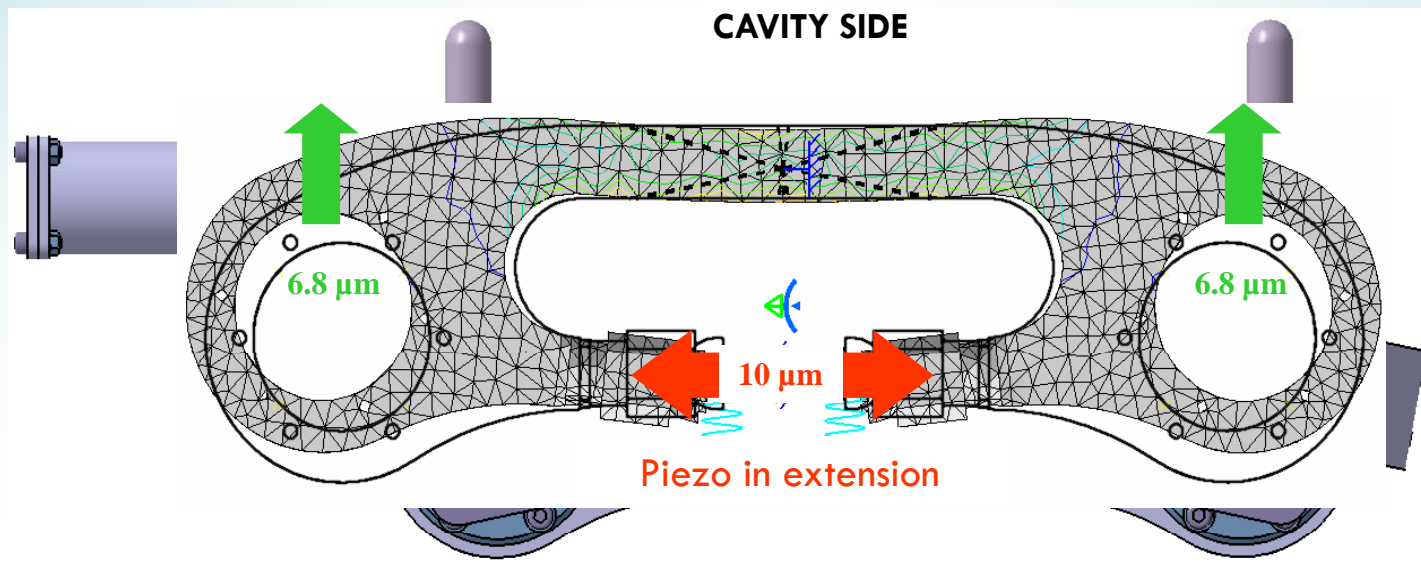
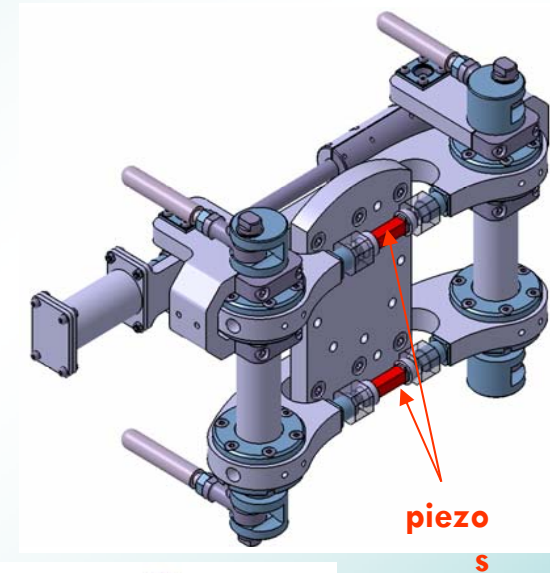




## Cold tuning system for spoke cavities

### *Parameters for fast tuning*

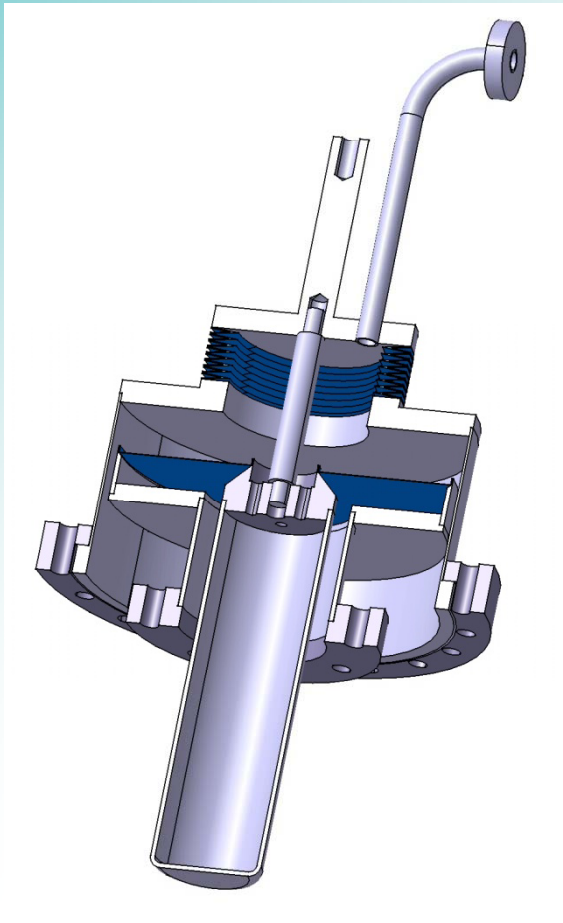
- Piezo tuner inserted within each “arm”
- Preloading of ~4 kN
- Displacement: ~3  $\mu\text{m}$  @ 4 K
- 68% of the piezo displ. transferred to the cavity
- Tuning range: ~2 kHz max



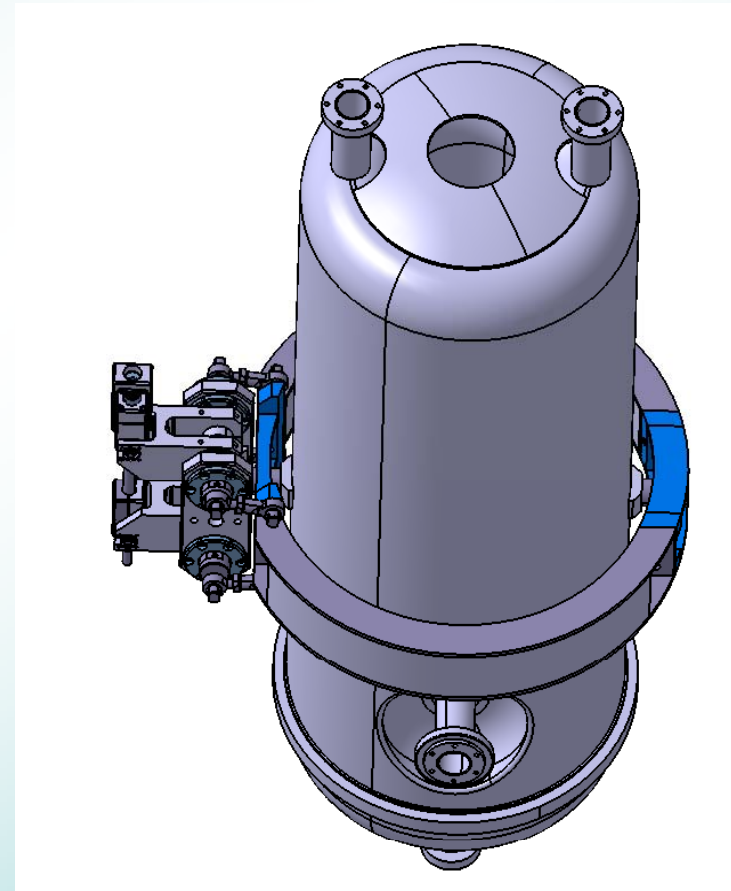


## SC Cavity : cold tuning system (2)

Plunger  
(innovative solution)

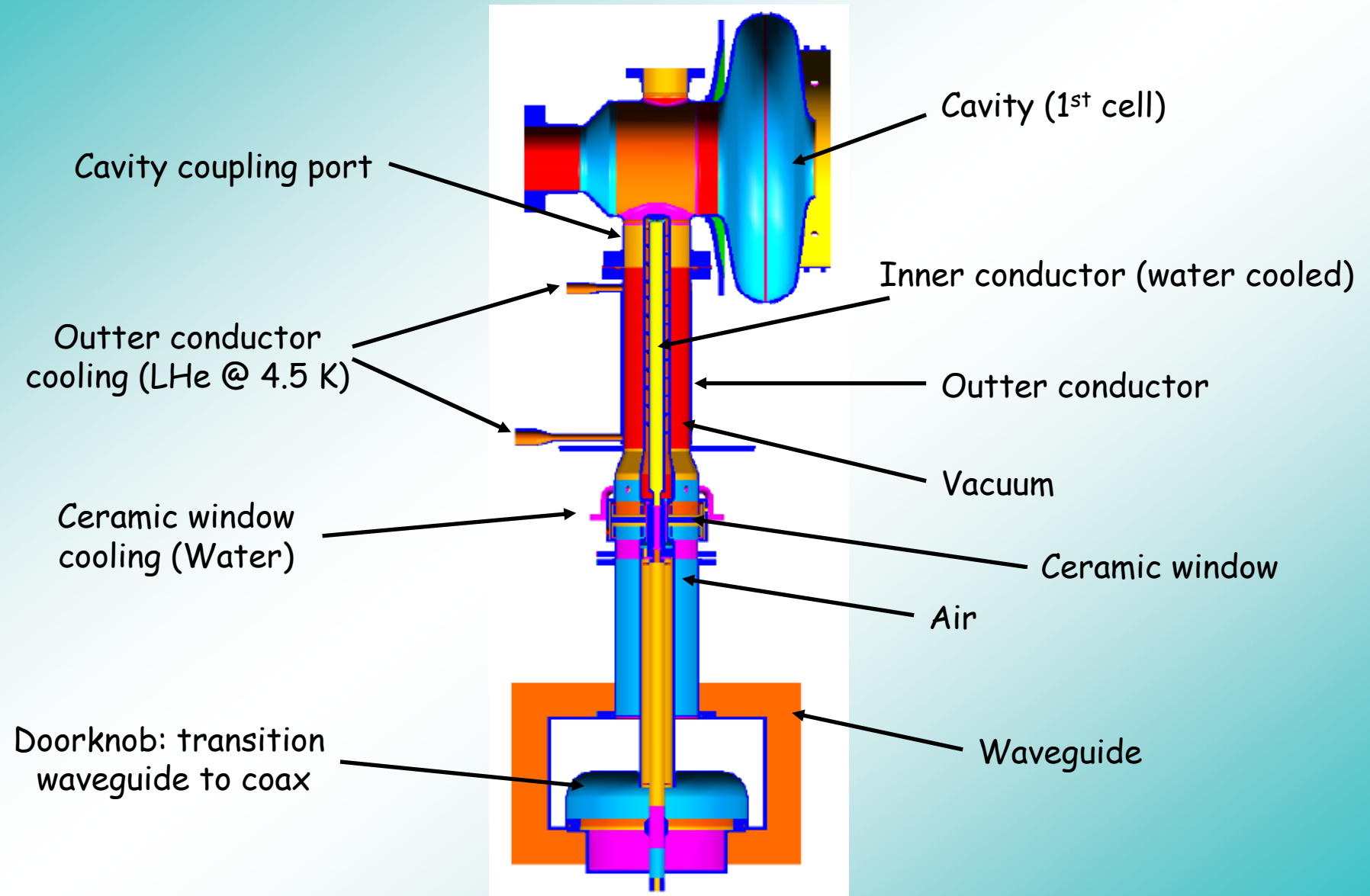


Mechanical deformation  
("classic" solution)





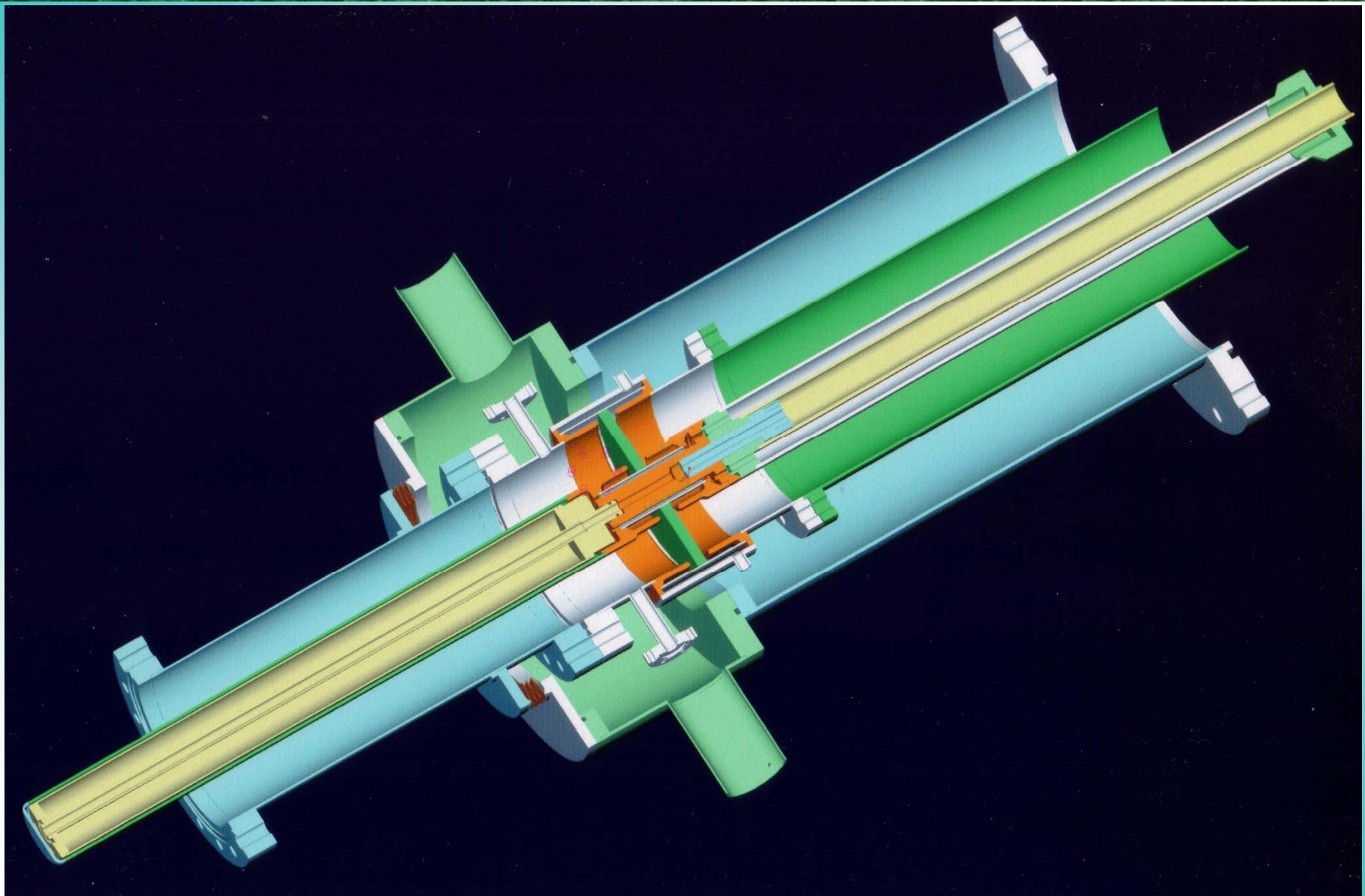
## Power couplers







## Power couplers

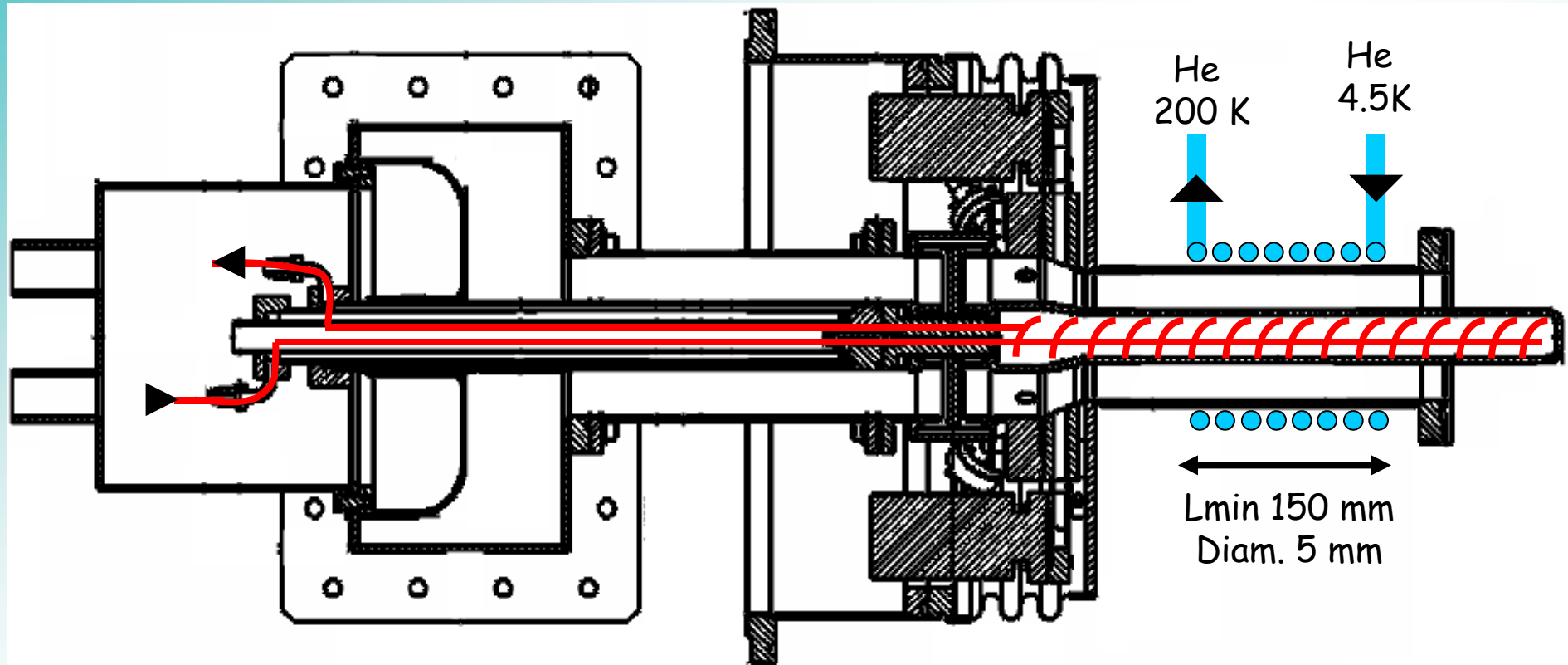






## Power couplers

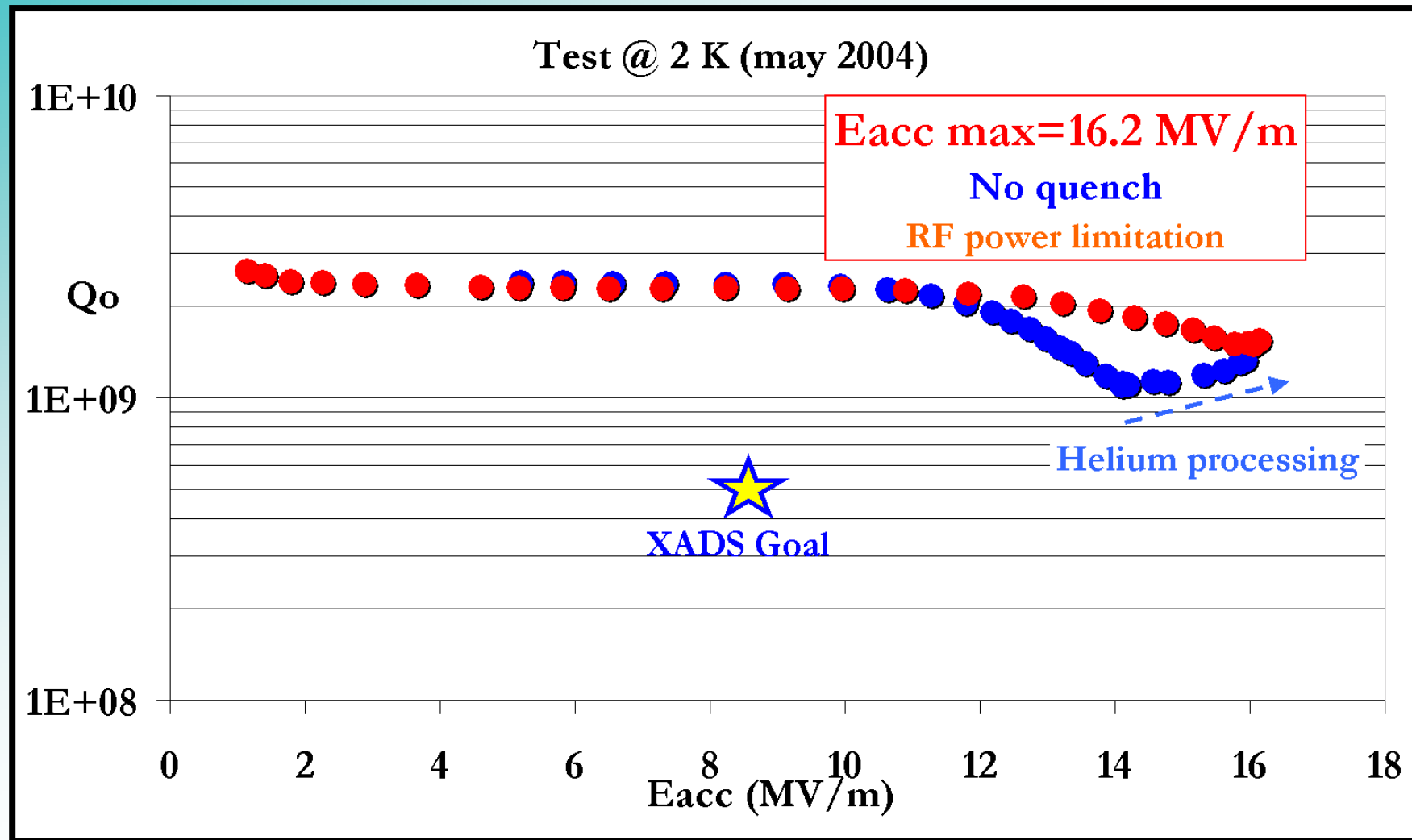
- Outer conductor: Helium cooling



- Inner conductor: Water cooling



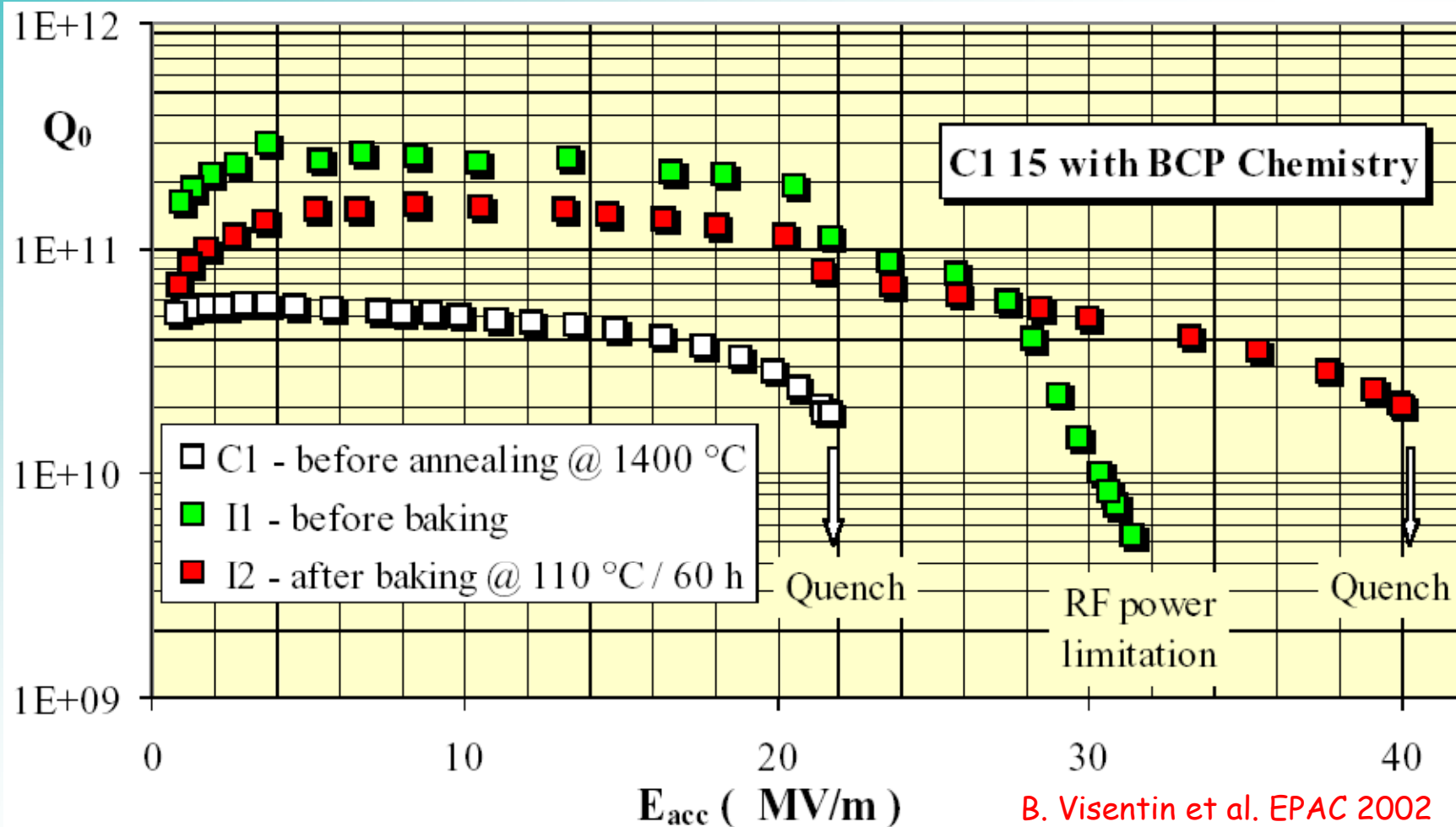
## One example : Performances of a spoke cavity (IPN Orsay)



$E_{acc} = 16.2 \text{ MV/m}$  means  $E_{peak} = 49.5 \text{ MV/m}$  &  $B_{peak} = 134 \text{ mT}$



## Another example : Performances of TESLA cavity





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

