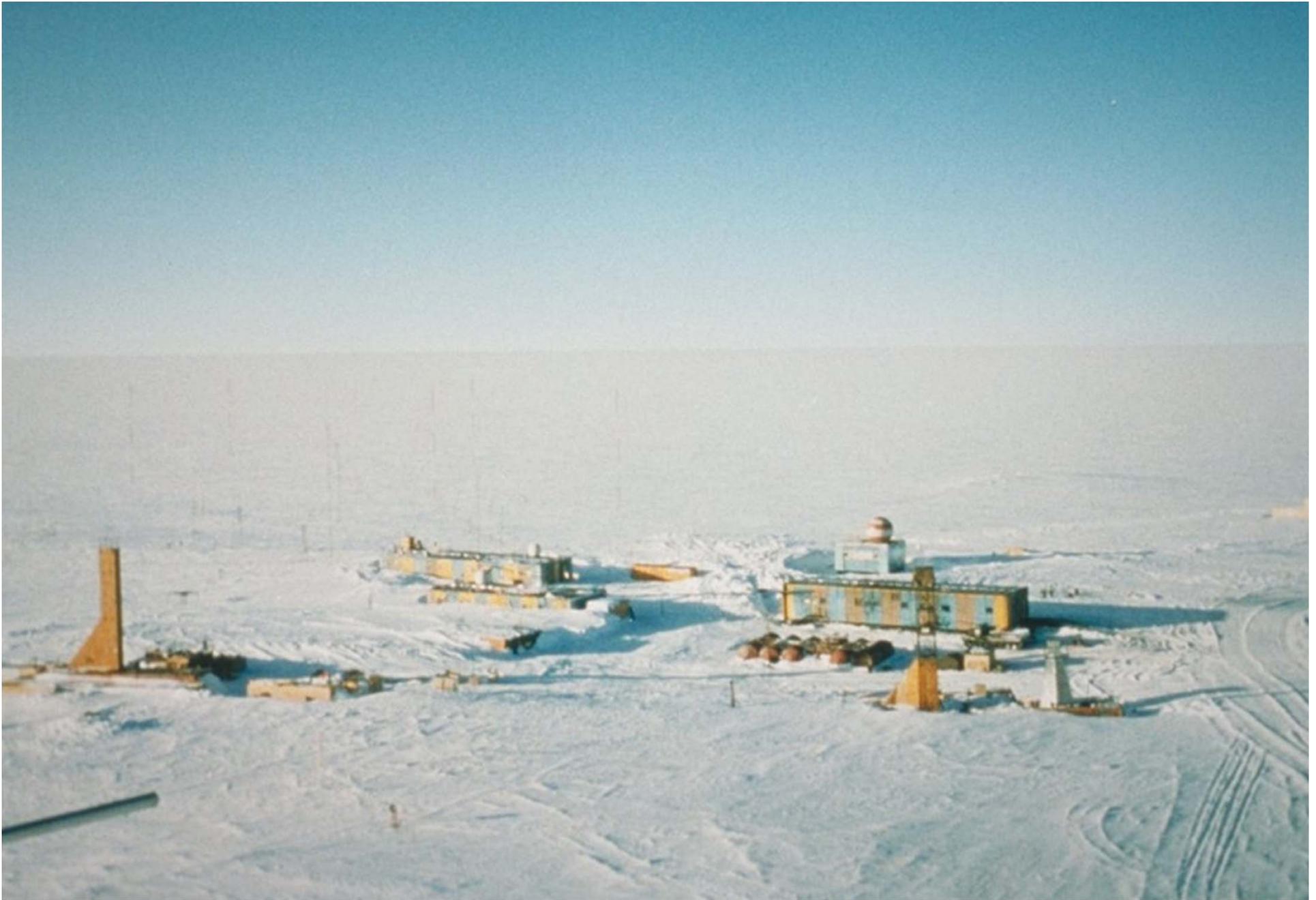


A scenic view of a glacier and a frozen lake with mountains in the background. The glacier is a massive, textured expanse of white and grey ice, extending from the base of the mountains towards the foreground. The mountains are dark, jagged peaks with patches of snow. The foreground shows a frozen lake with intricate patterns of blue and white ice, reflecting the sky and the surrounding landscape. The sky is a clear, deep blue.

# LA FISICA AL FREDDO

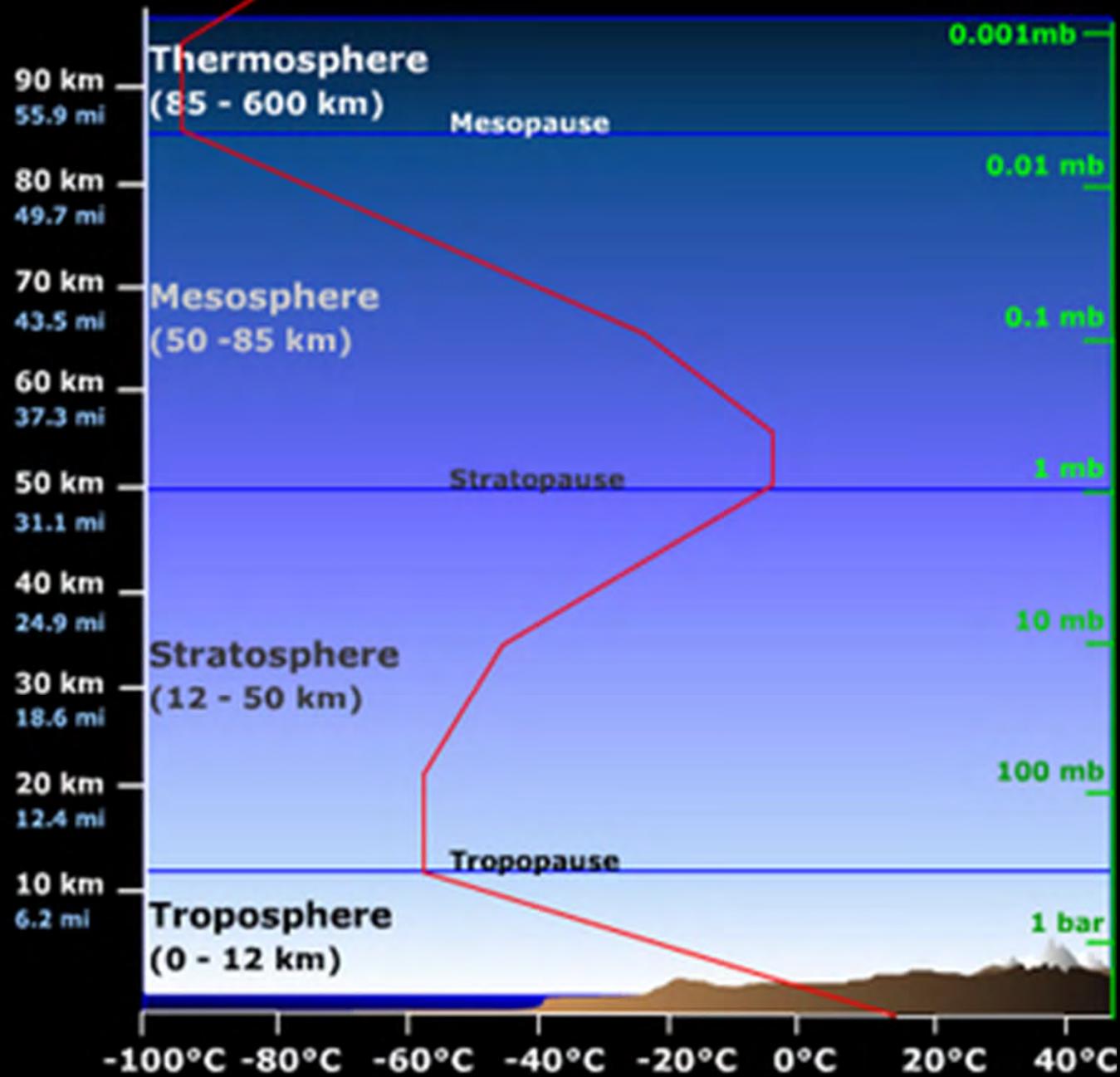
Riccardo Musenich

Istituto Nazionale  
di Fisica Nucleare

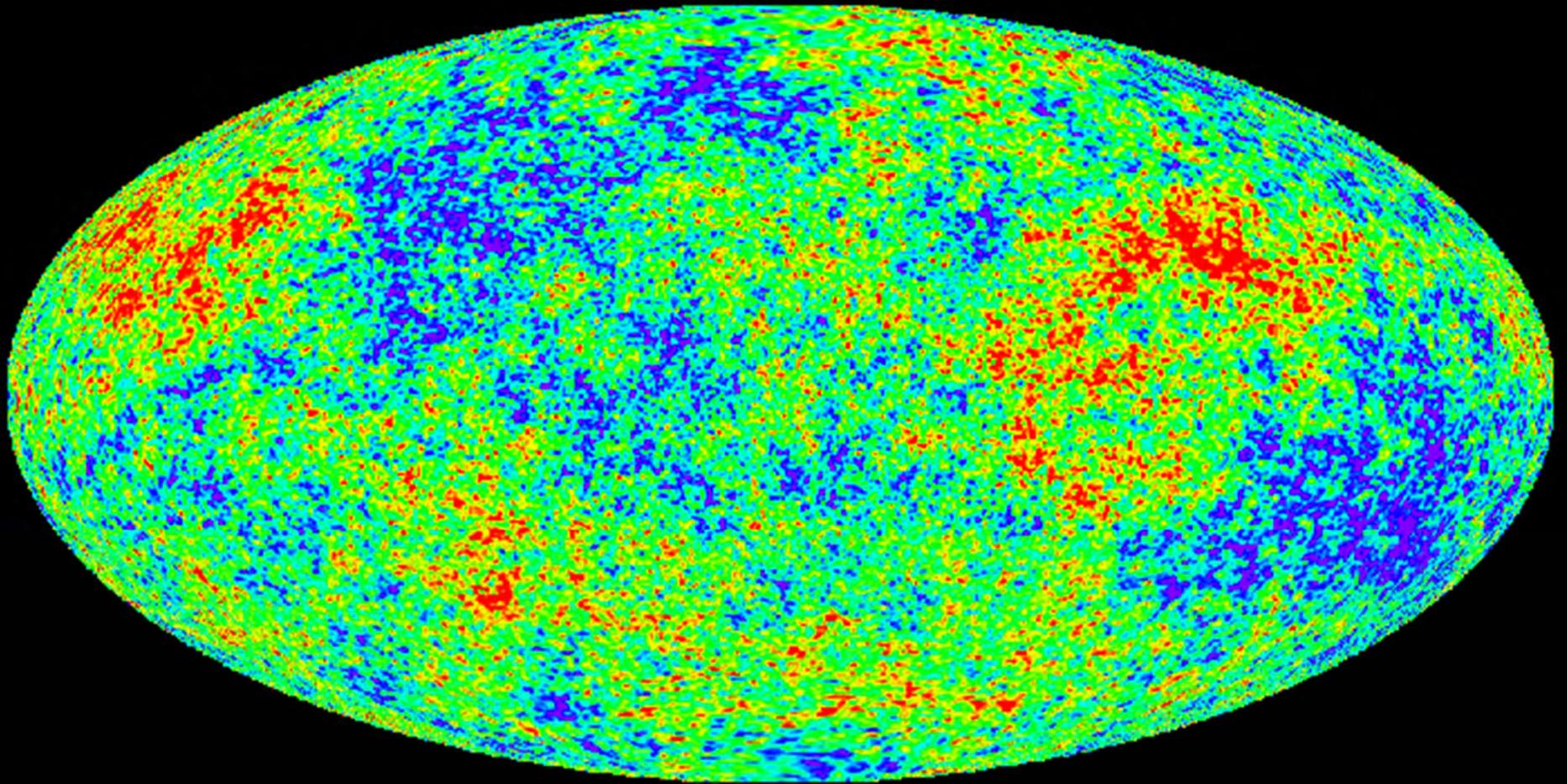


Base Vostok (Antartide)

$$T_{min} = -91,8^{\circ}C = 181.4 K$$



$$\langle T \rangle = 2.7 \text{ K} \approx -270^\circ\text{C}$$





Nebulosa Boomerang

$T \approx 1 K \approx -272^{\circ}C$



## Temperatura di ebollizione di gas liquefatti (a 1 atm)

Metano :	111 K
Ossigeno :	90 K
Argon :	87 K
Azoto :	77.3 K
Neon :	27.2 K
Idrogeno :	20.3 K
Elio :	4.2 K

1908

Liquefazione dell'elio ( $T \approx 4 K$ )

Heike Kamerlingh Onnes

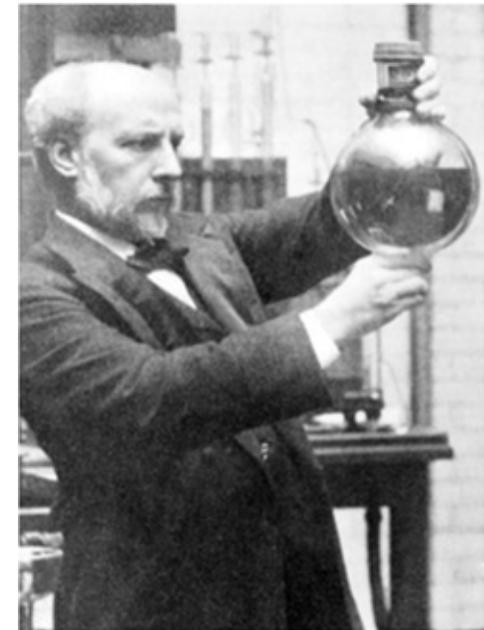


Dalla disponibilità, seppur limitata,  
di elio liquido nasce l'opportunità di  
studiare le proprietà della materia a  
basse temperature.





I liquidi criogenici vanno tenuti in appositi contenitori chiamati dewar dal nome del loro inventore, Sir James Dewar.



Superisolamento



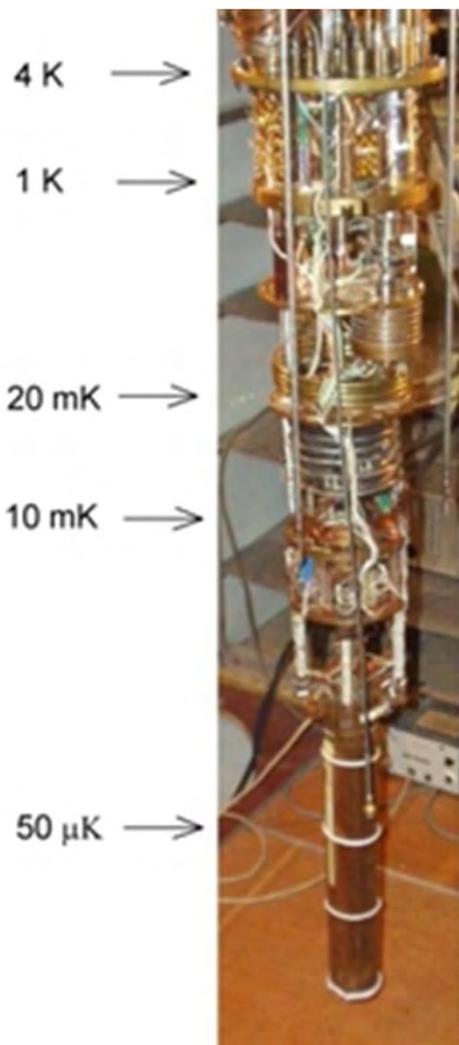


- 1/4 Watt @ 4.2K
- 2.5 kW -- Single Phase 208/220
- Air or Water Cooled

Elio liquido a pressione atmosferica:  $T_{\text{eb}}=4.2 \text{ K}$

Riducendo la pressione  $\rightarrow 0.7 \text{ K}$

refrigeratore a diluizione  $^3\text{He} - ^4\text{He}$   $T \sim 2 \text{ mK}$

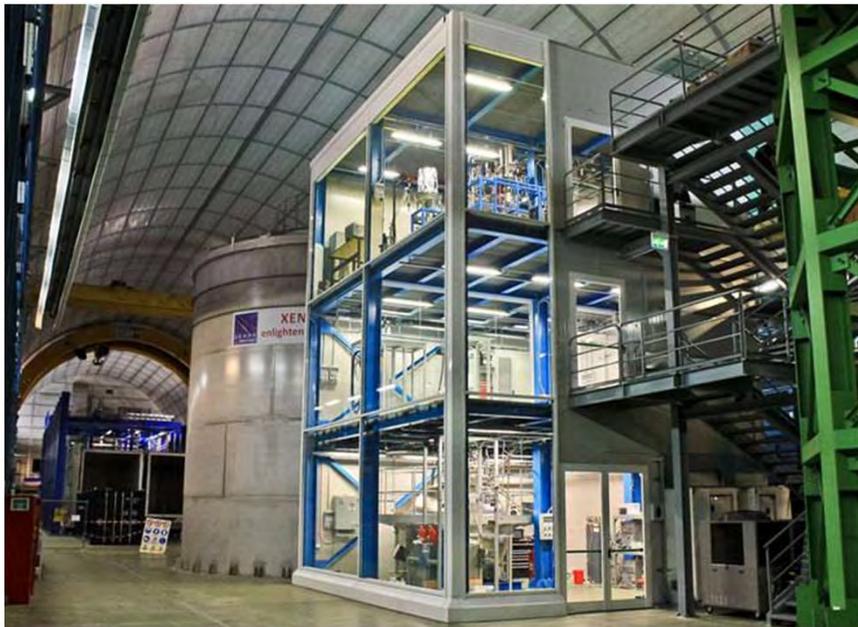


refrigeratore a smagnetizzazione adiabatica

$T \sim 1 \mu\text{K}$

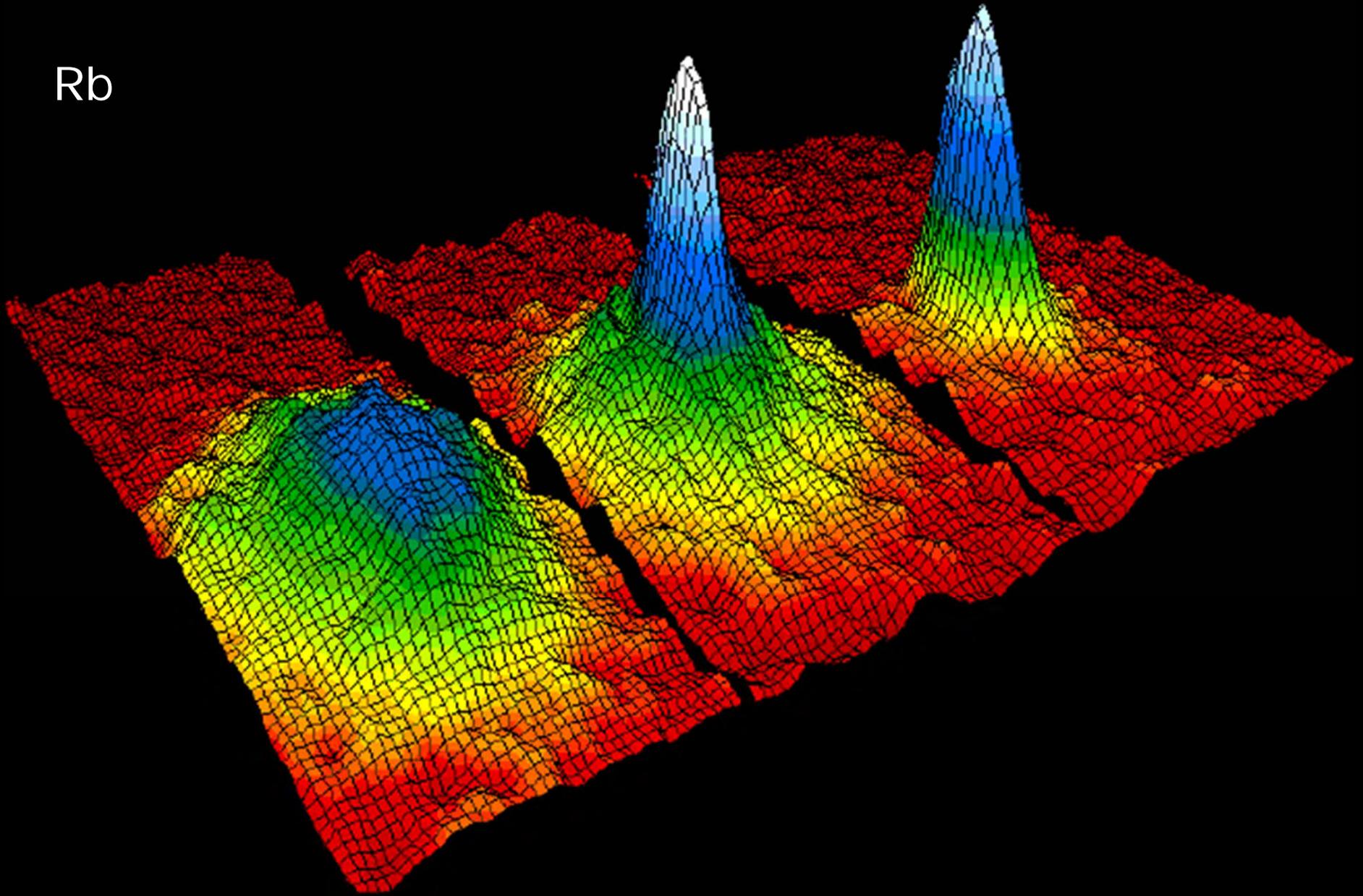


# INFN – Laboratori Nazionali del Gran Sasso

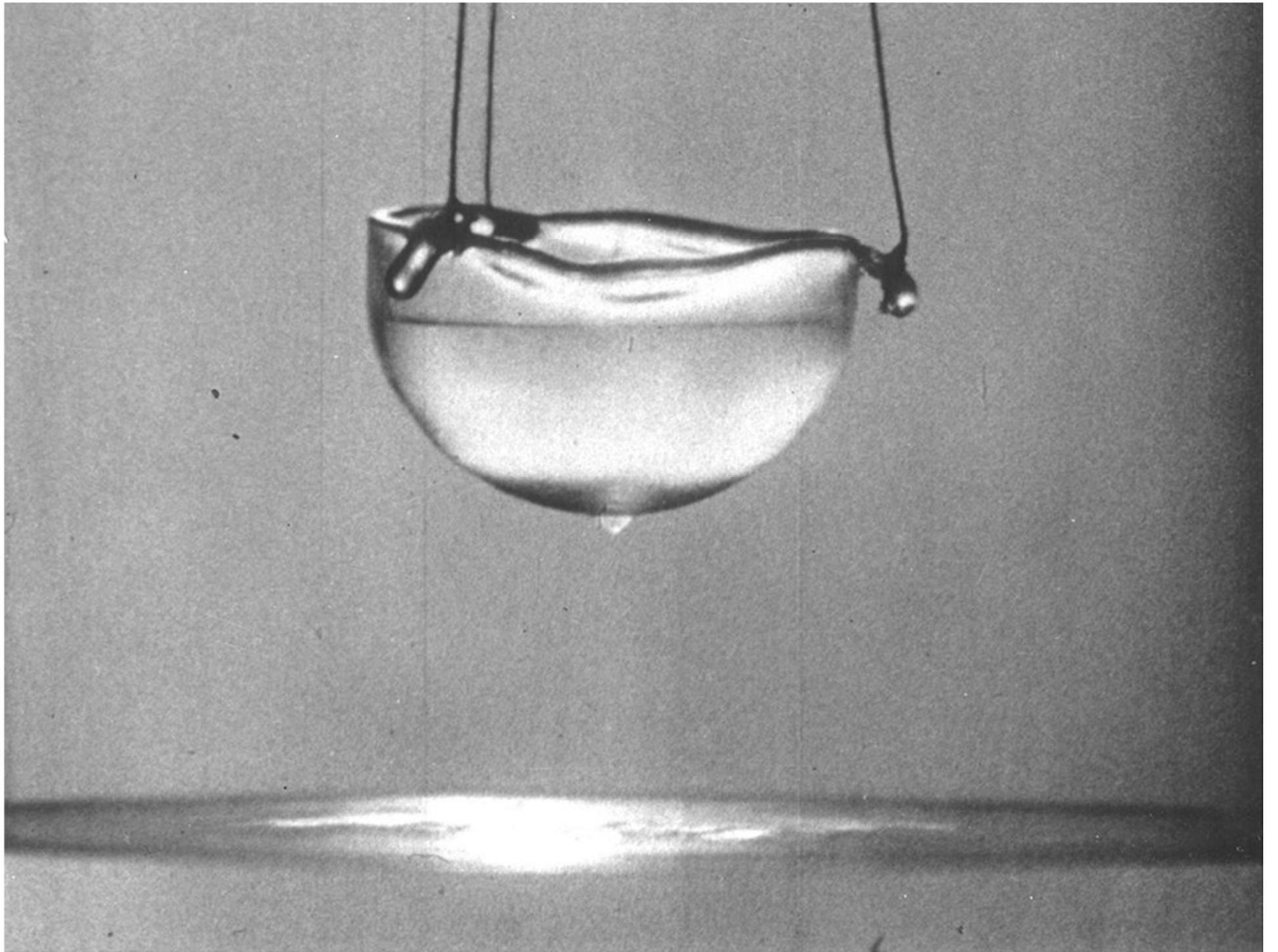


# Condensato di Bose-Einstein

Rb

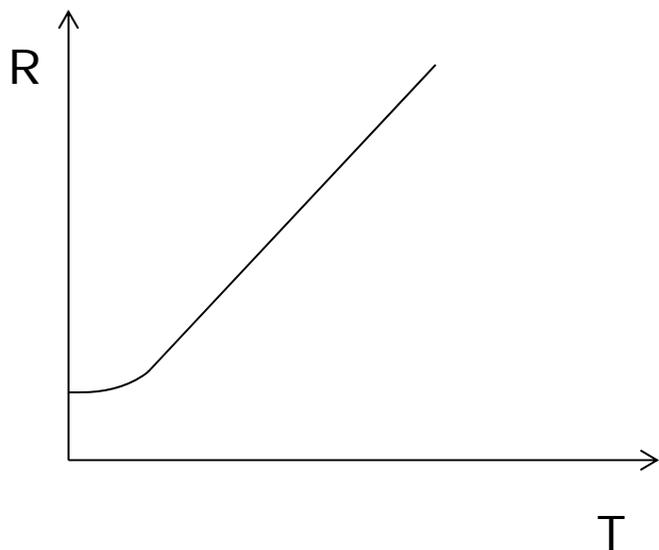
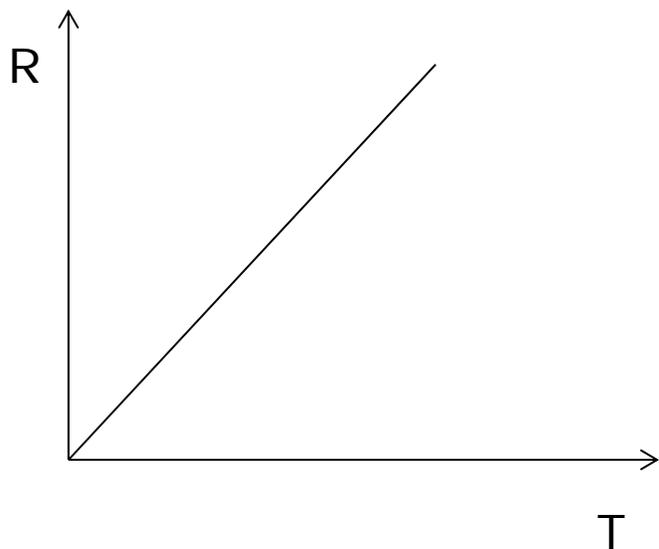


Condensato di Bose–Einstein

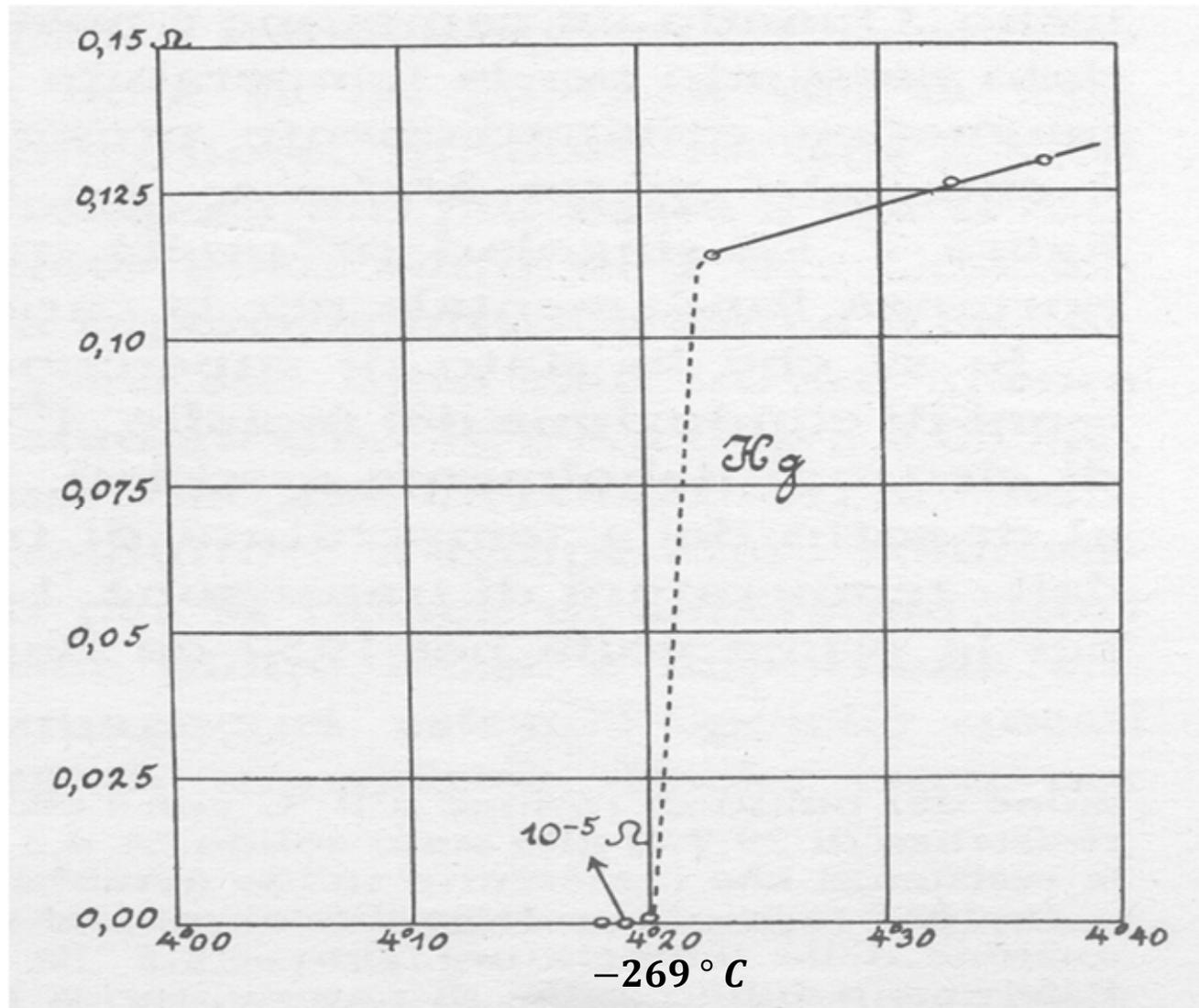




# Resistività dei metalli puri a bassa temperatura



# Kamerlingh Onnes (1911)



# KNOWN SUPERCONDUCTIVE ELEMENTS

1	IA	1	H	IIA	2	He	0																														
2		3	Li	4	Be	5	B	6	C	7	N	8	O	9	F	10	Ne																				
3		11	Na	12	Mg	13	Al	14	Si	15	P	16	S	17	Cl	18	Ar																				
4		19	K	20	Ca	21	Sc	22	Ti	23	Y	24	Cr	25	Mn	26	Fe	27	Co	28	Ni	29	Cu	30	Zn	31	Ga	32	Ge	33	As	34	Se	35	Br	36	Kr
5		37	Rb	38	Sr	39	Y	40	Zr	41	Nb	42	Mo	43	Tc	44	Ru	45	Rh	46	Pd	47	Ag	48	Cd	49	In	50	Sn	51	Sb	52	Te	53	I	54	Xe
6		55	Cs	56	Ba	57	*La	72	Hf	73	Ta	74	W	75	Re	76	Os	77	Ir	78	Pt	79	Au	80	Hg	81	Tl	82	Pb	83	Bi	84	Po	85	At	86	Rn
7		87	Fr	88	Ra	89	+Ac	104	Rf	105	Ha	106	106	107	107	108	108	109	109	110	110	111	111	112	112												

■ BLUE = AT AMBIENT PRESSURE  
■ GREEN = ONLY UNDER HIGH PRESSURE

*SUPERCONDUCTORS.ORG*

\* Lanthanide Series

+ Actinide Series

58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
90	91	92	93	94	95	96	97	98	99	100	101	102	103
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

A partire dagli anni '40 sono stati scoperti molti composti superconduttori, come il nitruro di niobio ( $\text{NbN}_{1-x}$ ) o il niobio stagno ( $\text{Nb}_3\text{Sn}$ )<sup>\*</sup>.

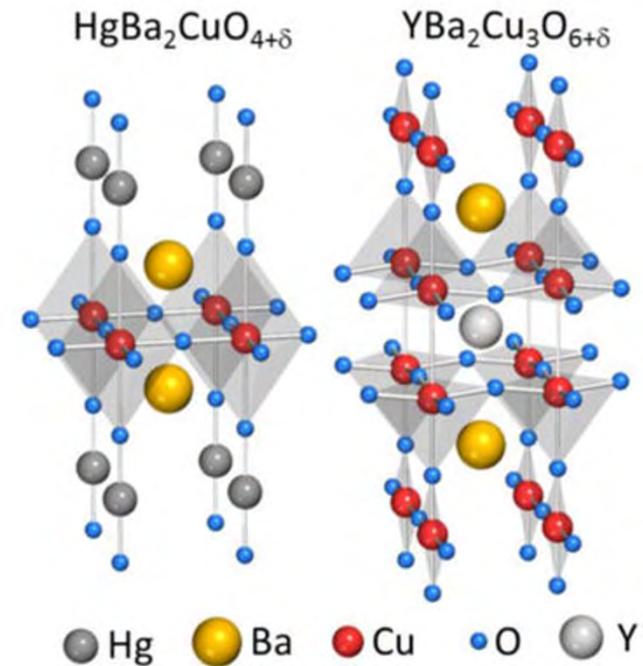
Solo nel 1962 si è arrivati a sviluppare il primo filo superconduttore su scala industriale (in lega niobio-titanio).

Fino agli anni '80 si riteneva che la temperatura critica di un superconduttore non potesse superare i 30 K ( $\text{Nb}_3\text{Ge}$ : 23.2 K) ma ...

<sup>\*</sup> B. T. Matthias et al., Phys. Rev. 95, 1435 (1954)

... nel 1986 sono stati scoperti i superconduttori ad alta temperatura critica

$\text{La}_{1.85}\text{Ba}_{0.15}\text{CuO}_4^*$	$T_c = 28 \text{ K } (-245 \text{ }^\circ\text{C})$
$\text{YBa}_2\text{Cu}_3\text{O}_7$	$T_c = 92 \text{ K } (-181 \text{ }^\circ\text{C})$
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$	$T_c = 95 \text{ K } (-178 \text{ }^\circ\text{C})$
$\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_8$	$T_c = 110 \text{ K } (-163 \text{ }^\circ\text{C})$



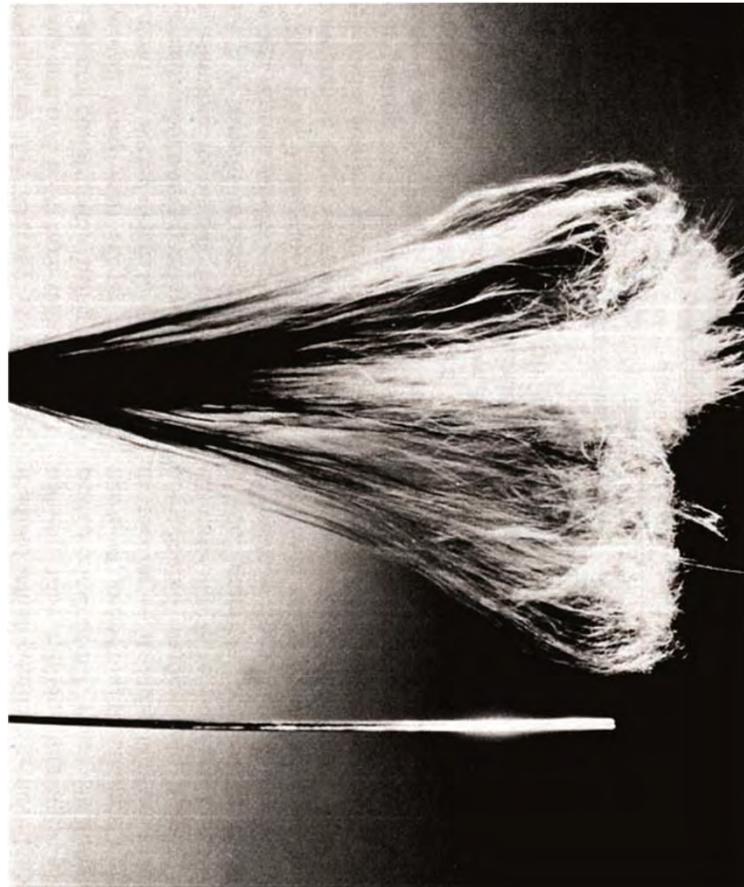
Attualmente il record di temperatura critica è di 203 K (-70°C) in H<sub>2</sub>S sotto altissima pressione (150 Gpa) \*\*

\* J.G.Bednorz, K.A.Müller, Z.Phys. B, Cond. Matter, 64, 189-193 (1986)

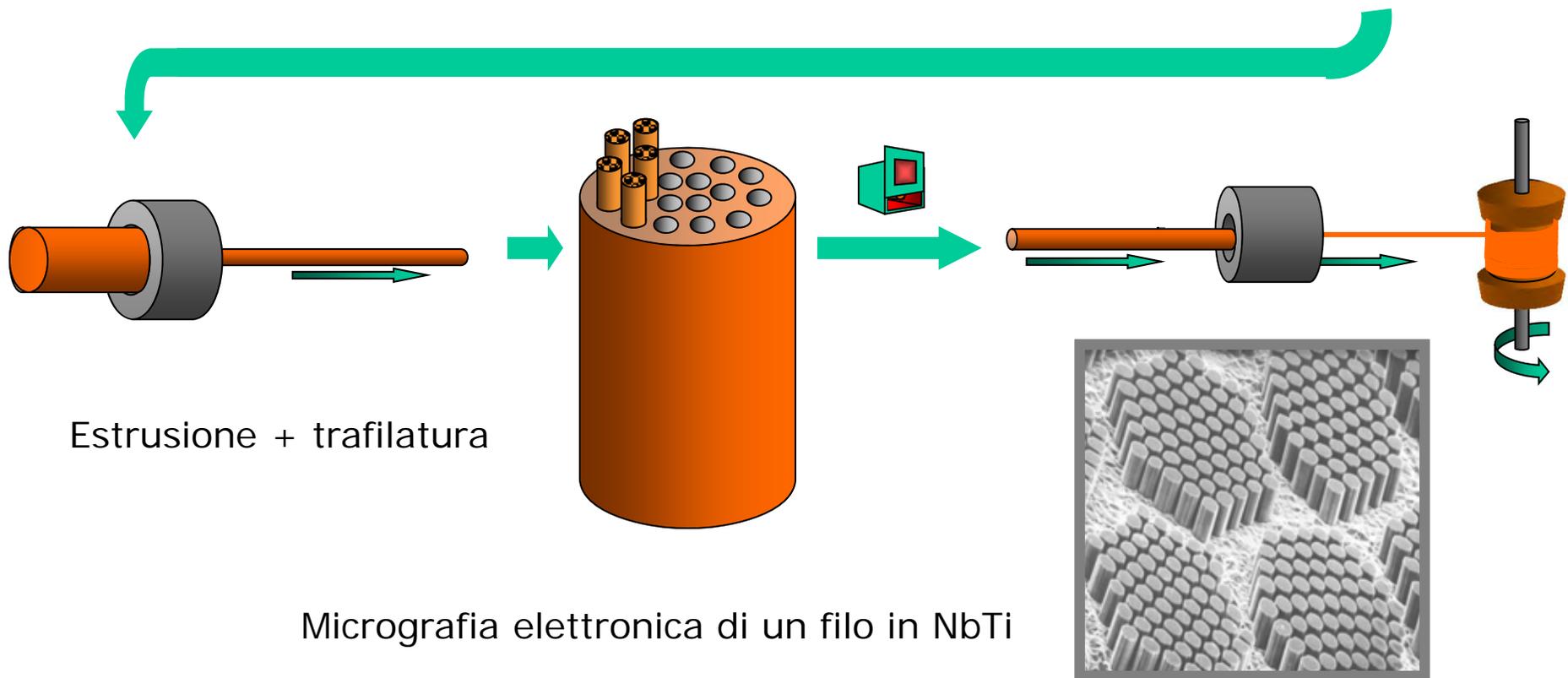
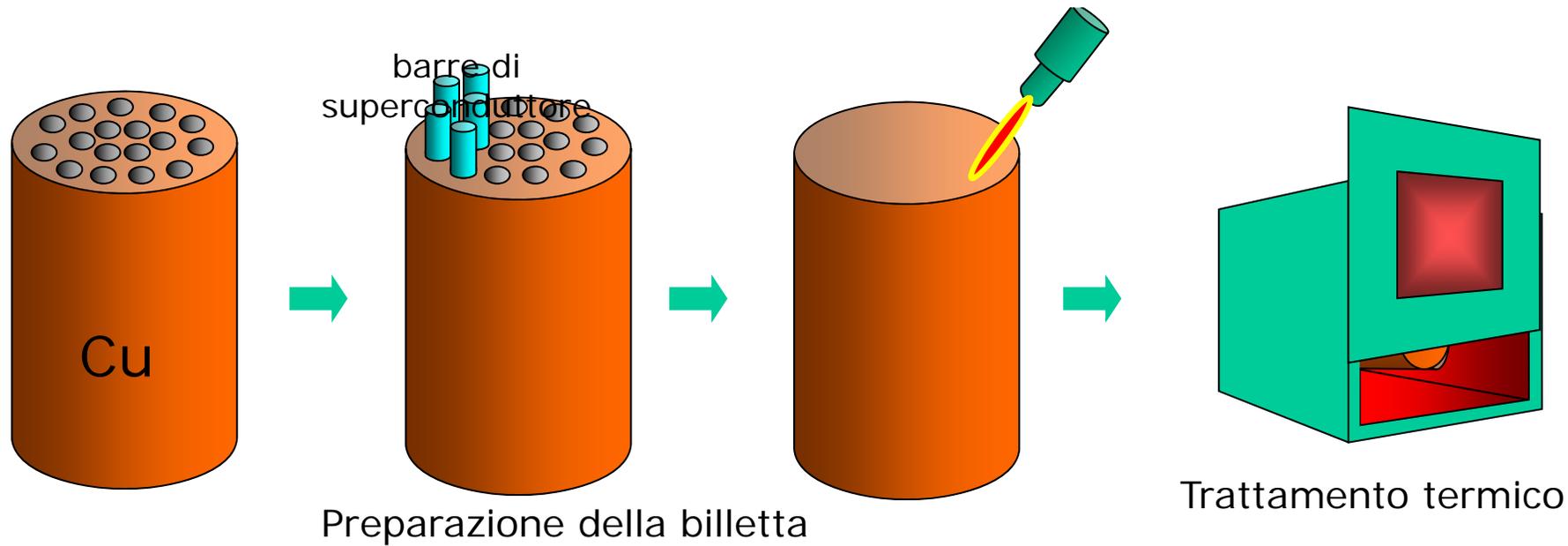
\*\* A.P.Drozdov, M.I.Eremets, I.A.Troyan, V.Ksenofontov, S.I.Shylin, Nature 525, 73–76 (2015)

# Materiali superconduttori per applicazioni a magneti

## Fili e cavi







## I cavi dei magneti per fusione (Cable in Conduit)



# Applicazioni attuali e potenziali dei superconduttori:

cavi  
magneti  
generatori  
trasformatori  
accumulatori  
fcl  
motori  
porte logiche  
antenne  
guide d'onda  
filtri  
squid  
rivelatori  
cavità risonanti

ricerca  
medicina  
generazione e distribuzione di energia  
industria  
trasporti  
elettronica  
telecomunicazioni

# Produzione e distribuzione di energia

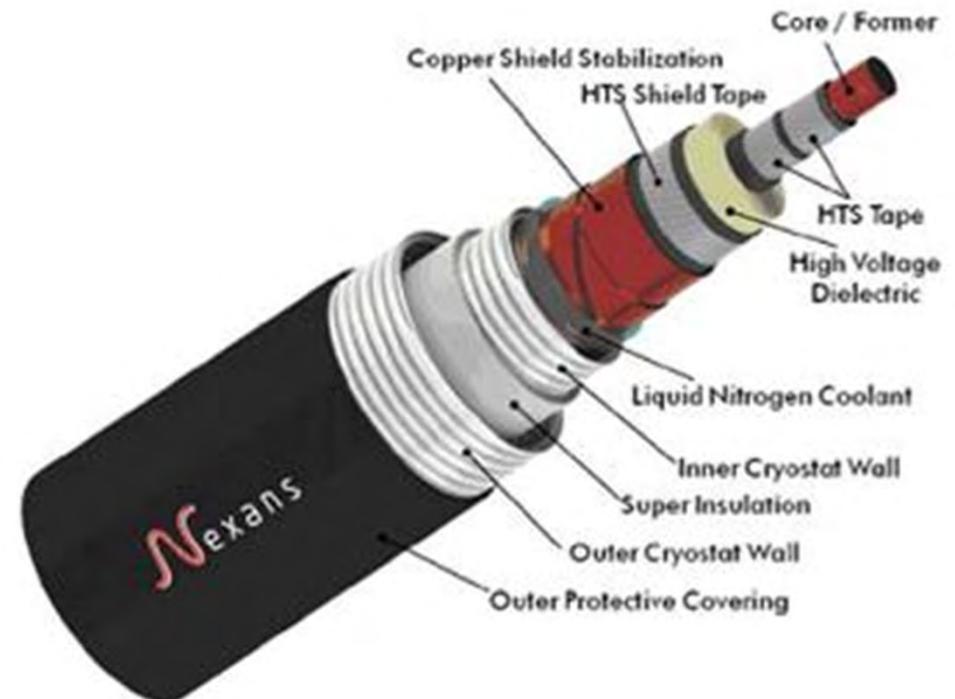
Cavi per trasporto di energia →

Generatori

Trasformatori

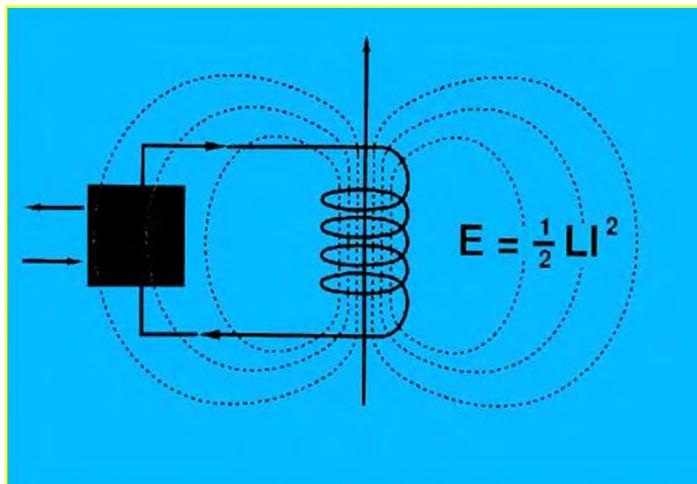
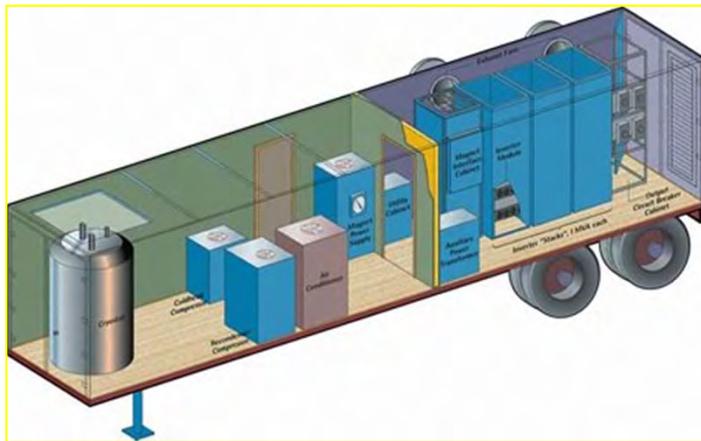
Accumulatori (SMES)

Limitatori di corrente (FCL)



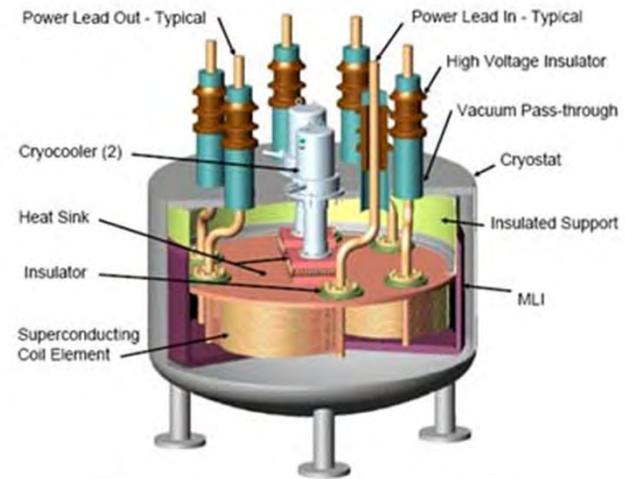
# SMES

Superconducting Magnetic Energy Storage



# FCL

Fault Current Limiter



Superconducting Fault Current Limiter

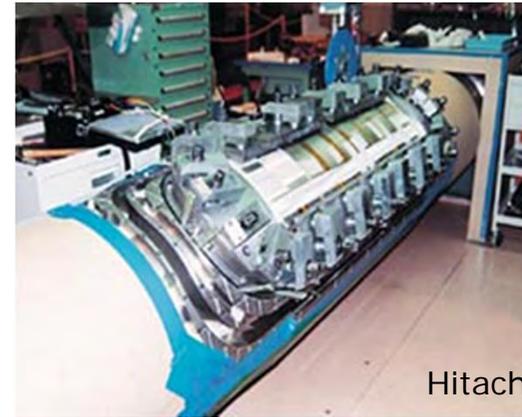
*hypertechenergy*



Trasformatore  
superconduttore

Trasformatore  
tradizionale

## Generatore superconduttore



Hitachi

# Applicazioni industriali

Magneti per:

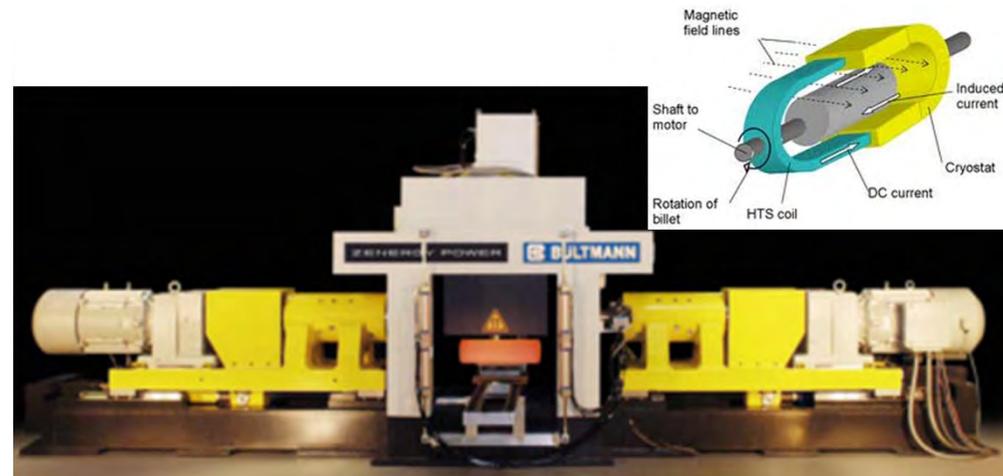
separazione magnetica

crescita di cristalli

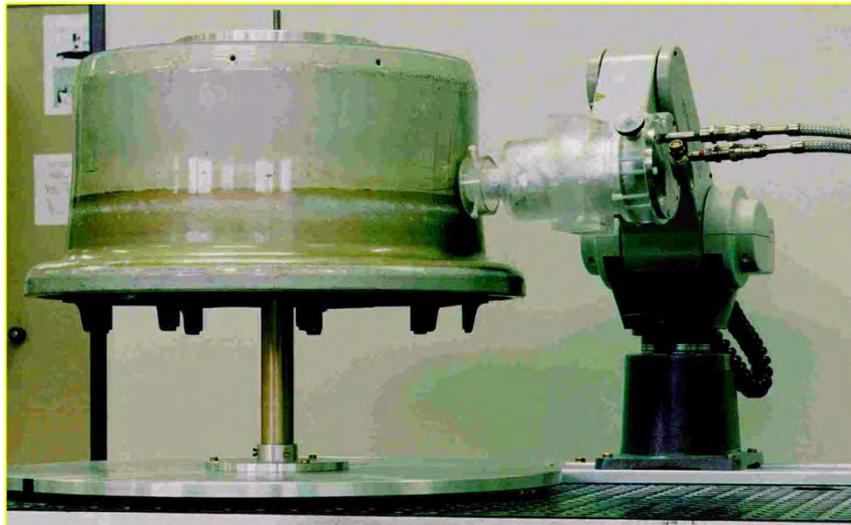
riscaldamento di billette



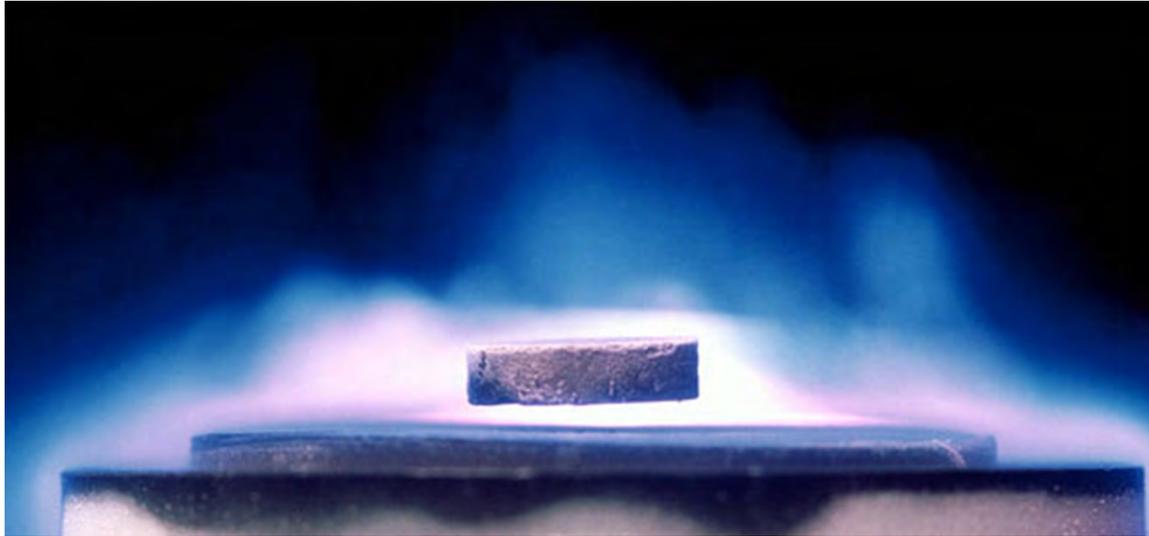
Separazione magnetica



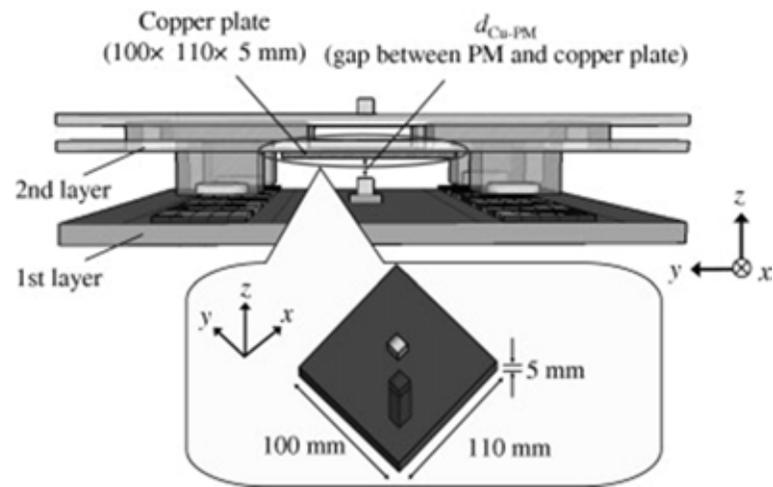
## Altre applicazioni



SQUID per verifiche su componenti di aerei, ponti, turbine e per esplorazioni geofisiche



## Isolamento sismico



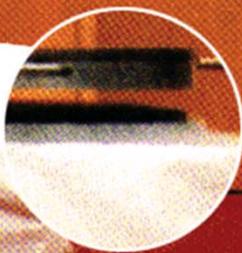
S.Sasaki et al, Phisica C, 470 (20) 2010

浮いた  
土佐ノ海

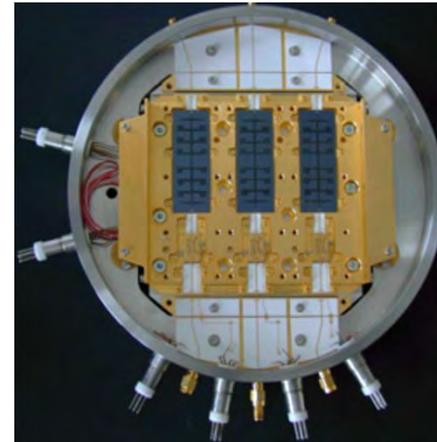
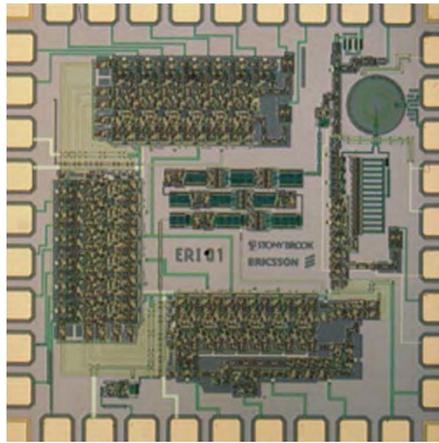
**TOSANOUMI**  
(Sumo Wrestler)

Height of Tosanoumi 186cm  
Weight of Tosanoumi 142kg  
Weight of disk 60kg  
Total weight 202kg

As of February '96



# Elettronica e telecomunicazioni



## Trasporti

levitazione magnetica

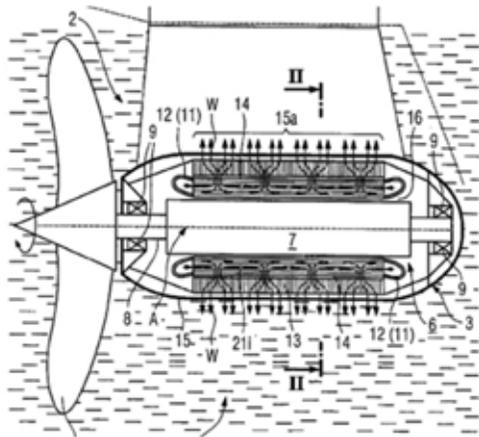
motori

propulsione MHD

propulsione a plasma



Yamanashi Maglev Test Line

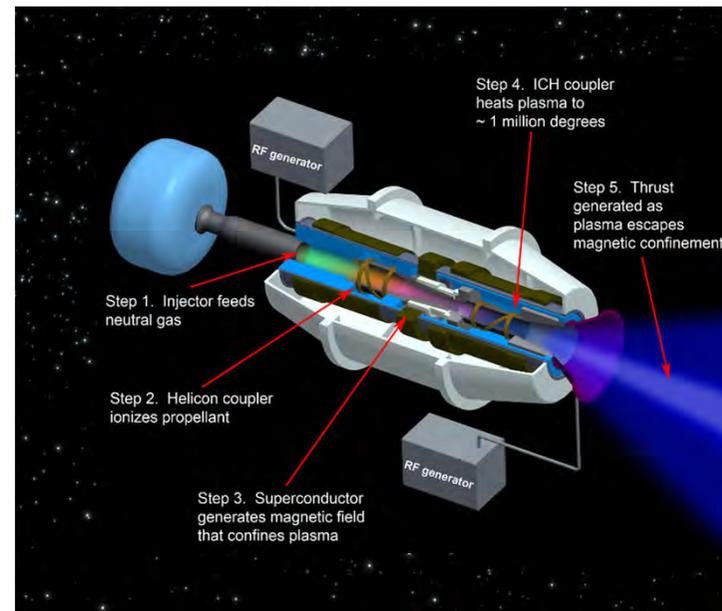


Motori navali

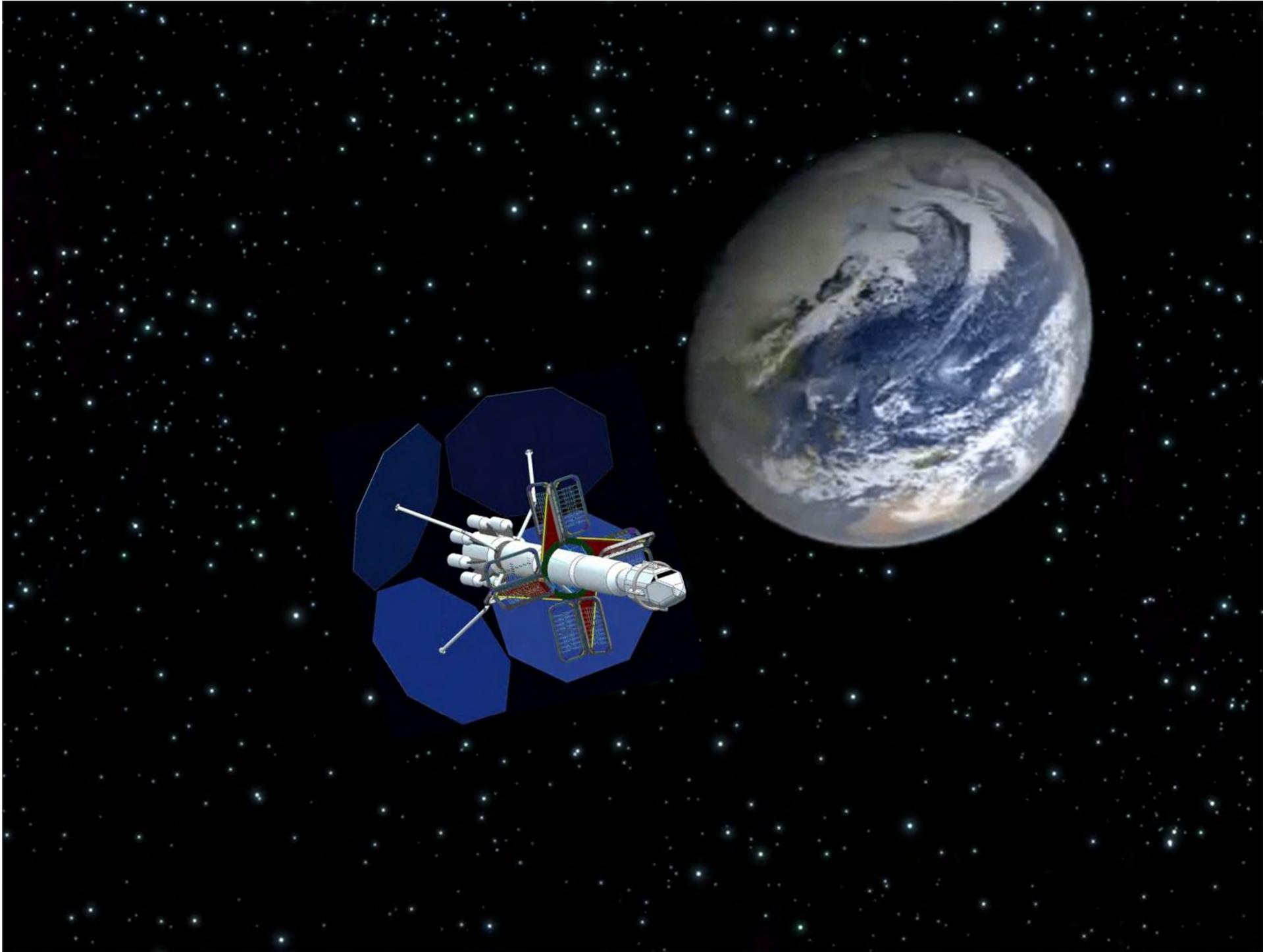


Propulsione MHD

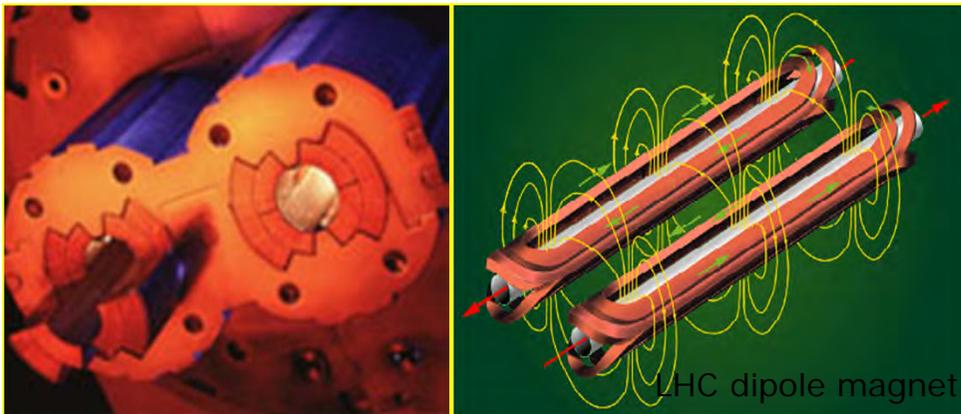
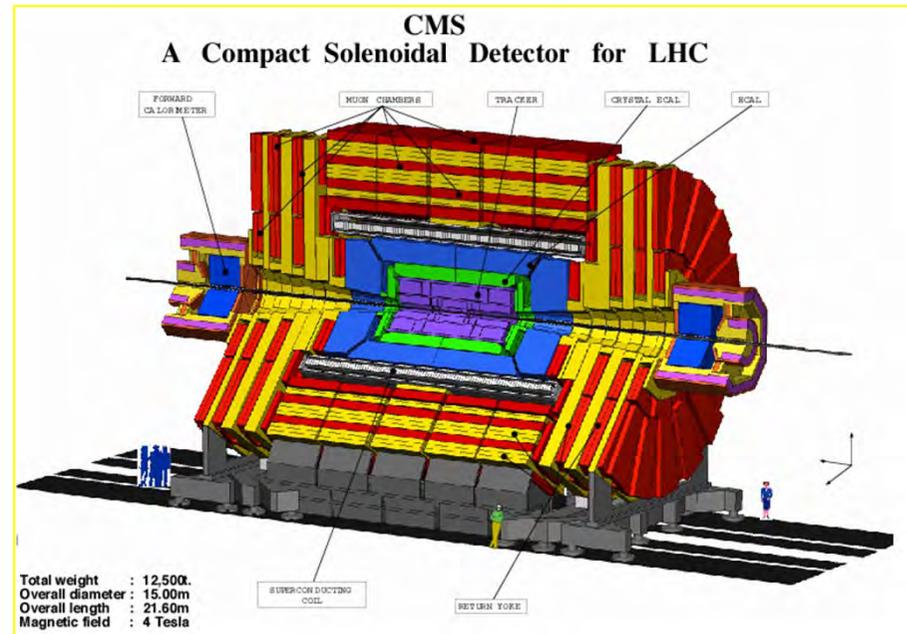
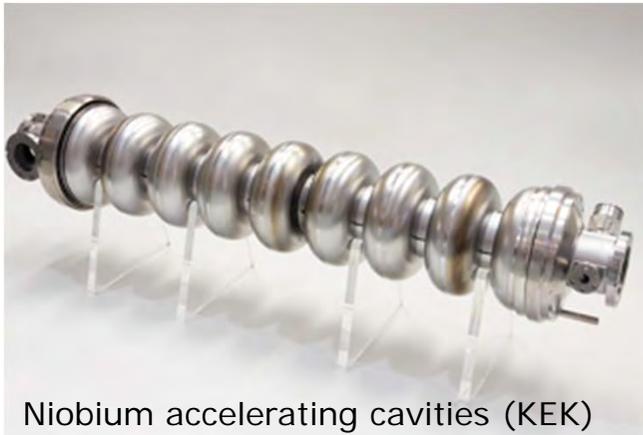


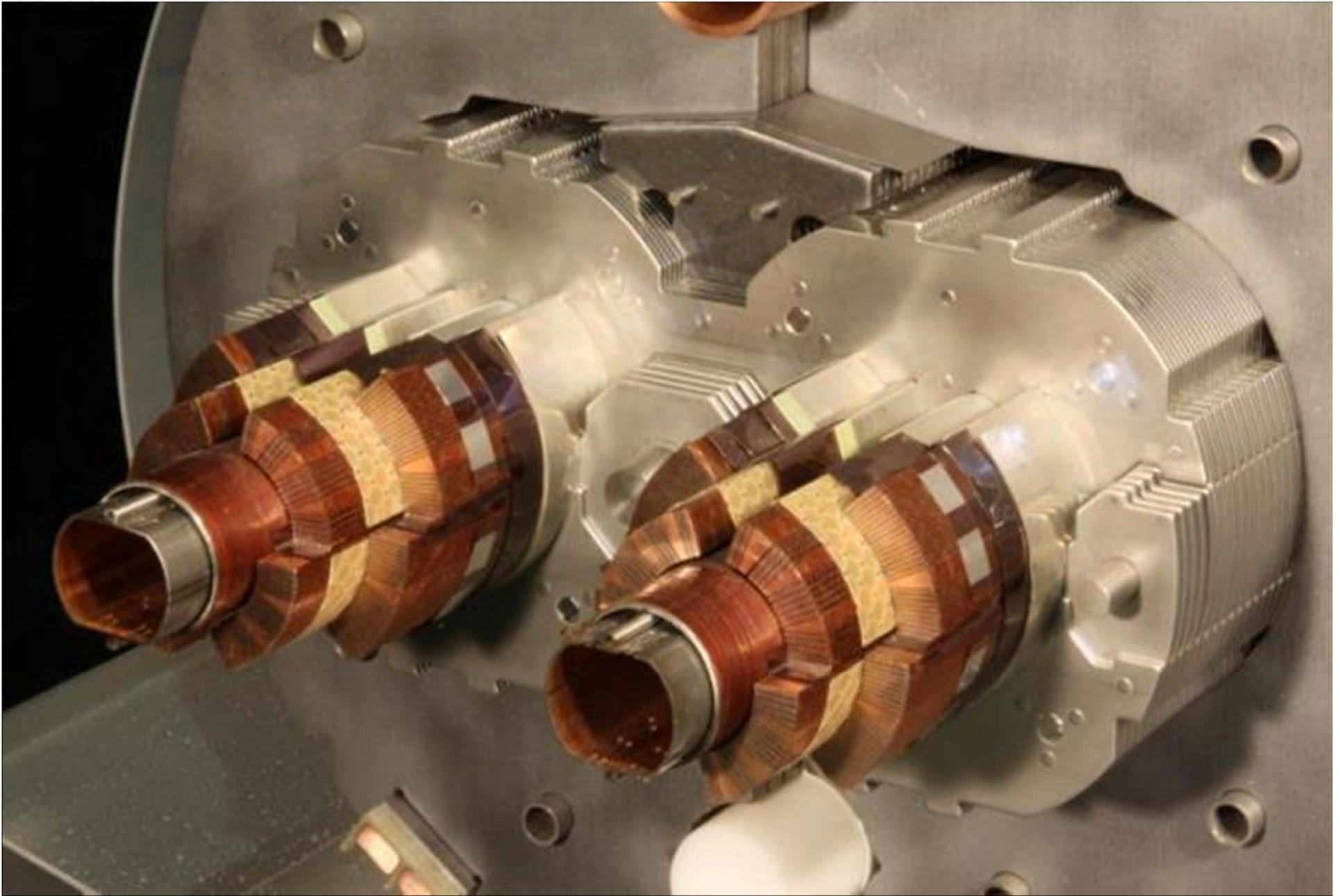


VASIMR  
Variable Specific Impulse Magnetoplasma Rocket

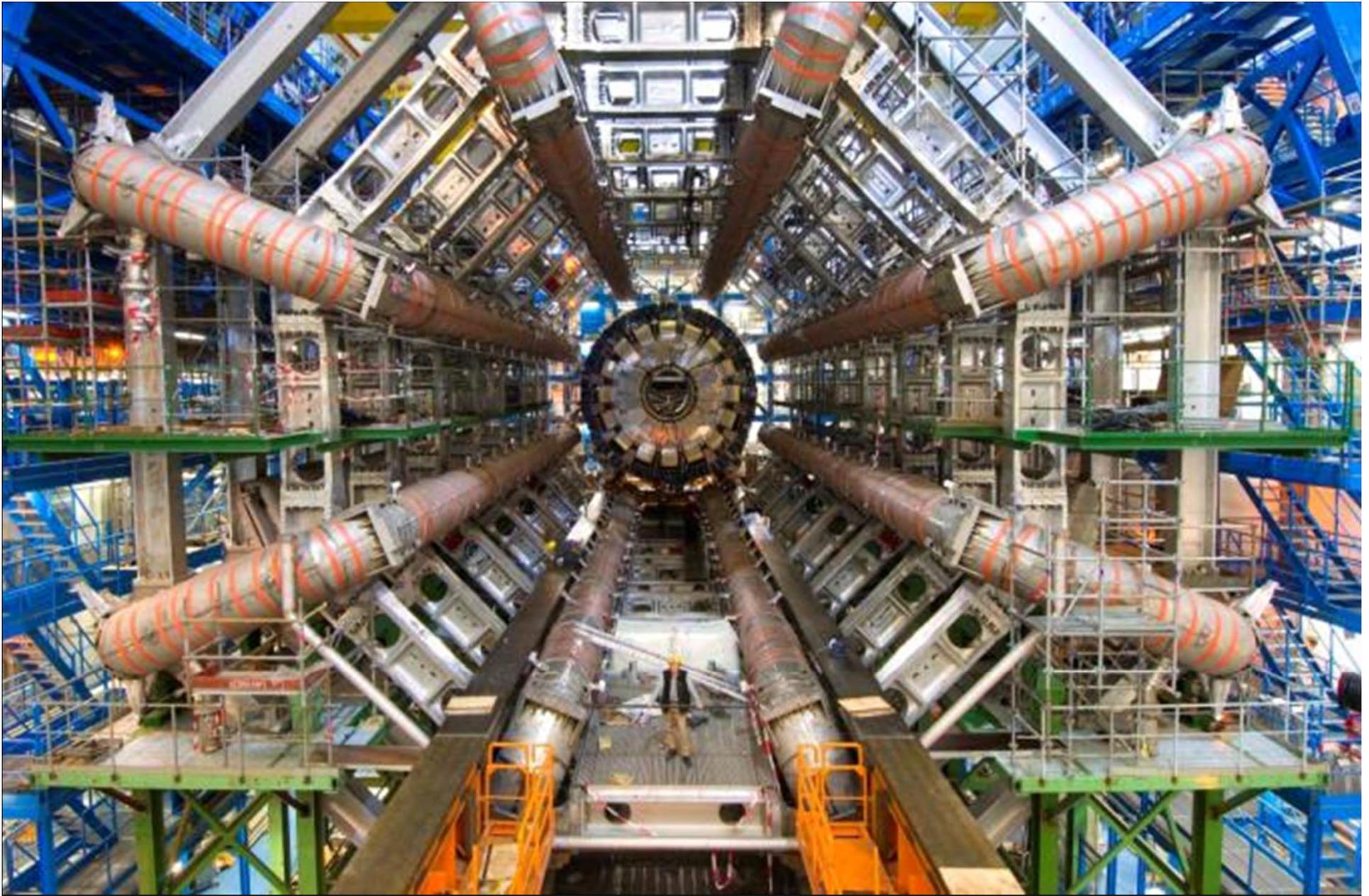


# Cavità e magneti superconduttori per la ricerca

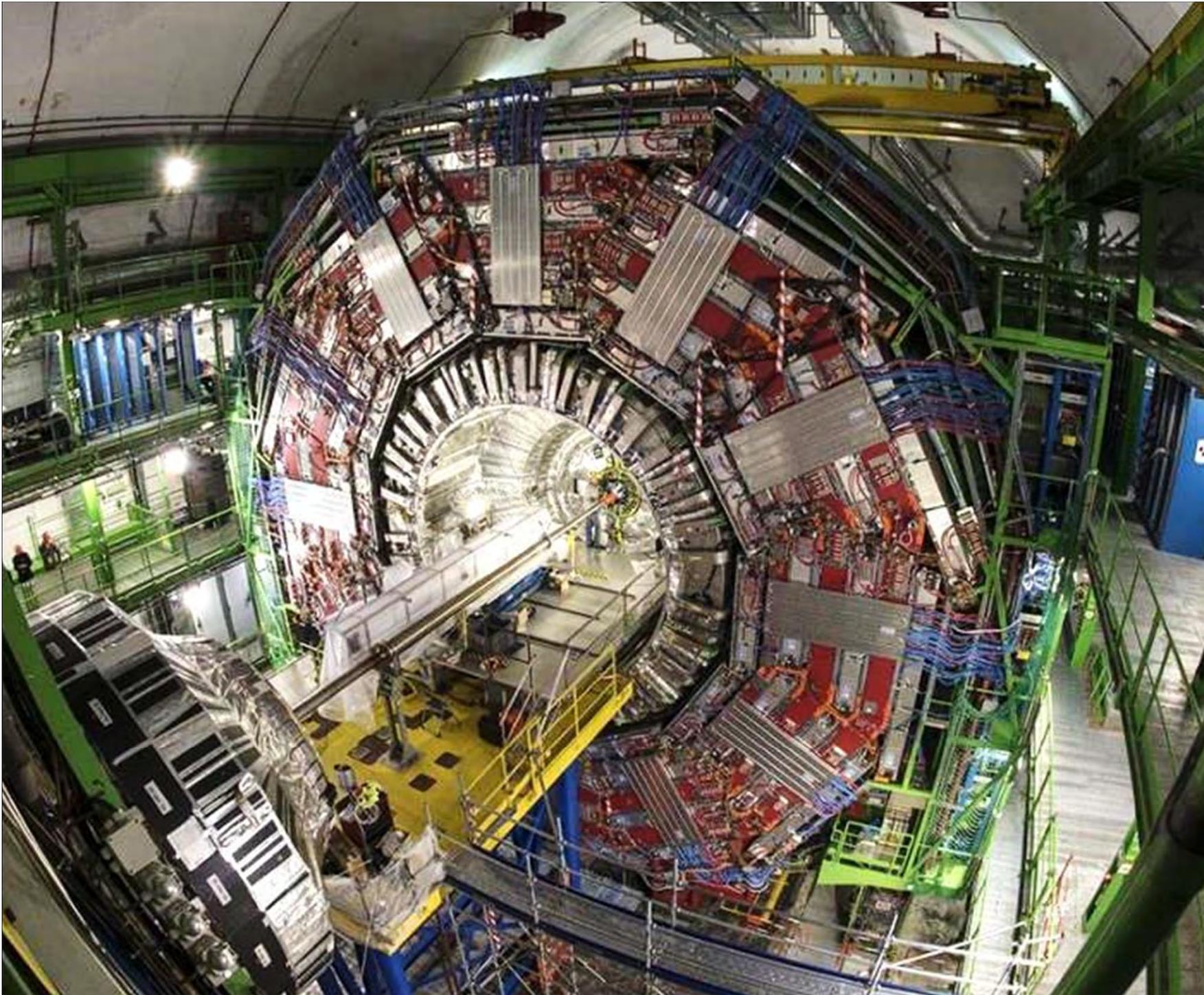




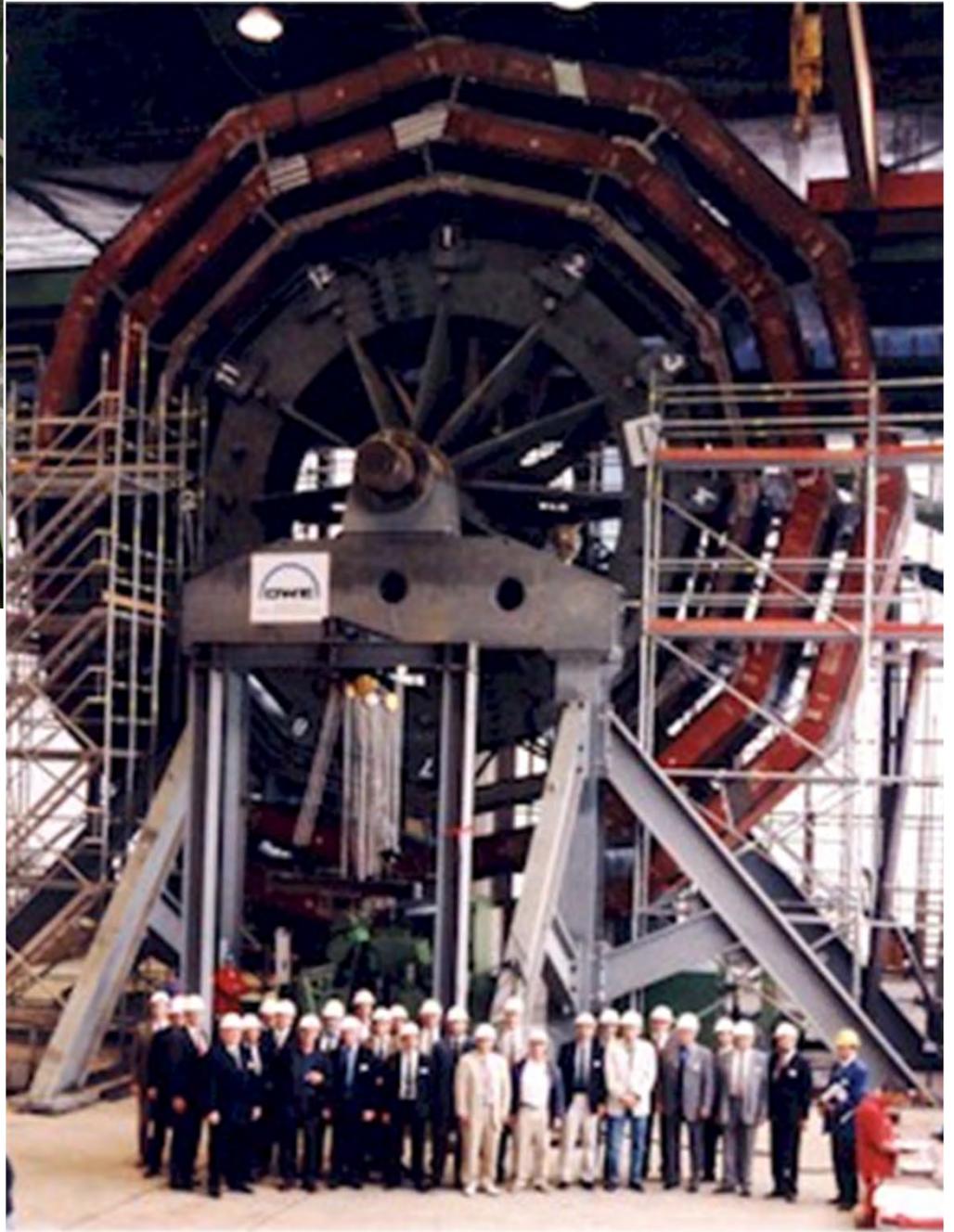
LHC dipoles



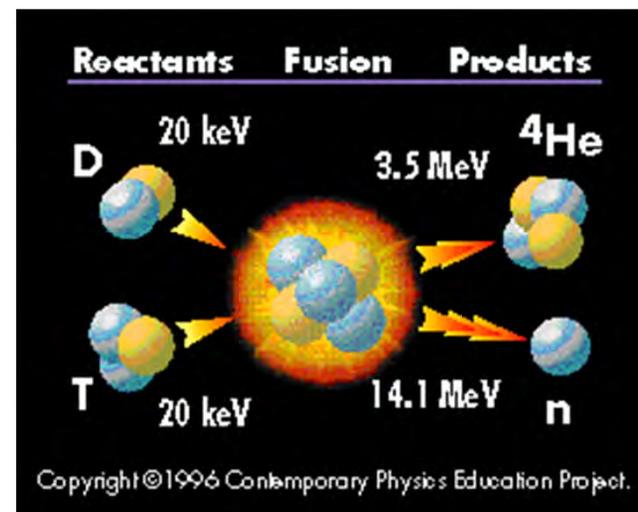
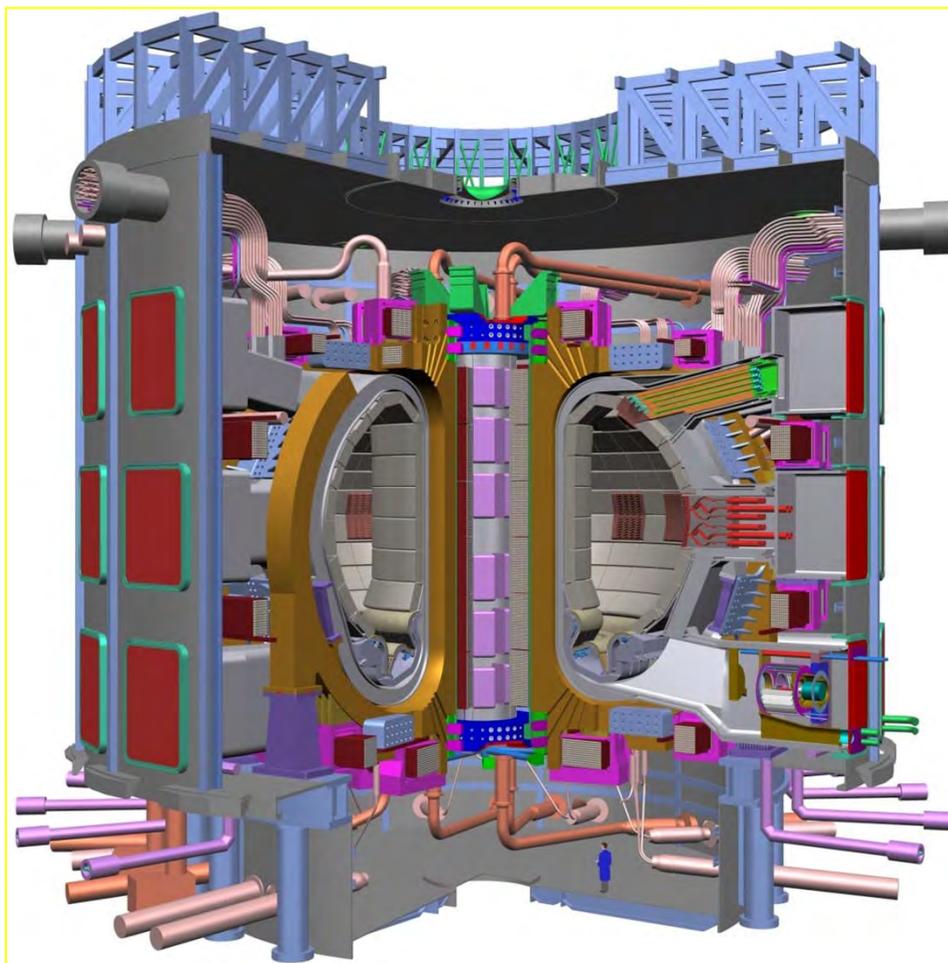
ATLAS



CMS



## magneti superconduttori per la ricerca





ITER

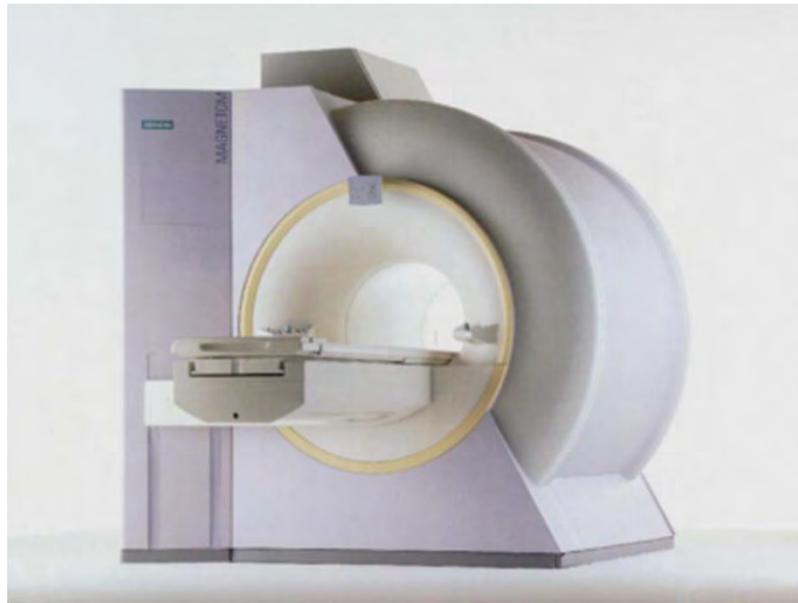
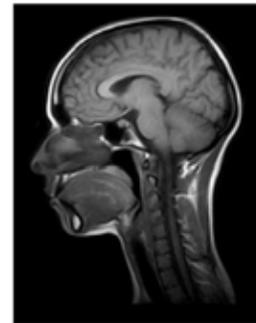
magneti superconduttori per la ricerca



900 MHz NMR

# Applicazioni mediche

## MRI



## Applicazioni mediche

MCG e MEG



MagnetoEncefaloGrafia

produzione di radioisotopi

Adroterapia



Ciclotroni superconduttori

The end