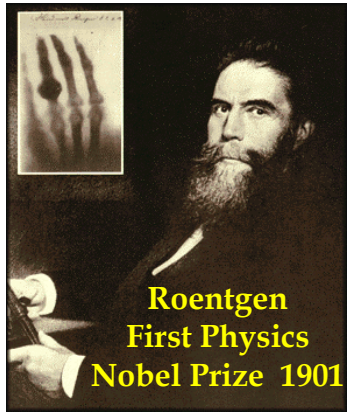
Disruptive Innovations in Image Acquisition: Is this the END?

Denis Le Bihan

Founding Director, NeuroSpin, Saclay, France

Two mainstreams for medical technology development



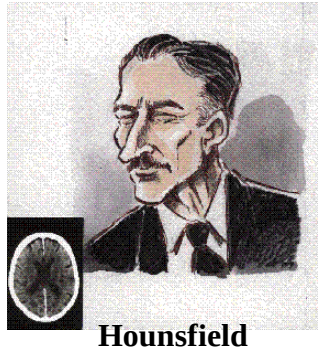
- ***Cumulative process***: **Progressive, incremental changes in basic knowledge of certain technologies over a long time, until *radical change* occurs**

- **Discovery or development of a technology initially *without medical purpose***

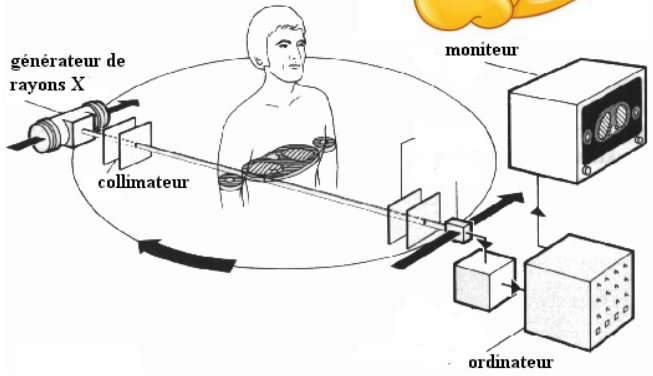
Disruptive Innovations in Image Acquisition: … UNPREDICTABLE!

"Röntgen photography" plaque published 1896,
"*Nouvelle Iconographie de la Salpetriere*"

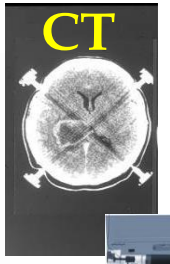
→ **The "radiology" field was created in 1930**

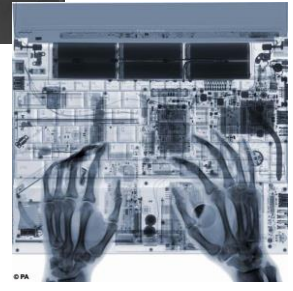


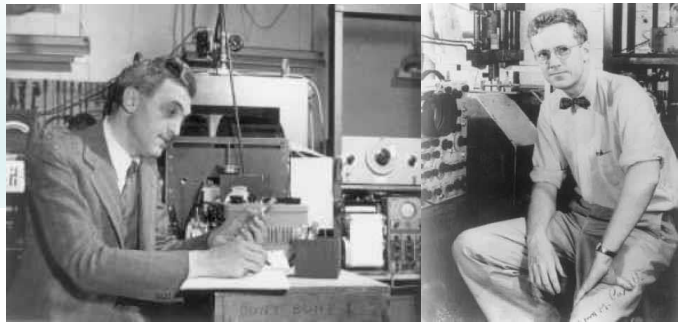
Hounsfield

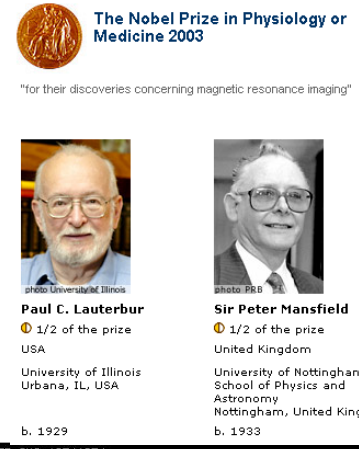


Nobel Prize in Medicine and Physiology, 1979

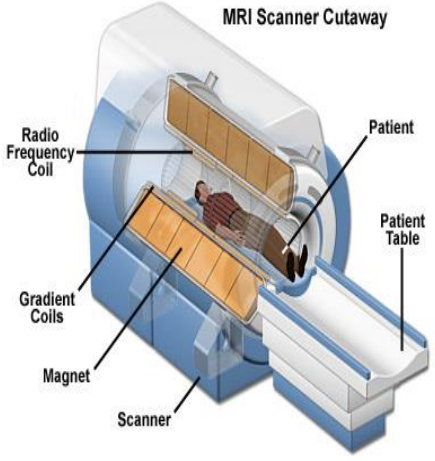


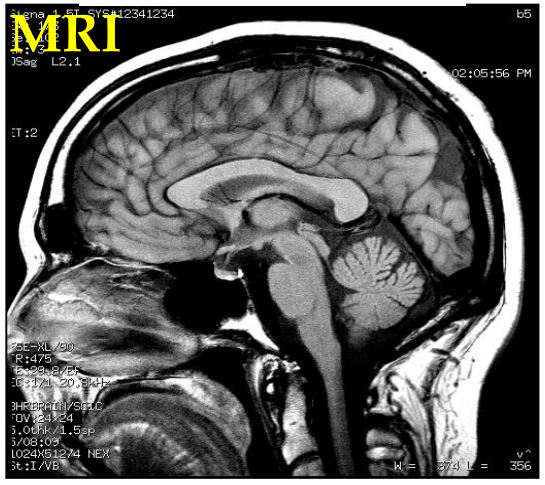






NMR:
Bloch & Purcell, Nobel Prize in Physics 1952





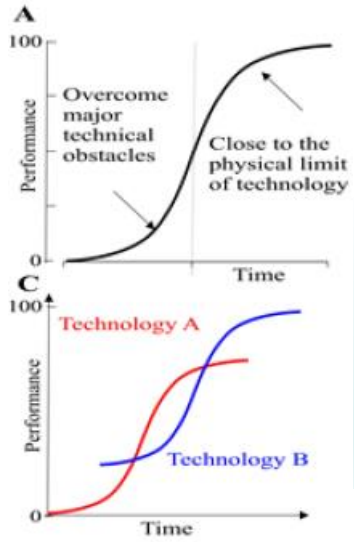
LIFE CYCLE OF TECHNOLOGY (LCT)

Technology travels in time: Is born, grows up, decline and die

➢ Understanding LCT+++

- To predict the ability to recover development investment
- To predict when to plan new projects
- To estimate future developments
- To decide whether or not to invest

Innovation is one of the most sensitive meeting points between *material and psychological viewpoints*.
Success of innovation is almost *independant from technical novelty*.



➢ LCT: S-curve

(Performance against unit of effort/money invested)

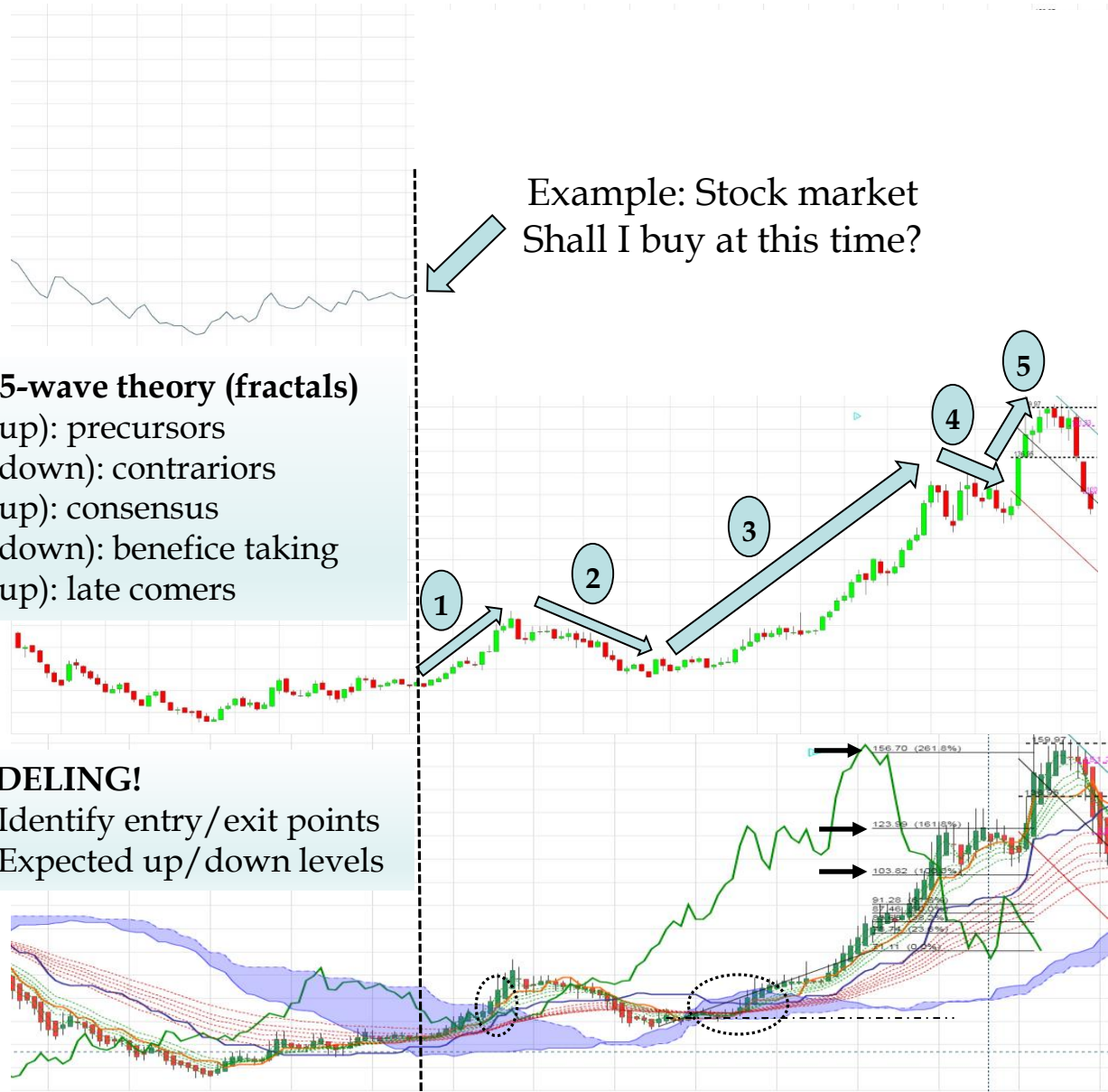
- Initial slow performance: fundamental not well understood
- Acceleration of performance (better understanding)
- Slows down when the technology reaches its limits

→ identify discontinuity in an emerging technology that replaces a mature technology

→ identify birth of new market opportunities

→ identify death or obsolesence of the technology market

→ technological progress: succession of S curves:
New S curve at the end of an Old S curve (ex: CT and PET-CT)

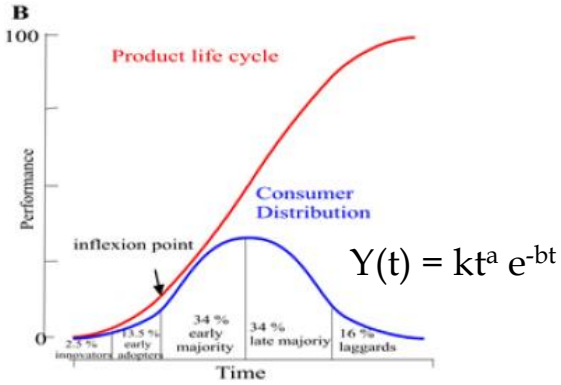


Time line connected to « market adoption »

(spread of technology)

- **S-curve: Diffusion of technology against cumulative number of adopters of technology over time:**
  - Slow at the begining (introduction to market)
  - Accelerates and is used in mass
  - Market saturated

  → Model to predict when a technology reaches its limits, identify and move to a new technology



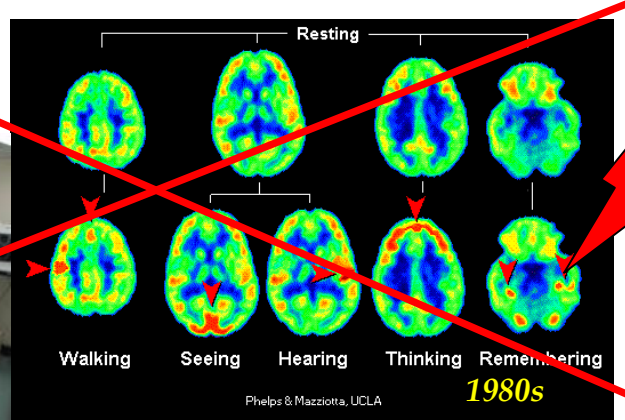
$Y(t) = kt^a e^{-bt}$

- **Modeling (Rogers 2003, Moore 2014) of the transition from early visionaries market to mass market**
  (Rogers 2003, Moore 2014)
  - Innovators (2.5%) & early followers (13.5%): understanding technology and performance
  - Early (34%) and late (34%) majority: solution and comfort
  - Sceptics (16%)

  → ***Chasm***: breakpoint between early followers and early majority. Point where technology dies or survives (expected performance/revenue)

- **Limitations:**
  - True limits not really known in advance, large disagreements between companies
  - Firms can modify the S-curves through their R&D
  - ***Unexpected changes may occur in the market***

O^{15} PET
functional neuroimaging

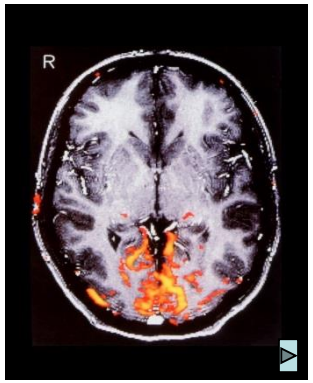


1980s

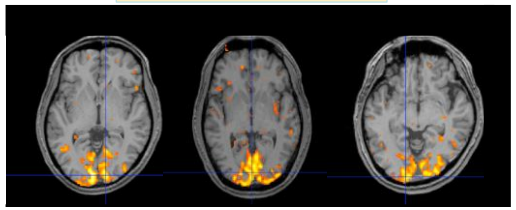
Gd based fMRI
1991

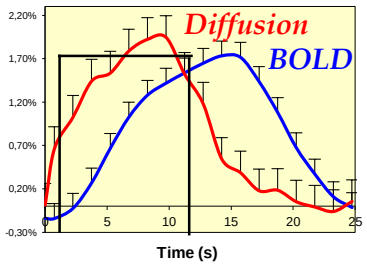
1991

BOLD fMRI
1990-1992



Diffusion fMRI?
2001-2006

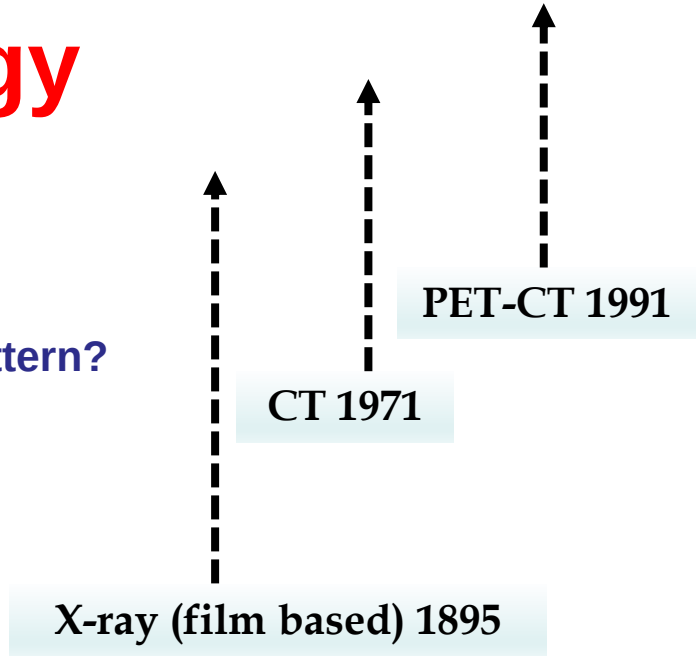




Example of X-ray technology

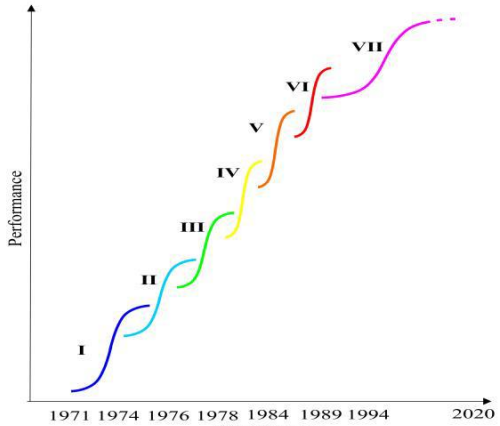
- X-ray technologies generate the largest Medical Imaging Technology income by far
- New CT users build up on X-ray imaging
- CT: incremental improvements (7th generation).

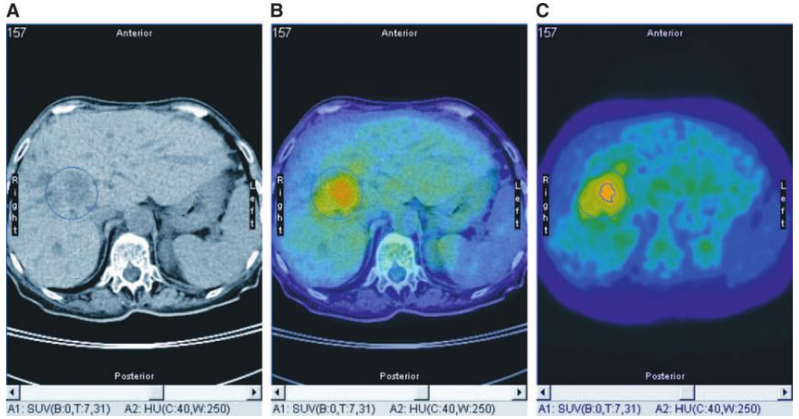
→ Vacuum market at the begining, now mature stage, decline expected from S-curve pattern?

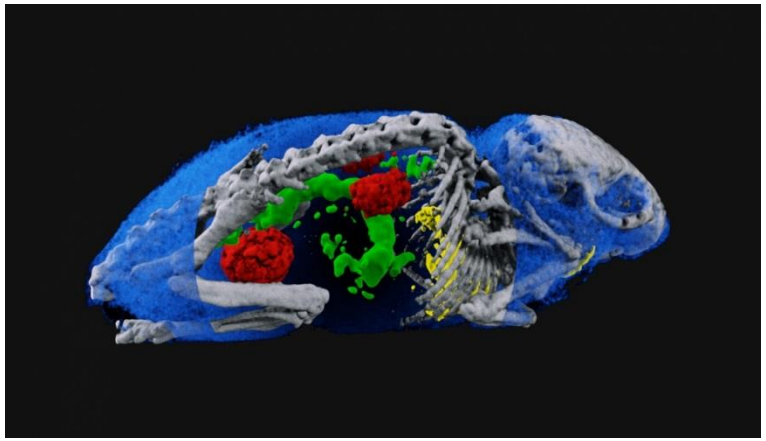


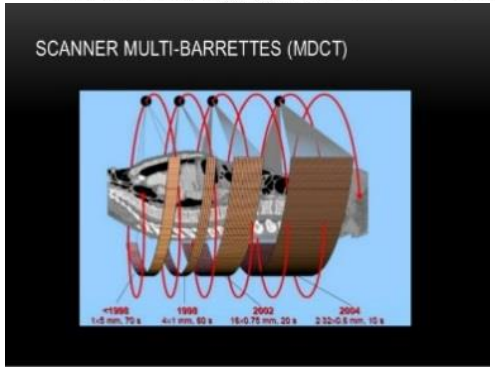
→ PET-CT 1st prototype: 1991, first sold: 2001, *currently growing phase*

HYBRID SYSTEMS: Anatomy AND Function





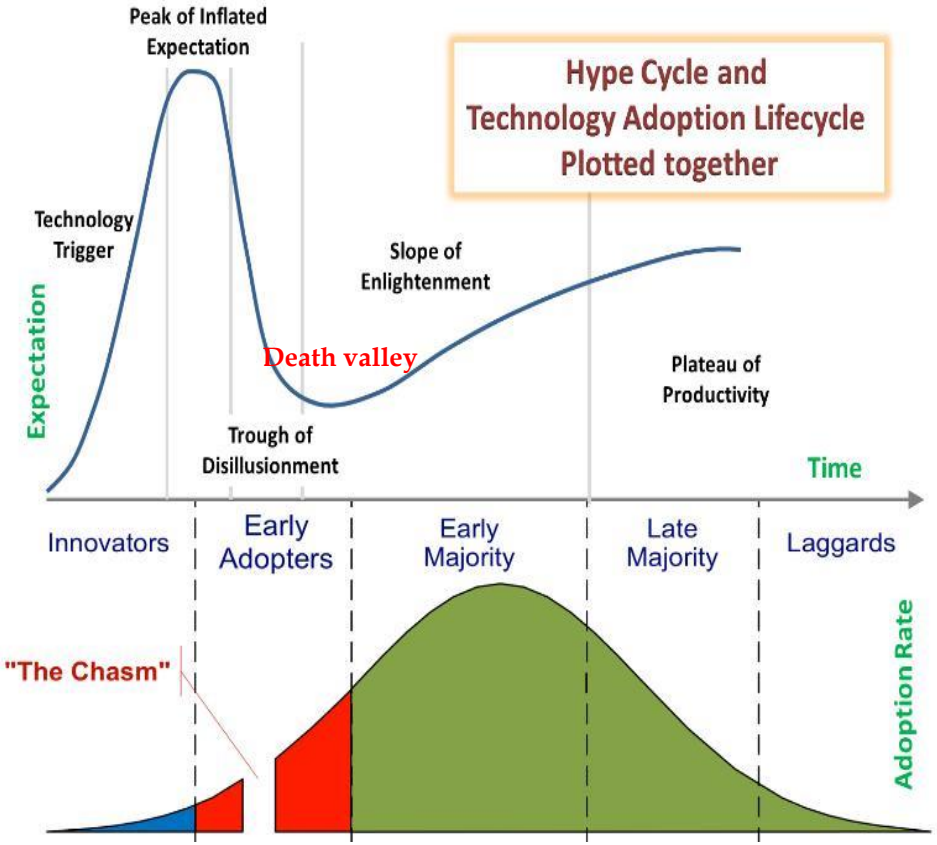




- Detector technology for the needs of the **CERN Large Hadron Collider** (LHC) experiments
→ Extension to the medical imaging field.
→Third generation of read-out chips allows 'colour' imaging during CT scans (***spectral imaging***) providing information about the density and the atomic structure of a tissue.
(still in the *emerging phase* and has not been widely adopted)

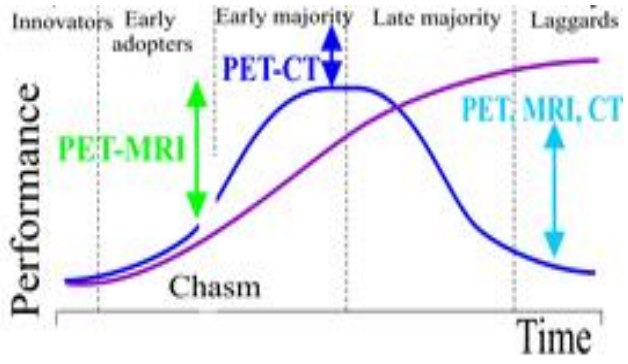
HYPE CYCLE (Gartner)

- **Technology Trigger**
  - Breakthrough, public, press and industry interest
- **Peak of Inflated Technology**
  - Over-enthusiasm, unrealistic projections, success
- **Trough of Disillusionment (« Death Valley », chasm)**
  - Growing failures toward the limits, disappointment
- **Slope of enlightment**
  - Solid hard work, true understanding of usage, risks,benefits
- **Plateau of Productivity**
  - Real benefits demonstrated and accepted, stability of tools, reduced risk, adoption



❖ **Death valley, chasm: need to reach « early majority » customers**

- Need for financial ressources to allow performance to generate enough revenues
- Segment the market, find niche within a larger market
- Attack competitors on small segments through proper positionning



- **CT, MRI, PET:** now adopted by « skeptics », productivity plateau, *slow decline phase will start soon?*
- **Hybrid PET-CT**: early majority, slope of enlightment
- **Hybrid PET-MRI**: development started in late 1990s, first prototype by Siemens 2008.
  High complexity, cost (equipment, hospital infrastructures, tracers+++)
  Early adopters, *enters the death valley* (performance? cost? Policymakers+++)

- Need to have pre-market information on **regulation mechanisms** which may affect cost-benefit, risk, effectiveness
- **Sensitivity to MARKET of raw materials**

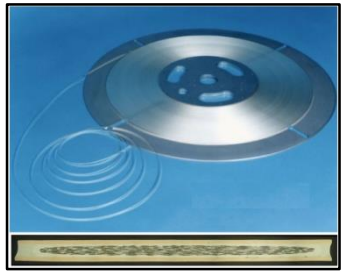
WORLD MRI MARKET 2018: $5 billions

The liquid helium crisis (MRI)

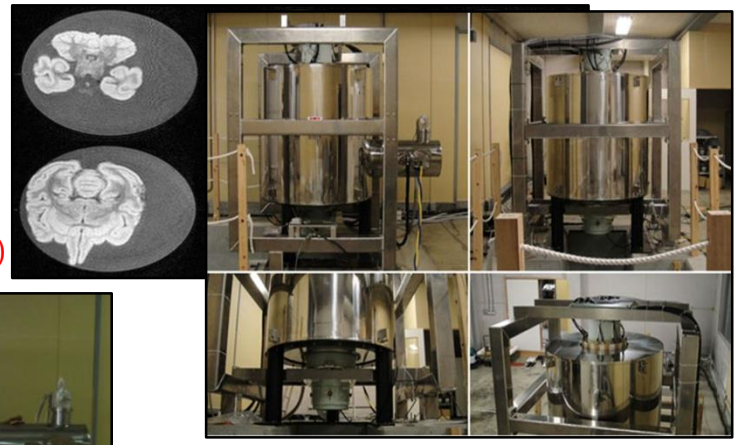
World Helium Resources	
Country	Billion Cubic Metres
United States	20.6
Qatar	10.1
Algeria	8.2
Russia	6.8
Canada	2.0
China	1.1

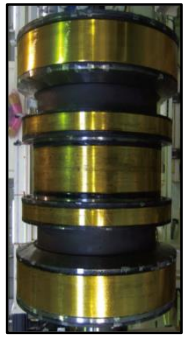
The values above are estimated helium resources from the USGS Mineral Commodity Summary

Helium free magnets?



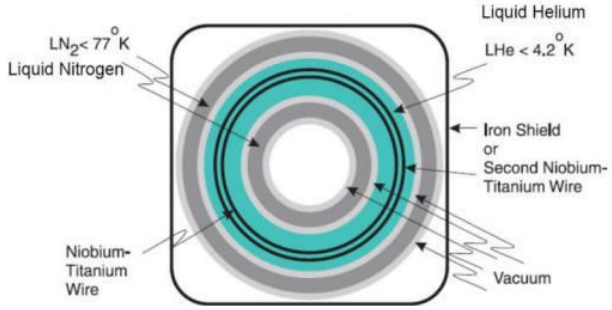
DI-BSCCO Type HT (Bi-2223)

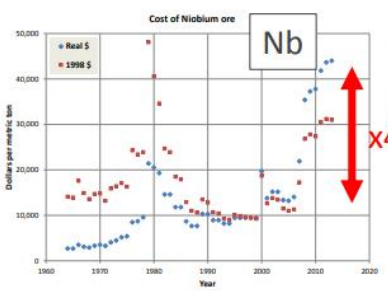


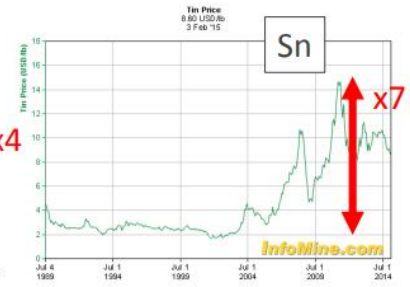


Kyoto U. 1.5-3T HTC MRI system
Can be turned on/off in <2 hours!
Urayama, Fukuyama et al.

Niobium-Titanium solenoid design @ 4.2°K (supraconductivity)



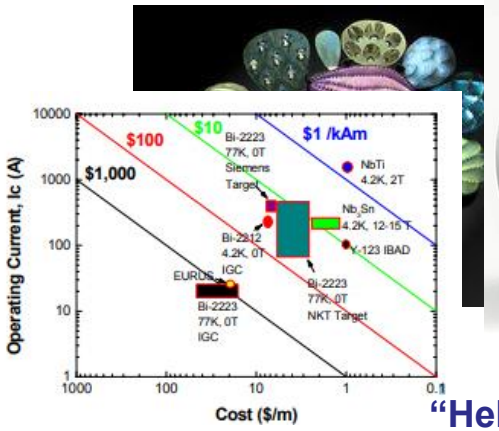


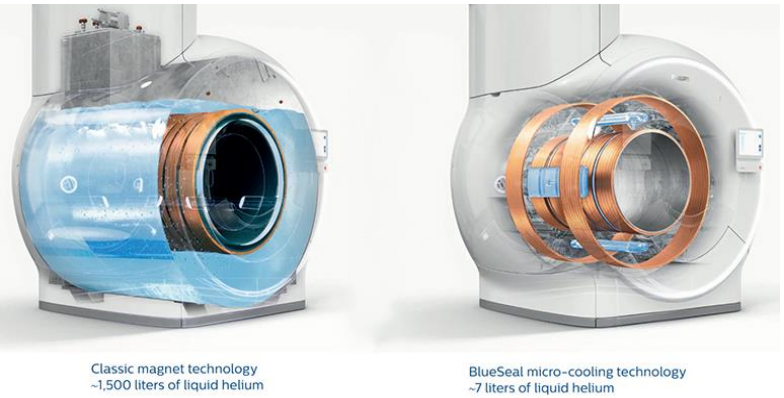


Type I Nb in 2014 ~$420/kg

Sn in 2014 ~$18/kg

Cu in 2014 ~$6/kg

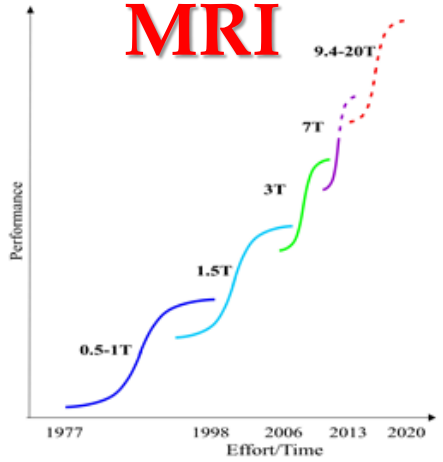




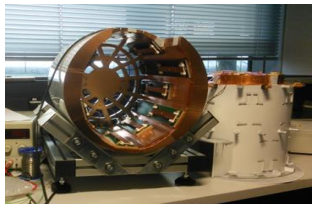
"Helium free" Philips Ingenia Ambition X 1.5T MR

- Slow start (imaging principle unclear, breakthrough, potential not clear compared to CT, cost), 80s economic recession
- Acceleration has been driven by increase in image quality (phased-array RF coils), **magnetic field** and cost decrease

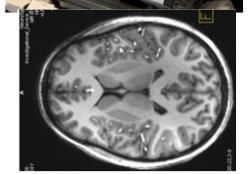
MRI

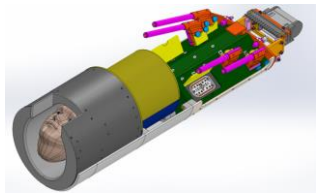


2018
- 3T : ≈ 6000 installed systems
- 7T : ≈ 50 installed systems (FDA certification in 2017!)
- 1 @ 8T and 5 @ 9.4T systems (USA, Germany)
- **1 system @ 10,5T (Minneapolis)**
- **3 orders @ 11.7T : F, USA, Corea**
- **1 project @ 11.7T or 14T**: Germany
- **1 project @ 14T or 20T: USA**

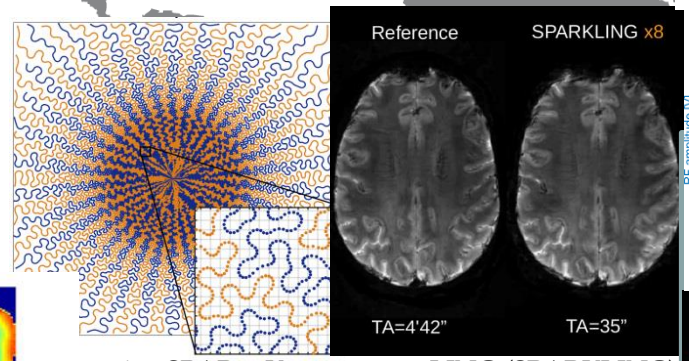


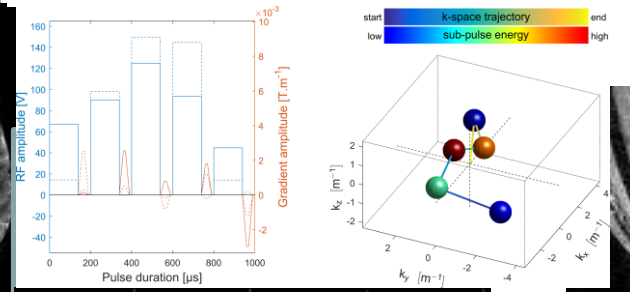
12Tx/22Rx coil (7T)

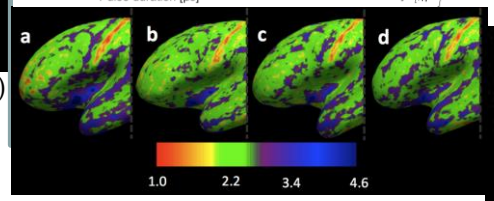




New signal spatial encoding strategies (sparse sampling)







pective SPARse K-space sampLING (SPARKLING)
Ph. Ciuciu, C. Lazarus et al. NeuroSpin

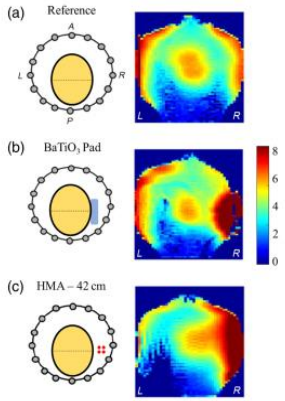
PHYSICAL REVIEW X **8,** 031083 (2018)

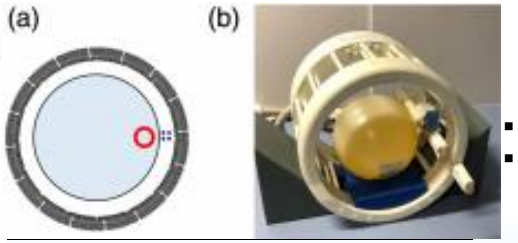
Featured in Physics

Hybridized meta-atom (HMA) passive insert boosts RF field

Kerker Effect in Ultrahigh-Field Magnetic Resonance Imaging

Marc Dubois,[1] Lisa Leroi,[2] Zo Raolison,[2] Redha Abdeddaim,[1,*] Tryfon Antonakakis,[3] Julien de Rosn
Alexandre Vignaud,[2] Pierre Sabouroux,[1] Elodie Georget,[2,†] Benoit Larrat,[2] Gérard Tayeb,[1] Nicolas Bo
Alexis Amadon,[2] Franck Mauconduit,[5] Cyril Poupon,[2] Denis Le Bihan,[2] and Stefan Enoch[1,‡]
[1]*Aix Marseille Univ, CNRS, Centrale Marseille, Institut Fresnel, 13013 Marseille, France*
[2]*CEA, DRF, JOLIOT, NeuroSpin, UNIRS, Université Paris-Saclay, 91191 Gif-sur-Yvette Cedex, France*
[3]*Multiwave Innovation AG, 1228 Geneva, Switzerland*
[4]*ESPCI Paris, PSL Research University, CNRS, Institut Langevin, 75005 Paris, France*
[5]*Siemens Healthineers, 93210 Saint Denis, France*





- Tomi-Tricot, Amadon A et al. (2018)
- M. Cloos, N. Boulant, M. Luong, G. Ferrand, E. Giacomini, M.-F. Hang, D. Le Bihan, and A. Amadon, NeuroImage 62:2140-50 (2012).

New RF coil designs & metamaterials

Acquisition and Image Reconstruction/Processing have become completely intermingled (*Machine Learning*)

The End

Toward 14 & 20T?

IOP Publishing — Superconductor Science and Technology
Supercond. Sci. Technol. 00 (2017) 000000 (20pp)

Topical Review

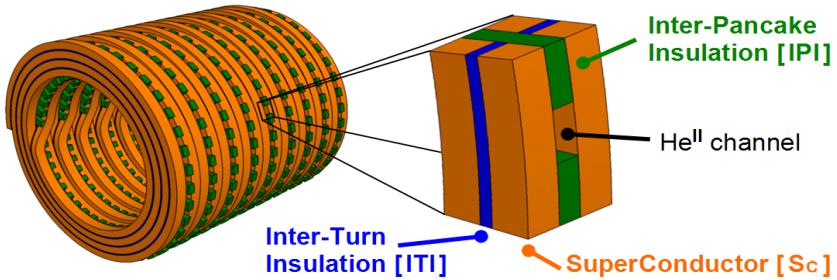
Human brain MRI at 500MHz, scientific perspectives and technological challenges

Denis Le Bihan and Thierry Schild

Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA), Division of Fundamental Research (DRF), Gif-sur-Yvette, F-91191, France

E-mail: denis.lebihan@cea.fr and thierry.schild@cea.fr

Received 18 July 2016, revised 4 October 2016
Accepted for publication 24 October 2016
Published DD MM 2017



Double pancake design (LHC/CERN, Iter/Nuclear Fusion)

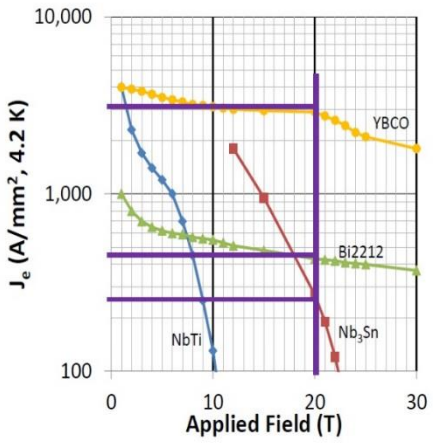
The Road to 20 Tesla for Human Studies: Barriers and 8 Rewards.

Thomas Budinger[1], Mark Bird[2], Lucio Frydman[2,3], Joanna Long[3], Thomas Mareci [3], Victor Schepkin[2], Dean Sherry[4], Daniel Sodickson[5], Charles Springer [6], Kamil Uğurbil [7], Lawrence Wald[8]

1.Lawrence Berkeley National Laboratory, Univ. of California, Berkeley
2. National High Magnetic Field Laboratory, Florida State Univ., Tallahassee
3. McKnight Brain Research institute, Univ. of Florida, Gainesville
4. University of Texas, Southwestern
5. New York University, School of Medicine
6. Oregon Health Sciences University
7. University of Minnesota
8. Massachuetts Gen. Hospital, Harvard

New directions in science are launched by new tools much more often than by new concepts.
The effect of a concept-driven revolution is to explain old things in new ways. The effect of a **tool-driven revolution** is to **discover new things that have to be explained.**
Freeman Dyson (1997) Imagined Worlds Havard University Press

Superconducting Materials for Magnets



The High-Temperature Superconductors (HTS) YBCO, Bi2212, Bi2223 will superconduct at fields >100T.

For 30 T SC, HTS is required.

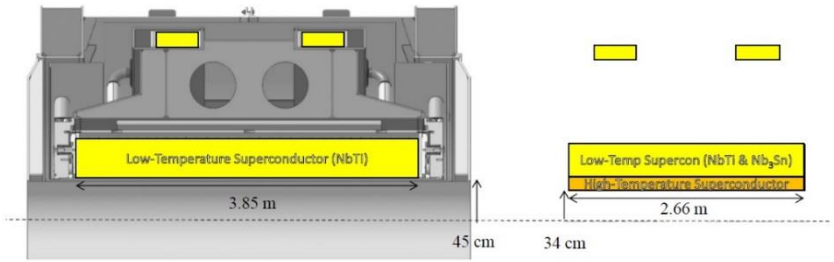
At 4 K, extremely high combinations of field and current-density attained!

For 20 T MRI, HTS will likely be preferred over Nb_3Sn.

Perspective on 20 T MRI Magnet

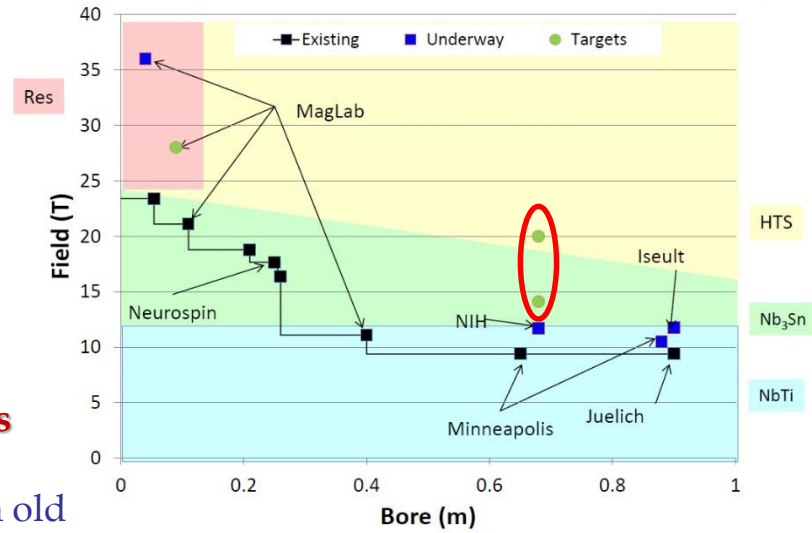
11.75 T, 90 cm Whole-Body
Under Construction, due 2014 (Iseult)

20 T, 68 cm Head-Only
Preliminary Concept



Parameter	Iseult	MagLab 20 T Concept
Conductor Mass (Ton)	65	~35
Stored Energy (MJ)	338	~350
Current Density (A/mm²)	26.4	~40
Magnet Design	CEA	MagLab

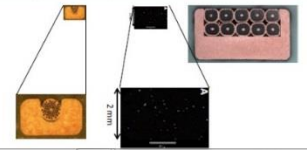
HTS + high-strength materials at 4 K operate at high field and current-density resulting in compact magnets.



NbTi only | Nb_3Sn Required | High Temperature Superconductors

MRI Magnet Conductor Design

	3 T, 90 cm	21 T, 10 cm	11.74 T, 90 cm (Iseult)	14 T, 68 cm (proposed)
Superconductor	NbTi	Nb_3Sn	NbTi	Nb_3Sn
# of strands	1	1	10	100
Current (Amps)	~300	285	1,500	10,000
Reinforcement	Cu	Steel	Cu	Steel
Strength (MPa)	>250	1,400	>250	1,400
Stiffness (GPa)	110	200	110	200
Stabilizer	Cu	Cu	He	He
C_p (mJ/cc/K)	1	1	552	552
Protection	Cu	Cu	Cu	Cu
J_{cu} (A/mm²)	~280	~230	~70	~250



1,400 / 250 = 5.6 > 3.14

Courtesy M. Bird, National High Magnetic Field Lab, Florida State U