Radiation safety for particle accelerator – synergies between Research Infrastructures and Industry

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European Spallation Source

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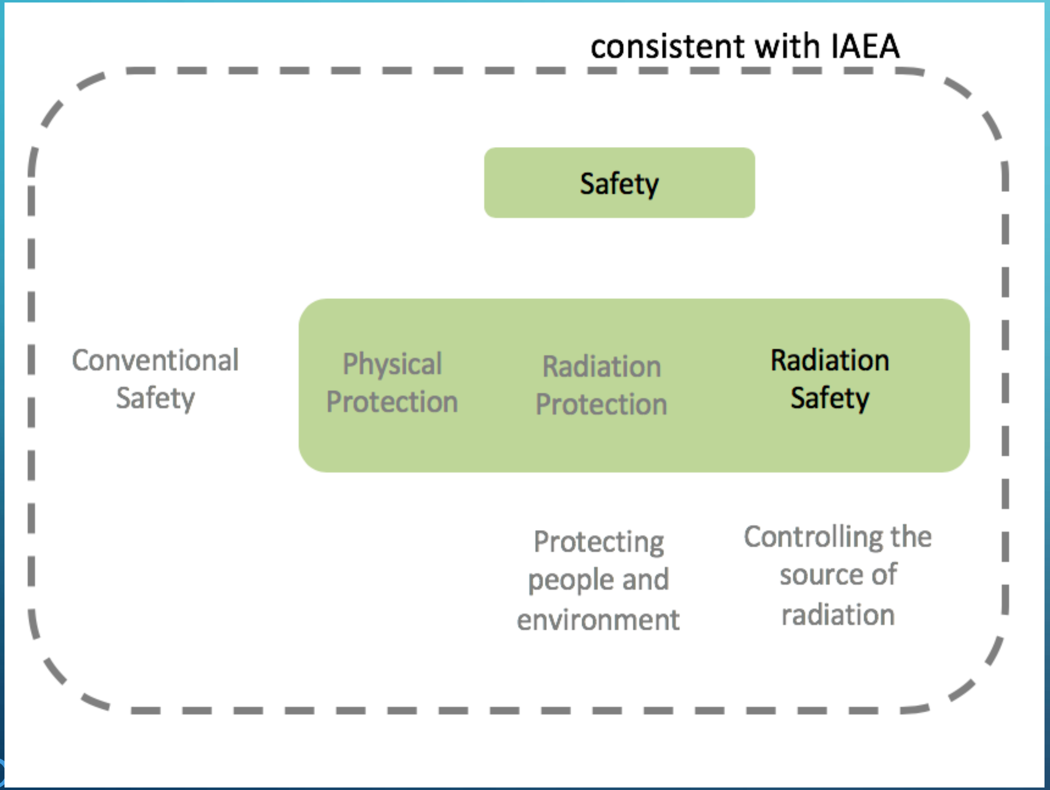
cdarve.web.cern.ch

OUTLINE

- Context for Radiation Safety
- Technological paradigms and particle accelerators
- Test Cases
  - CERN - Large hadron Collider
  - European Spallation Source – Proton Linear Accelerator

WHAT IS RADIATION SAFETY ?

Radiation safety is one of the components of safety and is concerned with maintaining control over radiations sources, whereas radiation protection is concerned with controlling exposure to radiation and its effects.



consistent with IAEA

Safety

Conventional Safety

Physical Protection

Radiation Protection

Radiation Safety

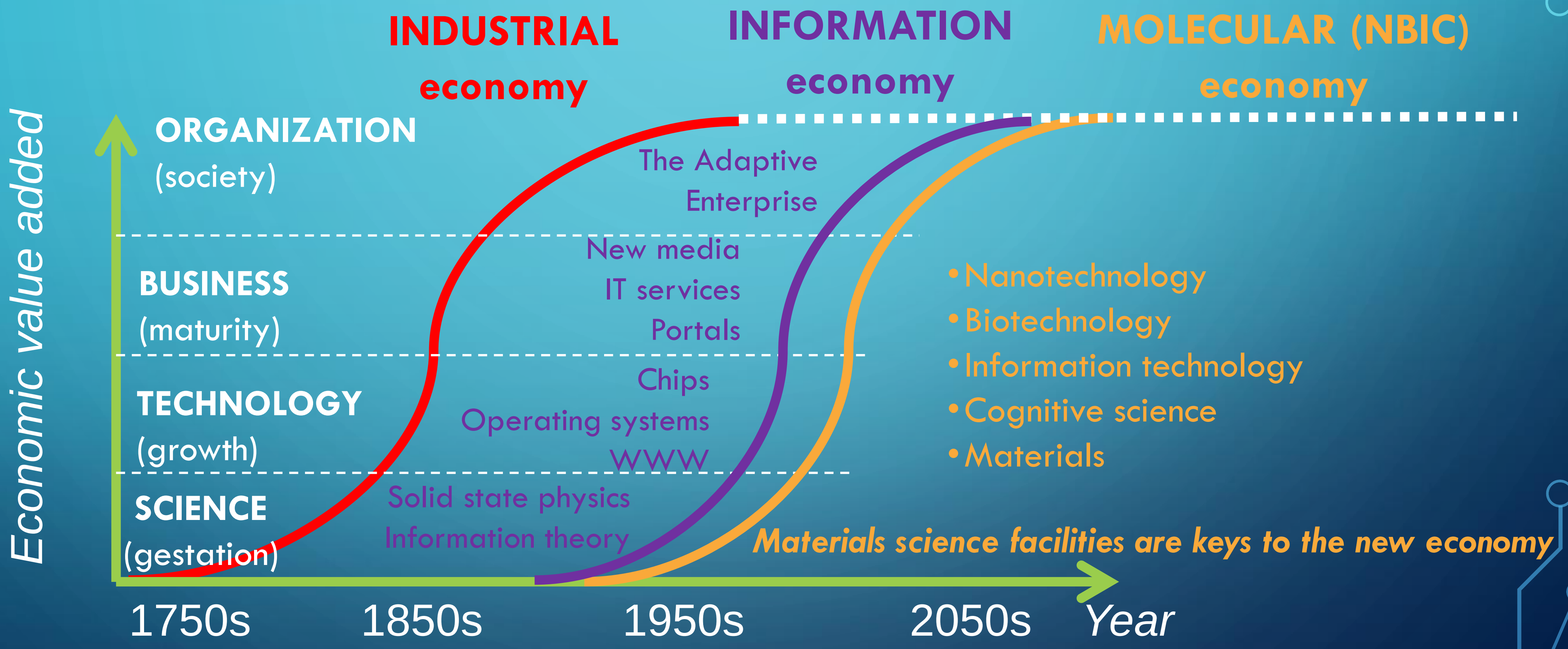
Protecting people and environment

Controlling the source of radiation

Radiation safety consists of the implementation of provisions at all stages of the facility lifecycle (**design**, **manufacturing**, **installation**, **commissioning**, **operation** including **maintenance, decommissioning**) in order to prevent accidents and mitigate their consequences.

Following the international recommendations by the IAEA, ICRP, EURATOM

TECHNOLOGICAL PARADIGM EVOLUTION



INDUSTRIAL economy

INFORMATION economy

MOLECULAR (NBIC) economy

Economic value added

ORGANIZATION
(society)

BUSINESS
(maturity)

TECHNOLOGY
(growth)

SCIENCE
(gestation)

The Adaptive
Enterprise

New media
IT services
Portals

Chips
Operating systems
WWW

Solid state physics
Information theory

- Nanotechnology
- Biotechnology
- Information technology
- Cognitive science
- Materials

Materials science facilities are keys to the new economy

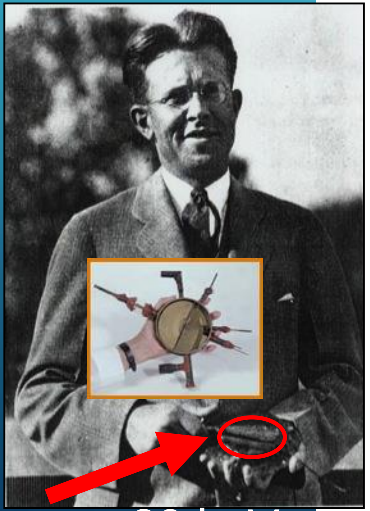
1750s 1850s 1950s 2050s *Year*

It's Alive - The Coming Convergence of Information, Biology, and Business Christopher Meyer 2003

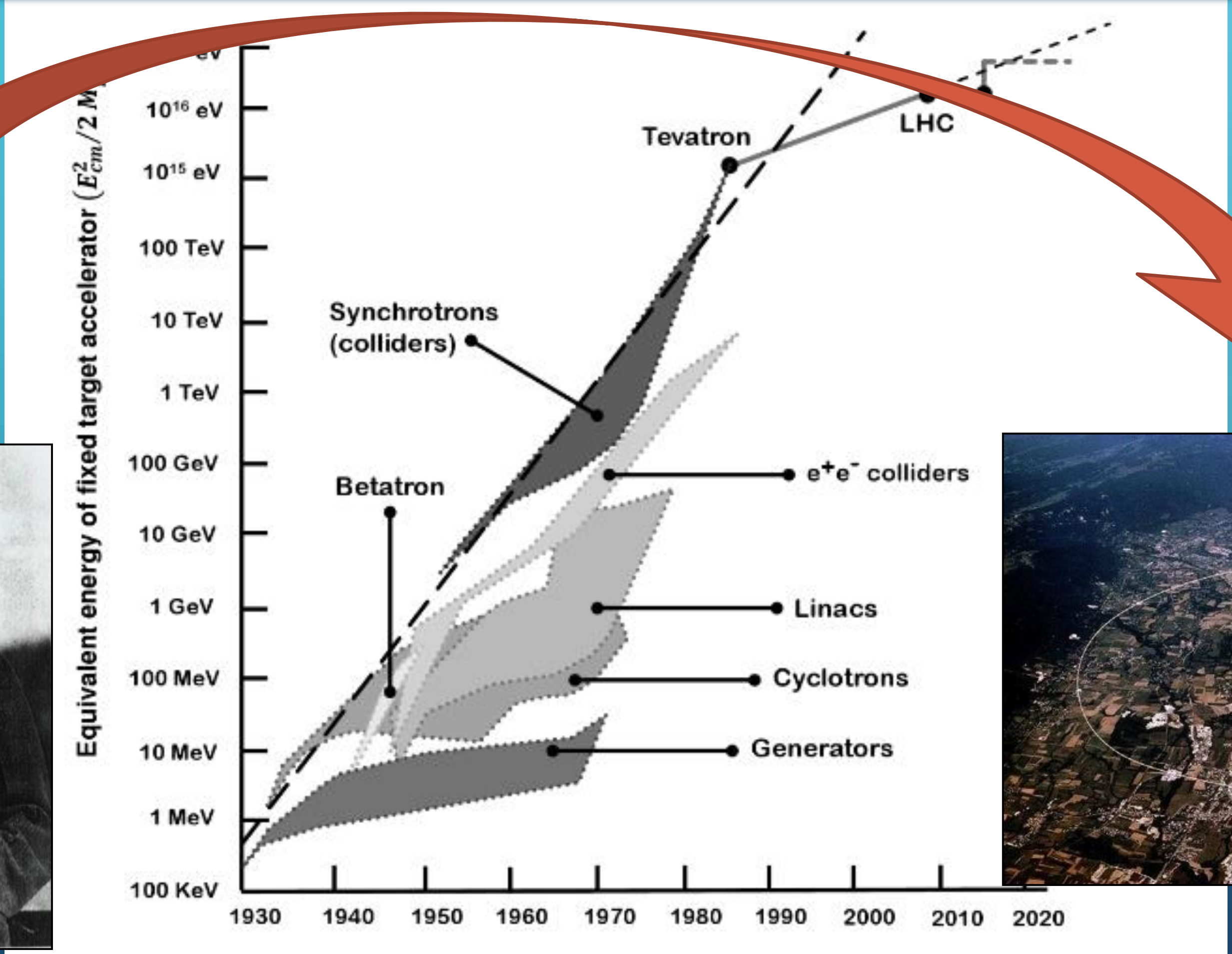
TYPE OF PARTICLE ACCELERATORS

Each generation built on the accomplishments of the previous ones raising the level of technology ever higher

Ernest
Lawrence
(1901 - 1958)



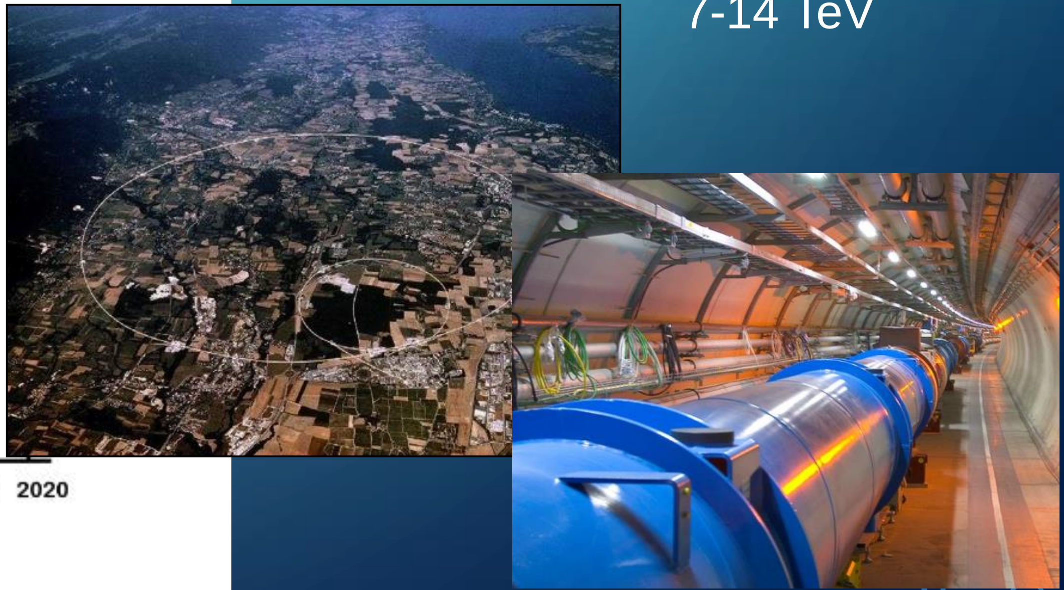
80 keV



Livingston's diagram

→ 1980 -Tevatron @ Fermilab
980 GeV

→2008 - LHC @ CERN
7-14 TeV

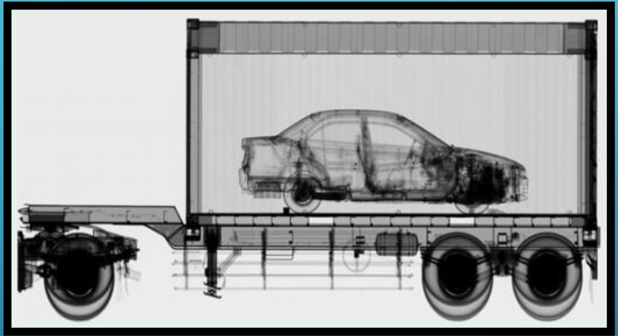


TYPE OF PARTICLE ACCELERATORS

- Discovery science: e.g. High Energy Physics

Swiss Light Source

- Materials research/manufacturing: e.g. light sources, spallation source, Accelerator Driven Systems (ADS)



- National security

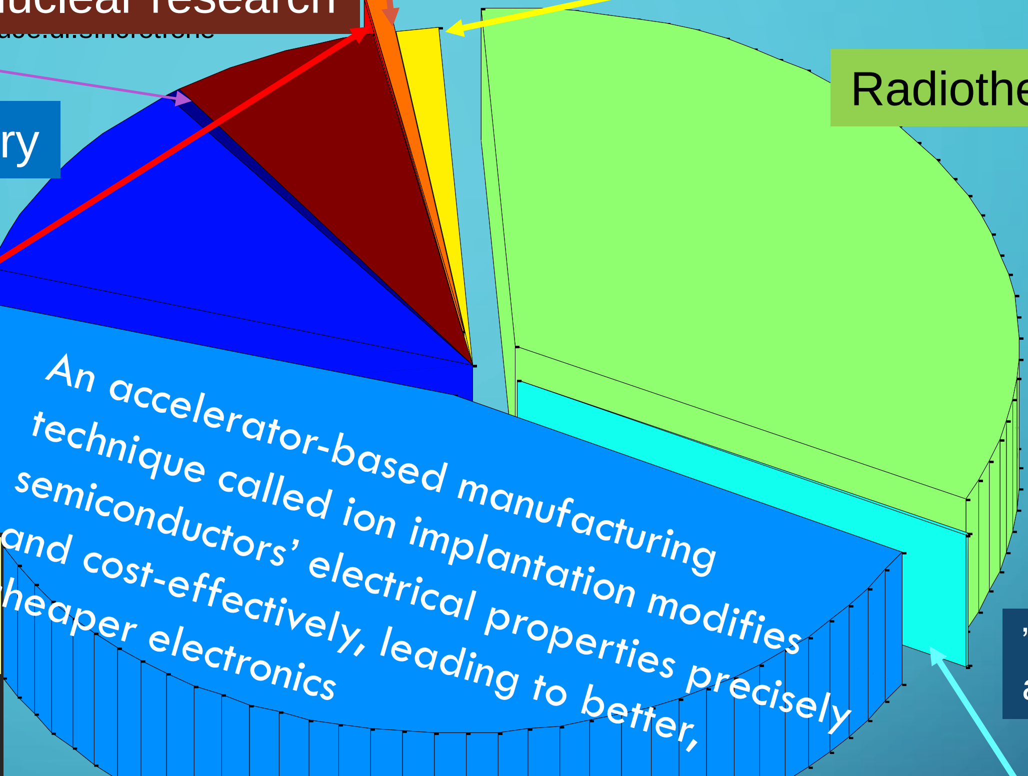
X-ray scanning

iThemba LABS

- Medical Applications: e.g. Photon, Neutron and Proton

Therapies, MRI and NMR

https://www.aps.org/units/dpb/news/edition4th.cfm



Nuclear research

Medical Isotopes

Non nuclear research

~ 60 Photon sources

+3 Proton LINAC for Neutron Sources

Industry

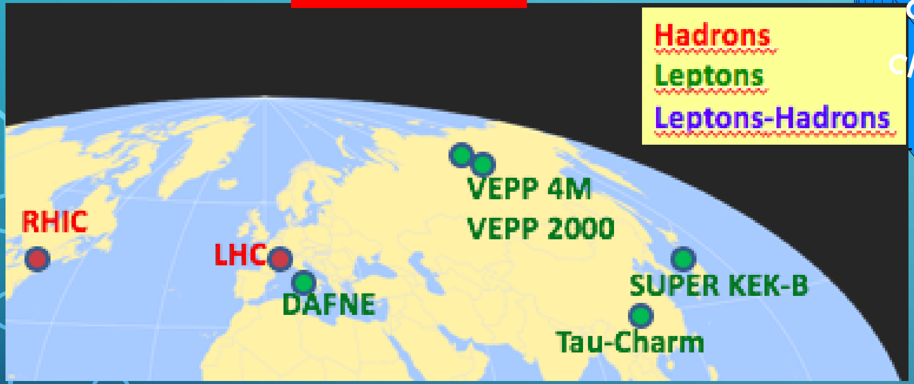
Radiotherapy

An accelerator-based manufacturing technique called ion implantation modifies semiconductors' electrical properties precisely and cost-effectively, leading to better, cheaper electronics

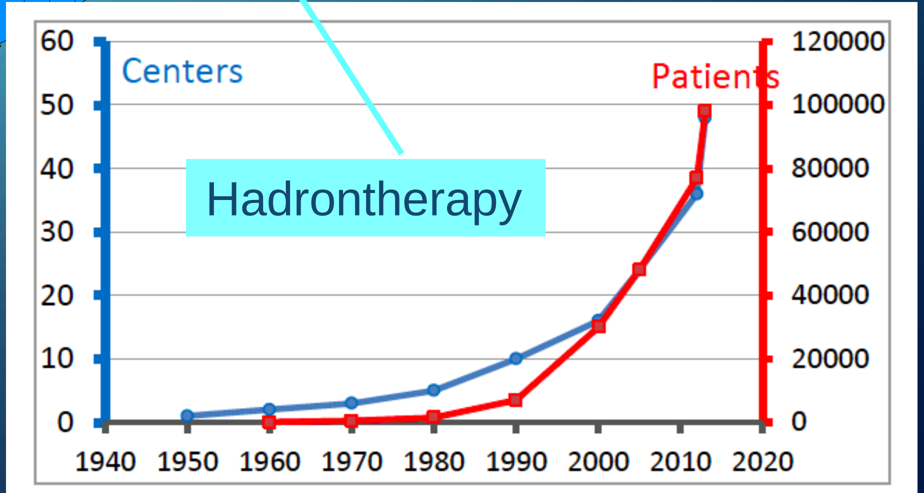
Ion implantation

IMAGE COURTESY OF VARIAN MEDICAL SYSTEMS OF PALO ALTO, CALIFORNIA. ©2009 VARIAN MEDICAL SYSTEMS. ALL RIGHTS RESERVED.

Colliders



"Medical Applications" by C.Biscari and L. Falbo CERN–2014–009



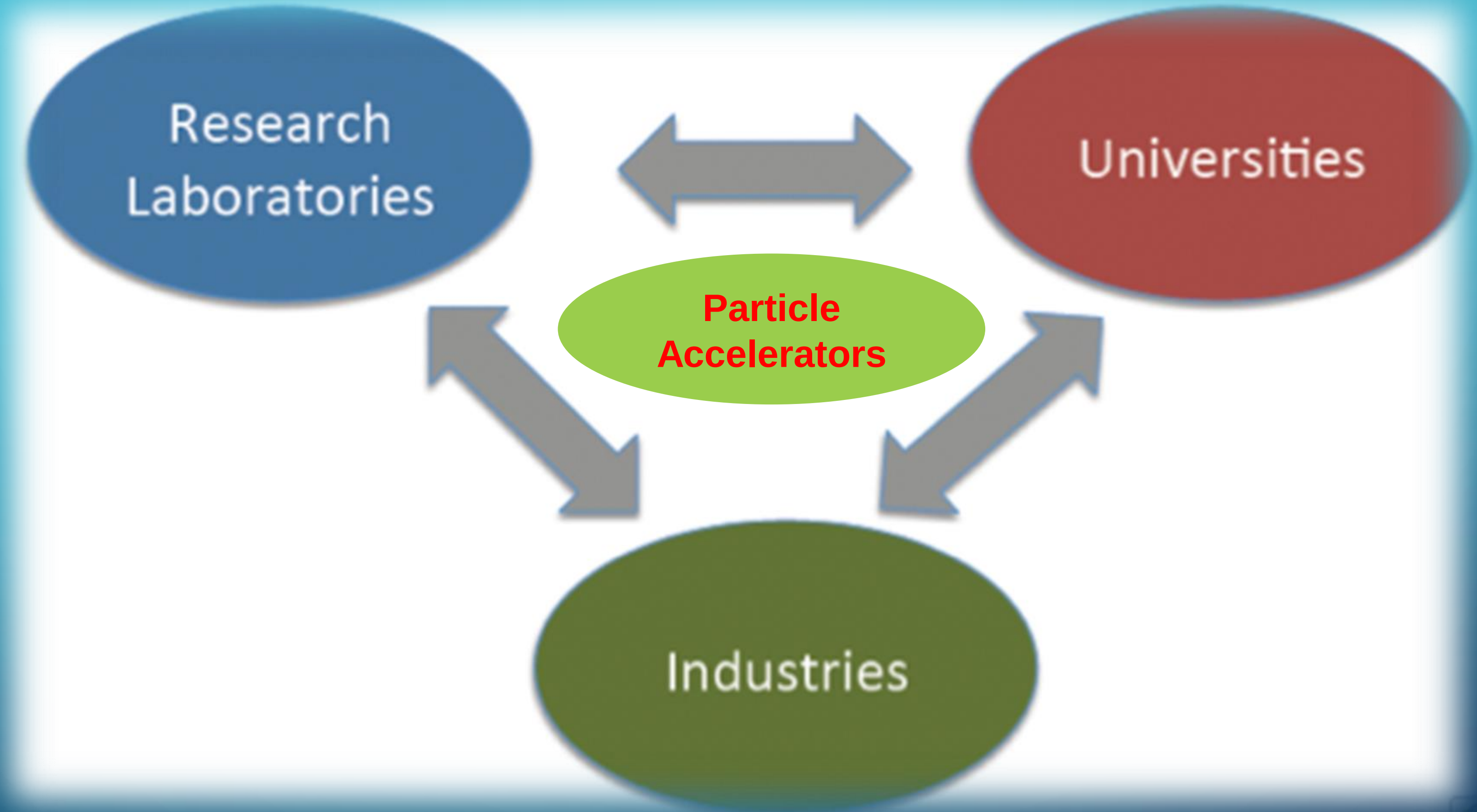
Hadrontherapy

Fig. 8: Growth of hadrontherapy centres and treated patients in the last 60 years

More than 35,000 Accelerators in the world

(15,000 in 2000)

TRIANGLE OF KNOWLEDGE – THE ECOSYSTEM



Research Laboratories

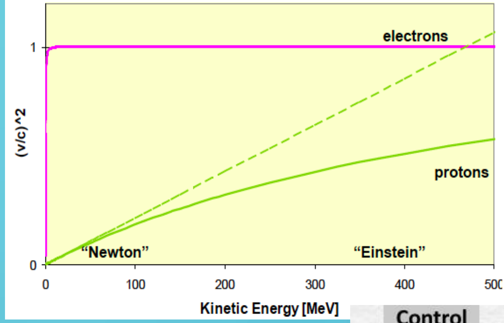
Universities

Particle Accelerators

Industries

All 3 Pillars are needed to design, build, commission a particle accelerator

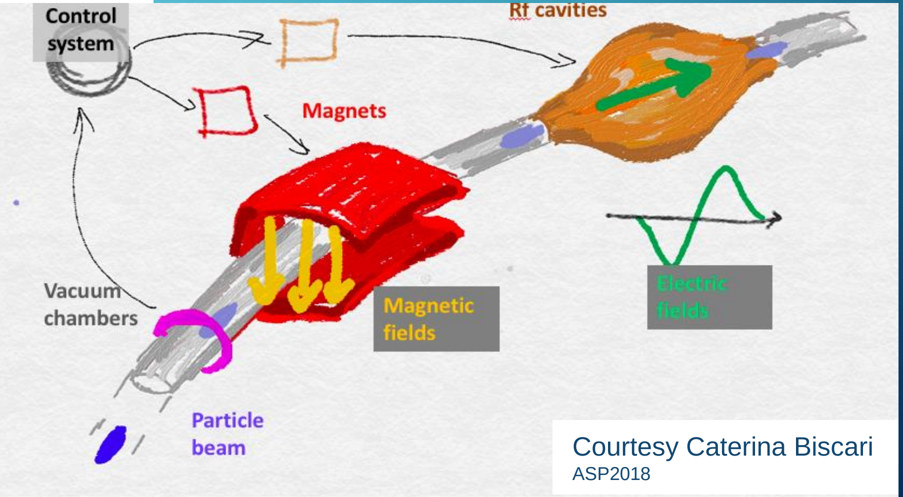
PARTICLE ACCELERATOR - MAIN INGRÉDIENTS



1- Ion Source to **produce the charged particles** to be accelerated (H$^+$ or H$^-$); electron gun

2- Accelerating structures to **accelerate** charged particles → SUPRACONDUCTOR

3- Magnets are used to **bend and focus** the particle trajectories → SUPRACONDUCTOR



Courtesy Caterina Biscari
ASP2018

4- Vacuum chamber to **minimize scattering** of the beam particles by gas particles

5- Cooling systems to **remove the heat** dissipated in accelerator components; use of superfluidity for superconducting magnets and cavities

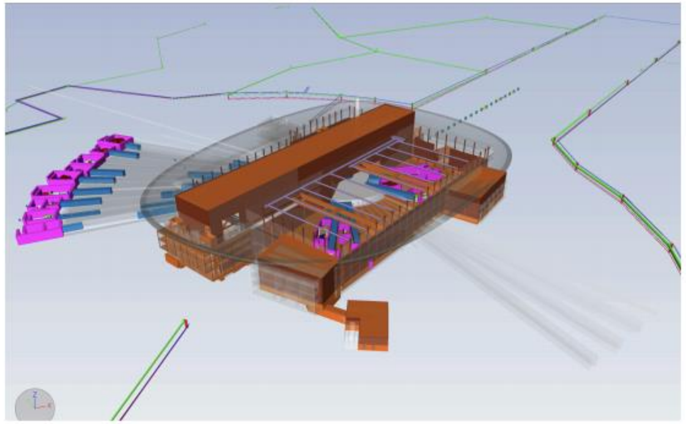
6- Beam diagnostics to provide **information** about the **beam** intensity (current), position, beam profile and beam loss

7- Control system to **record and control** each equipment

ENGINEERING DESIGN

ESS Materials Handbook

ESS Document Number: ESS-0028465



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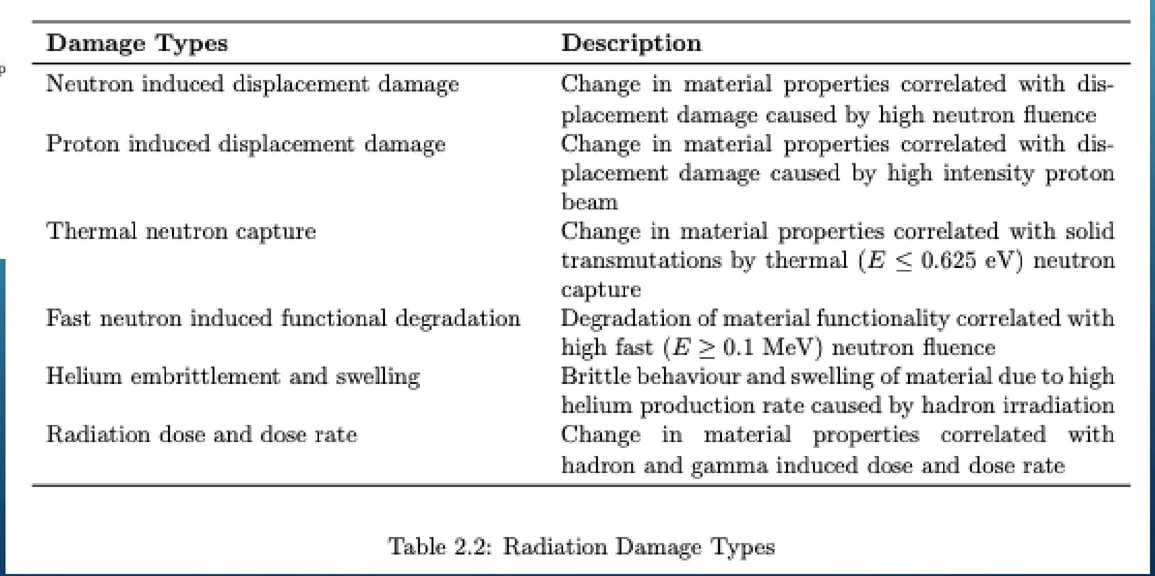
Last Update on July 9, 2020
towards Revision 6

- This risk-based graded approach provides safe, cost-effective and reliable designs.
- The implementation flexible to loop within the given sequences.

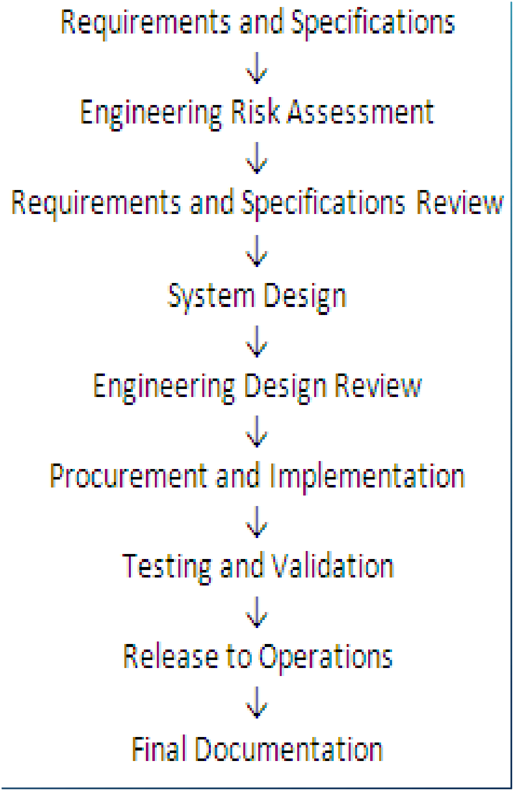


Damage Types	Description
Neutron induced displacement damage	Change in material properties correlated with displacement damage caused by high neutron fluence
Proton induced displacement damage	Change in material properties correlated with displacement damage caused by high intensity proton beam
Thermal neutron capture	Change in material properties correlated with solid transmutations by thermal ($E \leq 0.625$ eV) neutron capture
Fast neutron induced functional degradation	Degradation of material functionality correlated with high fast ($E \geq 0.1$ MeV) neutron fluence
Helium embrittlement and swelling	Brittle behaviour and swelling of material due to high helium production rate caused by hadron irradiation
Radiation dose and dose rate	Change in material properties correlated with hadron and gamma induced dose and dose rate

Table 2.2: Radiation Damage Types

Engineering process approach:

FNAL Engineering Manual



Requirements and Specifications
↓
Engineering Risk Assessment
↓
Requirements and Specifications Review
↓
System Design
↓
Engineering Design Review
↓
Procurement and Implementation
↓
Testing and Validation
↓
Release to Operations
↓
Final Documentation

TEST CASE

CERN

LARGE HADRON COLLIDER

PROTON ACCELERATOR

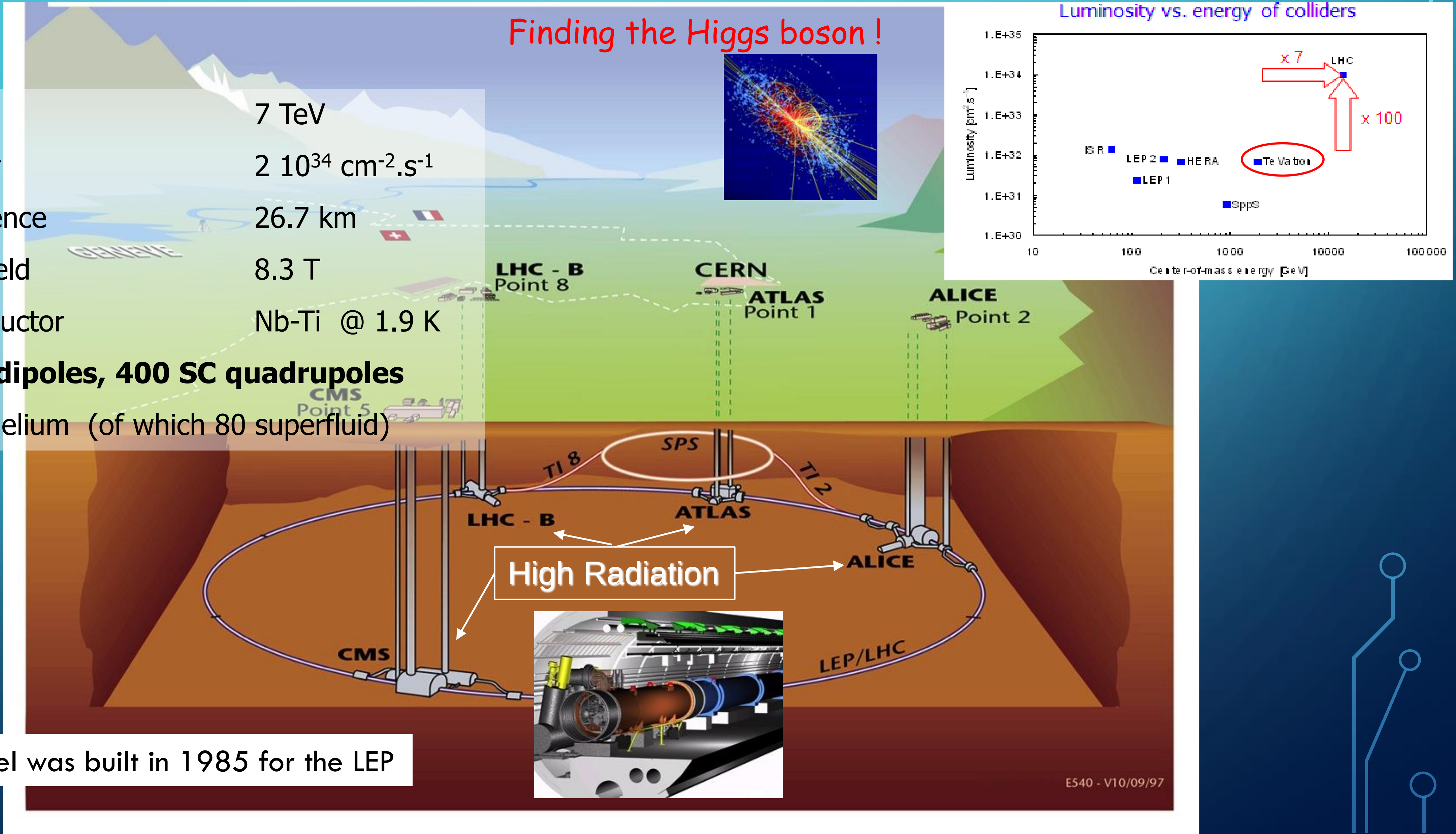
CERN AND THE LARGE HADRON COLLIDER

E_{beam}	7 TeV
Luminosity	2 10^{34} $cm^{-2}.s^{-1}$
Circumference	26.7 km
Bending field	8.3 T
Superconductor	Nb-Ti @ 1.9 K

1232 SC dipoles, 400 SC quadrupoles

120 tons helium (of which 80 superfluid)

Finding the Higgs boson !



High Radiation

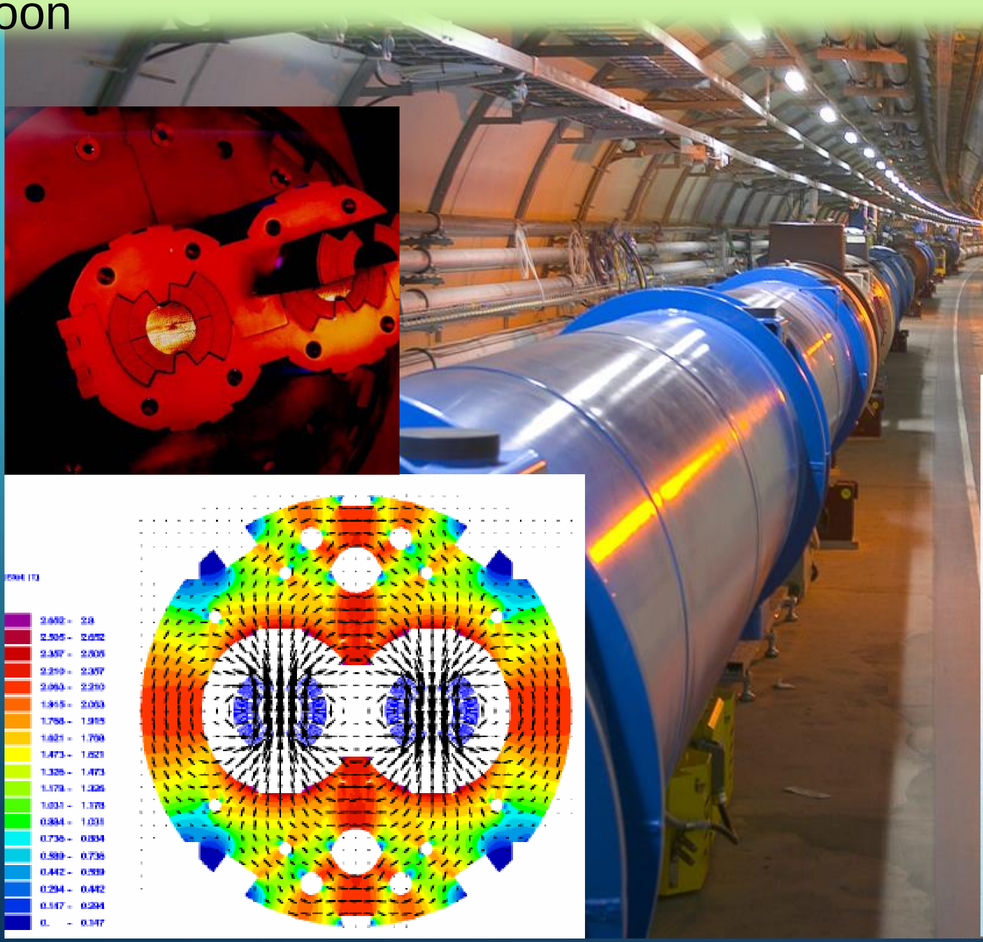
Tunnel was built in 1985 for the LEP

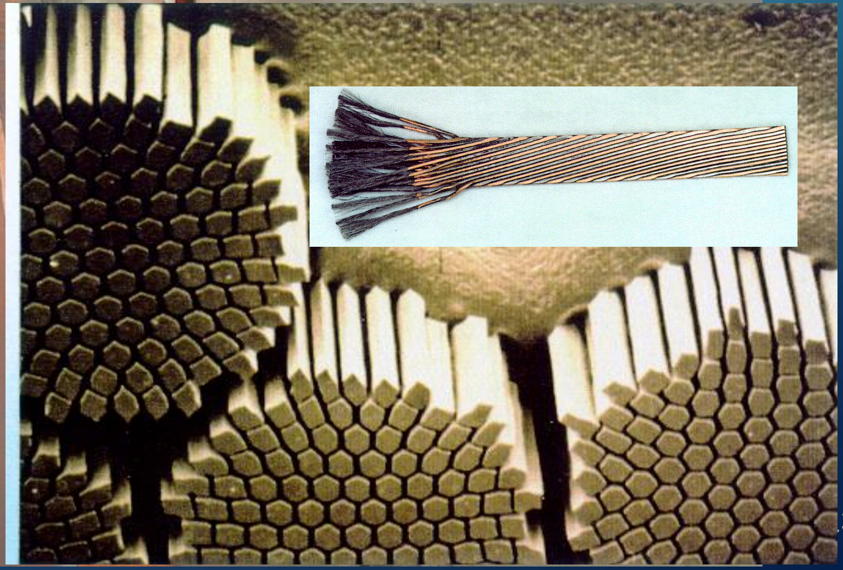
THE LHC MAGNETS

7,600 km of cable made of 270,000 km of strand (6 earth circumferences)

→ filaments : 6 times back and forth to the Sun + 150 trips to the moon

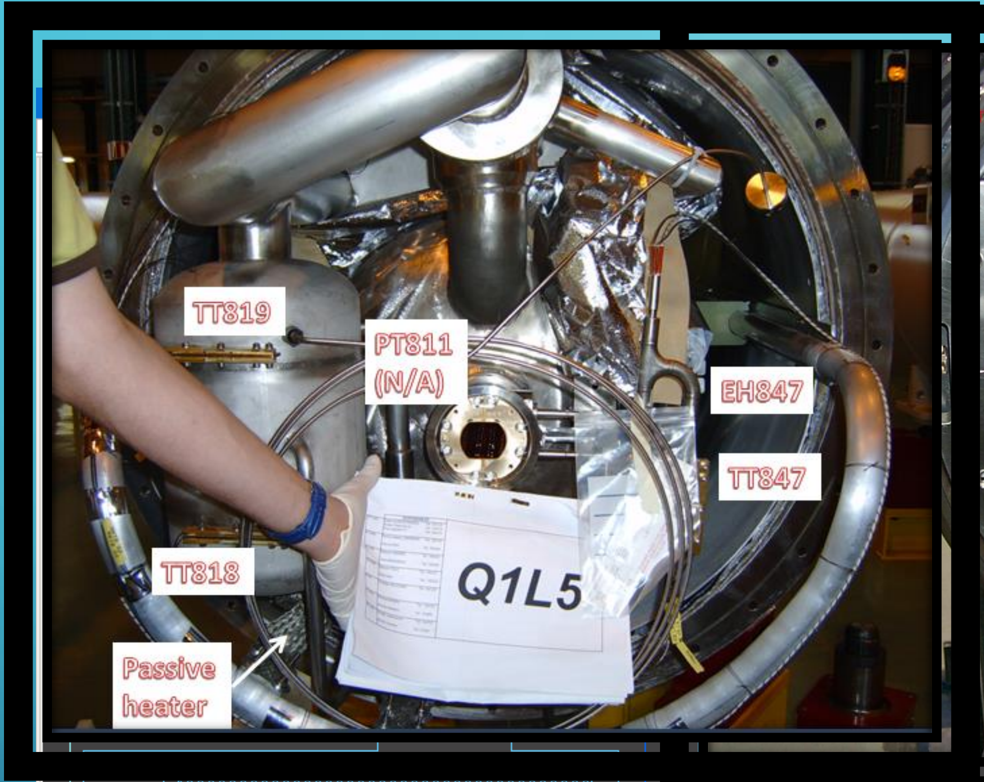
	Inner Cable	Outer Cable
Number of strands	28	36
Strand diameter	1.065 mm	0.825 mm
Filament diameter	7 µm	6 µm
Number of filaments	~ 8900	~ 6520
Cable width	15.1 mm	15.1 mm
Mid-thickness	1.900 mm	1.480 mm
Keystone angle	1.25 °	0.90 °
Transposition length	115 mm	100 mm
Ratio Cu/Sc	≥ 1.6	≥ 1.9

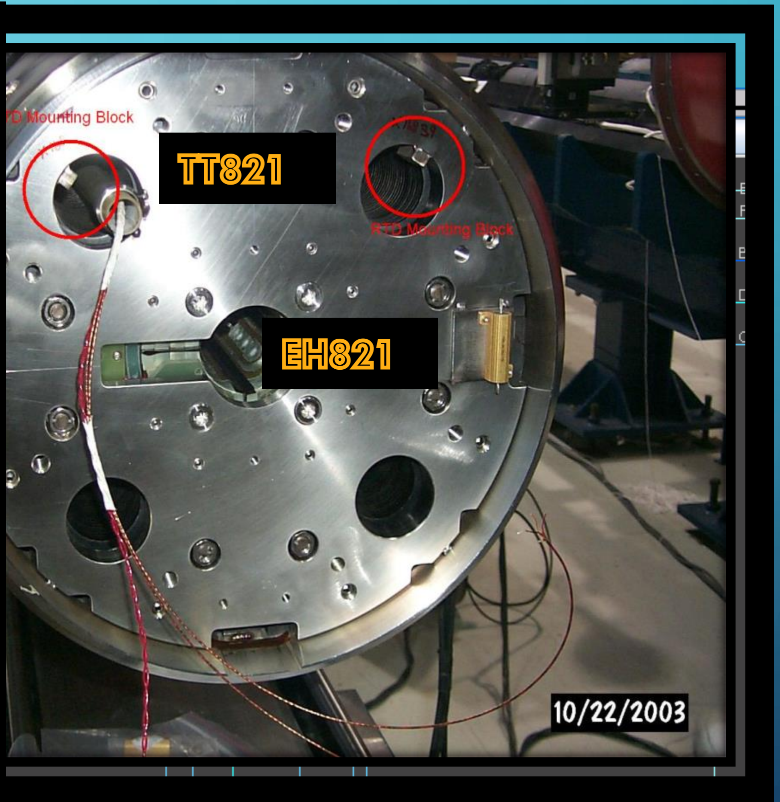




TYPE OF INSTRUMENTATION

Low-beta system Interface with QRL

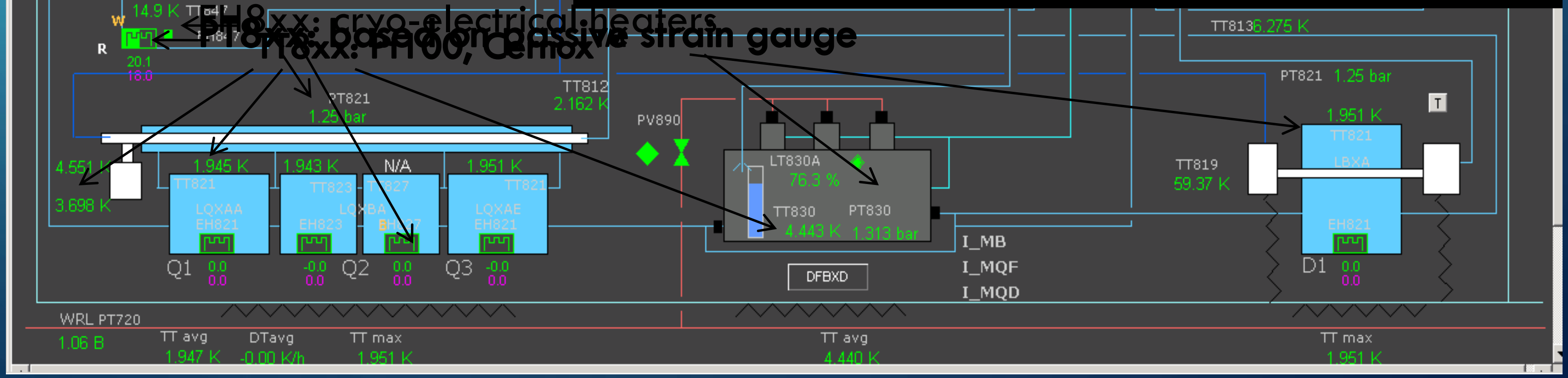




EH8xx: cryo-electrical heaters

PT8xx: based on passive strain gauge

TT8xx: PT100, Cernox



CRYOMAGNET SYSTEM SAFETY SPECIFICATION

Design and operation requirements:

- Critical system for LHC performance. The system operation and maintenance should remain safe for personnel and for equipment, e.g. escape path, absorbed radiation dose, embrittlement, polymer prop. decay.
- Equipment, instrumentation and design shall comply with the CERN requirements

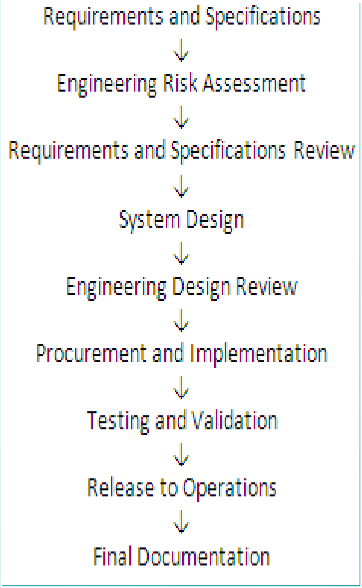
- ☐ Radiological → Use materials resistant to the radiation rate permitting an estimated machine lifetime, even in the hottest spots, exceeding 7 years of operation at the baseline luminosity of $10^{34}cm^{-2}s^{-1}$
- ☐ Personnel safety: Keep residual dose rates on the component outer surfaces of the cryostats below 0.1 mSv/hr
- ☐ Apply the ALARA principle (As Low As Reasonably Achievable)
- ☐ Risk Analysis → Failure Mode and Effect Analysis (FMEA), Use the Maximum Credible Incident (MCI) = Worst case scenario

RADIOLOGICAL RISK

Identify & Assess
↓
Simulations: Geometry, material (e.g. density)
↓
Power density estimation
↓
Mitigation
↓
Component design optimization
↓
Operation parameters optimization
↓
Maintenance Modes

Engineering process approach:

FNAL Engineering Manual



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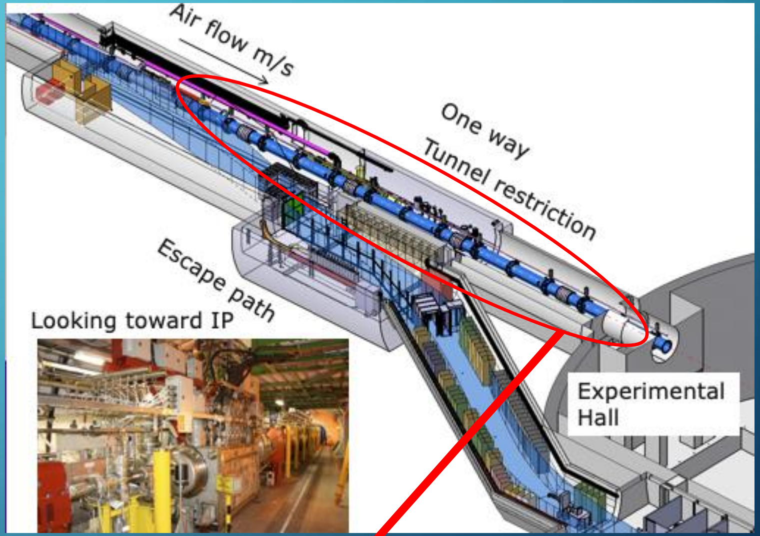
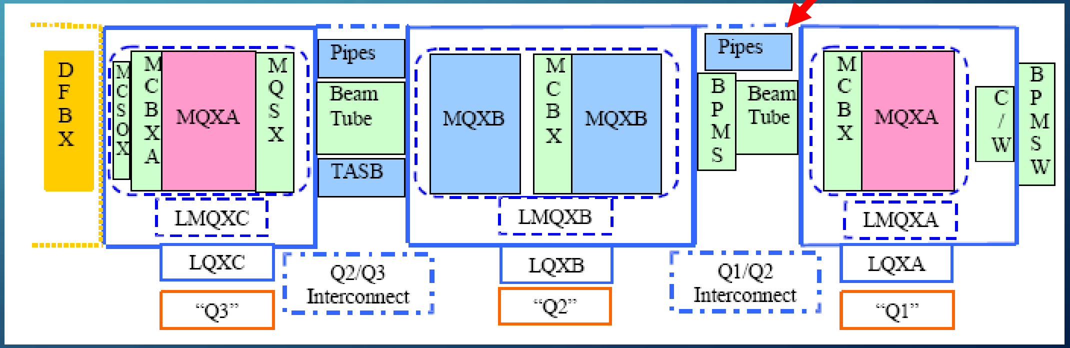
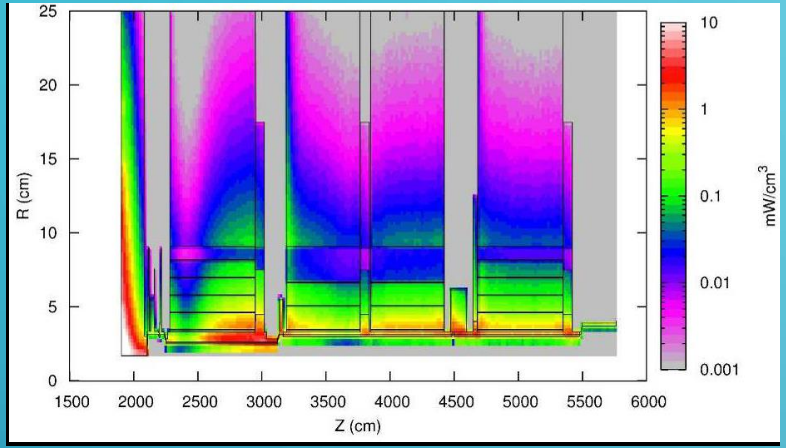


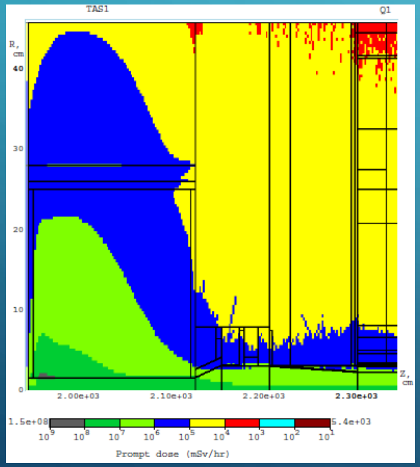


"Protecting LHC IP1/IP5 Components Against Radiation Resulting from Colliding Beam Interactions", by N.V. Mokhov et. al

RADIOLOGICAL RISK

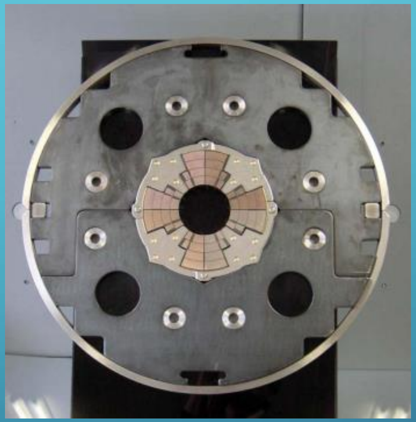


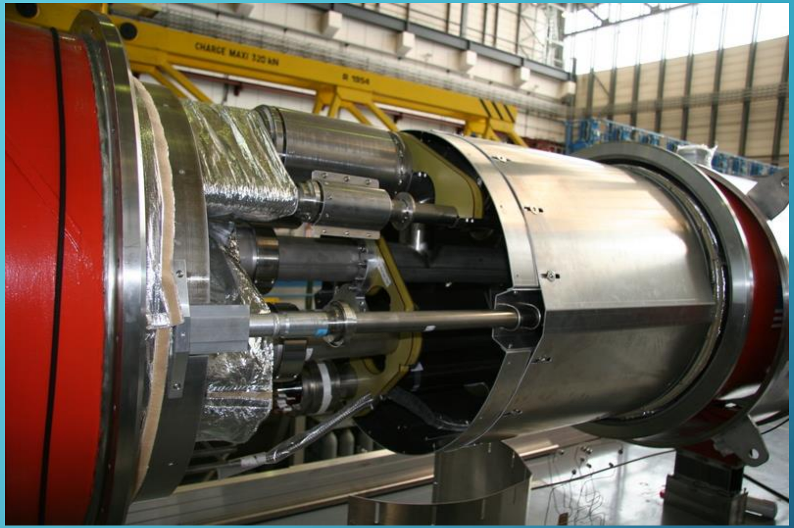
IR5 azimuthally averaged power distribution

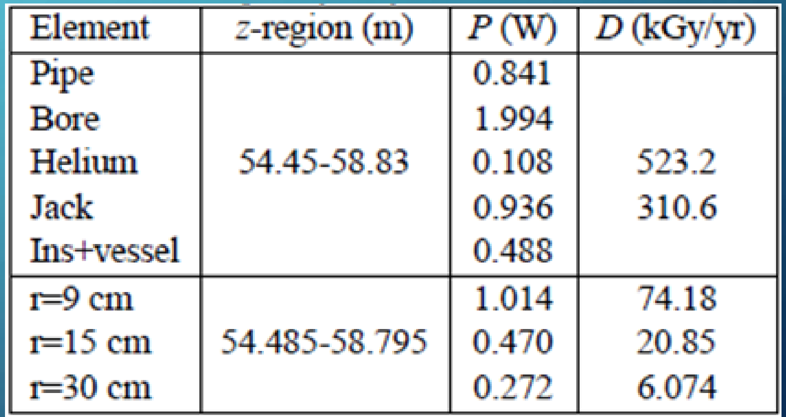


Radial distribution of azimuthally averaged dose (Gy/yr)

- Magnet quench limit =1.6 mW/g





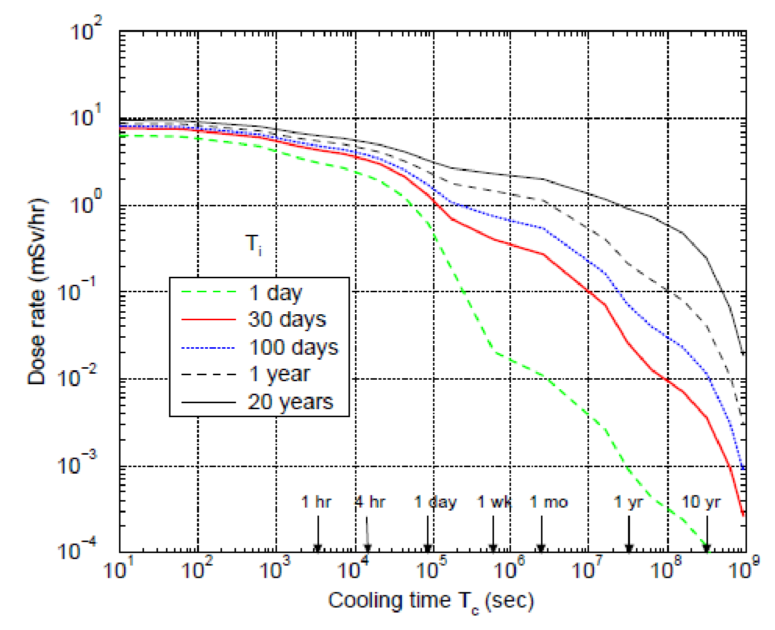


Element	z-region (m)	P (W)	D (kGy/yr)
Pipe	54.45-58.83	0.841	
Bore		1.994	
Helium		0.108	523.2
Jack		0.936	310.6
Ins+vessel		0.488	
r=9 cm	54.485-58.795	1.014	74.18
r=15 cm		0.470	20.85
r=30 cm		0.272	6.074

→ Maximum of 12.5 mW/g (or 100 MGy/yr) at 15 cm (z=1960 cm) is determined by photons and electrons coming to the absorber

→ For comparison : Arc magnet ~ 1 Gy/yr

RADIOLOGICAL RISK MITIGATION



Averaged over surface residual dose rate (mSv/hr) on the Q1 side (z=2125 cm, bottom) of the TAS vs irradiation and cooling times.

Based on Risk analysis:

Conceptual/Design choice

- The inner-triplet final design included additional radiation shielding and copper absorber
- Material choice: e.g. PEEK versus Kel-F for the DFBX low temperature gas seal
- The chosen instrumentation and equipment are radHard and halogen free (neutron irradiation experiment performed on temperature sensors : fluence values close to 10^{15} neutrons/cm^{2}, corresponding to 2.10^{4} Gy).
- Operating Modes: Process control w/ interlocks and alarm level for each operating mode

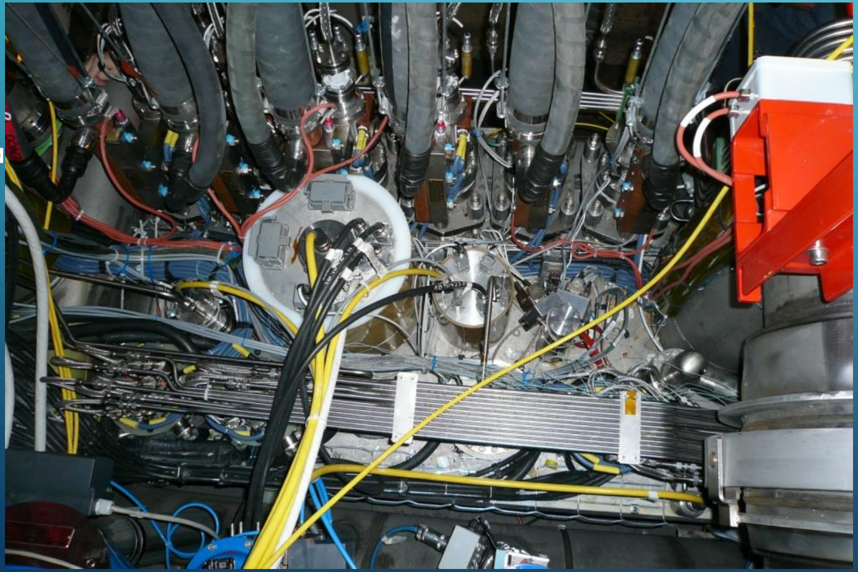
\- Procedures written based on lessons learned

- Radiological survey systematical performed < 0.1mSv/hr for low occup. high radiation zone
- LHC tunnel accesses modes were defined, e.g. control and restricted modes
- Limit the personnel exposition time

RISK MITIGATION : PERSONNEL TRAINING

- In addition to the use of software and hardware interlocks to limit risks, personnel's training is of prime importance.
- Courses to comply with the CERN safety policy. They train the personnel to behave safely in a cryogenic and radiation environment.
- Awareness and preventive actions are mandatory to complete each technical task. Dedicated hazard analyses are enforced to work in the low-b magnet system area.

“Compact” DFBX area



TEST CASE

EUROPEAN SPALLATION SOURCE

PROTON LINEAR ACCELERATOR

EUROPEAN SPALLATION SOURCE - LINAC

High Power
Linear Accelerator:
- Energy: 2 GeV
- Rep. Rate: 14 Hz
- Current: 62.5 mA

Target Station:
- He-gas cooled rotating W-target (5MW average power)
- 42 beam ports

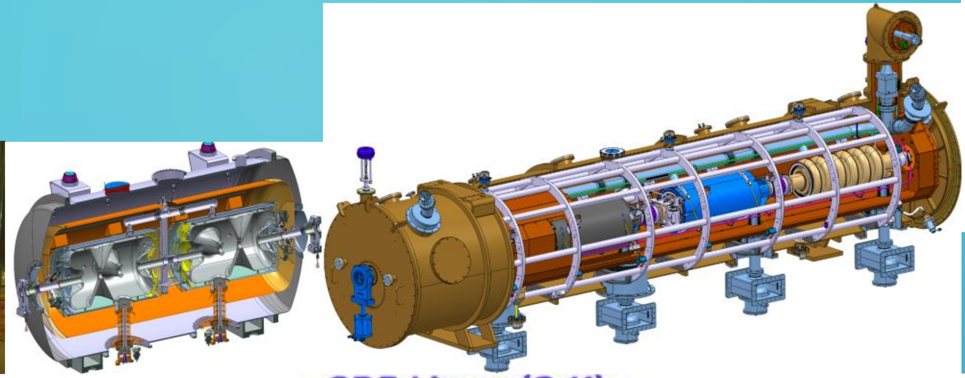
16 Instruments in Construction budget

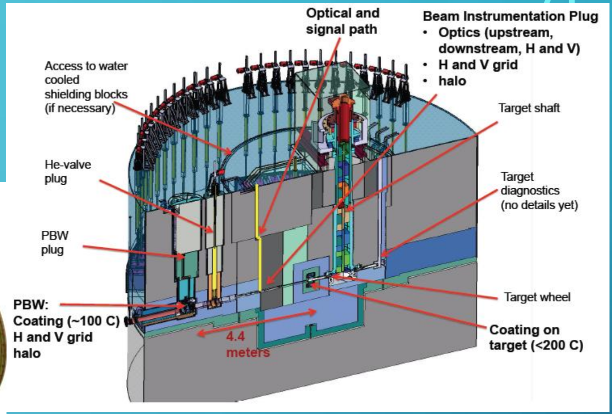
Committed to deliver 22 instruments by 2028

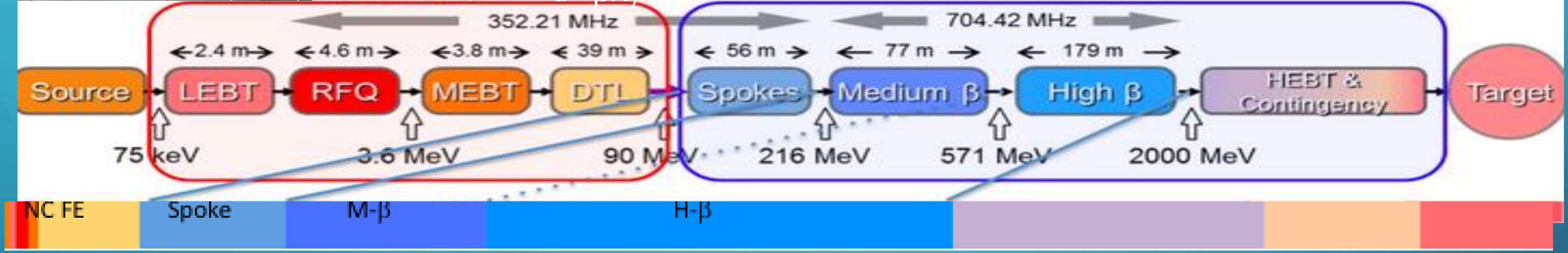
Peak flux ~30-100 brighter than the ILL

Total cost: 1843 MEuros $_{2013}$

LINEAR ACCELERATOR (SRF)
(SEE ALSO OCTOBER 21, 2020)







Specification:

- Radiation-hard components

(e.g. electronics, materials, instrumentation,)

- Risk Analysis

- Preventive maintenance and monitoring

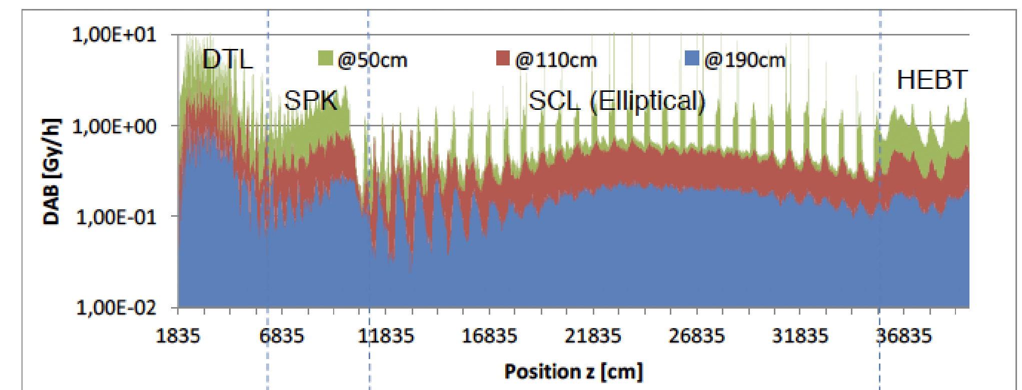
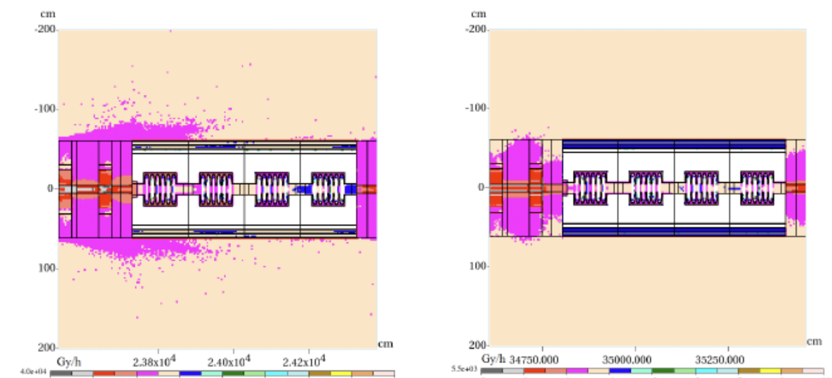


Figure 5 - Absorbed dose maps for 50, 110 and 190 cm from the beam centre [Gy/



SUITE AU PROCHAIN EPISODE …

LEARN MORE ABOUT PARTICLE ACCELERATORS

- Massive Open-Online Courses: www.npap.eu
- US-Particle Accelerator School, http://uspas.fnal.gov/materials/materials-table.shtml
- CERN Accelerator School http://cas.web.cern.ch/cas
- ASP2018: “Introduction to Accelerator” by Caterina Biscari
- ASP online Course: Radiation Measurements and Dosimetry by Marco Silari

  https://indico.cern.ch/event/926495; https://indico.cern.ch/event/926500/; https://indico.cern.ch/event/926502/; https://indico.cern.ch/event/926503/

Few books:

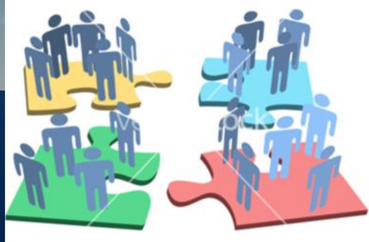
- RF Linear Accelerators, T.P. Wangler, Wiley, 2008
- RF Superconductivity for Accelerator, H. Padamsee, J. Knobloch, T. Hays, Wiley, 2011
- An introduction to particle accelerators, E.J.N. Wilson, Oxford Univ. Press, 2001
- An introduction to the physics of high-energy accelerators, D.A. Edwards & M.J. Syphers, Wiley, 1993
- The principles of circular accelerators and storage rings, P.J. Bryant & K. Johnsen, Cambridge Univ. Press, 1993

Radiation safety applied to particle accelerators permits us to design, fabricate, install and commission state-of-the-art equipment

Each accelerator generation built on the accomplishments of the previous ones, raising the quality of equipment performance and transferring knowledge and technology to industries

Synergies between Research Infrastructures and Industry are keys to an innovative Ecosystem

Thank you for your attention!



EXTRA SLIDES

NORDIC PARTICULE ACCELERATOR PROJECT

(NPAP.EU)

92/100

Erasmus Plus Project of
Excellence & Best Practice

@ 6 October 2020

MOOC1: Particle Accelerators introduction

→ Launched in August ’19
→ 2272 learners enrolled

- **Accelerators for Synchrotron Light**
  - Light and Light Sources
  - Accelerator to make light
  - The development of accelerators for synchrotron light
- **Photon light sources and MAXIV**
  - Synchrotron radiation
  - Bending magnets, wigglers and undulators
  - Free Electron Lasers
- **Spallation source and ESS**
  - Introduction and neutron science
  - European Spallation Source
- **Particles Colliders**
  - Introduction to Particles Colliders
  - The LHC and its experiments
  - Linear Colliders
  - Future Circular Colliders
- **Plasma Wakefield** (to be completed)

MOOC2: Fundamentals of accelerator technology

→ Launched in March ’19
→ 2000 learners enrolled

- **RF-System**
  - Introduction to RF-systems
  - RF cavities
  - Waveguides
  - RF Amplifiers
  - More about cavities
- **Magnets technology for accelerators**
  - Magnets part1/2/3
- **Beam Diagnostics**
  - An overview
  - Beam intensity and position
  - Transverse Beam Profile
  - Longitudinal Beam Profile
  - Beam Loss Monitoring
- **Basics of Vacuum techniques**
  - An overview and motivation
  - Residual gases and vacuum regions
  - Vacuum equipment
  - Other vacuum components

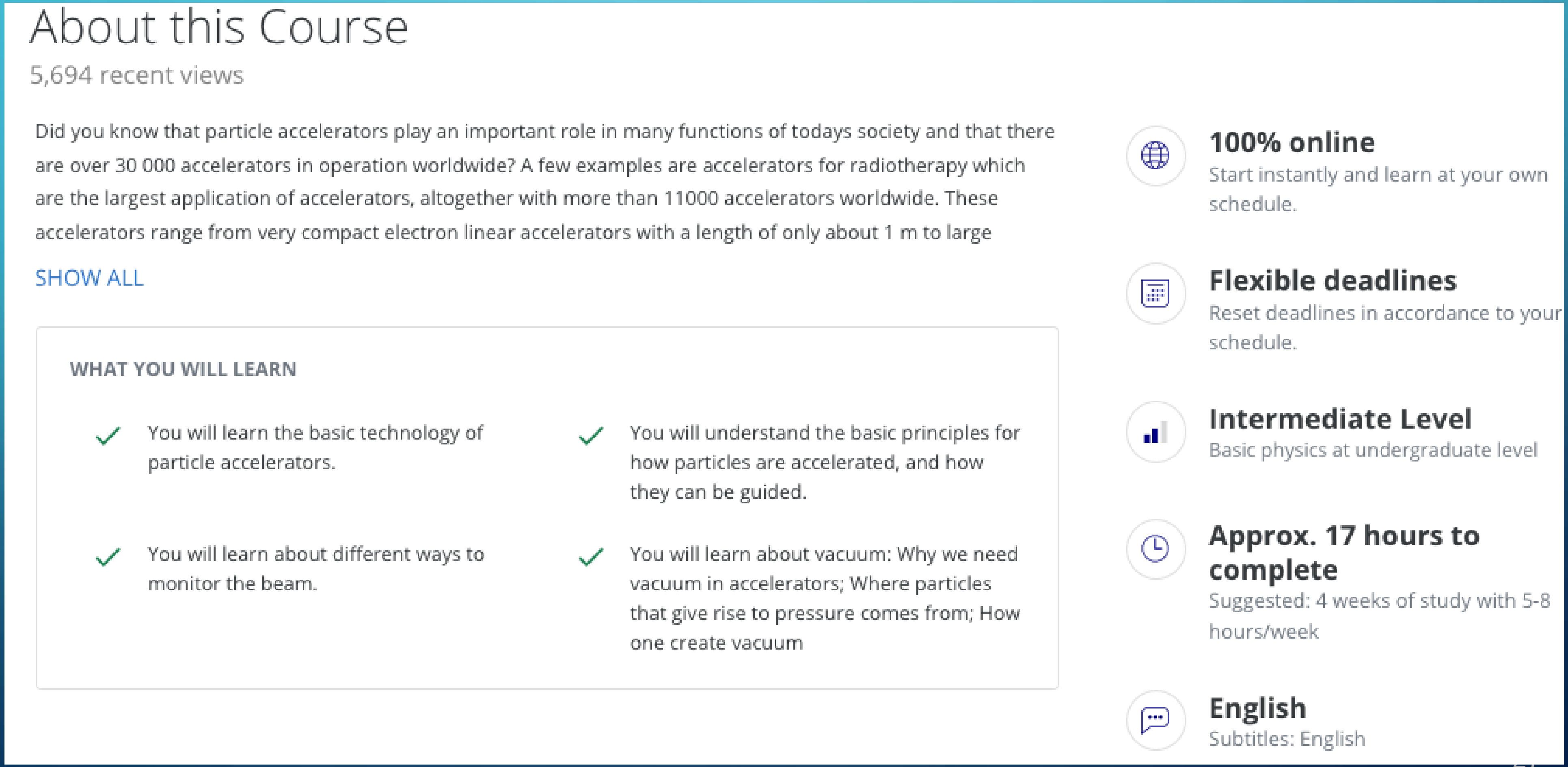
MOOC3: Medical Applications of Particle Accelerators

→ Launched in Nov. ’18
→ 3067 learners enrolled

- **Introduction to the course and radiotherapy**
  - Introduction
  - Biological rational for radiotherapy
  - Intro. to the electron linac for radiation therapy
- **Electron Linacs for radiation therapy**
  - The multi-energy electron Linac structure
  - Dose delivery to the patient
- **Proton therapy 1**
  - Rationale of proton therapy
  - Accelerators for proton therapy
  - Treatment delivery of proton therapy
- **Proton therapy II and production of medical radionuclides**
  - Heavy ion therapy
  - Challenges in pr. th. and heavy ion th.
  - Introduction to medical radionuclides
  - Production of medical radionuclides

EXAMPLE
MOOC2: FUNDAMENTALS OF ACCELERATOR TECHNOLOGY

https://www.coursera.org/learn/fundamentals-particle-accelerator-technology



About this Course

5,694 recent views

Did you know that particle accelerators play an important role in many functions of todays society and that there are over 30 000 accelerators in operation worldwide? A few examples are accelerators for radiotherapy which are the largest application of accelerators, altogether with more than 11000 accelerators worldwide. These accelerators range from very compact electron linear accelerators with a length of only about 1 m to large

SHOW ALL

WHAT YOU WILL LEARN

- ✓ You will learn the basic technology of particle accelerators.
- ✓ You will understand the basic principles for how particles are accelerated, and how they can be guided.
- ✓ You will learn about different ways to monitor the beam.
- ✓ You will learn about vacuum: Why we need vacuum in accelerators; Where particles that give rise to pressure comes from; How one create vacuum

100% online
Start instantly and learn at your own schedule.

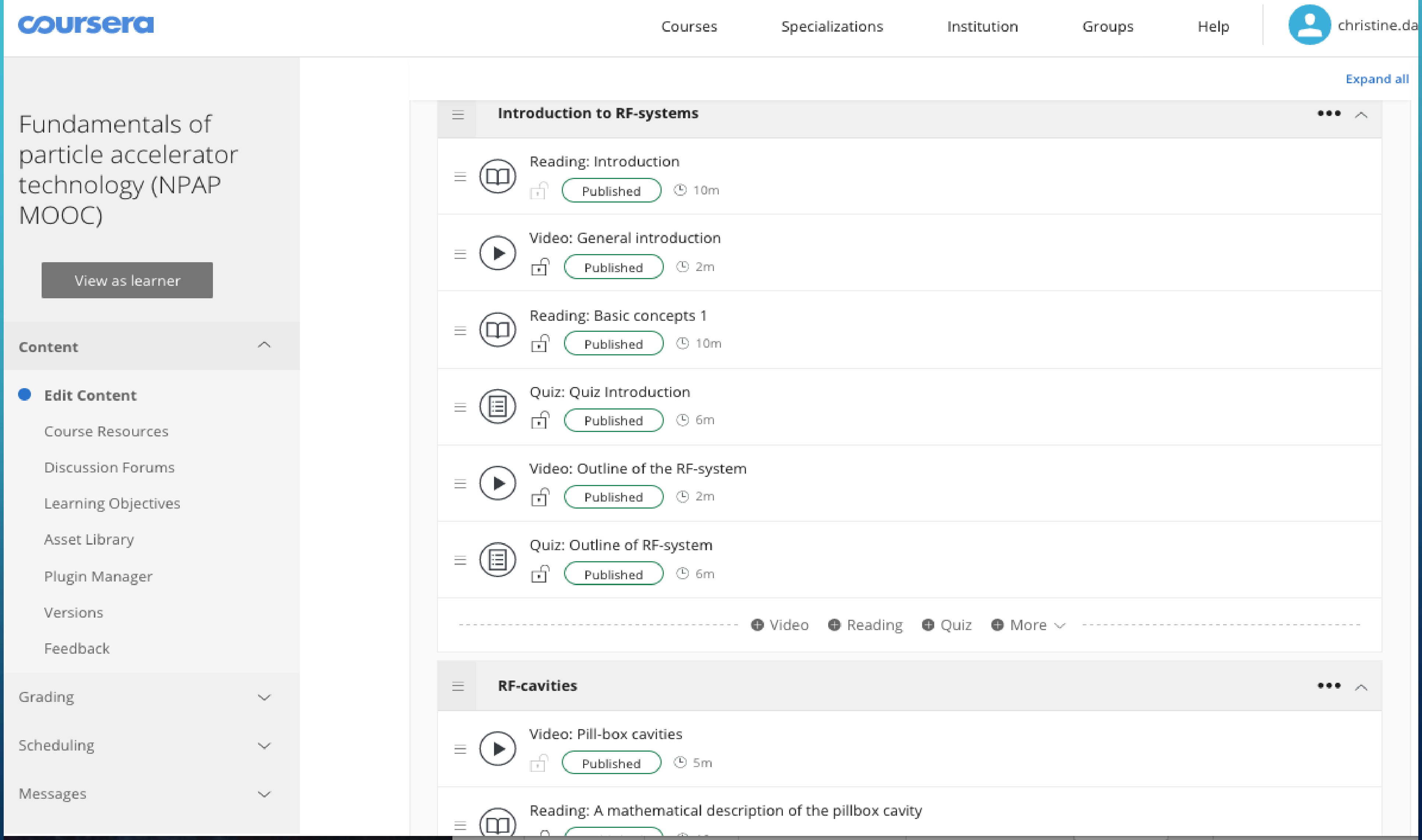
Flexible deadlines
Reset deadlines in accordance to your schedule.

Intermediate Level
Basic physics at undergraduate level

Approx. 17 hours to complete
Suggested: 4 weeks of study with 5-8 hours/week

English
Subtitles: English

COURSERA ARCHITECTURE



Fundamentals of particle accelerator technology (NPAP MOOC)

Content

- **Edit Content**
- Course Resources
- Discussion Forums
- Learning Objectives
- Asset Library
- Plugin Manager
- Versions
- Feedback

Grading

Scheduling

Messages

Introduction to RF-systems

Reading: Introduction
Published 10m

Video: General introduction
Published 2m

Reading: Basic concepts 1
Published 10m

Quiz: Quiz Introduction
Published 6m

Video: Outline of the RF-system
Published 2m

Quiz: Outline of RF-system
Published 6m

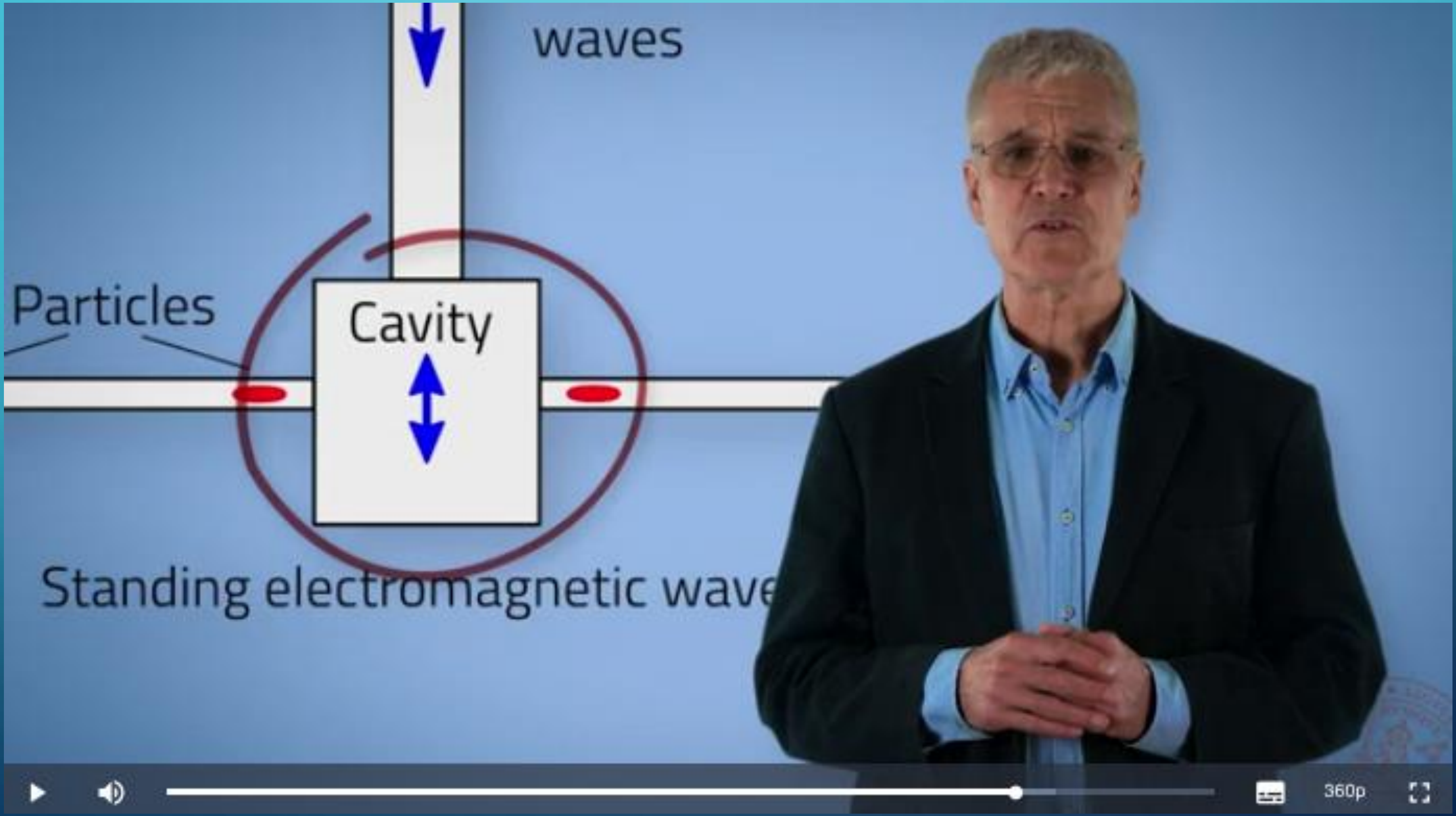
RF-cavities

Video: Pill-box cavities
Published 5m

Reading: A mathematical description of the pillbox cavity

EXAMPLE OF LECTURE

https://www.coursera.org/lecture/fundamentals-particle-accelerator-technology/general-introduction-wf3CB



https://drive.google.com/open?id=160EDKsTJiZruNpGNoDuu0hvxLYf0fafW

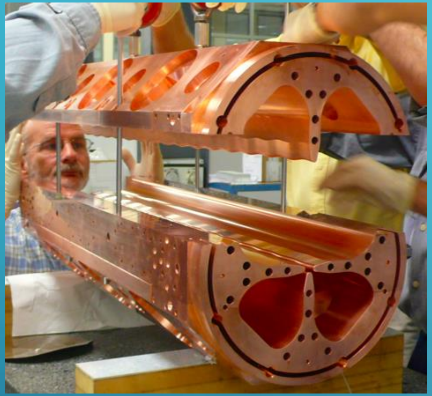
ACCELERATOR CHARACTERISTICS

FAMILY OF LINAC COMPONENT

RF Quadrupole

At low energy proton, the RFQ permits:

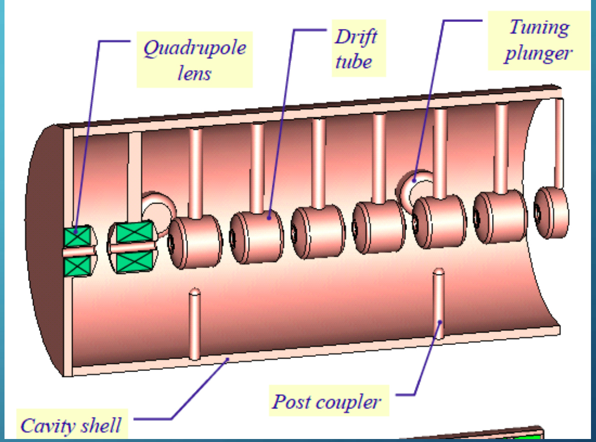
1. Bunching of the beam
2. Focusing quadrupole
3. Accelerating



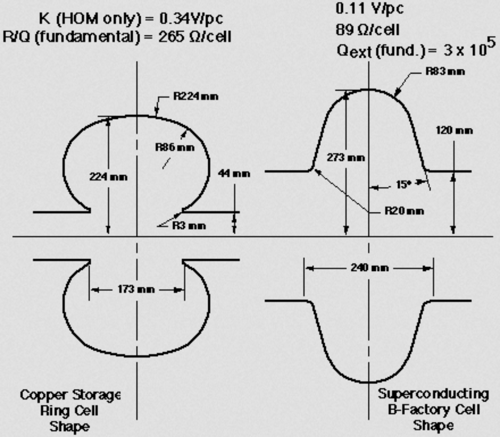
If f >10 MHz, the DTL acts like an antenna and radiates energy instead of using it for the acceleration

Drift Tube Linac

Every cell is different, focusing quadrupoles in each drift tube



RF cavity

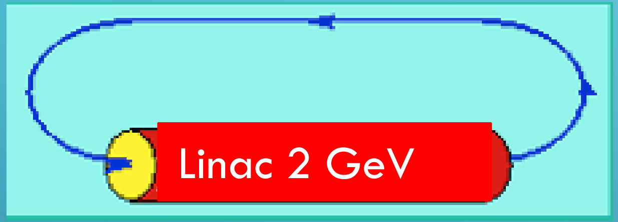


EM fields enclosed in a cavity with resonant frequency matching that of RF generator

ACCELERATOR CHARACTERISTICS

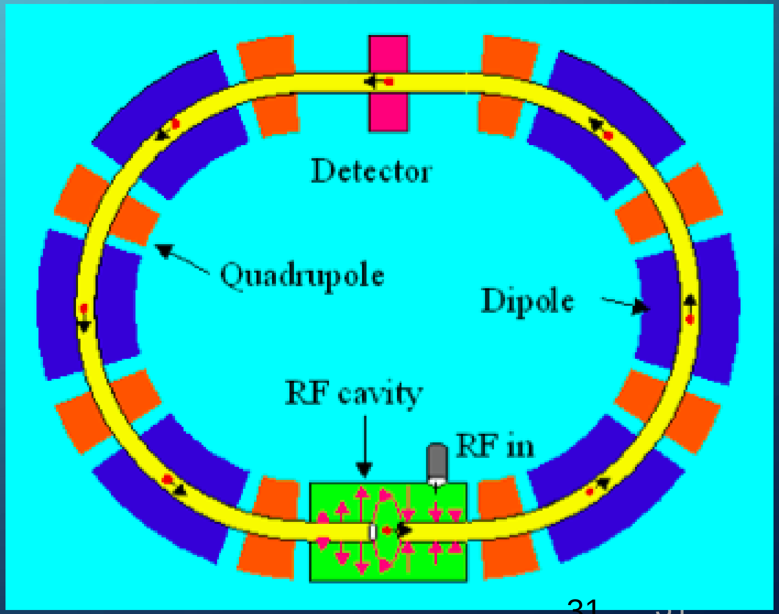
ESS LINAC is 600 m long (350m of acceleration) and reaches an energy of 2 GeV
Assuming we need a 7 TeV machine (LHC), the Linac should be 1,225 km long !

Linac over and over ?



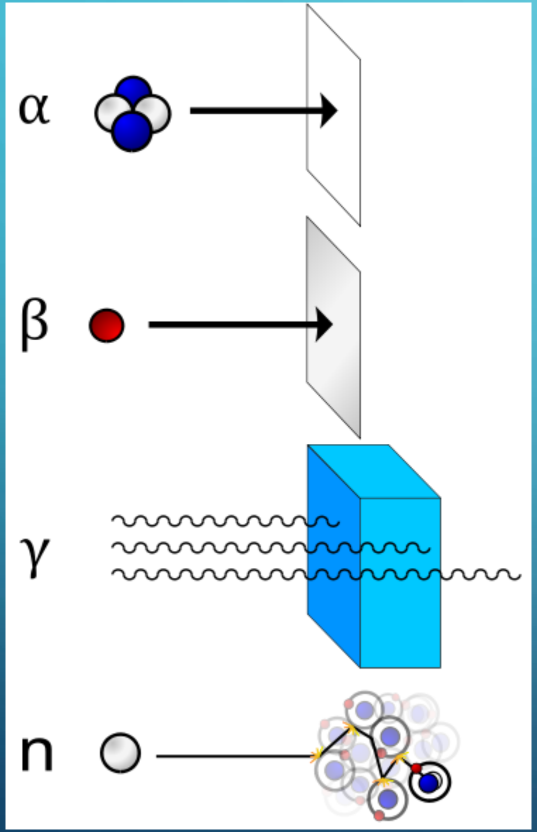
→ Synchrotron Accelerators:
Space charge effect becomes small

* Cover range where particle velocity is nearly cst.
e.g. LHC, Tevatron



IONIZING RADIATION

Ionizing radiation is radiation composed of particles that individually carry enough energy to liberate an electron from an atom or molecule without raising the bulk material to ionization temperature.



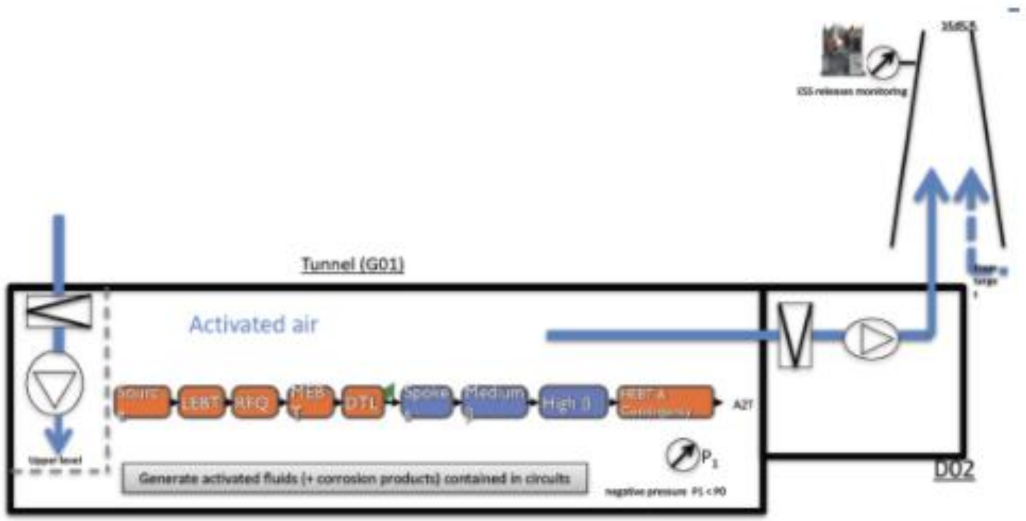
When ionizing radiation is emitted by or absorbed by an atom, it can liberate a particle. Such an event can alter chemical bonds and produce ions, usually in ion-pairs, that are especially chemically reactive.

Note: Neutrons, having zero electrical charge, do not interact electromagnetically with electrons, and so they cannot *directly* cause ionization by this mechanism.

➔ High precision non-destructive probe … why ?

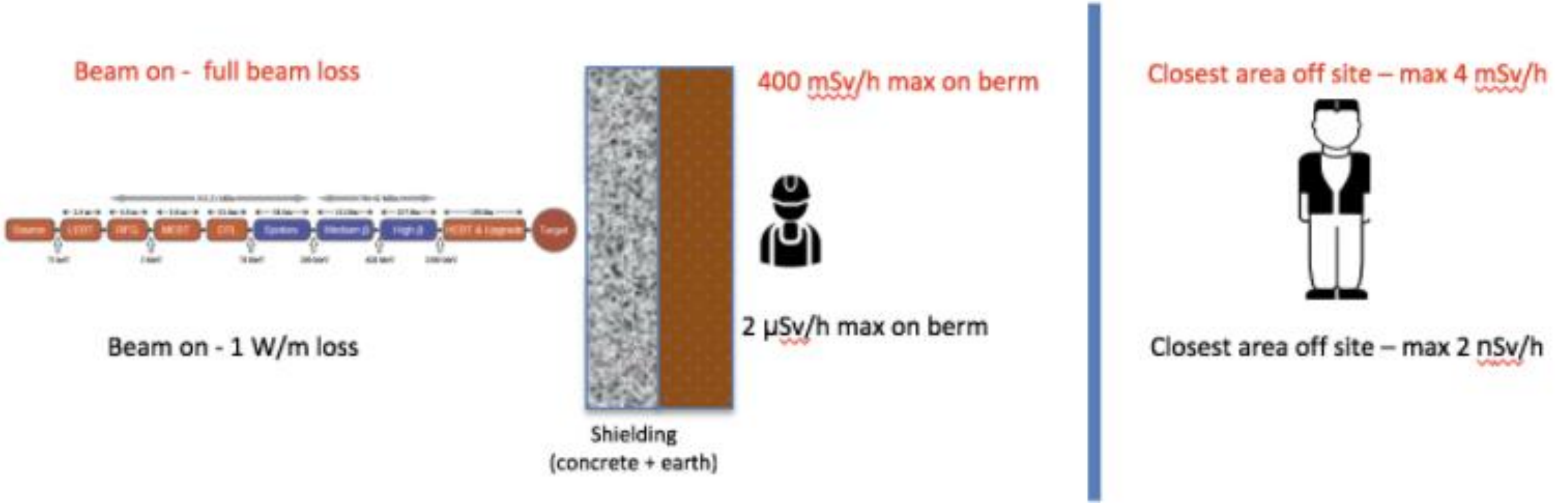
ACCELERATOR

Radioactive inventory from activated air from prompt radiation with beam losses of 1 W/m



15 DAC max (14 GBq) in the tunnel during operation and beam on (1 W/m loss) with renewal HVAC = 0 (with rHVAC = 0.5, 10 GBq corresponding to 9 DAC)

Prompt radiation


Beam on - full beam loss

400 mSv/h max on berm

Closest area off site – max 4 mSv/h

Beam on - 1 W/m loss

2 µSv/h max on berm

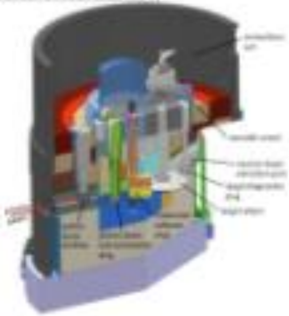
Closest area off site – max 2 nSv/h

Shielding
(concrete + earth)

TARGET

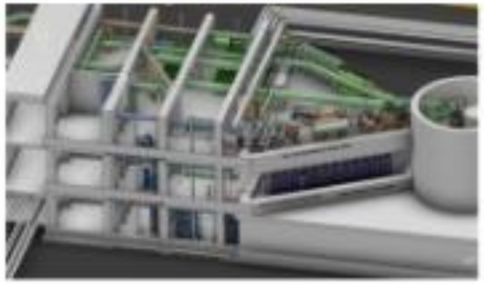
Radioactive inventory

Monolith area



~ 4.10^{17} Bq

Utility area

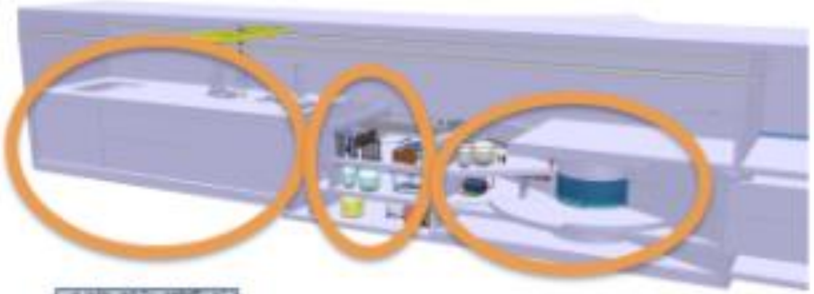


~ 4.10^{12}Bq

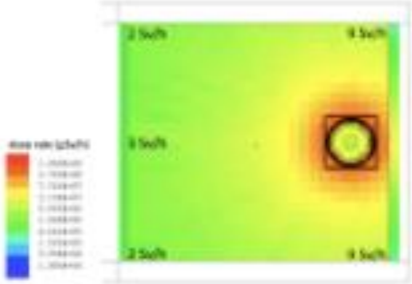
Active cells facility

~ 8.10^{16} Bq

prompt and residual dose rate



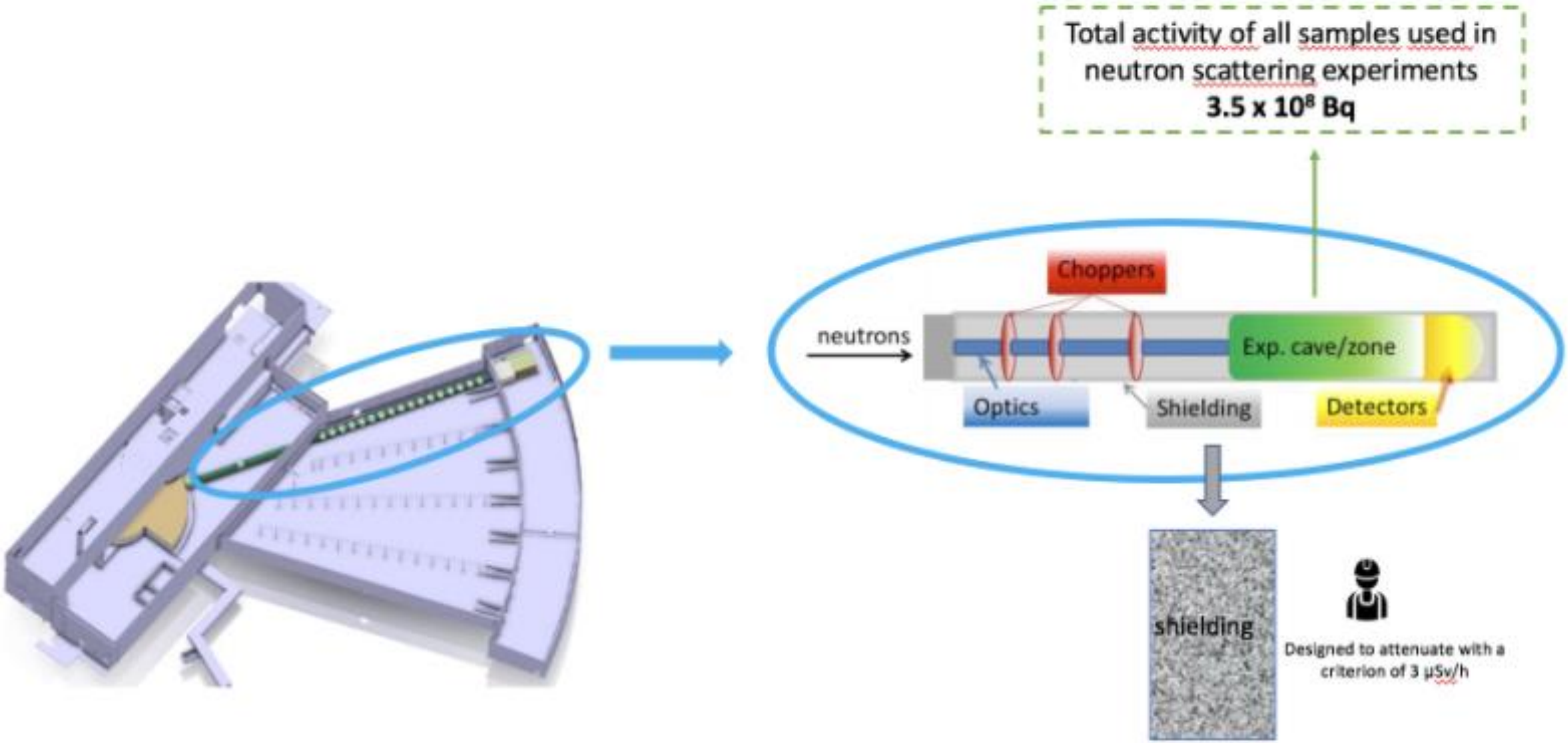
Designed to attenuate with a criterion of 3 µSv/h



Dose map of the target wheel (irradiated 5 years + 14 days of cooling time) in the active cell. (2000 Sv/h contact)

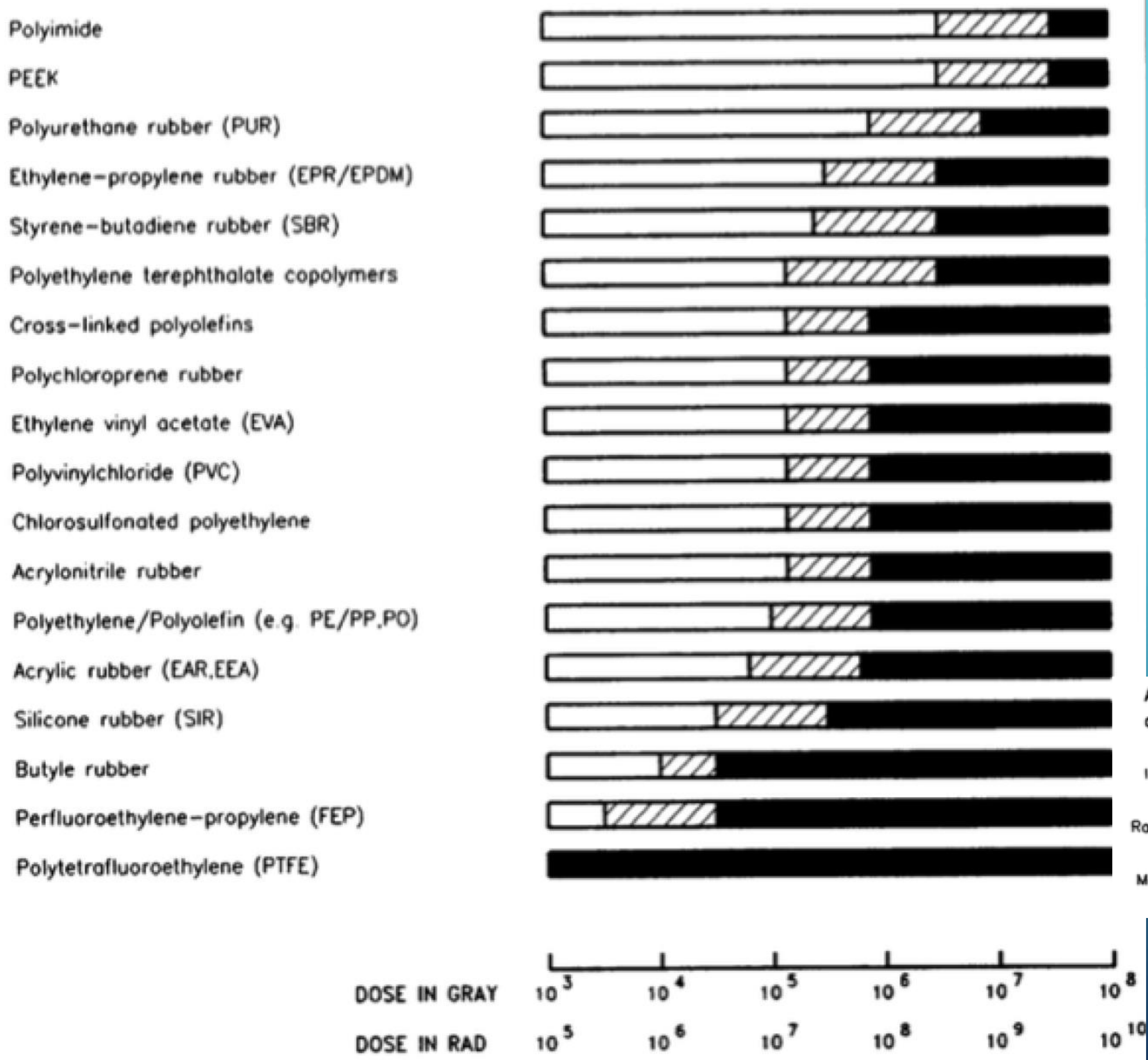
NSS

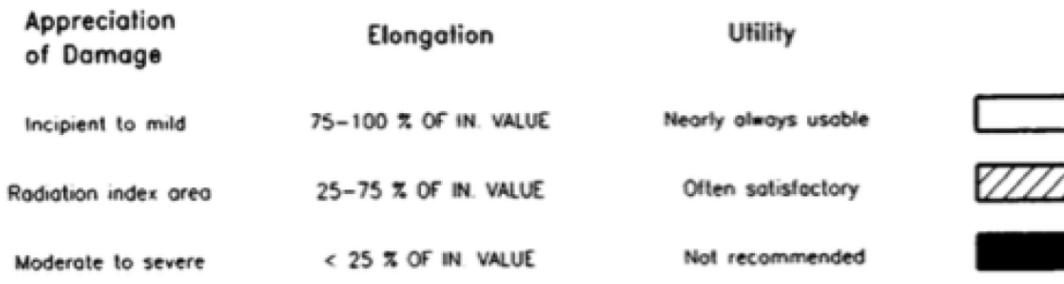
radioactive inventory and prompt radiation



Total activity of all samples used in neutron scattering experiments **3.5×10^8 Bq**

Designed to attenuate with a criterion of 3 µSv/h



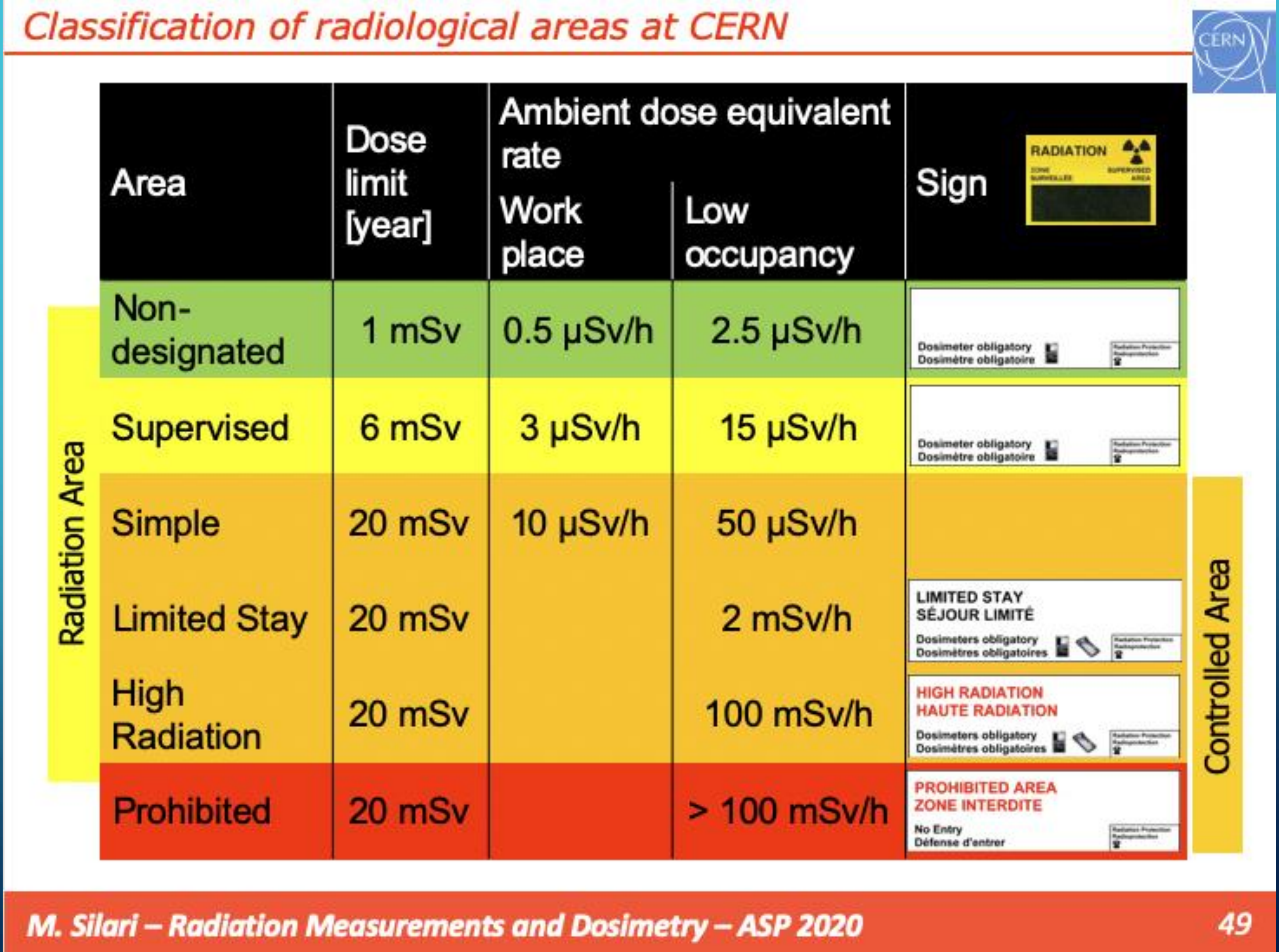


Appreciation of Damage	Elongation	Utility	
Incipient to mild	75–100 % OF IN. VALUE	Nearly always usable	☐
Radiation index area	25–75 % OF IN. VALUE	Often satisfactory	▨
Moderate to severe	< 25 % OF IN. VALUE	Not recommended	■

- Person **occupationally exposed** to radiation (> 1 mSv/y)
  - Category **A** workers: > 6 mSv/y
  - Category **B** workers: < 6 mSv/y
- **Supervised area**: area with dose > 1 mSv/y

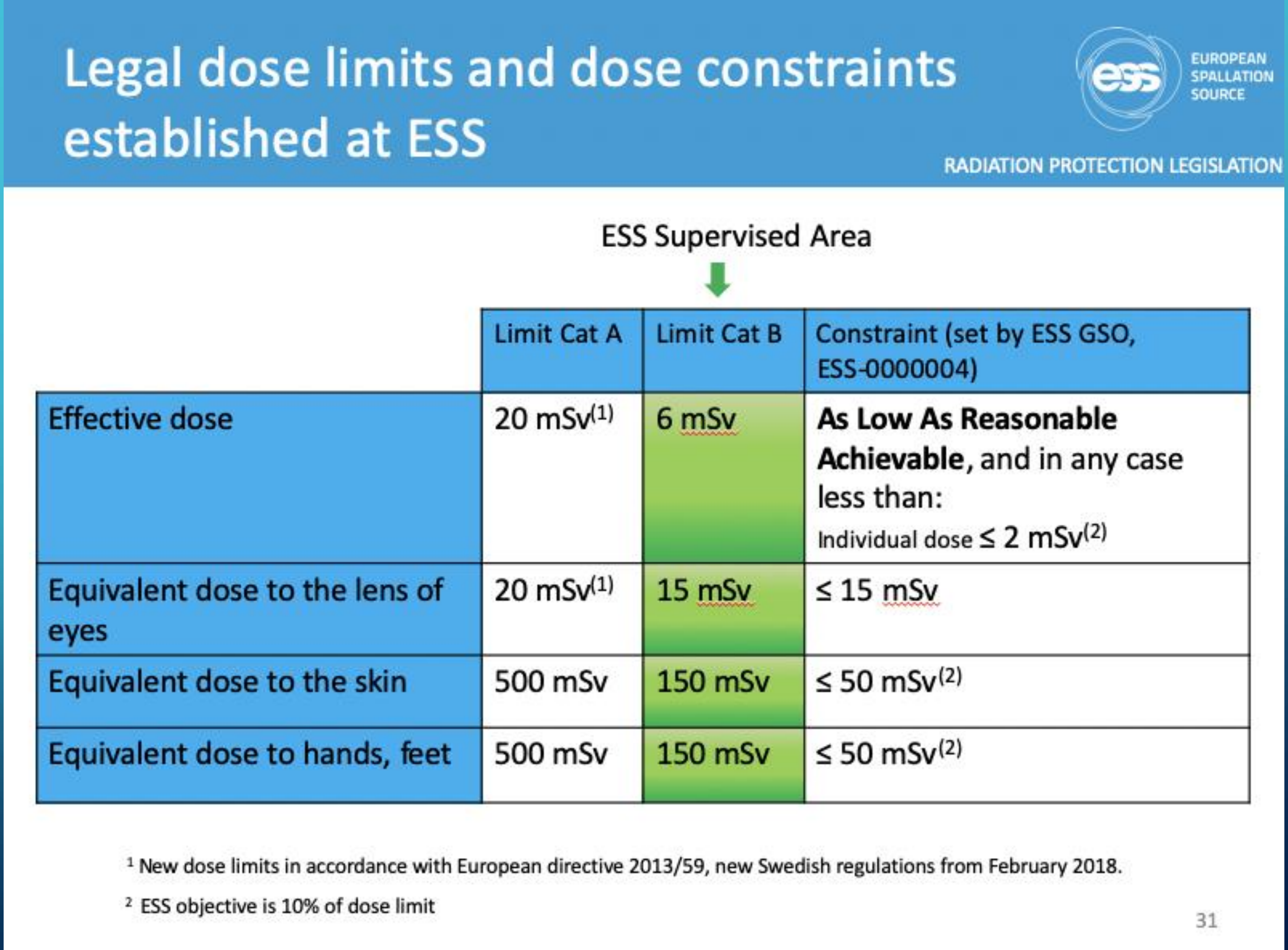
  (accessible to categories A and B workers)
- **Controlled area**: area with dose > 6 mSv/y

  (accessible to categories A workers, and with limited stay to category B workers)
- Exposure situations:
  - **risk of external exposure only** (sealed radioactive sources, radiation generators, for example X-ray tube)
  - **risk of internal and external exposure** (use of unsealed radioactive sources)



Classification of radiological areas at CERN

	Area	Dose limit [year]	Ambient dose equivalent rate Work place	 Low occupancy	Sign RADIATION ZONE SURVEILLÉE SUPERVISED AREA	
Radiation Area	Non-designated	1 mSv	0.5 µSv/h	2.5 µSv/h	Dosimeter obligatory Dosimètre obligatoire	
	Supervised	6 mSv	3 µSv/h	15 µSv/h	Dosimeter obligatory Dosimètre obligatoire	
	Simple	20 mSv	10 µSv/h	50 µSv/h		Controlled Area
	Limited Stay	20 mSv		2 mSv/h	LIMITED STAY SÉJOUR LIMITÉ Dosimeters obligatory Dosimètres obligatoires	
	High Radiation	20 mSv		100 mSv/h	HIGH RADIATION HAUTE RADIATION Dosimeters obligatory Dosimètres obligatoires	
	Prohibited	20 mSv		> 100 mSv/h	PROHIBITED AREA ZONE INTERDITE No Entry Défense d'entrer	



Legal dose limits and dose constraints established at ESS

EUROPEAN SPALLATION SOURCE

ESS Supervised Area

⬇

	Limit Cat A	Limit Cat B	Constraint (set by ESS GSO, ESS-0000004)
Effective dose	20 mSv(1)	6 mSv	**As Low As Reasonable Achievable**, and in any case less than: Individual dose ≤ 2 mSv(2)
Equivalent dose to the lens of eyes	20 mSv(1)	15 mSv	≤ 15 mSv
Equivalent dose to the skin	500 mSv	150 mSv	≤ 50 mSv(2)
Equivalent dose to hands, feet	500 mSv	150 mSv	≤ 50 mSv(2)

[1] New dose limits in accordance with European directive 2013/59, new Swedish regulations from February 2018.

[2] ESS objective is 10% of dose limit