The ESS as a gateway to applied science

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21st January, 2013

INFN - Pisa

Outline

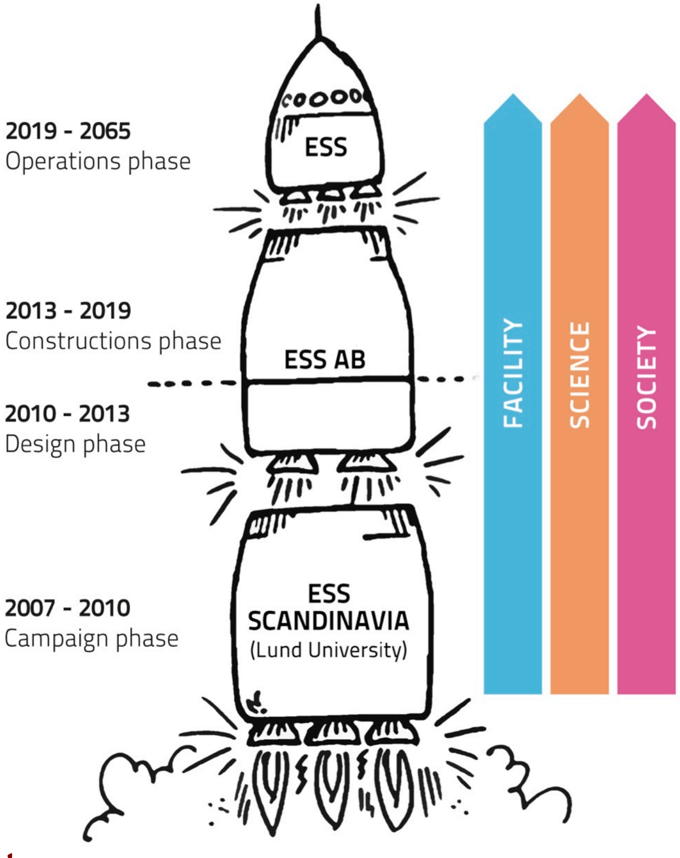
- ESS High-Story: From dreams to reality
- Applied science using neutrons
- The ESS technical complex
  - Target and the spallation process
  - The accelerator
- More support from INFN to an ESS-like initiative..

ESS High-Story: From dreams to reality

EUROPEAN SPALLATION SOURCE

The ESS program

- Vision & Raison d'etre: "Science for Society"
- Mission:
  - Design, construct and operate the worlds-leading neutron source
- Core Values:
  - Innovation
  - Openness
  - Sustainability
- ESS philosophy:
  - "Greenfield thinking on a greenfield site"



ESS phases and themes of communication

Goal: to deliver first neutrons before this decade is out
→ Goal oriented project

An unique program – ESS and Partners

Sweden, Denmark and Norway
50% of construction costs – 1479 M€
20% of operation cost

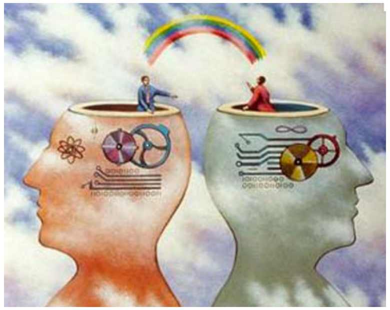
17 Partners today

The remaining 50%: Spain, France, Germany, Italy, Switzerland, Hungary, Czech Republic, Poland, Netherlands, Estonia, Latvia, Lithuania, Iceland & UK

The ESS Spirit

- Create a world leading European science laboratory

- Contribute to scientific breakthroughs



The fractality and entanglement …

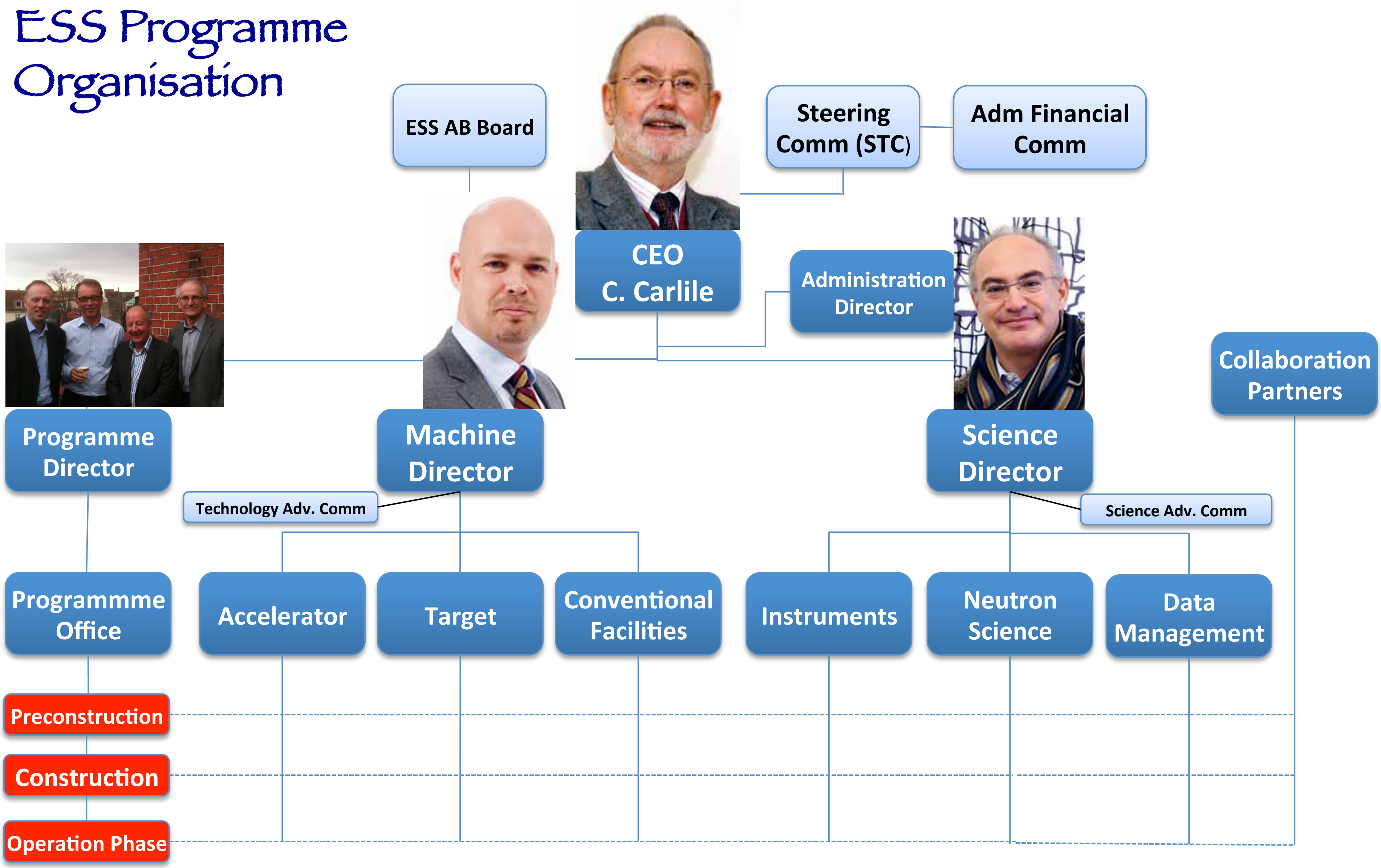
- Many challenges:
  - Challenging and complex technology (accelerator, target, moderator)
  - Large investments and significant annual budget
  - Political decision making, competition and negotiations
  - Commitment to minimize the environmental impact.

- **Synergies** with ongoing and planned projects on accelerator driven systems, transmutation, neutrino factories, HEP injectors, materials science

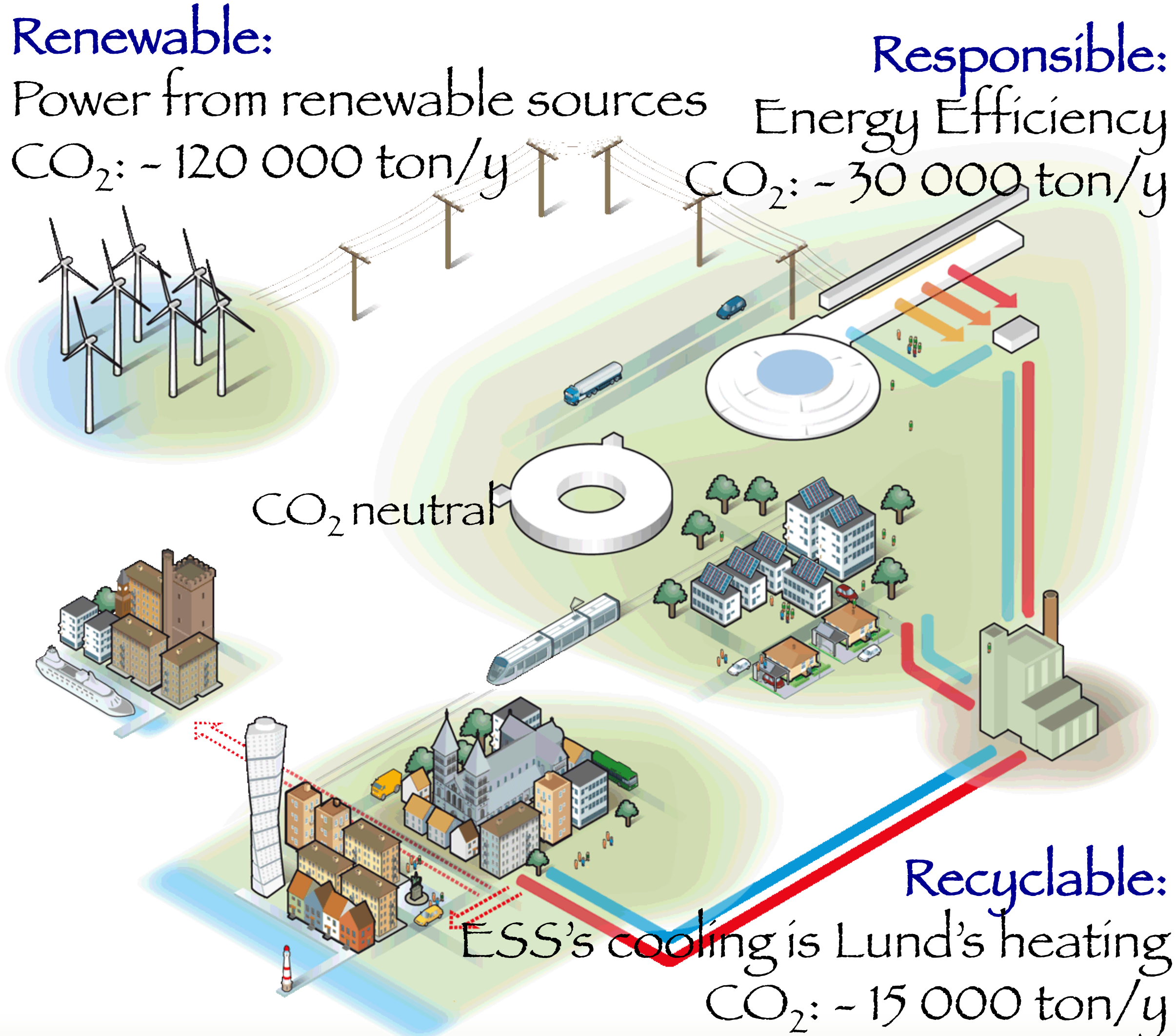
ESS – some numbers

- 5MW proton beam power (H^+) – 500 m LINAC
- 2.5 GeV Proton Energy
- 50 mA (2 mA) peak (average) proton current
- 2.86 msec pulse length
- 14 Hz pulse frequency
- 71.4 msec periods between pulses
- $3.1 \times 10^{14} n/cm^2 s$ average neutron flux
- $1 \times 10^{16} n/cm^2 s$ peak neutron flux
- Single Target Station
- Rotating Tungsten, helium cooled
- 22 Instruments
- Flexible design for future upgrades
- High reliability, low losses

ESS Programme Organisation

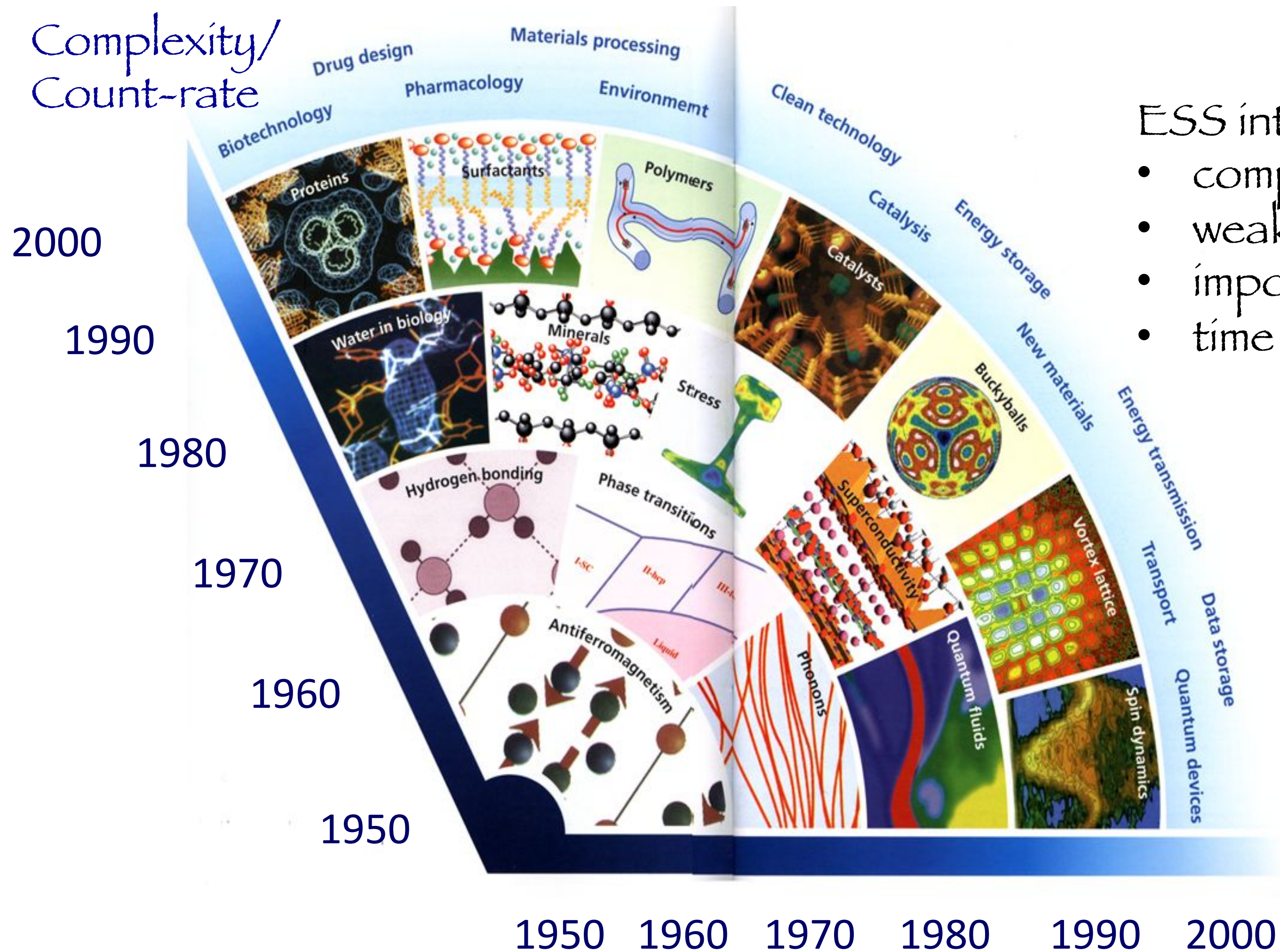


A Sustainable research facility



Applied science using neutrons

ESS/WHAT - Neutron scattering - an expanding field



ESS intensity allows studies of

- complex materials
- weak signals
- important details
- time dependent phenomena

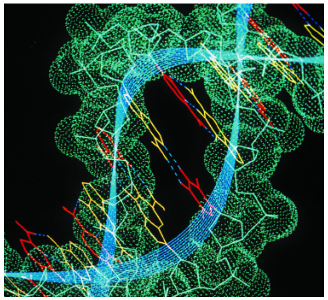
Because of their unique properties, neutrons are a powerful tool for investigating Nature at all levels, from testing theories about the evolution of the Universe to elucidating the complex processes of life.

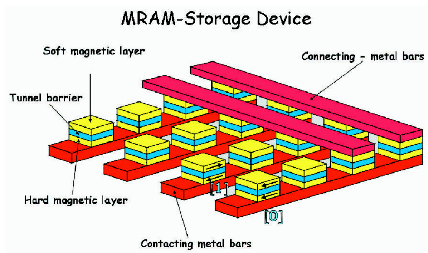
ESS/WHAT – Multi-science with neutrons

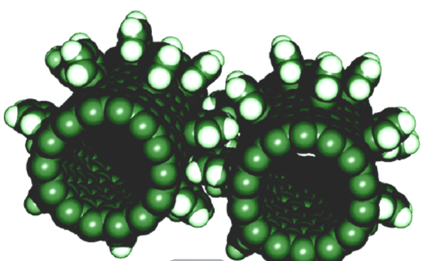
Materials science
Energy Technology

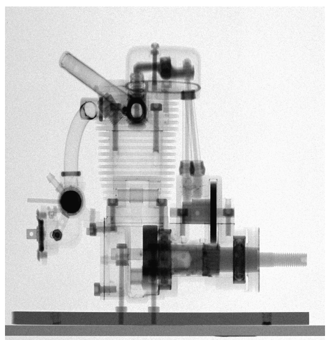
Bio-technology
Hardware for IT

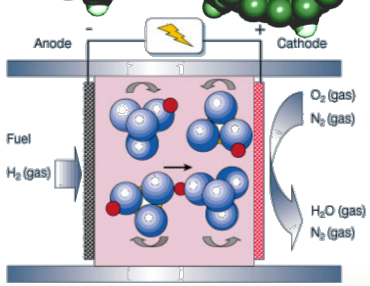
Nano science
Engineering science











- Neutrons can provide unique and information on almost all materials.

- Information on both structure and dynamics simulaneously. "Where are the atoms and what are they doing?"

- 6000 primary users in Europe today and 6000 secondary users. Access based on peer review.

- Science with neutrons is limited by the intensity of today's sources

ESS/WHAT - Fields of interest

A wide range of length and timescales

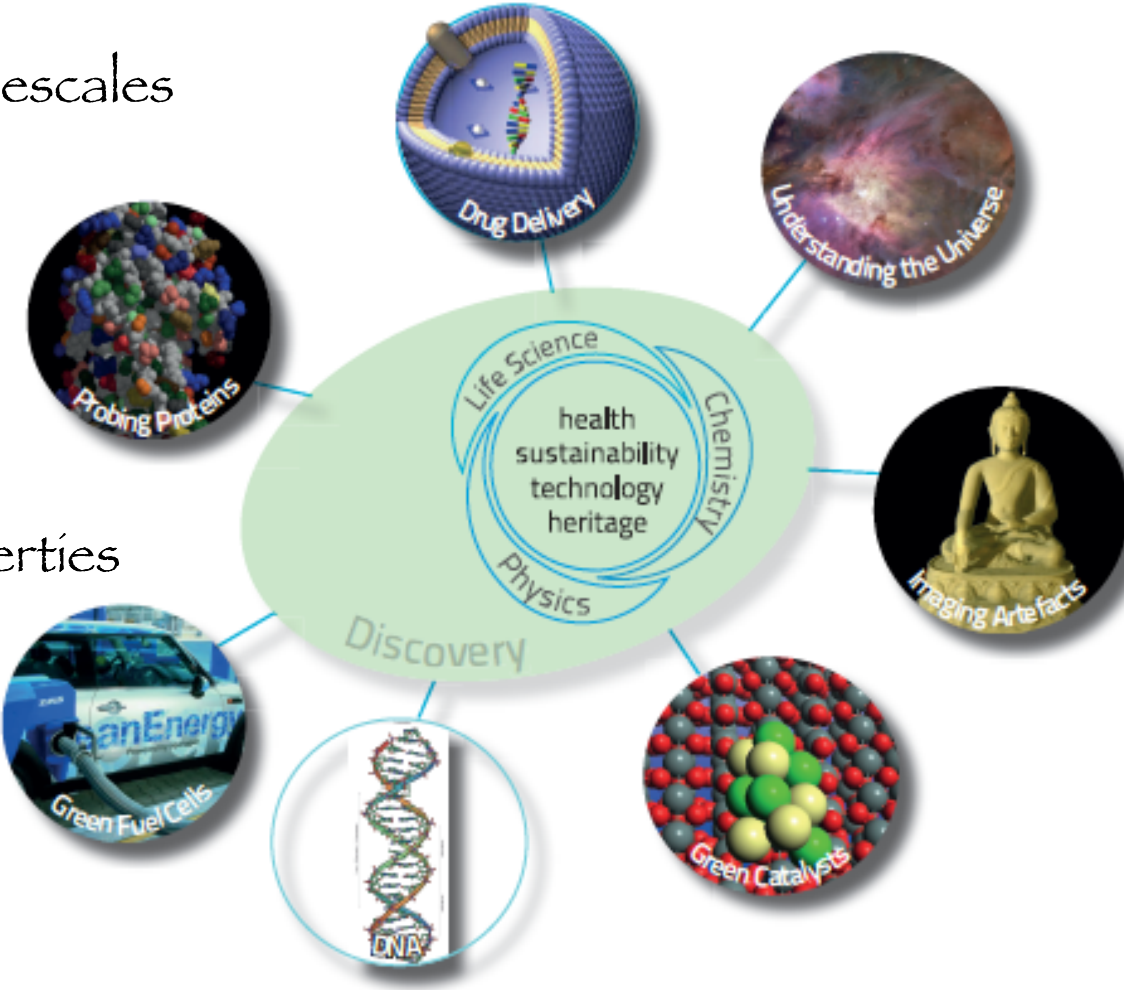
An ideal probe for magnetism

High sensitivity and selectivity

A probe of fundamental properties

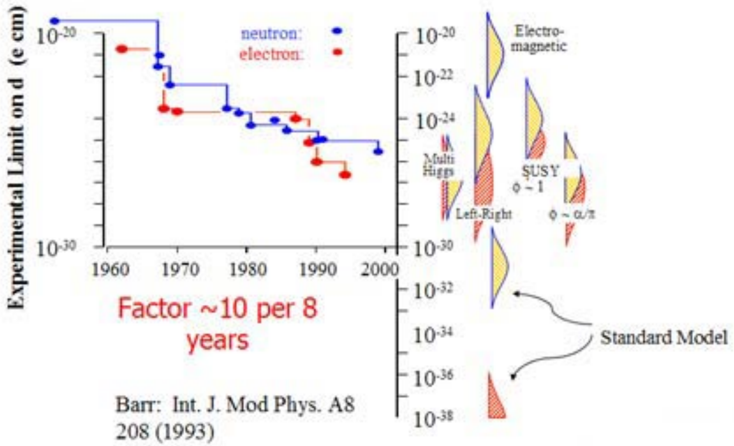
Deep penetration

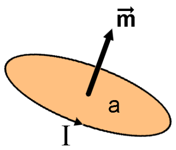
A precise tool



ESS/WHAT – Examples of queries

- Room Temperature Super Conductors
- Sterile neutrinos
- Hydrogen storage substrate
- Neutron electric dipole moment
- Efficient membrane for fuel cells
- Flexible and highly efficient solar cells
- Carbone nano-tubes for controlled drug release
- Self healing materials – smart materials
- Spin-state as a storage of data (10^{23} gain in capacity)
- CO_2 sequestration

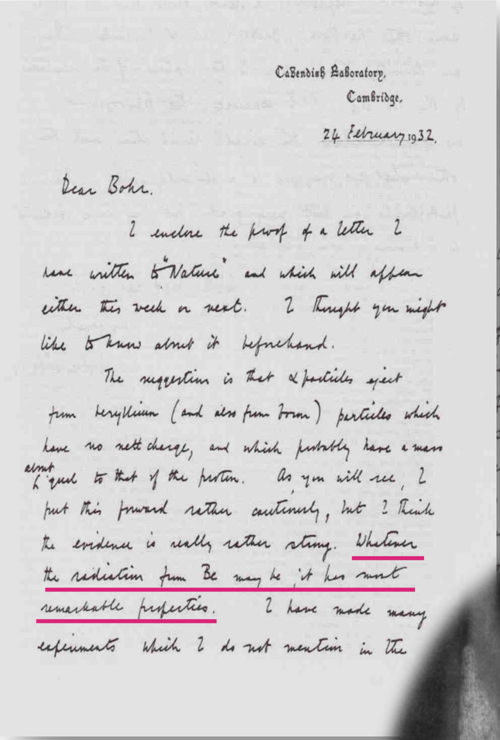




James Chadwick 1932 (α,n) reaction

$$^{4}_{2}He + ^{9}_{4}Be \rightarrow ^{12}_{6}C + ^{1}_{0}n$$

“Whatever the radiation from Be may be, it has most remarkable properties”

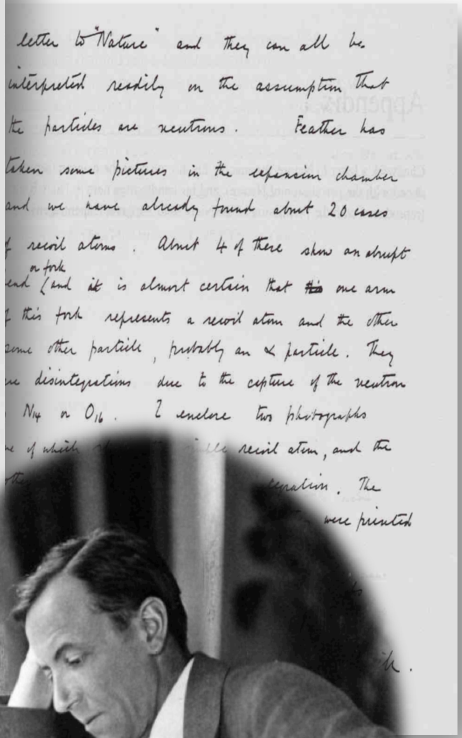


Cavendish Laboratory,
Cambridge.
24 February 1932.

Dear Bohr.

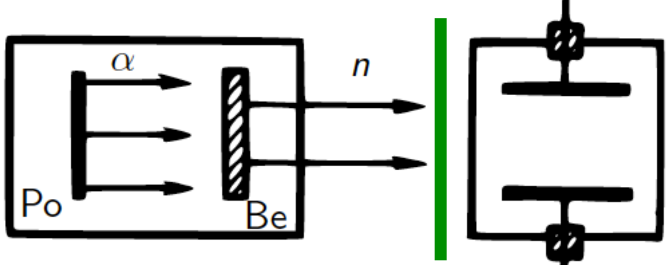
I enclose the proof of a letter I have written to "Nature" and which will appear either this week or next. I thought you might like to know about it beforehand.

The suggestion is that α particles eject from beryllium (and also from boron) particles which have no nett charge, and which probably have a mass about equal to that of the proton. As you will see, I put this forward rather cautiously, but I think the evidence is really rather strong. Whatever the radiation from Be may be, it has most remarkable properties. I have made many experiments which I do not mention in the



letter to "Nature" and they can all be interpreted readily on the assumption that the particles are neutrons. Feather has taken some pictures in the expansion chamber and we have already found about 20 cases of recoil atoms. About 4 of these show an abrupt fork end (and it is almost certain that one arm of this fork represents a recoil atom and the other some other particle, probably an α particle. They are disintegrations due to the capture of the neutron by N_{14} or O_{16}. I enclose two photographs

wax windows to visualize neutron



To amplifier and oscilloscope

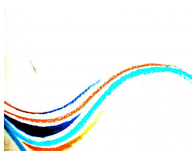
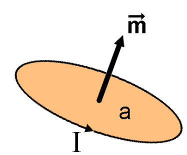
Neutron chamber

Ionization chamber

Why neutrons?

- Wavelengths comparable to interatomic spacings (1-5 Å)
- Energies comparable to structural and magnetic excitations (1-100 meV)
- Neutrons interact only weakly with matter/ non destructive – electrically neutral
- Neutrons are deeply penetrating (bulk samples can be studied)
- Neutrons are scattered with a strength that varies randomly from element to element (and isotope to isotope)

➔ *Neutron scattering is an ideal probe of magnetic, atomic structures and excitations*

Wave  Particle  Magnetic moment 

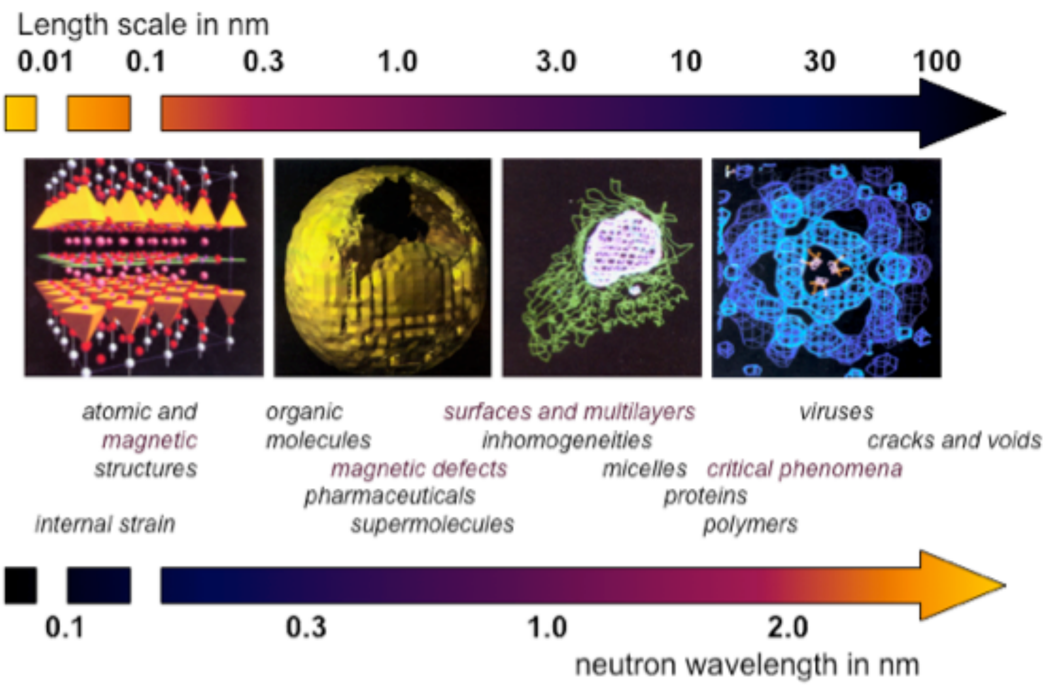
Neutral 

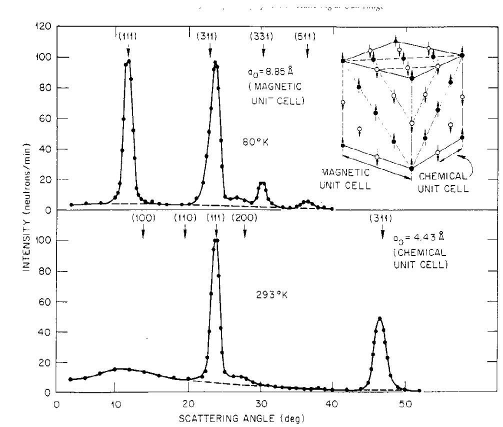
Neutron properties are used to understand the nature of the solid and liquid states of matter, as an analytical tool to aid the development of materials and as a tool to examine curiosity-driven research that spans from cosmology, superconductivity to the dynamics of the molecules of life.

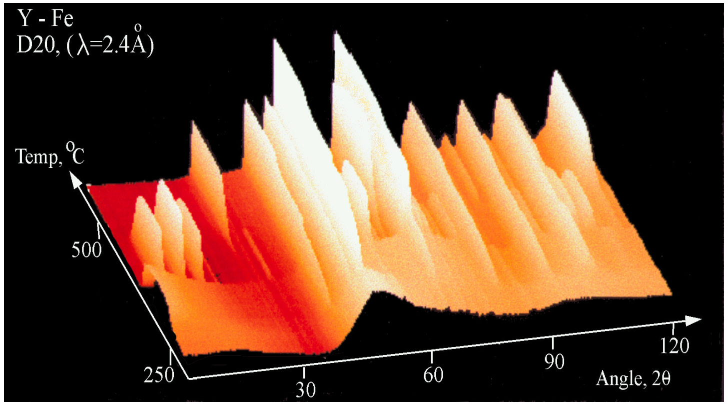
Neutron Microscope – Length scales – Diffraction

Showing where atoms are !

Wavelength of neutron ~ 0.01 to 100 nm
e.g. Use isotope sampling to measure diffraction/scattering
→ Space in molecule and atom
→ Position of atom







Nobel Prize 1994: Cliff Shull – Neutron diffraction

Neutron Microscope – Time and energy scales - Spectroscopy

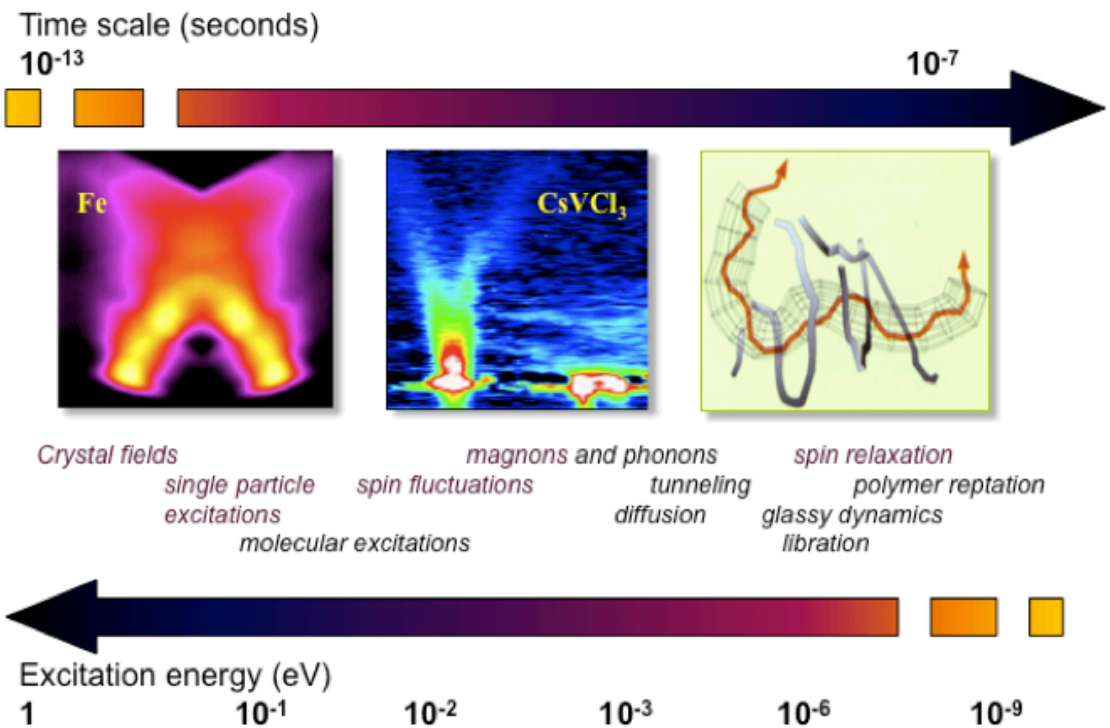
showing what atoms do !

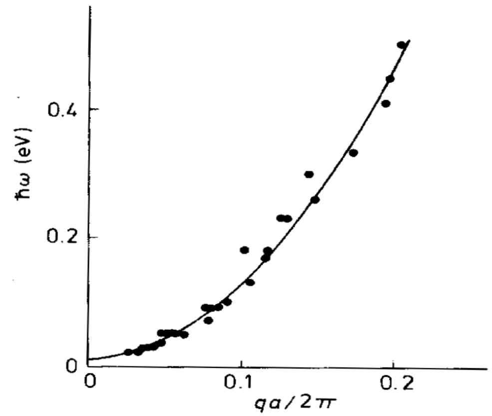
Energy of neutron ~ millielectronVolt

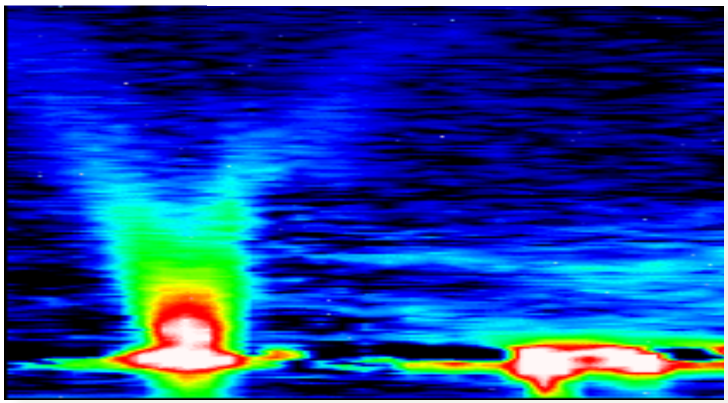
e.g. Use polarized neutron beam to probe magnetic moment change

→ Structure and excitation of electronic spins in magnetic materials

→ Motion of atoms and molecules in solids and liquids







Nobel Prize 1994: Bert Brockhouse – Spectroscopy

Neutrons Properties

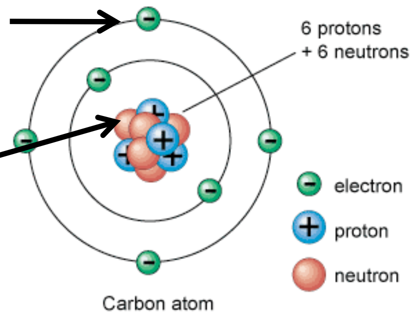
Neutrons are different things
to different people:

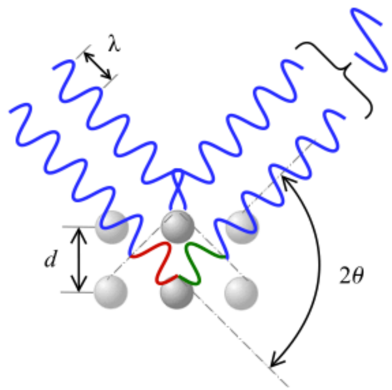
- HEP
- nuclear
- particle
- applied science

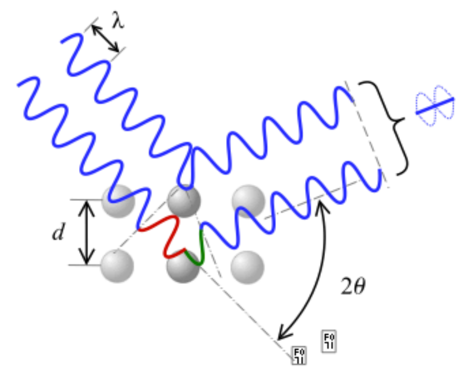
@ ESS: we use wavelength for scattering

Synchrotron X-rays

Neutrons

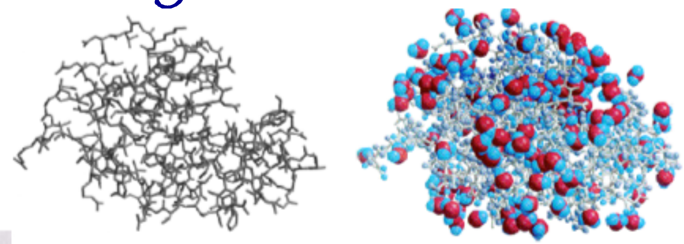


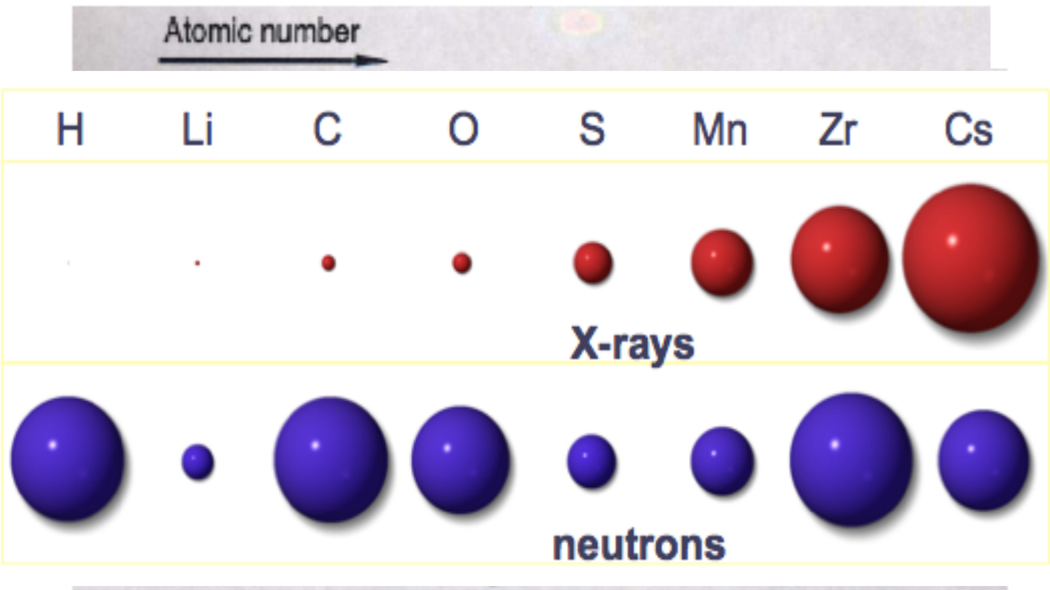




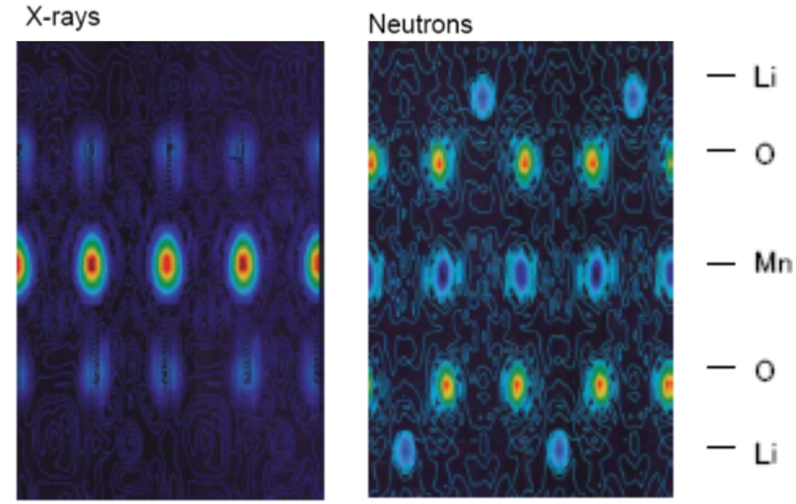
Mass	1.675×10^{-27} kg 939.57 MeV	$m_n \approx m_p + 2.5 m_e$
Mean lifetime	15 min	$n \longrightarrow p + e^- + \bar{\nu}_e$
Composition	udd	hadron
Electric charge	0	high penetration
Magnetic moment	$-1.04\,\mu_B$	feels the nucleus

Complementarity between X-rays and Neutrons





X-rays interact with electrons.
→ X-rays see high-Z atoms.
Neutrons interact with nuclei.
→ Neutrons see low-Z atoms.



Material for Li-battery seen by
X rays (left) and
Neutrons (right)

T. Kamiyama, et al.

Small Angle Neutron Scattering (SANS)

e.g. Selective Deuteration
sensitivity and selectivity by isotopic substitution/contrast variation

→ SANS gives the possibility of **not** seing everything at the same time....

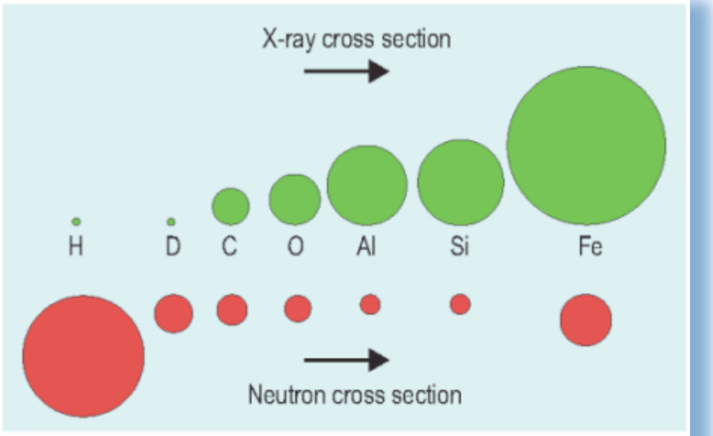
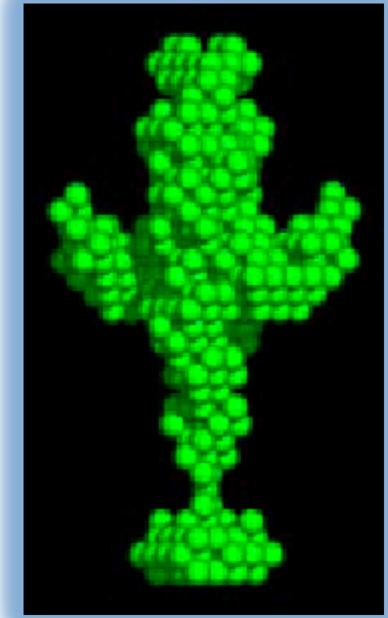


Fig. 2. Neutron and x-ray scattering cross-sections compared. Note that neutrons penetrate through Al much better than x rays do, yet are strongly scattered by hydrogen.



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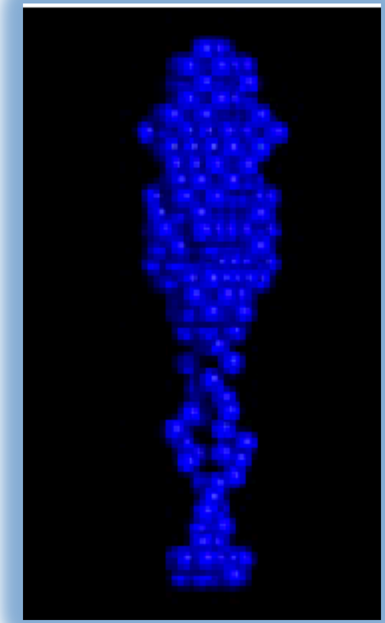

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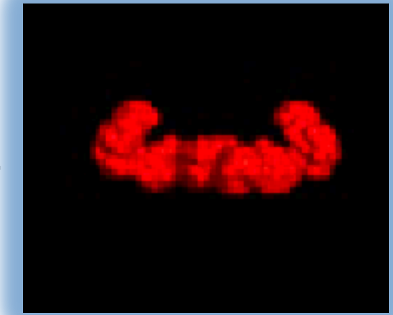

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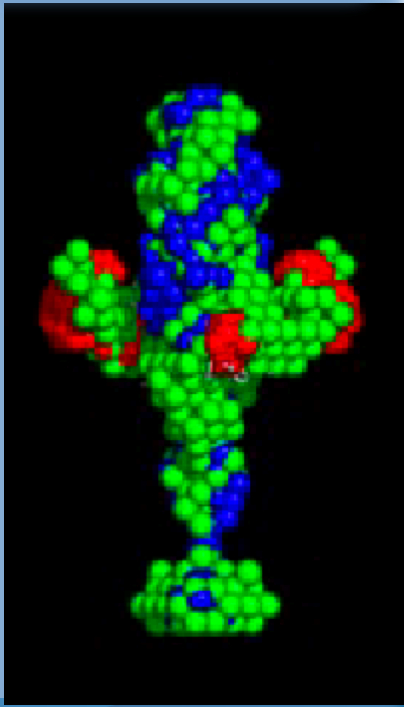
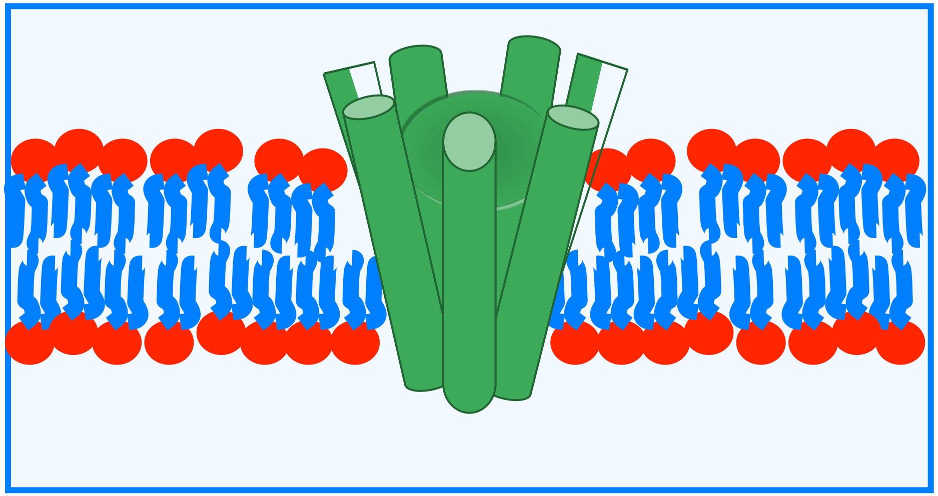
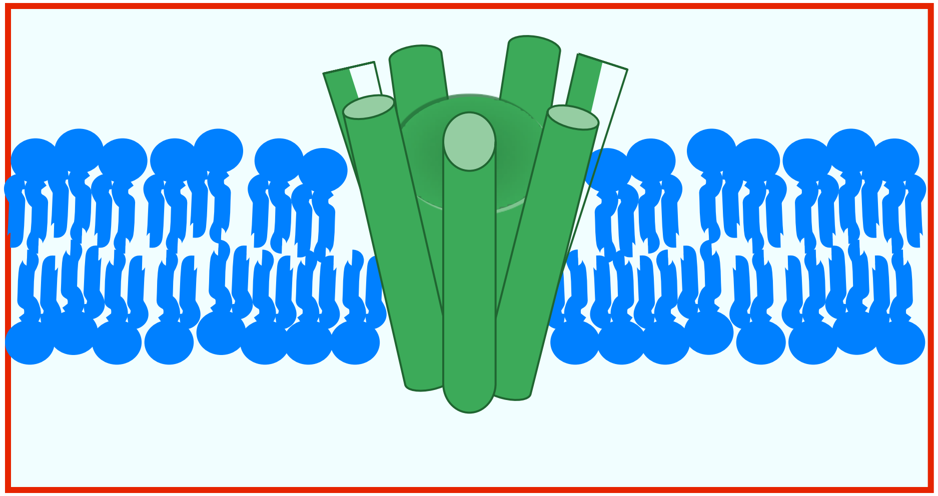


SANS versus SAXS

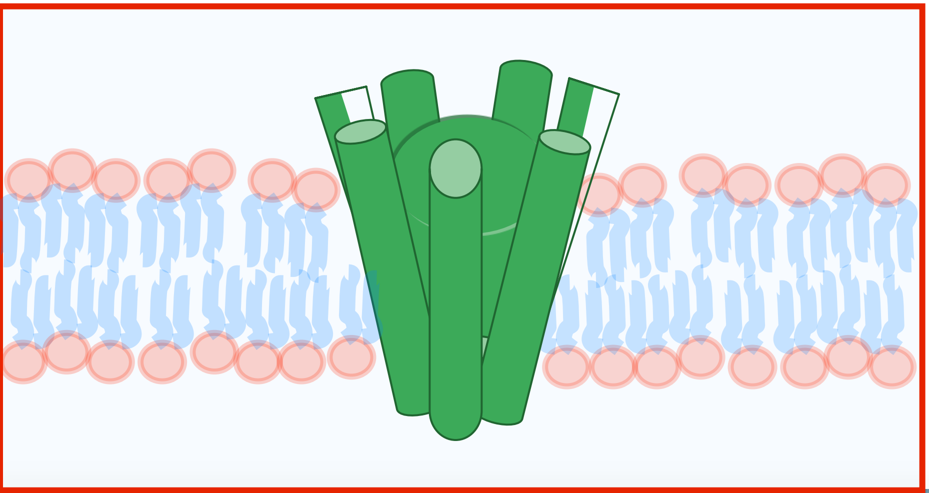
SAXS contrast



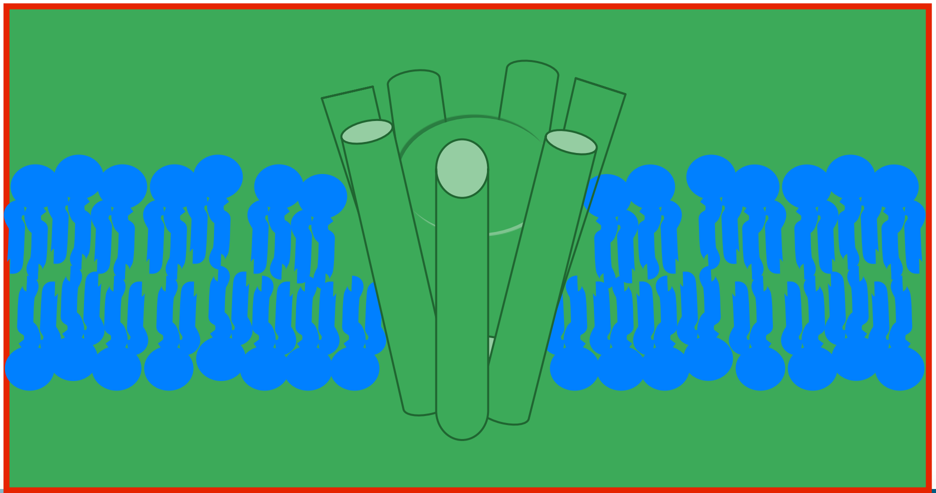
SANS contrast 1



SANS contrast 2



SANS contrast 3



Complementarity between X-rays and Neutrons

Neutrons	Synchrotron radiation
• Particle beam (neutral subatomic particle) • Interactions with the nuclei and the magnetic moment of unpaired electrons (in the sample) • Scattered by all elements, also the light ones like the hydrogen isotopes • Deep penetration depth (bulk studies of samples) • Less intense beam measuring larger samples	• Light beam (electromagnetic wave) • Interactions with the electrons surrounding the nuclei (in the sample) • Mainly scattered by heavy elements • Small penetration depth (surface studies of samples) • Very intense beam measuring small or ultra-dilute samples

Neutrons Applications	SR Applications
• Magnetic structures & excitations • Organic structures using the H-D isotope effect • Bulk studies (strains, excitations) • Low-energy spectroscopy e.g. molecular vibrations	• Protein-crystal structures • Fast chemical reactions • Surface studies (defects, corrosion) • High-energy spectroscopy e.g. measurements of electron energy-levels

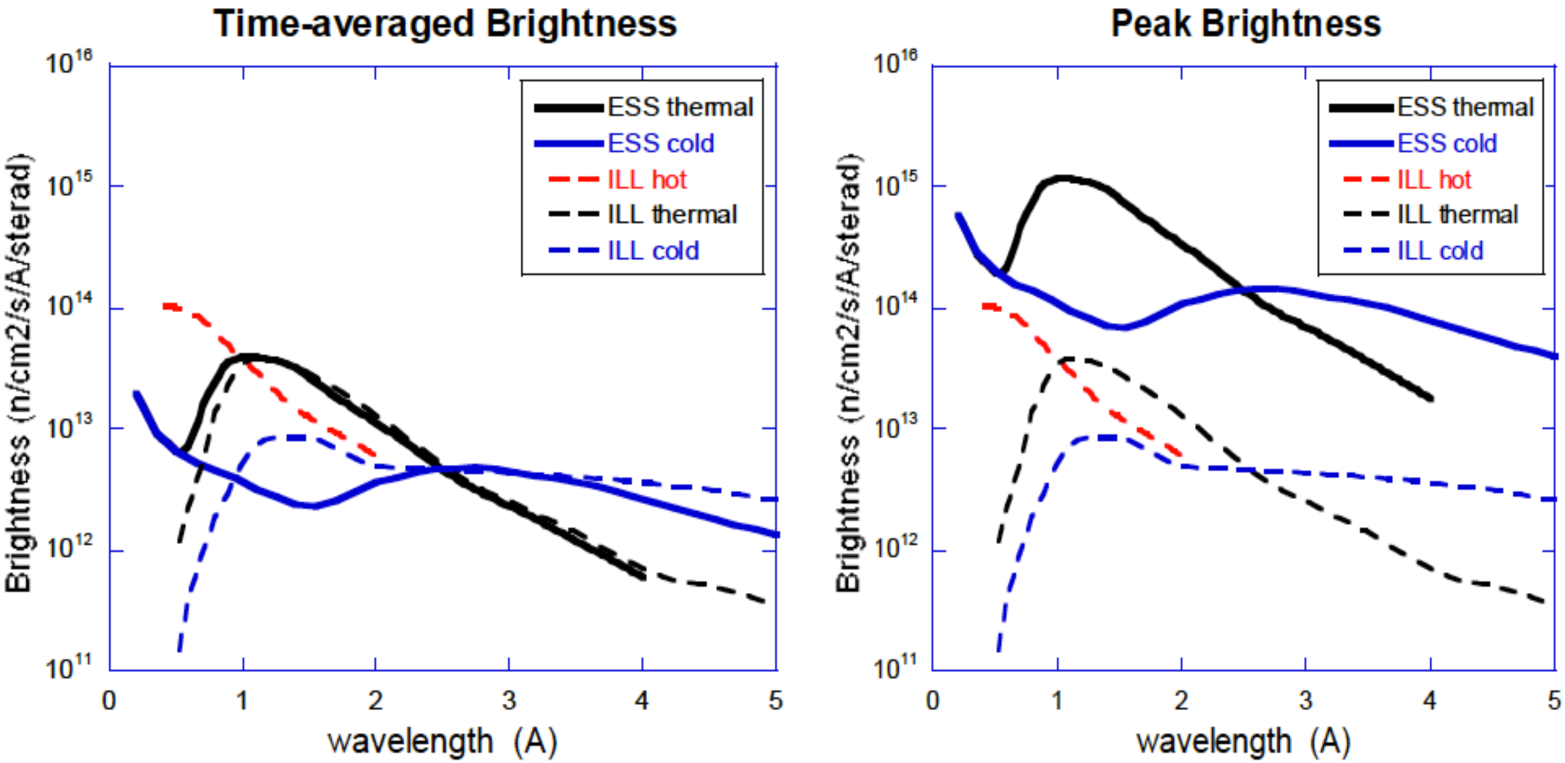
ESS and MAX IV

EUROPEAN
SPALLATION
SOURCE

MAX IV

Evolution of the performance of neutron sources

ESS

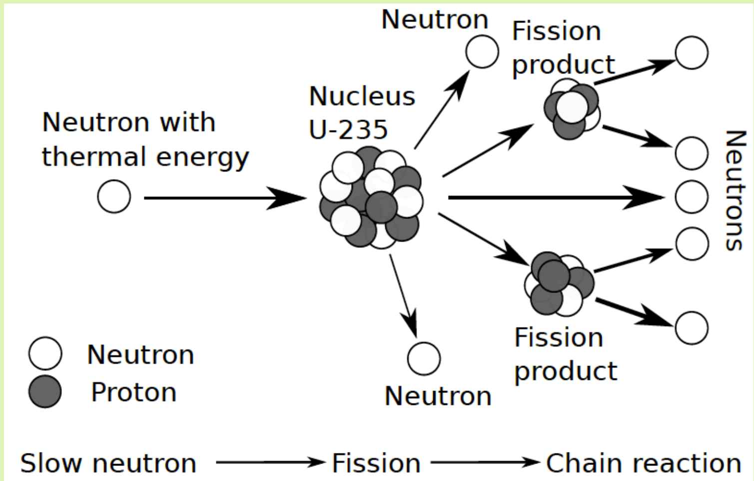


"Report from the ILL Associates' Working Group on Neutrons in Europe for 2025"

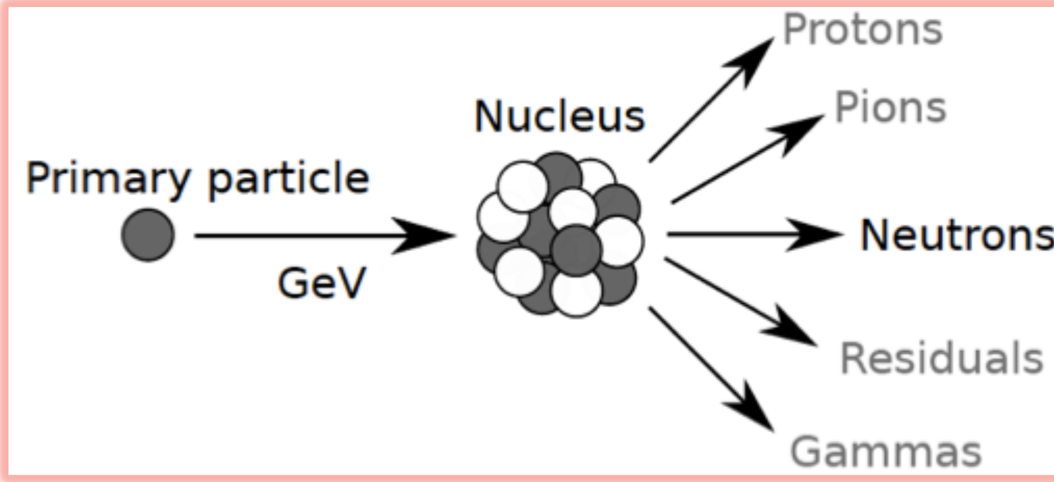
Figure 5 (a, left): Time-averaged brightness for neutrons produced at ILL through cold, thermal and hot moderators, and for ESS (5 MW, 16 2/3 Hz, 2ms pulse length) from thermal and cold moderators. (**b, right**): Peak brightness for the same cases.

ESS target and the spallation process

Recall: Fission and Spallation



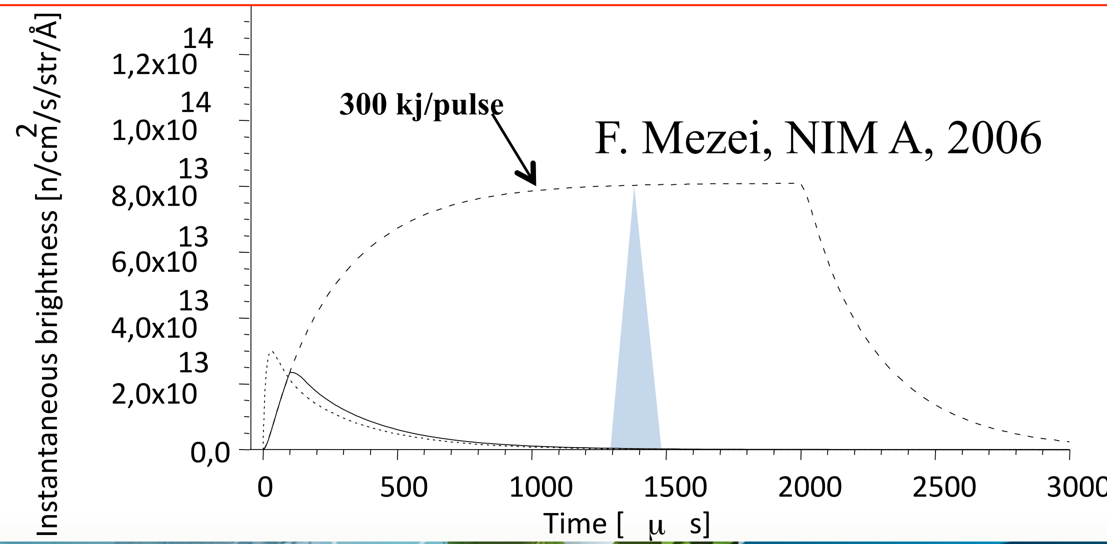
Spallation is a non-elastic nuclear interaction induced by a high-energy particle producing numerous secondary particles



Process	Reaction	Neutron yield	Energy deposition
Fission	$^{235}U(n,f)$	3 n/fission	190 MeV/n
Spallation	p 1 GeV $\rightarrow$ Hg	30 n/proton	55 MeV/n

Long Pulse and cold neutrons

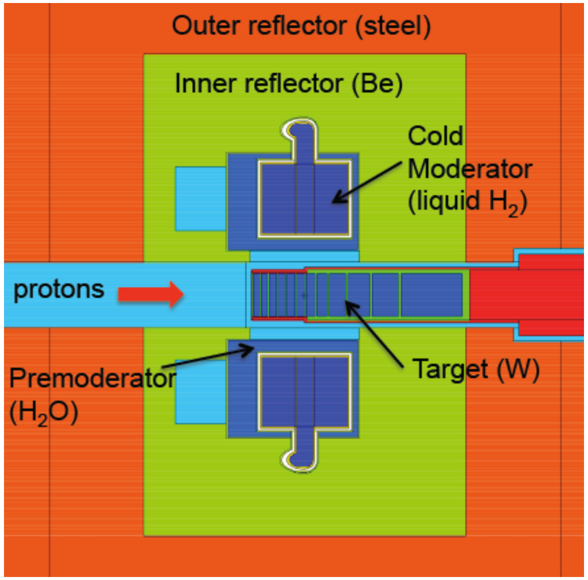
- Many research reactors in Europe are aging and will be closed before 2020
  - Up to 90% of the use is with cold neutrons
- There is a urgent need for a new high flux cold neutron source in Europe
  - The vast majority of users will profit from a pulsed structure
  - A large fraction of users are fully satisfied by a long pulse source
  - Existing short pulse sources (ISIS, JPARC and SNS) can supply the present and imminent future need of short pulse users
- Long pulse for physics flexibility (cold and thermal neutrons available)

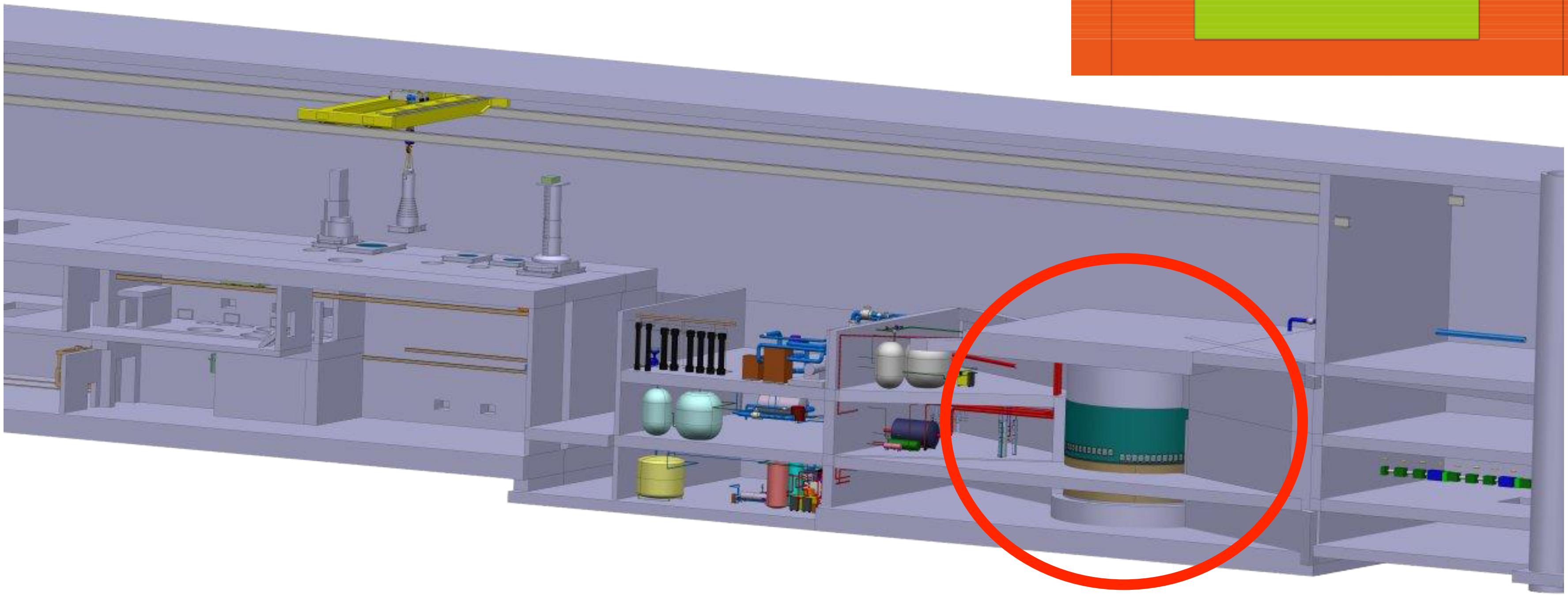


"Pulsed cold neutrons will always be long pulsed as a result of the moderation process"

Target station layout

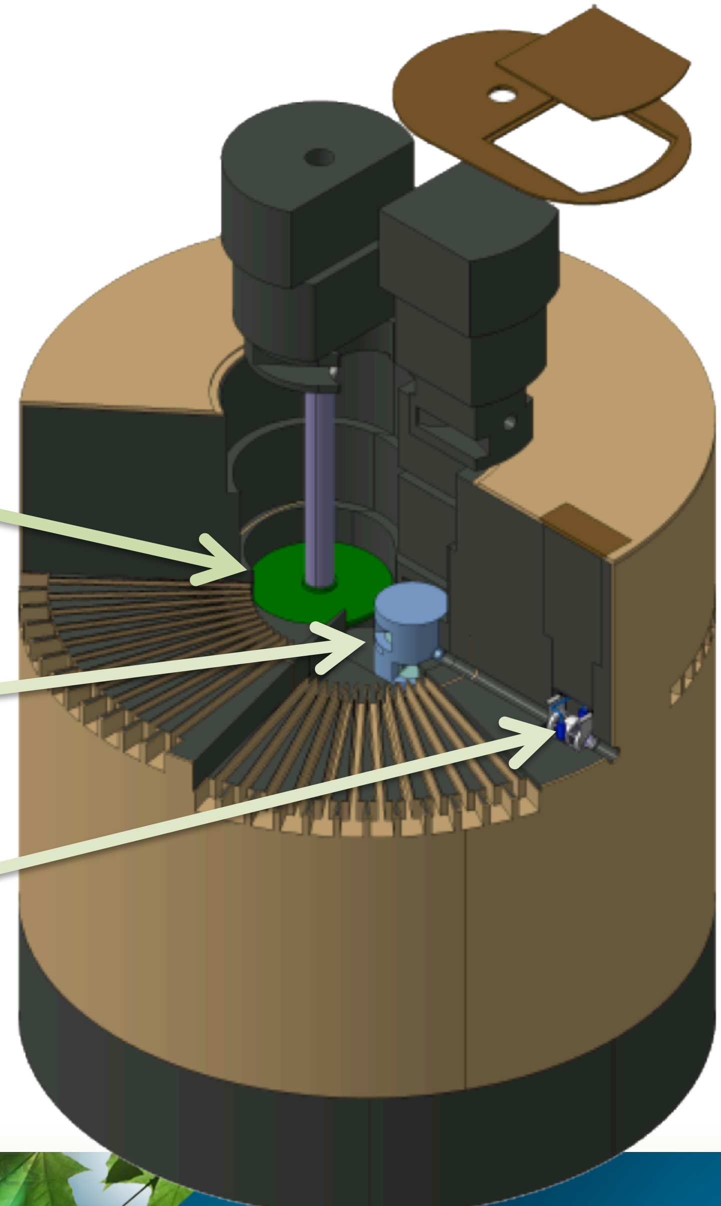
Handling procedures
Handling of active components
Redundancy of systems: 3 safety barriers



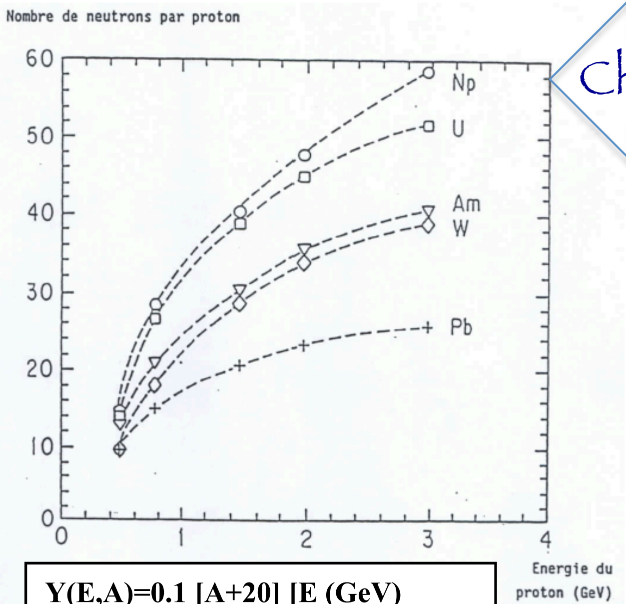


Target monolith

- "The source" of the neutrons
- Target wheel
  - 7 t, replaced ~ every 5 years
- Moderator-reflector plug (shown in position ready for vertical extraction)
  - 10 t, replaced every year
- Accelerator proton beam window

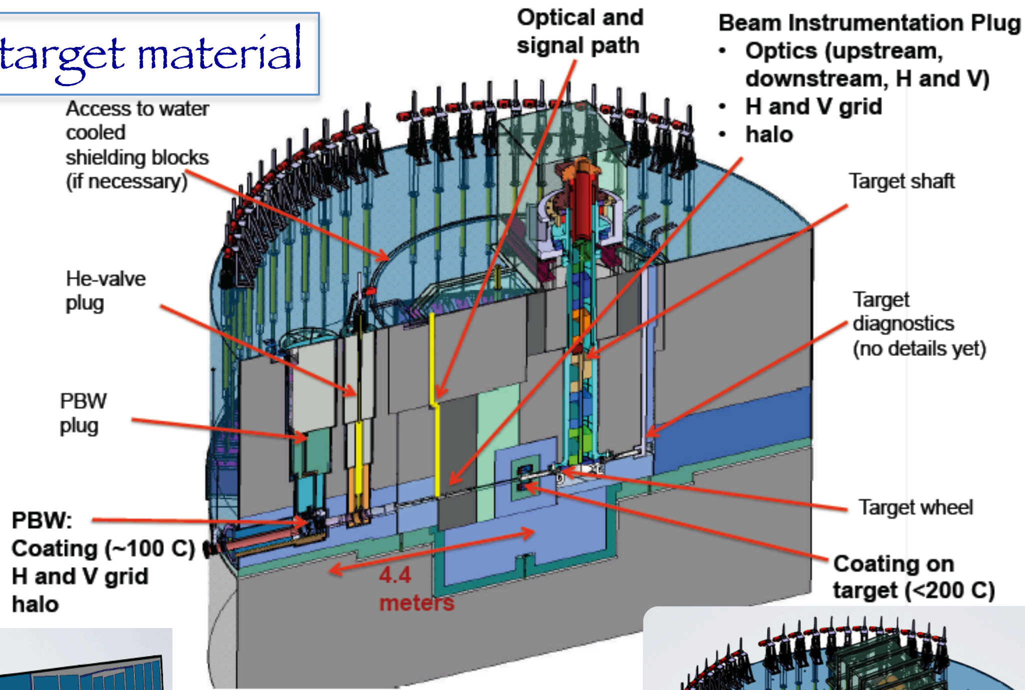


Target and Neutron guides

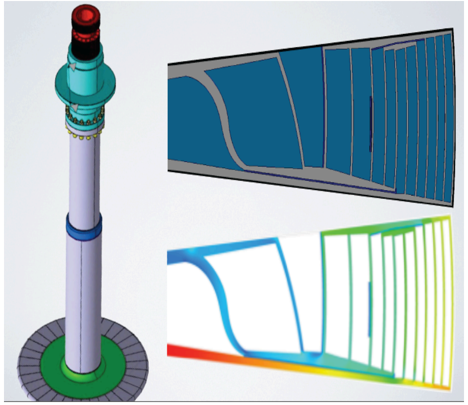


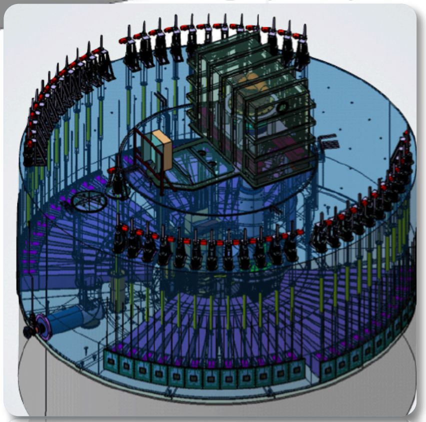
Y(E,A)=0.1 [A+20] [E (GeV) -0.12)] n/p

Choice of target material



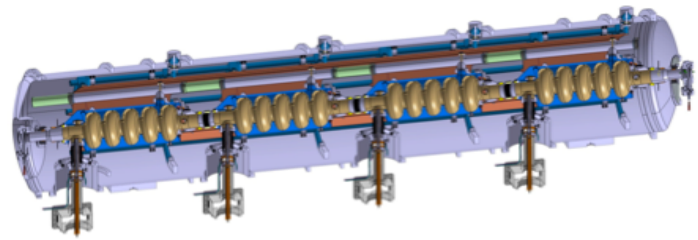
Rotating target





The ESS Accelerator

The ESS accelerator



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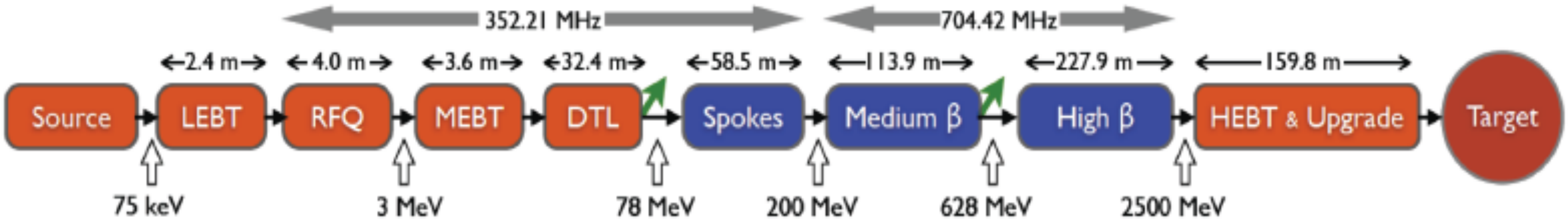


- Normal conducting / Italia-Denmark-Spain
  - Microwave Discharge Ion Source (MDIS-ECR)
  - Radio-frequency quadruple (RFQ)
  - Drift Tube Linac
  - Beam transport section
- Superconducting / France
  - Double spoke resonators
  - Elliptical cavities (medium beta and high beta)

ESS beam parameters		
Beam current	I_b	50 mA
Pulse length	σ_p	$2.83*10^{-3}$ s
Pulse period	T_p	1/14 s
Number of bunches per pulse	N	$1.01*10^{6}$
Bunch frequency	F_b	352.21 MHz
Bunch period	T_b	$2.84*10^{-9}$ s
Charge per bunch	q_b	$1,42*10^{-10}$ C

ESS Accelerator as a team work

2016 2017 2018 2019 2020 2021 2022
Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1
First Access to Upgrade space (test stand)(g)
Beam Liscense available (g)
Cryo-plant buildings for test stand ready (g)
Full Access to Accelerator Building (Gallery and tunnel) (g)
Target Building access (g)
Target Cryoplant comissioned (g)
Normal conducting beam commissioning starts
80MeV protons available
Super conducting beam commissioning starts
Medium Beta systems ready
Spoke systems ready
630 MeV Protons available
High Beta systems ready
First Proton to Target (g)
End of Construction ACCSYS

Operation phase

Now entering in
Construction phase (2013-2025)

Accelerator Design Upgrade
ADU WP (2010-2012)


Romuald Duperrier
(30 years ago)


Steve Peggs


Cristina Oyon


David McGinnis


Pierre Bosland

Work Package (work areas)

1. Management Coordination – ESS AB (Mats Lindroos)
2. Accelerator Science – ESS AB (Steve Peggs)
(3. Infrastructure Services – now ESS AB!)
4. SCRF Spoke cavities – IPN, Orsay (Sebastien Bousson)
5. SCRF Elliptical cavities – CEA, Saclay (Guillaume Devanz)
6. Front End and NC linac – INFN, Catania (Santo Gammino)
7. Beam transport, NC magnets and Power Supplies – Århus University (Søren Pape-Møller)
8. RF Systems – ESS AB (Dave McGinnis)
19. P2B: Test stands – Uppsala University (Roger Ruber)


Mats Lindroos


Guillaume Devanz

CEA - Saclay


Roger Ruber

UPPSALA UNIVERSITET


Søren Pape Møller


Santo Gammino


Sebastien Bou

ORSAY

Proton source

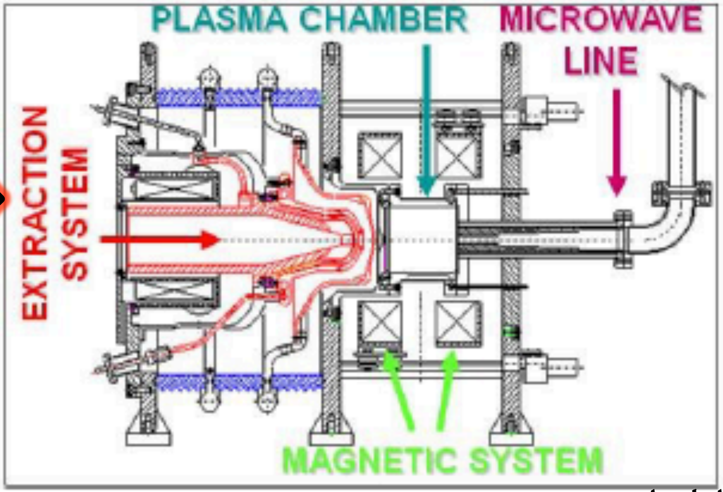
Based on knowledge acquired with TRIPS, SILHI and VIS high intensity proton sources

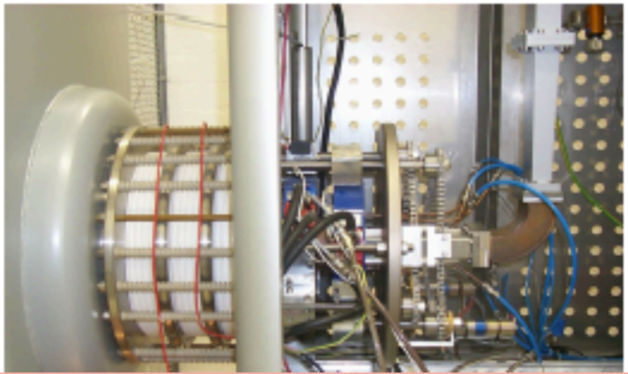
→ See TRASCO Program

	Status
Beam energy	80 keV
Proton current	55 mA
Proton fraction	≈80%
RF power, Frequency	Up to 1 kW @ 2.45 GHz
Axial magnetic field	875-1000 G
Duty factor	100% (dc)
Extraction aperture	6 mm
Reliability	99.8% @ 35mA (over 142 h)
Beam emittance at RFQ entrance	0.07πmmmrad @ 32 mA

TRIPS

courtesy Santo Gammino



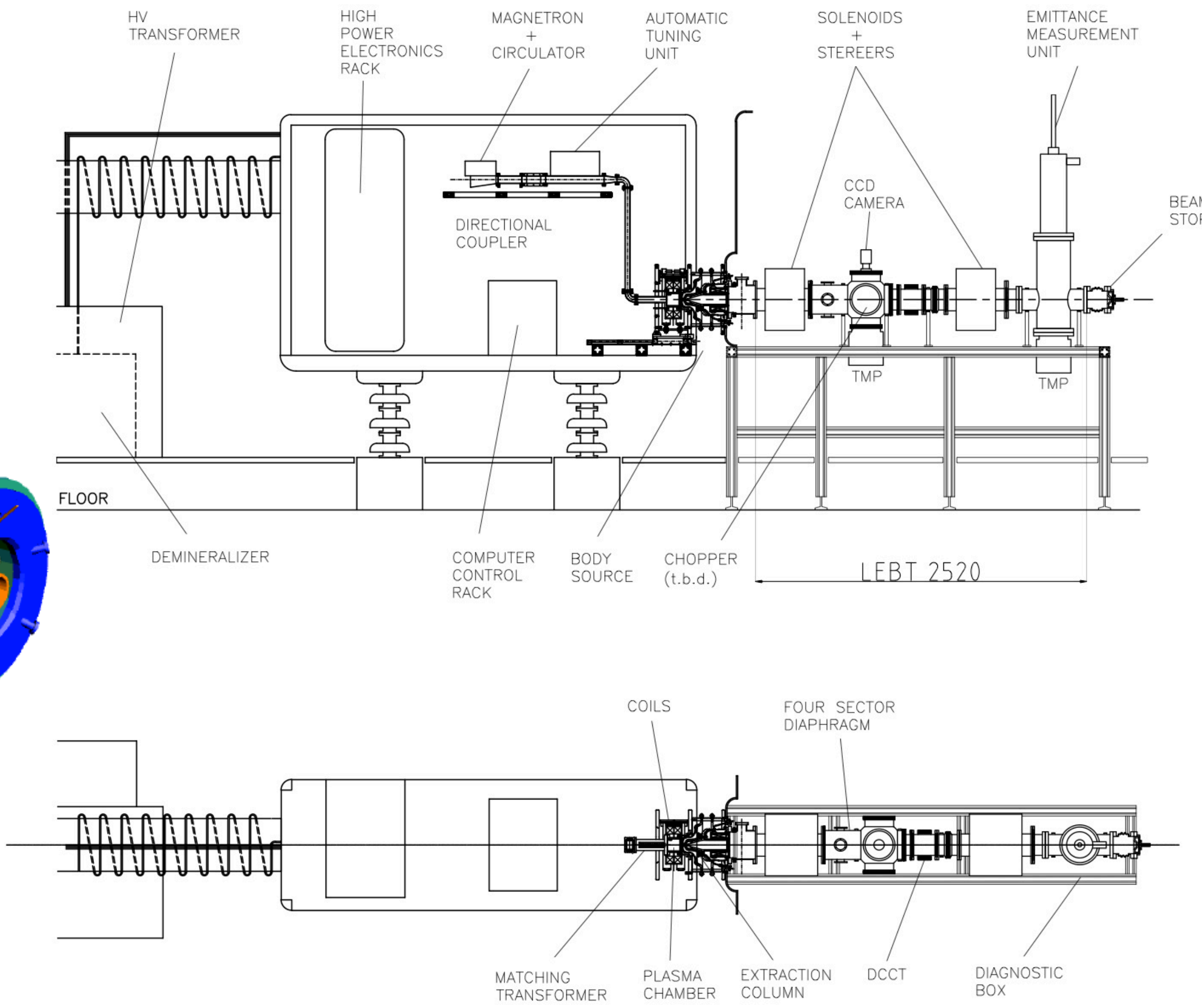


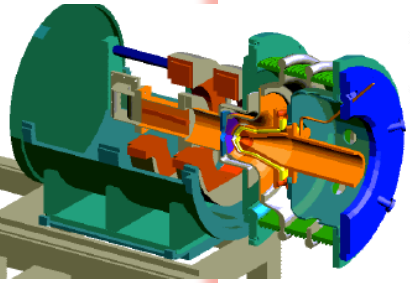
Electron Cyclotron Resonance (ECR) source reliable in term of current stability and availability

- **Movable magnetic system composed by two solenoids**
- **Five electrodes extraction system**

Prototype proton ion source operational (and under further development) in Catania

Proton source & LEBT



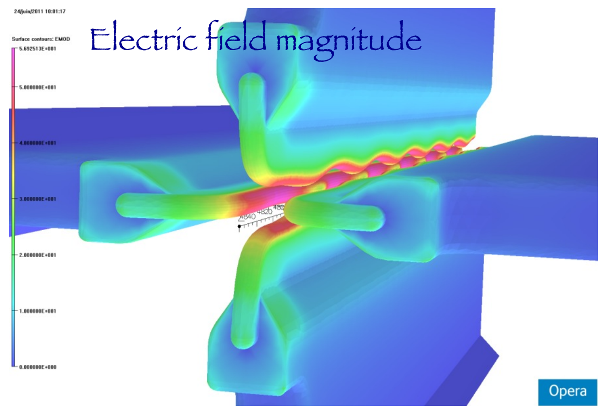


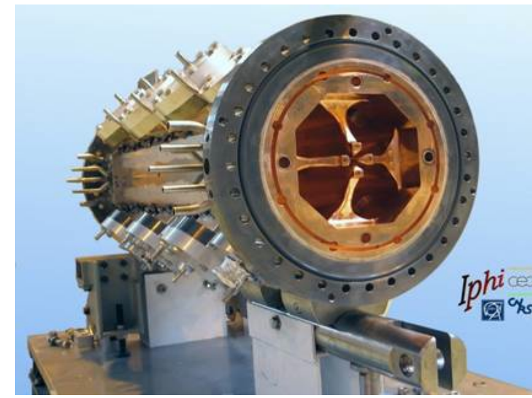
SILHI operates at 2.45 or 3 GHz! ECR zone at RF entrance~600~

Radio-Frequency Quadrupole

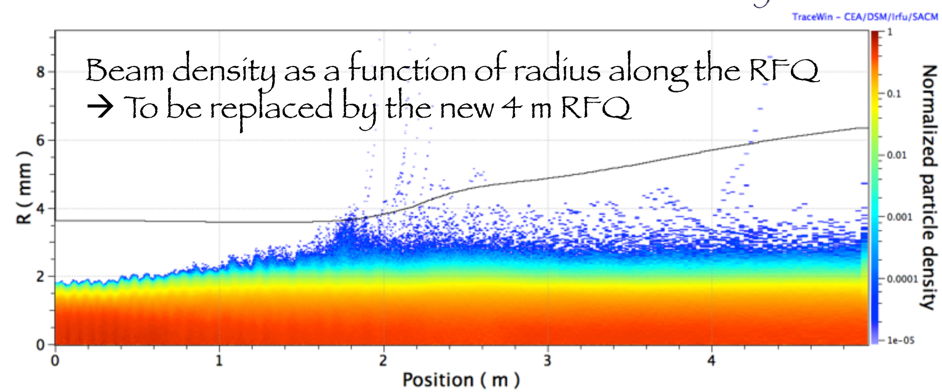
→ Structure to bunch and accelerate the beam of charged particles

→ Involve in determining the quality of the beam (high intensity and low emittance grown requested)





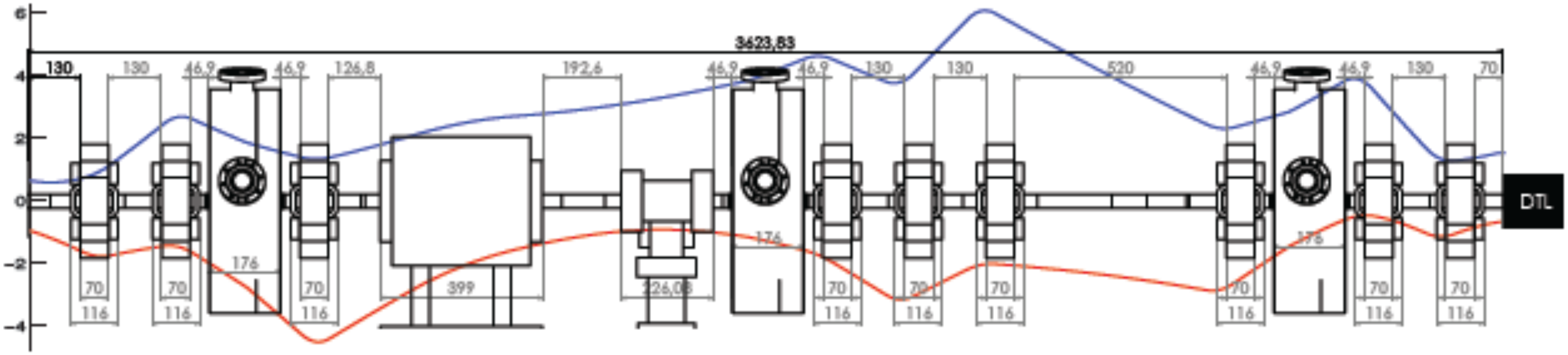
IPHI RFQ at CEA-Saclay



- RFQ tests for ESS conditions to be performed at CEA, in close collaboration with INFN-LNL

Medium-Energy Beam Transport – Spain

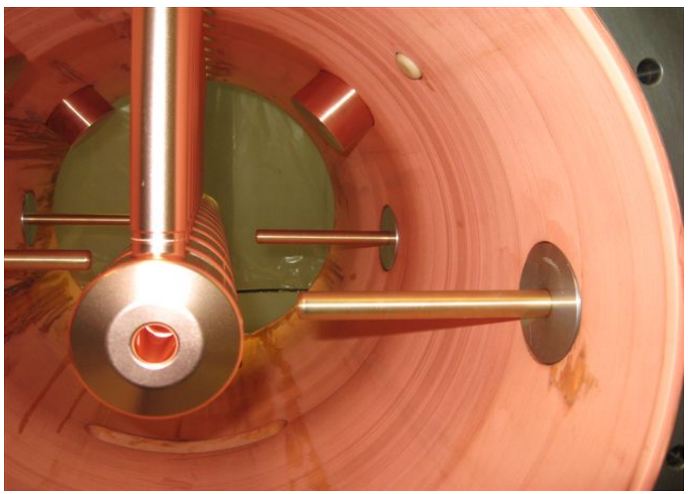
→ Beam transport to match to DTL parameters



Layout of the MEBT includes:
- Fast Chopping
- Collimator
- Beam Instrumentation
- 10 quadrupoles
- 2 buncher cavities

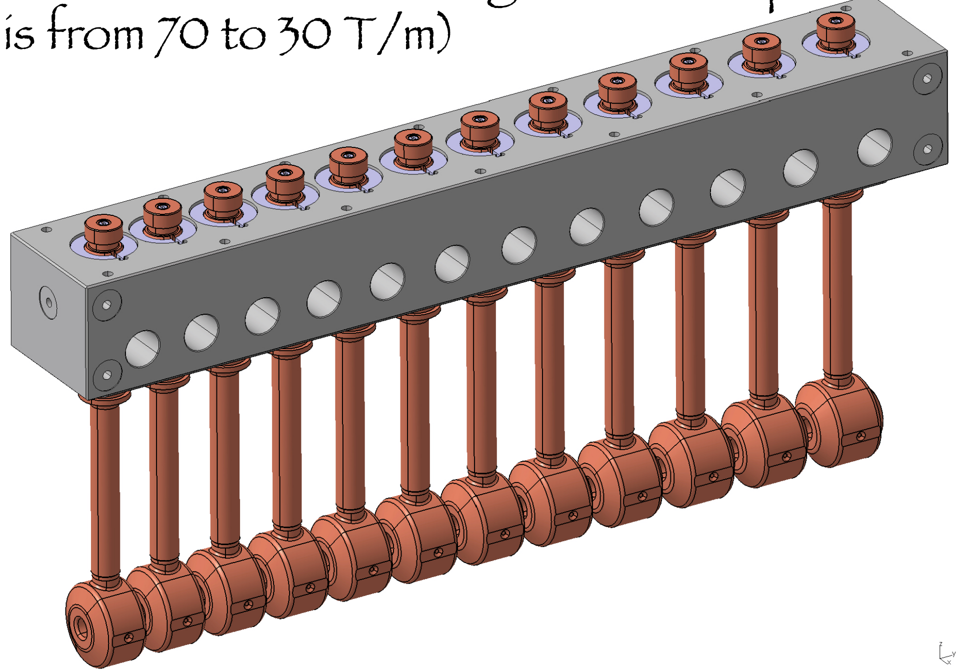
Parameter	Unit	Value
Input energy	MeV	3
Input speed, β		0.0798
Total Current	mA	50
Particle		protons (H^+)
Number of quadrupoles		10
Minimum quadrupole gradient	T/m	9
Maximum quadrupole gradient	T/m	30
Number of *buncher* cavities		3
Frequency	MHz	352.21
Peak power per cavity	kW	14
Effective Voltage, E_oTL	kV	150

Drift Tube Linac - Italia



→ to accelerate H^+ from 3 to 80 MeV at 352.21 MHz, with a duty cycle of 4%

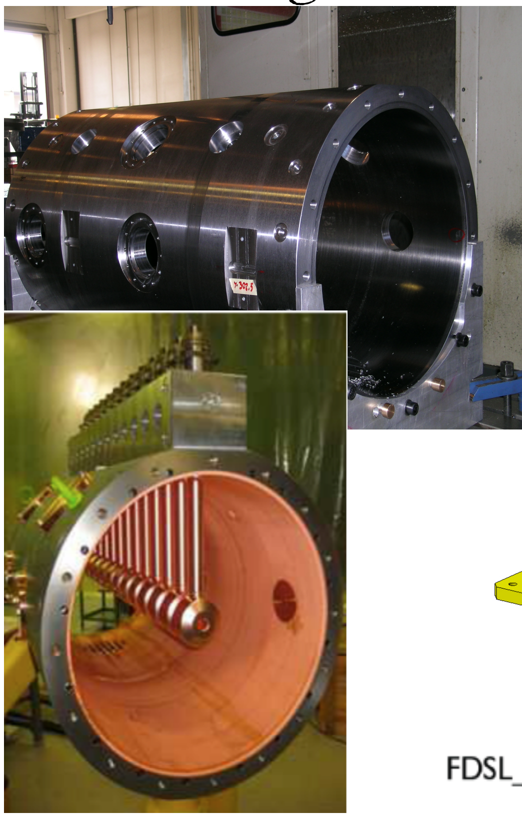
- The DTL esign is based on the mechanical design and prototyping of CERN Linac4, involving design work at ESS and in Legnaro
- Four tanks with Permanent Magnet Quadrupole (range is from 70 to 30 T/m)

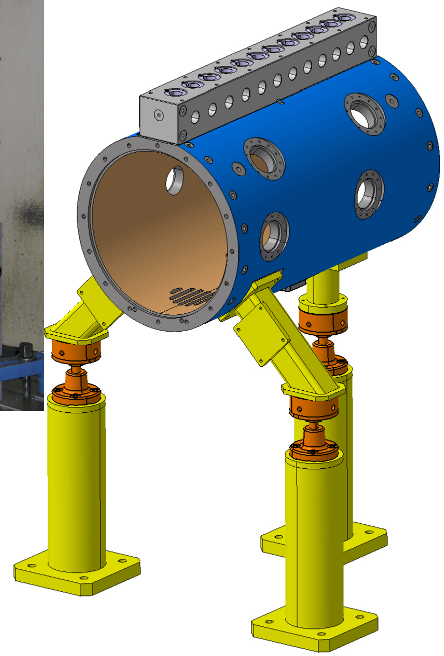


Tank machining at Cinel (Vigonza-Italy)

Drift Tube Linac as link to the superconducting Linac

Tank machining at Cinel (Vigonza-Italy)





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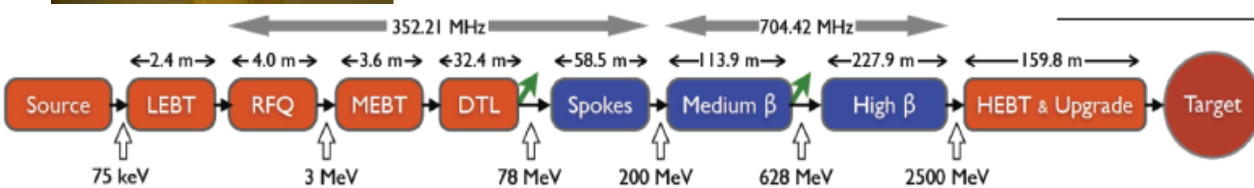
Main LINAC parameters for NC and SRF

Parameter	Unit	Device	Value
Length	m	LEBT	2.4
		RFQ	4.0
		MEBT	3.6
		DTL	32.4
		Spokes	58.5
		Medium-β	113.9
		High-β	227.9
Number of cryomodules		Spokes	14
		Medium-β	15
		High-β	30
Cavities per cryomodule		Spokes	2
		Medium-β	4
		High-β	4
Optimal β		Spokes	0.50
Geometric β		Medium-β	0.67
		High-β	0.92
Transition energy	MeV	Source–RFQ	0.075
		RFQ–DTL	3
		DTL–Spokes	78
		Spokes–medium-β	200
		Medium–high-β	628

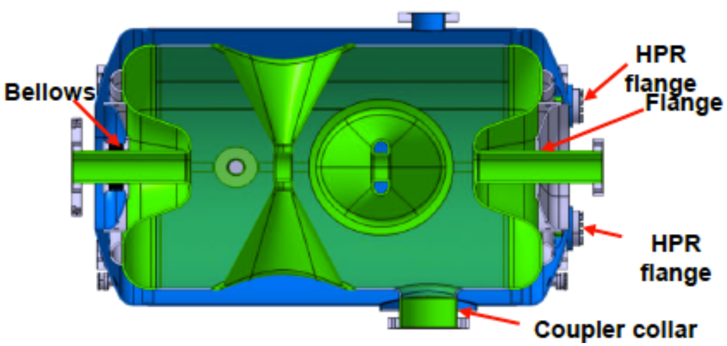


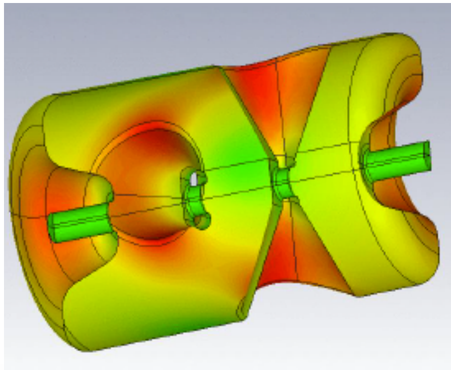
Spoke cryomodules – IPN Orsay/CNRS

→ First accelerator to integrate spoke cavities

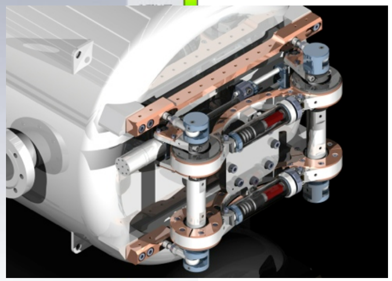
- Naturally stiff (less sensitive to mechanical perturbation such as vibrations)
- Exhibit high cell to cell coupling (no field flatness required, less sensitive to HOM or trapped modes)
- Not susceptible to dipole steering effect
- High longitudinal acceptance (accelerating efficiency over a wide range)

DOUBLE-SPOKE CAVITY SPECIFICATIONS	
Beam mode	Pulsed (4% duty cycle)
Frequency [MHz]	352.2
Beta_optimal	0.50
Temperature (K)	2
Bpk [mT]	70 (max)
Epk [MV/m]	35 (max)
Gradient Eacc [MV/m]	8
Lacc (=beta optimal x nb of gaps x λ /2) [m]	0.639
Bpk/Eacc [mT/MV/m]	< 8.75
Epk/Eacc	< 4.38
Beam tube diameter [mm]	50 (min)
P max [kW]	300 (max)



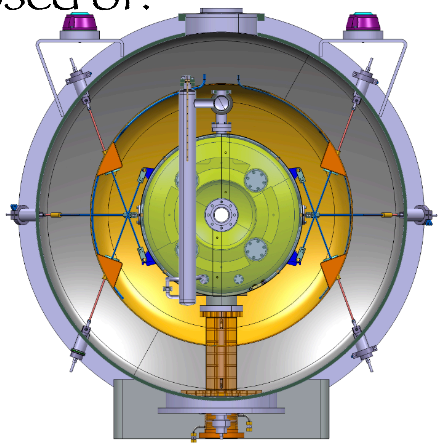


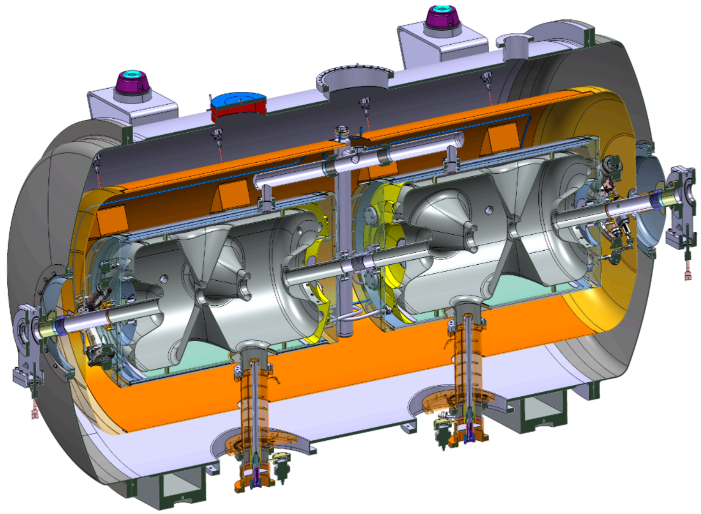
Eurisol coupler and cold tuning system

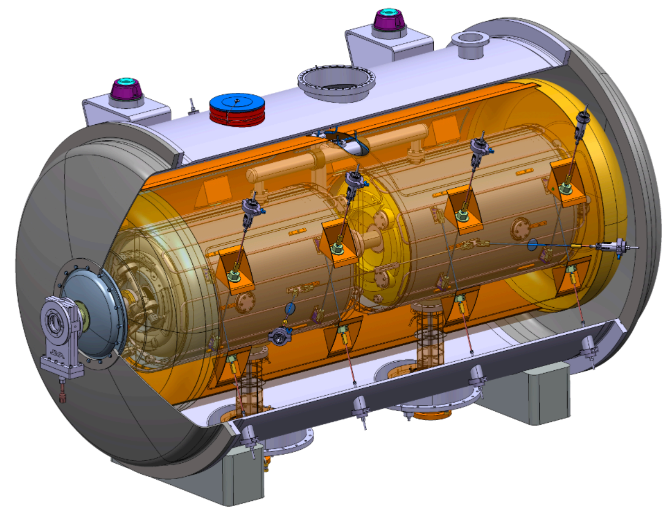


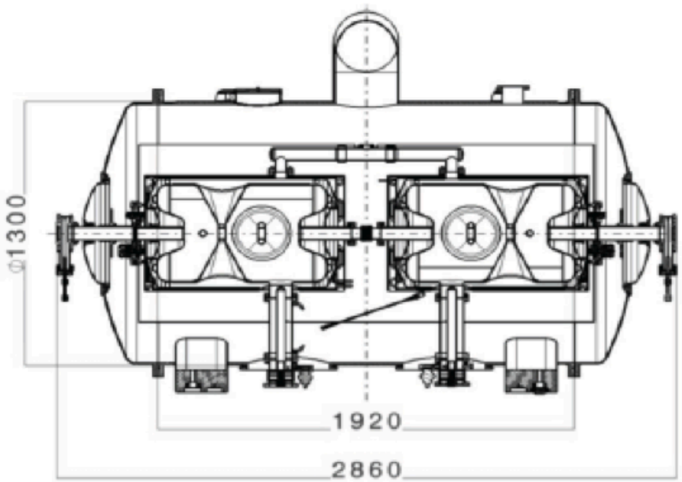
Spoke cryomodules - IPNO

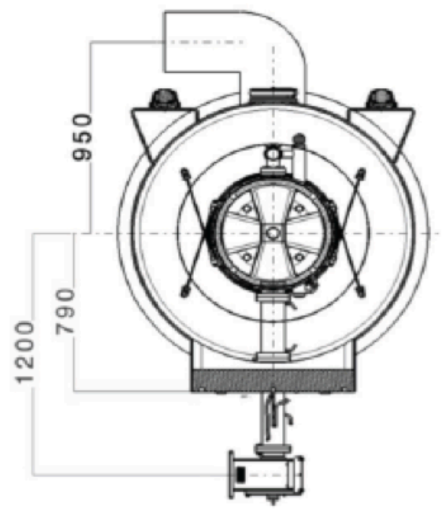
→ Cryomodule is mainly composed of:
- 2 SRF spokes cavities
- 2 power couplers
- 2 cold tuning systems
- Supporting system
- Thermal shielding
- Magnetic shielding



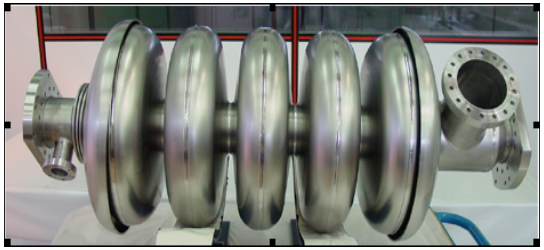




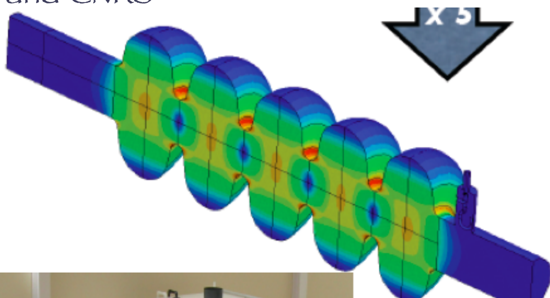


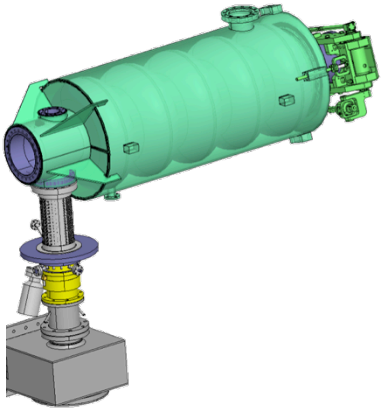


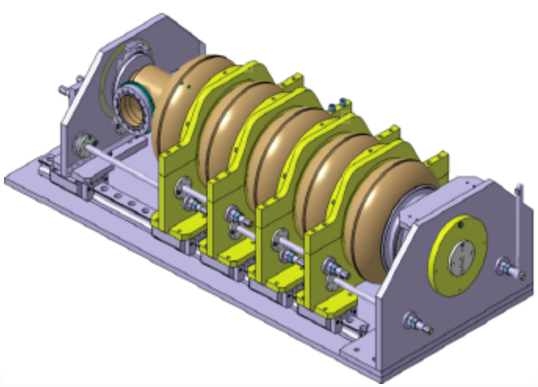
Elliptical Cryomodules – CEA



SC 5 cell cavity for 704 MHz, CEA and CNRS

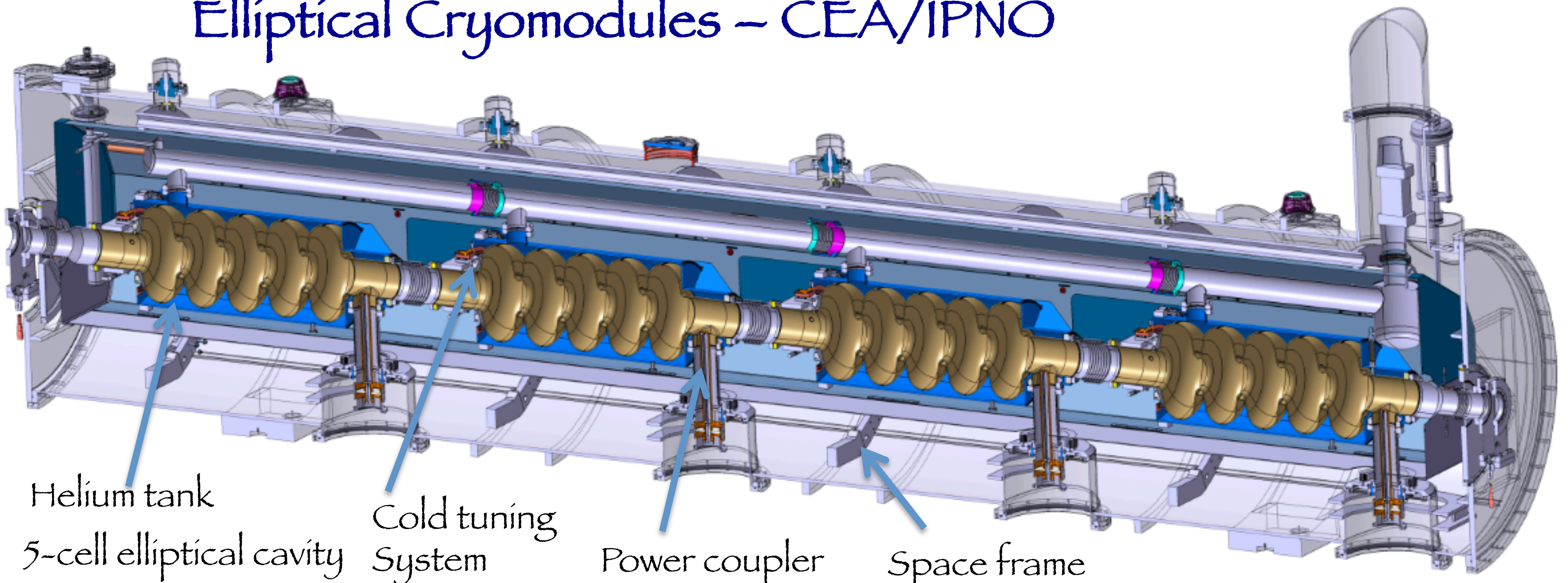






Parameter	Unit	Value
RF frequency	MHz	704.42
Temperature	K	2
MEDIUM-BETA		
Output energy	MeV	654
Number of cells per cavity		5
Geometric beta		0.67
Cavity length	m	1.145
Expected gradient, horizontal	MV/m	15
Expected gradient, vertical test	MV/m	17
Cavity Q_0		6×10^9
Fundamental mode Q_{ext}		6.8×10^5
Fundamental mode R/Q	W	340
Average heat load at nominal gradient	W	5.9
Power coupler power forward power	MW	1.2
Maximum Power transmitted to beam	MW	0.6
HIGH-BETA		
Output energy	MeV	2500
Number of cells per cavity		5
Geometric	beta	0.9
Cavity length	m	1.356
Nominal gradient in the linac	MV/m	18
Expected gradient, vertical test	MV/m	20
Geometric beta prototype		0.86
Optimum beta prototype		0.92
Cavity length prototype	m	1.315
Fundamental mode R/Q prototype	W	477
Fundamental mode Q_{ext} prototype		7.1×10^5
Cavity Q_0 at nominal gradient, prototype		6.0×10^9
Average heat load at nominal gradient, prototype	W	4.5
Power coupler power rating	MW	2
Power coupler forward power	MW	1.2
Maximum power transmitted to beam	MW	0.9
Cell to cell coupling	%	1.8
Epk/Eacc		2.2
Bpk/Eacc	mT/(MV/m)	4.3
Separation between π and $4\pi/5$ modes	MHz	1.2
Iris diameter	mm	120

Elliptical Cryomodules – CEA/IPNO



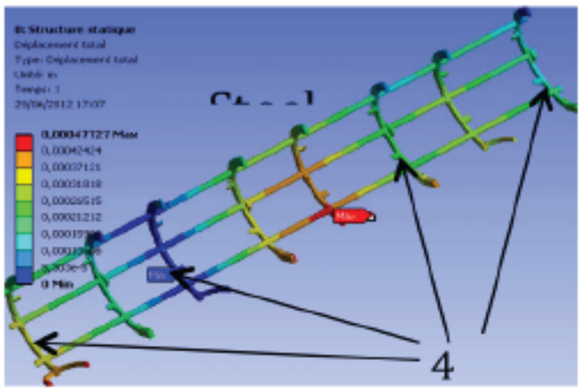
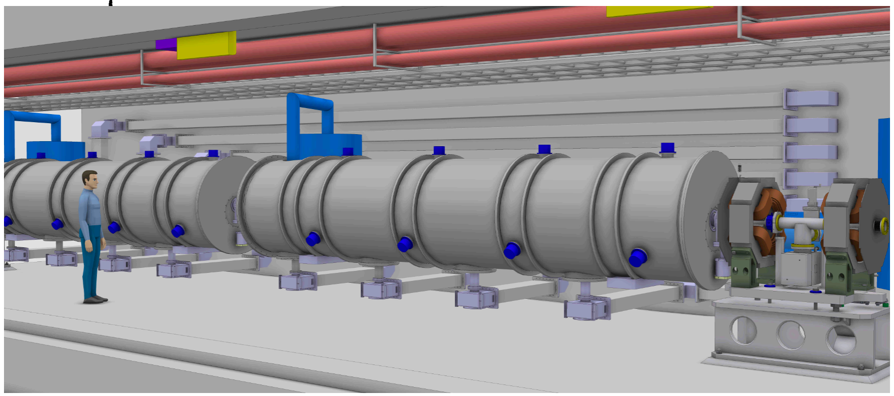


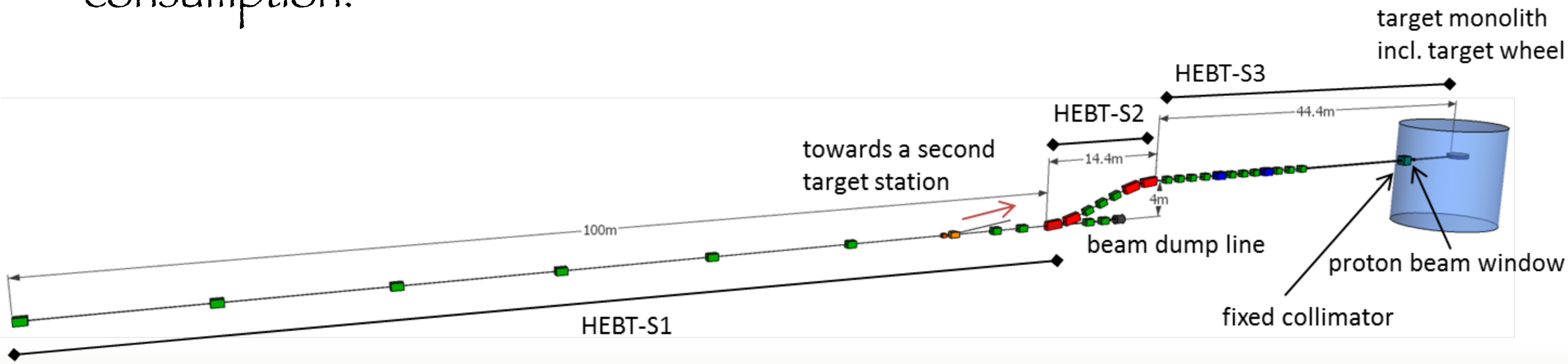
Figure 4.120: Helium vessel with hanging rod

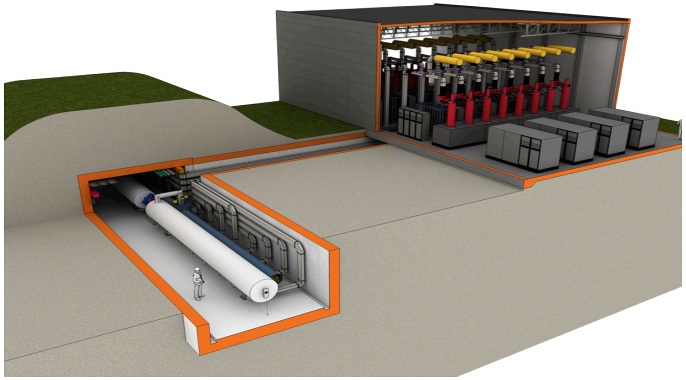


→ Elliptical Cavities Cryomodule Technology Demonstrator results by the end of 2015

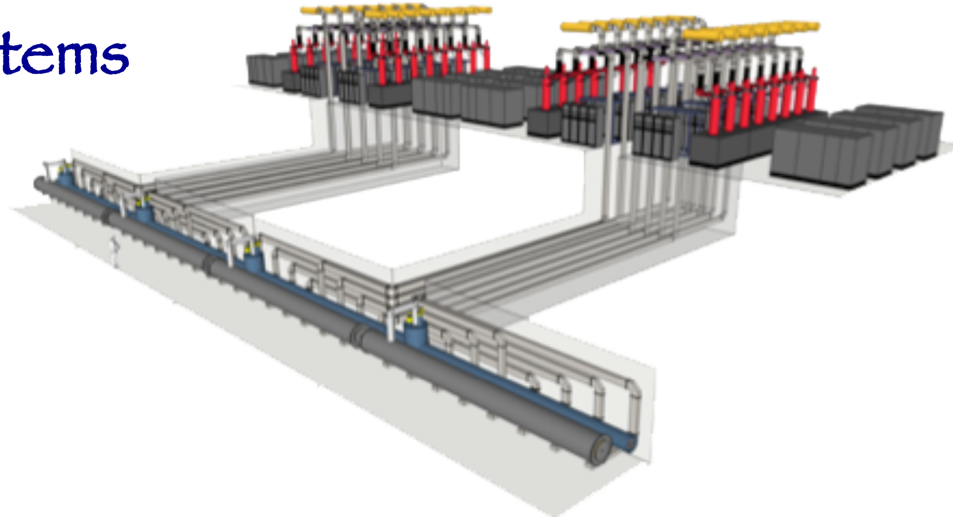
HEBT, magnets and power supplies

- Several optical designs of the High Energy Beam Transport system have been developed during the evolvement of the ADU project.
- The present design fulfill the requirements including layout geometry and the 6 × 16cm² beam footprint on target with a sufficiently low maximum current density to ensure a long target lifetime.
- The technologies to be used for building the magnets and power supplies have been studied including aspects of handling and optimization of power consumption.





RF systems



Main Features

- One RF power source per resonator
- RF Sources
  - Pulsed cathode klystrons for elliptical, DTL, and RFQ
  - Gridded tube for spokes (IOTs)
- Two klystrons per modulator for high beta elliptical and four klystrons per modulator for medium beta elliptical
- 30% overhead for RF regulation
  - Adaptive low level feed-forward algorithms and Low gain feedback
  - High bandwidth piezo tuners on superconducting cavities
- Bundled waveguide stub layout

Main Challenges

- Large number or resonators (>200)
- Large beam loading (QL < 7x105)
- Large Lorentz de-tuning (>50 degrees)
- Long Pulse length (3 mS ~3 Lorentz detuning time constants)
- Large dynamic range in power(elliptical cavities range from 50kW – to 900kW)
- Large average power (15 MW of AC power)

More support from INFN to an ESS-like initiative..

Beyond ESS Reality and thanks to INFN support

A non-profit organization created by a small group of worldwide scientists

→ To stimulate and include more talented physics students from the less developed countries in the world scientific community

→ The aim of the school is to build capacity to harvest, interpret, and exploit the results of current and future physics experiments with particle accelerators, and to increase proficiency in related applications and technologies.

→ To contribute to a world w/ equal access to knowledge

→ To establish a biennial school to be hosted across Sub-Saharan Africa

→ To cover the African students 3-week classes attendance

→ To provide high quality classes by international re-known Scientists

Founding Agencies and Institutes

Institutional Support

AIMS, SA
BNL, USA
CEA, France
CERN, Switzerland
CNRS/IN2P3, France
DESY, USA
DITANET, UK, Euro
EPFL, Switzerland
ESS, Sweden (+private donation)
FNAL, USA
ICTP, Italy
INFN, Italy
IUPAP, USA
JLAB, USA
JSA, USA
NEI – AIMS
NITheP, South Africa
PSI, Switzerland
SLAC, USA
Uppsala University, Sweden

Governmental Institutions

Department of Energy, USA
Department of Science and Technology, South Africa
French Embassy Accra
NRF, South Africa
NSF, USA

Conclusion

The ESS embodies a gateway to applied science, which recently entered in the "Construction phase"

- International sponsors to control the project and technical challenges
- Involvement of European industry in the coming year
- The success of the ESS accelerator design update project has been driven by the INFN and the EURISOL project
- The ESS team is eager to further collaborate