Beam Parameters and Challenges

Bilbao, CAS, 24/5/11

EUROPEAN
SPALLATION
SOURCE

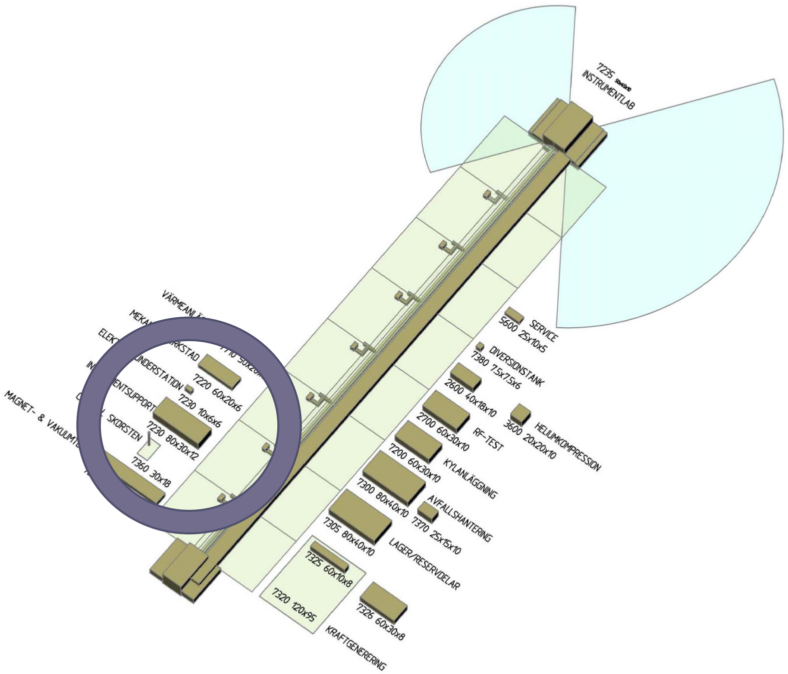
Mats Lindroos

Head of the ESS Accelerator Division

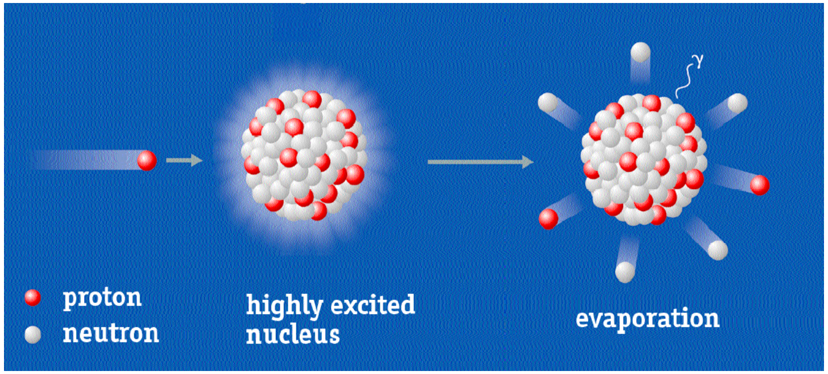
Outline

- Examples of facilities with typical parameters
- Some of the challenges, scientific and project
- Case Study
  - Neutron spallation sources: i) Short pulse sources, ii) long pulse sources and iii) continuous sources
  - Accelerator Driven Systems and Energy amplifies
  - Transmutation
  - Radioactive beam facilities

What is spallation?



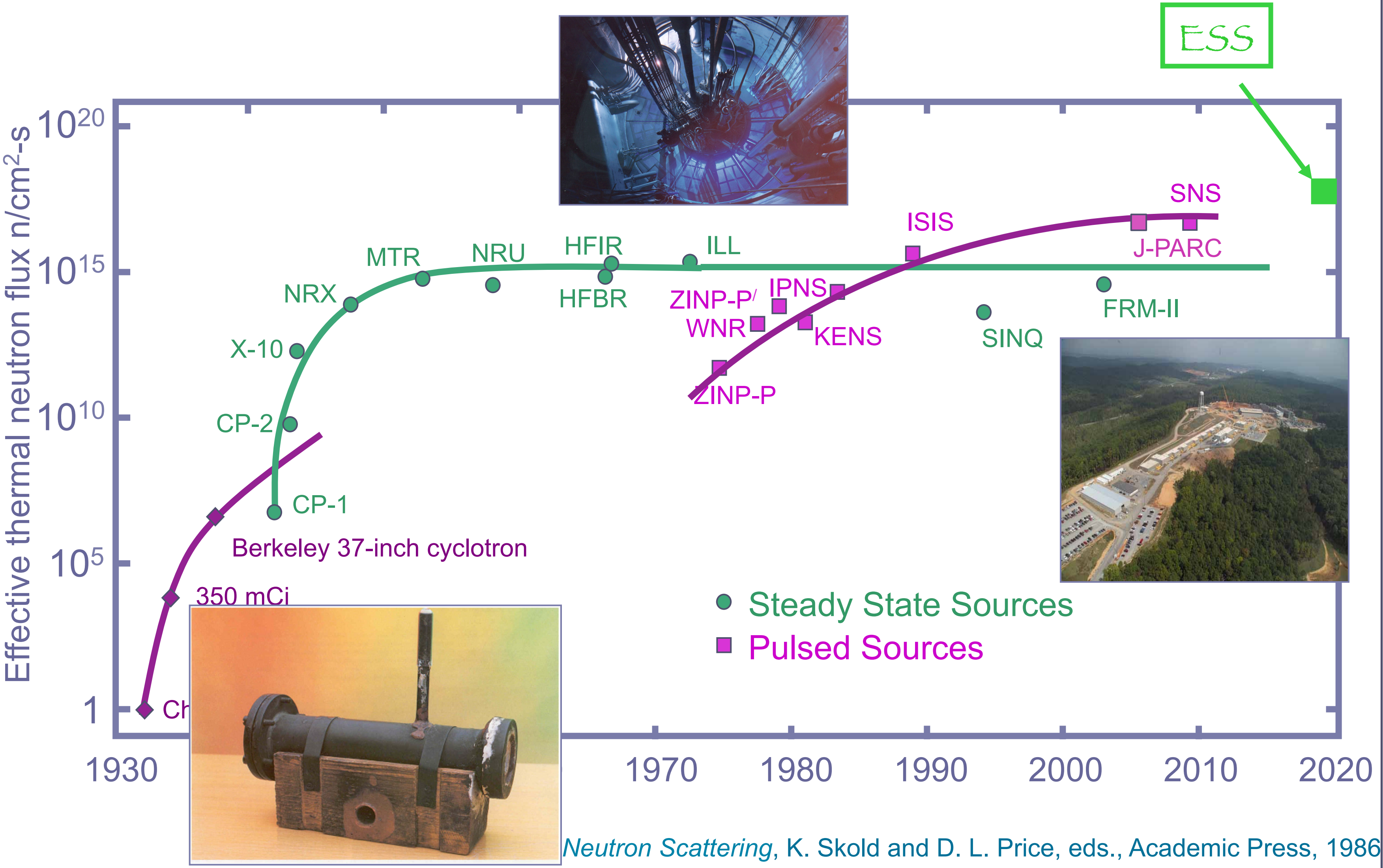
- An ion source creates positive hydrogen ions (protons).
- Pulses of protons are accelerated into a target with neutron rich atoms.
- In the target neutrons are liberated by a a spallation reaction.
- The neutrons are then guided to instruments where they are used for materials studies.



Spallation: A nuclear process in which a high energy proton excites a neutron rich nucleus which decays sending out neutrons (and other particles).

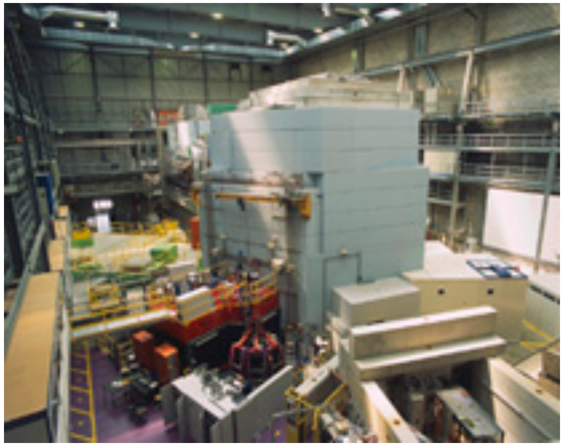
Neutron sources – High time average and peak flux

Evolution of the performance of neutron sources



(*Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

Continuous neutron source-PSI

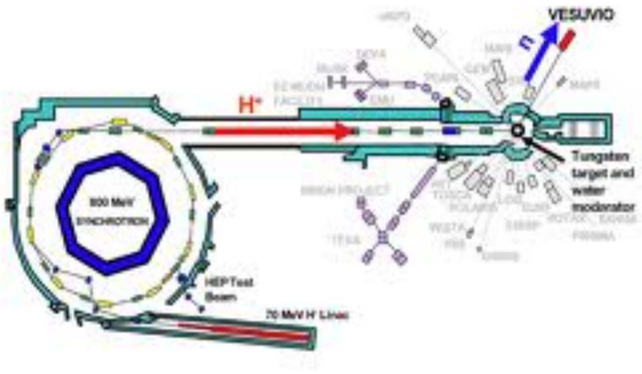


- PSI-SINQ, Cyclotron, 1974, 1.3 MW, 590 MeV, 2.2 mA extracted, Continuous beam
- Examples of challenges: High power NC segmented cyclotron, Extraction of high intensity continuous beam

Short pulse neutron sources-SNS

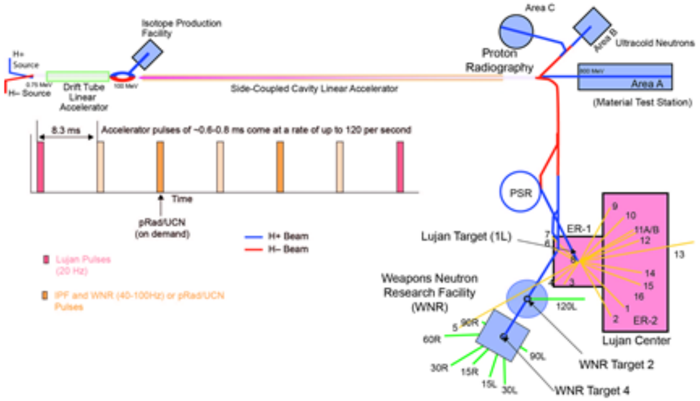
- SNS, SC LINAC/Storage ring, 2007, 1.4 MW, 1 GeV, 26 mA in linac, 627 ns long pulse, 60 Hz
- Examples of challenges: Understanding beam loss mechanism in linacs, accumulation in storage ring

Short pulse sources-ISIS



- ISIS, Rapid Cycling Synchrotron, 1984, 160 kW, 800 MeV, 200 mA extracted, 2 x 100 ns (< 1 μs), 50 Hz
- Examples of challenges: Ceramic vacuum chambers, high space charge synchrotron

Short pulse sources-LANCSE



- LANCSE, NC LINAC / Storage ring, 1972, 100 kW, 800 MeV, 17 mA in linac, 600 ns, 20 Hz
- Examples: Combined H- and H+ acceleration

Short pulse sources-JPARC

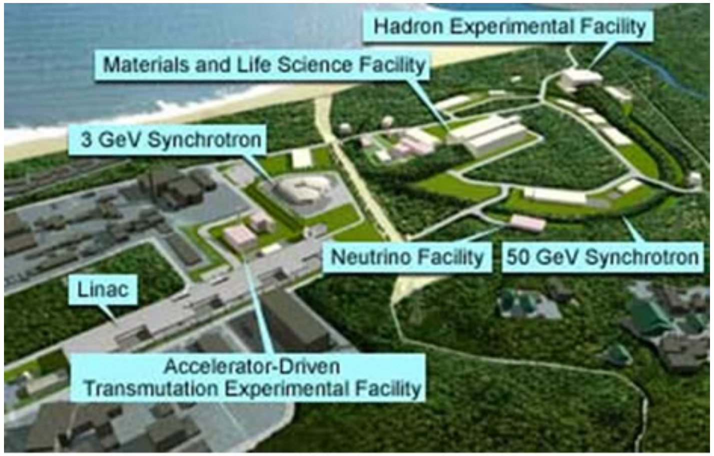
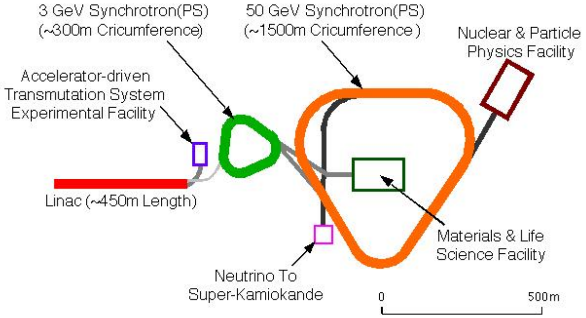


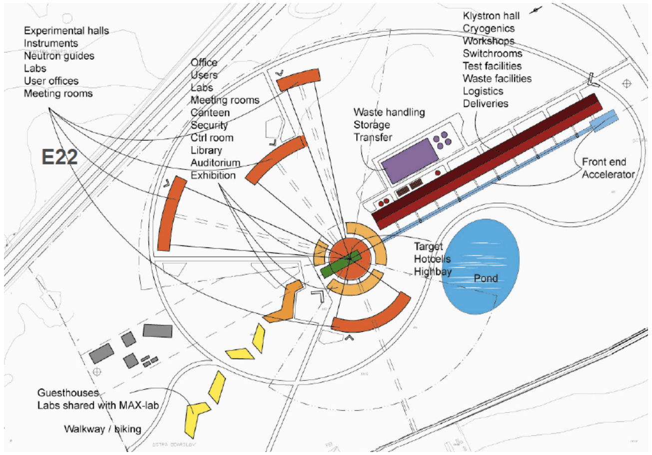
Figure 2 Overall image of J-PARC



High Intensity Proton Accelerator Project

- J-PARC, Neutron source, Rapid Cycling synchrotron, 2009,1 MW, 3.0 GeV, 330 mA extracted, < 1196 ns, 25 Hz
- Examples of challenges: Safe for earthquake and 10 m tsunami

Long pulse sources-ESS

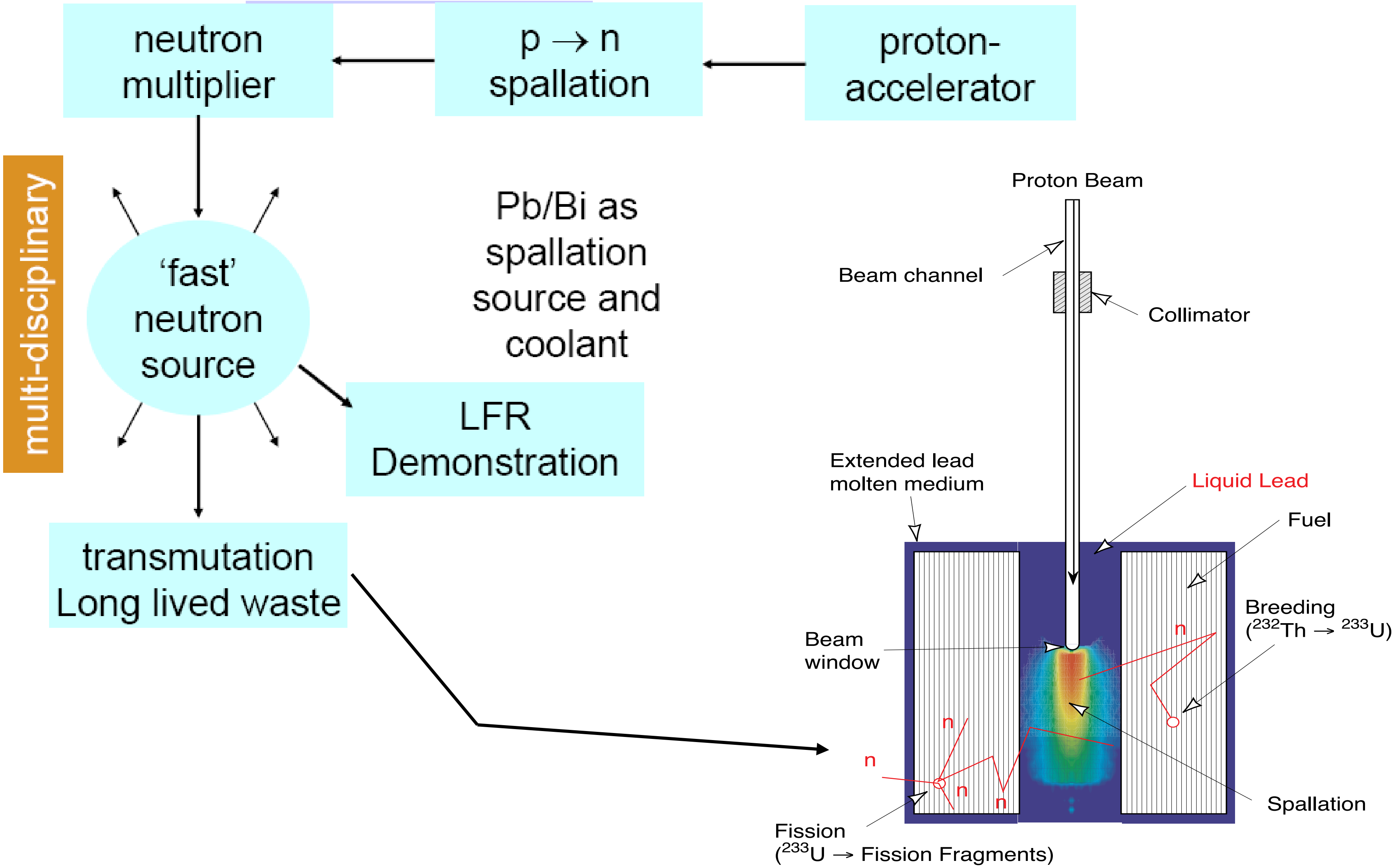


- European Spallation Source, SC LINAC, 2019, 5 MW, 2.5 GeV, 50 mA, 2.86 ms, 14 Hz
- Examples of challenges: Footprint of RF sources, Energy efficiency

Required Conditions for Sustainable Nuclear Power

- ☐ Extremely high level of **inherent safety**
- ☐ **Minimal production of long lived waste** and elimination of the need of the geologic depositories
- ☐ **High resistance to diversion**
- ☐ **More efficient use** of available natural fuel, without the need of isotopic enrichment
- ☐ **Lower cost of the heat** produced and **higher operating temperature**

Accelerator-Driven Systems (ADS)



neutron multiplier

p → n spallation

proton-accelerator

multi-disciplinary

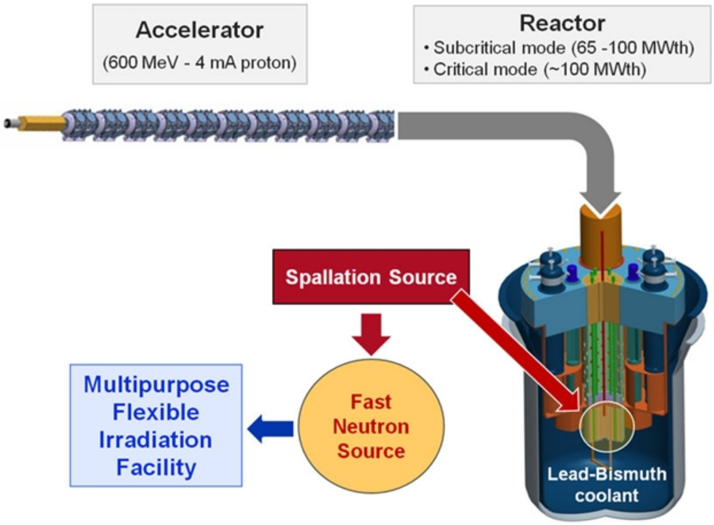
'fast' neutron source

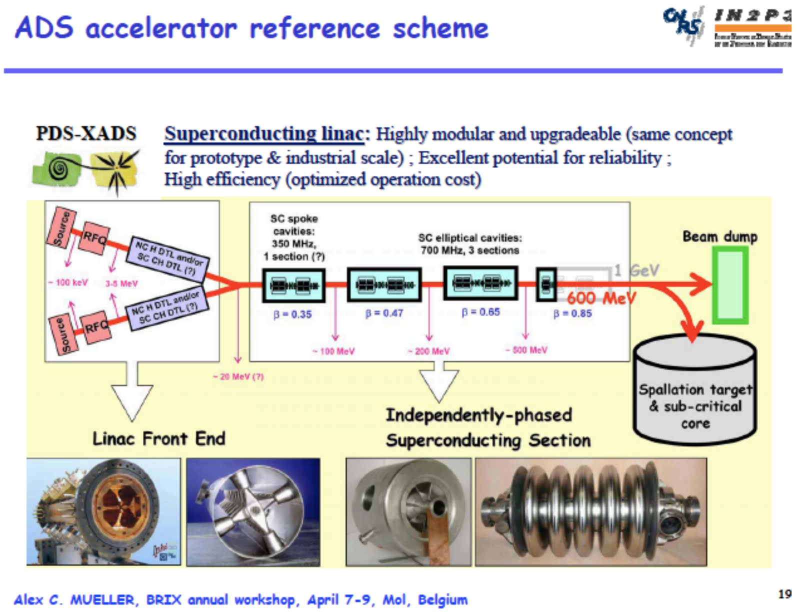
Pb/Bi as spallation source and coolant

LFR Demonstration

transmutation Long lived waste

Transmutation





ADS accelerator reference scheme

PDS-XADS <u></u>**Superconducting linac**: Highly modular and upgradeable (same concept for prototype & industrial scale) ; Excellent potential for reliability ; High efficiency (optimized operation cost)

Alex C. MUELLER, BRIX annual workshop, April 7-9, Mol, Belgium

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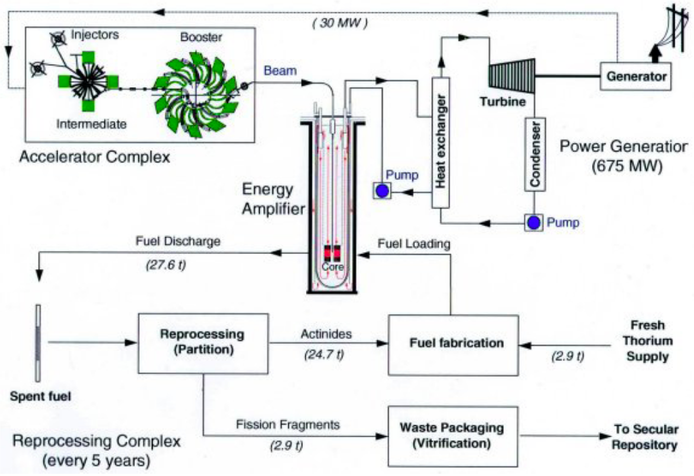
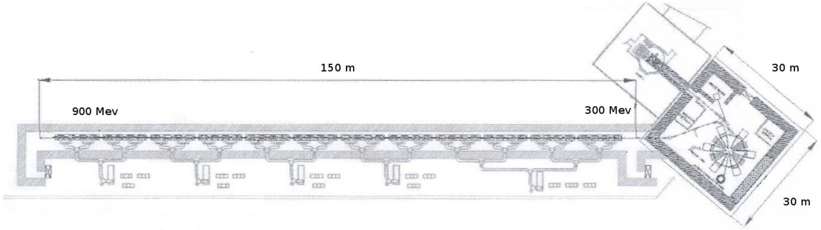
- MYRRHA, SC LINAC, 2.4 MW, 600 MeV, 4 mA, Continuous
- Examples of challenges: Reliability, NO interuptions so redundancy is crucial

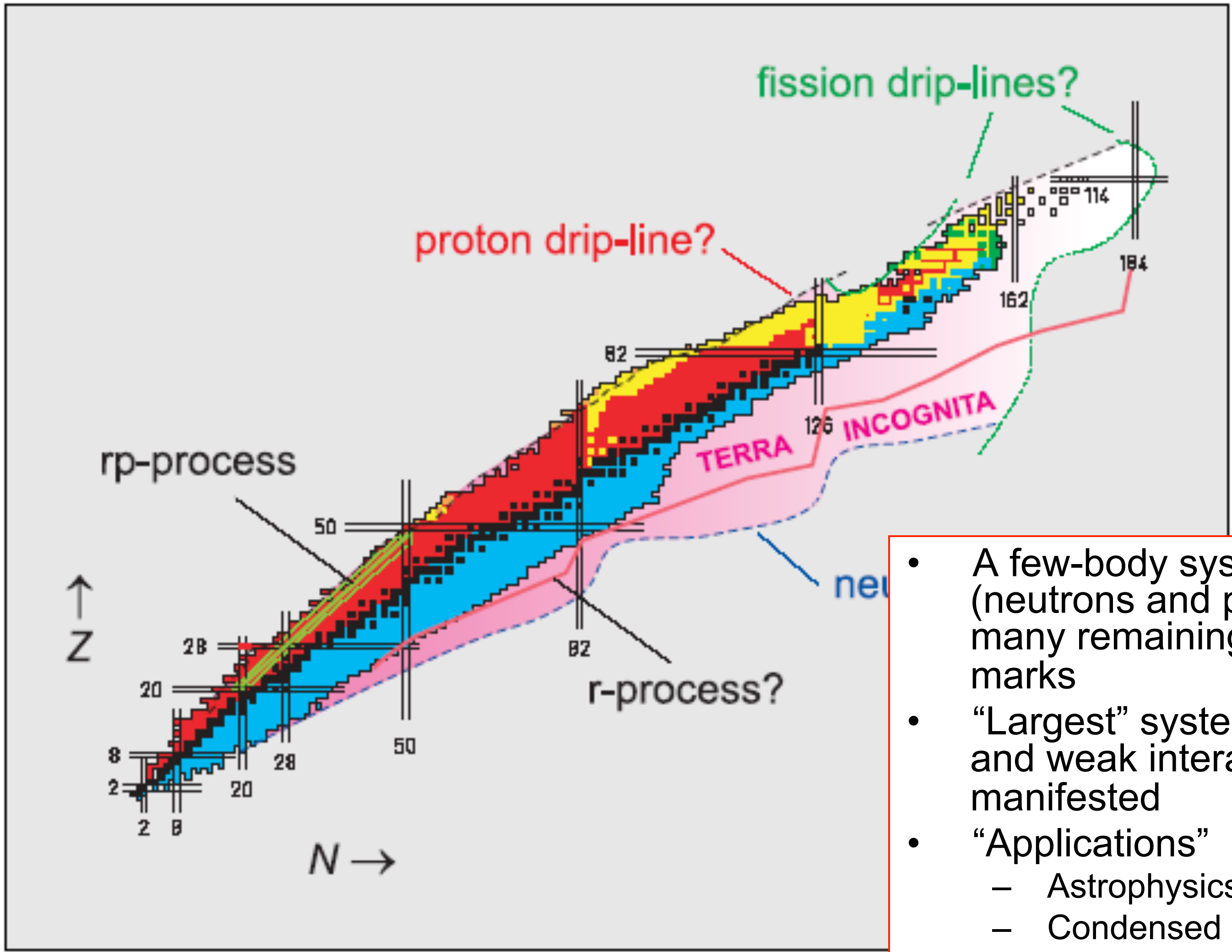
ADS





- SC LINAC, Multiple cyclotrons or FFAGs, 10 MW, 900 MeV, 11 mA, Continuous
- Examples of challenges: Long uninterruptible runs for power production on the grid, Nuclear power safety standards for accelerator

Exploring the nuclear landscape

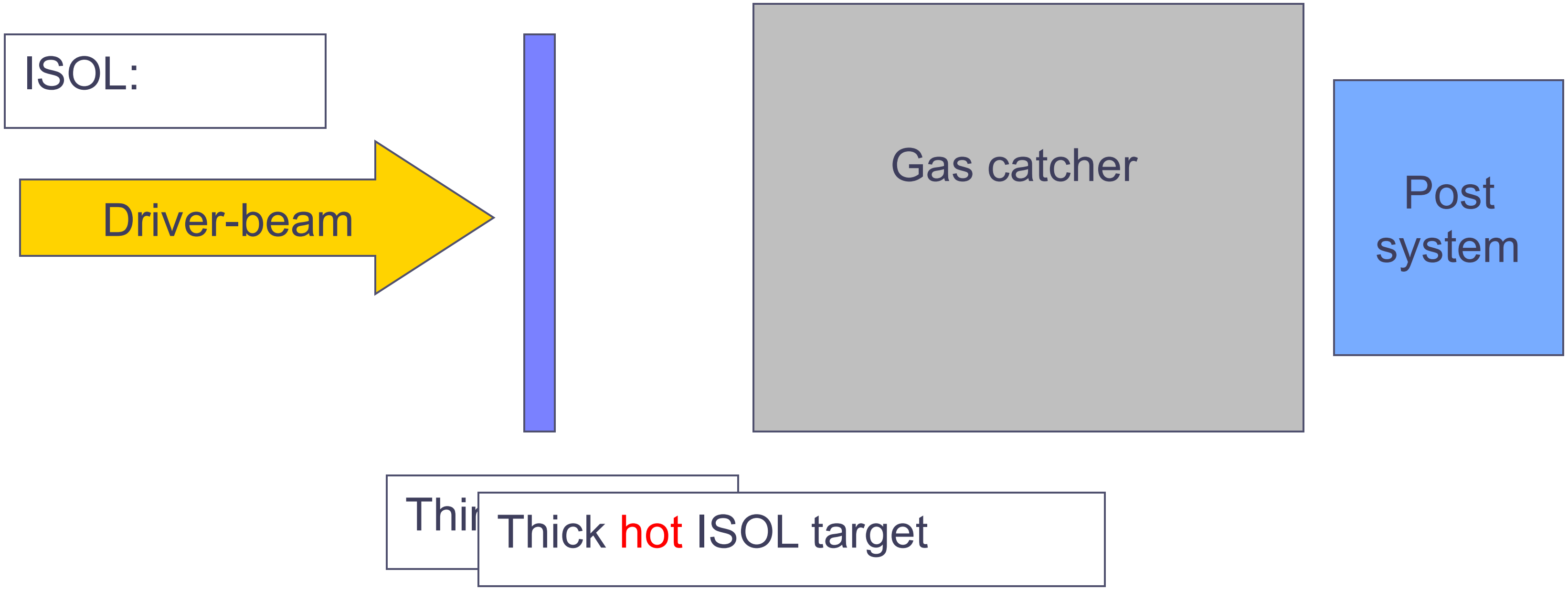


- A few-body system of hadrons (neutrons and protons) with many remaining question marks
- “Largest” system where strong and weak interaction are manifested
- “Applications”
  - Astrophysics – CERN PP
  - Condensed matter
  - Energy
  - Medicine

The two corners stones of RIB physics: In-flight and ISOL

"ISOL: Such an instrument is essentially a target, ion source and an electromagnetic mass analyzer coupled in series. The apparatus is aid to be on-line when the material analyzed is directly the target of a nuclear bombardment, where reaction products of interest formed during the irradiation are slowed down and stopped in the system.

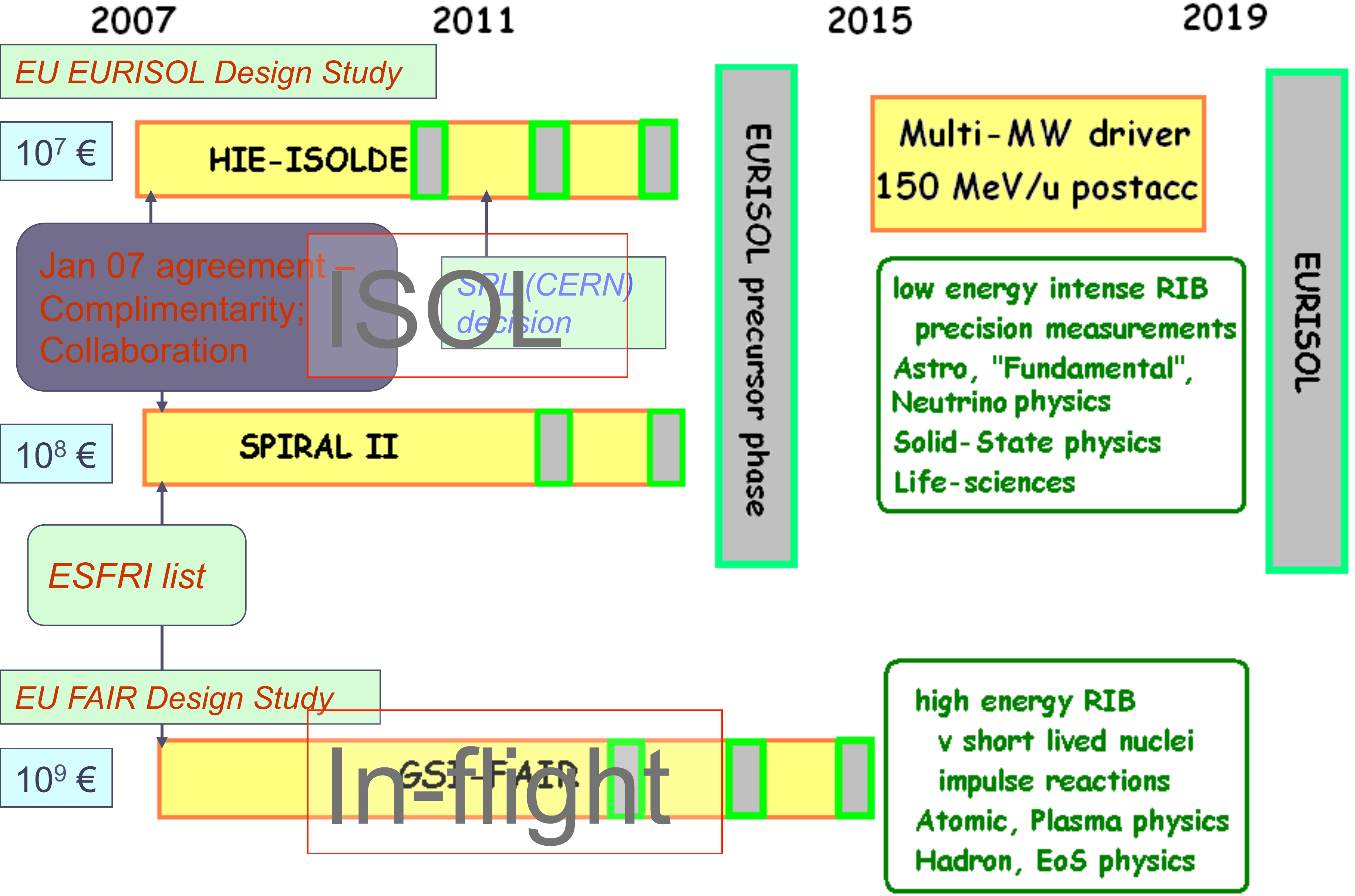
H. Ravn and B.Allardyce, 1989, Treatise on heavy ion science



EPAC-04
Mats Lindroos

ISOL facilities

European Roadmap for RIB facilities



2007 2011 2015 2019

EU EURISOL Design Study

10^7 €

HIE-ISOLDE

Jan 07 agreement – Complimentarity; Collaboration

ISOL

SPL (CERN) decision

10^8 €

SPIRAL II

ESFRI list

EU FAIR Design Study

10^9 €

GSI-FAIR

In-flight

EURISOL precursor phase

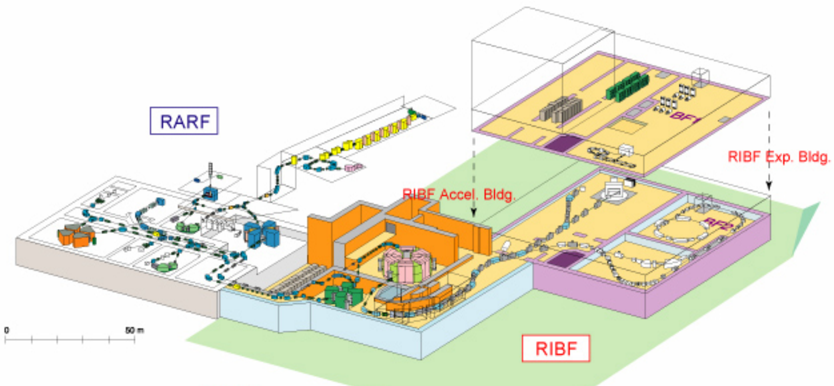
Multi-MW driver
150 MeV/u postacc

low energy intense RIB
precision measurements
Astro, "Fundamental",
Neutrino physics
Solid-State physics
Life-sciences

EURISOL

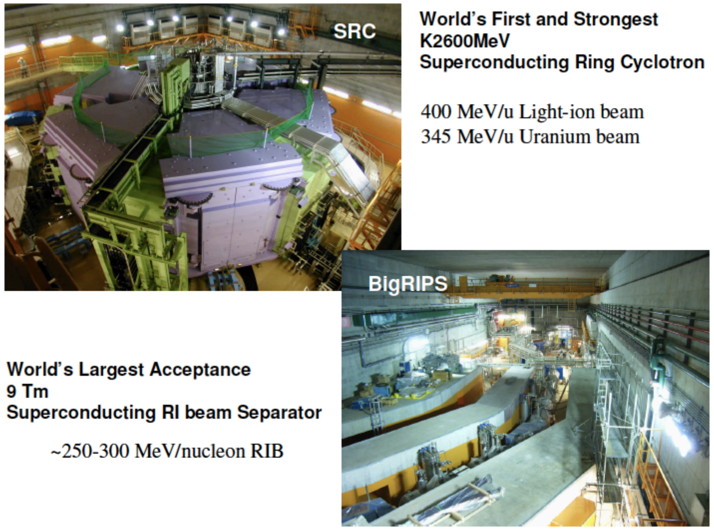
high energy RIB
v short lived nuclei
impulse reactions
Atomic, Plasma physics
Hadron, EoS physics

RIKEN



RIBF RI beam generator
featuring superconducting ring cyclotron (SRC)
and projectile fragment separator (BigRIPS)
will be commissioned late in 2006.

RIBF RI beam experiments
will be started in 2007,
with colored experimental installations.



World's First and Strongest
K2600MeV
Superconducting Ring Cyclotron

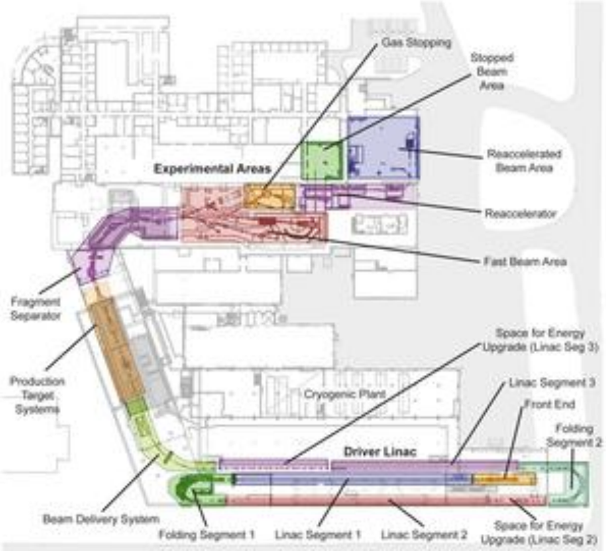
400 MeV/u Light-ion beam
345 MeV/u Uranium beam

World's Largest Acceptance
9 Tm
Superconducting RI beam Separator

~250-300 MeV/nucleon RIB

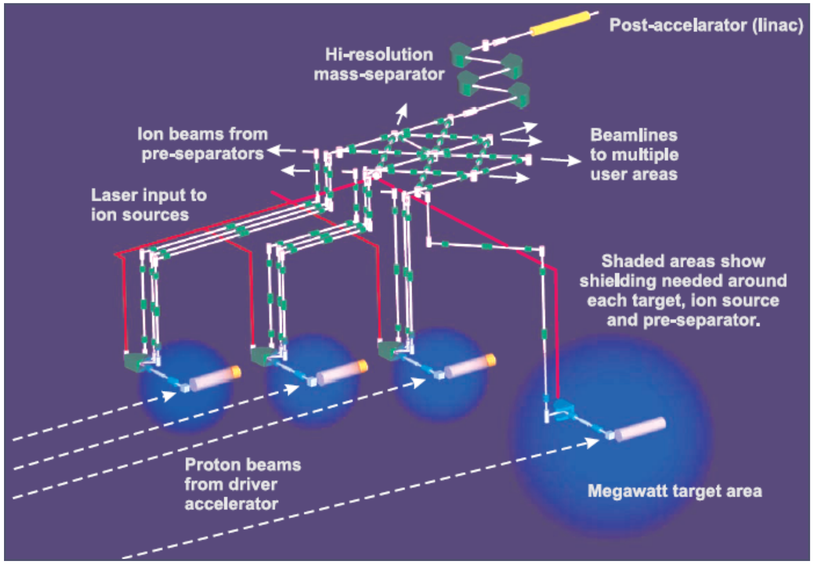
- RIKEN, Radioactive beam facility, Fragmentation of ions, ion up to Uranium available, 440 MeV/nucleon for light ions and 350 MeV/nucleon, up to 1 pμA, very advanced instrumentation for nuclear physics
- Examples of challenges: High K SC cyclotron for Heavy Ions

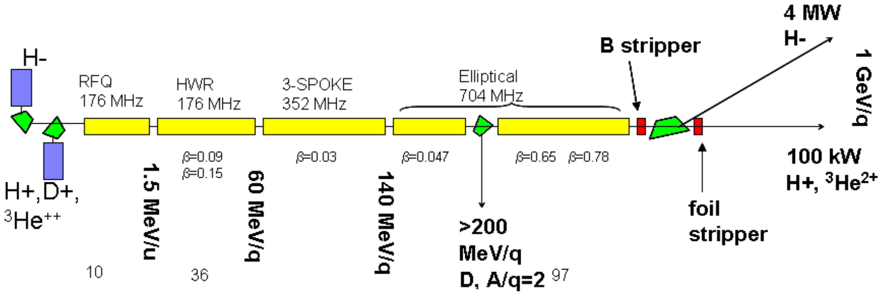
FRIB

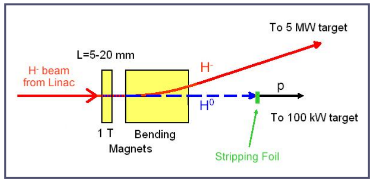


- FRIB at MSU, Radioactive beam facility, Fragmentation of ions, ion up to Uranium available, 610 MeV/nucleon for protons and 210 MeV/nucleon for Uranium, up to 400 kW, very advanced instrumentation for nuclear physics
- Examples of challenges: very intense heavy ion beams in folded SC linac

EURISOL





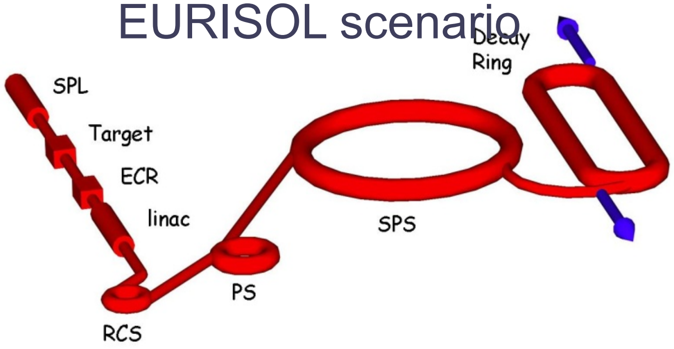


- EURISOL, H-, 5 MW, 1 GeV, 5 mA, Continuos
- Example of challenges: Beam splitting at high energy of high power beam

The EURISOL beta-beam

- Based on CERN boundaries
- Ion choice: ^{6}He and ^{18}Ne
- Relativistic gamma=100/100
  - SPS allows maximum of 150 (^{6}He) or 250 (^{18}Ne)
  - Gamma choice optimized for physics reach
- Based on existing technology and machines
  - Ion production through ISOL technique
  - Bunching and first acceleration: ECR, linac
  - Rapid cycling synchrotron
  - Use of existing machines: PS and SPS

EURISOL scenario



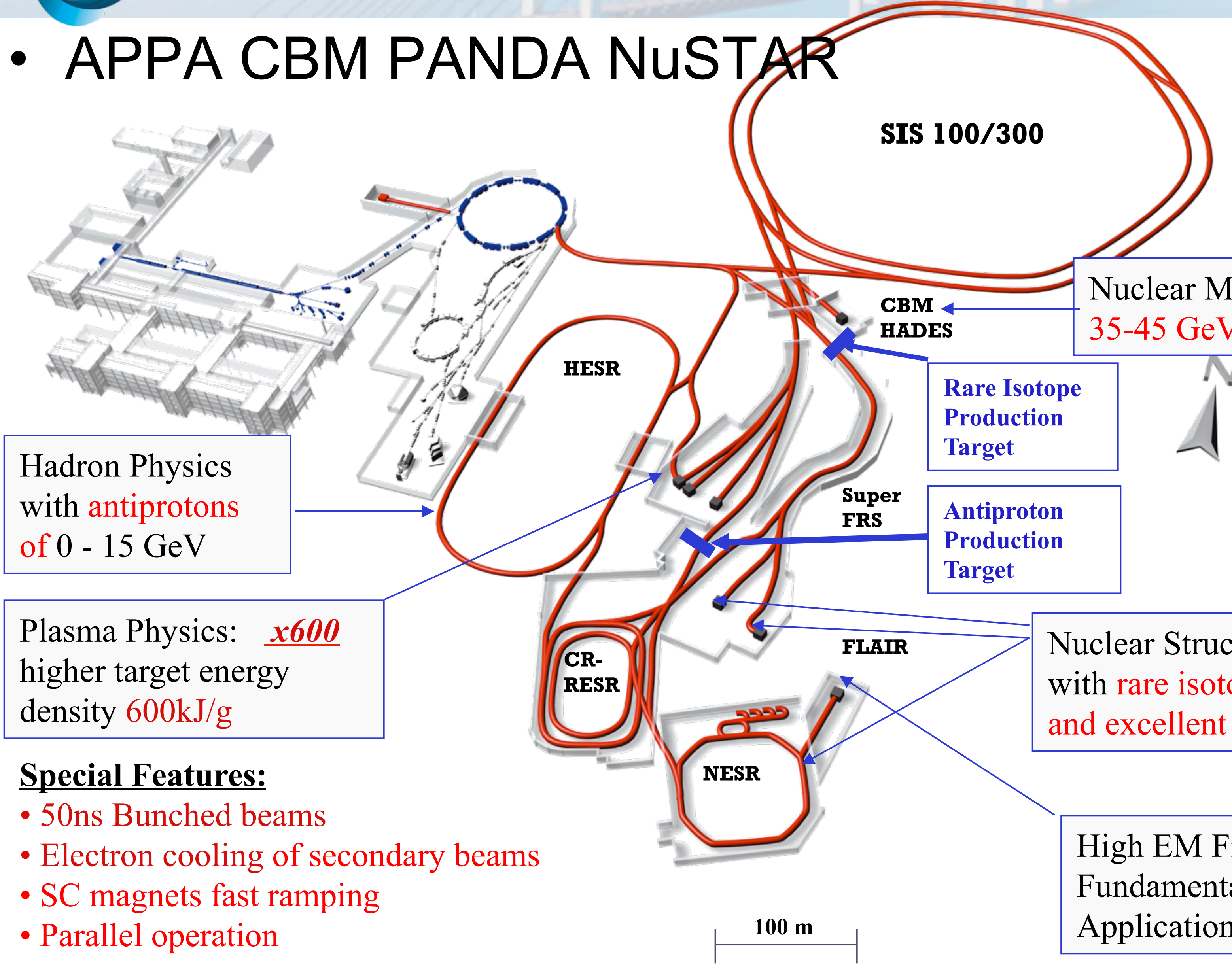
- Opportunity to share a Mton Water Cerenkov detector with a CERN superbeam, proton decay studies and a neutrino observatory

- Achieve an annual neutrino rate of either
  - 2.9*10^{18} anti-neutrinos from ^{6}He
  - Or 1.1 10^{18} neutrinos from ^{18}Ne

- Once we have thoroughly studied the EURISOL scenario, we can “easily” extrapolate to other cases. EURISOL study could serve as a reference.

FAIR

- APPA CBM PANDA NuSTAR



Nuclear Matter Physics with
35-45 GeV/u HI beams, ***x1000***

Rare Isotope Production Target

Antiproton Production Target

Hadron Physics
with antiprotons
of 0 - 15 GeV

Plasma Physics: ***x600***
higher target energy
density 600kJ/g

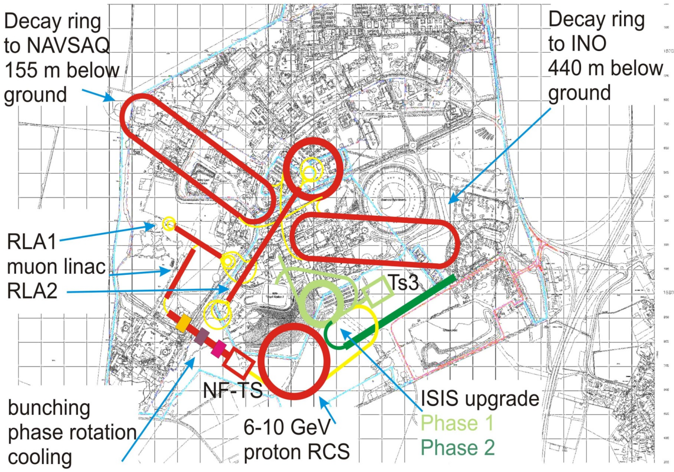
Nuclear Structure & Astrophysics
with rare isotope beams, ***x10 000***
and excellent cooling

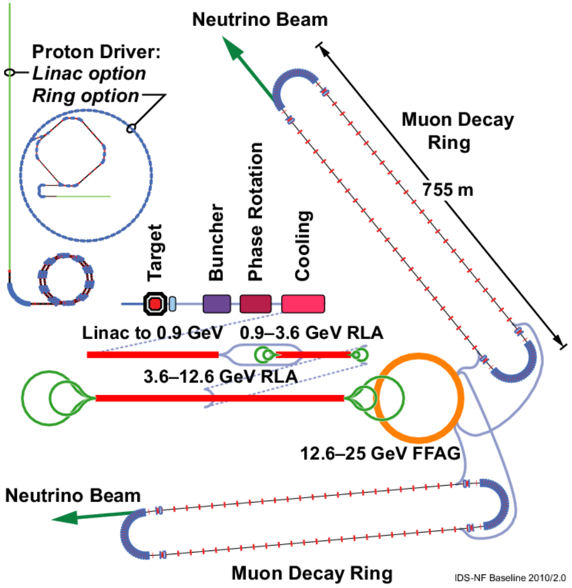
High EM Field (HI) _
Fundamental Studies(HI & p)
Applications (HI)

Special Features:

- 50ns Bunched beams
- Electron cooling of secondary beams
- SC magnets fast ramping
- Parallel operation

Neutrino factory





- Neutrino factory, Muon acceleration and Muon decay rings, SC linac or RCS, 3.5 GeV (CERN) and 30 GeV (RAL), 4 MW
- Examples of challenges: Physics limited by beam power so upgrades are desirable

Scientific and Technical challenges

Just a few examples from ESS…

Beam dynamics

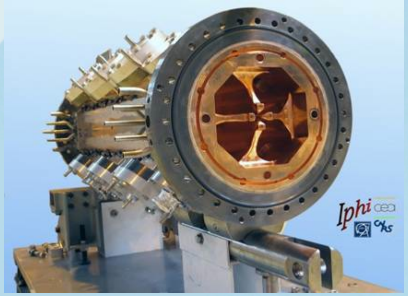
- In the design of the LINAC special care has been taken to avoid emittance increase, halo production and loss of particles, by respecting the key criteria:

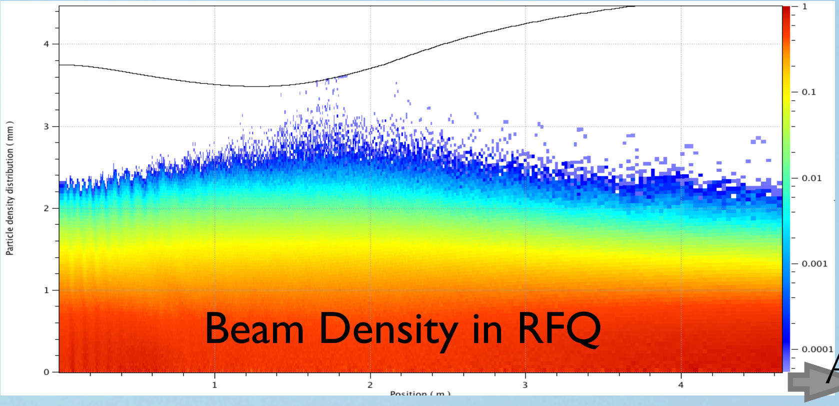
1: When the space charge is not negligible, i.e. $\sigma/\sigma_0 < 1$, zero current phase advance per period, σ_0, should be smaller than 90^o. This limit is as low as 60 degrees to avoid sextupule envelope resonance

2: Special care has to be taken to avoid the space charge resonances.

3: The average external force on the beam, $(\sigma_0/L_p)^2$, has to be smooth and continuous.

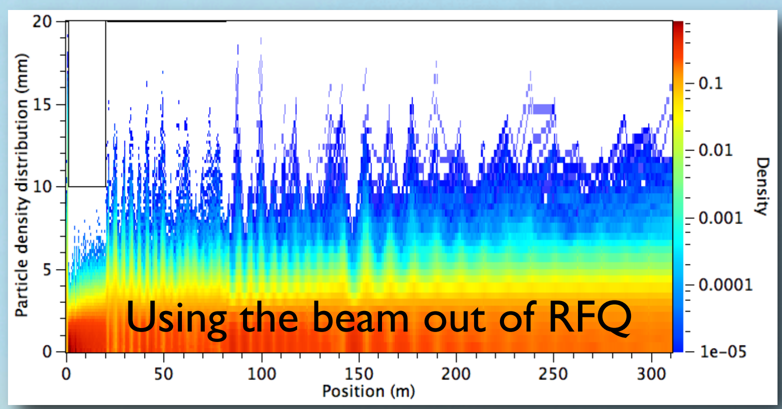
Density



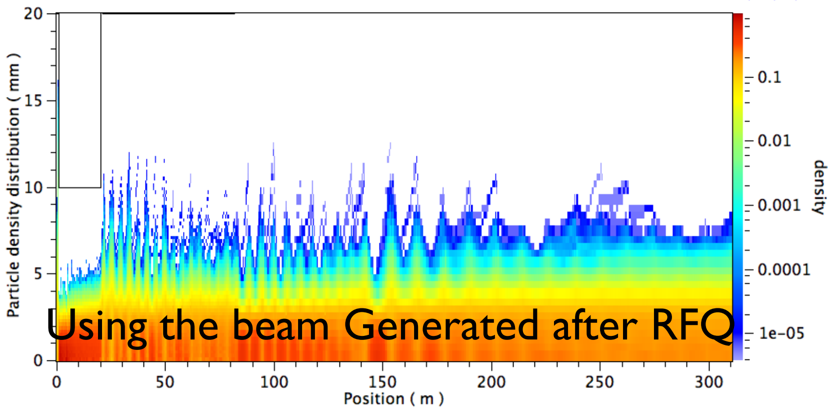


Beam Density in RFQ

Aurélien Ponton

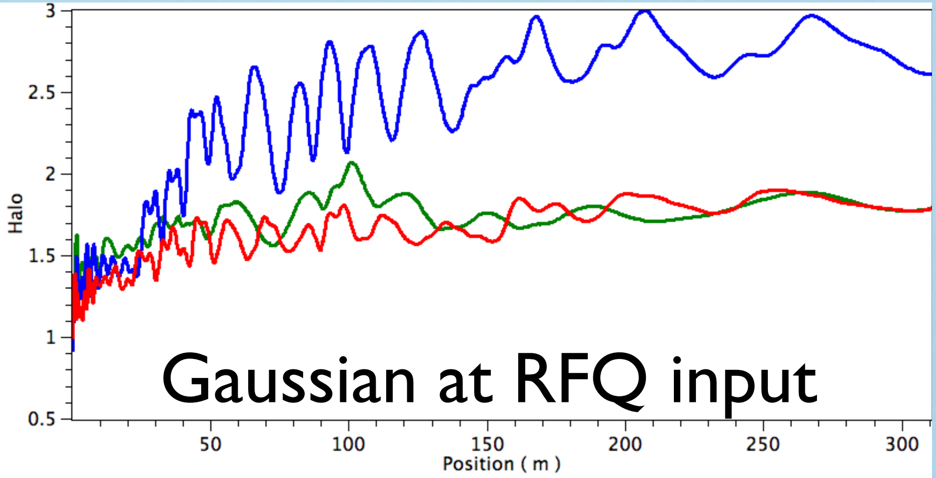


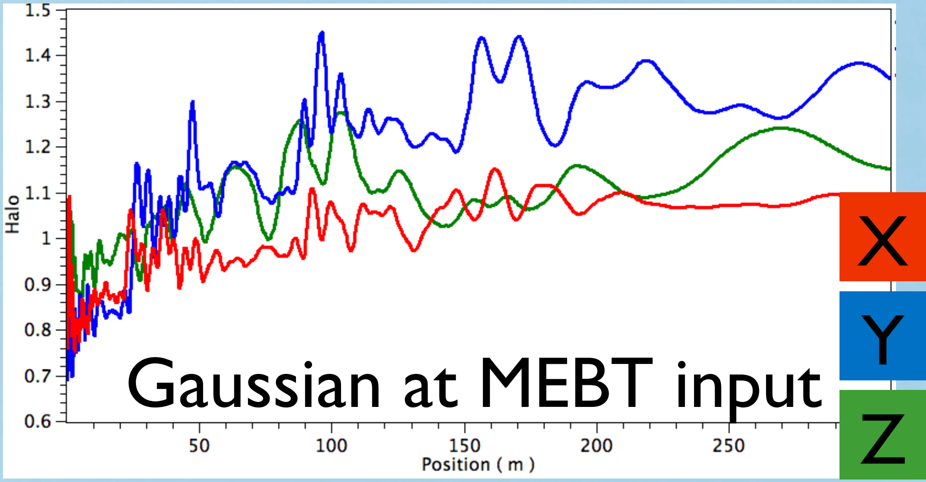
Using the beam out of RFQ



Using the beam Generated after RFQ

Halo Parameter

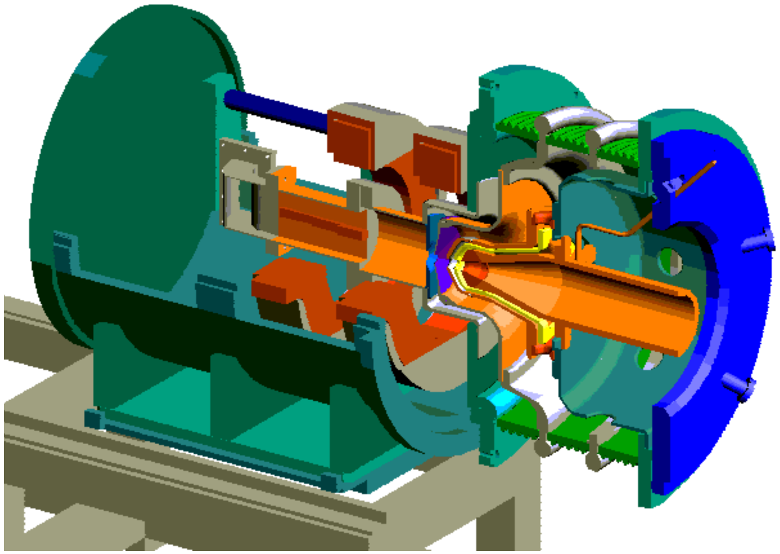

Gaussian at RFQ input

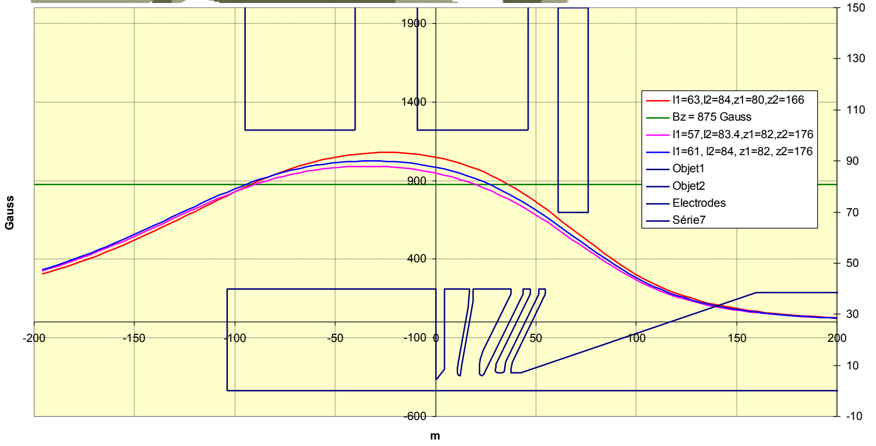

Gaussian at MEBT input

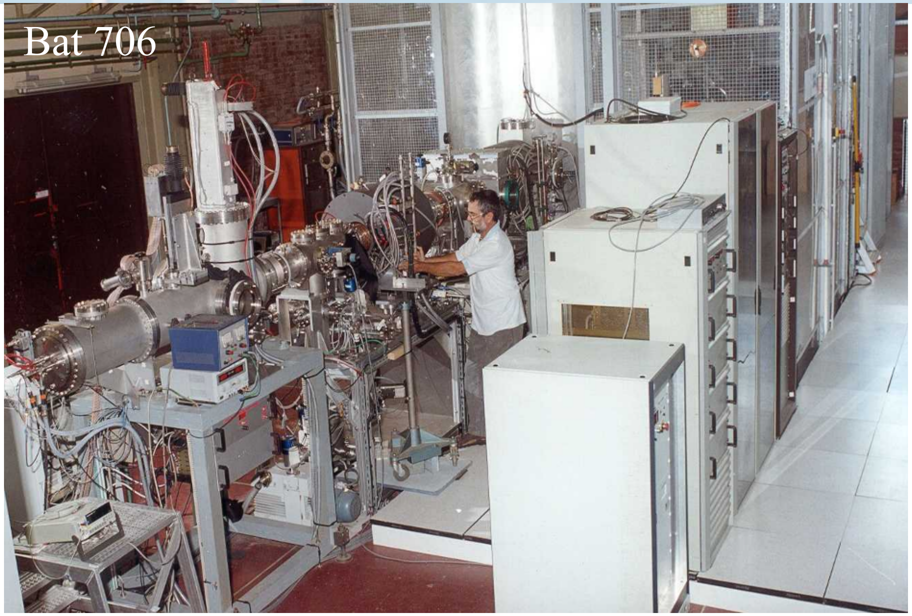
Note the different scale

SILHI source and LEBT

SILHI operates at 2.45 or 3 GHz
1 ECR zone at RF entrance







Since 1996, SILHI produces H+ beams with good characteristics:

H+ Intensity > 100 mA at 95 keV
H+ fraction > 80 %

Beam noise < 2%

95 % < Reliability < 99.9 %

Emittance < 0.2 π mm.mrad

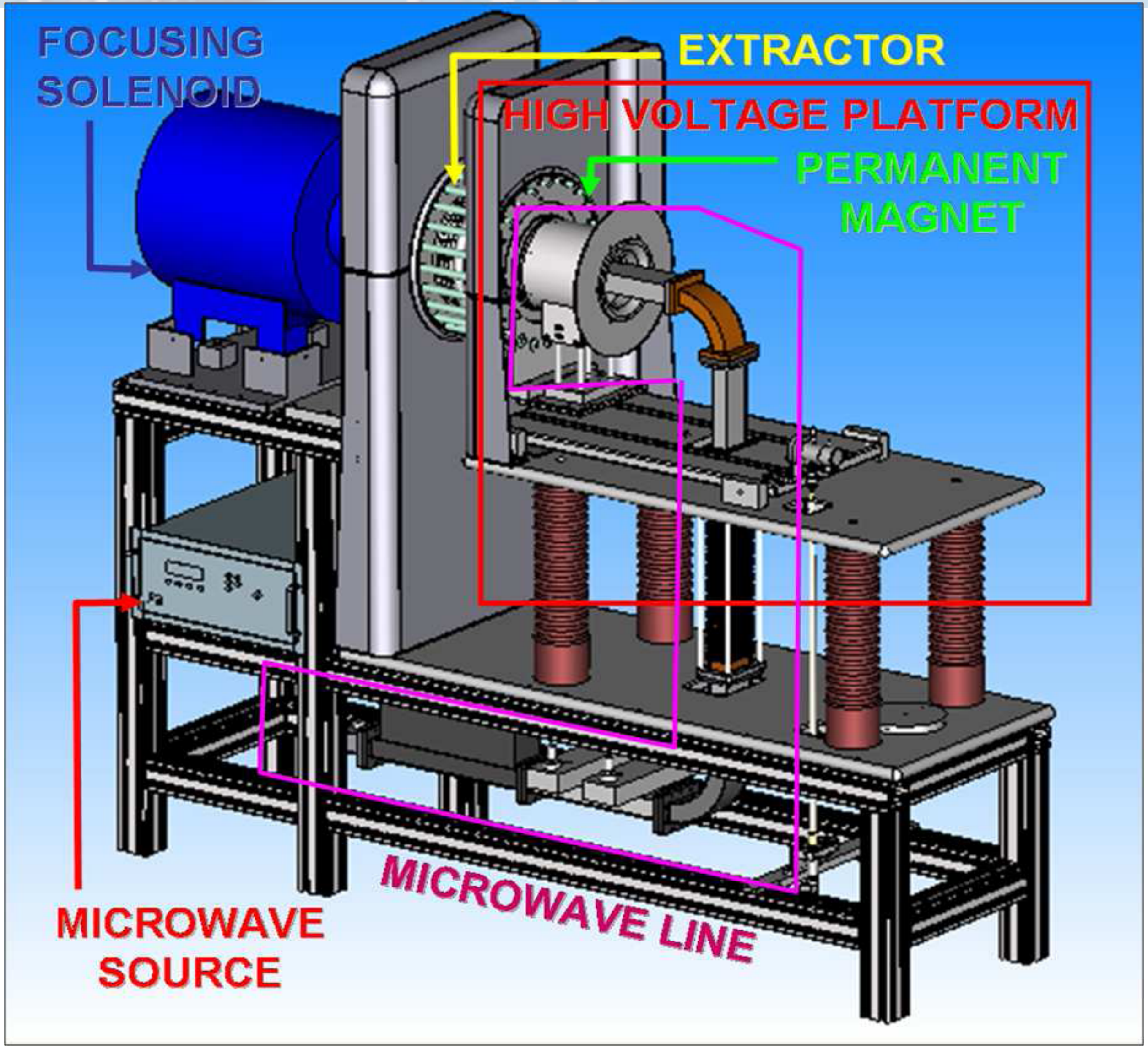
CW or pulsed mode

Vis Description

Extraction Voltage	60 kV
Repeller voltage	~ -2 kV
Total current	> 35 mA
Proton current	>30 mA
Proton fraction	> 85%
Microwave frequency	2.45 GHz
Axially magnetic field	875-1000 G

The principal source devices :

- Plasma copper chamber
- Magnetic system
- Microwave line
- Exctractor



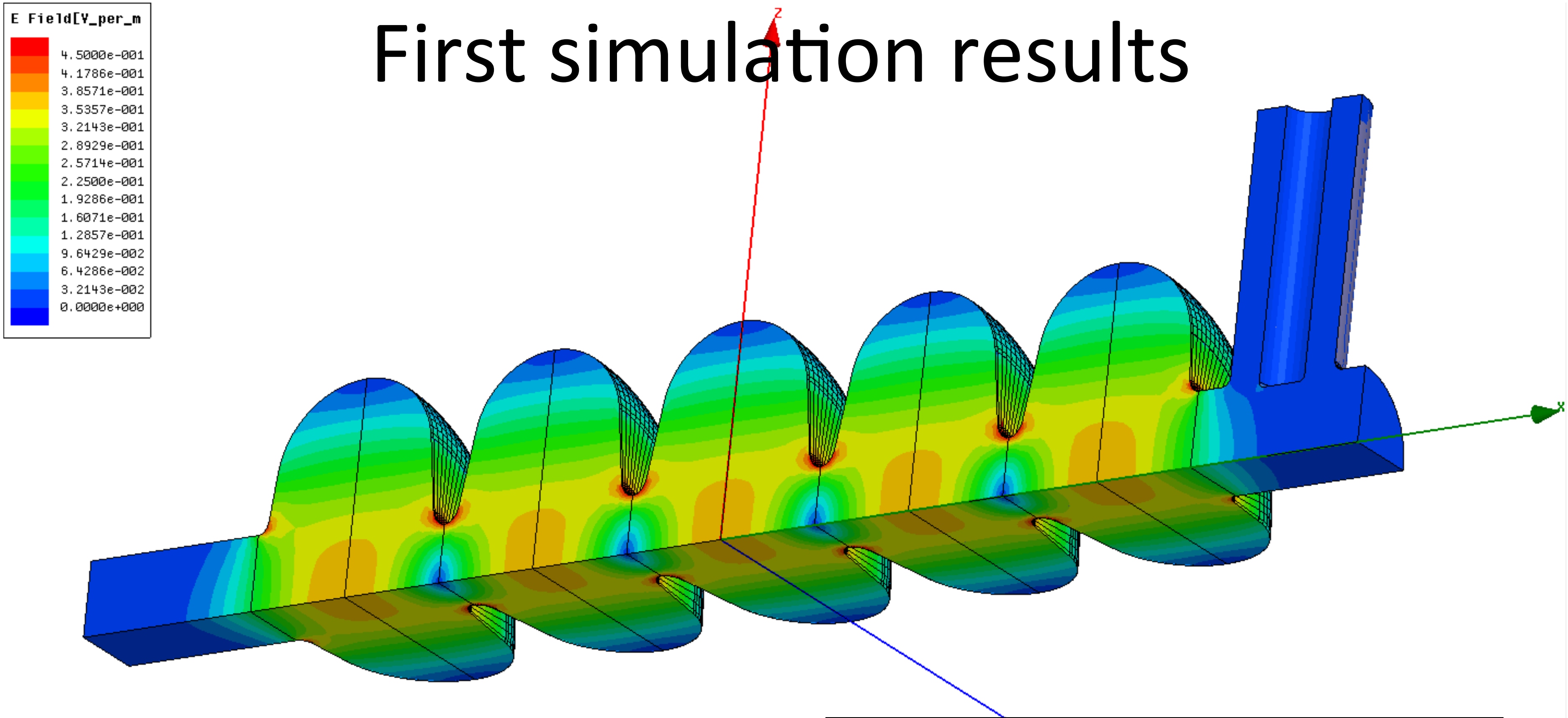
Control System: Reducing Organizational Risk

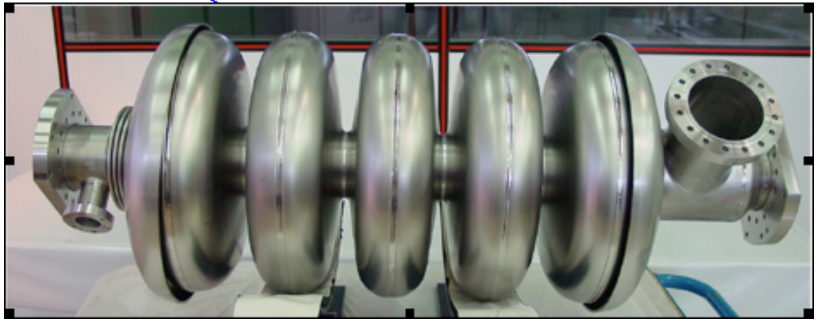
- Modern computer technology allows any reasonable implementation of software and hardware to function properly
- Organizational risk
  - Collaboration of partner institutions
  - Control system comes late in the project
  - Integrates with most of other subsystems
- CS is not about programming, but a very complex engineering discipline with all corresponding rules and procedures
- Preempt creativity, standardize on development procedures
  - Get all groups on board at the beginning
  - Provide a standardized Control Box for the 2012 milestone
- Focus on usability and longevity
  - Use similar technologies as are used in other projects

Spoke cavities

SC single spoke cavity, IPNO
(CNRS)

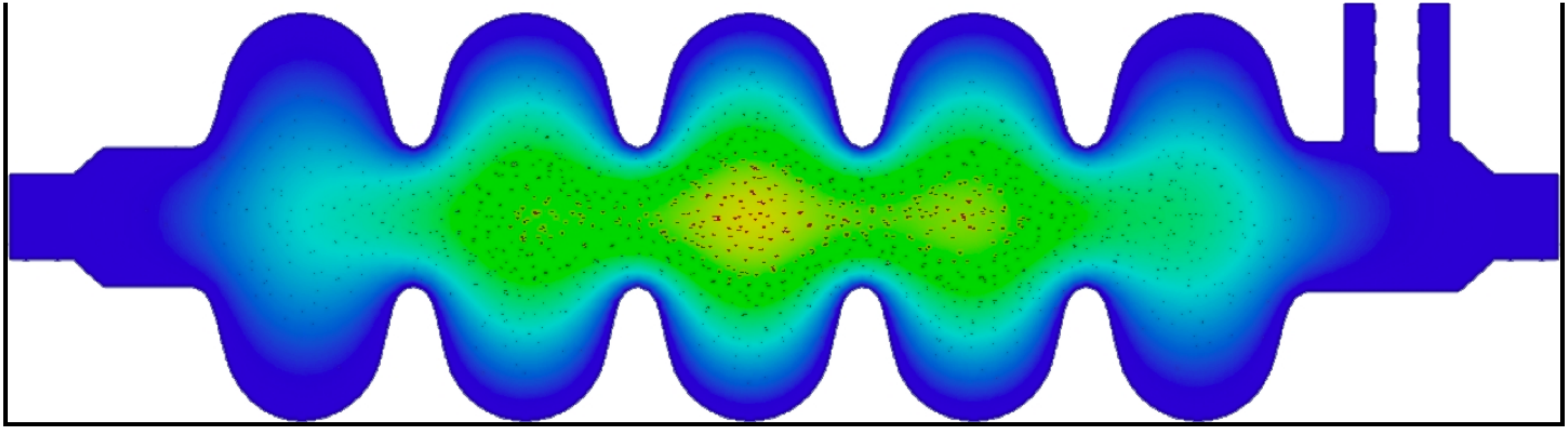
ESS Elliptical high beta cavities
First simulation results





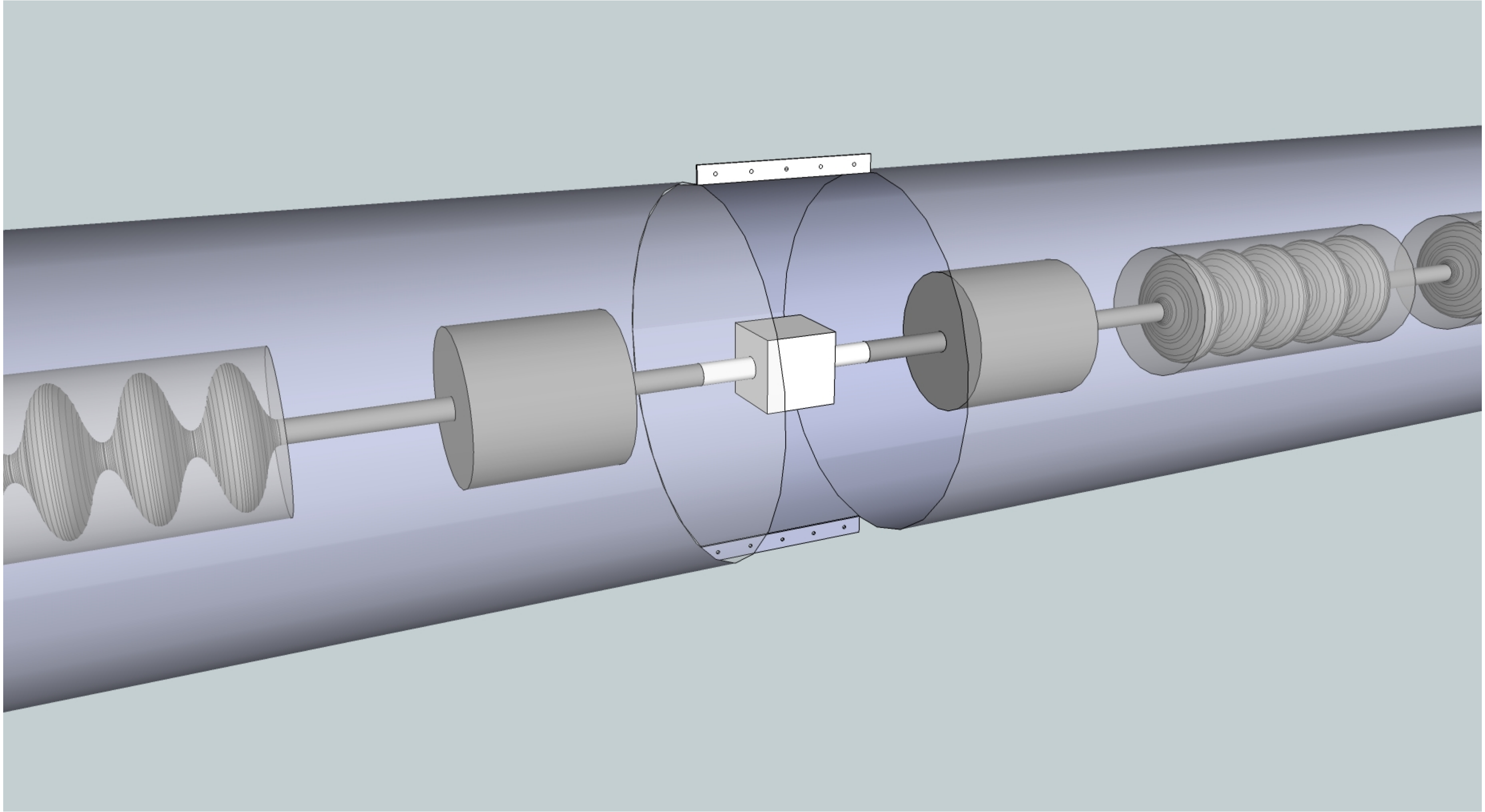
Guillaume Devanz, CEA-Saclay

Trapped Higher Order Modes

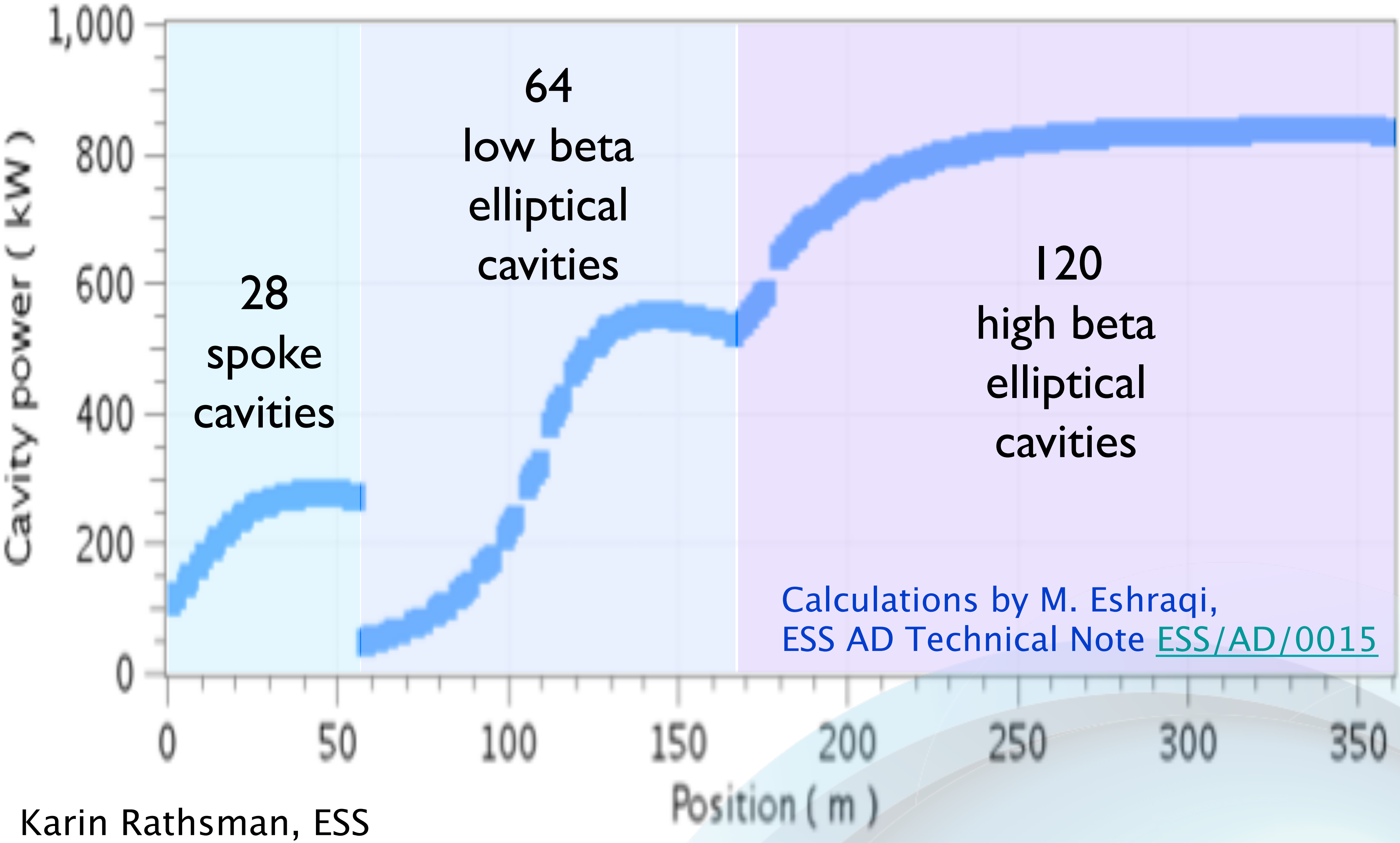


Stephen Molloy and Robert Ainsworth, ESS and RHUL

Hybrid cryomodule design



Power to beam Superconducting part



28
spoke
cavities

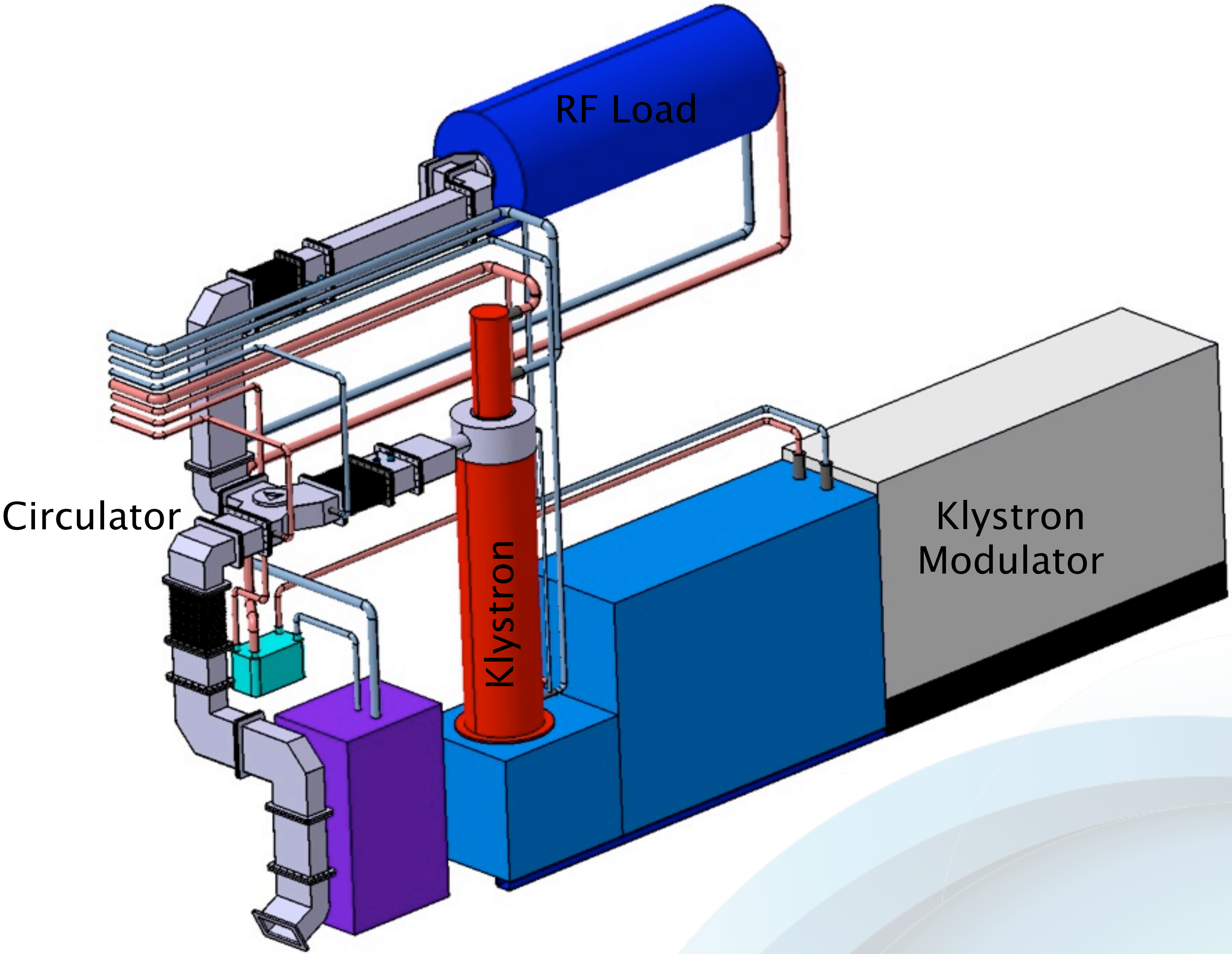
64
low beta
elliptical
cavities

120
high beta
elliptical
cavities

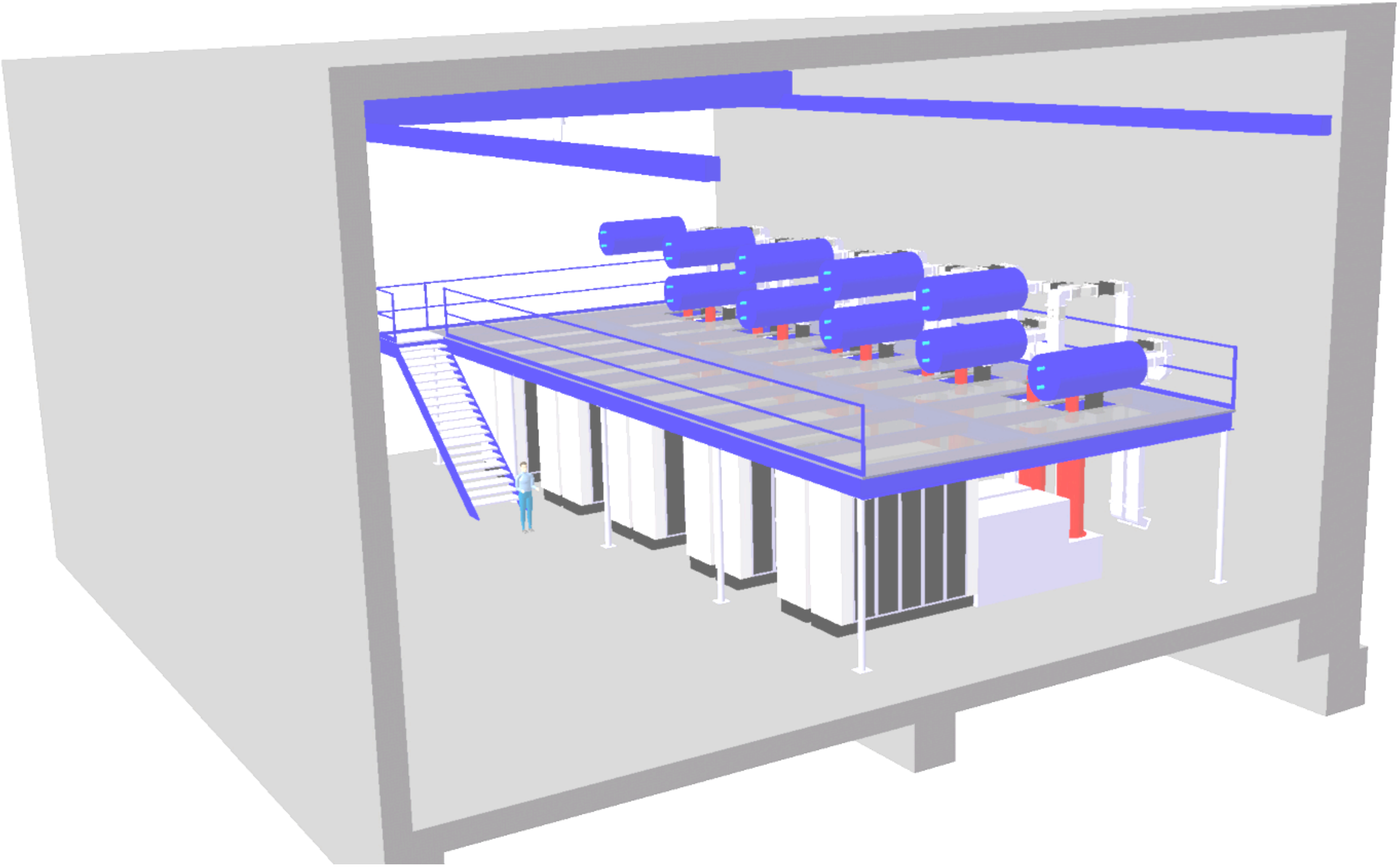
Calculations by M. Eshraqi,
ESS AD Technical Note ESS/AD/0015

Karin Rathsman, ESS

RF power system



1/20 of RF gallery



Reliability RF

✓ 95 % availability demand for ESS as a whole

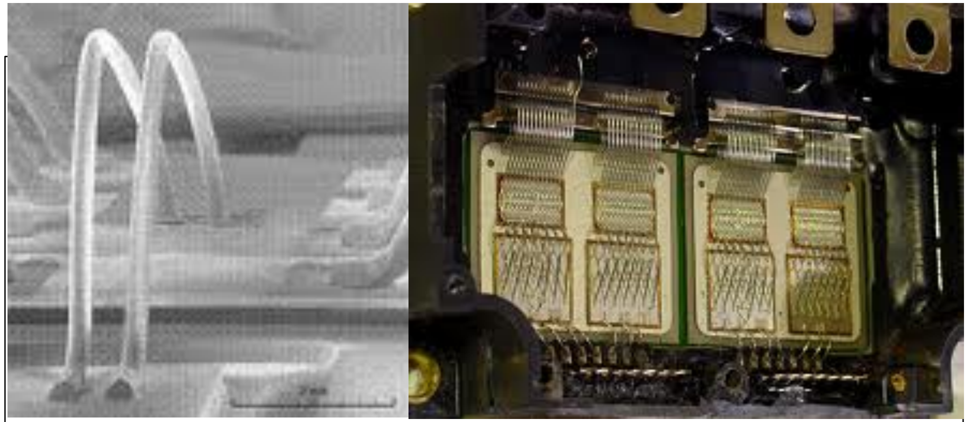
✓ 216 cavities in total

Assume 4 years MTBF per power source
=> maintenance every week

✓ Complex systems with many components.

✓ Solutions:

Well proven technologies only!
Chose robust solutions.
MTBF, MTTR and lifetime analysis.
One power source per cavity to allow cavity bypass in case of failure.
Fast replacement of modulators and klystrons in case of failure.



Many fragile parts in an IGBT and many IGBTs in a modulator...

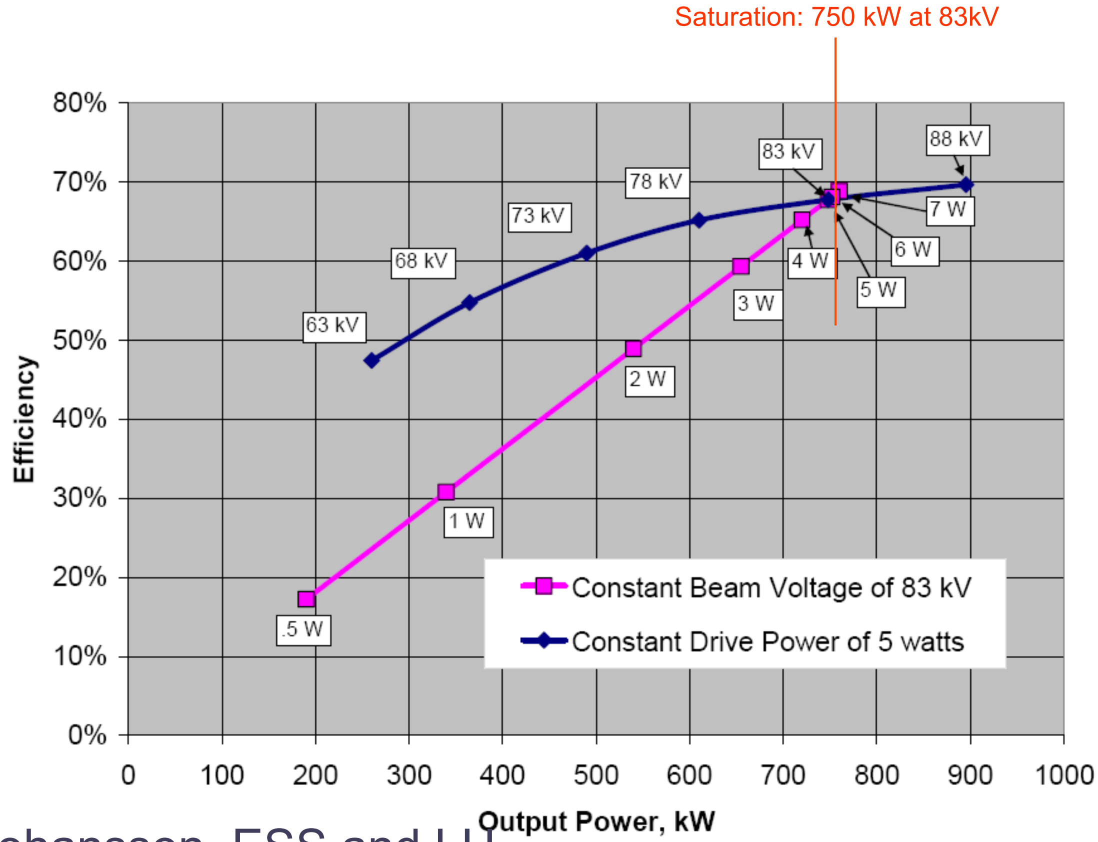
...to be compared with a modulator based on a few robust IGCTs

Challenges for LLRF System at ESS

- ✓ High availability (95% for the whole facility at ESS)
  - Requires careful designs, robust algorithm, redundancy and very high reliable hardware
  - Requires quick detect and recovery from exceptions and faults
  - Requires high degree of automated operation
- ✓ High efficiency (work near the saturation of klystron, >80%)
  - Klystron gain linearization
  - Monitor and Update the linearization table in time
- ✓ Large scale
  - Around 200 LLRF systems for a variety of cavities: RFQ, DTL, Spoke, low beta and high beta superconducting cavities (one klystron per cavity).
- ✓ Other: Long pulse(2.86ms beam pulse), high current(50mA),…

Klystron efficiency

- Highest efficiency close to saturation
- But this gives high distortion due to nonlinearities.
- Solution: Linearization of the nonlinear klystron by the LLRF system.

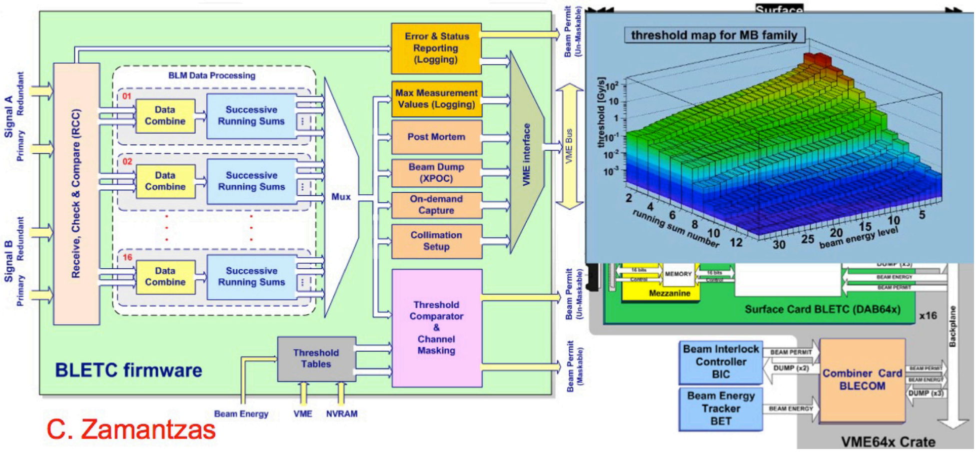


Rihua Zheng and Anders Johansson, ESS and LU

CPI VKP-8291B 805 MHz Klystron

Challenges for Beam Instrumentation
Beam Loss Monitors

- The higher the beam power, the higher the related damage potential of the accelerator components.
- BLM – part of a very complex machine protection system.
- BLM to MPS interface – very complicated. Has to be reliable and easy to operate.



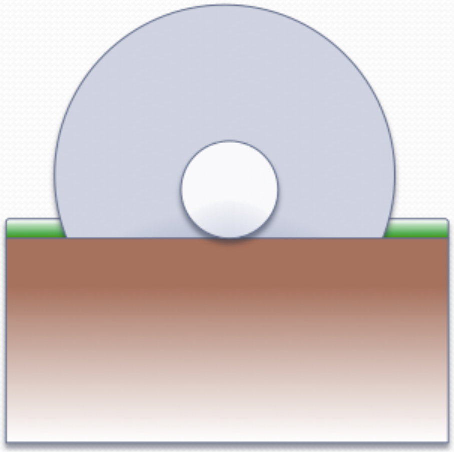
C. Zamantzas

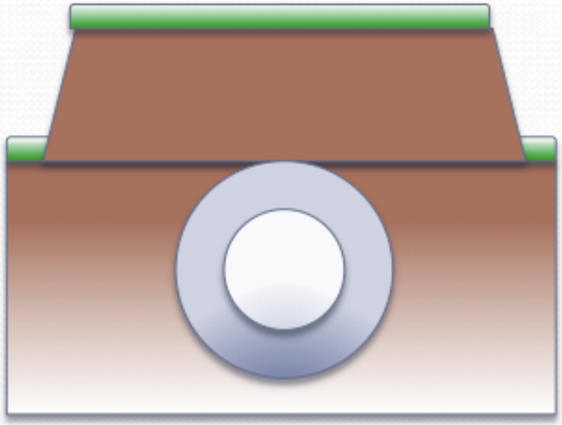
ESS Shielding

M. Jarosz,
Soltan Inst and ESS

- Most important question:

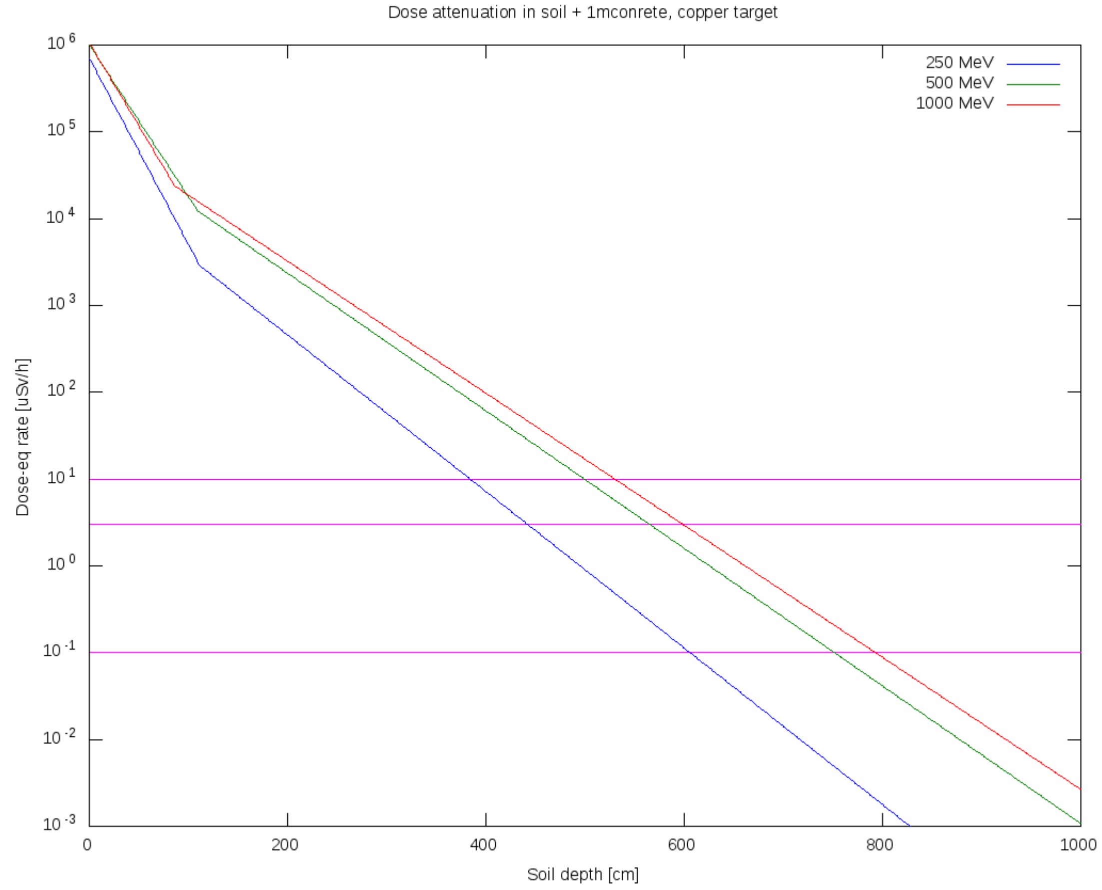
Which layout should be used ?





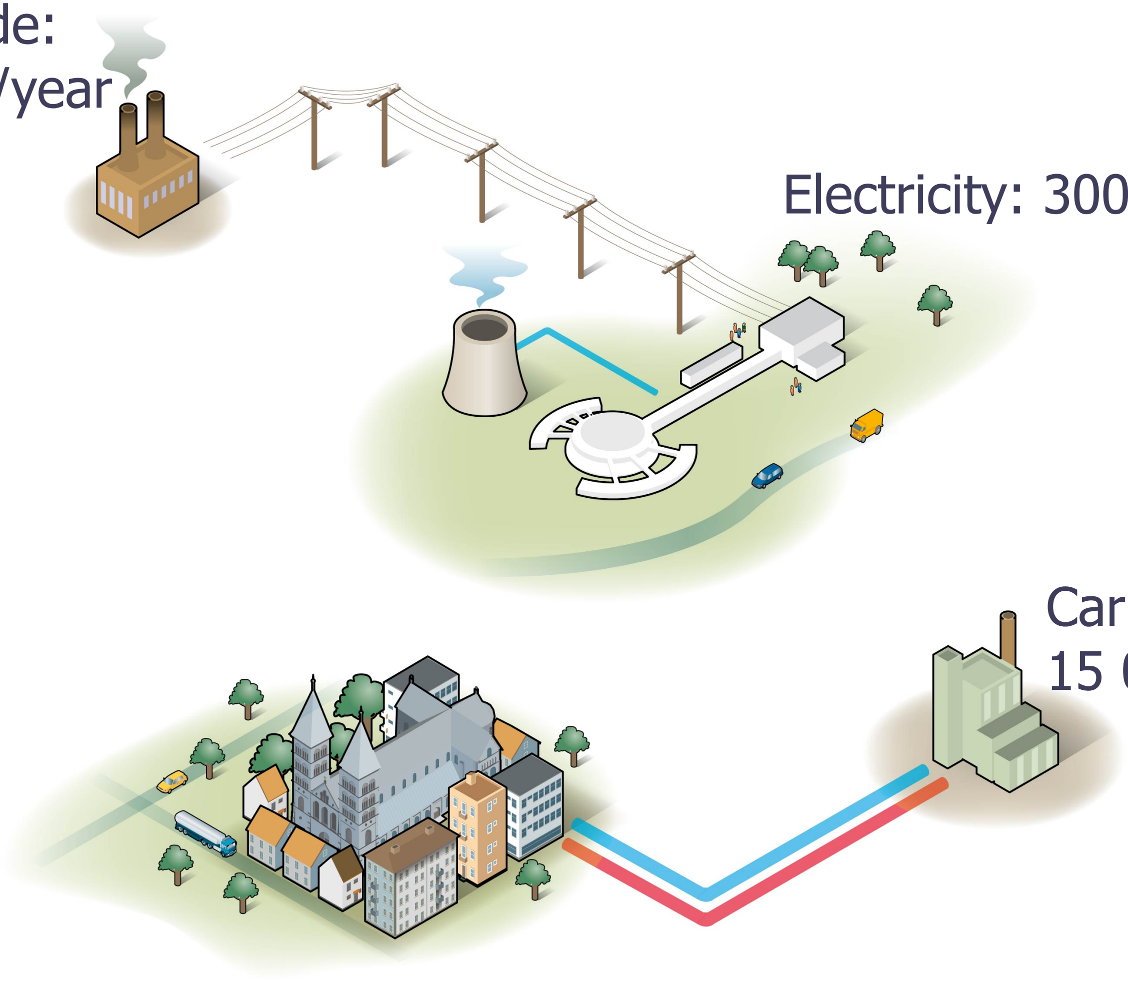
ESS Shielding – Simulations results

Concrete + soil



M. Jarosz,
Soltan Inst and ESS

Energy: This is the way we done it before!

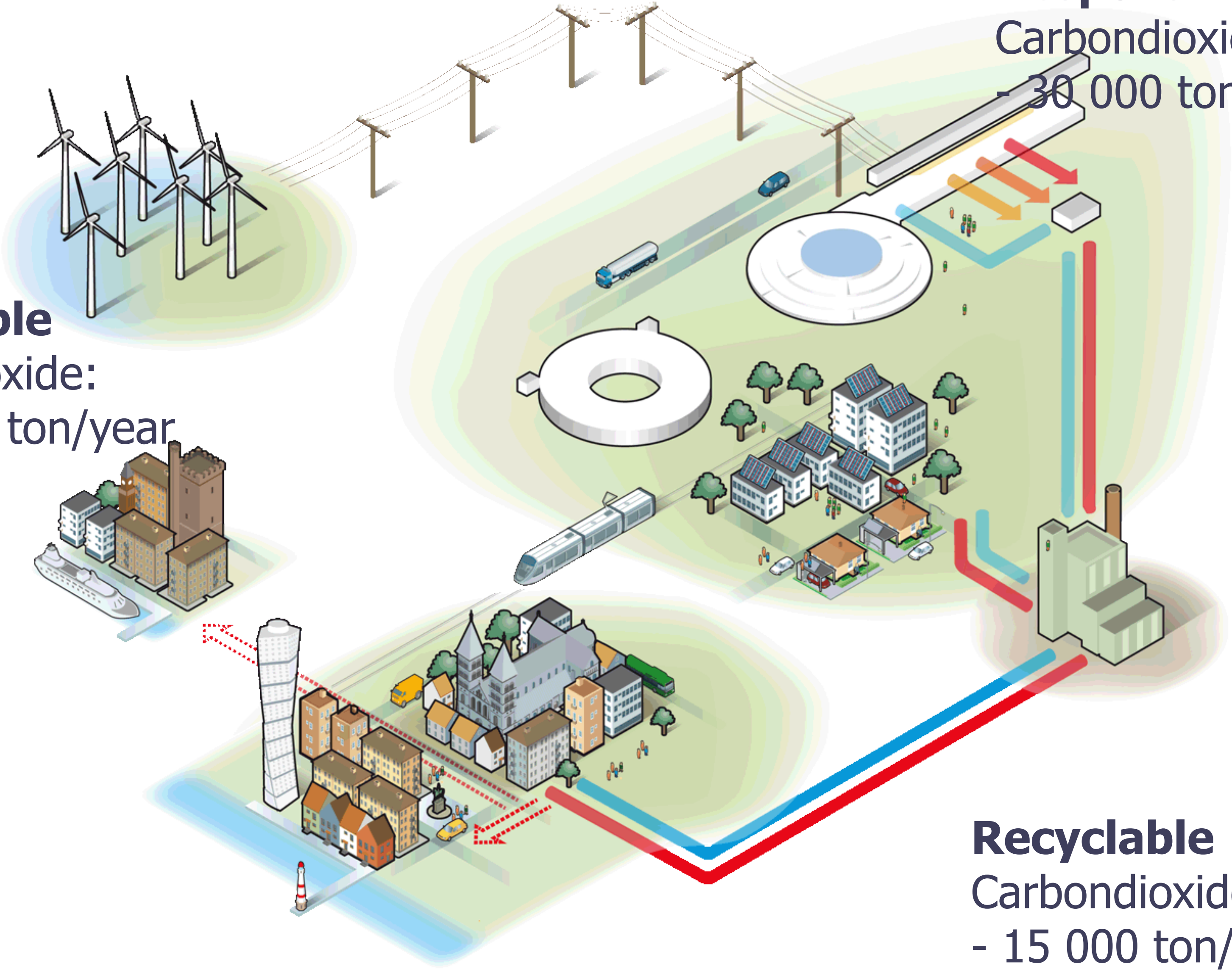


Carbondioxide:
150 000 ton/year

Electricity: 300 GWh/year

Carbondioxide:
15 000 ton/year

A sustainable research facility

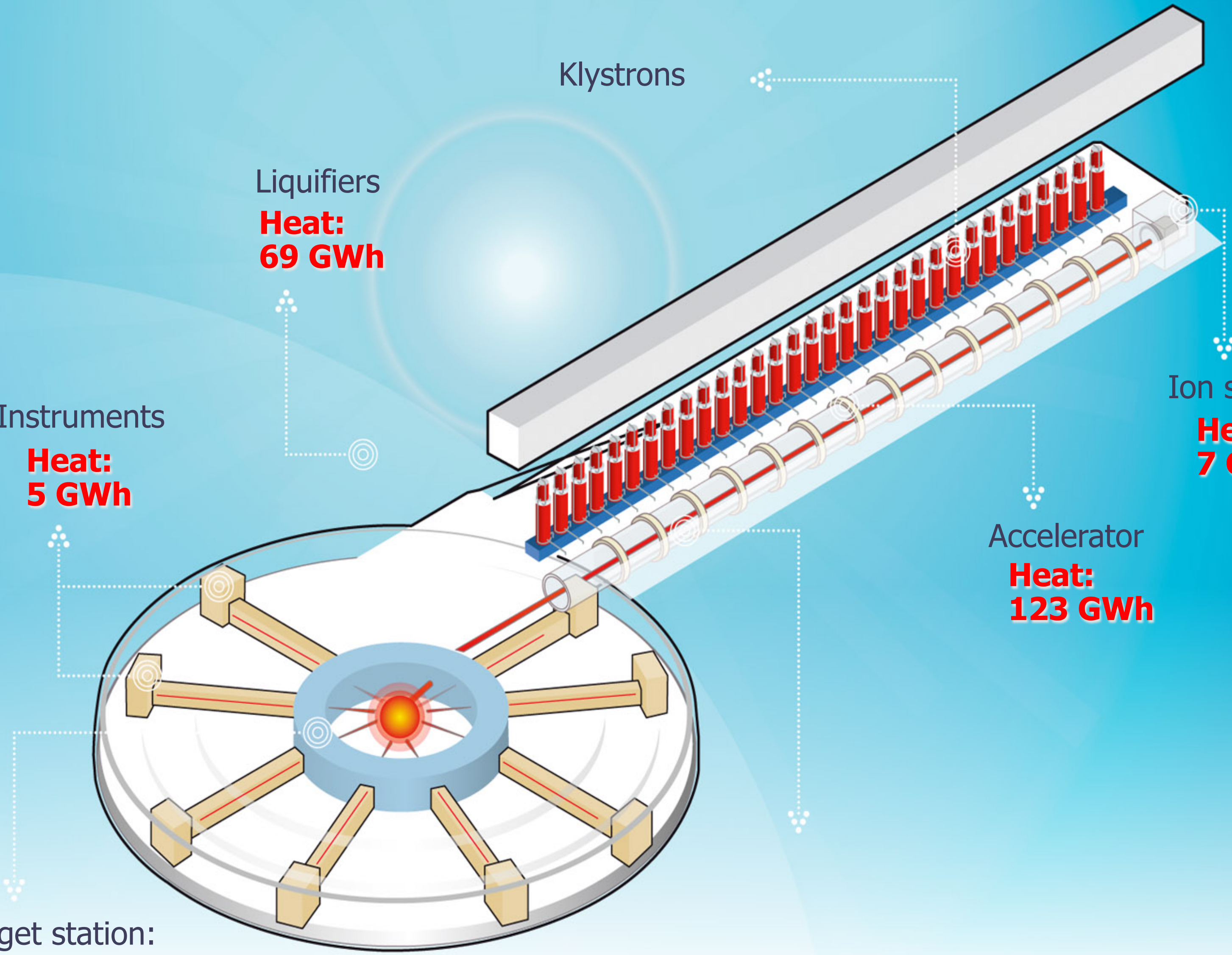


Responsible
Carbondioxide:
- 30 000 ton/year

Renewable
Carbondioxide:
- 120 000 ton/year

Recyclable
Carbondioxide:
- 15 000 ton/year

Heat from accelerator and Helium system



Klystrons

Liquifiers

Heat:
69 GWh

Instruments

Heat:
5 GWh

Ion source

Heat:
7 GWh

Accelerator

Heat:
123 GWh

Target station:

Heat:
11 GWh

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SPALLATION
SOURCE

SUSTAINABILITY PARTNERS

e·on LUNDS ENERGI

Summary

- High Q (Power and efficiency) is the challenge and not the gradient
- Most systems required to operate beyond “normal limits” and to do that very reliably
- Beam loss can result in major technical failures and stop operation for long periods
- Components are often design and prototyped at universities and must be “industrialized” as part of project. Very few components exists “on the shelf”.
- Energy aspects are very important, heat recovery is possible but requires a complete re-think of “cooling philosophy”

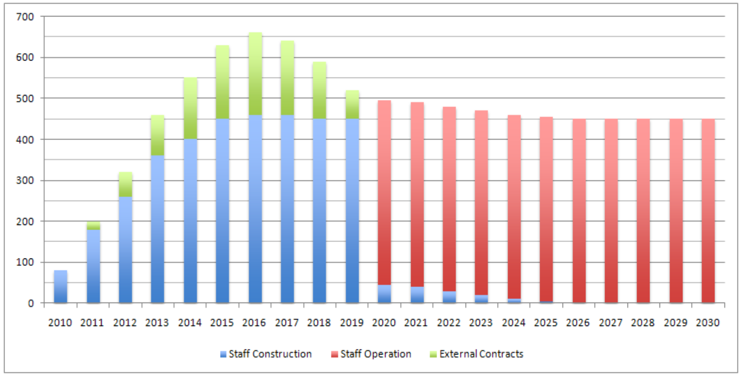
Project challenges

Just a few examples from ESS…

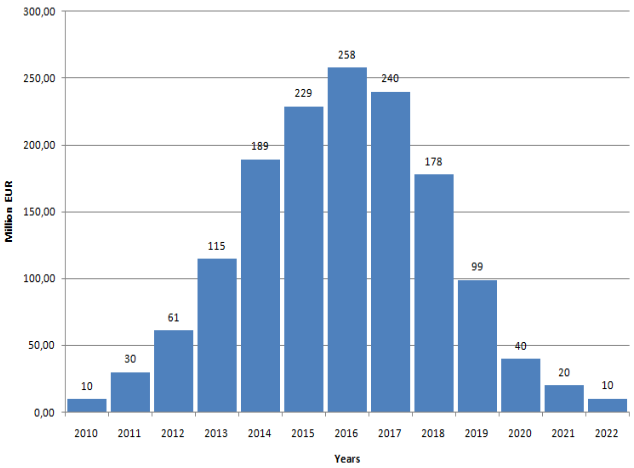
ESS construction cost estimates

Investment: 1478 M€ / ~10y
Operations: 106 M€ / y
Decomm. : 346 M€
(Prices per 2008-01-01)

Personel:



Investment:



What can you get for 1.5B€ today ?

You could buy four A380 airbuses…

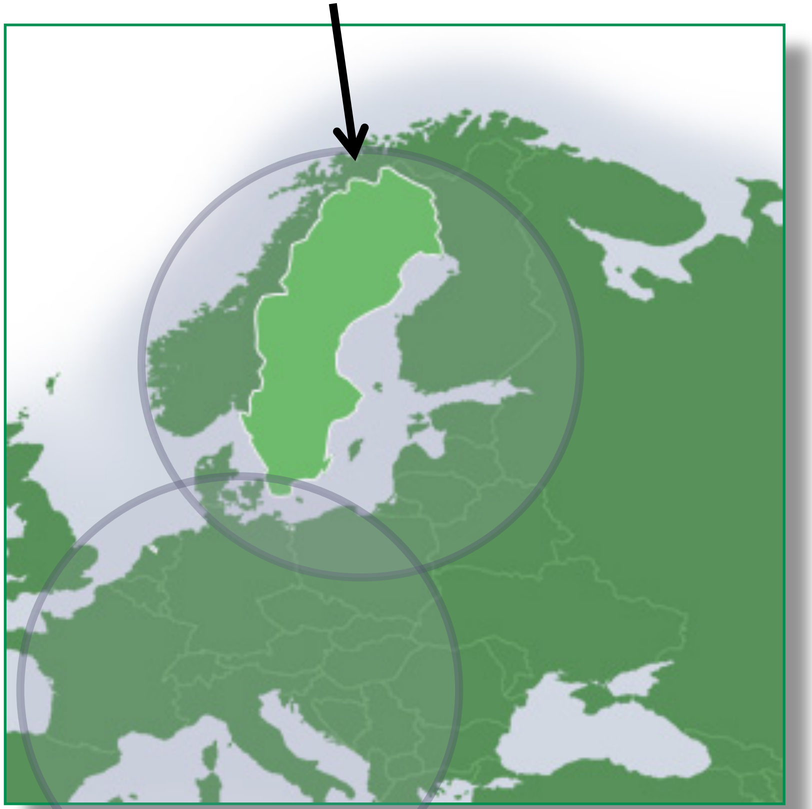
or, 25% of the Fehmarn Bridge

or, you could pay the bonuses of US bankers for…

24 days

International collaboration

Sweden, Denmark and Norway
covers 50% of cost



The remaining ESS members states together with EIB covers the rest!

17 Partners today

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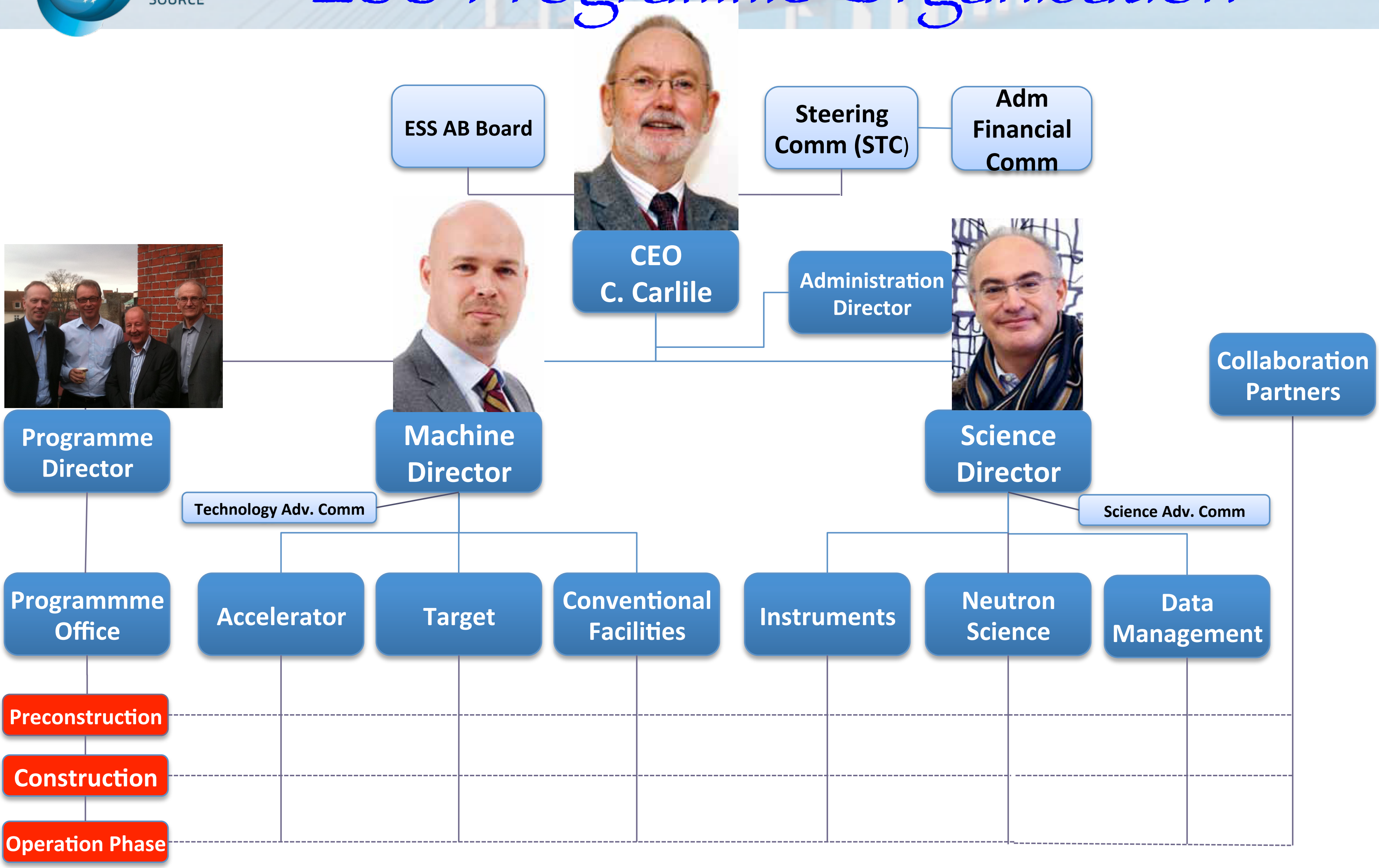
ESS Programme Organisation


ESS AB Board

Steering Comm (STC)

Adm Financial Comm

CEO
C. Carlile

Administration Director

Collaboration Partners

Programme Director

Machine Director

Science Director

Technology Adv. Comm

Science Adv. Comm

Programmme Office

Accelerator

Target

Conventional Facilities

Instruments

Neutron Science

Data Management

Preconstruction

Construction

Operation Phase

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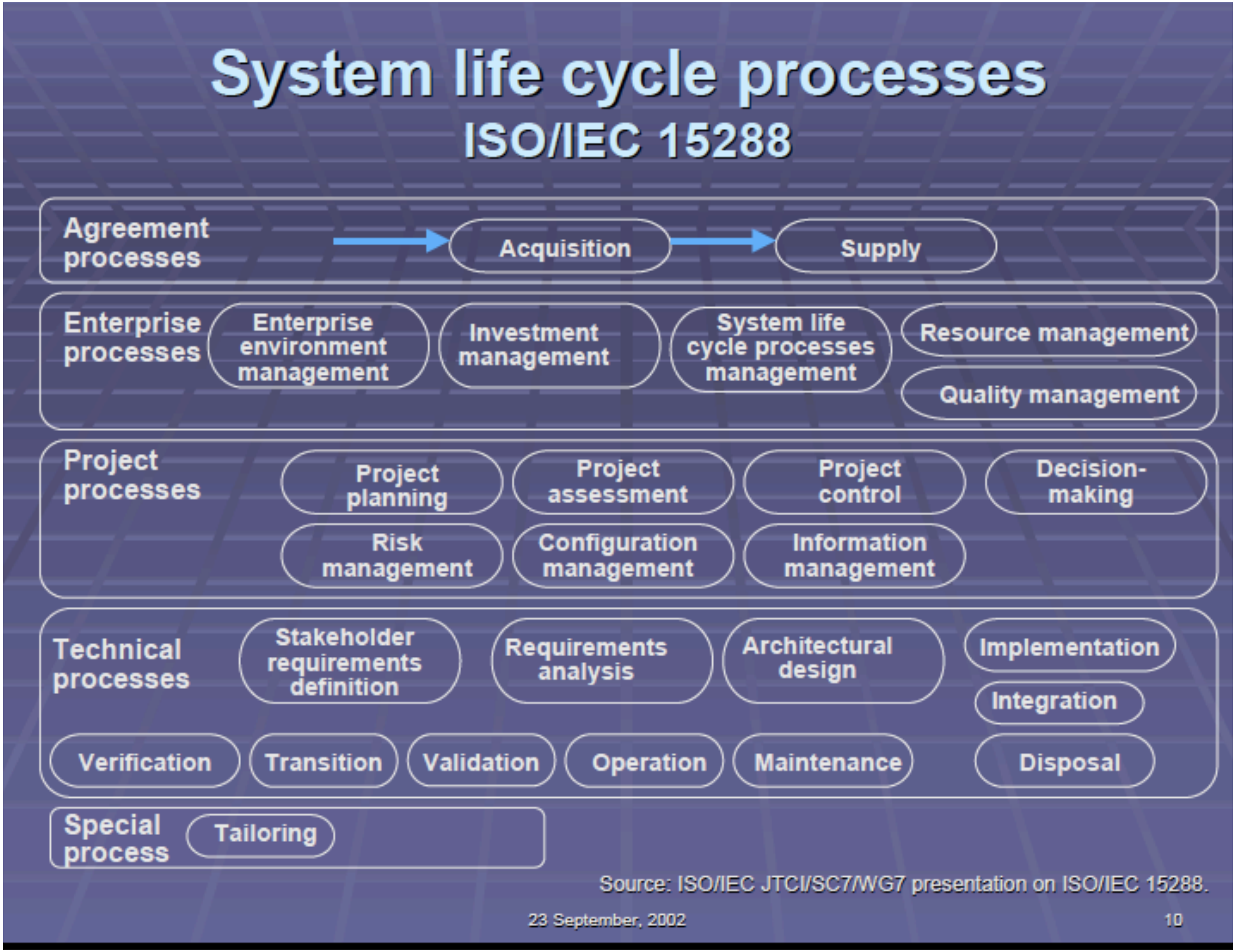
ISO Project methodology



System life cycle processes

ISO/IEC 15288

Agreement processes
- Acquisition
- Supply

Enterprise processes
- Enterprise environment management
- Investment management
- System life cycle processes management
- Resource management
- Quality management

Project processes
- Project planning
- Project assessment
- Project control
- Decision-making
- Risk management
- Configuration management
- Information management

Technical processes
- Stakeholder requirements definition
- Requirements analysis
- Architectural design
- Implementation
- Integration
- Verification
- Transition
- Validation
- Operation
- Maintenance
- Disposal

Special process
- Tailoring

Source: ISO/IEC JTCI/SC7/WG7 presentation on ISO/IEC 15288.

23 September, 2002

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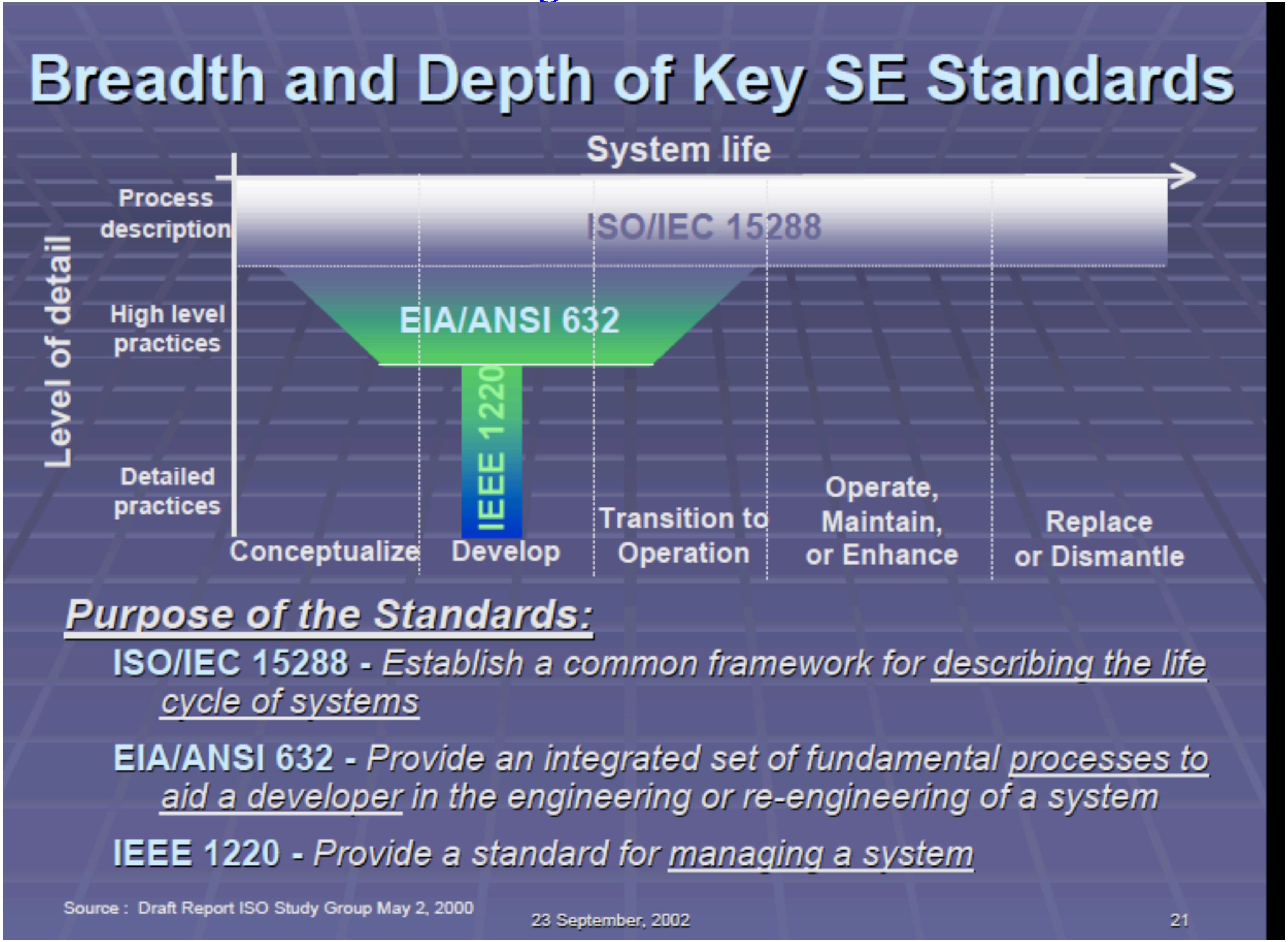
ISO project methodology



Breadth and Depth of Key SE Standards

System life

Level of detail

Process description

High level practices

Detailed practices

ISO/IEC 15288

EIA/ANSI 632

IEEE 1220

Conceptualize

Develop

Transition to Operation

Operate, Maintain, or Enhance

Replace or Dismantle

Purpose of the Standards:

ISO/IEC 15288 - *Establish a common framework for describing the life cycle of systems*

EIA/ANSI 632 - *Provide an integrated set of fundamental processes to aid a developer in the engineering or re-engineering of a system*

IEEE 1220 - *Provide a standard for managing a system*

Source : Draft Report ISO Study Group May 2, 2000

23 September, 2002

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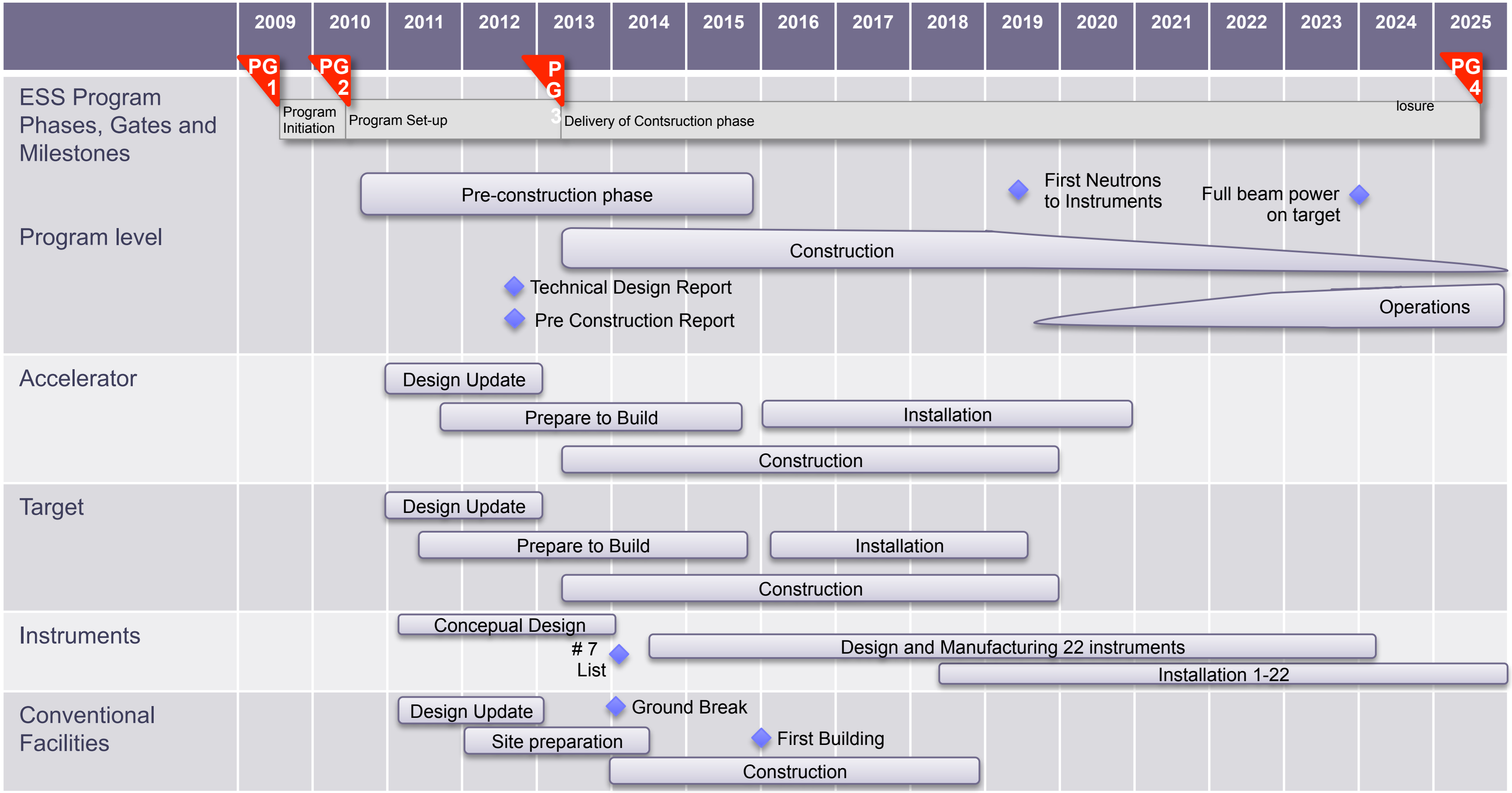
ESS Master Programme Schedule



Accelerator Design Update

Steve Peggs

Cristina Oyon

Romuald Duperrier
(30 years ago)

Josu Eguia

Work Package (work areas)

1. Management Coordination – ESS (Mats Lindroos)
2. Accelerator Science – ESS (Steve Peggs)
3. Infrastructure Services – Tekniker, Bilbao (Josu Eguia)
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 – Uppsala university (Roger Ruber)

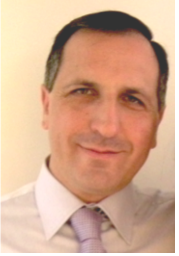
Mats Lindroos

Guillaume Devanz

Roger Ruber

UPPSALA UNIVERSITET

Søren Pape Møller



Santo Gammino

Sebastien Bousson

Summary

- New infrastructure is often built through collaboration to shorten the preparatory phase and optimize the use of existing infrastructure for construction
- Many new infrastructures are green field facilities AND organizations
- The new facilities are required to design, build and operate as high tech industry and not as laboratories
- The owners requires:
  - A very aggressive schedule to keep up with a very competitive research sector
  - That all work is done using PMI/ISO compliant project methodology and life cycle management
  - Strict cost control (design to cost)
  - That all upgrade potential must be costed as both initial preparatory cost and later investment cost and can't be left as "hidden potential"
  - That the operation cost is highly optimized with a only a nucleus staffing and strict control of running costs such as energy
- The budget is usually a mixture of "non-cash/in-kind" contributions and cash
  - All non-cash/in-kind contributions will encounter priority issues at the contributing labs and need a strict contract framework
  - The non-cash/in-kind models are still being developed, experience shows that it must be set under competition to avoid that parts of it disappear into national projects and priorities
  - The use of Quality control and Risk management methods are essential to assure that the non-sash/in-kind contributions are delivered on budget and in time

Challenges

- Accelerator physics
  - High beam power
  - Beam losses
- Technical
  - Reliability
  - Energy efficiency
  - Space considerations and “foot print”
  - Shielding and safety
- Project
  - Schedule and dead-lines
  - Cost control and/or Design to cost
  - In-kind contributions