EUROPEAN
SPALLATION
SOURCE

ESS – The first “green” accelerator

Andreas Jansson
Group Leader, Beam Diagnostics

oPAC School, RHUL, 11 July 2014

Credits

Thanks to

Mats Lindroos
Håkan Danared
Mohammad Eshraqi
Dave McGinnis
Thomas Parker
Morten Jensen

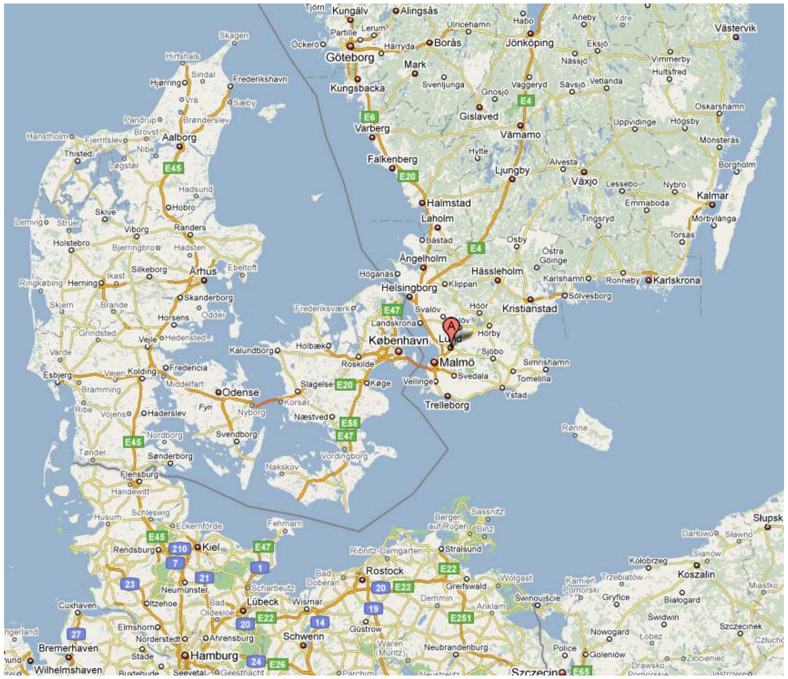
From whom I have borrowed and adapted most of the material

Overview of ESS, why neutrons?

- Introduction to ESS
- Why neutrons?
- Historical background of ESS
- Recent design process
  - Since Lund site decision
- Latest (cost) optimization round and current design
  - Performance, cost, risk and schedule optimization
- Energy efficiency and CO2

The European Spallation Source (ESS)

- ESS is a neutron spallation source that will be built by a collaboration of 17 European countries.
- ESS is located in southern Sweden adjacent to MAX-IV (A 4th generation light source)

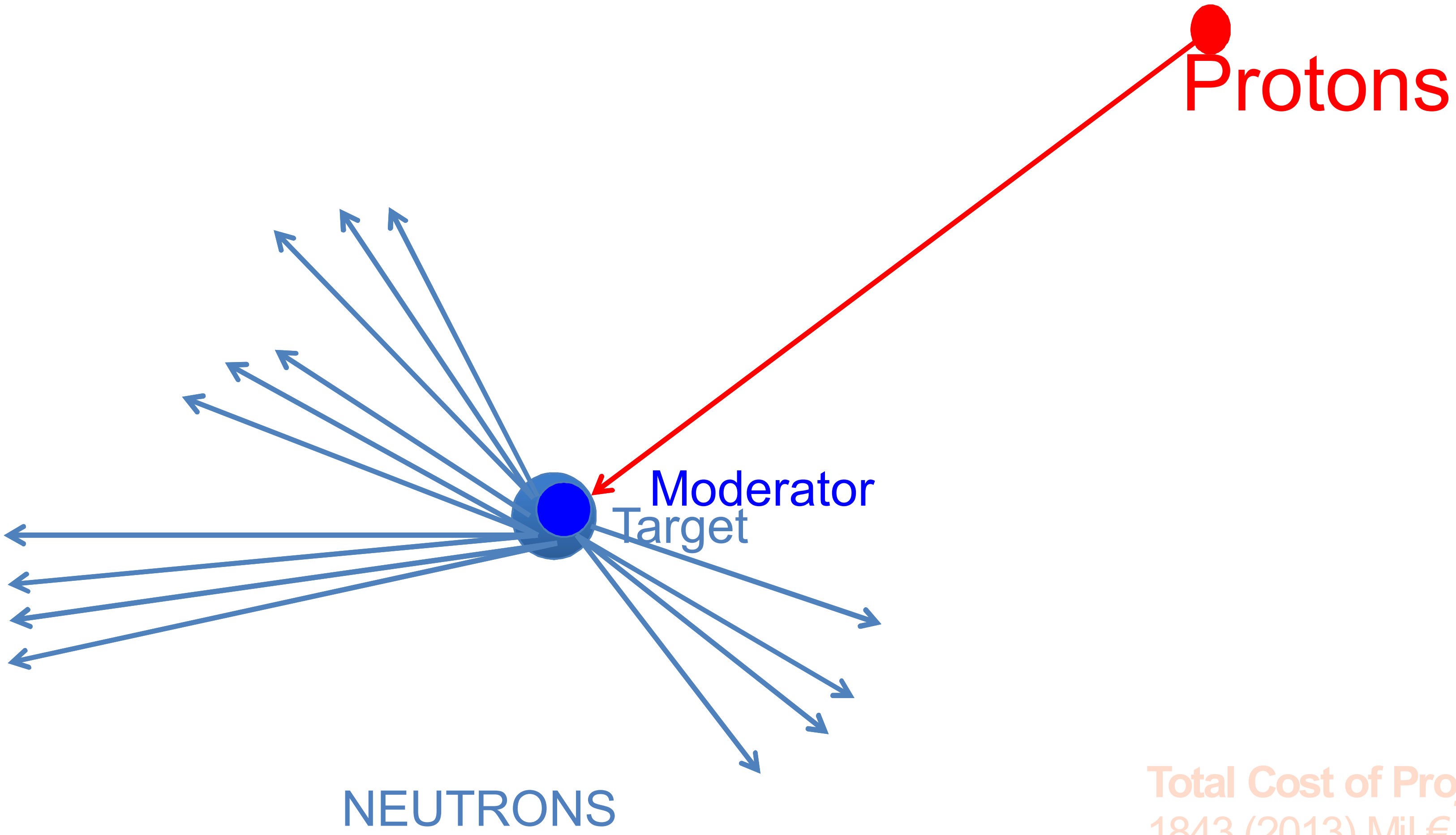


Our nearest neighbor, MAX-IV

ESS today (actually last week)

Helicopter view of ESS

Proton Accelerator



Protons

Moderator

Target

NEUTRONS

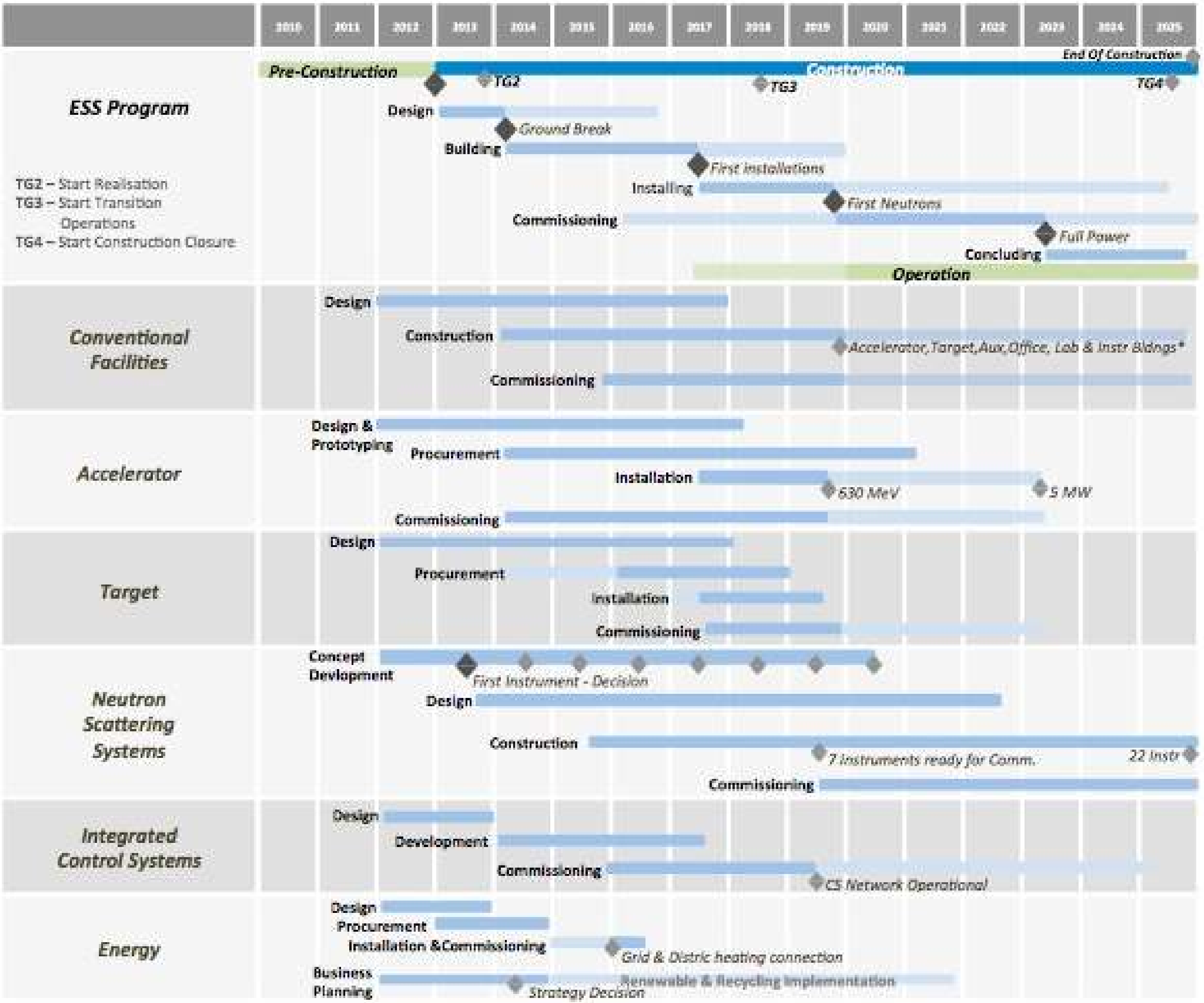
Total Cost of Project
1843 (2013) Mil €

The ESS Linac

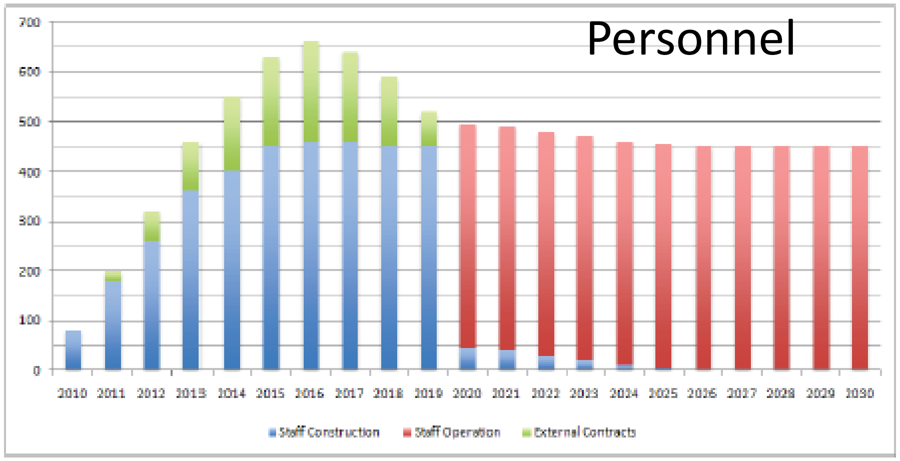
- The European Spallation Source (ESS) will house the most powerful proton linac ever built.
  - Average beam power of 5 MW.
  - Peak beam power of 125 MW
  - Acceleration to 2 GeV
  - Peak proton beam current of 62.5 mA
  - Pulse length of 2.86 ms at a rate of 14 Hz (4% duty factor)
- 97% of the acceleration is provided by superconducting cavities.
- The linac will require over 150 individual high power RF sources
  - with 80% of the RF power sources requiring over 1.1 MW of peak RF power
  - We expect to spend over 200 M€ on the RF system alone

ESS Schedule

- Full funding and ground-break in Fall 2014
- 1.25 MW of proton beam power by 2019
- 5 MW of proton beam power by 2022



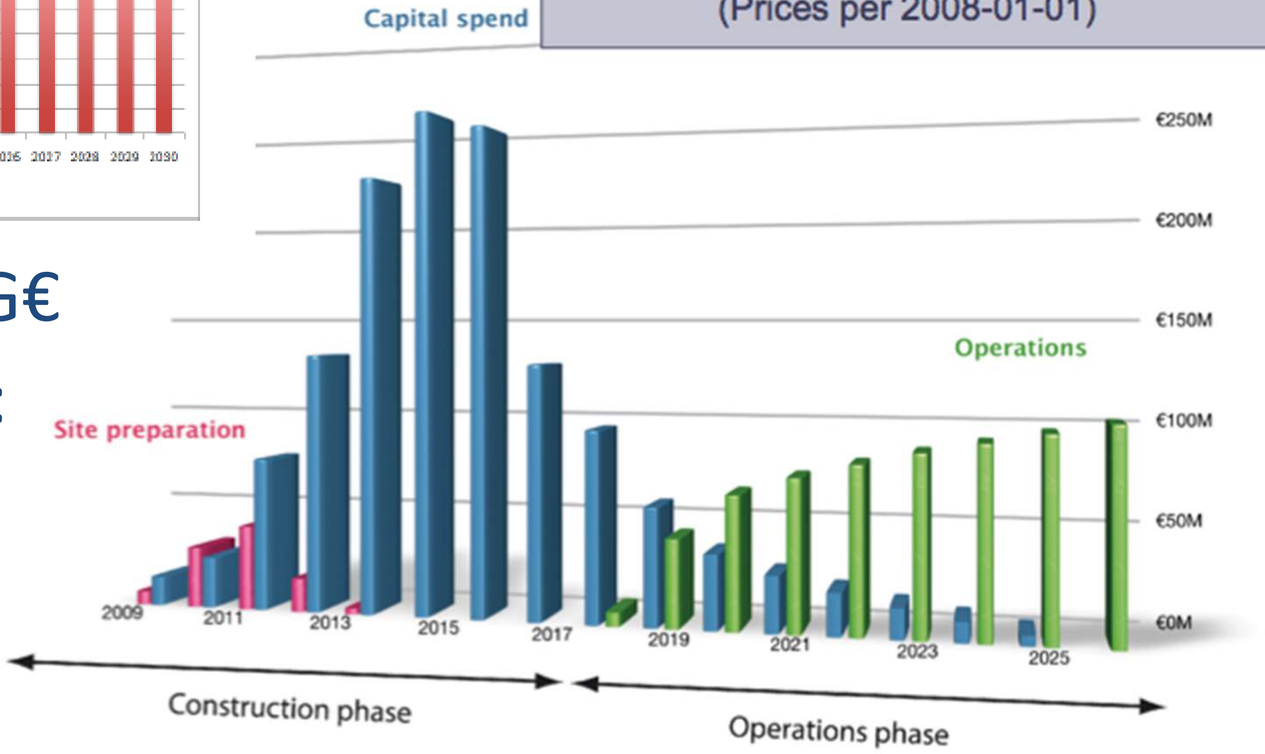
ESS Cost


Personnel

- Total cost: 1.86 G€
- Accelerator cost: 515 M € (excluding civil construction)

Investment:	1478 M€ / ~10y
Operations:	89 M€ / y
Decommissioning. :	346 M€

(Prices per 2008-01-01)

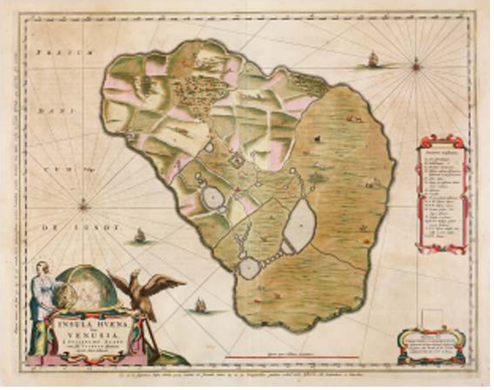


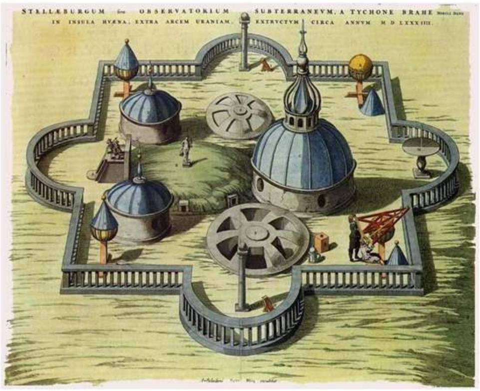
Investment

1.8 Billion Euros:
Biggest investment in Science ever in Scandinavia?

In modern time, definitely YES!

However, Tycho Brahe’s Stjärneborg costed the Danish king 1% of the state budget in 1580.





“With better measurements of the stars positions and movements I can make much better horoscopes for you, your majesty!”

ESS Funding Model

Sweden, Denmark and Norway covers 50% of cost

The remaining ESS members states covers the rest!

with in-kind and cash contributions.

Collaboration/In-kind

- The cost of the next generation of high intensity accelerators has become so large that no single institution can solely afford to fund the construction of the project.
- To fund these large projects, institutions have embarked on forming ambitious collaboration structures with other laboratories.
  - For example, 60% of the European Spallation Source linac will be funded with in-kind contributions.
- To induce other laboratories to join the collaboration
  - compromises must be made in the accelerator technical design
  - to offer interesting and challenging projects to partner institutions.
- The accelerator system designer must then
  - try to balance the cost and technical risks
  - while also satisfying the interests and external goals of the partner laboratories

EUROPEAN SPALLATION SOURCE

Artist's conception of the European Spallation Source.

European Spallation Source ready to start construction

By Tania Rabesandratana | 7 July 2014 3:15 pm | Comments

Having secured about 97.5% of its construction money from 13 member countries, the European Spallation Source (ESS) has announced that it will break ground in Lund, Sweden, in the fall—more than a year later than first planned.

"We are thrilled to be able to move ahead," ESS Director-General Jim Yeck said in a statement on Friday. In February 2011, ESS's 17 partner countries agreed to work together on the project, but each government then had to

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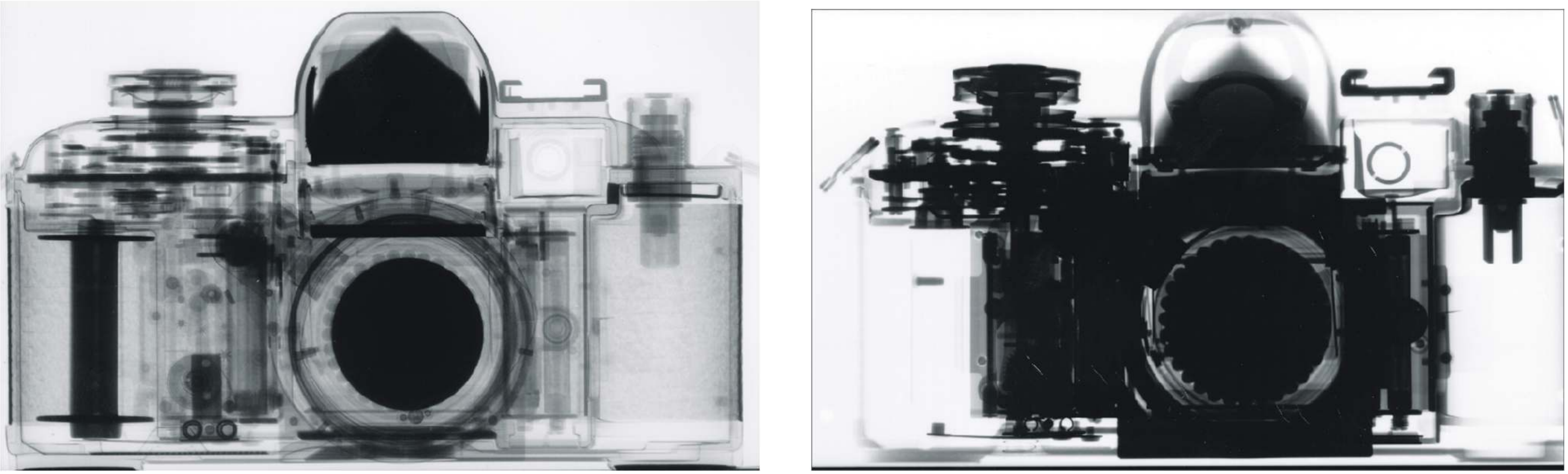
Rendition: ESS/Team Henning Larsen

Funding completed for Lund neutron source

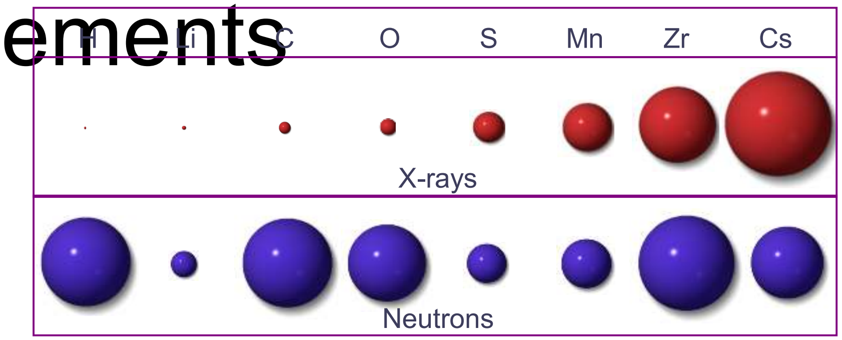
Published: 04 Jul 2014 16:05 GMT+02:00
Updated: 04 Jul 2014 16:05 GMT+02:00

Funding for the European Spallation Source (ESS), the world's most powerful neutron source, has been completed, Education Minister Jan Björklund announced on Friday. The ESS will be built in Lund, Sweden.

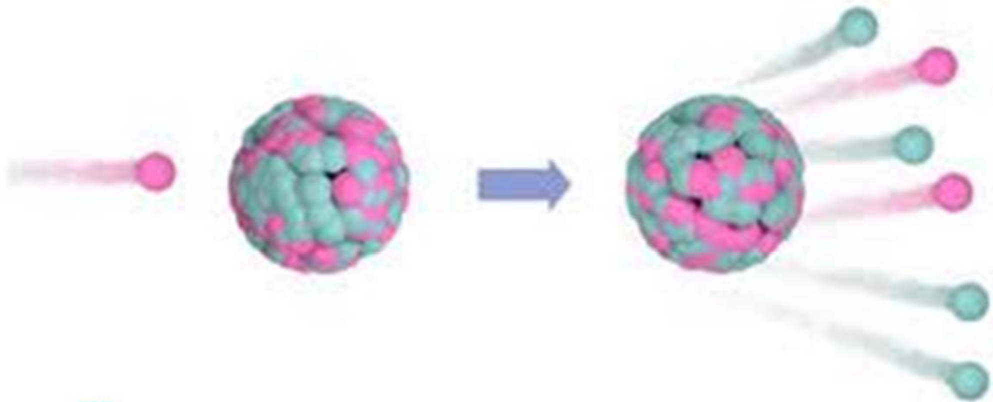
Complementarity between X-rays and Neutrons

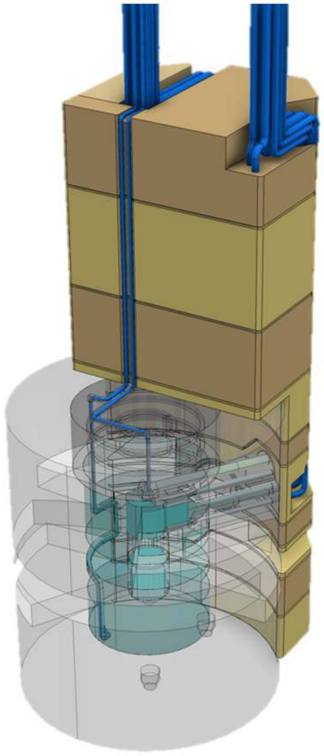


- Neutrons and x-rays sensitive to different things
- Neutrons particularly good to see hydrogen, while x-ray see heavier elements

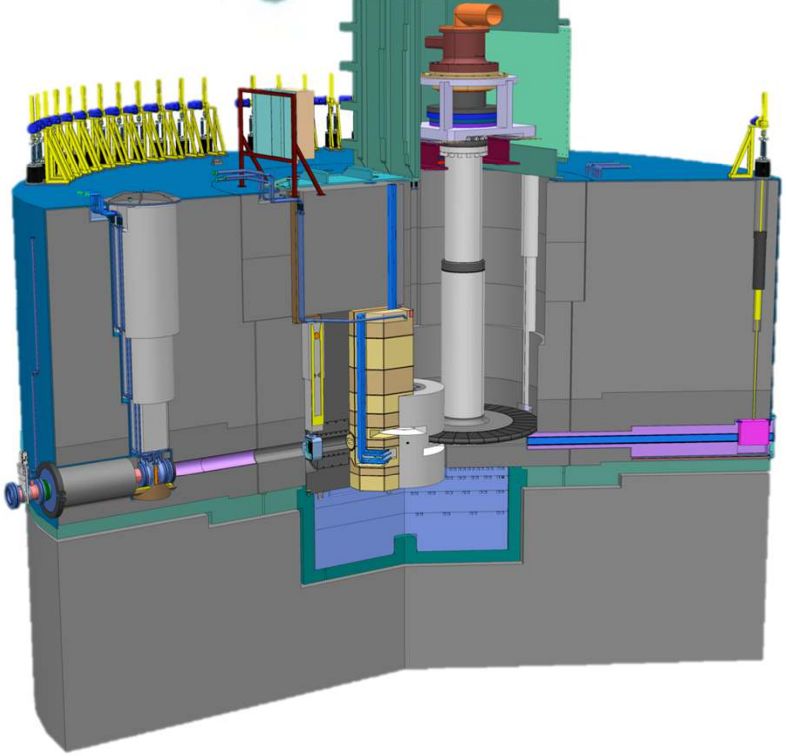


Spallation

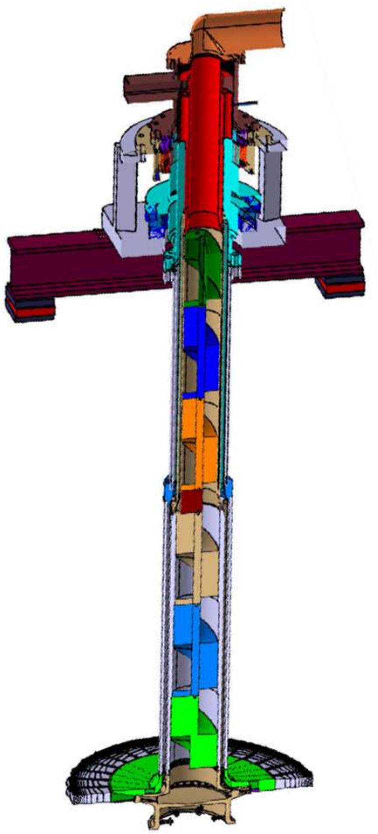




moderator



Target station

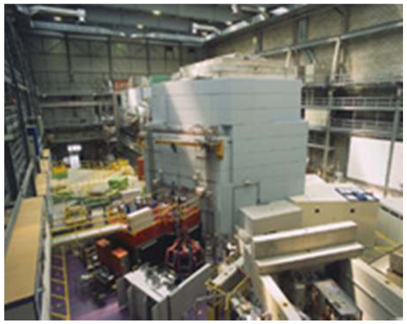


Target wheel

Operating Spallation Neutron Sources

LANSCE, USA
1977-
Linac+ring
800 MeV
17 mA in linac
100 kW

ISIS, UK
1984-
RCS
800 MeV
200 mA extracted
160 kW



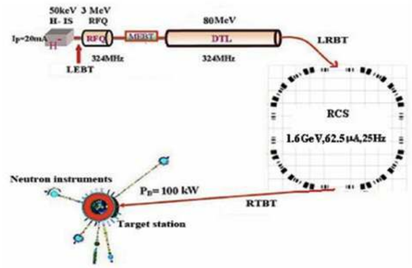
SINQ, Switzerland
1997-
Cyclotron
590 MeV
2.2 mA extracted
1.3 MW

SNS, USA
2006-
Linac+ring
1 GeV
26 mA in linac
1.4 MW

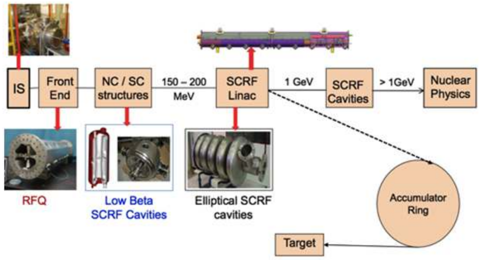
Figure 2 Overall image of J-PARC

J-PARC, Japan
2008-
RCS
3 GeV
330 mA extracted
1 MW (planned)

Planned Spallation Neutron Sources



CSNS, China
2018-
RCS
1.6 GeV
15 mA in linac
100 kW



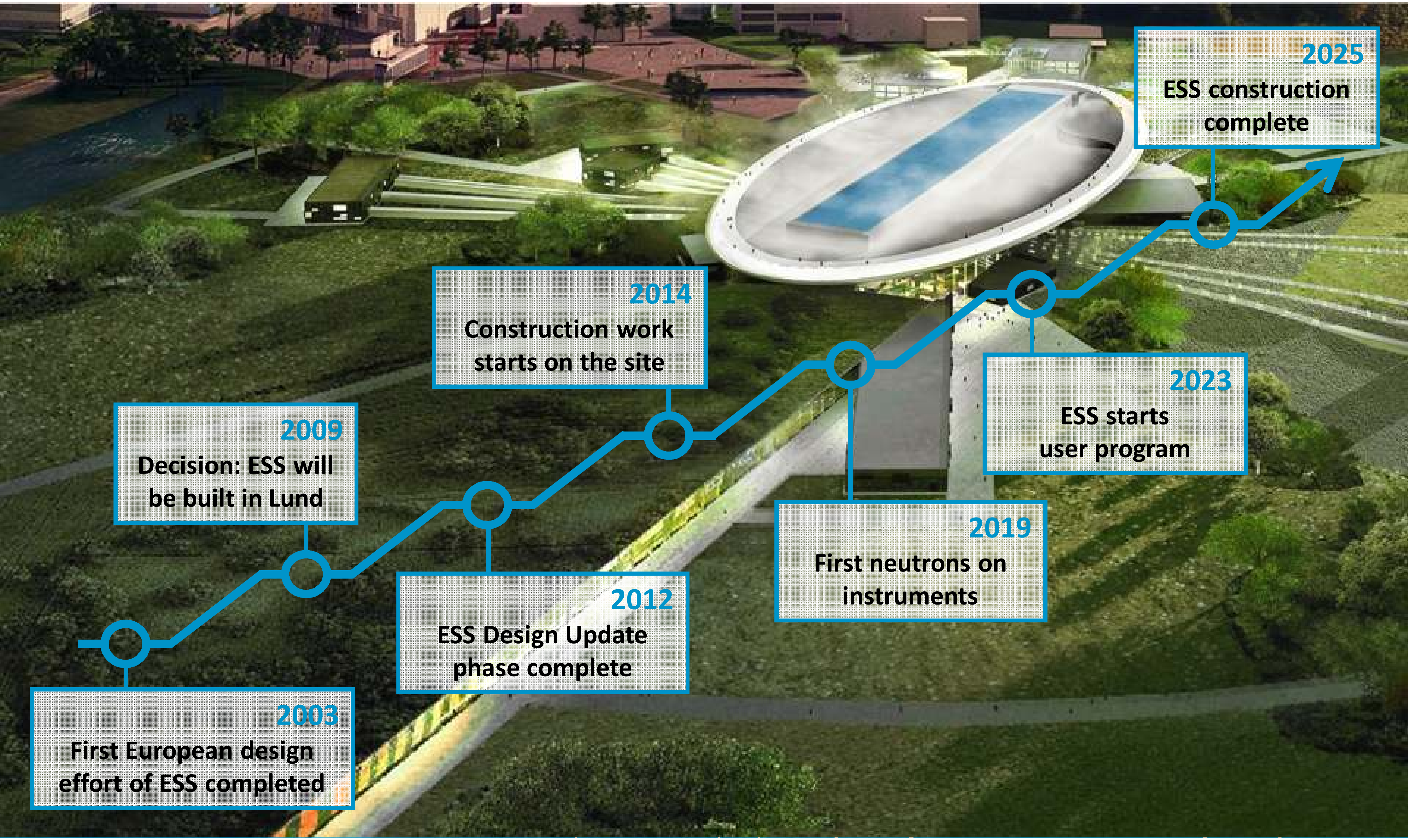
ISNS, India
Linac+ring
1 GeV
20-50 mA in linac
1 MW

ESS, Sweden
2019-
Linac
2 GeV
62.5 mA
5 MW

What is 5 MegaWatts?

- At 5 MegaWatts,
  - **one** beam pulse
    - has the same energy as a 16 lb (7.2kg) shot traveling at
      - 1100 km/hour
      - Mach 0.93
    - Has the same energy as a 1000 kg car traveling at 96 km/hour
    - Happens 14 x per second
  - You boil 1000 kg of ice in 83 seconds
    - A ton of tea!!!

Road to realizing the world's leading facility for research using neutrons



2003
First European design effort of ESS completed

2009
Decision: ESS will be built in Lund

2012
ESS Design Update phase complete

2014
Construction work starts on the site

2019
First neutrons on instruments

2023
ESS starts user program

2025
ESS construction complete

Historical Time Line

1992

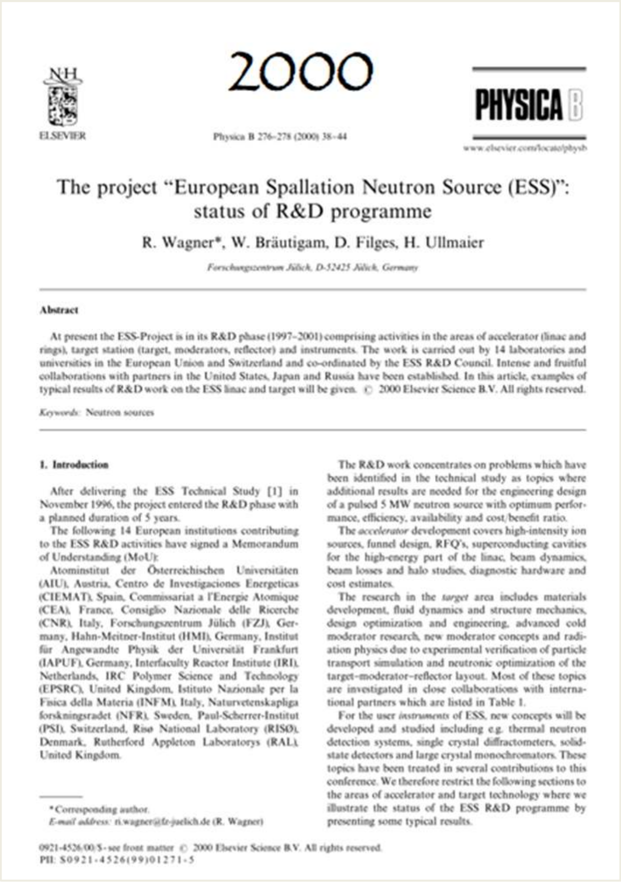
European Spallation Source workshop

Authors: A. D. Taylor ¹; G. H. Lander
Affiliation: ¹ Rutherford Appleton Laboratory,
Published in: Neutron News, Volume 3, Issue 2 1992 , page 4
Subjects: Atomic & Nuclear Physics; Particle & High Energy Physics

Abstract

A meeting of about 70 experts in condensed-matter science took place in late February at Abingdon, UK, to discuss the scientific opportunities and technological challenges of a new 3rd generation spallation source - the so-called European Spallation Source (ESS).

This Workshop was, in fact, the third in a series: the first, in September 1991 at Simonskall near Jülich, considered the accelerator options; the second in February 1992, in PSI, Villigen, Switzerland, considered the problems of providing targets and monochromators. The meeting opened with talks from S. Martin (Jülich), G. Bauer (PSI) and J. Carpenter (Argonne) on the accelerator, target, and moderator options, respectively. Although the problems are formidable in all areas, there don ot seem to be any insuperable obstacles for building a system with a 5 MW beam of protons with a short pulse length of ~1 μ delivered onto two (or more) stationary targets surrounded by a variety of moderators. The heat load on the target could approach 4 MW/litre, similar to that found in a high-flux reactor, but Bauer pronounced that "it can be done." The neutron production of such a source would be spectacular, with a peak flux of ~ 10^{17} n/sec/cm^2 and an average flux close to that of the ILL.



2000

NH
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Physica B 276–278 (2000) 38–44

PHYSICA B
www.elsevier.com/locate/physb

The project "European Spallation Neutron Source (ESS)": status of R&D programme

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Abstract

At present the ESS-Project is in its R&D phase (1997–2001) comprising activities in the areas of accelerator (linac and rings), target station (target, moderators, reflector) and instruments. The work is carried out by 14 laboratories and universities in the European Union and Switzerland and co-ordinated by the ESS R&D Council. Intense and fruitful collaborations with partners in the United States, Japan and Russia have been established. In this article, examples of typical results of R&D work on the ESS linac and target will be given. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Neutron sources

1. Introduction

After delivering the ESS Technical Study [1] in November 1996, the project entered the R&D phase with a planned duration of 5 years.

The following 14 European institutions contributing to the ESS R&D activities have signed a Memorandum of Understanding (MoU):

Atominstitut der Österreichischen Universitäten (AIU), Austria, Centro de Investigaciones Energeticas (CIEMAT), Spain, Commissariat a l'Energie Atomique (CEA), France, Consiglio Nazionale delle Ricerche (CNR), Italy, Forschungszentrum Jülich (FZJ), Germany, Hahn-Meitner-Institut (HMI), Germany, Institut für Angewandte Physik der Universität Frankfurt (IAPUF), Germany, Interfaculty Reactor Institute (IRI), Netherlands, IRC Polymer Science and Technology (EPSRC), United Kingdom, Istituto Nazionale per la Fisica della Materia (INFM), Italy, Naturvetenskapliga forskningsradet (NFR), Sweden, Paul-Scherrer-Institut (PSI), Switzerland, Risø National Laboratory (RISØ), Denmark, Rutherford Appleton Laboratorys (RAL), United Kingdom.

The R&D work concentrates on problems which have been identified in the technical study as topics where additional results are needed for the engineering design of a pulsed 5 MW neutron source with optimum performance, efficiency, availability and cost/benefit ratio.

The *accelerator* developement covers high-intensity ion sources, funnel design, RFQ's, superconducting cavities for the high-energy part of the linac, beam dynamics, beam losses and halo studies, diagnostic hardware and cost estimates.

The research in the *target* area includes materials development, fluid dynamics and structure mechanics, design optimization and engineering, advanced cold moderator research, new moderator concepts and radiation physics due to experimental verification of particle transport simulation and neutronic optimization of the target–moderator–reflector layout. Most of these topics are investigated in close collaborations with international partners which are listed in Table 1.

For the user *instruments* of ESS, new concepts will be developed and studied including e.g. thermal neutron detection systems, single crystal diffractometers, solid-state detectors and large crystal monochromators. These topics have been treated in several contributions to this conference. We therefore restrict the following sections to the areas of accelerator and target technology where we illustrate the status of the ESS R&D programme by presenting some typical results.

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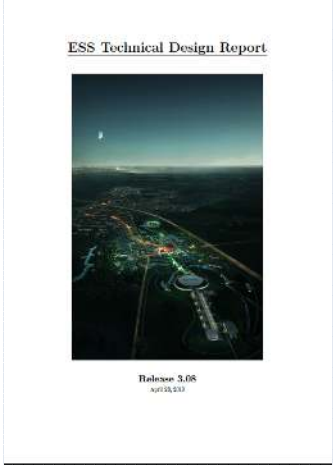
PII: S0921-4526(99)01271-5

Design
Report
2013



ESS Technical Design Report

Release 3.06

The ESS Project
Volume I

European Source
of Science

ess european spallation source

first design

2002-2003

ESFRI Report
2003

MEDIUM TO LONG-TERM
FUTURE SCENARIOS
FOR NEUTRON-BASED SCIENCE
IN EUROPE

Working Group on Neutron Facilities

European Strategy Forum
on Research Infrastructures

European Strategy Forum on Research Infrastructures

ESFRI

EUROPEAN ROADMAP
FOR RESEARCH
INFRASTRUCTURES

Roadmap 2008

UPDATE 2008

esss
European Spallation Source
Scandinavia

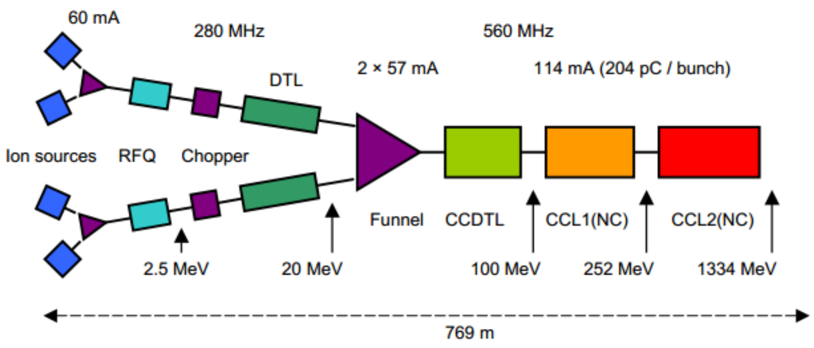
FOCUS
on
Lund!

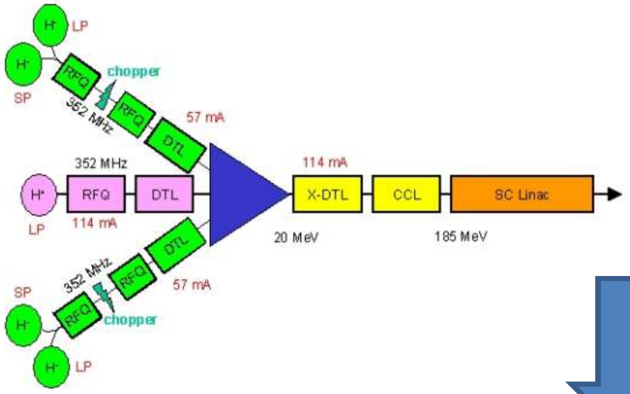
The
ESS Scandinavia
submission to the
ESFRI Working Group on ESS siting

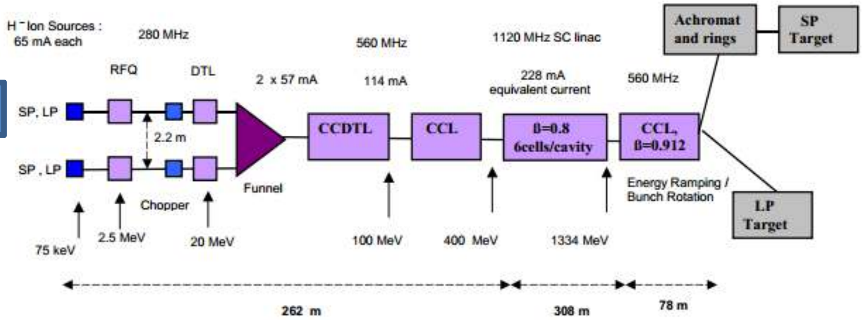
25th April 2008

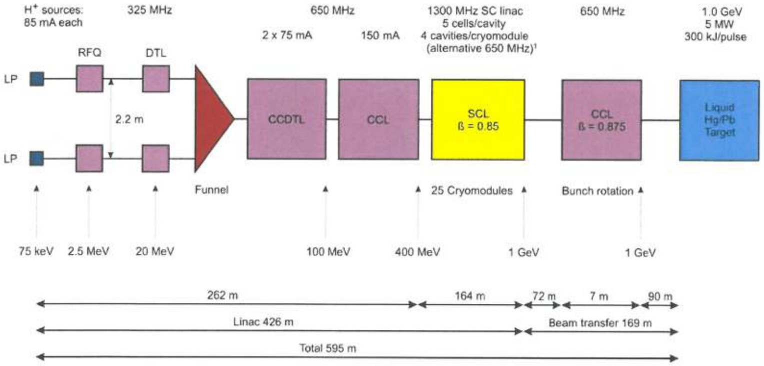
site
decision
2009

ESS Linac Evolution









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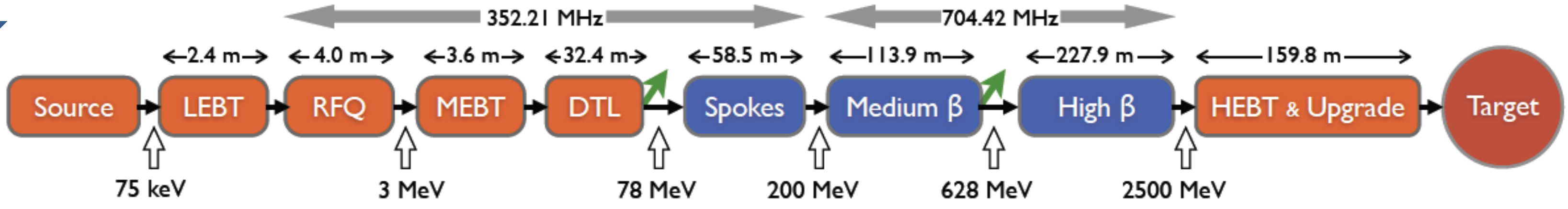
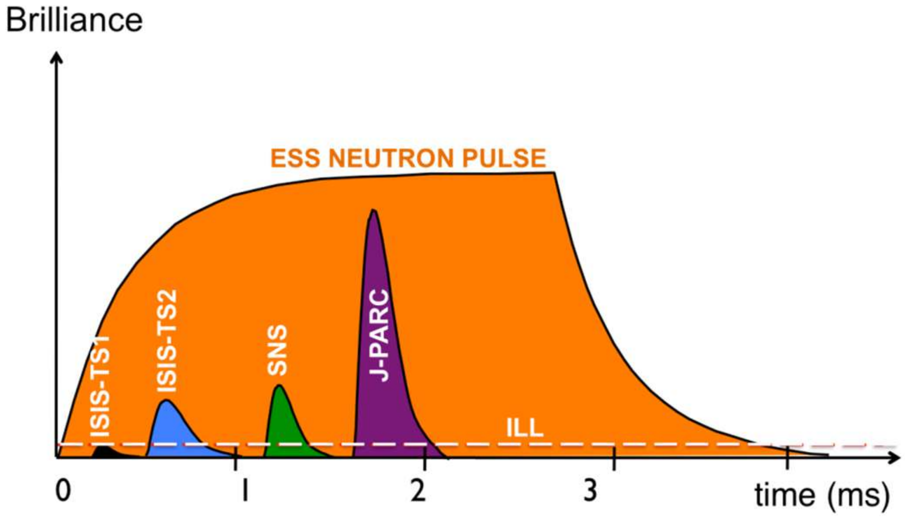
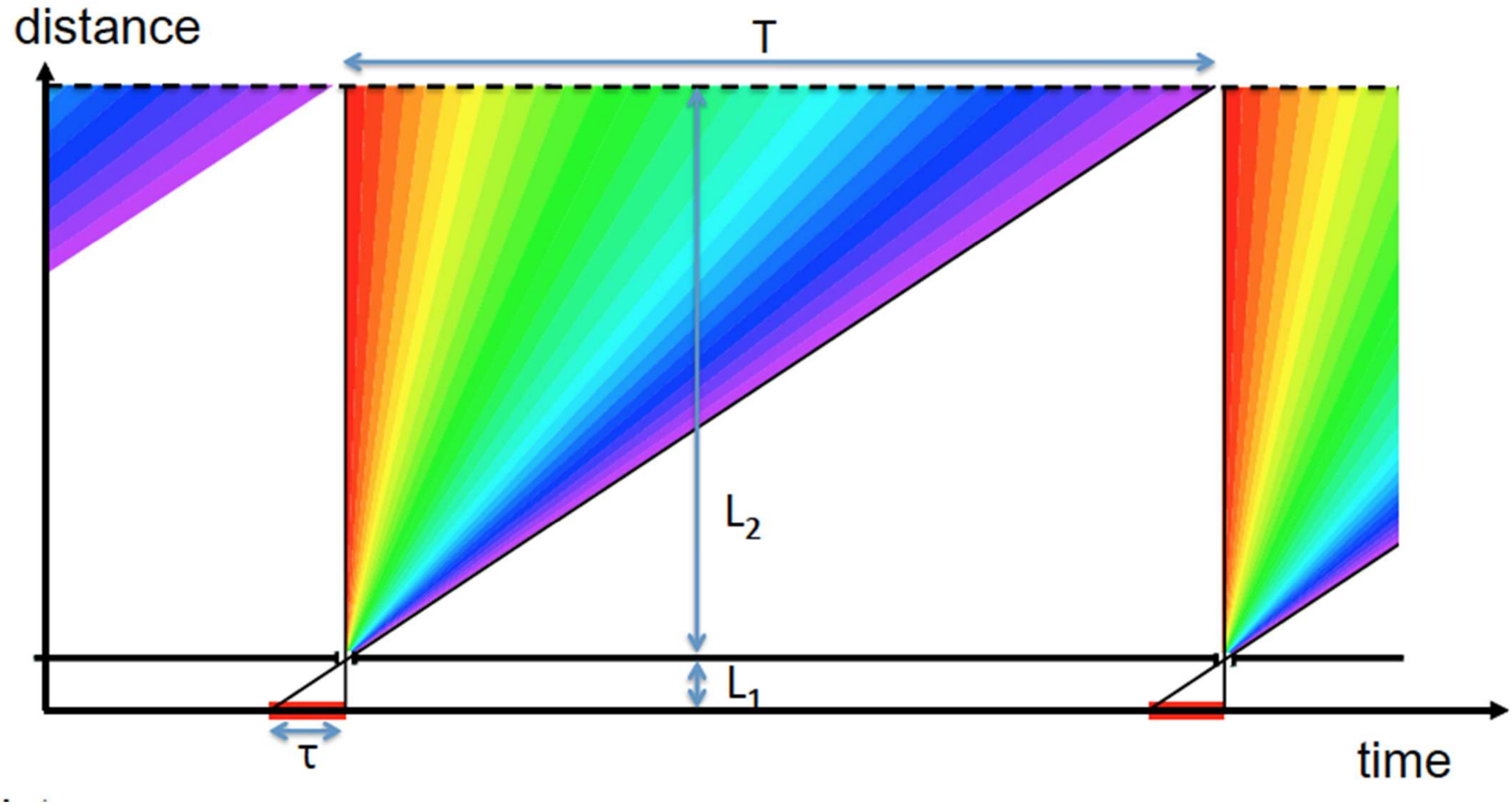


The Long Pulse Concept

- Advantage - No compressor ring required
  - No space charge tune shift so peak beam current can be supplied at almost any energy
  - Relaxed constraints on beam emittance
    - This is especially true if the beam expansion system for the target is based on raster scanning of the beam on the target.
  - No H- and associated intra-beam stripping losses
  - Permits the implementation of target raster scanning
- Disadvantage - Experiment requirements “imprint” Linac pulse structure
  - Duty factor is large for a copper linac
  - Duty factor is small for a superconducting linac



Neutron spectrometry



Note that pulse length, rep rate, chopper position and Instrument position are linked.

ESS reference suite of instruments

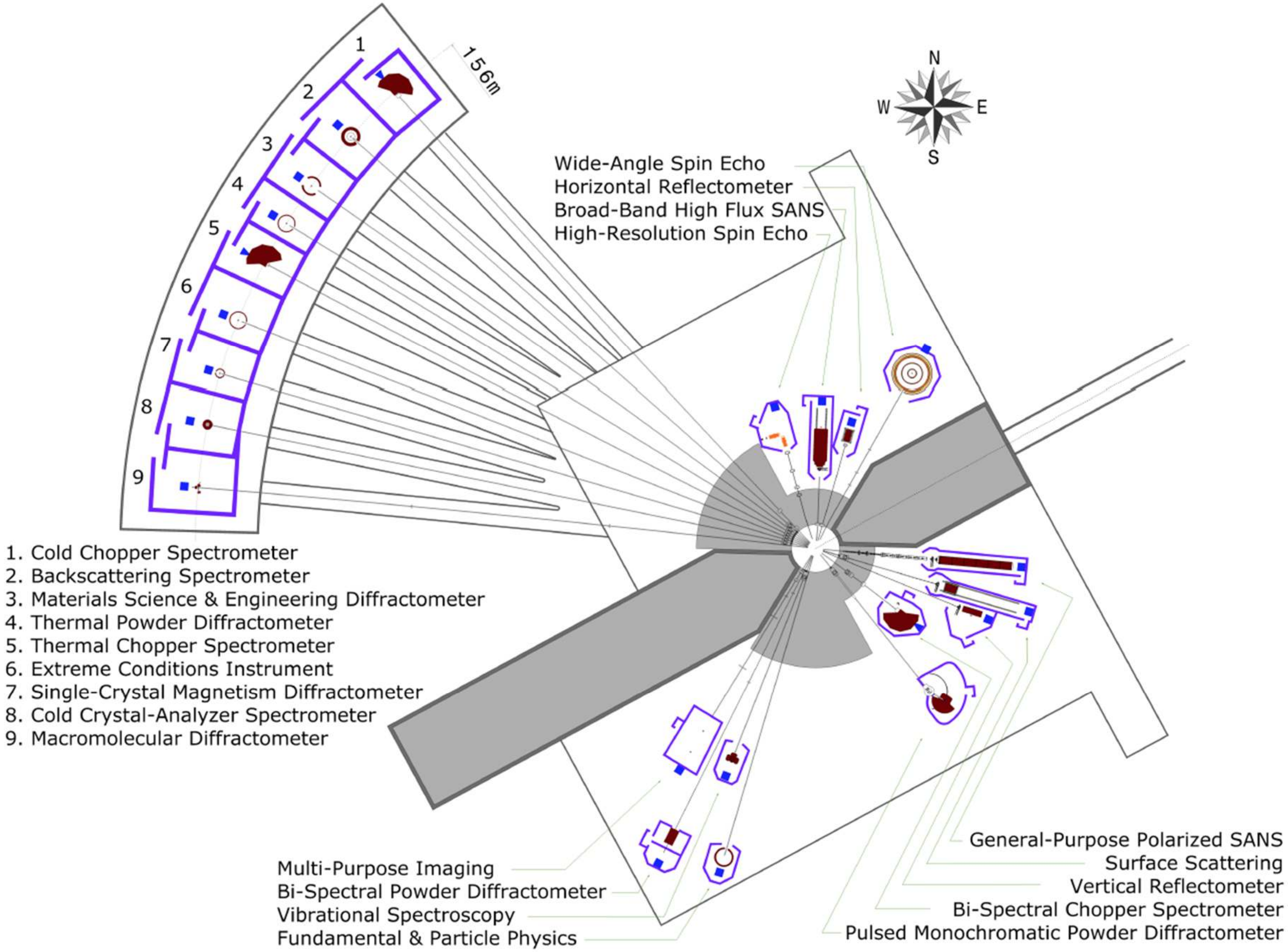
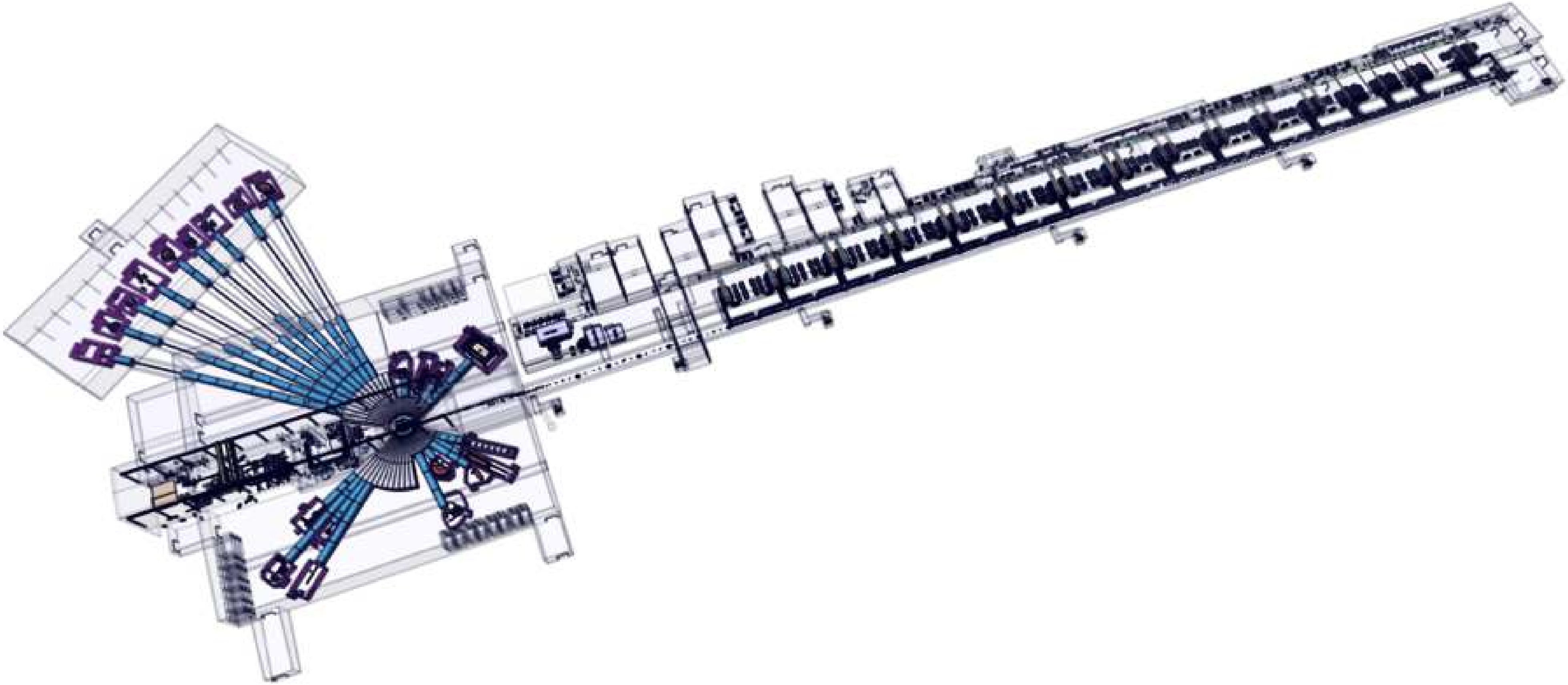


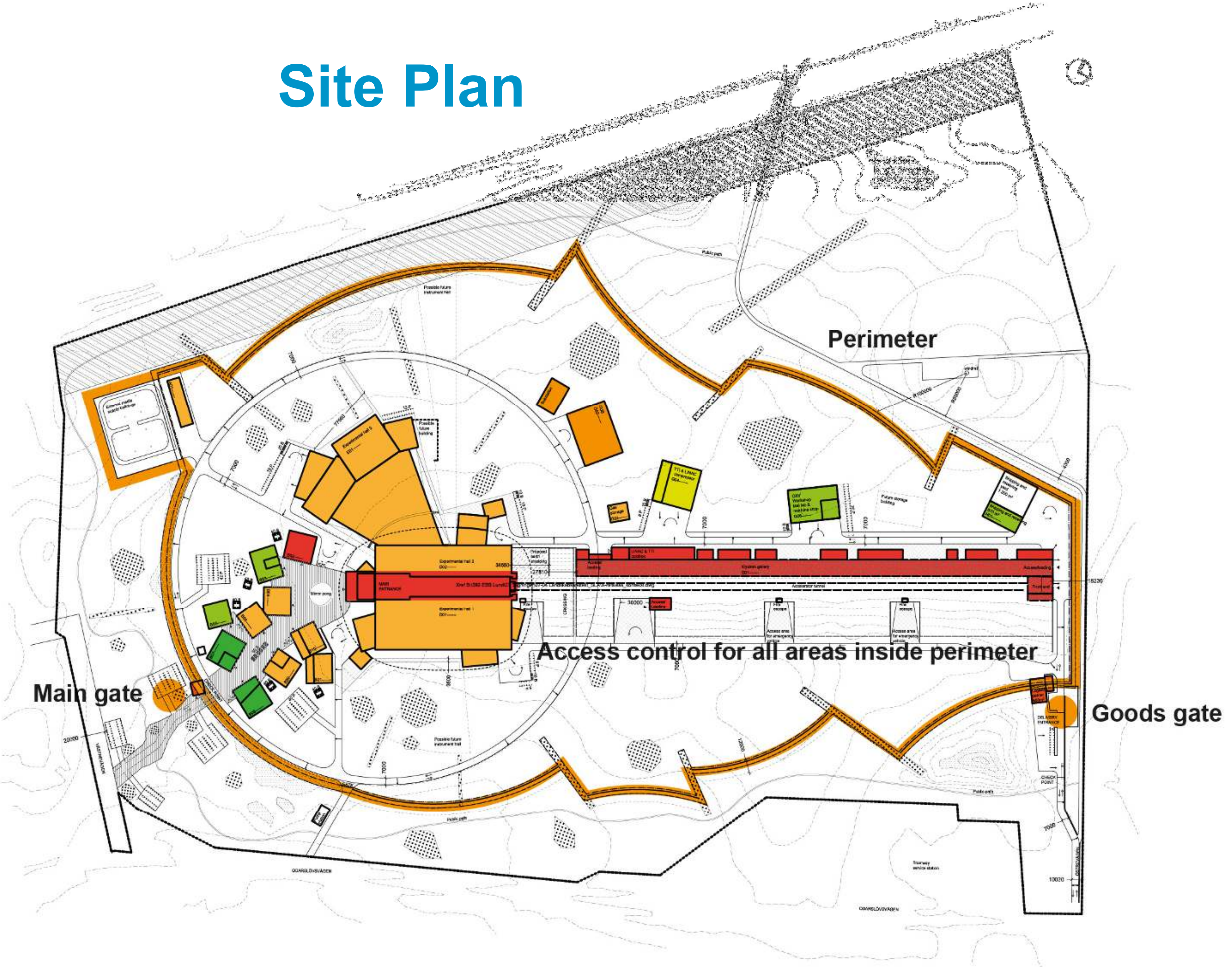
Figure 2.24: Neutron beamline and instrument layout of the reference instrument suite.

ESS facility



Accelerator Layout Nov 22, 2012

Site Plan



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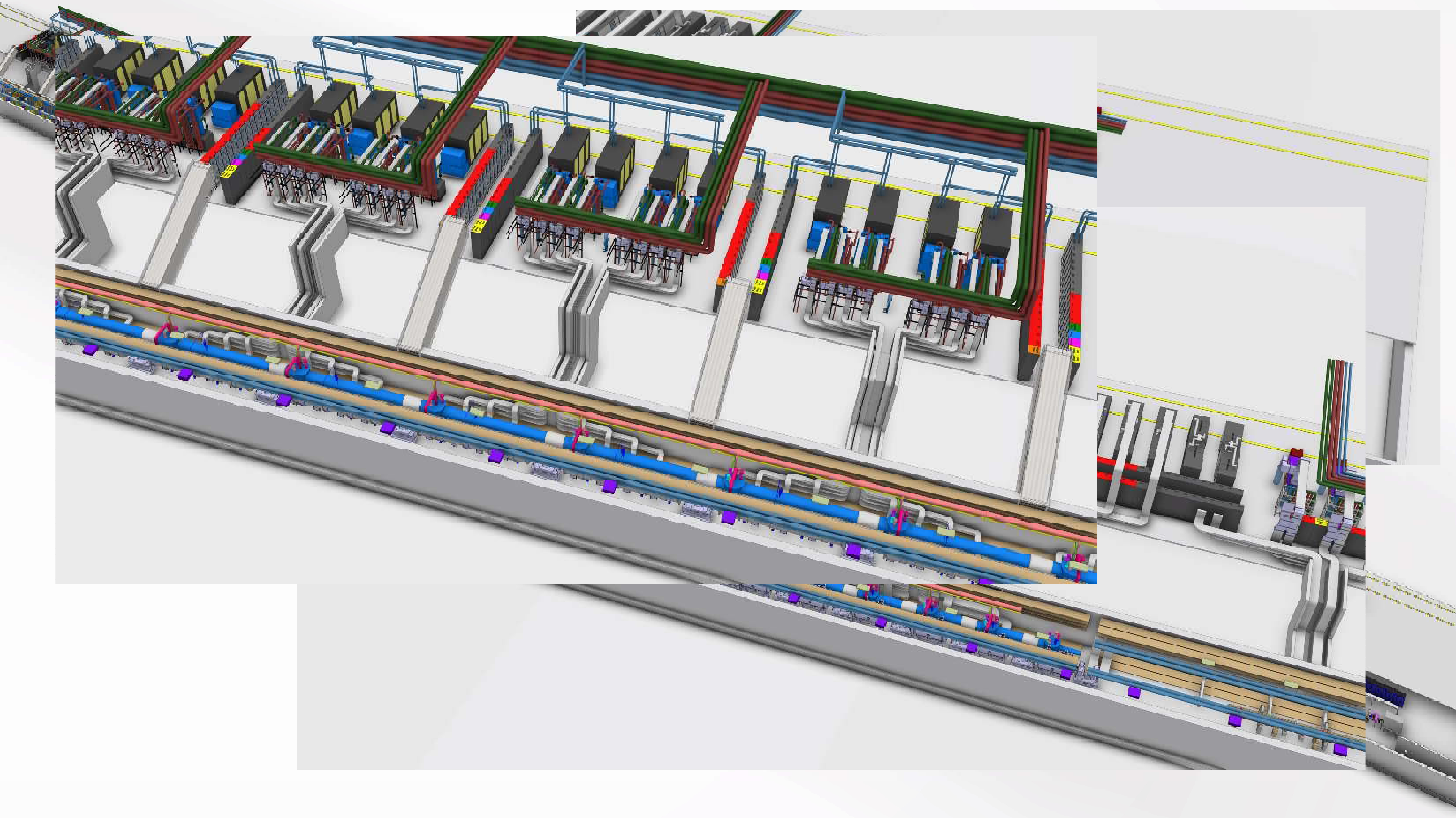
Linac layout



Collaboration During Pre-Construction

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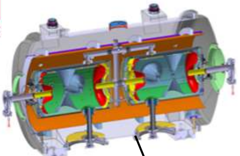
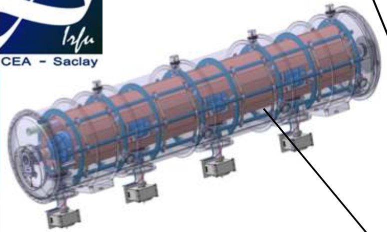


Sebastien Bousson

CEA - Saclay



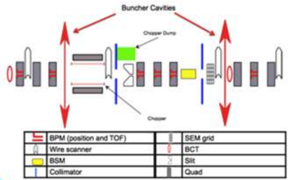
Pierre Bosland

CERN

CERN

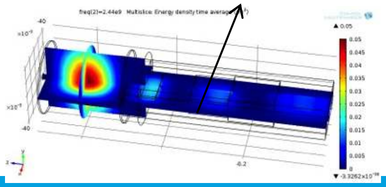
University of Huddersfield
Inspiring tomorrow's professionals

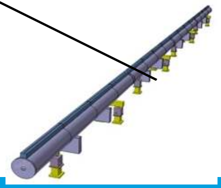
Roger Barlow

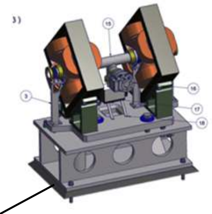


Ibon Bustinduy

ESS bilbao

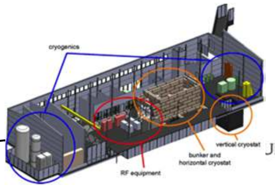






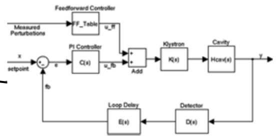
ISA

Søren Pape Møller



UPPSALA UNIVERSITET

Roger Ruber



LUNDS UNIVERSITET

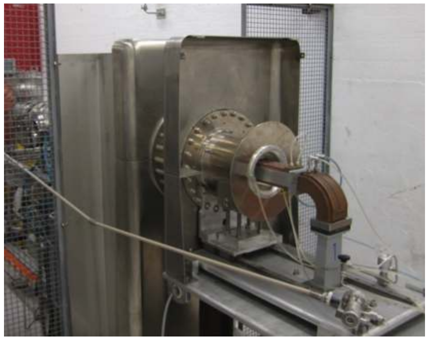
Anders J Johansson

The National Center for Nuclear Research, Swierk

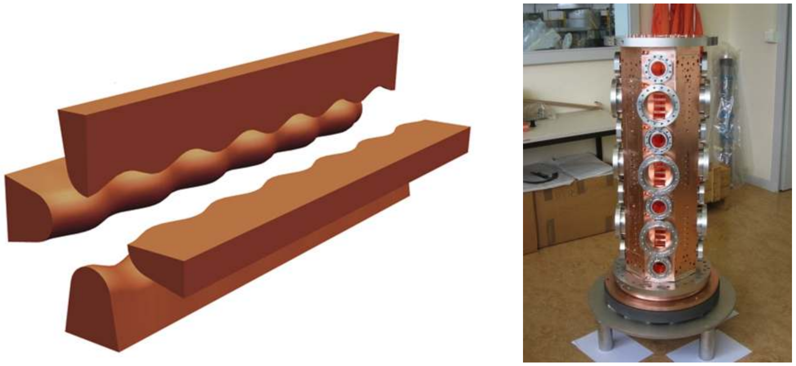
INFN Istituto Nazionale di Fisica Nucleare

Santo Gammino

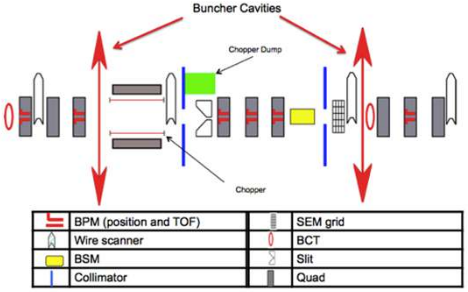
Ion Source and Normal-Conducting Linac



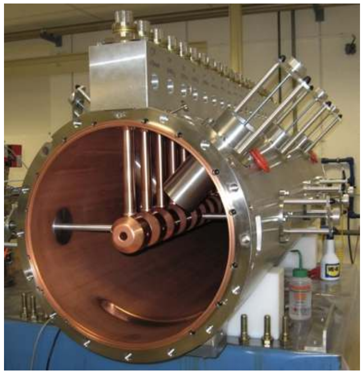
Prototype proton source operational, and under further development, in Catania. Output energy 75 keV.



Design exists for ESS RFQ similar to 5 m long IPHI RFQ at Saclay. Energy 75 keV->3.6 MeV.



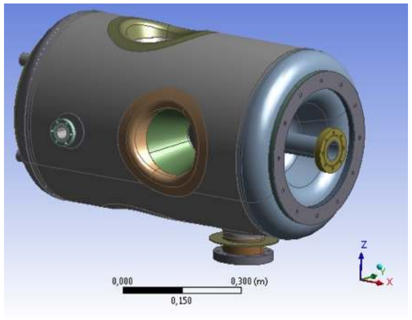
Design work at ESS Bilbao for MEBT with instrumentation, chopping and collimation.



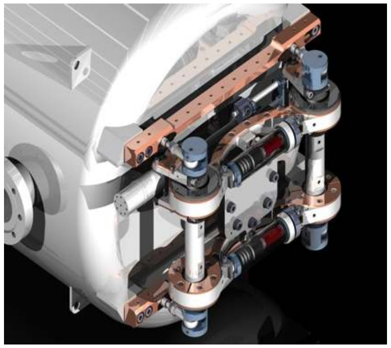
DTL design work at ESS and in Legnaro, 3.6 ->90 MeV.

Picture from CERN Linac4 DTL.

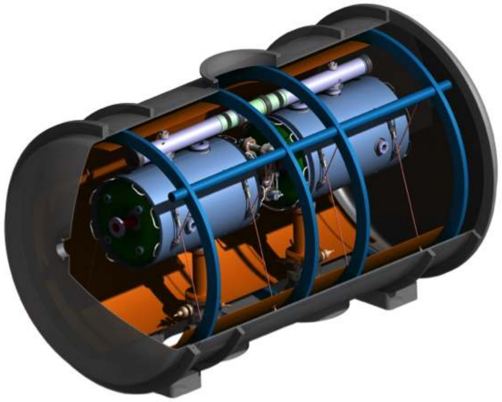
Spoke Cavities and Cryomodules



Superconducting double-spoke accelerating cavity, for particles with beta = 0.5, energy 90->216 MeV.



Cold tuner, to mechanically fine-tune the 352 MHz resonance frequency.



Cryomodule, holding two cavities at 2 K with superfluid helium. Length 2.9 m, diameter 1.3 m.

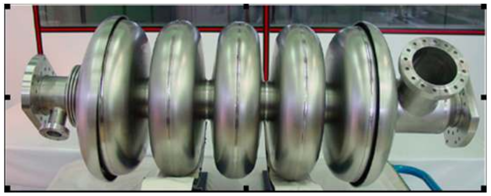
Power coupler, the antenna feeding up to 300 kW RF power to the cavities.

Single-spoke prototype for EURISOL

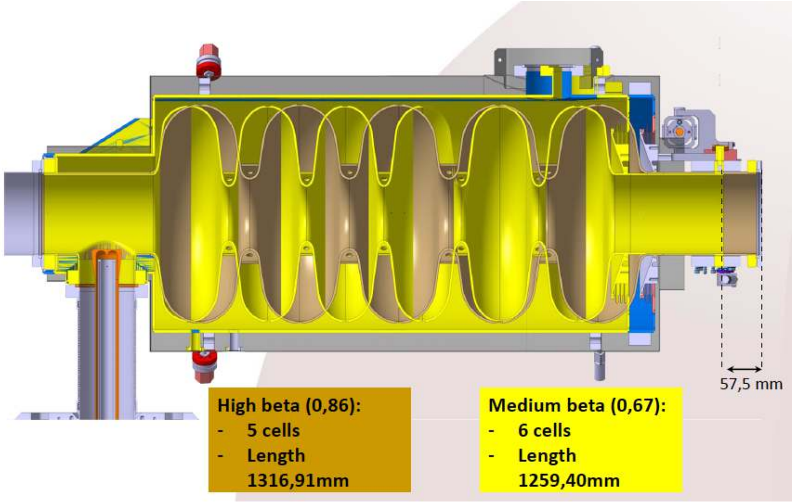
Cavity design done at IPN, Orsay, and prototype cavity has been ordered. Niobium procured and sent to manufacturer.

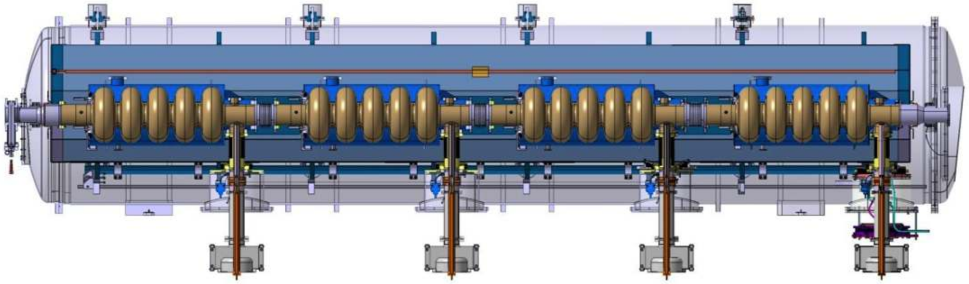
Cryomodule design highly advanced but not complete.

Elliptical Cavities and Cryomodules



Superconducting five-cell elliptical cavity (not ESS). Two families, for beta = 0.67, energy 216->561 MeV and beta = 0.86, energy 561->2000 MeV.





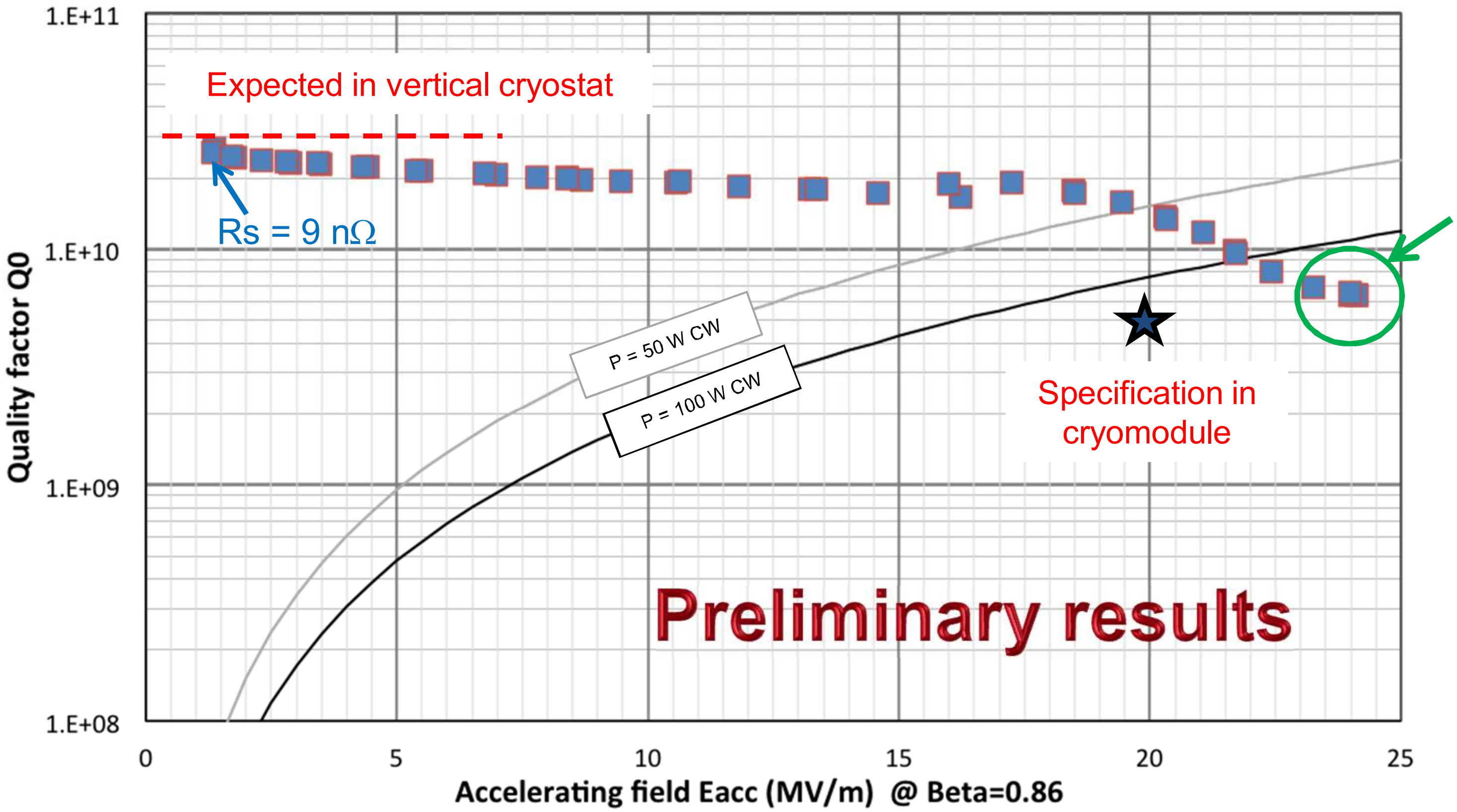
ESS elliptical cryomodule (not final) with 4 5-cell cavities and 4 power couplers for up to ~1 MW peak RF power.

Cavity and cryomodule design well advanced at Saclay.

Elliptical Cavities Cryomodule Technology Demonstrator, ECCTD, to be ready 2015.

First cold test result of first ESS high beta prototype cavity

- Measurements done the 22th of May 2014 in **vertical cryostat** at CEA Saclay
- Testing conditions: CW mode
- Operating temperature: 2 K
- Resonant frequency of π mode (measured): 704.292788 MHz
- External coupling (measured) : $Q_i = 6.5^{e}9 \pm 1^{e}9$, $Q_t = 6.8^{e}12$
- Parameters used : G = 241, R/Q = 435.35 Ω (at β = 0.86), L_{acc} = 0.92 m



Test limited by RF amplifier (saturation at 190 W) and high X-ray level

No quench observed

Next plans:

- Measurement of resonant frequency of 1st bandpass mode at 2K
- Measurement of resonant frequency of HOM at 2K
- If possible, increase accelerating field up to the quench limit
- Perform heat treatment at CERN at 650°C under vacuum

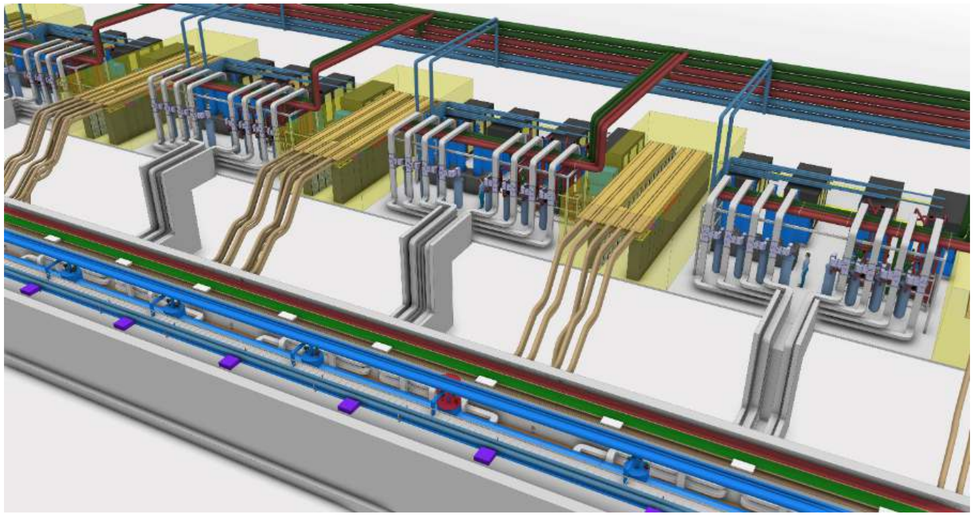
RF Systems

SNS klystron gallery

	Frequency (MHz)	No. of couplers	Max power (kW)
RFQ	352.21	1	900
DTL	352.21	5	2150
Spokes	352.21	26	350
Medium betas	704.42	32	900
High betas	704.42	88	1100

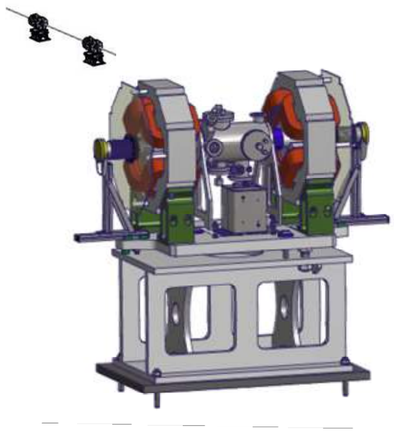
Main features:

- One RF power source (klystron, IOT, ...) per resonator
- Two klystrons per modulator for ellipticals
- Pulsed-cathode klystrons for RFQ, DTL
- Gridded tubes (tetrodes or IOTs) for spokes
- Klystrons for medium-beta ellipticals, and as backup for high-beta
- Developments with industry for high-power IOTs

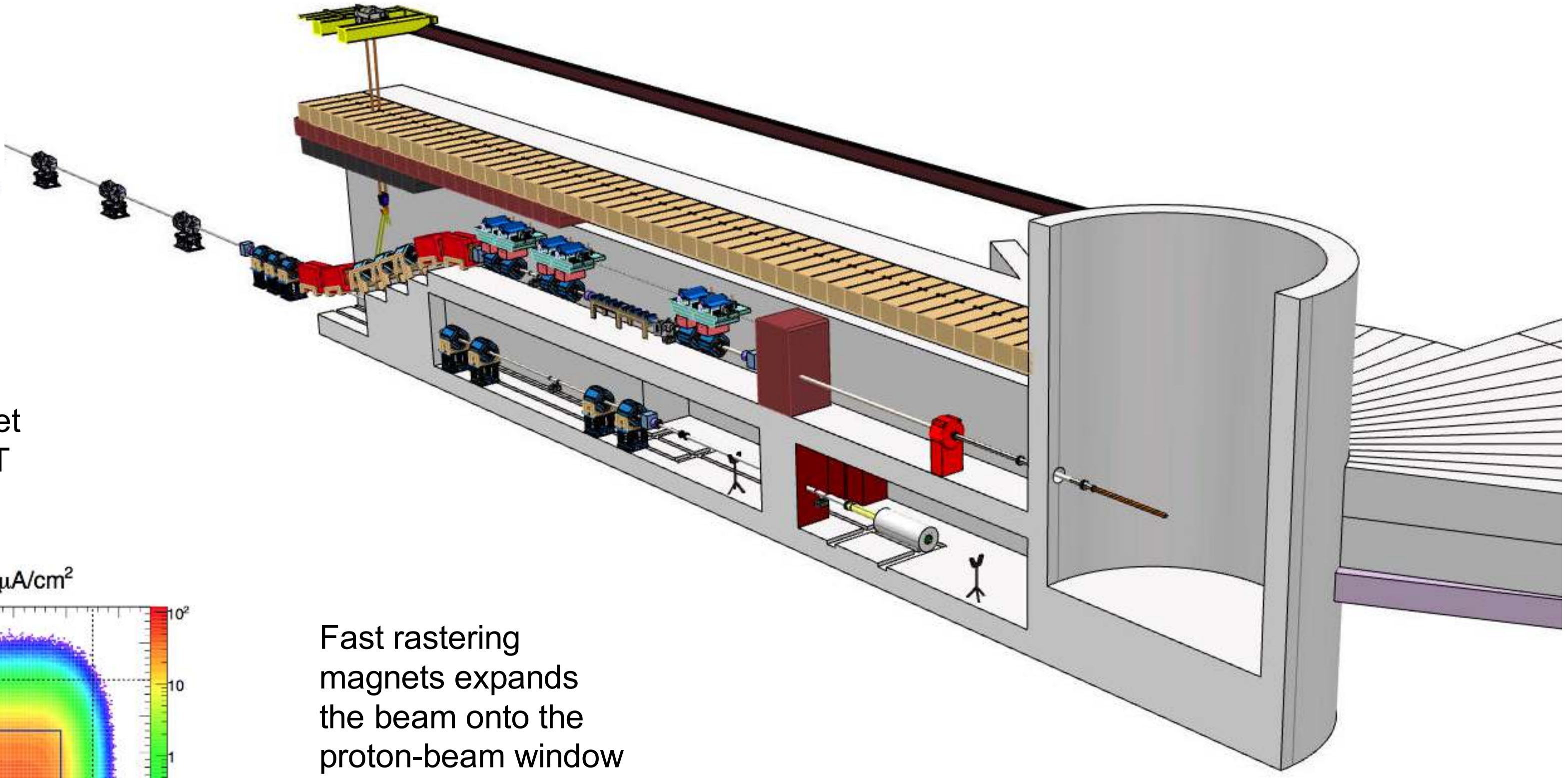


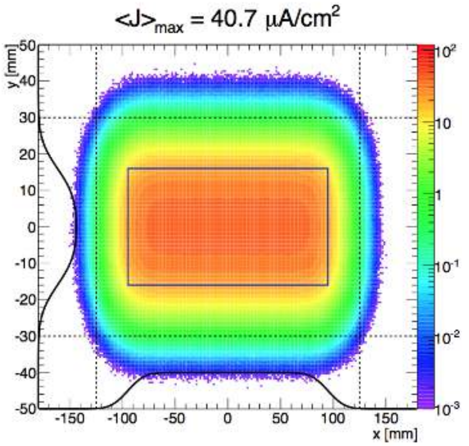
Layout of ESS linac tunnel and klystron gallery

High-Energy Beam Transport



Quadrupole doublet
for linac and HEBT

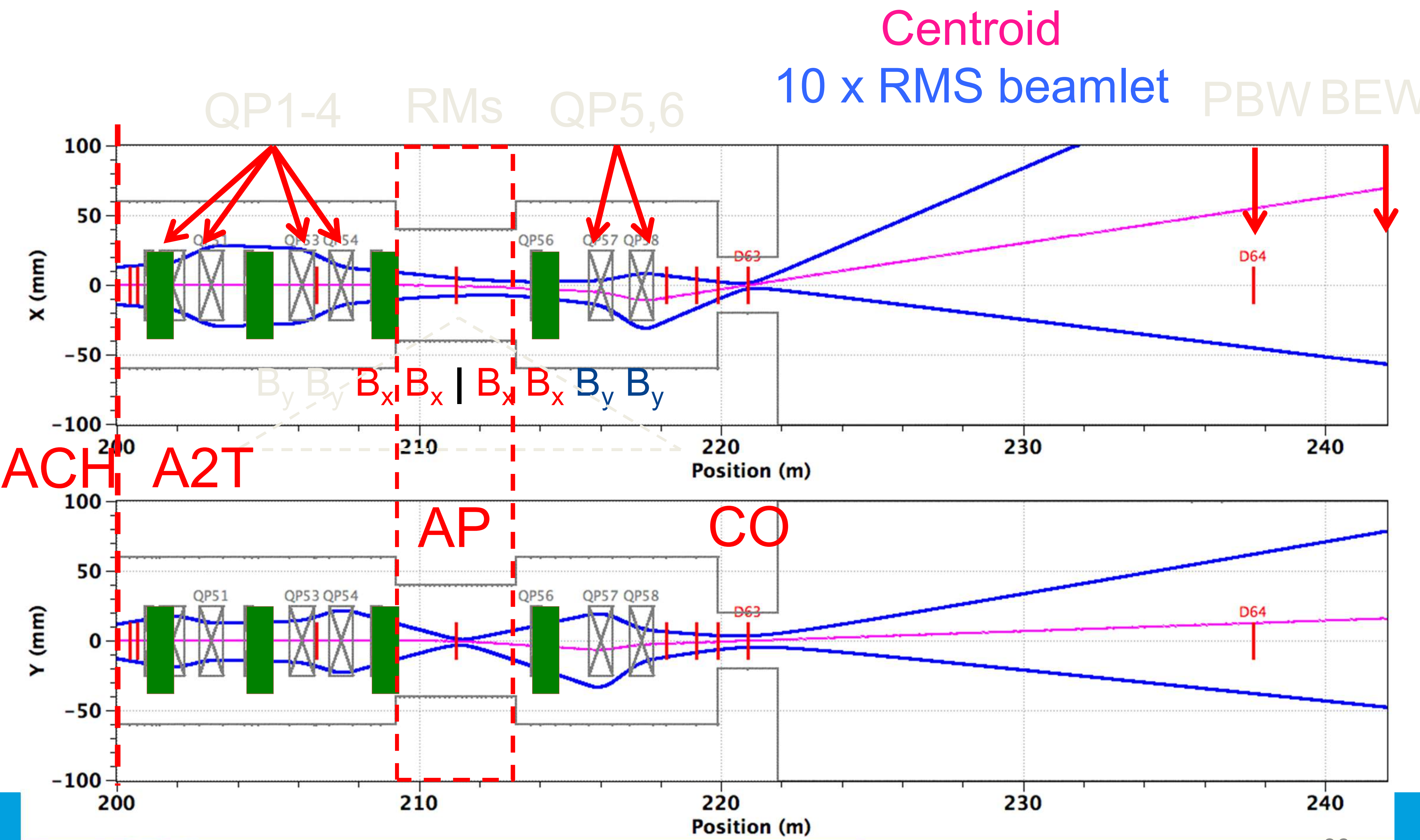




Fast rastering
magnets expands
the beam onto the
proton-beam window
and the 250 mm × 60
mm
beam entrance
window on the target
wheel

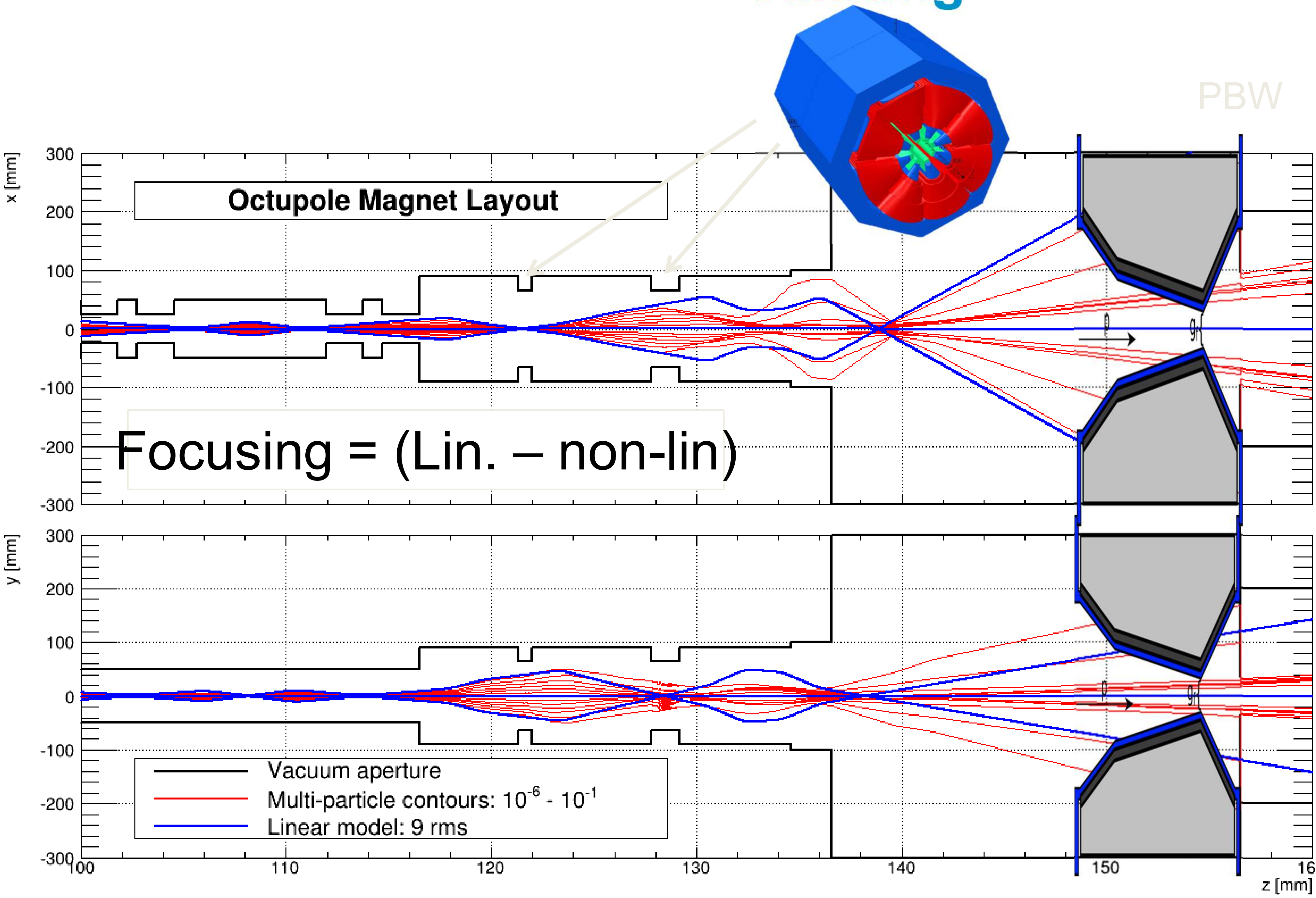
The HEBT design is a contribution from ISA, Århus.

Raster scanning



2.0 GeV: $B_x = \pm 1.96$ mT.m, $B_y = \pm 2.28$ mT.m, ±5 mT.m

Before raster scanning



Octupole Magnet Layout

Focusing = (Lin. – non-lin)

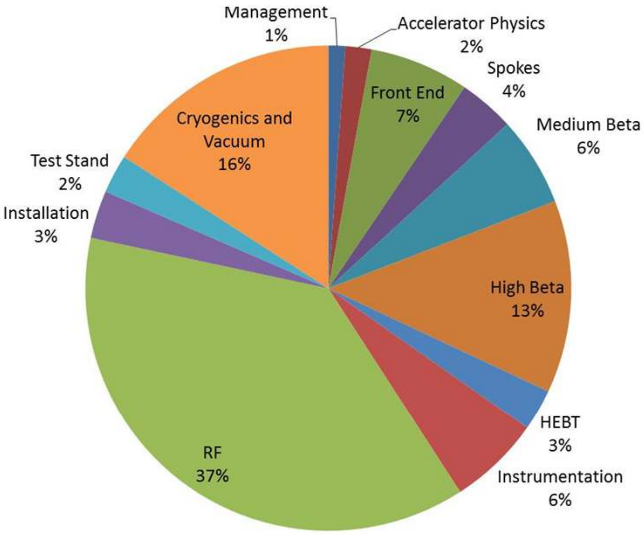
ESS Design Parameter Evolution

Cost Targets

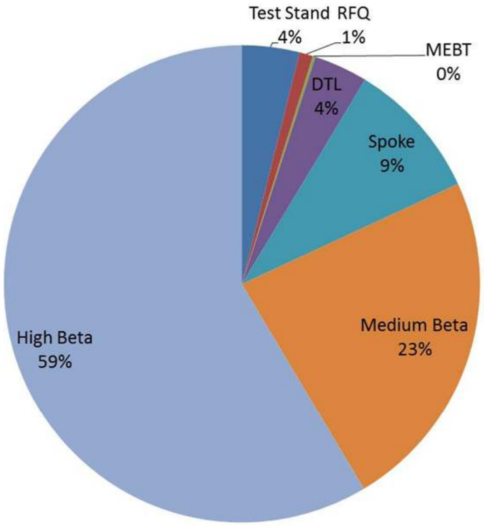
Design Update

		PAC09	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	TDR	Optimus+
		May-09	May-10	Sep-10	Oct-10	Sep-11	Dec-11	Oct-12	Nov-13
Pulse length (ms)		2	2	2	2	2,86	2,86	2,86	2,86
Rep rate (Hz)		20	20	20	20	14	14	14	14
Pulse current (mA)		50	50	50	50	50	50	50	62,5
Energy	Source	0,075	0,075	0,075	0,075	0,075	0,075	0,075	0,075
	RFQ	3	3	3	3	3	3	3	3,6
	DTL	50	50	50	50	50	50	78	89,8
	Spoke	200	200	200	240	188	191	200	216,6
	Low B	660	500	500	590	606	653	628	570,5
	High B	2500	2500	2500	2500	2500	2500	2500	2000
No Modules	DTL		3	3	3	3	3	4	5
	Spoke		14	16	15	14	18	16	13
	Low B		10	9	10	16	16	15	9
	High B		19	14	14	15	14	30	21
Geometric Beta	Spoke	0,35/0,5	0,45	0,54	0,64	0,5	0,46	0,5	0,5
	Low B	0,65	0,63	0,67	0,67	0,7	0,7	0,67	0,67
	High B	0,92	0,75	0,83	0,84	0,9	0,92	0,92	0,86

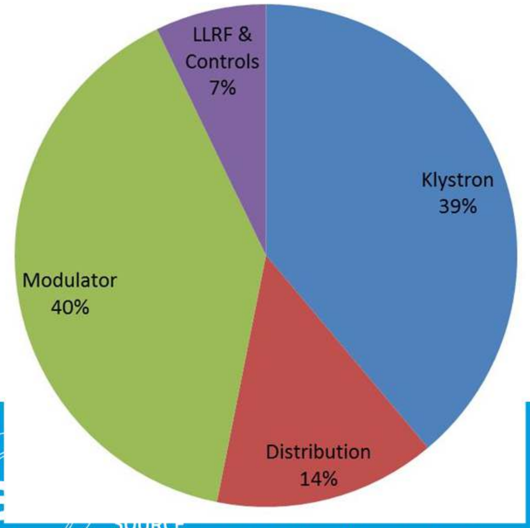
Cost Drivers (2012)



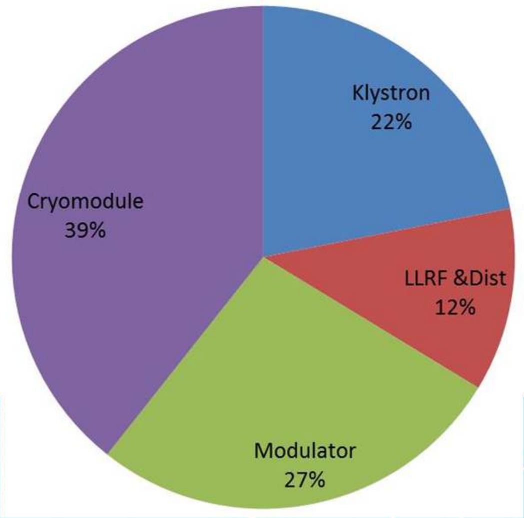
ESS Cost Distribution as of October 2012



RF System Cost Distribution



Cost breakdown for 704 MHz Elliptical RF systems

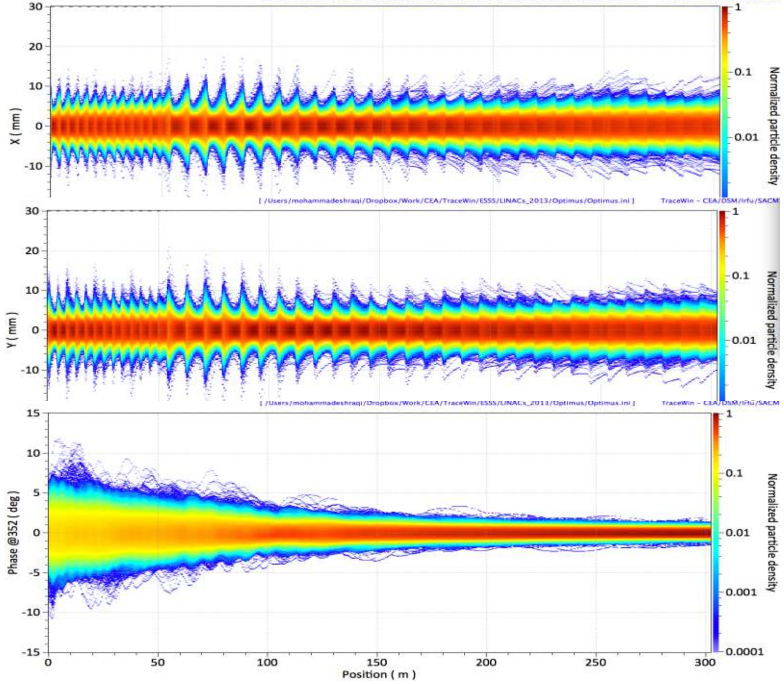


Cost breakdown for high beta cryomodule system.

- Elliptical cryomodules occupy 19% of the cost
  - There are 45 elliptical cryomodules
- The cryogenic plant absorbs 14% of the total cost.
- RF systems comprise 37% of the cost.
  - The RF costs are distributed over five major systems
  - The elliptical section comprises 82% of the RF system cost.
- For the elliptical section,
  - the klystrons and modulators comprise 80% of the RF system cost.
  - 62% of the total cost of the linac.
  - 92% of the acceleration energy

New (Optimus) Baseline Layout

Done by a professional: M. Eshraqi

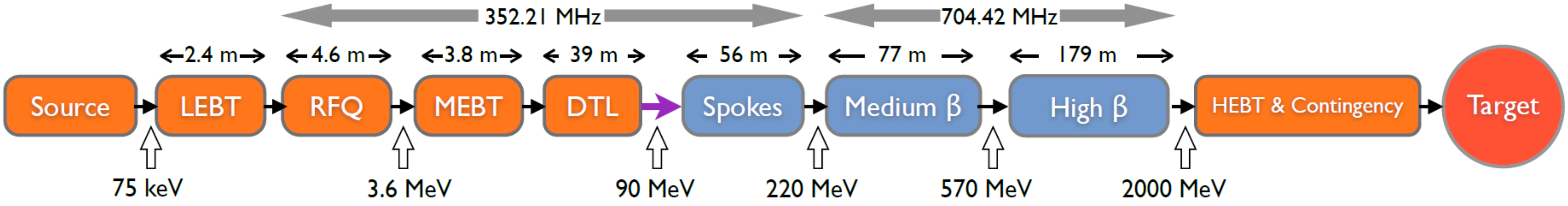


13 × Spoke cryo-modules

9 × Mβ cryo-modules

21 × Hβ cryo-modules

Optimus+



New Baseline

- New Baseline Headline Parameters
  - 5 MW Linac
    - 2.0 GeV Energy (30 elliptical cryomodules)
    - 62.5 mA beam current
    - 4% duty factor (2.86 mS pulse length, 14 Hz)
  - First beam by 2019 (1.0 MW at 570 MeV)
- The new baseline was achieved by:
  - Increasing beam current by 25%
  - Increasing Peak Surface Field by 12%
  - Setting High Beta β_g to 0.86
  - Adopting maximum voltage profile
  - Adopting a uniform lattice cell length in the elliptical section to permit
    - design flexibility
    - schedule flexibility.

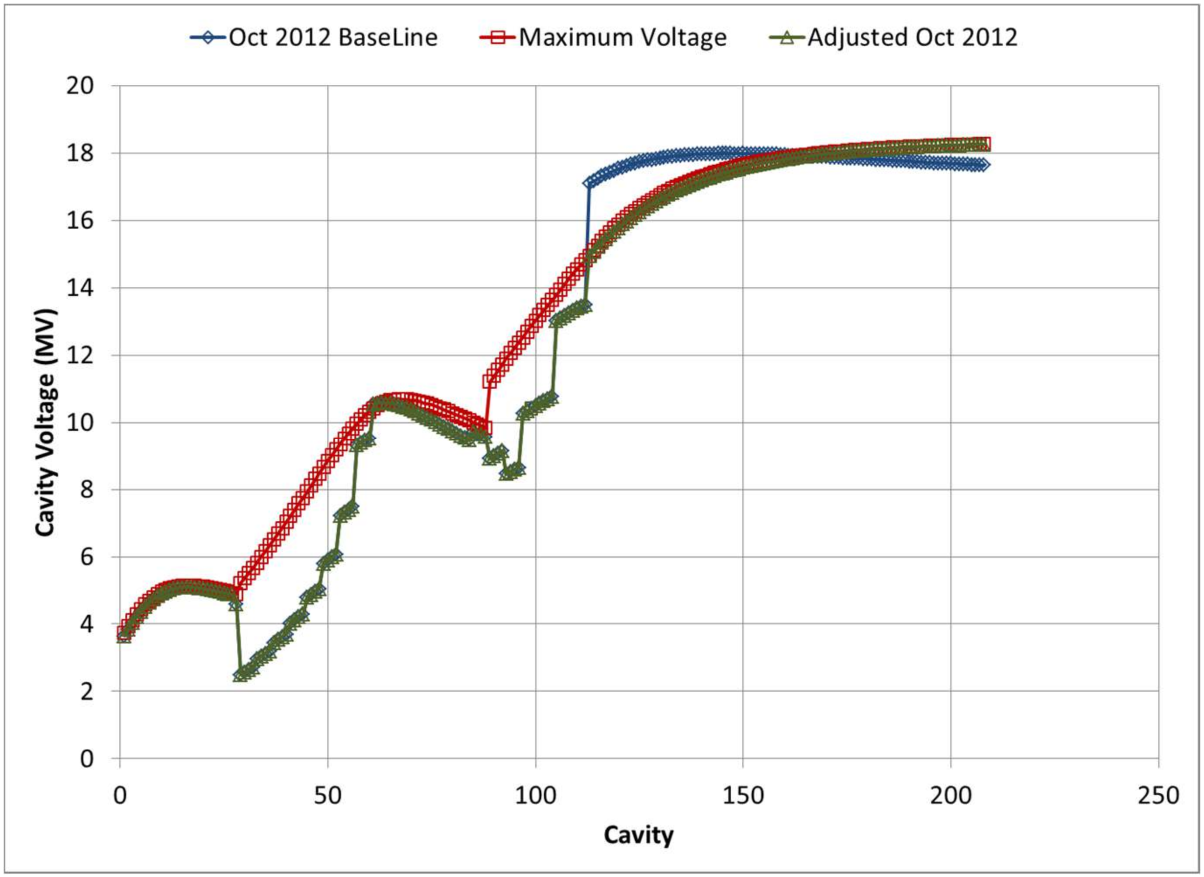
Increasing the Peak Surface Field

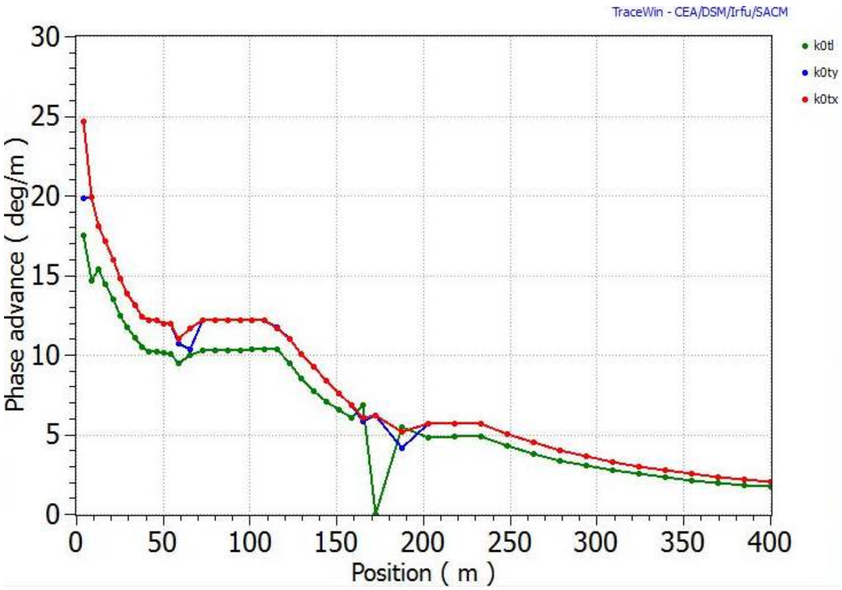
- The peak surface field in the 704 MHz elliptical superconducting cavities is limited to 40 MV/meter in the 2012 design.
- If the limit on the maximum surface field was
  - increased by 10% to a value of 44 MV meter,
  - three high beta cryomodules could be removed.
- 10% more RF power would be required by the remaining RF sources. The cost of the remaining
  - modulators will increase by 5%
  - klystrons will increase by 1.3%.
- However 81% of the cost of the removed cryomodules and RF systems could be recovered
- Providing a cost reduction of almost 3% for the entire linac.

Increasing the Beam Current

- There are a number of “soft” limits on the peak beam current which are difficult to quantify
  - Space charge forces
  - Halo, etc.
- A hard limit on beam current is the peak power in the RF couplers for the superconducting cavities.
  - The current coupler design has been tested to 1200kW
  - Due to the lack of test information, it is unknown if the couplers can be pushed harder.
  - As a result, 1200W in the couplers will be taken as a hard limit
- For a peak surface field of 44 MV/ meter, the beam current can be increased to 63.5 mA and keep the coupler power below 1200kW.
- If the beam current was increased to 55 mA and the peak surface field is increased to 44 MV/m, six high beta cryomodules could be removed.
  - 21% more RF power would be required by the remaining RF sources. The cost of the remaining
    - modulators will increase by 10%
    - klystrons will increase by 2.7%.
- However 81% of the cost of the removed cryomodules and RF systems could be recovered
- Providing a cost reduction of almost 5.8% for the entire linac.

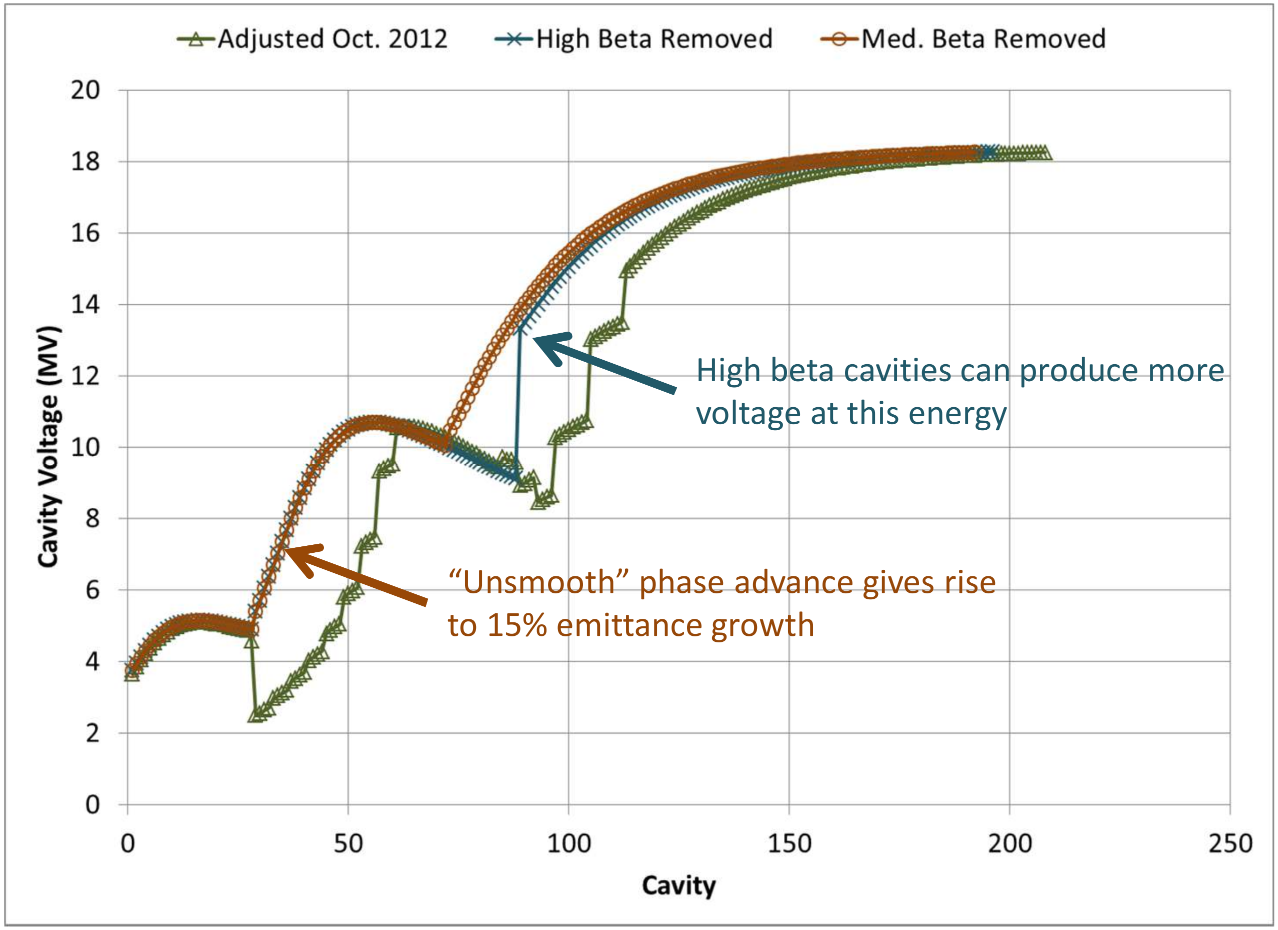
Adjusting the Voltage Profile





- The October 2012 voltage profile is not maximum
    - so as to have a smooth phase advance
    - Low emittance dilution

Alternative Voltage Profiles

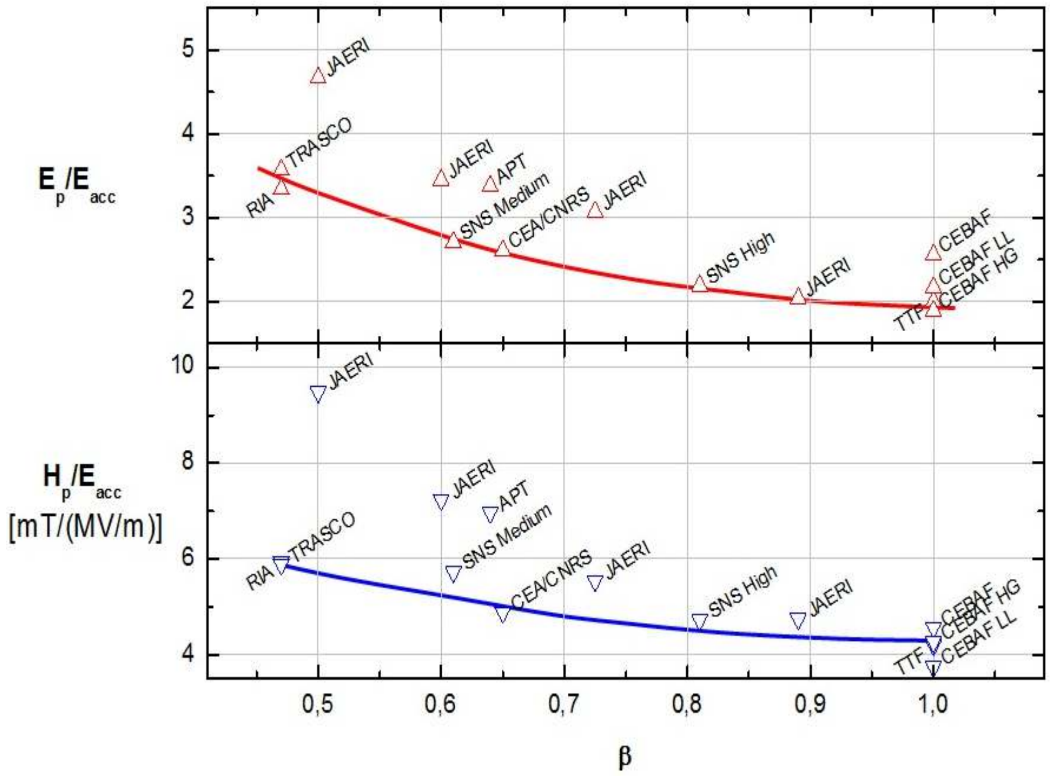


High beta cavities can produce more voltage at this energy

“Unsmooth” phase advance gives rise to 15% emittance growth

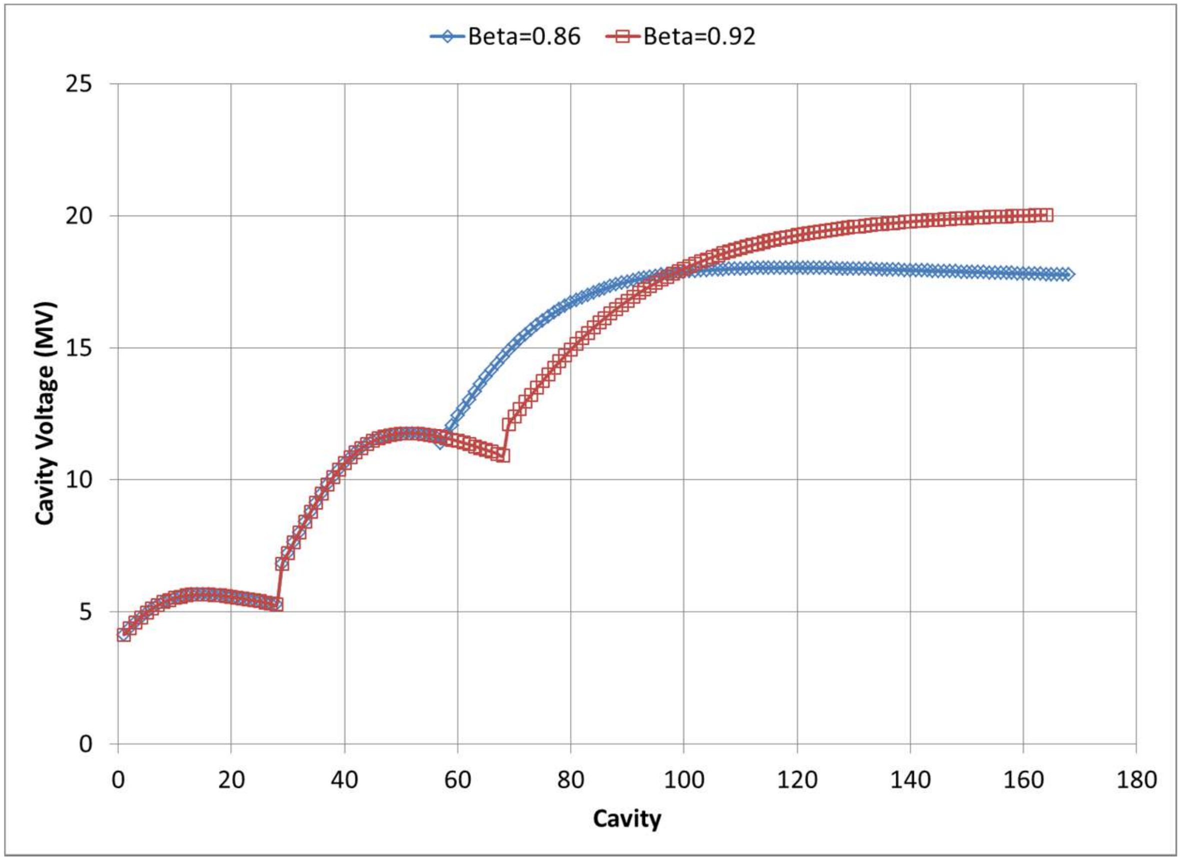
- October 2012 profile
  - 60 medium beta cavities in 15 C.M.
    - Smooth phase advance region
  - 120 high beta cavities in 30 C.M.
    - Voltage matching region
- “Med. Beta Removed” profile
  - 48 medium beta cavities in 12 cryomodules
    - “Unsmooth” phase advance gives rise to 15% emittance growth
  - 120 high beta cavities in 30 C.M.
    - No matching region required

Choice of Geometrical Beta



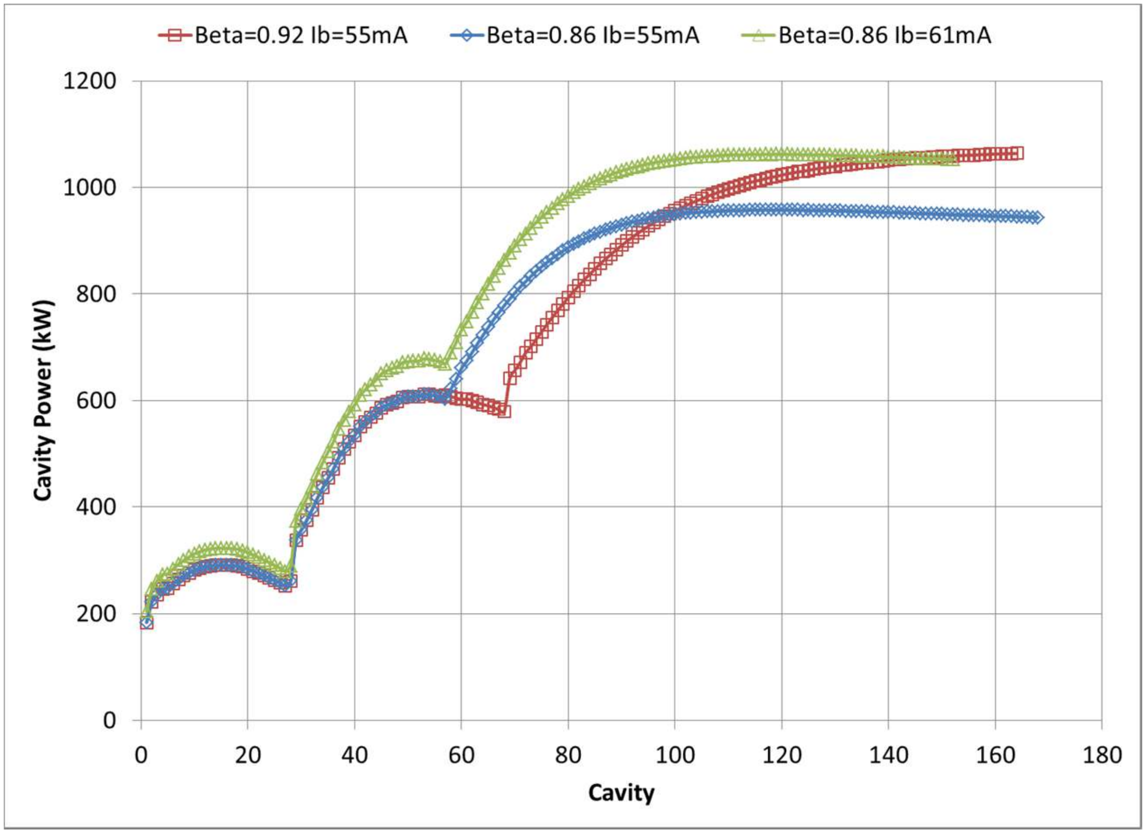
- There is experimental evidence that for a given peak surface field, higher accelerating gradient that can be achieved for higher geometrical beta cavities.
  - For example, the 0.86 cavity designed for ESS by CEA
    - has an accelerating gradient of 17.9 MV/m
    - for a peak surface field of 40 MV/meter.
  - A 0.92 cavity
    - could have an accelerating gradient of 18.7 MV/meter
    - for a surface field of 40 MV/meter.

Choice of Geometrical Beta



- For a peak surface field of 44MV/meter and a beam current of 55 mA.
  - the required energy of the linac is reduced to 2273 MeV
  - the corresponding beam beta becomes 0.956.
- For the profile with the geometrical beta of 0.92,
  - 40 medium beta cavities (10 cryomodules)
  - 96 high beta cavities (24 cryomodules) reach an energy of 2295 MeV.
- For the profile with the geometrical beta of 0.86,
  - Only 28 medium beta cavities (7 cryomodules) are required.
  - However, 112 high beta cavities (28 cryomodules) are needed to reach an energy of 2333 MeV.
- Thus the higher geometrical beta of 0.92 requires one less cryomodule than the 0.86 cavities to achieve a minimum of 5 MW of beam power

Choice of Geometrical Beta



- For a peak surface field of 44MV/meter and a beam current of 55 mA.
  - The 0.92 cavities require 1060 kW of peak RF power
  - compared to 960 kW required for the 0.86 cavities.
- Since the coupler design is independent of geometrical beta,
  - it is possible to run 1060 kW of power into the 0.86 cavities
  - if the beam current is increased to 62 mA
- A beam current of 62 mA requires a final energy of only 2049 MeV for the linac.
  - The number of 0.86 high beta cavities can be reduced to 96 cavities (24 cryomodules).
- For the 0.92 design at 1060kW/coupler
  - **34 elliptical cryomodules are required**
  - 10 medium beta and 24 high beta
- For the 0.86 design at 1060kW/coupler
  - **31 elliptical cryomodules are required**
  - 7 medium beta and 24 high beta

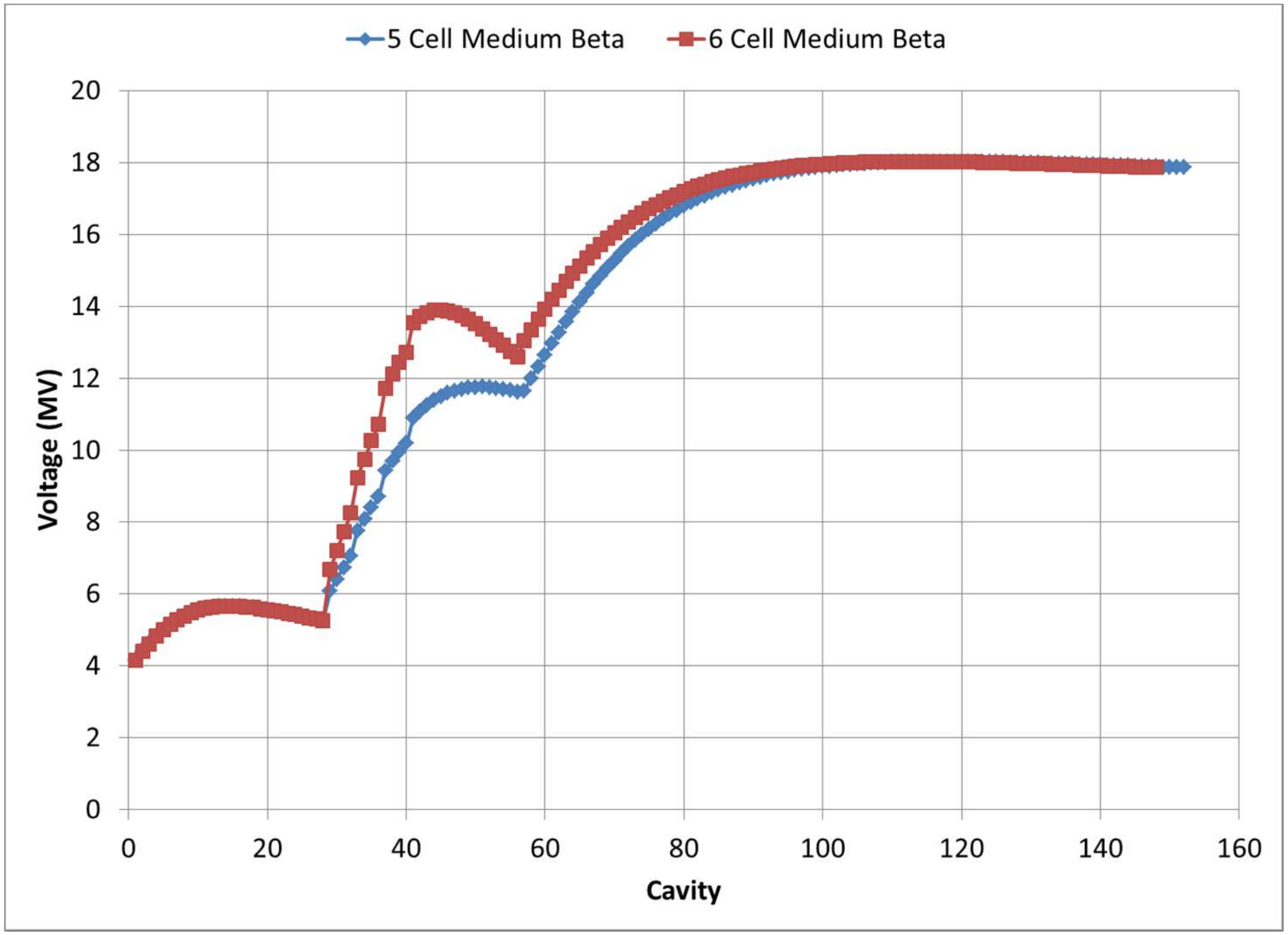
Lattice Cell Length

- For the October 2012 baseline design, the cell length along the linac changes substantially.
  - 4.18 meters in the spokes,
  - 7.12 meters in the medium beta section with one cryomodule per cell
  - 15.19 meters in the high beta section with two cryomodules per cell.
- For a maximized voltage profile, a high beta β_g=0.86, and an I_b=62mA,
  - over half the medium beta cryomodules are eliminated
  - the beginning of the high beta region is now 520 MeV
- At this energy, the current long high beta cells is too weak at to provide the desired phase advance per cell of 87 degrees with reasonable gradients in the quadrupoles.
- Thus a fourth type of cell with one high beta cryomodule per cell would be needed in this region.

Uniform Lattice Cell Length

- A tunnel design with many different cell lengths is very undesirable with the perspective of considering:
  - design contingency
  - future upgrades.
- In the future, it might be advantageous to interchange
  - spoke cryomodules with medium beta cryomodules.
  - medium beta cryomodules with high beta cryomodules.
- At the added expense of a longer linac, the new baseline has:
  - Spoke cell Length = 0.5 x Medium beta cell length
  - Medium beta cell length = High beta cell length
- A uniform cell length provides the possibility that the medium and high beta cryomodules could be interchangeable and possibly identical.
  - 6 cell medium beta cavities that would be close to the same length of the high beta cavities.
  - This would reduce the prototyping schedule (and cost) significantly because only one type cryomodule prototype would need to be constructed.
  - Also a 6 cell medium beta cryomodule requires one less high beta cryomodule to achieve 5 MW of beam power

6 Cell Medium Beta Cavities



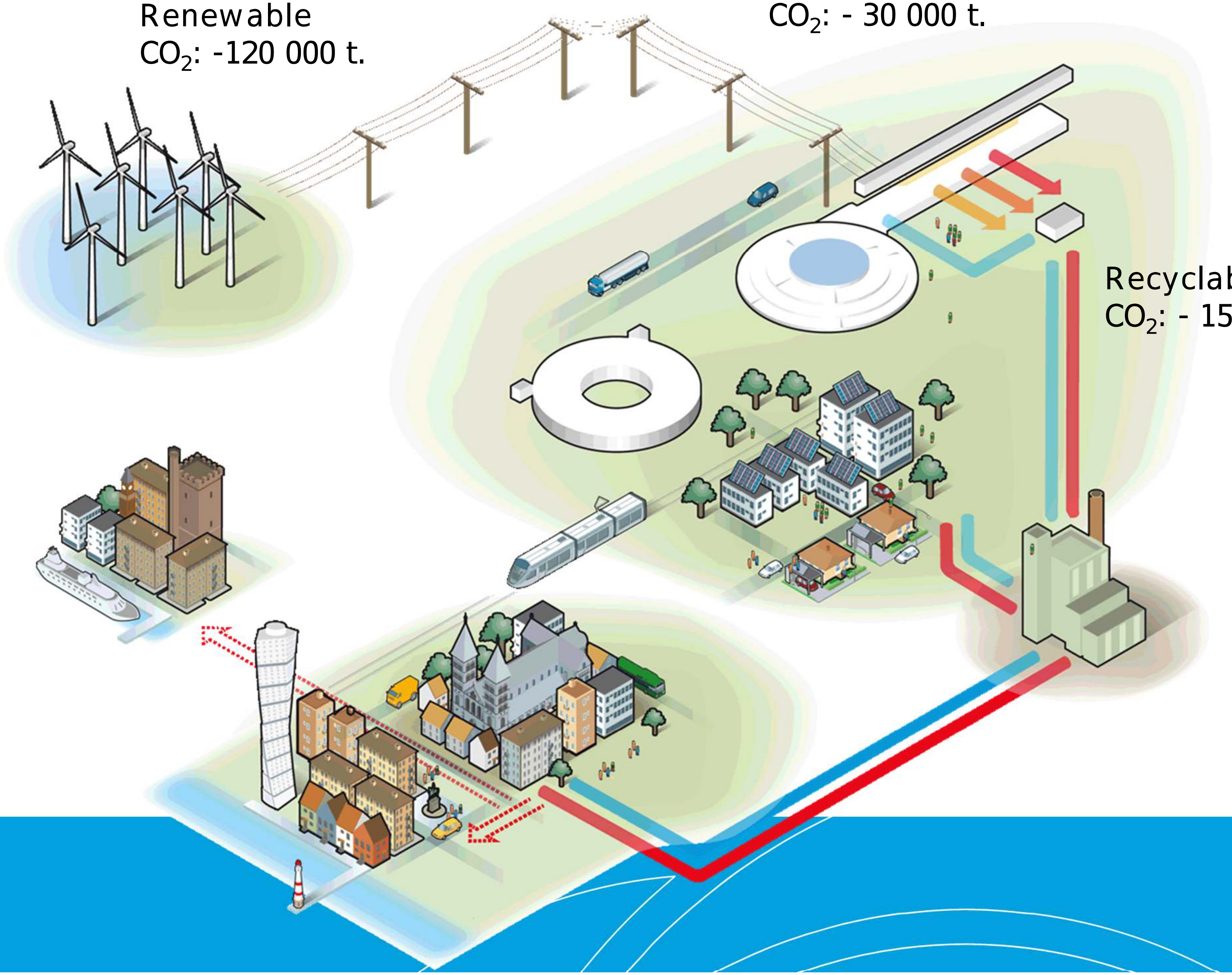
Design Contingency

- ESS uses the Long Pulse concept
  - No compressor ring is required
  - Peak beam current can be supplied at almost any energy
- If we fail to meet our goals on:
  - Beam current
  - Cavity gradient
  - Power coupler power
- The accelerator complex will still function but at a reduced beam power
- We can buy back the beam power in the future by adding high beta cryomodules to the end of the linac
  - As long as the additional space is reserved.
- We proposed to mitigate these risks by reserving the tunnel space for 15 cryomodules (127.5 meters) as “design contingency”.

Conventional Facility Costs

- The approximate costs for conventional facilities are:
  - Tunnel: 22,900 €/m (3270 k€ / m^2) including berm, auxiliary costs
  - Gallery: 46,200 €/m (2800 k€ / m^2)
- The cost of accelerator equipment is:
  - 6.5 M€ / cryomodule which includes the RF power
  - Average cost of superconducting RF accelerator equipment is:
    - 790,000 €/m
    - 35x more expensive than tunnel cost
    - 11.4x more expensive than total CF cost
  - Average beam power cost for the accelerator equipment in a cryomodule cell is **18kW / M€**.
- The cost of the 127 meter contingency space without stubs and gallery is **2.9 M€**
  - Equivalent to the cost of accelerator equipment needed to supply 0.052 MW of average beam power (1% of 5 MW)

Responsible – Renewable – Recyclable

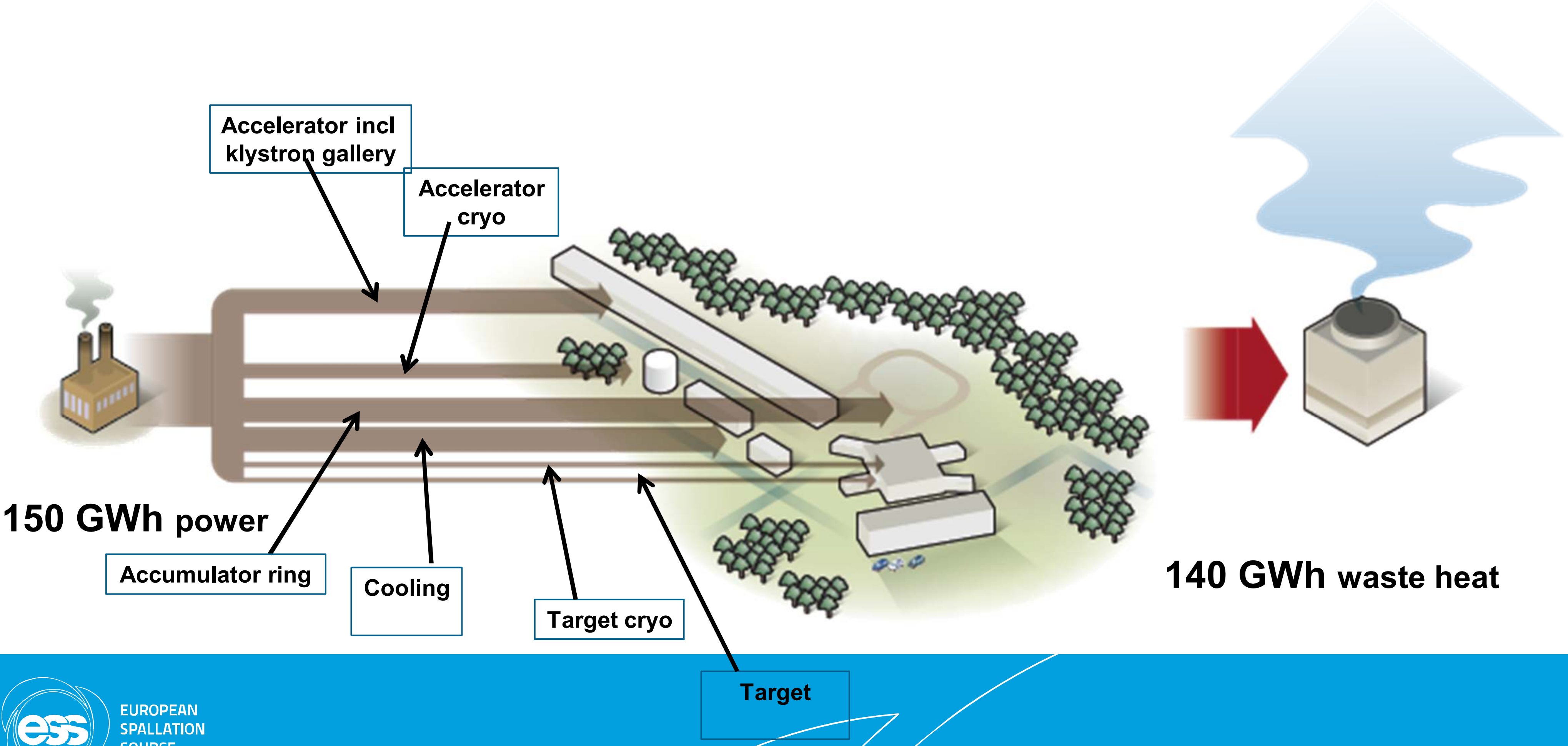


Renewable
CO$_2$: -120 000 t.

Responsible
CO$_2$: - 30 000 t.

Recyclable
CO$_2$: - 15 000 t.

Energy Inventory Spallation Neutron Source at Oak Ridge National Laboratory At 1 MW beam from accelerator



Accelerator incl klystron gallery

Accelerator cryo

150 GWh power

Accumulator ring

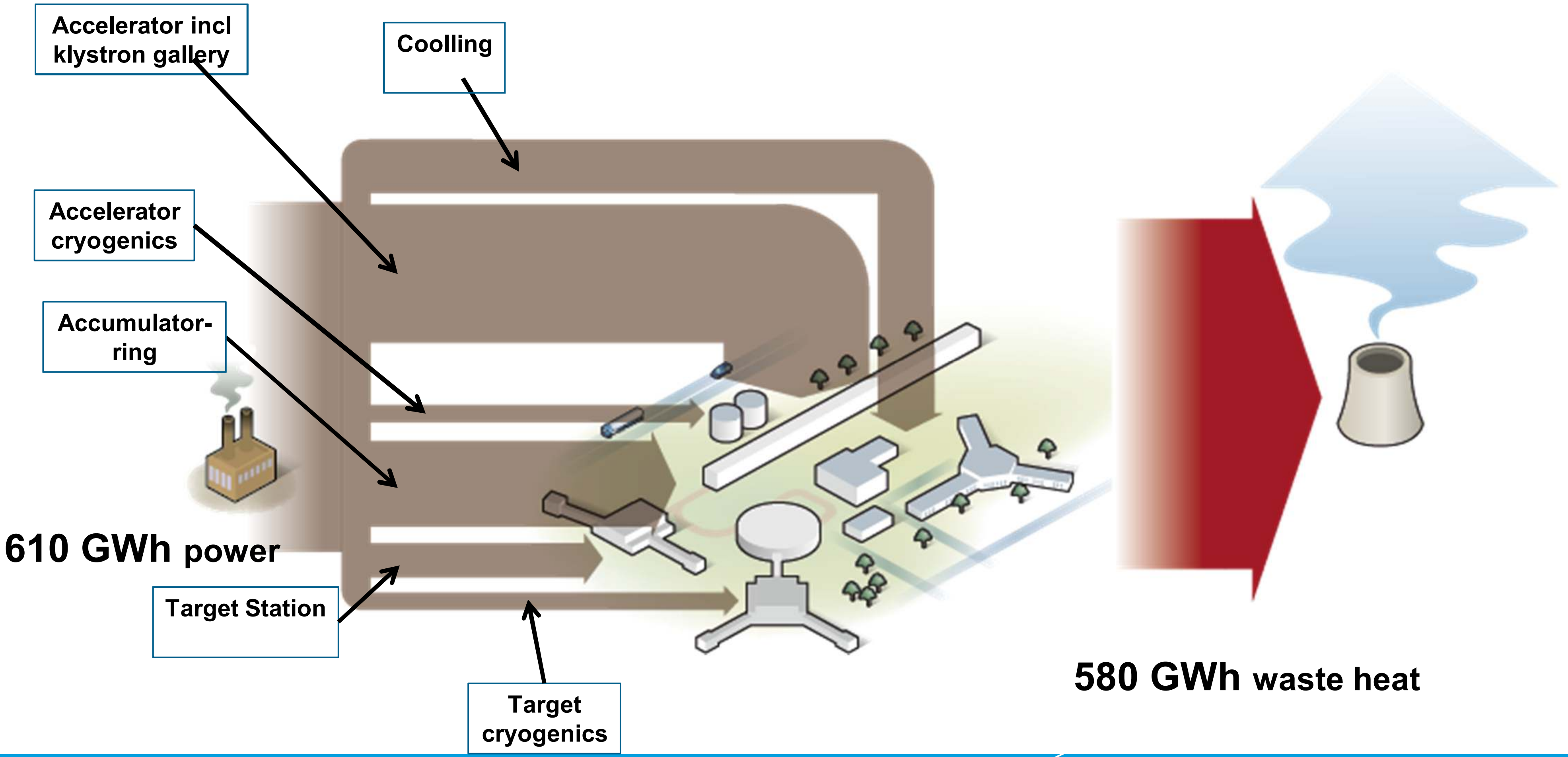
Cooling

Target cryo

Target

140 GWh waste heat

Energy Inventory
ESS Pan-European Project 2002
5 MW beam on target



Accelerator incl klystron gallery

Coolling

Accelerator cryogenics

Accumulator-ring

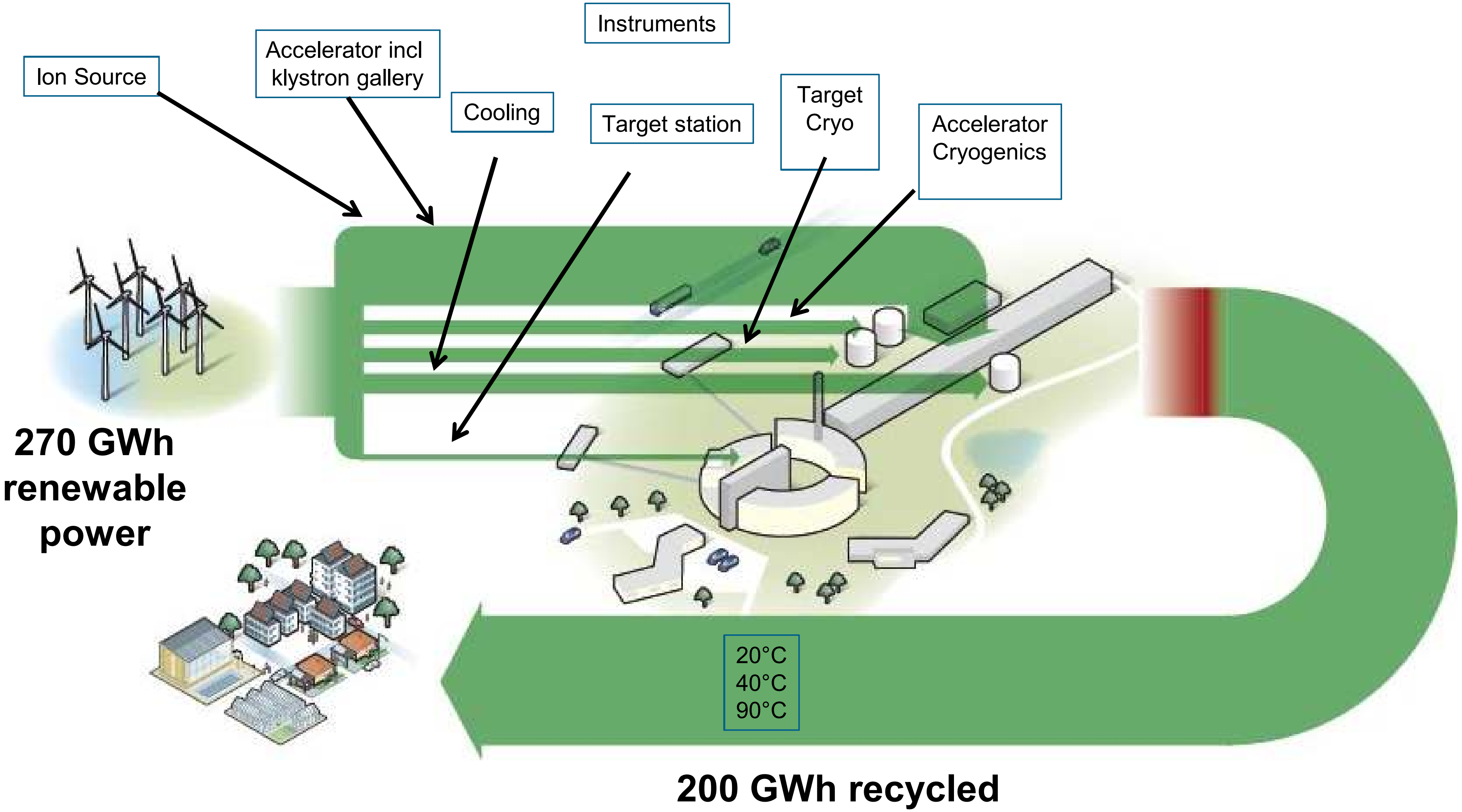
610 GWh power

Target Station

Target cryogenics

580 GWh waste heat

Energy Inventory ESS 2012, 5 MW



Ion Source

Accelerator incl klystron gallery

Cooling

Instruments

Target station

Target Cryo

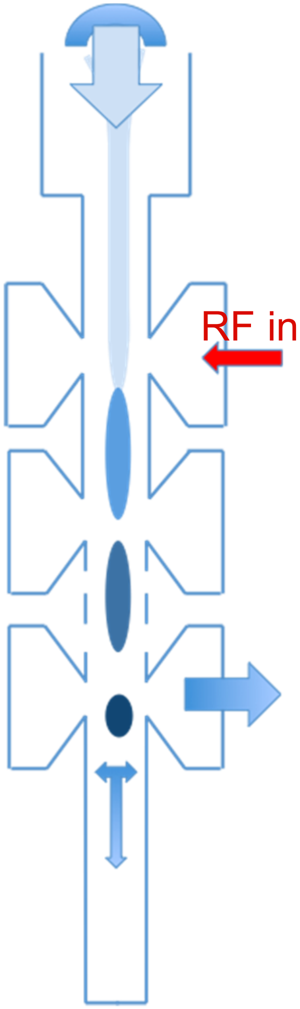
Accelerator Cryogenics

270 GWh renewable power

20°C
40°C
90°C

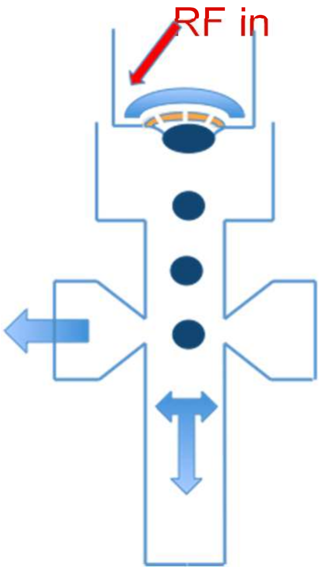
200 GWh recycled

High Power IOTs



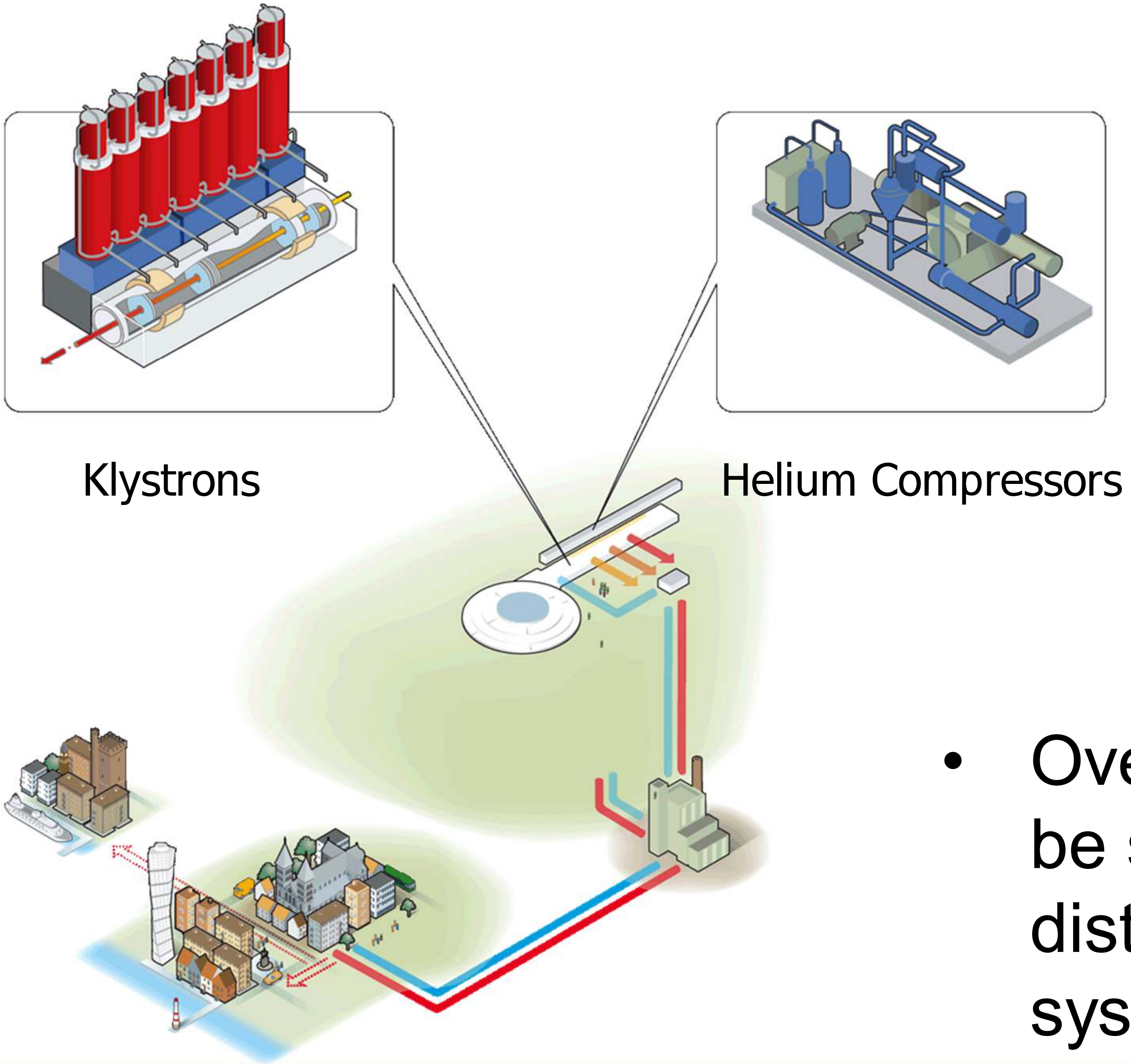
Klystron
Velocity Modulation

- A klystron uses an electron beam to amplify radio frequency signals
- This beam is created as a constant (DC) current, and then ‘tickled’ by the input signal. This causes the DC beam to develop into short bunches, from which the high power signal can be extracted.
- In an Inductive Output Tube (IOT), the electron beam is directly created with bunches at the right frequency.
- **This make the IOT much more efficient.**
- IOTs have been used in TV transmission since the 80’s, but have not been available with the power level required for ESS.
- Seems possible with advances in technology, so ESS is investing in developing such high power IOTs.
- **Possible energy savings in the order of 20GWh/year**



IOT
Density Modulation

High-temperature cooling



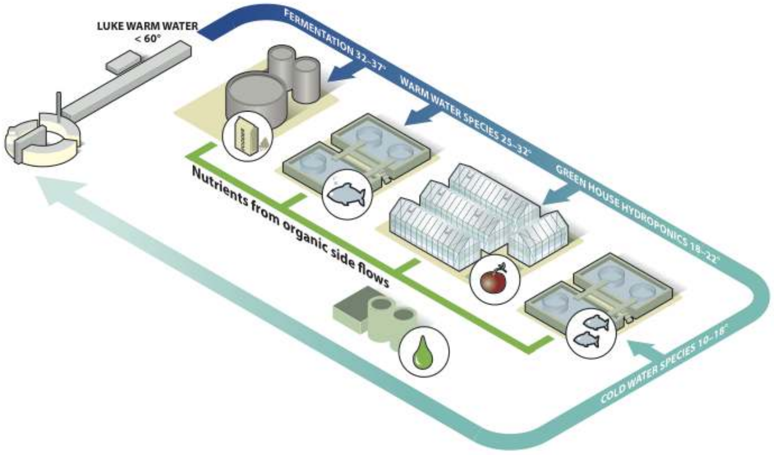
Klystrons

Helium Compressors

- Over 80C, heat can be sold directly to the district heating system

Low temperature heat recycling

- For lower temperature cooling water, heat pumps can be used to bring temperature to a sufficient level for the district heating system.
- But, heat pumps also consume energy (and produce heat).
- Investigating applications where lower temperature water can be used directly, e.g. heating green houses and fisheries



Renewable

- ESS plans to use renewable energy sources

Summary

- ESS is going be built in Lund!
- It will be the worlds most powerful accelerator, and also the first carbon neutral one.
- The accelerator design has changed many times over during the process to achieve site and funding decision.
- Optimization of an accelerator is not just about maximising performance (in some metric), but also about understanding the boundary conditions (e.g. cost) which may well change along the process.
- Important to keep flexibility

Thank You !

2019

ESS European Research Infrastructure Consortium

- "Operations Phase"

2014

ESS AB

- ”Project Phase"

2010

ESS AB

- "Design Update Phase"

2007

ESS Secretariat

- "Campaign Phase"

EUROPEAN
SPALLATION
SOURCE