European Spallation Source Update

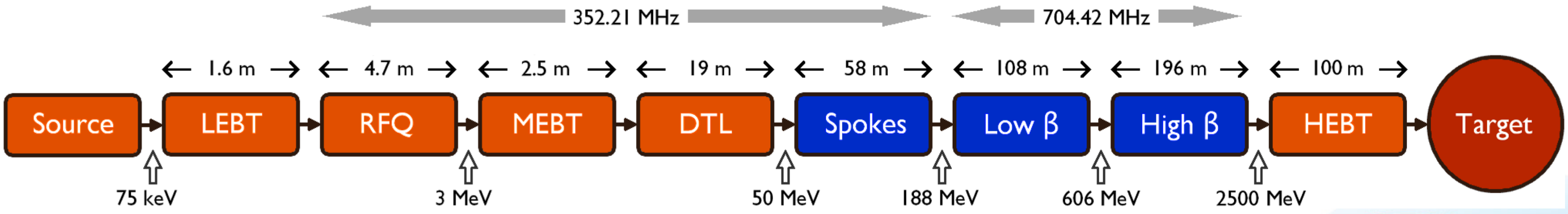
Project X Collaboration Meeting
25-October-2011

EUROPEAN
SPALLATION
SOURCE

Dave McGinnis
RF Group Leader
ESS Accelerator Division

Overview

- ESS is a long-pulse neutron spallation source
- The target is feed by a superconducting 5 MW proton linac
  - Pulse Length = 2.9 mS
  - Pulse Rate = 14 Hz
  - Beam Current = 50 mA
  - Energy = 2.5 GeV



352.21 MHz
704.42 MHz

1.6 m
4.7 m
2.5 m
19 m
58 m
108 m
196 m
100 m

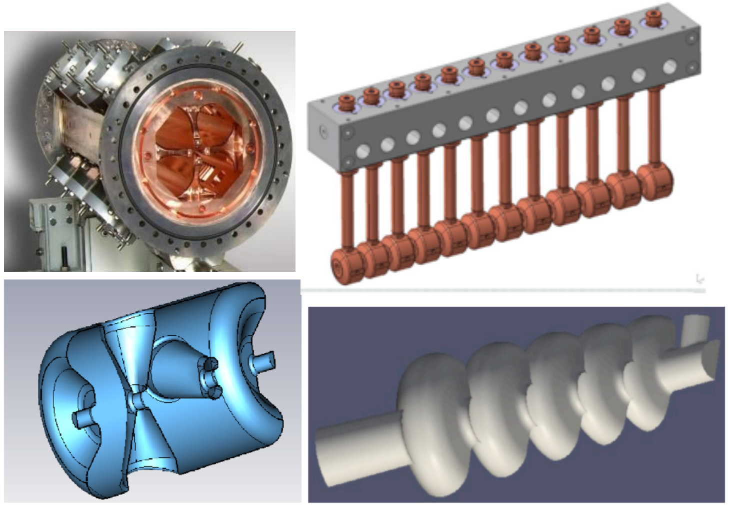
Source → LEBT → RFQ → MEBT → DTL → Spokes → Low β → High β → HEBT → Target

75 keV
3 MeV
50 MeV
188 MeV
606 MeV
2500 MeV

EUROPEAN
SPALLATION
SOURCE

Collaboration

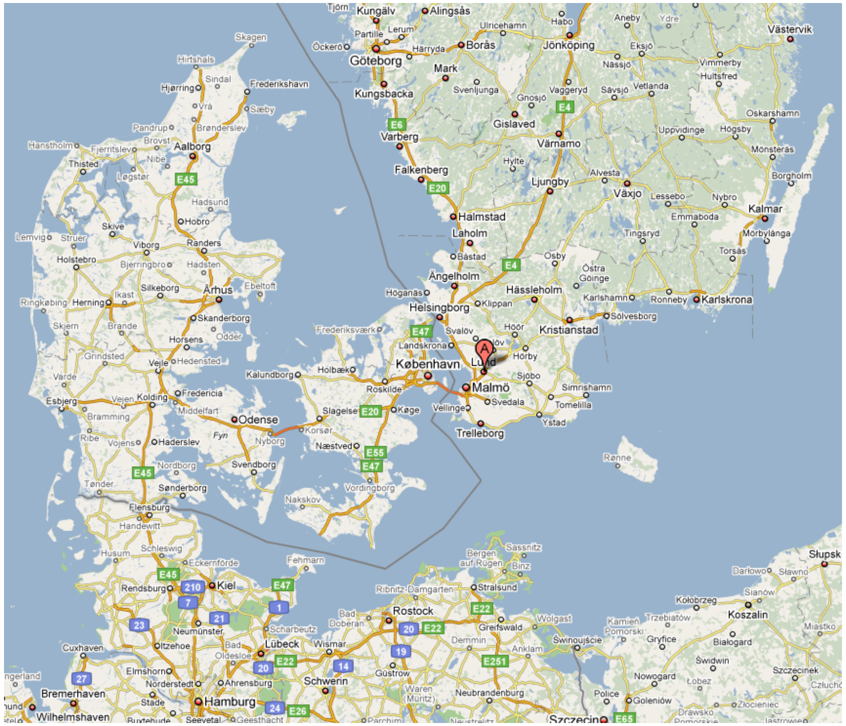
17 member states so far ...



- ESS is being built by a multi-national collaboration
- Accelerator collaboration
  - NC linac: Ion source (INFN), RFQ (CEA), MEBT (Bilbao), DTL (INFN)
  - SC linac: Spoke Cavities (CNRS), Elliptical cavities (CEA)
  - High Energy Beam Transport: Aarhus university
  - RF sources: High-power (Uppsala U), RF regulation, LLRF (Lund U)
  - Utilities: power, network, cooling, etc (Tekniker)

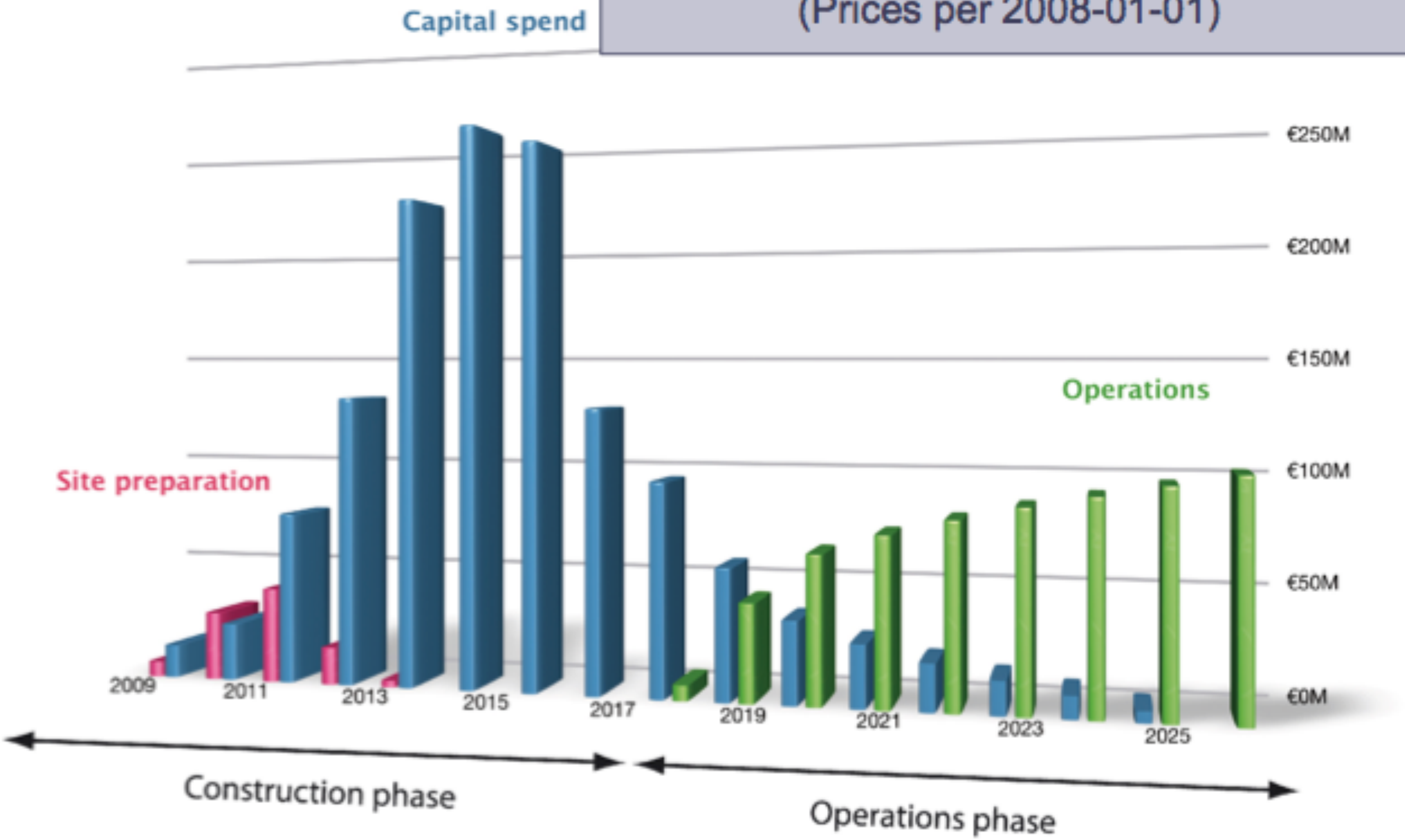
Location

- The ESS Site is in southern Sweden near the city of Lund



Cost

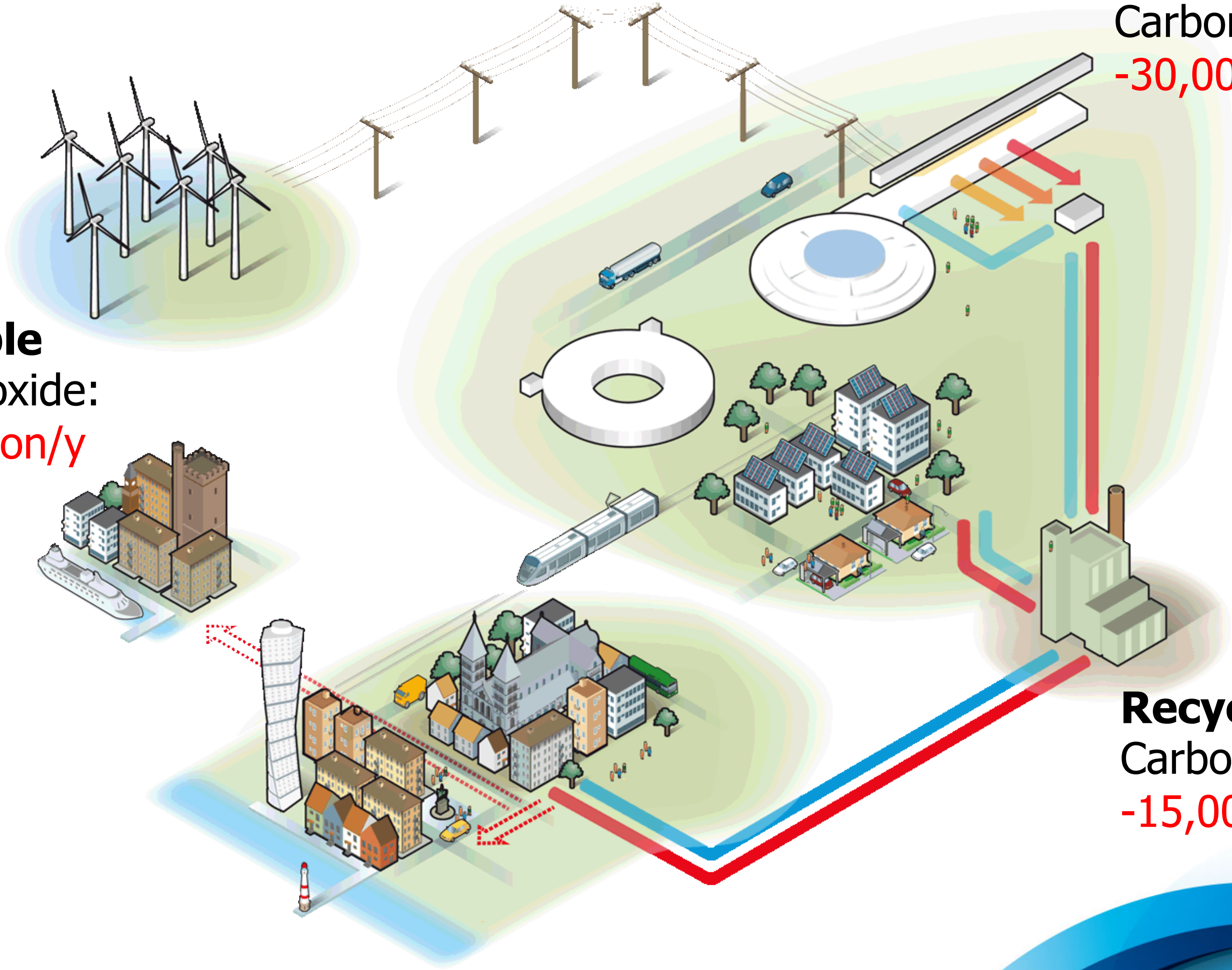
Investment: 1478 M€ / ~10y
Operations: 89 M€ / y
Decommissioning. : 346 M€
(Prices per 2008-01-01)



Funding Strategy

- Sweden, Denmark & Norway cover 50% of cost
- The other 14 member states covers the rest, with the European Investment Bank

Sustainable Energy Concept

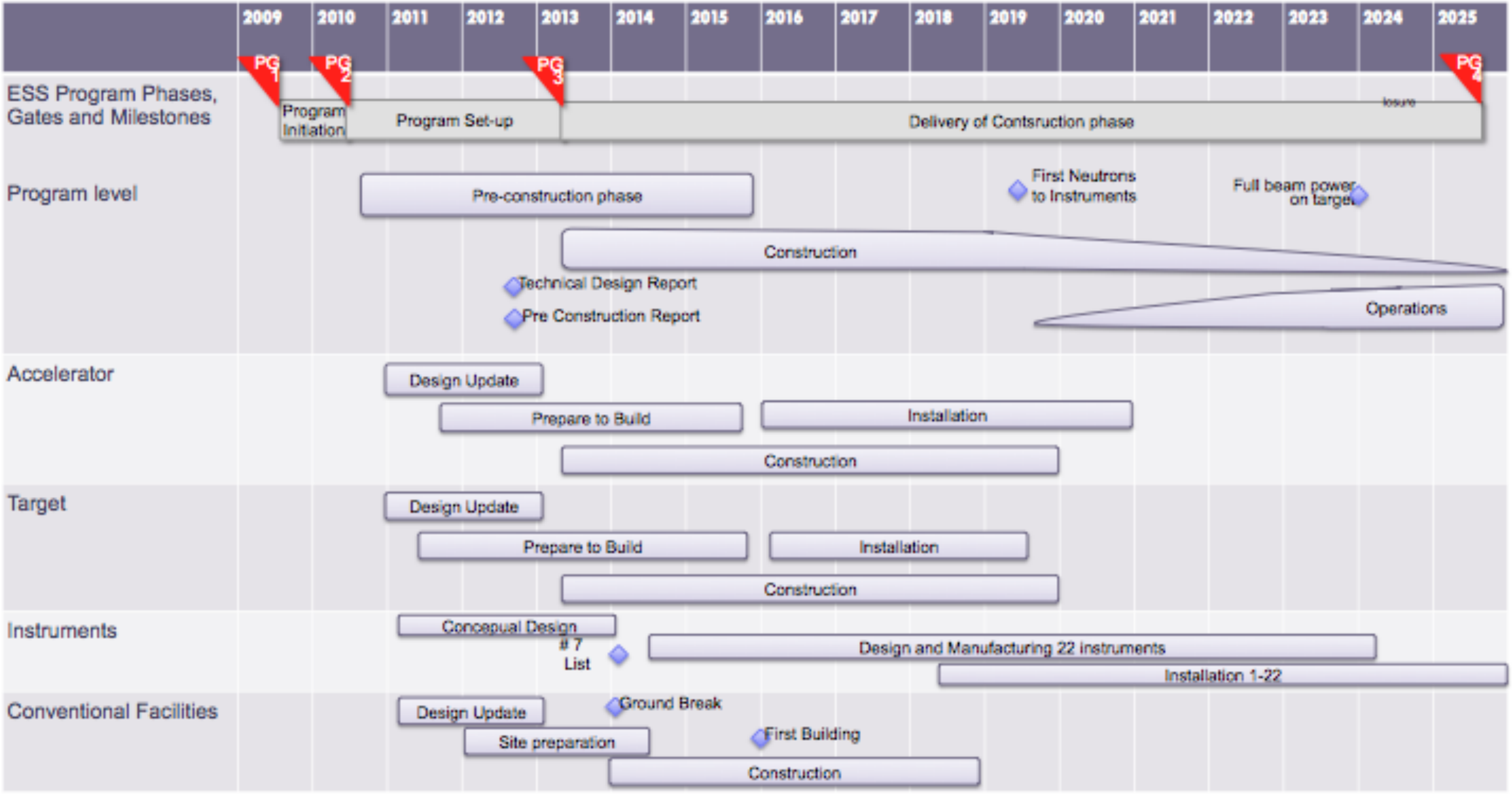


Responsible
Carbon dioxide:
-30,000 ton/y

Renewable
Carbon dioxide:
-120,000 ton/y

Recyclable
Carbon dioxide:
-15,000 ton/y

Schedule


2009
2010
2011
2012
2013
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2015
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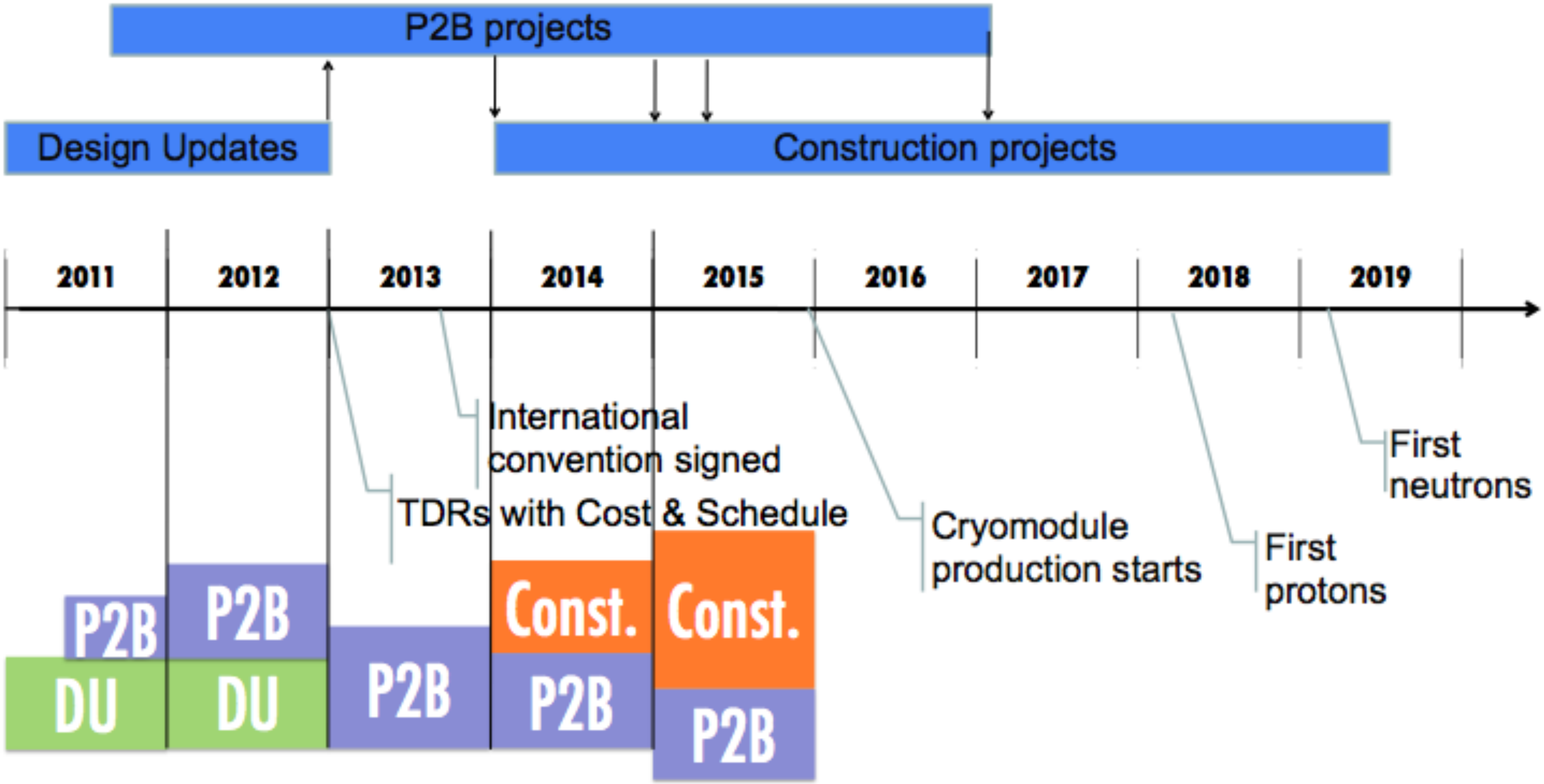
2019
2020
2021
2022
2023
2024
2025
PG 1
PG 2
PG 3
PG 4
ESS Program Phases, Gates and Milestones
Program Initiation
Program Set-up
Delivery of Contsruction phase
losure
Program level
Pre-construction phase
First Neutrons to Instruments
Full beam power on target
Construction
Technical Design Report
Pre Construction Report
Operations
Accelerator
Design Update
Prepare to Build
Installation
Construction
Target
Design Update
Prepare to Build
Installation
Construction
Instruments
Concepual Design
7 List
Design and Manufacturing 22 instruments
Installation 1-22
Conventional Facilities
Design Update
Ground Break
Site preparation
First Building
Construction

Schedule



P2B projects

Design Updates

Construction projects

2011
2012
2013
2014
2015
2016
2017
2018
2019

International convention signed

TDRs with Cost & Schedule

Cryomodule production starts

First protons

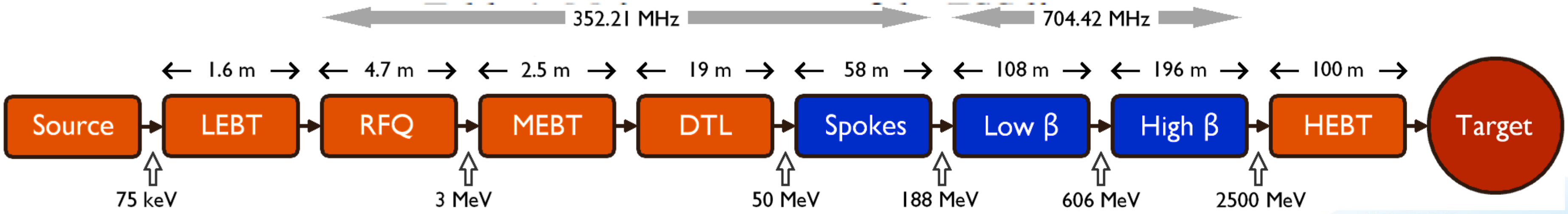
First neutrons

P2B
DU
P2B
DU
P2B
Const.
P2B
Const.
P2B

CONCEPTUAL DESIGN REPORT

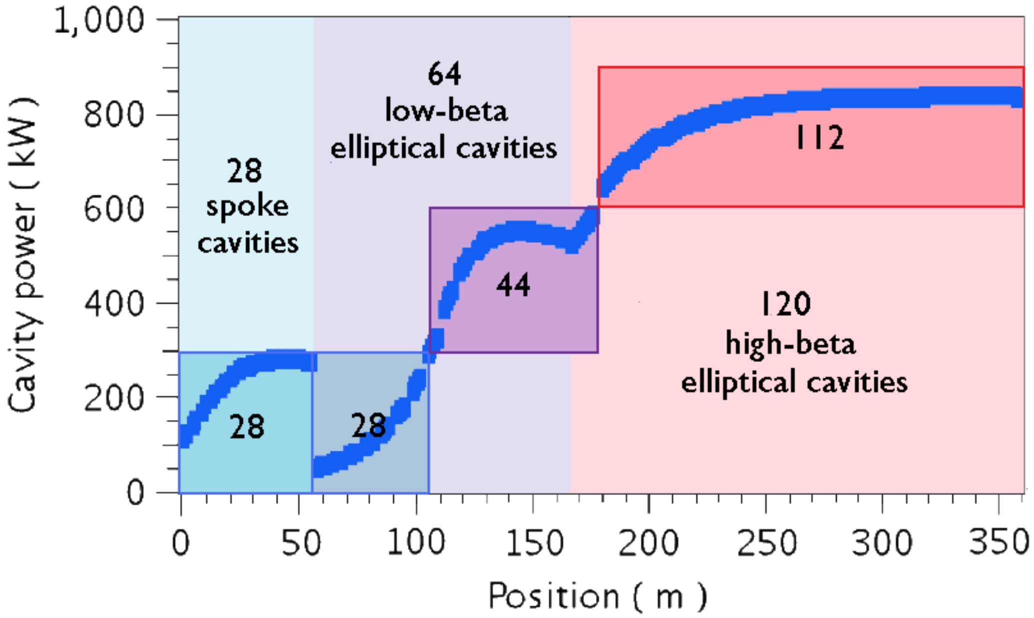
Main Parameters

Section	Energy$_{out}$	Beta$_{out}$	Length	Temp	Freq
Ion source	75 keV	0.01	2.5 m	300 K	–
RFQ	3 MeV	0.08	4.7 m	300 K	352 MHz
MEBT	3 MeV	0.08	2.5 m	300 K	352 MHz
DTL	50 MeV	0.31	19 m	300 K	352 MHz
Spokes, $\beta_{opt} = 0.50$	188 MeV	0.55	58 m	2 K	352 MHz
Ellipticals, $\beta_g = 0.70$	606 MeV	0.79	108 m	2 K	704 MHz
Ellipticals, $\beta_g = 0.90$	2500 MeV	0.96	196 m	2 K	704 MHz
HEBT	2500 MeV	0.96	100 m hor	300 K	–



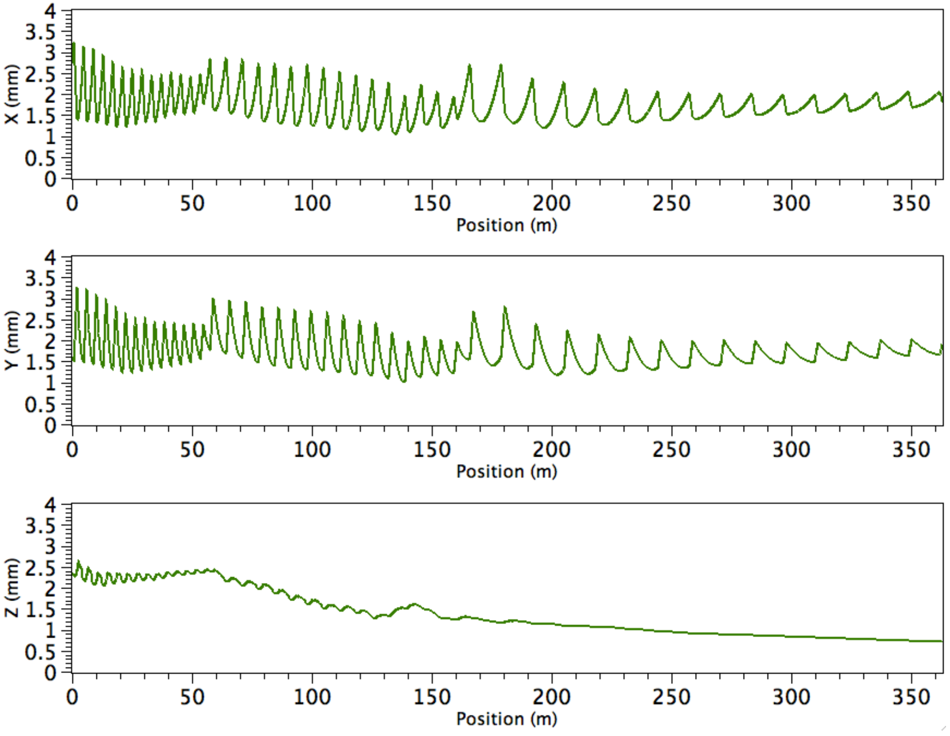
Superconducting Linac

	Spoke resonators	Low-beta ellipticals	High-beta ellipticals
Gaps or cells per cavity	3	5	5
Cavities per cryomodule	2	4	8
Cryomodules per family	14	16	15

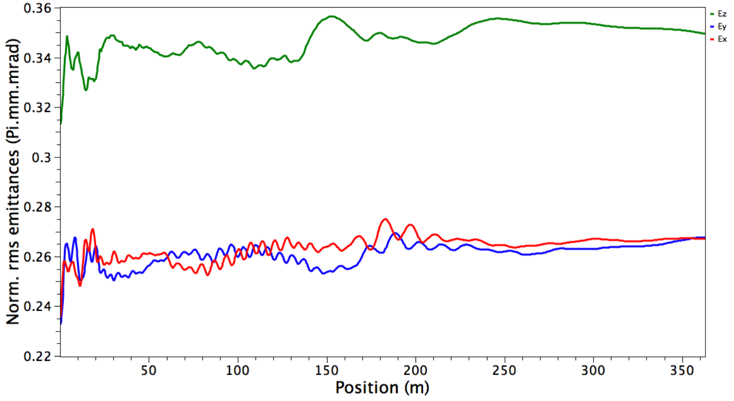


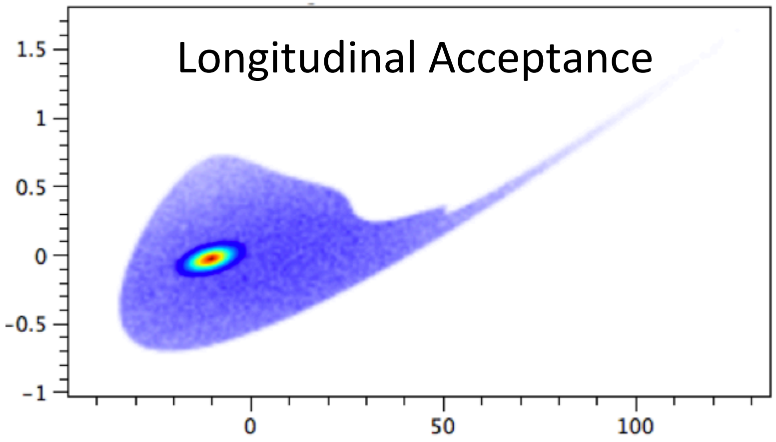
Lattice

Beam Size



Emittance

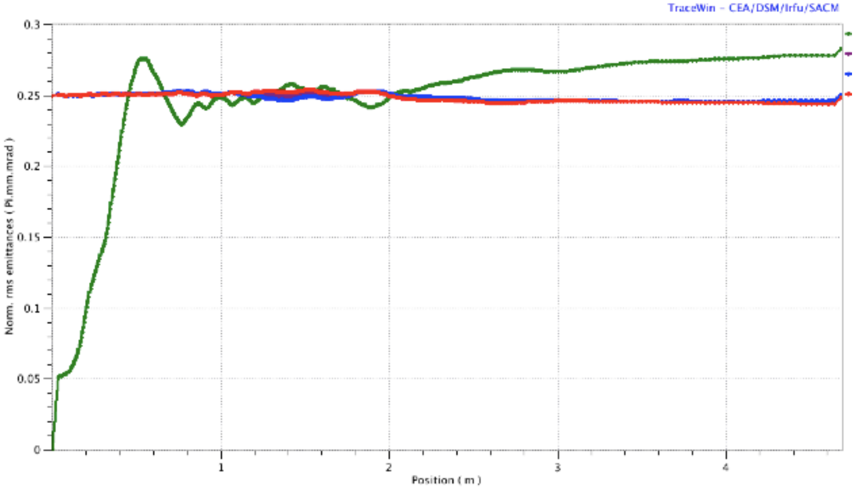




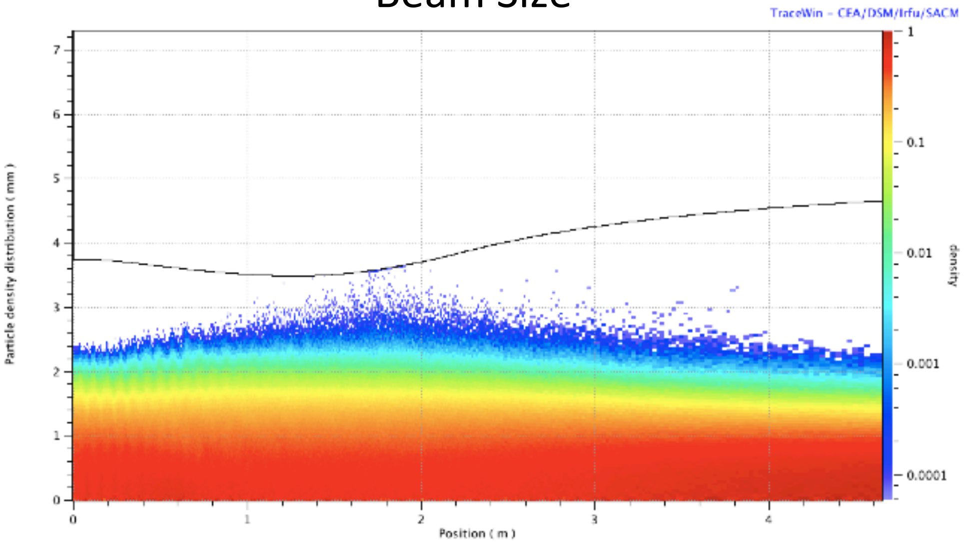
Longitudinal Acceptance

RFQ

Emmittance



Beam Size

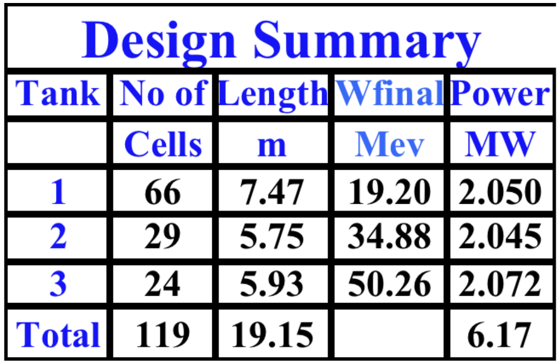


Drift Tube Linac

- 2.5 MW klystrons (about 2 MW per tank)
- Mechanical design based on tank design developed at CERN
  - accurate positioning and alignment of tube position, metallic gaskets
- Permanent magnet quadrupole
  - allow an improvement of shunt impedance with smaller dimensions of drift tubes)
  - substantial simplification of cabling and logistics
- Power couplers of Linac4 kind
  - planar window
  - wave guide slot.

Drift Tube Linac

- FODO Lattice (focusing period 4βl, O are empty drift tubes for BPMs and steerers) :
  - Space inside DTL for steering and BPM.
  - Optimizations of Shunt impedance by asymmetric cell.
  - Reduced number of PMQ.
  - High gradient of PMQ, from 54 T/m to 71 T/m.
- FFDD Lattice:
  - No space inside DTL.
  - Low gradient of PMQ.



Design Summary

Tank	No of Cells	Length m	Wfinal Mev	Power MW
1	66	7.47	19.20	2.050
2	29	5.75	34.88	2.045
3	24	5.93	50.26	2.072
Total	119	19.15		6.17

Lattice	FODO Const. G	FODO Equip. G	FFDD Const. G	FFDD Equip. G
# PMQ	62	62	119	119
G PMQ [T/m]	54	72 - 31	45.5	51.5 - 22.5
Emit(x,y) increase [%]	16	14	13	15
Emit(z) increase [%]	26	14	23	13
Halo(x,y) increase [%]	59	32	48	30
Halo(z) increase [%]	14	34	41	35

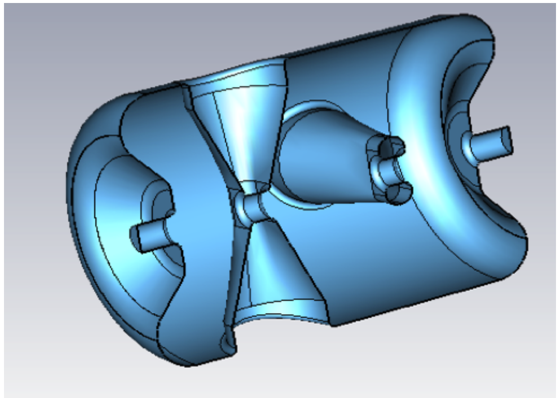
Spoke Cavity Section

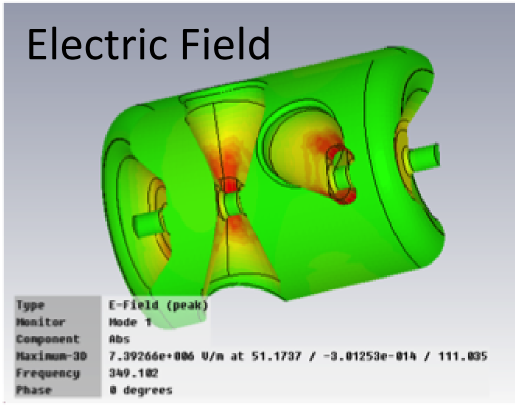
- Advantages of Spoke Cavities
  - have multi-gap capabilities (high real-estate gradients)
  - are compact and natural stiff (less sensitive to mechanical perturbation such as vibrations)
  - exhibit high cell to cell coupling (no field flatness required)
  - are less sensitive to HOM or trapped modes (due to the high cell to cell coupling)
  - are not submitted to dipole steering effect (contrary to other low beta cavities like quarter-wave resonators)
  - have a wide β range accessible
  - exhibit a high longitudinal acceptance (accelerating efficiency over a wide β range)

Spoke Cavity Design Constraints

- Operating accelerating field at 8 MV/m
  - peak field limited to 40 MV/m,
  - Limit set by risk of field emission.
- The required peak RF power is about 250 kW
  - for the 50 mA beam intensity
  - corresponding to 10 kW of average power.

Spoke Cavity Design



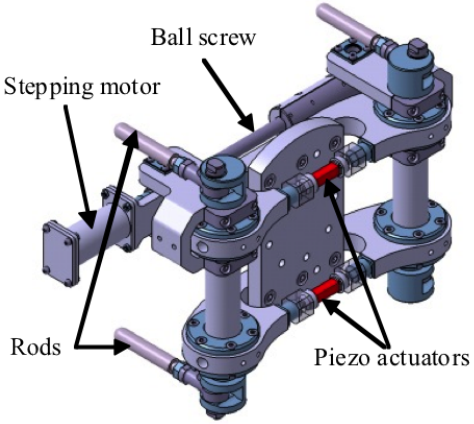


Electric Field

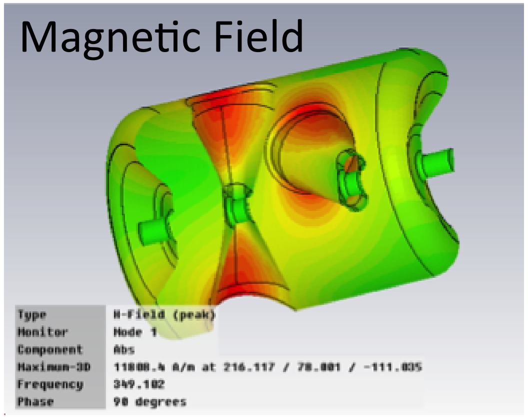
Type	E-Field (peak)
Monitor	Mode 1
Component	Abs
Maximum-3D	7.39266e+006 V/m at 51.1737 / -3.01253e-014 / 111.035
Frequency	349.102
Phase	0 degrees

Overall dimension of the cavity	
Cavity β	0.50
Cavity length	687 mm
Cavity diameter	492 mm

R/Q	394 Ω
G	105 Ω
Qo at 4K (with Rres = 10 nΩ)	1.8 109
Qo at 2K (with Rres = 10 nΩ)	9.3 109
E_{pk}/E_{acc}	5.4
B_{pk}/E_{acc}	8.7 mT/(MV/m)

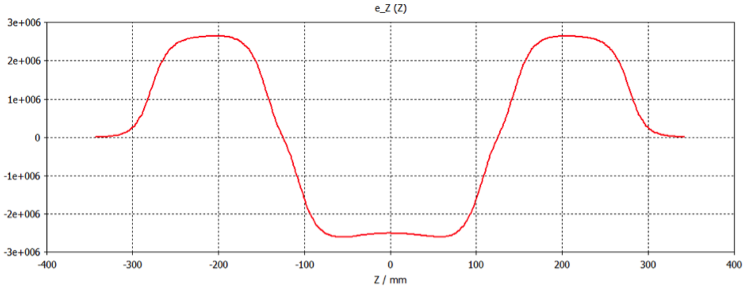


Tuner Design



Magnetic Field

Type	H-Field (peak)
Monitor	Mode 1
Component	Abs
Maximum-3D	11808.4 A/m at 216.117 / 78.001 / -111.035
Frequency	349.102
Phase	90 degrees



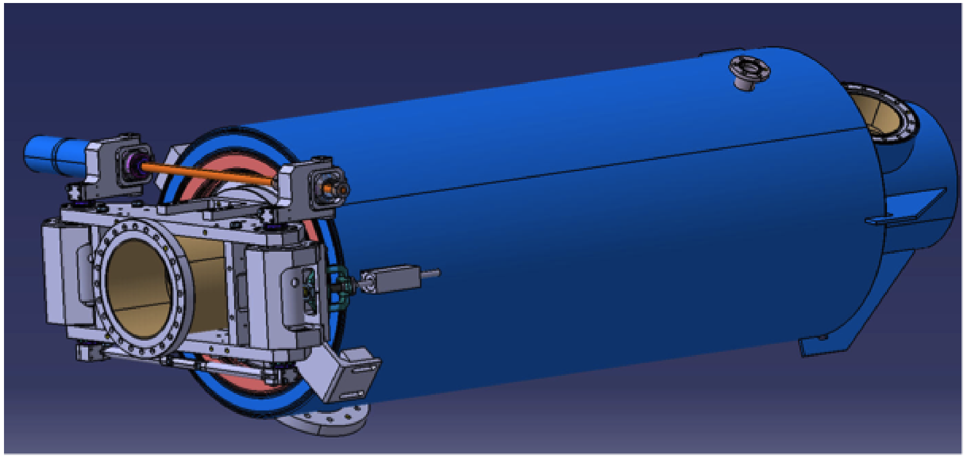
Elliptical Cavity

- An XFEL production run of 50 cavities
  - At a 20 MV/m gradient is obtained for about 80 to 90% of the cavities
  - 20 MV/m gradient corresponds to 40 MV/m peak surface electric field
- Investigated cavity coupling parameter to trade off cavity efficiency vs
  - Field flatness
  - Aperture
  - Pass-band separation
  - HOM propagation
- Investigated cavity wall angle vs Lorentz detuning

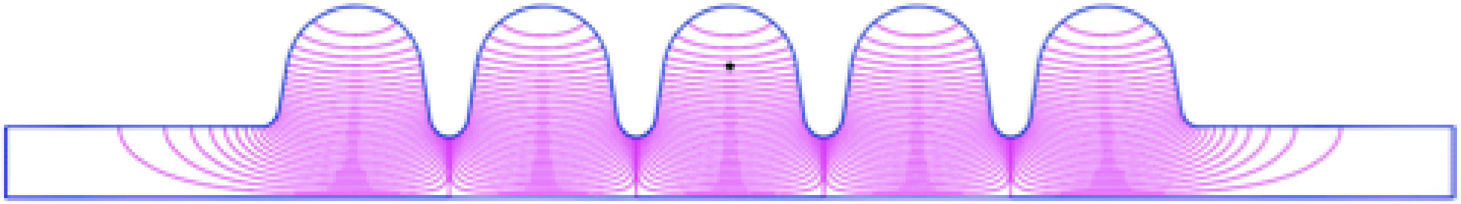
Elliptical Cavity Design

Frequency	[MHz]	704.42
Number of cells		5
Cell to cell coupling	%	1.8
Geometrical beta		0.86
Optimum beta		0.92
Maximum r/Q	Ω	477
E_{pk}/E_{acc}		2.2
B_{pk}/E_{acc}	mT/(MV/m)	4.3
G	Ω	241
π and $4\pi/5$ mode separation	MHz	1.2
Iris diameter	mm	120

KL fixed ends	$Hz/(MV/m)^2$	-0.36
KL free ends	$Hz/(MV/m)^2$	-8.9
Stiffness	kN/mm 2.59	
Δf/Δz	kHz/mm	197
max VM stress /1mm elongation	MPa	25
KP fixed ends	Hz/mbar	4,85
KP free ends	Hz/mbar	-150
max VM stress /1bar fixed	MPa	12
max VM stress /1bar free	MPa	15



High beta cavity with titanium helium vessel and integrated piezo tuner.



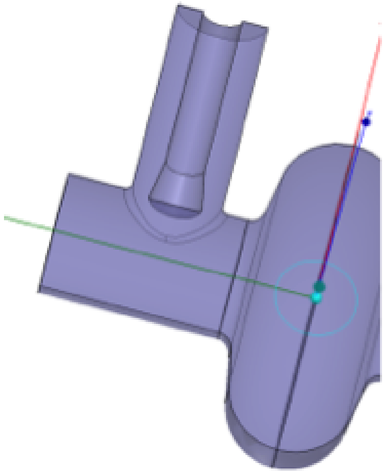
Elliptical Cavity Power Coupler

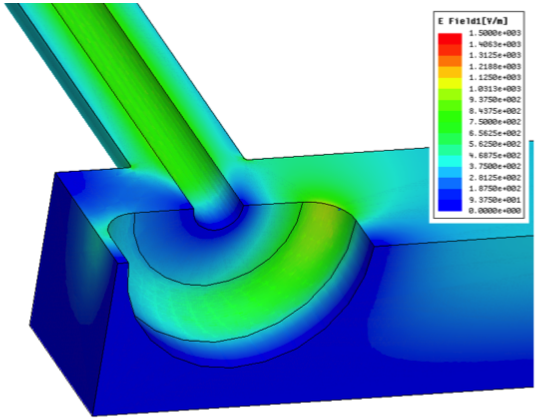
- Lots of power!
  - 900kW beam power per coupler (not including overhead for regulation)
  - 36 kW of average power per coupler
- Why not waveguides?
  - Warm window
    - long folded waveguide - big at 700 MHz – no more simple cryomodule design
    - Lots of material in the clean room
  - Cold window – yet to be demonstrated
  - Multi-pactoring – large amount of surface area of waveguide made out of niobium
- 1MW coaxial couplers designed and tested at Saclay
  - 1MW peak in full reflection
  - 35 kW average in full reflection
- Cryo-module design issues
  - At 1MW peak, 35kW average, the couplers should not move (much) during cool-down
  - Warm window highly desirable
  - cold windows problematic and not demonstrated at these high power levels – implications on the ILC cryo-module configuration

Elliptical Cavity Power Coupler

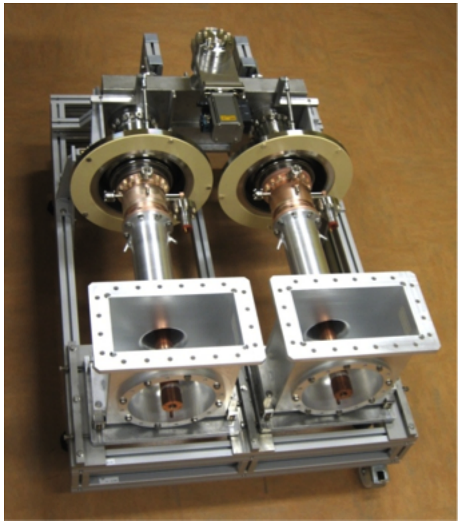
Table 11: Power coupler specifications.

Nominal peak input power	kW	900
Maximum admissible input power	kW	1200
Maximum duty cycle	%	10

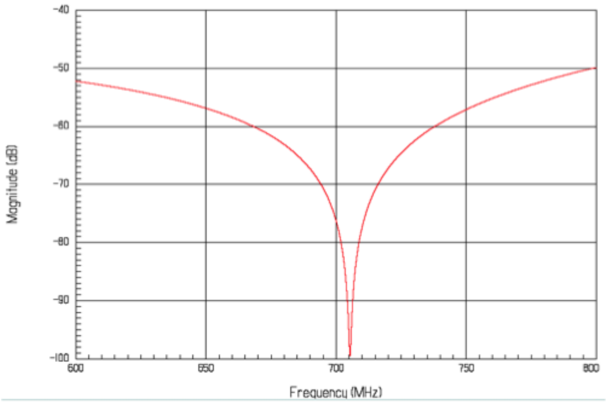




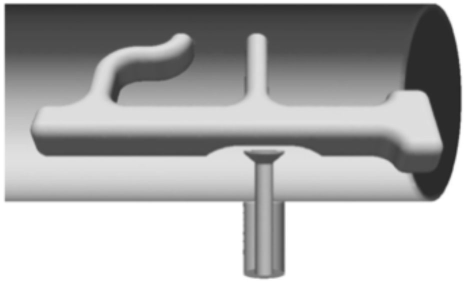
Electric Field in doorknob transition



CEA-Saclay 1MW power Coupler



S11 at the 704 MHz Window



HOM Coupler

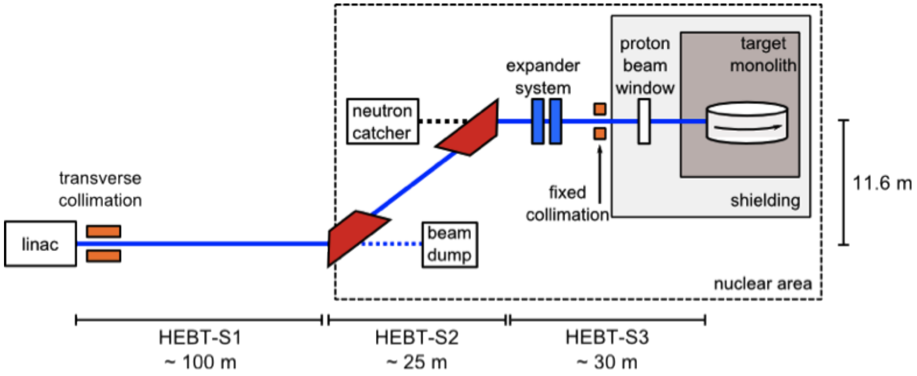
Cryo-modules

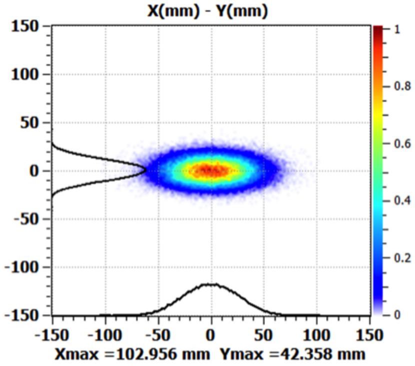
- There are three distinct sections of cavities:
  - 28 instances of 352 MHz spoke cavities,
    - housed in 14 cryo-modules (CMS)
    - which hold two cavities and two quadrupoles each
  - 64 instances of 704 MHz low-β elliptical cavities
    - housed in 16 cryo-modules (CML)
    - which hold four cavities and two quadrupoles each
  - 120 instances of 704 MHz high-β elliptical cavities
    - housed in 15 cryo-modules (CMH)
    - which hold eight cavities and two quadrupoles each
- This results in a total of 212 cavities in 45 cryo-modules, distributed over a length of 370 m.

Three Possible Configurations

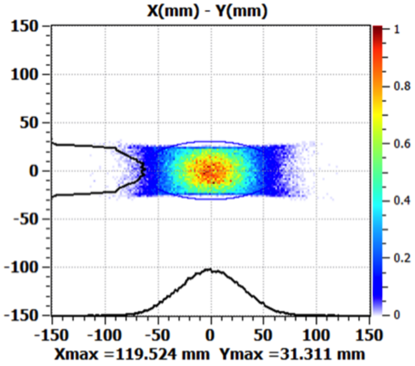
- Continuous cryo-module design
  - Advantages
    - no cold-warm transitions between cavity strings
    - No-need for an external cryo line
  - Disadvantages
    - Harder to repair– long MTTR
    - Lack of warm instrumentation
- Segmented cryo-module design
  - Advantages
    - Easier to repair
    - Warm instrumentation
    - Warm quads
      - Rapid beam based alignment possible
      - **Staging possible**
  - Disadvantages
    - Higher heat load from ends and external cryo transfer line
    - More space required
- Hybrid cryo-module design
  - Separate modules
  - An independent, external cryogenic distribution line,
  - Interconnecting sleeves between the modules
    - continuous cryogenic temperatures
    - isolation vacuum
  - Advantages
    - lack of the cold-warm transitions between CMs
    - easy transformation of any of the inter-module gaps from cold to warm
    - Modularity - replacement of any single cryomodule
  - Disadvantages
    - Added complexity
    - Actual heat load reduction unknown at this time

High Energy Beam Transport

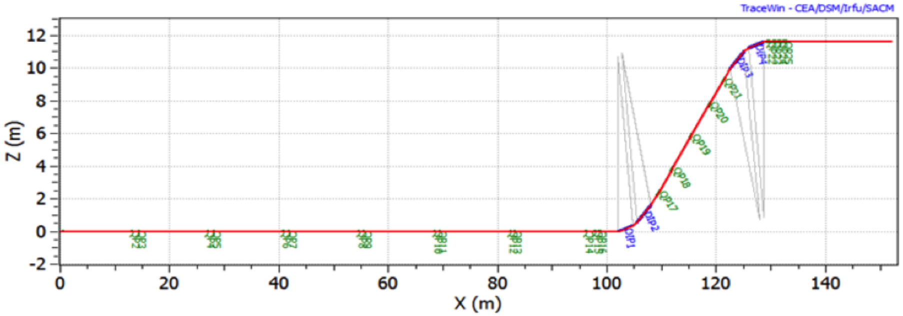


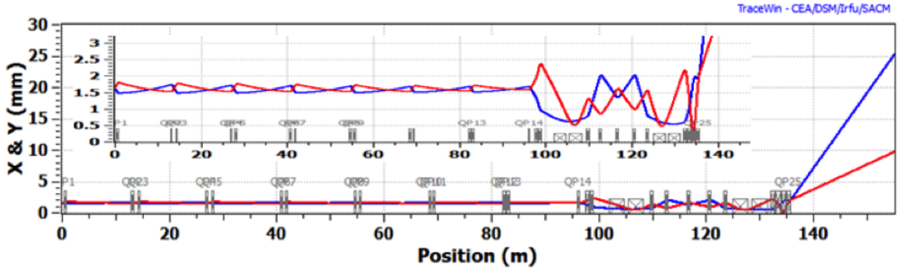


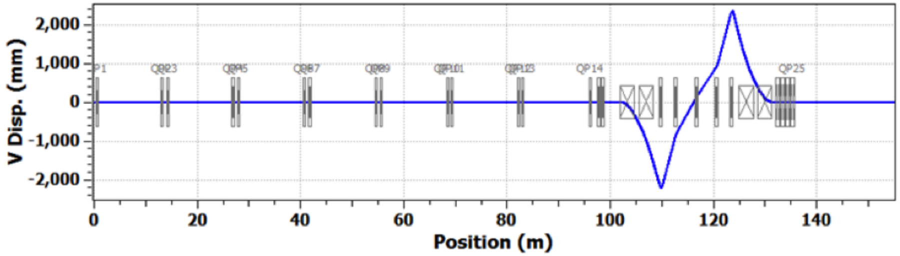
Quadrupole Expansion



Octrupole Expansion



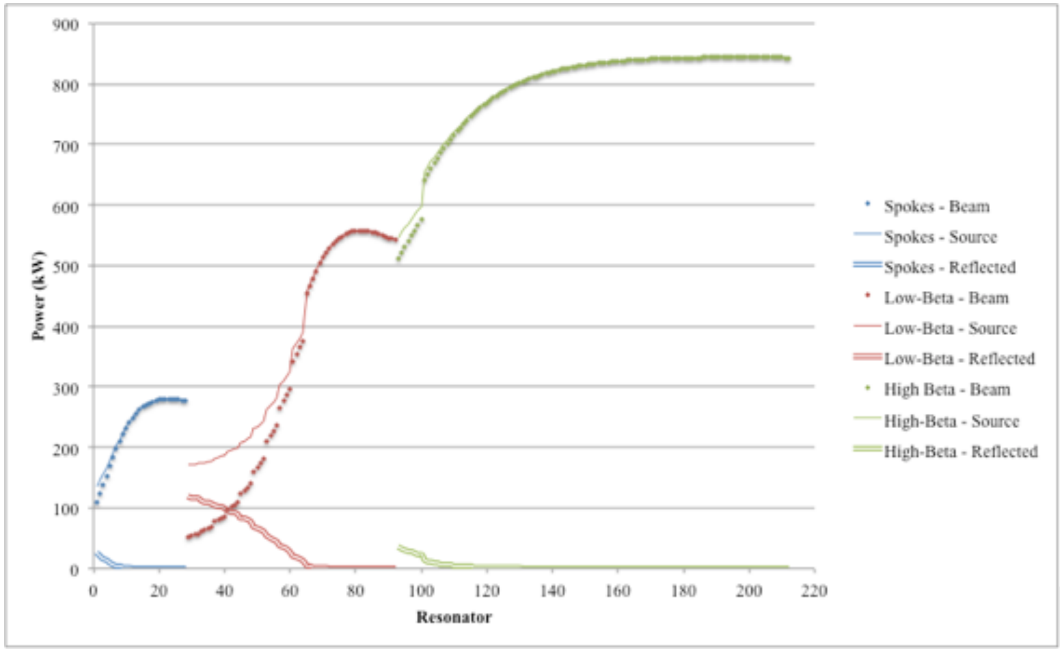


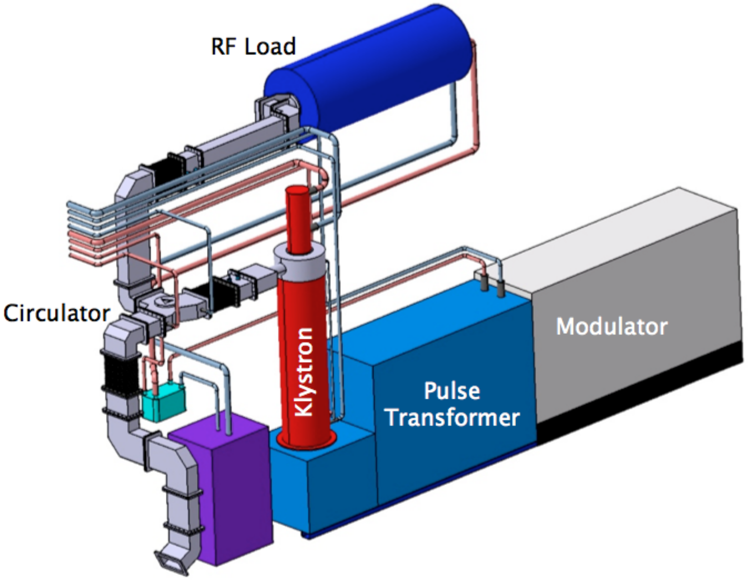


RF Systems

- Average gradient of 7.1MV / meter (2.5GeV within 350 meters)
- Average power delivered to the beam is 5 MW
  - Peak power > 123 MW(4% duty factor).
  - Peak power density > 350kW/meter
- Baseline Design
  - For ultimate flexibility, one klystron-modulator system per cavity
  - Only klystrons considered - IOT’s are at the limit of the range of the required 352 MHz pulse power
  - Peak klystron power 1.6x beam power
    - 1 dB loss budget from klystron to coupler
    - 30% overhead for low level RF regulation

RF Systems

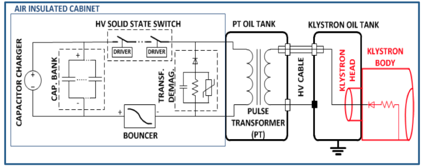




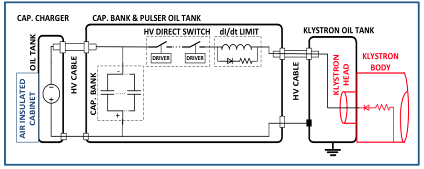
Module	Frequency [MHz]	Quantity	Max. Power to Beam [kW]	Source Output Power [kW]	R/Q [Ohms]	Q External	Band-width [kHz]	Average Cavity Spacing [m]
RFQ	352.21	1	900	1500				
DTL type A	352.21	1	1000	1500				
DTL type B	352.21	2	2000	2800				
Spoke	352.21	28	280	450	500	237,000	1.49	1.99
Elliptical low-β	704.42	64	560	900	300	800,000	0.89	1.67
Elliptical high-β	704.42	120	850	1360	477	750,000	0.94	1.62

Modulators

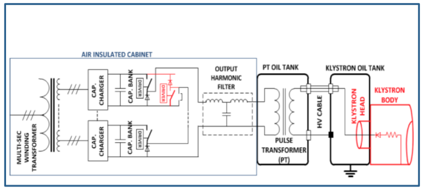
- Modulator Requirements
  - – 3.5 mS flattop
  - – 120 kV, 20Amps
  - – 14 Hz



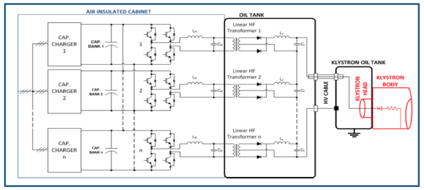
Monolithic Pulse Transformer Topology



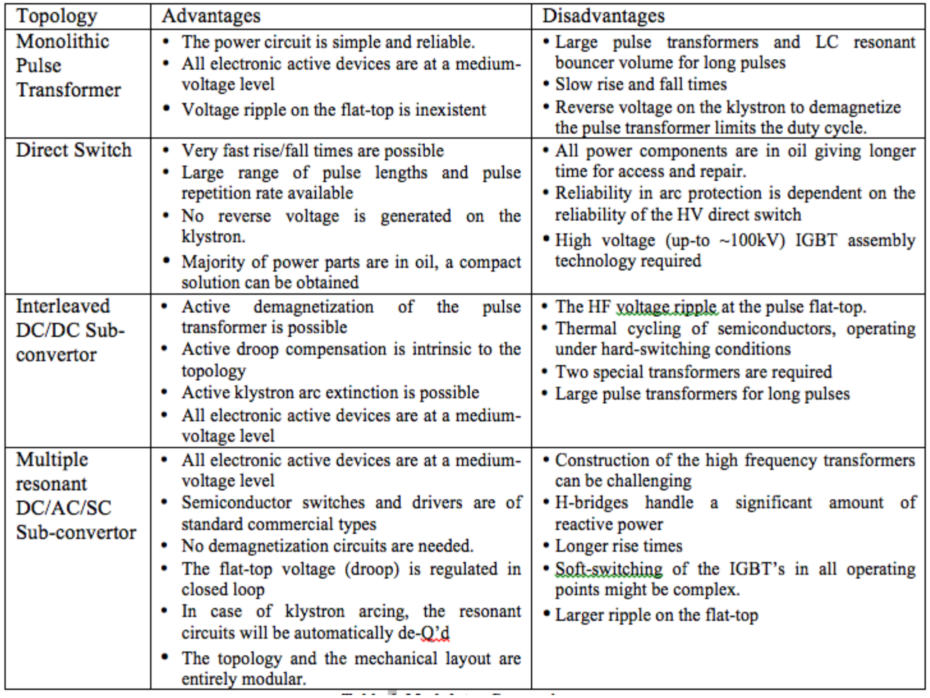
Direct Switch Topology



Interleaved DC/DC Subconvertor Topology

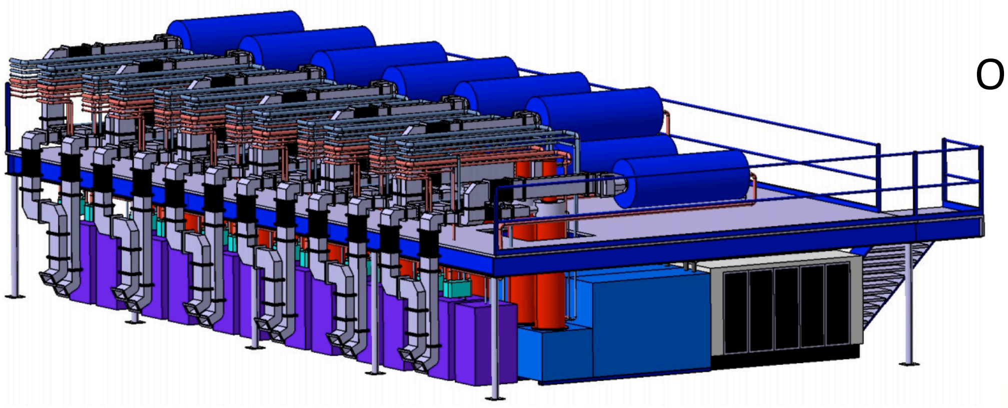


Multiple resonant DC/AC/SC Subconvertor Topology

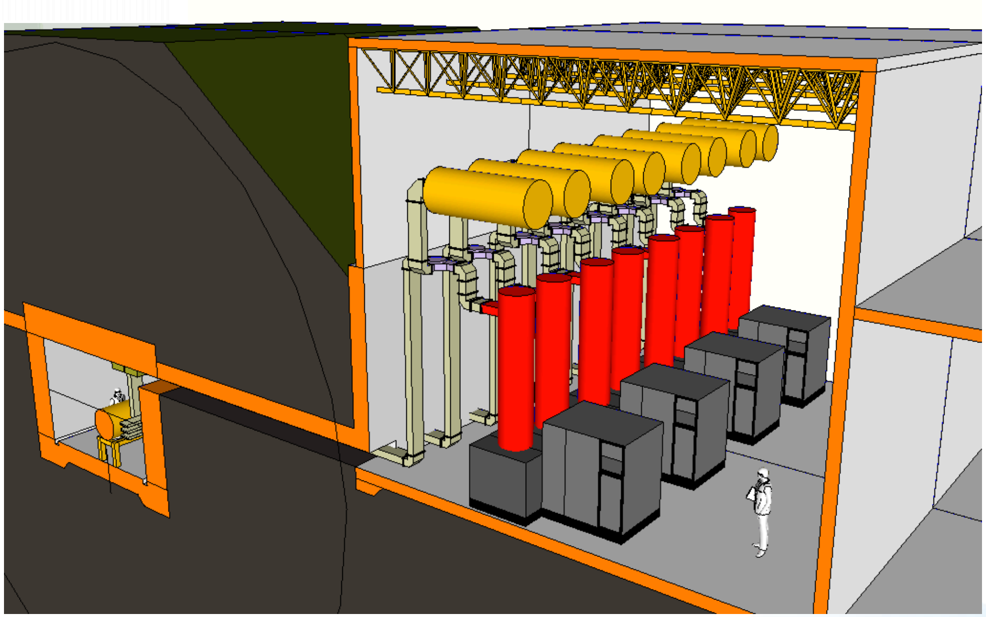


Topology	Advantages	Disadvantages
Monolithic Pulse Transformer	• The power circuit is simple and reliable. • All electronic active devices are at a medium-voltage level • Voltage ripple on the flat-top is inexistent	• Large pulse transformers and LC resonant bouncer volume for long pulses • Slow rise and fall times • Reverse voltage on the klystron to demagnetize the pulse transformer limits the duty cycle.
Direct Switch	• Very fast rise/fall times are possible • Large range of pulse lengths and pulse repetition rate available • No reverse voltage is generated on the klystron. • Majority of power parts are in oil, a compact solution can be obtained	• All power components are in oil giving longer time for access and repair. • Reliability in arc protection is dependent on the reliability of the HV direct switch • High voltage (up-to ~100kV) IGBT assembly technology required
Interleaved DC/DC Sub-convertor	• Active demagnetization of the pulse transformer is possible • Active droop compensation is intrinsic to the topology • Active klystron arc extinction is possible • All electronic active devices are at a medium-voltage level	• The HF voltage ripple at the pulse flat-top. • Thermal cycling of semiconductors, operating under hard-switching conditions • Two special transformers are required • Large pulse transformers for long pulses
Multiple resonant DC/AC/SC Sub-convertor	• All electronic active devices are at a medium-voltage level • Semiconductor switches and drivers are of standard commercial types • No demagnetization circuits are needed. • The flat-top voltage (droop) is regulated in closed loop • In case of klystron arcing, the resonant circuits will be automatically de-Q'd • The topology and the mechanical layout are entirely modular.	• Construction of the high frequency transformers can be challenging • H-bridges handle a significant amount of reactive power • Longer rise times • Soft-switching of the IGBT's in all operating points might be complex. • Larger ripple on the flat-top

Klystron Gallery



One Klystron / Modulator



Two Klystrons / Modulator

Summary

- ESS will be the most powerful proton linac to be built this decade
- The beam power gives rise to numerous technical challenges
- The schedule is demanding
- We are in the middle of completing our CDR
- We will hope to complete our TDR by the end of 2012
- We can use assistance in a variety of areas
  - Cryomodule design
  - RF system design
  - Modulator design
  - Instrumentation

Sweden is a Nice Place To Live