European Spallation Source RF Systems

Uppsala RF Workshop
13-December-2011

EUROPEAN
SPALLATION
SOURCE

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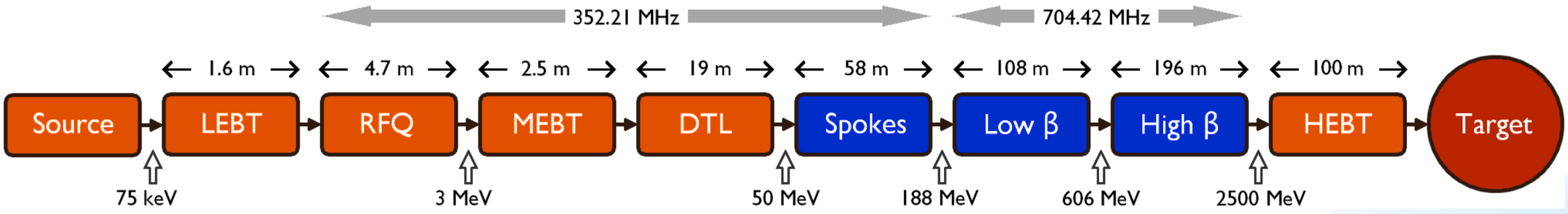
ESS Accelerator Division

Overview

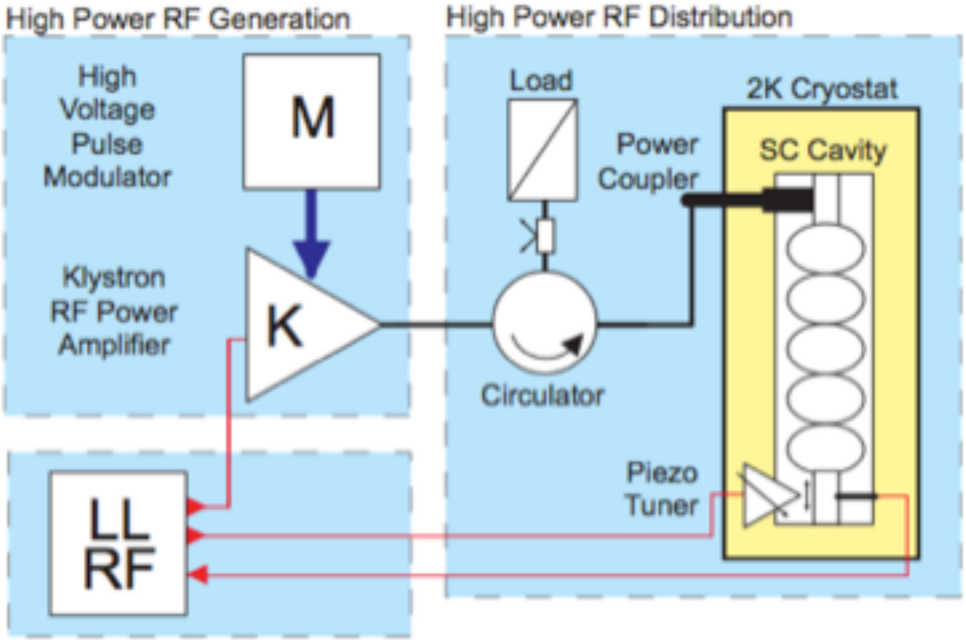
- 5 MW proton linac
  - Pulse Length = 2.9 mS
  - Pulse Rate = 14 Hz
  - Beam Current = 50 mA
  - Energy = 2.5 GeV

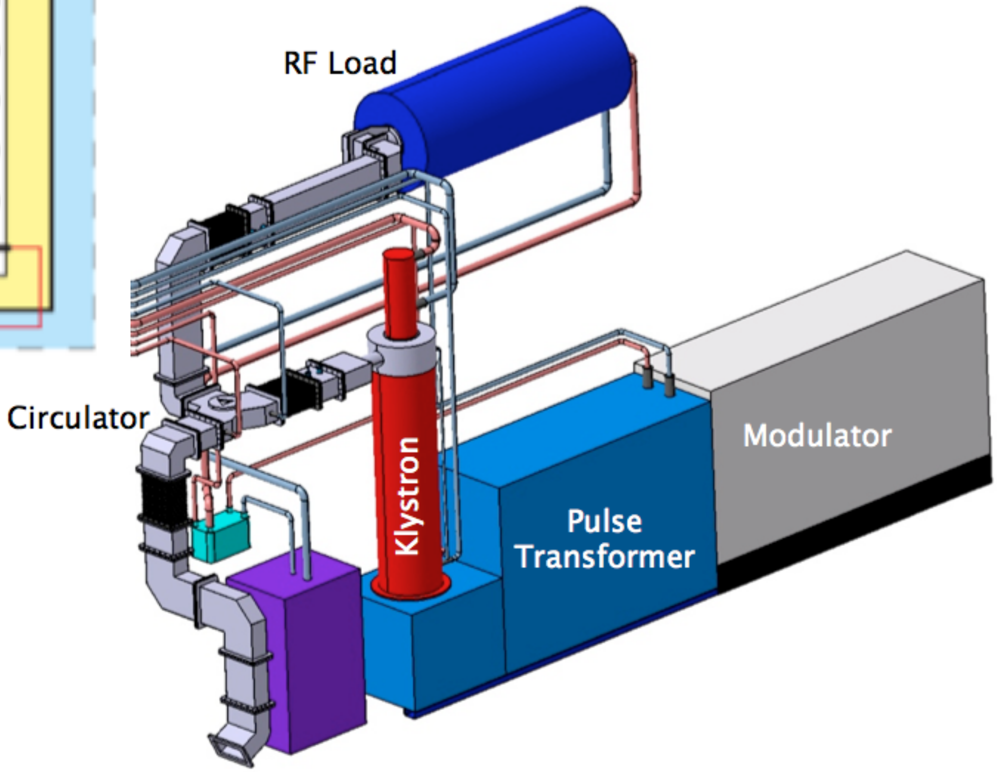


What is 5 MegaWatts?

- 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 1000kg car traveling at 96 km/hour
    - **Happens 14 x per second**
  - You boil 1000 kg of ice in 83 seconds
    - A ton of tea!!!

RF System – Wall Plug to Coupler



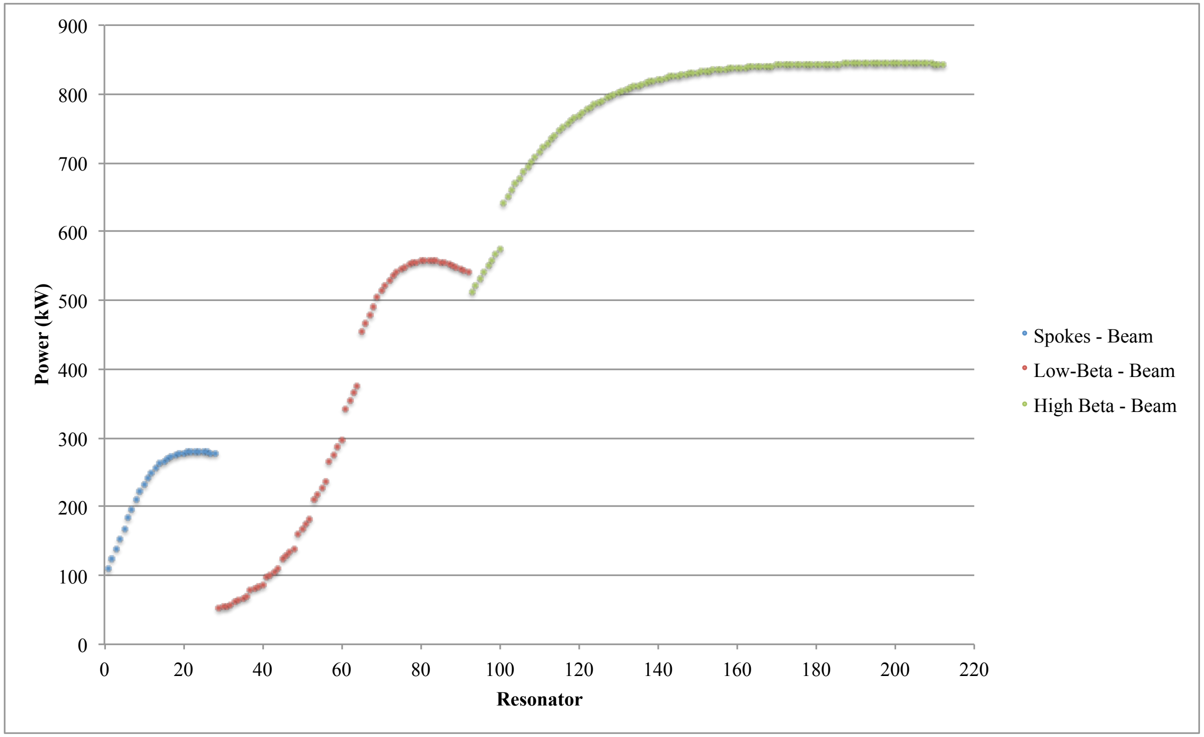


SNS Gallery

DTL Klystrons

ESS RF System Overview

Module	Frequency [MHz]	Quantity	Max. Power to Coupler [kW]
RFQ	352.21	1	900
DTL type A	352.21	1	2100
DTL type B	352.21	2	2100
Spoke	352.21	28	280
Elliptical low-β	704.42	64	560
Elliptical high-β	704.42	120	850



System Bandwidth

- Dominated by large beam loading of 50 mA
- Spokes:
  - R/Q = 500 Ohms, V_{max} = 5.7 MV
  - Q_L = 240,000, Bandwidth = 1500 Hz
- Medium Beta:
  - R/Q = 300 Ohms, V_{max} = 11.3 MV
  - Q_L = 800,000, Bandwidth = 900 Hz
- High Beta:
  - R/Q = 470 Ohms, V_{max} = 17.3 MV
  - Q_L = 750,000, Bandwidth = 940 Hz

De-Tuning

- Lorentz detuning
  - Max Gradient = 18 MV/meter
  - K_L ~ 1.25 Hz/ $(MV/m)^2$
  - Detuning ~ 400 Hz => 75 degrees
  - **Time constant ~ 1mS**
    - Pulse length ~ 3 mS
    - Cannot offset by a static de-tune
    - Piezo-compensation looks to be necessary (unlike SNS)
      - Or else pay for it with RF power!!!
- Micro-phonics ~ 10 Hz => 2.0 degrees
  - Active damping by piezo-tuners does not seem necessary

RF Regulation

- Since Linacs are single pass, no overhead required for instabilities like in rings
- The majority of RF regulation can be compensated by adaptive feed-forward
  - Dynamic Lorentz detuning compensated by piezo tuners
  - Modulator droop and ripple are consistent pulse to pulse
  - Beam current droop and ripple are consistent pulse to pulse (especially H+ sources).

System Overhead

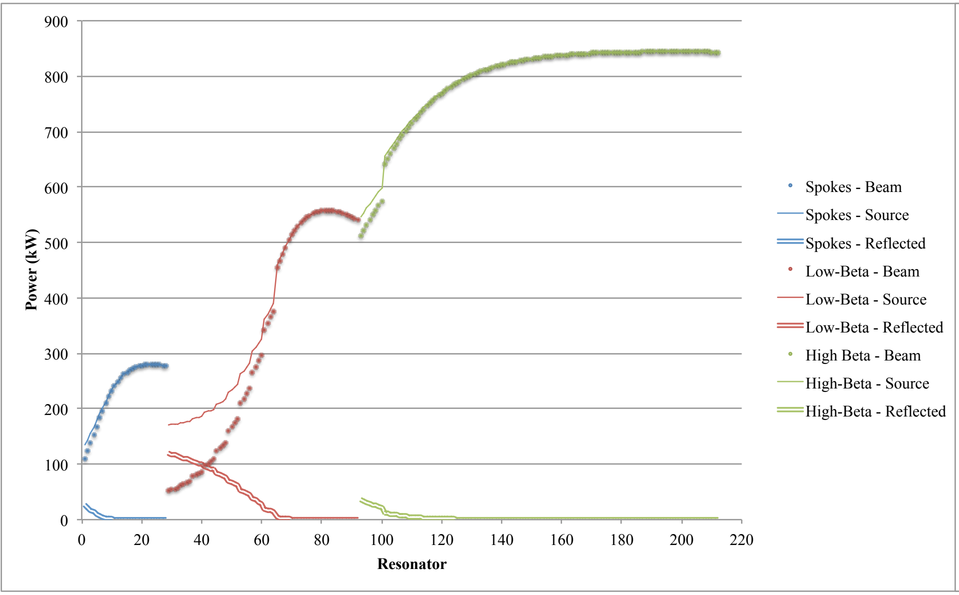
- Is required for pulse to pulse variations
- Required for beam startup
  - How much can the beam current be changed in between a single pulse interval and still accelerate the beam on the next pulse
  - This requirement will dominate the overhead requirements
  - ESS is currently working with a 25% overhead (SNS experience)
  - 5% for loss in distribution

Module	Source Output Power [kW]	R/Q [Ohms]	Q External	Bandwidth [kHz]
RFQ	1200			
DTL type A	2600			
DTL type B	2600			
Spoke	365	500	237,000	1.49
Elliptical low-β	730	300	800,000	0.89
Elliptical high-β	1100	477	750,000	0.94

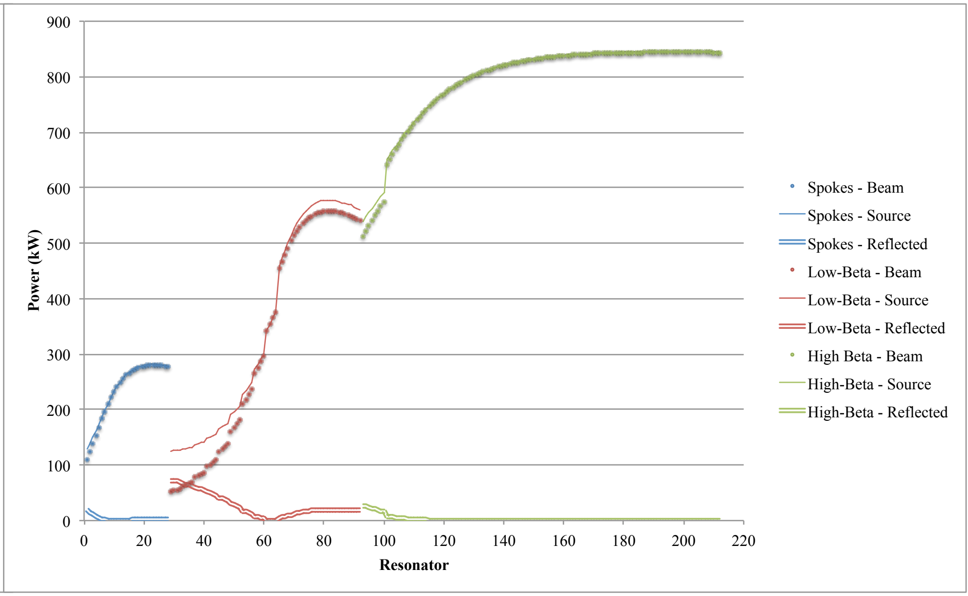
Cavity Coupling

- Unlike electron linacs, the gradient profile along the linac is not flat.
- How is the coupling set?
  - At maximum gradient?
  - Minimal reflected power for a cavity family?
- Can we set coupling cavity-to-cavity?
  - Adjustable couplers not an option
  - Over-couple the cavity couplers and use
    - Custom iris couplers in the waveguides
    - Or stub tuning in the waveguides

Forward and Reflected Cavity Power during beam pulse



Coupling set at optimum at Maximum gradient



Coupling set at optimum to minimize average reflected power

Number of Power Sources Per Cavity

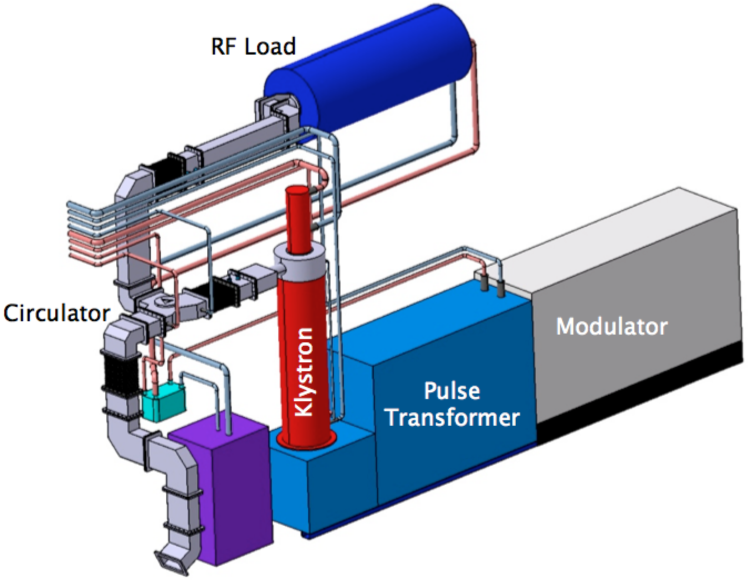
- At high energy, the issue becomes cost.
- Consider
  - Two 1.0 MW Klystron + two Modulators
    - ~280 k€ /klystron + ~570 k€ /modulator
    - 1700 k€
  - Two 1.0 MW Klystron + one Modulator
    - ~280 k€ /klystron + ~800 k€ /modulator
    - 1360 k€
  - One 2.0 MW klystron + one Modulator
    - ~330 k€ /klystron + ~800 k€ /modulator
    - 1130 k€
    - Savings = 230 k€ ~ 20%
    - Neglects the cost of extra distribution or vector modulators

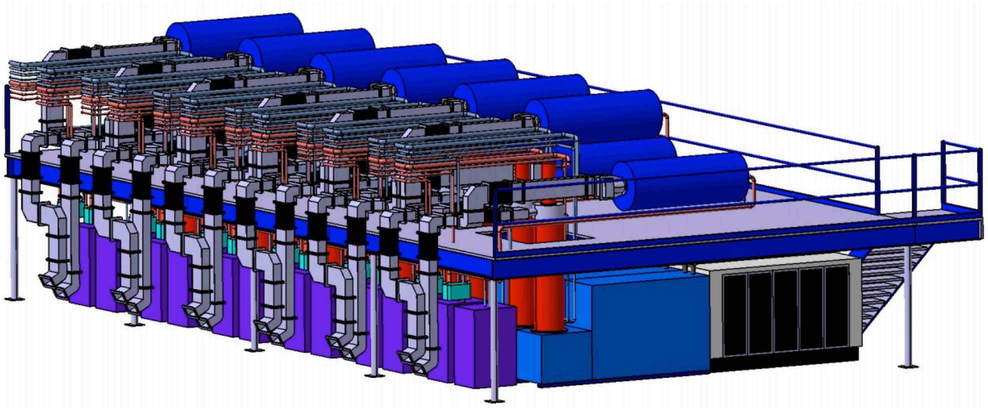
Number of Power Sources Per Cavity

- At low energy (beta), the question becomes cavity to cavity variations for vector regulation
- Cavity to cavity variations
  - Lorentz detuning variations and control (-> 70 degrees over three time constants)
  - Coupling variations
  - Field flatness
- Most likely would need fast vector modulation
  - About the same cost of a klystron?
  - Bandwidth limitations?
  - Power handling?
  - Efficiency?
- Long lead time for klystron procurement
  - klystron procurements would begin before vector modulation development can be completed
- For the Baseline – ESS will choose one power source per cavity

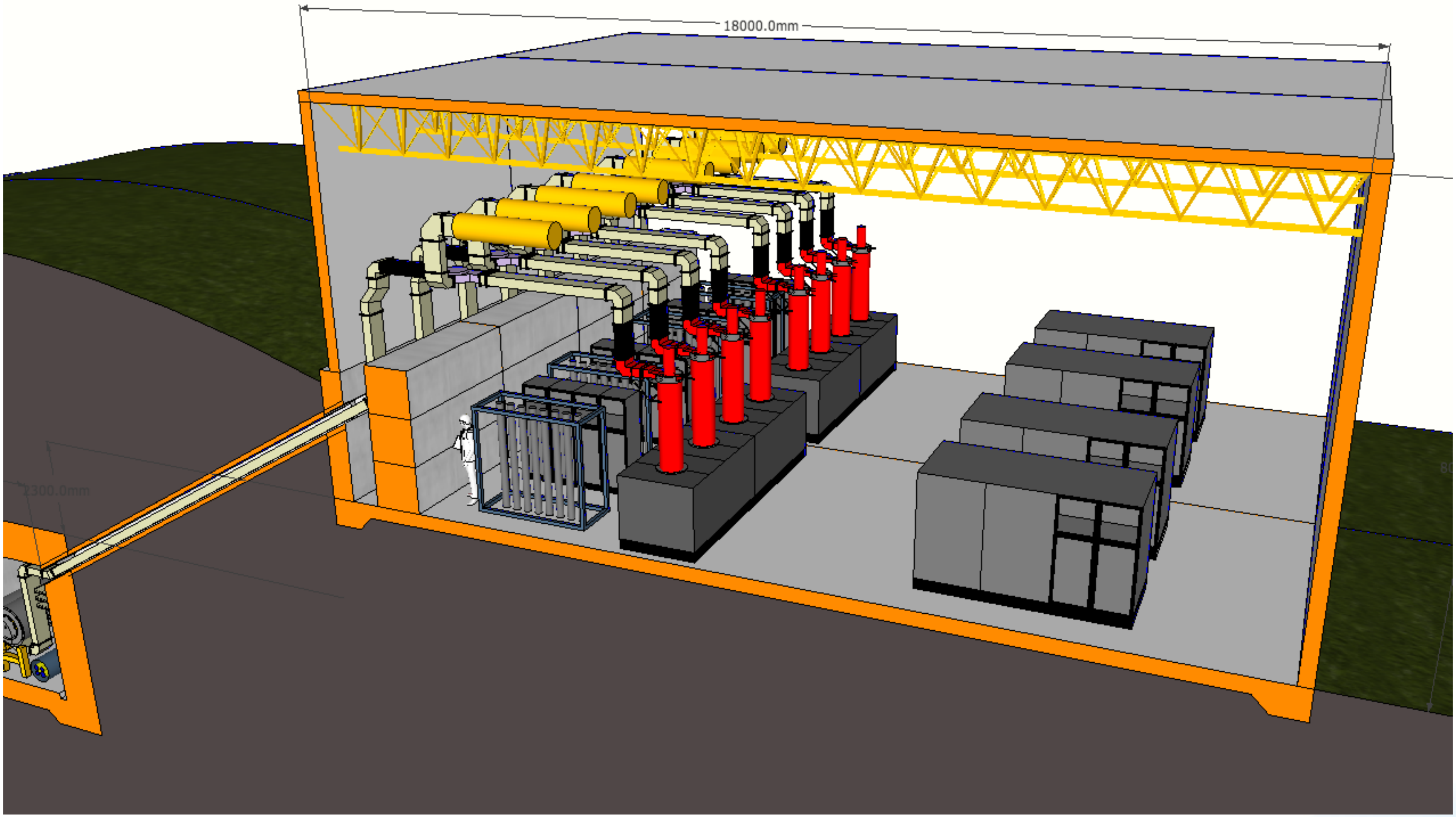
One Modulator Per Klystron

- Limited space for assembly and repair





Two Klystrons per Modulator



Modulator Cost (Carlos Martins)

- Capacitor charger power supplies:
  - 30%
- Capacitor banks:
  - 5%
- Solid state switch assembly(ies):
  - 15%
- Transformers (if existent):
  - 15%
- All other ancillaries
  - 10%
- Assembling and testing work + overheads:
  - 25%

Doubling the Power of a Modulator (Carlos Martins)

- Capacitor charger power supplies:
  - The rated power doubles.
  - In many topologies several identical modules are used in parallel.
  - In this case we should double the number of modules.
  - We can then consider that the cost of capacitor charger power supplies doubles;
- Capacitor banks:
  - The stored energy will double.
  - Indeed, since the current is doubled the capacitance value needs to be doubled for the same tolerated voltage droop.
  - The cost of capacitor banks will then double;
- Solid state switch assembly(ies):
  - The peak current and RMS current will double.
  - Depending on the topologies and switch technology adopted, this might have a little impact on the size and cost of the switch assemblies or might have an impact corresponding to a factor of 2.
  - Let's suppose a factor of 1.5 in average;
- Transformers (if existent):
  - The fact that the peak power is roughly the double, the size of the transformer will be higher but not a factor of 2.
  - Assume about 30% in extra volume.
  - We can then consider that the price is multiplied by 1.3;
- All other ancillaries
  - cabinets, wiring, control system, HV cables, mechanical work, cooling circuit, electrical distribution components, etc. will be more or less the same.
- Assembling and testing work + overheads:
  - Will be about the same.
- Doubling the power of a modulator increases the cost by 1.45x

Modulator Requirements

- 109 modulators with one modulator for every two klystrons
- 3.4 mS pulse flat-top at a rate of 14 Hz
- 120kV and 40 Amperes at flat-top
- Cost range – 1.0 M€ per modulator (max)
  - CERN Modulator = 0.6 M€ for 2.5mS flat-top at 20Hz with 120kV and 20A
  - 1.16x for longer pulse length, 1.45x for higher current
- Production rate 2 modulators per month for 4.5 years (Sept 2013 – March 2018)

Modulator Strategy

- Few number of vendors each with their own unique topology
  - For example, CERN modulator: 4 different vendors, 4 completely different topologies
  - Results in:
    - Operational risk
    - Cost risk
    - Schedule risk
- The only way to minimize these risks is to have multiple vendors building to the **same** modulator concept.
- ESS must "own" the modulator as-built
  - Including design data
  - key components of the modulator cannot be proprietary

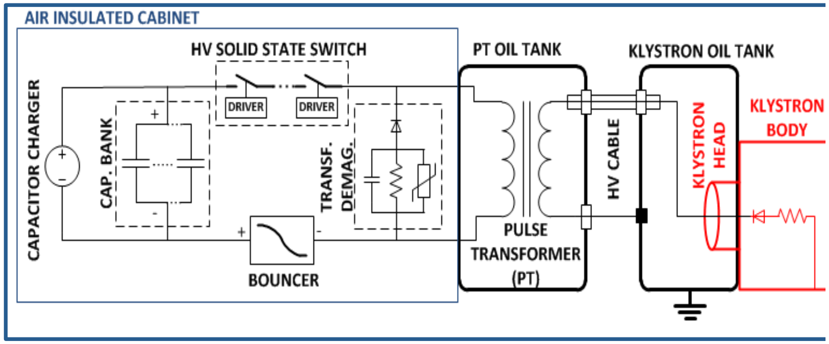
The Baseline Design

- ESS would like the baseline design
  - To be modular
    - Easier repair
    - Easier to involve multiple vendors
  - Avoid single source suppliers in components such as:
    - Pulse transformers
    - High voltage switch assemblies
- An <u>example</u> modular design is the multiple resonant sub-convertor design
  - Advantages
    - Open source topology
    - 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.
  - Disadvantages
    - Construction of the high frequency transformers can be challenging
    - H-bridges handle a significant amount of reactive power
    - Soft-switching of the IGBT's in all operating points might be complex.

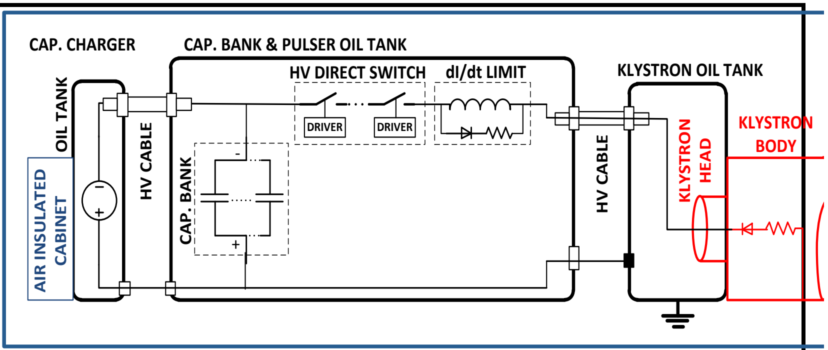
Modulator Backup Design

- The backup design will use Pulse Transformer Bouncer modulator topology.
  - Advantages
    - Open source topology
    - The power circuit is simple and reliable.
    - All electronic active devices are at a medium-voltage level
    - Voltage ripple on the flat-top is small
    - Solid, reliable topology for long pulses
    - Large experience at other laboratories.
  - Disadvantages
    - 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.
- Prototypes
  - The CERN 704 MHz test stand will use this topology and will be a pre-prototype for ESS.

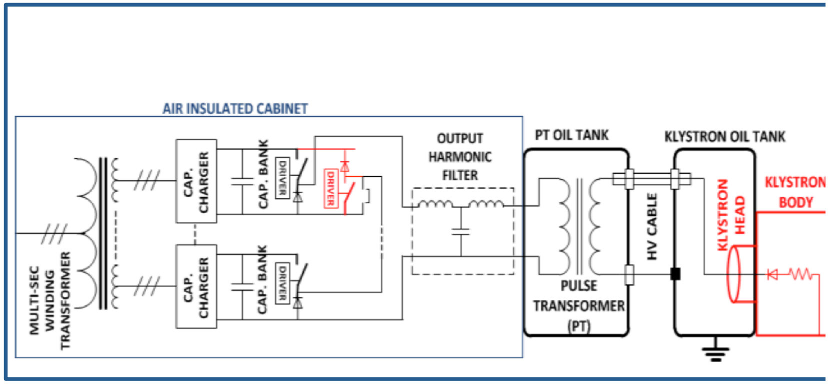
Example Modulator Concepts



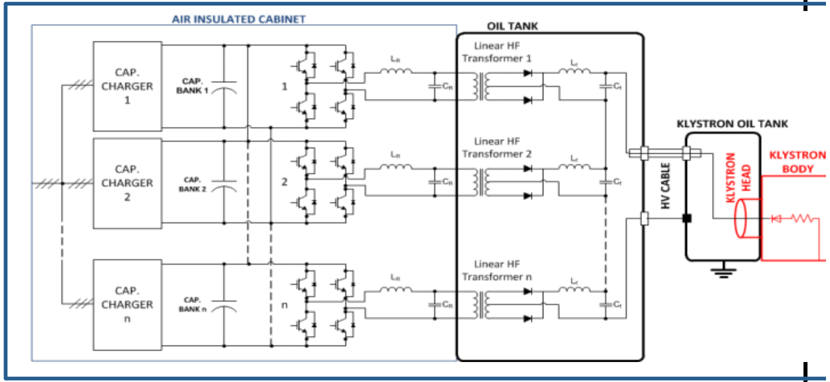
Monolithic Pulse Transformer Topology



Direct Switch Topology



Interleaved DC/DC Subconvertor Topology



Multiple resonant DC/AC/SC Subconvertor Topology

Spoke Cavities

- For an efficient high power linac,
  - All the power should go into the beam
    - The cavities should be superconducting
- At the beginning of the linac, space charge forces are the dominant issue!
  - Normal conducting structures are used (drift tubes) because of
    - large gradients,
    - large aperture,
    - ability to handle beam loss

Spoke Cavities

- Where should the transition to superconducting cavities occur?
  - Tradeoff between loss, gradient, and efficiency
- Superconducting spoke cavities is a **new** technology offers a solution for efficient cavities at low energies
  - Large velocity acceptance
  - Large aperture
  - Large R/Q
  - Efficient (superconducting)
- ESS will be the first linac to use spokes in operations

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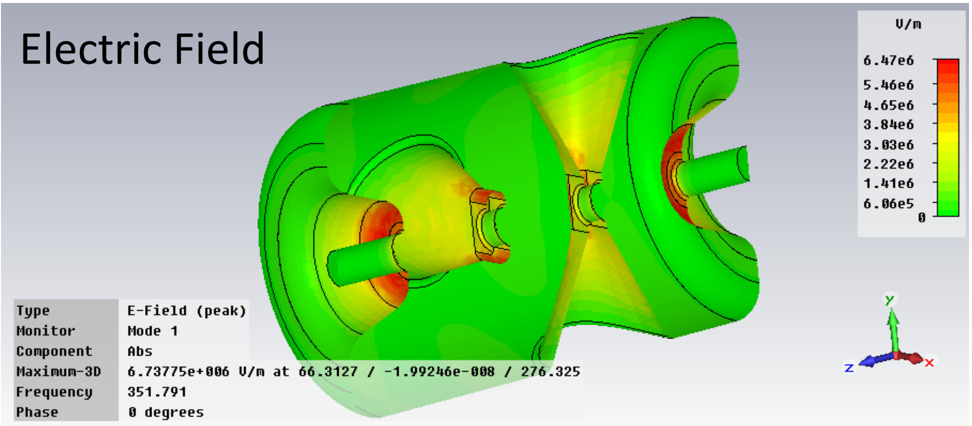
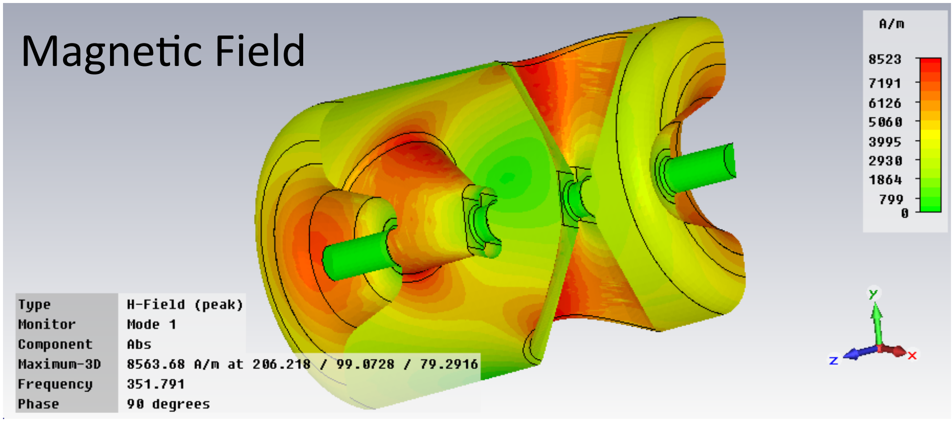
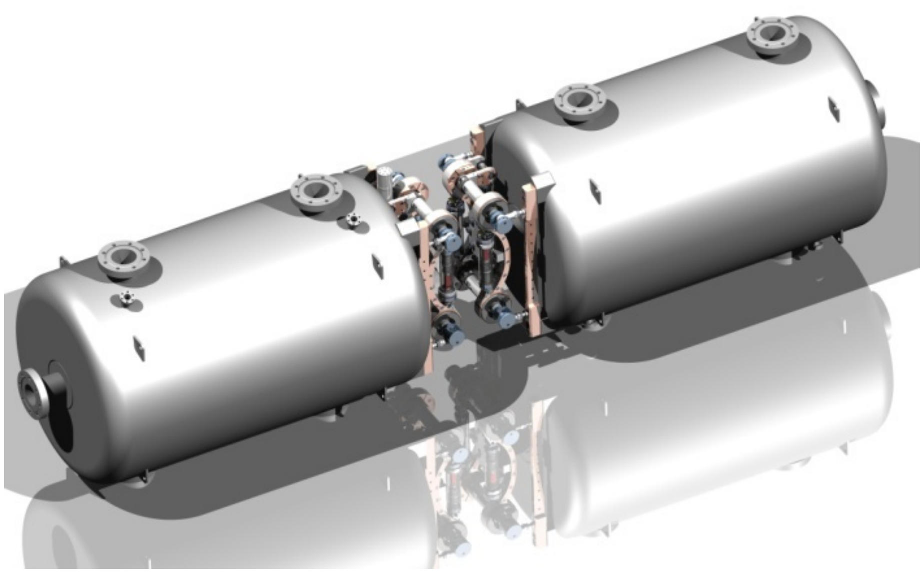
ESS Spoke Cavities

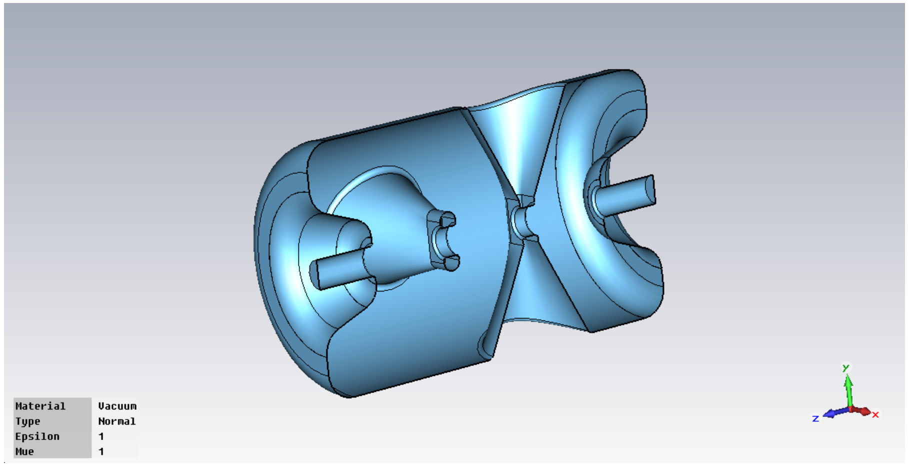

Electric Field

Type	E-Field (peak)
Monitor	Mode 1
Component	Abs
Maximum-3D	6.73775e+006 V/m at 66.3127 / -1.99246e-008 / 276.325
Frequency	351.791
Phase	0 degrees


Magnetic Field

Type	H-Field (peak)
Monitor	Mode 1
Component	Abs
Maximum-3D	8563.68 A/m at 206.218 / 99.0728 / 79.2916
Frequency	351.791
Phase	90 degrees





Material	Vacuum
Type	Normal
Epsilon	1
Mue	1

352 MHz Spoke Cavity Power

- Spoke Power
  - one power source per cavity!
  - 28-39 power sources
  - peak power capability of 370 kW
- Power level and frequency is in kind of a “no-man’s-land” for RF power sources
  - Low frequency makes klystrons big.
  - Klystron power level overkill (and expensive!) for required power
  - At the upper frequency range for gridded tubes

352 MHz Spoke Power

- We need to define the power source for the 352 MHz Spokes
- What type of power source ?
  - Solid state
  - IOT
  - Triode/tetrode
  - Klystron
- Efficiency
- What type of modulator
  - DC with the power amplifier in Class-C
  - How many power sources per modulator (8?)

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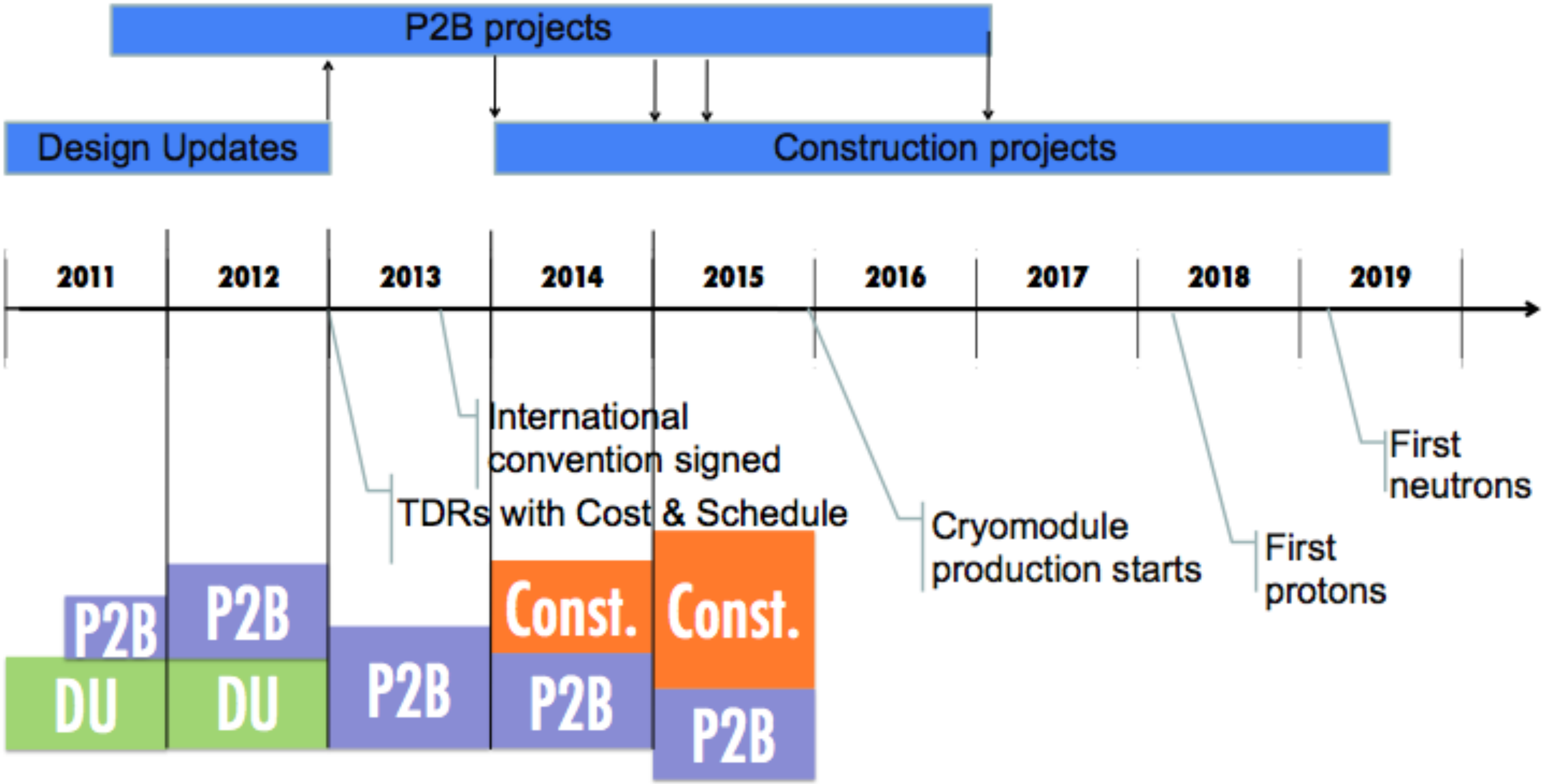
ESS DESIGN REPORT

Accelerator Design Update

- The purpose of the Accelerator Design Update (ADU)
  - technical design report (TDR)
  - a cost estimate
  - a construction plan

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

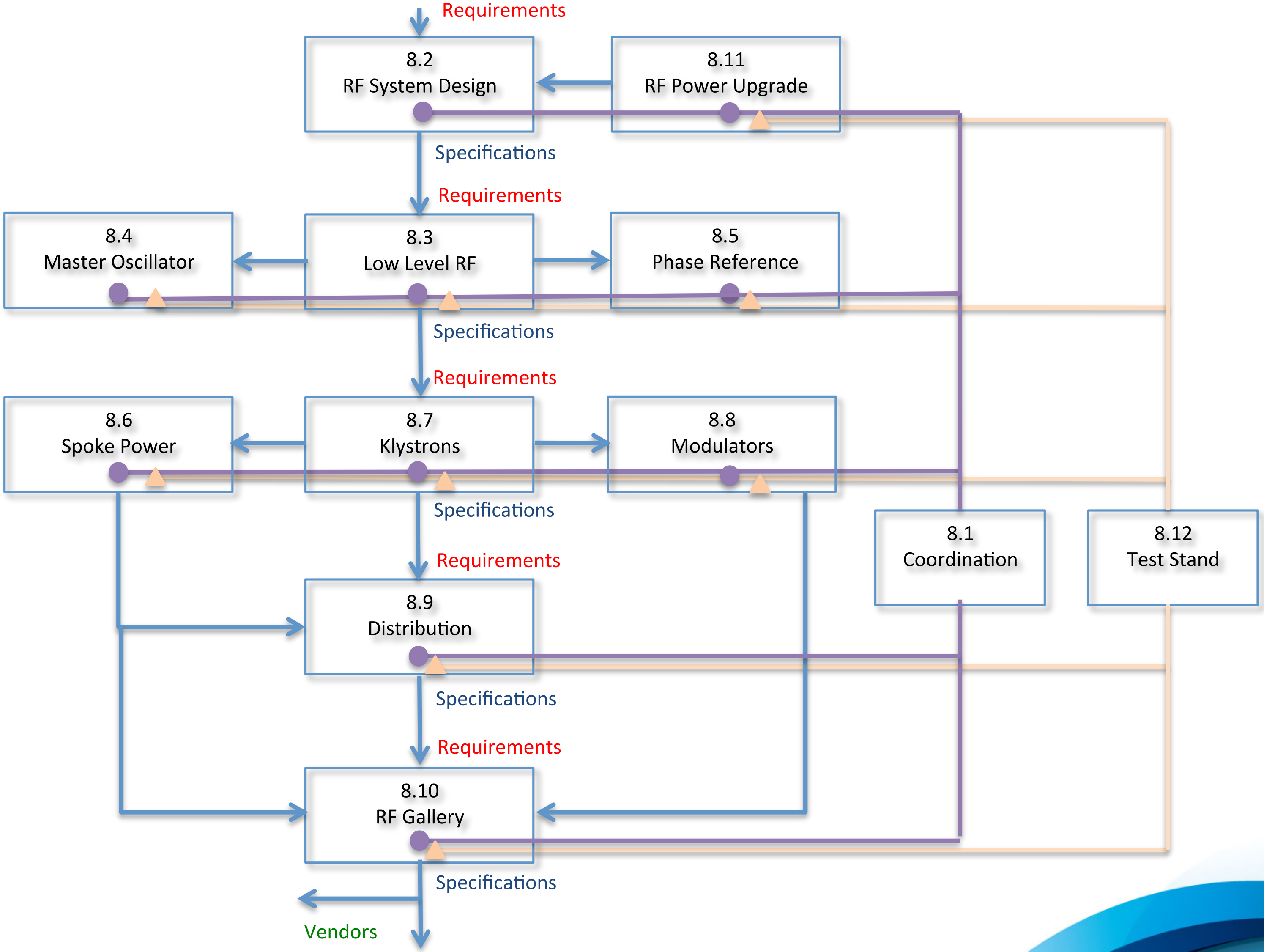
Const.

P2B

Organization

WBS8	Task Name	WP / WU Leader	Institute
8	RF Systems		
8.1	Coordination and communication	David McGinnis	ESS-AB
8.2	RF System Design	Stephen Molloy	ESS-AB
8.3	Low Level RF Control	Anders Johansson	Lund University
8.4	Master Oscillator	Anders Johansson	Lund University
8.5	Phase Reference Distribution	Rihua Zeng	ESS-AB
8.6	352 MHz Spoke Cavity Power		Uppsala University
8.7	High Power Klystrons	Anders Sunesson	ESS-AB
8.8	High Power Klystron Modulators	Carlos Martins	Laval University
8.9	RF Distribution		Uppsala University
8.10	RF Equipment Gallery	Anders Sunesson	ESS-AB
8.11	RF Power Upgrade		Uppsala University
8.12	RF Test Stands		Uppsala University

Organization



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ADU Schedule

[1] 8.1.1 Requirements Milestones

   a. Requirement document - February 1, 2012

[2] 8.1.2 Design Milestones

   a. Conceptual Design – September 30, 2011
   b. Conceptual Design Update – November 20, 2011
   c. Conceptual Design Final Update - February 1, 2012
   d. TDR first draft – April 20, 2012
   e. TDR second draft – August 17, 2012
   f. Design review – September 1, 2012
   g. TDR final document – October 08, 2012

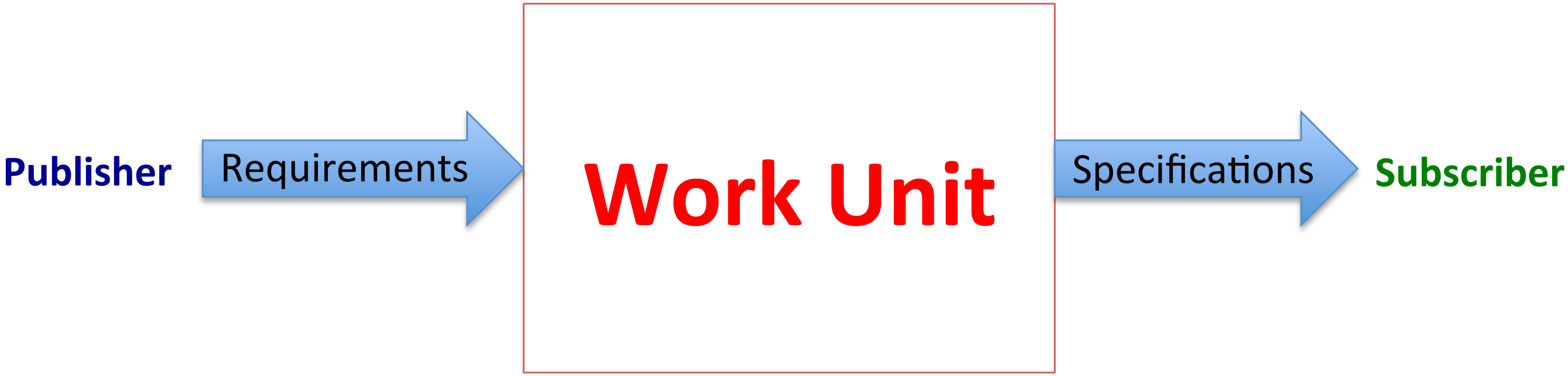
[3] 8.1.3 Costing Analysis

   a. Costing estimate 1st iteration – December 2, 2011
   b. Costing estimate 2nd iteration – May 17, 2012
   c. Costing plan final – October 15, 2012

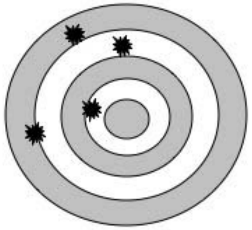
[4] 8.1.4. Costing and Construction WBS

   a. ROM Schedule and Cost – March 1 2012
   b. Construction WBS first iteration – December 2, 2011
   c. Construction WBS plan draft – May 17, 2012
   o Construction WBS plan final – October 08, 2012

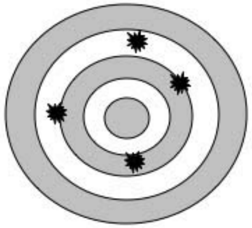
Requirements & Specifications



Publisher → Requirements → **Work Unit** → Specifications → **Subscriber**



Not Accurate
Not Precise



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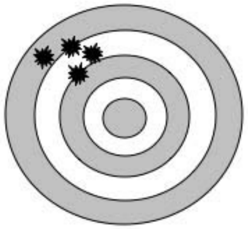

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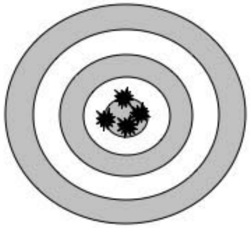

Accurate
Precise

General Requirements

General

Parameter	Value	Unit	Publisher
Beam Current	50	mA	General
Beam Current Precision	1	%	Ion Source
Beam Current Accuracy	1	%	Ion Source
Beam Current Ripple	1	%	Ion Source
Beam Current Pulse Length	2.86	mS	General
Beam Current Pulse Length Precision	1	ppm	Chopper
Beam Current Pulse length accuracy	1	ppm	Chopper
Repetition Rate	14	Hz	General
Cavity Gradient Amplitude regulation	0.5	%	Beam Physics
Cavity Gradient Phase regulation	0.5	degrees	Beam Physics
Allowed AC Grid Load Variation (Flicker)	1	%	Energy

System Requirements

Parameter	RFQ	Buncher	DTL	Spoke	Med. Beta	High Beta	Unit	Publisher
Number of Couplers	1	2	3	28	64	120		Beam Physics
Power to Coupler			2100	0.28	0.56	0.85	MW	Beam Physics
Frequency	352	352	352	352	704	704	MHz	Beam Physics
Synchronous phase		90	30	15	15	10	degress	Beam Physics
R/Q				300	300	470	Ohms	Cavity X Design
Qo	20000	20000	20000	5.E+09	5.E+09	5.E+09		Cavity X Design
Lorentz de-tuning coefficient	0	0	0				kHz/Volt^2	Cavity X Design
Tuner range	100		100	5	5	5	kHz	Cavity X Design
Tuner slew rate	1		1	5000	5000	5000	kHz/sec	Cavity X Design
Tuner bandwidth	1		1	1000	1000	1000	Hz	Cavity X Design
Cavity phase noise	0		0	10	10	10	degrees	Cavity X Design
Cavity drift rate	0		0				degrees/sec	Cavity X Design

System Specifications

Parameter	RFQ	Buncher	DTL	Spoke	Med. Beta	High Beta	Unit	Subscriber
RF Regulation Overhead	25	25	25	25	25	25	%	System Design
RF Distribution Loss Budget	5	5	5	5	5	5	%	System Design
RF pulse Length	2.86	2.86	2.86	3.5	3.5	3.5	mS	System Design
Loaded Q	15000	15000	15000	237000	800000	750000		Cavity X Design
Number of Couplers per Power Source	1	1	1	1	1	1		System Design
Saturated RF Power per Power Source			2.8	0.37	0.73	1.1	MW	System Design
Number of Power Sources per Modulator	3	3	1	8	2	2		System Design
Minimum Efficiency at Operating Power	47	47	47	47	47	47	%	Energy
Modulator Efficiency	95	95	95	95	95	95	%	Energy
Total AC Power			0.56	0.85	4	12	MW	Energy
Cooling Rate			0.2	0.2	0.9	2.5	MW	Energy

Summary

- The ESS RF system will be one of the largest accelerator RF systems ever built.
- There are many challenges ahead.
  - The klystron modulator system
    - is likely to be the most costly accelerator component
    - And will have significant schedule risk
    - We propose an open source design and invite laboratory/university/industrial collaborators to participate in a consortium to develop the design
  - We need a solution for the 352 MHz spoke cavity
- RF Vendorama – Lund, Sweden - February 2012