ESS RF Systems

ESS Klystron Modulator
Workshop
24-April-2012

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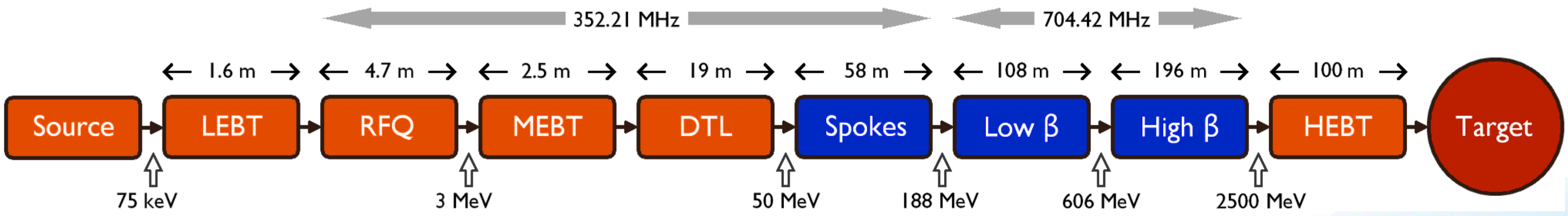
EUROPEAN
SPALLATION
SOURCE

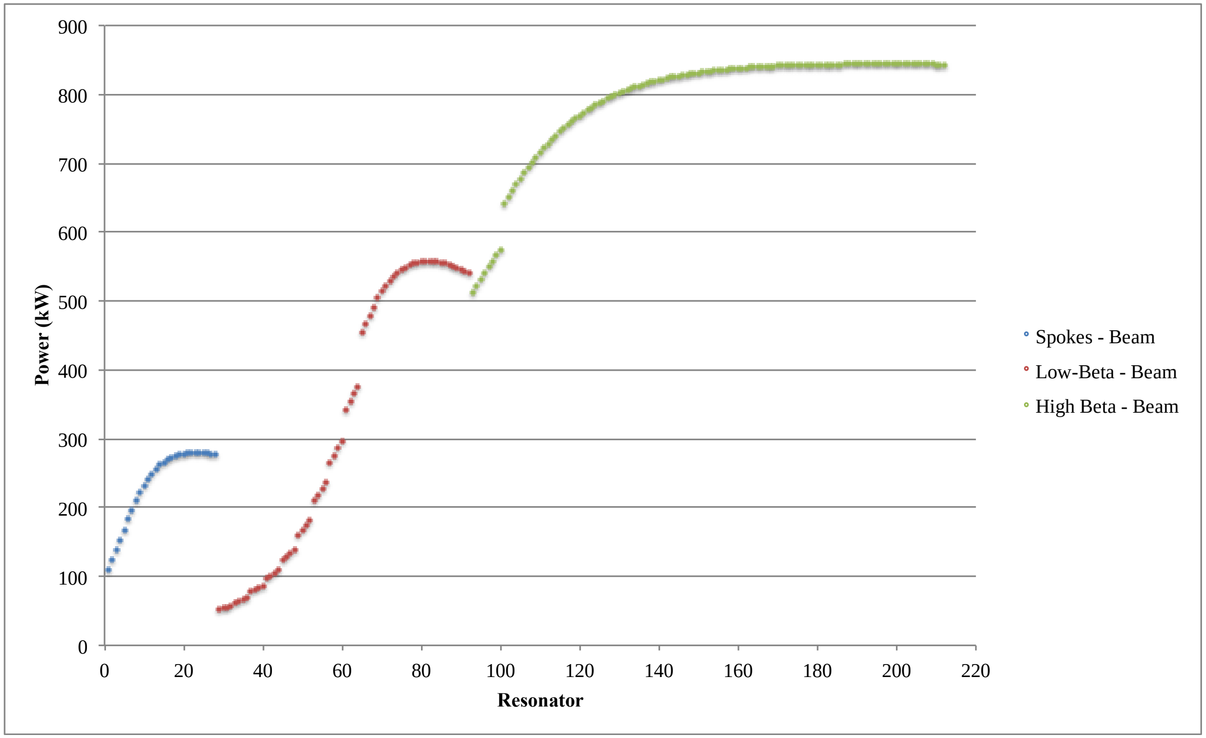
Overview

- ESS is a long-pulse neutron spallation source
- The target is feed by a superconducting 5 MW proton linac
  - Energy = 2.5 GeV
    - Target design
    - Linac cost
  - Beam Current = 50 mA
    - Space charge
  - Pulse Rate = 14 Hz
    - Neutron energy
    - location of neutron choppers
  - Pulse Length = 2.9 mS
    - Adjusted for 5 MW of average power on target



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-b	704.42	64	560
Elliptical high-b	704.42	120	850



RF System Main Components

- The RF system for the ESS linac is defined as the system that:
  - converts AC line power to RF power at either 352 or 704 MHz
  - to be supplied to the RF accelerating cavity couplers.
- Main components
  - Modulator
    - Converts conventional AC power into pulse power
    - ESS requires 90 modulators
  - RF Power Amplifiers
    - Takes pulse power from the modulators and converts the power into RF waves at 352 or 704 MHz
    - Typically klystrons
      - Require ~180 klystrons
      - 1 MW peak power per klystron (40kW average)
  - RF Distribution
    - Transports the RF from power amplifiers to cavity coupler couplers
    - Typically waveguides with other components (circulators, directional couplers, etc…)
  - Low Level RF Control
    - Regulates RF amplitude to 0.5% and phase to 0.5 degrees
    - Requires both feedback and adaptive feed-forward algorithms

General Requirements

General Requirements		
Parameter	Value	Unit
Maximum Beam Current	50	mA
Beam Current Stability	1	%
Beam Current Control	1	%
Beam Current Ripple	1	%
Beam Current Pulse Length	2.86	mS
Beam Current Pulse Length Stability	1	ppm
Beam Current Pulse length Control	1	ppm
Repetition Rate	14	Hz
Cavity Gradient Amplitude regulation	0.5	%
Cavity Gradient Phase regulation	0.5	degrees
Allowed AC Grid Load Variation (Flicker)	1	%

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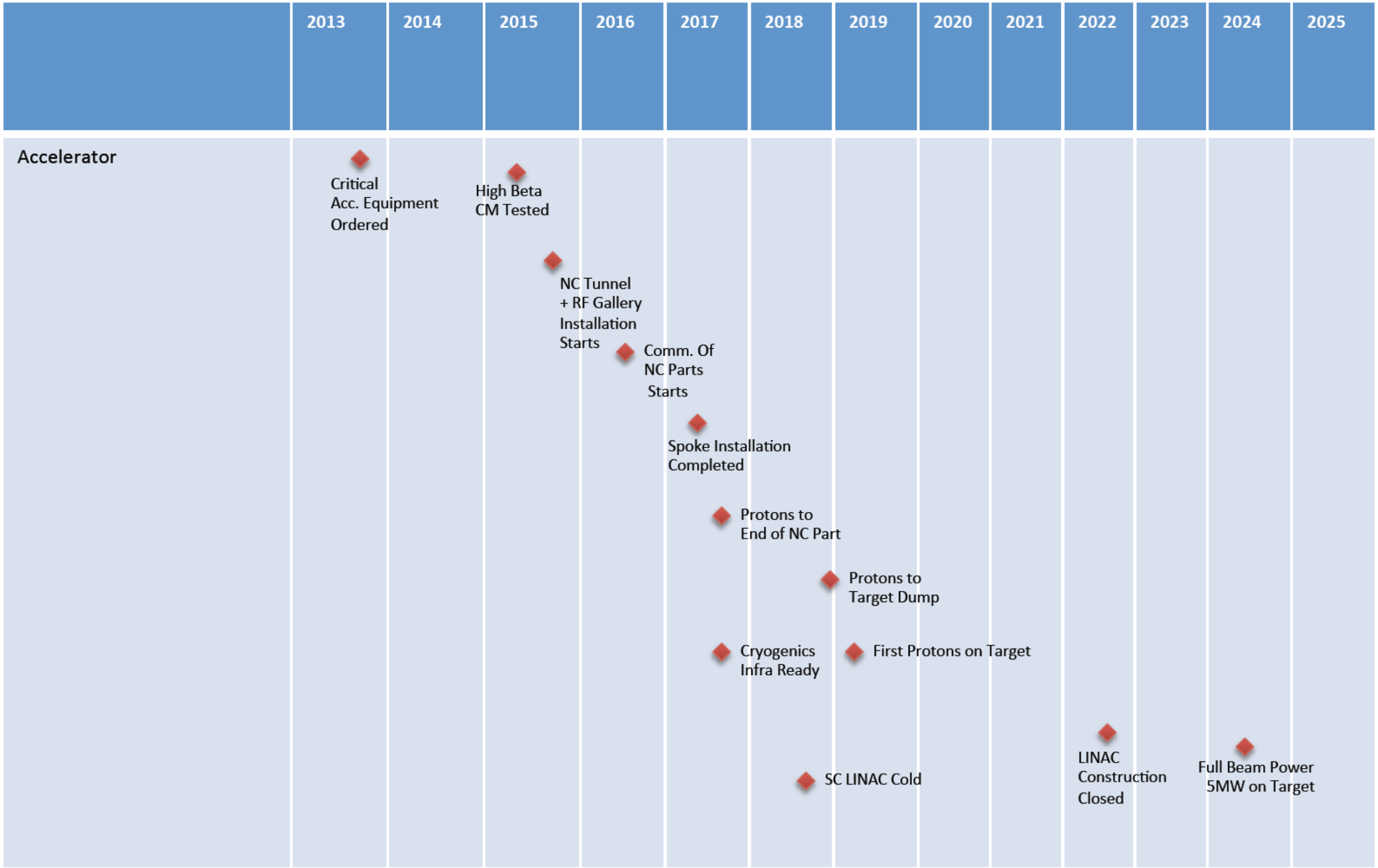
System Requirements

Requirements							
Parameter	RFQ	Bunchers	DTL	Spokes	Low Beta	High Beta	Unit
Number of Couplers	1	2	3	36	64	120	
Average Coupler Spacing	0	1	7	2.1	1.8	1.8	meters
Maximum Power Delivered to Coupler	1000	10	2100	245	610	950	kW
Minimum Power Delivered to Coupler	1000	10	2100	100	50	610	kW
Average Power Delivered to Coupler	1000	10	2100	215	400	900	kW
Maximum Reflected Energy per Pulse	15	0.2	35	60	160	250	J
Maximum reflected power	1000	10	2100	245	610	950	kW
Frequency	352	352	352	352	704	704	MHz
Average Synchronous phase	0	90	30	15.2	15.9	14	degrees
Loaded Q	15	15	15	160	640	820	103
Maximum Cavity Fill Time	50	50	50	400	250	250	uS
Lorentz de-tuning coefficient	0	0	0	1	1	1	Hz/(MV/m)2
Lorentz de-tuning Time constant	0	0	0	1	1	1	mS
Slow Tuner Range	100	100	100	100	100	100	kHz
Slow Tuner Slew Rate	1	1	1	1	1	1	kHz/sec
Maximum Slow Tuner Cycles	1	1	1	.1	.1	.1	106
Fast Tuner Range	0	0	0	10	10	10	kHz
Fast Tuner Bandwidth	1	1	1	1000	1000	1000	Hz
Cavity phase noise (microphonics)	0	0	0	10	10	10	Hz
Cavity drift rate	1	1	1	1	1	1	Hz/sec

Example Specifications

Specifications							
Parameter	RFQ	Bunchers	DTL	Spokes	Low Beta	High Beta	Unit
RF Regulation Overhead	25	25	25	25	25	25	%
RF Distribution Loss Budget	5	5	5	5	5	5	%
RF pulse Length	2.91	2.91	2.91	3.26	3.11	3.11	mS
Number of Couplers per Power Source	1	1	1	1	1	1	
Saturated RF Power per Power Source	1300	15	2750	350	800	1250	kW
Minimum Efficiency at Operating Power	43	43	43	50	43	43	%
Number of Power Sources per Modulator	1	3	1	9	2	2	
Max. Modulator Stored Energy per Pulse	6.8	0.2	14.5	14.5	9	14	kJ
Modulator Efficiency	85	85	85	97	85	85	%
Total Average AC Power to modulator	117	2.3	750	800	3250	13550	kW
Total Average Cooling Rate	91	0.0	544	459	3199	10983	kW
Total Average AC power	132	2.3	795	800	4210	15350	kW

ESS Accelerator Schedule



ADU Deliverables

- The purpose of the Accelerator Design Update (ADU) in WP8 is to produce
  - a technical design report (TDR)
  - a cost estimate
  - a construction plan
- for the RF systems for the ESS linac.

WP8 Organization

WBS8	Task Name	WP / WU Leader	Institute
8	RF Systems	David McGinnis	ESS-AB
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	Rutambhara Yogi	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	Rutambhara Yogi	Uppsala University
8.10	RF Equipment Gallery	Anders Sunesson	ESS-AB

ADU Milestones

- 8.1.1 Requirements Milestones
  - Requirement document first draft - February 10, 2012
  - Requirement document final draft – May 20, 2012
- 8.1.2 Design Milestones
  - Conceptual Design – September 30, 2011
  - Conceptual Design Update – November 20, 2011
  - Conceptual Design Final Update - February 1, 2012
  - TDR first draft – April 20, 2012
  - TDR second draft – August 17, 2012
  - Design review – September 1, 2012
  - TDR final document – October 08, 2012
- 8.1.3 Costing Analysis
  - Costing estimate 1st iteration – December 2, 2011
  - Costing estimate 2nd iteration – May 17, 2012
  - Costing plan final – October 15, 2012
- 8.1.4. Costing and Construction WBS
  - ROM Schedule and Cost – March 1 2012
  - Construction WBS first iteration – December 2, 2011
  - Construction WBS plan draft – May 17, 2012
  - Construction WBS plan final – October 15, 2012

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-b	730	300	800,000	0.89
Elliptical high-b	1100	477	750,000	0.94

Number of Power Sources Per Cavity

- 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

Mod-Anode Configuration

- Advantages
  - Compensation of flat-top droop possible
  - Individual klystron trimming
  - Simpler and more straight-forward power configuration
- Disadvantages:
  - Instability at high efficiency (back-streaming electrons)
  - Requires a special klystron with Mode-Anode terminal (about 10% more expensive, less reliable);
  - Requires a CROWBAR directly in the HV line (>80kV), to divert the large energy stored in the filter capacitors.
    - Bulky and costly
  - Large voltage droop shall be compensated by the LLRF.
    - A droop compensation system (switch mode type) directly connected to the HV line could be used, but that is not a trivial piece of equipment;
  - Requires a floating Mode-Anode supply system.
    - Most commonly, this is done with a floating tetrode, which is not a solid state device;
  - HV is permanently applied to the cathode, which increases insulation stress and probability of arc;
  - All power devices and subsystems, including the capacitor charger, main capacitor bank, Crowbar, floating mode anode supply systems shall be placed in a oil tank.
    - The total quantity of oil will therefore increase considerably
    - The access for repair is much more difficult than in other solutions where most parts can be placed into air insulated cabinets.

Pulsed Cathode Configuration

- With the appropriate choice of modulator topology, pulsed cathode klystrons systems can have
  - Tailored voltage supply
  - Excellent regulation characteristics
  - Simplified fault circuits
  - High efficiency, stable, less expensive klystrons
- The ESS linac baseline design will use pulsed cathode klystron systems without mod-anodes.

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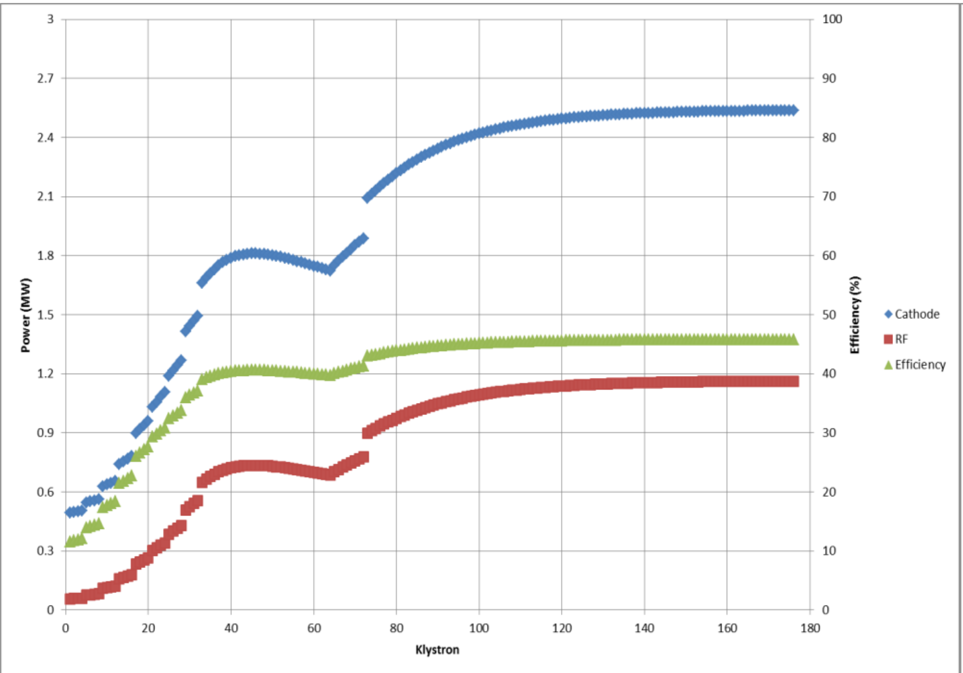
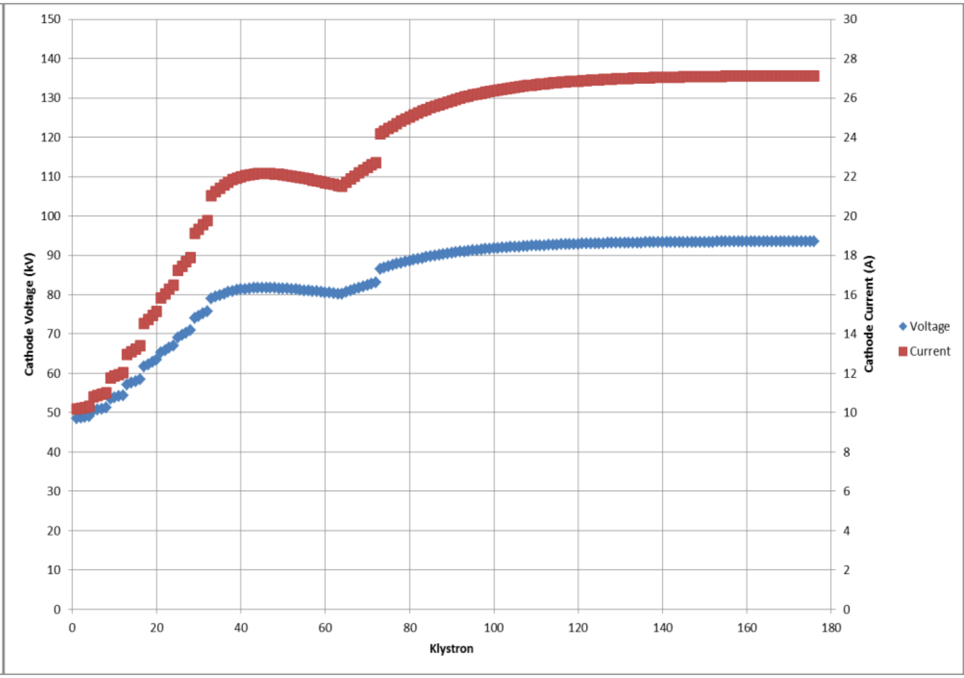
Klystron Cathode Voltage Profile

Constant Perveance Operation



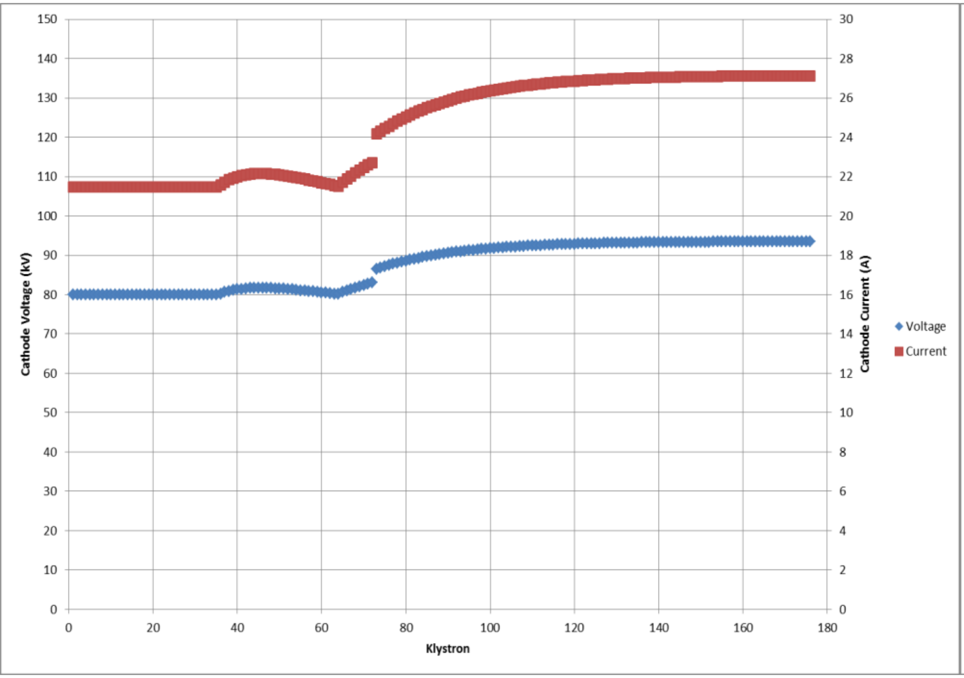
Klystron Power Profile



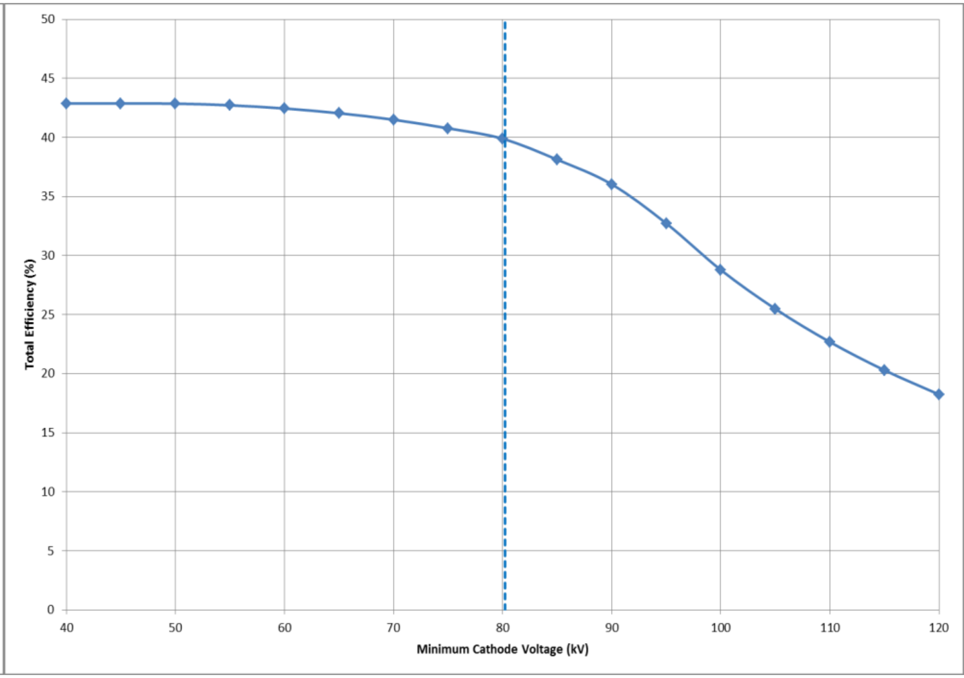
Klystron Cathode Voltage and Current Profile

Overall System Efficiency vs Minimum Cathode Voltage

Constant Perveance Operation



Klystron Cathode Voltage and Current Profile for minimum Cathode Voltage of 80 kV



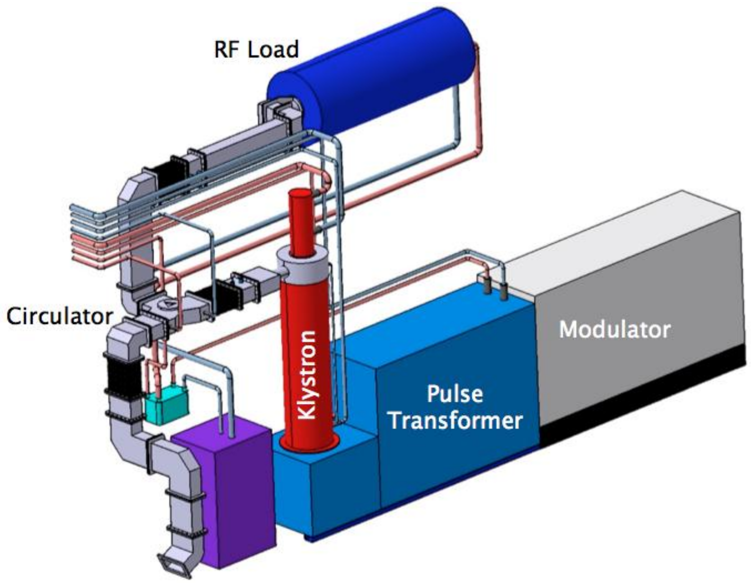
Overall Accelerator Efficiency vs minimum Cathode Voltage

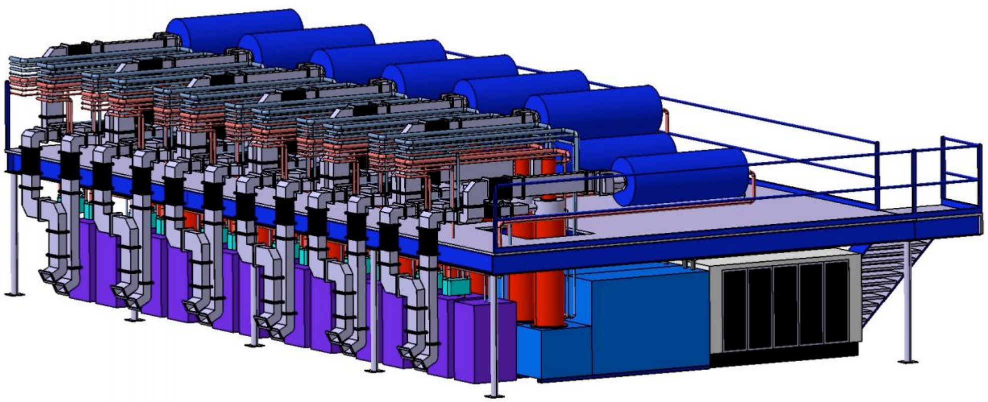
Number of Klystrons Per Modulator

- The average spacing per cavities along the Linac is 1.8 meters
- It is difficult to fit one klystron / modulator into the gallery
- We estimate that ~50% of the modulator cost and footprint is dominated by the stored energy in the modulator
- More klystrons per modulator
  - Is cheaper
  - Makes better use of klystron gallery space
- ESS baseline design current has 2 Klystrons per modulator (12-14kJ / pulse / modulator)

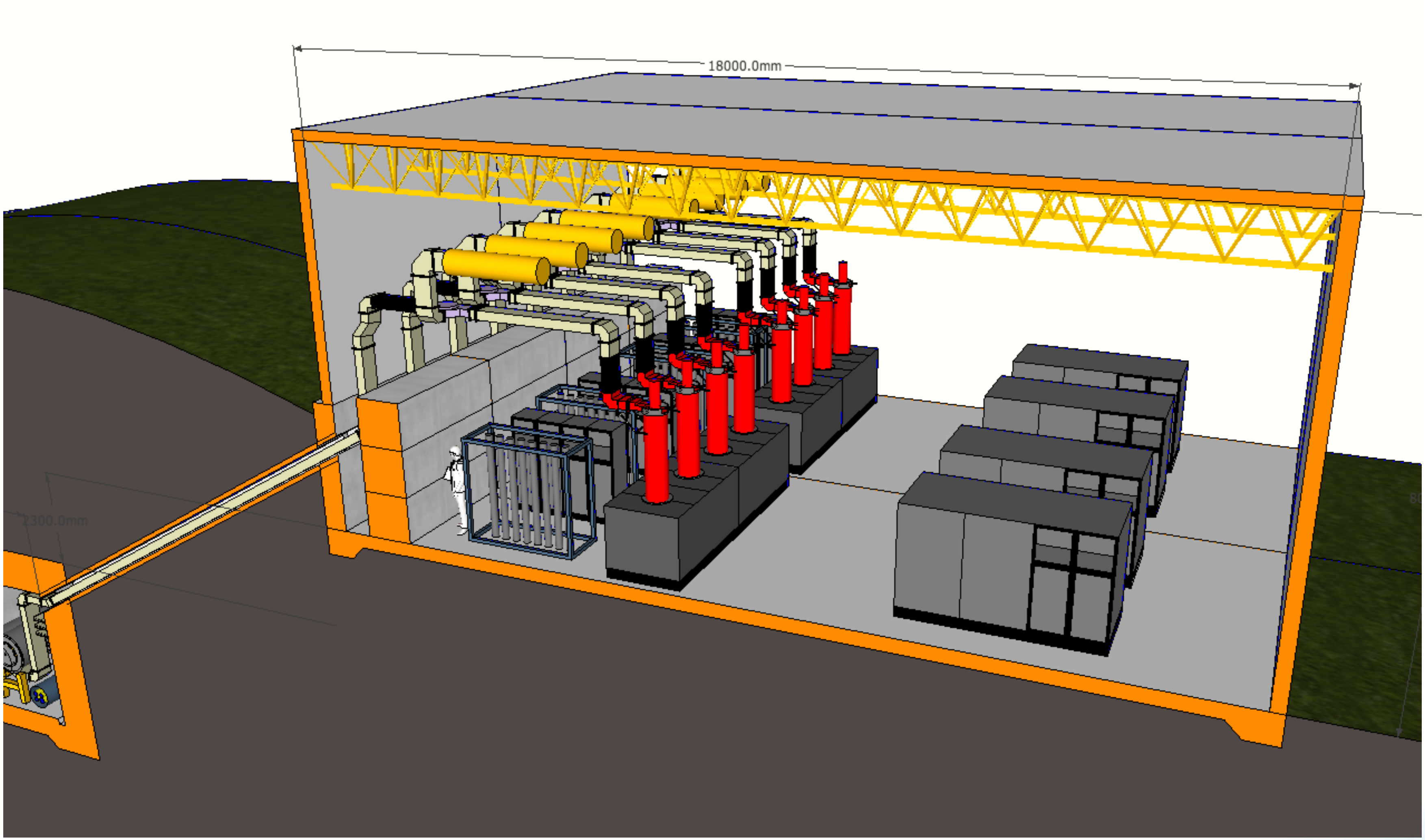
One Modulator Per Klystron

- Limited space for assembly and repair

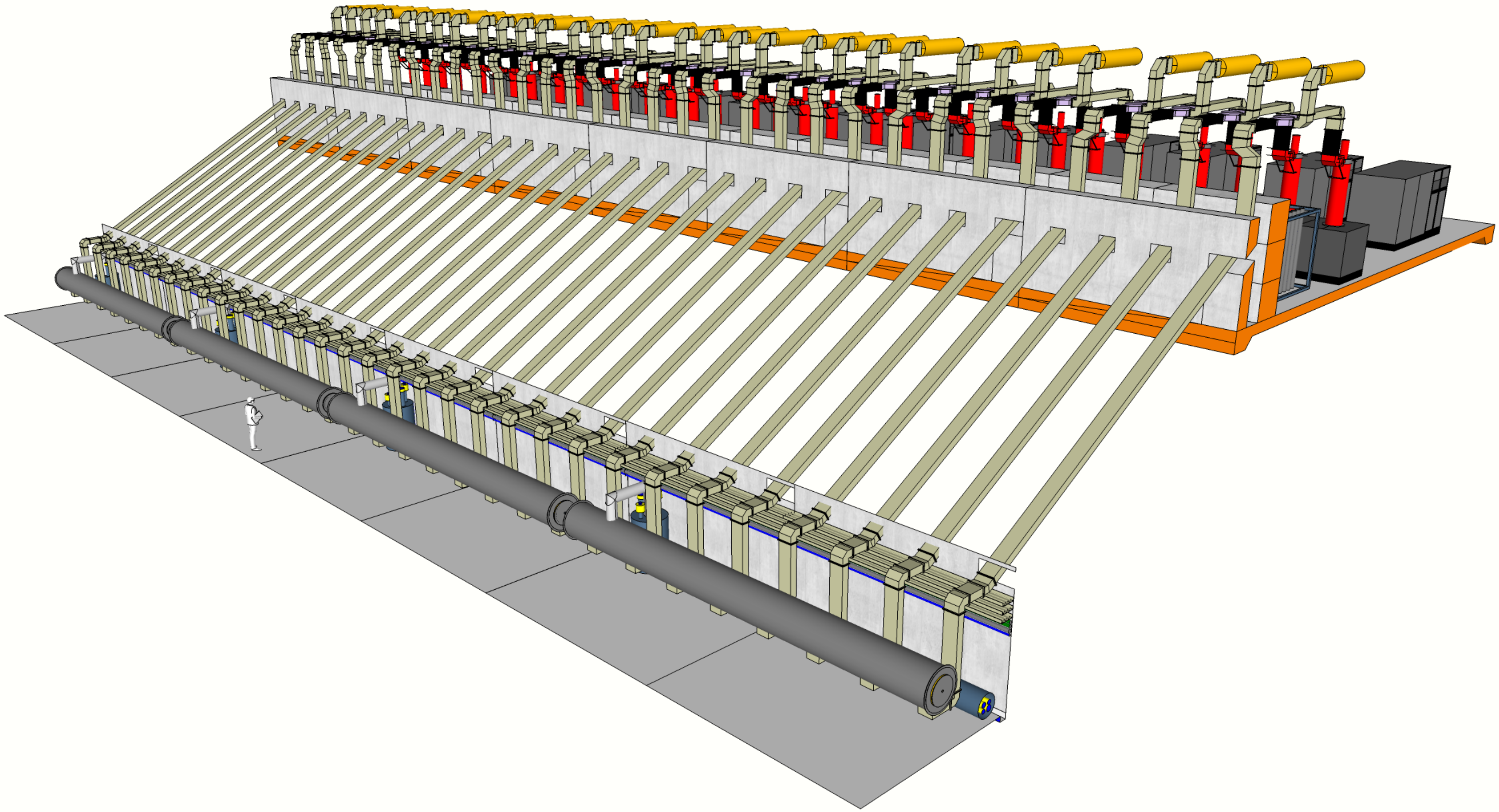




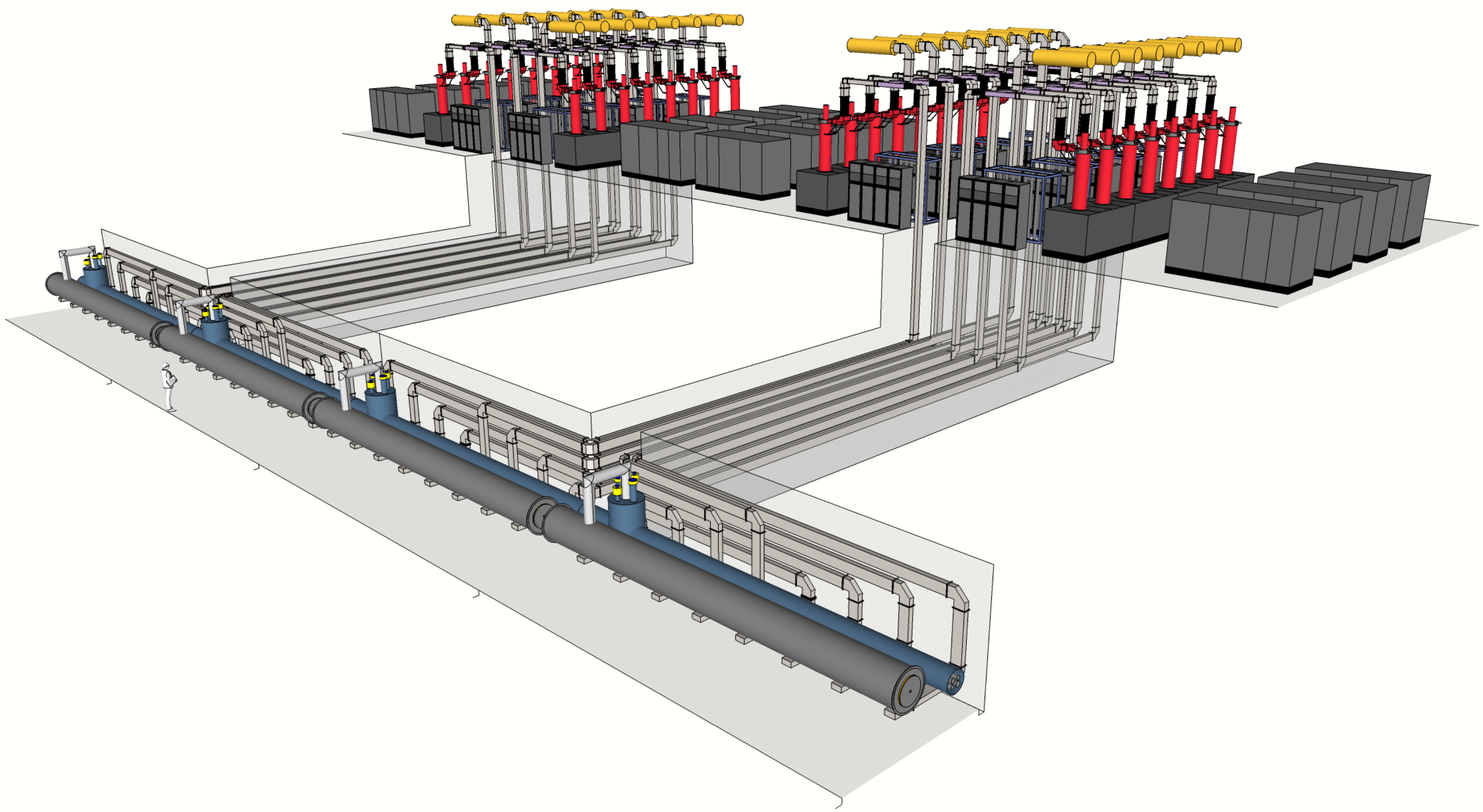
Two Klystrons per Modulator



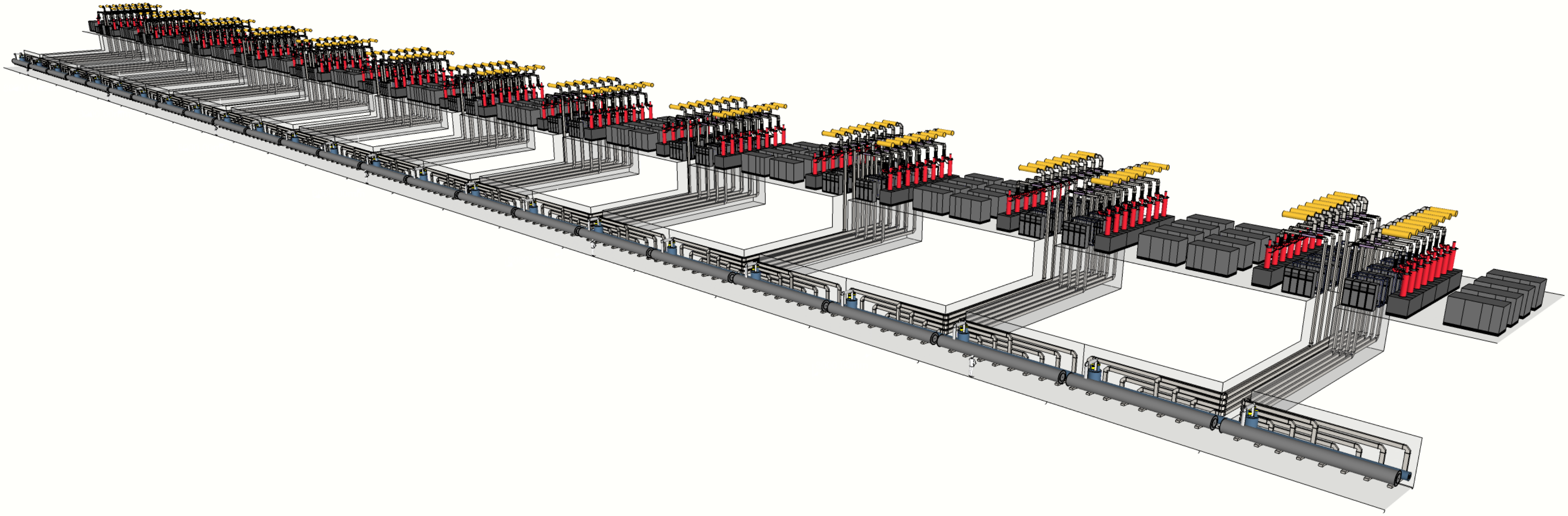
Chute Concept



Stub Concept



Stub Concept



Modulator Issues

- The cost of the modulators will dominate the cost of the RF system
- 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

Modulator Workshop

- The purpose of the Modulator Workshop is to choose and validate an ESS modulator strategy
- The deliverables of the workshop is:
  - A choice of modulator topology
  - A prototyping strategy
  - A procurement strategy

Workshop Agenda

- Session 1: Talks
  - An introduction giving an overview on the state of the art (presentation of all topologies known to date)
  - Survey talks by 8 modulator experts from accelerator laboratories discussing topologies and experiences.
- Session 2. Discussion Panel
  - Invited modulator experts on panel.
  - Determine topology, protytoping, and procurement strategy
  - Non-panel participants observing
- Session 3. Close-out
  - Results of topology choice protytoping, and procurement strategy summarized.
  - Comments by non-panel participants