

# ESS RF Systems

CW and High Average Power RF  
Workshop  
8-May-2012



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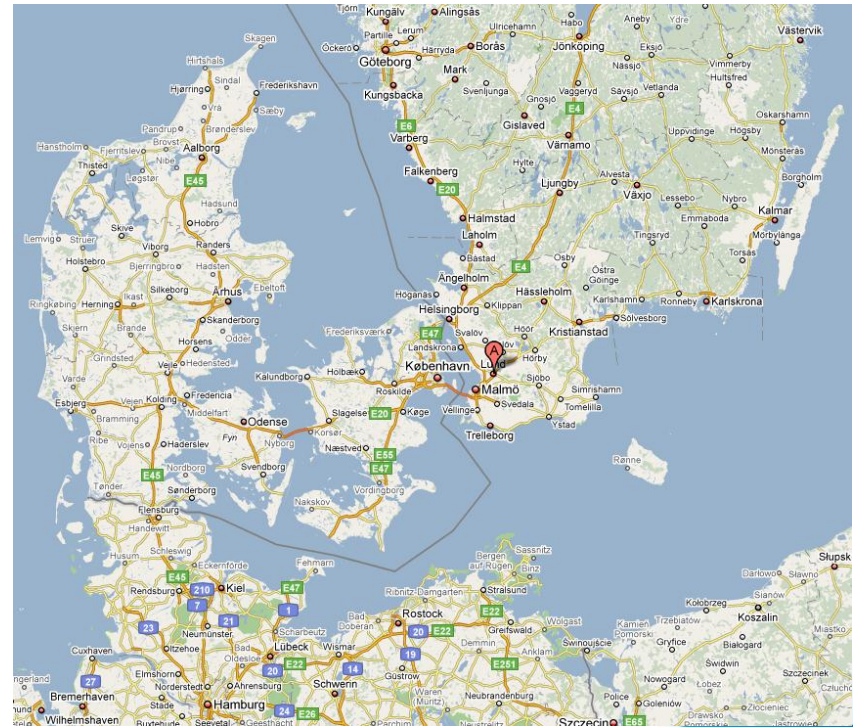
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RF Group Leader  
ESS Accelerator Division



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# European Spallation Source

- ESS is a long-pulse neutron spallation source
- Based on a superconducting 5 MW proton linac
- The ESS Site is in southern Sweden near the city of Lund

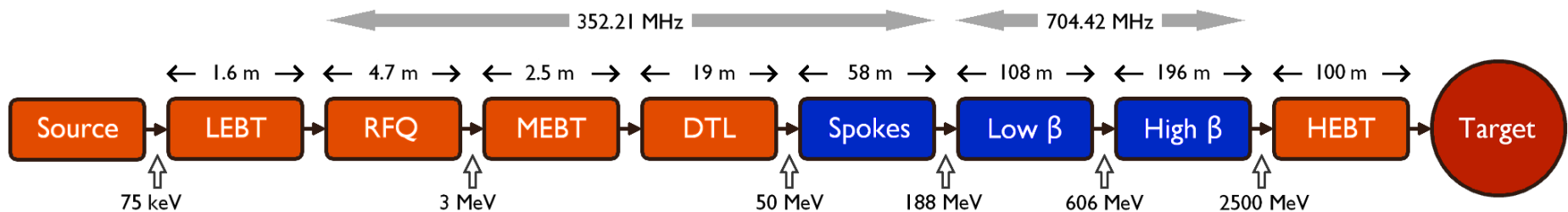


- ESS is being built by a multi-national collaboration
- Accelerator collaboration
  - NC linac: Ion source (INFN), RFQ (CEA), MEBT (Bilbao), DTL (INFN)
  - SC linac: Spoke Cavities (CNRS), Elliptical cavities (CEA)
  - High Energy Beam Transport: Aarhus university
  - RF sources: High-power (Uppsala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

The figure consists of four sub-images illustrating components of a tokamak fusion reactor. The top-left image is a photograph of the toroidal chamber, showing its complex, multi-segmented structure. The top-right image is a 3D model of the poloidal field coils, which are arranged in a ring around the toroidal chamber. The bottom-left image is a 3D model of the divertor, a component used to handle the heat and exhaust from the plasma. The bottom-right image is a 3D model of the toroidal field coils, which are arranged in a ring around the toroidal chamber.

# Superconducting 5 MW Proton Linac

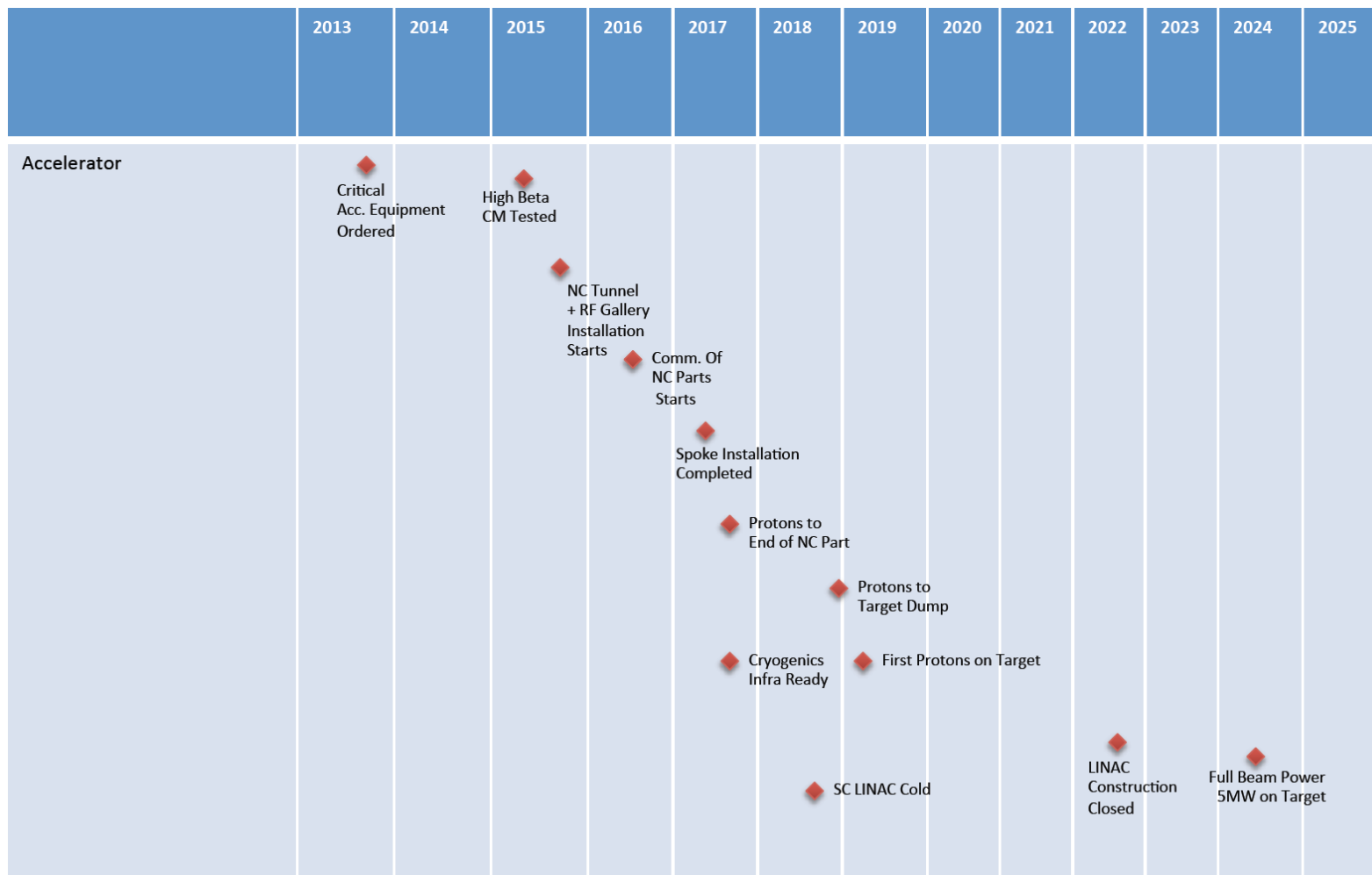
- Energy = 2.5 GeV
  - Target design
  - Linac cost
- Beam Current = 50 mA
  - Space charge
- Pulse Rate = 14 Hz
  - Neutron energy
  - location of neutron choppers
- Pulse Length = 2.9 mS
  - Adjusted for 5 MW of average power on target





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# ESS Accelerator Schedule





# RF System Main Components

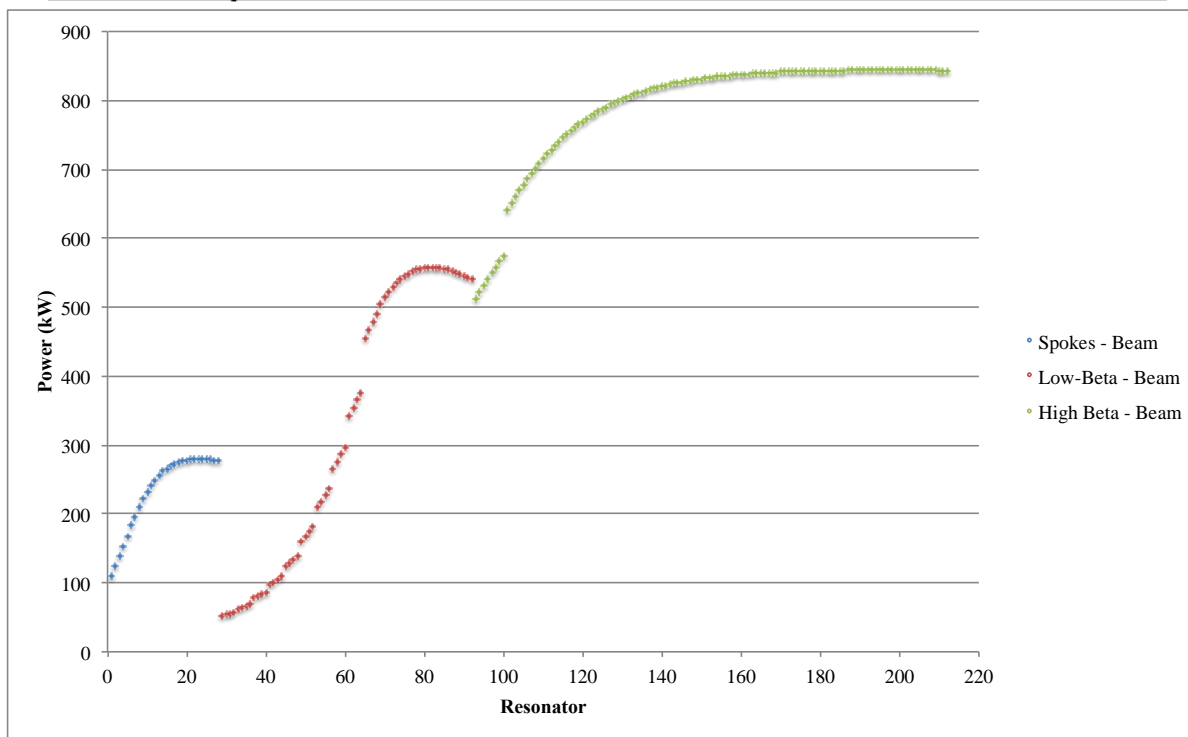
- The RF system for the ESS linac is defined as the system that:
  - converts AC line power to RF power at either 352 or 704 MHz
  - to be supplied to the RF accelerating cavity couplers.
- Main components
  - Modulator
    - Converts conventional AC power into pulse power
    - ESS requires 90 modulators
  - 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



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# 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- $\beta$	704.42	64	560
Elliptical high- $\beta$	704.42	120	850





# 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	%





# 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) <sup>2</sup>
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	10 <sup>6</sup>
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

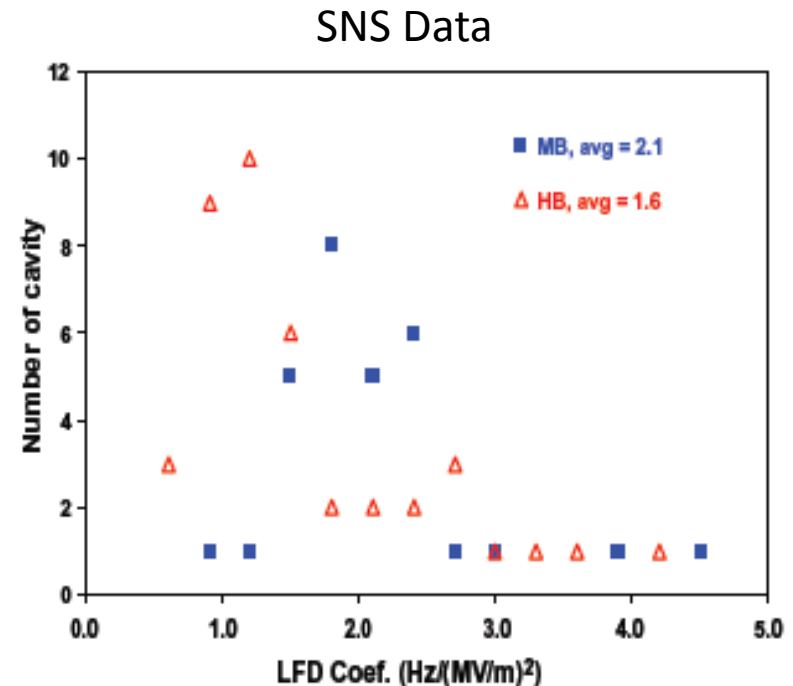
Specifications							
Parameter	RFQ	Bunchers	DTL	Spokes	Low Beta	High Beta	Unit
RF Regulation Overhead	25	25	25	25	25	25	%
RF Distribution Loss Budget	5	5	5	5	5	5	%
RF pulse Length	2.91	2.91	2.91	3.26	3.11	3.11	mS
Number of Couplers per Power Source	1	1	1	1	1	1	
Saturated RF Power per Power Source	1300	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

# System Bandwidth

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

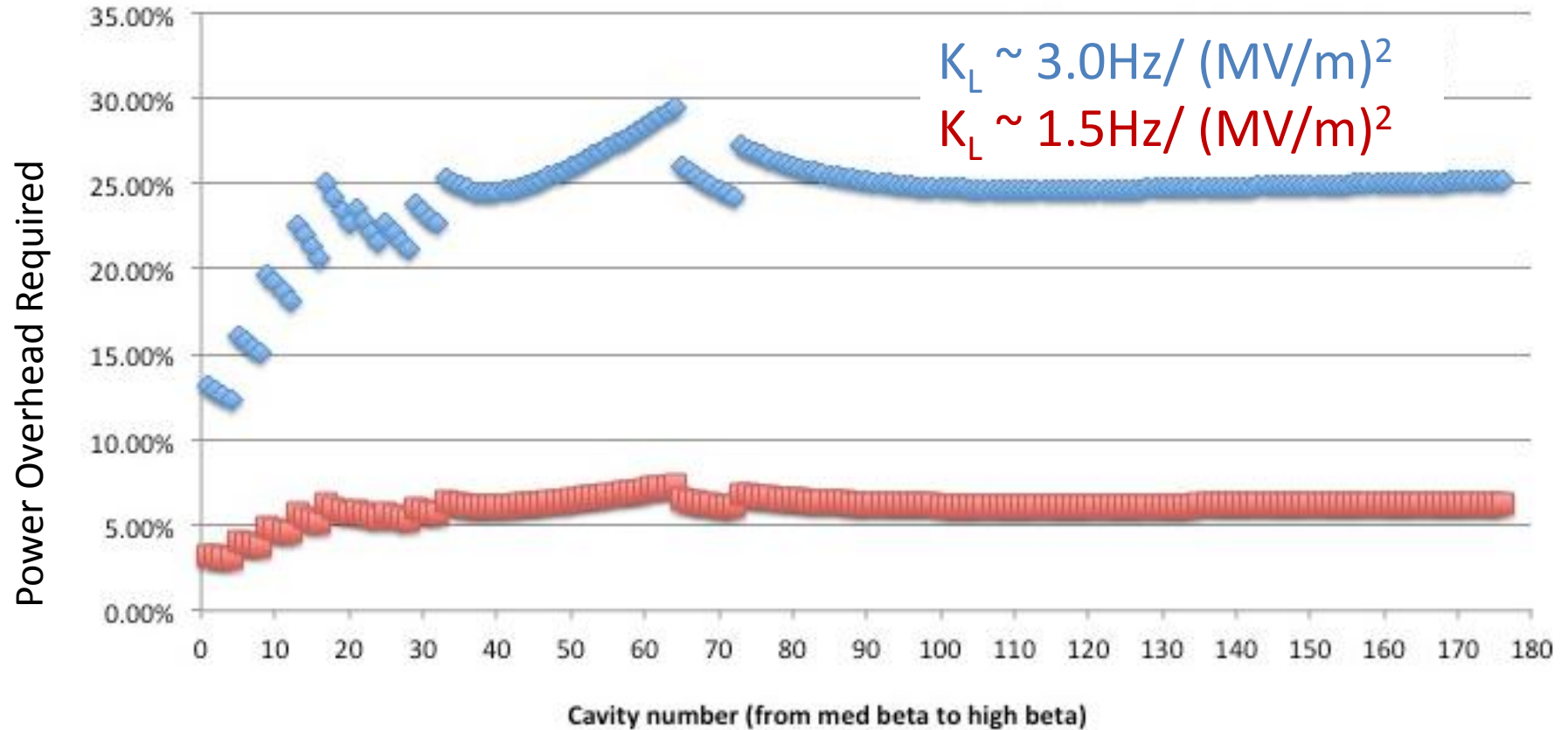
# De-Tuning

- Lorentz detuning
  - Max Gradient = 18 MV/meter
  - $K_L \sim 1.25 \text{ Hz}/(\text{MV/m})^2$
  - Detuning  $\sim 400 \text{ Hz} \Rightarrow 40 \text{ degrees}$
  - **Time constant  $\sim 1\text{ms}$** 
    - Pulse length  $\sim 3 \text{ ms}$
    - Offset by a static de-tune?
    - Piezo-compensation looks to be necessary (unlike SNS)
      - Or else pay for it with RF power!!!
- Micro-phonics  $\sim 10 \text{ Hz} \Rightarrow 2.0 \text{ degrees}$ 
  - Active damping by piezo-tuners does not seem necessary





# Lorentz Detuning



Static pre-tuning assumed

# 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<sup>+</sup> 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- $\beta$	730	300	800,000	0.89
Elliptical high- $\beta$	1100	477	750,000	0.94

# Number of Power Sources Per Cavity

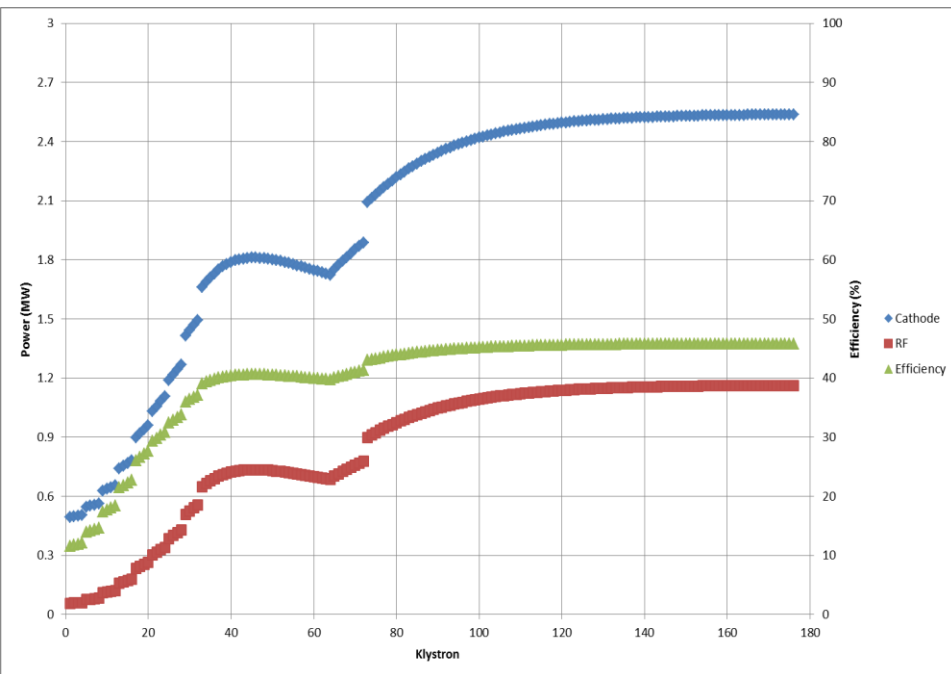
- Cavity to cavity variations
  - Lorentz detuning variations and control (-> 70 degrees over three time constants)
  - Coupling variations
  - Field flatness
- Most likely would need fast vector modulation
  - About the same cost of a klystron?
  - Bandwidth limitations?
  - Power handling?
  - Efficiency?
- 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

# Pulsed Cathode Configuration

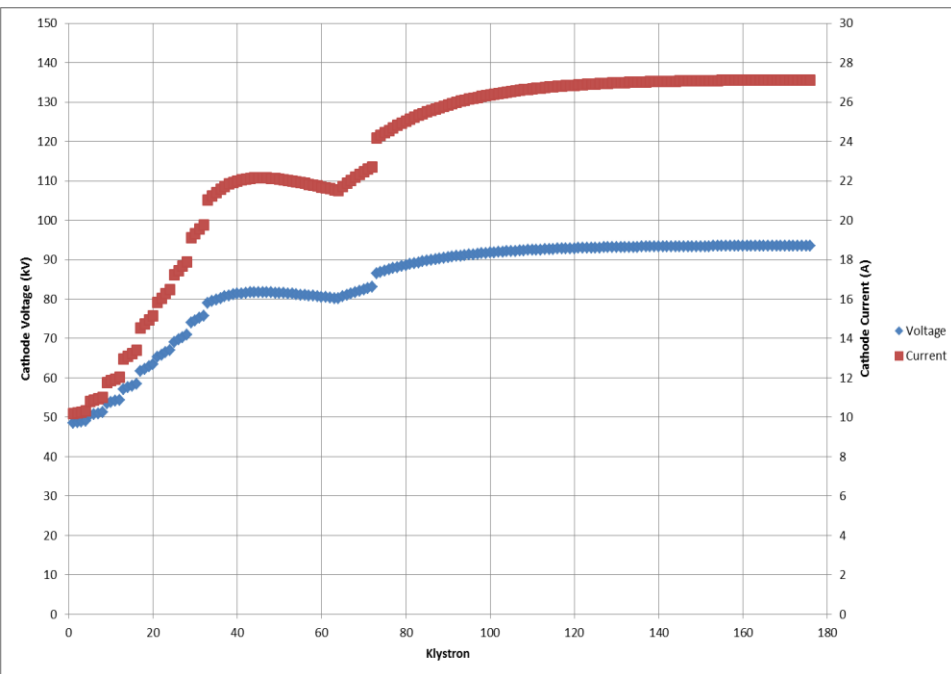
- With the appropriate choice of solid-state modulator topology, pulsed cathode klystrons systems can have
  - Tailored voltage supply
  - Excellent regulation characteristics
  - Simplified fault circuits
  - High efficiency, stable, less expensive klystrons
- The ESS linac baseline design will use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

# Klystron Cathode Voltage Profile

## Constant Perveance Operation



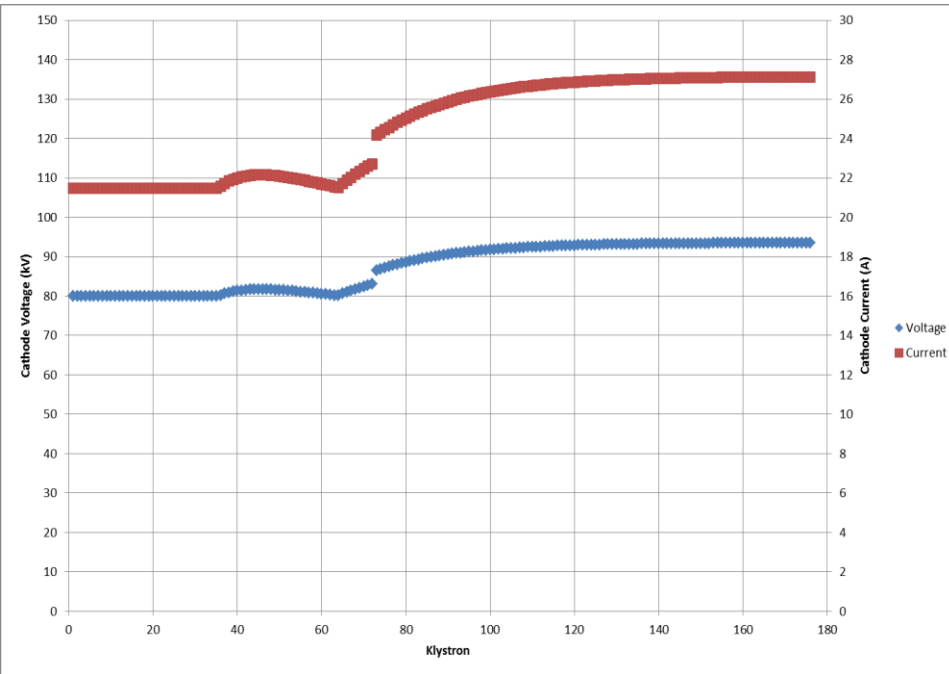
Klystron Power Profile



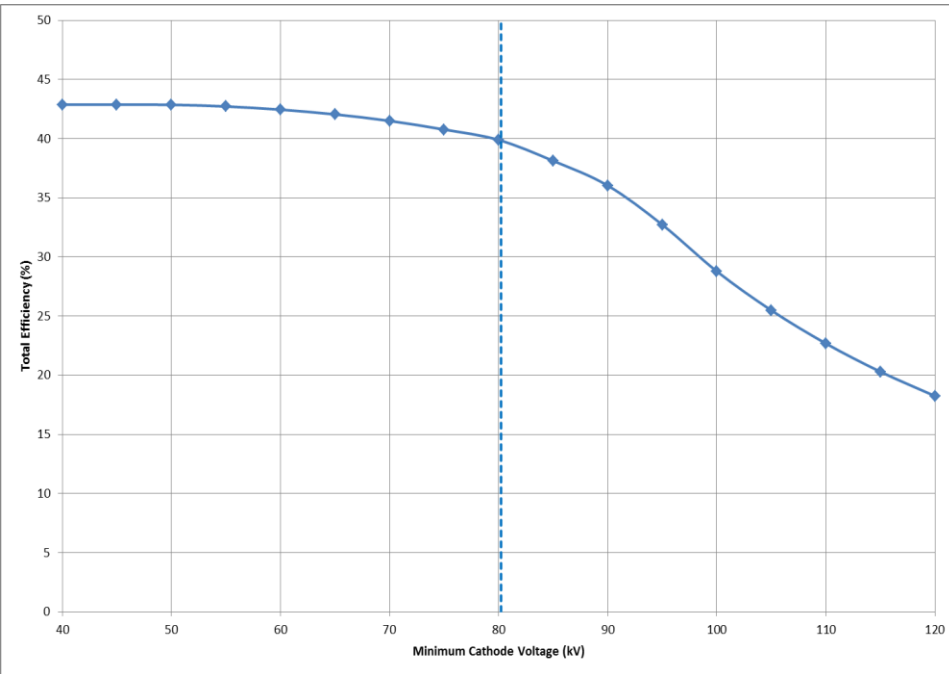
Klystron Cathode Voltage  
and Current Profile

# 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

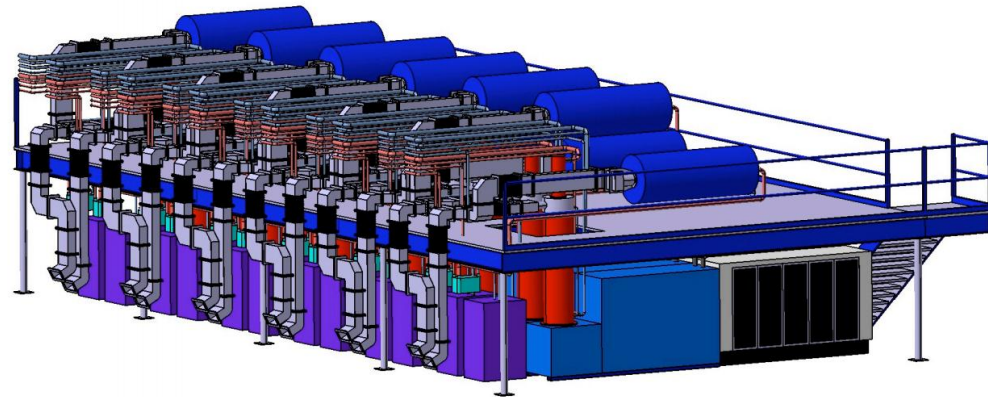
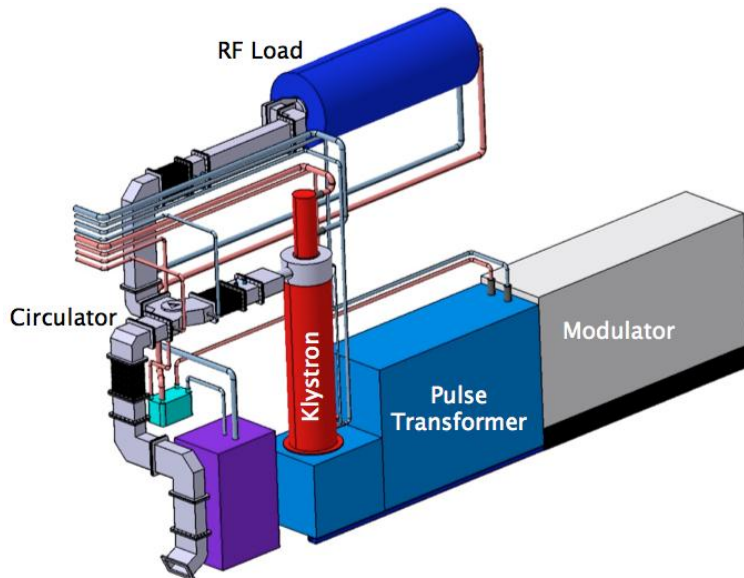
- The average spacing per cavities along the Linac is 1.8 meters
- It is difficult to fit one klystron / modulator into the gallery
- We estimate that  $< 50\%$  of the modulator cost and footprint is dominated by the stored energy in the modulator
- More klystrons per modulator
  - Is cheaper
  - Makes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





# One Modulator Per Klystron

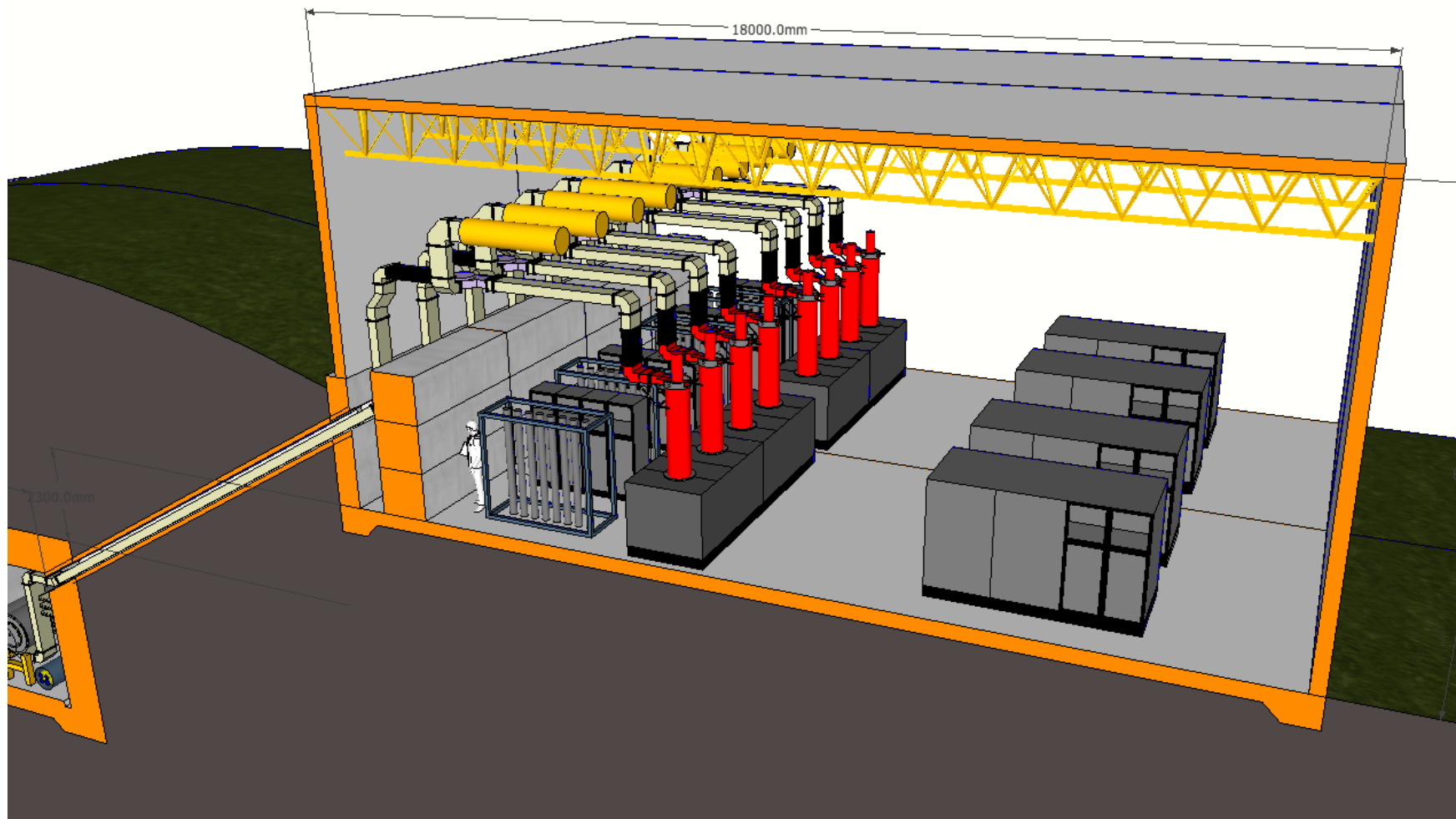
- Limited space for assembly and repair





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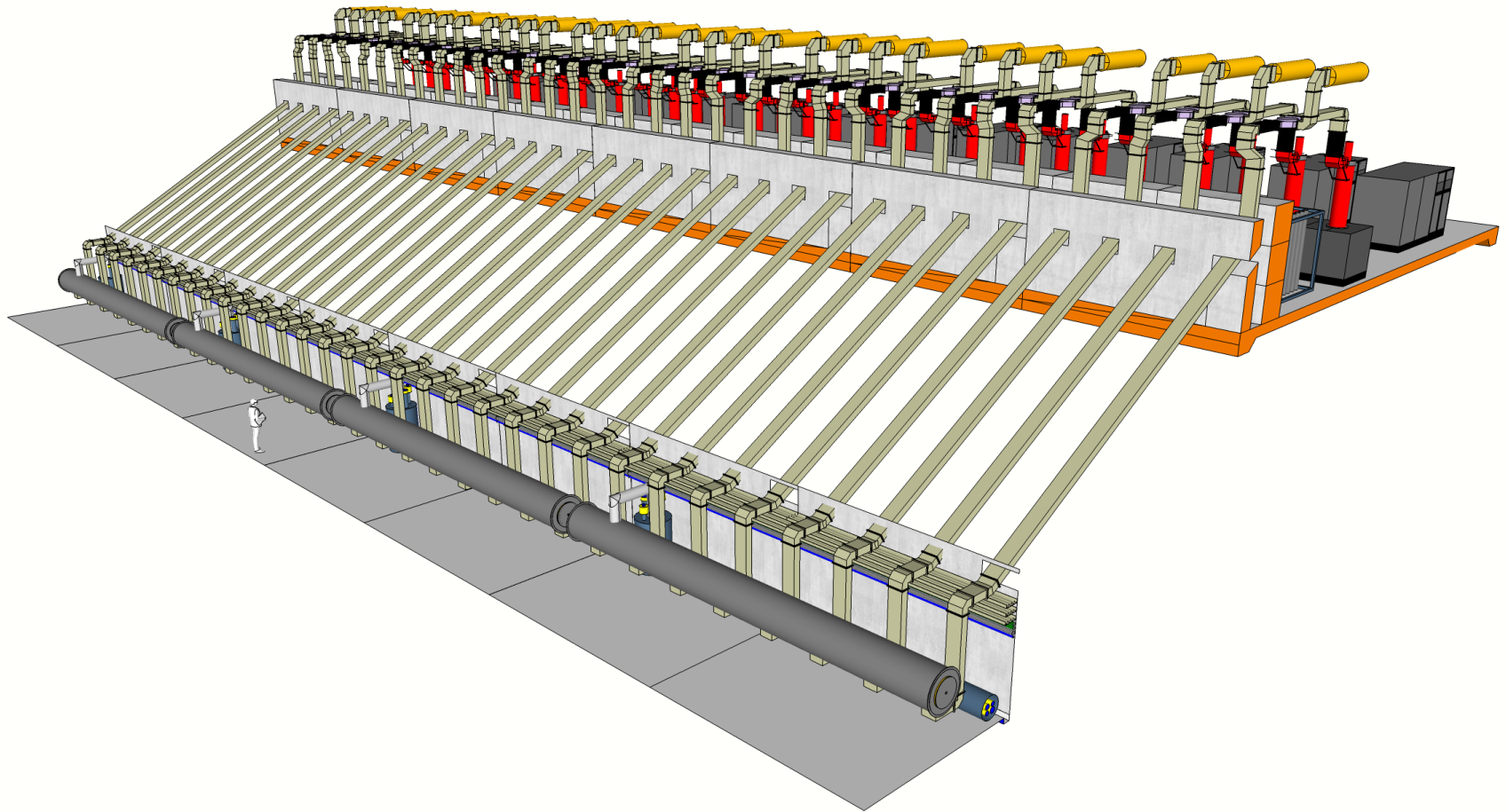
# Two Klystrons per Modulator





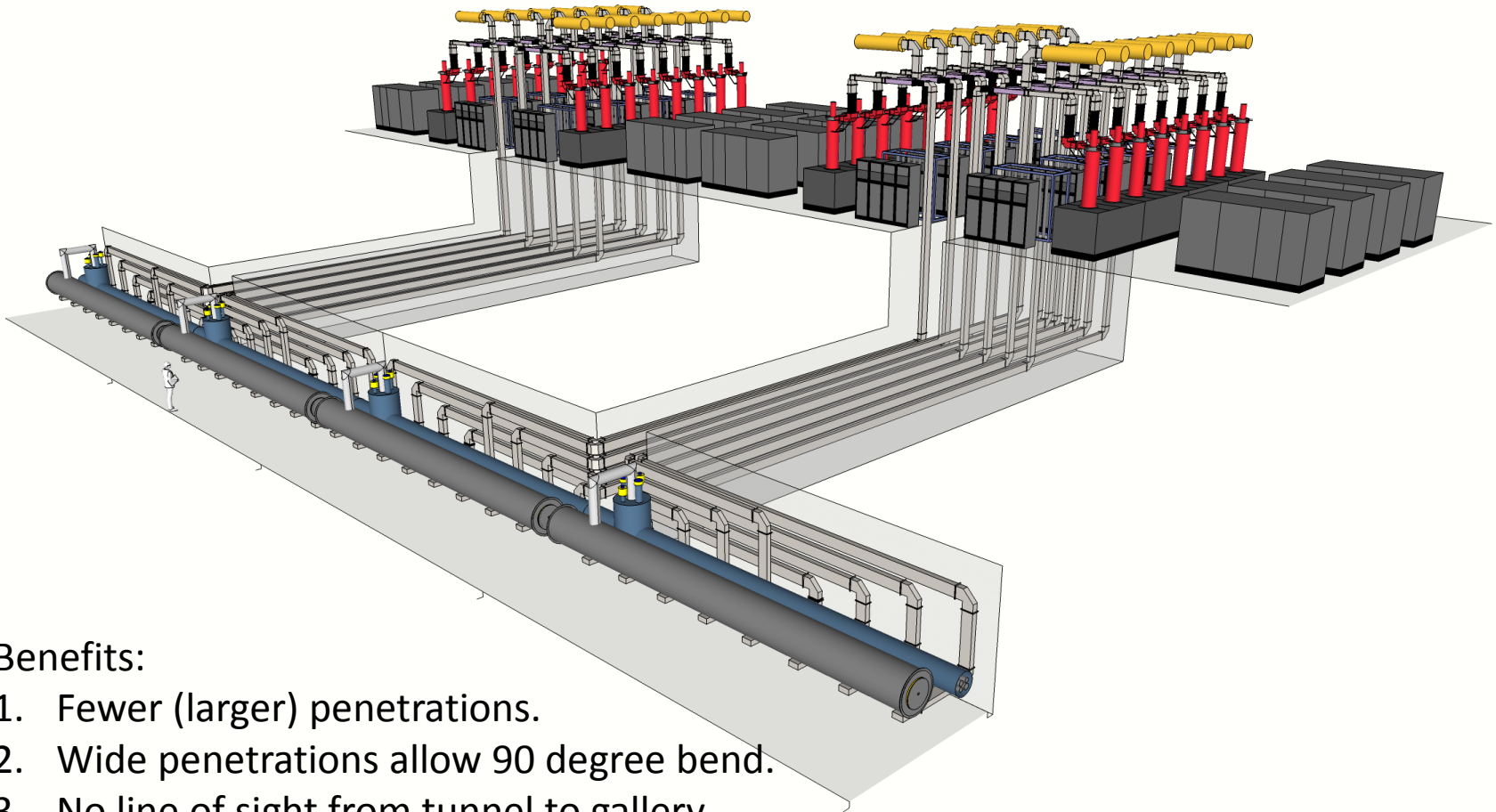
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# Chute Concept





# Stub Concept



## Benefits:

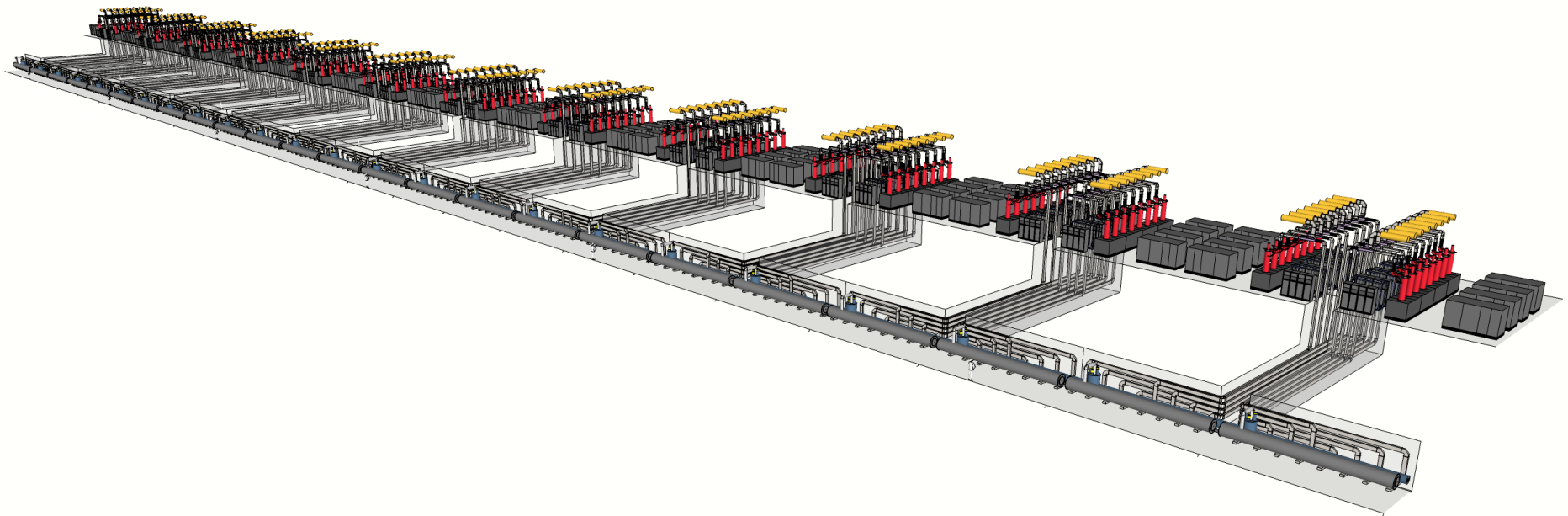
1. Fewer (larger) penetrations.
2. Wide penetrations allow 90 degree bend.
3. No line of sight from tunnel to gallery.
4. Freedom to alter cryomodule positions





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# Stub Concept



# Modulator Issues

- The cost of the modulators will dominate the cost of the RF system
  - ESS will require ~100 modulators
- Few number of vendors each with their own unique topology
  - For example, CERN-ESS modulator: 4 different vendors, 4 completely different topologies
  - Results in:
    - Operational risk
    - Cost risk
    - Schedule risk



# Modulator Workshop

- Was held in Lund April 24-25.
- Participants
  - Expert panel - experts from:
    - CERN, DESY, SNS, SLAC, LANL, RRCAT, FNAL
  - Vendors – representation from:
    - DTI, Imtech, Scandinova, Thomson, PPT, Jema, Transtech, Stangenes, AFT, Thales, CPI, Toshiba
  - Laboratories – attendees from:
    - ESS, Laval University, LIT, Uppsala Univ., ETH, RWTH-Aachen, IPNO
  - Total attendance – 70 people
- The deliverables of the workshop is:
  - A choice of modulator topology
  - A prototyping strategy
  - A series production strategy

# Strategy Discussion

- We discussed a number of prototype and series production strategies based on the following criterion (in order of importance)
  - Schedule
  - Cost
  - Technical Risk
- The discussion resulted in a combination of strategies in which schedule was strongly emphasized
- Draft strategy emerged from the meeting
  - ESS will write functional technical specifications
    - **Does \*not\* impose a topology on the vendors**
  - Will have at least 2 vendors produce modulators for series production
  - Call for tender for production of multiple (3) prototypes
    - Possibility for multiple vendors to be successful
    - At least 1 year soak test on prototypes
  - Call for tender for series production based on vendors with successful prototypes

# Modulator Strategy Tradeoff

- Advantages

- Less schedule risk because it involves multiple vendors
- Lets vendors provide product they know best to build
- Relieves ESS of burden of engineering design
- Multiple vendors competing should provide lower cost

- Risks

- More than one modulator topology to maintain
- Designs will be old technology
- ESS loses technical control of design which might affect reliability in the long run
- Requires multiple prototypes with a 1 year soak test

# 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

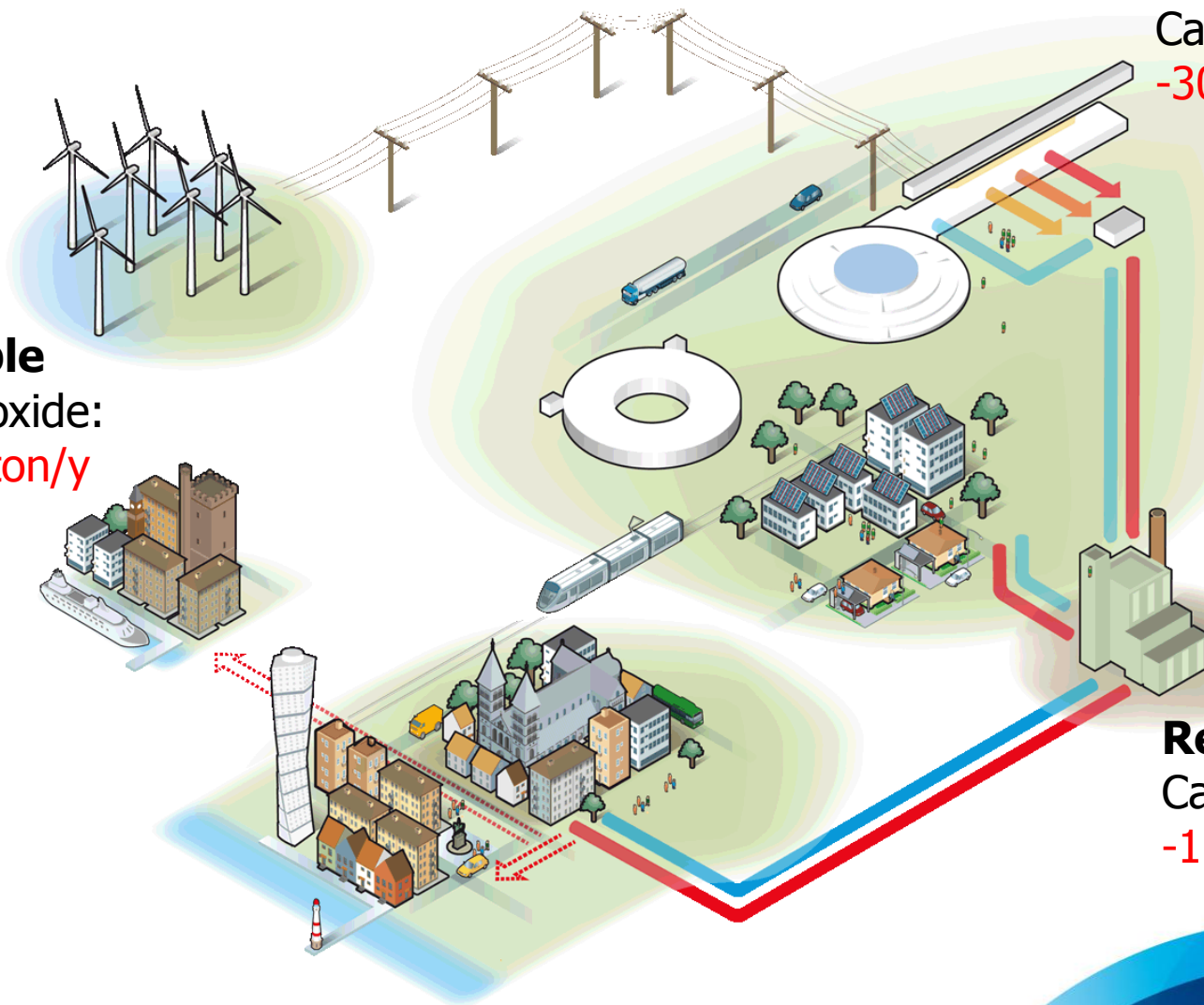


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# Sustainable Energy Concept

## Renewable

Carbon dioxide:  
-120,000 ton/y



## Responsible

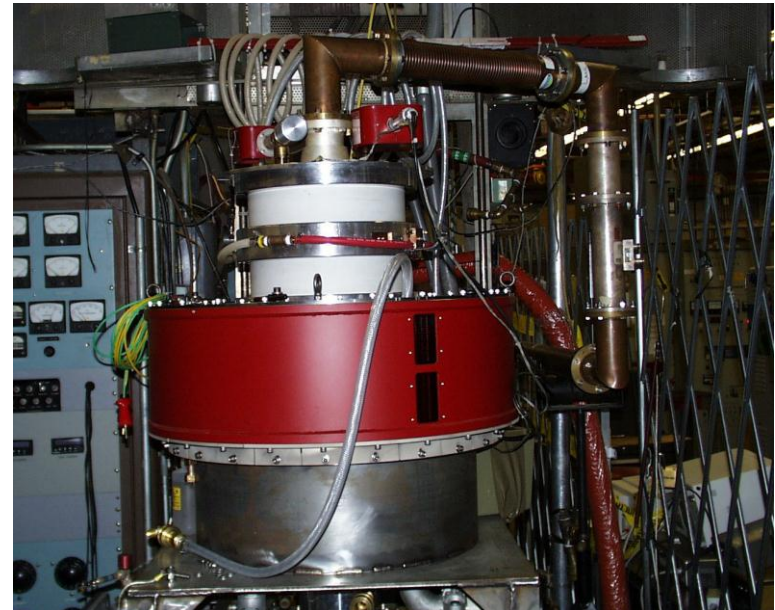
Carbon dioxide:  
-30,000 ton/y

## Recyclable

Carbon dioxide:  
-15,000 ton/y

# A Green RF System?

- High Intensity superconducting proton linacs require:
  - a large range of power
  - large overhead
  - one power source per cavity
- ESS is going to make an enormous investment in klystrons and klystron modulators
  - We will run with an overall wall-plug efficiency of less than 35% (assuming 60% efficient klystrons)
- **High Intensity superconducting proton linacs is a growth business**
- Does it pay to do R&D on a greener power source?







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# RF Help Wanted

