The SCRF Proton Driver

A New High Intensity Proton Source (and more!) at Fermilab

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SRF2005

July 15, 2005

Outline

- The Concept
- Fermilab Strategic Context
- Proton Driver SRF Linac Design
- Ferrite Vector Modulator R&D
- Hardware in Progress

8 GeV SCRF Proton Driver

New idea incorporating concepts from TESLA, SNS, RIA, TRASCO, APT…

- Copy SNS, RIA, and JPARC Linac designs up to 1.3 GeV
- Use "TESLA" Cryomodules from 1.3 - 8 GeV
- Direct 8 GeV H- Injection into Fermilab Main Injector

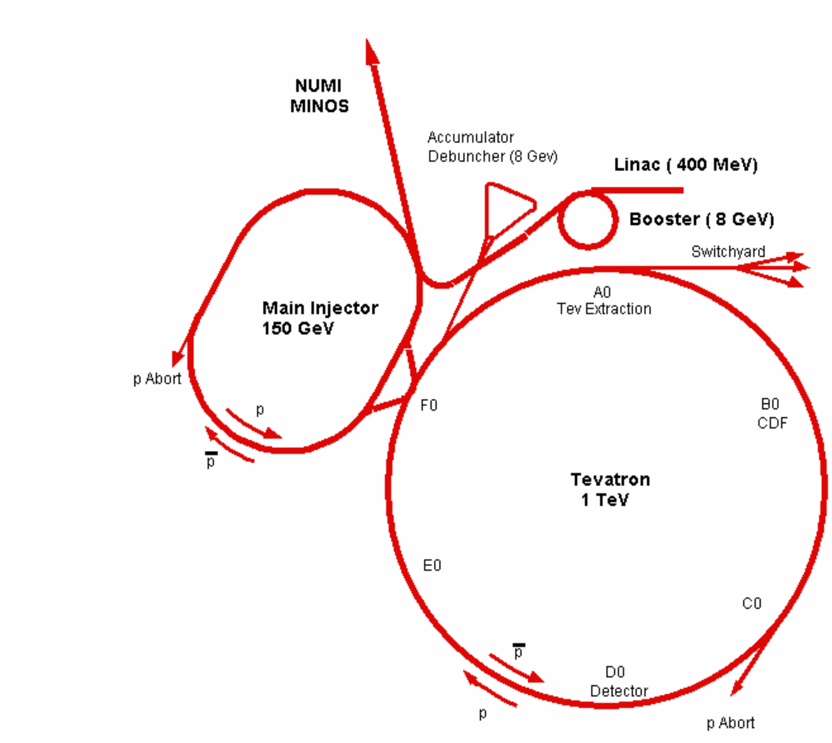
➔ "Super-Beams" in Fermilab Main Injector

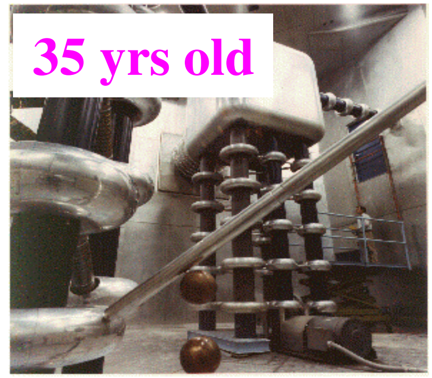
- 2+ MW Beam power at BOTH 8 GeV and 120 GeV
- Small linac emittances ➔ Small losses in Main Injector
- Very simple operation of the accelerator complex
- Minimum (1.5 sec) cycle time (eventually faster)
- MI Beam Power Independent of Beam Energy

→ *(flexible neutrino program)*

Fermilab's Existing Proton Source

FNAL Accelerator Complex
7 major accelerators !)





Cockroft-Walton
H^- ions →(750 KeV)

Drift Tube LINAC
750 KeV → 116 MeV

8 GeV Booster
Rapid-Cycling
Synchrotron

Proton Source = Linac, Booster, Main Injector

Q: WHAT IS THE SIGNIFICANCE OF THIS NUMBER ?

451

A: this is the number of vacuum tubes required to accelerate beams to 8 GeV in Fermilab’s current Proton Source.

Advantages of the 8 GeV Linac

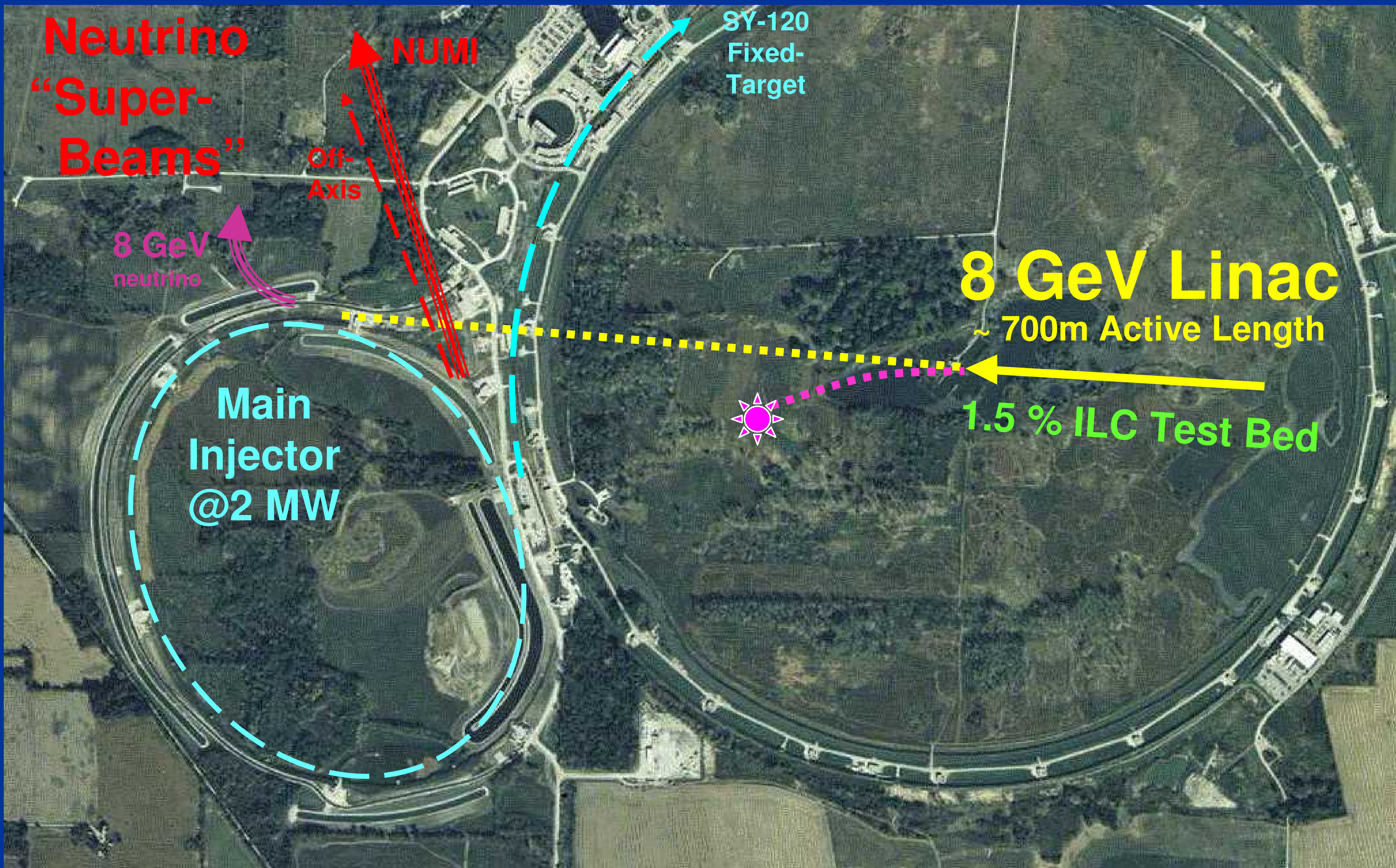
Replacing a Rapid-Cycling Synchrotron with a SCRF Injector Linac results in an accelerator complex that is:

- **Simpler**
  - Many fewer components to design and maintain
  - Simpler Beam Dynamics → Lower Beam Losses
- **Lower Wall Power**
  - 5 MW AC Power vs. ~20 MW for RCS
- **More Flexible**
  - Broader Physics Program (direct uses of 8 GeV linac beam)
  - More Upgrade Potential to >> 2 MW beam power

8 GeV Superconducting Linac

With X-Ray FEL, 8 GeV Neutrino & Spallation Sources, LC and Neutrino Factory

The Baseline Missions:
Super Beams in the Main Injector & ILC Test Bed



8 GeV SC Linac Proton Driver

- A Bridge Program to the Linear Collider
- Near Term Physics Program (neutrinos+)
- Multiple HEP Destinations & Off-Ramps
- A seed project for Industrial Participation

  50 cryomodules, 12 RF stations, ~1.5% of LC

Fermilab's Fork in the Road

IF (ILC 2006 CDR looks affordable) THEN

- Push for ILC ~2010 construction start at Fermilab
- Proceed with 120 GeV Neutrino Program at >1 MW

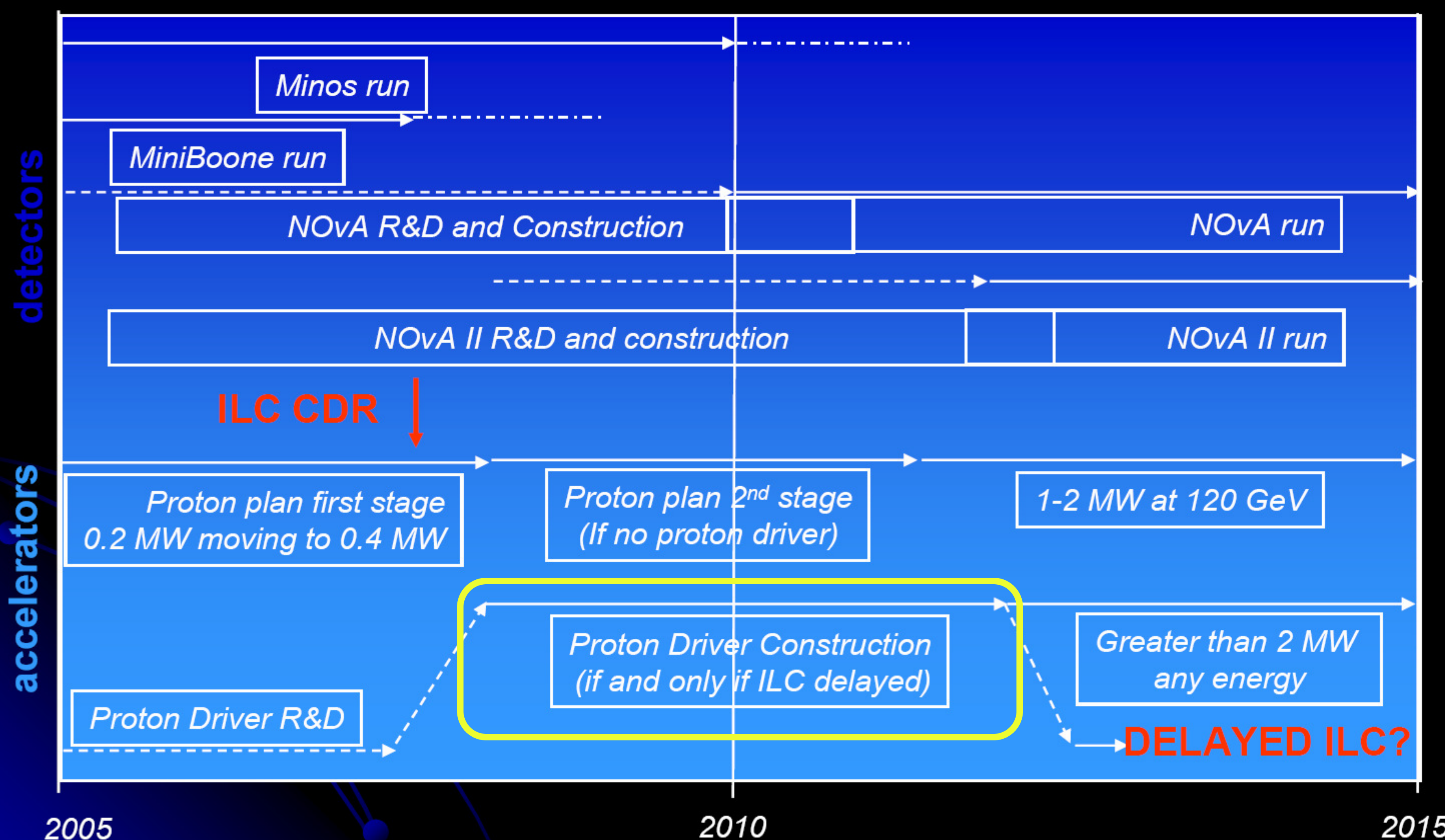
ELSE

- Superconducting 8 GeV Proton Driver starting 2008
- 30-120 GeV and 8 GeV Beams at 2-4 MW
- Stepping-Stone to delayed ILC construction start ~2012

ENDIF

Pier Oddone's presentation to EPP 2010:

Neutrino Program (delayed ILC)



Proton Driver Project Planning Currently Supports a FY2008 Construction Start

The Building Block of the 8 GeV Linac

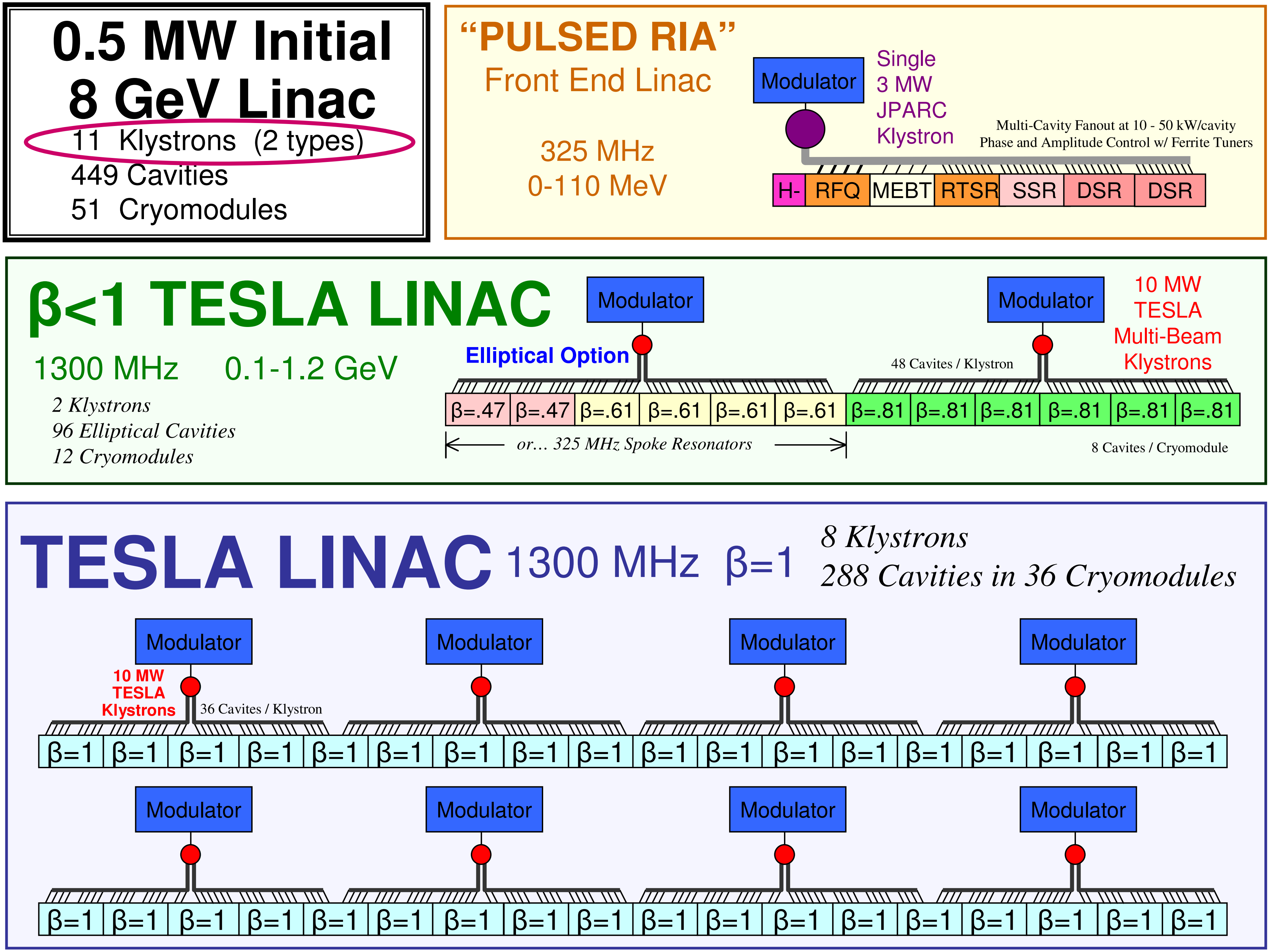
… is the TESLA RF Station:

- **1 Klystron**
- **1 Modulator**
- **~ 4 Cryomodules**
- **36 SCRF CAVITIES**

~1 GeV of Beam Energy

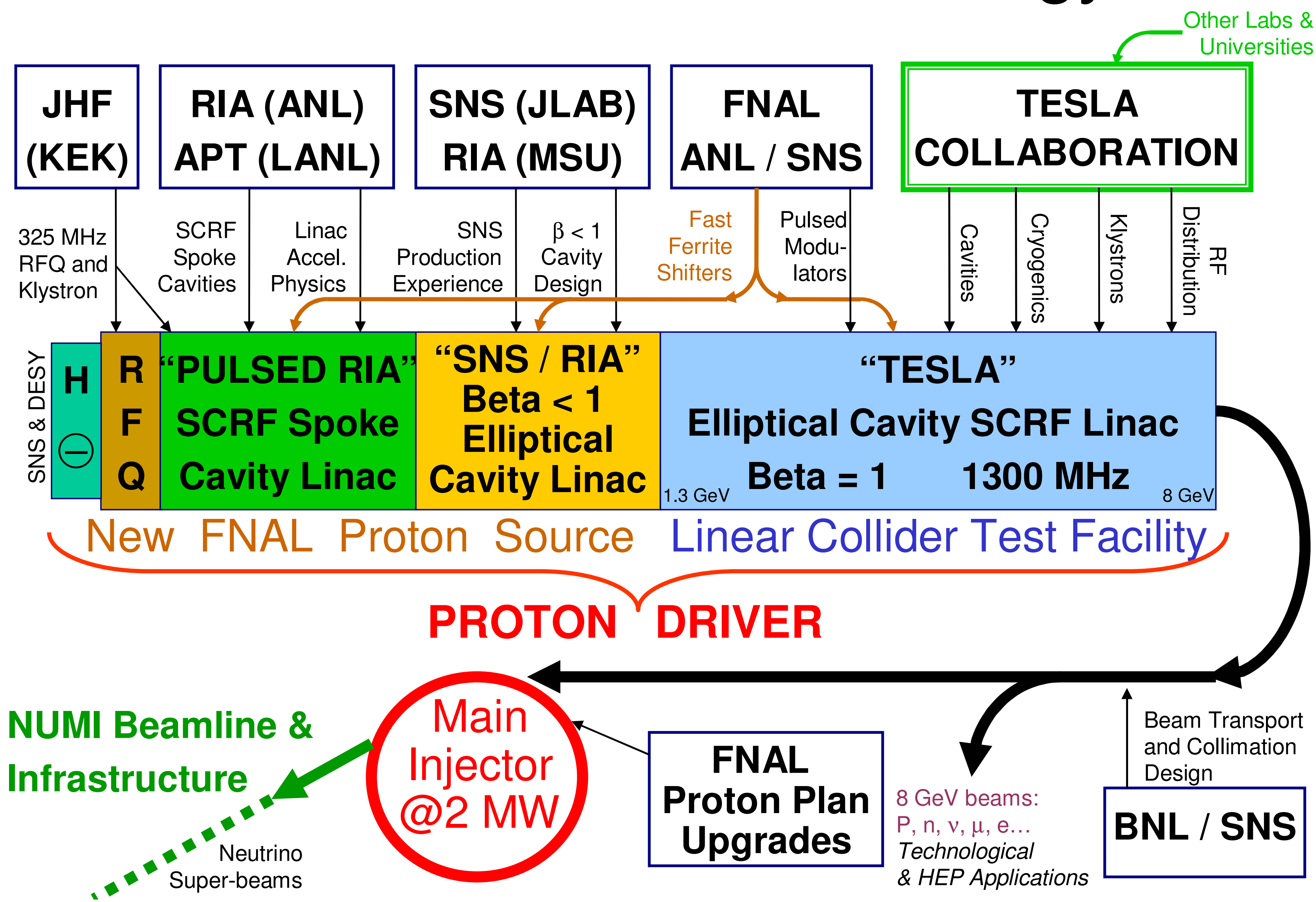
Proton Driver: 8 RF Stations
Linear Collider: 500 RF Stations

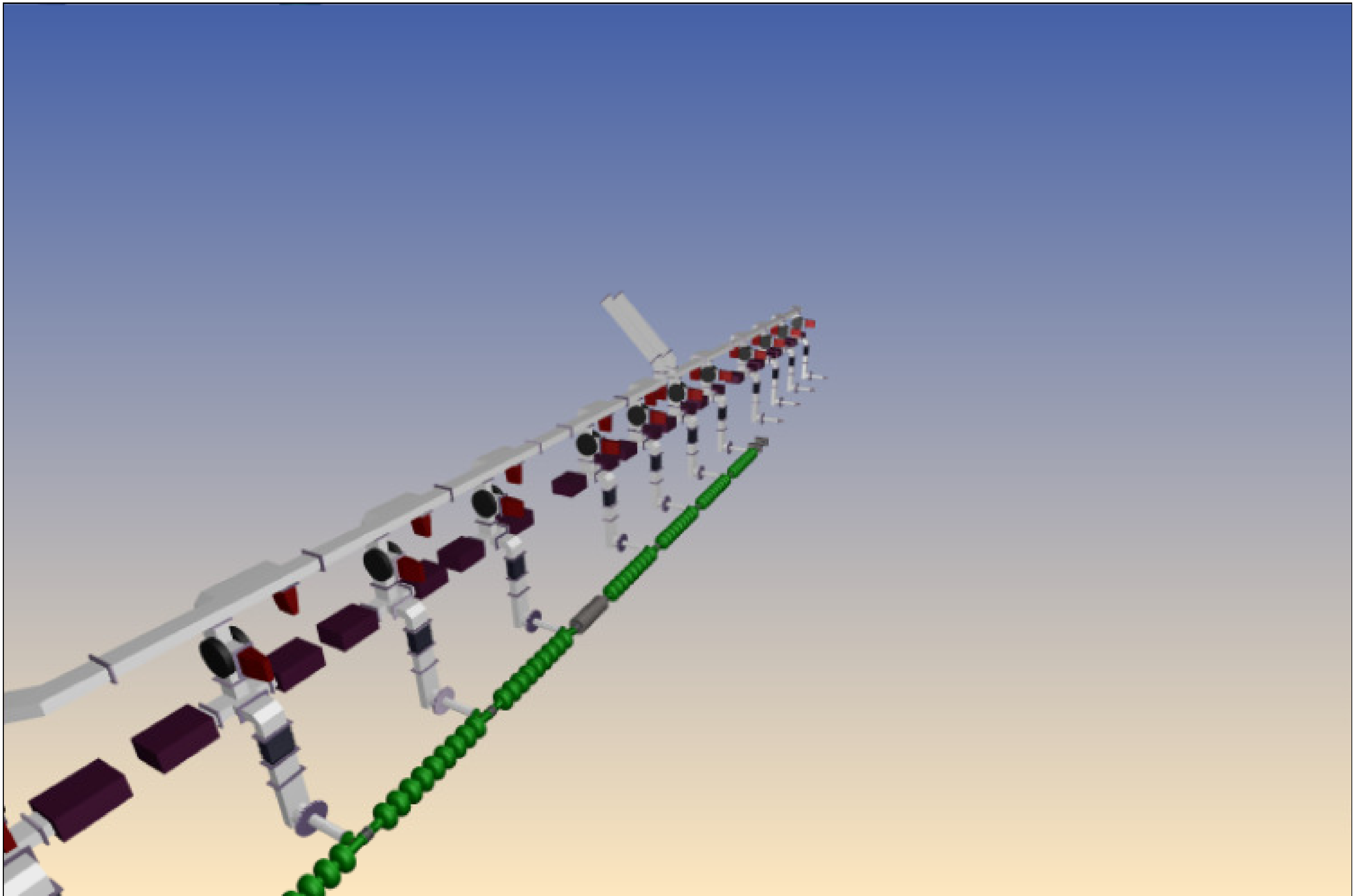
Understanding the production cost of the TESLA RF station is the most important question in (US) HEP.

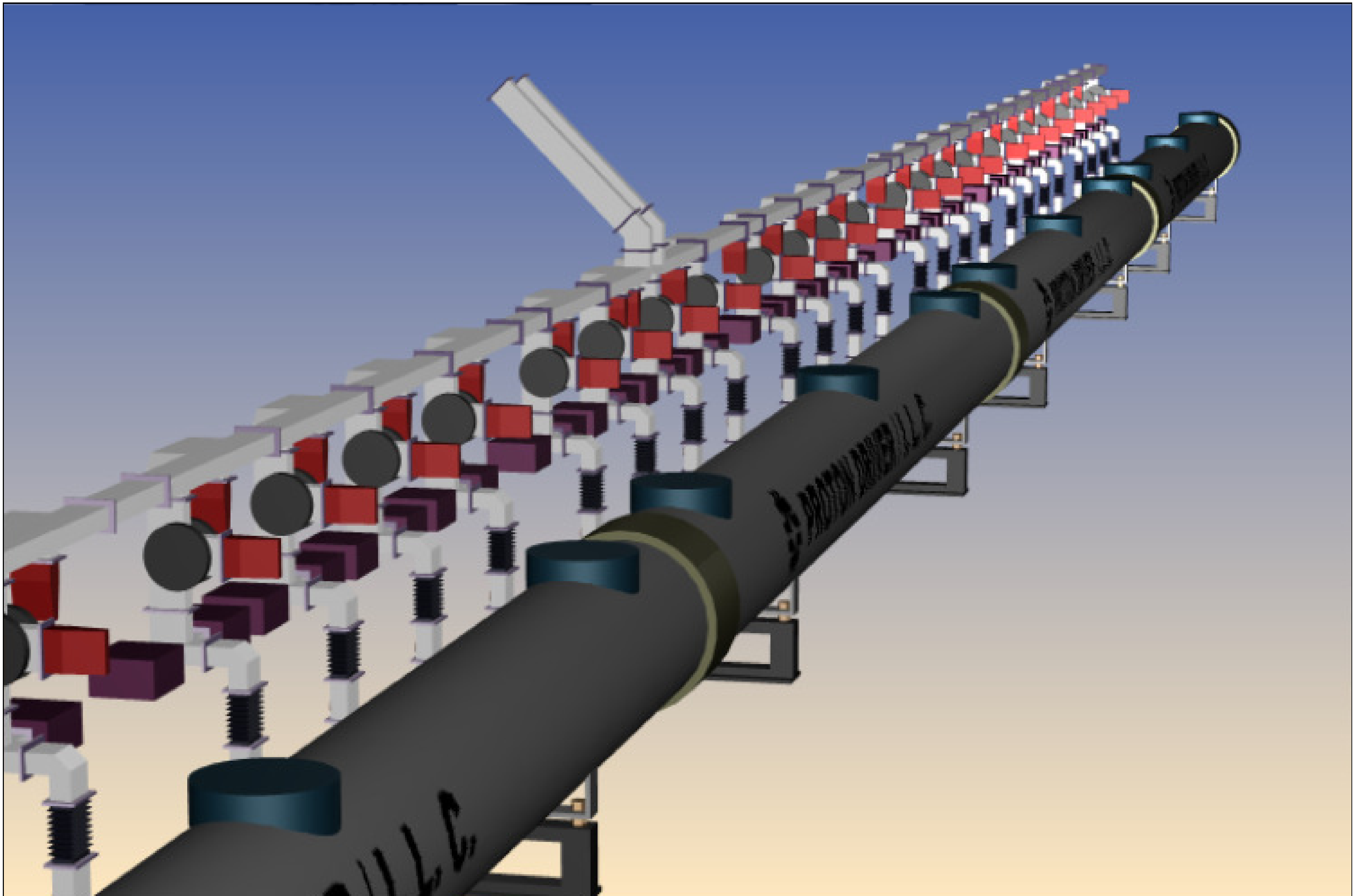


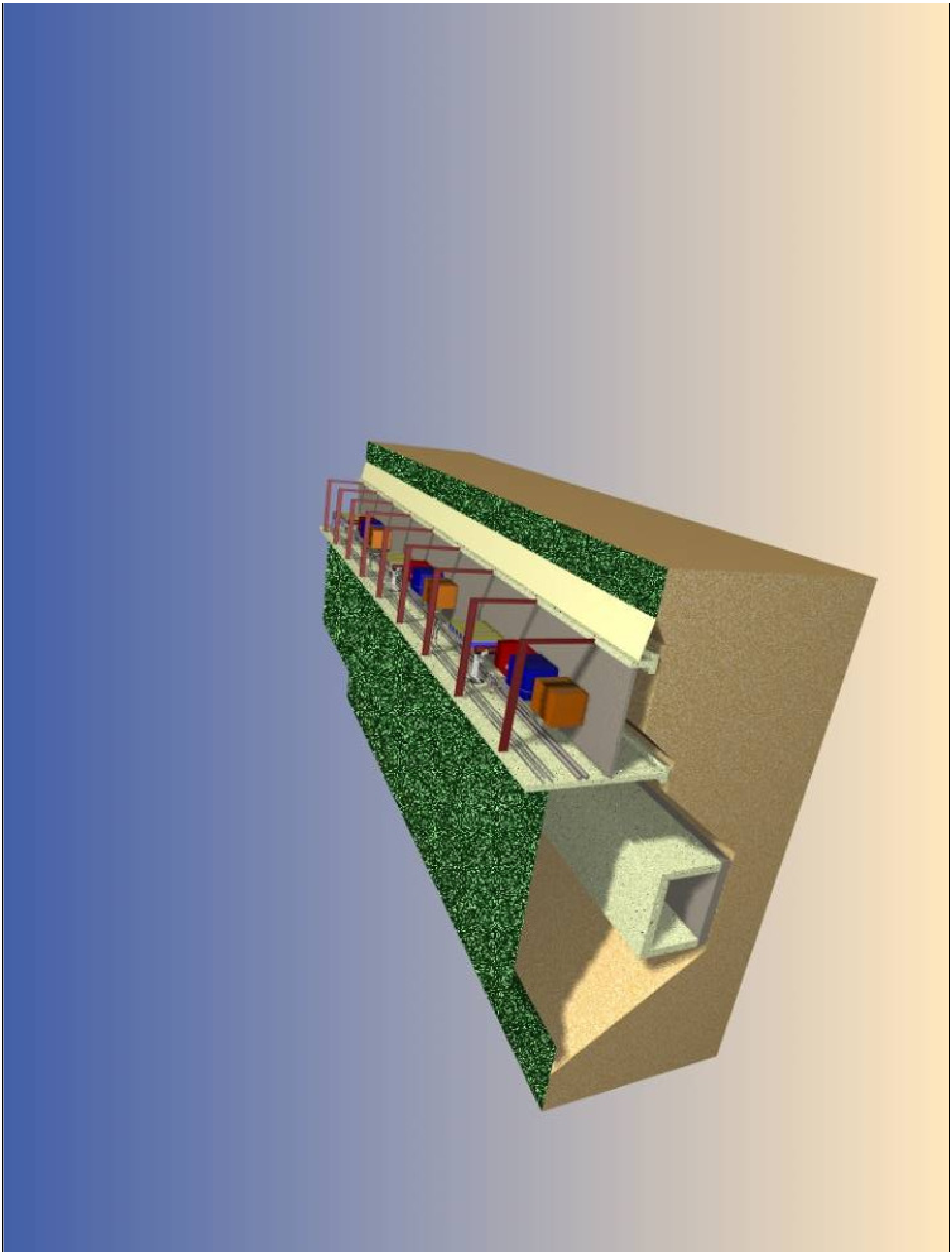
0.5 MW Initial
8 GeV Linac
11 Klystrons (2 types)
449 Cavities
51 Cryomodules
"PULSED RIA"
Front End Linac
325 MHz
0-110 MeV
Modulator
Single
3 MW
JPARC
Klystron
Multi-Cavity Fanout at 10 - 50 kW/cavity
Phase and Amplitude Control w/ Ferrite Tuners
H-
RFQ
MEBT
RTSR
SSR
DSR
DSR
β<1 TESLA LINAC
1300 MHz 0.1-1.2 GeV
2 Klystrons
96 Elliptical Cavities
12 Cryomodules
Elliptical Option
Modulator
Modulator
10 MW
TESLA
Multi-Beam
Klystrons
48 Cavites / Klystron
β=.47 β=.47 β=.61 β=.61 β=.61 β=.61 β=.81 β=.81 β=.81 β=.81 β=.81 β=.81
or… 325 MHz Spoke Resonators
8 Cavites / Cryomodule
TESLA LINAC 1300 MHz β=1
8 Klystrons
288 Cavities in 36 Cryomodules
Modulator
10 MW
TESLA
Klystrons
36 Cavites / Klystron
β=1

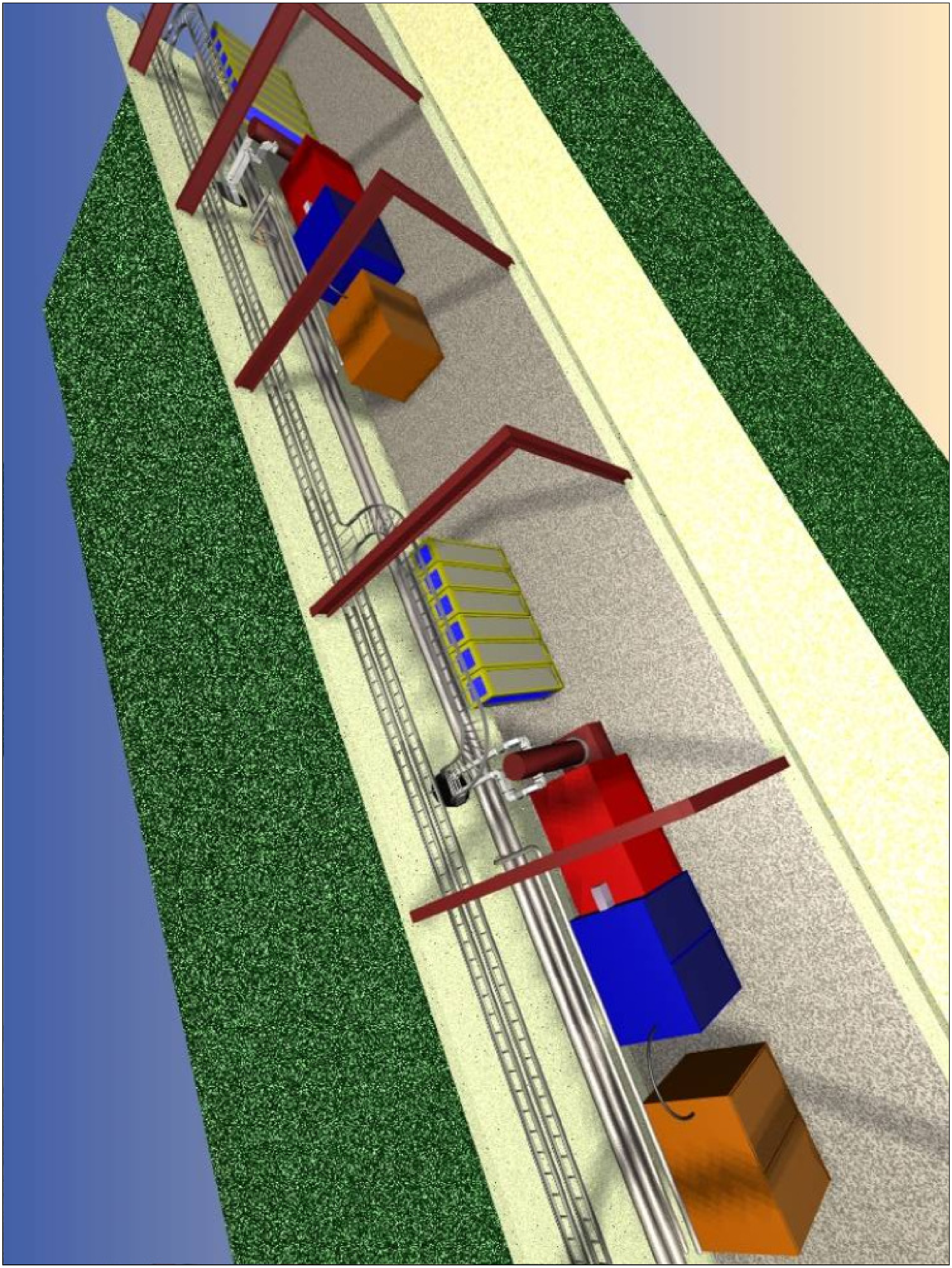
Proton Driver Linac - Technology Flow

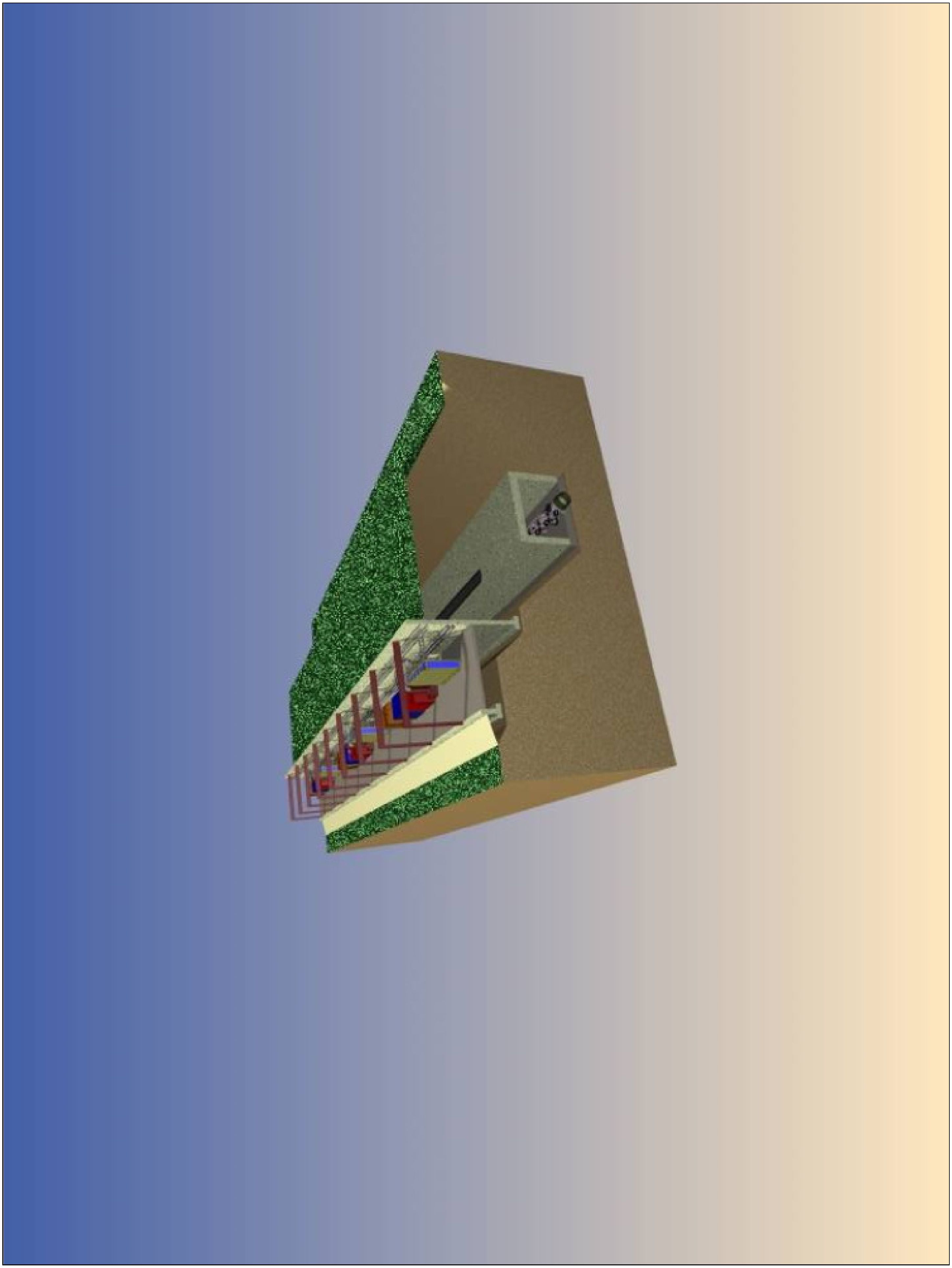


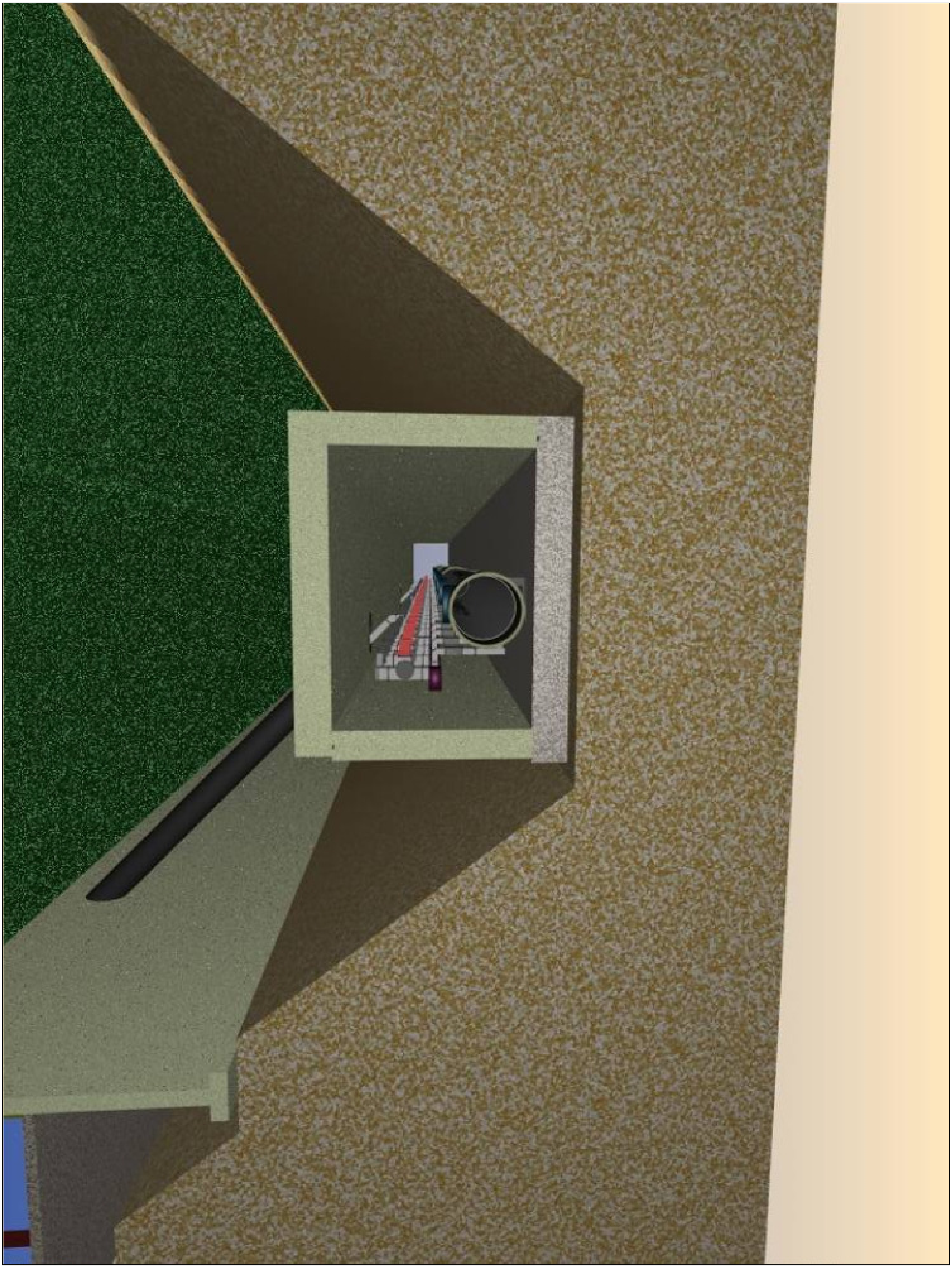


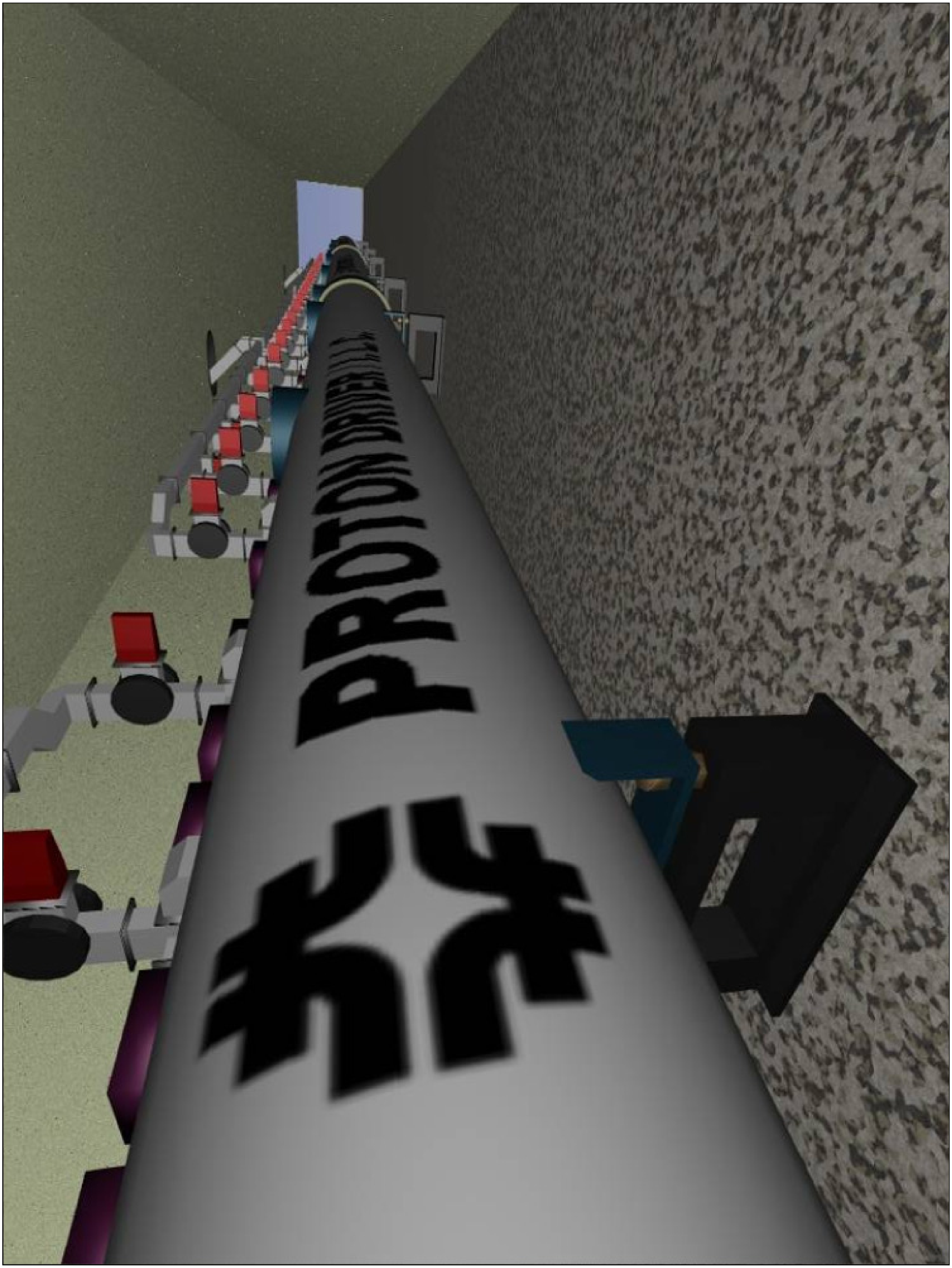


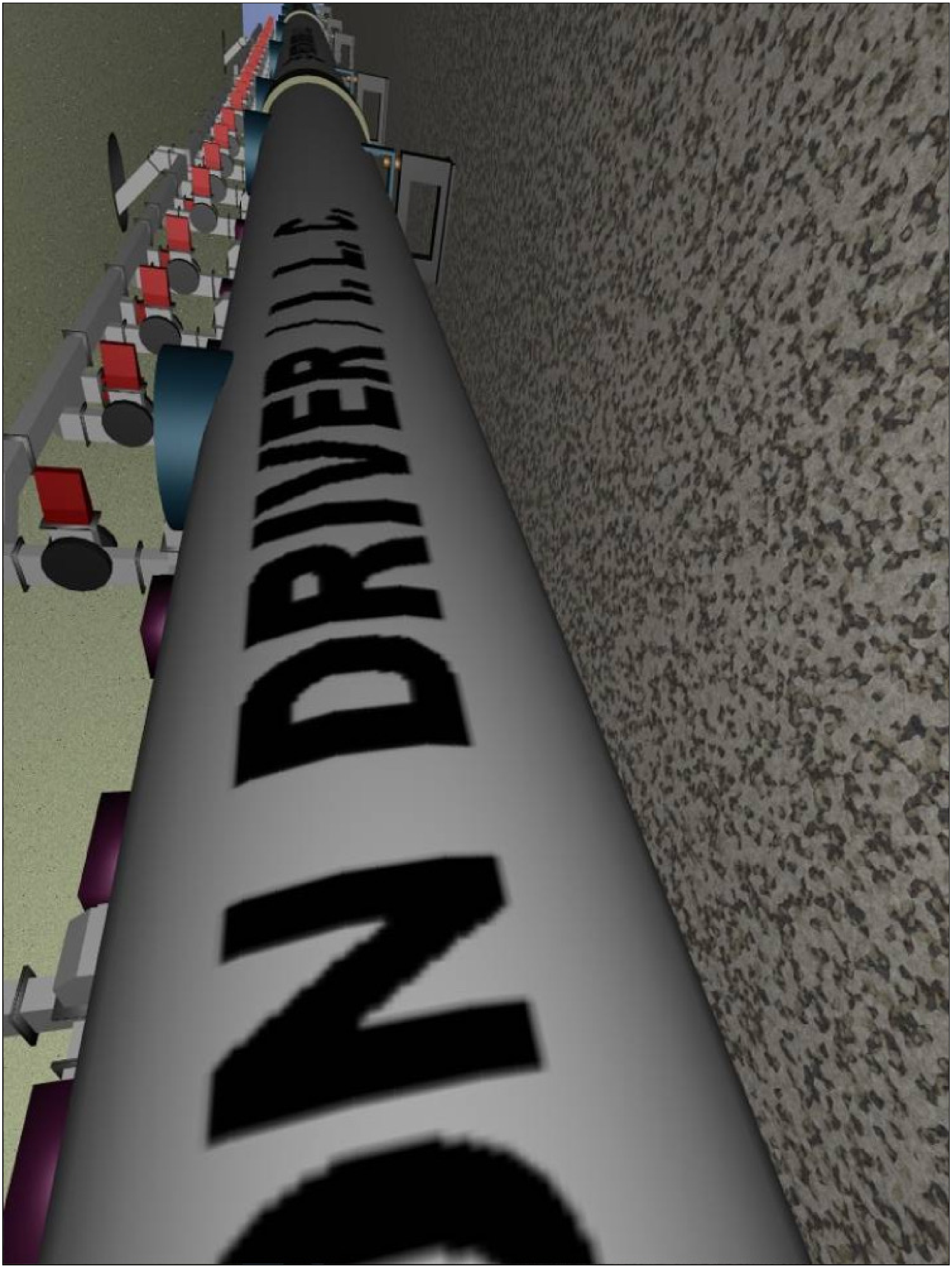


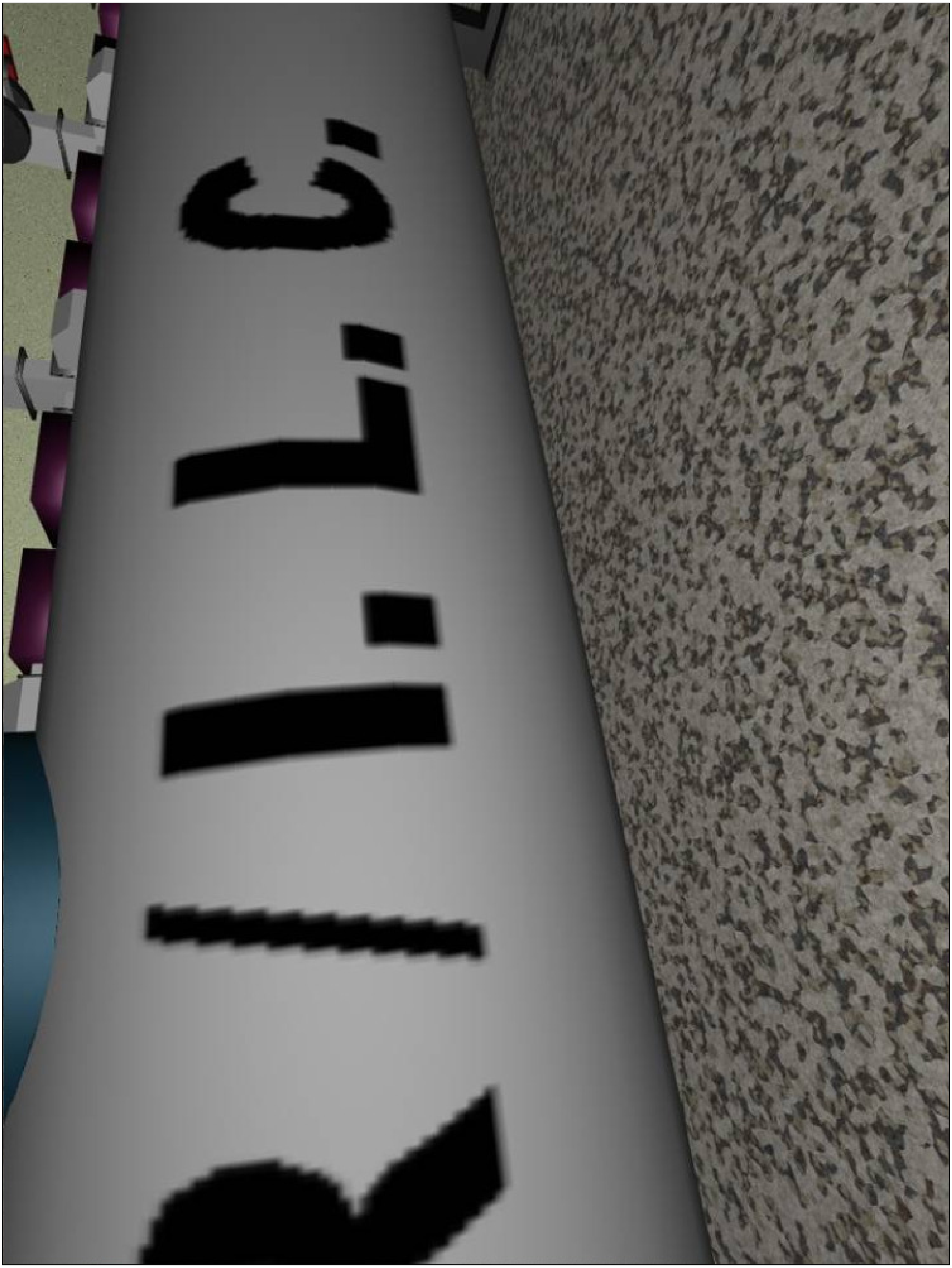


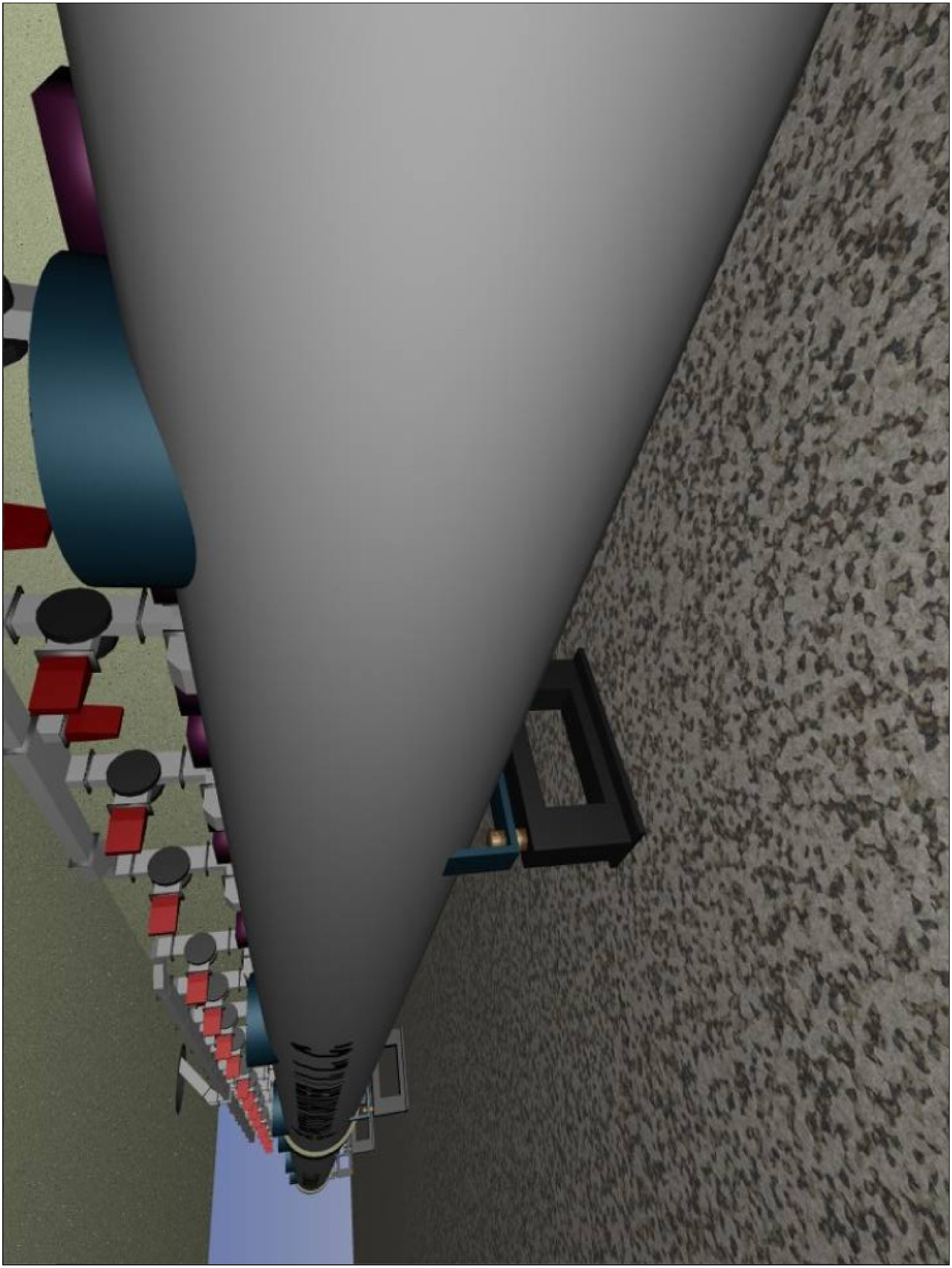





PROTON DRIVER


N DRIVER L.L.C.





Main Parameter Decisions

1. **Main Injector Beam: (1.5 E14, 1.5 sec, 2 MW)**
2. **Pulse Parameters: (8 mA x 3 msec x 2.5 Hz)**

   Ultimate Upgrade: (25 mA x 1 msec x 10 Hz)

3. **Operating Frequency: (1300 MHz / 325 MHz)**
4. **Copper – to – SCRF transition: (15 MeV)**
5. **Spokes–to–Elliptical transition: (110 - 400 MeV)**
6. **Design Margins on 8 GeV H- Transport**

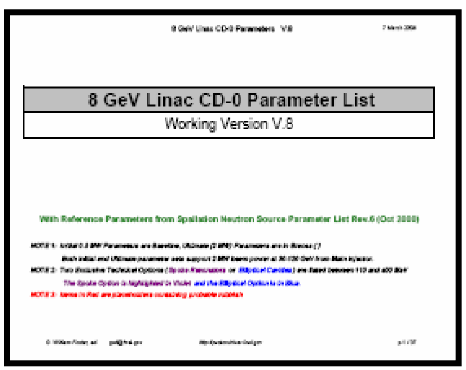
Primary Parameter List (for reference)

PRIMARY PARAMETERS	8 GeV Initial 0.5 MW {Ultimate 2MW in Brackets}		
Linac beam kinetic energy	8 GeV		
Linac Particle Types	H - ions		Baseline Mission
	Protons		via foil stripping in transfer line
	Electrons		Possible w/upgrade of Phase Shifters & Injector
Linac Stand-Alone Beam power	0.5 {2.0} MW		8 GeV beam power available directly from linac
Linac Pulse repetition rate	2.5 {10} Hz		
Linac macropulse width	3.0 {1.0} ms		
Linac current (avg. in macropulse)	8.7 {26} mA		
Linac current (peak in macropulse)	9.3 {28} mA		
Linac Beam Chopping factor in macropulse	94 %		For adiabatic capture with 700ns abort gap.
Linac Particles per macropulse	1.56E+14		
Linac Charge per macropulse	26 uC		
Linac Energy per macropulse	208 kJ		
Linac average beam current	0.07 {0.26} mA		
Linac beam macropulse duty factor	0.75 {1.0} %		
Linac RF duty factor	1.00 {1.3} %		
Linac Active Length including Front End	614 m		Excludes possible expansion length
Linac Beam-floor distance	0.69 m	=27 in.	same as Fermilab Main Injector
Linac Depth Below Grade	9 m		same as Fermilab Main Injector
Transfer Line Length to Ring	972 m		for MI-10 Injection point
Transfer Line Total Bend	40 deg		two 20-degree collimation arcs
Ring circumference	3319.4 m		Fermilab Main Injector
Ring Beam Energy	8-120 GeV		MI cycle time varies with energy
Ring Beam Power on Target	2 MW		~ independent of MI Beam Energy
Ring Circulating Current	2.3 A		
Ring cycle time	0.2-1.5 sec		depends on MI beam energy & flat-top
Ring Protons per Pulse on Target	1.50E+14 protons		
Ring Charge per pulse on target	25 uC		
Ring Energy per pulse on target	200-3000 kJ		at 8-120 GeV
Ring Proton pulse length on target	10 us		1 turn, or longer with resonant extraction
Linac Wall Power	5.5 {12.5} MW		approx 3 MW Standby + 1MW / Hz

Linac Segment Details (for reference)

Open Technical Choice: 3-spoke or Elliptical

	RFQ	Room Temp TSR	SRF 1-spoke	SRF 2-spoke	Spoke Option 3-spoke	Elliptical Option Low	Elliptical Option Medium	High	TESLA
Frequency, MHz	325	325	325	325	325	1300	1300	1300	1300
Energy Range, MeV	0.065-3	3-15	15-33	33-110	110-400	110-175	175-400	400-1200	1200-8000
Beta geometrical	-	0.08 to 0.18	0.21	0.4	0.61	0.47	0.61	0.81	1.00
Number of cavities or resonators	4	21	16	28	42	16	32	48	288
Number of accelerating gaps / cavity	-	4	2	3	4	6	6	8	9
Epeak, MV/m	32.1	TBD	32	32	32	52	52	52	52
Eacc, MV/m	-	2.3 to 3.7	10.67	10.67	10.67	15.2	19.2	23.7	26
Cavity effective length, cm	-	15 to 32	13	36.9	85.8	32.5	42.2	74.8	103.8
Synchronous phase, deg (typ.)	-	-40 to -30	-30	-30	-30 to -20	-30	-25	-20	-16
Length of Segment, m	~4	10.4	12.5	17.2	64	18.8	38.5	70.1	438.3
Number of Cryomodules	-	-	1	2	6	2	4	6	36
Cavities per Cryomodule	-	-	16	14	7	8	8	8	8
Magnetic Focusing Type	-	Solenoid	Solenoid	Solenoid	Quad	Quad	Quad	Quad	Quad
Coupler Power Initial {Ultimate}, kW	125	40 {54}	9 {26}	34 {102}	80 {238}	42 {125}	72 {214}	133 {398}	220 {660}
Cavities per Klystron Initial {Ultimate}	72 {36}				42 {14}	48 {24}		48 {24}	36 {12}
Number of Klystrons Initial {Ultimate}	1 {2}				1 {3}	1 {2}		1 {3}	8 {24}


8 GeV Linac CD-0 Parameter List
Working Version V.8

- **Parameter List gives subsystem details for <u>technically feasible baseline</u>**

http://tdserver1.fnal.gov/8gevlinacPapers/ParameterList2005/CD0_Parameter_List_Current_Version.pdf

Fermilab

G. W. Foster – SRF 2005

Linac Pulse Parameters

Comparison with Other SRF Linacs

	8 GeV Initial	8 GeV {Ultimate}	SNS (Spallation Neutron Source)	TESLA-500 (w/ FEL)	TESLA-800
Linac Energy	8 GeV	8 GeV	1 GeV	500 GeV	800 GeV
Particle Type	H^-, e+, or e^-	H^-, e+, or e^-	H^-	e+, e^-	e+, e^-
Beam Power	0.5 MW	2 MW	1.56 MW	22.6 MW	34 MW
AC Power (incl. warm FE)	5.5 MW	13 MW	~15 MW	97 MW	150 MW
Beam Pulse Width	3 msec	1 msec	1 msec	0.95 msec	0.86 msec
Beam Current(avg. in pulse)	8.6 mA	26 mA	26 mA	9.5 mA	12.7 mA
Pulse Rate	2.5 Hz	10 Hz	60 Hz	5(10) Hz	4 Hz
# Superconducting Cavities	384	384	81	21024	21852 / 2
# Cryomodules	48	48	23	1752	1821
# Klystrons	12	33	93	584	1240
# Cavities per Klystron(typ)	36	12	1	36	18
Cavity Surface Fields (max)	52 MV/m	52 MV/m	35 MV/m	46.8 MV/m	70 MV/m
Accel. Gradient (max)	25 MV/m	25 MV/m	16 MV/m	23.4 MV/m	35 MV/m
Linac Active Length	614 m	614 m	258 m	22 km	22 km

Two Design Points for 8 GeV Linac

Initial: 0.5 MW Linac Beam Power (BASELINE)

8.3 mA x 3 msec x 2.5 Hz x 8 GeV = 0.5 MW

Twelve Klystrons Required

Ultimate: 2 MW Linac Beam Power

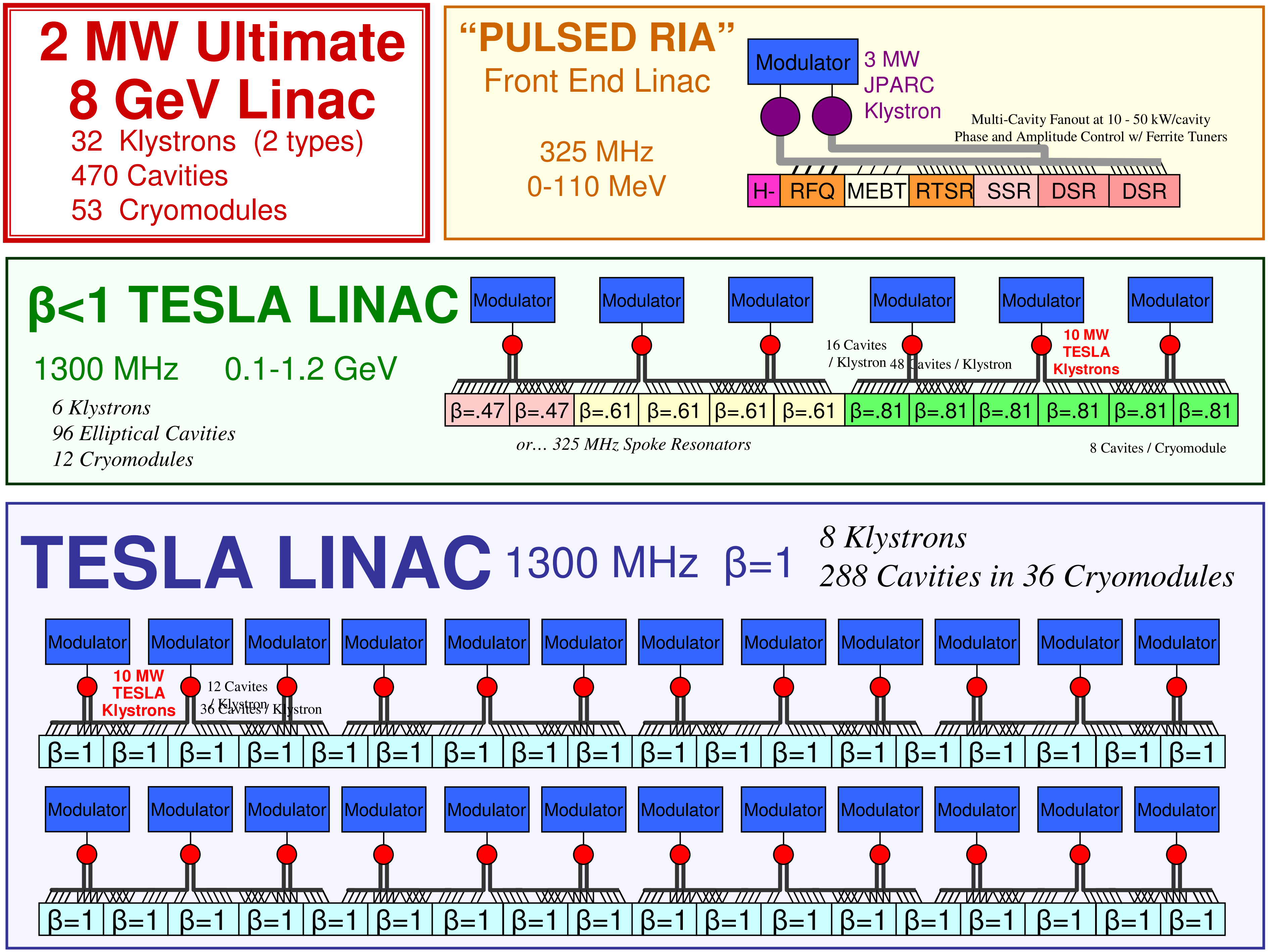
25 mA x 1 msec x 10 Hz x 8 GeV = 2.0 MW

33 Klystrons Required

Either Option Supports:

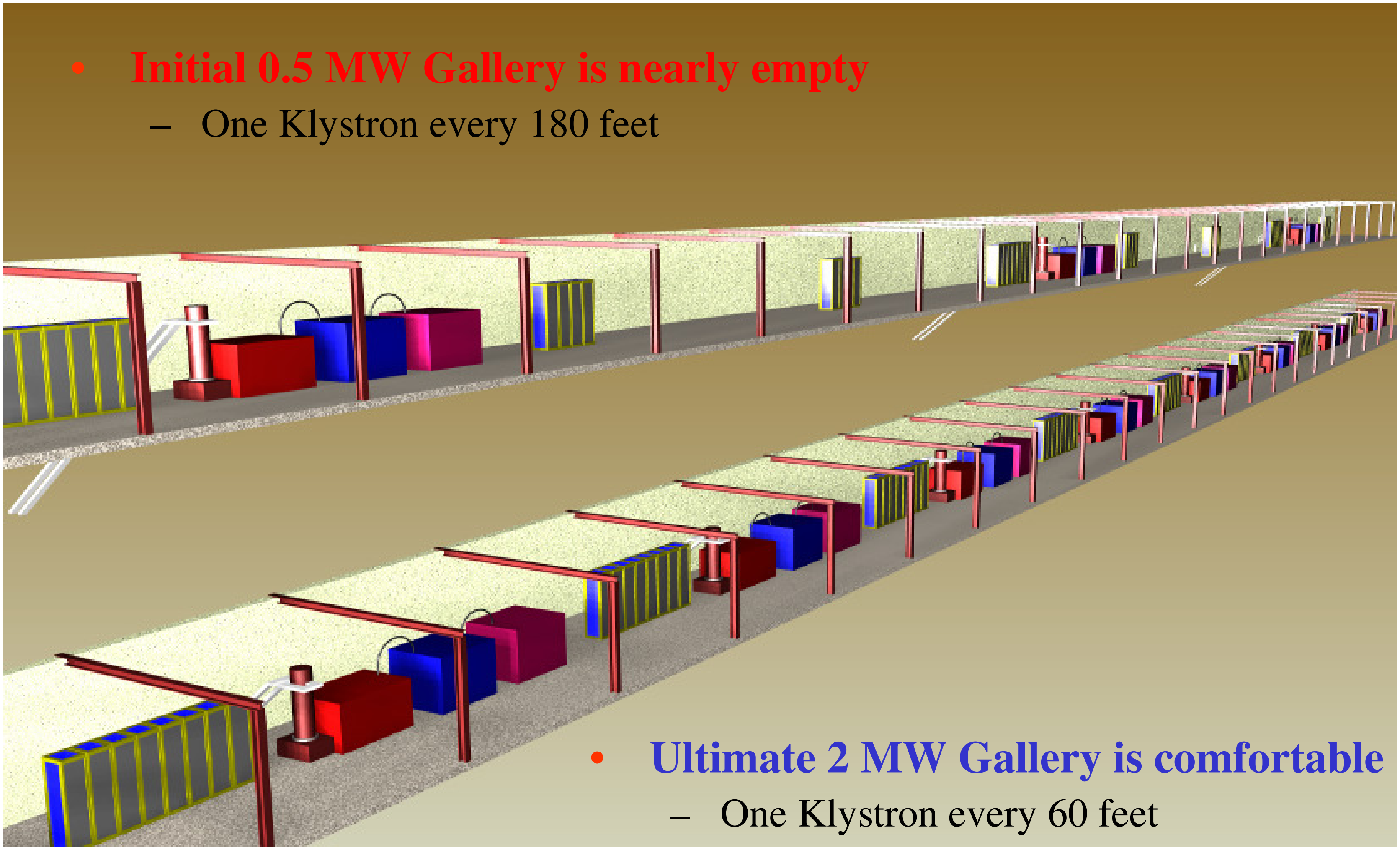
1.5E14 x 0.7 Hz x 120 GeV

= 2 MW Beam Power from Fermilab Main Injector



2 MW Ultimate
8 GeV Linac
32 Klystrons (2 types)
470 Cavities
53 Cryomodules
"PULSED RIA"
Front End Linac
325 MHz
0-110 MeV
Modulator
3 MW
JPARC
Klystron
Multi-Cavity Fanout at 10 - 50 kW/cavity
Phase and Amplitude Control w/ Ferrite Tuners
H-
RFQ
MEBT
RTSR
SSR
DSR
DSR
β<1 TESLA LINAC
1300 MHz
0.1-1.2 GeV
6 Klystrons
96 Elliptical Cavities
12 Cryomodules
Modulator
16 Cavites / Klystron
48 Cavites / Klystron
10 MW TESLA Klystrons
β=.47
β=.61
β=.81
or… 325 MHz Spoke Resonators
8 Cavites / Cryomodule
TESLA LINAC
1300 MHz
β=1
8 Klystrons
288 Cavities in 36 Cryomodules
Modulator
10 MW TESLA Klystrons
12 Cavites / Klystron
36 Cavites / Klystron
β=1

Initial → Ultimate Upgrade Equipment



ILC – Compatible Operating Frequencies

Following the selection of the Cold SCRF Option for the ILC,

We have chosen TESLA/XFEL Compatible Frequencies:

- **1300 MHz** Main Linac (= ILC / TESLA / XFEL)
- **325 MHz** (=1300MHz/4) Front-End Linac (= JPARC) ***(a gift !)***

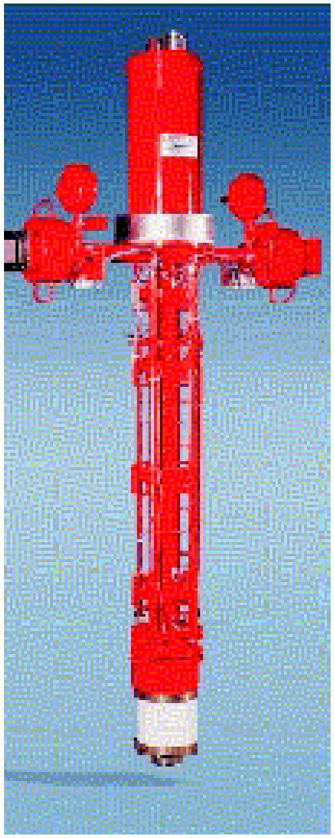
Valuable assets at these frequencies:

SRF Cavities, RF Couplers, Cryomodule Designs, Klystrons,

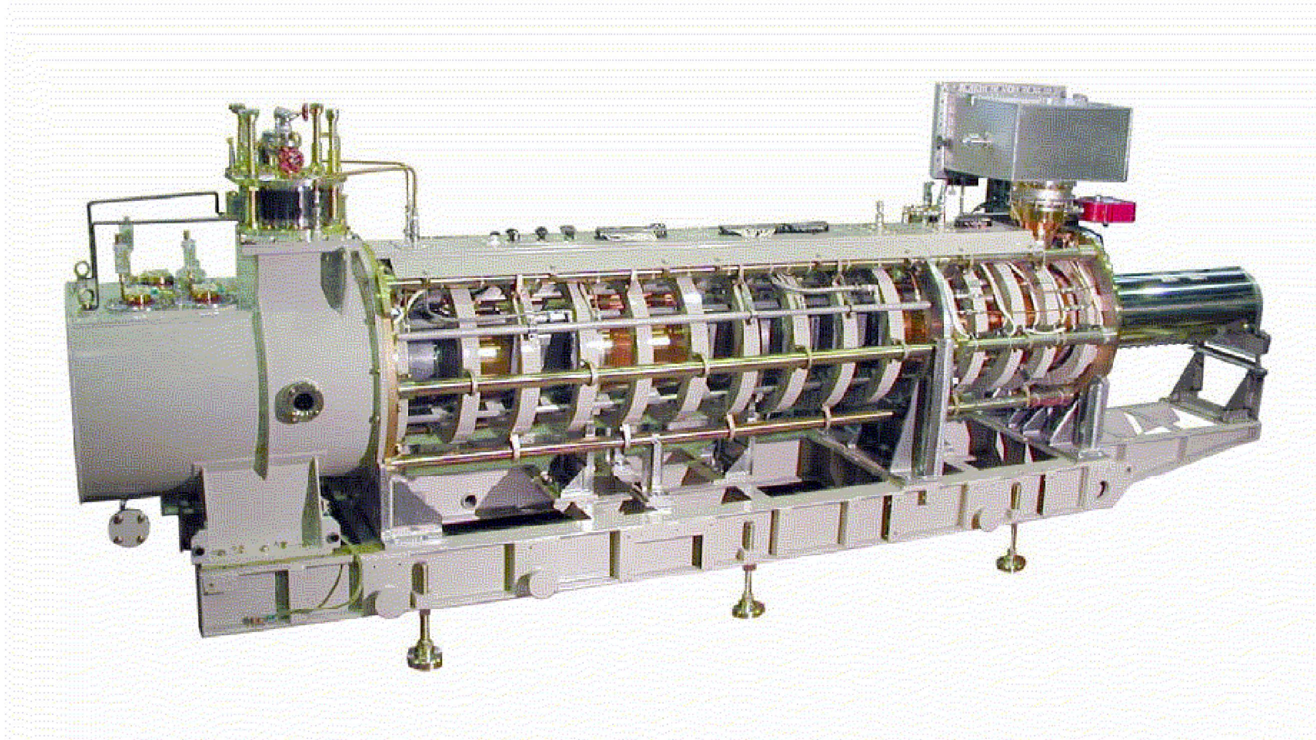
Front-End Linac Designs, Collaborators (e.g. ILC, Euro-XFEL, JPARC…)

In the final analysis, it is much easier these days to develop a new SRF cavity design than to develop a new Klystron.

8 GeV Linac Klystrons – 2 Types



Thales TH1801
1300 MHz
10 MW
Multiple Vendors



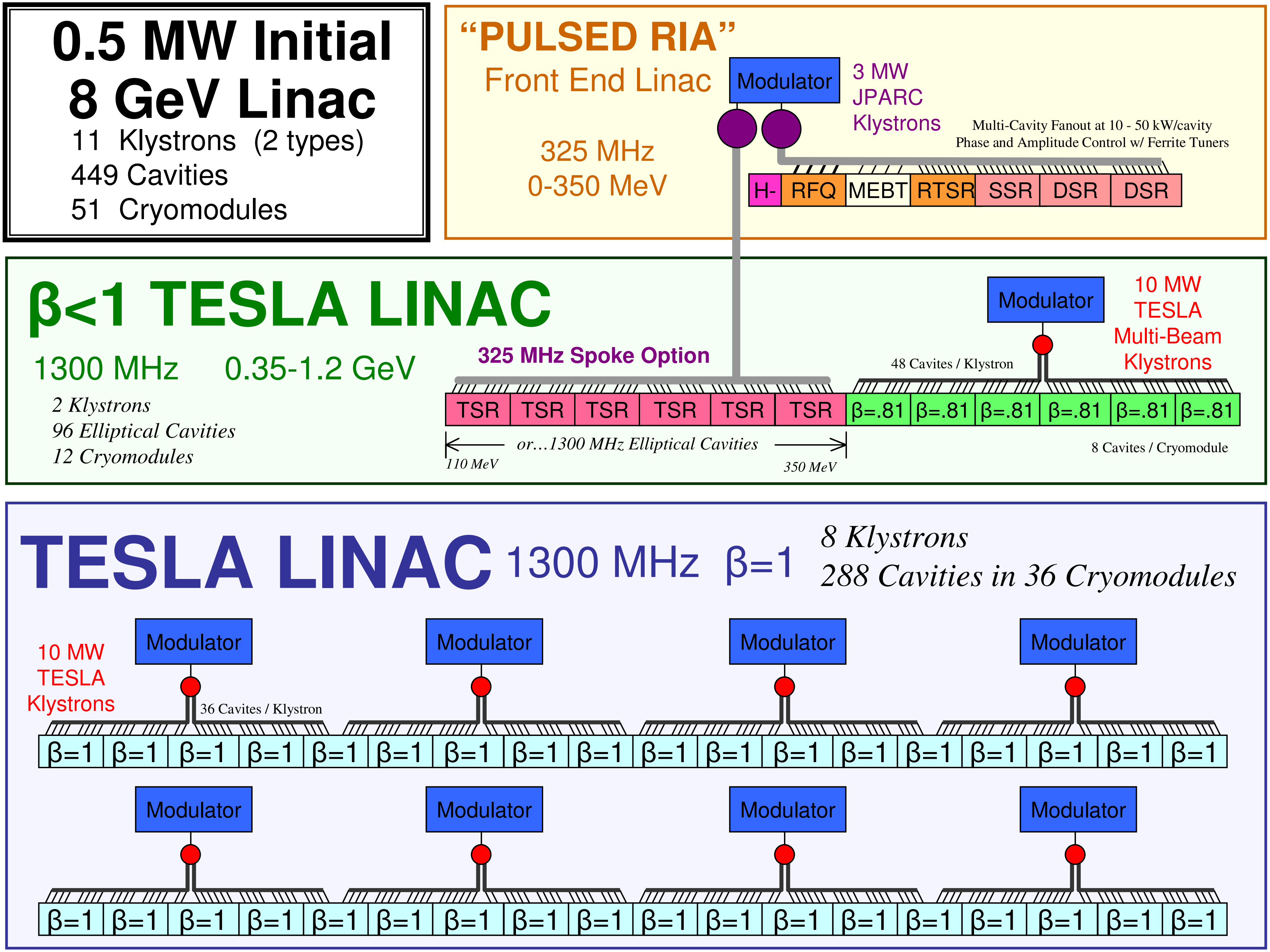
Toshiba E3740A
325 MHz   3 MW
(17 Delivered for JPARC)

Copper-to-SCRF Transition

- **We have chosen 15 MeV (RFQ + warm TSRs.)**
  - Much lower than SNS (~ 186 MeV)
  - Allows Single Klystron to drive linac up to 110 MeV
  - Leverages uses of Fast Phase Shifters to produce many channels of RF from a single Klystron
- **Previous Design Study assumed 85 MeV DTL**
  - Conventional Solution, still valid
  - Modified Commercial Product at 325 MHz
  - Required 7 Klystrons, $30M + contingency etc.

Spokes-to-Elliptical Transition

1. **Preserving two technical options (110-400 MeV):**
    1. 325 MHz triple-spoke Resonators **(BASELINE)**
    2. 1300 MHz Elliptical Cavities
2. **The tradeoffs have been extensively discussed for the Rare Isotope Accelerator (RIA).**
3. **Our Decision Will be based on:**
    1. Accelerator Physics
    2. Cost
    3. Collaboration



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11 Klystrons (2 types)
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Front End Linac
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0-350 MeV
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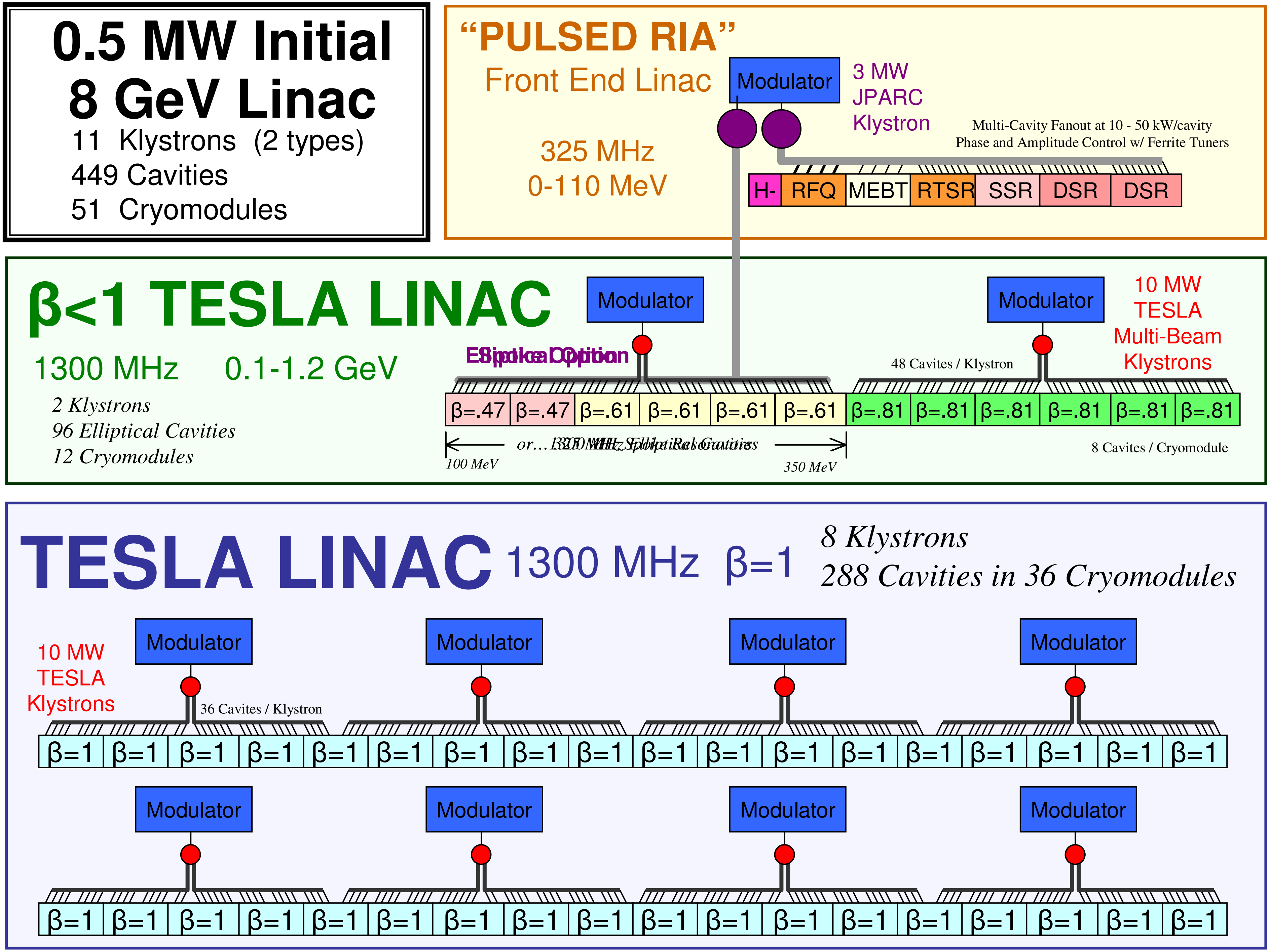
Multi-Cavity Fanout at 10 - 50 kW/cavity
Phase and Amplitude Control w/ Ferrite Tuners
H-
RFQ
MEBT
RTSR
SSR
DSR
DSR
β<1 TESLA LINAC
1300 MHz
0.35-1.2 GeV
2 Klystrons
96 Elliptical Cavities
12 Cryomodules
325 MHz Spoke Option
TSR
or...1300 MHz Elliptical Cavities
110 MeV
350 MeV
Modulator
10 MW
TESLA
Multi-Beam
Klystrons
48 Cavites / Klystron
β=.81
8 Cavites / Cryomodule
TESLA LINAC
1300 MHz
β=1
8 Klystrons
288 Cavities in 36 Cryomodules
10 MW
TESLA
Klystrons
Modulator
36 Cavites / Klystron
β=1



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β=.47
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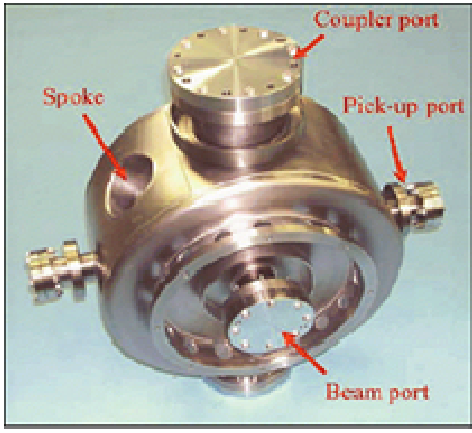
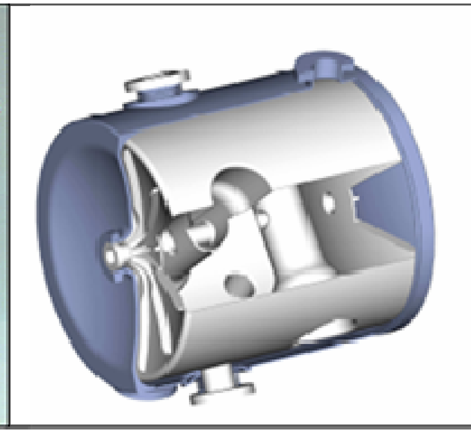
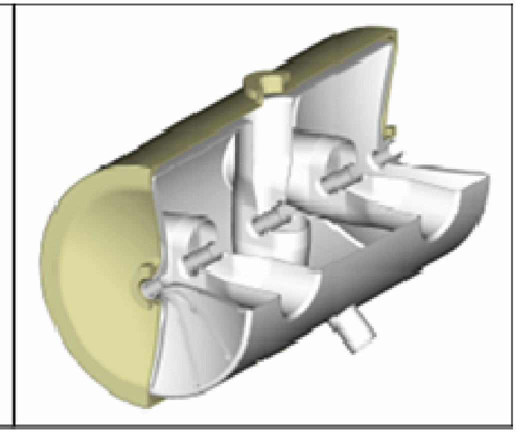
β=.61
β=.61
β=.61
β=.61
β=.81
β=.81
β=.81
β=.81
β=.81
β=.81
100 MeV
350 MeV
8 Cavites / Cryomodule
TESLA LINAC
1300 MHz
β=1
8 Klystrons
288 Cavities in 36 Cryomodules
10 MW
TESLA
Klystrons
Modulator
36 Cavites / Klystron
β=1

325 MHz Spoke Resonators

Ken Shepard's Talk

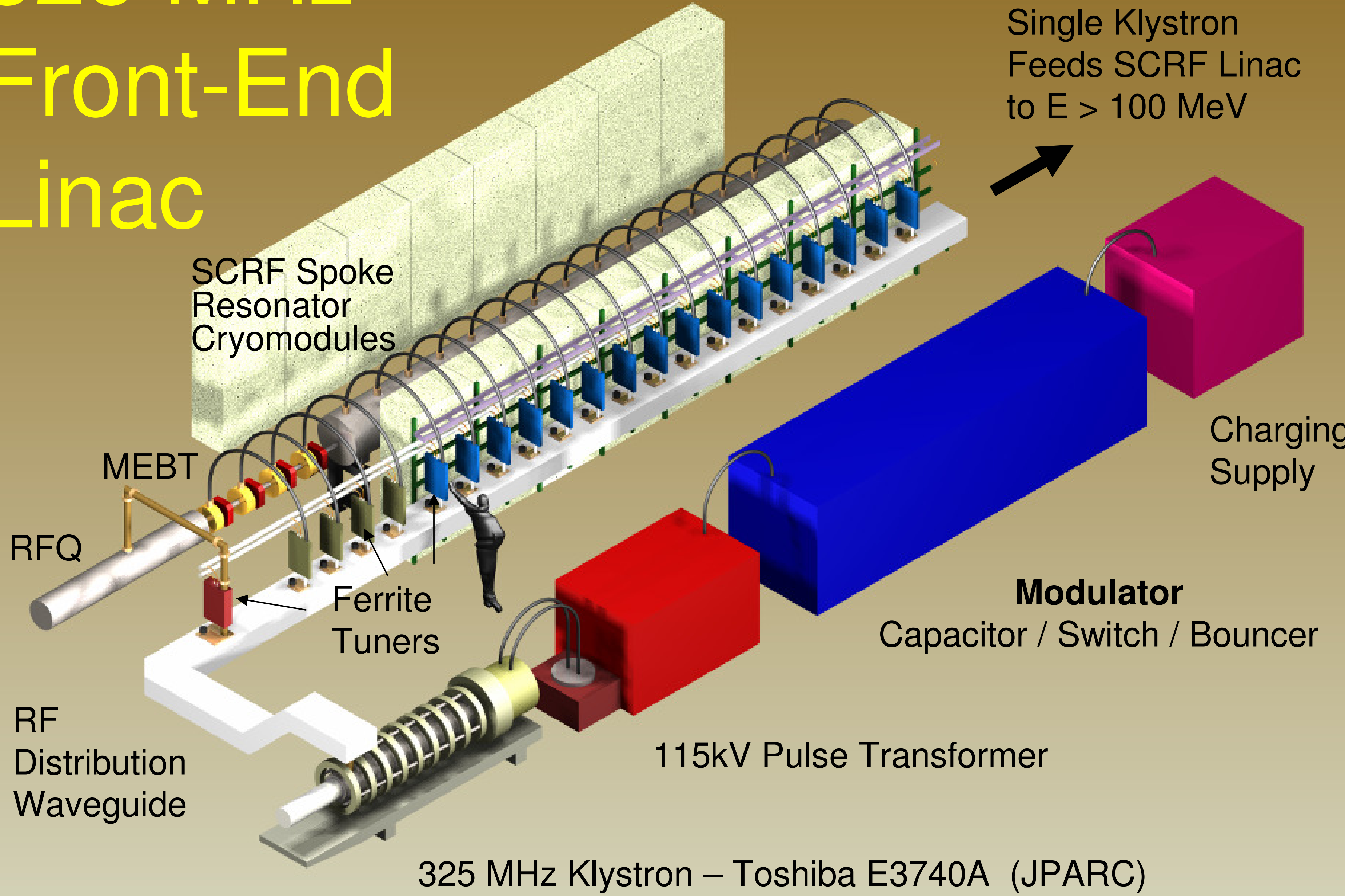




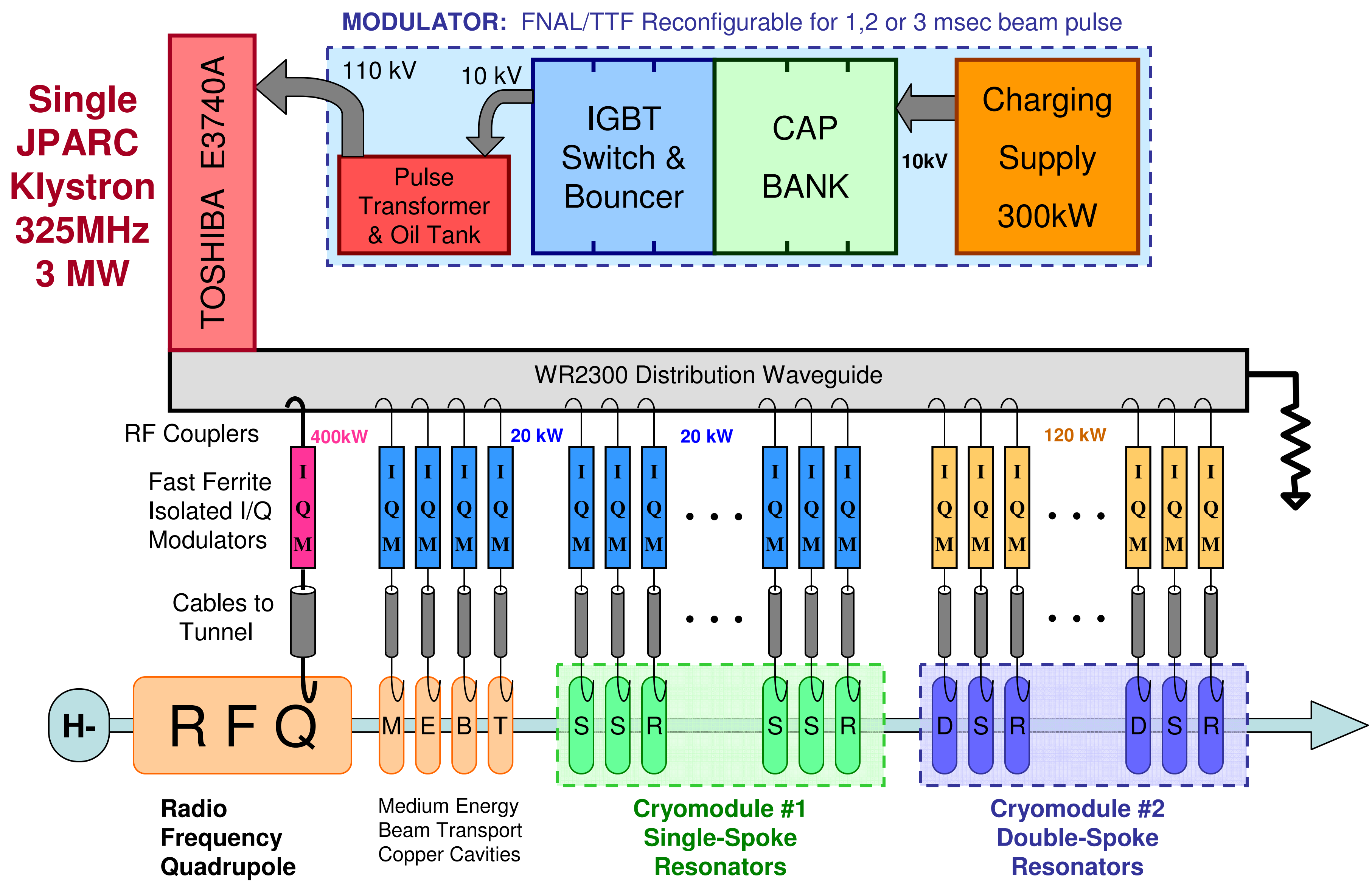


- Well Developed Technology for RIA, APT,...
- Simulations indicate excellent beam dynamics
- Runs Pool-Boiling at 4.5K – Simple Cryosystem
- R&D Demonstration (SMTF):
  → beam properties with pulsed operation.

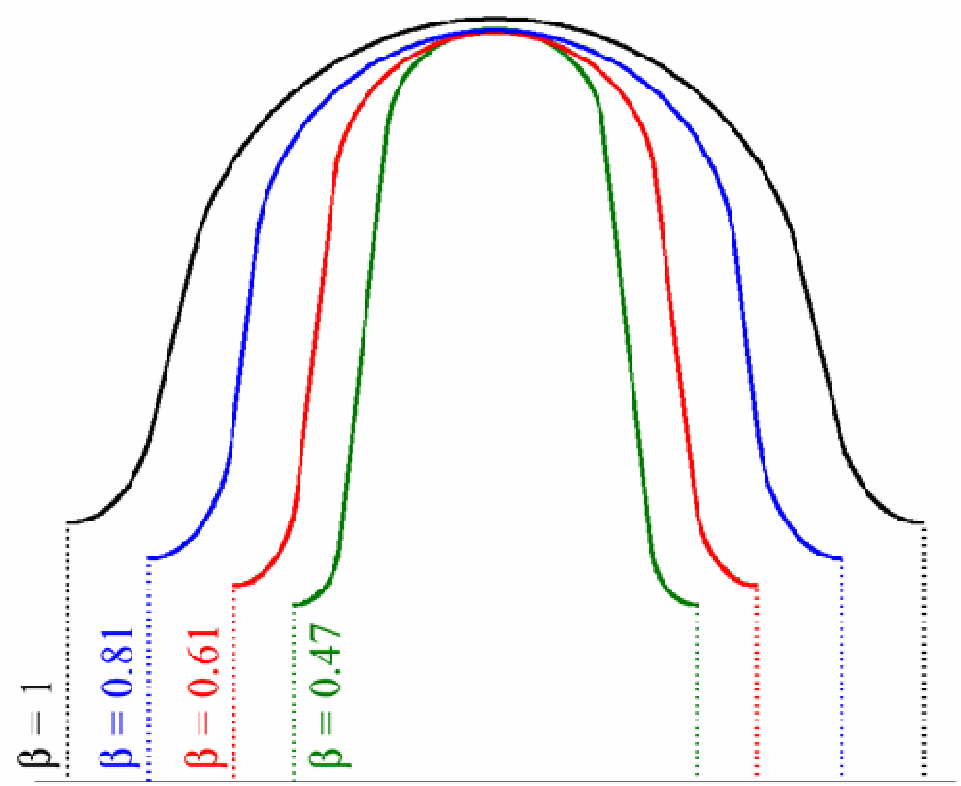
325 MHz Front-End Linac



325 MHz RF System



1300 MHz Elliptical Cavites

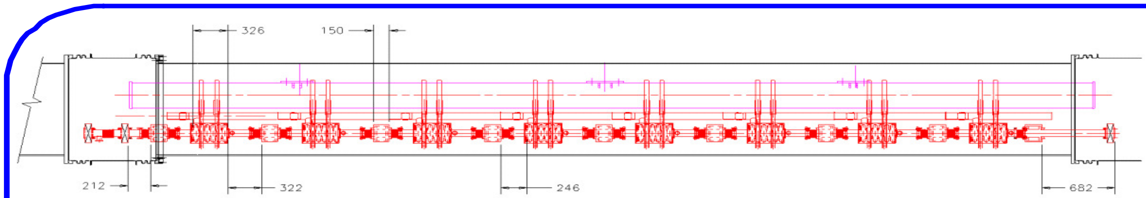


- **Beta<1 cavities are frequency scaled from 805 MHz designs for SNS/JLAB and RIA/MSU/JLAB**
- **FNAL/MSU Design collaboration investigating "low-loss" geometries for 1300 MHz Beta=0.81**

1300 MHz Cryomodules

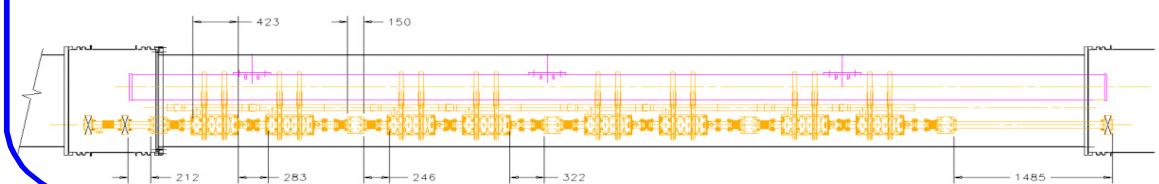
Giorgio Apolinari's Talk

1300 MHz ELLIPTICAL CAVITY CRYOMODULES: 2-4 TYPES

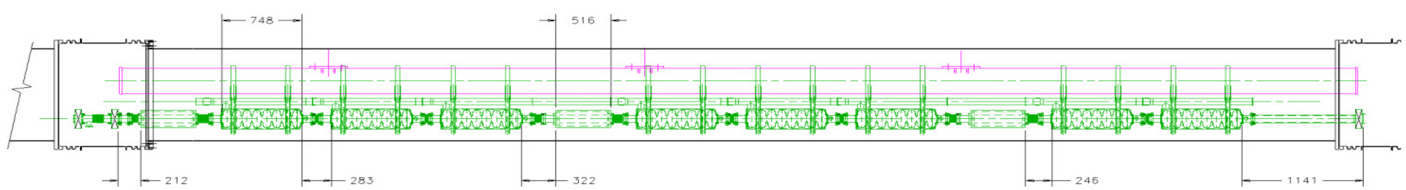


Beta = 0.47
2 Cryomodules
16 Cavities

OPTION OF ELLIPTICAL MEDIUM-BETA CAVITES 110 - 400 MeV

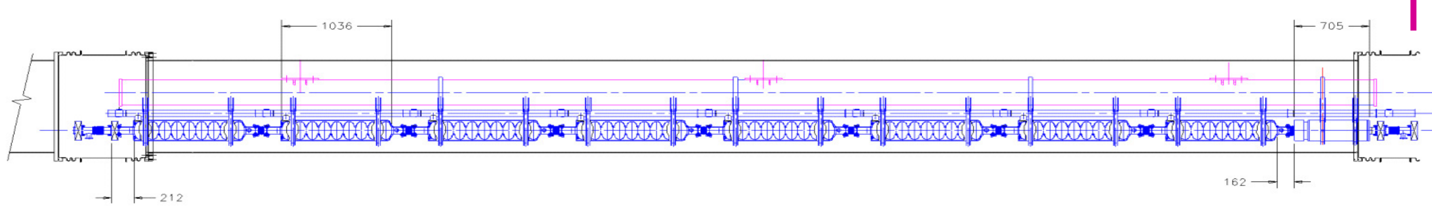


Beta = 0.61
4 Cryomodules
32 Cavities



Beta = 0.81
6 Cryomodules
48 Cavities

TESLA (TTF3)



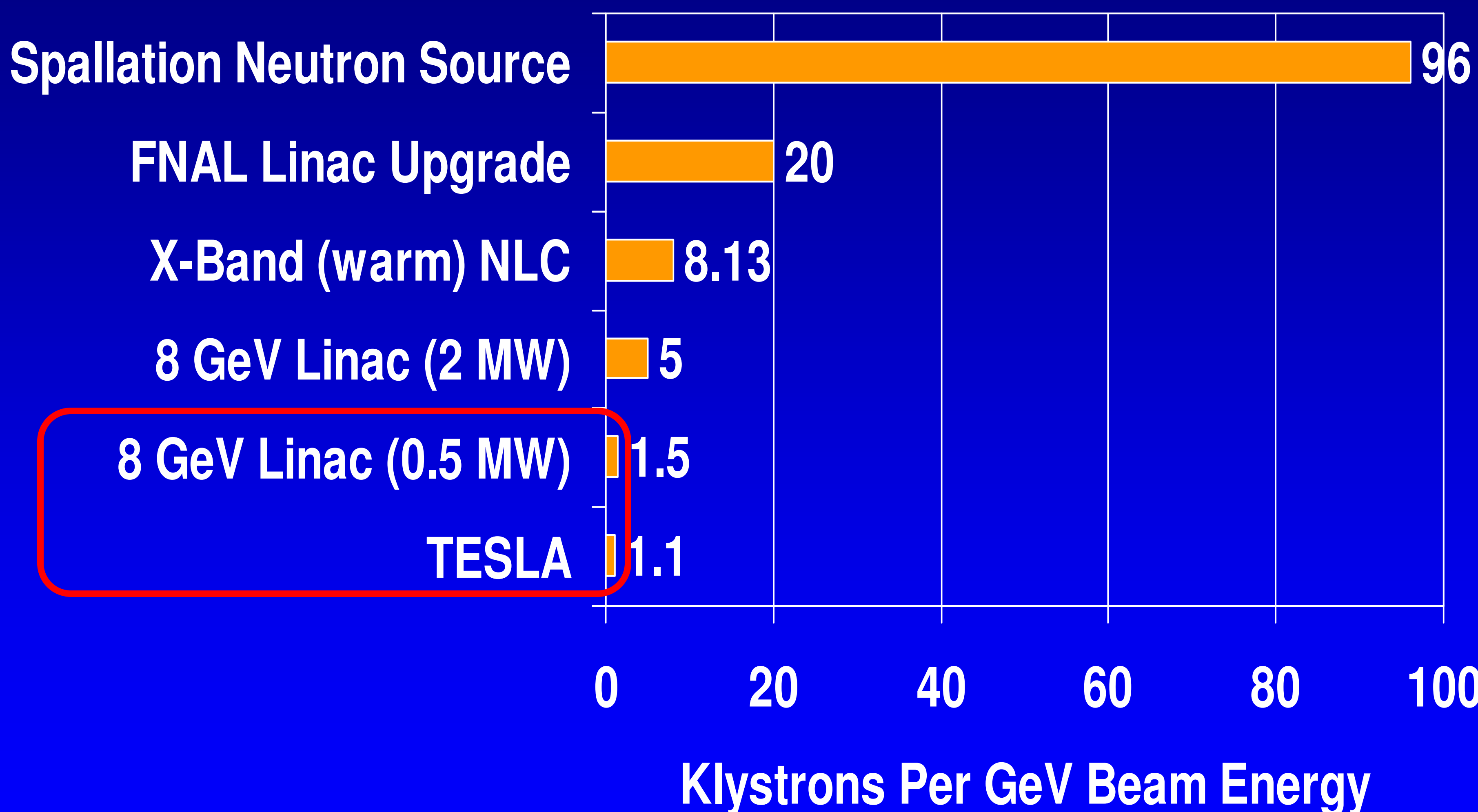
Beta = 1.00
36 Cryomods
288 Cavities

Ferrite Vector Modulator R&D

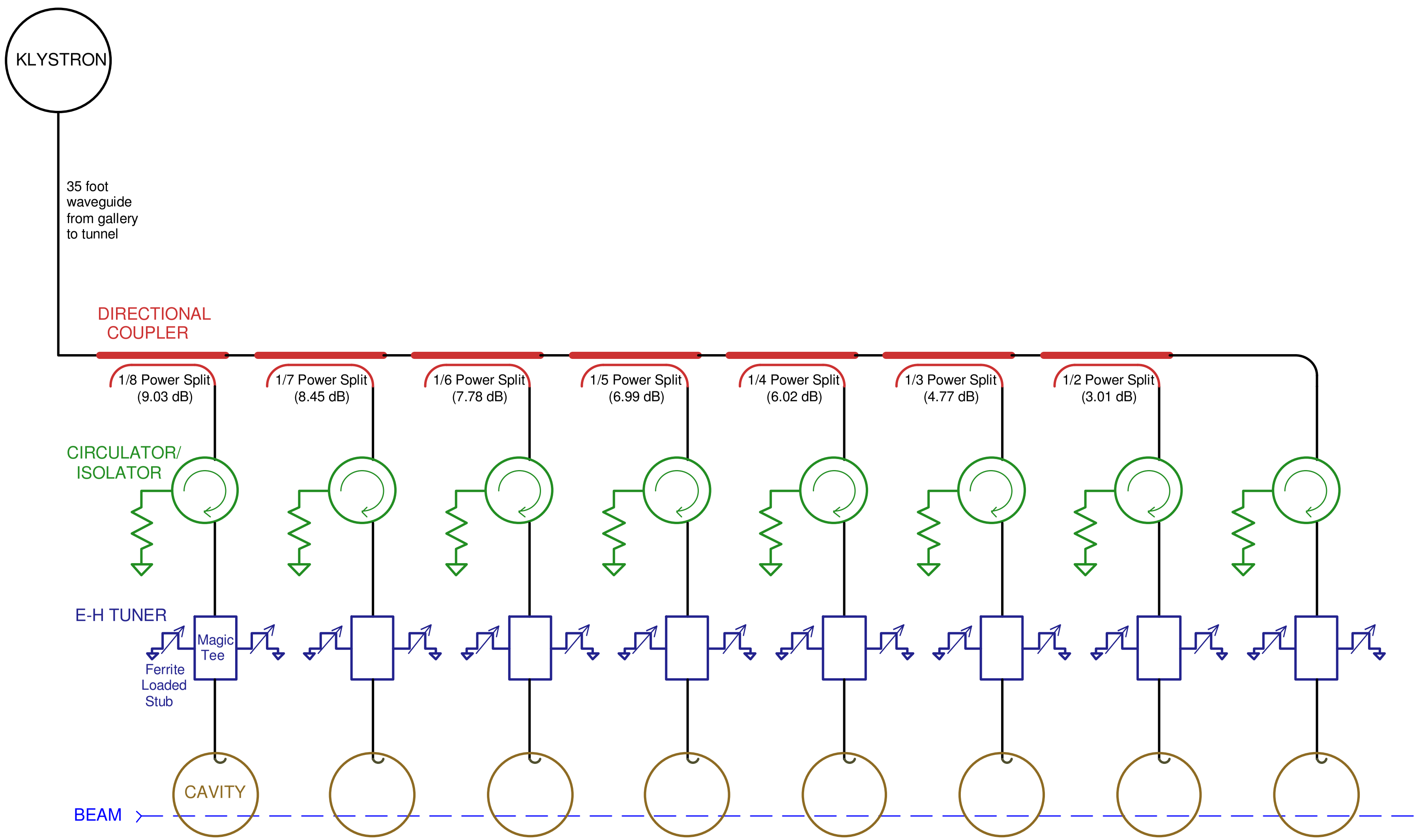
- Provides fast, flexible drive to individual cavites of a proton linac, when one is using a TESLA-style RF fanout. *(1 klystron feeds 36 cavities)*
- Also needed if Linac alternates between e- and P.
- This R&D was started by SNS but dropped due to lack of time. SNS went to one-klystron-per-cavity which cost them a lot of money ($20M - $60M).

Making this technology work is important to the financial feasibility of the 8 GeV Linac.

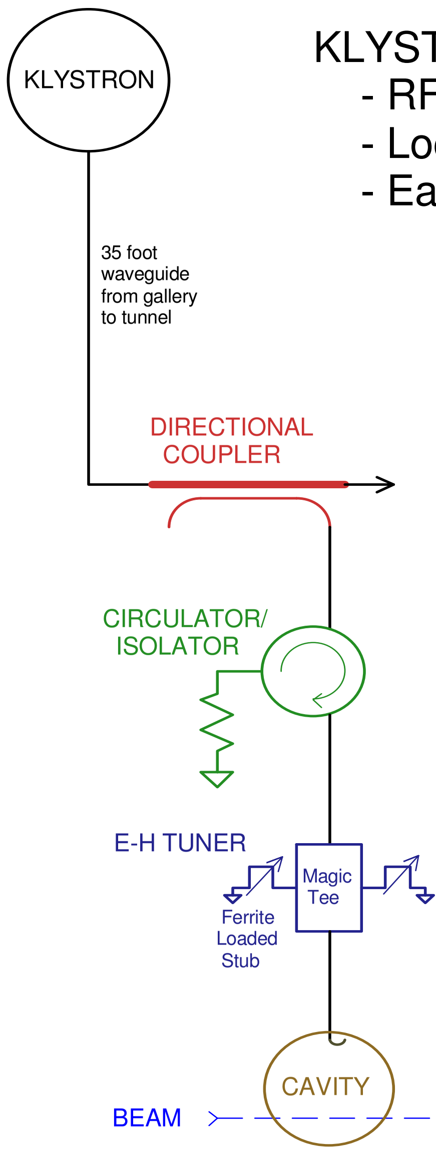
Cost Driver: Klystrons per GeV



RF Fan-out for 8 GeV Linac



RF Fanout at Each Cavity



KLYSTRON
- RF Power Source
- Located in Gallery above tunnel
- Each Klystron Feeds 8-16 Cavities

DIRECTIONAL COUPLER
- Picks of a fixed amount of RF power at each station
- Passes remaining power downstream to other cavities

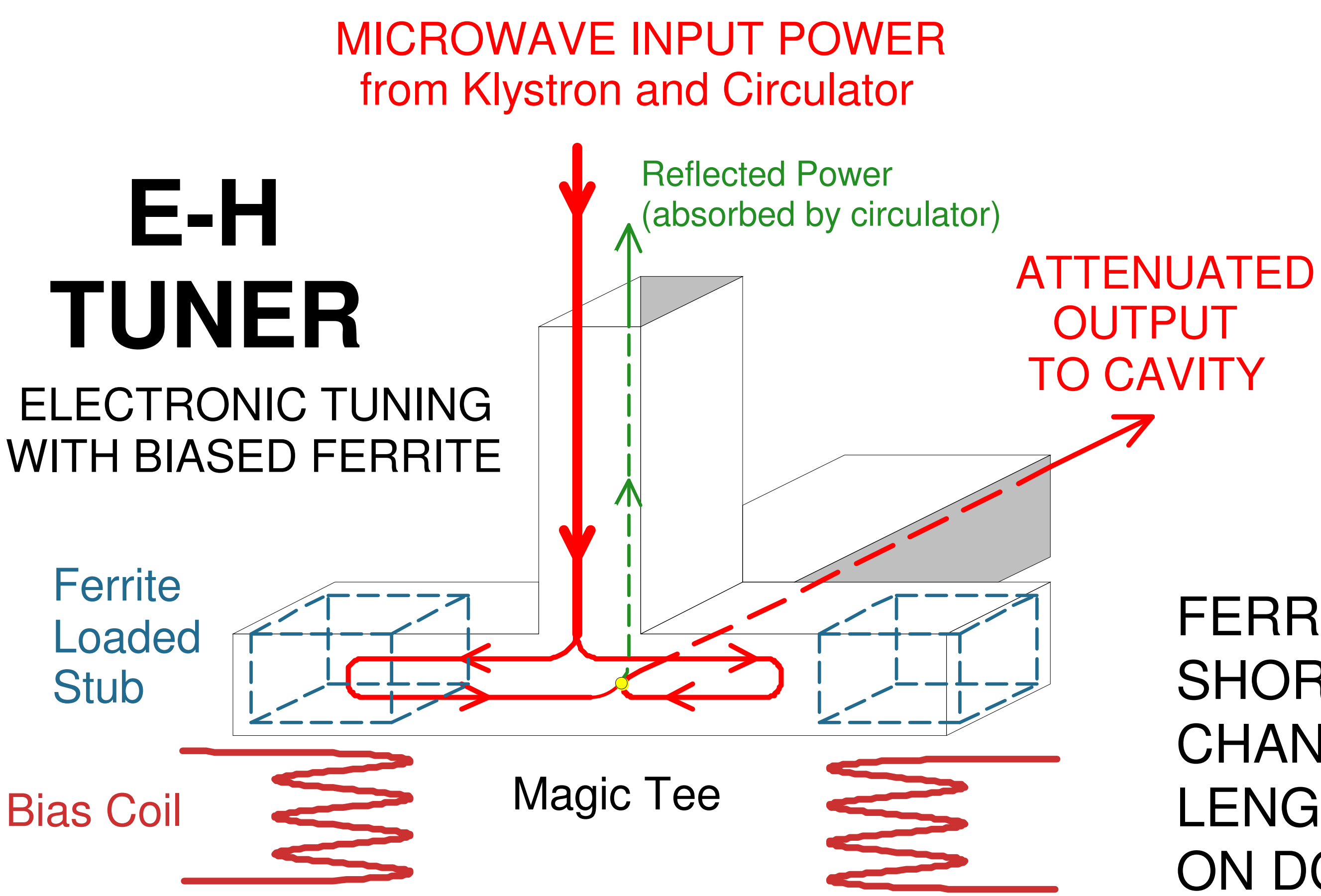
CIRCULATOR / ISOLATOR
- Passes RF power forward towards cavity
- Diverts reflected power to water cooled load

E-H TUNER
- Provides Phase and Amplitude Control for Cavities
- Biased Ferrite Provides Electronic Control

SUPERCONDUCTING RF CAVITY
- Couples RF Power to Beam

FERRITE VECTOR MODULATOR

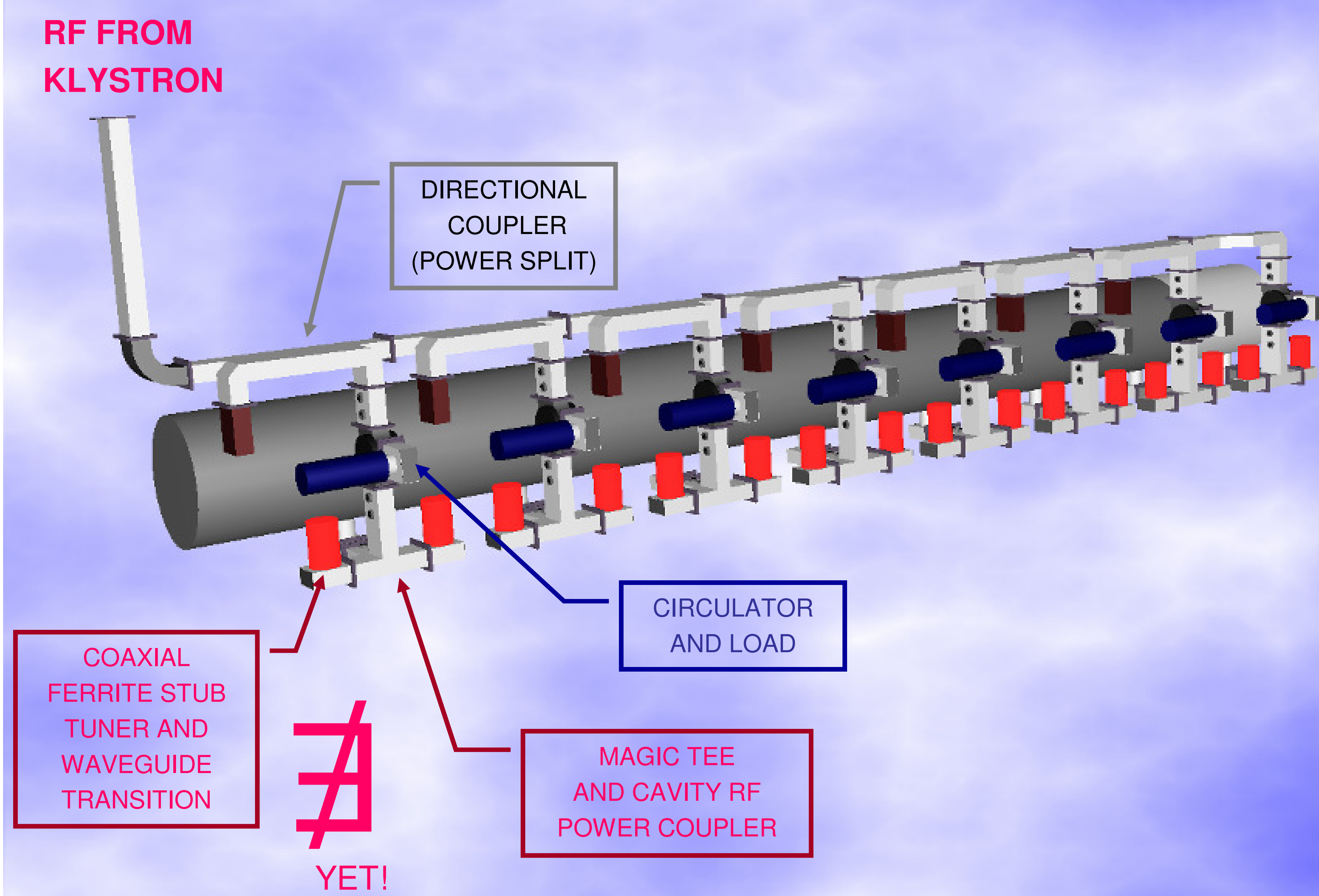
(1300 MHz Waveguide Version)



FERRITE LOADED SHORTED STUBS CHANGE ELECTRICAL LENGTH DEPENDING ON DC MAGNETIC BIAS.

TWO COILS PROVIDE INDEPENDENT ***PHASE AND AMPLITUDE*** CONTROL OF CAVITIES

Advanced RF Distribution



3 Types of Fast-Ferrite Tuners

Iouri Terechkine's Talk

1. **Waveguide Style (prototyped in house)**
2. **Coaxial Style (prototyped in-house)**
3. **Strip Line Style (commercial procurement via AFT)**

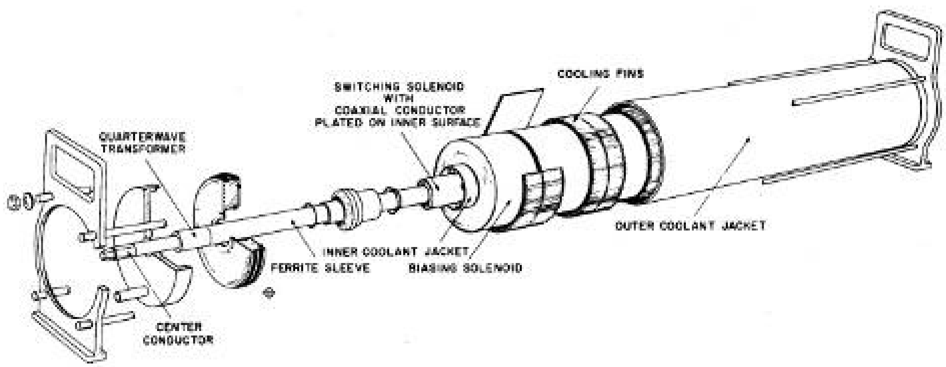
- **Because of this device's importance to the PD, all three are being pursued in parallel.**
- **At present, it appears that all 3 approaches will lead to workable full-spec devices.**

Key Specification of Ferrite Tuners

- **Power Handling 0.6 MW…50kW**
  - x4 for full reflected standing wave
  - exceeded by prototypes (after some work!)
- **Range of adjustment: +/- 45 degrees**
  - Larger is possible
- **Speed of Response: 1 degree per microsecond**
  - Simulations indicate 3-5x slower might be OK
- **Insertion Loss: 0.1-0.2 dB**
  - Cooling easy at 600kW peak, 1.5% duty factor
  - Not dominant contributor to RF Distribution Losses

Examples of Phase Shifters

Coaxial Device, Bell Labs 1968



L band (1.2 – 1.4 GHz)

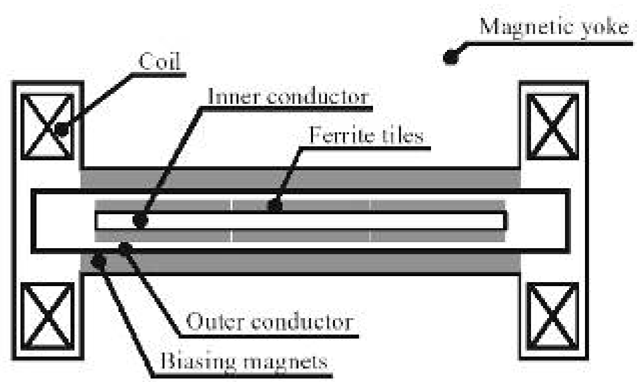
350 kW peak power

Field Range 800 – 1500 Oe

Phase shift - 600°

Insertion loss - 0.2 dB

Strip-line-based design, by AFT for ANL and CERN, 1998 ~ 2004



352 MHz

250 kW peak power

25% duty cycle

130° phase shift

SNS Waveguide Phase Shifter R&D

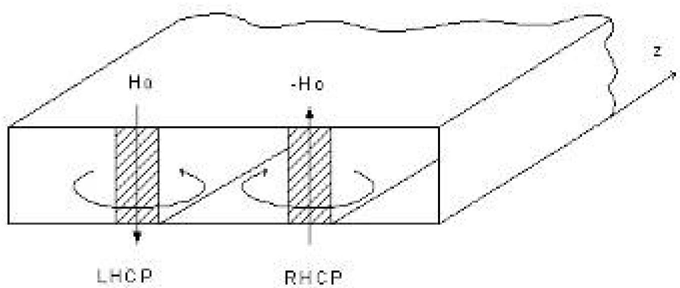
Waveguide-based device,
Yoon Kang (ANL) for SNS ~ 2000

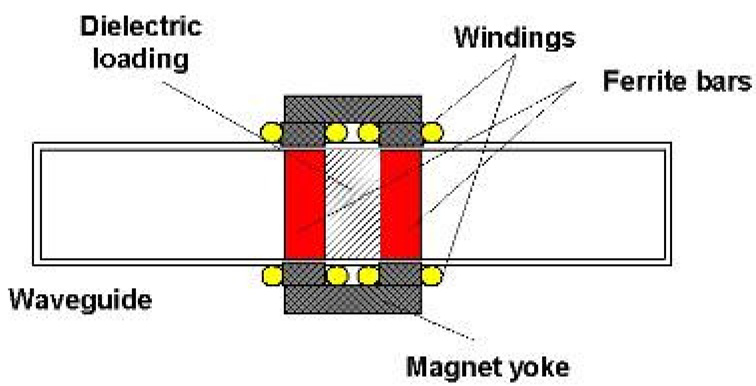
805 MHz

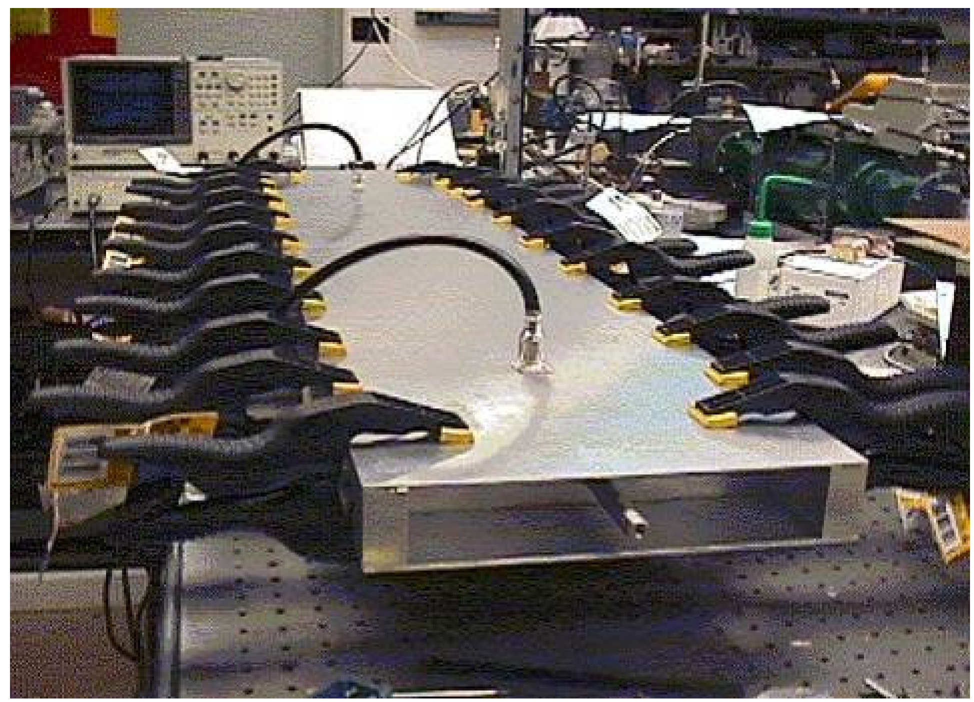
500 kW peak power

8% duty cycle

0.15 dB insertion loss







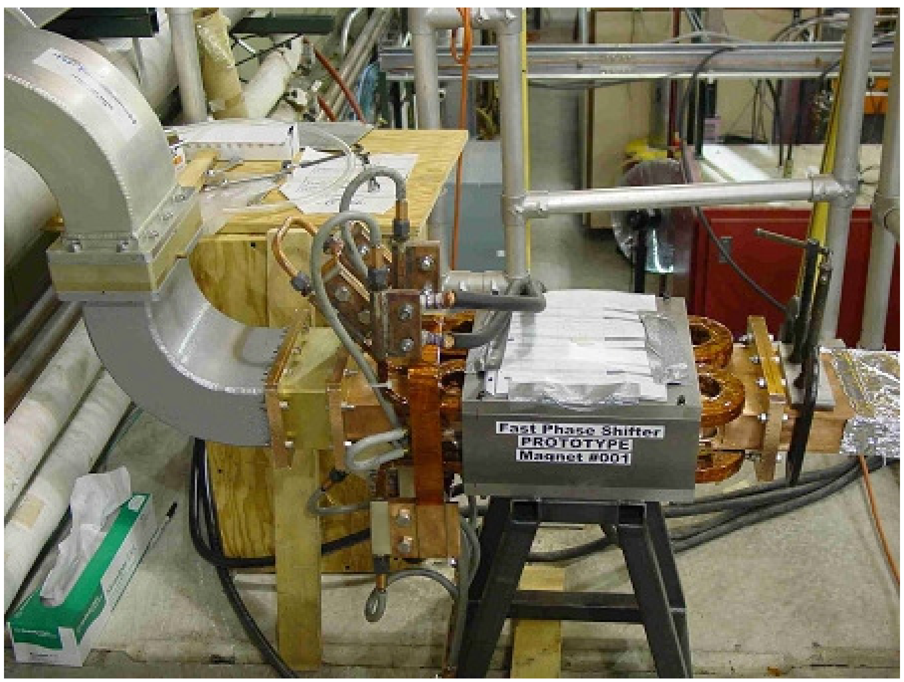
Fermilab

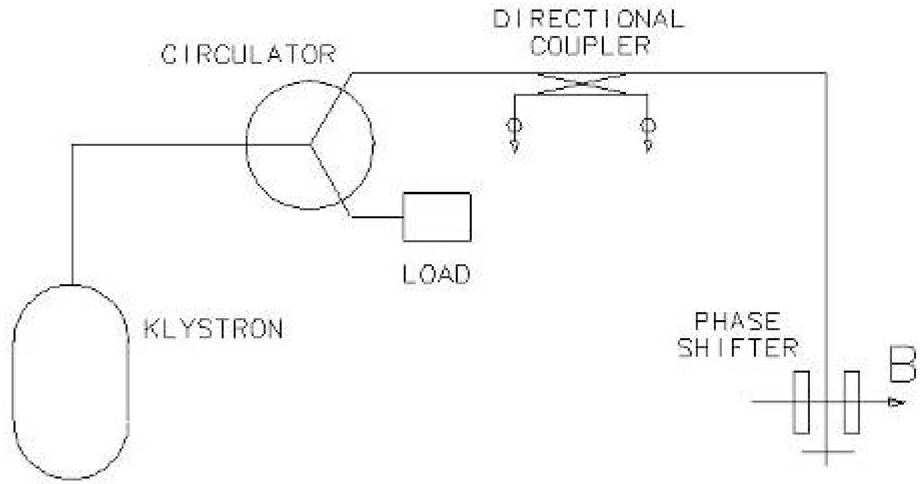
High Power 1300 MHz FVM Test

A0 1300 MHz Klystron

T = 250 μsec

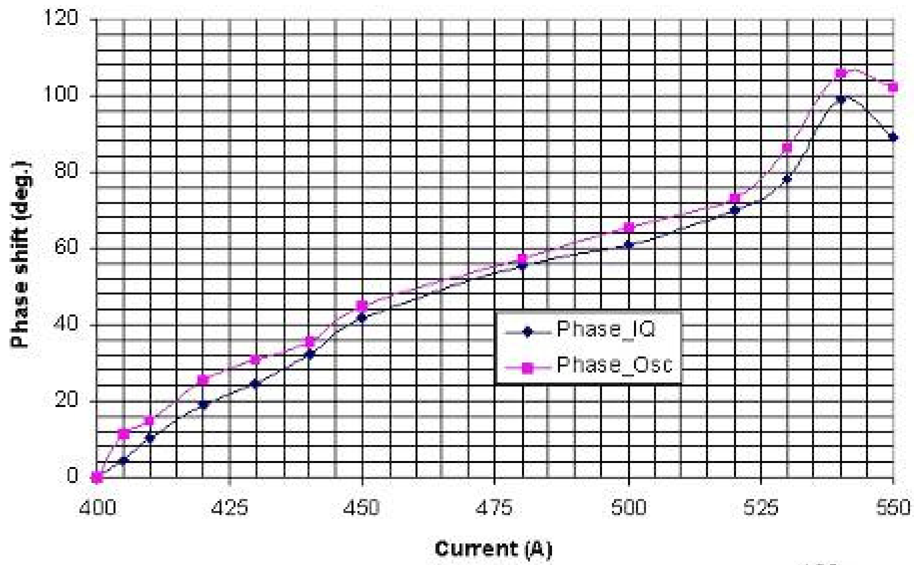
F = 5 Hz





We snuck onto Helen's Klystron when she was out of town….

High Power Ferrite Tuner Test

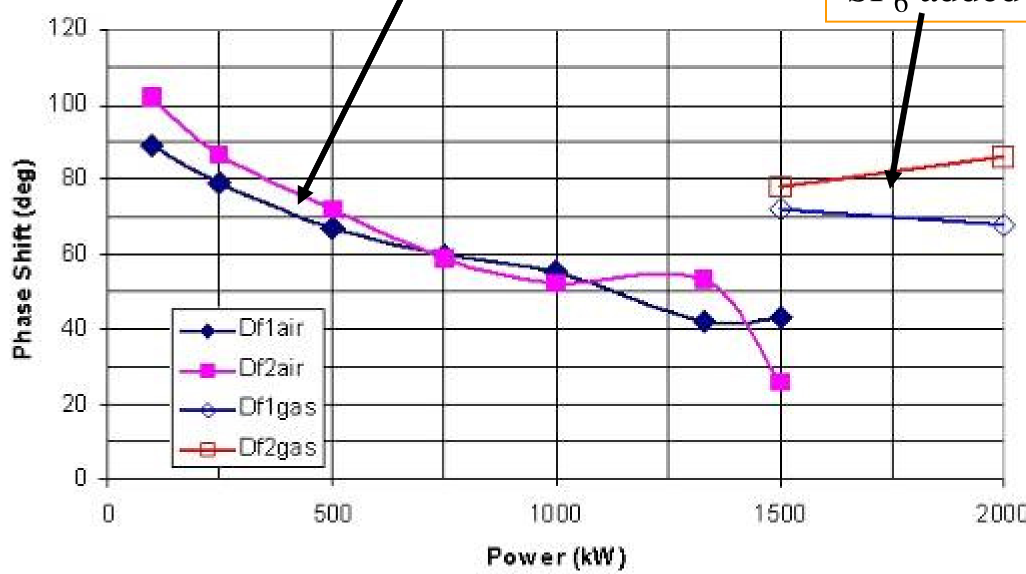


Two methods of phase measurements:

1. Oscilloscope measurements
2. Using available IQ modulator

Available phase range was limited by sparking that develops near the HOM resonance frequencies

SF_6 added



Max Power - 2000 kW
(requirement: 600 kW)

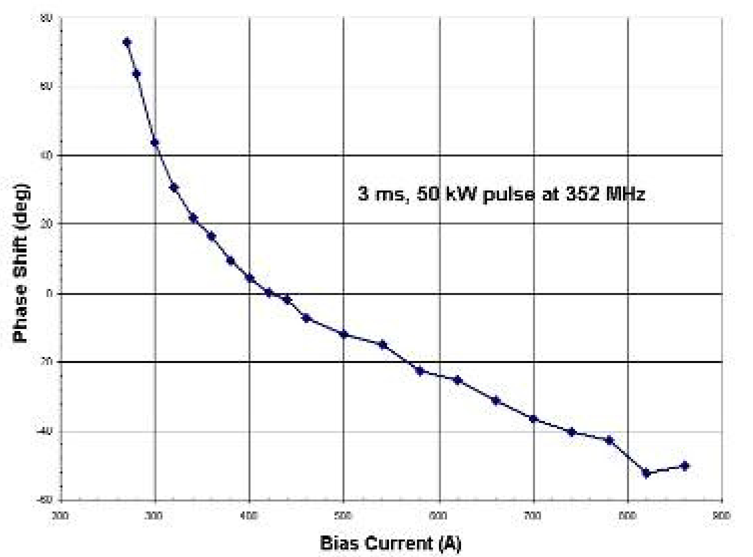
Useable Phase shift ~ 80°
(requirement: ~90 degrees)

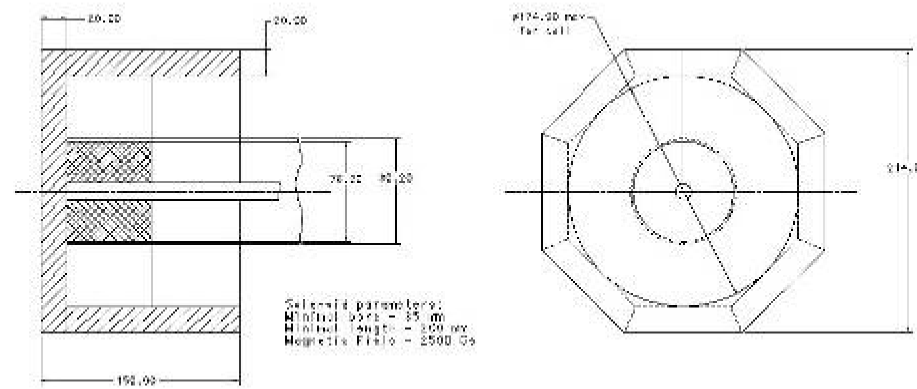
Elimination of HOM resonances has increased usable range to ~360 degrees at low power levels.

Fermilab

Coaxial Phase Shifter

- Coax design is preferred at 325MHz
- In-house design tested to 660kW at 1300 MHz
- Tested at 300 kW at ANL with APS 352MHz Klystron
- Fast coil and flux return should respond in ~50us





Ran for 1 Hour at 300kW x 3 msec x 2 Hz with 4°C Temp Rise → very low losses

MORE INFORMATION

- **Project site:**
  http://protondriver.fnal.gov
- **Physics and Machine "CD-0" Documents**
- **Recent Director's Review:**
  http://protondriver.fnal.gov/PDrev15Mar05.htm
- **Recent ICFA Workshop:**
  http://www.niu.edu/clasep/HPSLconf/