The SCRF Proton Driver

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

Bill Foster

~~**SLAC Accelerator Seminar**~~

~~**LBL Research Progress Seminar**~~

FNAL URA Visiting Committee

April 22, 2005

Outline

- **The Concept**
- **8 GeV SCRF Linac Design**
- **Recent Director's Review**
- **Hardware in Progress (SMTF)**
- **Reactions to the FY06 Tsunami**

TECHNICAL DETAILS

- **Project site:**

  http://protondriver.fnal.gov

- **Detailed (35 page) Parameter List**

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

- **Soon: Physics and Machine "CD-0" Documents**

- **Recent Director's Review:**

  http://protondriver.fnal.gov/PDrev15Mar05.htm

- **Upcoming Workshop:**

  http://www.niu.edu/clasep/HPSLconf/

8 GeV Superconducting Linac

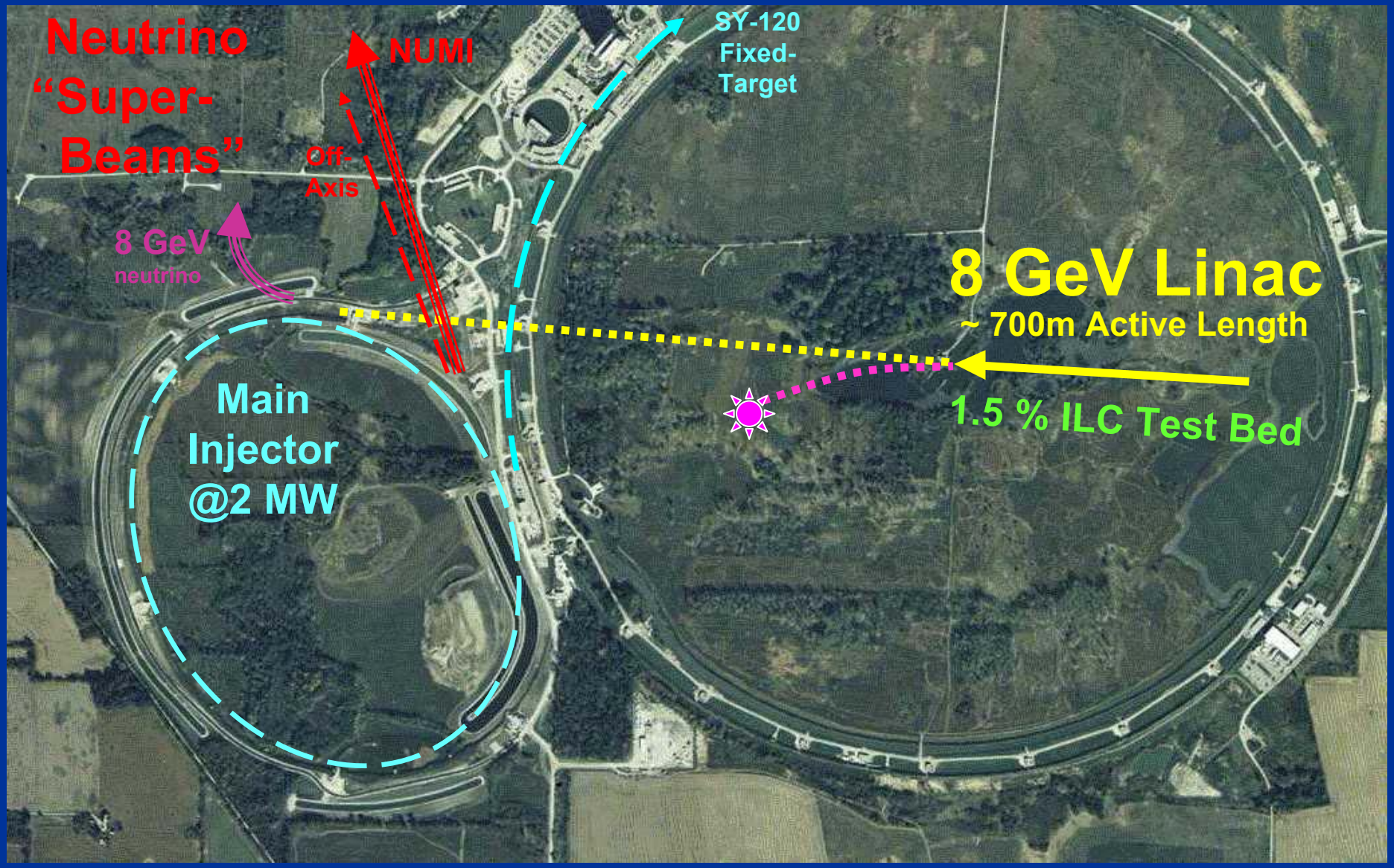
- New* idea incorporating concepts from the ILC, the Spallation Neutron Source, RIA and APT.
  - Copy SNS, RIA, and JPARC Linac designs up to 1.3 GeV
  - Use "TESLA" Cryomodules from 1.3 - 8 GeV
  - H^- Injection at 8 GeV in Main Injector

➔"Super-Beams" in Fermilab Main Injector

- 2+ MW Beam power at BOTH 8 GeV and 120 GeV
- Small emittances ➔ Small losses in Main Injector
- Minimum (1.5 sec) cycle time (or less)
- MI Beam Power Independent of Beam Energy

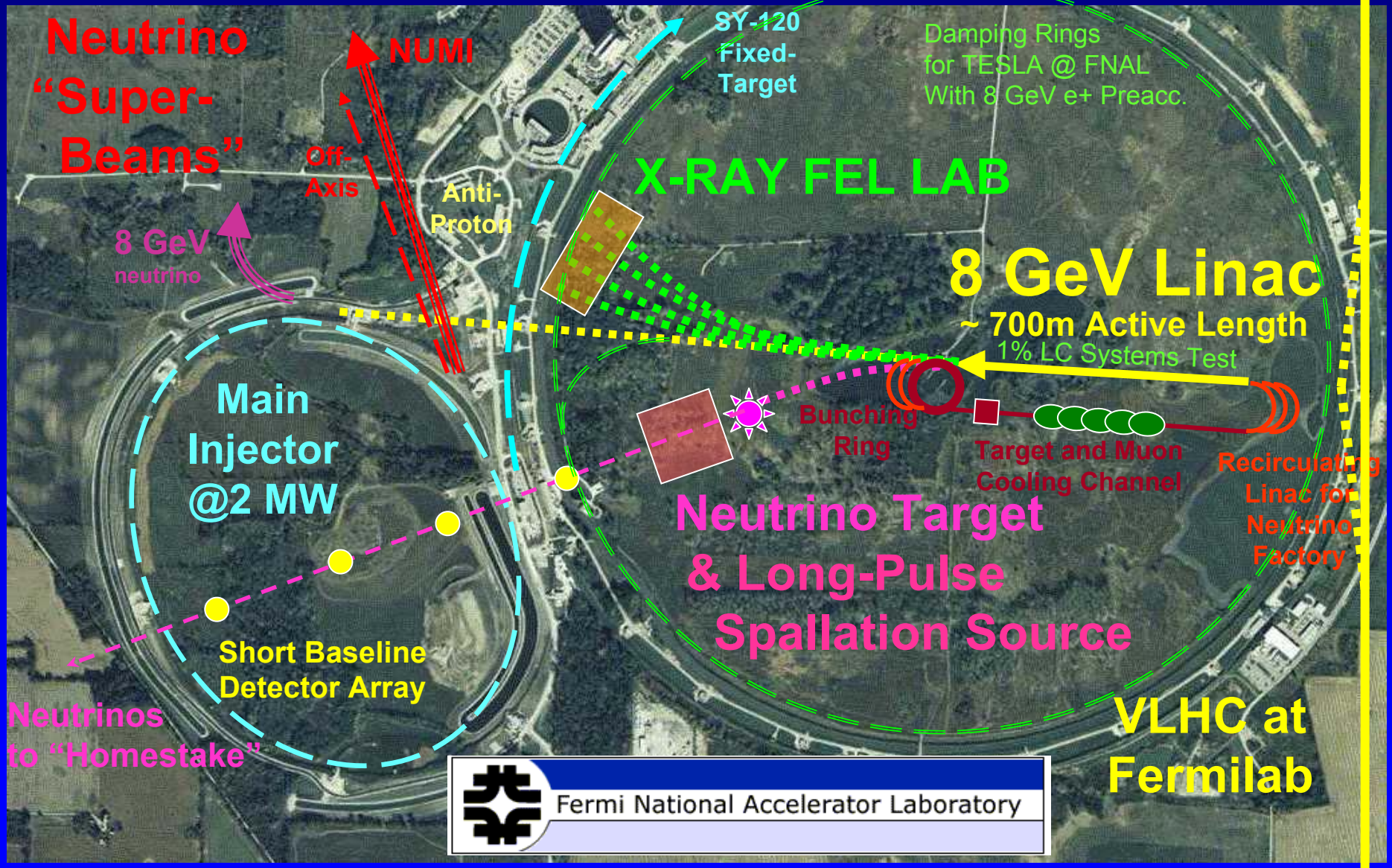
→ *(flexible neutrino program)*

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



8 GeV Superconducting Linac

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



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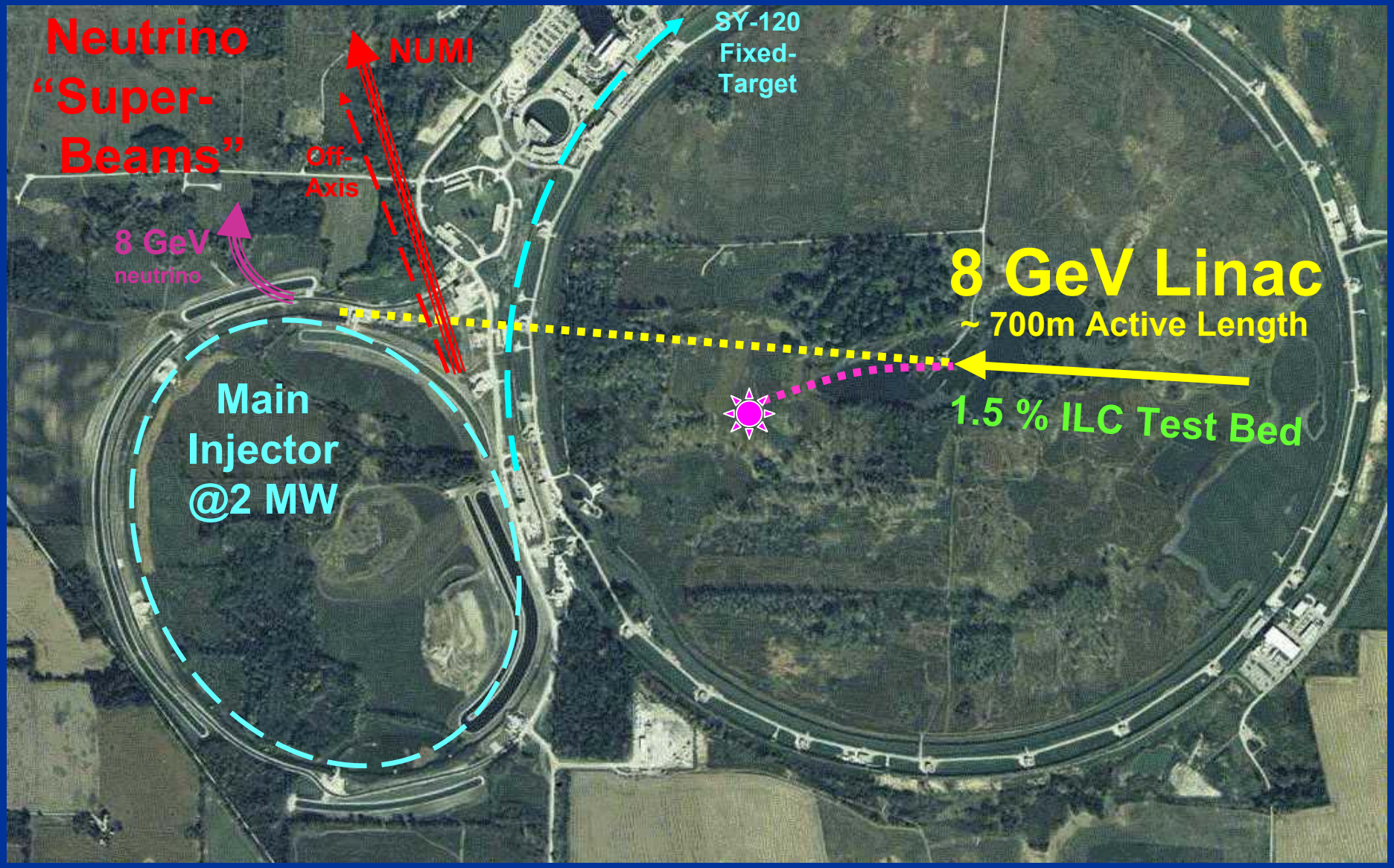


* New Idea?

- The 8 GeV Linac concept actually originated with Vinod Bharadwaj and Bob Noble (both then FNAL, now both at SLAC).

"A 8 GeV Proton Linac as an Injector for the Fermilab Main Injector", Vinod Bharadwaj, Robert Noble, abstract submitted to EPAC1994 (no paper); also V. Bharadwaj, Presentation to John People's Future Working Group, ca. 1994 (unpublished).

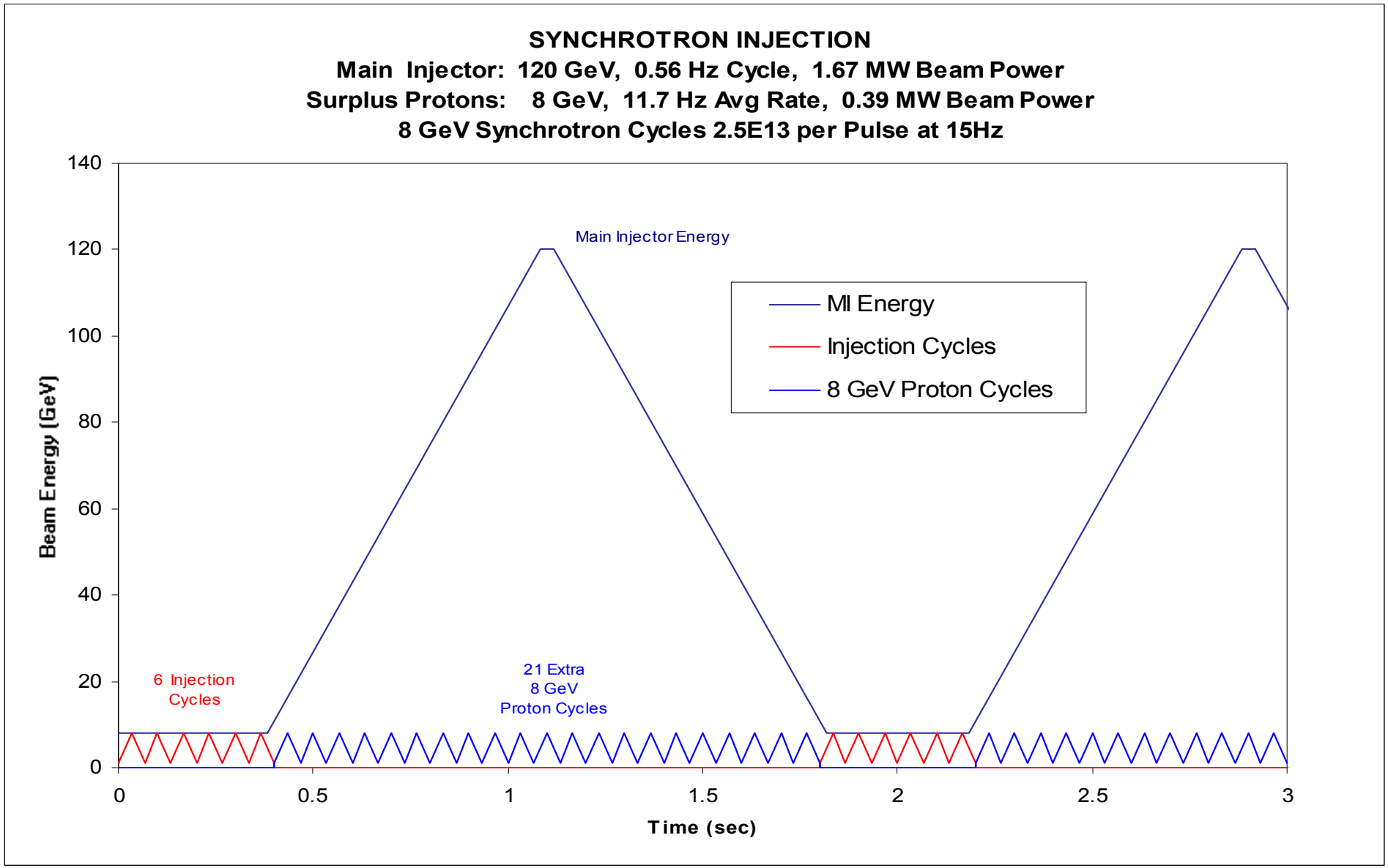
- In 1994 it made no sense because the SCRF gradients weren't there.

8 GeV SC Linac Proton Driver

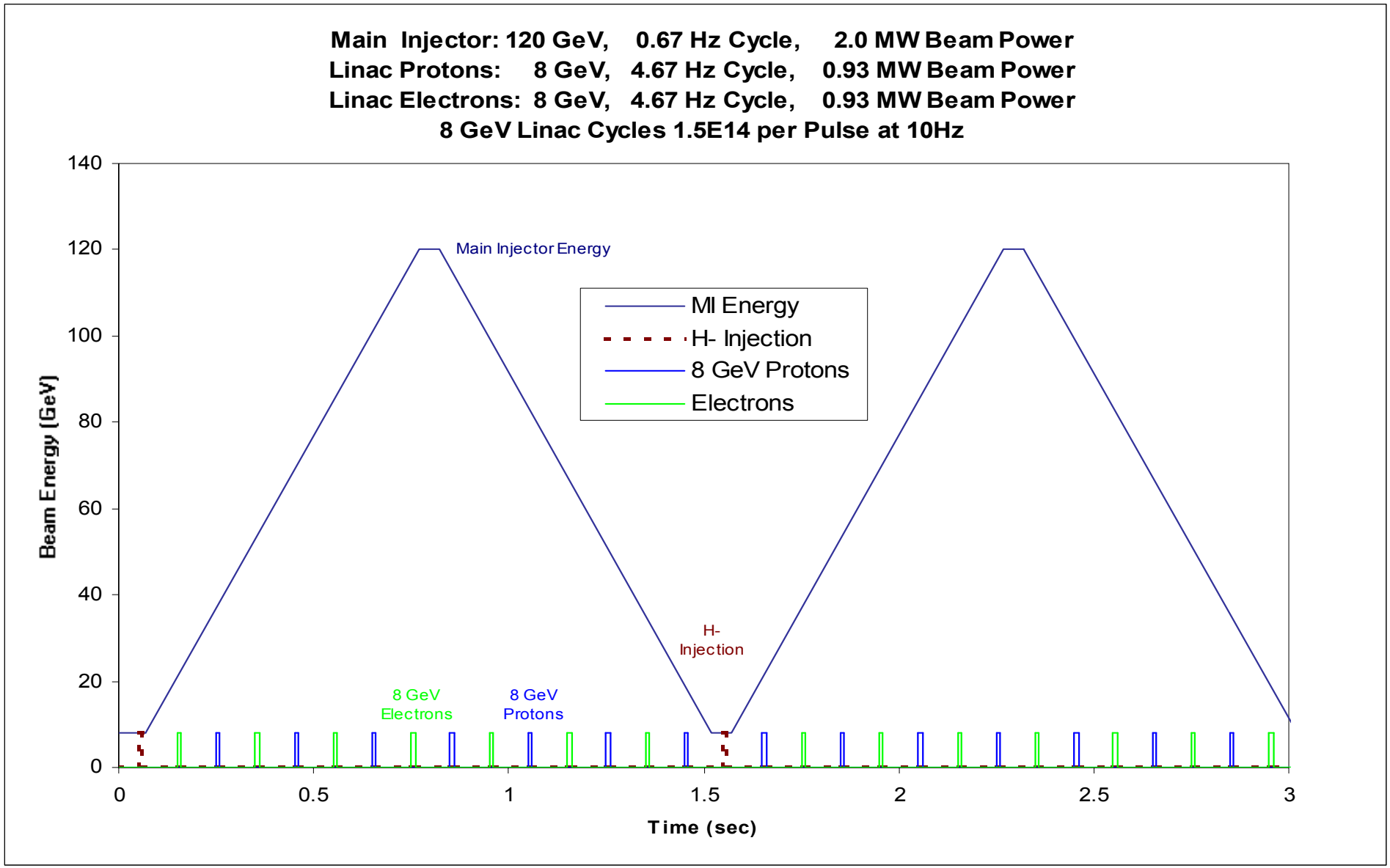
- A Bridge Program to the Linear Collider
- Near Term Physics Program (neutrinos+)
- Multiple HEP Destinations & Off-Ramps
- A seed project for Industrial Participation

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

120 GeV Main Injector Cycle with 8 GeV Synchrotron

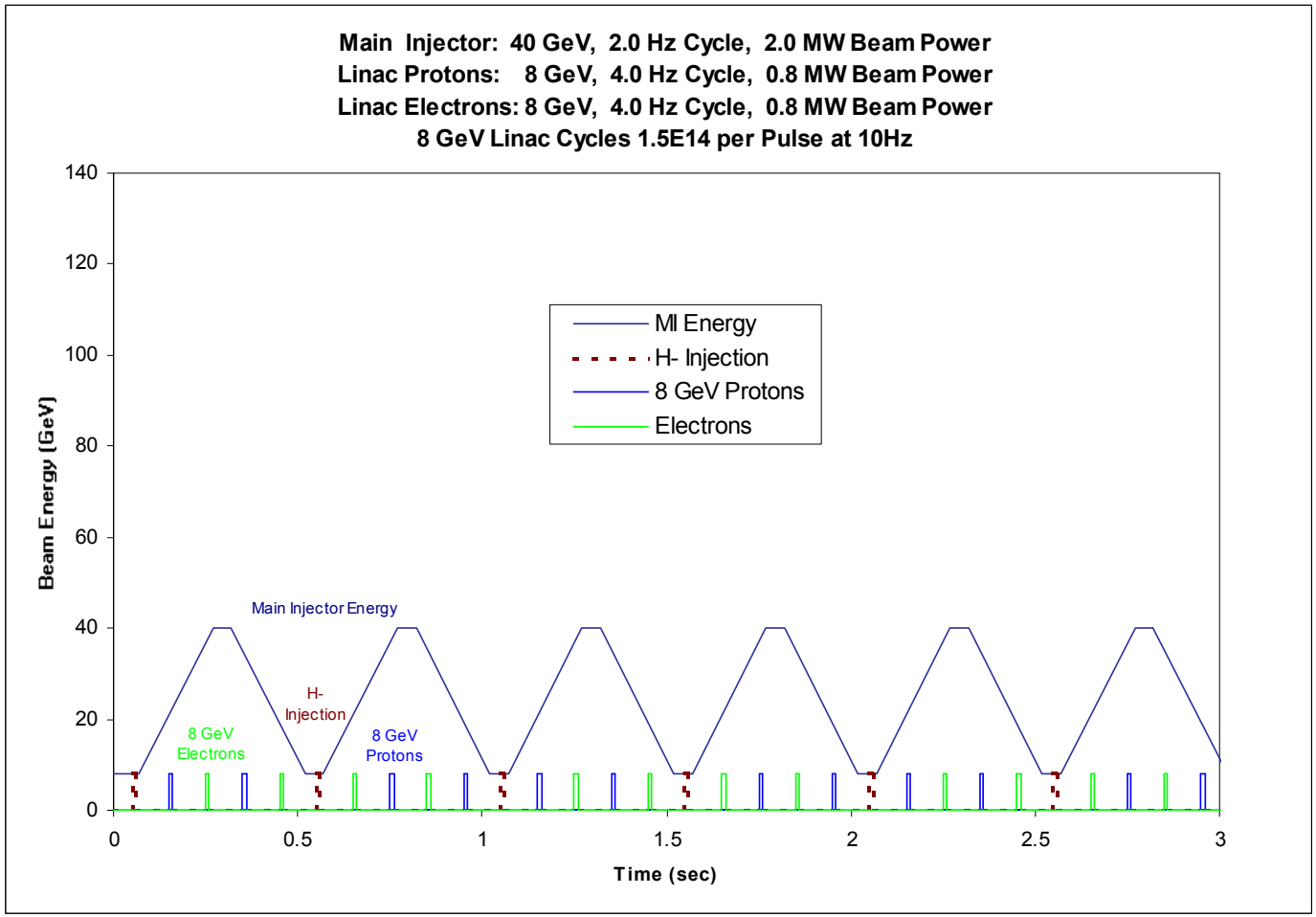


120 GeV Main Injector Cycle with 8 GeV Linac



Linac Allows Reduced MI Beam *Energy* without Compromising Beam *Power*

MI cycles to 40 GeV at 2Hz, Retains 2 MW MI beam power



- # neutrino evts. ~ same vs. E
- Reduces tail at higher neutrino energies.
- *Permits Flexible Neutrino Program*

2 MW @40 GeV

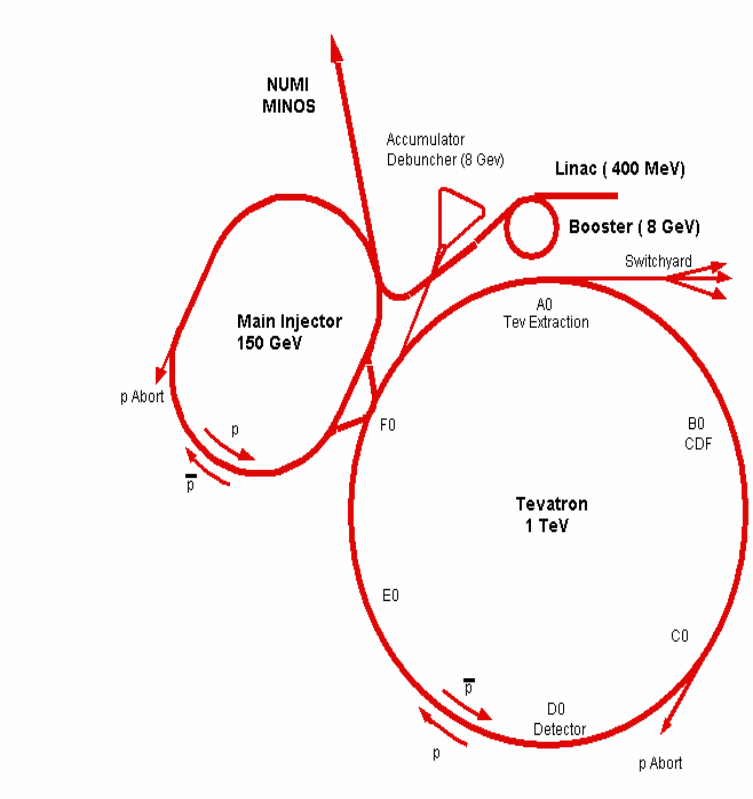
NOT POSSIBLE

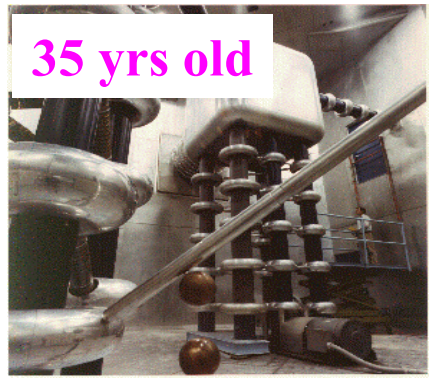
FOR SYNCHROTRON

Fermilab's Existing Proton Source

FNAL Accelerator Complex

7 major accelerators !)





Cockroft-Walton

H^- ions → (750 KeV)

Drift Tube LINAC

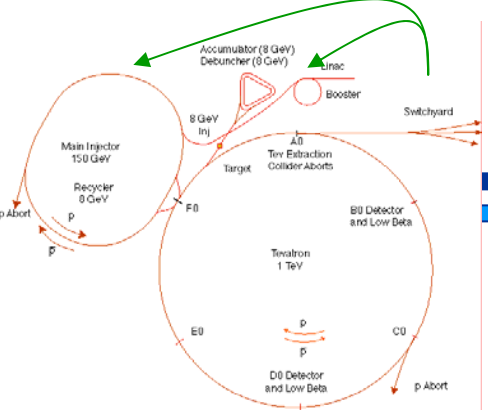
750 KeV → 116 MeV

"New" LINAC

116 MeV → 400 MeV

Proton Source = Linac, Booster, Main Injector

Booster & Main Injector



Booster Synchrotron

15 Hz resonant magnet cycle

400 MeV H^- stripped→ 8 GeV Protons

Protons →MI or Mini-BooNE

Main Injector Synchrotron

8 GeV → 150 GeV

Protons or Pbars for TeV Collider

→ 120 GeV for PBAR production or to the NUMI target

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.

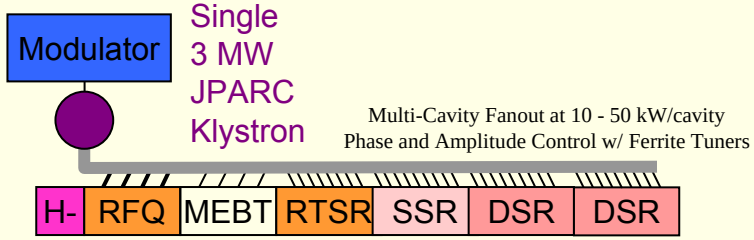
0.5 MW Initial 8 GeV Linac

11 Klystrons (2 types)
449 Cavities
51 Cryomodules

"PULSED RIA"

Front End Linac

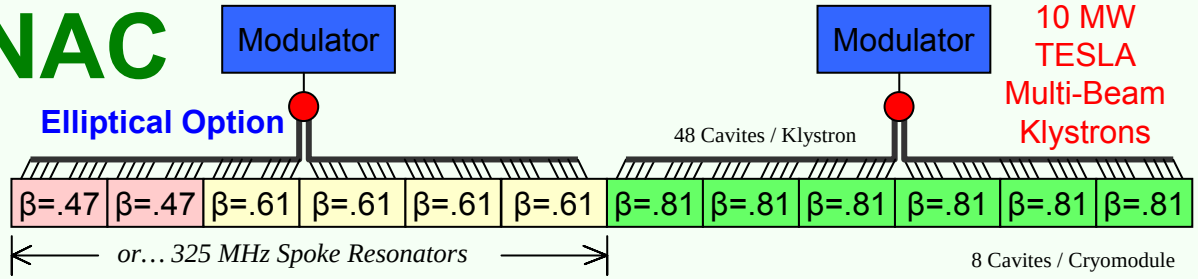
325 MHz
0-110 MeV



β<1 TESLA LINAC

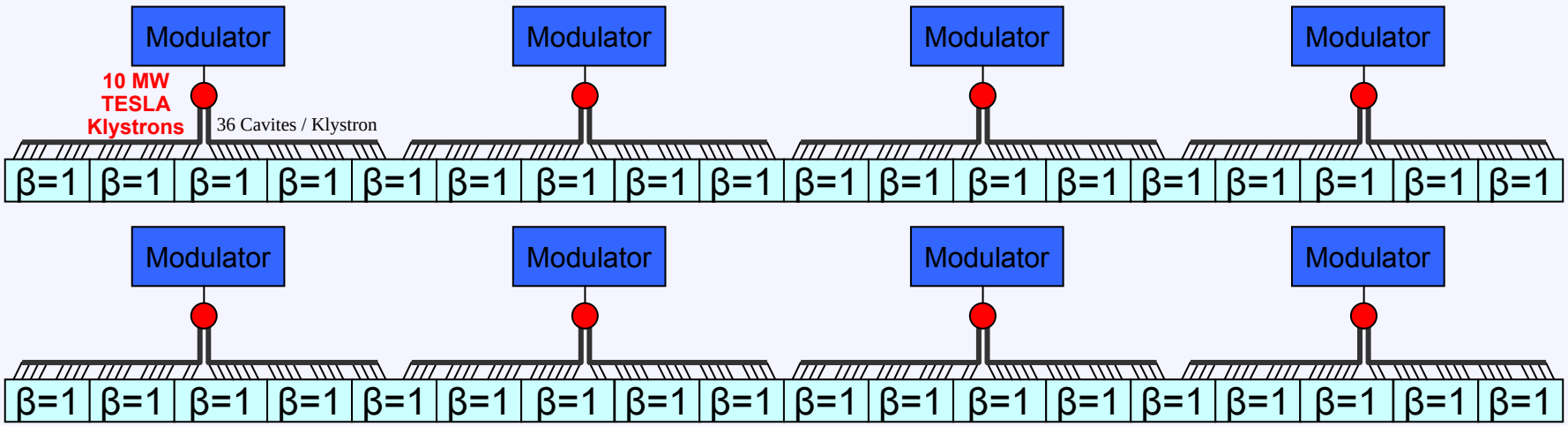
1300 MHz 0.1-1.2 GeV

2 Klystrons
96 Elliptical Cavities
12 Cryomodules



TESLA LINAC 1300 MHz β=1

8 Klystrons
288 Cavities in 36 Cryomodules

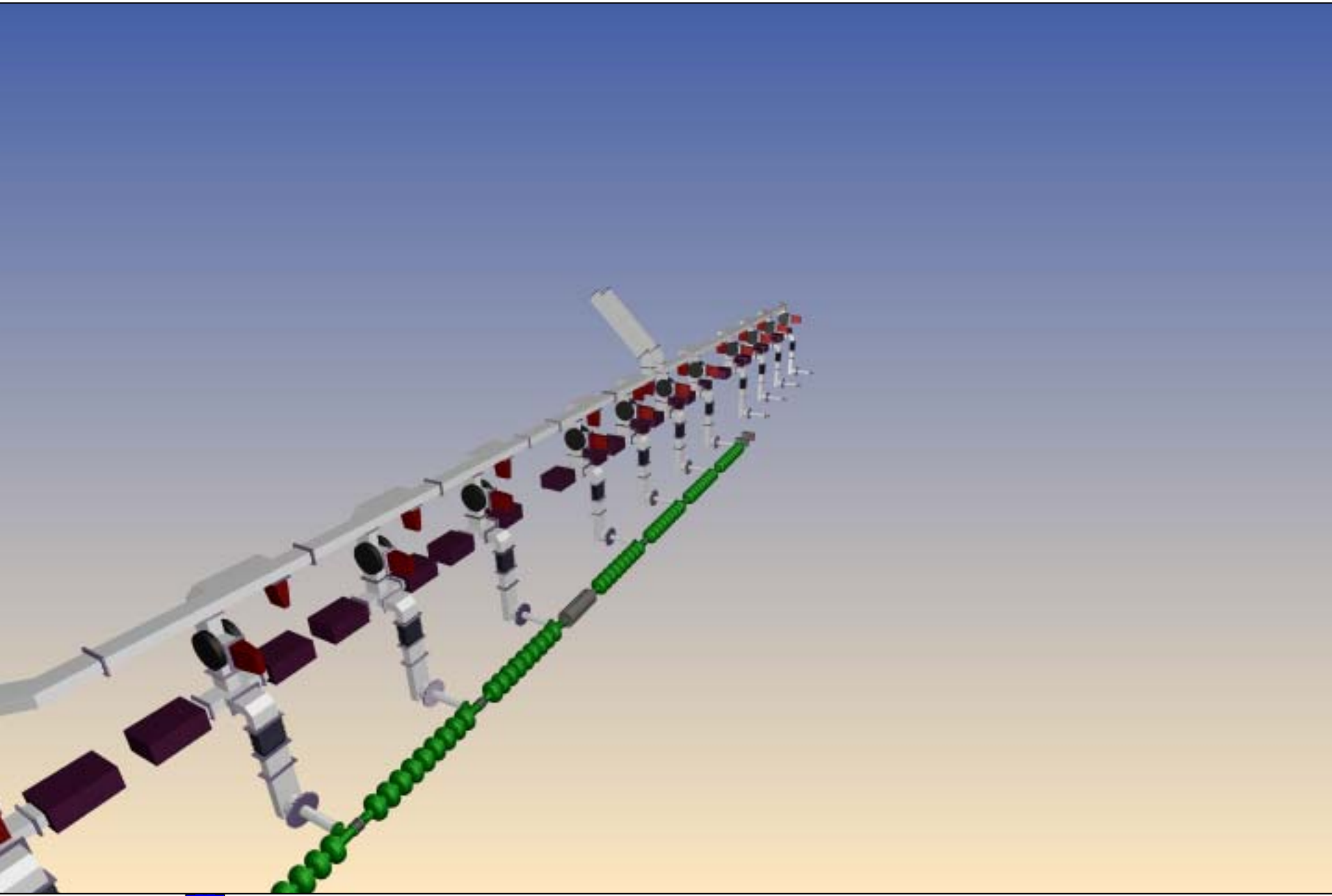


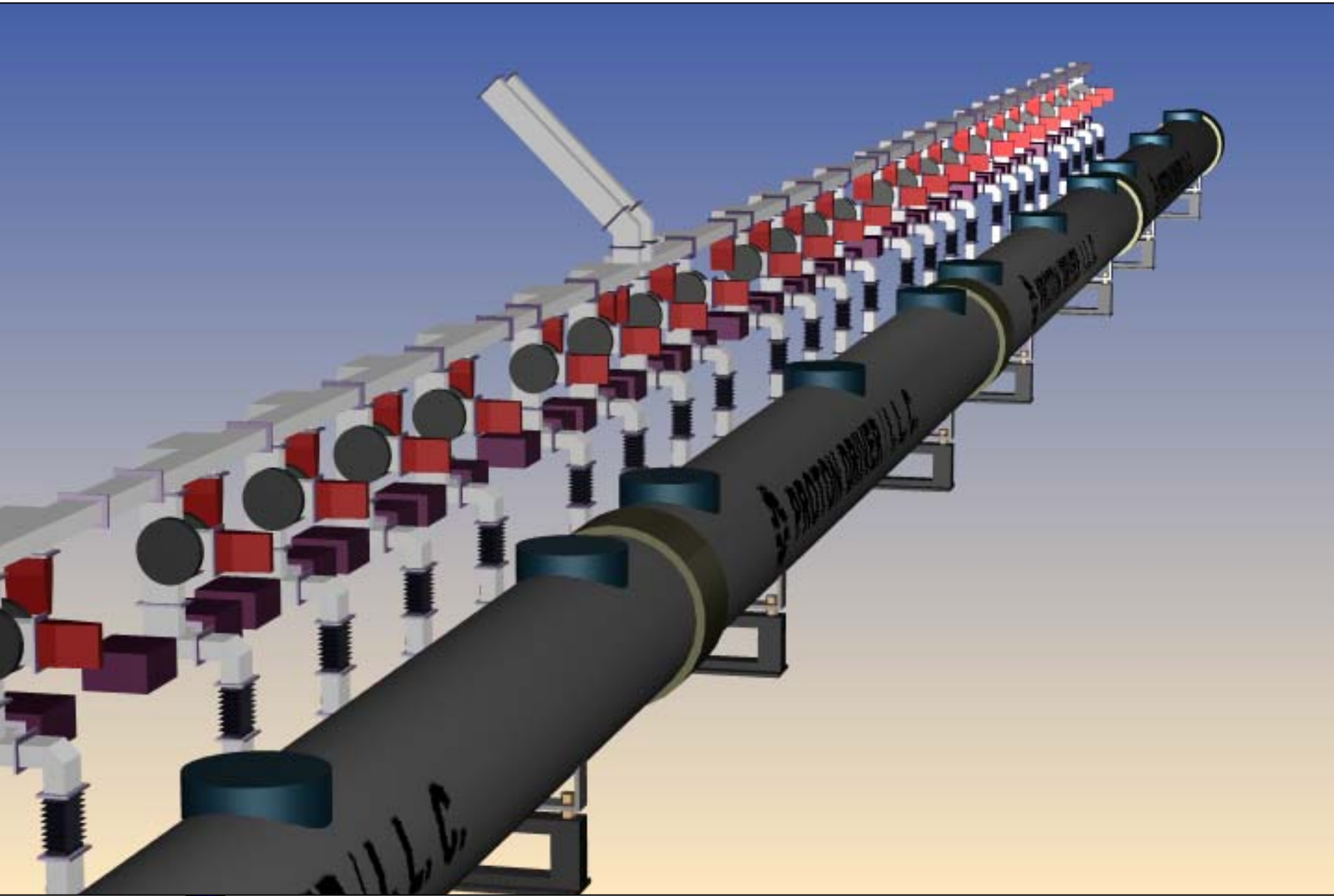
The Building Block of the 8 GeV Linac

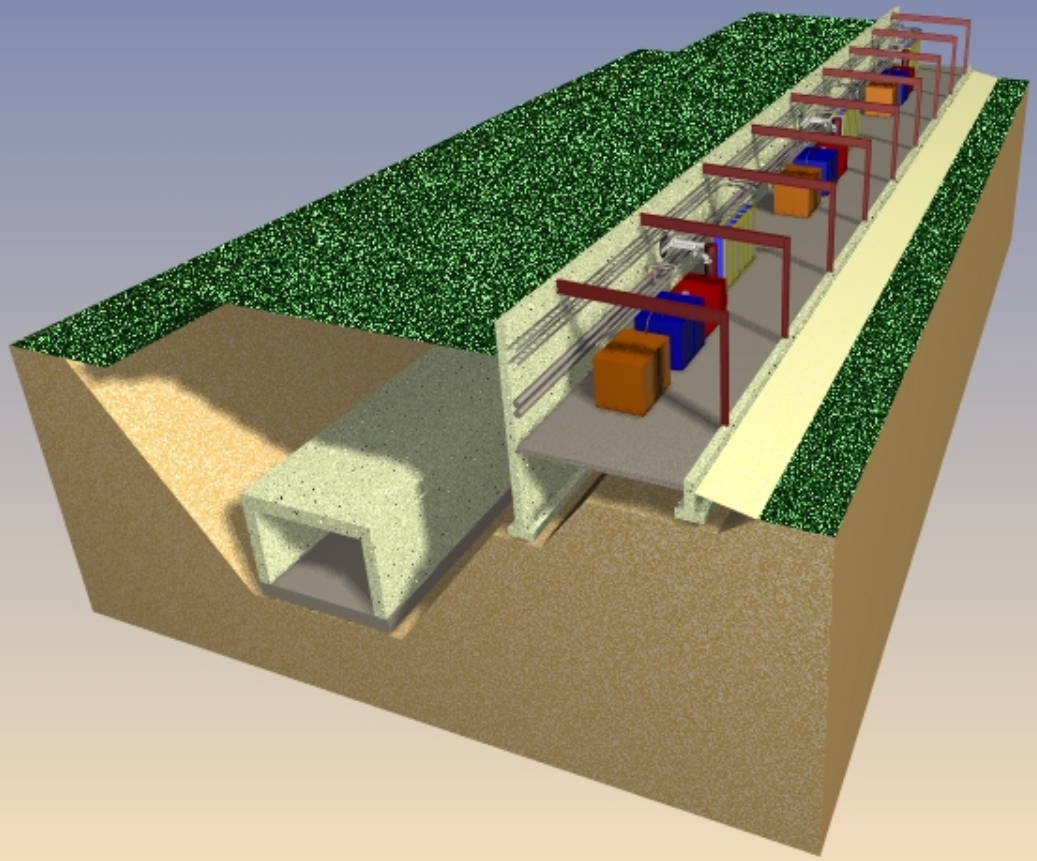
… is the <u>TESLA RF Station</u>:

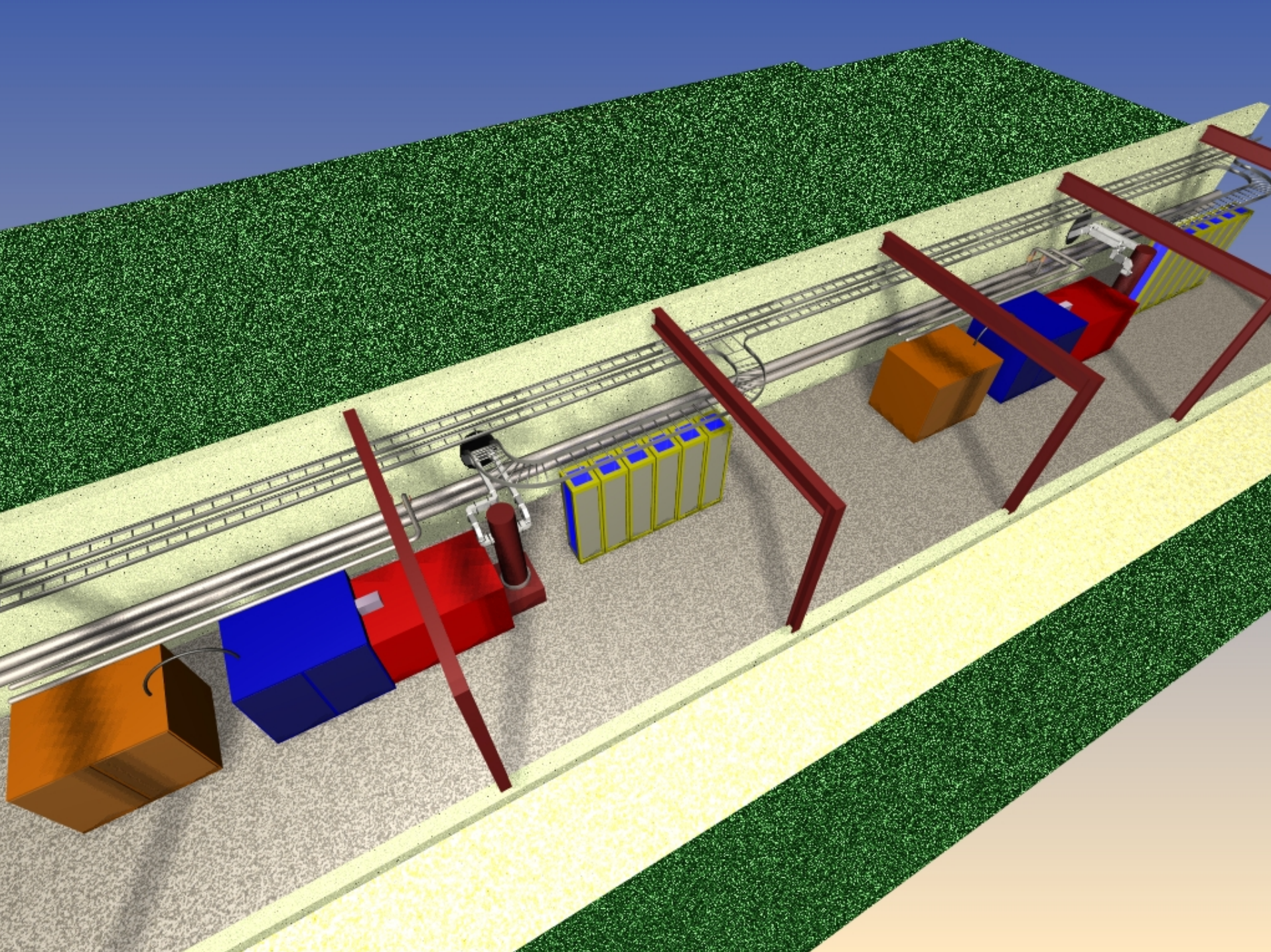
- **36 SCRF CAVITIES**
- **~ 4 Cryomodules**
- **1 Klystron**
- **1 Modulator**
- ***~<u>1 GeV of Beam Energy</u>***

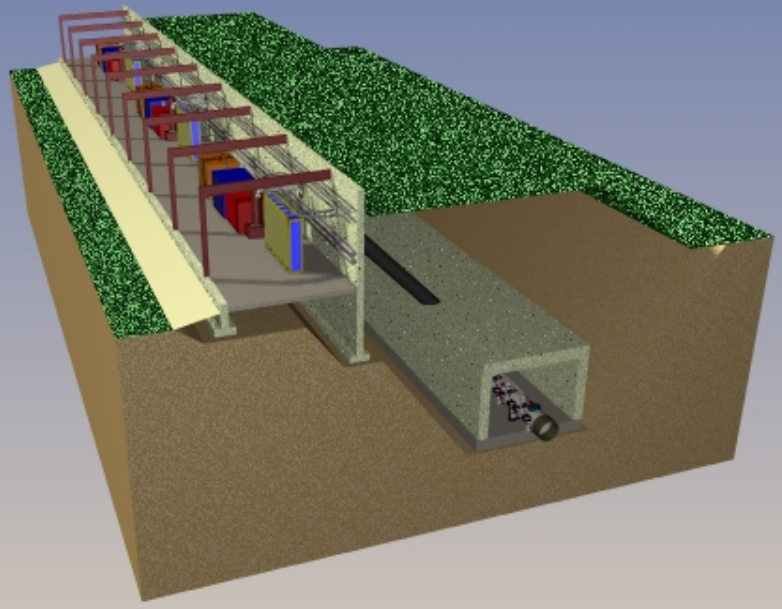
Extending this technology to Proton Linacs is the Key to the Proton Driver.

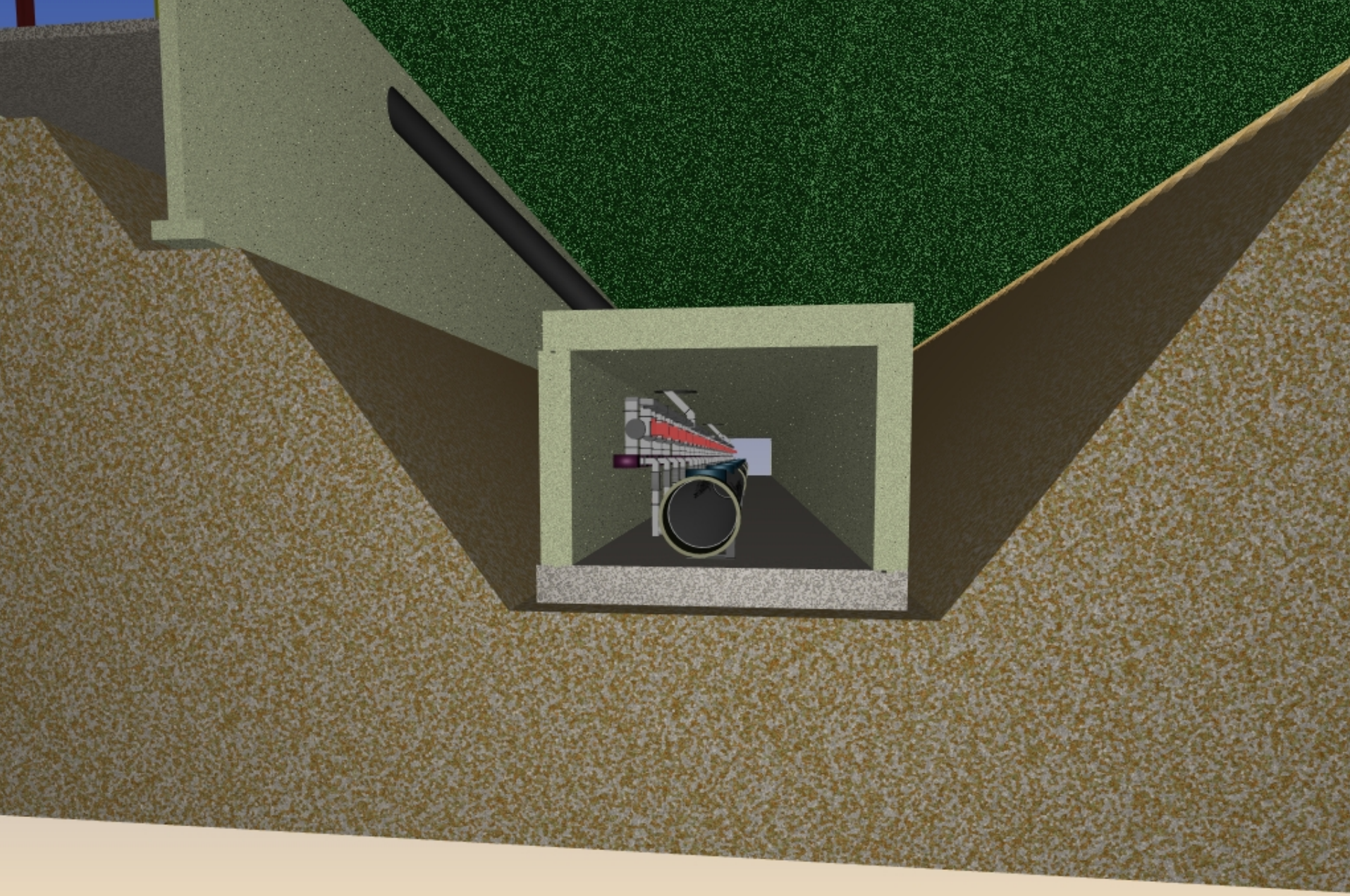






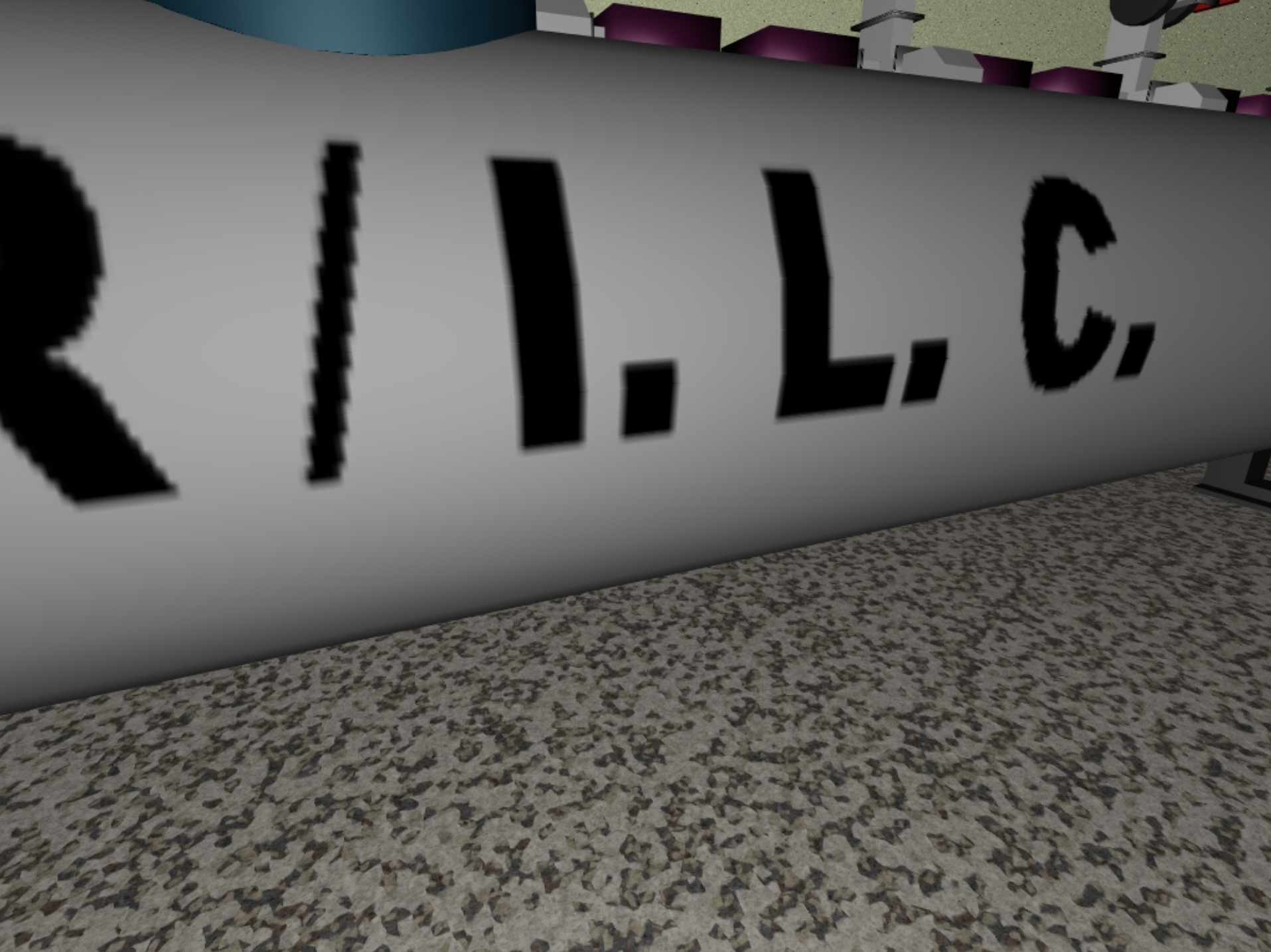


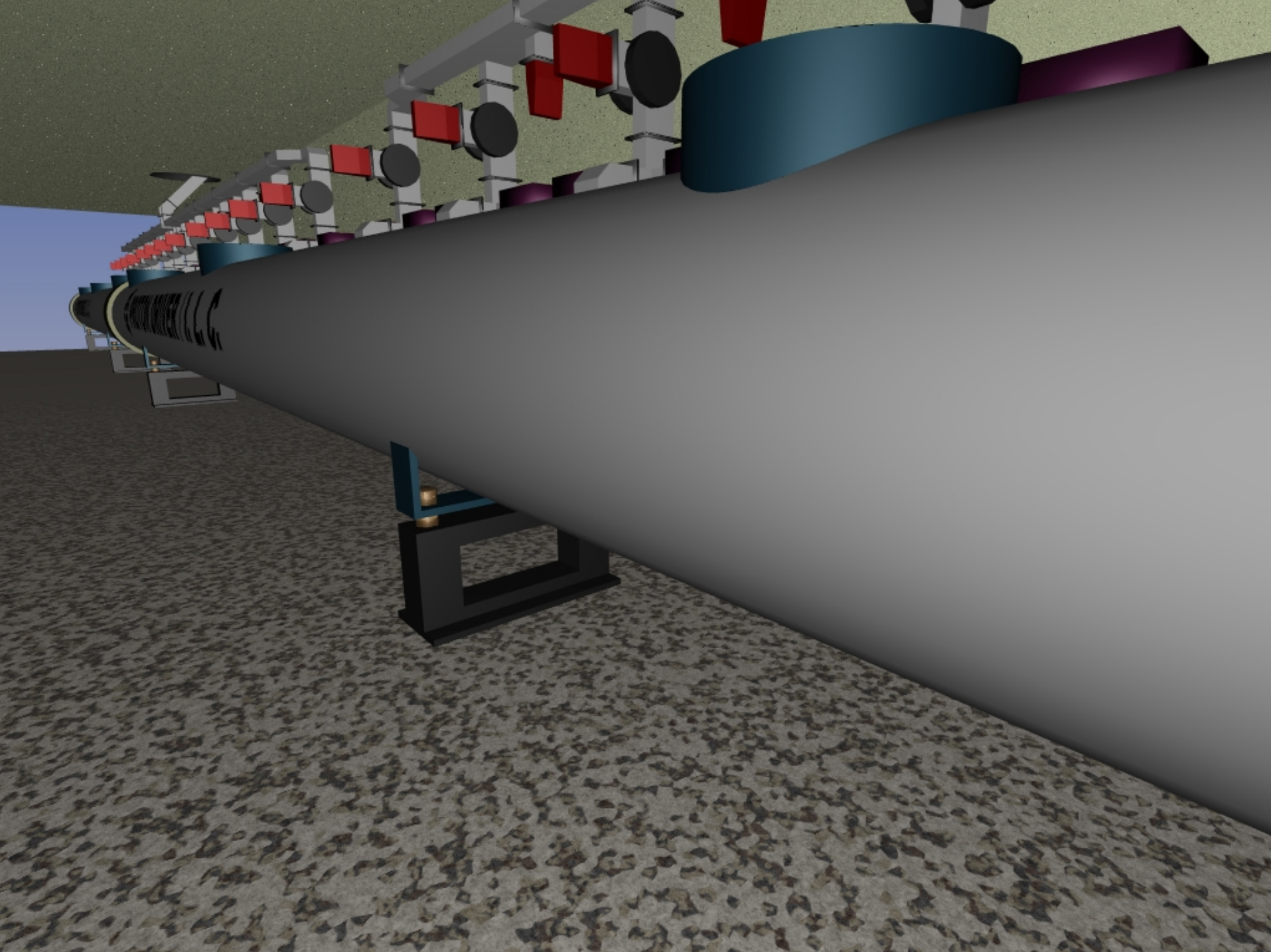




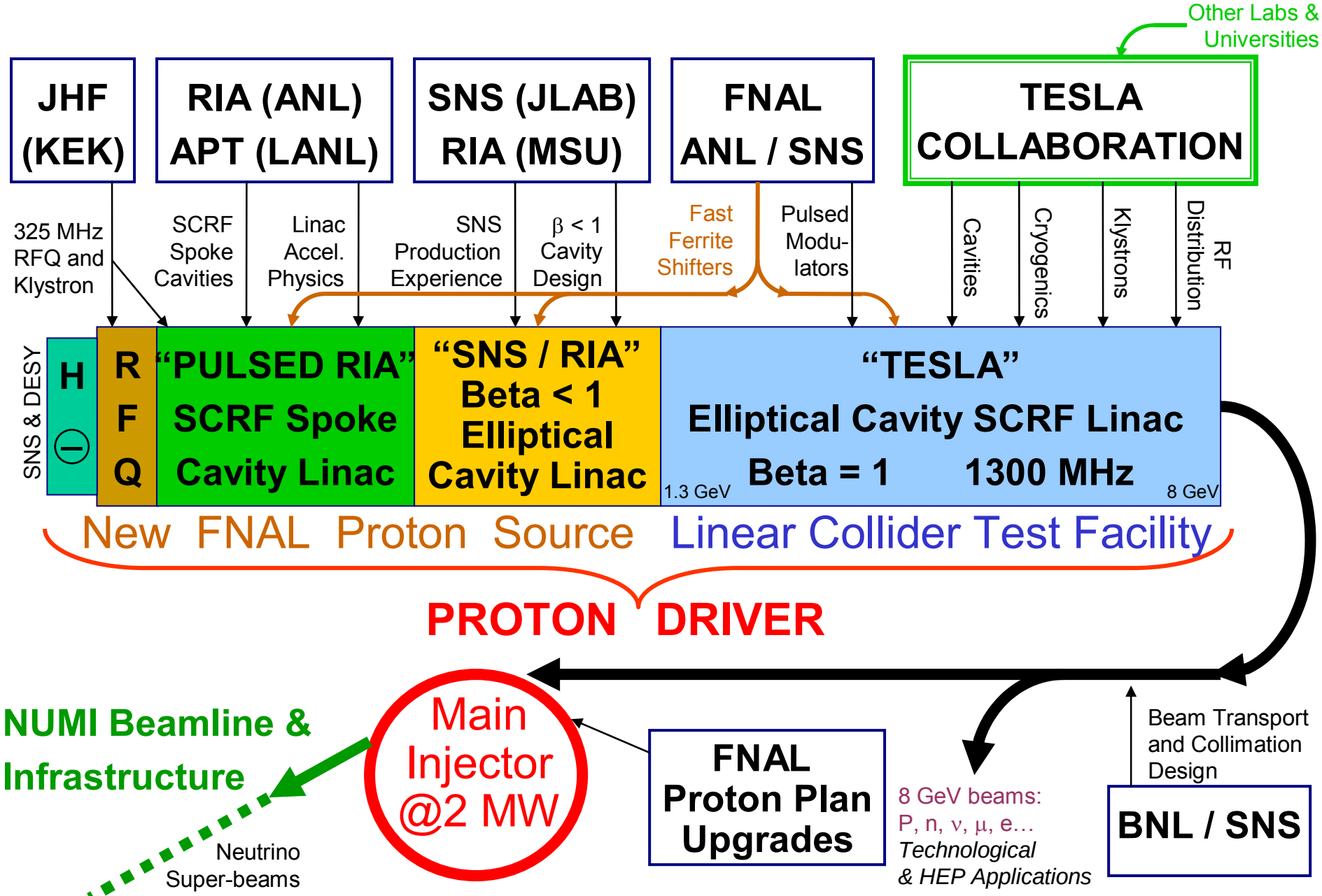
PROTON DRIVER

ON DRIVER I.L.C.


R I.L.C.



Proton Driver Linac - Technology Flow



RECENT WORKSHOPS & STUDIES

- **A number of recent workshops have focused on the physics possibilities with intense (MW class) Proton Sources**
- **BNL/UCLA –APS workshop**
  - BNL, March 3-5, 2004
  - http://www.bnl.gov/physics/superbeam/presentations.asp
- **Physics with Multi-MW Proton Source (SPL)**
  - CERN, May 25-27, 2004
  - http://physicsatmwatt.web.cern.ch/physicsatmwatt/
- **HIF04**
  - Elba Italy, June 2004
  - http://www.pi.infn.it/pm/2004/
- **APS Neutrino Study** (year long effort)
  - www.interactions.org/neutrinostudy
- **Fermilab Proton Driver Physics Workshop**
  - Fermilab Oct 6-9, 2004
  - http://www-td.fl.gov/projects/PD/PhysicsIncludes/Workshop/index.html

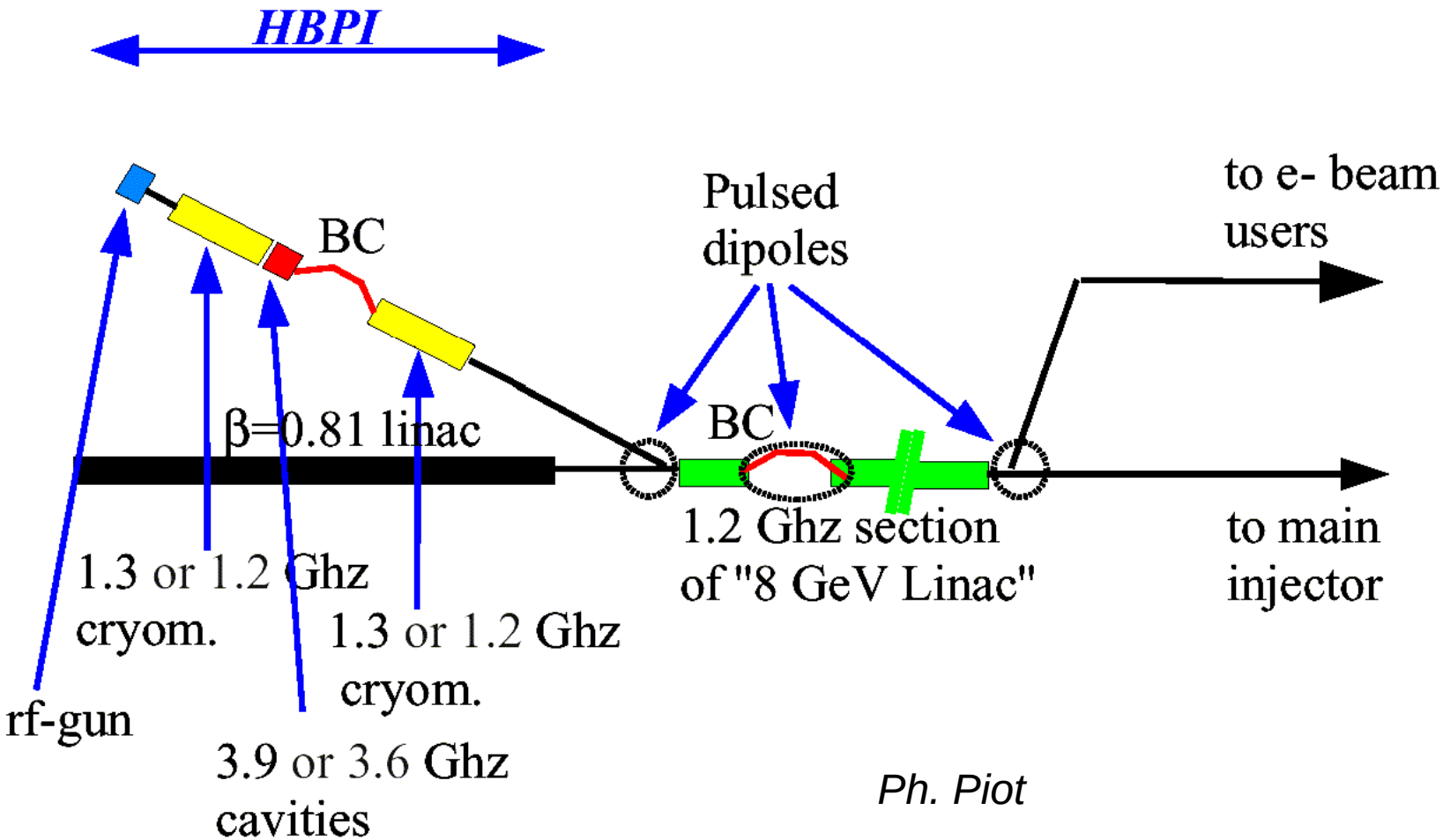
UPCOMING WORKSHOPS

- **HIF05 – Physics & Technology of High-Intensity Proton Sources**
  - Elba, Italy, May 28-June 1 2005
    http://www.pi.infn.it/hif/

- **HPSL05 – ICFA/FNAL/ANL/NIU**
  High-Power Superconducting
  Ion and Multi-Species Linacs
  - Naperville IL May 22-24, 2005 ←Right after PAC
    http://www.niu.edu/clasep/HPSLconf/

Worshop Topic: AP Issues for e/P Linac?

HBPI as an e- injector for the proposed 8 GeV superconducting booster linac



Ph. Piot

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

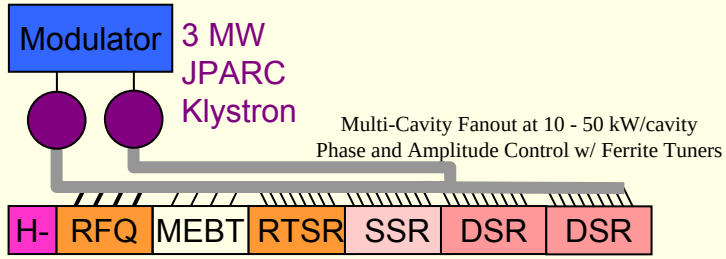
2 MW Ultimate 8 GeV Linac

32 Klystrons (2 types)
470 Cavities
53 Cryomodules

"PULSED RIA"

Front End Linac

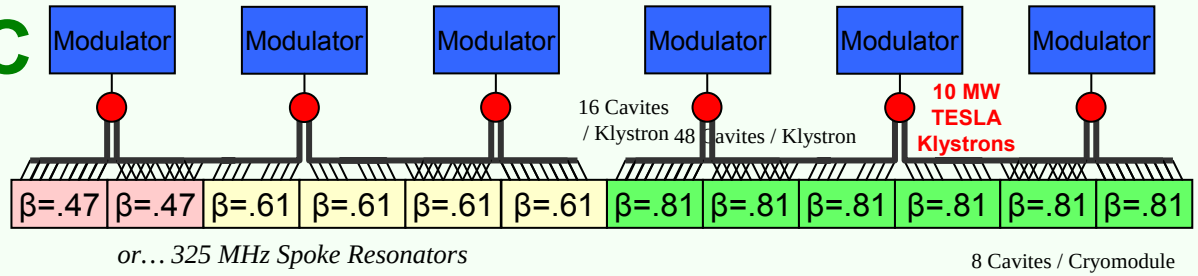
325 MHz
0-110 MeV



β<1 TESLA LINAC

1300 MHz 0.1-1.2 GeV

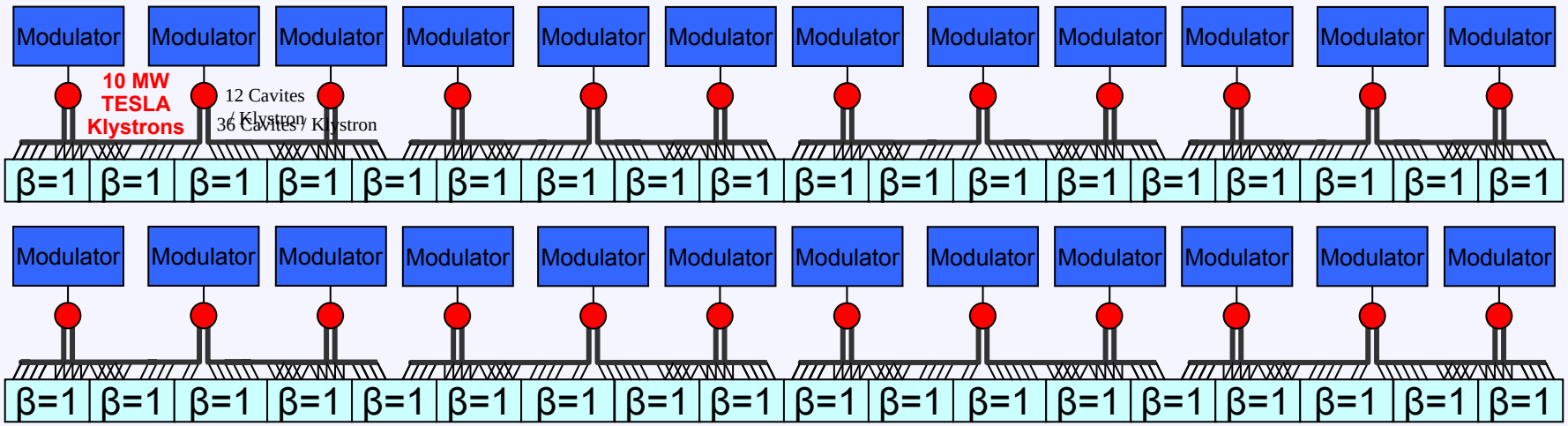
6 Klystrons
96 Elliptical Cavities
12 Cryomodules



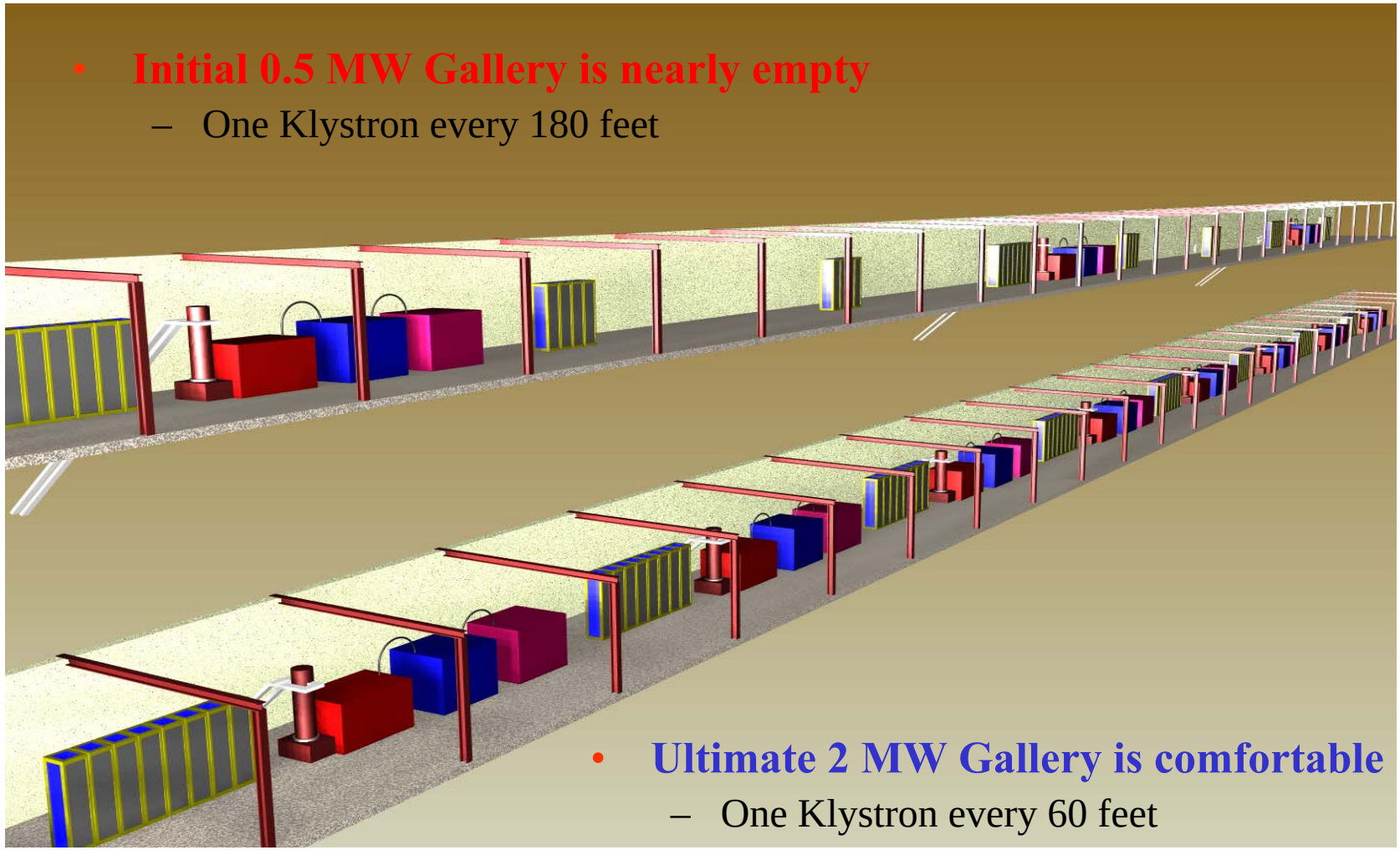
or… 325 MHz Spoke Resonators

TESLA LINAC 1300 MHz β=1

8 Klystrons
288 Cavities in 36 Cryomodules



Initial ➔ Ultimate Upgrade Equipment



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}

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

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

6. Design Margin on 8 GeV H- Transport

1. **8 GeV H- Transport is new to accelerators**
2. **Issues:**
   1. Magnetic Stripping
   2. **Blackbody Stripping**
   3. Foil Lifetime
   4. Injection losses

3. **Mini-Workshop Dec 9-10, 2004**

   Conclusion: <u>no problems with baseline design</u>

http://www-bd.fnal.gov/pdriver/H-workshop/hminus.html

Accelerator Physics

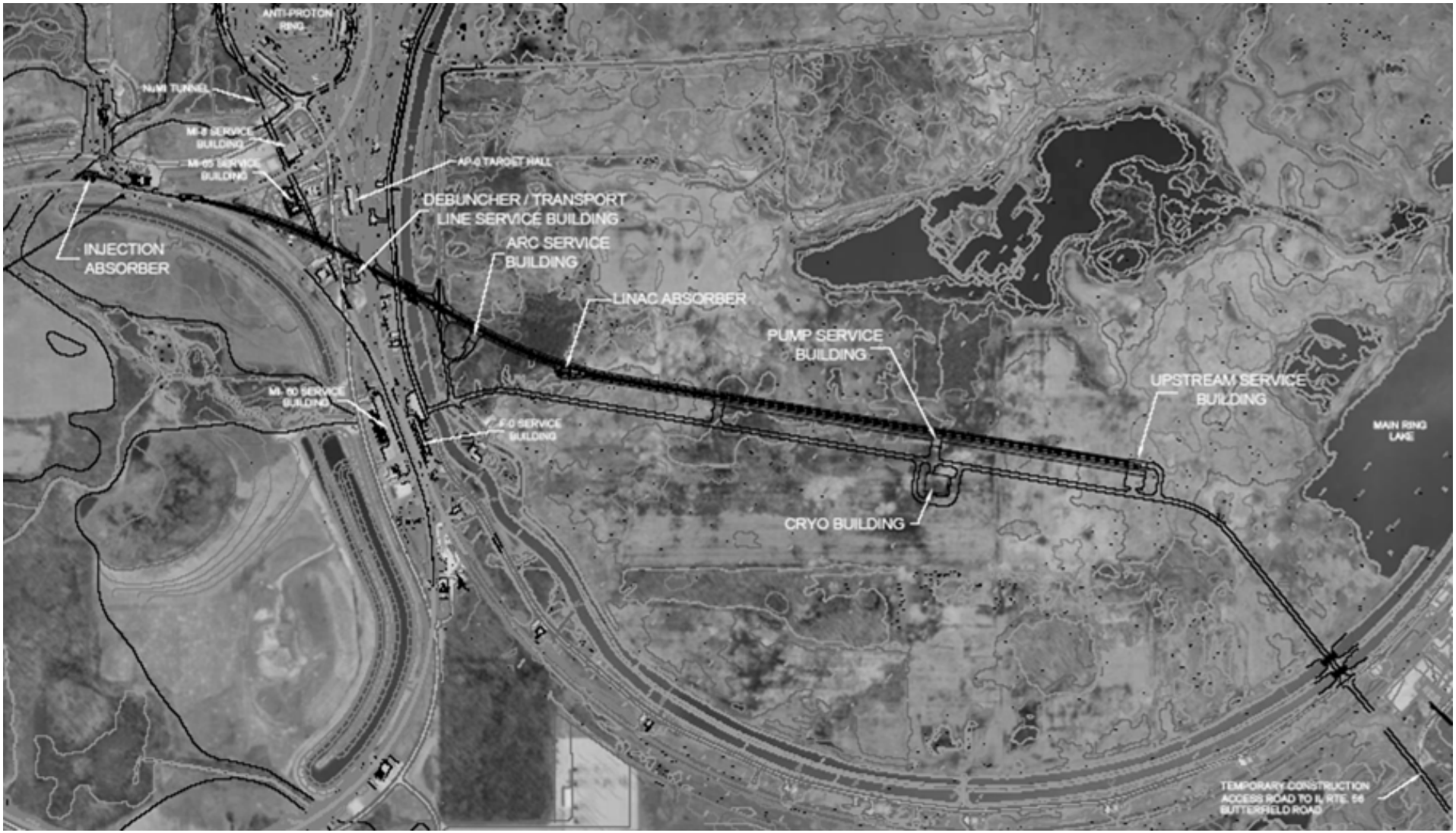
Petr Ostroumov's Talk

- **We are approaching an end-to-end simulation of the exact linac hardware we plan to build**
  - Cryomodule slot lengths, magnet & cavity types,…
  - Based on Trace-3d and ANL TRACK codes so far
- **Still to come:**
  - Cross-checking codes (already done for RIA)
  - Error Monte Carlos for Assembly Tolerances
- **Evaluation of Non-baseline Options:**
  - Elliptical cavity option 100-400 MeV
  - Chopping vs. Adiabatic capture in Main Injector

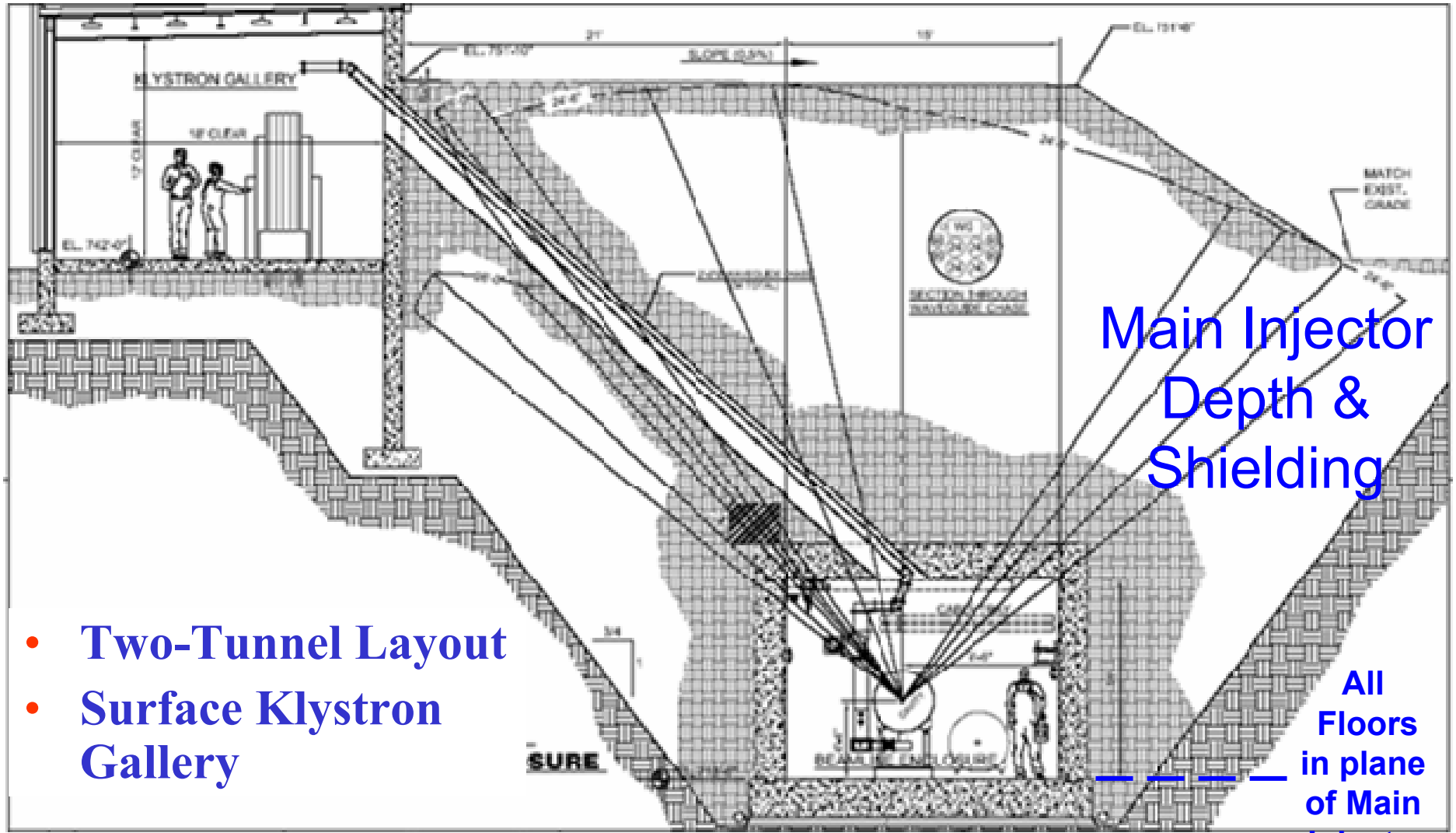
Civil Construction – Siting Options

8 GeV Civil Construction

Dixon Bogert's Talk



Gallery & Tunnel Cross Sections



- **Two-Tunnel Layout**
- **Surface Klystron Gallery**

Civil Construction vs. Main Injector

High-Level Comparison:

		Main Injector	8 GeV Linac	%
Tunnel Length	meters	4000	1600	40%
Surface Buildings	sq. ft.	60000	82000	137%
Surface Area for Site Prep	acres	50	30	60%
Excavated Volume	cu. yd.	475000	332000	70%
Concrete Volume	cu. yd.	40000	38000	95%
AC Power & Heat Rejection	MW	22	6.5	30%

- **Scope of Civil Construction is comparable to, or smaller than, the Main Injector project.**

MAIN LINAC

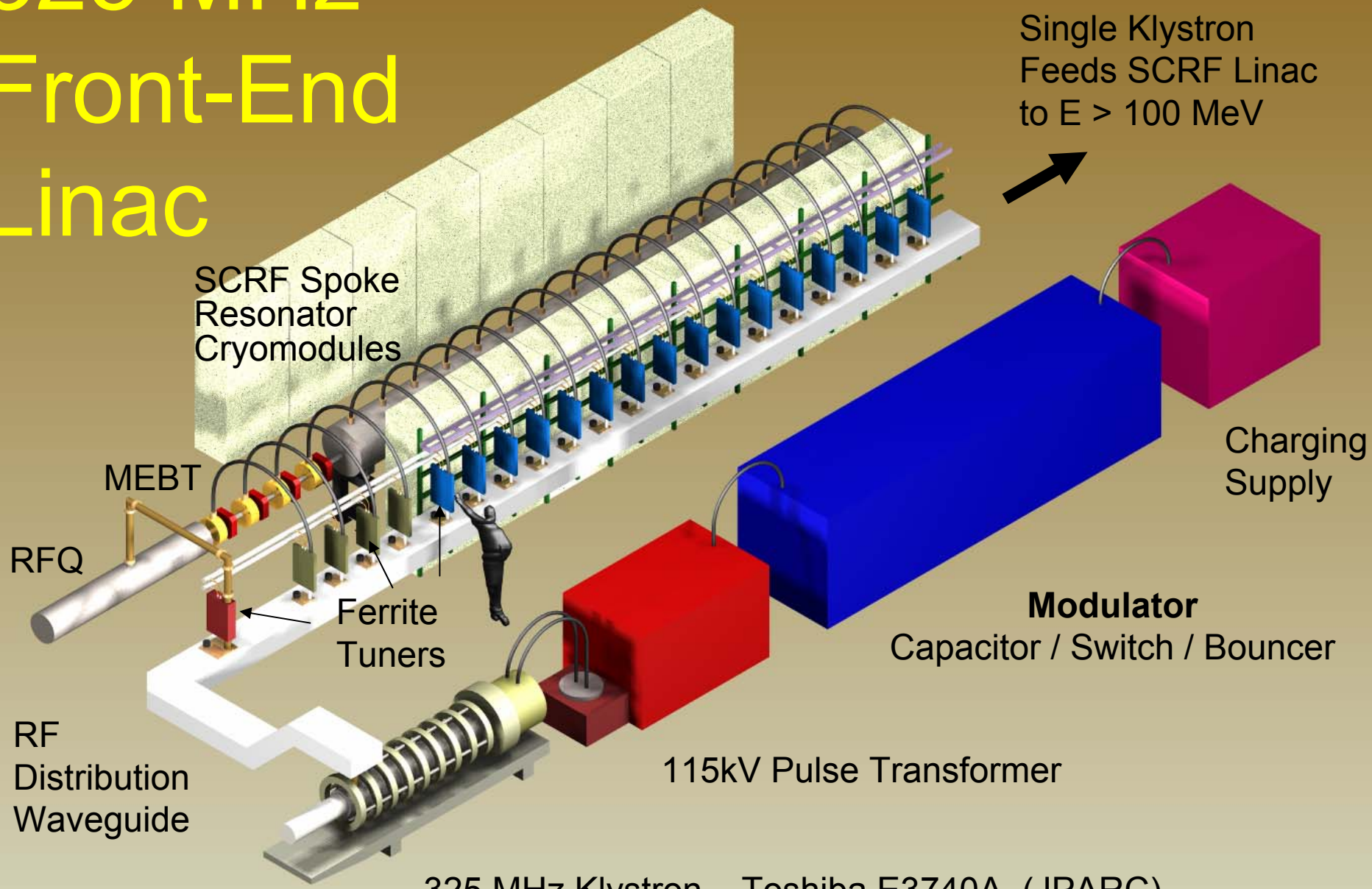
Technical Subsystems

Main Linac Technical Subsystems

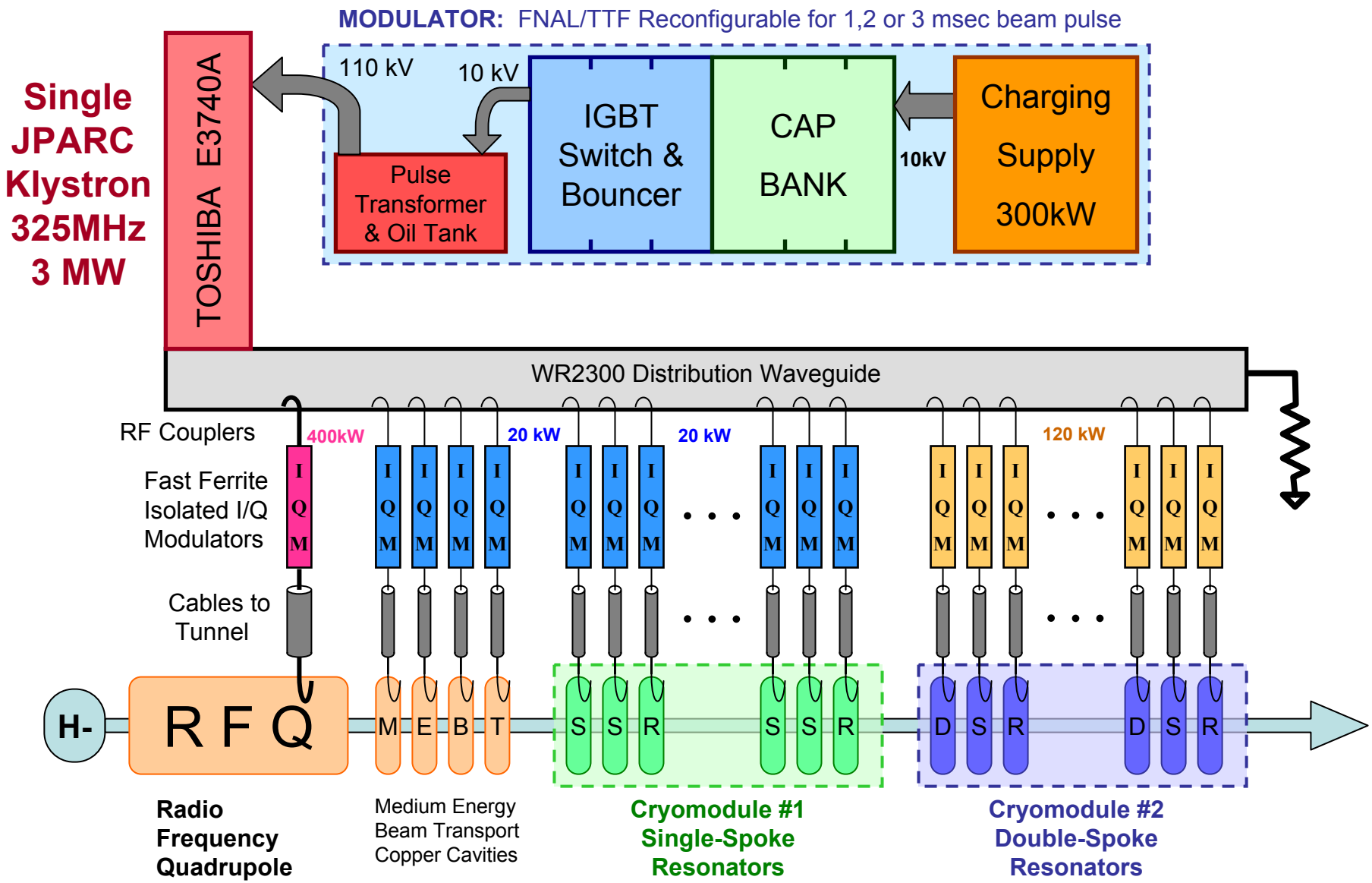
- **Much of the Technical Complexity is in the Front End**
  - Copy Existing Designs Wherever Possible
  - Start the Front End Development Early *(Now!)*
  - Use this beam test at SMTF to drive demonstration of phase shifters with proton beams

- **Most of the Cost is in the beta=1 Main Linac**
  - Collaborate with the Euro-FEL and the ILC
  - Collaborate to Gain In-House SRF Experience ASAP
  - Shared Interest with ILC in Cost Reduction

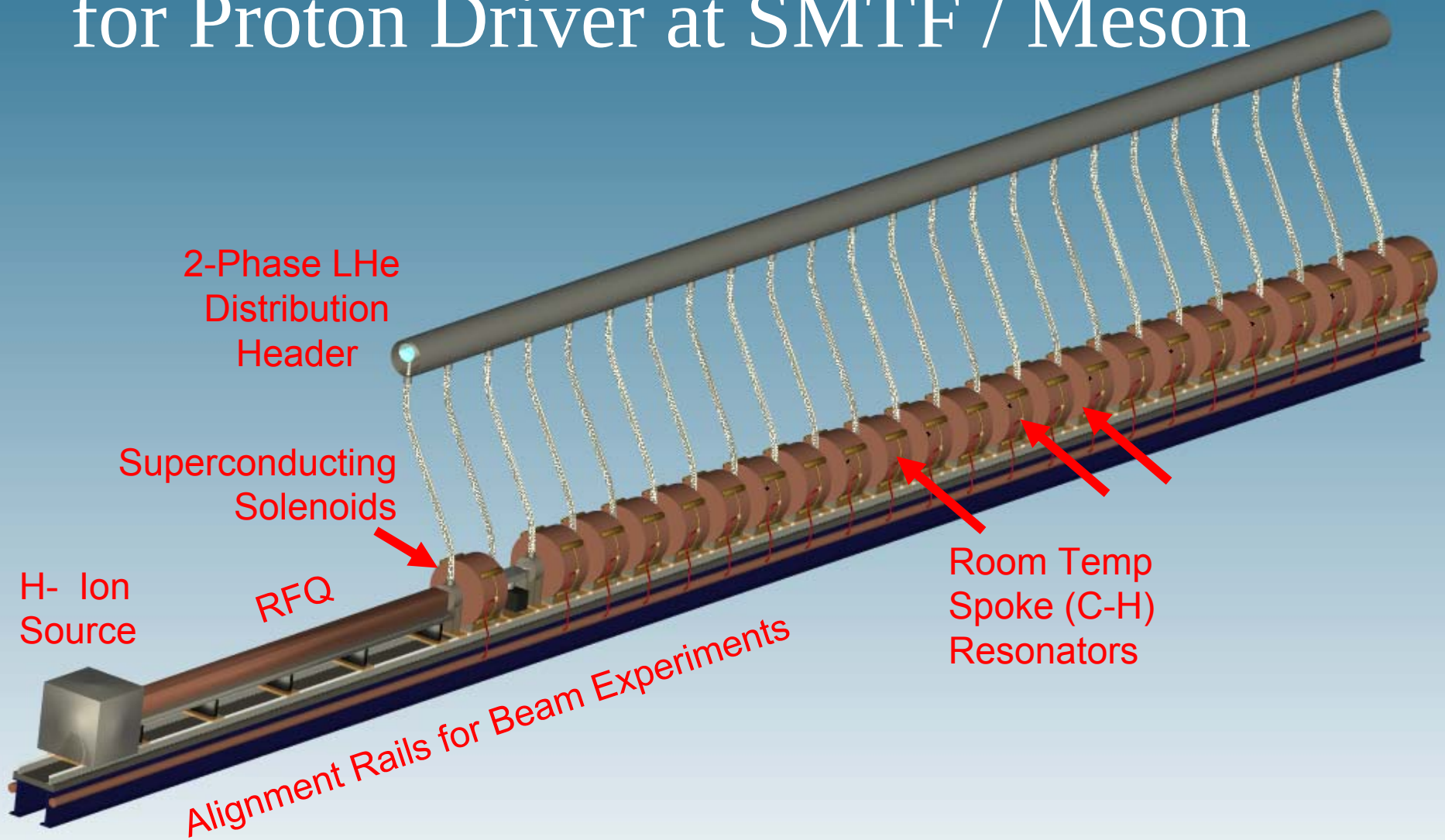
325 MHz Front-End Linac



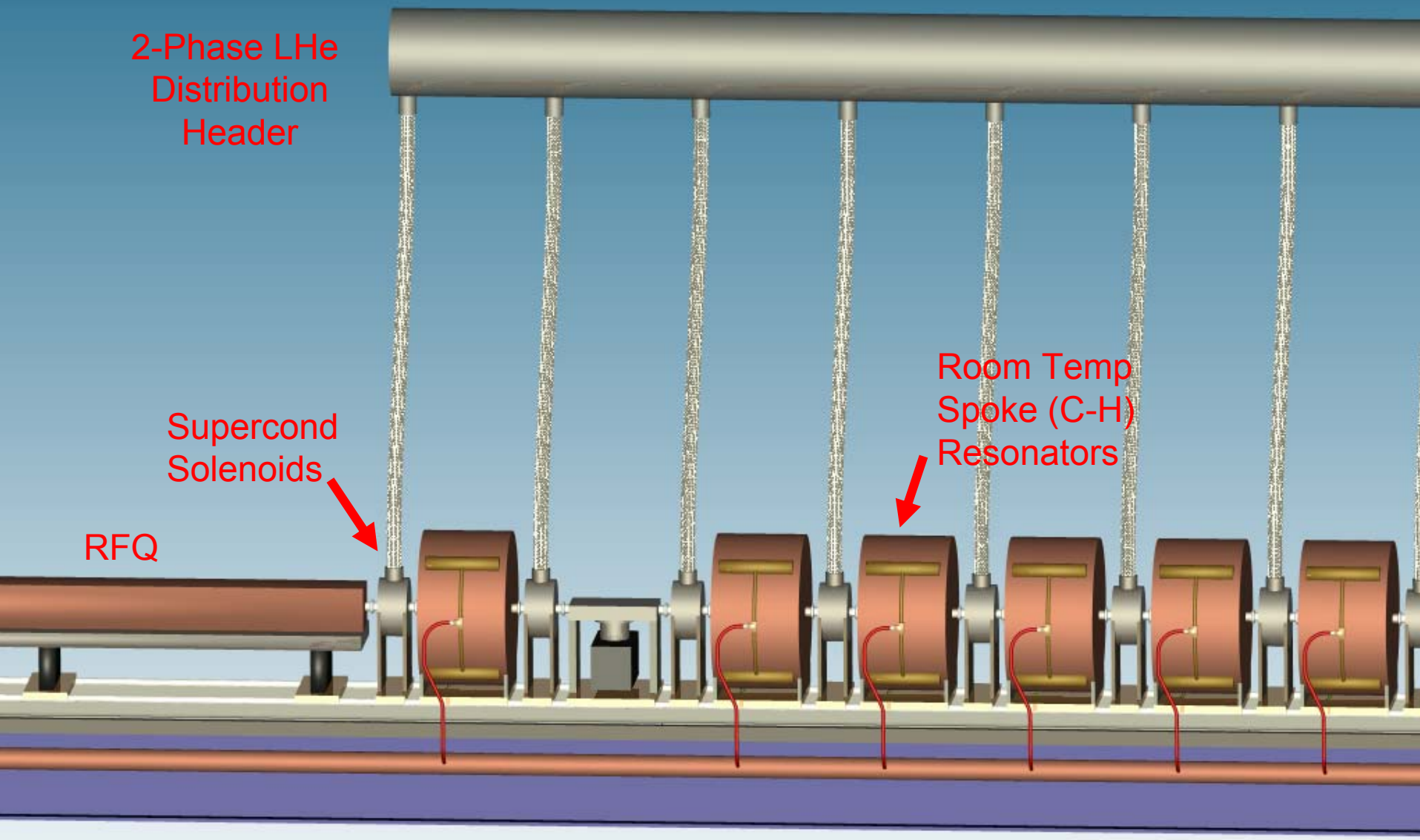
325 MHz RF System



Room-Temperature Front End for Proton Driver at SMTF / Meson

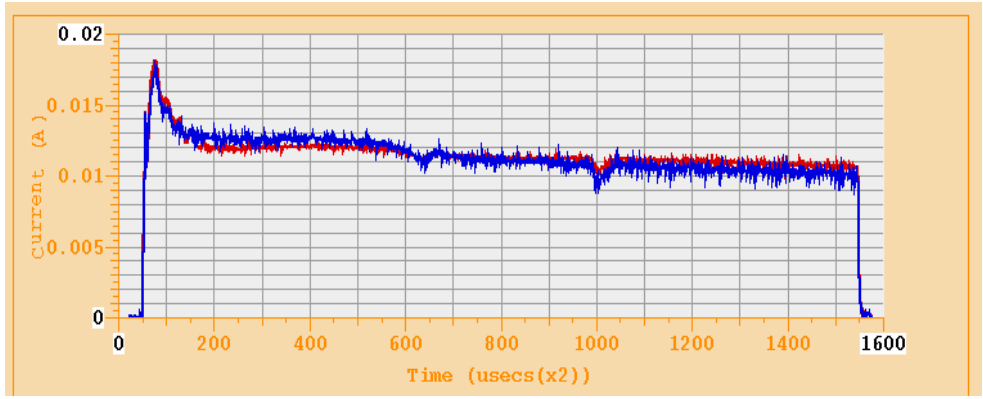


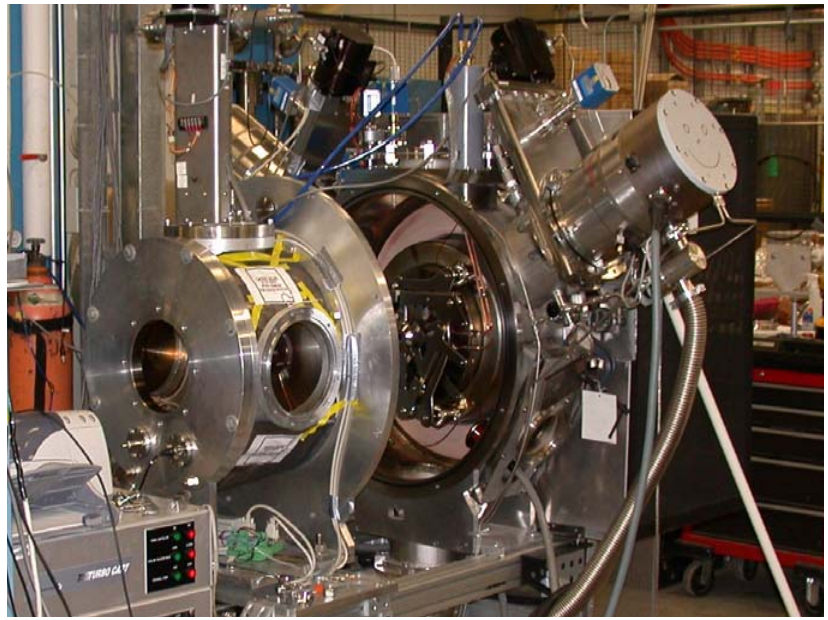
MEBT, Chopper & Beginning of RT-TSR



Alignment Rail for Beam Experiments

Toward Selecting an H^- Ion Source





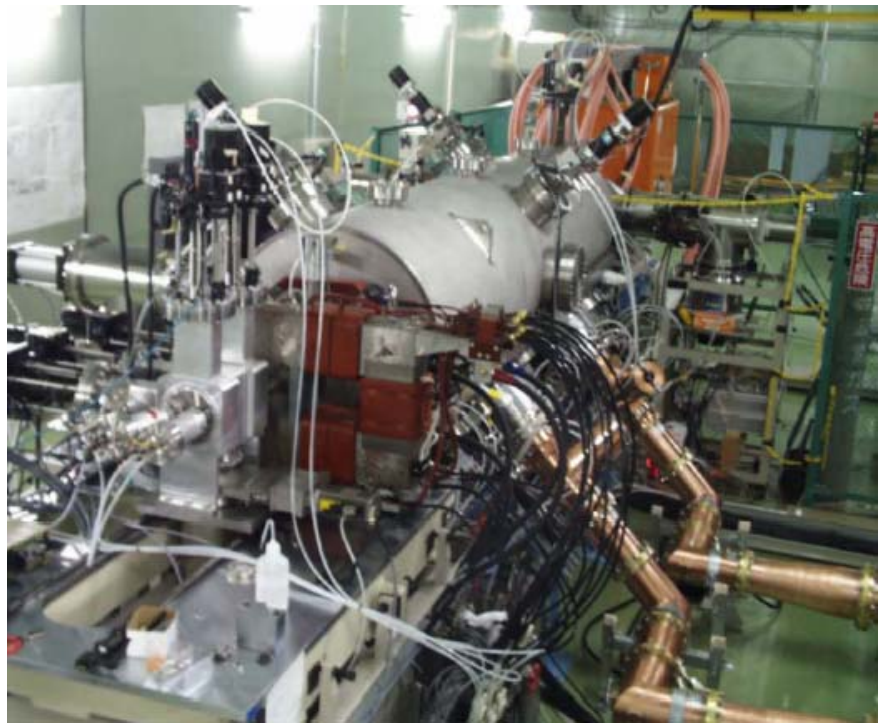
The SNS Ion Source Test Bench and LEBT

- **Beam tests on the SNS RF H^- ion source (Doug Moehs)**
  - 3.1 ms long pulse, 11.5 mA average, at 5 Hz
  - The SNS routinely runs 1 ms long pulses, 30 mA at 60 Hz

- **Plan to test the DESY H^- source at 3 msec in next few months**

RFQ

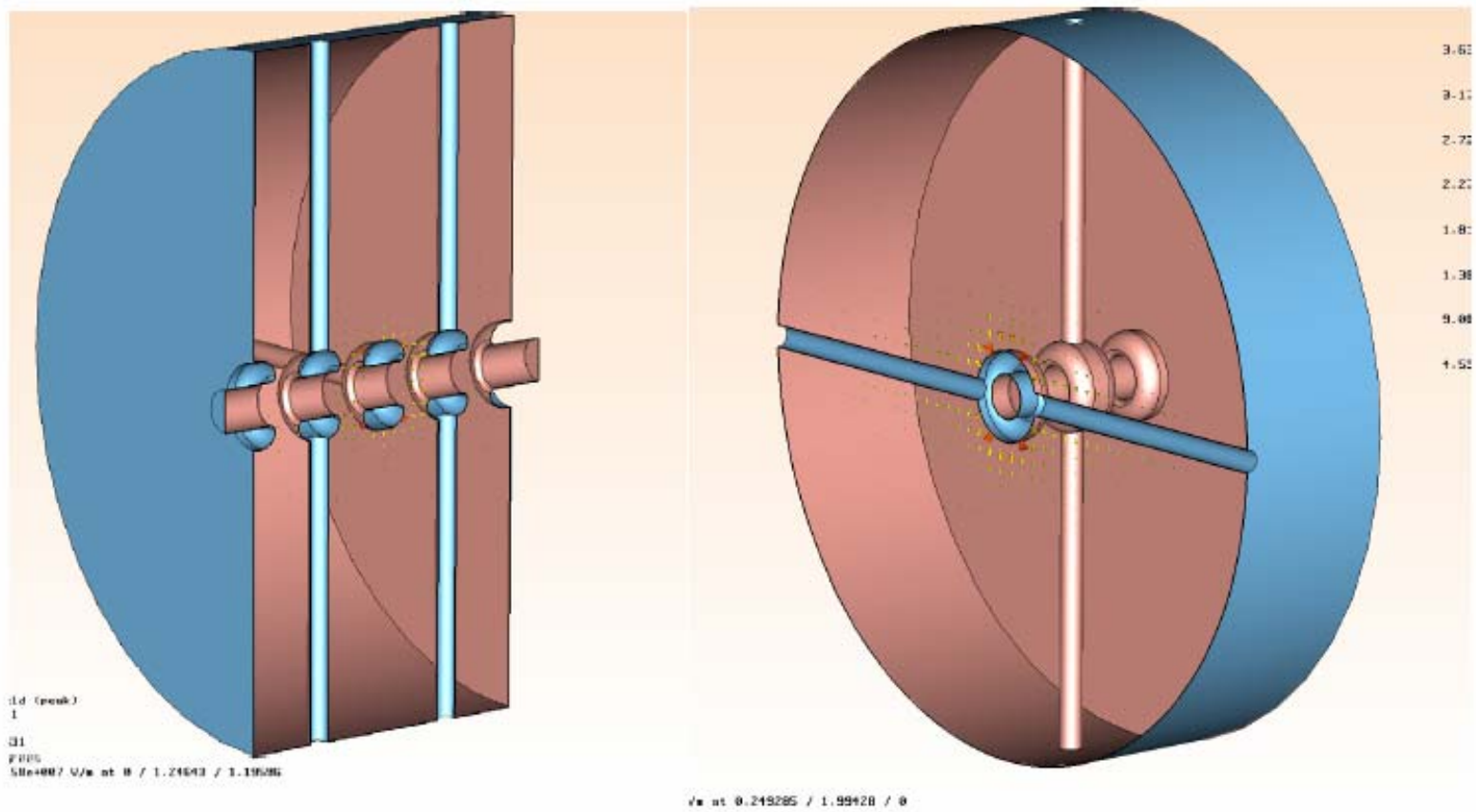
- **RFQ accelerates H^- from 0.065 to 3 MeV , Ip –up to 28 mA**
- **Now RFQs are standard devices for proton machines. There are good designs (J-PARC, SNS) and we can copy appropriate technical solutions.**
- **Our additional requirement for RFQ beam dynamics design is axisymmetric output beam to reduce halo formation in MEBT and RT TSR section. (P.Ostroumov's proposal).**



J-PARC 30 mA RFQ

Room-Temperature Triple-Spoke Resonator (RT TSR)

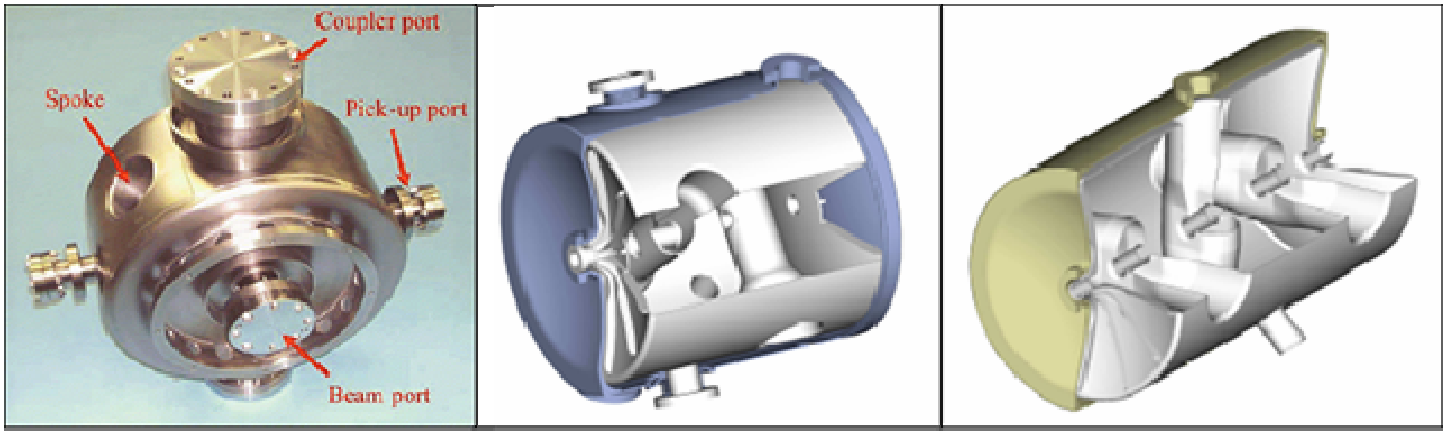
(aka Cross-bar H-type resonators) used from 3 MeV to 15 MeV



Shunt Impedance: 160 MΩ/m to 80 MΩ/m

325 MHz Spoke Resonators

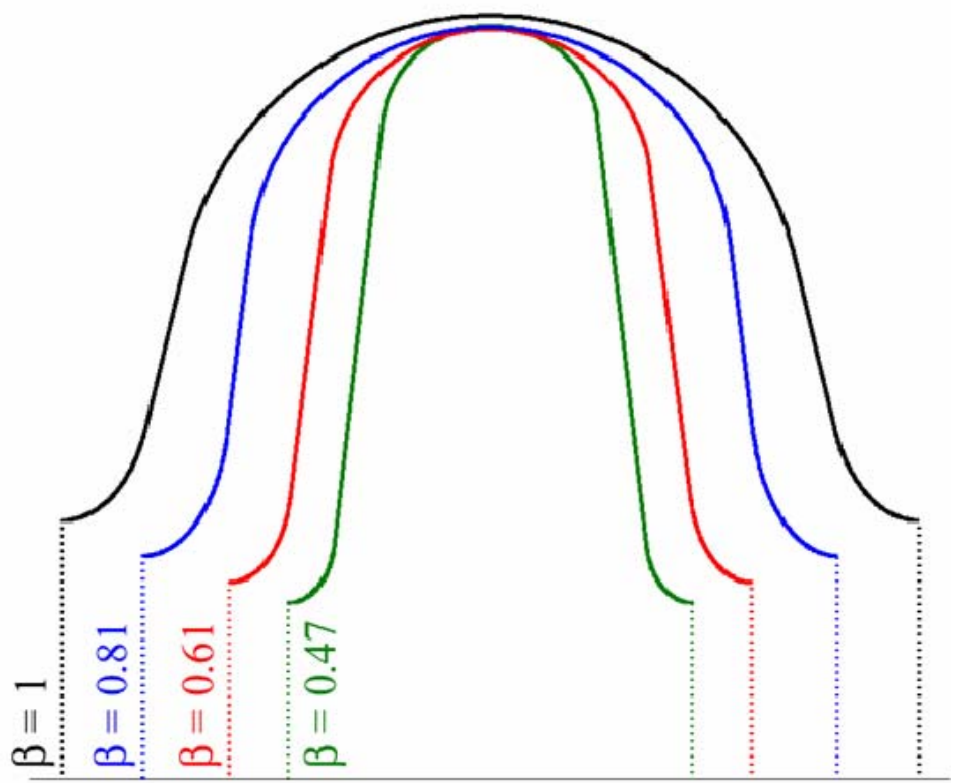
Ken Shepard's Talk



- **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.

1300 MHz Elliptical Cavites

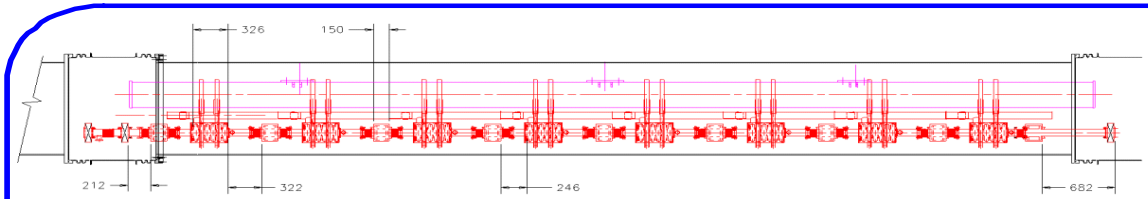


- **Beta<1 cavities are frequency scaled from 805 MHz designs for SNS/JLAB and RIA/MSU/JLAB**

1300 MHz Cryomodules

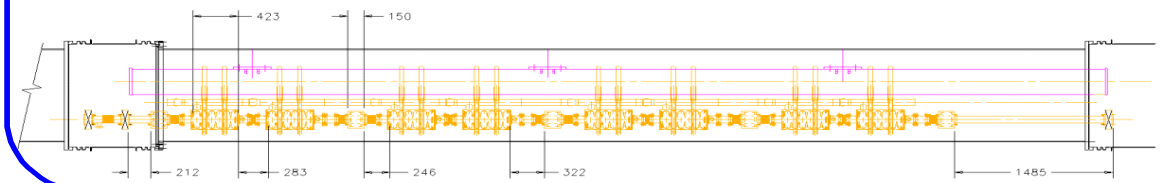
Giorgio Apolinari's Talk

1300 MHz ELLIPTICAL CAVITY CRYOMODULES: 2-4 TYPES

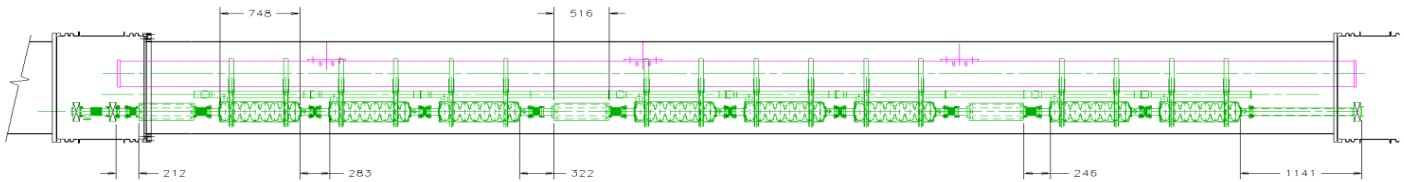


Beta = 0.47
2 Cryomodules
16 Cavities

OPTION OF ELLIPTICAL MEDIUM-BETA CAVITES 110 - 400 MeV

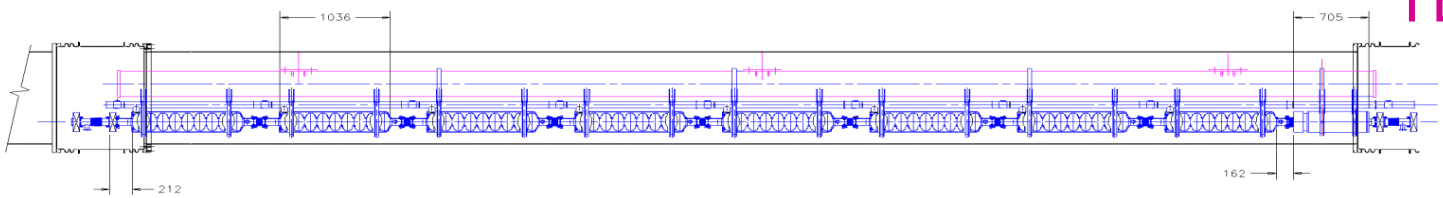


Beta = 0.61
4 Cryomodules
32 Cavities



Beta = 0.81
6 Cryomodules
48 Cavities

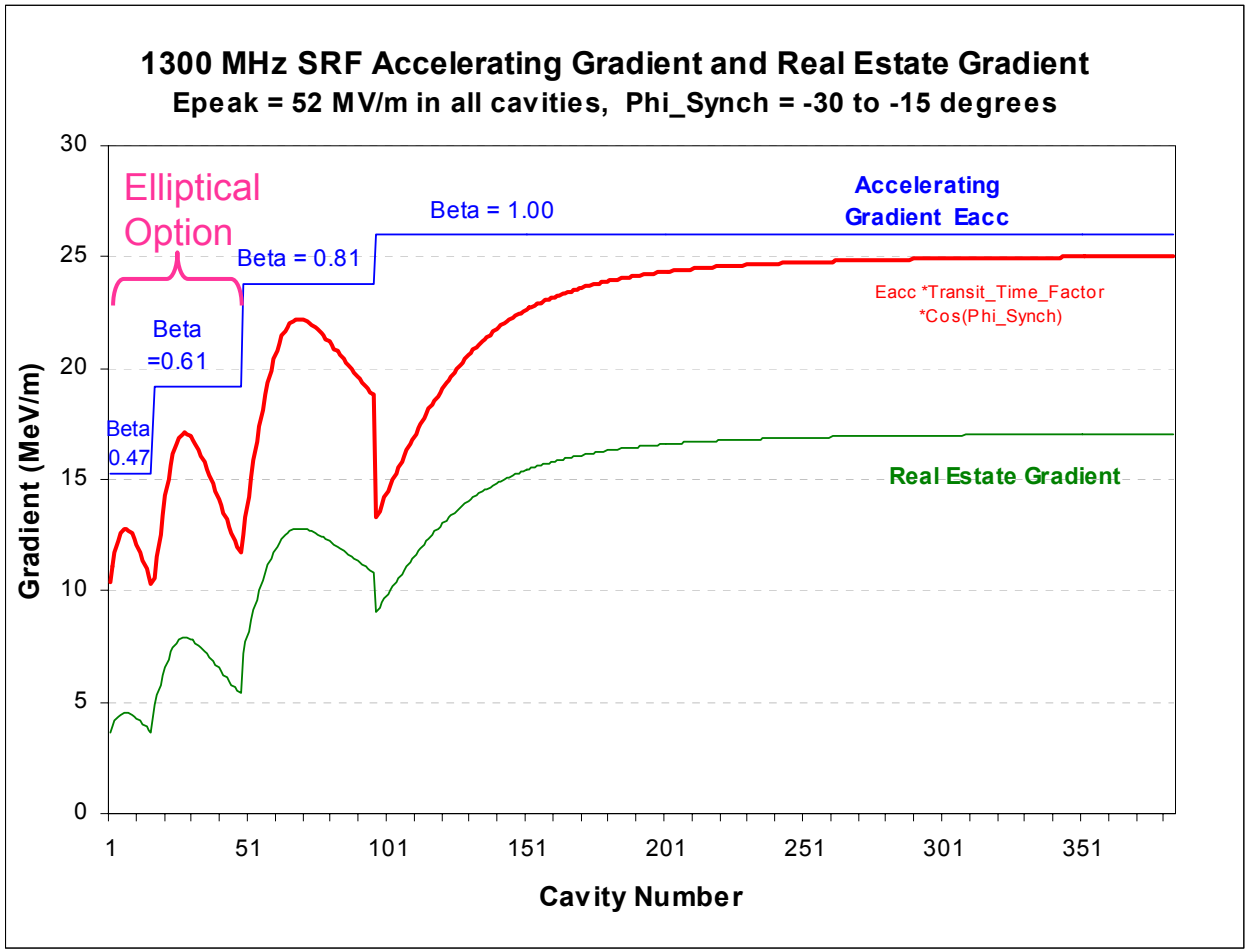
TESLA (TTF3)



Beta = 1.00
36 Cryomods
288 Cavities

1300 MHz Elliptical Cavites

Helen Edwards' Talk



- **2 types in baseline:**

  β=1 TESLA

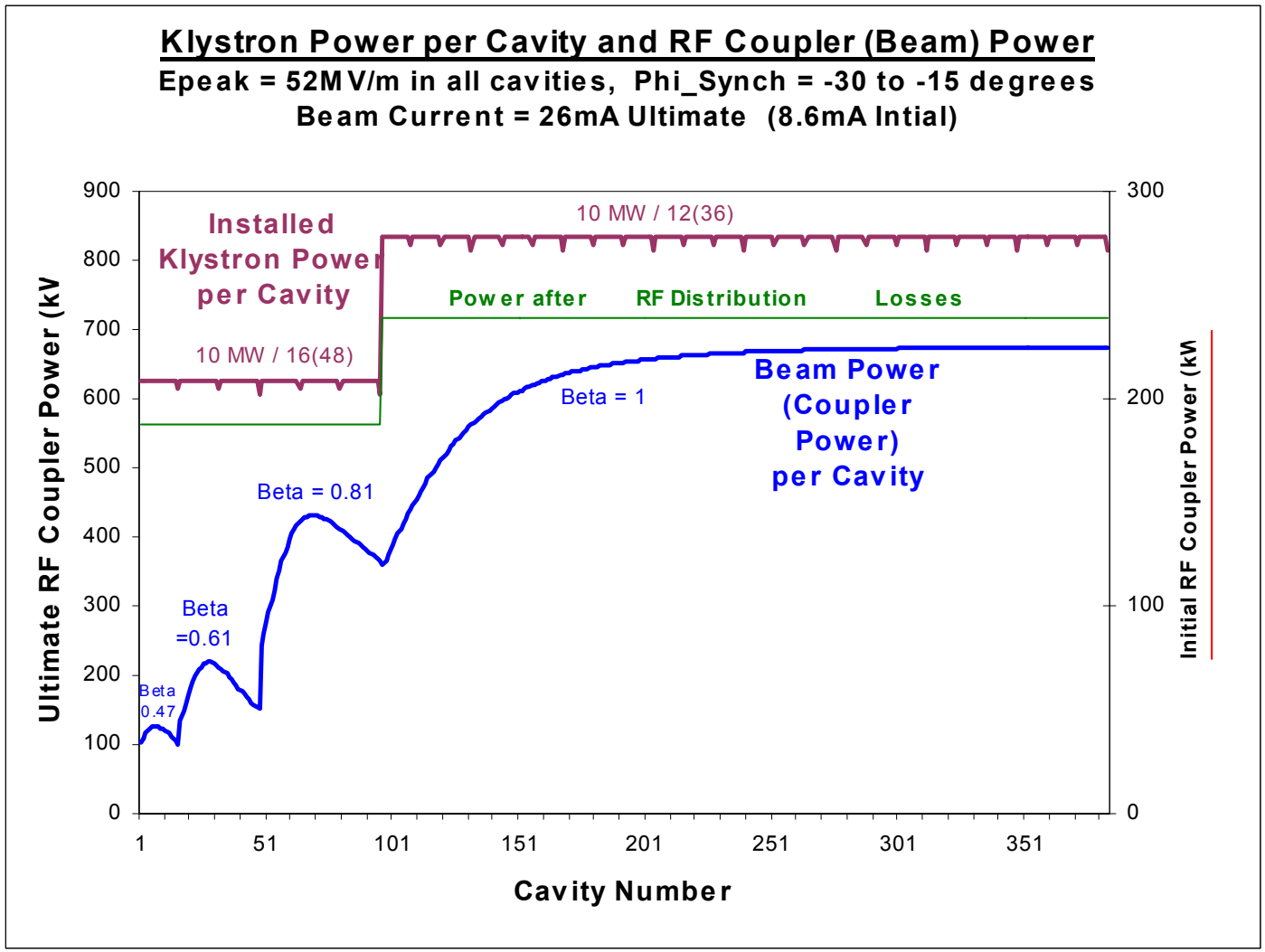
  β=0.81 ~ "SNS"

- **2 more types if Elliptical option taken:**

  β=0.61 ~ SNS

  β=0.47 ~ RIA

RF Power Couplers – 1300 MHz



- **RF Power Required for "Initial" Scenario is met by TESLA-500 Couplers**
- **"Ultimate" scenario has same specs as TESLA-800 RF Power couplers**

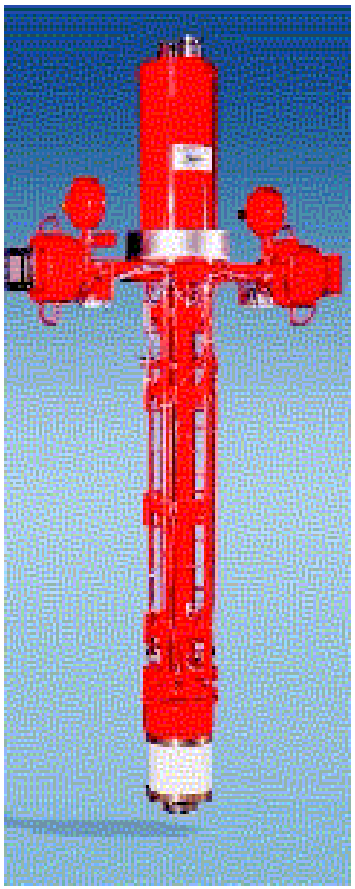
Klystrons

Al Moretti's Talk

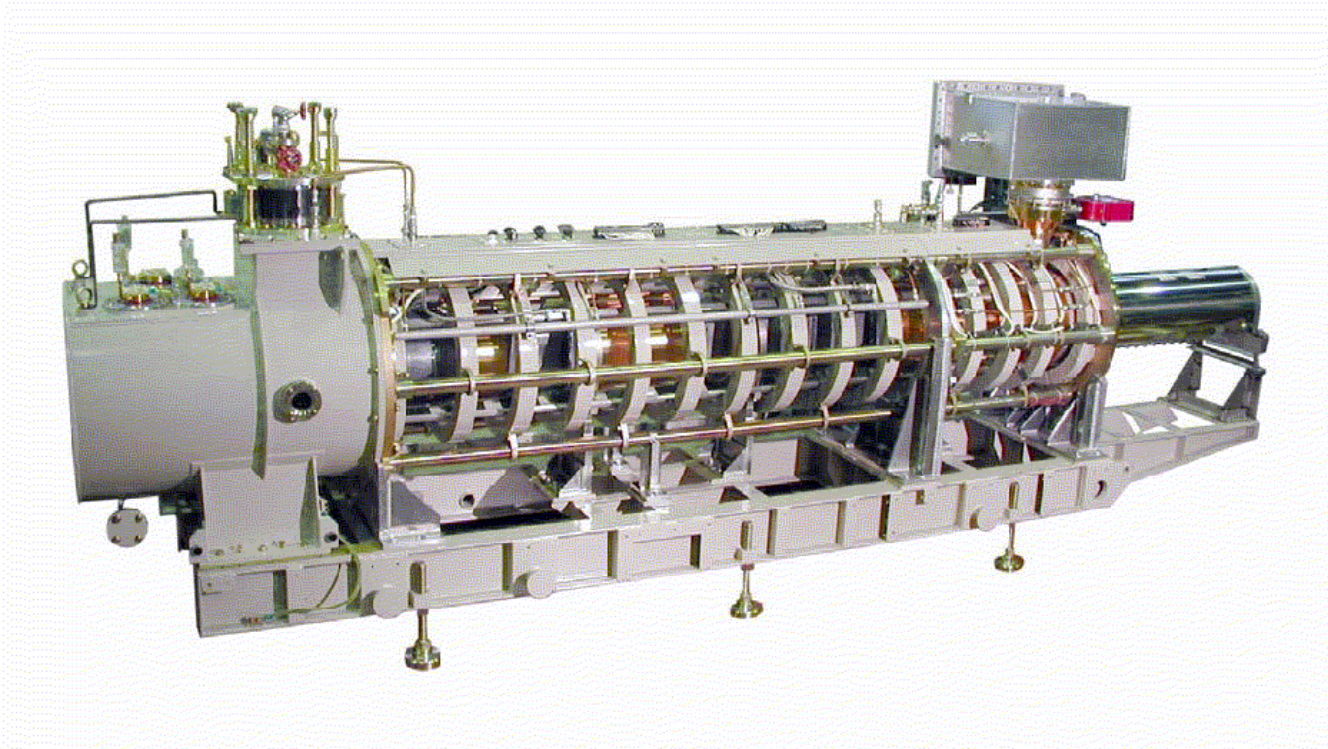
- **"Catalog Items" at selected frequencies**
- **1300 MHz – Tesla MBK (3 Vendors)**
- **325 MHz – Toshiba has delivered 17 for KEK**

- **4.5 msec pulse width needed for Initial Scenario**
  - Specified but not factory tested by the manufacturer
  - Necessary for "Initial" scenario
  - Motivation for building 4 msec Modulator ASAP

8 GeV Linac Klystrons – 2 Types



Thales TH1801
1300 MHz
10 MW
3 Delivered,
8 More Ordered



Toshiba E3740A
325 MHz 3 MW
(17 Delivered for JPARC
…we've ordered one…)

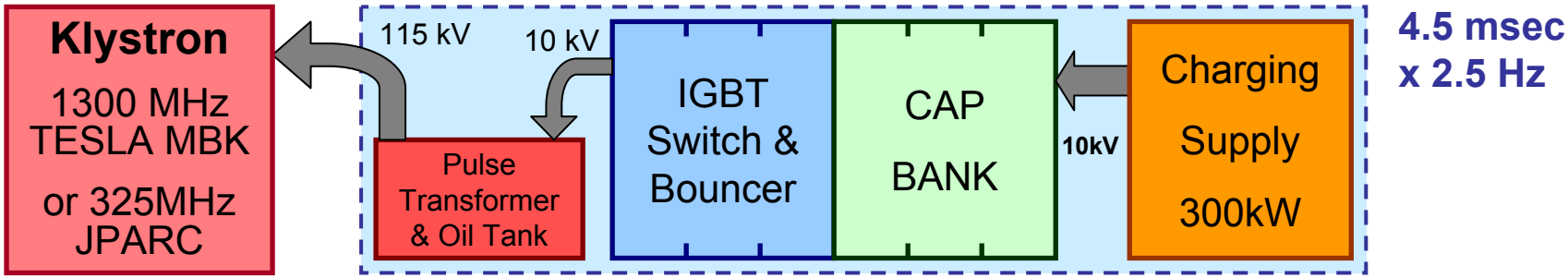
Modulators for Klystrons

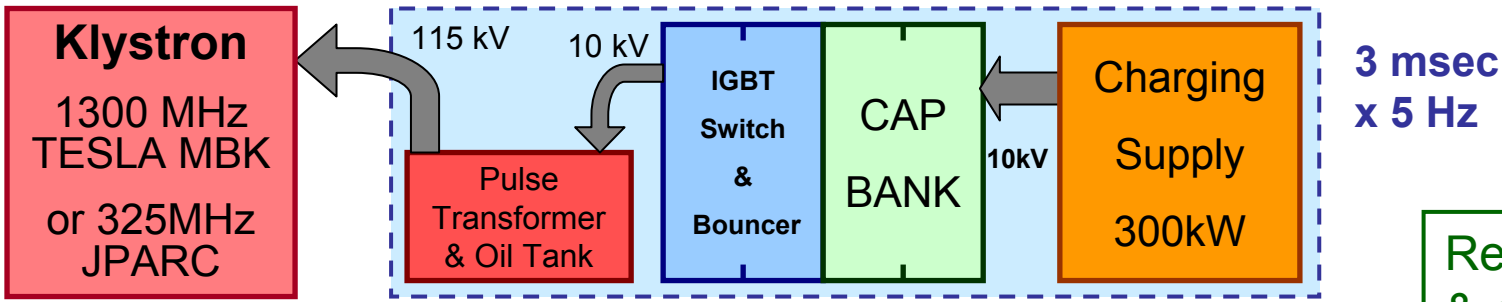
Dan Wolff's Talk

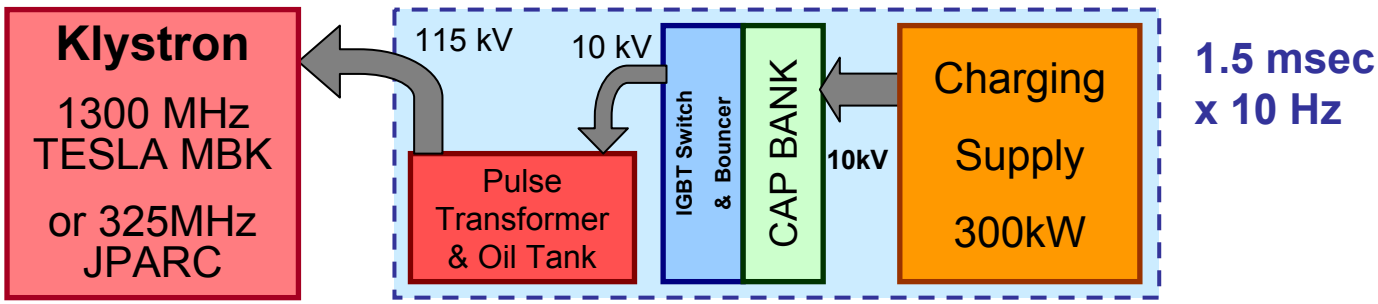
- **Biggest single component in RF costs**
- **Pfeffer, Wolff, Jensen & Co. (FNAL AD) have been making TESLA spec modulators for years**
- **FNAL Bouncer design in service at TTF since 1994**

Reconfigurable Klystron Modulators

Modulators can be reconfigured & parts re-used for RF power upgrade scenarios







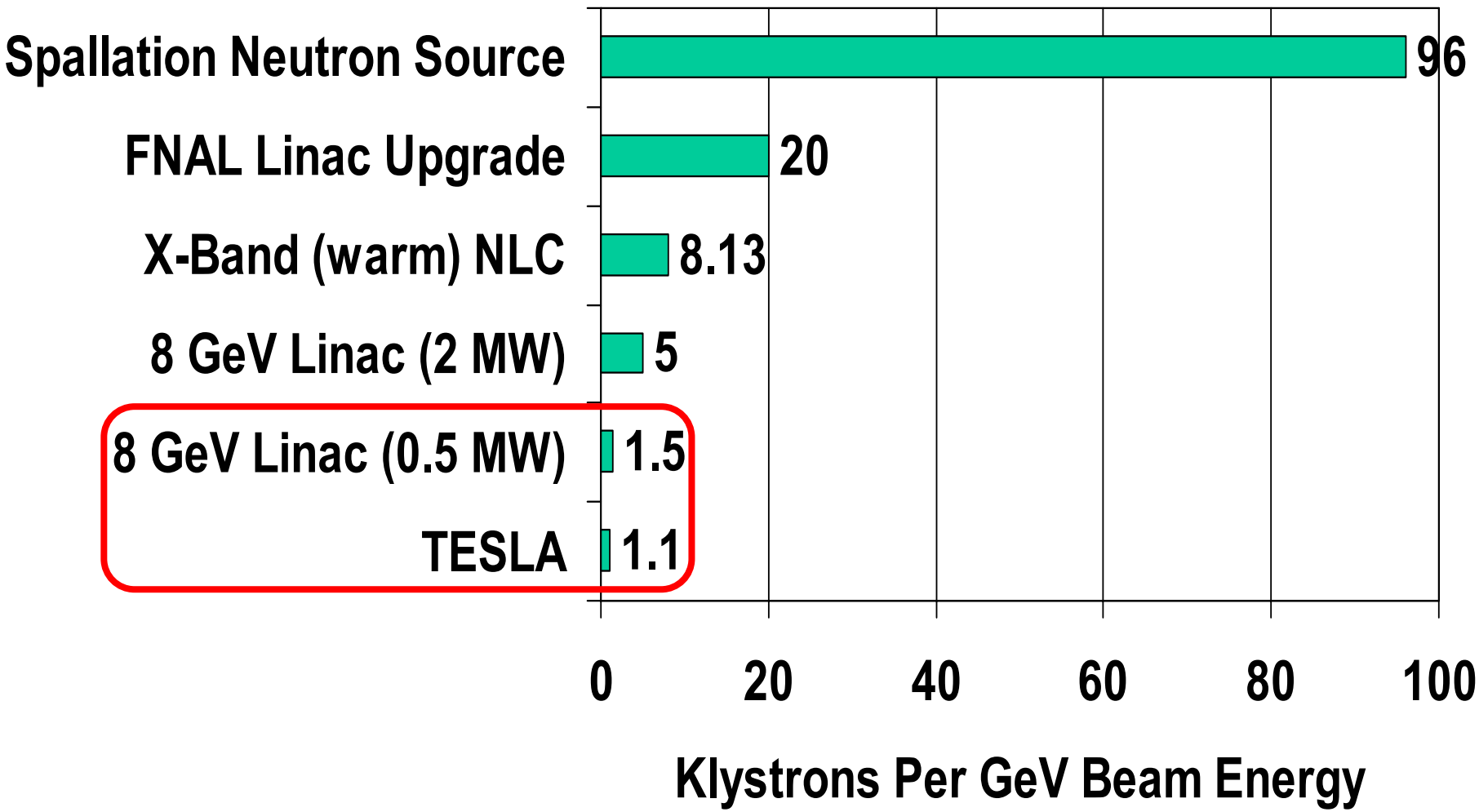
Reconfigure & add new modulators for 3, 2, or 1 msec beam pulse widths for upgrade scenarios

Fast Ferrite Phase Shifter R&D

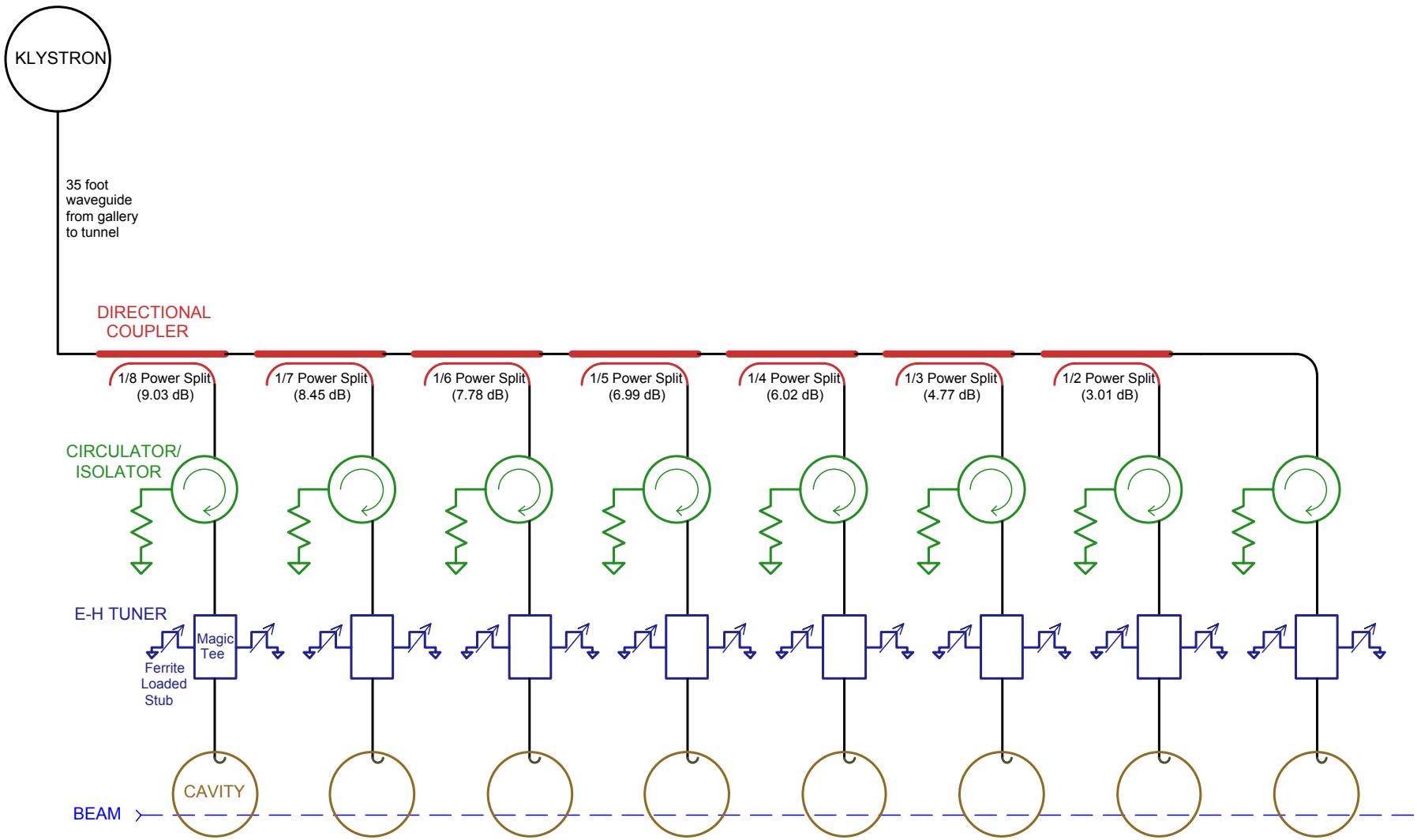
- **Provides fast, flexible drive to individual cavites of a proton linac, when one is using a TESLA-style RF fanout.** ***(1 klystron feeds 36 cavities)***
- **Also needed if Linac alternates between e and P.**
- **This R&D was started by SNS but dropped due to lack of time. They went to one-klystron-per-cavity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

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

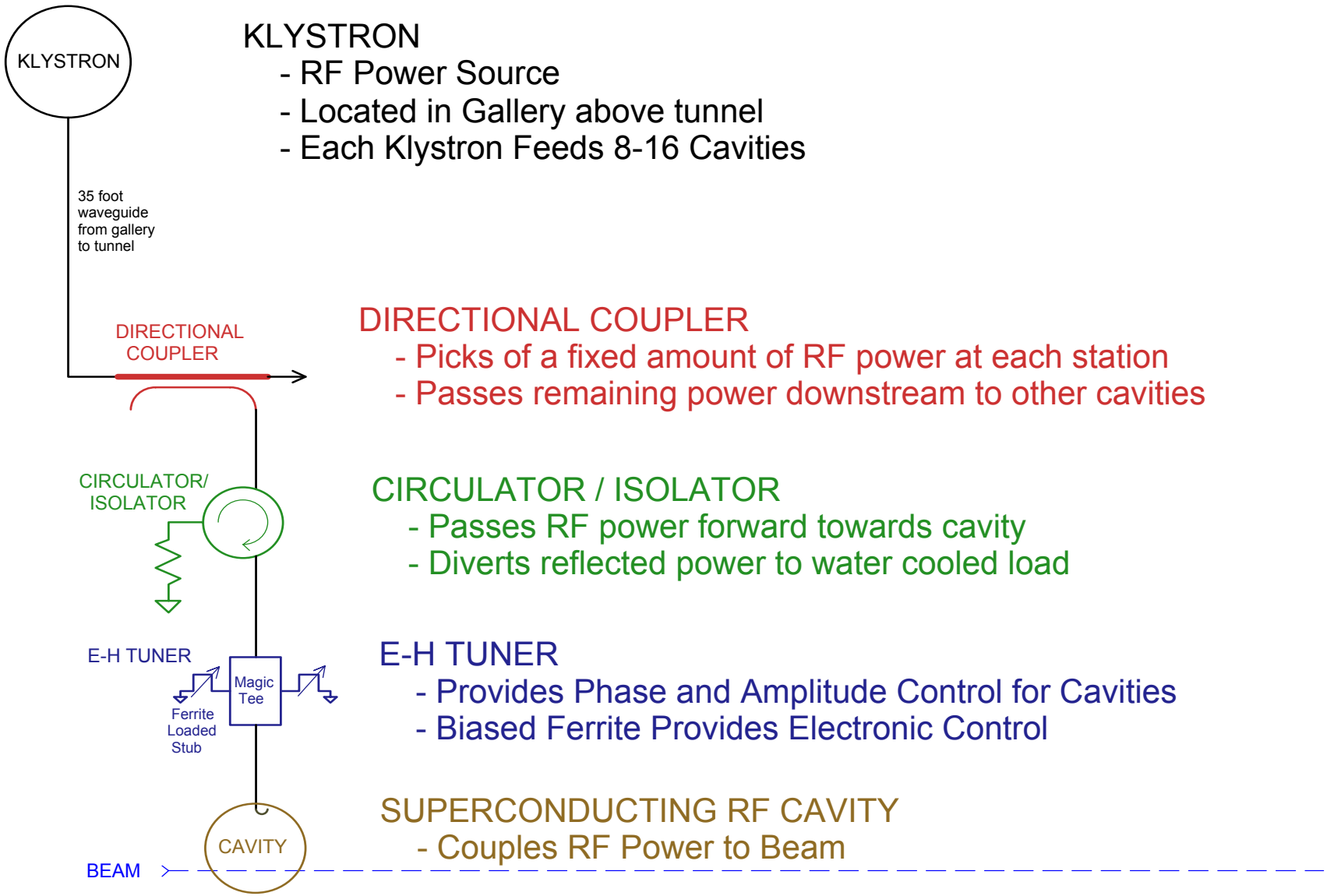
Cost Driver: Klystrons per GeV



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

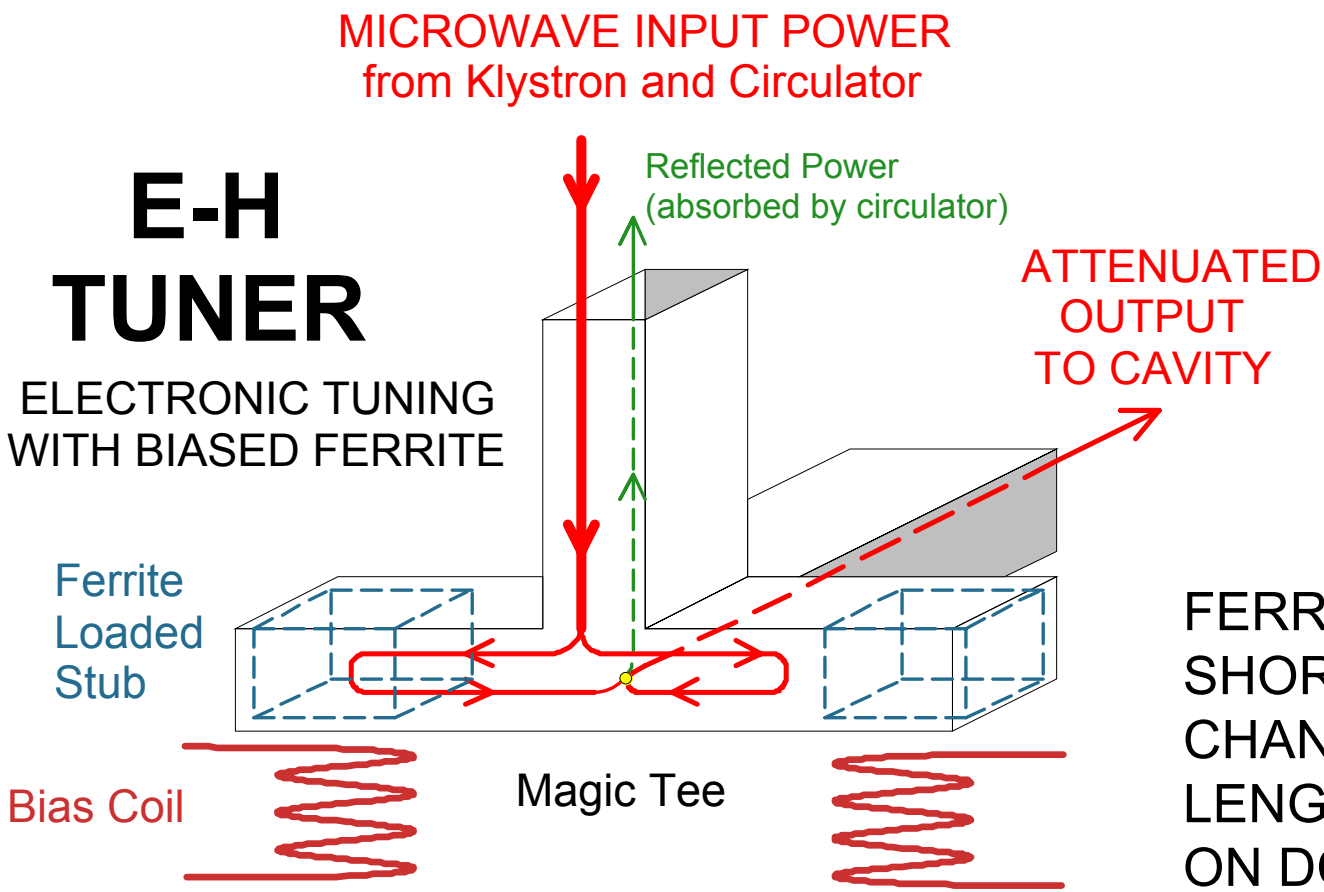
DIRECTIONAL COUPLER
- Picks of a fixed amount of RF power at each station
- Passes remaining power downstream to other cavities

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

ELECTRONICALLY ADJUSTABLE E-H TUNER (1300 MHz Waveguide)



E-H TUNER

ELECTRONIC TUNING
WITH BIASED FERRITE

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

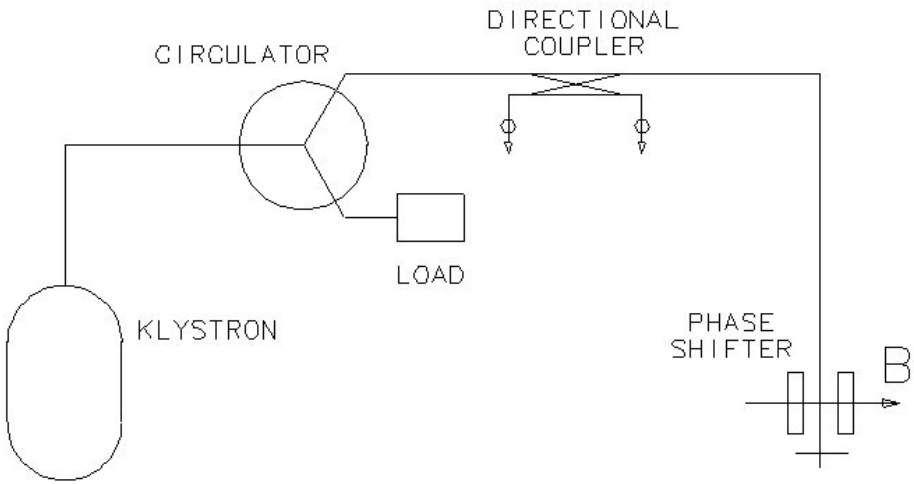
TWO COILS PROVIDE INDEPENDENT
PHASE AND AMPLITUDE CONTROL OF CAVITIES

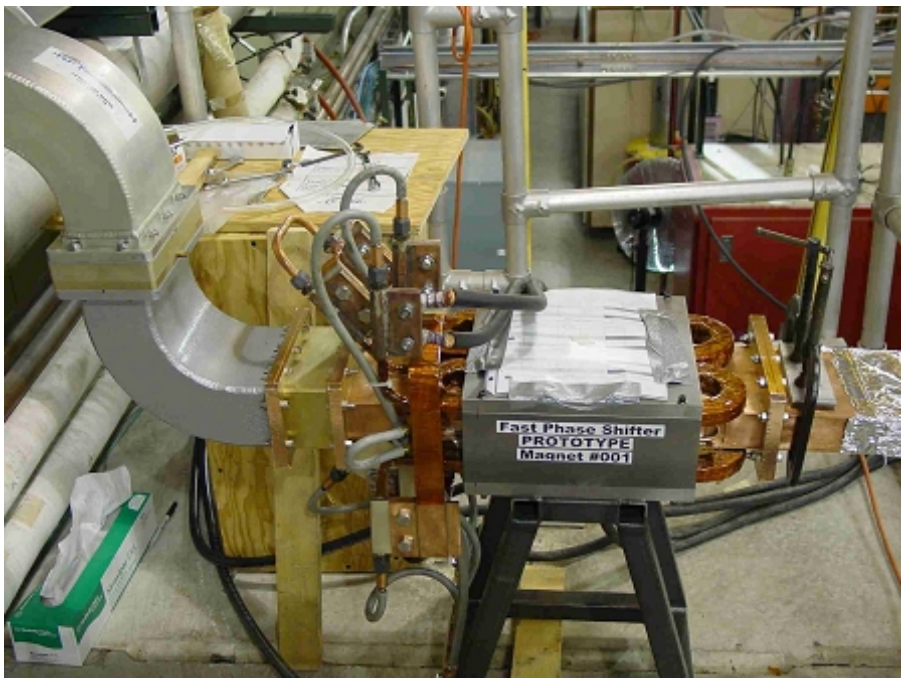
High Power Test at FNAL

A0 1300 MHz Klystron

T = 250 µsec

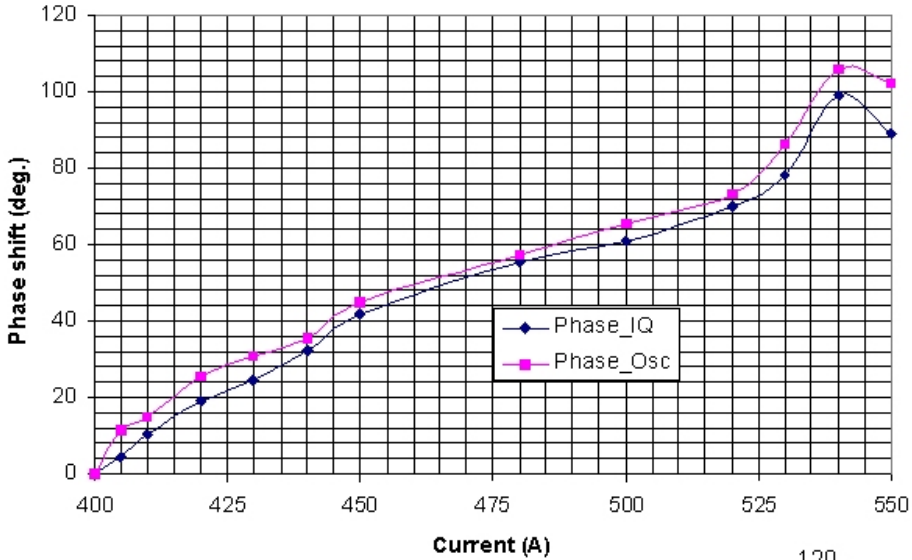
F = 5 Hz





Existing A0 interface was used for testing

High Power Test

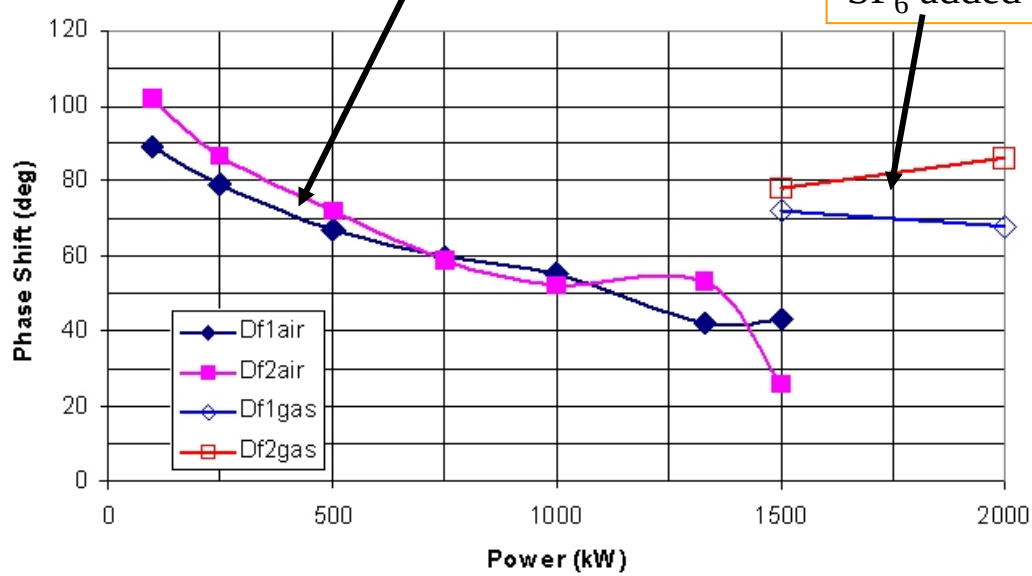


Two methods of phase measurements:

1. Oscilloscope measurements
2. Using available IQ modulator

Available phase zone is limited by sparking that develops near the resonance frequencies

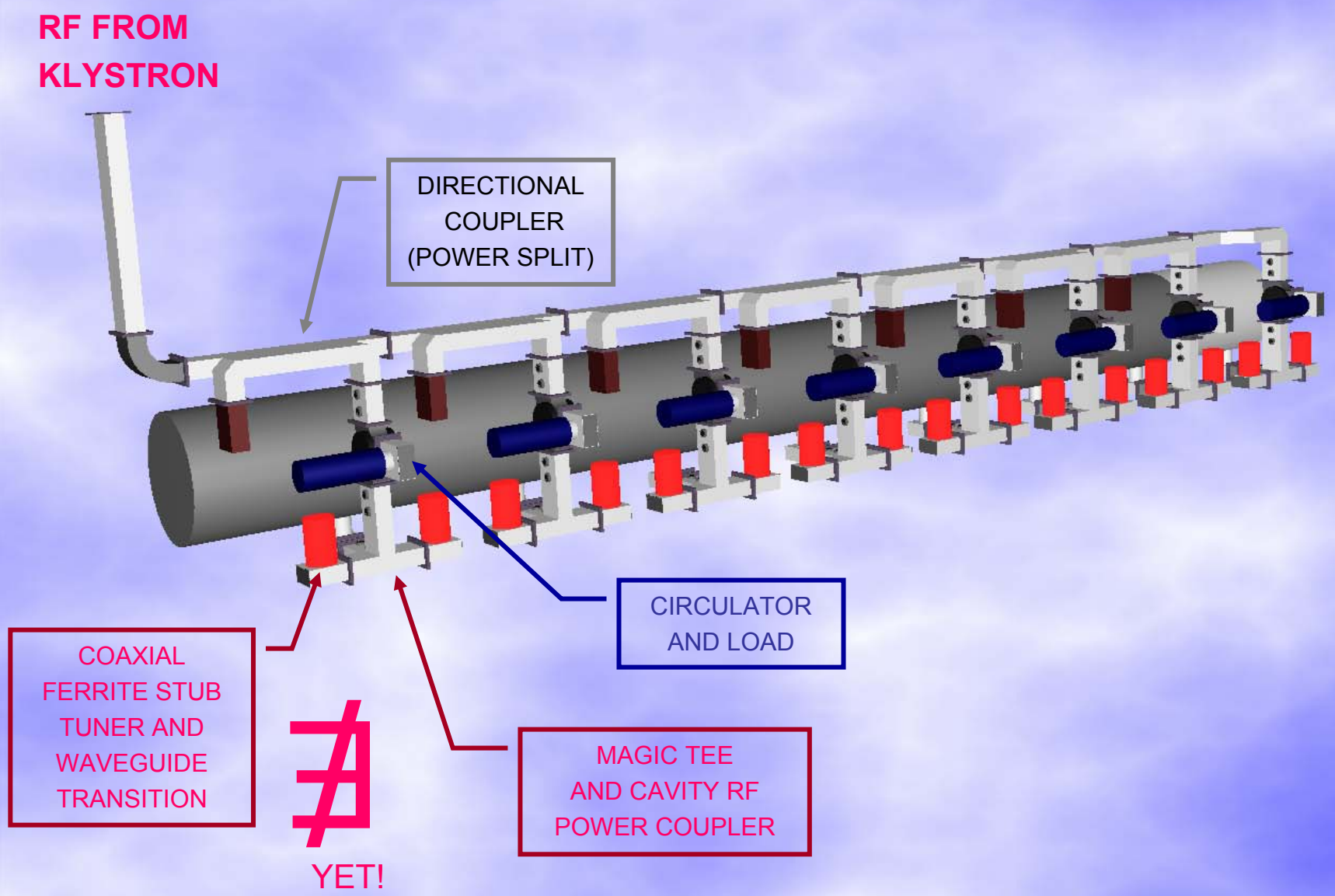
SF_6 added



Max Power - 2000 kW (req. 600 kW)

Phase shift - ~ 80° (req. 90°)

Advanced RF Distribution



3 Types of Fast-Ferrite Tuners

Iouri Terechkine's Talk

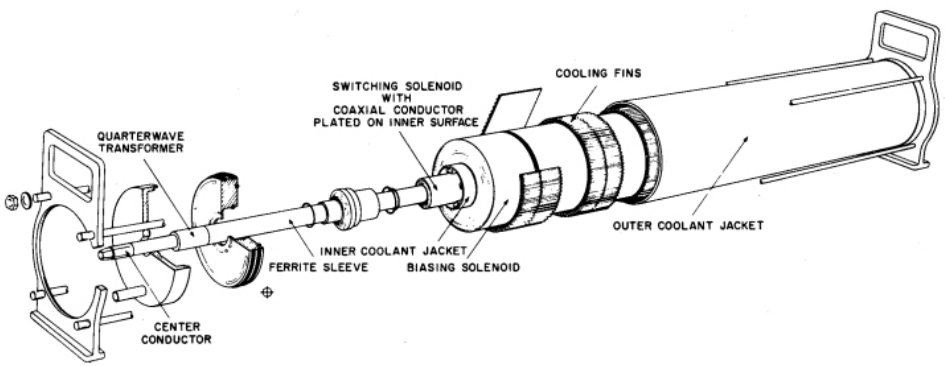
1. **Waveguide Style (prototyped in house)**
2. **Coaxial Style (prototyped in-house)**
3. **Strip Line Style (commercial procurement via AFT)**

- **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.**

Examples of Phase Shifters

Coaxial Device, 1968



L band (1.2 – 1.4 GHz)

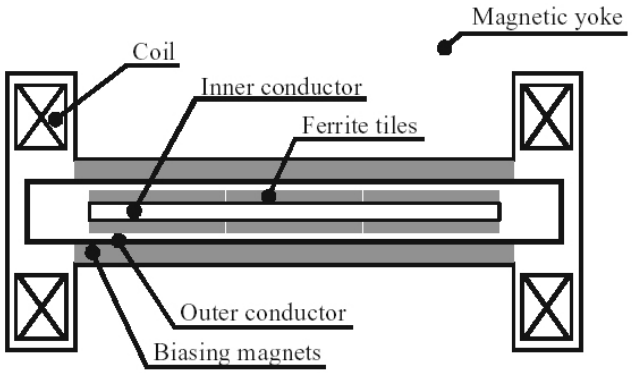
350 kW peak power

Field Range 800 – 1500 Oe

Phase shift - 600°

Insertion loss - 0.2 dB

Strip-line-based design,
AFT for CERN, ~ 2004



352 MHz

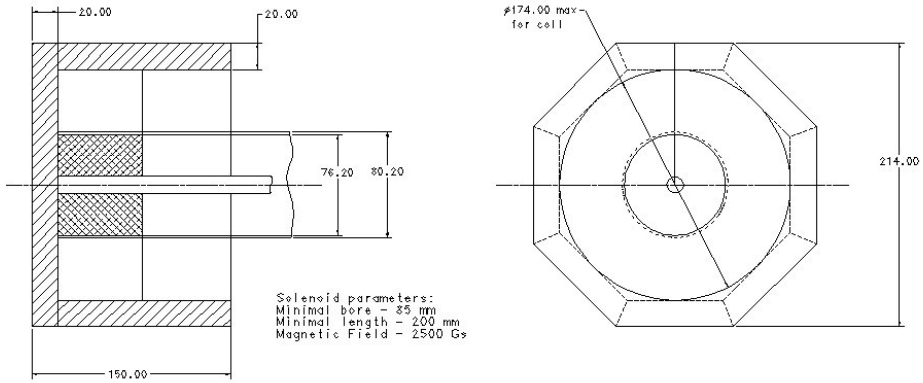
250 kW peak power

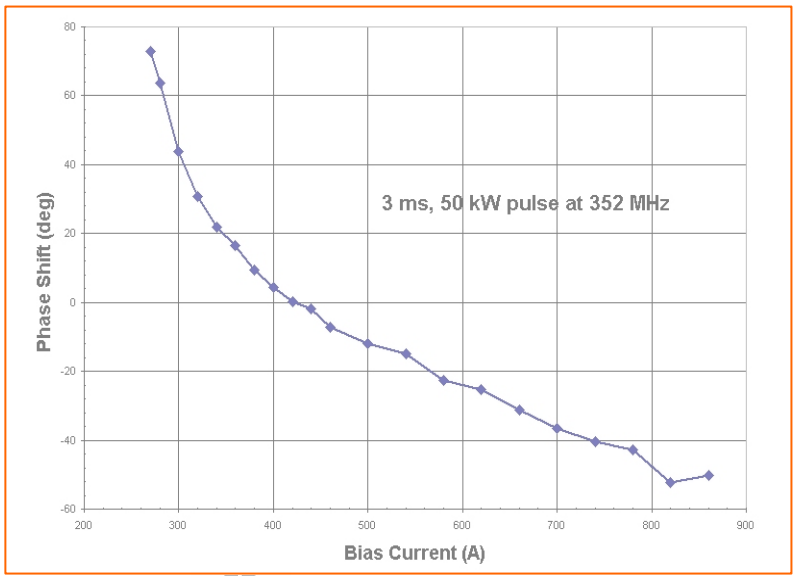
25% duty cycle

130º phase shift

Coaxial Phase Shifter

- Coax design is preferred at 325MHz
- In-house design tested to 660kW at 1300 MHz
- Tested at 250 kW at Argonne with APS 352MHz Klystron
- Fast coil and flux return should respond in ~50us





Energy Stability & Resonance Control

- **Linac Energy Stability Specification**
  - Momentum acceptance at MI injection: > +/- 50 MeV
  - Transition Crossing: +/-15 MeV ← Driving Spec
- **Resonance Control Drives Specs for Fast Ferrite Phase Shifters (response time)**
  - M. Huening's Simulations ➔ 200 usec marginally OK
  - Prototypes being designed for 30-50 usec response
  - Believe present specs for phase shifters = overkill
- **Simulations, FPGA based LLRF, & Beams at SMTF will be key**

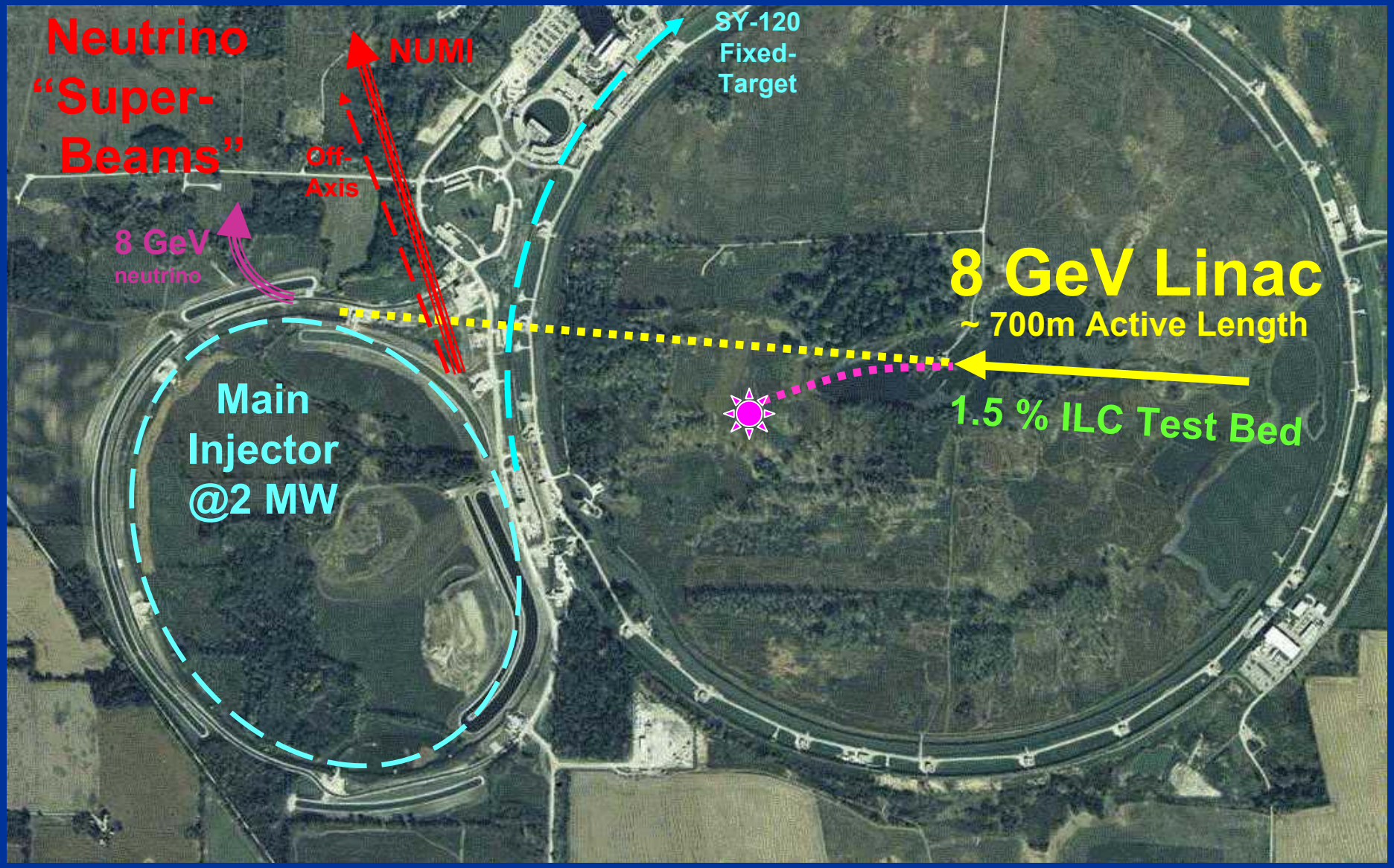
Cryogenics

Jay Theilacker's Talk

- **Back End: 0.4 →8 GeV : copy of TESLA**
- **Front End: (4.5K pool boiling): copy of RIA**

- **Load ~ 5 kW @ 4.5K equiv, (9kW Installed)**
- **Comparable to SNS in scope (& cost)**

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



The FY06 Budget Tsunami

- Cancellation of BTeV
- Tevatron shuts off for good in ~2009
- B-factory operations cease ~2008

➔ No collider physics in US after ~2009

- Consequences for Nuclear Physics worse:
  - Choice of shutting down RHIC or CEBAF
    - See NSC charge letter: http://usnuclearscience.org
  - RIA project on indefinite hold

Spectrum of Reactions to the FY06 Budget at FNAL

Reaction from the "Blue States":

" The FY06 budget alows us to use the money freed up by the cancellation of BTeV and Tevatron operations and B-Factory operations to push for the Linear Collider as fast as possible"

(the SCRF Proton Driver is somewhere in the center …)

Reaction from the "Red States":

" The FY06 budget proves the Linear Collider is not going to happen in our lifetimes, and we should put our money into an affordable neutrino program with big detectors and the cheapest possible accelerator upgrades to get more protons as soon as possible"

There are good people on both sides of this debate, and it is impossible to prove either one of these reactions is wrong…

The SCRF Proton Driver Occupies the Middle Ground in this Debate

- Build a ~$500M Linear Collider Test Facility (the Proton Driver) to show that we know what it costs to build the US – ILC
  - Probably pays for itself in contingency reduction alone
- Use the Neutrino program of the Proton Driver to generate the "guaranteed physics payoff" for this demonstration facility… should make funding easier given uncertainties in ILC time line.
- Put ourselves in a position to make a fast start to the ILC when LHC physics and international politics solidifies: "go" in 2010 ➔ funds in 2013
  - Use the Proton Driver project to prototype a multi-lab collaboration capable of building the US-ILC.

A Budget Profile that Might be Successfully Defended

- FY08 - FY12: ~$100 M/yr PD/ILC facility
  - Mostly redirected, hope for some new money
  - Neutrino detector initiatives through both redirection and collaboration
- FY13 -- start of US-ILC construction
  - U.S. $500M/yr not unreasonable following successful completion of $500M SCRF Proton Driver project
  - Number of years depends on progress on ILC cost reduction:
  - *I'm personally very hopeful on SCRF cost reduction, and the Proton Driver is the vehicle to demonstrate it.*