A Compact X-band Drive Linac for an FEL

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SLAC

Overview

The history of X-Band (11.4 GHz) rf technology development naturally divides into two parts:

1) From the late 1980’s to 2004, development aimed at demonstrating viability for the proposed Next Linear Collider (NLC)
    - SLAC spearheads this effort with a major contribution from KEK, and later, FNAL on structure development
2) After the 2004 International Technology Review Panel (ITRP) selected L-Band superconducting rf technology for the International Linear Collider (ILC):
    - Continue X-band structure and rf source work at a low level
    - In 2007, CERN Compact Linear Collider (CLIC) chooses 12 GHz (from 30 GHz) and the SLAC/CERN/KEK X-band structure collaboration ramps up along with the more forward looking US High Gradient Program
    - LCLS success with low bunch charge operation makes a compact X-band linac driven XFELs a possibility
    - ILC cost, LHC delay and the CLIC drive beam risk has prompted interest in using X-band klystrons for the initial stage of CLIC

X-Band (11.4 GHz) RF Technology

Chose X-Band technology as an evolutionary next step for the Next Linear Collider (NLC) from the SLAC Linac S-Band (2.86 GHz) technology.

In general want higher rf frequency because:

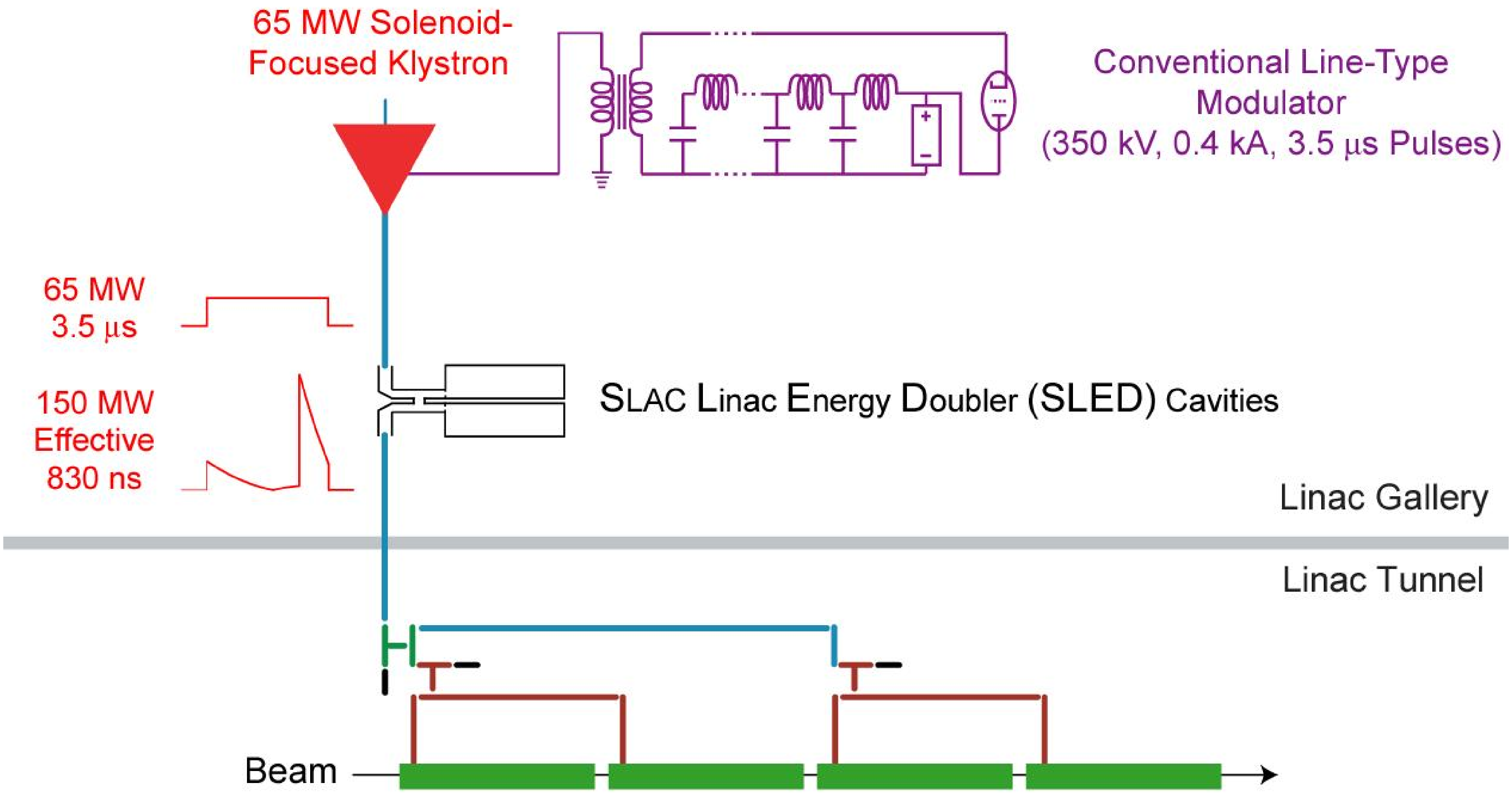
- Less rf energy per pulse is required, so fewer/smaller rf components.
- Higher gradients achievable, so shorter linacs (with reasonable efficiencies)

Offsetting these advantages are the requirements of:

- High power (100’s MW) HV pulses with fast rise times (100’s ns).
- High surface gradients in the klystrons, waveguide transport system and accelerator structures.
- Tight alignment tolerances due to stronger wakefields (much less an issue for light sources where the bunch charge is low, and bunch length short).

SLAC Linac RF Unit

(One of 240, 50 GeV Beam)



65 MW Solenoid-Focused Klystron

Conventional Line-Type Modulator
(350 kV, 0.4 kA, 3.5 µs Pulses)

65 MW
3.5 µs

150 MW
Effective
830 ns

SLAC Linac Energy Doubler (SLED) Cavities

Linac Gallery

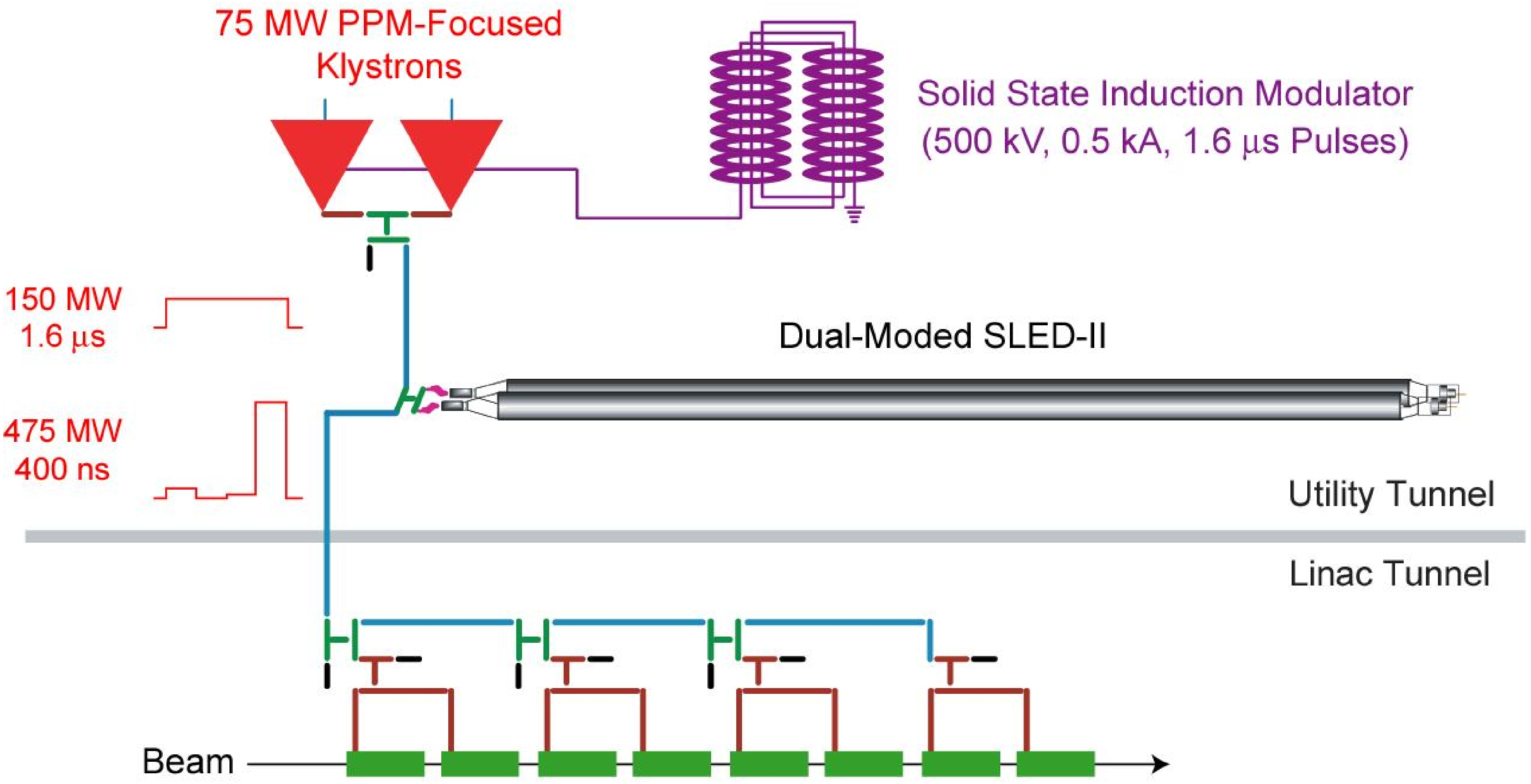
Linac Tunnel

Beam

Four 3.0 m Accelerator Structures (20 MV/m Unloaded)

NLC Linac RF Unit

(One of ~ 2000 at 500 GeV cms, One of ~ 4000 at 1 TeV cm)



75 MW PPM-Focused Klystrons

Solid State Induction Modulator (500 kV, 0.5 kA, 1.6 μs Pulses)

150 MW 1.6 μs

Dual-Moded SLED-II

475 MW 400 ns

Utility Tunnel

Linac Tunnel

Beam

Eight 0.6 m Accelerator Structures (65 MV/m Unloaded, 52 MV/m Loaded)

Next Linear Collider Test Accelerator (NLCTA)

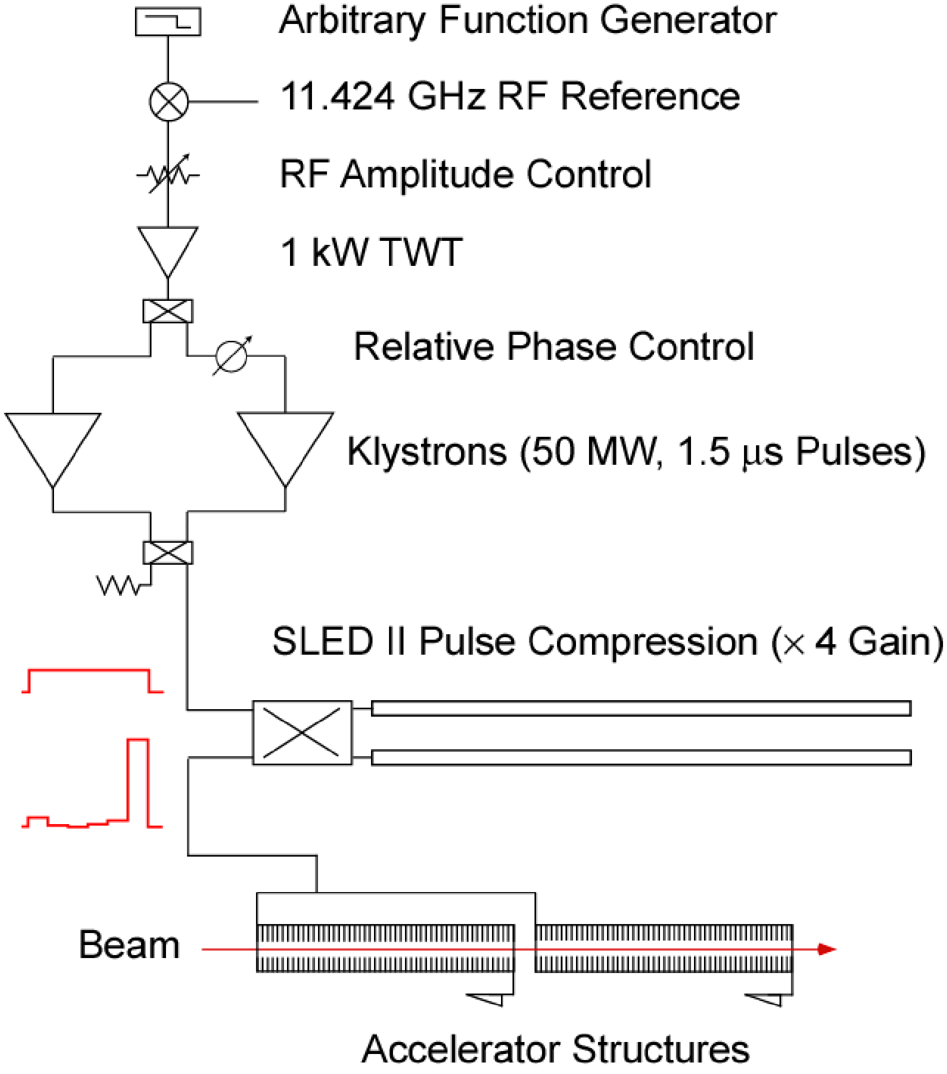
In 1993, construction began using first generation X-Band components.

In 1997, demonstrated 17% beam loading compensation in four, 1.8 m structures at ~ 40 MV/m.

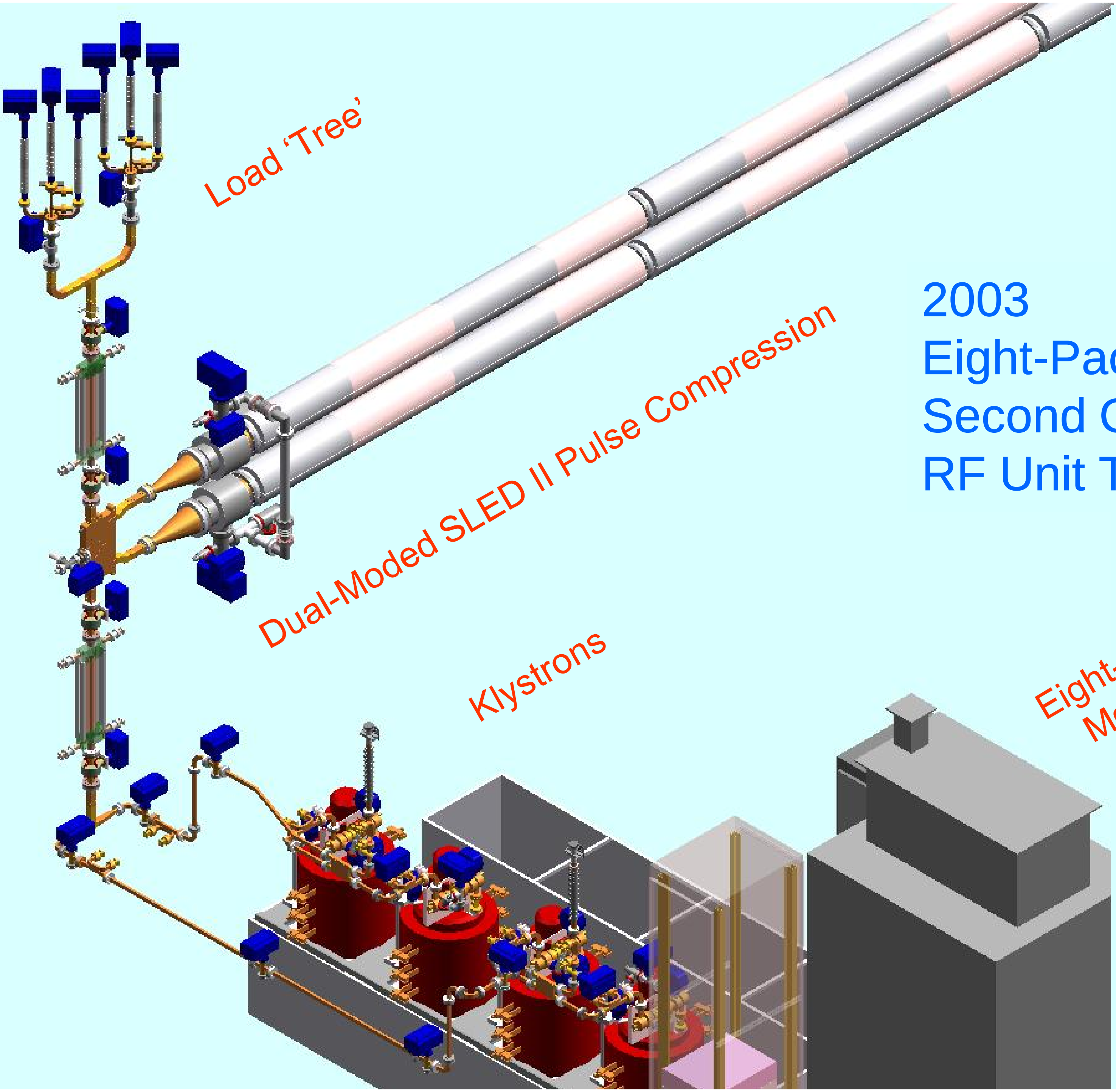
In 2000-10, used for high gradient studies and other programs (E163, Echo)

Future: Test X-band guns, rf systems and light source bunching/emittance schemes

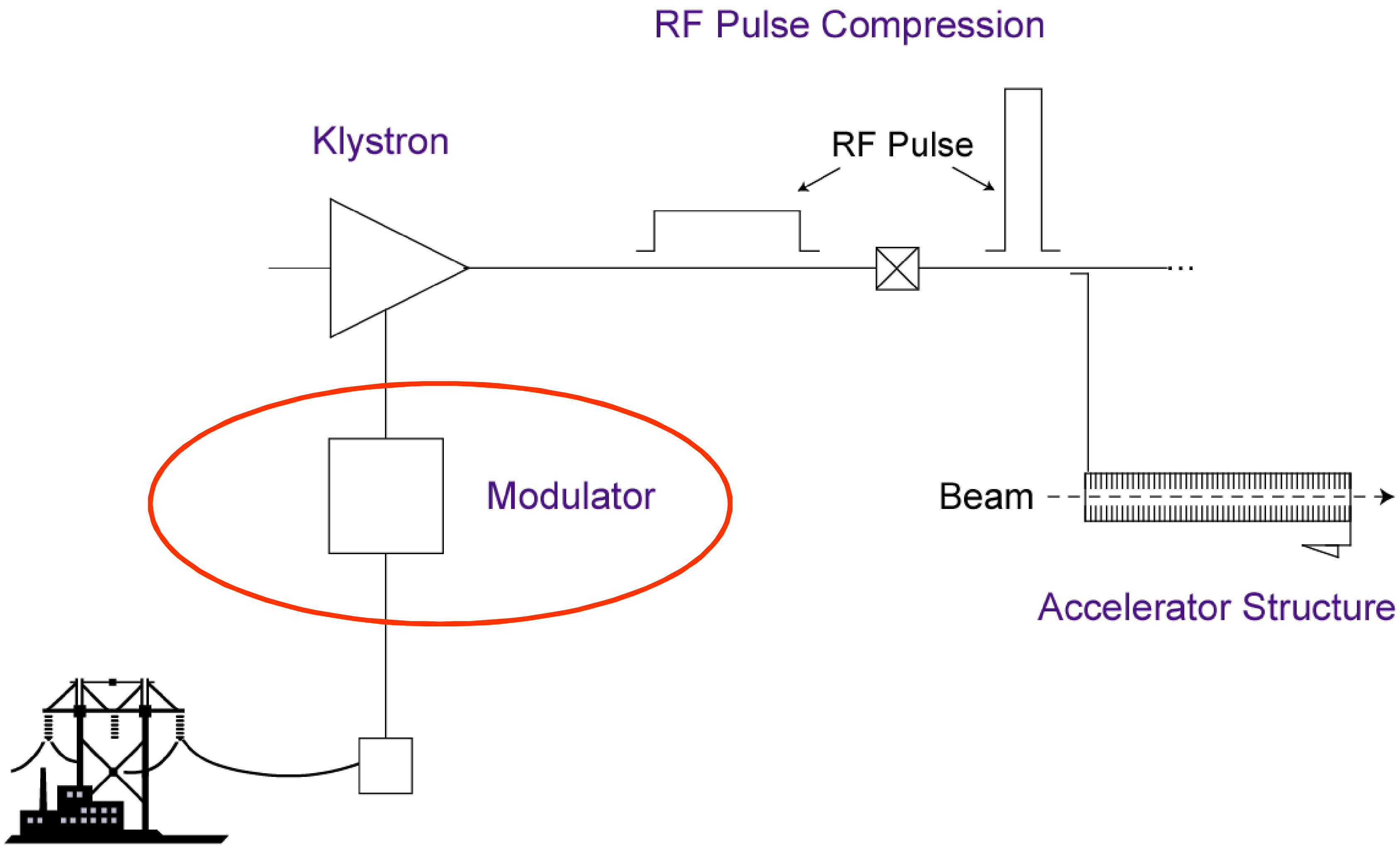
NLCTA Linac RF Station (One of Two)



2003
Eight-Pack Project: Second Generation RF Unit Test



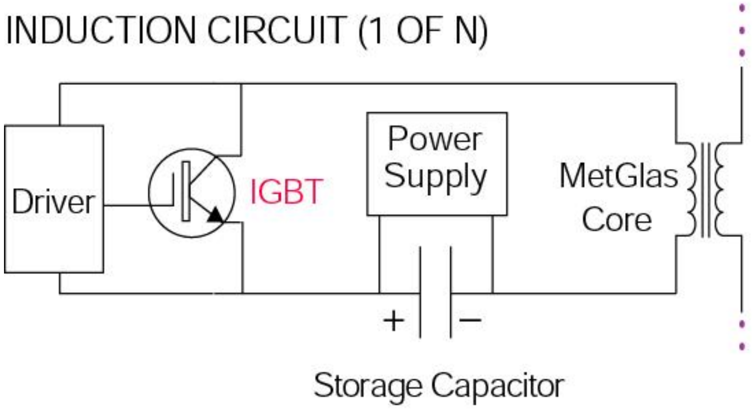
RF Component Performance

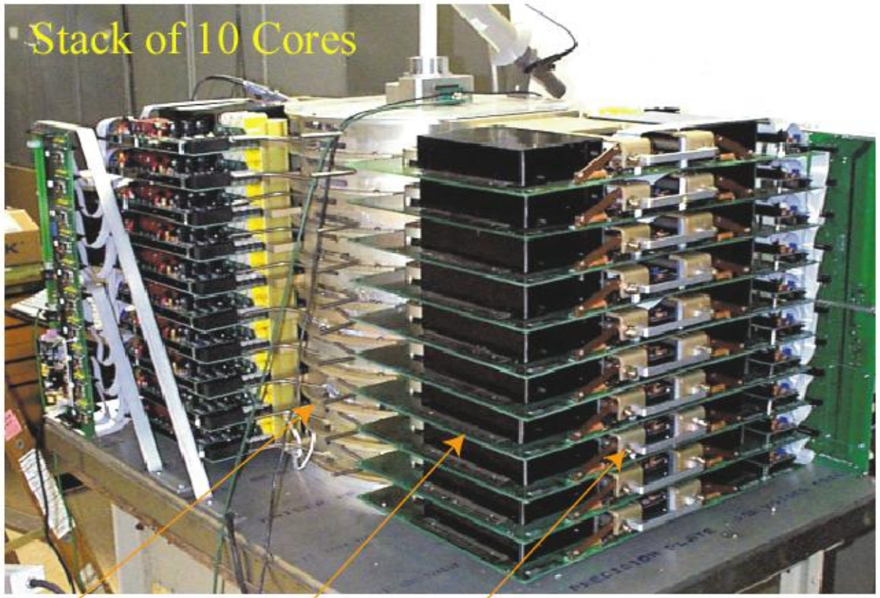


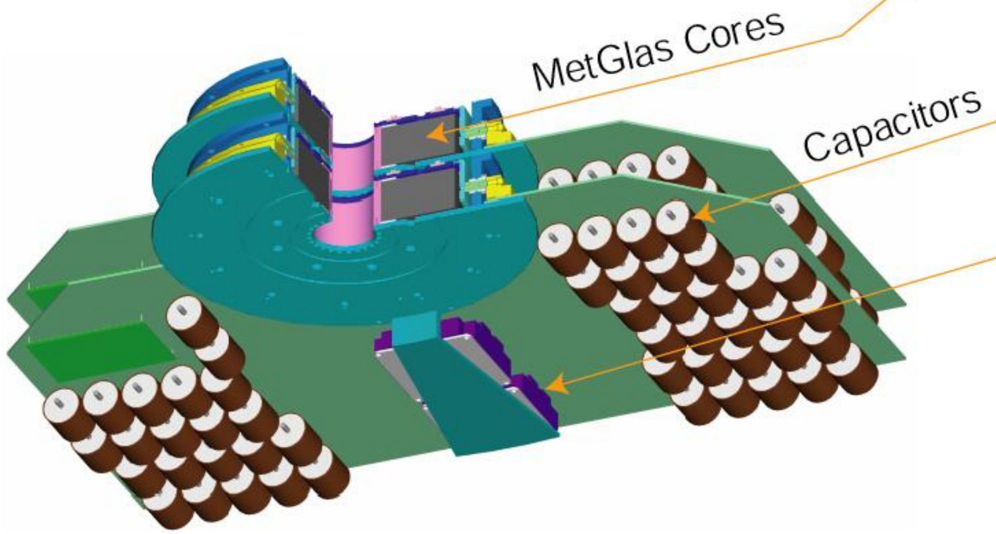
Solid State Induction Modulator

SUM MANY LOW VOLTAGE (~ 2 kV)
SOURCES INDUCTIVELY

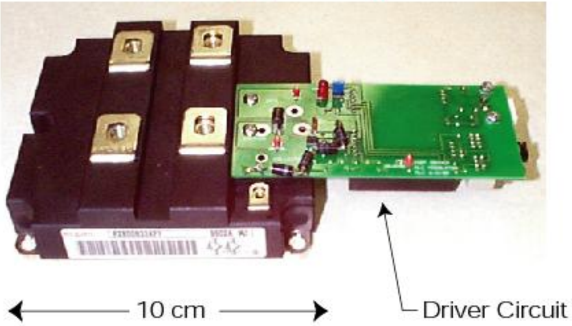
INDUCTION CIRCUIT (1 OF N)







Insulated Gate Bipolar Transistors



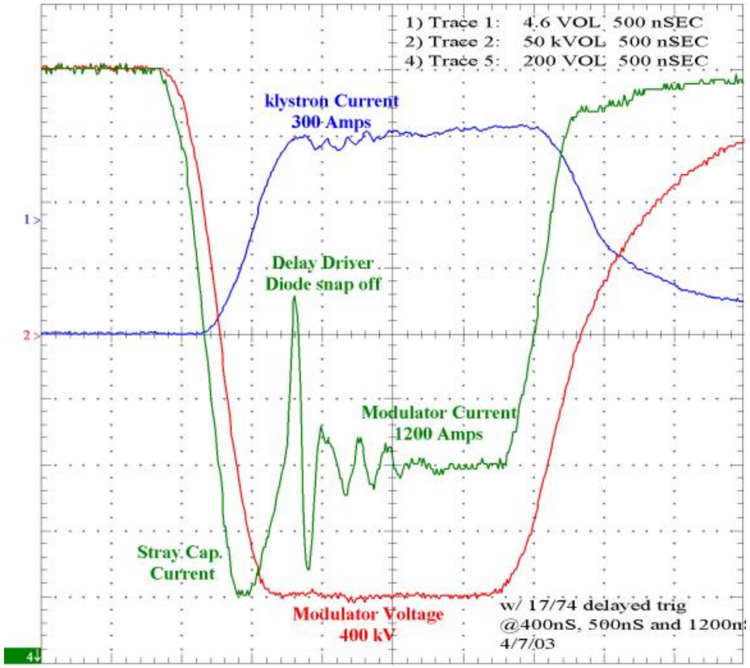
Eight-Pack Modulator

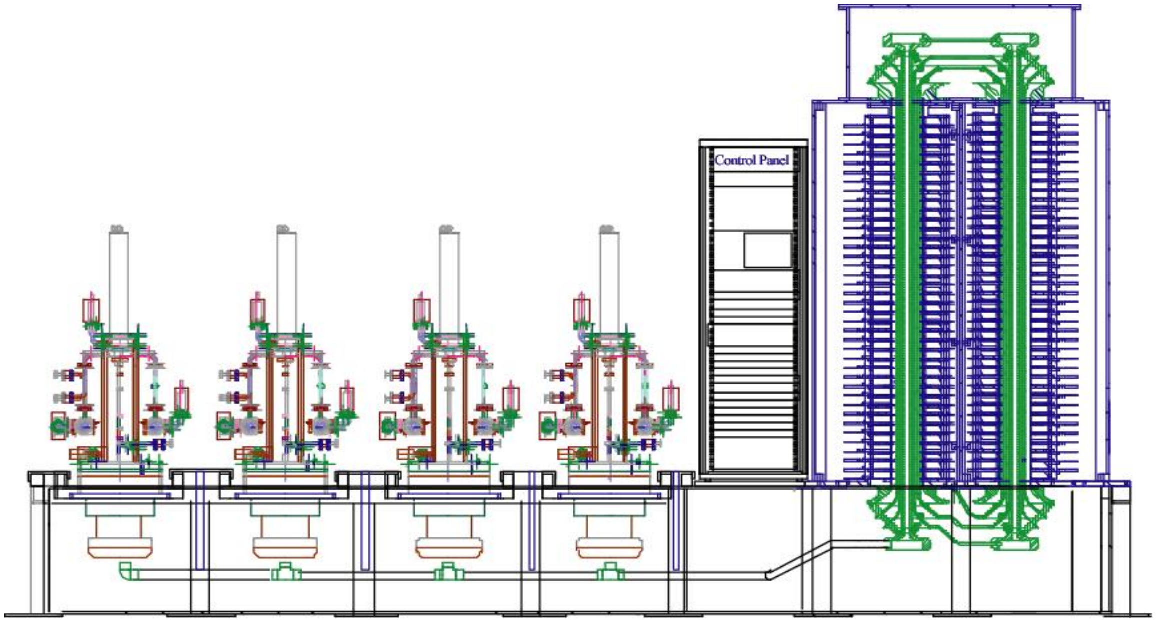
76 Cores

Three-Turn Secondary

> 1500 Hours of Operation

Waveforms When Driving Four 50 MW Klystrons at 400 kV, 300 A Each

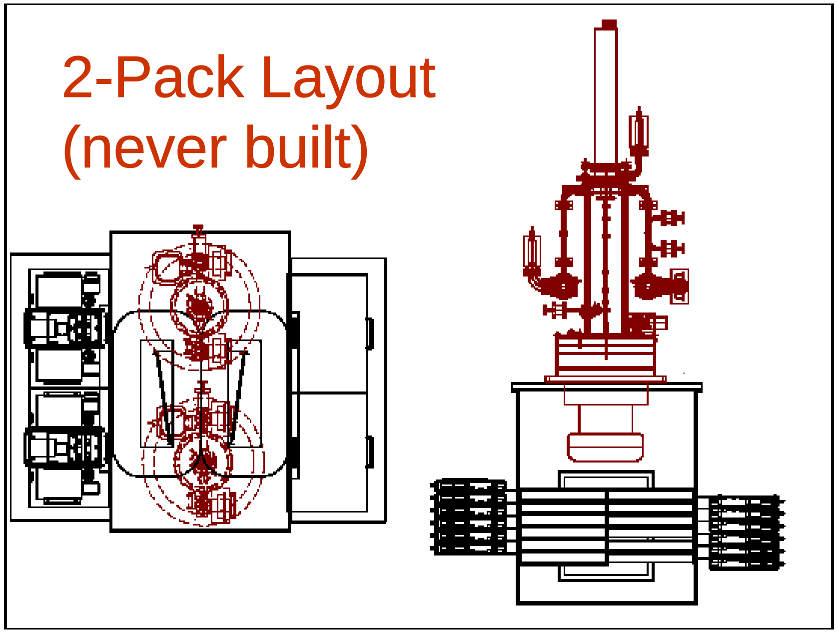




Next Generation Induction Modulator: The ‘Two-Pack’

Features

- 6.5 kV IGBTs with in-line multi-turn 1:10 transformer.
- Industrialized cast casings.
- Improved oil cooling.
- Improved HV feed through.



2-Pack Layout (never built)

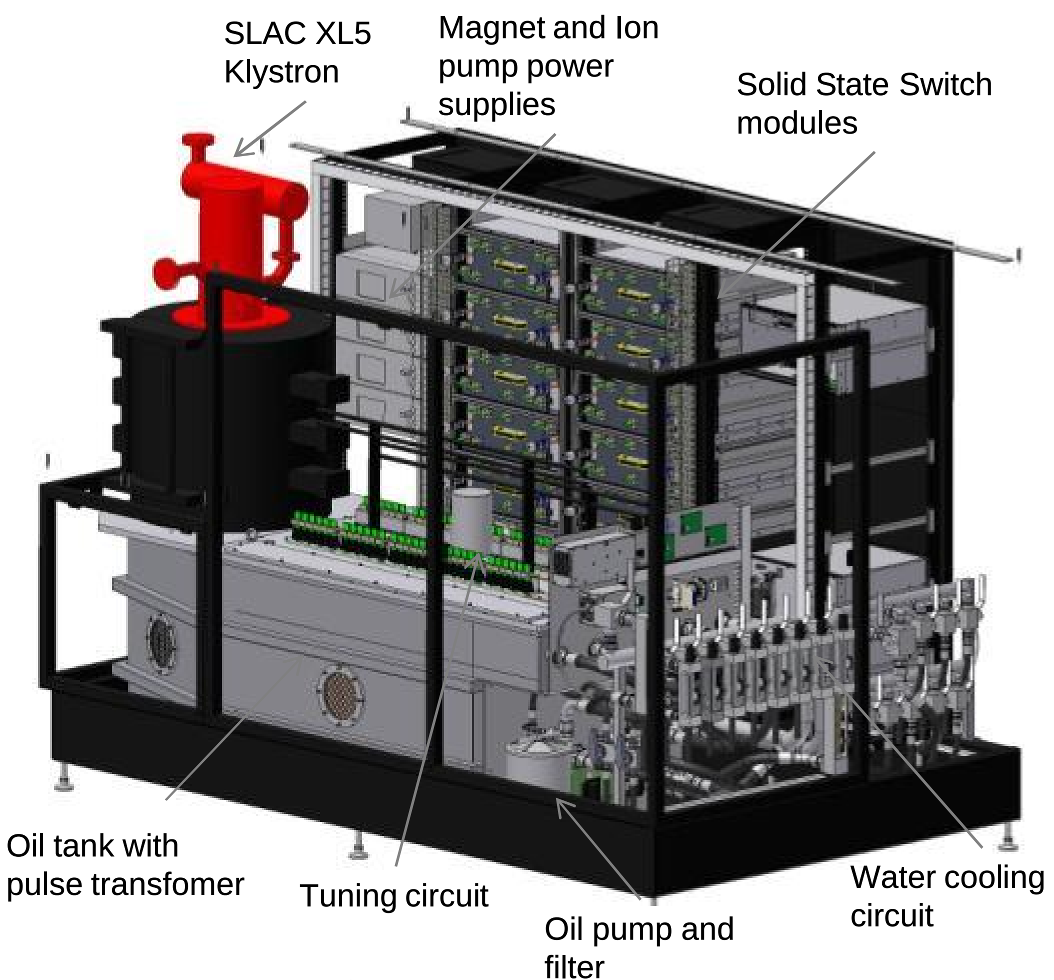
Bechtel-LLNL-SLAC 20 kV Test Stack

A Hybrid 2-Pack Modulator (15 core stack driving a conventional 1:10 transformer) was built and is still being used – also built a version to drive a single ‘5045’ S-Band Tube

Recent Industrialization of Solid State Induction Modulators

SCANDINOVA

Specification :	
High Voltage :	450 kV
Current :	335 A
Flat pulse length:	1.5 µs
Pulse length at 50%:	2.3 µs
Repetition rate:	50 Hz
HV ripple:	± 0.25 %
Pulse to pulse stability:	± 0.1 %

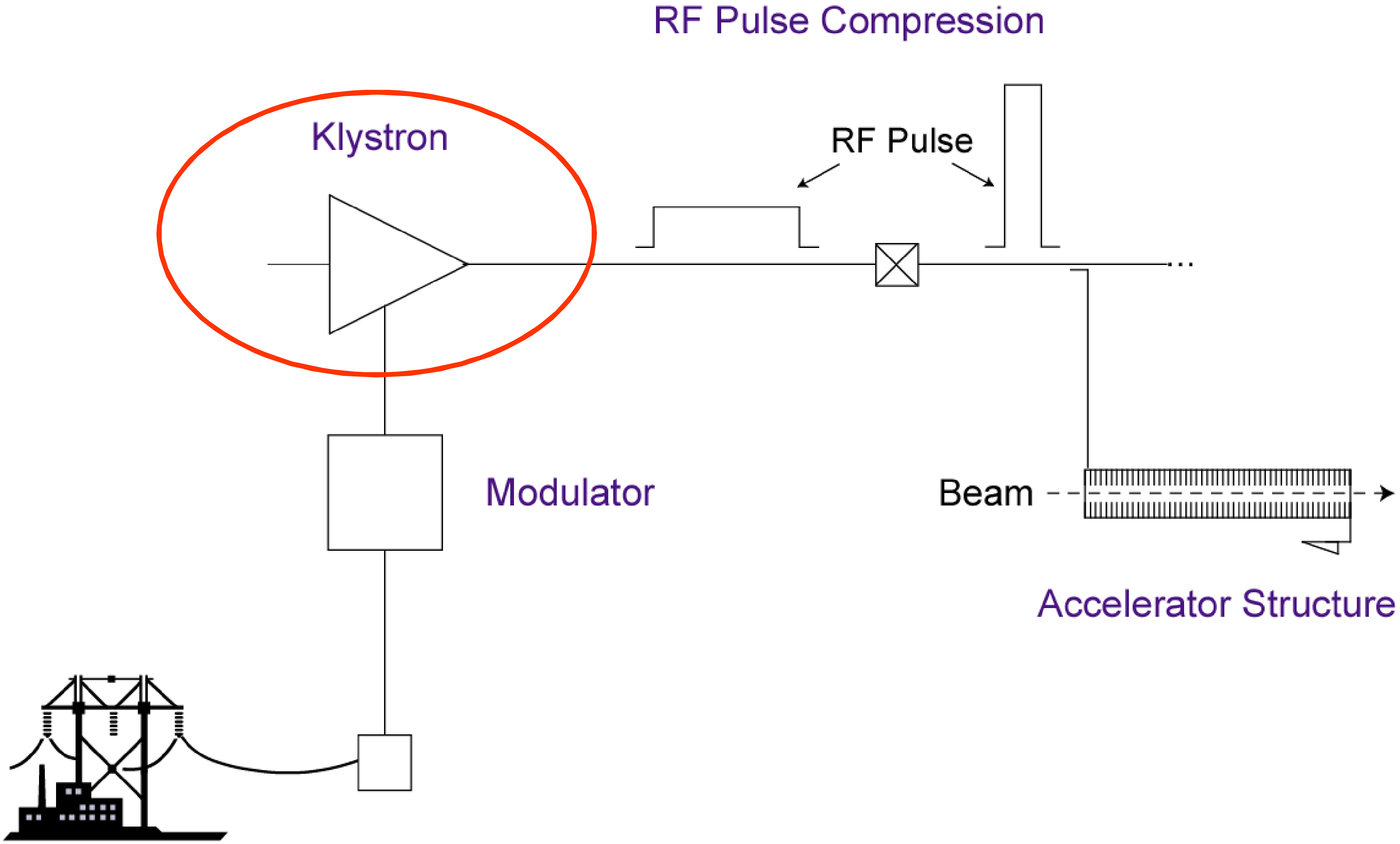


(1.8 x 3 x 2 m^3)

NLC legacy: employ solid state switching technology in a 120 kV Marx (capacitive adder) Modulator for ILC

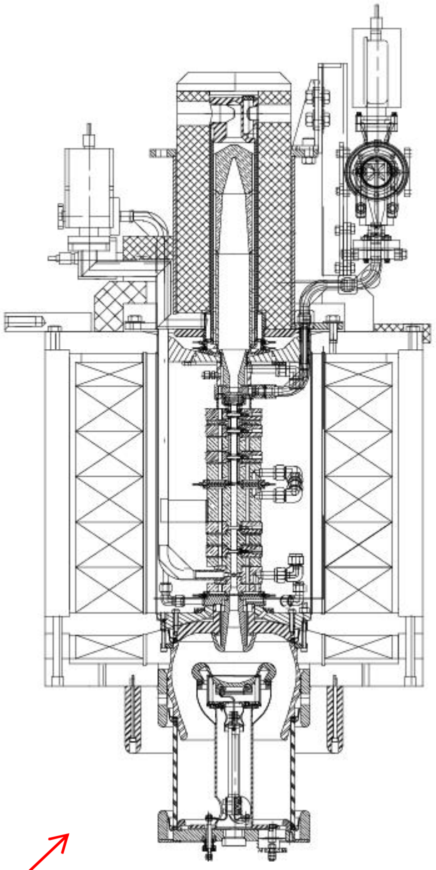
SLAC Marx Modulator driving a 10 MW L-Band (1.3 GHz) Multi-Beam Klystron at ESB

RF Component Performance

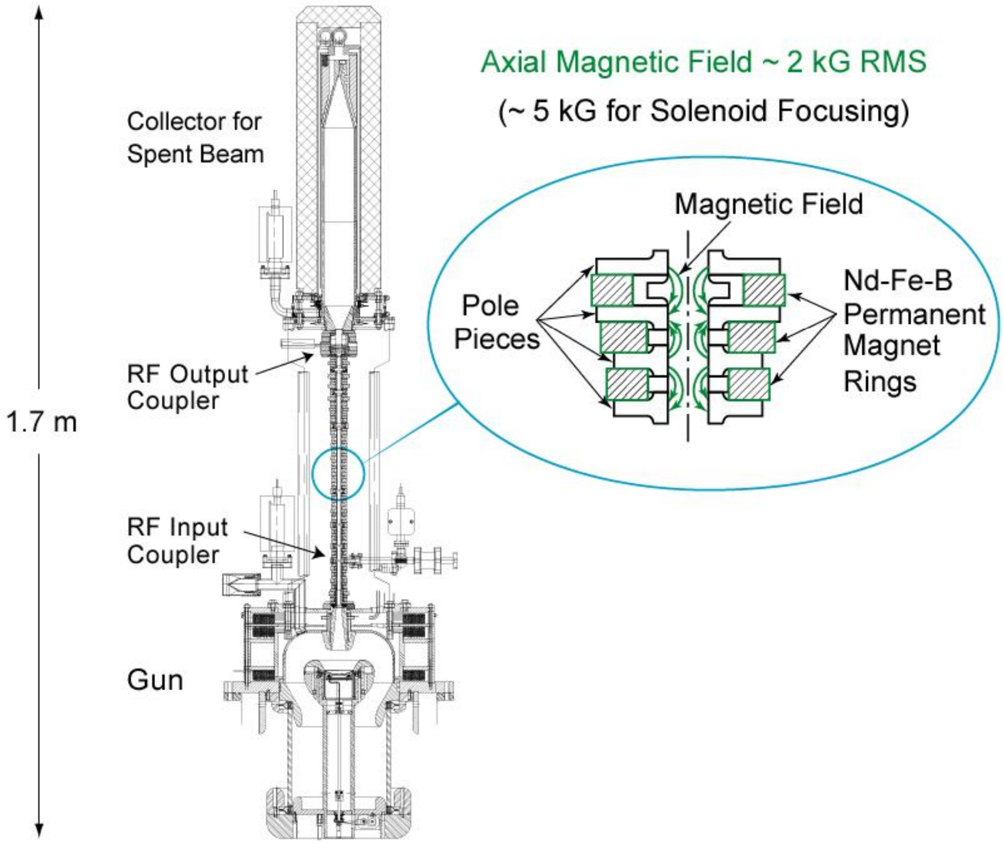


X-Band Klystrons

Solenoid-Focused Tubes: Have
Twelve, 50 MW Tubes for Testing,
However Solenoid Power = 25 kW.

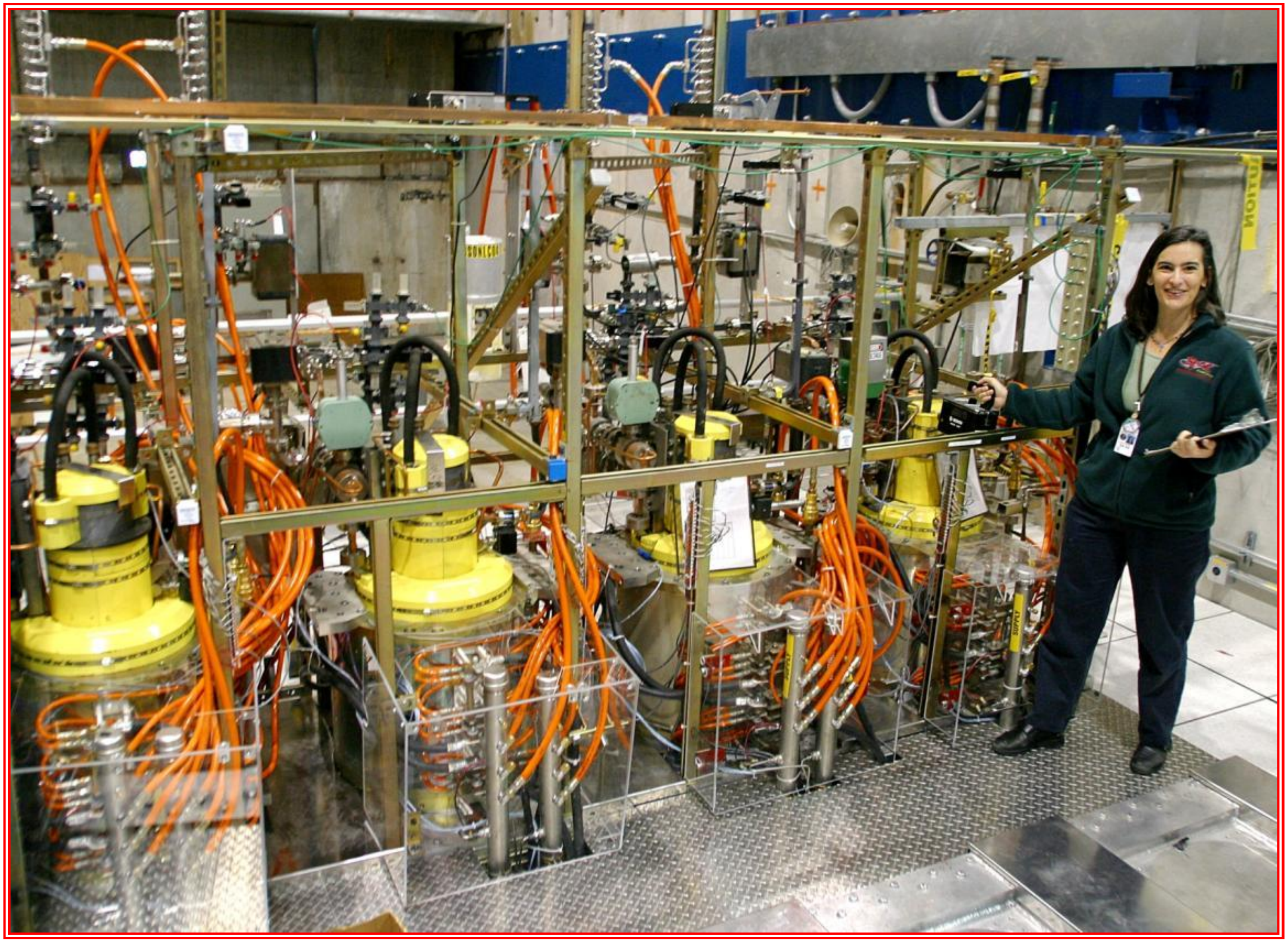


Developing Periodic Permanent Magnet (PPM)
Focused Tubes to Eliminate the
Power Consuming Solenoid.



‘XL4’ – Have built at least 15, now producing 12 GHz ‘XL5’ versions

Four 50 MW XL4 Klystrons Installed in the Eight-Pack Modulator in 2004



PPM Klystron Performance

(75 MW, 1.6 μs, 120/150 Hz, 55% Efficiency Required)

KEK/Toshiba

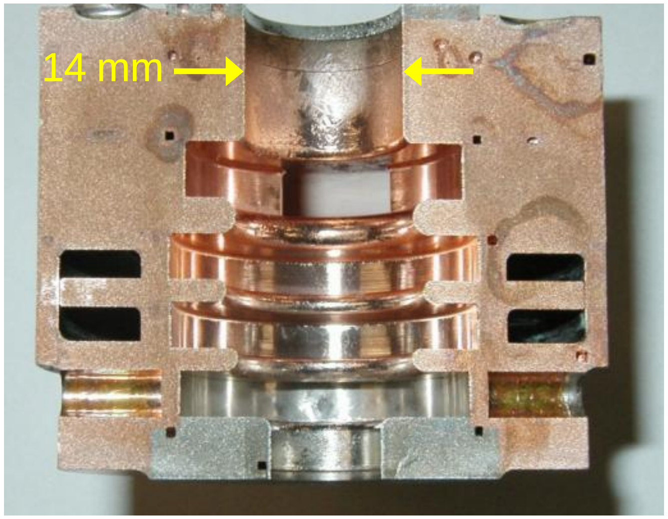
Four tubes tested at
75 MW with
1.6 μs pulses at
50 Hz (modulator limited).
Efficiency = 53-56%.

SLAC

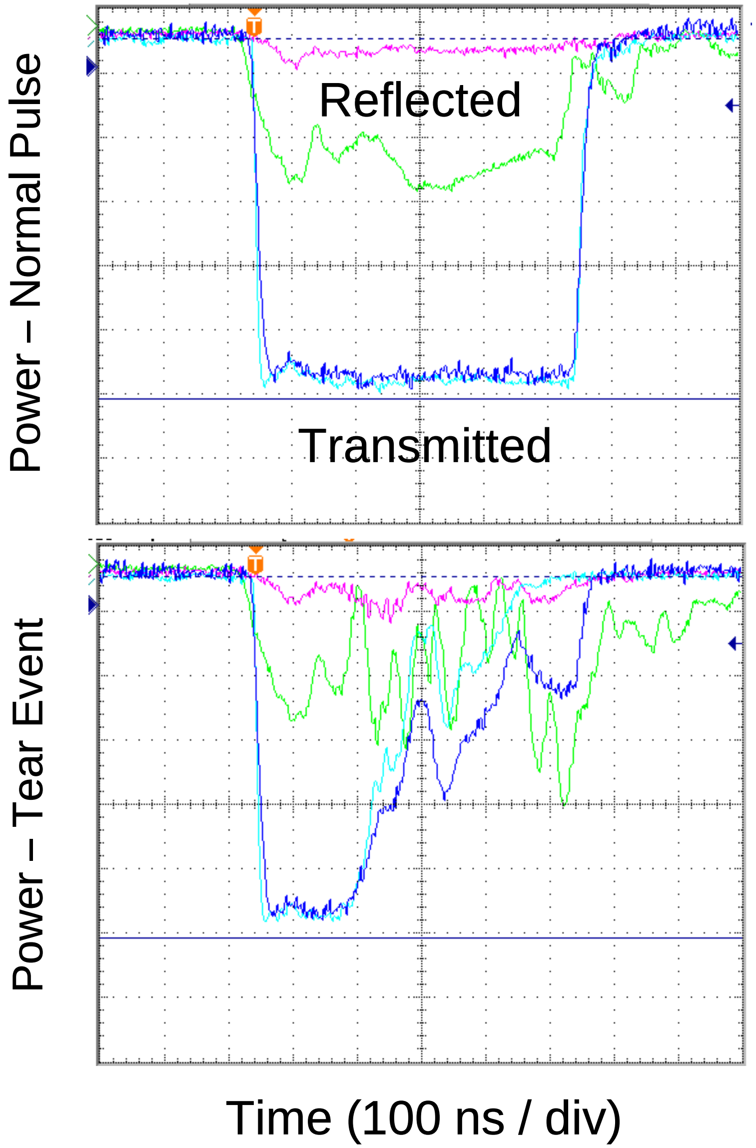
Two tubes tested at
75 MW with
1.6 μs pulses at
120 Hz.
Efficiency = 53-54%.

Klystron Tear Events

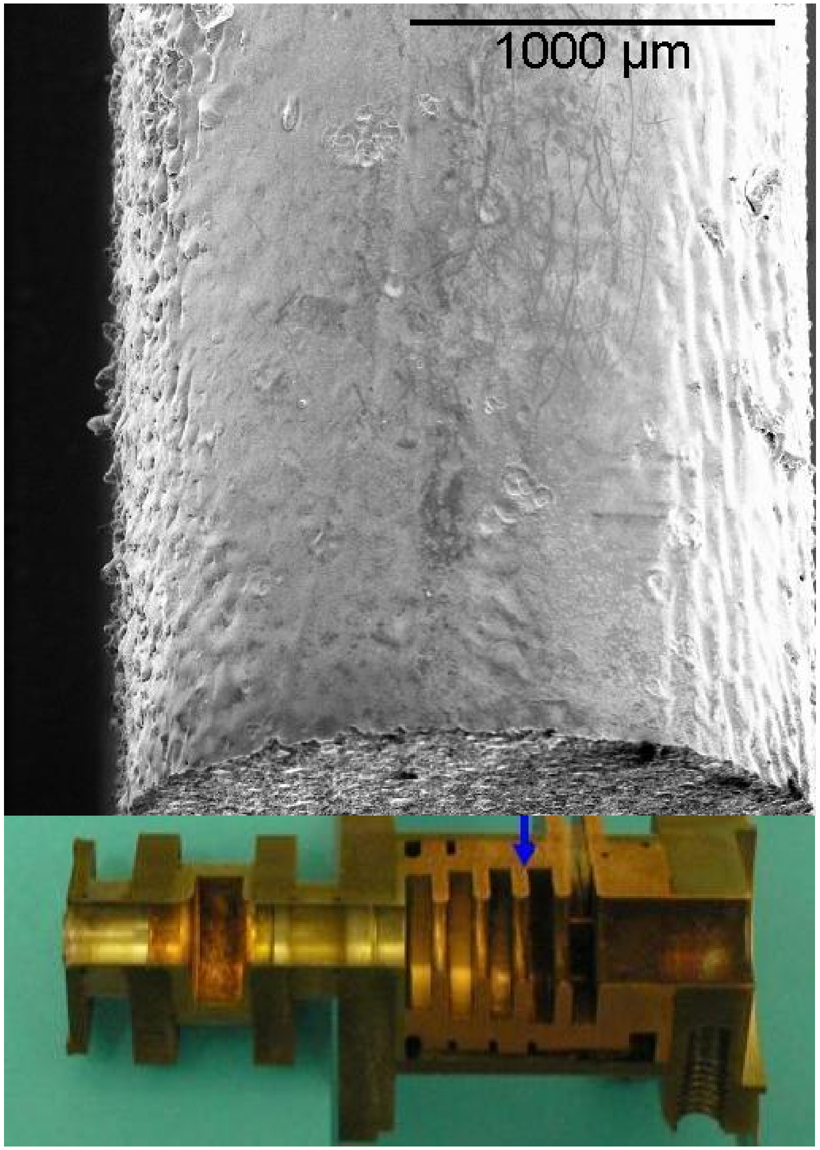
- At 75 MW, iris surface field ~ 70 MV/m, lower than in structures (~ 200 MV/m), but higher than sustainable (~ 50 MV/m) in waveguide with comparable group velocity (~ 20%).
- May require multi-beam klystron approach for stable > 50 MW, 1.6 μs operation.

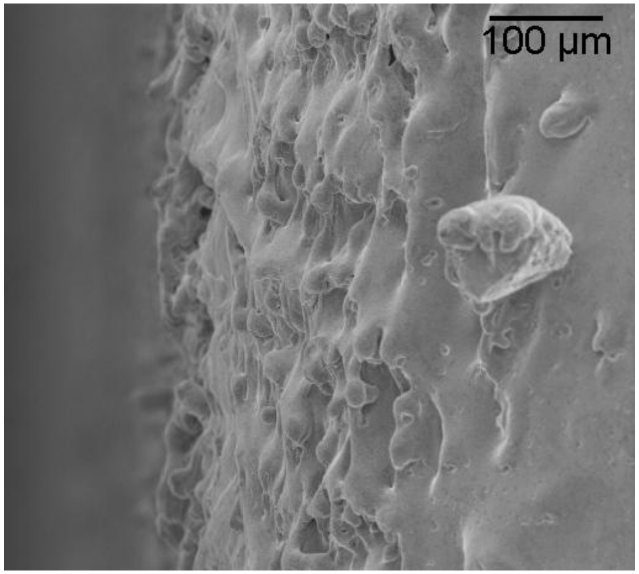


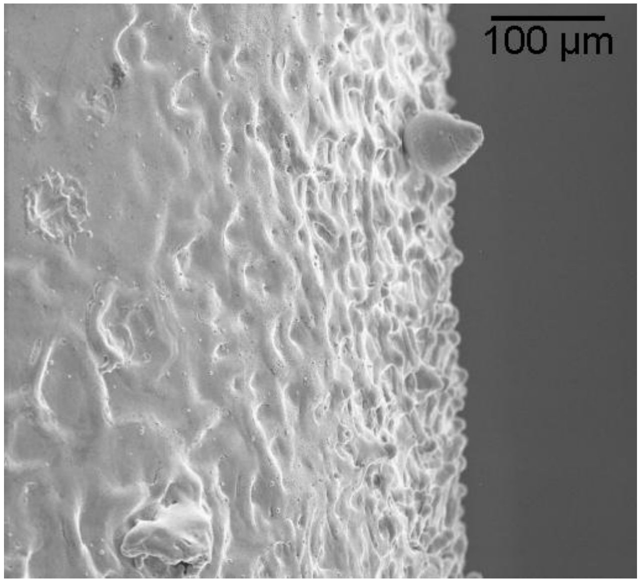
KEK PPM2
Output
Structure



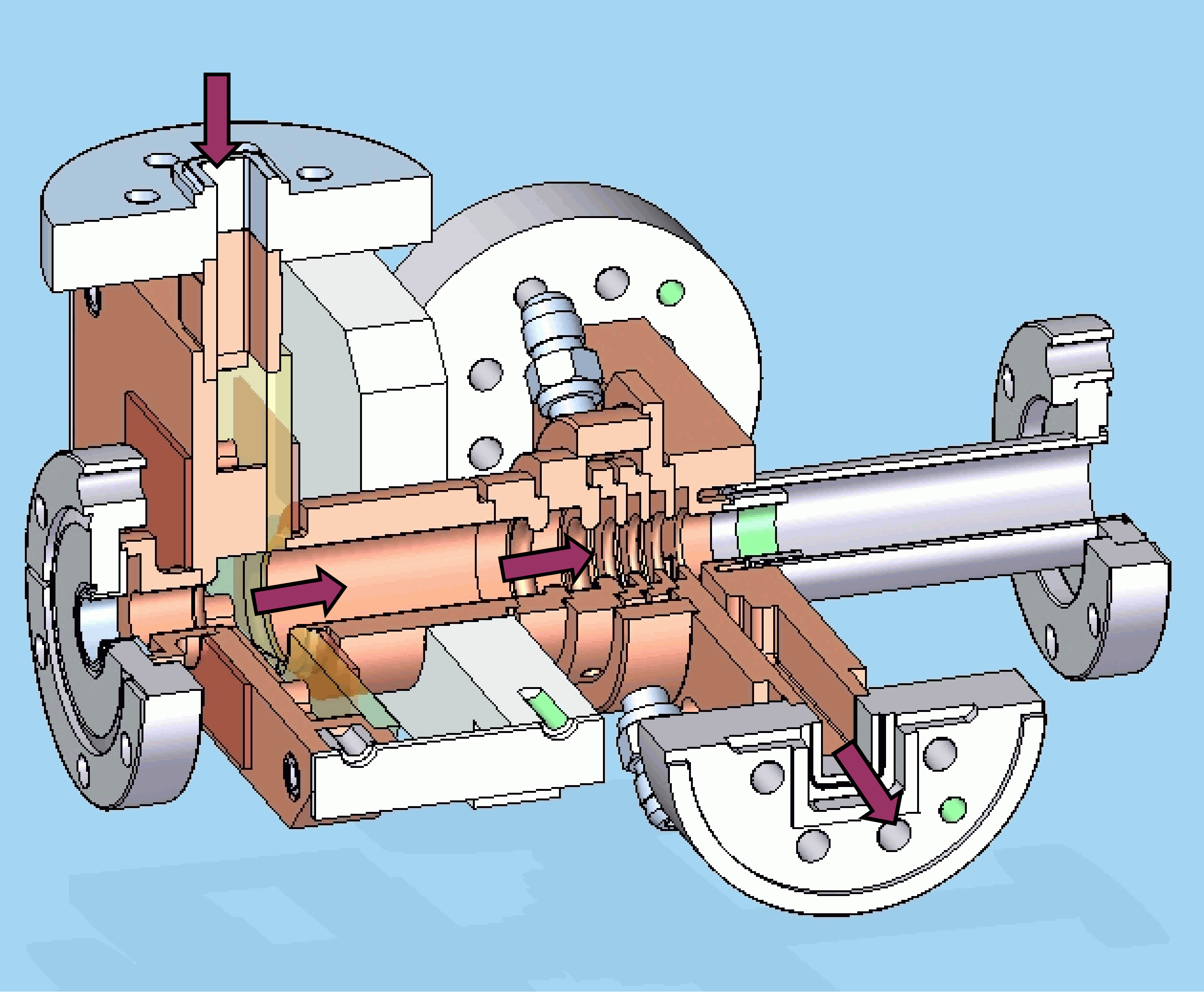
SEM Photos of a 75 MW PPM Klystron Output Section



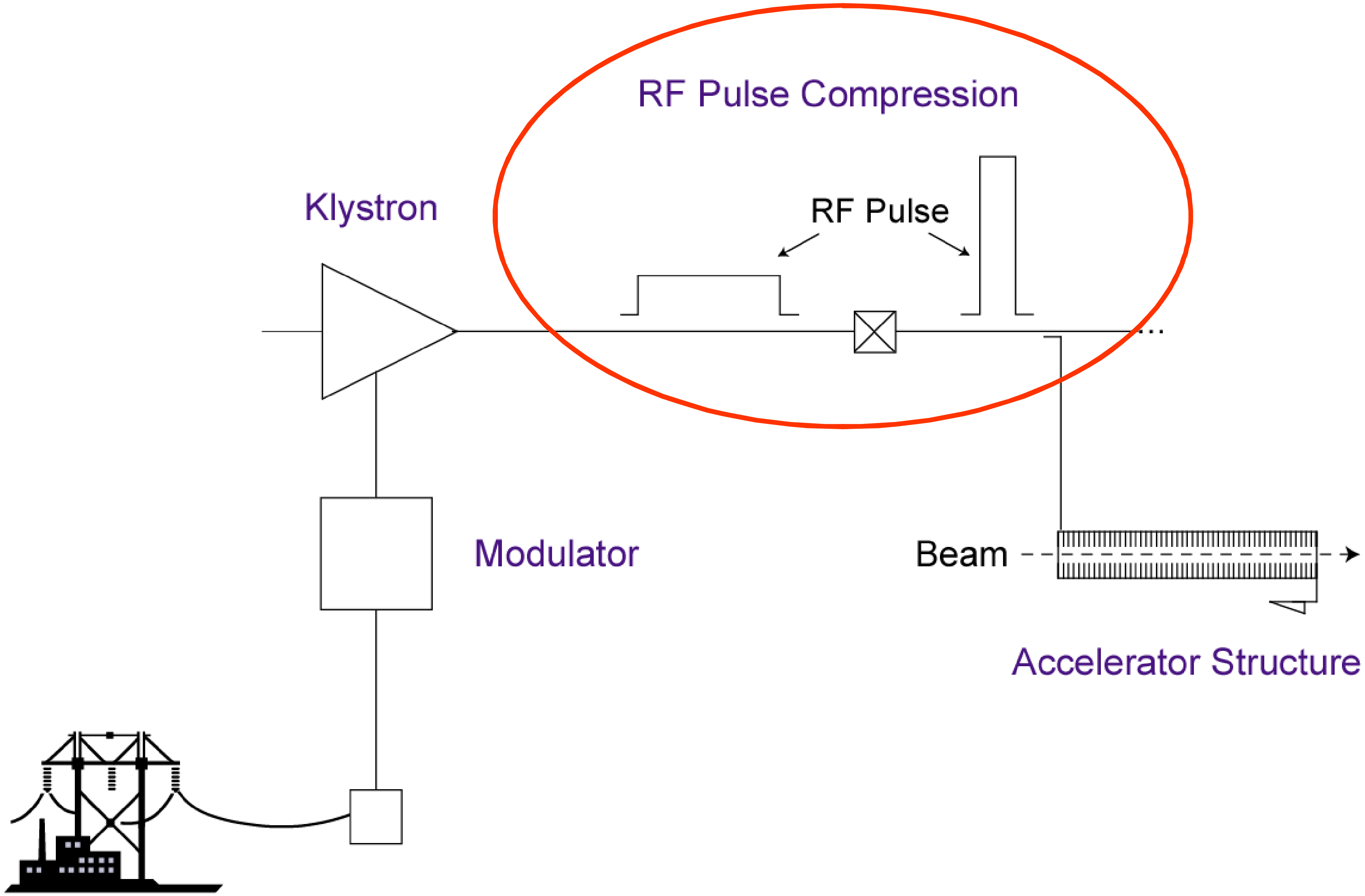




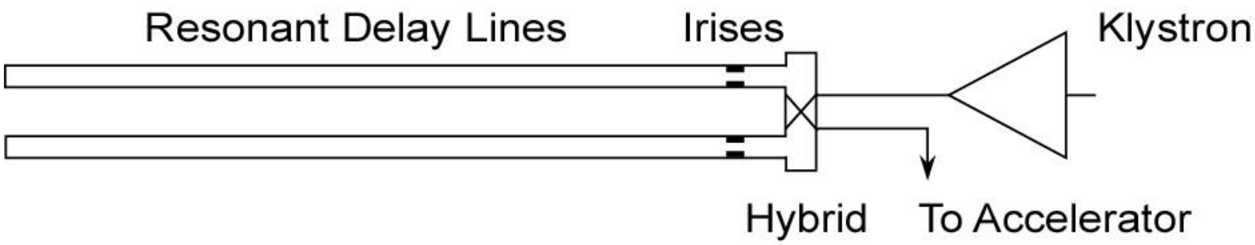
Currently using rf-driven klystron output sections to study stability and evaluate future designs



RF Component Performance



First Generation RF Pulse Compression (SLED II) at NLCTA



Resonant Delay Lines

Irises

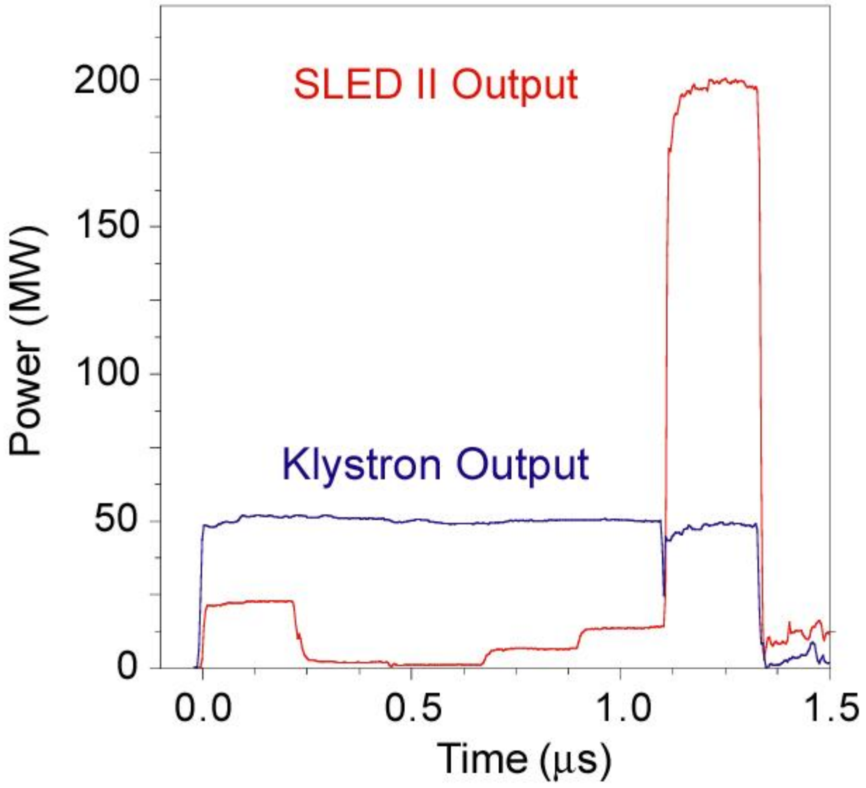
Klystron

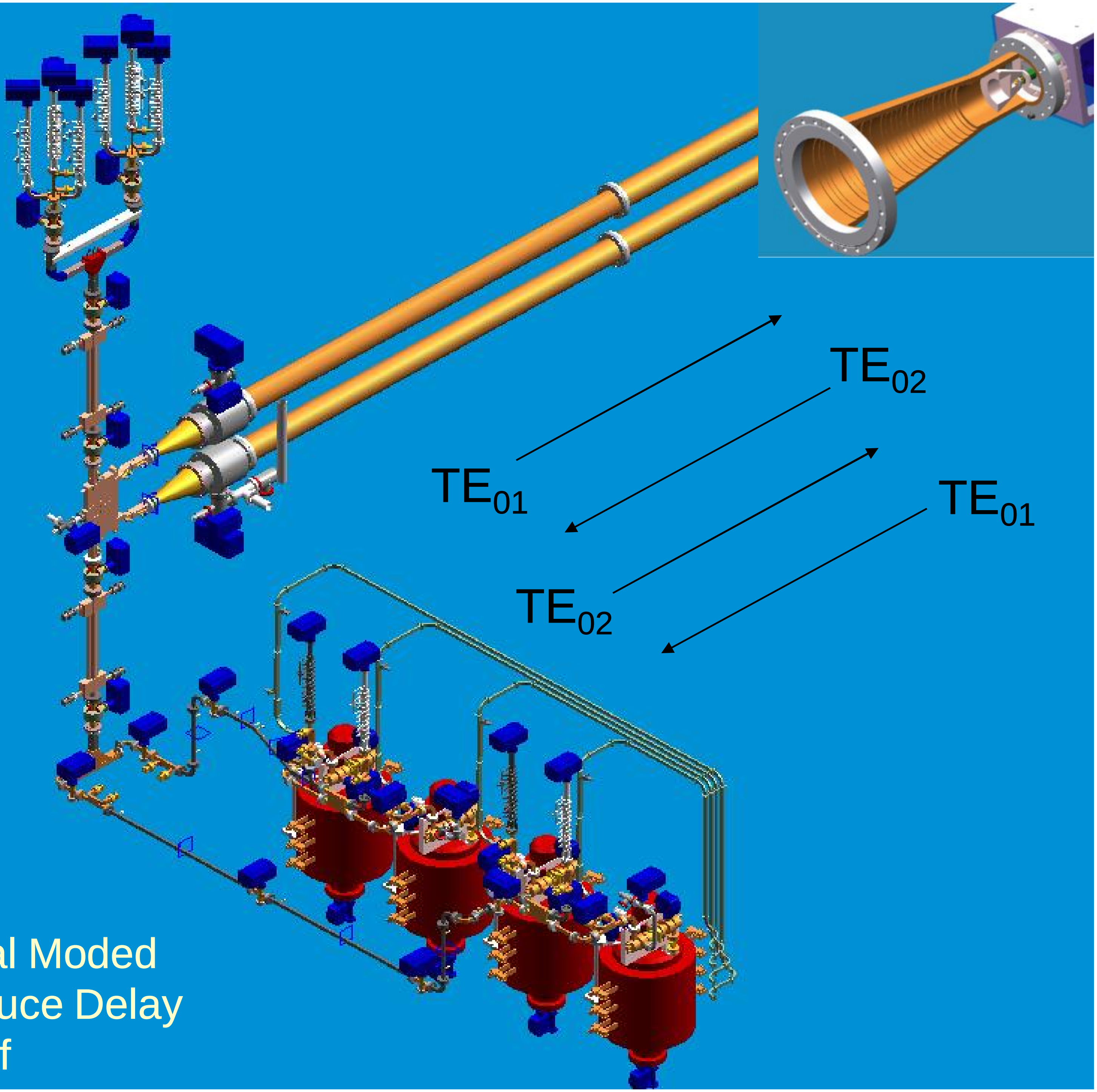
Hybrid

To Accelerator

40 m Long Circular Waveguide

3 dB Hybrid Using a 'Magic Tee'



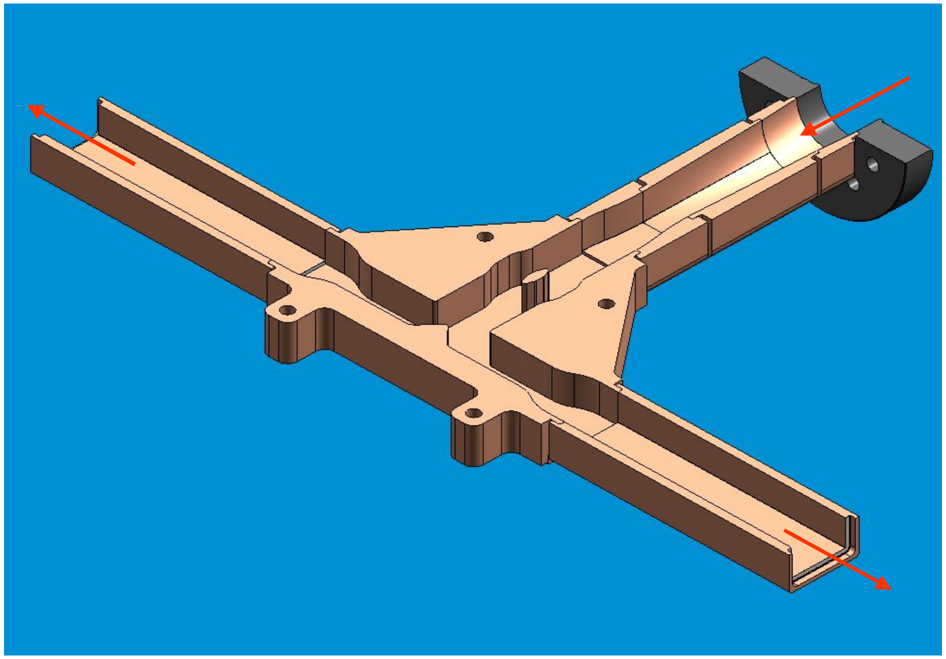


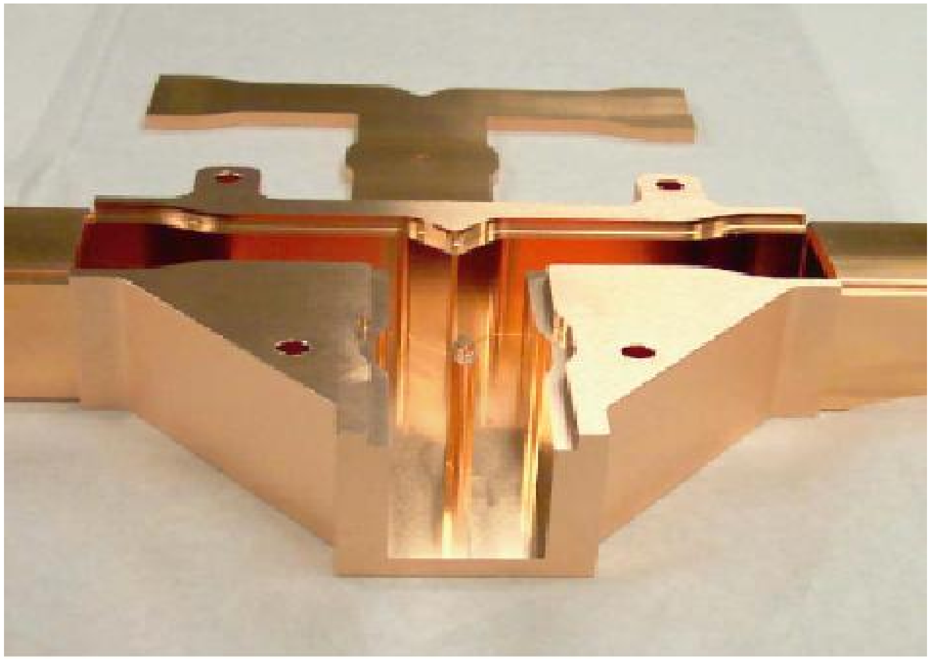
For NLC, Use Dual Moded Delay Line to Reduce Delay Line Length in Half

Also Use Over-Height Planar Waveguide to Lower Surface Fields

Design for < 50 MV/m for 400 ns pulses

Example: Power Splitter

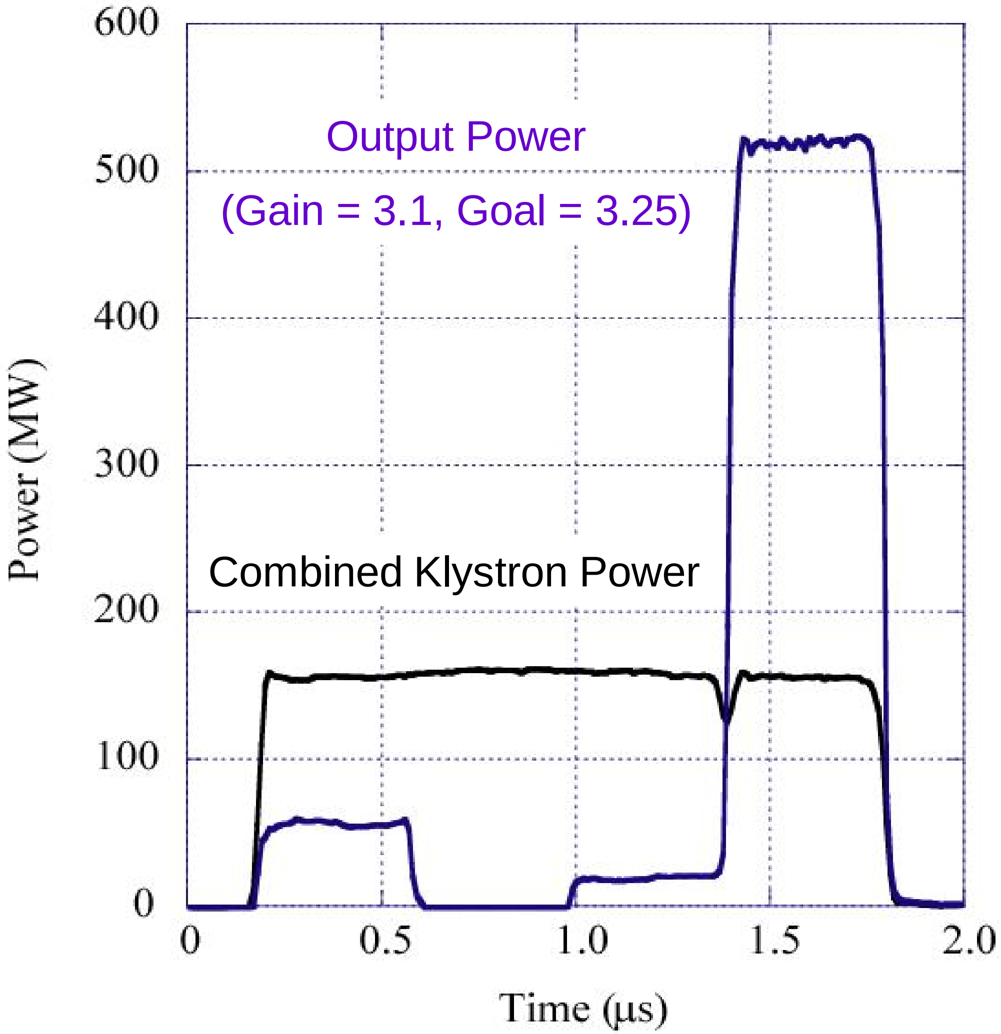




Dual-Moded SLED-II Performance

(475 MW, 400 ns Pulses Required for NLC)

Since 2004, have done low power tests using silicon and plasma switches to improve efficiency

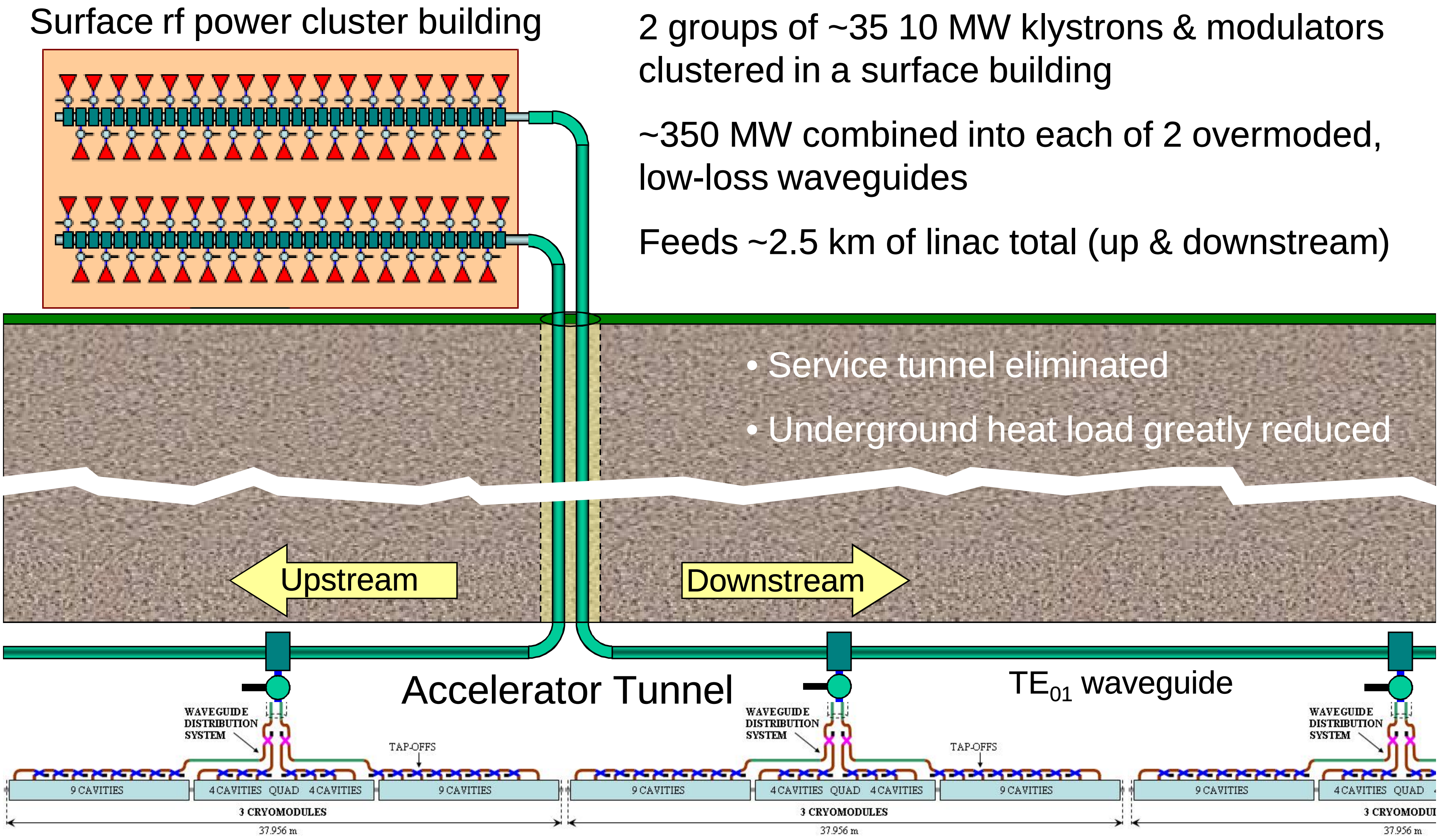


NLC legacy: use waveguide mode conversion/transport techniques to power ILC from klystron clusters

2 groups of ~35 10 MW klystrons & modulators clustered in a surface building

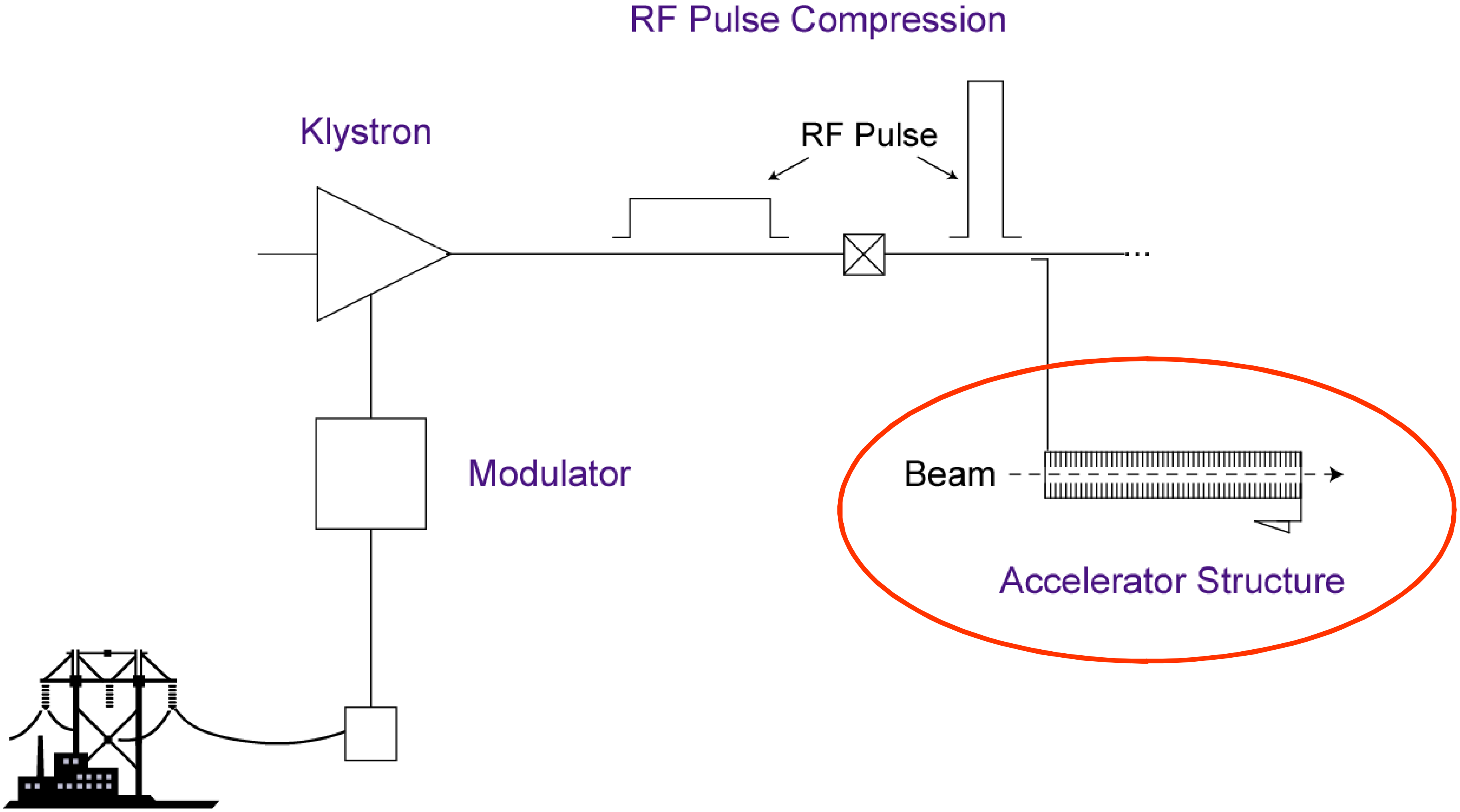
~350 MW combined into each of 2 overmoded, low-loss waveguides

Feeds ~2.5 km of linac total (up & downstream)



- Service tunnel eliminated
- Underground heat load greatly reduced

RF Component Performance



RF Pulse Compression

Klystron

RF Pulse

Modulator

Beam

Accelerator Structure

NLC Accelerator Structure Requirements

Convert rf energy to beam energy efficiently.

Short-range transverse wakefields small to limit linac emittance growth: iris radius limited to 17% of rf wavelength (i.e. a/λ = 17%).

Long-range wakefields suppressed so bunch train effectively acts as a single bunch.

Dipole mode power coupled out for use as guide for centering the beam in the structure.

Operate reliably at the design gradient and pulse length.

NLC/GLC Structures were developed by a FNAL/KEK/SLAC collaboration –

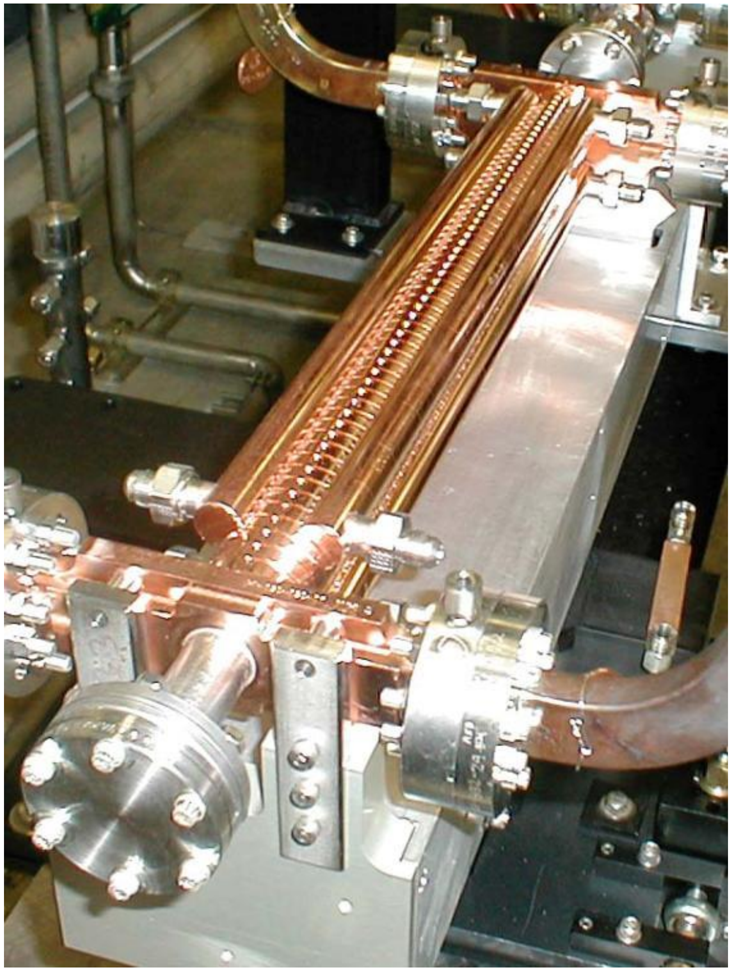
CERN/KEK/SLAC now developing 11%-13% a/λ structures that run at ~ 100 MV/m

NLC High Gradient Structure Development

Since 1999:

- Tested about 40 structures with over 30,000 hours of high power operation at NLCTA.
- Improved structure preparation procedures - includes various heat treatments and avoidance of high rf surface currents.
- Found lower input power structures to be more robust against rf breakdown induced damage (CLIC has 'pushed' this further and also shortened the rf pulse length)
- Developed NLC-Ready 'H60' design with required wakefield suppression features.

50 cm 'T53' Structure



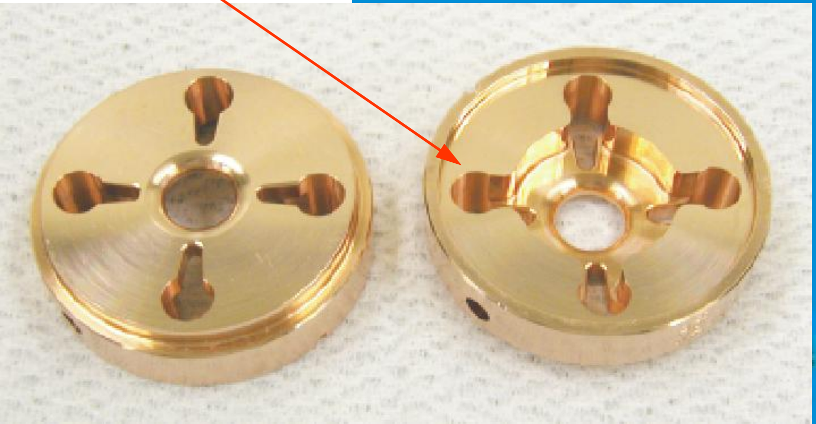
Structure Fabrication at SLAC

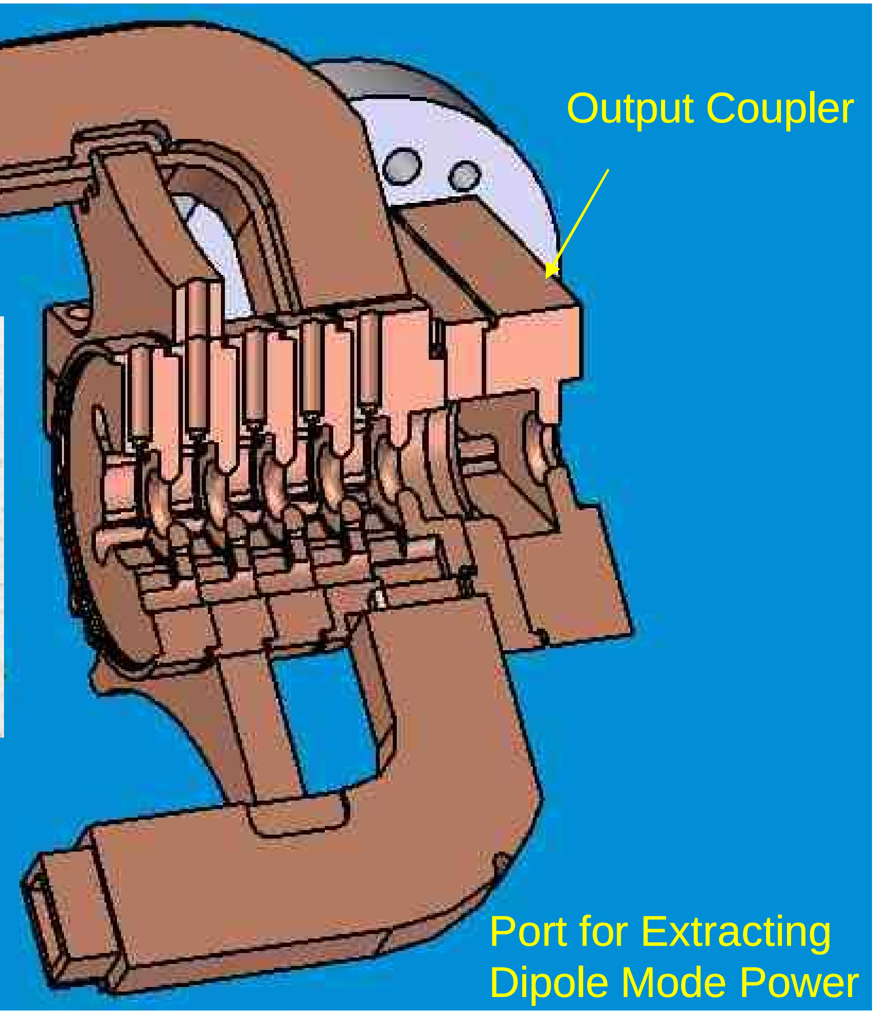
Ready for Coupler Braze

After Braze

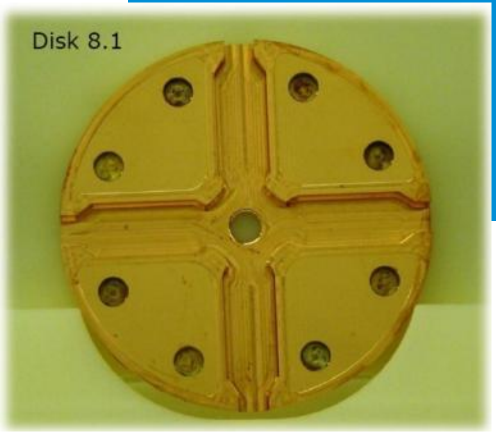
H60 Structure Cells and Coupler Assembly

Cells with Slots
for Dipole Mode
Damping

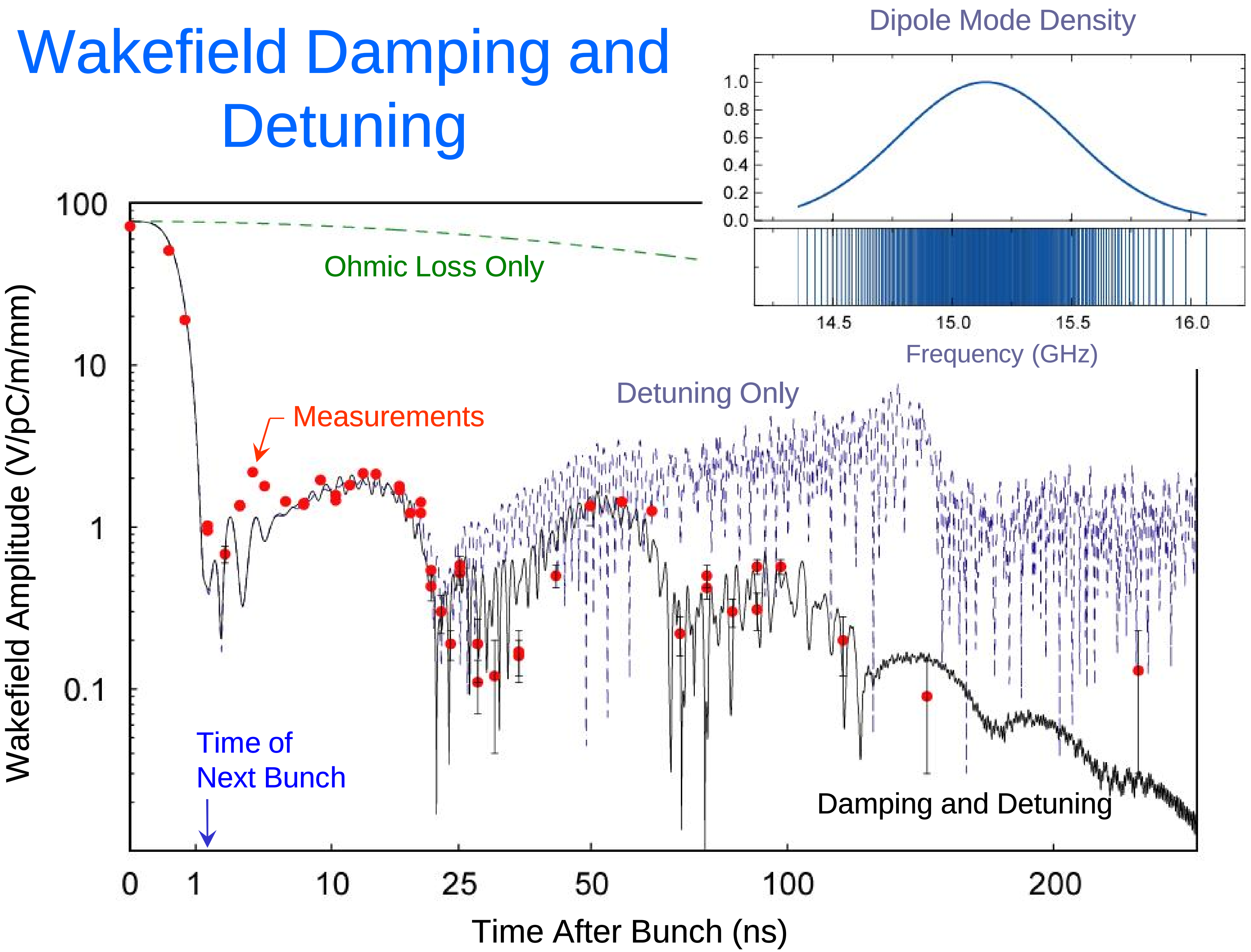




CLIC Cells Have
Large Waveguide
Openings for
Faster Damping

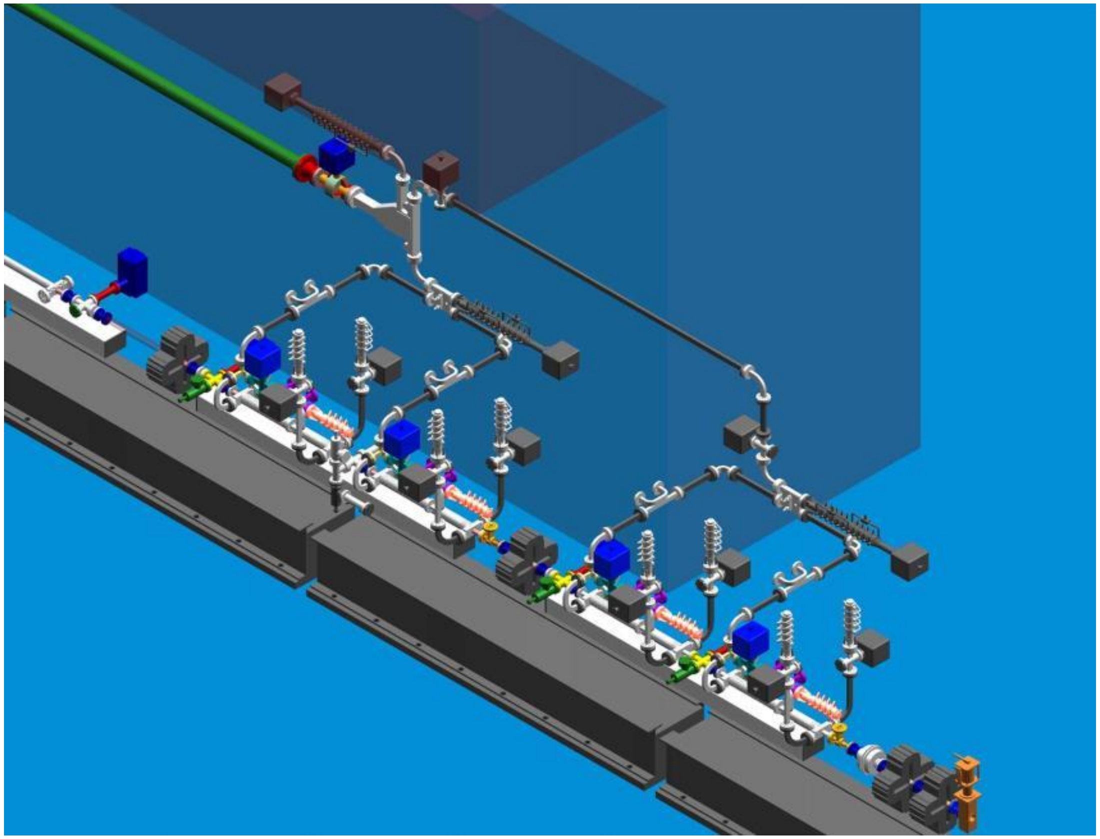


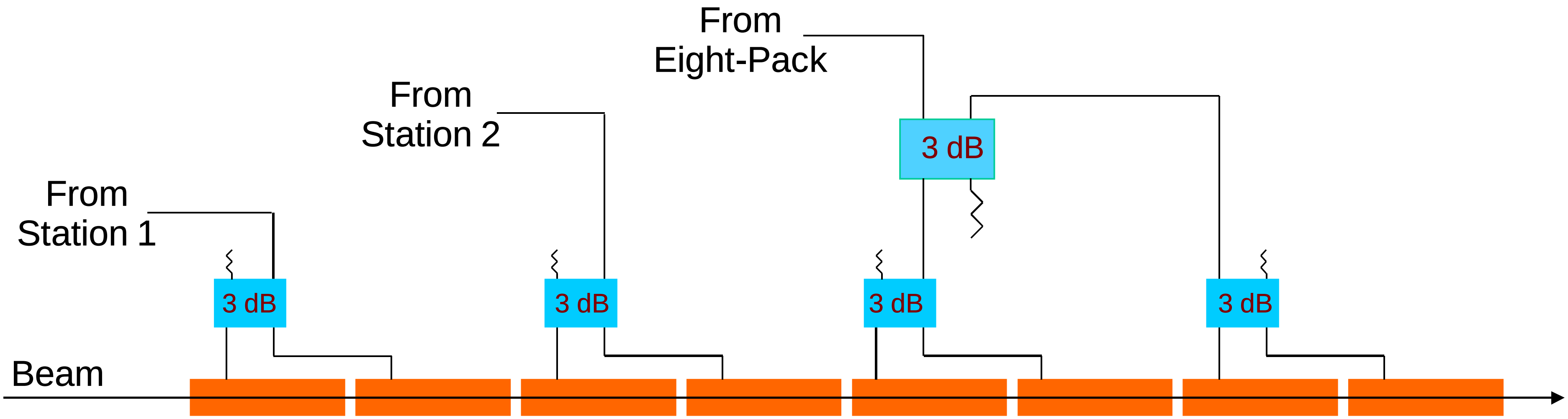
Wakefield Damping and Detuning



RF Unit Test in 2003-2004

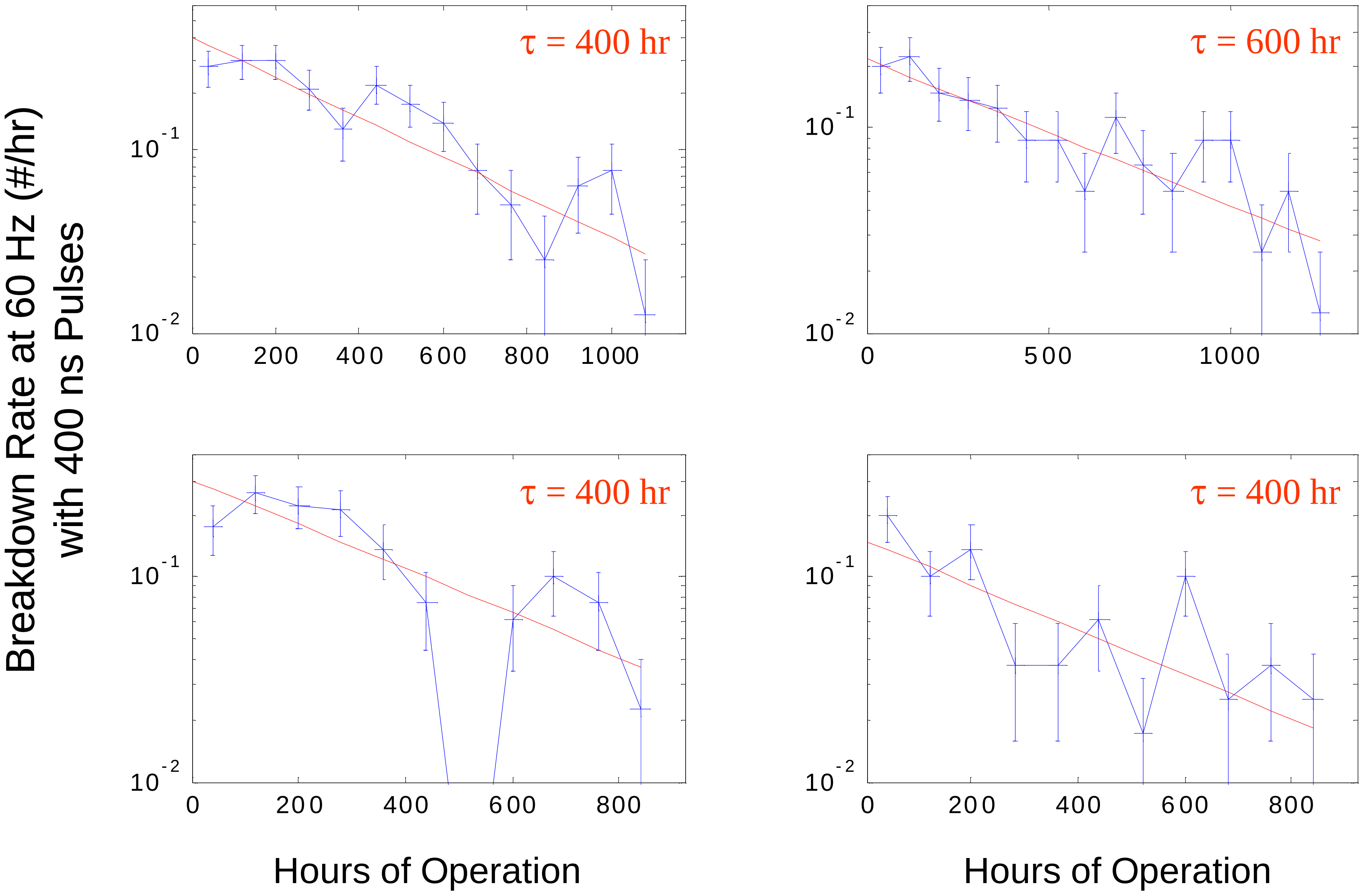
Powered Eight H60 accelerator structures in NLCTA for 1500 hours at 65 MV/m with 400 ns long pulses at 60 Hz and accelerated beam



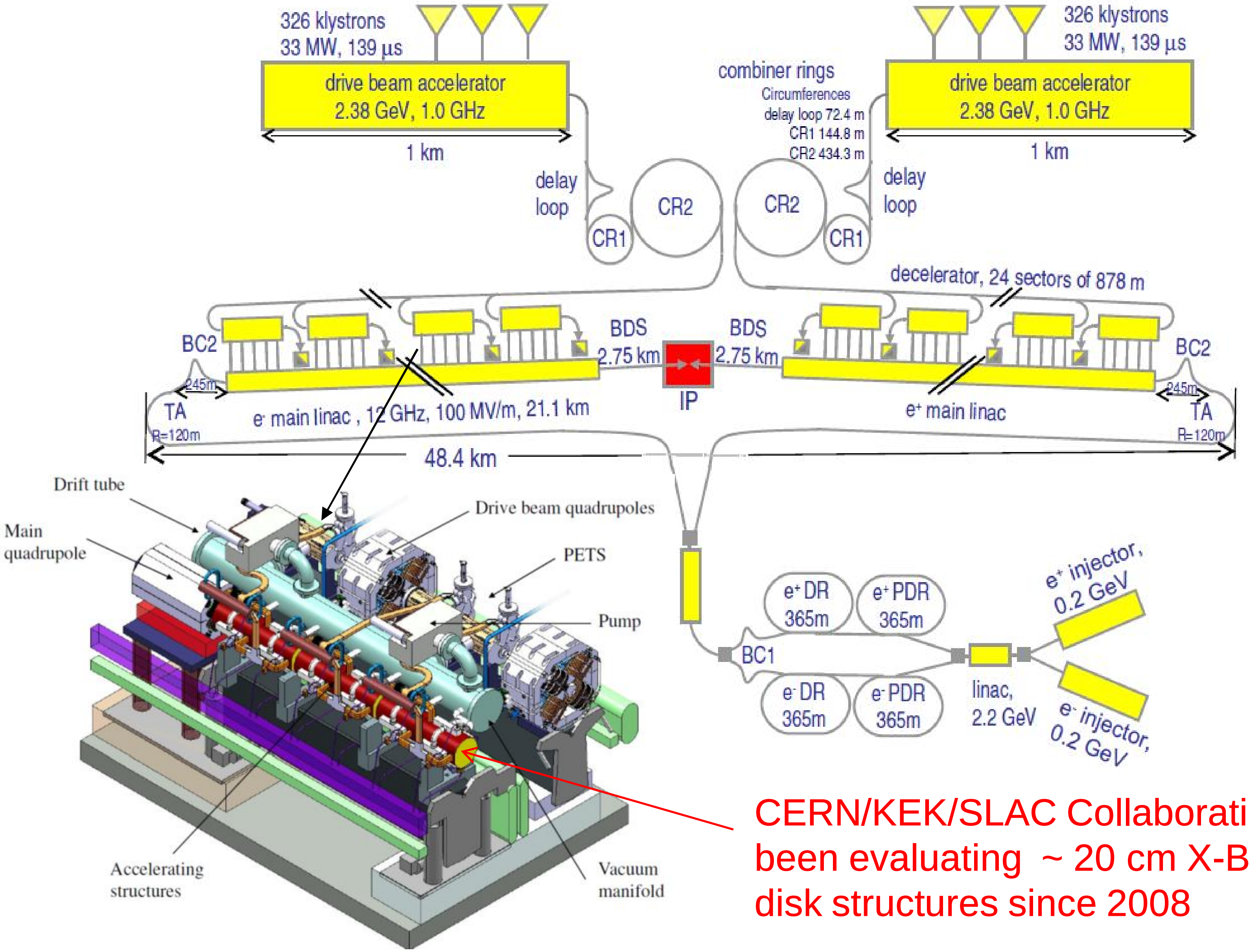


Breakdown Rate History (Goal < 0.1/hr)

Four H60 Structures at 65 MV/m



CLIC 3-TeV Layout



CERN/KEK/SLAC Collaboration has been evaluating ~ 20 cm X-Band disk structures since 2008

CLIC T18-Disk Structure

(First attempt at an optimal CLIC structure)

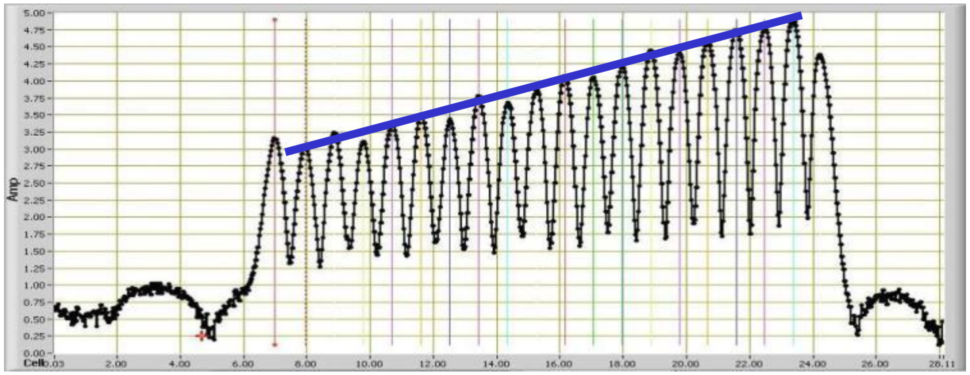
Cells	18+input+output
Filling Time: ns	36
Active Length: cm	17.5
a/λ (%)	15.5 ~ 10.1
v_g/c (%)	2.6 - 1.0
Phase Advance Per Cell	$2\pi/3$
Power Needed $\langle E_a \rangle$ = 100 MV/m	55.5 MW
E_s/E_a	2

Require breakdown rate < 4e-7 /pulse/m with 230 ns pulses

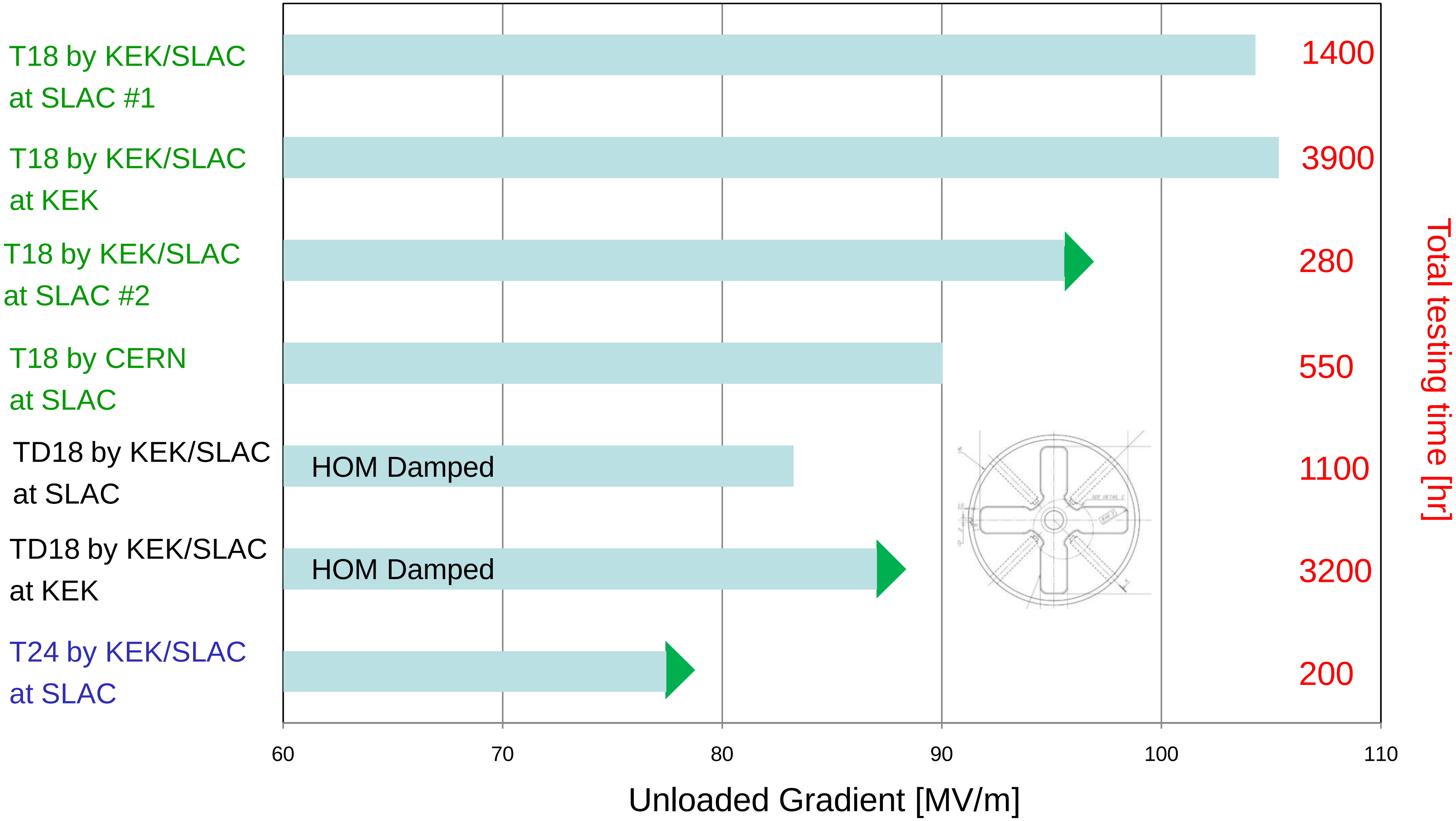
Undamped (no waveguides) T18 achieved this at ~ 102 MV/m

Damped T18 (with waveguides) achieved this at ~ 85 MV/m

As with NLC, the gradient including beam loading will be 10-20 MV/m smaller


Field Profile Along the Structure

Gradients Achieved at a CLIC-Acceptable Breakdown Rate

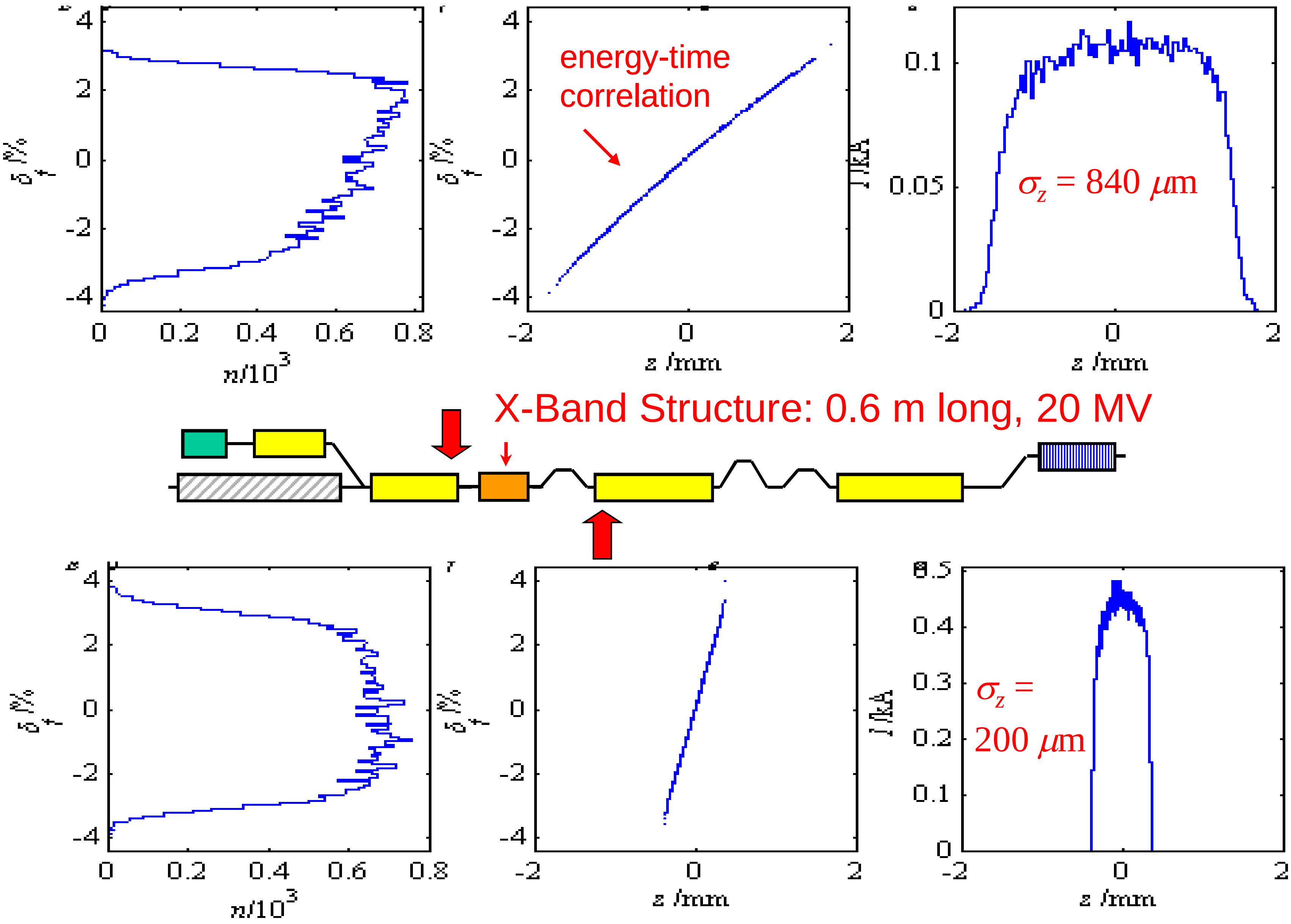


Scaling to CLIC conditions: Scaled from lowest measured BDR to BDR = $4*10^{-7}$ and τ =180 ns (CLIC flat-top is 170 ns), using $E^{29}\tau^{5}/BDR$ = constant assumption

High Power (Multi-MW) X-Band Applications

- Short bunch FELs
  - Energy Linearizer: in use at LCLS, planned for BNL, PSI, Fermi/Trieste and SPARX/Fascati
  - Deflecting Cavity for Bunch Length Measurements
- 100’s of MeV to Many GeV Linacs
  - LLNL 250 MeV linac for gamma-ray production
  - ELI 600 MeV linac for gamma-ray production
  - SLAC 600 MeV energy ‘dither’ linacs for LCLS II
  - LANL 6-20 GeV linac for an XFEL source to probe dense matter
  - SPARX 1-2 GeV X-Band linac for their FEL
  - SLAC study of a 6 GeV Linac for a Compact XFEL (CXFEL) source

X-Band Energy ‘Linearizer’ at LCLS

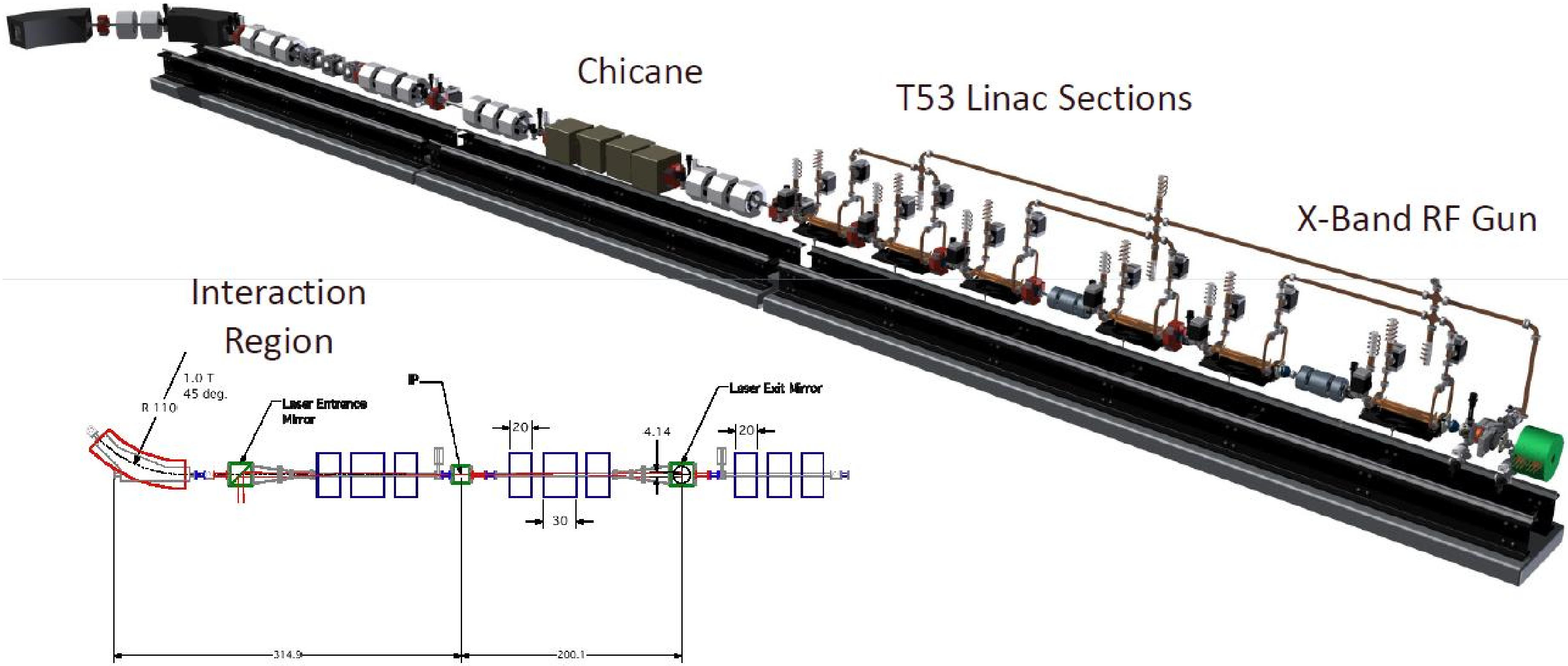

energy-time correlation

$\sigma_z = 840\ \mu m$

X-Band Structure: 0.6 m long, 20 MV

$\sigma_z =$ 200 μm

LLNL 250 MeV X-band Linac for Compton Gamma Ray Production



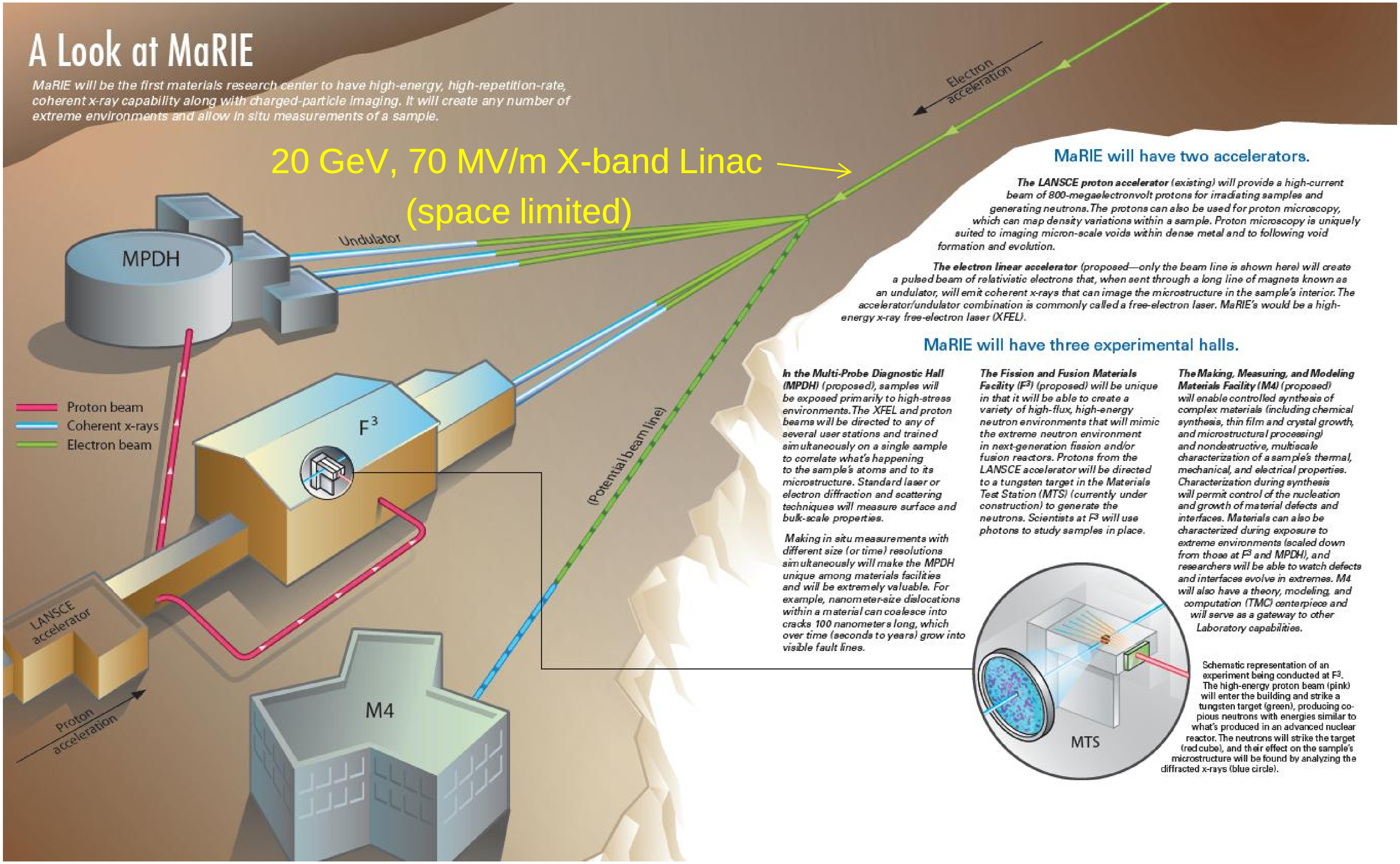
Chicane

T53 Linac Sections

X-Band RF Gun

Interaction Region

LANL MaRIE Project: 50 keV XFEL



20 GeV, 70 MV/m X-band Linac
(space limited)

A Look at MaRIE

MaRIE will be the first materials research center to have high-energy, high-repetition-rate, coherent x-ray capability along with charged-particle imaging. It will create any number of extreme environments and allow in situ measurements of a sample.

MaRIE will have two accelerators.

The LANSCE proton accelerator *(existing) will provide a high-current beam of 800-megaelectronvolt protons for irradiating samples and generating neutrons. The protons can also be used for proton microscopy, which can map density variations within a sample. Proton microscopy is uniquely suited to imaging micron-scale voids within dense metal and to following void formation and evolution.*

The electron linear accelerator *(proposed—only the beam line is shown here) will create a pulsed beam of relativistic electrons that, when sent through a long line of magnets known as an undulator, will emit coherent x-rays that can image the microstructure in the sample's interior. The accelerator/undulator combination is commonly called a free-electron laser. MaRIE's would be a high-energy x-ray free-electron laser (XFEL).*

MaRIE will have three experimental halls.

In the ***Multi-Probe Diagnostic Hall (MPDH)*** *(proposed), samples will be exposed primarily to high-stress environments. The XFEL and proton beams will be directed to any of several user stations and trained simultaneously on a single sample to correlate what's happening to the sample's atoms and to its microstructure. Standard laser or electron diffraction and scattering techniques will measure surface and bulk-scale properties.*

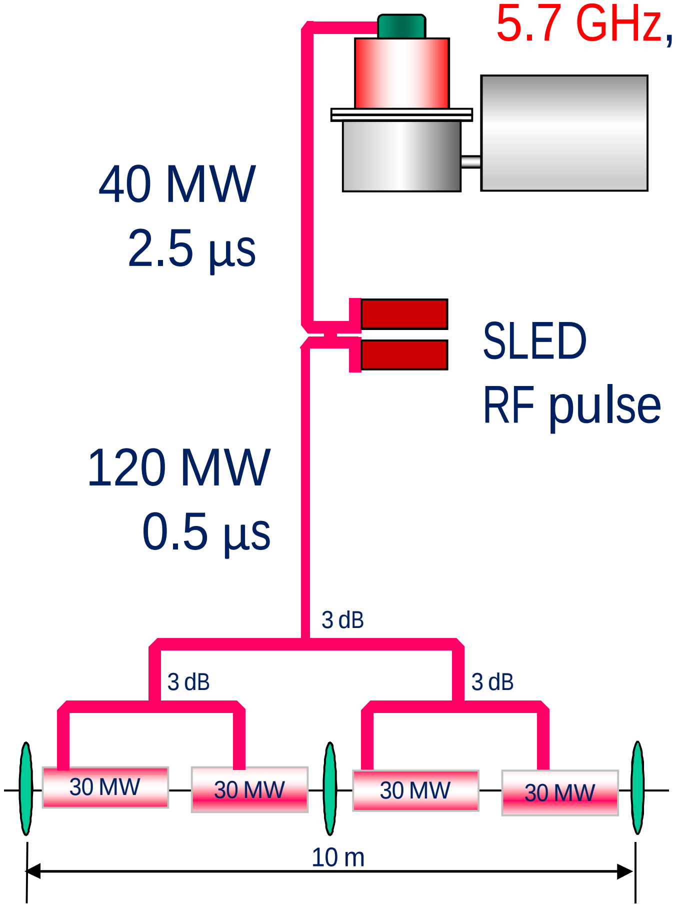
Making in situ measurements with different size (or time) resolutions simultaneously will make the MPDH unique among materials facilities and will be extremely valuable. For example, nanometer-size dislocations within a material can coalesce into cracks 100 nanometers long, which over time (seconds to years) grow into visible fault lines.

The Fission and Fusion Materials Facility (F³) *(proposed) will be unique in that it will be able to create a variety of high-flux, high-energy neutron environments that will mimic the extreme neutron environment in next-generation fission and/or fusion reactors. Protons from the LANSCE accelerator will be directed to a tungsten target in the Materials Test Station (MTS) (currently under construction) to generate the neutrons. Scientists at F³ will use photons to study samples in place.*

The Making, Measuring, and Modeling Materials Facility (M4) *(proposed) will enable controlled synthesis of complex materials (including chemical synthesis, thin film and crystal growth, and microstructural processing) and nondestructive, multiscale characterization of a sample's thermal, mechanical, and electrical properties. Characterization during synthesis will permit control of the nucleation and growth of material defects and interfaces. Materials can also be characterized during exposure to extreme environments (scaled down from those at F³ and MPDH), and researchers will be able to watch defects and interfaces evolve in extremes. M4 will also have a theory, modeling, and computation (TMC) centerpiece and will serve as a gateway to other Laboratory capabilities.*

Schematic representation of an experiment being conducted at F³. The high-energy proton beam (pink) will enter the building and strike a tungsten target (green), producing copious neutrons with energies similar to what's produced in an advanced nuclear reactor. The neutrons will strike the target (red cube), and their effect on the sample's microstructure will be found by analyzing the diffracted x-rays (blue circle).

SwissFEL Main Linac Building Block



C-band- Klystron
5.7 GHz, 50 MW, 2.5 µs, 100 Hz

40 MW
2.5 µs

SLED
RF pulse compressor

120 MW
0.5 µs

Four 2 m long C-band structures, 26 MV/m
Total energy gain per modulator = 208 MeV

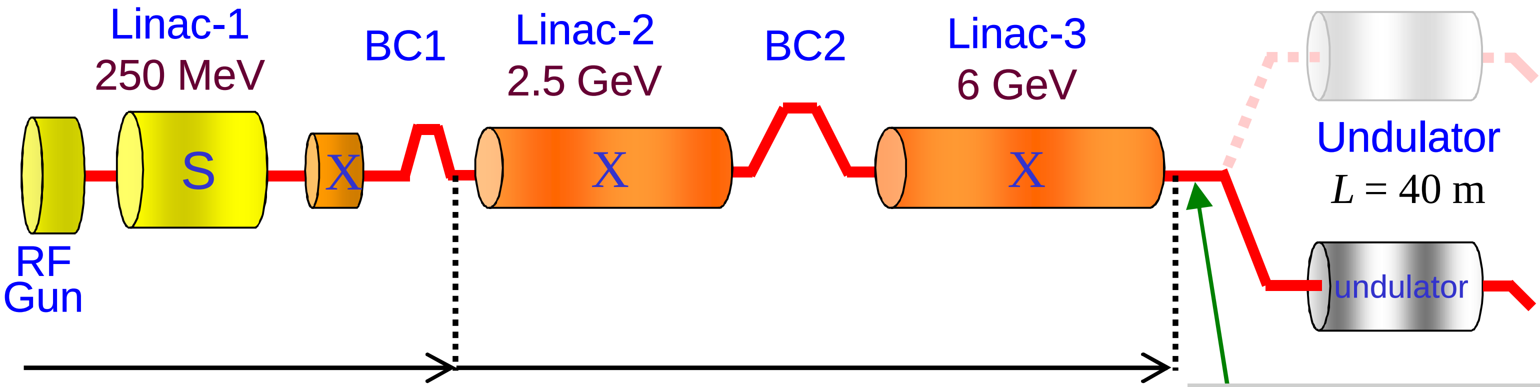
Hans Braun: "X-band was not considered because no commercial klystrons available"

⇨ Recently issued bid to have two vendors each build a 50 MW XL4 klystron

Compact X-Ray (1.5 Å) FEL

Parameter	**symbol**	***LCLS***	**CXFEL**	**unit**
Bunch Charge	Q	250	250	pC
Electron Energy	E	14	6	GeV
Emittance	$\gamma\varepsilon_{x,y}$	0.4-0.6	0.4-0.5	µm
Peak Current	I_{pk}	3.0	3.0	kA
Energy Spread	σ_E/E	0.01	0.02	%
Undulator Period	λ_u	3	1.5	cm
Und. Parameter	K	3.5	1.9	
Mean Und. Beta	$\langle\beta\rangle$	30	8	m
Sat. Length	L_{sat}	60	30	m
Sat. Power	P_{sat}	30	10	GW
FWHM Pulse Length	ΔT	80	80	fs
Photons/Pulse	N_γ	2	0.7	10^{12}

X-band Linac Driven Compact X-ray FEL



Linac-1
250 MeV

BC1

Linac-2
2.5 GeV

BC2

Linac-3
6 GeV

Undulator
$L = 40$ m

RF
Gun

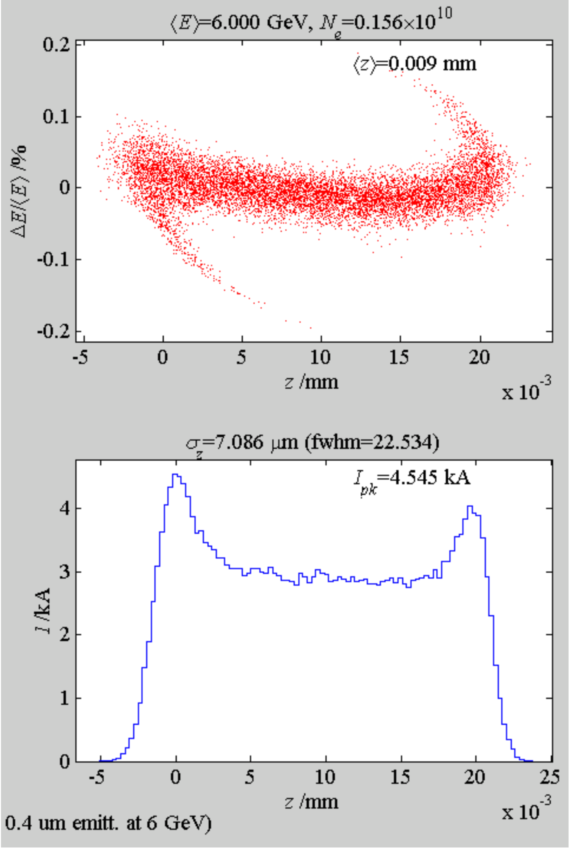
LCLS-like injector

L ~ 50 m

250 pC, $\gamma\varepsilon_{x,y} \approx 0.4\ \mu$m

X-band main linac+BC2

G ~ 70 MV/m, L ~ 150 m



Use LCLS injector beam distribution and H60 structure (a/λ=0.18) after BC1

LiTrack simulates longitudinal dynamics with wake and obtains 3 kA "uniform" distribution

Similar results for T53 structure (a/λ=0.13) with 200 pC charge

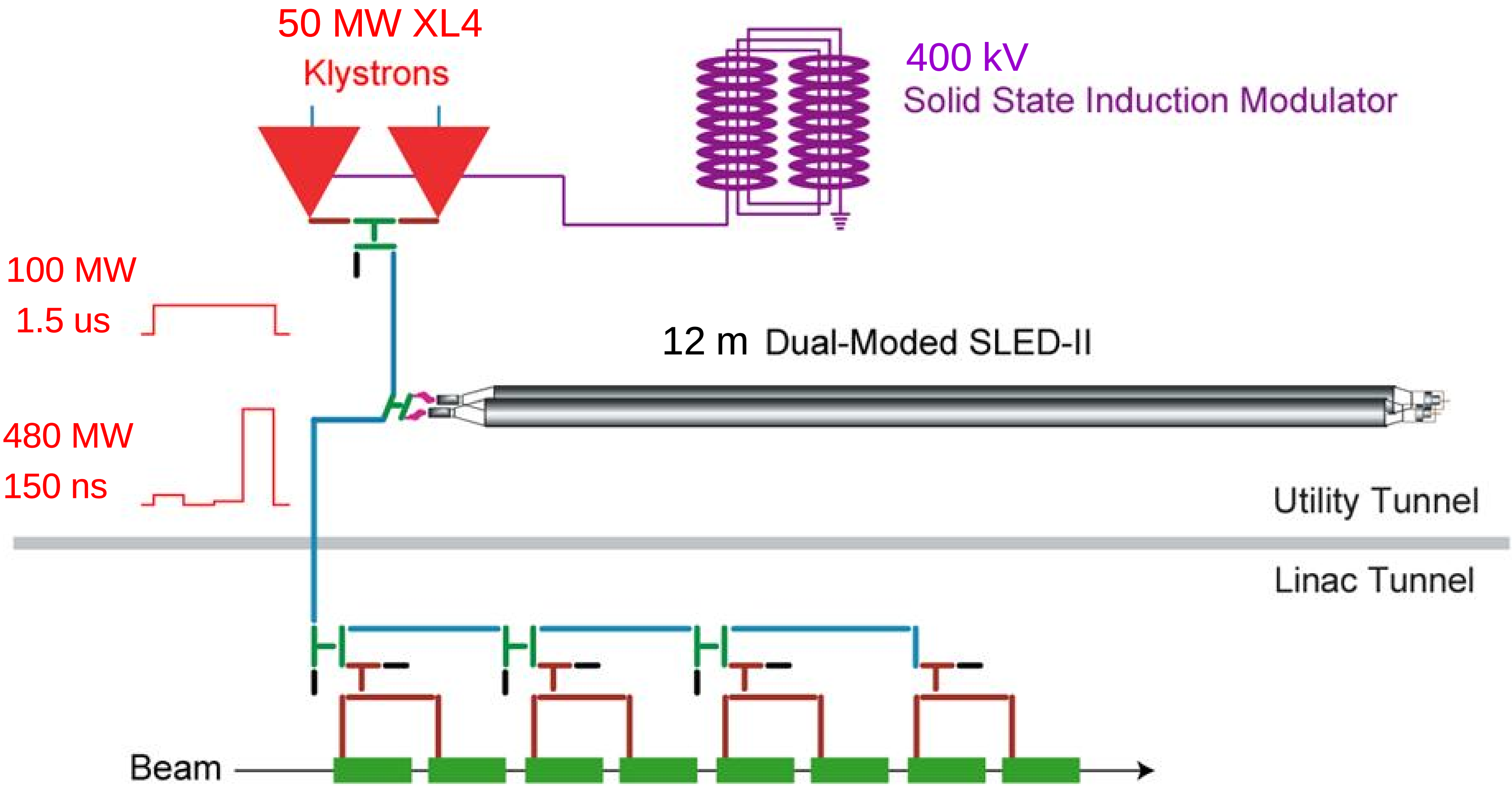
Operation Parameters

	Units	CXFEL	NLC
Beam Energy	GeV	0.25-6	2-250
Bunch Charge	nC	0.25	1.2
RF Pulse Width*	ns	150	400
Linac Pulse Rate	Hz	120	120
Beam Bunch Length	μm	56, 7	110

* Allows ~ 50-70 ns multibunch operation

CXFEL wakefield effects are comparable at the upstream end of the linac as the lower bunch charge and shorter bunch length offset the lower energy, however the bunch emittance is 25 times larger

Layout of CXFEL Linac RF Unit



50 MW XL4
Klystrons

400 kV
Solid State Induction Modulator

100 MW
1.5 us

12 m Dual-Moded SLED-II

480 MW
150 ns

Utility Tunnel

Linac Tunnel

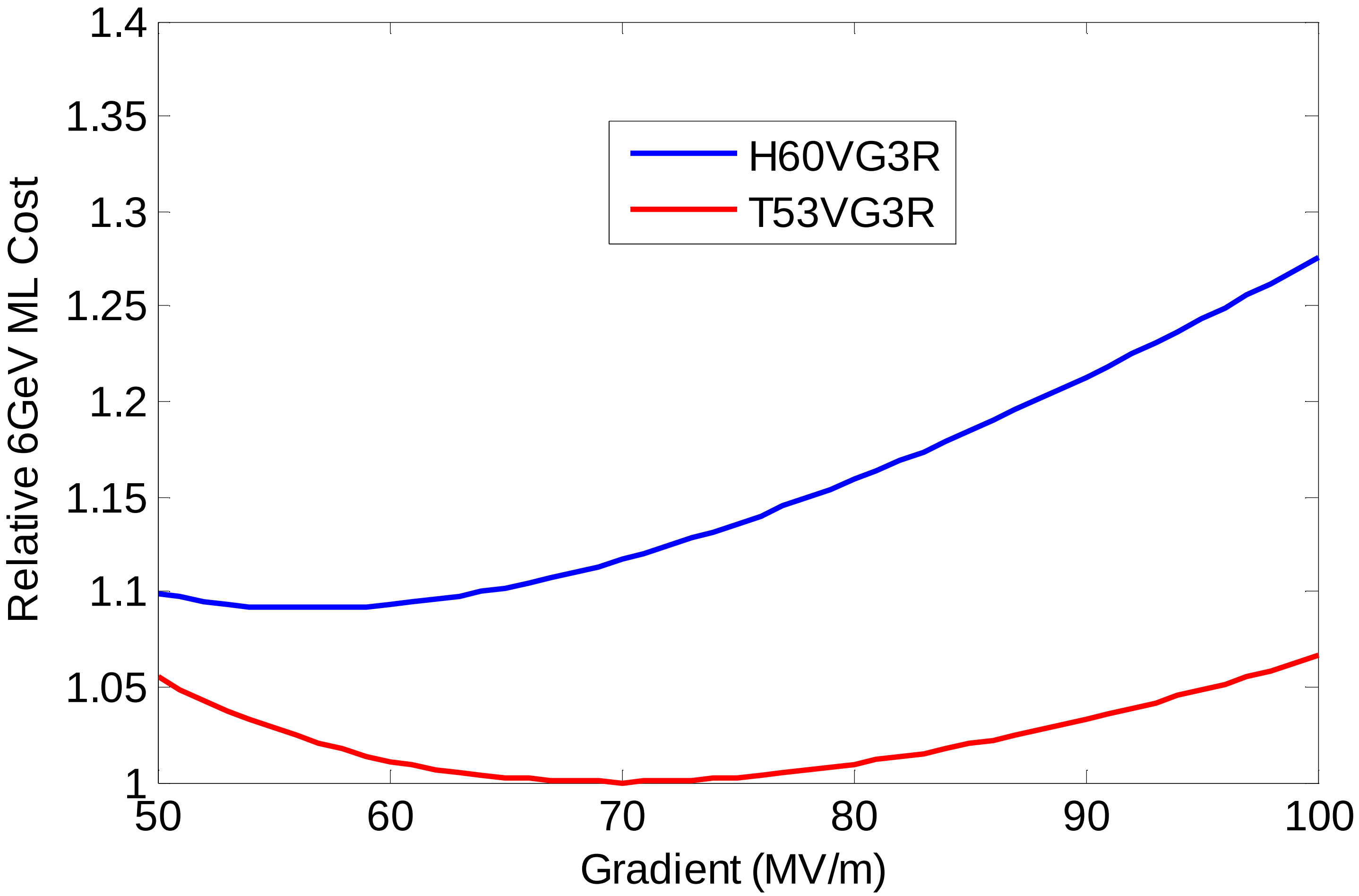
Beam

Nine T53 Structures (a/λ = 13%) or Six H60 Structures (a/λ = 18%)

Two Accelerator Structure Types

	Units	T53	H60
Structure Type		Constant E_surface	Detuned
Length	cm	0.53	0.6
Filling time	ns	74.3	105
Phase Advance/ Cell	π	2/3	5/6
<a>/λ	%	13.4	17.9
Power Needed for <Ea> = 70 MV/m	MW	48	73

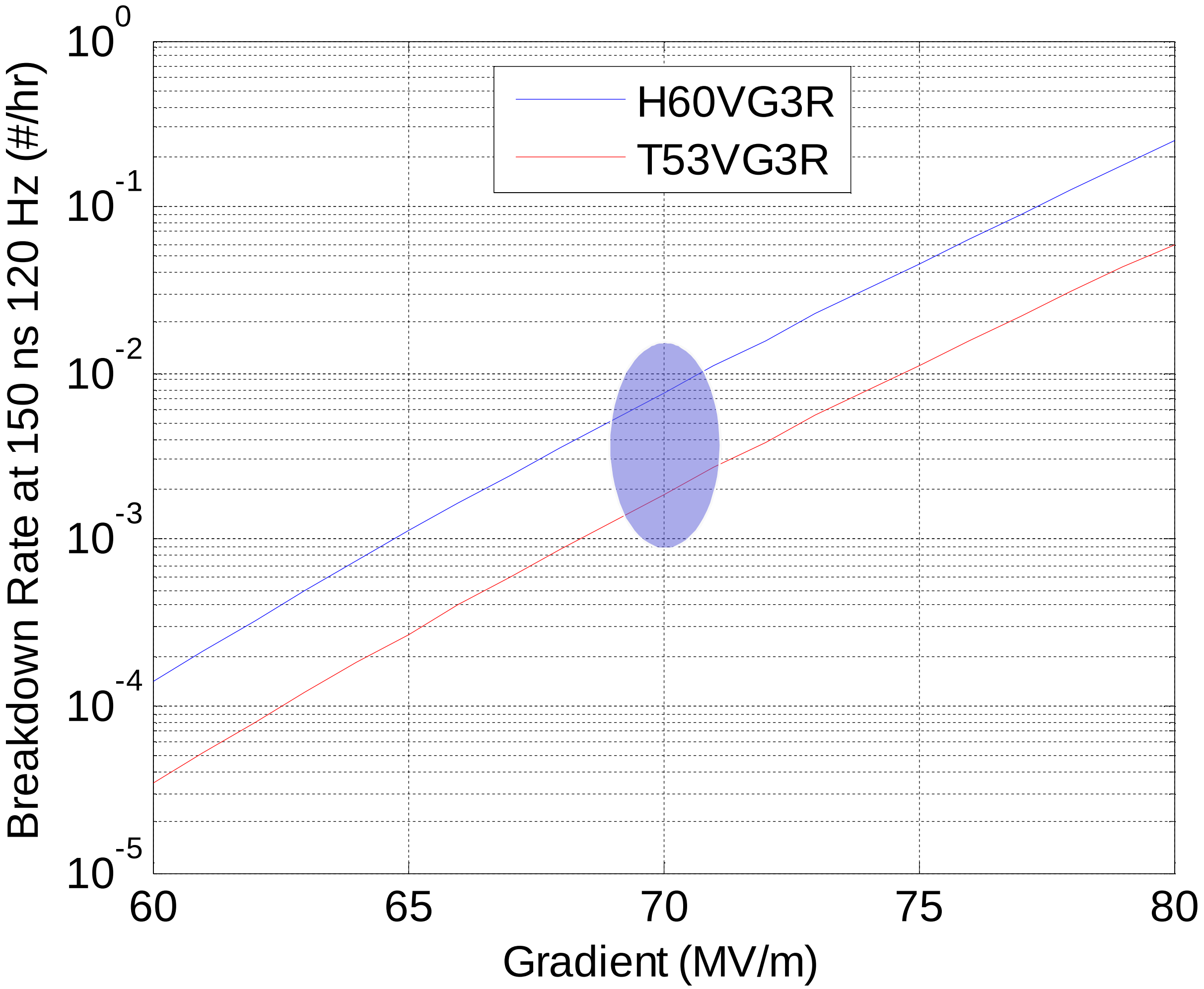
Gradient Optimization



Assuming 1) Tunnel cost 25 k$/m, AC power + cooling power 2.5 $/Watt

2) Modulator efficiency 70%, Klystron efficiency 55%.

Structure Breakdown Rates with 150 ns Pulses



At 70 MV/m, Rate Less Than 1/100hr at 120 Hz

1) H60VG3R scaled at 0.2/hr for 65 MV/m,400 ns, 60Hz
2) T53VG3R scaled at 1/hr for 70 MV/m, 480 ns, 60 Hz
3) Assuming BDR ~ G^{26}, ~ PW^6

RF Unit for Two Structure Types Operating at 70 MV/m*

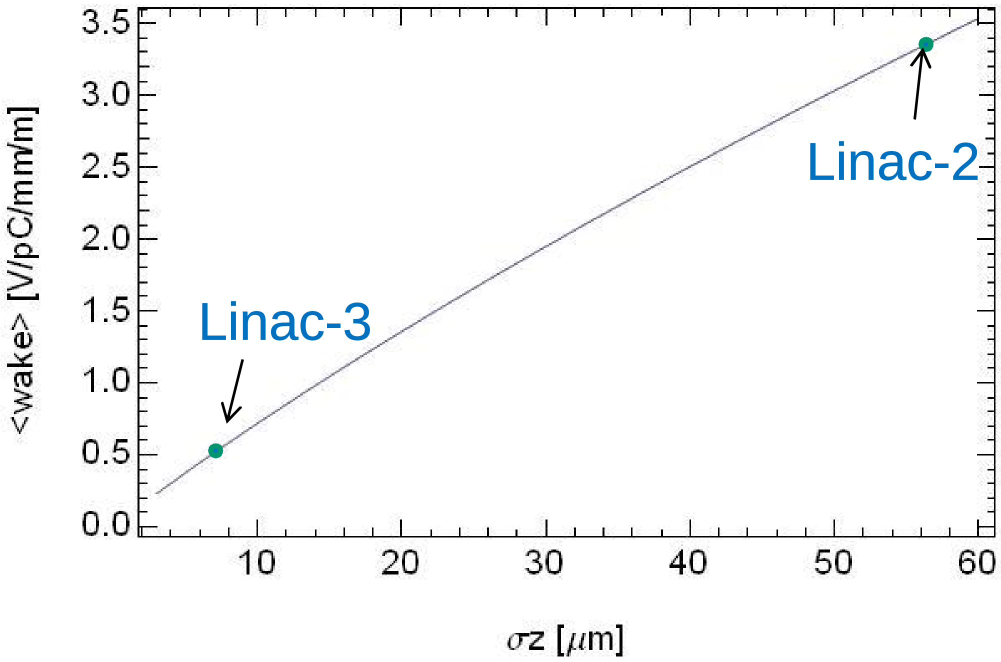
	Units	T53	H60
Average RF Phase Offset$^+$	Deg	2.6	2.6
Power Gain		4.83	4.83
Klystrons per Unit		2	2
Acc. Structures per Unit		9	6
RF Unit Length (Scaled to NLC)	m	6.75	4.5
Total RF units		18	24
Main Linac Length	m	122	108
Total Linac Length$^\#$	m	192	178

*Assume 13% RF overhead for waveguide losses

+ scaled to NLC for single bunch loading compensation

$^\#$ including ML, 50m injector and 20 m BC2 at 2.5 GeV

Transverse Wake Averaged over a Gaussian Bunch



Emittance Growth

Strength parameter: $\Upsilon = \frac{eN\ell\langle W\rangle\beta_0}{2E_0} g(E_f/E_0,\zeta)$ Chao, Richter, Yao

$$g(x,\zeta) = \frac{1}{\zeta}\frac{x^{\zeta-1}}{x-1}$$ (for $\beta \sim E^{\zeta}$)

Emittance growth due to injection jitter xo if Υ is small: $\delta\epsilon = \frac{x_0^2\Upsilon^2}{2\sigma_{x0}^2}$

- For CXFEL, eN= 250 pC, ε_N= .4 μm, ζ= 0, and

  Linac-2: E_0= .25 GeV, E_f= 2.5 GeV, σ_z= 56 μm, *l*= 32 m, β_0= 10 m (σ_{x0}= 90 μm) => Υ= .14

  Linac-3: E_0= 2.5 GeV, E_f= 6 GeV, σ_z= 7 μm, *l*= 50 m, β_0= 10 m (σ_{x0}= 29 μm) => Υ= .01

- For random misalignment, let x_0^2-> x_{rms}^2/M_p
- l_{cu}= $a^2/2\sigma_z$= 1.6 m (Linac-3)—catch-up distance, estimate of distance to steady-state

Single Bunch Tolerance Summary

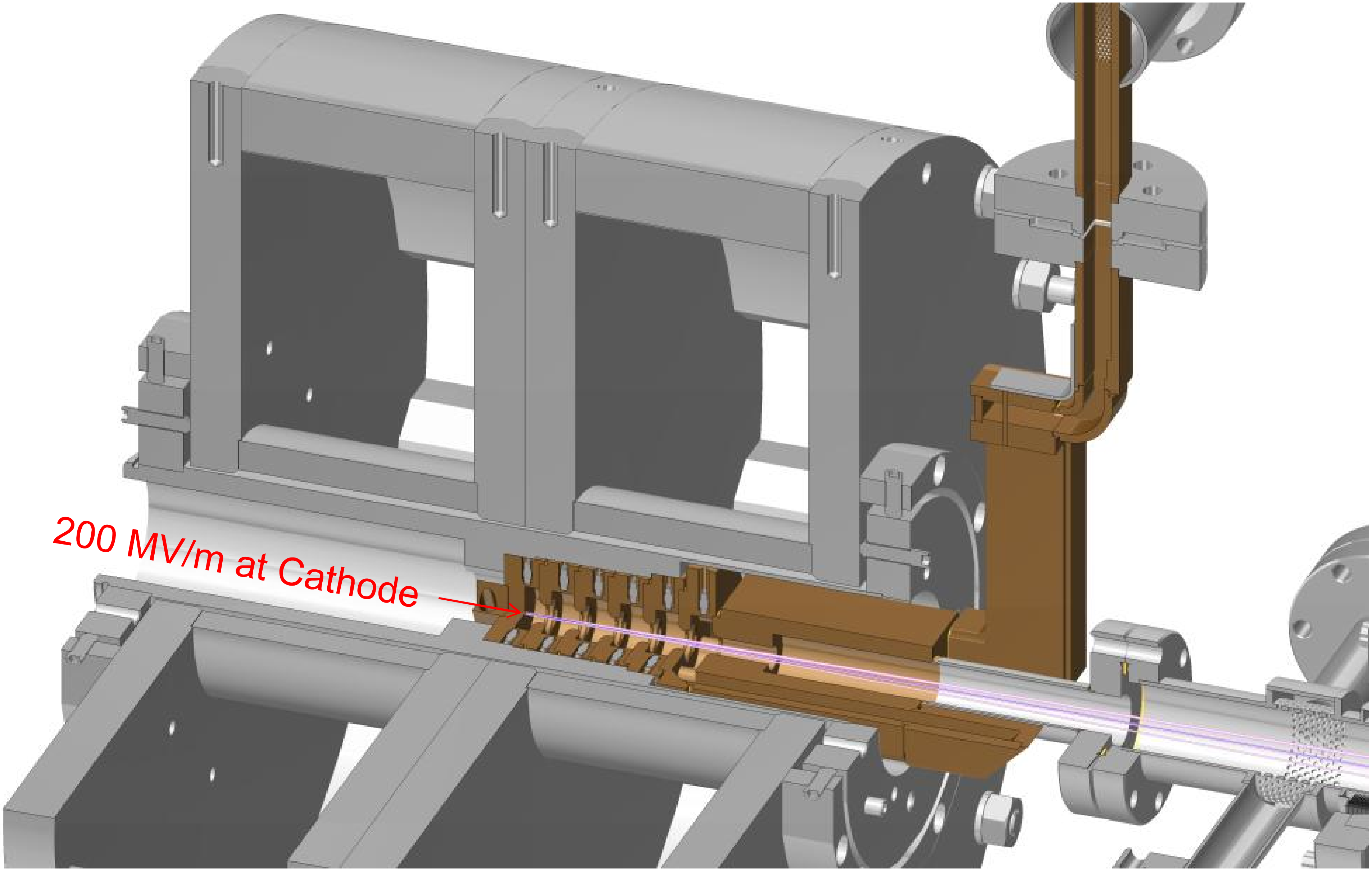
- In both Linac-2 and Linac-3, Υ<< 1, => short-range, transverse wakefields in H60VG3 are not a major issue in that:

  An injection jitter of σ_{x0} yields 1% emittance growth in Linac-2 and .003% in Linac-3

  Random misalignment of 1 mm rms, assuming 50 structures in each linac, yields an emittance growth of 1% in Linac-2, 0.1% in Linac-3

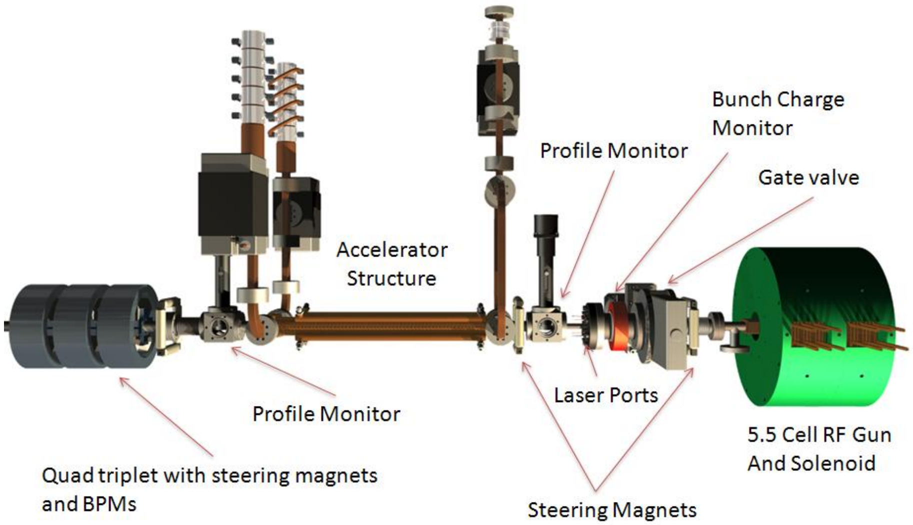
- With the T53VG3R structure, the jitter and misalignment tolerances are about three times smaller for the same emittance growth.
- The wake effect is weak mainly because the bunches are very short.

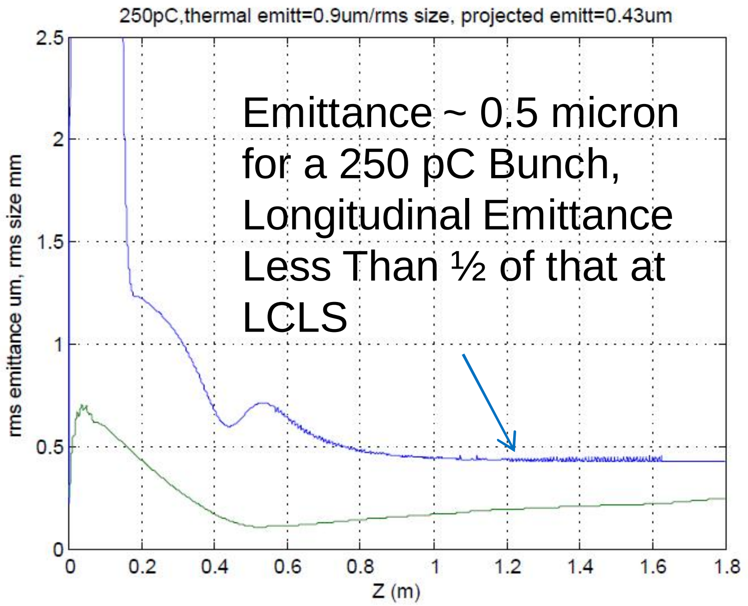
5.59 Cell X-band Gun



200 MV/m at Cathode

X-Band Gun Development (with LLNL)





Emittance ~ 0.5 micron for a 250 pC Bunch, Longitudinal Emittance Less Than ½ of that at LCLS

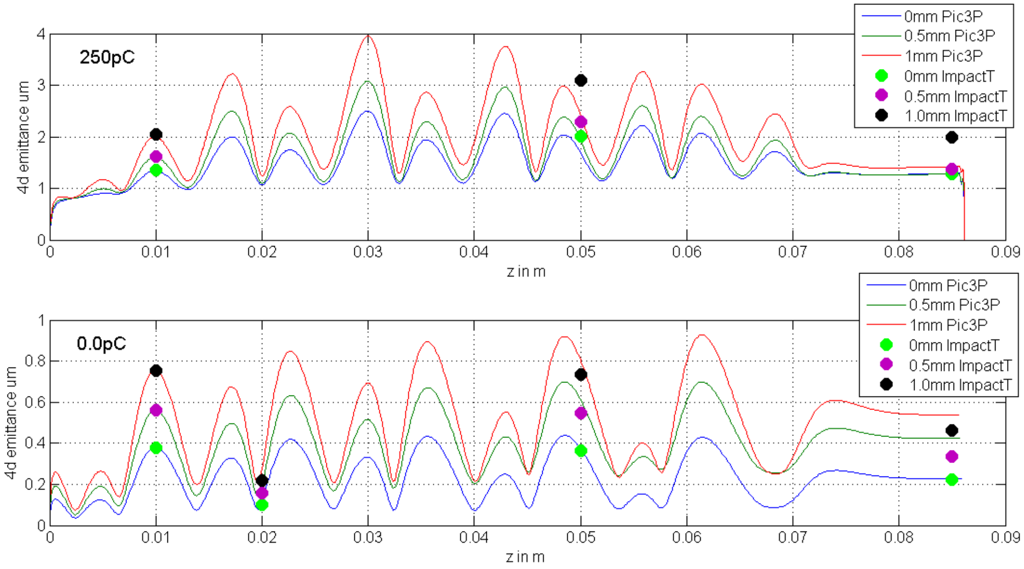
Comparison of 4D emittance along the gun computed with

ImpactT ('instant' space charge)

and

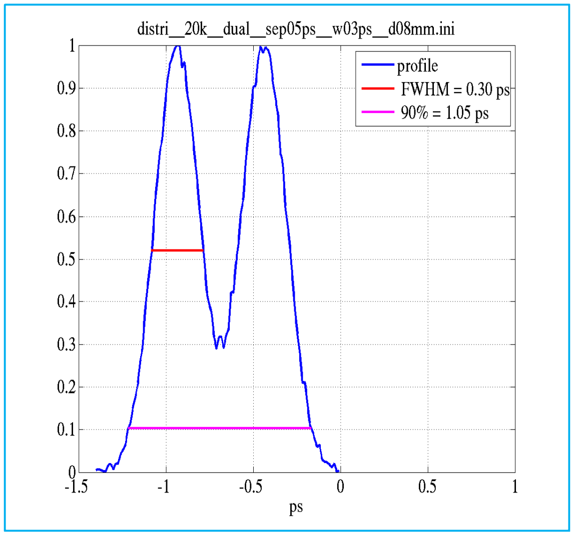
PIC 3D ('delayed' space charge plus wakes with true geometry)

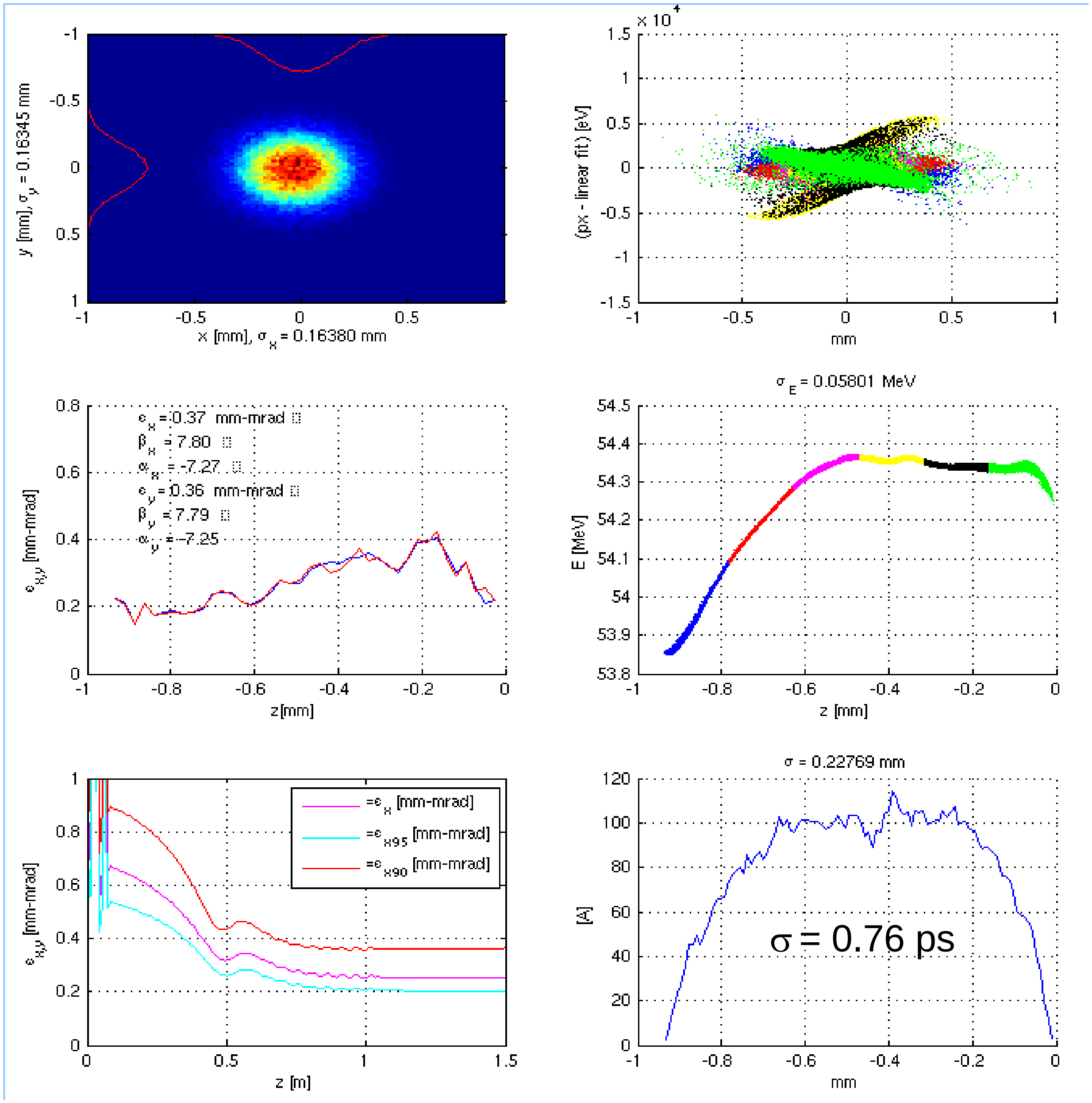
at two bunche charges and three laser offsets



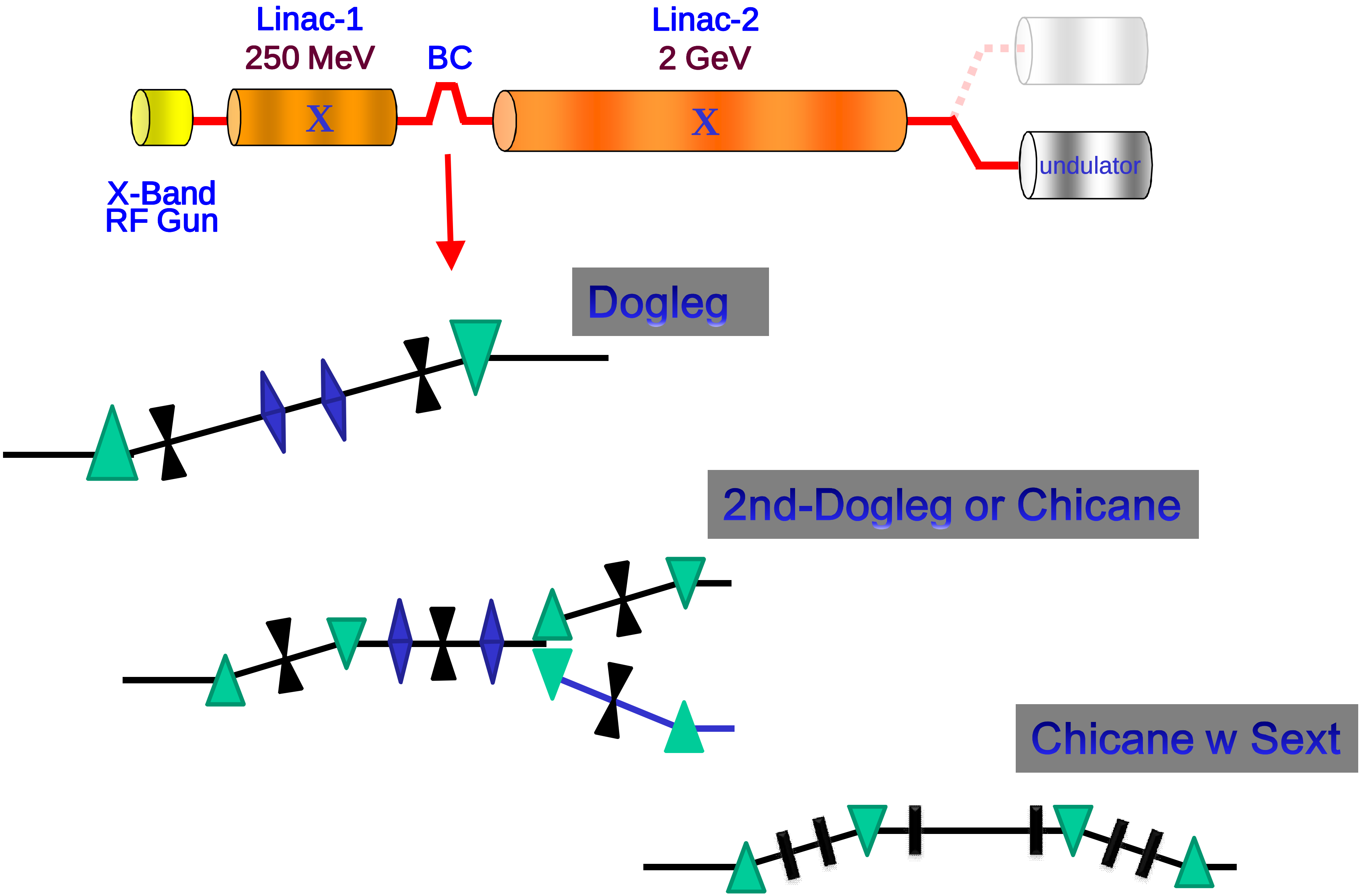
Optimization Using Stacked Lasers

- At NLCTA, will be able to run short laser pulses and stack two pulses.
- For 250 pC bunches, emittance = 0.3 μm (95% particles) with single Gaussian (500 fs FWHM) vs 0.25 μm (95% particles) with stack of two Gaussians (300 fs FWHM each).





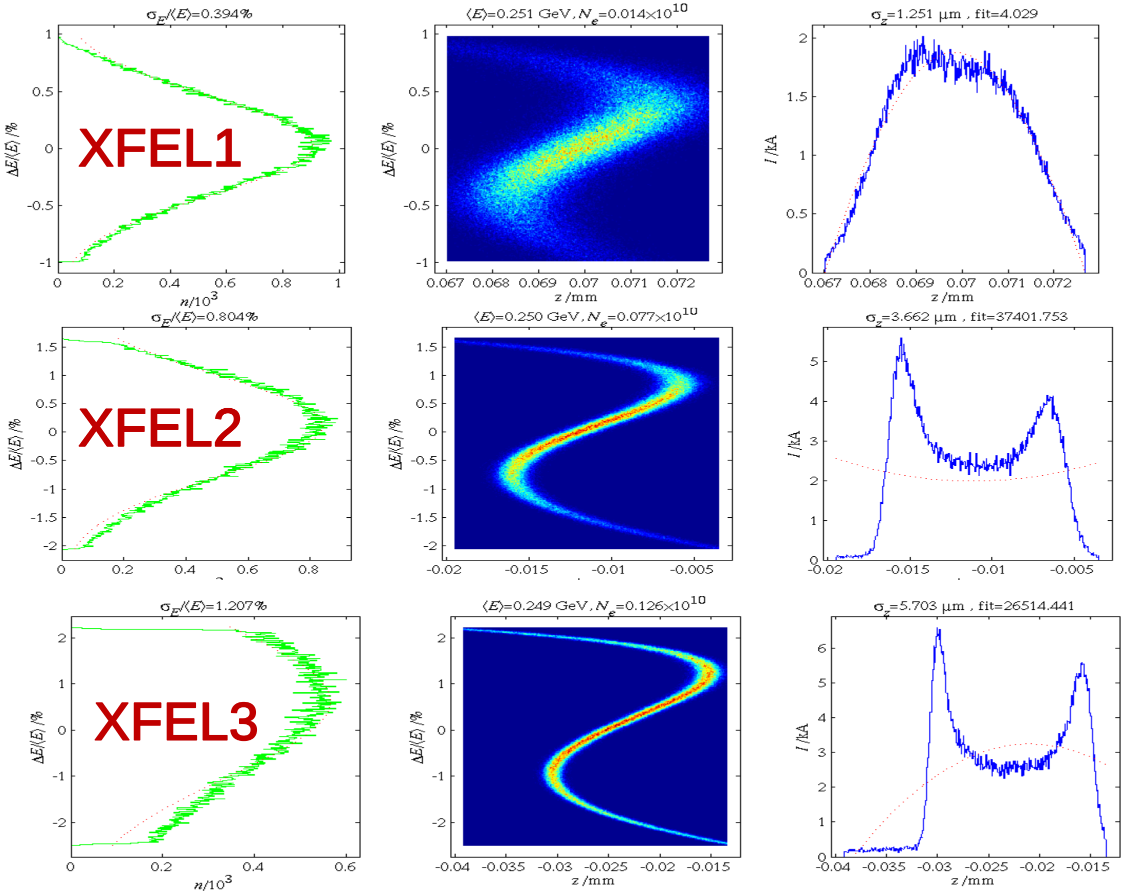
Linearization Without Higher Harmonic RF



Parameter	**Sym.**	***LCLS***	**XFEL1**	**XFEL2**	**XFEL3**	**unit**
bunch charge	Q	**250**	**20**	**120**	**250**	pC
Energy	E	***14***	***0.25***	***0.25***	***0.25***	GeV
N. emittance	$\gamma\varepsilon_{x,y}$	**0.4-0.6**	**TBD**	**TBD**	**TBD**	µm
peak current	I_{pk}	**3.0**	**1.8**	**3.0**	**3.0**	kA
Slice espread	σ_E/E	**0.01**	**~0.1**	**~0.1**	**0.1**	%
FWHM	ΔT	**80**	**12**	**30**	**50**	fs

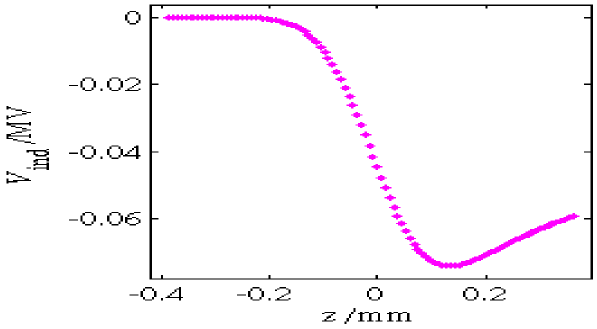
After BC

Adjust R_{56} and T_{566} to achieve ~ flat 3 kA bunches

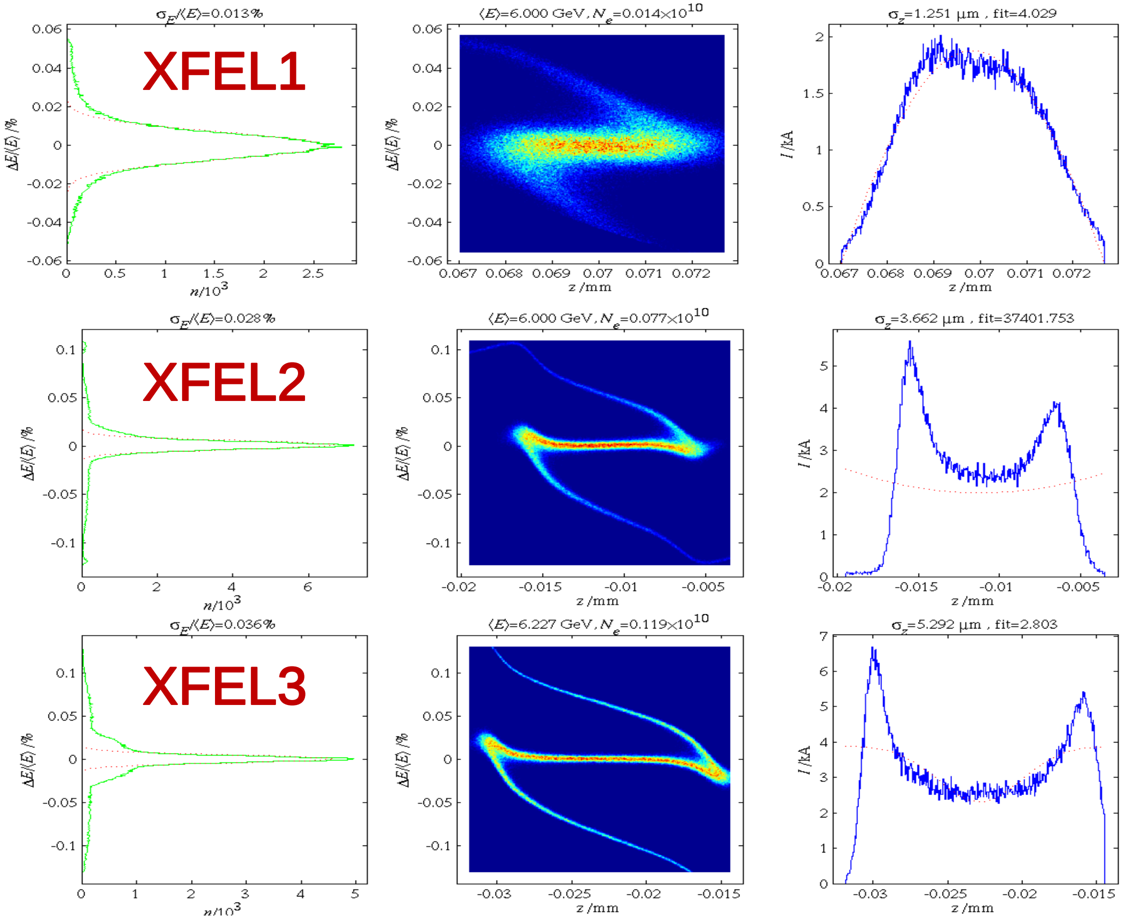


Parameter	**Sym.**	***LCLS***	**XFEL1**	**XFEL2**	**XFEL3**	**unit**
bunch charge	Q	**250**	**20**	**120**	**250**	pC
Energy	E	***14***	***6***	***6***	***6***	GeV
N. emittance	$\gamma\varepsilon_{x,y}$	**0.4-0.6**	**TBD**	**TBD**	**TBD**	µm
peak current	I_{pk}	**3.0**	**1.8**	**3.0**	**3.0**	kA
Slice espread	σ_E/E	**0.01**	**0.01-0.02**	**0.01-0.02**	**0.01-0.02**	%
FWHM	ΔT	**80**	**12**	**30**	**50**	fs

End of Linac



With above Longitudial wake, adjust rf phase to minmize energy spread



X-Band Revival

- The 15 year, ~ 100 M$ development of X-band technology for a linear collider produced a suite of robust, high power components.
- With the low bunch charge being considered for future XFELs, X-band technology affords a low cost, compact means of generating multi-GeV, low emittance bunches.
- Would operate at gradient/power levels already demonstrated.
- Modulators industrialized, klystrons will soon be and waveguide and structures can be readily bulit in industry.
- To further simply such a linac, a low emittance X-band gun and non-rf linearizing techniques are being developed.