Design Studies and Optimization of Future X-ray FELs Based on Advanced High Frequency Linac

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2011 Particle Accelerator Conference

SLAC NATIONAL ACCELERATOR LABORATORY

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Outline

1. Advantages of High Frequency Linacs
2. RF to Beam Energy Conversion Efficiency
3. Short Beam (e.g., Single or Two Bunch XFEL)
4. Long Beam
5. Scaling Laws for XFEL Linacs
6. Costs, Risk and Tolerances
7. X-band Driven Linacs Light Sources
8. Summary

NC Linac Driven Light Sources

(Operating, Under Construction, Proposed)

	GHz	MV/m	GeV	nC	Hz
LCLS (U.S.)	S (2.9)	17	4 ~ 14	0.02~ 0.25	120
SCSS (Japan) 🟡	C (5.7)	35 ~ 39	6 ~ 8	0.3	60
LLNL/SLAC MEGA-ray 🟡	X(11.4)	80	0.25	0.25	60
SwissFEL 🟢	C	26	2.1 ~ 5.8	0.2	100
PAL (Korea) 🟡	S/C	25~27/40	10	0.2	60
SPARX-FEL (Italy) 🟡	S/C	23.5/35	2.6	1	
MAX IV (Sweden) 🟡	S/C	> 25/>35	3.5	0.1	100
Shanghai XFEL (China) 🟡	C	40	6.4	0.2	
ZFEL (Netherlands) 🟡	X	100	2.1	0.01 ~ 0.1	10 ~ 1000

- 🟡 Compact – Affordable site size
- 🟢 High Efficiency – Available AC Power

High Frequency Advantages

- ✓ High gradient -- a compact Linac
- ✓ High efficiency-- less AC Power Needed

Potential drawback -- larger transverse wakefields

- × **May need larger iris radius to reduce short-range wakes**
- × **May need HOM damping to reduce long-range wakes**

XFELs: bunch charge low (< 250 pC) and short (< 30 microns). wake effects generally small

How about Cost, Risk and Tolerance ?

2. RF to Beam Energy Conversion Efficiency

Normal Conducting

Constant Gradient

Very Low Beam Loading

Travelling Wave Structure

Quality factor, Q

Beam current, I_b

Shunt impedance, r_s

RF frequency, ω

Acceleration gradient, G

Beam train length, T_b

Field attenuation constant, τ

$$\eta = \frac{r_s I_b T_b}{G}\left(1-e^{-2\tau}\right)\Big/\left(T_b + 2\tau Q/\omega\right)$$

To maximize, η

$$e^{2\tau_{opt}} - 2\tau_{opt} = T_b\omega/Q + 1$$

$$\tau_{opt} \approx \begin{cases} \sqrt{\dfrac{T_b\omega}{2Q}} & \textbf{Single/Two Bunch (SB)} \\ \dfrac{1}{2}\log\left(\dfrac{T_b\omega}{Q}+1\right) & \textbf{Long Bunch Train (LB)} \end{cases}$$

For constant average iris radius / rf wavelength (a/λ), efficiency (η) increases and power per unit length (P/L) decreases at higher frequency

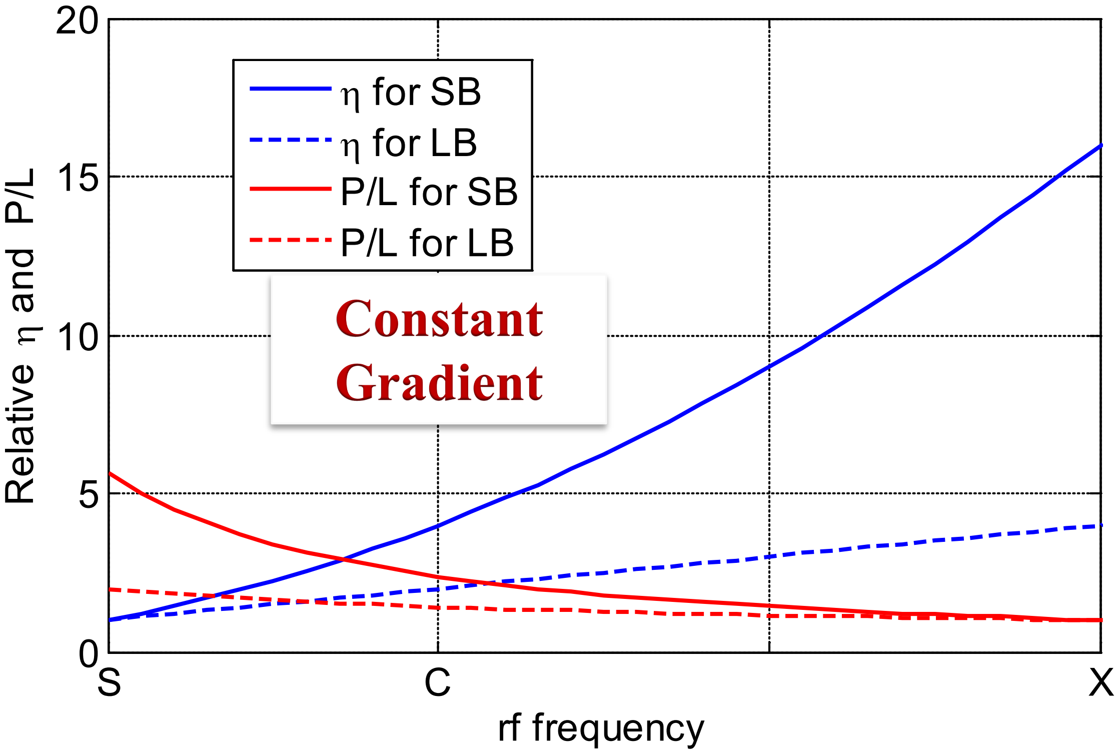
$$r_s \sim \omega^{1/2},\ Q \sim \omega^{-1/2}$$

$$\eta \approx \begin{cases} \dfrac{I_b T_b}{G}\dfrac{r_s \omega}{Q} \propto \omega^2 G^{-1} \\[2ex] \dfrac{I_b T_b r_s}{G} \propto \omega\, G^{-1} \end{cases}$$

SB

LB

$$\left.\begin{matrix} \dfrac{G^2}{2\tau \cdot r_s} \propto G^2 \omega^{-5/4} \\[2ex] \dfrac{G^2}{r_s} \propto G^2 \omega^{-1/2} \end{matrix}\right\} \approx P/L$$



G = const.

S → X

SB/LB

η ↗16/4

P↘6/2

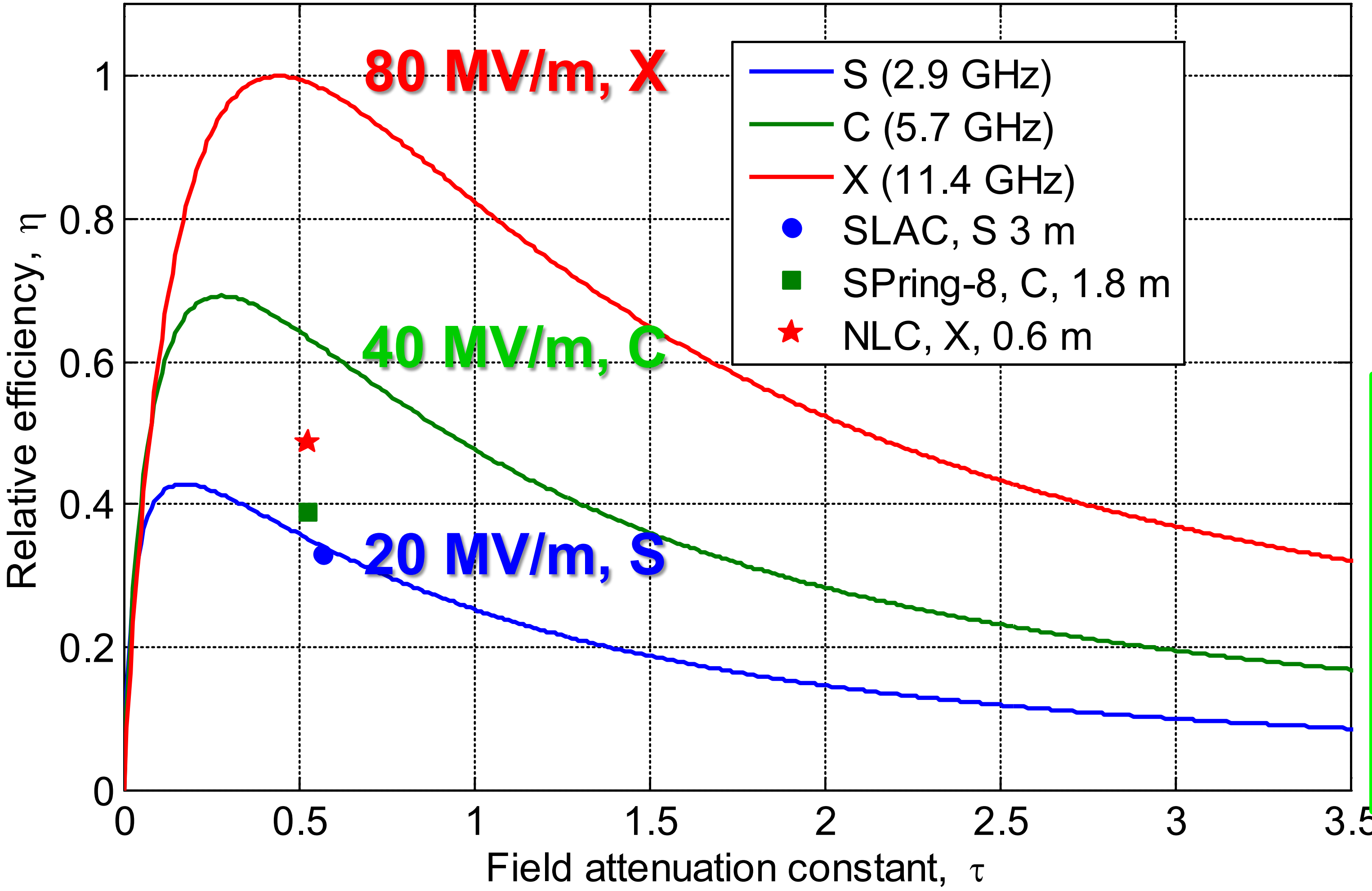
However, a/λ and gradient generally not constant with frequency

Existing Accelerators for Linear Colliders

(Optimized for Higher Beam Loading)

	S	C	X	Unit
Structure	**SLAC S-band**	**SCSS C-band**	**NLC H60VG3**	
RF Frequency	**2.9**	**5.7**	**11.4**	**GHz**
Length	**3**	**1.8**	**0.6**	**m**
Filling time, T_f	**830**	**286**	**105**	**ns**
Shunt Impedance	**53 ~ 60**	**53.1**	**48.8 ~ 77.8**	**MΩ/m**
Gradient	**20**	**35**	**65**	**MV/m**
U_{rf}/U_b, $U_{rf} = P_{rf}*(T_f+T_b)$	**0.46**	**0.34**	**0.25**	**J/MeV (T_b = 50ns)**
	1.08	**1.55**	**2.20**	**J/MeV (T_b=1250ns)**

CG-TW Structure Efficiency for T_b = 50 ns and Low Beam Loading



τ_{opt}

0.44

0.28

0.17

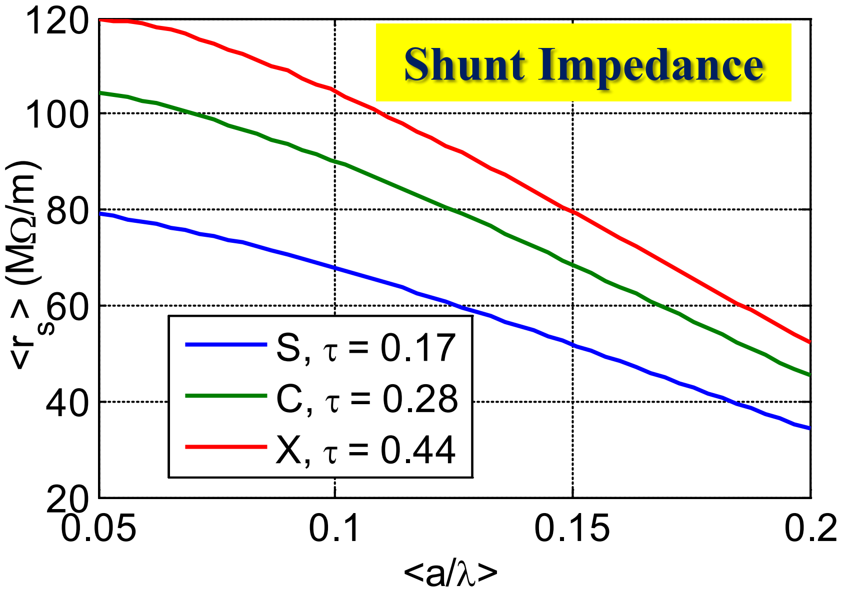
Curves assume the same a/λ where $r \sim \omega^{1/2}$, $Q \sim \omega^{-1/2}$

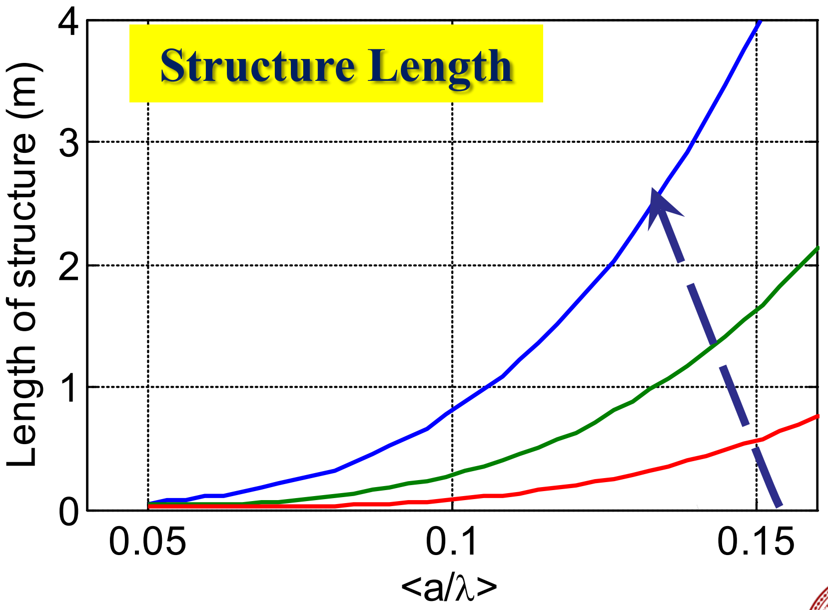
Choosing a/λ -vs- Frequency

Want high shunt impendence (rs) but reasonable wakefields

Also want long TW structure length to minimize cost (SW cavities also considered but would lose a factor of two in efficiency)

Choose average a/λ = 0.13-0.15 (dashed line) so structures similar in length to those for linear colliders – wakes manageable at X-band





Optimum Structures for T_b = 50 ns

Frequency	**S (2.9)**	**C (5.7)**	**X (11.4)**	GHz
Length	2.4	1.2	0.6	m
Fill time, T_f	265	150	77	ns
Iris radius, $\langle a/\lambda \rangle$	0.13	0.14	0.15	
Average Shunt impedance	58	74	87	MΩ/m
Gradient	**20**	**40**	**80**	MV/m
Peak rf power	57	60	77	MW
RF to beam energy ratio, U_{rf}/U_b	**0.37**	**0.25**	**0.20**	J/MeV

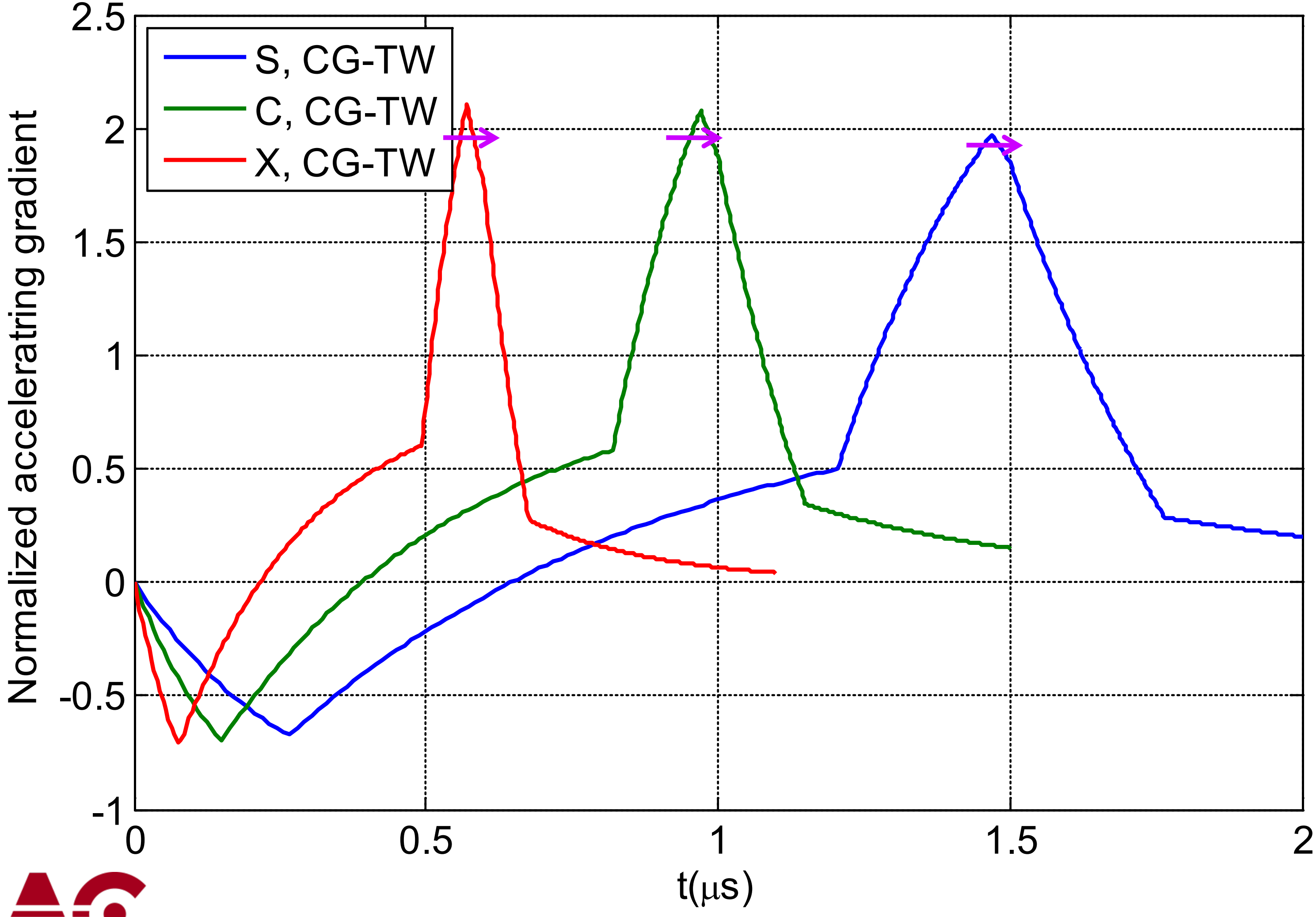
Available RF Power Sources

	S	C	X	Unit
Klystron	5045	E3746	XL4	
Maximum Pulse Width, $T_{k,\ max}$	3.5	2.5	1.5	μs
Structure Fill Time, T_f	265	150	77	ns

Given $T_f << T_{k,\ max}$, use SLED (SLAC Linac Energy Doubler) to boost rf peak power – not particularly efficient, but cost effective

Acceleration Boost with SLED Cavities

(for two bunch operation)



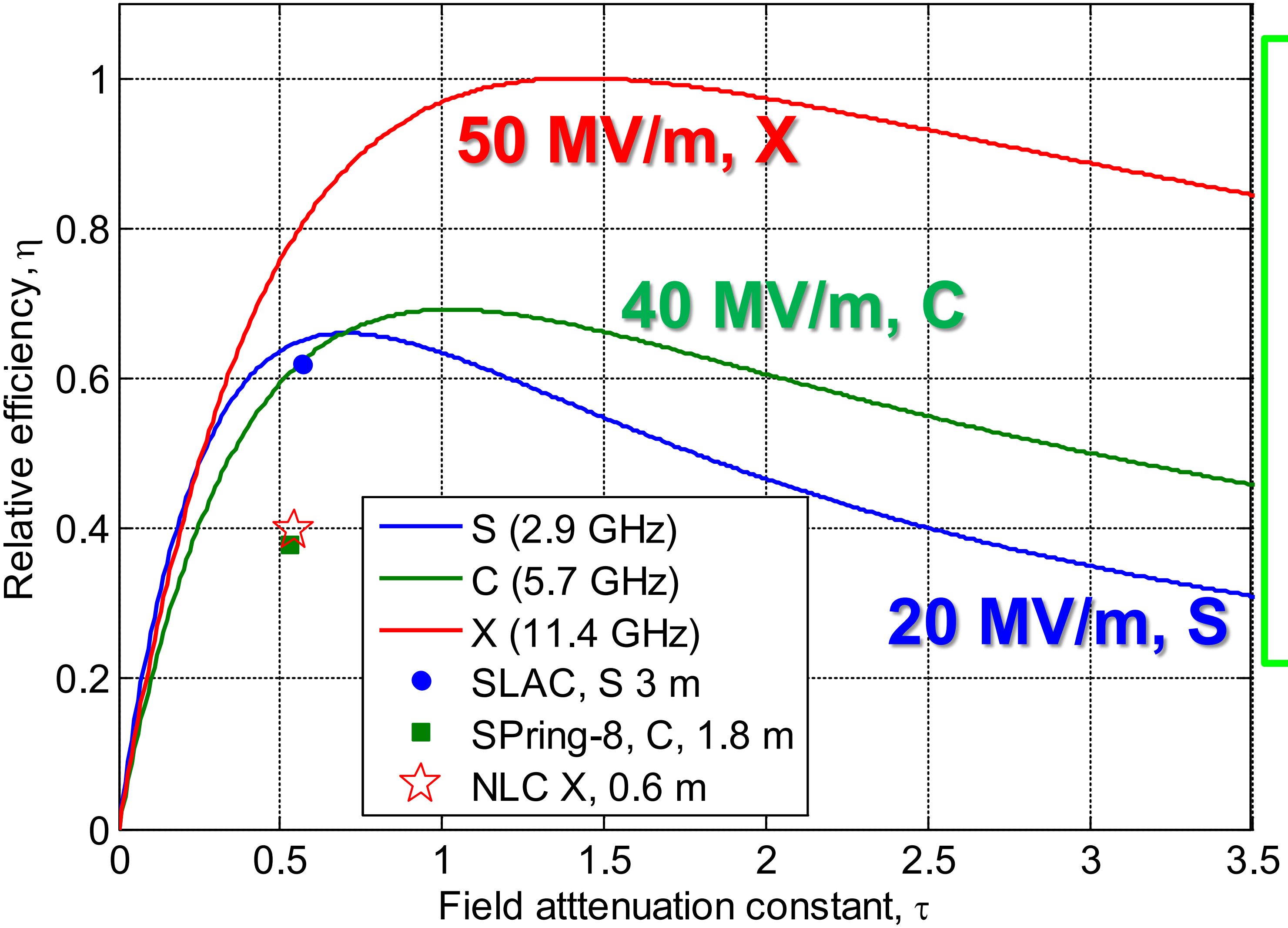
Summary Per RF Station for $T_b = 50$ ns

	S (2.9)	C (5.7)	X (11.4)	GHz
Peak rf power, P_k	1×65	1×50	2×50	MW
RF pulse length, T_k	1.5	1	0.6	μs
Efficiency of SLED	71	65	64	%
Gradient, G	20.3	40	77.4	MV/m
Number of Structures	4	3	5	
Beam energy, U_b	196	145	234	MeV
Rf to beam energy ratio, ($U_{rf} = P_k * T_k$), U_{rf}/U_b	0.5	0.34	0.26	J/MeV

~ ½ U_{rf}/U_b with ×4 Gradient !

Long Beam Optimization

(consider T_b = 1250 ns, which is close to the maximum at X-band)



τ_{opt}

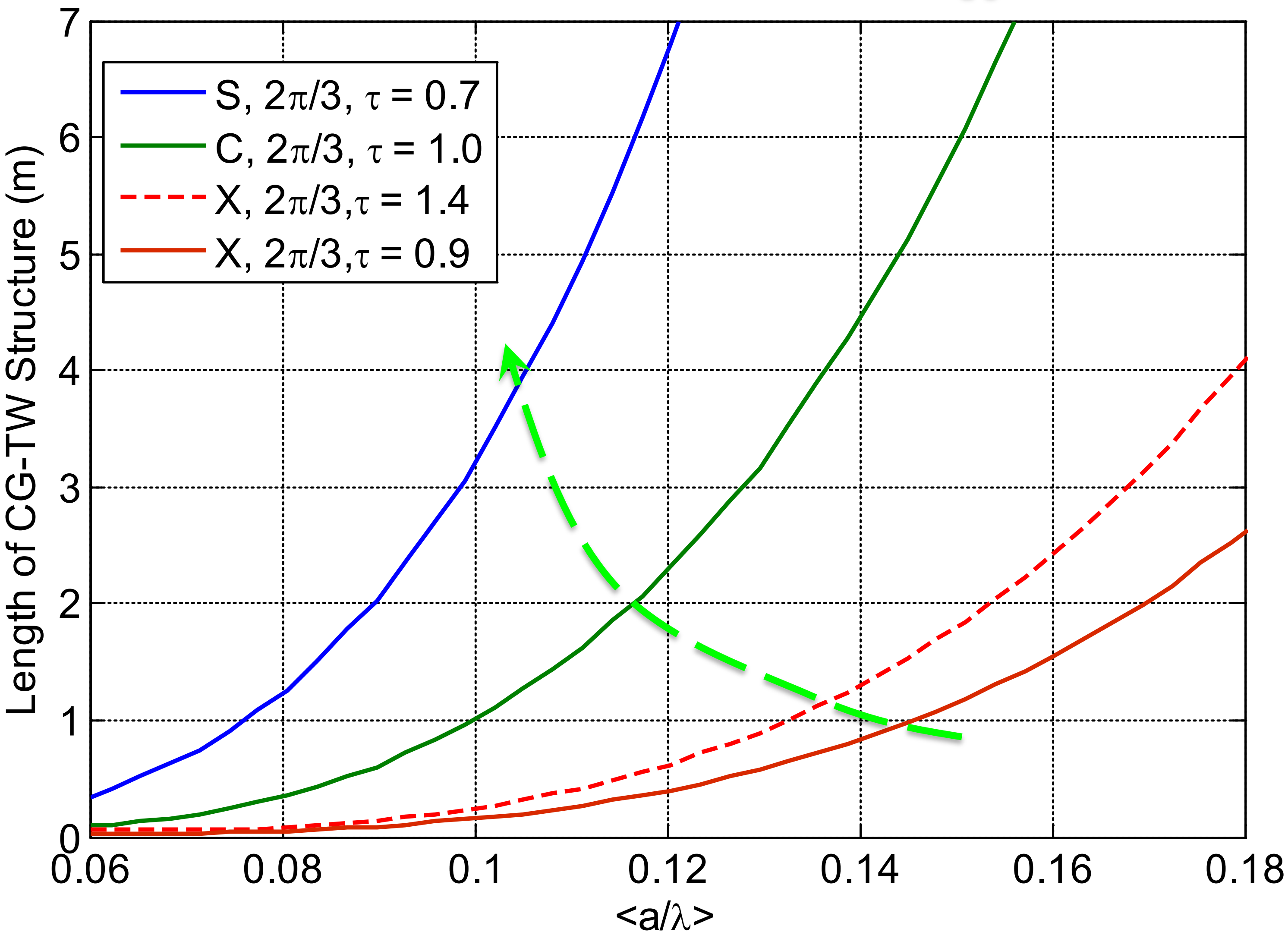
1.4

1.0

0.7

Curves assume the same a/λ where $r \sim \omega^{1/2}$, $Q \sim \omega^{-1/2}$

Accelerator Design for T_b = 1250 ns



Again choose a/λ so the TW structures are of a reasonable length and the wakefields are manageable

Optimum Structures for $T_b = 1250$ ns

	S	C	X	
Length	4	2	1	m
Fill time, T_f	999	511	159	ns
Iris size, $\langle a/\lambda \rangle$	0.11	0.12	0.15	
Shunt impedance	65	83	91	MΩ/m
Gradient	20	40	50	MV/m
Peak rf power	34	47	34	MW
U_{rf}/U_b	0.85	0.93	0.95	J/MeV

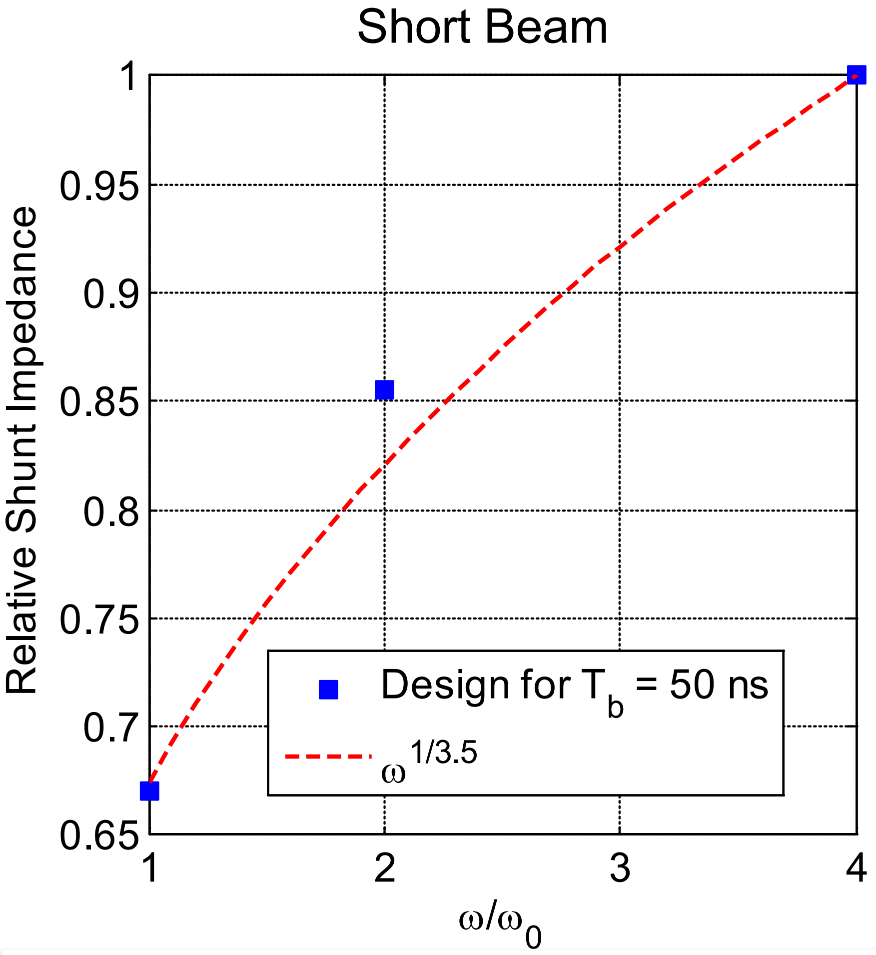
Summary Per RF Station for T_b = 1250 ns

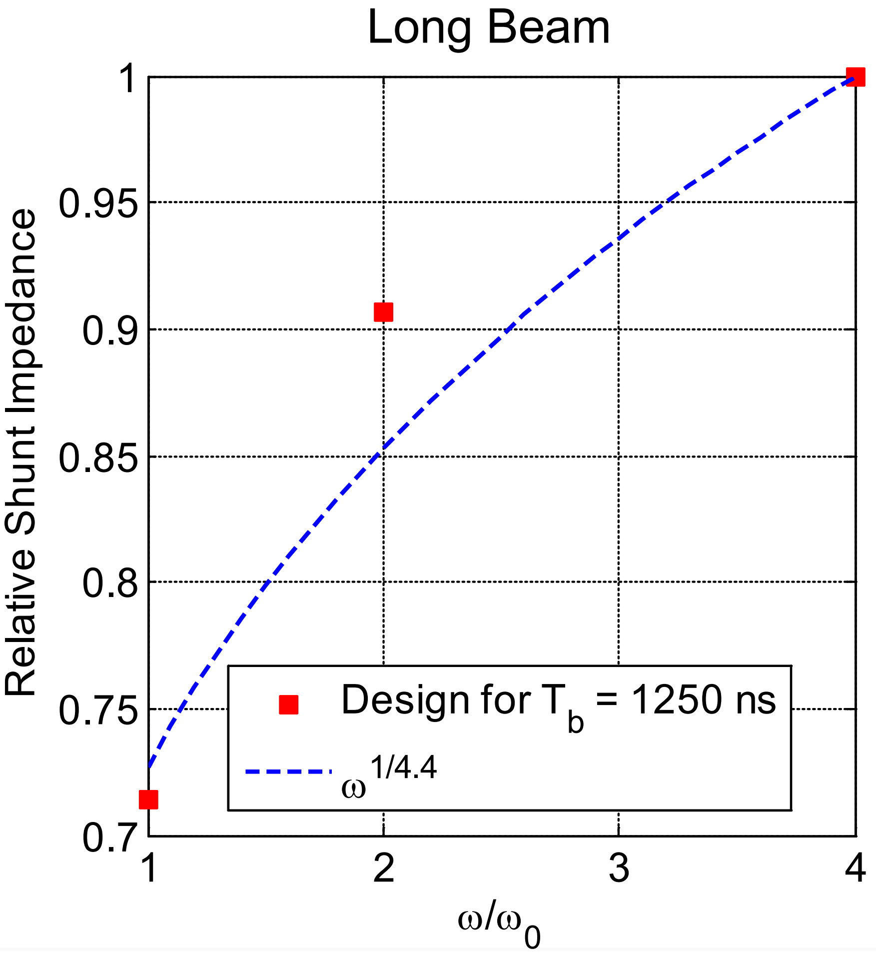
(With long beam, cannot use SLED effectively)

	S (2.9)	C (5.7)	X (11.4)	
Klystron Peak Power	65	50	50	MW
Rf Pulse Width	2.25	1.75	1.5	µs
Number of Accelerators	2	1	3	
Gradient	19.5	41.4	49.7	MV/m
Beam Energy, U_b	157	83.5	148.9	MeV
U_{rf}/U_b	0.93	0.95	0.99	J/MeV

Similar U_{rf}/U_b with x2.5 Gradient

Scaling Law: Shunt Impedance





For realistic structures and tolerances : **$r \sim \omega^{1/4}$**

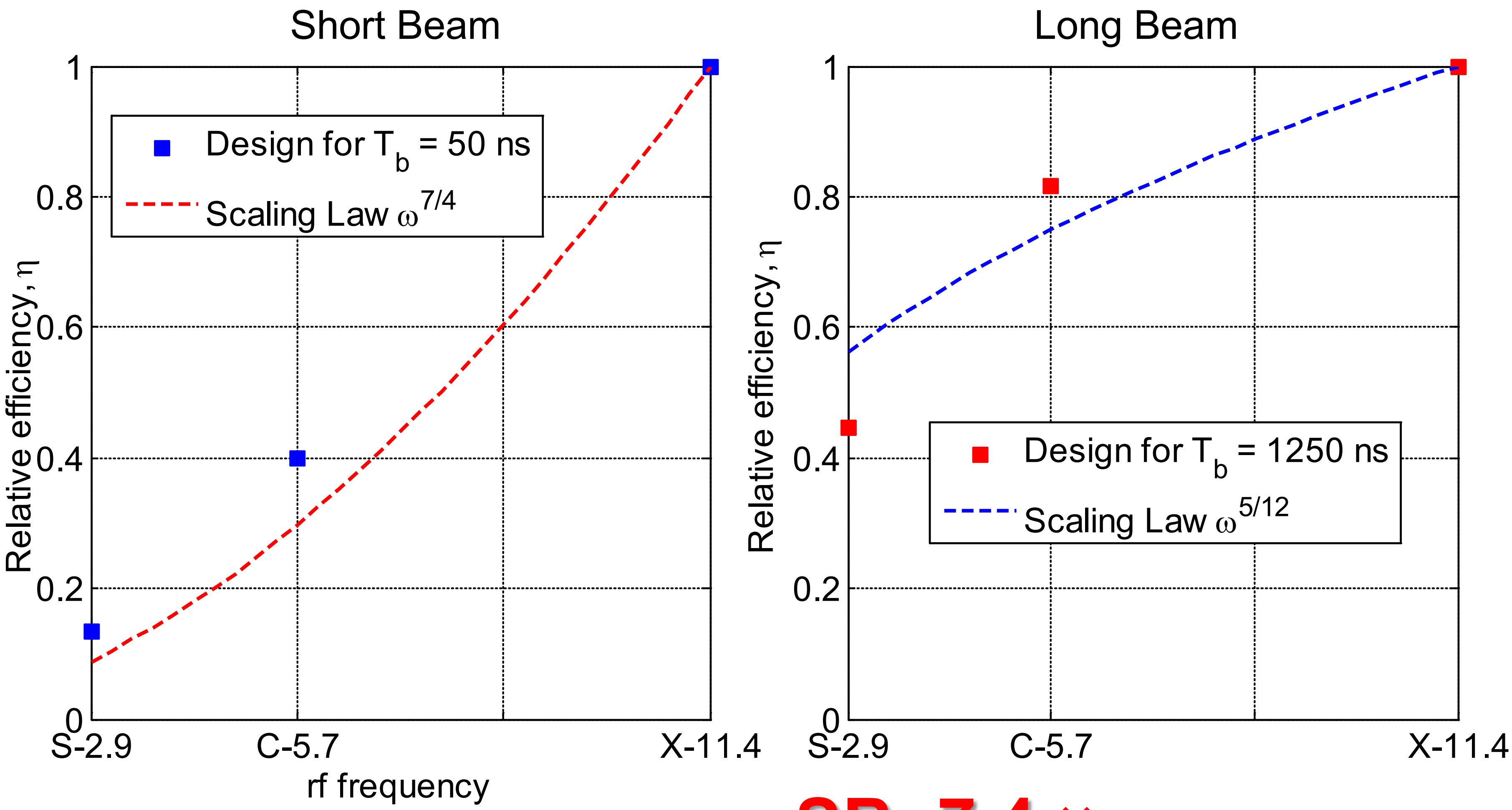
Scaling Relations

(follows from shunt impedance scaling)

	Short beam pulse $T_b \ll T_f$	**Long beam pulse** $T_b \gg T_f$
Shunt impedance	$\sim \omega^{1/4}$	$\sim \omega^{1/4}$
Q factor	$\sim \omega^{-1/2}$	$\sim \omega^{-1/2}$
Filling time	$\sim \omega^{-3/4}$	$\sim \omega^{-7/6}$
RF power per unit length	$\sim G^2\omega^{-1/2}$	$\sim G^2\omega^{-1/4}$
Efficiency, η	$\sim G^{-1}\omega^{7/4}$	$\sim G^{-1}\omega^{5/12}$
Repetition rate*	$\sim G^{-2}\omega^{-5/4}$	$\sim G^{-2}\omega^{-5/12}$

* at a constant cooling rate per unit surface area

Structure Efficiency: Design versus Values Predicted by Scaling Relations



At same efficiency, S→X

SB: 7.4 ×

LB: 2.5 ×

Gradient

Rough Cost Comparison by Component

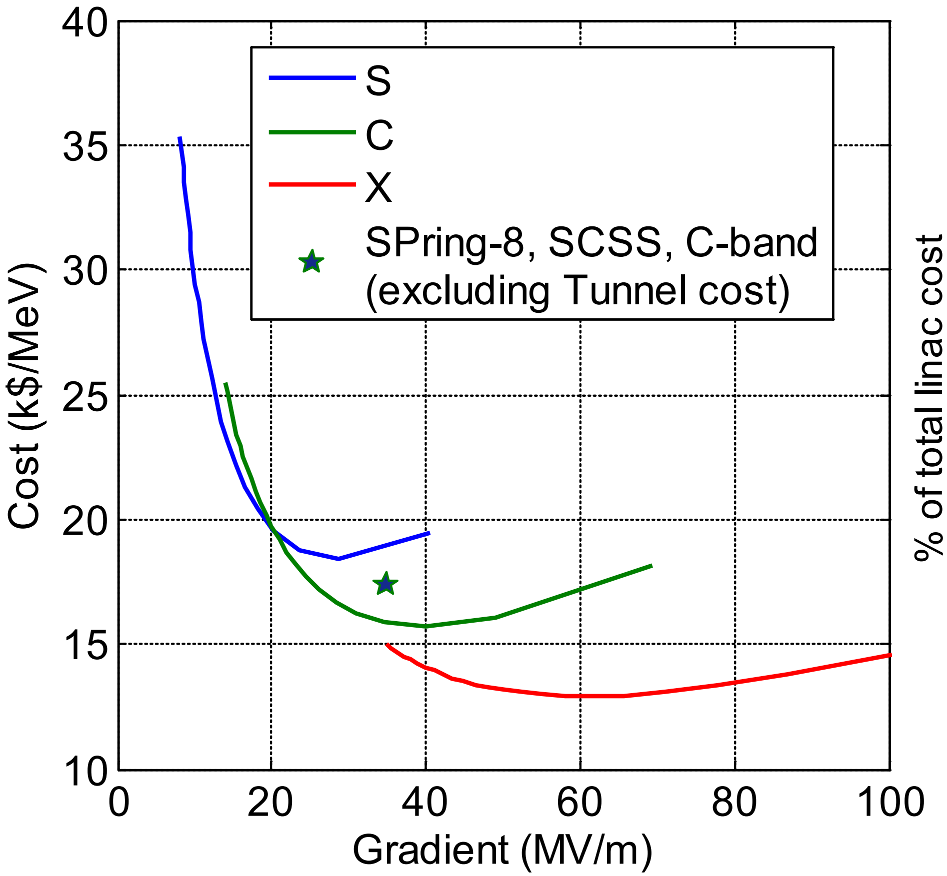
	S	C	X
Klystron	0.73	0.86	1
Modulator$^{1)}$	1.5	1.1	1
1m Structure $^{2)}$	0.7	0.8	1
RF Distribution per MeV	1.5	0.94	1
LLRF per Klystron	1	1	1
AC Power + Cooling	Same per Watt		
Tunnel	Same per Unit Length		

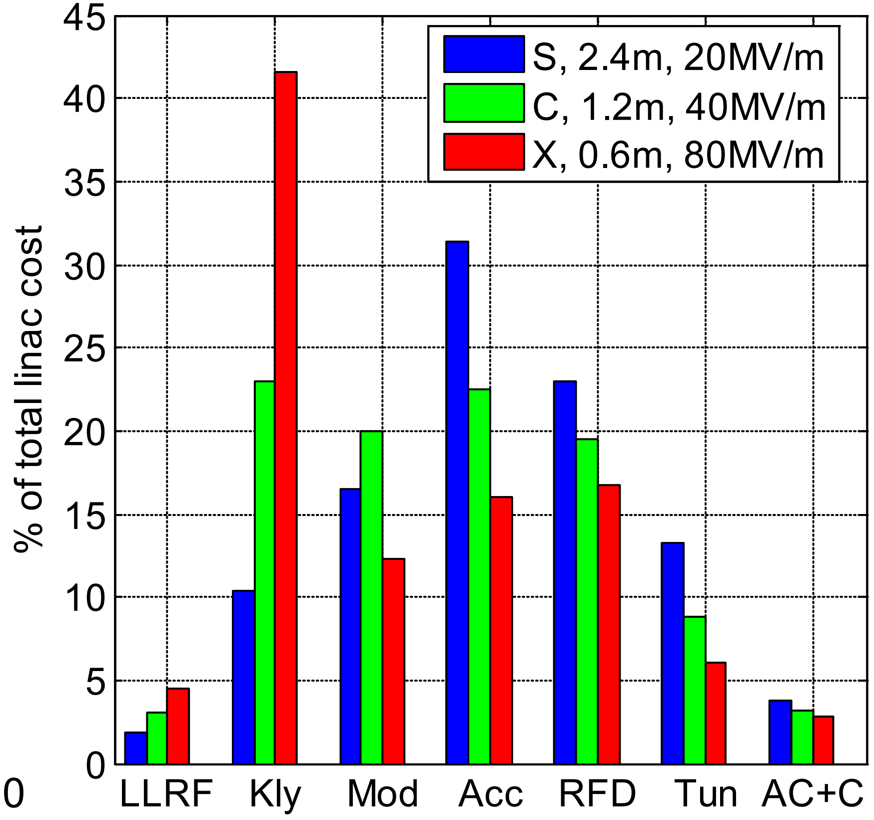
1) $0.5 + 0.5*(T_k/1.5)*(P_{rf}/50)$
2) 0.5/freq + 0.5*sqrt(freq)

Efficiency of modulator = 85%
efficiency of klystron = 48 %

Rough Estimated Cost per MeV

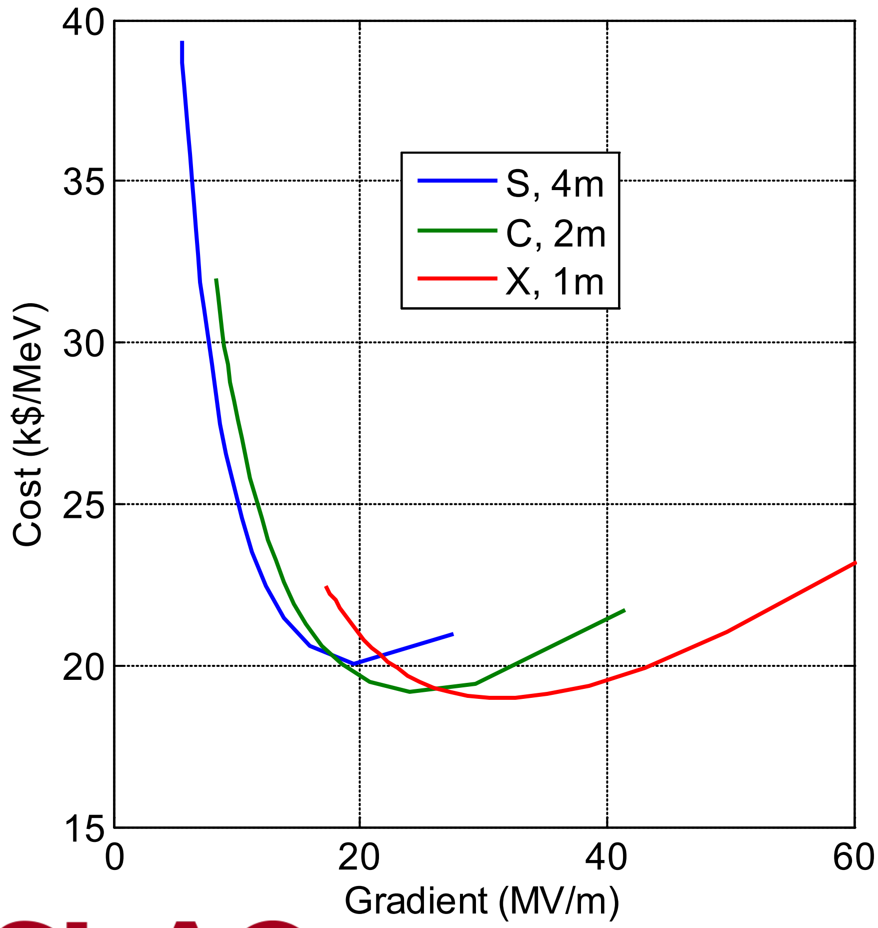
T_b = 50 ns, at 60 Hz

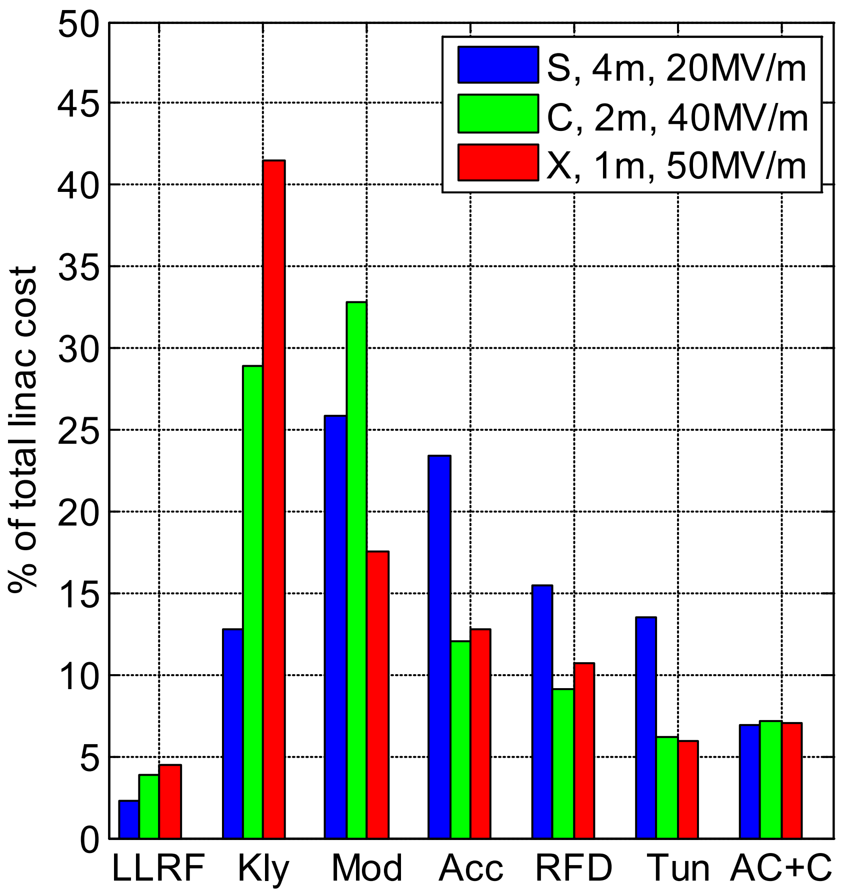




Rough Estimated Cost per MeV

T_b = 1250 ns, 60 Hz





Technical Risk Comparison Versus Frequency

Michael Fazio

	S	C	X
Basis	SLAC Linac Operation	XFEL/Spring-8 Test Linac	NLC Test Accelerator
Klystron	🟢 • SLAC 5045 • 65 MW, 3.5 μs, 120 Hz • 46% efficiency • 30 million hours of operation (since 1984) • **> 1100 tubes** • MTBF 75K-100K hrs	🟡 • Toshiba E3746 • 50 MW, 2.5 μs, 60 Hz • 47% efficiency • Successfully operated in Test Accelerator • **72 installed on Main 8 GeV linac** • Commissioning begins March 2011 • No MTBF Data	🔴 • SLAC XL4 and XL5 • 50 MW/9 kW avg, 1.5 μs, 60 Hz • **23 XL4/5 klystrons produced** • Several have > 10,000 hrs but mostly below 35 MW • Life test starting on a new tube
Modulator	🟢 Line type modulator	🟢 "Compact" line type modulator	🟢 Solid state or Line type modulator
Linac	🟡 • 20 MV/m • SLAC Trf = 800ns	🟡 • 40 MV/m • SCSS Trf = 250 ns	🟡 • 80 MV/m • NLC Trf = 400 ns

🟢 Low Risk
🟡 Med. Risk
🔴 High Risk

SLAC
5045

Compact modulators and klystrons
For XFEL/SPring-8 (72 total)

SLAC
XL4

SLAC
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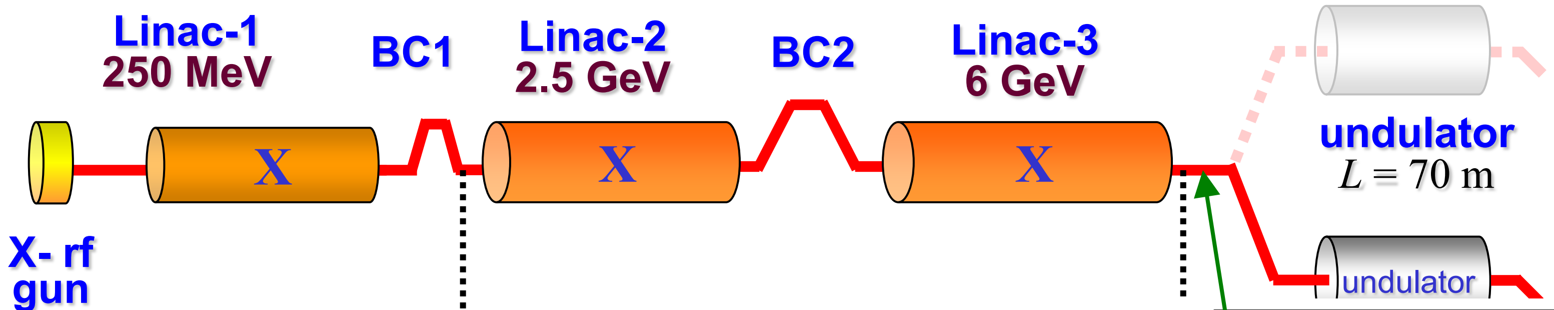
X-band Linac Driven Compact X-ray FEL

(Design Example: Juhao Wu, Feng Zhou)



X-band injector
L~20 m

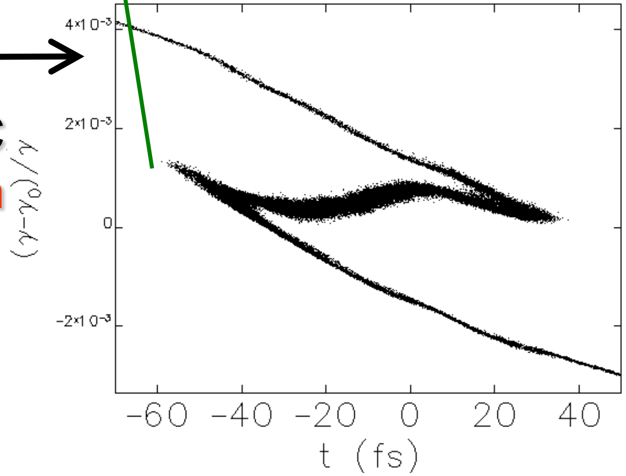
X-band main linac+BC
G~80 MV/m, L~130 m

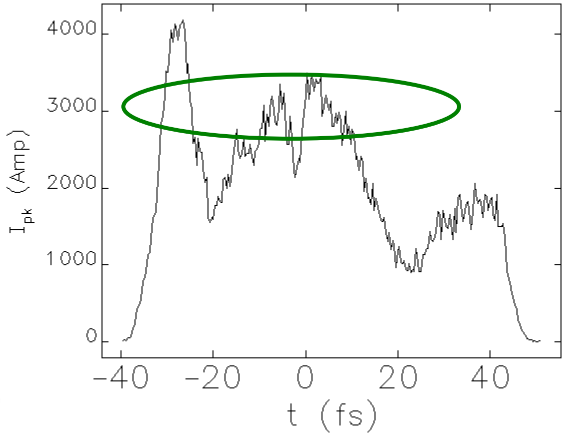
250 pC, $\gamma\varepsilon_{x,y} \approx 0.4\ \mu m$

- x-band structure (<a>/λ=0.17) through

- *Impact-T*, *Elegant* simulate beam dynamics with wake, CSR, and space charge and obtains 3 kA “Gaussian” distribution

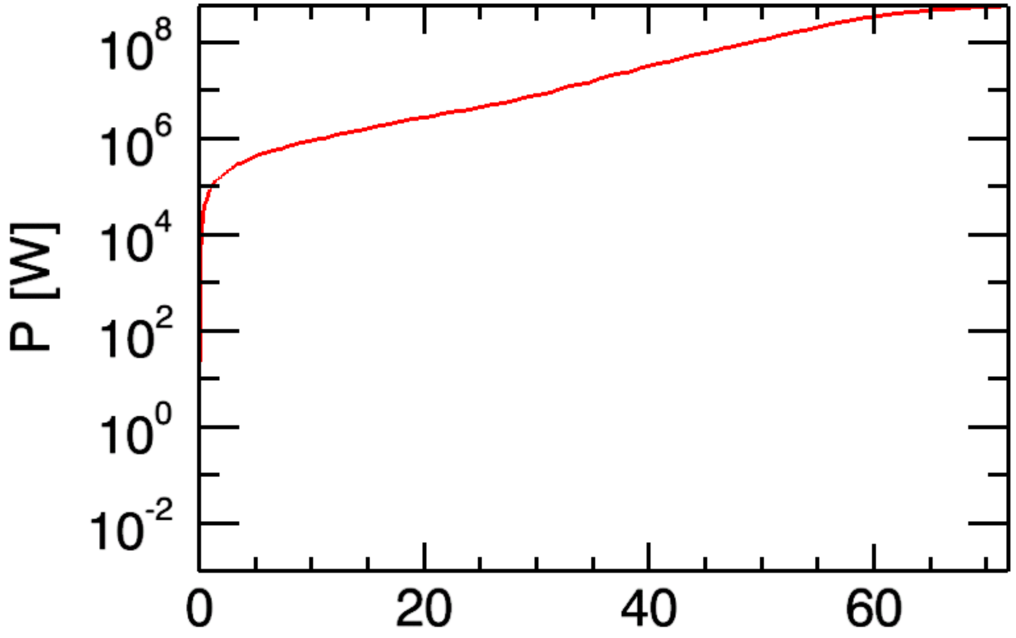
- *Genesis* simulation for FEL lasing at 1.5 Å

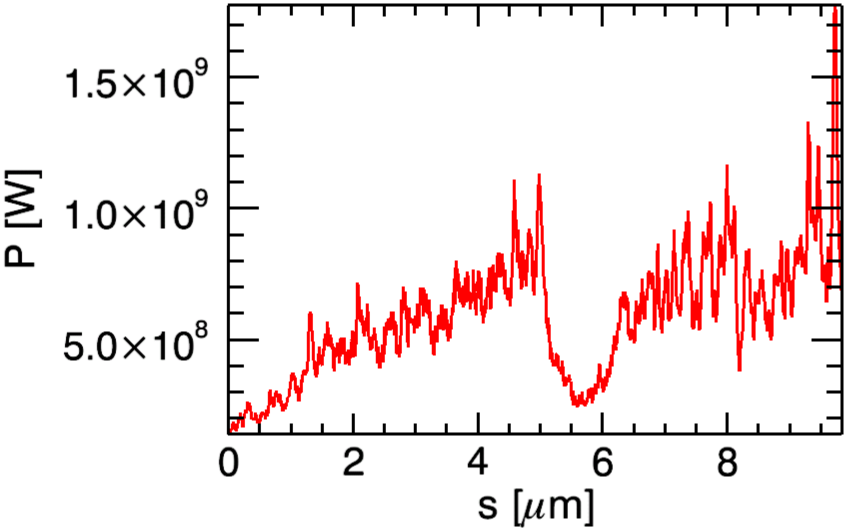


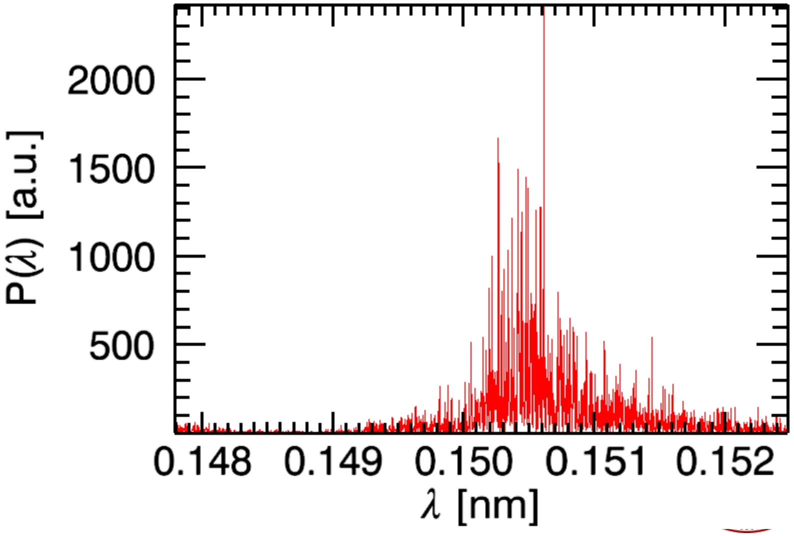


FEL @ 1.5 Å

- Undulator: λ_w=1.5 cm, reach GW around 70 m

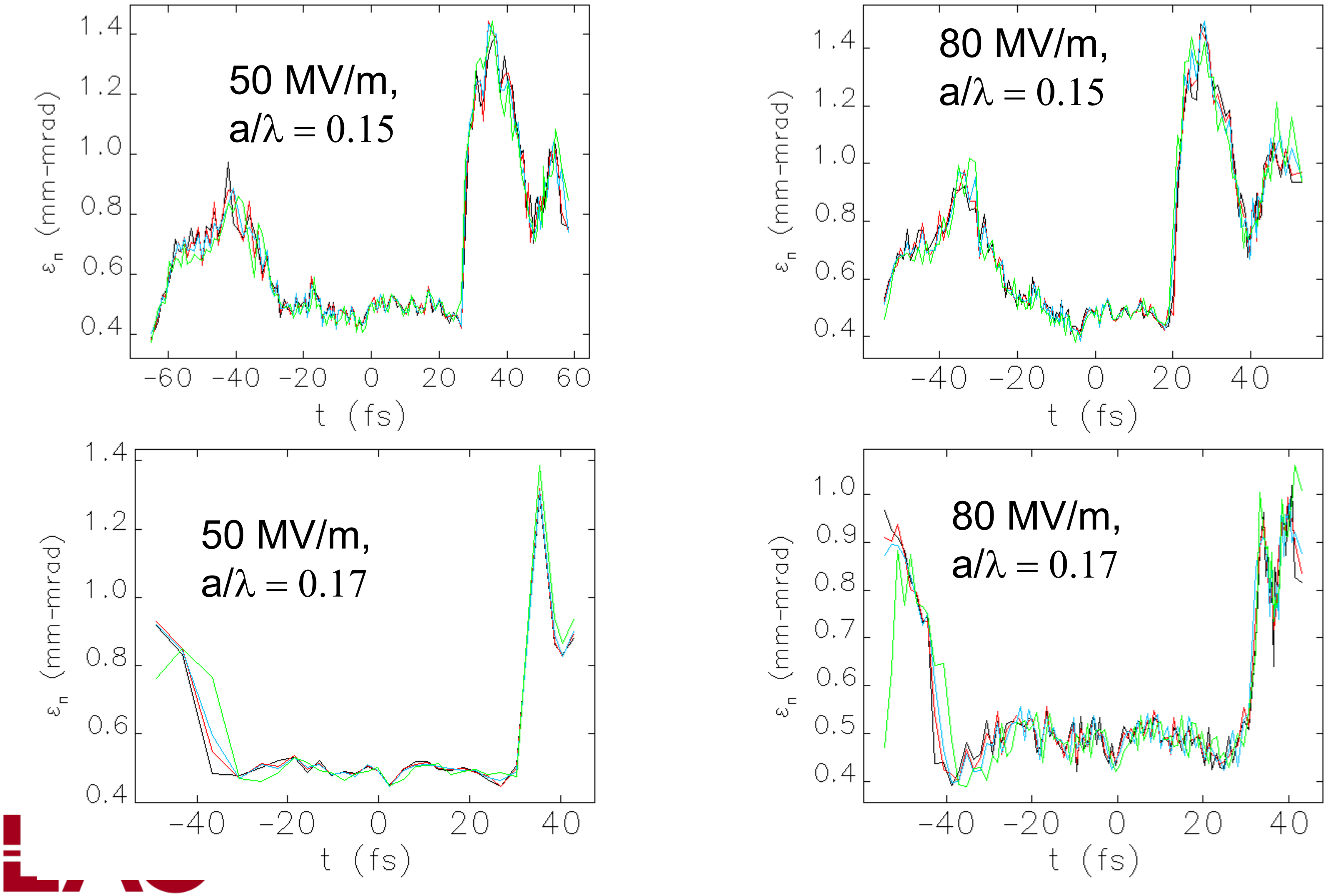






Misalignment in *x*—plane

Misalignment (μm): 0 (black), 100 (red), 200 (blue), and 500 (green);



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Tolerance for Single Bunch Operation

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 **small:** $\delta\epsilon = \frac{x_0^2\Upsilon^2}{2\sigma_{x0}^2}$

- For, 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) => Y= .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) => Y= .01

- **<a/λ> = 0.18**

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

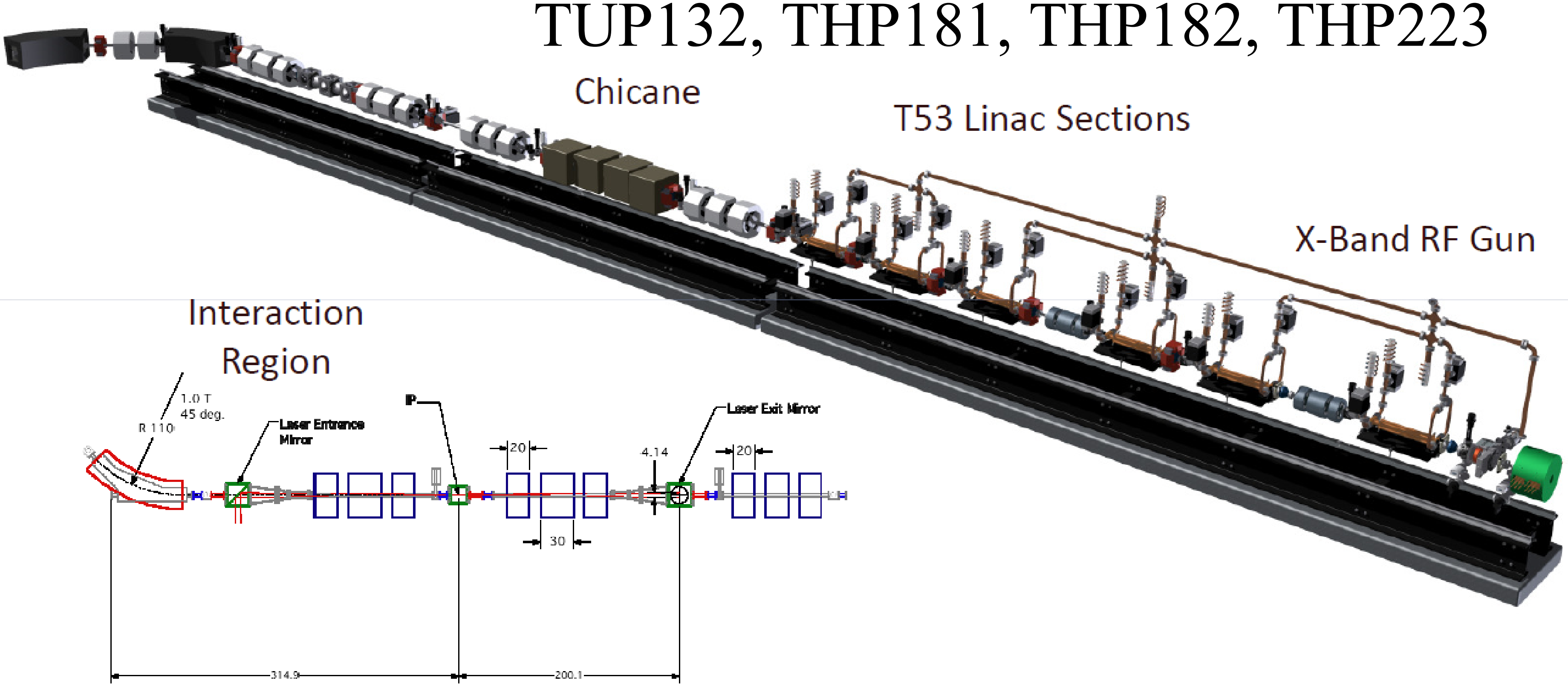
Misalignment of 1 mm rms → an emittance growth of 1% in Linac-2, 0.1% in Linac-3

- **<a/λ> = 0.13** tolerances are 3 times smaller
- **The wake effect is weak mainly because of high gradient, short bunch and low charge.**

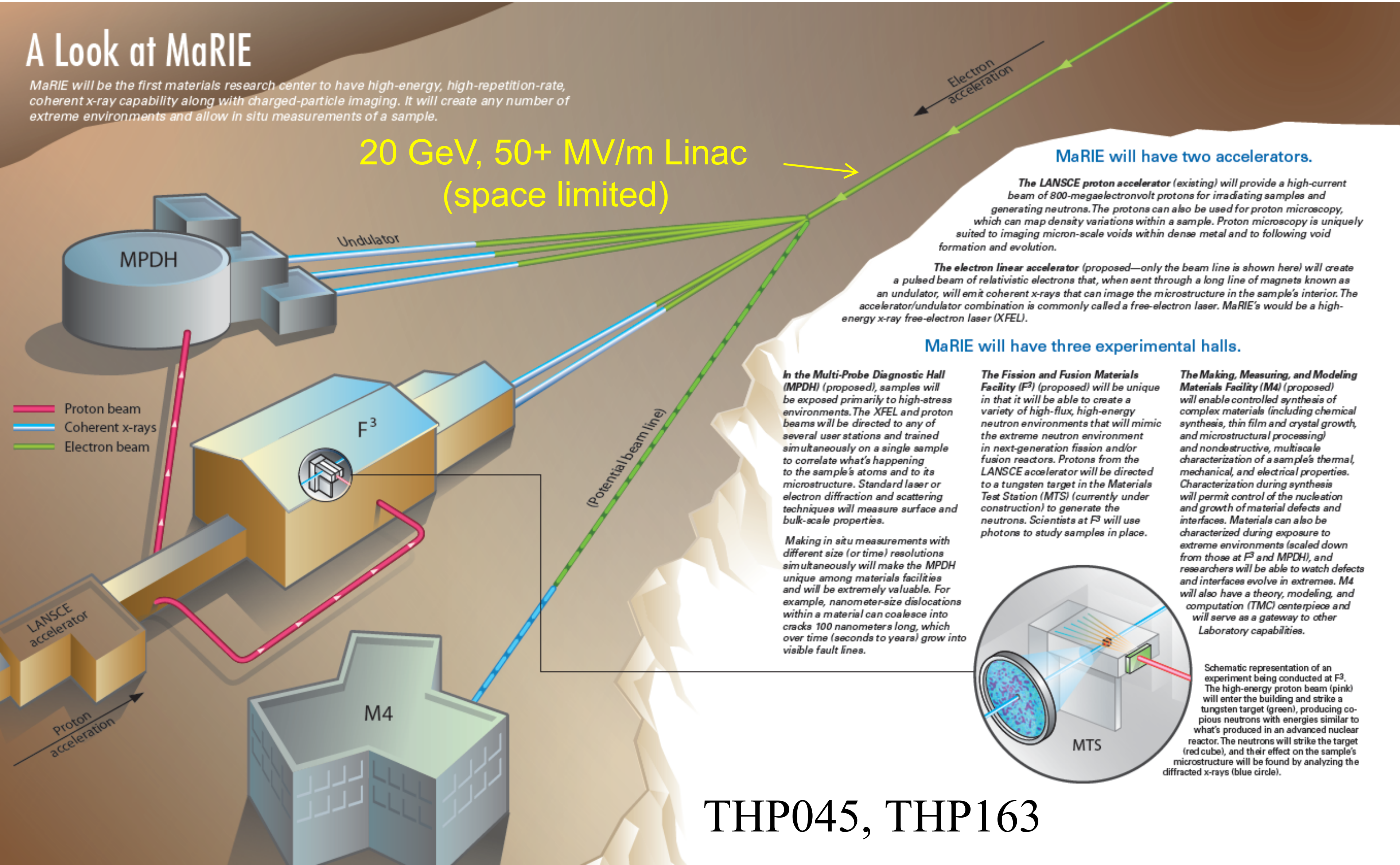
LLNL 250 MeV X-band Linac for Compton Gamma Ray Production

(Injector under Construction)

MOP127, MOP128, TUP023, TUP132, THP181, THP182, THP223



LANL MaRIE Project: 50 keV XFEL
(in pre-conceptual design phase)



20 GeV, 50+ MV/m 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).

THP045, THP163

Summary: Advantages of High Frequency Linacs for XFEL Drivers

- Single bunch (S: 20 MV/m, C: 40 MV/m, X: 80 MV/m)
  - ✓ Compact
  - ✓ High efficiency
  - ✓ Less expensive
- Long beam pulse (S: 20 MV/m, C: 40 MV/m, X: 50 MV/m)
  - ✓ Compact
  - ✓ Similar efficiency & cost
  - ✓ Have solution for long-range wakefield suppression at X-band

Acknowledge

I would like to thank :

C. Adolphsen , T. Raubenheimer, J. Wu, F. Zhou

PAC'11 committee