Progress on Comparison to X-band Klystron-based CLIC Option

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Special thanks to A. Grudiev, B. Jeanneret, Ph. Lebrun, G. McMonagle, I. Syratchev

CLIC-ACE February 3rd, 2010

Rational

- Two concerns exist
  - A klystron-based machine can more easily demonstrate the basic RF unit
  - A klystron-based machine may be cheaper at lower energies
- Want to address these issues with no prejudice
- Focus on 500GeV machine since this is the point where concerns are most relevant

Strategy

- Use current CLIC 500GeV design and simply replace the drive beam with klystrons
  - Minimal changes
  - May not be the optimum klystron based design
- Optimise the CLIC 500GeV design for klystron, using heavily damped structures and remaining compatible with up-grade
  - We limit ourselfs to structures which have been developed in the process of the CLIC 500GeV optimisation
- Full optimisation of CLIC for klystrons
  - Not done
  - Significant amount of work
- Obviously profit from JLC-X/NLC work

Luminosity Comparison to NLC

		CLIC 500GeV	NLC (TRC II)
Luminosity	$10^{34}cm^{-2}s^{-1}$	2.0	2.0
Beam Power	MW	9.62	12.8
Horizontal/vertical emittance	nm	2400/25	3600/40
Particles per bunch	10^9	6.8	7
Bunches per pulse		354	192
Repetition rate	Hz	50	120

$$L \propto \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_f \propto \frac{N}{\sigma_x}\frac{1}{\sigma_y} P_{beam}$$

Lower beam current per luminosity is due to smaller vertical emittance in CLIC

Smaller horizontal emittance in CLIC allows to run at smaller bunch charges
beamstrahlung fixes optimum N/σ_x

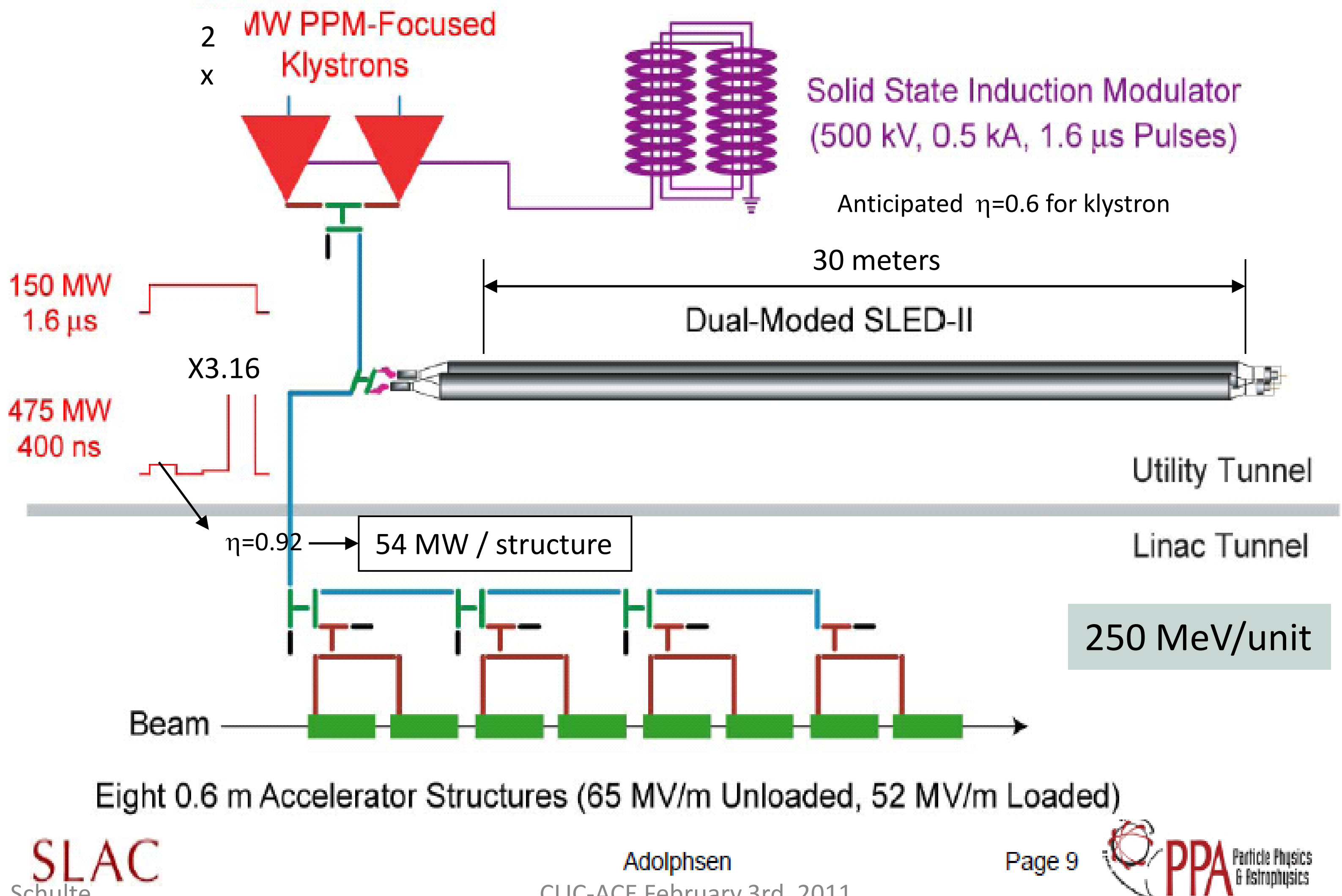
RF Comparison to NLC

		CLIC 500GeV	NLC (TRC II)	NLC later
Loaded gradient	MV/m	80	50	52
Structure length	mm	230	900	600
Energy gain per structure	MV	18.4	45	31.2
Structure input power	MW	74.2	75	54
Inst. input RF power per GeV	GW	4.03	1.666	1.89
RF pulse length	ns	242	400	400
Number of bunches / spacing	ns	354 x 0.5	192 x 1.4	192 x 1.4
Beam current in pulse	A	2.2	0.8	0.8
RF input energy / pulse / GeV	J	975	666	666

Replacing Drive Beam with Klystrons

NLC/GLC Linac RF Unit

(One of 2232 for 500 GeV cms Energy)



NLC Initial Baseline Design

- 75 MW Klystron (approx 2000 per LINAC)
  - Solenoid focussing (25kW per klystron)
  - 55% efficiency
  - 0.0002 duty cycle (120 Hz, 1.6µs)
    - Average RF output power of klystron 14.4kW
  - 1 kW heater power per klystron
- Line type modulator
  - Pulse transformer 20% wasted power with rise and fall time
  - Thyratron switch, 600 W per thyratron
- Overall Power Requirement per Klystron/Modulator
  - 55.3 kW
  - 246 MW/two linac (2264 klystrons)
- This technology is known and works

NLC Baseline Design circa 2002

- 75 MW Klystron (approx 2000 per LINAC)
  - ppm periodic permanent magnet focussing (no solenoids)
  - 55% efficiency
  - 0.0002 duty cycle (120 Hz, 1.6μs)
    - Average RF output power of klystron 14.4kW
  - 1 kW heater power per klystron

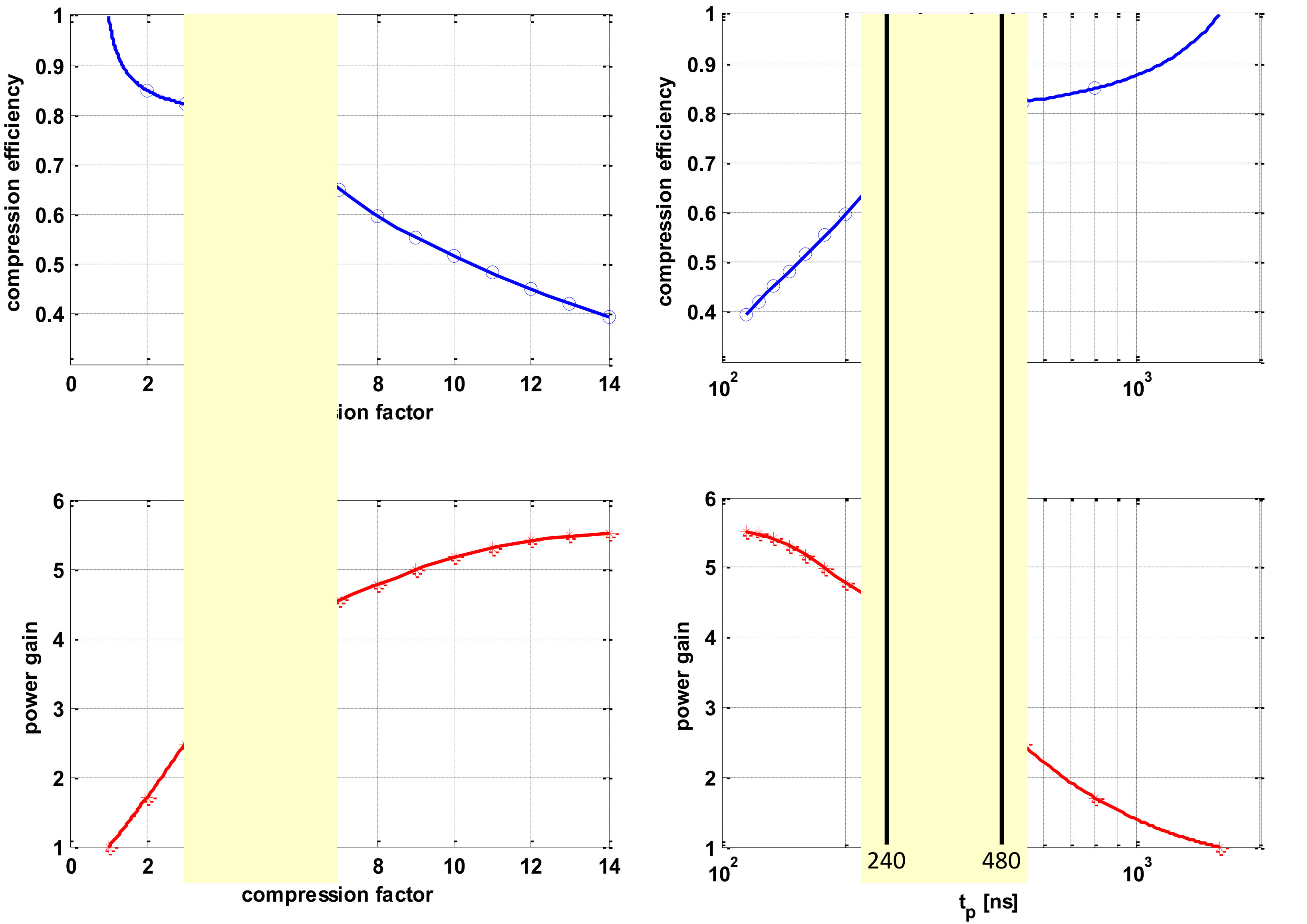
- Solid State Modulator (1 per two klystrons)
  - Pulse transformer 20% wasted power with rise and fall time

- Overall Power Requirement per Klystron/Modulator(0.5)
  - 37.5 kW (would at 50Hz be 16.2kW)
  - 167 MW/two linacs

- Klystron development was not finished, some problems with pulse width and high rep rate, peak power achieved
- Modulators
  - Many iterations were done on different types of solid state switches, but still with pulse transformer. Only recently can we confidently say that this technology is properly developed

- This will be our baseline, even if work is needed to fully demonstrate it

Pulse Compression Efficiency



Efficiency

Consider drive beam based machine up to roughly twice as efficient

But more work to be done at 500GeV drive beam based CLIC
- some inconsistencies between Igor and Bernard

Need to include other systems in comparison
- e.g. magnets of drive beam complex

Klystron

Efficiency [%]	NLC	CLIC	achieved
Modulator	70	70	60
Klystron	55	55	53-56
SLED II	81	65	(78)
Waveguide	92	92	77
total	28.3	23	19.5

Drive beam

	Design	ready
Modulator	90*	86?
Klystron	70	66
Waveguide 1GHz	95	
Structure	97	95.3
Power extraction	87	
Waveguide 12GHz	99	98
total	50	

*strongly depends on rise and fall time

Klystron Number

- We use

$$N_{klystron} = 1.1 \frac{E_{cm} n_b N}{\eta_{RF\rightarrow beam} \eta_{klystron\rightarrow structure} G_{sled} P_{klystron} \tau_{RF}}$$

- No parameter adjustment for
  - Integer number of structures per klystron pair
  - Integer compression factor

- To be done done once we fix a design
  - But will not change the conclusions very much
  - Will adjust other parameters a bit, e.g. klystron power, RF pulse length

- 7200 klystrons for CLIC 500 baseline

Wall Plug Power

$$P_{linac} = N_{klystron} \frac{1.6\mu s P_{klystron} f_r}{\eta_{modulator} \eta_{klystron}} \approx 15.6kW \frac{f_r}{50Hz}$$

- Drive beam CLIC 500
  – Average total RF input power 24.3MW
  – Wall plug 53.5MW (Igor), 89MW (Bernard)

Note: 10% overhead included

- Klystrons-based CLIC 500
  – Average total RF input power 24.3MW
  – 112 MW wall plug (7200 klystrons)

- NLC
  – Average total RF input power 47.3MW
  – Wall plug 167MW (4464 klystrons)

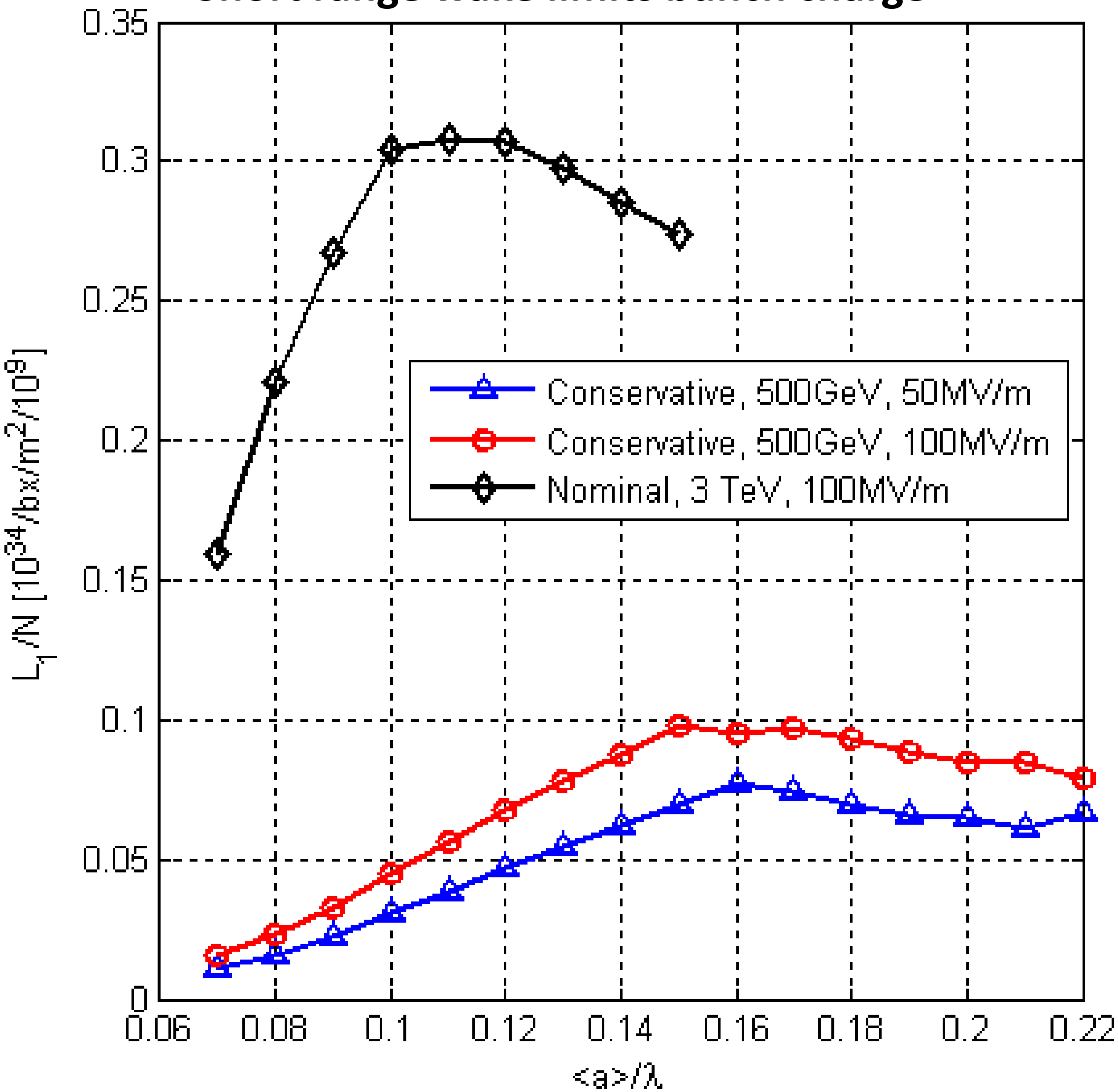
Semi-optimised Structure

Reminder: 500 GeV Structure Choice

- Structure has been optimised for luminosity per unit power
  - Figure of merit: $L_{bx} / N \eta_{RF\text{->}beam}$
- Larger emittances than at 3TeV have been assumed
- Upgrade potential has been included by requiring
  - Structure length be 23 or 48 cm
    - i.e. a 500 GeV structure replaces 1 or 2 3TeV-structures
  - RF pulse length be 240 or 480 ns
    - 240ns for 23cm long structures
    - i.e. for 48cm long structures the drive beam decelerator can be 2 times longer
  - Input power per structure is similar to 3TeV
    - Did not quite make it but came close

Luminosity at 500GeV

Short range wake limits bunch charge



Calculate:

Bunch charge N(G,a,f)

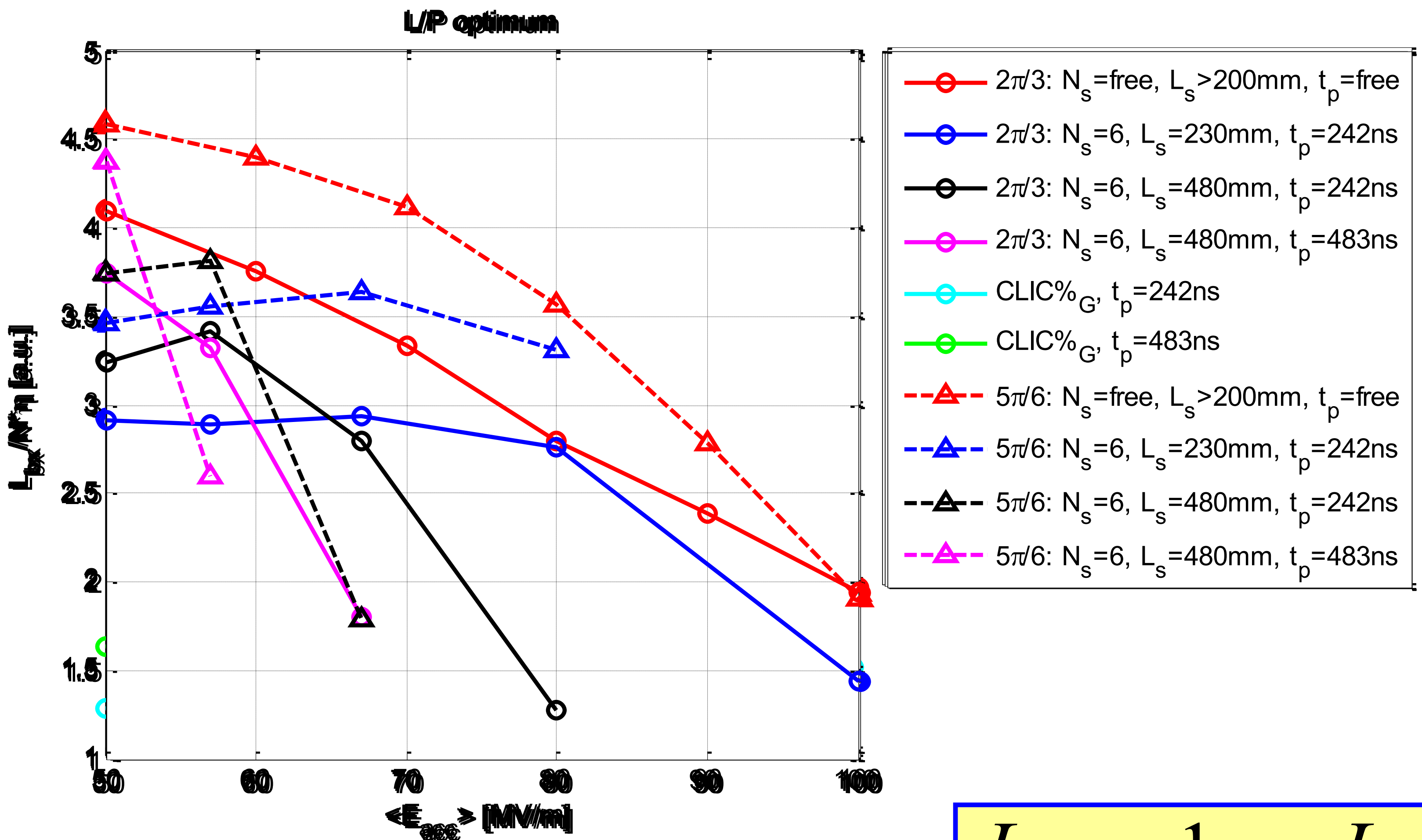
Luminosity $L_{0.99}$(G,a,f)

Limit on long-range wake at second bunch

Depends on assumptions on

- emittances
- beta-functions

Figure of Merit

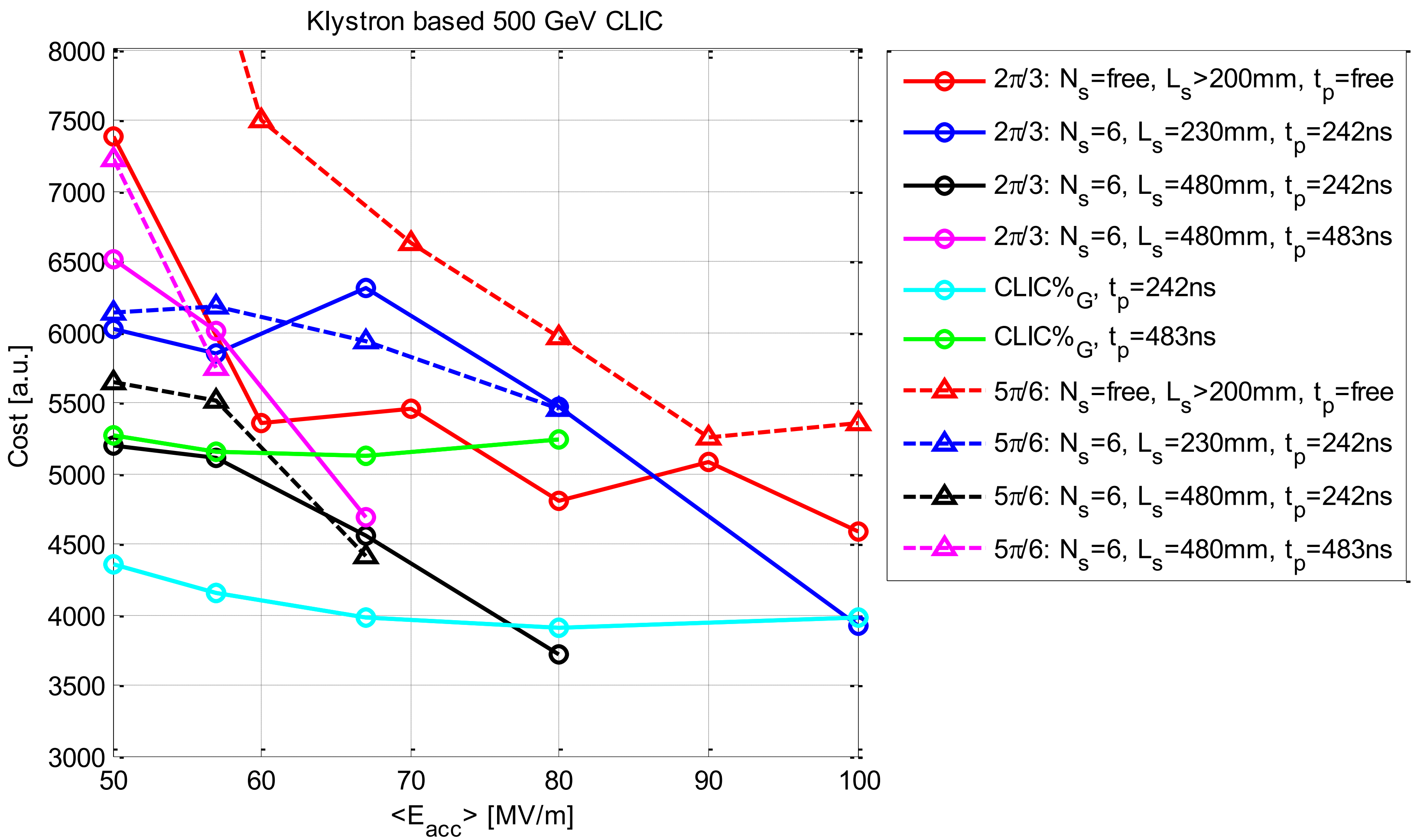


$$\frac{L}{P_l} = \frac{1}{eE_{cm}} \bullet \frac{L_{b\times}}{N}\eta$$

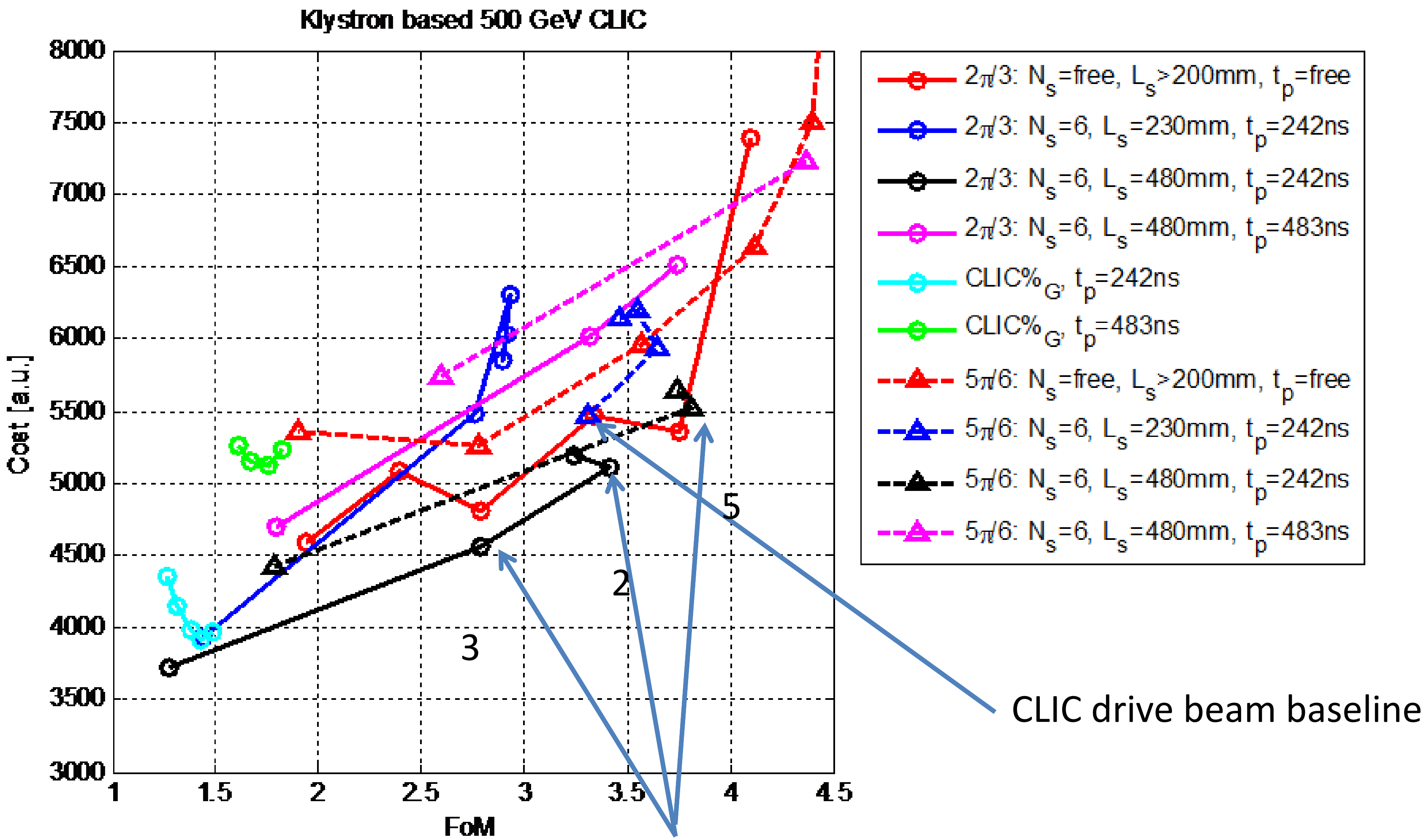
Cost Calculation

- Klystron-based machine has some cost reduction
  - No drive beam generation complex
  - No drive beam turn-arounds
  - No decelerators
- But some cost increase
  - Second tunnel is needed for klystron, modulators and pulse compressors
  - Klystrons, modulators, pulse compressors etc.
- Do not yet have a cost comparison of klystron-based vs. drive beam based machine
  - More work needed
- But we have an estimate of the relative linac cost for the klystron-based machine
  - Allows to identify the best klystron-based machine

Cost versus Gradient



Linac Cost versus Luminosity per Power



NLC is at FoM 1.7/2.15
for E_y=40/25nm

Structure Parameters

Case	2	3	5	basel.	NLC
Average accelerating gradient: $<E_a>$ [MV/m]	57	67	57	80	52
rf phase advance: $\Delta\phi$[°]	120	120	150	150	150
Average iris radius/wavelength: $<a>/\lambda$	0.145	0.14	0.16	0.145	0.17
Str. Length: l [mm]	480	480	480	229	600
Bunch separation: N_s [rf cycles]	6	6	6	6	16
Bunch population: N	5.49×10^9	4.95×10^9	7.01×10^9	6.8×10^9	7×10^9
Number of bunches in a train: N_b	382	335	337	354	190
Pulse length: τ_p [ns]	242	242	242	242	400
Input power: P_{in} [MW]	76	84	89	74.2	54
Max. surface field: E_{surf}^{max} [MV/m]	215.6	260	260	250	
Max. temperature rise: ΔT^{max} [K]	27.6	43	42	56	
Structure efficiency: η [%]	49.5	41.9	48	39.6	~31
Figure of merit: $\eta L_{b\times}/N$ [a.u.]	3.41	2.79	3.81	3.3	1.7/2.15
Relative lumi in peak @ 50 Hz	0.73	0.55	0.94	1.0	1.0
Number of 75MW-klystrons per linac	2520	2358	2934	3600	2232
Number of structures per klystron	4.4	4	3.75	4.5	4
Power / two linacs [MW]	78.6	73.6	91.4	112	167
Linac cost [arb. units]	5107	4559	5521	5443	?

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Future

- Documenting the current status
  - Report is being prepared
  - Some inconsistencies need to be fixed
    - E.g. power efficiency

- Establish some cost model for 500GeV
  - Also needed for drive beam based machine
  - Based on CLIC cost evaluation

- Further work once we have a scenario for CLIC energy staging
  - Emittances at 500GeV have strong impact on structure choice
  - Upgrade will place many constraints

Conclusion

- Using current CLIC 500 design with klystrons requires 7200 klystrons
  - Prediction for wall plug to RF efficiency could indicate that drive beam is twice more efficient
  - But needs careful detailed evaluation on drive beam side
  - RF to beam efficiency is about 33% larger than for NLC structure due to heavy damping
- Reducing the gradient to reduce the klystron number leads to about 5000 klystrons
  - But cost cannot be reduced strongly (<20% for main linac)
- The cost for the different options does not seem to vary very strongly
  - Error of the model is still large
- Comparison of cost klystron vs. drive beam remains to be done