Drive beam RF System

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CERN BE-RF

Outline

- Power sources
  - What power source?
  - MBK's: existing ones and future R&D
  - Optimum power level? Re-adaptation of acc. structure size
  - Cost?
    - per klystron
    - per MW
    - per MWh
- Modulators
  - "Natural" optimum size?
- Phase stability/stabilisation issues
  - noise sources, noise propagation
  - filtering of noise
    - by CLIC recombination scheme
    - by accelerating structure
- Conclusions

Drive beam RF system

- **Luckily, the drive beam RF system is not a feasibility issue for CLIC ...**
- **... however, some important issues to address:**
  - **Very large total power (≈23 GW peak, 170 MW average)**

    What power source?

    Optimum size? - Many small or few large units?

    related: system complexity, reliability, operability, maintenance
  - **Phase stability (phase jitter < 50 fs)**

    phase errors multiplied by recombination scheme!
  - **Overall efficiency**

    The 2-beam scheme has more stages!
  - **Cost**

The needs of CLIC

- **Past parameter changes:**
  - **Nov. 2006: 937 MHz (30 GHz/32) → 1.333 GHz (12 GHz/9)**
  - **Sep. 2007: 1.333 GHz → 999.52 MHz (12 GHz/12)**
- **Total peak RF power required per linac is about 11.5 GW (from 4.21 A · 2.38 GV / 93.5% / 93.2%).**
- **With a rep. rate of 50 Hz and an RF pulse length of – say – 150 µs (total CLIC length/*c*), we get:**
- **Duty factor 150 µs · 50 Hz = 0.75 % → avg. power 86 MW per linac!**
- **Of major importance for the RF power source in the specifications are**
  - **the phase stability,**
  - **the power conversion efficiency,**
  - **overall system reliability.**

What Power source?

- **Magnetrons?**
  - **Injection-locked oscillators**
  - **Potentially better efficiency, but *phase noise requirement* would either be a show-stopper or at least require longer RF pulses for phase to stabilize and thus decrease the effective efficiency.** **NO!**
- **IOT's?**
  - **Present day IOT's are ≈ 100 kW. They're less reliable today. Much less gain!** **NO – maybe reconsider later!**
- **Pencil-beam klystrons?**
  - **Why not? You need a much larger number (say 10'000) but that would be extremely well studied and reliable objects.**
    - Several tube companies would participate. Competition combined with quantity would drive costs down. (20 k$/MW possible?)
    - Graceful system degradation (!)
    - Higher reliability (?)
    - For *n* tubes replacing 1, uncorrelated noise decreases by factor $\sqrt{n}$! **YES**
- **Multi-beam klystron?**
  - **Definitely the closest to existing, ready-to-use technology! I would put my money on these! Say 12 beams, 140 kV, 10 to 15 MW.** **YES**
- **Sheet-beam klystrons?**
  - **They promise to be much cheaper for larger quantities, but there is no demonstration today that would support this claim** **Once demonstrated: YES**

Existing ILC MBK's:

1. **CPI: VKL-8301B (6 beam): 10.2 MW, 66.3 %, 49.3 dB gain**
2. **Thales: TH 1801 (7 beam): 10.1 MW, 63%, 48 dB gain**
3. **Toshiba: E3736 (6 beam): 10.4 MW, 66 %, 49 dB gain**

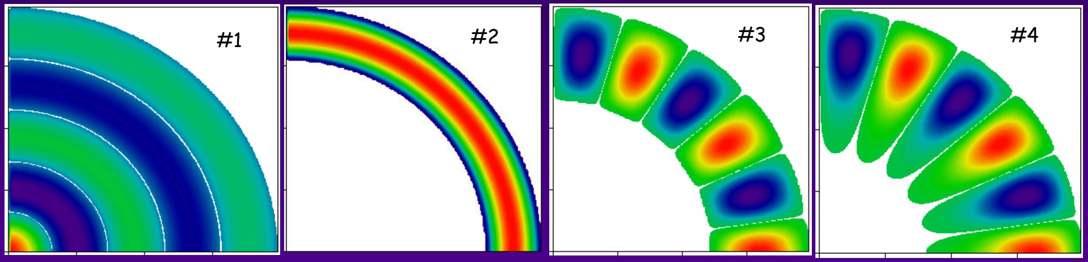
1.

2.

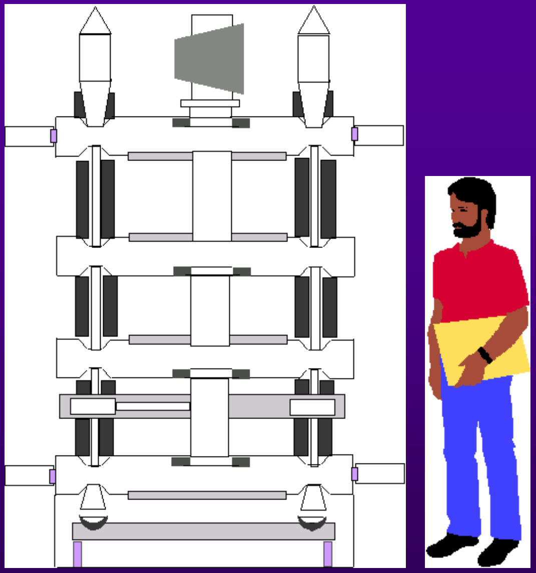
3.

Whispering Gallery MBK?

- Cf. Jensen, Syratchev: "CLIC 50 MW L-Band Multi-Beam Klystron", CLIC-Note-640, 2005



- **The main idea: use a mode like the one depicted as #4 (whispering gallery mode) for many beams; the advantage of this mode: It can be made very pure!**
- **For high *η*, perveance can be made extremely small (0.25 μperv).**
- **The problem: This device became really big: How do you braze this? Imagine a little problem in one of the ≈22 beams!**
- **Study ongoing in collaboration with Thales and Lancaster University (PhD work Chris Lingwood).**



Directions for MBK R&D ?

- R&D on **high power, high η MBK's** is interesting for both ILC and CLIC.
- Unless the risk is covered, industry is reluctant to undertake large scale R&D with an uncertain market.
- My personal proposal:
  - R&D – jointly with industry – in small (time & money) steps:
  - Possible 1st step: design and build a single beam, ultra-low perveance (0.25 μperv) klystron to demonstrate record efficiency. ☺ *Efficiency Record Klystron – short ERK* ☺
  - This could later be optimized as either a pencil beam klystron or as one beamlet of an MBK ...
- For CDR, assume ILC/X-FEL type klystrons!

2008 parameter list

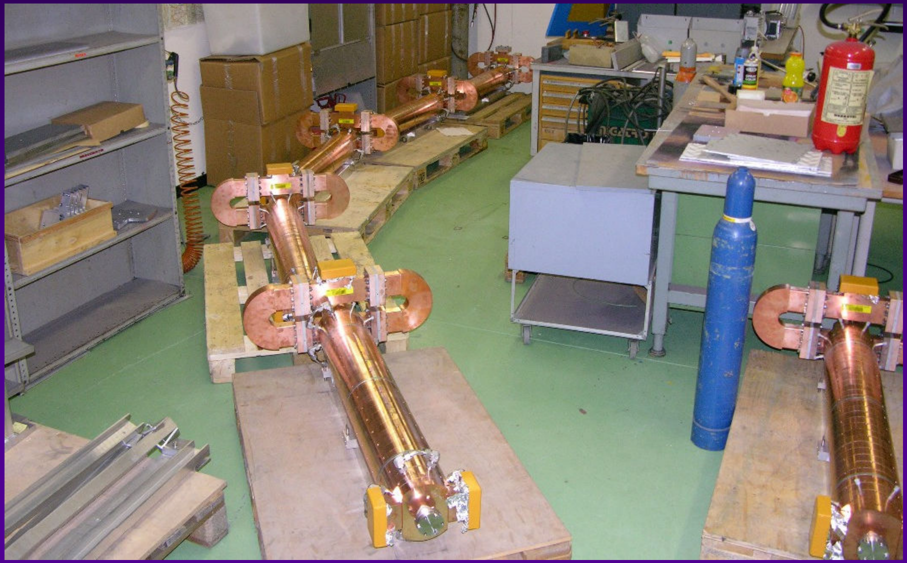
- For the CLIC 2008 parameter list, it was assumed that 40 MW klystrons with 70 % efficiency exist.
- It had been assumed that 33 MW peak could be made available at the input of each accelerating structure. This resulted in 326 klystrons with 40 MW peak power and 326 accelerating structures per linac.
- The accelerating structures were scaled from the existing 3 GHz structures and not yet optimized for 1 GHz.
- The number of cells was adjusted to be fully beam-loaded for the nominal current and power.
- Keeping the beam current at its nominal value of 4.21 A, the following table illustrates how the necessary input power varies with the number of cells.
- Importance of the group delay: the structure will “filter out” noise from the klystron and from the beam.

P_{in}(# of cells)

# cells	P_{in}[MW]	η	length [m]	τ [ns]	acc [MV]	# struct	total length [km]	P_{tot} [GW]
15	6.33	98.81%	1.500	142.0	1.49	1602	2.402	10.139
16	7.21	98.73%	1.600	151.4	1.69	1407	2.251	10.146
17	8.14	98.66%	1.700	160.8	1.91	1247	2.119	10.154
18	9.12	98.58%	1.800	170.2	2.14	1114	2.005	10.162
19	10.2	98.51%	1.900	179.5	2.38	1000	1.900	10.170
20	11.3	98.43%	2.000	188.9	2.64	901	1.802	10.150
21	12.4	98.36%	2.100	198.3	2.90	821	1.724	10.185
22	13.6	98.28%	2.200	207.7	3.18	749	1.647	10.193
23	14.9	98.21%	2.300	217.1	3.48	685	1.575	10.201
24	16.2	98.13%	2.399	226.5	3.78	630	1.512	10.208
25	17.6	98.06%	2.499	235.9	4.10	580	1.450	10.216
26	19.1	97.98%	2.599	245.3	4.45	535	1.391	10.224
27	20.6	97.91%	2.699	254.7	4.79	497	1.342	10.232
28	22.1	97.84%	2.799	264.0	5.14	463	1.296	10.239
29	23.7	97.76%	2.899	273.4	5.50	432	1.253	10.247
30	25.4	97.69%	2.999	282.8	5.89	404	1.212	10.255
31	27.1	97.61%	3.099	292.2	6.28	379	1.175	10.263
32	28.9	97.54%	3.199	301.6	6.70	355	1.136	10.270
33	30.8	97.47%	3.299	311.0	7.13	334	1.102	10.278
34	32.7	97.39%	3.399	320.4	7.57	315	1.071	10.286
35	34.6	97.32%	3.499	329.8	8.00	298	1.043	10.294
36	36.6	97.25%	3.599	339.2	8.46	281	1.011	10.302
37	38.7	97.17%	3.699	348.6	8.93	266	0.984	10.309
38	40.8	97.10%	3.799	358.0	9.41	253	0.961	10.317
39	43.0	97.03%	3.899	367.3	9.91	240	0.936	10.325
40	45.3	96.95%	3.999	376.7	10.43	228	0.912	10.333

present "nominal" → 33

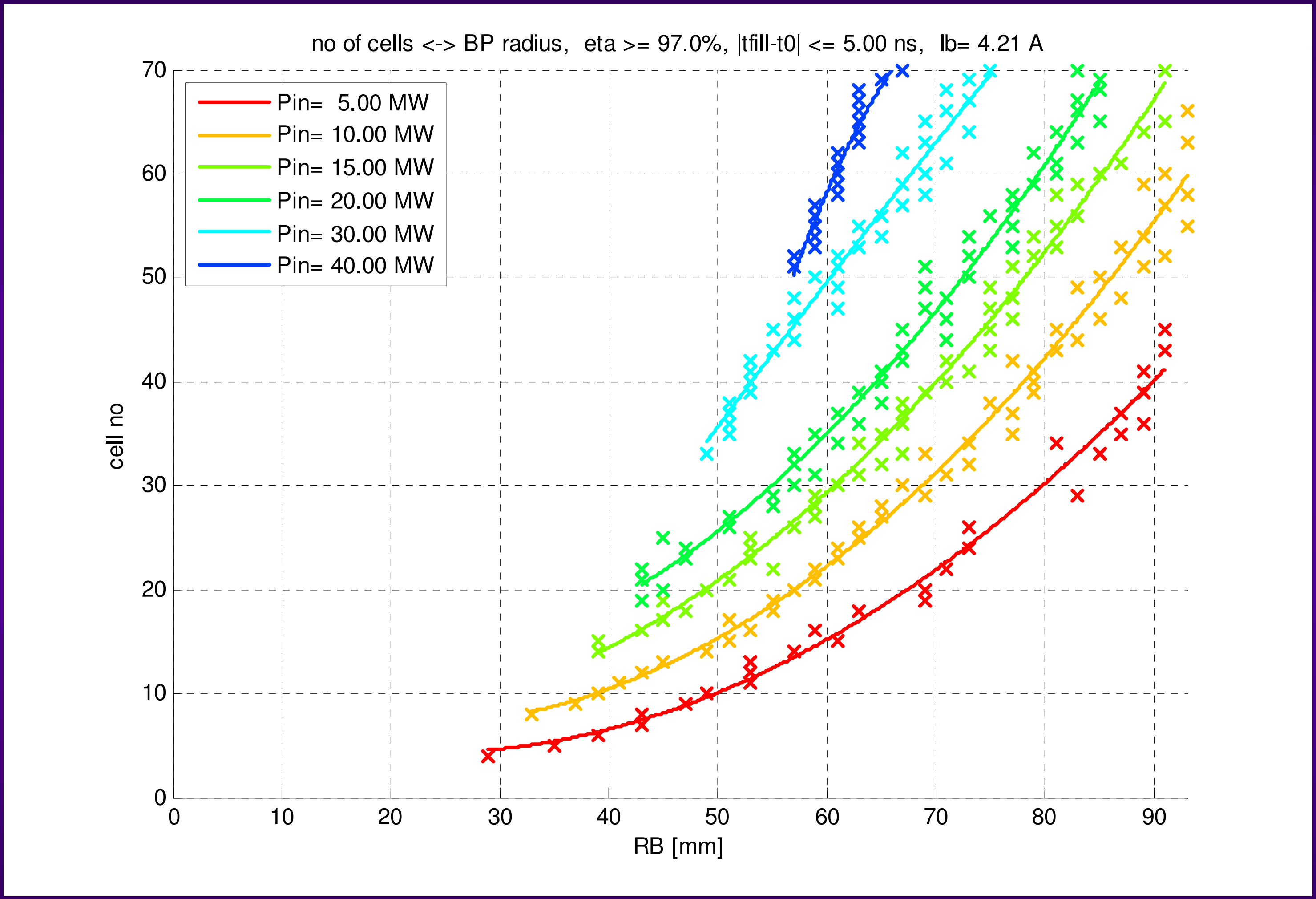
Re-optimizing the structure



3 GHz DBA structures for CTF3 stored after tuning and ready for installation, (2004)

- **Just scaling the CTF3 structures from 3 GHz to 1 GHz is of course no optimum**
- **➔ Rolf Wegner will talk on his structure re-optimisation this afternoon in WG4.**
- **Rolf looks more look closely at (more realistic) klystron powers of 10 to 15 MW.**

First results from Rolf:



Structures with
$\eta_{RF} \geq 97$ %

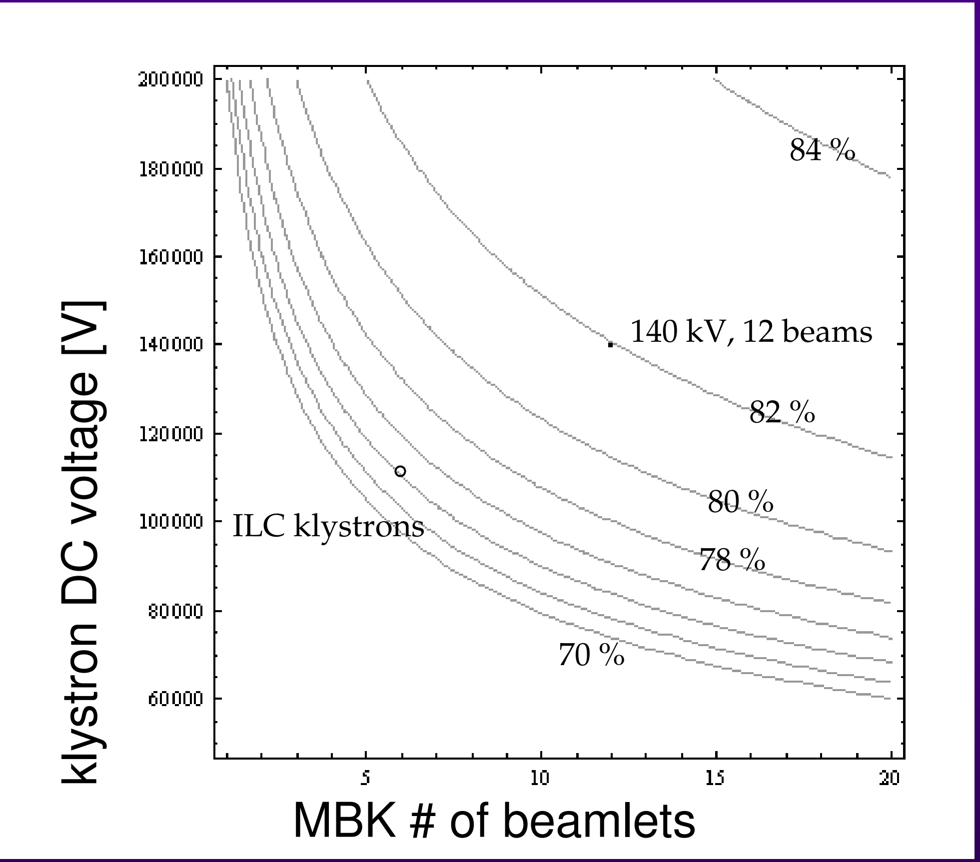
t_{fill} = 245 ns ± 5 ns

Realistic: Ø 80 mm, 10 ... 15 cells, 10 ... 15 MW

more on structures by Rolf ...

Klystron efficiency

- The CLIC 2008 Parameters assume a tube efficiency of 70%, existing tubes reach 66%. For the CDR, 66% should be used.
- It is generally accepted that maximum obtainable efficiency is a function of the perveance $I/V^{3/2}$. Using an empirical model, here is what one could expect (numbers for 13 MW DC):

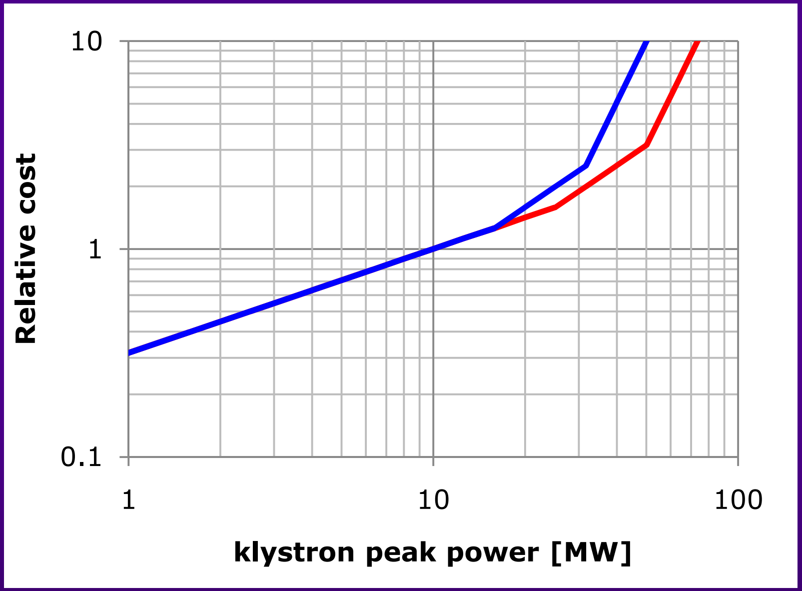


- For practical reasons, the voltage should be kept moderate (say below 140 kV).
- To limit the complexity, the number of beamlets should remain reasonable.
- I marked a point which I find interesting: 12 beams, 140 kV; it could reach above 70%.

Cost scaling of pulsed klystrons?

How does the klystron cost depend on the peak power?

- **Probably: cost per klystron proportional to (peak power)$^{1/2}$ (*)**
- **At a level of around 15 MW peak, the slope will become steeper due to increased system complexity.**
- **This leads to the following model:**

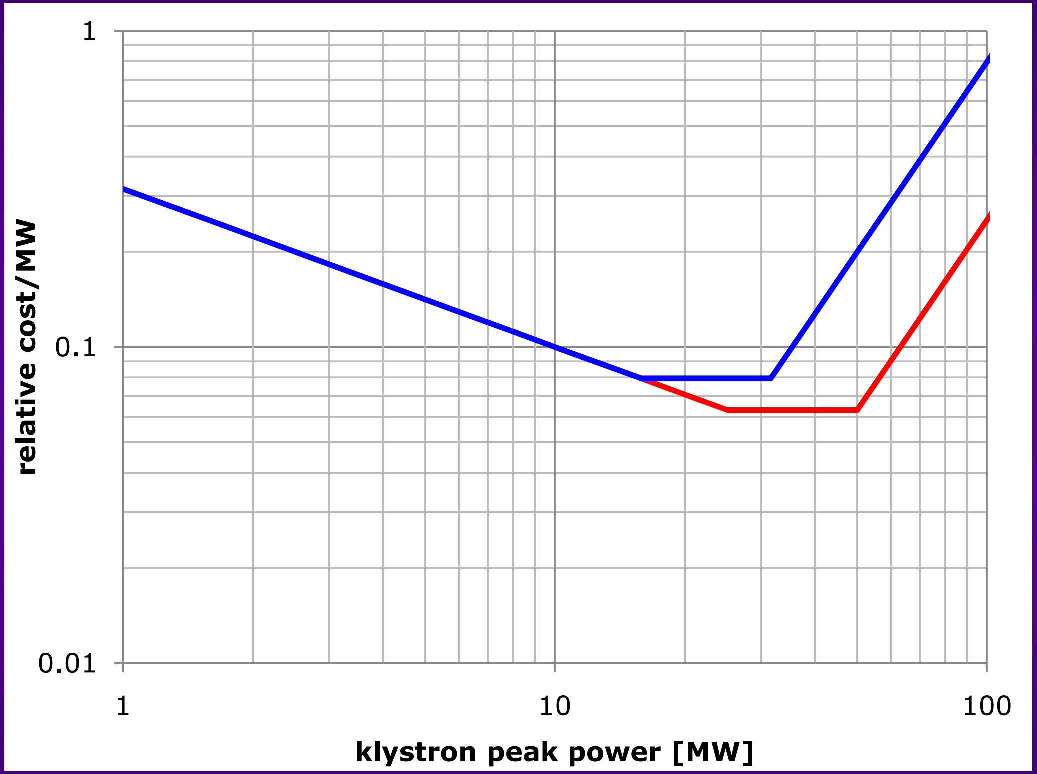


- **Blue: present state of the art**
- **Red: assuming a major investment into the development of a dedicated 30 MW tube**

(*) rule of thumb given by T. Habermann/CPI. Rees/LANL estimates $P^{0.2}$ for 0.5 to 5 MW tubes.

Cost per MW

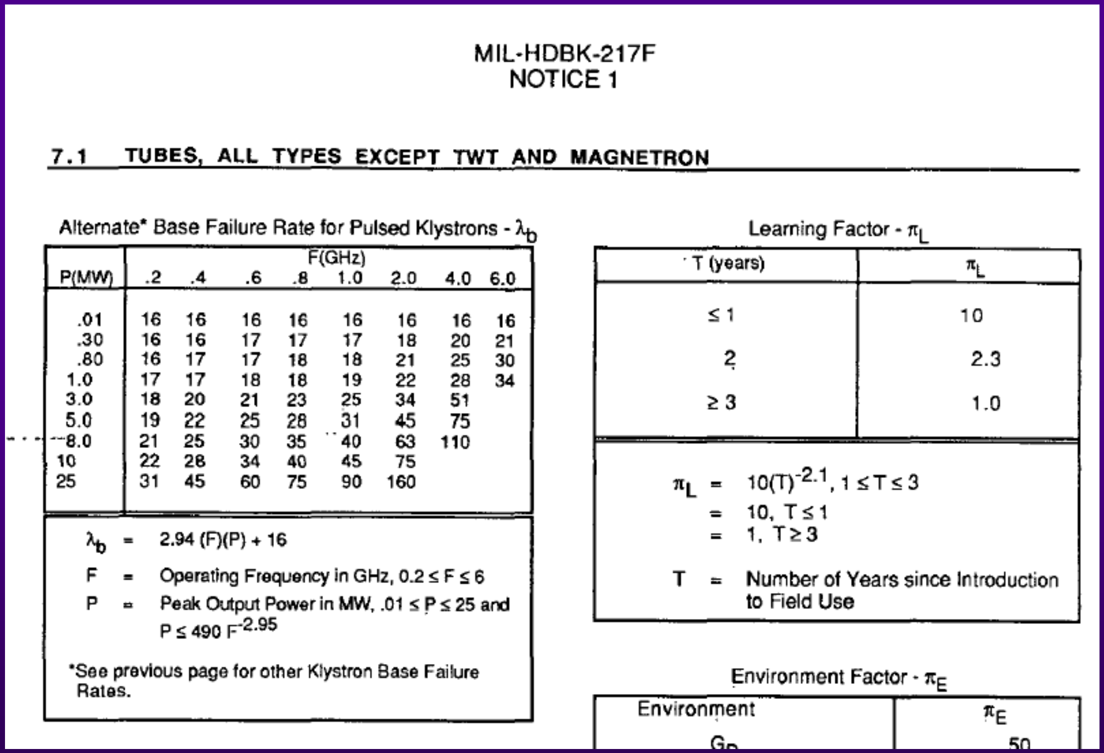
- Using the above model, here's the klystron cost per MW (peak)



- Blue: present state of the art
- Red: assuming a major investment into the development of a dedicated 30 MW tube

Considering tube lifetime

- In spite of its price, a klystron is a consumable!
- A klystron has a finite lifetime; this will also depend on its internal complexity (and on the peak power!).
- The lifetime will depend on many parameters, primarily the current density, but here's one estimate ...



MIL-HDBK-217F
NOTICE 1

7.1 TUBES, ALL TYPES EXCEPT TWT AND MAGNETRON

Alternate* Base Failure Rate for Pulsed Klystrons - λ_b

P(MW)	F(GHz) .2	.4	.6	.8	1.0	2.0	4.0	6.0
.01	16	16	16	16	16	16	16	16
.30	16	16	17	17	17	18	20	21
.80	16	17	17	18	18	21	25	30
1.0	17	17	18	18	19	22	28	34
3.0	18	20	21	23	25	34	51	
5.0	19	22	25	28	31	45	75	
8.0	21	25	30	35	40	63	110	
10	22	28	34	40	45	75		
25	31	45	60	75	90	160		

λ_b = 2.94 (F)(P) + 16

F = Operating Frequency in GHz, $0.2 \le F \le 6$

P = Peak Output Power in MW, $.01 \le P \le 25$ and $P \le 490\ F^{-2.95}$

*See previous page for other Klystron Base Failure Rates.

Learning Factor - π_L

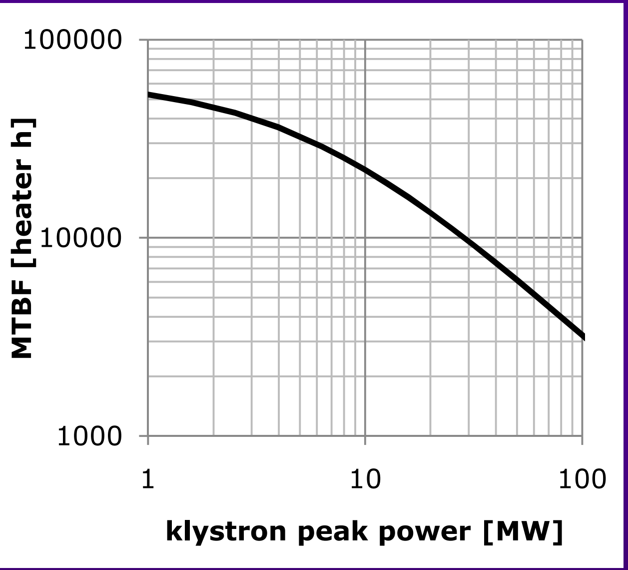
T (years)	π_L
≤ 1	10
2	2.3
≥ 3	1.0

π_L = $10(T)^{-2.1}$, $1 \le T \le 3$
= 10, $T \le 1$
= 1, $T \ge 3$

T = Number of Years since Introduction to Field Use

Environment Factor - π_E

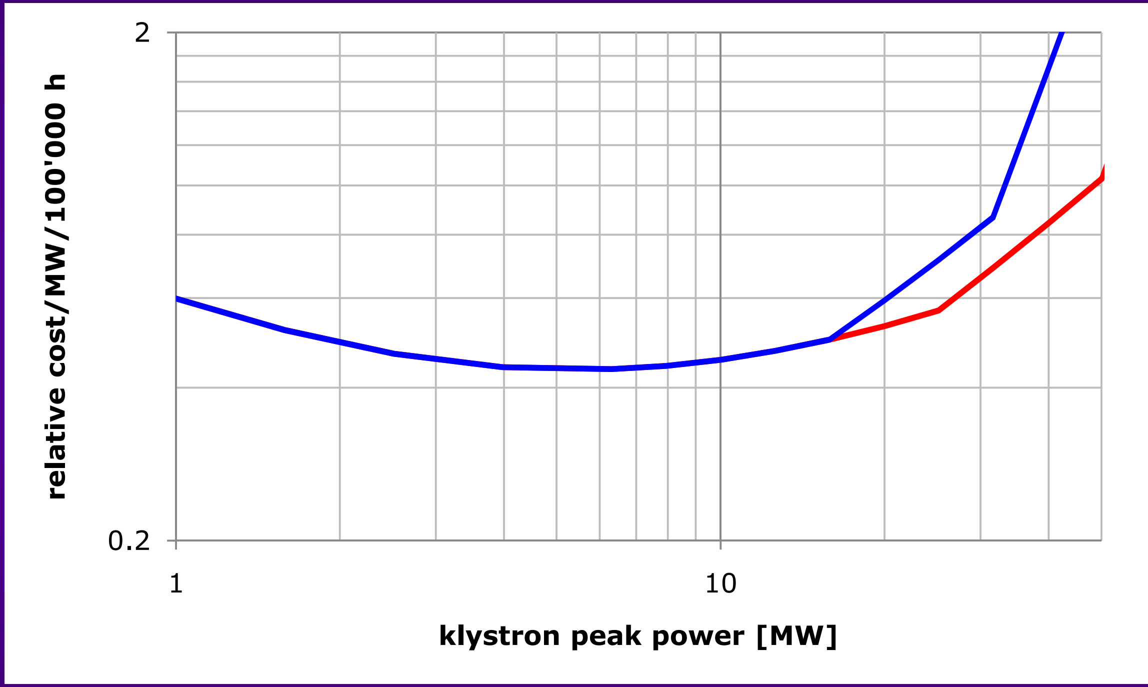
Environment	π_E
G_B	50



What about an MBK?: is the tube dead if one of *n* beams fails? If the design is good, the *n* beams would fail at around the same time ...

Cost per MWh

- Even if this model may be wrong, there will be a cost per MW and per operating hour: With the above model, this becomes:



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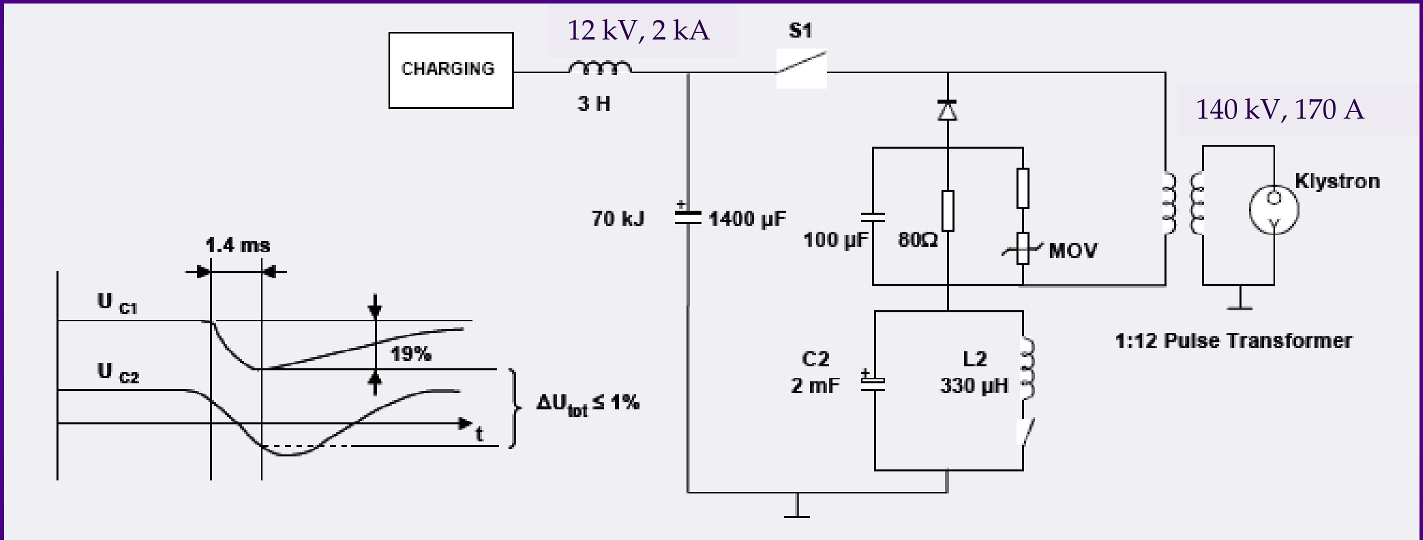
Conclusion from cost/MWh

- **The lifetime model presented here may be wrong; the scaling for the unit cost may be wrong, but for a correct cost estimate, both these influences must be included.**
- **Assuming that the models used above are somehow reasonable, the optimum size of an individual tube would be not significantly above 10 MW. This conclusion may change depending on a better model.**
- **It may also change after dedicated R&D, but in my opinion this R&D should rather address the reliability, cost and lifetime than the peak power.**
- **Anticipating from the phase noise analysis:**
  - **The klystron phase pushing gets better for shorter tubes and higher voltage (see below)**
  - n **individual sources instead of 1 will decrease the (uncorrelated) noise by a factor** $\sqrt{n}$

Concerning modulators

- R&D is going on for ILC, SPL, … we should take full advantage!
- Our CERN modulator experts explain:
  - A classical "bouncer" type modulator for a size of 12 kV, 2 kA can be considered feasible.
  - It would look like this (just the topology, picture taken from ILC):



  - A larger modulator would combine a number of these; it's cost would scale at best linearly with peak power – the "modular modulator" – no saving from making it bigger. This (20 MW peak or so) seems to be the natural module size. A modulator with 3 modules would cost around 1 MCHF.
  - The numbers given here would be consistent with a 15 MW MBK.

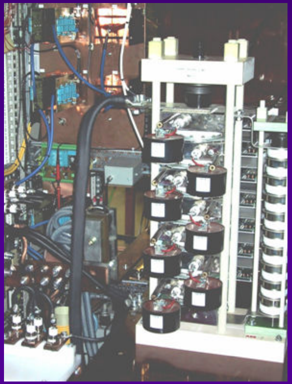
Modulator

This is some really big object!

Some ILC examples:

HVPS and pulse forming unit:

IGCT stack:



Pulse transformer:

ILC estimate:
300 ... 400 k$/unit

Commercial modulator 20 MW,
average power around a factor 10 too small.

One would need 1 of those every 2 to 3 m for the total length of the DBL!

Conclusion modulators

- Base line: bouncer type modulator is quasi “commercial”.
- 12 kV/2kA is a natural module size (24 MW DC);
- pulse transformer 12:1, ➔ 140 kV/170 A
- Larger modulators of this type would not be cheaper per MW.
- Modulators of other types require R&D!
- With a 70% efficient klystron, this would correspond to 15 MW RF.
- Anticipating from phase noise analysis:
  - Feed-forward to compensate for systematic voltage variation (droop) must be provided!
  - Stabilisation of the voltage to the 10^{-5} level is hard!
  - Again: the noise from more, smaller modulators will add only as $\sqrt{n}$.

Phase stability/stabilisation

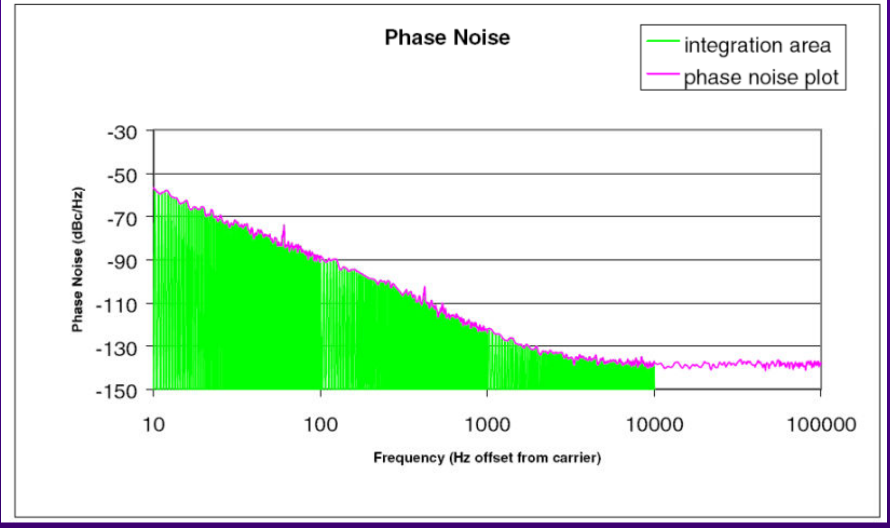
- Drive beam phase jitter leads to luminosity drop.
- $\Delta\varphi$ at 1 GHz causes 12 $\Delta\varphi$ at 12 GHz!
- Any R_{56} transforms drive beam energy jitter to phase jitter.
- With full beam loading, drive beam current error transforms to energy error (and then phase error).
- Requirement (order of magnitude):
  drive beam phase jitter $<0.02°$ (3.5E-4, 50 fs)
  drive beam energy jitter $<\mathcal{O}$(1E-4)

  (With a feed-forward, this may be relaxed by a factor 10!)
- Accelerating structures and recombination scheme act as filters for the noise – that may help.

Principal origins of noise

- We look at "noise", which is meant to include both amplitude and phase noise. The difference is the correlation between sidebands.
- Strictly speaking, noise is characterized with its spectral power density *S* (W/Hz), so the jitter specification should be called "integrated jitter" $\sigma_\varphi = \sqrt{\int S_{\varphi\varphi}(f)df}$

total area under integral	phi rms (radians)	trms (s)
1.70512E-05	0.004129311	4.22582E-12



- Principal origins of noise:
  - Drive beam Gun: intensity variations
  - Phase reference generation and distribution!
  - SH pre-buncher (500 MHz, flips phase every 244 ns ! ➔ creates also systematic error at 2.05 MHz!)
  - Klystrons (modulator, temperature, drive ...)
- Propagation of noise:
  - Noise propagates like any other signal, the analysis is similar (uses $|H(f)|^2$)
- Spectrum relevant for CLIC DB: about 5 kHz ... 20 MHz

Noise sources

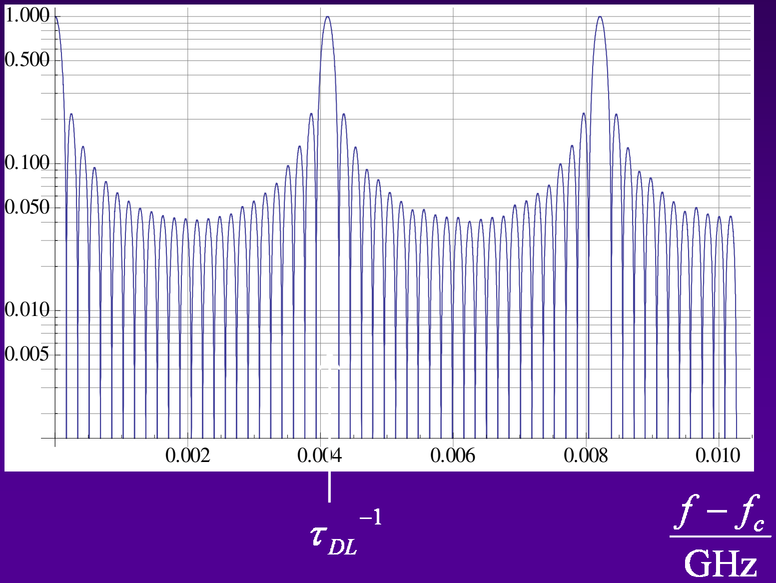
- **via klystron:**
  - Voltage (phase pushing) $\delta\varphi = -\frac{L}{\lambda}\left(V(2+V)\right)^{-3/2}\delta V$
  - Klystron body temperature: $\delta\varphi \approx 1^\circ \frac{\delta T}{K}$
  - Drive power $\delta\varphi \approx 2.3^\circ \frac{\log \delta P_{in}}{\mathrm{dB}}$
  - … filament current, magnet current, waveguides…
- **via the beam:**
  - Beam current changes acceleration! $\frac{\delta V}{V} = -\frac{R}{V_0/I - R}\frac{\delta I}{I}$

    at full loading: $\frac{\delta V}{V} = -2\frac{\delta I}{I}$
  - Phase jitter from the source
  - …

Filtering the noise

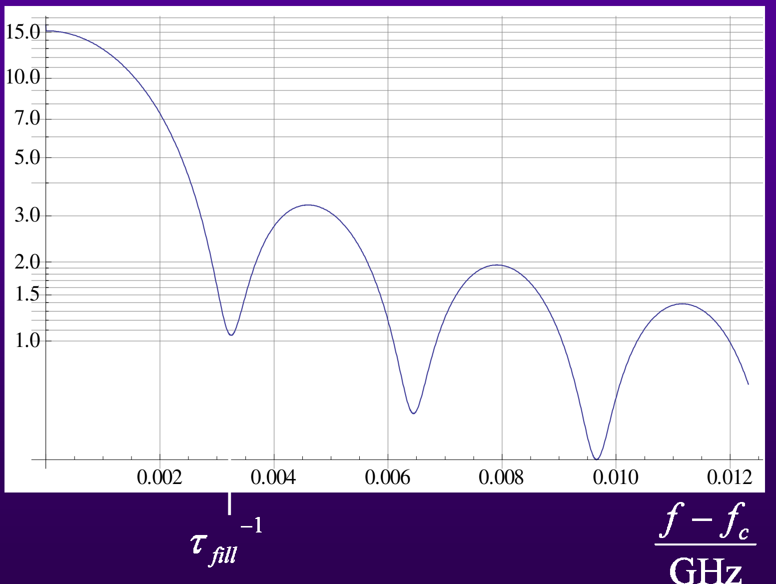
- **Much like a recursive filter, the delay loop and the combiner rings filter out certain spectral components of the noise, transfer function:**

$$(1+e^{-p\cdot\tau_{DL}})\times(1+e^{-p\cdot\tau_{CR1}}+e^{-2p\cdot\tau_{CR1}})$$
$$\times(1+e^{-p\cdot\tau_{CR2}}+e^{-2p\cdot\tau_{CR2}}+e^{-3p\cdot\tau_{CR2}})$$



- **Due to its group delay, also the accelerating structure has a beneficial filtering effect:**

- **The overall effect is maximized if the structure group delay is made equal to the delay loop length.**



Conclusions

- For CDR, stay with 10 MW MBK's – we know (from ILC) that they can be done.
- The re-optimization of the accelerating structures is in progress – first results are encouraging for a DBL of about 1 km length.
- ➔ Concentrate R&D on a modular RF system with peak powers of 10...15 MW peak, addressing – in addition to the RF parameters (η!) – cost, reliability, tube lifetime, serviceability, graceful degradation, and phase stability. Include the modulator in this design.
- Only some of this R&D is required for CDR, but most for TDR.
- For reference, ➔ re-evaluate the potential of SBK's and PBK's!
- The numbers presented above for cost scaling and MTBF are the result of some emails, telephone calls and google searches; I believe however that they indicate which way to go ... ➔ One should dig deeper and improve the simplified models I've used – maybe this will even change the conclusions I've made!
- It is not clear whether the required phase stability can be reached. The main suspects: modulator voltage jitter, SH pre-buncher, source! Accelerating structure and recombination scheme help filter the noise.