CLIC parameters

The CLIC Parameter working group:

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Follow-up of CLIC Parameter study in 2005

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - AB DEPARTMENT

CLIC Note 627

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UPDATED CLIC PARAMETERS 2005

H. Braun, R. Corsini, A. De Roeck, A. Grudiev, S. Heikkinen, E. Jensen, M. Korostelev, D. Schulte, I. Syratchev, F. Tecker (editor), W. Wunsch, F. Zimmermann, CERN, Geneva

for the CLIC study team

Abstract

This note presents the CLIC parameter set as of mid 2005 and describes the different sub-systems, stressing how the design of the different components is driven.
This design emerged from a better understanding of limitations for normal conducting accelerating structures, which led to a new optimised design for the CLIC 30 GHz accelerating structure. The structure parameters and improvements in other sub-systems have resulted in a major revision of the parameters. The overall layout and efficiencies for CLIC with this updated parameter-set are presented.

Geneva, Switzerland
May 12, 2006

Revisiting CLIC major parameters

- **Accelerating Gradient**
  - **What gradient could reasonably be demonstrated by 2010 ?**
  - **What should be the nominal CLIC gradient ?**

- **RF Frequency**
  - **What should be the CLIC nominal RF frequency ?**
  - **What should be the RF frequency of the RF components in CLEX ?**

8 meetings in 2006:

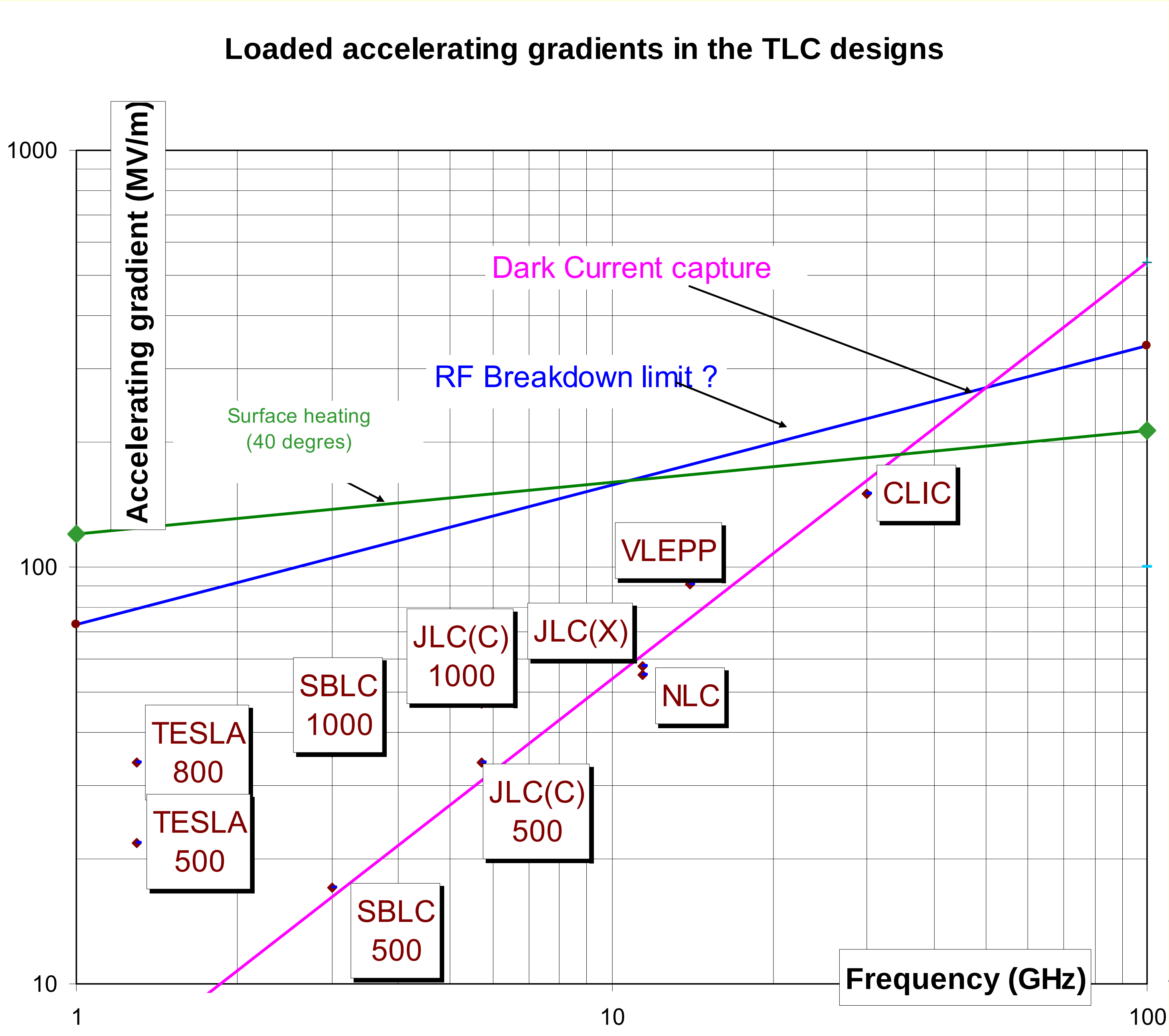
15/02 – 26/03 – 19/09 – 17/10 – 31/10 – 14/11 – 28/11 – 14/12

http://clic-study.web.cern.ch/CLIC-Study/CLIC_Parameter%20Mtgs.htm

Motivation

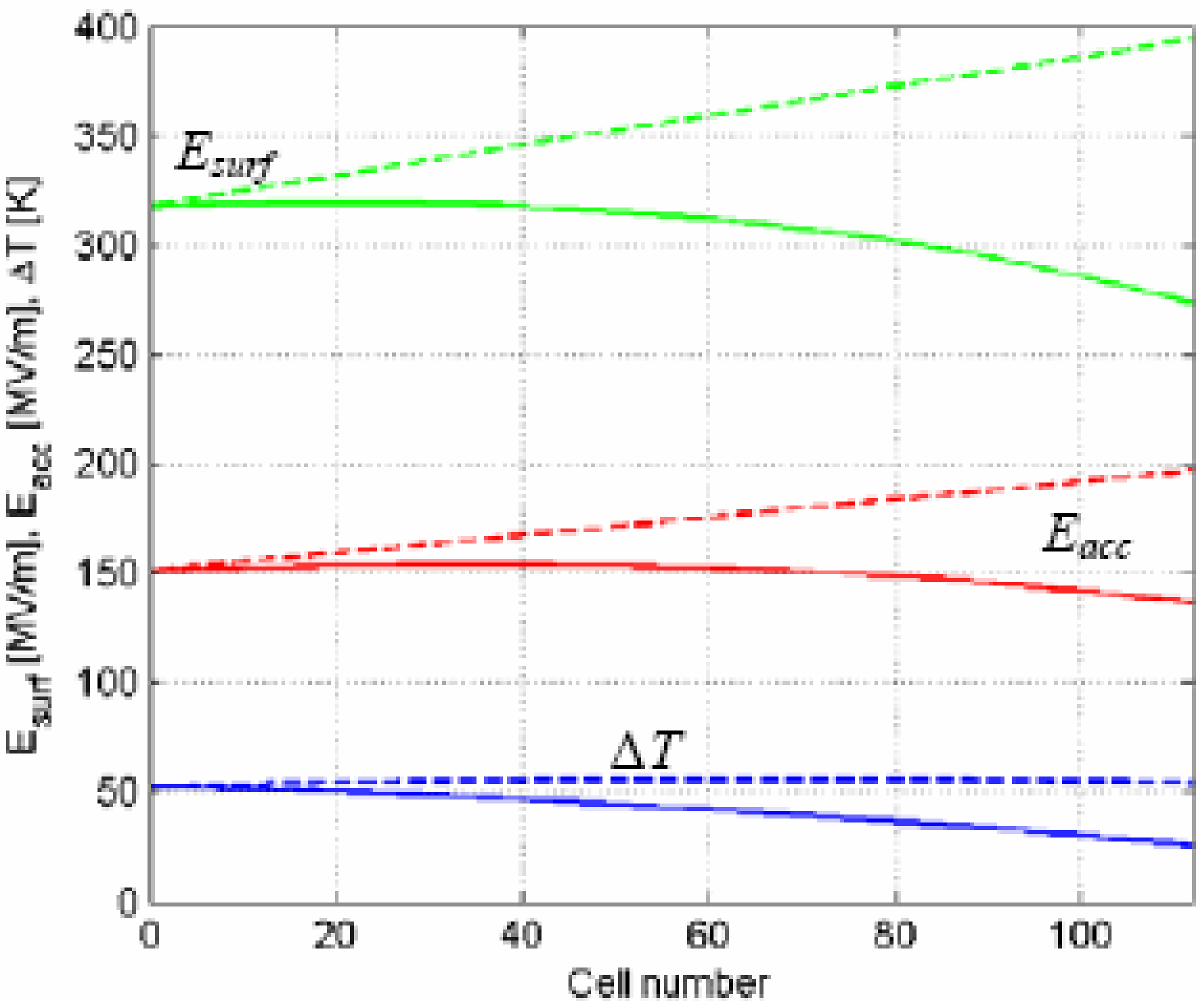
- **Credibility**
  - Trade off between attractive performances and parameters which can be reasonably demonstrated in the next three years
- **Ordering of components in CLEX**
  - TBL, Two Beam Test stand, ….
- **Stand Alone Power Source (SAPS) developments:**
  - Project definition with THALES and UK
  - FP7 bid next year (frequency dependent technology from 18 GHz?)
- **Optmisation of resources**
  - Focus and minimisation of developments
  - Complementary with SLAC and KEK
- **Schedule**
  - RF Frequency in CLEX to be defined now
  - CLIC Accelerating Field anf Frequency could possibly wait, but better decide simultaneusly for better coherency and work planning

Reminder: CLIC Gradient Specification in 1996?



Operational accelerating field

- Operation at 10^{-6} Breakdown Rate (BR)
- Structure able to work without damage at 10^{0} BR for efficient RF conditioning
- Damage induced by surface field or power?
- Temperature rise per pulse limited by fatigue



Max surface field during RF commissioning

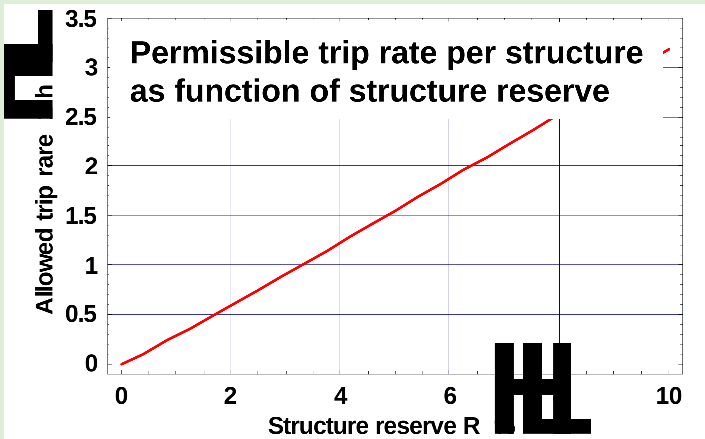
Max accelerating gradient during RF conditionning

Operational average accelerating gradient

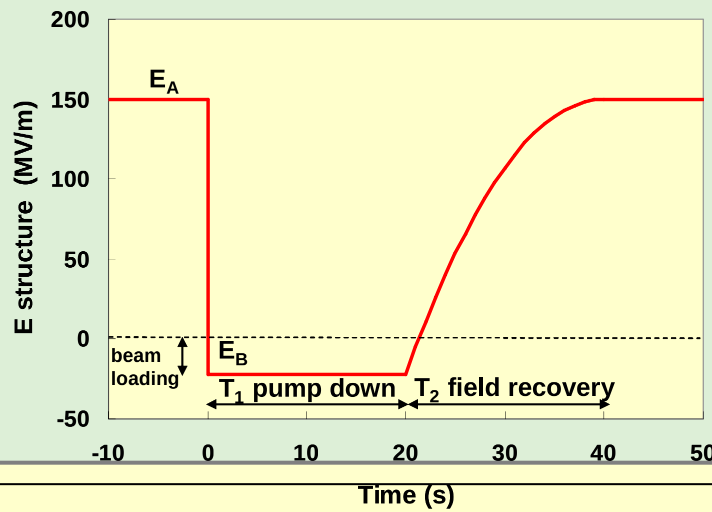
Acceptable Trip Rate of CLIC accelerating structures

(H.Braun for JPD presentation to ITRP on 28/06/04)

Limits imposed by energy management



assuming this trip recovery scenario:

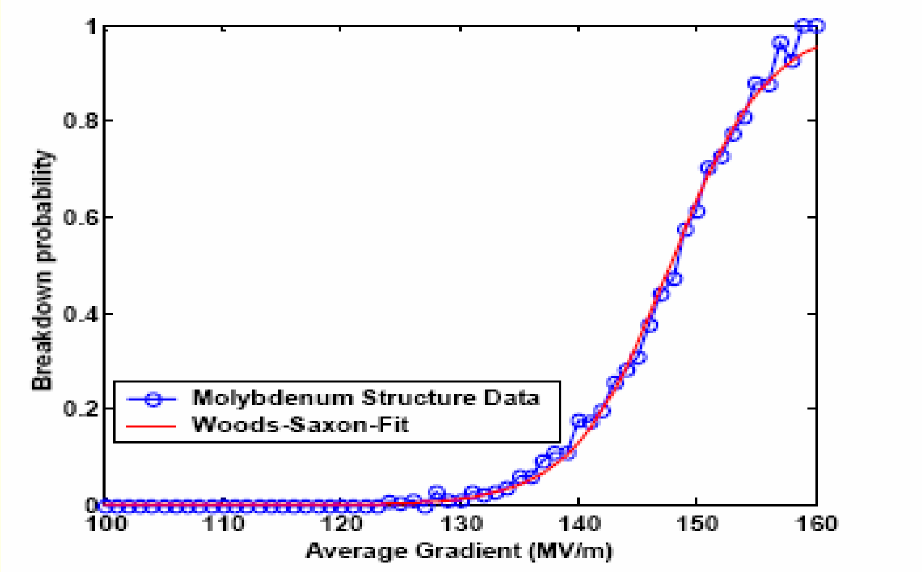


Limits imposed by effect of RF break-down on beam

- Effect on beam of RF break-down in a structure not well known
  Can be measured in CTF3 with probe beam (available 2007).
- Vertical kick of $\Delta P_Y \approx 20$keV/c is sufficient to take beam out of collision.
- Assuming, in the worst case, that every beam pulse having suffered from one single structure breakdown does not contribute to the integrated luminosity::

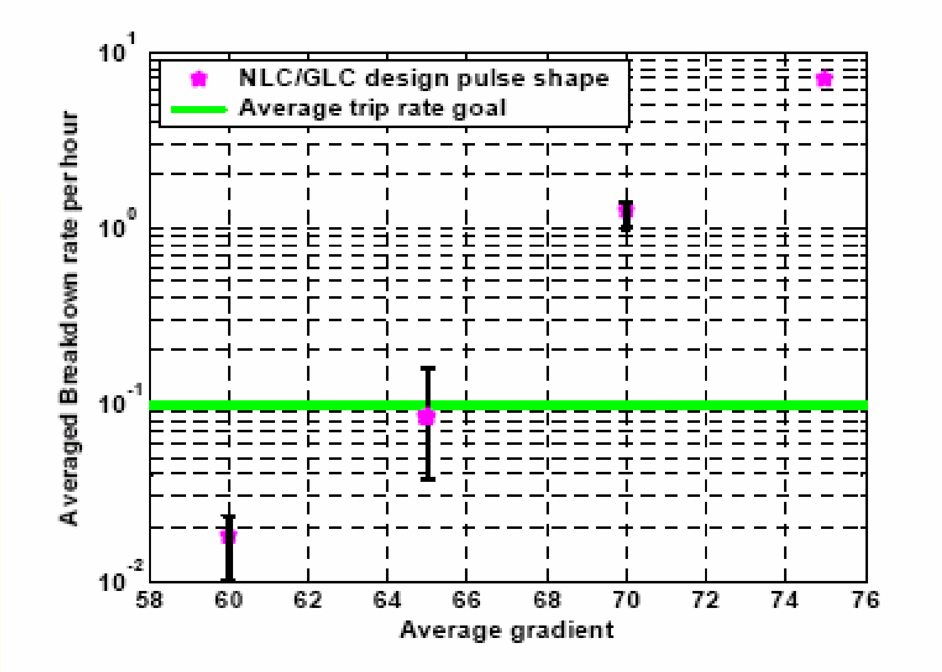
For <1% luminosity loss:
Trip rate per structure < *0.05 h*$^{-1}$
1 over 10 ^{6} RF pulses at 100 Hz repetition rate

RF Breakdown rates in structures



Breakdown rates during RF conditioning of a CLIC structure equipped with Mo iris

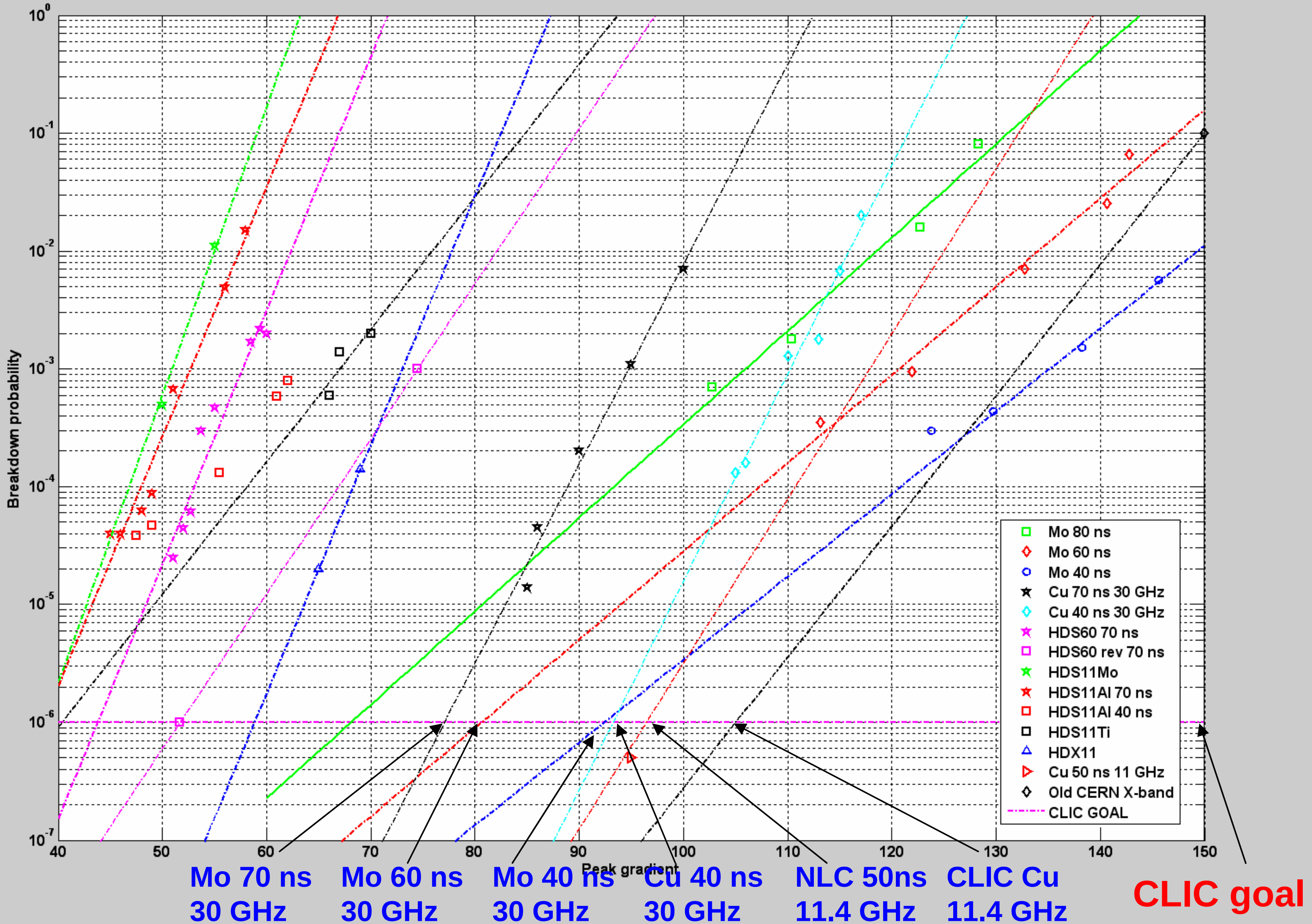
No reliable breakdown rates available for CLIC structures after RF conditioning



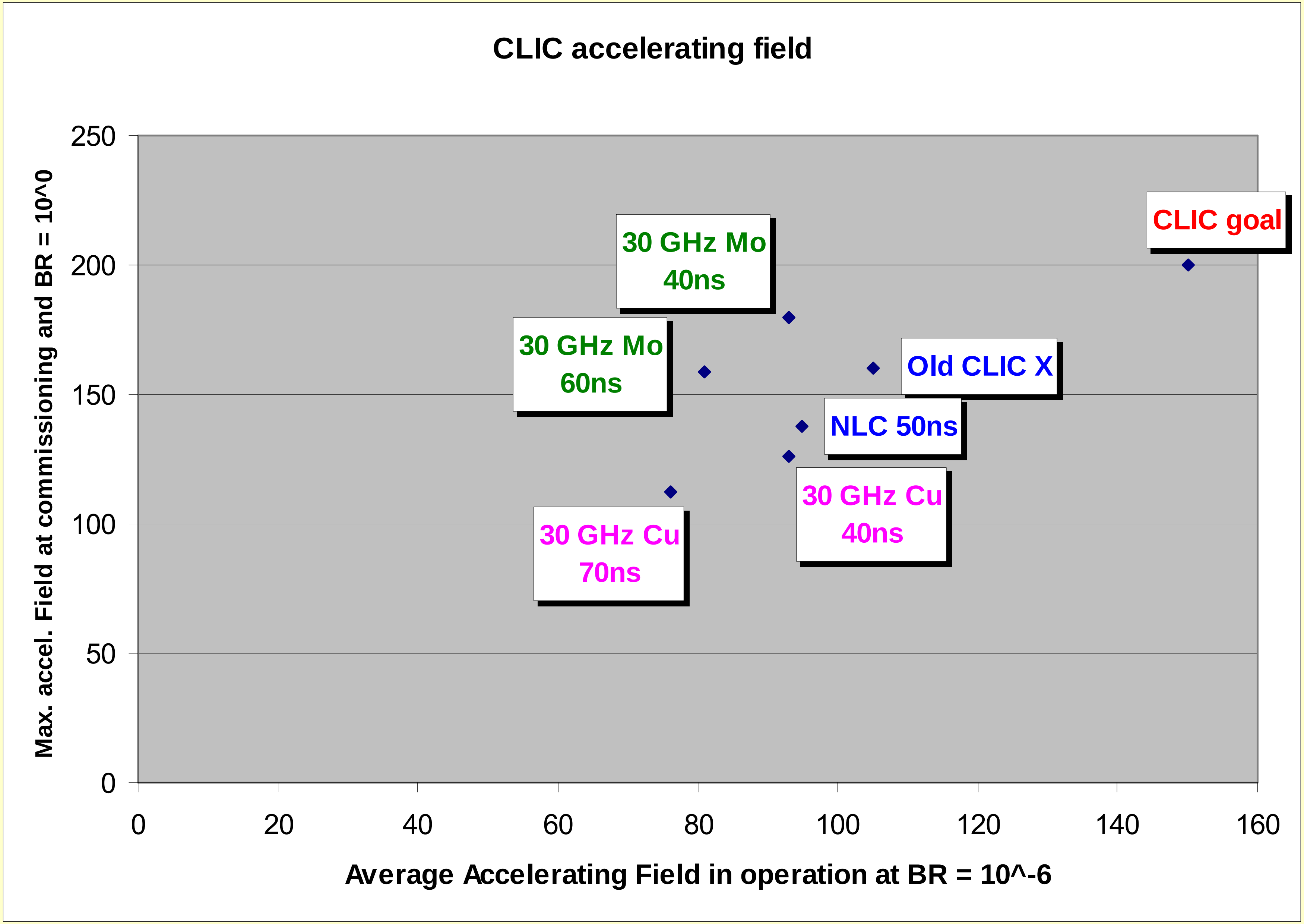
Factor 10 reduction of breakdown rate of NLC structure by 5.5 MeV reduction in accelerating field (SLAC-PUB-10463, S.Doebert May 2004)

35 MeV/m reduction in field for a 10^6 reduction in RF breakdown

Achieved Accelerating Gradient



Achieved or scaled Field & Breakdown rates



Accelerating Gradient at 10-6 breakdown rate

- **Which can be reasonably demonstrated by 2010: 100 MV/m**
  - **Unanimously recommended**
  - **Nearly already demonstrated several years ago with short pulses at 11.4 GHz**
    - with CLIC (small aperture) and NLC structures with short pulses (40 to 50 ns)
    - But with RF designs not compatible with acceptable luminosity performances (damping not sufficient)
    - HDS design = damping strong enough but presently lower performances
  - **At 30 GHz:**
    - Best performance achieved so far 95 MV/m with CU circular and 40 ns
  - **Higher field not excluded but high(er) risk of failure**
    - Magic material with max field of Mo and BR slope of Cu? 1
    - New ideas?
  - **Optimum trade off between optimism and realism**

CLIC MAIN PARAMETERS

- **Accelerating Gradient**
  - **What gradient could reasonably be demonstrated by 2010 ?** **100 MV/m**

    What should be the nominal CLIC gradient ?

    Recommended: ?
- **RF Frequency**
  - **What should be the CLIC nominal RF frequency ?**

    Recommended: ?
  - **What should be the RF frequency of the RF components in CLEX ?**

    Recommended: ?

CLIC overall optimisation model (A.Grudiev)

Accelerating structure limitations:

rf breakdown and pulsed surface heating (rf) constraints:

Peak surface field: $E_{surf}^{max} < 380MV/m$

Temperature rise per pulse: $\Delta T^{max} < 56K$

Power flow: $P_{in} t_p^{1/3} F_{RF}/C < 600\ MWns^{1/3}\ GHz/mm$

Beam dynamics constraints:

Beam quality preservation during acceleration in main linac with high wake fields environment

Beam focusing in Beam Delivery System and collision in detector in high beamstrahlung regime

Deduce CLIC parameters and performance:

> 200 millions structures

Optimization figure of merit

Luminosity per linac input power:

$$\int L dt / \int P dt \sim L_{b\times} / N \eta$$

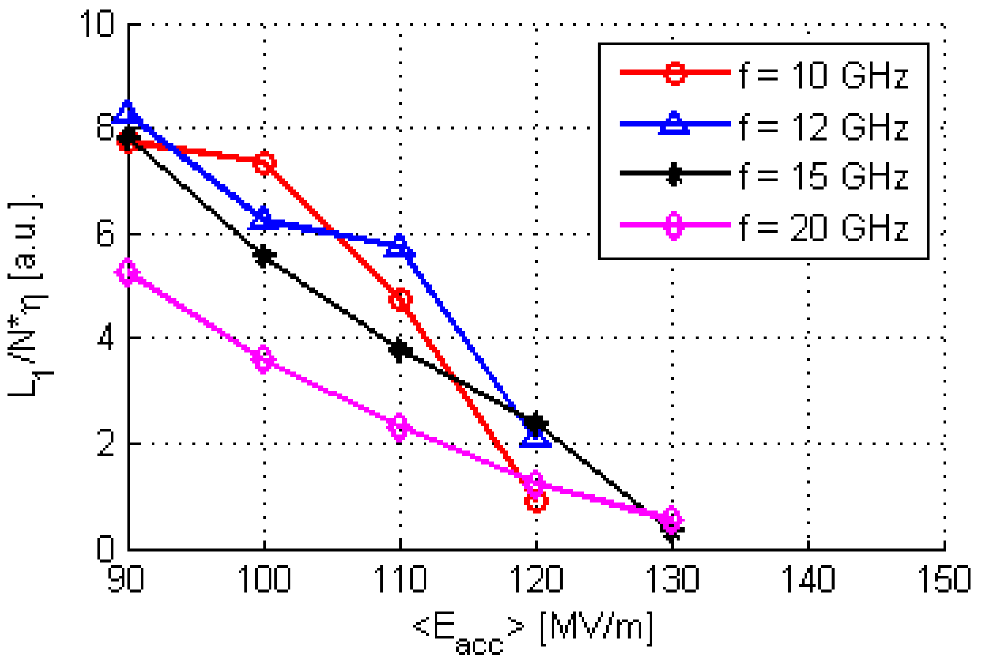
Cost estimation of the overall complex at 3 TeV

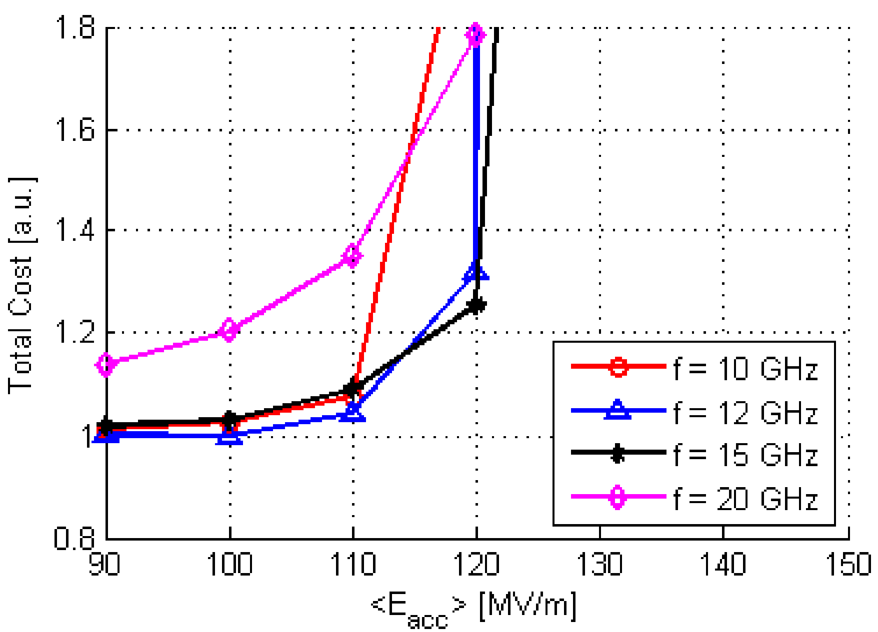
(invest. & exploit. 10 years)

and scaling with Energy

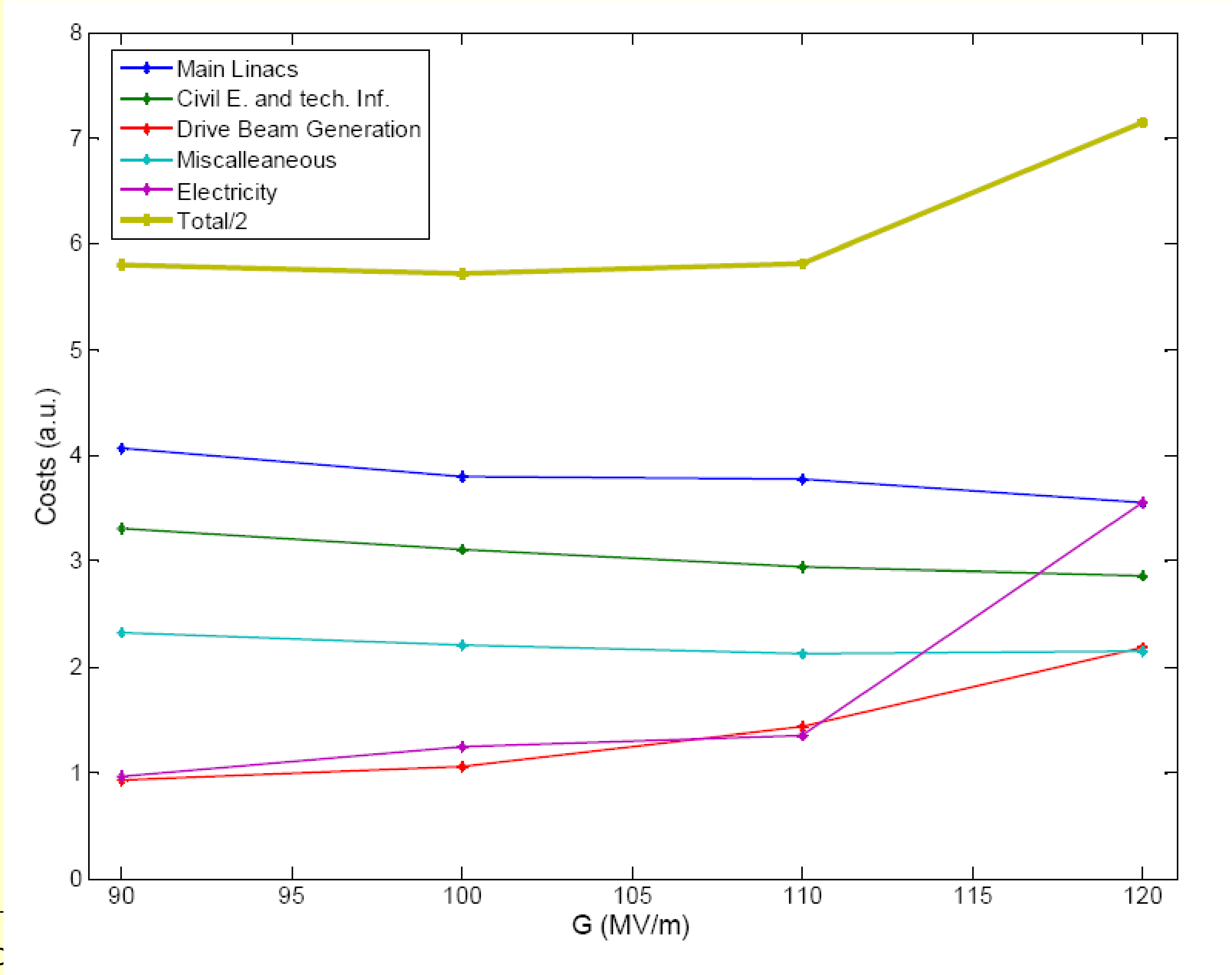
CLIC performances (FoM) and cost optimisation as function of accelerating gradient (A.Grudiev)

E_{cms} = 3 TeV $L_{(1\%)}$ = 3.3 10^{34} $cm^{-2}s^{-1}$





Cost drivers variation with accelerating field (H.Braun and C.Wyss)



Structure limitations (W.Wuensch)

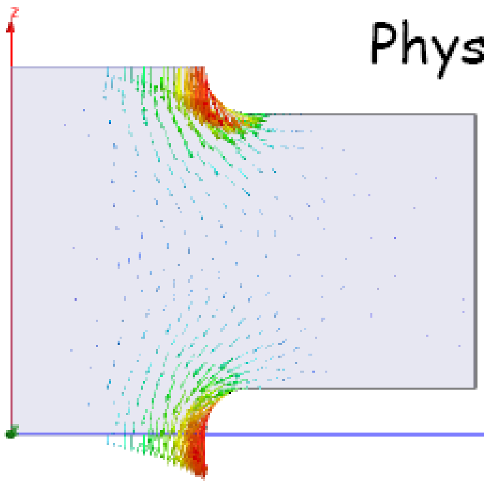
The case for a material dependent rf-breakdown limit scaling of

$$\frac{P\tau^{\alpha}}{C}$$

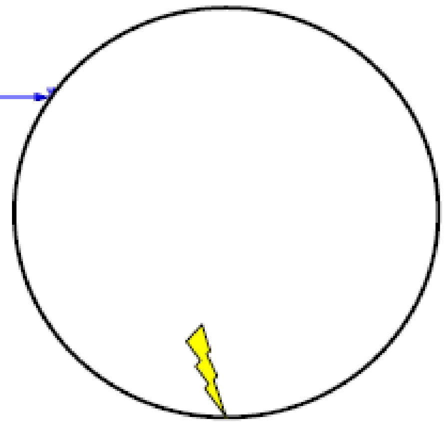
- P is power flow,
- τ is pulse length,
- C is the smallest structure circumference
- α is empirically determined with values around 1/2 (Mo) to 1/3 (Cu).

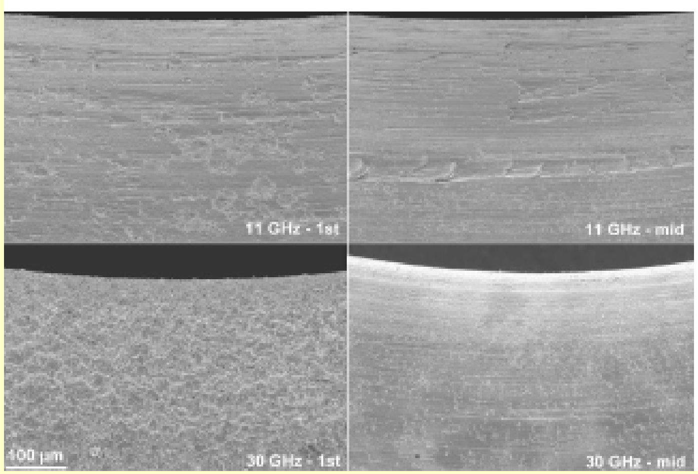
Physics model of the structure limitation

Physical arguments



Poynting vector





- Power flows in a thin layer above structure irises.
- Melted spots left by breakdown are small compared to the iris circumference as are images of light.
- Energy to melt spot small compared to total pulse energy.
- Melted spots evolve into damage.
- Power density available to feed discharge above spot of fixed transverse dimension is *P/C*.
- Surface field only needs to be high enough to *initiate* breakdown.
- Above a certain threshold the effect of the breakdown on the surface geometry is greater than on the field holding capability - material dependent saturation.

Optimisation based on present model of structure limitations

- **Lower is the accelerating field (range 90 to 150 MV/m):**
  - **Higher is the figure of Merit for any RF frequency**
  - **Lower is the cost for any RF frequency**

- **Cost flat bottom more or less independent of RF frequency and field in the range:**

90 MV/m > Field > 100 MV/m

10 GHz > RF Frequency > 15 GHz

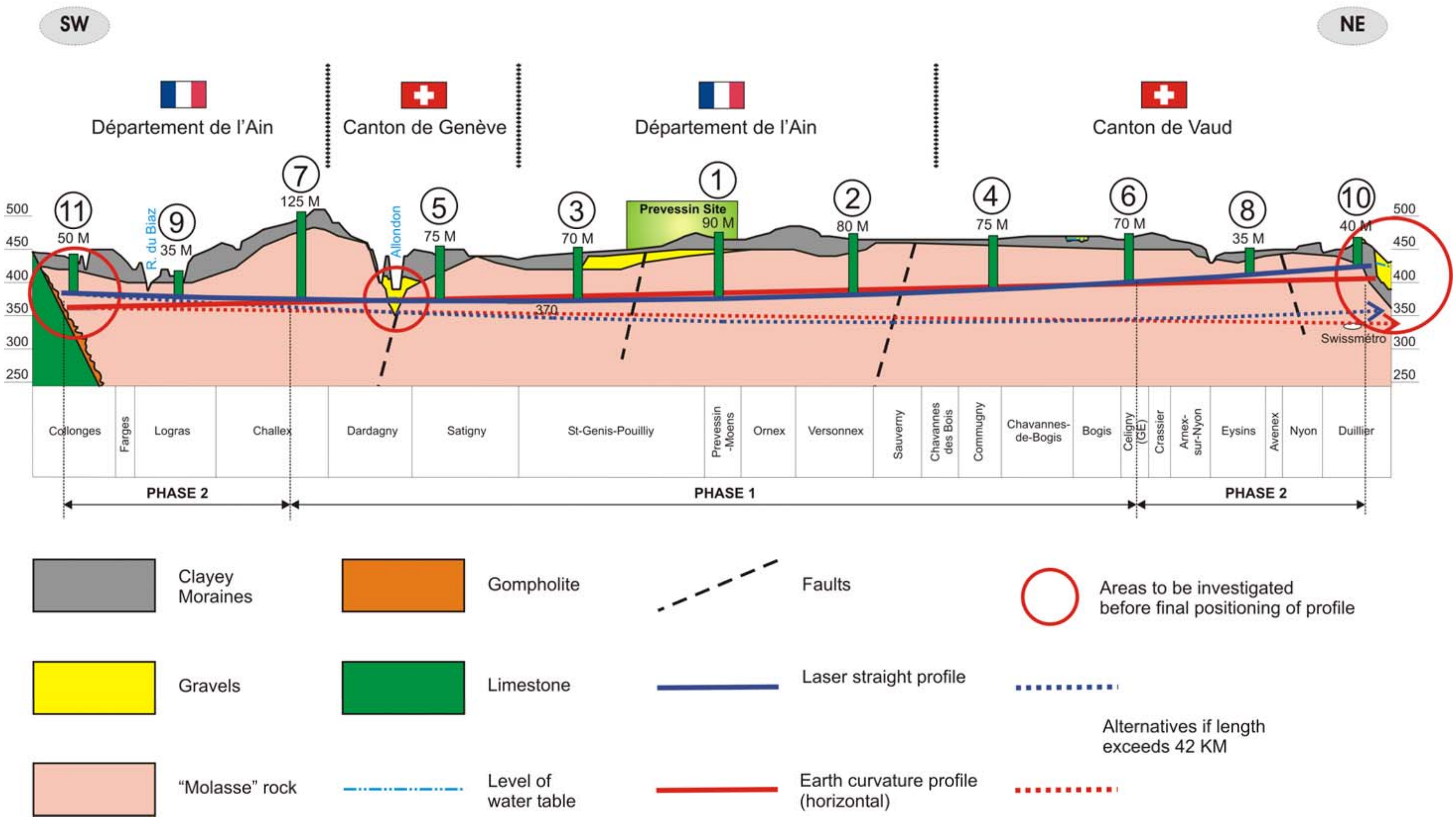
- **Improved FoM for low gradient due to higher efficiency**

- **Cost (flat) minimum by trade off between Civil engineering and Power costs**
  - **Cost optimisation with lower field (30 MV/m for comparison with ILC?) in order to better identify minimum cost parameters?**

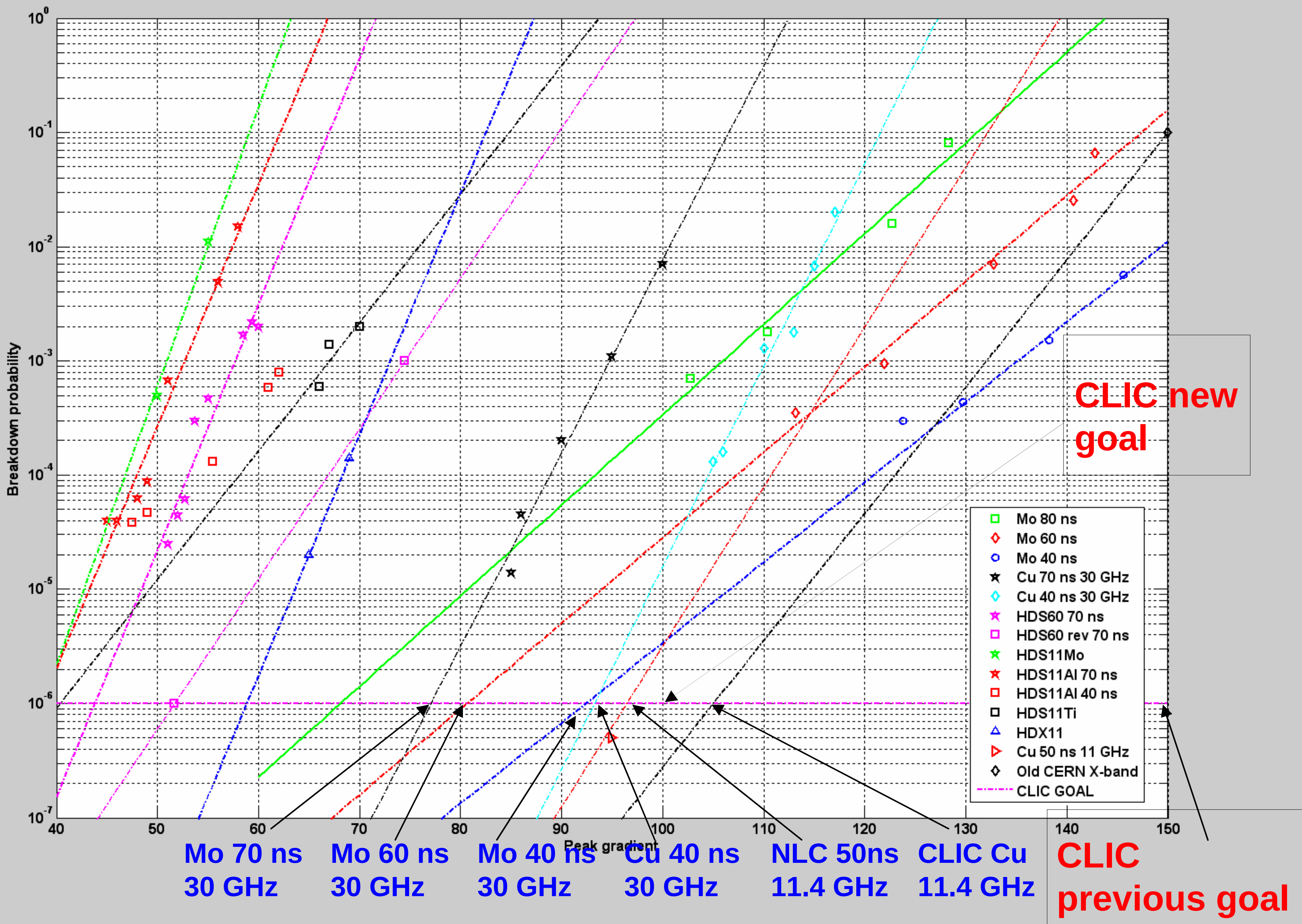
CLIC Nominal accelerating Gradient

- Unanimously recommended: 100 MV/m
- Corresponding to the optimum cost with present structure limitations
  - Trade off between Civil engineering and power costs
  - Factor two in P/C limitation could possibly raise minimum cost to 130 MV/m
- Could possibly be demonstrated by 2010
- An increase of field in 2010 would be positively received
  - In case higher fields are demonstrated
  - In case optimum cost is shifted to higher fields due to lower structure limitations
- Compatible with a 3 TeV design on the CERN site
  - Up to 3 TeV with overall extension of 47 km:
    (3 TeV/100 MV/m/ 0.79 (filling factor) + 4 km (RF overhead) + 5 km (BDS)
  - IP under Prevessin site and still shorter than ILC @ 1 TeV (about 50 km)
  - extension to 5 TeV more problematic with overall extension of 63 km and IP North of Prevessin
    Possible improvement of field (150 MV/m?) in the (far) future?
- Attractive enough in comparison with ILC
  - CLIC Acc. Fields >3 larger than 31.5 MV/m at 500 GeV @ILC (presently unacceptable spread of fields in SC cavities)
  - Considered as the lowest field for which CLIC is worth pursuing
- Higher fields not excluded but with (too) high risk of failure

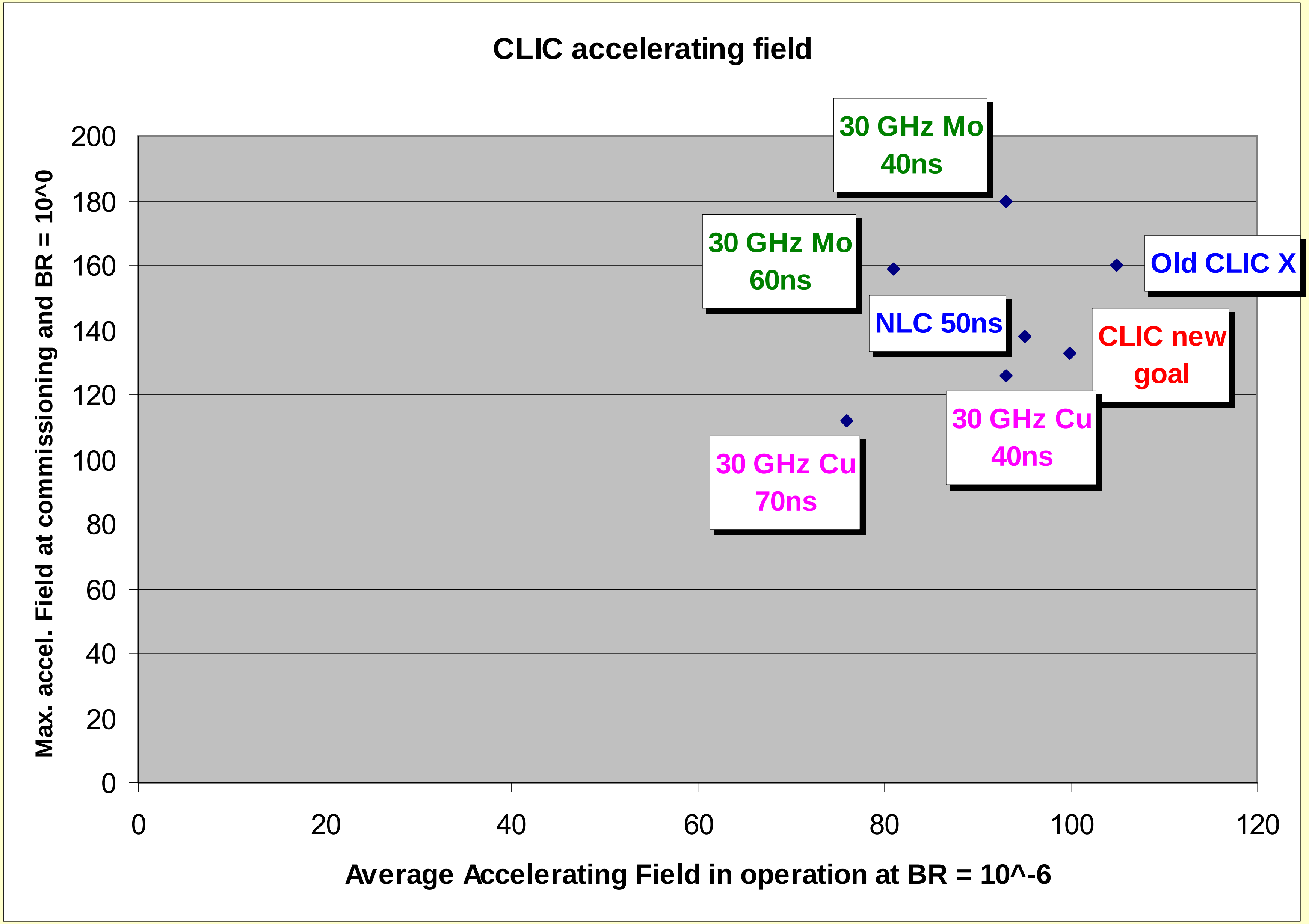
Longitudinal section of a Linear Collider on CERN site–



Achieved Accelerating Gradient



CLIC new target



CLIC MAIN PARAMETERS

- **Accelerating Gradient**
  - **What gradient could reasonably be demonstrated by 2010 ?** **100 MV/m**
  - **What should be the nominal CLIC gradient ?**

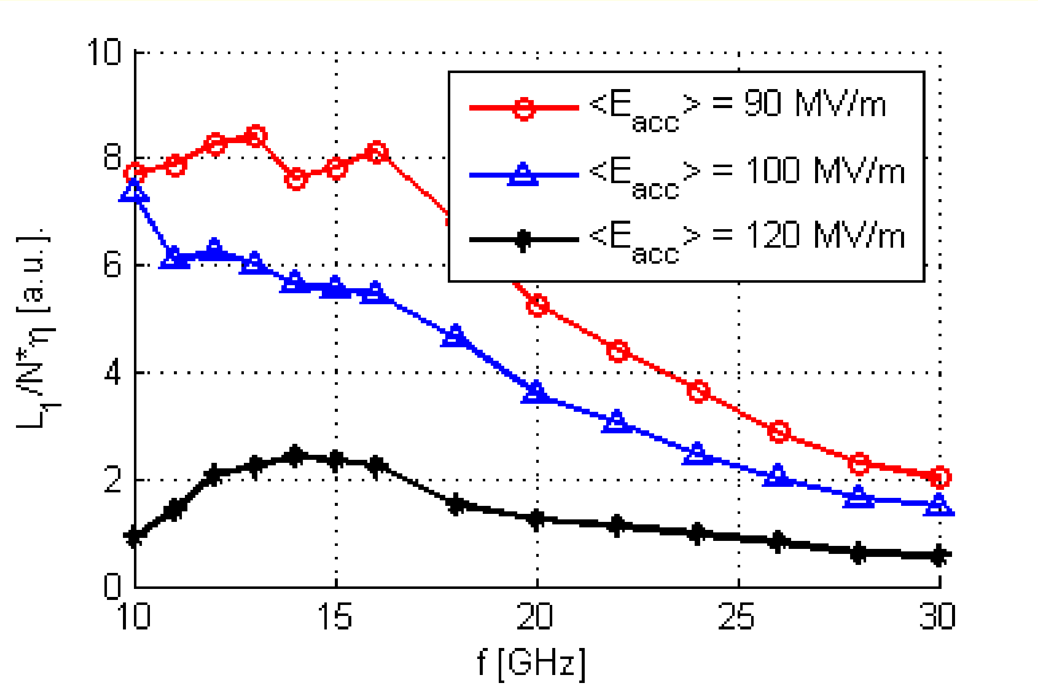
    100 MV/m
- **RF Frequency**
  - **What should be the CLIC nominal RF frequency ?**

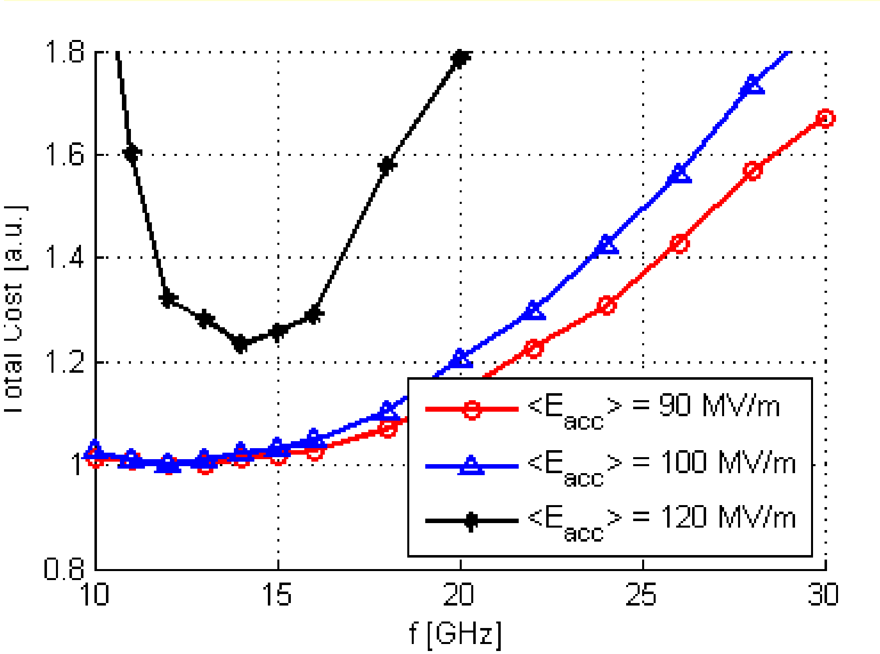
    Recommended: ?
  - **What should be the RF frequency of the RF components in CLEX ?**

    Recommended: ?

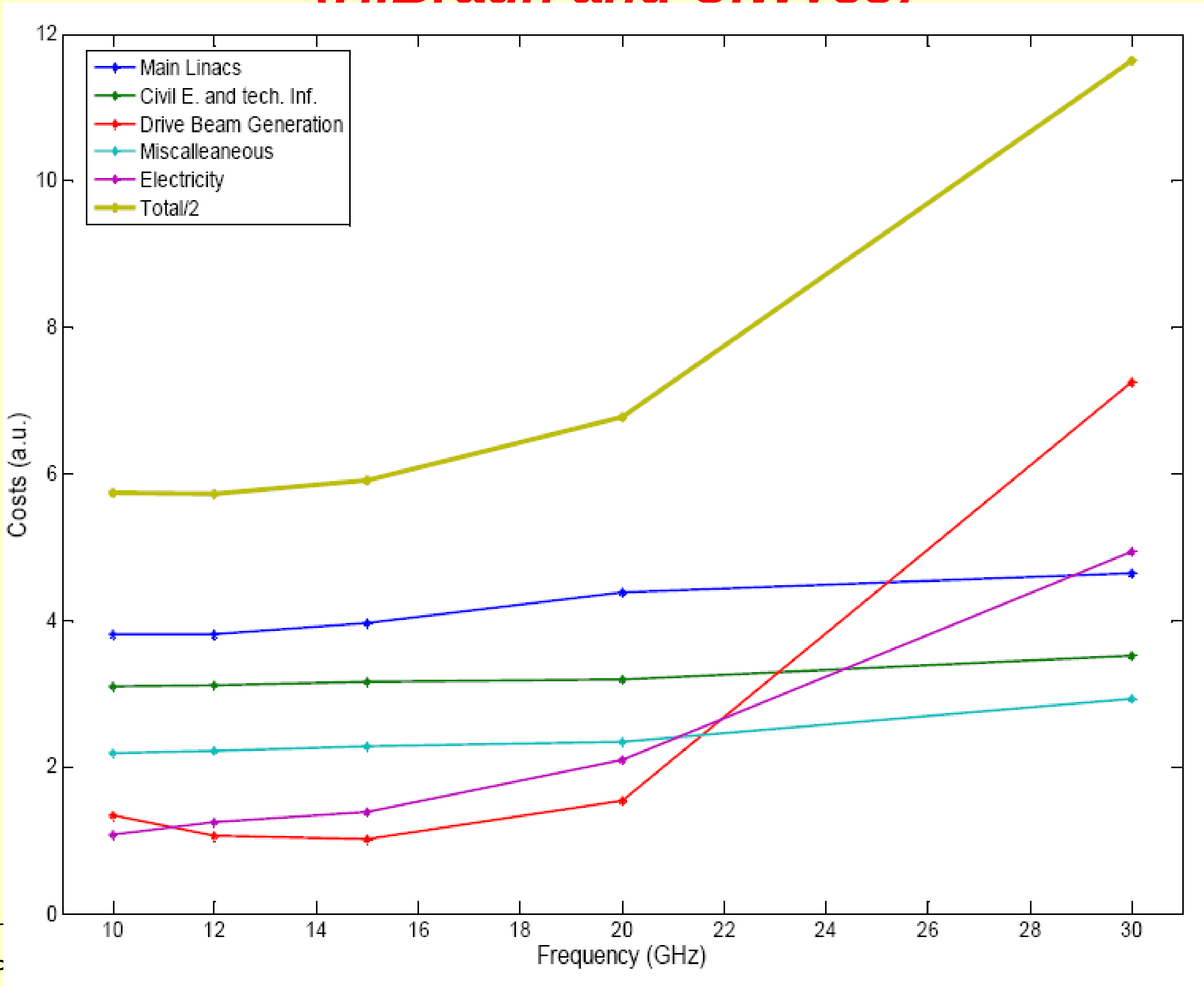
CLIC performances (FoM) and cost optimisation as function of RF frequency (A.Grudiev)

E_{cms} = 3 TeV $L_{(1\%)}$ = 3.3 10^{34} $cm^{-2}s^{-1}$





Cost drivers variation with RF frequency (H.Braun and C.Wyss)



Parameters of 5 structures at 100 MV/m

Structure number	1	2	3	4	5
Accelerating gradient: $\langle E_{acc} \rangle$ [MV/m]	100	100	100	100	100
Frequency: f [GHz]	10	12	15	18	20
RF phase advance per cell: $\Delta\varphi$ [°]	60	70	60	50	50
Average iris radius over wavelength: $\langle a \rangle/\lambda$	0.09	0.09	0.1	0.11	0.11
Input/Output iris radii: $a_{1,2}$ [mm]	3.51, 1.89	2.93, 1.58	2.6, 1.4	2.38, 1.28	2.15, 1.16
Input/Output iris thickness: d [mm]	0.75	0.625	0.5	0.42	0.375
Number of cells, structure length: N_c, l [mm]	29, 160	28, 151	32, 117	35, 88	33, 75
Bunch separation: N_s [rf cycles]	5	5	5	5	5
Number of bunches in a train: N_b	144	146	141	159	202
Pulse length, rise time: τ_p, τ_r [ns]	174.5, 56.5	144.9, 44.1	97.5, 26.3	77.7, 18.2	79.8, 16.4
Input power: P_{in} [MW]	57	42	34	28	23
Max. surface field: E_{surf}^{max} [MV/m]	234	236	245	256	255
Max. temperature rise: ΔT^{max} [K]	28	28	25	25	27
Efficiency: η [%]	16.4	16.0	16.5	16.8	17
Luminosity per bunch X-ing: $L_{b\times}$ [m^{-2}]	1.96×10^{34}	1.08×10^{34}	0.71×10^{34}	0.47×10^{34}	0.27×10^{34}
Bunch population: N	4.37×10^{9}	2.78×10^{9}	2.12×10^{9}	1.69×10^{9}	1.30×10^{9}
Figure of merit: $\eta L_{b\times}/N$ [a.u.]	7.35	6.23	5.55	4.64	3.58

Parameters of 5 linacs at 100 MV/m

For CLIC design luminosity: $L_1 = 3.3x10^{34} cm^{-2} s^{-1}$

Structure number	1	2	3	4	5
Frequency: f [GHz]	10	12	15	18	20
Repetition frequency: f_{rep}[Hz]	117	210	329	446	595
RF input power: P_l [MW/linac]	108	127	143	171	221
RF energy per pulse: P_l/f_{rep} [kJ/linac]	921	606	434	383	372

CLIC RF frequency?

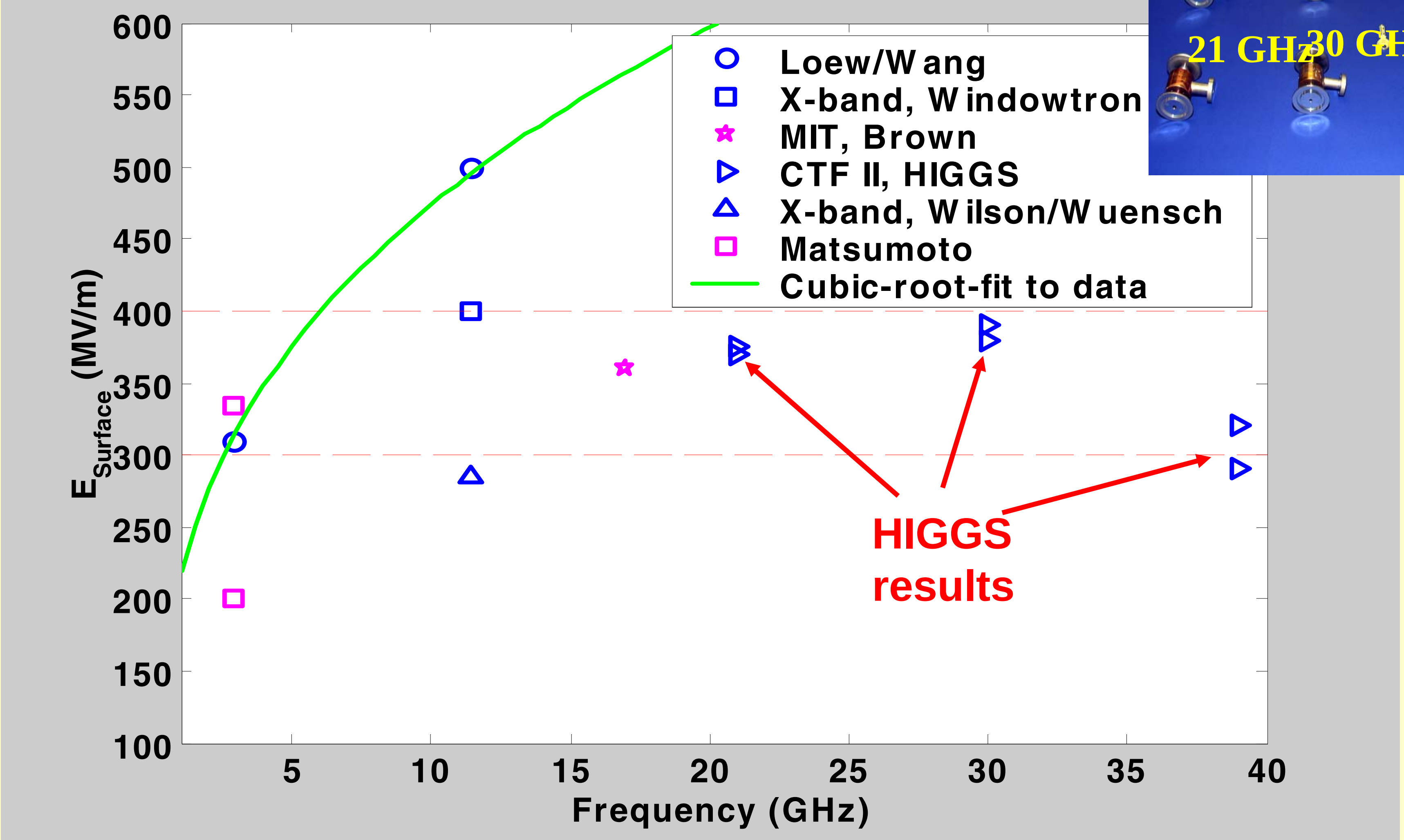
- **At 100 MV/m and following Alexej's optimisation based on present model of structure limitations:**
  - **Figure of Merit maximum at 10 GHz (or lower?)**
    - **Flat maximum in the range 10 to 15 GHz**
  - **Cost minimum at 12 GHz**
    - **Flat minimum in the range 10 to 15 GHz**
- **Sensitivity to structure limitations (Improvement of P/C by factor 2)**
  - **Figure of Merit maximum at 14 GHz (or lower?)**
    - **Flat maximum in the range 12 to 18 GHz**
  - **Cost minimum at 16 GHz**
    - **Flat minimum in the range 10 to 20 GHz**
- **Challenging parameters (structure and linac) although more favorable at low frequency:**
  - **Longer structure length, larger and thicker iris,**
  - **Smaller repetition frequency but higher beam energy per pulse**

RF frequency

- **Unanimity**
  - **No support in favor of 30 GHz**
  - **Any (?) lower frequency more favorable**
  - **Model of structure limitations certainly not perfect (especially scaling with frequency), lack of convincing physical explanation but coherent with the (too limited) available data and good enough to estimate the trend**
  - **Accelerating field (nearly) independent of frequencies:**
    - already demonstrated with HIGGS cavities in 2004 (?)
    - confirmed with experiments (highest field at acceptable Breakdown rate achieved at X band frequencies)
- **Two various schemes (both valids with advantages and drawbacks):**
  - **Exploration of frequency range from 11.4 to 30 GHz**
    - Measurements at 11,4 GHz at SLAC and KEK (taking advantage of existing power sources)
    - Measurements at 30 GHz in CTF2 and 18 GHz in CLEX (middle of range between 12 and 30)
    - Decide optimum frequency in 2010
    - In the meantime define CLIC parameters at 12 and 18 GHz
  - **Focus on one single frequency at 12 GHz**
    - Corresponding to minimum cost and maximum FoM
    - Even if optimum shifts to (slightly) higher frequencies, close to flat minimum and on the low frequency side
    - Distribute and share structure tests between CLEX, SLAC and KEK
    - Continuation of frequency scaling studies at 30 GHz in CTF2 but no expected (good) surprise at intermediate frequency between 12 and 30 GHz

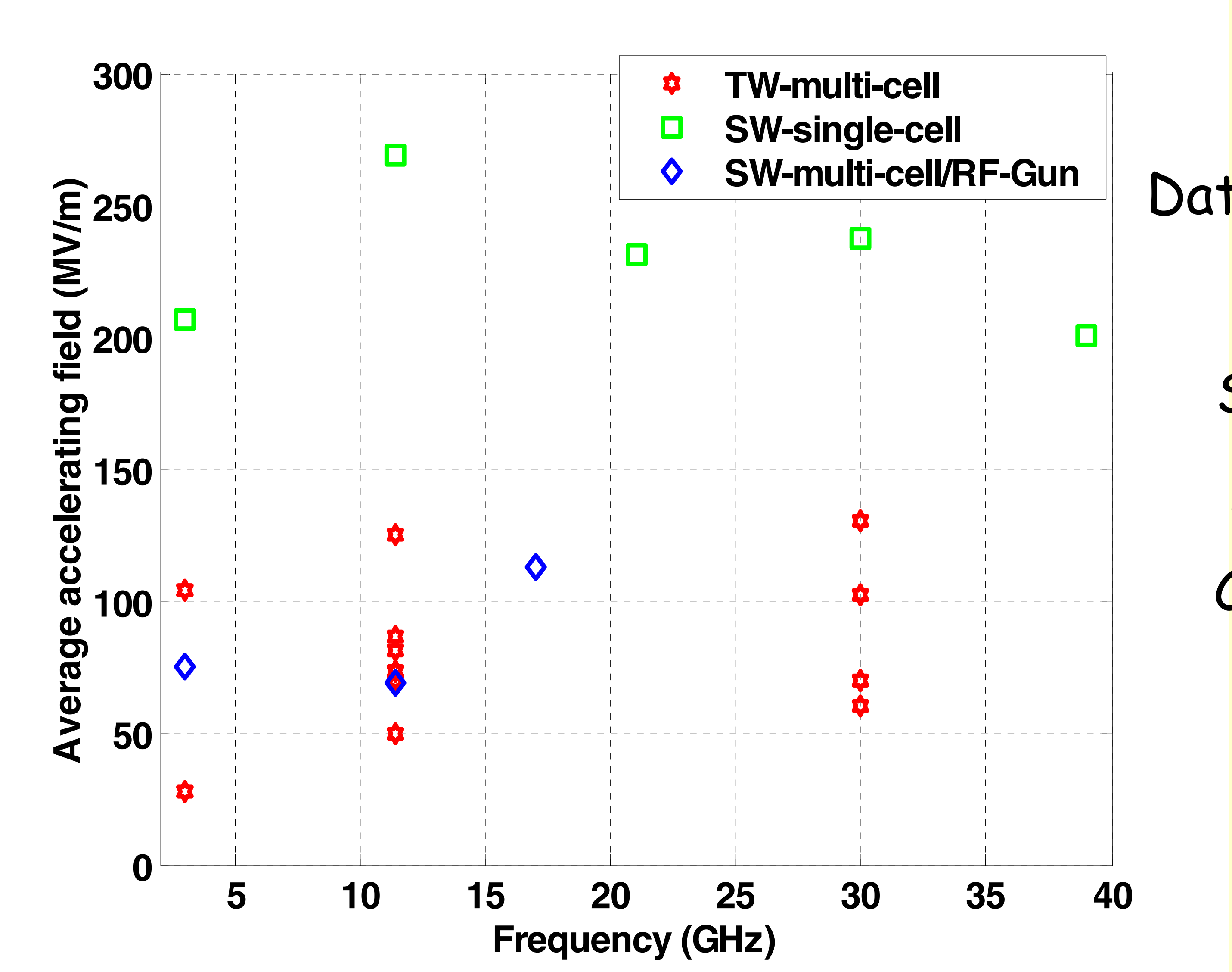
FIELD LIMITS ON COPPER SURFACES

(CLIC @ ITRP : 28/06/04)



ACCELERATING FIELD PERFORMANCES

CLIC @ ITRP (28/06/04)



Data from:

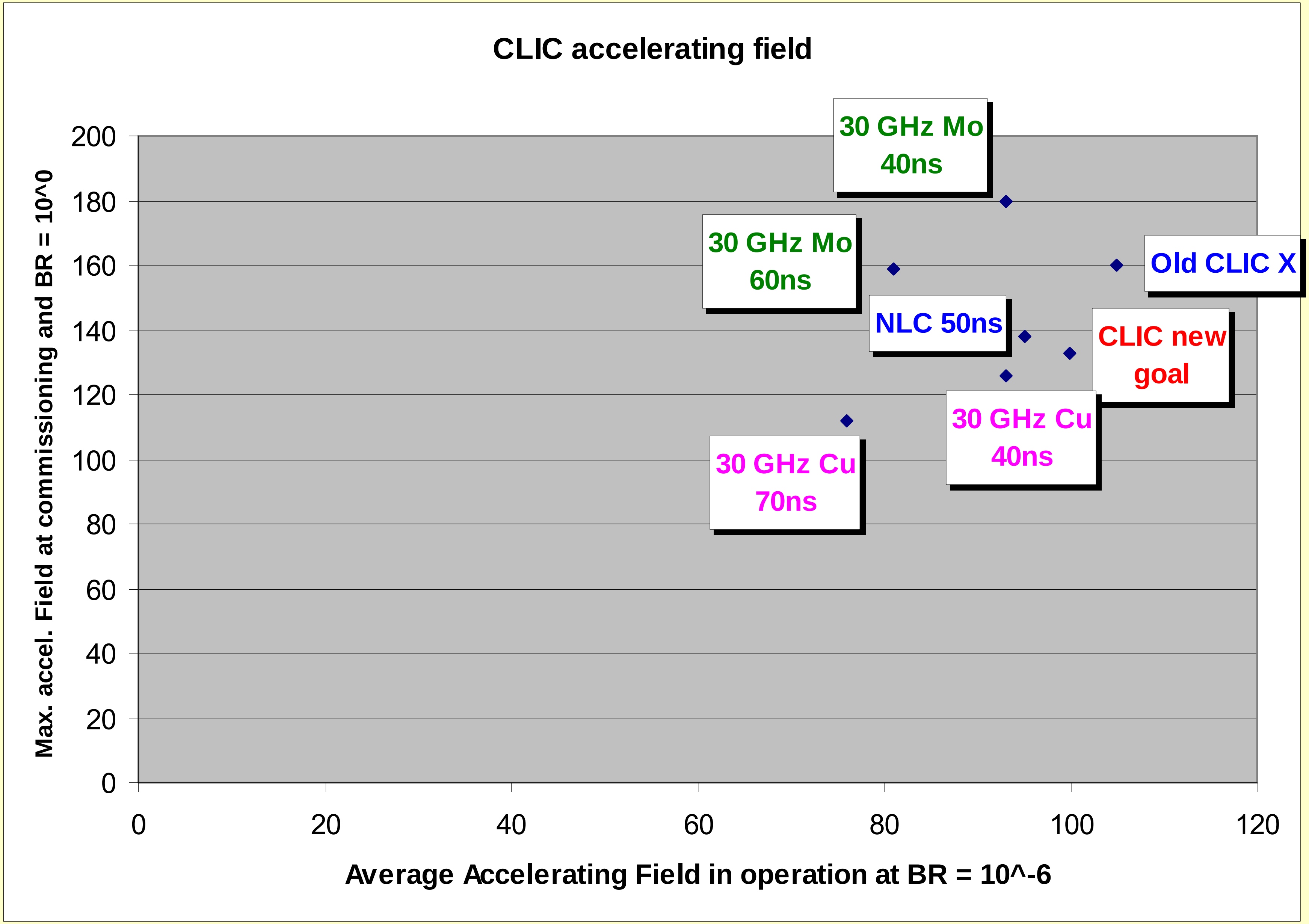
KEK

SLAC

MIT

CERN

CLIC new target



Rational

- **Favor RF frequency as low as possible close to optimum FoM & cost**
- **Limited possible tests till 2010:**
  - **at CERN: 6 structures/year * 4 years = 24 structure tested distributed between CTF2 and CLEX including accelerating structures, PETS, etc…**
    - About 12 accelerating structures at the CLEX frequency: 6 structures at 30GHz and 6 PETS
  - **At SLAC: presently 2 test per year possibly doubled**
  - **At KEK: presently zero, not guaranteed (ILC commitment, ATF2 focus)**
- **Limited resources available:**
  - **Necessary RF developments and instrumentation for each frequency**
  - **Design at the new frequency (ies)**
- **More chances of success if (too limited) resources and number of tests concentrated on one single frequency**
  - **RF scaling studied at 30 GHz in CTF2**
  - **No magic frequency**
- **Coherence between tests and design at the same (unique) frequency**

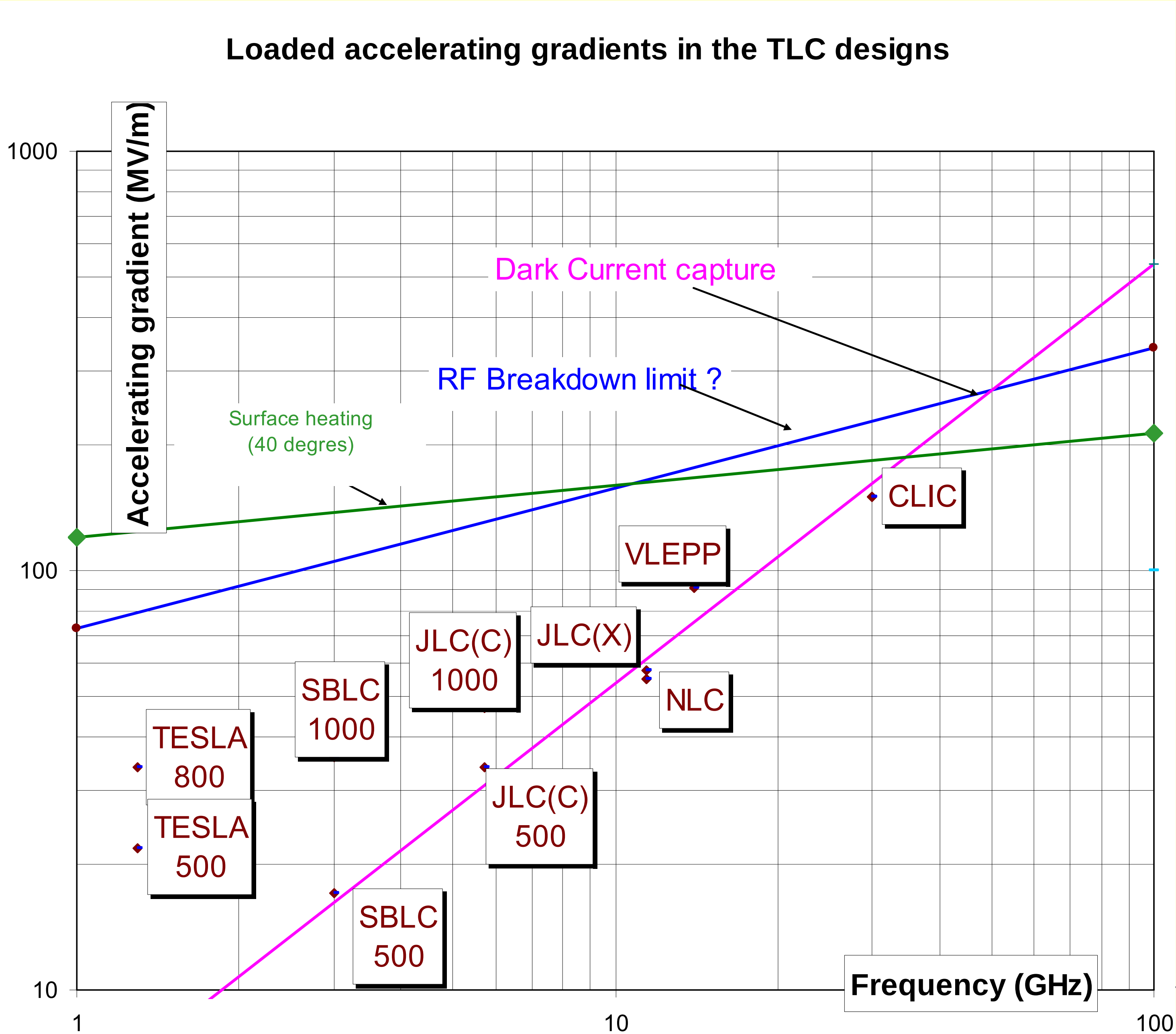
Motivation for RF frequency as low as possible

- **Close to present standards and accumulated experience (except 30 GHz at CLIC)**
- **Easier fabrication (larger tools and more solid tools)**
- **Reduced mechanical tolerances for some parts**
- **More realistic design with longer pulse length and longer structures**
- **Smaller damages and effect of breakdowns (spot dimension independent of frequency)**
- **Easier pumping and vacuum conditions**
- **Simplified instrumentation due to larger beam dimensions and lower frequency spectrum**
- **More efficient feedback due to longer pulse length**
- **Less sensitivity to time and phase stability between drive and probe beams**
- **Easier Power production (smaller multiplication in drive beam generation= one single combiner ring?, RF deflector at low frequency)**
- **Easier Stand Alone Power Source (Klystrons possibly available, No gyroklystrons need in SAPS?)**
- **……**

The beauty of 12 GHz?

- Maximum FoM and minimum cost with the present model
- Gradient nearly already demonstrated with short pulse (structure design or strong damping)
- Reasonable (still too challenging) parameters
  - structure length = 15 cm; iris diameter = 3 to 6 mm; iris thickness = 0.625mm
  - RF pulse length 150ns; Rep frequency=210 Hz (130 Hz for L=2 10^34)
- CTF3 easily adaptable: RF frequency multiplication by 4 in combiner ring (easier than 5 = nominal CTF3 and equal to nominal CLIC)
- RF power generation by PETS at first harmonic
- Various possible RF multiplications in CLIC with interesting RF freq.
  - 3*3*1.33 Ghz (with possible synergy with ILC MBK developments at 1.3 GHz)
  - Or 3*4*1.0 Ghz or 4*4*750 MHz (similar multiplication as present design)
- Stand alone power sources available: No gyroklystron necessary
  - Makes the best use of developments and equipments at SLAC and KEK
  - Possible use of power sources presently developed at 11.4 GHz at LNF and PSI for X-FEL applications
- Common and complementary study with SLAC and KEK
  - Share and distribute the work
- Possible problem of Dark current capture (threshold at 60 MV/m)?

Reminder: CLIC Gradient Specification in 1996?



Home work

- **Need to convince (ourselves) and explain (community) why higher fields than 50 mV/m (65 MV/m unloaded) at NLC could be reached at the same frequency:**
  - **Shorter pulse length: 65 MV/m/(150/400)^(1/6) = 76 MV/m**
  - **Advantage of HDS for Strong Damping**
  - **Advantage of Two Beam scheme to produce short pulses**
  - **Small iris aperture by factor 2 for reduction of RF Power flow limitation:**
    - Strong wakefields = 2^4 = 16 with beam dynamics and alignment issues
    - Compensation by lower bunch charge (4), stronger focusing (?), larger momentum spread (BNS?), tighter alignment (?)

- **Design of CLIC scheme adapted to 12 GHz and 100 MV/m**

- **Raise any possible problem?**

CLIC – NLC

	CLIC 12 GHz, 100 MV/m Alexej, 14.11.06	NLC ILC-TRC 03
Accelerating Gradient (MV/m)	100	65/50
Frequency (GHz)	12	11.4
Phase advance per cell	70	150
a/λ	0.117-0.063	0.21-0.148
Structure length (mm)	151	900
Structure input power (MW)	42	75
Pulse length (ns)	145	400
P/C x $T^{1/3}$ (MW/m $s^{1/3}$)	12	15.9
Bunch charge (e_0)	2.78×10^9	7.5×10^9
Bunch separation (rf cycles)	5	16
Beam current (A)	1.07	0.86
Bunches per train	146	192
RF to beam efficiency %	16	31.5
Rep. rate (Hz)	210	120
No. Klystrons per TeV (E_{CMS})	77	8256
Average power per klystron (kW)	780	14.4
σ_z (μm)	52 0r 71 ?	110
β_X^* / β_Y^* (mm)	7 / 0.09 ?	13 / 0.11
$\varepsilon_X^* / \varepsilon_Y^*$ (nm)	660 / 10	3600 / 40

CLIC MAIN PARAMETERS

- **Accelerating Gradient**
  - **What gradient could reasonably be demonstrated by 2010 ?** **100 MV/m**
    - **What should be the nominal CLIC gradient ?** **100 MV/m**
- **RF Frequency**
  - **What should be the CLIC nominal RF frequency ?**

    12 GHz
  - **What should be the RF frequency of the RF components in CLEX ?**

    12 GHz

Conclusion

- **Reduction of field to 100 MV/m**
  - with realistic chances of demonstration before 2010
  - Attractive enough in terms of performances and cost.
- **Limitation surface field and temperature rise not anymore an issue:**
  - Review design to address RF power flow limitation
  - Are short pulses and strong damping still necessary?
  - Explore new RF design (large phase advance and new ideas)
  - Dark current capture issues?
- **Focus on 12 GHz in CLIC and CLEX with complementary program at SLAC and KEK (additional tests at PSI and LNF)**
- **Review consequences on CTF3 and work programme**
  - Pursue 30 GHz in CTF2 with Drive Beam Linac
  - Develop RF components at 12 GHz
  - CTF3 Adaptation to new multiplication factor and RF (beam) pulse length
  - no RF power source at CERN at the nominal frequency before late 2008
- **Re-design of the CLIC complex adapted to 100 MV/m and 12 GHz**
  - New parameters (before?) the end of the year 07
  - (new) parameter working group
- **Approved by the CERN management and CLIC Physics coordinators**