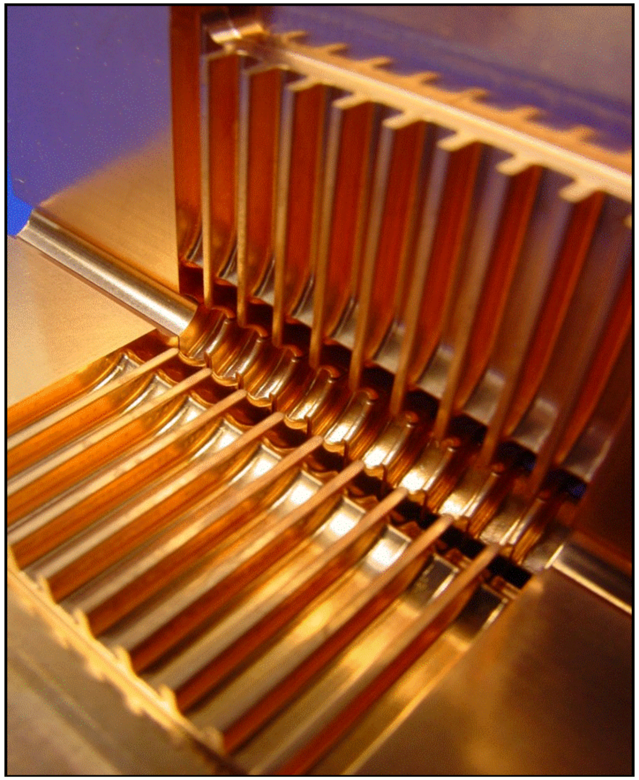
Room temperature RF and CLIC

Frank Tecker – CERN

- Introduction
- Room temperature RF cavities
- CLIC (Compact Linear Collider)
- CTF3 (CLIC Test Facility)

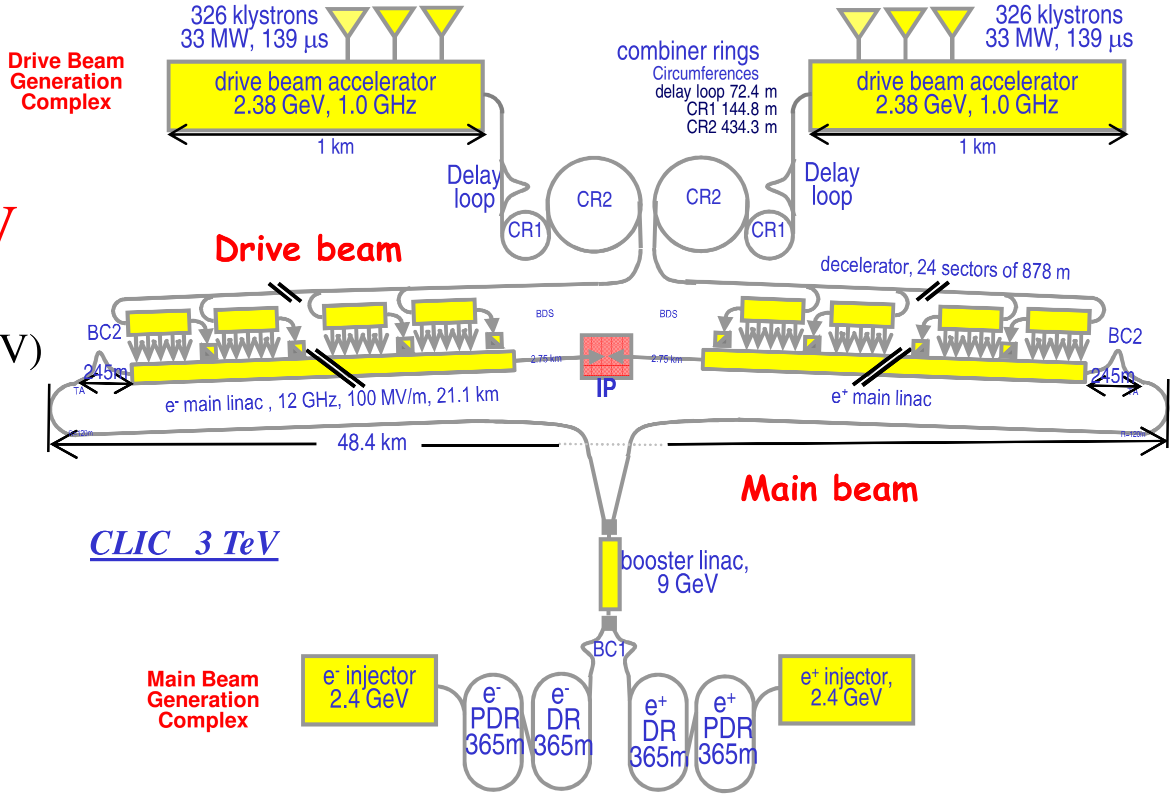


Preface

- Complex topic
- Approach:
  - Explain the fundamental effects and principles that leads to differences between SuperConducting (SC) and normal conducting (NC) technology
  - I will not go much into technical details
  - Try to avoid formulae as much as possible
- Goal: You understand
  - Basic principles
  - The driving forces and limitations in NC linear collider design
  - The basic building blocks of CLIC
- Ask questions at any time! Any comment is useful! (e-mail: tecker@cern.ch)

CLIC – in a nutshell

- Compact LInear Collider
- e+/e- collider for up to 3 TeV
- Luminosity $6 \cdot 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (3 TeV)
- Normal conducting
  RF accelerating structures
- Gradient 100 MV/m
- RF frequency 12 GHz
- Two beam acceleration principle
  for cost minimisation and efficiency
- Many common points with ILC, similar elements,
  but different parameters



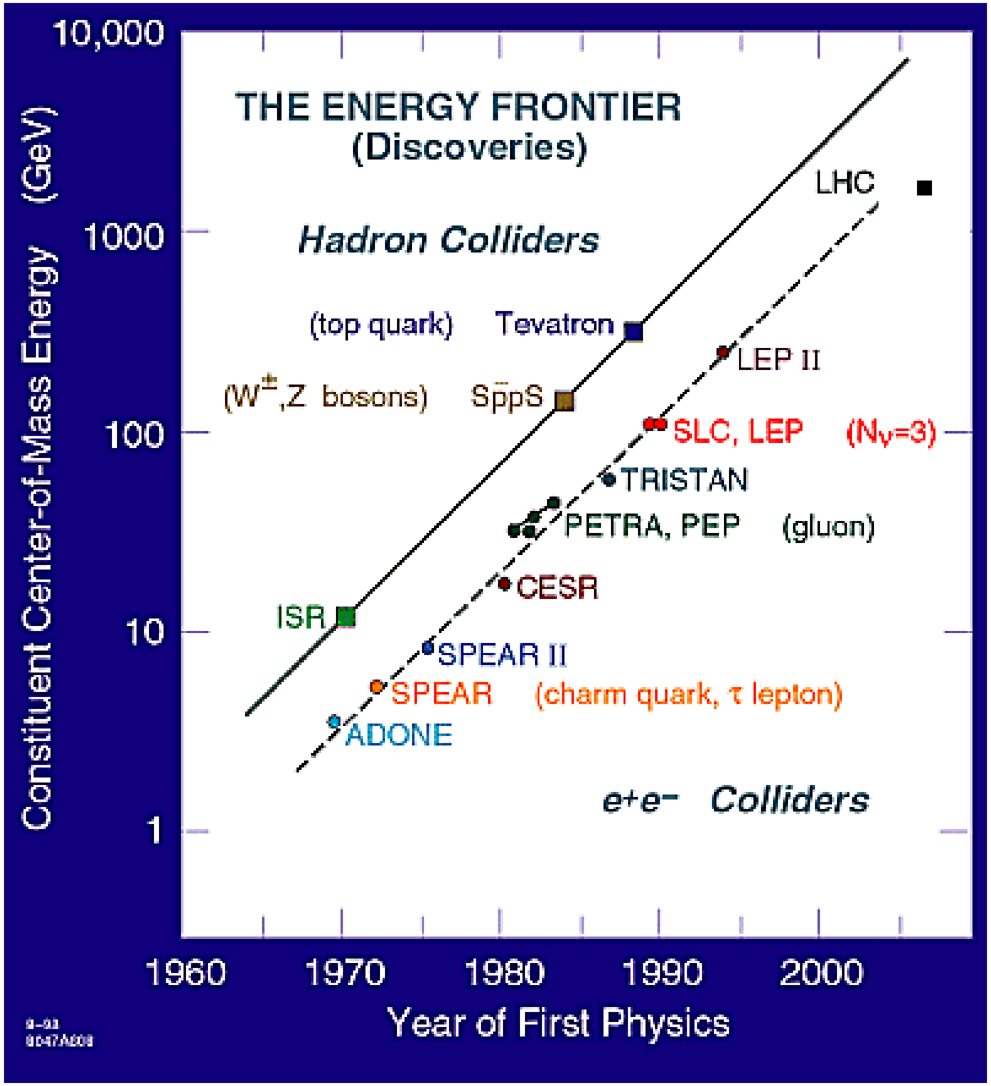
Lecture 1 (this morning)

- ‘warm’ RF technology basics:
  - A linear collider at higher energy
  - Normal conducting RF structures
    - Gradient limits
    - Pulsed surface heating and Fatigue
    - Breakdown mechanism and phenomenology
  - Frequency choice
  - Wakefields and damping
  - RF power manipulation options
  - Pulse train formats
  - Differences ‘warm’ and ‘SC’ RF collider

Lecture 2 (this afternoon)

- CLIC scheme and CTF3:
  - CLIC layout at different energies
  - CLIC two-beam acceleration scheme
  - CLIC drive beam generation
    - Bunch train combination
    - Fully loaded acceleration
  - Demonstrations at the CLIC Test Facility CTF3
  - RF power production
  - CLIC main beam generation and dynamics
  - CLIC damping rings
  - CLIC alignment and stability

Path to higher energy



- History:
  - Energy constantly increasing with time
  - Hadron Collider at the energy frontier
  - Lepton Collider for precision physics

- LHC coming online now
- Consensus to build Lin. Collider with $E_{cm} > 500$ GeV to complement LHC physics (*European strategy for particle physics* by CERN Council)

TeV e+e- physics

- Higgs physics
  - Tevatron/LHC should discover Higgs (or something else)
  - LC explore its properties in detail
- Supersymmetry
  - LC will complement the LHC particle spectrum
- Extra spatial dimensions
- New strong interactions
- . . .

=> a lot of new territory to discover
beyond the standard model

- Energy can be crucial for discovery!

- “Physics at the CLIC Multi-TeV Linear Collider”
CERN-2004-005
- “ILC Reference Design Report – Vol.2 – Physics at the ILC”
www.linearcollider.org/rdr

CERN-2004-005
10 June 2004
Physics Department

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
CERN-EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS AT THE CLIC MULTI-TeV
LINEAR COLLIDER

CLIC

Editors:
M. Battaglia
A. De Roeck
J. Ellis
D. Schulte
GENEVA 2004

Report of the CLIC Physics Working Group

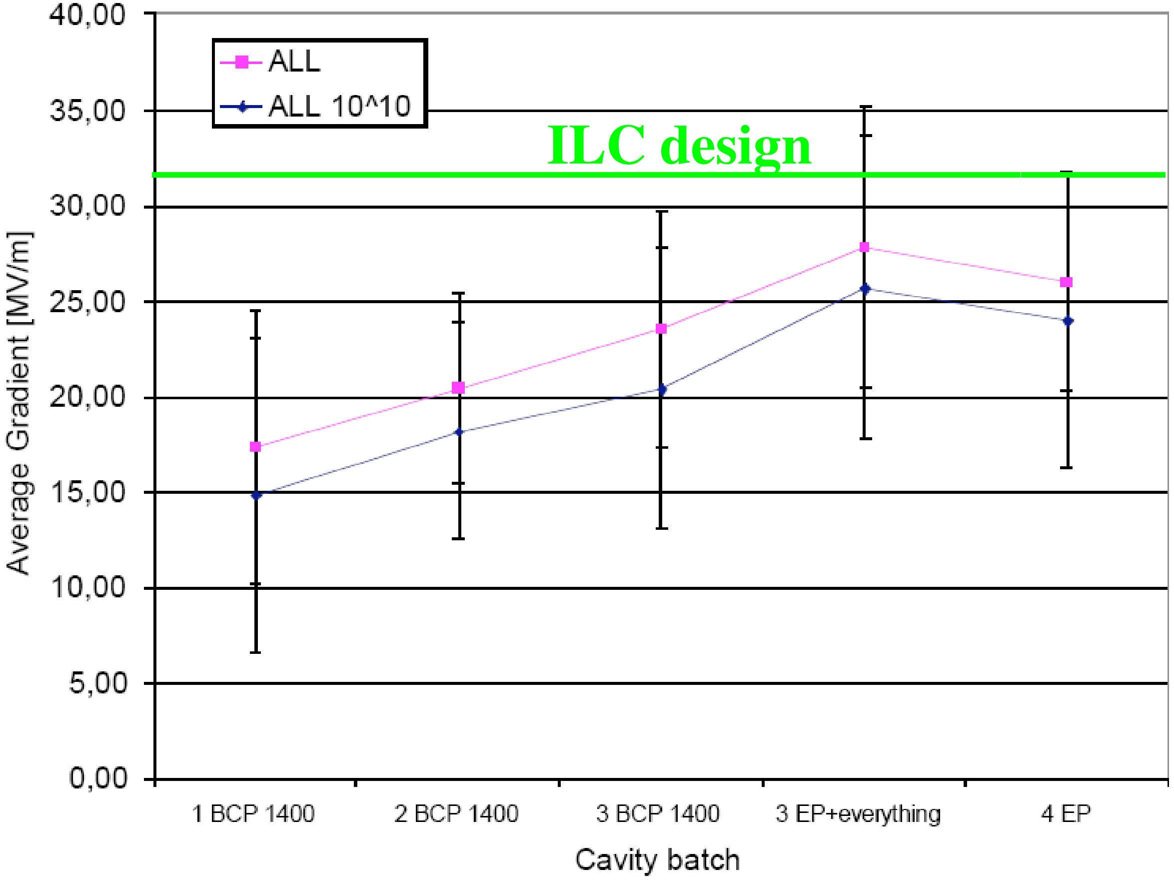
Reference Design Report
Physics at the ILC

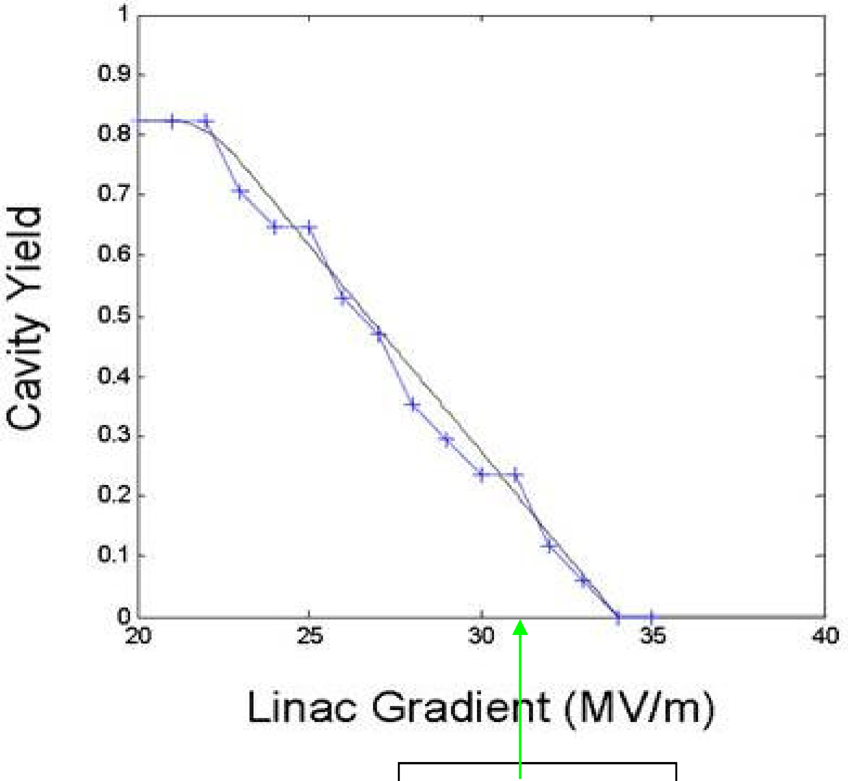
Linear Colliders - Energy

- Historical background: 2004 – ILC-TRC review
  - Evaluation of linear collider (LC) projects (NLC/JLC, TESLA and CLIC)
  - Decision for Superconducting Accelerator Technology for LC with $E_{cm} = 0.5\text{-}1$ TeV
- Consequences:
  - End of competition between normal conducting and SC schemes
  - Concentration of R&D on superconducting ILC scheme

- What about if interesting physics needs $E_{cm} \gg 0.5\text{-}1$ TeV ???
  LHC results will determine the required energy!
  - LC size has to be kept reasonable (<50km?)
    gradient >100MV/m needed for $E_{cm} = 5$ TeV
  - SC technology excluded, fundamental limit ~60 MV/m
  - Normal conducting RF structures, but not trivial either!
  - CLIC study for multi-TeV linear collider

Achieved SC accelerating gradients





ILC design

With the presently available technology average 28 MV/m:

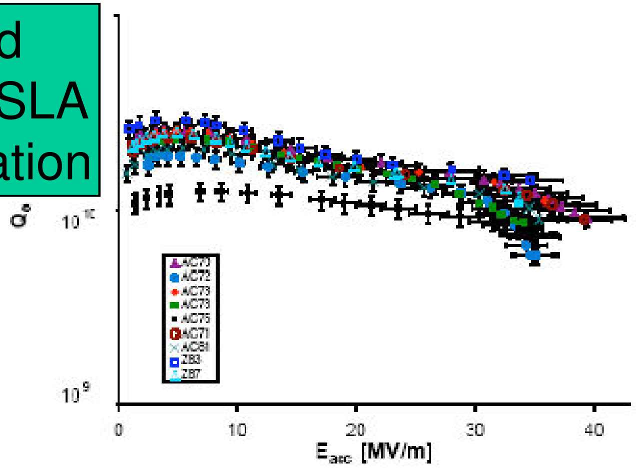
Cost increase ~7 %

B. Foster

R&D of SC RF cavities

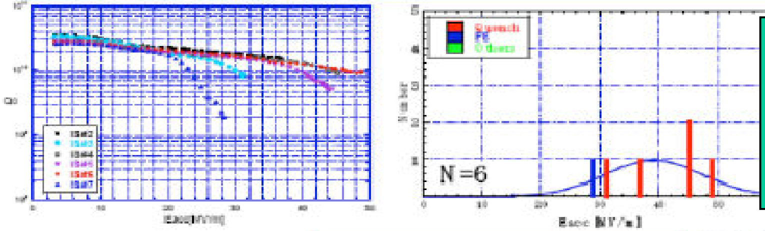
Derived From TESLA Collaboration

TESLA Nine-Cells: (Proof-of-Principle)
Best tests of 9 best Cavities (Vertical Test Results)



(A) CBP+CP+Anneal+EP(80μm) +HPR+Baking(120C*48hrs)

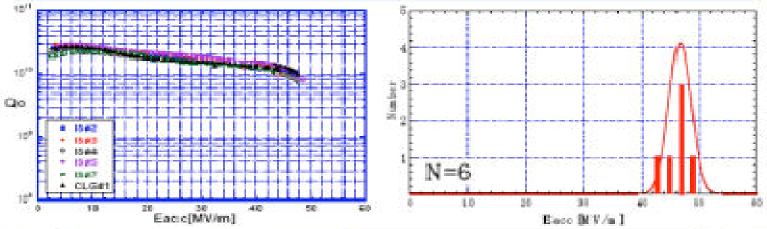
K. Saito et al.



New preparation techniques

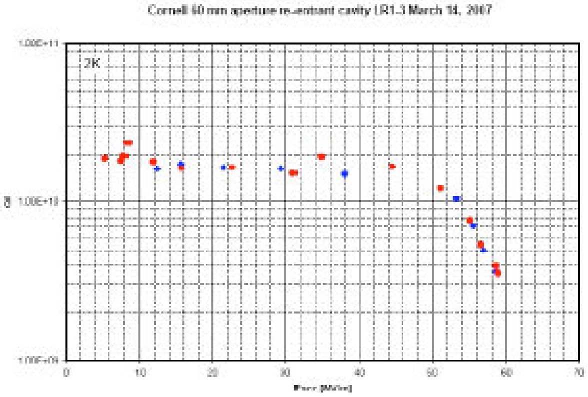
(D) +EP(20μm)+EP(3μm, fresh, closed) +HPR+Baking (120C*48hrs)

K. Saito et al.



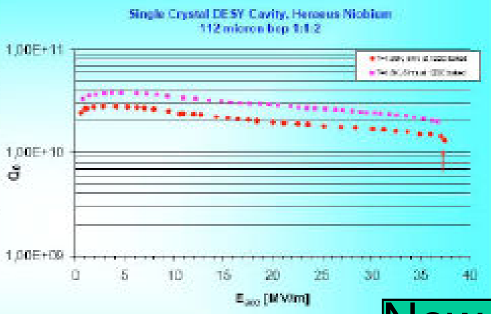
60mm-Aperture Re-Entrant Cavity, 58 MV/m!

KEK/Cornell Collaboration



New cavity shapes

DESY single crystal cavity 1AC8 build from Hereeus disc by rolling at RWTH, deep drawing and EB welding at ACCEL



Q(Eacc) curve after only 112 μ
and in situ baking 120°C for

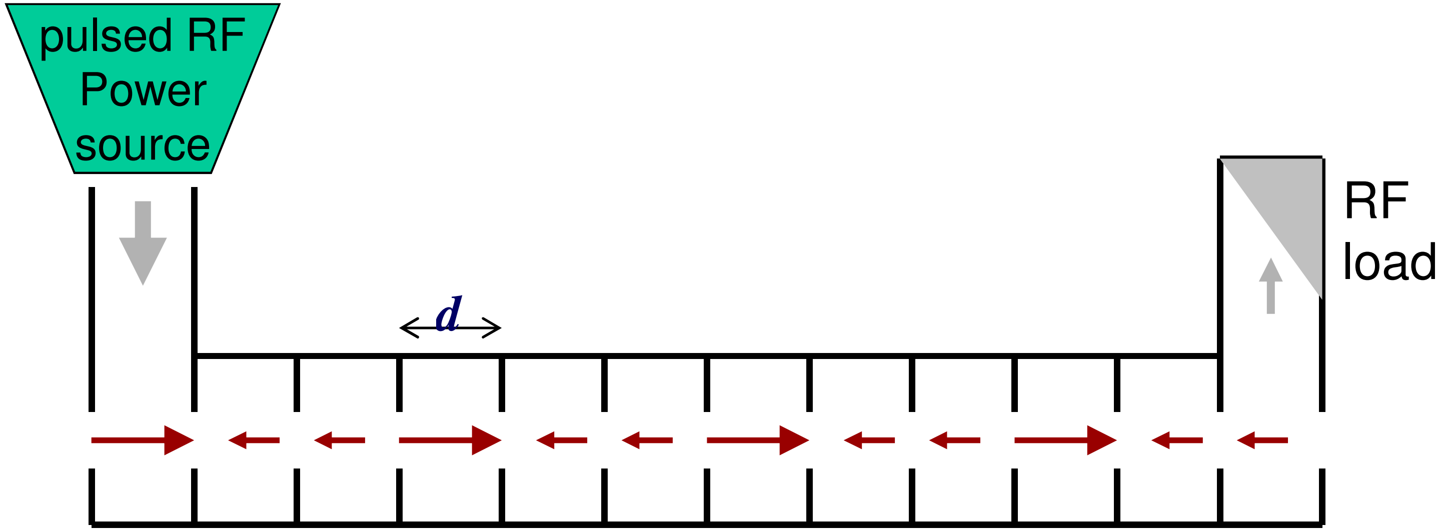
Preparation and RF tests
P.Kneisel, JLab

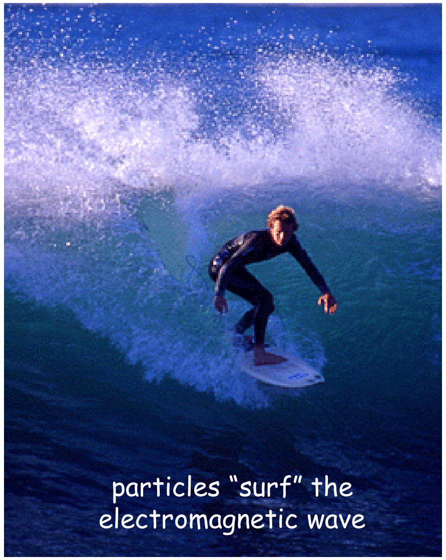
W. Singer. Single Crystal Nb Technology Workshop, CBMM. Brazil. Oct. 30-Nov. 1, 20

New material
Large grains
Higher perf
Lower cost

Traveling wave structures

- NC standing wave structures would have high Ohmic losses
- => traveling wave structures





- RF 'flows' with group velocity v_G along the structure into a load at the structure exit
- Condition for acceleration: $\Delta\varphi = d \cdot \omega / c$ ($\Delta\varphi$ cell phase difference)
- Shorter fill time $T_{fill} = \int 1/v_G \, dz$ - order <100 ns compared to ~ms for SC RF

Normal conducting structures

- Higher gradients reachable with normal conducting structures

- But! Compare to advantages of SC RF cavities:
  - Very low losses due to tiny surface resistance
  - High efficiency
  - Long pulse trains possible
  - Favourable for feed-backs within the pulse train
  - Standing wave cavities with low peak power requirements
  - Lower frequency => Large dimensions and lower wakefields

- => Important implications for the design of the collider

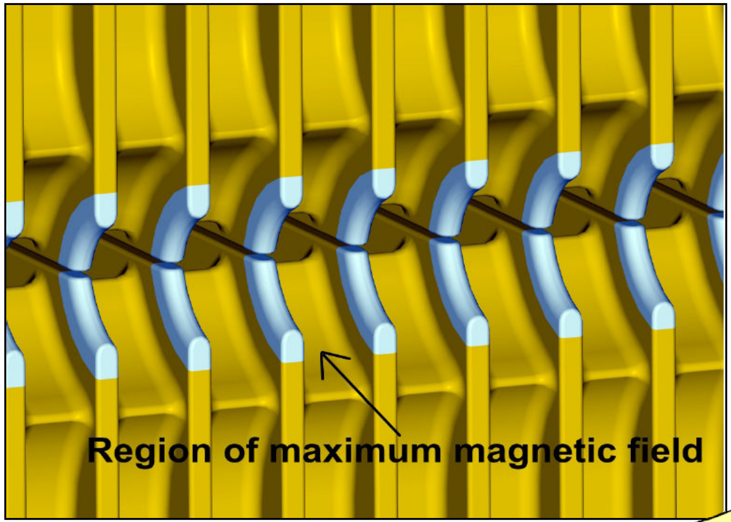
RF efficiency: cavities

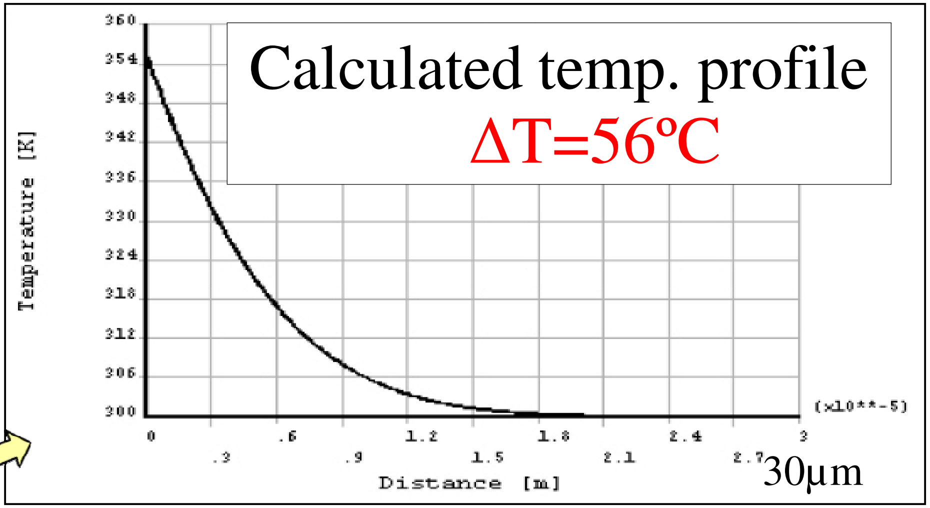
- Fields established after cavity filling time (not useful for beam)
- Steady state: power to
  beam, cavity losses, and (for TW) output coupler
- Efficiency: $$\eta_{RF\rightarrow beam} = \underbrace{\frac{P_{beam}}{P_{beam}+P_{loss}+P_{out}}}_{\approx 1 \text{ for SC SW cavities}} \frac{T_{beam}}{T_{fill}+T_{beam}}$$
- => long pulse length favoured
- NC TW cavities have smaller filling time T_{fill}
  => Second term is higher for NC RF
- Typical values SC: $\eta = 0.6$
  NC: $\eta = 0.3$

Limitations of Gradient E_{acc}

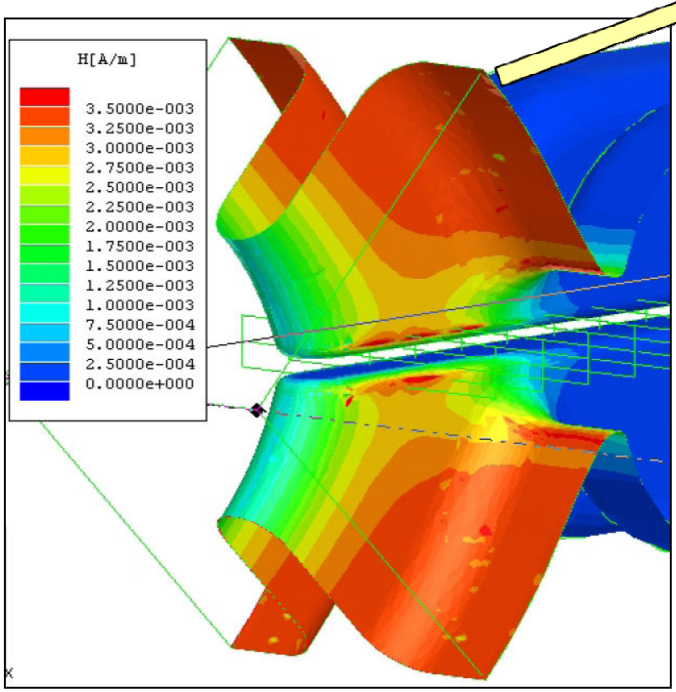
- Surface magnetic field
  - Pulsed surface heating ⇒ material fatigue ⇒ cracks
- Field emission due to surface electric field
  - RF break downs
  - Break down rate ⇒ Operation efficiency
  - Local plasma triggered by field emission ⇒ Erosion of surface
  - Dark current capture
    ⇒ Efficiency reduction, activation, detector backgrounds
- RF power flow
  - RF power flow and/or iris aperture apparently have a strong impact on achievable E_{acc} and on surface erosion. Mechanism not fully understood

Pulsed surface heating - Fatigue





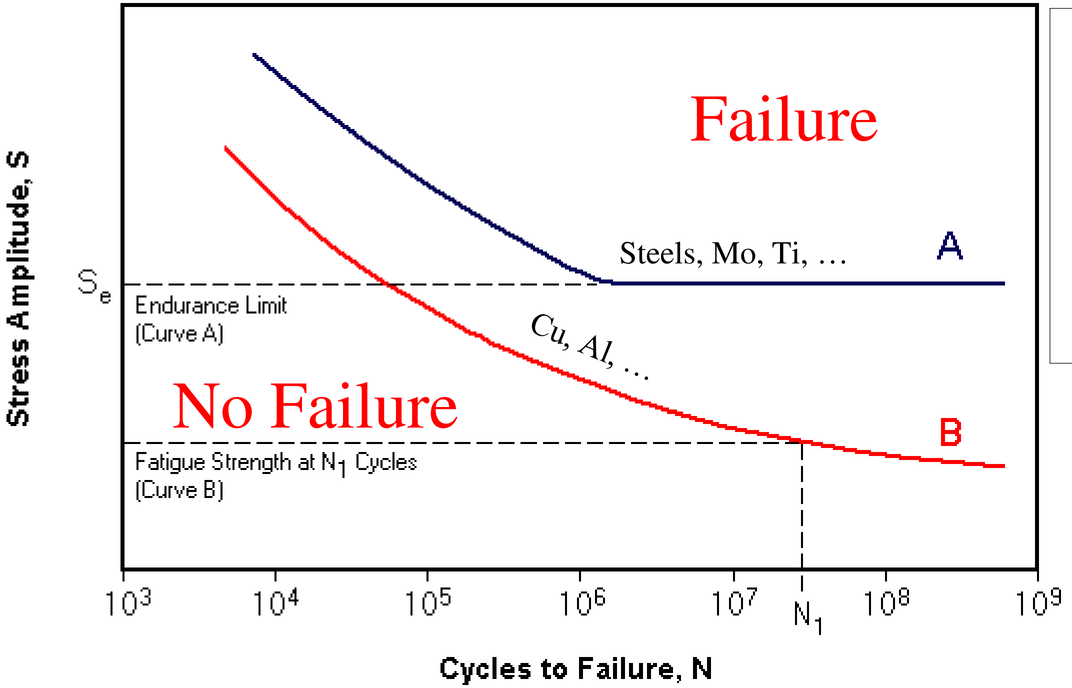
Calculated temp. profile
ΔT=56ºC



Cyclic compressive stresses

- Magnetic RF field heats up cavity wall
- Extension causes compressive stress
- Can lead to fatigue

Fatigue curves



H_{peak}

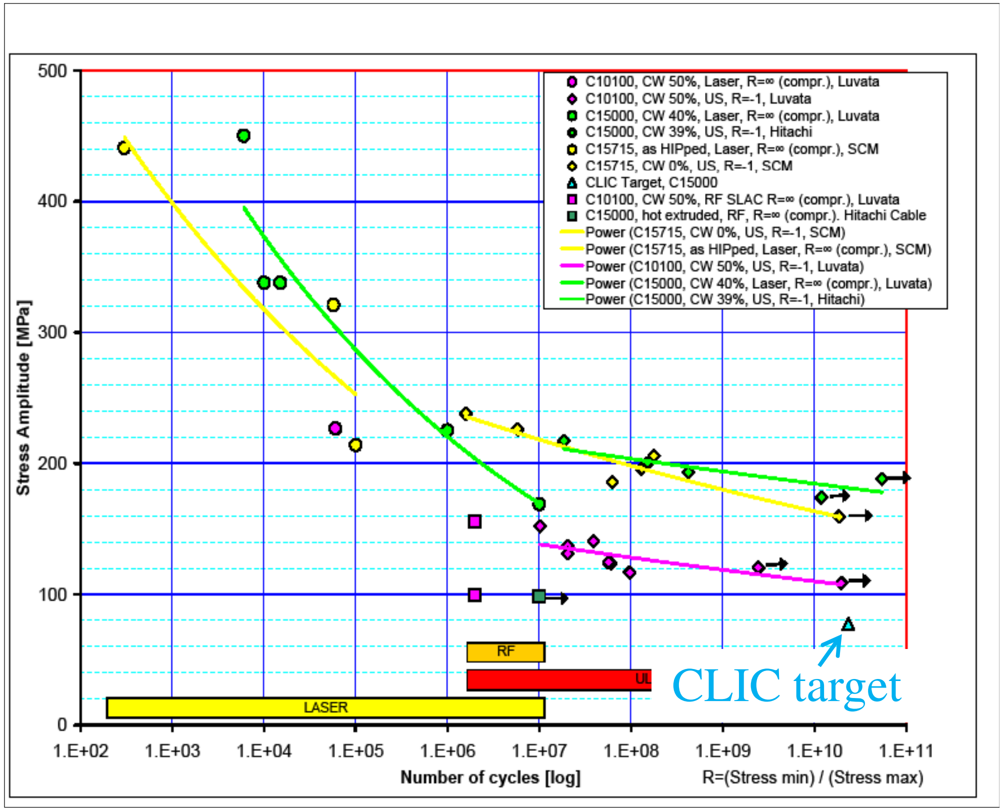
↕

ΔT

↕

σ

Candidates: Cu-OFE (C10100), CuZr (C15000), GlidCop Al-15



- High number of cycles limits to smaller stresses
- 20 years operation => ~10^{10} cycles!
- Limits maximum ΔT and peak magnetic field

Pulsed surface heating

- Pulsed surface heating proportional to
  - Square root of pulse length
  - Square of peak magnetic field
- Field reduced only by geometry, but high field needed for high gradient
- Limits the maximum pulse length => short pulses (~few 100ns)

$$\Delta T = \sqrt{\frac{\mu_0}{2\pi}\frac{\omega \boxed{t_P}}{\sigma\,\lambda\,\rho\,c_H}}\,\hat{H}^2$$

Numerical values for copper

$$\Delta T \approx 4\cdot 10^{-17}\left[\frac{\mathrm{K\,m}^2}{\mathrm{V}^2}\right]\sqrt{t_P\,f}\;E_{acc}^2$$

$$\Delta T_{\max} \approx 50\ \mathrm{K}$$

$$t_P < \left(\frac{\Delta T_{\max}}{4\cdot 10^{-17}}\right)^2 \frac{1}{f\,E_{acc}^4}$$

ΔT	temperature rise,	σ	electric conductivity
λ	heat conductivity,	ρ	mass density
c_H	specific heat,	t_P	pulse length
$\hat{H}$	peak magnetic field		

$$\hat{H} = \frac{g_H}{377\,\Omega}E_{acc}$$

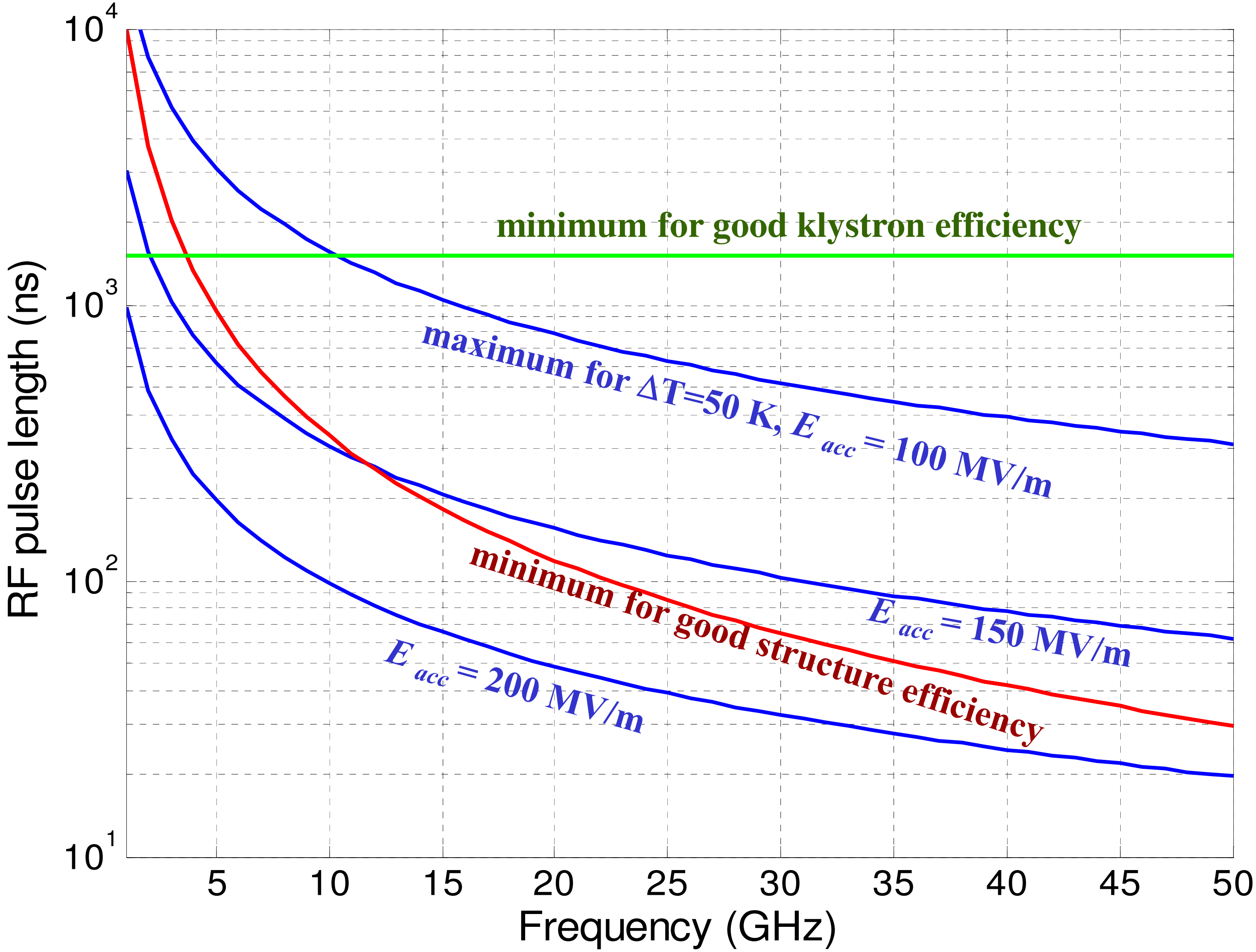
g_H geometry factor of structure design

typical value $g_H \approx 1.2$

=> see homework

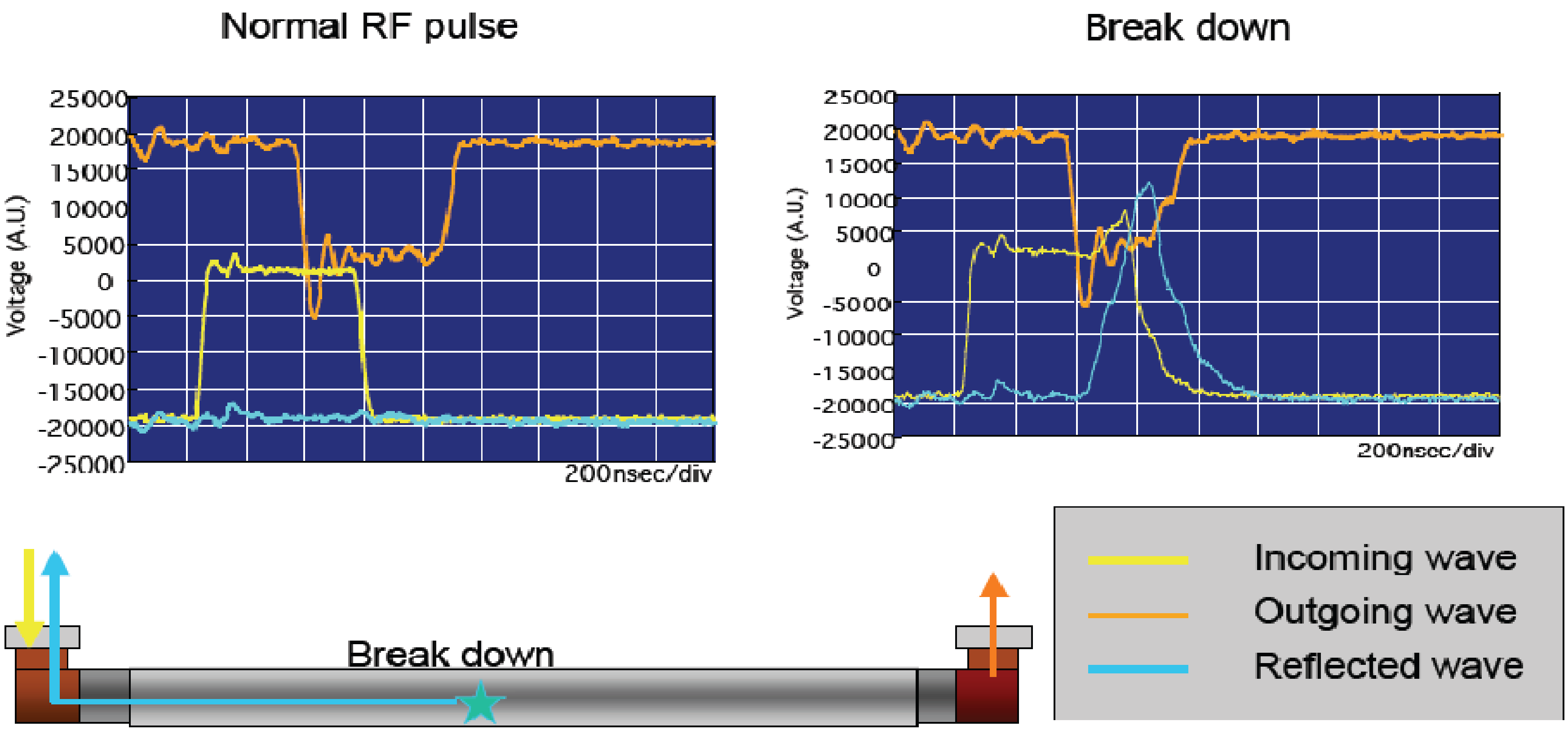
Frequency scaling of RF pulse length limits

(for a typical accelerating structure geometry)



Hans Braun

Breakdowns - RF wave form



from S.Fukuda/KEK

- Pulses with breakdowns not useful for acceleration
- Low breakdown rate needed

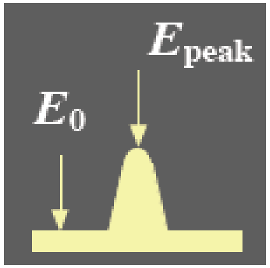
=> see homework

Phenomenology of RF breakdowns

- Breakdown events characterised by
  - always
    - disappearance of transmitted power
    - reflection of incident power
    - emission of intense bursts of fast electrons (E_{Kin}~100 keV)
    - acoustic shock wave (can be detected with accelerometer)
    - build up time ~ 20 ns
  - often
    - fast rise of gas pressure
    - emission of visible and UV light,
      light pulse longer than incident RF pulse (~ few ms)
    - emission of positive ions (E_{Kin}~few 100 eV),
      pulse longer than incident RF pulse (~ few ms)
- usually no precursor signals !

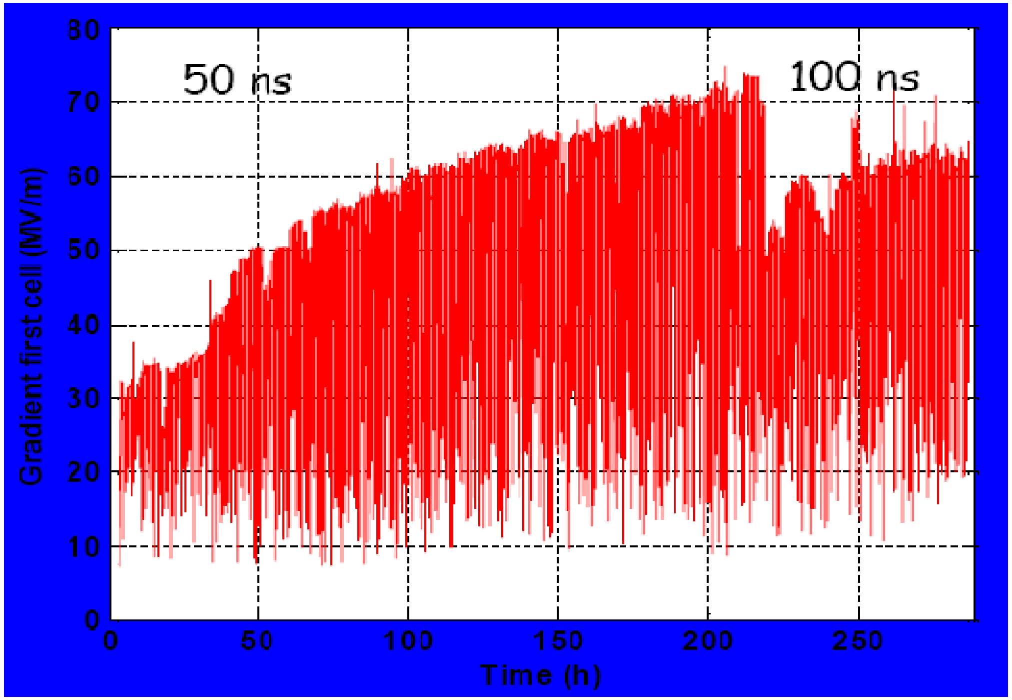
Structure conditioning

- Material surface has some intrinsic roughness (from machining)
- Leads to field enhancement $E_{\text{peak}} = \beta E_0$
  β field enhancement factor



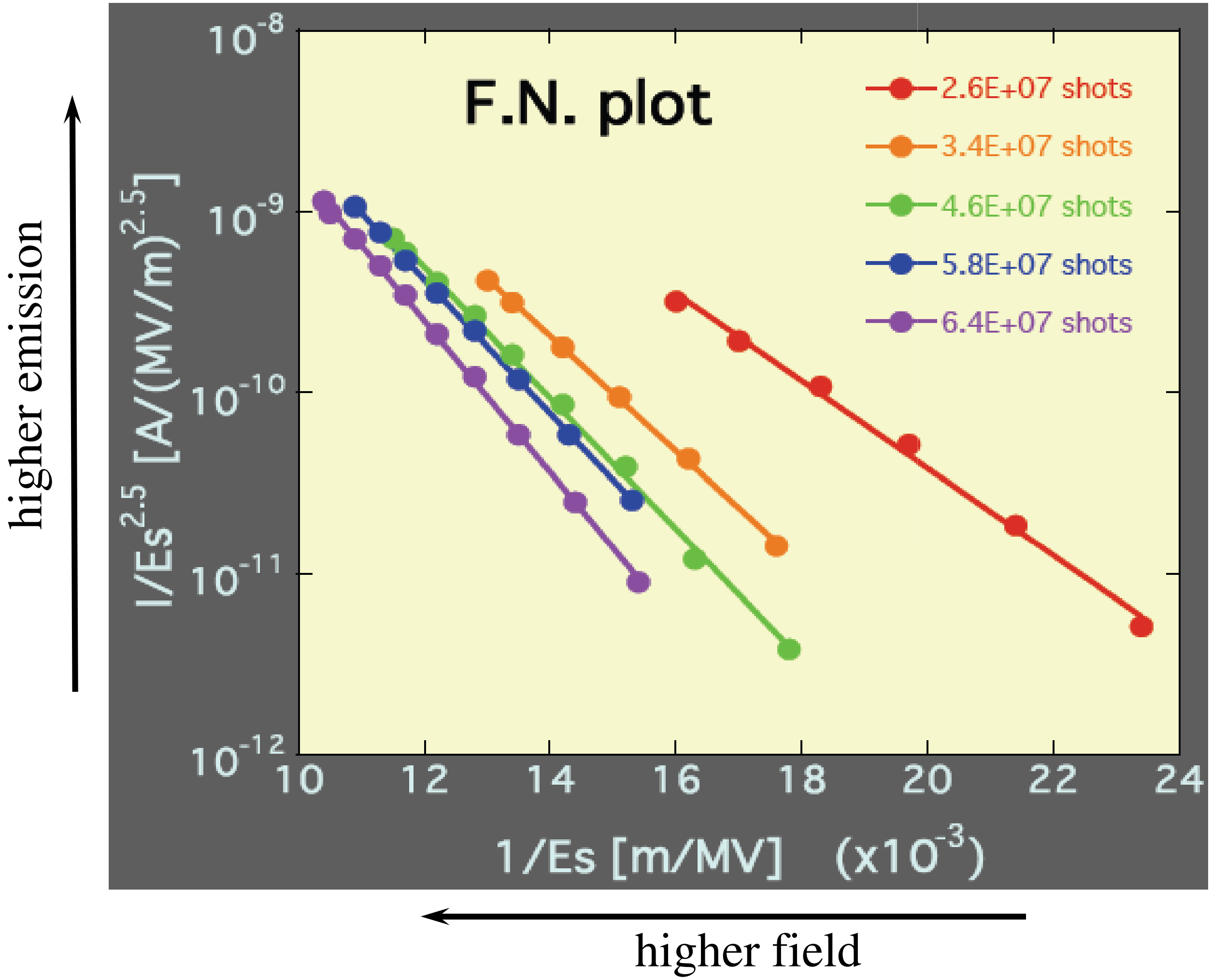
- Need conditioning to reach ultimate gradient
  RF power gradually increased with time

from S.Doebert



- RF processing can melt
  field emission points
  - Surface becomes smoother
  - field enhancement reduced
  - ⇒ higher fields
    less breakdowns

Improvement by conditioning



Fowler Nordheim law of field emission

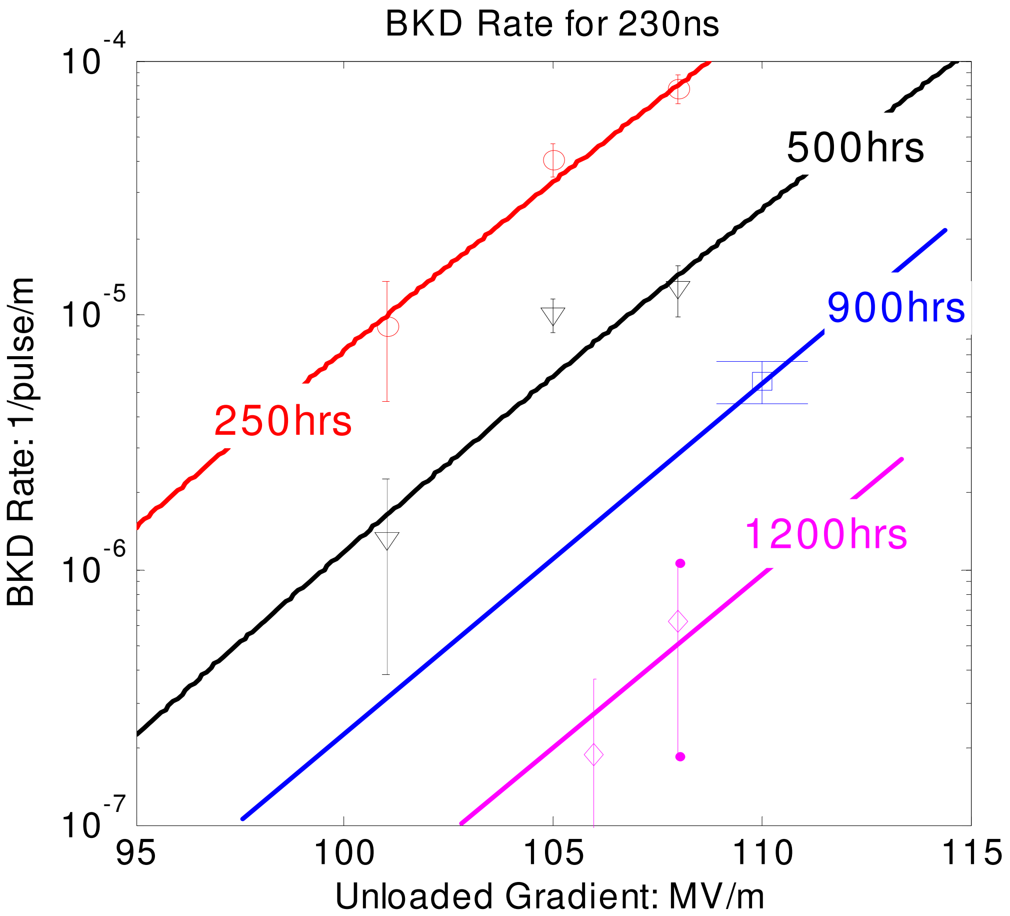
$$j_{FN} \propto \frac{E_{peak}^{\;2}}{\phi} e^{\frac{-k\phi^{1.5}}{E_{peak}}}$$

ϕ work function

from S.Yamaguchi

- Higher fields reachable
- Lower breakdown rate at a given field

BD Rate at Different Conditioning Time

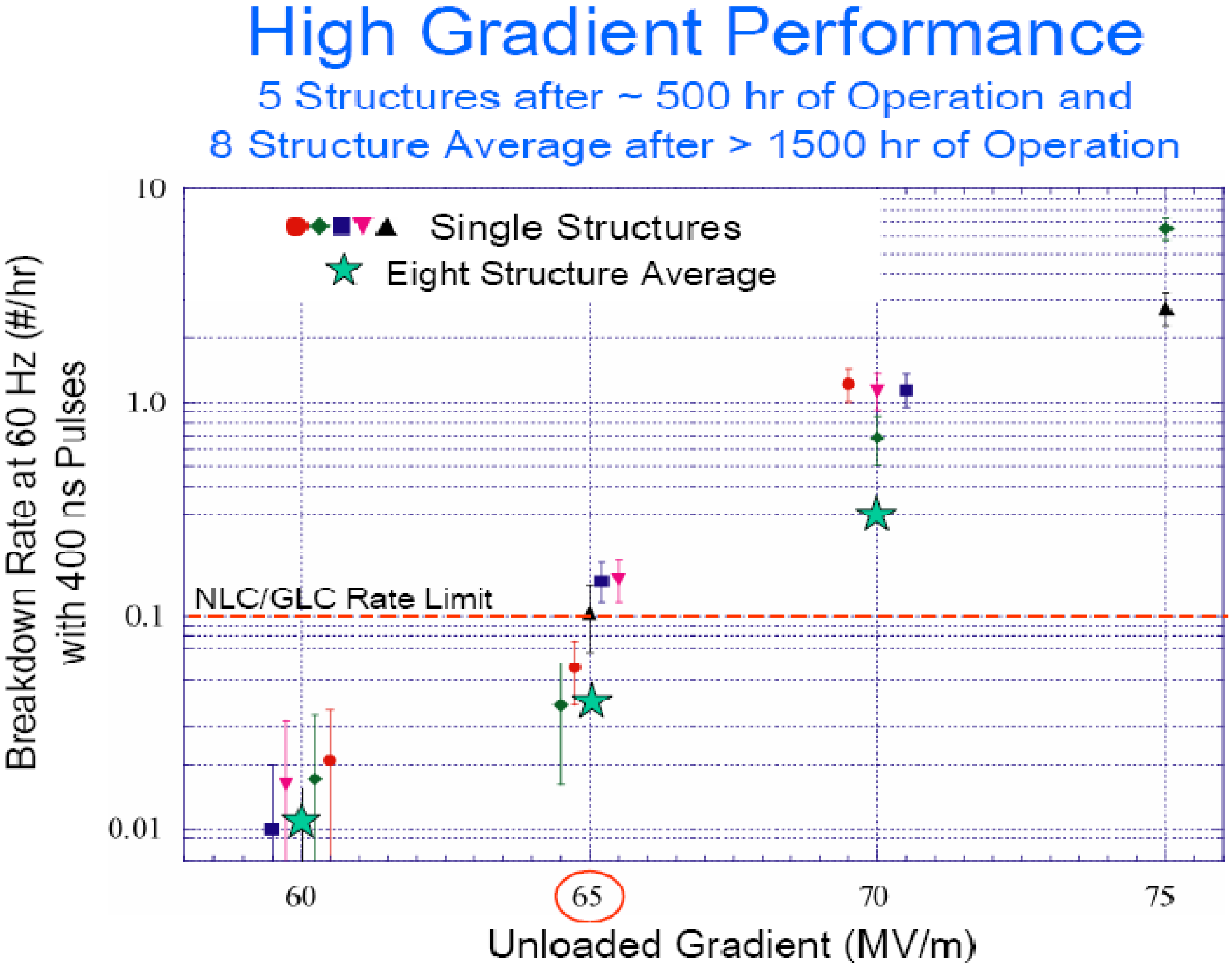


- After conditioning:
  - Higher fields reachable for constant BDR
  - Lower breakdown rate at a given field

Faya Wang

Breakdown-rate vs gradient

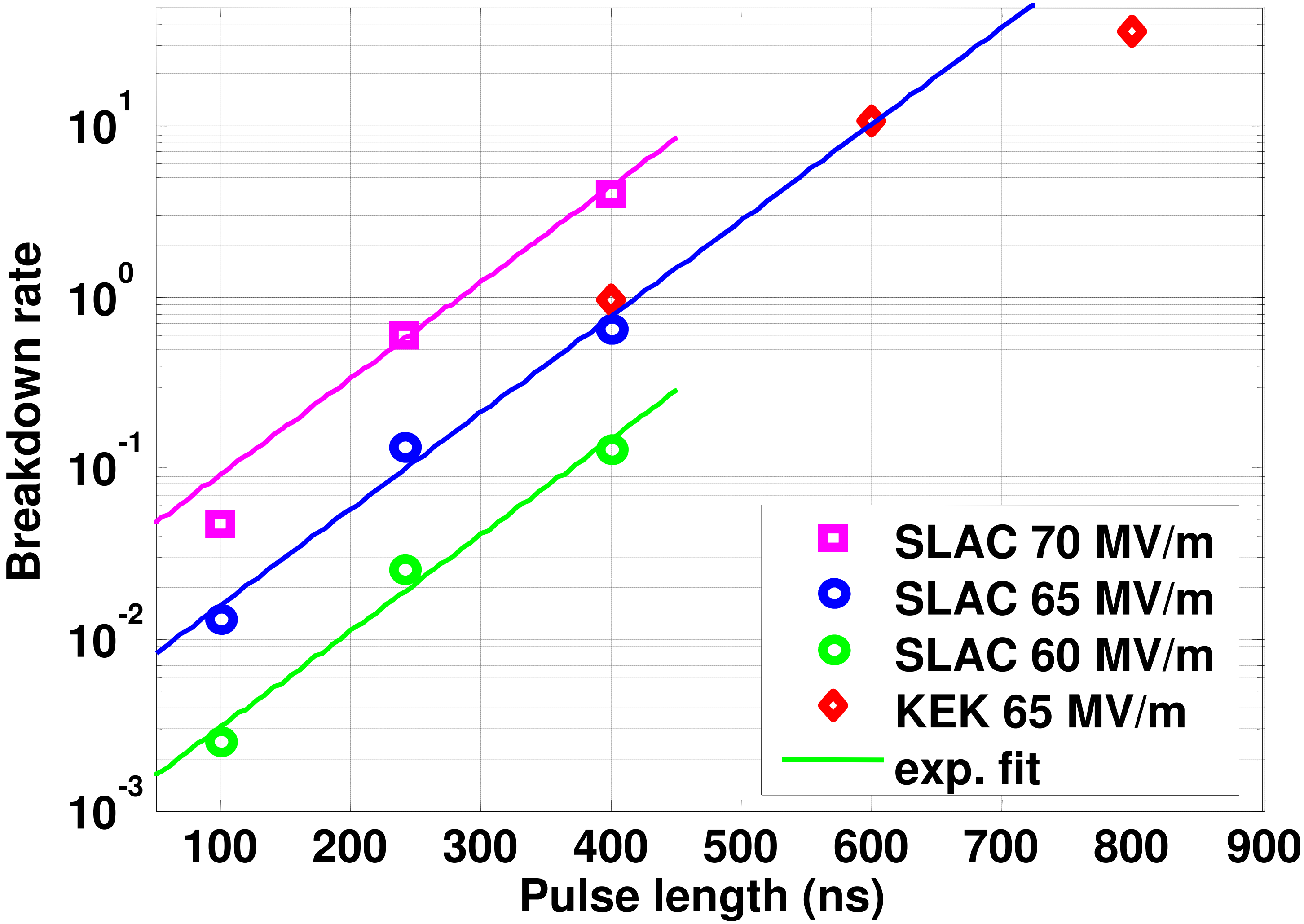
- Higher breakdown rate for higher gradient



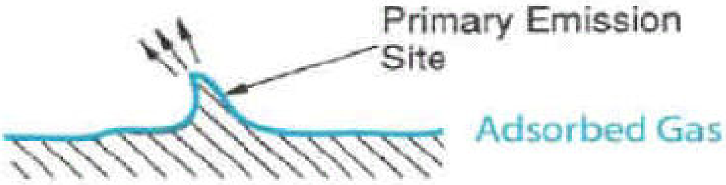
C. Adolphsen /SLAC

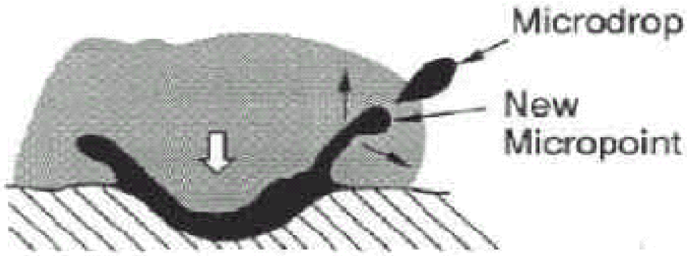
Breakdown-rate vs pulse length

- Higher breakdown rate for longer pulses

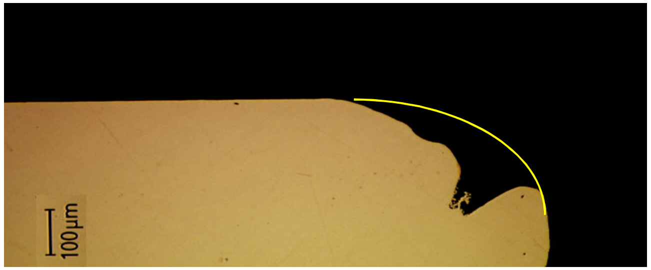


Conditioning limits

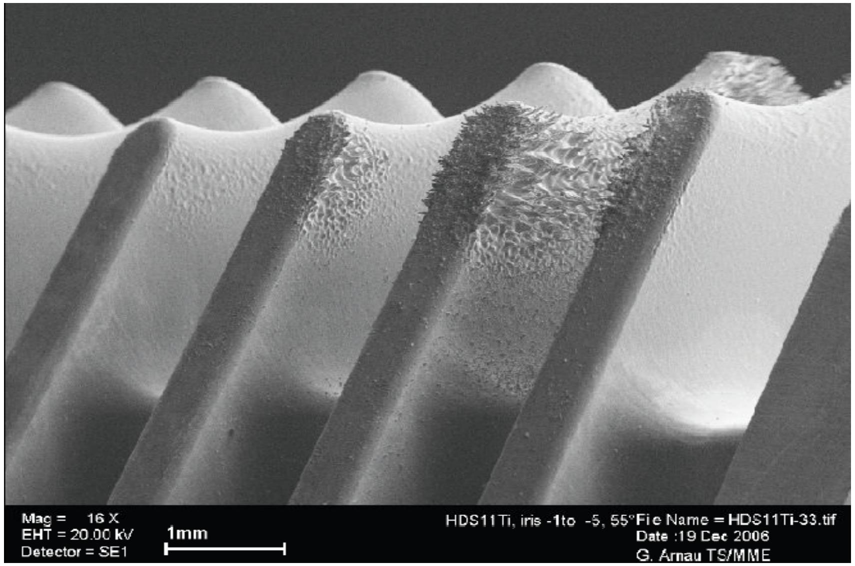




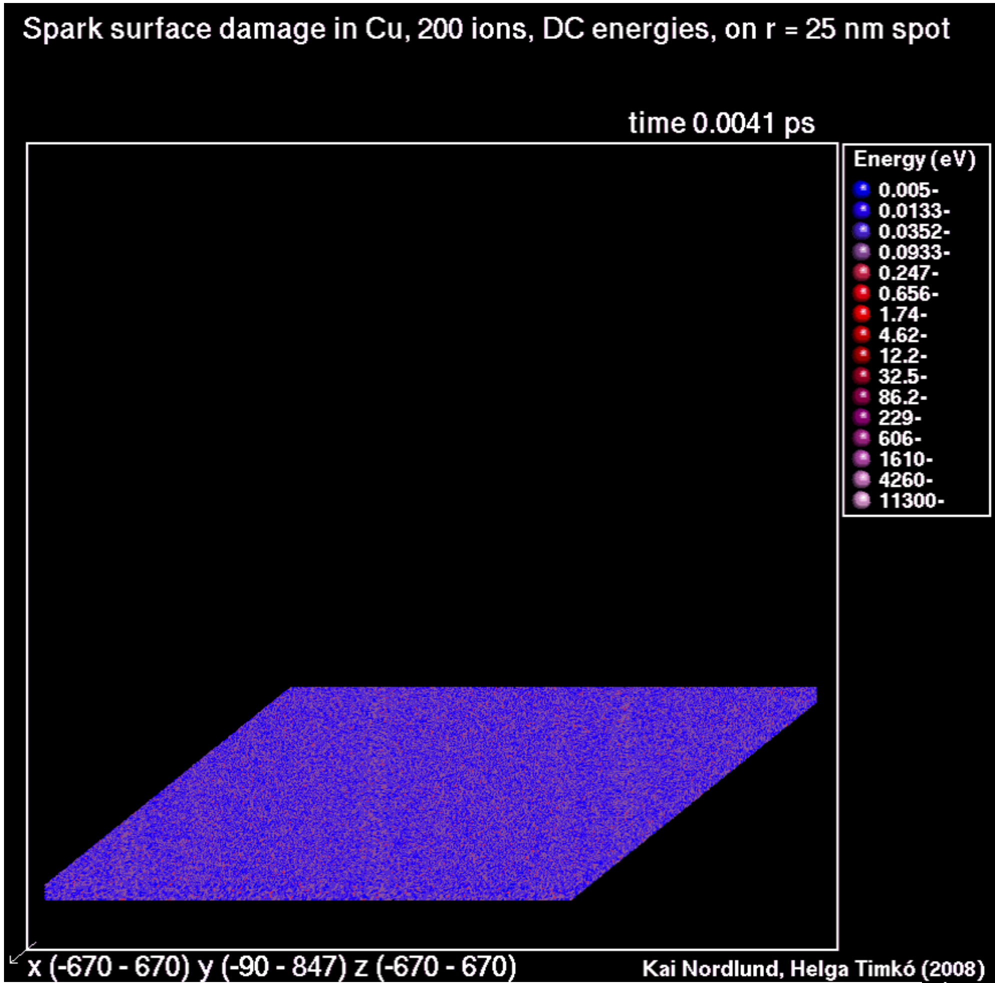
- More energy: electrons generate plasma and melt surface
- Molten surface splatters and generates new field emission points!
  ⇒ limits the achievable field
- Excessive fields can also damage the structures
- Design structures with low E_{surf}/E_{acc}
- Study new materials (Mo, W)



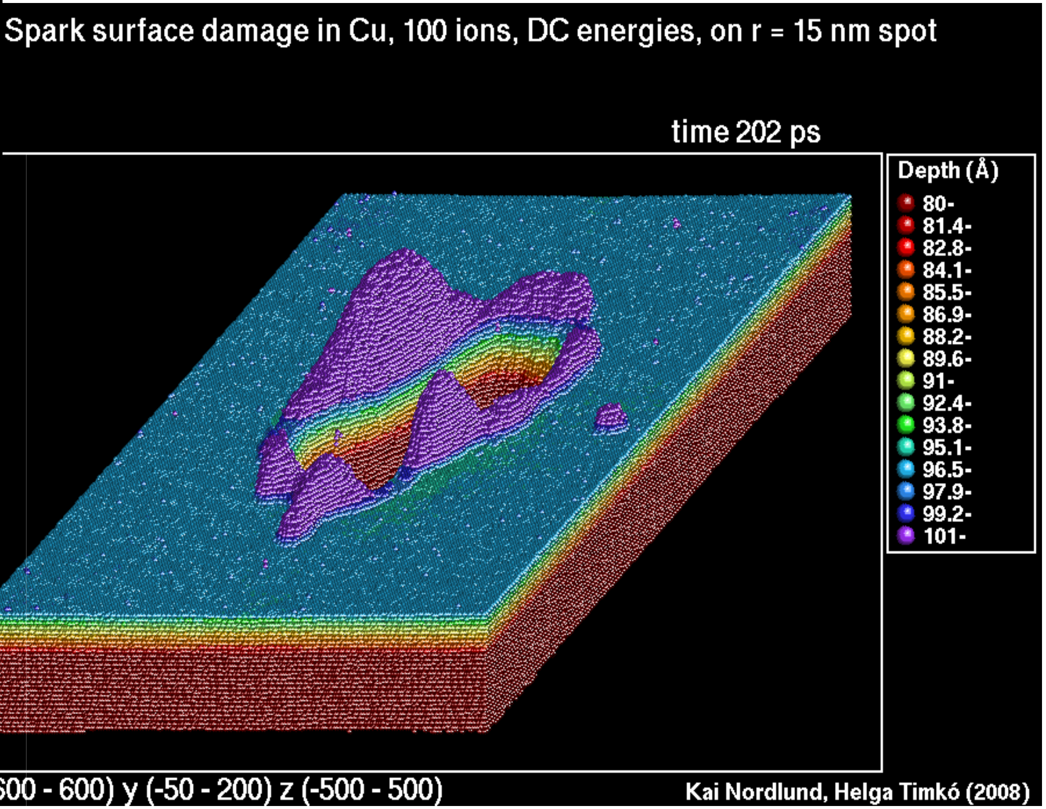
Damaged CLIC structure iris



Surface damage from arcing



- The end result is cratering

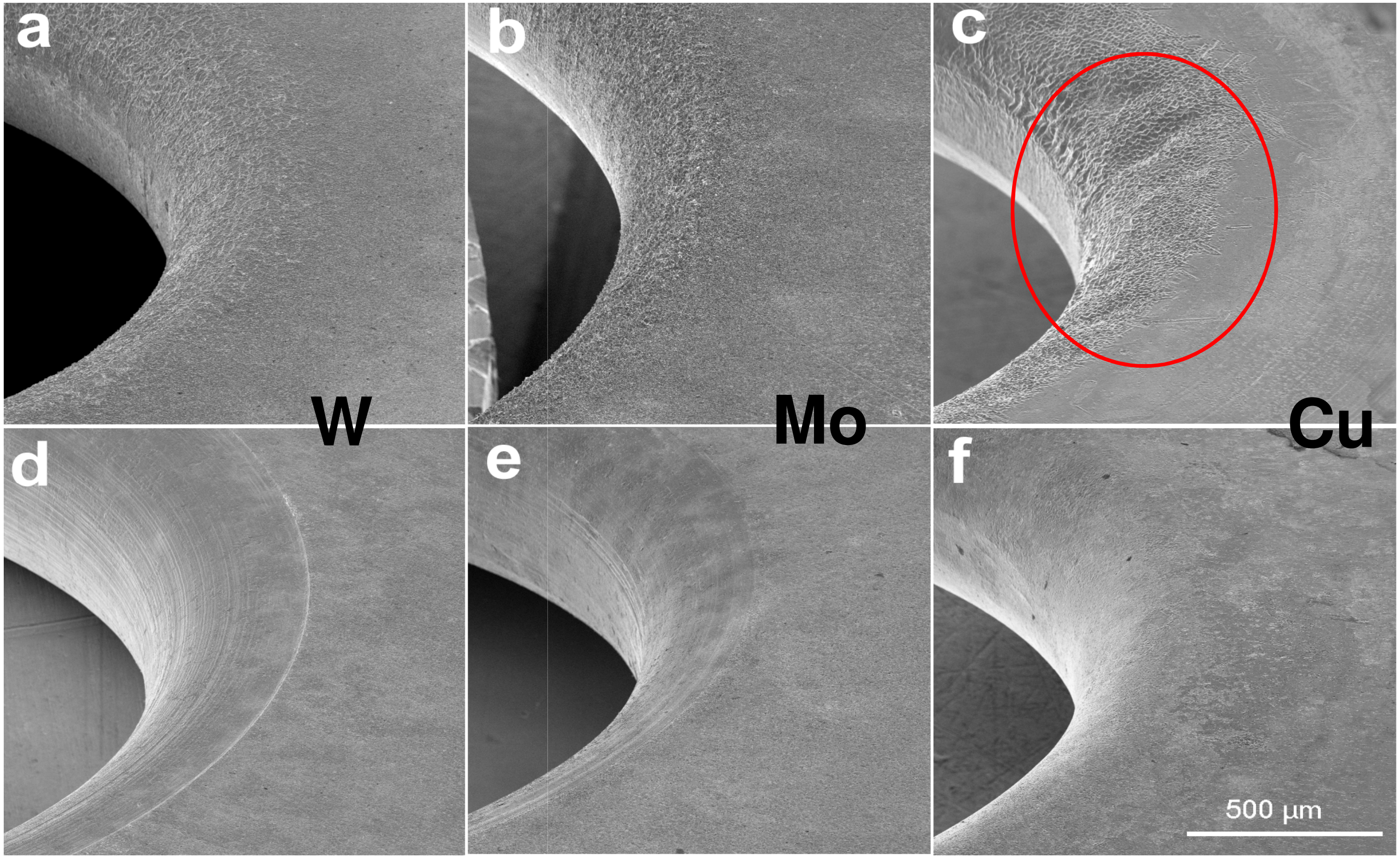


- Molecular Dynamics simulations from Helsinki University, Finland
  Kai Nordlund, Helga Timkó

Iris material tests in CTF2

First iris
(highest
field)

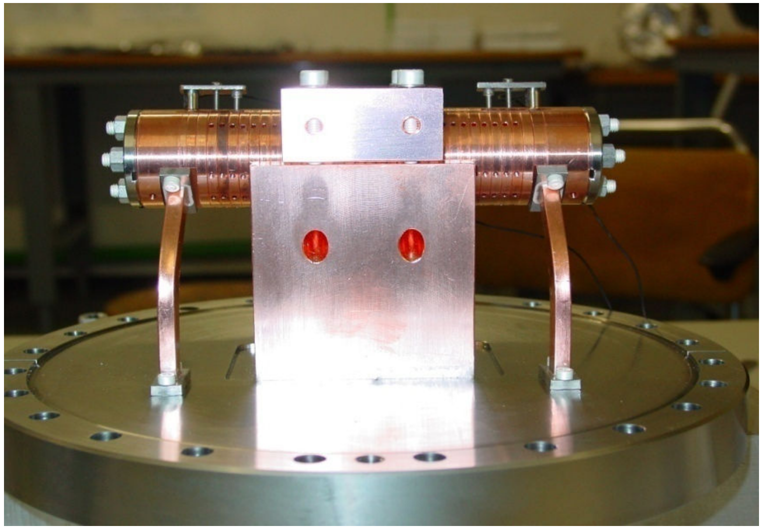
downstream
iris



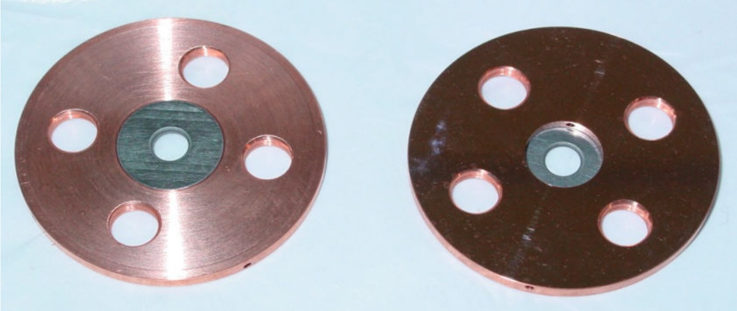
Damage on iris after runs of the 30-cell clamped structures tested in CTFII.
First (a, b and c) and generic irises (d, e and f) of W ,Mo and Cu structures respectively.

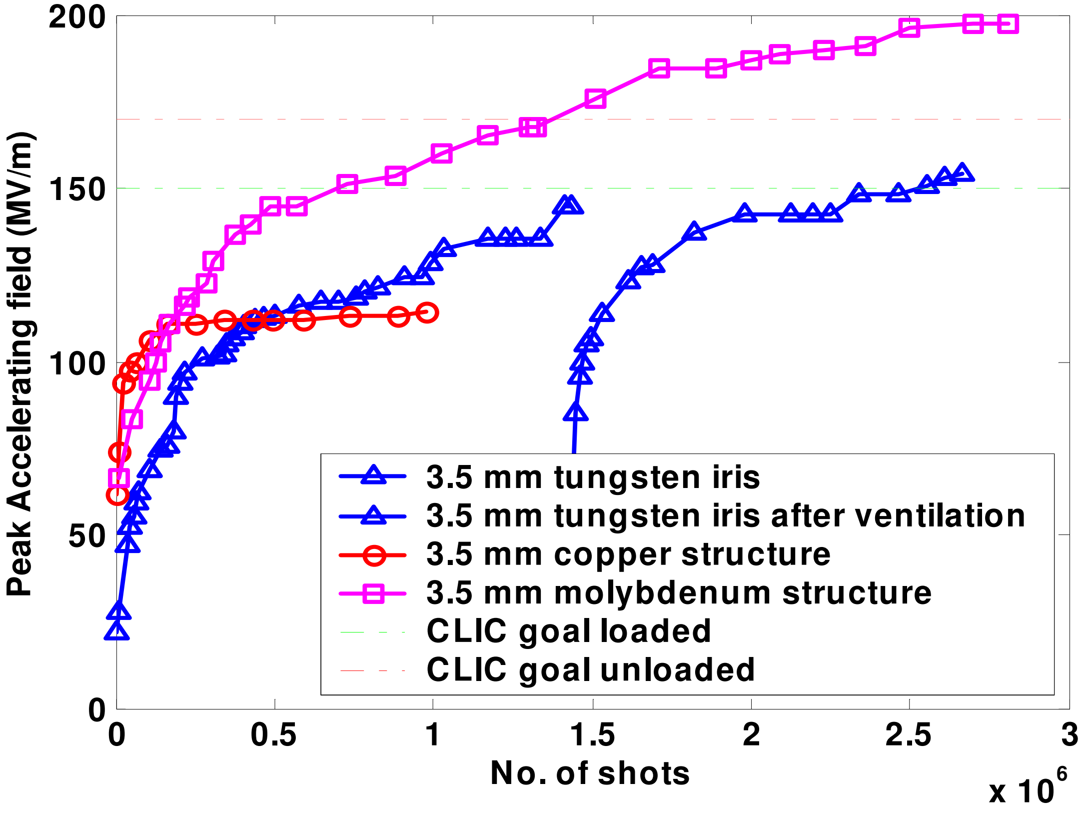
Achieved accelerating fields in CTF2

High gradient tests of new structures with molybdenum irises reached 190 MV/m peak accelerating gradient without any damage well above the nominal CLIC accelerating field of 150 MV/m but with RF pulse length of 16 ns only (nominal 160 ns)



30 cell clamped tungsten-iris structure





A world record !!!

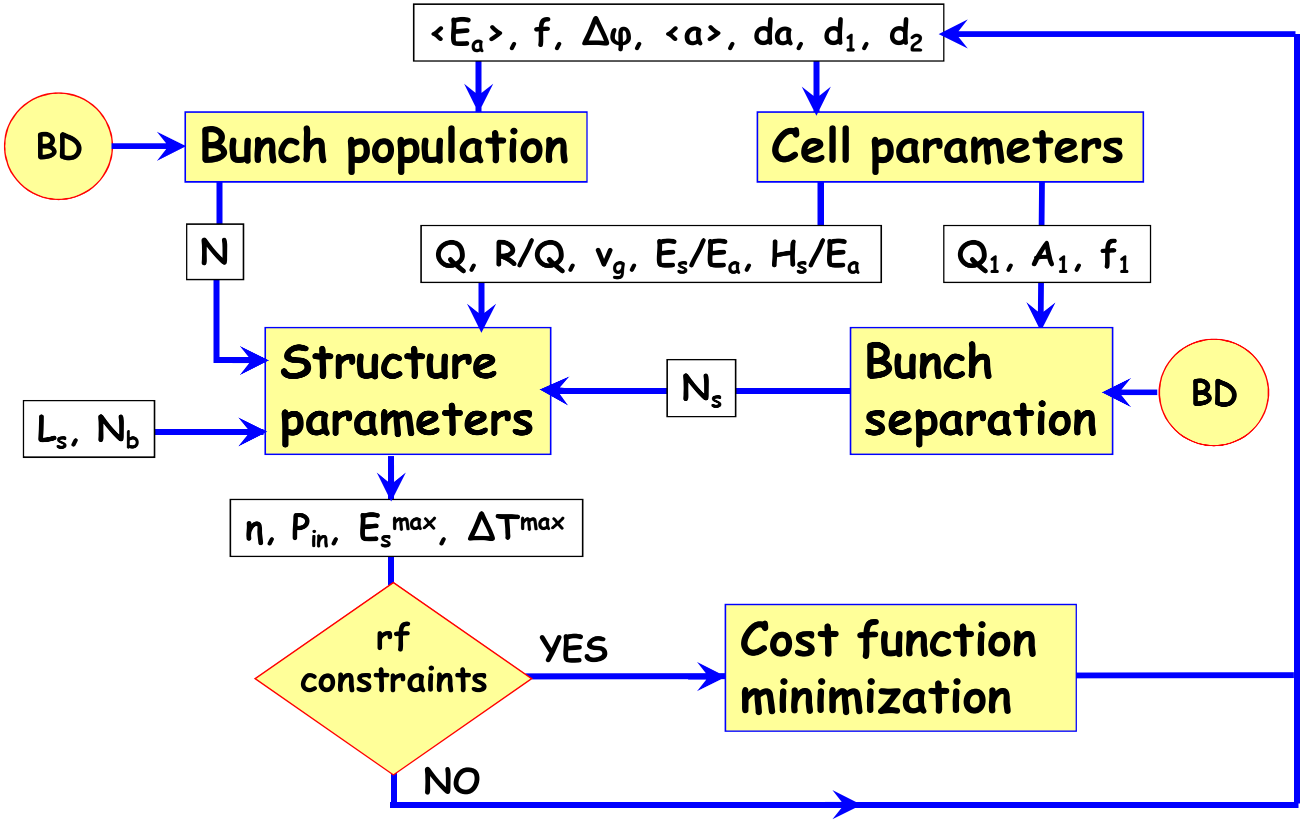
Frequency choice for NC RF

Shunt impedance	$R_s \propto f^{1/2}$	(higher acceleration, as $R_s = V^2/P$)
RF peak power	$P_{rf} \propto 1/f^{1/2}$	
Stored energy	$E \propto 1/f^{2}$	
Filling time	$T_{fill} \propto 1/f^{3/2}$	
Structure dimensions	$a \propto 1/f$	
Wakefields	$W_{\perp} \propto f^{3}$	

- The choice of frequency depends on the parameters above (cost issues!)
- Higher frequency is favourable for NC structures if you can manage the wakefield effects
- Actual frequency also depends on availability of RF power sources (high power klystrons up to ~17 GHz)

A real life frequency choice

- Many more parameters in collider design
  - Take beam dynamics (BD) into account
  - Bunch charge and distance (wakes!), cell geometry, fields, efficiency,...



$\langle E_a \rangle$, f, $\Delta\varphi$, $\langle a \rangle$, da, d_1, d_2

BD

Bunch population

Cell parameters

N

Q, R/Q, v_g, E_s/E_a, H_s/E_a

Q_1, A_1, f_1

Structure parameters

N_s

Bunch separation

BD

L_s, N_b

η, P_{in}, E_s^{max}, ΔT^{max}

rf constraints

YES

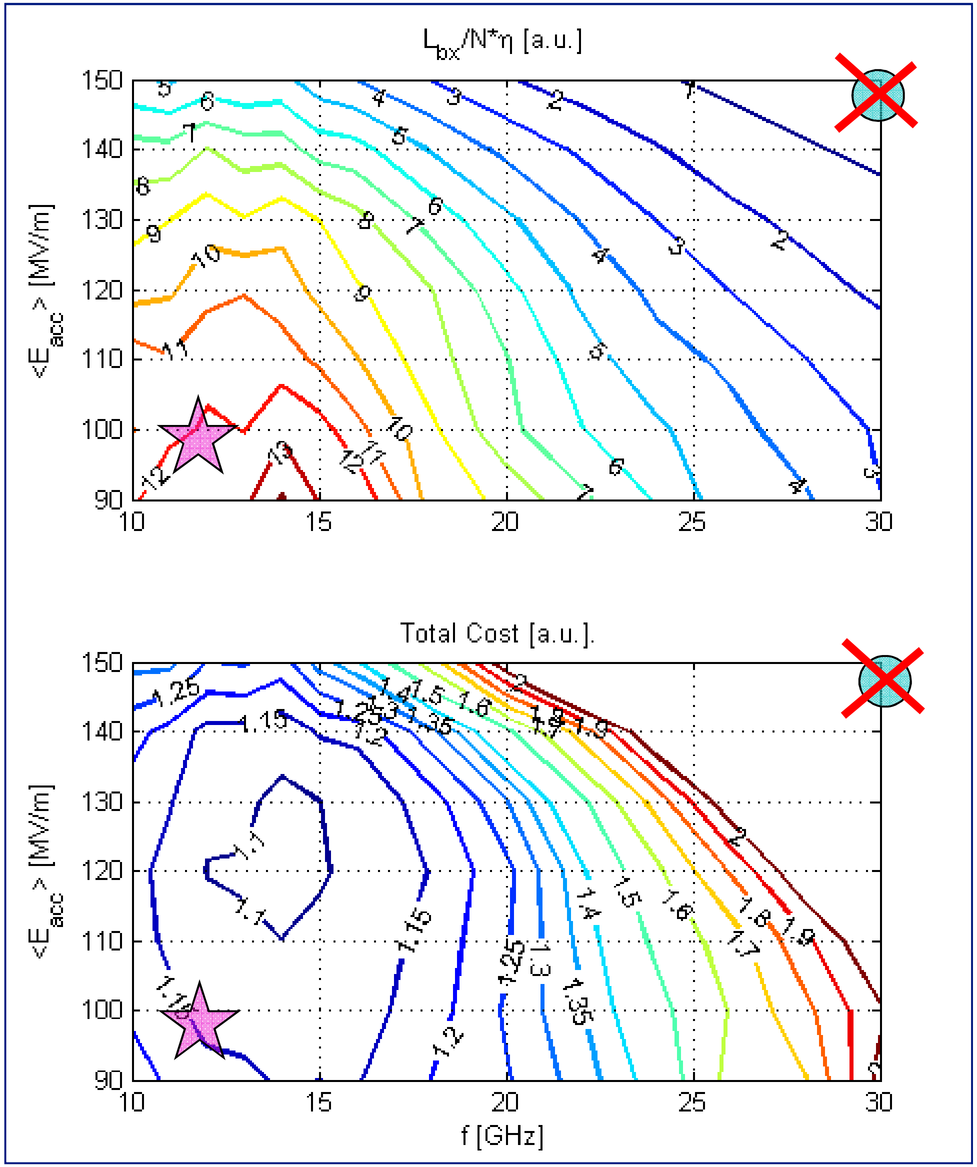
Cost function minimization

NO

CLIC: Why 100 MV/m and 12 GHz ?

- Optimisation:
- Structure limits:
  - RF breakdown – scaling (E_{surf}<260MV/m , P/C$\tau^{1/3}$ limited)
  - RF pulse heating (ΔT<56°K)
- Beam dynamics:
  - emittance preservation – wake fields
  - Luminosity, bunch population, bunch spacing
  - efficiency – total power
- Figure of merit:
  - Luminosity per linac input power
- take into account cost model

after > 60 * 10^6 structures:
100 MV/m 12 GHz chosen,
previously 150 MV/m, 30 GHz

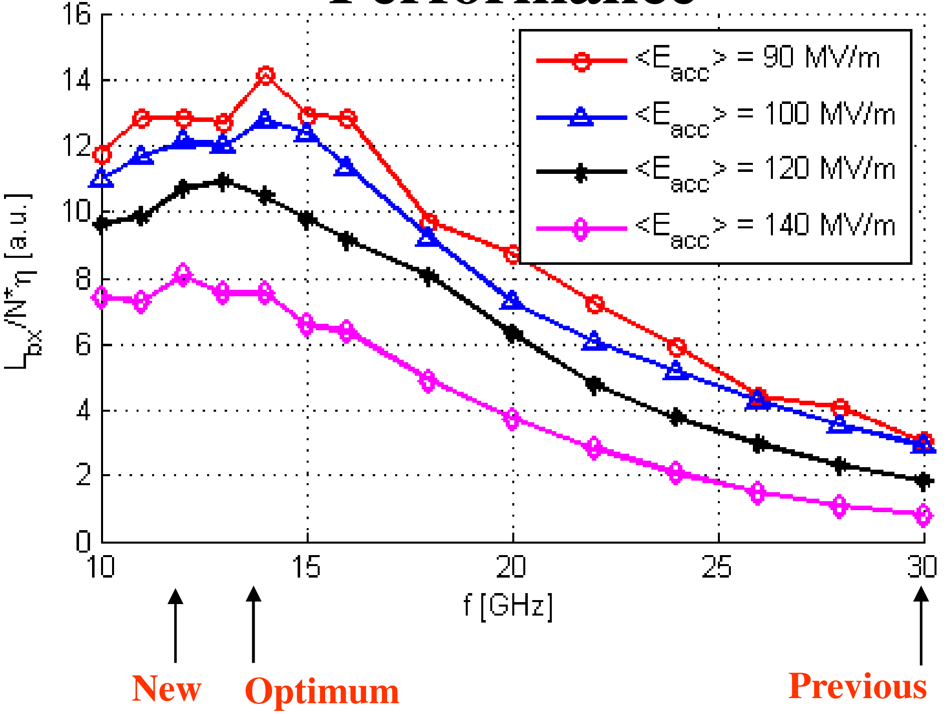


A.Grudiev

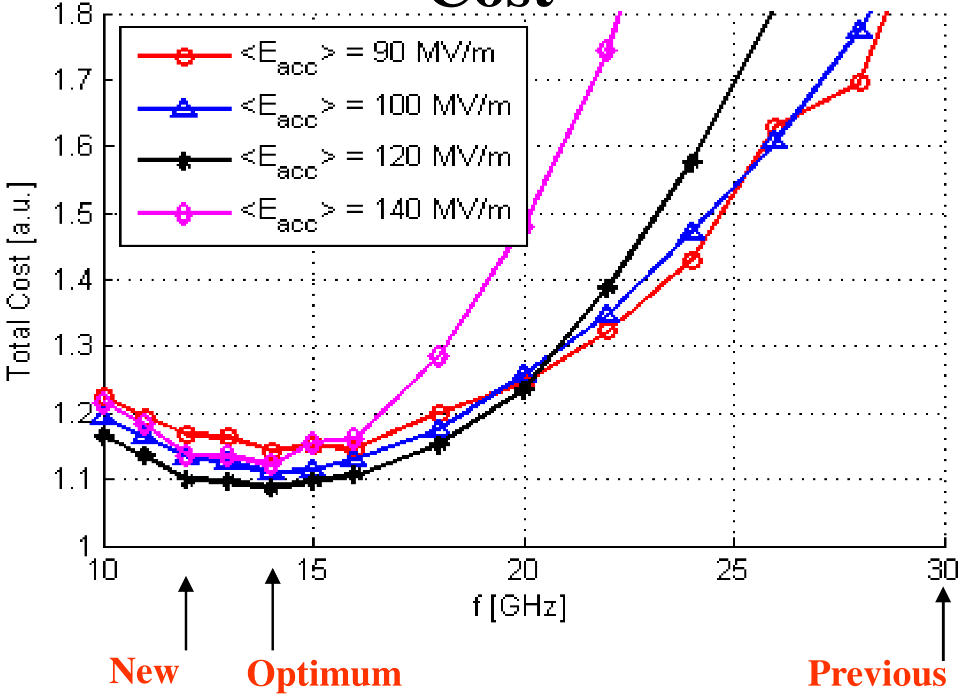
CLIC performance and cost vs frequency

E_{cms} = 3 TeV $L_{(1\%)} = 2.0\ 10^{34}\ cm^{-2}s^{-1}$

Performance



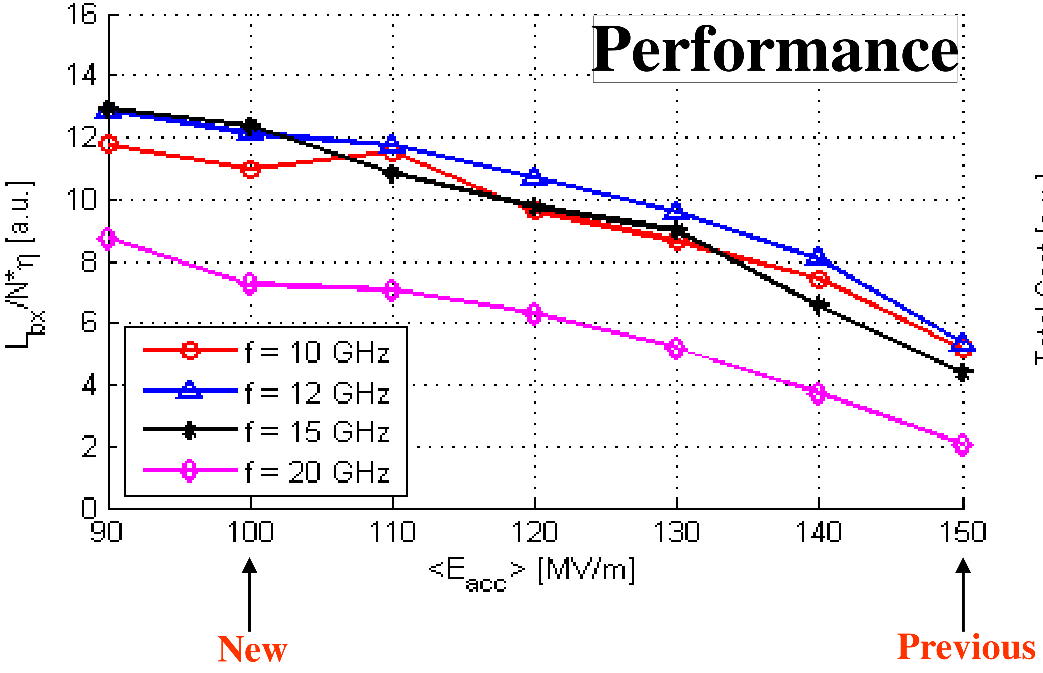
Cost

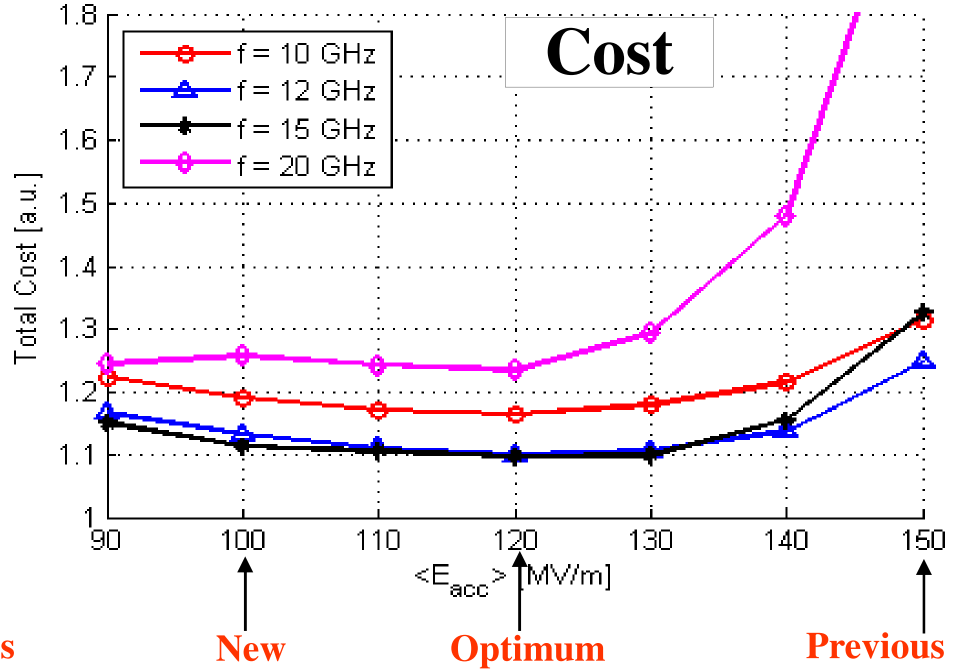


- Maximum Performance around 14 GHz
- Flat cost variation in 12 to 16 GHz frequency range with a minimum around 14 GHz

CLIC performance and cost vs gradient

E_{cms} = 3 TeV $L_{(1\%)} = 2.0\ 10^{34}\ cm^{-2}s^{-1}$





- Performance increases with lower accelerating gradient (mainly due to higher efficiency)
- Flat cost variation in 100 to 130 MV/m with a minimum around 120 MV/m

Power requirements

- Accelerating field:
  (transit time, field geometry)

$$E_{acc} = g\,E_0, \quad \text{with} \quad g_{Typical} \approx 0.6$$

- Stored e.m. energy:

$$W_{Linac} \approx \tfrac{\pi}{2}\varepsilon_0\, L\, \frac{E_{acc}^2}{g^2}\left(2.405\,\tfrac{c}{\omega}\right)^2 J_1(2.405)^2$$

$$\approx 140000 \left[\frac{\mathrm{J\,m}}{\mathrm{V^2 s^2}}\right] \frac{L\,E_{acc}^2}{f^2} \propto \frac{V\,E_{acc}}{\boxed{f^2}}$$

- Peak power:
  (neglecting beam power)

$$P = -\frac{\omega}{Q} W \quad \text{power lost,} \quad Q \approx \frac{7\cdot 10^8}{\sqrt{f}} \quad \text{(typical value for Cu)}$$

$$\approx \frac{2\pi\, f^{-\frac{3}{2}}}{7\cdot 10^8} W \qquad \approx 0.0013 \left[\frac{\mathrm{J\,m}}{\mathrm{V^2 s^{3/2}}}\right] \frac{V\,E_{acc}}{\boxed{\sqrt{f}}}$$

- Example:

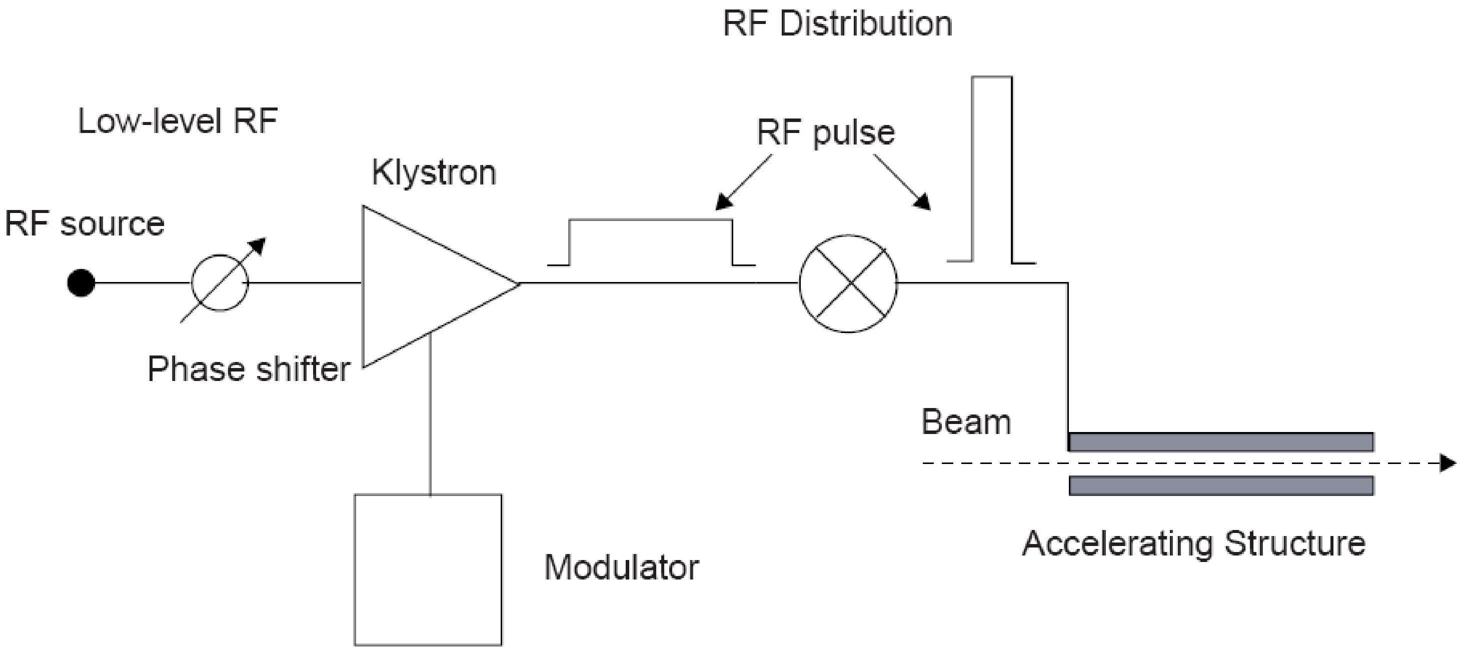
$V = 1$ TeV $E = 50$ MV/m $L = 20$ km $f = 3$ GHz

=> $W = 0.8$ MJ $P = 1.2$ TW $P' = 60$ MW/m

- Would need 20000 60 MW klystrons, Not very practical!
  => higher frequency, pulse compression (NLC/JLC), drive beam (CLIC)

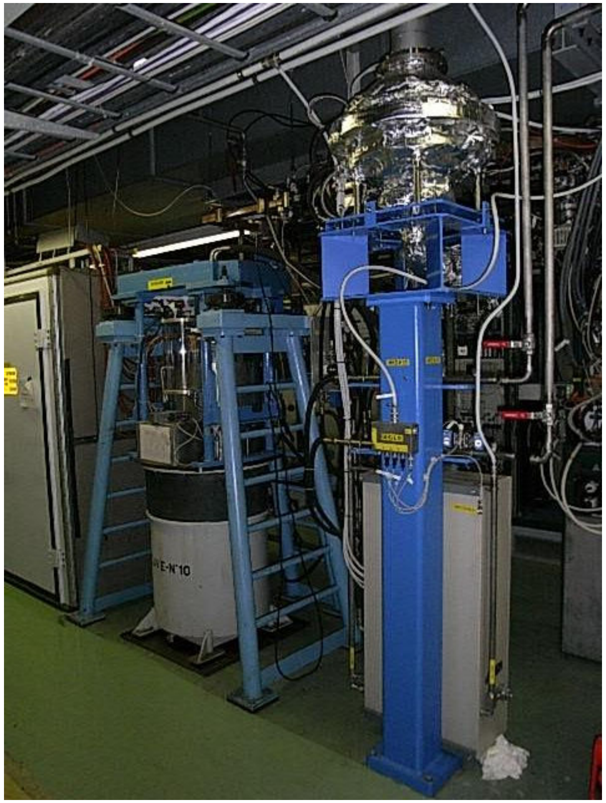
RF pulse compression

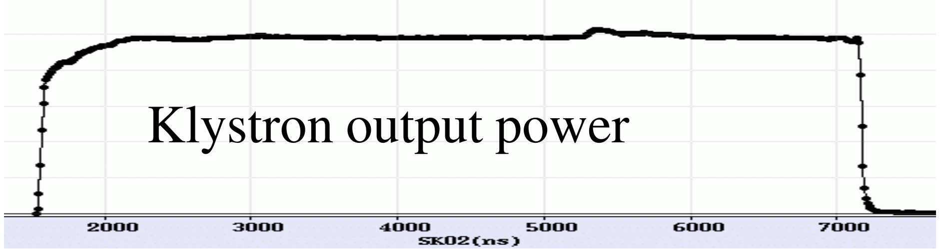
- NC structures: short pulses of very high power needed
- Klystrons produce longer pulses and are power limited
- Way out: transform long RF pulses into shorter with higher power

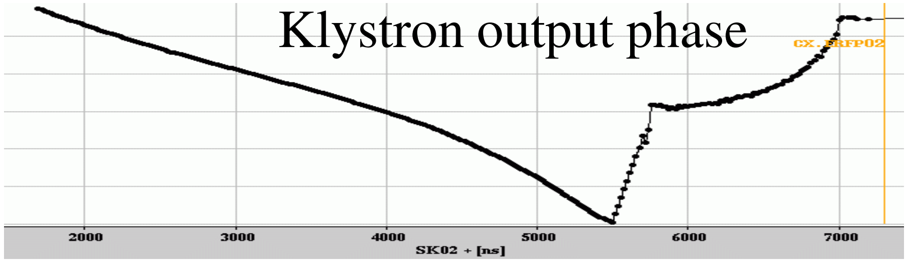


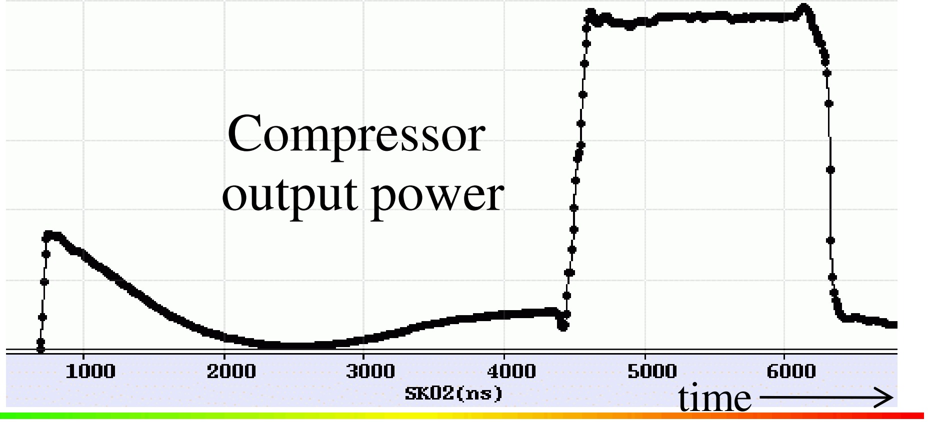
RF pulse compression at CTF3

- RF sent into and stored in high-moded cavity
- Klystron phase modulated, constructive superposition of waves
- High output power



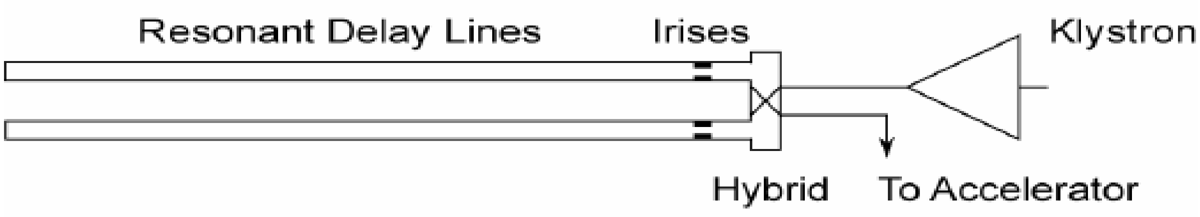

Klystron output power


Klystron output phase

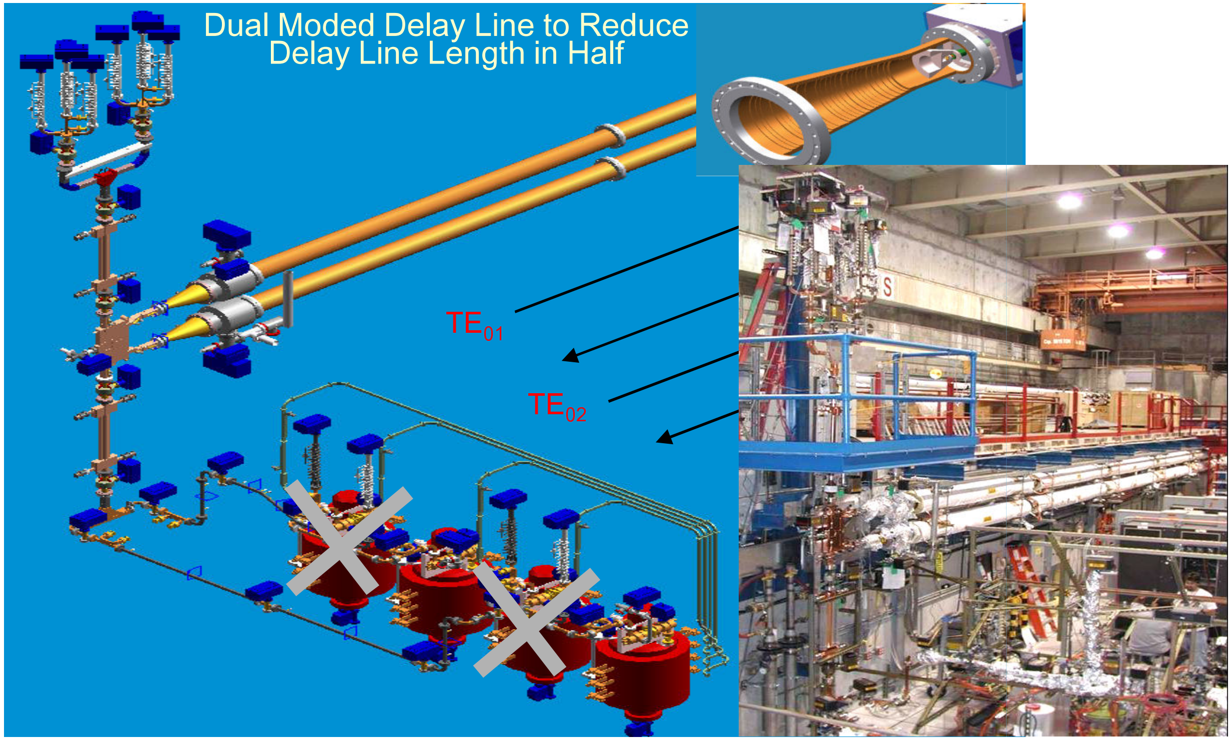

Compressor
output power

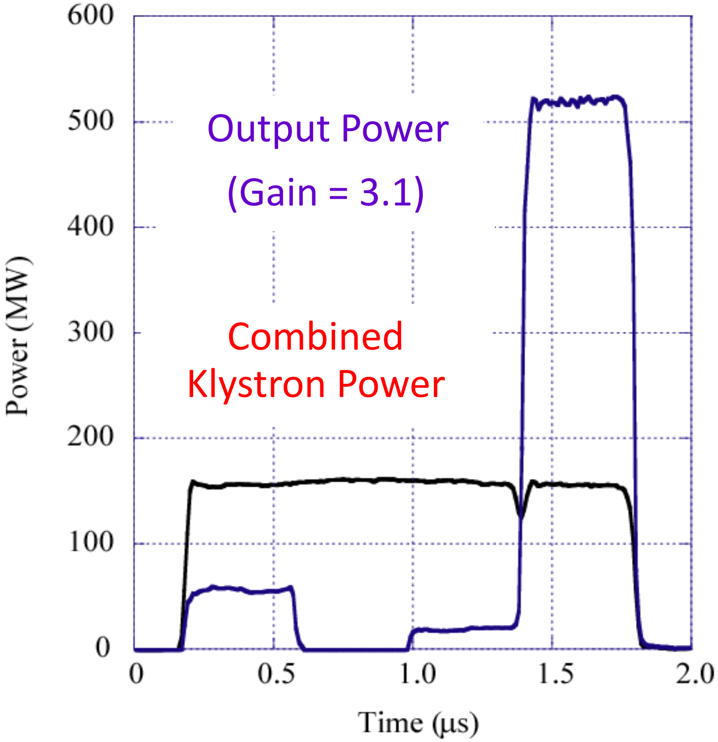
RF pulse compression at NLCTA

- RF sent into delay lines and constructive superposition



Pulse compressor tested up to 500 MW

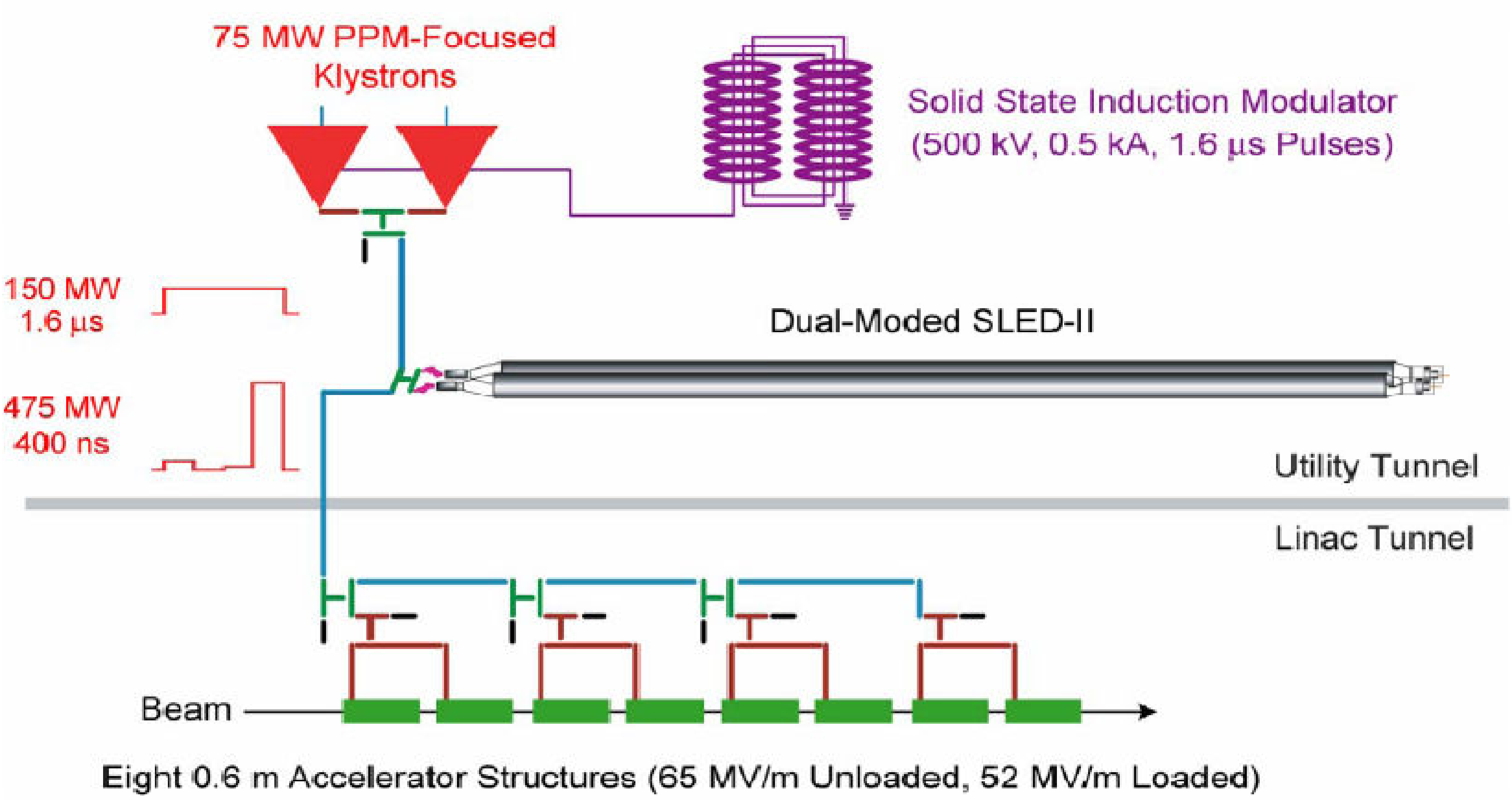




Initial NLC Linac RF Unit

NLC/GLC Linac RF Unit

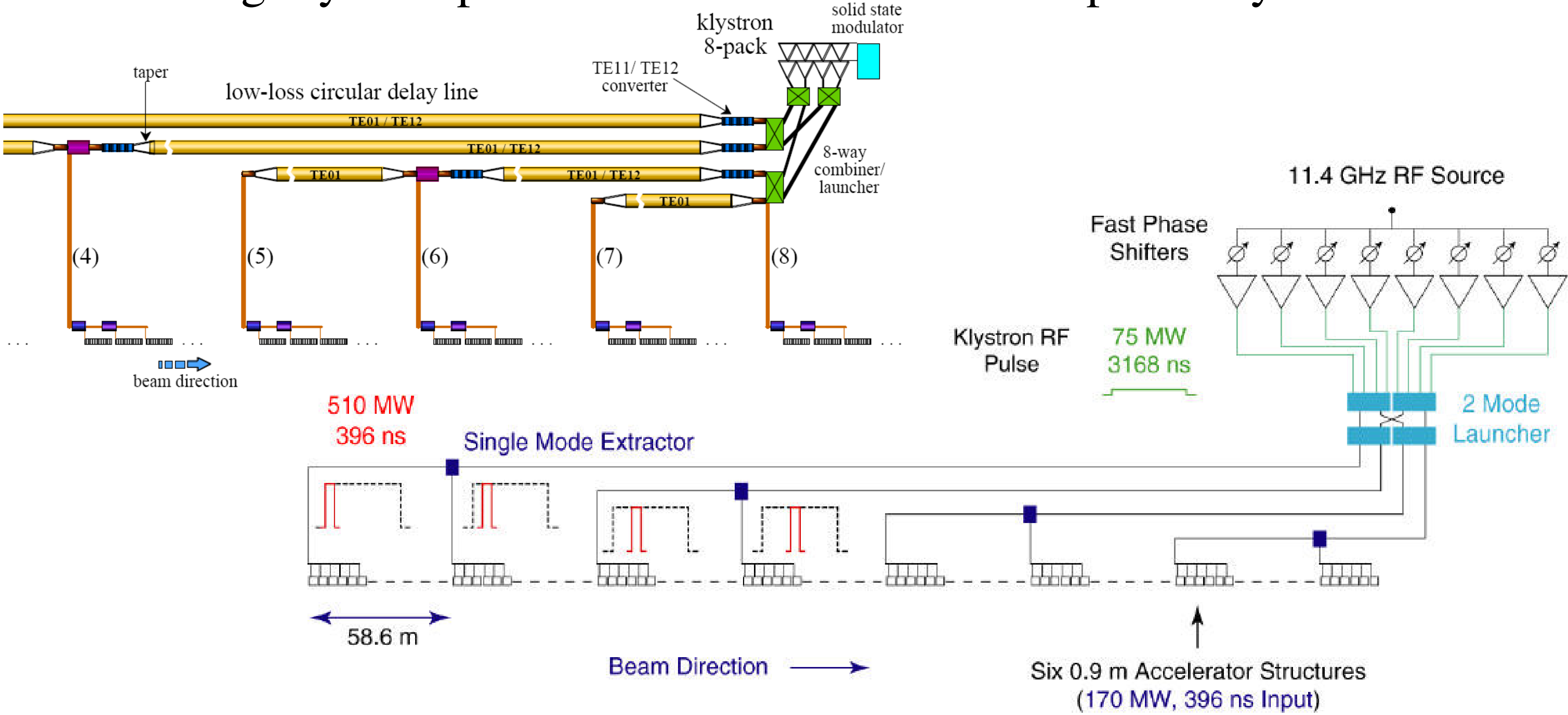
(One of ~ 2000 at 500 GeV cms, One of ~ 4000 at 1 TeV cm)



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

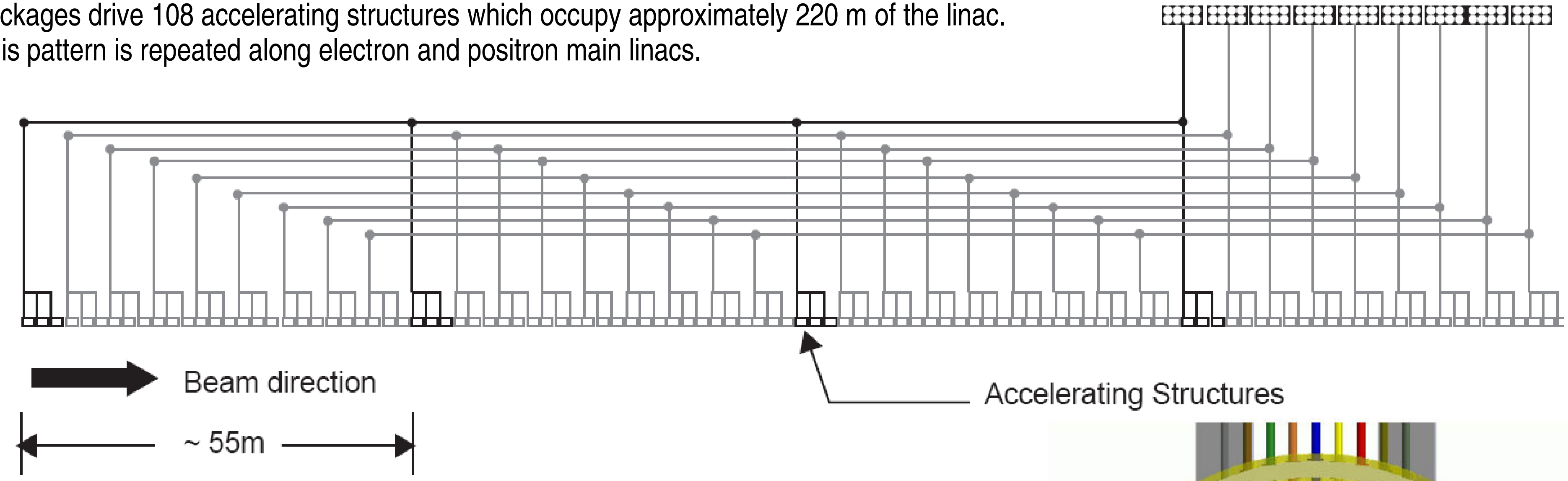
NLC Linac RF Unit

- The output pulses of 8 klystrons are phase modulated and combined
- Depending on the phase combination, the power takes a different path
- The long klystron pulses are converted in shorter pulses by this

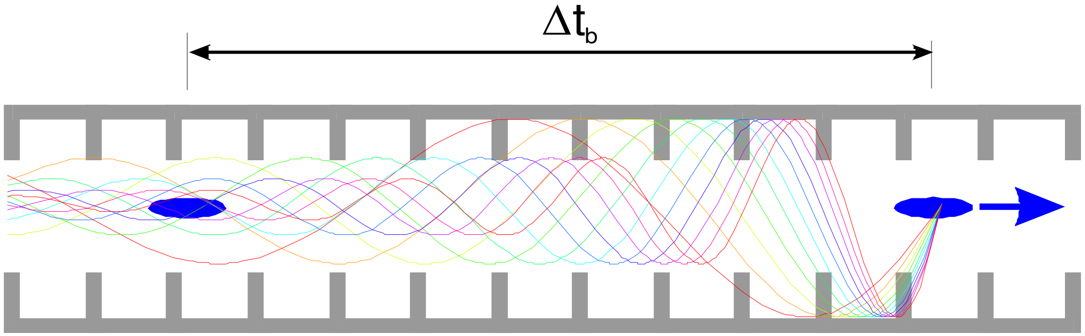


Delay line distribution system

Schematic diagram of the DLDS system for JLC/NLC. Nine ensembles of 8-klystron packages drive 108 accelerating structures which occupy approximately 220 m of the linac. This pattern is repeated along electron and positron main linacs.



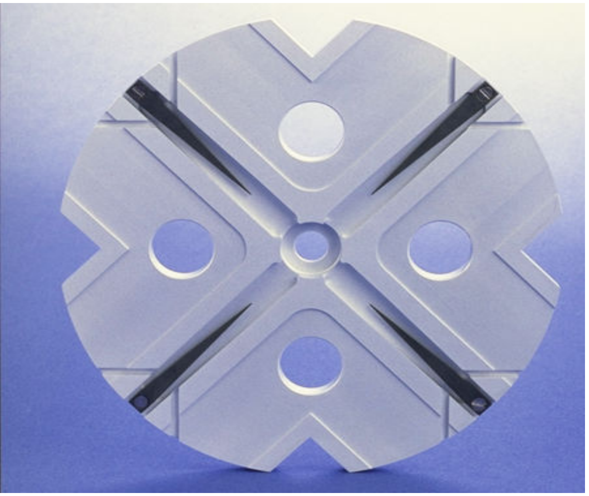
RF structures: transverse wakefields

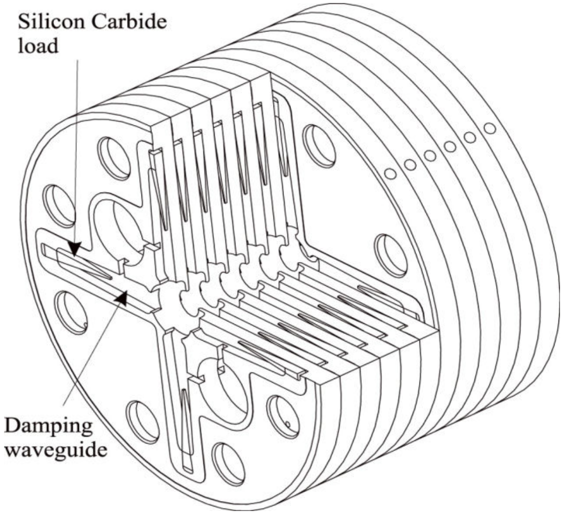


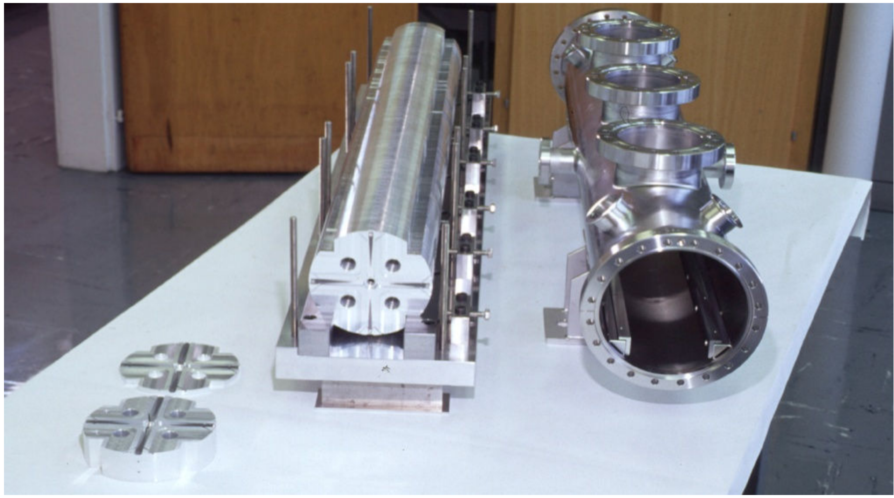
- Bunches induce wakefields in the cavities
- Later bunches are perturbed by these fields
- Can lead to emittance growth and instabilities!!!

- Effect depends on a/λ (a iris aperture) and structure design details
- transverse wakefields roughly scale as $W_\perp \propto f^3$
- less important for lower frequency:
  Super-Conducting (SW) cavities suffer less from wakefields
- Long-range minimised by structure design

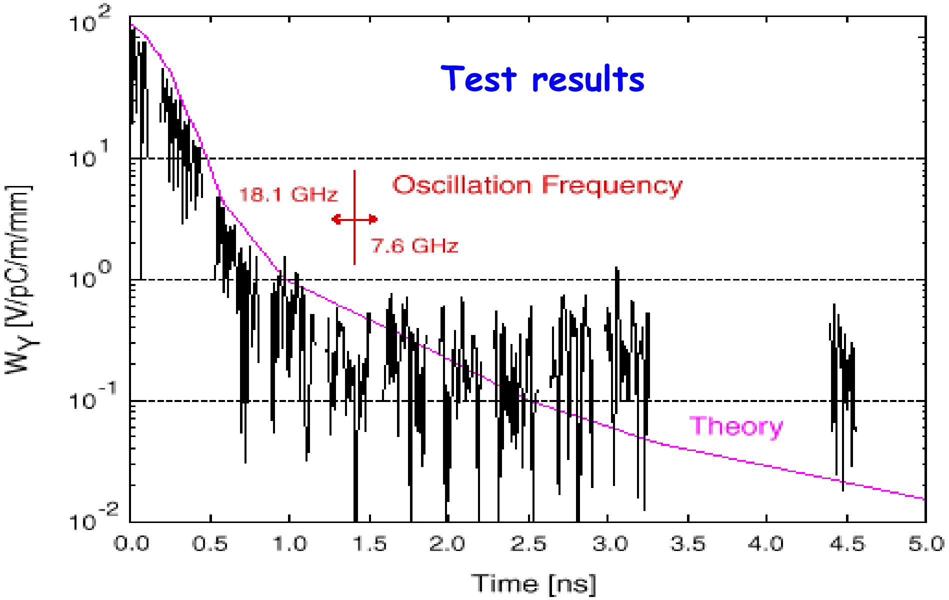
Accelerating structure developments





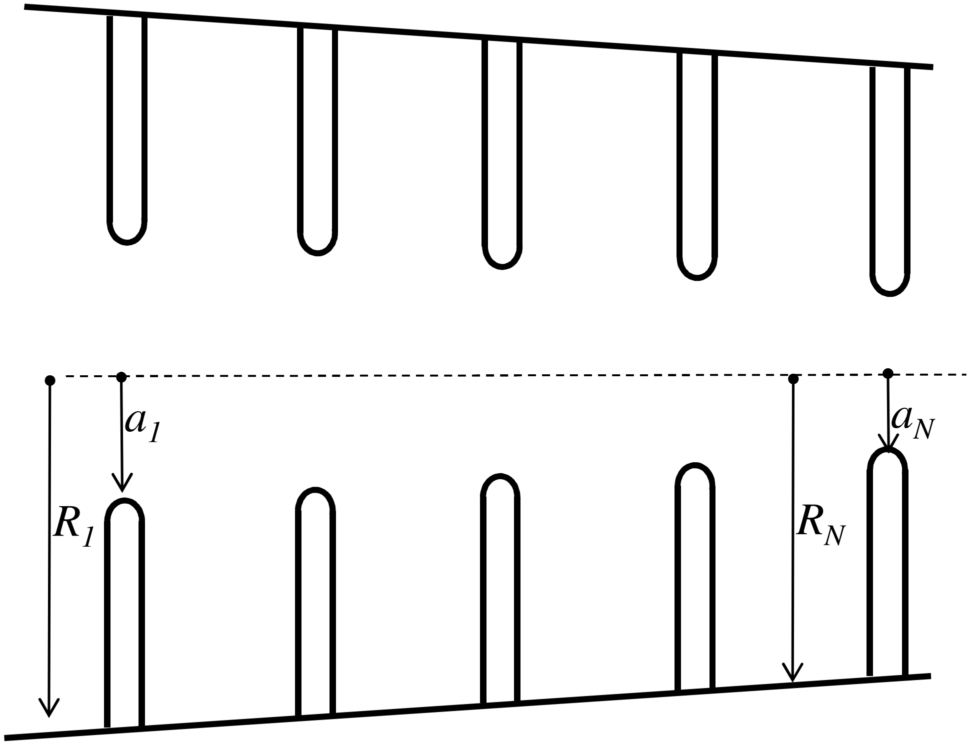


- Structures built from discs
- Each cell damped by 4 radial WGs
- terminated by SiC RF loads
- Higher order modes (HOM) enter WG
- Long-range wakefields efficiently damped

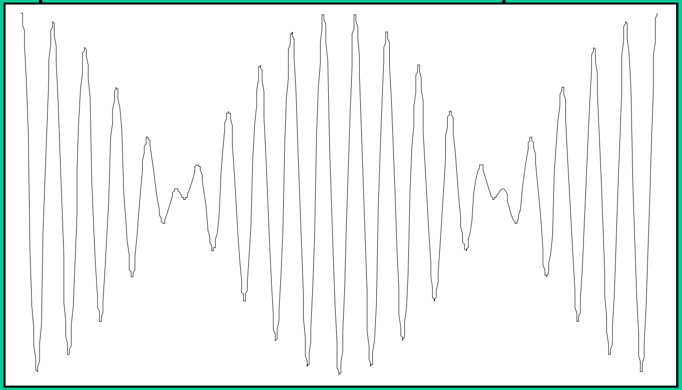


Dipole mode detuning

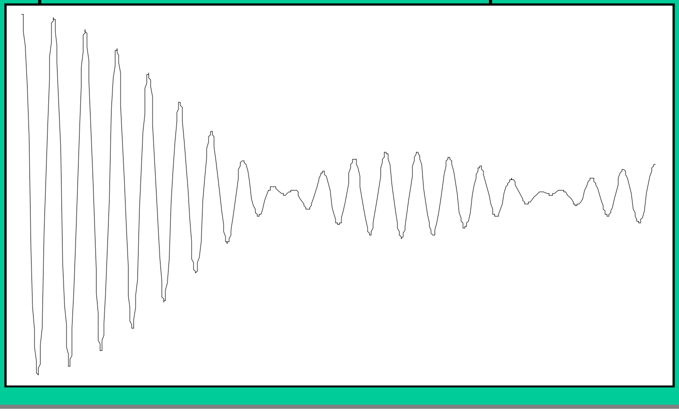
Structure parameters can be varied along structure keeping synchronous frequency for accelerating mode constant but varying synchronous frequencies of dipole modes



Long range wake of a dipole mode spread over **two** different frequencies



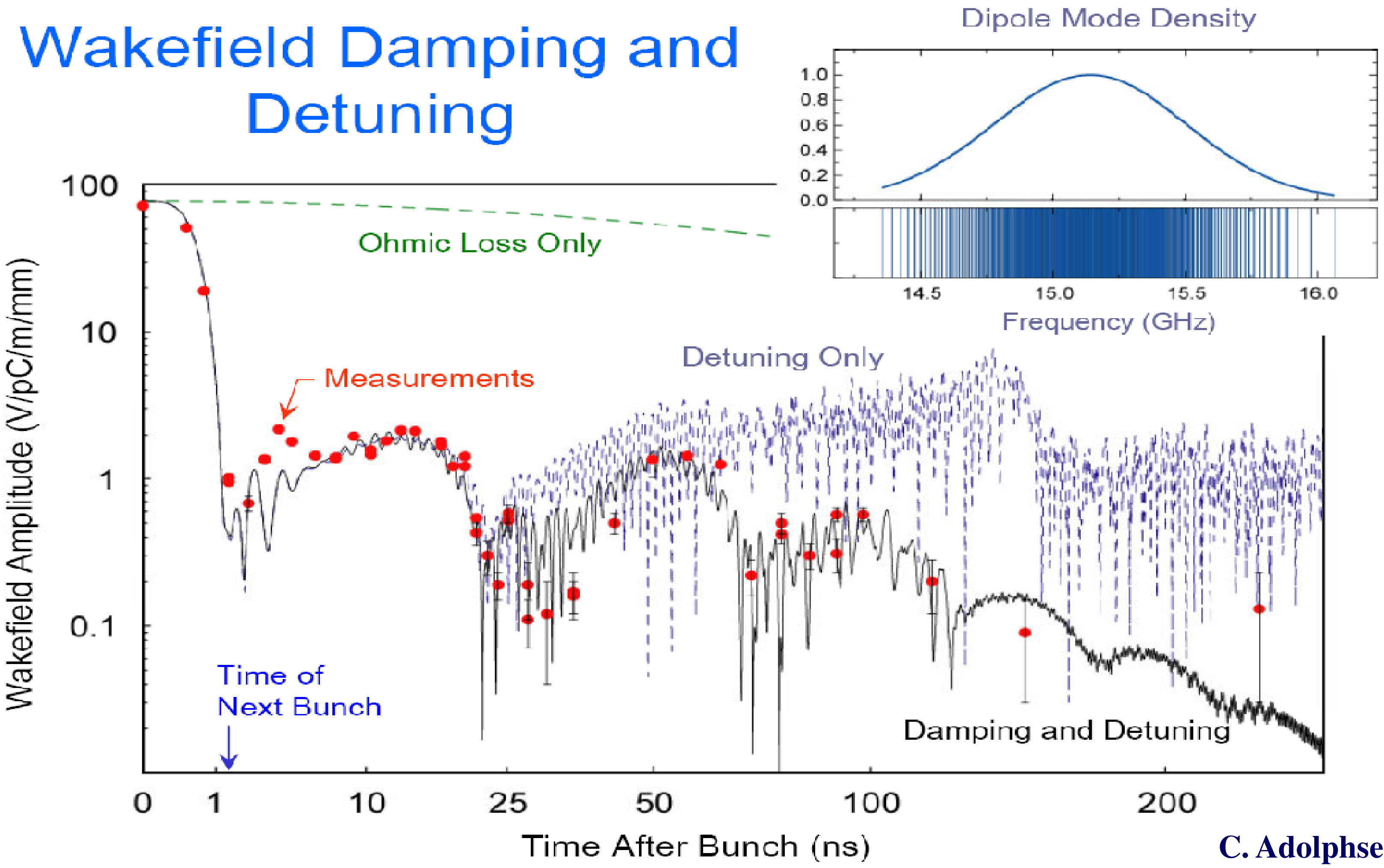
Long range wake of a dipole mode spread over **six** different frequencies



Ideal is a Gaussian weighting of frequency distribution, but finite number of cells leads always to re-coherence after some time !

Damping and detuning

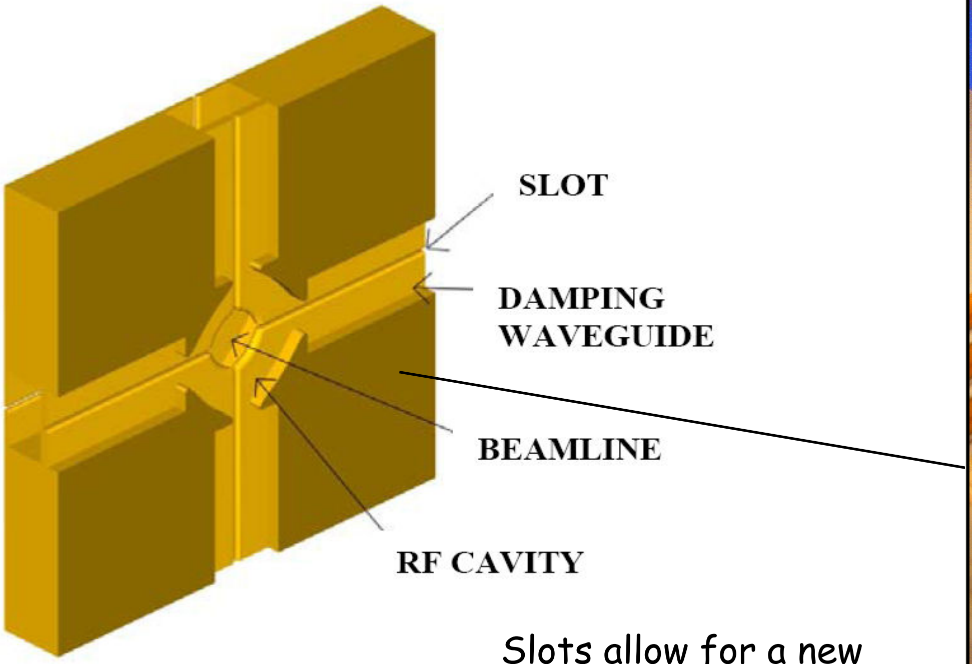
- Slight random detuning between cells makes HOMs decohere quickly
- Will recohere later: need to be damped (HOM dampers)



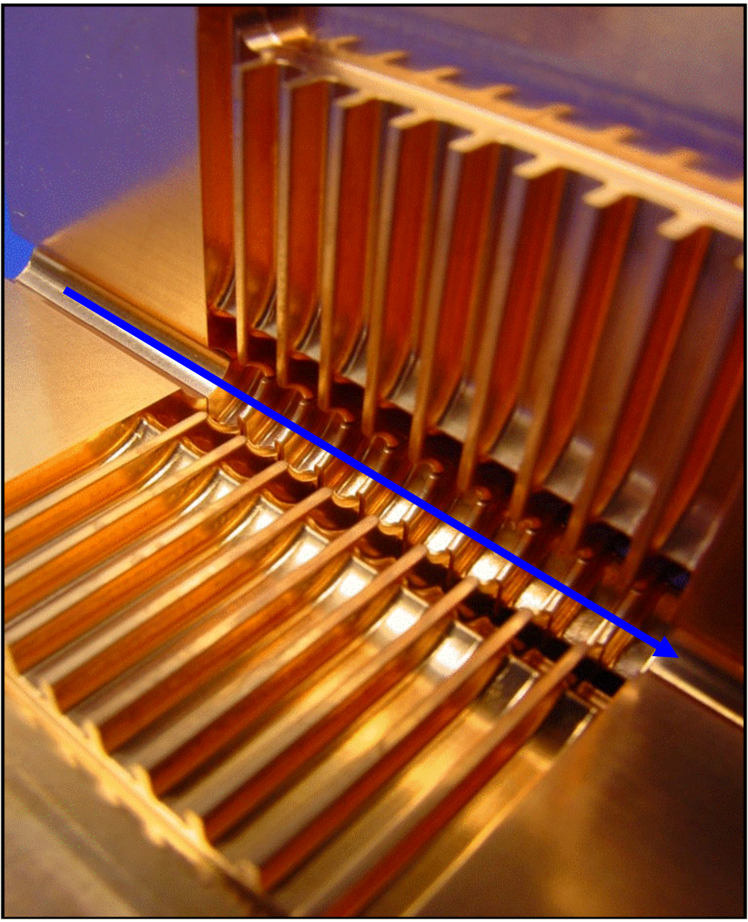
C. Adolphsen / SLAC

Accelerating structure development

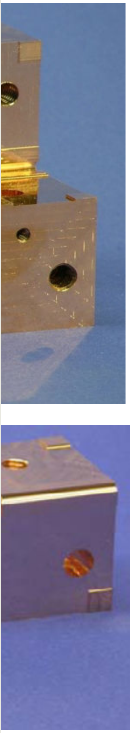
- Recent optimization of CLIC structure for Luminosity/power including RF constraints
- New construction concept



Slots allow for a new construction method, with 4-quadrant assembly



Quadrant prototype

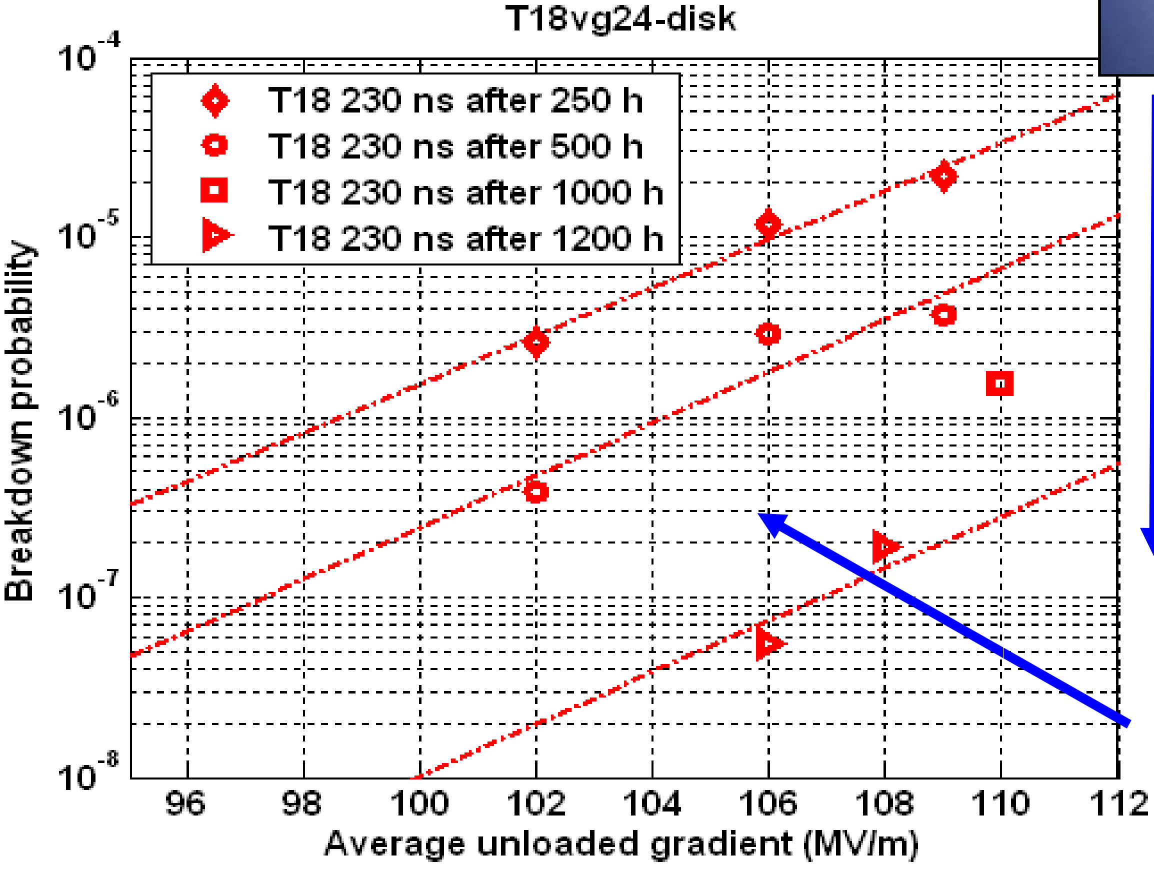


3 quadrants assembled

Present best Structure Performance

- ***T18_VG2.4_disk:*** ***Designed at CERN,***
  (without damping) ***Built at KEK,***
  RF Tested at SLAC

- Exceeded 100 MV/m at nominal CLIC breakdown rate



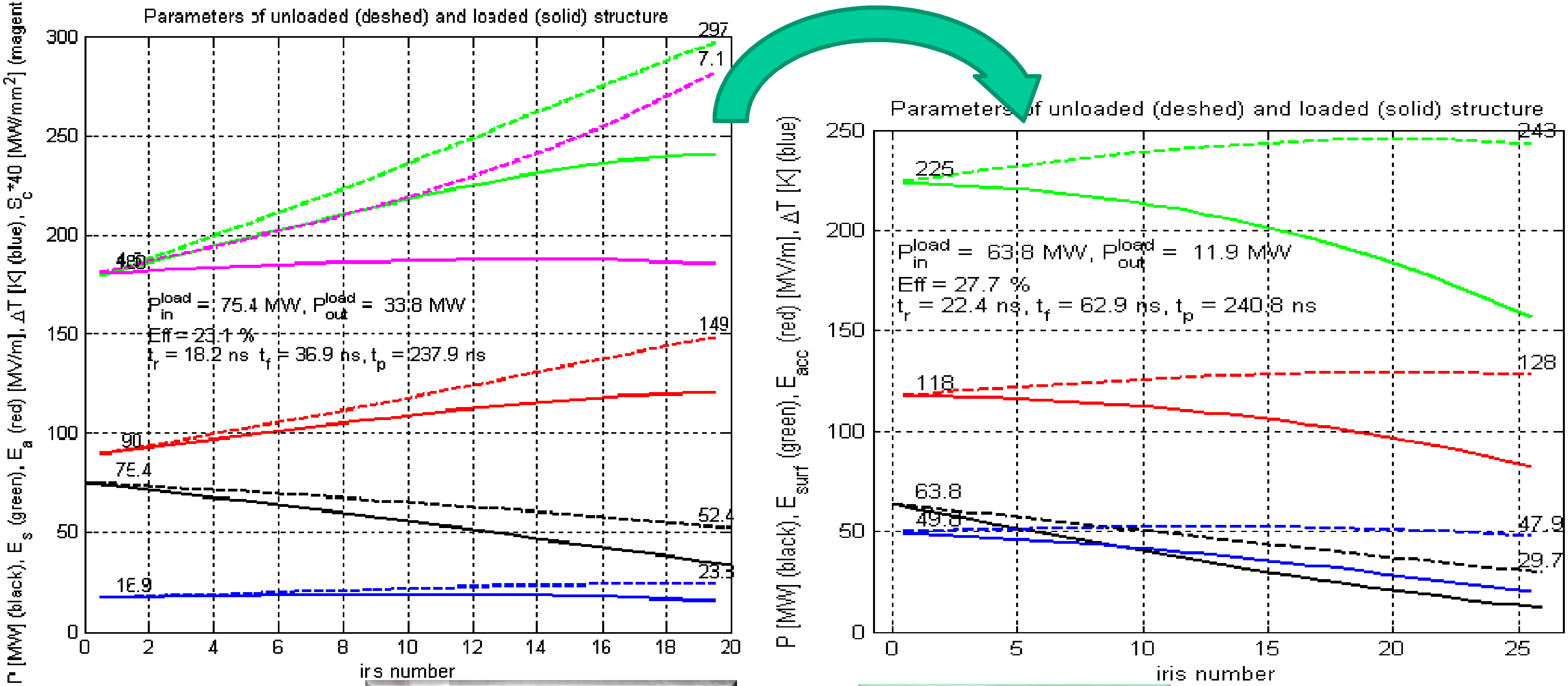
Improvement by conditioning

CLIC nominal

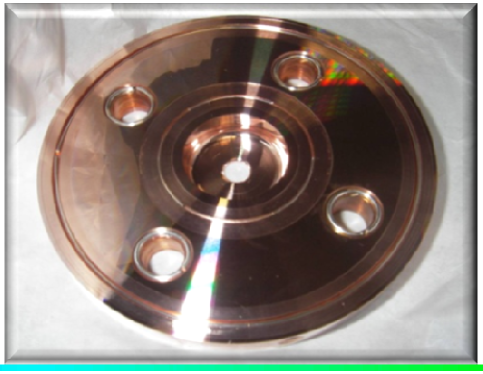
Frequency:	**11.424 GHz**
Cells:	**18+2 matching cells**
Filling Time:	**36 ns**
Length: active acceleration	**18 cm**
Iris Dia. a/λ	**0.155~0.10**
Group Velocity: vg/c	**2.6-1.0 %**
Phase Advace Per Cell	**2π/3**
Power for <Ea>=100MV/m	**55.5 MW**
Unloaded Ea(out)/Ea(in)	**1.55**
Es/Ea	**2**

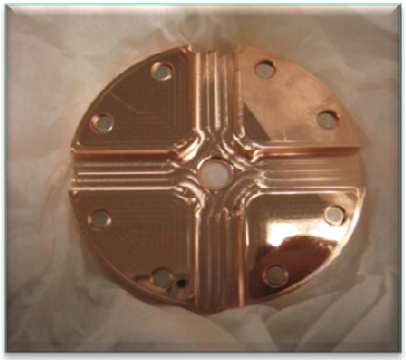
W.Wuensch & S.Doebert

Achieved results to prototype CLIC structure



T18 test structure





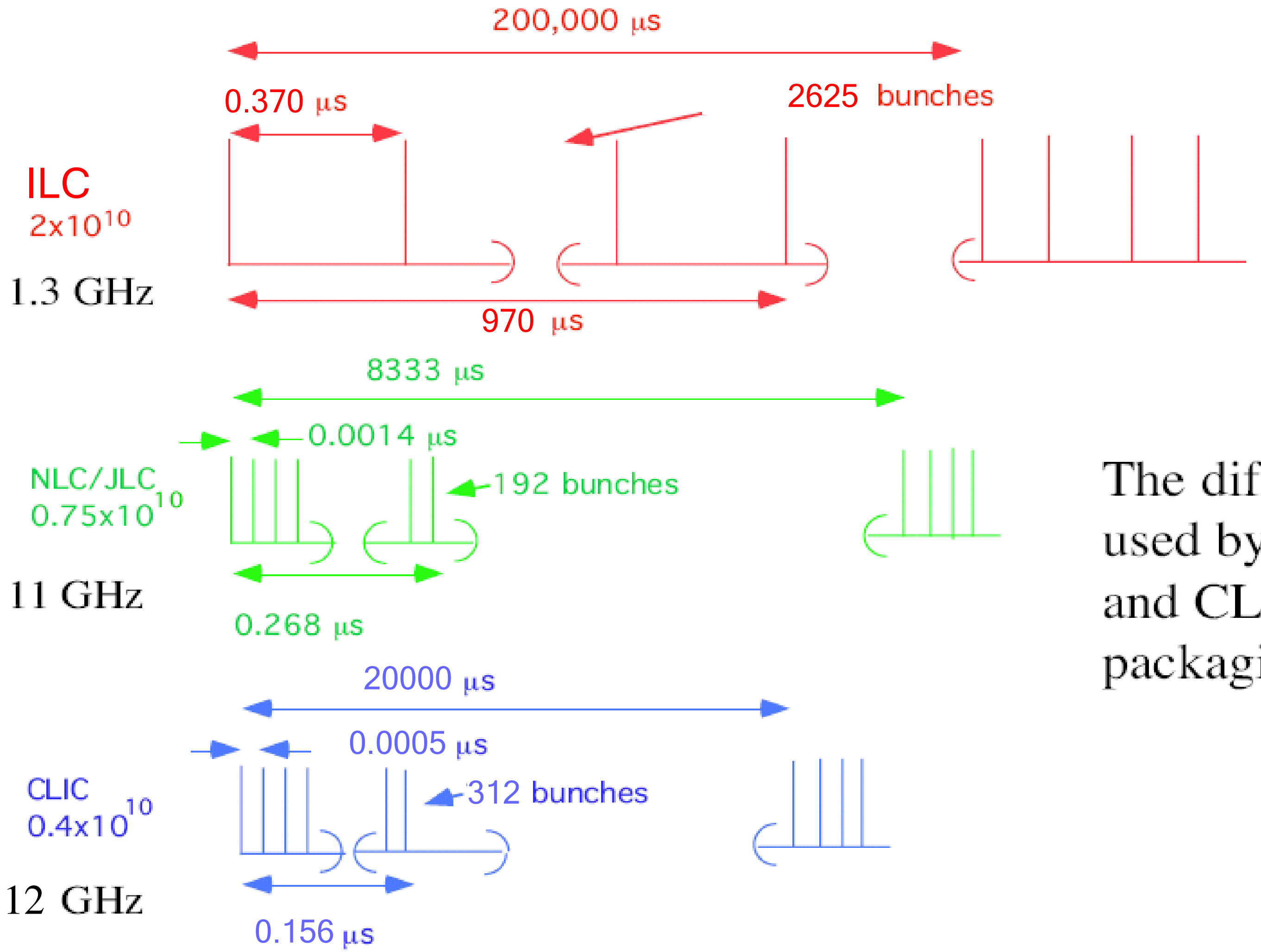
CLIC prototype

NC RF structures - Summary

- Traveling wave structures
  - Short RF pulses ~few 100ns (still as long as possible - for efficiency)
- Higher frequency preferred (power reasons)
  - Smaller dimensions and higher wakefields
  - Careful cavity design (damping + detuning)
  - Sophisticated mechanical + beam-based alignment
- Higher gradients achievable
  - Limited by
    - Pulsed surface heating
    - RF breakdowns
    - Structure damage
- Klystrons not optimal for high power short pulses
  => RF pulse compression and Drive beam scheme

Bunch structure

- SC allows long pulse, NC needs short pulse with smaller bunch charge

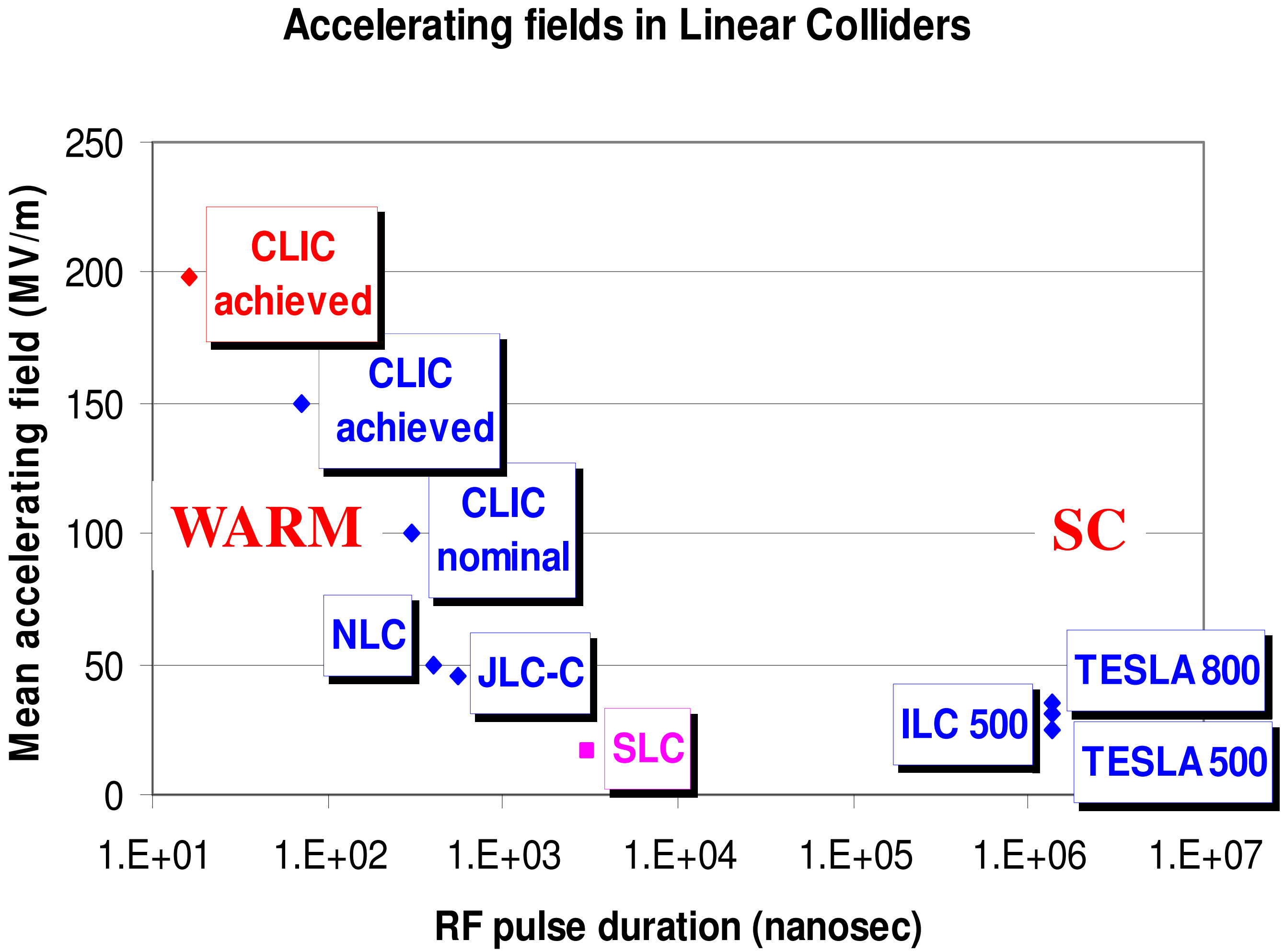


The different RF technologies used by ILC , NLC/JLC and CLIC require different packaging for the beam power

Accelerating gradient

- Superconducting cavities have lower gradient (fundamental limit) with long RF pulse

- Normal conducting cavities have higher gradient with shorter RF pulse length



Warm vs Cold RF Collider

Normal Conducting

- High gradient ⇒ short linac ☺
- High rep. rate ⇒ ground motion suppression ☺
- Small structures ⇒ strong wakefields ☹
- Generation of high peak RF power ☹

Superconducting

- long pulse ⇒ low peak power ☺
- large structure dimensions ⇒ low WF ☺
- very long pulse train ⇒ feedback within train ☺
- SC structures ⇒ high efficiency ☺
- Gradient limited <40 MV/m ⇒ longer linac ☹ (SC material limit ~ 55 MV/m)
- low rep. rate ⇒ bad GM suppression (ε_y dilution) ☹
- Large number of e+ per pulse ☹
- very large DR ☹☹

Comparison ILC - CLIC

		ILC	CLIC	remarks
No. of particles / bunch	10^9	20	3.7	CLIC can't go higher because of short range wakefields
Bunch separation	ns	370	0.5	Short spacing essential for CLIC to get comparable RF to beam efficiency, but CLIC requirements on long range wakefield suppression much more stringent
Bunch train length	μs	970	0.156	One CLIC pulse fits easily in small damping ring, simple single turn extraction from DR. But intra train feedback very difficult.
Charge per pulse	nC	8400	185	Positron source much easier for CLIC
Linac repetition rate	Hz	5	50	Pulse to pulse feedback more efficient for CLIC (less linac movement between pulses)
$\gamma\,\varepsilon_x$, $\gamma\,\varepsilon_y$	nm	10000, 40	660, 20	Because of smaller beam size CLIC has more stringent requirements for DR equilibrium emittance and emittance preservation (partly offset by lower bunch charge and smaller DR)

Parameter comparison

	SLC	TESLA	ILC	J/NLC	CLIC
Technology	NC	Supercond.	Supercond.	NC	NC
Gradient [MeV/m]	20	25	31.5	50	100
CMS Energy E [GeV]	92	500-800	500-1000	500-1000	500-3000
RF frequency f [GHz]	2.8	1.3	1.3	11.4	12.0
Luminosity L [10^{33} cm^{-2}s^{-1}]	0.003	34	20	20	23
Beam power P_{beam} [MW]	0.035	11.3	10.8	6.9	4.9
Grid power P_{AC} [MW]		140	230	195	129
Bunch length σ_z* [mm]	~1	0.3	0.3	0.11	0.07
Vert. emittance $\gamma\varepsilon_y$ [10^{-8}m]	300	3	4	4	2.5
Vert. beta function β_y* [mm]	~1.5	0.4	0.4	0.11	0.1
Vert. beam size σ_y* [nm]	650	5	5.7	3	2.3

Parameters (except SLC) at 500 GeV