Technological challenges of CLIC

2. RF Power Generation and High-Gradient

- Introduction

  CLIC, Two beam scheme

- 30 GHz Power Generation

  Drive Beam Generation and Power Extraction Structure

- 30 GHz Acceleration Structure

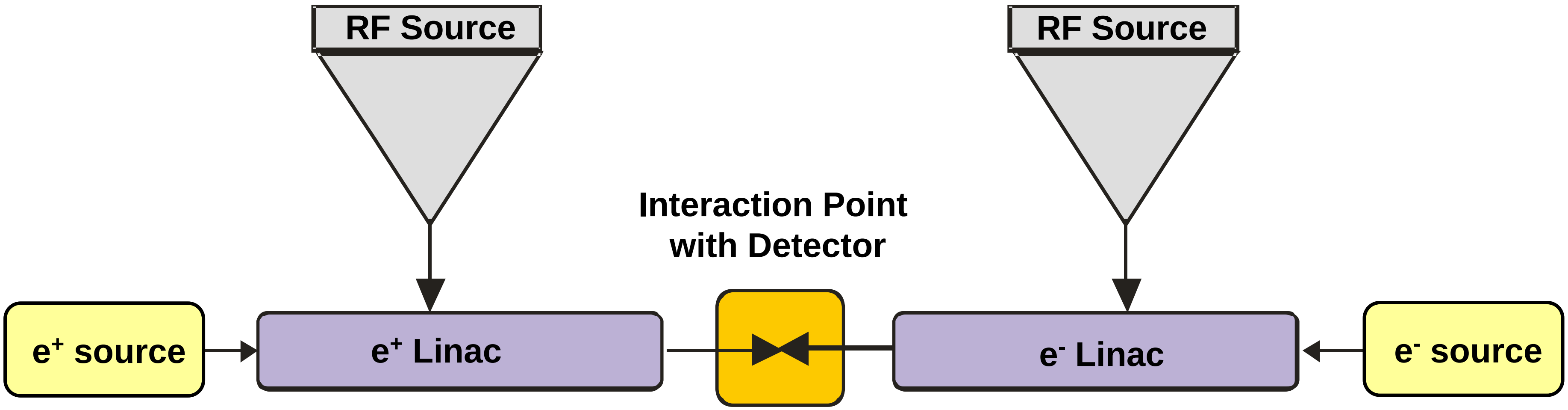
  Design, Constraints, Technology

- High-Gradient

- Conclusions and Outlook

Steffen Döbert, AB/RF, CERN Academic Training, 13 June 2006

What is a Linear Collider



- No big bending magnets
- But a lot of RF acceleration
- High Accelerating Gradient to minimize size and cost
- Exceptional beam quality needed (colliding nm-size beams)

Linear Collider Projects

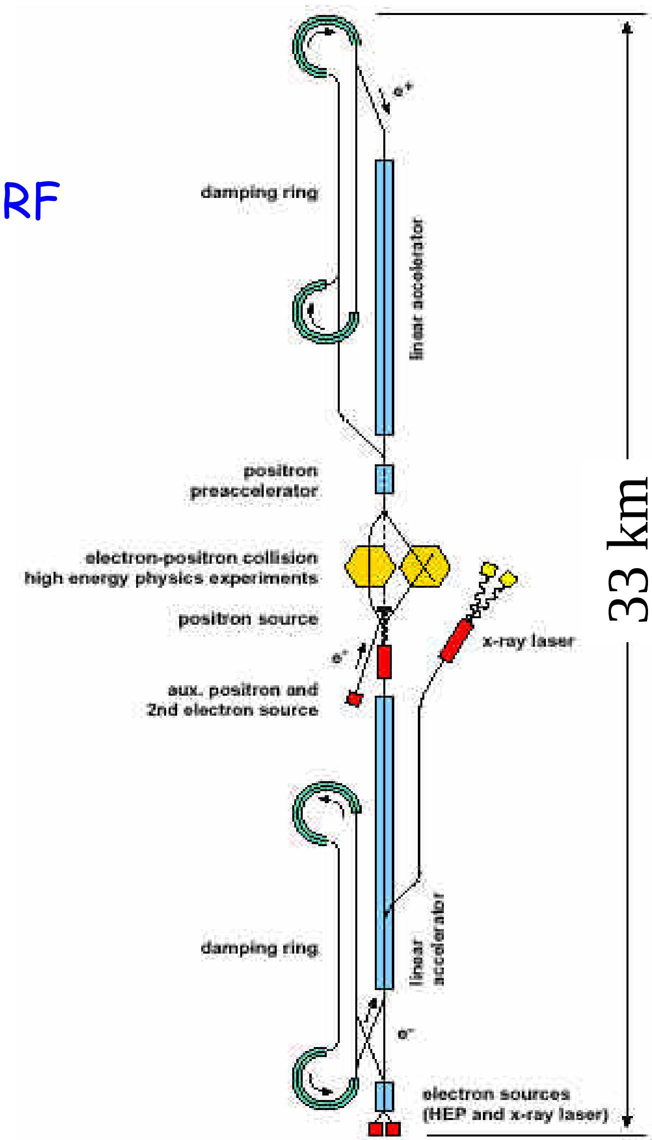
Two projects under study:

ILC (International Linear Collider)

- TESLA Technology, 1.3 GHz superconducting RF
- 30 MV/m, powered by Klystrons
- E_{cm} = 0.5-1 TeV
- Huge international effort to produce TDR

CLIC (Compact Linear Collider)

- 30 GHz normal conducting RF
- 150 MV/m, powered by a Drive Beam
- E_{cm} = 3 TeV (0.5-5)
- Modest effort to demonstrate feasibility



Decisions ~ 2010

Why such a high gradient ?

- Higher Gradient = shorter Accelerator
- Lower Cost
- Cultural threshold for maximum site length: 30-40 km
- Advantages for the beam dynamics

Gradient as high as possible or economical:
150 MV/m for CLIC

Accelerating gradient ?

We need higher gradient per unit length (cost)

10 MV/m

15 – 30 MV/m: Routinely achieved (LIL)

50 MV/m: Super-conducting limit

100 MV/m

50 –150 MV/m:
Normal-conducting linear collider

Future: Plasma/Laser/Wakefield acceleration

> 1 GV/m

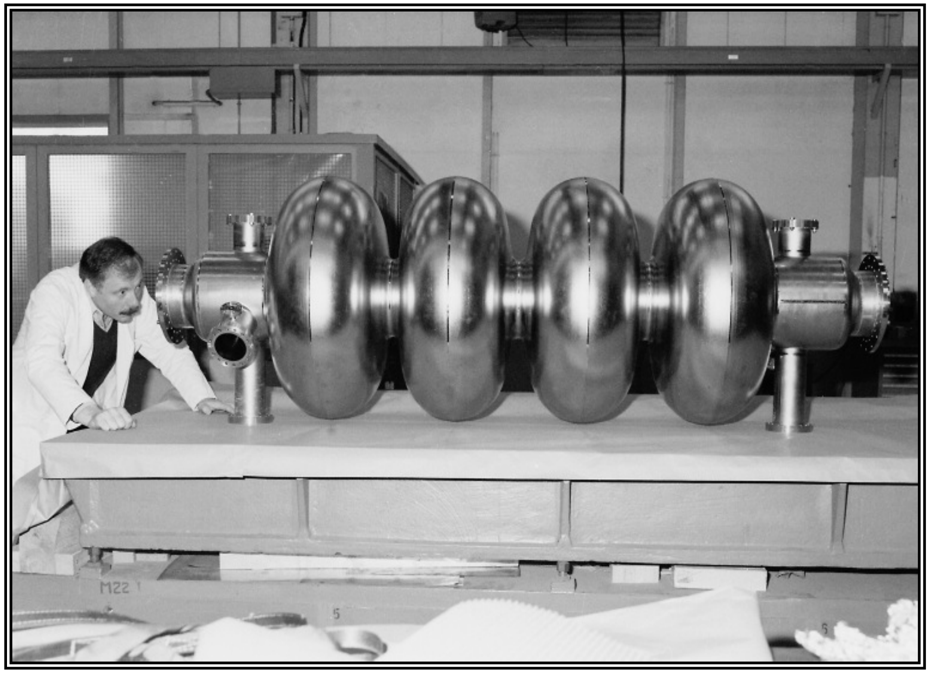
Why very high frequency ?

- Historically: Higher Gradient
- Lower Peak Power
- Higher Efficiency
- Compact → Cost

30 GHz chosen for CLIC

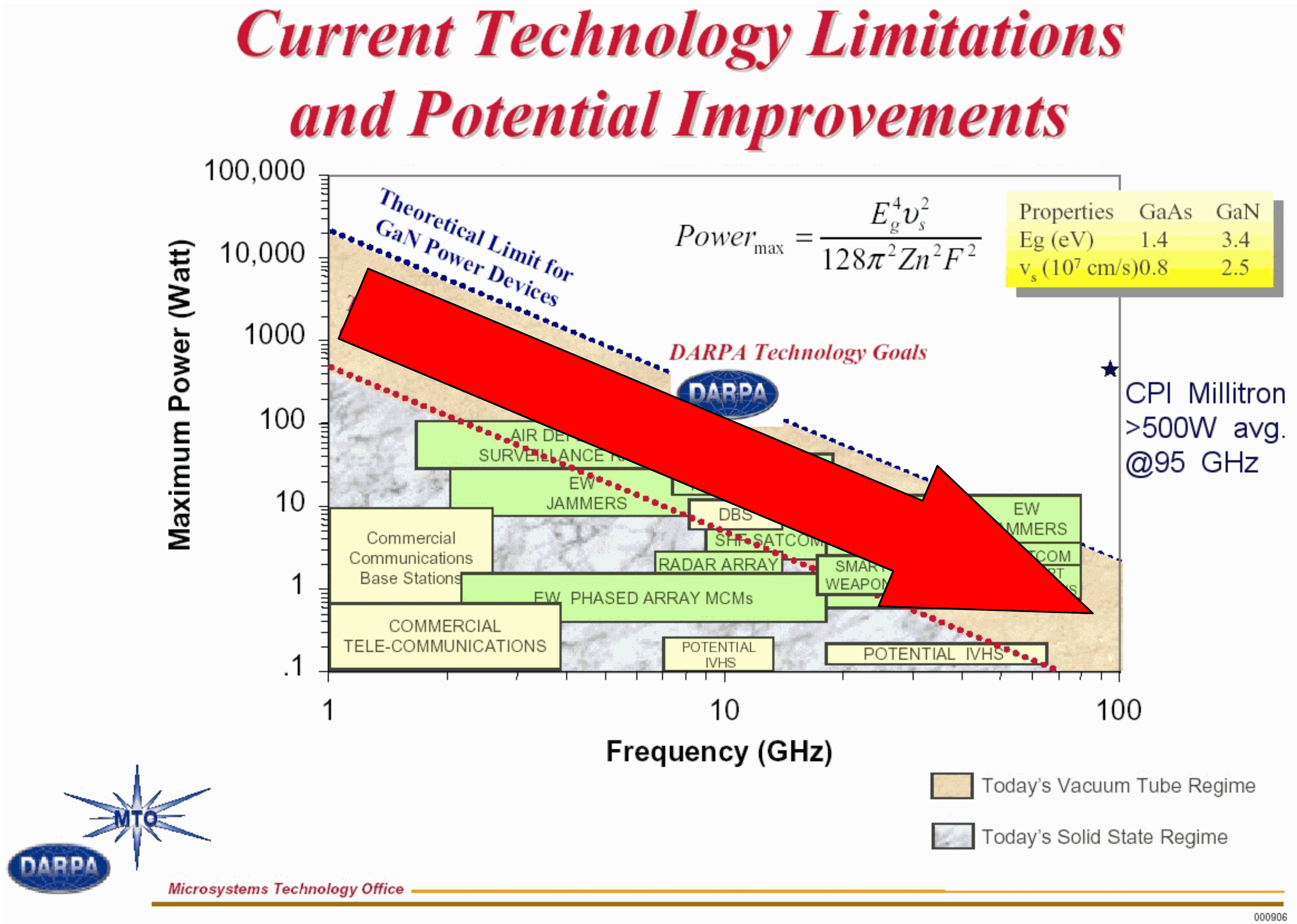
Why very high frequency ?

LEP-Cavity 350 MHz



CLIC-Cavity 30 GHz

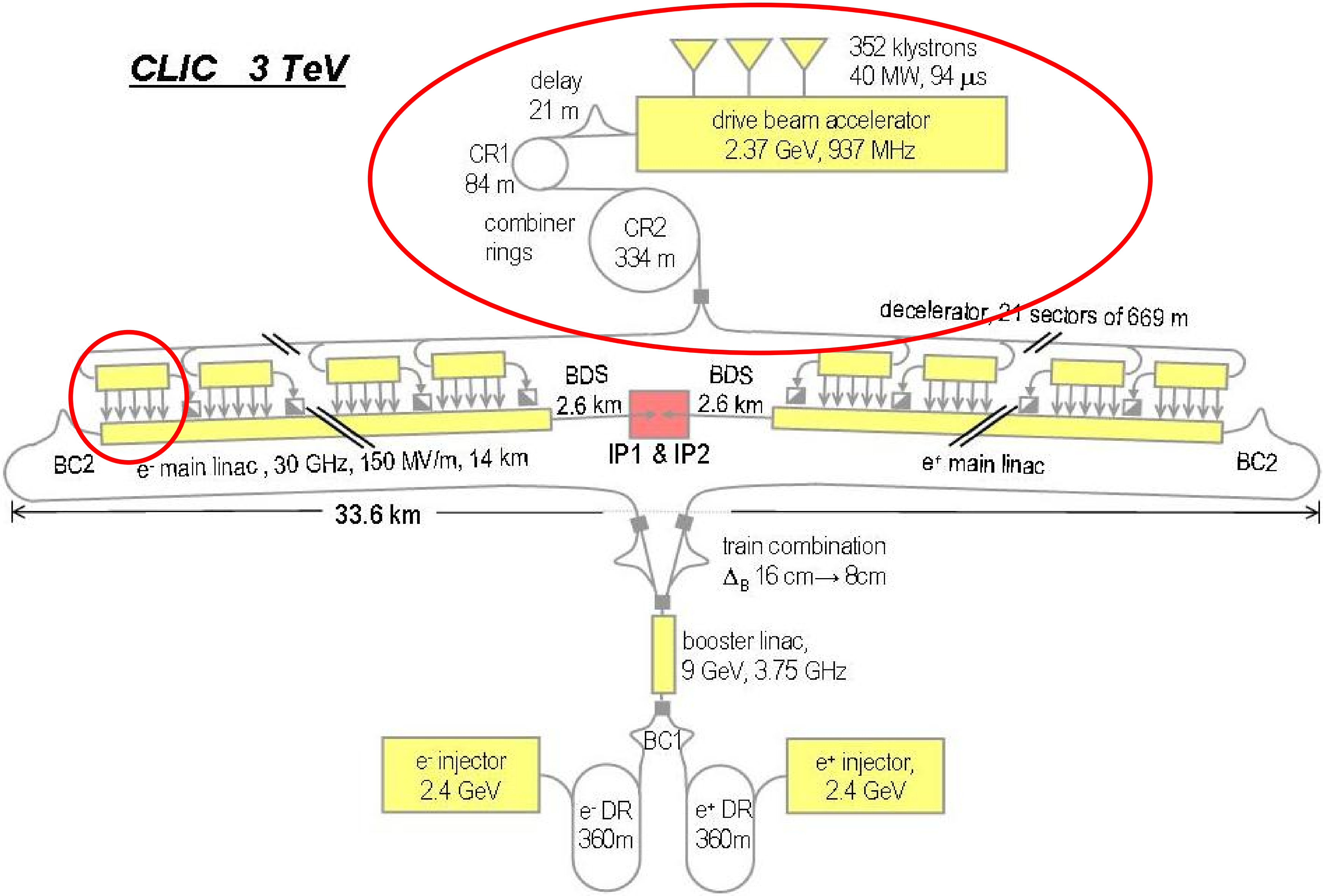
Klystron, the conventional RF power source



CPI Millitron
>500W avg.
@95 GHz

Limited by space charge and power density
Relativistic Klystron, Two beam accelerator scheme

CLIC schematic



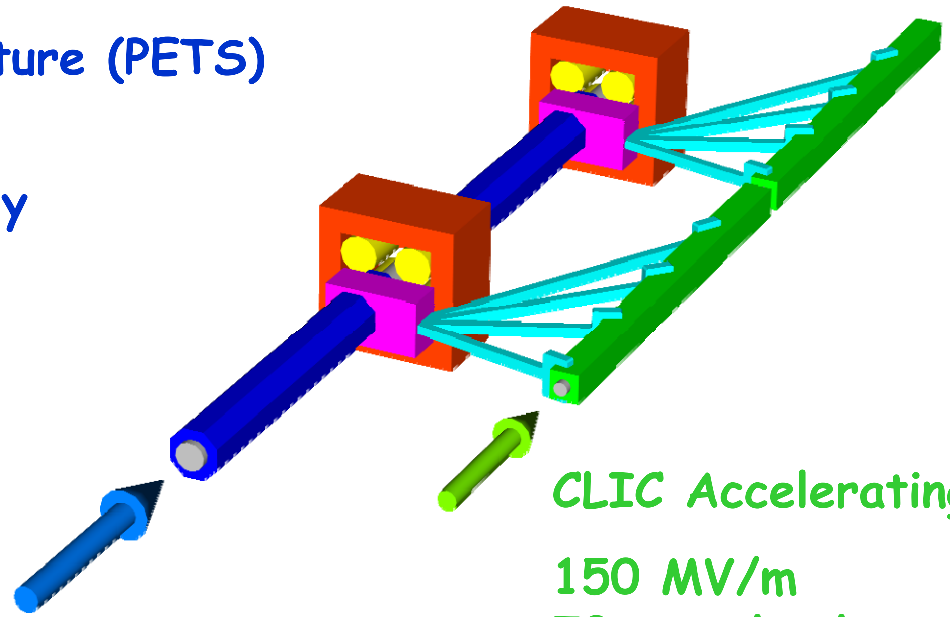
Two Beam Accelerator

Power Extraction Structure (PETS)

642 MW output Power
94 % transfer efficiency

Drive beam:

2.37 - 0.237 GeV
181 A
70 ns



CLIC Accelerating Structure

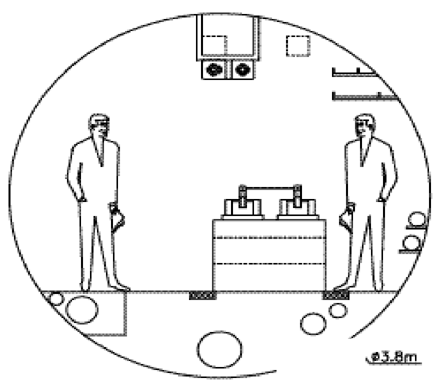
150 MV/m
70 ns pulse length
150 MW input Power

Main Beam:

9-1500 GeV
1.5 A
60 ns

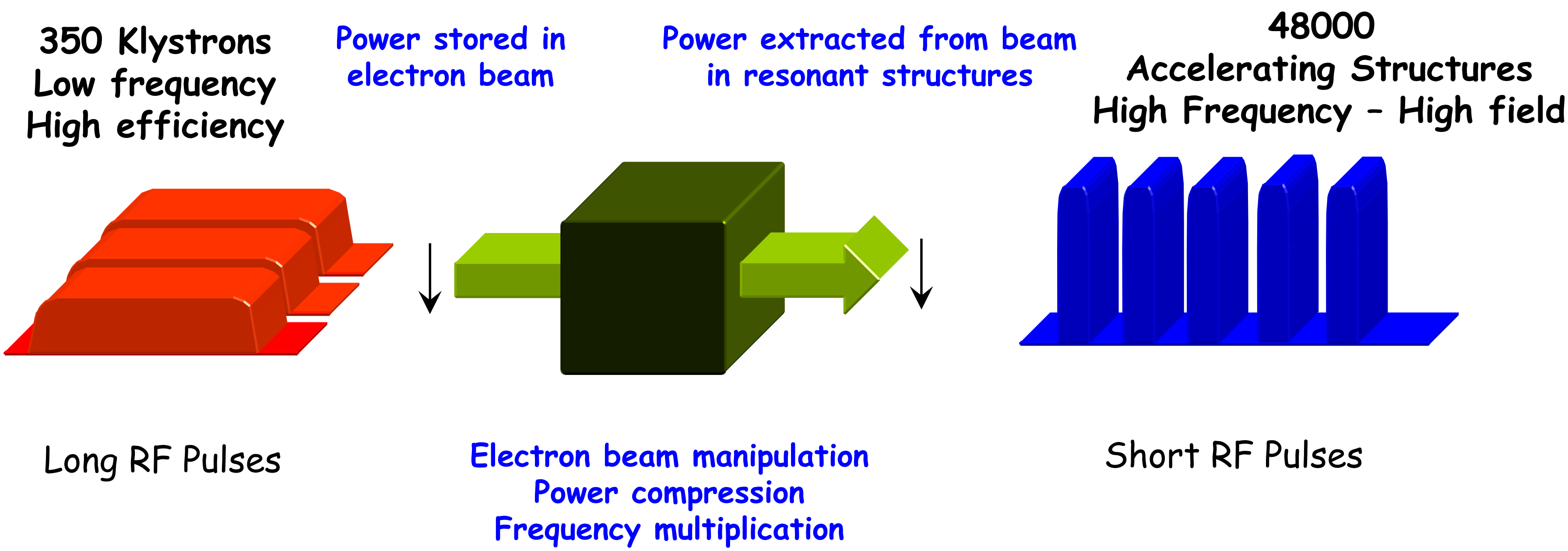
CLIC TUNNEL
CROSS-SECTION

3.8 m diameter



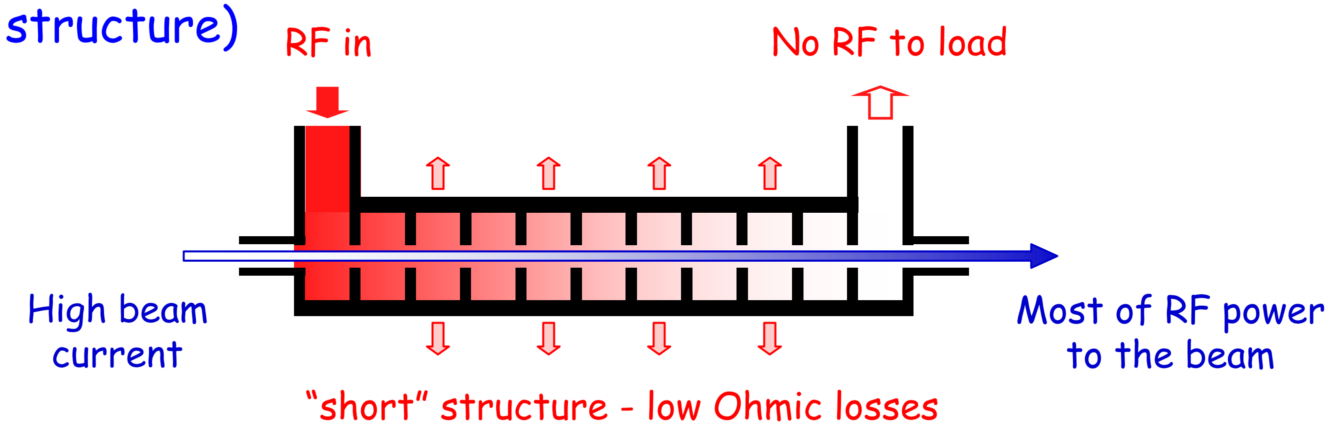
Drive Beam, an efficient power source

- No conventional power source (klystrons) existing
- Extract RF power at 30 GHz from an intense e- "drive beam"
- Generate efficiently long pulse and compress it (in power + frequency)

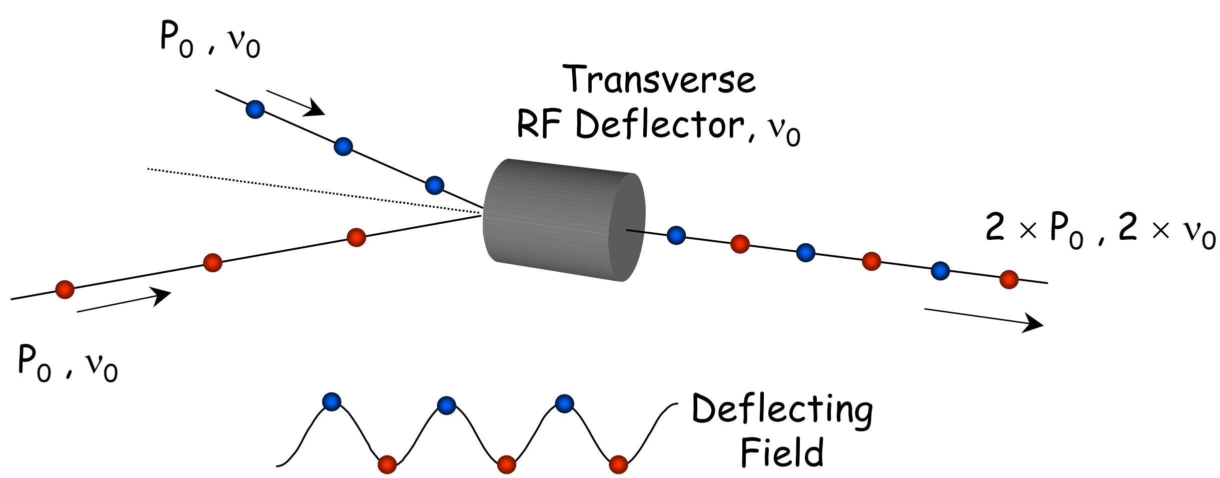


Drive Beam Generation

Efficient acceleration
(Full beam loading in nc structure)

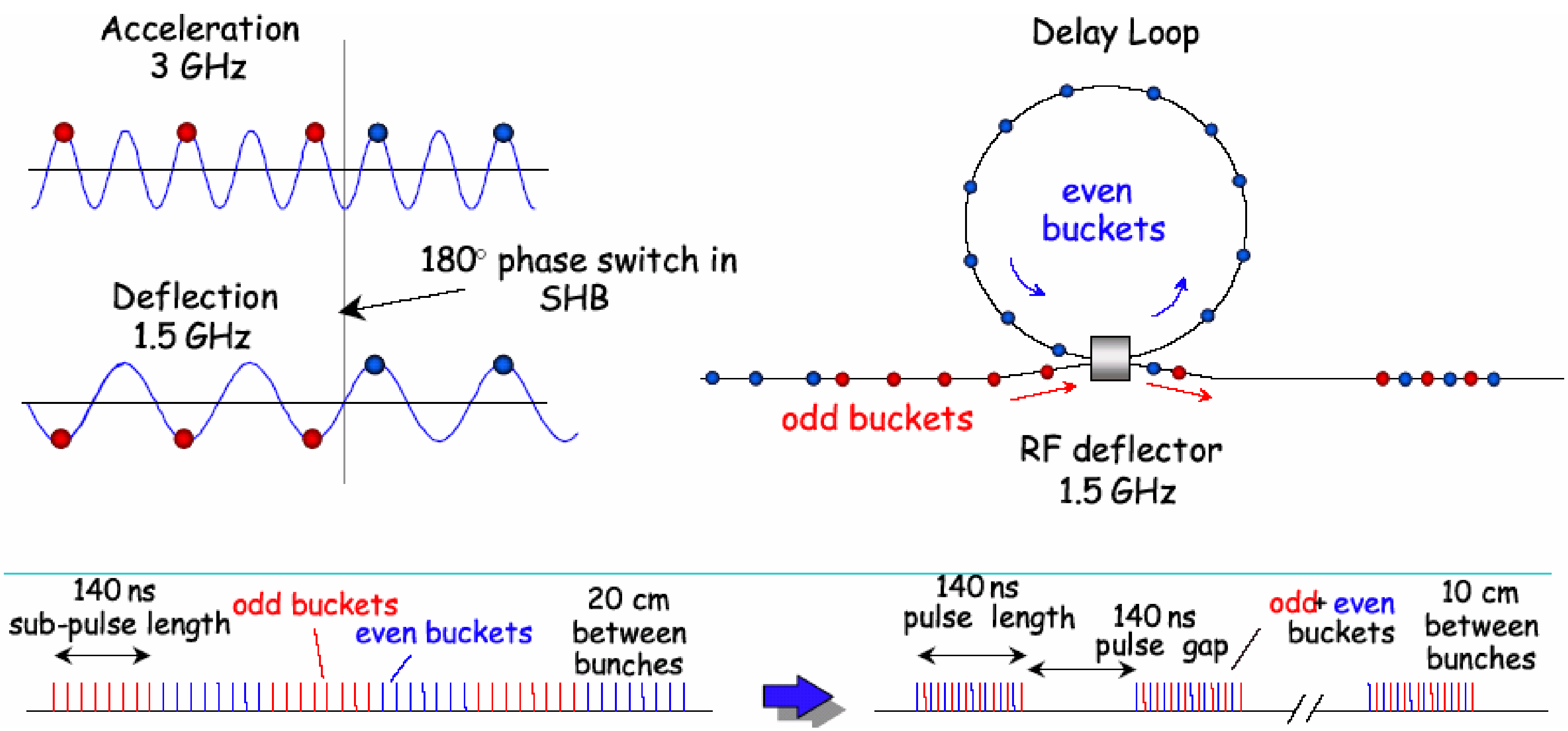


Frequency Multiplication
(Beam combination using
RF deflectors)

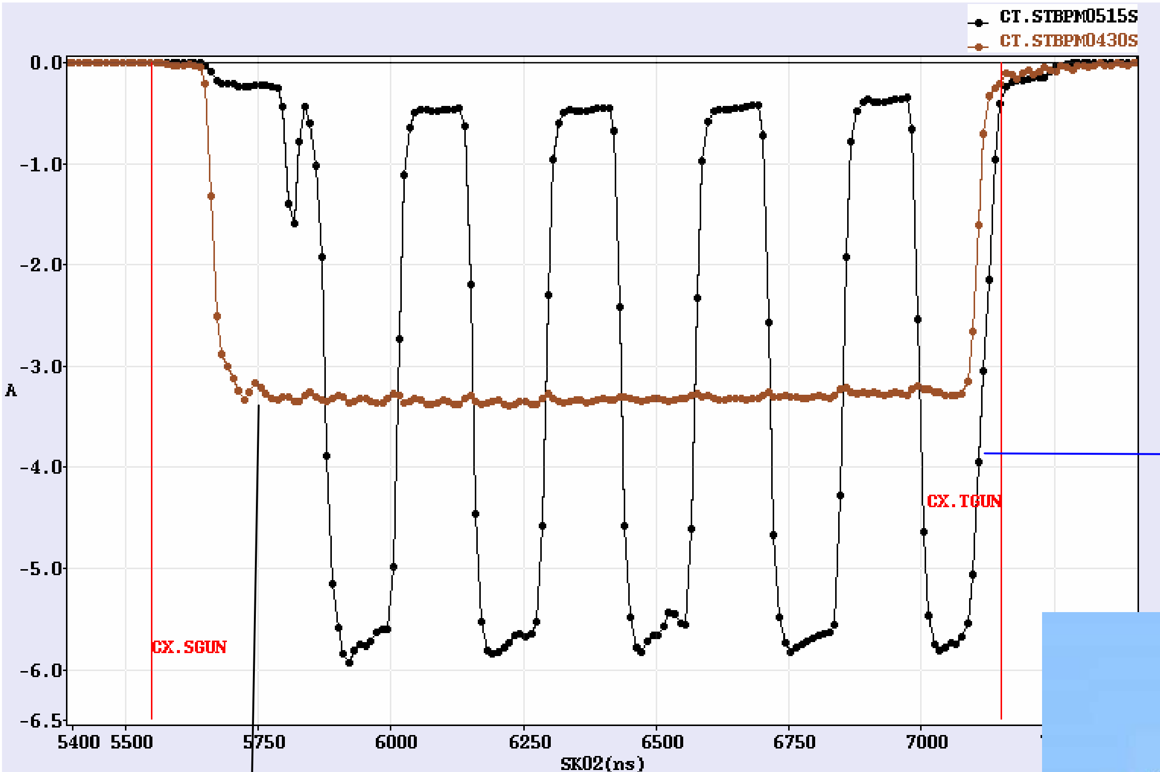


Delay Loop

- Double repetition frequency and current
- Parts of bunch train delayed in loop
- RF deflector combines the bunches

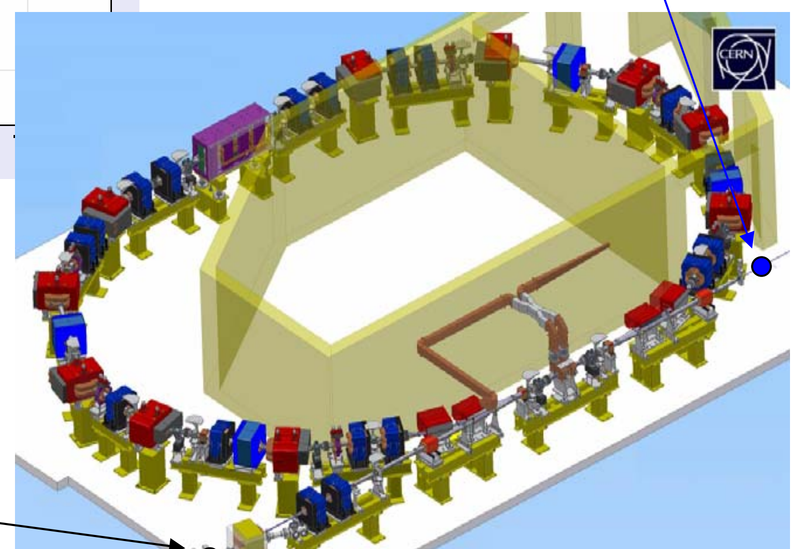


Delay Loop, First Results

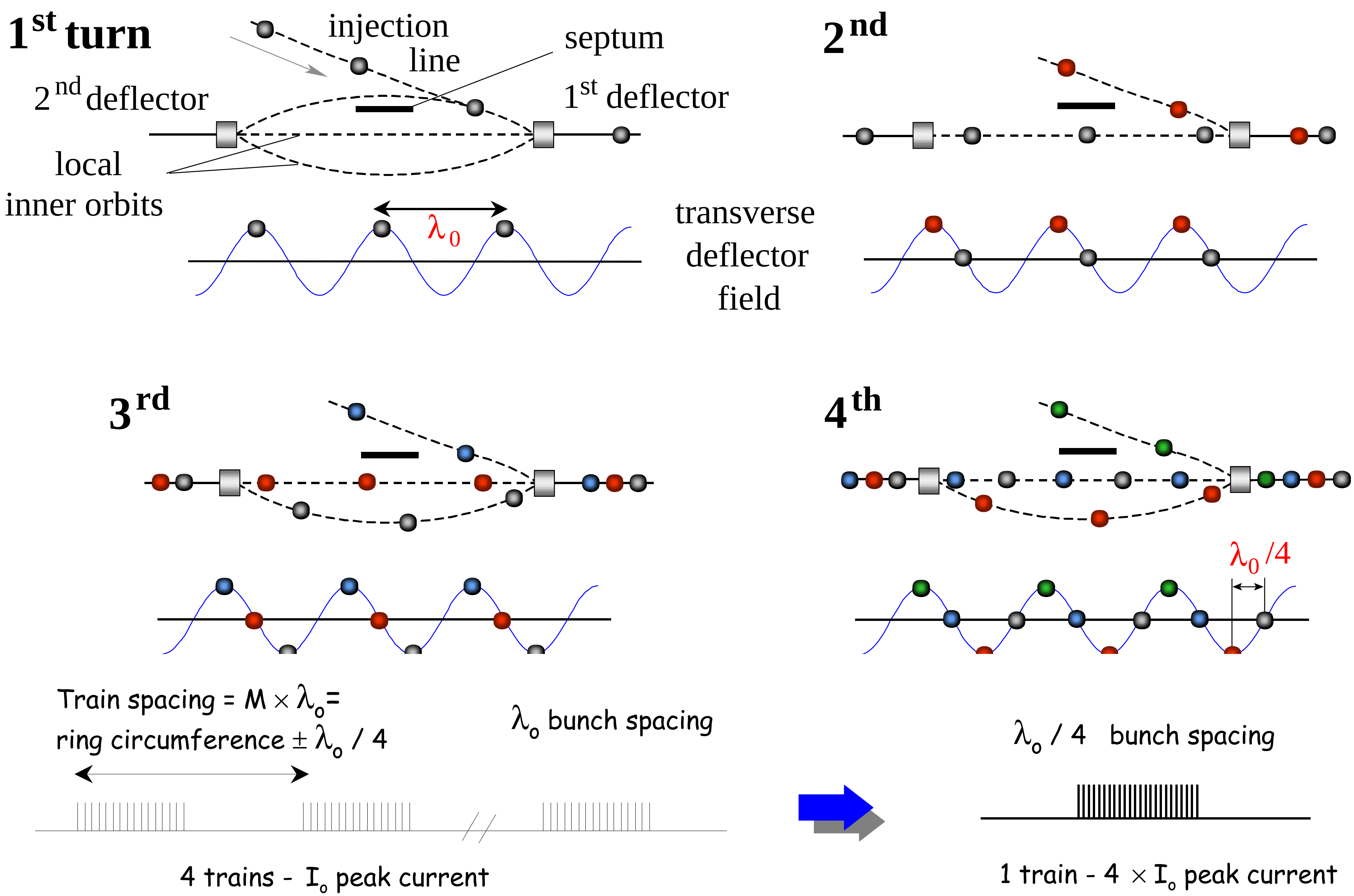


CT.BPM 515
5.8 A + 0. 5 A

CT.BPM 430
3.3 A



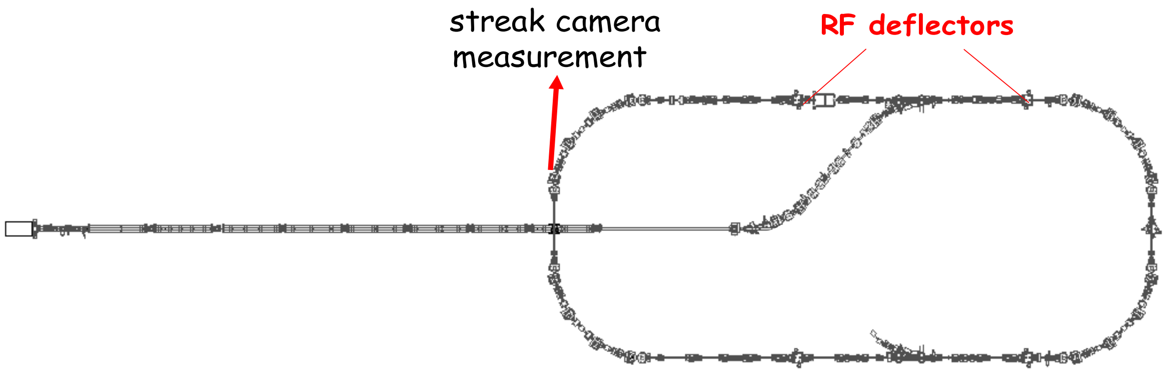
Combiner Ring

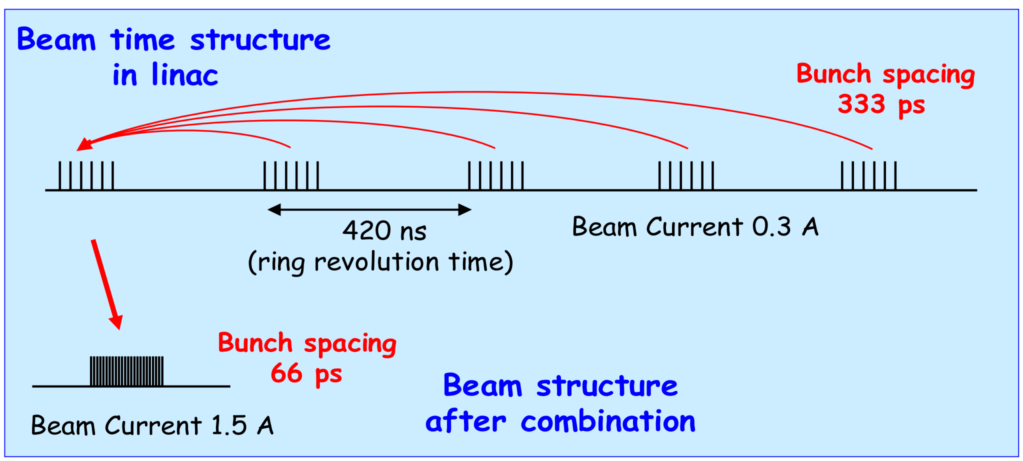


Proof of Principle

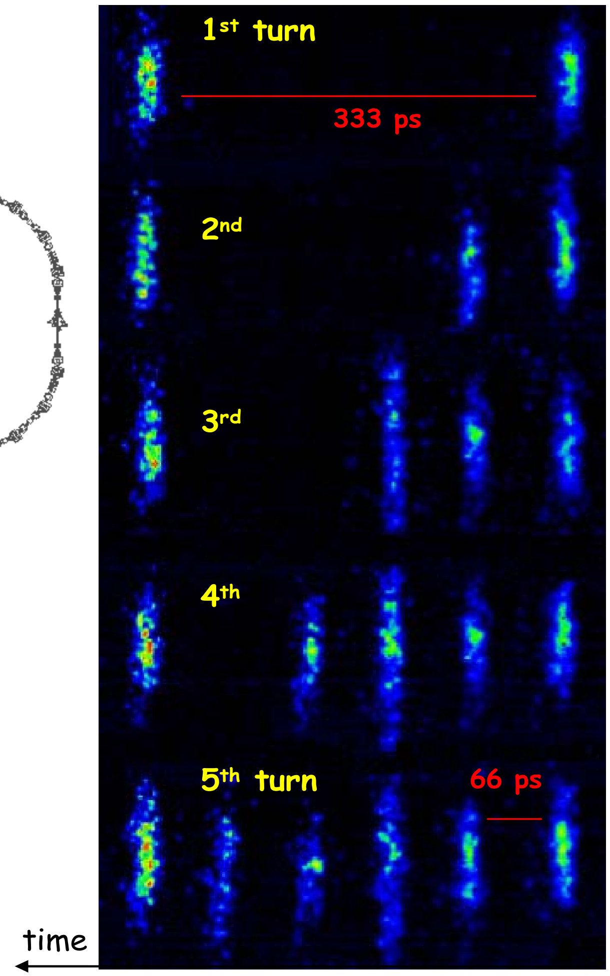
CTF3 - PRELIMINARY PHASE

Successful low-charge demonstration of electron pulse combination and bunch frequency multiplication by up to factor 5



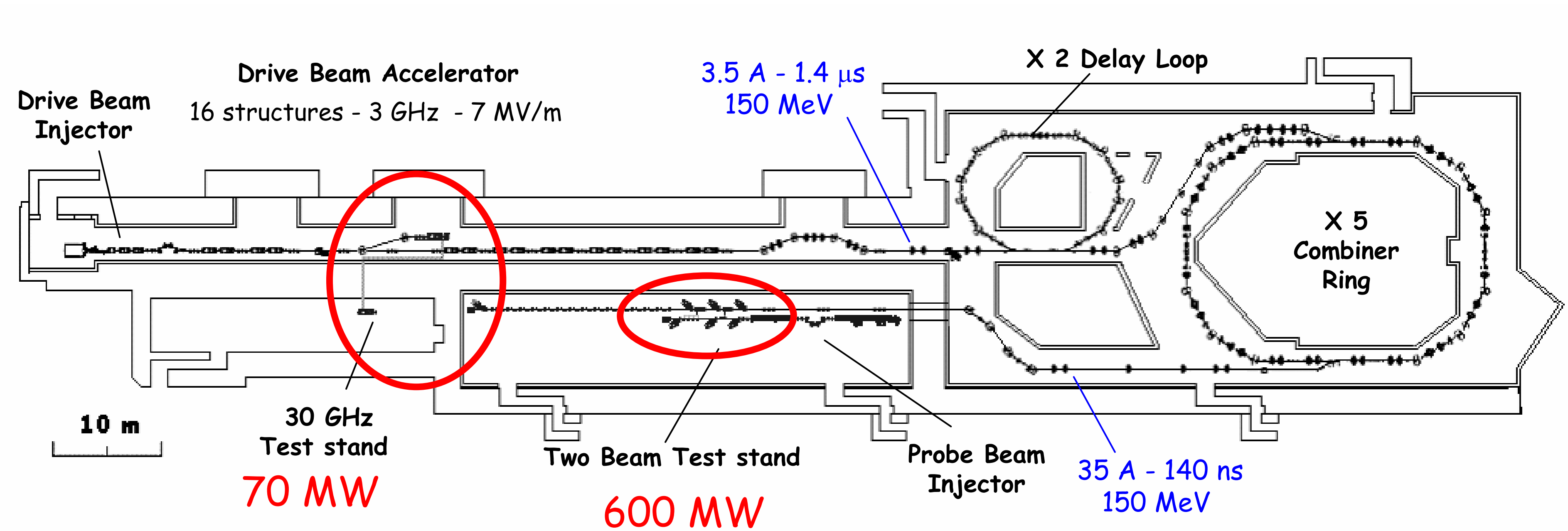


Streak camera image of
beam time structure evolution

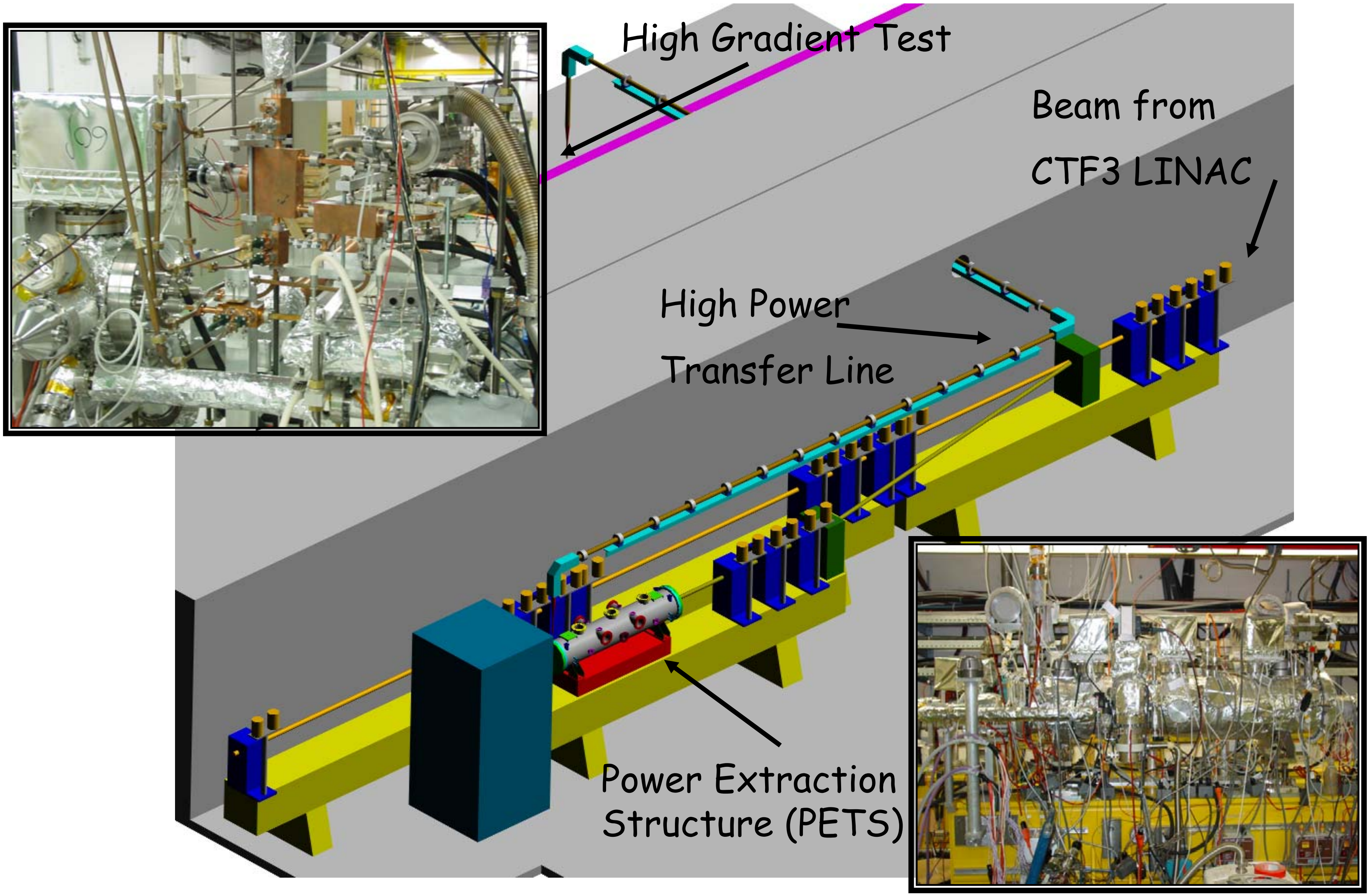


CTF3 overview

30 GHz power production

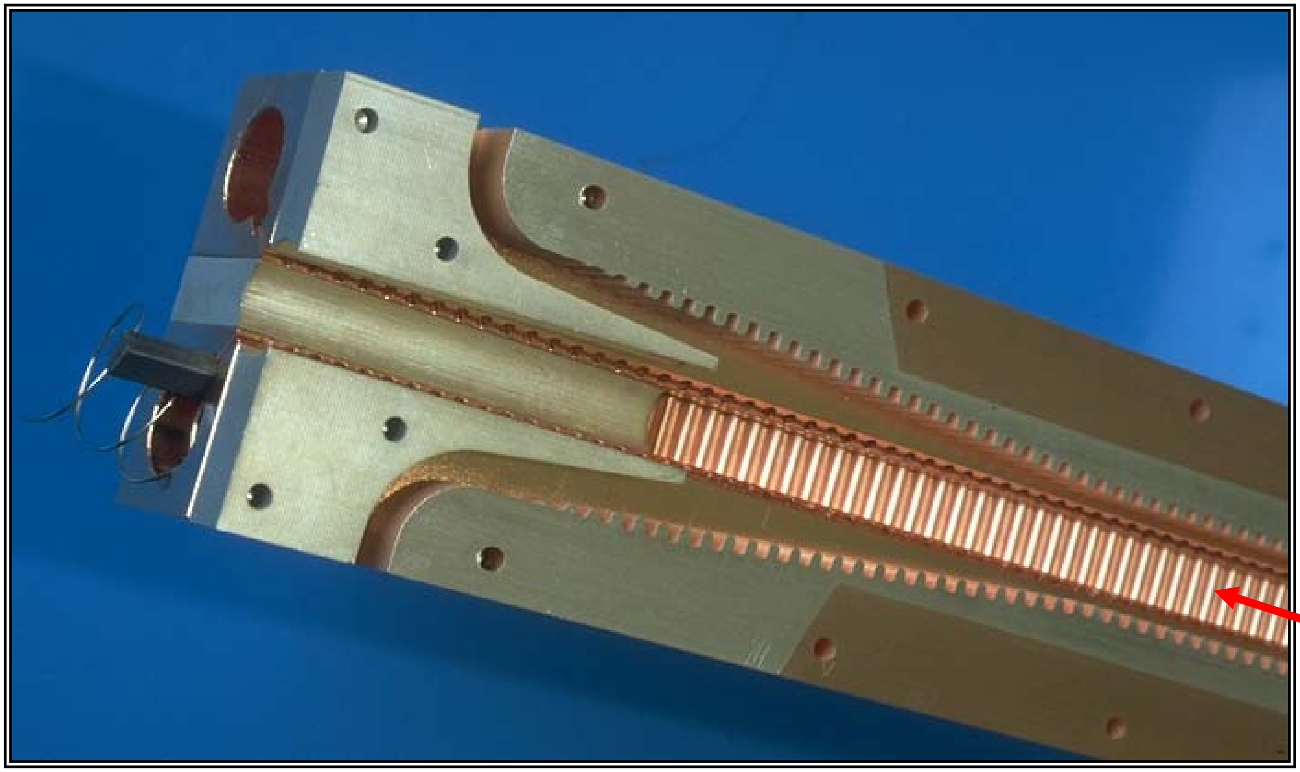


30 GHz Power Production in CTF3



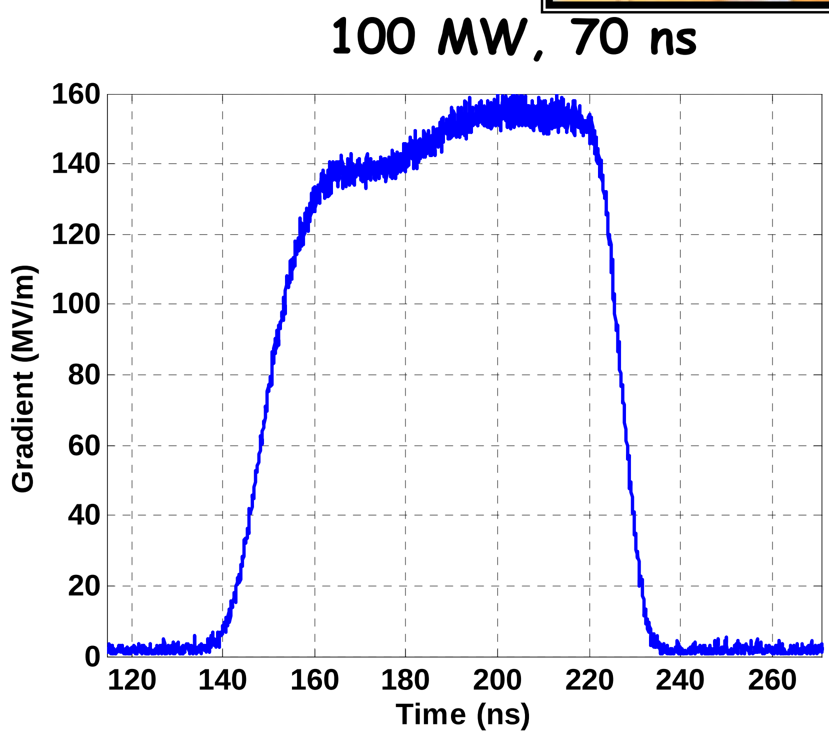
30 GHz Power Production in CTF3

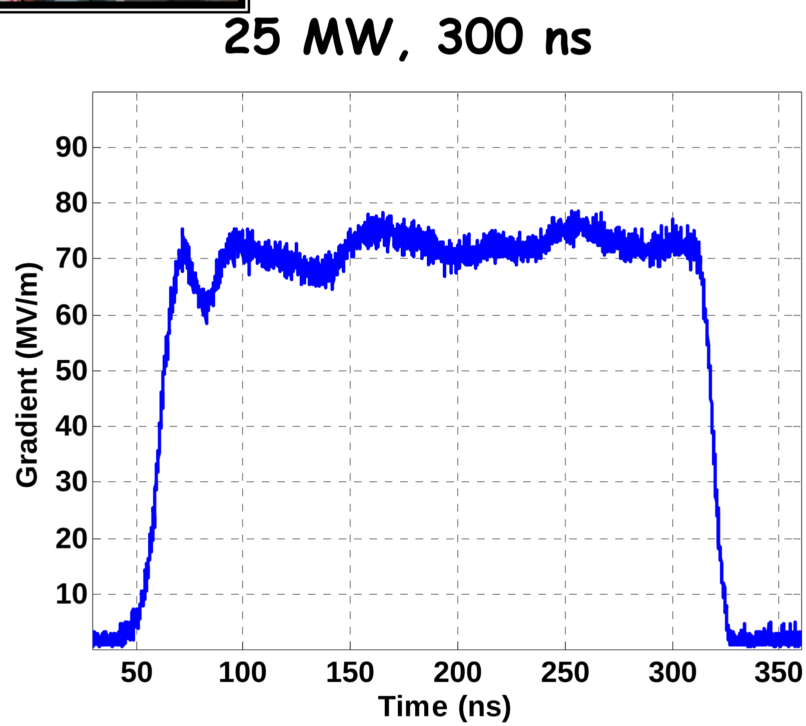
PETS = Power Extraction Structure



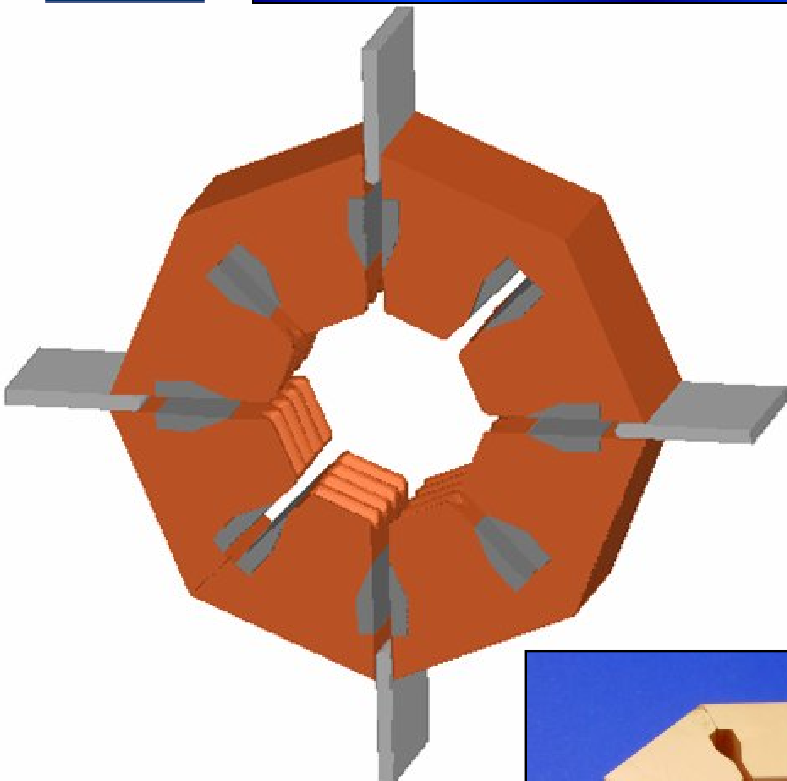
Beam

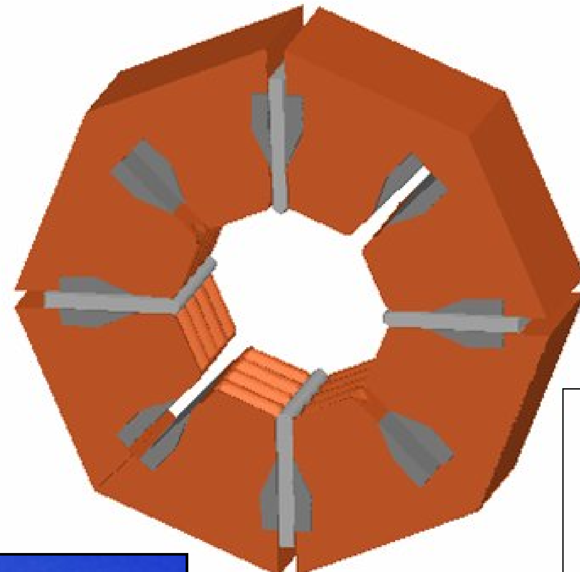
30 GHz Power Production in CTF3

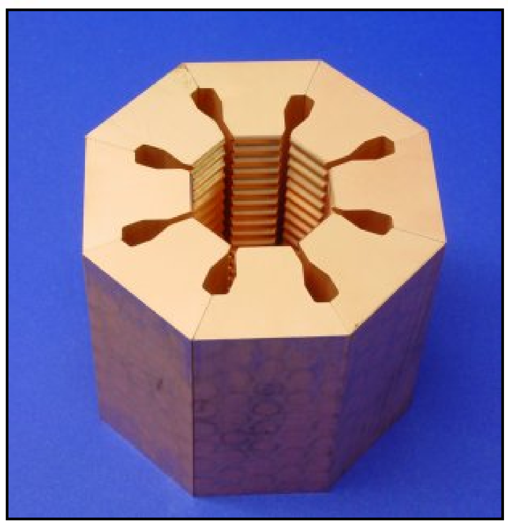




30 GHz Power Production for CLIC







PETS parameters:

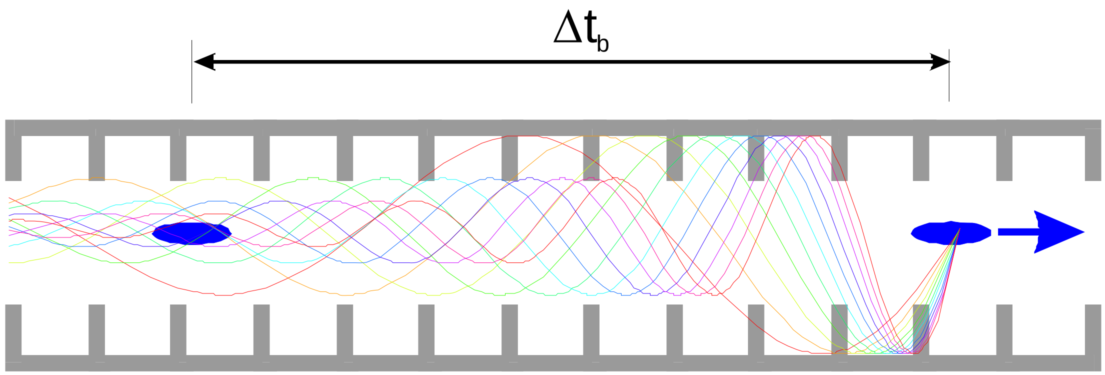
F= 29.9855 GHz
Aperture = 22.5 mm
R/Q = 320.2 Ohm/m
Beta = 0.798 *C*
$\Delta\varphi$/cell = 140^0
Active length = 0.6 m
Total length = 0.77 m
$I_{\text{Drive beam}}$ = 176 A
RF power = 642 MW
Damping slots: 8 x 2 mm
Extraction and
transfer efficiency = 94%

Igor Syratchev

Structure Design Constraints and Performance Requirements

- Wakefield control
  - aperture size, coupling slots
- Efficiency
  - pulse length, structure length, structure material
- Reliability (large scale accelerators)
  $< 10^{-6}$ trip probability
- RF breakdown and Pulse heating
  - surface fields (H and E), input power, pulse length, surface preparation, material

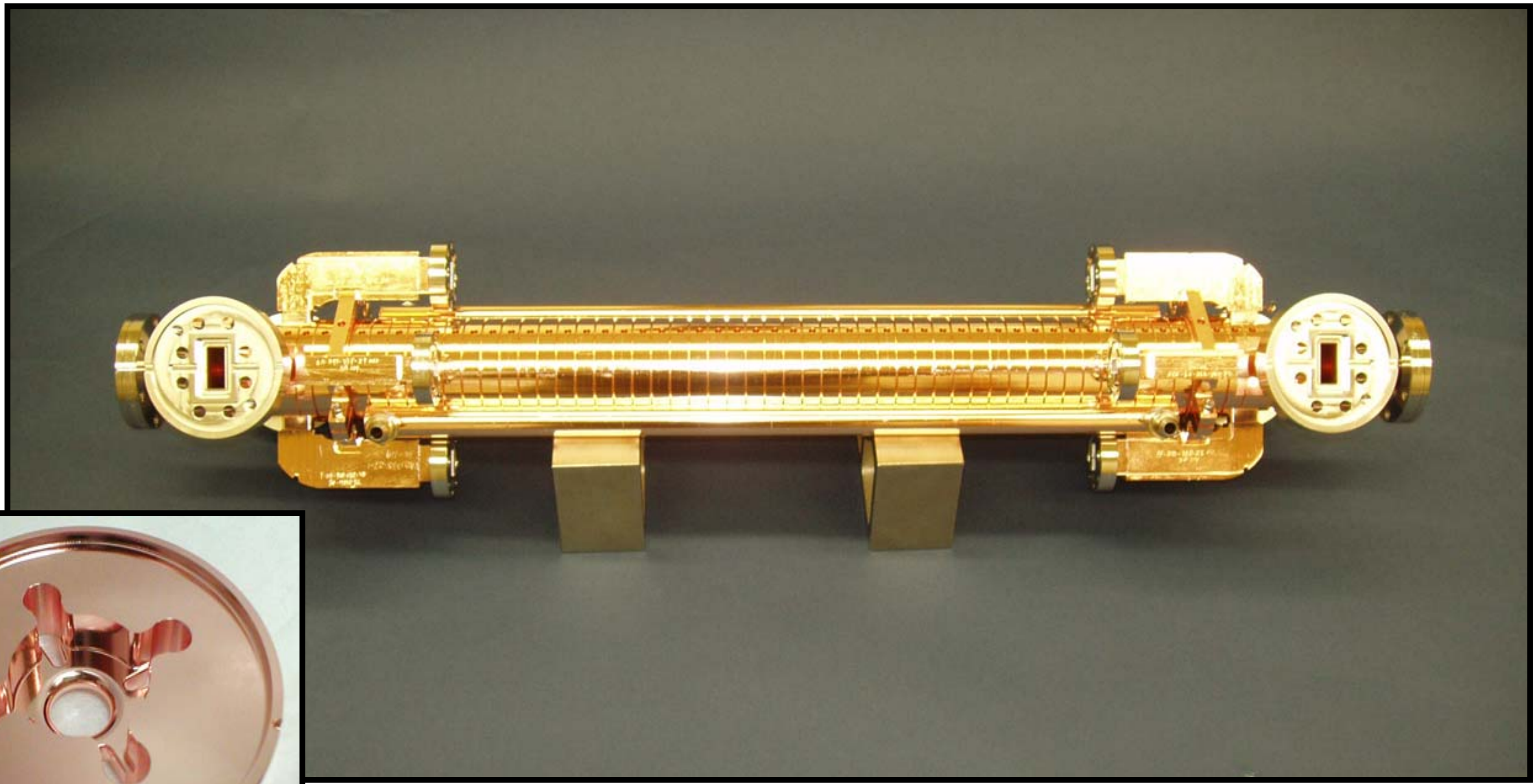
Wake fields



- Bunches induce fields which perturbs later bunches
- Fields can build up resonantly
- Bunches passing off-centre excite transverse higher order modes (HOM)
- Later bunches are kicked transversely
  → Emittance growth!!!
- Long-range wakes minimized by structure design
- Short-range wakes minimized by alignment

Classical structure from NLC

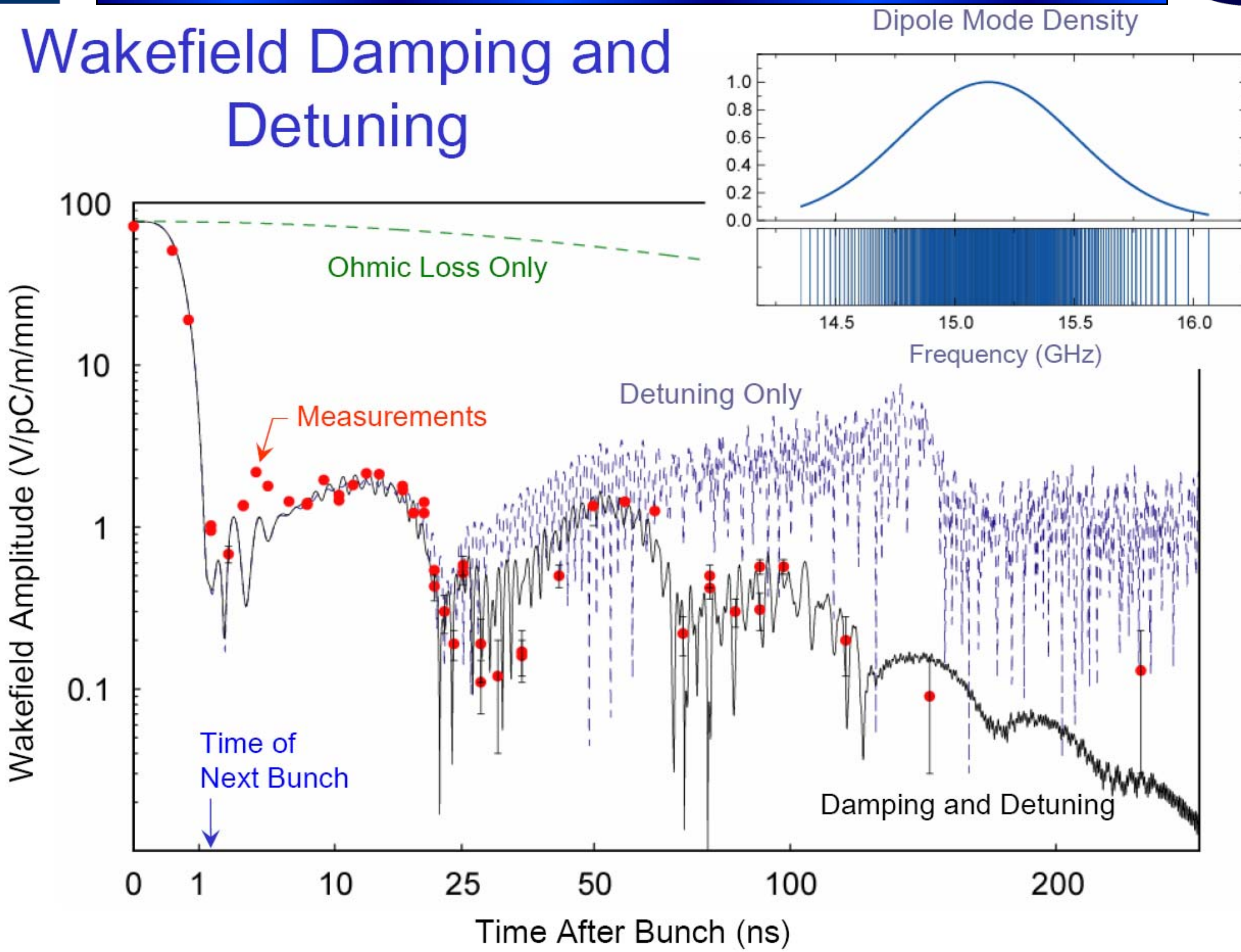
NLC/GLC development by SLAC/KEK/FNAL



11 GHz, 65 MV/m, 400 ns

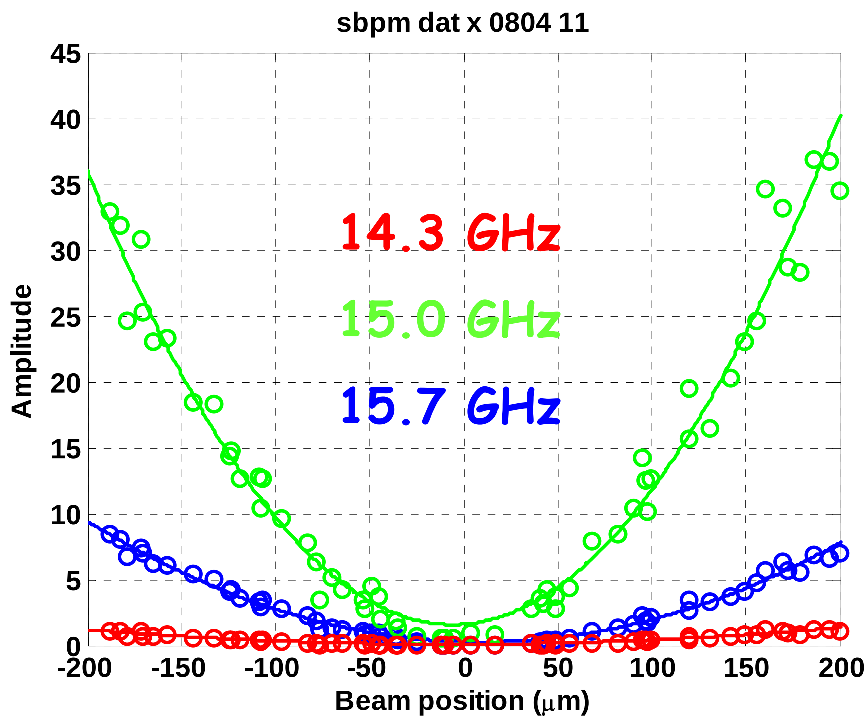
Wake fields

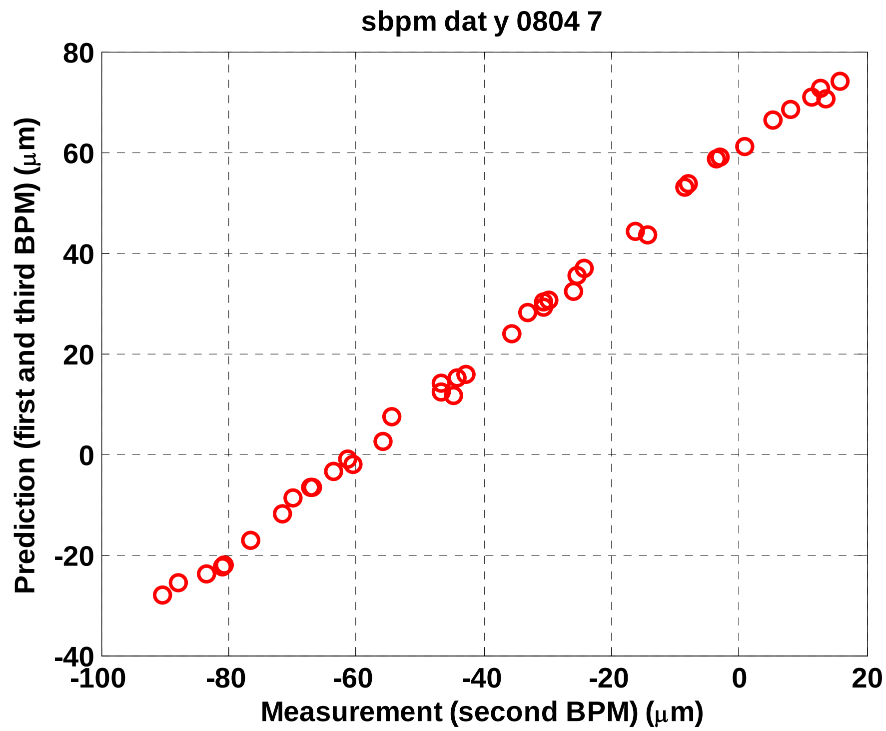
Wakefield Damping and Detuning



Beam Based Alignment

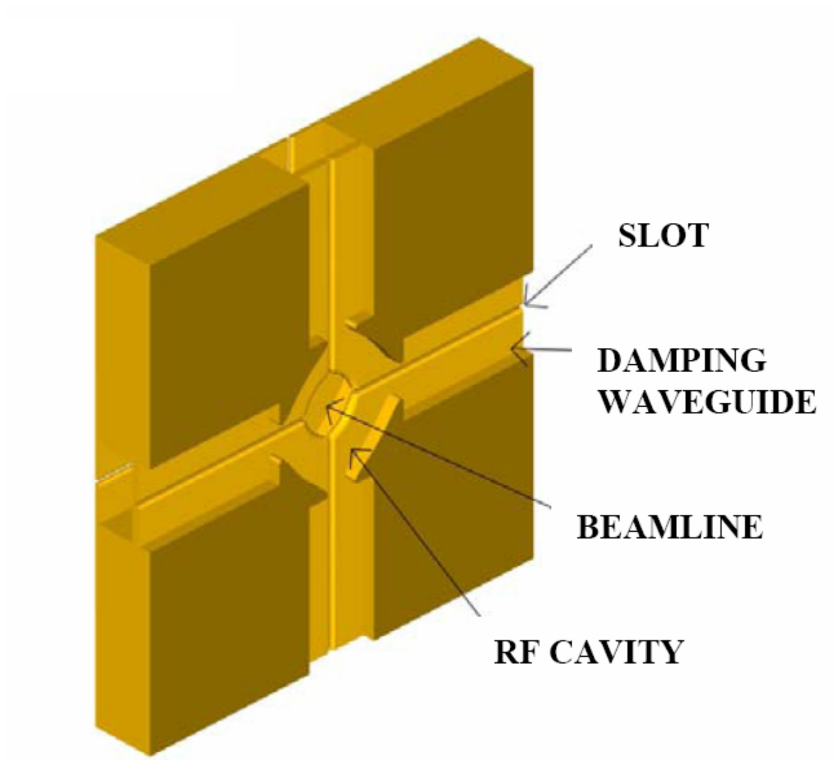
ASSET 2005 – S-BPM Measurements

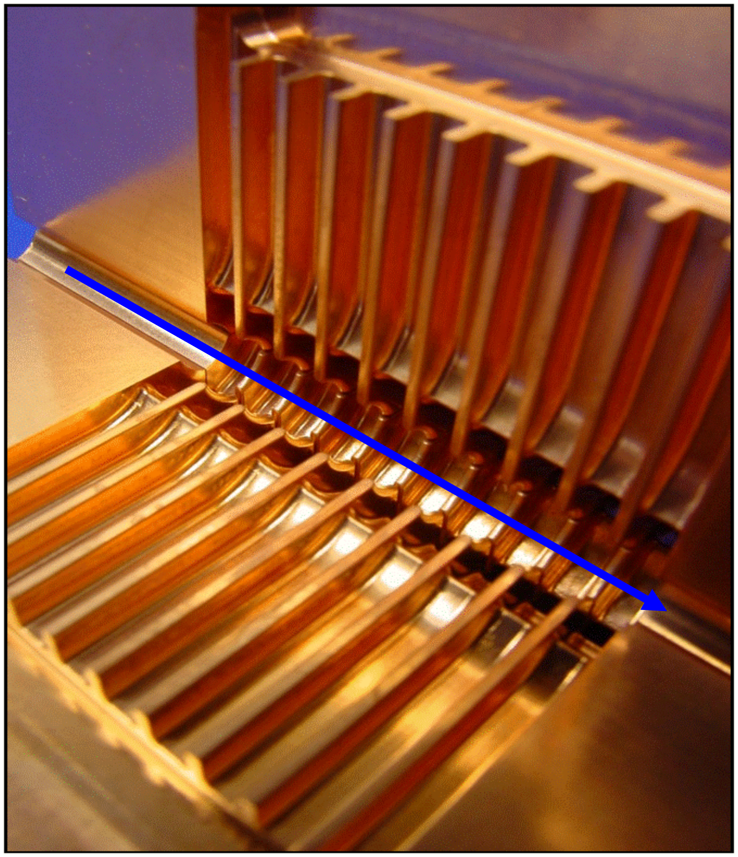




Measured resolution: below 1 micron

New Ideas from CLIC

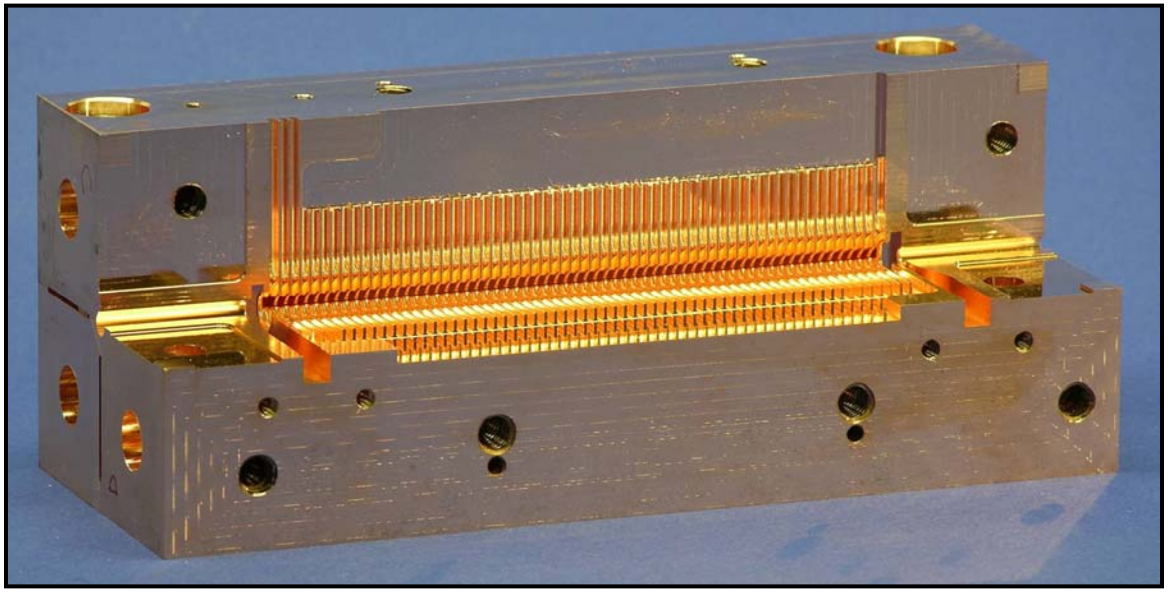


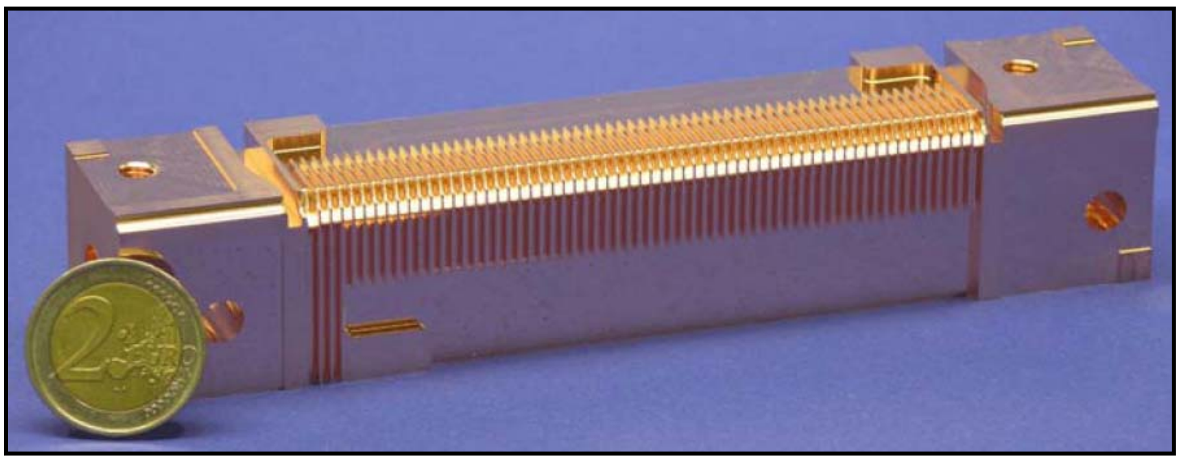


30 GHz, 150 MV/m, 70 ns, < 10^{-6} trip probability

Alexej Grudiev

New Ideas from CLIC





Currently being installed for testing !

Alexej Grudiev

What Happens in an RF breakdown

Breakdown Trigger

Field emission: Es*β

Es high

β,Hs high

Local heating, ion creation

Ohmic heating, particle bombardment, gas desorption and ionization
melting and vaporization
resonant secondary emission

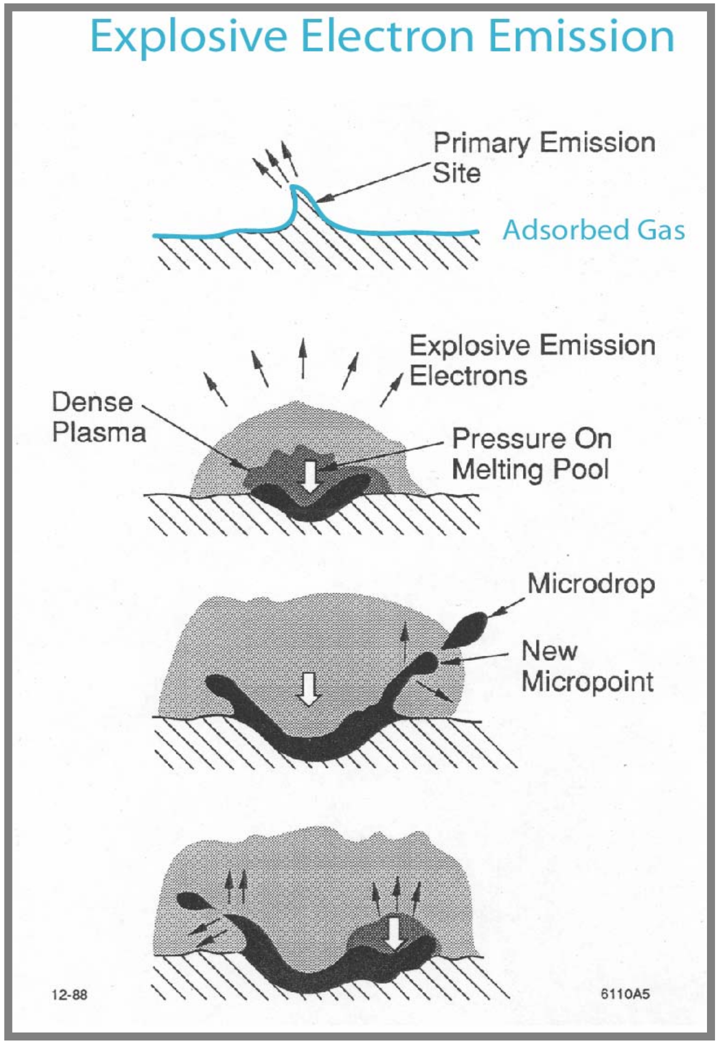
Plasma phase, energy absorption, run-away condition

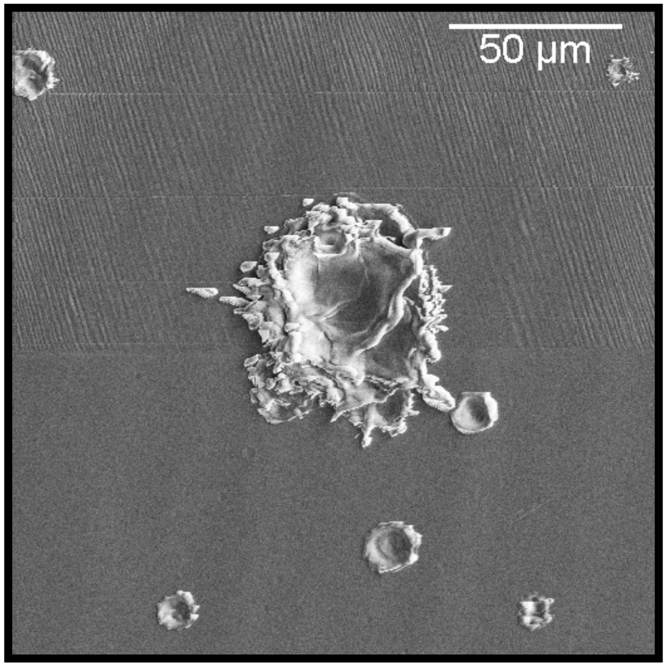
High density Plasma builds up and absorbs most energy

RF fields driven:
high electrical surface fields

Defect driven:
Particles, voids, oxides

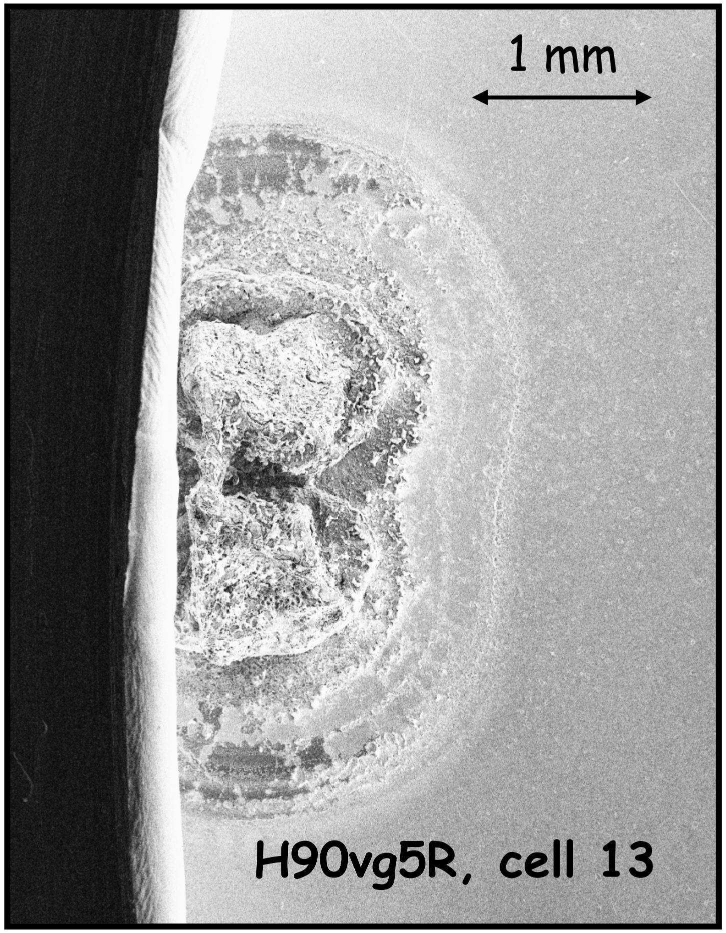
What Happens in an RF breakdown



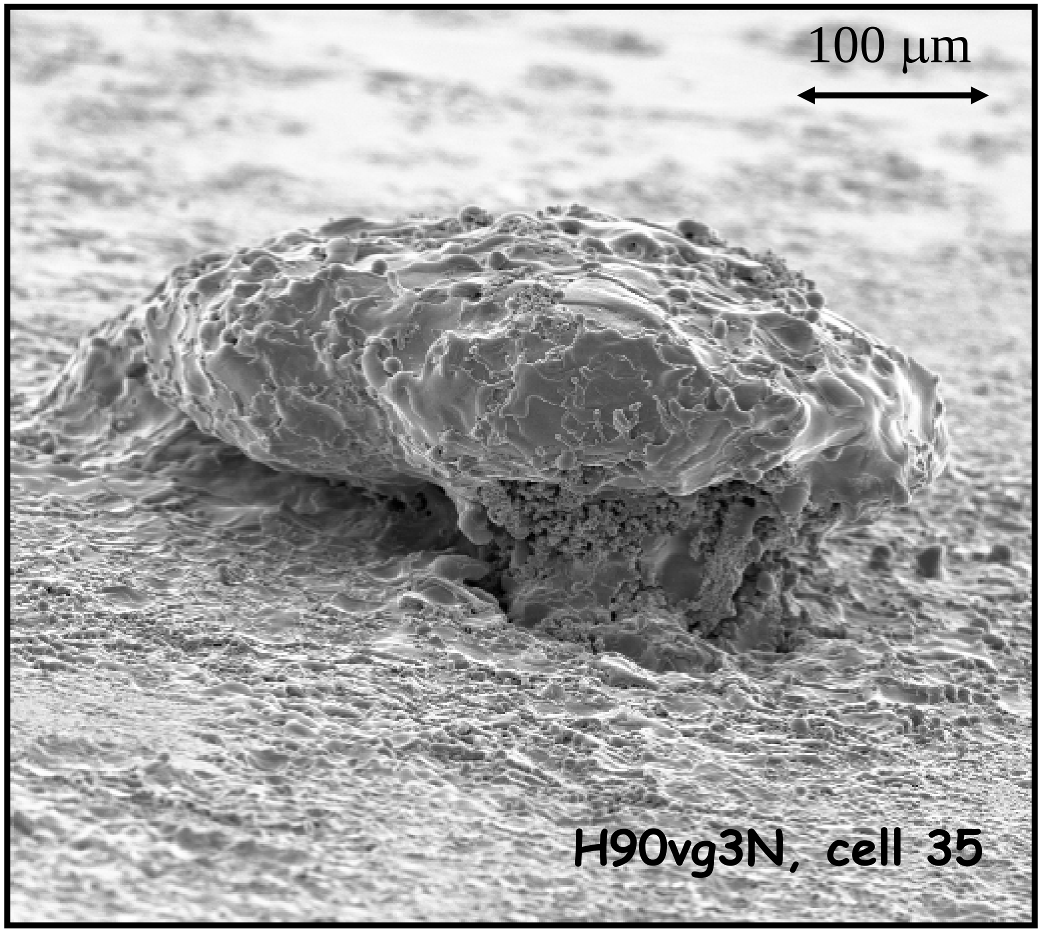


What Happens in an RF breakdown

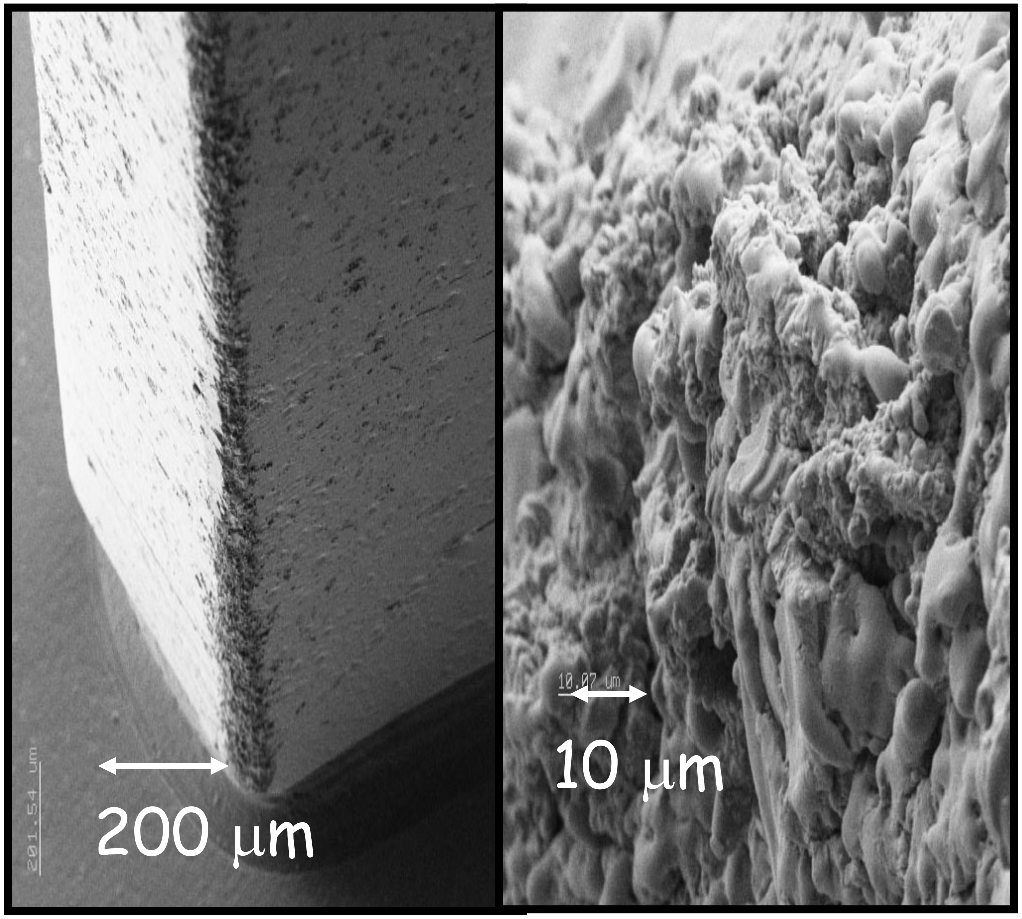
Aluminum

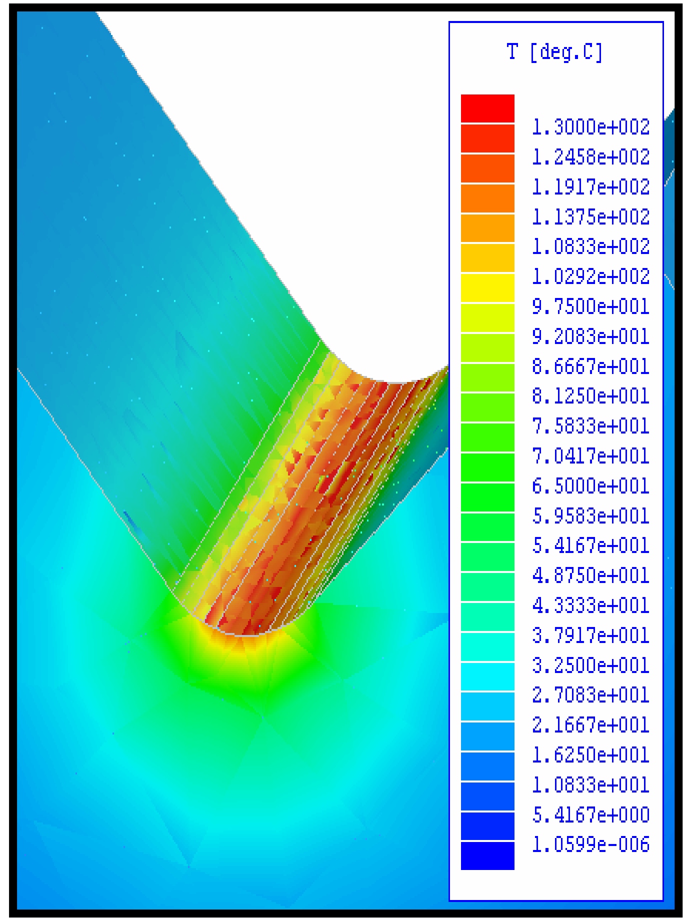


Stainless steel



What Happens in an RF breakdown

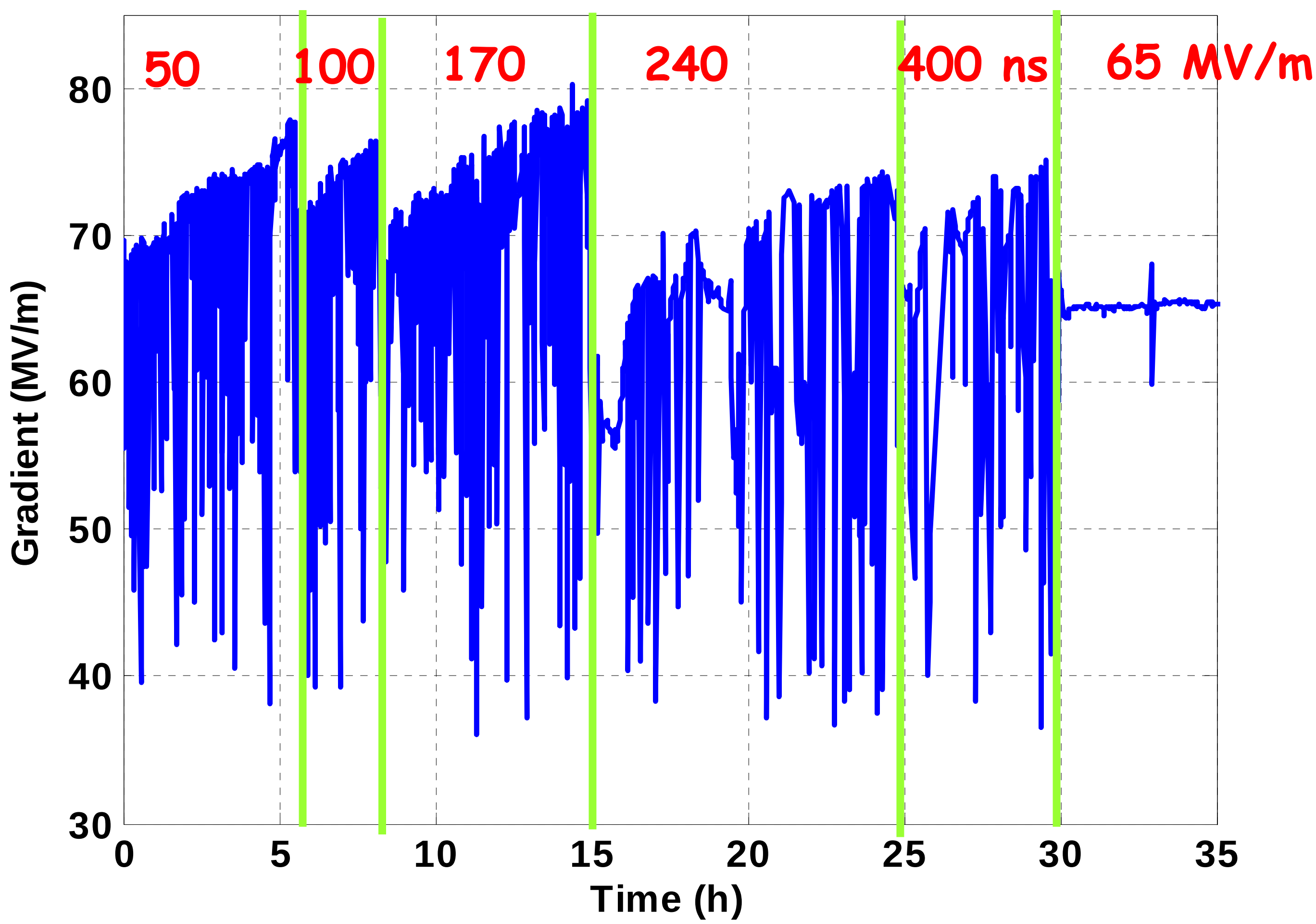




130 K pulse heating at 400 ns pulse length

Rule of thumb: < 50 k pulse heating is safe

Structure processing

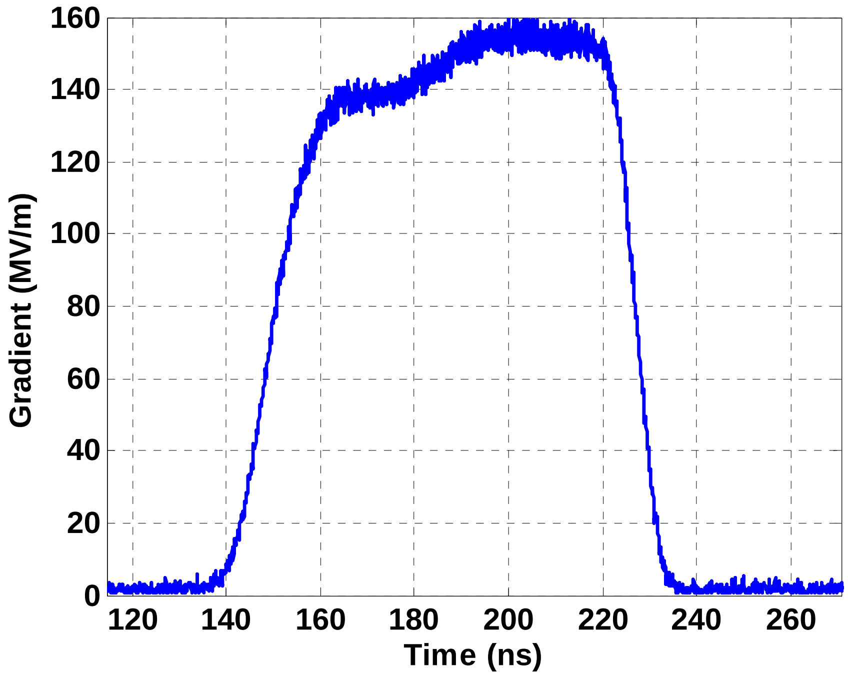


Examples from CTF3

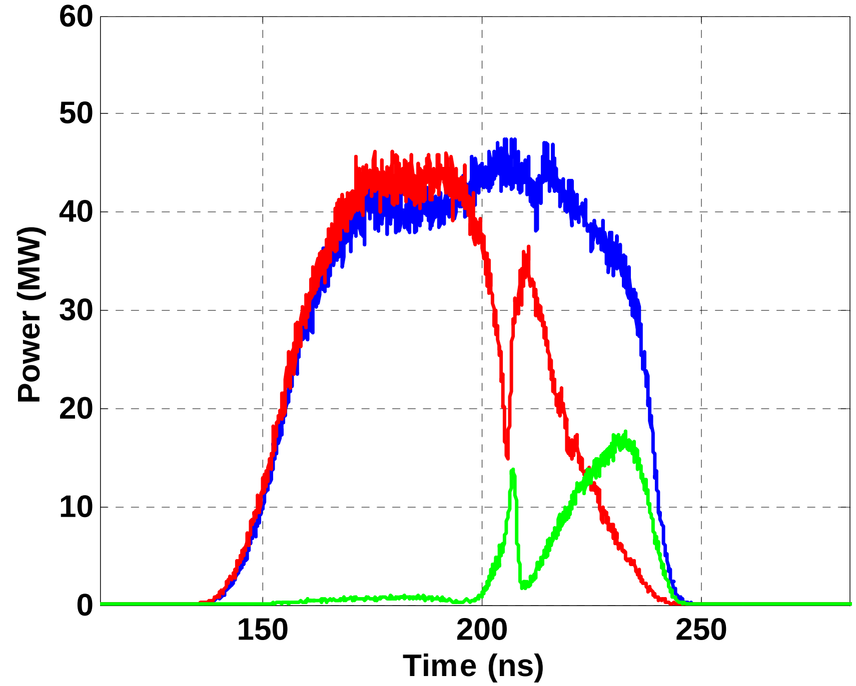
Molybdenum Structure

~ 60 ns, 150 MV/m

RF Pulse Example



with break down



Trip Rate a figure of merit

NLC a example of a large scale accelerator (30 km)

18000 structures , 2% operational overhead,
10 s trip recovery, 100% availability

→ trip rate > 0.1/h at 60 Hz

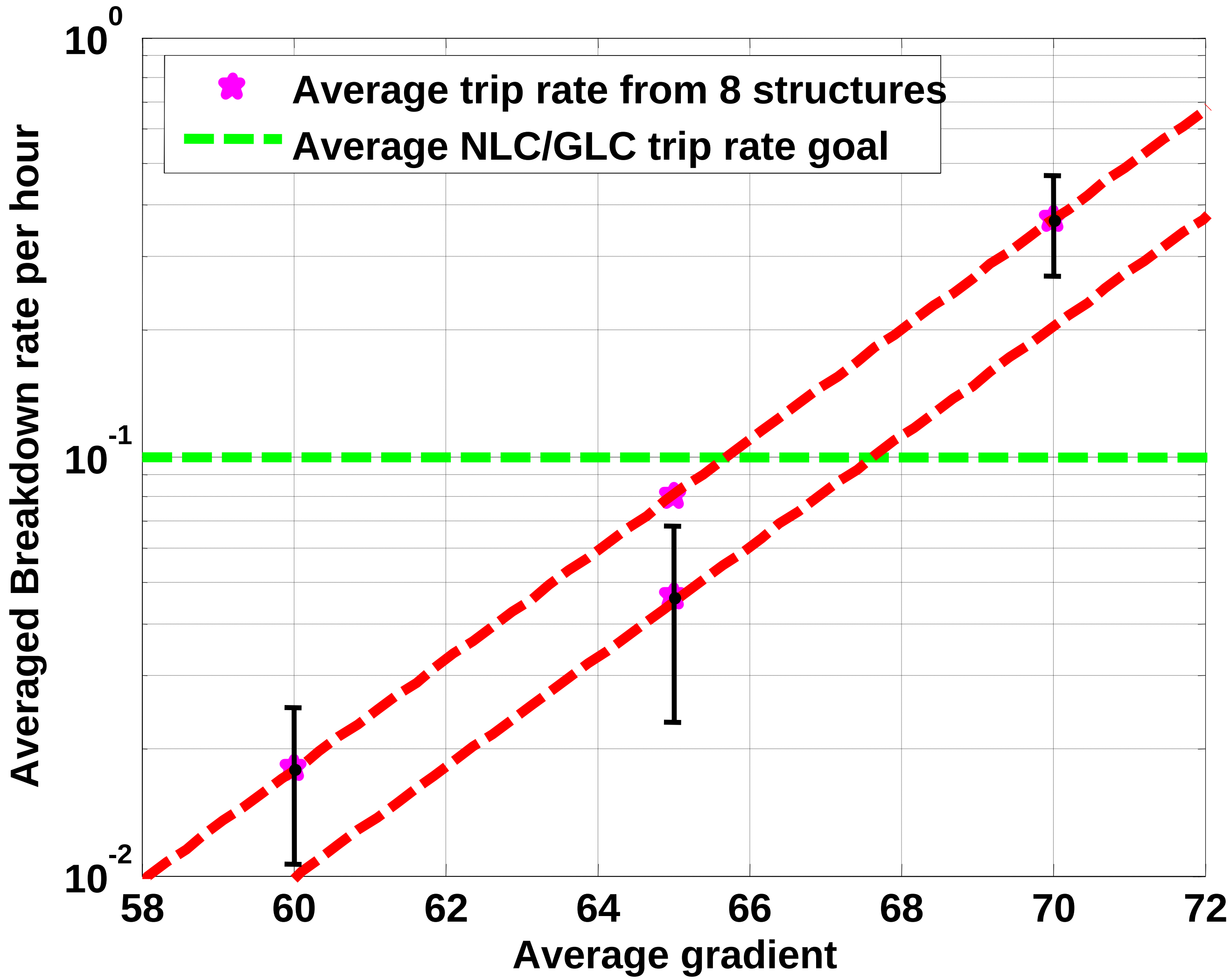
(5 s, 99% availability → trip rate 0.4/h)

Still a trip every second !

Assumption that breakdown kicks reduce luminosity on the pulse but wouldn't hit the collimators

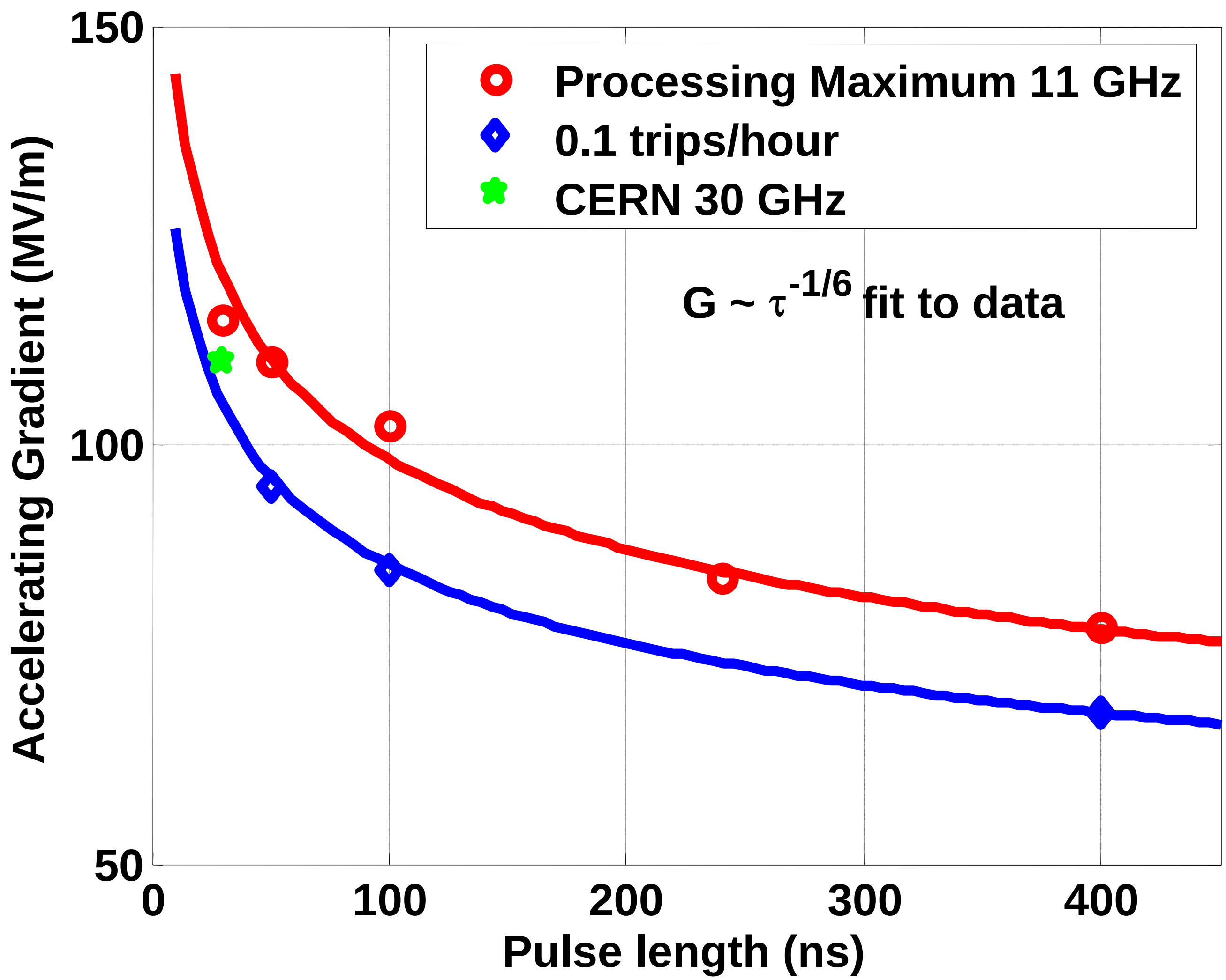
Very similar number for CLIC

Trip Rate vs Accelerating Gradient



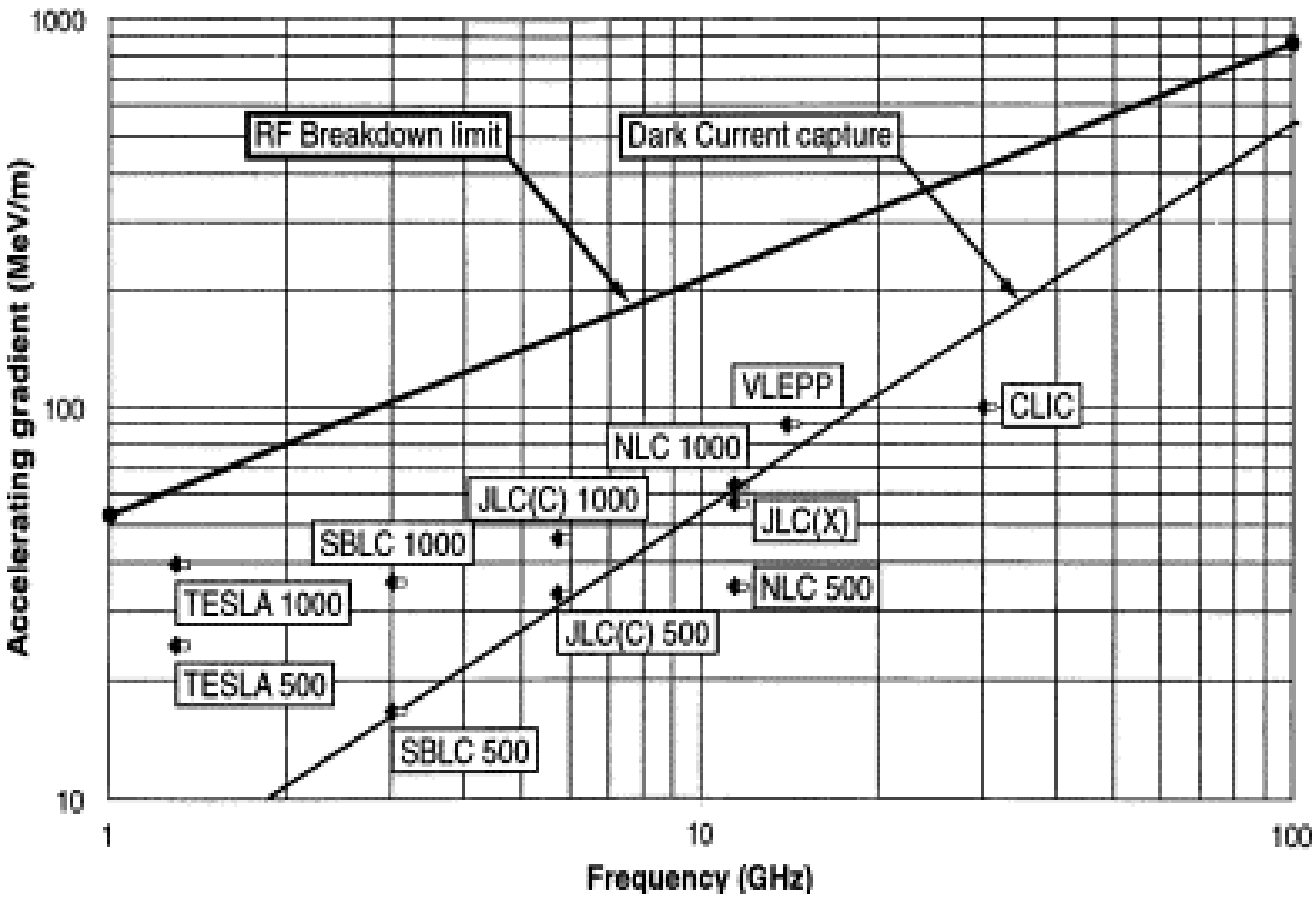
Average trip rate after 500 h and 1500 h at 65 MV/m

Pulse Length Dependence



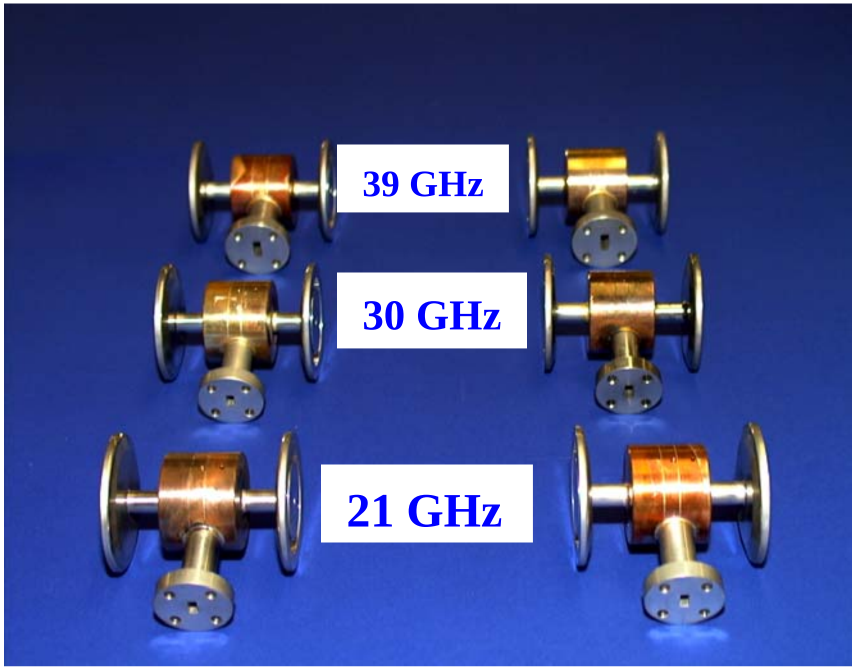
Frequency Dependence

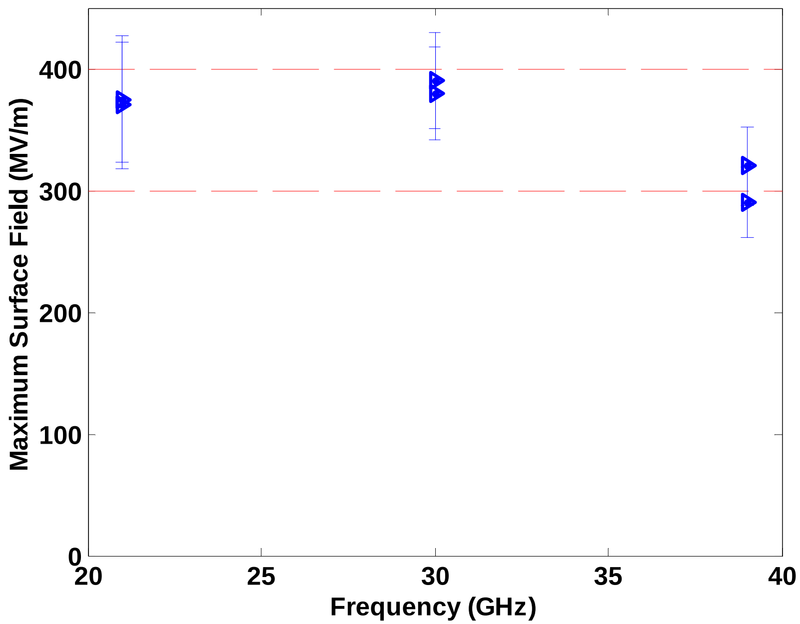
Kilpatrick type $G \sim f^{1/2}$



Frequency Dependence

High Gradient Single cells, CERN

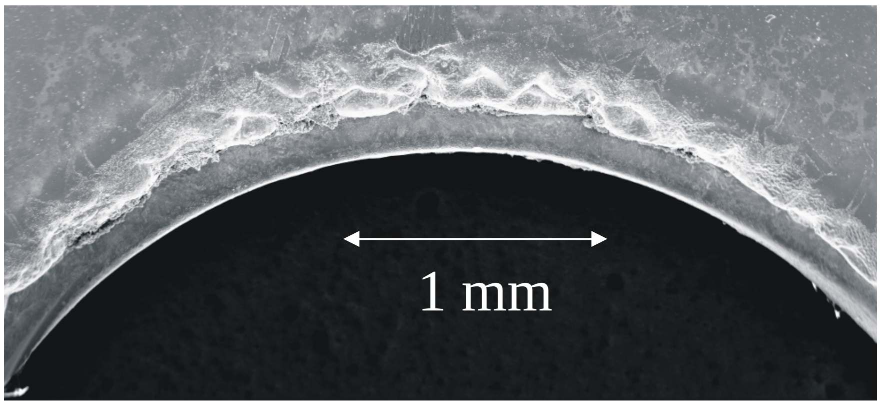


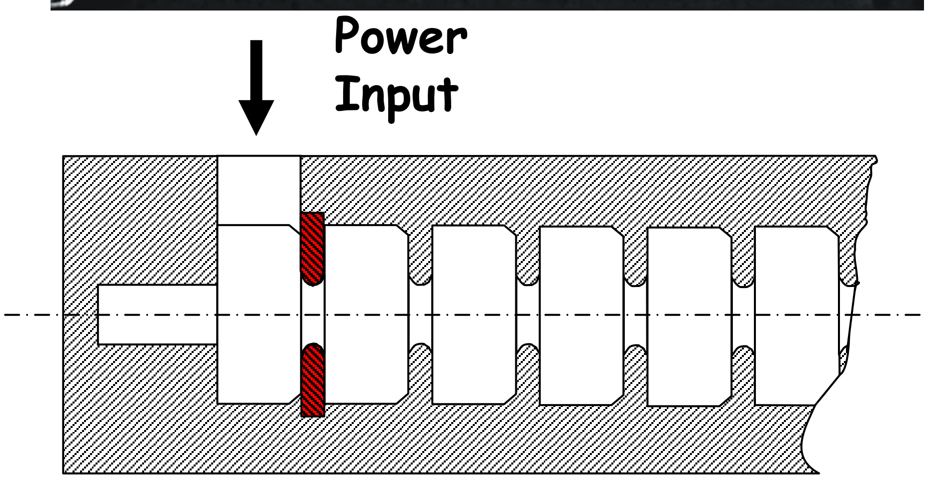


PRL, 2003, Vol. 90, No 22, 224801

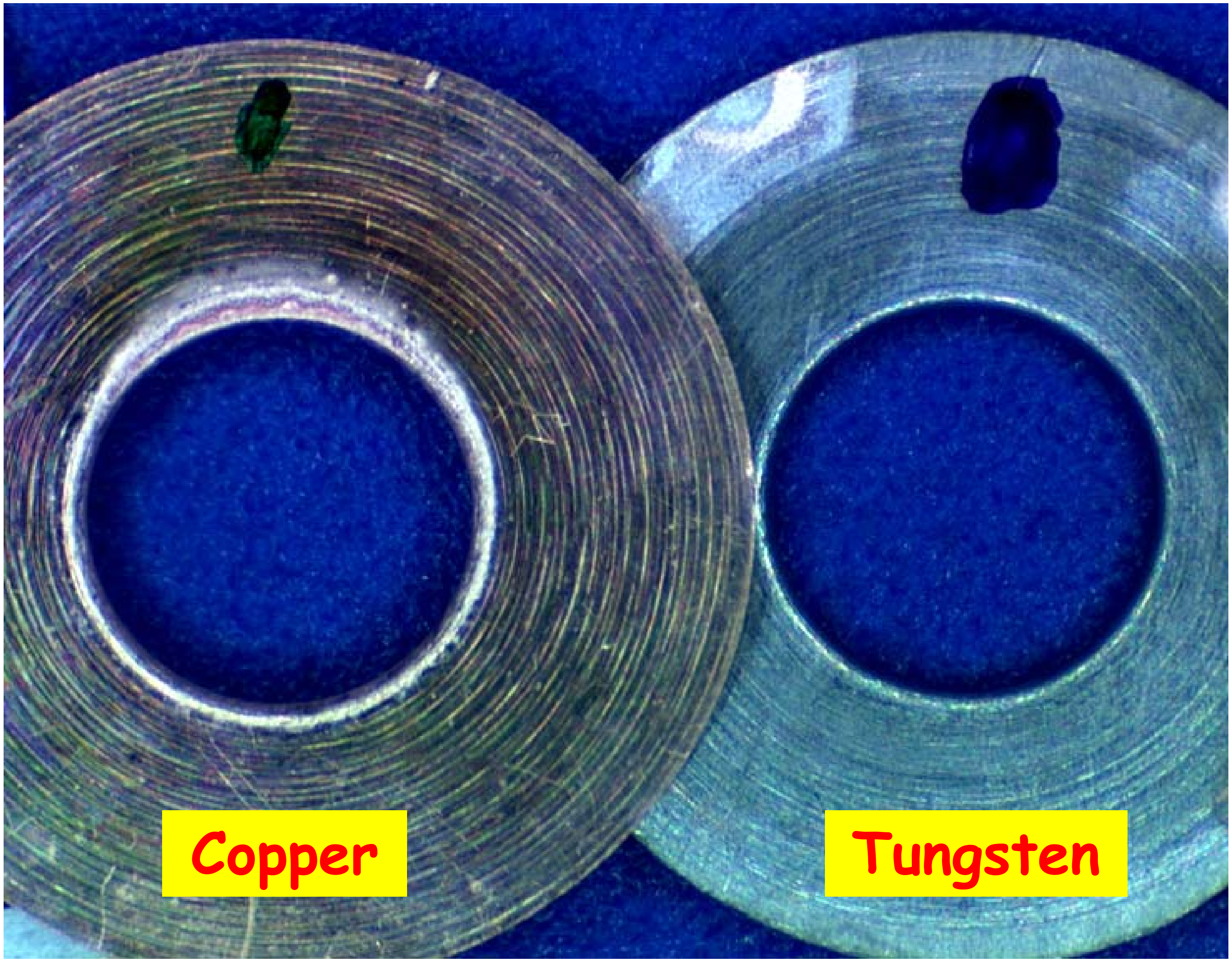
The beginning of a long story, Damage in high field areas

In 1999, damage was found in high field areas of the first CLIC prototype accelerating structures at a gradient ~ 60-70 MV/m (Surface field on Copper ~ 300 MV/m)



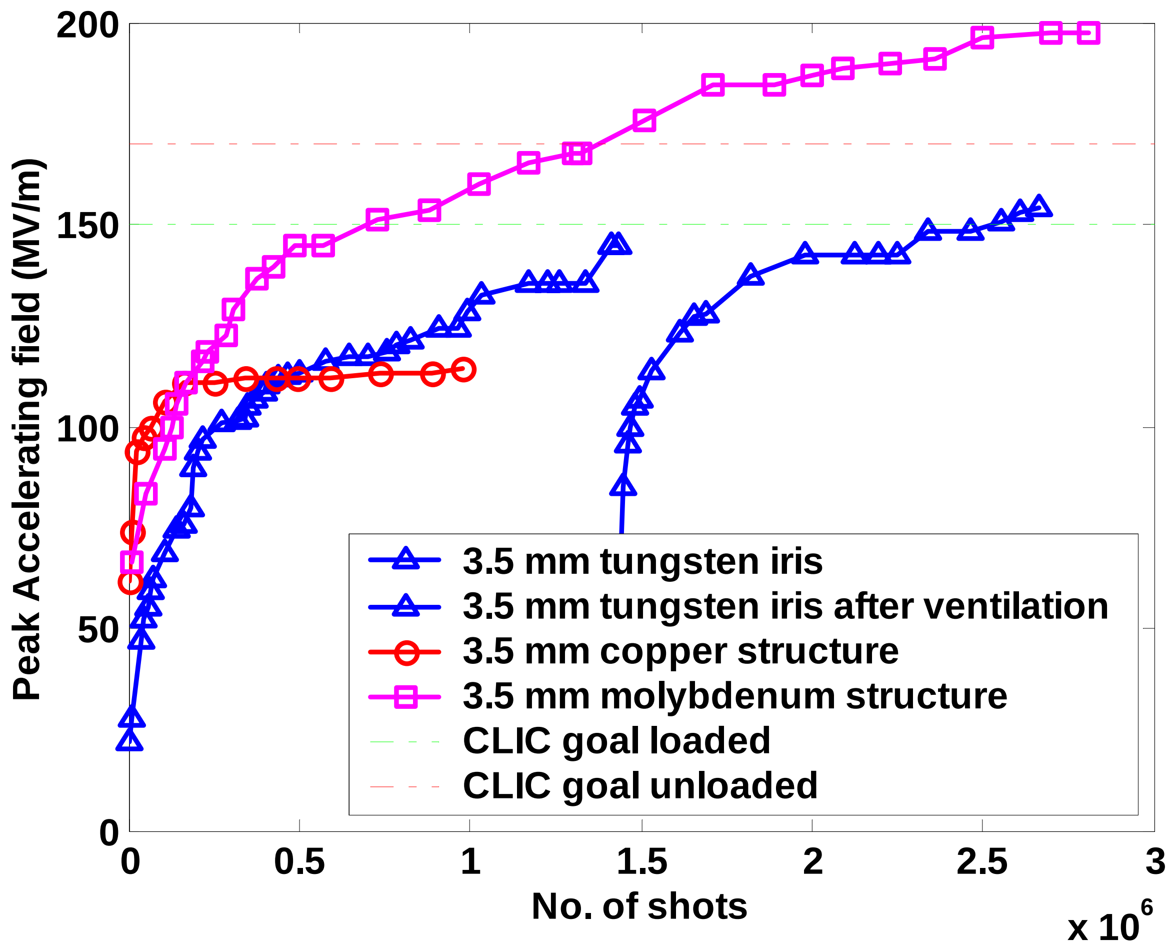


Damage in high field areas



Accelerating Structure Tests in CTF II

Accelerating Structure Tests in CTF II

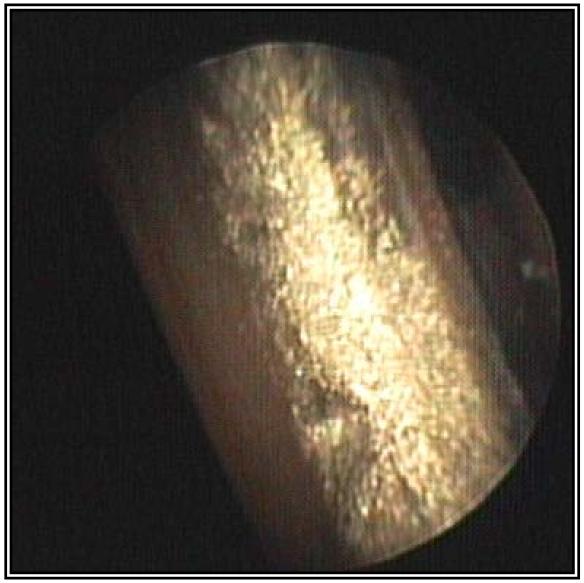


Short, 16 ns rf pulses

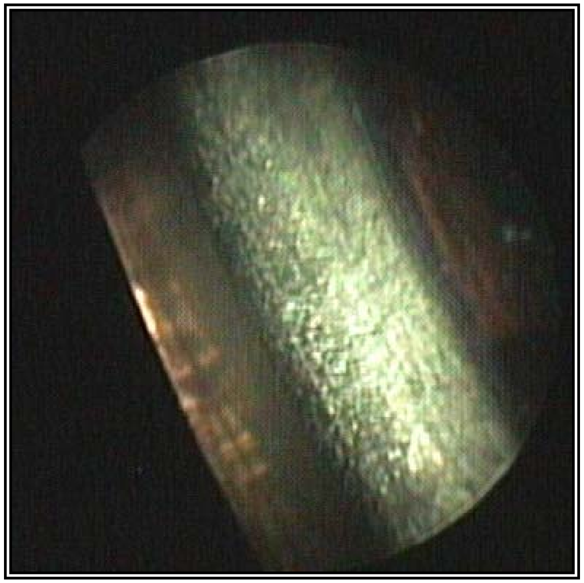
Accelerating Structure Tests in CTF II

Surface field on first iris

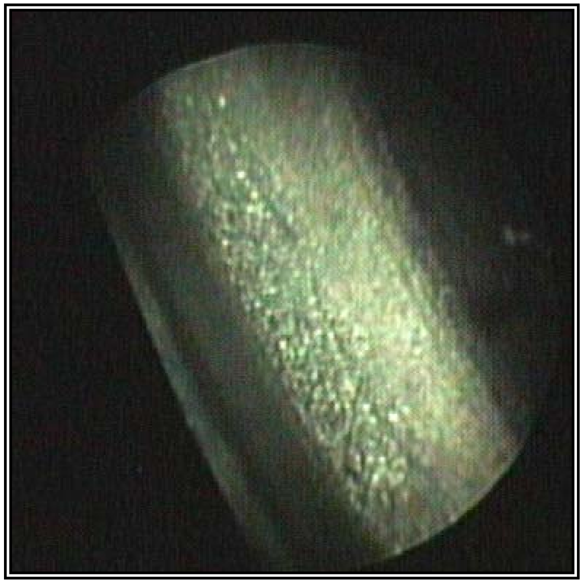
Copper 260 MV/m



Tungsten 340 MV/m



Molybdenum 426 MV/m



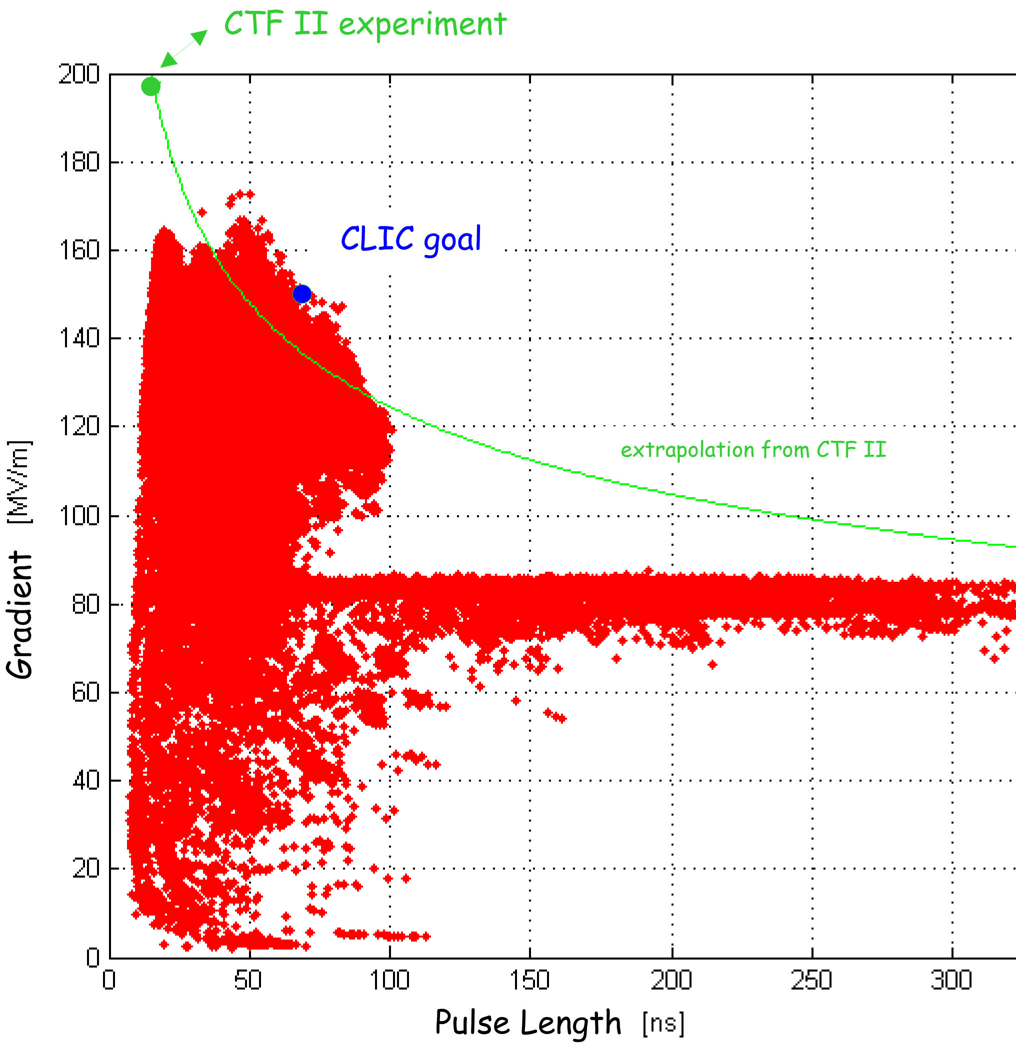
Accelerating Structure Tests in CTF II

177 MV/m average acceleration gradient
at 30 GHz with 8 ns RF pulses

228 MV/m peak acceleration gradient

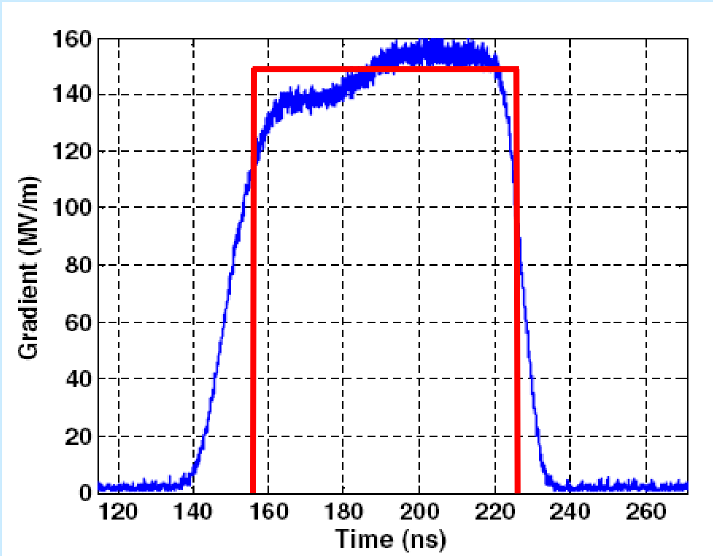
Recent Results from CTF3

Molybdenum Structure Conditioning

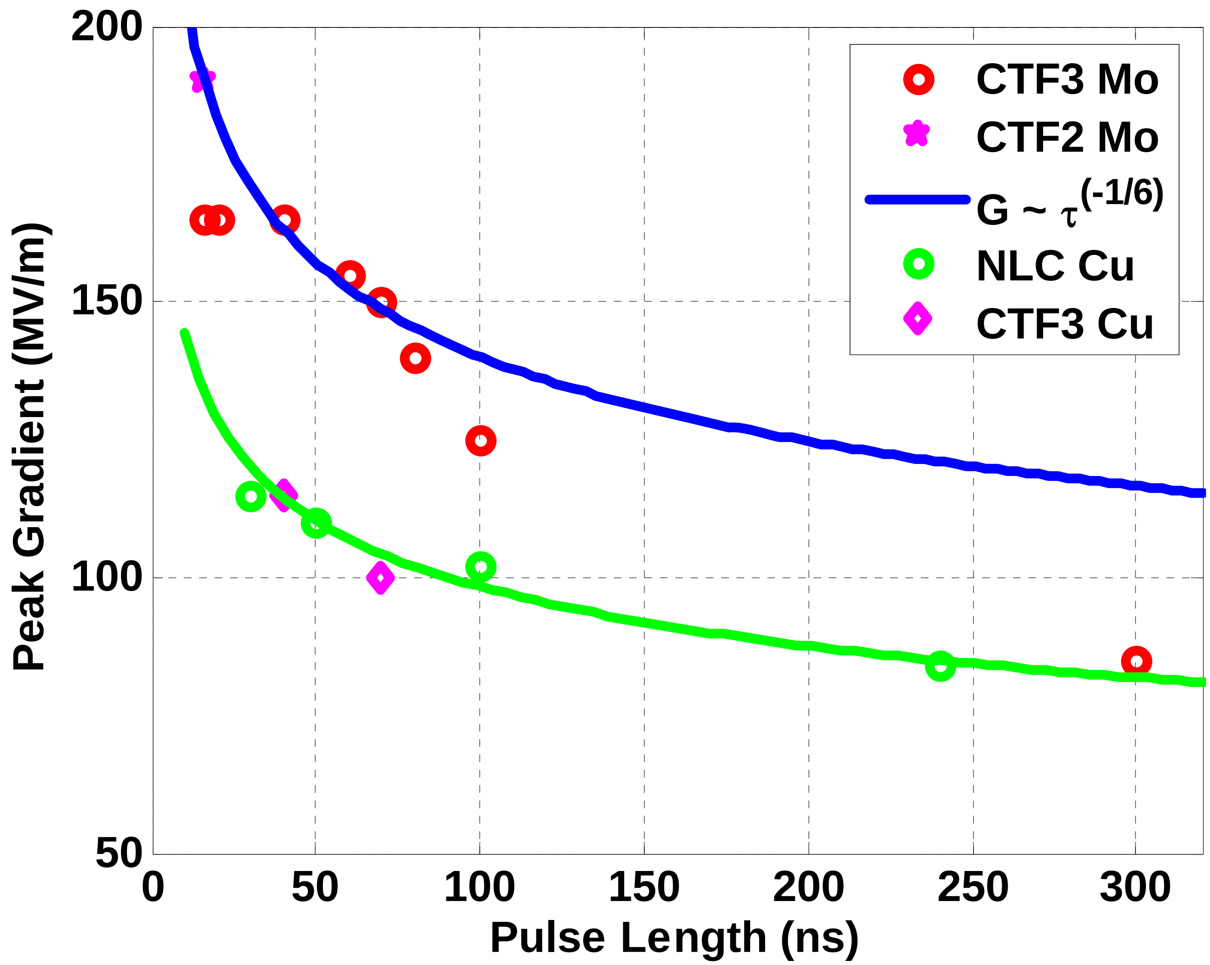


Reached nominal CLIC values :

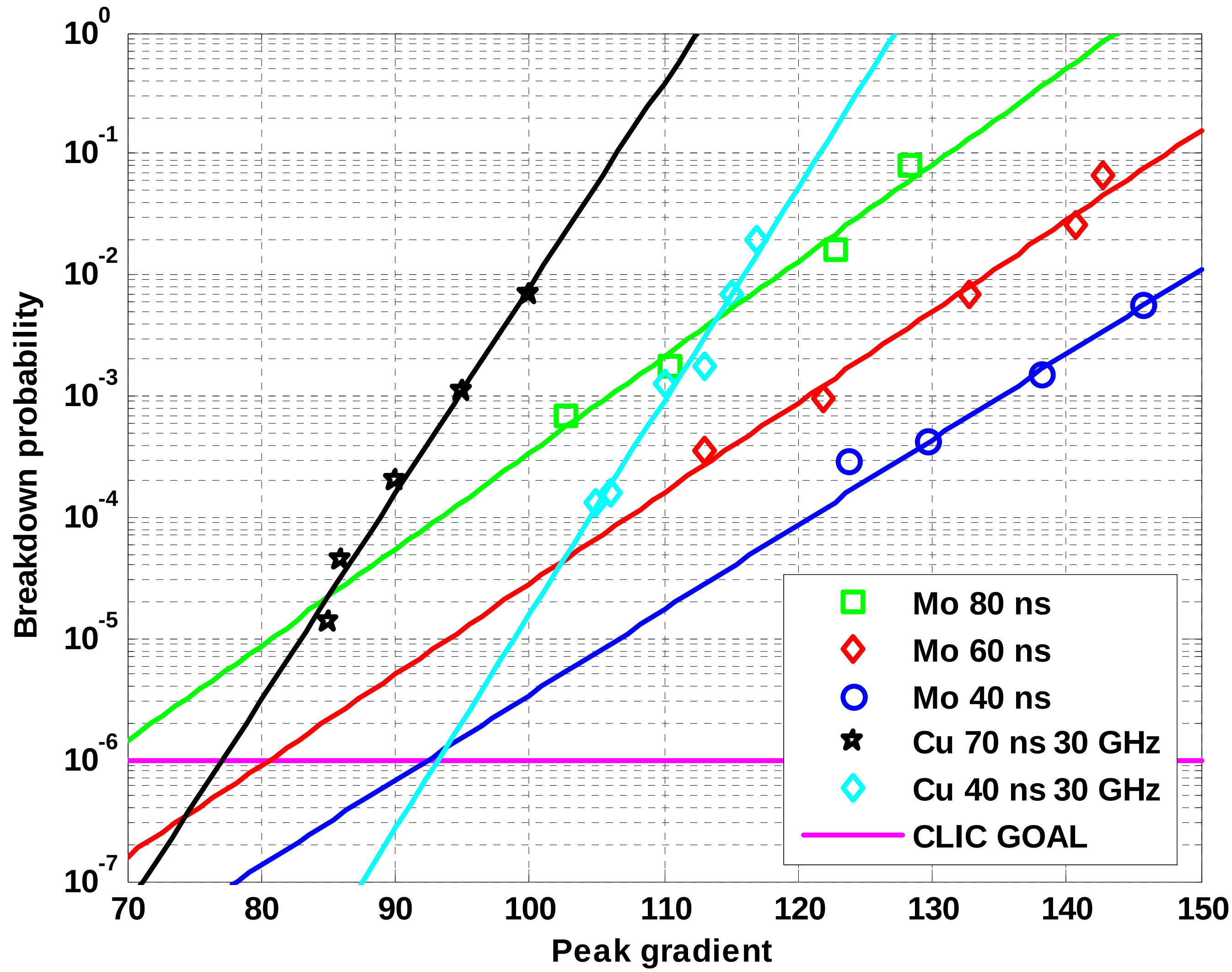
150 MV/m 70 ns



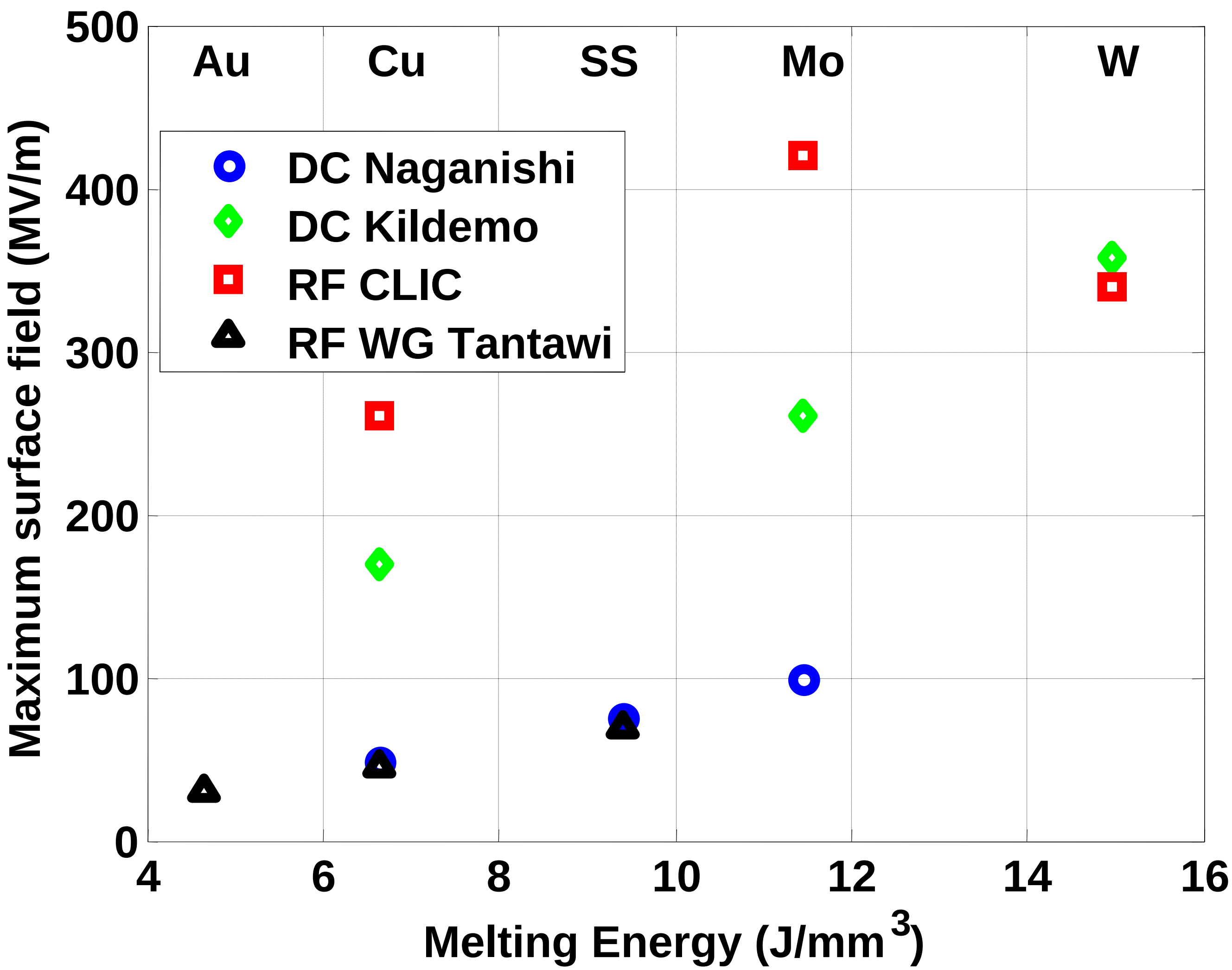
Pulse Length Dependence



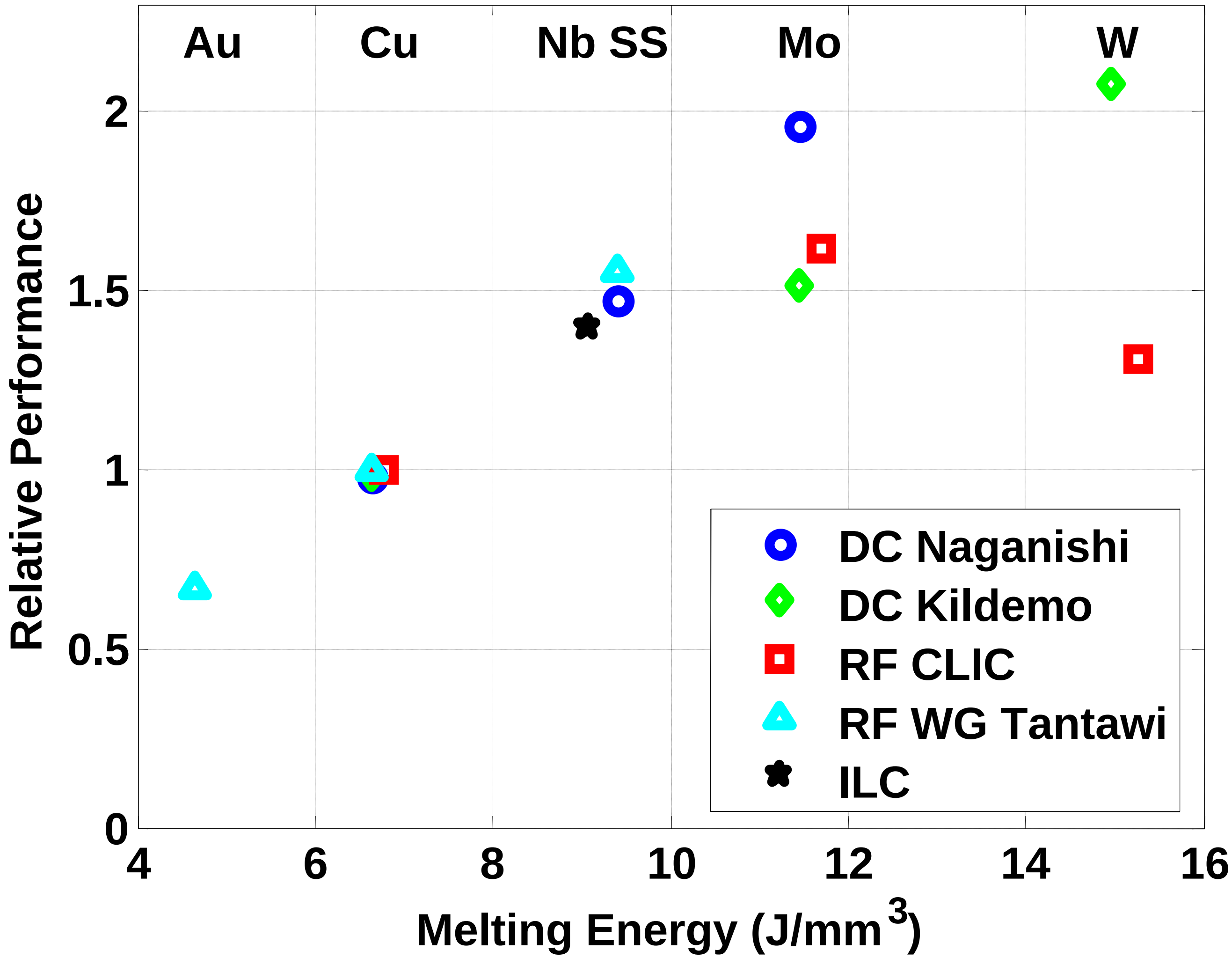
Recent Results from CTF3



New Materials



New Materials



30 GHz results so far

Power Production (642 MW, 70 ns):

280 MW (350 peak) for 16 ns (CTF II)

100 MW for 70 ns (CTF3)

600 MW for 400 ns (NLCTA, SLAC, 11 GHz)

Accelerating structure (150 MV/m, 70 ns):

150 MV/m (193 peak) for 16 ns (CTF II)

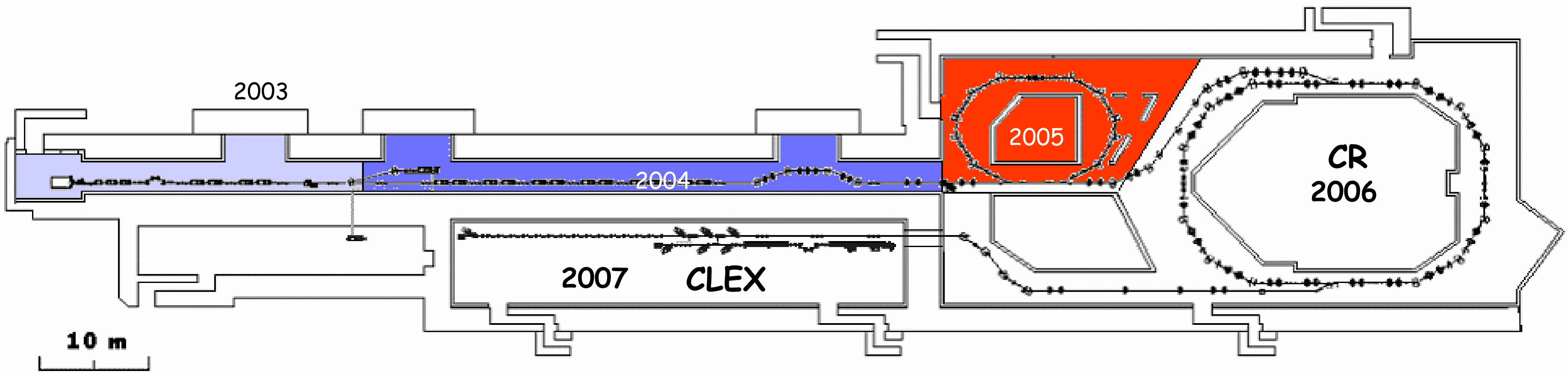
150 MV/m peak for ~ 60 ns (CTF3, Dec 2005)
(but the breakdown rate is to high, surface erosion)

Two Beam acceleration demonstrated at low Power in CTFII

30 GHz Conclusions

- Visionary parameters of CLIC based on scaling laws turned out to be very challenging
- Proof of existence for the 150 MV/m gradient achieved
- but, for a real machine we likely have to reduce the gradient (100 – 120 MV/m)
- Approaching the limits of normal conducting accelerators
- New materials are promising, but not yet understood

CTF3 Evolution



Milestones towards CLIC feasibility

- 2007 Demonstrate Drive Beam Generation
- 2008 Demonstrate relevant CLIC PETS and accelerating structure as well as stable Drive Beam deceleration
- 2009 Operate relevant CLIC LINAC sub-unit

CTF3 Evolution

CLIC Experimental Area

Outlook

- Trying to demonstrate CLIC feasibility
- Test new HDS design at 30 GHz and 11 GHz
- Test New Materials (Mo, Al, Ti, stainless, Nb)
- Complete CTF3

- It is not easy but a lot of fun !

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