UPPSALA UNIVERSITET

Multi-TeV Collider R&D in the Two-beam Test Stand

Roger Ruber

Dept. of Physics and Astronomy

Div. of Nuclear and Particle Physics

25 Sep 2008

Outline

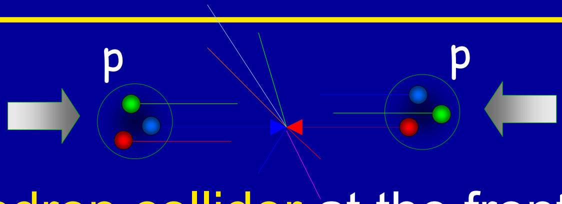
This lecture

- technologies for a future linear collider
- related R&D in the Two-beam Test Stand

Sections

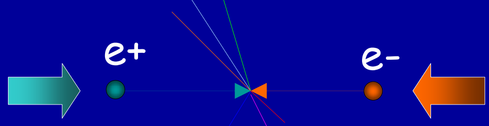
1. introduction
2. accelerating gradient
3. RF power production
4. R&D projects for a future linear collider
   and the Two-beam Test Stand

Collider History



hadron collider at the frontier of physics

- huge QCD background
- not all nucleon energy available in collision

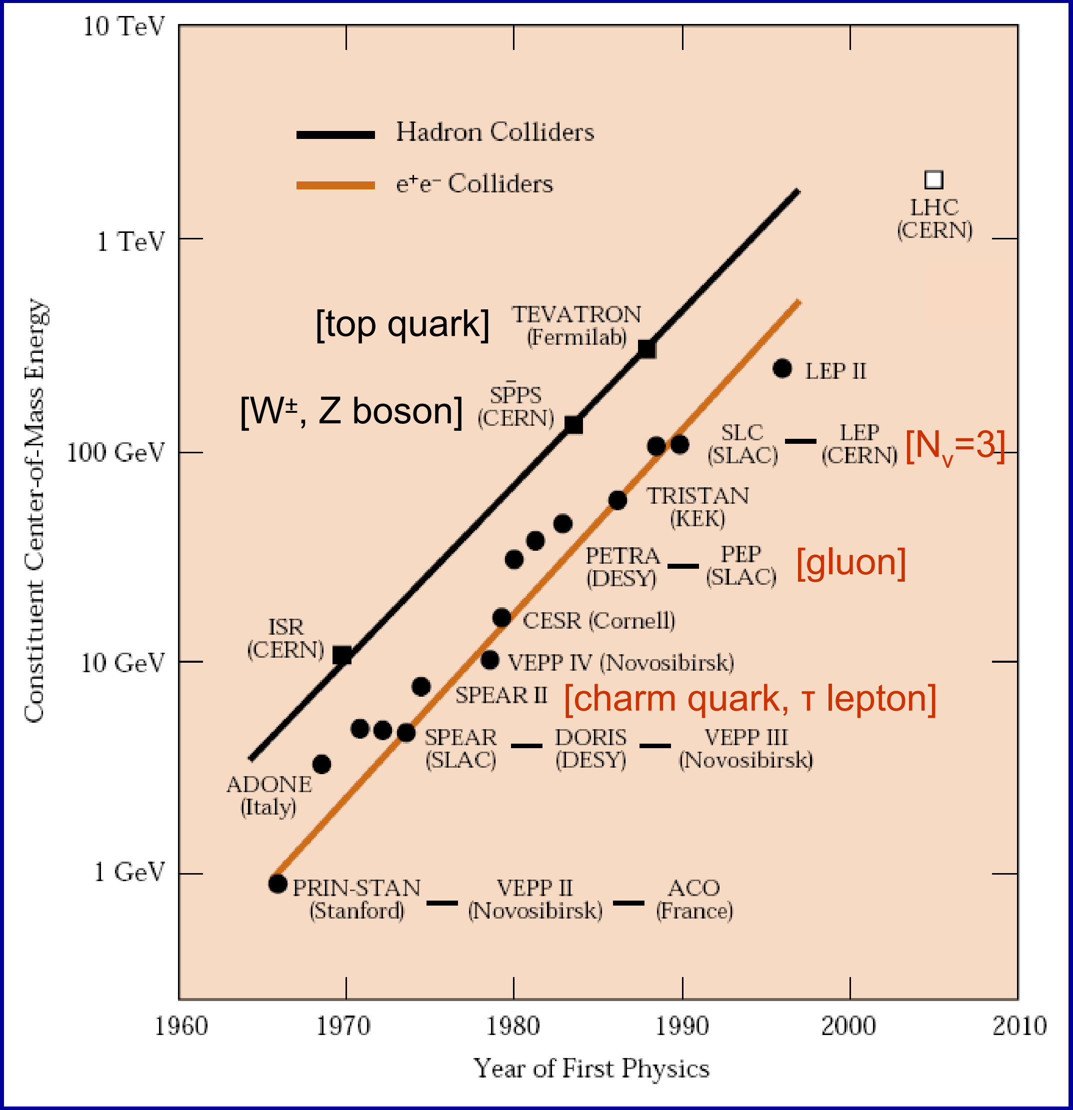


lepton collider for precision physics

- well defined CM energy
- polarization possible

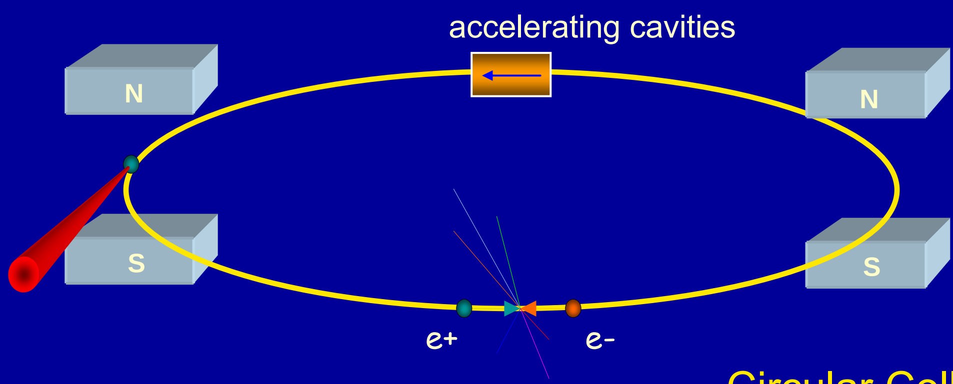
LHC starting up

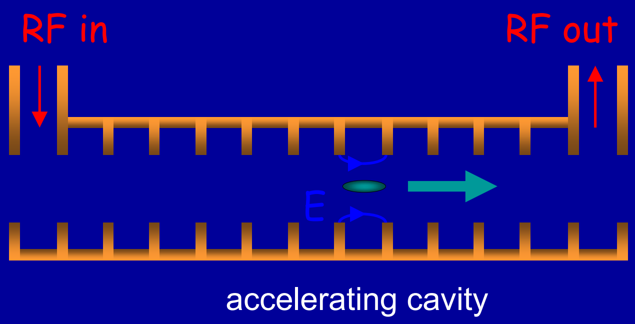
- energy constantly increasing
- consensus for next machine $E_{cm} \geq 0.5$ TeV for e^+e^-



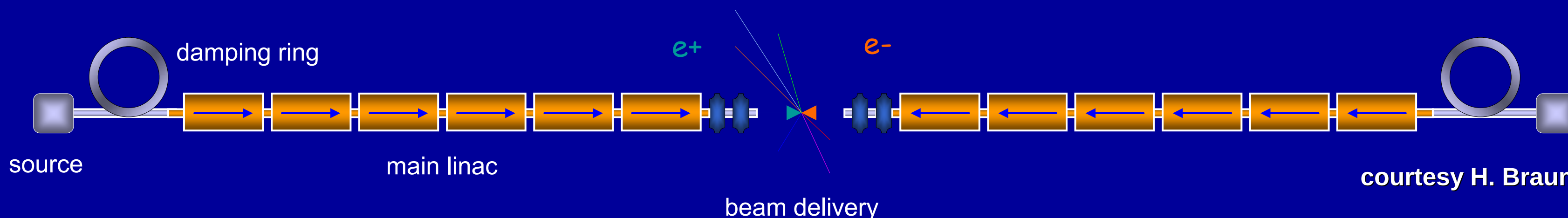
"Livingstone" plot (adapted from W. Panofsky)

Circular versus Linear Collider





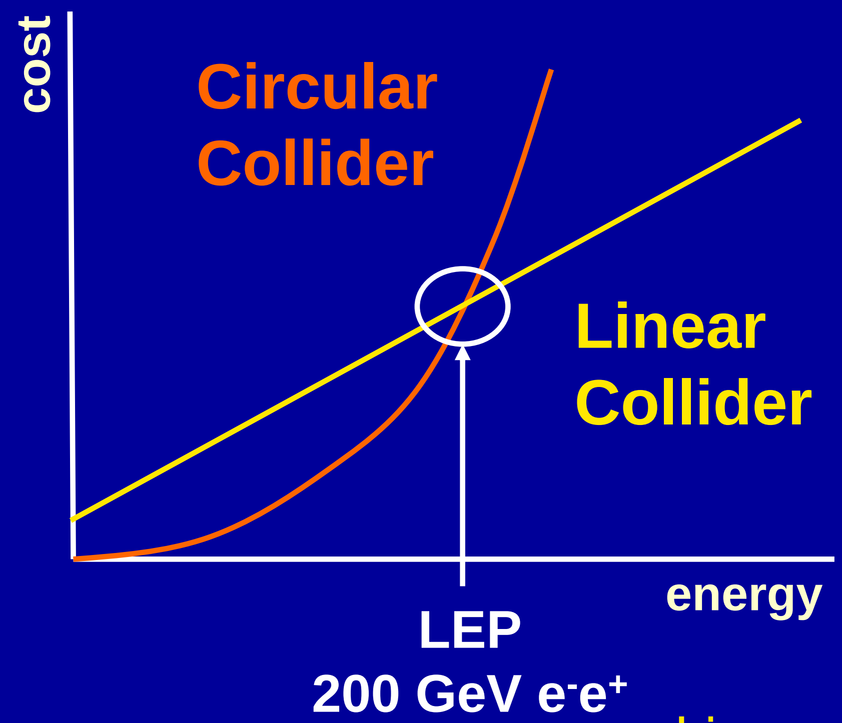
Circular Collider
many magnets, few cavities → need strong field for smaller ring
high energy → high synchrotron radiation losses ($\propto E^4/R$)
high bunch repetition rate → high luminosity



courtesy H. Braun

Linear Collider
few magnets, many cavities → need efficient RF power production
higher gradient → shorter linac
single pass → need small cross-section for high luminosity:
(exceptional beam quality, alignment and stabilization)

Cost of Circular & Linear Accelerators



Circular Collider

$\Delta E \sim (E^4/m^4R)$

cost ~ aR + b ΔE

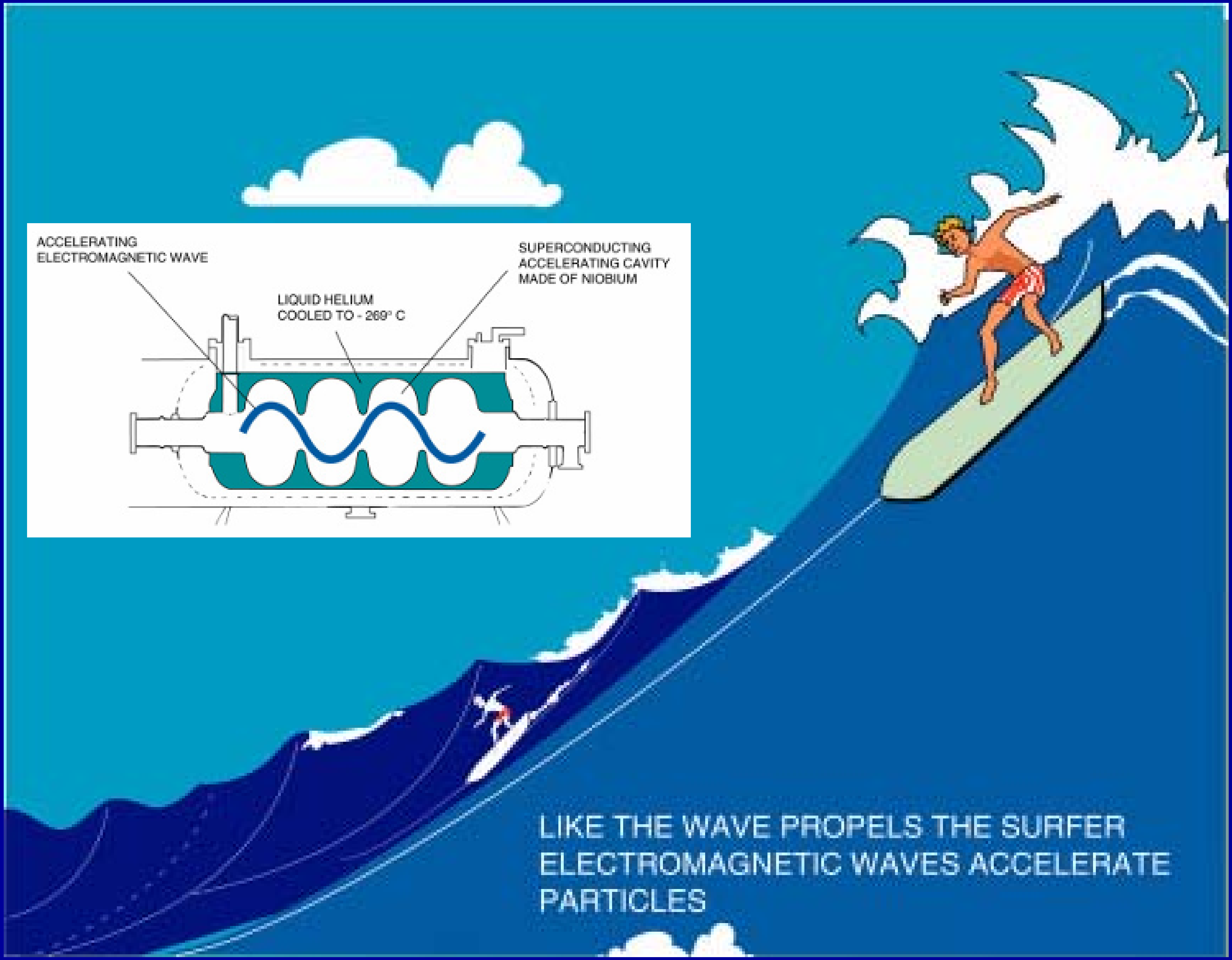
optimization: $R \sim E^2 \rightarrow$ cost ~ cE^2

Linear Collider

$E \sim L$

cost ~ aL

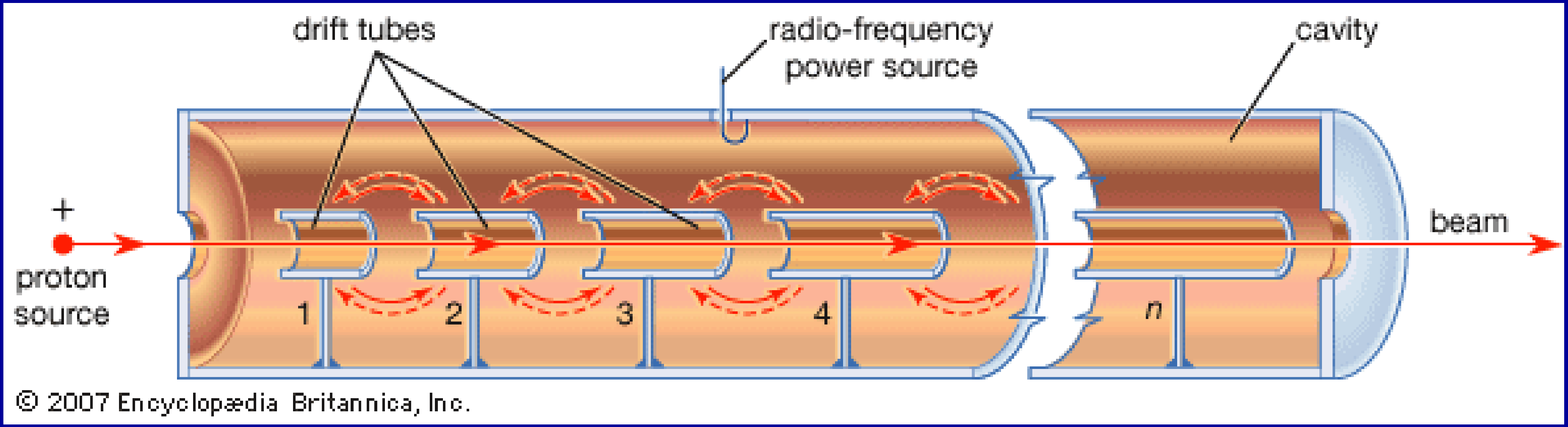
2. Accelerating Gradient



Drift Tube Linear Accelerator

Non-relativistic particles

- standing wave
- drift tube size and spacing adapted to
  - electro-magnetic field oscillation at high radio frequency (RF)
  - particle speed



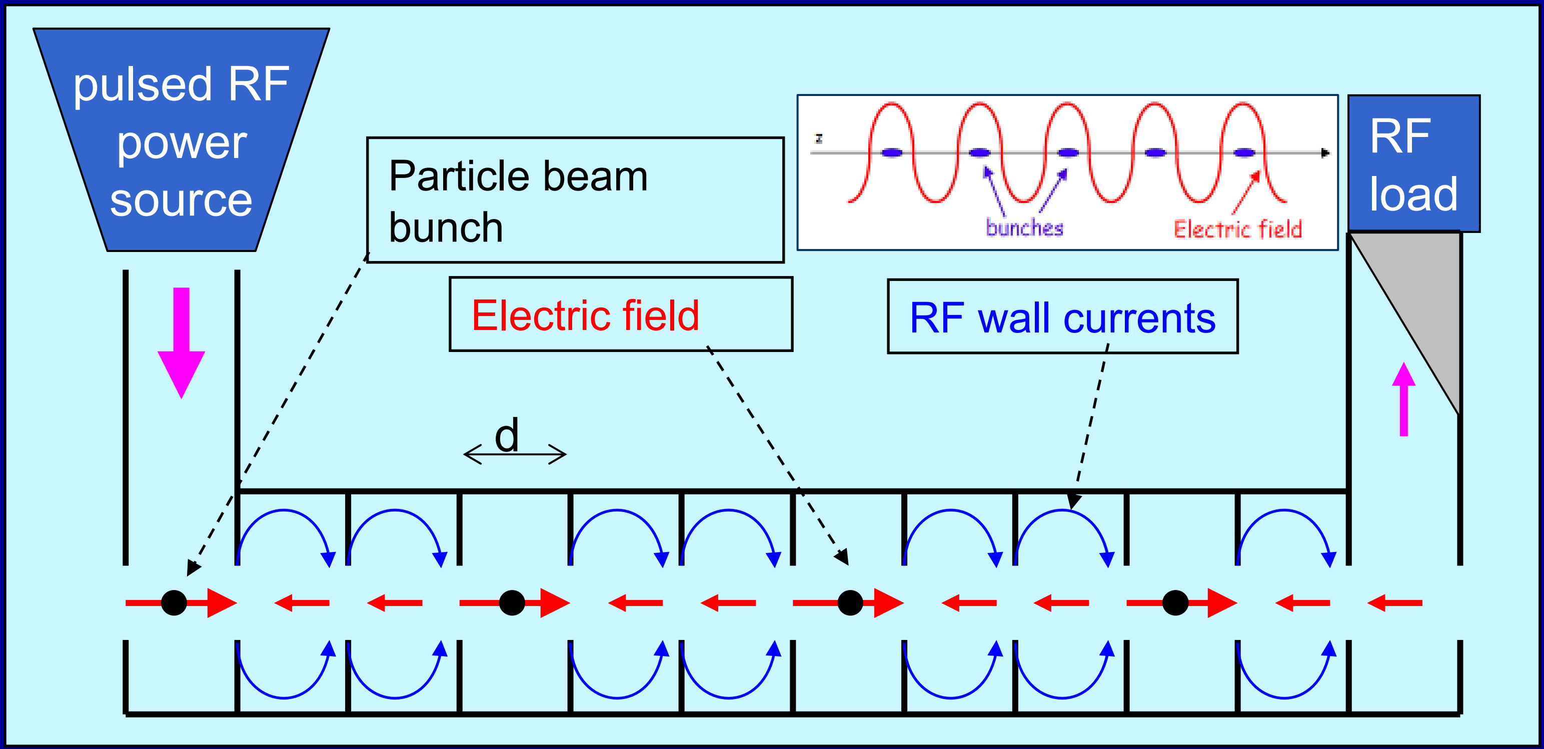
Accelerating Structure

Relativistic particles

- electro-magnetic wave too fast in free space
  → couple to resonating structures → group velocity

example shows **travelling wave structure** with

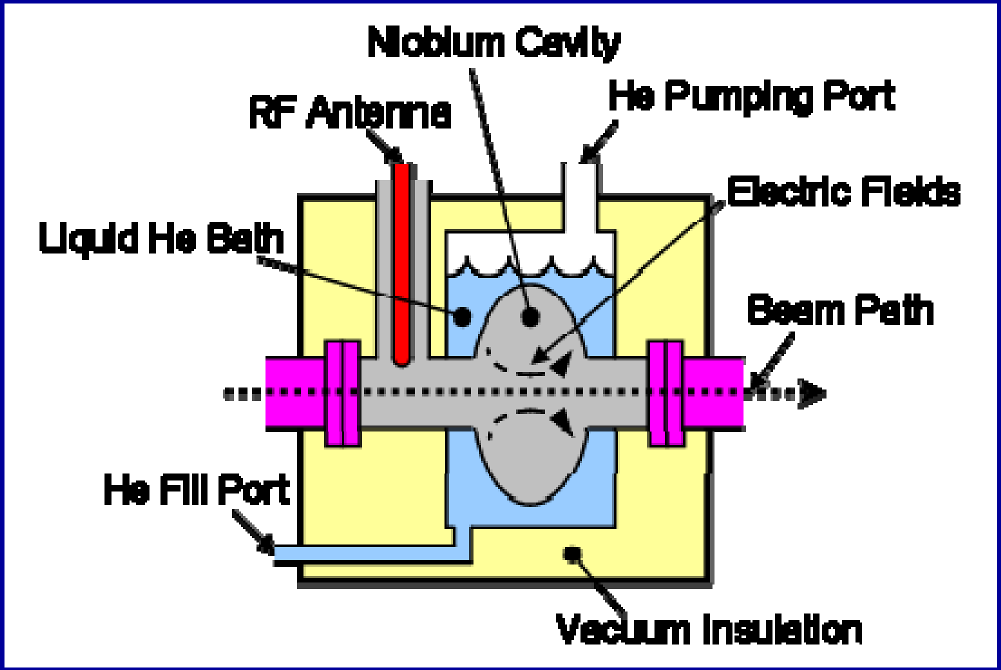
- 2π/3 phase advance per cell
- field frozen in time, note distance between bunches



Superconducting RF Cavities (SCRF)

E_{acc} limited by $B_{critical}$

- ~50 MV/m
  (single cell cavity)
- ~32 MV/m
  (multi-cell cavity)



Advantages Superconducting RF

Very low losses due to tiny surface resistance
→ standing wave cavities with
low peak power requirements

- High efficiency
- Long pulse trains possible
- Favourable for feed-backs within the pulse train

- Low frequency → large dimensions (larger tolerances), large aperture and small wakefields

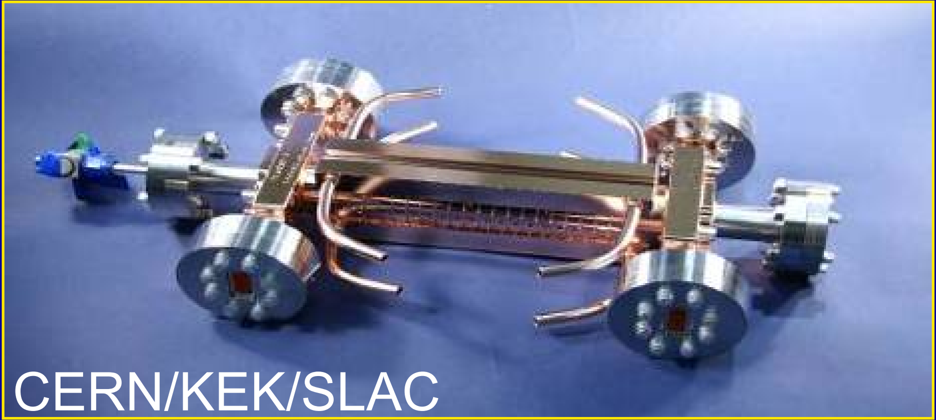
⇒ Important implications for the design of the collider

But higher gradients achievable with normal conducting structures!

Normal Conducting Accelerator Structures

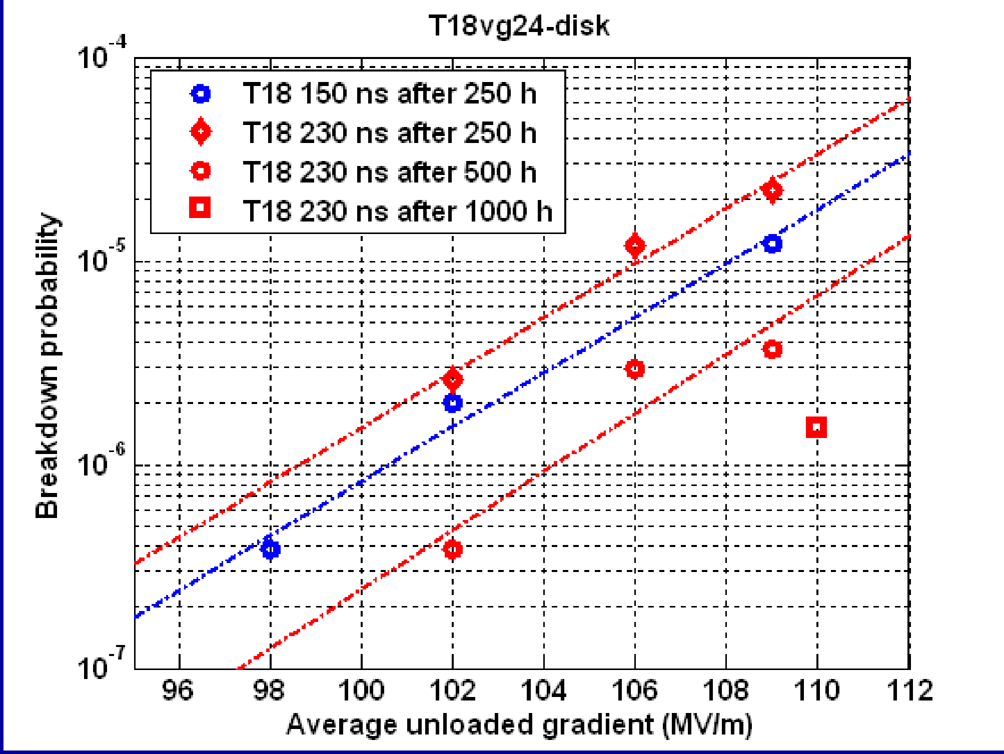
E_{acc} > 60 MV/m

- high ohmic losses
  → travelling wave
  (not standing as SCRF)
- short pulse length
- fill time $t_{fill} = \int 1/v_G\, dz$
  <100 ns (~ms for SCRF)



CLIC T18_vg2.4_disk

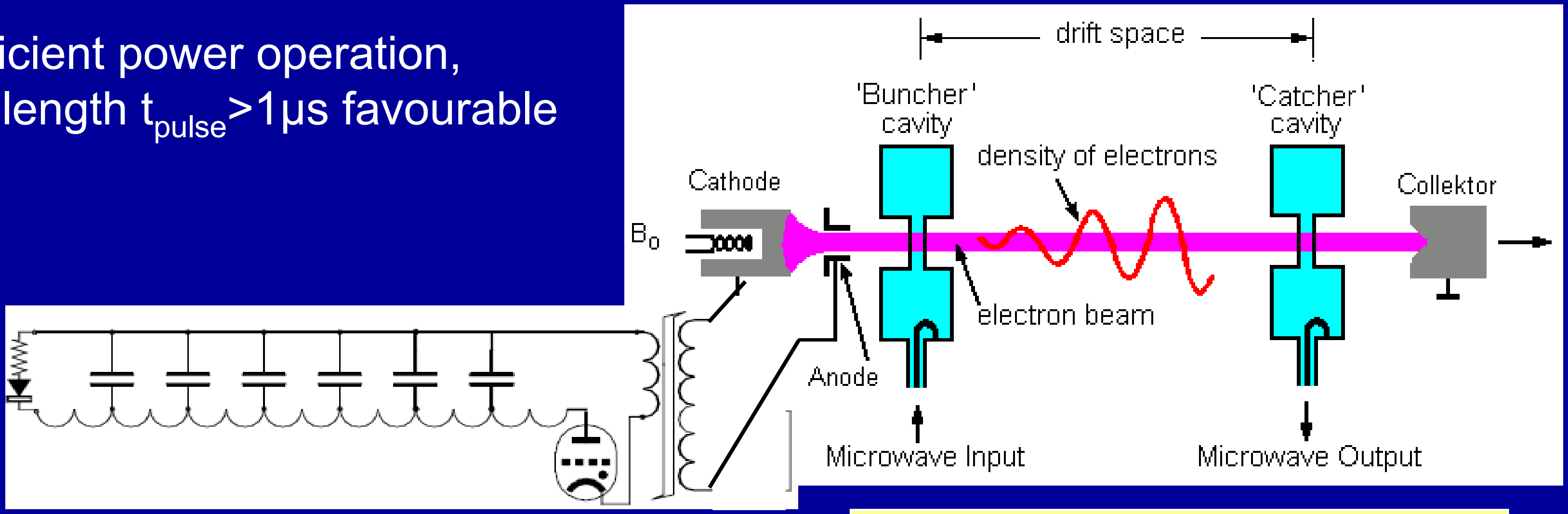
- 100 MV/m
- 230 ns pulse length
- 10^{-7} breakdown rate (BDR)
- w/o HOM damping



3. RF Power Production

Traditional Klystron Microwave Amplifier

for efficient power operation,
pulse length t_{pulse}>1μs favourable



Modulator

Energy storage in capacitors
charged up to 20-50 kV (between pulses)

high voltage
switching and
voltage transformer
rise time > 300 ns

Klystron

U 150 -500 kV
I 100 -500 A
f 0.2 -20 GHz

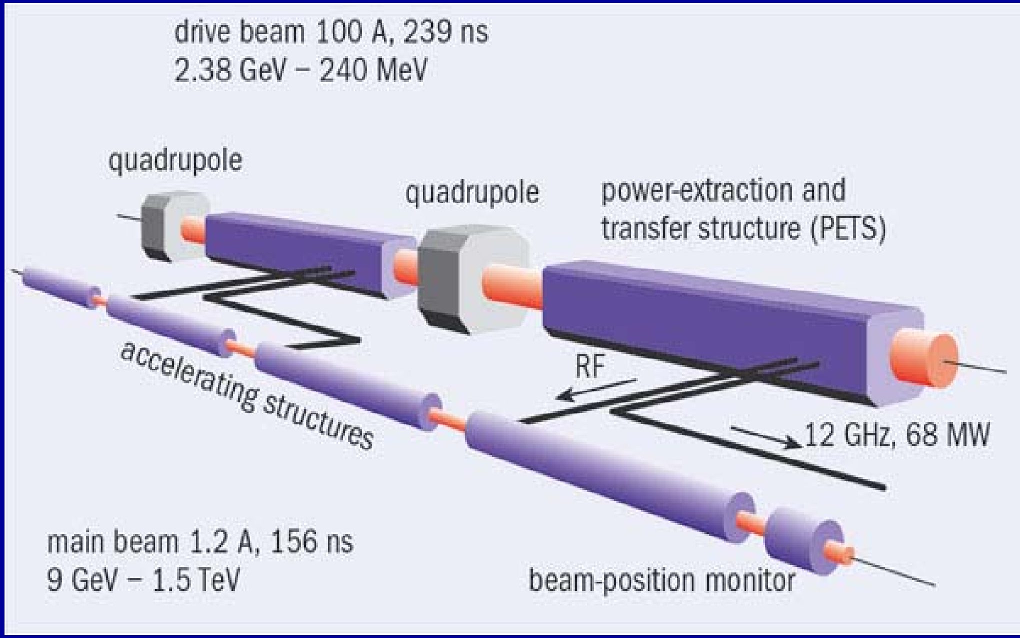
P_{ave} < 1.5 MW
P_{peak} < 150 MW

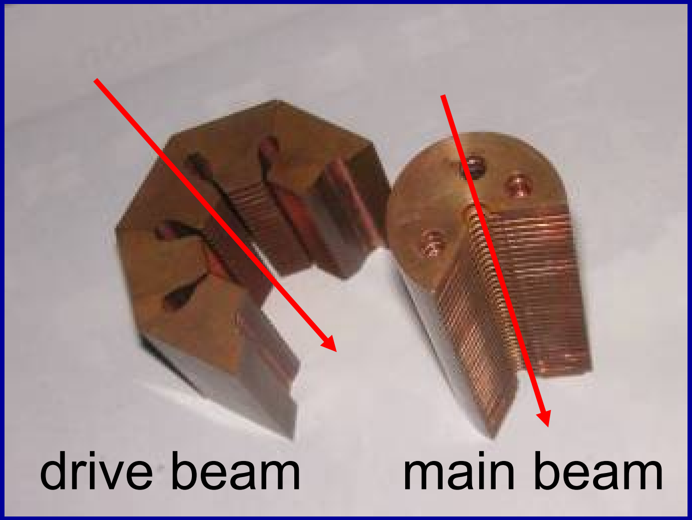
efficiency 40-70%

Two-beam Power Distribution

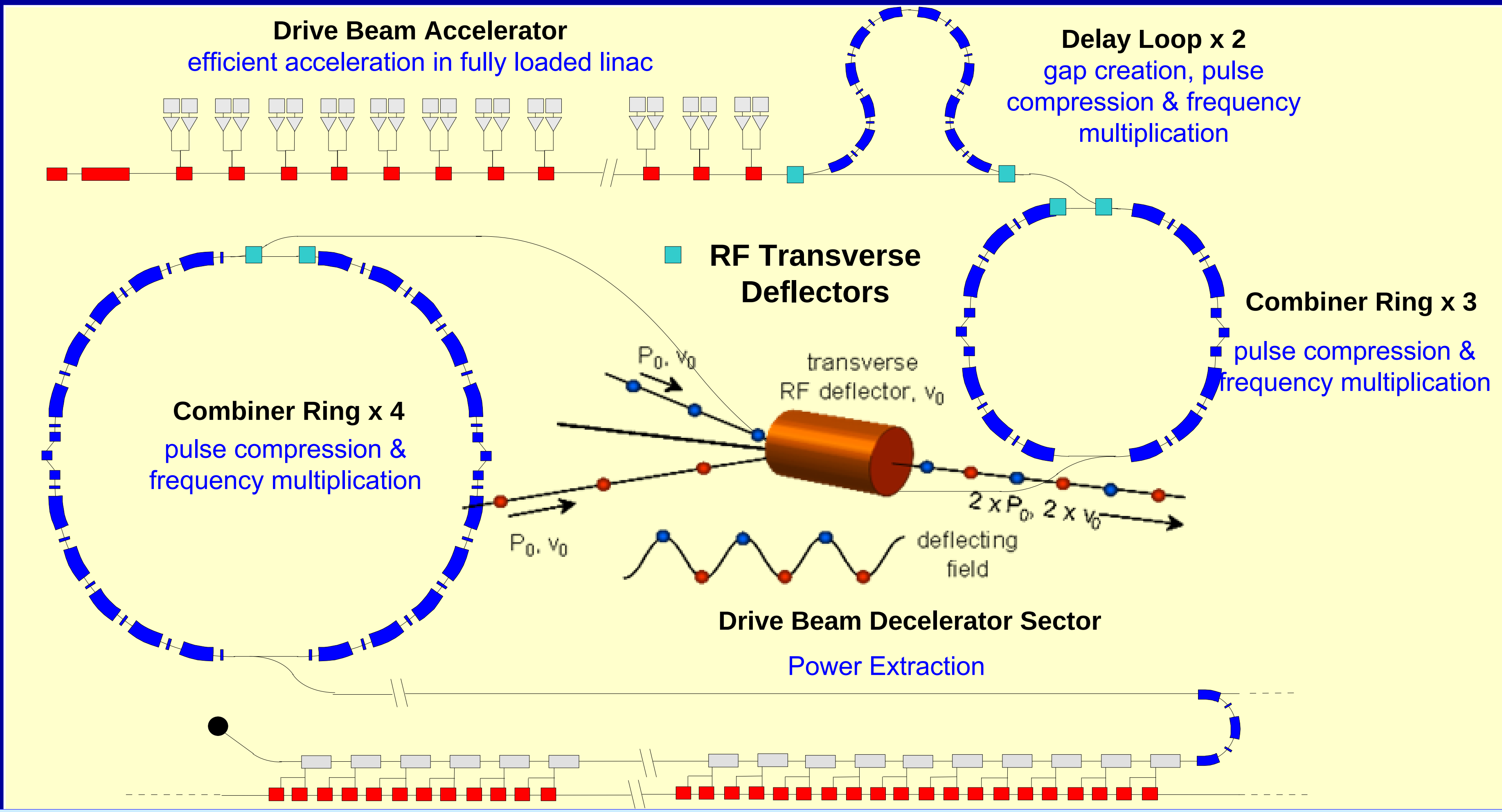
Two-beam Scheme

- high power drive beam like the modulated klystron beam
- power extraction in a deceleration structure (PETS)
- sub-harmonic frequency of main beam
- compress energy density: “transformer” function
- only passive elements

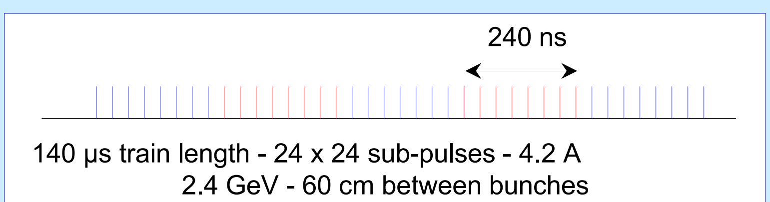




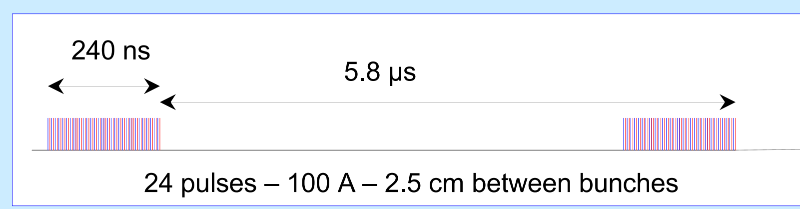
High Power Drive Beam Generation Scheme



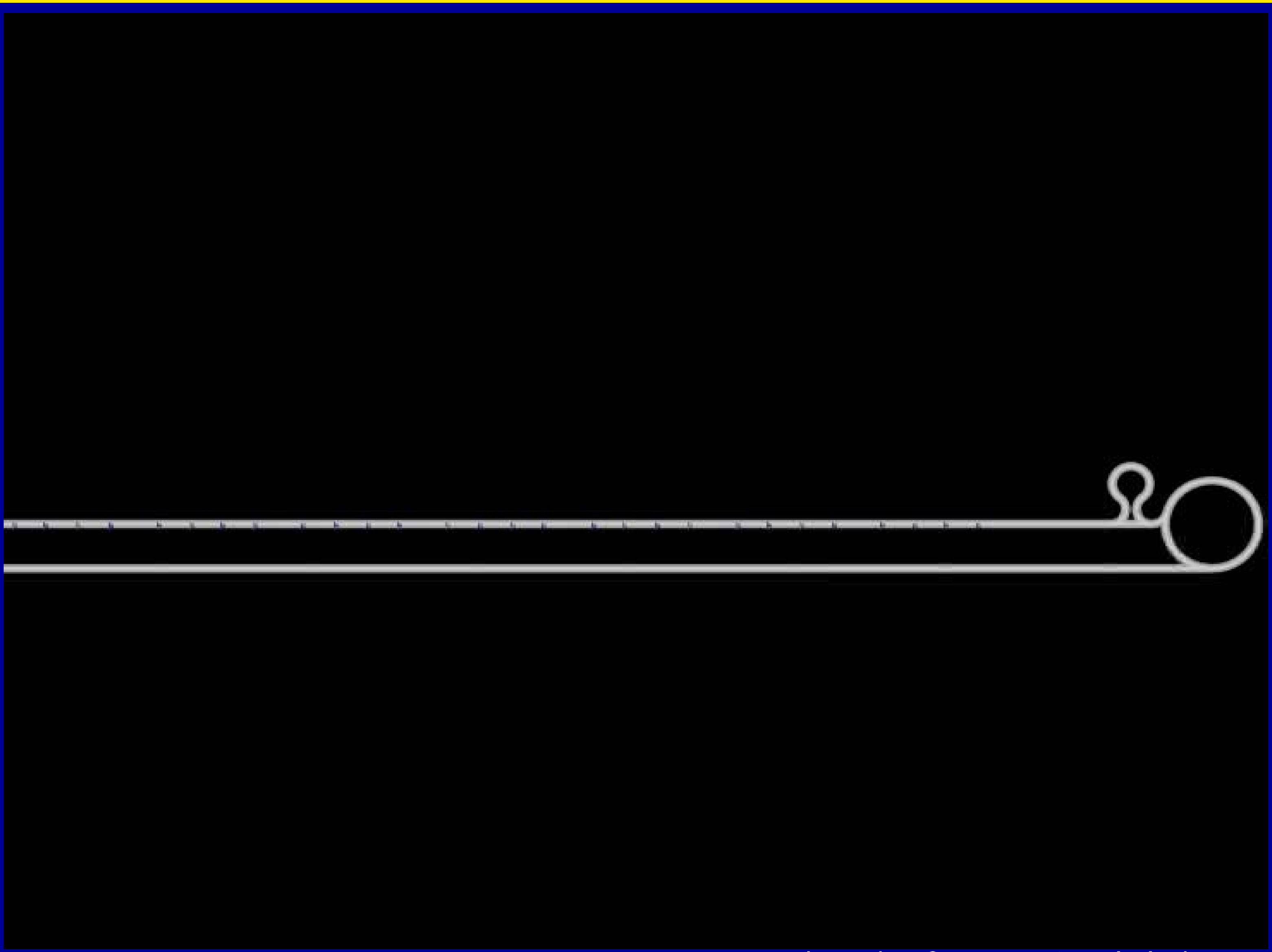
Drive beam time structure - initial



Drive beam time structure - final



Drive Beam Generation Scheme

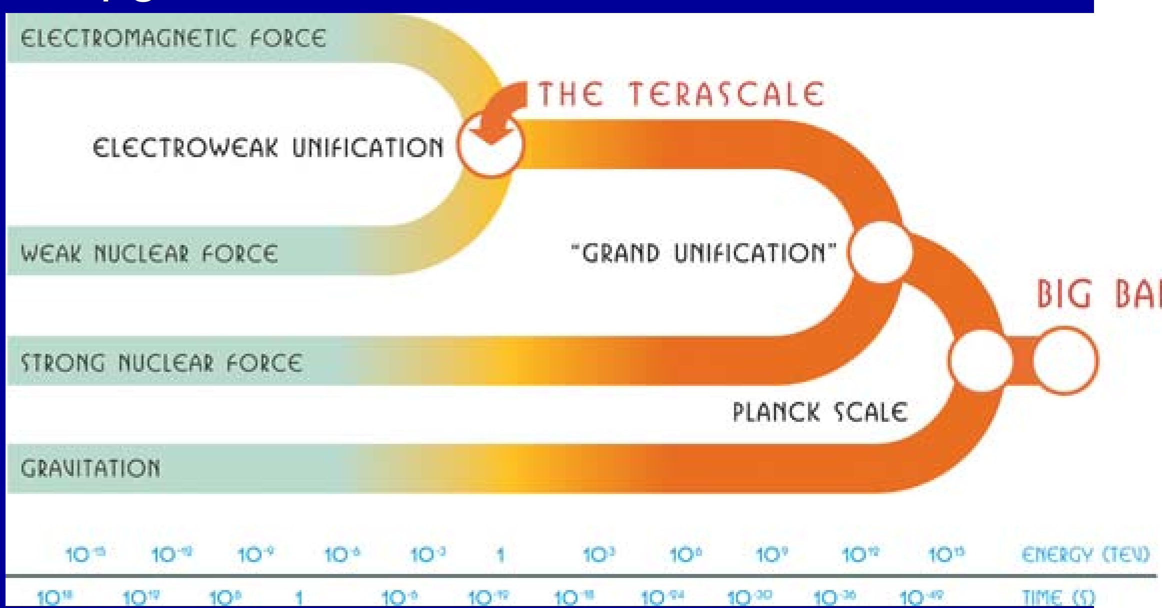


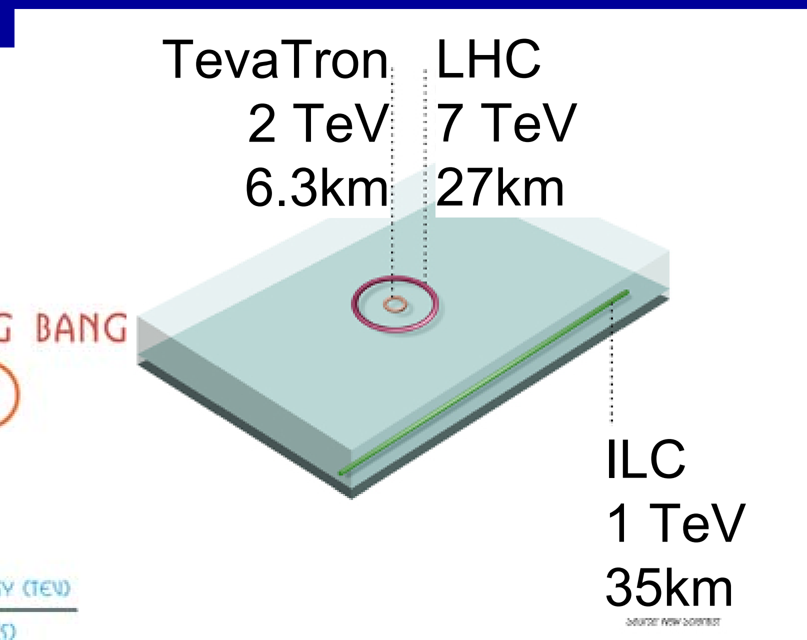
Lemmings6.mpg courtesy A. Andersson

LHC should indicate which energy level is needed

ILC International Linear Collider
- superconducting technology
- RF frequency 1.3 GHz
- acceleration gradient ~31 MV/m
- centre of mass energy 500 GeV
- upgrade to 1 TeV

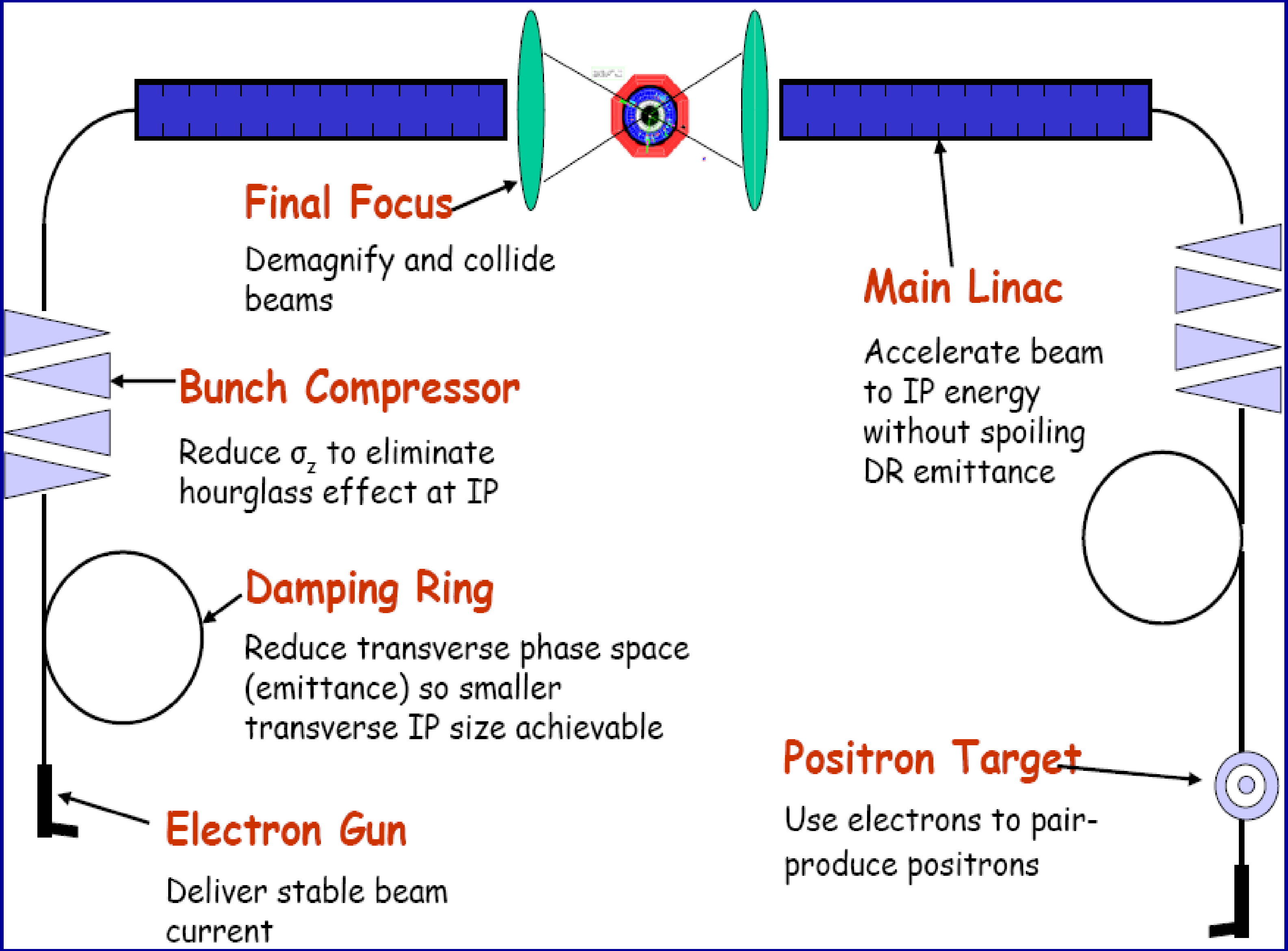
CLIC Compact Linear Collider
- normal conducting technology
- 12 GHz
- ~100 MV/m
- multi-TeV, nominal 3 TeV





Courtesy Sandbox Studio / interactions.org

Basic Layout of an e⁻e⁺ Linear Collider



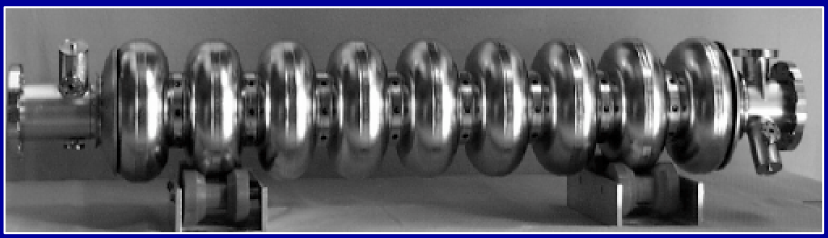
ILC: The International Linear Collider

SC linacs: 2x11 km, 2x250 GeV

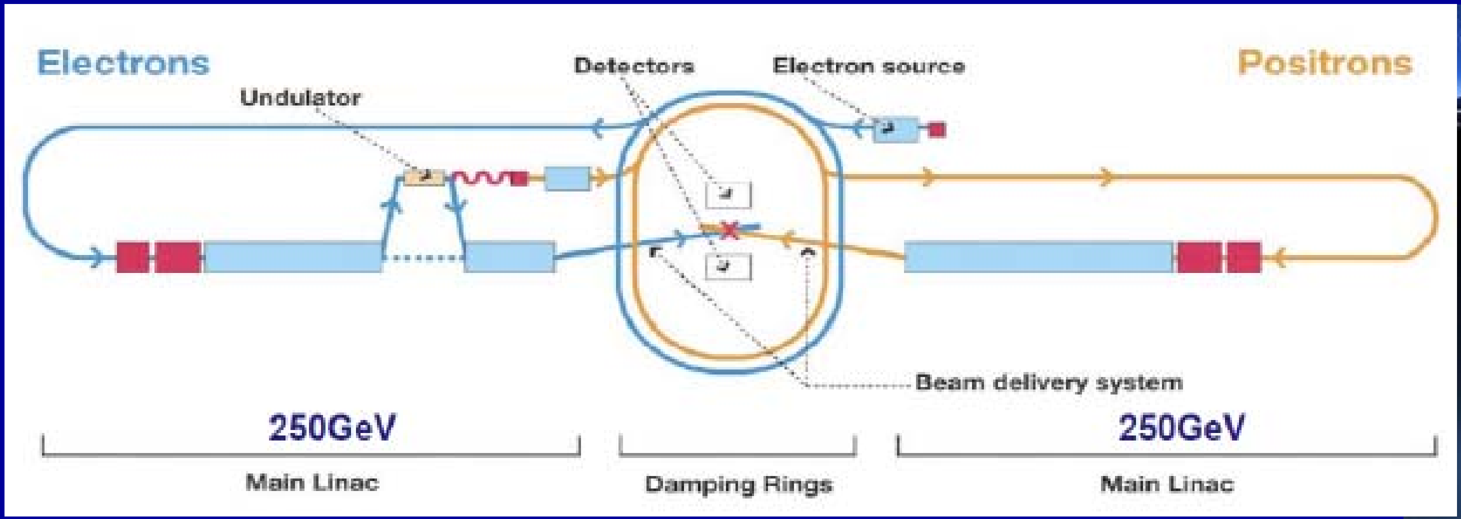
Central injector

circular damping rings

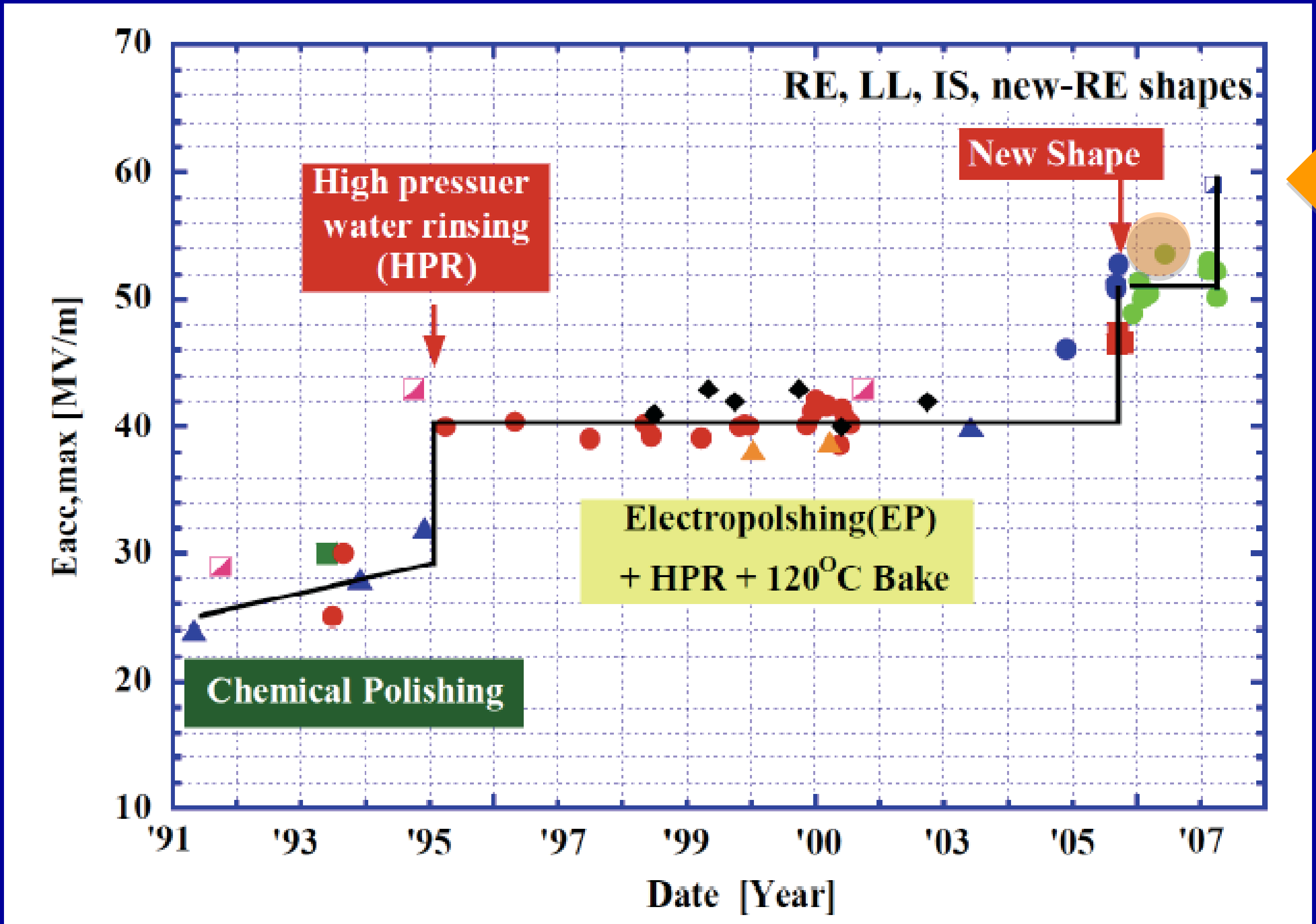
IR with 14 mrad crossing angle



Parameter	**Value**
C.M. Energy	500 GeV
Peak luminosity	$2x10^{34}$ $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse time duration	1 ms
Average beam current	9 mA (in pulse)
Average field gradient	**31.5 MV/m**
# 9-cell cavity	14,560
# cryomodule	1,680
# RF units	560



Progress in Single Cell SCRF Cavity

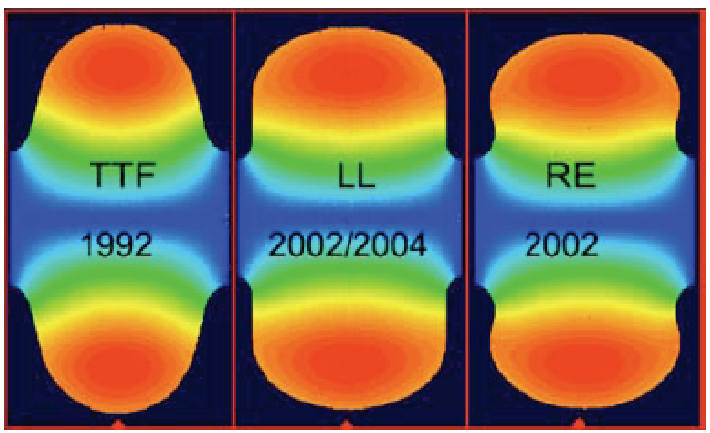


Record **59 MV/m** achieved with the RE cavity shape at 2K, electro-polishing (EP), chemical-polishing (BCP) and pure-water rinsing (HPR) (collaboration of Cornell and KEK) K. Saito, H. Padamsee et al., SRF-07

Evolution SCRF Cavity Shape

TABLE II. CAVITY SHAPES STUDIED FOR THE ILC.

Parameter	TESLA	LL/IS	RE
Iris aperture (mm)	70	60/61	66
E_{peak}/E_{acc}	1.98	2.36/2.02	2.21
B_{peak}/E_{acc} (mT/(MV/m))	4.15	3.61/3.56	3.76
Char. shunt impedance: R/Q (Ω)	114	134/138	127
Geometric factor: G (Ω)	271	284/285	277
$G \times R/Q$ $(\Omega \times \Omega \times 10^5)$	3.08	3.80/3.93	3.51



TESLA design

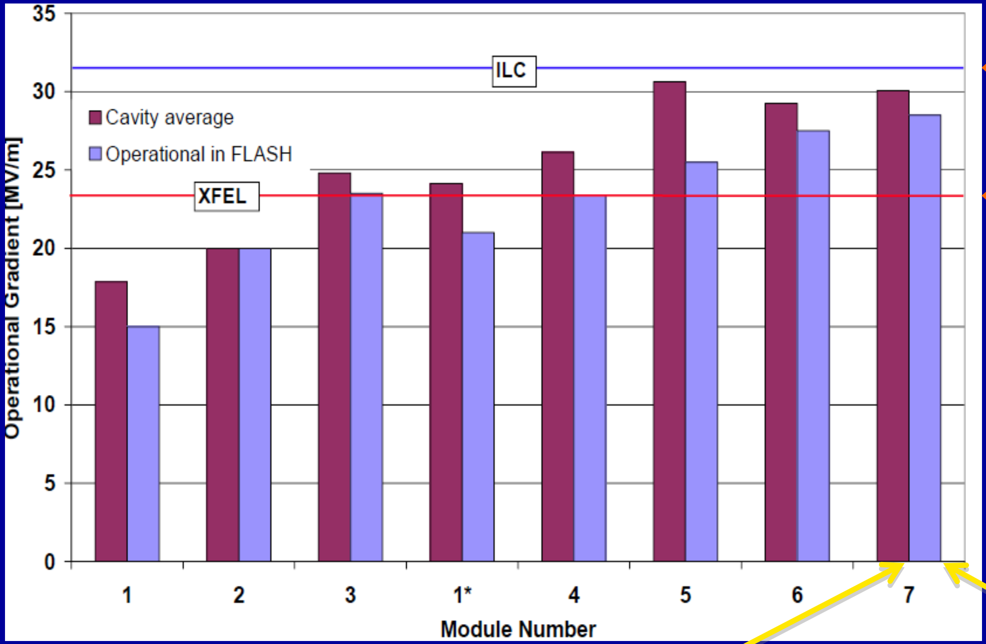
- **Lower E-peak**
- Lower risk of field emission

LL/IS, RE design

- **Lower B-peak**
- Potential to reach higher gradient

LL: low-loss, IS: Ichiro-shape, RE: re-entrant

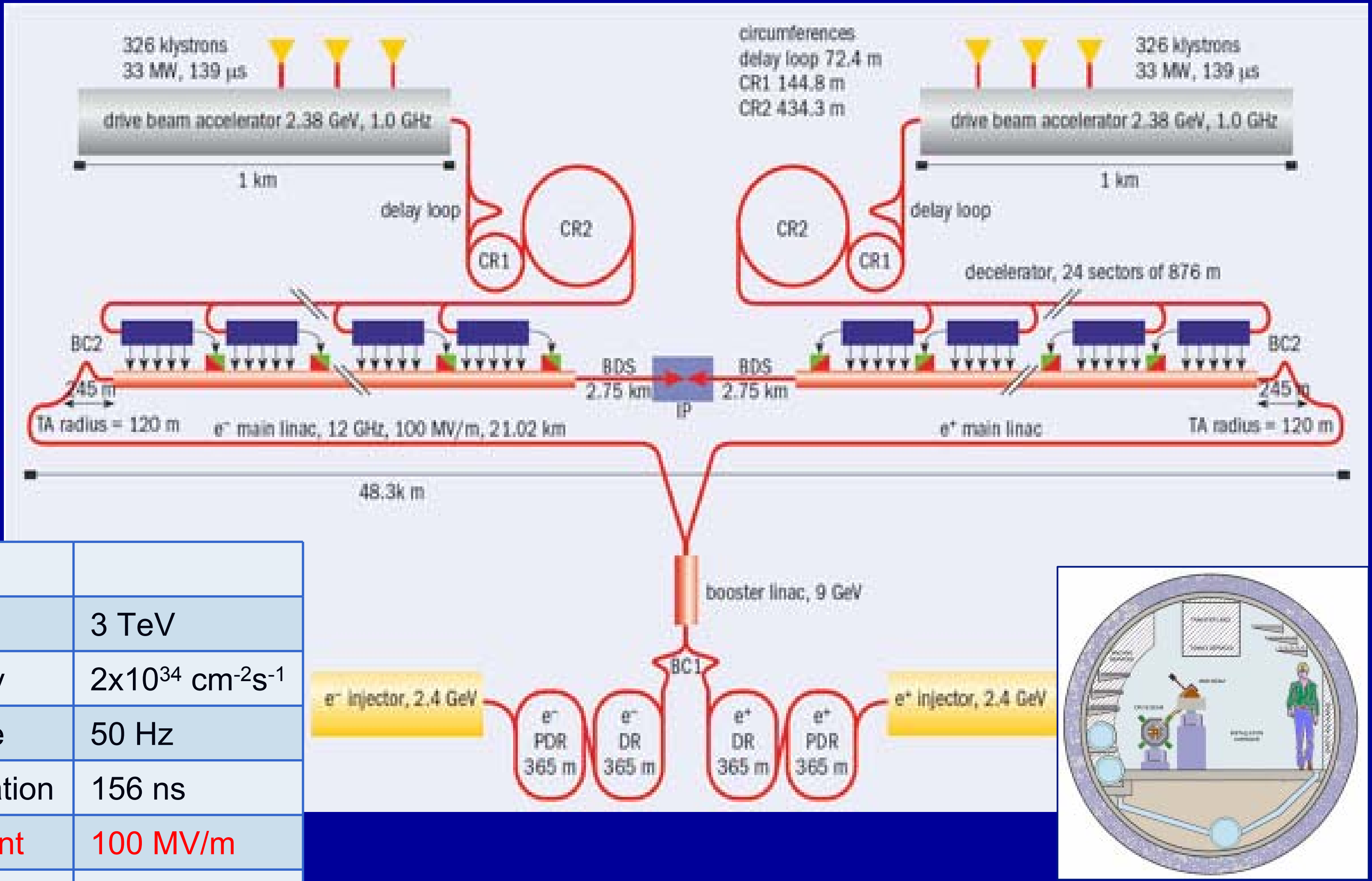
Field Gradient progress at TESLA/FLASH



- ILC operation <31.5> MV/m
- R&D status ~30 MV/m
- XFEL requires <23.6> MV/m

20% Improvement needed to meet ILC requirement 35 MV/m.
Improved processing already demonstrated 36 MV/m.

CLIC: The Compact Linear Collider



Main Linac	
C.M. Energy	3 TeV
Peak luminosity	$2x10^{34}$ $cm^{-2}s^{-1}$
Beam Rep. rate	50 Hz
Pulse time duration	156 ns
Average gradient	100 MV/m
# cavities	2 x 71,548

Φ4.5m tunnel

The Key to CLIC Efficiency

CLIC accelerating gradient: **100 MV/m**

RF frequency: 12 GHz

64 MW RF power / accelerating structure

of 0.233m active length

➔ **275 MW/m**

Total active length for 1.5 TeV: **15 km**

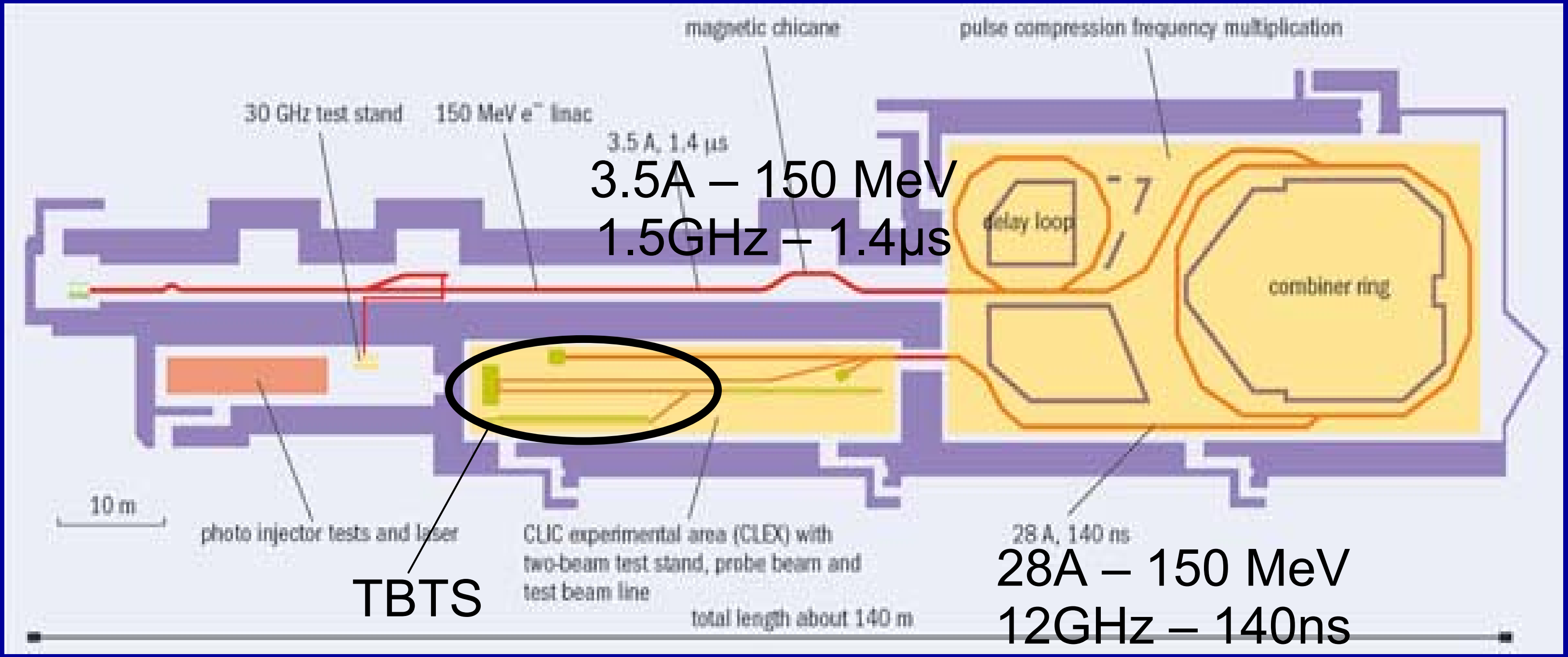
➔ individual klystrons not realistic

Note: pulse length 240 ns, 50 Hz repetition rate

Estimated wall power 400 MW at 7% efficiency

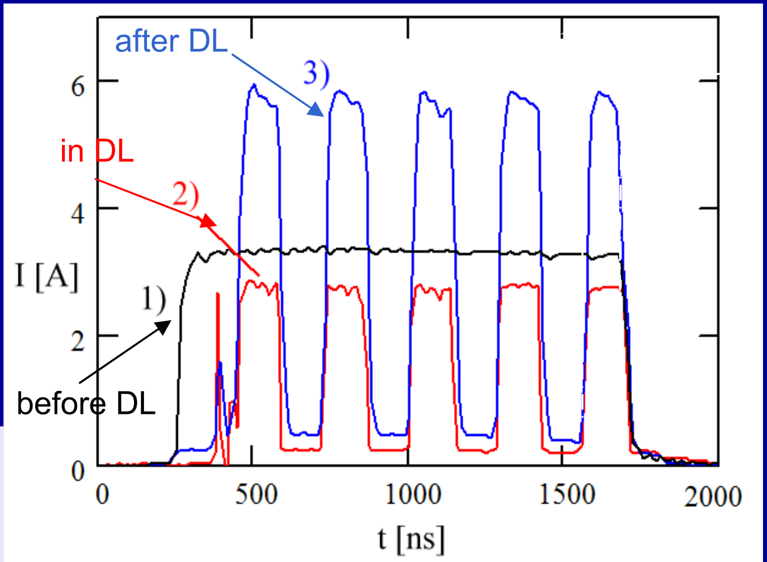
CTF3: CLIC Test Facility

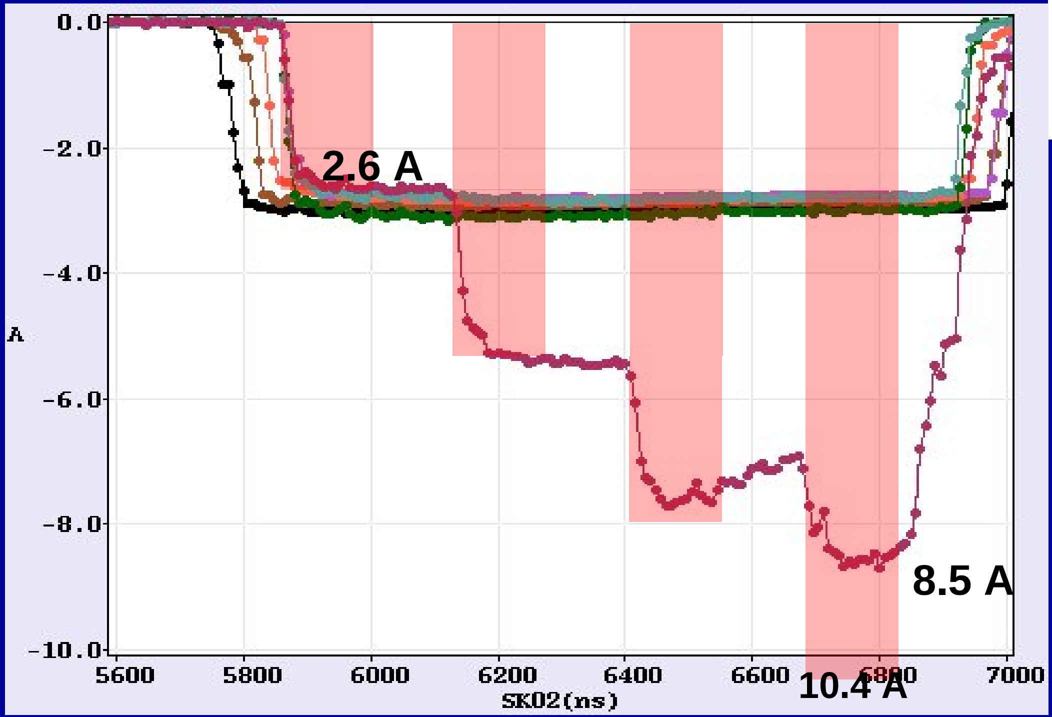
- demonstration **drive beam generation** (fully loaded acceleration, bunch interleaving)
- evaluate **beam stability & losses** in deceleration
- development **power production & accelerating structures** (damping, PETS on/off, beam dynamics effects)

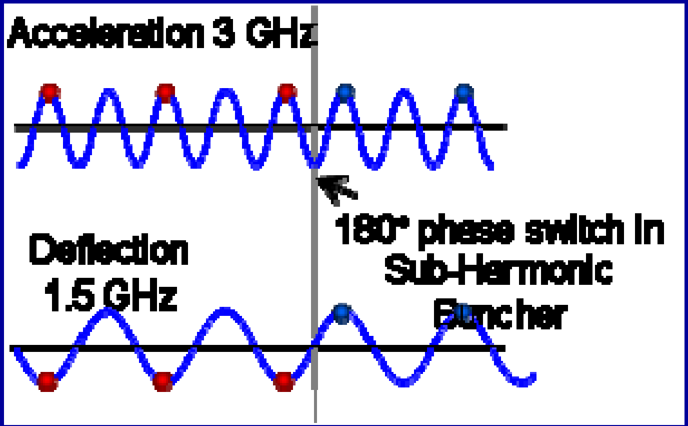


Demonstration Beam Re-combination

- delay loop (DL) gap creation (for CR extraction) and doubling frequency + intensity
- combiner ring bunch interleaving (delay loop bypass, instabilities)

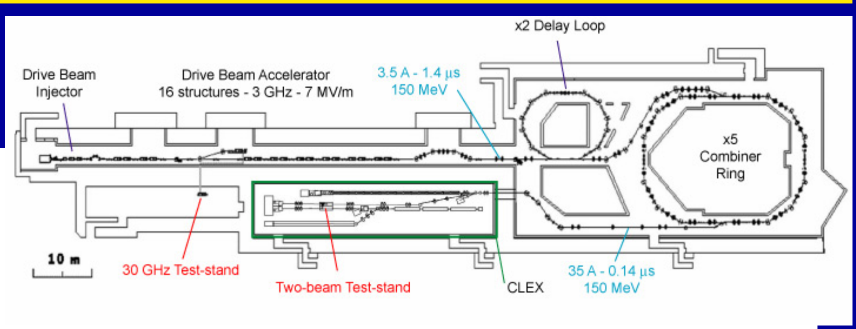


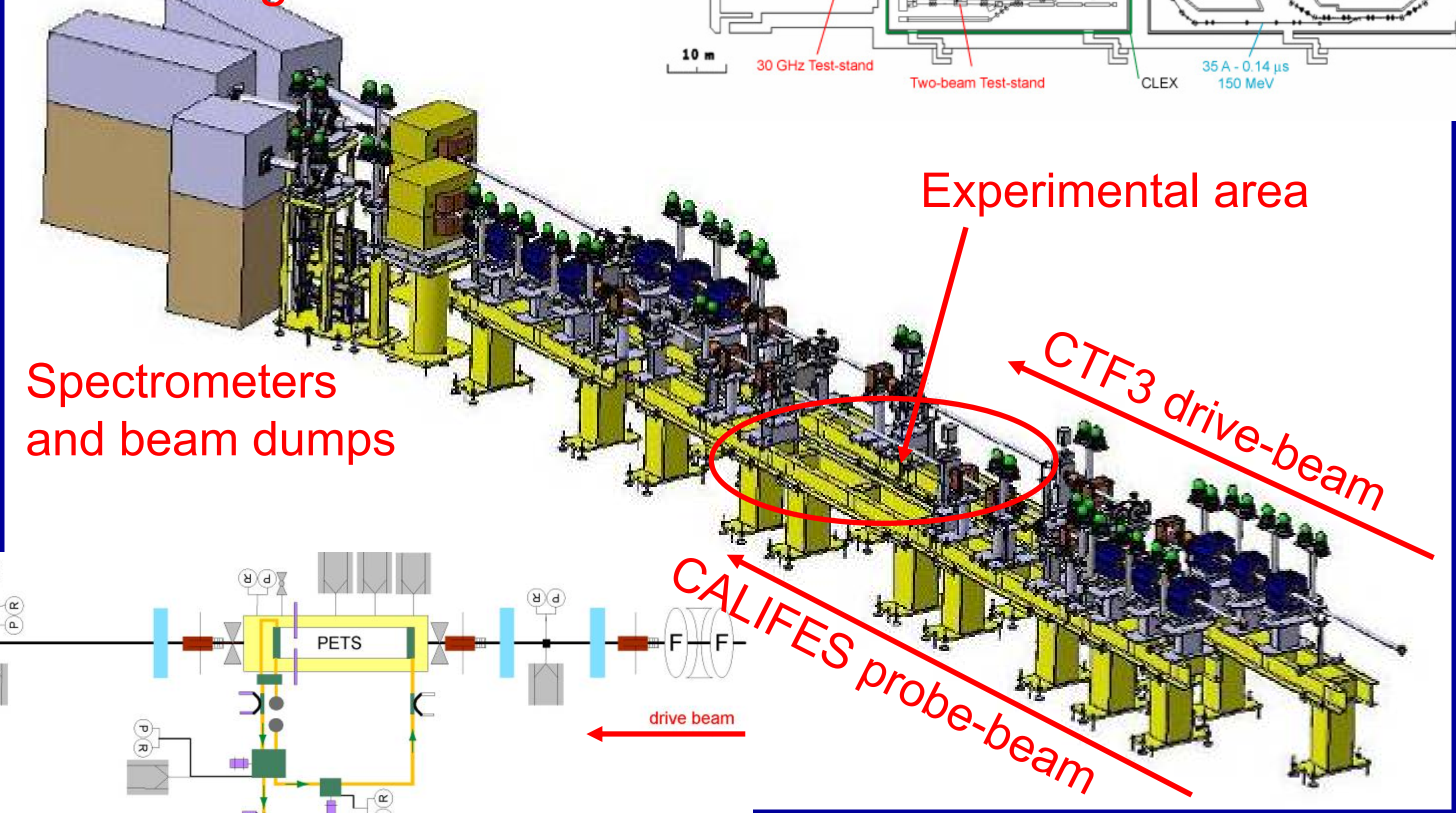


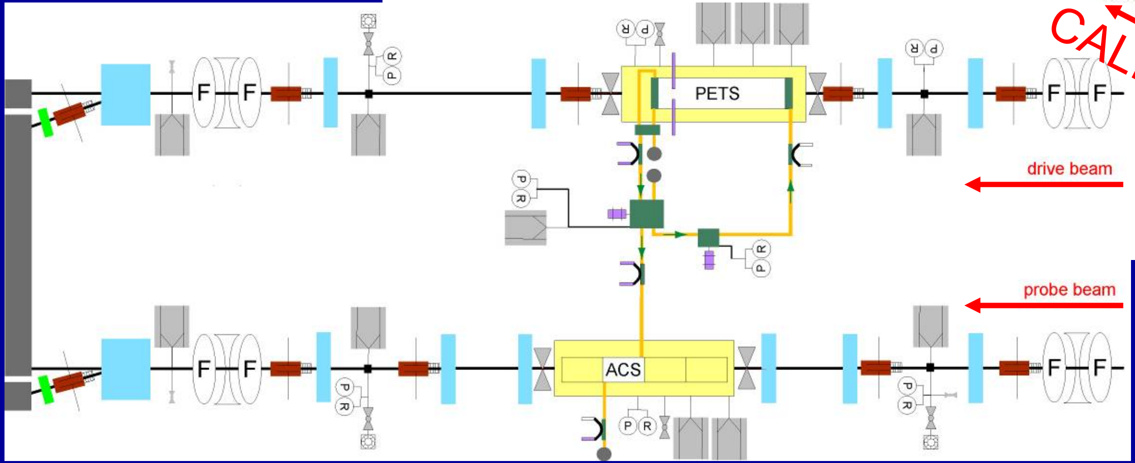


Two-beam Test Stand Layout

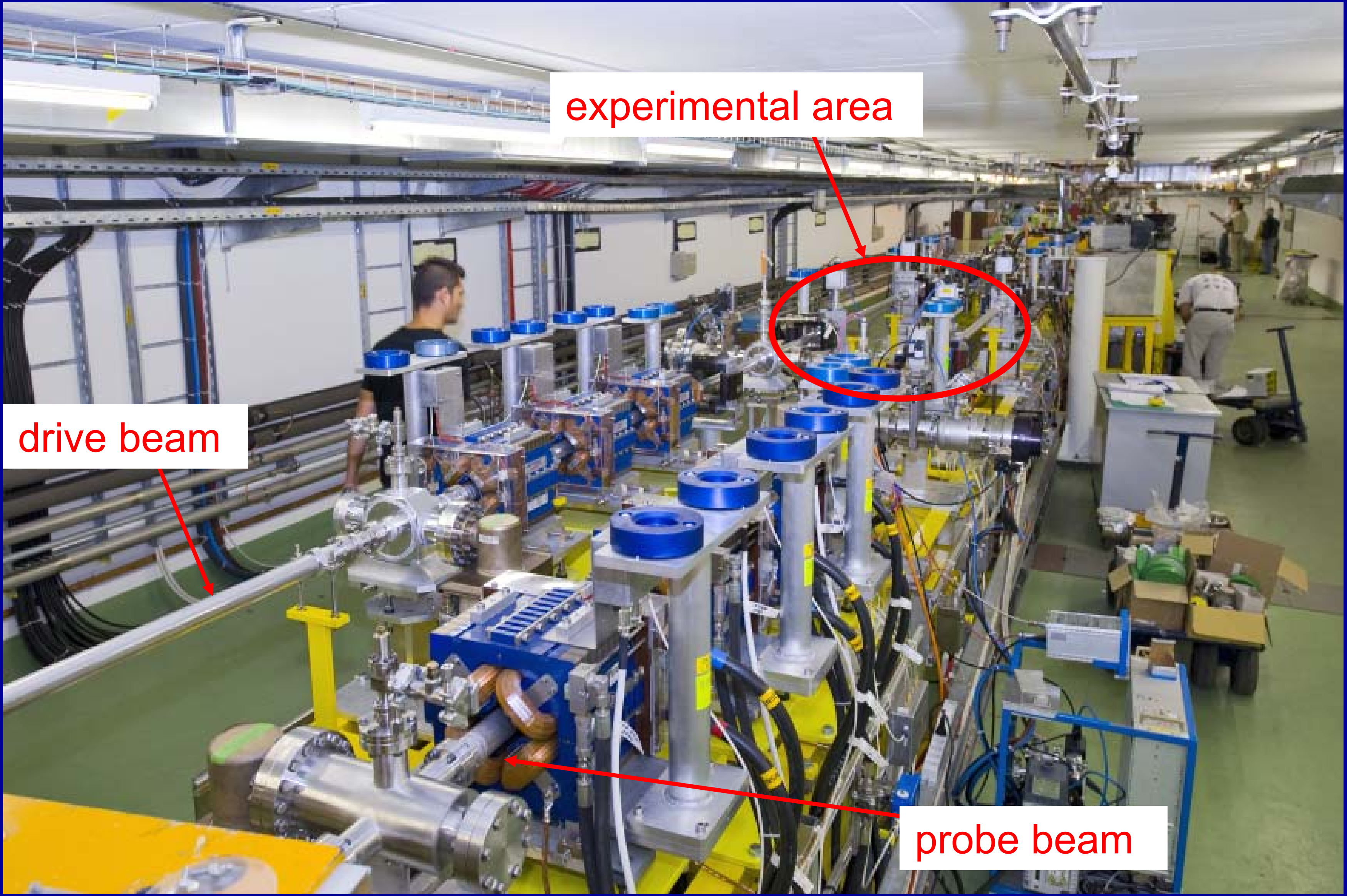
Construction supported by the Swedish Research Council and the Knut and Alice Wallenberg Foundation







CTF3 Two-beam Test Stand



CTF3 Two-beam Test Stand Prospects

Versatile facility

- two-beam operation
  - high power drive-beam [32A to 100A at CLIC]
  - high quality probe-beam [0.9A to 1.0A at CLIC]
- excellent beam diagnostics, long lever arms
- easy access & flexibility for future upgrades

Unique test possibilities

- power production & accelerating structures
  - beam loading
  - beam kick
  - beam dynamics effects
- full CLIC module
  - beam-based alignment

Demonstration Fully Loaded Operation

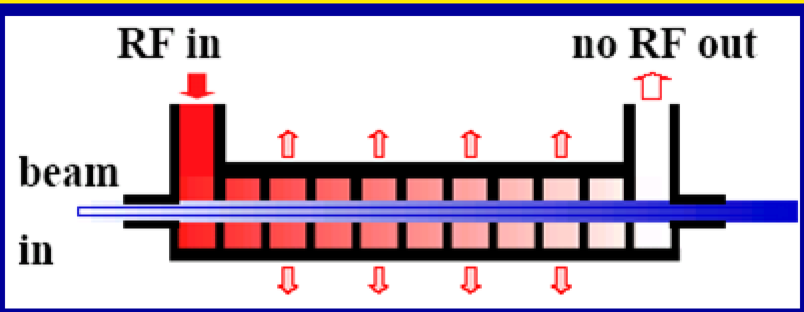
Efficient power transfer

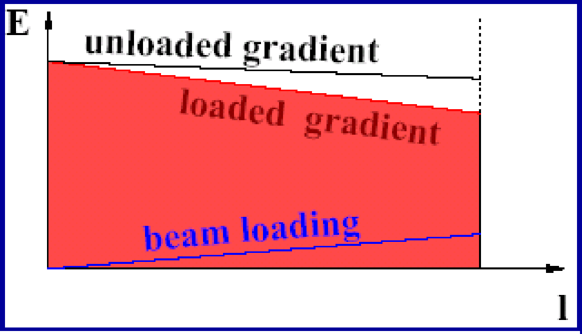
"Standard" situation:

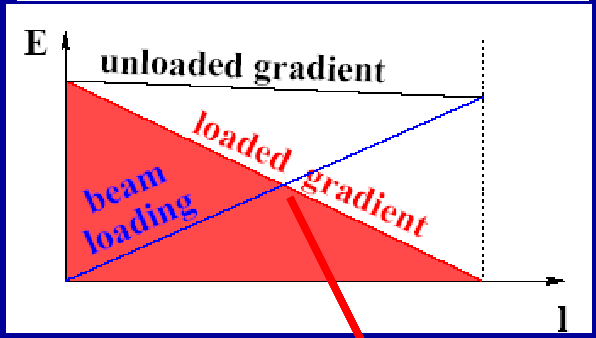
- small beam loading
- power at exit lost in load

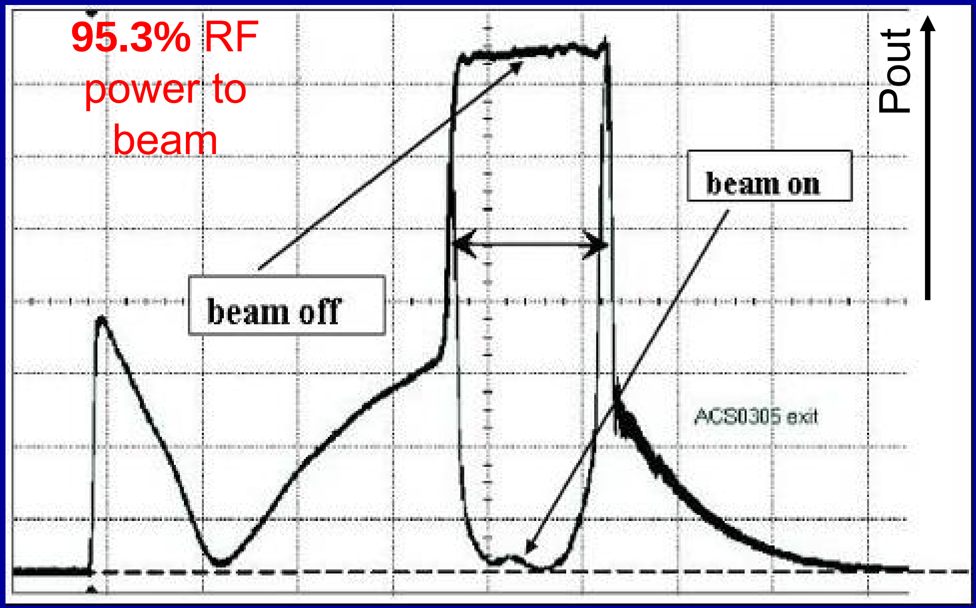
"Efficient" situation: $V_{ACC} \approx 1/2\ V_{unloaded}$

- high beam loading
- no power flows into load

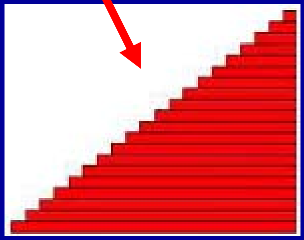




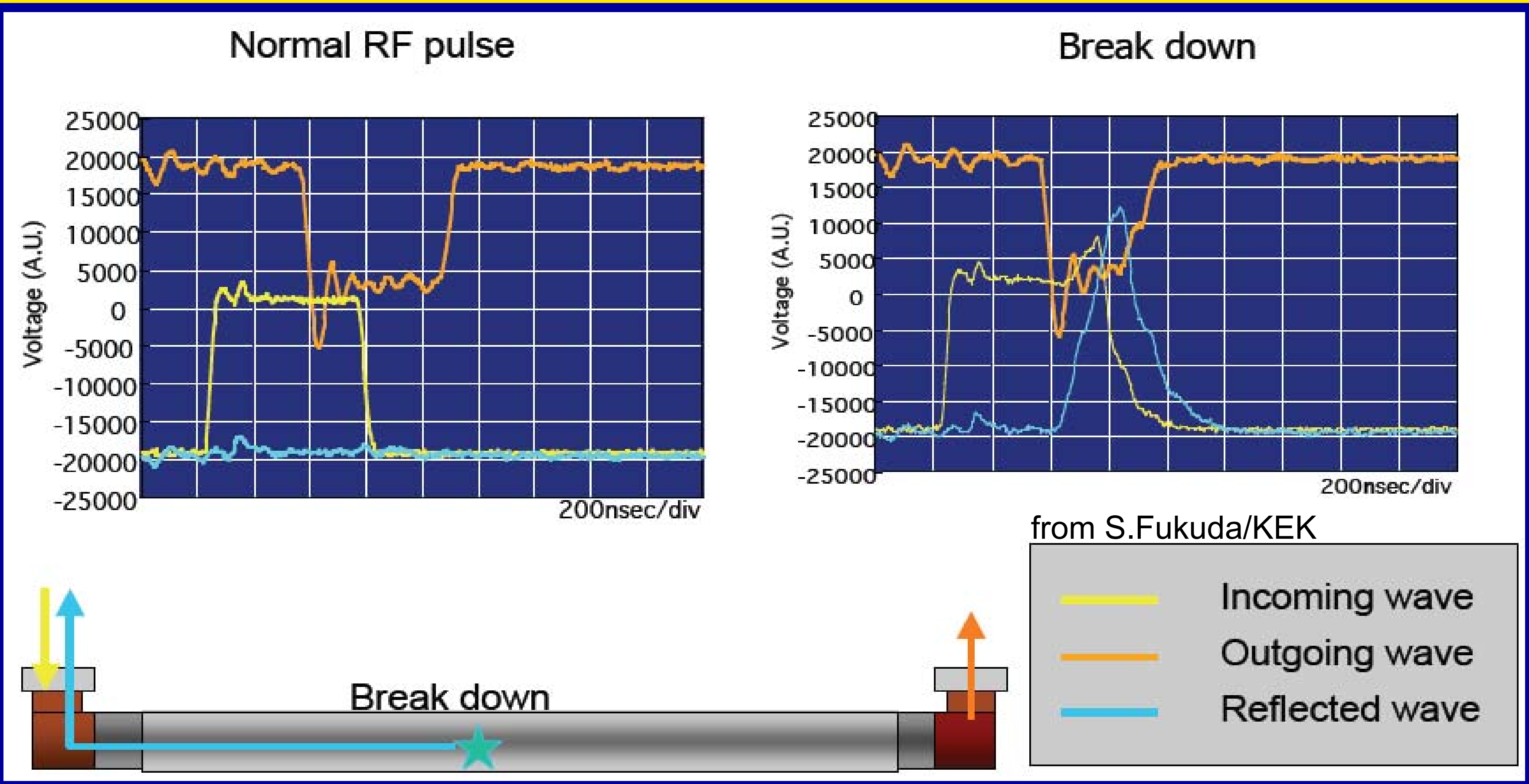




field builds up linearly (and stepwise, for point-like bunches)



RF Pulse Distortion on Breakdown



Pulses with breakdown not useful for acceleration due to beam kick

→ transverse oscillations depending on kick amplitude & momentum spread

→ low breakdown rate required ($<10^{-6}$) for useful operation

RF Breakdown: a Reliability Issue

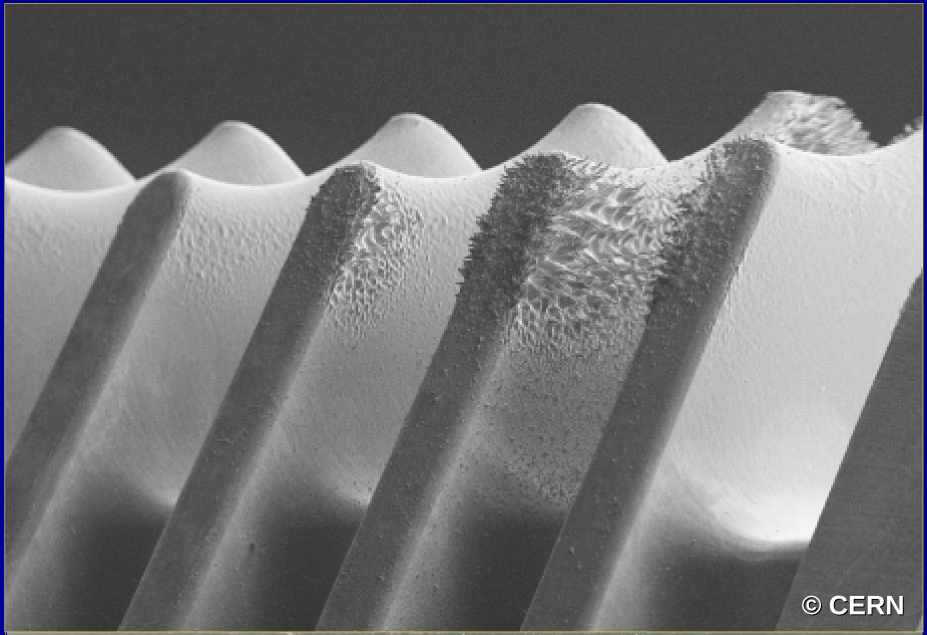
Conditioning required

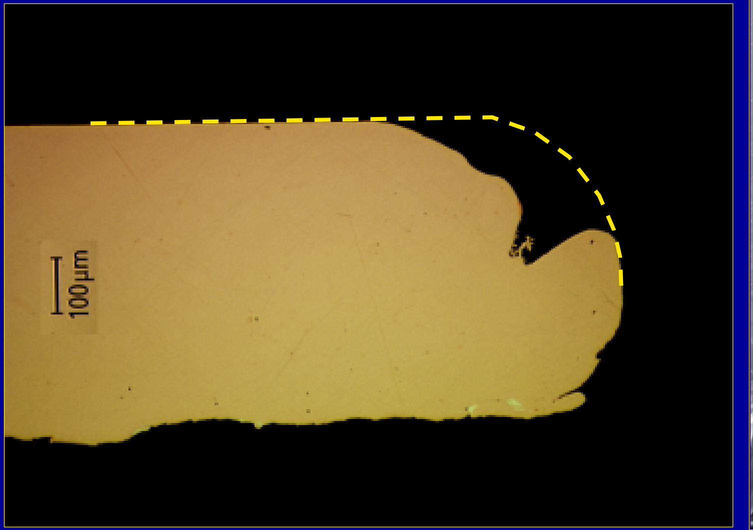
- to reach nominal gradient

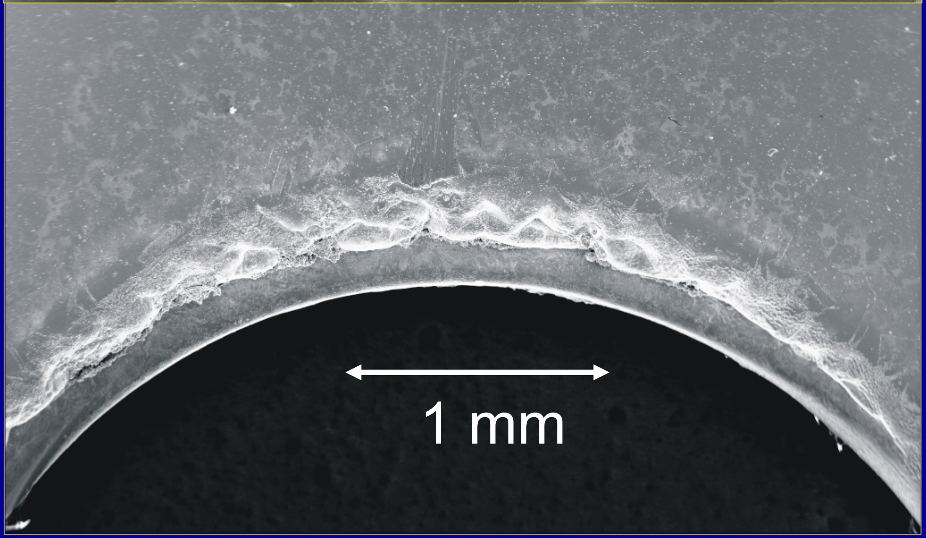
but

- damage by excessive field

Physics phenomena not yet completely understood!





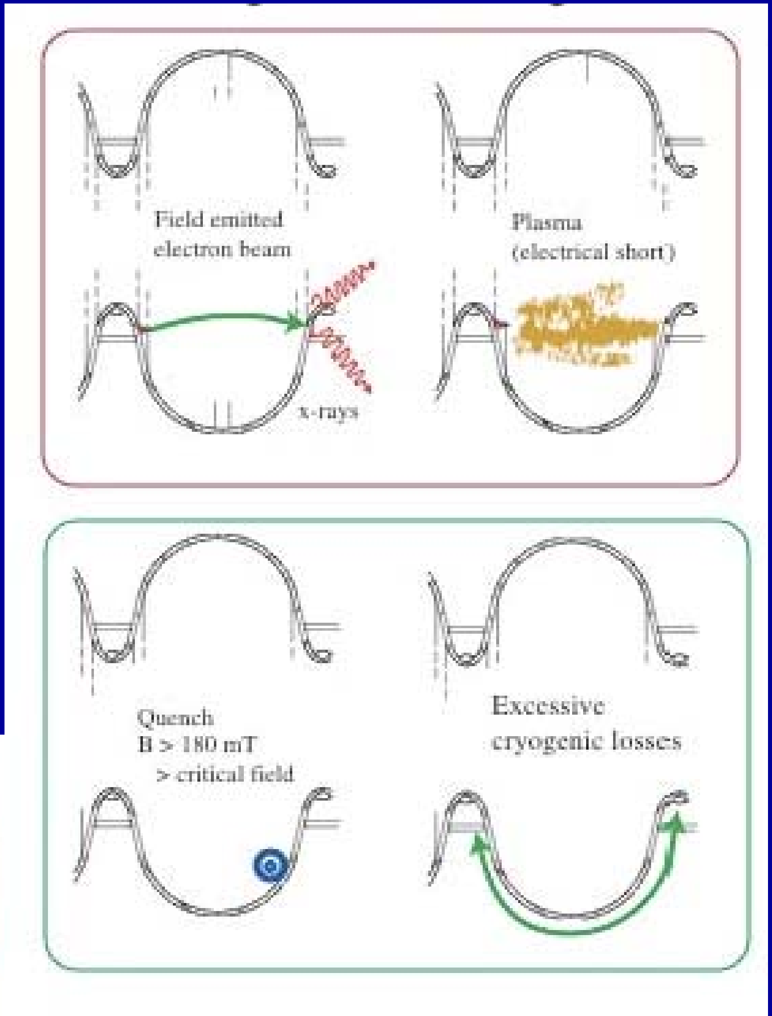


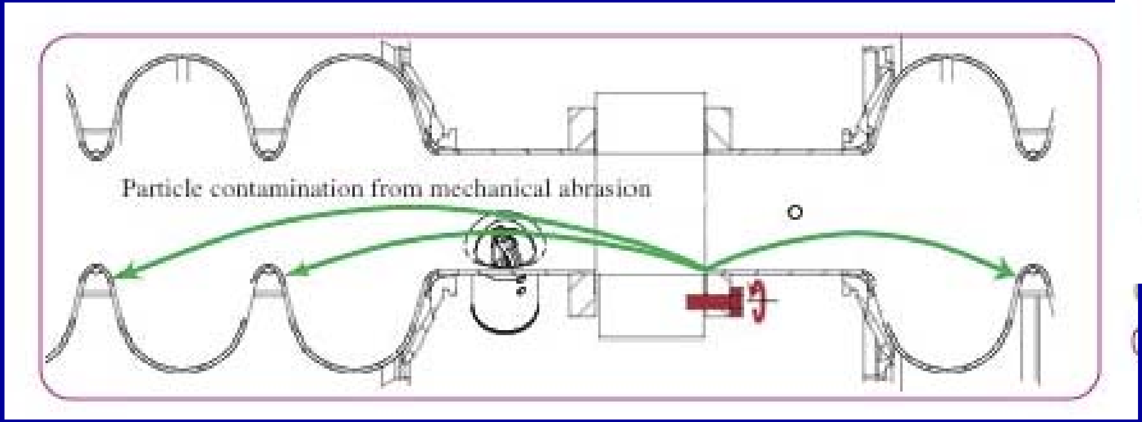
Field Gradient Limitations in RF Cavities

Field Emission
- due to high **electric field** around the iris

SCRF Quench
- caused by surface heating from dark current, or
- **magnetic field** penetration around “Equator”

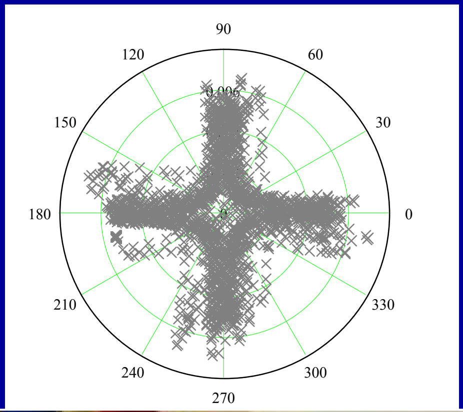
Contamination
- during assembly

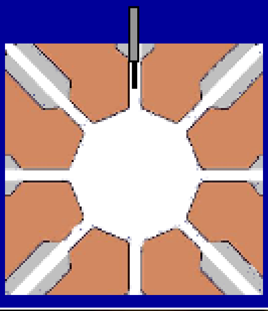


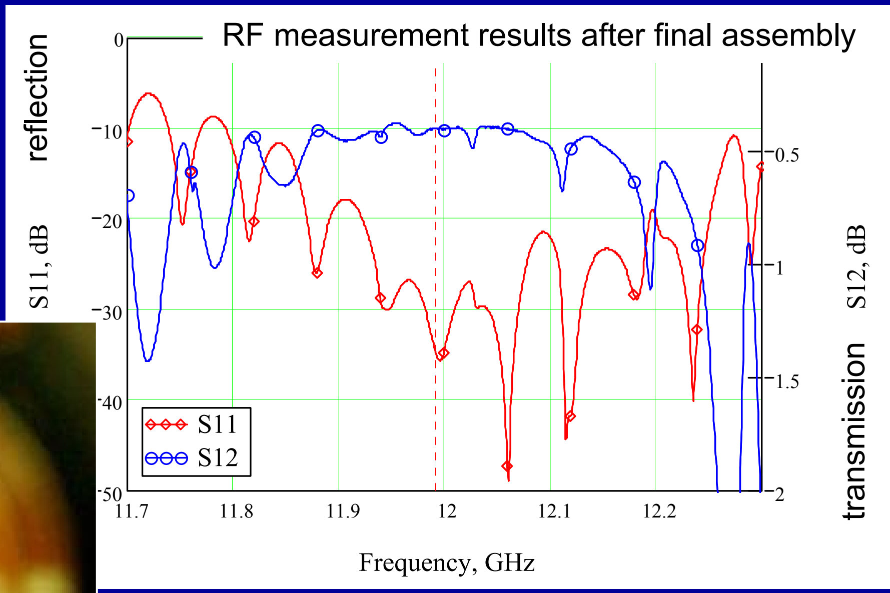


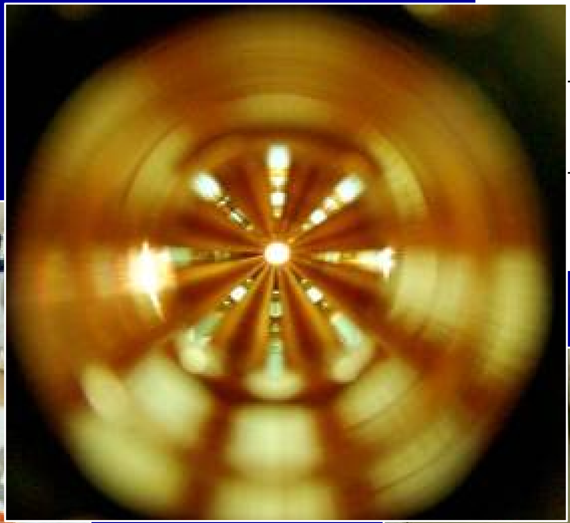
TBTS PETS Assembly & Test

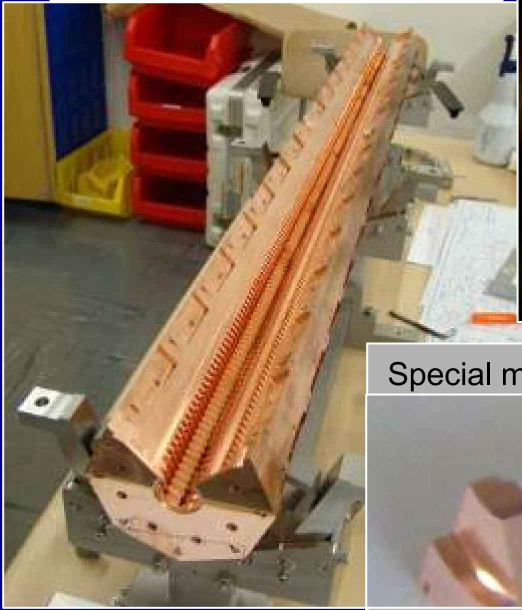
Sliding antenna measurements (F=11.992 GHz)

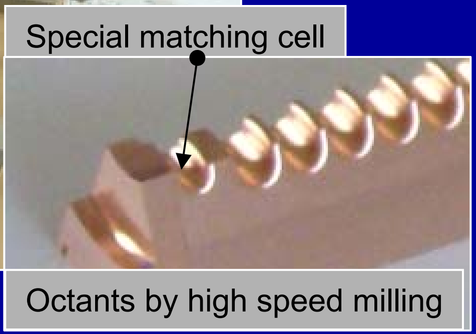


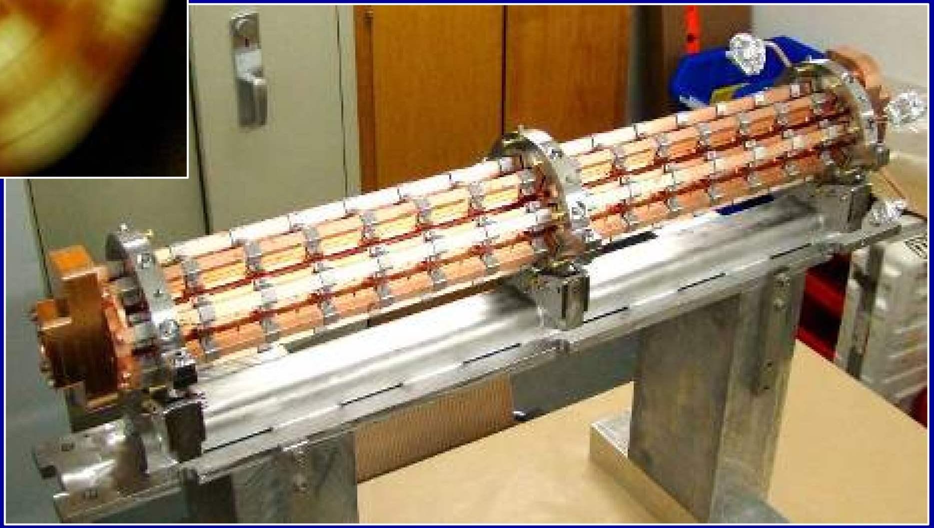








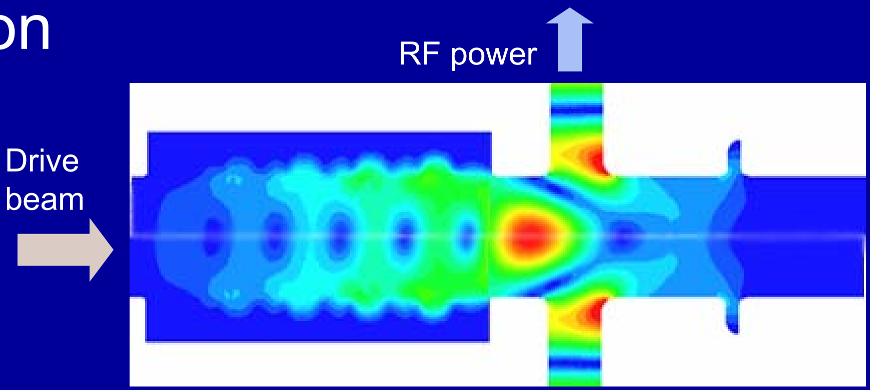


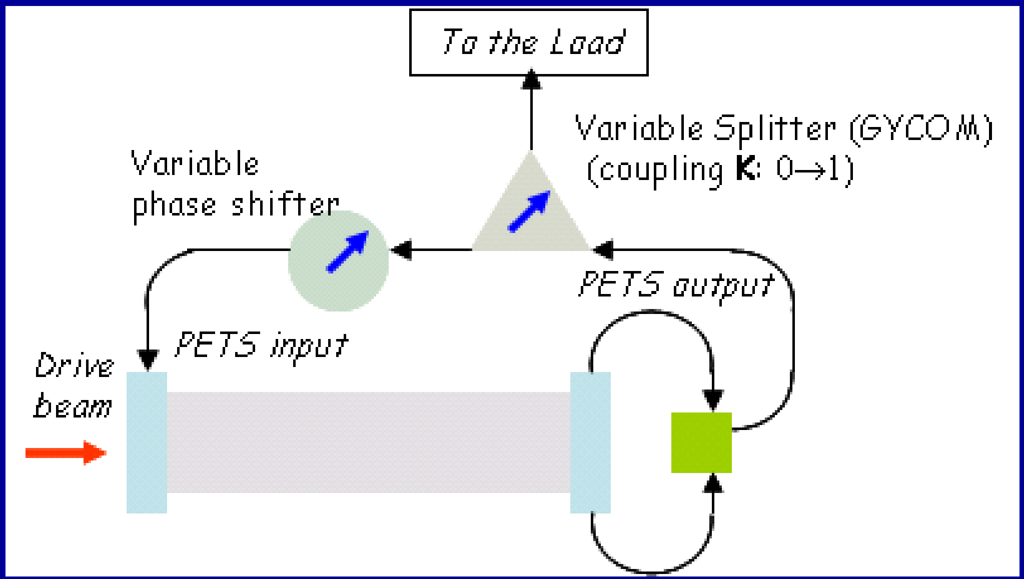


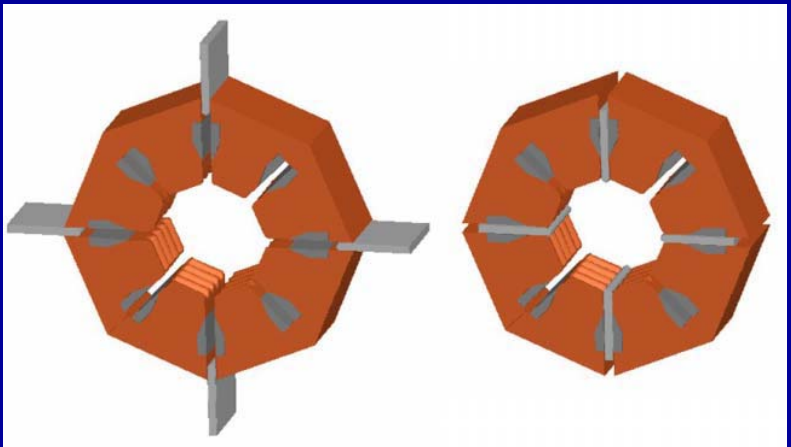
TBTS PETS Power Production Demonstration

Through drive beam deceleration

- demonstrate reliability
- TBTS only available facility
- use RF power recirculation due to low drive beam power
- 2nd stage: on/off mechanism to be tested







PETS on & off configurations with detuning wedges

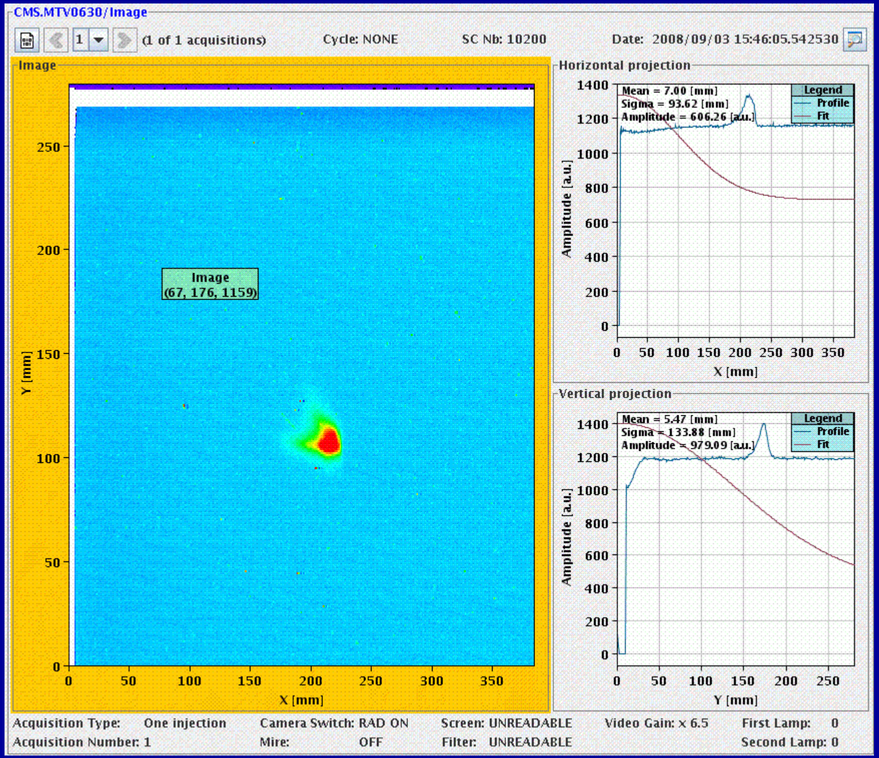
Aims of the TBTS Test Programme

Demonstration

- power production in prototype CLIC PETS
- two-beam acceleration

Experiments

- beam loading compensation
- beam dynamics effects
- beam kick due to breakdown or dipole modes
- breakdown rate
- dark & ion currents



First beam, 3 Sep 2008

see Magnus' talk tomorrow

Acknowledgements

For the contribution of material and advice, without which I would not have been able to make this presentation. My grateful thanks to

- Alex Andersson, Erik Adli, Hans Braun, Daniel Schulte, Igor Syratchev, Frank Tecker, Akira Yamamoto and Volker Ziemann

CERN and KEK.