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Beyond LHC
The Path Towards Future Linear Colliders

Roger Ruber

Dept. of Physics
and Astronomy

Div. of Nuclear
and Particle
Physics

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Outline

This lecture

- technologies for a future linear collider
- highlights of related research

Sections

1. circular versus linear colliders
2. accelerating gradient
3. radio frequency power generation
4. R&D projects for a future linear collider

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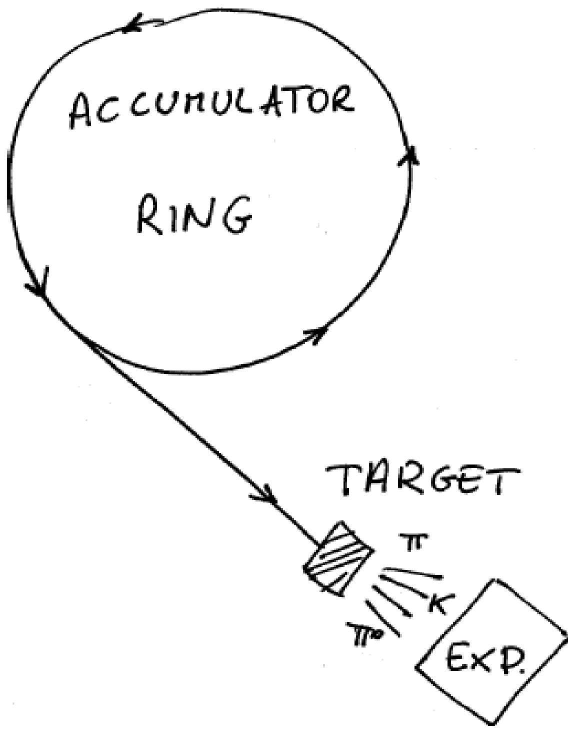
Outline

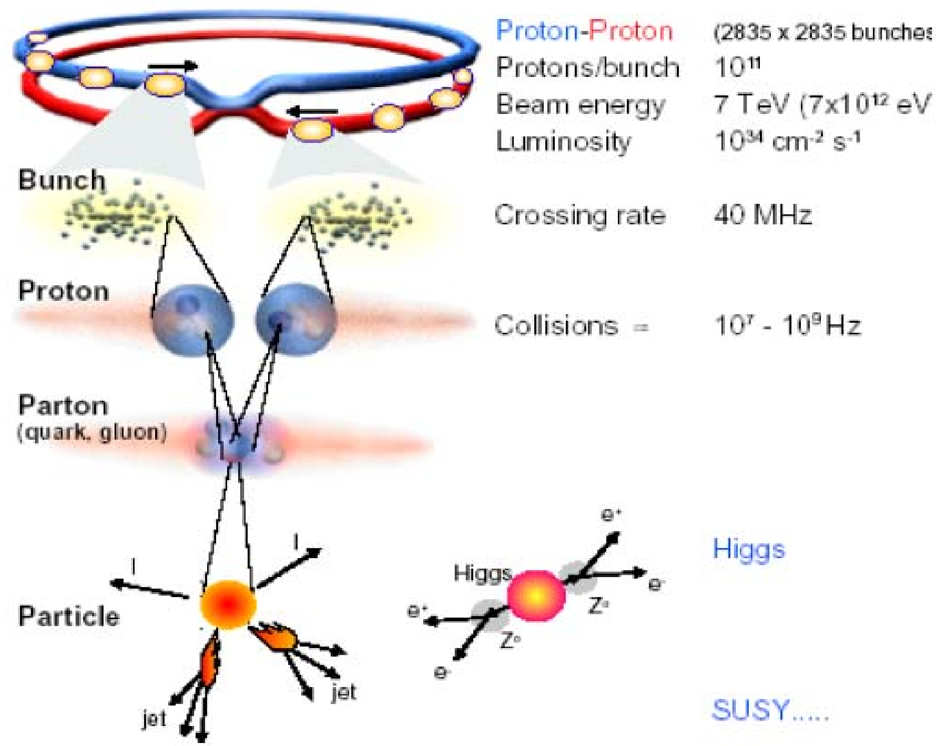
1. Colliders
2. Cavities
3. RF power
4. Projects

1: Particle Collider History

Fixed Target



Collider



$$E_{CM} = \sqrt{2\left(E_{beam}mc^2 + m^2c^4\right)} \quad << \quad E_{CM} = 2\left(E_{beam} + mc^2\right)$$

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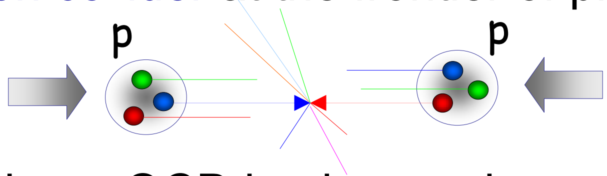
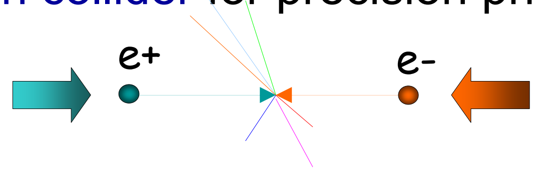
Hadron versus Lepton Colliders

hadron collider at the frontier of physics



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

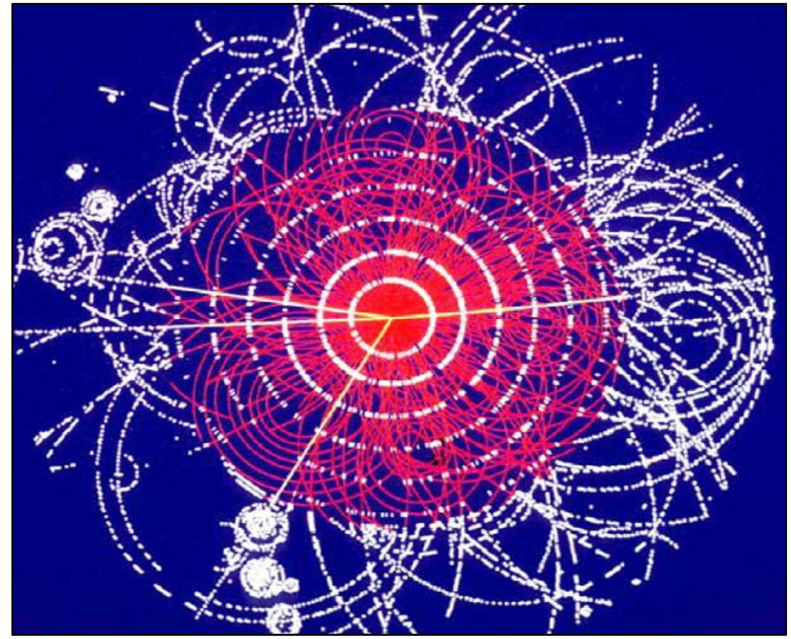
lepton collider for precision physics

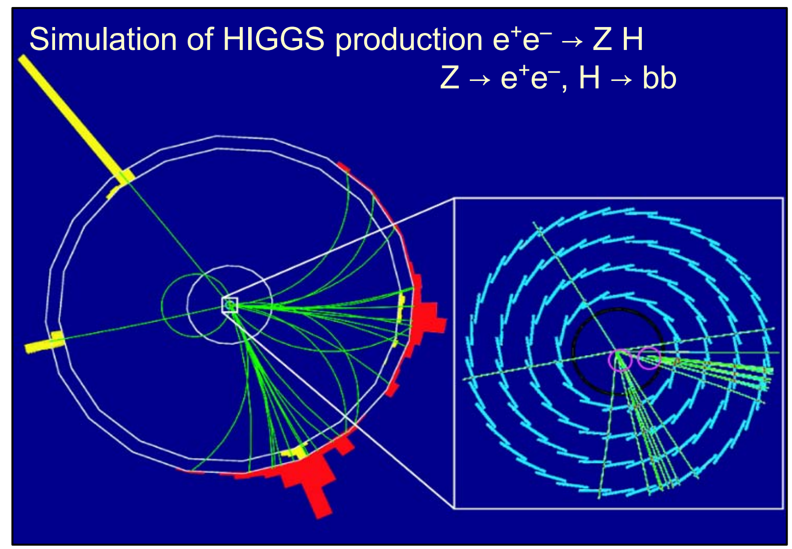


- well defined CM energy
- polarization possible

after LHC → lepton collider

- energy determined by discoveries
- consensus $E_{cm} \geq 0.5$ TeV





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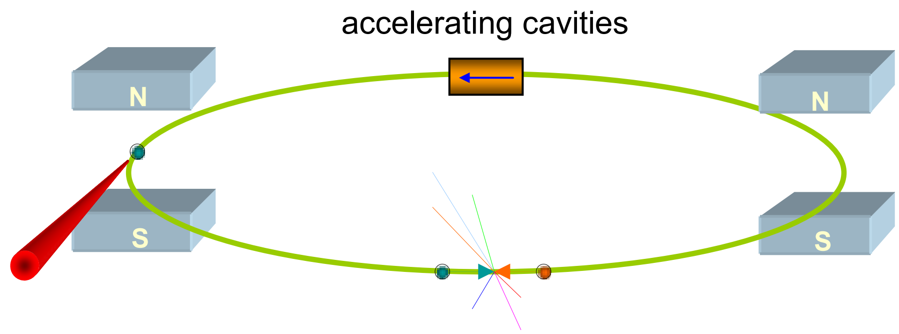
Circular versus Linear Collider

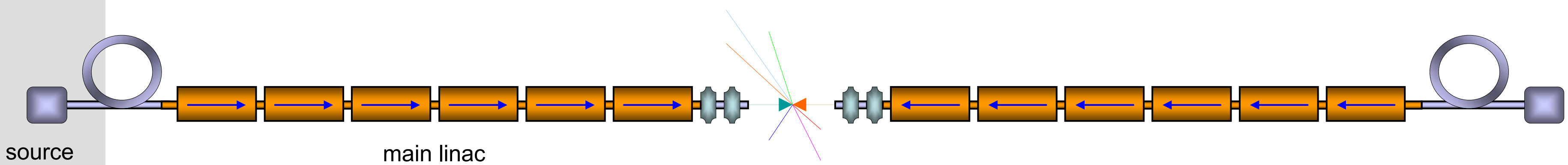


Circular Collider

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



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)

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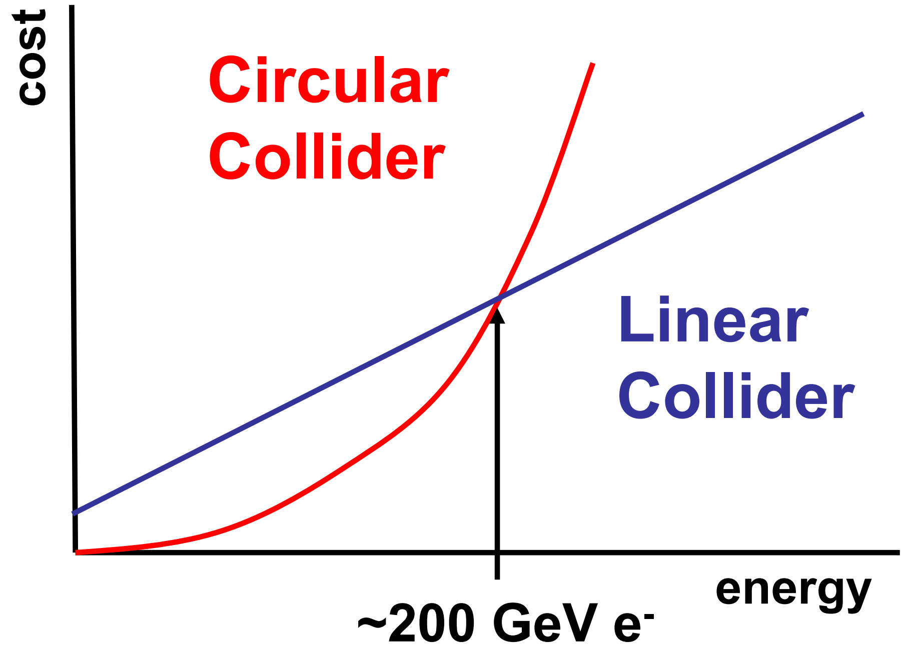
Cost of Circular & Linear Accelerators



Circular Collider

- $\Delta E_{turn} \sim (q^2E^4/m^4R)$
- cost ~ aR + b ΔE
- optimization: $R \sim E^2 \rightarrow$ cost ~ cE^2

LEP200: ΔE ~ 3%; 3640 MV/turn

Linear Collider

- E ~ L
- cost ~ aL

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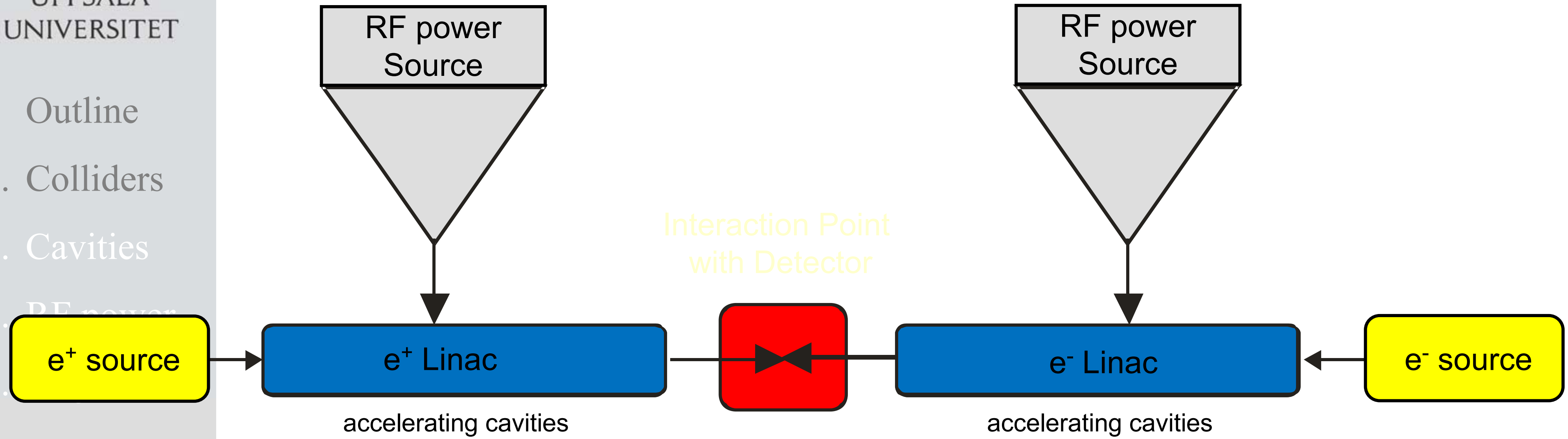
Linear Collider R&D



1. high energy → high accelerating gradient
2. high luminosity → high current & small beam size
3. efficient radio frequency power production
4. feasibility demonstration

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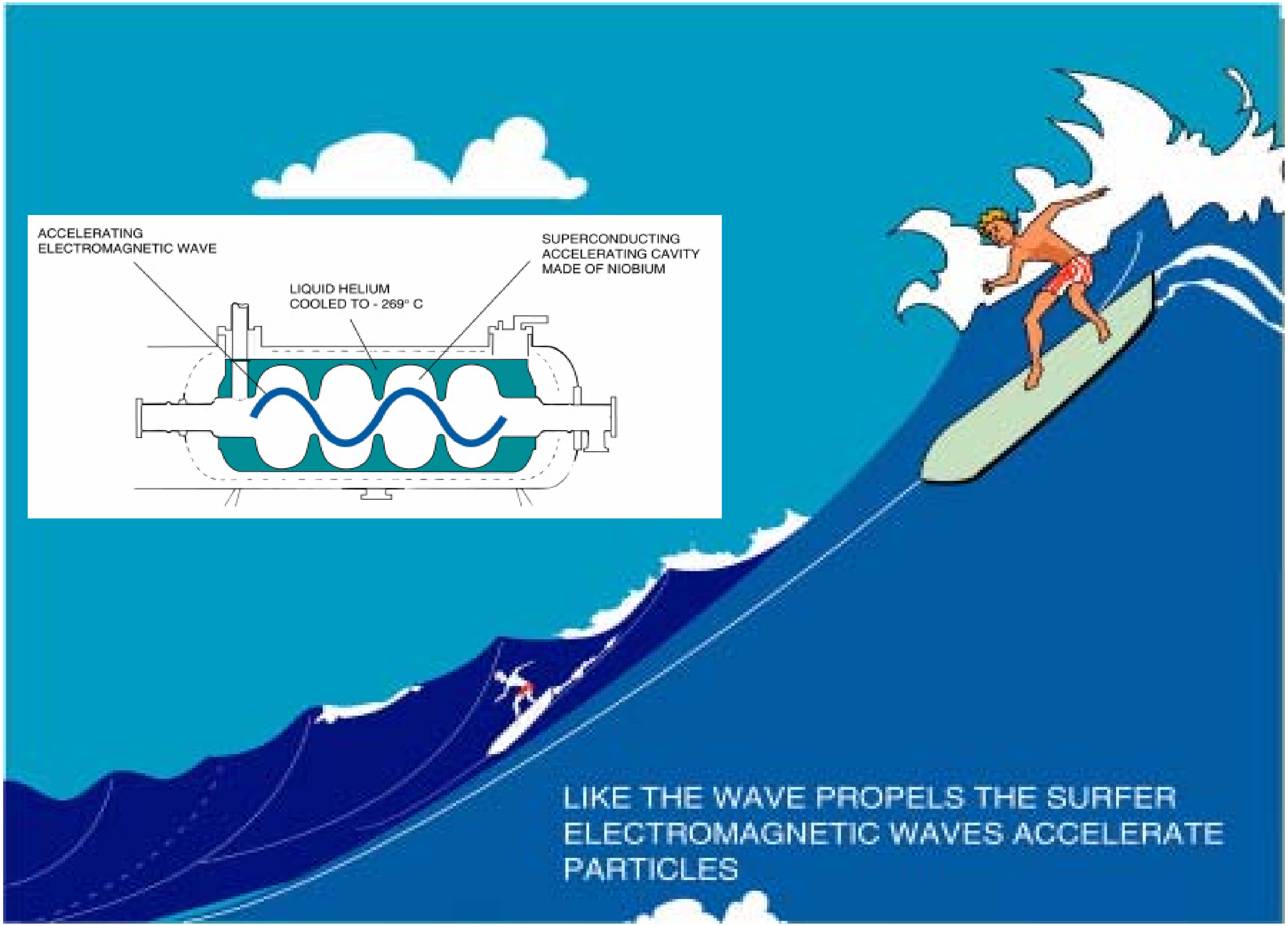
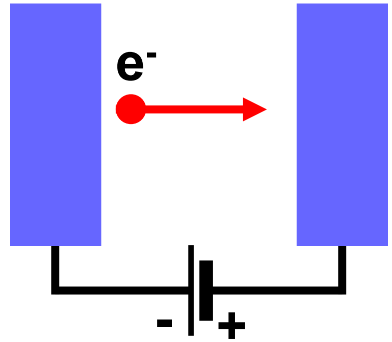
2. Accelerating Gradient



Accelerating Gap and Gradient



Gap voltage required for acceleration

- cannot be DC,
  because beam tube on ground potential

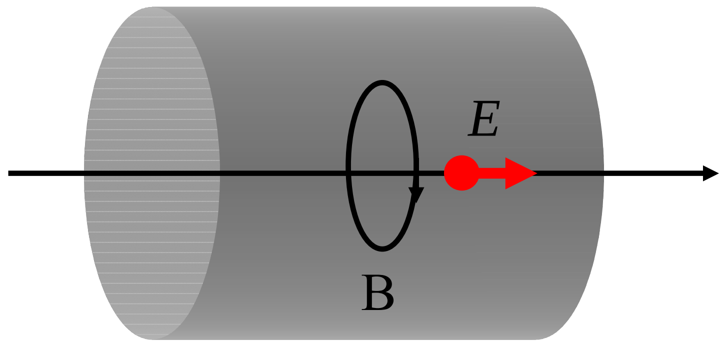
- use cavity with RF field (Maxwell equations)

$$\nabla \times \vec{E} = -\frac{\partial}{\partial t}\vec{B} \qquad \oint \vec{E} \cdot d\vec{s} = -\iint \frac{\partial \vec{B}}{\partial t} \cdot d\vec{A}$$

- breakdown limit
  (vacuum, Cu surface, T_{room})

$$24.67\sqrt{f} = E_c e^{-\frac{4.25}{E_c}}$$

  → high E_c requires high f



- frequency f determines cavity shape

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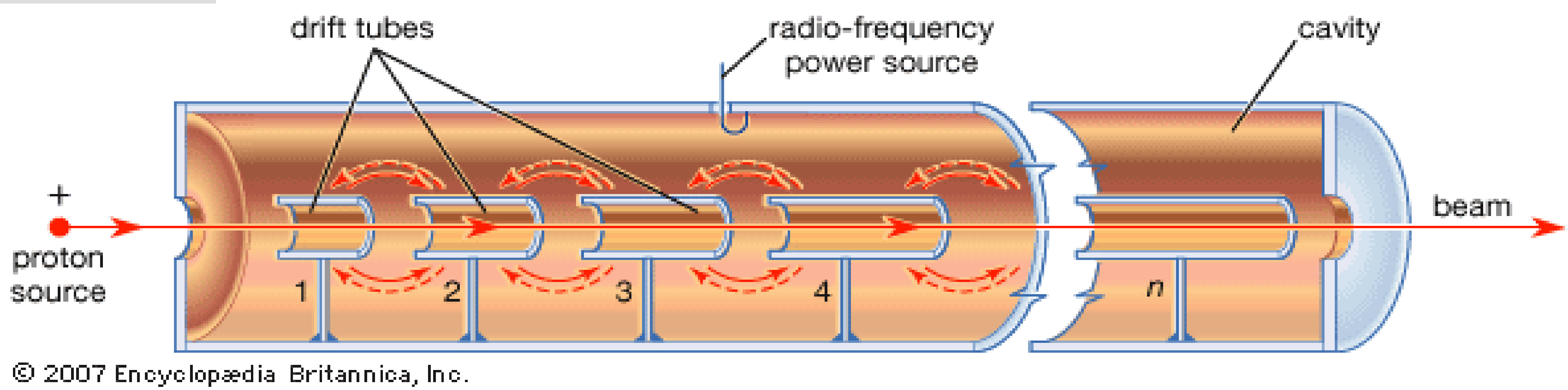
Drift Tube Linear Accelerator Structure

Low velocity particles

- for velocity < 0.4 c (50 keV e^-; 100 MeV p)
- standing wave
- drift tube size and spacing adapted to
  - RF frequency
  - particle speed



Drift Tube Linac: How It works

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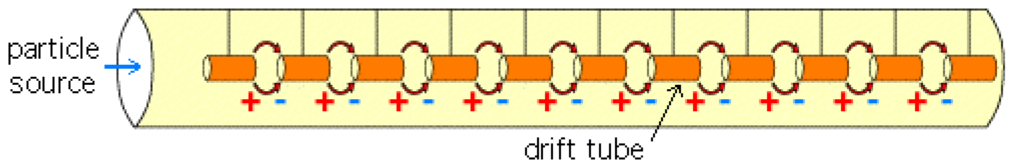
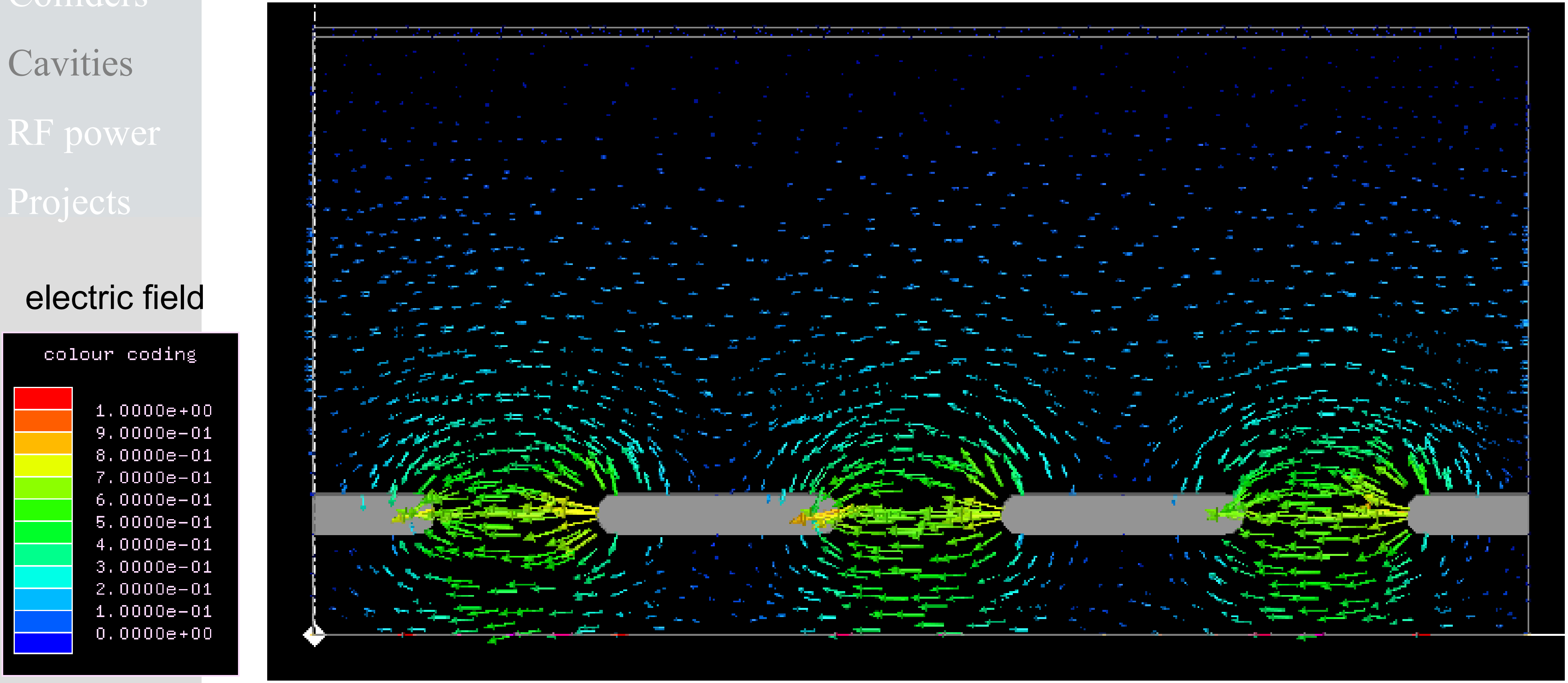
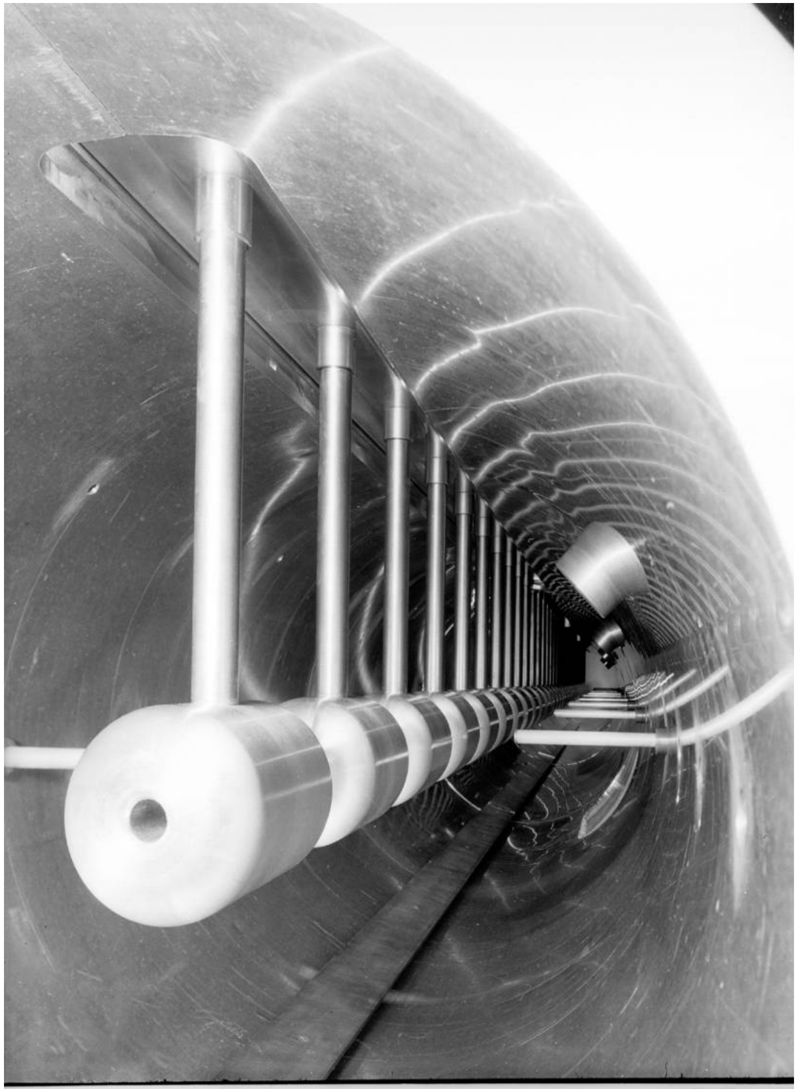


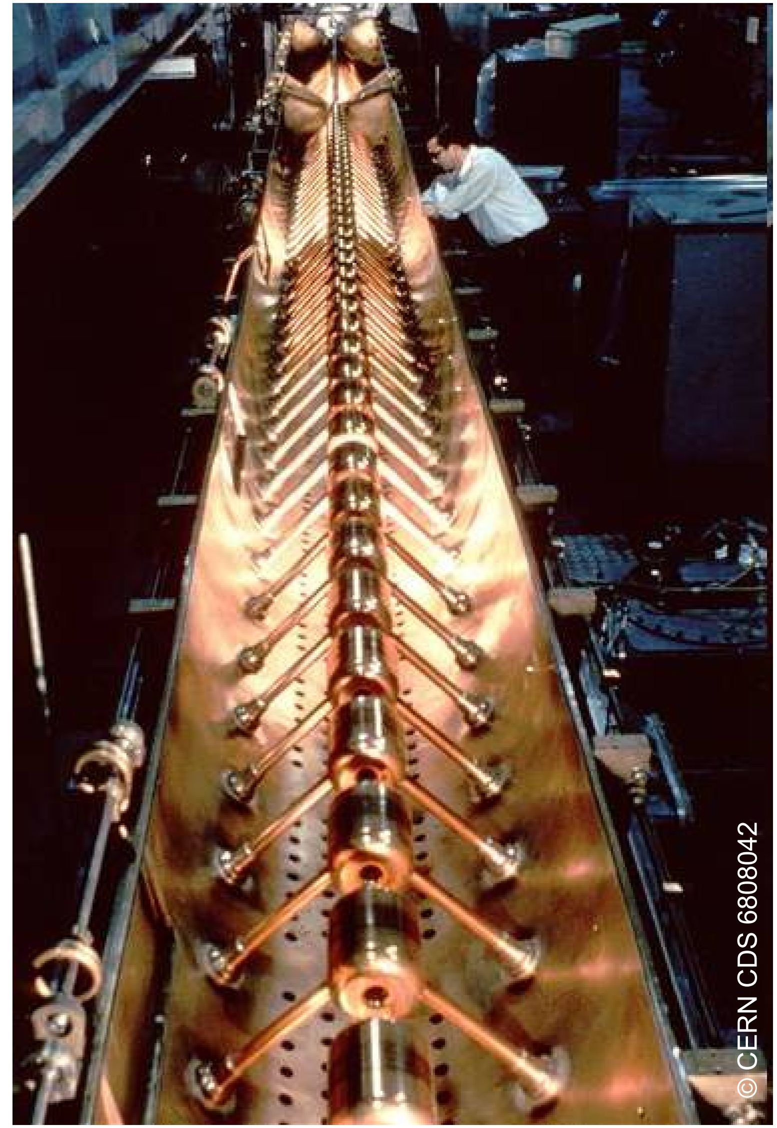
Courtesy E. Jensen

electric field



Example of Drift Tube Linacs

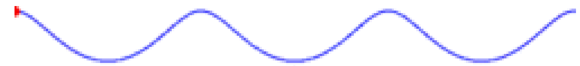




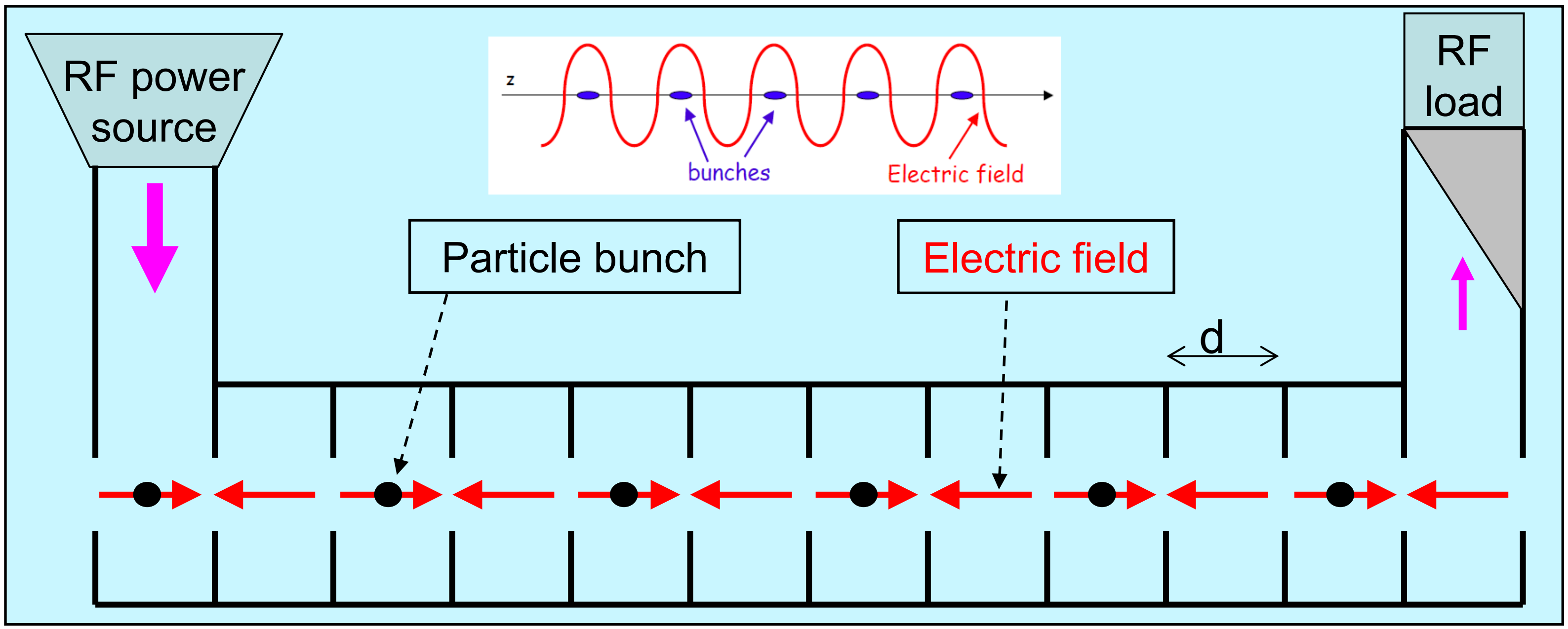
Disk-loaded Accelerating Structure

In free space,

electro-magnetic wave travels faster than particles
→ couple wave to resonating structures
→ particle velocity equal to phase velocity



Example shows standing wave structure (v_{group}=0) with
- π phase advance per cell



Superconducting RF Cavities (SRF)

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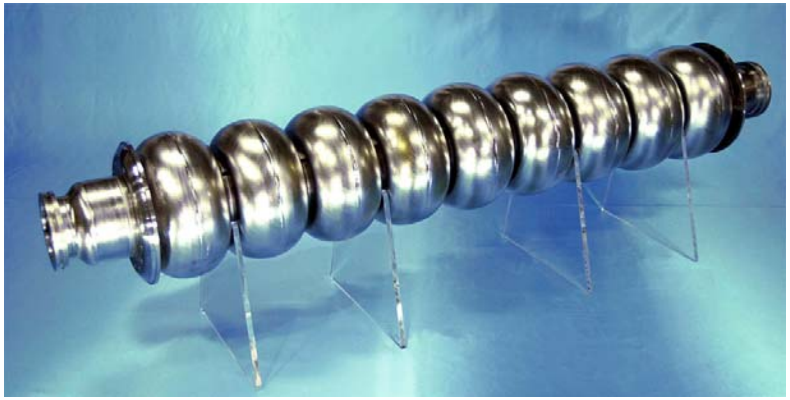

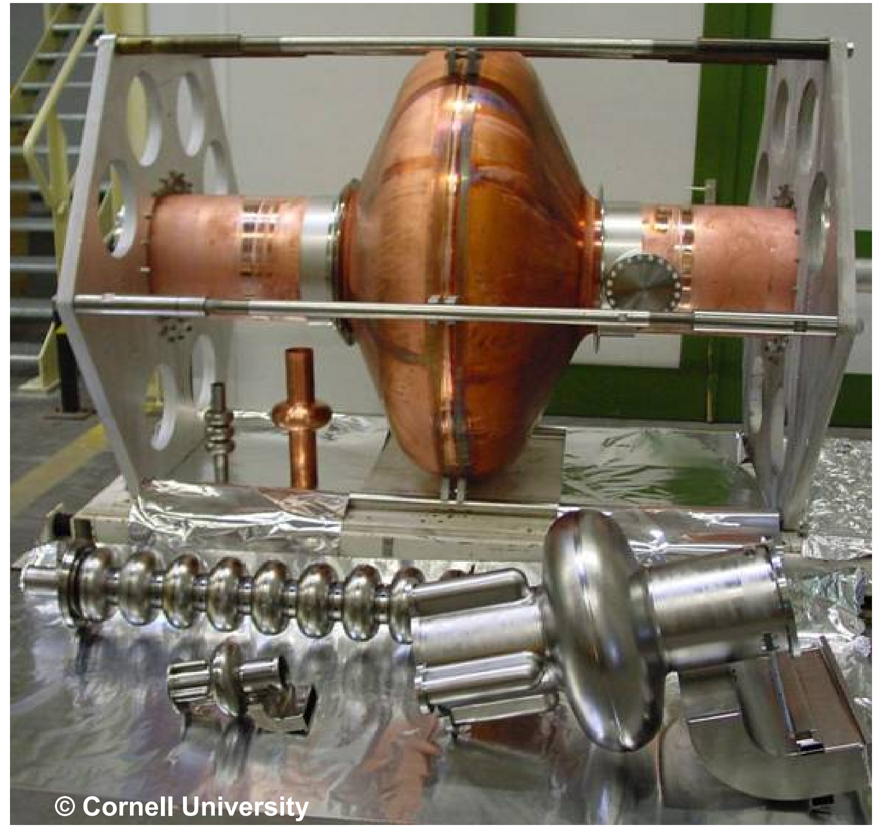

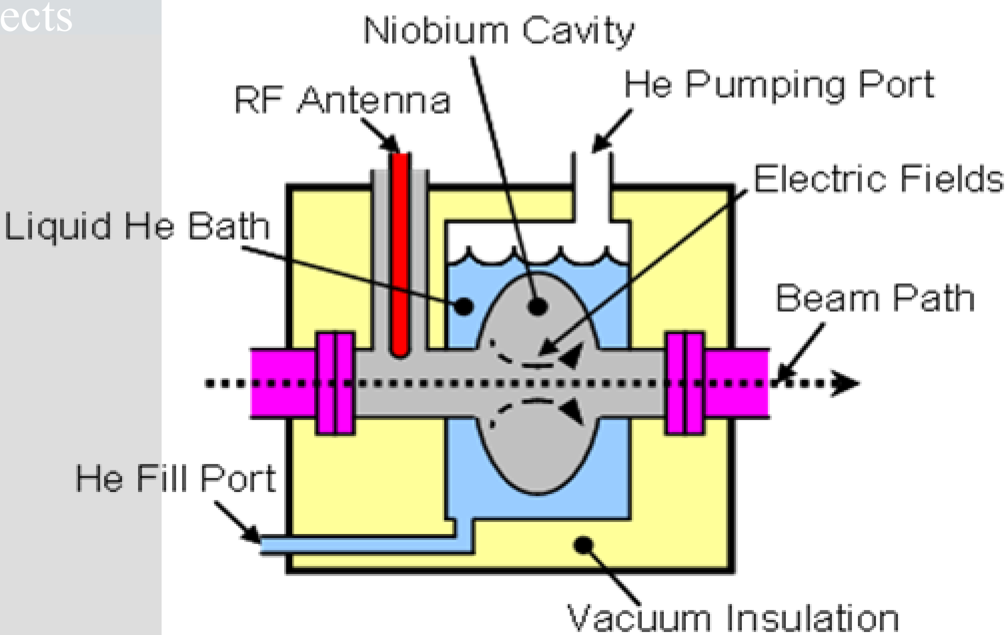

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Advantages Superconducting RF

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

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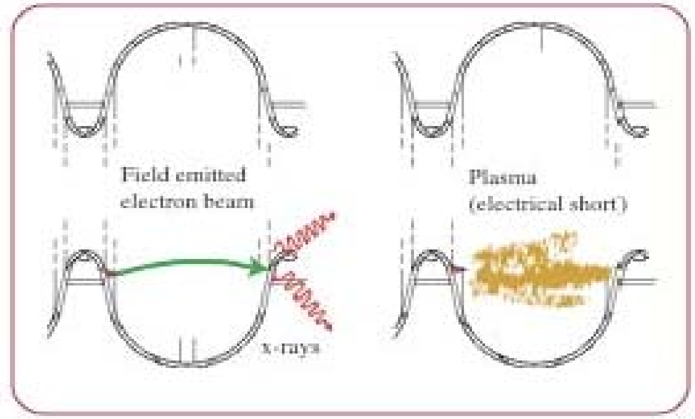
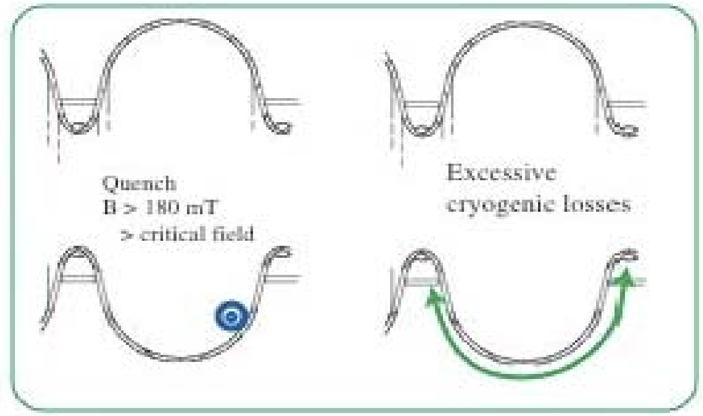
SRF Field Gradient Limitations

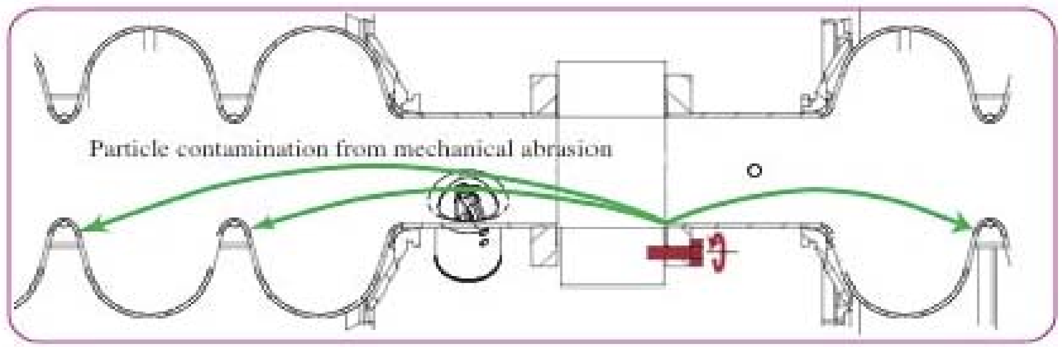
E_{acc} limited by $B_{critical}$

- ~59 MV/m (single cell)
- ~32 MV/m (multi-cell)



- Field Emission
  - due to high electric field around iris
- Quench
  - caused by surface heating from dark current, or
  - magnetic field penetration around “Equator”
- Contamination
  - during assembly





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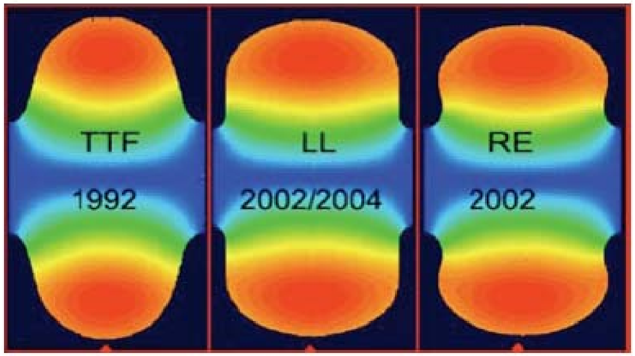
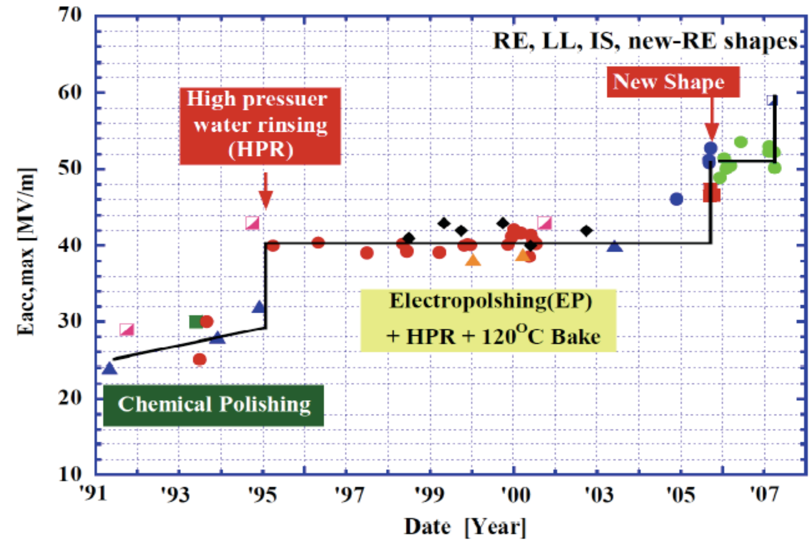
Progress in SCRF

Record **59 MV/m** achieved with single cell cavity at 2K

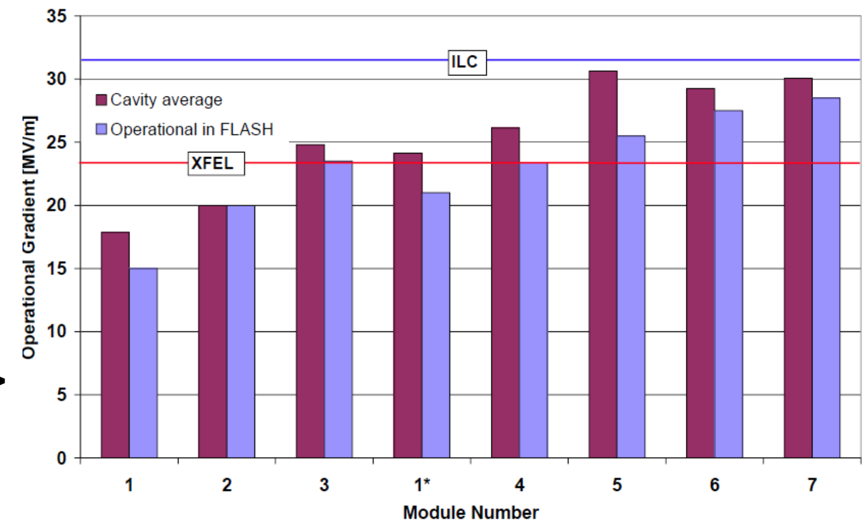
- improved surface treatment
- shape optimization



TTF = TESLA, LL: low-loss, RE: re-entrant



- 9 cell cavities in operation at DESY (FLASH/XFEL):
  - R&D Status ~30 MV/m
  - DESY XFEL requires <23.6>
  - ILC requires <31.5> MV/m



Normal Conducting Accelerator Structures

E_{acc} limited by breakdown RF-field

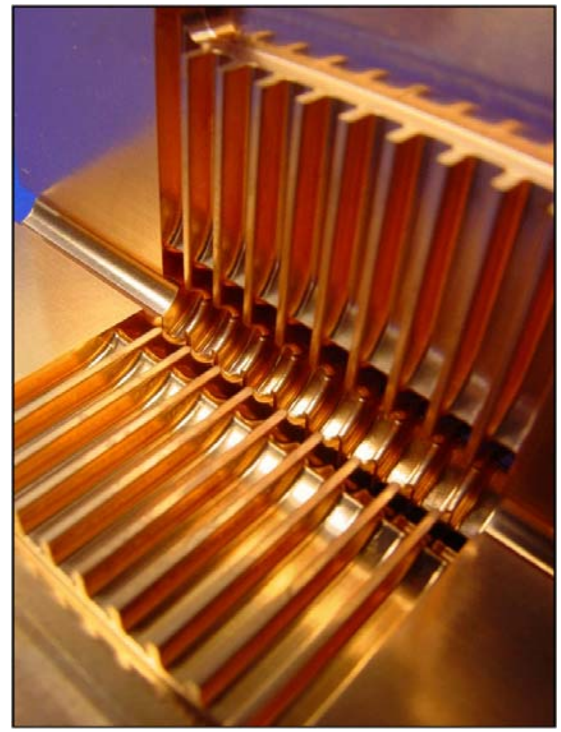
- > 60 MV/m

Higher gradients than SCRF cavities, but requires

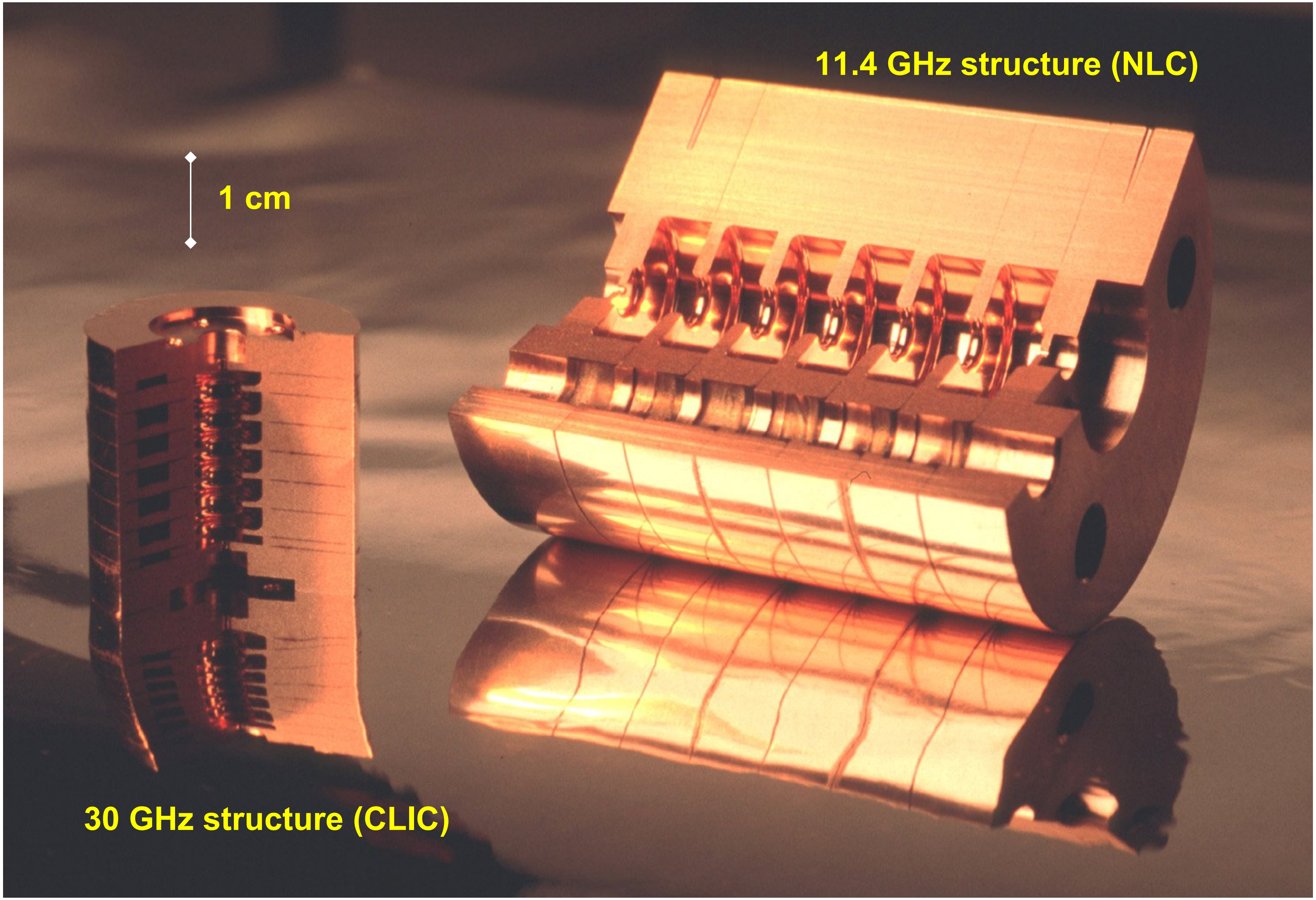
- very high frequency: >10 GHz
- very short pulse lengths: < 1μs

- high ohmic losses
  → travelling wave
  (unlike standing wave in SCRF or low gradient NCRF)

- fill time $t_{fill} = \int 1/v_G \, dz$
  order <100 ns (~ms for SCRF)



High Frequency Iris Loaded Waveguide Structures



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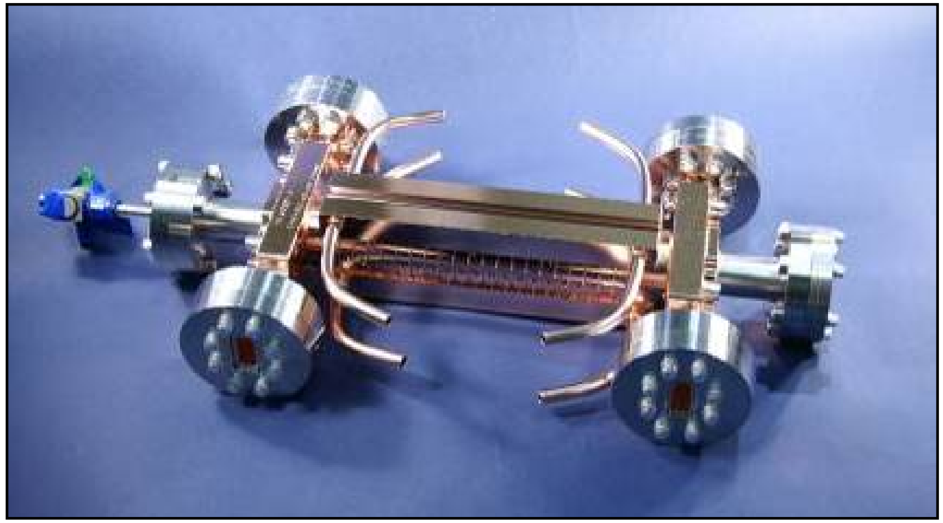
High Frequency Structures

CLIC type
T18_vg2.4_disk

designed at CERN
build by KEK
tested at SLAC



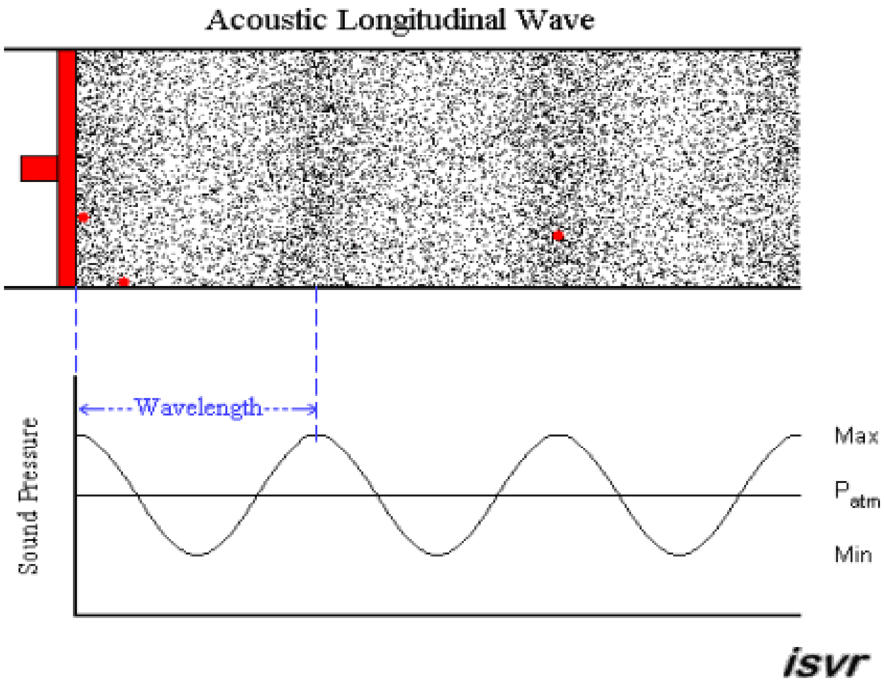
E_{acc} = 106 MV/m
- 11.424 GHz
- 230 ns pulse length
- 10^{-6} breakdown rate (BDR)

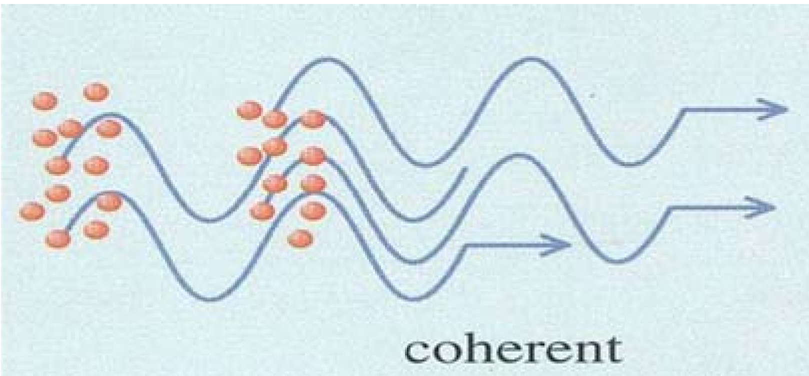
Frequency	11.424	GHz
Cells	18+input+output	
Filling Time	36	ns
Length	29	cm
Iris Dia. a/λ	15.5~10.1	%
Group Velocity: v_g/c	2.61-1.02	%
S_{11}/ S_{21}	0.035/0.8	
Phase Advace Per Cell	2π/3	
Power Needed $<E_a>$=100MV/m	55.5	MW

3. RF Power Source

Electromagnetic Waves

- static electron
  → electric field
- moving electron
  → electromagnetic
  wave
- constant electron beam
  → static electric field
  + static magnetic field
- bunched electron beam
  → electromagnetic wave





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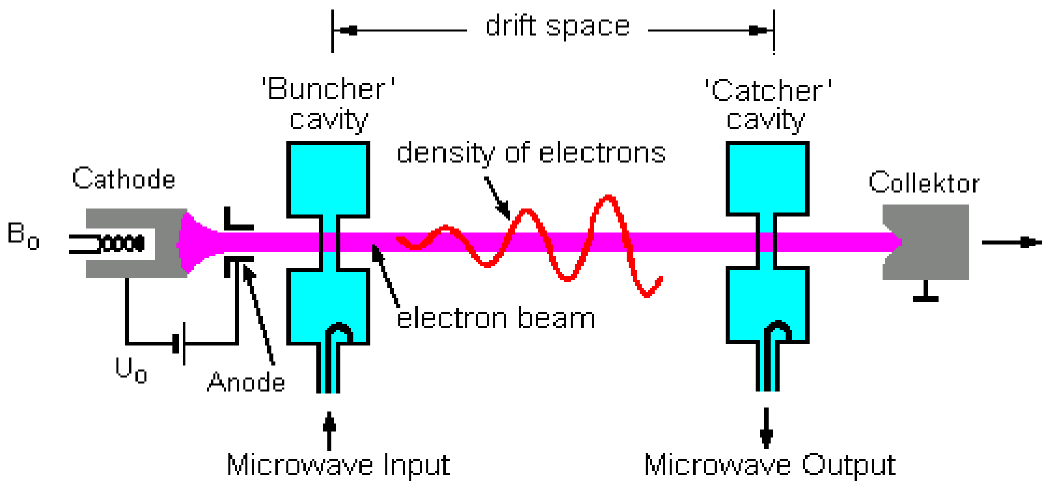
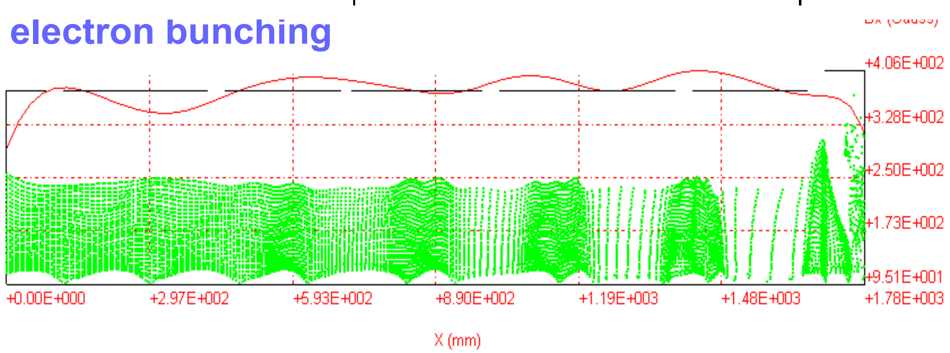
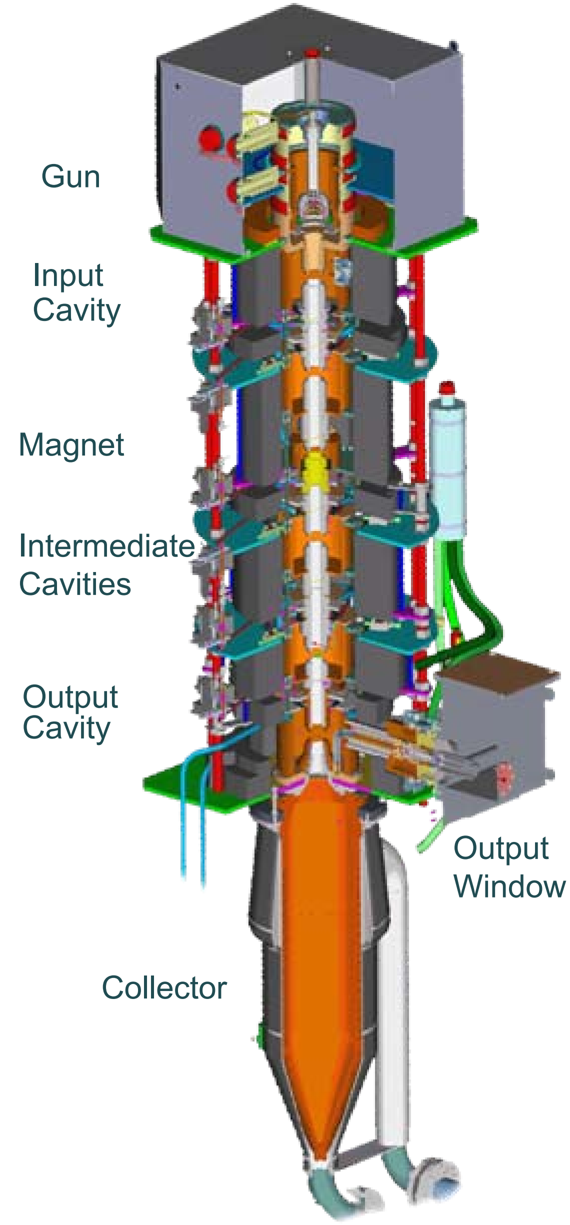
Klystron Microwave Amplifier

- vacuum tube amplifier by electron density bunching
- 200 MHz – 20 GHz
- <1.5 MW ave.; <150 MW peak



electron bunching



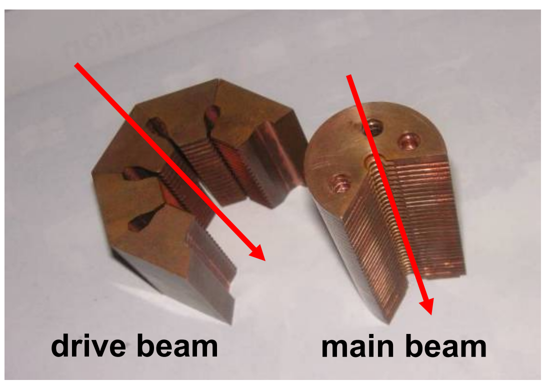


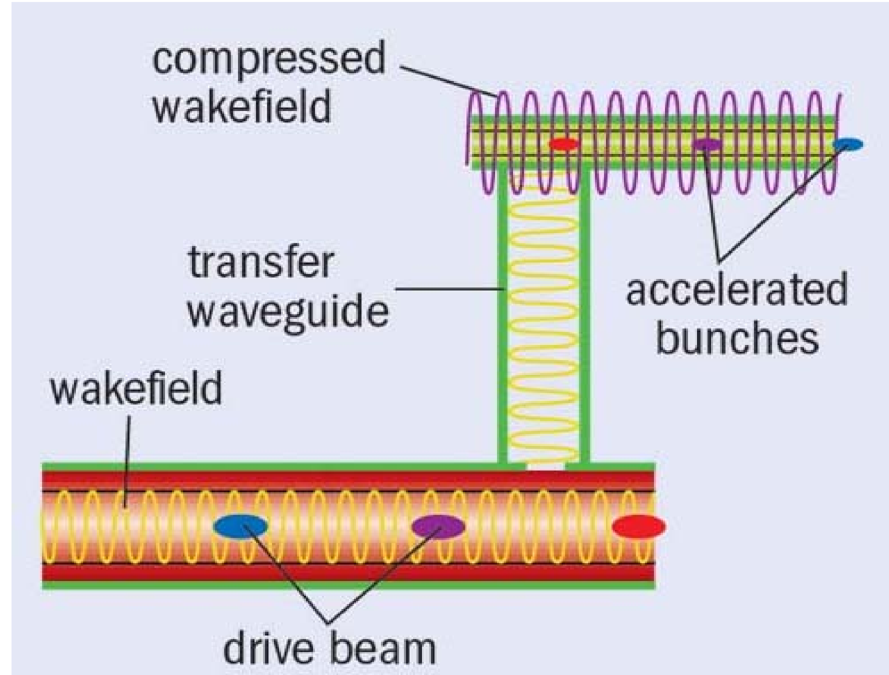
Two-beam Acceleration Concept

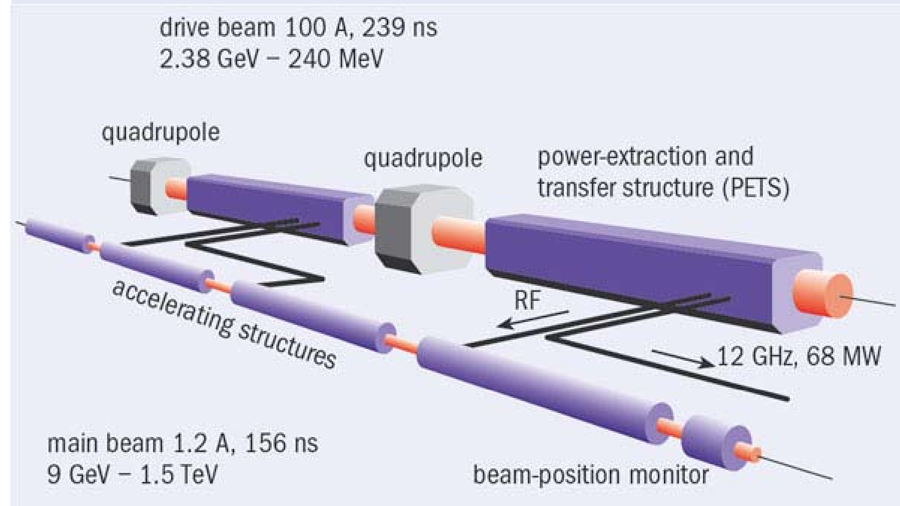
- 12 GHz modulated and high power drive beam
- RF power extraction in a special structure (PETS)

→ only passive elements

- use RF power to accelerate main beam
- compress energy density







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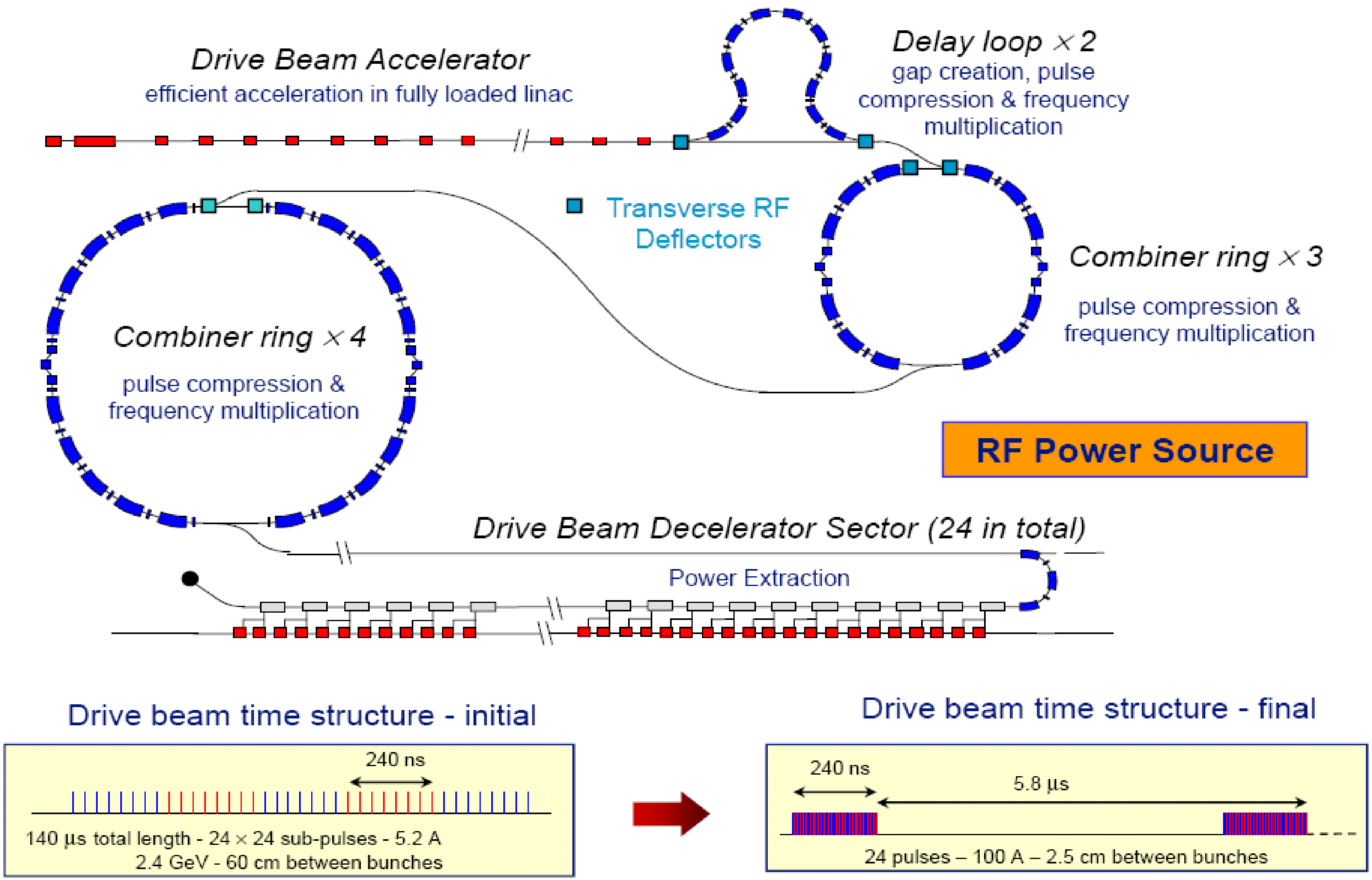
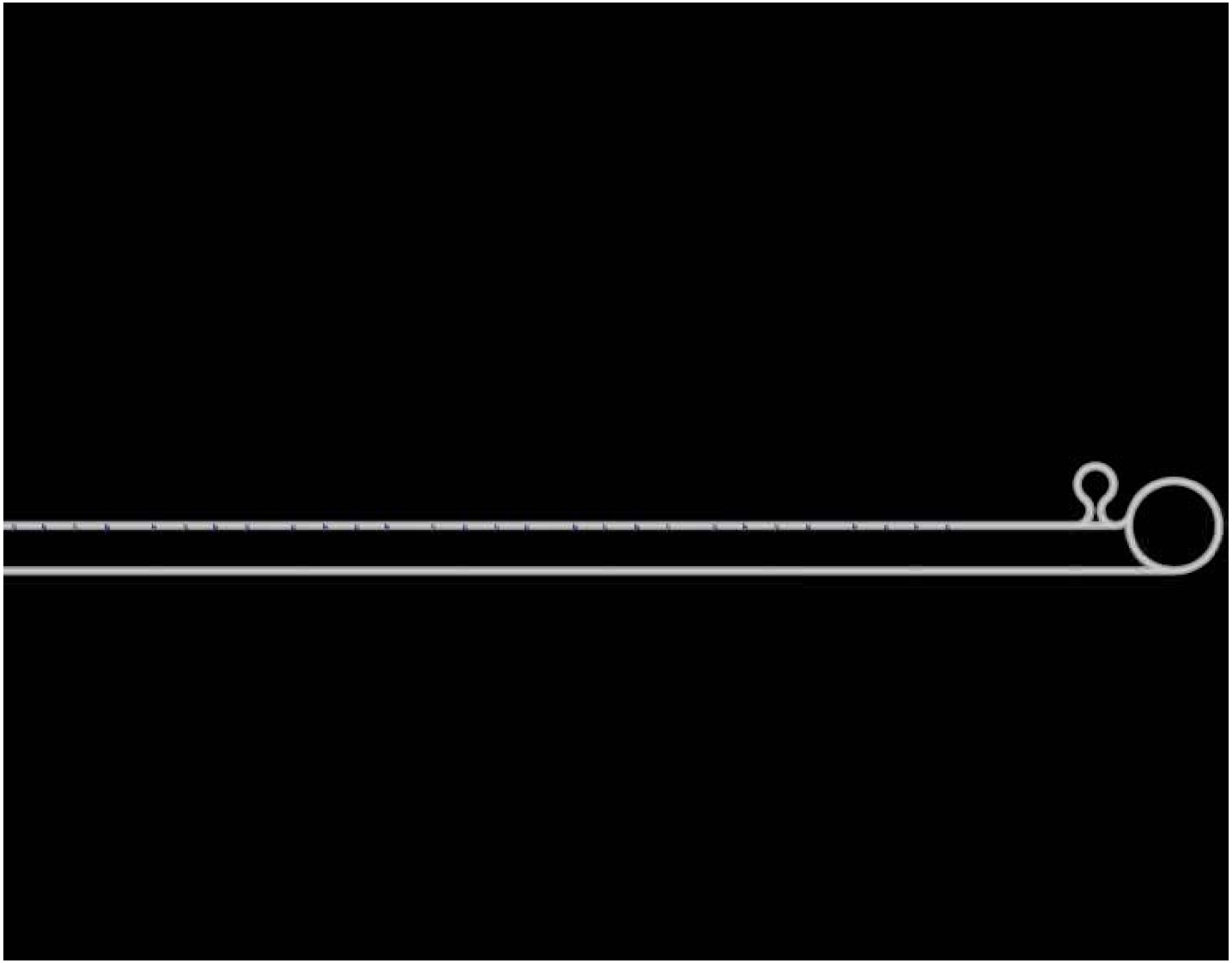
Drive-beam Generation by Beam Gymnastics



Drive Beam Generation



Courtesy A. Andersson

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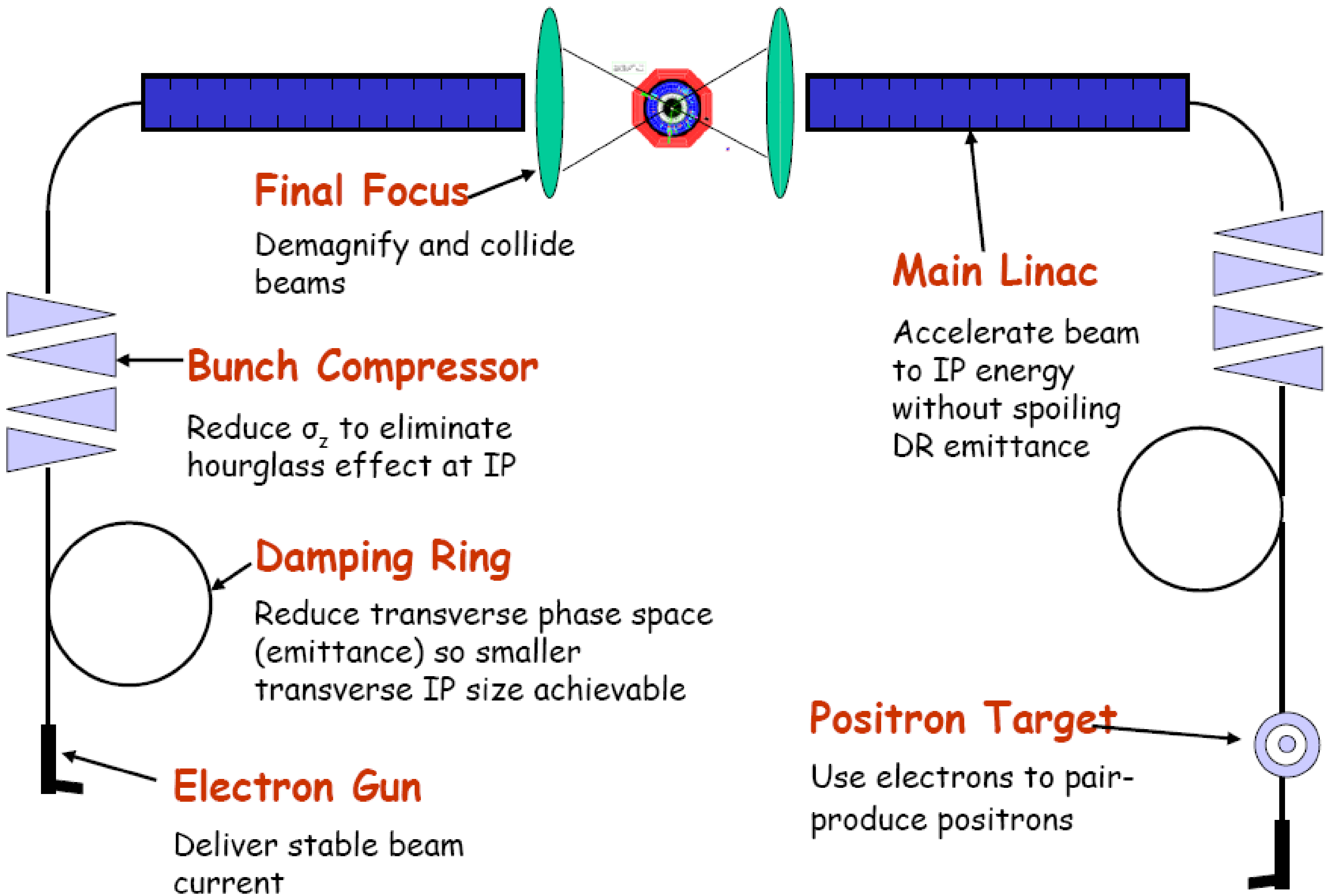
4: Projects for a Future Linear Collider

Basic Layout of a Linear Collider

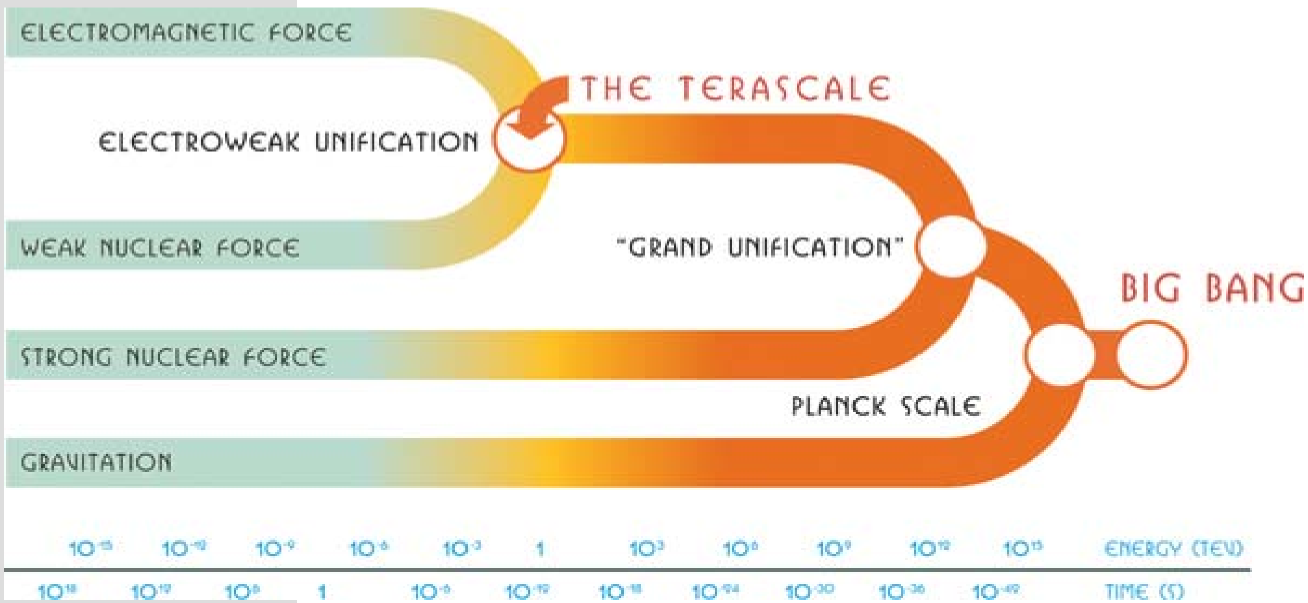


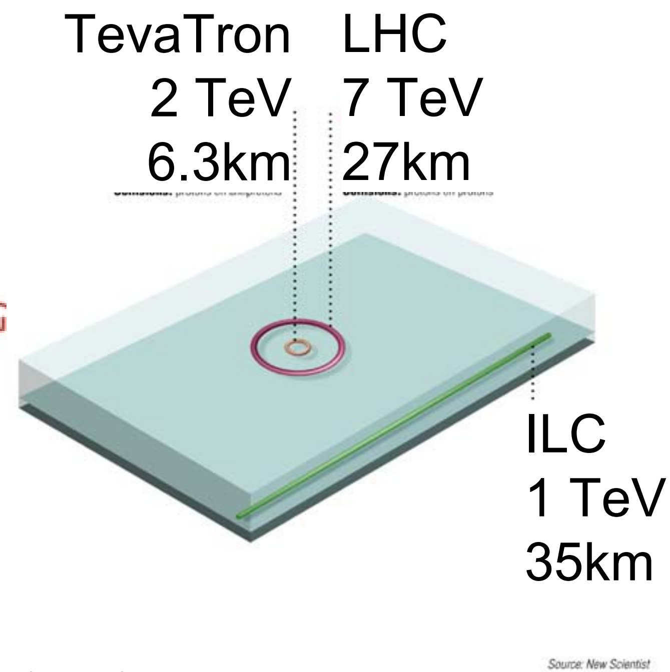
The ILC and CLIC

LHC should indicate which energy level is needed

ILC International Linear Collider
- superconducting technology
- 1.3 GHz
- 31.5 MV/m
- E_{CM} = 500 GeV
- upgrade to 1 TeV

CLIC Compact Linear Collider
- normal conducting technology
- 12 GHz
- 100 MV/m
- E_{CM} = 3 TeV





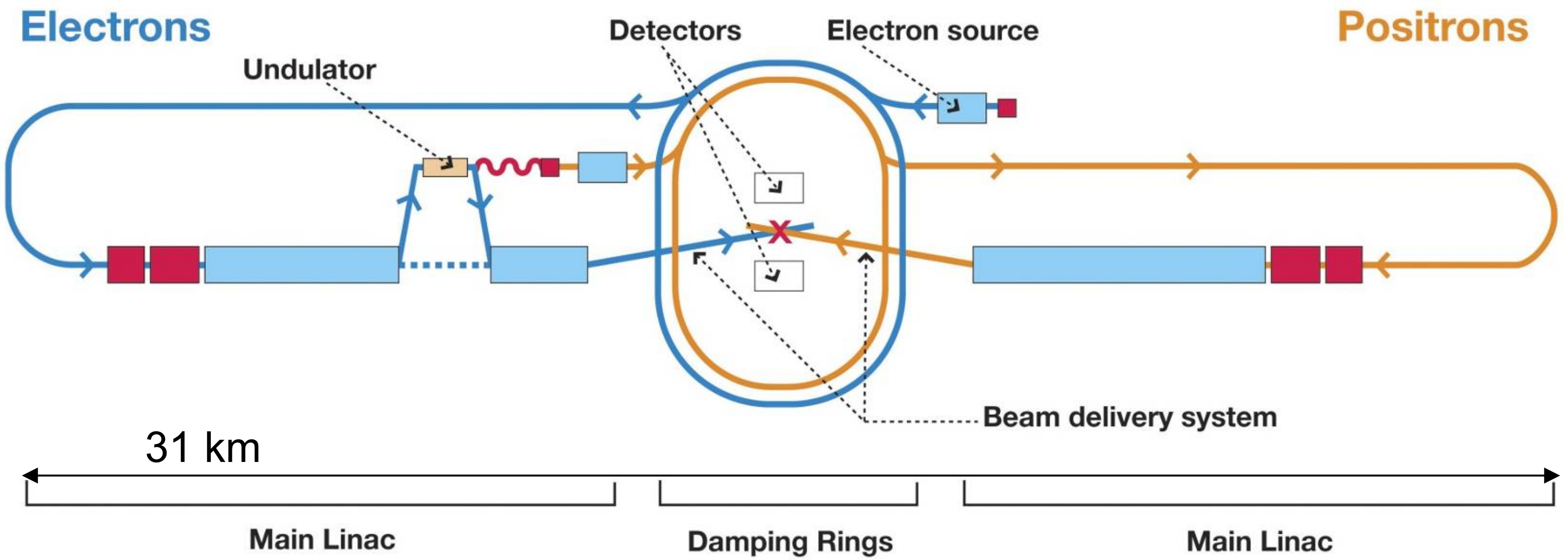
Courtesy Sandbox Studio / interactions.org

ILC: The International Linear Collider

Baseline:

- 2 x 250 GeV superconducting linac
- $2x10^{34}$ $cm^{-2}s^{-1}$ (14 mrad X-angle)
- polarized electron photo-gun
- undulator positron source at 150 GeV
- 5 GeV damping rings (C=6.7 km)
- 4.5 km long beam-delivery system to make spot sizes of 640 x 5.7 nm

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



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Linear Collider Siting

- Where to build?
- Deep/shallow tunnel
- Geometry
  - Laser straight?
  - follow curvature?

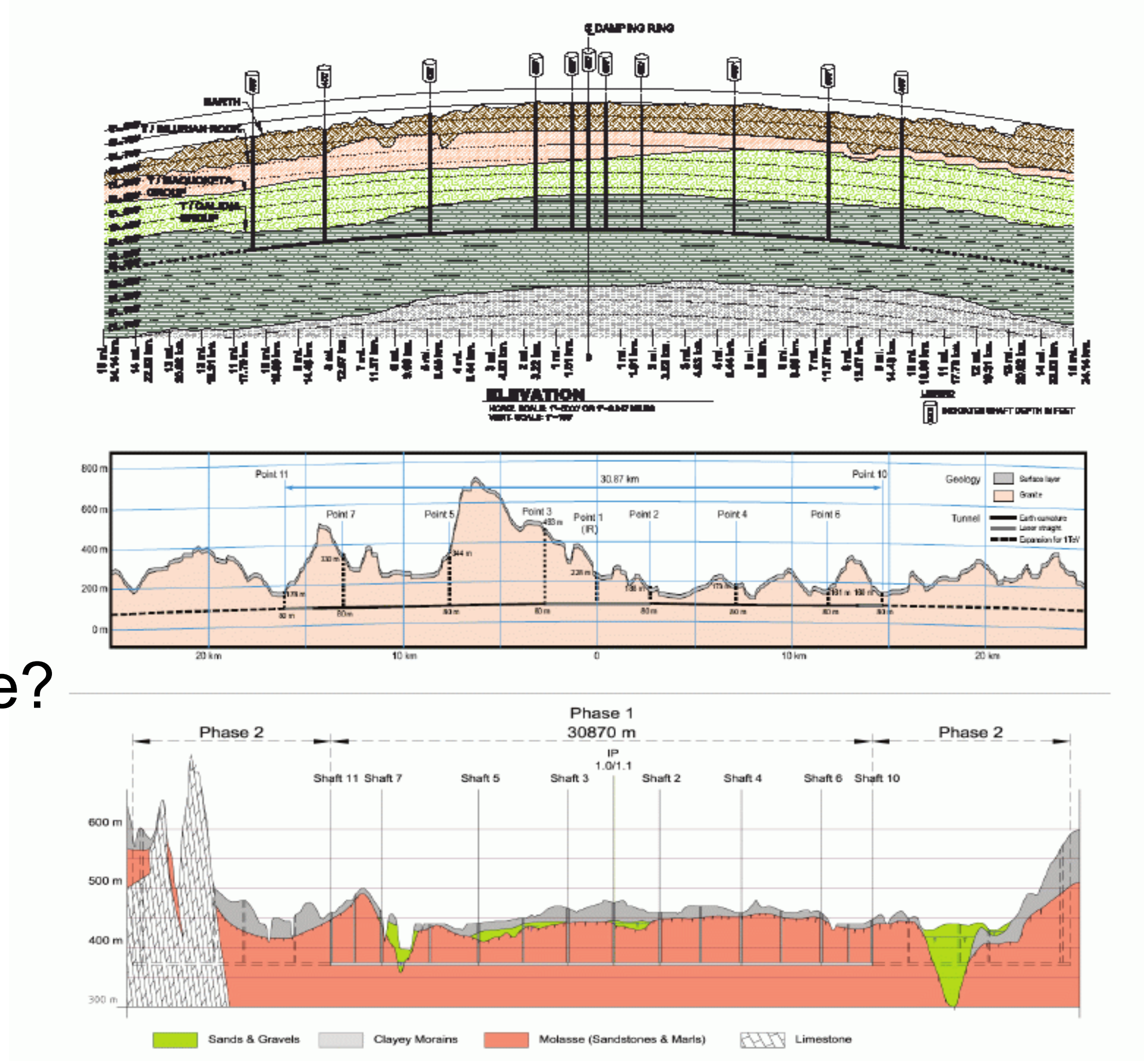

FIGURE 2.13. Geology and tunnel profiles for the three regional sites, showing the location of the major access shafts (tunnels for the Asian site). Top: the Americas site close to Fermilab. Middle: the Asian site in Japan. Bottom: the European site close to CERN.

CLIC: Compact Linear Collider

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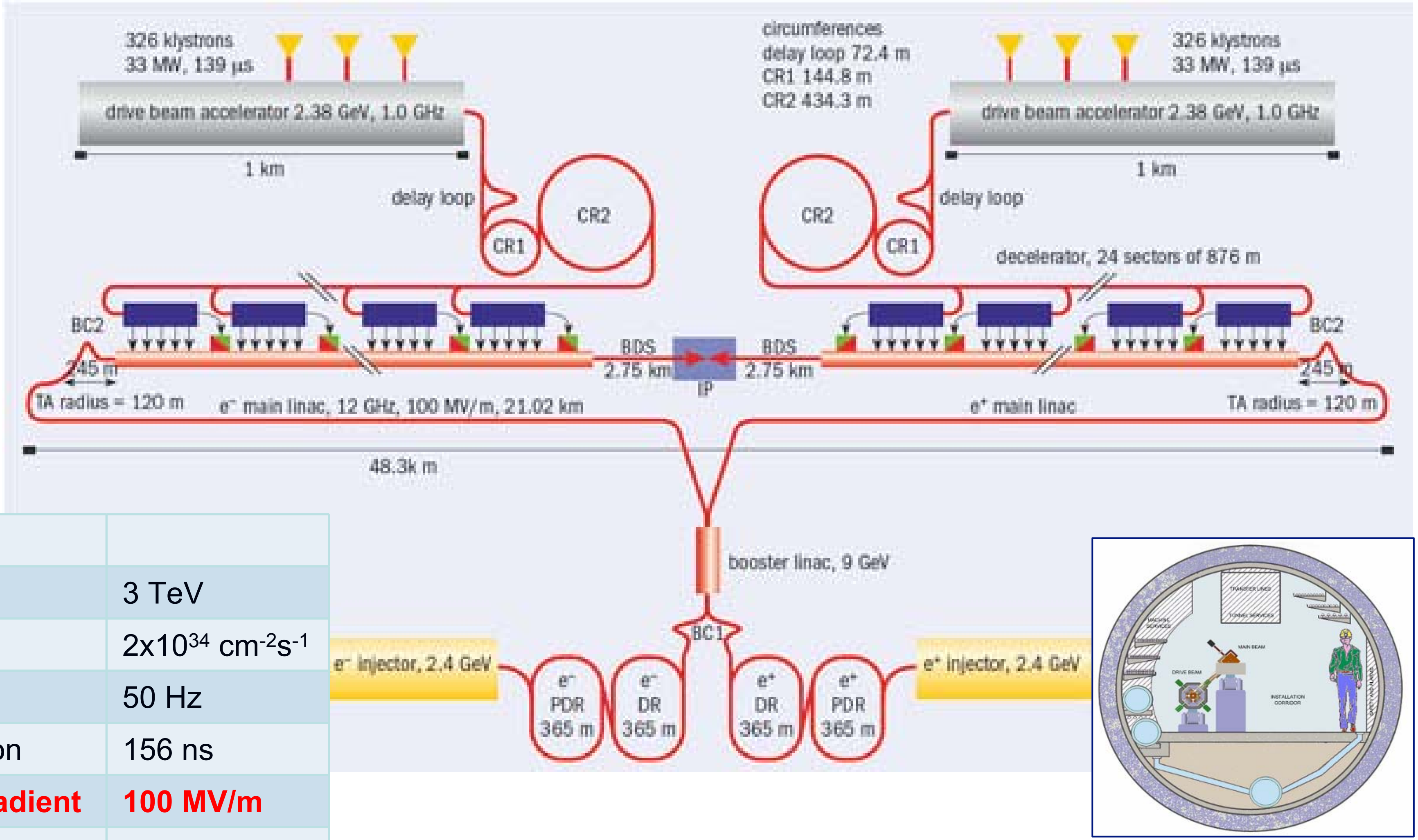

Main Linac	
C.M. Energy	3 TeV
Peak luminosity	$2x10^{34}$ $cm^{-2}s^{-1}$
Beam Rep. rate	50 Hz
Pulse time duration	156 ns
Average field gradient	100 MV/m
# accelerating cavities	2 x 71,548

Φ4.5m tunnel

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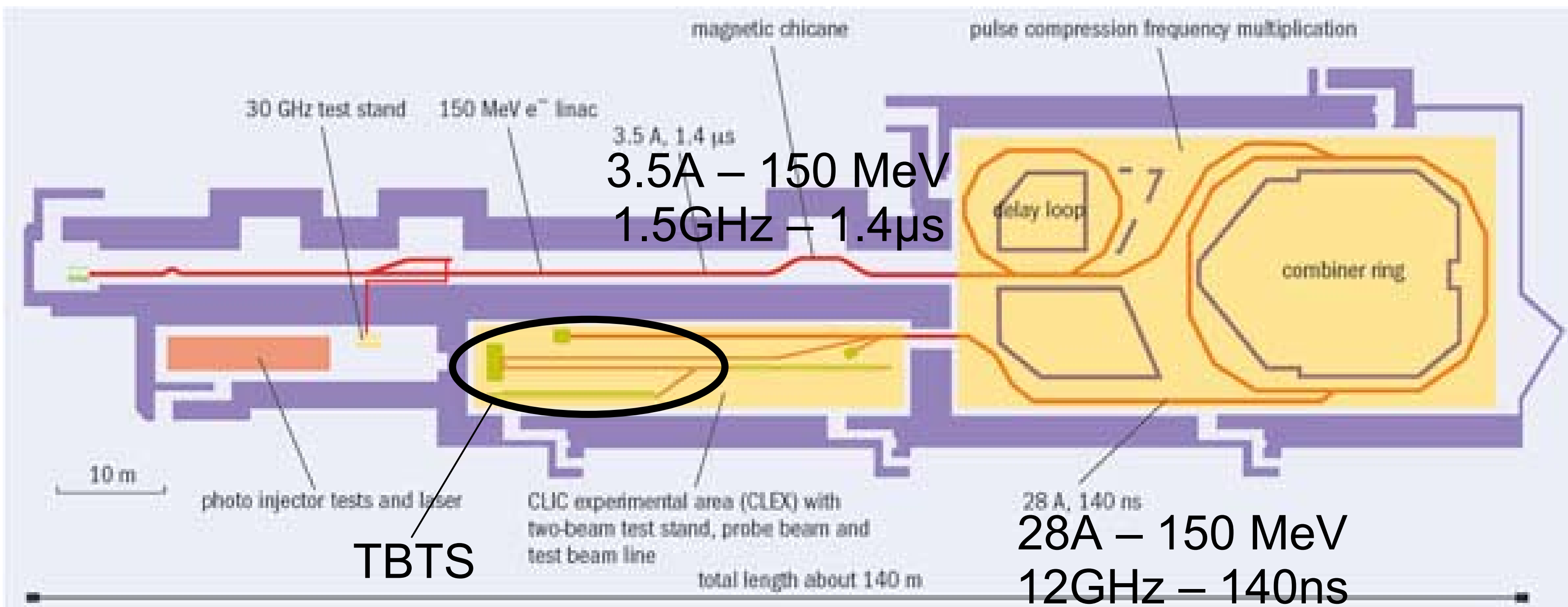
CTF3: CLIC Test Facility

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



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Outline

1. Colliders
2. Cavities
3. RF power
4. Projects

Demonstration Fully Loaded Operation

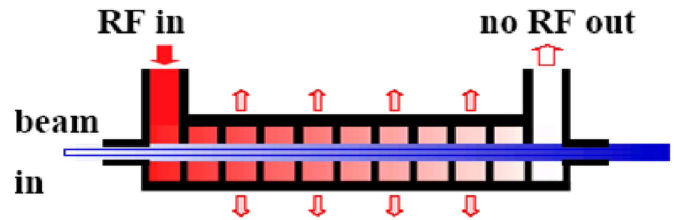
Efficient power transfer

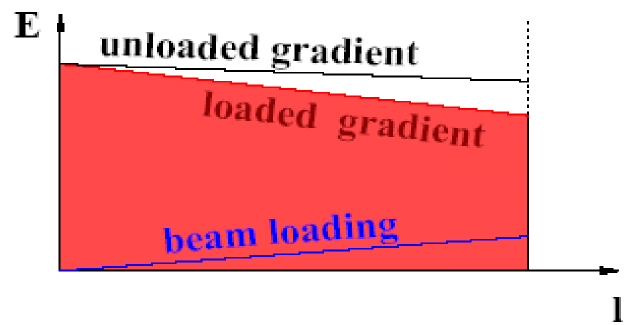
"Standard" situation:

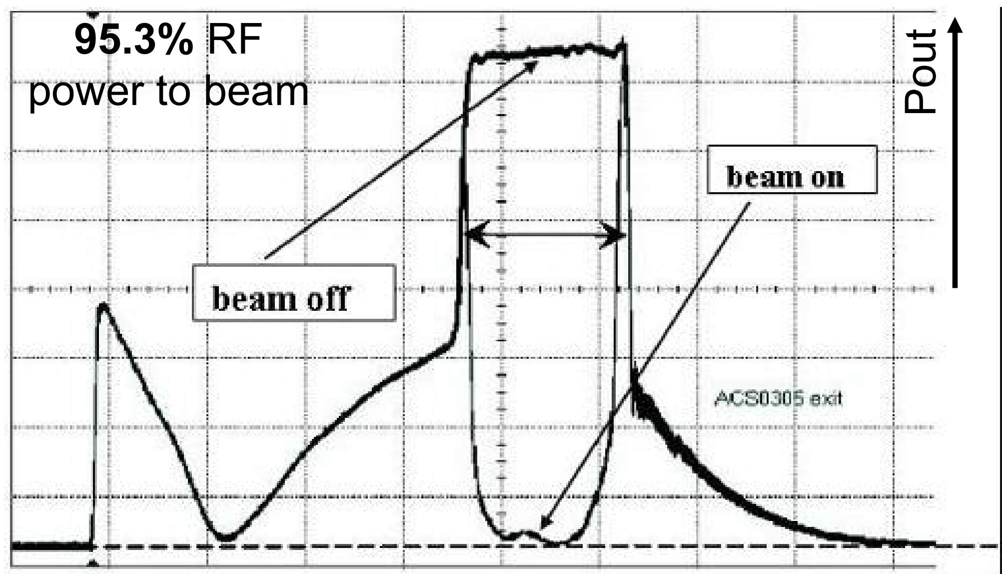
- small beam loading
- power at exit lost in load

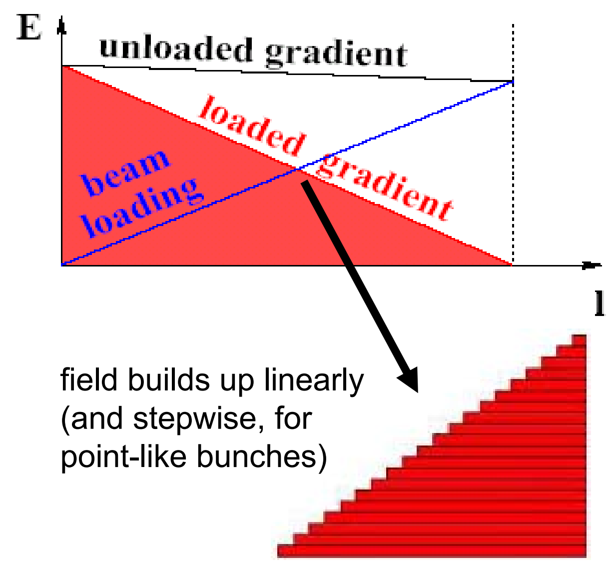
"Efficient" situation: $V_{ACC} \approx 1/2\ V_{unloaded}$

- high beam loading
- no power flows into load









Demonstration Beam Re-combination

Outline

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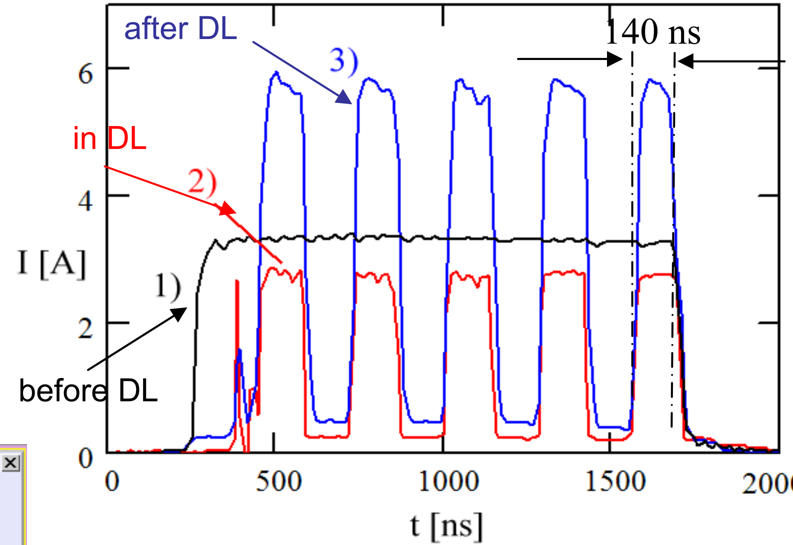
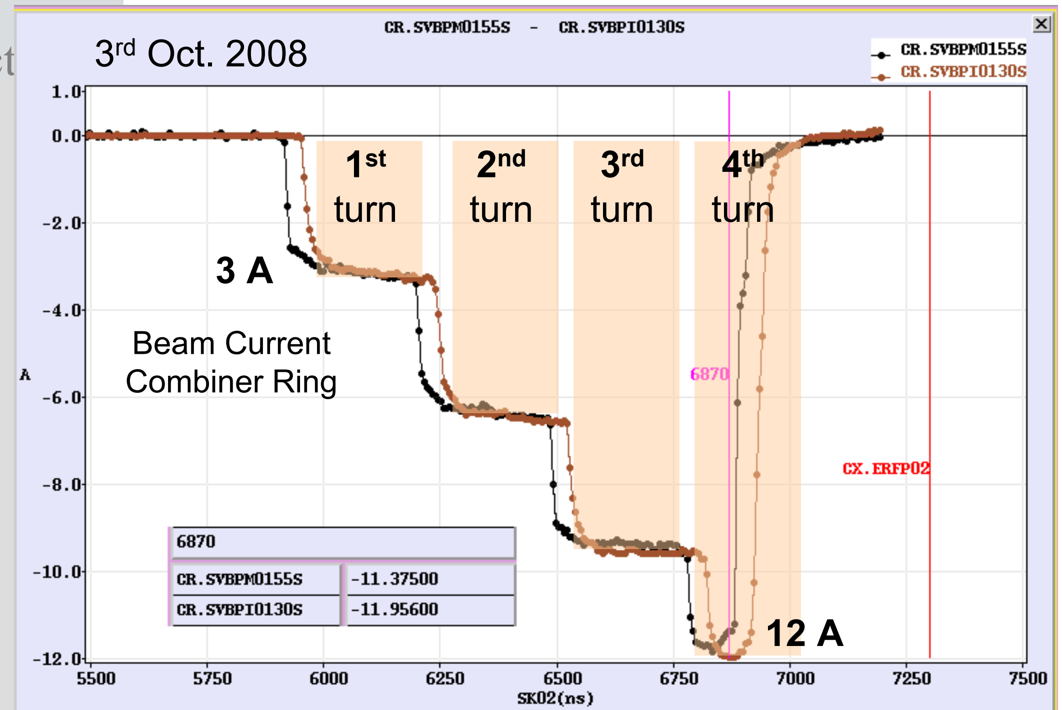
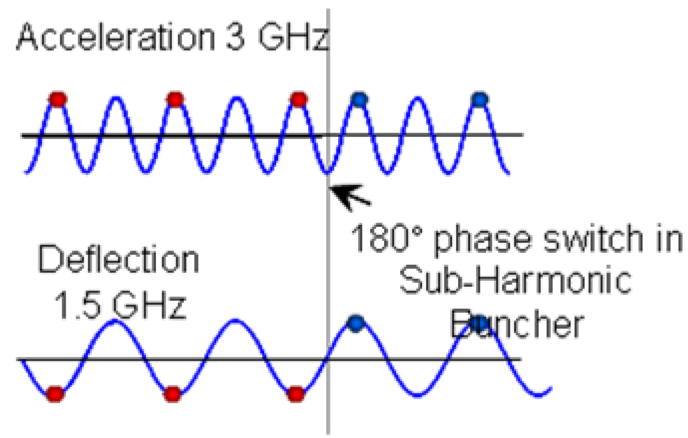
4. Project

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





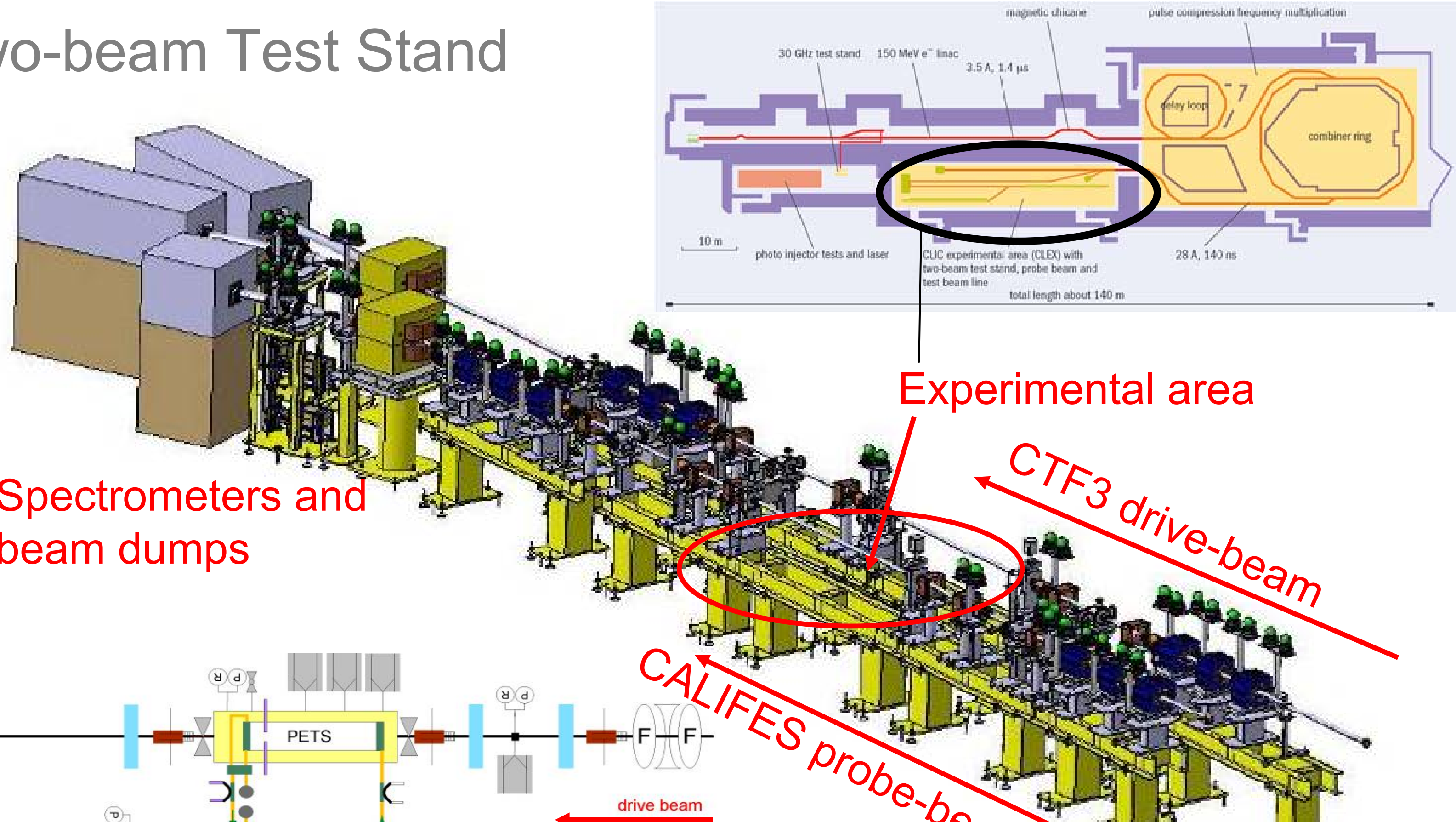


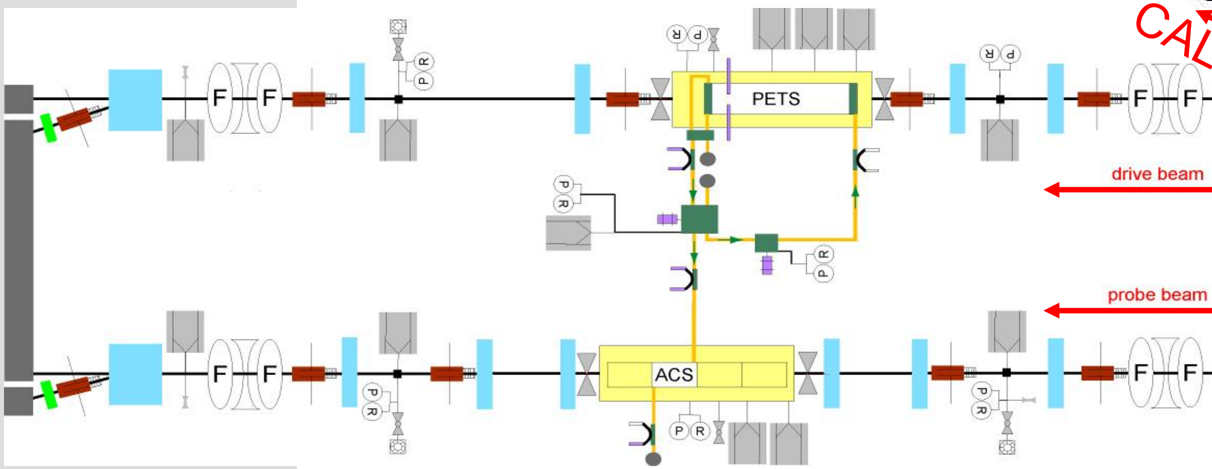
Demonstration Two-beam Acceleration

Outline

1. Colliders
2. Cavities
3. RF power
4. Projects

Two-beam Test Stand





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

Two-beam Test Stand

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Outline

1. Colliders
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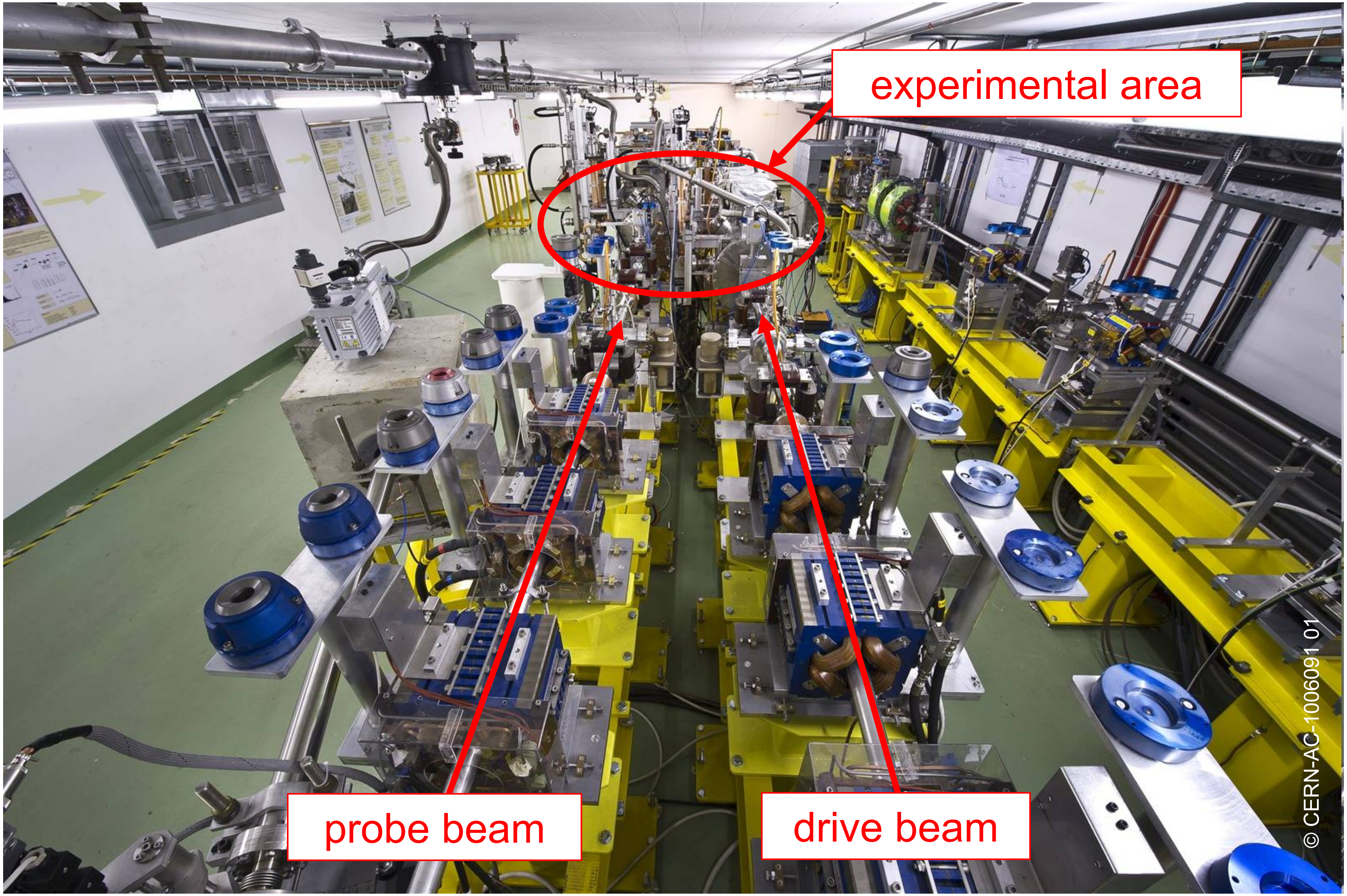

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Outline
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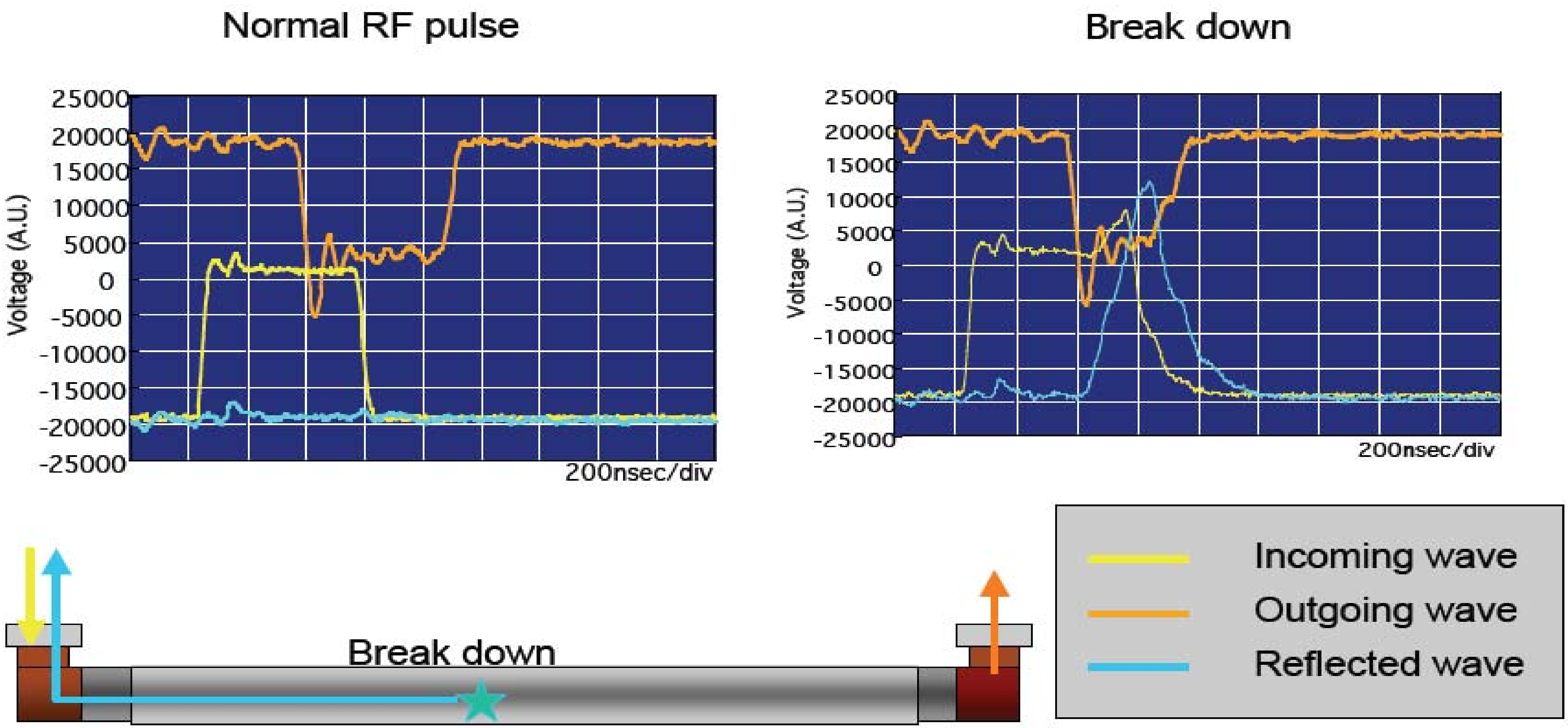
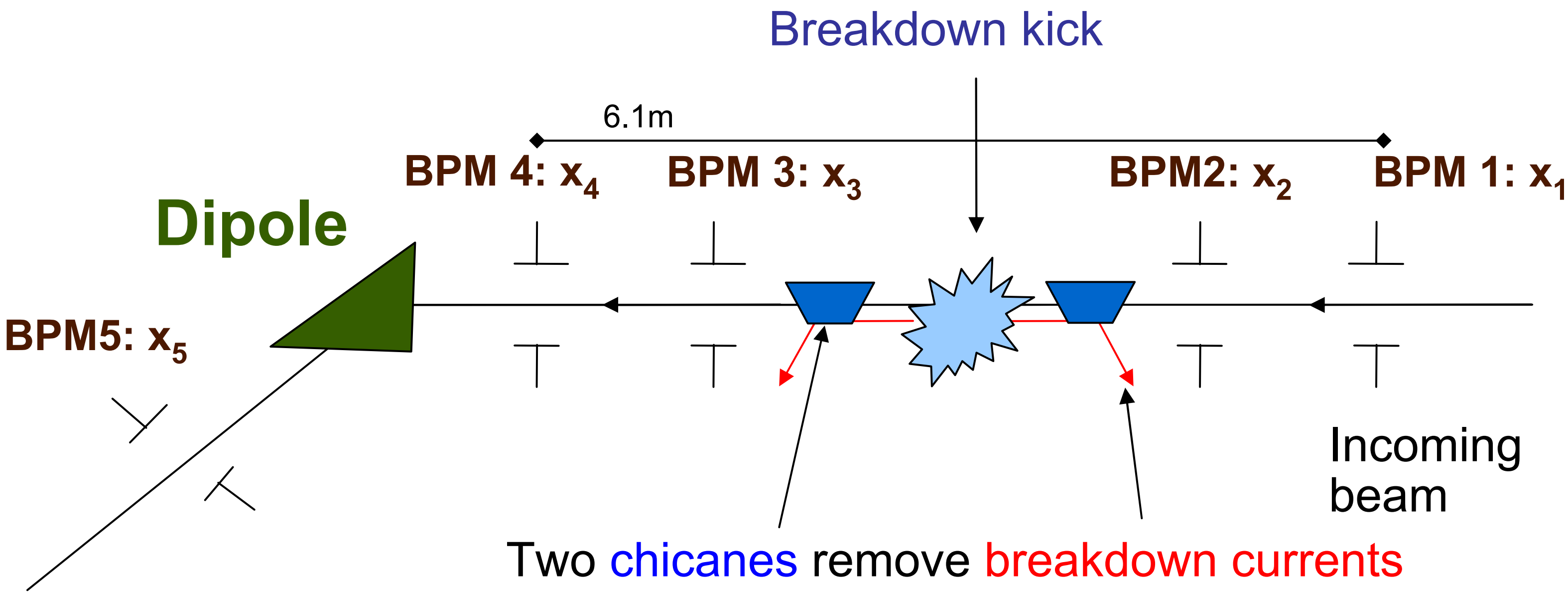
RF Waveform Distortion on Breakdown



from S.Fukuda/KEK

- Pulses with breakdowns not useful for acceleration (beam kick and instabilities)
- Low breakdown rate required (< 10^{-6}) for useful operation

Beam Kick Measurements



Estimated error

- beam position: 10 µm, angle: 7 µrad
- kick position: 31 µm, angle: 11 µrad
- relative energy change from kick: 32×10^{-6}

(see M. Johnson, CLIC Note 710, CERN-OPEN-2007-022)

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RF Breakdown: a Reliability Issue

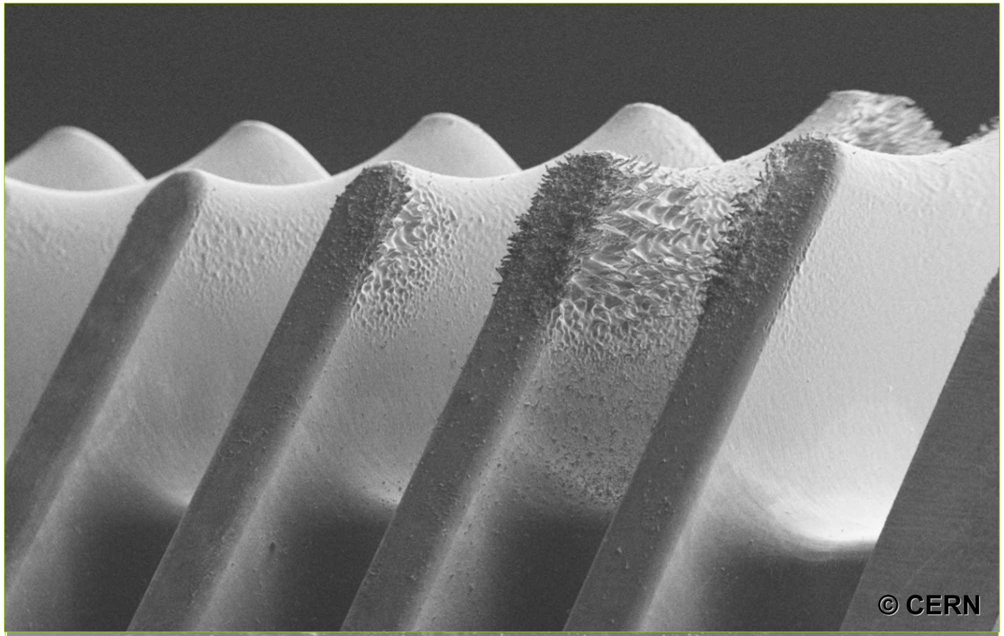
Conditioning required

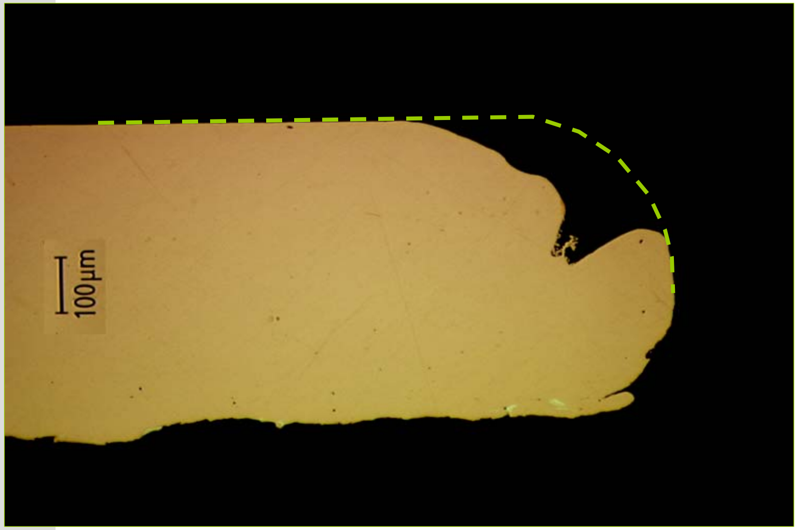
- to reach nominal gradient

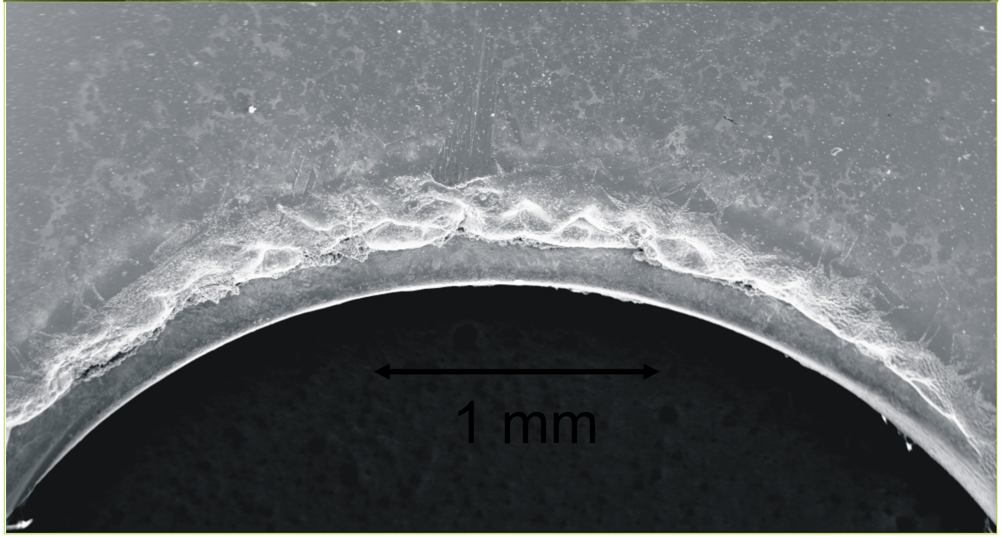
but

- damage by excessive field

Physics phenomena not yet completely understood!







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