The CLIC Study

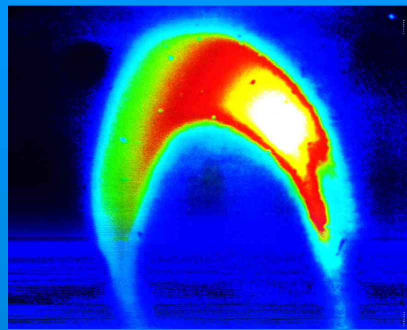
Lecture to the CERN summer students

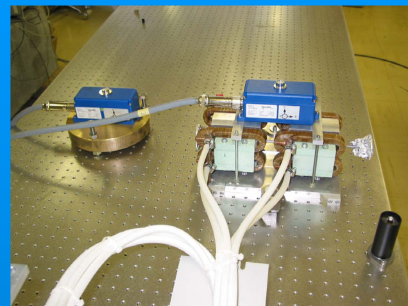
28 July 2004

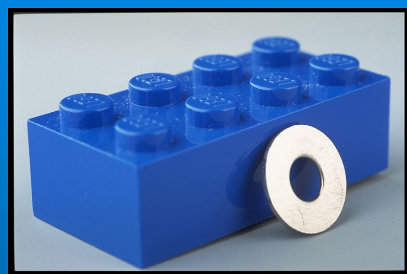
R. Aßmann

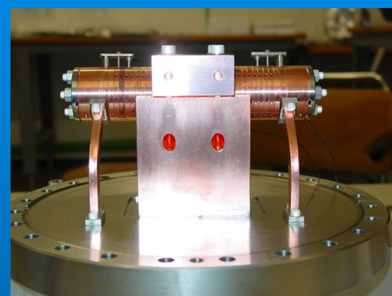
CERN AB/ABP

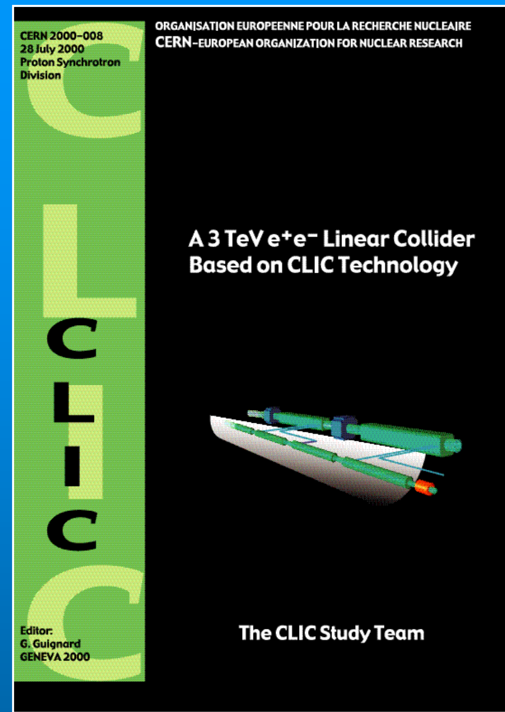
For the CLIC Study Team











CERN 2000-008
28 July 2000
Proton Synchrotron Division

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

CLIC

A 3 TeV e^+e^- Linear Collider Based on CLIC Technology

The CLIC Study Team

Editor:
G. Guignard
GENEVA 2000

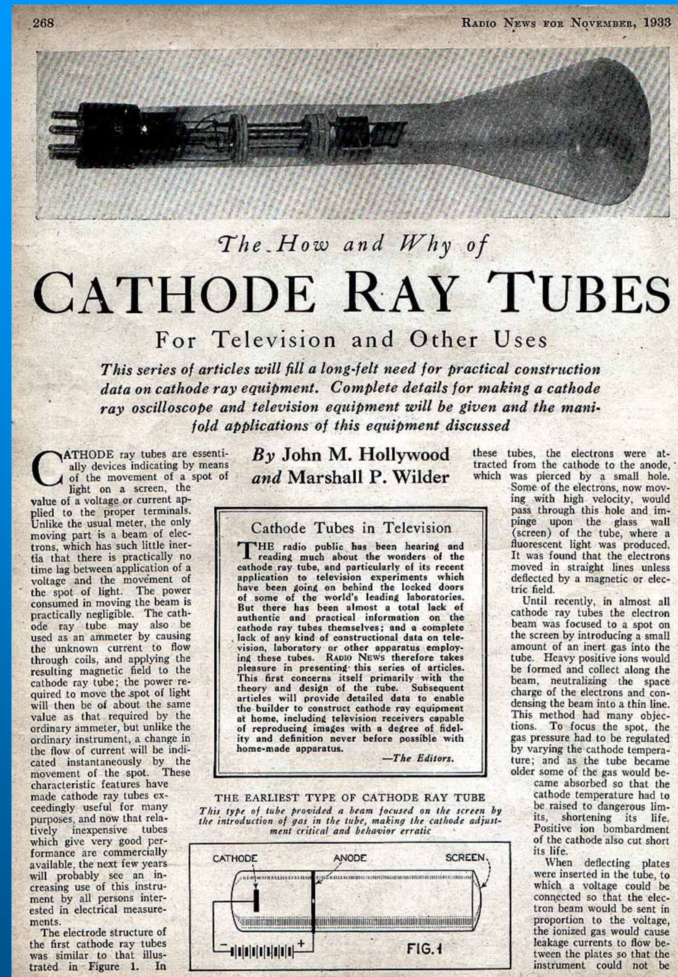
Acknowledgements to R. Corsini, J.P. Delahaye, G. Guignard, S. Redaelli, D. Schulte, F. Tecker, I. Wilson, W. Wuensch, F. Zimmermann for help in preparing this lecture. Several illustrations from K.J. Kim.

http://clic-study.web.cern.ch/CLIC-Study/

Contents

The electron accelerator in your living room:

(1931)



268 RADIO NEWS FOR NOVEMBER, 1933

The How and Why of

CATHODE RAY TUBES

For Television and Other Uses

This series of articles will fill a long-felt need for practical construction data on cathode ray equipment. Complete details for making a cathode ray oscilloscope and television equipment will be given and the manifold applications of this equipment discussed

By John M. Hollywood *and* Marshall P. Wilder

CATHODE ray tubes are essentially devices indicating by means of the movement of a spot of light on a screen, the value of a voltage or current applied to the proper terminals. Unlike the usual meter, the only moving part is a beam of electrons, which has such little inertia that there is practically no time lag between application of a voltage and the movement of the spot of light. The power consumed in moving the beam is practically negligible. The cathode ray tube may also be used as an ammeter by causing the unknown current to flow through coils, and applying the resulting magnetic field to the cathode ray tube; the power required to move the spot of light will then be of about the same value as that required by the ordinary ammeter, but unlike the ordinary instrument, a change in the flow of current will be indicated instantaneously by the movement of the spot. These characteristic features have made cathode ray tubes exceedingly useful for many purposes, and now that relatively inexpensive tubes which give very good performance are commercially available, the next few years will probably see an increasing use of this instrument by all persons interested in electrical measurements.

The electrode structure of the first cathode ray tubes was similar to that illustrated in Figure 1. In these tubes, the electrons were attracted from the cathode to the anode, which was pierced by a small hole. Some of the electrons, now moving with high velocity, would pass through this hole and impinge upon the glass wall (screen) of the tube, where a fluorescent light was produced. It was found that the electrons moved in straight lines unless deflected by a magnetic or electric field.

Until recently, in almost all cathode ray tubes the electron beam was focused to a spot on the screen by introducing a small amount of an inert gas into the tube. Heavy positive ions would be formed and collect along the beam, neutralizing the space charge of the electrons and condensing the beam into a thin line. This method had many objections. To focus the spot, the gas pressure had to be regulated by varying the cathode temperature; and as the tube became older some of the gas would become absorbed so that the cathode temperature had to be raised to dangerous limits, shortening its life. Positive ion bombardment of the cathode also cut short its life.

When deflecting plates were inserted in the tube, to which a voltage could be connected so that the electron beam would be sent in proportion to the voltage, the ionized gas would cause leakage currents to flow between the plates so that the instrument could not be

Cathode Tubes in Television

THE radio public has been hearing and reading much about the wonders of the cathode ray tube, and particularly of its recent application to television experiments which have been going on behind the locked doors of some of the world's leading laboratories. But there has been almost a total lack of authentic and practical information on the cathode ray tubes themselves; and a complete lack of any kind of constructional data on television, laboratory or other apparatus employing these tubes. RADIO NEWS therefore takes pleasure in presenting this series of articles. This first concerns itself primarily with the theory and design of the tube. Subsequent articles will provide detailed data to enable the builder to construct cathode ray equipment at home, including television receivers capable of reproducing images with a degree of fidelity and definition never before possible with home-made apparatus.

—The Editors.

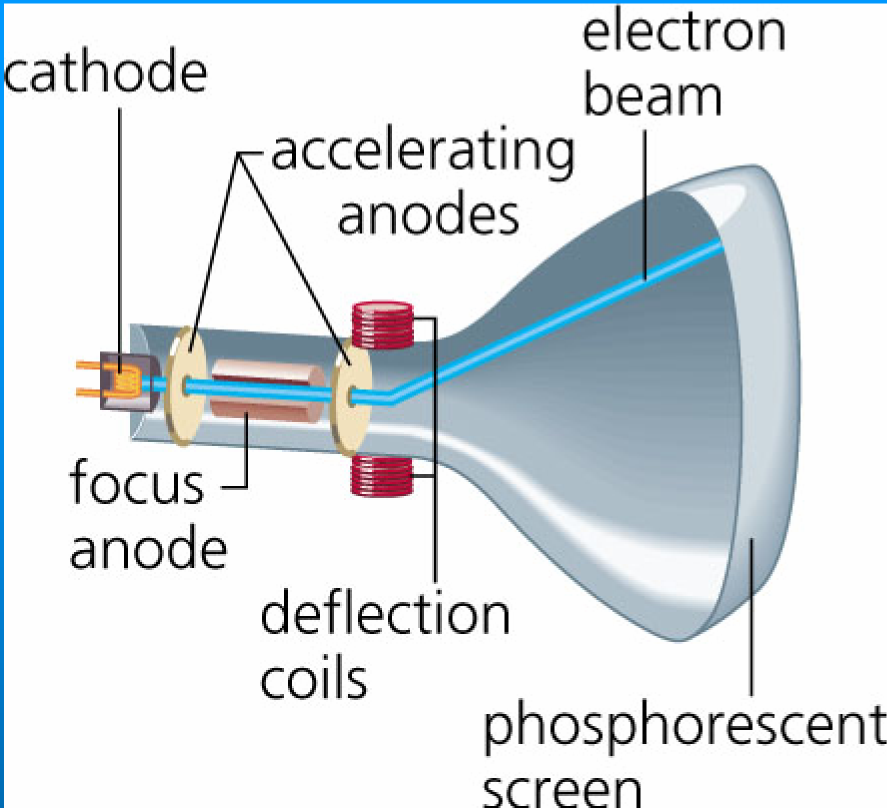
THE EARLIEST TYPE OF CATHODE RAY TUBE

This type of tube provided a beam focused on the screen by the introduction of gas in the tube, making the cathode adjustment critical and behavior erratic

CATHODE ANODE SCREEN

FIG. 1

(1938)



Cathode Ray Tube (CRT) has the basic ingredients of a scientific accelerator:

- Particle source
- Acceleration scheme
- Focusing scheme
- Beam steering
- Beam observation

Particle motion given by Lorentz Force:

$$\frac{d\vec{p}}{dt} = \vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

$\vec{p} =$ Particle momentum

$\vec{p} =$ Particle velocity $\quad q =$ Particle charge $\quad \vec{E} =$ Electric field $\quad \vec{B} =$ Magnetic field

Particle acceleration:

$$\frac{d\vec{p}}{dt} = \vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

Kinetic energy of particle:

$$E_{kin} = \frac{1}{2} m \vec{v}^2$$

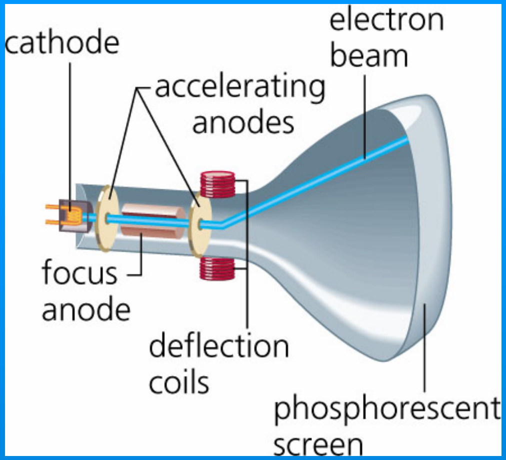
Change in kinetic energy:

$$\frac{dE_{kin}}{dt} = \vec{v} \cdot \vec{F} = q \vec{v} \cdot \vec{E}$$

Acceleration from electric field component parallel to particle velocity!

$$\Delta E_{kin} = \Delta t \; q \; \vec{v} \cdot \vec{E} = q \; L_{acc} \; E_{\parallel}$$

$\Rightarrow$ $\Delta E_{kin} = q \, U_{acc}$ with $U_{acc} = L_{acc} \, E_{\parallel}$



Accelerating voltage:	~ 200,000 V
Energy gain/electron:	200,000 eV
	200 keV
	0.2 MeV
	0.0002 GeV
	0.0000002 TeV

1 eV = 1.6×10^{-19} Joules

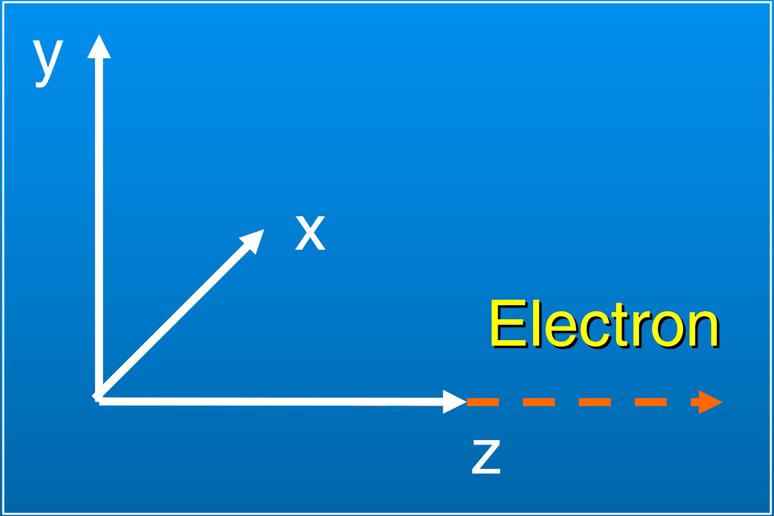
	Television set	Existing colliders	CLIC
Energy gain	200 keV	× 1,000,000	× 10,000,000
Number particles	~ 1,000,000	× 10,000	× 4,000
Beam size	~ mm	÷ 1,000	÷ 1,000,000

Scientific accelerators are very powerful!

Transverse deflections:

$$\frac{d\vec{p}}{dt} = \vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

Transverse magnetic fields are used for beam deflections!



$$F_x = q v_z B_y$$

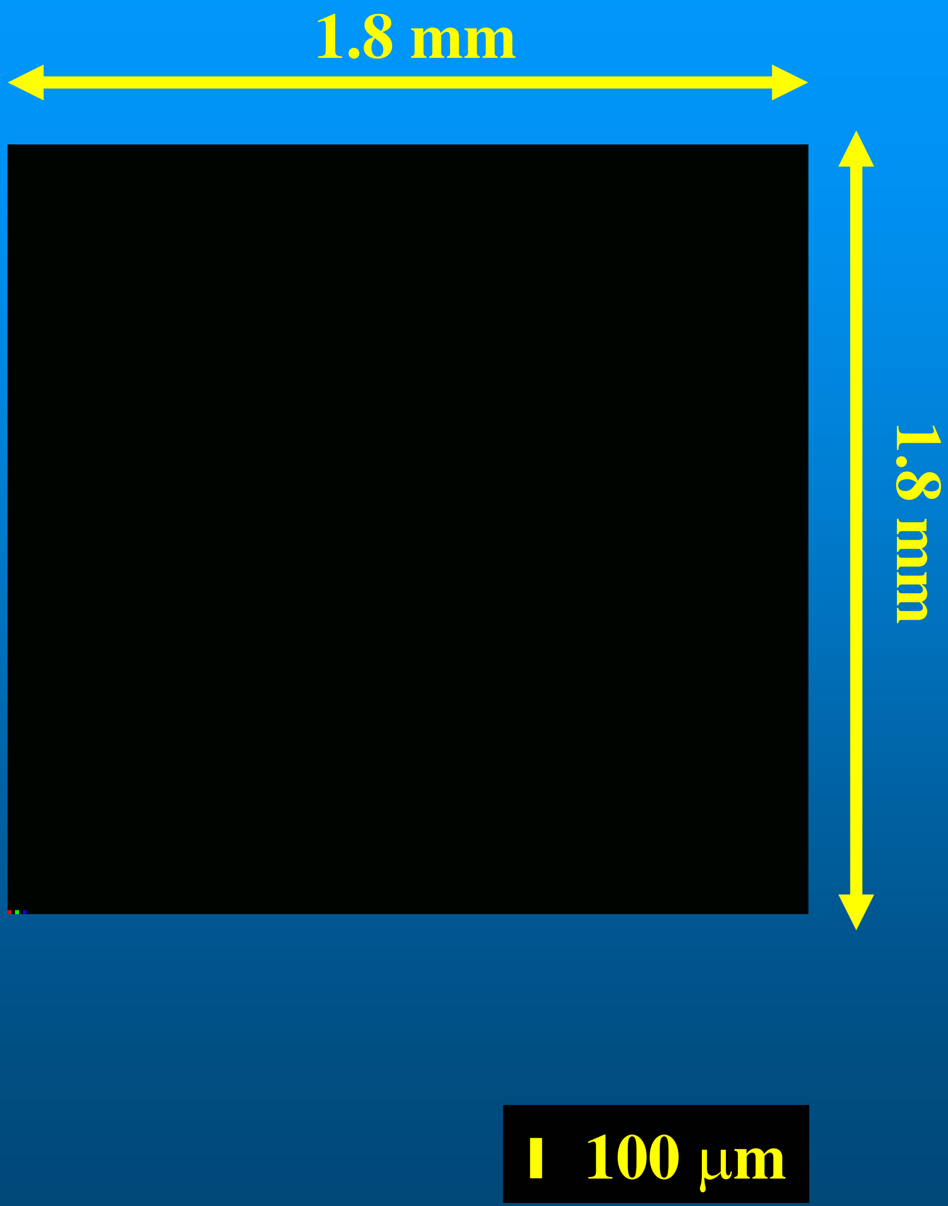
$$F_y = q v_z B_x$$

Depends on particle energy and transverse field

Transverse fields used for:

Focusing lattice
Bending (esp. circular)
De-magnifying
Steering

Transverse effects are very important:



Transverse beam spot in a linear collider

30 GeV electrons
(~150,000 times TV voltage)

about 20 billion particles
(~10,000 times TV beam)

Movie from the Stanford Linear Collider (1999)

More on this later…

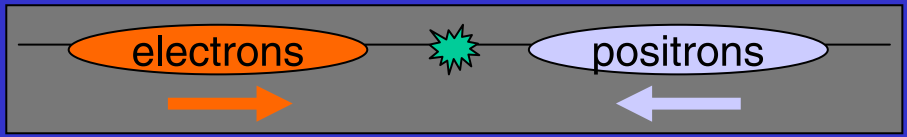
Contents

The need for high energy E:

Einstein's famous formula: $E = mc^2$

Mass can be converted into energy!

Collide electrons (matter) and positrons (anti-matter):



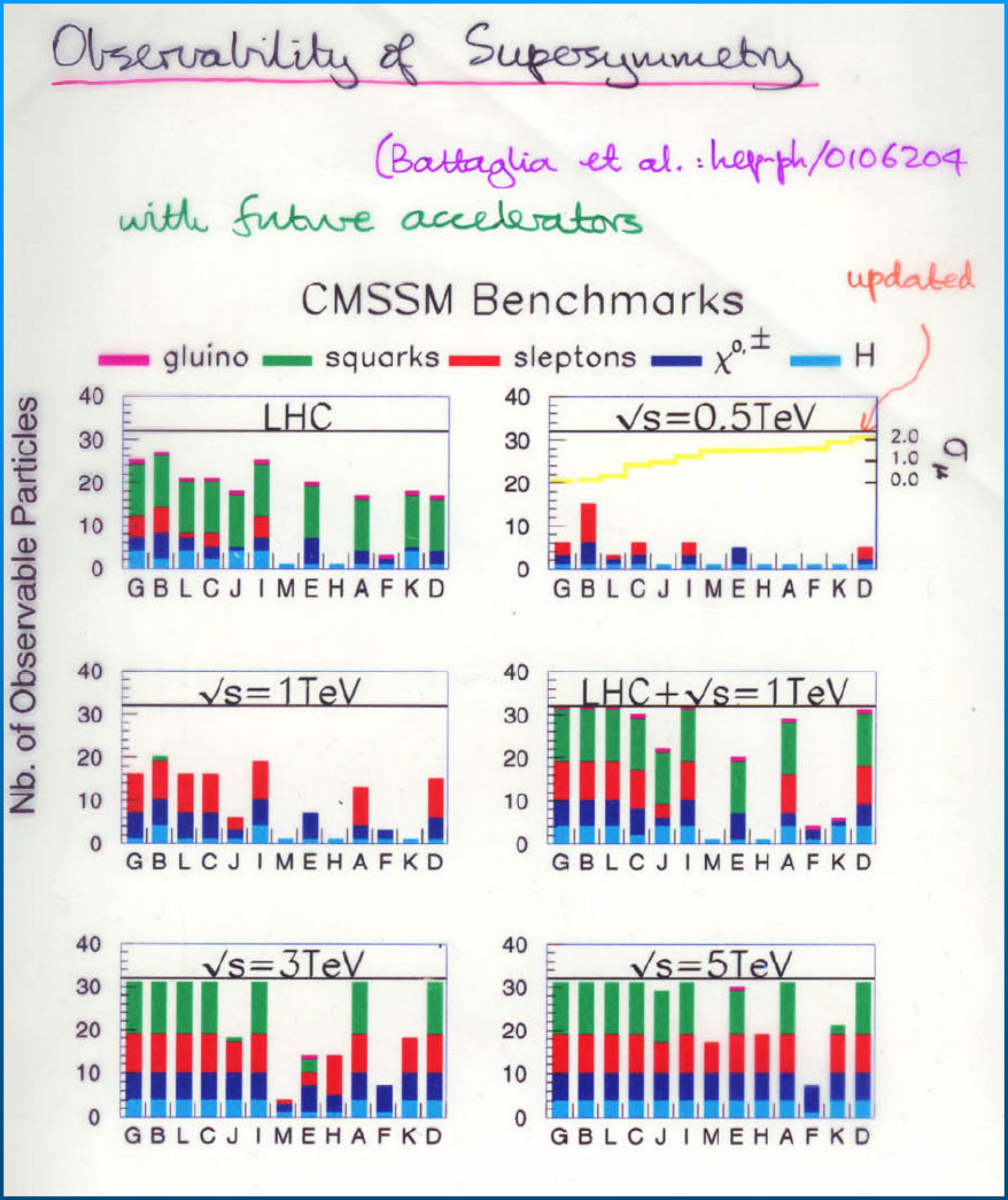
$$e^+ + e^- \longrightarrow (2E) \longrightarrow \text{particles}$$

If energy is high enough new particles can be produced…

Maximum beam energy
for
highest discovery potential!

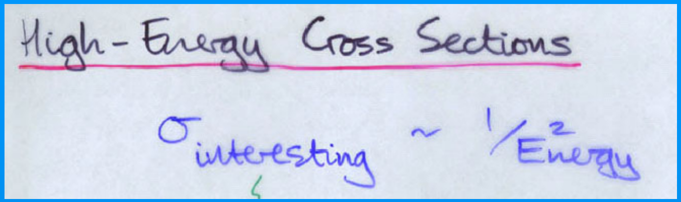
LHC

CLIC



J. Ellis

The need for high luminosity L:



J. Ellis

Number e+e-

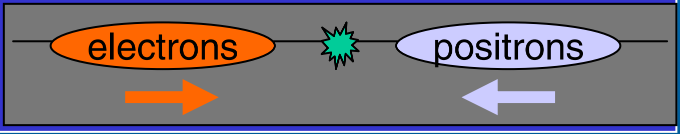
Collision rate

Cross section physics process

$$\text{Event rate} = \frac{N_{e^-} N_{e^+}}{A_{beam}} f_{coll} \cdot \sigma_{e^+e^- \to X}$$

Transverse beam area

Luminosity L



CLIC: E = 3 TeV c.m. L = 10^{35} cm^{-2} s^{-1}

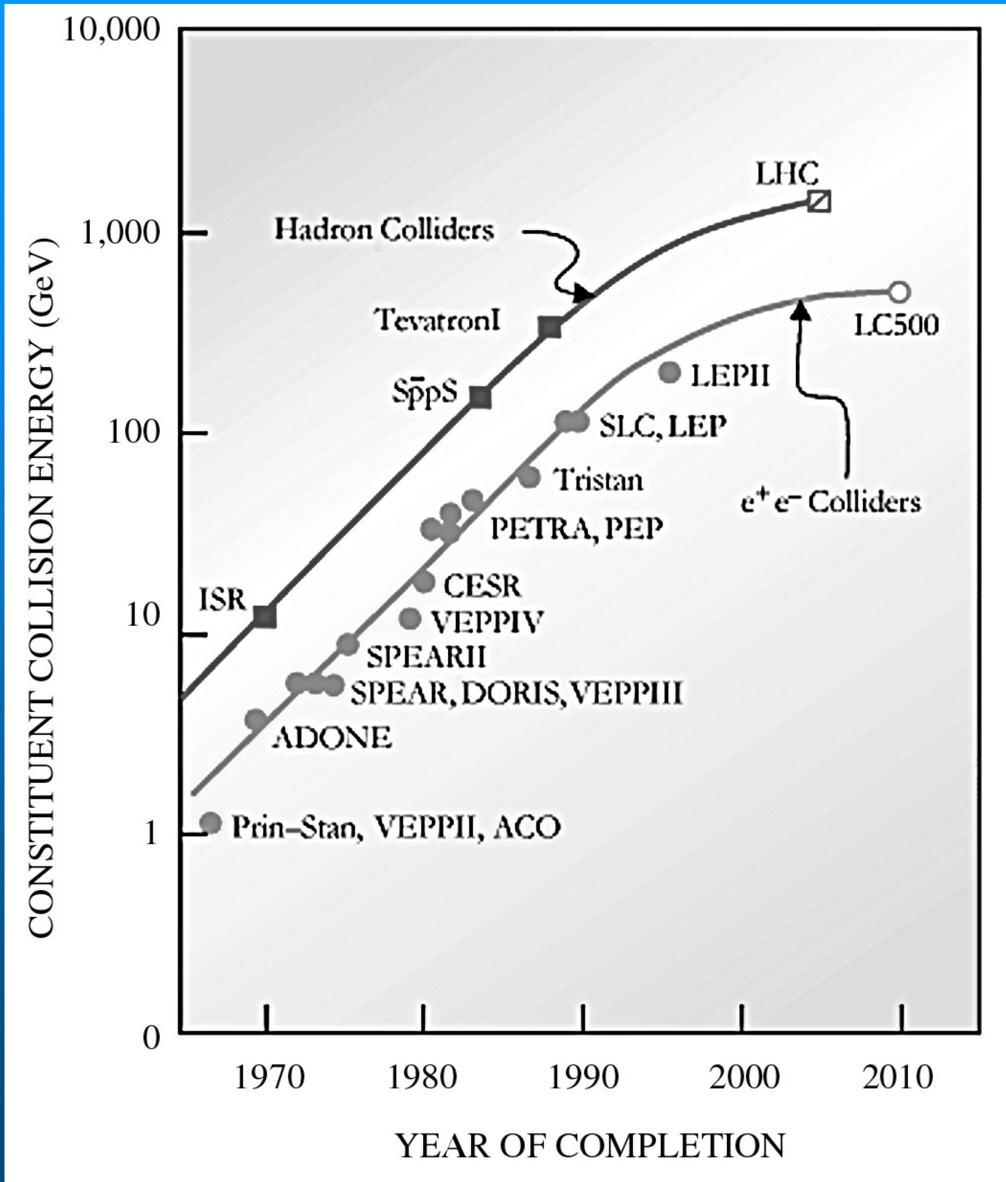
Challenges for future accelerators:

Accelerators are the biggest scientific instruments human mankind has built:

- Large size (~ 30 km footprint)
- High cost (~ billion Euro)
- Needs lots of electricity
- Technology pushed to its limits
- ~ 20-30 years to make one
- Fewer facilities
- Global co-ordination
- Accelerator specialists

All this effort justified by the chance to discover new particles, forces, properties of matter!

The Livingston plot:



(M. Tigner)

Great success of accelerators in the past:

Exponential increase in collision energy with time (Livingston plot)!

Progress has slowed down:

Technological limits in conventional accelerators (circular lepton and proton colliders)!

The limits in “conventional” colliders:

conventional = circular lepton or proton colliders

a) Hadron (p) circular collider

Limited by available bending field strength (even super-conducting):

$p = e\,R\,B_y$ (increase momentum by increasing radius times bending field)

b) Lepton (e-,e+) circular collider

Limited by synchrotron radiation losses U_{loss}:

$U_{loss} \propto \frac{E^4}{R}$ E.g. LEP2: 3% of energy lost per turn, 10000 turns/s

(increase momentum by increasing radius and lowering bending field)

→ Change of concept, technology…

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Luminosity issues (nanometer size beams)
What is the right technology?

The CLIC study at CERN (basics)

R&D issues

Getting the accelerating field
Generating 30GHz power
Maintain nanometer size beams
Collide nanometer size beams

Outlook into the future

A future particle collider:

The next machine beyond LHC: **Linear collider**

Research groups in Europe, North America, Asia, Russia.
Major proponents:

TESLA (super-conducting linear accelerator)

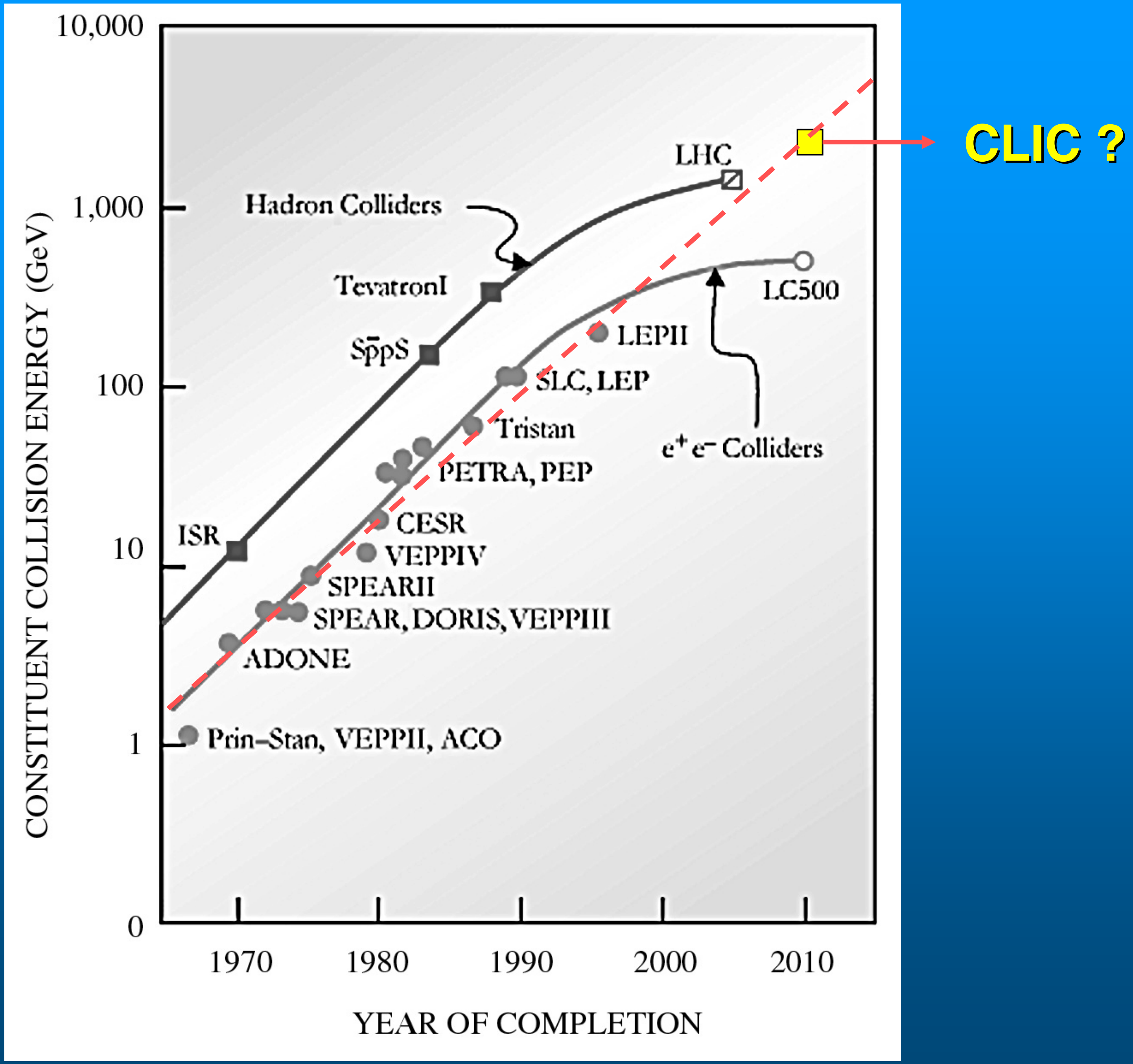
NLC (normal-conducting linear accelerator)

JLC (normal-conducting linear accelerator)

CLIC (normal-conducting two-beam linear accelerator)

CLIC has most ambitious goals, most innovative technology, most R&D work to be done.

Exciting time: International committee expected to take decision on normal-conducting versus super-conducting technology in the next month!



10,000
1,000
100
10
1
0
CONSTITUENT COLLISION ENERGY (GeV)
1970
1980
1990
2000
2010
YEAR OF COMPLETION
Hadron Colliders
LHC
TevatronI
S$\bar{p}$pS
ISR
LEPII
LC500
SLC, LEP
Tristan
e^+e^- Colliders
PETRA, PEP
CESR
VEPPIV
SPEARII
SPEAR, DORIS, VEPPIII
ADONE
Prin–Stan, VEPPII, ACO
CLIC ?

Principle of a linear collider:

Injectors	*Provide the beam*
Damping rings	***Provide small emittance***
Bunch compression	*Provide short bunch length*
Linear accelerator	*Provide beam energy*
Collimation	*Provide small background*
Final Focus	*Provide demagnification* ***Collide beams***
Collimation	
Linear accelerator	
Bunch compression	
Damping rings	
Injectors	

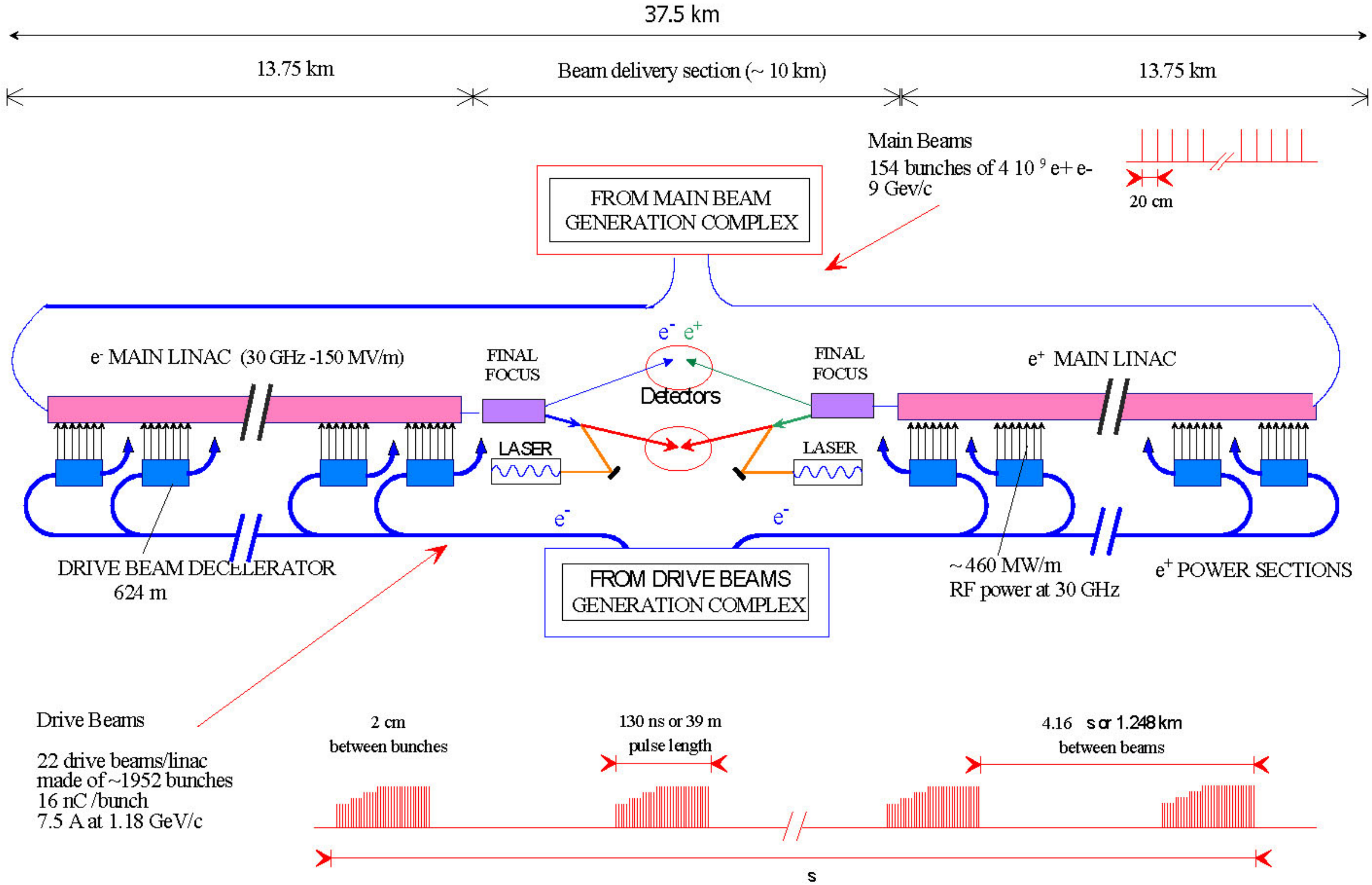
Like two guns aiming at each other

Shoot not only one packet of e- or e+ (bunch) but many (multi-bunch)

The packets hit head-on and collide inside a big detector (nanobeams)

Shoot about 100 times per second

Overall Layout of the CLIC complex at 3 TeV c.m.



Now, let's design a linear collider:

Particle physics: E_{coll} = 3 TeV c.m. L = 10^{35} cm^{-2} s^{-1}

(a) Required acceleration:

Beam energy: E = 1.5 TeV

Desired linac length: 10 km

Required accelerating field:

$$E_{acc} = \frac{1.5\,\text{TeV}}{10\,\text{km}\ \ e} = 150\ \text{MV/m}$$

Important design parameter: 150 MV/m acc. field
150 million Volts/m

(acceleration from about 1000 TV tubes per m)

(b) Required beam sizes:

L = 10^{35} cm^{-2} s^{-1} ⇒ $$L = \frac{f_{coll}\ N_{bunches}\ N_{e^-}\ N_{e^+}}{4\pi\sigma_x\sigma_y}$$

Assume 100 Hz collision rate, 150 bunches, 4 billion particles per bunch:

$\sigma_x \sigma_y = 2\ 10^{-13}\ \mathrm{cm}^2 = 2\ 10^{-17}\ \mathrm{m}^2$

For example: **$\sigma_x = 20$ nm**
$\sigma_y = 1$ nm

1 nm = 0.000000001 m = 10 Angstrom = size of water molecule

Accelerate 4 billion particles to high energy, preserve emittance over 10 km, compress into nanometer area, and collide…

(c) Other considerations

Can we pay for the electrical bill? 1 eV = 1.6×10^{-19} Joules

Energy stored in beam:

$$E_{stored} = 150 \text{ bunches } \times \ 4 \cdot 10^9 \text{ /bunch } \times \ 1{,}500{,}000{,}000 \text{ eV} = 144{,}000 \text{ J}$$

Average power in one beam:

$$P = f_{coll} \times E_{stored} = 100 \times 144{,}000 \text{ J/s} \approx 15 \text{ MW}$$

Two beams with 10% **efficiency** from wall plug power to beam:

$$P_{\text{wall plug}} = \frac{2 \times 15 \text{ MW}}{0.10} = 300 \text{ MW}$$

This is acceptable!

Big power station: ~ 700 MW

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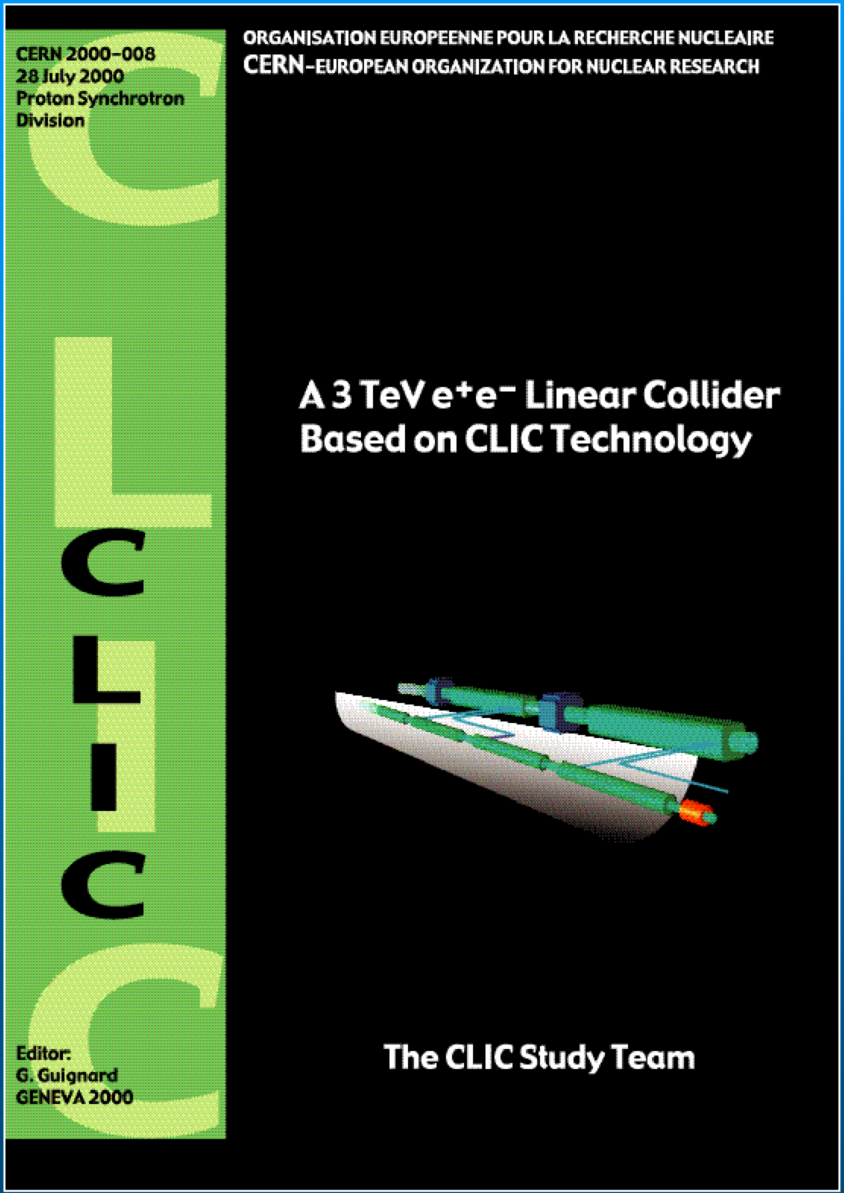
Outlook into the future

The CLIC study at CERN: Compact Linear Collider



International collaboration:

Berlin Technical University (Germany)
Finnish Industry (Finland)
LAL (France)
LLBL / LBL (USA)
INFN/LNF (Italy)
SLAC (USA)
JINR & IAP (Russia)
Uppsala University (Sweden)
KEK (Japan)
North Western University (USA)
RAL (Great Britain)
LAPP/ESIA (France)

The CLIC team:

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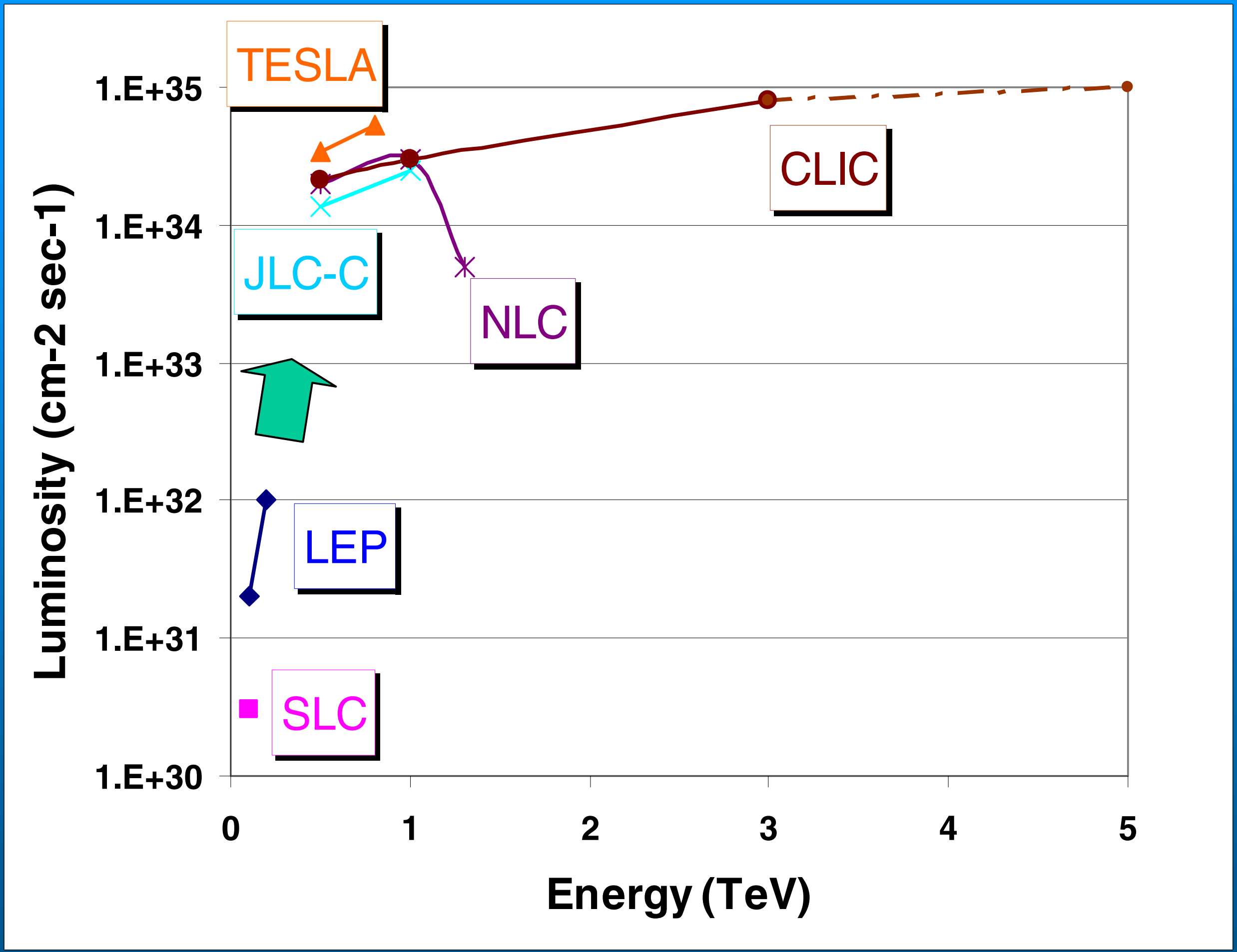
What is special about CLIC?



Highest accelerating gradient & smallest beam sizes:

Highest energy and luminosity reach!

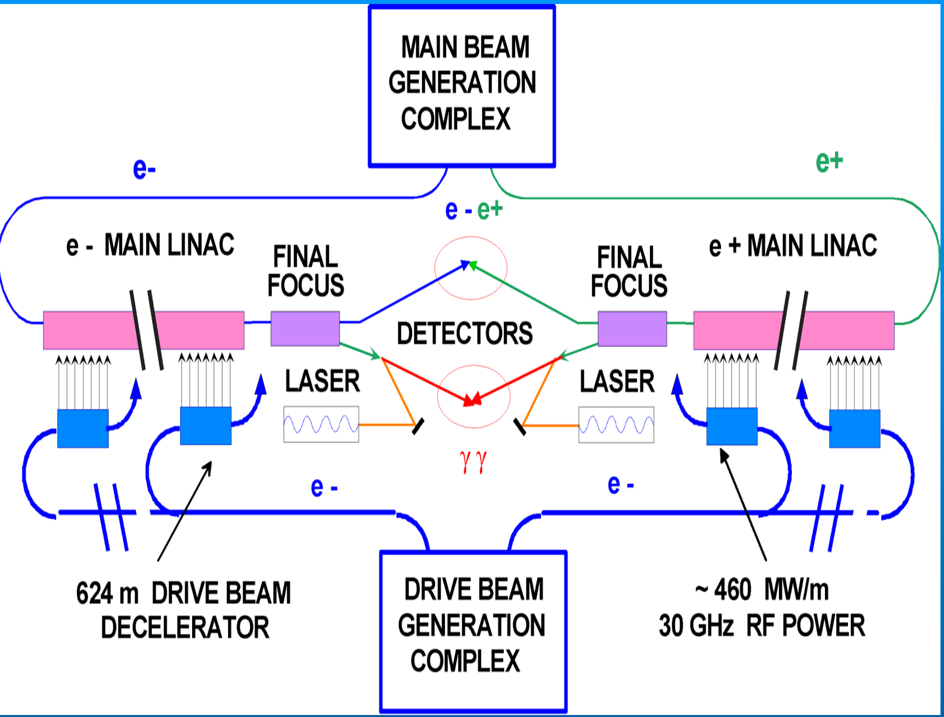
J.P. Delahaye

Status: R&D activity for the CERN future beyond LHC!

The FUTURE project for CERN…

Basic features of the CLIC scheme

33.2 km



5.2 km

Overall layout for a center of mass energy of ***3 TeV/c***

- **High acceleration gradient (150 MV/m)**
  - "Compact" collider-overall length ≈33 km
  - Normal conducting accelerating structures
  - High acceleration frequency (30 GHz)
- **Two-Beam Acceleration Scheme**
  - RF power generation at high frequency
  - Cost-effective & efficient (~ 10% overall)
  - Simple tunnel, no active elements
- **Central injector complex**
  - "modular" design, can be built in stages
  - Easily expendable in energy

J.P. Delahaye

CLIC parameters

Center of mass Energy (TeV)	0.5 TeV	3 TeV
Luminosity (10^{34} $cm^{-1}s^{-1}$)	2.1	8.0
Mean energy loss (%)	4.4	21
Photons / electron	0.75	1.5
Coherent pairs per X	700	6.8 10^8
Rep. Rate (Hz)	200	100
10^9 $e^{\pm}$ / bunch	4	4
Bunches / pulse	154	154
Bunch spacing (cm)	20	20
H/V ε_n (10^{-8} rad.m)	200/1	68/1
Beam size (H/V) (nm)	202/1.2	60/0.7
Bunch length (μm)	35	35
Accelerating gradient (MV/m)	150	150
Overall length (km)	7.7	33.2
Power / section (MW)	230	230
RF to beam effficiency (%)	23.1	23.1
AC to beam efficiency (%)	9.3	9.3
Total AC power for RF (MW)	105	319
Total site AC power (MW)	175	410

J.P. Delahaye

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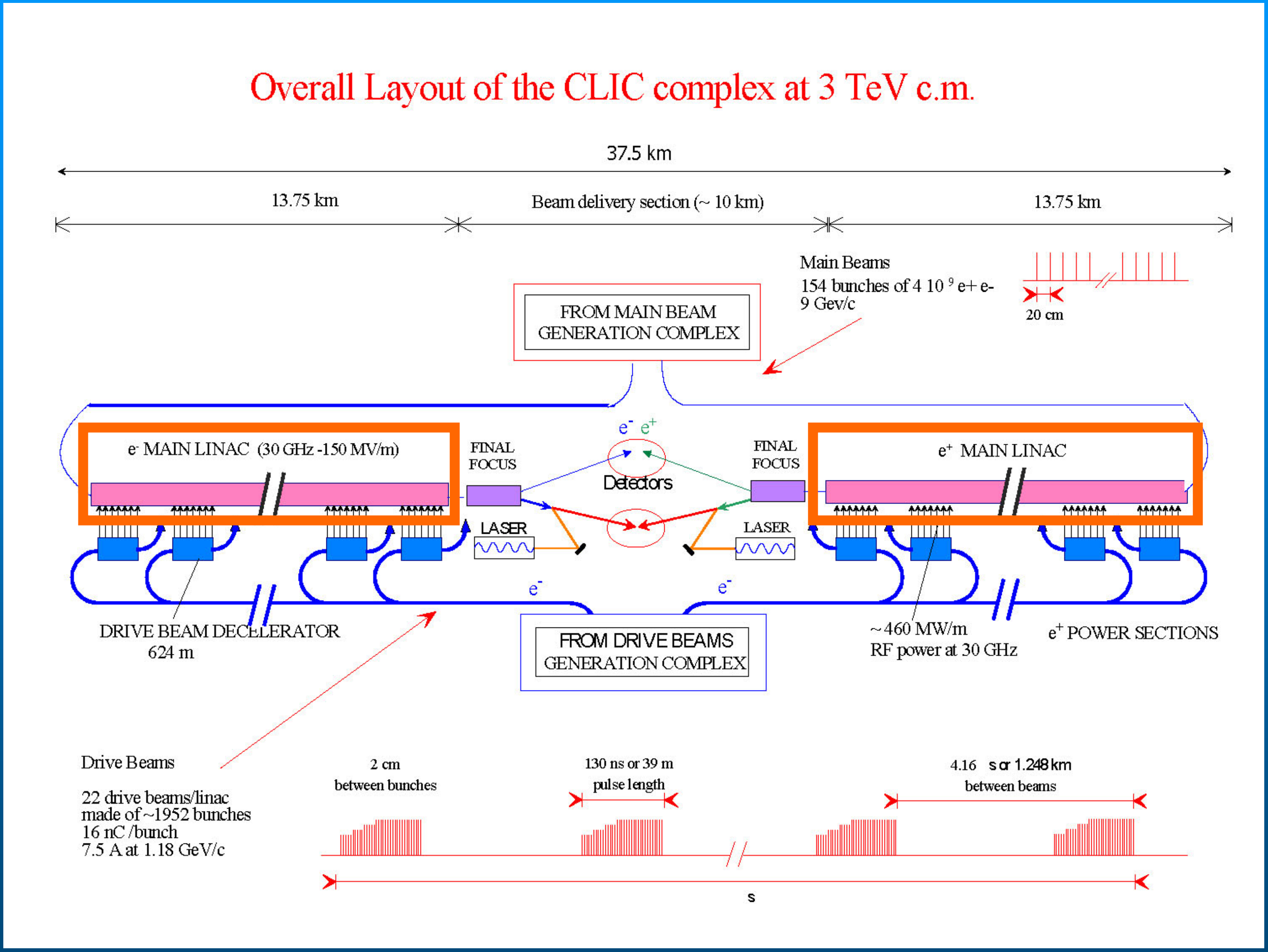
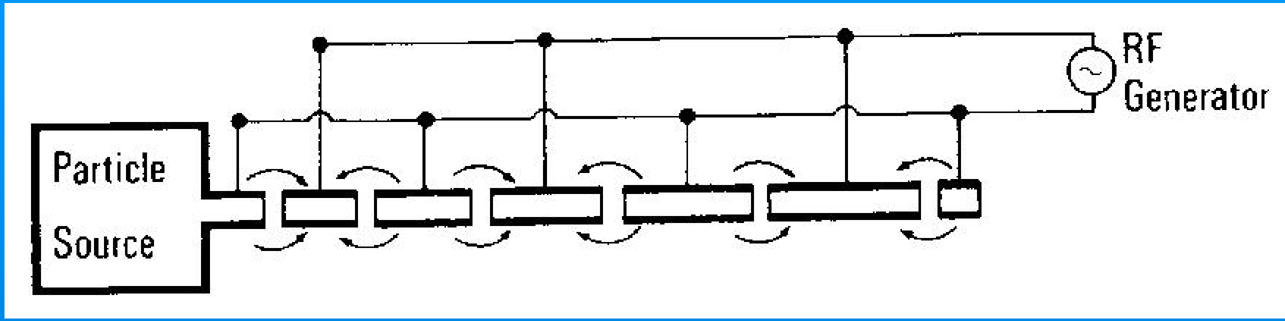
Outlook into the future

R&D topic 1: Getting the accelerating field

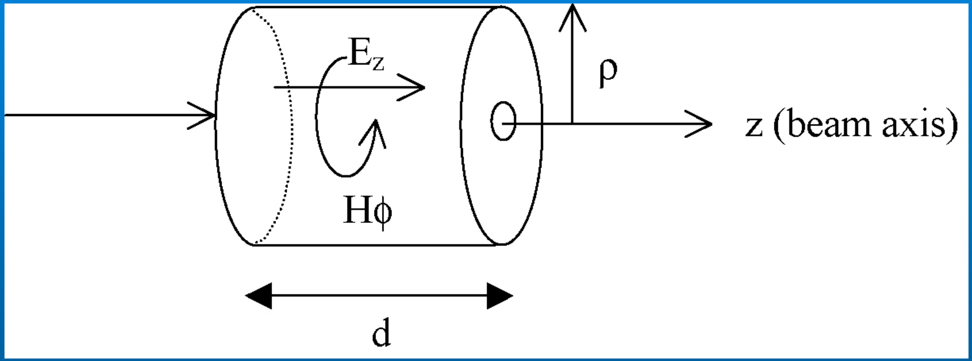


Reminder RF acceleration:



Wideroe accelerator

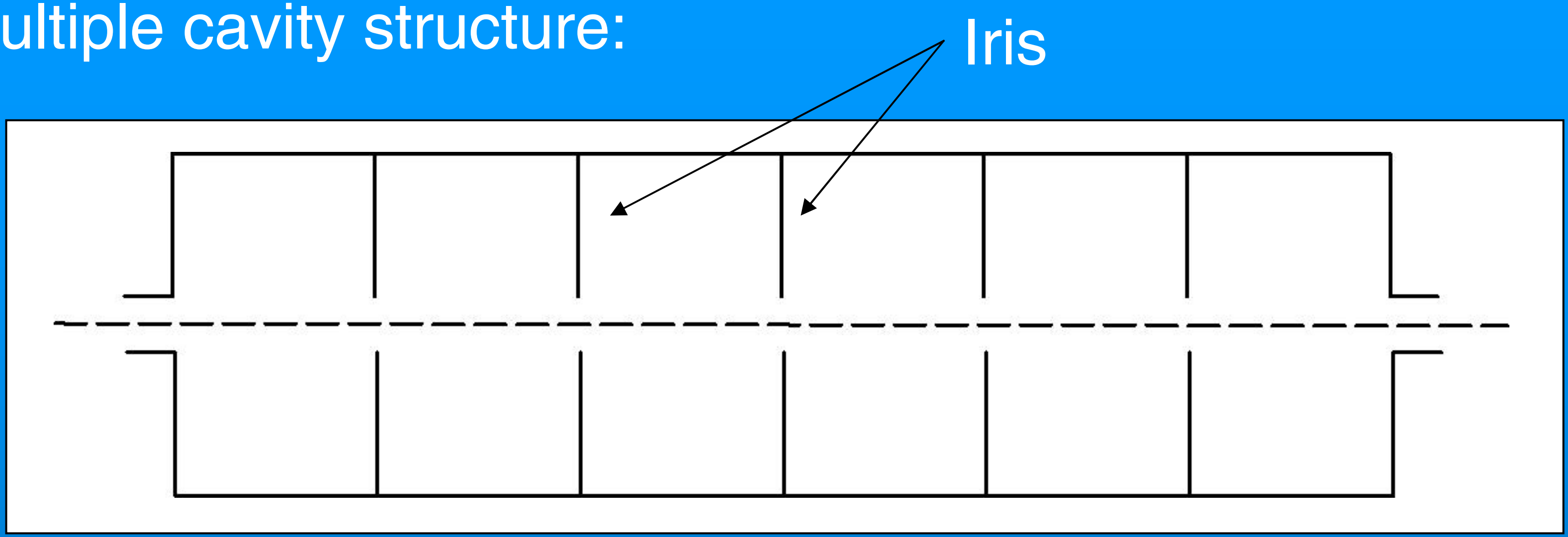
Cylindrical cavity



E.g. $d = \lambda_{RF}/2$: λ_{RF} is the RF wavelength $\lambda = \frac{v}{f_{RF}} = \frac{c}{f_{RF}} = 2\pi c / \varpi_{RF}$

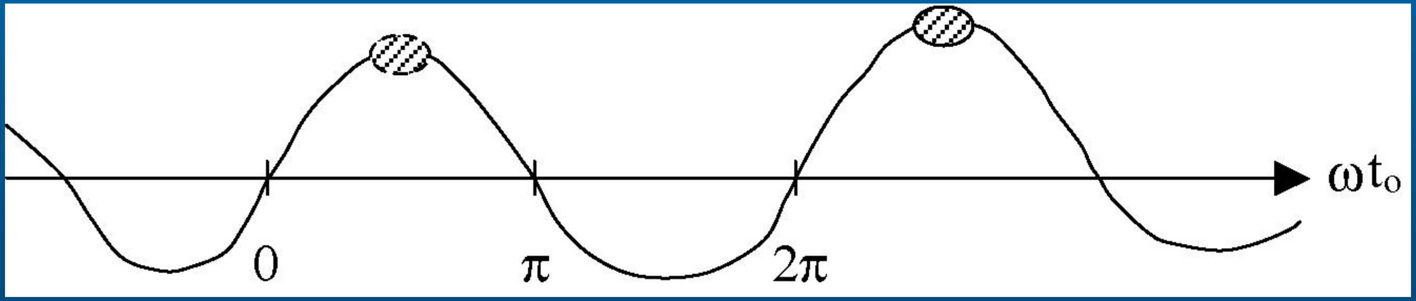
$f_{RF} = 30$ GHz ➡ $\lambda_{RF} = 1$ cm ➡ **d = 5 mm**

Multiple cavity structure:



Smooth waveguide: $v_{ph} > c$

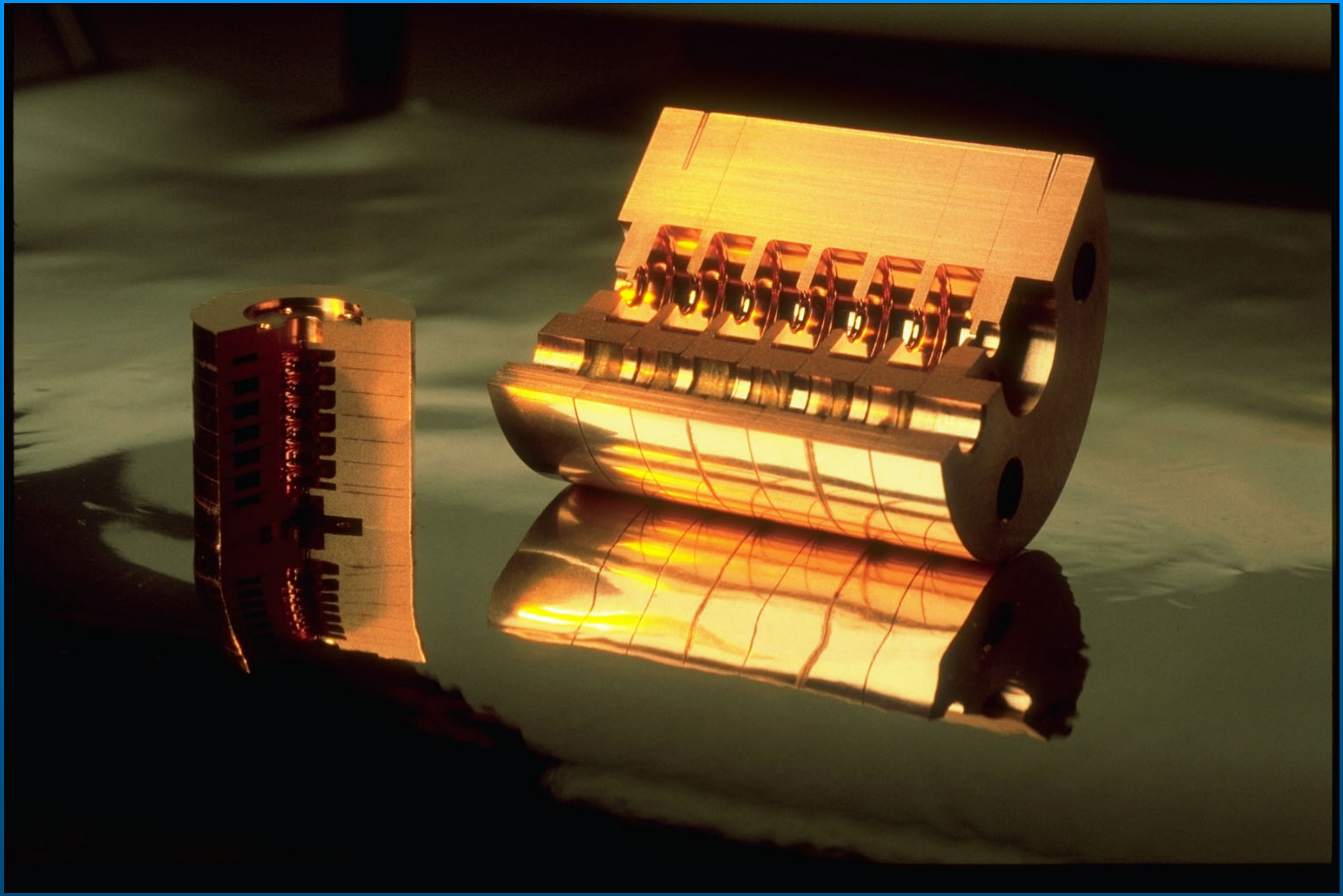
Obstacles (irises) to slow down accelerating wave for synchronous acceleration:



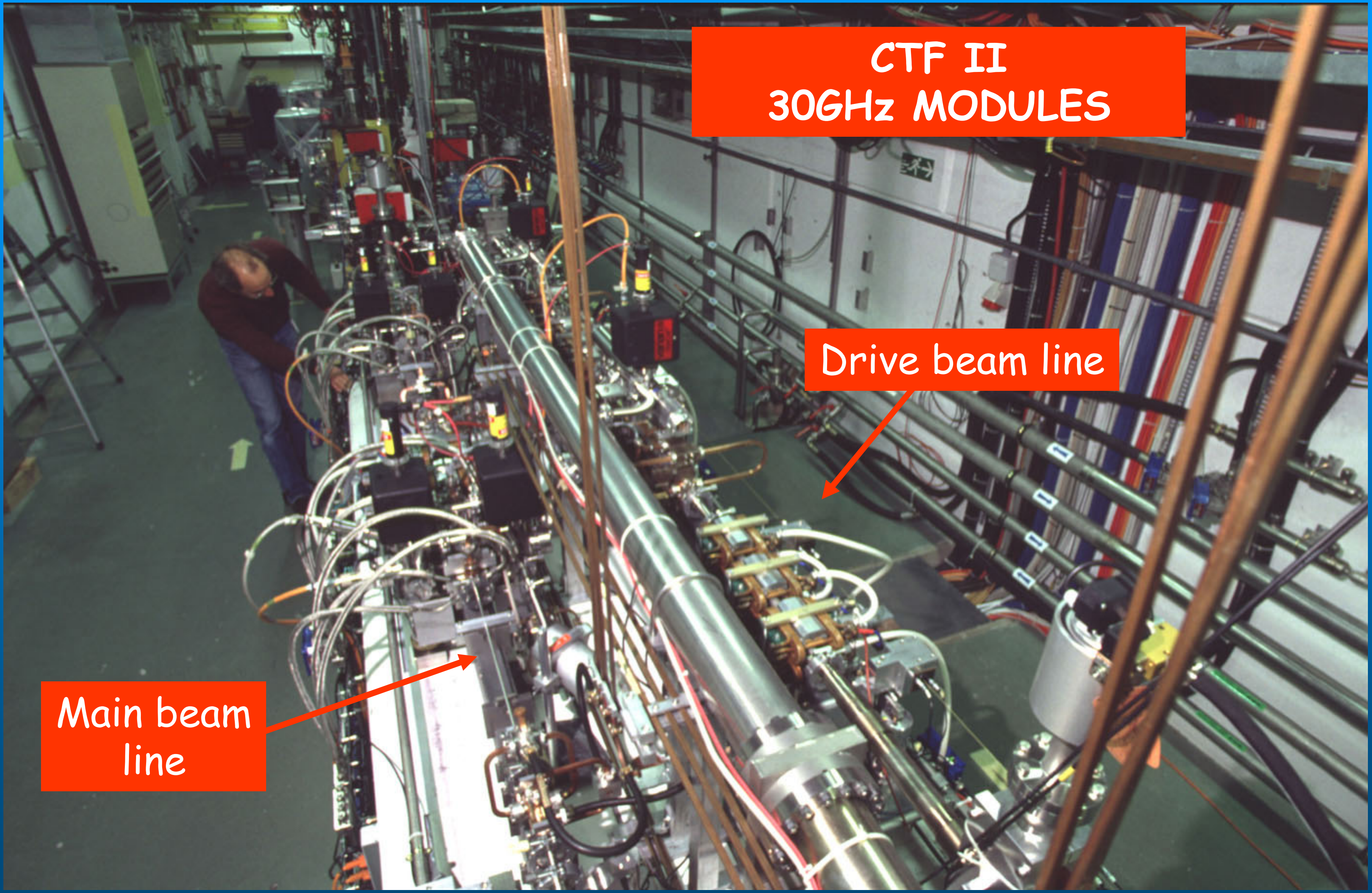
Bunch length shorter than λ_{RF}

Prototypes and results

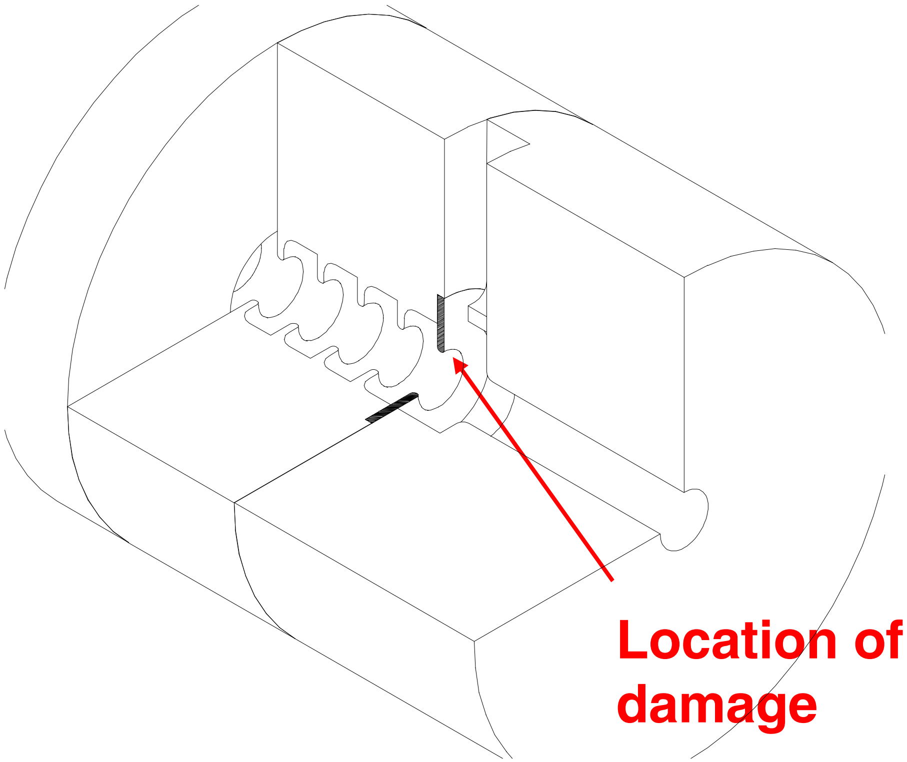
Internal view:



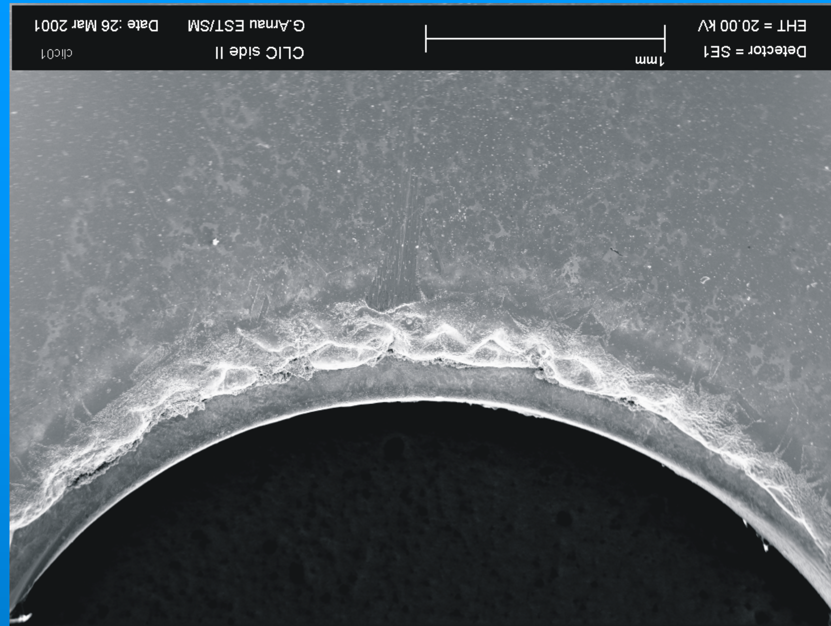
Two Beams set-up in CTF2

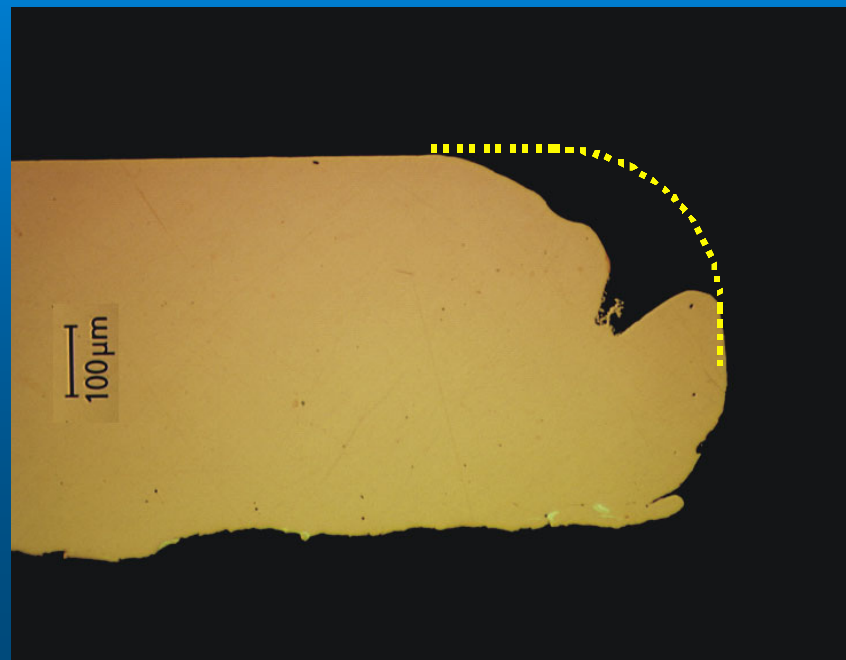


Damage due to breakdown



Single feed power coupler
30 GHz, 16 ns,
66 MV/m local accelerating gradient

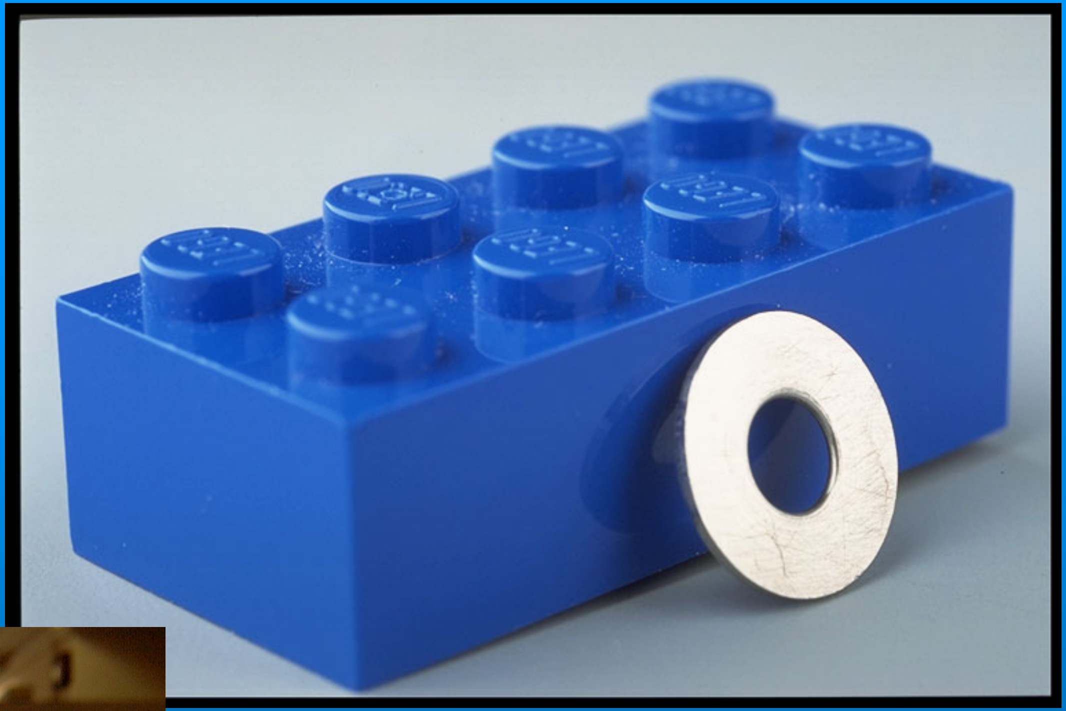


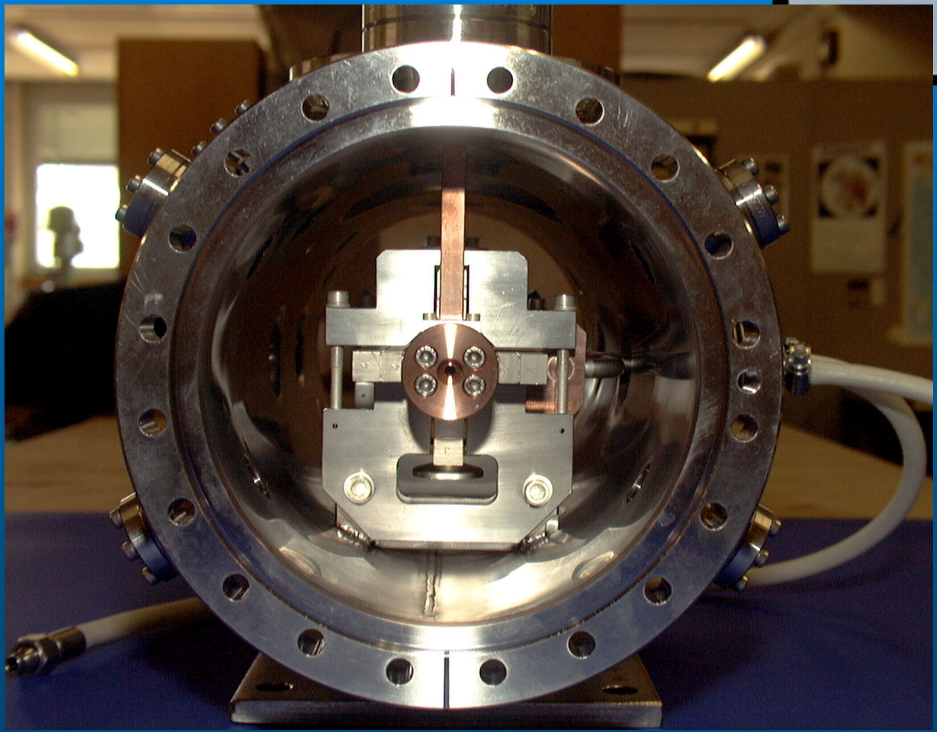


W. Wuensch

Replace copper iris with tungsten iris

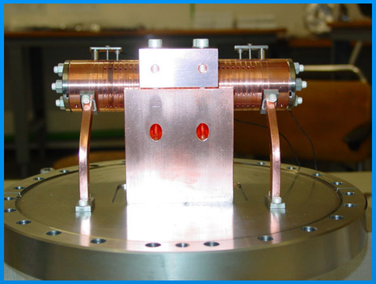
good electrical conductivity, high melting point, low vapor pressure

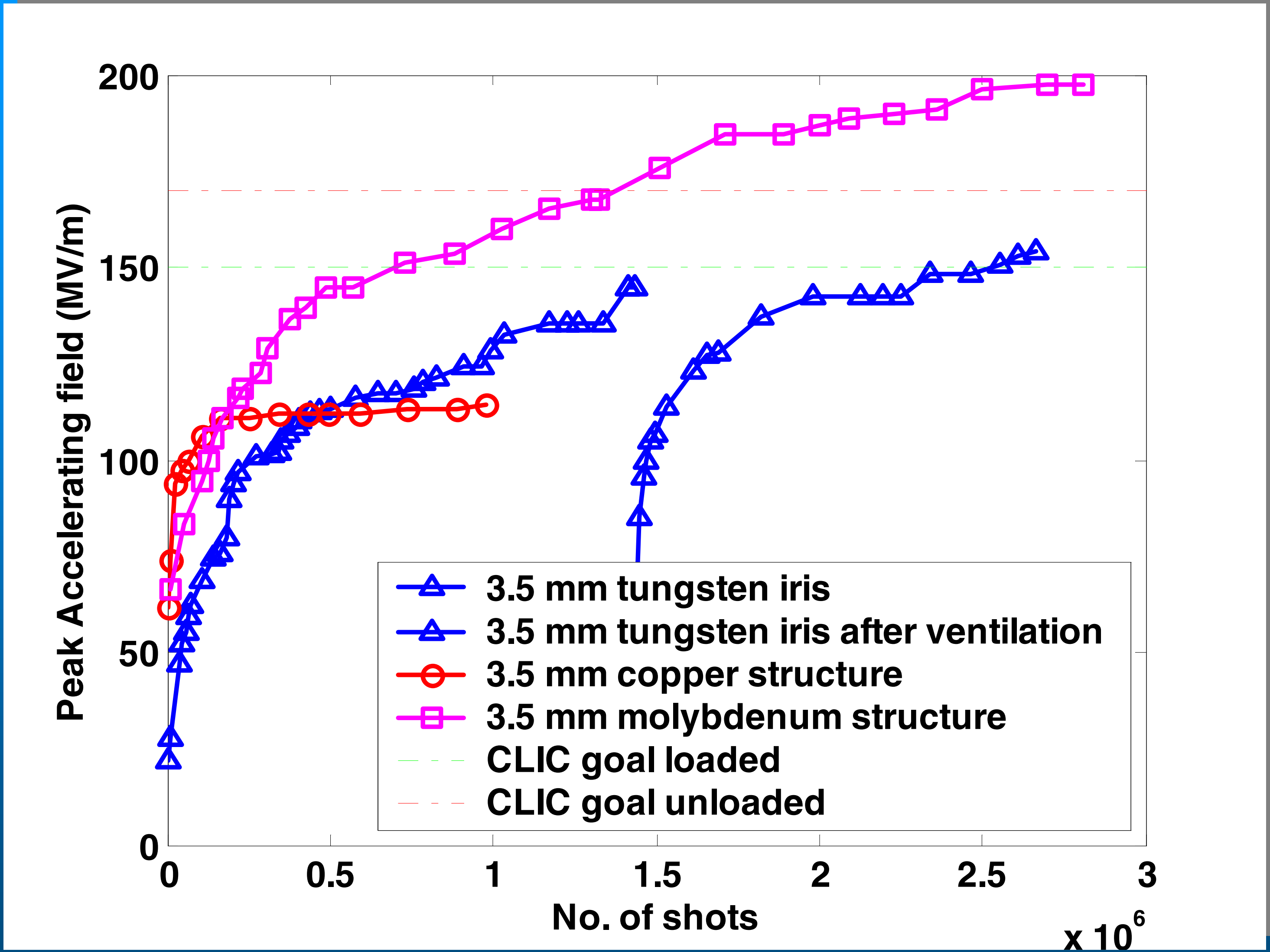




W. Wuensch

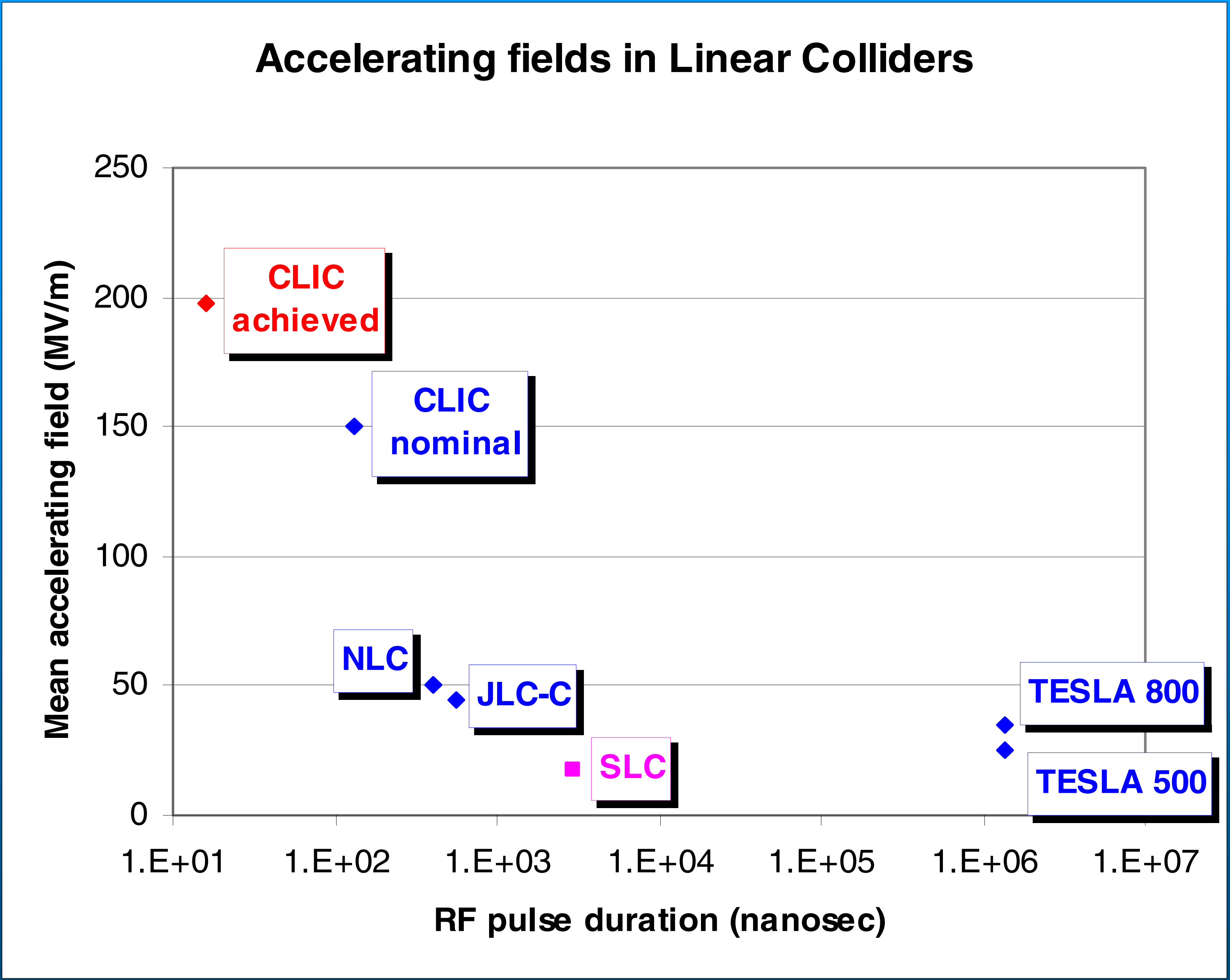
Measured peak accelerating field:





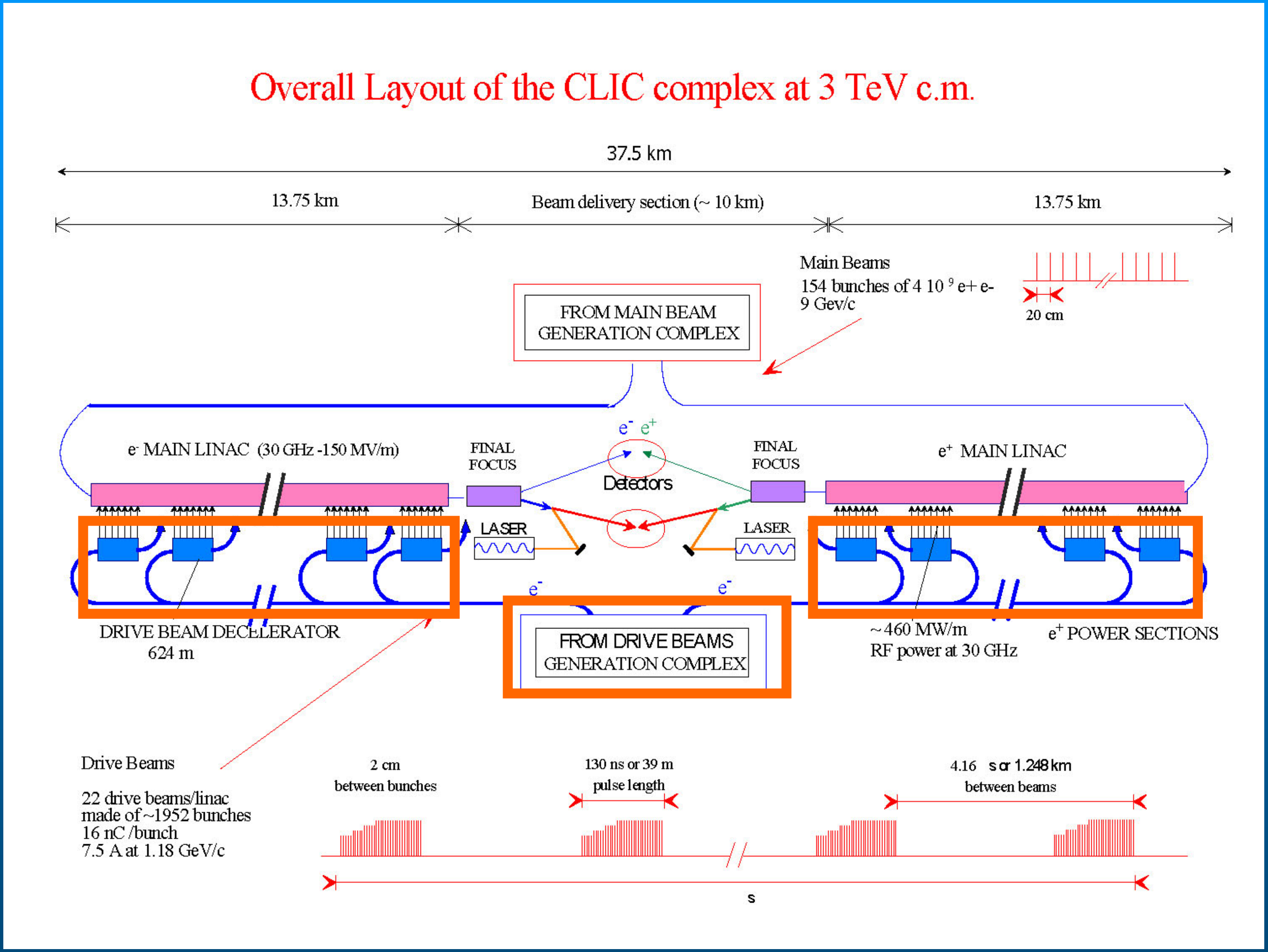
W. Wuensch

Field levels calibrated by accelerated beam!

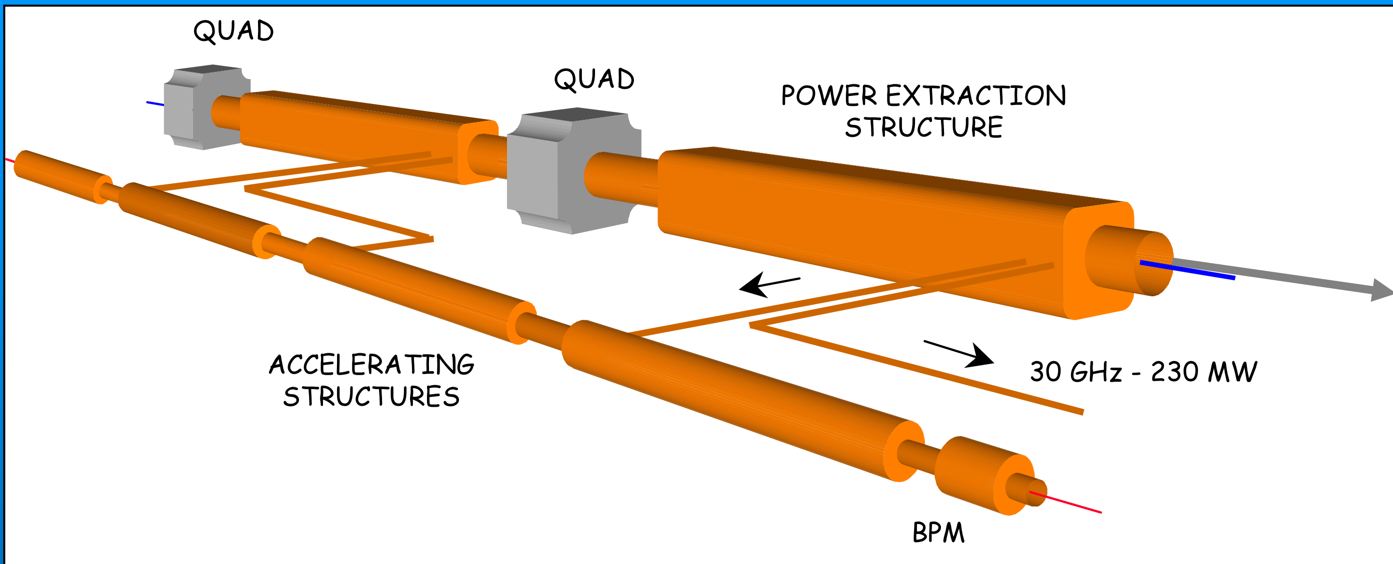

Accelerating fields in Linear Colliders
250
200
150
100
50
0
Mean accelerating field (MV/m)
CLIC achieved
CLIC nominal
NLC
JLC-C
SLC
TESLA 800
TESLA 500
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
RF pulse duration (nanosec)

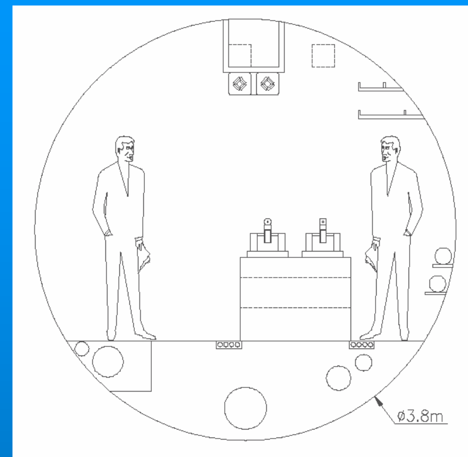
J.P. Delahaye

R&D topic 2: Generating 30 GHz power



Innovative two-beam scheme…



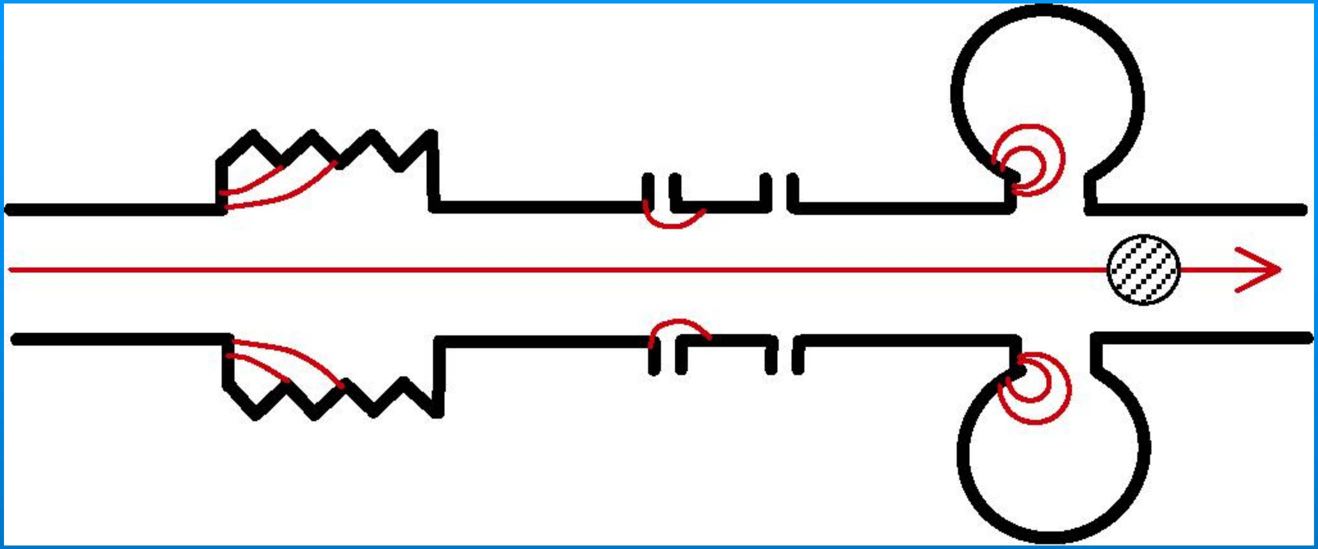


Generate 30 GHz power with high power, low energy beam (drive beam)

Drive beam must have 30 GHz bunch structure

➔ Tested in CLIC Test Facility 3 (CTF3) during the next years!

Wakefields…



Charged particles interact with metallic walls through electro-magnetic fields

Wakefields occur at discontinuities (cavity iris)

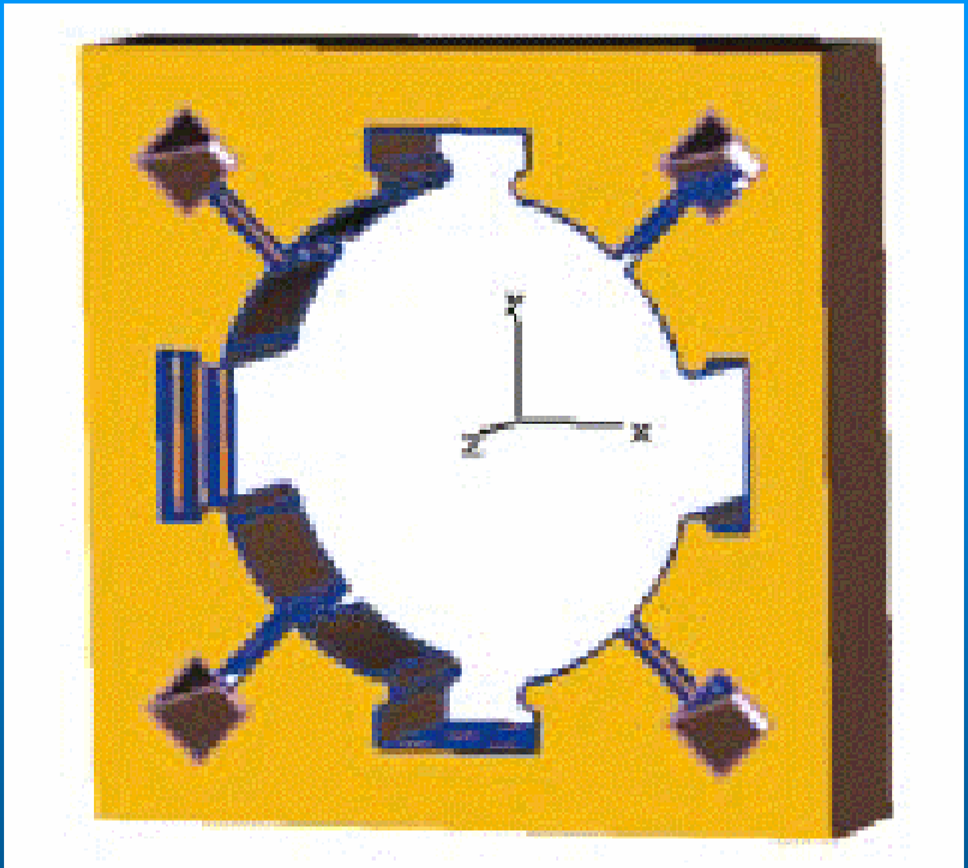
Sophisticated programs used for calculating wakefields

Charged beam feeds energy to the cavity

Energy can be fed resonantly

Energy is extracted for acceleration of main beam

PETS (Power Extraction and Transfer Structure)

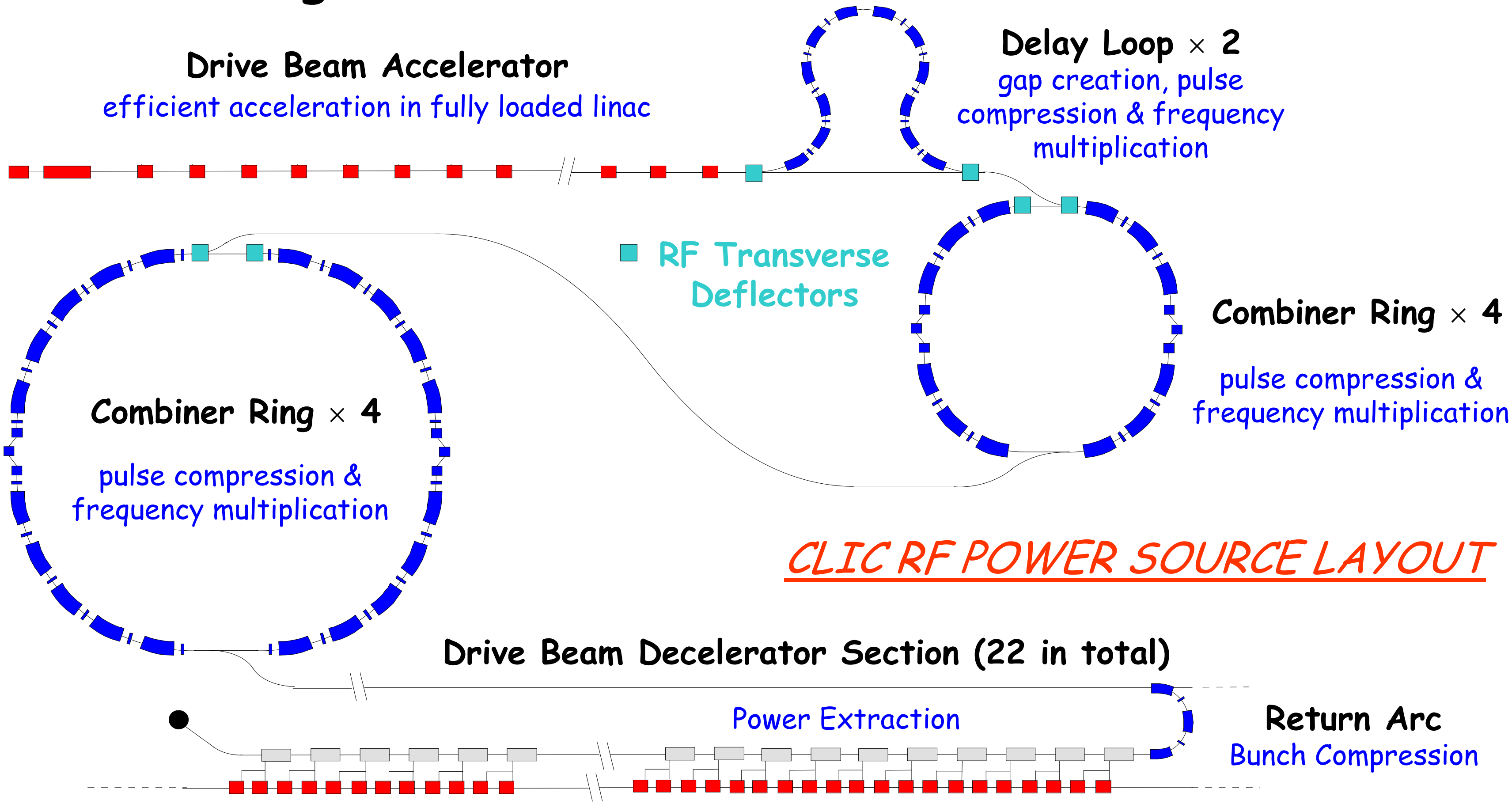


Beam chamber diameter: 26 mm

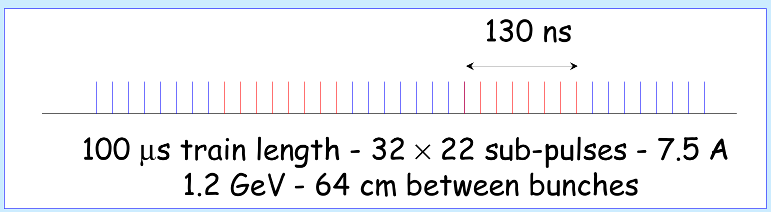
Decelerating gradient:	2.4 MV/m
Power extracted per meter:	458 MW

W. Wuensch

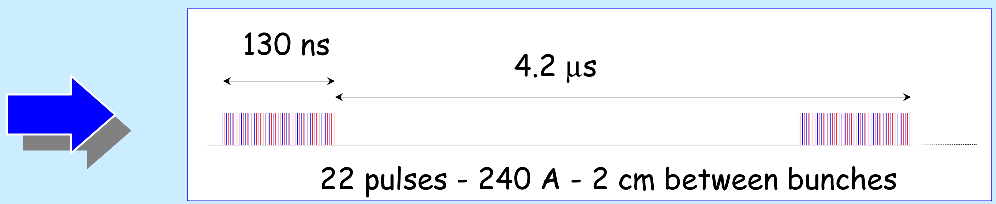
Drive beam generation

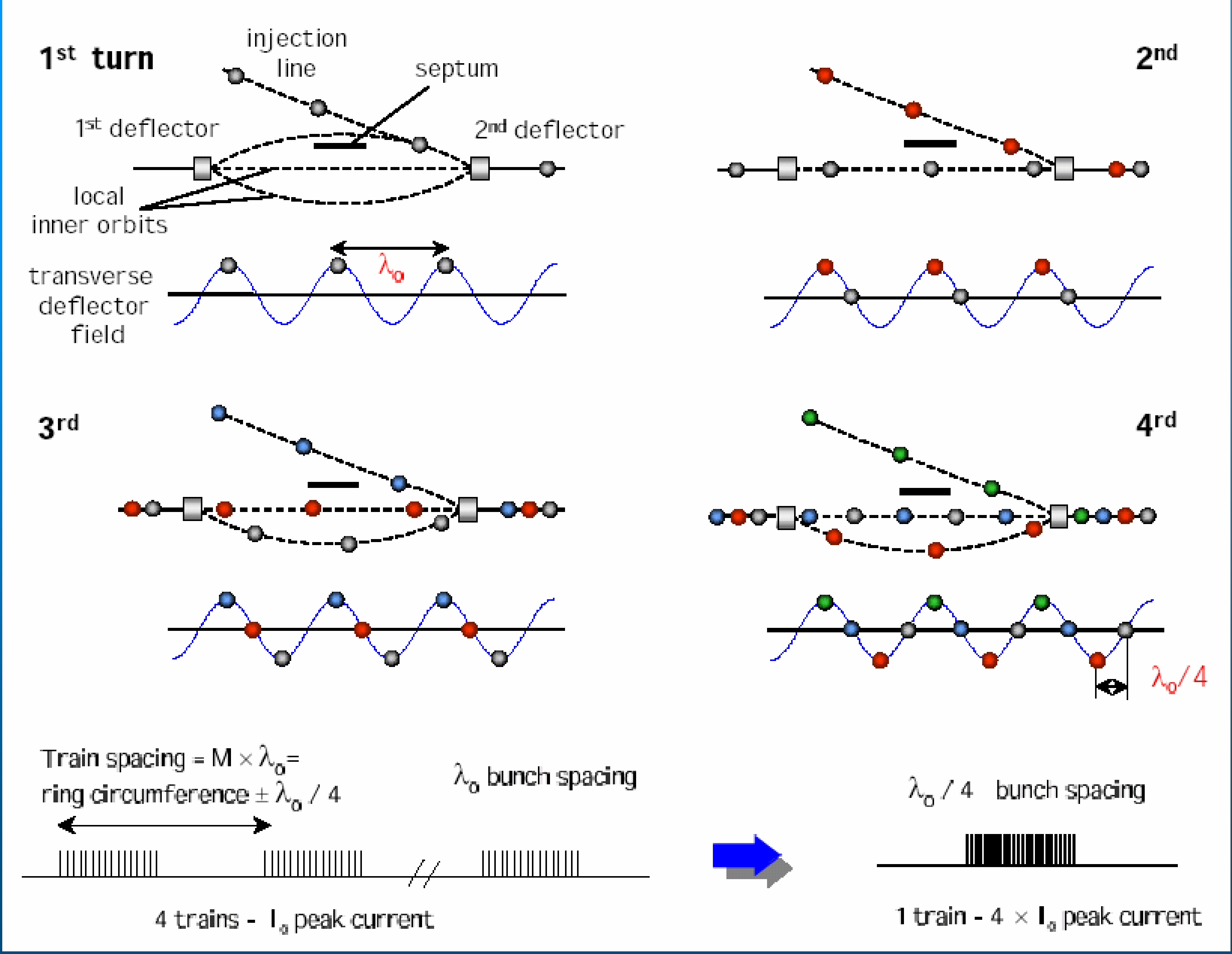


Drive beam time structure - initial



Drive beam time structure - final





1st turn
injection line
septum
1st deflector
2nd deflector
local inner orbits
transverse deflector field
λo
2nd
3rd
4rd
λo/4
Train spacing = M × λo= ring circumference ± λo / 4
λo bunch spacing
λo / 4 bunch spacing
4 trains - Io peak current
1 train - 4 × Io peak current

F. Tecker

CTF3 : Recombination factor of 5

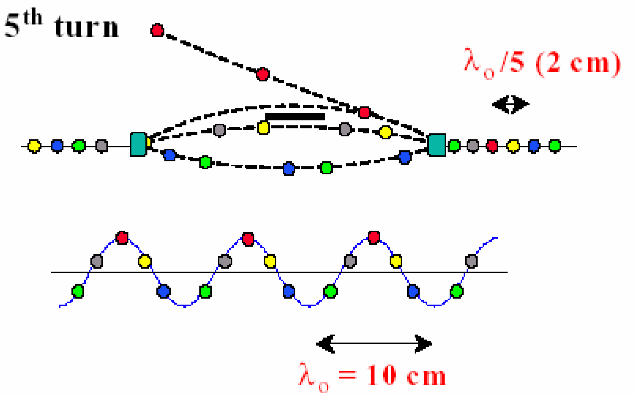
Charge: 1×10^{10} e- / pulse or 0.1 nC / bunch

Beam energy: 350 MeV

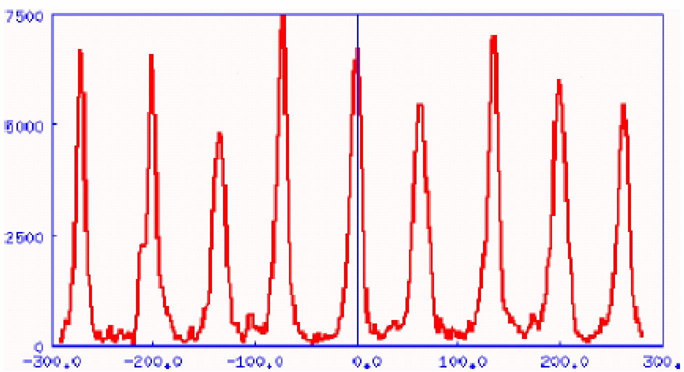
RF frequency : f_0 + 119.300 kHz = 2 998 669.300 kHz

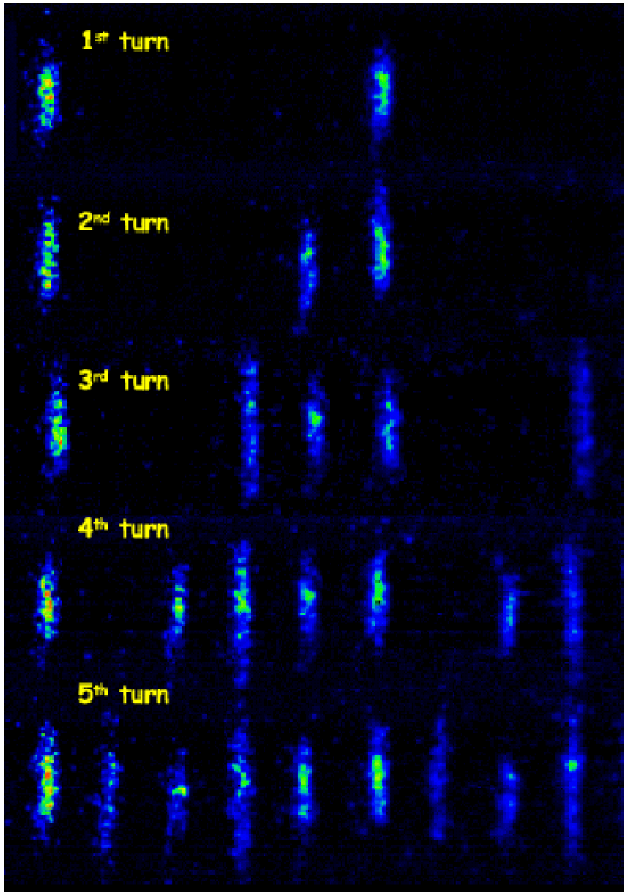
Bunch length (rms): $7.5 < \sigma < 9$ ps

Temperature of the bunching system + accelerating structures: $T_0 - 2\ ^\circ C = 28\ ^\circ C$

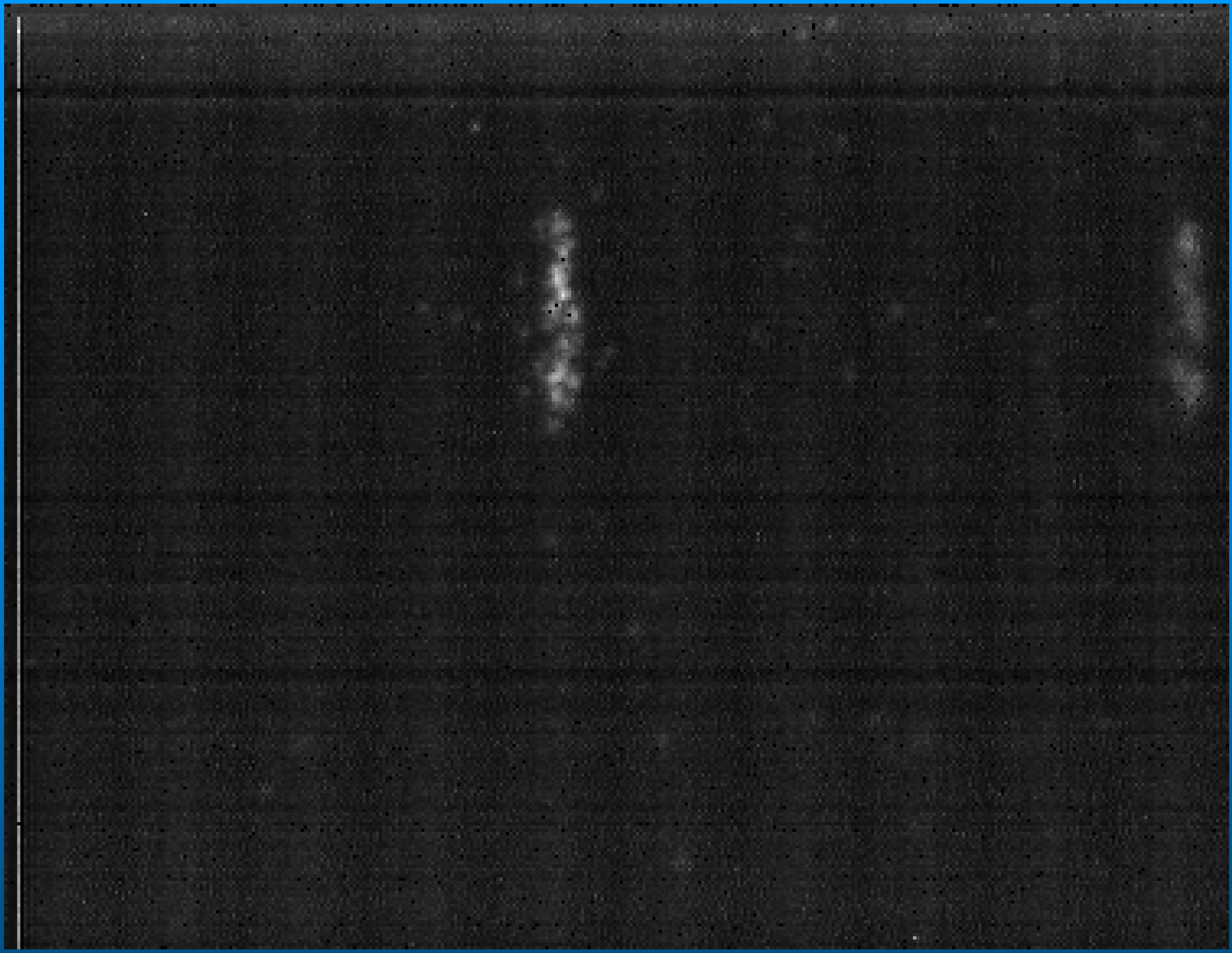


- bunch distance 333 ps → 67 ps
- frequency 3 GHz → 15 GHz



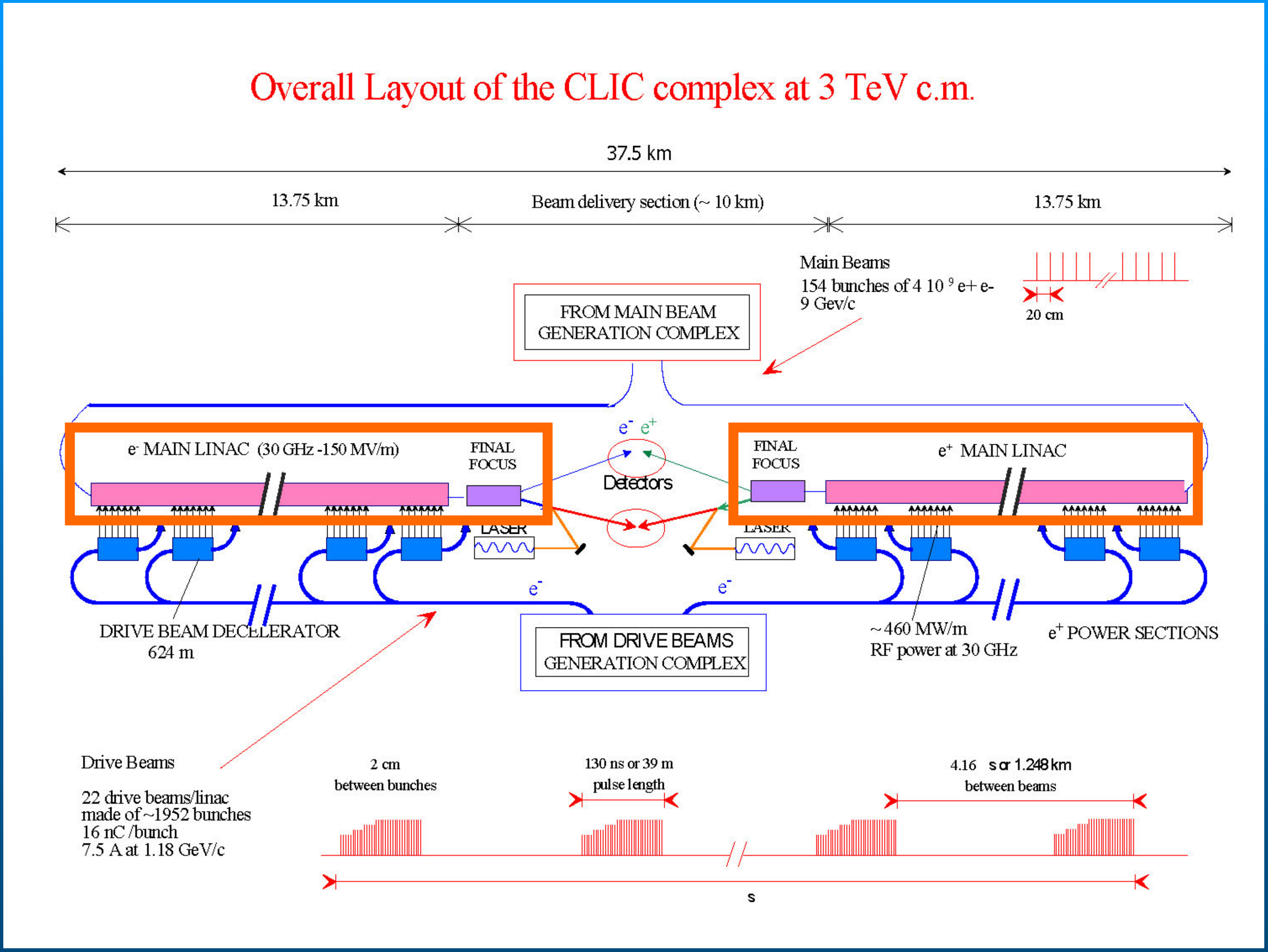


I. Wilson
F. Tecker



F. Tecker

R&D topic 3: Maintaining nanometer size beams



Wakefield emittance growth:

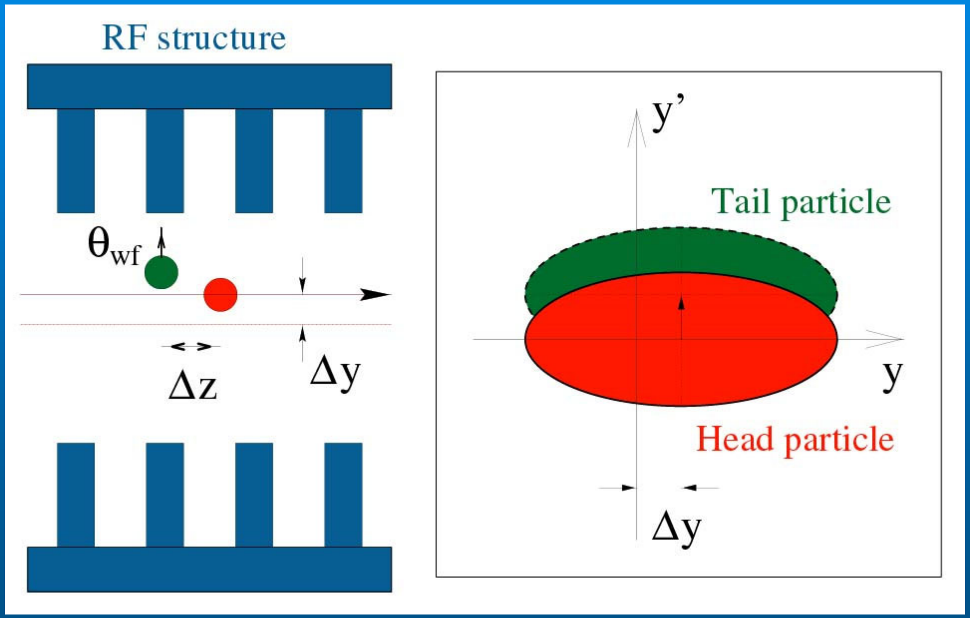
Structure is offset with respect to head of bunch (tolerance ~ 10 μm)

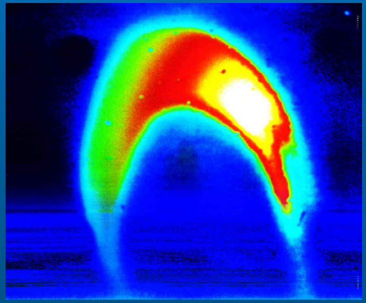
Head trajectory remains unchanged but wakefield is induced

Tail of bunch sees a wakefield deflection

Projected emittance is increased

$$\theta_{wf} = W_t(\sigma_z) \cdot \frac{eN_e L_{struc}}{2E_0} \cdot \Delta y_1$$





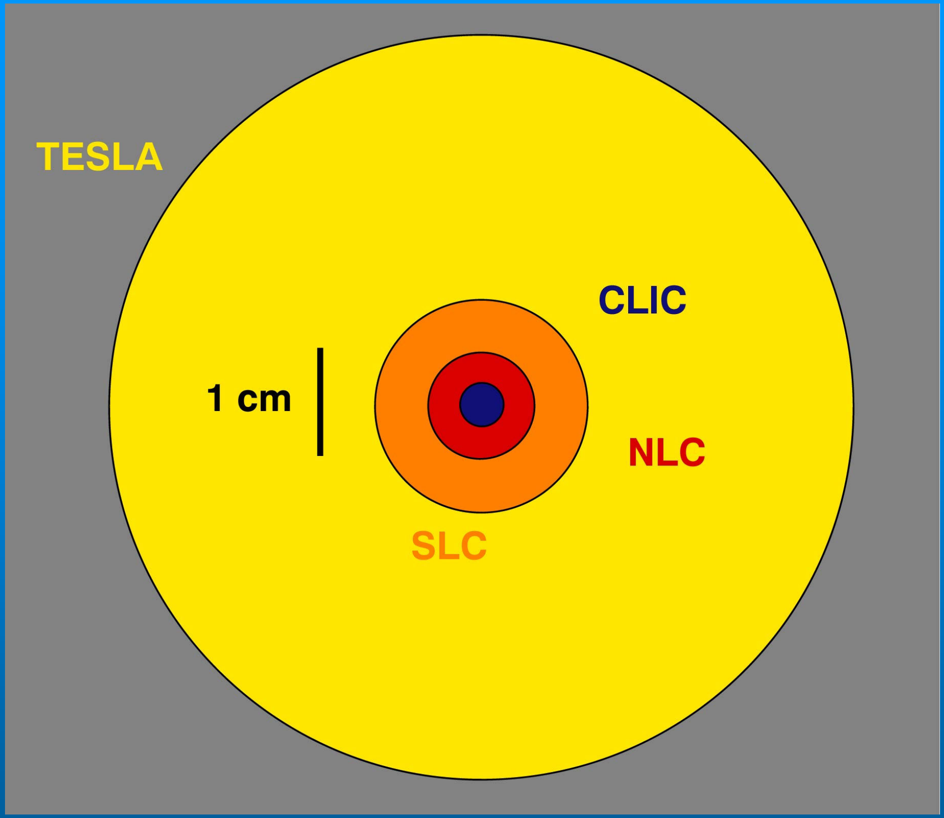
Beam dynamics depends on: Bunch population, particle energy, …

Amplitude of wakefields

Choice of technology determines radius of structure iris a:

High frequency – small a

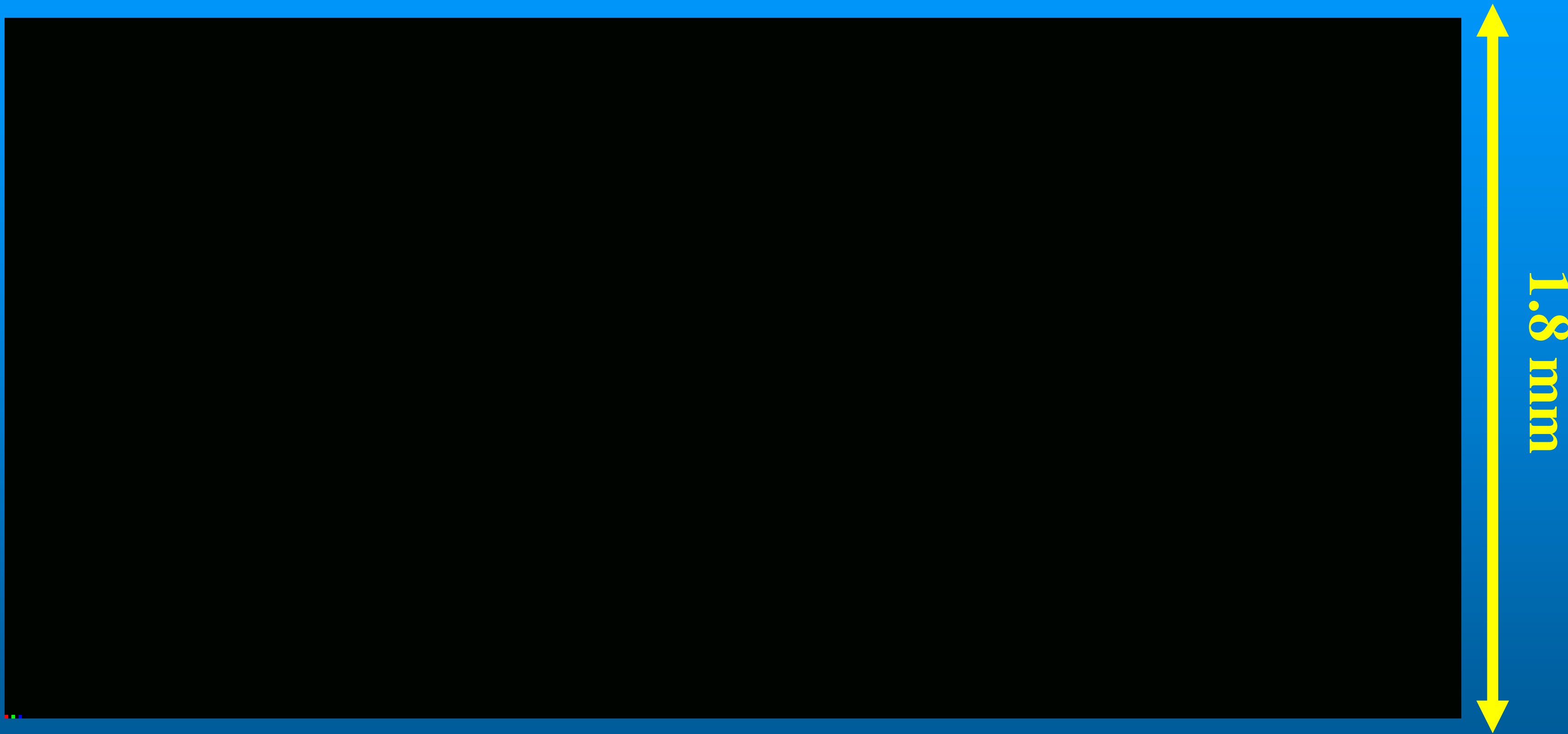
Low frequency – large a



Stronger wakefields (beam induced electro-magnetic fields) with smaller iris radius!

Beam is closer to metallic walls…

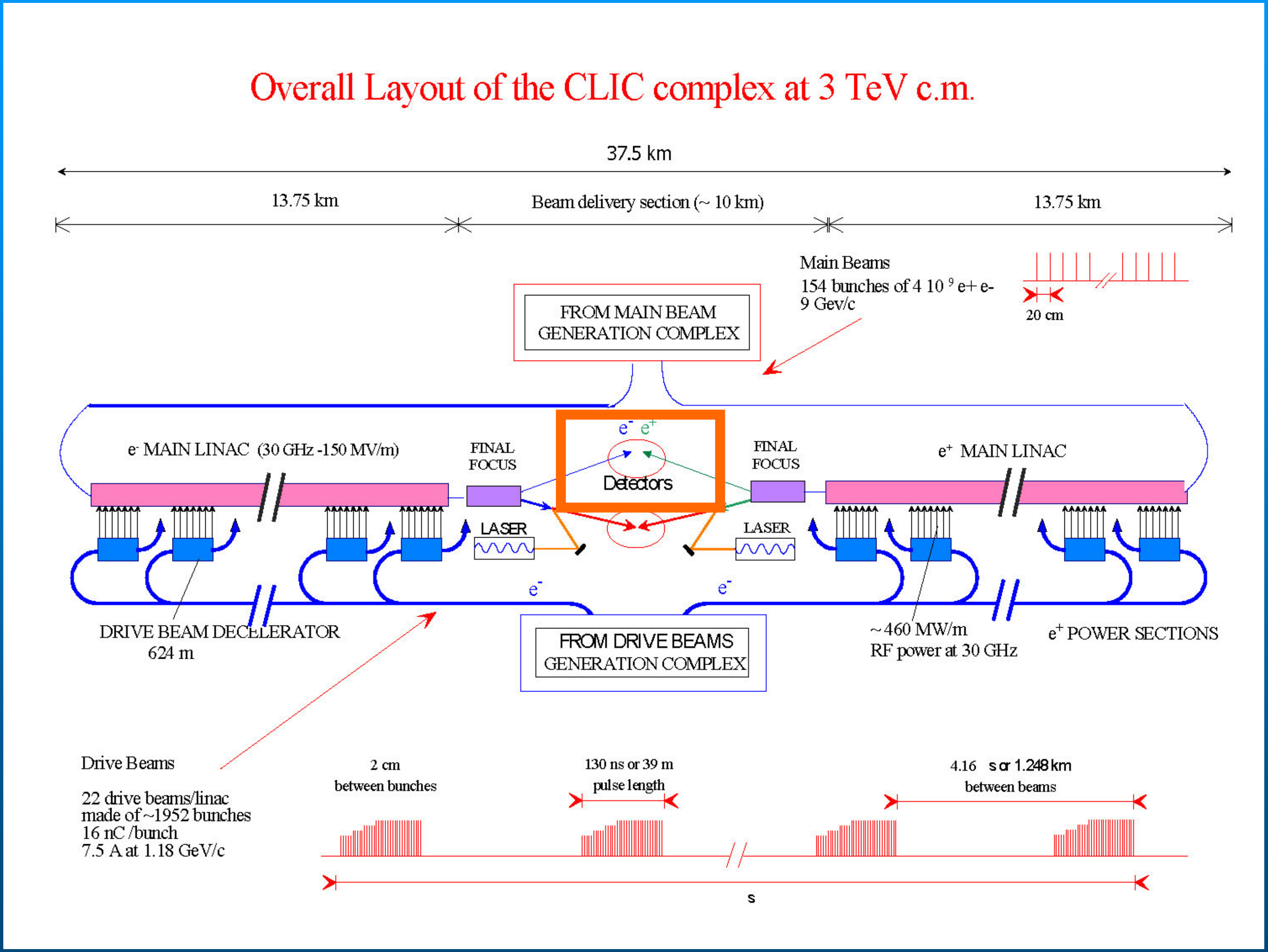
The effect of tuning in the SLC (5 days)



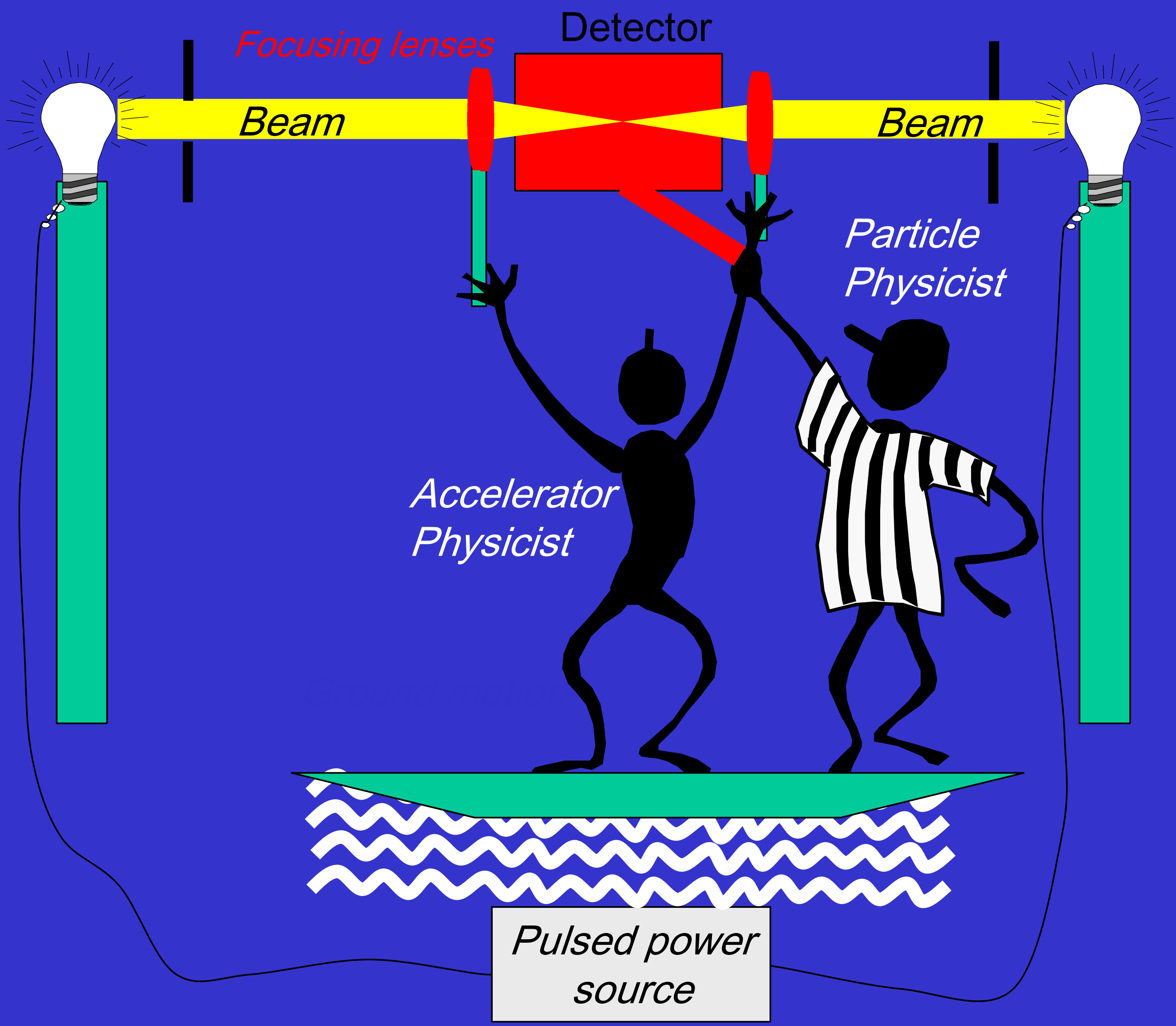
We can tune it up, though it might be ugly!

100 μm

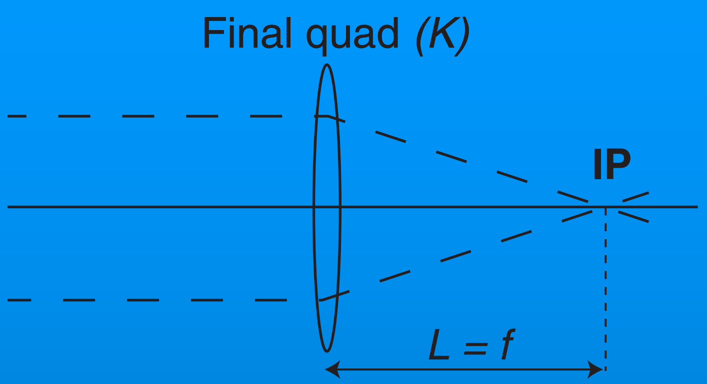
R&D topic 4: Colliding nanometer size beams



Poor Physicist's Final-Focus Experiment: Understanding the challenge!



Tolerances on displacement final quadrupole



$$\begin{pmatrix} y_{\rm IP} \\ y'_{\rm IP} \end{pmatrix} = \begin{pmatrix} 1 & f \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ -K\Delta y_{\rm FF} \end{pmatrix}$$

$$= \begin{pmatrix} -fK\Delta y_{\rm FF} \\ -K\Delta y_{\rm FF} \end{pmatrix} \approx \begin{pmatrix} -\Delta y_{\rm FF} \\ -K\Delta y_{\rm FF} \end{pmatrix}$$

$$\Rightarrow \Delta y_{\rm IP} \approx \Delta y_{\rm Quad,FF}$$

Spot size 1 nm ⇒ Final quadrupole should move less

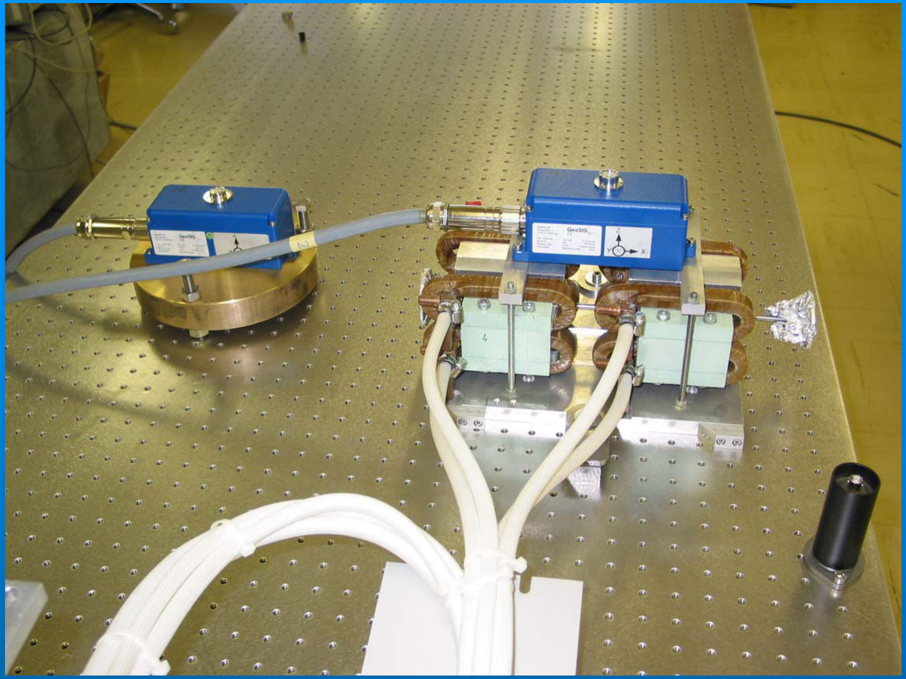
E.g. 30 % tolerance

$$\Delta y_{\rm IP} \lesssim 0.3 {\rm nm}$$

We must worry about **sub-nanometer movements** of magnetic elements!

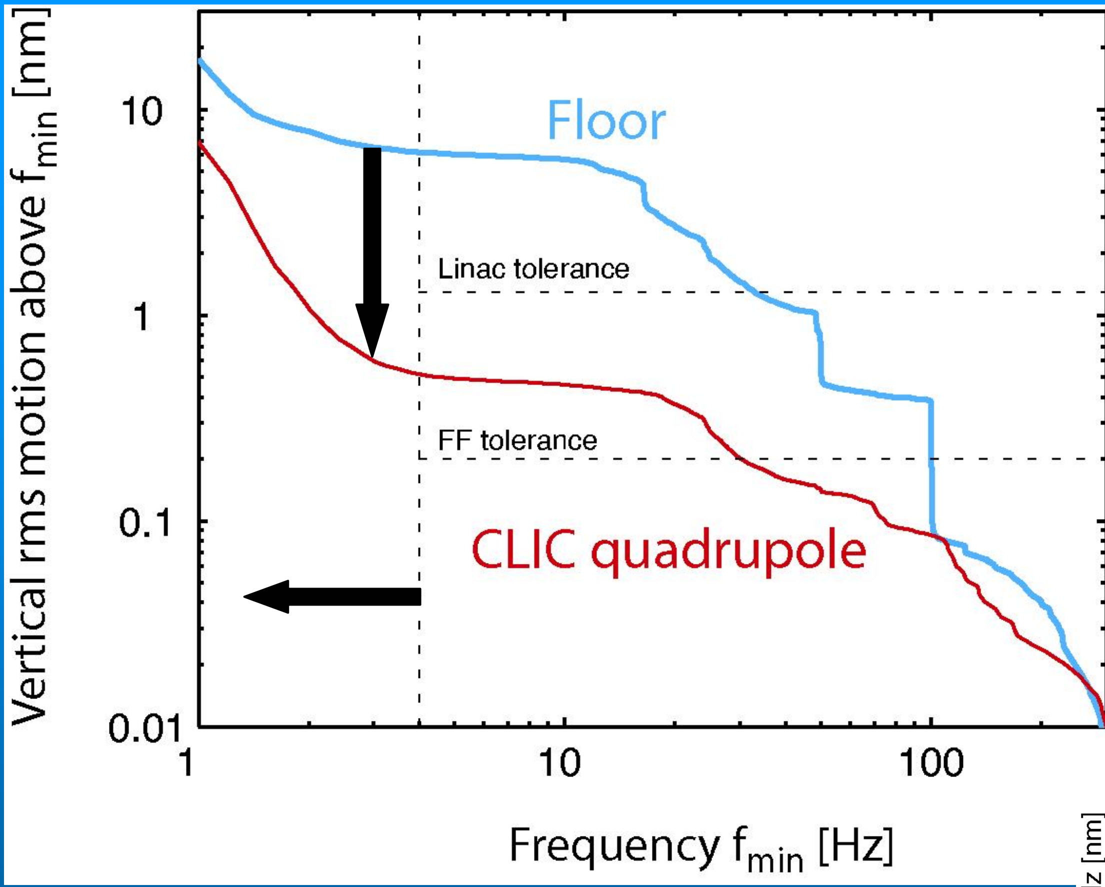
The human hand can feel vibrations of 1 μm or more…

Latest stabilization technology applied to the accelerator field
(passive and active vibration damping in 6D with rubber and piezos)



Experimental set-up in the CERN-CLIC vibration test stand in Building 169.

On the table: One of the most stable places on the Earth!

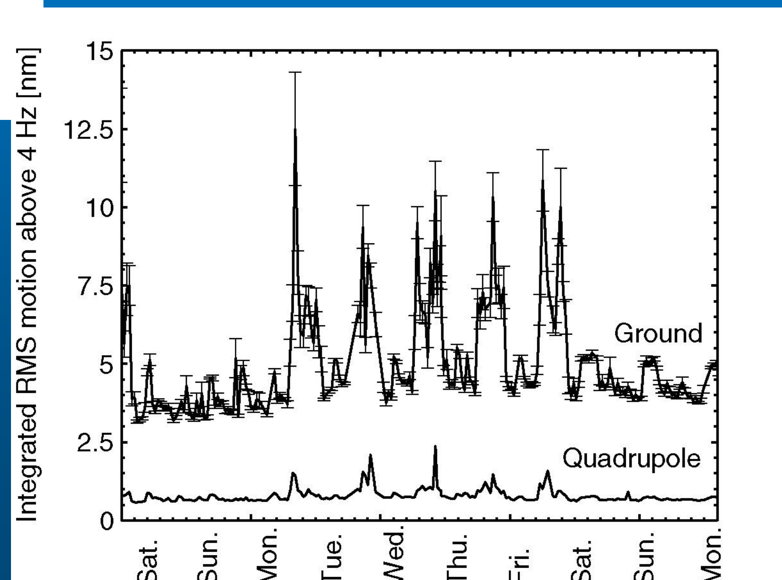


CLIC tolerances indicated

1 nm

CLIC stability study team

Monitoring over 9 days:



Big step towards believing that **colliding nanobeams** (CLIC) are feasible!

R&D topics not discussed in detail

Beam sources (electron, positrons)

Polarization of particle beams

Emittance reduction in damping rings

Instabilities in damping rings

Beam-based feedbacks

Collimation (removal of beam tails)

Background control

Beam-beam effects

Luminosity spectra

Advanced beam diagnostics

Advanced computer simulations

Contents

Reminder: Particle accelerators

The energy frontier for particle physics

The need for high energy
The need for high "luminosity"
Big science and the Livingston plot

Requirements for a future collider

Energy issues (strong acceleration)
Luminosity issues (nanometer size beams)
What is the right technology?

The CLIC study at CERN (basics)

R&D issues

Getting the accelerating field
Generating 30GHz power
Maintain nanometer size beams
Collide nanometer size beams

Outlook into the future

Outlook into the future

CERN has a **viable R&D activity** for the future beyond the LHC. CLIC is "CERN's dream for the future"…

The **Compact Linear Collider CLIC** is the most ambitious linear collider proposal world-wide (energy frontier and high event rate).

Innovative technological solutions have been proposed and are being demonstrated. Universities and students are involved.

Available R&D resources at CERN are concentrating on proving viability of **"fundamental" CLIC technology**.

R&D activities of most urgent concerns (accelerating field, power generation, generation of small beam, collision of nanometer size beams, …) have been discussed. **Results are very encouraging**.

Fundamental R&D is done now in order to be able to bring CLIC on its way in 10 years or so.

The end