Challenges in Future Linear Colliders

Swapan Chattopadhyay
Jefferson Lab, USA

and

Kaoru Yokoya,
KEK, Japan

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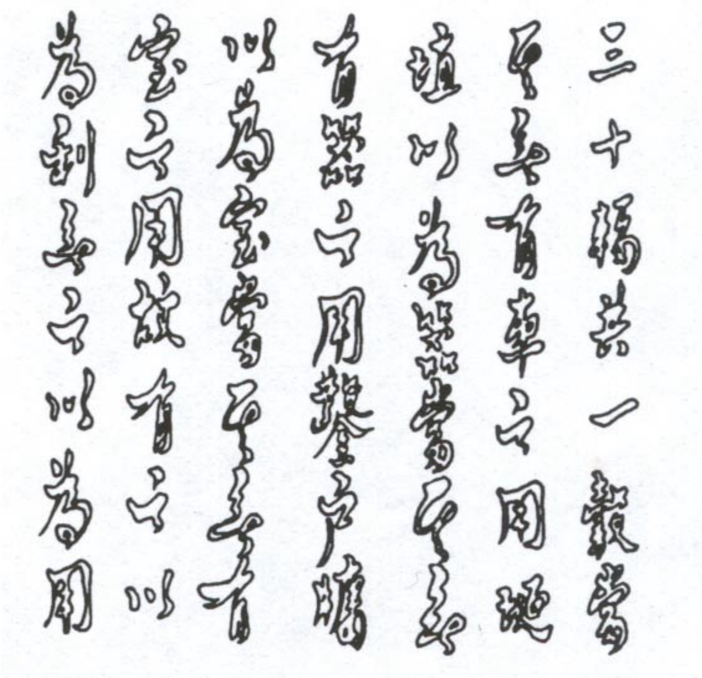
Why LC (Linear Collider) ?

- p-p (proton-proton) colliders can reach higher energy than e^+e^-, but
  - The energies of the constituents (quarks) are lower
  - p-p interaction is too complicated – not easy to analyze the collision data
- e^+e^- colliders are cleaner
- p-p and e^+e^- are complementary
  - Particle discovery by p-p colliders
  - Finer study by e^+e^- colliders

⇒LHC would be “gainful” in <u>discovery</u>!

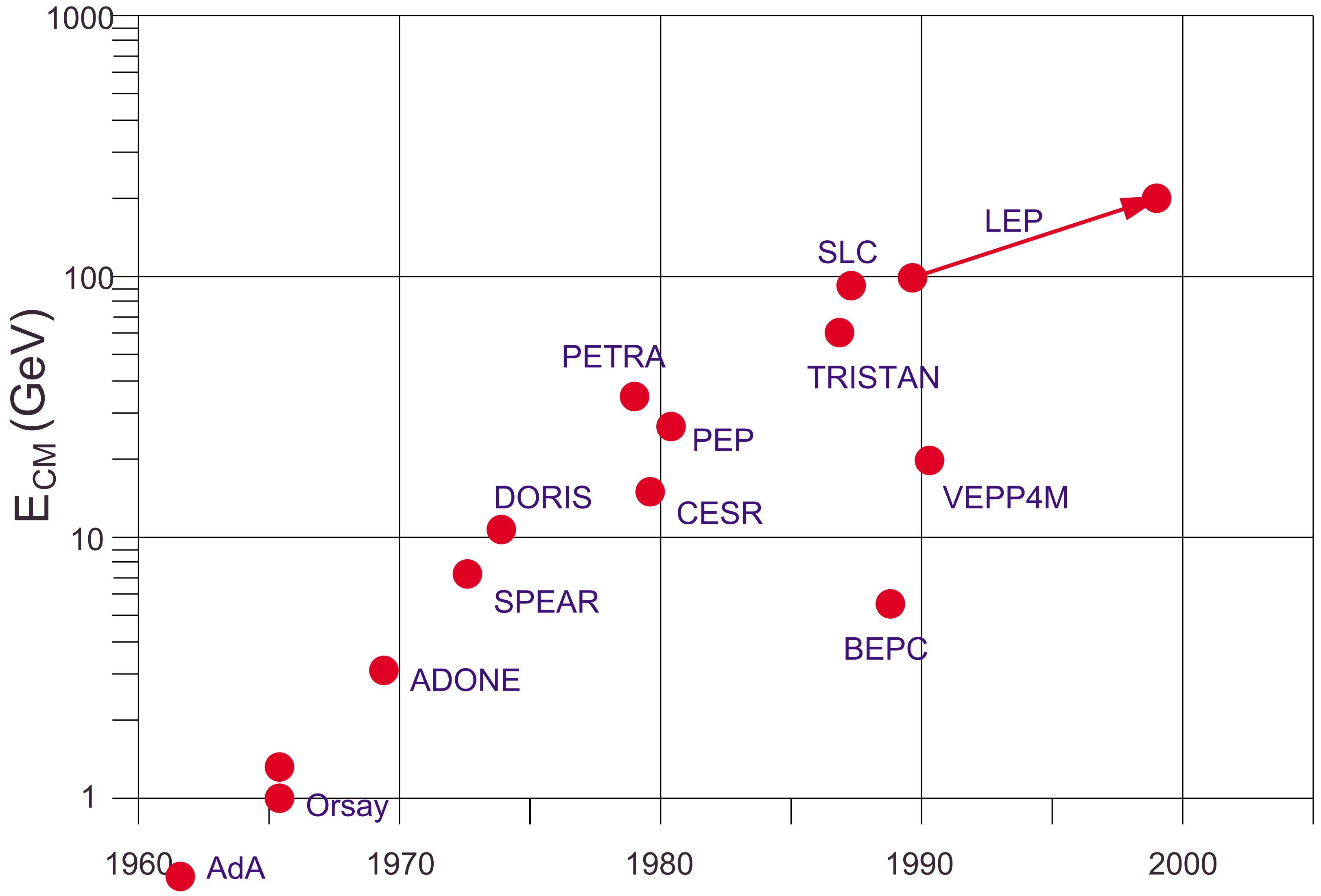
⇒LC would be “useful” in <u>understanding</u>!



"Thirty spokes unite at the wheel's hub;
It is the center hole [literally, "from their not being"]
that makes it useful.
Shape clay into a vessel;
It is the space within that makes it useful.
Cut out doors and windows for a room;
It is the holes which make it useful.
Therefore profit comes from what is there;
Usefulness from what is not there."

\- Lao-tzu

e^+e^- Collider's in the World



LEP

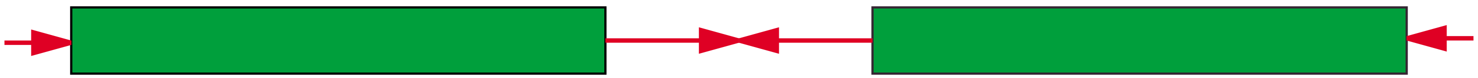
- The largest e+e- collider **LEP** at CERN reached about 200GeV
- High energy electron on circular orbit looses energy by synchrotron radiation
- The energy loss in one turn is proportional to

$$\frac{(\text{beam energy})^{4}}{(\text{radius})}$$

- → impossible to build higher energy e+e- ring
- → straight collider

What is Linear Collider

- Use 2 linear accelerators

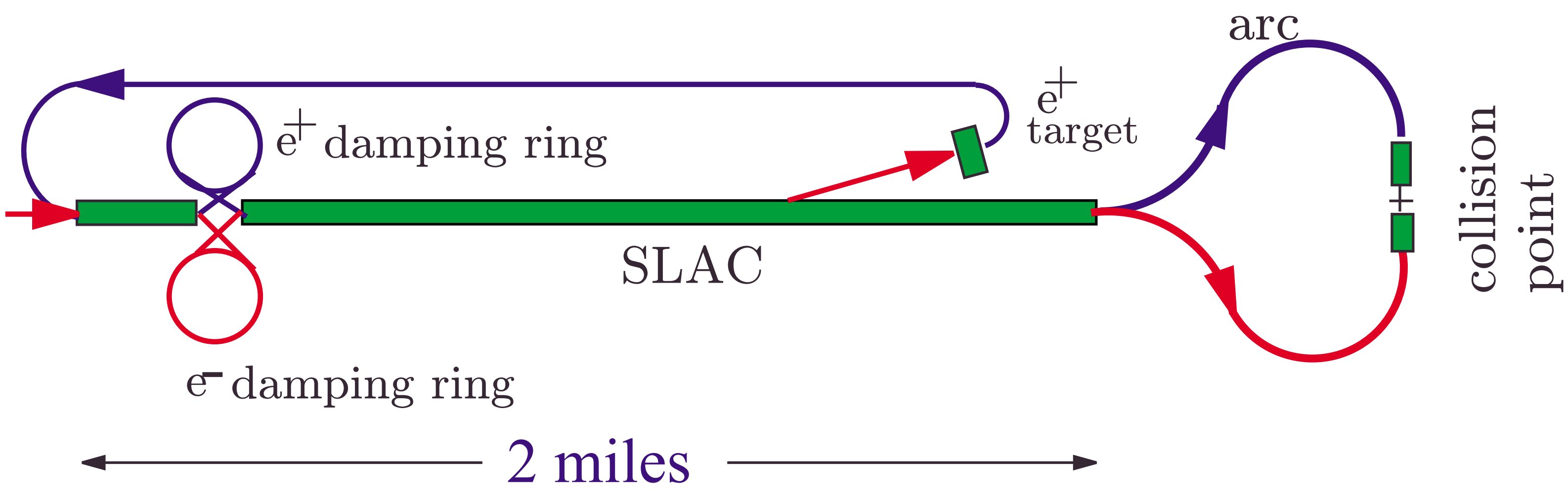


- Throwaway beam
- Repeat
  - beam generation
  - acceleration
  - collision

  quickly

The First Linear Collider SLC

(Stanford Linear Collider)



- Use only 1 (existing) linac
- 2 single-pass arcs
- Up to 50+50=100 GeV

SLC

Accelerator Physics Issues in NLC

- Two issues:
  - – Energy (rf technology)
  - – Luminosity (small spot and beam power)

- Small spot sizes:
  - – Low emittance damping rings
  - – Final focus system
  - – Alignment and jitter tolerances
  - – Beam-based alignment and feedback

- Beam power (long bunch trains):
  - – Charge from sources
  - – Long-range wakefields
  - – Radiation damage

- Both issues: (very high charge densities)
  - – Damping ring instabilities
  - – Beam collimation and machine protection

Luminosity: only few x 10^4 larger than SLC!

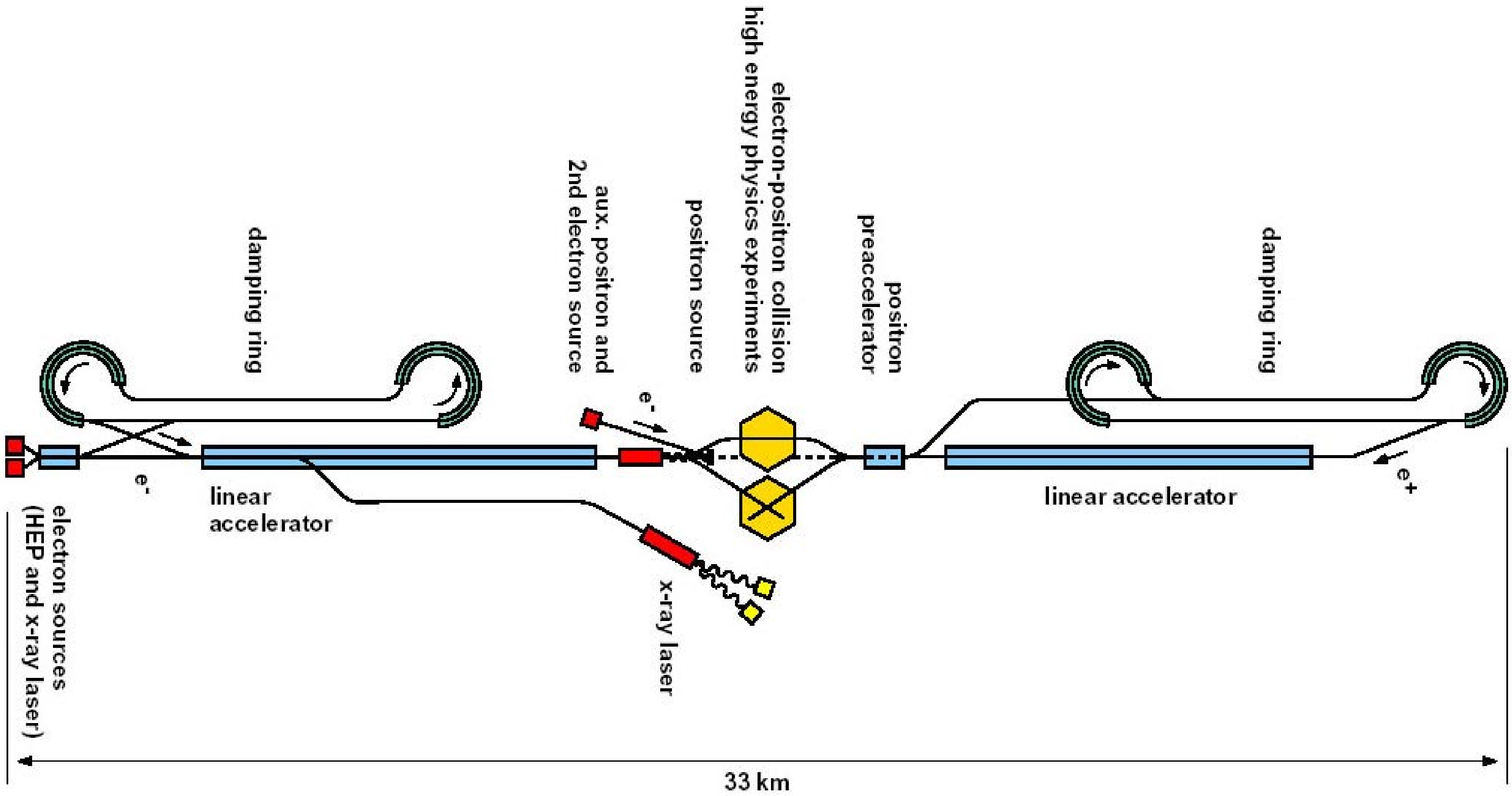
$$L = \frac{f_{rep}}{4\pi} \frac{n_b N^2}{\sigma_x \sigma_y} H_D \quad \Rightarrow \quad L = \frac{2P_b}{4\pi \, E_{cms}} \frac{N}{\sigma_x \sigma_y} H_D$$

- Increased beam power from long bunch trains
  - SLC: 120 Hz x 1 bunch @ 3.5×10^{10}
  - NLC: 120 Hz x 190 bunches @ 0.75×10^{10} → 200x
  - TESLA: 5 Hz x 2820 bunches @ 2.0×10^{10} → 340x
  - Control of long-range wakefields is essential to assure multi-bunch
- Larger beam cross-sectional densities: N / (σ_x σ_y)
  - SLC: 3.5×10^{10} x 1.6 μm x 0.7 μm(FFTB: 0.6×10^{10} x 1.7 μm x 0.06 μm)
  - NLC: 0.75×10^{10} x 250 nm x 3.0 nm → 330x SLC
  - TESLA: 2.0×10^{10} x 550 nm x 5 nm → 230x SLC
  - Factor of 5 from energy (adiabatic damping) and factor of 10 from stronger focusing (similar to Final Focus Test Beam) but higher energy
  - Factor of 15 ~ 30 from decrease in beam emittance!

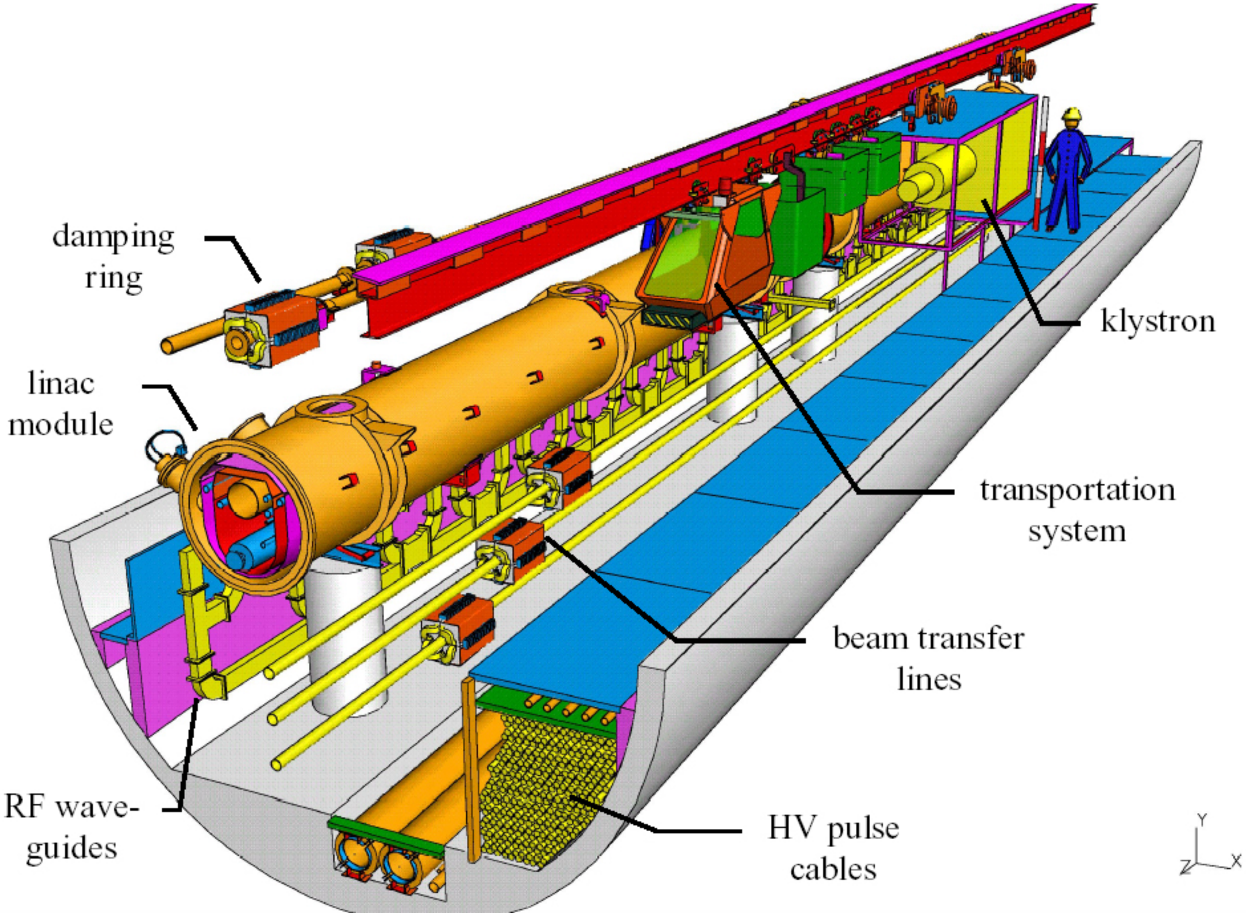
Competing Projects of the Next LC

- JLC/NLC (Japan/USA)
  - Use normal-conducting cavity
  - Aim at up to 1TeV or 1.5TeV
- TESLA (Germany)
  - Use super-conducting cavity
  - Aim at up to 0.8TeV
- CLIC (Europe)
  - Aim at higher energies (> 3TeV)
  - Use long drive beam

Layout of TESLA

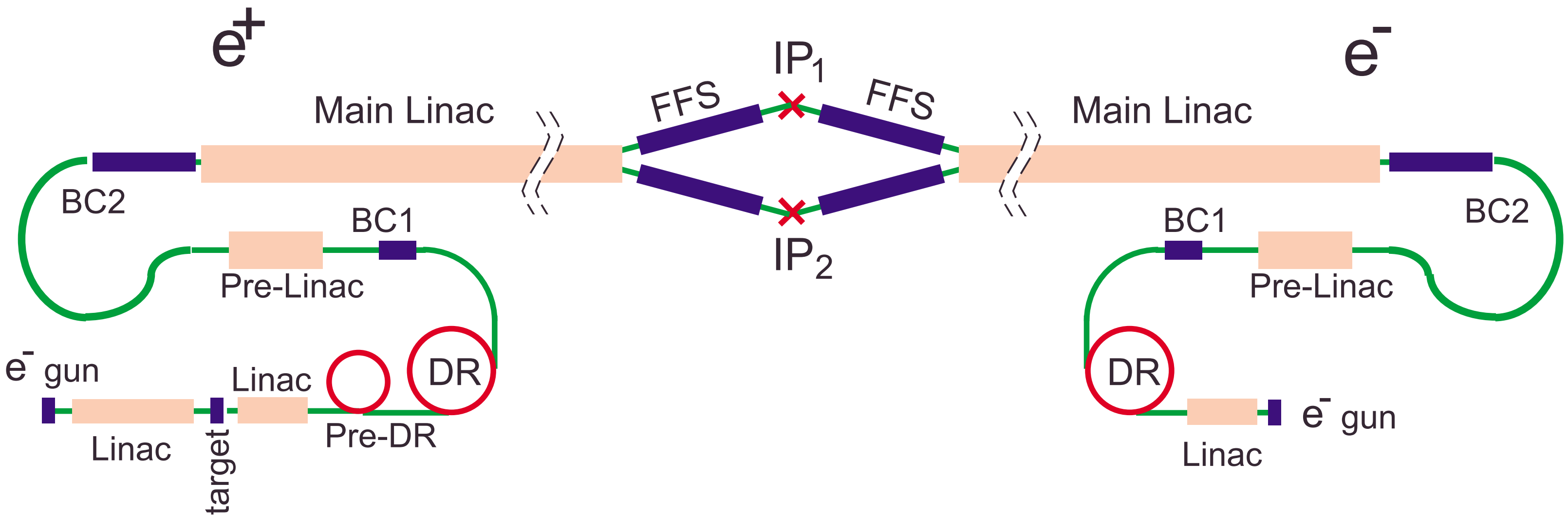


From TESLA Technical Design Report



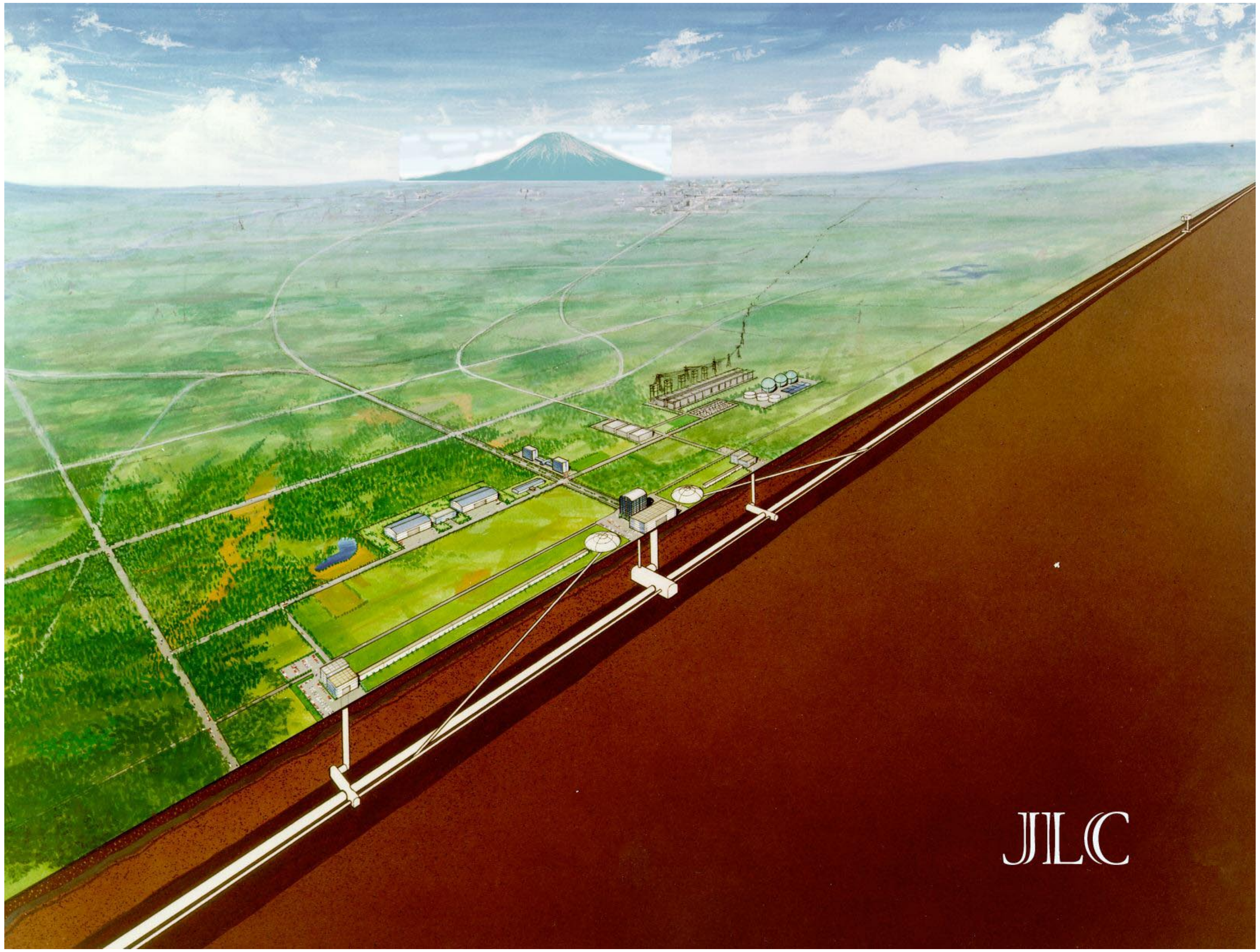
From TESLA Technical Design Report

JLC/NLC



e+
e-
Main Linac
FFS
IP1
FFS
Main Linac
BC2
BC1
Pre-Linac
IP2
BC1
Pre-Linac
BC2
e- gun
Linac
DR
DR
Linac
target
Pre-DR
e- gun
Linac

JLC artist's impression



High Quality Beams, Why?

What we really want is Particle-Particle Collision

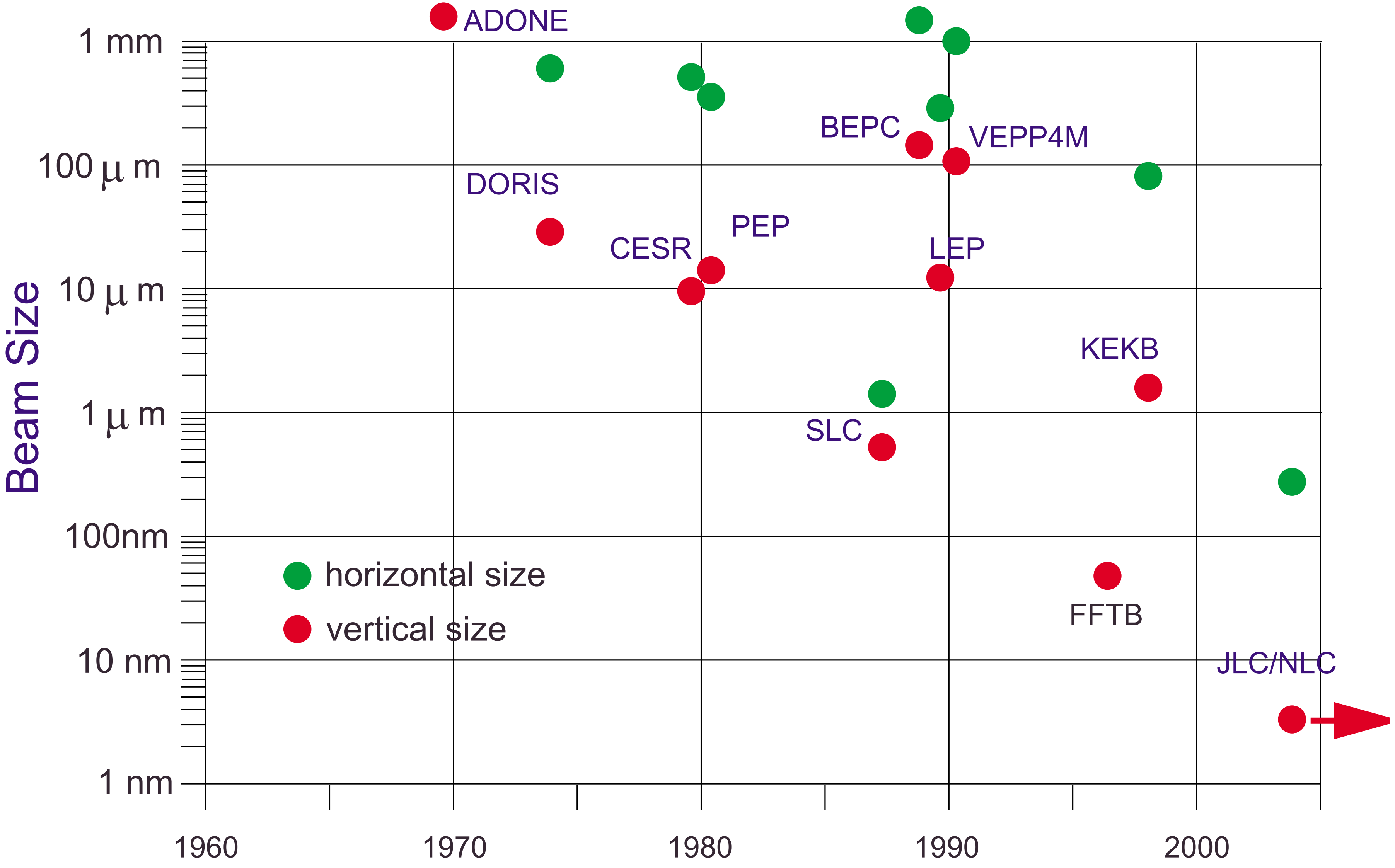
Not a Beam-Beam Collision

100 times smaller area

→ 100 times more Particle-particle collision

→ 100 year experiment → 1 year experiment

History of Beam Size in e^+e^- Colliders



Creating High Quality Beams

•Electrons loose energy

by synchrotron radiation

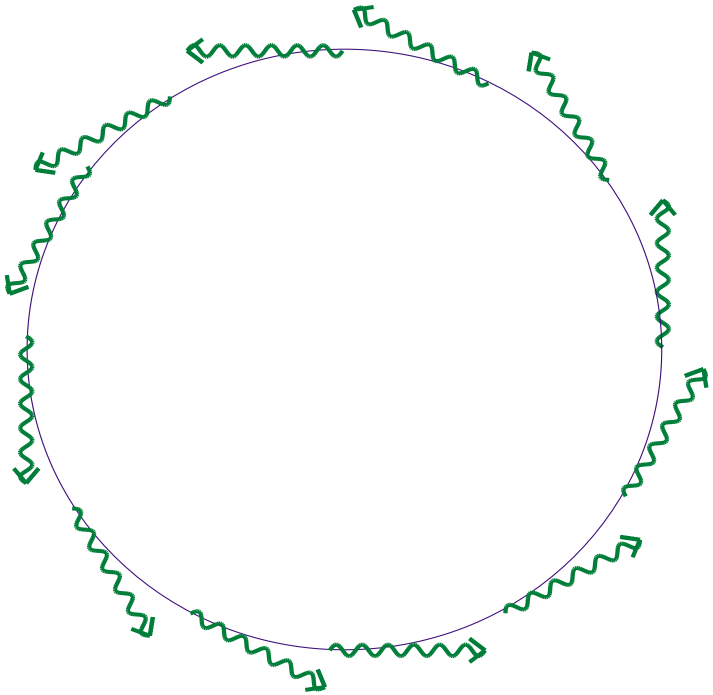
•Beam becomes small

in this process

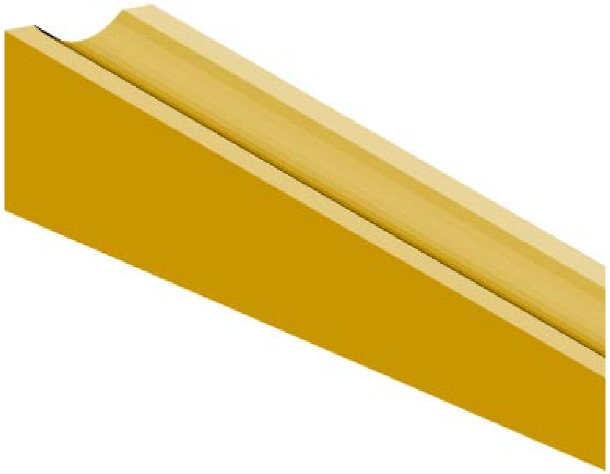
•World smallest beam

obtained at KEK-ATF

(Accelerator Test Facility)

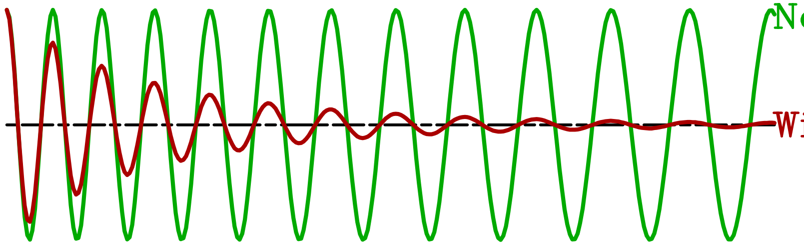


Synchrotron Radiation



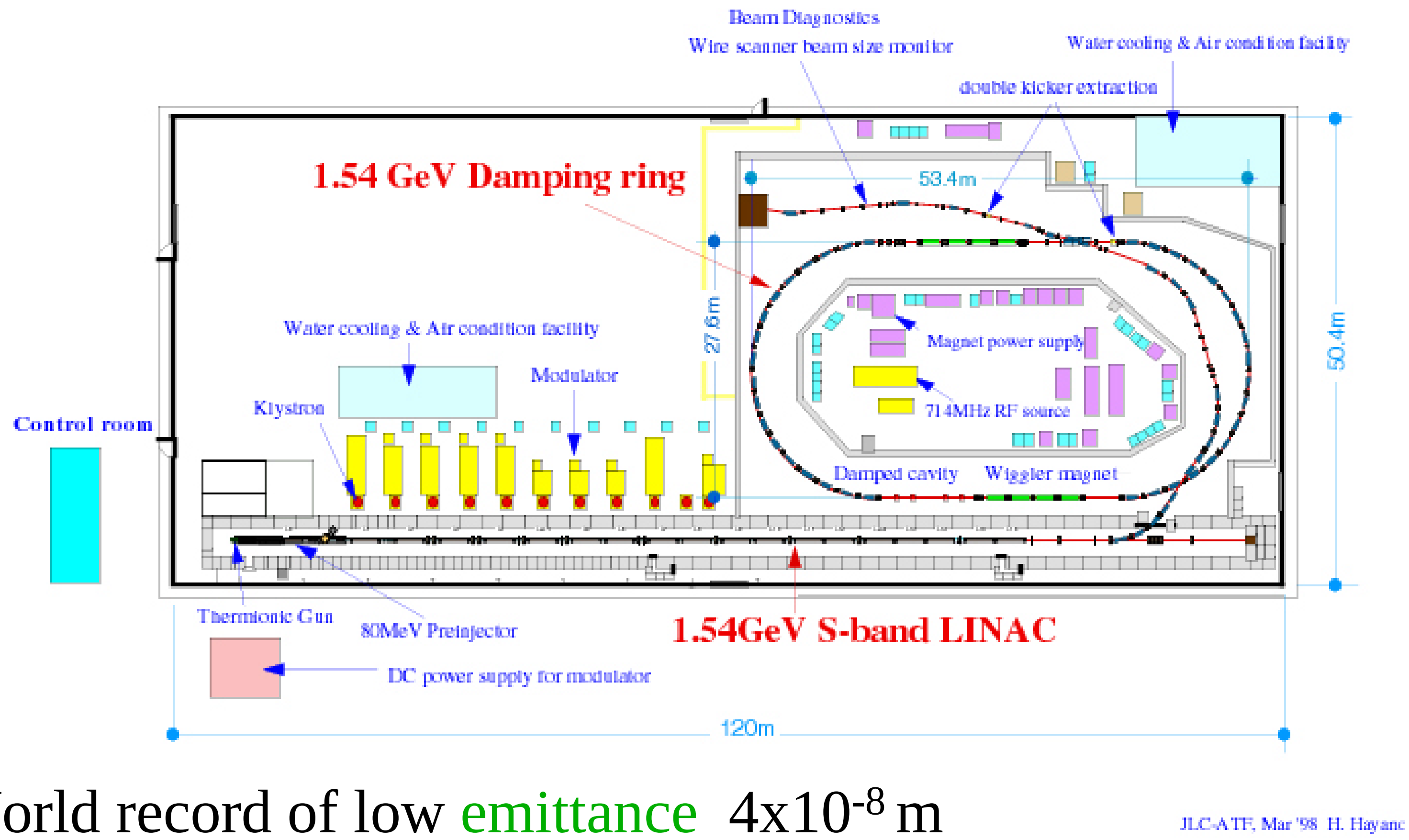
Synchrotron radiation works as friction

Get a high quality beam in less than a second



Lowest Emittance Achieved

Accelerator Test Facility for JLC



World record of low emittance 4×10^{-8} m

(almost what we need for next LC)

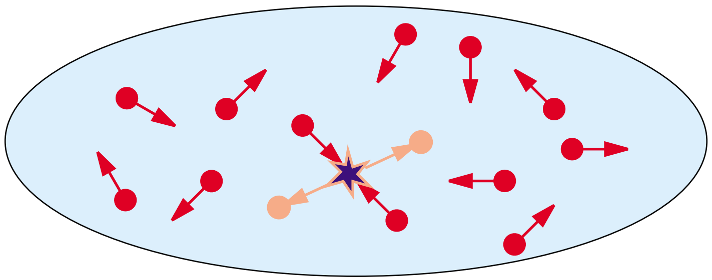
KEK-ATF Damping Ring

Deleterious Processes

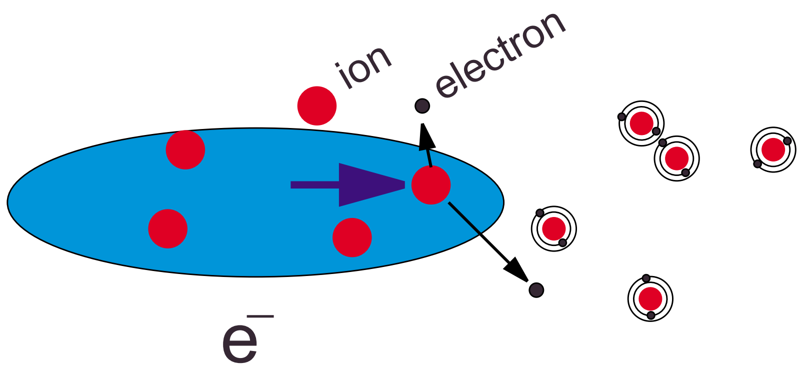
Many problems are awaiting

since we aim at extremely high quality

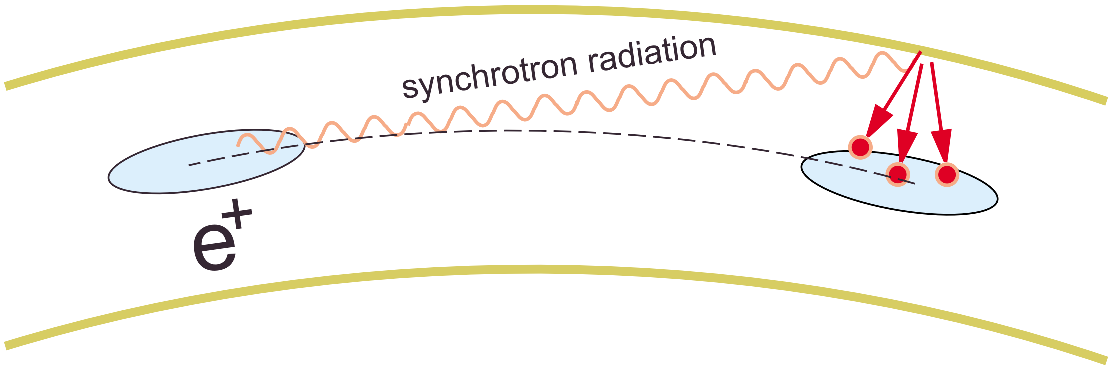
Intrabeam scattering



Fast ion instability



Electron cloud instability



We believe

we know how to manage

Acceleration of High Quality Beams

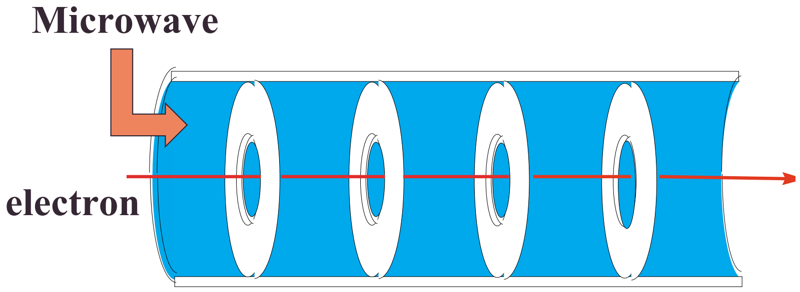
•Use Linear Accelerator

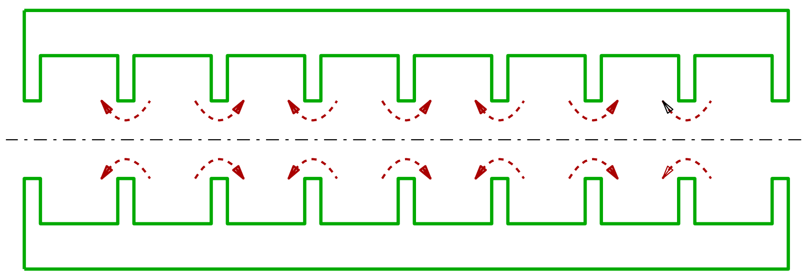
(Linac)

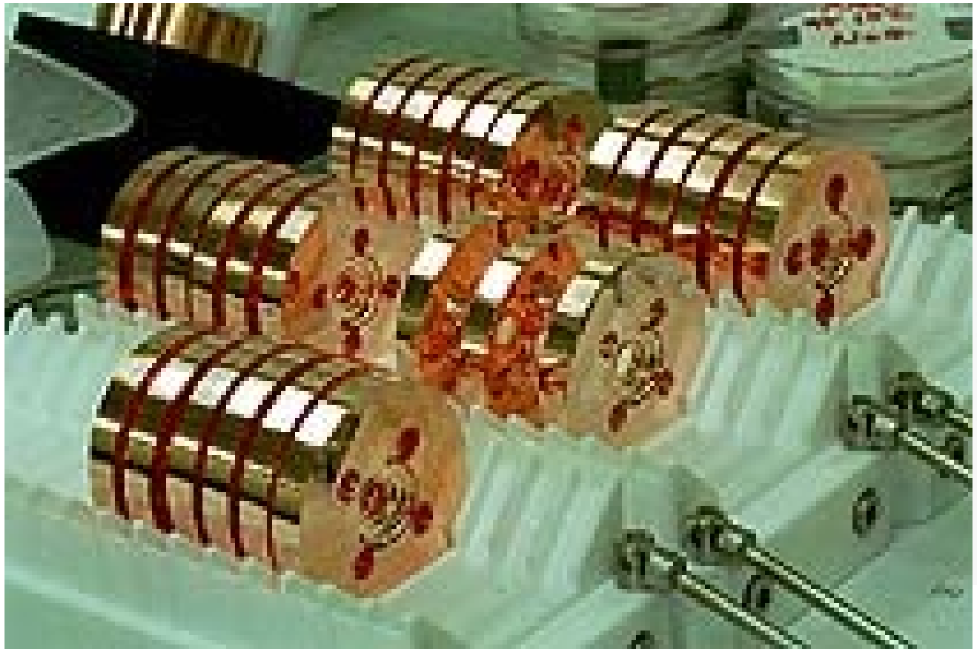
•Accelerate by Microwave

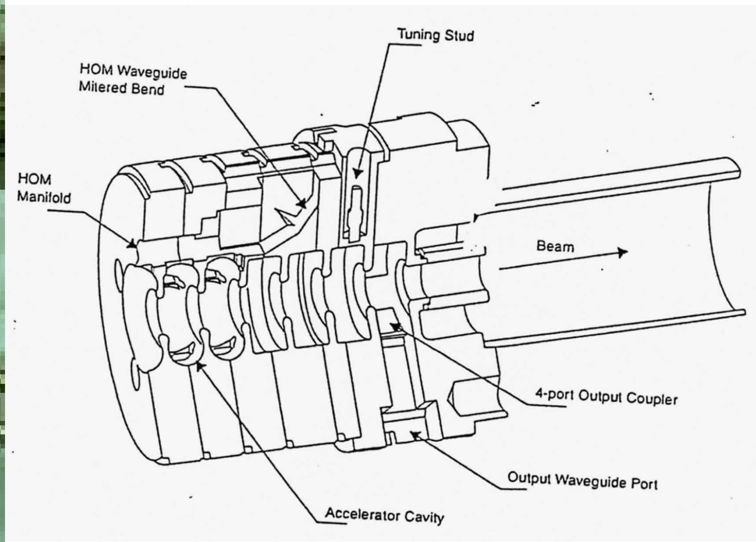
frequency 11.4 GHz

wavelength 26mm









Inner surface accurate to 1μm

Must be aligned straight within 10μm

Guiding the Beam

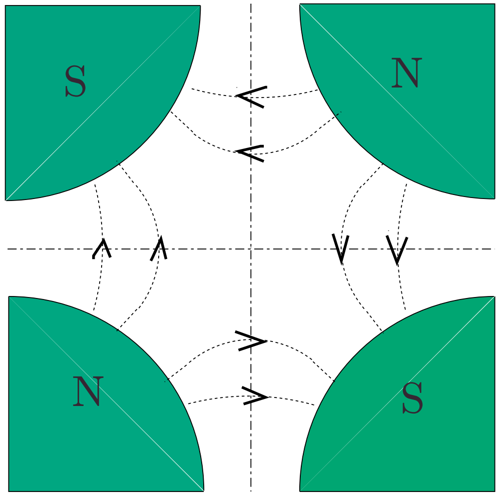
•Use magnet: Well-known technology since many, many years ago

•But

- •10nm vibration can cause miss-collision
- •500nm shift can make the beam fat
- •Ground is moving

→ Computer control of magnet position

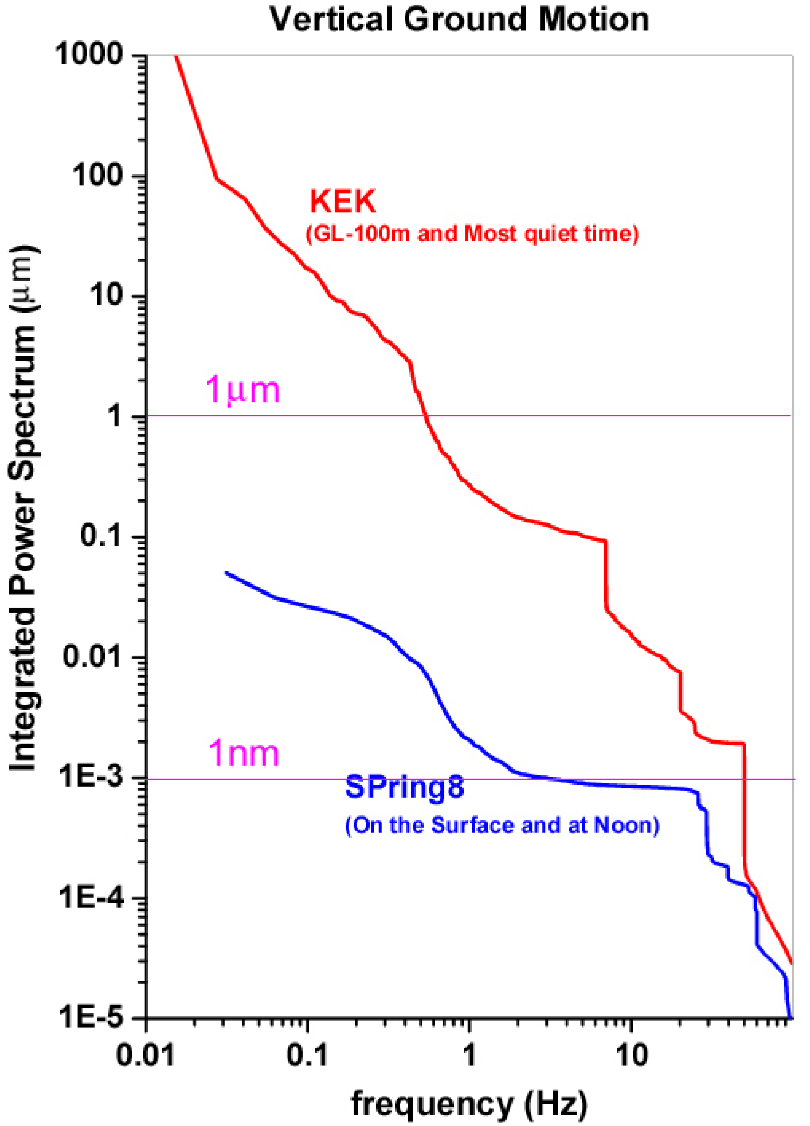
Quadrupole Magnet



Ground Motion

Ground is moving

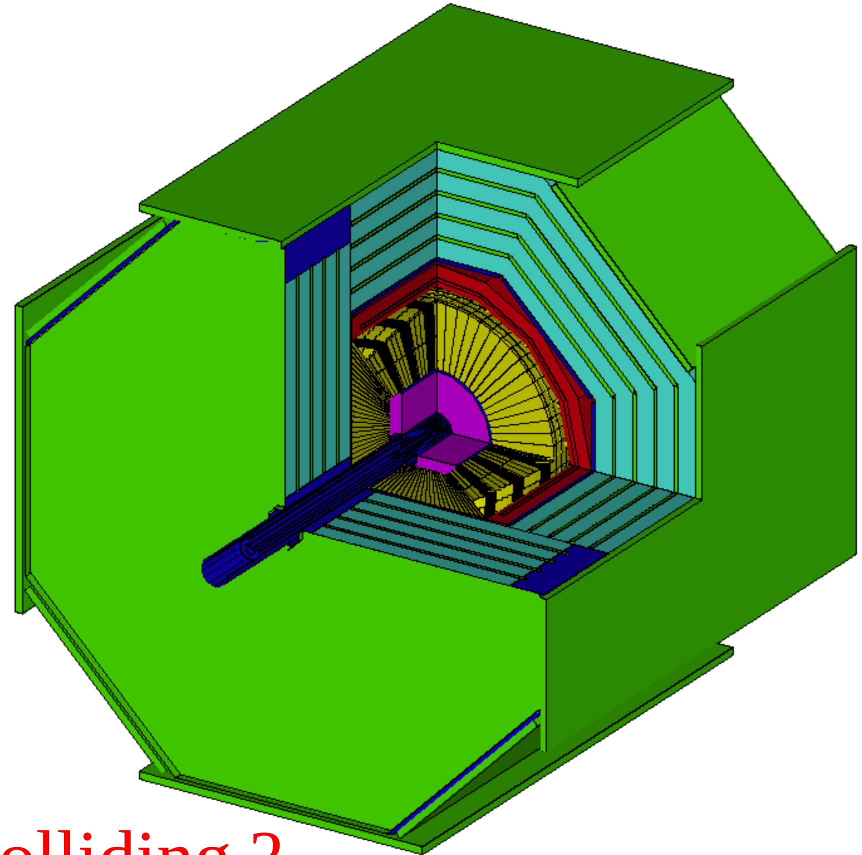
- We cannot stop the ground
- But instead
  we can steer the beam
- Faster ground motion
  is harder to correct



S.Takeda, H.Matsumoto, S.Matsui, K.Togawa and H.Yoshioka

Collide Tiny Beams

Beam size at collision point



•100 µm long

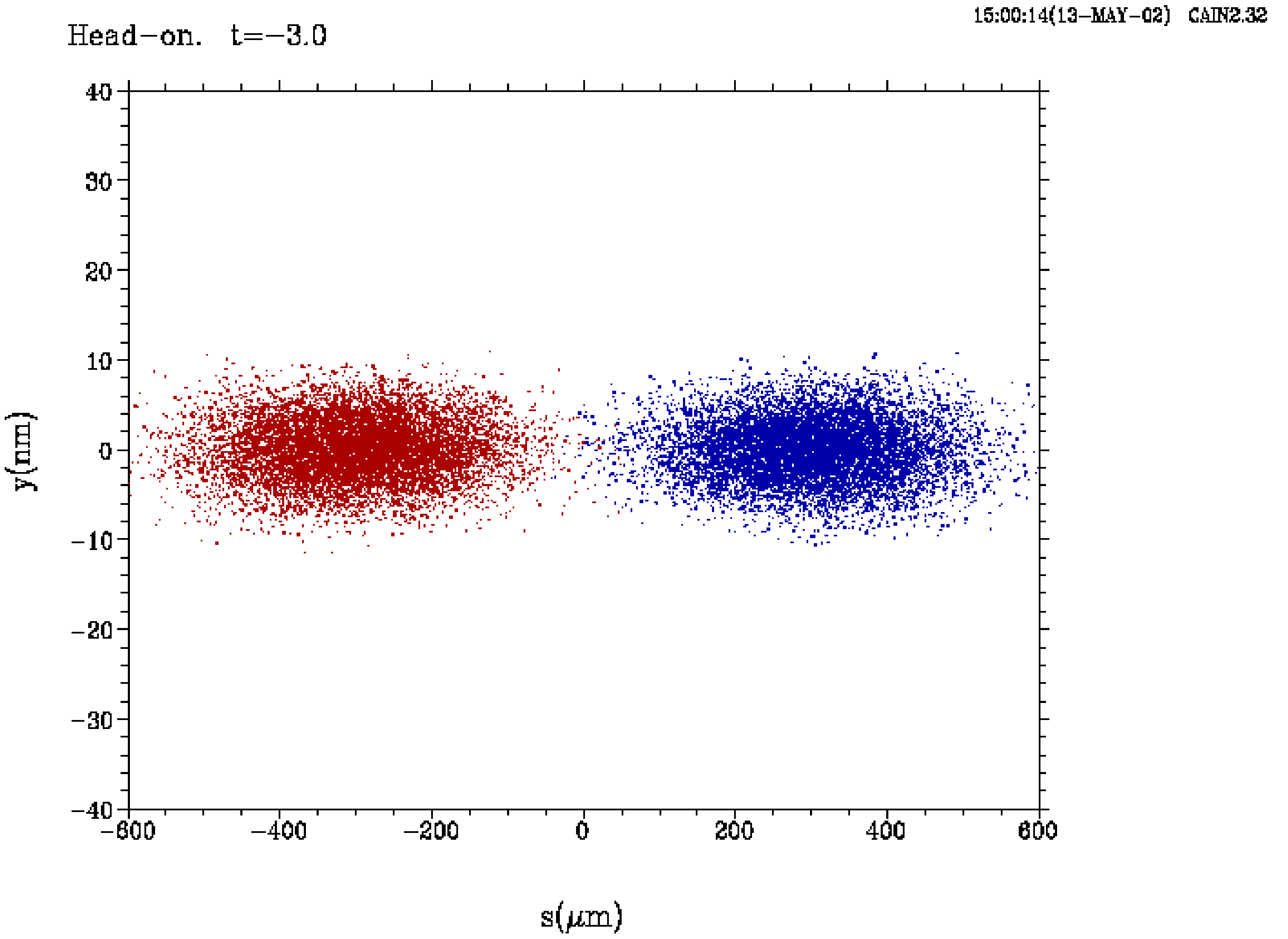
•0.3 µm wide

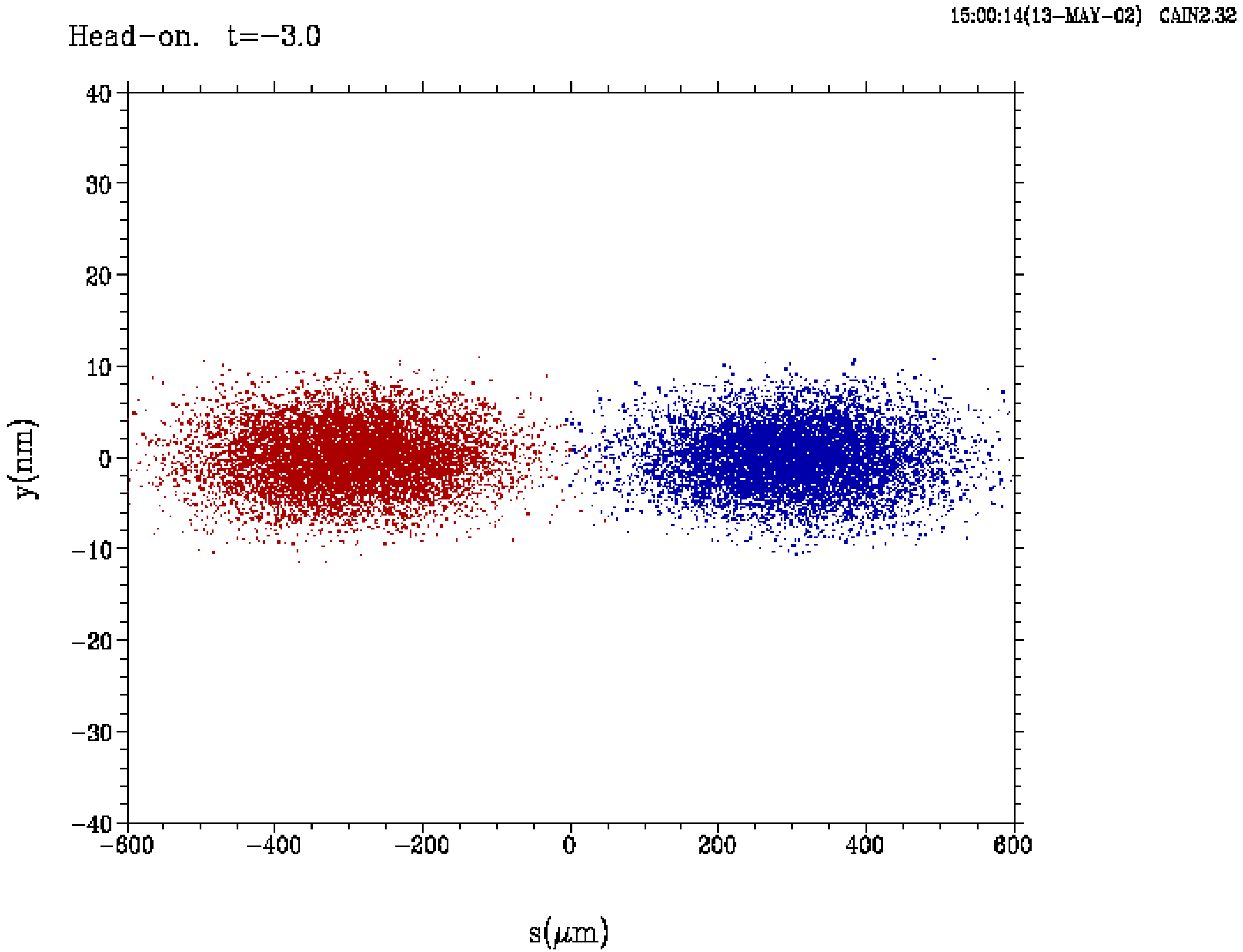
•0.003 µm (3 nm) thick

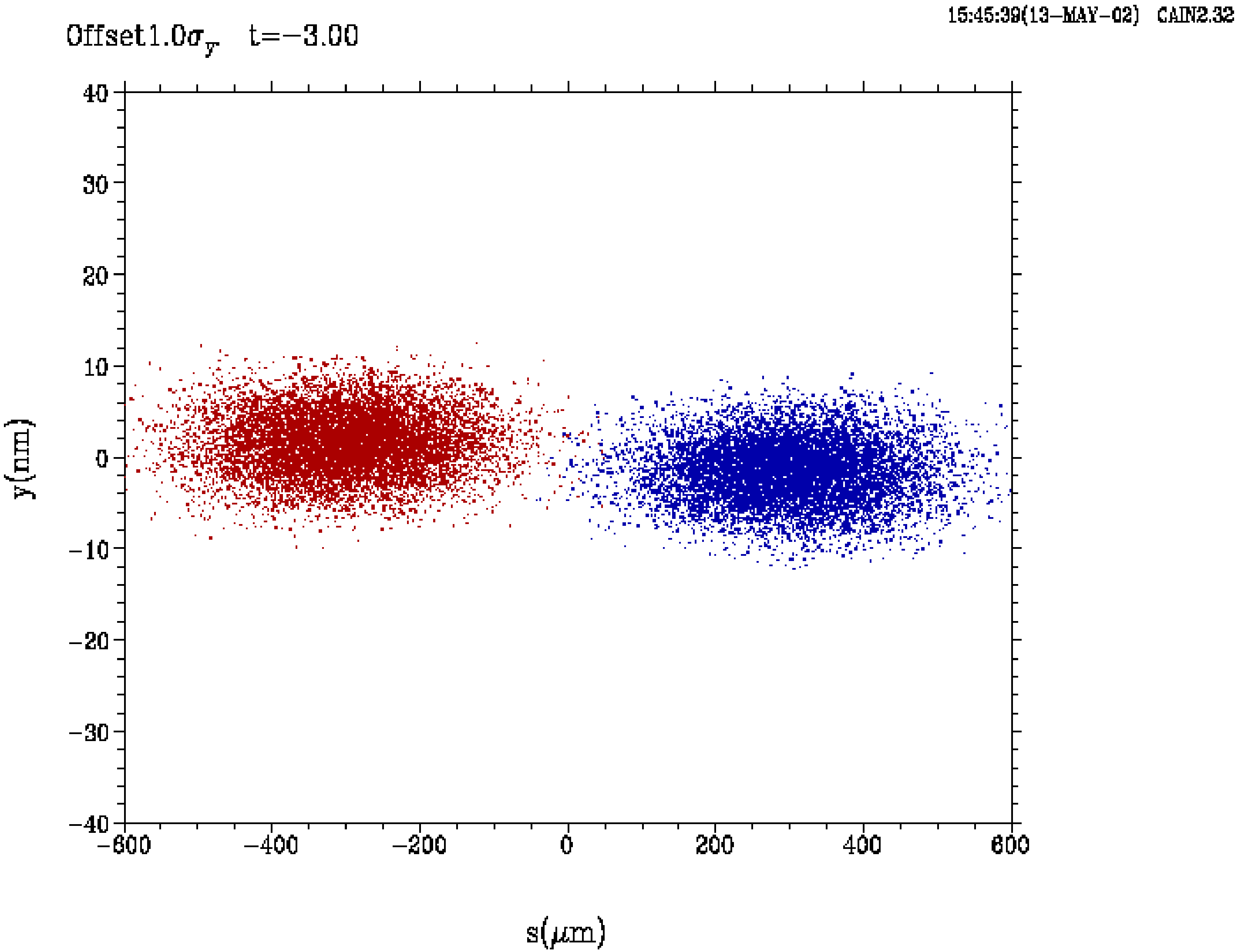
(These are RMS values)

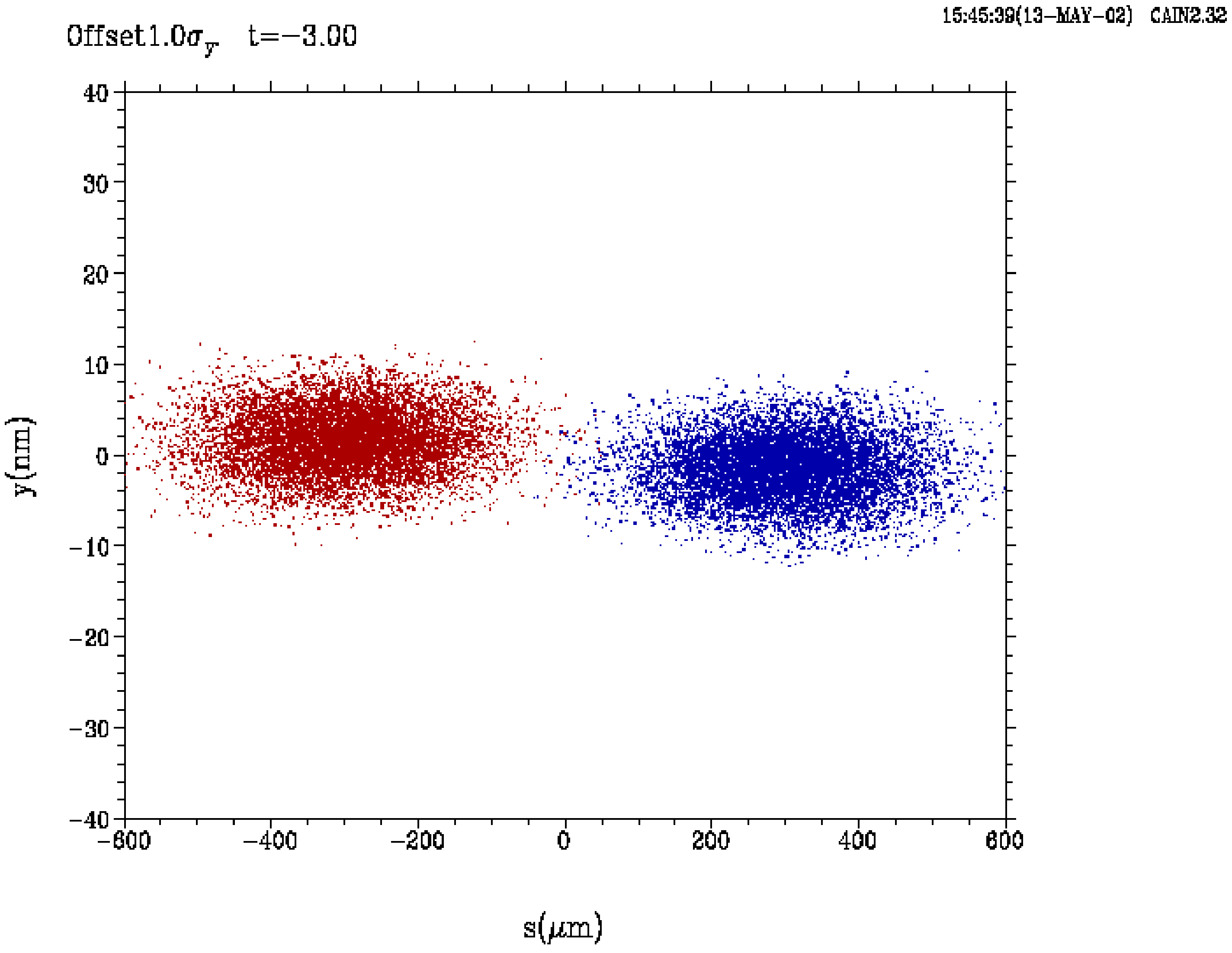
How can you keep them colliding ?

Beam-Beam Simulation

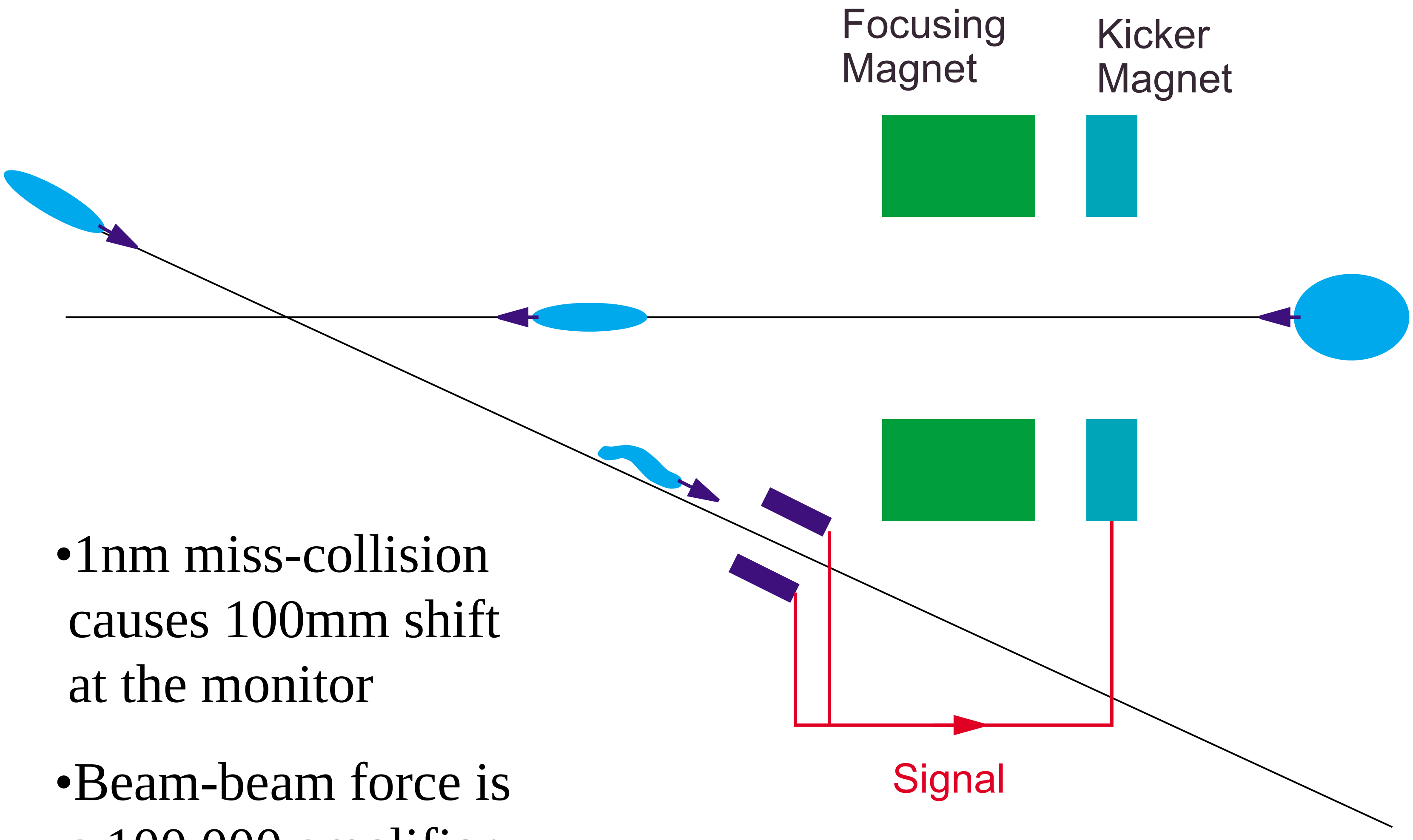



15:00:14(13-MAY-02) CAIN2.32
Head-on. t=-3.0
40
30
20
10
0
-10
-20
-30
-40
-600
-400
-200
0
200
400
600
y(nm)
s(μm)


15:45:39(13-MAY-02) CAIN2.32
Offset1.0σ_y t=-3.00
y(nm)
s(μm)
40
30
20
10
0
-10
-20
-30
-40
-600
-400
-200
0
200
400
600


Offset1.0σ_y t=−3.00
15:45:39(13−MAY−02) CAIN2.32
40
30
20
10
0
−10
−20
−30
−40
y(nm)
−600
−400
−200
0
200
400
600
s(μm)

Feedback System



•1nm miss-collision causes 100mm shift at the monitor

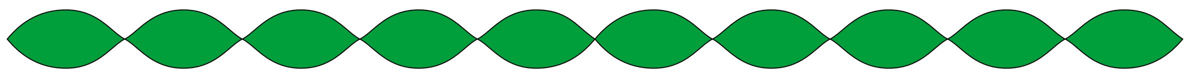
•Beam-beam force is a 100,000 amplifier

How do you know it’s really small?

How can we measure the size of a beam
which is running at speed of light ?

Interference of 2 laser waves

Can create a pattern like



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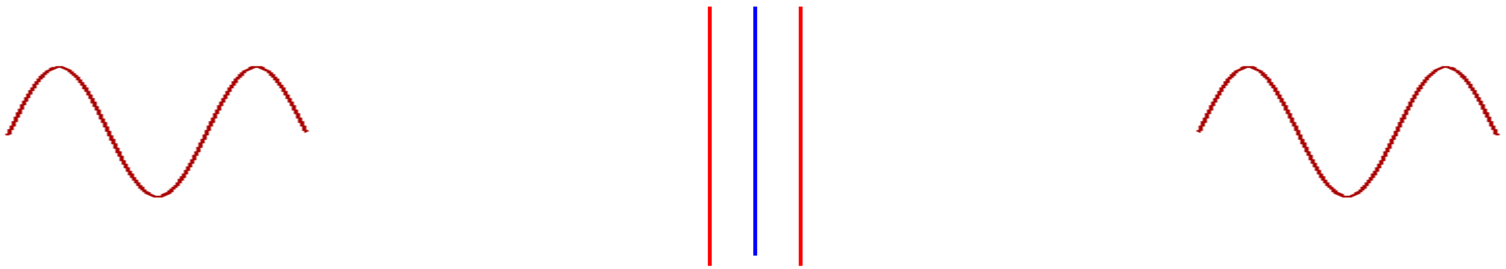
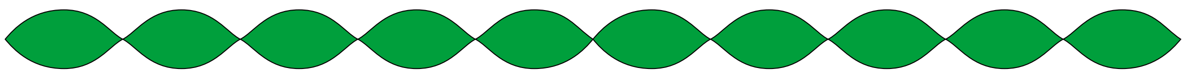


Can create a pattern like



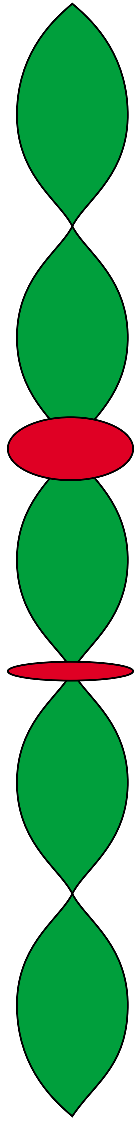
Monitoring Scheme

When an electron beam comes to the node,

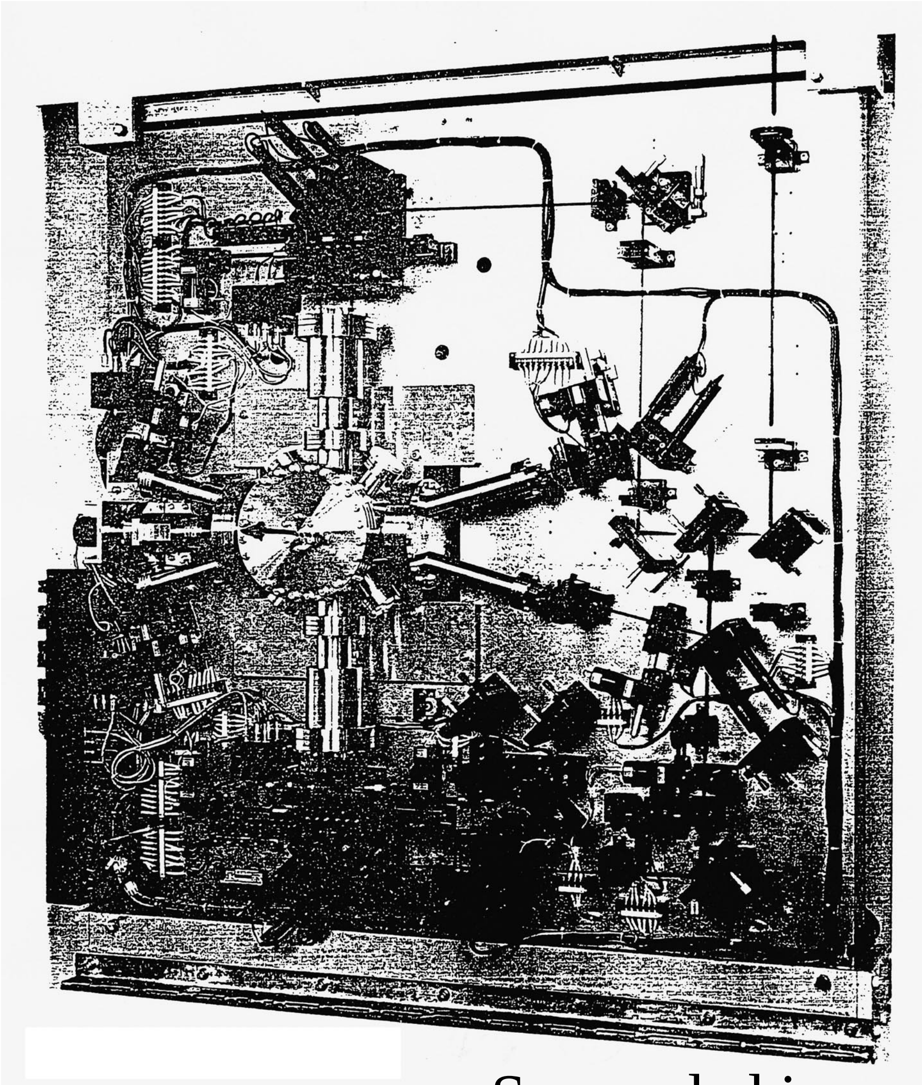
- If the beam is very thin,
  almost no interaction with laser.
- But if the beam is fat,
  many high energy photons come out.

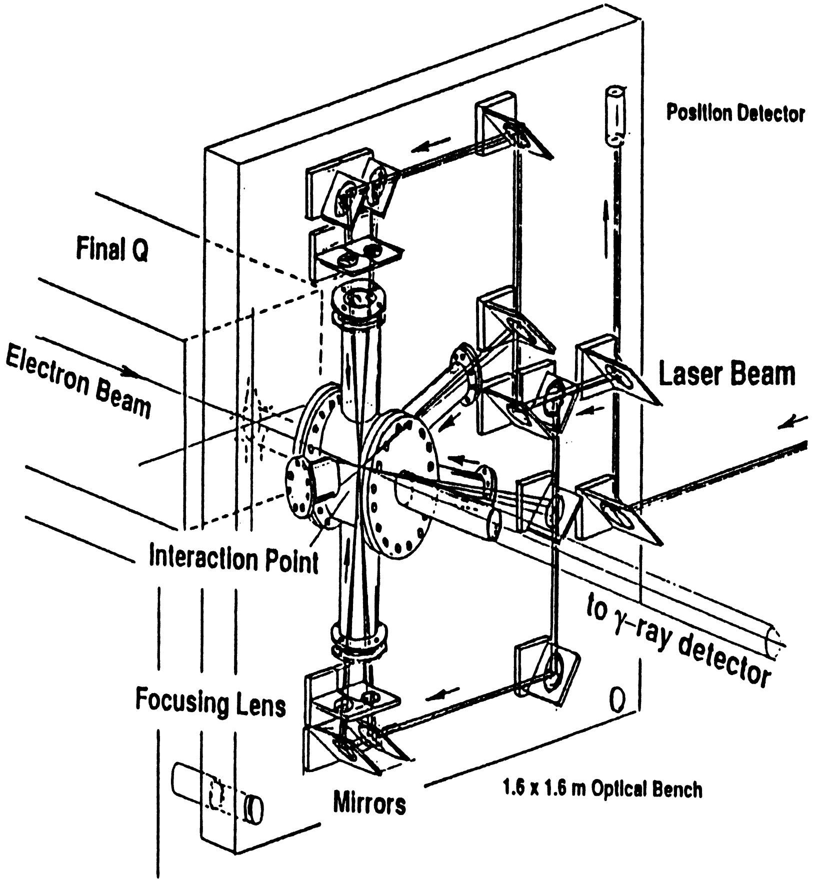
$e + \gamma\ (\text{laser}) \rightarrow e + \gamma\ (\text{high energy})$

(Compton scattering)



FFTB Nanometer Monitor





Succeeded in measuring 50nm beam at FFTB

Other Monitoring Schemes

Using a shorter-wavelength laser,
we can measure down to 10nm but not less

How can we measure 1nm?

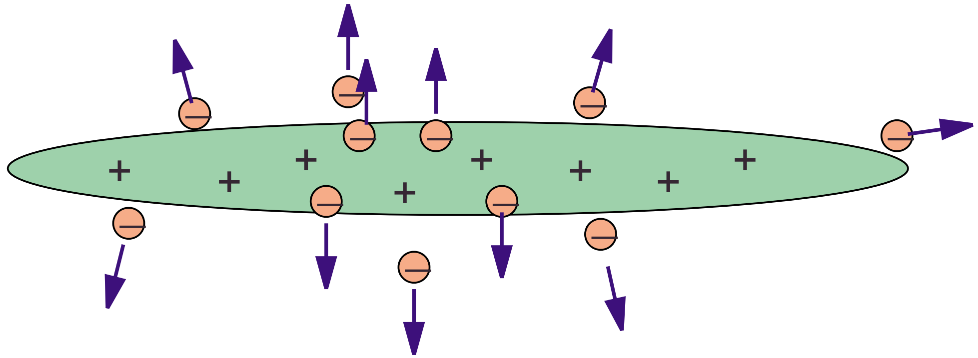
•Many low-energy debris (electron and positron) are created during collision

•They are annoying for experiments

•But are useful for measuring the beam size

They are bent vertically

If the beam is very flat



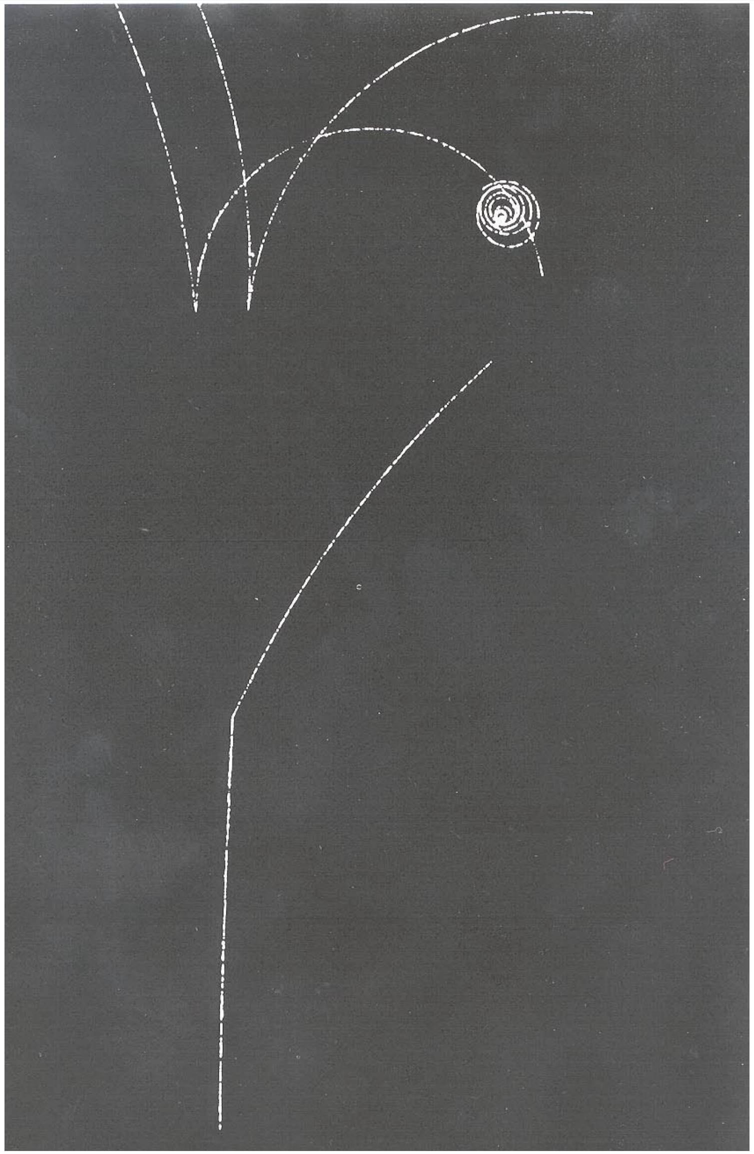
Experimental test needed

Outlook

⇒ **Where to we go from here??**

⇒ **Need further simplification to reduce complexity.**

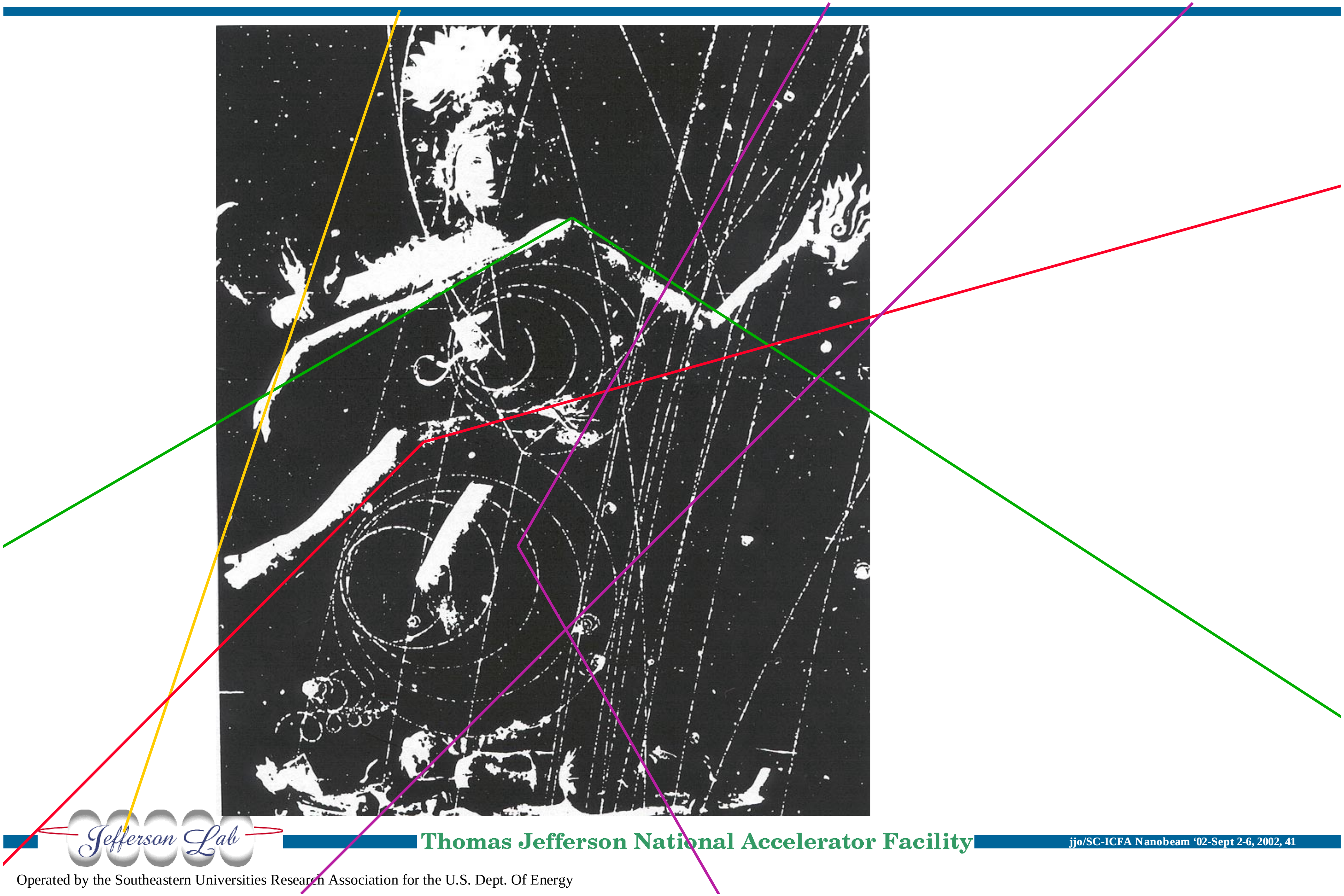
Emptiness and Form



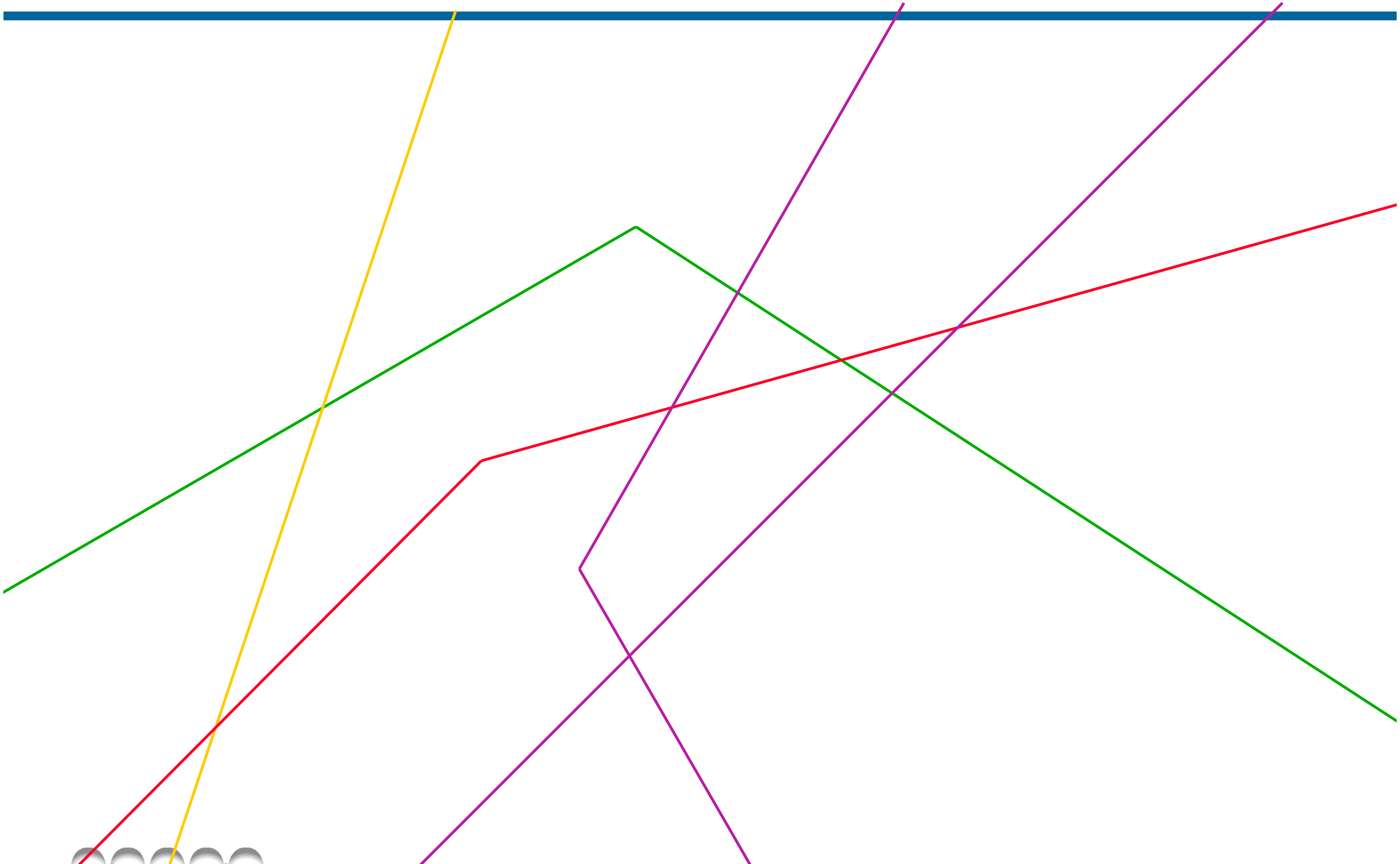
Fluctuating concepts give "emptiness" form.

Further contemplation yields complex design and form

Slowly, “simplicity” emerges as patterns and symmetries



Ultimately all that's left are abstracted simplicities



Challenges

- **Technical**
  - **Simplify design further e.g. TESLA damping rings**
  - **Reduce cost: do we need damping rings?**

    ⇒R&D on sources
- **Socio-economic and Political:**
  - **Reduce ambition: energy and luminosity**
  - **If ~$1B – one country can host**
  - **If ~several B$ – international collaboration with several countries**
  - **Learn how to collaborate globally**