The Eloisatron Project:
Physics at the Energy Frontier

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Some ideas about circular accelerators

- Beam dynamics – motion of particle under the influence
  - Of external fields
  - Of the interaction of the particles with the electromagnetic environment created by other particles

- The *ideal particle* has zero amplitude motion on a closed orbit along the axis of the synchrotron

- Beam particles will not have identical orbital positions & velocities

- In practice, they make transverse oscillatory motion set by radial restoring forces
Integer Resonances

- Tune is the number of oscillations that a particle makes about the ideal trajectory
- Imperfections in dipole guide fields perturb the particle orbits
  - Can be caused by off-axis quadrupoles
- Unbounded displacement if the perturbation is periodic
- The motion is periodic when
  \[ mQ_x + nQ_y = r \]
  \[ M, n, & r \] are small integers
Tune shifts & spreads

- Causes of tune shifts
  - Field errors
  - Intensity dependent forces
    - Space charge
    - Beam-beam effects

- Causes of tune spread
  - Dispersion
  - Non-linear fields
    - Sextupoles
  - Intensity dependent forces
    - Space charge
    - Beam-beam effects
At the IP currents cancel; but the space charges add $\Rightarrow$ the IP is a “lens”

i.e., it adds a gradient error to the lattice, $(k_{\text{space charge}}\Delta s)$

where $(k_{\text{space charge}}\Delta s)$ is the kick ("spring constant’’) of the space charge force

Therefore the tune shift is

$$\Delta Q = -\frac{1}{4\pi} \beta^*(s)(k\Delta s)$$

For a Gaussian beam, the space charge kick gives

$$\Delta Q \approx \frac{r_e \beta^* N}{2\gamma A_{\text{int}}}$$
Early steps toward ELN have lasting impact

- 1976 - International School of Accelerator Physics at Erice
  - Directly led to establishing the USPAS and the CERN School
  
  \textit{Result: Blossoming of education in accelerator science}

- 1979 - Superconducting Cyclotron Project resumed
  - 1981 Start of the CS construction (Ansaldo-LMI-Zanon)

  \textit{Result: Cyclotrons remain a strong tool for discovery physics}

- 1981 - HERA Project is presented to the INFN Council
  - Critical insight: Involve industrial labs very early in the R&D
  - 1985 Begin construction in Italy of prototype superconducting magnets for HERA
  - 1988 Complete construction of the HERA magnets

  \textit{Result: Industry plays a critical role in magnet R&D}
The ELN Project
Thirty years ago: (1984-1988)

INFN finances ELOISATRON (ELN) Project

- Full Scale ELOISATRON PROJECT:
  - 1st step - Conceptual Design Report (Kjell Johnson)
  - 2nd - R&D in fundamental technologies
  - 3rd - Construction of long (15 m) superconducting magnets

- 1989 Start model magnet construction for 10% ELN
  
  *By 1992 feasibility of LHC magnets was demonstrated*

- 1991, 1992 ELN conceptual design workshop 1
  
  *Feedback systems from ALS can scale to 100 TeV protons*

- 1991, 1992 ELN conceptual design workshop 1 & 2
  
  *No fundamental obstacle to 200 TeV collider at 10^{35} \text{ cm}^{-2}\text{s}^{-1}*

- 1995, 1999 ELN workshops on magnets beyond the LHC
  
  *Inspired the 2001 US multi-lab study of VLHC*
“Authentic innovations stem from the discovery of new, fundamental Laws of Nature.”
- “This is a field where Italy has engaged its intellectual forces.”

“It is not a wise idea to wait for new ideas”
- It takes a long time to transform new ideas into reality
  - 25 years from SC magnets to the Tevatron

Do not start to build a new Laboratory if the work needed can be carried out within existing structures

Involve Industry in the implementation of the project.
Key technological insights in ELN project

- We know how to build a proton synchrotron for 100 TeV
- Invest in R&D to learn how to build an adequate detector
  - Hermeticity is important
- Build a large tunnel (300 km)
  - Minimize the magnet & vacuum challenges
  - Minimize costs
  - Maximize the potential of the facility
- Devote equal effort to experimental set-ups & to machine construction

Focused engineering development is no substitute for innovative R&D

ELN - 300 km (1985)

A. Zichichi, The Superworld II - 1990
Fast-forward to the present

Then move forward to the future
Proton-proton colliders
Technology options

- Unlike $e^+e^-$, there are no new concepts for $p-p$ machines
  - They are proton synchrotrons, with the major variables being circumference and luminosity

- The world stage will be dominated by the LHC and its high luminosity upgrade (HL-LHC) for the next two decades.

Source: M. Breidenbach & W. Barletta
“If there is a desert, it is a desert of our imagination” - Nino

Accelerator-based physics: Origin of Mass, Beyond Standard Model (BSM), Superworld

Astrophysics: BSM physics, The Dark Universe

Relic radiation: Neutrino astronomy, quantum gravity
ELN => decades of forefront particle physics

- Large interest worldwide in a 100-TeV-class pp collider
  - Interest in any LHC energy upgrade depends on results from Run-II & on developing practical magnet technology at ≥16 T

- A new collider should be a large advance beyond LHC
  - The last big tunnel
  - Multi-step scenarios are the most realistic
  - Eventually 50 to >100 TeV per beam

- Discovery potential far surpasses that of lepton colliders
  - Much higher energy plus high luminosity
  - The only sure way to the next energy scale
As long as Standard Model continues to work, “Higher energy is always better” - Zichichi

- What is the cost vs benefit for
  - Higher energy
  - Higher luminosity
  - What is the Energy vs Luminosity tradeoff?

- Physics case studies must generate answers to these questions

- Naturalness arguments push towards higher masses => higher energy
  - Collider energy wins rapidly at higher masses

- Dark Matter, electroweak baryogenesis may relate to physics at lower masses & smaller coupling => high luminosity is more important
  - At 100 TeV, 10x increase in luminosity => 7 TeV increase in mass reach

- For a 100 TeV scale collider, discovery luminosity ~2x10^{35}
  - Studies of high mass particle will need ~10x more luminosity

**Different physics call for different machine optimizations**
“The machine should be designed with the highest possible luminosity & energy” - Nino
“Required” luminosity for a 100 TeV-class discovery machine is a complex issue.

- Lower mass particles (e.g. Higgs) have increasing cross sections with energy
  - Luminosities could be lower than the LHC for these studies.

- Maintaining the same reach high mass particle discovery requires luminosity scaling faster than $s$ because of parton density functions

- For a 100 TeV scale machine, the discovery luminosity is $\sim 2 \times 10^{35}$

- Being able to study a high mass, newly discovered particle may require a luminosity $\sim 10\times$ that required for a $5\sigma$ discovery, i.e. $\sim 10^3$

- Nominal proposed luminosities:
  - SppC: $1.2 \times 10^{35}$
  - FCC: $5 \rightarrow 20 \times 10^{34}$

Source: [Hinchcliffe et.al.; arXiv:1504.06108]
Luminosity in hadron colliders

Source: Plot from Wolfram Fischer
Present view of detector challenges

Detectors need R&D

- Measure all detectable particles over as much of the angular phase space as possible

- Minimize reducible backgrounds from misidentified particles
  - Hermeticity is important

- Enable data-taking in high instantaneous luminosity environment
  - Very large track multiplicity, hundreds of uninteresting events per crossing
  - Total exposure of sensors to radiation flux scales with integrated luminosity & falls off with distance from collision point
    - Radiation damage degrades sensor efficiency & increases noise

- Undetectable particles like neutrinos & Dark Matter can only have their transverse momentum sum inferred
  - Catch all visible momentum; impose transverse momentum conservation
  - Hermeticity is important
What sets the discovery potential of colliders?

1. Beam Energy
   - Determines the energy scale of phenomena to be studied

2. Luminosity $\mathcal{L}$ (collision rate)
   - Determines the production rate of “interesting” events
     
     $$\mathcal{L} = \frac{N_1 \times N_2 \times \text{frequency}}{\text{Overlap Area}} = \frac{N_1 \times N_2 \times f}{4 \times x \times y}$$
     
     - Scale $\mathcal{L}$ as $E^2$ to maximize discovery potential at a given energy
       - Conventional Wisdom: 2x in energy is worth 10x in luminosity

Note: $\mathcal{L}$ changes in time as collisions deplete the bunches

$\Rightarrow$ Luminosity lifetime
Luminosity: The fundamental challenge of the energy frontier

Assume that bunch length, $\sigma_z < \beta^*$ (depth of focus)
Neglect corrections for crossing angle
Set $N_1 = N_2 = N$
Collision frequency $= (\Delta t_{\text{coll}})^{-1} = c/S_{\text{Bunch}}$

$$L = \frac{N^2 c}{4 n S_B} = \frac{1}{\epsilon_i m c^2} \left( \frac{N r_i}{4 n} \right)$$

Collision Efficiency $= \frac{1}{\epsilon_i m c^2} \left( \frac{N r_i}{4 n} \right)$
Beam Power $= \frac{P_{\text{beam}}}{\epsilon_i m c^2} \left( \frac{N r_i}{4 n} \right)$

Other parameters remaining equal
$L_{\text{nat}} \propto \text{Energy} \quad \text{but} \quad L_{\text{required}} \propto (\text{Energy})^2$

“Pain” associated with going to higher energy grows non-linearly

Most “pain” is associated with increasing beam currents.
What drives parameter choices?

- How do we choose $N$, $S_B$, $\beta^*$, and $\varepsilon_n$ as a function of energy?

  - Detector considerations
    - Near zero crossing angle
    - Electronics cycling $\geq 20$ ns between crossings
    - Event resolution $\leq 1$ event/crossing
    - Radiation damage

  - Accelerator physics
    - Tune shifts - keep $N$ small, lower $S_B$, lower $\varepsilon_n$
    - Beam instabilities - keep $N$ small, lower $S_B$, lower $\varepsilon_n$
    - Luminosity lifetimes - raise $N$, raise $\varepsilon_n$
    - Emittance control - raise $N$, raise $\varepsilon_n$
    - Synchrotron radiation handling - Keep $I$ small
    - Radiation damage
Crucial detector issue is coupled to collider design: Bunch spacing vs. event pile-up

Most probable # events per crossing

\[ \langle n \rangle = \frac{L \sigma_{\text{inel}} S_B}{c} \]

Fractional luminosity for \( k \) events per crossing

\[ L_k = L \langle n \rangle^k \frac{\exp(- \langle n \rangle)}{k!} \]

\( \sigma_{\text{inel}} \sim \ln E_{cm} \)

At 200 TeV and \( 2 \times 10^{35} \text{cm}^{-2}\text{s}^{-1} \) we expect \(~600\) events per crossing at 20 MHz
Resetting electronics every 5 ns demands increasing crossing angle of beams

- Minimum bunch spacing is set by filling every rf-bucket
  - BUT, to avoid excessive long rang tune shift, \( \Delta v_{LR} \)
  \[ \Rightarrow \text{larger crossing angle, } \alpha \Rightarrow \text{decreased hermeticity} \]

\[
\Delta_{LR} = \Delta_{HO} 2n_{LR} \left( \frac{\sigma}{\beta^* \alpha} \right)^2
\]

\[
\Delta_{HO} = \frac{N_B r_p}{4 \pi n}
\]

\[
\Delta v_{tot} = N_{IP} \left[ 1 + 2n_{LR} \left( \frac{\sigma}{\beta^* \alpha} \right)^2 \right] \Delta v_{HO}
\]

At 20 ns spacing ~ 10 - 20% effect
Components that limit energy & luminosity

- **Main ring**
  - Dipoles - bend beam in “circle”
  - Feedback - stabilizes beam against instabilities ( \( \sim N_B I \) )
  - Vacuum chamber - keeps atmosphere out
  - Cooling - removes waste heat
  - Beam dumps & aborts - protects machine and detectors

- **Interaction Regions and detectors**
  - Quadrupoles to focus beam
  - Septa to decouple beams electromagnetically
  - Detector to do particle physics (via radiation damage)
Three design strategies for ELN

- Low field (2T), superferric magnets
  - Very large tunnel & very large stored beam energy
  - Minimal influence of synchrotron radiation

- “Medium” field design
  - Large tunnel & large stored beam energy
  - Uses ductile superconductor at 4 - 7 T (RHIC-like)
  - Some luminosity enhancement from radiation damping

- High field magnets with brittle superconductor (>10 T)
  - Maximizes effects of synchrotron radiation
  - Highest possible energy in given size tunnel
  - Greatest technical risk and greatest cost

Does synchrotron radiation raise or lower the collider $/TeV?
Cost drivers set design & R&D priorities (based on SSC “green field” experience)

Build at an existing hadron laboratory

Lowering dipole cost is the key to cost control

Note: The cost per T-m increases with B
Infrastructure matters: Injection chain for a 200 TeV Collider

Collider ring: 100 TeV, 342 km circumference

Transfer Line to avoid HEB polarity change?

High Energy Booster, 10 TeV, 34 km

Medium Energy Booster, 400 GeV, 6.9 km

Low Energy Booster, 25 GeV, 0.43 km

H-minus Linac, 1.27 GeV, 400 m length
One irreversible decision: the radius of the collider tunnel

- China: 77 km
- CERN FCC: 100 km
- VLHC: 233 km
- ELN: 300 km
- Texas: 270 km
Proton colliders: Magnets

- For a 100 TeV machine:
  - 270 km requires 4.5 T
  - 100 km requires 16 T
- LHC dipoles operate at 8T *
  * Level at which all dipoles operate reliably, less than the highest test field.

- The LHC dipoles are wound with Nb-Ti.
  - They are industrialized, but expensive
  - ~1/2 total cost of collider ring
- 16 T magnets will require Nb$_3$Sn or HTS (or both)
Dipole fields of ~15T are within reach
But need ~10 year engineering readiness program

A 2-d cross-section is not an engineering design

Multi-step development of QXF aperture quadrupole in LARP for HL-LHC
Proton colliders beyond 14 TeV: CERN is leading “100 km tunnel” collider study

- Reach of an LHC energy upgrade is very limited (~26 TeV)
  - No engineering materials beyond Nb$_3$Sn (Practical limit ~16 T)
  - Synchrotron radiation management is challenging

- Proton colliders at 50 - 100 TeV
  - US multi-lab study of VLHC (circa 2001) is still valid - 233 km ring

\[
P_{\text{proton}}(kW) = 6.03 \frac{E(\text{TeV})^4 I(A)}{(m)}
\]

Breakpoints in technology are also breakpoints in cost \([1::8::20(?) \text{ per kA-m}]_{\text{cern}}\)
Scaling of collider cost with machine size
Is this practical in any scenario?

- For a given conductor technology, dipole cost scales as
  \[ C_{\text{dipole}}(\$) = \text{const.} \ast B \rho \ast \left(\frac{r+0.5}{2}\right)^{0.43} \left[0.25+0.55\left(\frac{8}{L_d}\right)\right]^{0.6} \left[0.3+0.7\left(\frac{B}{4.3}\right)\right] \]

Breakpoints in technology are also breakpoints in cost \([1::8::20(\text{per kA-m})]_{\text{cern}}\)

Tunneling costs are highly geology dependent & must carry large contingency
Protons radiate!

- Proton synchrotron radiation (SR) is important at the LHC (7 TeV Beam, 27 km circumference, 0.5 A); 7.5 kW total; 0.22 W/m.
  - A LHC energy doubler would have ~4.5 W/m

- At 100 km (50 TeV Beam, 0.5 A) SR power is 4 MW; 26 W/m.
  - At 100 TeV, SR determines the beam dynamics.
  - The collider needs a cold surface (<2.7K) to pump desorbed hydrogen.

The positive:
Luminosity rises initially because of radiation damping

Source: M. Breidenbach & W. Barletta
At > 50 TeV/beam:
Synchrotron radiation dominates beam physics

- Radiation damping of emittance increases luminosity
  - May ease injection & loosen tolerances
  - May save money

\[ \mathcal{L} = \frac{N^2 c \gamma}{4 \pi \varepsilon_n \beta^* S_B} = \frac{1}{e r_i m c^2} \frac{N r_i}{4 \pi \varepsilon_n} \left( \frac{E l}{\beta^*} \right) = \frac{1}{e r_i m c^2} \frac{N r_i}{4 \pi \varepsilon_n} \left( \frac{P_{\text{beam}}}{\beta^*} \right) \; \; \; \; \; \; \; i = e, p \]

- Energy loss via SR limits $I_{\text{beam}}$
  - 1 - Increases rf-power to replace beam energy
  - 2 - Heats walls $\Rightarrow$ cryogenic heat load $\Rightarrow$ wall resistivity $\Rightarrow$ instability
  - 3 - Photo-desorption $\Rightarrow$ beam-gas scattering $\Rightarrow$ quench of SC magnets
  - Will cost money

What is the cost impact of synchrotron radiation?
Vacuum/cryo systems are surprisingly expensive.
Scaling LHC is not an option.

- Beam screen for high field options
  - Increases required aperture & cost
  - Physical or chemical absorption

- Cryogenics
  - Superfluid systems are impractical at this scale

- Let photons escape in low field option
  - No conductor in mid-plane
  - Warm bore / ante-chambers

Managing synchrotron radiation power becomes challenging as $P_{sr} > 5 \text{ W/m}$.
Scaling of radiation from hadronic shower

- Power in charged particle debris (per side)

\[ P_{\text{debris}} = 350 \, \text{W} \left( \frac{L}{10^{33}} \right) \left( \frac{\sigma_{\text{inel}}}{90 \, \text{mb}} \right) \left( \frac{E}{20 \, \text{TeV}} \right) \]

- Radiation dose from hadronic shower

\[
D \propto N_{\text{collision}} \times \sigma_{\text{inel}} \times \text{Charged multiplicity/event} \times \frac{dE}{dx}
\]

\[
D(E,r) = 26.1 \, \text{Gy/yr} \left( \frac{L}{10^{33}} \right) \left( \frac{\sigma_{\text{inel}}}{90 \, \text{mb}} \right) \left( \frac{H(E)}{7.5} \right) \left( \frac{\langle p_\perp \rangle}{0.6 \, \text{GeV}} \right)^{0.9} \cosh^{2.9} \eta \frac{1}{r^2}
\]

where

- \( r = \) distance from IP in meters
- \( \eta = \) psuedo-rapidity = - ln (tan \( \theta/2 \))
- \( H = \) height of rapidity plateau = 0.78 \( s^{0.105} \)
  - \( \approx \) constant for \( \eta < 6 \) (\( \theta > 5 \) mr)
  - for \( \eta > 6 \), \( H(E) \rightarrow 0 \) linearly @ kinematic limit
- \( \langle p_\perp \rangle = 0.12 \log_{10} 2E + 0.06 \)
- \( s = 4 \, E^2 \)
Radiation damage of IR components severely limits maximum luminosity

- Distance to first quad,
  \[ Q1: l^* \propto \beta^* \propto (\gamma / G)^{1/2} \]
  \[ l^* = 20 \text{ m} \left( \frac{E}{20 \text{ TeV}} \right)^{1/2} \]

- Let Q1 aperture = 1.5 cm \implies
  
  At 100 TeV per beam & \( \mathcal{L} = 10^{35} \text{ cm}^{-2}\text{s}^{-1} \)
  
  \[ P_{\text{debris}} = 180 \text{ kW/side} \]

  With no shielding
  
  \[ D (Q1) \approx 4 \times 10^8 \text{ Gy/year} \implies \approx 4.5 \text{ mW/g in Q1 (6 mo lifetime)} \]

  Estimate is confirmed by detailed Monte Carlo calculations

\[ \text{At } L = 10^{35} \text{ cm}^{-2}\text{s}^{-1} \text{ Q1 requires extensive protection with collimators} \]
Machine protection will be challenging

- Proton colliders have enormous stored energy in their magnets & beams

For luminosity = $10^{35} \text{cm}^{-2}\text{s}^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>$E_{cm}$ (TeV)</th>
<th>Circumference (km)</th>
<th>Energy in beams (GJ)</th>
<th>Energy in dipoles (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC-14</td>
<td>14</td>
<td>27</td>
<td>~2 x 0.35</td>
<td>11</td>
</tr>
<tr>
<td>FCC-100 km*</td>
<td>100</td>
<td>100</td>
<td>~2 x 8.4</td>
<td>~180</td>
</tr>
<tr>
<td>Texas-270 km*</td>
<td>100</td>
<td>270</td>
<td>~2 x 30</td>
<td>~60</td>
</tr>
</tbody>
</table>

* Needs many more machine sectors to keep dipole energy per sector similar to LHC
- Needs many more beam abort lines to keep energy per abort line similar to LHC

8 GJ can melt 12 tonnes of Cu or drill a 300 m long hole in Cu

Any beam loss is important! e.g. beam-gas scattering, non-linear beam dynamics
- can quench arc magnets
- background for the experiments
- activation of the machine
Tunneling costs vary significantly with geography

- Detailed geological studies have been done in some locations
- Scaled costs/m for 4m diameter tunnel:
  - CERN (LEP) molasse/limestone 35 K€
  - FNAL dolomite 14 K€
  - Dallas chalk/marl 5 K€
Electrical power: Another societal impediment

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Magnet Circuits</td>
<td>20</td>
<td>86.4</td>
<td>Wall-plug, worked out estimate</td>
</tr>
<tr>
<td>RF</td>
<td>18</td>
<td>32</td>
<td>Rough estimate</td>
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<tr>
<td>Cryogenics</td>
<td><strong>32</strong></td>
<td><strong>190</strong></td>
<td>To be revisited/refined</td>
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<tr>
<td>Cooling</td>
<td>20</td>
<td>71</td>
<td>Power in cooling water</td>
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<tr>
<td>Ventilation</td>
<td>14</td>
<td>56</td>
<td>Rough, 4 x LHC</td>
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<tr>
<td>Other Machine</td>
<td>2.5</td>
<td>10</td>
<td>Rough, 4 x LHC</td>
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<td>General services</td>
<td>13</td>
<td>52</td>
<td>Rough, 4 x LHC</td>
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<tr>
<td>Experiments</td>
<td>22</td>
<td>30</td>
<td><em>(10 + 10 + 5 + 5)</em></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>147.5</strong></td>
<td><strong>527.4</strong></td>
<td></td>
</tr>
</tbody>
</table>

Drive down items proportional to tunnel size ==> allows lower optimum B
**VLHC study conclusions for large ring:**
No insurmountable technical difficulties

<table>
<thead>
<tr>
<th></th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>ELN-90</th>
</tr>
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<tbody>
<tr>
<td><strong>Total Circumference (km)</strong></td>
<td>233</td>
<td>233</td>
<td>300</td>
</tr>
<tr>
<td><strong>Center-of-Mass Energy (TeV)</strong></td>
<td>40</td>
<td>175</td>
<td>200</td>
</tr>
<tr>
<td><strong>Number of interaction regions</strong></td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Peak luminosity ($10^{34}$ cm$^{-2}$ s$^{-1}$)</strong></td>
<td>1</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Dipole field at collision energy (T)</strong></td>
<td>2</td>
<td>9.8</td>
<td>10</td>
</tr>
<tr>
<td><strong>$\beta^*$ at collision (m)</strong></td>
<td>0.3</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td><strong>Bunch Spacing (ns)</strong></td>
<td>18.8</td>
<td>18.8</td>
<td>100</td>
</tr>
<tr>
<td><strong>Interactions per bunch crossing at $L_{\text{peak}}$</strong></td>
<td>21</td>
<td>58</td>
<td>1</td>
</tr>
<tr>
<td><strong>$P_{\text{synch}}$ (W/m/beam)</strong></td>
<td>0.03</td>
<td>4.7</td>
<td>1.9</td>
</tr>
<tr>
<td><strong>Total installed power (MW)</strong></td>
<td>30</td>
<td>250</td>
<td>~150</td>
</tr>
</tbody>
</table>

**Going to 300 km would retain proven NiTi magnet technology**
Why not about radically new acceleration techniques? Can ELN be a linear proton collider?

- Imagine that $L_{\text{coll}} < 125 \text{ km} \implies E_{\text{acc}} \sim 2 \text{ GeV/m} \implies f_{\text{rf}} \approx 100 \text{ GHz}$

$$L \left(10^{33} \text{ cm}^{-2} \text{ s}^{-1}\right) = \frac{D H_D}{30} \left(\frac{1 \text{ mm}}{\sigma_z}\right) \left(\frac{P_{\text{beam}}}{1 \text{ MW}}\right)$$

$H_D$ is the luminosity degradation due to space charge.
$D$ is the disruption parameter that measures the anti-pinch.

$$D = \frac{r_p N_B \sigma_z}{\gamma \sigma_{x,y}^2} = r_p N_B \left(\frac{\sigma_z}{\beta^* \varepsilon_n}\right)$$

For $D < 2$, the value of $H_D \approx 1$.

At 100 TeV/beam, $\beta^* \sim 1 \text{ m}$ & $\varepsilon_n \sim 10^{-6} \text{ m-rad}$

- For $f_{\text{rf}} = 100 \text{ GHz}$ (typical of plasmas), $\sigma_z \sim 10^{-6} \text{ m} \implies \sigma_z/\beta^* \varepsilon_n \approx 1 \text{ m}^{-1}$
- Assume 1) bunches of 100 nC & 2) preserve emittance in the linac

$$r_p N_B \approx 10^{-6} \text{ m}$$

- Hence at only $10^{33} \text{ cm}^{-2} \text{ s}^{-1} \implies P \approx 30 \text{ GW per beam!}$

$\implies \textit{the ultimate supercollider must be a synchrotron}$
What About An LHC Energy Doubler?
How big is a PeV collider?

1 PeV?

Romania
There are no insurmountable technical obstacles to realizing a high luminosity, 100 TeV class proton collider

- Many considerations favor building a very large ring (200 - 300 km)
- Radiation damage to detectors & IR components is a serious issue
- A 300 km synchrotrons might reach up to 0.5 PeV c.m. energy
  - Find a way to remove synchrotron radiation from the cold beam tube
  - BUT is the management & sociology of such a project is practical?

We high energy physicists have to thank Antonino Zichichi for his deep insights, his leadership and his persistent dedication to a bold idea for over 50 years
Backup slides
Beam distribution may change $\Delta \nu_{\text{max}}$ consistent with acceptable backgrounds.

Beam dynamics of marginally damped collider needs experimental study.

Damping decrement = fractional damping per turn

$\xi = 0.006 + 0.024 (\delta/10^{-4})^{0.33}$
Physics & technology of vacuum chamber in arcs seriously limits collider performance

- Considerations that can limit luminosity: residual gas, instabilities
- Holes for heat removal & pumping must be consistent with low Z(ω)
- As plenum gets larger & more complex cost rises rapidly

\[ P_{\text{compress}} \approx 5.4 \left( \frac{300 \, ^\circ \text{K} - T_{\text{wall}}}{T_{\text{wall}}} \right) P_{\text{synch}} \]

Major determinant of operating costs
Discovery science requires discovery technology

The Energy Frontier
(Discoveries)

**Hadron colliders**
- Tevatron
- SC cable
- (W, Z bosons)SppS
- (top quark)

**Lepton colliders**
- PETRA, PEP (gluon)
- CESR
- SLED
- Linear collider
- RF pulse compression
- STS
- STS

New detectors
- (Higgs)
- Superfluid cryogenics
- μ-coll (?)
- ILC (?)
- LHC

ELN

The Future?

Constituent Center of Mass Energy (GeV)

Year of First Physics

**Dated**
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020
- 2030
- 2040

US Particle Accelerator School