PROCEEDINGS OF SCIENCE

Colliders and Accelerators for Particle Physics: A look at the horizon and future developments

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Ambleside, UK

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PoS(LCPS2009)013

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of Accelerator Science and Technology

Colliders and Accelerators for Particle Physics:

A look at the horizon and future developments

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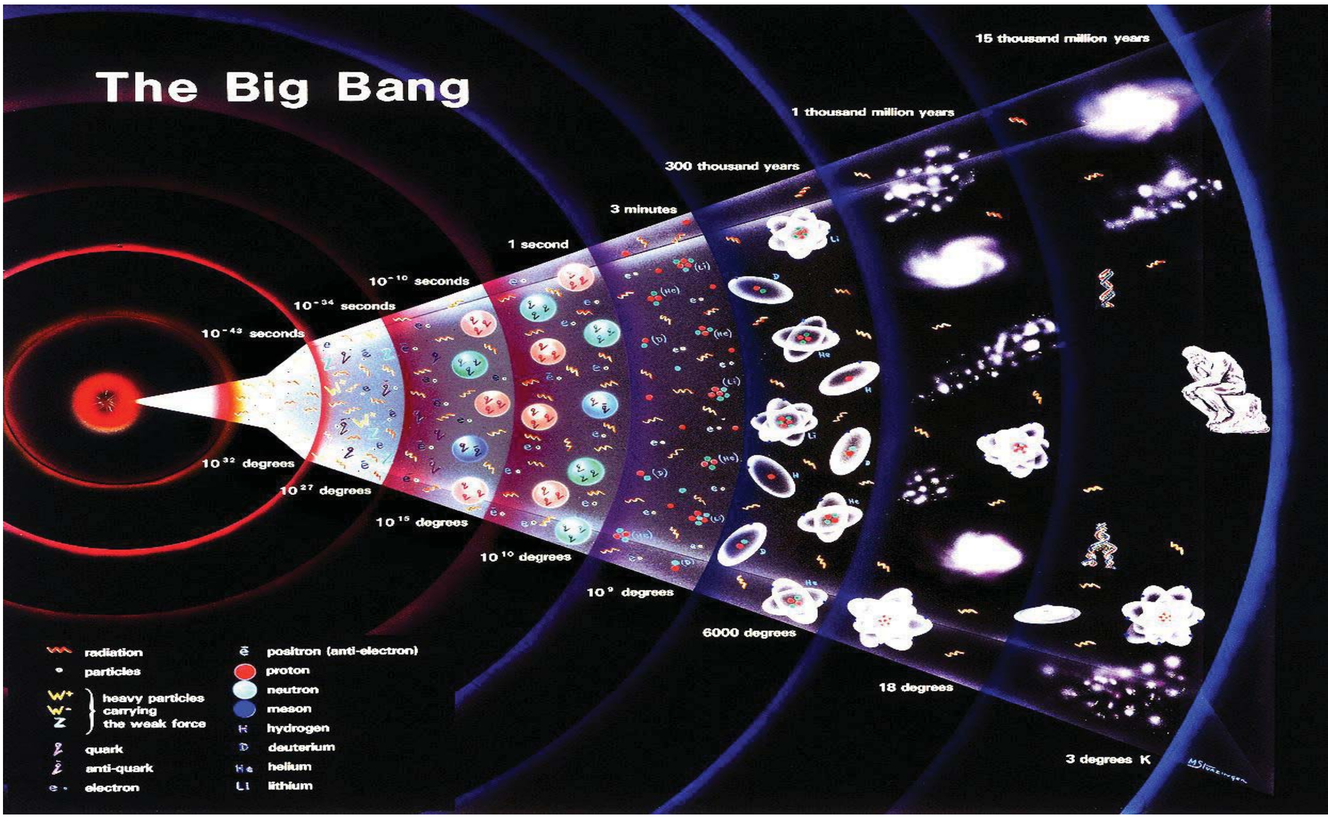
OUTLINE

- The first Cyclotron and today's LHC
- Advanced Colliders and Facilities
- Hadron Colliders
- Lepton Colliders
- Neutrinos and Muons
- Novel Concepts
- Musings on Einstein and Tagore

Microcosm and Macrocosm

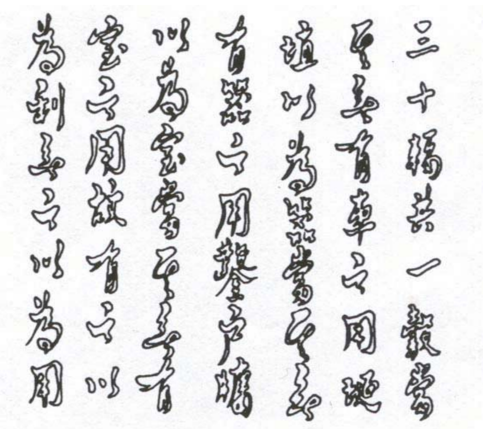


DISCOVERY vs. ANALYSIS

⇒**Exploration**: **"gainful" in discovery!**

⇒**Analysis/Spectroscopy**: **"useful" in understanding!**

Lao-tzu



"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."

From Cyclotrons to the Large Hadron Collider

1st cyclotron, ~1930 E.O. Lawrence
11-cm diameter
1.1 MeV protons

LHC, 2008
9-km diameter
7 TeV protons

after ~80 years
~10^7 x more energy
~10^5 x larger

LHC: A DISCOVERY MACHINE beginning 2009/2010;
ILC/CLIC PRECISION MACHINES beginning ??????

Advanced Particle Colliders/Facilities

Large Hadron Collider (LHC) → Higgs, extra-dimensions, supersymmetry,…

Large Hadron-electron Collider (LHeC) → structure of quarks and electrons

TeV-scale Electron-Positron Collider → precision TeV-scale physics

Super B-factory → CP Violation: fundamental symmetries

Super Beams, Neutrino Factory, Beta Beams → Flavour physics: neutrino sector

Muon Collider at TeV-scale → Discoveries hitherto unknown

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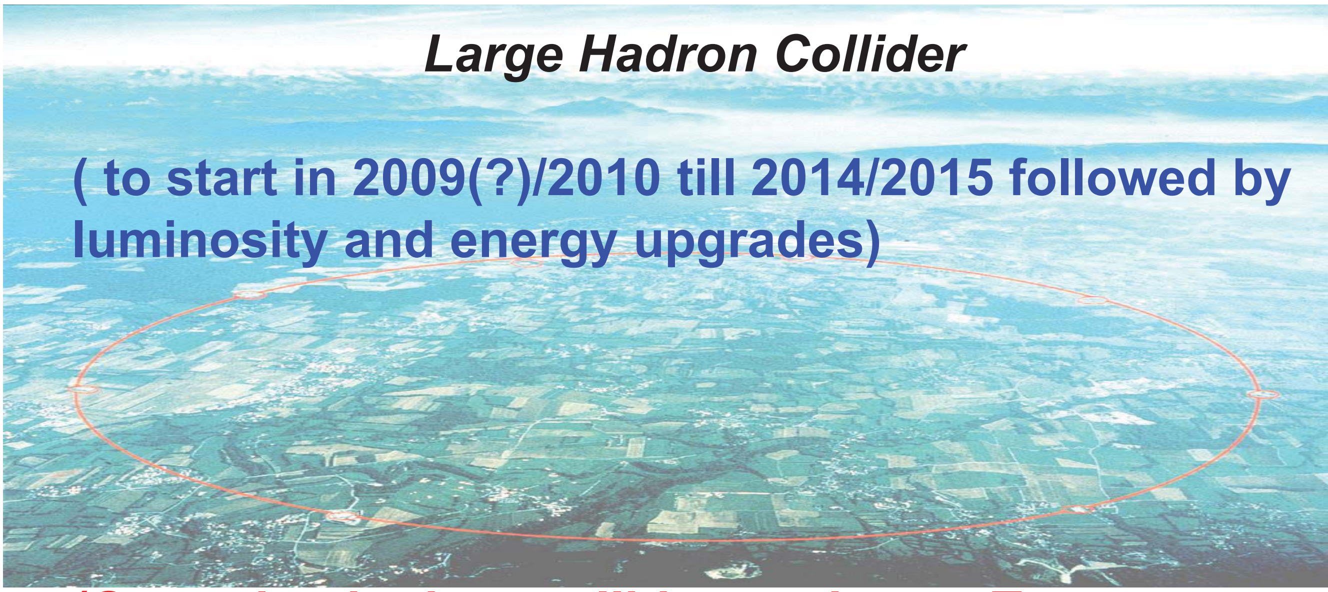
Large Hadron Collider



(to start in 2009(?)/2010 till 2014/2015 followed by luminosity and energy upgrades)

(Operating hadron colliders today areTevatron at Fermilab and RHIC at Brookhaven)

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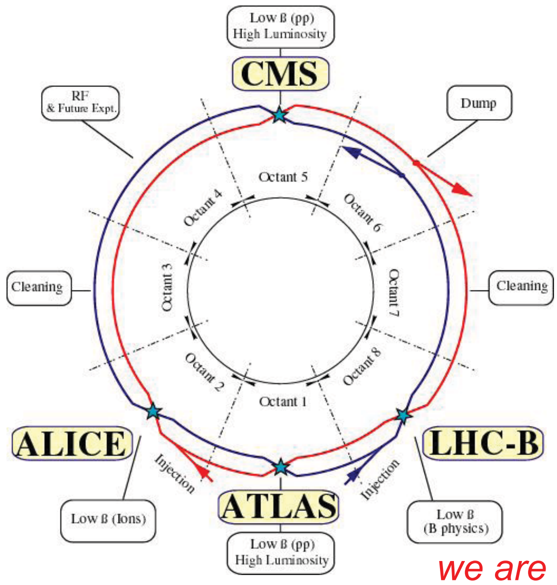
Large Hadron Collider (LHC)



proton-proton collider, ~27 km circumference, next energy-frontier discovery machine

c.m. energy 14 TeV (7x Tevatron), design luminosity 10^{34} cm^{-2}s^{-1} (~100x Tevatron)

450-GeV calibration run followed by 1st 3-TeV physics from late autumn 2009/winter 2010

we are now studying the upgrade of this facility!

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Ultimate LHC “upgrade”: higher beam energy

7 TeV→14 (21) TeV?

R&D on stronger magnets

(28 TeV cm LHC in the 2020-2030 time frame)

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develop and construct a large-aperture (up to 88 mm), high-field (up to 15 T) dipole magnet model that pushes the technology well beyond present LHC limits.

NED

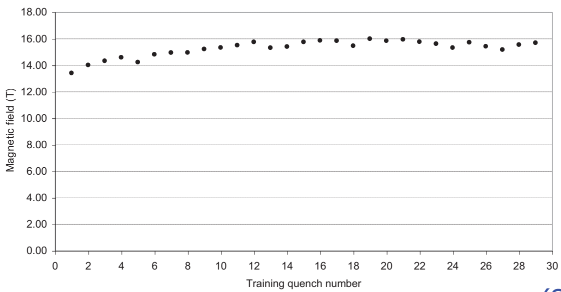
Next European Dipole

European Joint Research Activity

Six institutes: CCLRC/RAL (UK), CEA/DSM/DAPNIA (France), CERN/AT (International), INFN/Milano-LASA & INFN/Genova (Italy), Twente University (the Netherlands), Wroclaw University (Poland).

Three s.c. wire manufacturers (also contributing financially): Alstom/MSA (France), ShapeMetal Innovation (the Netherlands), Vacuumschmelze (now European Advanced Superconductors, Germany)

proof-of principle & world record: 16 T at 4.2 K at LBNL (in 10 mm aperture).



(S. Gourlay, A. Devred)

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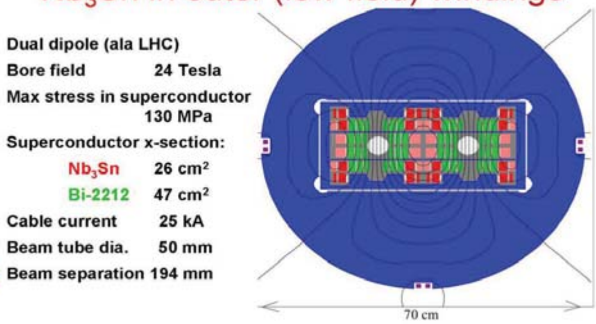
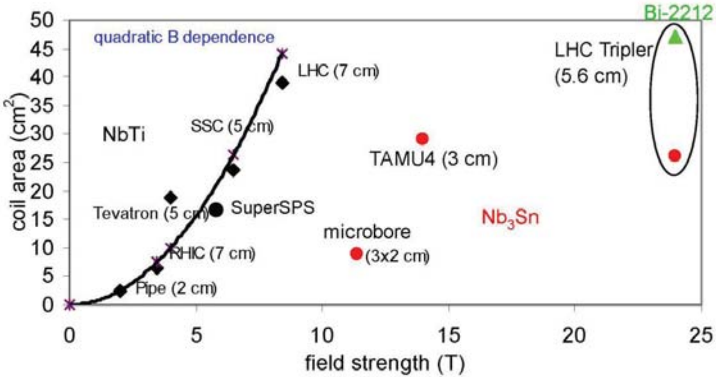
proposed design of 24-T block-coil dipole for LHC energy tripler

P. McIntyre, Texas A&M, PAC'05

Bi-2212 in inner (high field) windings, Nb_3Sn in outer (low field) windings





magnets are getting more efficient!

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Emerging Initiative

The Large Hadron-electron Collider (LHeC)

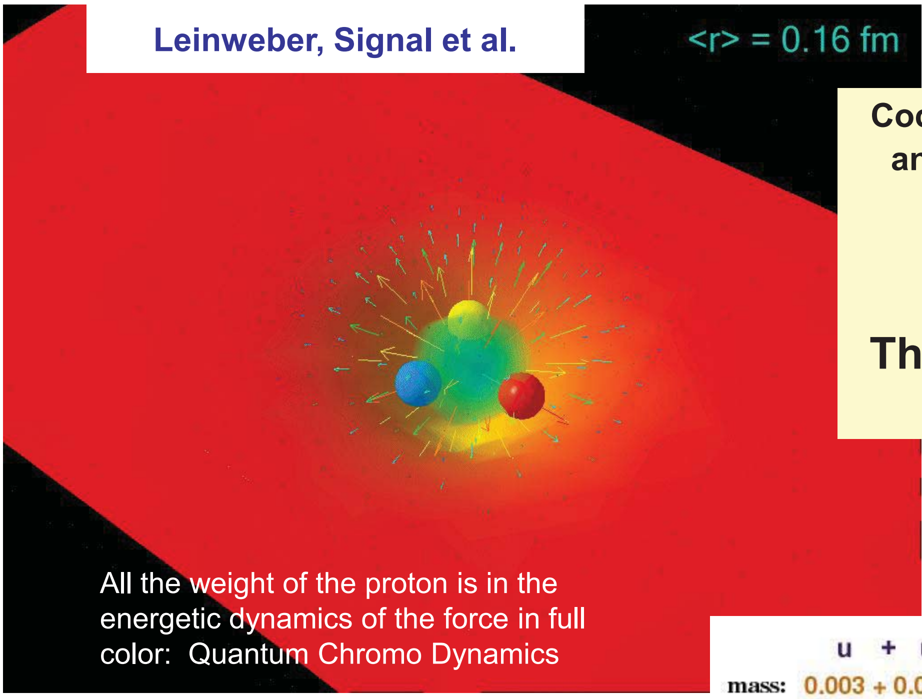
70-100 GeV electrons X 7 TeV protons at 10^{32}-10^{35} $cm^{-2}s^{-1}$ luminosity

Approved for feasibility study by ICFA, ECFA, CERN and DIS community

→***Requires a 70-100 GeV high current electron ring in the LHC tunnel or a cw superconducting energy recovering linac***

→ ***Probably a $1B project in the 2015-2025 time frame***

STRUCTURES and FORCES
Discovery Class Science: Particle Physics
Dynamics of the **Gluon**: Quantum ChromoDynamics (QCD)

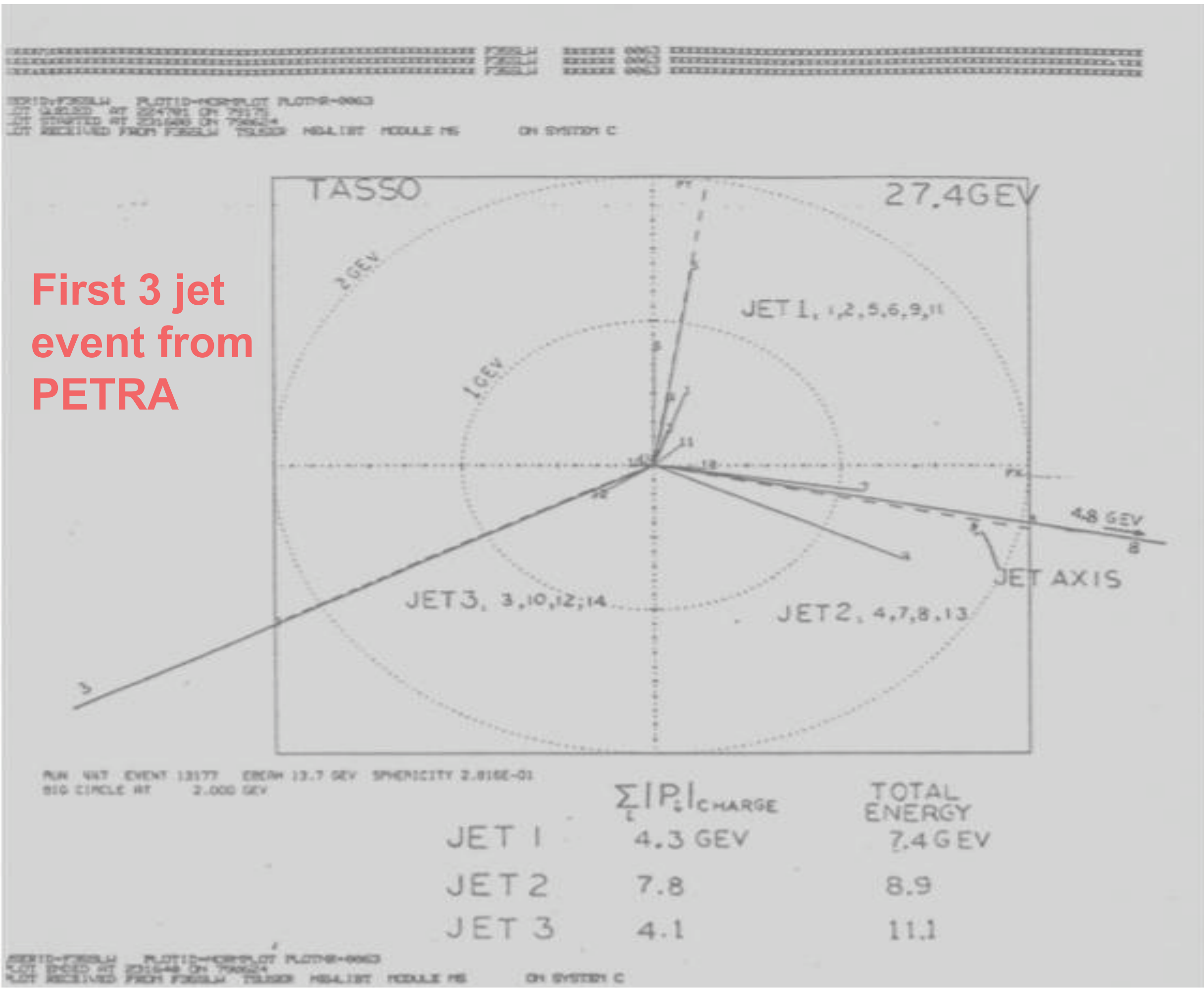


Cockcroft showed in an Atomic System

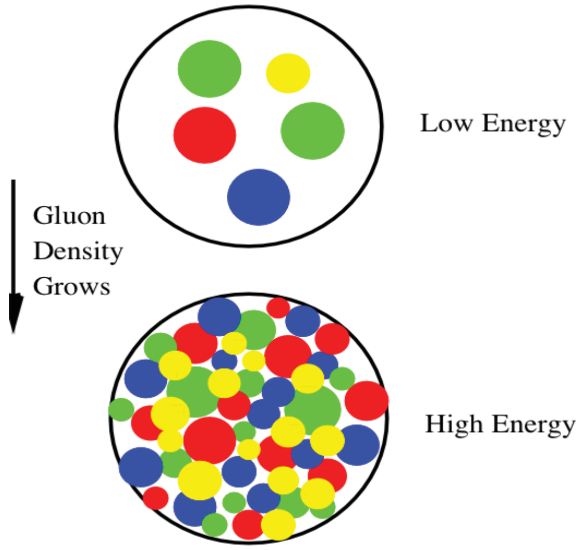
$E=mc^2$

This shows in a Nucleus

	u + u + d	= proton
mass:	0.003 + 0.003 + 0.006	≠ 0.938



Resolving the Nucleon



Gluon density saturates eventually at a certain resolution

Regge-Gribov Limit

Very high energy, very short distances, keeping the same momentum transfer in scattering

Regge

Gribov

$$x_{\rm Bj} \rightarrow 0\ ;\ s \rightarrow \infty\ ;\ Q^2 = \text{fixed}$$

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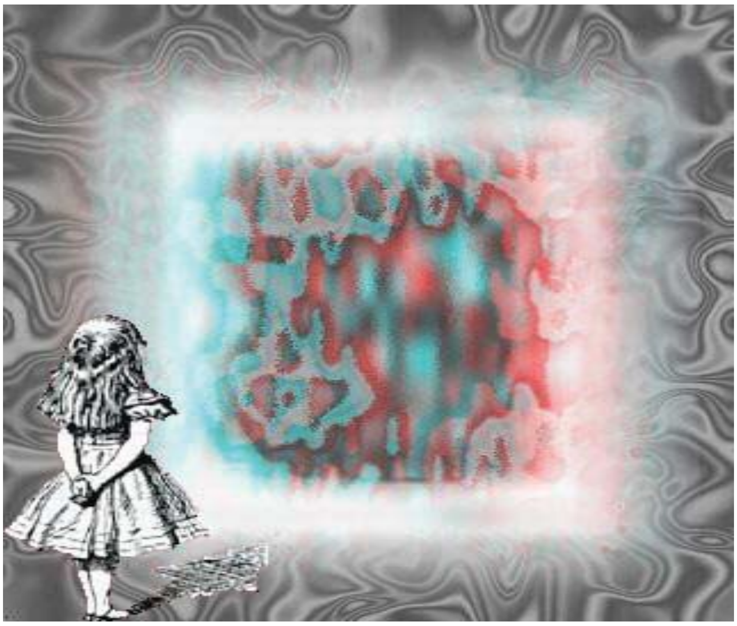
Wonderland of the New World of matter at the Heart of the QCD Vacuum!!! Structure of the physical “zero” down to sub-Attometres (10^{-19} m!!)



Sticky……..glassy……”plasmy” i.e. plasma-like……”melty”……….

New constituents? New forces? “Glasma”??

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Large Hadron-electron Collider (LHeC)

Understanding the fundamental constituents of matter down to sub-atto-metre resolution via probing dep into the Nucleon…….beyond 10^{-19} meter
100 GeV electrons X 7 TeV protons
@10^{32} -10^{35} $cm^{-2}s^{-1}$

Fascinating possibilities with the fast developing superconducting linac, energy recovery and electron cooling techniques

TeV-scale Electron-Positron Linear Colliders

- physics: probing beyond the standard model: origin of mass, unification of forces, origin of flavors
- complementary with LHC
- key features: either superconducting or two-beam and frequency multiplication technology

➢ **Gradient ~ 30MV/m, low frequency 1.3 GHz superconducting technology; less limitation from "Beamstrahlung", mechanical tolerances etc., many many bunches with low charge/bunch colliding;**

➢ **Gradient ~ 100 MV/m, high frequency ~ 11.6 GHz; room temperature "pulse combiner" technology, higher gradients, more energy efficient, but beam-beam and alignment tolerances severe.**

two-beam acceleration: energy stored in drive beam, transport over long distances with small losses, rf power generated locally where required.

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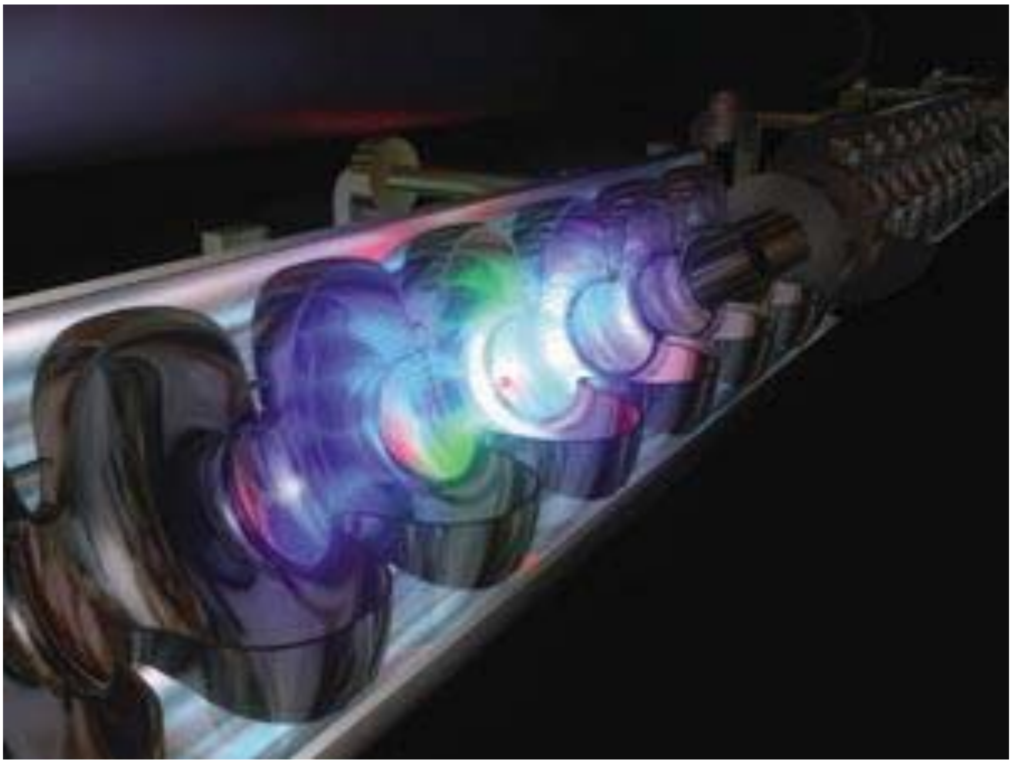
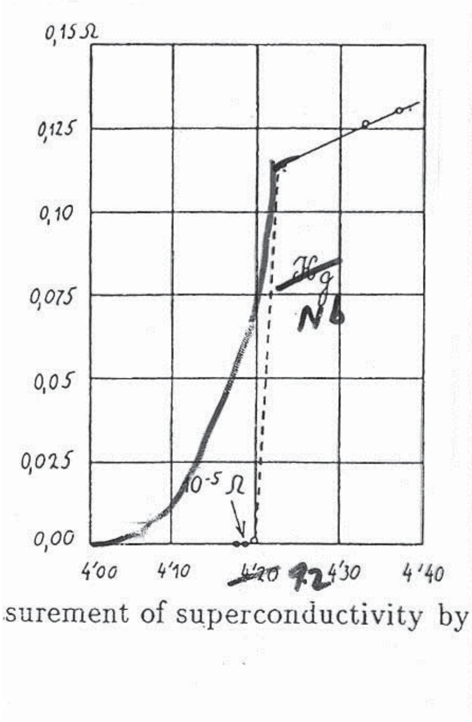
The Superconducting Linear Accelerator (ILC)



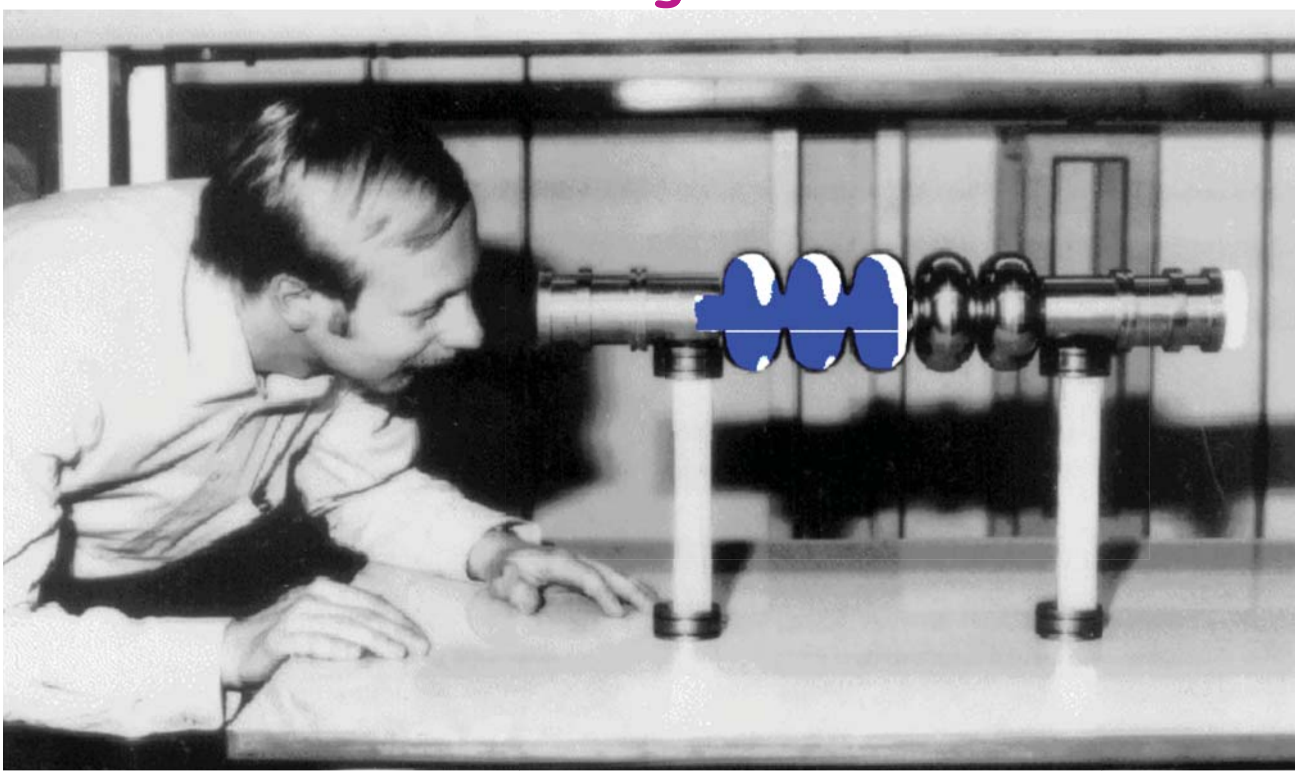
Superconductivity

Heike Kammerlingh-Onnes, 1911: SC in mercury

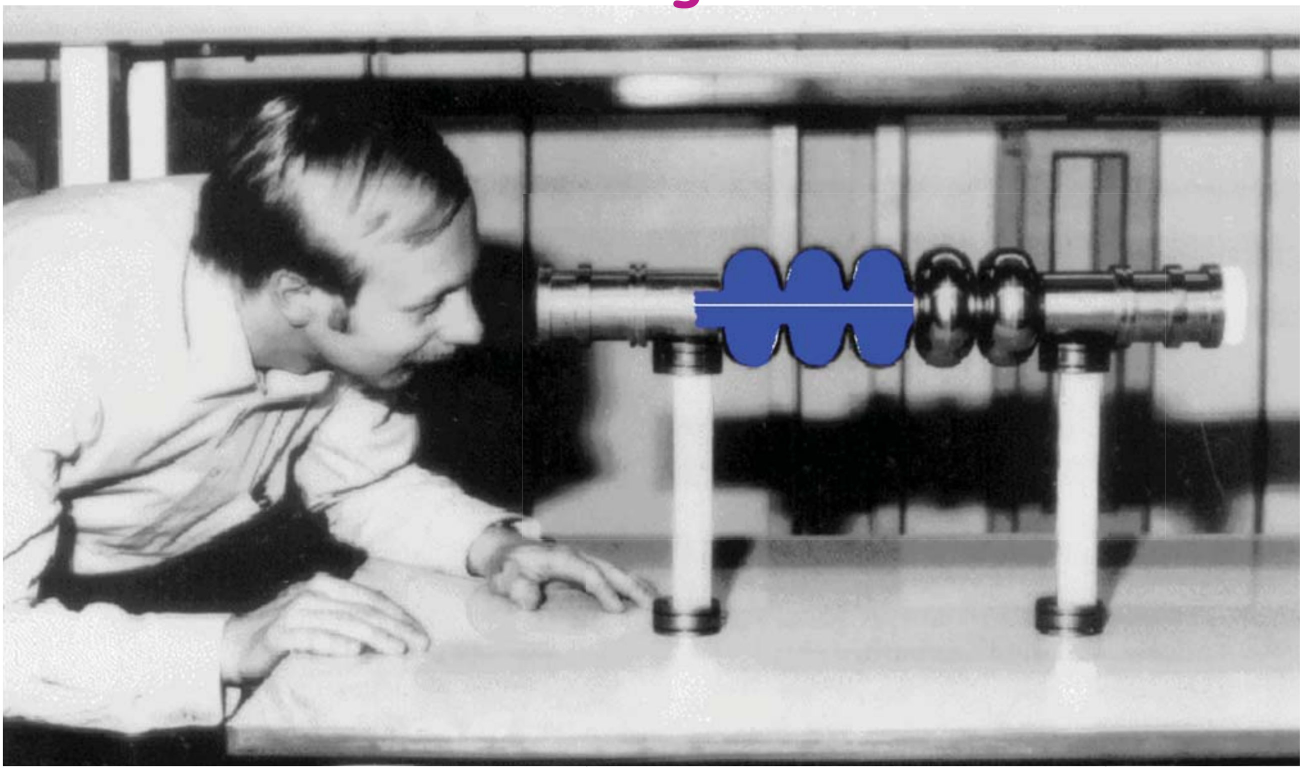


In fact, the "Onnes Road" at Jefferson Lab, home of much of Superconducting Radio Frequency Science and Technology, is named after him.

"Pulsed" Operation of "Normal" Conducting Accelerating Cavities



"Continuous" Operation of "Superconducting" Accelerating Cavities



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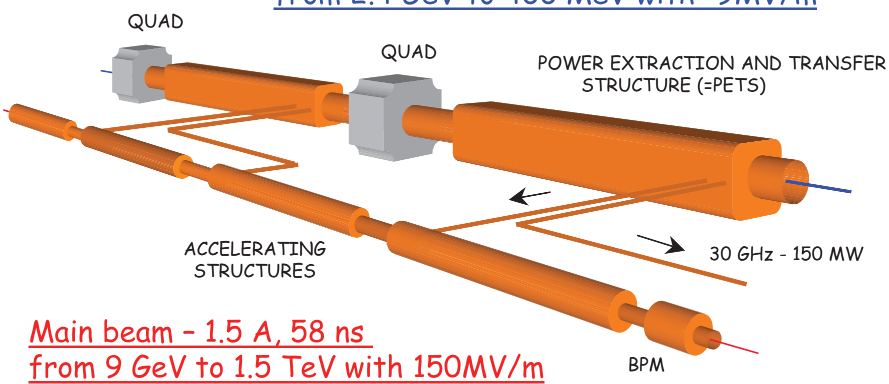
TWO-BEAM SCHEME-CLIC

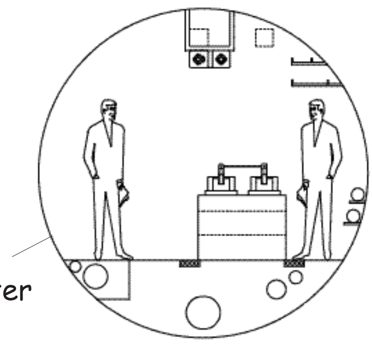
Drive beam - 180 A, 70 ns
from 2.4 GeV to 400 MeV with -9MV/m

A. Sessler 1982,
W. Schnell 1986



Main beam – 1.5 A, 58 ns
from 9 GeV to 1.5 TeV with 150MV/m

CLIC TUNNEL CROSS-SECTION



3.8 m diameter

simple tunnel, no active elements

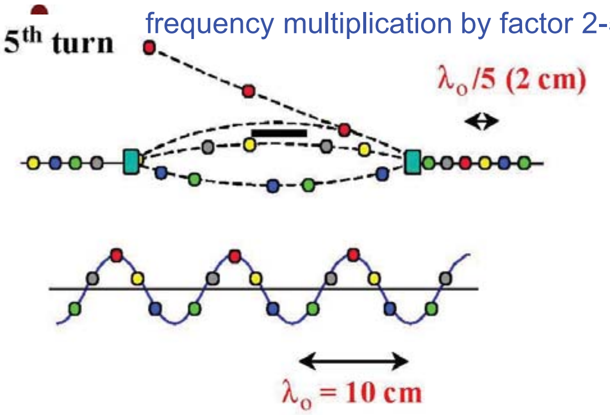
CLIC MODULE

(6000 modules at 3 TeV)

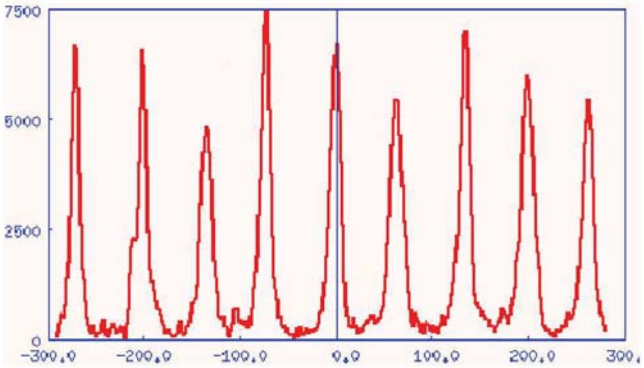
CLIC can be built in stages

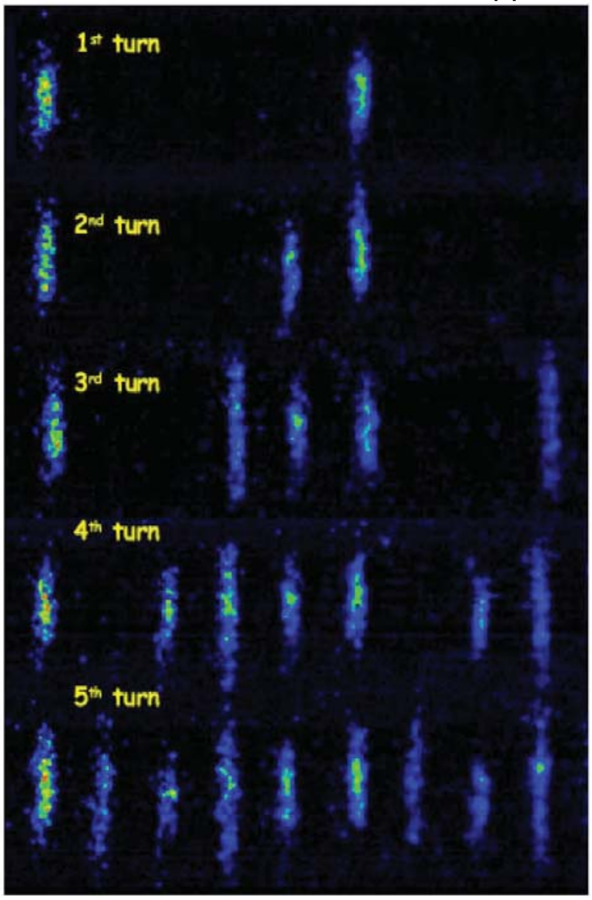
frequency multiplication by factor 2-5 demonstrated in CTF3 preliminary phase

CERN, INFN, SLAC, RAL, LAL, Uppsala



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





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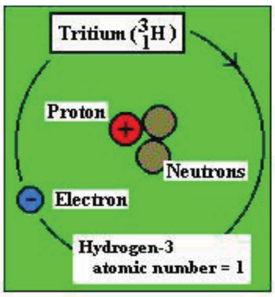
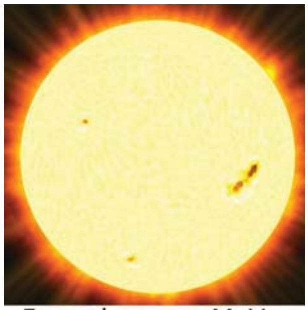
Ubiquitous Neutrinos



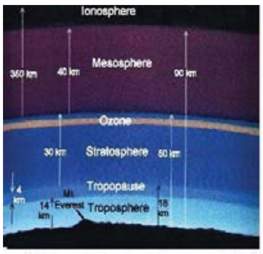
From radioactivity ~ MeV

From reactors - ~MeV

From accelerator - ~GeV

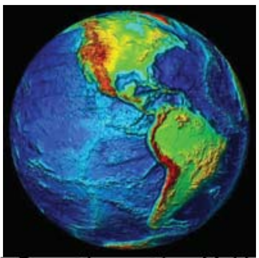


From the sun ~ MeV

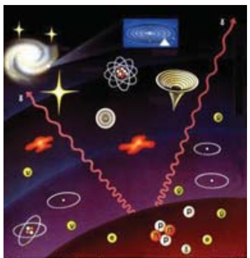


From atmosphere ~GeV

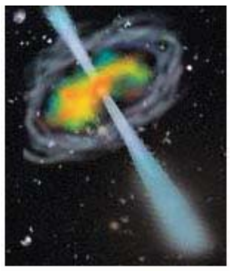
From Supernova ~ 10 MeV



From the earth ~ MeV



From Big Bang - ~10-4 eV



Extragalactic - ~TeV

Neutrino Beams as 'Super Beams' from Existing Facilities

Relative to the main ν_μ component:

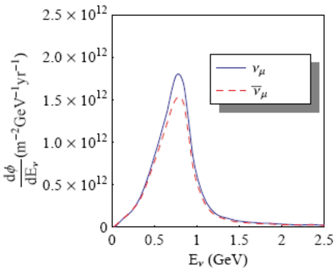
$\nu_e / \nu_\mu = 0.8$ %

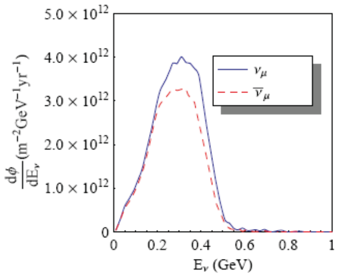
anti-$\nu_\mu / \nu_\mu = 2.1$ %

anti-$\nu_e / \nu_\mu = 0.07$ %

GOAL: Nu-mu "disappearance" and Nu-mu → Nu-e "appearance" Studies

J-Parc
T2HK
Japan



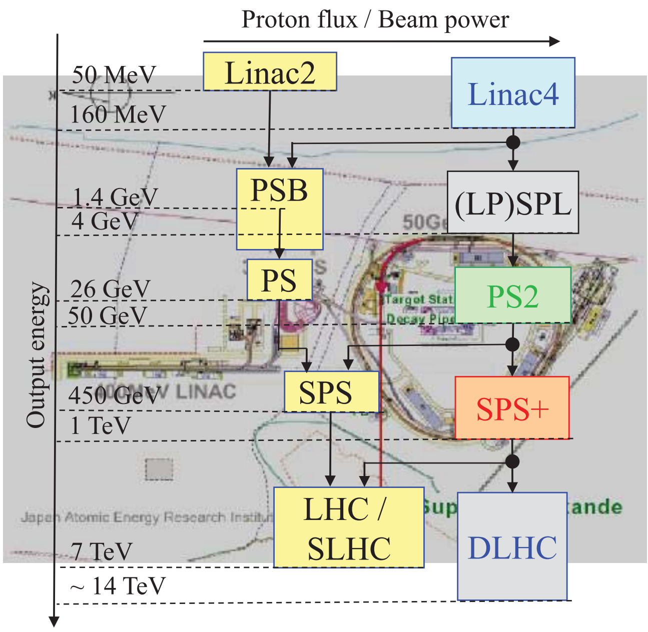


SPL to
Frejus
CERN

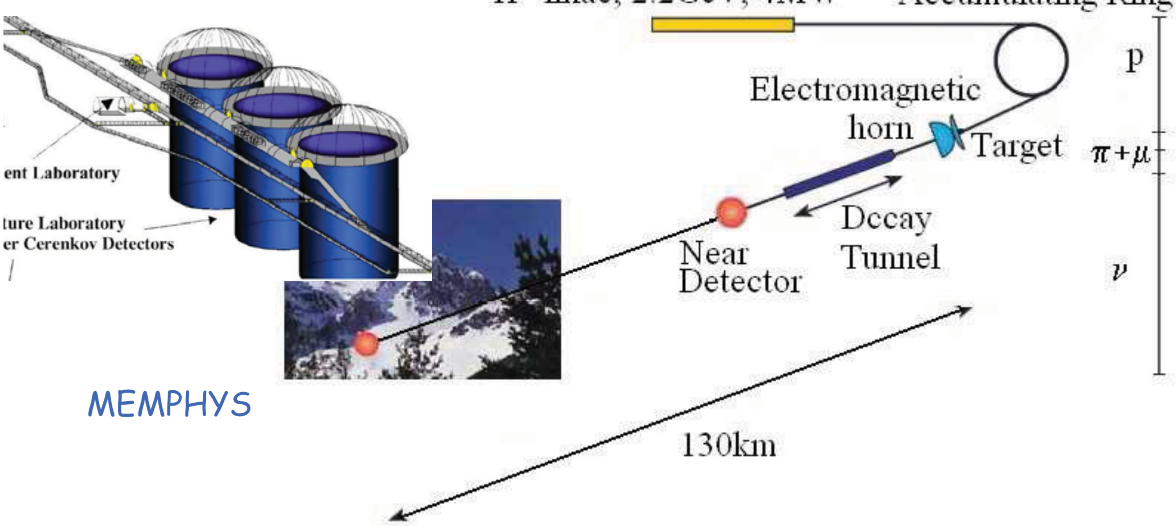
Proton drivers and Compressor Rings

- **An H- linac with a 50-Hz booster RCS and a 50-Hz non-scaling, non-linear, Fixed-Field Alternating Gradient (NFFAG) driver ring**
- An H- linac with pairs of 50 Hz booster and 25 Hz driver synchrotrons (RCS)
- An H- linac with a chain of three non-scaling FFAG rings in series
- An H- linac with two slower cycling synchrotrons and two holding rings
- **A full energy H- linac with an Accumulator and Bunch Compression ring(s)**

EU-CERN

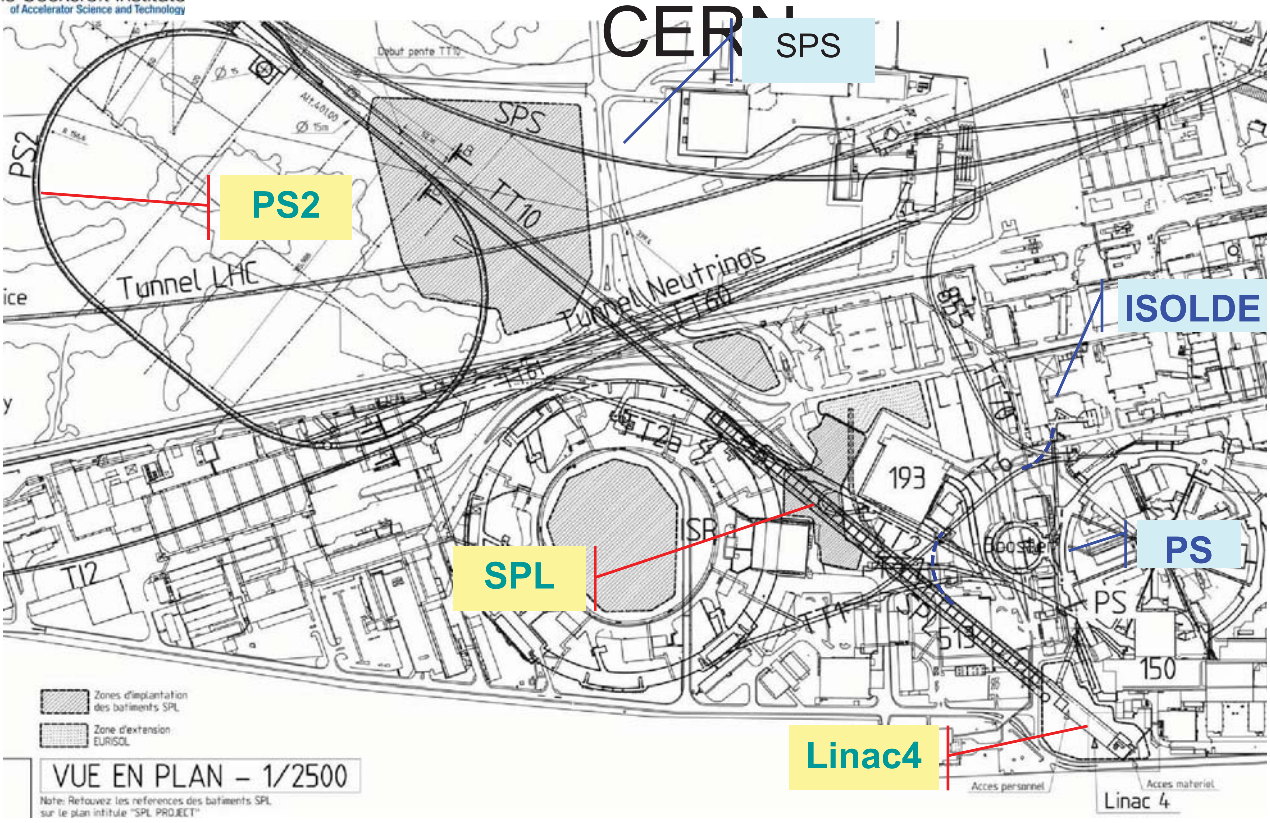


Super-Beams

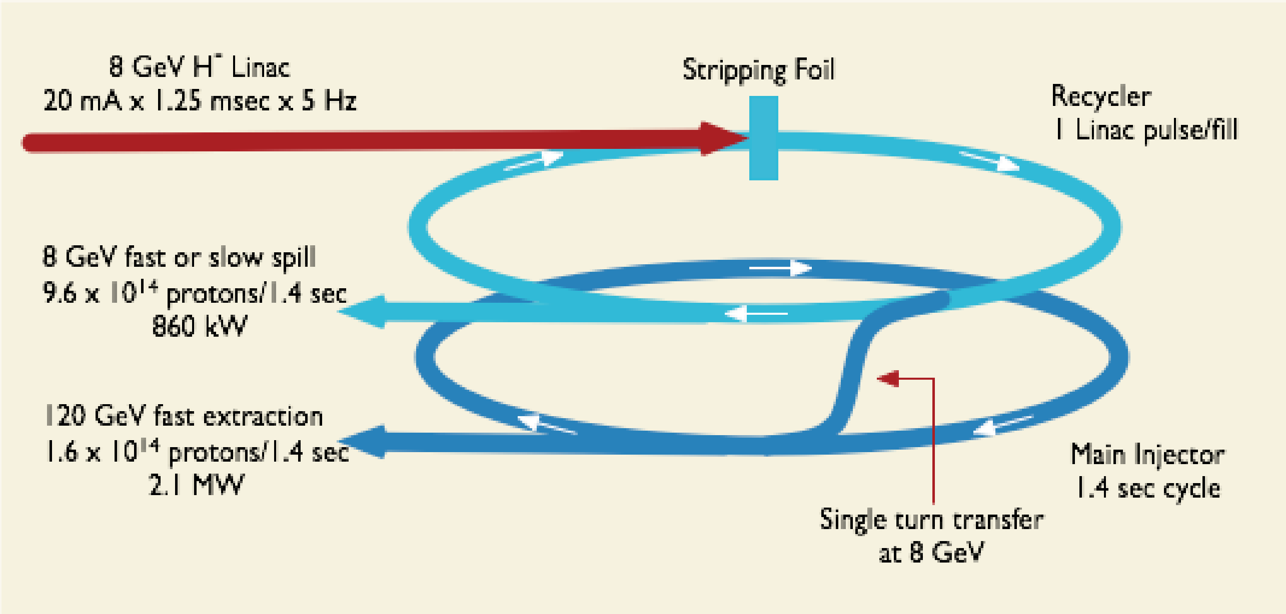


In this project, the planned 4 MW Superconducting Proton Linac (SPL) would deliver a 2.2 GeV/c proton beam on a heavy metal target to generate an intense π^+ (π^-) beam focused by a suitable magnetic horn in a short decay tunnel. As a result, an intense ν_μ beam will be produced mainly via the π decay, $\pi^+ \to \mu^+ + \nu_\mu$, providing a flux of 3.6 x 10^{11} ν_μ/year/m^2 at 130 km distance, and an average energy of 0.27 GeV. The ν_e contamination from kaons will be suppressed by threshold effects and the resulting ν_e/ν_μ ratio (~0.4%) will be known within 2% error. The use of a near and a far detector (the latter at L = 130 km in the Fréjus area) will allow for both ν_μ disappearance and $\nu_\mu \to \nu_e$ appearance studies.

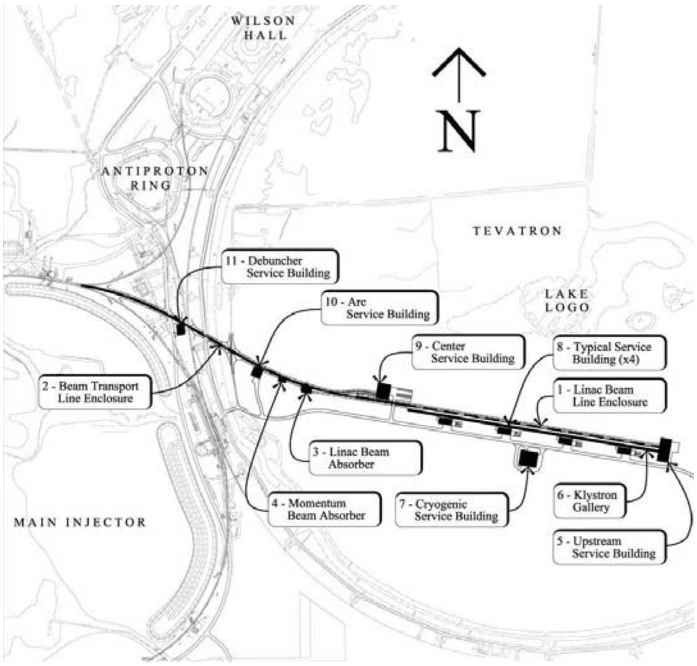
Layout of the new injectors at CERN



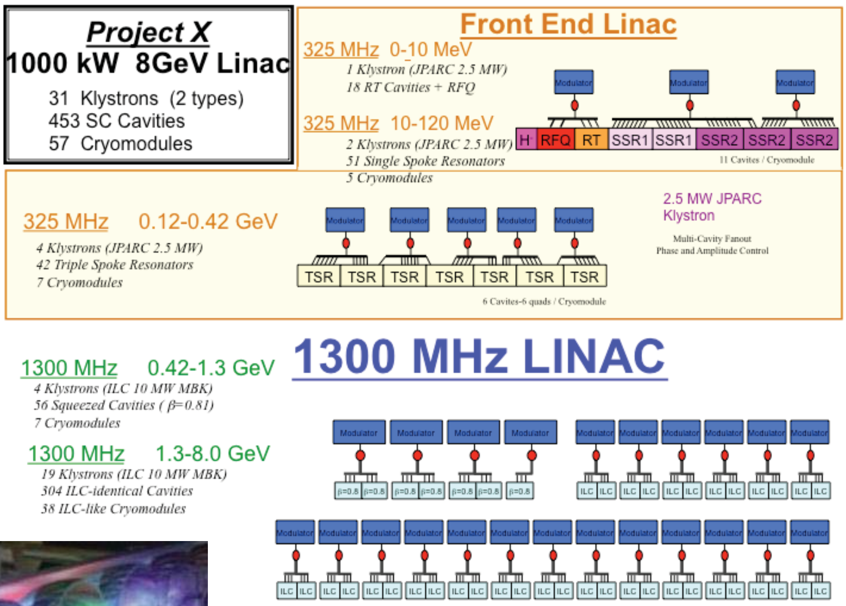
PROJECT-X at Fermilab
Accelerator Systems

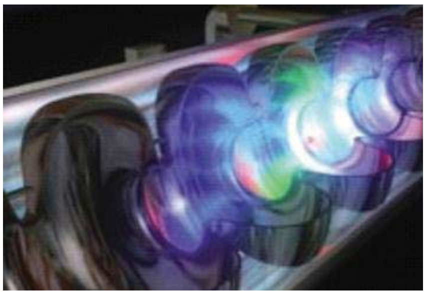


PROJECT-X Site Plan



PROJECT-X LINAC SYSTEMS



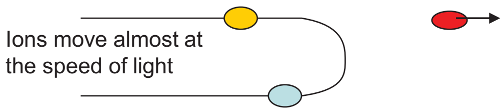


Global Network of Collaborations in Superconducting Radio-Frequency Science and Technology

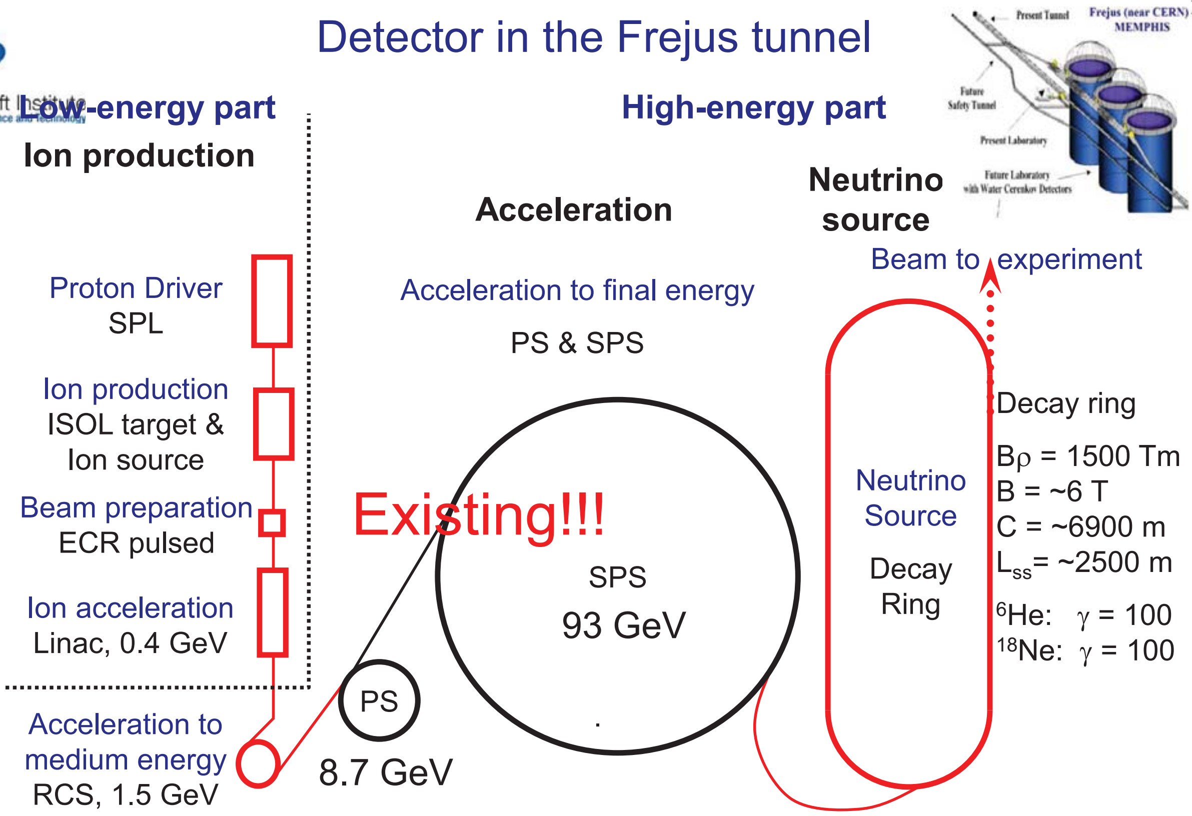
Deliberate progress of existing highly successful international collaboration towards further focus and coherence

Introduction to Beta-Beams

- **Beta-beam proposal by Piero Zucchelli**
  - ***A novel concept for a neutrino factory: the beta-beam*, Phys. Let. B, 532 (2002) 166-172.**
- **AIM: production of a pure beam of electron neutrinos (or antineutrinos) through the beta decay of radioactive ions circulating in a high-energy (γ~100) storage ring.**

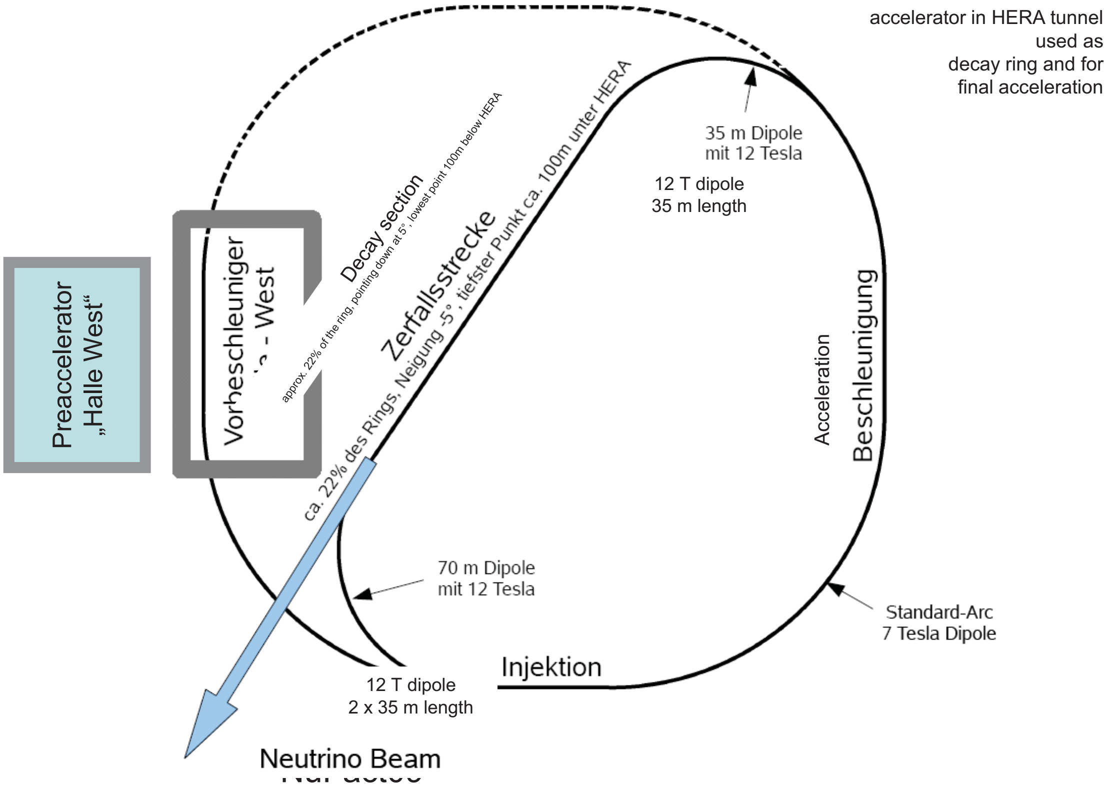


- **First study in 2002**
  - **Makes maximum use of the existing infrastructure.**



A Possible Beta-Beam Complex at CERN

Beta-Beam at DESY



Beta-beam at FNAL

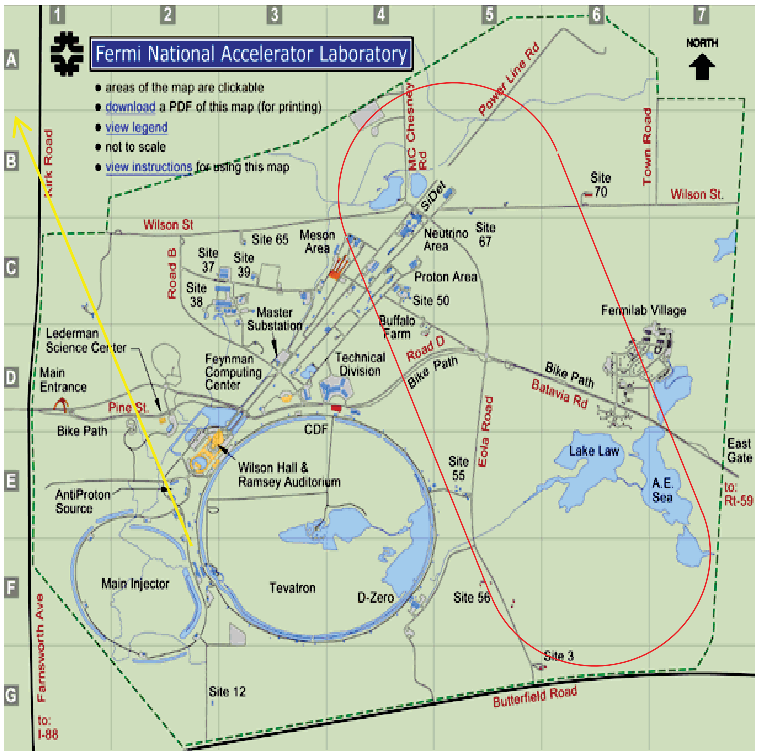
“Stretched Tevatron“

$B\rho$ = 3335 Tm
R = <u>1000 m</u> (75% 4.4T dipoles)
L_{SS}= ~3500

Total circumference:
approximately 2 x Tevatron

320m elevation @ 58 mrad

26% of decays in SS

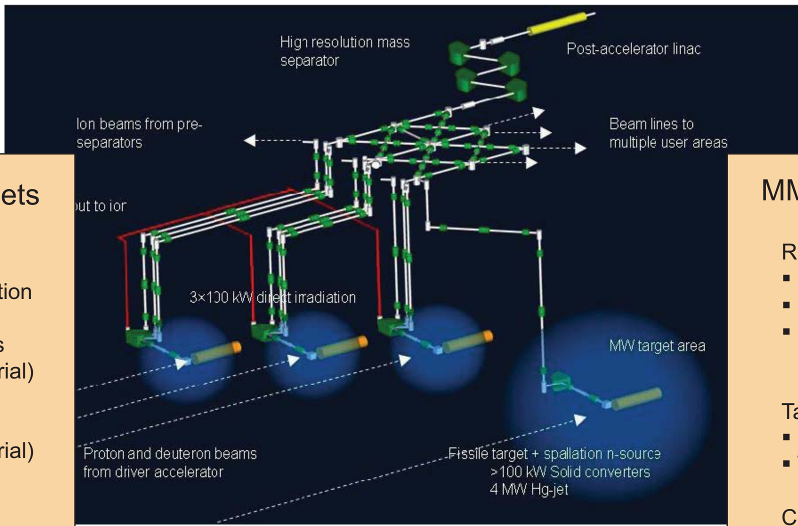


POSSIBILITIES AT A FUTURE EURISOL

100 kW direct targets

RIB production:
- Spallation-evaporation
- Main: P-rich
  (10 to 15 elements
  below target material)
- Residues: N-rich
  (A few elements
  below target material)

Target materials:
- Oxides
- Carbides
- Metal foils
- Liquid metals



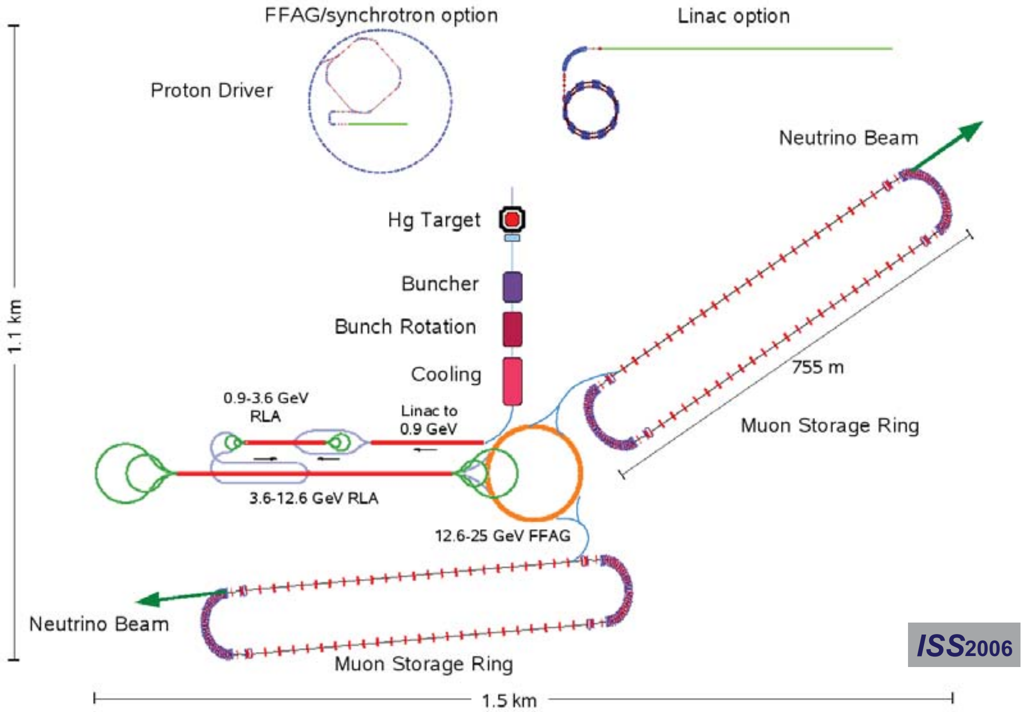
MMW fission target

RIB production:
- Fission
- N-rich
- Wide range
  Z = 10 to Z = 60

Target material:
- U (baseline)
- Th

Converter:
- Hg

Neutrino Factory - ISS



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Muon Beam Challenges

- Muons created as tertiary beam ($p \rightarrow \pi \rightarrow \mu$)
  - low production rate
    - **need target that can tolerate multi-MW beam**
  - large energy spread and transverse phase space
    - need solenoidal focusing for the low energy portions of the facility
      - solenoids focus in both planes simultaneously
    - need emittance cooling
    - high-acceptance acceleration system and decay ring
- Muons have short lifetime (2.2 μs at rest)
  - puts premium on rapid beam manipulations
    - high-gradient RF cavities (in magnetic field) for cooling
    - presently untested **ionization cooling** technique
    - **fast acceleration system**
- Decay electrons give rise to heat load in magnets and backgrounds in collider

Intense muon beams of good phase-space quality are challenging to produce within a muon's lifetime!

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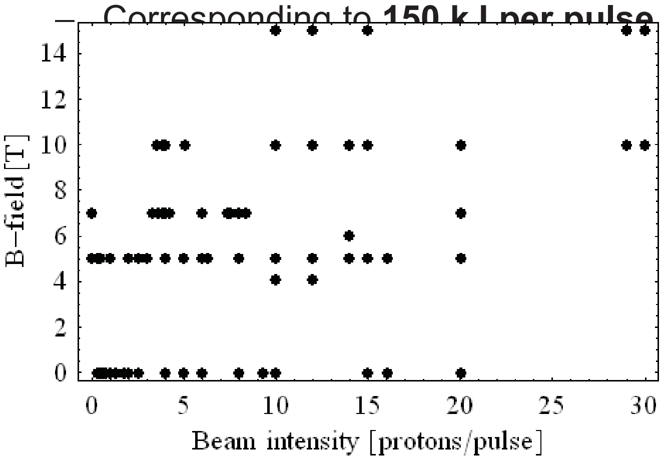
The MERIT experiment

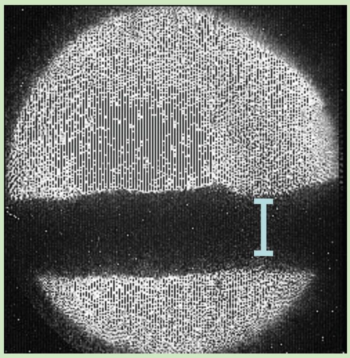
- The experiment could fully exploit the potential of the PS machine to validate the liquid metal target concept

PS record intensity:

- **3×10^{13} protons/pulse @ 24 GeV/c**
- Corresponding to **150 kJ per pulse**



Beam-target interaction example

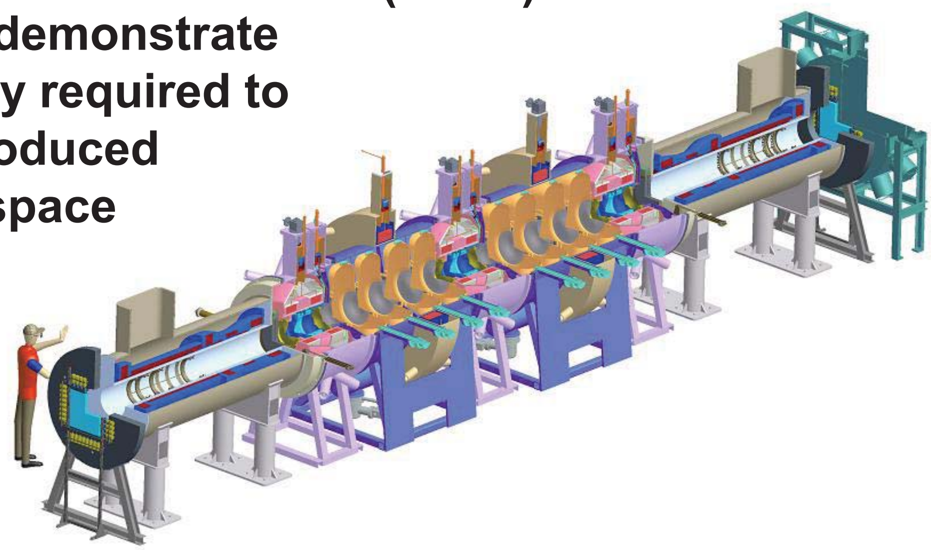


- 14 GeV/c beam
- 1.6×10^{13} protons/pulse
- 5 Tesla B-field

Images recorded at 2000 frames/sec
Video displayed 400 times slower
Splash velocities up to 60 m/s

The Muon Ionization Cooling Experiment (MICE)

- **Purpose: To demonstrate the technology required to reduce the produced muon phase space**



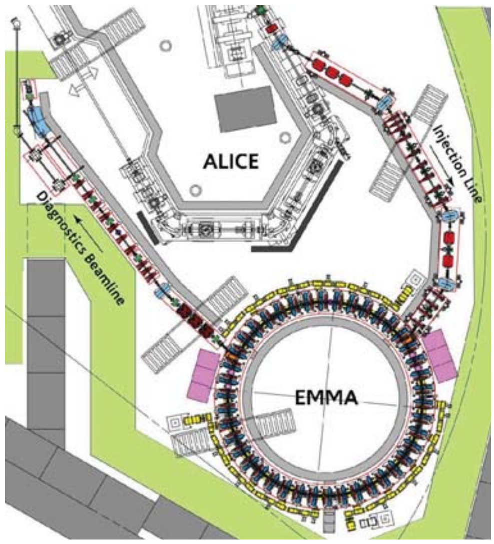
Challenges:

- High-gradient, low-frequency (201MHz) rf cavities operating in high-magnetic fields (~3T)
- Design and safely operated LH_2 absorbers

EMMA at Daresbury/Cockcroft Institute

- **Purpose:**

Demonstrate fast acceleration and understand the beam dynamics of non-scaling FFAGs

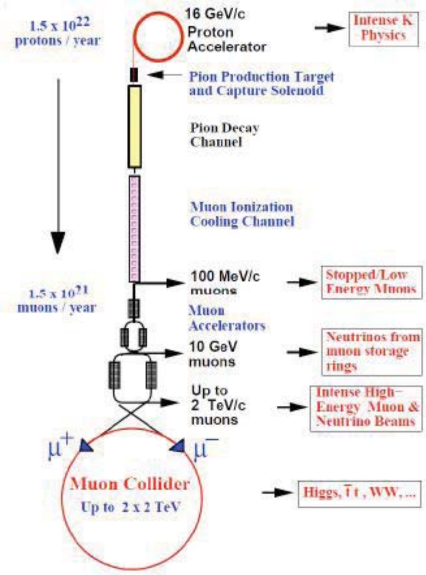


Challenge: No non-scaling FFAGs have previously been designed, built and operated

EMMA is an electron analog machine designed for 10-20MeV/c operation

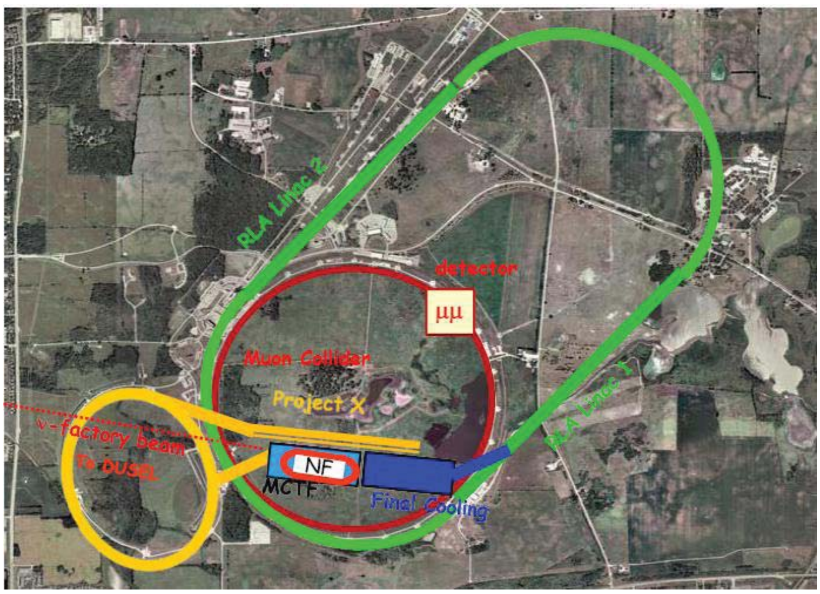
Muon Collider

- Muon Collider comprises these sections (similar to NF)
  - Proton Driver : primary beam on production target
  - Target, Capture, and Decay
    - create π; decay into μ ⇒ MERIT
  - Bunching and Phase Rotation
    - reduce ΔE of bunch
  - Cooling : orders of magnitude higher demands than NF
    - reduce long. and transverse emittance ⇒ MICE → 6D experiment: a first step
  - Acceleration: much higher than NF
    - 130 MeV → ~1 TeV with RLAs, FFAGs, or RCSs
  - Collider Ring: new accelerator physics issues: luminosity, beam-be
    - store for 500 turns



Much of Muon Collider R&D is common with Neutrino Factory R&D

Project-X → Neutrno Factory → Muon Collider at FNAL?



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Accelerators in Space

Radiation of Synchrotron Light from the Crab Nebula, Gamma-Ray Bursts, Cosmic Acceleration

The Inverse of the Acceleration process (energy gain) is the process of Radiation (energy loss)!!

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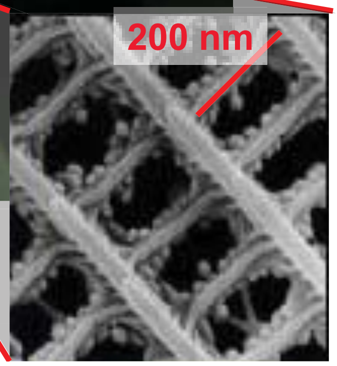
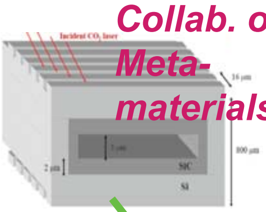
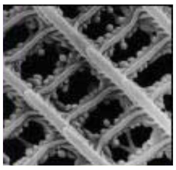
And in Nature……
Amazing Light and Particles!

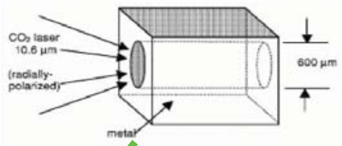


The inverse of Acceleration (energy gain) is Radiation (energy loss) and vice-versa

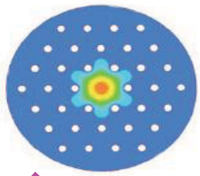
Cavendish Collab. on Meta-materials?

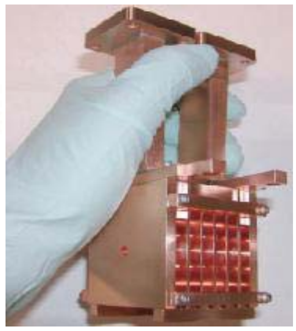


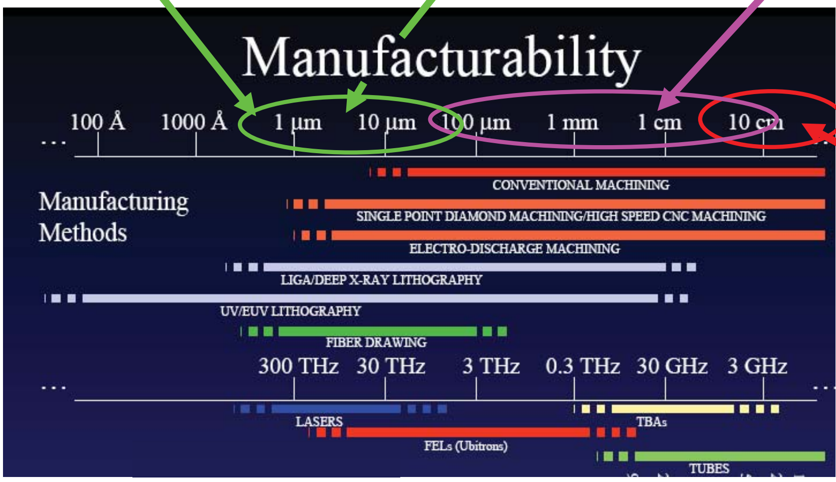




E. Smirnova et. al. (MIT), metallic photonic fiber, 17 GHz







CESR cavities

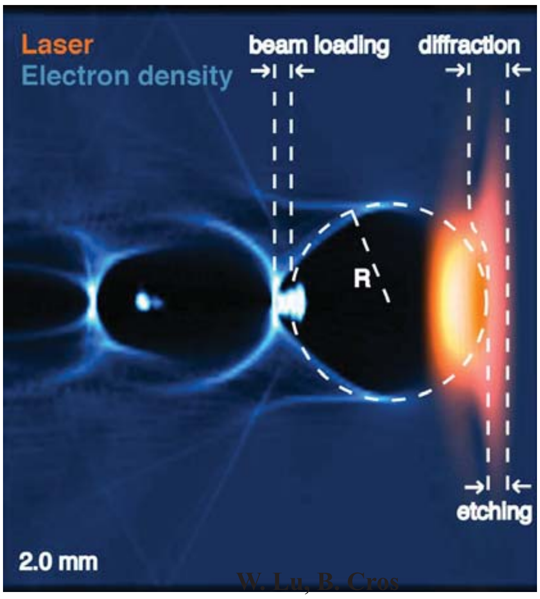
Photonic Structures and meta-materials

LASER-PLASMA ACCELERATION

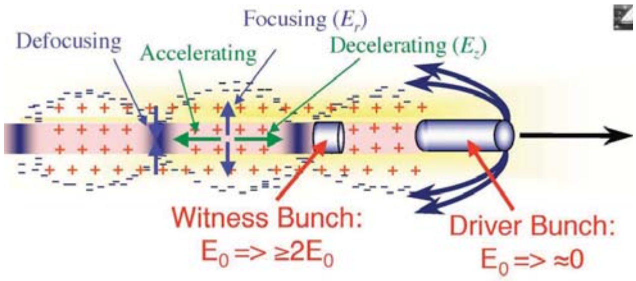
principle: plasma can sustain high accelerating gradients ~10-100 GV/m

→Requires staging 1000 modules of 1 GeV or 100 modules of 10 GeV each, with increasingly dense plasmas;

→Energy Efficiency from wall-plug to laser then from laser to plasma very very poor;



plasma excitation by drive bunch



P. Muggli

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laser-plasma acceleration

J. Faure et al., C. Geddes et al., S. Mangles et al. ,
3 articles in Nature 30 September 2004

recent breakthrough in beam quality from laser-plasma acceleration

next step:
1 GeV compact module,
100 TW laser,
& plasma channel;

LBNL, MPQ,Oxford, Paris

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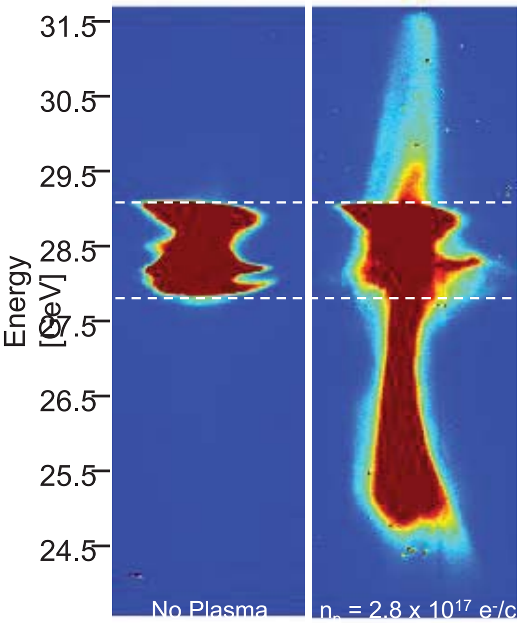
BEAM-PLASMA ACCELERATION:

Accelerating Gradient > 27 GeV/m! (Sustained Over 10cm)



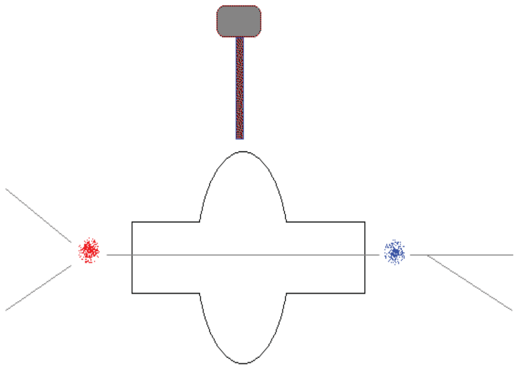
- Large energy spread after plasma is artifact of single bunch experiment
- Electrons have gained > 2.7 GeV over maximum incoming energy in 10cm
- Confirmed the predicted dramatic increase in gradient for short bunches
- First time a PWFA has gained more than 1 GeV
- Two orders of magnitude larger than previous beam-driven results
- Future experiments will accelerate a second "witness" bunch

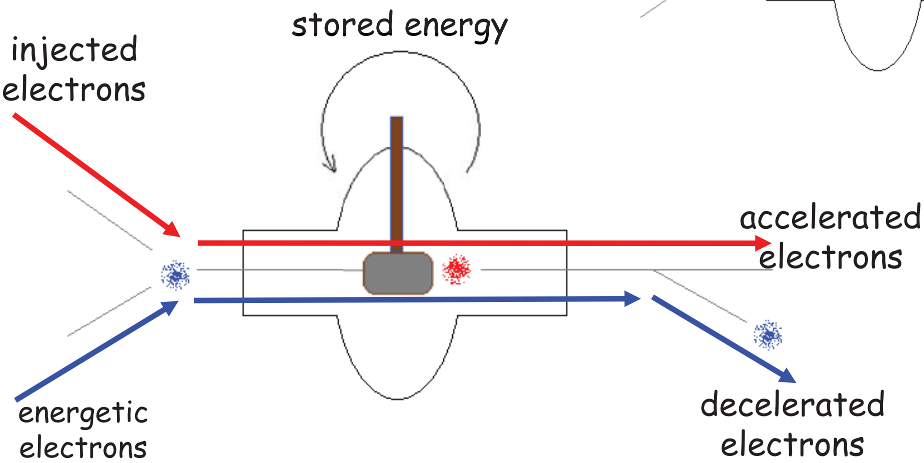
M. Hogan, P. Muggli, R. Siemann, et al.

Accepted for publication Phys. Rev. Lett. 2005

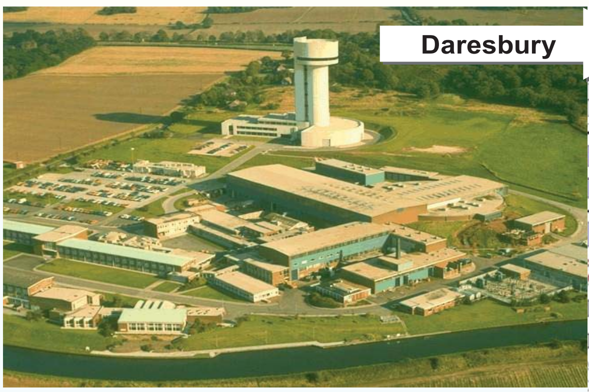
ADVANCED CONCEPTS: Energy Recovery

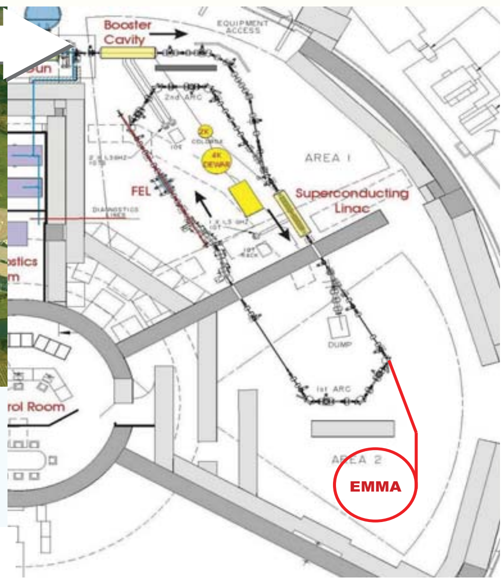
Efficient Recovery and Recycling of Energy is critical to future high luminosity low-cost colliders



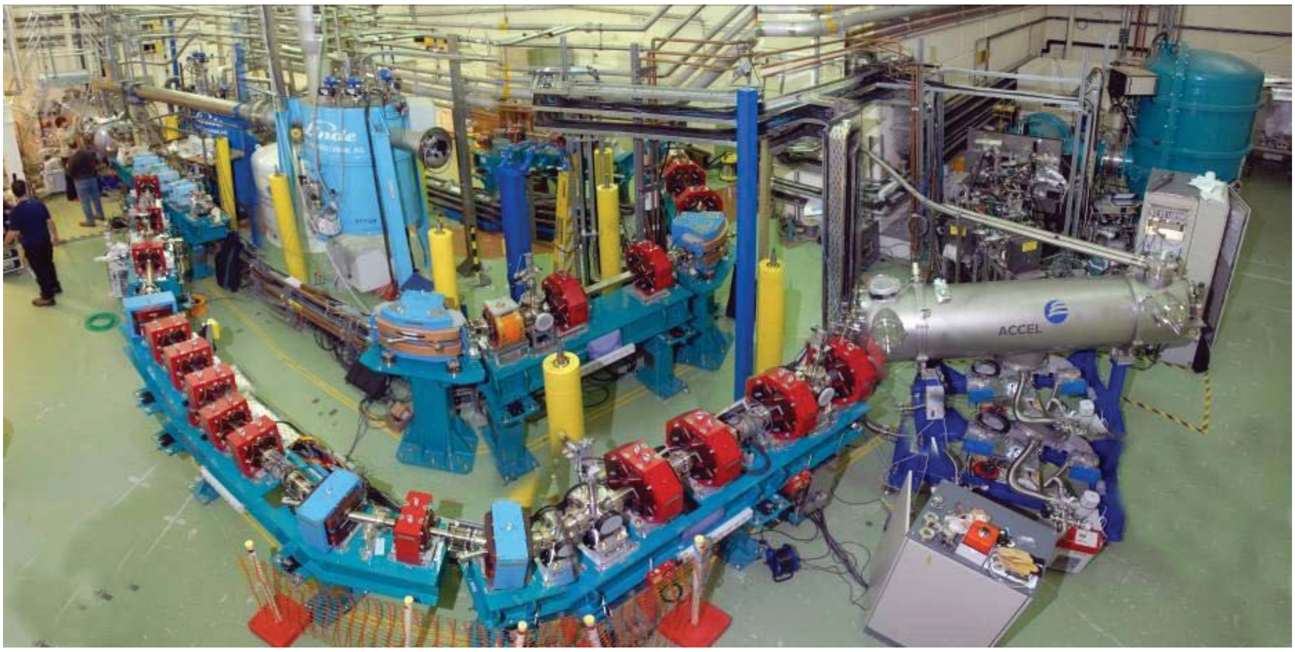


Location of ALICE at Daresbury…..





ALICE: A prototype with Energy Recovery and Ultra Short Pulses of Particles and Light at Daresbury Laboratory



Energy Recovery in ALICE

ACCELERATORS

ALICE achieves energy recovery at Daresbury and Cockcroft Institute

At 2.00 a.m. on 13 December 2008, the commissioning team at the ALICE facility of the UK's Daresbury Laboratory and Cockcroft Institute successfully demonstrated "energy recovery" from a relativistic electron beam at 11 MeV back into the microwave source that powers the linear accelerator. Although the FEL facility and the CEBAF at Jefferson Lab in the US recently demonstrated energy recovery, this is a first for a European team.

ALICE is designed to produce ultrabright and ultrashort pulses of electrons, coherent-synchrotron radiation, FEL and tailored Compton-scattered light, which can be used – in conjunction with modern ultrafast lasers – in cutting-edge experiments in physical and life sciences. At the same time, accelerator research at the facility could revolutionize the way that high-energy particle accelerators, colliders and accelerator-based photon- and neutron-research facilities are designed in the future. A major design goal is to achieve efficient energy recovery (i.e. the repeated exchange and recycling of energy between particles and microwaves). This is a critical requirement for both the scientific reach in beam brightness and the economic viability and affordability of future high-power, high-energy particle accelerators. High-energy beams from ALICE will also be used to explore technology for new cancer treatments in a linked demonstration project known as EMMA.

After more than four years of planning and construction, ALICE achieved its first high-energy beam at 12.54 a.m. on 24 October in the 4 MeV booster. This consists of a superconducting accelerator cavity fed by a photoinjector. The photoinjector is a high-brightness electron gun capable of generating extremely short pulses of electrons, which are fired into the booster at a rate of 81 million shots a second.

At 5.00 p.m. on 7 December, after the booster had accelerated the high-quality electron beam from the photoinjector to 4 MeV, the commissioning team took the beam from the booster up to relativistic energies of 11 MeV in a linear superconducting microwave accelerator (figure 1). The stage was then set for the final act, where the beam is threaded through 360° of beam-transport systems back to the start of the same linac. By recirculating in the opposite microwave phase, the beam undergoes deceleration to achieve energy recovery, where the energy used to accelerate the beam can be recovered and reused after each circuit of the machine.

Less than a week later, at 2.00 a.m. on 13 December, the superconducting linac accelerated electrons to a total energy of 11 MeV and the beam was successfully sent round the total circuit, demonstrating energy recovery for the first time outside the US. At 10.50 p.m. on 20 December, energy recovery was achieved at 20.8 MeV (figure 2).

The next stage will be to commission the facility to its full operating energy of 35 MeV.

● ALICE is financed by the UK's Science and Technology Facilities Council with seed funding from the North West Development Agency. It is operated by the ASTeC team within the Cockcroft Institute which is developing its advanced accelerator-research programme.

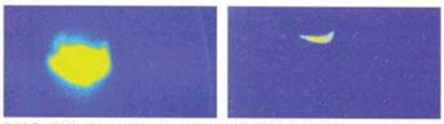


Fig. 1. The 4 MeV booster beam (left) accelerates on to relativistic energies (right) in the linac.

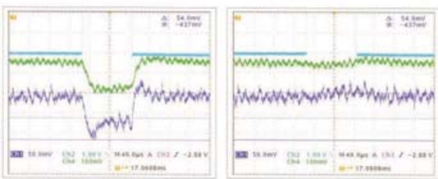


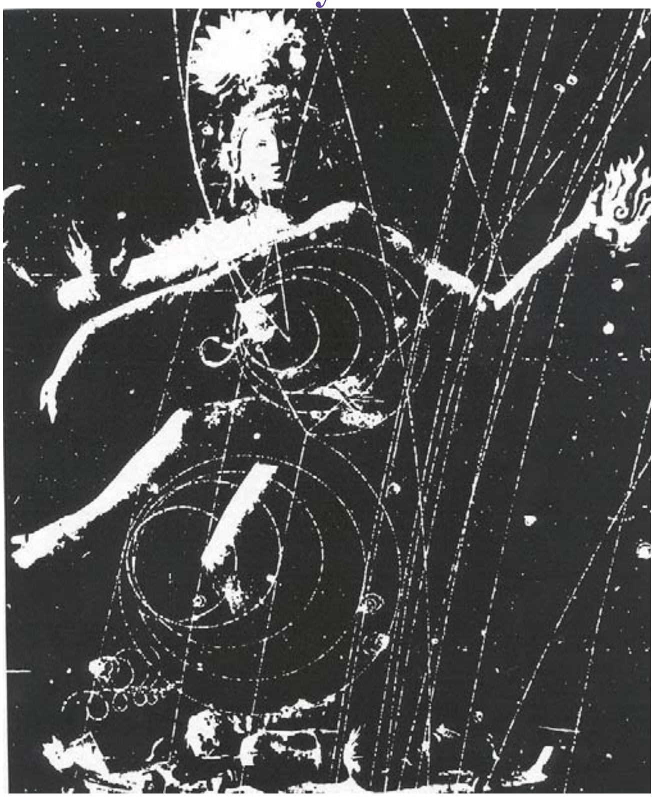
Fig. 2. The RF-gradient demand in the linac at 10.50 p.m. on 20 December, showing the effect of energy recovery (right) compared with no energy recovery (left). (All figures courtesy STFC Daresbury.)

Susan Smith of the Cockcroft Institute and group leader for accelerator physics in its ASTeC/STFC partnership at Daresbury celebrates with the ALICE commissioning team.

OUTLOOK

- We need new technologies and methods to further push the frontiers of energy and luminosity;
- There are many novel ideas, already useful for photon and neutron sciences;
- But very high energies and luminosities are proving to be a challenge on the laboratory scale;
- Particle physicists should join accelerator scientists over a long-term engagement in addressing these challenges head-on, while remaining active in a major current experimental collaboration.

Current situation: complex designs and forms
Community fragmented into many special interest groups, multiple ideas, facilities, ….
Lack of affordability forces us into simplicity….



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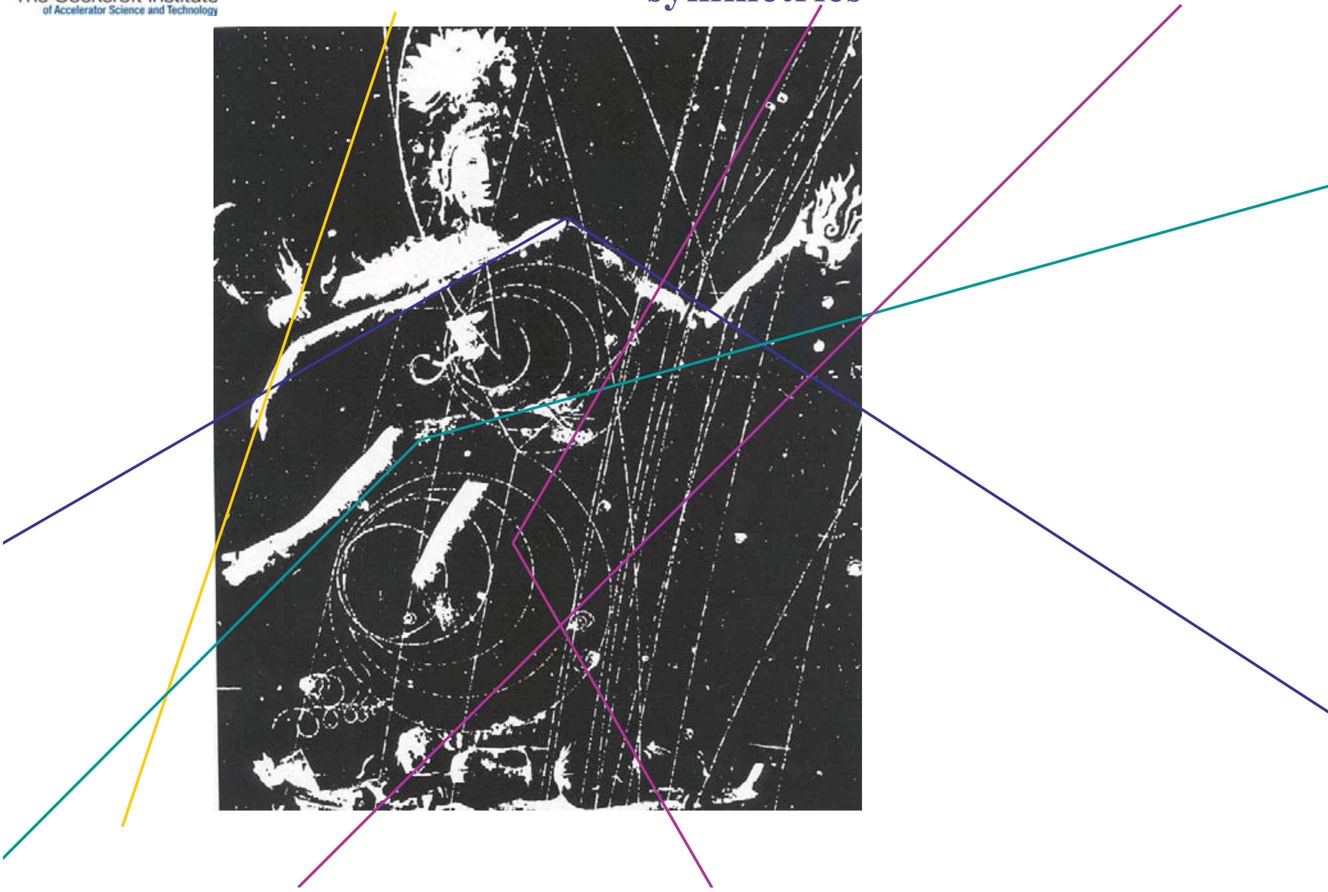
Slowly, “simplicity” emerges as patterns and symmetries



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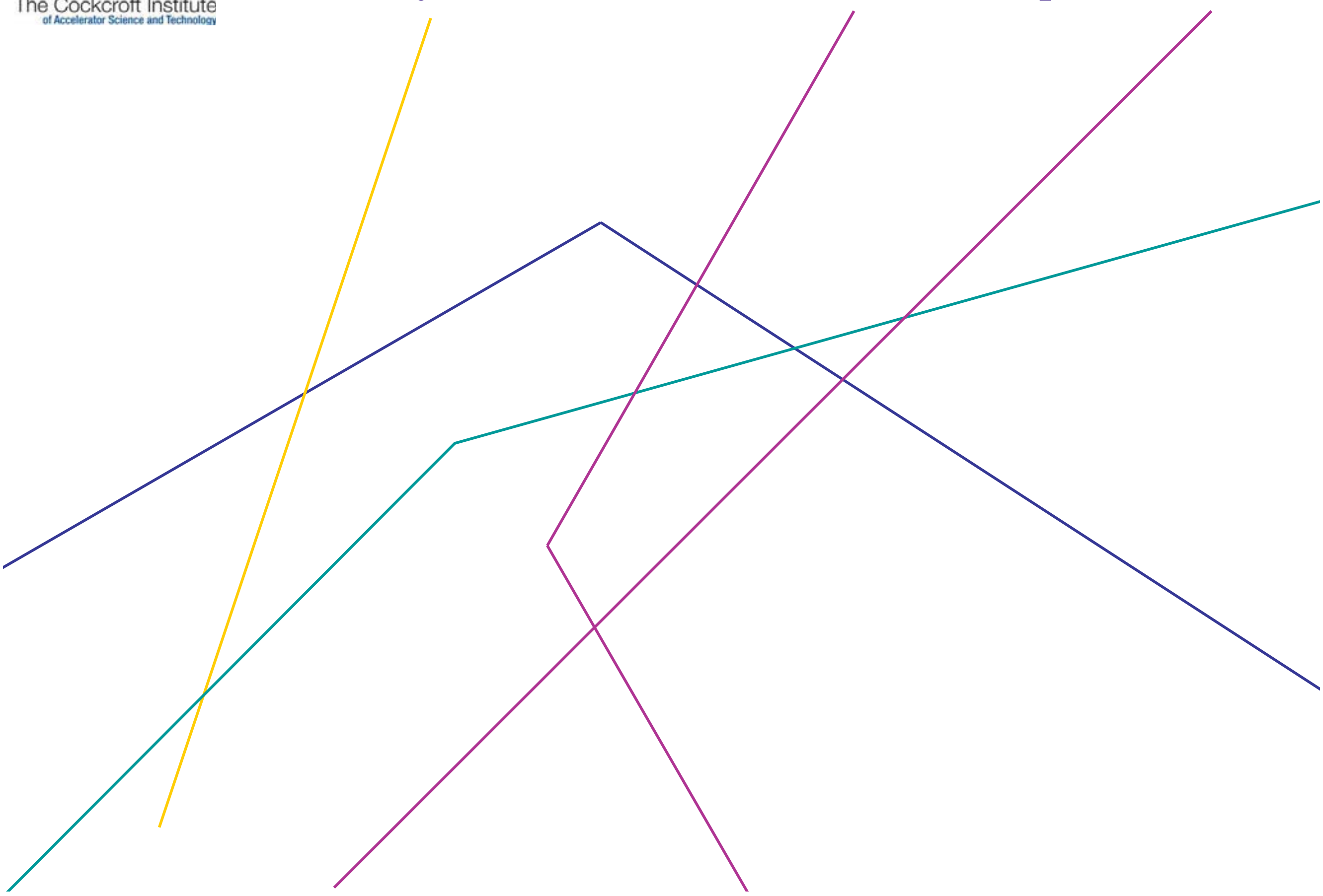
Ultimately all that’s left are abstracted simplicities



Musings on :

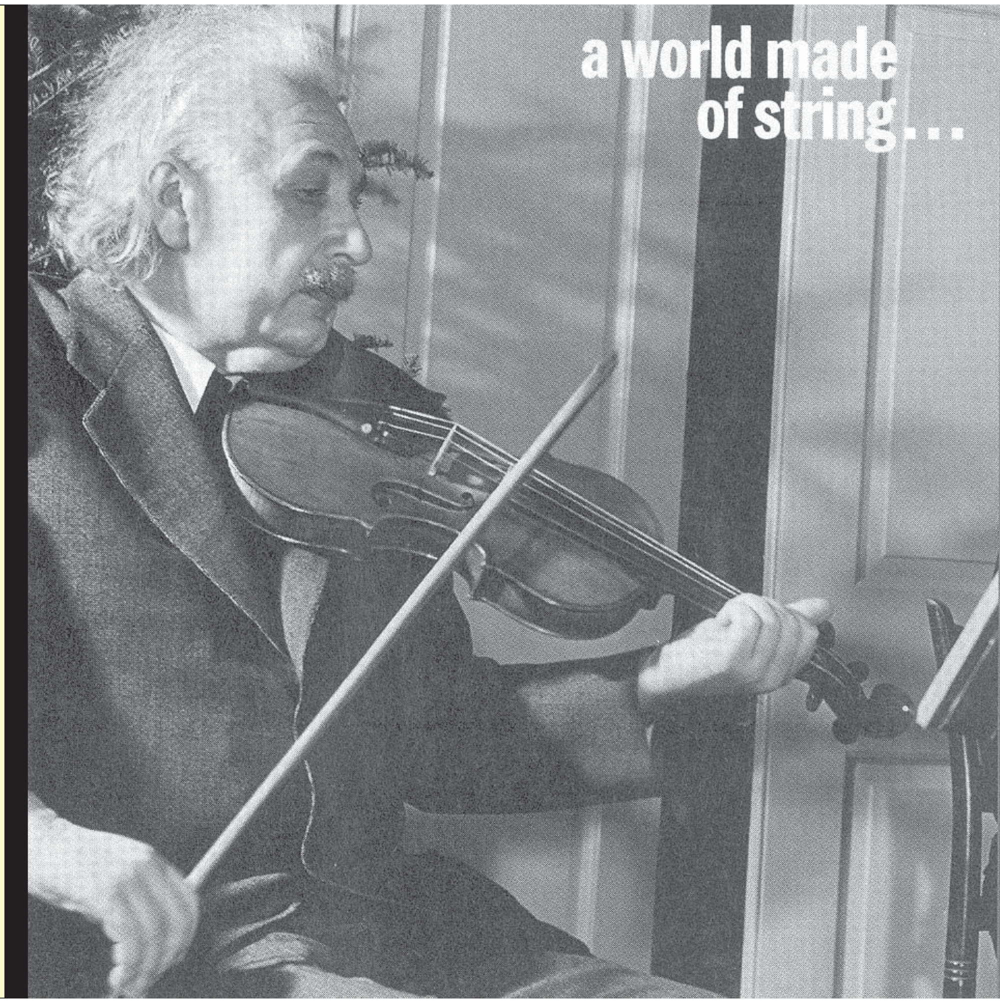
Einstein and Bose

Music and Diversity

Einstein and Bose, both musicians, believed in the oneness of all things human and connected ‘unity’ with ‘diversity’ via their music

Plate 6: Albert Einstein and S.N. Bose shared a talent and love for music: Einstein played the violin since his childhood.
Courtesy: Birla Industrial and Technological Museum, Calcutta

Plate 7: S.N. Bose was a master on the esraj.
Courtesy: Birla Industrial and Technological Museum, Calcutta


a world made
of string...

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Sir John Douglas Cockcroft FRS (1897-1967)

The Nobel Prize in Physics 1951

"…think of the incredible feats achieved by humans in other spheres of life with so little in their hands but by pure imagination…….may be we can be inspired in science by contemplating on such …….."