



Future Accelerator Challenges in Support of High-Energy Physics

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Introduction

- Historically, HEP has depended on advances in accelerator design to make scientific progress
 - cyclotron → synchrocyclotron → synchrotron → collider (circular, linear)
- Advances in accelerator design and performance require corresponding advances in accelerator technology
 - magnets, vacuum systems, RF systems, diagnostics, ...
- Accelerators enable the study of particle physics phenomena under (more or less) controlled conditions
- Cost of today's accelerator projects is high
 - international cooperation and collaboration are no longer optional
 - there is a danger of “pricing ourselves out of the market”



Accelerator Deliverables

- Particle accelerators are designed to deliver two parameters to the HEP user
 - energy and luminosity
- Energy is by far the easier parameter to deliver
 - and is easier to accommodate by the experimenters
 - higher luminosity invariably presents challenges to the detector
 - ...and to the accelerator physicist!
- Luminosity is a measure of collision rate per unit area
 - event rate for a given event probability (“cross section”) is given by

$$R = \mathcal{L} \sigma$$

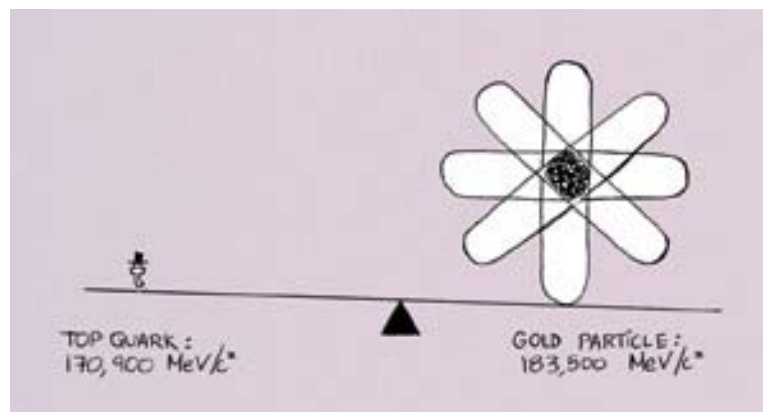
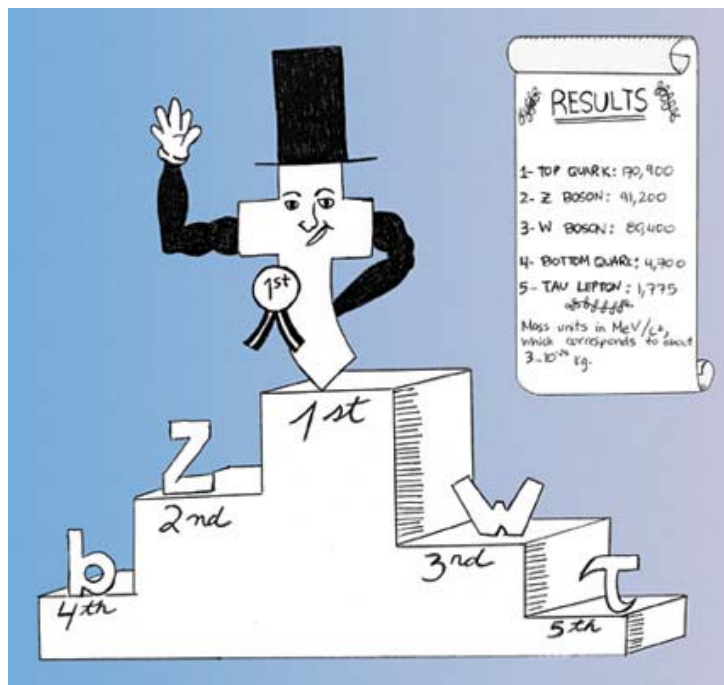
- For a collider with equal beam sizes at the IP, luminosity is given by

$$\frac{N_+ N_- f_c}{4\pi \sigma_x^* \sigma_y^*}$$

⇒ Need intense beams and small beam sizes at IP

Particle Physics Questions (1)

- There are two primary accelerator-related thrusts
 - understanding the origins of mass
 - what gives particles such different masses?
 - top quark has mass comparable to Au nucleus
 - neutrino mass is likely a fraction of an eV





Particle Physics Questions (2)

- understanding why we live in a matter-dominated universe
 - why are we here?
- After Big Bang, equal amounts of matter and antimatter created
 - why didn't it all annihilate?
 - believed to be due to slight differences in reaction rates between particles and antiparticles
 - charge-conjugation-parity (CP) violation
- CP violation observed experimentally in “quark sector”
 - B factories were built to study this
 - unfortunately, CP violation in quark sector **not large enough** to explain observed baryon asymmetry
 - prevalent view is that required additional CP violation occurs in lepton sector
 - never observed; neutrinos are the hunting ground

Today's Machines

- High energy physics typically uses **colliders** (counter-propagating beams that collide at one or more interaction points "IPs")
 - until recently, colliders were single-ring machines that required beams of particles and antiparticles, e.g., e^- and e^+
 - to get higher intensities and more bunches, modern colliders use two rings and thus no longer require two beams that have opposite sign

$$\frac{N_+ N_- f_c}{4\pi \sigma_x^* \sigma_y^*}$$

- Colliders typically store one of two types of particles
 - hadrons (protons, heavier ions)
 - Tevatron ($p - \bar{p}$), RHIC (nuclear physics), LHC ($p-p$)
 - leptons (electrons)
 - CESR-c, PEP-II, KEKB



Today's Machine Limitations (1)

- Hadron colliders

- protons are composite particles

- only $\approx 10\%$ of the beam energy is available for the hard collisions that make new particles

- need $\mathcal{O}(10 \text{ TeV})$ collider to probe the 1 TeV mass scale

- desired high beam energy requires very strong magnets to store and focus beam in a reasonable-sized ring

- antiprotons difficult to make

- takes hours to replace them if beam is lost

- using p-p collisions bypasses the second issue, but not the first

- the demand for ever-higher luminosity has led the LHC to choose

- p-p collisions

- many bunches

- two separate rings that intersect at select locations

Today's Machine Limitations (2)

- Lepton colliders (e^-e^+)

- synchrotron radiation is the biggest challenge
- emitted power in circular machine is

$$P_{SR}[\text{kW}] = \frac{88.5 E^4 [\text{GeV}] I [\text{A}]}{\rho [\text{m}]}$$

- for a 1 TeV c.m. collider in the LHC tunnel ($C = 27$ km) with a 1 mA beam, radiated power would be 2 GW
 - would need to provide this power with RF
 - and remove it from the vacuum chamber!

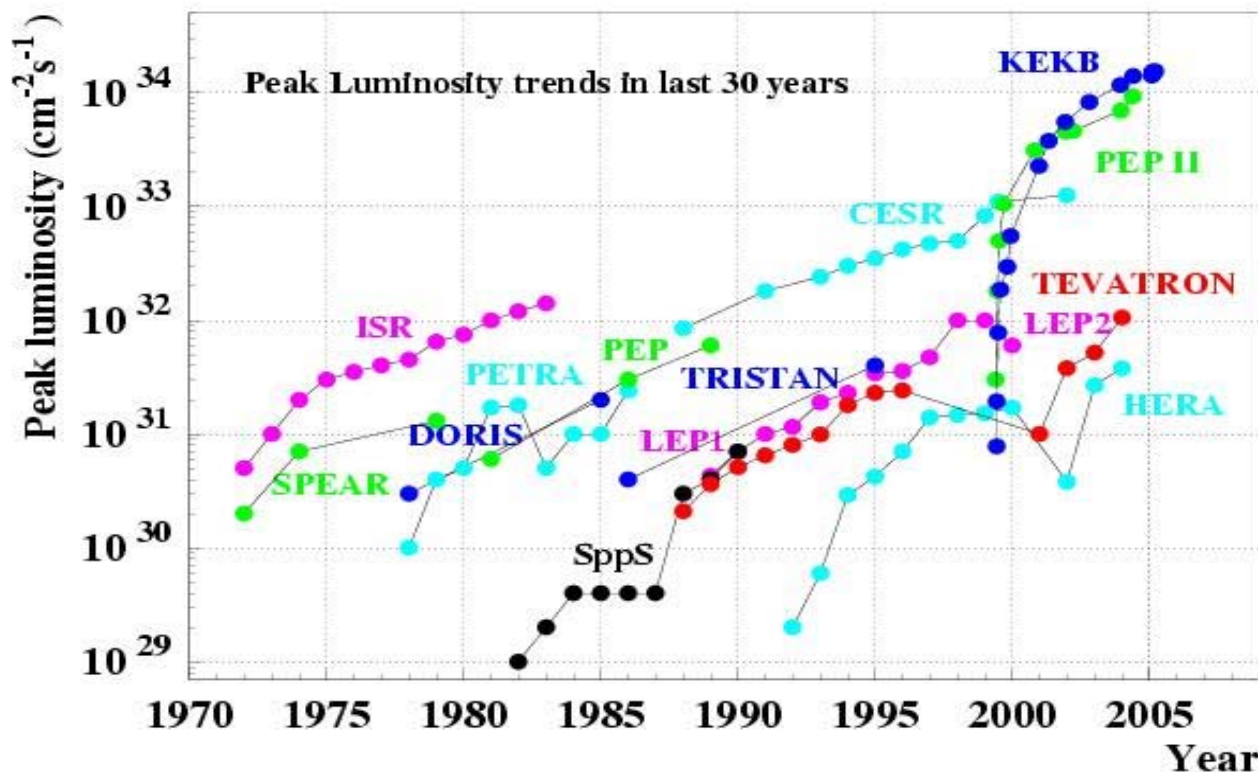
- Approach for high energies is linear collider (ILC, CLIC)

- footprint is large: 31 km in length (ILC); 48 km in length (CLIC)
 - too big to fit on-site at existing lab
- single-pass acceleration is inefficient (no reuse of hardware)

Luminosity Performance

- e^+e^- colliders have made great strides in delivering luminosity in recent years
- Both KEKB and PEP-II quickly reached luminosities beyond $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

New machines likely to be judged in comparison to these standards!



Future Machines

- At present, there are several machines on the drawing board to address the high-priority physics issues
 - not all of these are at the same stage of development
 - ILC and CLIC are furthest along in terms of R&D activities
 - most of these machines are very expensive
 - it is not likely that all of these will be built
- Precision frontier
 - ILC (e^+e^-)
 - Neutrino Factory (μ^+ or μ^-)
 - Super-B Factory (e^+e^-)
- Energy frontier
 - CLIC (e^+e^-)
 - Muon Collider ($\mu^+\mu^-$)

For reasons of personal taste and familiarity, I will tend to emphasize muon machines in this talk; these are the most novel, but not the most advanced, designs

Muon Accelerator Advantages

- Muon-beam accelerators can address both of the outstanding accelerator-related particle physics questions

- neutrino sector

- Neutrino Factory beam properties

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \Rightarrow 50\% \bar{\nu}_e + 50\% \nu_\mu$$

Produces high
energy neutrinos

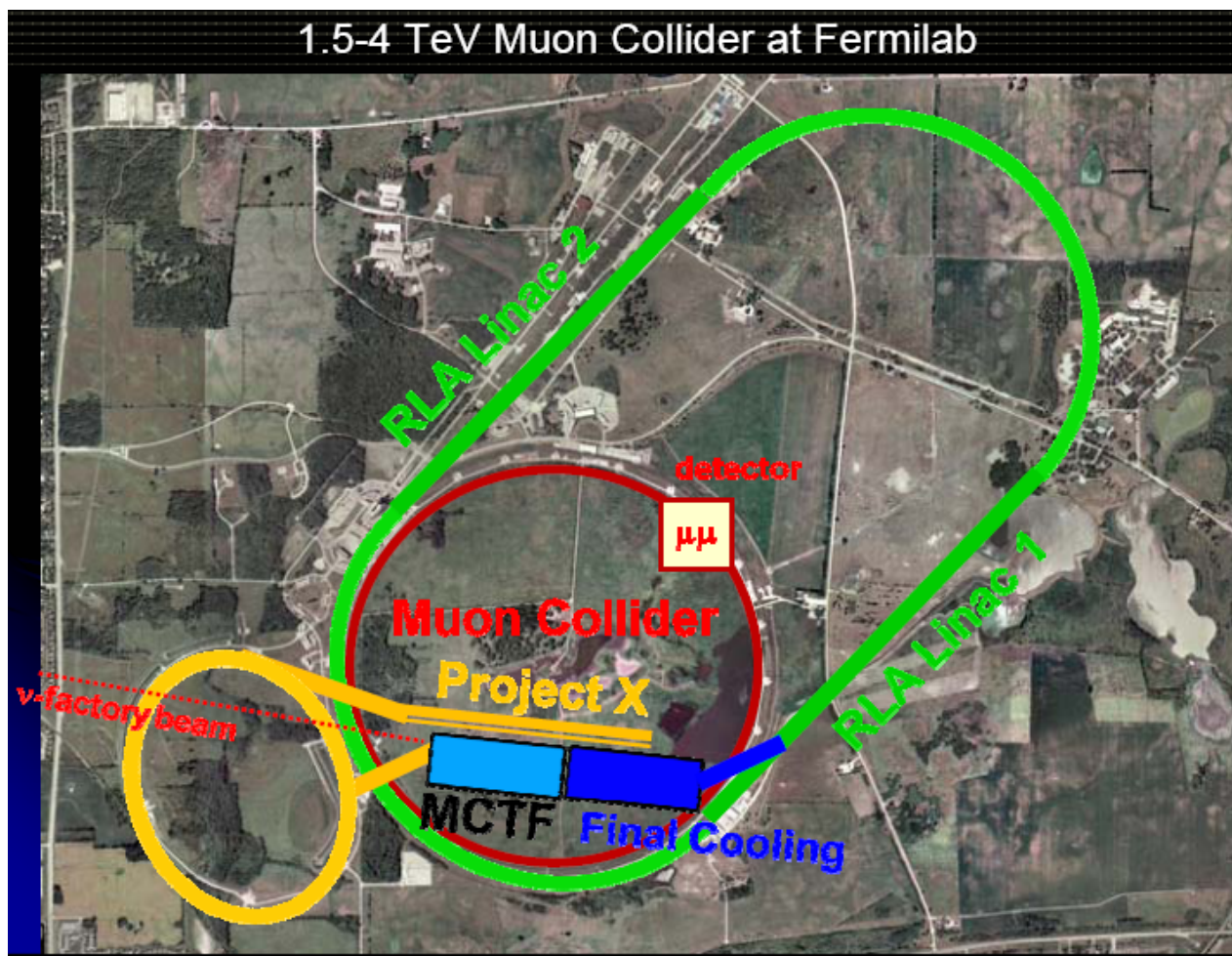
- decay kinematics well known
 - minimal hadronic uncertainties in the spectrum and flux
 - $\nu_e \rightarrow \nu_\mu$ oscillations give easily detectable “wrong-sign” μ

- energy frontier

- point particle makes full beam energy available for particle production
 - couples strongly to Higgs sector
 - Muon Collider has almost no synchrotron radiation
 - narrow energy spread
 - fits on existing Lab sites

Muon Collider at Fermilab

- Schematic of Muon Collider on Fermilab site
 - it fits comfortably





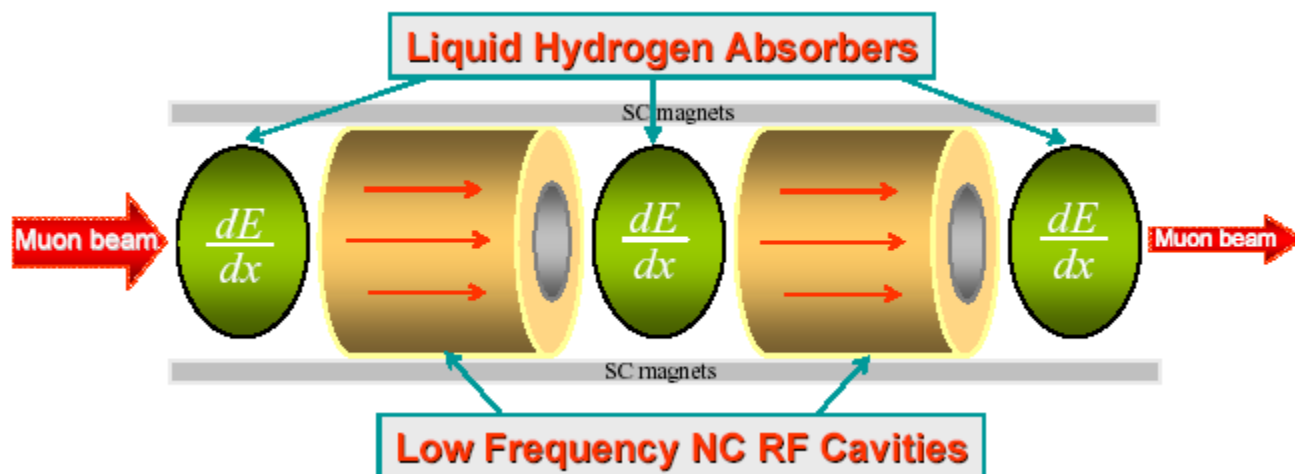
Muon Beam Challenges

- 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 ($2.2 \mu\text{s}$ at rest)
 - puts premium on rapid beam manipulations
 - presently untested ionization cooling technique
 - high-gradient RF cavities (in magnetic field)
 - fast acceleration system
- Decay electrons give backgrounds in collider detector and instrumentation, and heat load to magnets (NF and MC)

If intense muon beams were easy to produce, we'd already have them!

Ionization Cooling (1)

- Ionization cooling analogous to familiar SR damping process in electron storage rings
 - energy loss (SR or dE/ds) reduces p_x , p_y , p_z
 - energy gain (RF cavities) restores only p_z
 - repeating this reduces $p_{x,y}/p_z$ (\Rightarrow 4D cooling)
- presence of LH_2 near RF cavities is an engineering challenge
 - we get lots of “design help” from Lab safety committees!



Ionization Cooling (2)

- There is also a heating term
 - for SR it is quantum excitation
 - for ionization cooling it is multiple scattering
- Balance between heating and cooling gives equilibrium emittance

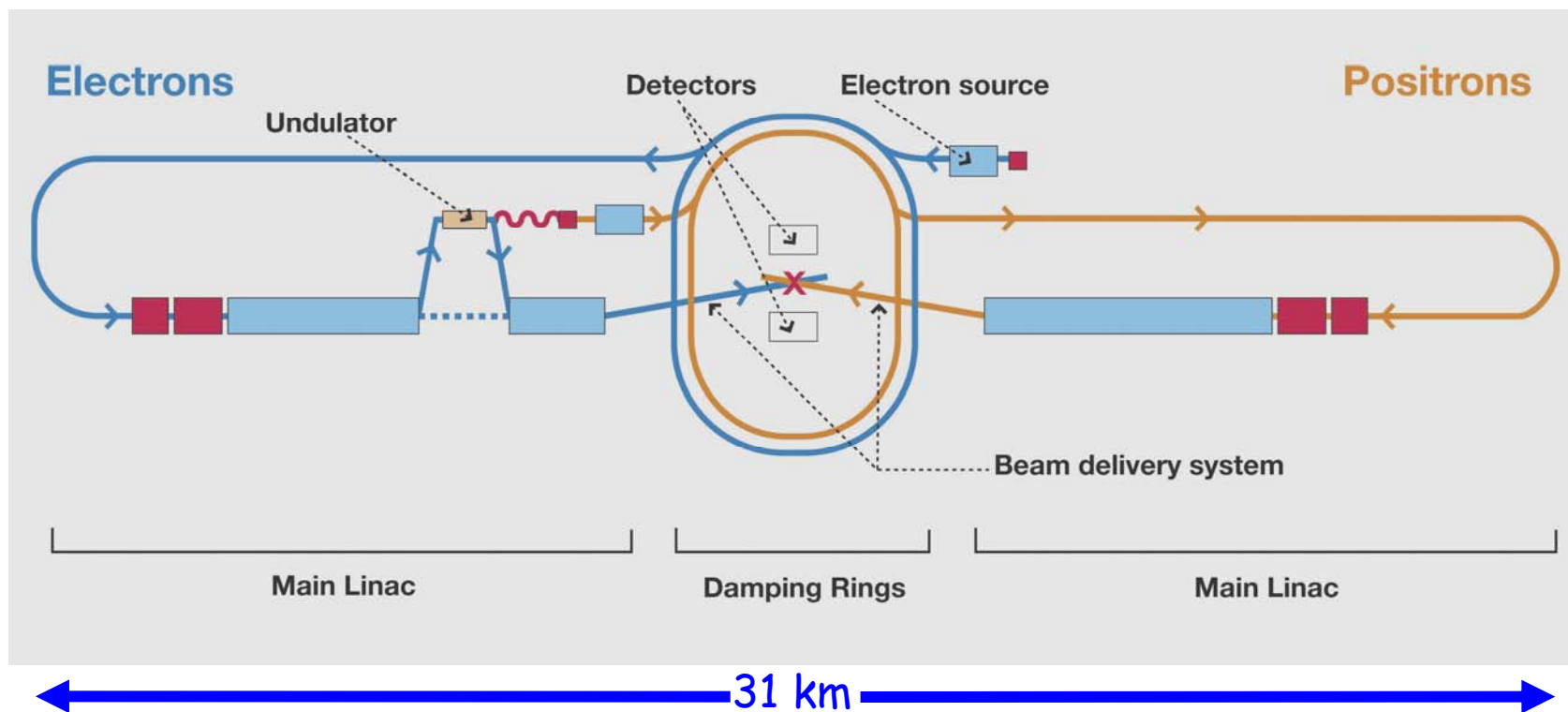
$$\frac{d\varepsilon_N}{ds} = - \underbrace{\frac{1}{\beta^2} \left| \frac{dE_\mu}{ds} \right| \frac{\varepsilon_N}{E_\mu}}_{\text{Cooling}} + \underbrace{\frac{\beta_\perp (0.014 \text{ GeV})^2}{2 \beta^3 E_\mu m_\mu X_0}}_{\text{Heating}}$$

$$\varepsilon_{x,N, \text{equil.}} = \frac{\beta_\perp (0.014 \text{ GeV})^2}{2 \beta m_\mu X_0 \left| \frac{dE_\mu}{ds} \right|}$$

- prefer low β_\perp (strong focusing), large X_0 and dE/ds (H_2 is best)

ILC

- ILC is aimed initially at 0.5 TeV energy scale
 - two linacs + central damping ring complex
 - damping rings produce **2 pm-rad** vertical emittance
 - technical challenges: low emittance, SRF gradient (31.5 MV/m)



Neutrino Factory

• Neutrino Factory comprises these sections

— Proton Driver

- primary beam on production target

— Target, Capture, and Decay

- create π ; decay into $\mu \Rightarrow$ **MERIT**

— Bunching and Phase Rotation

- reduce ΔE of bunch

— Cooling

- reduce transverse emittance

\Rightarrow **MICE**

— Acceleration

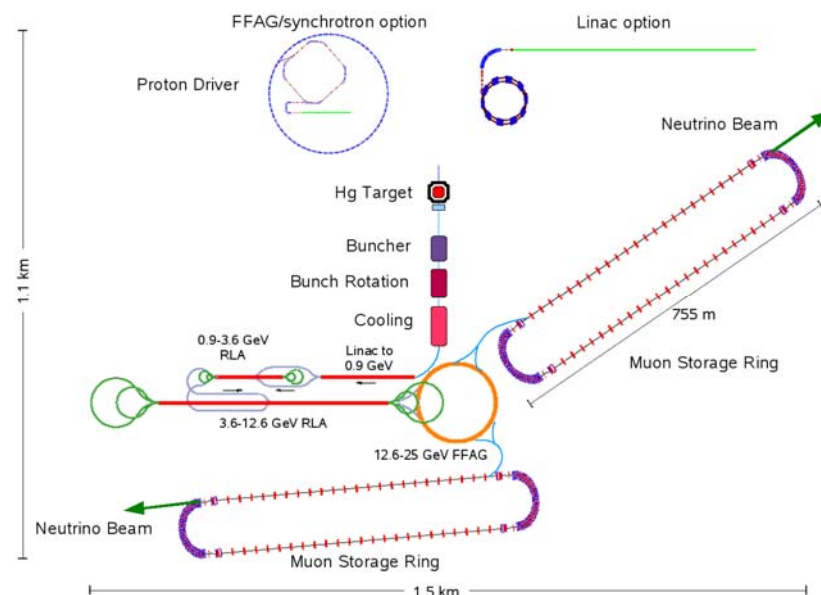
- 130 MeV \rightarrow 20-50 GeV
with RLAs or FFAGs

— Decay Ring

- store for 500 turns;
long straight(s)

Aim for 10^{21} ν_e per year
aimed toward detector(s)

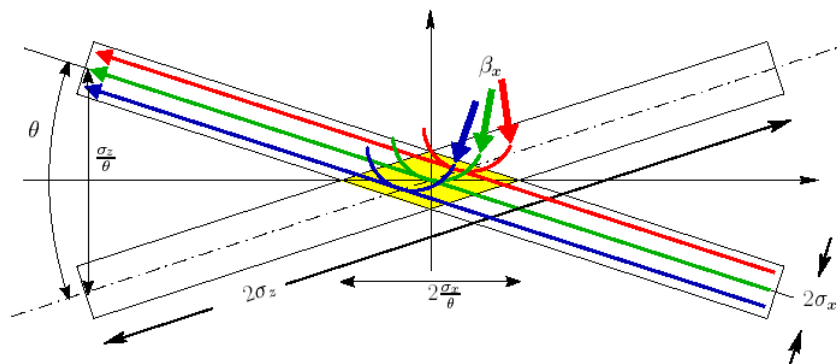
ISS Baseline



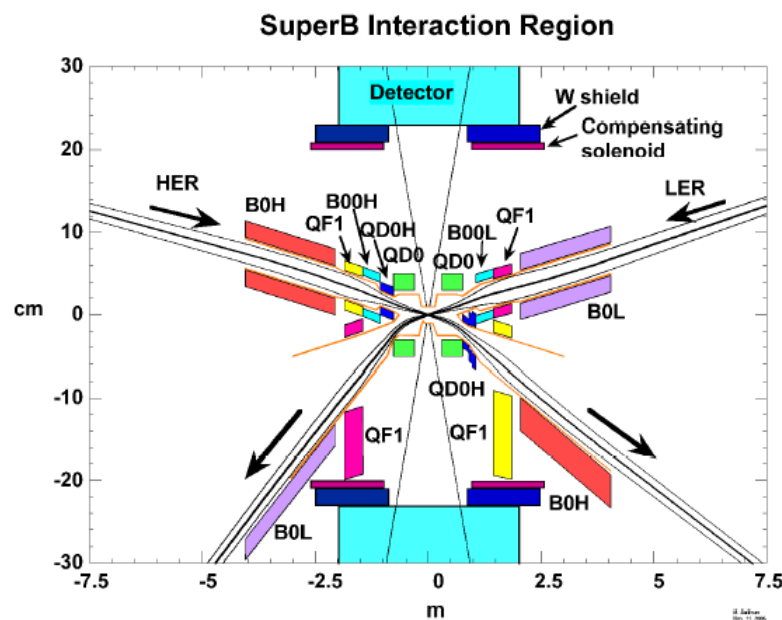
Super-B Factory

- Goal: run at $Y(4S)$ with luminosity of $\sim 1 \times 10^{36} \text{ cm}^{-2} \text{ s}^{-1}$
- Use low-emittance rings with "crab waist" scheme to reduce effective beam size at IP
 - IR sextupoles suppress harmful synchrotron resonances

Rings patterned after ILC DR design; would reuse many PEP-II components

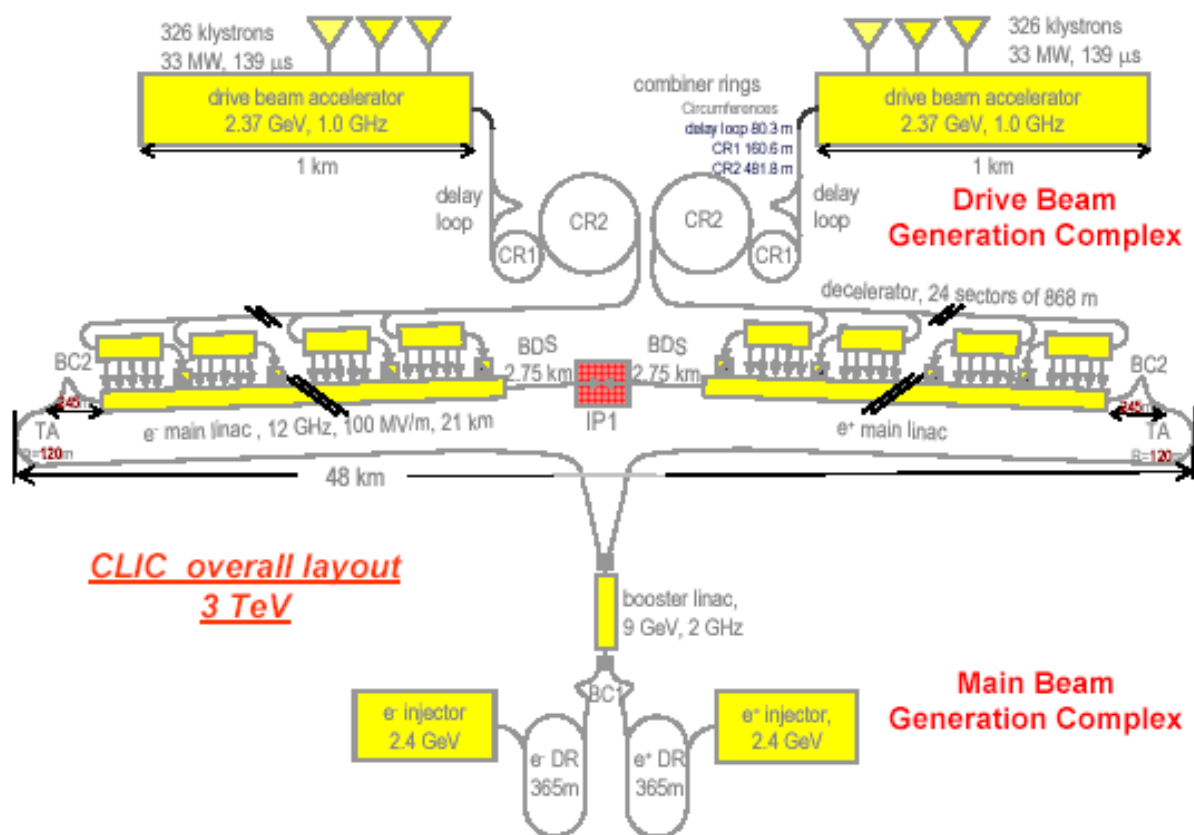


Frascati-SLAC design effort



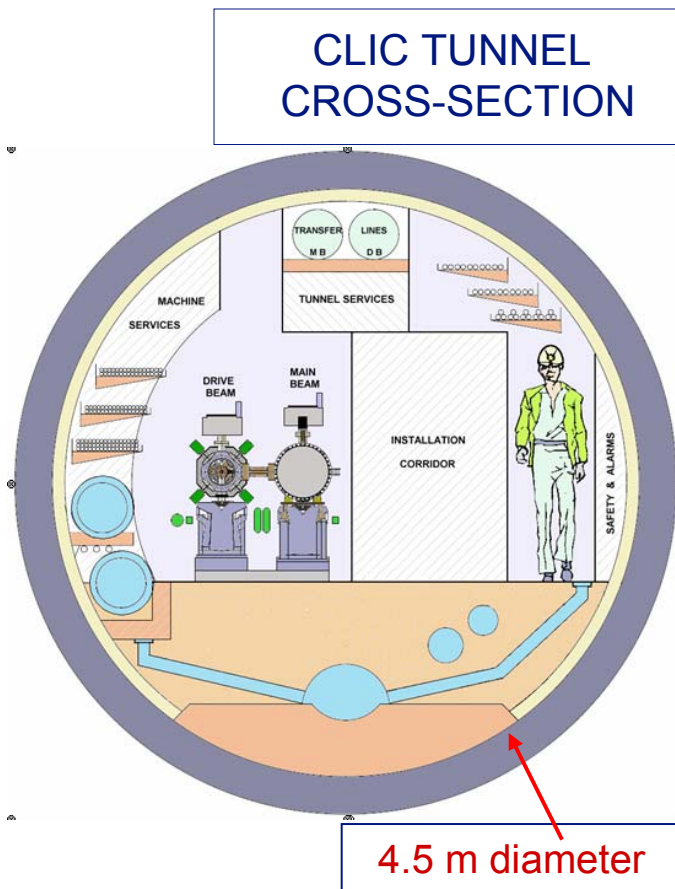
CLIC Layout

- CLIC is designed for a 3 TeV collision energy
 - has comparable E reach to LHC
 - uses “drive beam” for RF power generation



CLIC Features

- Novel two-beam acceleration concept
 - efficient, reliable, cost-effective
 - no active elements in main tunnel
 - modular; easily upgradeable to higher energies
 - high gradients (>100 MV/m)
 - “compact” for 3 TeV linear machine (cf. ILC)



Drive beam - 95 A, 240 ns
from 2.4 GeV to 240 MeV

QUAD

QUAD

POWER EXTRACTION
STRUCTURE

ACCELERATING
STRUCTURES

BPM

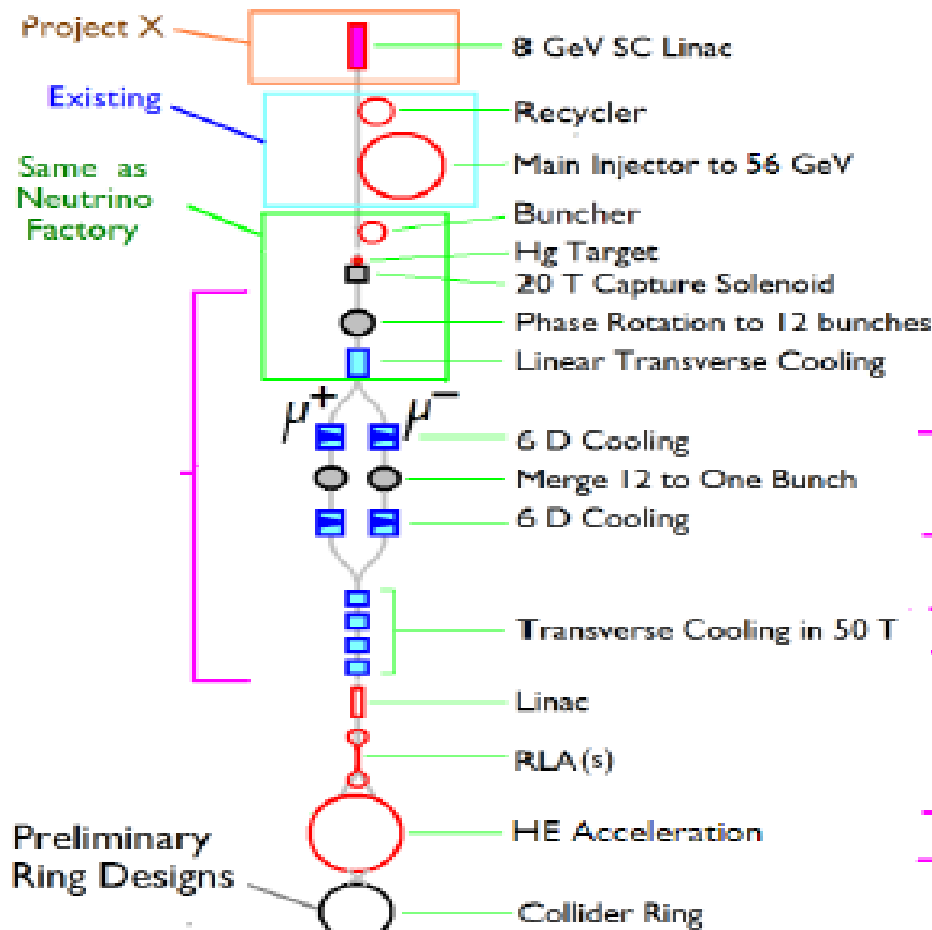
Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV
100 MV/m

Muon Collider Scheme

Scheme

Based on
Project X at
Fermilab

Fits on Fermilab site



Options

* Probably favored
& used in next slide

Guggenheim *
HCC
Guggenheim + gas
Wiggler

50 T solenoids *
REMX

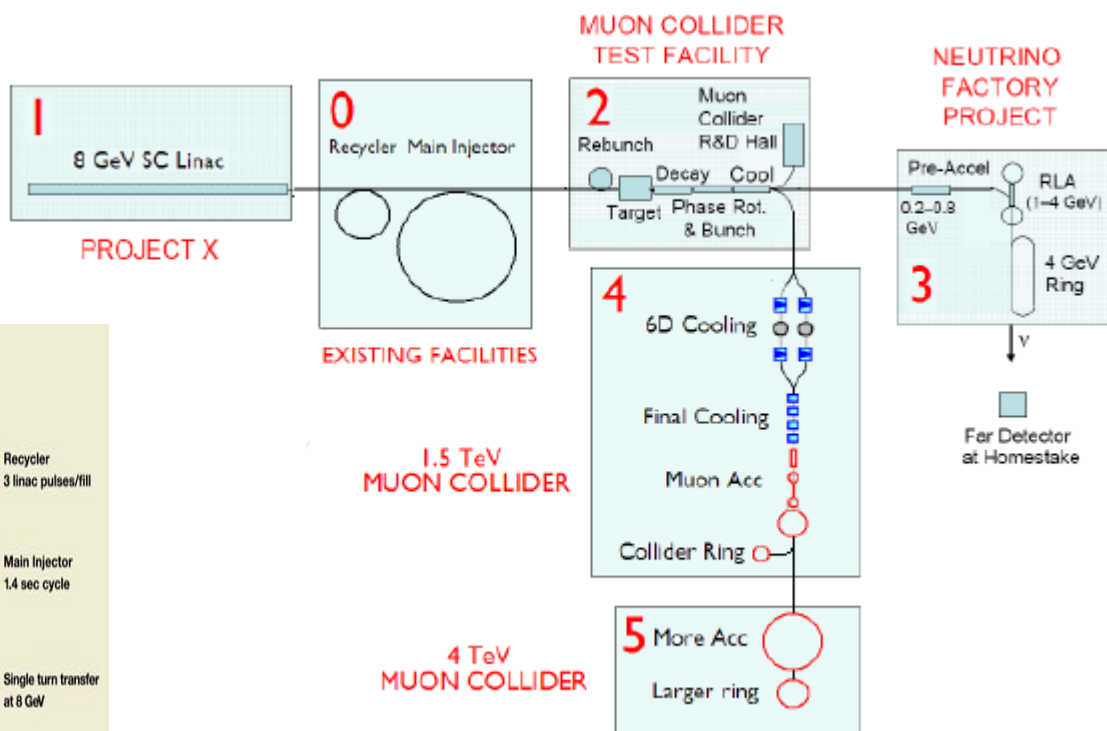
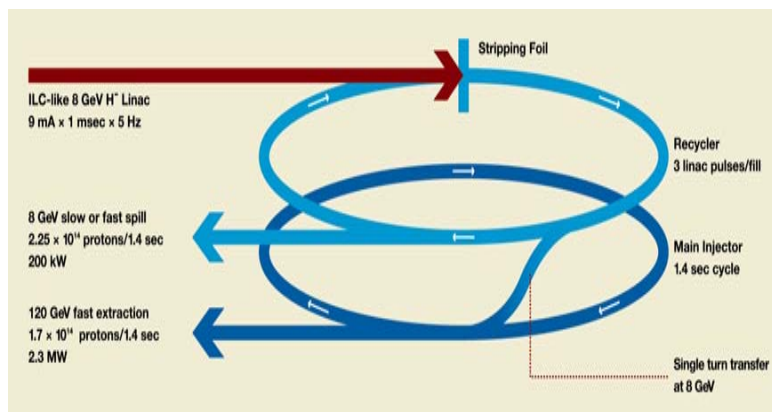
RLA
Pulsed Synchrotron *
FFAG

Phased Approach to Muon Facility

- Fermilab exploring path toward future muon beam facility
 - “imperative” is to keep Fermilab (the only active U.S. HEP lab) scientifically productive in the era when Tevatron has been shut down
 - expected in approx. 2010

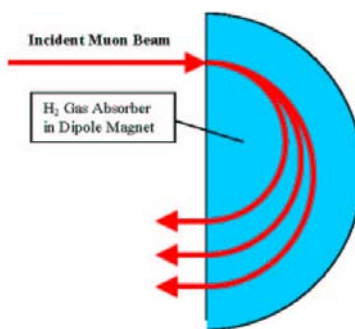
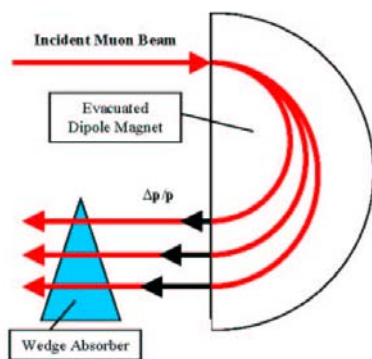
Project X is the key!

It also develops U.S. capabilities toward ILC



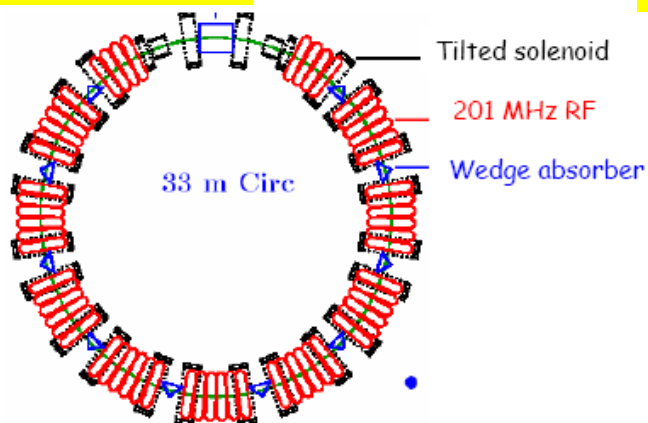
6D Cooling

- For 6D cooling, add emittance exchange to the mix
 - increase energy loss for high-energy compared with low-energy muons
 - put wedge-shaped absorber in dispersive region
 - use extra path length in continuous absorber

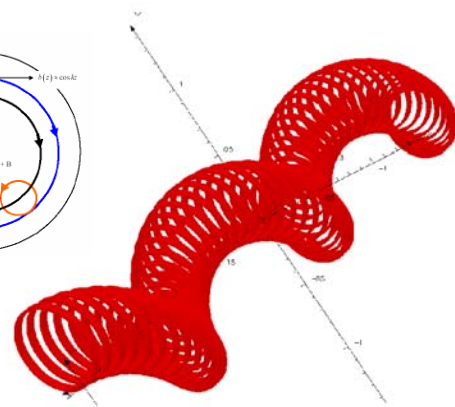
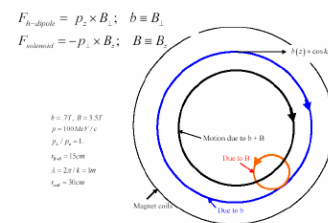
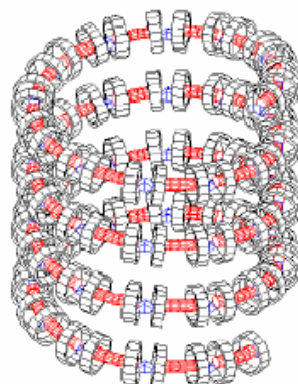


Gas-filled helical channel
Issue: how to realistically incorporate RF into design

Cooling ring



"Guggenheim" channel





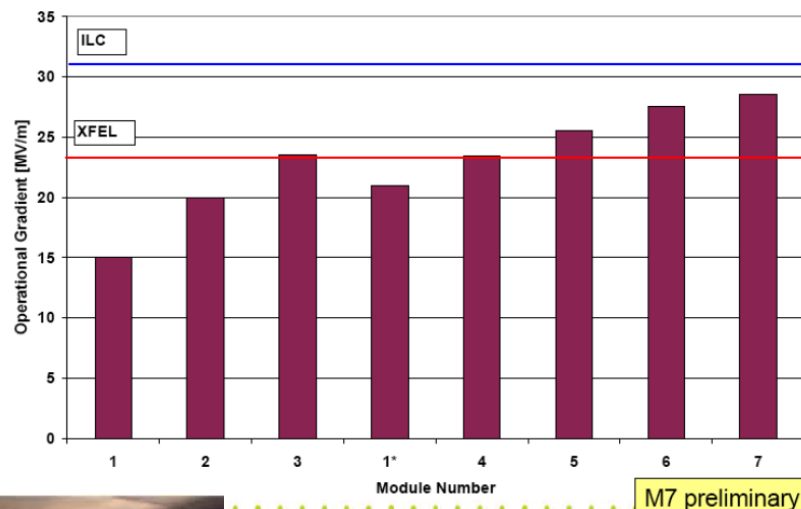
R&D Activities

- Putative projects covered here are embarked on R&D to:
 - prove physics concepts
 - validate technology choices
 - develop realistic, defensible cost estimates
- There are several “audiences” for the R&D results
 - the project advocates
 - the scientific community
 - ≥ 1 Laboratory directors
 - ≥ 1 funding agencies/governments
- Intensity and emittance **will place high demands on instrumentation**
- While I cannot do justice to the complete R&D programs, I will attempt to give a flavor of what is under way

ILC R&D Program (1)

- Primary effort for ILC is reaching design gradient with production cryomodules

Producing Cavities



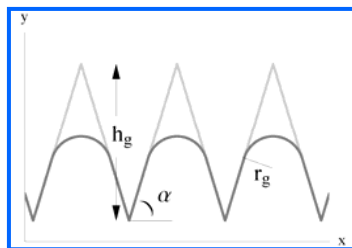
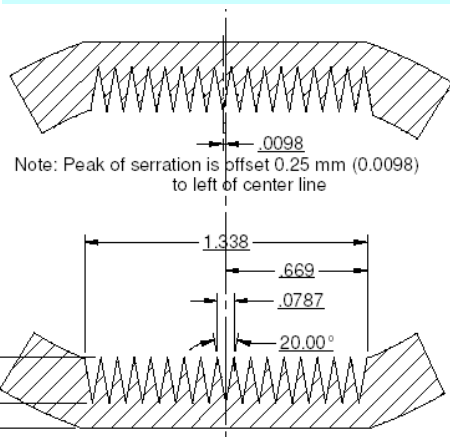
Making progress;
not there yet

Cryomodule
tests at DESY

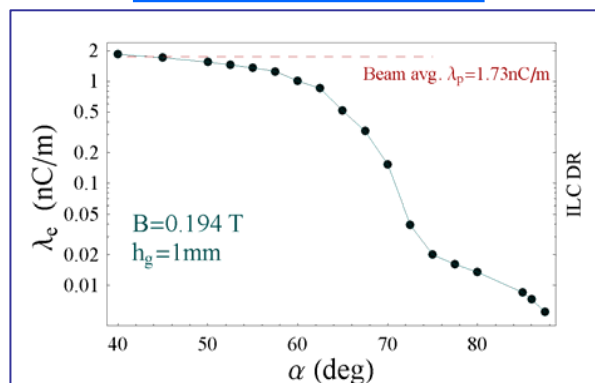
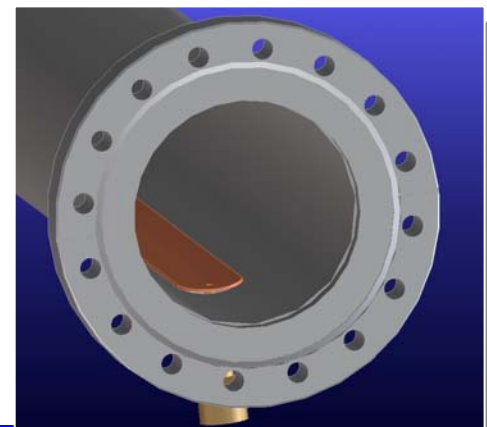
ILC R&D Program (2)

- Another big technical concern is e-cloud effect in PDR
 - issue is degradation of vertical emittance due to interaction with e-cloud
- Initially addressed by simulations and tests of modified vacuum chamber designs at PEP-II
 - testing “grooved” chambers and clearing electrodes
 - simulations indicate beneficial effects will keep DR parameters below instability threshold

Grooved chamber



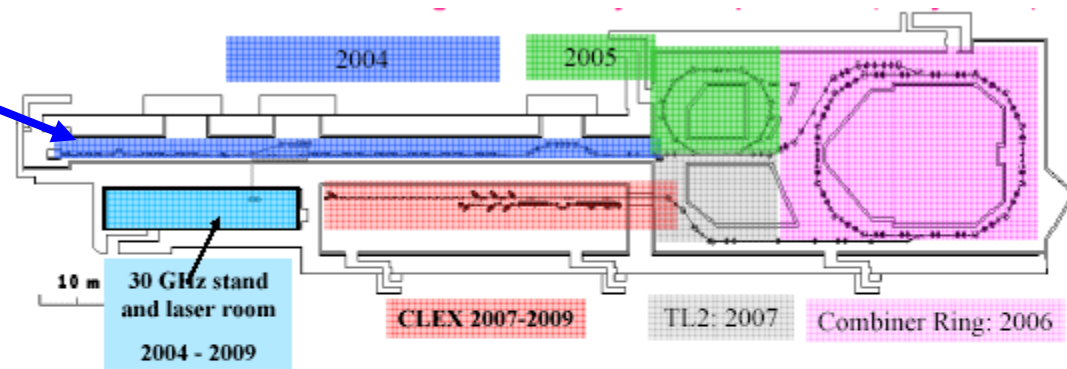
Clearing electrode chamber



CLIC R&D Program (1)

- Primary effort for CLIC is to demonstrate feasibility of CLIC technology (CTF3)
 - and estimate its cost
 - 19 countries currently involved in CLIC effort (centered at CERN)
 - coordination with ILC on issues of common interest, e.g., DRs

INJECTOR



Key issues

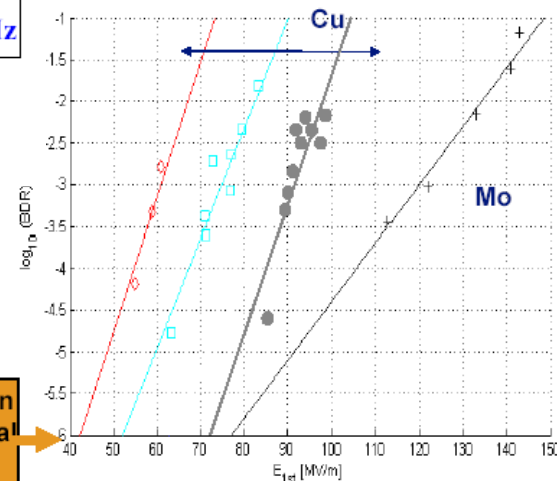
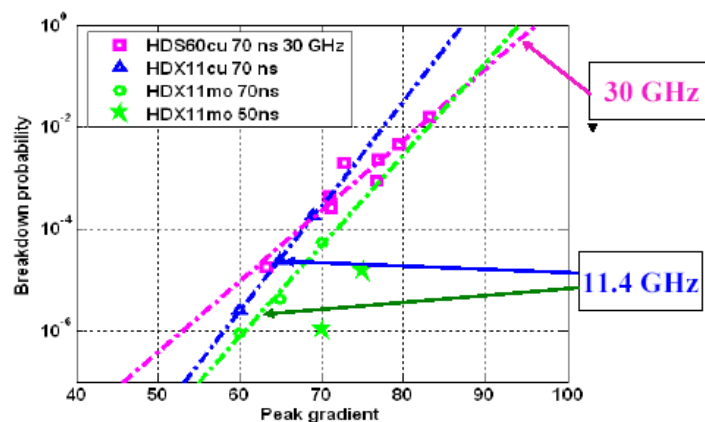
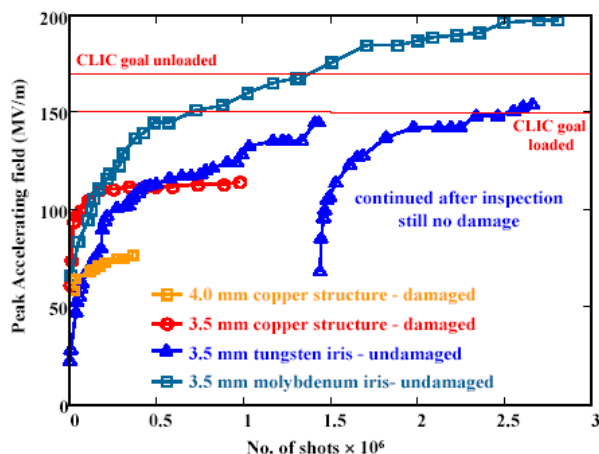
From 2005: Accelerating structures Development & Tests (R2.1)

2007- 2008: Drive beam generation scheme (R1.2)

2008- 2009: Damped accelerating structure with nominal parameters (R1.1)
ON/OFF Power Extraction Structure (R1.3)
Drive beam stability bench marking (R2.2)
CLIC sub-unit (R2.3)

CLIC R&D Program (2)

- High gradients with “hard” materials demonstrated in CTF2
 - both Mo and W irises look workable (up to 190 MV/m!)
 - issue is breakdown rate, which is not yet acceptable for operation
 - breakdown criterion shows little frequency dependence



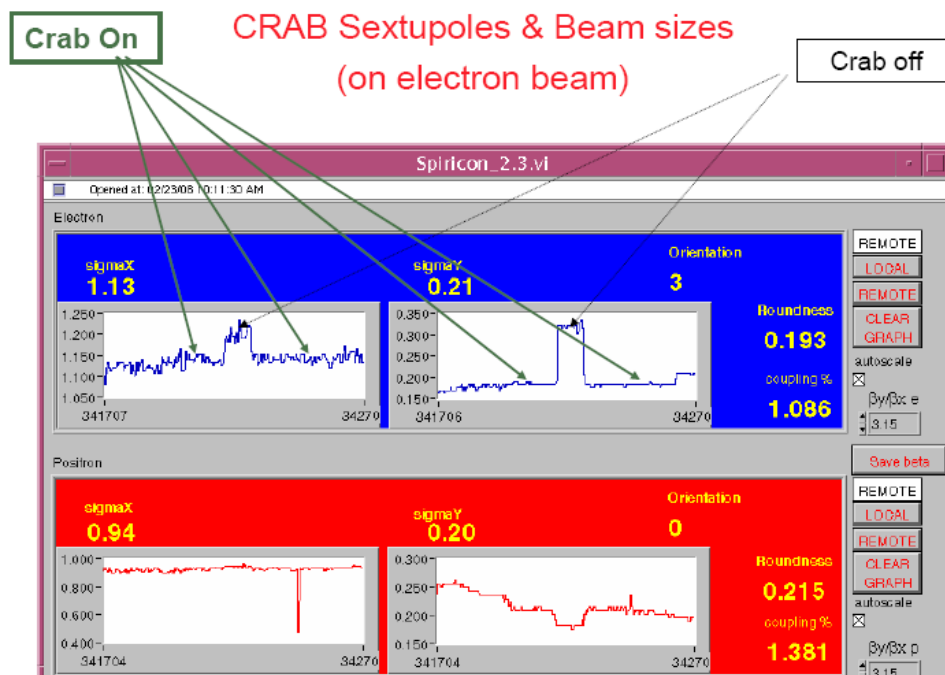
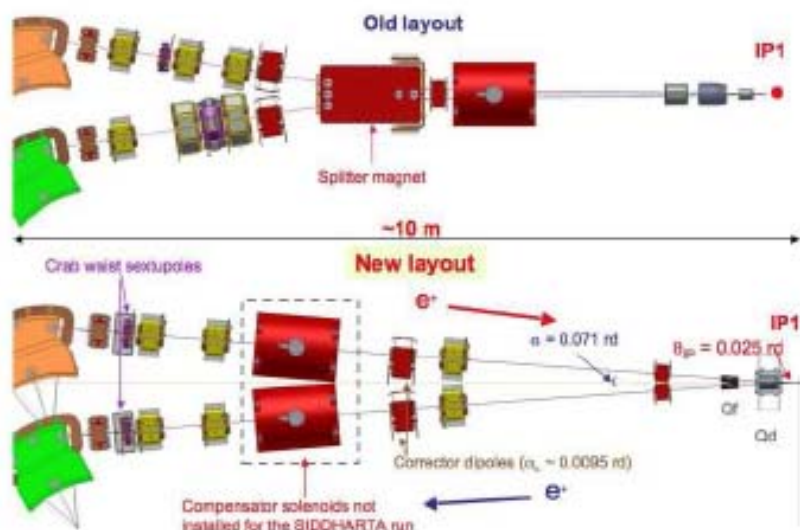
Super B Factory R&D

• Primary issues

- does crab waist scheme work as expected?
- can the IP beta value be low enough to get a $\times 100$ luminosity increase?

• Test of crab waist scheme at DAΦNE getting under way

- modified IR to give crossing angle
 - sextupoles added to IR





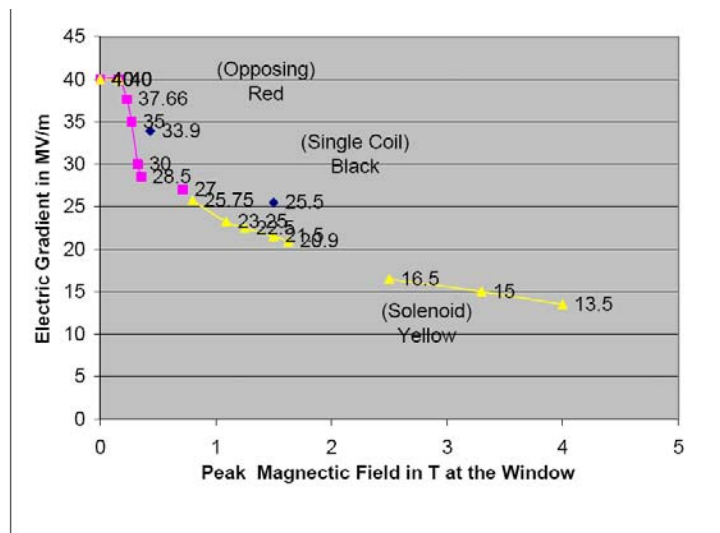
Muon Beam R&D Program

- Broad R&D program under way in all regions
 - Europe: various institutions sponsored by **BENE** and **UKNF**
 - Japan: **NuFact-J** group supported by university and some US-Japan funds
 - US: **NFMCC** program sponsored primarily by DOE with help from NSF
- Includes several international efforts already
 - **MERIT** (target test)
 - **MICE** (ionization cooling test)
 - **EMMA** (electron model of non-scaling FFAG)
 - **IDS-NF** (Neutrino Factory design study)
- Other experiments in planning stage
 - **MANX** (6D cooling)
 - Target test facility at CERN

Note: R&D effort relevant both to NF and MC

Cooling Channel RF

- Cooling channel requires high-gradient 201 MHz RF in a strong (solenoidal) magnetic field
 - prototype cavity built by LBNL-Jlab collaboration (Li, Rimmer, Virostek)
 - easily reached 19 MV/m design gradient without magnetic field at MTA
 - waiting for a Coupling Coil to test in high magnetic field
- 805 MHz experiments indicate substantial degradation of gradient in such conditions



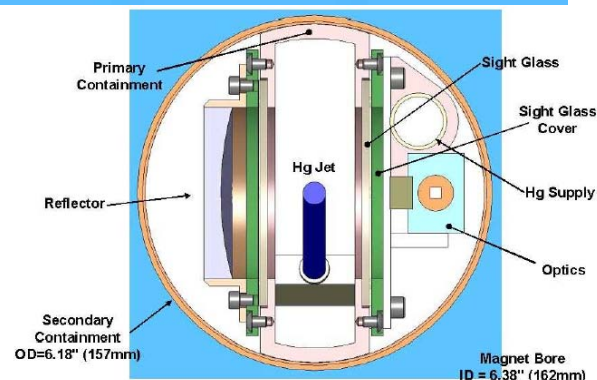
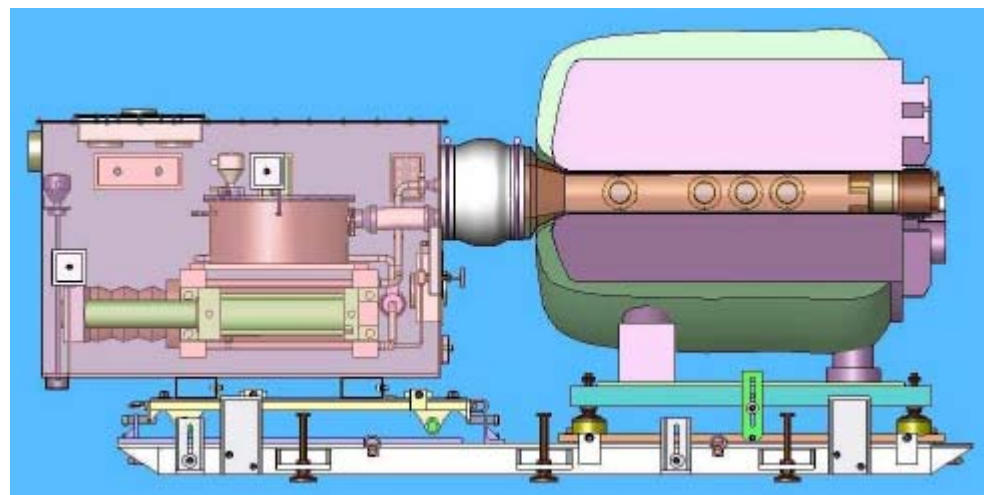
MERIT

- **MERIT** experiment tested Hg jet in 15-T solenoid (**Kirk, McDonald, Efthymiopoulos**)
 - 24 GeV proton beam from CERN PS
 - completed October 2007

P_{beam} beyond 4 MW is feasible



15-T solenoid and Hg jet installed in TT2A tunnel at CERN



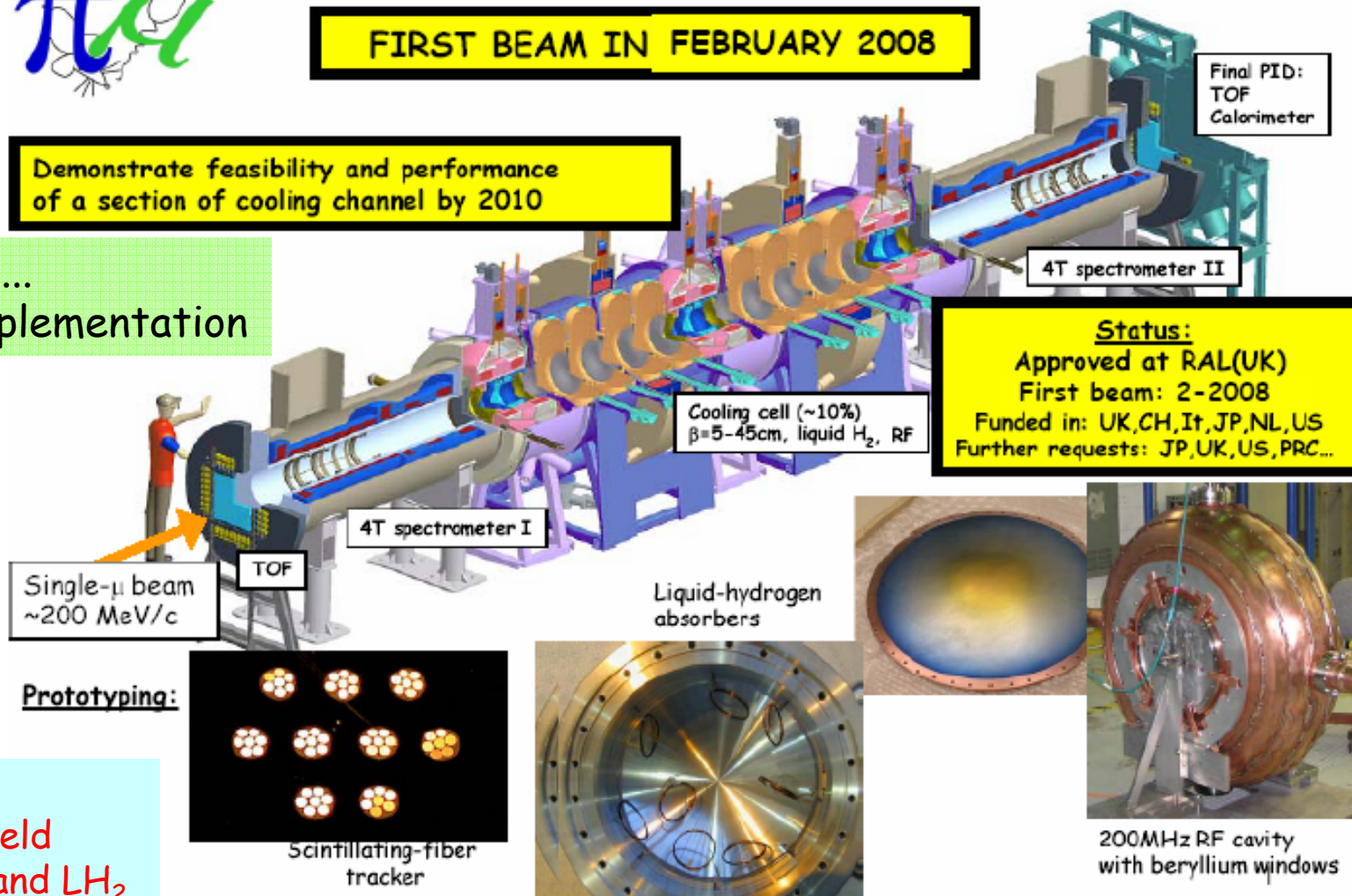


Muon Ionization Cooling Experiment

FIRST BEAM IN FEBRUARY 2008

Demonstrate feasibility and performance of a section of cooling channel by 2010

Simple concept...
complicated implementation



Challenges:
RF in magnetic field
Proximity of RF and LH_2



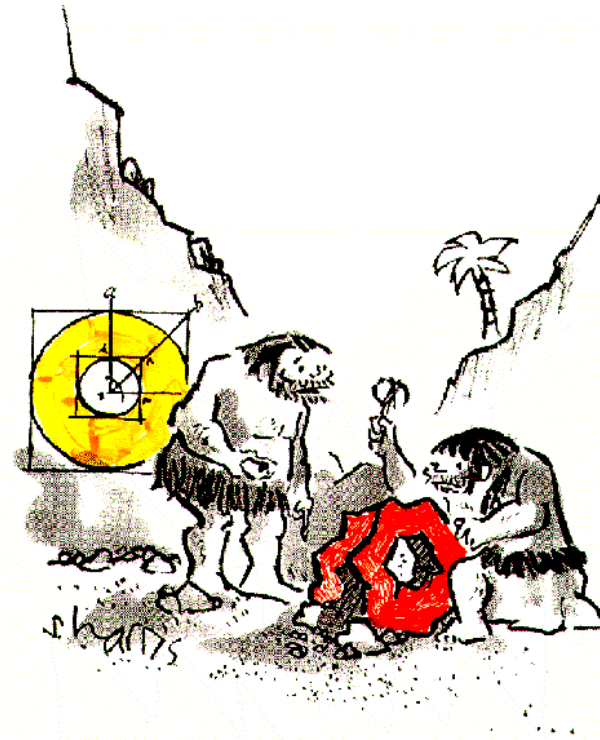
Summary

- Facilities now in the planning stage offer great potential to **address the key outstanding questions in HEP**
 - origins of mass
 - origin of matter-dominated universe
- R&D toward design of these new HEP facilities **progressing on many fronts**
 - from U.S. perspective, **Project X** is key to maintaining future options
- As with all accelerator R&D, **success depends on synergy between accelerator physics and accelerator technology**
 - in particular, control of instabilities and emittance will require state-of-the-art diagnostics (to ensure “blame” goes to the right group 😊)
- The **skills of the instrumentation builders will be critical** in turning accelerator physicists' dreams into the cutting-edge scientific tools of the future

Final Thought

- Challenges of a future accelerator complex go well beyond those of today's beams
 - developing solutions requires substantial R&D effort to specify
 - expected performance, technical feasibility/risk, cost (**matters!**)

Critical to do experiments
and build components.
Paper studies are not
enough!



*"I guess there'll always be a gap between
science and technology."*