Frontier Capabilities Working Group Summary

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for the Study Group Conveners

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Fermilab

Outline

- Study Group Structure
  - Underground detector facilities (M. Gilchriese)
  - Accelerator-based facilities (W. Barletta)
- Underground Detector Facility Overview
  - ⇨ Summary
- Accelerator Capabilities Overview
  - ⇨ Summary

In advance: My acknowledgments particularly to Bill and Gil, as well as the sub-group conveners and various contributors to the Frontier Capabilities Group

STUDY GROUP STRUCTURE

Underground Detector Capabilities

- Convener: Murdoch Gilchriese (LBNL)
- Sub-groups
  - NAF1: Underground facilities to support very large detectors for neutrino physics, proton decay and other science requiring detectors on the multi-kiloton scale
    - K. Heeger (Wisconsin), K. Scholberg (Duke), H. Sobel (UC-Irvine)
  - NAF2: Underground facilities for dark matter experiments, neutrinoless double beta decay experiments, underground accelerators for nuclear astrophysics or other physics, low background assay of materials, and related topics
    - P. Cushman (Minnesota), J. Klein (Pennsylvania), M. Witherell (UCSB)
  - Underground facilities in support of instrumentation development in both working groups
    - P. Cushman (Minnesota), M. Gilchriese (LBNL)
  - Neutrinos and Society (primarily detectors for non-proliferation monitoring and geo-antineutrino detection)
    - A. Bernstein (LLNL)

Accelerator Capabilities

- Convener: Bill Barletta (MIT, USPAS)
- Sub-groups
  - Proton Colliders
    - M. Battaglia (UCSC), M. Klute (MIT), S. Prestemon (LBNL), L. Rossi (CERN)
  - Lepton Colliders
    - M. Klute (MIT), M. Battaglia (UCSC), M. Palmer (FNAL), K. Yokoya (KEK)
  - Intensity Frontier Protons
    - J. Galambos (ORNL), M. Bai (BNL), S. Nagaitsev (FNAL)
  - Intensity Frontier Electrons and Photons
    - G. Varner (Hawaii), J. Flanagan (KEK), J. Byrd (LBNL)
  - Accelerator Technology:
    - G. Hoffstaetter (Cornell), W. Gai (ANL), M. Hogan (SLAC), V. Shiltsev (FNAL)

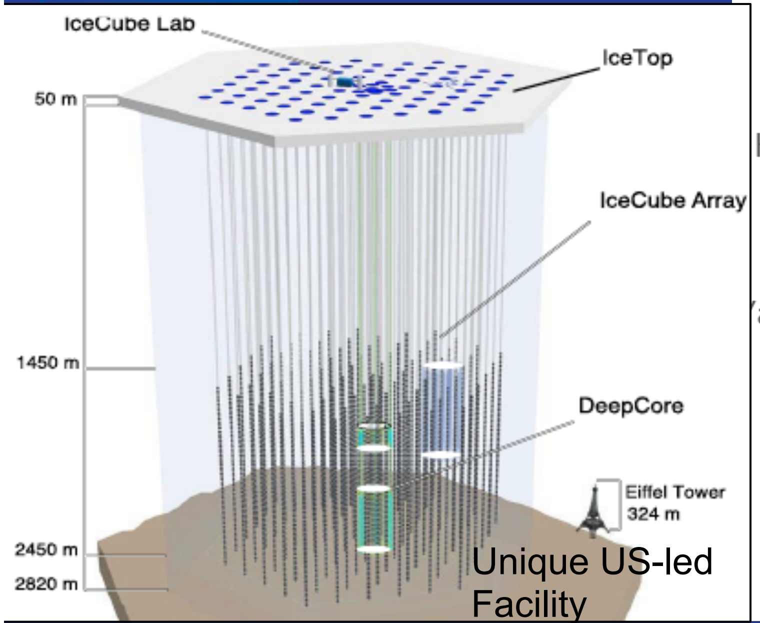
UNDERGROUND DETECTOR FACILITY SUMMARY

Underground Detector Capabilities

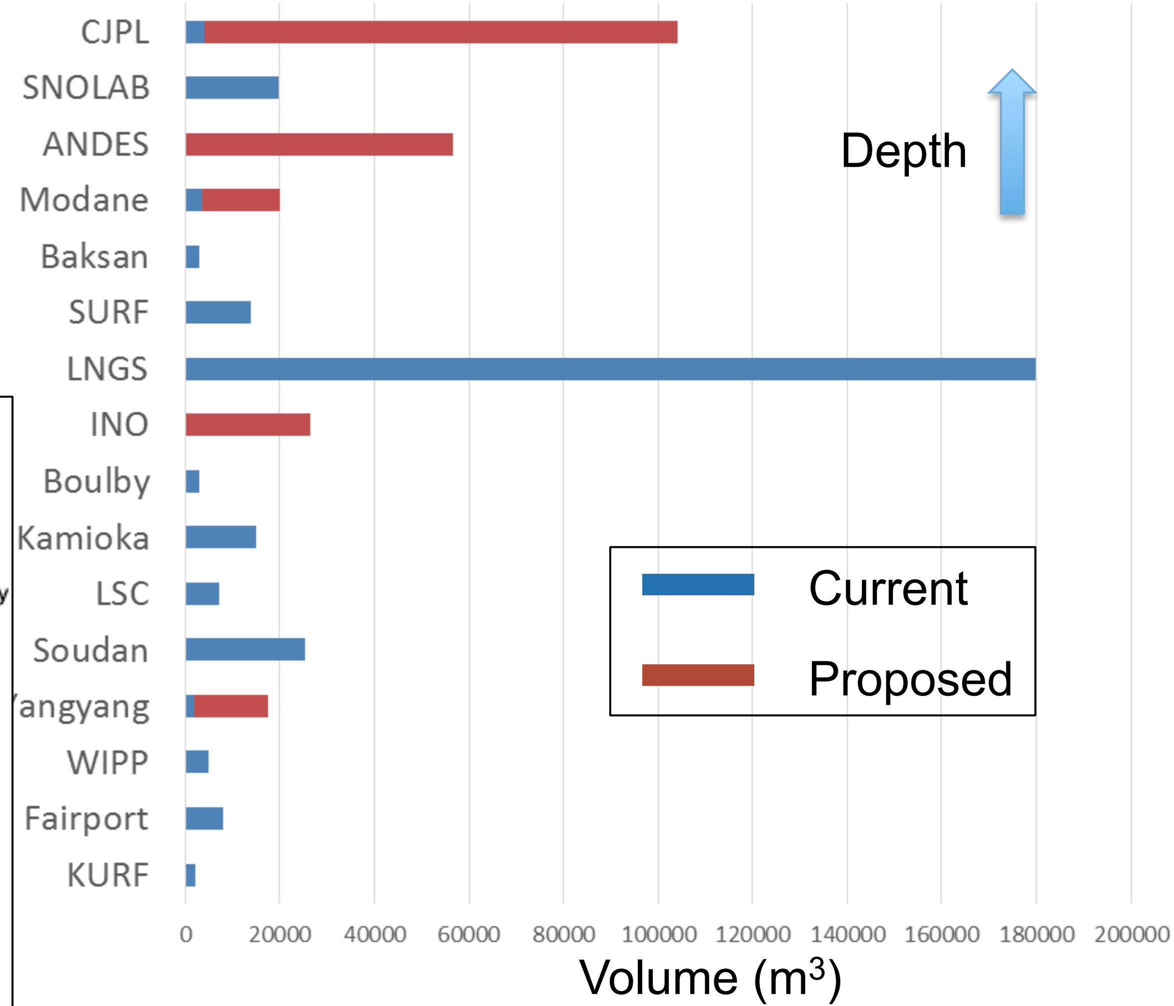
- Underground facilities/capabilities are essential for the support of the world-wide experimental program
  - Direct dark matter experiments
  - Neutrinoless double-beta decay ($0\nu\beta\beta$) experiments
  - Atmospheric, long-baseline, reactor, solar, supernova…. neutrino experiments
  - Proton decay
  - Connections to astrophysics, nuclear and earth science, and detectors for non-proliferation
- US participation
  - Roughly 1,000 US scientists participating in underground experiments (including US-led Antarctica effort)
  - ~30-50% future growth?

Existing/Planned Facilities

- Space Requirements
  - No technical showstoppers in creating and outfitting underground/ice space for planned activities on the 10-20 year timescale
  - World-wide "general purpose" space expected to double by end of decade



Unique US-led Facility



Underground Capabilities: Experiments I

Dark Matter

- G2 experiments can be accommodated by existing/planned facilities
- Most G2 experiments outside US, but strong US participation and (in many cases) leadership
- G3 experiments
  - ~5-10x volume of G2
  - Depth requirements not clear, but depth of major G2 facilities *probably* OK
  - No present US underground hall is sufficiently large & deep
- Not yet ready to develop facility plans for a large directional experiment

$0\nu\beta\beta$

- Several experiments under construction (all but 1 outside US) with strong US involvement in many
- Next Generation Experiments (ton-scale)
  - Space available in existing/planned facilities, but competing with G2/3 DM exp'ts
  - Depth requirements depend on technology – more information likely on 2-year timescale
  - US plan – large participation in one new experiment (some participation possible in others)
  - Not clear whether an existing US facility could host such an experiment
- Longer term – path to >ton-scale experiments not clear (new space/facilities?)

Underground Capabilities: Experiments II

Long Baseline νs, Nucleon Decay and Atmospheric νs

- International effort proposed for CP violation search (ν beams/massive detectors)
- Atmospheric neutrinos + large underground detector ⇨ potentially gives sensitivity to all currently unknown oscillation parameters
- Underground detectors could simultaneously support the search for nucleon decay, atmospheric neutrinos and other physics

⇨ Plan for HyperK and LBNO – a ***lost opportunity*** if not achieved with LBNE

Low-Energy νs in Large Detectors

- Opportunities for physics/astrophysics from supernova ν burst
  - SN capability typically ***free*** with an ***underground*** detector (surface detector ***very difficult***)
  - Bursts are rare (~30 yr intervals) ⇨ must gather as much information as possible
  - Diverse flavor sensitivity important (eg, LNBE ν_e sensitivity) – lost with surface detector
- Future solar ν detector requires large underground detector
  - Observation of MSW transition region and searches for new physics
  - Measurement of CNO νs and resolution to the solar "metallicity problem"
- Other physics opportunities exist (diffuse supernova, geological,…)

Underground Capabilities: Experiments III

Reactor and Other νs

- Detectors for Reactor Experiments
  - At >100m baseline require hundreds of mwe overburden
  - Strong US involvement in recent overseas experiments
- Future Reactor Experiments
  - Overseas efforts directed towards medium (~50km) baselines
  - Funding commitments from host countries (RENO-50, JUNO)
  - Potential US involvement but no US facilities
- Potential for Synergies with Non-Proliferation Activities
  - kT-scale water detectors for non-proliferation
  - Example: Detector with 1600 mwe at Fairport Mine (near Cleveland, former IMB site)
- Potential for New Sources
  - Cyclotrons, intense sources or modular reactors may enable new oscillation experiments in the US and around the world

Underground Capabilities: Infrastructure & Access

Infrastructure

- Global Underground Facilities Needs
  - Required for materials assay, storage and, in some cases (eg, radiopure Cu) production
  - Assay needs: world-wide requirements outstrip existing capabilities ⇨ more required
  - Required for small prototype testing, experiments and R&D ⇨ only way to validate background performance of new technologies
- US Facilities
  - Current infrastructure space appears sufficient *if maintained*
  - Past agency investments along with leveraging state, university, private and non-proliferation funds could make it cost effective to maintain the current infrastructure
  - Will require improved coordination among the US labs to realize this potential

Access

- Access to facilities varies around the world
  - Domestic competition (not fully open) ⇔ Proposals and PAC-like structure (as with accelerator labs)
  - *Important to move towards open, competitive access as experiments grow in size*
- International Balance
  - Governments: *Ideally each major country (or region) would support a major facility capable of hosting forefront experiments*
  - Not clear whether international support could be maintained if one country chose to take a major role in the research without supporting a facility

Underground Capabilities: Summary

- Significant expansion in non-US underground capabilities is expected by the end of this decade
- It is critical that US scientists continue to be supported in order to take advantage of future international and domestic underground facilities
- Key goals for the US Planning Process:

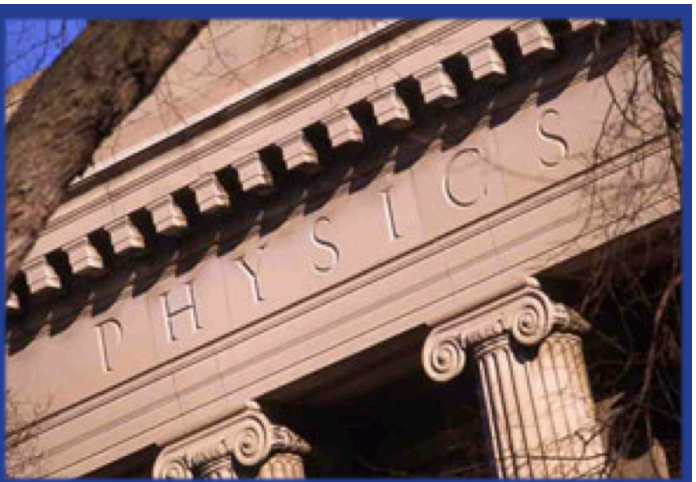
Put LBNE underground

⇨ Realize it's full science potential!

⇨ Makes it an anchor of possible future domestic underground capabilities at SURF

Maintain the leading roles held by the US in many of the future dark matter, $0\nu\beta\beta$ and a large variety of ν experiments.

- Improved coordination and planning of underground facilities (overseas and domestic) is required to maintain this leading role, including the use of US infrastructure
- Maintaining an underground facility that can be expanded to house the largest dark matter and $0\nu\beta\beta$ experiments would guarantee the ability of the US to continue its strong role in the world-wide program of underground physics



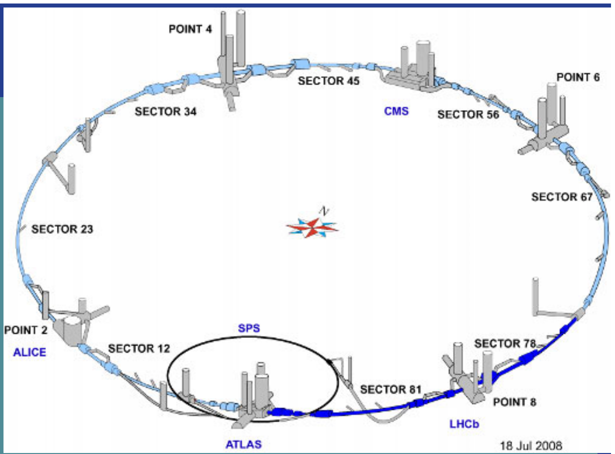
ACCELERATOR-BASED FACILITY SUMMARY

The HEP Accelerator *"Big Questions"*

The Following Questions Are Inherently Long Term

- ***How would one build a 100 TeV scale hadron collider?***
- ***How would one build a lepton collider at >1 TeV?***
- ***How would one generate 10 MW of proton beam power?***
- ***Can multi-MW targets survive? If so, for how long?***
- ***Can plasma-based accelerators achieve energies & luminosities relevant to HEP?***
- ***Can accelerators be made 10x cheaper per GeV? Per MW?***

Energy Frontier Proton Colliders I



The Key Questions

- What luminosity is possible for the LHC?
  - Strategies for increased integrated luminosity
  - Avoid impaired data and degradation of the detectors
- What energy can be achieved in the LHC tunnel?
- What is the future for the Energy Frontier Hadron Colliders beyond the LHC?
  - What are the challenges of a 100 TeV collider?
- What is the accelerator R&D roadmap for LHC and post-LHC capabilities?

The Near-Term Priorities – Full Exploitation of the LHC

- Continue a strong LHC Accelerator R&D Program ⇨ Hi Lumi LHC Construction Project
- Develop the technologies required for a High Energy LHC ⇨ Achieve Engineering Readiness
  - Next generation Nb_3Sn magnets (~15T scale)
  - Advanced beam control technology
  - ⇨ Represents the most critical near-/mid-term development effort for higher energy hadron colliders
- However, the high energy reach of the LHC is limited…
  - without magnet engineering materials beyond Nb_3Sn (high temperature SC development being pursued)
  - with challenges in managing synchrotron radiation
  - ⇨ Focused engineering is not a substitute for innovative R&D

Energy Frontier Proton Colliders II

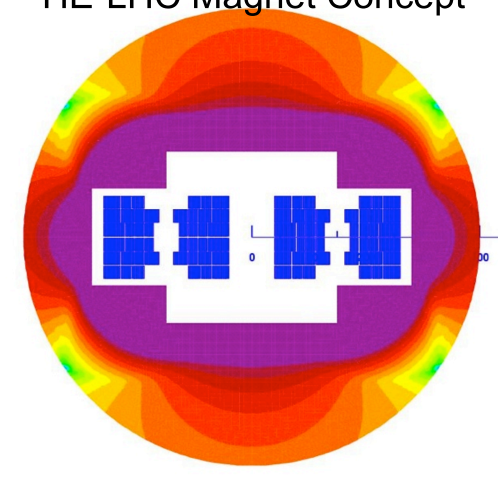
Long-Term Options Beyond the LHC

- *Extensive interest was expressed at Snowmass in a 100 TeV pp collider*
  - US-led VLHC study (~2001) still valid ⇨ updated with a Snowmass whitepaper
  - Interest at CERN (coupled to TLEP study)
  - US participation in a new design study would help inform plans for future technology R&D
    ⇨ Participation in such a study is recommended

Accelerator R&D Roadmap: LHC Upgrades ⇨ post-LHC

- Advanced magnets
  - New engineering conductors (e.g., small filament HTS)
  - Improved temperature margin, stress management techniques, magnet protection, and structural materials
- Beam dynamics
  - Effects of marginal synchrotron radiation damping
  - Beam physics of the injection chain
  - Control of beam halo
  - Noise & ground motion effects
- Machine protection & beam abort dumps (multi-GJ beams)
- Interaction Region design & technology options

HE-LHC Magnet Concept



NOTE: Strong technology overlap with muon / intensity machines

Energy Frontier Lepton & Photon Colliders I

The Key Questions

- Can ILC & CLIC designs be improved using new technologies?
  - Can they be constructed in stages? what is a staging plan?
  - What would be the parameters of a Higgs factory as a first stage?
- Higgs factories
  - Could a Higgs factory be constructed in the LHC tunnel?
  - What would be parameters of a photon collider Higgs factory
  - Could one build a μ+μ- collider as a Higgs factory?
- Could one design a multi-TeV μ+μ- collider?
- What is the accelerator R&D roadmap?

Excitement & boundary conditions are driven by the Higgs discovery

The Japanese Initiative – Proposal to Host the ILC

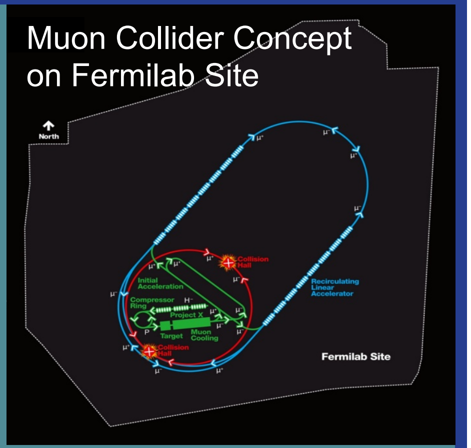
- The Japanese initiative is welcomed
- With the release of the TDR by the ILC Global Design Effort, *the ILC technical design is ready for a decision*
  - Major US contributions to and leadership roles in machine physics & technology: SRF, high power targetry (e+ source), beam delivery, damping rings, and beam dynamics
  - *Importance of an upgrade path to higher energy (> 500 GeV) & luminosity (> 10^{34} $cm^{-2}s^{-1}$) has been emphasized*
- The US accelerator community is capable of contributing…
  As supported by the physics case and as part of a balanced program
  The US can offer an experienced & ready team

Energy Frontier Lepton & Photon Colliders II

Alternative Higgs Factory Approaches

- e^+e^- ring in a very large tunnel (50-100km circumference)
  - Significant extrapolation, but from large experience base
  - Energy reach & luminosity are very strongly coupled
    - Largest luminosity at Z peak, falling rapidly √s increases
  - Tunnel could support a 100 TeV proton collider option
- Muon collider – Feasibility assessment underway
  - Options for Higgs Factory (s-channel H production) ⇨ 10 TeV collider - on Fermilab site
- Photon collider
  - Options for add-on to a linear collider and for a standalone facility presented
  - Builds on US expertise in high power lasers (overlap with laser wakefield accelerator needs)

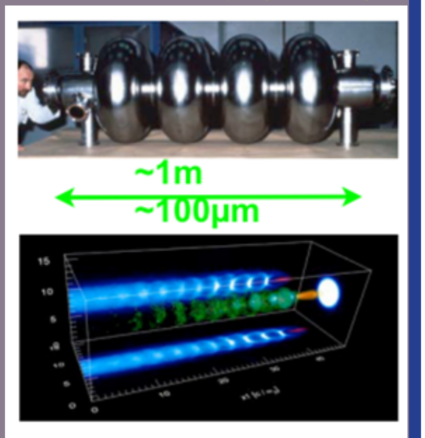
HF Concepts span a broad range of technical readiness



Accelerator R&D Roadmap: Research For a Compact Multi-TeV Collider

Motivated by lower cost, smaller footprint, and higher energy capability

- Support the integrated US R&D program toward demonstrating muon collider feasibility (MAP)
  - Enable completion of the feasibility assessment near the end of this decade
  - Closely connected with intensity frontier & intense neutrino sources
  - Strong magnet synergies with LHC energy upgrades
- Stay involved in high gradient, warm linac approach (CLIC)
  - Practical energy reach: wakefield control, accelerating gradient
  - Industrialization path to be developed
- Continue R&D in wakefield accelerators (plasmas & dielectric)
  - Fruitful physics programs with high intellectual content
  - Feasibility issues: Positron acceleration, multi-stage acceleration, control of beam quality, plasma instabilities at 10’s of kHz rep rate
  - All variants require an integrated proof-of-principle test



Maximizing RF Efficiency is Crucial!

High Intensity Proton Sources I

The Key Questions

1) What secondary beams are needed for IF experiments?
2) What proton beams are needed to generate these?
   - > 1 MW , flexible timing structure
3) Can these be made by existing machines?
4) What new facilities are needed to deliver 1) ?
5) What accelerator / target R&D is needed to realize 4?

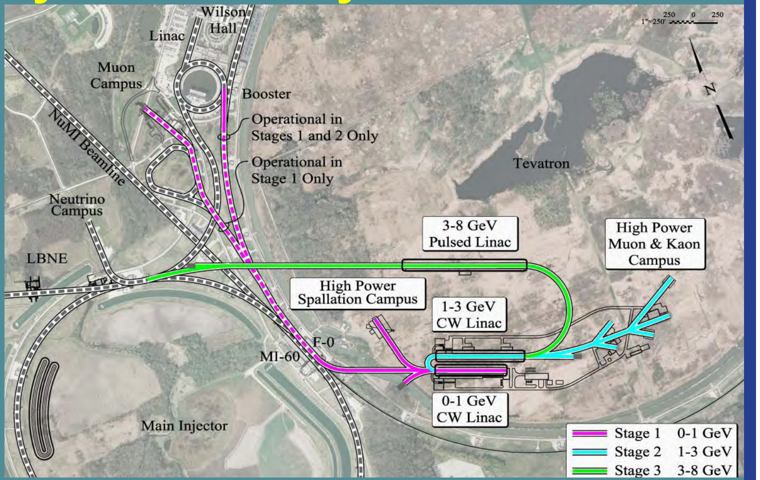
Approach to Setting Priorities – Intensity Frontier ⇨ Diversity

- Survey of anticipated particle physics requirements for secondary beams (i.e. neutrino, kaon, muon, neutron,…)
  - 19 secondary beam requests filled out by experiment advocates
- Derived primary proton beam characteristics
- Common characteristics of required beams
  - High average power (> 1 MW)
  - Flexible time structure
- Compared with existing proton beam characteristics
  - 20 existing proton beam lines + 14 planned upgrades

⇨ *Conclusion: Next generation of intensity frontier experiments will require proton beam intensities & timing structures beyond the capabilities of any existing accelerators*

High Intensity Proton Sources II

Project X – Can Provide a World-Leading Facility for Intensity Frontier Research



- Based on a modern multi-MW SCRF proton linac
  - Flexible “on-demand” beam structure
- Could serve multiple experiments over broad energy range
  - Supports 0.25 – 120 GeV
- Platform for future muon accelerator facilities: IF/ν Factory (NuMAX) & EF/Muon Collider
- Complete, integrated concept Reference Design Report
  - arXiv:1306.5022
- R&D program underway to mitigate risks in Reference Design
  - Undertaken by 12 U.S. & 4 Indian laboratories and universities

⇨ *Construction could be initiated in the last half of this decade*

Capabilities with Narrower Experimental Scope

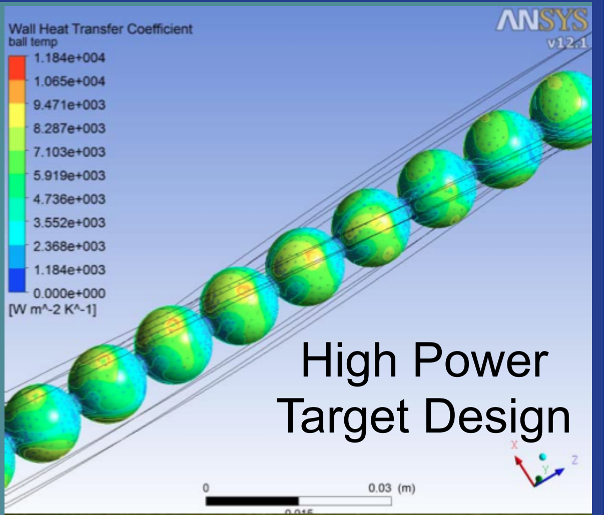
- DAEδALUS: Decay At Rest anti-neutrinos – short baseline ν oscillations
  - 3 multi-MW H_2^+ cyclotrons/target stations located ~2-20km from experiment large hydrogenous detector
  - First stage: IsoDAR – compact cyclotron 15 m from Kamland
  - International collaboration with strong industry connection
- nuSTORM: Neutrinos from STORed Muons
  - Supports sterile neutrino & neutrino cross-section experimental program *using existing accelerator technology* - also muon accelerator R&D
  - Muon storage ring sends well-characterized beams to near & far detectors at 50 m & 1900 m
  - Potential first step towards a long baseline neutrino factory capability

High Intensity Proton Sources III

Intensity Frontier Accelerator R&D Issues

- High quality, high current injection systems
  - Low emittance, high current ion sources
  - Effective beam chopping
  - Space charge control
- SCRF acceleration (Project X, muons)
- Multi-MW cyclotrons DAEδALUS
- Radiation resistant magnets
- Very high efficiency extraction

& *Understanding and controlling beam loss*
  - Efficient collimation
  - Beam dynamics simulations of halo generation
  - Large-dynamic-range instrumentation



High Power Targetry – *A Particularly Challenging R&D Issue*

- Displacements & gas production are the main underlying damage mechanisms
  - Particulars depend on primary beam characteristics, material, …
  - Can not simply scale from nuclear power experience
- Targets are difficult to simulate
  - Radiation effects need validating (inhomogeneous, time-varying)
  - Thermo-mechanical models complex
  - Poorly understood failure criteria (classical limits may be too conservative)
- Need controlled, instrumented in-beam tests & Need a source before you can test materials
  - Takes a long time to build up data (accelerated testing)

Requires a structured R&D program ⇨ International RADIATE collaboration has been formed

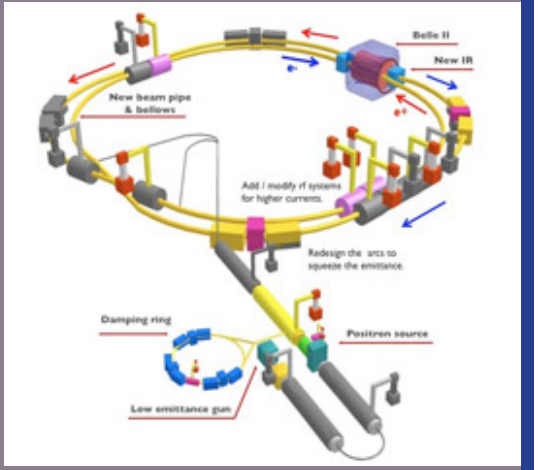
High Intensity Electron and Photon Beams I

The Key Questions

- What additional accelerator capabilities at heavy flavor factories are required to realize the full range of physics opportunities?
- What new or existing accelerator-based facilities provide opportunities for dark sector / axion searches ?
- What are new physics opportunities using high power electron and photon physics?
- What accelerator and laser R&D is required to realize the physics opportunities in these areas?

Capabilities Desired For Heavy Flavor Factories

- Super B-Factory (SuperKEKB):
  - Important US contributions to design by both labs & universities
  - Participation in commissioning & machine studies desirable
  - Luminosity upgrades (needs physics case)
  - Polarized beams (refine physics case)
    - Technical feasibility
- Tau-charm Factory beyond BEPC-II
  - What kind of facility would be interesting? (needs physics case)
  - What luminosity is needed? Is polarization necessary?



Factory machines require BOTH high intensity & low emittance beams

⇨ Many areas of overlap with LC damping ring & light source R&D efforts
History of fruitful international collaborations/cooperation

High Intensity Electron and Photon Beams II

Opportunities for HEP Using FEL Facilities

- "Flashlight through a wall" experiments using high-intensity photon beams in strong magnetic fields
  - JLab/MIT: Dark Light axion search
- Search parameters are unconstrained
  - Use existing facilities
- keV level searches can use X-ray FELs
- More speculative: Generating low emittance muon beams from intense positron beams

Accelerator Development Roadmap for e^+e^- Intensity Frontier Machines:

Exploit synergy with light sources

- Beam stability & control
  - Examples: Electron cloud & fast ion instabilities
- Coherent Synchrotron Radiation issues with short bunches
- High-rate injection
  - High top-up rate to compensate for low lifetimes
  - Timing jitter, and attendant energy jitter
- Low-emittance beam issues
- Beam instrumentation

Presents an ongoing opportunity for collaboration across a broad accelerator community

Accelerator Technology Test Beds I

The Charge

- Identify broad range of test capabilities existing or needed
- Category 1: Provides testing beam physics / accelerator components to manage technical risks in planned projects
- Category 2: Integrates proof-of-practicality tests
- Category 3: Provides tests of physics feasibility of concepts / components

Identified Capabilities

- 35 existing facilities were identified
  - Beam / no-beam
  - US & overseas

Hadron Colliders: LHC Lumi & Energy Upgrades, VLHC

Technical Challenges	Existing Capabilities	Planned Capabilities
High performance SC wire	Critical industry couplings	
High Field SC magnets	LBNL, FNAL, BNL, CERN	
SR and photon stops	Electron storage rings	
Collimation	LHC, RHIC, FNAL-MI	
Injectors - SCRF	SNS (limited)	PXIE@FNAL
Injectors – Space charge	FNAL-Booster, AGS, PS	ASTA@FNAL
Beam cooling (optical, coherent)		ASTA@FNAL, RHIC Cool

Injector studies need new, dedicated facilities

Lepton Colliders: ILC and Beyond

Risk Reduction Areas	Existing Capabilities	Planned Capabilities
ILC: SRF-system no beam	JLab, Cornell, Industry	
ILC: SRF system with beam	DESY, KEK, Cornell, LLNL	ASTA@FNAL
ILC: FF, Damping Rings, e+ Production	KEK, Cornell, LLNL	
Practicality/Feasibility Tests	**Existing Capabilities**	**Planned Capabilities**
CLIC NCRF 2-beam	CERN	
Muon Colliders – technical components	MuCool Test Area (MTA@FNAL)	
Muon Colliders – 4D/6D ionization Cooling	MICE@RAL	nuSTORM
Wakefield accelerators – acceleration demo/staging	SLAC, LBNL, ANL	Upgrades to existing facilities
Wakefield accelerators – luminosity / beam control		Needs integrated testbed

Energy reach beyond the ILC will need new test capabilities

Intensity Frontier Accelerators: Includes Project X, DAEδALUS, Neutrino Factory

Technical Challenges	Existing Capabilities	Planned Capabilities
Project X: H^- source & chopping	SNS	PXIE@FNAL
Project X: CW SC RF (low beta)	Atlas@ANL	PXIE@FNAL
Project X: Pulsed SC RF, space charge		ASTA@FNAL
DAEδALUS: H_2^+ source	LNS Catania	
DAEδALUS: Multi-MW cyclotrons	PSI, RIKEN, ORNL, Best	
Neutrino Factory	See Muon Collider	
Instabilities, collimation, extraction	FNAL, RHIC	
Dedicated high power targetry		***Critical Need***

A new generation of IF machines needs new test facilities

Intensity Frontier Accelerators: Flavor Factories and Electron-Ion Colliders

Technical Challenges	Existing Capabilities	Planned Capabilities
Beam instabilities, Interaction region optics	Existing Rings	
IP designs, collimation	BNL, CERN	
Non-standard beam-beam		Needed
Intense polarized e^- source	JLab, BNL, Cornell	
CW SRF ($\beta = 1$)	Cornell, JLab, BNL, KEK	CERN
Heavy ion sources	MSU, LBNL	

Good test facility basis for technical design of HEP machines

Accelerator Capabilities: Summary

- A broad range of accelerator-based capabilities has been reviewed
- Key goals for the US Planning Process:

- ***Fully exploit LHC capabilities and its upgrade path***
  - ➪ Complete its physics program
  - ➪ Support the R&D for the next steps
- ***The Japanese initiative to host a linear collider as a Higgs Factory is welcome***
  - ➪ The US accelerator community is capable of making significant contributions
  - ➪ A clear upgrade path to higher energy and luminosity is necessary
- ***The next generation of Intensity Frontier experiments require proton intensities and timing structures which are beyond current capabilities***
  - ➪ Project X can provide a world-leading facility to satisfy these needs
  - ➪ Facilities with more narrowly defined scope may also have a role to play
- ***Intensity Frontier colliders and photon sources have strong synergies with other parts of the accelerator community (eg, light sources)***
- ***Support for key R&D is required***
  - ➪ Participate in planning for a 100 TeV Collider
  - ➪ Continue the R&D efforts toward a more compact multi-TeV lepton collider capability: Muon Collider, LC technologies (warm RF, wakefield)
  - ➪ Dedicated test facilities will be required to develop future HEP capabilities

THANK YOU