Novel Accelerators:
Building a Physics-Producing Machine

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I. While the overall content has been informed by the Snowmass capabilities study, the emphasizes, evaluations & priorities are my own.

II. Most of “novel” approaches are not so new, their reach of application to HEP is.

Accelerators for hadron colliders

"Big Questions"

How could one build a collider at the 10 - 20 TeV constituent mass scale (~100 TeV protons)?

What is the farthest practical energy reach of accelerator-based high energy physics?

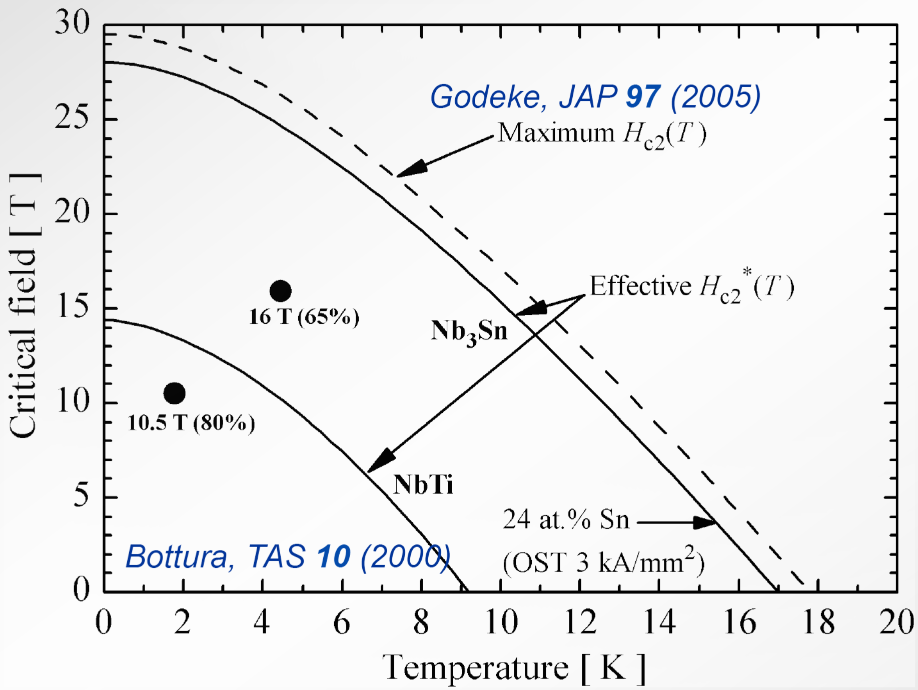
Could a 100 TeV machine be 10x cheaper per GeV than LHC?

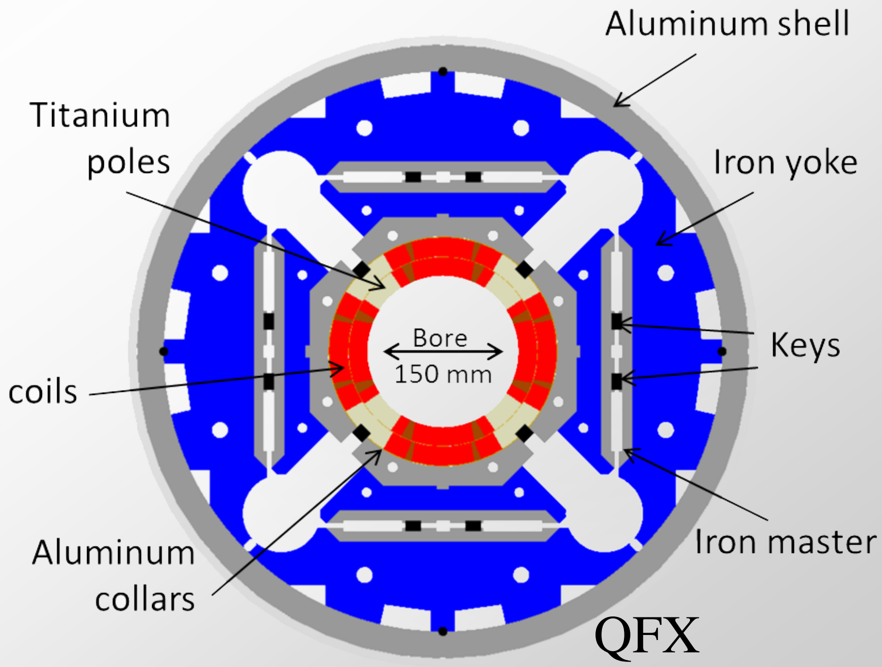
Critical technologies:

SC dipole magnets, synchrotron radiation control

Snowmass Capabilities conclusion:
Priority: Full exploitation of LHC

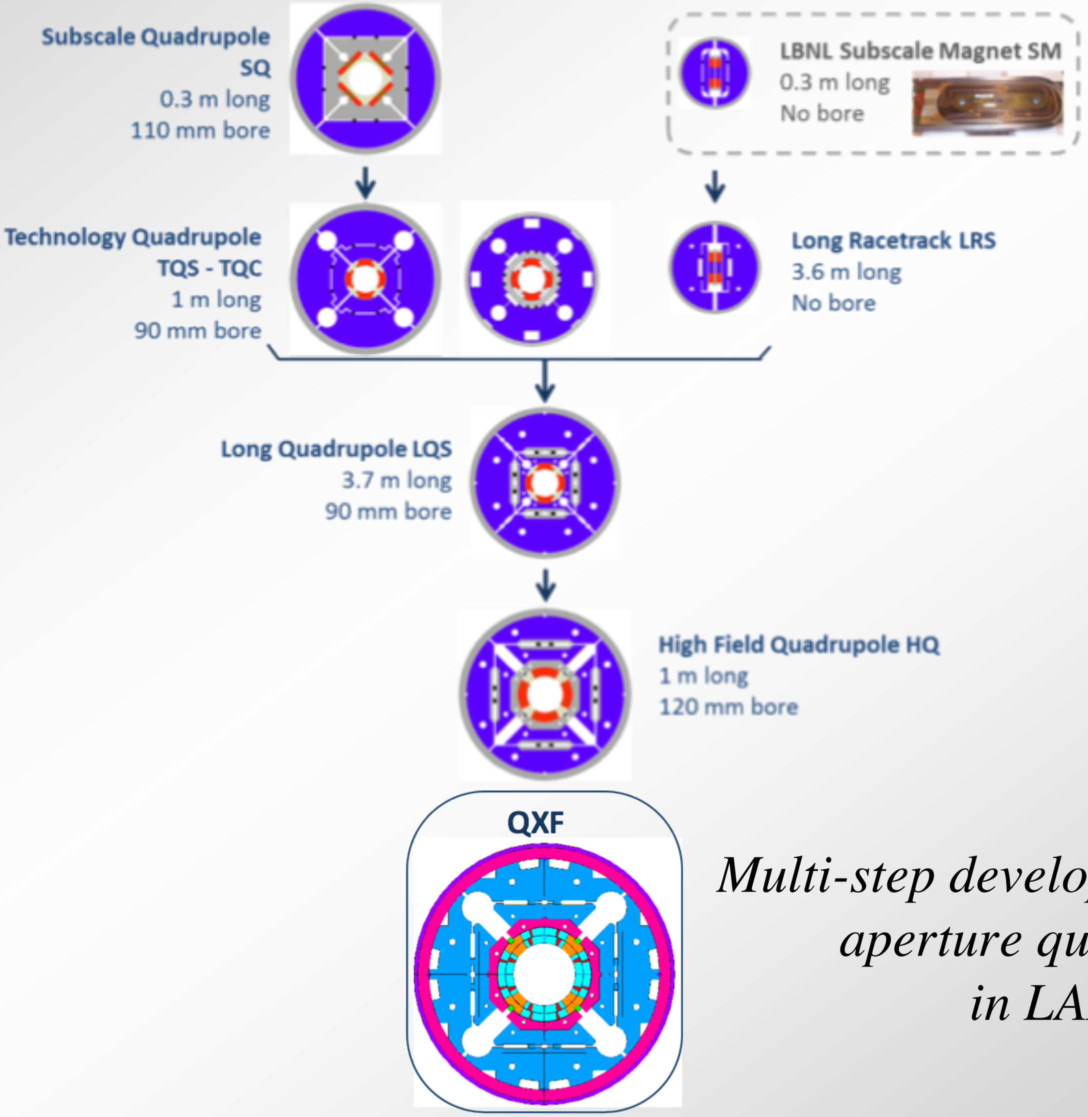
- ❖ LHC dipoles stretched NbTi technology to its limit
  - ➢ Based on 30 years of engineering development
    - 8.3 T in central region via operation at 1.8K (9 T on conductor)
- ❖ Even High Luminosity LHC needs new technology: Nb_3Sn
  - ➢ 12 T LARP quadrupoles with 150 mm aperture to shrink ß*





Dipole fields of ~15T are within reach

But need ~10 year “LARP-like” readiness program



Subscale Quadrupole SQ
0.3 m long
110 mm bore

LBNL Subscale Magnet SM
0.3 m long
No bore

Technology Quadrupole TQS - TQC
1 m long
90 mm bore

Long Racetrack LRS
3.6 m long
No bore

Long Quadrupole LQS
3.7 m long
90 mm bore

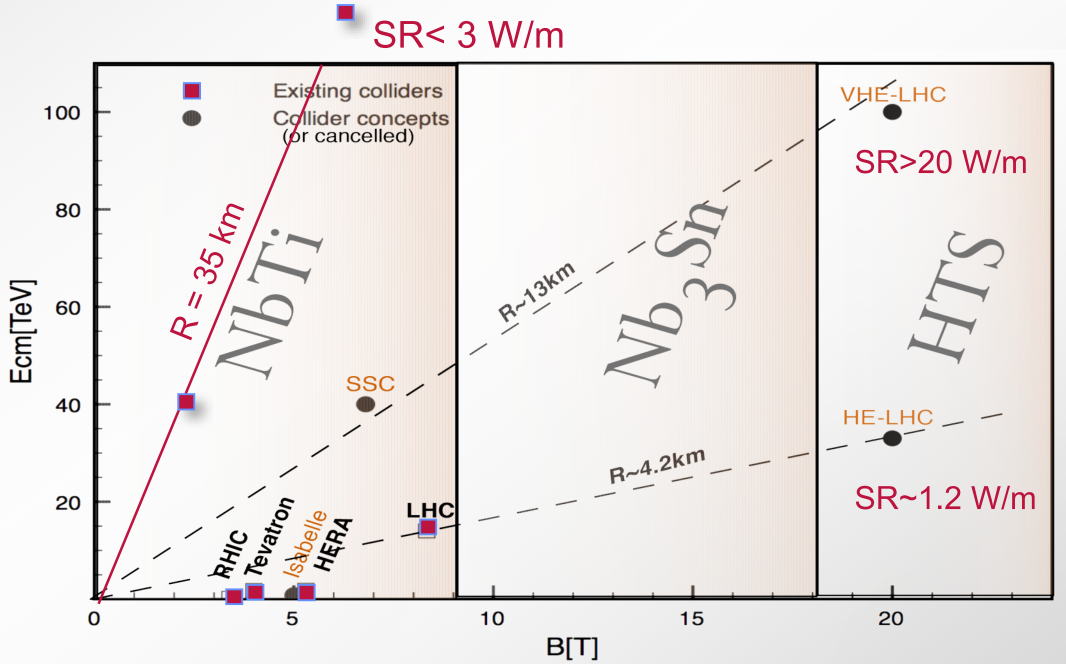
High Field Quadrupole HQ
1 m long
120 mm bore

QXF

Multi-step development of QXF aperture quadrupole in LARP

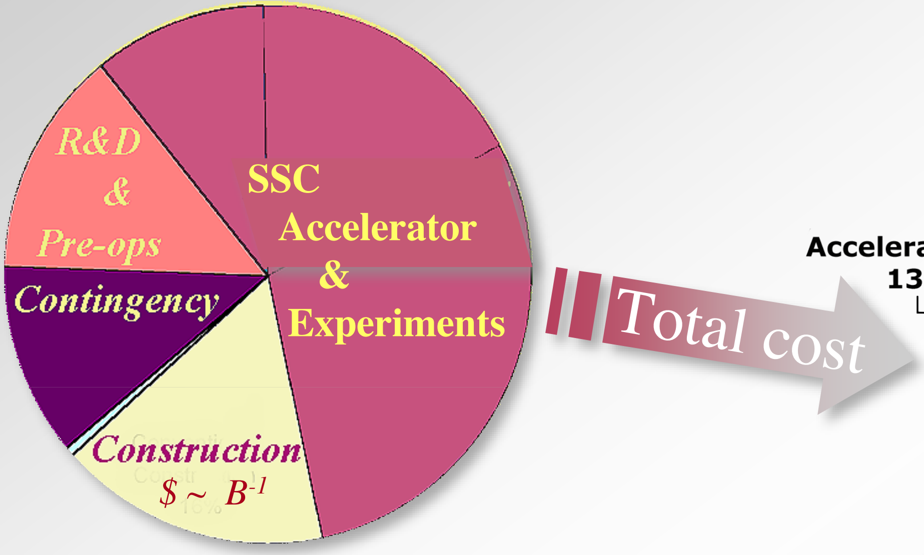
Proton colliders beyond 14 TeV:
CERN will lead “100 km tunnel” collider study

- Reach of an LHC energy upgrade is very limited (~26 TeV)
  - No engineering materials beyond Nb_3Sn (Practical limit <16 T)
  - Difficult synchrotron radiation management $P_{proton}(kW) = 6.03 \frac{E(TeV)^4 I(A)}{\rho(m)}$
- Proton colliders at 50 - 100 TeV
  - US multi-lab study of VLHC (circa 2001) is still valid - 233 km ring



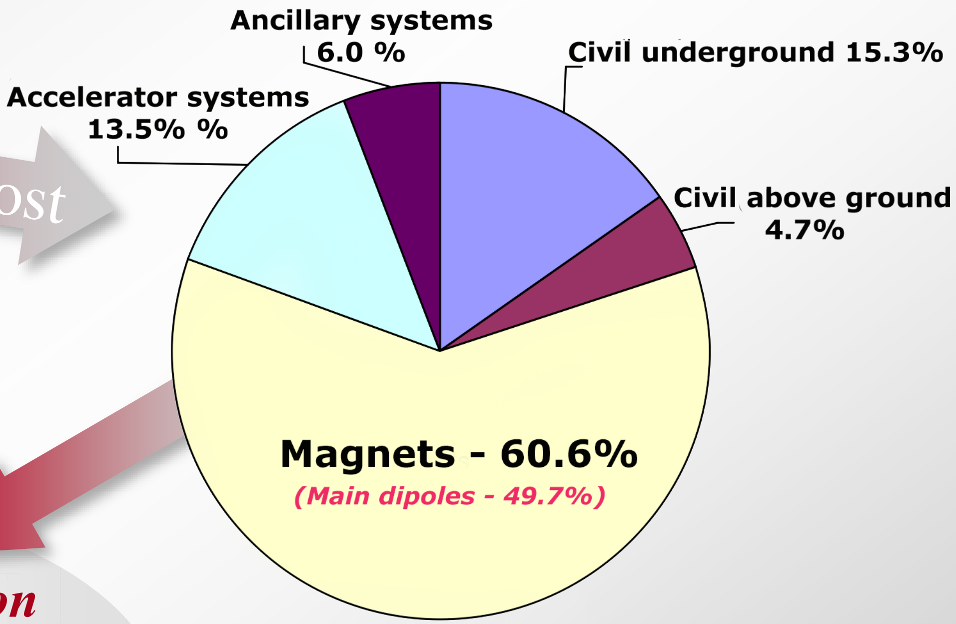
Breakpoints in technology are also breakpoints in cost [1::8::20(?) per kA-m]$_{cern}$

Cost drivers set design & R&D priorities
(based on SSC "green field" experience)



Accelerator cost distribution

SSC Fractions



Build at an existing hadron laboratory

Lowering dipole cost is the key to cost control

$\$/m \sim B^2$

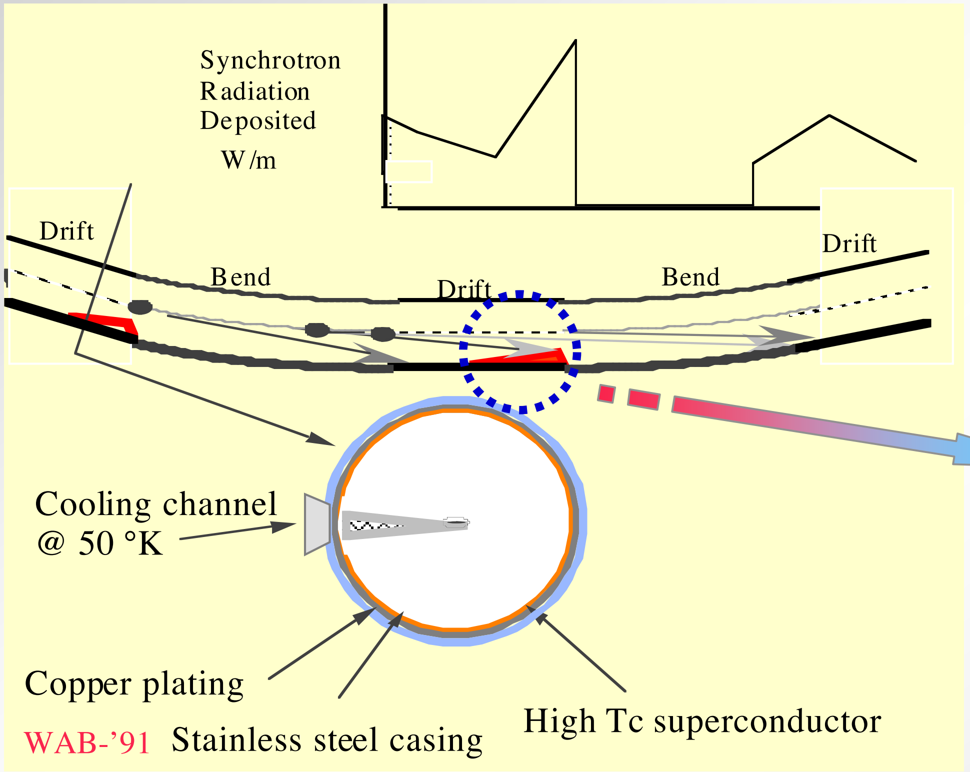
Caution:
Tunneling costs
are highly geology dependent
& must carry large contingency

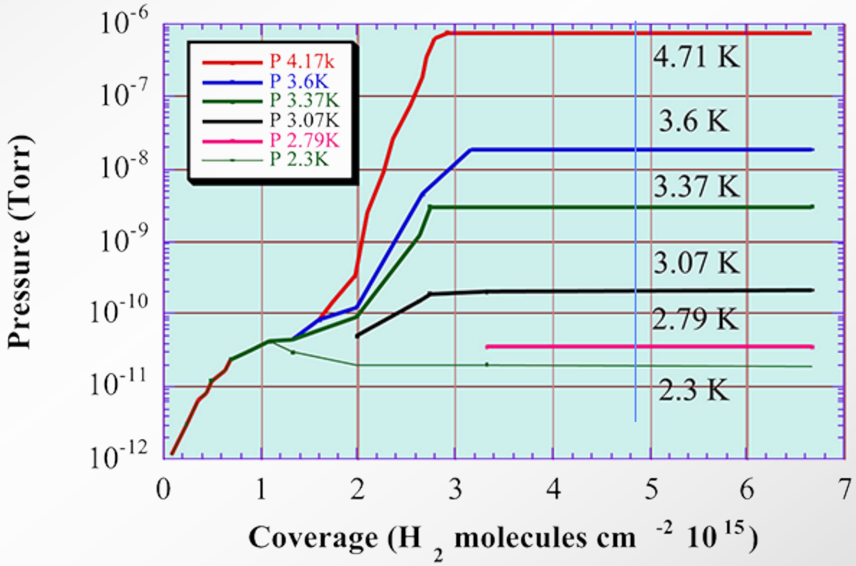
Hadron colliders:
Long term innovative R&D

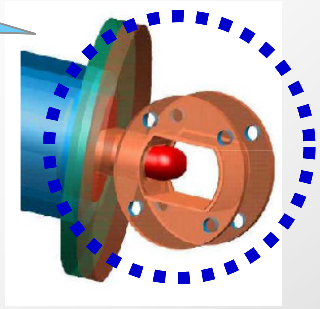
- New engineering conductors (e.g., small filament HTS)
- Advanced magnets – stress management, magnet protection
- Managing synchrotron radiation power
  - Vacuum system & cryogenics challenges (surprisingly expensive)
  - Becomes highly challenging as $P_{sr} > 5$ W/m
- Beam instabilities & feedback - largest risk factor
  - Effects of marginal synchrotron radiation damping
  - Control of beam halo
  - Noise & ground motion effects
- Machine protection (multi-GJ beams, tens of GJ in magnets)

Magnet issues have strong technology overlap with muon accelerator

Radiation masks & coatings (YBCO)
require extensive R&D







$P \sim kT^4$

Synchrotron Radiation mask

***BUT**, masks work best in sparse lattices & with ante-chambers*

Accelerators for hadron colliders

“Big Questions” answered

Proton synchrotrons collider can reach the 20 TeV constituent mass scale (~100 - 200 TeV protons) at $\mathcal{L} = 10^{35}\ \mathrm{cm^{-2}s^{-1}}$

Synchrotron radiation will limit even this technology to << 1 PeV

(Power consumption, site limits, project management)

Perhaps a 100 TeV collide might be 2x cheaper per GeV than LHC

Accelerators for lepton colliders

"Big Questions"

How could one build a collider at the 10 - 20 TeV mass scale?

Could a 10 TeV machine be 10x cheaper per GeV than LHC?

Critical technologies: High gradient, beam quality & control

Energy-frontier lepton & photon colliders

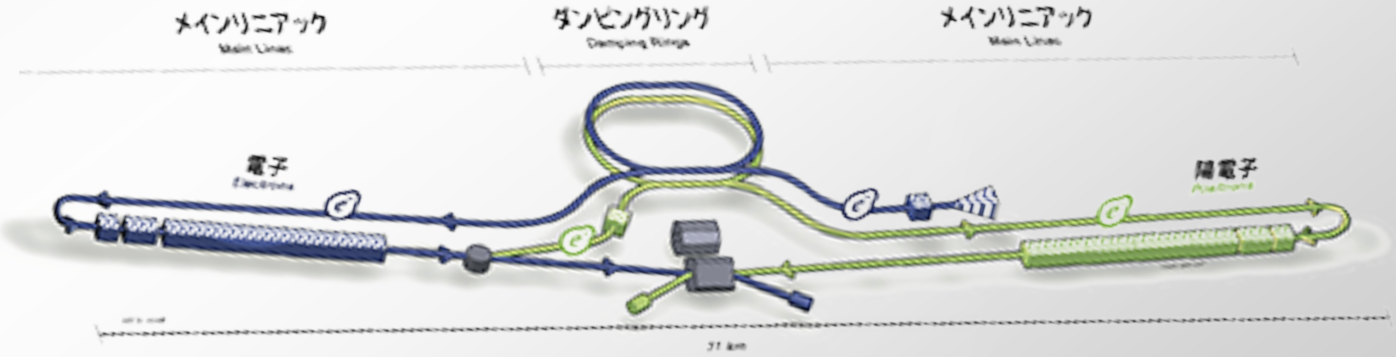
Questions we addressed

- Can ILC & CLIC designs be improved using new technologies?
  - 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?
  - 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 driven by Higgs discovery

Our conclusion:
ILC design is technically ready to go

- ❖ High gradient technology choice is well established
  - ➢ Embodied in European XFEL
  - ➢ Risk issue is manufacturing acceptance v. gradient
    - SCRF performance continues to improve
- ❖ TDR incorporates leadership U.S. contributions
    - SCRF, beam delivery, damping rings, beam dynamics
- ❖ Potential upgrade to > 500 GeV @ > 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - ➢ Higher gradient SCRF build out
  - ➢ Plasma-wakefield "afterburner"

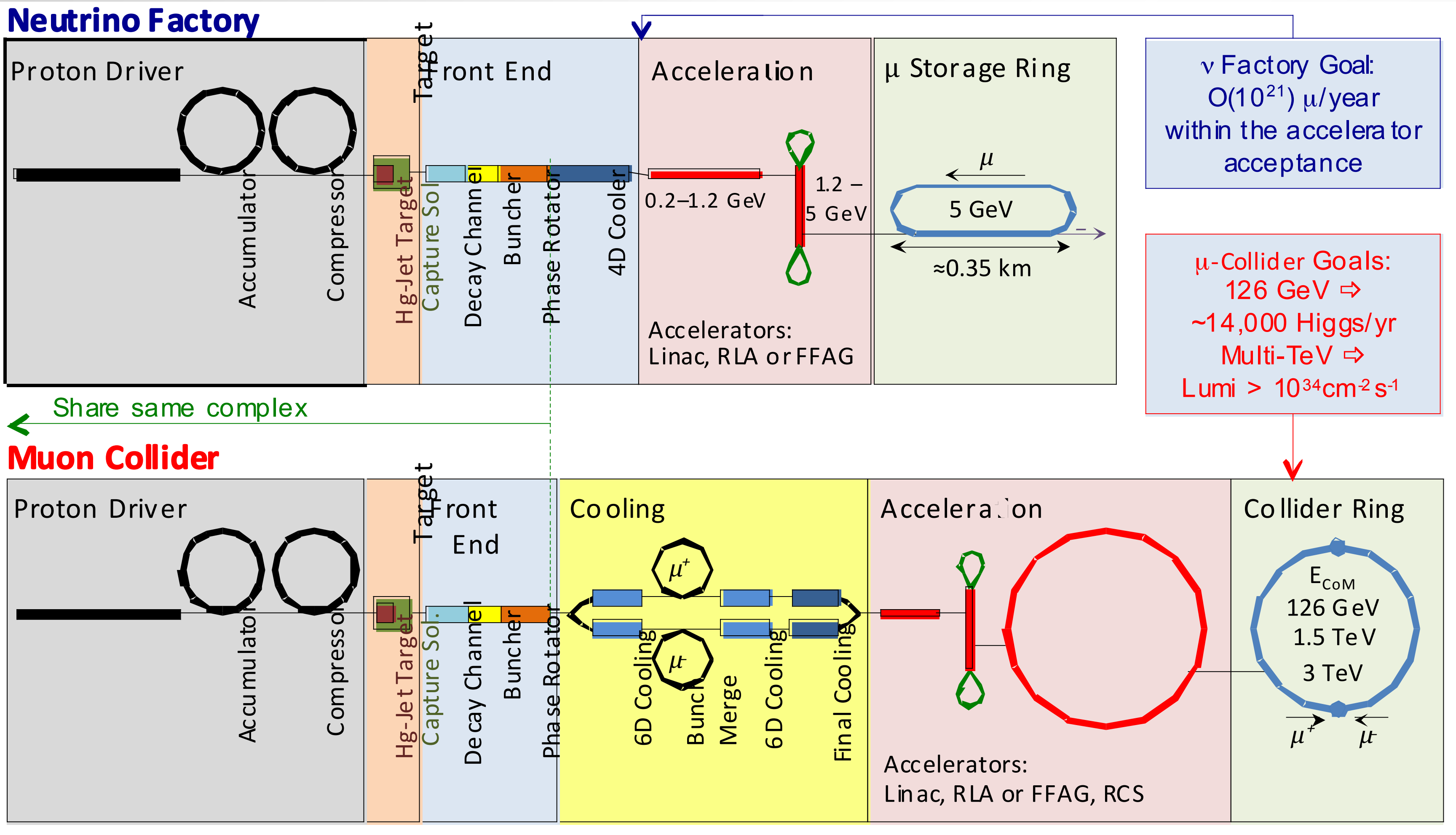


Higgs factory: Alternate approaches

- Circular e+e- in very large tunnel (50 – 100 km)
  - Substantial extrapolation albeit from large experience base
    - Requires optics with very large momentum acceptance
      - Key physics is strong beamstrahlung
      - LEP/LHC tunnel marginal for physics & programmatic reasons
  - Energy reach & luminosity are very strongly coupled – details!
    - Very large luminosity at Z peak: falls rapidly as $\sqrt{s}$ increases
    - Tight linkage to 100 TeV proton collider opportunity
- Muon collider: Feasibility study is underway (see next slide)
  - Could provide options from Higgs to multi-TeV
- Gamma-gamma collider
  - Can be ILC option or stand-alone facility
  - Laser technology overlap with laser wakefield accelerators

Recommendation: Vigorous, integrated R&D to demonstrate feasibility of a muon collider

- Closely connection with intensity frontier sources



ν Factory Goal:
O(10^{21}) μ/year
within the accelerator acceptance

μ-Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > $10^{34} cm^{-2} s^{-1}$

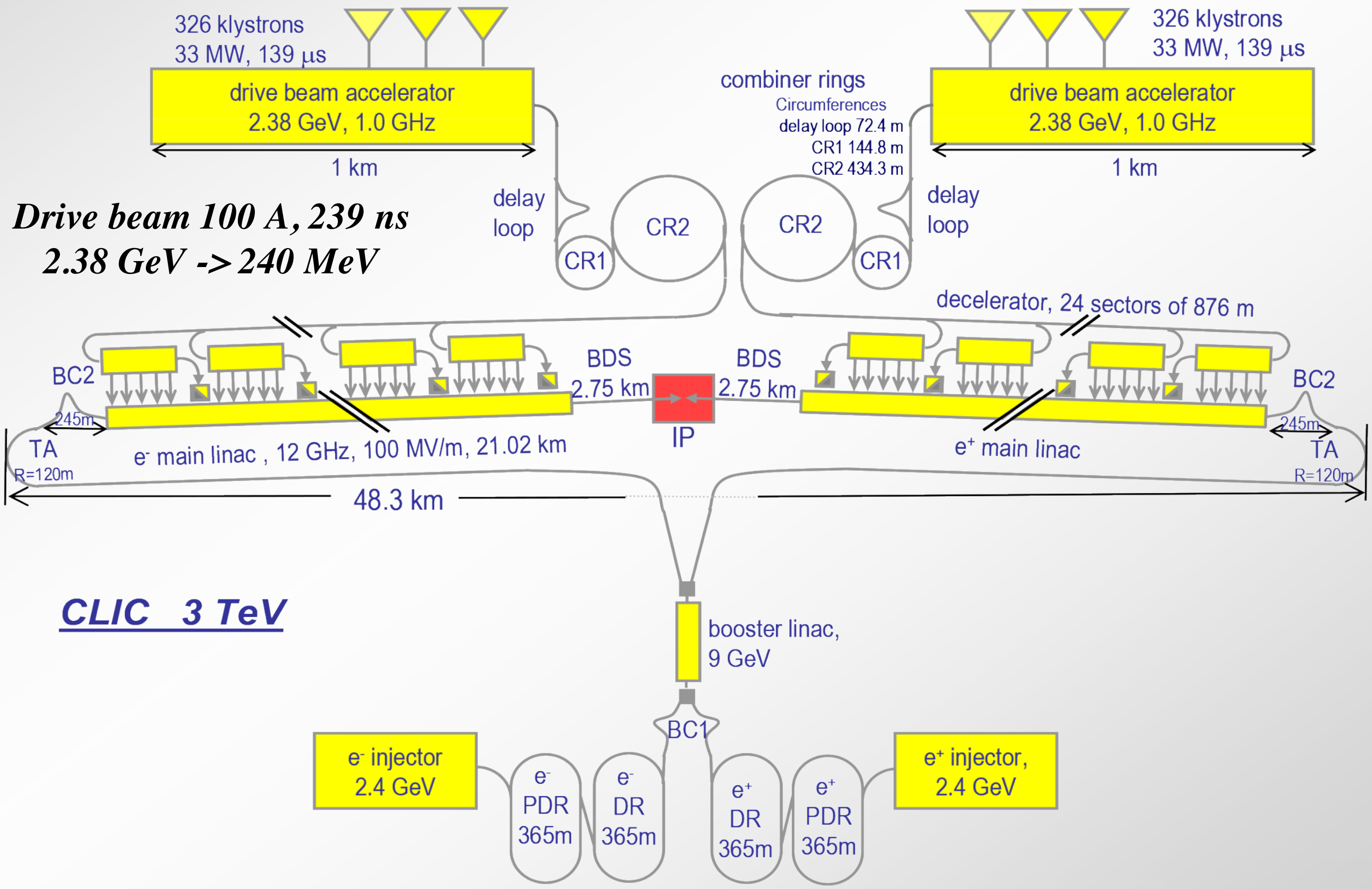
Muon colliders: Feasibility issues
Each step needs considerable R&D

- Multi-MW, magnetized production target
- Longitudinal phase space rotation with multi-harmonic rf
- 6-D phase space beam cooling by 10^6
  - High gradient cavity operation in strong magnetic field
  - High gradient cavity operation in significant radiation field
  - Large aperture focusing magnets for cooling channel
- Very large aperture, internally shielded dipoles for collider
  - Luminosity ~ Muon lifetime (revolutions) ≈ 300 B(T)
- NuSTORM would be a big step forward

Muon program deserves better
than ~20 years of sub-critical funding

Stay involved with the CLIC approach:
Complex 100 MeV/m, two-beam accelerator

- ❖ Promises 100 MeV/m in Cu structure - still, hardly compact
- ❖ Powered by low energy drive beam



Drive beam 100 A, 239 ns
2.38 GeV -> 240 MeV

CLIC 3 TeV

CLIC must master formidable challenges
for 3 TeV operation

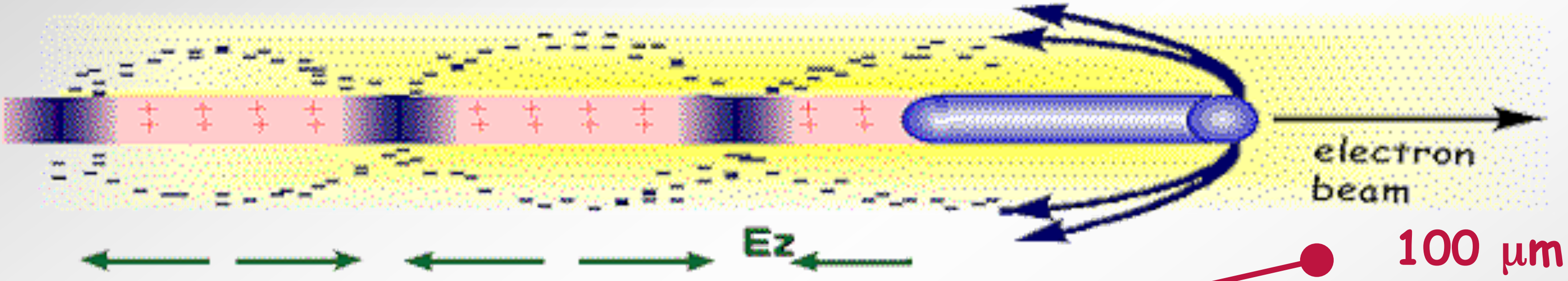
- Efficient generation of the high-intensity drive beam
- Power Extraction Structures to generate required power (unique to CLIC)
- Mass produced 12 GHz accelerating structures
- Generation & preservation of a small emittance main beam
  - Unprecedented level of wakefield-instability control
- Focusing of the beam to 1 nm beam size (for 3 TeV)
  - Higher energy ==> even smaller beams
  - Component stability at 2 Å level for 50 km
- Precision alignment of all components
  - Femtosecond timing control of beam arrival at IP
  - Micron-level trajectory control
- Energy & luminosity limited: power consumption, emittance growth in IR
  - Can plasma lenses overcome beamstrahlung induced, "Oide limit"?

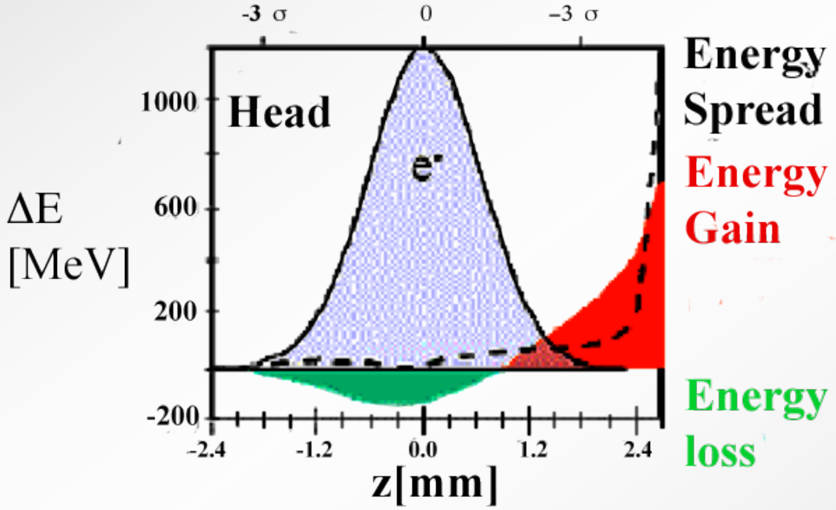
And this must be ~10x cheaper per GeV than ILC

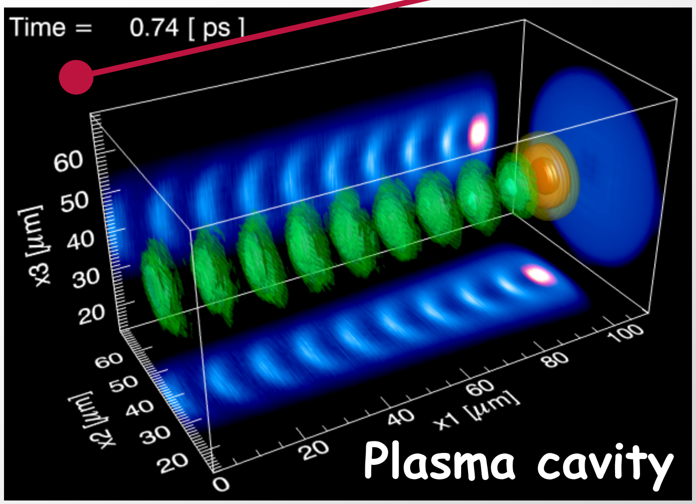
Continue R&D into wakefield accelerators

Two plasma approaches (beam driven & laser driven)

- Basic concept: drive strong standing plasma waves
  - Peak $E_z \sim 10 - 100$ GeV/m proportional to $\sqrt{n_{plasma}}$







Fruitful physics programs with high intellectual content

Many hurdles lie ahead on the track

- Two large programs in U.S. with major facilities
  - FACET @ SLAC ; Beam driven wakefields (PWFA)
  - BELLA@LBNL: Laser driven wakefields (LWFA)
- Highly competitive programs in outside the U.S.
- Feasibility issues:
  - Positron acceleration, multi-stage acceleration,
  - Control of beam quality, energy & stability
  - Plasma instabilities at 10's of kHz rep rate
- Practicality issues:
  - Efficiency of energy conversion to beam
  - Laser technology

All variants require an integrated proof-of-principle test

Accelerators for lepton colliders

"Big Questions"

How could one build a collider at the 10 - 20 TeV mass scale?

As $E_{cm} > 3$ *TeV parameters look increasingly improbable*

Could a 10 TeV machine be 10x cheaper per GeV than LHC?

Effective gradient of LHC is ~300 MeV/m; this is highly unlikely

Critical technologies:

High gradient, beam quality, stability & control

Accelerators for the Intensity Frontier

"Big Questions"

How would one generate 10 MW of proton beam power?

Can multi-MW targets survive? If so, for how long?

Can accelerators be made 10x cheaper per MW?

Overarching conclusion
of Snowmass capabilities study

Next generation of intensity frontier experiments

will require proton beam intensities & timing structures

beyond the capabilities of any existing accelerators

> 1-5 MW, flexible time structure

For example neutrino experiments

ask for ~Avogadro's number of neutrinos

==> ~Avogadro's number of primary protons

Proton linacs can deliver 100 mA $_{CW}$

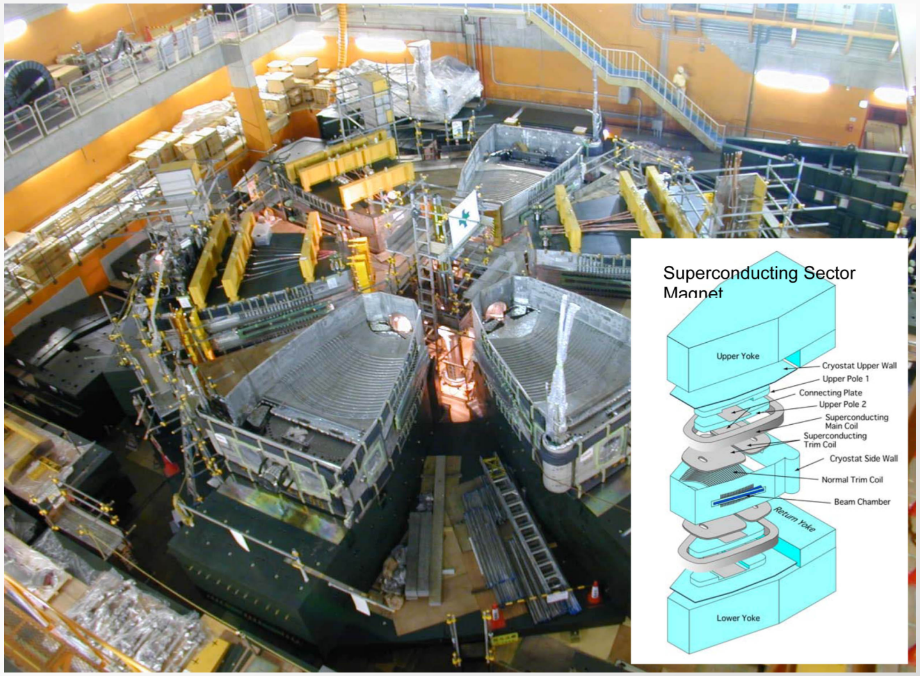
- LEDA, 6.7 MeV, 100-mA beam (100x state-of-the-art)
  - Normal conducting, standing wave linac ($150 M facility-FY96$)
  - Operated successfully at Los Alamos from 1999 - 2001
- Changing technology to a modern SCRF linac
  - Increases accelerating gradient ~3x - allows for a multi-GeV design
  - Reduces operating cost ~2x
  - Allows flexible “on-demand” time structure for IF experiments
  - H- beam allows for injection into storage ring/synchrotrons (120 GeV)

    ==> Project X as a world leading facility for HEP

  - Multi-stage scenario 1 GeV (CW) to 3 GeV (CW) to 8 GeV (pulsed)
- The first GeV is the most complex
  - Multiple families of SCRF cavities matched to (v/c) of the beam
    - Similar to approach of SNS, ESS

Modern cyclotrons offer exciting possibilities
for capabilities of narrower scope

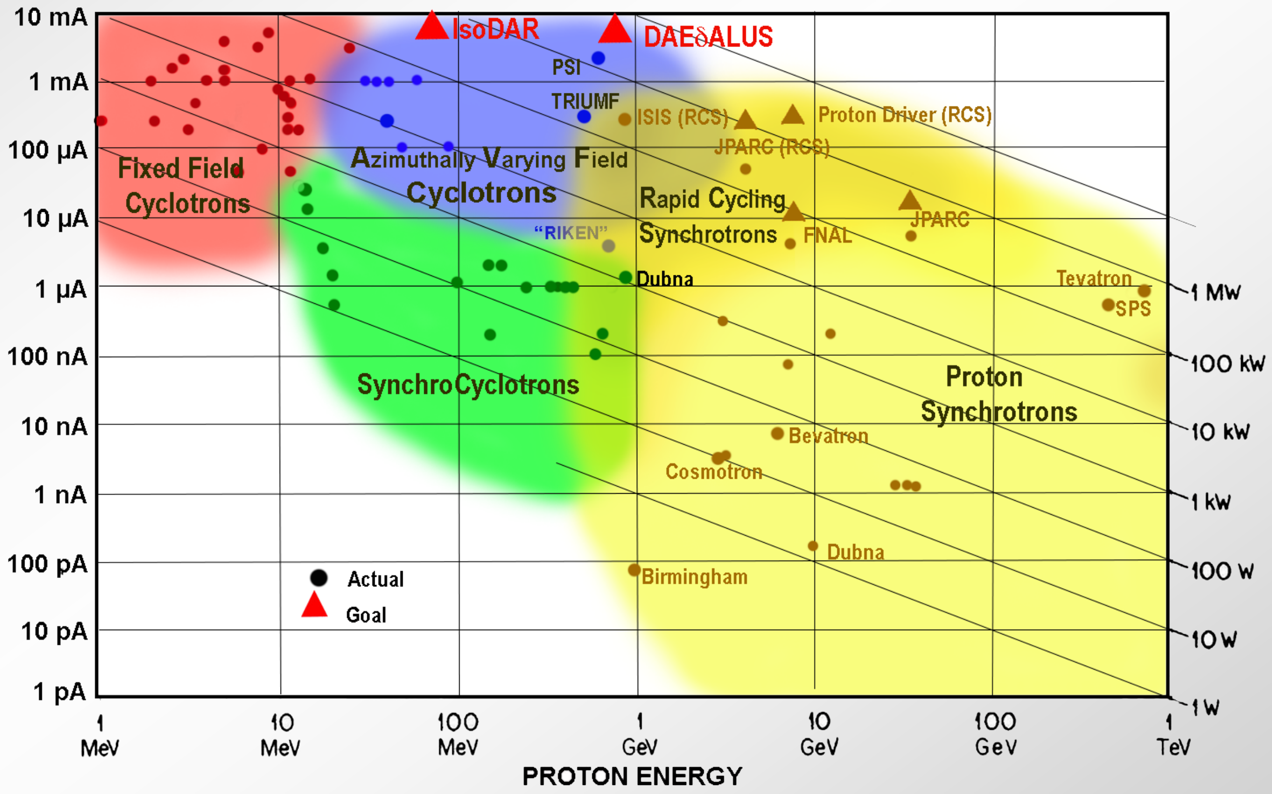
- DAEδALUS: Decay At Rest anti-neutrinos – experiments based on short baseline oscillations
  - Three multi-MW H_2^+ cyclotrons & targets ~2-20 km from detector
    - First stage: IsoDAR – compact cyclotron 15 m from Kamland
  - Basis: 1.4 MW PSI & RIKEN SC ring cyclotron scaled to 800 MeV



140-ton cold mass

Design pushes cyclotron to realm of ADS
(~1 GeV, 10 MW)

- Current limit ~ 5 mA (space charge at injection) < Linac
- Energy limit ~ 1 GeV << Linac potential
- $$ per MW ~ 1/4 of Linac of same beam parameters



Common IF issues of accelerator R&D

- 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 & controlling beam loss

Efficient collimation

Beam dynamics simulations of halo generation

Large-dynamic-range instrumentation

High power targets are a hard problem
that limits facility performance

- 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
  - Ill defined failure criteria (classical limits may be too conservative)
- Need controlled, instrumented in-beam tests
  - But, need a source before you can test materials
    - Takes a long time to build up data (accelerated testing)

Requires a structured R&D program for accelerator-based science

(International RADIATE collaboration has formed)

Proton Accelerators for the Intensity Frontier

"Big Questions"

How would one generate 10 MW of proton beam power?

Linacs & cyclotrons can reach this regime

Can multi-MW targets survive? If so, for how long?

We don't know limits; Depends on W/gm deposited

Can accelerators be made 10x cheaper per MW?

2x may be within reach; needs structured R&D

Cyclotrons are cheaper than linacs, but over limited parameter range

We are meeting the challenge

of the

Big Questions

given the time, money &

a little bit of luck

Thank you