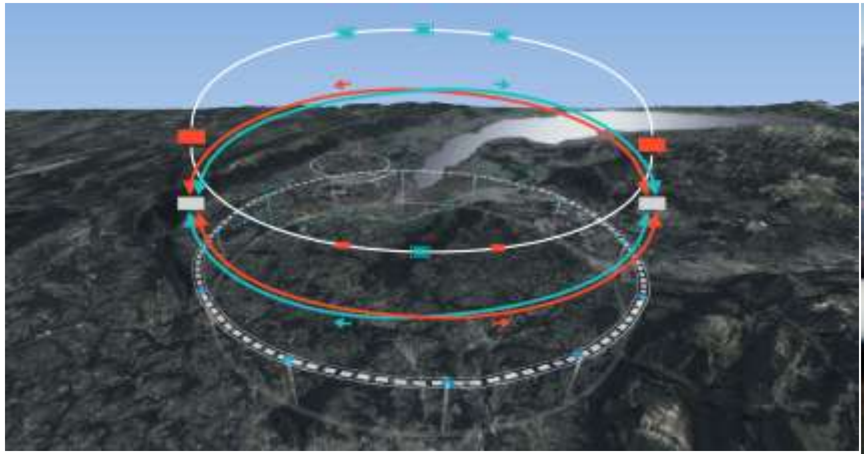


Potential US Technology Contributions to [Off-Shore] Future Colliders

Vladimir Shiltsev (NIU)

HFCC Strategy Meeting

Stony Brook University - November 8, 2024

Content:

Areas (SRF, magnets, design, etc) and Elements of possible US Accelerator Technology contributions to future colliders:

- Circular *e+e- HFs*
- Linear SRF *e+e- HFs*
- Linear NCRF *e+e- HFs*
- Circular *pp 10+TeV pCM*
- Circular *mu-mu 10+ TeV pCM*

- **Where the expertise resides**

Special thanks to **Sergey B.** and **Emilio** for slides on *e+e-* SRF and NCRF machines and to the

2023 US-FCCee Planning Panel

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John Byrd (ANL)
Steve Gourlay (FNAL)
Matthias Liepe (Cornell)
Sergei Nagaitsev (JLab)
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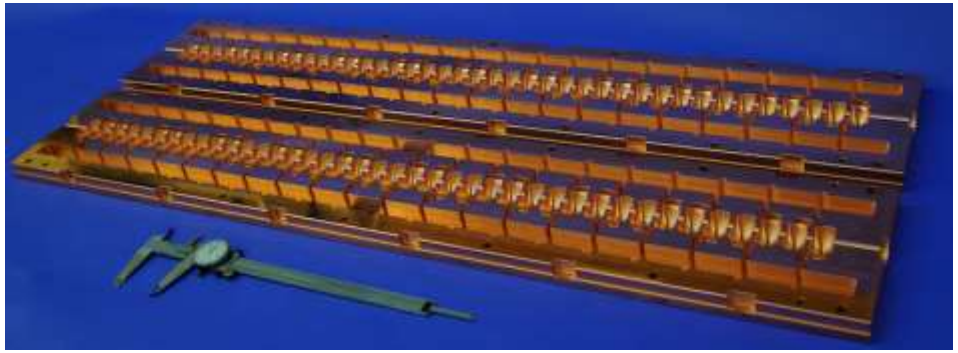
Circular e+e- Higgs Factories:

- Several feasible Higgs factory options are on the table at present:
  - FCCee (the leader) - Technology development is well advanced, a host (CERN) has been identified and supports a Feasibility Study (and US participates), P5 support
  - LEP-3 in the LHC tunnel – not favorite at CERN, same technologies as FCCee
  - CEPC (not for this meeting) – TDR published in Dec. 2023, uncertainties of various kind
- US has a lot of expertise in most related accelerator technologies:
  - (Relatively recent) experience in B-factories: CESR, PEP-II, (S-KEKB)
  - Decadal investments in relevant technologies via GARD (SRF, MDP, etc) and ILC R&D
  - Several 3rd and 4th generation light sources built recently/under. construction: NSLS-II, APS-U, ALS-U
  - Many synergies with NP facilities: EIC project, TJNAF, (less with FRIB)

Possible US-FCC: RF Systems *(as presented to P5)*

1. 800 MHz SRF cavities with Q0 = (3→6)e10 at 25 MV/m; then 4-cavity Cryomodules
   - **28 RF cryomodules** are needed for the Higgs operation,
   - Follow up possibility - **another 244 CMs (later)** for Booster/Collider Rung at *ttbar*

2. High efficiency power sources for 800 MHz with η > 80%
   - R&D and design

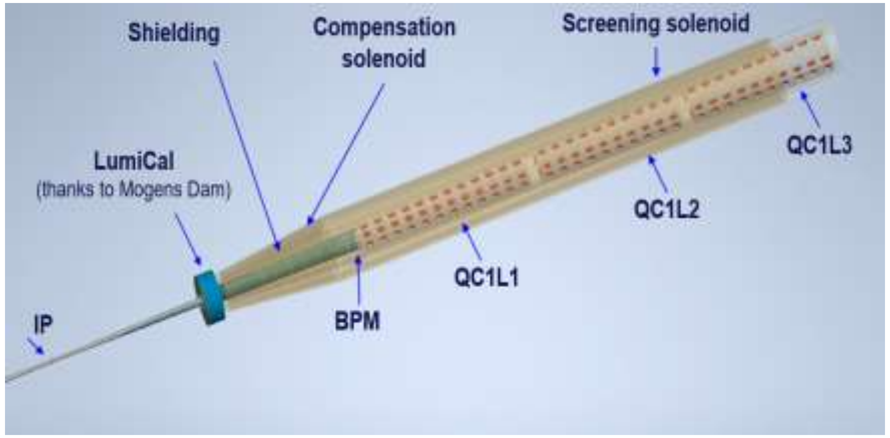


3. High gradient 70 MV/m 150 MOhm/m C3 copper RF for injector (eg C^3 type):
   - **6-20 GeV RF** high gradient inj. Linac

US-FCC: Magnets and MDI *(as presented to P5)*

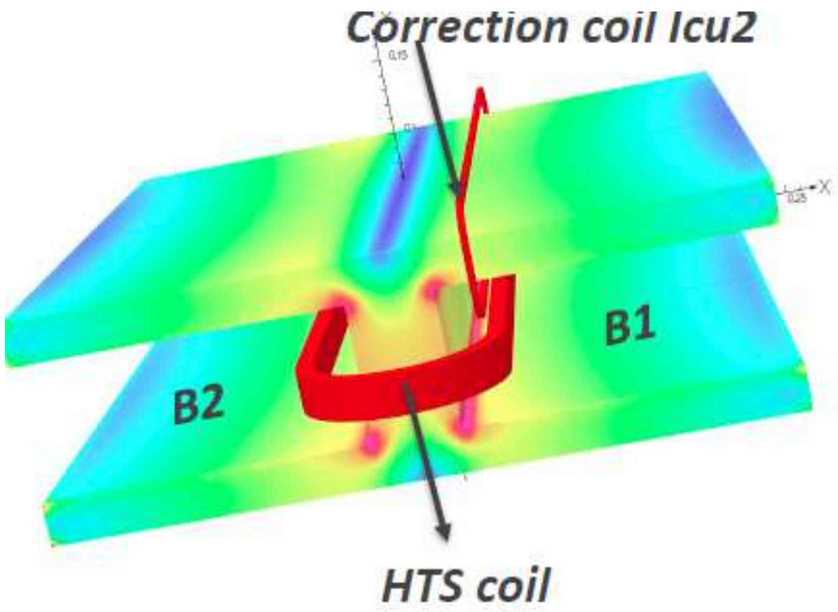
1)IR magnets and cryostats

- R&D: Comparative analysis of technical options
- Design/Prototyping of two most critical magnets
- IR Magnets engineering design
- **Construction of IR magnets for 4 IRs**



2)Collider ring magnets (low field):

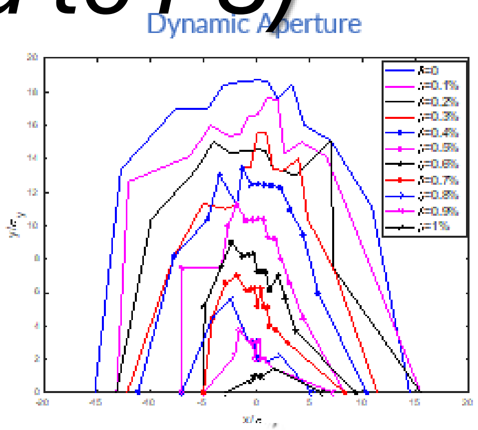
- R&D: comparative analysis of technical options
- Design/Prototype of HTS cable-based solution
- Design/Prototype of PM dipole
- **Decision on construction - tbd**



3) Booster ring magnets (~1s) - tbd

* see Soren Prestemon talk

UC-FCC : Modeling & Design / Collimation / Polarization /Instrumentation *(as presented to P5)*

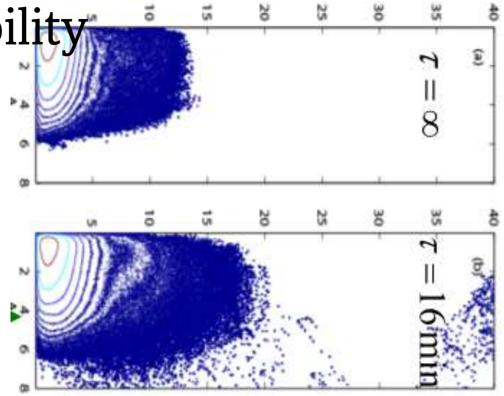


1) Interaction region design, and integrated machine design:

- **Modeling/simulations**: DA, optics, crab waist and beam-beam/beamstrahlung
- **Design**: as needed for the "US-FCC-ee magnets" hardware

2) Losses, collimation and background:

- **Modeling/design**: halo formation/collimation, background in detectors, instability
- **Possible fabrication: collimation system (IRs and Rings)**

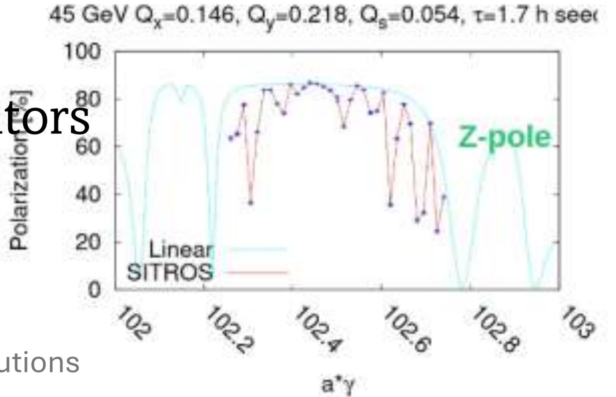


3) Polarization:

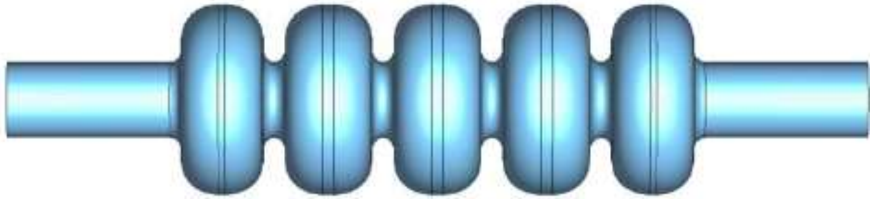
- **Modeling/design**: energy calibration, polarimeters, polarized sources
- **Fabrication: wigglers for 45 GeV ops and 2 polarimeters, sources**

4) Beam Instrumentation.:

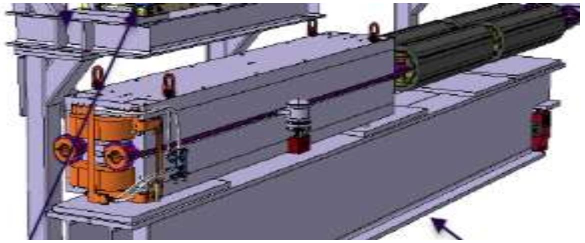
- **Design and prototyping:** BPMs, Lumi, instability FB, emittance, halo monitors
- **Fabrication: Instability feedback, halo monitors, LLRF (other)**



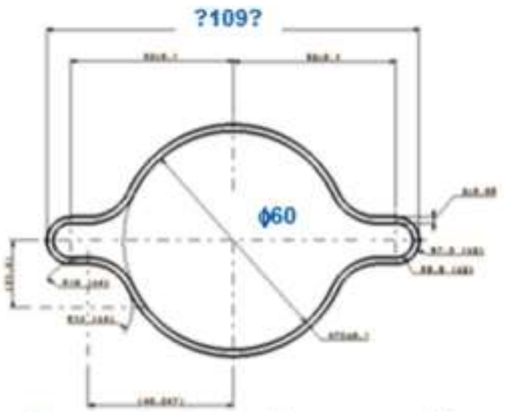
Possible US-FCC Fabrication Elements
(as presented to P5 - TBD)



1) 2.1 GV 800 MHz SRF for Higgs, 28 CMs *O*(0.2B$)
2) 18.4 GV of 800 MHz SRF for *ttbar*, 244 CMs *O*(1.7B$)



3) 6-20 GeV S-band C^3 type linac *O*(0.25B$)
4) IR magnets for 4 IPs *O*(0.6B$)
5) Magnets for the collider and booster rings *O*(1B$)
6) 270 km of vacuum pipes (collider, booster) *O*(0.3B$)
7) Several km RF bypass (switch btw *tt* and *ZH*) - TBD
8) Beam instrumentation/polarization *O*(0.15B$)
   - Collimation, halo monitors | Polarization wigglers, meters, sources | TMCI feedback



Vacuum chamber prototype cross-section

9) Technical Infrastructure contributions - TBD
   - Alignment | Radiation protection | Safety systems | Power converters

Relevant US Expertise in Circular e+e- HFs

	ANL	BNL	FNAL	LANL	LBNL	JLab	SLAC	Universities
SRF cavities/CMs			■			■	■	Cornell, ODU ...
RF sources/modul.	■						■	IIT, Stanford
Copper RF linac	■			■			■	NIU, IIT
IR magnets		■	■		■			FSU, MIT, TAMU
Booster/MR magnets	■	■	■		■			
Beam Optics	■	■	■	■	■	■	■	Cornell, ...
Collimation		■	■				■	
Polarization		■	■			■		Cornell, UNM, ...
Instrumentation	■	■	■		■	■	■	many
Infrastructure	■	■	■	■	■	■	■	

Linear SRF e+e- Higgs Factories:

- ILC is one of the most feasible Higgs factory options:
  - >10 yrs since TDR…No host country has been identified (yet?)
  - (in preparation to EPPSU) updated cost will be reviewed by Xmas
  - HELEN: Recently proposed 1.3 GHz Travelling Wave SRF modification for (more than double) gradient of ~70 MeV/m
- US has expertise in all related accelerator technologies:
  - The US once considered to host the project
  - Decadal investments in all relevant technologies and design work via the ILC R&D program, and, later, via International collaborations (GDE, TDR, US-Japan) and GARD
  - LCLS-II X-FEL built recently and LCLS-II-HE under construction
  - Synergies with NP facilities: TJNAF, (also with SNS and the EIC)

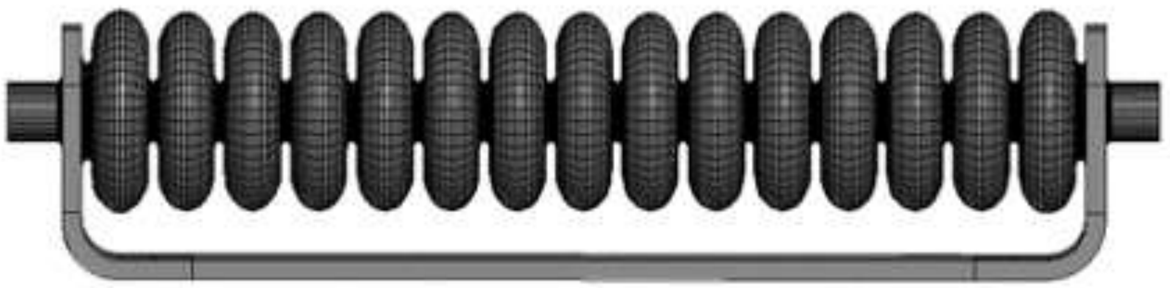
Potential U.S. contributions to ILC (as presented to P5)

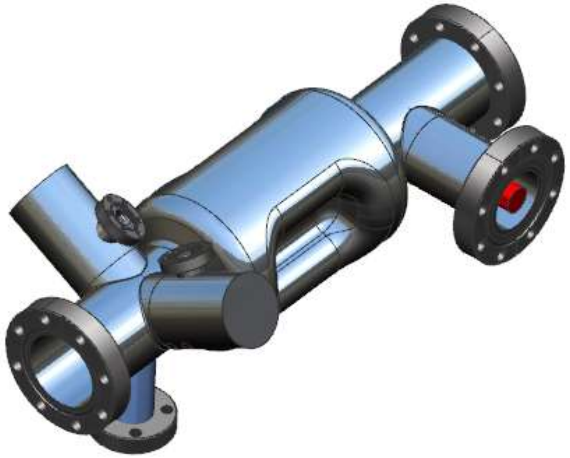
"…The U.S. community is interested in partnering on the following areas:

1. Main Linac (ML) and SRF, including crab cavities
2. Polarized electron source
3. Polarized and electron-driven positron source options
4. Damping rings
5. Beam delivery system
6. Simulations, software management and global systems"

US Technologies for the ILC

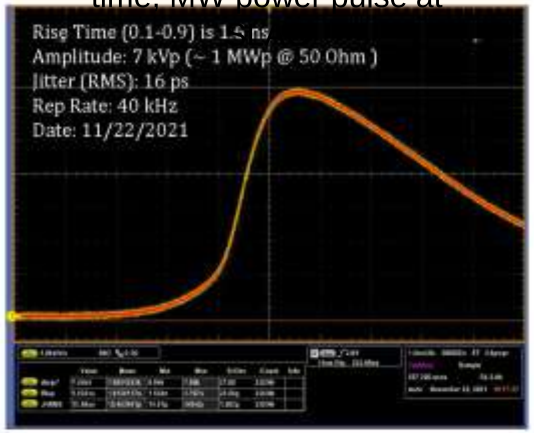
- SRF cavities, traveling wave SRF
- CM design, industrialization
- Better cavities (Q_0, Nb_3Sn)



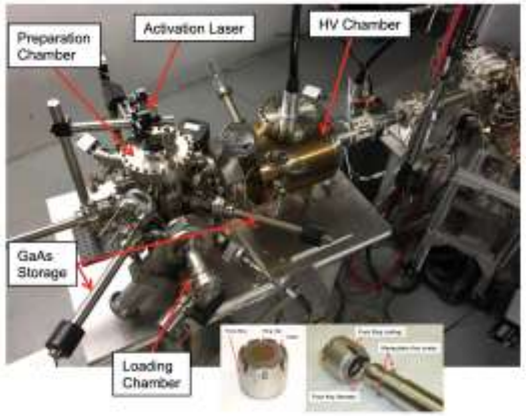


Crab-cavities
1.3 GHz RFD
2.6 GHz QMiR

Demonstration of ns rise time, MW power pulse at

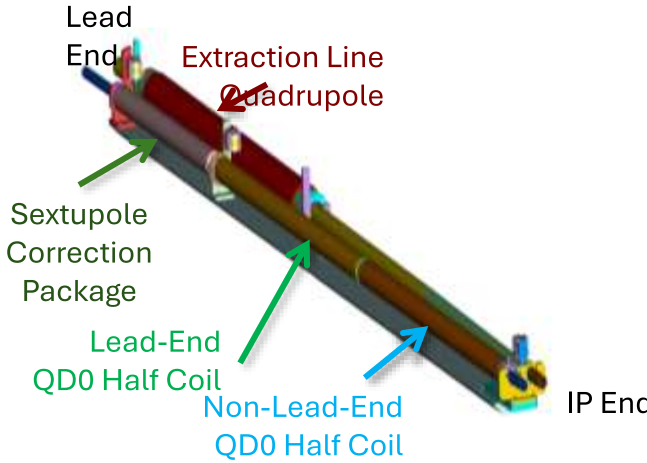


Damping Rings
Collective effects, FB
Injection/extraction



Polarized electron source at JLab,
P. Adderley et al., Phys. Rev. Acc. Beams (2010)

Pol. *e+e-* sources
Baseline
Backup



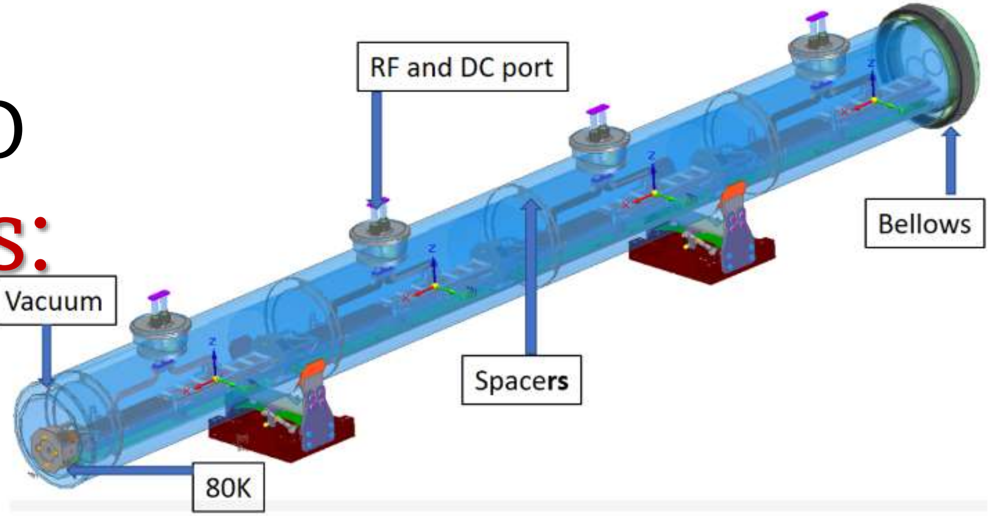
BDS
Magnets, optics
Collimation

Linear NCRF e+e- Higgs Factories:

- CLIC covers Higgs physics, expands to 3 TeV *e+e-*:
  - 12 GHz, two RF source options: drive beam and klystrons; very active R&D program at CTF3 concluded years ago, CDR
  - 5.7 GHz Cool Cooper Collider (C3) technology offers comparable gradients (lower cost? - tbc)
- US used to be the leader in the NCRF technologies:
  - SLC operated till the end of 1990s
  - NLC was designed and considered a viable project in early 2000s
  - Since then, modest level investments in the NCRF R&D and relevant technologies via GARD (RF, AARD-SWFA); highly synergistic with the ILC design work via the ILC R&D program, and, later, via International collaborations… industrial spin-offs
  - That expertise is now greatly reduced (…true for all colliders)

Possible NCRF Contributions to e+e- *HFs*:

- ❑ (Limited) involvement in CLIC Project Readiness Report
  - ❑ upcoming EPSSU, then US contr. TBD
- ❑ R&D in C3 collider technologies:
  - ❑ Cryomodule design and test (tbc)
  - ❑ Studies of gradient, cryo, vibrations
- ❑ Studies of C3 suitability for:
  - ❑ FCCee e+e- injectors
  - ❑ e+e- LC sources
  - ❑ (muon collider cooling channel)



Relevant U.S. Expertise in Linear e+e- HFs

	ANL	BNL	Cornell	FNAL	JLAB	LBNL	ODU	SLAC	UCLA
Main Linac SRF			✗	✗	✗			✗	
Polarized e- source		✗	✗		✗			✗	
Undulators for polarized e+ source	✗					✗		✗	
Main Linac NCRF	✗			✗				✗	✗
Crab cavities				✗	✗		✗		
DR system design & subsystems (SRF, vacuum, magnets, instrumentation ...)	✗	✗	✗	✗	✗	✗		✗	
Beam optics, collective effects ...	✗	✗	✗	✗	✗	✗		✗	
Fast kickers				✗				✗	
BDS design				✗	✗			✗	
Final doublet		✗		✗		✗			

US Strength: Accelerator Facilities

- SRF test/production facilities:
  - FNAL, JLab, SLAC, Cornell, …
- High field magnets test/production facilities:
  - FNAL, LBNL, BNL, …
- NCRF test/R&D facilities:
  - SLAC, ANL, BNL…
- Beam test/R&D facilities (physics, sources, etc)
  - FNAL, JLab, Cornell, SLAC, ANL, BNL, UCLA…

Summary

- A $e+e-$ Higgs Factory is slated to be the **next high-priority HEP collider**, operating following the completion of the HL-LHC program.
- 2023 P5 Report calls **for impactful US accelerator contribution to an off-shore Higgs factory:**
  - The US has to be a leading partner in the successful realization of the HF
  - Contribution depends on the choice: circular, linear SRF, linear NCRF
  - US national labs and universities have significant expertise and a suit of relevant facilities to contribute to [any off-shore HF] project.

- Caveats:
  - Decadal accelerator workforce challenges
  - Accelerator developments towards 10+ TeV pCM colliders

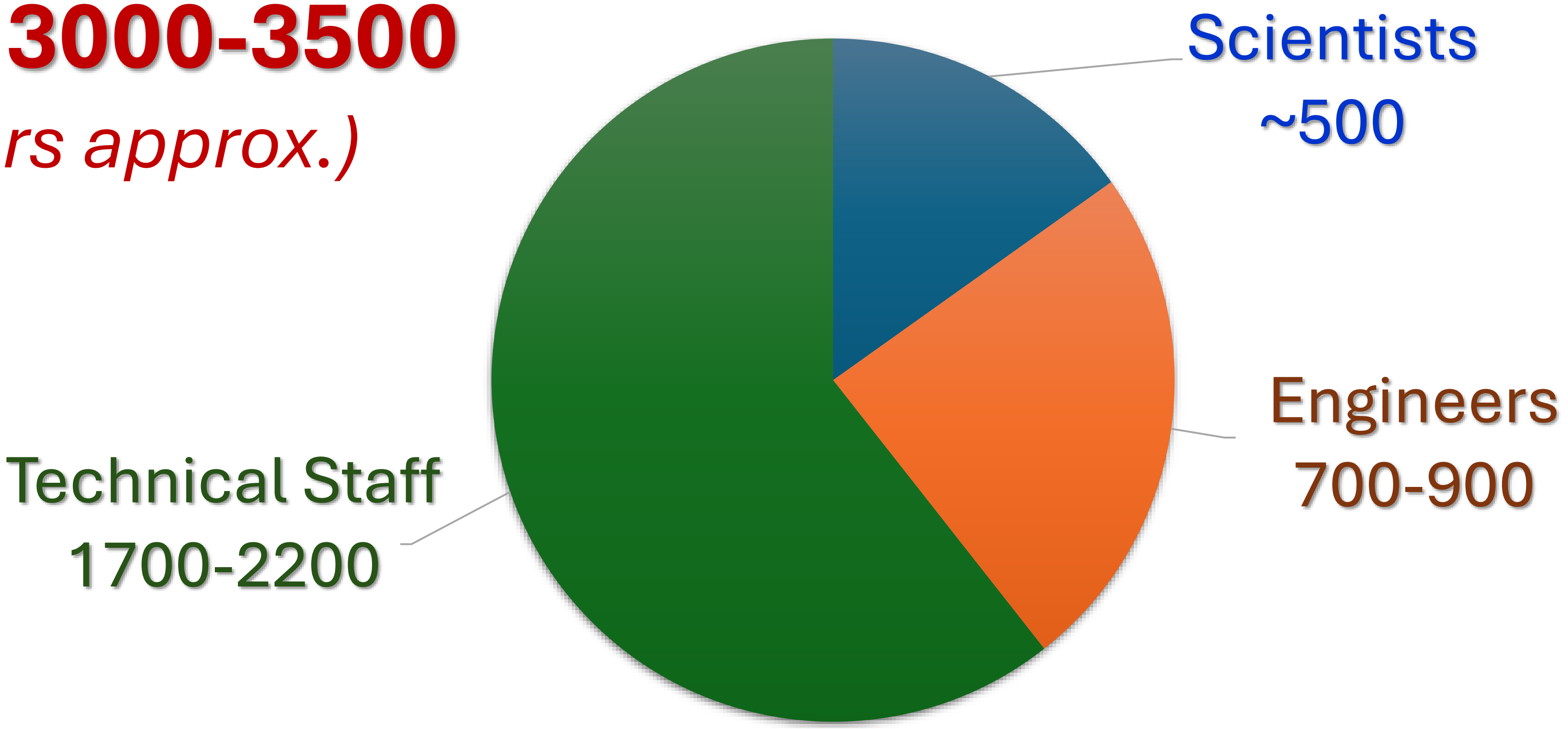
Accelerator Workforce in the US (mid 2020's)

incl Natl. Labs and Universities; operations, projects, and research,

supported by DOE HEP/BES/NP/..., NSF, ...

Total: 3000-3500

(numbers approx.)



US Contribution to an Off-Shore HF:

PIP-II EIC

- Scale of investment (P5 estimate) **~(1-3) B$**
  - over 15-20 yrs → peak ~200-300M$/yr
  - 1/3 - ½ to SWF → 60-150 M$/yr or 180-450 FTEs
  - With a typical accelerator project distribution, that's
    - 20-40 Scientists = 5-10% of total Sci.
    - 60-140 Engineers = 10-20% of total Eng.
    - 100-300 Tech. = 5-15% of total Tech.

*More than **5%** in the "longer training workforce" is a decadal problem*
*More than **10%** in the "short-training workforce" is a serious problem*

OF RELEVANCE TO THIS DISCUSSION:

Circular *pp* and *μμ* 10+ TeV pCM Colliders :

- FCChh to follow FCCee in the 91 km tunnel:
  - 100 TeV with 16T Nb3Sn magnets, ~50 TeV with NbTi, now 81-155 TeV (14T Nb3Sn – 20T HTS magnets)…Also, recently discussed: ~28TeV HE-LHC with Nb3Sn magnets and 24 TeV Fermilab site-filler (with 24T HTS)
- 6-14 TeV *μμ* collider in LHC-size tunnel or FNAL site-filler
- For long-while, the US was at the *pp* and *μμ* Frontier:
  - 25 years of the Tevatron ended in 2011, VLHC proposal in early 2000s
  - 3 decades of muon collider R&D and design work
  - Decadal support via LARP, MAP, GARD (HFM, SRF, targets, ABP, etc)
  - Synergistic with FNAL proton complex ops, incl. PIP-II (HEP), RHIC and EIC (NP), and SNS (BES facility)
  - (Reduced) expertise remains in the ~same labs and universities

10+ TeV pCM Colliders Design Challenges

	FCChh	10 TeV MuCol
RF systems		
High field magnets		
Fast Booster magnets		
6D muon cooling		
Inj./Extr. kickers		
Emittance preservation		
DD/IP spot size		
High power target		
Proton driver		
Beam screen		
Collimation system		
Power efficiency and consumption		

From ITF REPORT T.Roser et al, 2023 JINST JINST 18 P05018

10+ TeV pCM R&D: Relevant to this Discussion

- (According to P5) 10+ TeV pCM options:
  - FCChh, muon collider, and *possibly AAC collider*
  - (per ITF report) 20-25 yrs of R&D and pre-project R&D, totaling 1-2 B$ (ie ~100M$/yr peak)
  - That will require 100-240 FTEs:
    - 40-70 Scientists = 10-15% of total Sci.
    - 30-70 Engineers = 5 - 10% of total Eng.
    - 40-100 Tech. = 2-5% of total Tech.

*More than **5%** in the "longer training workforce" is a decadal problem*

Thank you for your attention!

- Back up slides