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AN 8 GeV LINAC AS THE BOOSTER REPLACEMENT IN THE FERMILAB POWER UPGRADE

D. Neuffer, S. Belomestnykh, M. Checchin, D. Johnson, S. Posen, E. Pozdeyev, V. Pronskikh, A. Saini, N. Solyak, V. Yakovlev

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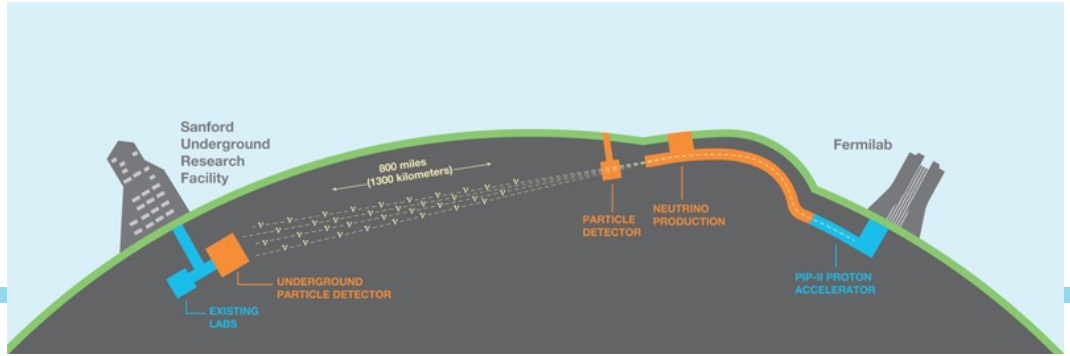
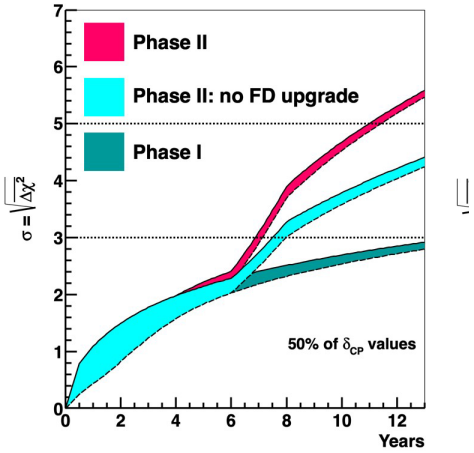
Abstract

Increasing the Fermilab Main Injector beam power available to the high-energy neutrino experiments above ~1.2 MW requires replacement of the 8 GeV Booster by a higher intensity alternative. Rapid-cycling synchrotron and Linac solutions were considered for this purpose. We consider the linac version that produces 8 GeV H- beam for injection into the Recycler Ring or Main Injector. The new linac takes ~1 GeV beam from the PIP-II linac and accelerates it to ~8 GeV in SRF structures. The linac components incorporate recent improvements in SRF technology.

- Main Injector power to DUNE > 2.4 MW
  - Requires more beam at 8GeV to MI
  - Requires Booster replacement



δ_{CP} Discovery, sigmas over time



Outline

➢ PIP-II → ???

- Requires 0.8 → 8 GeV upgrade to be fully useful

  Linac → RCS (or FFAG)

  Linac → **8 GeV Linac → Main Injector (2.4 MW +)**

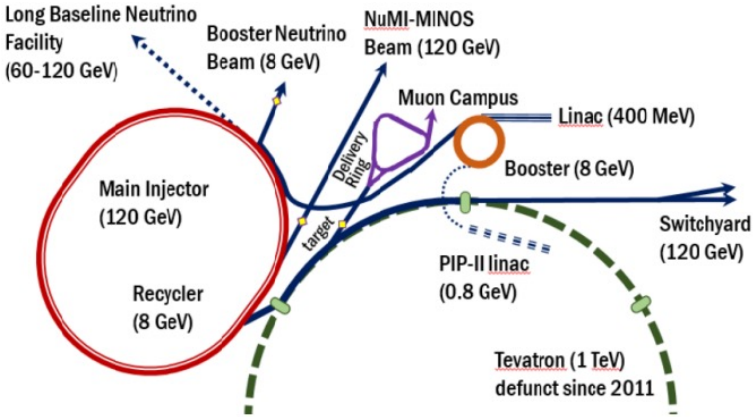
  ~Project X: 3GeV cw → 8 GeV pulsed

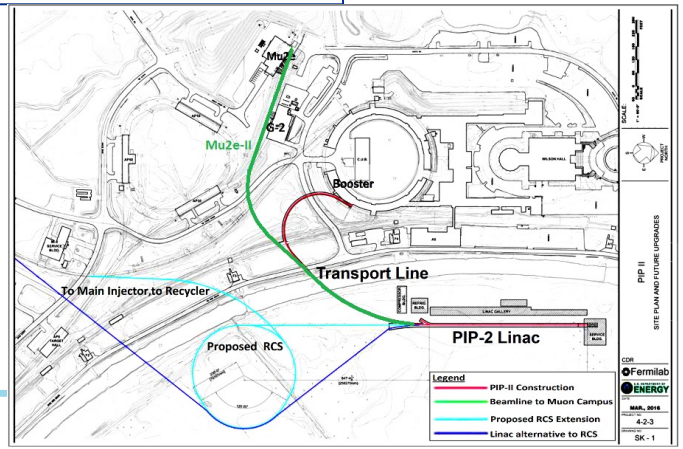
- Snowmass white paper: https://arxiv.org/pdf/2203.05052.pdf

An 8 GeV Linac as the Booster Replacement in the Fermilab Power Upgrade: a Snowmass 2021 White Paper

- Fermilab Proton Intensity Upgrade

Parameter	PIP-I	PIP-II	Booster Replacement	Unit
Linac Energy	400	800	8000	MeV
Beam Current	25	2	2	ma
Pulse length	0.03	0.54	2.2	ms
Pulse Rep. Rate	15	20	20	Hz
Protons/pulse	4.2	6.5	27.5	10^{12}
8 GeV beam power	80	166	700	kW
Power to MI	50	83-142	176-300	kW
MI protons/pulse	4.9	7.5	**15.6**	**10^{13}**
MI cycle time (120 GeV)	1.5	1.2	1.2	s
MI Power to DUNE(120GeV)	**0.7**	**1.2**	**2.5**	**MW**
8 GeV - other users	30	83	500	kW

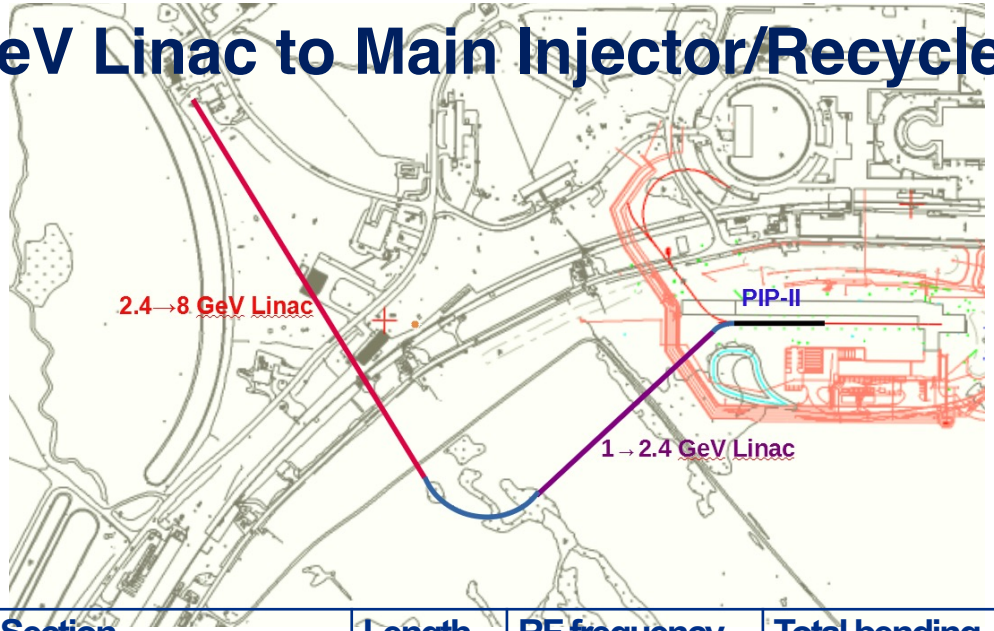




Why an SRF Linac?

1. **Strong expertise** – at Fermilab, after producing CMs for LCLS-II –
   - Fermilab Cryomodule design, with continuing SRF improvements
2. **Key production facilities exist already** – Fermilab and others have key infrastructure for fabrication and test
3. **Cost effective** – based on previously developed technology
4. **Low technical risk** – well understood technology after previous projects
5. **Low cost risk** – cost drivers are well understood after LCLS-II and LCLS-II-HE
6. **Flexibility** – tap off at other energies, can increase beam power to X MW?
7. **Efficiency** – “green” technology to deliver power to beam

8 GeV Linac to Main Injector/Recycler



Section	Length	RF frequency or bending field	Total bending angle or Linac operation	Cav/mag /CM	Cryomodule length
1GeV transport	32 m	0.25T	-45°		
1→2.4 GeV Linac	290 m	650 MHz	CW or 20 Hz	60/10/10	9.92m
2.4 GeV bend	165 m	0.13T	105°		
2.4→8 GeV Linac	310 m	1300 MHz	Pulsed, 20 Hz	160 /20/20	12.5 m
8GeV injection	200 m	0.05T			

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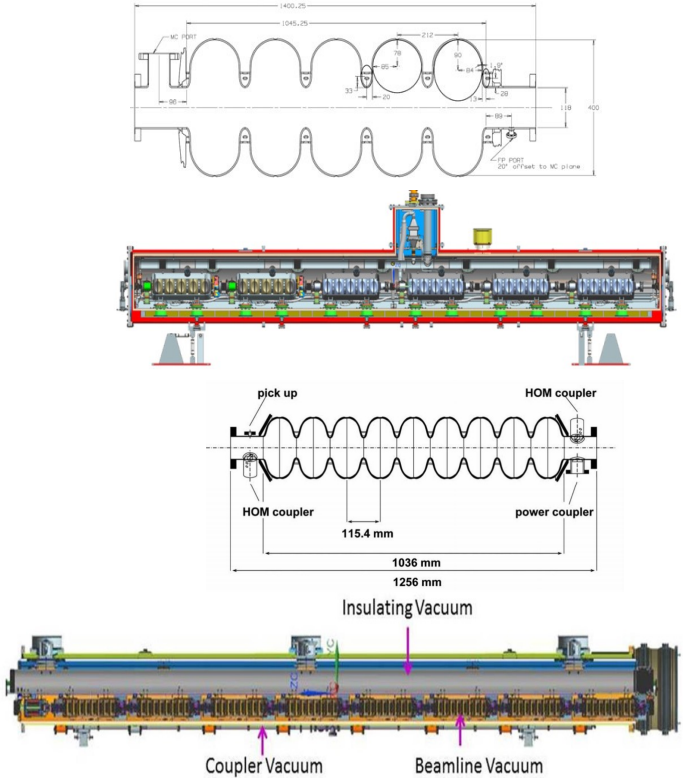
650 MHz and 1300 MHz SRF

based on PIP-II and LCLS-II



- **SRF parameters**

Parameter	650 MHz	1300 MHz
β (v/c)	0.92	1.0
Cells/cavity	5	9
Cavity length	1.061 m	1.38m
R/Q	610	1036 Ω
$G=Q_0R_s$	255	270Ω
Gradient E_{acc}	**22.6 MV/m**	**30→35 MV/m**
E_{max}	46.8 MV/m	52→60 MV/m
B_m	88 mT	120 mT
Q_0	**6.0×10^{10}**	**2.0×10^{10}**
Beam current	2—5 ma	2—5 ma
Q_L	$0.7—2.0\times10^{7}$	$0.7—1.7\times10^{7}$
Losses @2K	15.7 W	65.5 W
Cavity rf power	120 kW	184 kW
Cavities/cryo	6	8
Cryomodule L	9.9	12.5 m
Scenario req.	60 cavities	160 cavities

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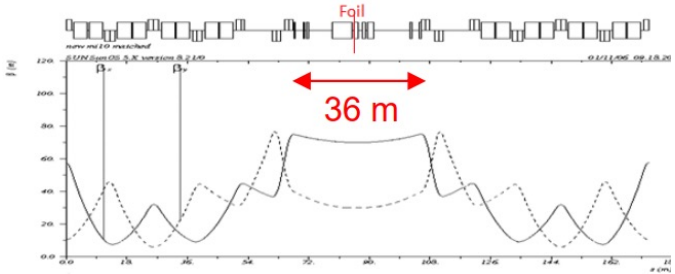
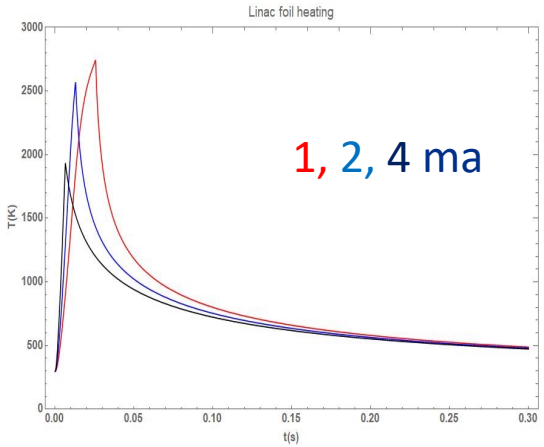
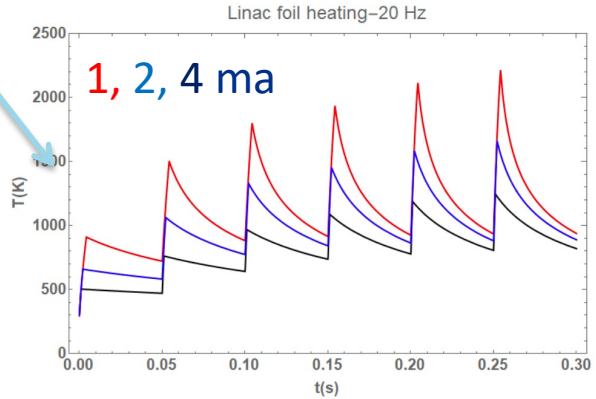
Injection into RR/MI

- **Foil heating problem**
  - **Single pulse into MI not safe for foil**
    - **Unless I > 4ma**
  - **Multi pulse into RR to reduce T at foil**
    - **2ma, 2 ms, 6 pulses**

- **Placement in existing RR/MI ?**
  - **Need injection absorber**







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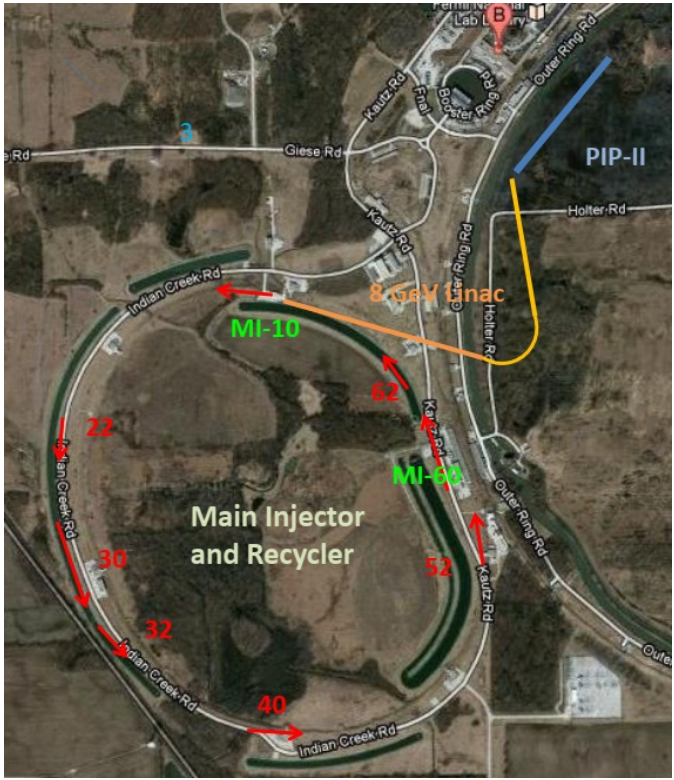
Problem with MI/RR 10 Injection

- **But…** LBNF-DUNE is using MI-10 for extraction
  - No room for Injection in MI-10
  - Could use RR-10 – space is very restricted
    - Losses in MI enclosure are undesirable

- Potential solution --Beams-Doc 8874
  - Use Accumulator 8 GeV ring for injectin
  - MI-60 or MI-62 injection
    - Stack in RR or MI
    - Location could also be used for RCS
    - Ring could provide beam to



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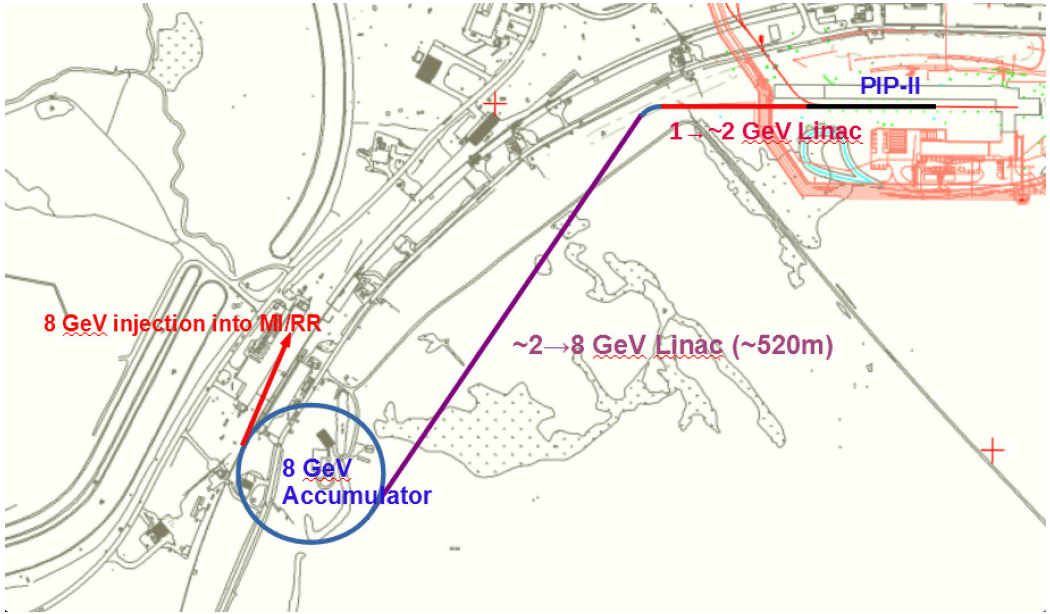
8 GeV Linac- Alternative Layout



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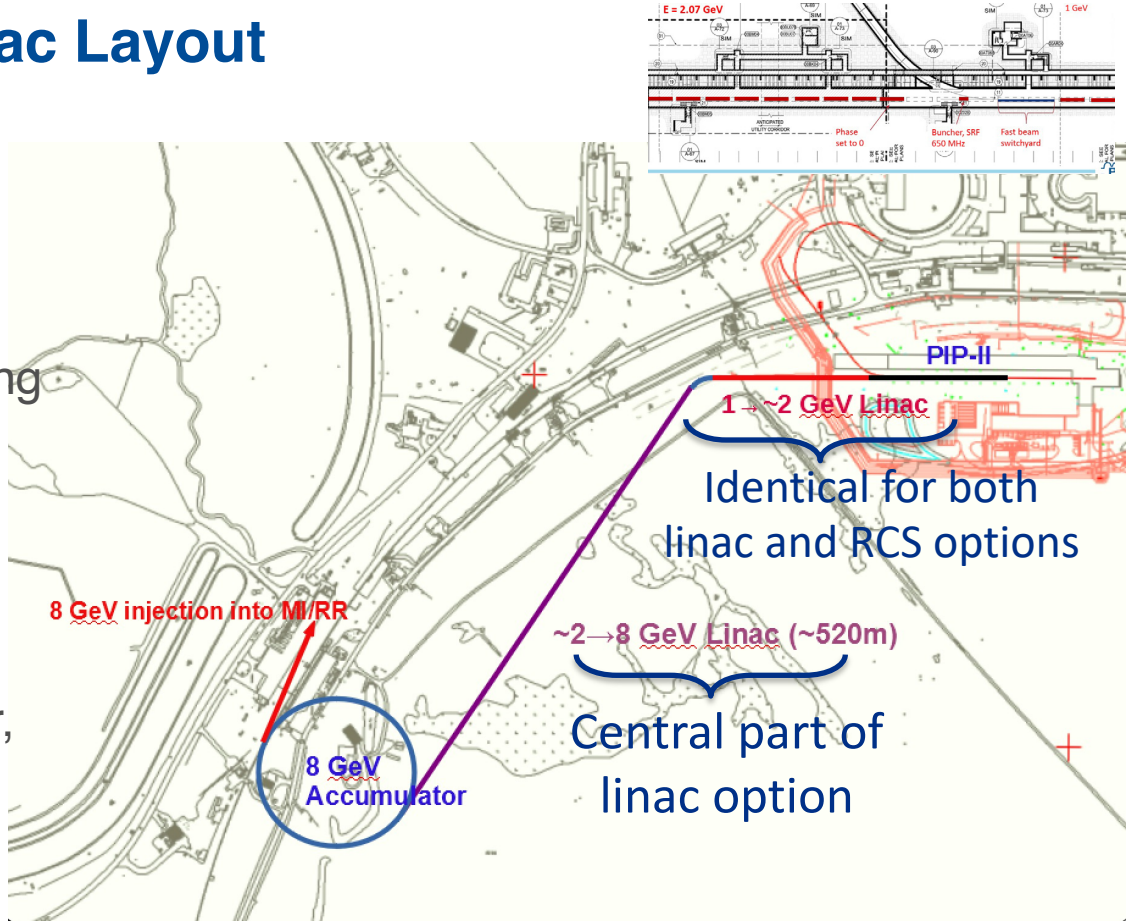
2.4→8 GeV Linac	310 m	1300 MHz	Pulsed, 20 Hz	160 /26/26	12.5 m
8GeV injection	200 m	0.05T			
8 GeV Accumulator Ring	480 m	1 T	360°		

Booster Replacement Linac Layout

- Extension of PIP-II to ~2 GeV,
- then high gradient pulsed SRF linac to 8 GeV
- Strip H- to H+ in accumulator ring – bunch for RR/MI
- Accumulator would be ~500 m racetrack with 100 m long straights
- Inject into recycler/main injector, then beam to LBNF
- 8 GeV beam available for other experiments



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2 → 8 GeV Superconducting RF Linac

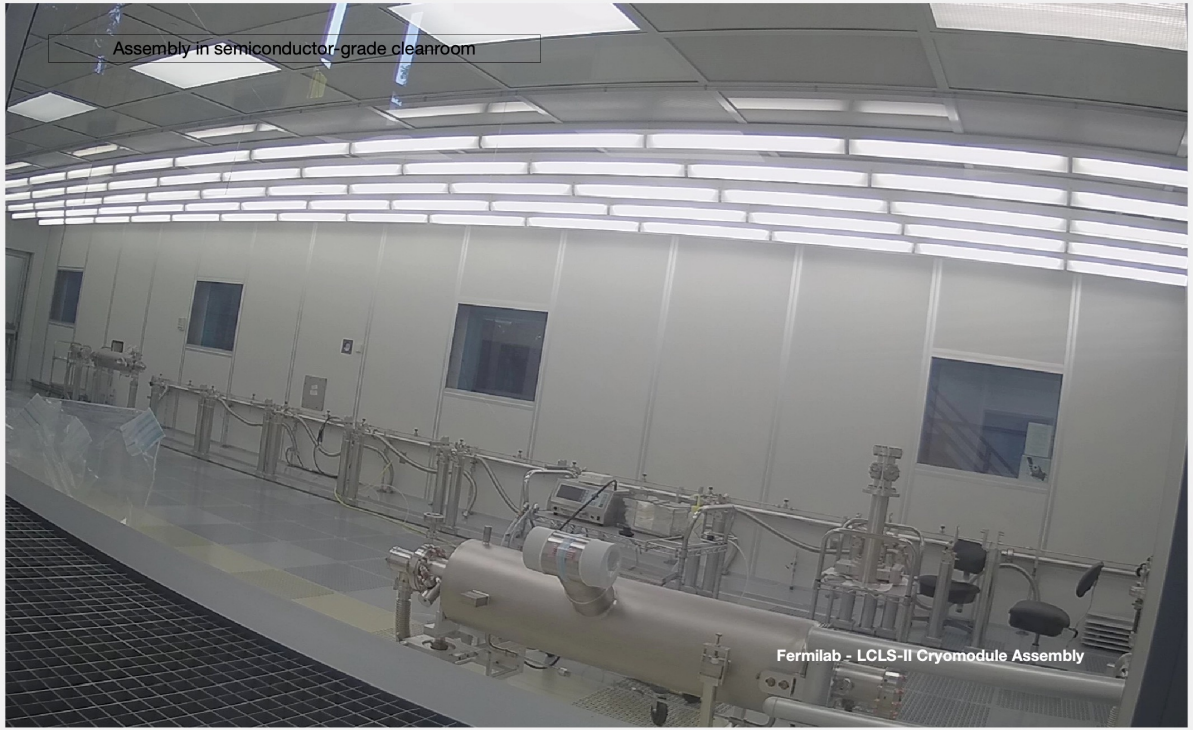
- Linac would be based on well-established 1.3 GHz SRF cryomodules
- Developed by international partners for ILC, extensive pioneering studies at DESY in TTF/FLASH
- First major implementation at DESY's European XFEL – 17.5 GeV via 800 cavities in 100 cryomodules
- Design adjusted for CW operation for SLAC's LCLS-II and LCLS-II-HE – 8 GeV via 440 cavities in 55 cryomodules
- Each cryomodule will have 8 cavities and a quadrupole magnet, very similar to LCLS-II design, including support for relatively high 2K RF heat load – but cavities will operate pulsed, similar to EXFEL/ILC

ILC

European XFEL (DESY)

LCLS-II (SLAC)

Fermilab Cryomodule Assembly Timelapse Video



Laser Stripping

- Foil stripping is baseline plan
- Laser assisted stripping would reduce losses, avoid foil damage problems

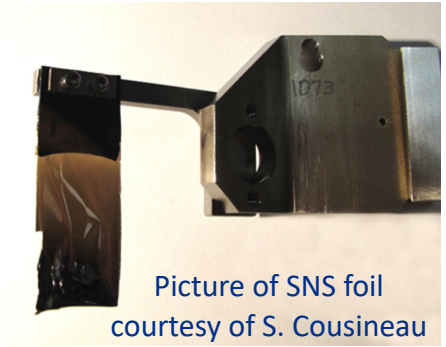
Laser much easier at 8 GeV based on laser wavelength

$$\nu_{beam} = \nu_{lab}\gamma(1 + \beta\cos\alpha)$$
$$P_{beam} = P_{lab}(\gamma(1 + \beta\cos\alpha))^{2}$$

- Infrared lasers can be used

  1064/1900 nm Lasers

- Directed R&D activity on this subject could be useful



Picture of SNS foil courtesy of S. Cousineau

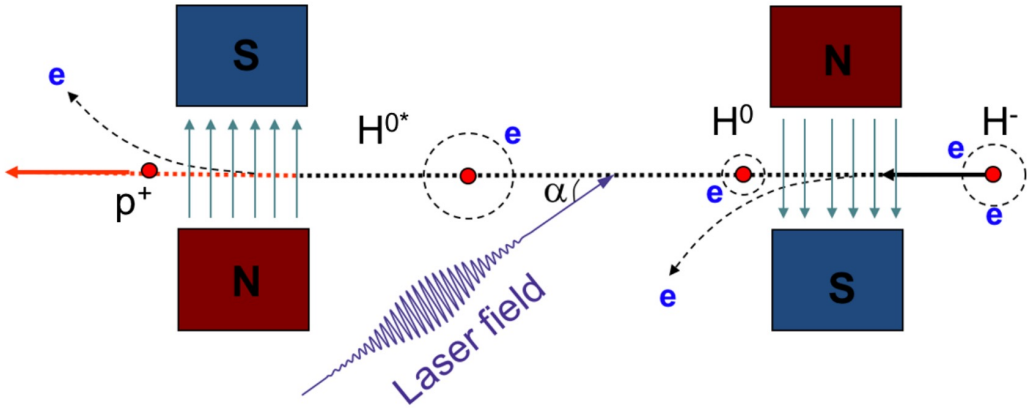


Image from S. Cousineau et al. PRL 118, 074801 (2017)

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Summary

- An SRF linac can replace the Fermilab booster in order to reach 2.4 MW of protons on target for LBNF/DUNE
- Would use well-established (ILC, EXFEL, LCLS-II) 1.3 GHz cryomodule technology to go from 2 GeV to 8 GeV, including recent improvements
- Builds on existing expertise and facilities; 1.3 GHz technology chosen for low cost and **highly efficient transfer of power to beam**
- Foil Injection from linac to ring is harder at 8 GeV than 2 GeV, but is possible
- laser stripping should be better
- **Can expand to higher power** (i. e., 5ma, 2.5ms, 20 Hz → 2MW)
- Next steps: finalize parameters, make cost estimates, prepare CDR-type (or pre-CDR-type) document for input to P5 – suggestions and input from the community are welcome!

Comments and questions ??

- **Thank you for your attention**

"Any questions?"

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