Lepton Colliders at the Energy Frontier

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Lepton Energy Frontier Collider Options

1. e+/e- storage ring
2. e+/e- linear collider with E < 1 TeV
3. e+/e- linear collider with E > 1 TeV
4. μ+/μ- collider

→ Also γ-γ option

Electron-Positron Storage Rings

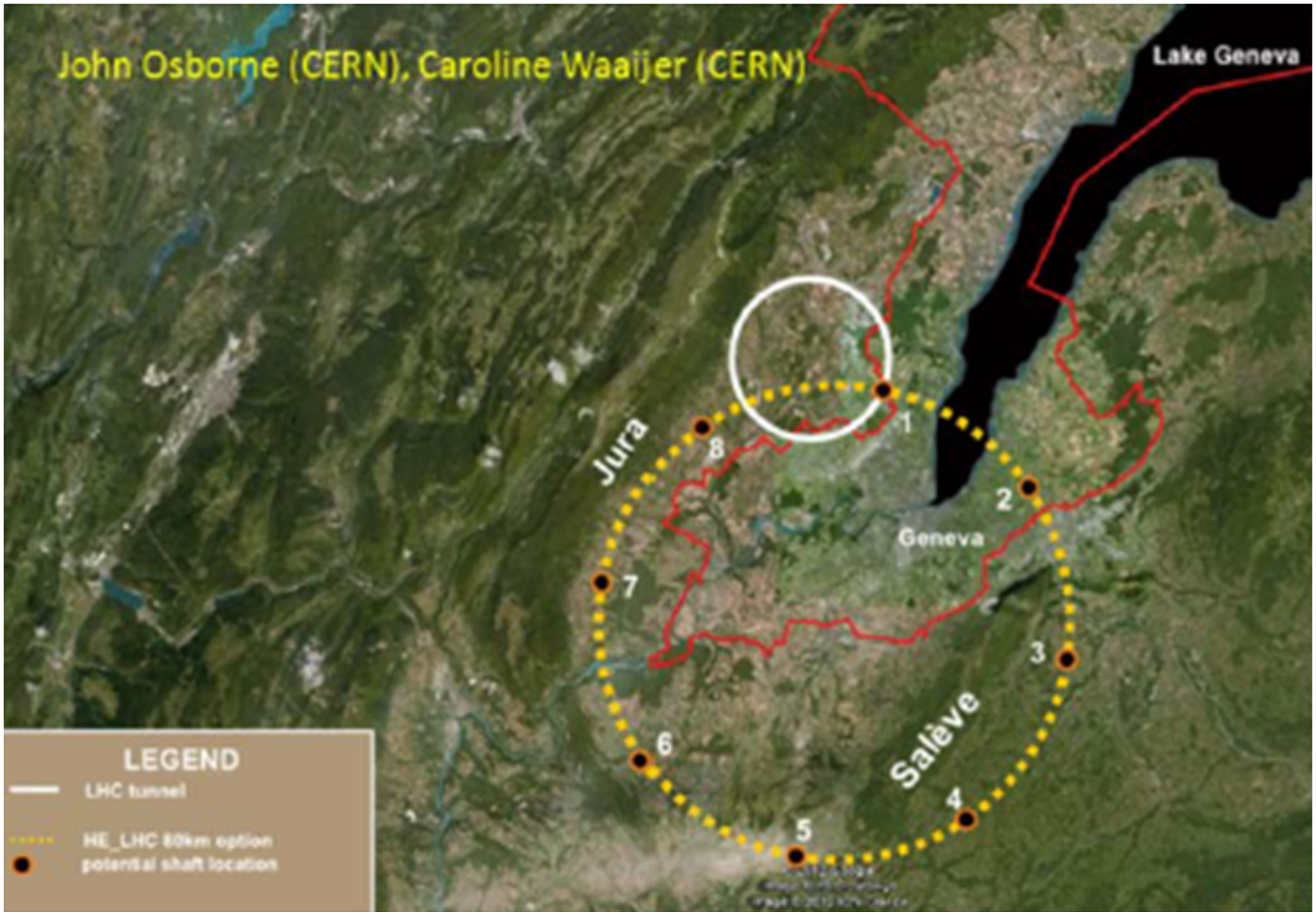
- LEP2 nearly got to the Higgs
  - Rings are relatively robust technology
- Higher energy and luminosity designs have been suggested
  - LEP3: 1e34 $cm^{-2}s^{-1}$ at 240 GeV in the LEP tunnel
  - TLEP: 1e34 $cm^{-2}s^{-1}$ at 240 GeV in an 80 km new tunnel → upgrade to 80 TeV p-p collider (Blondel, et al, **arXiv:1208.0504.)**
- Hard to get to much higher energies than 120 GeV
  - Limited by SR power as: $L = \frac{3c}{8\pi r_e^3} \frac{\xi_y \rho}{\gamma^3 \beta_y^*} \frac{P_b}{P_A} R_h$ B. Richter, Nucl. Instr. Meth. 136 (1976) 47-60
- Significant challenges
  - Requires large energy bandwidth and difficult collective effects
  - Installation with LHC would be difficult
  - Optimization ongoing

Electron-Positron Storage Rings (cont.)

	LEP2	LEP3	LEP3**	TLEP**
Beam Energy [GeV]	104.5	120	120	175
Circumference [km]	26.7	26.7	26.7	82.4
Beam current [mA]	4	7.2	7.2	6.4
Number of bunches	4	4	50	466
Bunch population [10^{10}]	57.5	100	8.0	2.36
Horizontal emittance [nm]	48	25	4.3	1.03
Vertical emittance [nm]	0.25	0.1	0.02	0.005
β_x^* [mm]	1500	200	50	50
β_y^* [mm]	50	1	1	1
Hourglass factor	0.98	0.67	0.76	0.80
SR power [MW]	11	50	50	50
Bunch length [mm]	16	2.3	1.5	1.3
Momentum acceptance [%]	1.25	4.2	3.0	3.0
Beam-beam parameter / IP	0.07	0.09	0.07	0.06
Luminosity [10^{34} cm^{-2}s^{-1}]	0.0125	1.01	1.01	1.16

** Optimized slightly differently than in: Blondel, et al, **arXiv:1208.0504.**

Possible 80 km TLEP option
(future upgrade to ~80 TeV p-p collider)



Linear Colliders with E < 1 TeV

- Lots of options
  - ILC design is the most robust
  - CLIC design also possible
  - $\gamma-\gamma$ collider options may be a lower cost approach
  - Advanced accelerator concepts may be possible in far future

- If ultimate goal is multi-TeV lepton collisions, probably should think about pursuing options with upgrade possibilities
  - Cost of demonstrating technology can be challenging

ILC Parameters

Centre-of-mass energy	E_{cm}	**GeV**	**250**	**350**	**500**		**1000**
Beam energy	E_{beam}	GeV	125	175	250		500
Estimated AC power	P_{AC}	MW	128	142	162		300
Collision rate	f_{rep}	Hz	5	5	5		4
Electron linac rate	f_{linac}	Hz	10	5	5		4
Number of bunches	n_b		1312	1312	1312		2450
Bunch separation	Dt_b	ns	554	554	554		366
Pulse current	I_{beam}	mA	5.8	5.8	5.79		7.6
RMS bunch length	σ_z	mm	0.3	0.3	0.3		0.250
Electron polarisation	P_-	%	80	80	80		80
Positron polarisation	P_+	%	30	30	30		20
Luminosity (inc. waist shift)	L	**$\times 10^{34}$ $cm^{-2}s^{-1}$**	**0.75**	**1.0**	**1.8**		**3.6**
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%		59.2%

Superconducting Rf Cavities

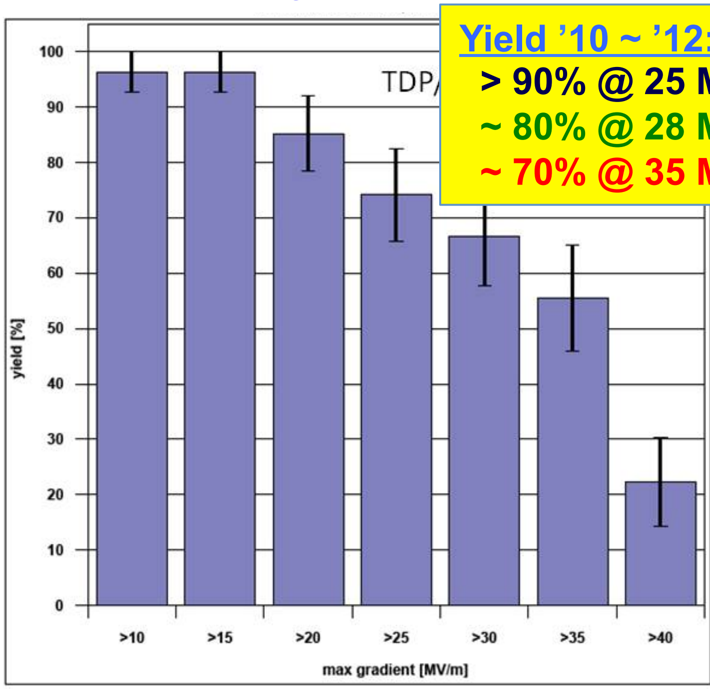
SLAC

ILC based on high gradient superconducting rf cavities

- Potential for still higher gradients from geometry or new materials

ILC cavities reaching 35 MV/m routinely
~75% of magnetic field limit

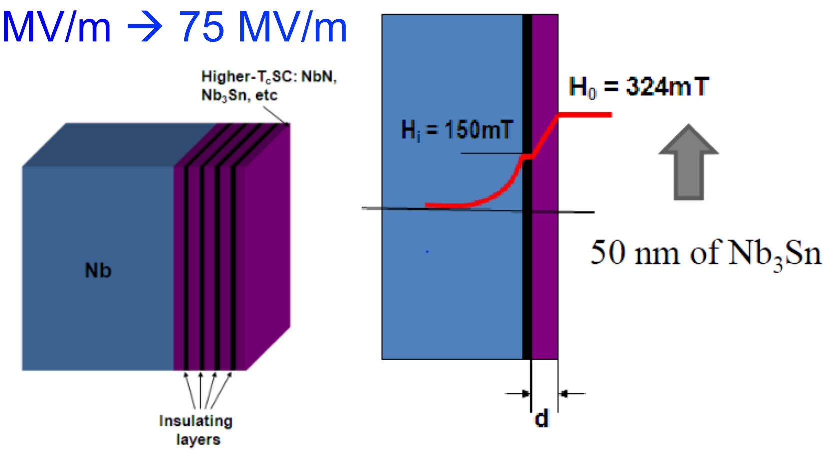
Yield of ILC 1.3 GHz cavities



Yield '10 ~ '12:
> 90% @ 25 MV/m
~ 80% @ 28 MV/m
~ 70% @ 35 MV/m

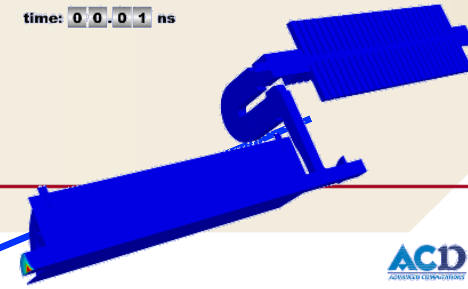
- R&D towards new materials and geometries for higher gradients
  - Materials with higher H_c and lower Rs: MgB_2, NbN, Nb_3Sn, …
  - Multi-layer materials to reduce fields in bulk material

50 MV/m → 75 MV/m



From *Grigory Eremeev SFR'09*

CLIC layout at 500 GeV



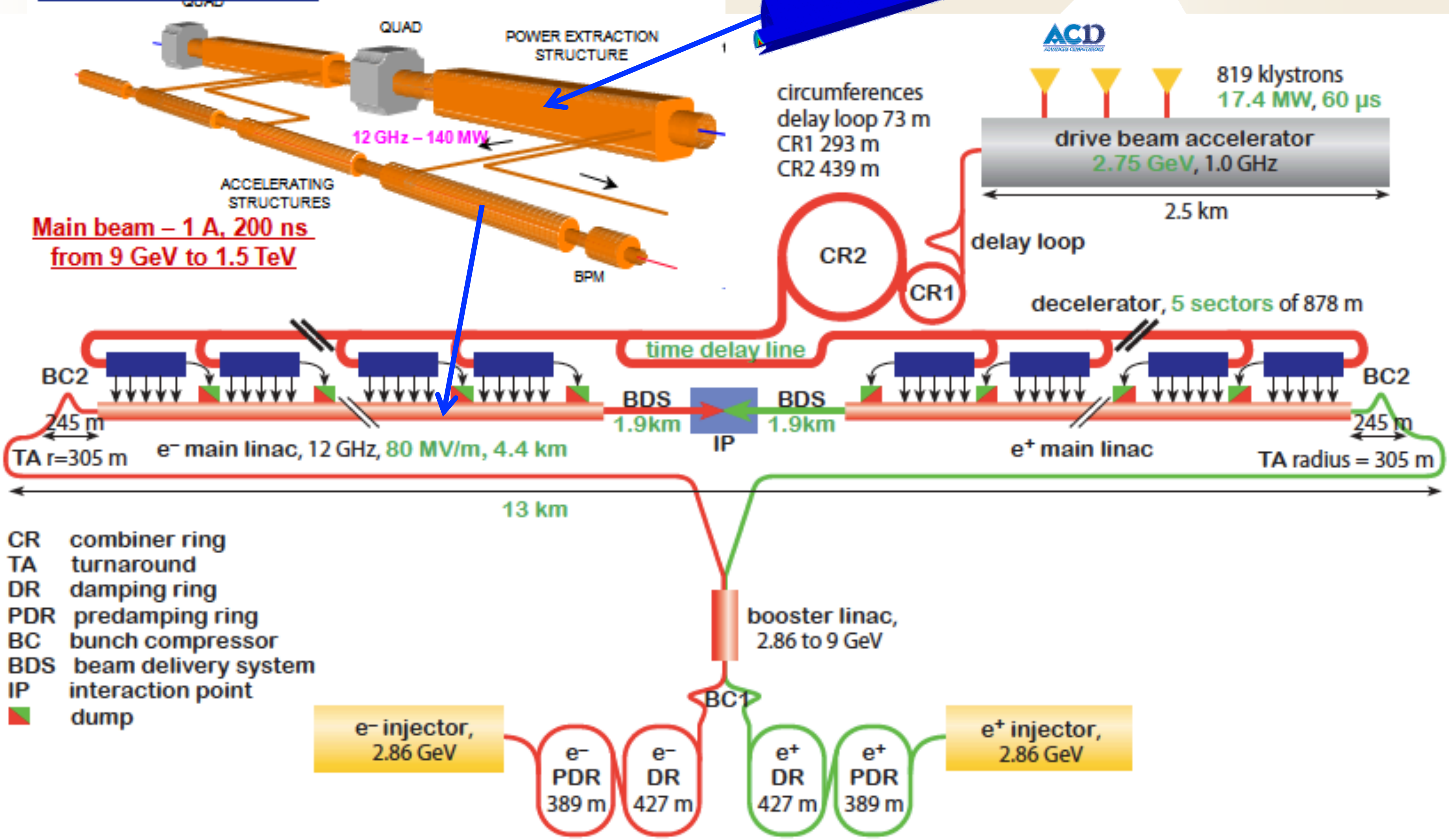


Fig. 3.2: Overview of the CLIC layout at $\sqrt{s}$ =500 GeV.

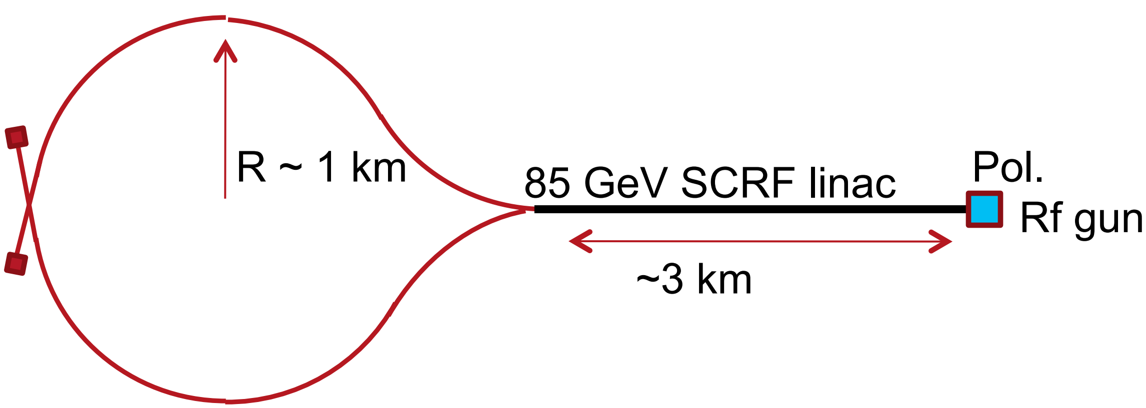
Potential Staged CLIC Parameters

D. Schulte

parameter	symbol			
centre of mass energy	E_{cm} [GeV]	500	1400	3000
luminosity	$\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	2.3	3.2	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} cm^{-2}s^{-1}]	1.4	1.3	2
gradient	G [MV/m]	80	80/100	100
site length	[km]	13	28	48.3
charge per bunch	N [10^9]	6.8	3.7	3.7
bunch length	σ_z [μm]	72	44	44
IP beam size	σ_x/σ_y [nm]	200/2.26	$\approx$ 60/1.5	$\approx$ 40/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20	660/20
bunches per pulse	n_b	354	312	312
distance between bunches	Δ_b [ns]	0.5	0.5	0.5
repetition rate	f_r [Hz]	50	50	50
est. power cons.	P_{wall} [MW]	271	361	582

Gamma-Gamma Linear Collider Options

- A Higgs factory might provide an entry for a 'low-cost' $\gamma-\gamma$ linear collider and technology demonstration
  - $e^-{-}e^-$ cms energy of only ~160 GeV ($\gamma-\gamma$ cms is roughly 80%)
  - Eliminates large portion of ILC infrastructure (e+ source, damping rings, bunch compressors, …) and should save significant $
  - Many options:
    - SLC configuration with single 85 GeV linac
    - Sapphire: 22 GeV recirculating linac in SLC-configuration
    - Expandable dual 85 GeV e- linacs in classic LC configuration



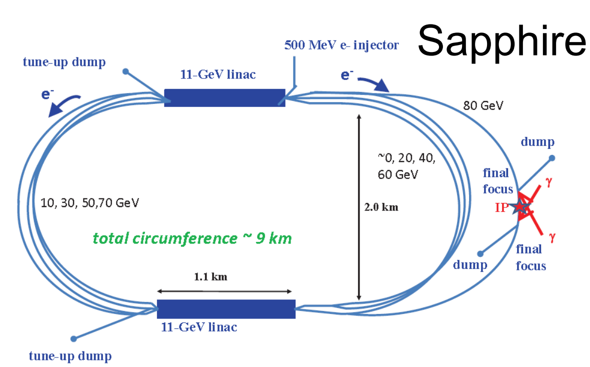


Figure 3: *Sketch of a layout for a γγ collider based on recirculating superconducting linacs – the SAPPHiRE concept.*

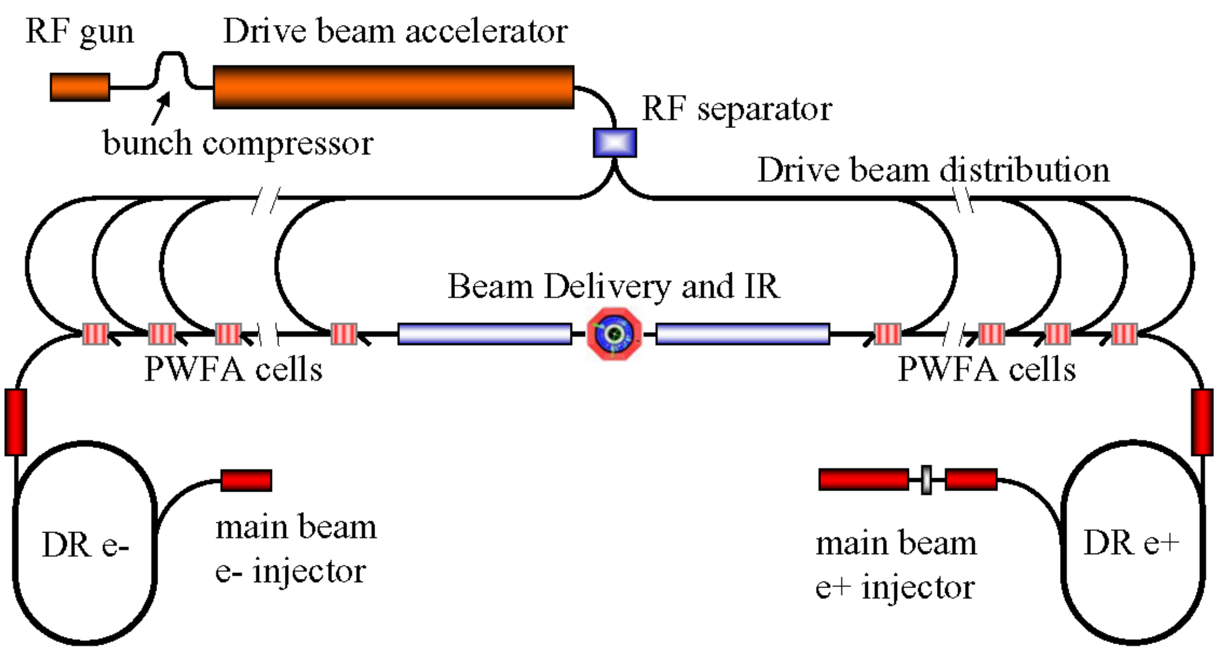
Linear Colliders with E > 1 TeV

- ILC is ~ 50 km at 1 TeV
  - Possible to consider higher gradient SCRF materials or PWFA boost
- CLIC design is aimed at upgradable design → 1.5 or 4 TeV
  - Geographic gradient of 4x higher than ILC
- Advanced acceleration options (plasma, dielectric)
  - Plasma acceleration has made great progress however still huge challenges in beam quality and stability
  - Extremely low charge dielectric-laser accelerators may provide only reasonable parameters in multi-TeV regime
  - None of AARD options are close to being ready
- Some plasma and dielectric options act as transformers taking high power beams → high energy beams
  - Possible to develop upgrade options for ILC-like technology?

Concept of Beam-Driven Plasma Linac

Concept for a 1 TeV plasma wakefield-based linear collider

- Use conventional Linear Collider concepts for main beam and drive beam generation and focusing and PWFA for acceleration
  - Makes good use of PWFA R&D and 30 years of conventional rf R&D
- Concept illustrates focus of PWFA R&D program
  - High efficiency
  - Emittance pres.
  - Positrons
- Allows study of cost-scales for further optimization of R&D



Possible Linear Collider Parameters

Case	0.5 TeV ILC	3 TeV CLIC	10 TeV Dielectric Beam Acc.	10 TeV Plasma Accelerator	10 TeV Dielectric Laser Acc.
Energy per beam (TeV)	0.25	1.5	5	5	5
Luminosity (10^{34} $cm^{-2}s^{-1}$)	2	6.4	49	71.4	105
Electrons per bunch ($\times 10^9$)	20	3.7	4	4	0.002
Rep. rate (Hz) / number / train	5 / 1312	50 / 312	50 / 416	17,000 / 1	25,000,000 / 1
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	10,000	660	1000	200	0.1
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	30	20	10	200	0.1
β^* x/y (mm)	11 / 0.2	4 / 0.1	10 / 0.1	0.2	0.4
Horizontal beam size at IP σ^*_x (nm)	474	49	32	2	0.06
Vertical beam size at IP σ^*_y (nm)	3.8	1.0	0.3	2	0.06
Luminosity enhancement factor	1.6	1.9	1.9	1.35	6.05
Bunch length σ_z (μm)	300	50	20	1	335
Beamstrahlung parameter Υ	0.07	6.7	56	8980	0.4
Beamstrahlung photons per electron n_γ	1.7	1.5	1.4	3.67	0.5
Beamstrahlung energy loss δ_E (%)	4.3	33	37	48	4.3
Accelerating gradient (GV/m)	0.031	0.1	0.5	10	0.5
Average beam power (MW)	5.3	13.9	55	54	38
Wall plug power (MW)	200	568	~1200	~1200	~550
One linac length (km)	15.5	23.5	10	1.0	10.5

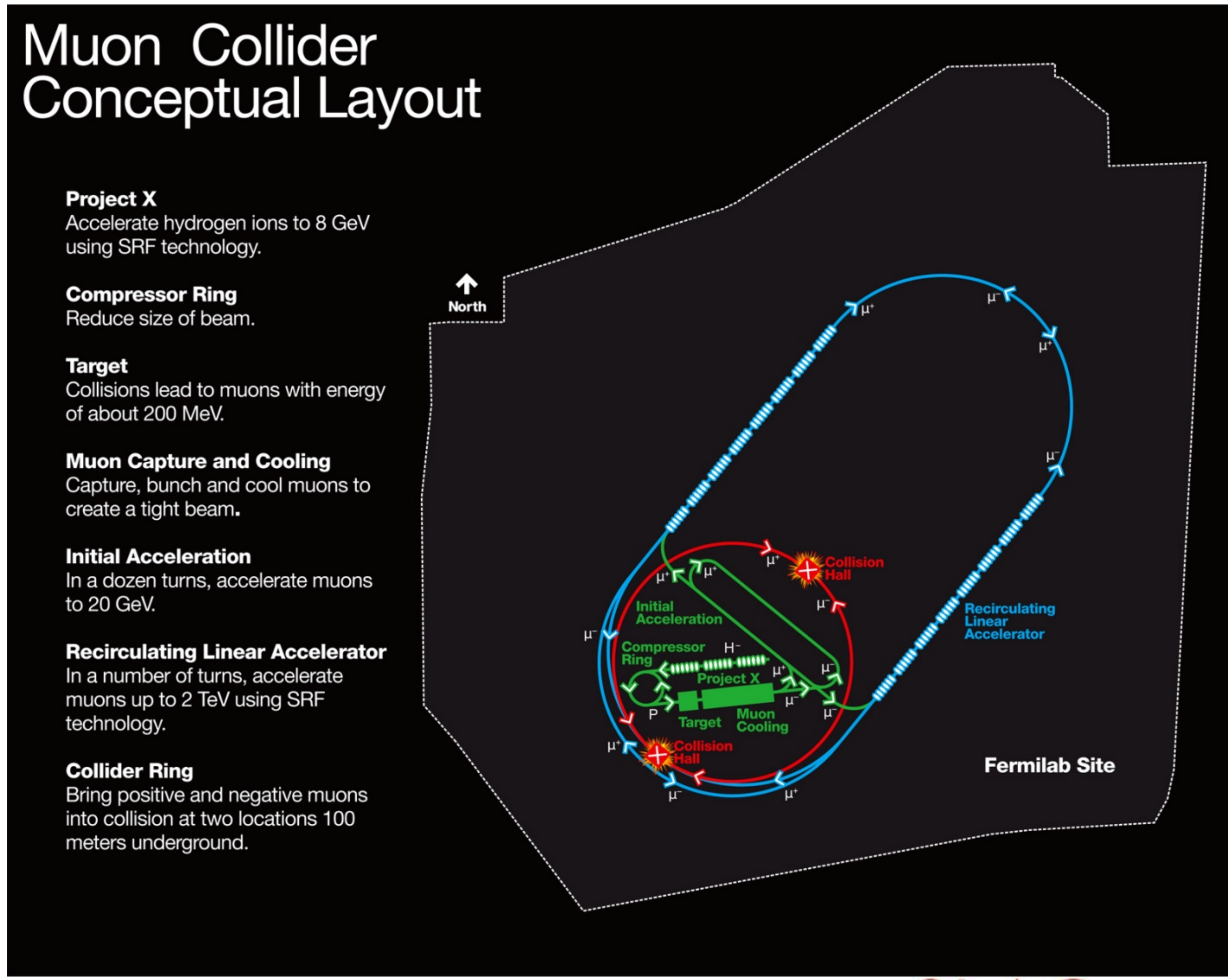
ILC and CLIC parameters from design reports; 10 TeV DBA scaled from Wei Gai communication; 10 TeV DLA and Plasma Accelerator from 2010 ICUIL/ICFA Workshop

Muon Collider

Compact facility accelerating muons with recirculating linacs and rings

Major Challenges

1. Muon generation
2. Cooling of muons
3. Cost-efficient acceleration
4. Collider ring and backgrounds from decays



Being studied as part of MAP & proposed Lepton Collider Physics Framework

Muon Collider Parameters

s-channel: factor of ~4×10^4 in rate

Depends on cooling scenario: $10^{31} \Rightarrow \sim 10^{32}$ cm^{-2}sec^{-1}

	Higgs[1]	Design	Design	Extrap[2]	
C of m Energy	0.126	1.5	3	6	TeV
Luminosity	0.002	1	4	12	10^{34} cm^{-2}sec^{-1}
Muons/bunch	2	2	2	2	10^{12}
Total muon Power	1.2	7.2	11.5	11.5	MW
Ring circumference	0.3	2.6	4.5	6	km
β^* at IP = σ_z	80	10	5	2.5	mm
rms momentum spread	0.004	0.1	0.1	0.1	%
Repetition Rate	30	15	12	6	Hz
Proton Driver power	4	4	3.2	1.6	MW
Muon Trans Emittance	300	25	25	25	μm
Muon Long Emittance	2	72	72	72	mm

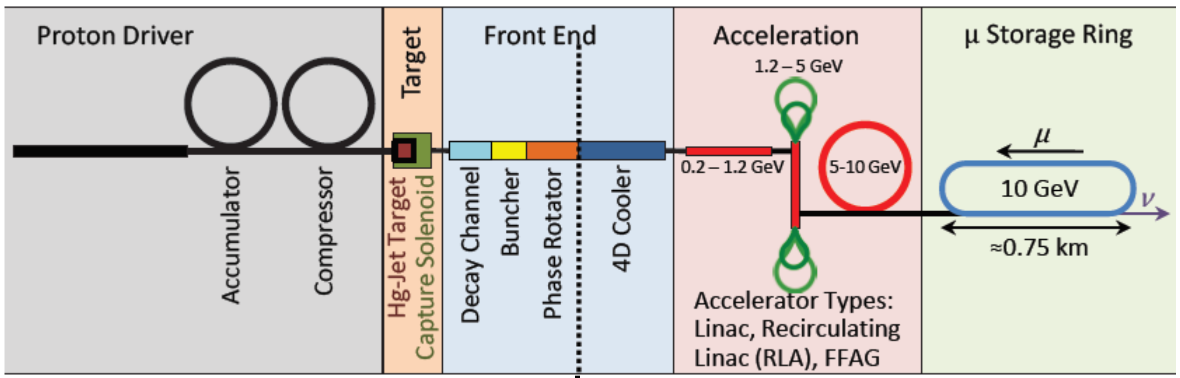
P_{Wall} < 300 MW

Steps Toward a Muon Collider

1. Project-X is being designed to deliver 4 MW of 8 GeV
2. Muon test facility would demonstrate capture and 1st cooling

NEUTRINO FACTORY

3.

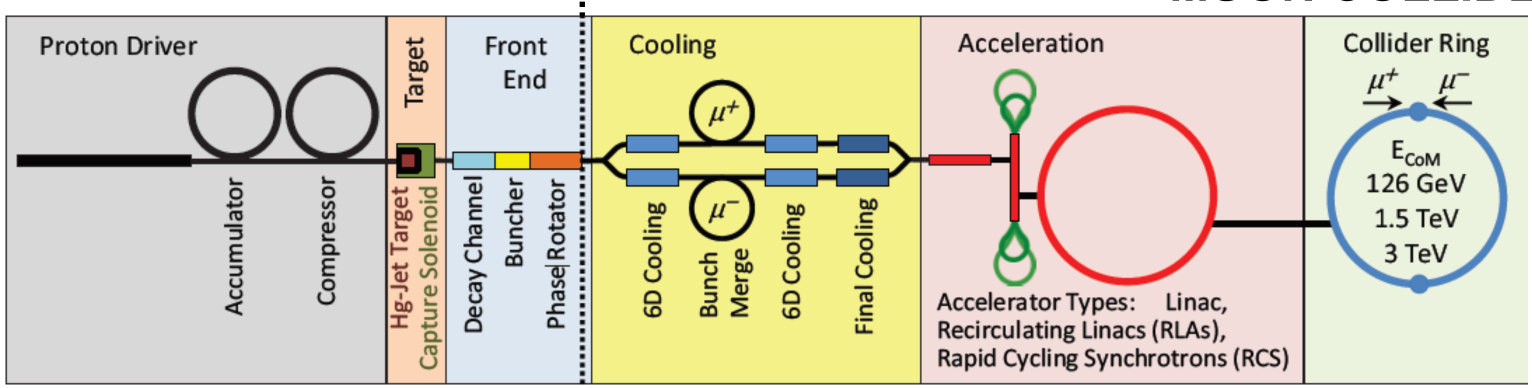


ν Factory Goal:
O(10^{21}) μ/year
within the
accelerator
acceptance

Share same complex

MUON COLLIDER

4.



Summary

- Many options for next-generation lepton colliders
- Storage rings can access Higgs but limited in energy reach
- ILC-technology is essentially ready for construction
  - Important to understand upgrade options
- CLIC/NCRF technology might provide an alternate approach with different upgrade possibilities and technology risks
- Advanced accelerator concepts not ready but may provide path to future upgrades for LC concepts
- Muon collider synergistic with US Intensity Frontier program and may provide path to future Energy Frontier