Status of CLIC and Muon Colliders

Daniel Schulte

Introduction

CLIC and muon colliders are both lepton colliders

- Both aim at high energy

• CLIC is being developed by a global collaboration hosted at CERN

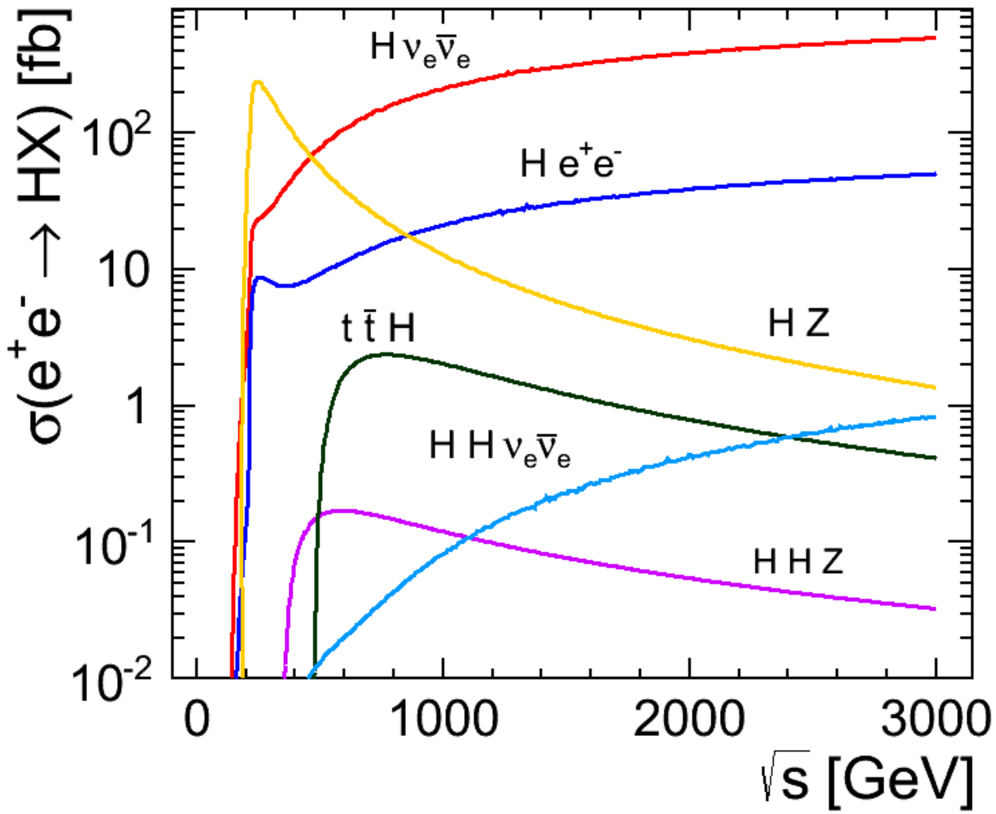
• CLIC is being considered as the next project for Europe, in competition with other options

• Muon collider activities do not have a formal framework right now

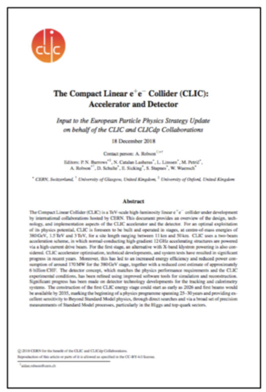
  • there has been one in the US a few years ago

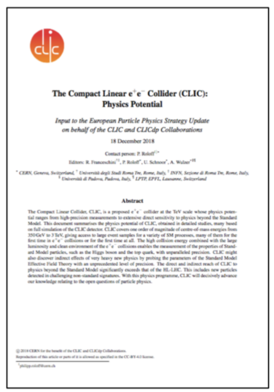
  • but some activity at INFN and in the UK

• It is being considered whether muon collider R&D should be increased in Europe



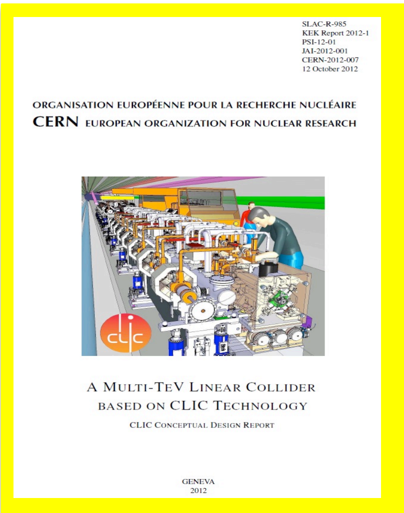
Documents

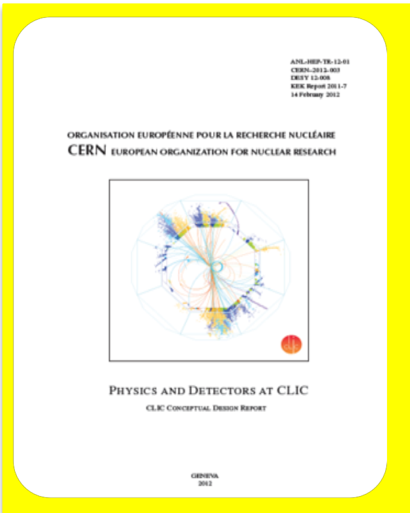




Submissions, PIP and physics case :
https://clic.cern/european-strategy
More about CLIC: https://clic.cern

CLIC delivered a CDR in 2012





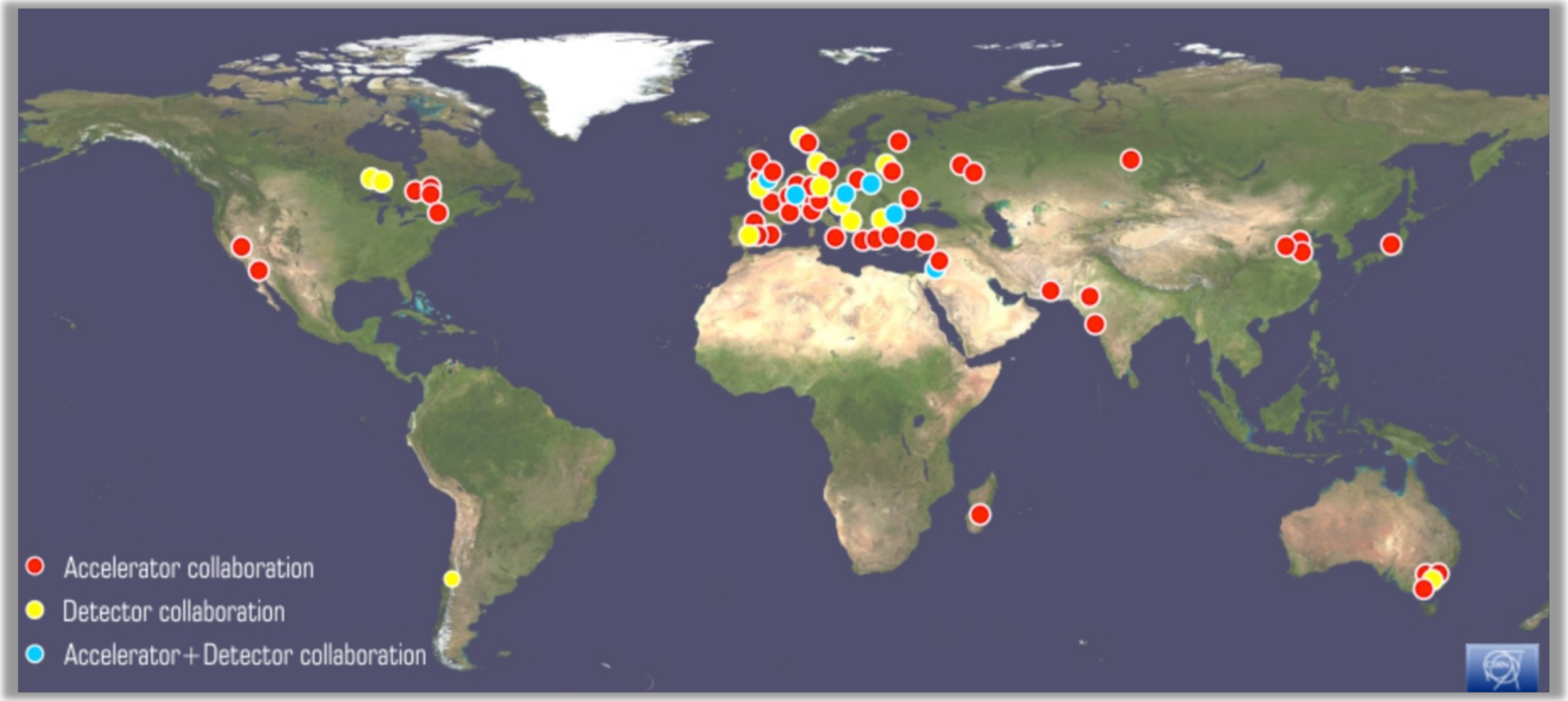
The CERN Laboratory Directors Group appointed in September 2017 Jean Pierre Delahaye, CERN, Marcella Diemoz, INFN, Italy, Ken Long, Imperial College, UK, Bruno Mansoulie, IRFU, France, Nadia Pastrone, INFN, Italy (chair), Lenny Rivkin, EPFL and PSI, Switzerland, Daniel Schulte, CERN, Alexander Skrinsky, BINP, Russia, Andrea Wulzer, EPFL and CERN

to prepare the Input Document to the European Strategy Update
"Muon Colliders," arXiv:1901.06150

No CDR exists, even in the US

Information can be found in different journal publications and talks

CLIC Collaboration



Lepton Colliders at High Energies

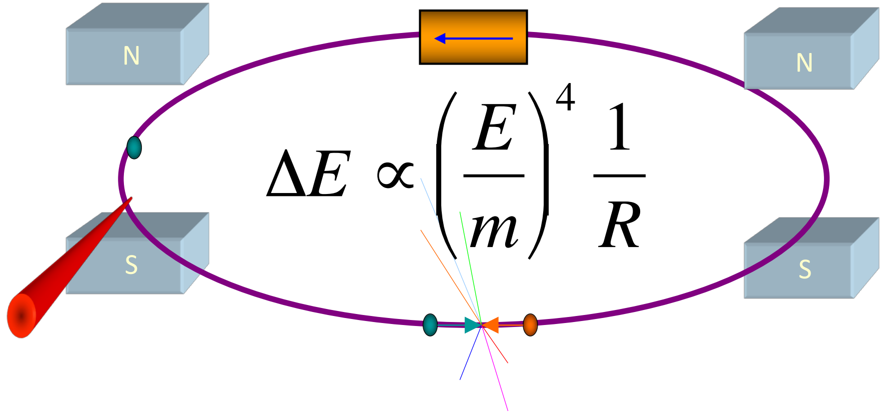
Accelerate beam in many turns

Use beam many times

Synchrotron radiation grows rapidly with energy

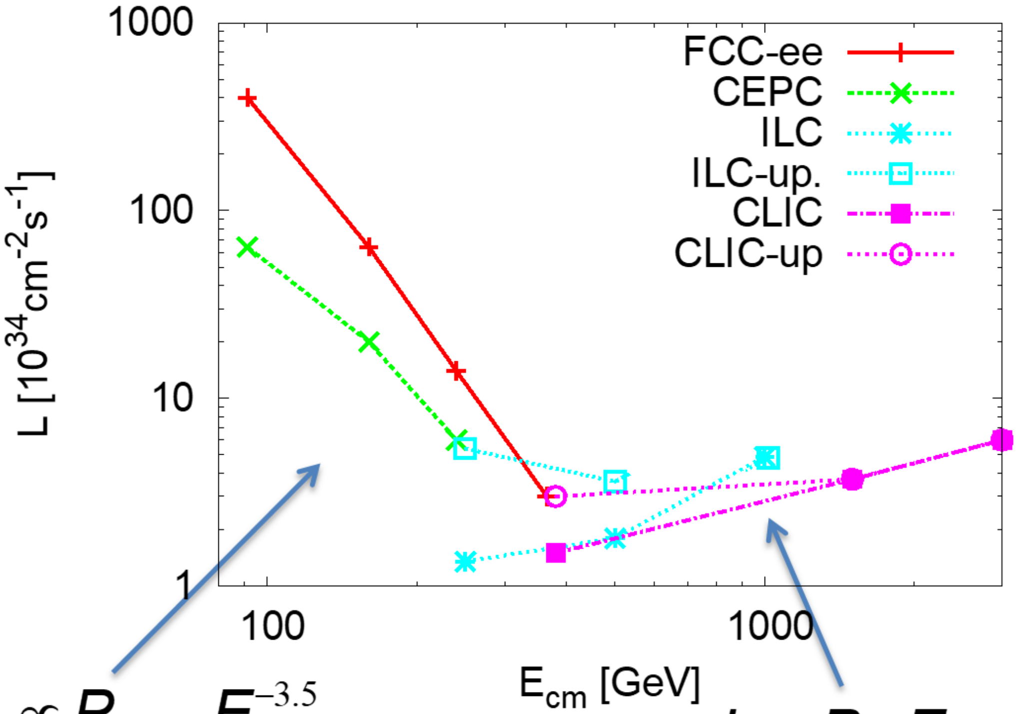
- At LEP2 lost 2.75GeV/turn for E=105 GeV

accelerating cavities



$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

Luminosity per facility

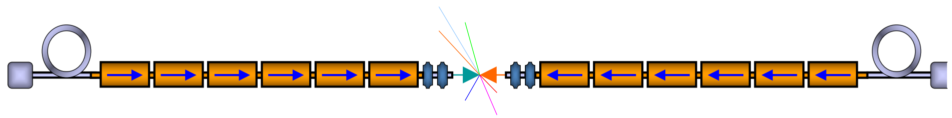


$$L \propto P_{synrad} E_{cm}^{-3.5}$$

$$L \propto P_{RF} E_{cm}$$

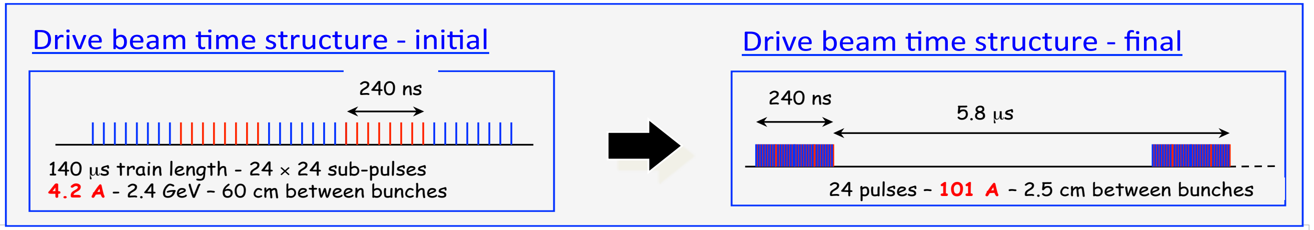
Use a linac to avoid synchrotron radiation

Use muons

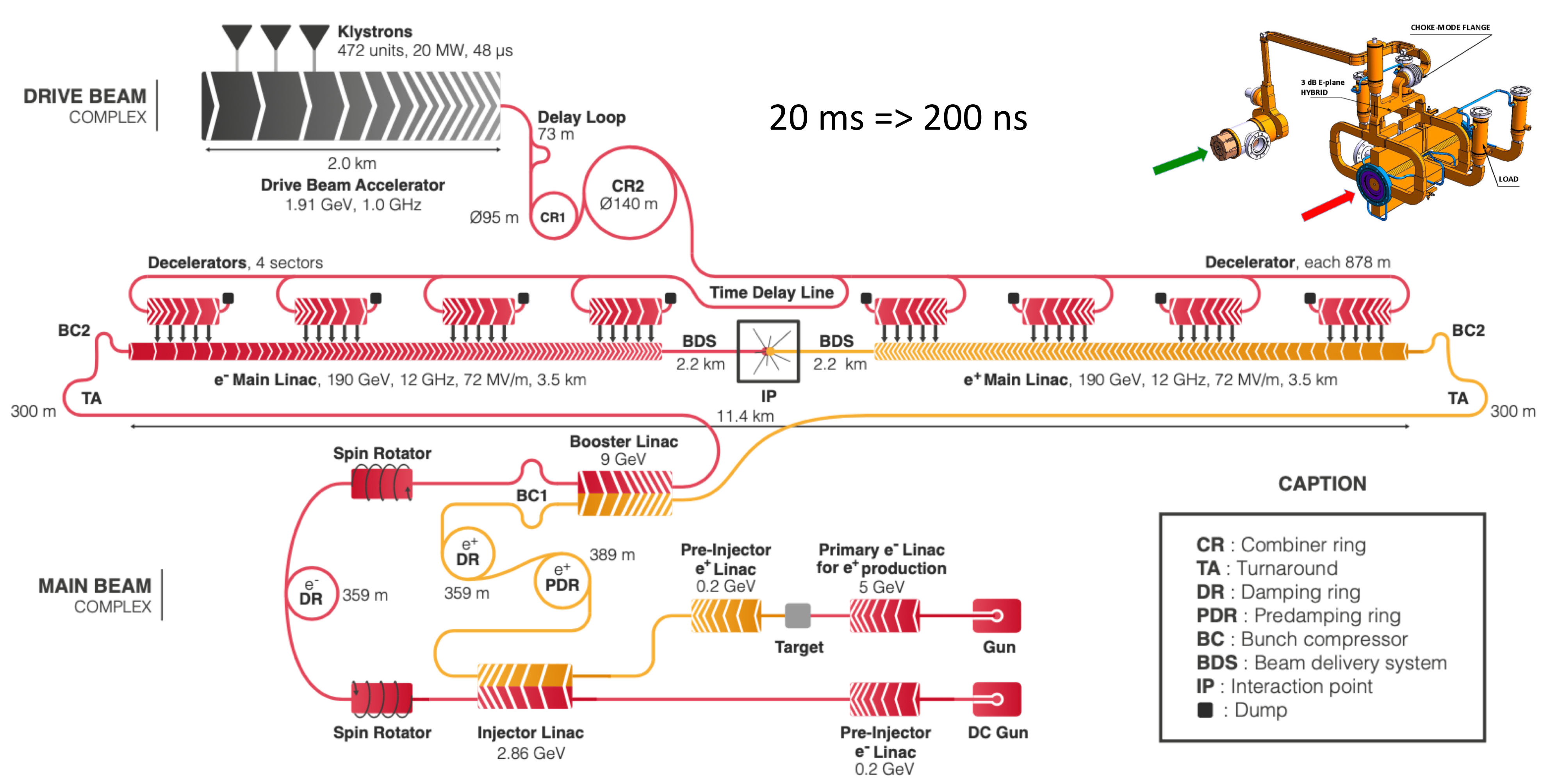


CLIC at 380 GeV

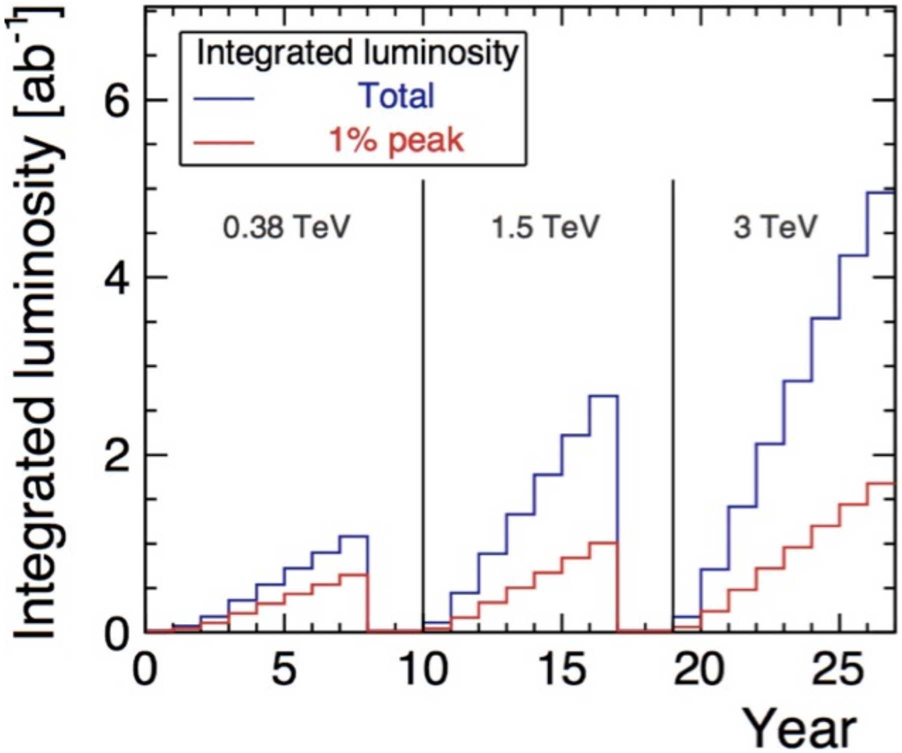
High field => NC structures
High stored energy => high losses => short, high power pulses



20 ms => 200 ns



CLIC Staging Scenario



Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0
2	1.5	2.5
3	3.0	5.0

Ramp up in first years
- 10%, 30%, 60% at 380 GeV
- 25%, 75% for 1.5 and 3 TeV

Baseline polarisation scenario
- electrons (-80%:+80%)
- positrons 0%

Operation ratio
- (50:50) at 380 GeV
- (80:20) at 1.5 TeV and 3 TeV

Implementatio
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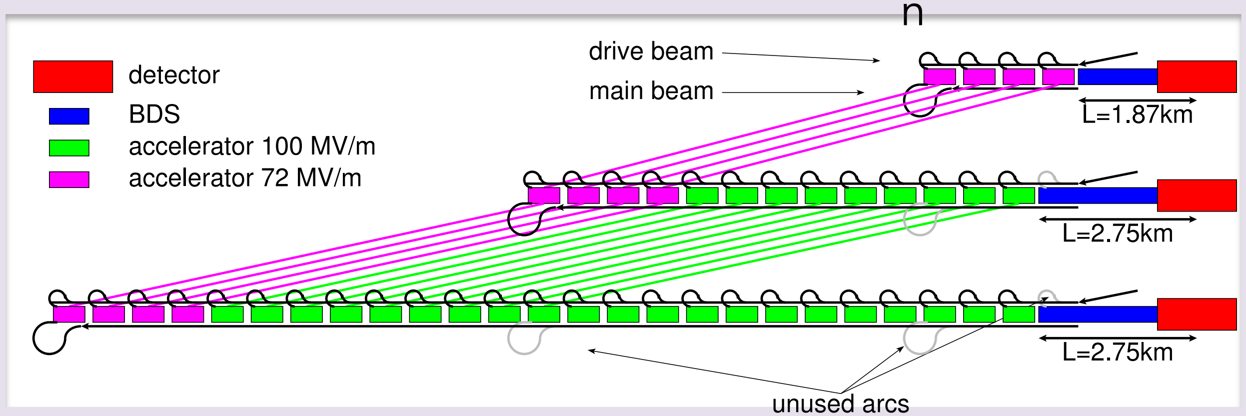
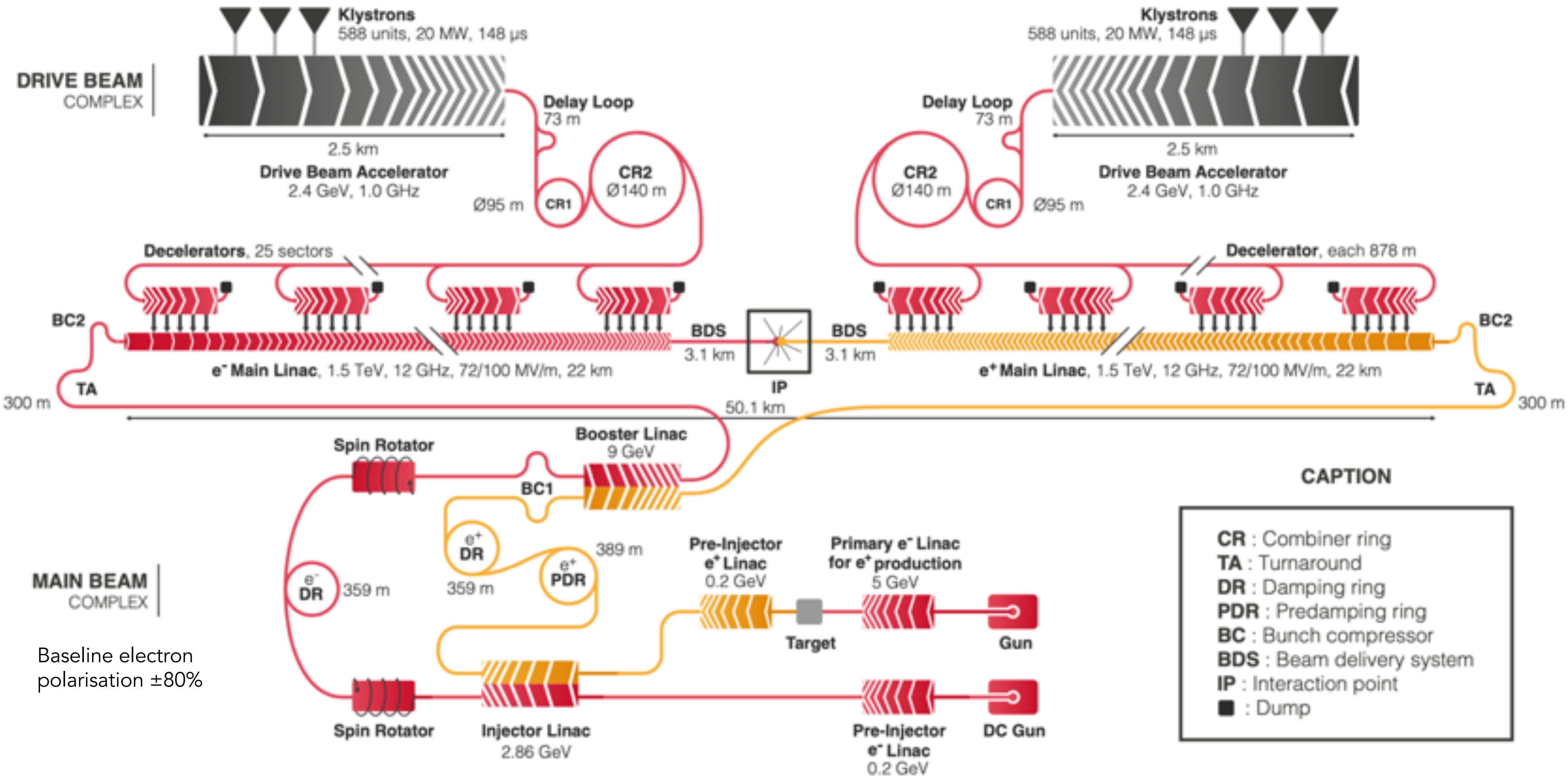


CLIC at 3 TeV

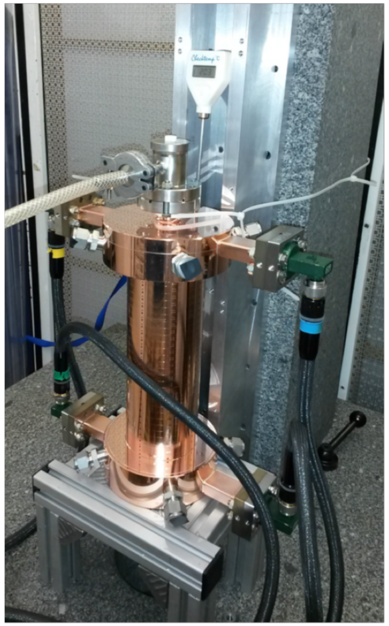


Baseline electron polarisation ±80%

Key Parameters

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	$10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\text{int}}$	fb^{-1}	180	444	708
Main linac tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

Accelerating Structures and Gradient

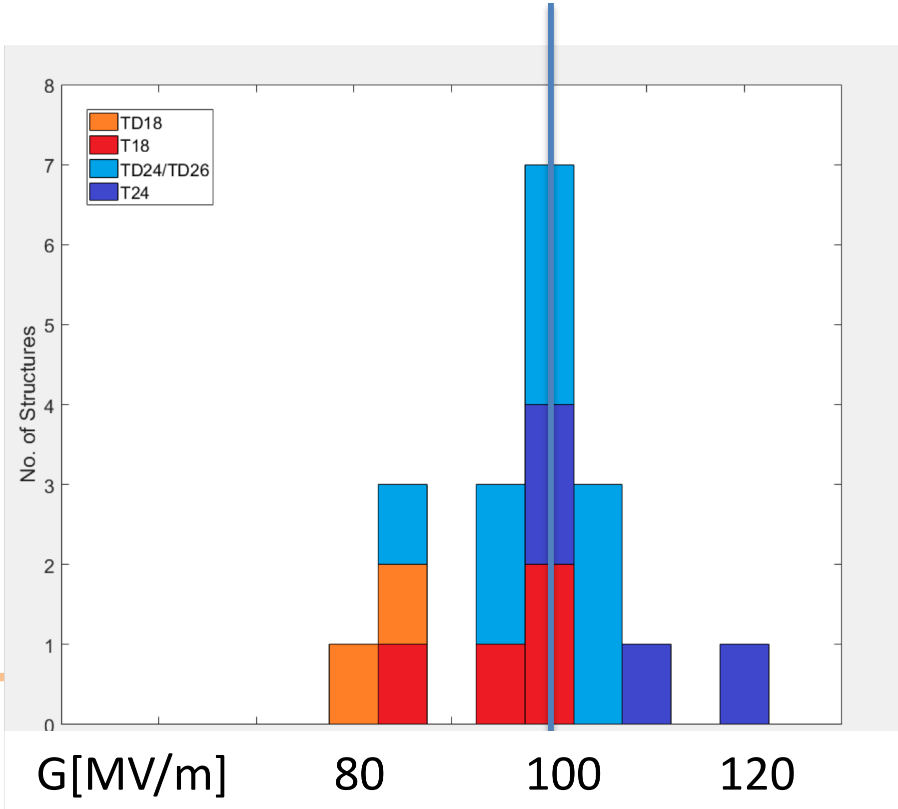


Accelerating structures are tested in specific test stand

- Limit is the breakdown rate

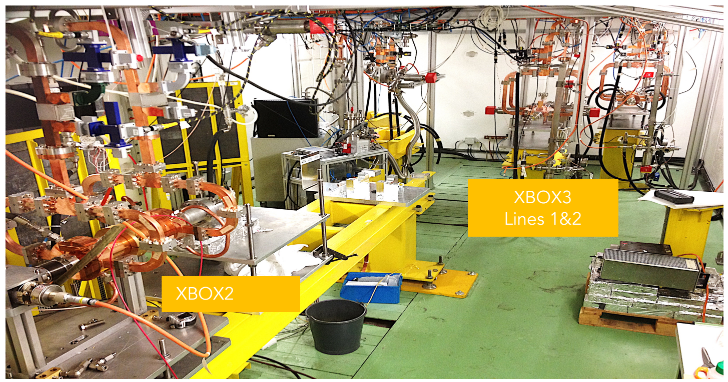
Important production of normal conducting structure in many places

- e.g. SwissFEL (at C-band) demonstrated high precision production

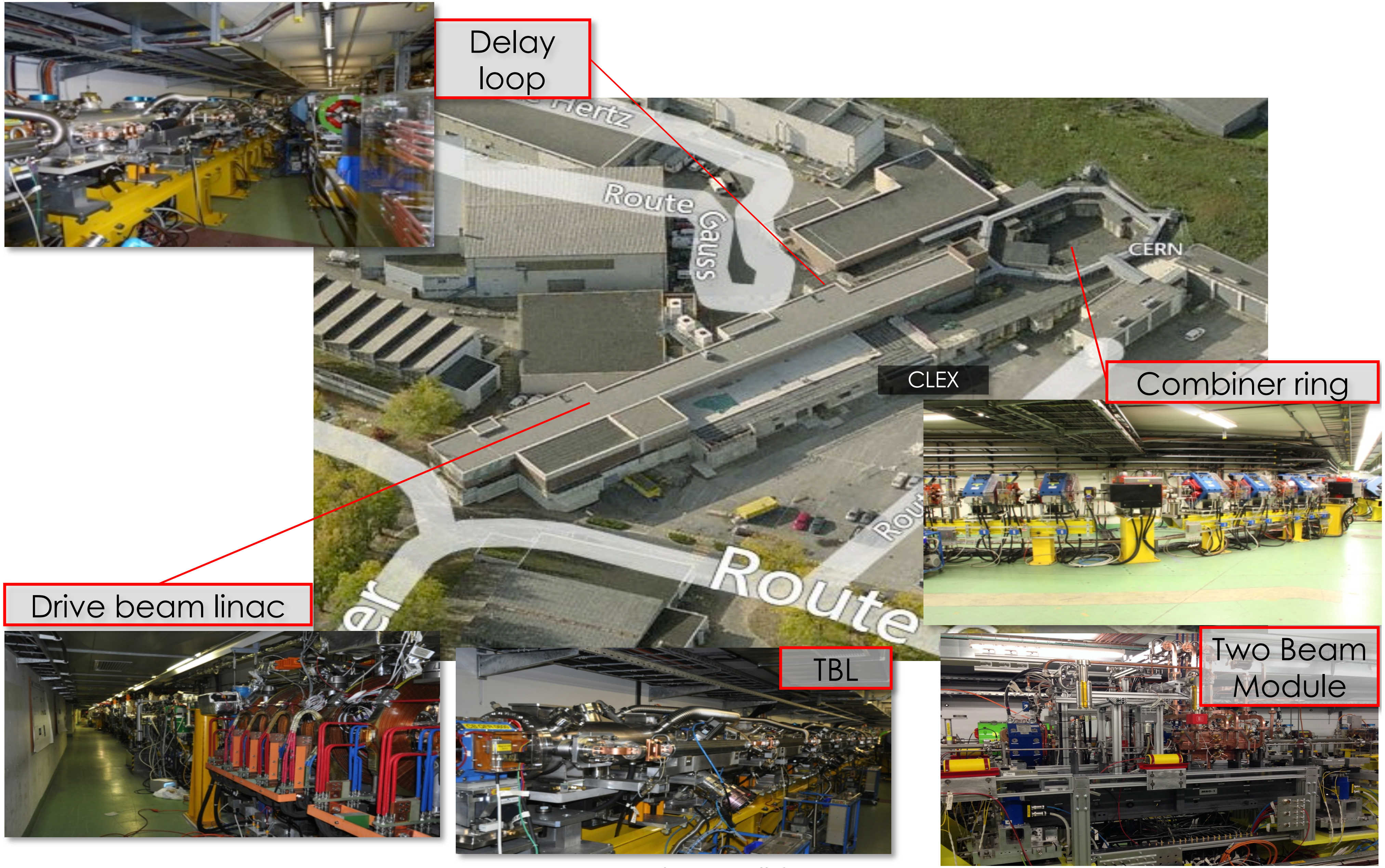


X-band Systems and facilities

- XBoxes at CERN
- (NEXTEF KEK)
- Test stand at Tsinghua
- Frascati
- NLCTA SLAC
- Linearizers at Electra, PSI, Shanghai and Daresbury
- Deflectors at SLAC, Shanghai, PSI and Trieste
- NLCTA
- Smart*Light
- FLASH

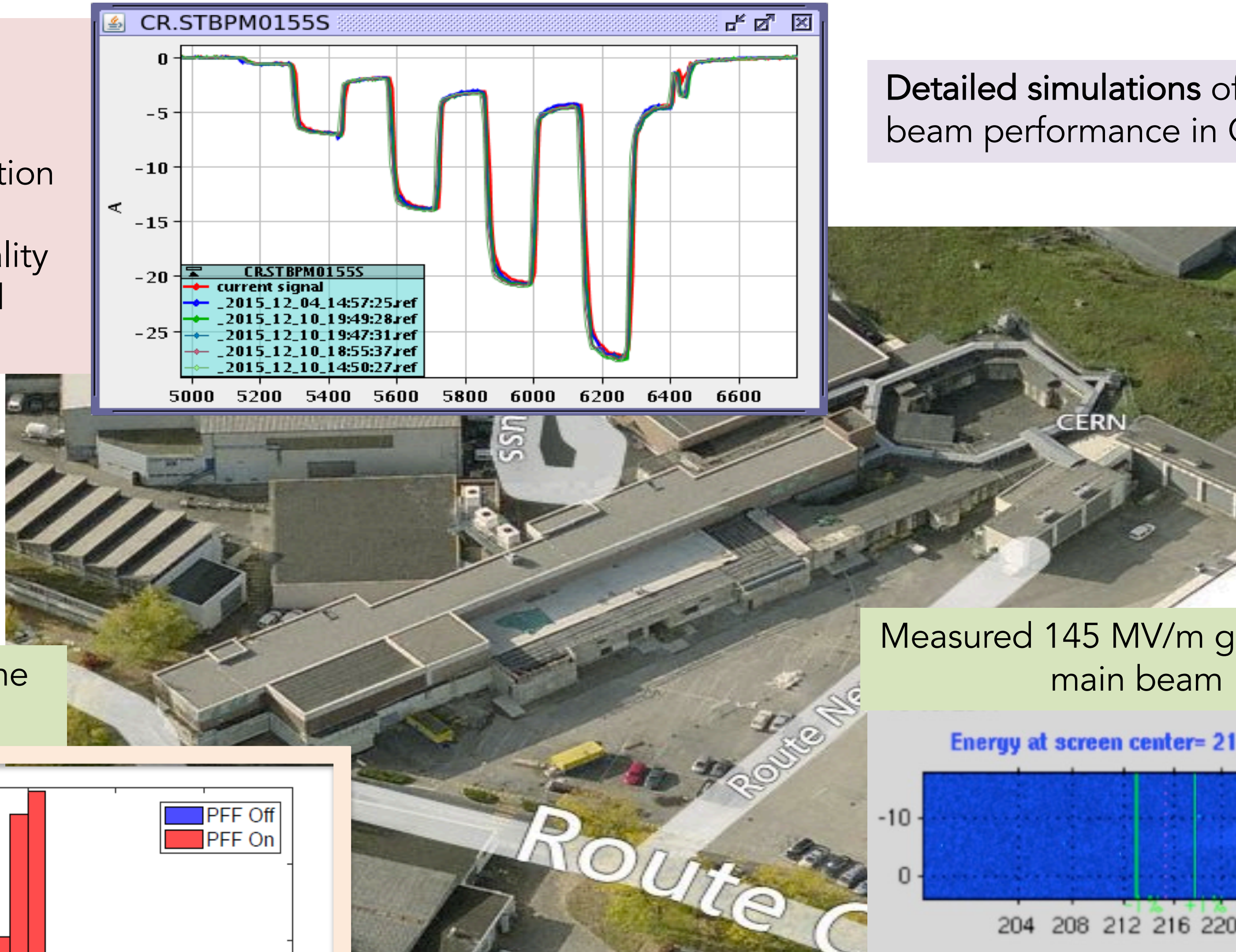


Drive Beam Demonstration (CTF3)



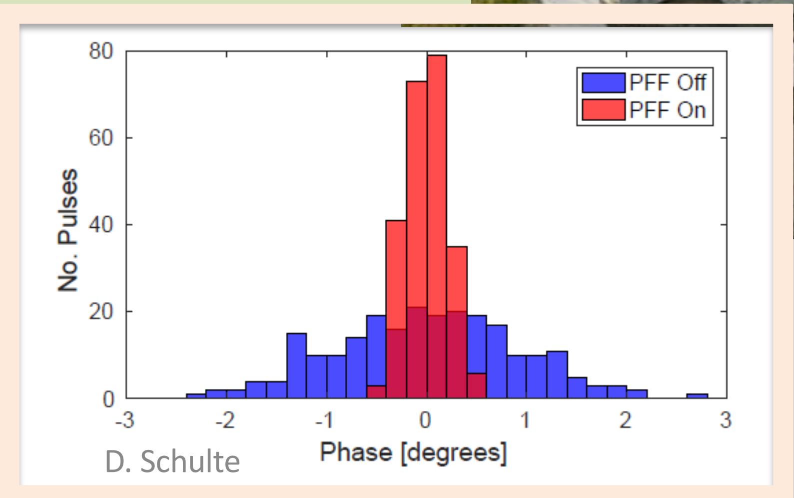
Drive Beam Results

CTF3 measurements:
- RF to drive beam efficiency > 95%
- Current multiplication factor 8
- Most of beam quality
- 145 MV/m X-band acceleration



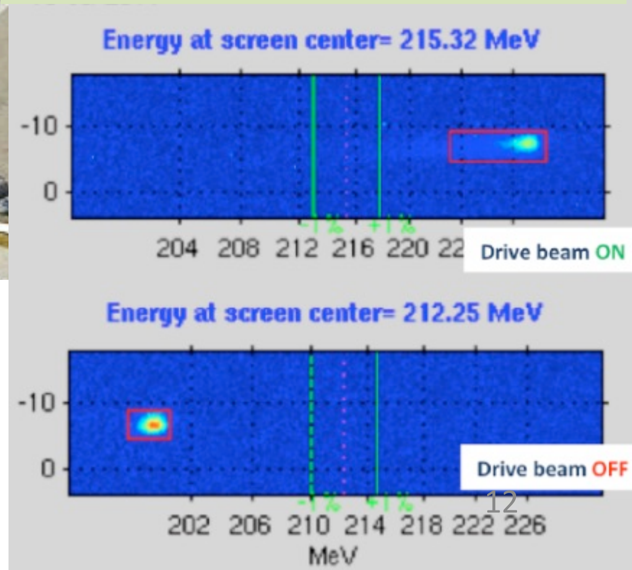
Detailed simulations of drive beam performance in CLIC

Drive beam arrival time with feedback



New facility: CLEAR
Focus on main beam

Measured 145 MV/m gradient on main beam



Luminosity

Can re-write normal luminosity formula

$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$

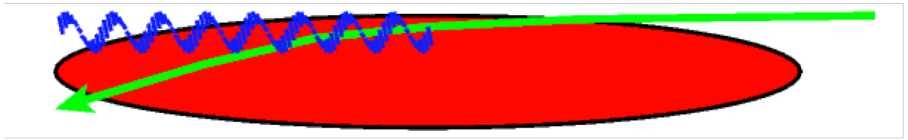
$$\mathcal{L} \propto H_D \; \frac{N}{\sigma_x} \; N n_b f_r \; \frac{1}{\sigma_y}$$

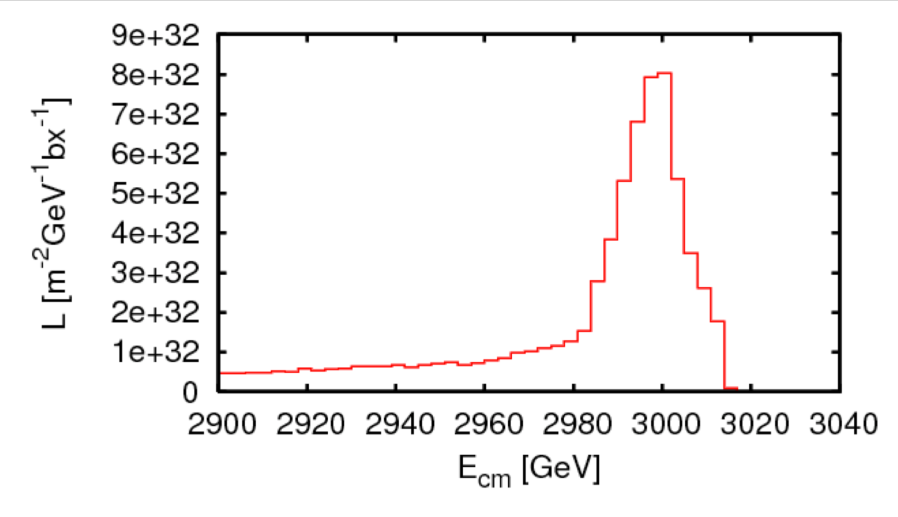
Luminosity spectrum

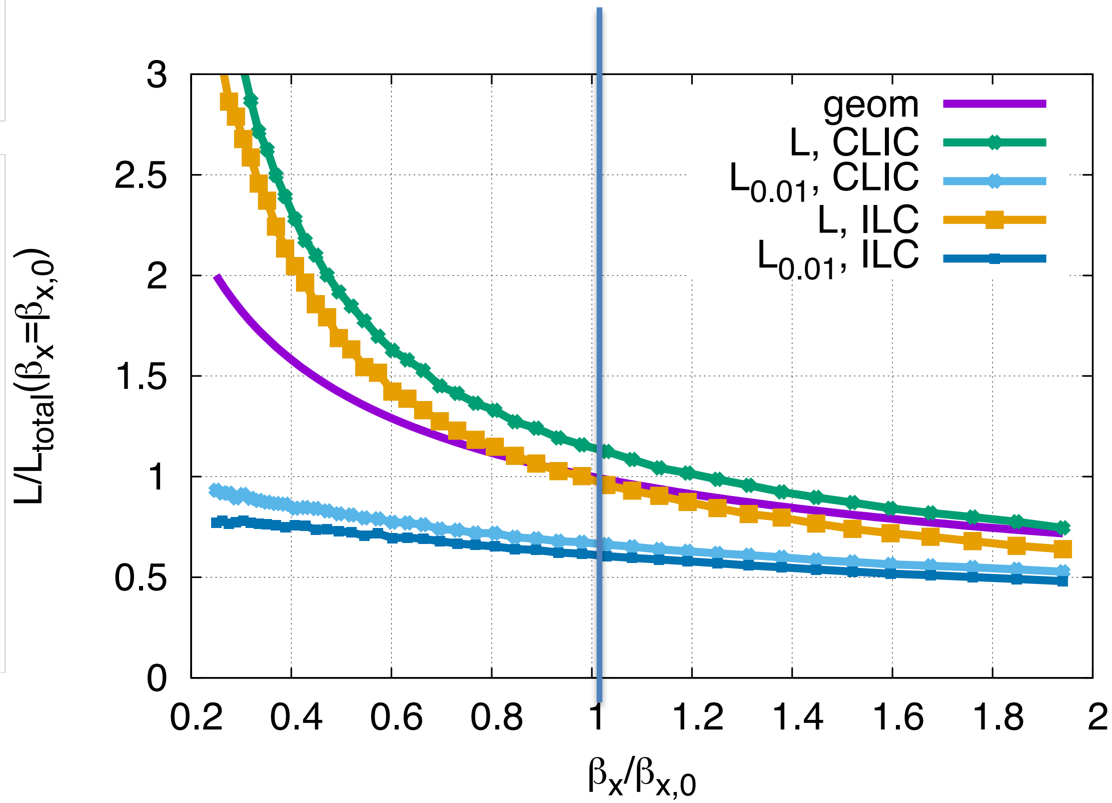
Beam current

Beam Quality (+bunch length)

Beamstrahlung Optimisation







$$n_\gamma \propto E_\gamma \propto \frac{N}{\sigma_x + \sigma_y}$$

$$\sigma_x \gg \sigma_y$$

$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

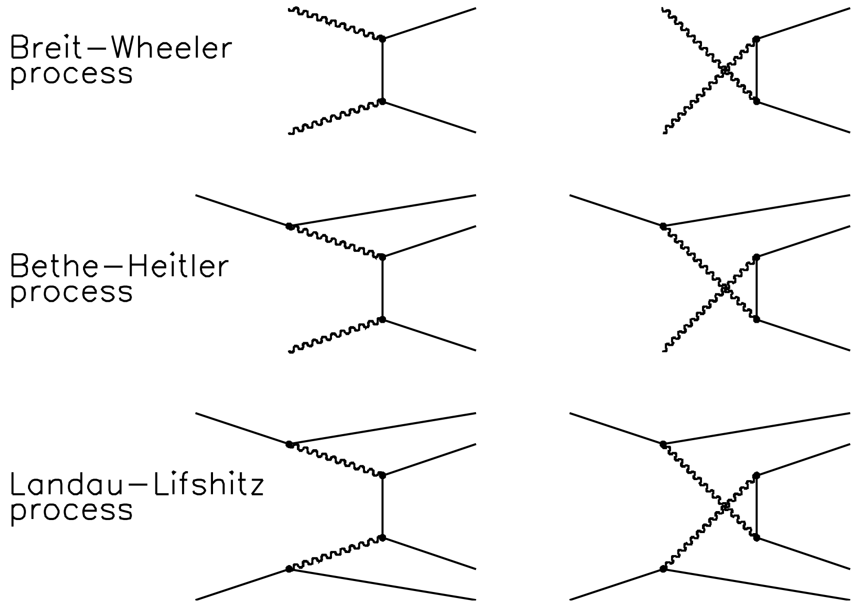
Choose $n_\gamma \approx 1$

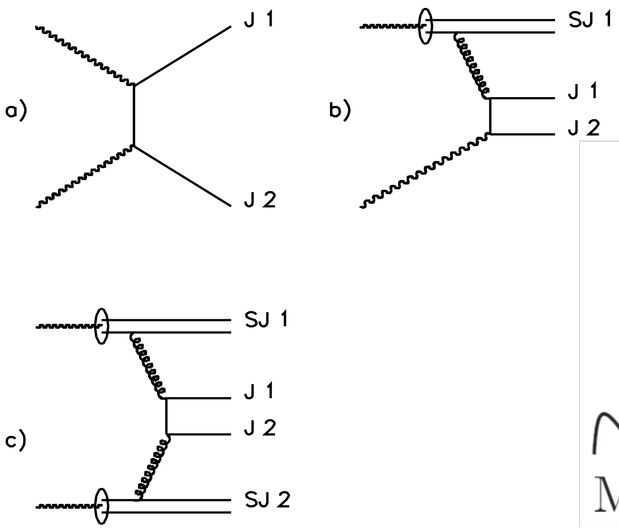
Similar to initial state radiation

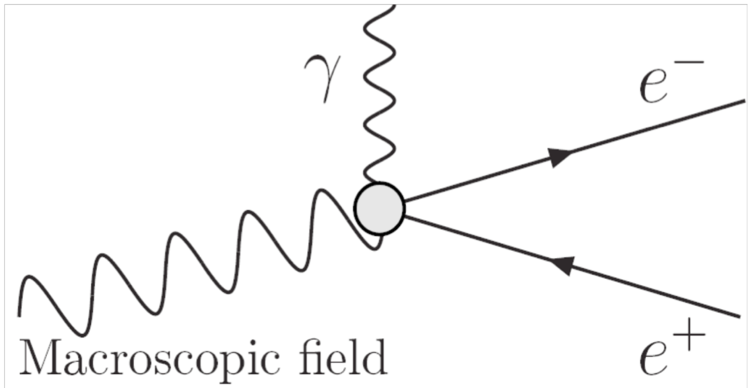
Note: Beam-beam and Background

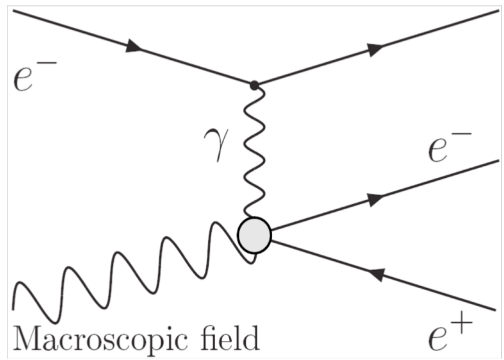
Physics studies include luminosity spectrum and background

Beam-beam effects generate leptonic and hadronic background
- Taken into account in the detector design









Emittance and Luminosity

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

$$\sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

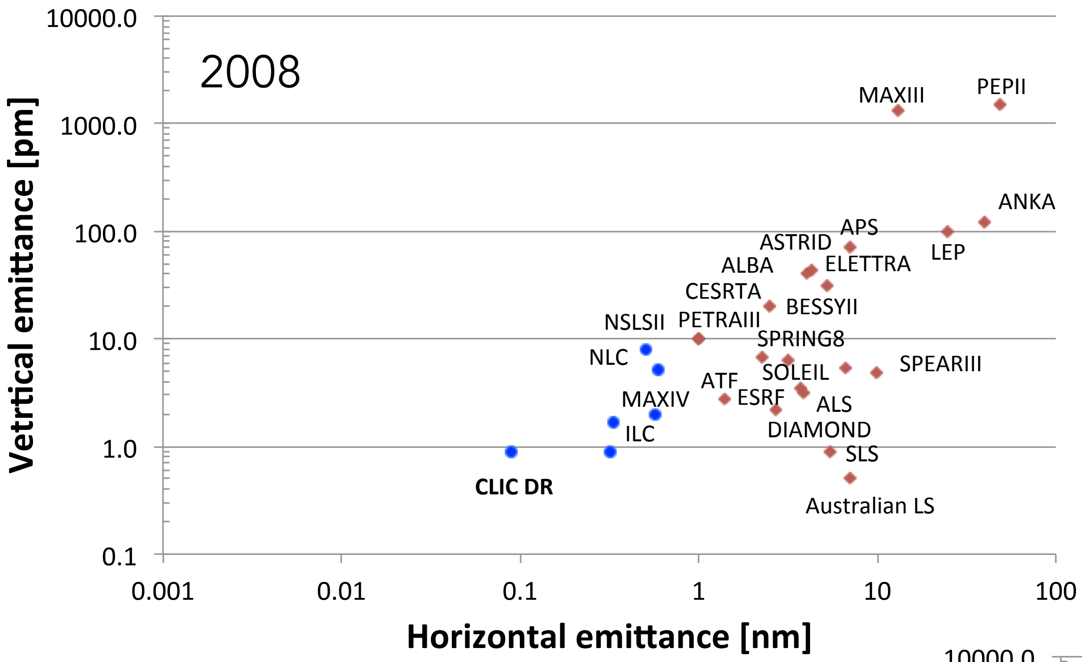
Damping ring main source of horizontal emittance

Imperfections are main source of final vertical emittance
Otherwise would have L = 4.3×10^{34} $cm^{-2}s^{-1}$

Require 90% likelihood to meet static emittance growth target

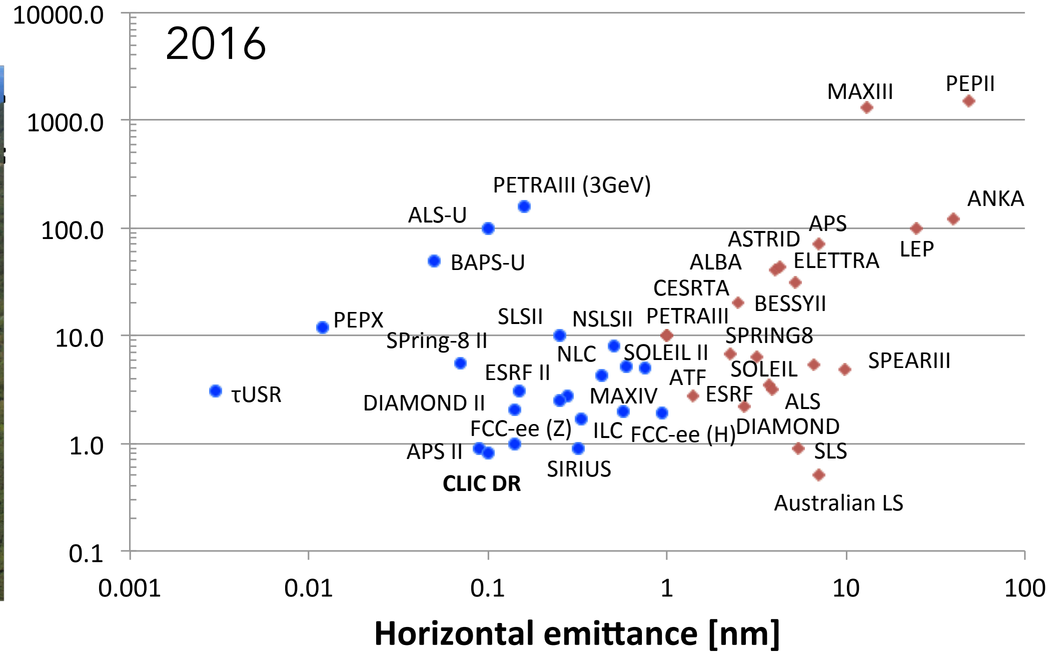
	Norm $\Delta\varepsilon_x$ [nm]	$\Delta\varepsilon_y$ [nm]		
	Total contribution	Design limits	Static imperf.	Dynamic imperf.
Damping ring exit	700	5	0	0
End of RTML	150	1	2	2
End of main linac	50	0	5	5
Interaction point	50	0	5	5
sum	950	6	12	12

Low-emittance Generation



Generation of low-emittance beams now standard in light sources

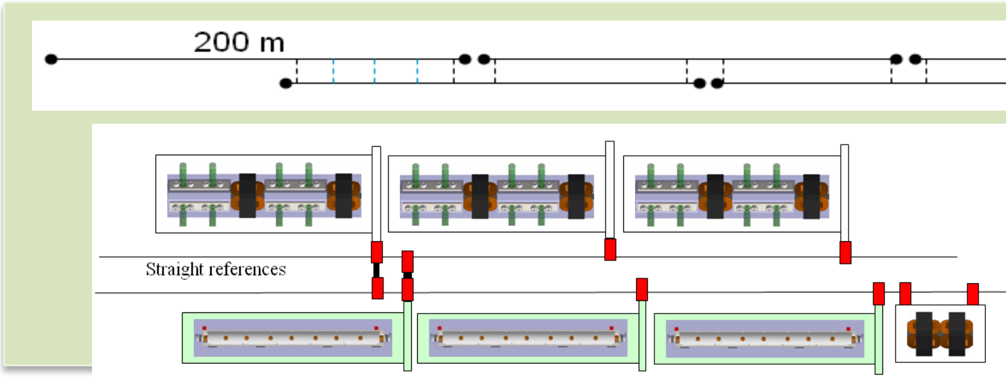
Work for CLIC was instrumental in improving ring performances



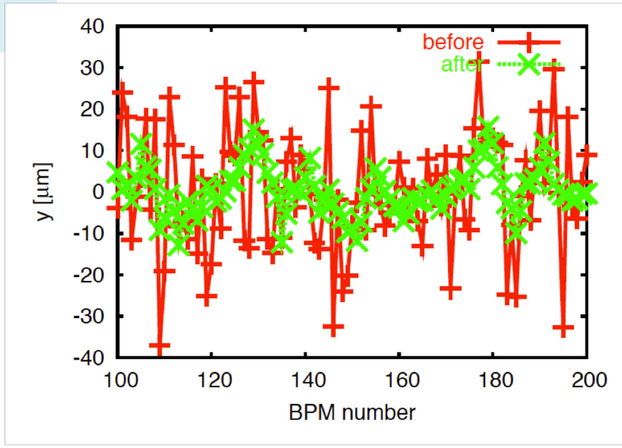
Emittance Preservation Example: Main Linac

Goal 90% less than 5 nm emittance growth

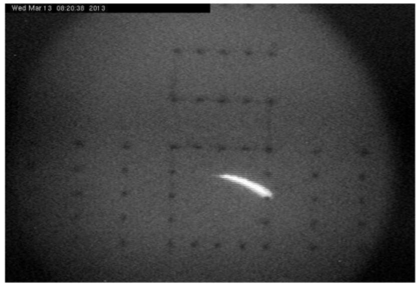
- Optimised design for stability
- Developed prototype alignment system
- Model system with codes
- Apply beam-based methods
- Tested methods at SLAC



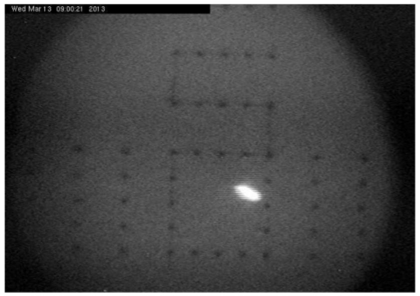
Alignment accuracy, O(10µm)
Further improvement with beam



Before correction



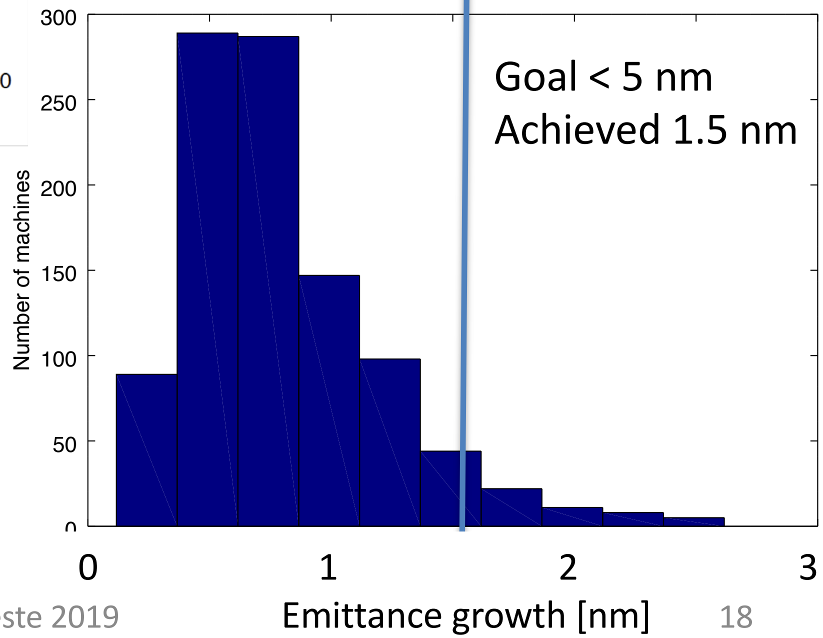
After 3 iterations



90% likelihood to stay below 1.5 nm
Expectation value: less than 1 nm

Luminosity expectation value
including also RTML and BDS
3 x 10^{34} $cm^{-2}s^{-1}$, i.e. twice the target

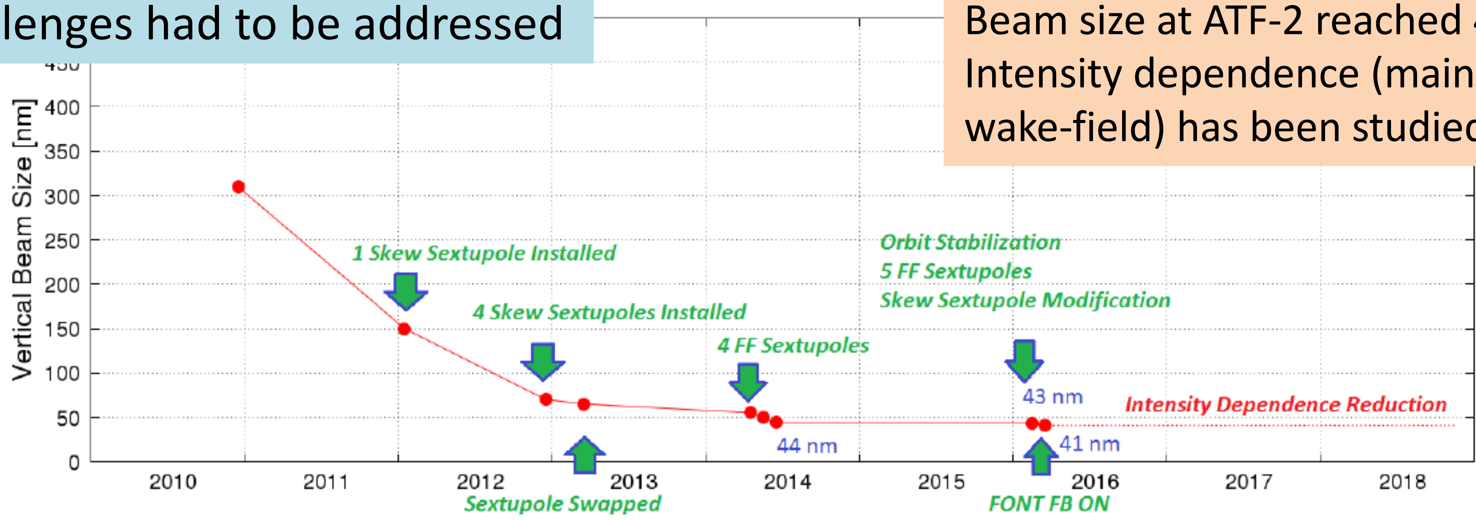
Important margin is kept
Studies show also margin for 3 TeV

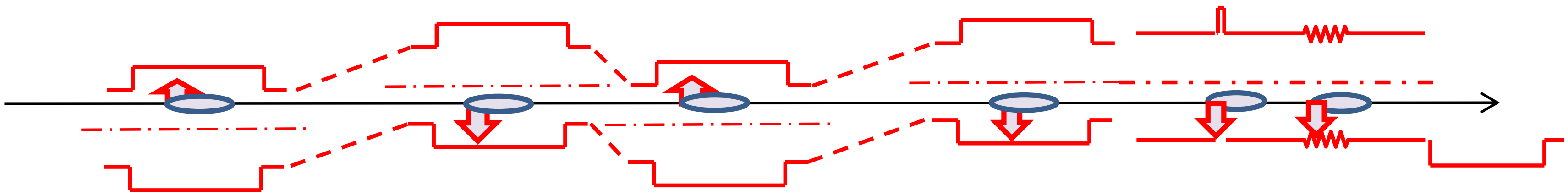


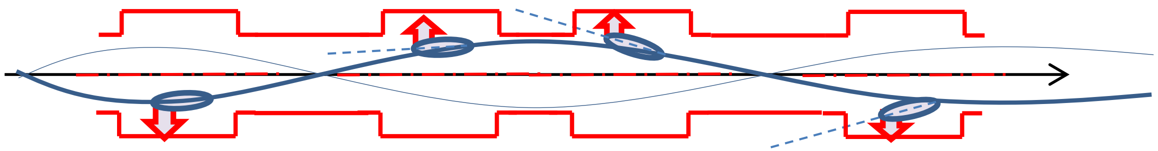
Example: Beamsize at ATF2

Many challenges had to be addressed

Beam size at ATF-2 reached 41 nm. Intensity dependence (mainly by wake-field) has been studied.



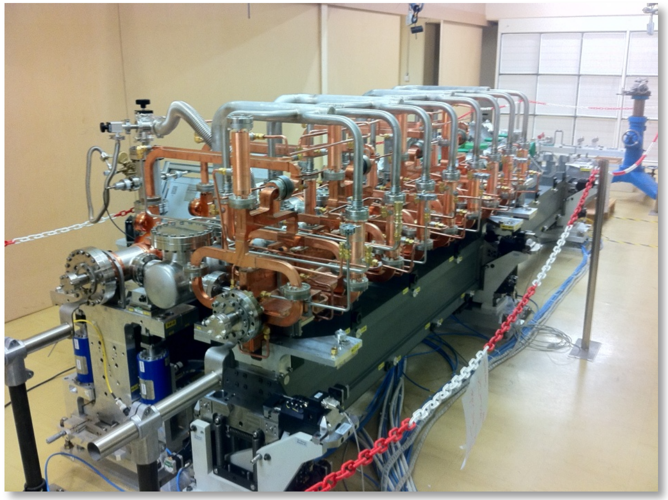




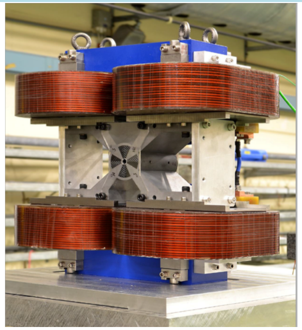
Seem to understand wakefield effects, would not be sever in colliders

Technologies

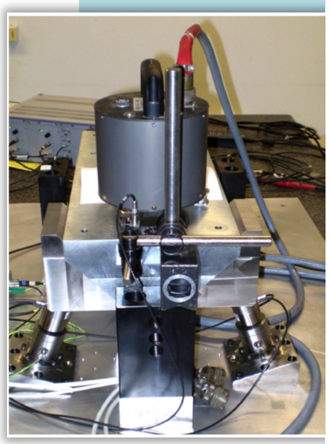
Test module



Short final quadrupole prototype

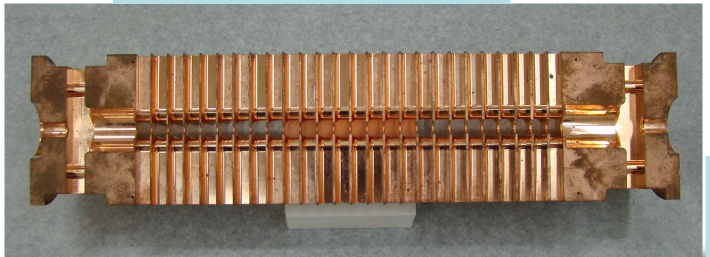


Magnet stabilisation

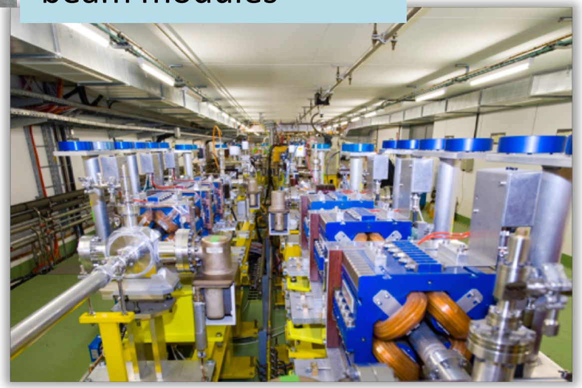


High efficiency klystrons,
Instrumentation, kickers, …

Accelerating structure

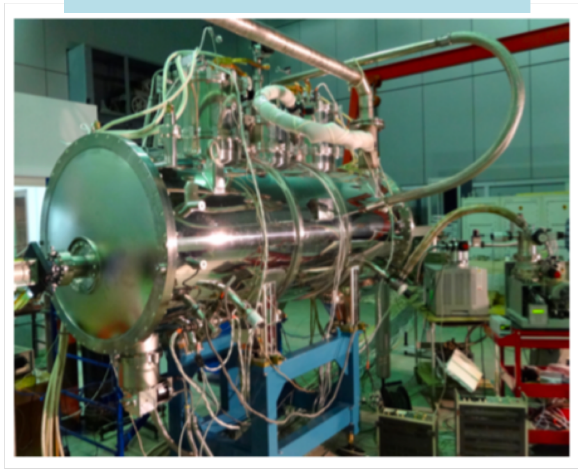


Drive beam and main beam modules



Short BDS sextupole prototype

NbTi damping ring wiggler



Examples of Technology Use

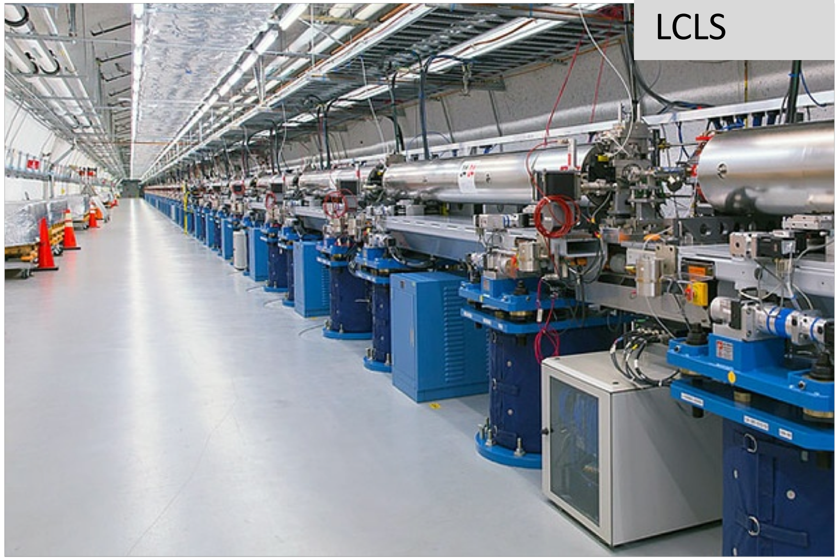
SwissFEL

Normal-conducting FELs exist worldwide

RF frequency increases

SmartLight: EU co-funded study on cheap high-frequency FEL (led by Trieste)

LCLS

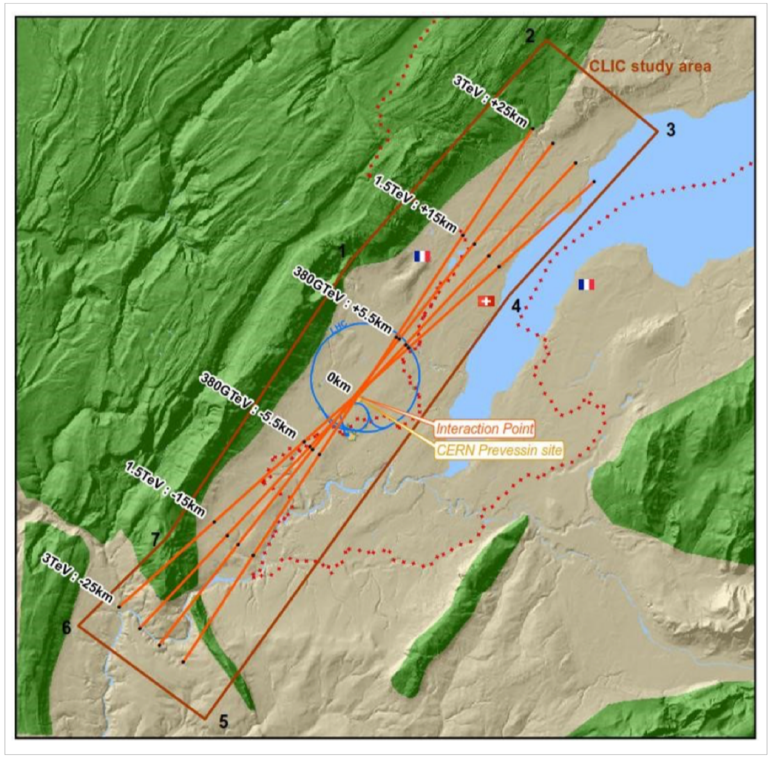


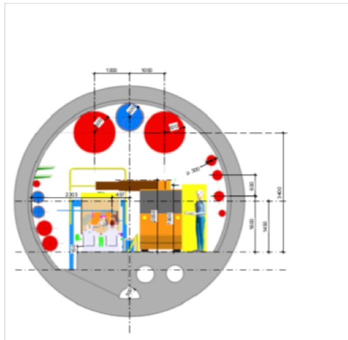
FERMI

SACLA

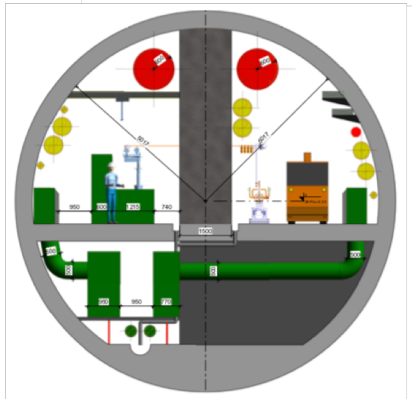
CLIC at CERN

Studies of:
- Civil engineering
- Electrical systems
- Cooling and ventilation
- Transport, logistics and installation
- Safety, access and radiation protection systems



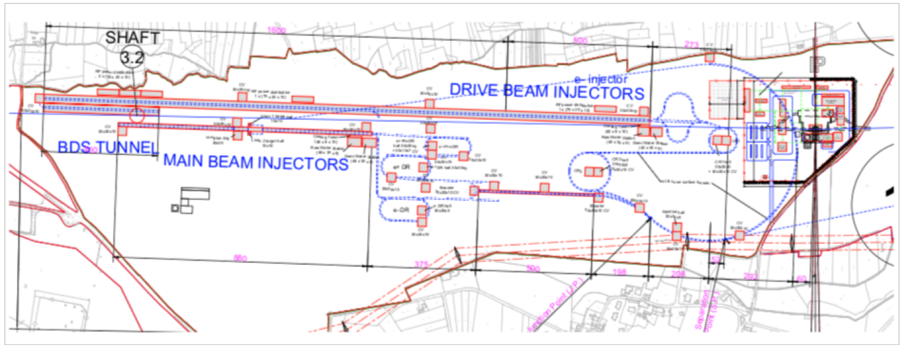


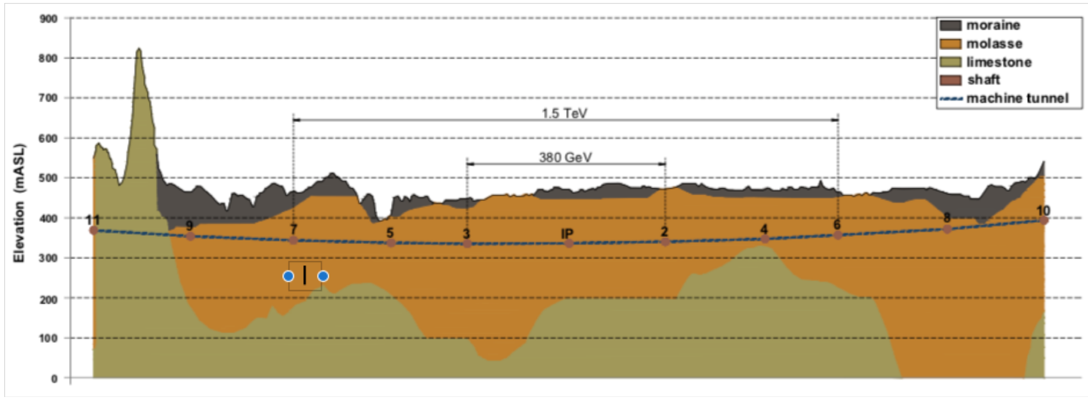
(a)



(b)

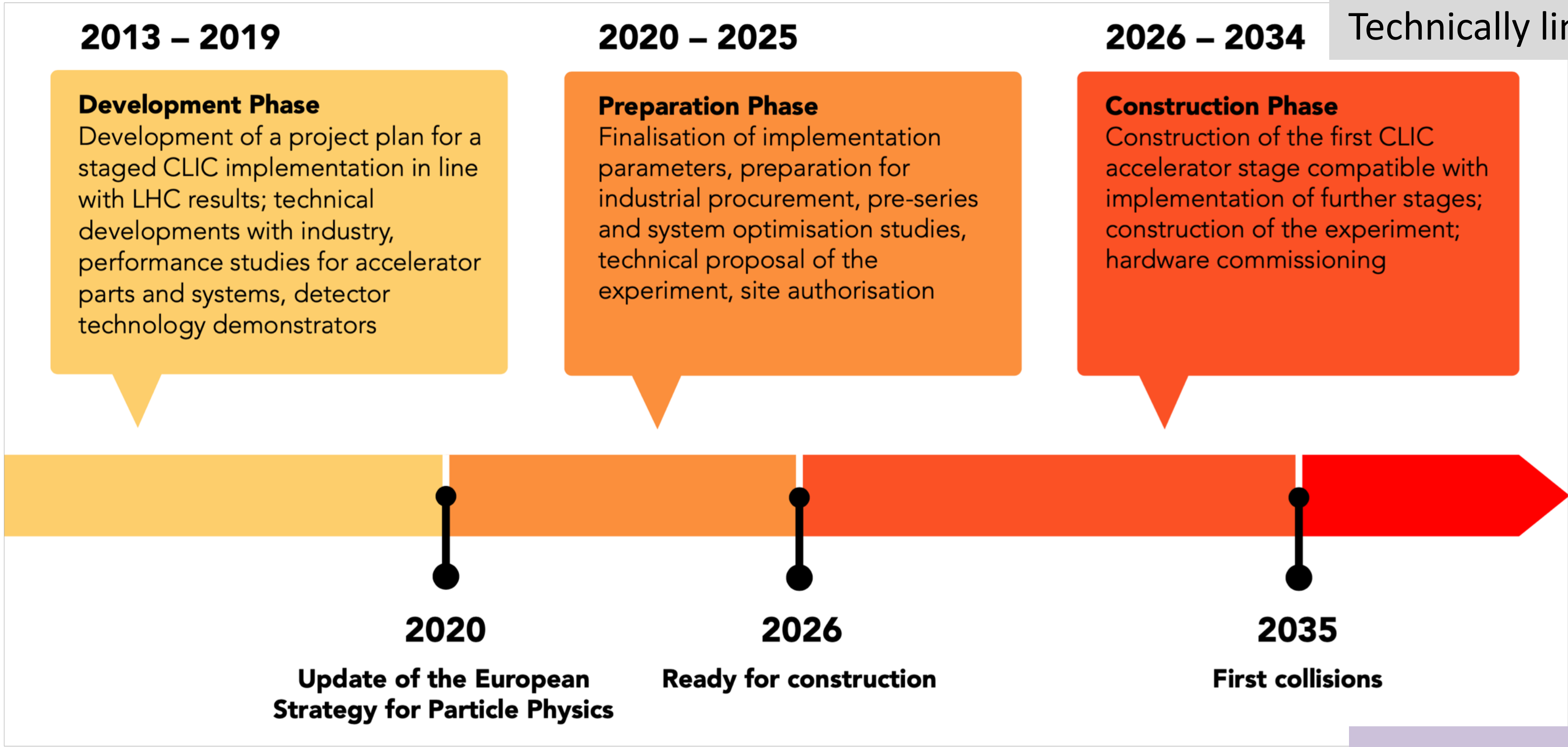
Crucial for cost/power/schedule

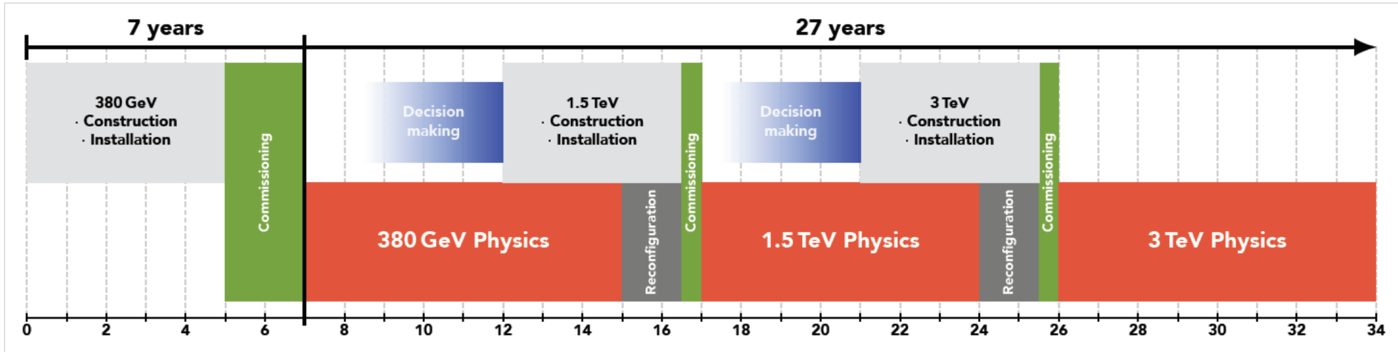




Schedule

Technically limited schedule





Costs 5.9 GCHF (380 GeV)
+ 5.1 GCHF (1.5 TeV)
+ 7.3 GCHF (3 TeV)

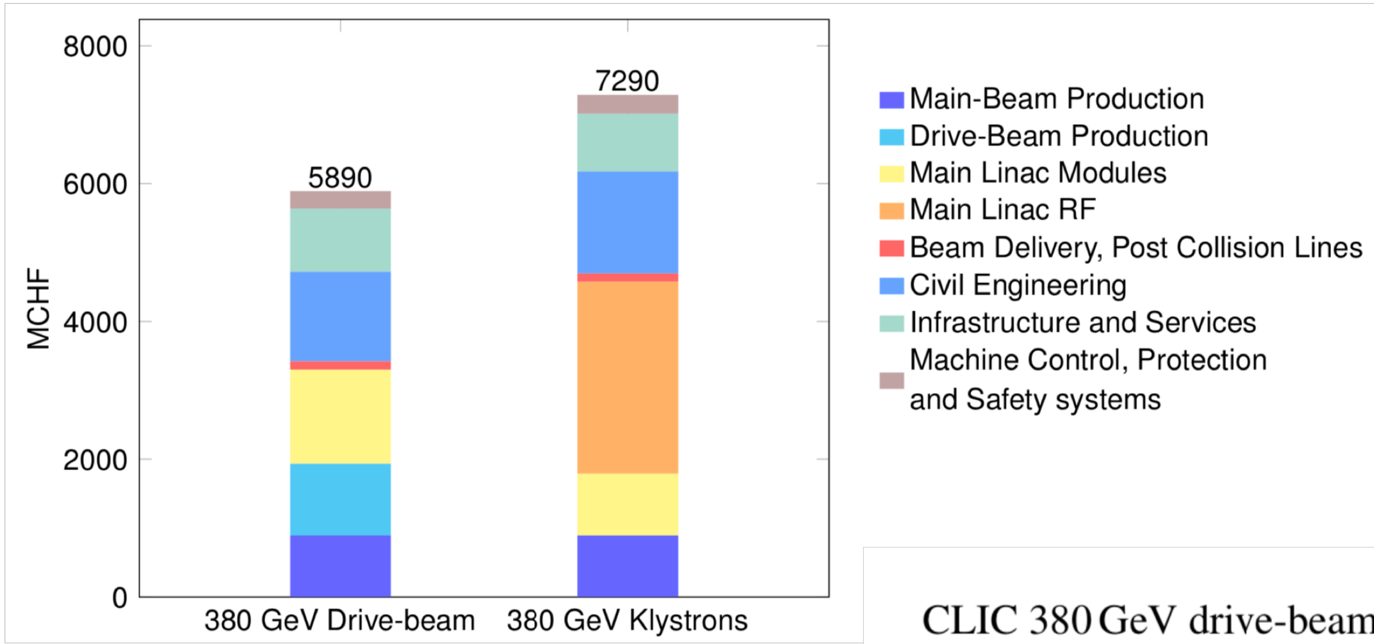
0.4 GCHF for the detector

First collisions in 2035

Ready for construction in 2026
Time for R&D until then could be sufficient

CLIC Cost

Machine has been re-costed bottom-up in 2017-18
- Methods and costings validated at review on 7 November 2018 – similar to LHC, ILC, CLIC CDR
- Technical uncertainty and commercial uncertainty estimated



Domain	Sub-Domain	Cost [MCHF] Drive-beam	Klystron
Main-Beam Production	Injectors	175	175
	Damping Rings	309	309
	Beam Transport	409	409
Drive-Beam Production	Injectors	584	—
	Frequency Multiplication	379	—
	Beam Transport	76	—
Main Linac Modules	Main Linac Modules	1329	895
	Post decelerators	37	—
Main Linac RF	Main Linac Xband RF	—	2788
Beam Delivery and Post Collision Lines	Beam Delivery Systems	52	52
	Final focus, Exp. Area	22	22
	Post-collision lines/dumps	47	47
Civil Engineering	Civil Engineering	1300	1479
Infrastructure and Services	Electrical distribution	243	243
	Survey and Alignment	194	147
	Cooling and ventilation	443	410
	Transport / installation	38	36
Machine Control, Protection and Safety systems	Safety systems	72	114
	Machine Control Infrastructure	146	131
	Machine Protection	14	8
	Access Safety & Control System	23	23
Total (rounded)		**5890**	**7290**

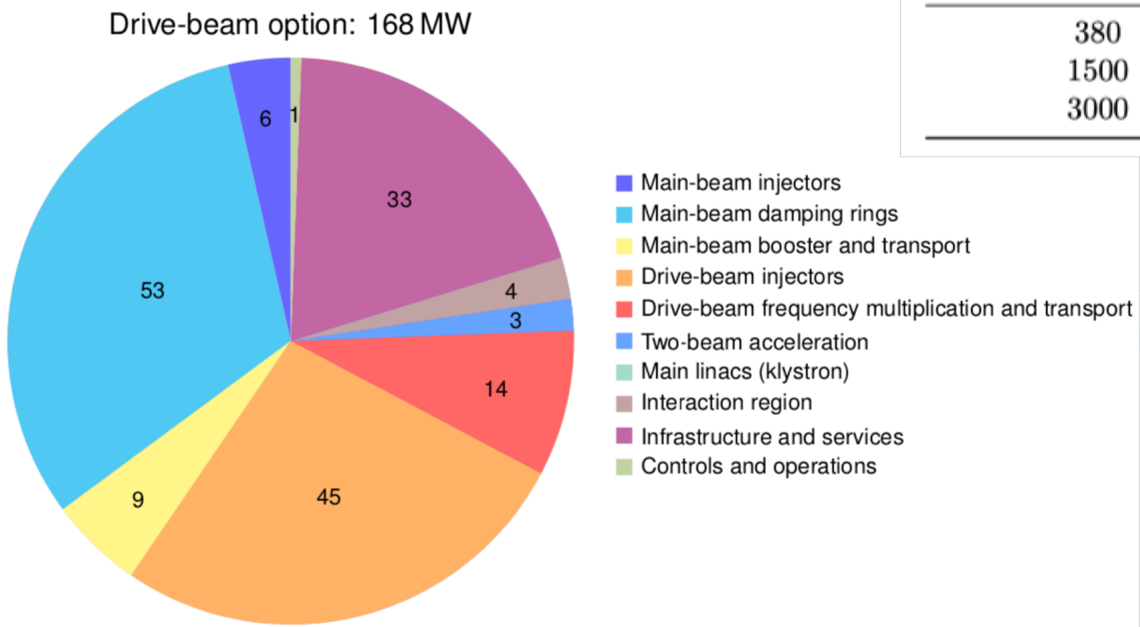
Based on industrial study, reviewed by Jim Clarke, Mike Harrisson, Philippe Lebrun, Akira Yamamoto, Lyn Evans

$$\text{CLIC 380 GeV drive-beam based} \quad : \quad 5890^{+1470}_{-1270}\,\text{MCHF} \quad ;$$

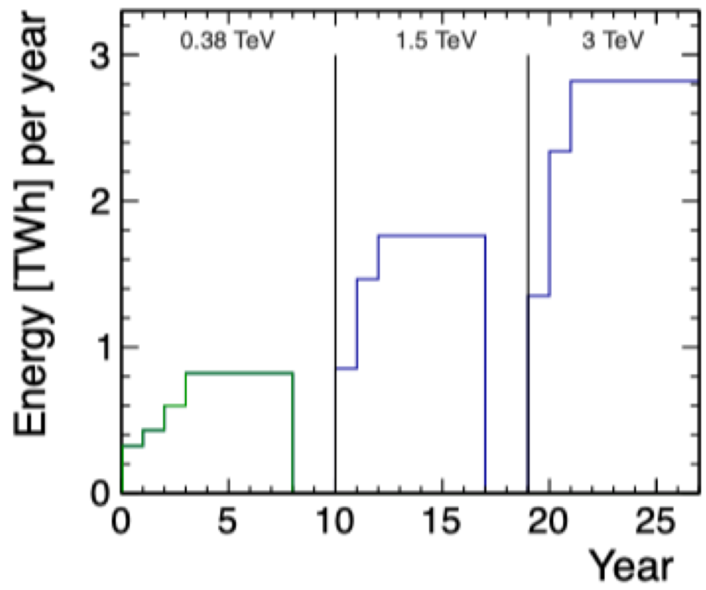
$$\text{CLIC 380 GeV klystron based} \quad : \quad 7290^{+1800}_{-1540}\,\text{MCHF} \quad .$$

Construction of higher energy stages:
- From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of ML)
- From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of ML)
- Labour estimate: ~11500 FTE for the 380 GeV construction

CLIC Power



Collision Energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	168	25	9
1500	364	38	13
3000	589	46	17



Power estimate bottom up (concentrating on 380 GeV systems)

- Very large reductions since CDR, better estimates of nominal settings, much more optimised drivebeam complex and more efficient klystrons, injectors more optimisation, etc

Further savings possible, main target damping ring RF
Will look also more closely at 1.5 and 3 TeV numbers – these numbers are from the CDR in 2012

CERN is currently consuming ~1.2 TWh yearly (~90% in accelerators)

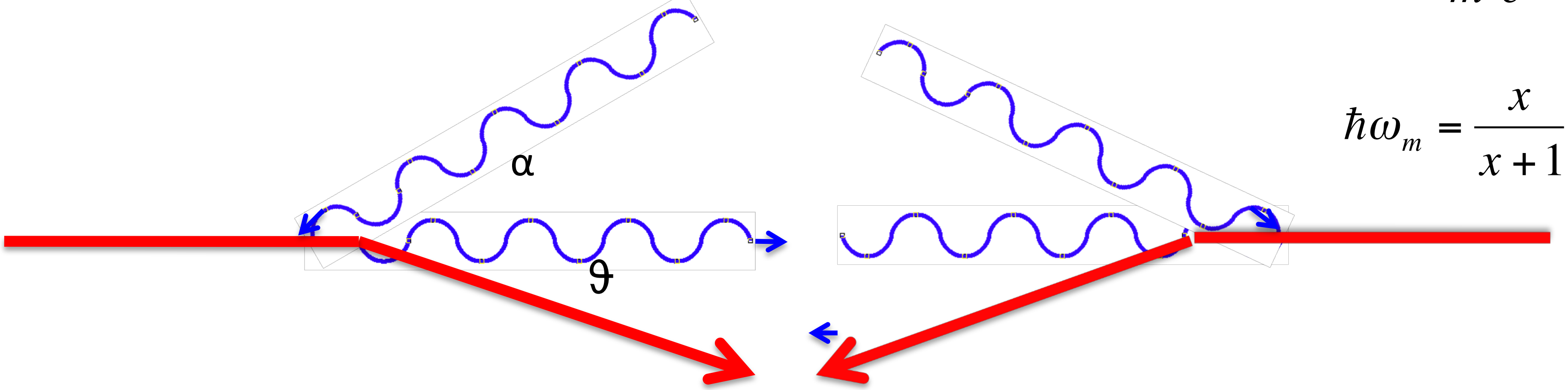
Note: Gamma-gamma Collider Concept

Based on e⁻e⁻ collider

Collide electron beam with laser beam before the IP

$$x = \frac{4E_0\hbar\omega_0}{m^2c^4}$$

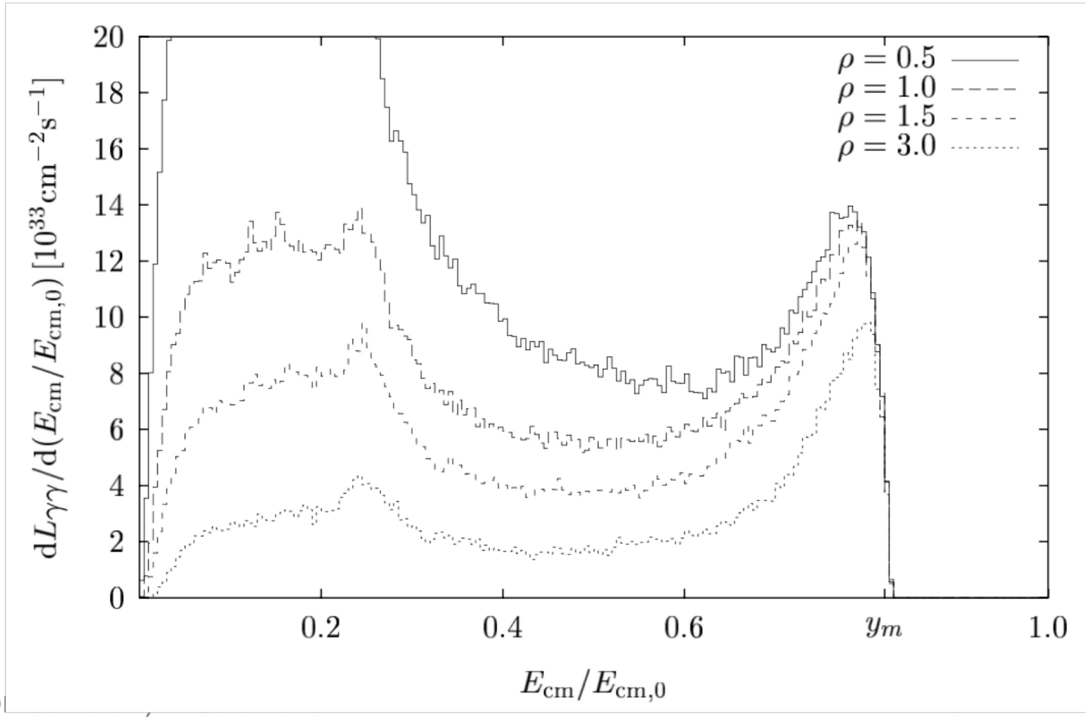
$$\hbar\omega_m = \frac{x}{x+1}E_0$$



Backscattered photons form a spectrum

Practical maximum energy is 83% of electron energy

Luminosity

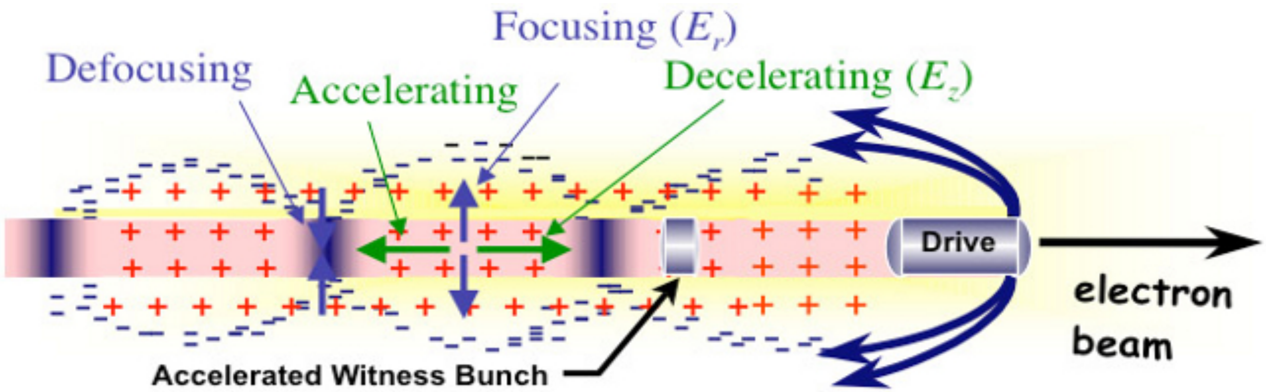


Note: Novel Acceleration Technologies

Mainly replace the main linac of linear colliders with novel technology acceleration

Plasma acceleration achieves very high gradients (> GV/m)

- Powered with beam or laser



But are only now starting to consider beam quality

- There are good reasons to worry about beam quality, so need to wait for R&D results

Dielectric accelerating structures promise more modest increase in gradient

Might become interesting in the longer run but not right now

- R&D should be supported if possible

Might become interesting in the longer run

- but not right now
- R&D is interesting

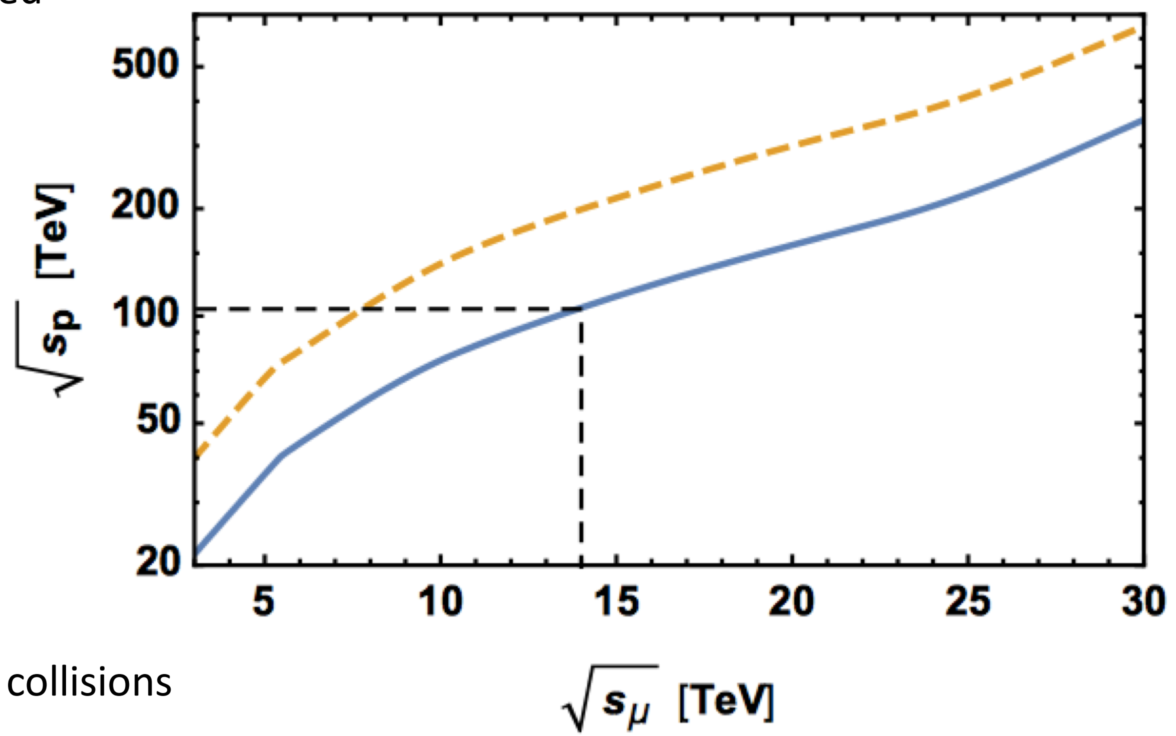
Muon Collider Motivation

Lepton colliders offer the potential of precision measurements

- Well defined initial conditions
- Low background levels
- …

At high energies they are efficient discovery machines

- Full collision energy available for particle production
- But sufficient luminosity is required



14 TeV lepton collisions
Are comparable to 100 TeV proton collisions

Luminosity Goal

To investigate s-channel processes, luminosities have to increase quadratically with energy

- From the physics a luminosity goal is defined as

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2} \text{s}^{-1}$$

The main difficulty of electron-positron colliders is to provide the luminosity at high energies

- Circular collider radiate dramatically at high energy
- Linear colliders can provide linear increase of luminosity for constant beam current
- Or a constant luminosity per beam power

A muon collider might break this limit and provide a luminosity that increases linearly with energy for constant beam power

Linear Collider Scaling with Energy

Low energy

$$n_\gamma \propto E_\gamma \propto \frac{N}{\sigma_x + \sigma_y}$$

High energy

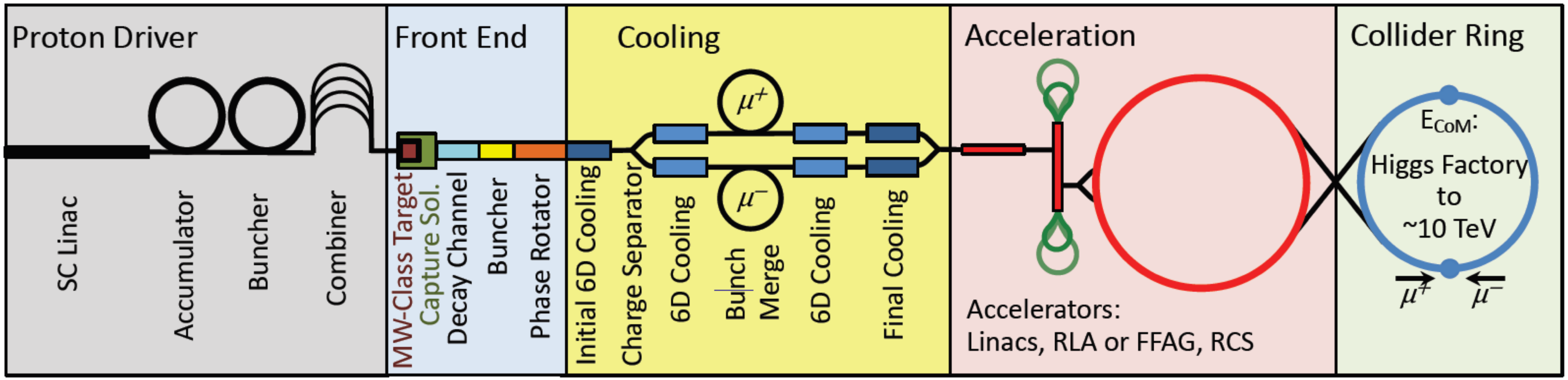
$$n_\gamma \propto \left(\frac{\sigma_z}{\gamma}\right)^{\frac{1}{3}} \left(\frac{N}{\sigma_x + \sigma_y}\right)^{\frac{2}{3}}$$

$$\mathcal{L} \propto H_D \frac{n_\gamma^{\frac{3}{2}}}{\sqrt{\sigma_z}} \frac{1}{\sqrt{\epsilon_y \beta_y}} \frac{R+1}{R} \frac{\eta P_{wall}}{mc^2}$$

Luminosity per power is independent of energy

$R=\sigma_x/\sigma_y$

Proton-driven Muon Collider Concept



Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muons are captured, bunched and then cooled

Acceleration to collision energy

Collision

Collider Parameter Examples

From the MAP collaboration: Proton source

Muon Collider Parameters

		Higgs	**Multi-TeV**		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
β^*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1.5	70	70	70
Bunch Length, σ_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Key to Luminosity

Integrated luminosity of one bunch

$$\Delta \int \mathcal{L} \approx \sum_{i=0}^{\infty} \frac{\left(N_0 e^{-i\Delta t/\gamma\tau}\right)^2}{4\pi\sigma_x\sigma_y}$$

High bunch charge

High energy

For constant longitudinal emittance

$$\mathcal{L} \propto B \frac{N_0}{\epsilon} \gamma P_{beam}$$

High beam power

High field in collider ring

Small emittance

Win luminosity per power as the energy increases

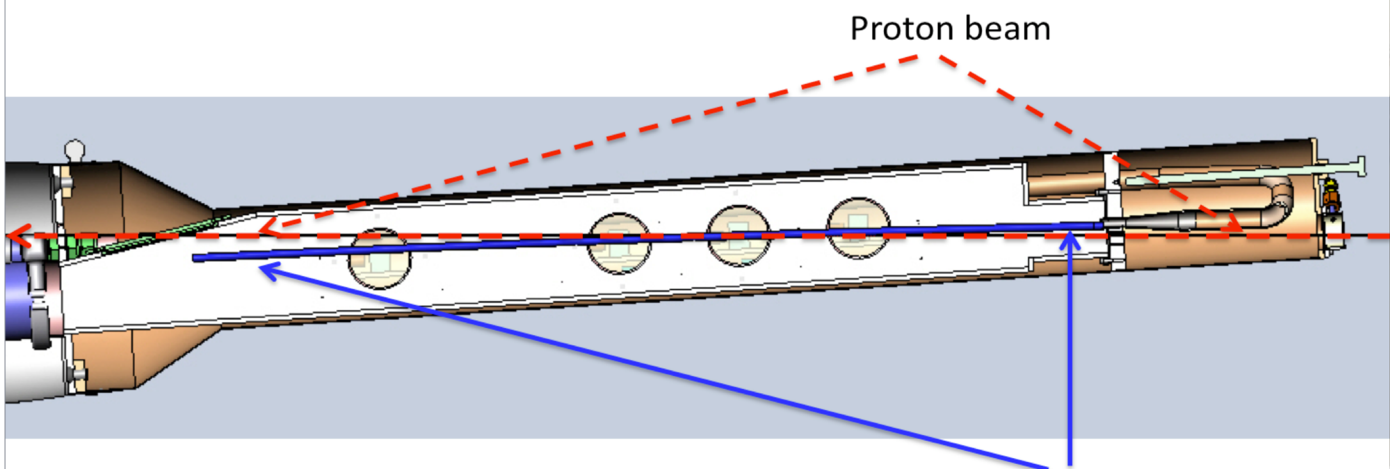
In linear colliders, luminosity per power tends to be energy independent

- except if one changes technology (very short bunches, smaller vertical emittance)

In circular electron-positron colliders luminosity drops rapidly with energy (power ≈3.5)

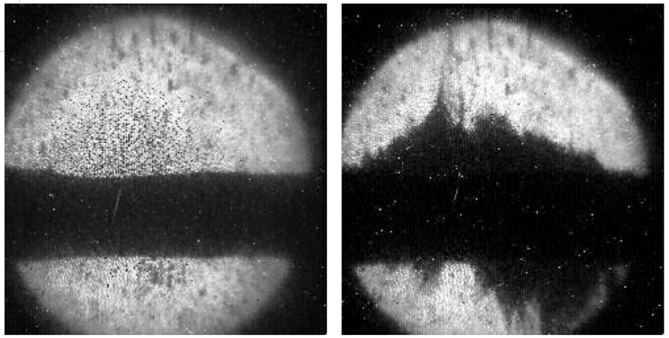
Source

Protons → Target → Pions → Muons



MERIT experiment at CERN

Liquid mercury target to avoid destruction



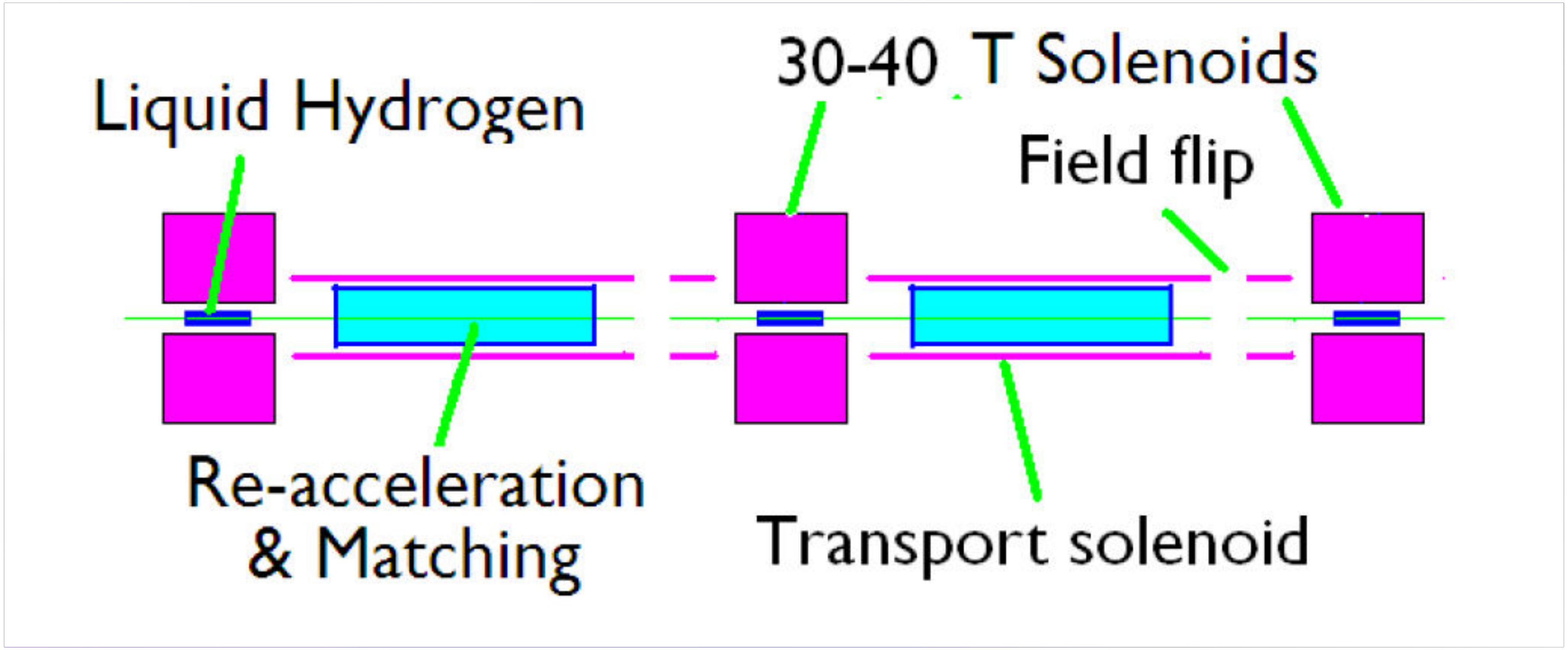
High power target (8 MW vs. 2-4 MW required) has been demonstrated

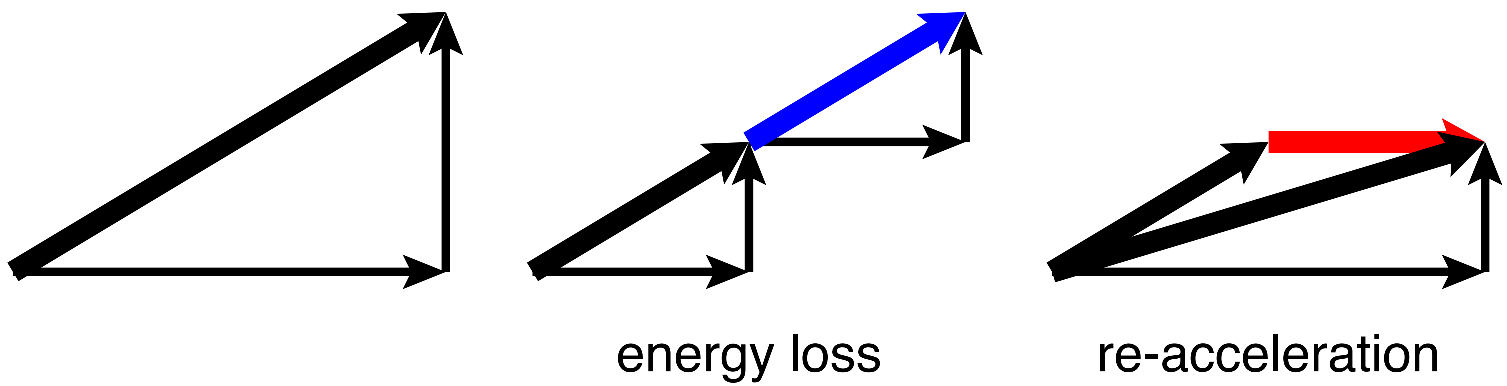
Maximum of 30×10^{12} protons with 24 GeV

But radiation issues?

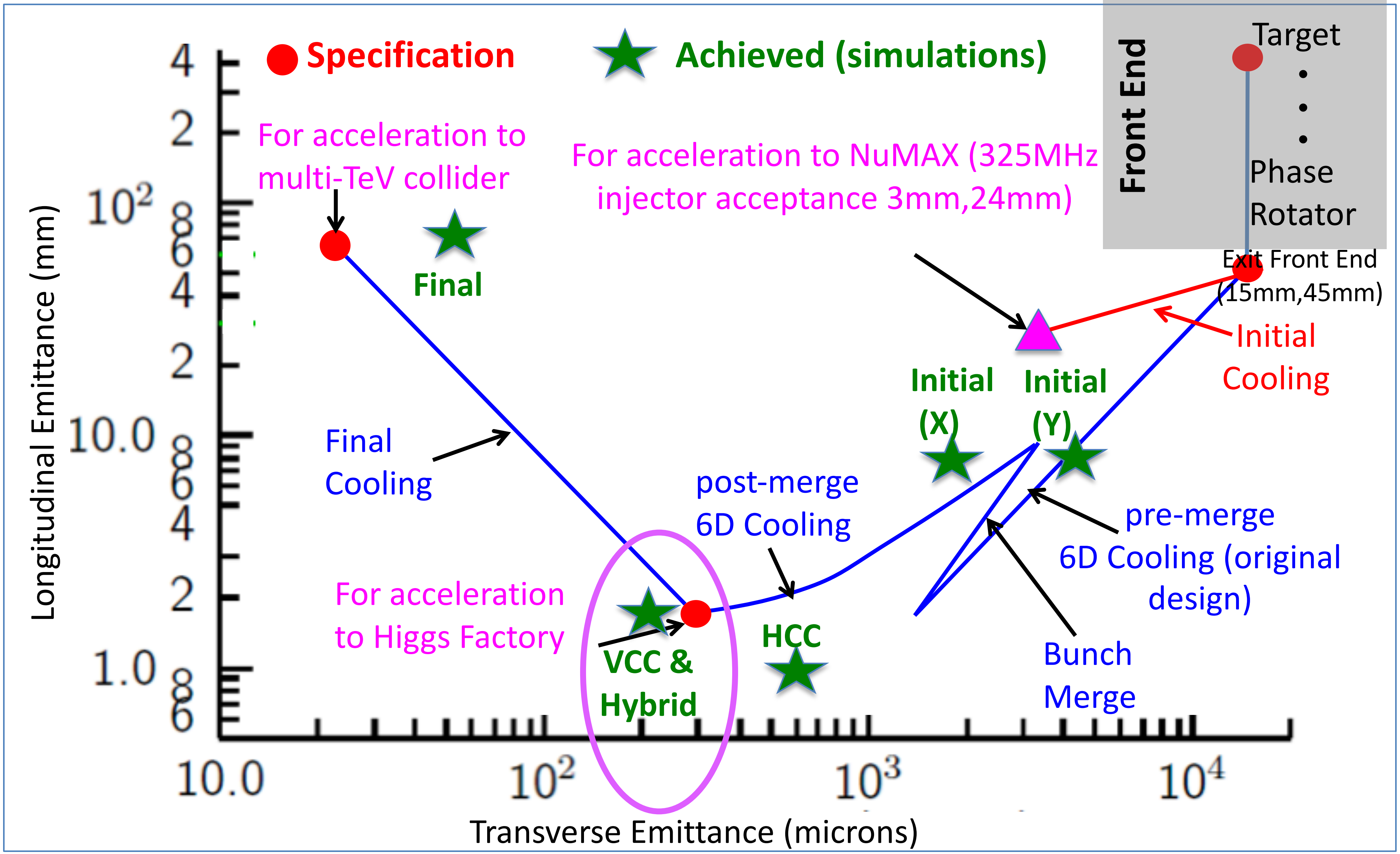
What could be made available at CERN (or elsewhere) as a proton driver for a potential test facility?

Transverse Cooling

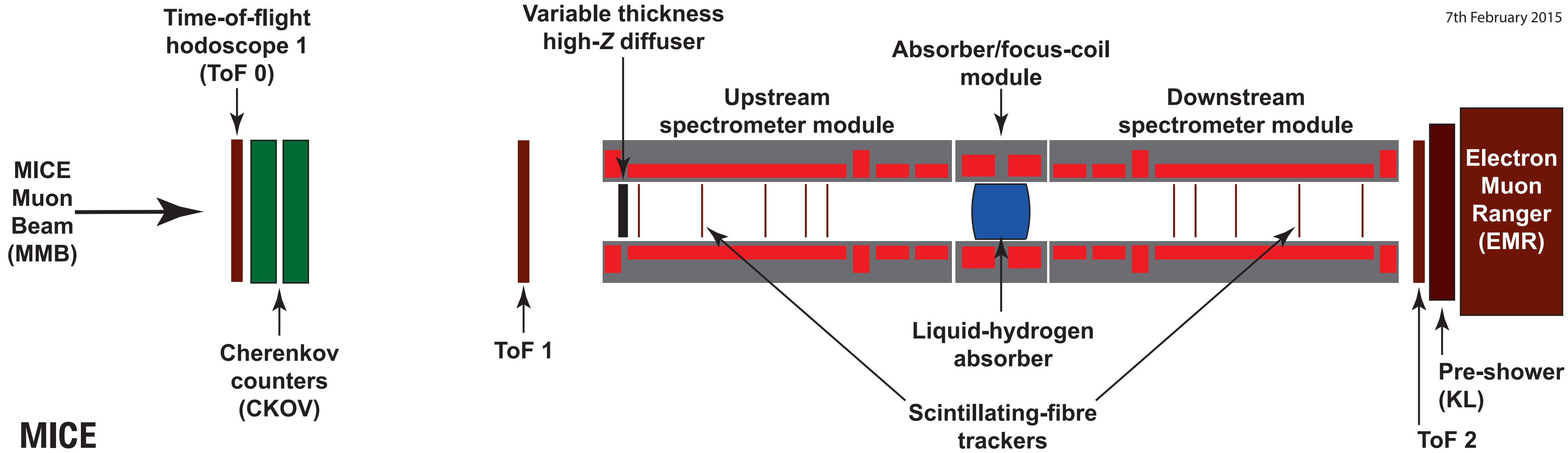




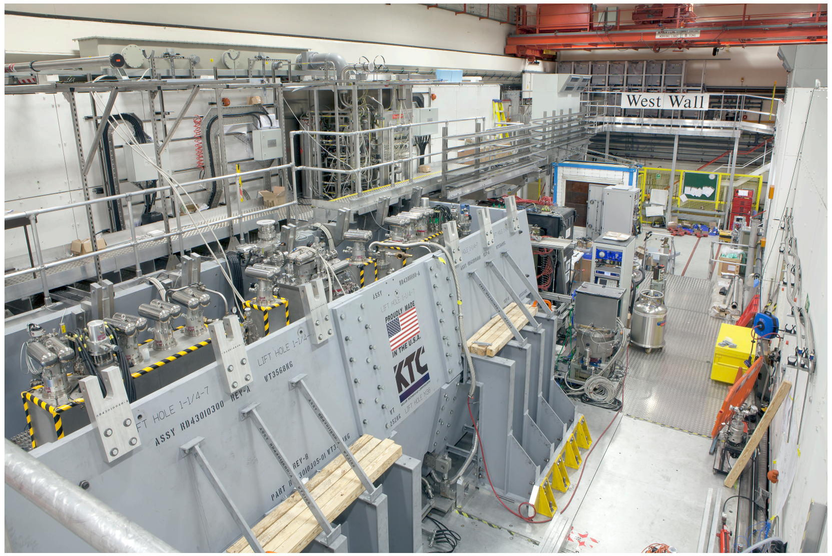
Cooling: The Emittance Path



MICE



$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

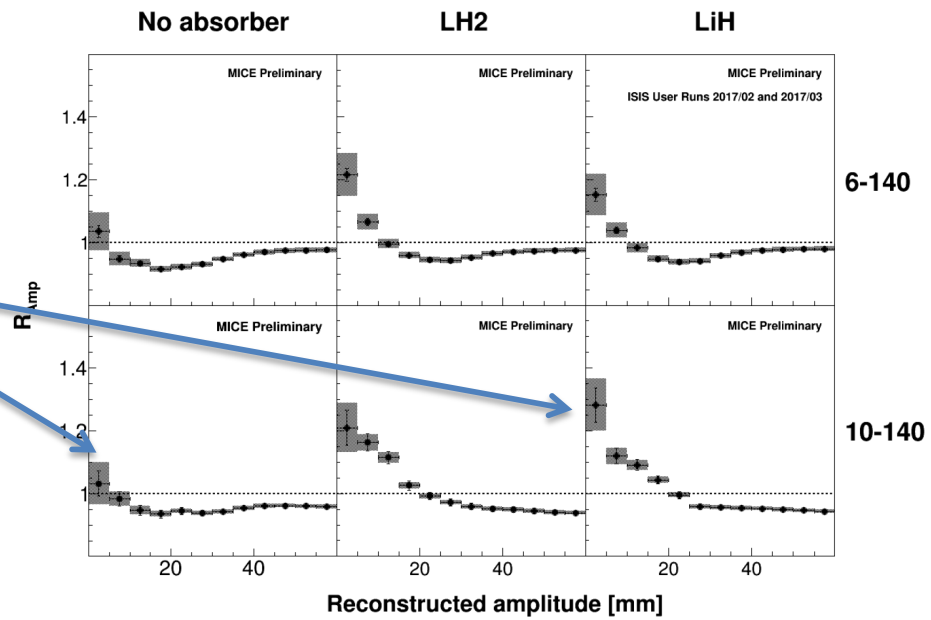


MICE allows to address 4D cooling with low muon flux rate

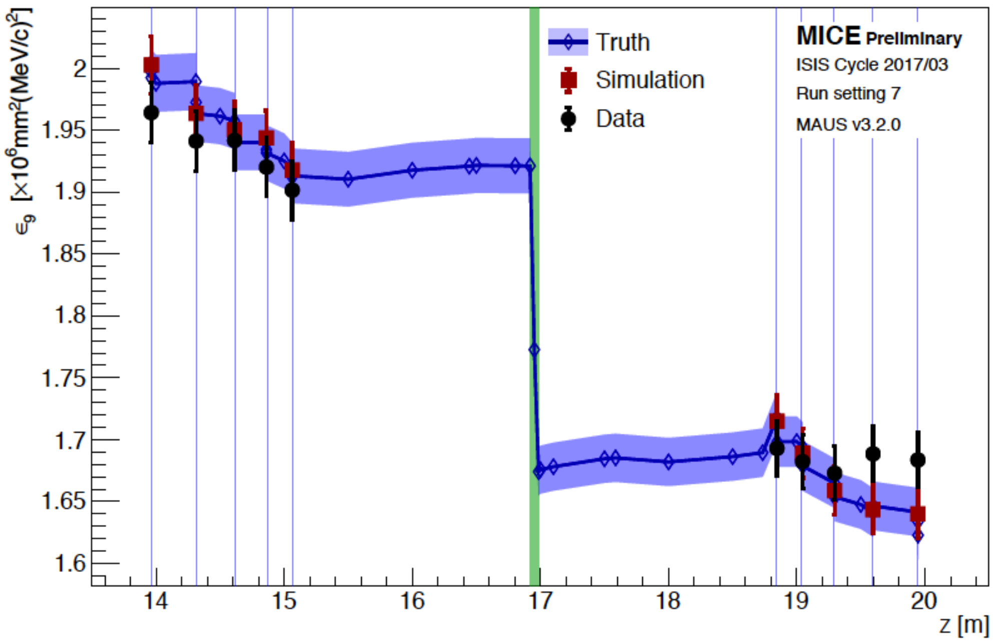
MICE Results

The absorber reduces the number of particle with large amplitude

They appear with smaller amplitude



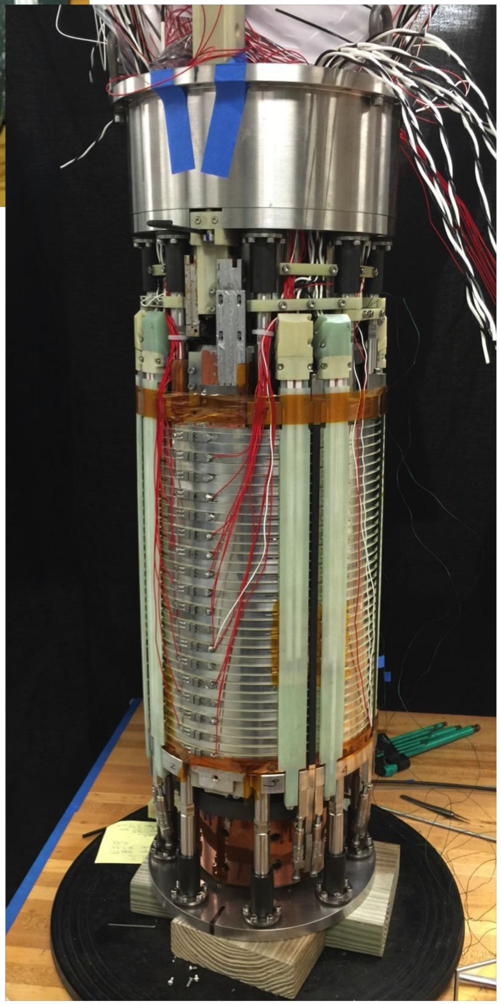
Noticeable reduction of 9% emittance



But still some way to go
- 6D cooling
- Stages
- Small emittances

Other Tests

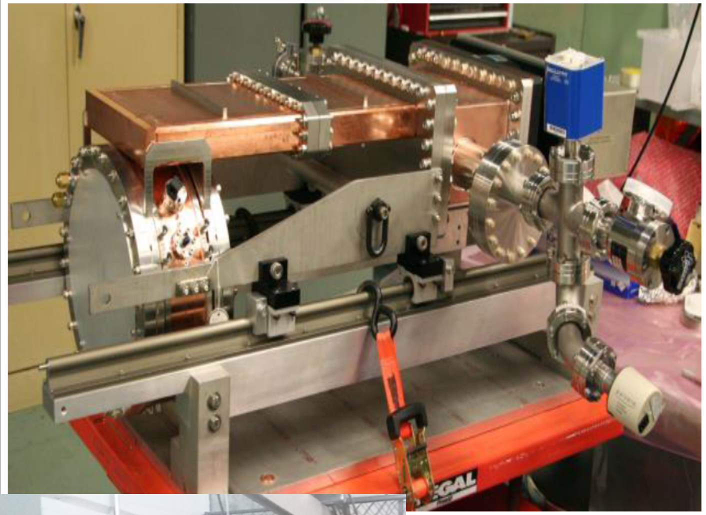
FNAL
Breakthrough in HTS cables



NHFML
32 T solenoid with low-temperature HTS

A number of components has been developed

MuCool: >50MV/m in 5 T field



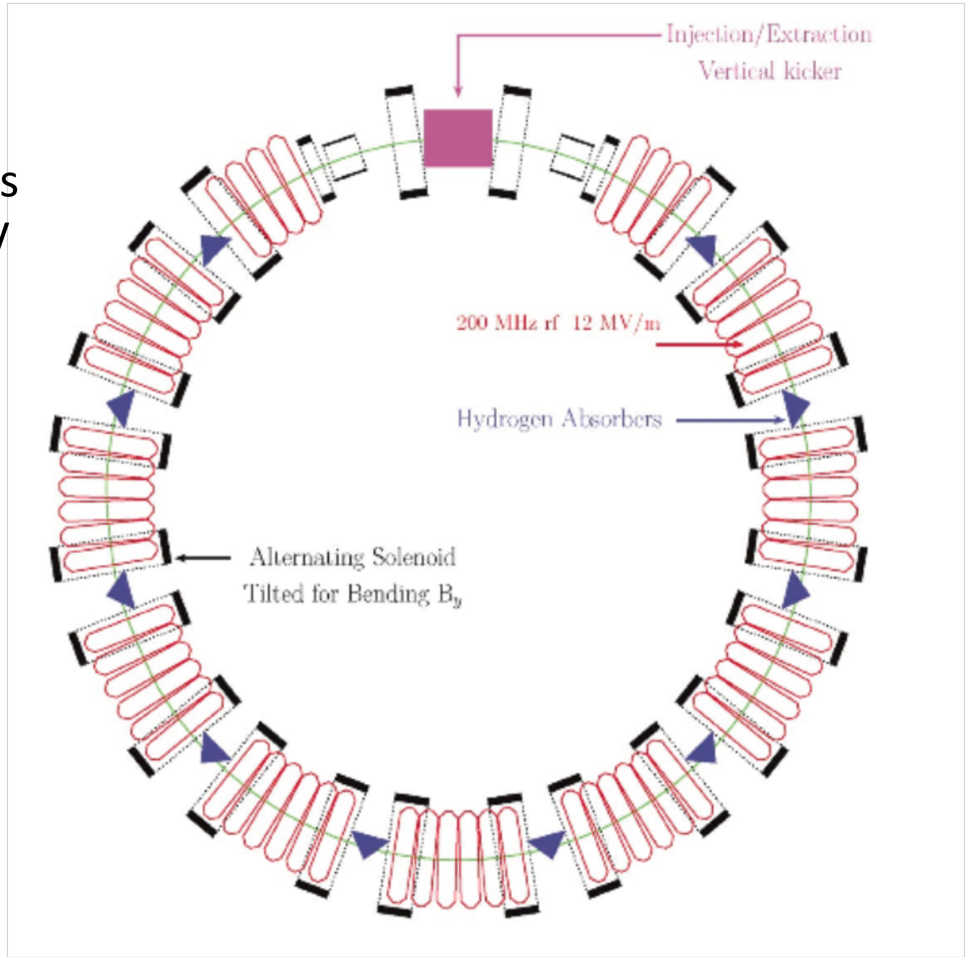
FNAL
12 T/s HTS
0.6 T max

Mark Palmer

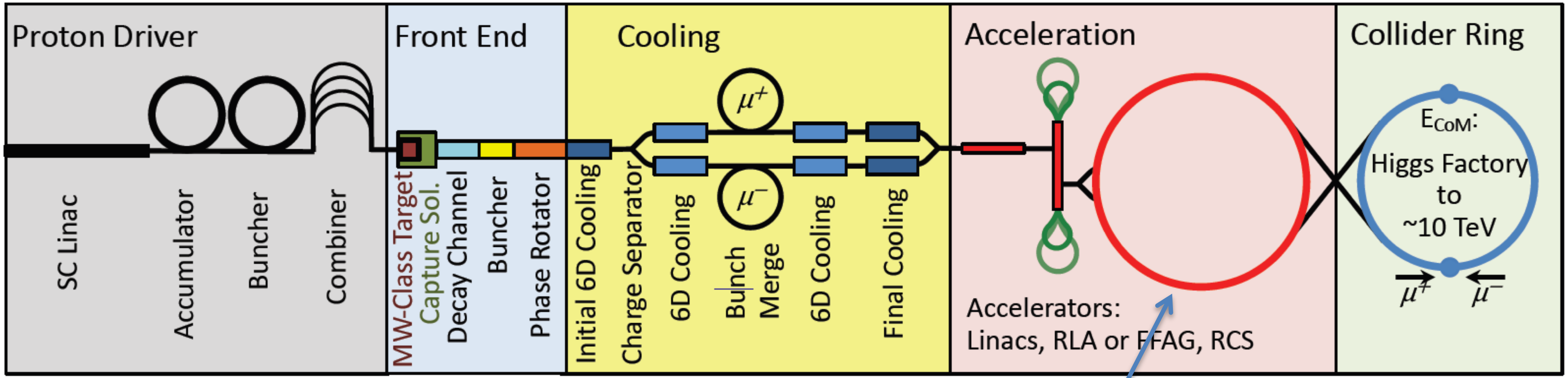
Test Facility Example

Carlo Rubbia: The experimental realization of the presently described μ+μ- Ring Collider may represent the most attractive addition of the future programs on the Standard Model to further elucidate the physics of the Ho, requiring however a substantial amount of prior R&D developments, which must be experimentally confirmed by the help of the Initial Muon Cooling Experiment(al) program.

Initial Cooling Experiment
Use 100 ns ESS pre-pulse with 3×10^{11} protons
Yields 3×10^{7} μ^{-} and 6×10^{7} μ^{+} around 250 MeV



Beam Acceleration



Much larger than collider ring

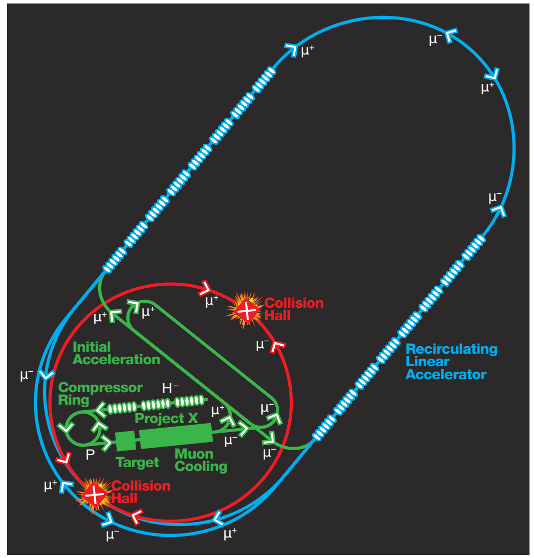
An important cost driver

Important for power consumption

A trade-off between cost and muon survival

Not detailed design, several approaches considered

- Linacs
- Recirculating linacs
- FFAGs

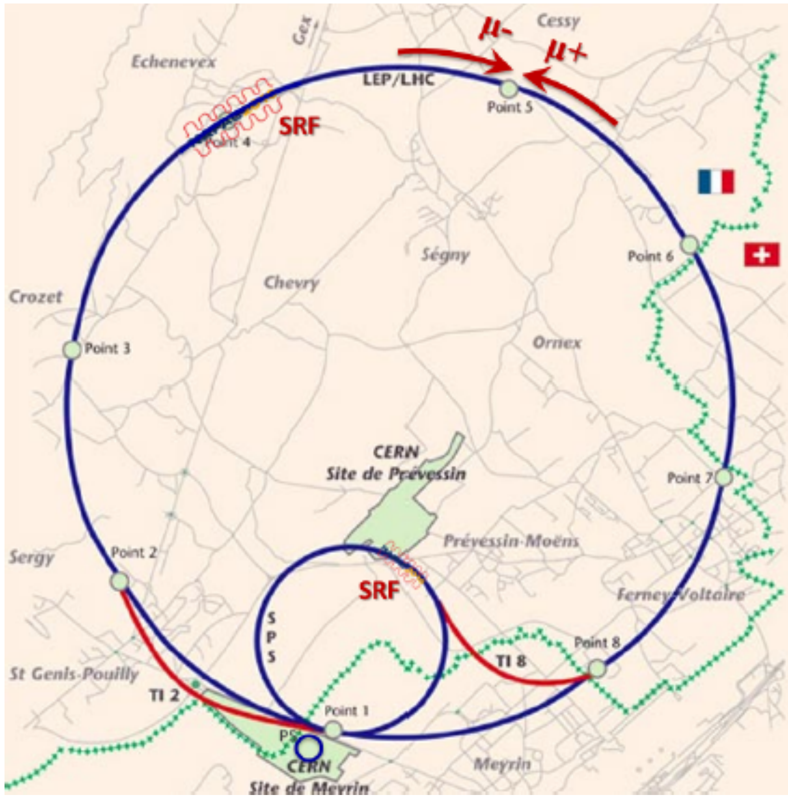


Challenge is large bunch charge but single bunch

Collider Ring

$$\beta \propto \frac{1}{\gamma}$$

Strong focusing at IP to maximise luminosity
Becomes harder with increasing energy

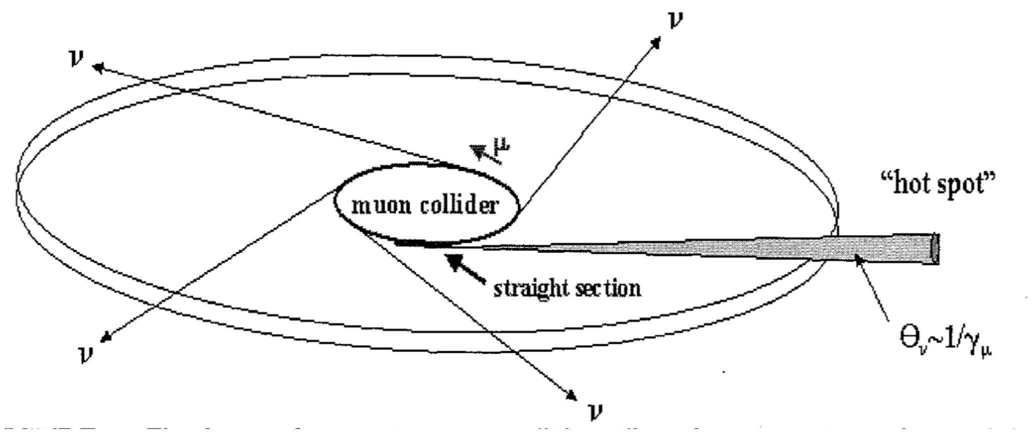


High field dipoles to minimise collider ring size and maximise luminosity
Minimise distances with no bending

Decaying muons impact accelerator components, detector and public
The latter becomes much worse with energy

Radiation to public in case LHC tunnel use

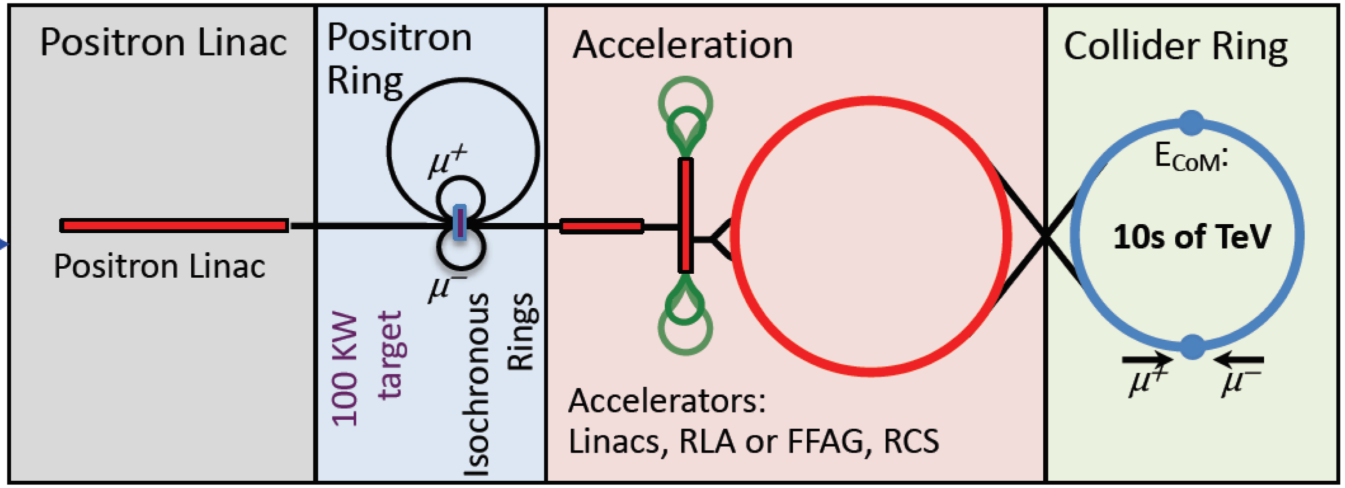
Might be best to use LHC tunnel to house muon accelerator and have dedicated new collider tunnel



Proposal to use LHC as last accelerator ring and collider ring (Neuffer/Shiltsev) might reduce cost but creates many specific challenges

The LEMMA Scheme

Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



Key concept:
Produce muon beam with low emittance using a positron beam
No cooling required

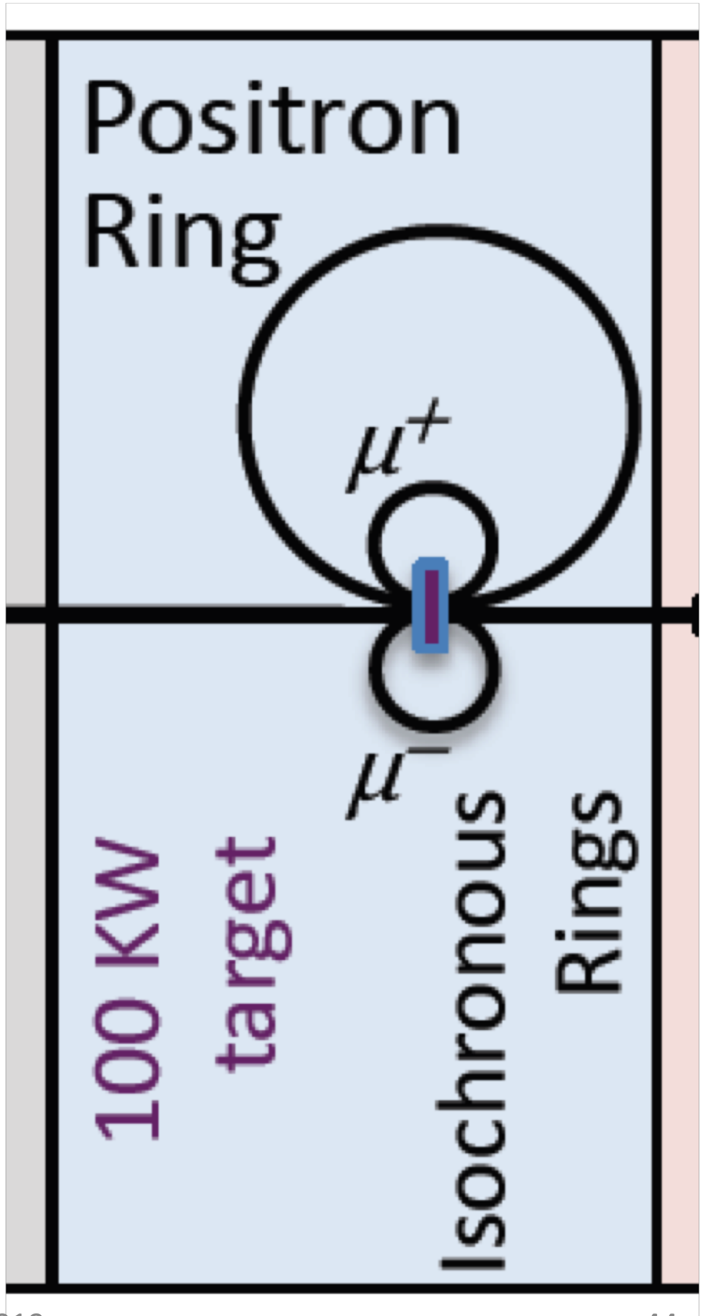
The LEMMA Scheme

Key concept (original numbers in brackets)

Produce muon beam with low emittance using a positron beam (40 nm vs. 25 μm in proton scheme)

- No cooling required, use lower muon current

- Positron beam (45 GeV, 3×10^{11} particles every 200 ns) passes through target and produces muon pairs
- Muon bunches are circulated through target O(2000) times accumulating more muons (4.5×10^{7})
- Every 0.5 ms, the muon bunches are extracted and accelerated
- They are combined in the collider ring, where they collide



Key Issues

Small efficiency of converting positrons to muon pairs

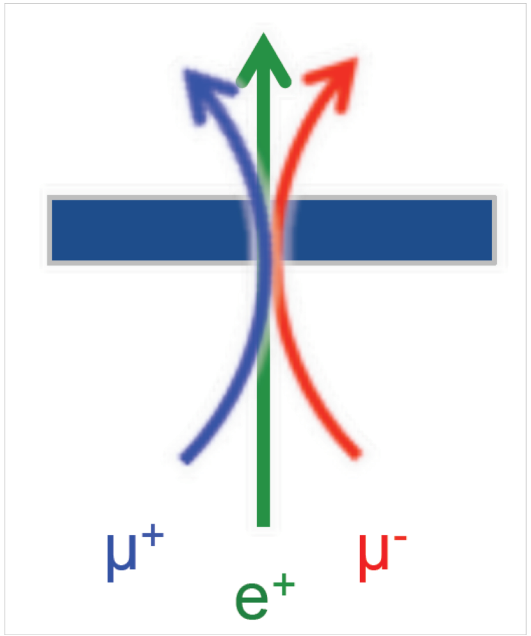
- Muon pair production is only small fraction of overall cross section ($O(10^{-5})$)
- Most positrons lost with no muon produced
- Have to produce many positrons (difficult)
- O(100MW) synchrotron radiation
- High heat load and stress in target (also difficult)

$$e^+e^- \rightarrow \mu^+\mu^-$$ O(1μb)

$$e^+e^- \rightarrow e^+e^-\gamma$$ O(100mb), $E_\gamma \geq 0.01\ E_p$

Two additional severe issues were identified

- The multiple scattering of the muons in the target
  - Theoretical best emittance of 600 nm instead of assumed 40 nm
  - Reduction of luminosity by factor 15
- Small bunches were accelerated and later merged but no design exists for the merger
  - The combination factor is proportional to beam energy
  - If the combination does not work, loose a large factor of luminosity



Working on a better design but have to wait and see the outcome

Ongoing LEMMA Effort

Address found issues

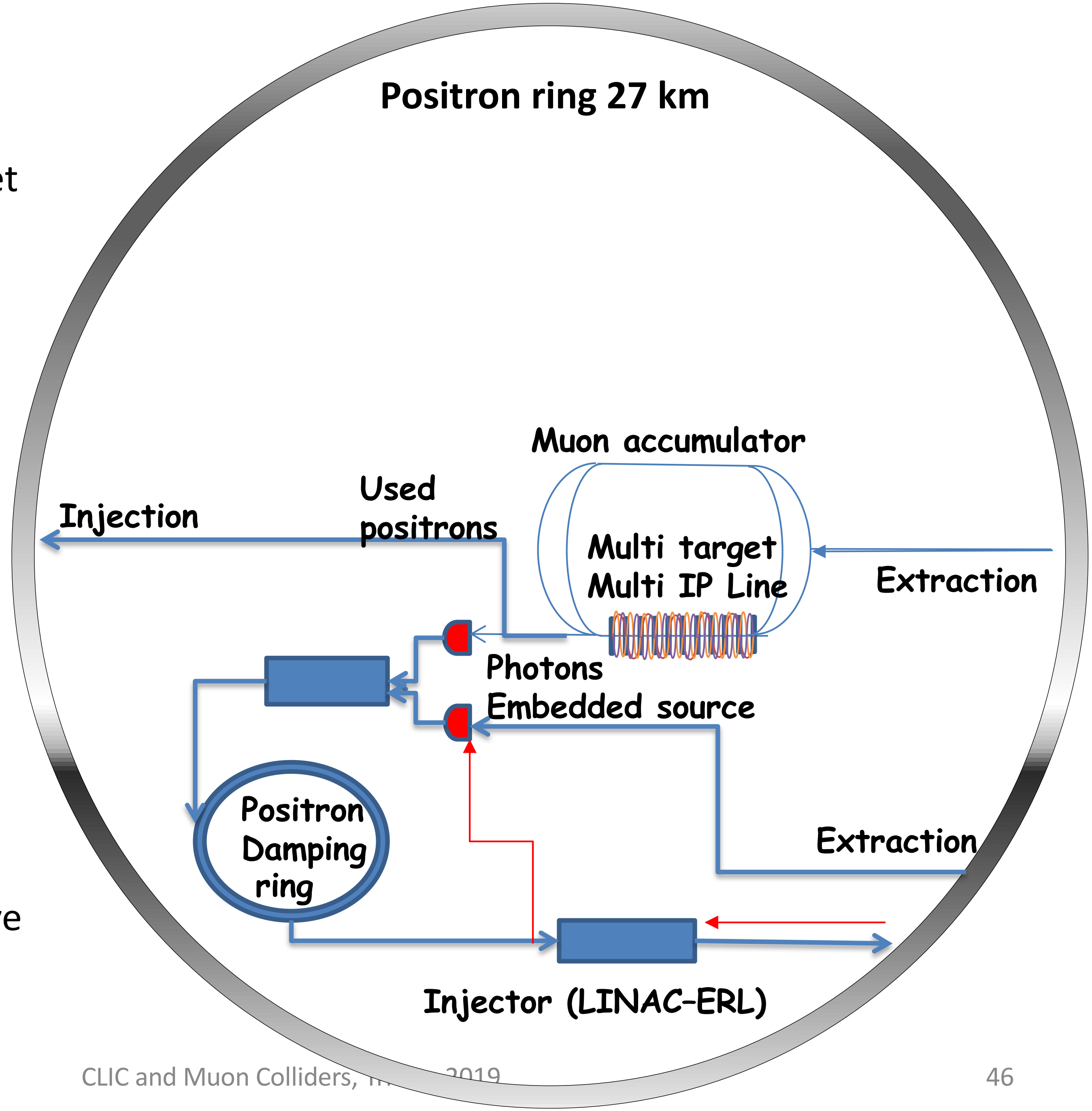
- Large emittance from target
    - use sequence of thin targets

- Difficulty of combining bunches at high energy
    - producing bunches in pulses fashion

- Positron ring challenge
    - larger ring

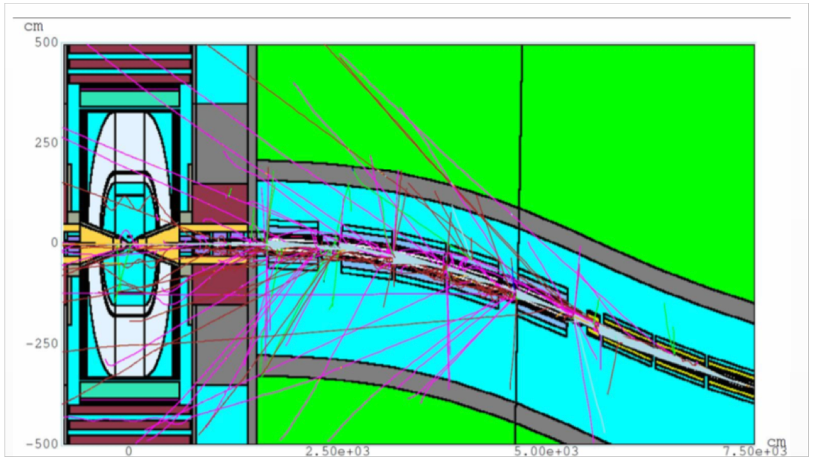
- Positron production
    - Improved concepts

Did not yet reach competitive performance
- but work is ongoing



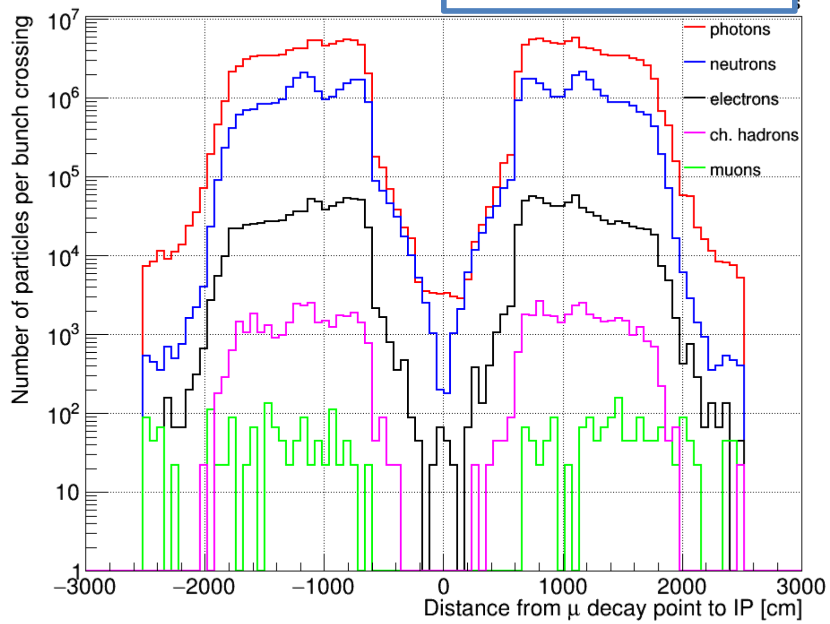
Beam induced background studies on detector at $\sqrt{s}$ =1.5 TeV

arXiv:1905.03725

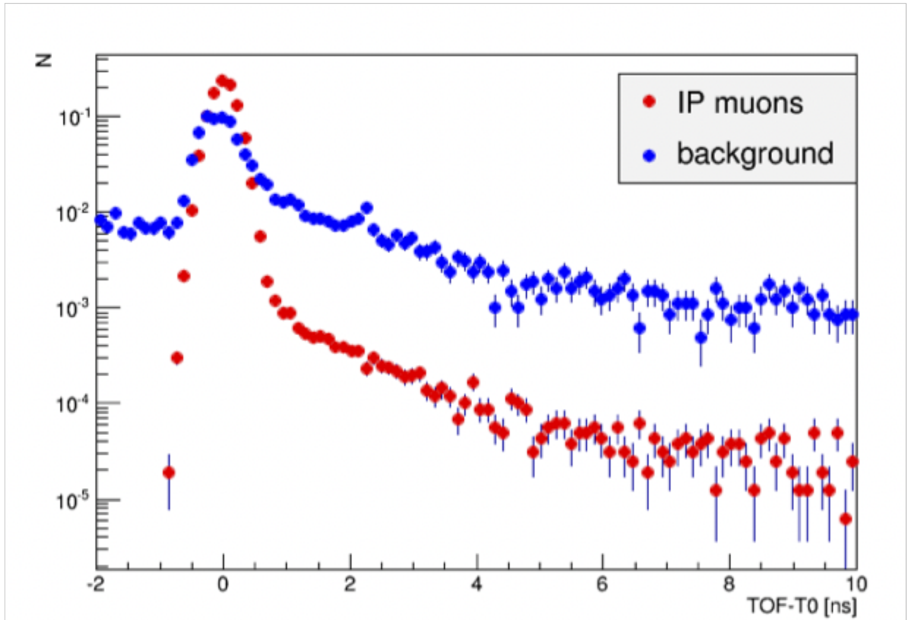


MARS15 simulation in a range of ±100 m around the interaction point

750 GeV beam



Particle composition of the beam-induced background as a function of the muon decay distance from the interaction point



Simulated time of arrival (TOF) of the beam background particles to the tracker modules with respect to the expected time (T0) of a photon emitted from IP

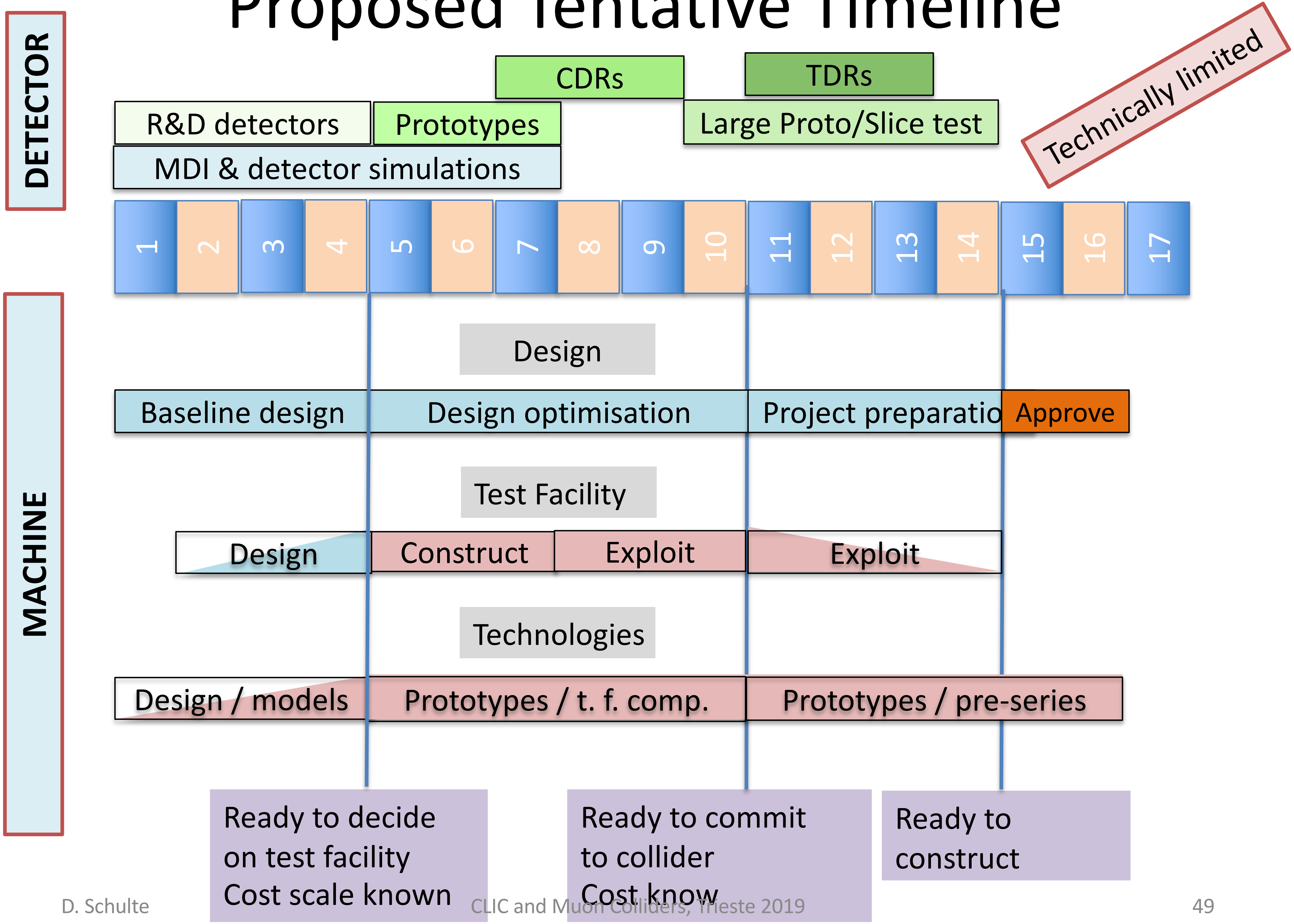
Conclusion on Muon Collider

- **Can muon colliders at this moment be considered for the next project?**
  - Enormous progress in the proton driven scheme and new ideas emerged
  - But at this moment not mature enough for a proposal

- **Is it worthwhile to do muon collider R&D?**
  - Yes, it promises the potential to go to very high energy
  - It may be the best option for very high lepton collider energies, beyond 3 TeV
  - It has strong synergies with other projects, e.g. magnet and RF development
  - Has synergies with other physics experiments
  - Should not miss this opportunity

- **What needs to be done?**
  - Set-up an international collaboration to promote muon colliders
  - Develop a muon collider concept based on the proton driver and considering the existing infrastructure.
  - Consolidate the positron driver scheme
  - Carry out the R&D program toward the muon collider.
    - Muon production and cooling is key => A new test facility is required.
    - A conceptual design of the collider has to be made
    - Many components need R&D, e.g. fast ramping magnets, background in the detector
    - Site-dependent studies to understand if existing infrastructure can be used
      - limitations of existing tunnels, e.g. radiation issues
      - optimum use of existing accelerators, e.g. as proton source

Proposed Tentative Timeline



Conclusion

CLIC is based on mature technology and can reach 3 TeV
An implementation in stages is foreseen

- 380 GeV
- 1.5 TeV
- 3 TeV

The cost of each stages is roughly equivalent to the LHC cost
The project is technically ready to produce a TDR and to start construction in several years

It is now up to the European Strategy for Particle Physics to decide how to continue with the project

The muon collider has promises to be able to go to multi-TeV energies
A baseline has to be developed
A test facility will be essential
Two approaches currently exist, the proton driver and the positron driver, which has to be consolidated

It is now up to the European Strategy for Particle Physics to define the priority of this R&D in preparation of the long-term future

Reserve

Comparison

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Key to Luminosity

$$\Delta \int \mathcal{L} \approx \sum_{i=0}^{\infty} \frac{\left(N_0 e^{-i\Delta t/\gamma\tau}\right)^2}{4\pi\sigma_x\sigma_y}$$

$$\sum_{i=0}^{\infty} \left(N_0 e^{-i\Delta t/\gamma\tau}\right)^2 \propto N_0^2 B$$

$$\Delta \int \mathcal{L} \propto \frac{BN_0^2}{4\pi\epsilon\beta/\gamma}$$

$$\beta \approx \sigma_z$$

$$\beta \propto \frac{1}{\gamma}$$

Note: this might be limited by technology

$$\frac{\sigma_E}{E} = \text{const}$$

$$\sigma_E \sigma_z = \text{const}$$

$$\sigma_z \propto \frac{1}{\gamma}$$

$$\Delta \int \mathcal{L} \propto B \frac{N_0^2 \gamma^2}{\epsilon}$$

$$\mathcal{L} \propto B \frac{N_0}{\epsilon} \gamma P_{beam}$$

Collider Parameter Examples

Muon Collider Parameters

		Higgs	**Multi-TeV**		
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Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
β^*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1.5	70	70	70
Bunch Length, σ_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Potential Approaches

Acceleration is important for cost and power consumption
No conceptual baseline design yet
But different options considered
A whole chain is needed from source to full energy

Recirculating linacs

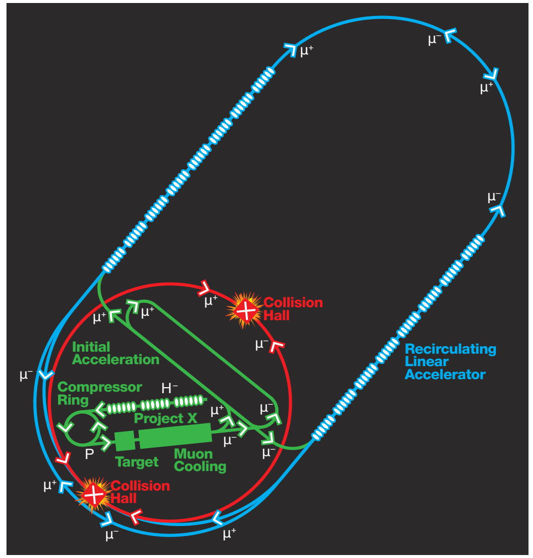
- Fast acceleration but typically only a few passages through RF, hence high RF cost

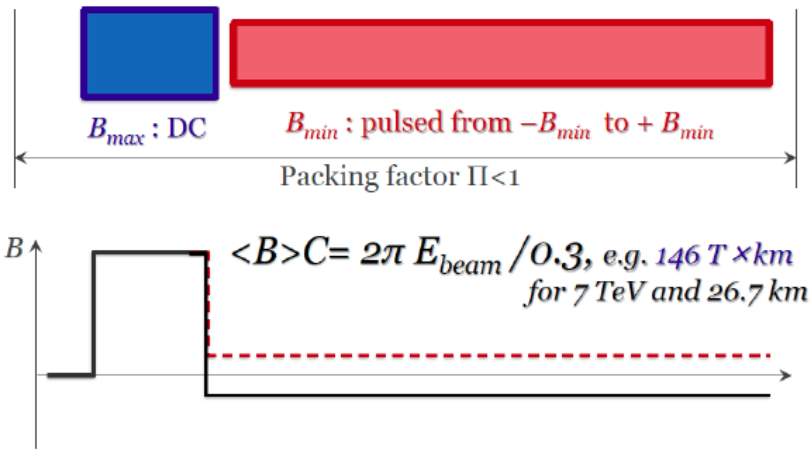
FFAGs

- Static magnets, but only limited increase in energy possible

Rapid cycling synchrotron (RCS)

- Potentially larger acceleration range at affordable cost
- Could use combination of static superconducting and ramping normal-conducting magnets
- But have to deal with energy in fast pulsing magnets



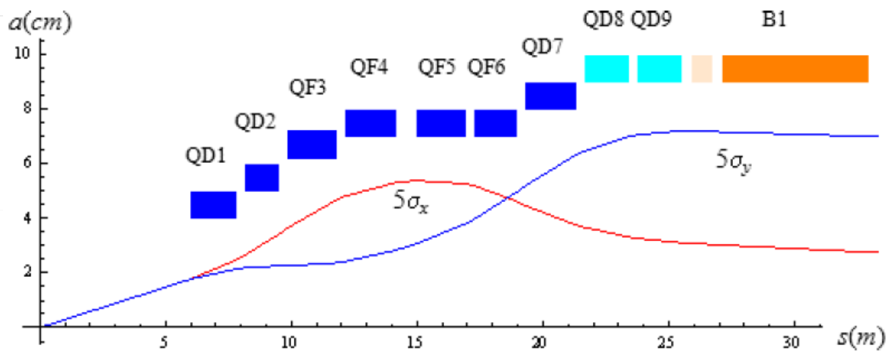


Challenge to achieve a combination of high efficiency, low cost and good beam quality

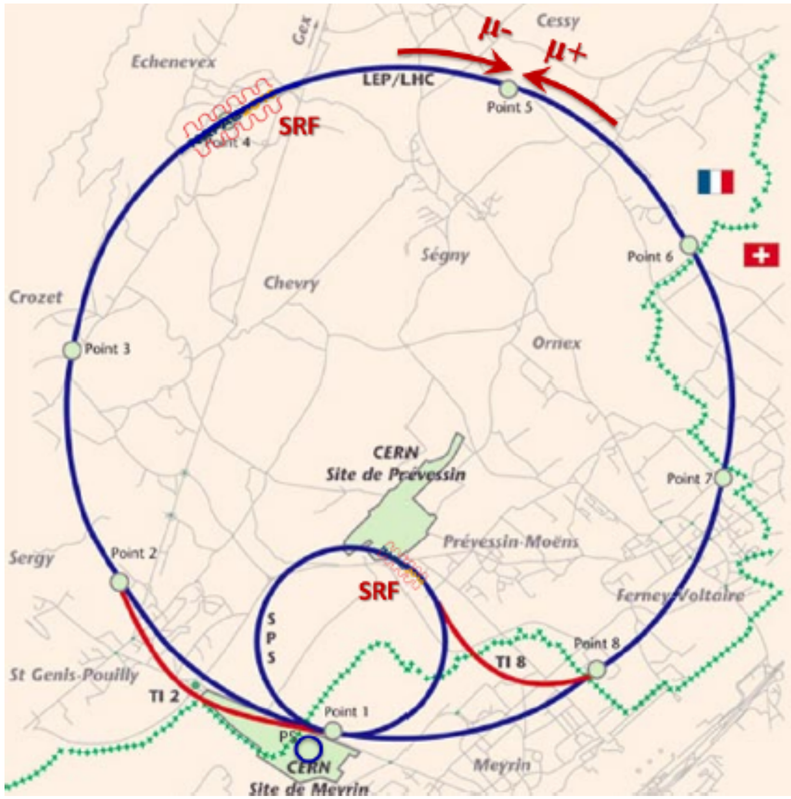
Collider Ring

Strong focusing at IP to maximise luminosity
Becomes harder with increasing energy

$$\beta \propto \frac{1}{\gamma}$$



High field dipoles to minimise collider ring size and maximise luminosity
Minimise distances with no bending



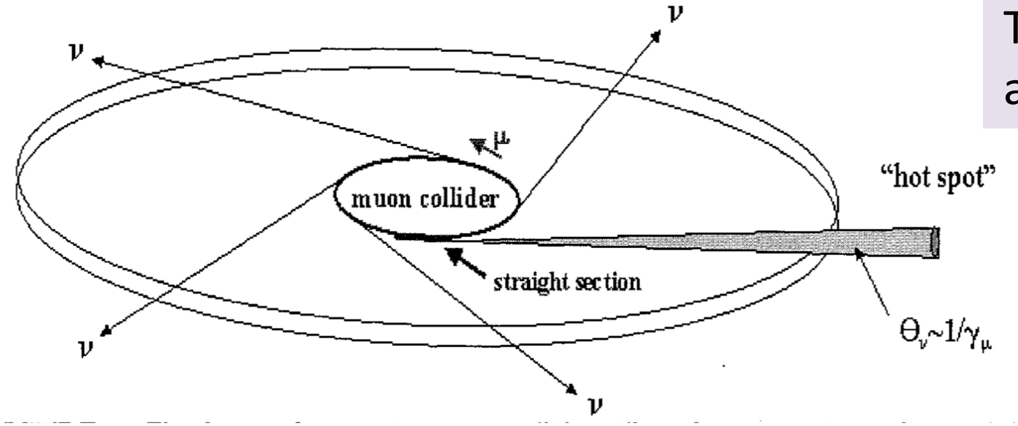
Proposal to combine last accelerator ring and collider ring (Neuffer/Shiltsev) might reduce cost but creates many specific challenges

Decaying muons impact accelerator components, detector and public
The latter becomes much worse with energy

Radiation to public in case LHC tunnel use

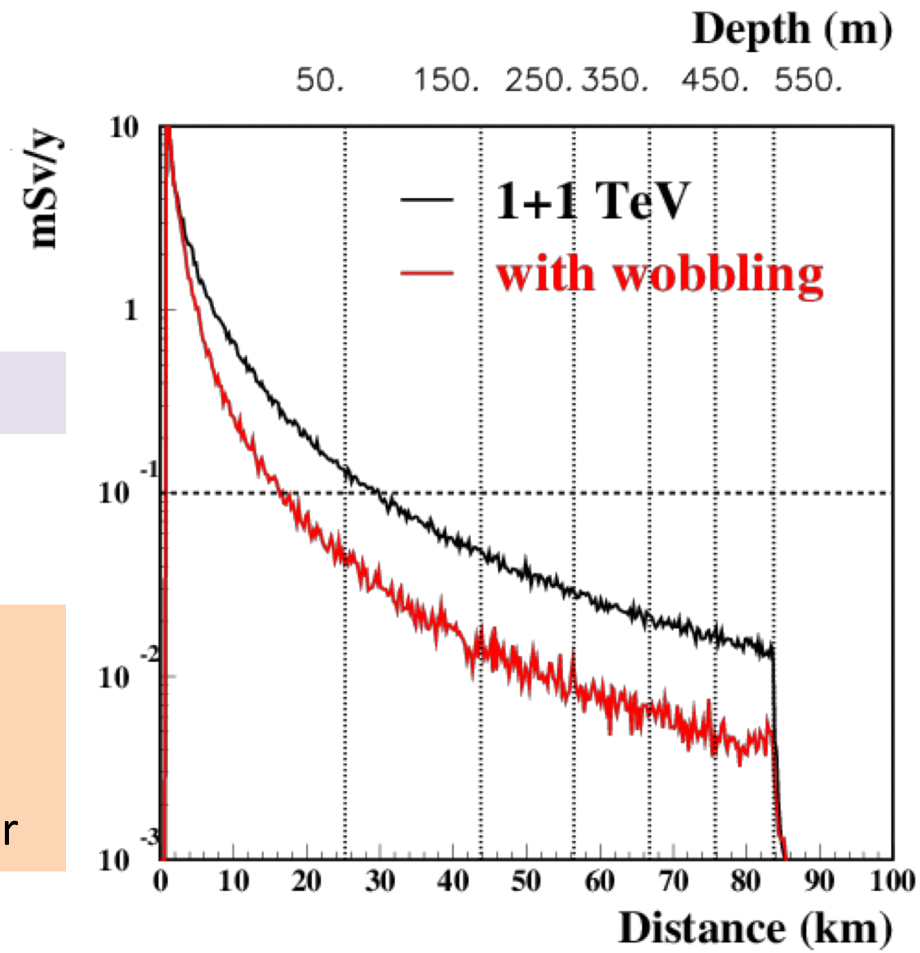
Might be best to use LHC tunnel to house muon accelerator and have dedicated new collider tunnel

Beam induced background studies
neutrino radiation hazard



The source, ring or section, is placed at the fixed depth of 550 m.

Ambient dose assuming 1.2×10^{21} decays/year



Need to study for higher energies (scaling E^3)

Straights in LHC might increase problem

⇒ Another reason to consider this as accelerator

Conclusion

We think we can answer the following questions

- **Can muon colliders at this moment be considered for the next project?**
  - Enormous progress in the proton driven scheme and new ideas emerged
  - But at this moment not mature enough for a proposal

- **Is it worthwhile to do muon collider R&D?**
  - Yes, it promises the potential to go to very high energy
  - It may be the best option for very high lepton collider energies, beyond 3 TeV
  - It has strong synergies with other projects, e.g. magnet and RF development
  - Has synergies with other physics experiments
  - Should not miss this opportunity

- **What needs to be done?**
  - Muon production and cooling is key => A new test facility is required.
  - A conceptual design of the collider has to be made
  - Many components need R&D, e.g. fast ramping magnets, background in the detector
  - Site-dependent studies to understand if existing infrastructure can be used
    - limitations of existing tunnels, e.g. radiation issues
    - optimum use of existing accelerators, e.g. as proton source

Recommendations

Set-up an international collaboration to promote muon colliders and organize the effort on the development of both accelerators and detectors and to define the road-map towards a CDR by the next Strategy update.

Develop a muon collider concept based on the proton driver and considering the existing infrastructure.

Consolidate the positron driver scheme addressing specifically the target system, bunch combination scheme, beam emittance preservation, acceleration and collider ring issues.

Carry out the R&D program toward the muon collider. Based on the progress of the proton-driver and positron-based approaches, develop hardware and research facilities as well as perform beam tests. Preparing and launching a conclusive R&D program towards a multi-TeV muon collider is mandatory to explore this unique opportunity for high energy physics. A well focused international effort is required in order to exploit existing key competences and to draw the roadmap of this challenging project. The development of new technologies should happen in synergy with other accelerator projects. Moreover, it could also enable novel mid-term experiments.

Muon Collider Working Group Findings

Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration.

The development of the challenging technologies for the frontier muon accelerators has shown enormous progress in addressing the feasibility of major technical issues with R&D performed by international collaborations.

In Europe, the reuse of existing facilities and infrastructure for a muon collider is of interest. In particular the implementation of a muon collider in the LHC tunnel appears promising, but detailed studies are required to establish feasibility, performance and cost of such a project.

A set of recommendations at the end will allow to make the muon collider technology mature enough to be favorably considered as a candidate for ehigh-energy facilities in the future.