Future Accelerator Machines and R&D

D. Schulte, CERN

Overview

Following the charge, I will cover the main future projects with a collaboration pushing forward

Circular colliders:

- FCC (Future Circular Collider)
- CEPC / SppC (Circular Electron-positron Collider/Super Proton-proton Collider)

Linear colliders

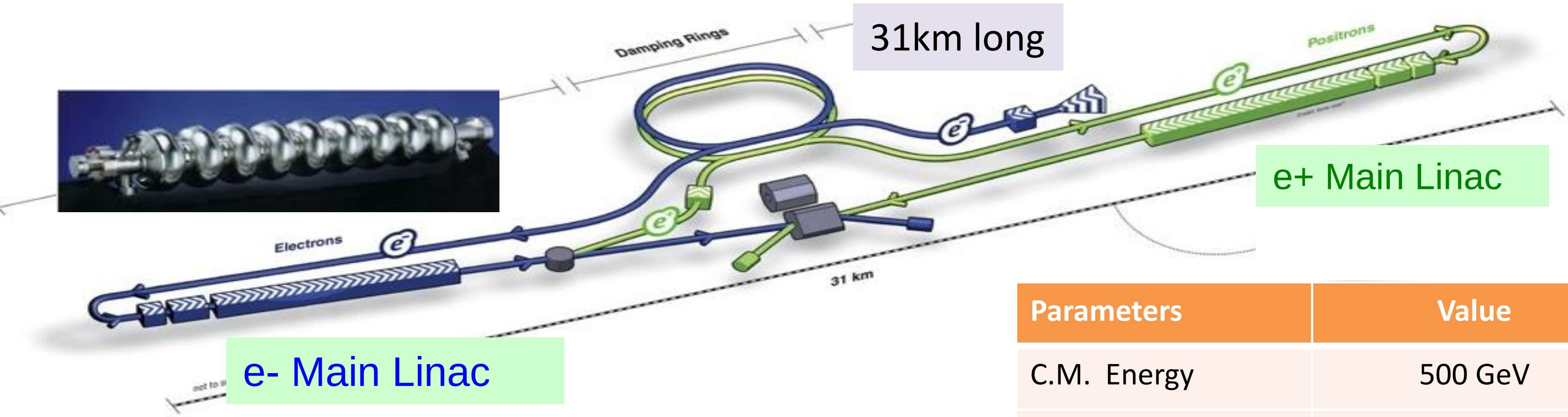
- ILC (International Linear Collider)
- CLIC (Compact Linear Collider)

Others will not be covered

- Detectors, physics, …
- Muon collider, effort strongly reduced but some recent progress with the source (MICE and novel idea)
- Photon-photon collider
- Gamma factory based on ions
- …

ILC

31km long



e+ Main Linac

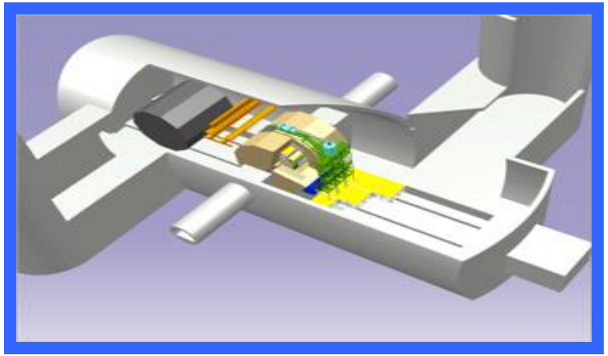
e- Main Linac

Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	**31.5** MV/m +/-20% Q_0 = 1E10

TDR exists

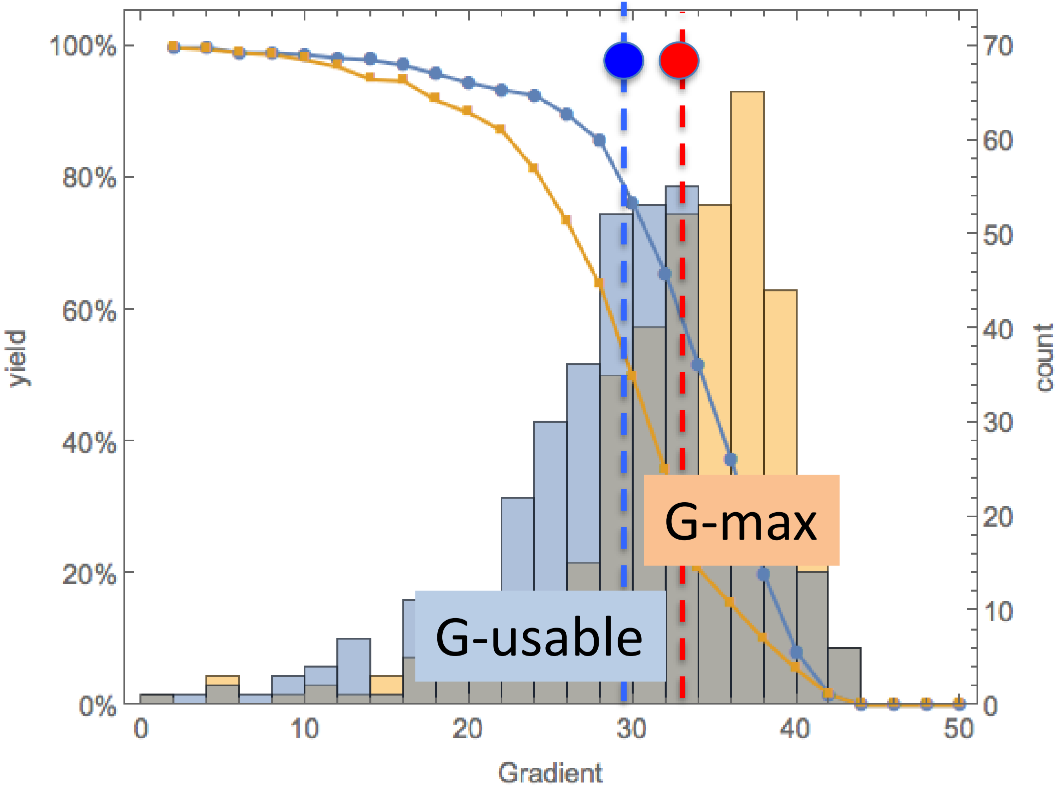
Aim for cost reduction

Political process in Japan ongoing



ILC Cavities

N. Walker, D. Reschke, SRF'15



800 cavities produced for European XFEL

Goal 24 MV/m

In vertical test stand (one Vendor):
Average gradient for $Q_0 > 10^{10}$
G = 29.4 MV/m

ILC goal 31.5 MV/m installed

ILC Development

L. Evans
A. Yamamoto

Cost saving studies, e.g.

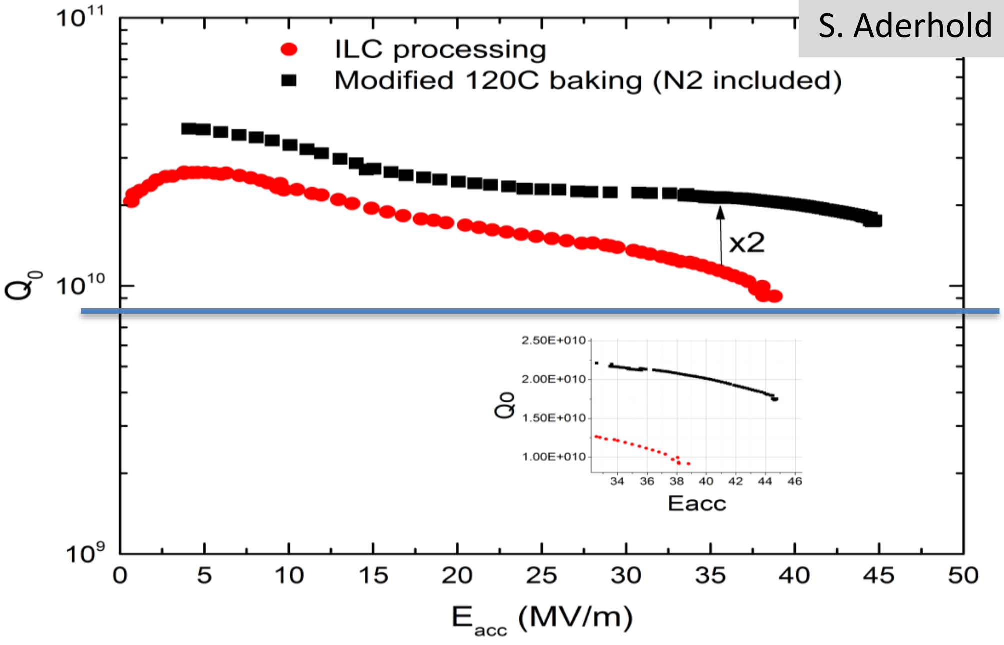
- Coupler design 1-2%
- Cavity material 2-3%
- No more hydrofluoric acid for chemical treatment 1-2%
- Higher gradient and more efficient cavities 4-5%
- …

Modified exposure to nitrogen (from FNAL)
Before: doping with few minutes at 800 °C
Now: a day or so at 120 °C

Nitrogen infusion appears very promising

- Increase in gradient
- Increase in Q_0

A. Grassellino,
S. Aderhold



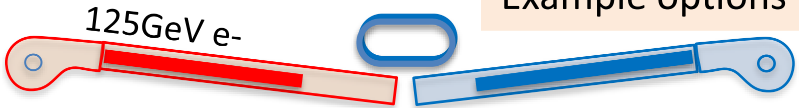
ILC Staging Scenarios

Technical improvements can decrease cost by 10-20%

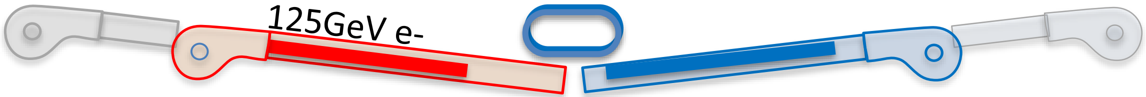
More seems to be required, so staging is being considered

Example options

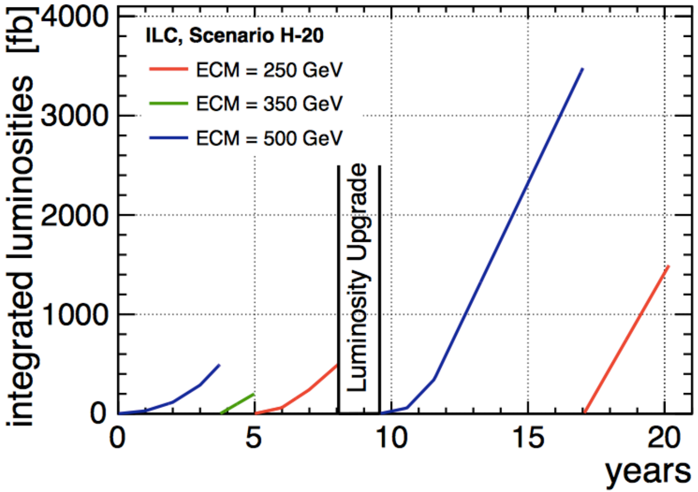
Option C:



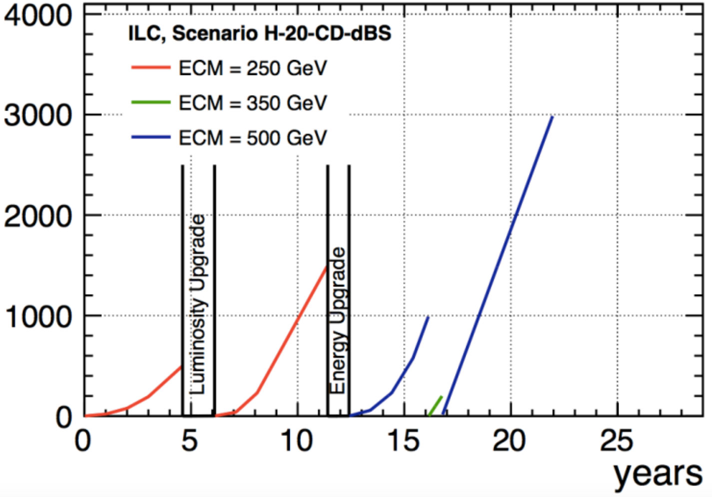
Option D:



Baseline 500 GeV running example



Example: 250 GeV (F) and upgrade

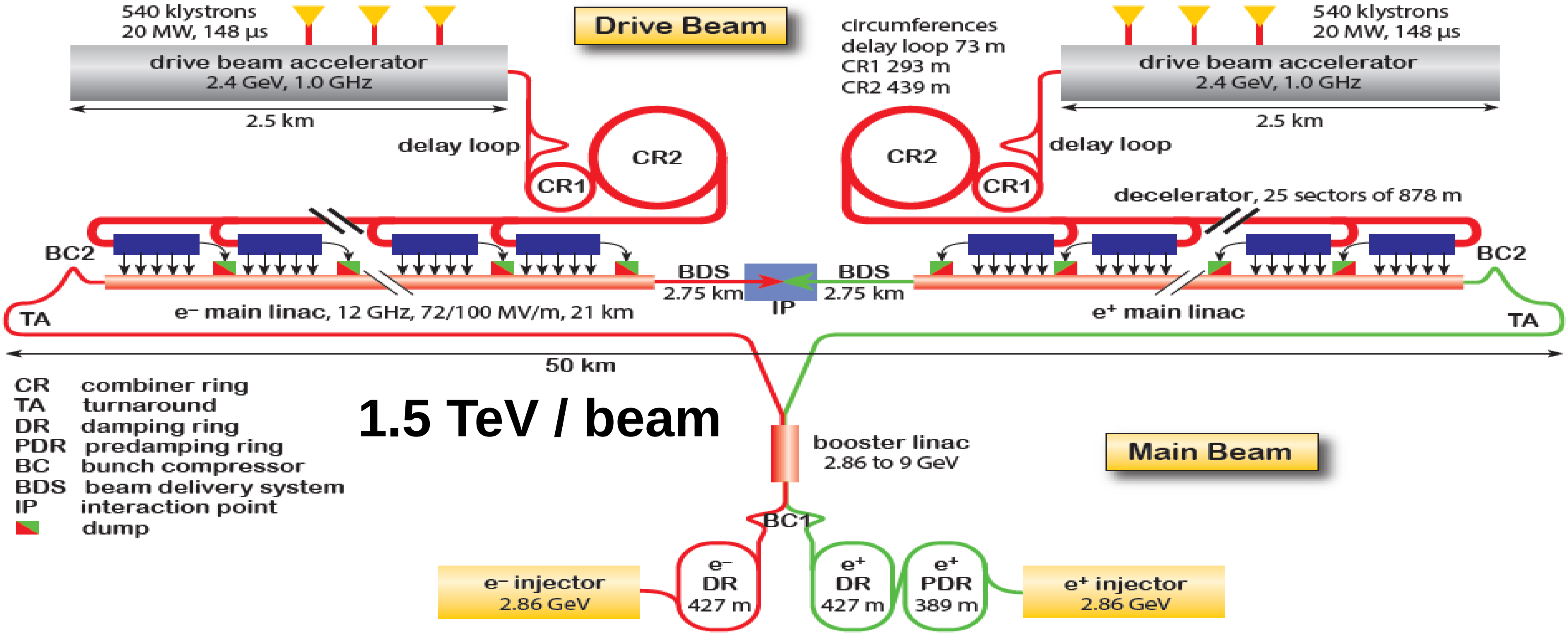


Goal:
4 ab^{-1} @ 500 GeV
100 fb^{-1} @ 350 GeV
2 ab^{-1} @ 250 GeV

Luminosity increase

- 2 x by increasing RF
- 2 x by increasing cryogenics and repetition rate

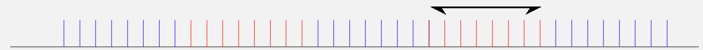
CLIC (3 TeV)



540 klystrons
20 MW, 148 μs
Drive Beam
circumferences
delay loop 73 m
CR1 293 m
CR2 439 m
540 klystrons
20 MW, 148 μs
drive beam accelerator
2.4 GeV, 1.0 GHz
drive beam accelerator
2.4 GeV, 1.0 GHz
2.5 km
2.5 km
delay loop
CR2
CR1
CR2
CR1
delay loop
decelerator, 25 sectors of 878 m
BC2
BDS
2.75 km
IP
BDS
2.75 km
BC2
TA
e⁻ main linac, 12 GHz, 72/100 MV/m, 21 km
e⁺ main linac
TA
50 km
CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump
1.5 TeV / beam
booster linac
2.86 to 9 GeV
Main Beam
BC1
e⁻ injector
2.86 GeV
e⁻
DR
427 m
e⁺
DR
427 m
e⁺
PDR
389 m
e⁺ injector
2.86 GeV

CLIC (3 TeV)

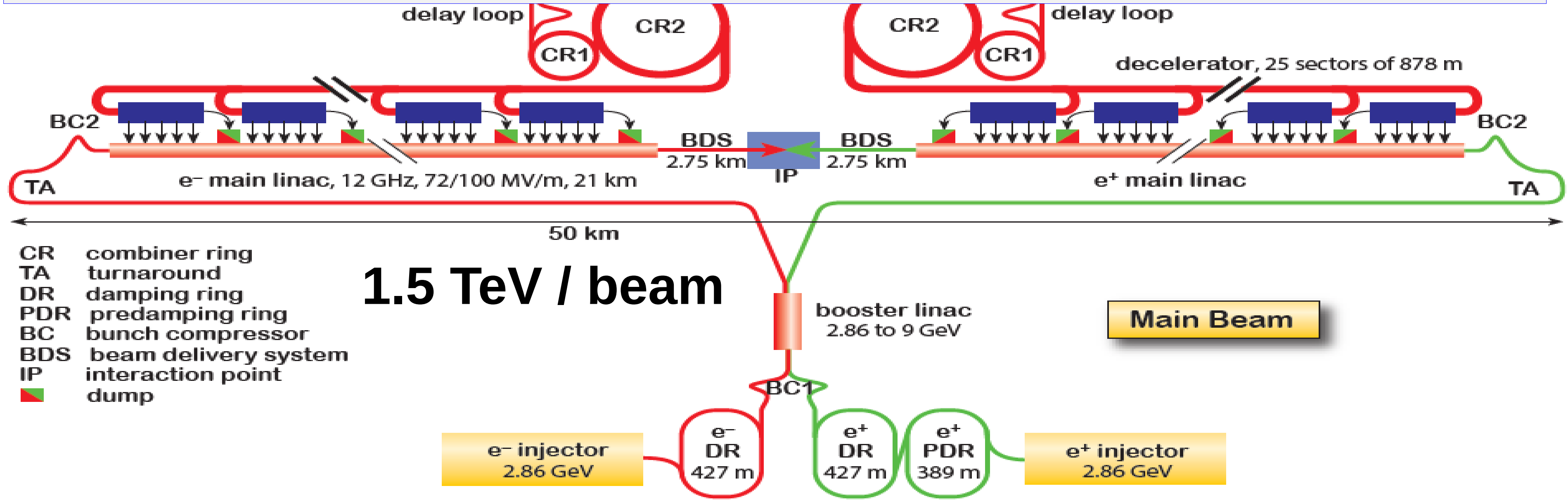
Drive beam time structure - initial



140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final

24 pulses – 101 A – 2.5 cm between bunches

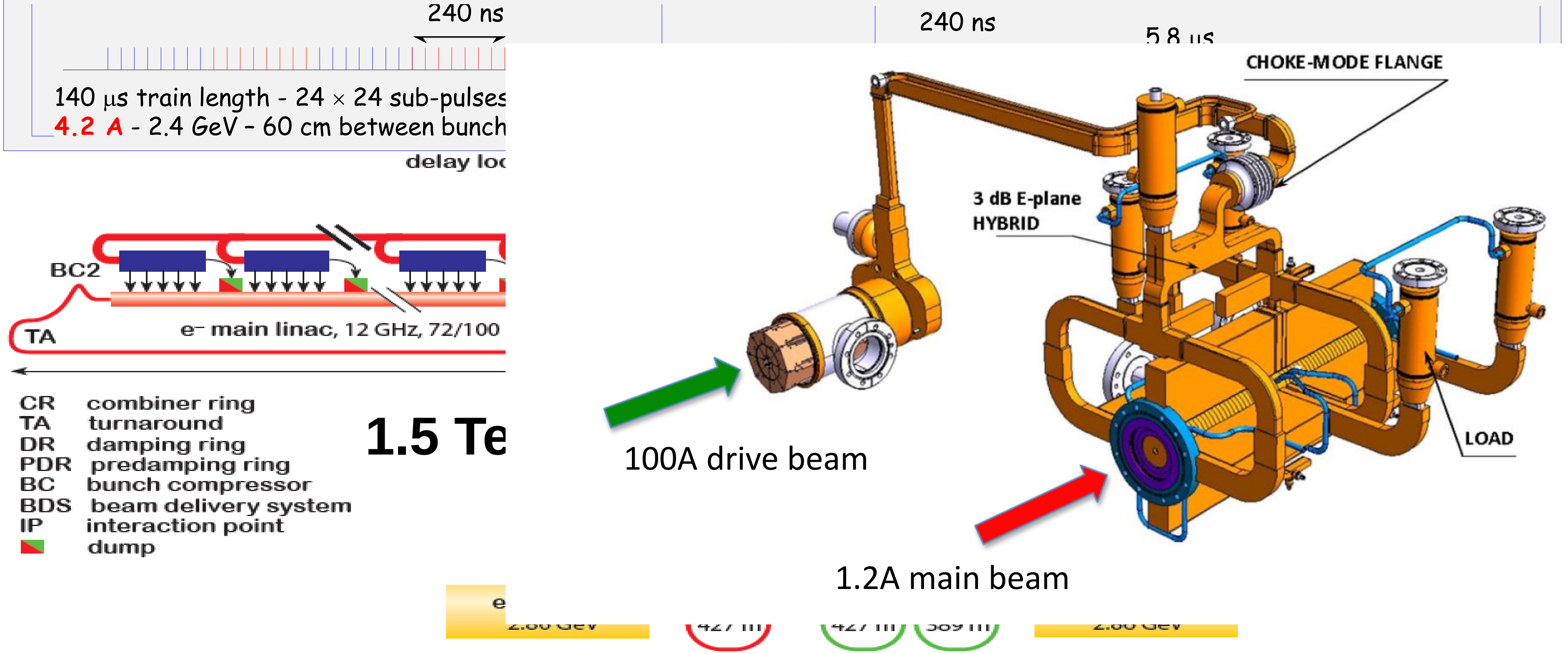


1.5 TeV / beam

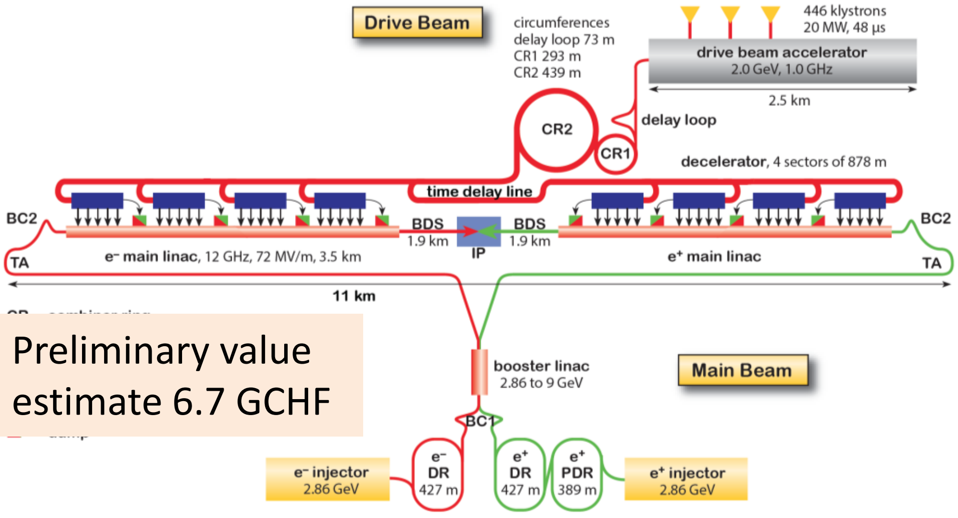
CLIC (3 TeV)

Drive beam time structure - initial

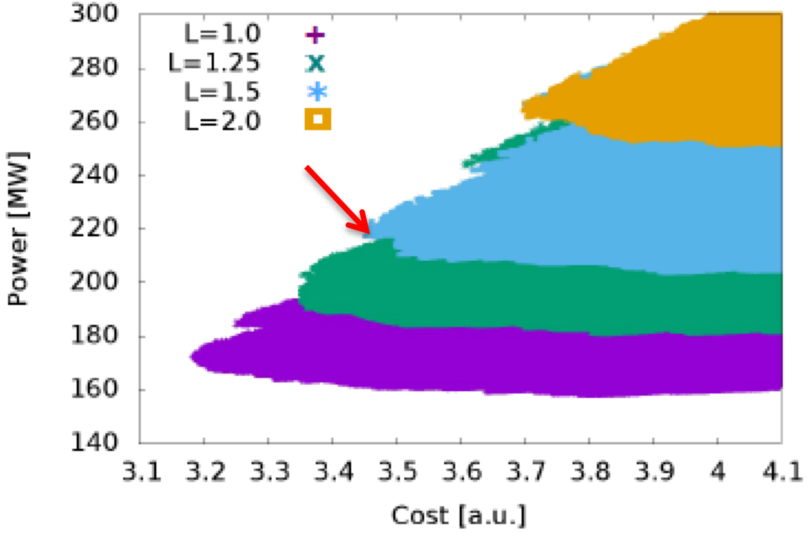
Drive beam time structure - final



Plenty of good physics at lower energies
⇒ First stage at 380 GeV
⇒ HZ, WW fusion, top asymmetry
Further stages re-use infrastructure and equipment



Preliminary value estimate 6.7 GCHF

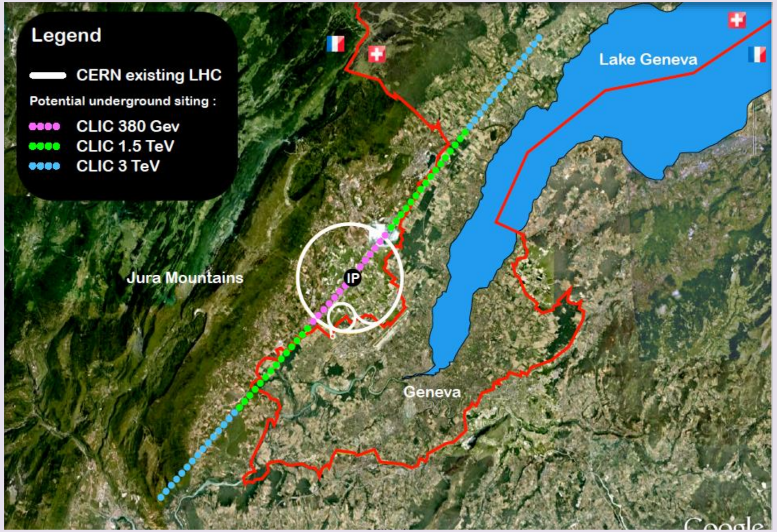


Parameter	unit	380 GeV	3 TeV
L	10^{34} cm^{-2}s^{-1}	1.5	5.9
G	MV/m	72	72/100
Length	km	11	50

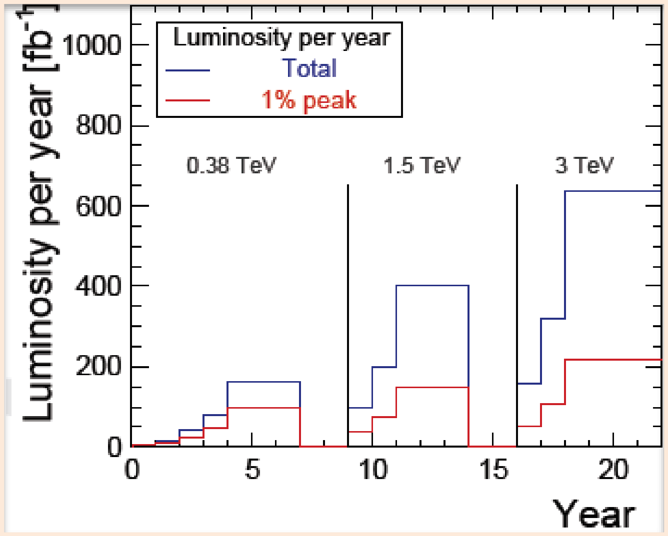
CLIC Staged Scenario

Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{int}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

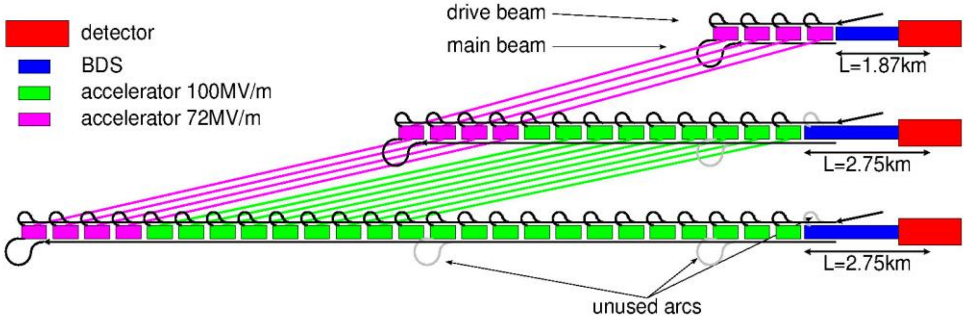
Luminosity targets from Physics Study group
Hopefully input from LHC



Central complex on Prevessin site



Luminosity evolution



CLIC Roadmap

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

S. Stapnes

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

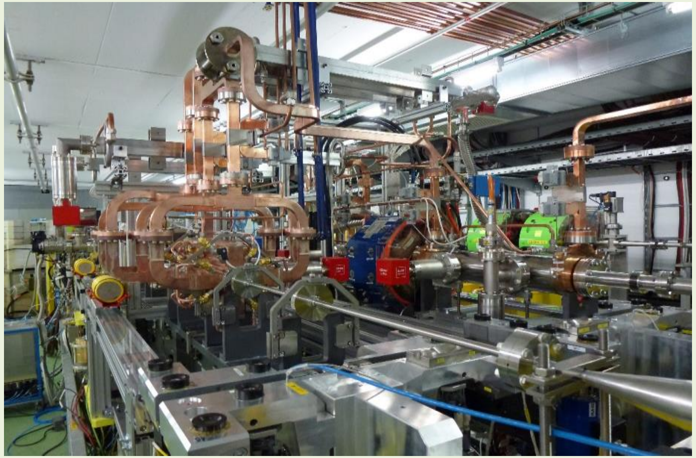
2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

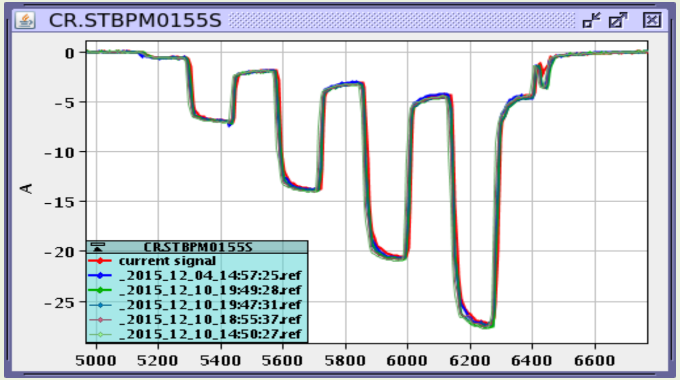
From CTF3 to CLEAR



CTF3 has demonstrated drive beam production and main beam acceleration

- Technology
- Beam quality
- Operation

Closed end 2016



New facility is coming online: CLEAR
CERN Linear Electron Accelerator for Research

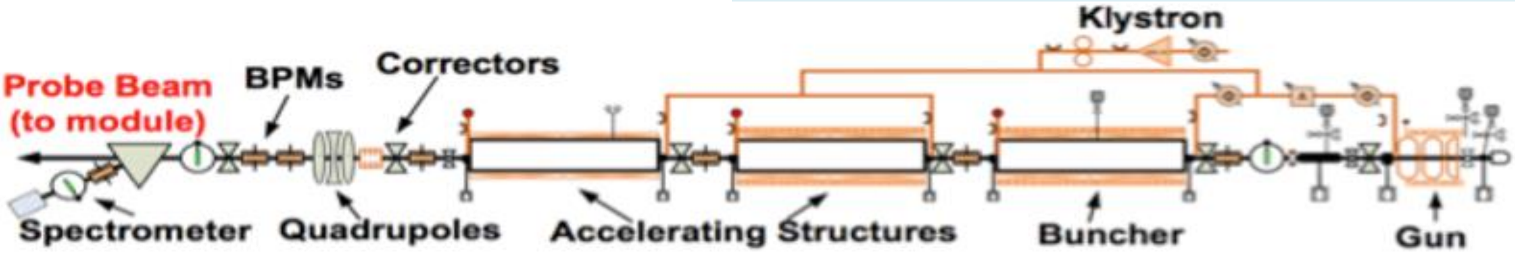
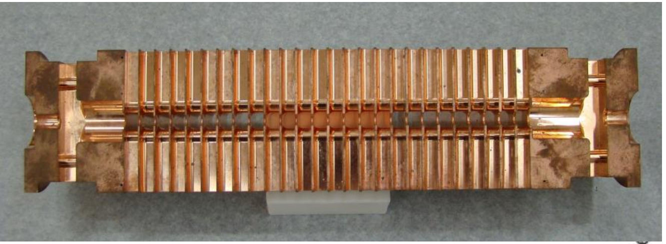


Figure 1: The current CALIFES beam line. The length of the facility (as shown) is ~20m.

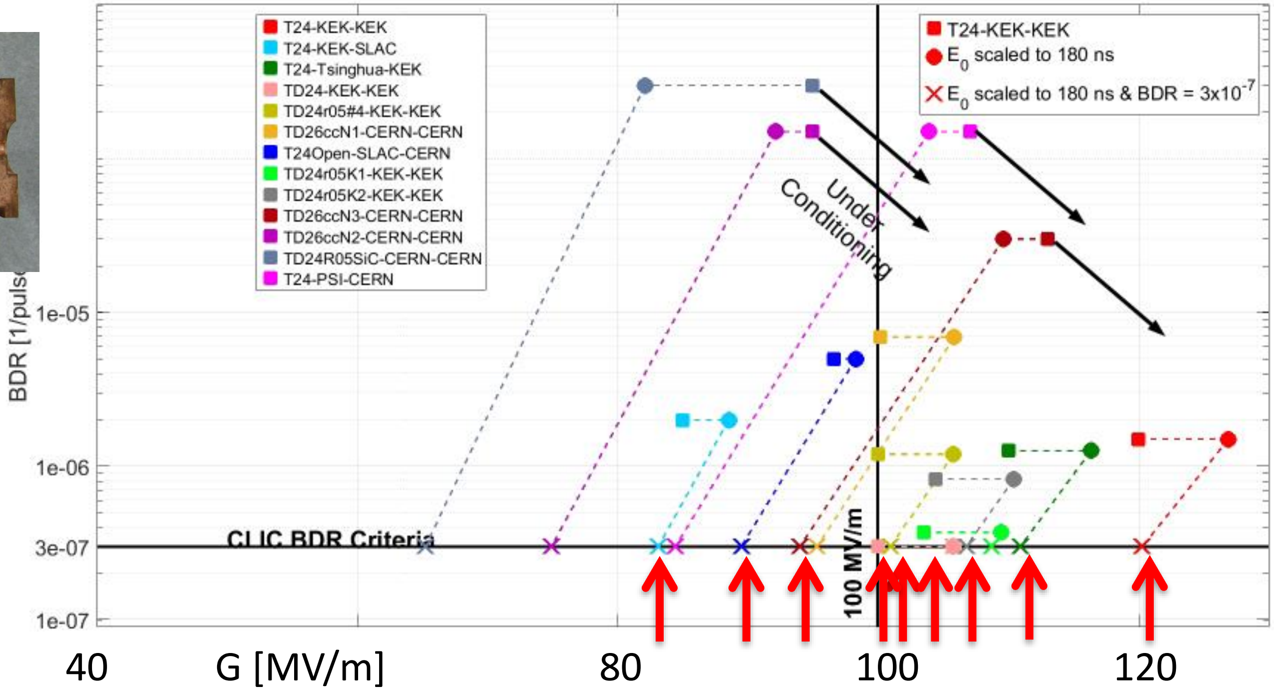
CLIC X-band Structure Development



Further development and industrialisation of accelerating structures is ongoing

Several klystron-based test stands exist that test structures (X-boxes)

Conditioning procedure is being optimised



Growing interest in X-band (FELs, novel technologies, …)

- DESY, PSI, INFN, Cockcroft, …
- CompactLight proposal to EU, 24 partners

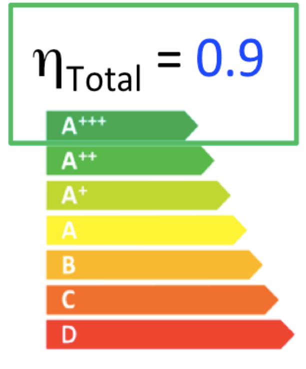
Other CLIC Technology Development

I. Syratchev et al.

Redesign CLIC modulators and klystrons

Increase efficiency from 62% to 90%

Reduce cost (low voltage, no oil)



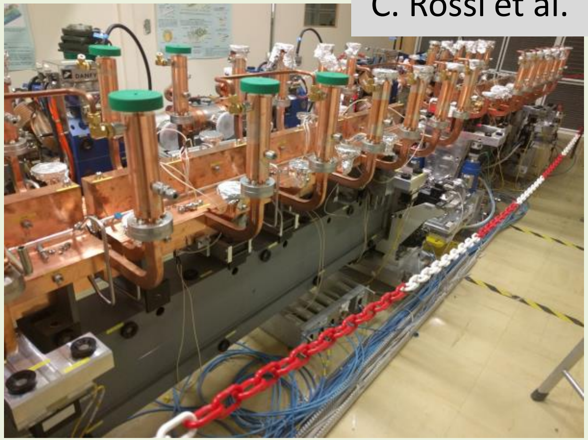
Permanent magnets

Use tunable permanent magnets where possible

- Quadruoles in drive beam
- Strongest permanent magnet developed in UK

J. Clarke et al.

C. Rossi et al.



New module design

Reduce cost of mechanical system and control

Klystron-based first energy stage

As alternative

Main beam injector

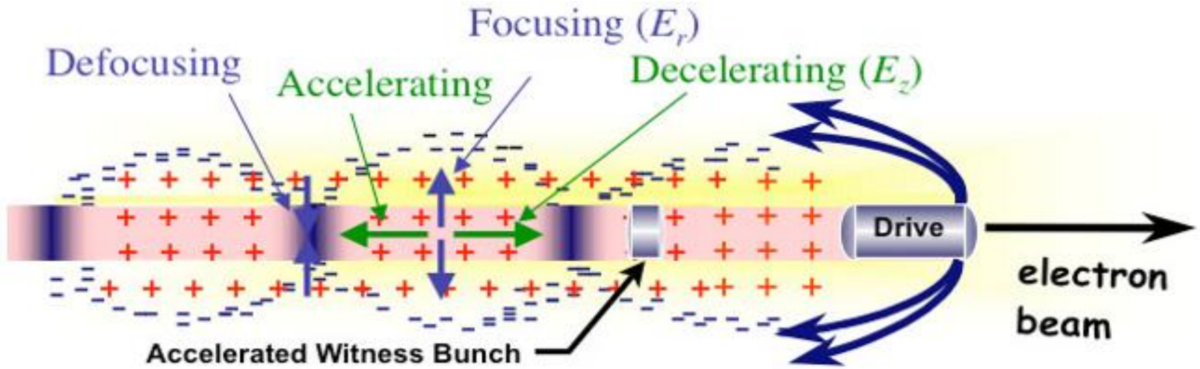
e.g. halved power for positron production

Plasma Acceleration as Upgrade Option?

Very high gradients of 50 GV/m demonstrated

Can use laser or particle beam to generate field

R&D programmes are ongoing



Require excellent beam quality and high efficiency

- Preservation of beam quality during acceleration has to be studied in theory and experimentally
- This is particularly tough for high efficiency

Application of novel technologies to colliders

- Started a working group for CLIC to understand potential
- Plasma community started a working group on colliders

FCC and CEPC/SppC

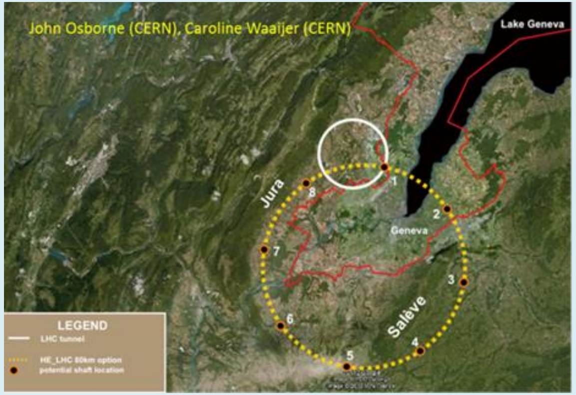
Proposal for project at CERN
- CDR for EU strategy end 2018

FCC-hh
- pp collider with 100 TeV cms
- Ion option
- Defines infrastructure

FCC-ee
- Potential e^+e^- first stage

FCC-eh
- additional option

HE-LHC
- LHC with high field magnets

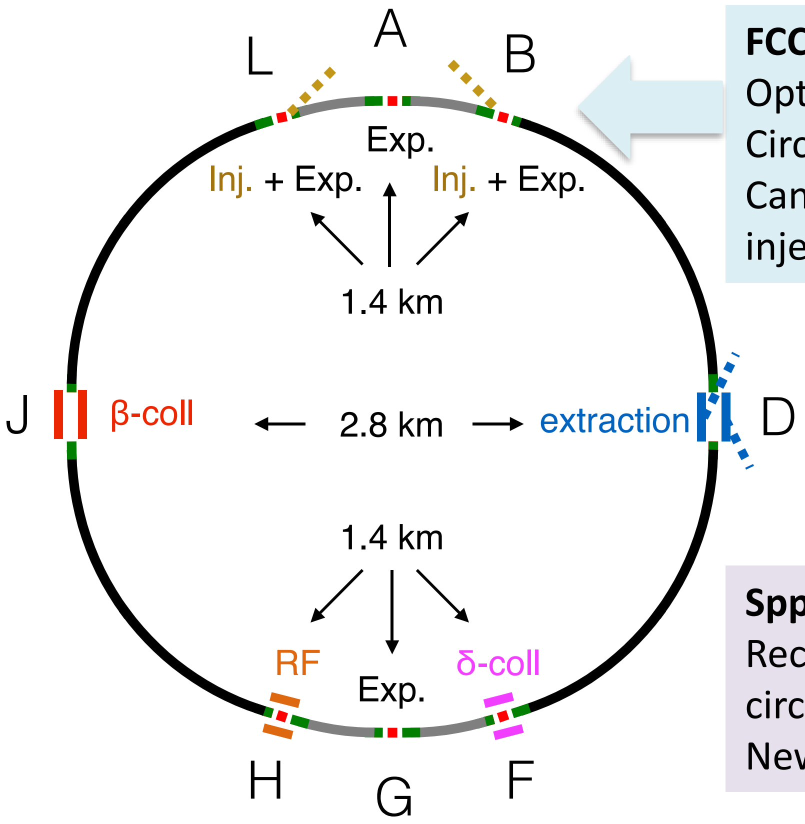


Proposal for project in China
- CDRs exist but changes since

CEPC
- e^+e^- collider 90-240 GeV
- focus on higgs

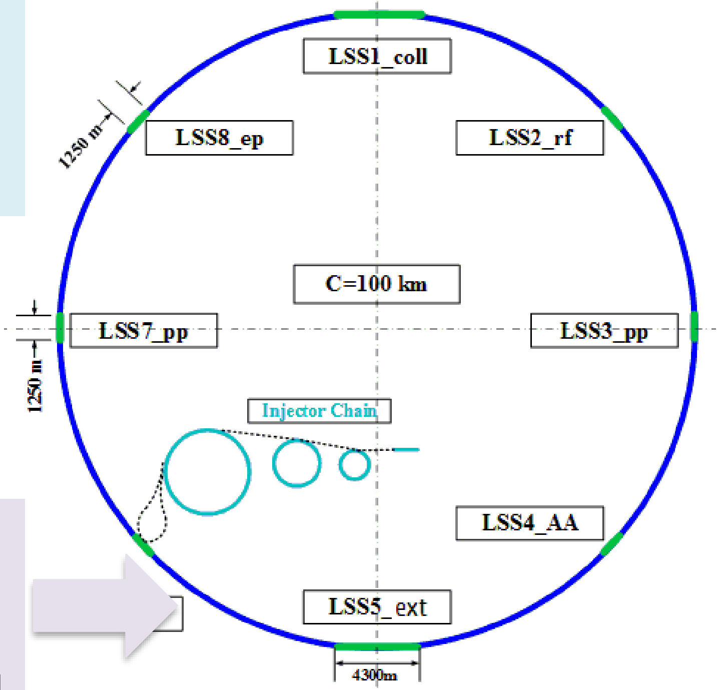
SppC
- Hadron collider to later be installed in the same tunne 75 to O(150) TeV

FCC-hh / SppC Layouts



FCC-hh layout
Optimised for Geneva site
Circumference 97.75 km
Can use LHC or SPS as injector

SppC layout
Recently adopted 100 km circumference
New injectors are required



Hadron Collider Parameters

	LHC (HL-LHC)	HE-LHC (tentative)	FCC-hh Baseline	FCC-hh Ultimate	SppC	SppC ultimate
Cms energy [TeV]	14	27	100	100	75	150
Luminosity [$10^{34} cm^{-2} s^{-1}$]	1 (5)	25	5	< 30	10	?
Machine circumference	27	27	97.75	97.75	100	100
Arc dipole field [T]	8	16	16	16	12	24
Bunch distance [ns]	25	25 (5)	25	25 (5)	25 (10/5)	?
Background events/bx	27 (135)	800 (160)	170	< 1020 (< 202)	490 (196/98)	?
Bunch length [cm]	7.5	7.5	8	8	7.55	?

FCC integrated luminosity goal is 17.5 ab^{-1}
L^{*}= 40 m

5 ns to limit background, but more challenging and will lose some luminosity

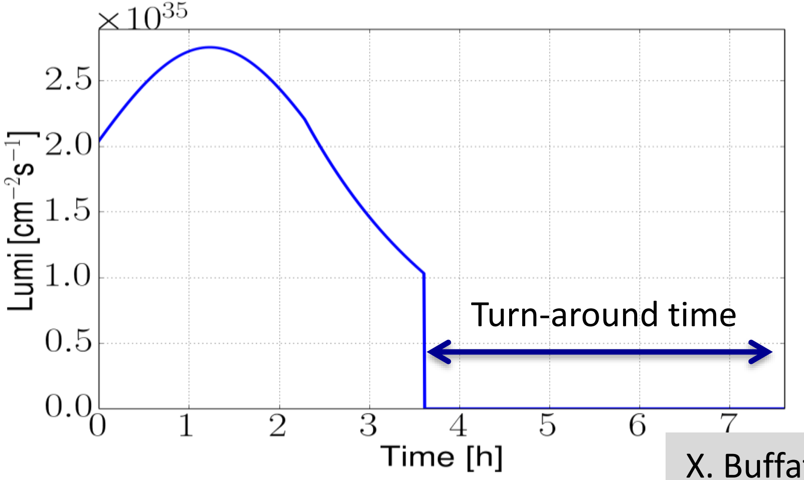
Luminosity Evolution (FCC-hh)

Significant damping of the proton beam

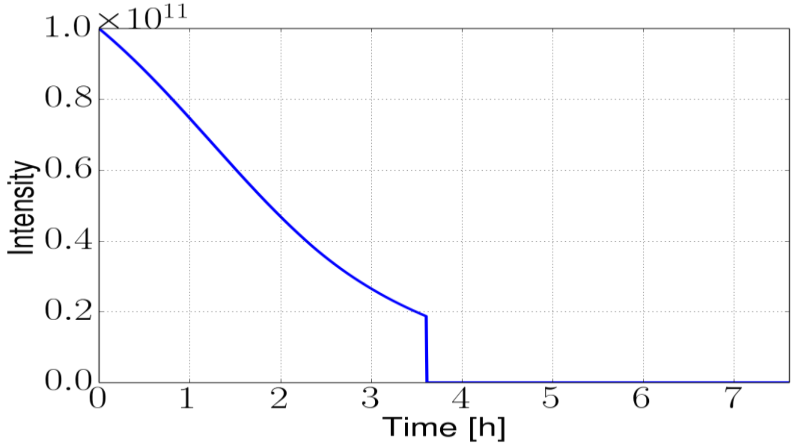
Burn beam rapidly

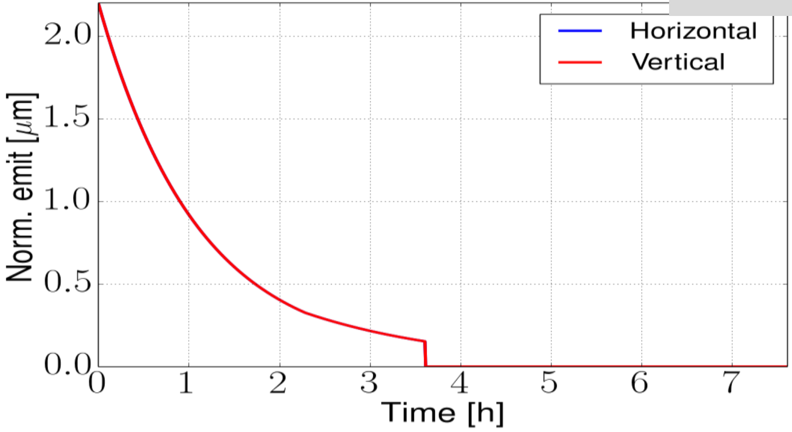
Have to inject enough beam

Can consider luminosity levelling



X. Buffat, D.S.





FCC-hh Magnet Development

FCC goal is 16 T operating field
- Requires to use Nb_3Sn technology
- At 11 T used for HL-LHC

$\Rightarrow$ Strong synergy with HL-LHC

Key cost driver
16 T demonstrated in coil
Hope for US model test early 2018: 14-15 T
Short magnet models in 2018 – 2023
12 T for HL-LHC

R&D on cables in test stand at CERN

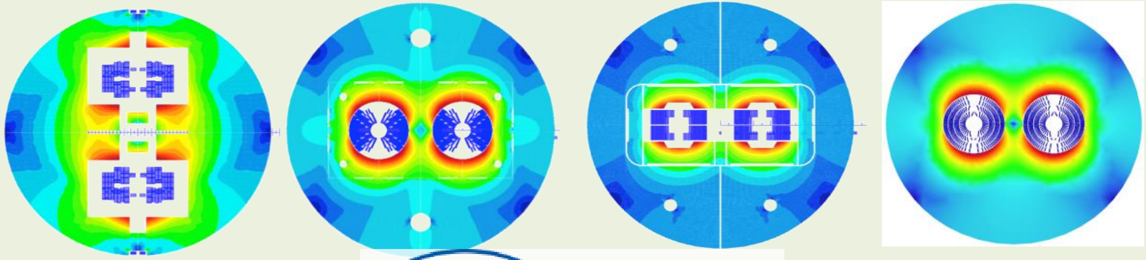
Target: $J_C > 2300$ A/mm^2 at 1.9 K and 16 T (**50% above HL-LHC**)

Industrial fabrication:
Target cost: 3.4Euro/kAm

Magnet design to **minimise material** use and limit margins to essential level

D. Tommasini at al.

Common coils | Cos-theta | Blocks | Canted Coil



CIEMAT, CEA, INFN

EuroCirCol – A key to New Physics

Swiss contribution via PSI

FCC-hh Magnet Development

FCC goal is 16 T operating field
- Requires to use Nb_3Sn technology
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⇒ Strong synergy with HL-LHC

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R&D on cables in test stand at C

Target: $J_C > 2300$ A/mm^2 at 1.9 K and 16 T (**50% above HL-LHC**)

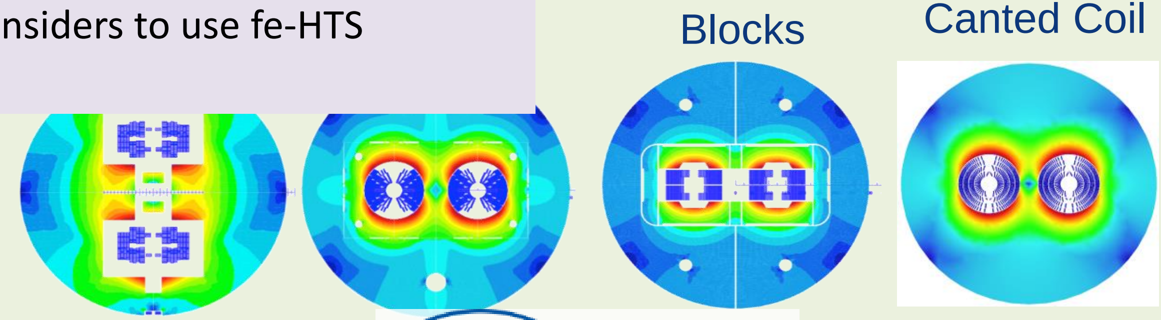
Industrial fabrication:
Target cost: 3.4Euro/kAm

High-temperature superconductors (HTS) are also explored
- Fields of 20+ T

SppC considers to use fe-HTS

aterial use
level

D. Tommasini at al.



CIEMAT, CEA, INFN

Swiss contribution
via PSI

FCC-hh Technology Example

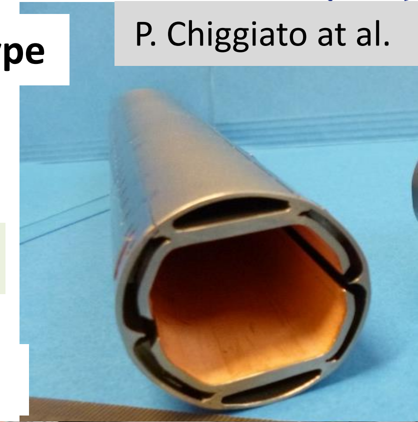
30 W/m synchrotron radiation (LHC: 1 W/m)
Make it small to make magnet cheap

Magnet aperture 50 mm (LHC 56 mm)

EuroCirCol
A key to New Physics

Prototype

P. Chiggiato at al.

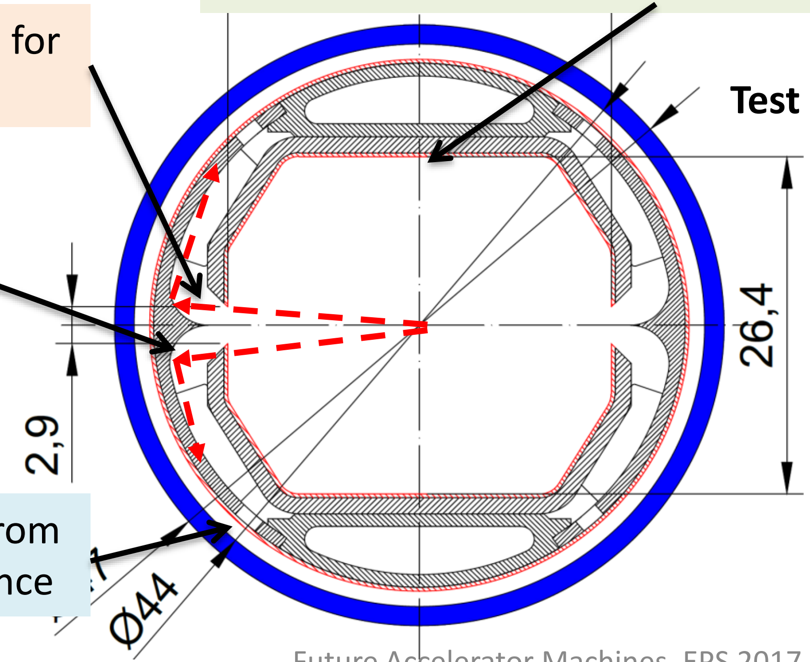


Laser treatment / carbon coating against ecloud

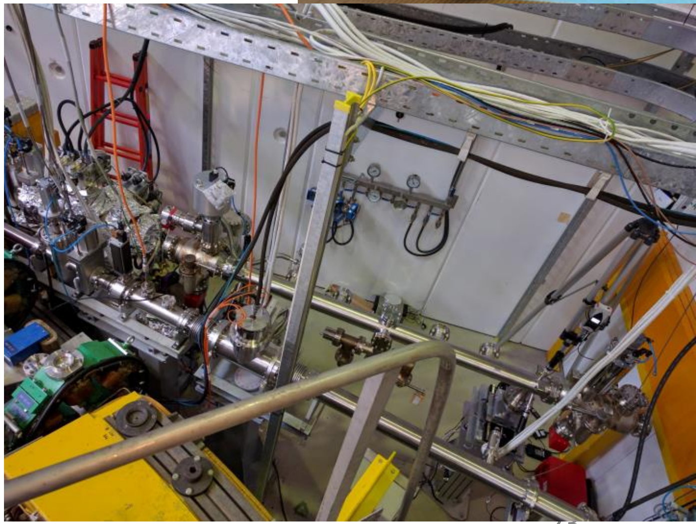
Extract photons for great vacuum

Strong to withstand quench

Hide pumping holes from beam for low impedance



Test station in ANKA

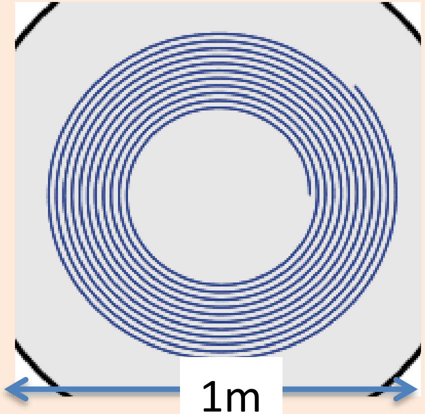


FCC-hh Beam Losses

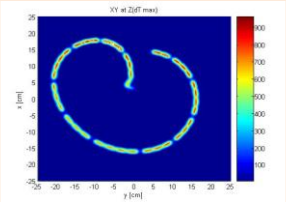
8 GJ kinetic energy per beam

- Airbus A380 at 720 km/h
- 2000 kg TNT
- 400 kg of chocolate
  - Run 25,000 km to spent calories
- O(20) times LHC

FCC-hh beam dilution pattern at dump

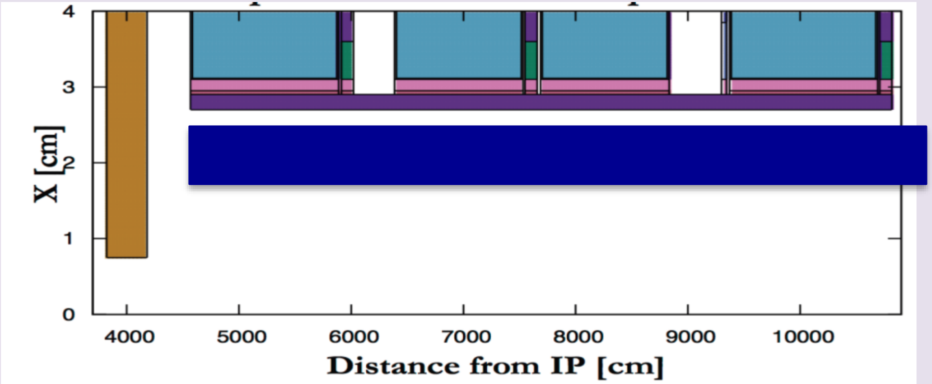


LHC beam dilution pattern at dump



B. Goddard al.

Up to 500 kW collision debris per experiment
Mainly lost in triplets, challenge for lifetime and quench



Triplet design allows for thick shielding

- Up to 1 of 300 atoms displaced in conductor
- Can survive project lifetime

F. Cerutti et al.

Collimation system design ongoing

- Identified hot spots
- Will implement ideas to get rid of them

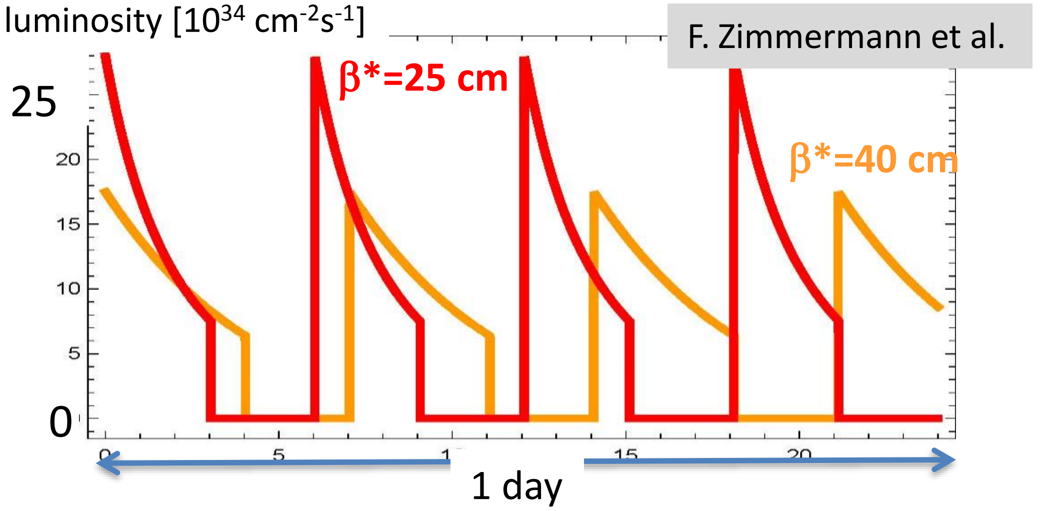
R. Bruce et al.

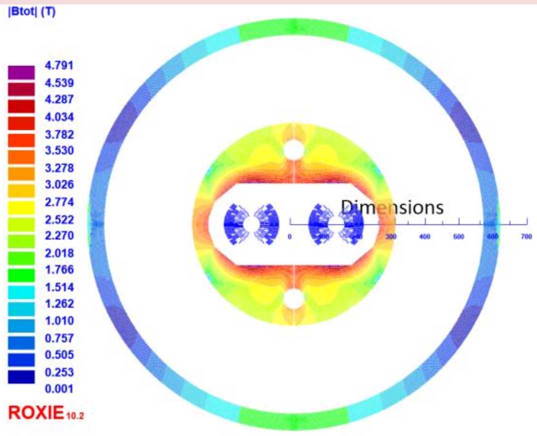
HE-LHC

Goal is 4 x HL-LHC luminosity
HL-LHC injectors
FCC-hh magnets and vacuum system

Make FCC-hh magnets more compact to fit in LHC tunnel

- Challenge is field leakage into tunnel
- Use kryostat as partial return yoke
- Active compensation



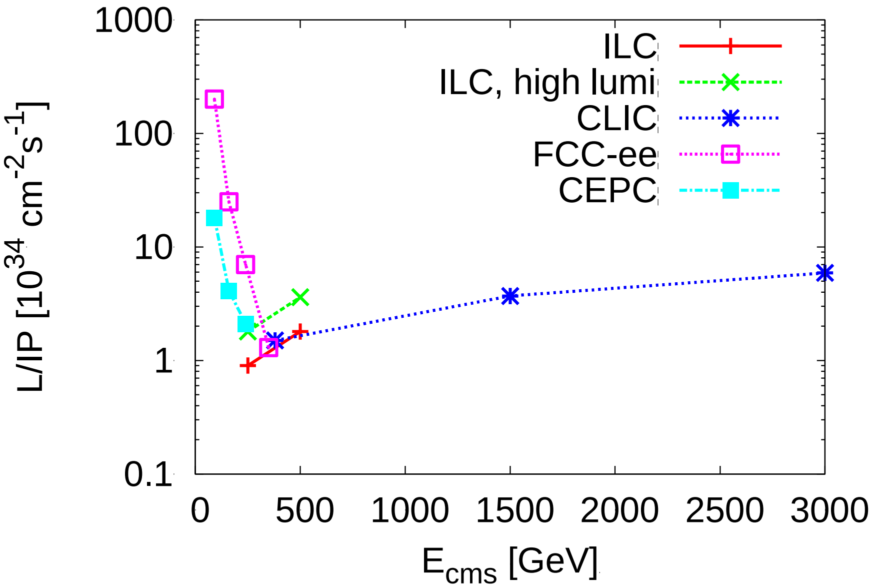


Only magnetic elements shown

Cannot increase lengths of insertions

- Currently beta-function around 0.4 m
  - 0.7ab^{-1} per year
  - Hope to improve
- Beam extraction is a challenge
- Collimation to be looked at

FCC-ee / CEPC Parameters



Energy	years	Int. Luminosity [ab^{-1}]
91.2	4 / 2	2 x 75 / 2 x 1.25
160	2 / not spec.	2 x 5 / not specified
240	3 / 10	2 x 2.5 / 2 x 2.5
350	5 / ---	2 x 1.5 / ----

Still moving targets

L. Wang et al. IHEP-AC-2017-01
F. Zimmermann et al. priv. comm.

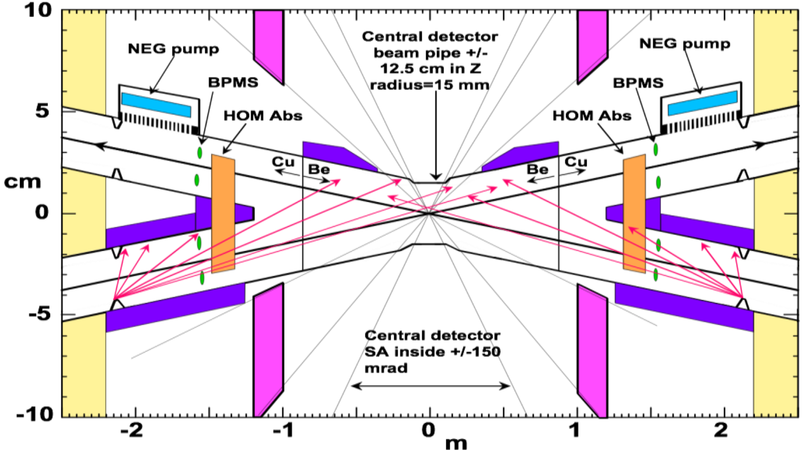
Parameter	Z	W	H	t	LEP2
Cms E [GeV]	91.2	160	240	350	208
I [mA]	1390 / 370-1450	147 / 51	29 / 11-30	6.4 / --	4
L [10^{34} $cm^{-2}s^{-1}$]	200 / 18-71	25 / 4.1	7 / 2.1-5.4	1.3 / --	0.012

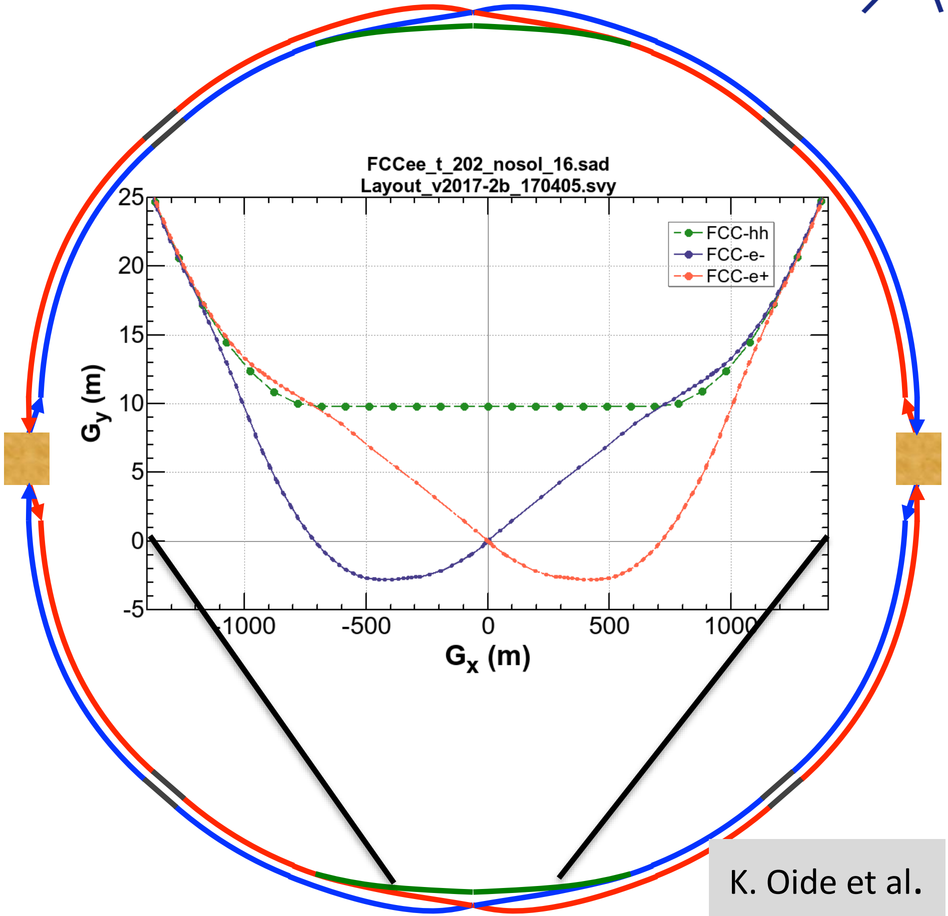
FCC-ee

Detailed MDI design ongoing

Large crossing angle requires additional tunnel

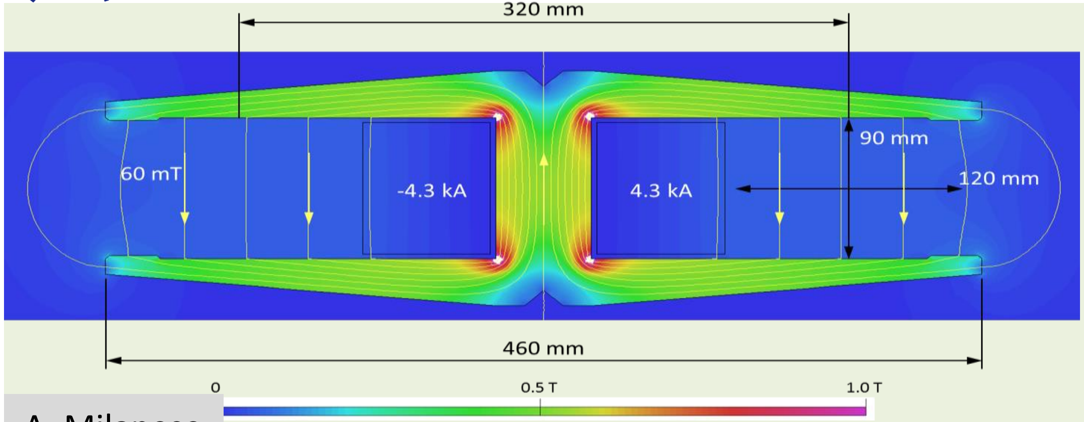
Short beam lifetime at high energy requires top-up scheme





K. Oide et al.

FCC-ee Technologies

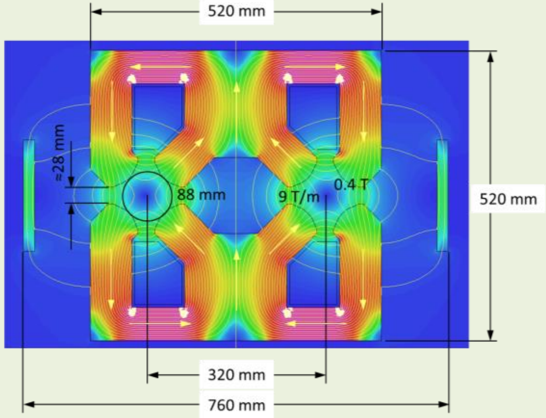


A: Milanese

Cost effective magnets

Two-in-one design of dipoles and quadrupoles

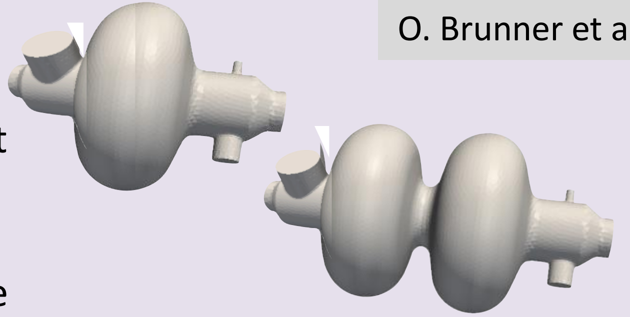
Optimised windings to reduce cost and power consumption



Optimised RF cavities

Single cells at low energy:
Low voltage but high current

Double cells at high energy:
Low current but high voltage

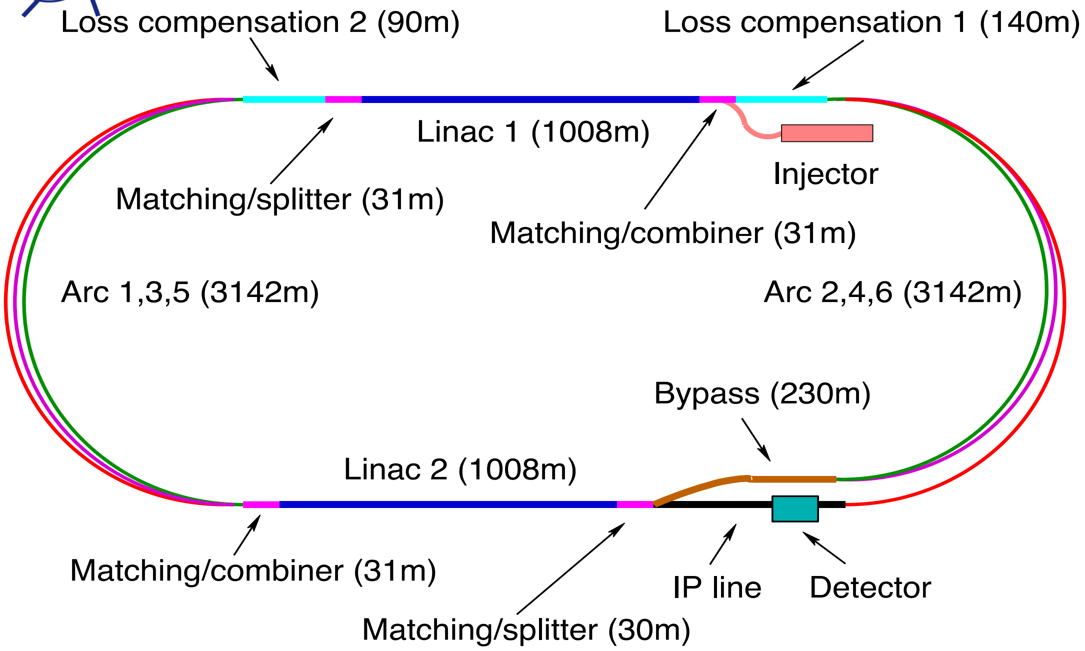


O. Brunner et al

Efficient klystrons, based on design ideas for CLIC

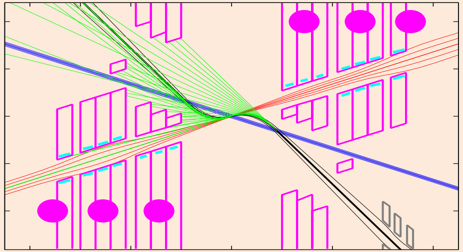
I. Syratchev et al

LHeC / FCC-he



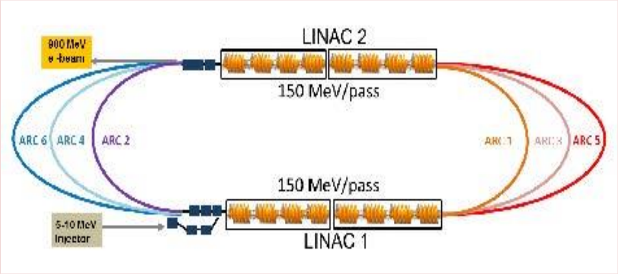
	LHeC CDR	HL-LHeC	HE-LHeC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
L [10^{33} $cm^{-2}s^{-1}$]	1	8	12	15

Interaction region
design ongoing



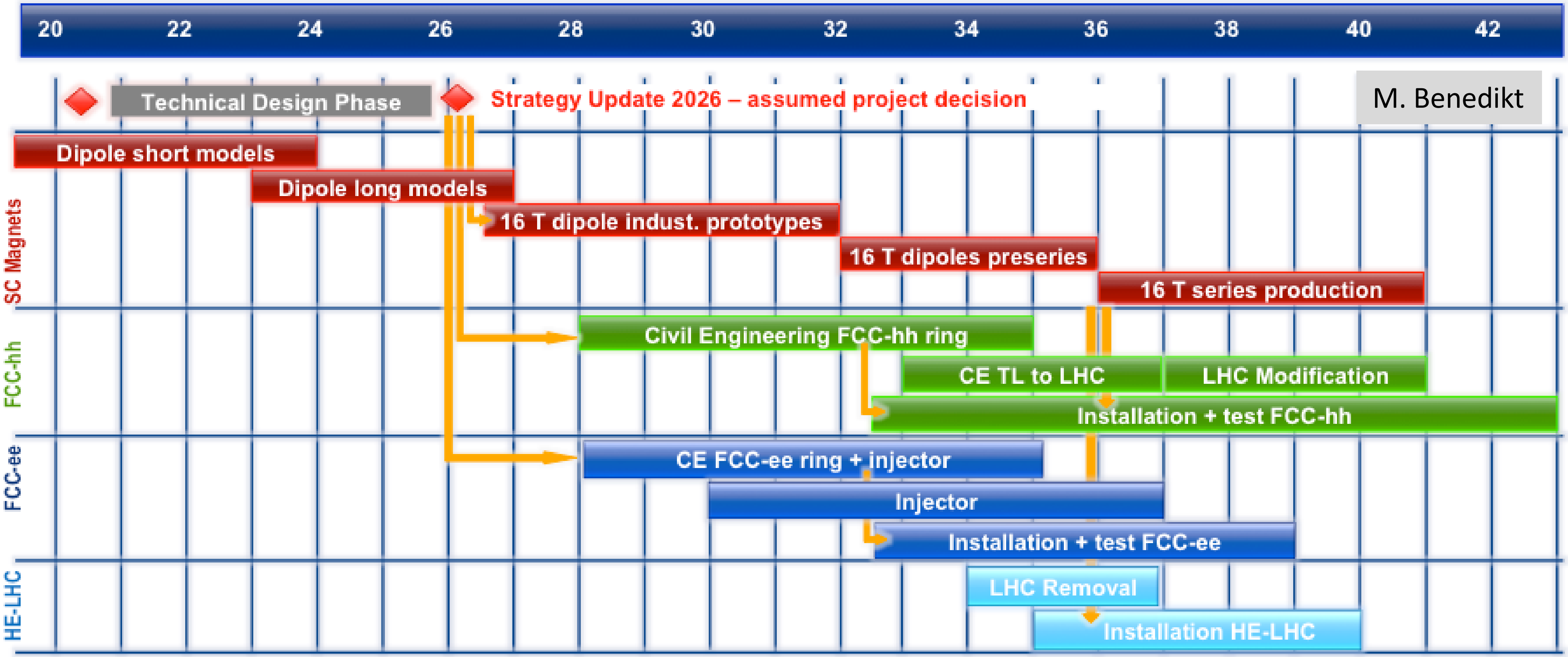
M. Klein et al

Development of accelerator technology
E.g. RF power required to control cavities
Test facility (PERLE) planned in Orsay



Preliminary FCC Draft Schedules

Technically limited schedule



Conclusion

Important progress toward the EU strategy

- ILC
  - Focus on cost reduction
  - Political process
- CLIC
  - Further optimising 380 GeV first energy stage
  - Work on further stages, including novel technologies
  - Project Implementation Plan for 2018
- SppC and CEPC
  - CDRs available
- FCC
  - CDR end of 2018 for hh (with he) , ee and HE-LHC options
  - Including R&D plan

Many thanks to L. Evans, S. Stapnes, W. Wuensch, Ph. Burrows, I. Syratchev, M. Benedikt, K. Oide, F. Zimmermann, M. Klein, …, the ILC, CLIC, FCC and SppC/CEPC teams

Reserve

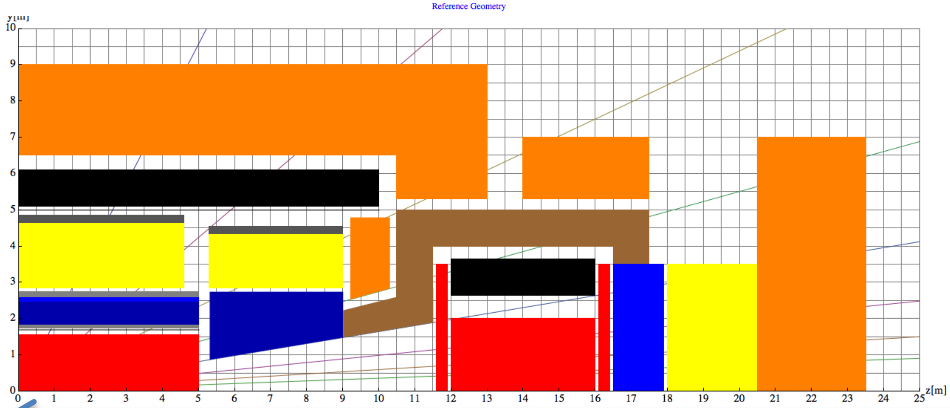
FCC-hh MDI

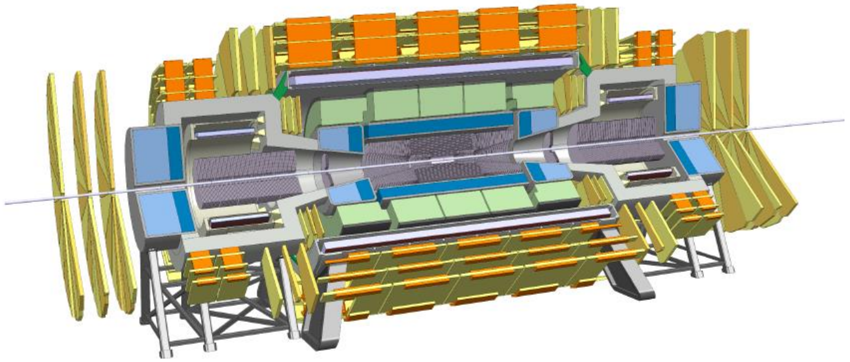
W. Riegler at al.

Tracking
Ecal
HCAL
Magnets and cryostat
Muons

Uses forward solenoid

Alternative option with forward dipole considered





Add. protection

TAS

Triplet

Hall half length: 33m

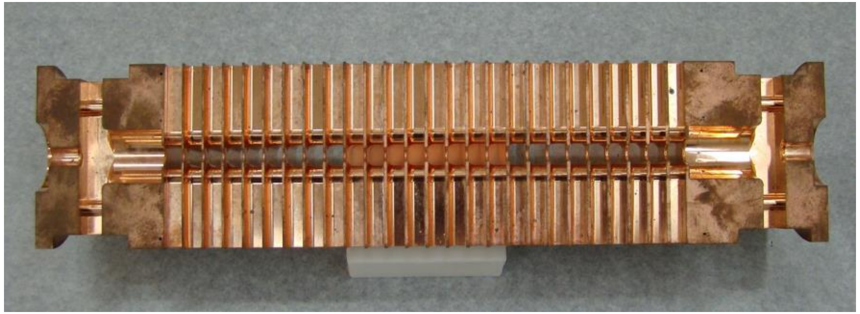
Tunnel before triplet: 7m

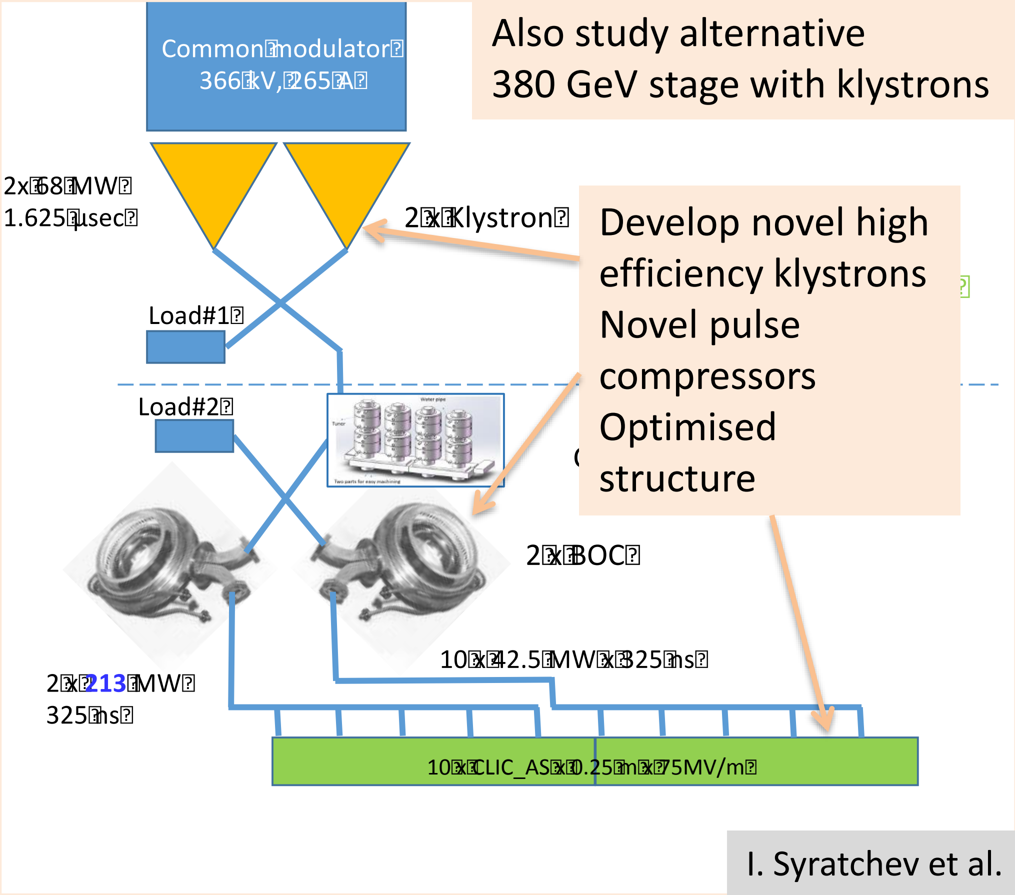
L^{*}=40 m

Detector half length 23.5m

Space to open 9.5m

CLIC RF Technology Development





Also study alternative 380 GeV stage with klystrons

- Develop novel high efficiency klystrons
- Novel pulse compressors
- Optimised structure

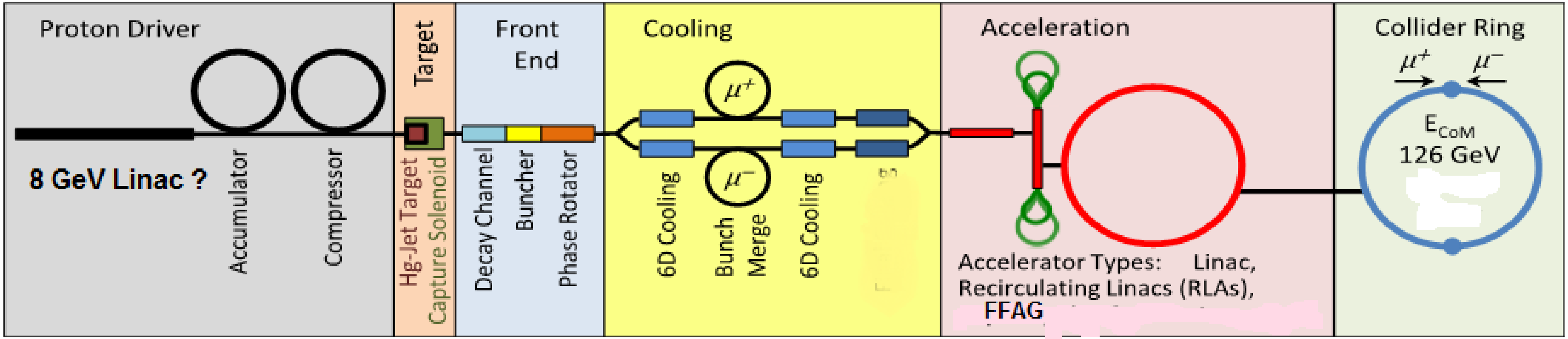
I. Syratchev et al.

Muons Collider

Muon collider
effort has been reduced dramatically

Effort on source still ongoing (MICE)

New idea to generate muon beam
- But need to evaluate efficiency



M. Boscolo

Proposal of a Low emittance muon beam production from positrons on target

direct μ pair production: $e^+e^- \rightarrow \mu^+\mu^-$ just above the $\mu^+\mu^-$ production threshold with minimal muon energy spread, with direct annihilation of $\approx$ **45GeV e^+** with atomic e^- in a thin target O(0.01 radiation length)

very small emittance at μ production point → **no cooling** needed!

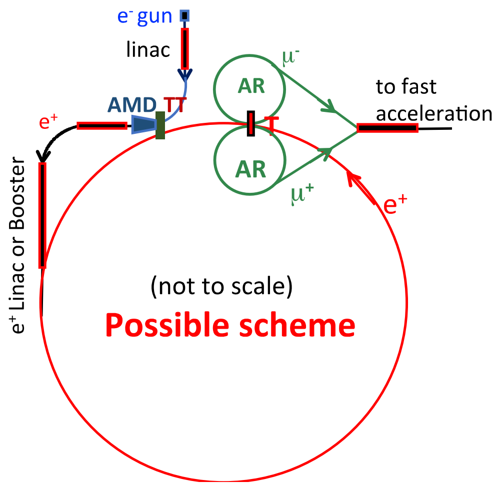
Goal

very low emittance, sufficient rate

normalized muon emittance ε_N **= 40 nm**

muon production rate at target $\approx 10^{11}$ μ/s

allows competitive luminosity at low fluxes



Advantages:

1. **Low emittance possible:** can be **very small** close to the $\mu^+\mu^-$ threshold
2. **Low background:** Luminosity at low emittance will allow low background and low ν radiation (easier experimental conditions, can go up in energy)
3. **Reduced losses from decay:** muons can be produced with a relatively high boost in asymmetric collisions
4. **Energy spread:** muon energy spread **also small at threshold**

Disadvantage: **rate:** much smaller cross section wrt protons ($\approx$ mb)

Key topics for feasibility

- **Low emittance and high momentum acceptance 45 GeV e^+ ring**
- **O(100 kW) class target in the e^+ ring for $\mu^+\mu^-$ production**
- **High rate positron source**
- **High momentum acceptance muon accumulator rings**

Ref. NIM A 807 101-107 (2016), WEOBA3 in Proc. of IPAC17]