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The Future of e^+e^- colliders

Brian Foster (Uni Hamburg/DESY/Oxford)

Humboldt Kolleg on Particle Physics

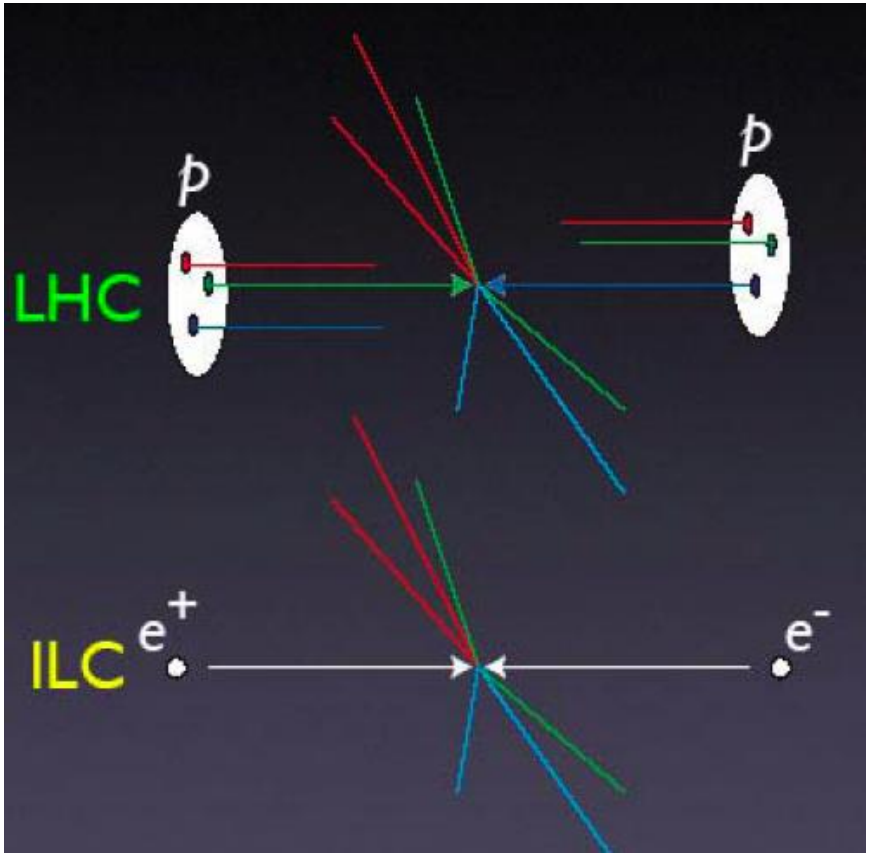
June 28th 2016

Outline

- **Why e^+e^-?**
- **Linear vs Circular Machines**
- **Status of current LC designs**
  - ILC, CLIC
- **The future? Plasma-wave acceleration**

e^+e^- vs pp

- Simple particles
- Well defined:
  energy, angular mom.
- E can be scanned precisely
- Particles produced ~ democratically
- Final states generally fully reconstructable



Circular e^+e^- machines

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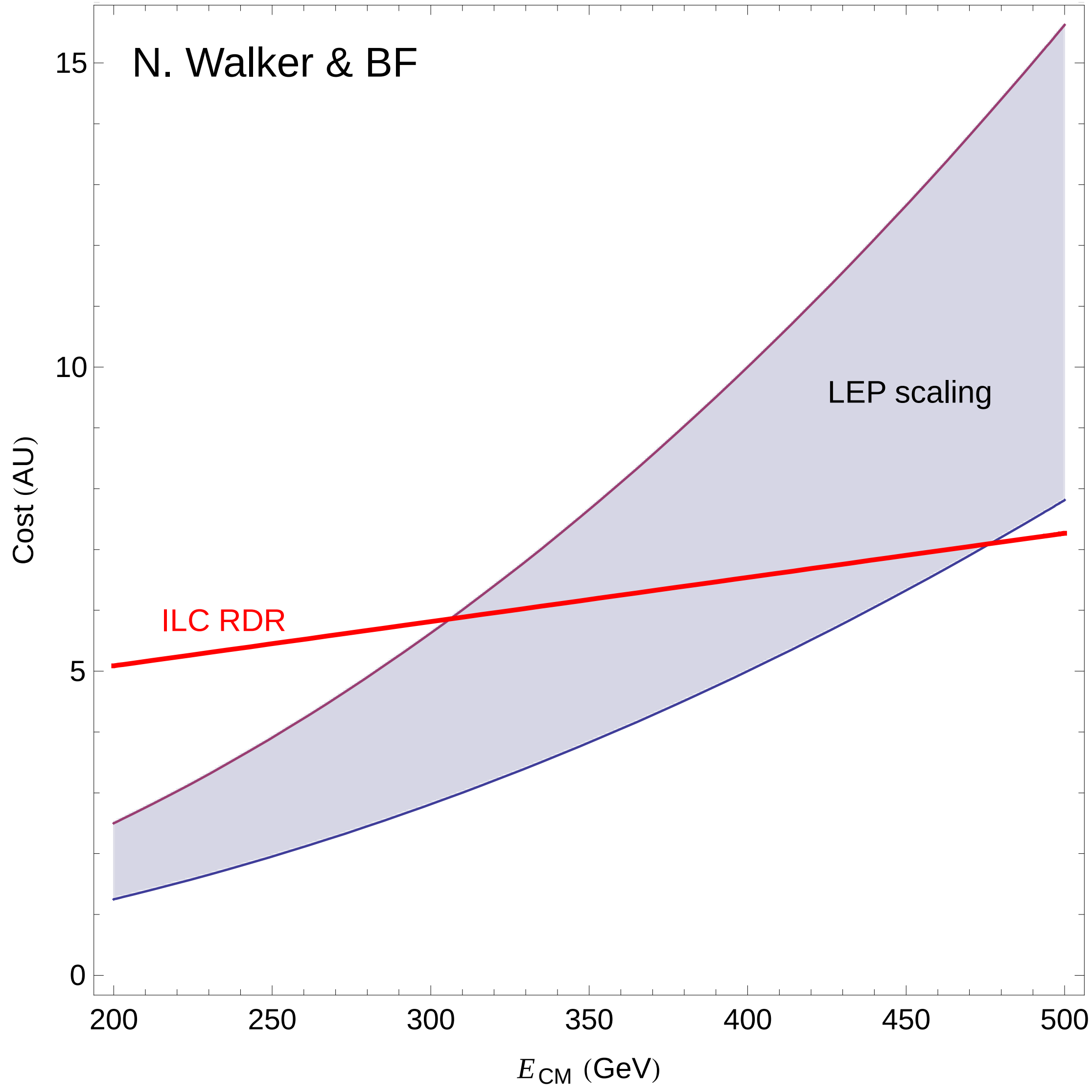
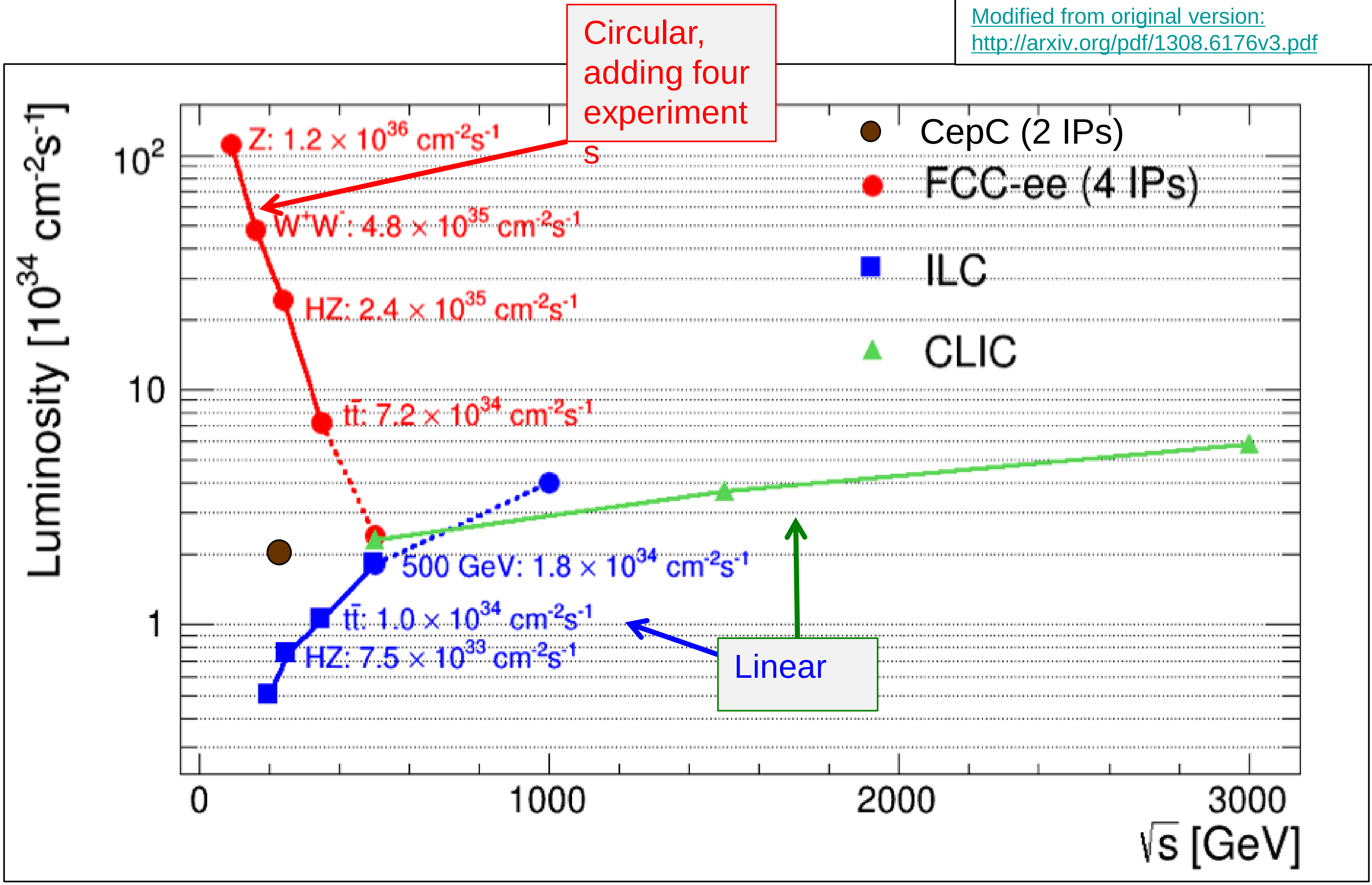
Very approximate cost LC vs circular based on minimum of cost model Cost = $aE^4/R + bR$ where a,b "fixed" from LEP – two curves are most optimistic and pessimistic LEP cost.

BUT – luminosity of circular machine in this picture dropping steeply with E.



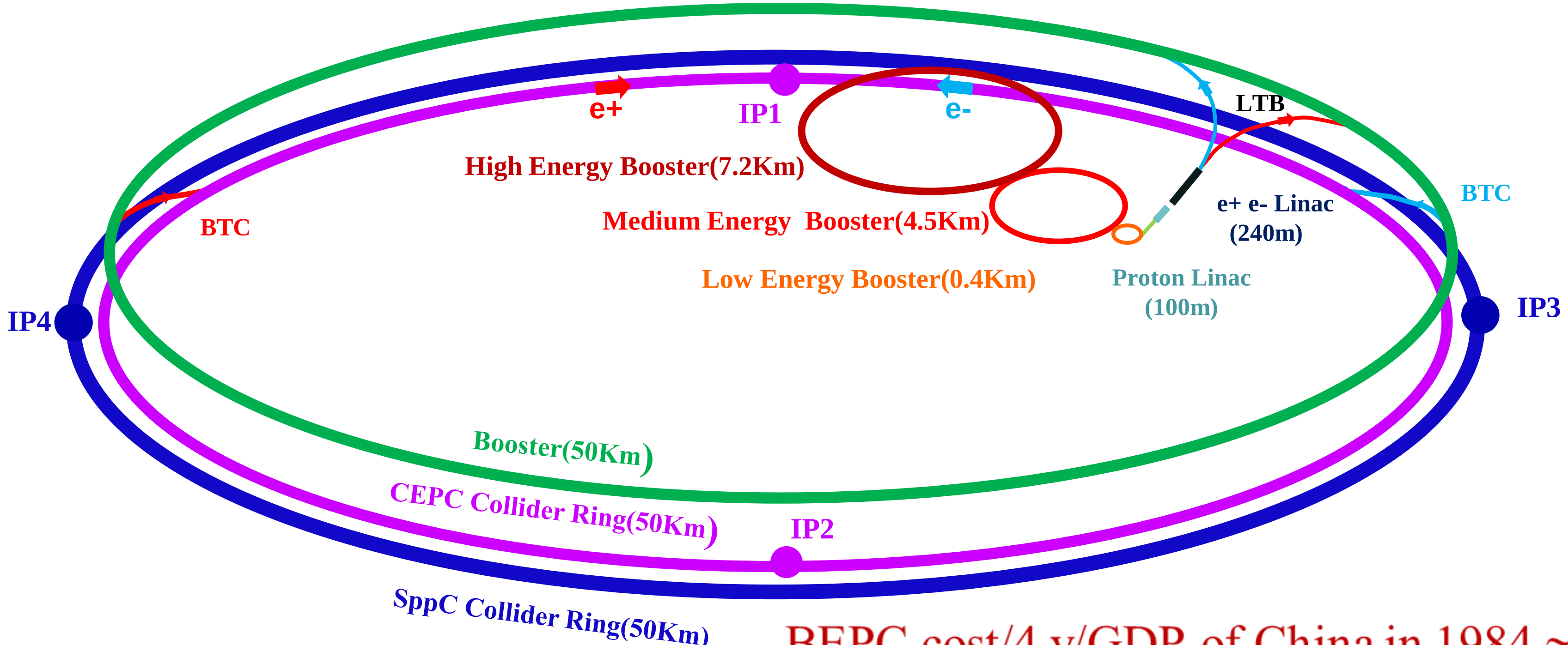
Circular e^+e^- machines

Modified from original version: http://arxiv.org/pdf/1308.6176v3.pdf



(D. Schulte)

CEPC & SppC Layout



SC predicts 2020 China GDP = $24.6 Trillion

=> Cost of CEPC ~ 0.07*24.6*6 B ~ $10B

Current Status – funding awarded in next 5-year plam for R&D – not as much as requested, but still significant. Further funding will be sought and work going ahead as planned.

- BEPC cost/4 y/GDP of China in 1984 ≈ 0.0001
- SSC cost/10y/GDP of US in 1992 ≈ 0.0001
- LEP cost/8y/GDP of EU in1984 ≈ 0.0002
- LHC cost/10y/GDP of EU in 2004 ≈ 0.0003
- ILC cost/8y/GDP of Japan in 2018 ≈ 0.0002
- CEPC cost/6y/GDP of China in 2020 ≈ 0.00007
- SPPC cost/6y/GDP of China in 2036 ≈ 0.0001

ILC - Overview

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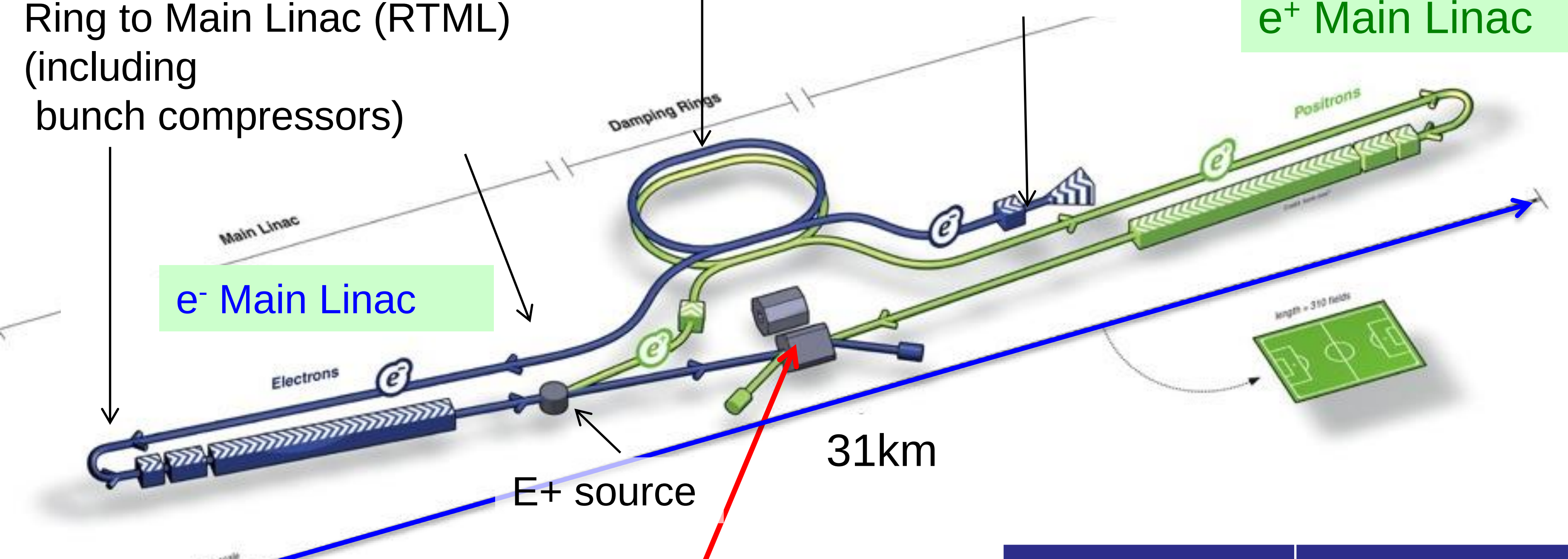
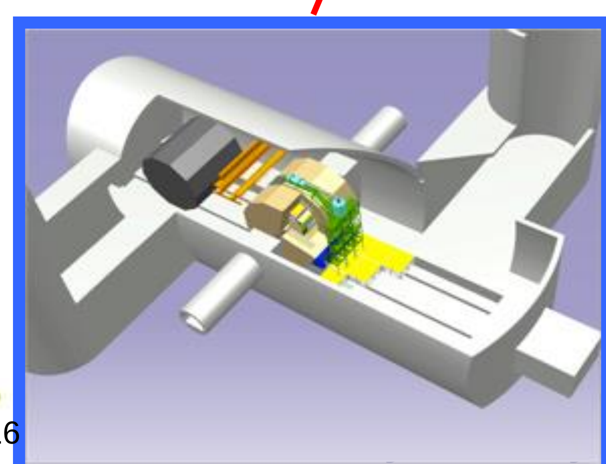




Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} cm^{-2}s^{-1}
Beam power	10.5 MW
Beam Rep. rate	5 Hz
E gradient	31.5 MV/m +/-20%

SCRF Linac Technology

- solid niobium
- standing wave
- 9 cells
- operated at 2K (Lqd. He)
- 35 MV/m
- $Q_0 \geq 10^{10}$

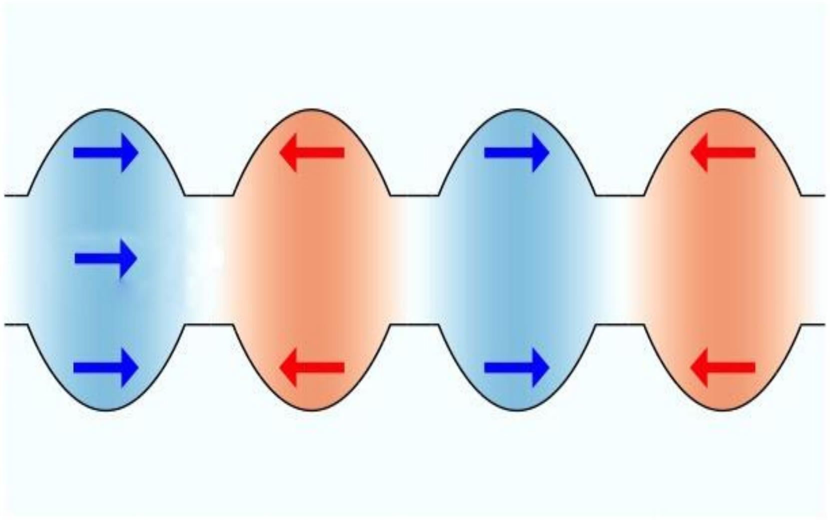
1.3 GHz Nb 9-cell Cavities	16,024
Cryomodules	1,855
SC quadrupole package	673
10 MW MB Klystrons & modulators	436 / 471*

* site dependent

Approximately 20 years of R&D Worldwide → Mature technology

Cavities accelerate particles via EM standing waves

RF Cavity



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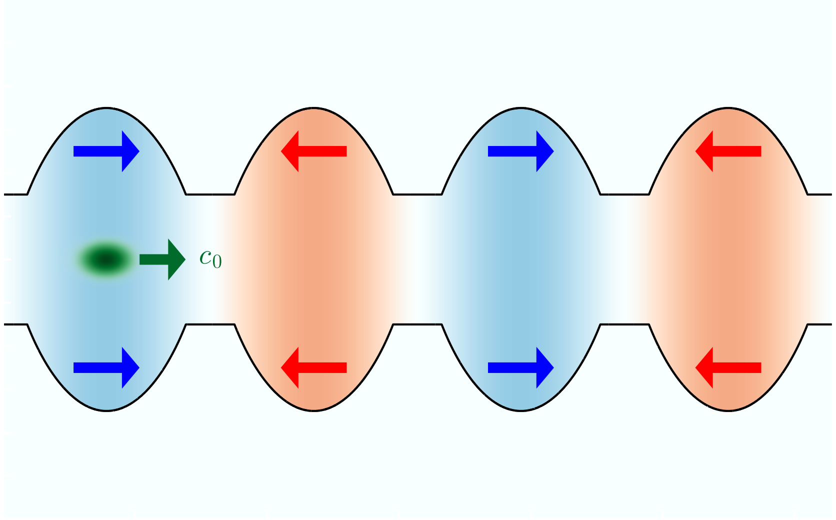

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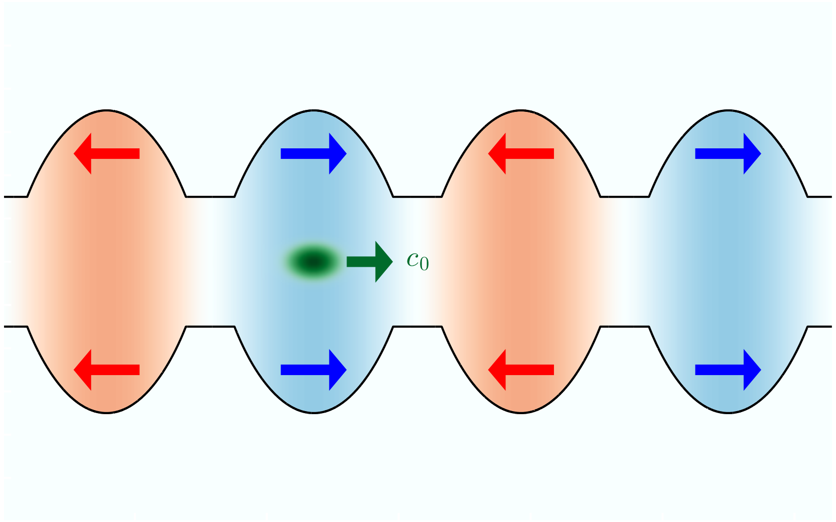

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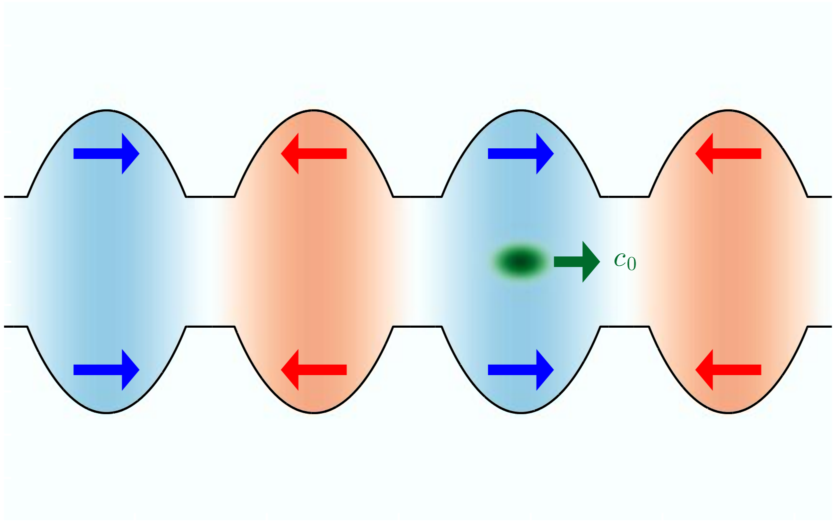

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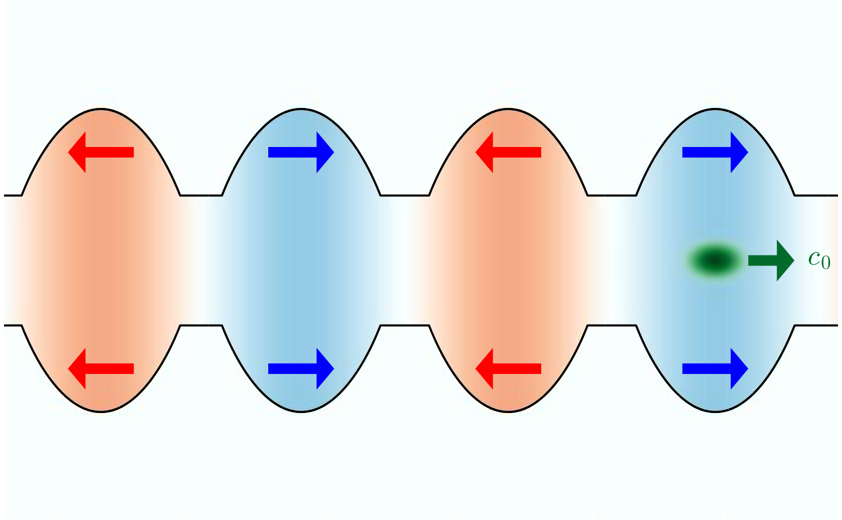
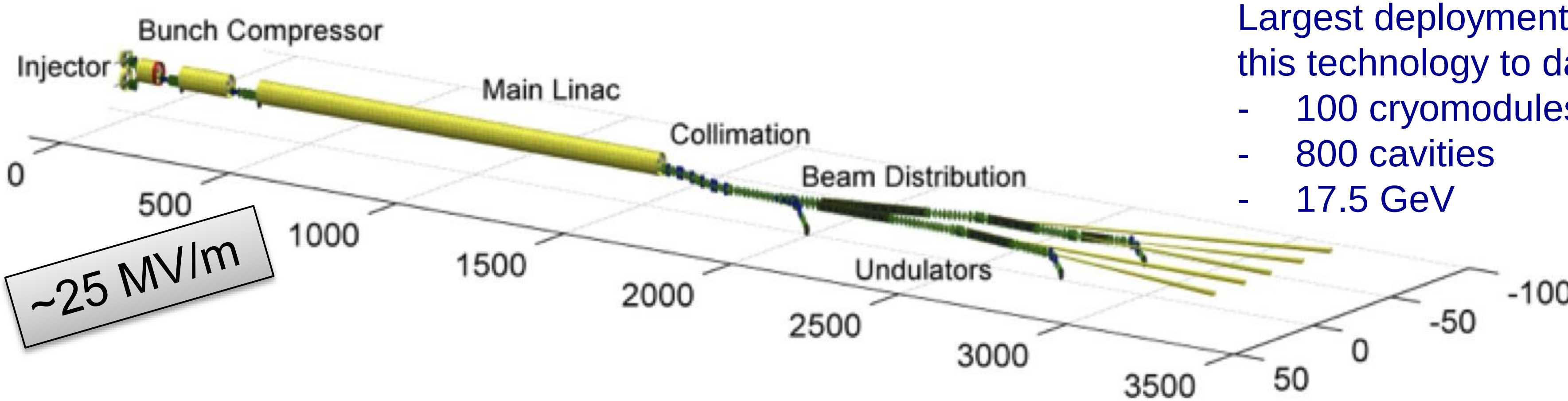


European XFEL @ DESY



Largest deployment of this technology to date
- 100 cryomodules
- 800 cavities
- 17.5 GeV

The ultimate 'integrated systems test' for ILC. Commissioning with beam begins 2016

Industrial production - XFEL

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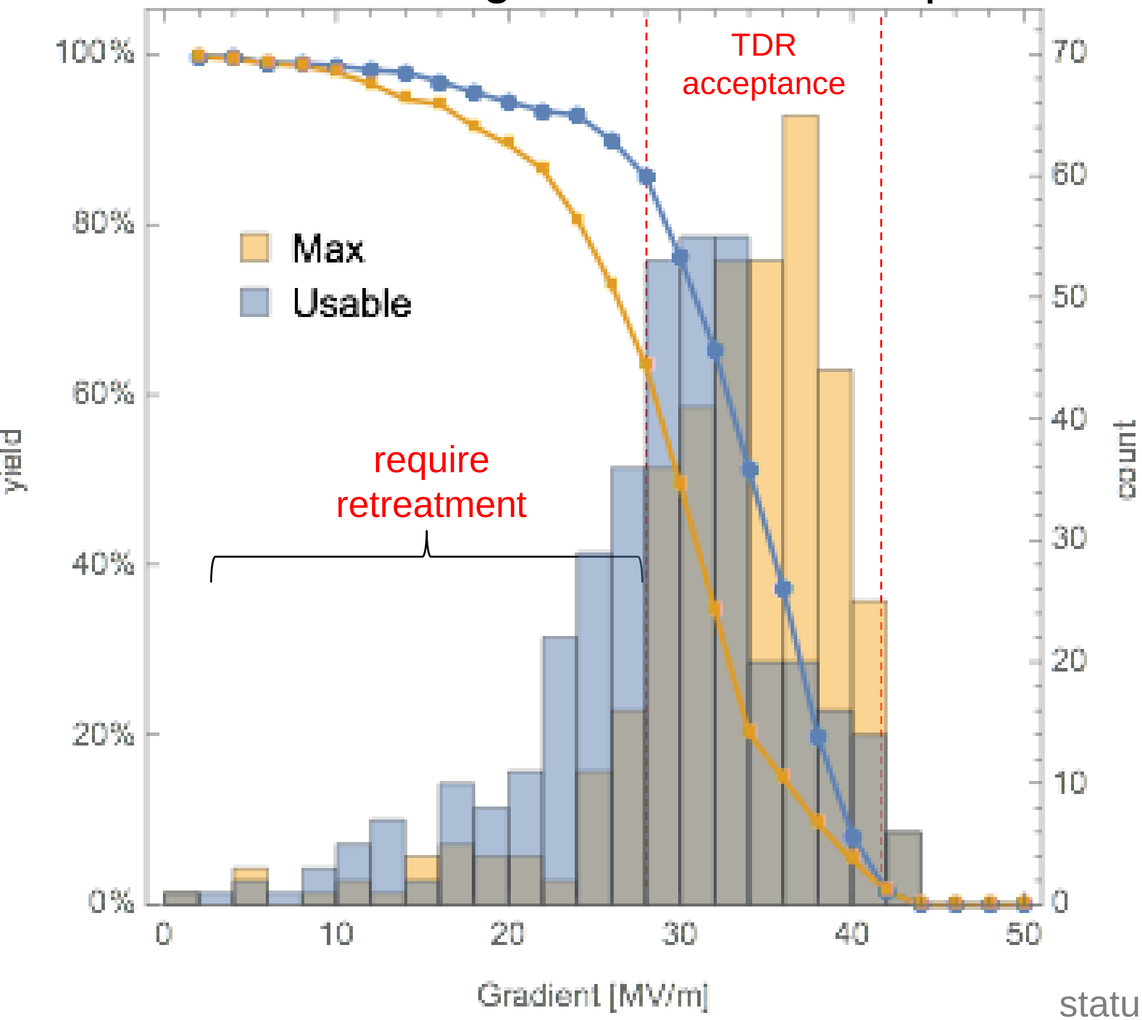
One vendor following ILC baseline recipe



Maximum
Usable

quench limit

Field emission
Limit (XFEL spec.)

	Max	Usable
Number of tests	377	377
⟨G⟩ (MV/m)	33.	29.
G_{RMS} (MV/m)	6.6	7.4
Yield @ 28 MV/m	86%	63%
Yield @ 35 MV/m	44%	18%

status:01.06.2016

(Thanks to Nick Walker)

CLIC

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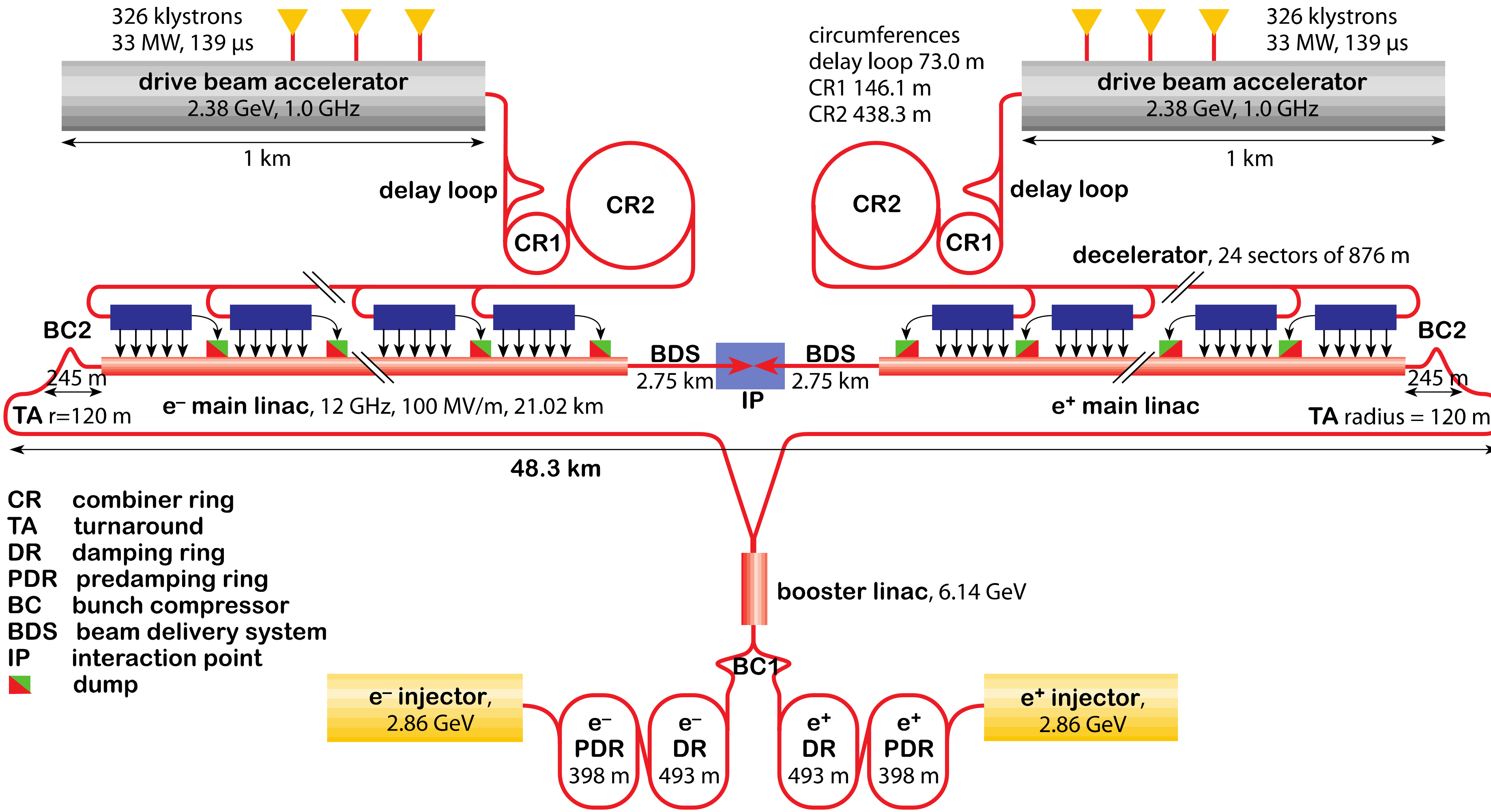

CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump

Current status

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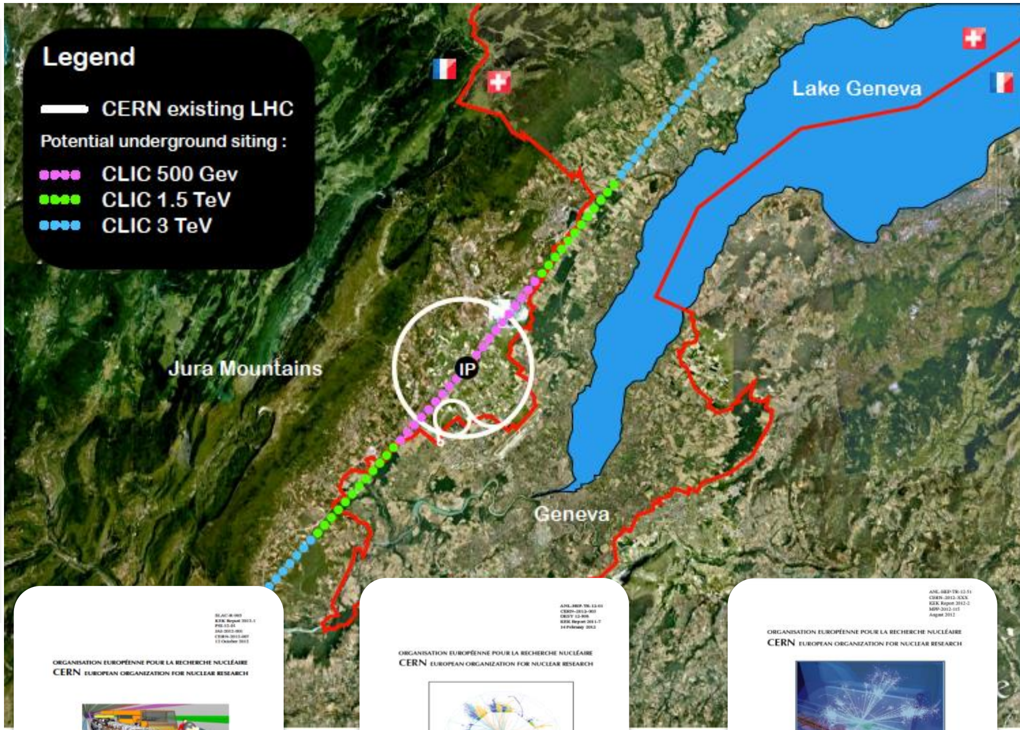
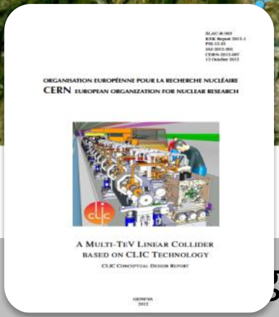
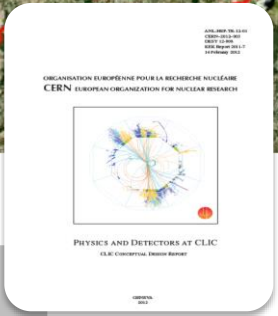
Luminosity

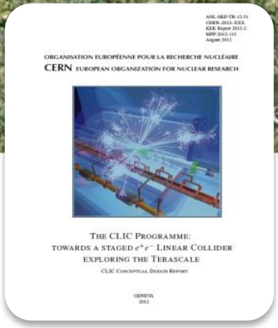
- Damping ring like an ambitious light source, no show stopper
- Alignment system principle demonstrated
- Stabilisation system developed, benchmarked, better system in pipeline
- Simulations on or close to the target



Conceptual design complete







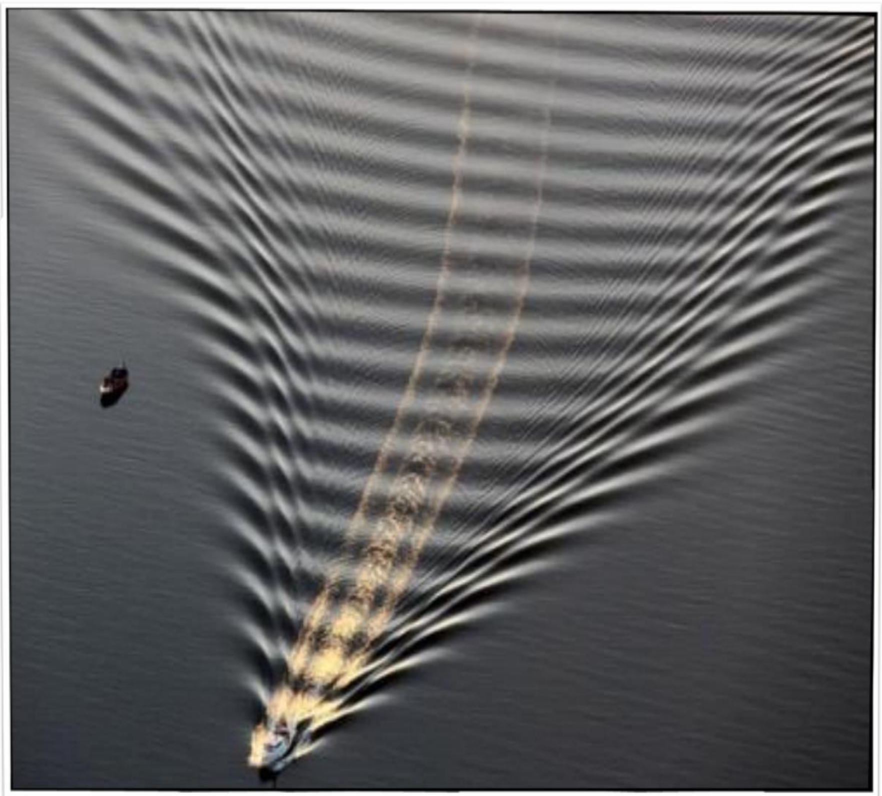
Operation & Machine Protection

- Start-up sequence … gy operation defined

Implementation

- Consistent staged implementation scenario defined
- Schedules, cost and power developed and presented
- Site and CE studies documented

Plasma Wave Acceleration

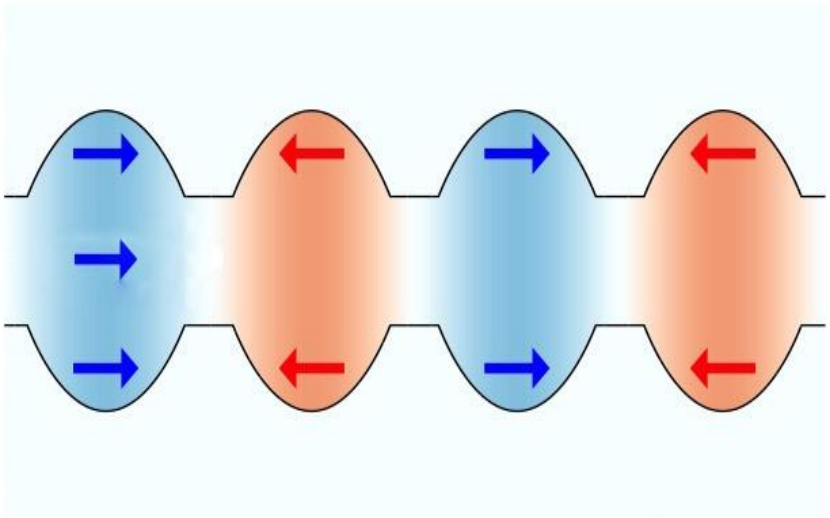


Wake excitation

Particle injection

Cavities accelerate particles via EM standing waves

RF Cavity



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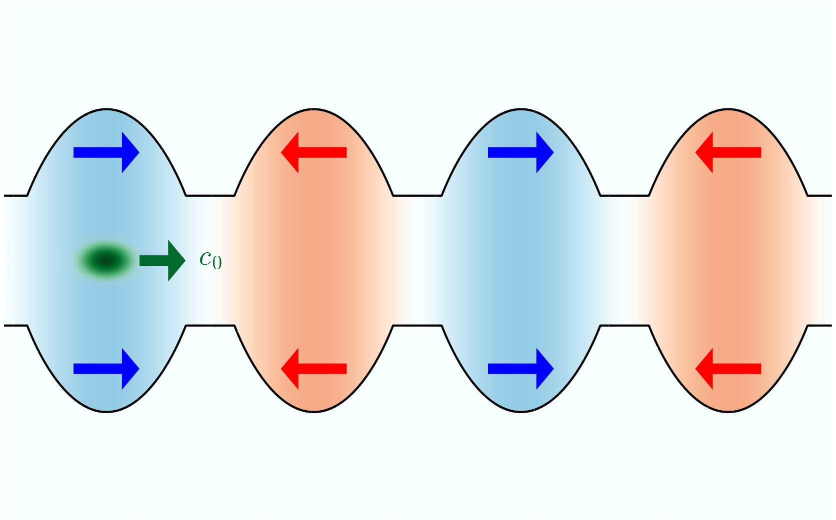

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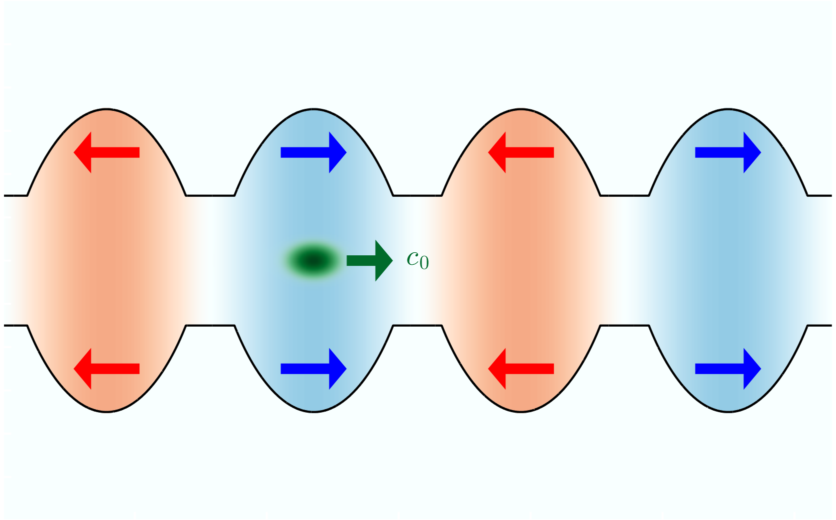

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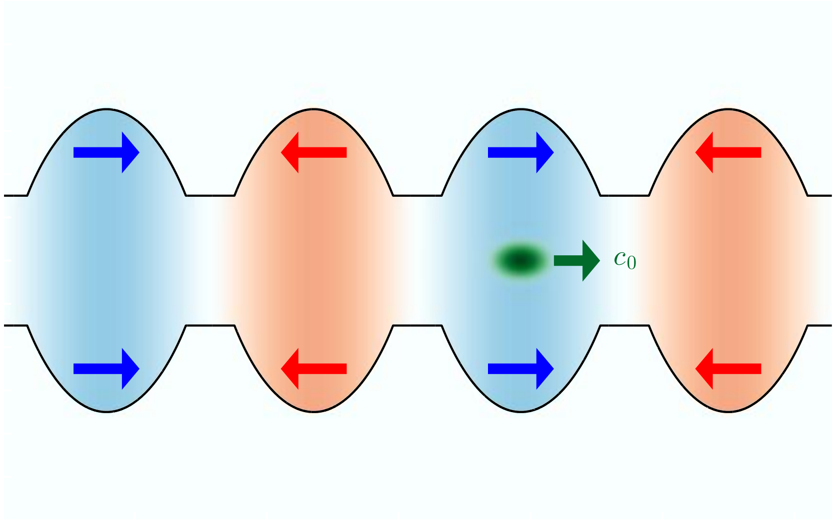
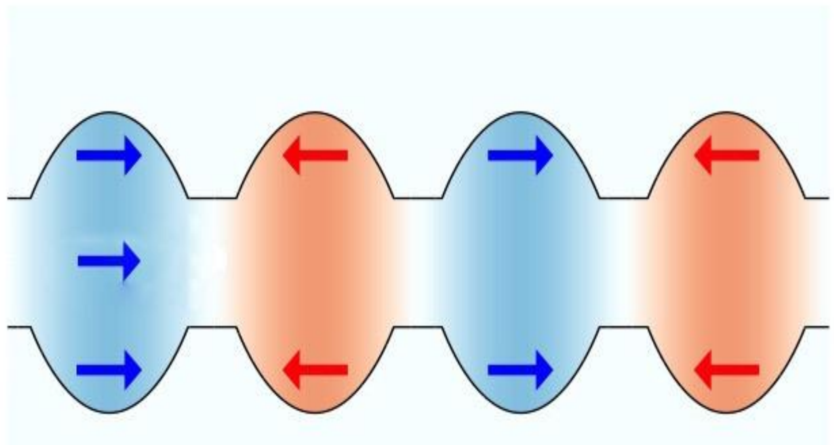


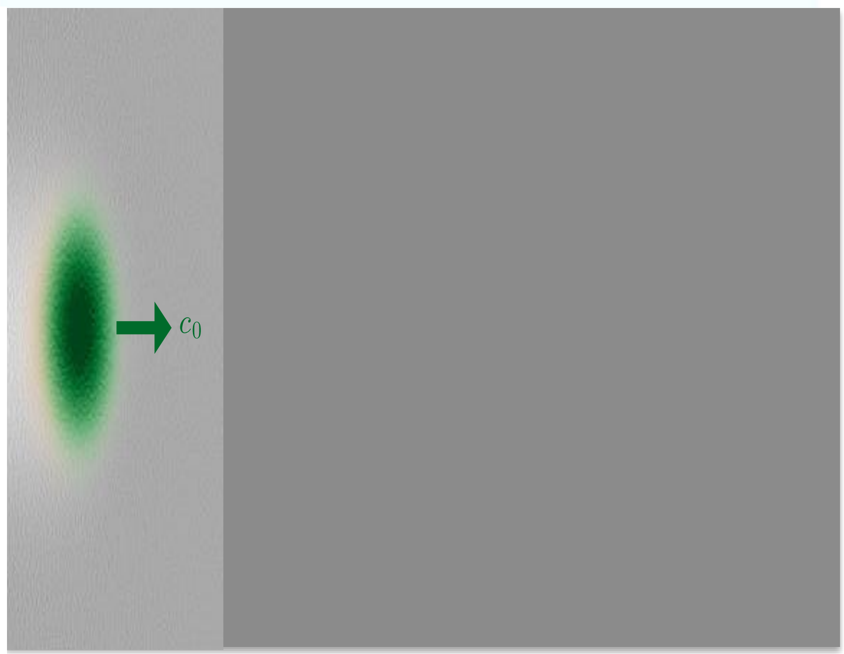
20 – 40 MV/m

Cavities accelerate particles via EM standing waves

RF Cavity



Plasma wakefield



Cavities accelerate particles via EM standing waves

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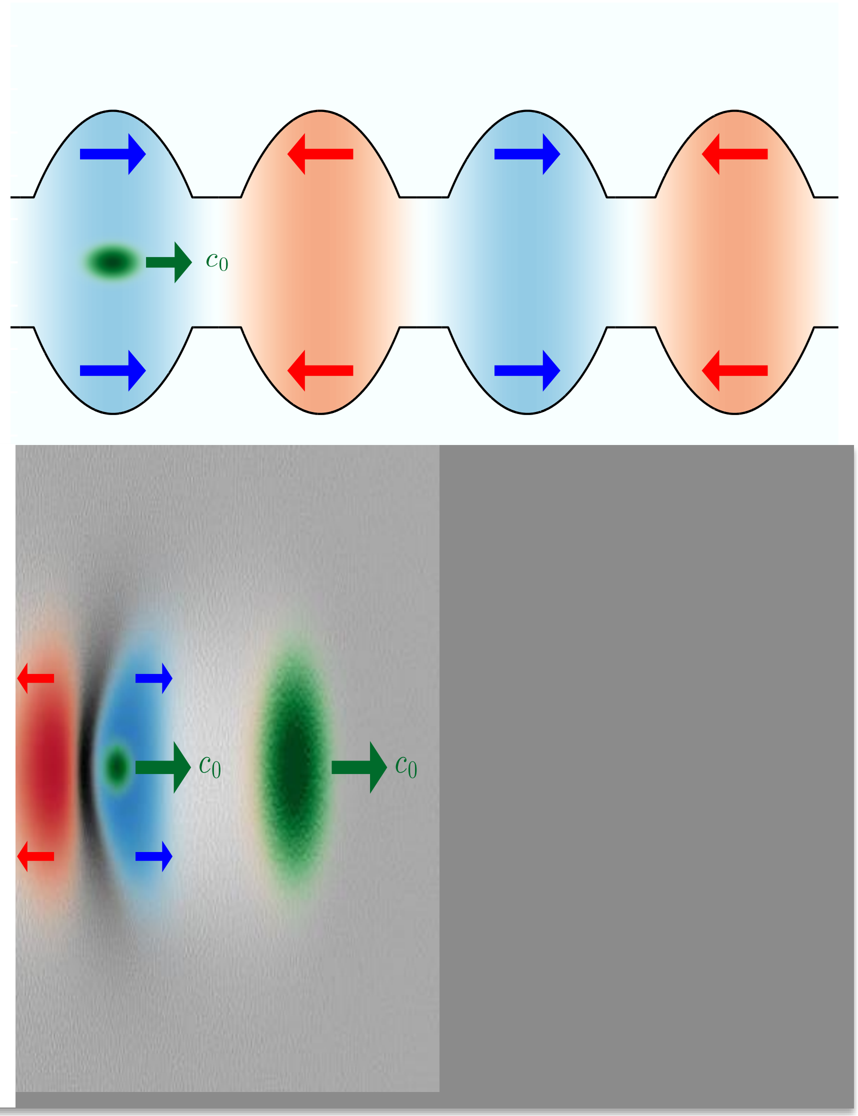
Plasma wakefield



Cavities accelerate particles via EM standing waves

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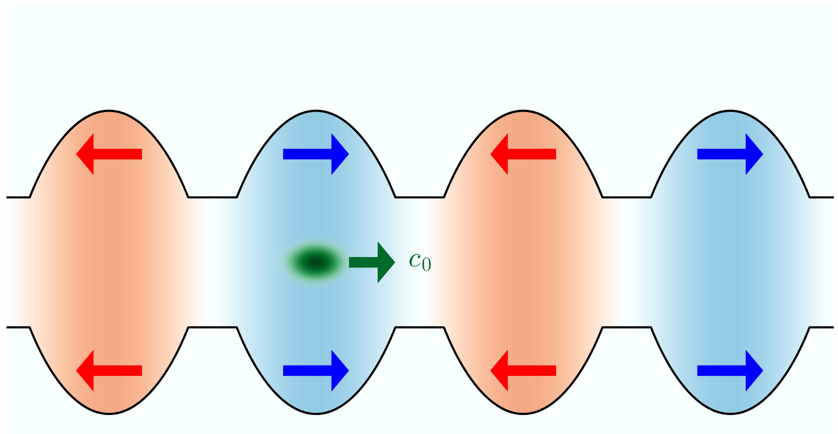
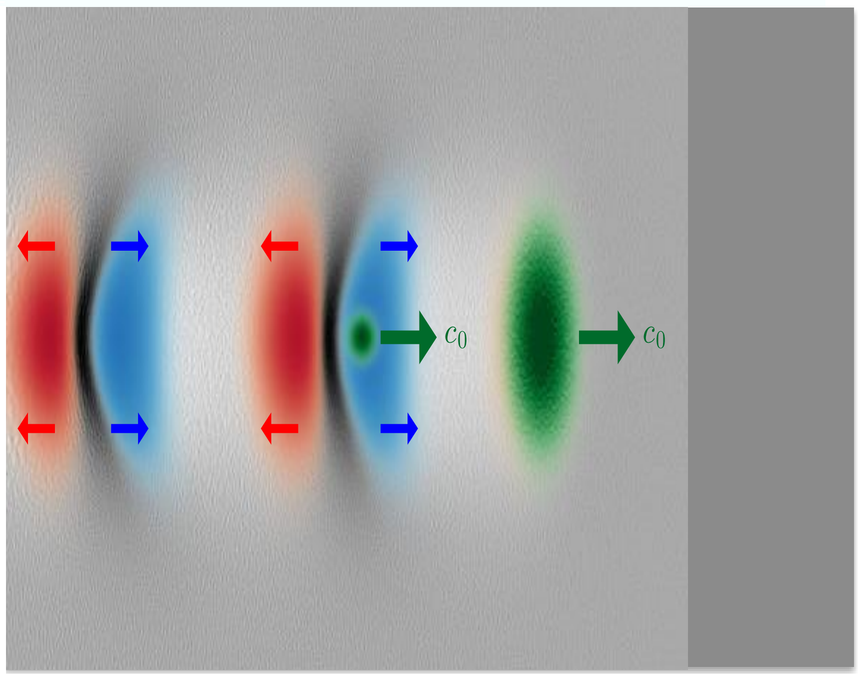


Plasma wakefield



Cavities accelerate particles via EM standing waves

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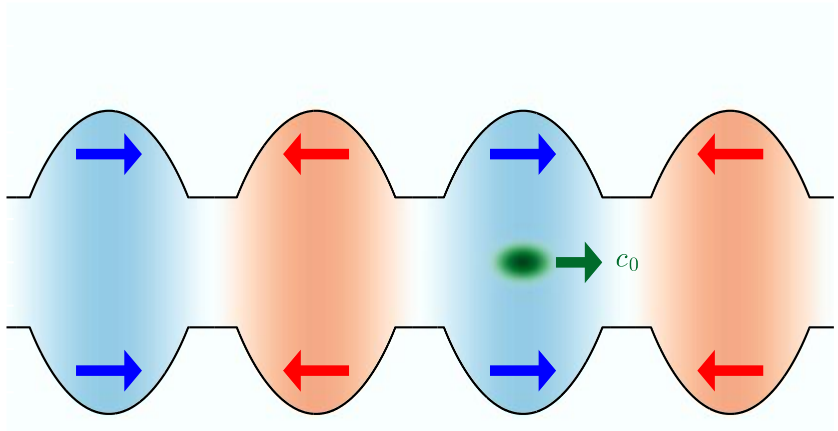
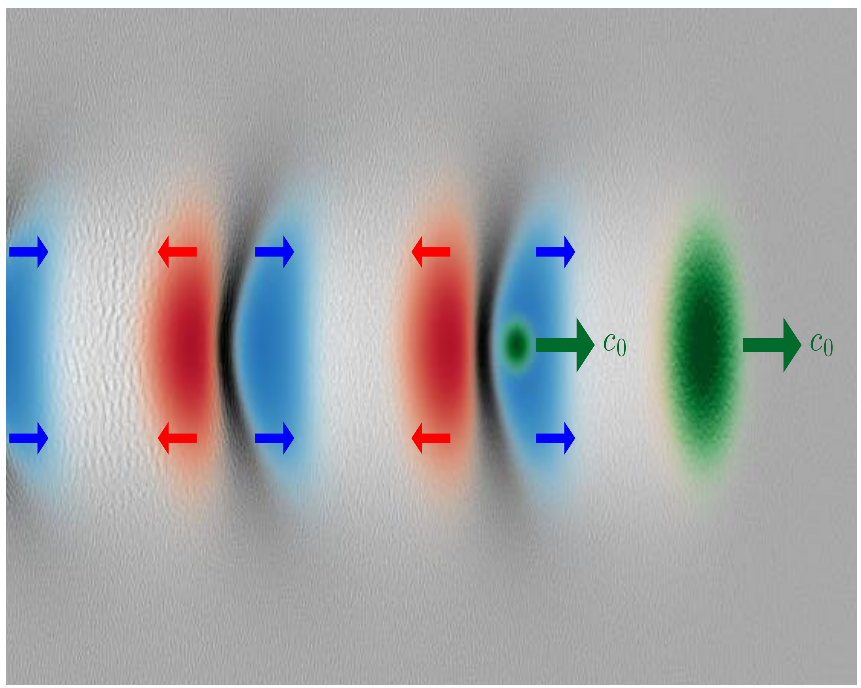


20 – 40
MV/m

Plasma
wakefield



10 – 1000
GV/m

Enables “table-top” Accelerators & promises major reduction in pp collider length/cost

Inject beam

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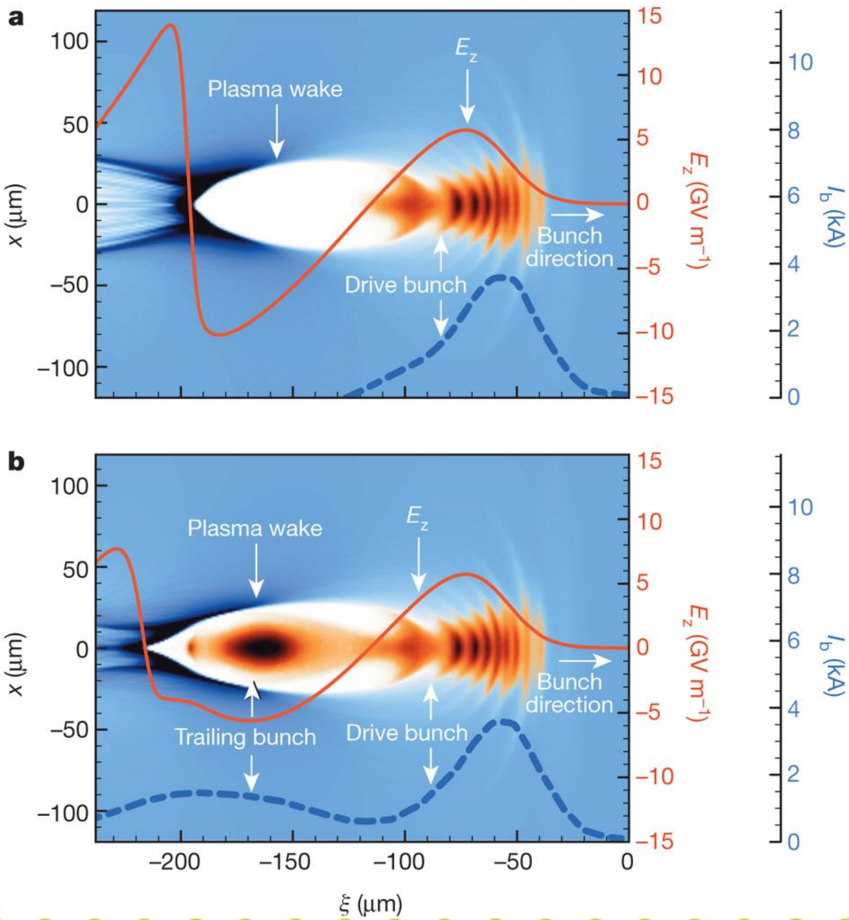
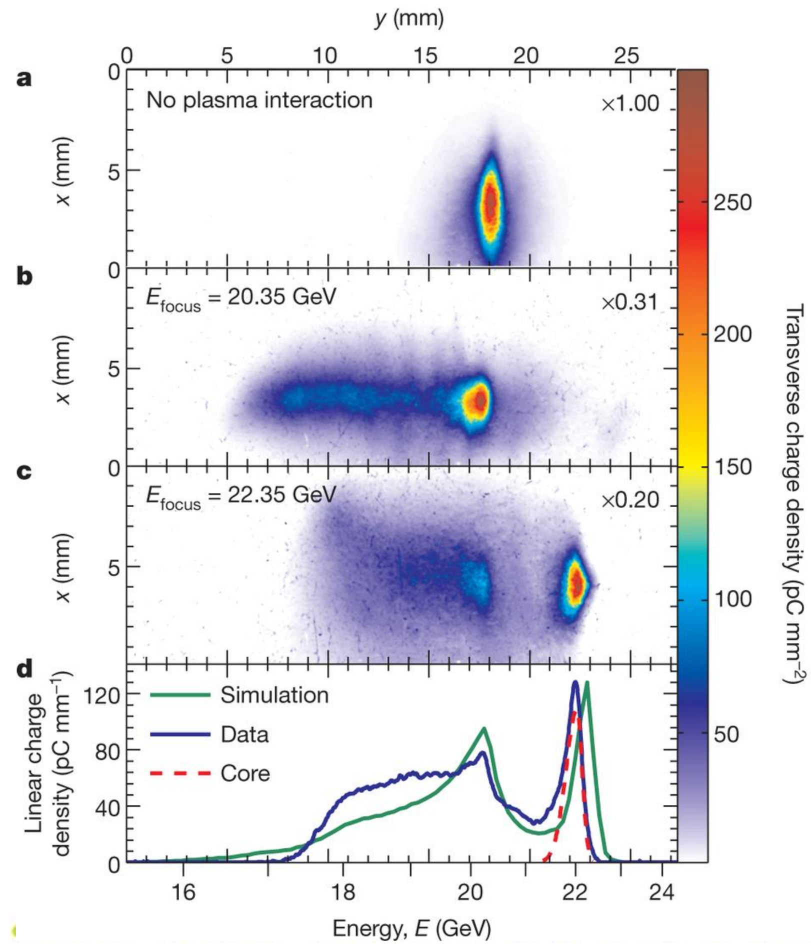
- **To understand acceleration in plasma, inject high-quality beam into plasma – requires excellent time and spatial precision.**

Litos et al., Nature 515, 92-95 (06.11.2014)





The New Livingston Plot

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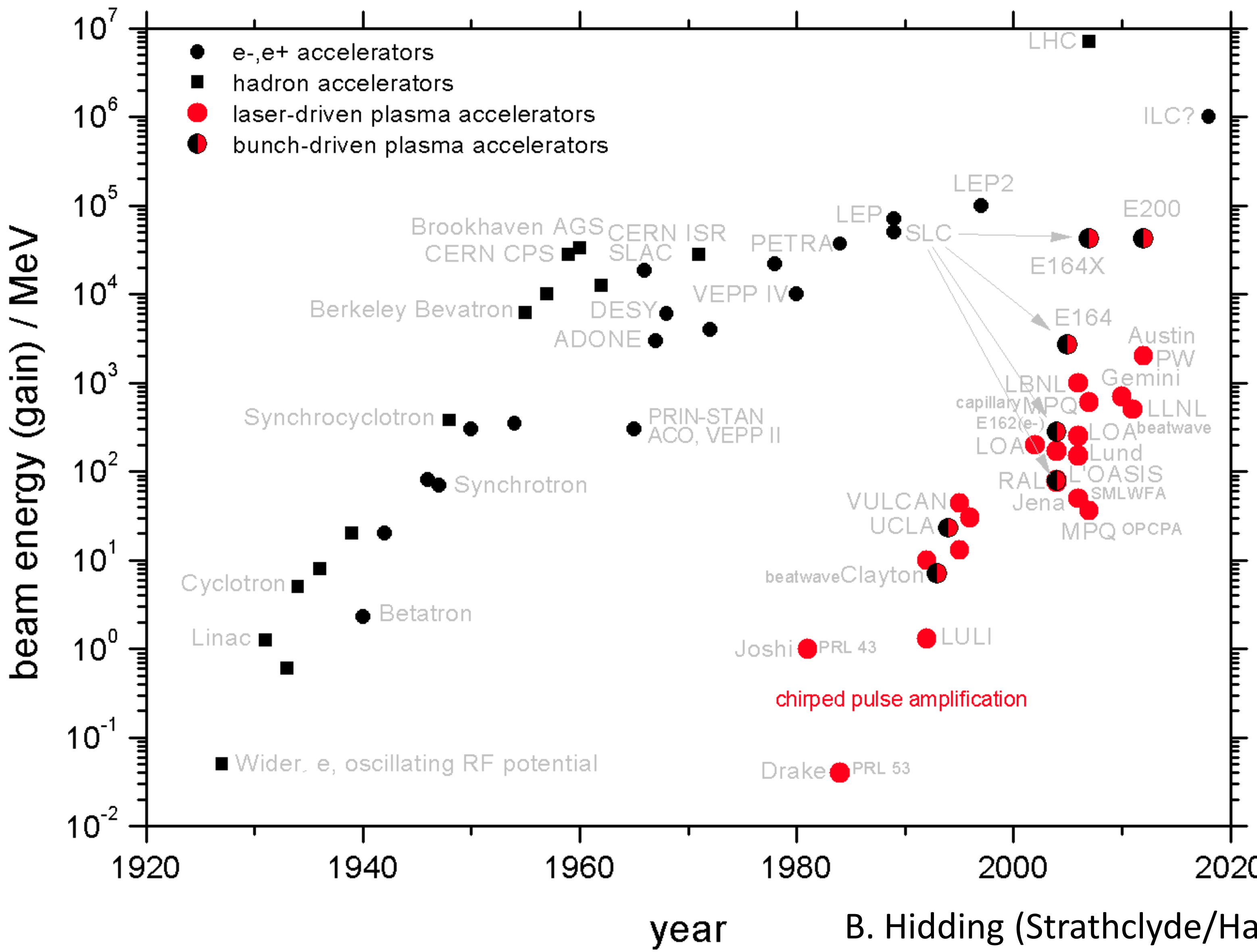

B. Hidding (Strathclyde/Hamburg)

FLASHforward @ DESY

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Mission and goals of the FLASHForward▸▸ project

Mission

> To demonstrate the potential of beam-driven plasma wakefield accelerators for the production of high-quality electron beams supporting free-electron laser operation as a first step towards future high-energy physics applications

Scientific goals

> Characterization of **externally injected** electron beams and controlled release from a wakefield accelerator with energies > 1.6 GeV

> Exploration of novel **in-plasma beam-generation** techniques to provide > 1.6 GeV energy, < 100 nm transverse normalized emittance, ~1 fs duration, and > 1 kA current electron bunches

> Assessment of beams for **free-electron laser gain** at wavelengths on the few-nanometer scale

FLASHforward @ DESY

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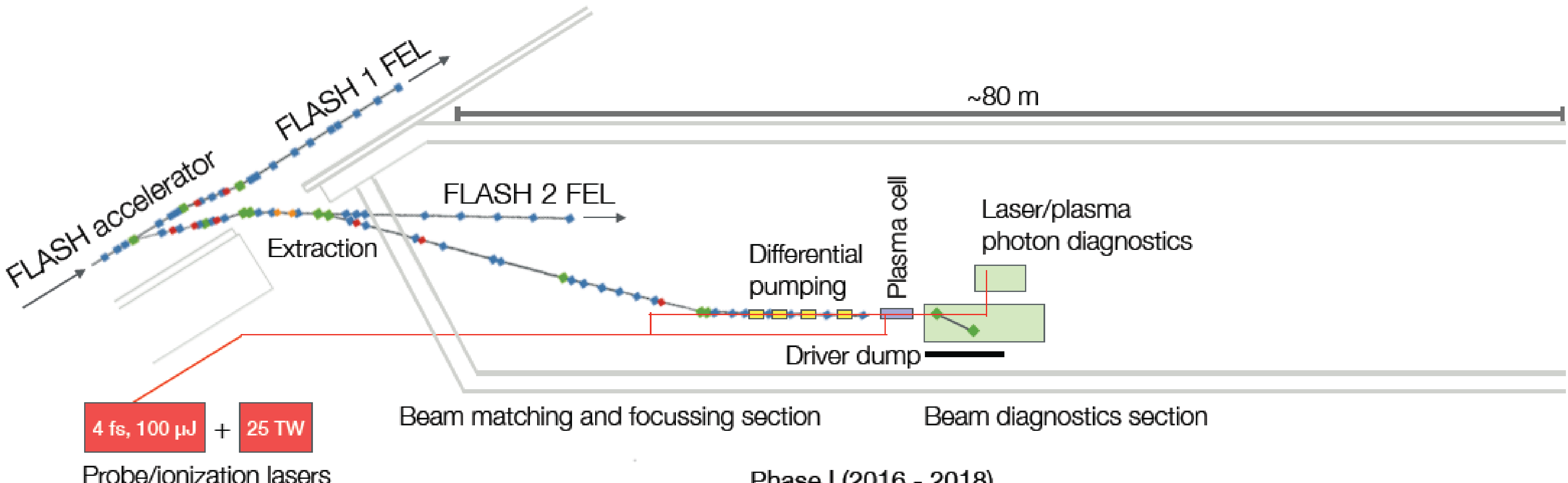
FLASHForward▸▸ beamline overview

Conceptual design finished
Technical design in progress
Operation to start in ~2016, run for 4 years+

Capabilities of the plasma-wake driver beam

- FLASH FEL-quality (~1.25 GeV, ~0.1% energy spread, ~2 μm transverse norm. emittance)
- Variable longitudinal beam shape (e.g. triangular)
- Sub 30 fs laser-to-beam synchronization for diagnostics/laser-triggered injection schemes
- 10 Hz repetition rate with up to 2 bunches at 1 μs separation
  + optional witness beam at ~100 fs separation, simultaneous with FLASH 1 and 2



Phase I (2016 - 2018)

FLASHforward @ DESY

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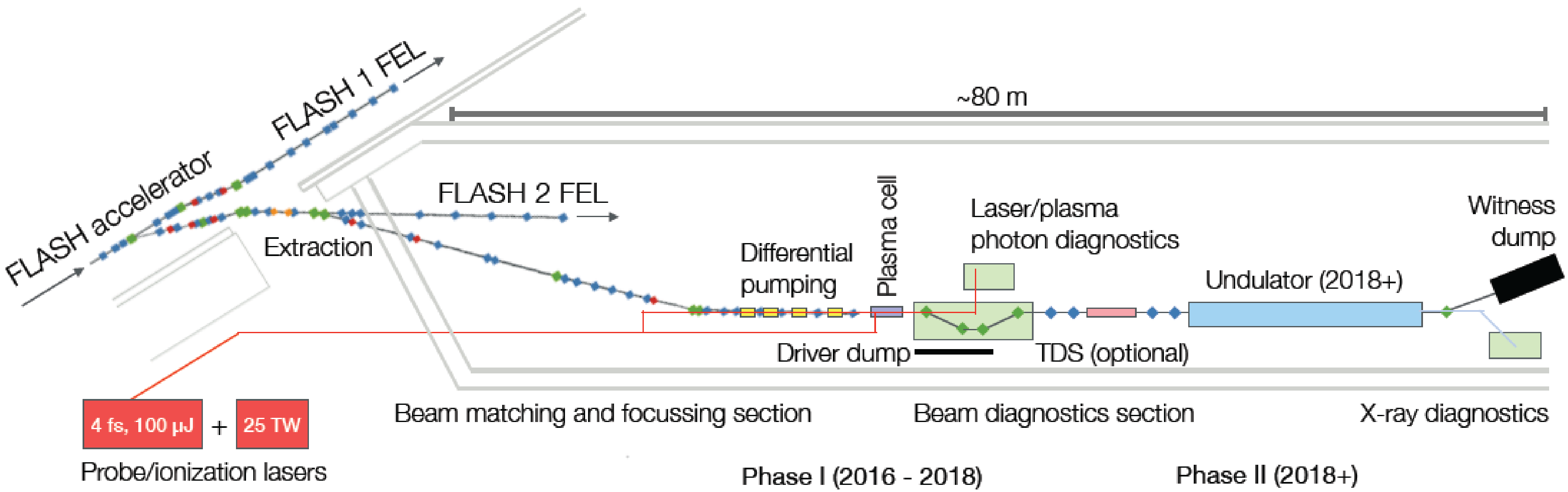
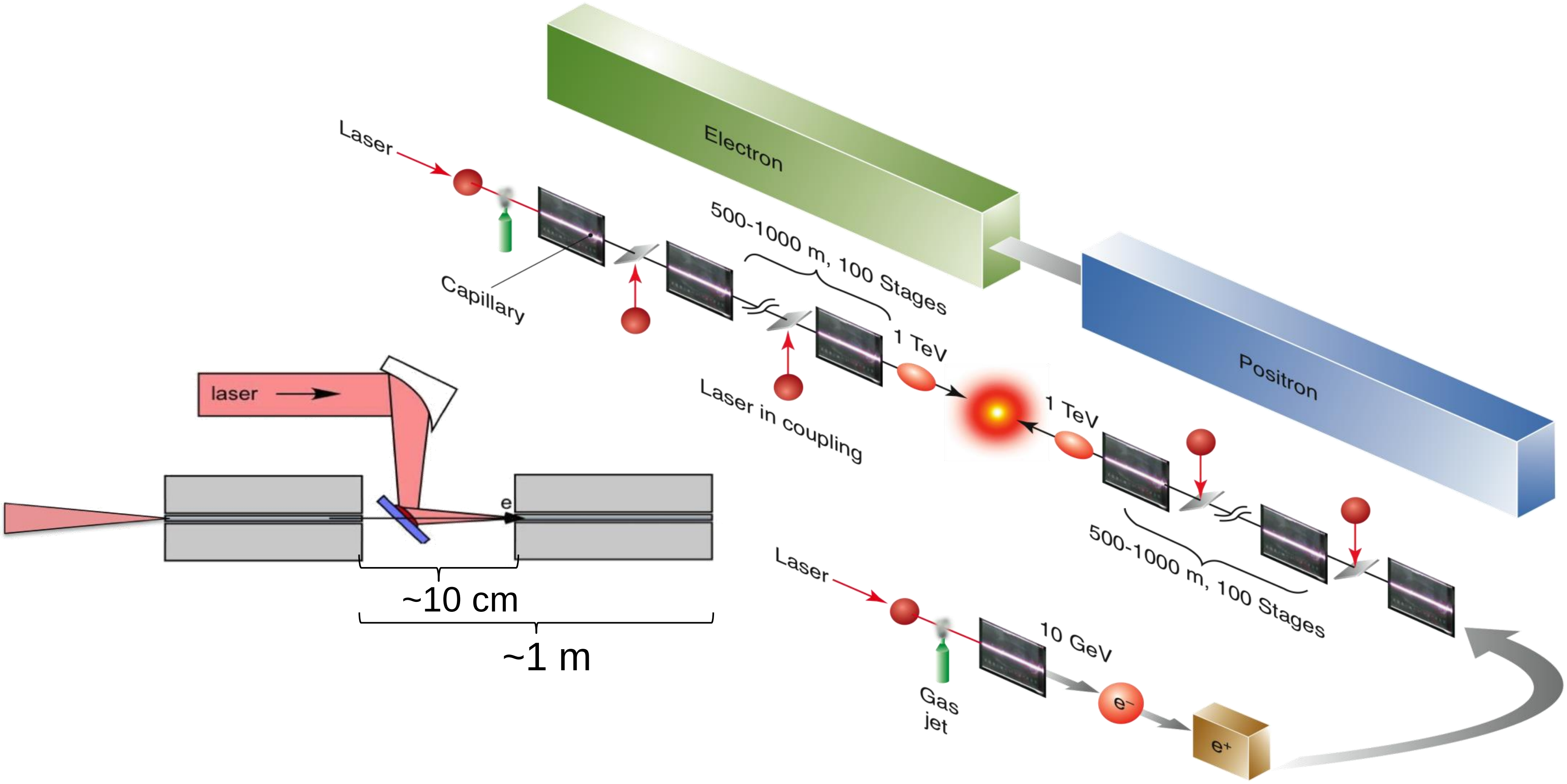


Realising the dreams?

- **A laser-plasma-driven linear collider?**



Beam-driven PWFA LC?

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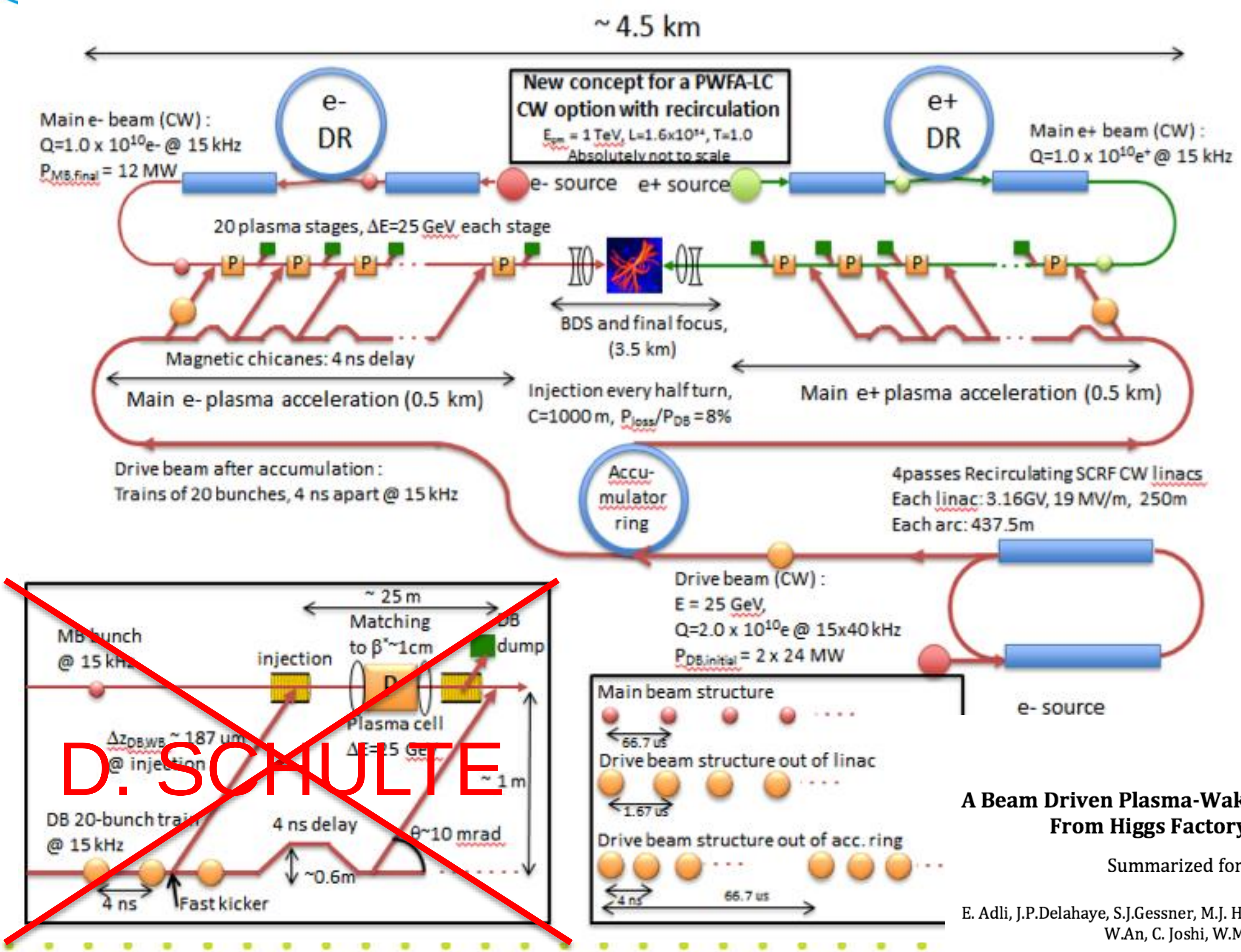

SLAC-PUB-15426
arXiv:1308.1145

A Beam Driven Plasma-Wakefield Linear Collider: From Higgs Factory to Multi-TeV

Summarized for CSS2013

E. Adli, J.P.Delahaye, S.J.Gessner, M.J. Hogan, T. Raubenheimer (SLAC)
W.An, C. Joshi, W.Mori (UCLA)

Conclusion – D. Schulte

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– **Plasma acceleration is an interesting and promising technology**
  - Might be useful for linear colliders
– **Some work to arrive at a parameter baseline**
  - Needed in order to identify the relevant issues
– **Important R&D required to establish feasibility of collider**
  - Positron acceleration
  - Beam-plasma interaction (hollow plasma, …)
  - Efficiencies
  - Tolerances: timing, emittance preservation - ~ 3 nm tolerance required?
  - Cost
  - …
– **Interesting future R&D**
  - Collaboration of linear collider and plasma experts is essential

Summary and Outlook

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- Particle & accelerator physics very lively – many ideas out there
- Recently, great upsurge of interest in new large rings, aimed at ~ 100 TeV pp but with possibility of initial e^+e^-
- ILC – technically mature – but expensive
- CLIC – significant development required – < 1 TeV, cost ~ ILC
- Circular e^+e^- – Higgs factory cheaper than LC – but not trivial accl. physics & no energy-upgrade path…
- PWA – very exciting, but long way from a LC for particle physics – requires very large lumi = amps & exquisite beam sizes, stability
- Many "off-ramps" for PWA to produce interesting devices such as "table-top" XFELs – but is there "off-ramp" for particle physics?
- Needs high-energy beam driver and large cross-section physics
- I commend our next speaker to you…..

Backup slides

Inject beam

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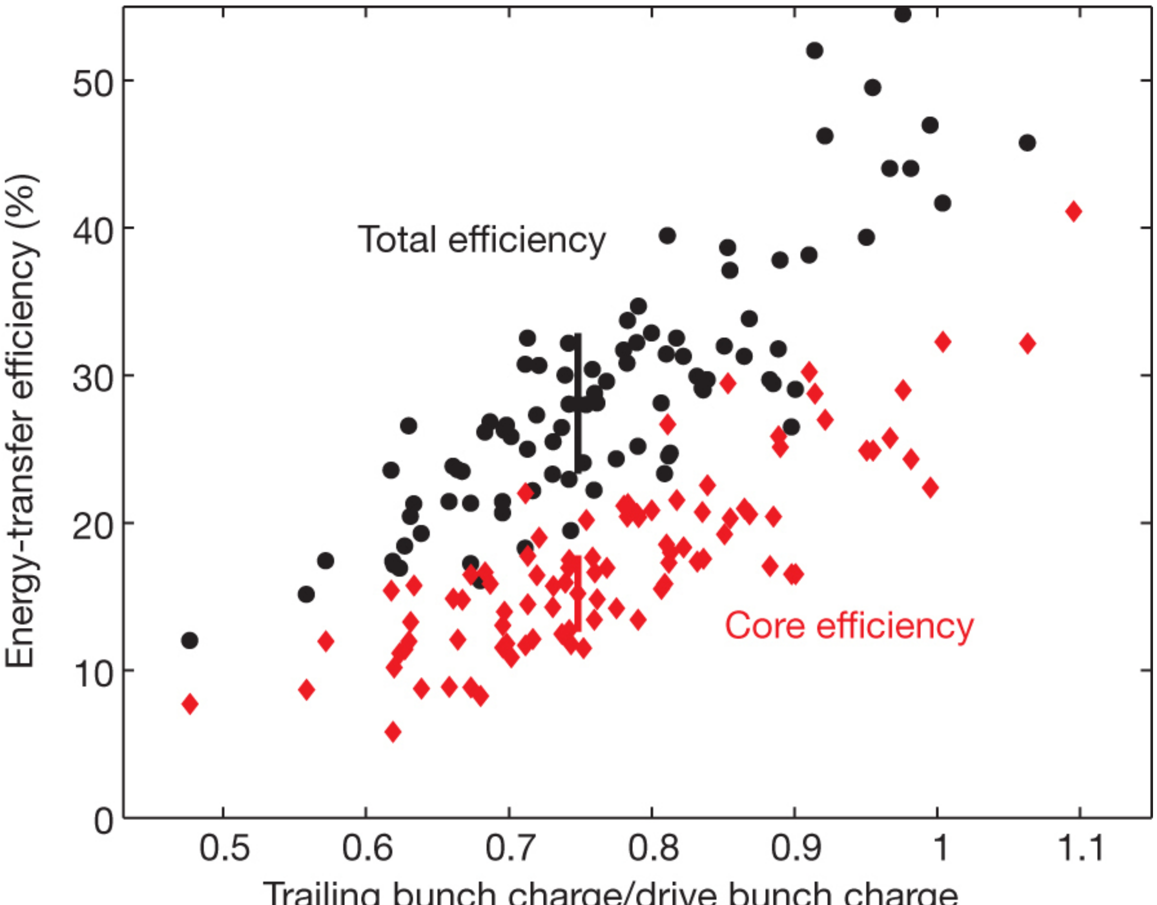
Litos et al., Nature 515, 92-95 (06.11.2014)



World-wide acceleration

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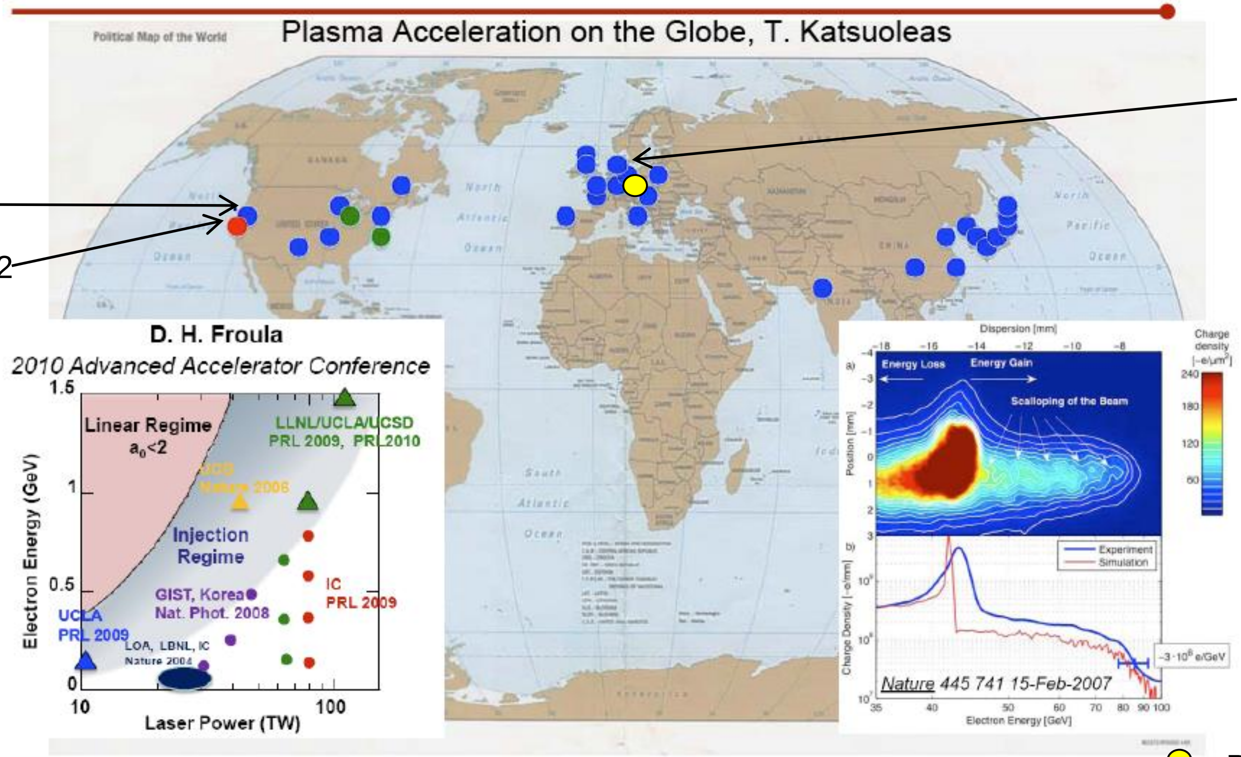
- **Enormous growth in activity world-wide – interesting experiments can be done at Universities but most activity at accelerator labs.**

World-Wide Interest in Plasma Acc.



BELLA

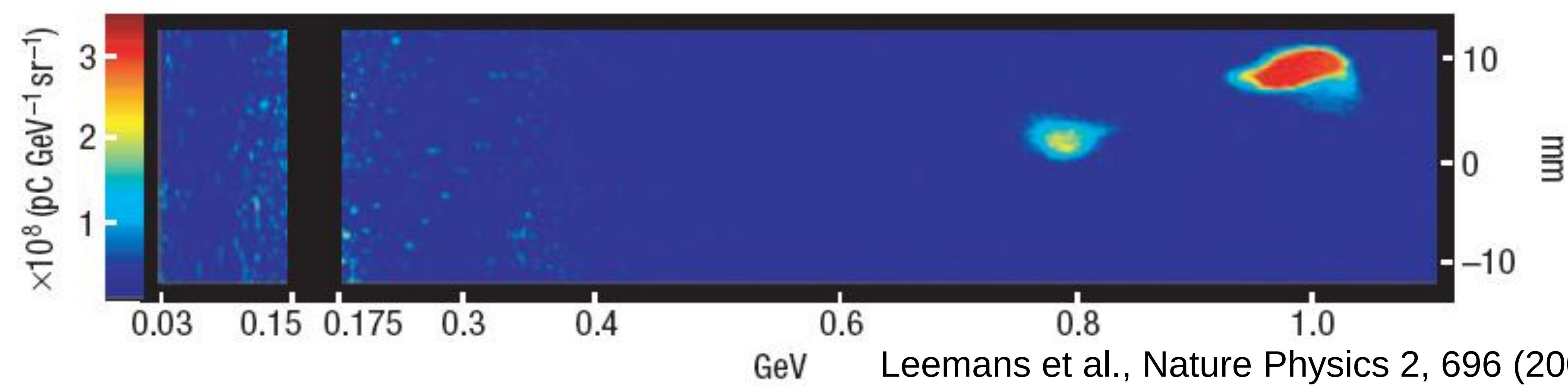
FACET, FACET2

LAOLA:
Helmholtz VI,
ELI, FLASH,
PITZ, REGAE

Laser Wake Expts   Electron Wake Expts   e-/e+ Wake Expts   Proton driven

Plasma Wake-Field Acceleration

- **Development of much higher gradient accelerator not only pushes back frontier for particle physics – also permits current accelerators to be built much smaller/cheaper.**
- **1 GeV electron beams on “table top”.**



Leemans et al., Nature Physics 2, 696 (2006)

Site-specific work plan

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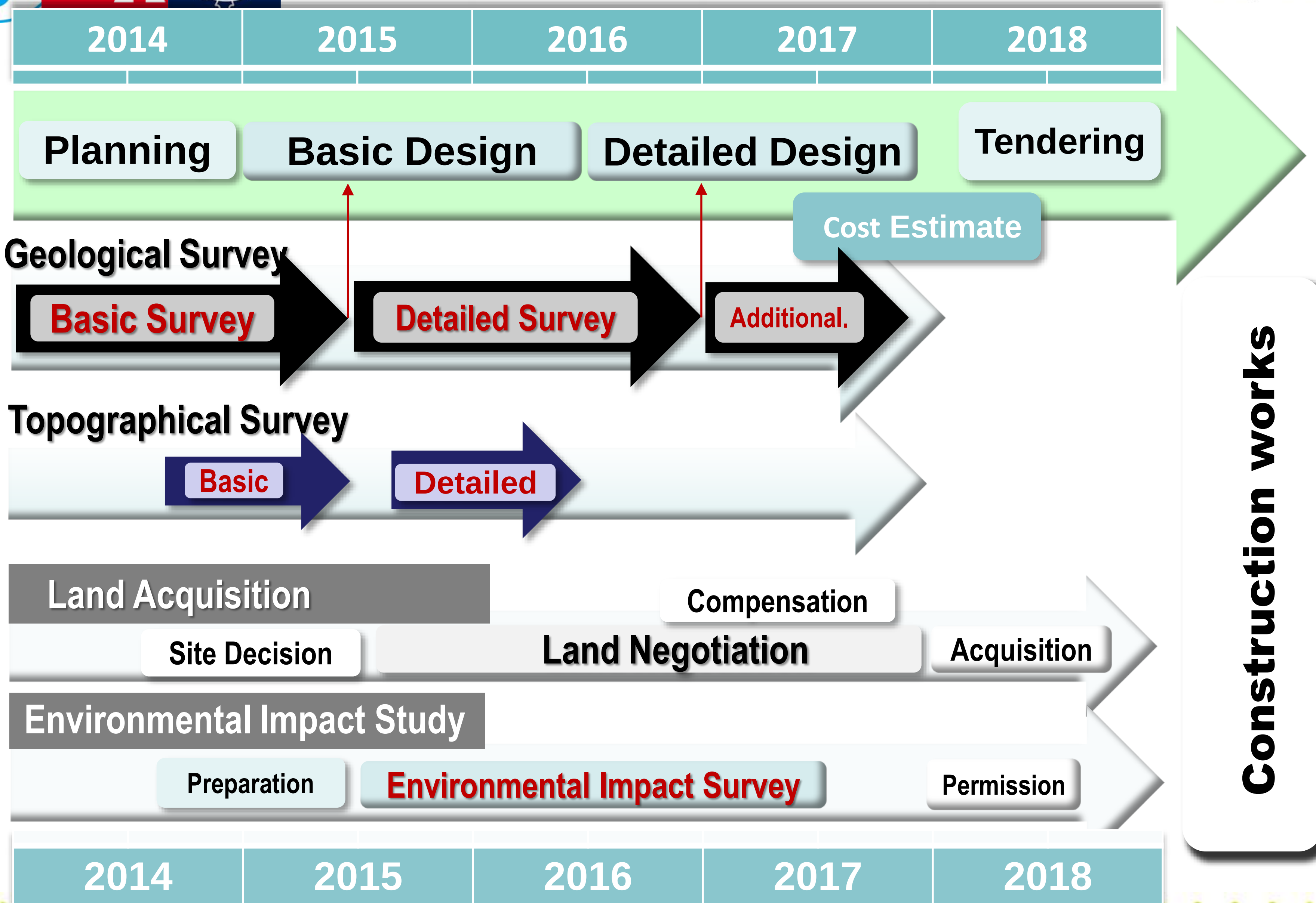

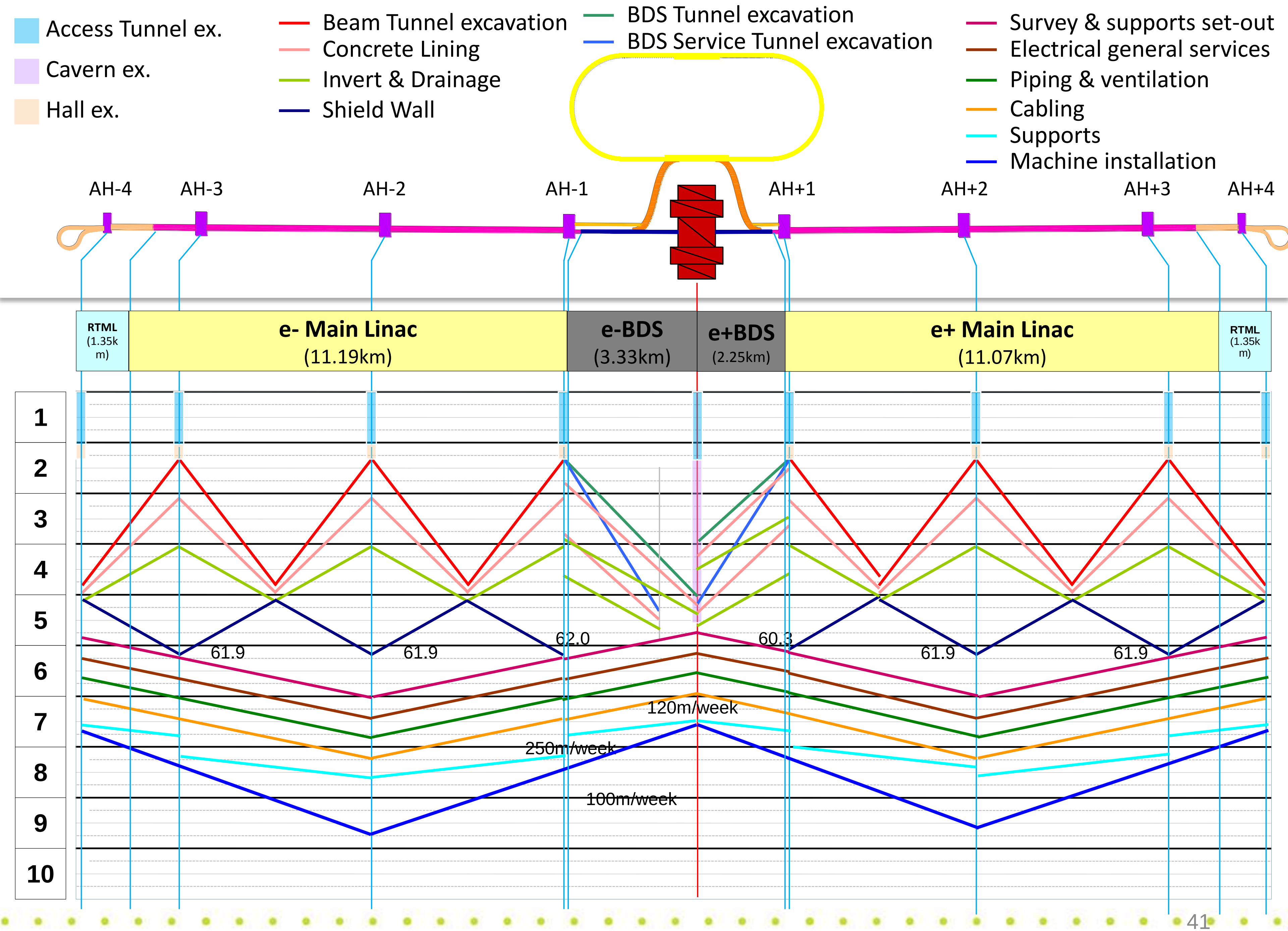
Access Tunnel ex.
Cavern ex.
Hall ex.
Beam Tunnel excavation
Concrete Lining
Invert & Drainage
Shield Wall
BDS Tunnel excavation
BDS Service Tunnel excavation
Survey & supports set-out
Electrical general services
Piping & ventilation
Cabling
Supports
Machine installation
AH-4
AH-3
AH-2
AH-1
AH+1
AH+2
AH+3
AH+4
RTML (1.35km)
e- Main Linac (11.19km)
e-BDS (3.33km)
e+BDS (2.25km)
e+ Main Linac (11.07km)
RTML (1.35km)
1
2
3
4
5
6
7
8
9
10
61.9
61.9
62.0
60.3
61.9
61.9
120m/week
250m/week
100m/week

Ring collider parameters

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Name		LEP2 for comparison	LEP3	TLEPt	SuperTRISTAN	CW250	Summers
Circumference	km	26.7	26.7	80	60	233	15.00
Beam energy	GeV	104.5	120	175	200	250	120
Bunch population	10^10	57.5	100	75	249.2	48.5	48.5
Number of bunches/beam		4	4	12	1	41	3
Number of IP		4	2	2	1	1	1
Bunch collision frequency	kHz	44.91	44.91	44.97	5.00	52.75	65.10
geo.emit(x)	nm	48	25	20	3.2	3.6	3.6
geo.emit(y)	nm	0.25	0.1	0.1	0.017	0.00022	0.00099
betax	mm	1500	200	200	30	20	20
betay	mm	50	1	1	0.32	0.6	0.6
sigx	micron	268	71	63	9.8	8.5	8.5
sigy	micron	3.536	0.32	0.32	0.0738	0.0244	0.0244
sigz	mm	16.1	2.3	2.5	1.4	6.67	6.67
half.cross.angle	mrad	0	0	0	35	17	34
bending radius	km	3.096	2.62	9	7.65	29	1.9
radiation loss/turn	GeV	3.408	6.99	9.3	18.5	11.9	9.7
Damping partition		1.1	1.5	1	2	2	2
radiation power (2beams)	MW	22	100	100	74	98	98
Tune shift/IP (x)		0.025	0.09	0.05	0.017	0.0007	0.0014
Tune shift/IP (y)		0.065	0.08	0.05	0.155	0.23	0.2
Equilibrium energy spread	%	0.22	0.23	0.22	0.196	0.126	0.236
Luminosity per IP	10^34	0.0125	1.07	0.65	5.2	7.6	4.4

SCRF Linac Technology

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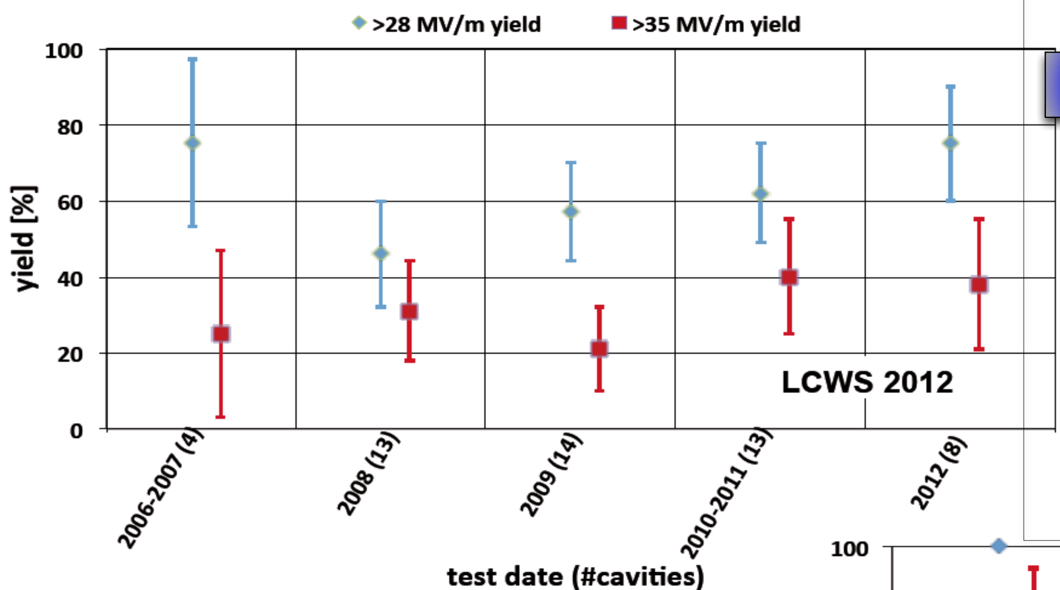
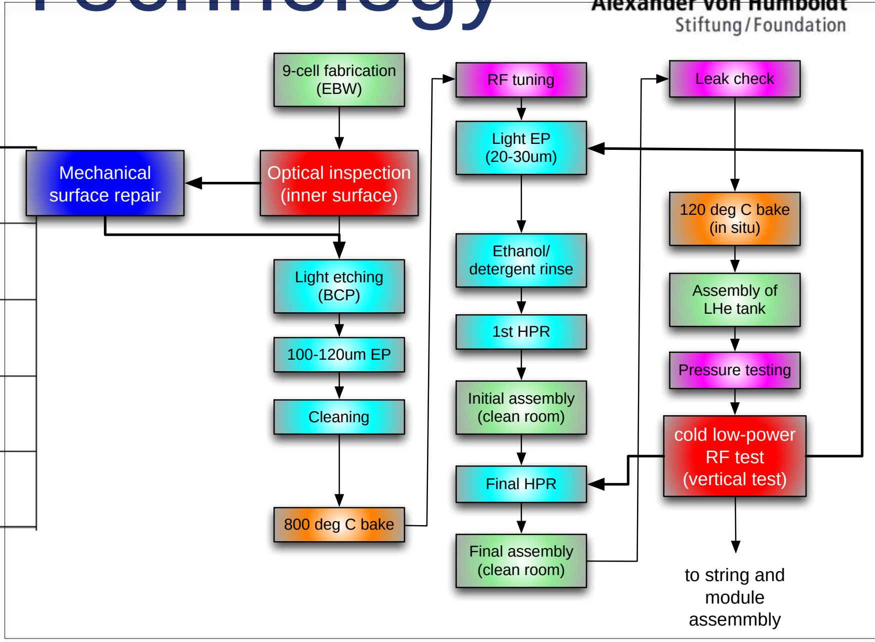
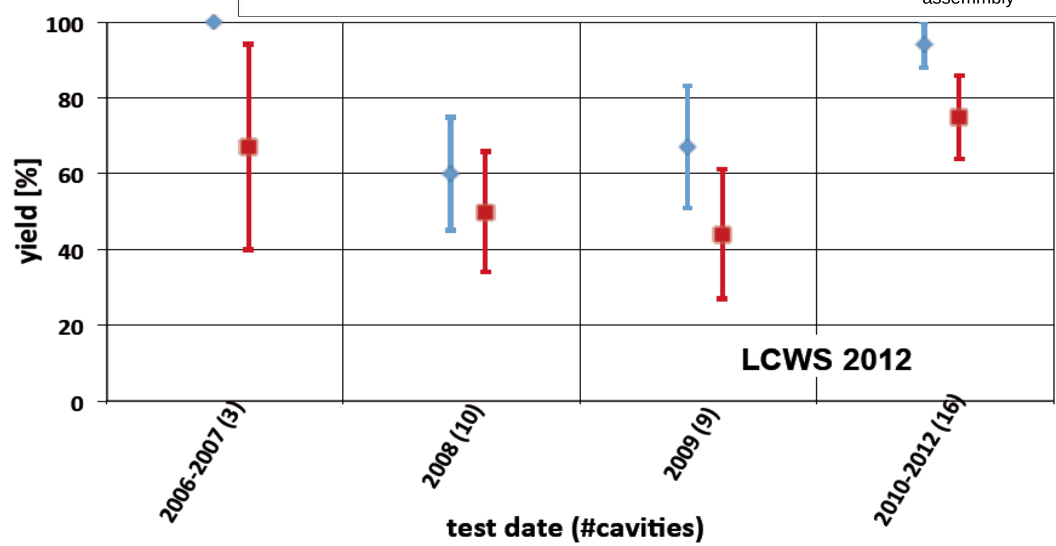


(a) First-pass yield





(b) Second-pass yield

Cryomodule

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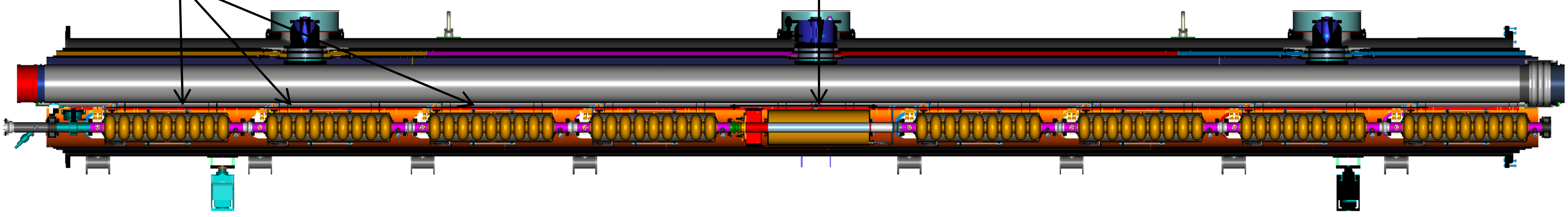
cavities (8)

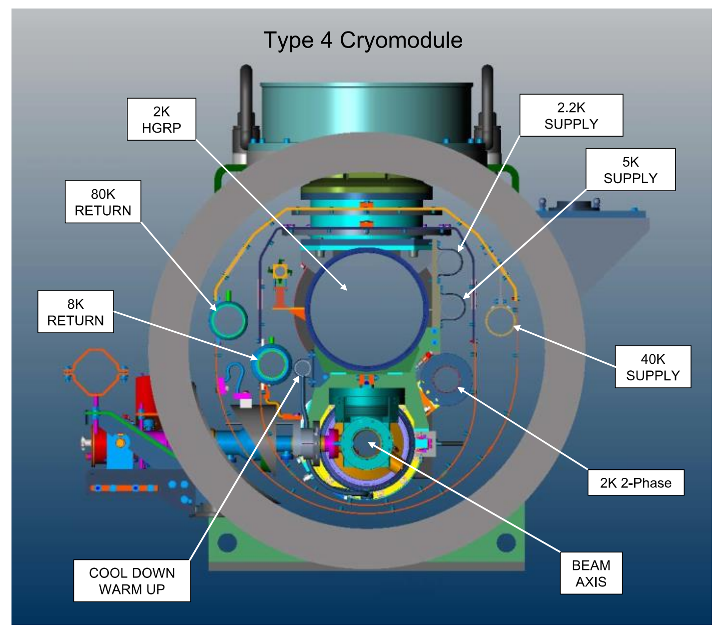
SC quad package

Type-B module

Type-A has 9 cavities and no quadrupole



12.652 m (slot length)



Cryomodule at FLASH

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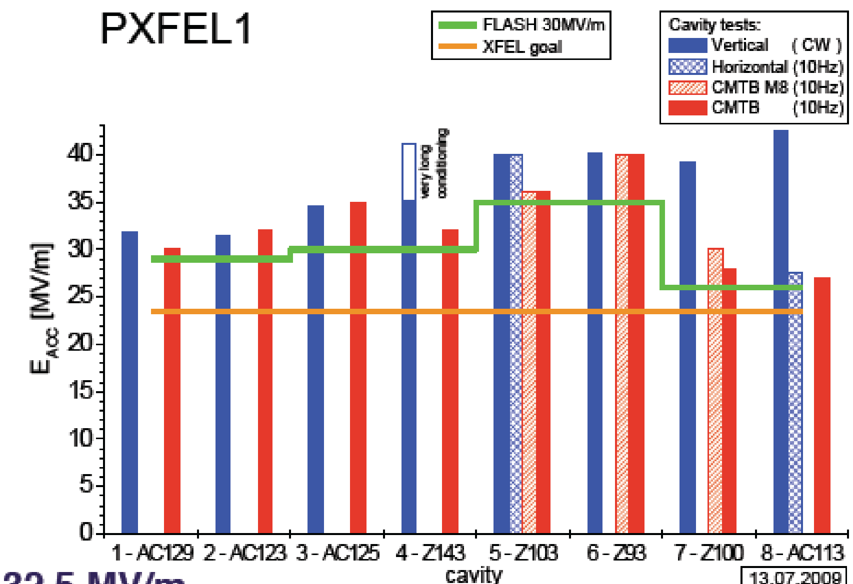
The European XFEL

European XFEL

PXFEL1 - The *Chinese* Module at CMTB



- The accelerator module PXFEL1 was conditioned and tested at the Cryo-Module Test Bench (CMTB).
- The average maximum gradient is **32.5 MV/m.**
- After string and module installation we have seen a **gradient reduction of only 5%.**
- PXFEL1 has been installed at FLASH and **can be operated** there with an average gradient of **30 MV/m.**
- The **XFEL waveguide distribution** is used.

TTC Meeting, Fermilab, April 19/22, 2010
Hans Weise / DESY

FLASH Achievements

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High beam power and long bunch-trains *(Sept 2009)*

Metric	ILC Goal	Achieved
Macro-pulse current	9mA	9mA
Bunches per pulse	2400 x 3nC (3MHz)	1800 x 3nC 2400 x 2nC
Cavities operating at high gradients, close to quench	31.5MV/m +/-20%	4 cavities > 30MV/m

Gradient operating margins *(Feb 2012)*

Metric	ILC Goal	Achieved
Cavity gradient flatness (all cavities in vector sum)	2% ΔV/V (800μs, 5.8mA) (800μs, 9mA)	<0.3% ΔV/V (800μs, 4.5mA) *First tests of automation for Pk/Ql control*
Gradient operating margin	All cavities operating within 3% of quench limits	Some cavities within ~5% of quench (800us, 4.5mA) *First tests of operations strategies for gradients close to quench*
Energy Stability	0.1% rms at 250GeV	<0.15% p-p (0.4ms) <0.02% rms (5Hz)

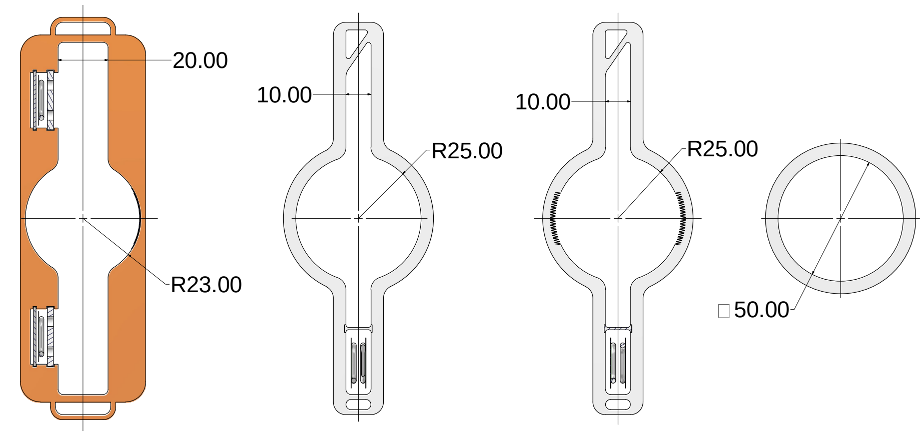
SCRF Linac Technology

Table 2.2. Main achievements of the SCRF R&D effort.

Achievements
Understanding and mitigation of field emission at low gradient.
Establishment of a baseline sequence of cavity fabrication and surface preparation for ILC.
Achievement of a production yield of 94 % at 28 MV/m and of 75 % at 35 MV/m ± 20 %.
Achievement of an average gradient of 37.1 MV/m in the ensemble.
Achievement of an average field gradient of 32 MV/m in a prototype cryomodule for the European XFEL program.
Demonstration of the technical feasibility of assembling ILC cryomodules with global in-kind contributions.

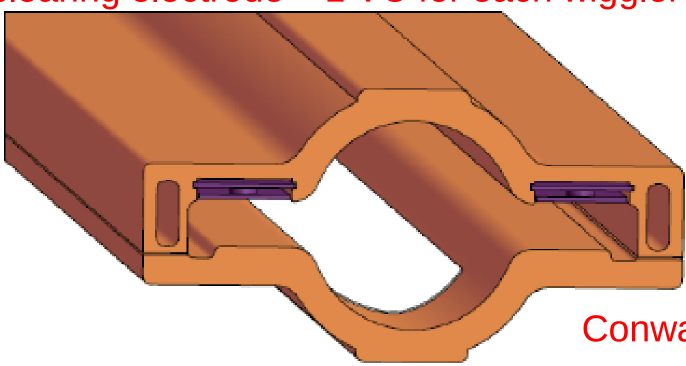
DR: Vacuum (Electron Cloud)

- Reduction of **electron cloud build-up** in e+ ring critical for ILC parameters
- Full e-cloud mitigation concepts included into vacuum design
  - CesrTA (and other) R&D results
- Vacuum System Design/Costing
  - **Super-KEK-B VCs in production with similar designs to ILC DR**



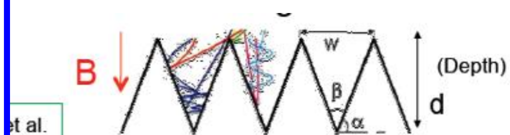
(a) WIGGLER CHAMBER (b) ARC CHAMBER (c) DIPOLE CHAMBER (d) DRIFT CHAMBER

DR Wiggler chamber concept with thermal spray clearing electrode – 1 VC for each wiggler pair.

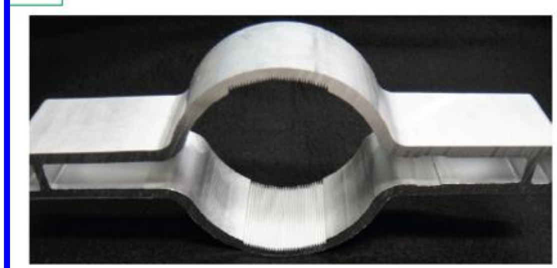


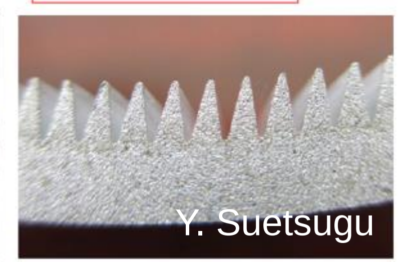
Conway/Li

SuperKEKB Dipole Chamber Extrusion

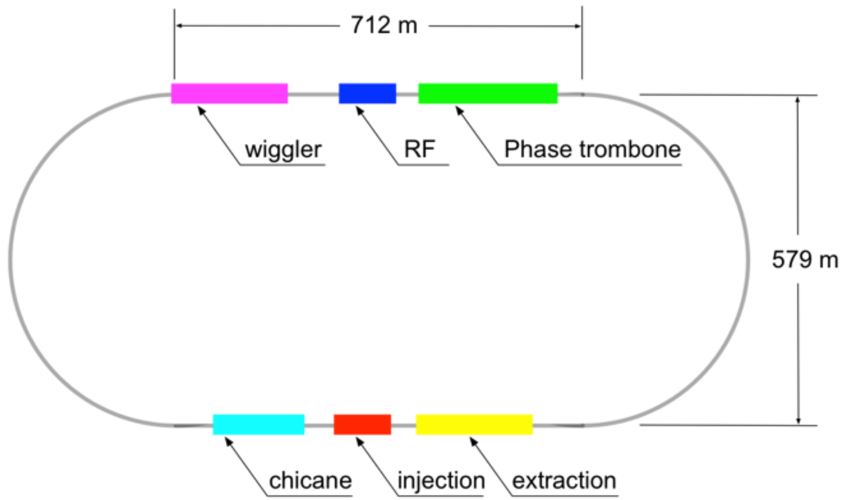


Valley : R0.1~0.12
Top : R0.15
Angle : 18~18.3°





Damping Rings



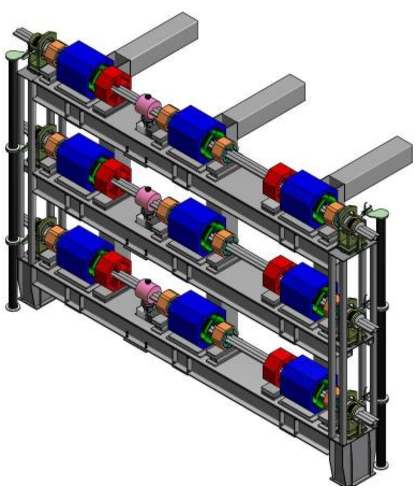
Circumference		3.2	km
Energy		5	GeV
RF frequency		650	MHz
Beam current		390	mA
Store time		200 (100)	ms
Trans. damping time		24 (13)	ms
Extracted emittance	x	5.5	µm
(normalised)	y	20	nm
No. cavities		10 (12)	
Total voltage		14 (22)	MV
RF power / coupler		176 (272)	kW
No.wiggler magnets		54	
Total length wiggler		113	m
Wiggler field		1.5 (2.2)	T
Beam power		1.76 (2.38)	MW

Values in () are for 10-Hz mode

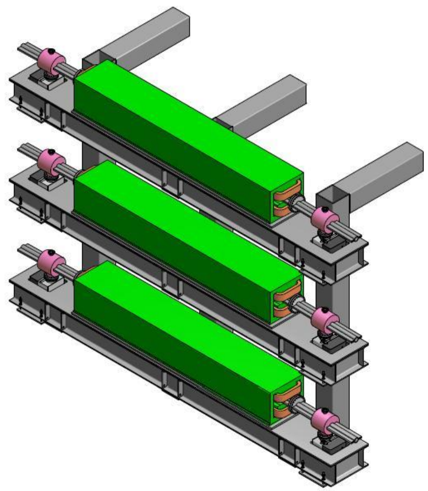
Positron ring (upgrade)

Electron ring (baseline)

Positron ring (baseline)



Arc quadrupole section



Dipole section

Many similarities to modern 3rd-generation light sources

Positron Source

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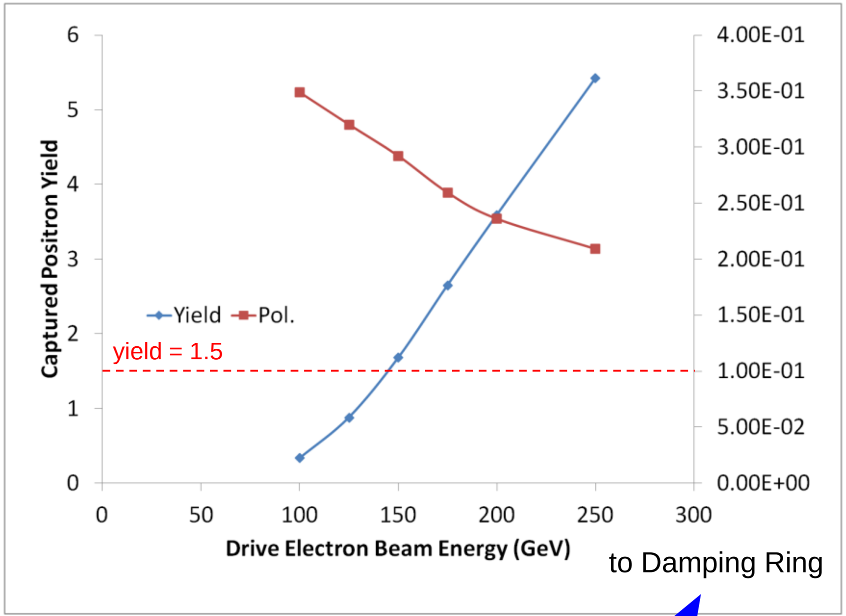
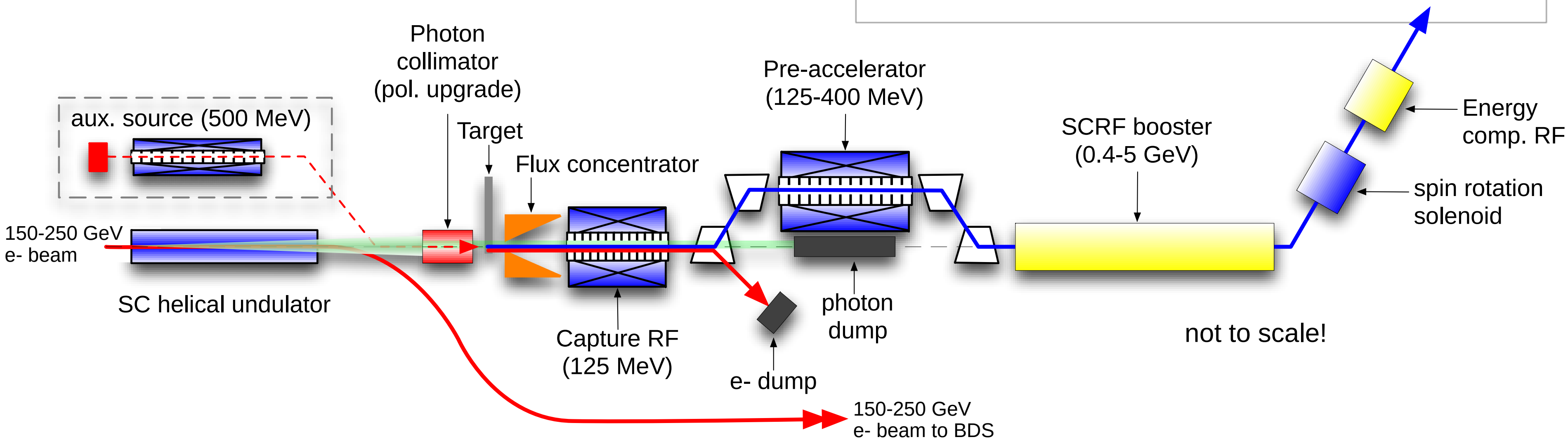
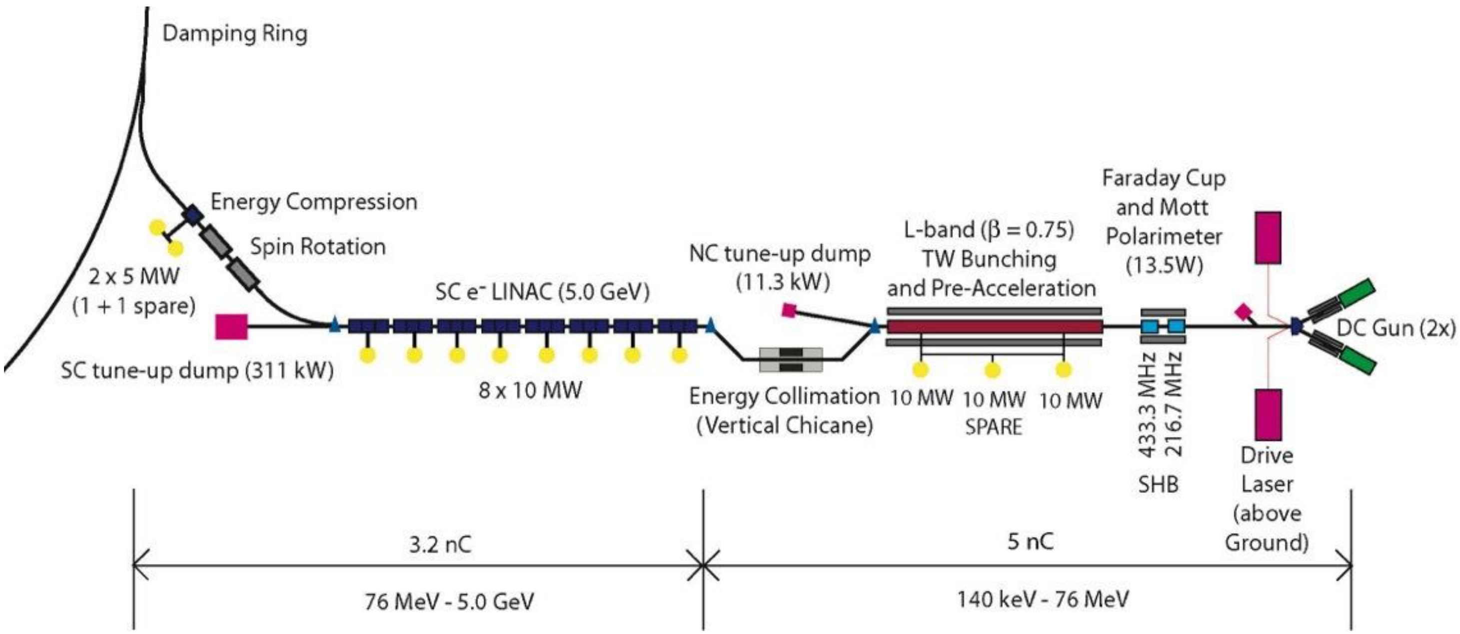
- located at exit of electron Main Linac
- 147m SC helical undulator
- driven by primary electron beam (150-250 GeV)
- produces ~30 MeV photons
- converted in thin target into e^+e^- pairs



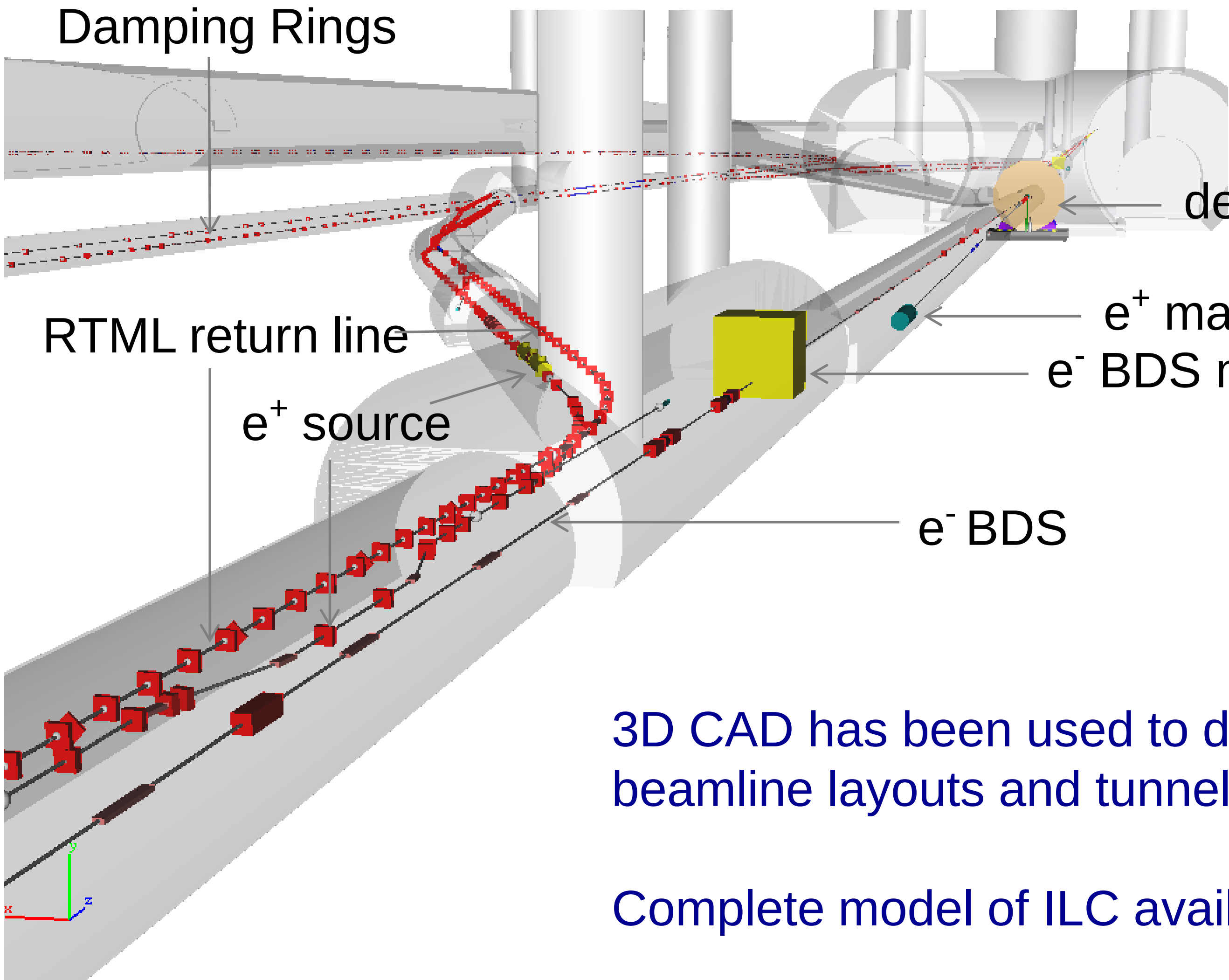


Polarised Electron Source

- Laser-driven photo cathode (GaAs)
- DC gun
- Integrated into common tunnel with positron BDS



Central Region Integration



3D CAD has been used to developed beamline layouts and tunnel requirements.

Complete model of ILC available.

Japanese Sites

- GDE-CFS group visited two sites, Oct., 2011.
- GDE EC visit in Jan. 2012.

250 GeV CM (first stage)

Relative to TDR 500 GeV baseline

Half linacs solution
G = 31.5 MV/m

POSITRON linac straightforward
~50% ML linac cost (cryomodules, klystrons, cryo etc.)
~50% ML AC power

ELECTRON linac needs 10Hz mode for e+ production
ΔE = 135 GeV instead of 110 GeV (+25 GeV)
~57% ML linac cost (cryomodules, klystrons etc)

Main Linac infrastructure
Linac components: 50%
Cryogenics: 65%
RF AC power: 80%

10Hz needs (1/2 linac × 10Hz/5Hz):
100% ML AC power
(1/2 linac × 10Hz/5Hz)
80% cryo cost
(50% static + 100% dynamic)

Increasing SCRF Gradient

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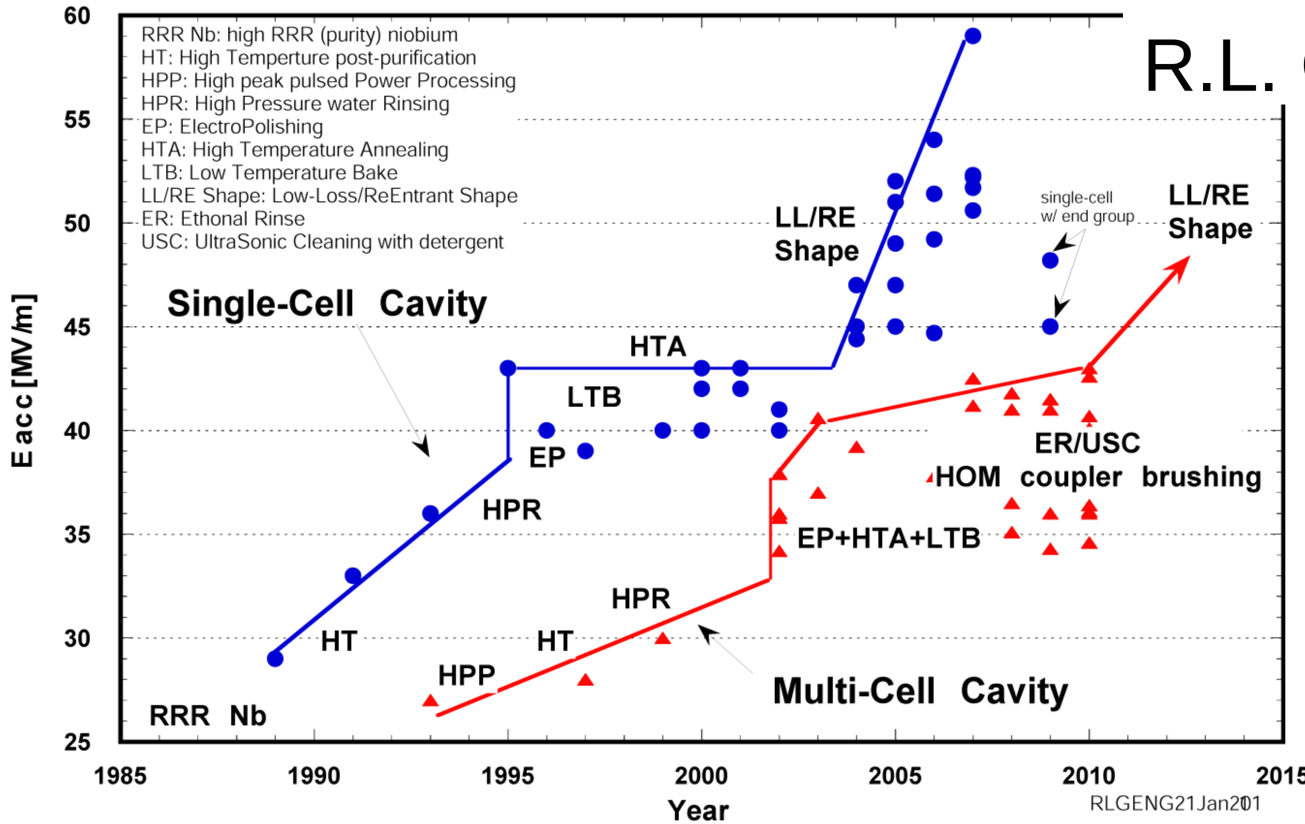
L-Band SRF Niobium Cavity Gradient Envelope Evolution

R.L. Geng



Understanding in gradient limits and inventing breakthrough solutions are responsible for gradient progresses. This has been a tradition in SRF community and rapid gradient progress continues. Up to 60 MV/m gradient has been demonstrated in 1-cell 1300 MHz Nb cavity. 45-50 MV/m gradient demonstration in 9-cell cavity is foreseen in next 5 years.

Collider 'Wall Plug' AC Power

ILC and 80 km ring:	ILC -H	ILC-nom	Ring - H	Ring - t
E_cm (GeV)	250	500	240	350
SRF Power to Beam (MW)	5.2	10.5	100	100
Eff. RF Length (m)	7,837	15,674	600	1200
AC to RF efficiency (%)	10	14	45	45
klystron operating margin, HVPS, Klystron Aux and klystron water cooling (%)			20*	20
Cryo (MW)	16	32	20	40
Normal Conducting (exc. Injector complex) (MW)	6	10	120**	120
Injector complex	32	32	16***	16
Conventional (Air, lighting, ..)	6	6****	18	18
Total (exc. detector)	**112**	**153**	**396**	**416**

*** 5% for operating margin, 2% for auxiliaries, 3% for HVPS and 10% for water cooling**
**** assume 1.5 kW / m tunnel inclusive (ILC avg. 3 kW / m)**
****** from SSC / Fermilab injector (linac + LEB + MEB)**
******** 6 MW for 30 km beam tunnel complex; ~3x more for 80 ring**

Cf. Blondel et al. est. ~ 260 MW

TLEP Cost (Very Preliminary) Estimate

Cost in billion CHF

Bare tunnel	3.1 [1]
Services & Additional infrastructure (electricity, cooling, service cavern, RP, ventilation, access roads ...)	1.0 [2]
RF system	0.9 [3]
Cryo system	0.2 [4]
Vacuum system & RP	0.5 [5]
Magnet system for collider & injector ring	0.8 [6]
Pre-injector complex SPS reinforcements	0.5
Total	**7.0**

(1): J. Osborne, Amrup study, June 2012

(2): Extrapolation from LEP

(3): O. Brunner, detailed estimate, 7 May 2013

(4): F. Haug, 4th TLEP Days, 5 April 2013

(5): K. Oide : factor 2.5 higher than KEK, estimated for 80 km ring

(6): 24,000 magnets for collider & injector; cost per magnet 30 kCHF (LHeC);

Note: detector costs not included – count 0.5 per detector (LHC)

Similar to ILC500 – but site exists already

Parametric 'value' costing for TeV–class machines (KILCU)*:

- Civil Construction: 35 / m
- Utilities: 5000 / MW
- Superconducting RF 180 / m (inclusive)**
- 'Conventional Acc.' 35 / m

		TLEP-t quantity	MILCU	ILC quantity	MILCU
Civil Construction	km	80	3000	34	1200
Power and cooling	MW	416	2000	162	800
SRF (incl. packing)	km	1.2 / .7	250	22	4000
'Conventional'	km	160	5500 ***	12	800
Installation	km	80	100	34	100
Total			**11000**		**7800****

*** 1 ILCU = USD 01.2012**
**** cryogenics not included – reuse LHC assumed; 900 MILCU included for ILC**
***** Conventional cost – scale reduced 2x for ring**

Institutional Labor is part of the project cost and must also be analyzed.

Upgrades

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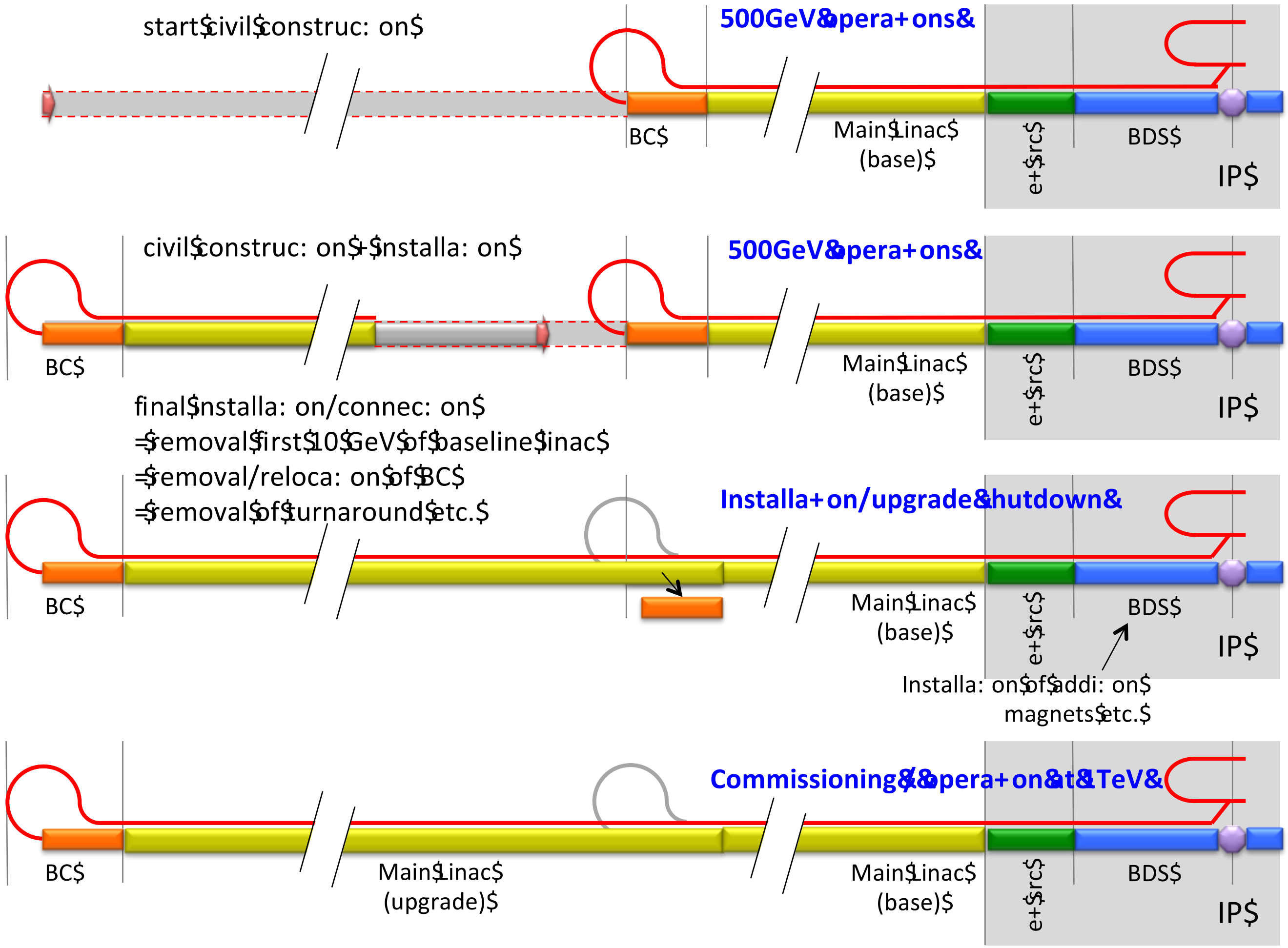

Shown is initial 500 GeV -> 1 TeV. Similar scenario for starting with 250 GeV Higgs factory – or could build complete 500 GeV tunnel and half-populate.

Gamma-Gamma General Status

- γ-γ technology is still premature
  - need > 5 years of R&D
- Cannot start with γ-γ at the lowest energy if early start is planned
  - need 100% confidence at the time of project approval
- From technology view point it is reasonable to start with e^+e^- at ZH and, if needed, convert to γ-γ later
  - importance of γ-γ must be evaluated before the construction of e+e- (possible constraints in IR, e.g., the crossing angle)

(Yokoya LCWS12)

Fermilab CM2 results

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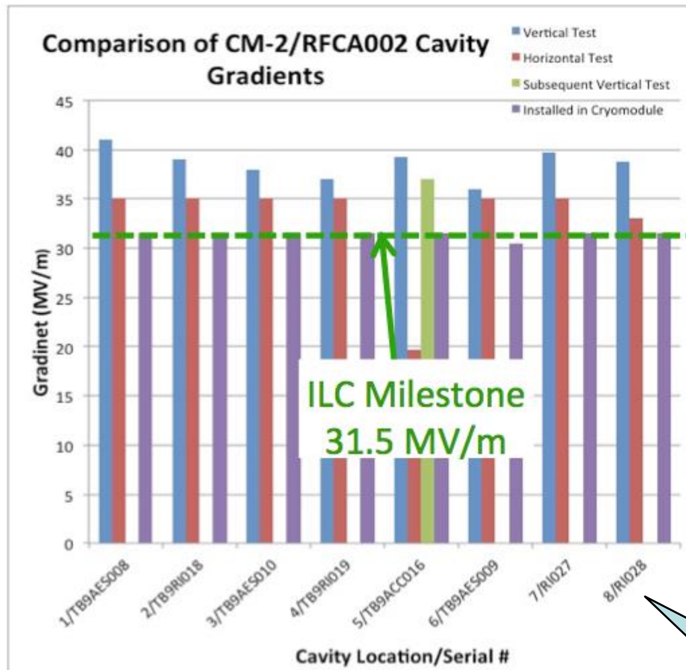
CM-2 installed in ASTA cave

Single cavity results

- Operating conditions
  - 2 Kelvin (23 Torr)
  - Pulsed operation
  - 1.6 ms pulse
    - 590 µs fill + 969 µs flattop
  - 5 Hz repetition rate
  - Q_L set to 3.5 E6, variable coupling
  - LFDC active
- Results
  - 7/8 cavities achieve 31.5 MV/m (administrative limit)
  - Cavity #6 quenches at 30.5 MV/m



Fermilab

7 E. Harms | CM-2 Status 08/10/2014

NEW!

courtesy E. Harms (FNAL)

MICE Schedule

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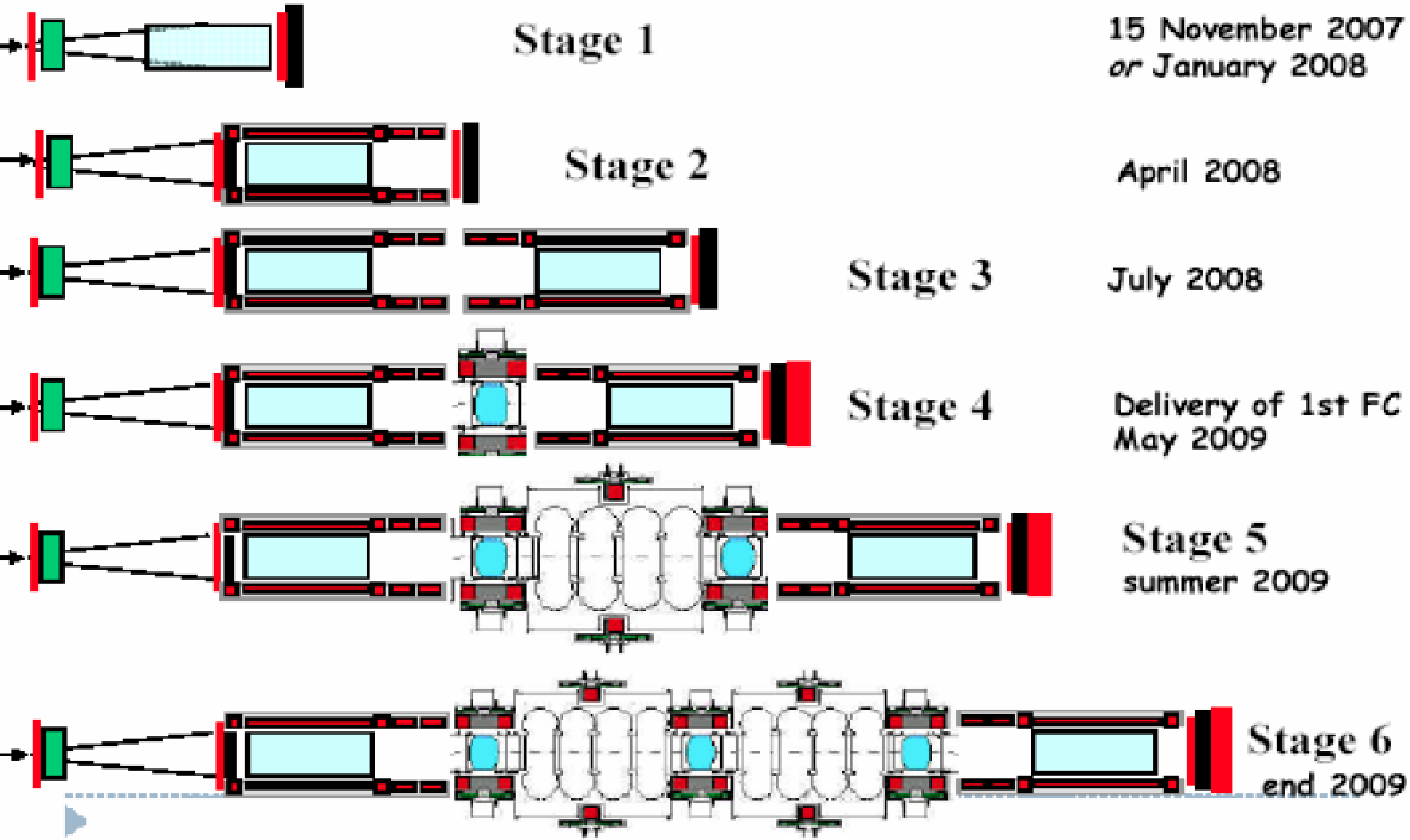

Run complete Q2 2017