Linear e^+e^- Colliders: ILC and CLIC

Technical readiness
Timelines
Upgrade paths

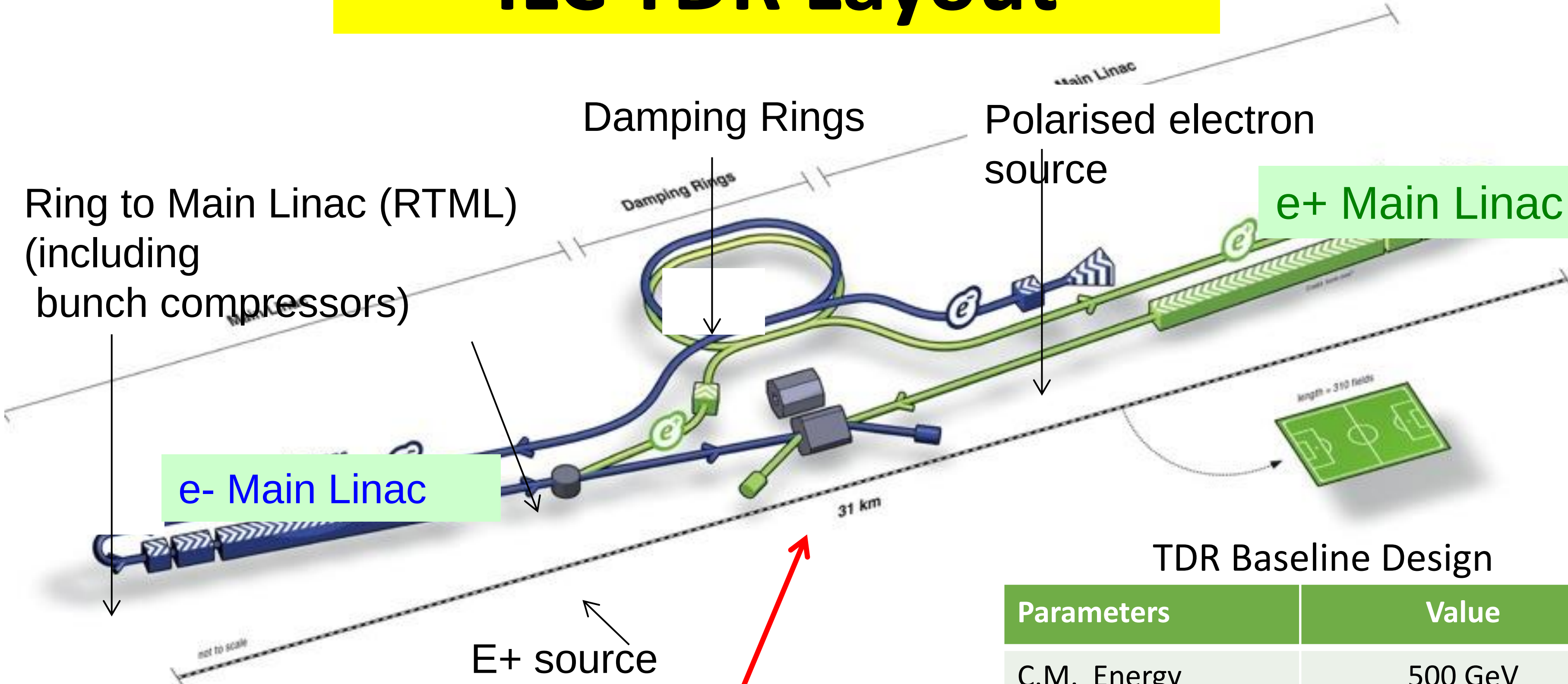
K. Yokoya (KEK)

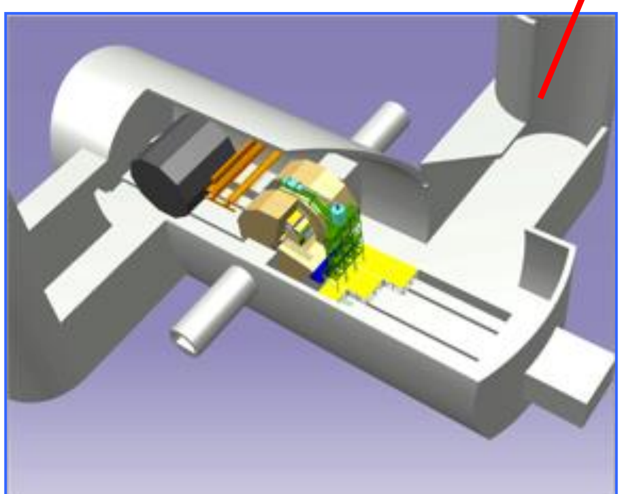
Aug.14, 2014,

Physics at LHC and Beyond, Quy-Nhon, Vietnam

Thanks to P.Burrows, D.Schulte, A.Yamamoto, K.Kubo, S.Kuroda, …. for the slides stolen.

ILC TDR Layout





TDR Baseline Design

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

SCRF Technology

- Cavity: High Gradient R&D (EU, AMs, AS) :
  - 35 MV/m with >90% yield by 2012(TDR)
  - Manufacturing with cost effective design
- Cryomodule performance (EU, AMs, AS)
- Beam Acceleration
  - 9 mA: FLASH (DESY)
  - 1 ms: STF2 (KEK)- Quantum Beam
- E-XFEL construction in progress
- LCLS at SLAC to be constructed

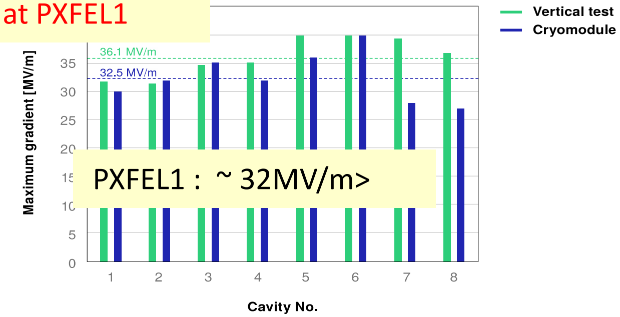
Cryomodule System Test

2014/07/05, A. Yamamoto

DESY: FLASH

- 1.25 GeV linac (TESLA-Like tech.)
- ILC-like bunch trains:
- 600 ms, 9 mA beam (2009); ← Demonstrated
  800 ms 4.5 mA (2012)
- RF-cryomodule string with beam → PXFEL1 operational at FLASH

XFEL Prototype at PXFEL1

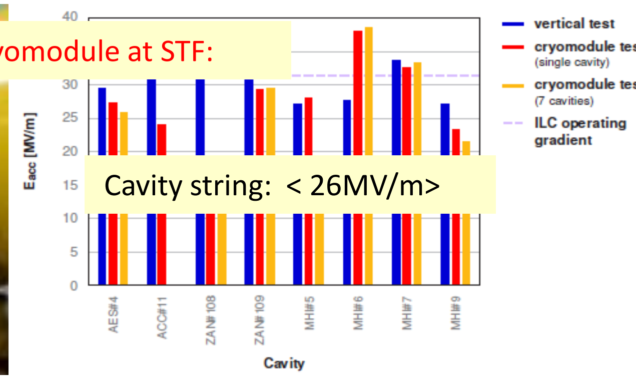


PXFEL1 : ~ 32MV/m>

KEK: STF/STF2

- S1-Global: completed (2010)
- Quantum Beam Accelerator (Inverse Llaser Compton): 6.7 mA, 1 ms ← Demonstrated
- CM1 test with beam (2014 ~2015)
- STF-COI: Facility to demonstrate CM assembly/test in near future

S1 Global Cryomodule at STF:



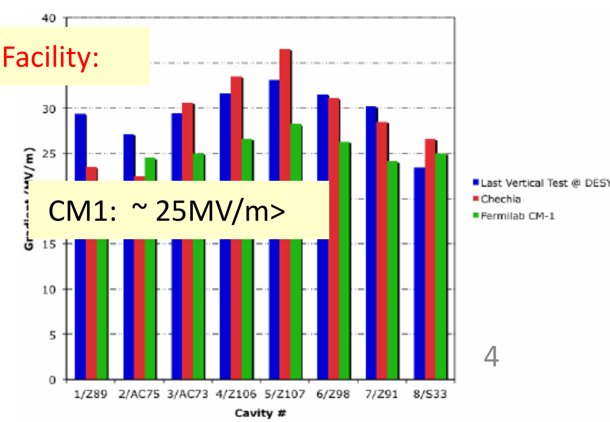
Cavity string: < 26MV/m>

FNAL: ASTA

(Advanced Superconducting Test Accelerator)

- CM1 test complete
- CM2 operation (2013)
- CM2 with beam (soon)

CM1 at NML Facility:



CM1: ~ 25MV/m>

IPAC14: Courtesy: H. Weise

100 s.c. Modules for the European XFEL

European XFEL

An Accelerator Complex for 17.5 GeV

3

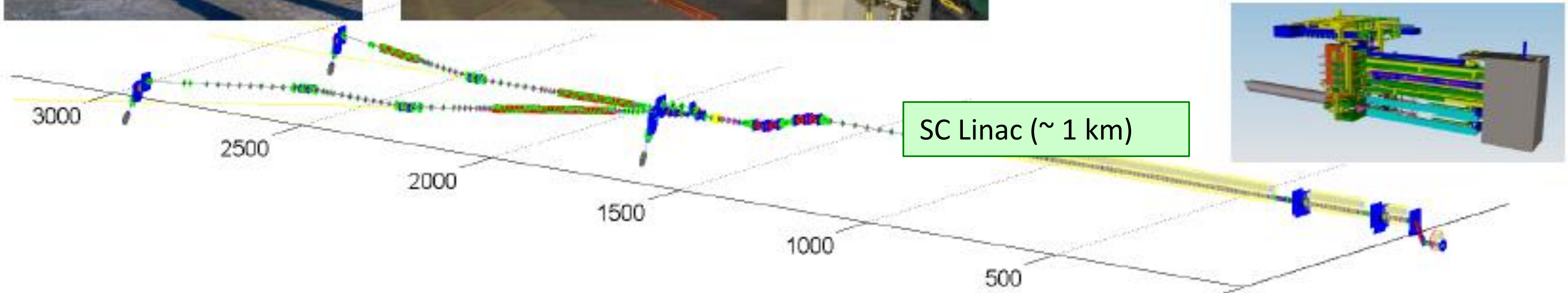
100 accelerator modules

Some specifications

- Photon energy 0.3 - 24 keV
- Pulse duration ~ 10 - 100 fs
- Pulse energy few mJ
- Superconducting linac. 17.5 GeV
- 10 Hz (27 000 b/s)

800 accelerating cavities
1.3 GHz / 23.6 MV/m

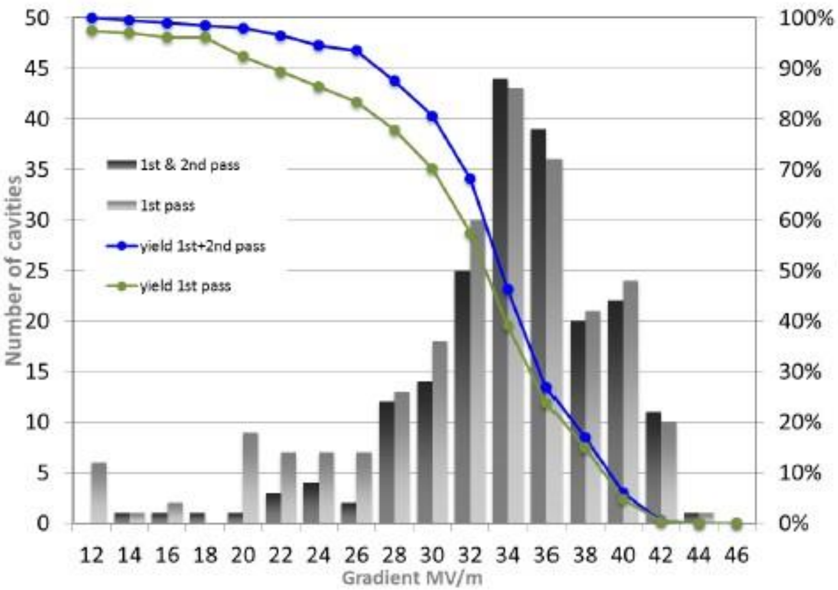
25 RF stations
5.2 MW each

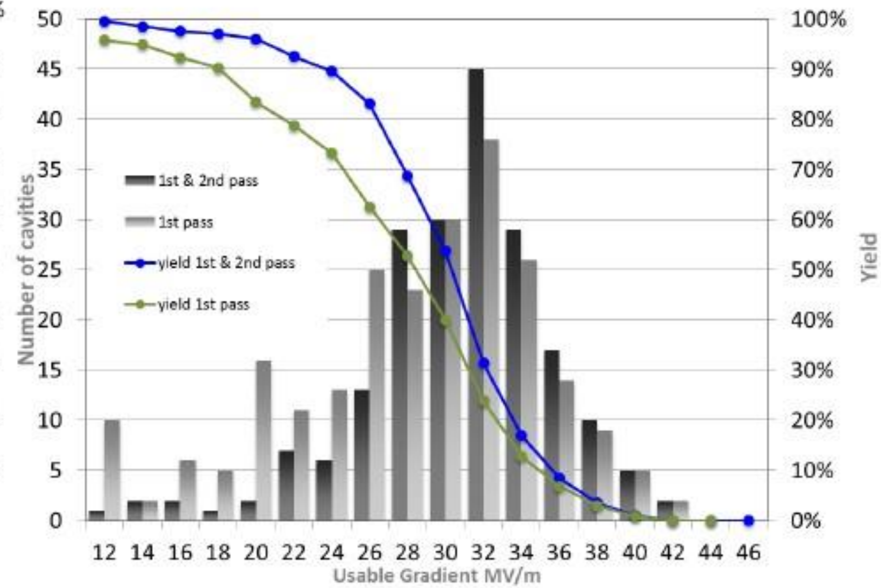


EXFEL: 1/20 Scale Project on going, Industrialization being verified !!

Yield of gradients: After 1. re-treatment (2. pass)

- Yield of usable and maximum gradient of ~207 cavities (2.pass) **=> 85%** (cavities that passed in 1. pass + results of cavities after re-treatment)
- **Average** gradients **increased + spread reduced**





Average **maximum** gradient: **(32.8 ± 4.9) MV/m**

Average **usable** gradient: **(29.3 ± 5.1) MV/m**

given errors are standard deviation

D. Reschke, TTC 2014

Detlef Reschke, DESY ***Preliminary data; results are not published***

SCRF Main Linac Parameters, Demonstrated

2014/07/05, A. Yamamoto

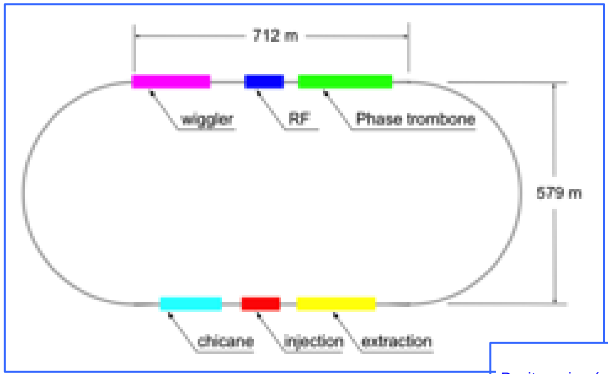
Characteristics	Parameter	Unit	Demonstrated
Average accelerating gradient	31.5 (±20%)	MV/m	**DESY, FNAL, JLab, Cornell, KEK,**
Cavity Q_0	10^{10}		
(Cavity qualification gradient	35 (±20%)	MV/m)	
Beam current	5.8	mA	**DESY-FLASH, KEK-STF**
Number of bunches per pulse	1312		
Charge per bunch	3.2	nC	
Bunch spacing	554	ns	
Beam pulse length	730	ms	**DESY-FLASH, KEK-STF**
RF pulse length (incl. fill time)	1.65	ms	**DESY-FLASH, KEK-STF, FNAL-ASTA**
Efficiency (RF→beam)	0.44		
Pulse repetition rate	5	Hz	
Peak beam power per cavity	190*	kW	* at 31.5 MV/m

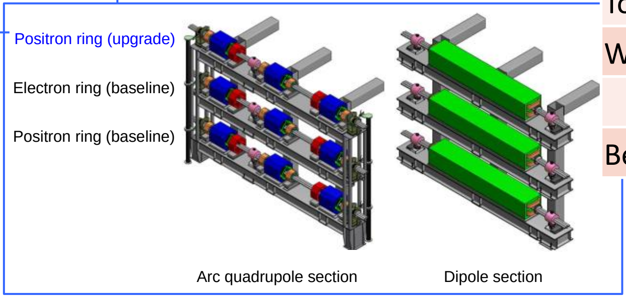
Damping Rings

- Requirements
  - $\gamma\varepsilon_x$ = 5.5 μm, $\gamma\varepsilon_y$ = 20nm
  - Time for damping 200 (100) ms
  - 1st step 1312 bunches, 2^{nd} 2625 bunches
  - bunch-by-bunch injection/extraction

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
(normalized)	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

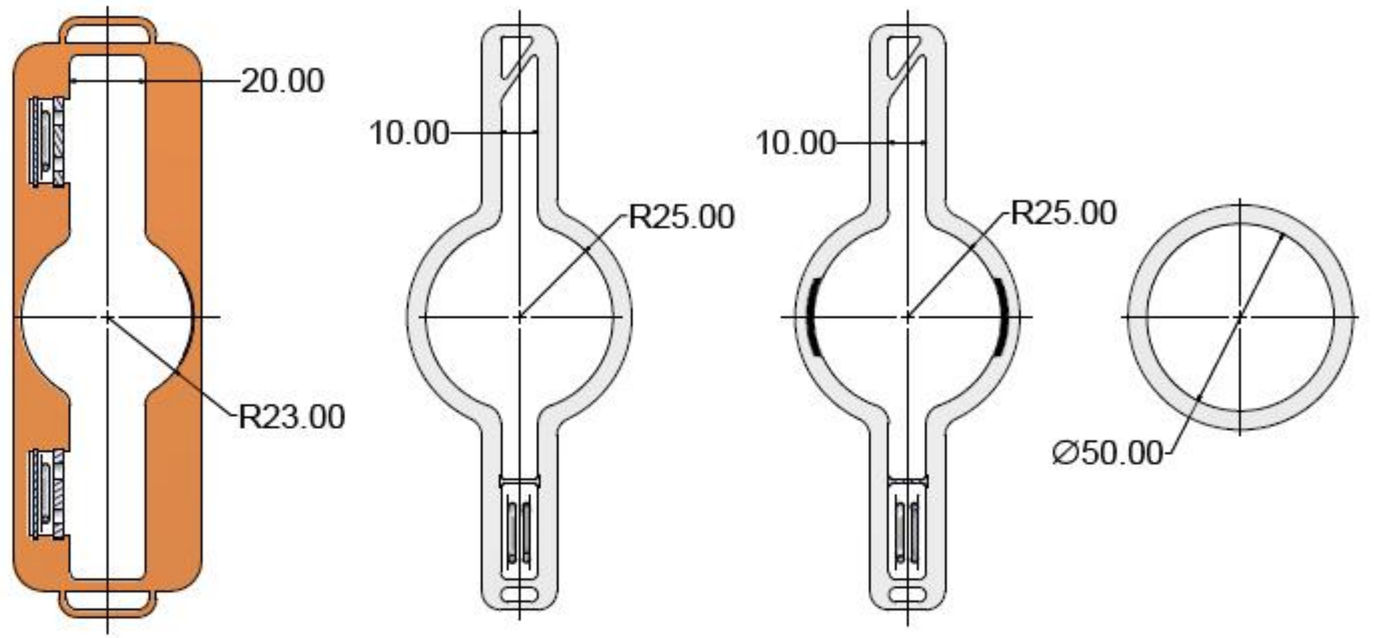
Values in () are for 10-Hz mode





Vacuum Chamber of Positron Damping Ring

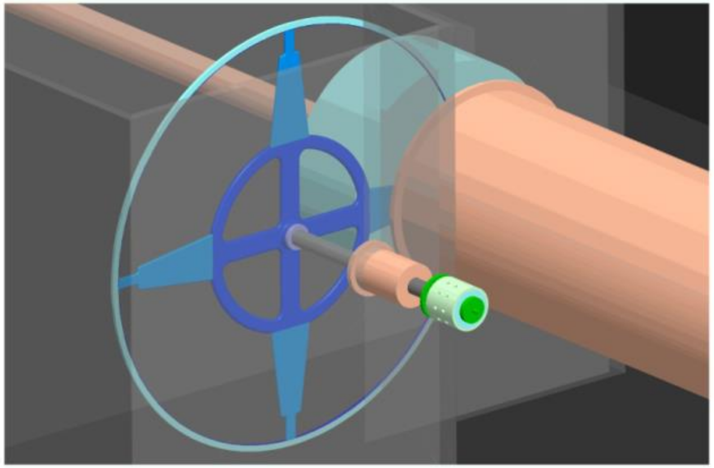
- Recommended by CESR-TA team
- Instabilities other than ecloud are less serios
- FII (Fast Ion Instability) is the most important in electron DR



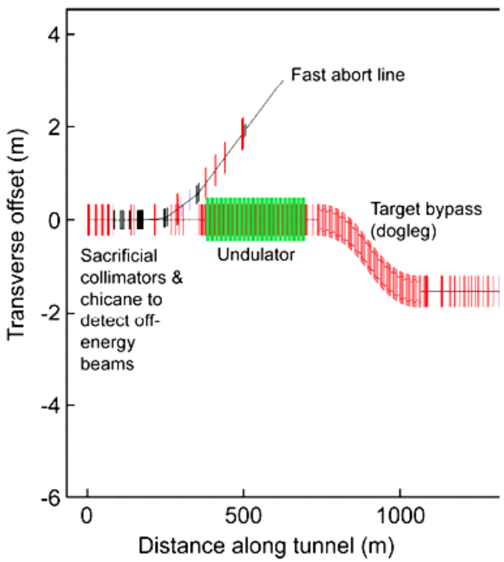
(a) WIGGLER CHAMBER (b) ARC CHAMBER (c) DIPOLE CHAMBER (d) DRIFT CHAMBER

Positron Production

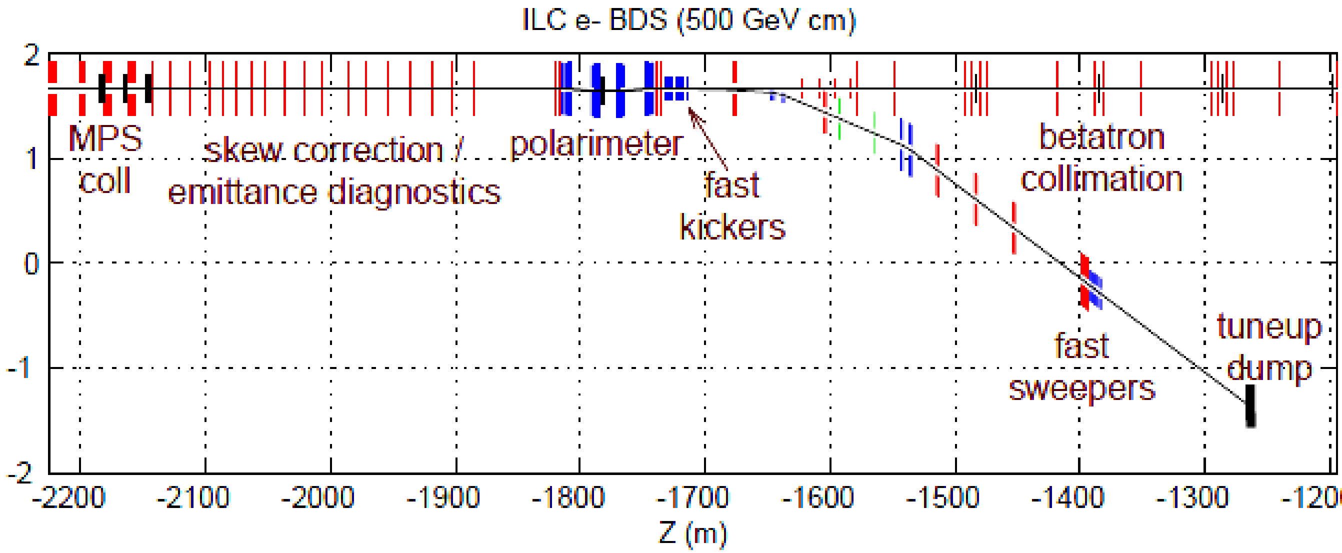
- Target still under R&D
  - Rotating wheel of Titanium alloy
  - 2000rpm, 1m diameter (rim velocity 100m/s) to avoid heat accumulation in 1ms
  - In high vacuum
- Model test with magnetic fluid done at LLNL.
  - Results not satisfactory. Outgassing spikes still being observed
  - Stopped due to budget short
- Now to be further investigated in USFY2015 (presumably)
  - Concrete plan will be discussed in POSIPOL2014 (Aug.27-29 @Ichinoseki)
- Backup scheme: Conventional e-driven source (but lose polarization)



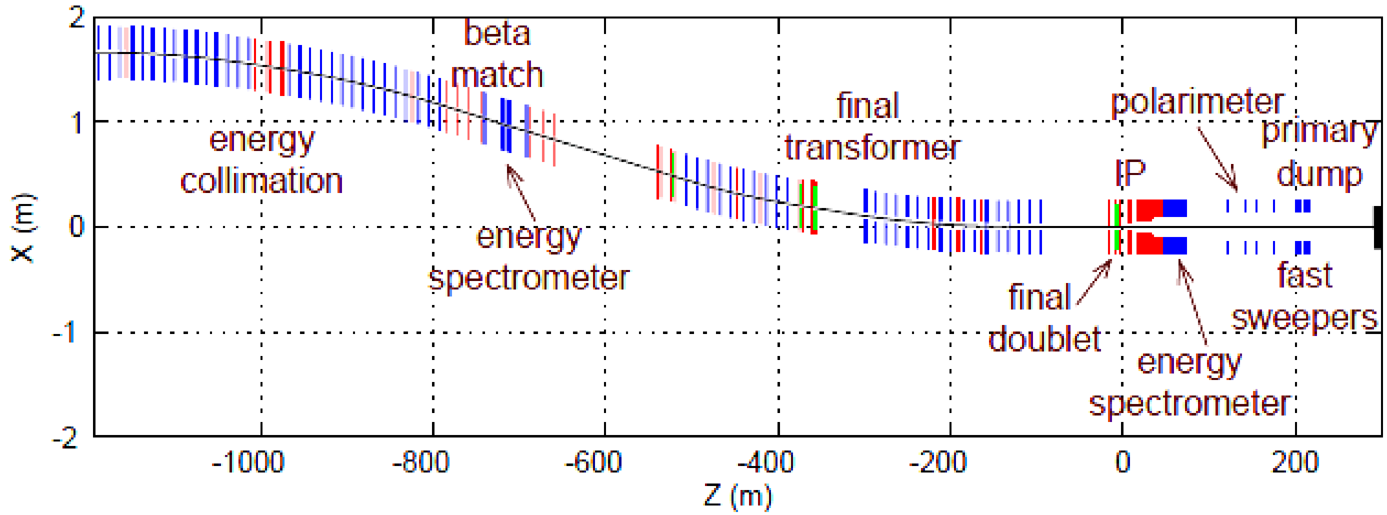
BDS Layout



Fast abort line
Target bypass (dogleg)
Sacrificial collimators & chicane to detect off-energy beams
Undulator
Transverse offset (m)
Distance along tunnel (m)

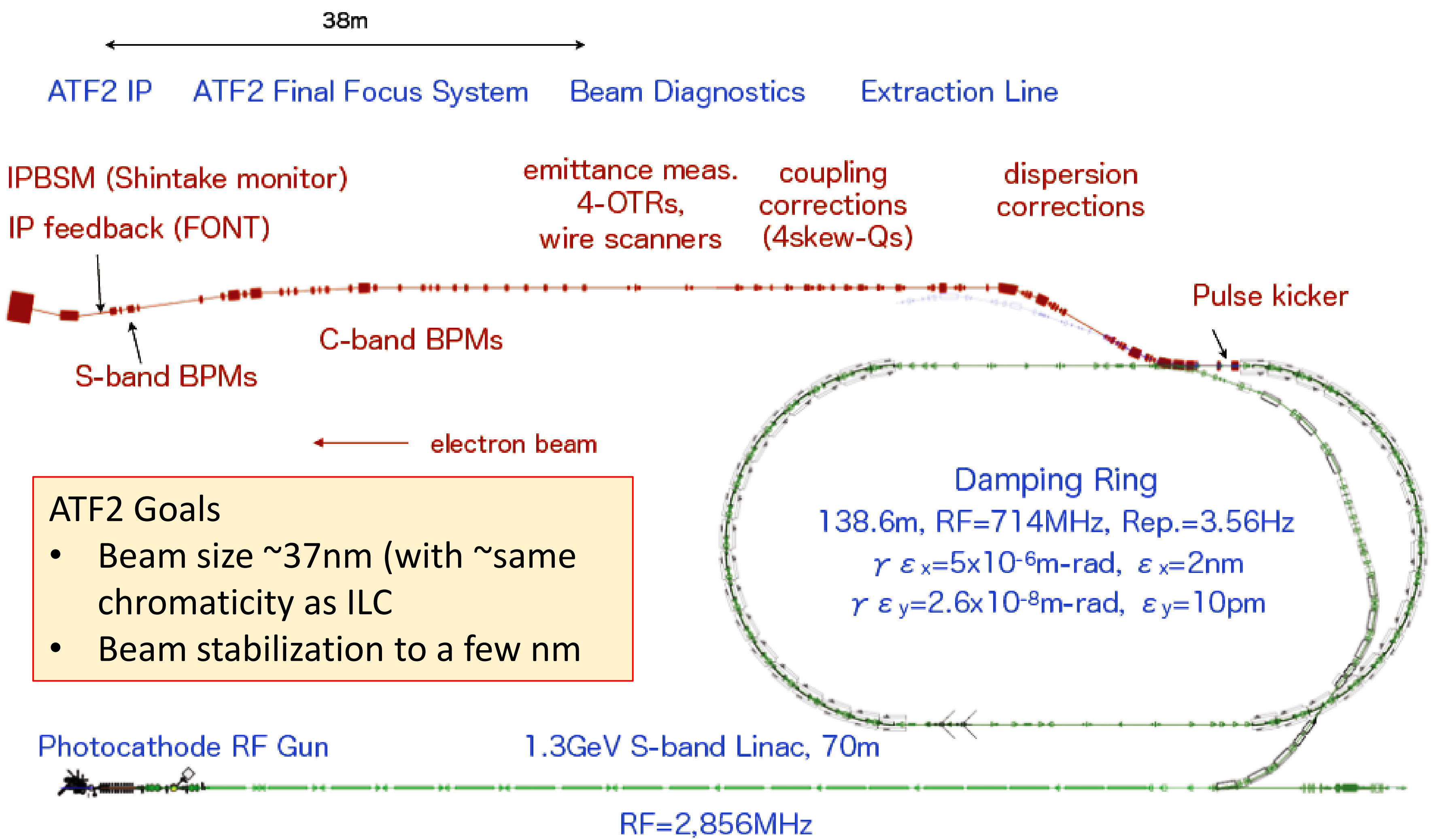


ILC e- BDS (500 GeV cm)
MPS coll
skew correction / emittance diagnostics
polarimeter
fast kickers
betatron collimation
fast sweepers
tuneup dump
Z (m)



beta match
energy collimation
energy spectrometer
final transformer
polarimeter
primary dump
IP
final doublet
fast sweepers
energy spectrometer
X (m)
Z (m)

Test Facility : ATF and ATF2

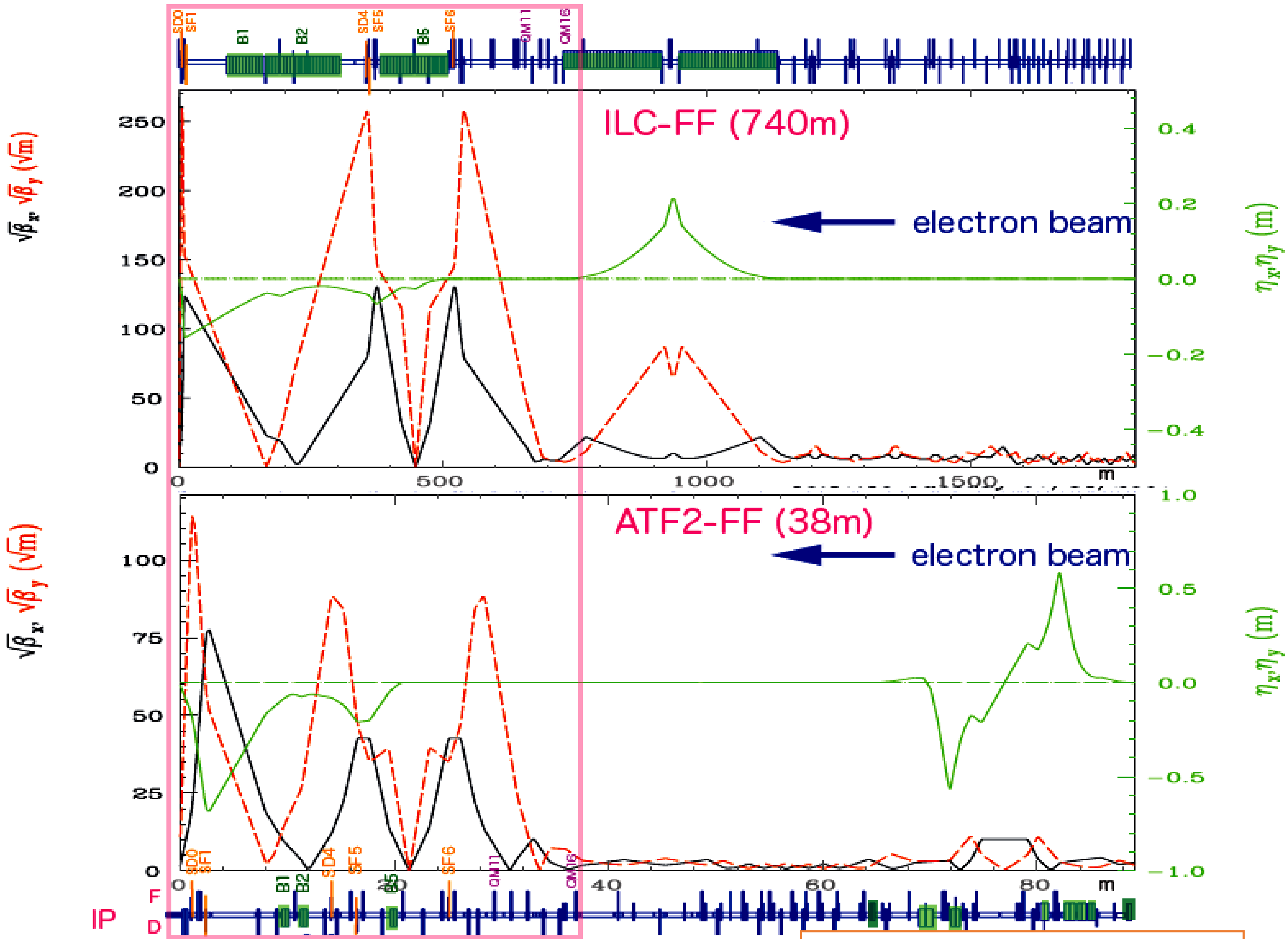


ATF2 Goals

- Beam size ~37nm (with ~same chromaticity as ILC
- Beam stabilization to a few nm

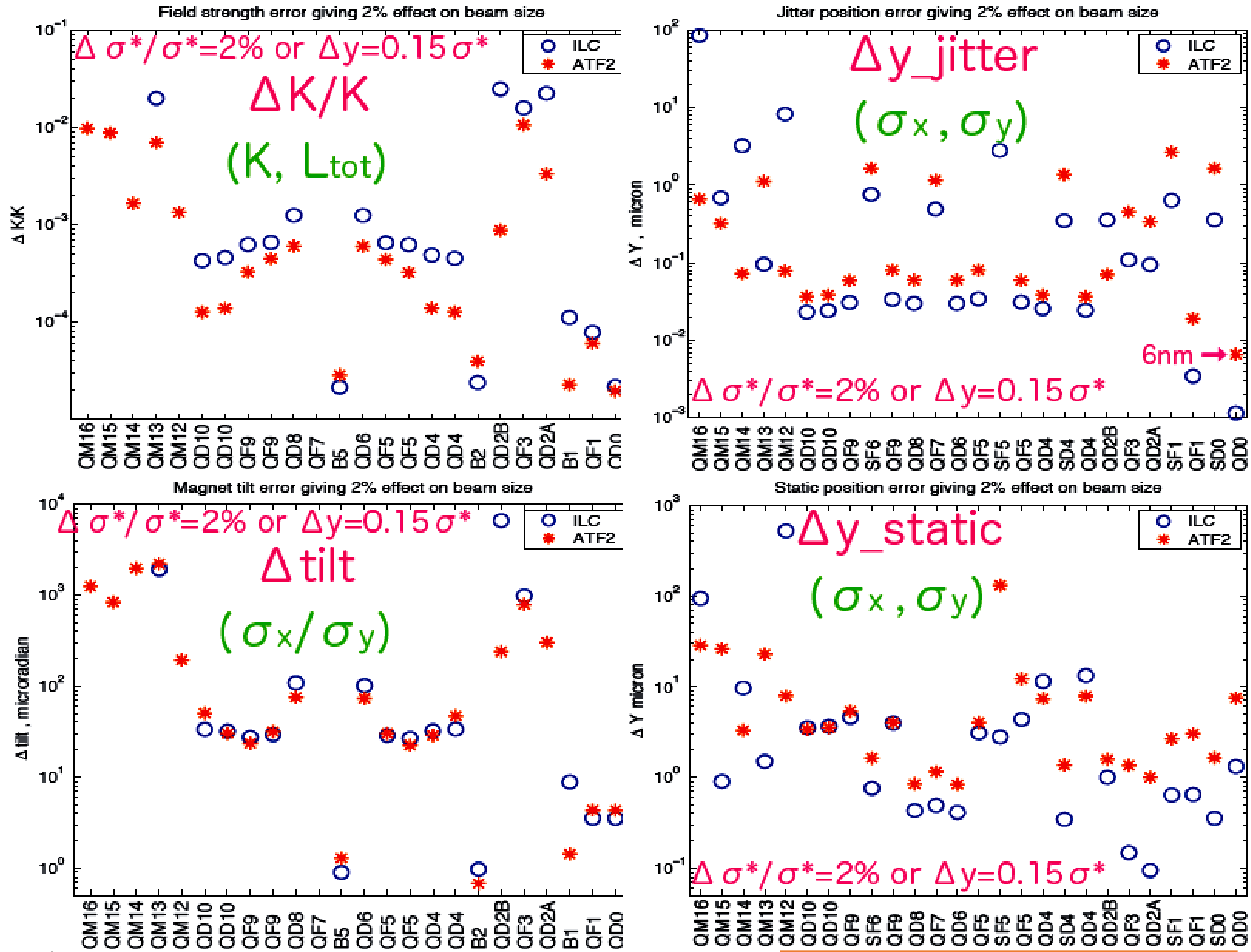
T.Tauchi, ILC camp 2013

Comparison of ILC-FF and ATF2



T.Tauchi, ILC camp 2013

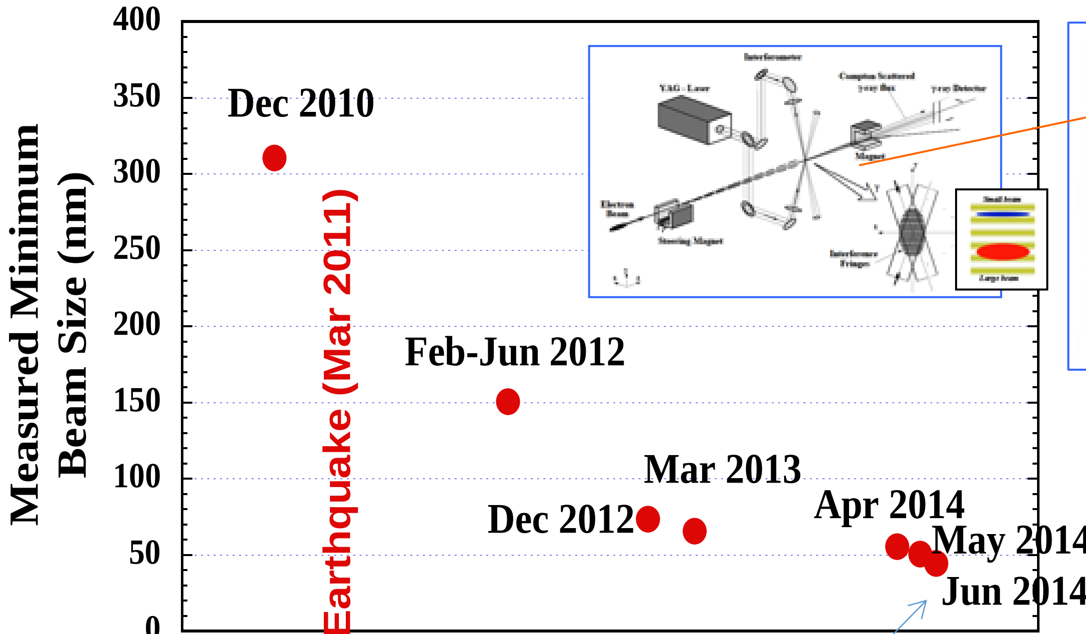
Comparison of Tolerances

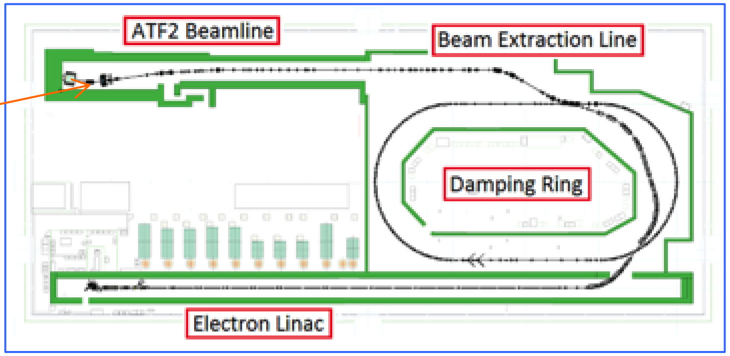


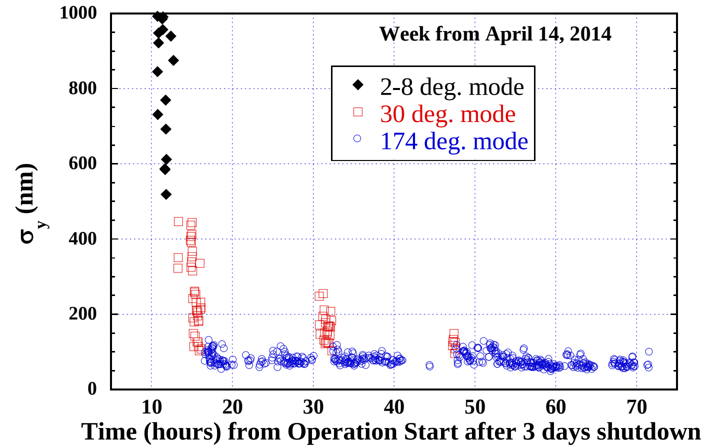
T.Tauchi, ILC camp 2013

Progress in measured beam size at ATF2

IPAC2014, K. Kubo + ICHEP S.Kuroda





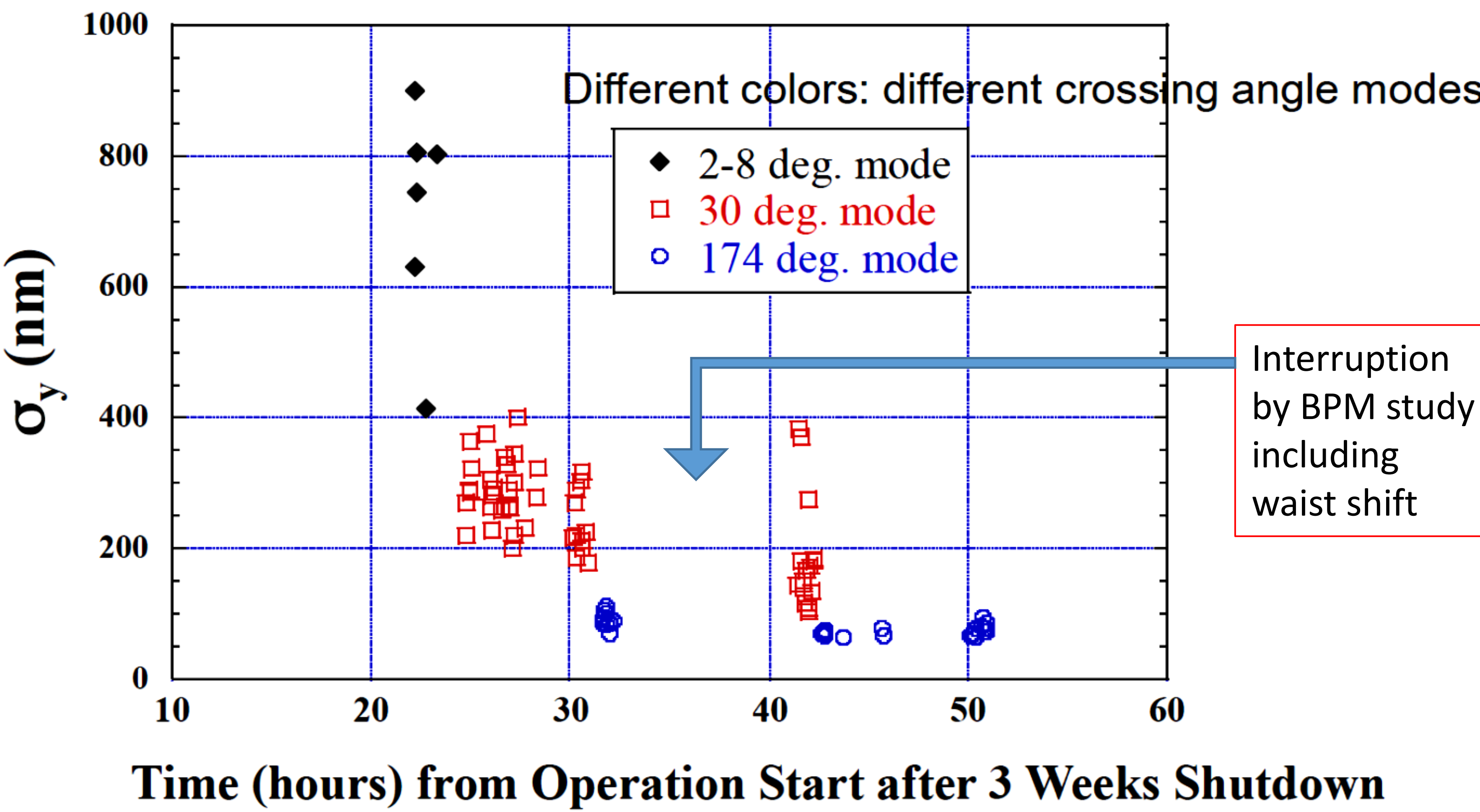


Beam Size 44 nm observed,
(Goal : 37 nm)

Beam Size Tuning after 3 weeks shutdown

Small beam (~60 nm) observed ~32 hours from operation start

By April 2014



Interruption by BPM study including waist shift

Week 2014 April 7

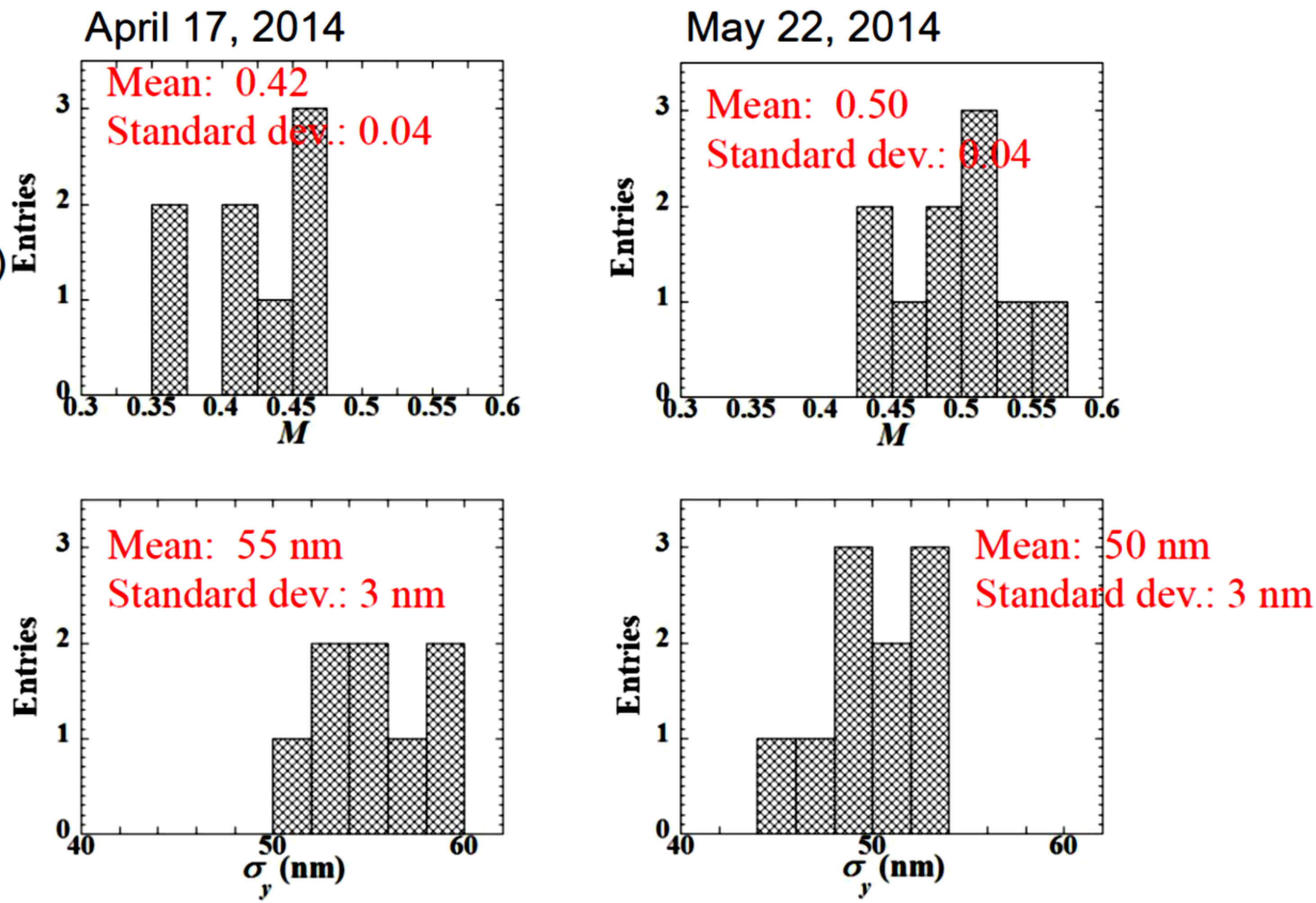
K.Kubo IPAC14

Beam is stable for 30 – 60 min. without tuning.

Examples of consecutive beam size measurements

IPBSM Modulation (174 degree Crossing angle)

Beam size Evaluated from Modulation (no systematic error assumed)



K.Kubo IPAC14

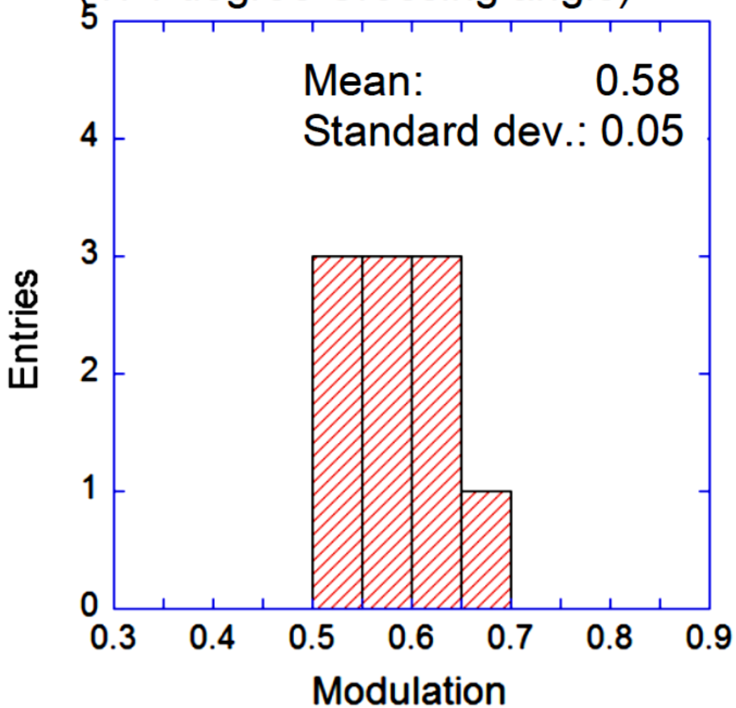
Bunch charge ~ 0.16 nC

Bunch charge ~ 0.09 nC

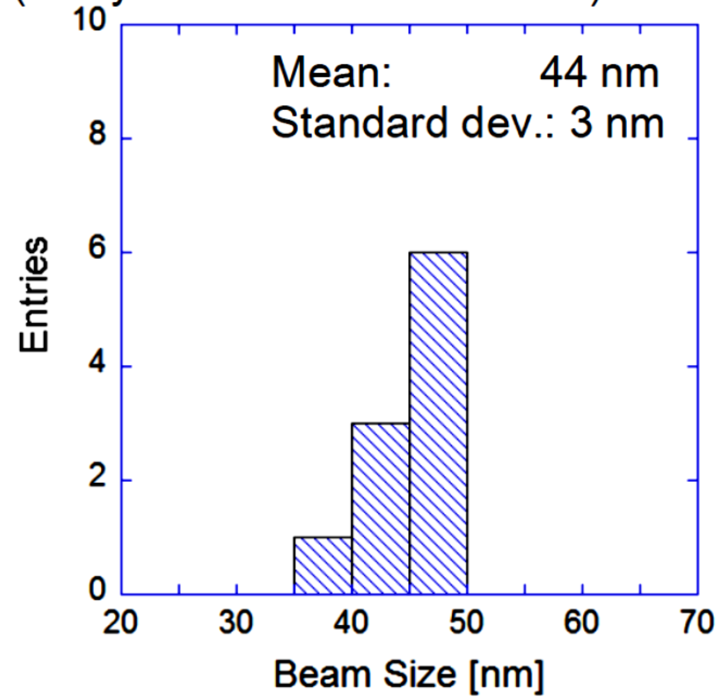
Data of June 12

After removal of OTR monitors

IPBSM Modulation
(174 degree Crossing angle)



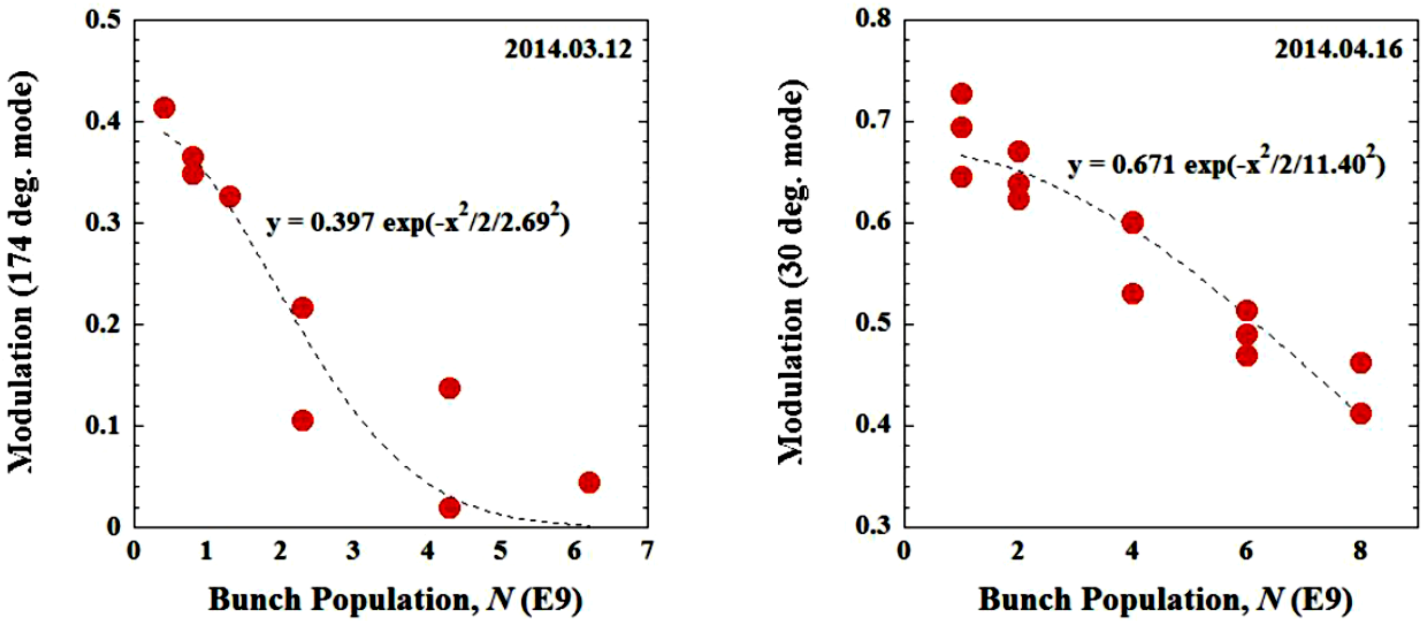
Beam Size Evaluated from Modulation
(no systematic error assumed)



Bunch charge ~ 0.16 nC

S.Kuroda, ICHEP2014

Beam Size Depends on Bunch Intensity



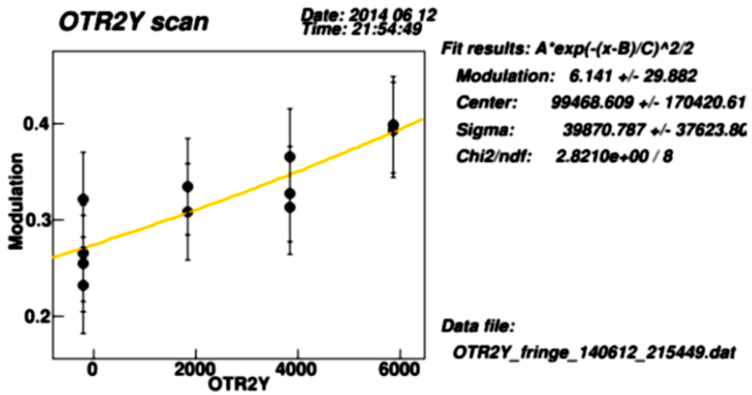
IPBSM modulation as function of bunch population. Measured with crossing angle 174 degrees (left) and 30 degrees (right).

Assuming $\sigma_y^2(q) = \sigma_y^2(0) + w^2 q^2$, w is fitted as 100 nm/nC.

$\Rightarrow$ Measured minimum beam size (at 0.1 - 0.16 nC) may be larger than zero - intensity beam size by 2 - 3 nm.

K.Kubo IPAC14

Operation in the Last Week June 2012

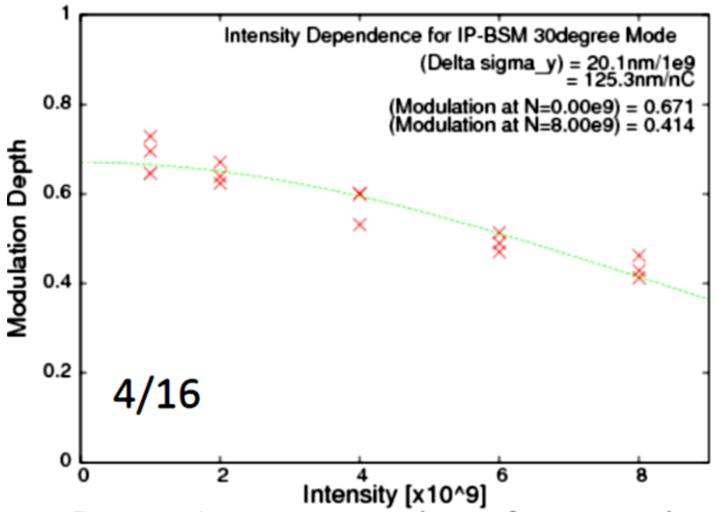


We observed strong dependence on OTR position(174deg mode, I=3e9)

S.Kuroda, ICHEP2014

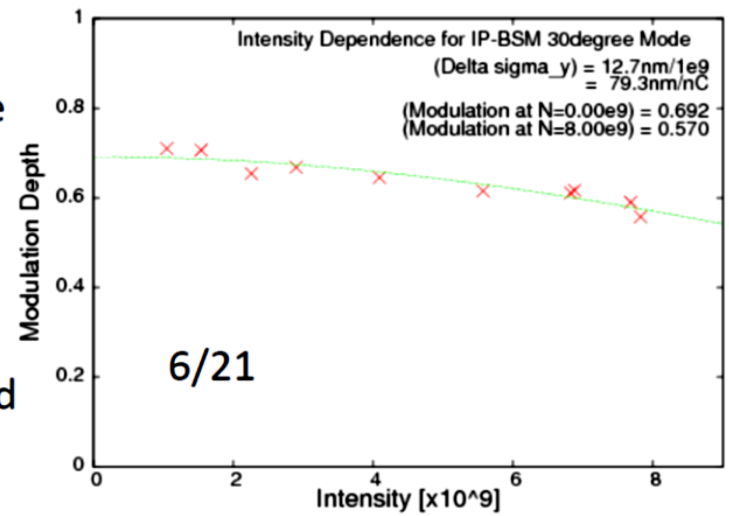
All the OTR stations were uninstalled.

Situation has completely changed(orbit, dispersion, matching,…)



30 deg mode modulation

OTR removed

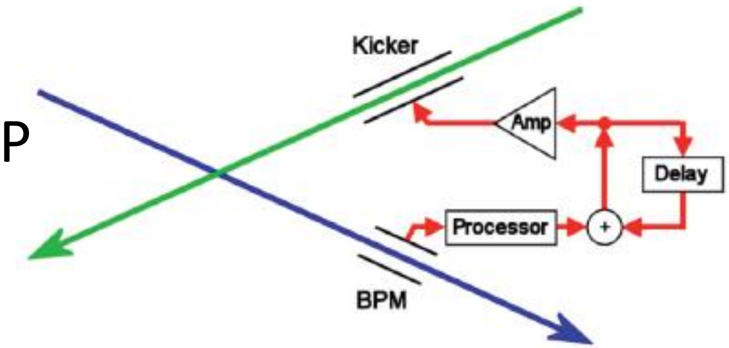


Beam time was so short for complete beam tuning.

Possibility of OTR cancelling the effect from other source. Need to confirm in the next operation

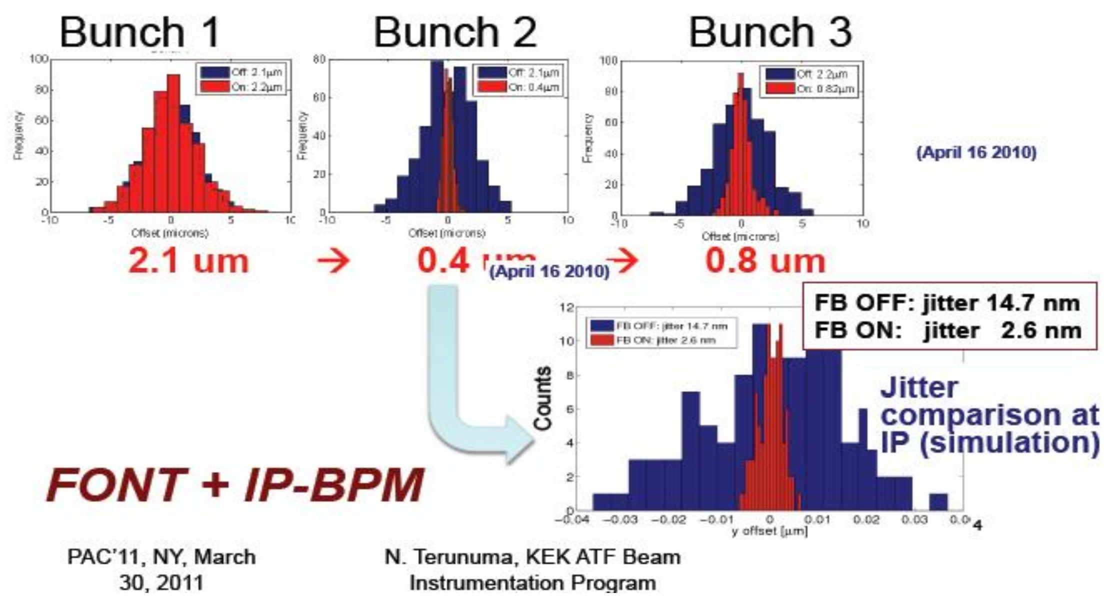
Goal 2 Status

- Intra-pulse feedback demonstrated in the middle of ATF2 (micron to sub-micron level)
  - BPM resolution limited
- For nanometer level stabilization at IP
  - High resolution BPM installed
  - BPM performance studies going on



IP Feedback

- Bunch interval is long enough for intra-train digital feedback
  - Advantage of SC collider
- Large disruption parameter
  - Dy = 25



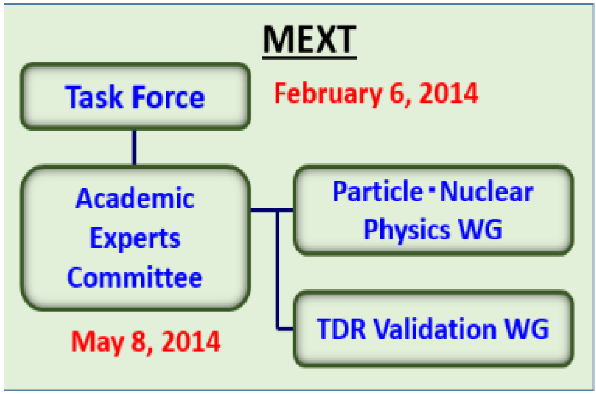
Further Action Plan before Construction

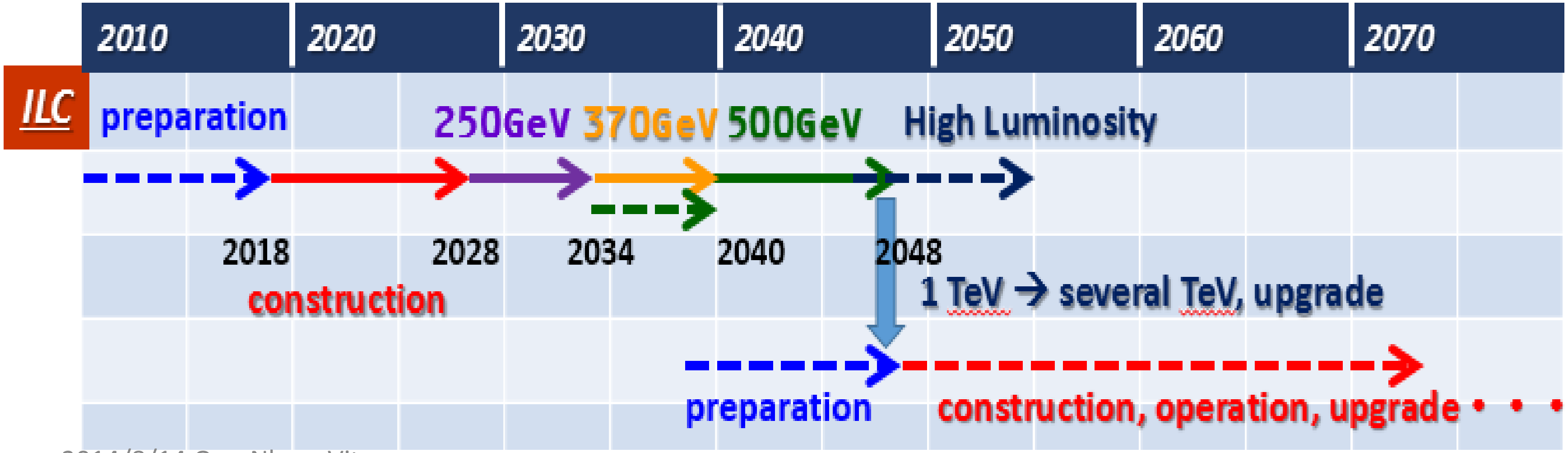
	2014	2015	2016	2017	2018

Engineering R&D Schedule *(LCC-PreLab)* [2014 – 2017]

Pre-construction Schedule *(LCC-PreLab)* [2014 – 2016]

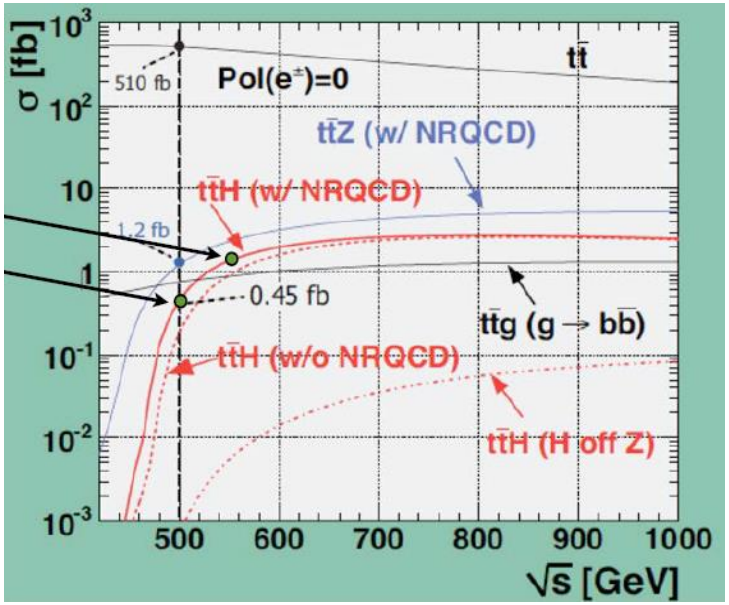
Staging Scenario *(LCB, LCC)* [2014]





Energy Staging

- TDR adopted 500GeV as the design reference
  - Not knowing Higgs mass
- Staging strategy for actual construction under study
- Energy related to the thresholds of various processes
  - 250GeV ZH
  - 350GeV tt
  - 500GeV ttH
- Starting with energy << 500GeV
  - earlier start
  - Relaxed cryomodule production rate
- Tunnel length should be prepared for 500GeV
  - Or ~550GeV ?
    - 500GeV is too close to ttH
    - Can gain factor ~4 at 550GeV
- Will be decided soon (~this year)



Possible Low Energy Operation

- Low energy targets
  - Z-pole
  - W pair threshold
  - Scan below ZH
- These are not the major concern for ILC physics team
  - We are now preparing operation scenario for ~20 years but these low energy operations are not on the table yet
- In principle ILC can be operated at these energies
  - Positron production would be poor with undulator scheme
  - TDR prepared a scheme to operate the electron linac at 10Hz, 5Hz for positron production and 5Hz for collision
    - Damping rings can be operated at 10Hz. No problem in electron linac
  - The luminosity would scale linearly as CM energy (may be a bit less)., e.g., 3e33 at Z-pole with 1312 bunches, but no serious studies have been made.
  - E-riven scheme can double the luminosity (10Hz collision) at free, but lose positron polarization

Luminosity Upgrade

- Baseline (1326 bunches)
  - Possible to double the luminosity at E_{CM}=250GeV by doubling the collision rate to 10Hz
  - ~ up to 7Hz at E_{CM}=350GeV
- High power (2625 bunches)
  - Reinforcement of RF system (plus 2nd positron DR depending on e-cloud)
  - This will double the luminosity
  - Another factor 2 (250GeV) or 1.4 (350GeV) by 10Hz collision

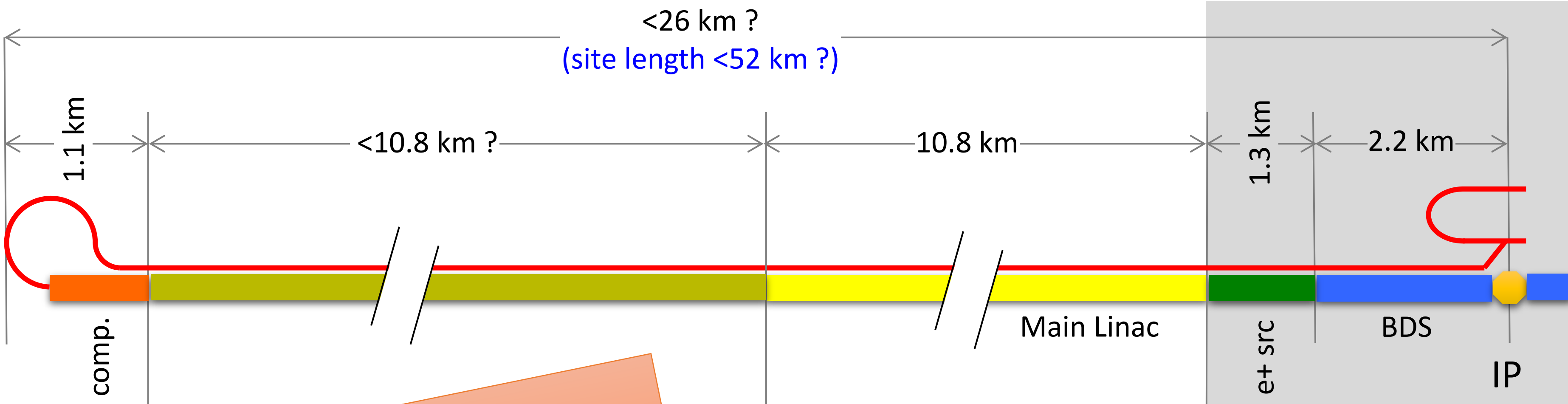
Luminosity ($x10^{34}$ $/cm^2/s$)

	#of bunches	Collison freq.	250GeV	350GeV	500GeV
Baseline	1312	5	0.75	1.0	1.8
		10(7)	1.5	(1.4)	
Hi power	2625	5	1.5	2.0	4.9 (3.0)
		10(7)	3.0	(2.8)	

CM Energy vs. Site Length

- Under the assumption
  - Keep the modules for the initial 500GeV linac
  - Available total site length L km
  - Operating gradient G MV/m
    (to be compared with 31.5 in the present design)
  - Assume the same packing factor
- Then, the final center-of-mass energy is
  Ecm = 500 + (L-31)*(G/45)*27.8 (GeV)
  - e.g., L=50km, G=31.5MV/m → 870GeV
    L=50km, G=45MV/m → 1030GeV
    L=67km, G=45MV/m → 1500 GeV
    L=67km, G=100MV/m → 2700 GeV
- This includes the margin ~1% for availability
- But does not take into account the possible increase of the BDS for Ecm>1TeV
  - Present design of BDS accepts 1TeV without increase of length
  - A minor point in increasing BDS length: laser-straight

TeV Upgrade : From 500 to 1000 GeV



Assume Higher Gradient

<u>Main Linac</u>

$\langle G_{cavity} \rangle$ = 31.5 MV/m

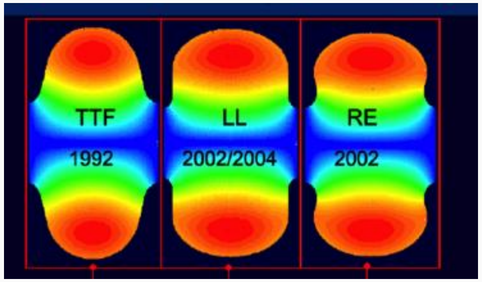
G_{eff} ≈ 22.7 MV/m

(fill fact. = 0.72)

<u>Snowmass 2005 baseline recommendation for TeV upgrade:</u>

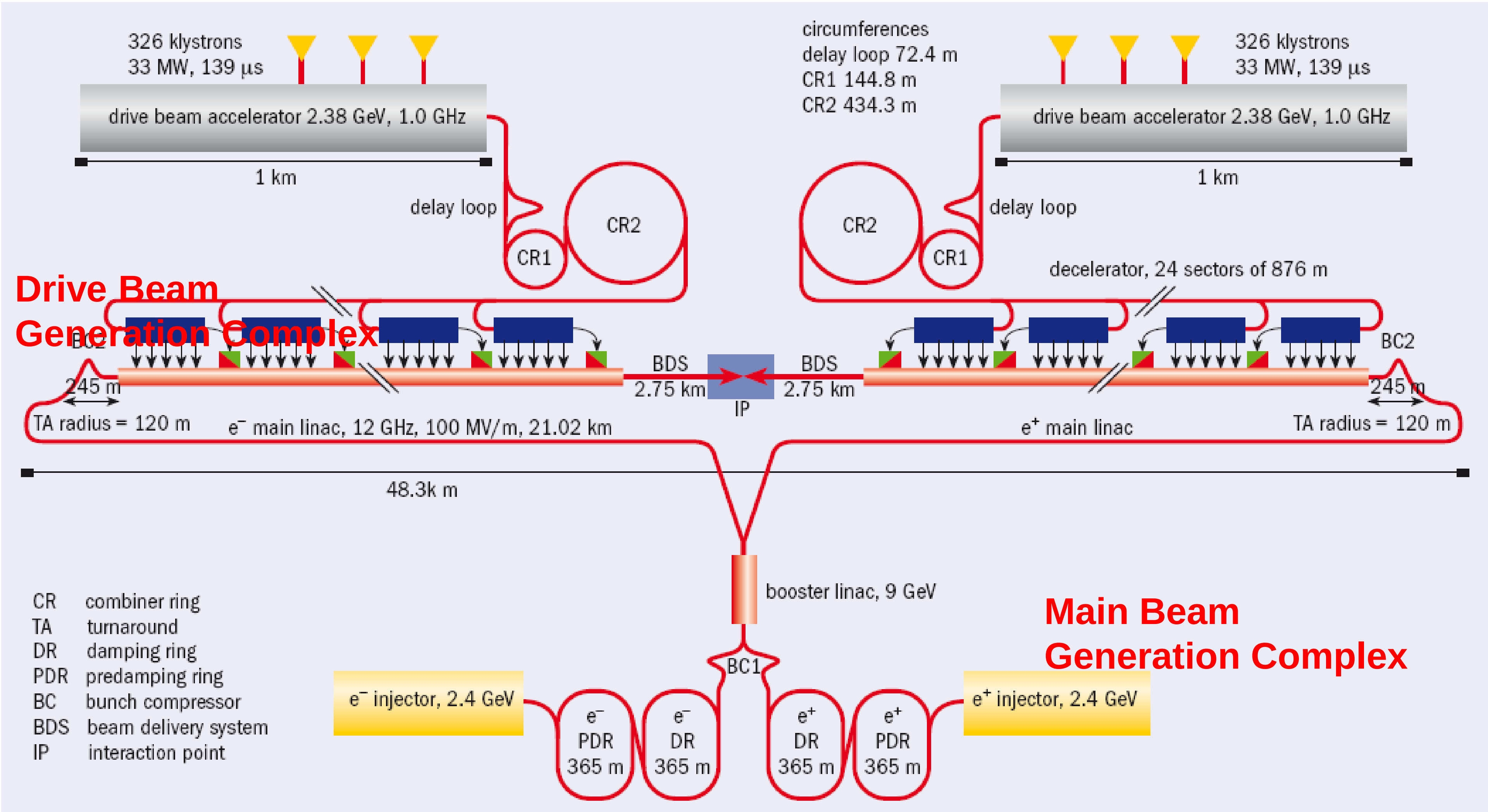
G_{cavity} = 36 MV/m ⇒ 9.6 km

(VT ≥ 40 MV/m)



Based on use of low-loss or re-entrant cavity shapes

CLIC Layout 3 TeV



Drive Beam Generation Complex

Main Beam Generation Complex

Rebaselining Studies

- CDR (2012)
  - Optimized for 3TeV
  - Overall cost not optimized
  - X-band demonstration limited by test stand capacity
- Energy staging and optimization for each stage
  - 350GeV
  - ~1500GeV
  - 3000 GeV (CDR)
- Cost and power reductions, e.g.,
  - Use of permanent/hybrid magnets for the drive beam
  - Optimize drive beam klystron system
  - Eliminate electron pre-damping ring
- New staged parameter sets and upgrade path
- Possibility of use of klystron in the initial stage

Main Activities in the Next Phase

D.Schulte, AWLC2014

Staged implementation plan: Rebaselining, cost, power and risk optimisation

Moving from theory to practice, industrialisation, system tests, …

X-band RF	Drive beam	Modules	Beam performance
Structures Test stations Industrialisation FELs	CTF3 Drive beam frontend Klystron development	Design verification Design for cost reduction Industrialisation PACMAN	ATF2 FACET, FERMI Damping ring tests Simulations

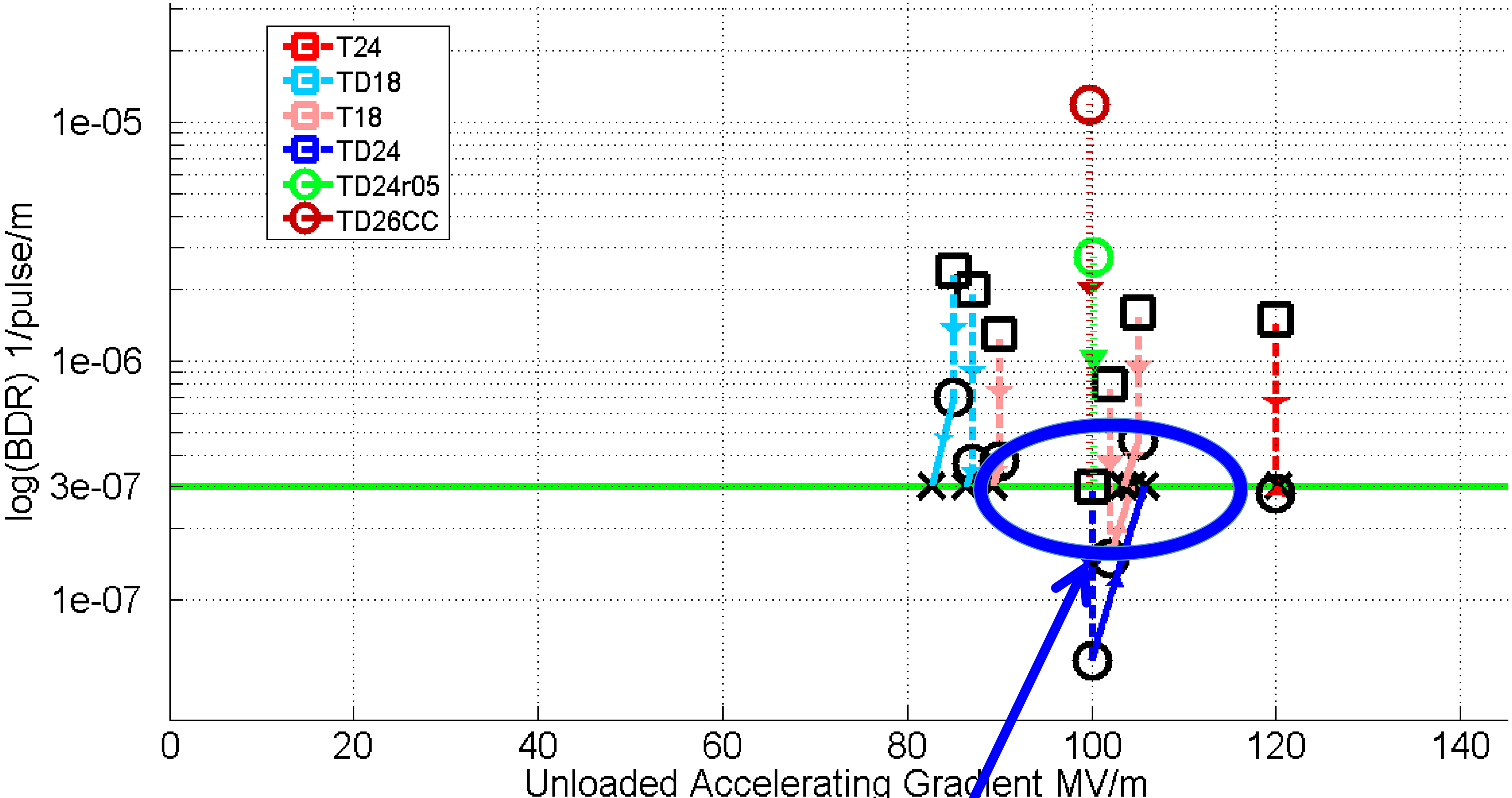
Technical basis development of key components

Infrastructure and civil engineering, power consumption

Achieved Gradient for CLIC

Tests at KEK, SLAC, CERN

D. Schulte, The CLIC 5-year R&D program technical goals, May 2014



Measurements scaled according to

$$p \propto G^{30}\tau^{5}$$

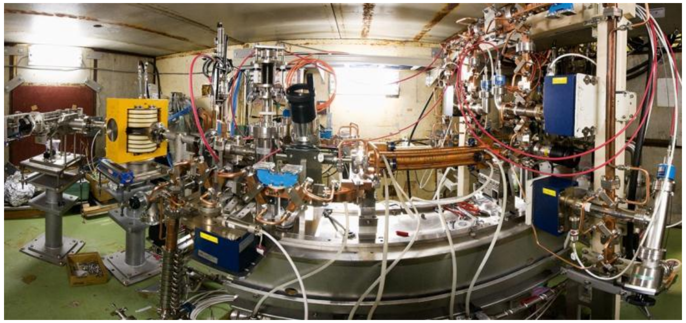
Unloaded 106MV/m
With loading 0-16% less

RF Team

Structure Tests

- Up to now
  - Promising results
  - But number of structures is limited
  - Limited experience of industrial production
- Next target
  - Gain more experience in conditioning / acceptance testing
  - Exploring industrial-scale fabrication
  - Extend the availability of test capacity

Structure Test Infrastructure (X-boxes)



Previous (at 11.4GHz):
NEXTEF at KEK, ASTA at SLAC

Clockwise from top-left:

- Modulator/klystron (50MW, 1.5us pulse)
- Pulse compressor (250ns, ratio 2.8)
- DUT + connections
- Acc. structure (TD26CC)

Gallery

Bunker

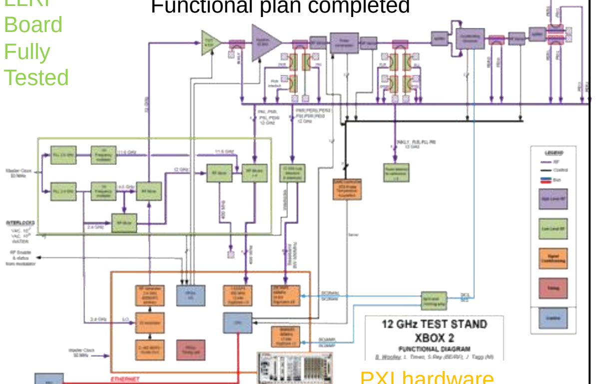
X-box 1 ready again (with new CPI klystron), 1 slot in CTF3

X-box 2 soon (July) to be ready using old SLAC klystron, 2 slots

X-box 3 planned for 2016, 4 slots

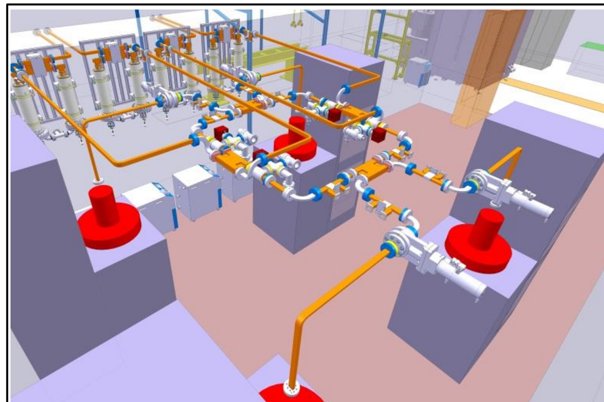
LLRF Board Fully Tested

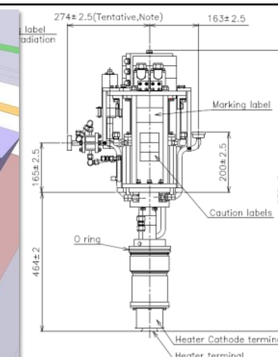
Functional plan completed



CPI-XL5 tube fully conditioned at SLAC

PXI hardware purchased and Software partially completed

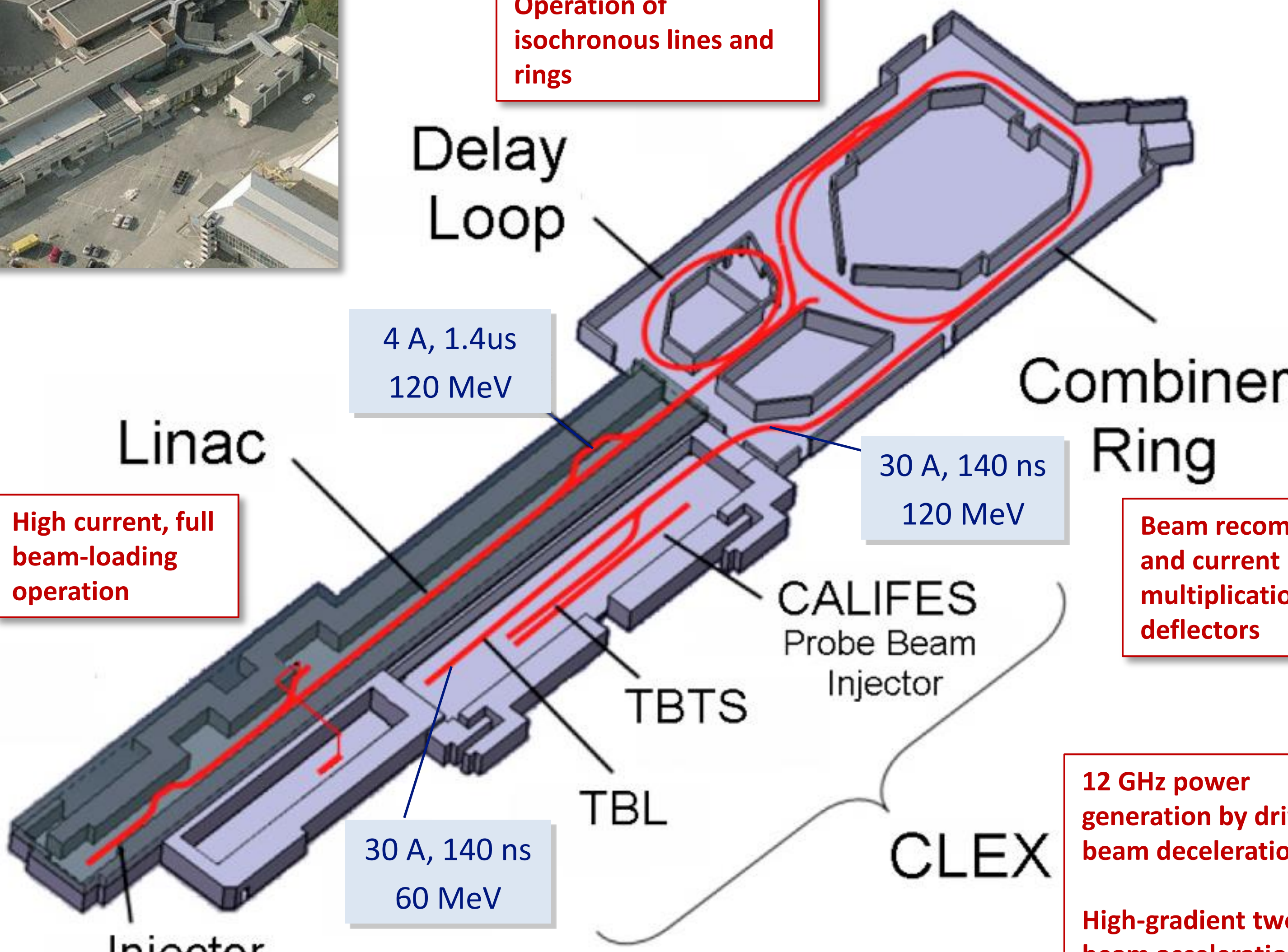




- 4 turn-key 6 MW, 11.9942 GHz, 400Hz power stations (klystron/modulator) have been ordered from industry.
- The first unit is scheduled to arrive at CERN in October 2014. The full delivery will be completed before July 2015.

CLIC Test Facility (CTF3)

Will finish in 2016



Operation of isochronous lines and rings

4 A, 1.4us
120 MeV

30 A, 140 ns
120 MeV

30 A, 140 ns
60 MeV

High current, full beam-loading operation

Beam recombination and current multiplication by RF deflectors

12 GHz power generation by drive beam deceleration

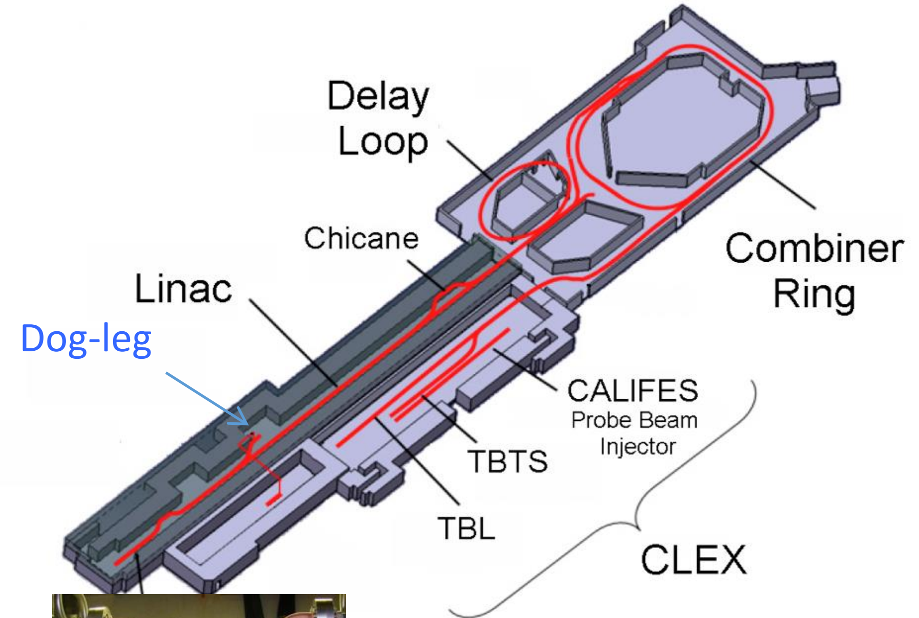
High-gradient two-beam acceleration

Bunch phase coding

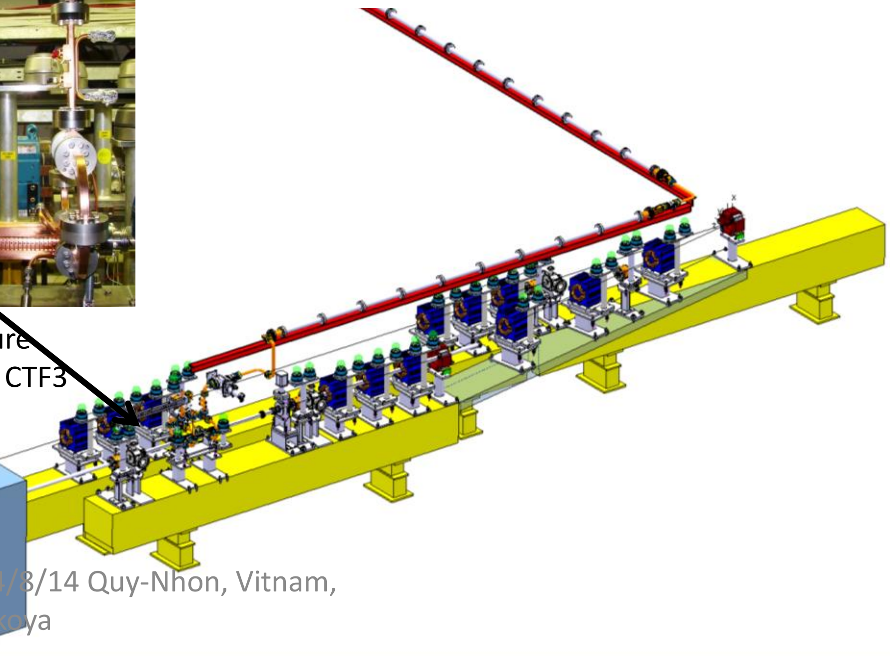
Achievements in CTF3

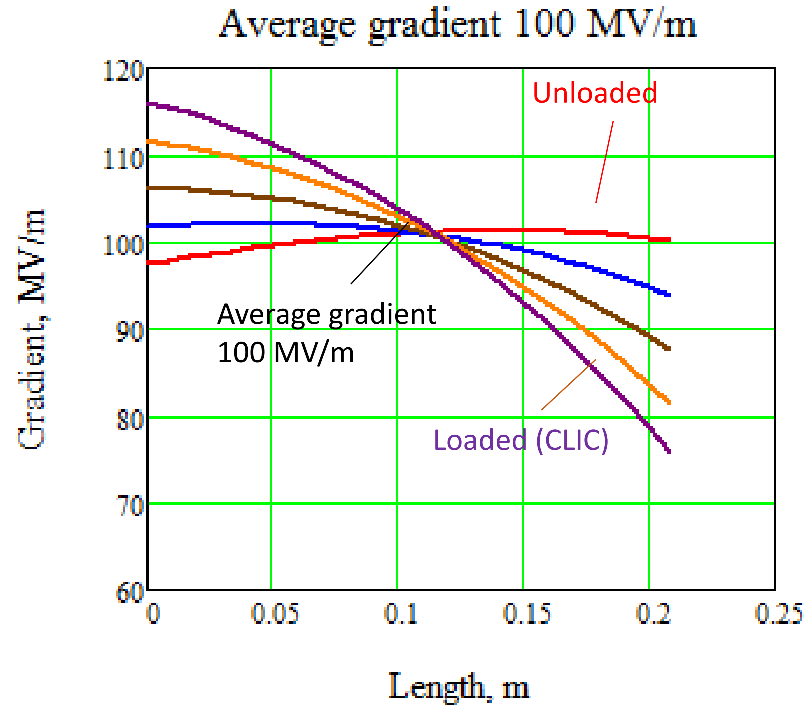
- Drive beam generation
  - Linac operation with full beam loading
  - Phase-coding of beam with sub-harmonic buncher system
  - Factor of ~8 current amplification by beam recombination
  - Power extraction from drive beam at 2 x CLIC nominal
- Two beam test stand + TBL
  - 2-beam acceleration in CLIC structures up to 1.5 x nominal
  - Drive-beam stable deceleration to 35% of initial energy
  - 12 GHz RF power @ ~ 1 GW in string of 13 decelerators

Beam Loading Test Facility



T24 structure installed in CTF3





Test stand in CTF3 dog-leg to test gradient with beam loading

- Structure can be powered with klystron
- Can send drive beam through structure

System is commissioned
Conditioned structure to come in summer

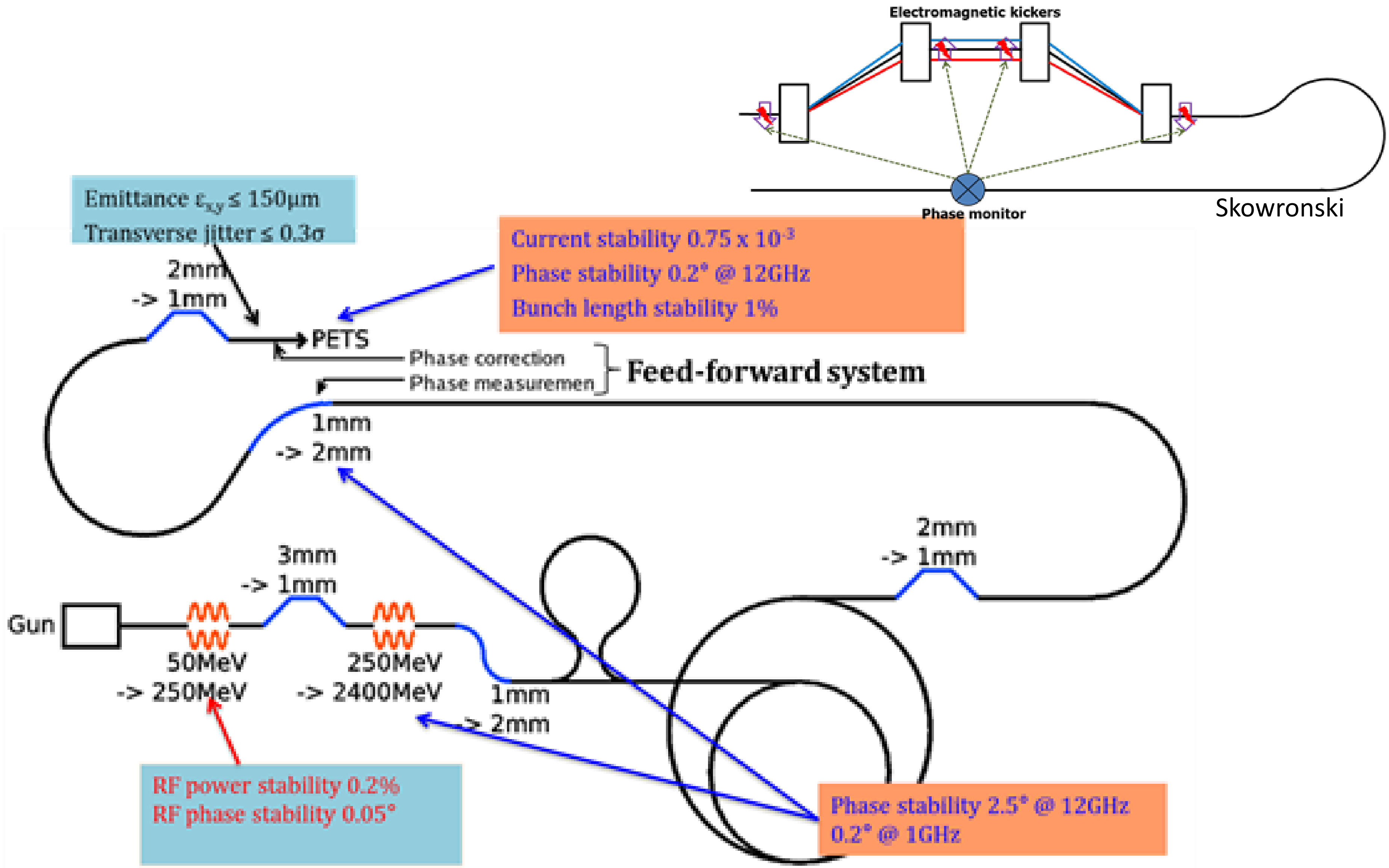
CTF3 program 2014-16 (1)

- Drive beam
  - emittance + bunch-length control (x8 combination)
  - stability: current, RF amplitude + phase
  - lot of feedbacks in development
  - control of beam losses
  - phase feed-forward experiment
- Power production
  - stability + control of RF profile (beam loading comp.)
  - RF phase/amplitude drifts along TBL
  - PETS switching at full power
  - beam deceleration + dispersion-free steering in TBL
  - routine operation

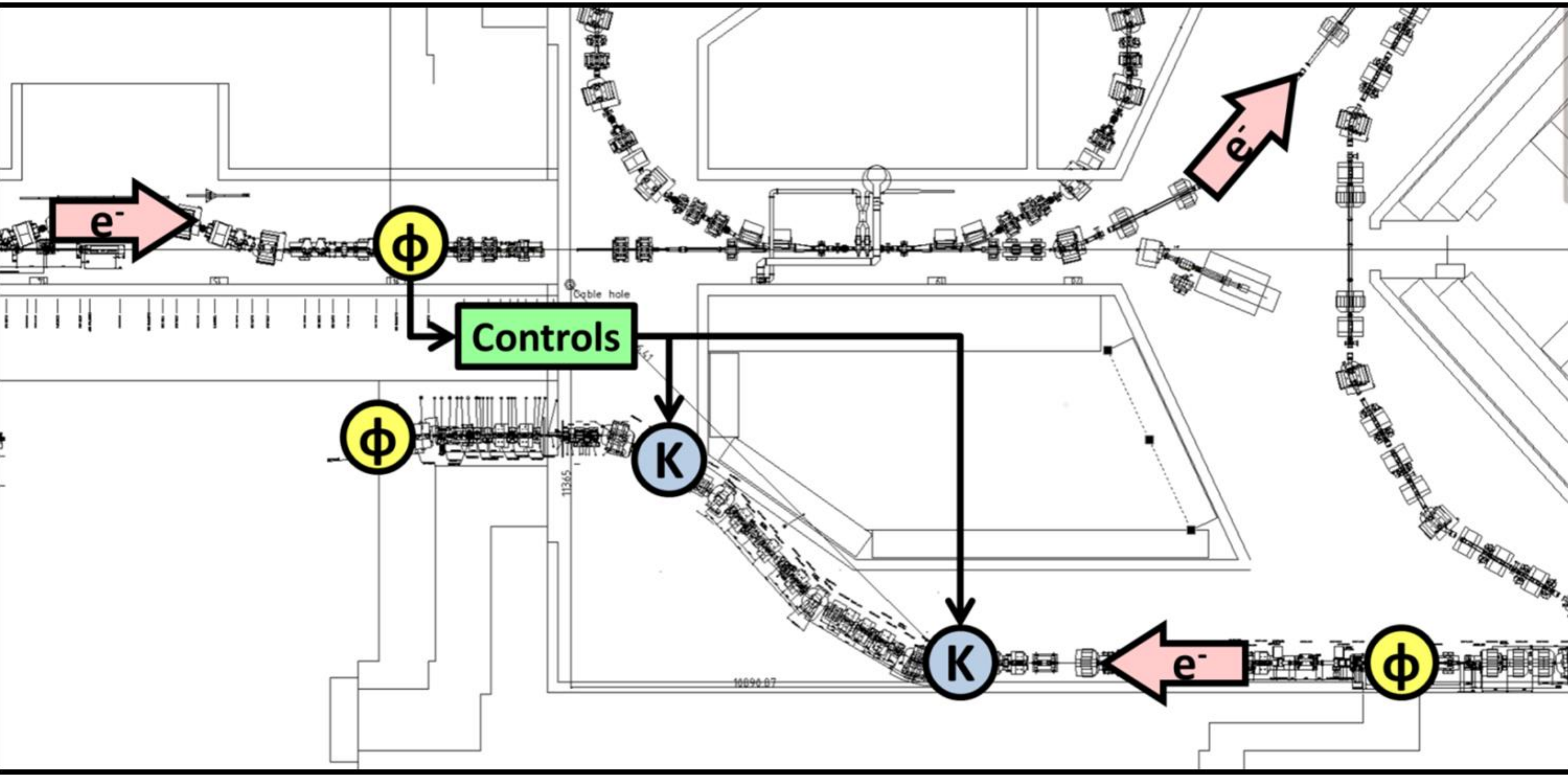
CTF3 program 2014-16 (2)

- Diagnostics tests
  - main-beam cavity BPMs (TBTS)
  - drive-beam stripline BPMs (TBL)
  - electro-optic bunch-profile monitors (CALIFES)
  - optical transition radiation beam size monitor
  - diamond beam-loss detectors
- CLIC module tests
  - 3 modules to be mechanically characterised + tested:
  - Active alignment, fiducialisation + stabilisation (PACMAN)
  - One module to be installed + tested at CLEX (June)

Drive beam phase feed-forward



CTF3 phase FF prototype
(Oxford, CERN, Frascati)



BDS Parameters of ILC and CLIC

			ILC	CLIC
Beam parameters				
	Bunch population	e10	2	0.39
	Bunch spacing	ns	554	0.5
	Number of bunches per train		1312	312
	Repitition rate	Hz	5	50
	Normalized emittance (horizontal)	nm	10000	500*
	Normalized emittance (vertical)	nm	35	5*
	Relative energy spread (e−/e+)	%	0.13	0.07
	Nominal bunch length	μm	300	44
BDS Parameters				
Length per side		m	2254	2750
	Maximum beam energy	GeV	250	
	Maximum beam energy (with more magnets)	GeV	500	1500
	Distance from IP to first quad (ILD/SiD)	m	3.51/4.5	3.5
	Crossing angle at IP	mrad	14	20
	Horizontal beta function at IP	mm	11	10
	Vertical beta function at IP	mm	0.48	0.07
	Horizontal beam size	nm	474	45
	Vertical beam size	nm	5.9	1

Beam Delivery System Goals

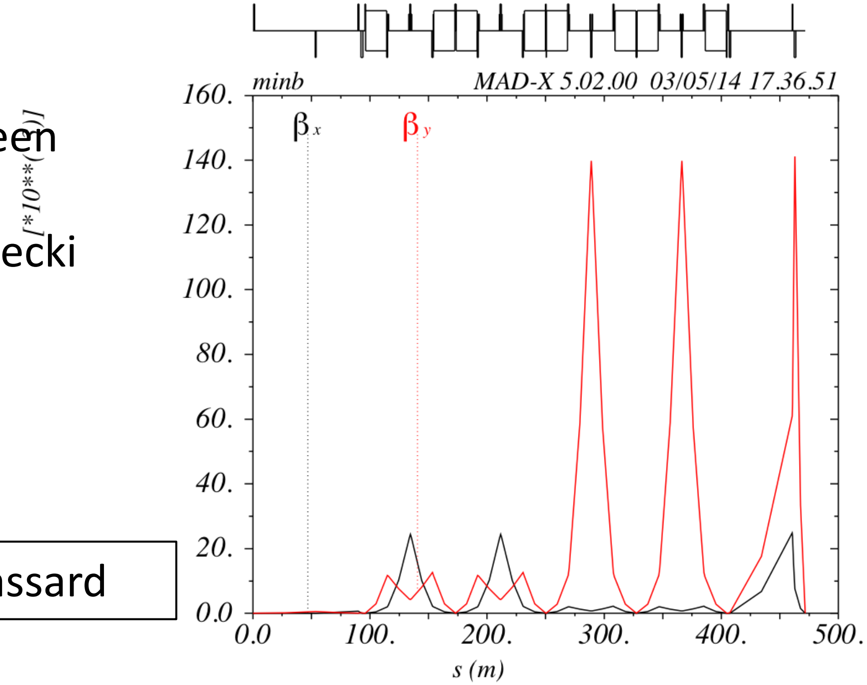
R. Tomas et al.

Most important is experimental programme at ATF2

System optimisation,
-> e.g. smaller horizontal beta-function for CLIC (8->4mm), see Hector Garcia

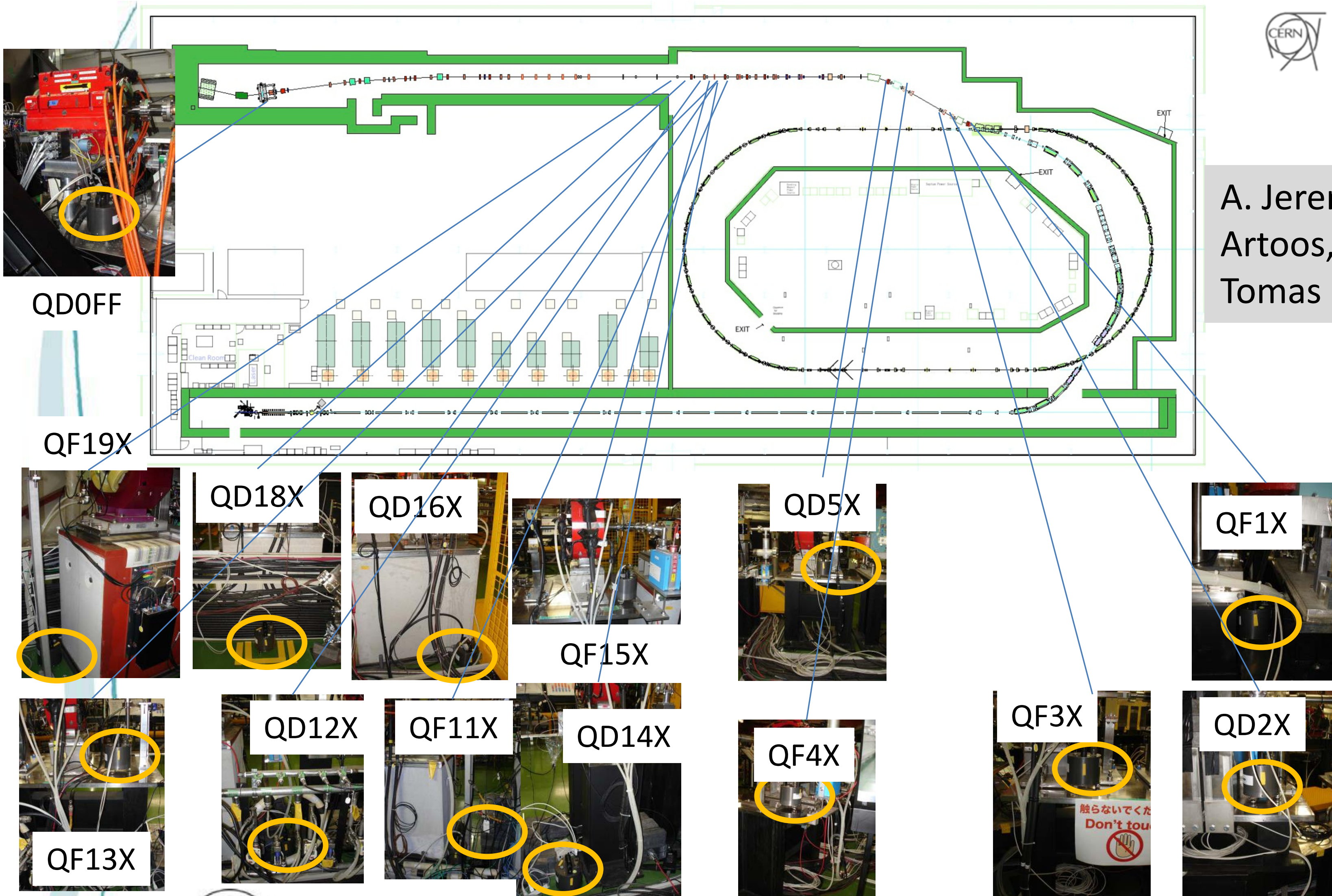
Tuning studies, in particular tuning with two beams (a difference to ATF2) and optimisation of system design for tuning

Exploitation of synergy with ILC
-> Rogelio already contributes to ILC, this has been formalised
-> L*=8m design adapted for ILC, see Marcin Patecki



Fabien Plassard

Stabilisation Experiment



A. Jeremie, K. Artoos, R. Tomas et al.

Beam-based Steering Tests at FACET

(1) Sectors 02-04, first 200 meters of SLAC linac

Emittance before correction (S04)

X = 2.79 x 10^{-5} m

Y = 0.54 x 10^{-5} m

E. Adli, A.Latina, J.Pfingstner, D. Schulte

After:

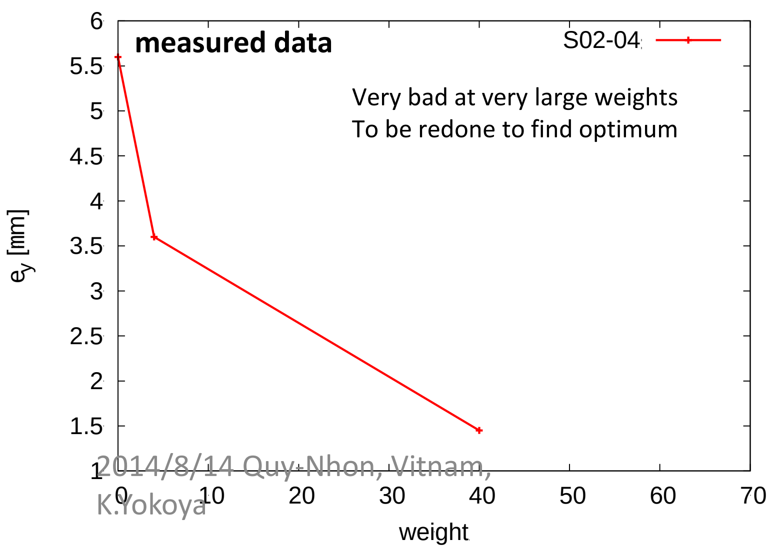
X = 3.38 x 10^{-5} m

Y = 0.14 x 10^{-5} m

- Vertical emittance got reduced by a factor ~3.8.
- Considerable incoming jitter on the H-axis jeopardized the X-axis

(2) Vertical emittance vs. weight scan:

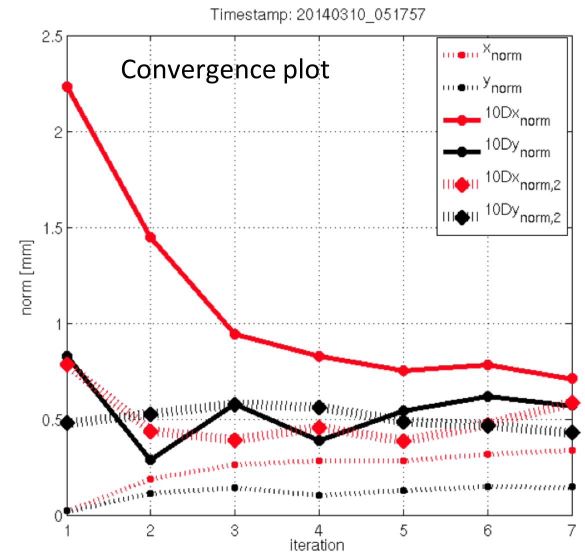
It matches the expected behavior



(3) First tests of simultaneous

Orbit + Dispersion + Wakefield correction

in sectors S05-11, 700 meters of SLAC linac



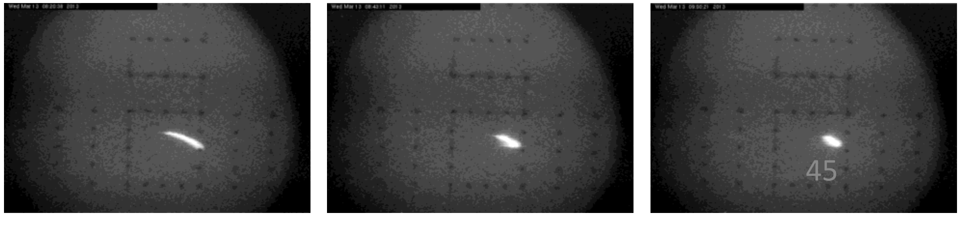
Vertical emittance got reduced from

from 1.58 x 10^{-5} m

to 0.40 x 10^{-5} m

(factor ~4)

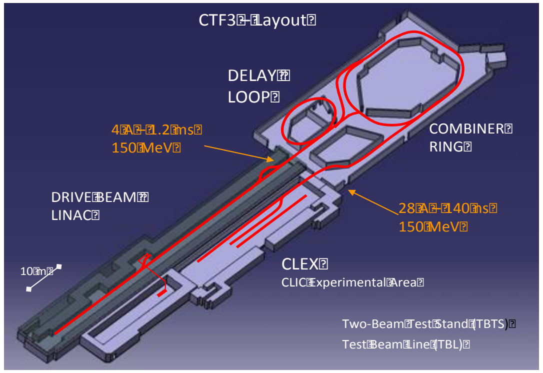
Beam transverse profile per iteration step (DFS correction)



CLIC roadmap

2013-18 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.



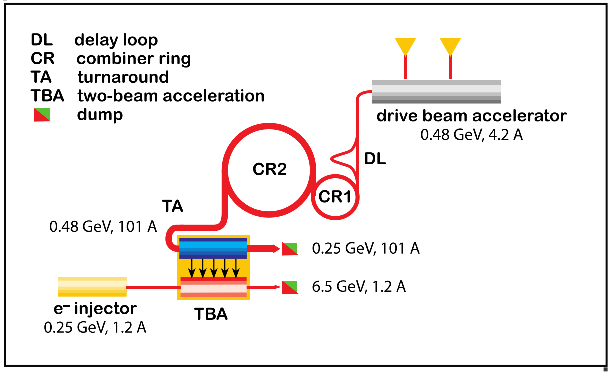
2018-19 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

4-5 year Preparation Phase

Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

Prepare detailed Technical Proposals for the detector-systems.



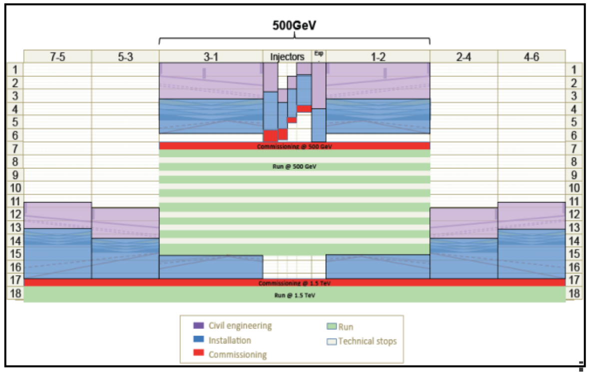
2024-25 Construction Start

Ready for full construction and main tunnel excavation.

Construction Phase

Stage 1 construction of CLIC, in parallel with detector construction.

Preparation for implementation of further stages.



Commissioning

Becoming ready for data-taking as the LHC programme reaches completion.