# Final Results From the CLIC Test Facility (CTF3)

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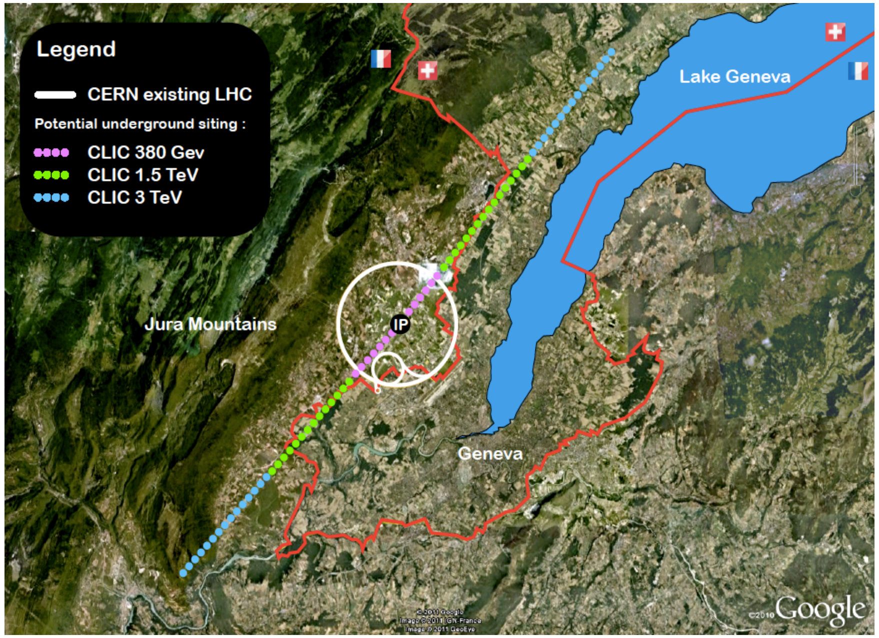
For the CLIC Collaboration

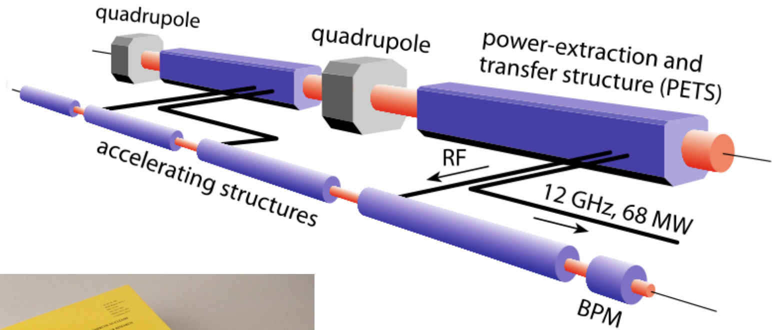
# CLIC in a nutshell

CLIC will be built in stages of increasing collision energy: starting from 380 GeV, then ~ 1- 2 TeV, and up to a final energy of 3 TeV.

To limit the collider length, the accelerating gradient must be very high - CLIC aims at 100 MV/m, 20 times higher than the LHC.

CLIC is based on a two-beam acceleration scheme, in which a high current e- beam (the drive beam) is decelerated in special structures (PETS), and the generated RF power is used to accelerate the main beam.




The feasibility of CLIC has been demonstrated and documented in the [CLIC Conceptual Design Report]


The CLIC accelerator and detector concepts, together with the physics potential of the project, are being studied and developed within world-wide coordinated efforts.

# CLIC Timeline

**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

**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)

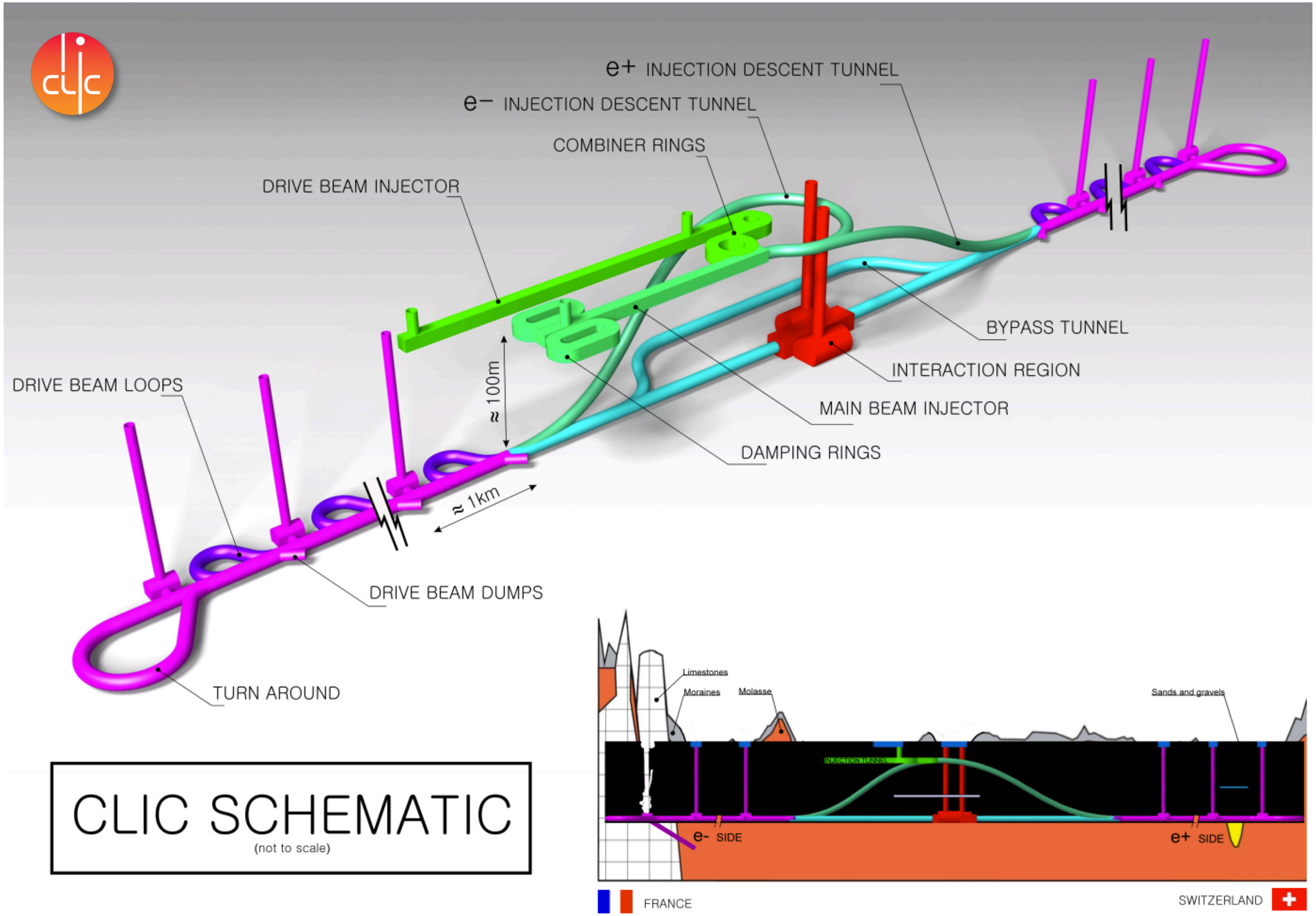
**2025 Construction Start**

Ready for construction; start of excavations

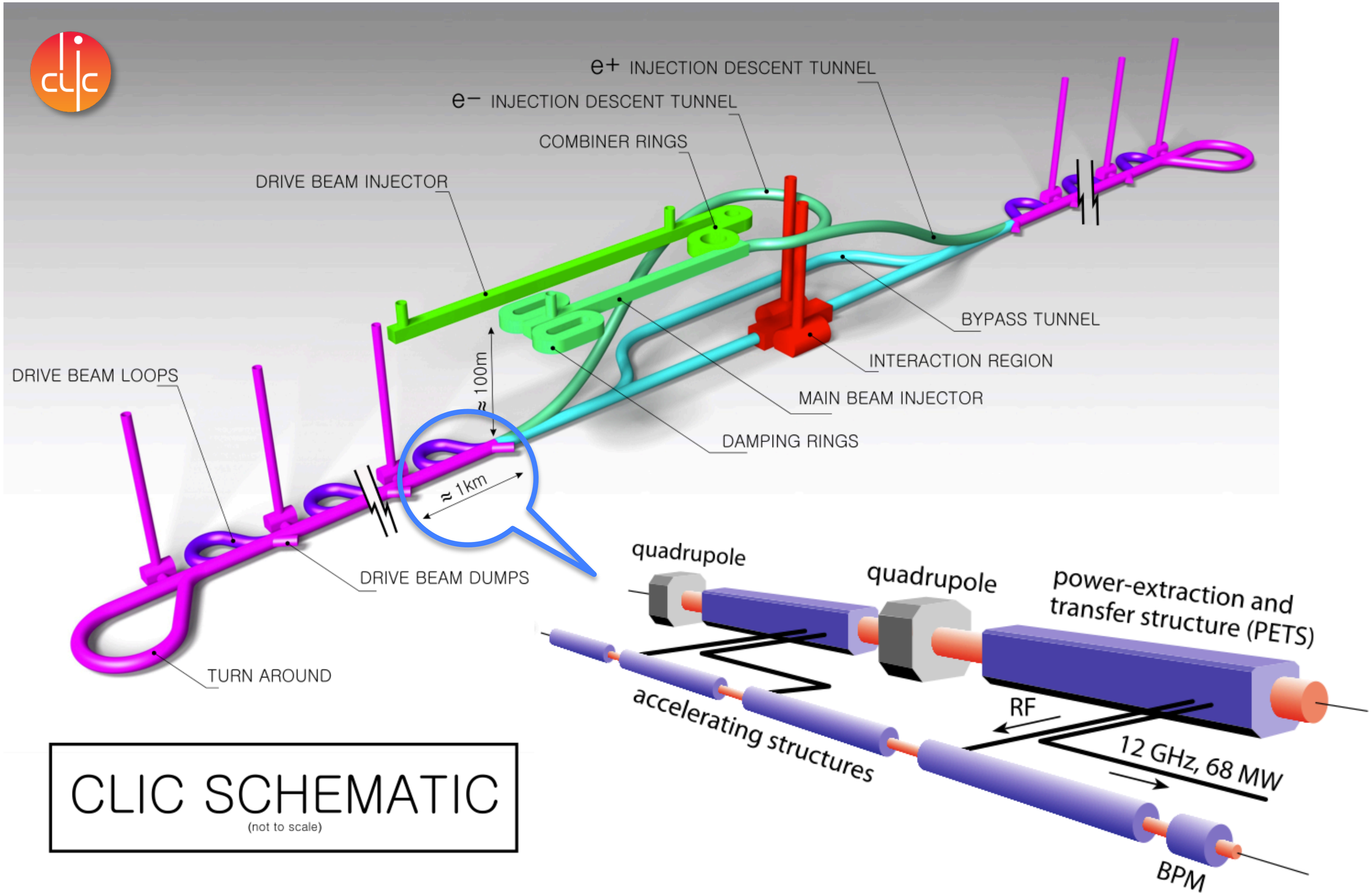
**2035 First Beams**

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

# The CLIC study



# The CLIC study



# What matters in a linear collider ?

Energy reach

$$E_{cm} \approx L_{linac} G_{acc}$$

High gradient

X-band normal conducting

Luminosity

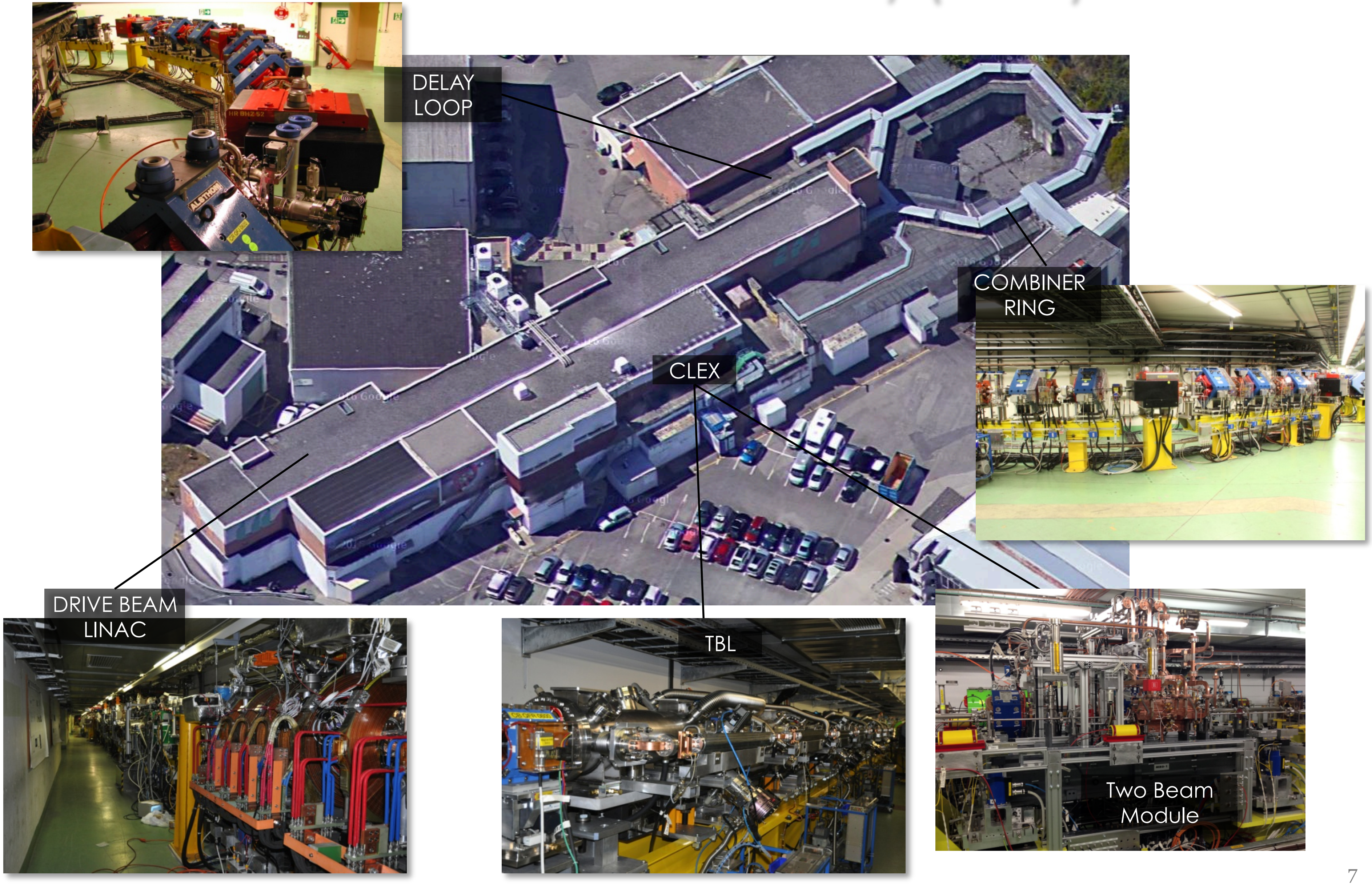
$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x^* \sigma_y^*} \times H_D \propto \frac{\eta_{beam}^{AC} P_{AC}}{\varepsilon_y^{1/2}} \frac{\delta_{BS}^{1/2}}{E_{cm}}$$

N.B.: $\sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\epsilon_{x,y}}{\gamma}}$

CLIC specific Issues

- Acceleration efficiency — Two-beam scheme
- Generation of small emittance — Damping rings
- Conservation of small emittance — Wake-fields, alignment, stability
- Extremely small beam spot at IP — Beam delivery system, stability

# CLIC Test Facility (CTF3)



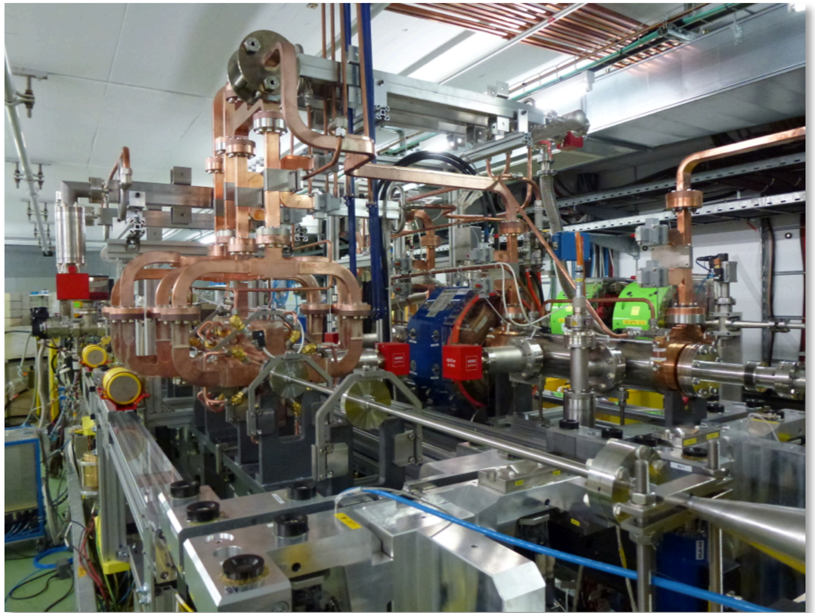
# Two-beam scheme issues

## Drive Beam Generation

- Full beam loading acceleration ✓
- High current stable acceleration ✓
- Bunch length control, isochronous beam lines ✓
- Phase coding ✓
- Combination with RF deflectors ✓
- Drive Beam stability (phase, charge, …) ✓

## RF Power Production

- RF power level and pulse length (break-down limit) ✓
- Extraction efficiency, HOMs ✓
- Drive Beam deceleration (efficiency, transport, stability) ✓
- On-off mechanism (break-down protection) ✓
- RF pulse shape (beam loading compensation) ✓



# Two-beam scheme issues

## Drive Beam Generation

- Full beam loading acceleration ✓
- High current stable acceleration
- Bunch length control, isochronous beam lines
- Phase coding
- Combination with RF deflectors
- Drive Beam stability (phase, charge, …)

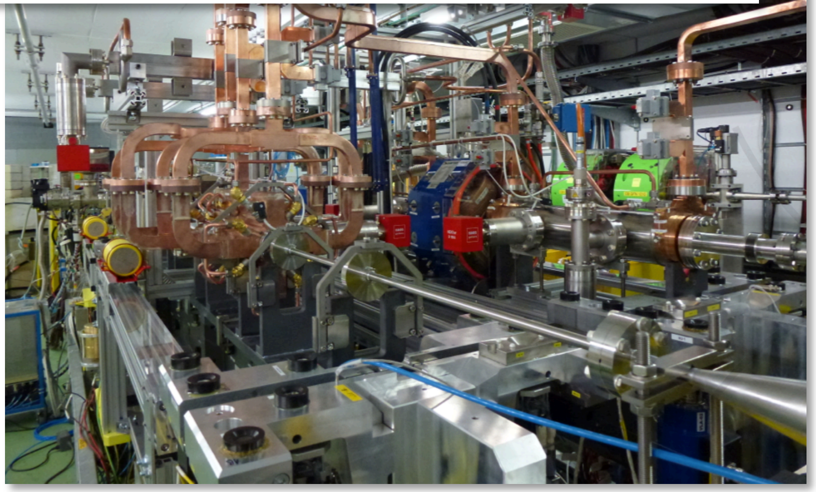
## All covered in CTF3

## Two-Beam Acceleration

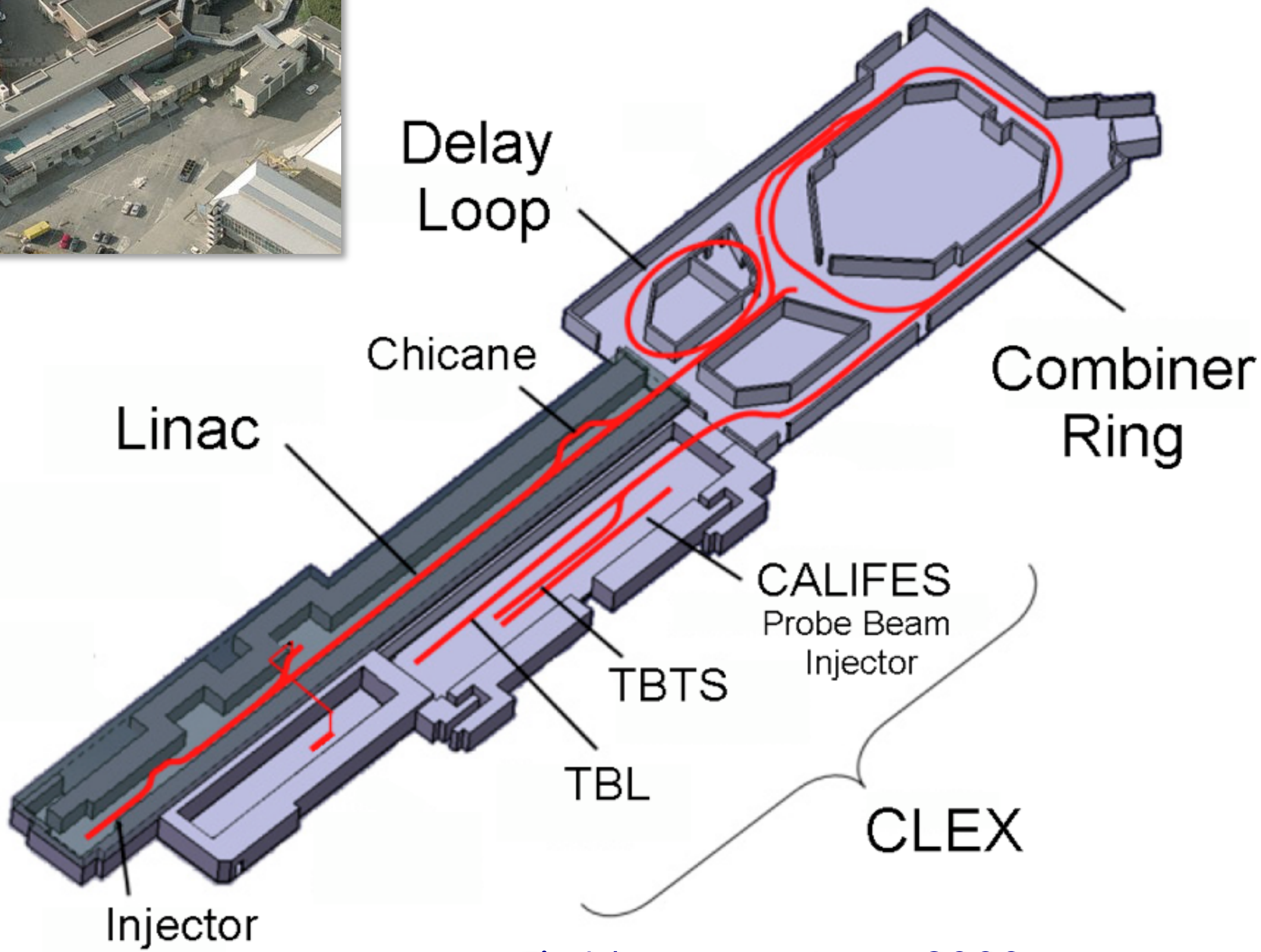
- Gradient, pulse length (break-down limit) ✓
- Consistency with expectations ✓
- Break-down kicks ✓
- Test with full-fledged module ✓
- Wake-field monitors ✓

## RF Power Production

- RF power level and pulse length (break-down limit) ✓
- Extraction efficiency, HOMs ✓
- Drive Beam deceleration (efficiency, transport, stability) ✓
- On-off mechanism (break-down protection) ✓
- RF pulse shape (beam loading compensation) ✓



# CTF3 – the original mission




First beam – June 2003

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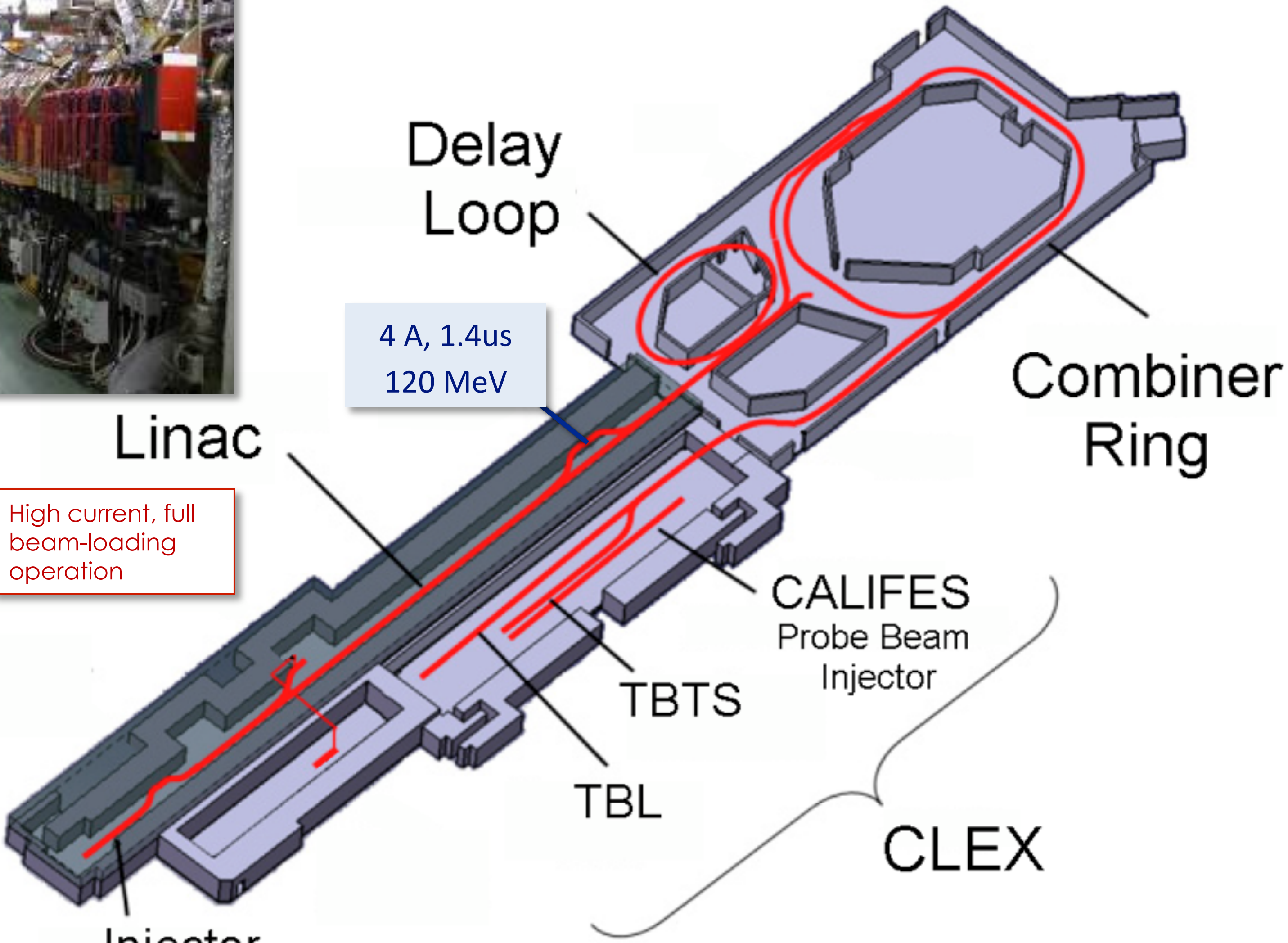


First beam – June 2003

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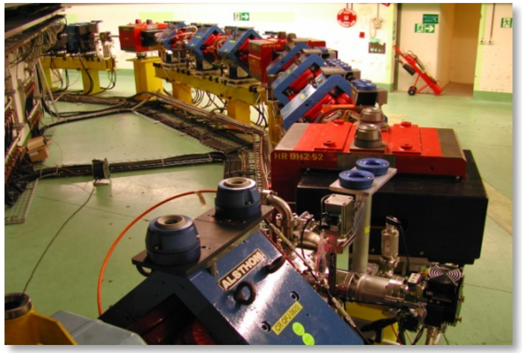
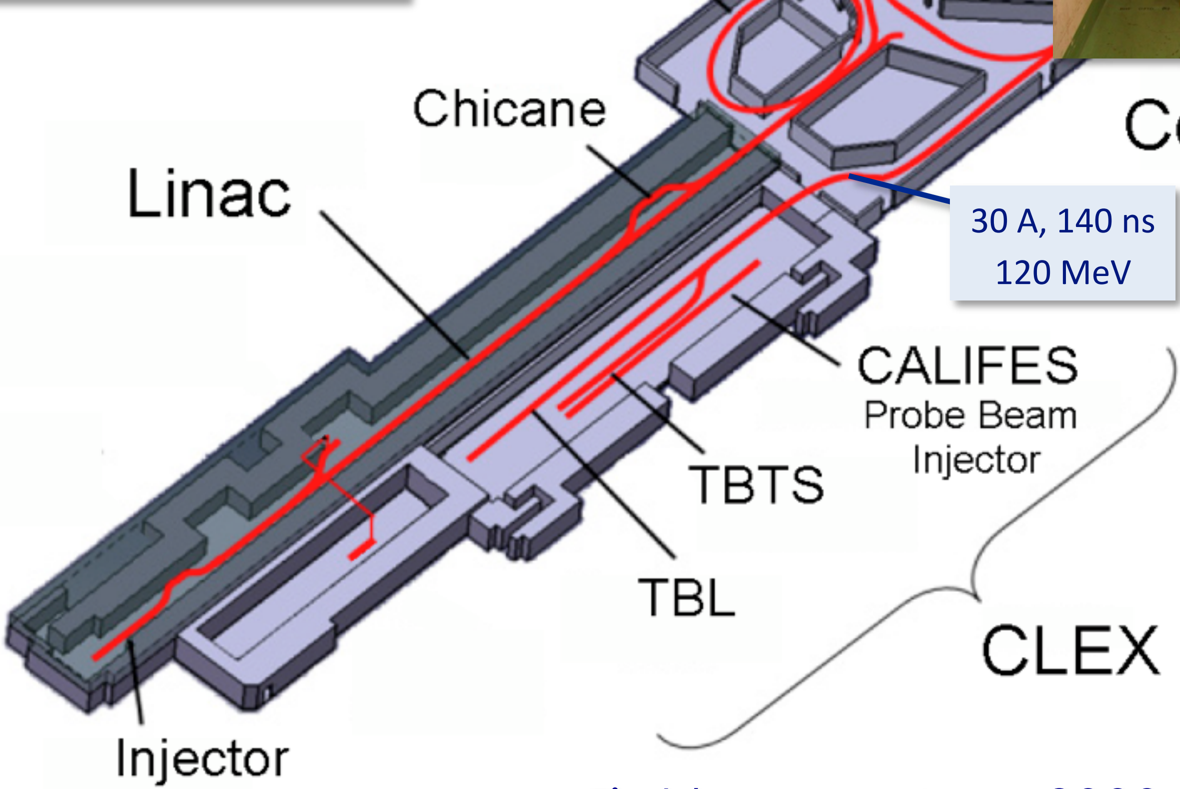
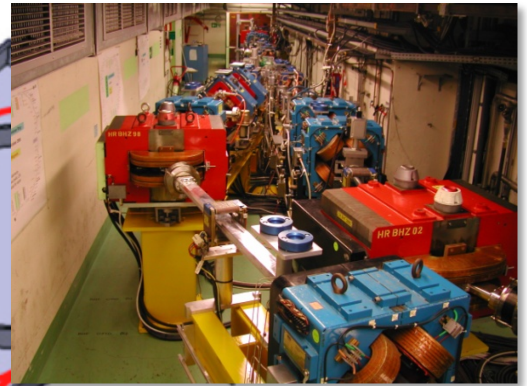


Operation of isochronous lines and rings



Beam recombination and current multiplication by RF deflectors

First beam – June 2003

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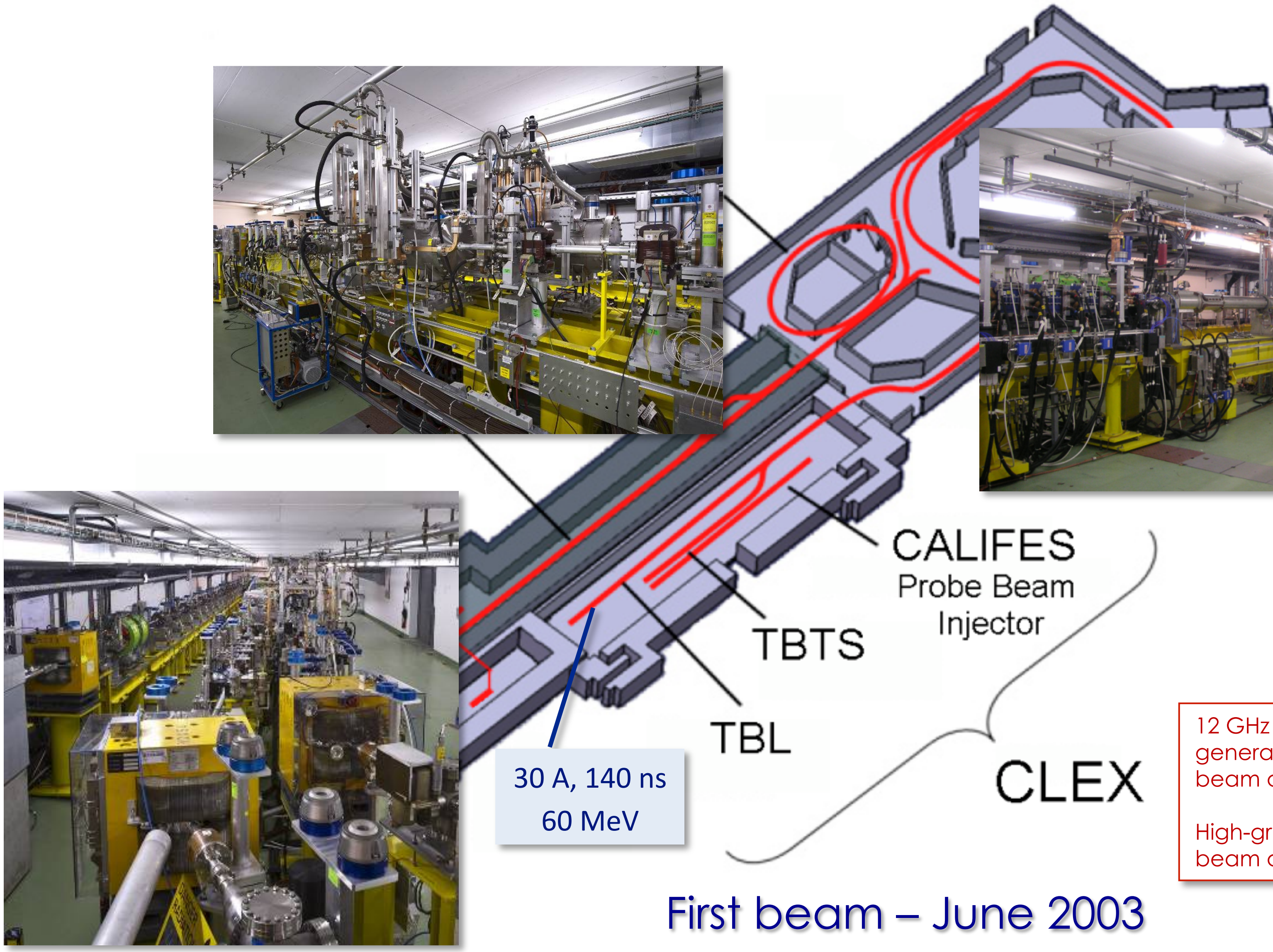


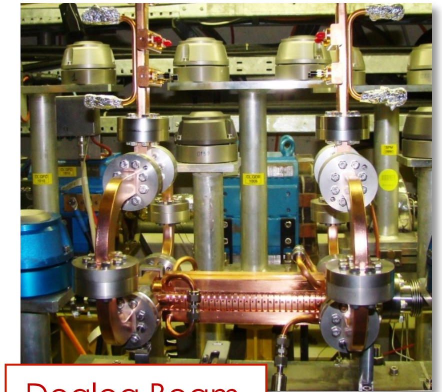

30 A, 140 ns
60 MeV

12 GHz power generation by drive beam deceleration

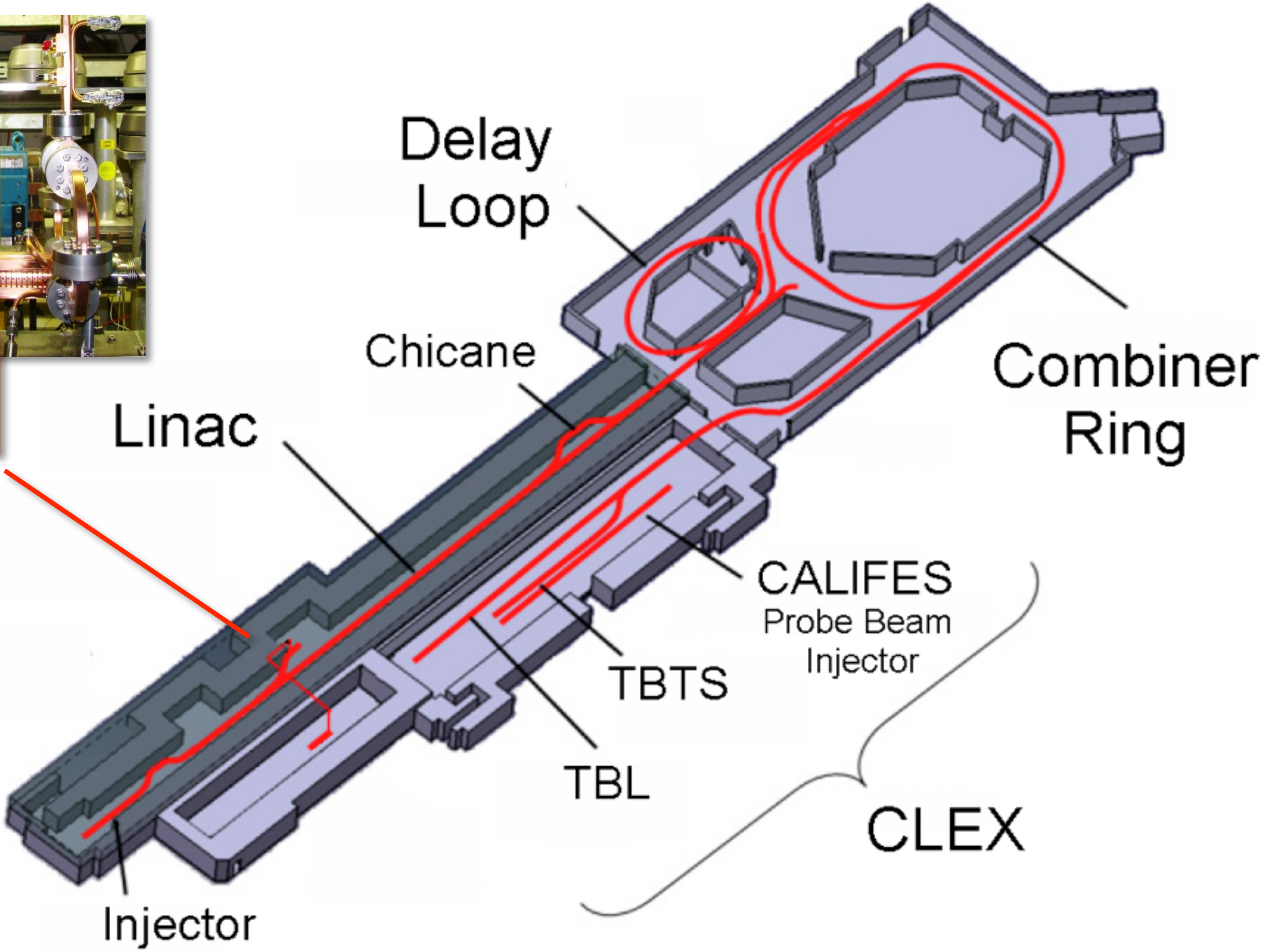
High-gradient two-beam acceleration

First beam – June 2003

# CTF3 in 2015-2016

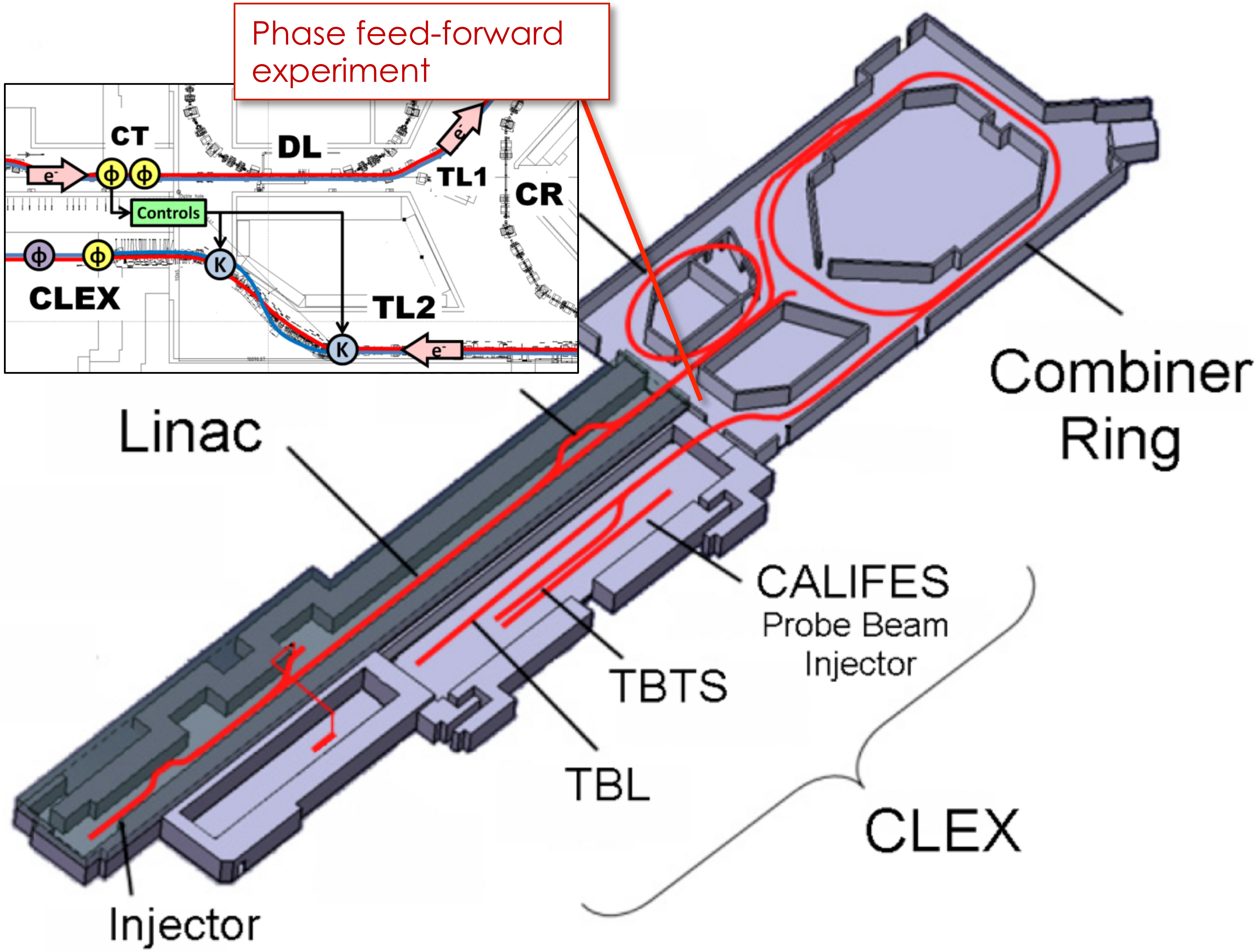


Dogleg Beam loading experiment




Last beam – December 2016

# CTF3 in 2015-2016

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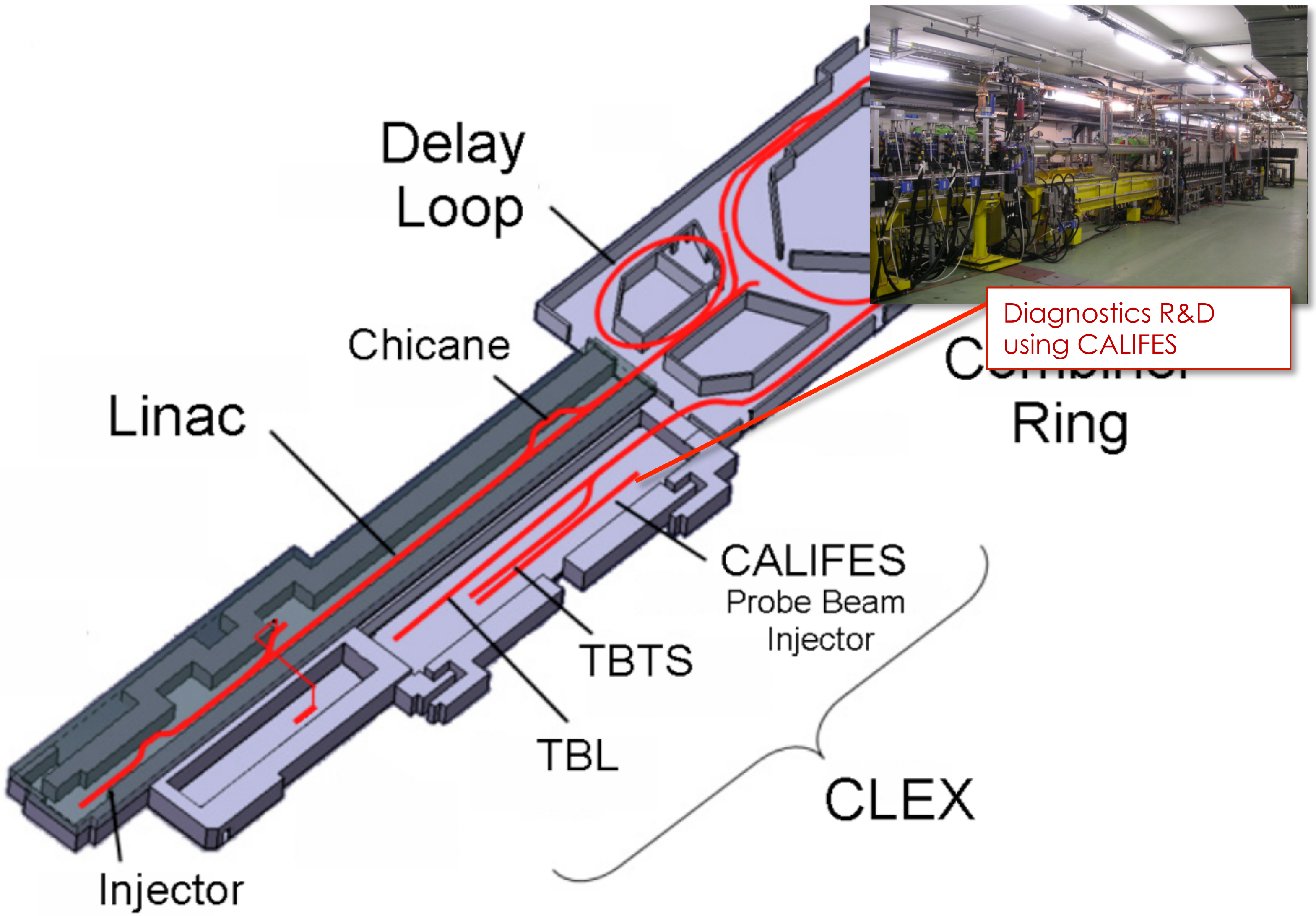


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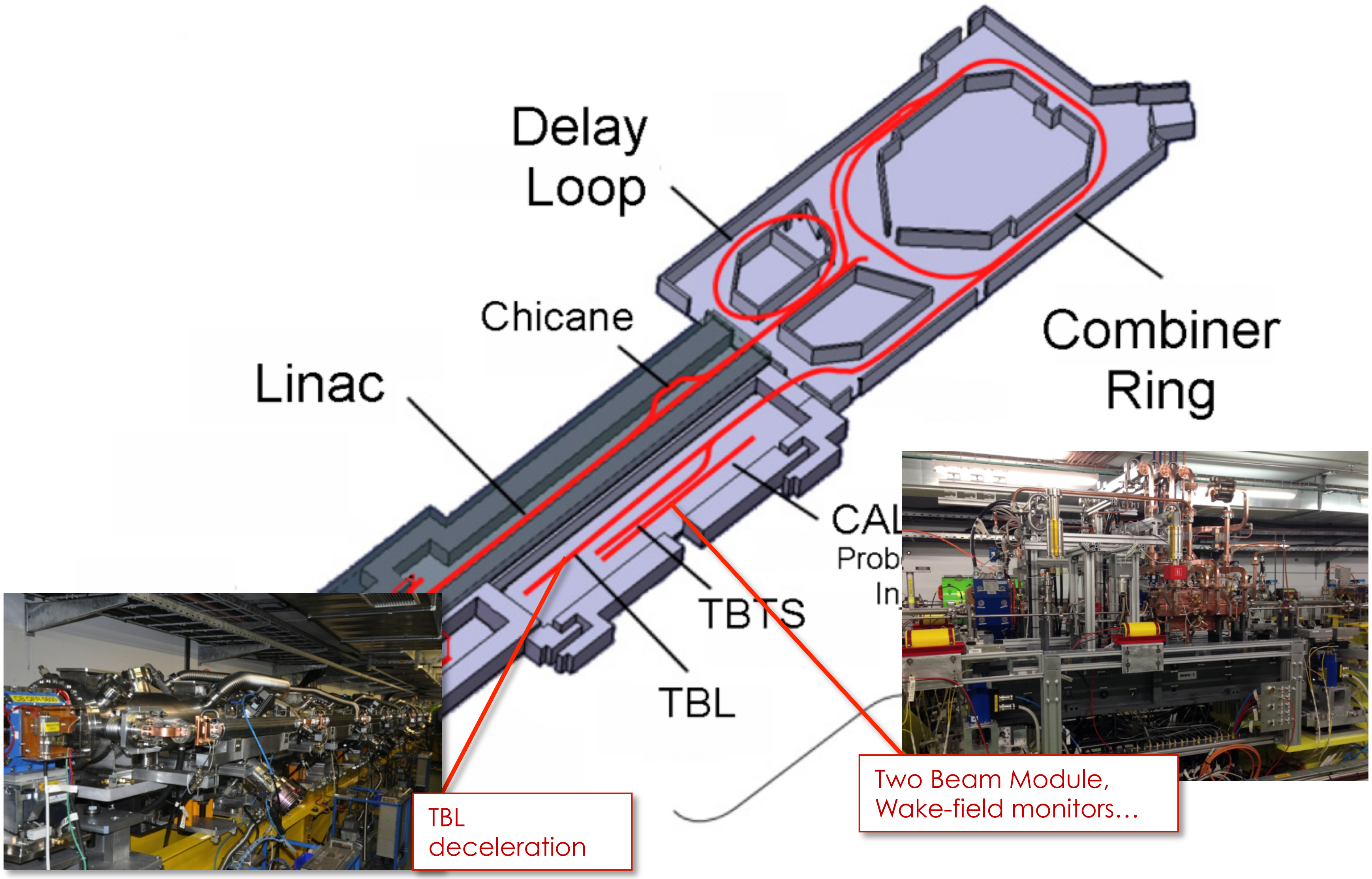
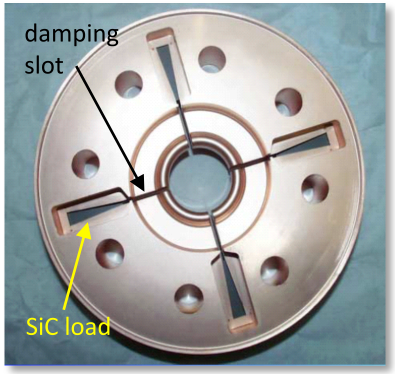
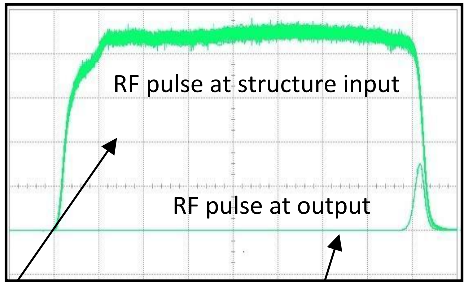



Last beam – December 2016

# Drive Beam Generation

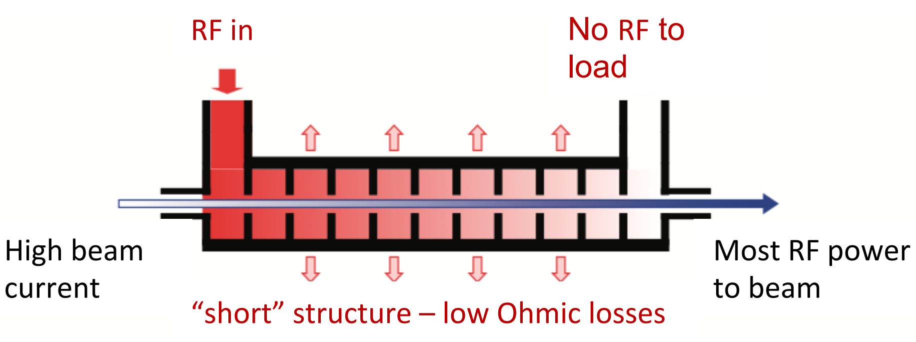


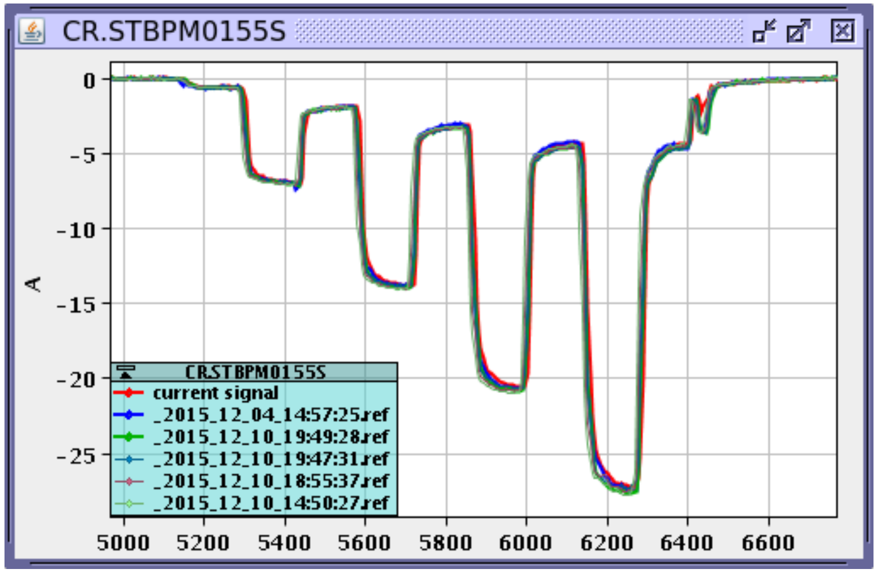

Full beam loading acceleration




95.3% RF to beam efficiency
Stable high current acceleration

Factor 8 current & frequency multiplication



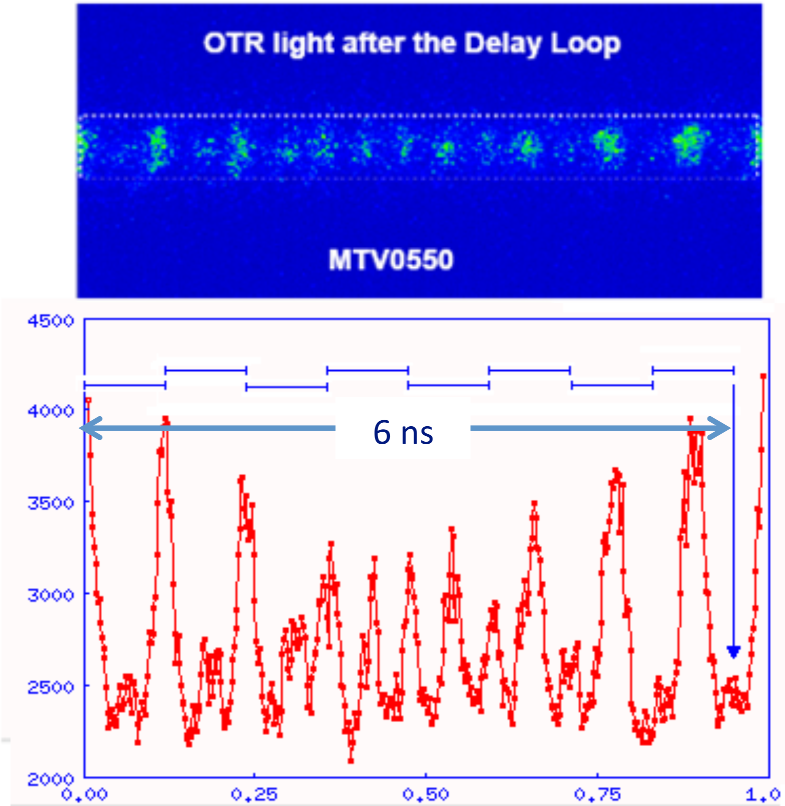



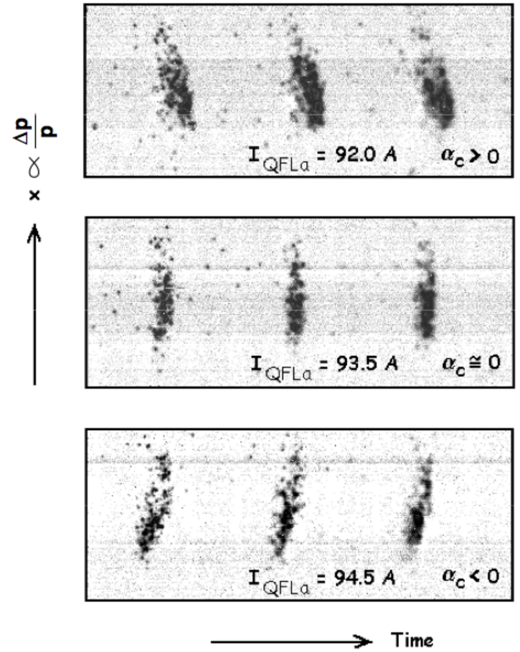

Factor 8 combination

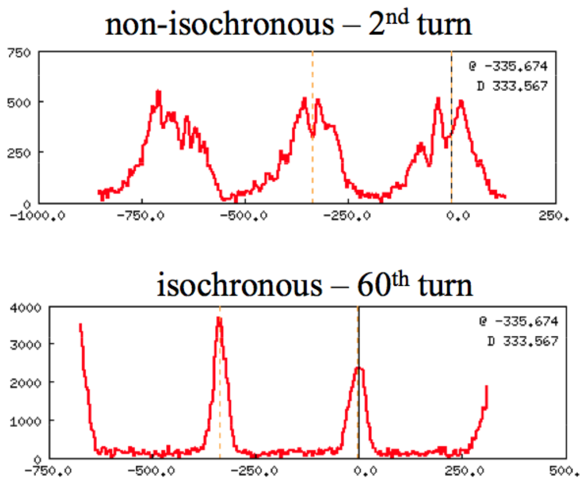
# Drive Beam Generation

## Beam recombination

- Fast bunch phase switch in SHB system
- Operation of isochronous rings and beam lines



# Drive Beam Stability

## CLIC Drive Beam requirements

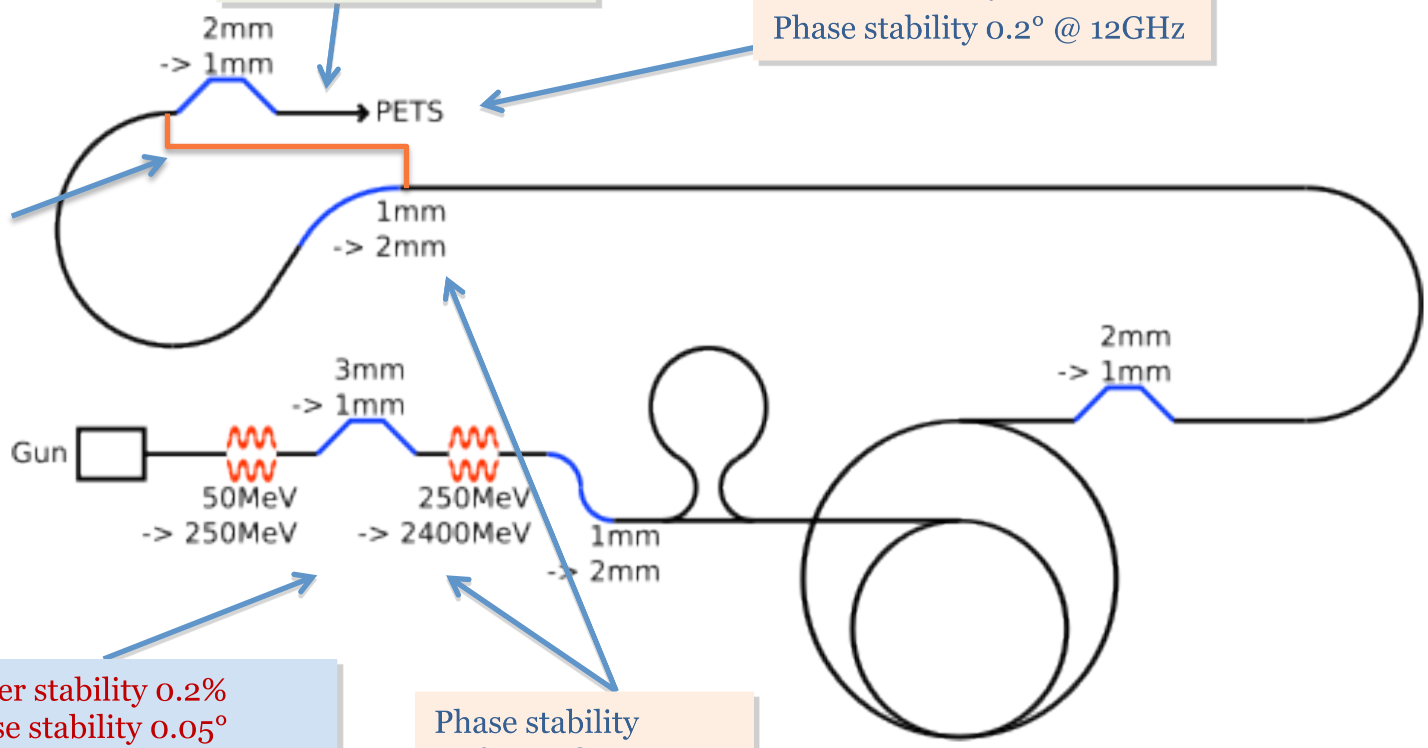
**Tests in CTF3**
$\varepsilon_x \leq 250\mu m$, $\varepsilon_y \leq 100\mu m$
$\leq 0.1\sigma$

Emittance $\varepsilon_{x,y} \leq 150\mu m$
Transverse jitter $\leq 0.3\sigma$

**Verified in CTF3**
1 to 3 $\times 10^{-3}$
< 0.2°

Current stability 1 $\times 10^{-3}$
Phase stability 0.2° @ 12GHz

**Feed-forward tests in CTF3**




RF power stability 0.2%
RF phase stability 0.05°
Current stability 0.75 $\times 10^{-3}$

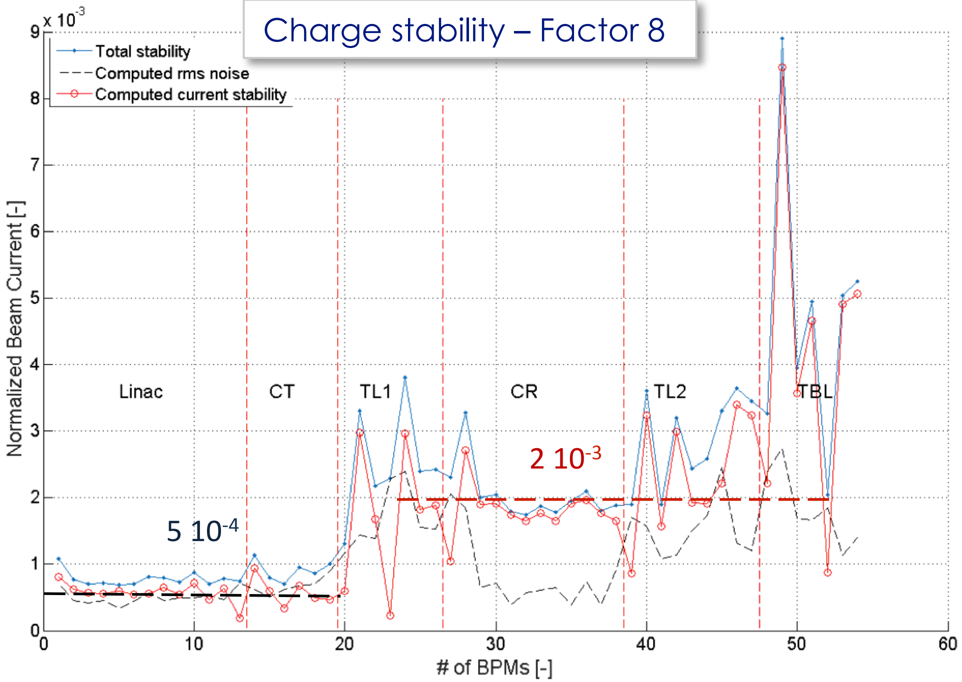
**Verified in CTF3**
0.21%
0.035°
0.2 $\times 10^{-3}$

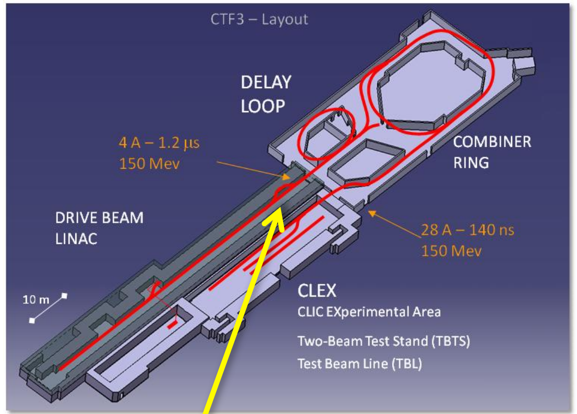
Phase stability
2.5° @ 12GHz

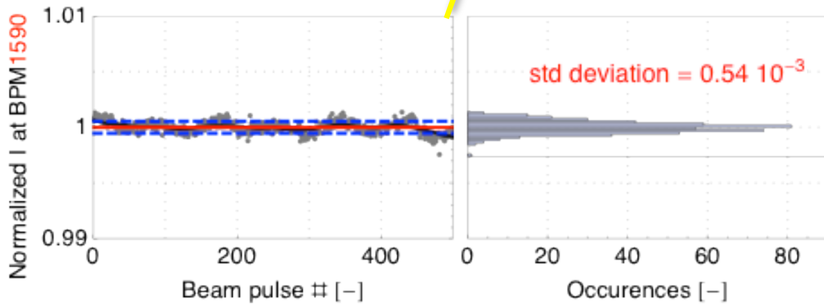
**Verified in CTF3**
~1° @12 GHz

# Drive Beam Stability

Pulse charge stability at end of the linac better than CLIC requirements

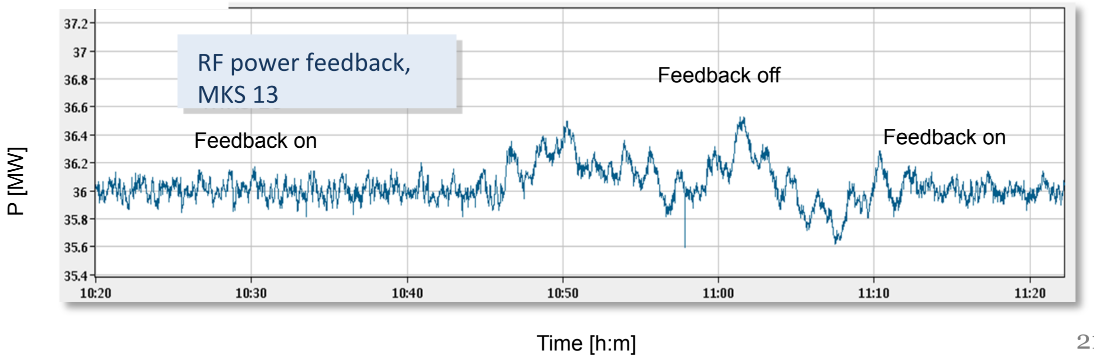



Repeatibility and long term current stability greatly improved in final years.

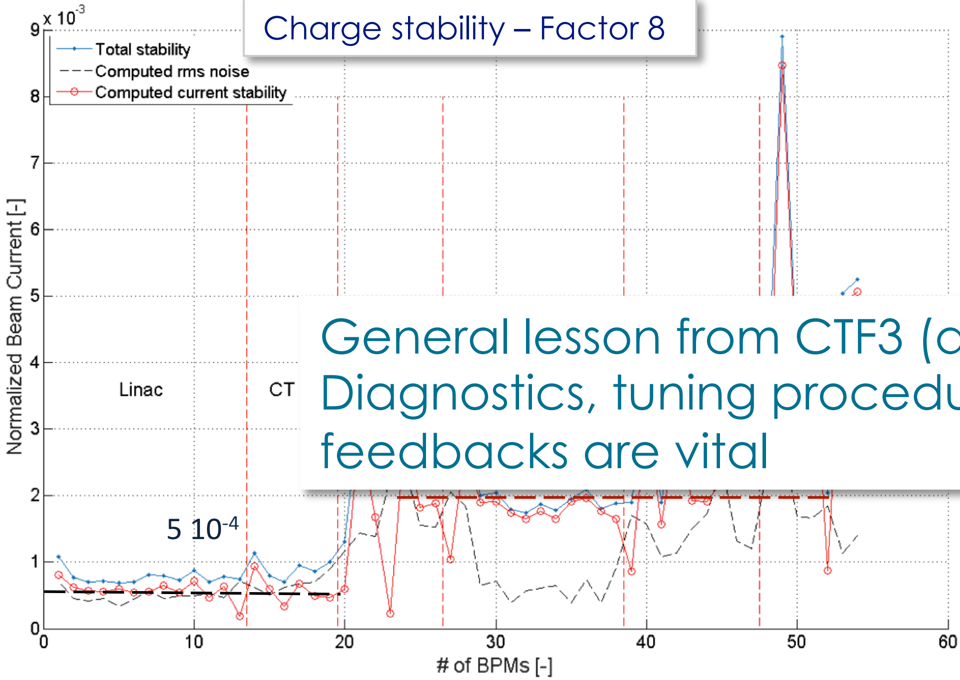
Many feed-back loops operational, for temperature, RF phase and power and gun current.

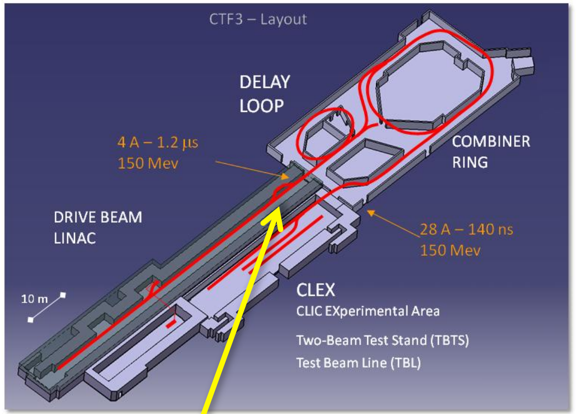


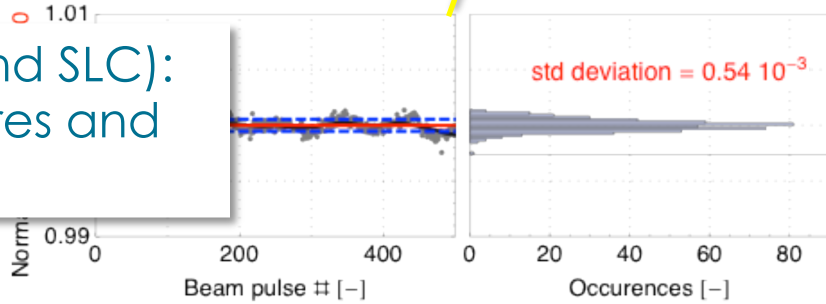
# Drive Beam Stability

Pulse charge stability at end of the linac better than CLIC requirements

Charge stability – Factor 8



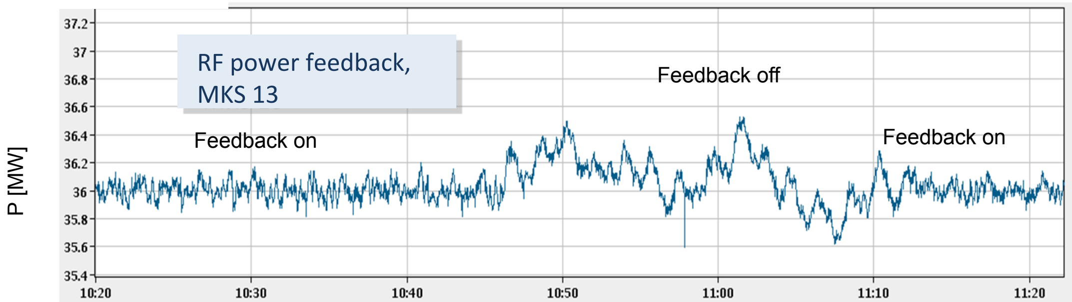




General lesson from CTF3 (and SLC): Diagnostics, tuning procedures and feedbacks are vital

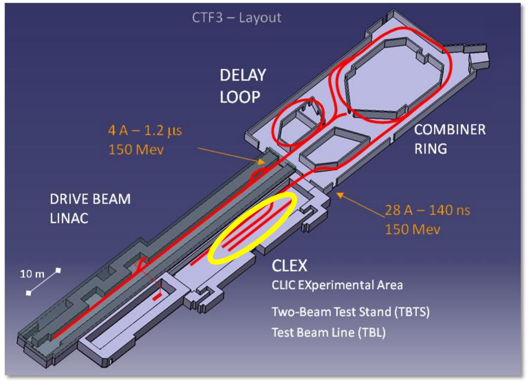
Repeatibility and long term current stability greatly improved in final years.

Many feed-back loops operational, for temperature, RF phase and power and gun current.

RF power feedback, MKS 13



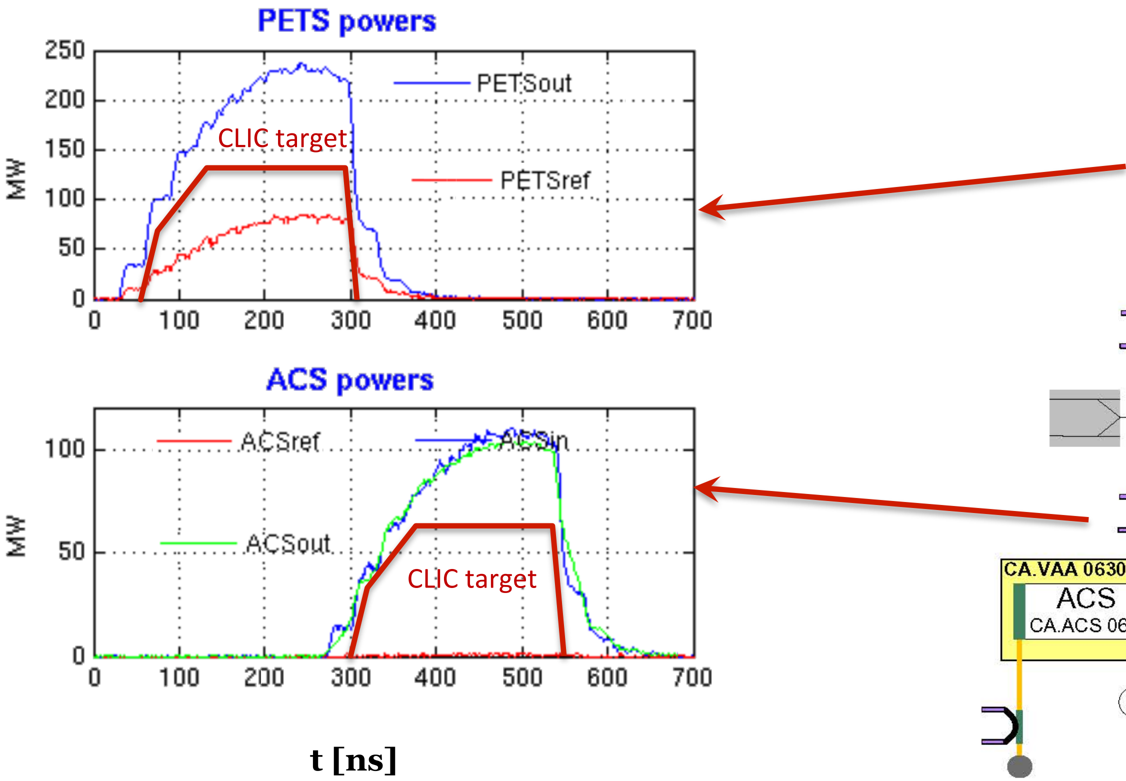
# Power production in the Two-Beam Test Stand

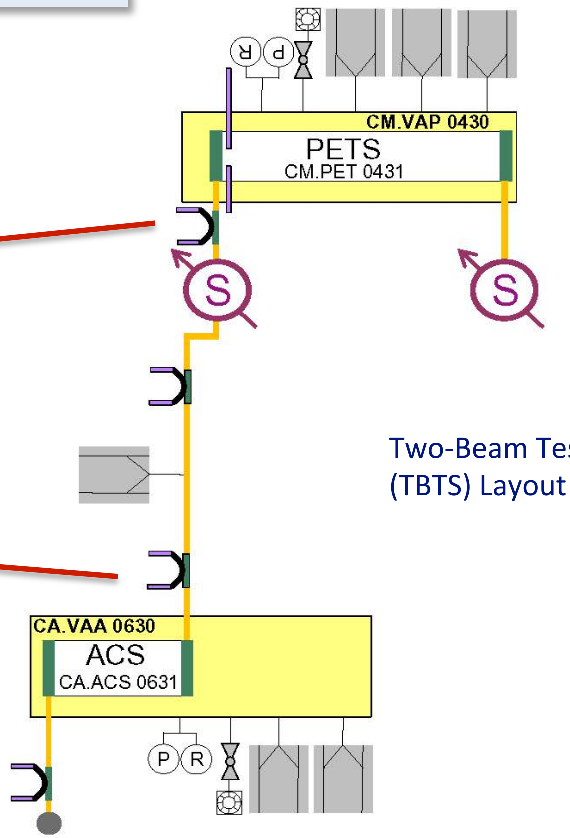



PETS operated routinely above **200 MW** peak RF power

providing reliably pulses ~ 100 MW to accelerating structure.

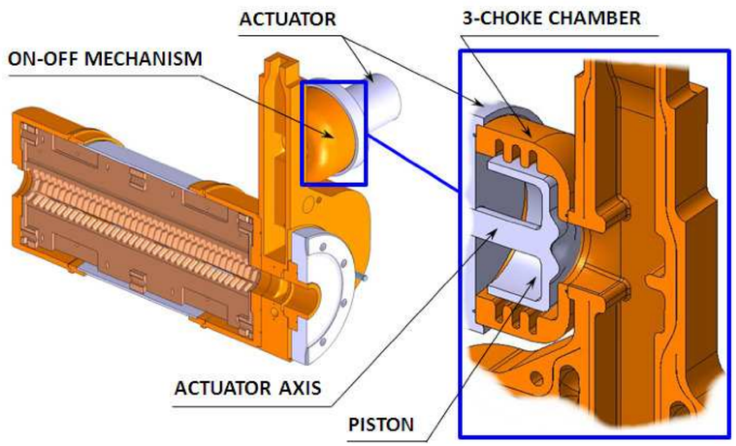
About twice the power needed to demonstrate 100 MV/m acceleration in a two-beam experiment with the nominal CLIC structure.

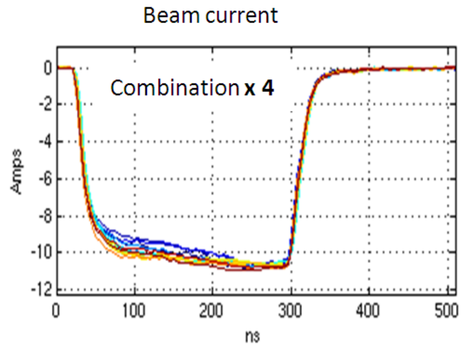


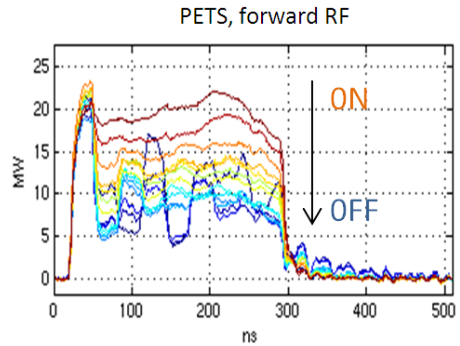



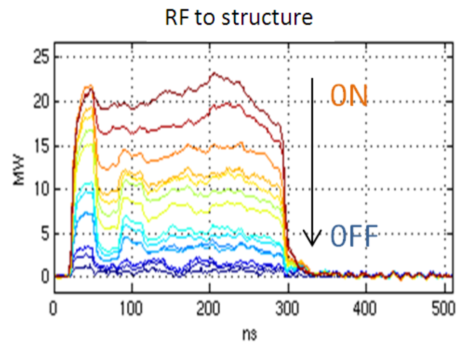

Two-Beam Test Stand (TBTS) Layout

# TBTS – PETS On-off mechanism



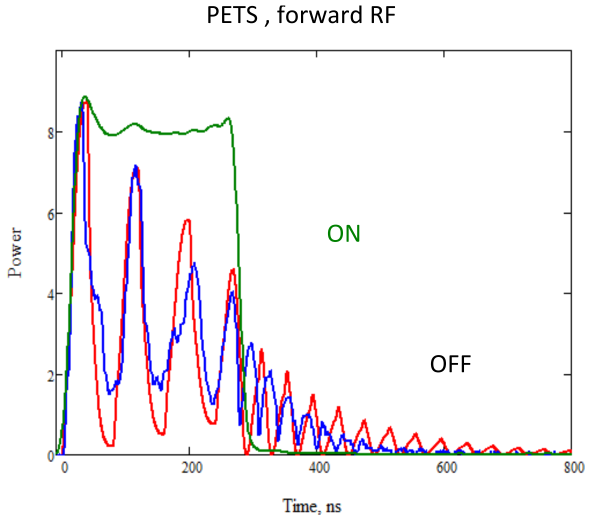



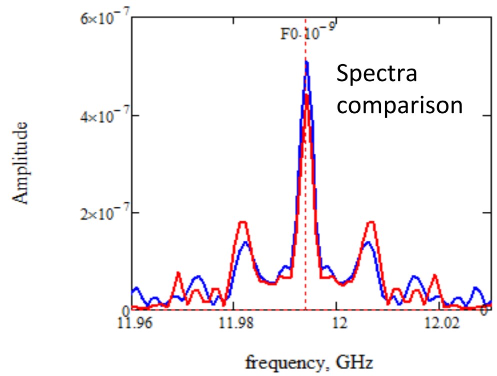




Demonstration of PETS of-off mechanism

- Feasibility issue
  - Switch off power from individual PETS to accelerating structure in case of breakdown
  - Reduce substantially power in PETS, to cope with PETS breakdowns
- PETS on-off principle fully tested
- Conditioned at high power (135 MW - nominal) by recirculation
- System routinely used in CTF3 for power enhancement and tuning

Simulation vs. experiment



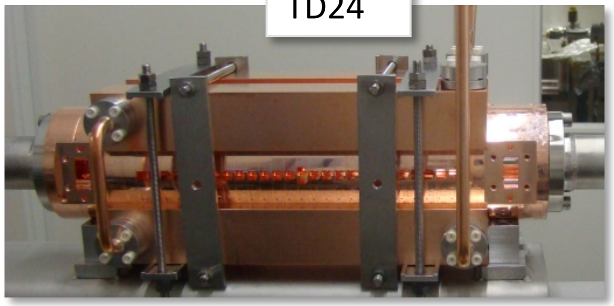
# Two-Beam Acceleration

Two-Beam Acceleration demonstration in TBTS

Up to 145 MV/m measured gradient

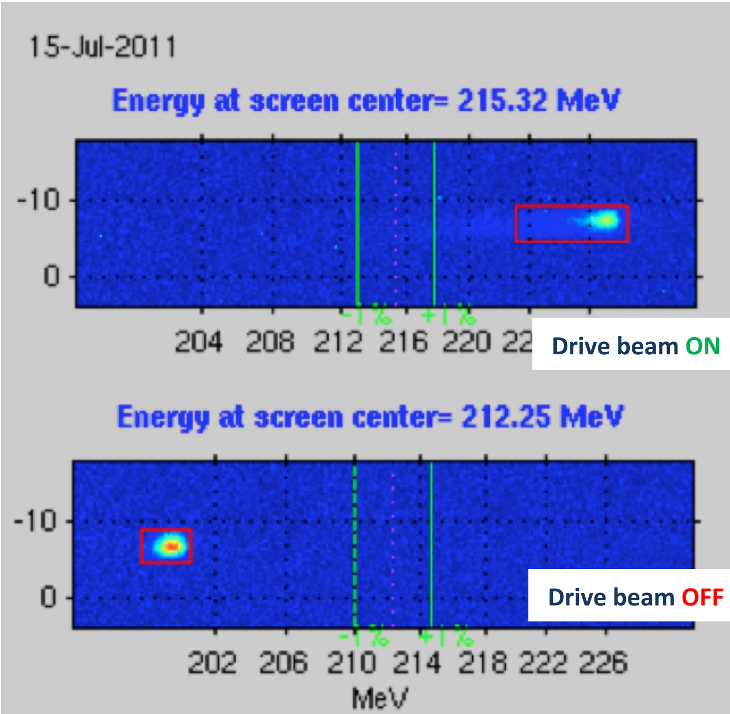
Good agreement with expectations (power vs. gradient)

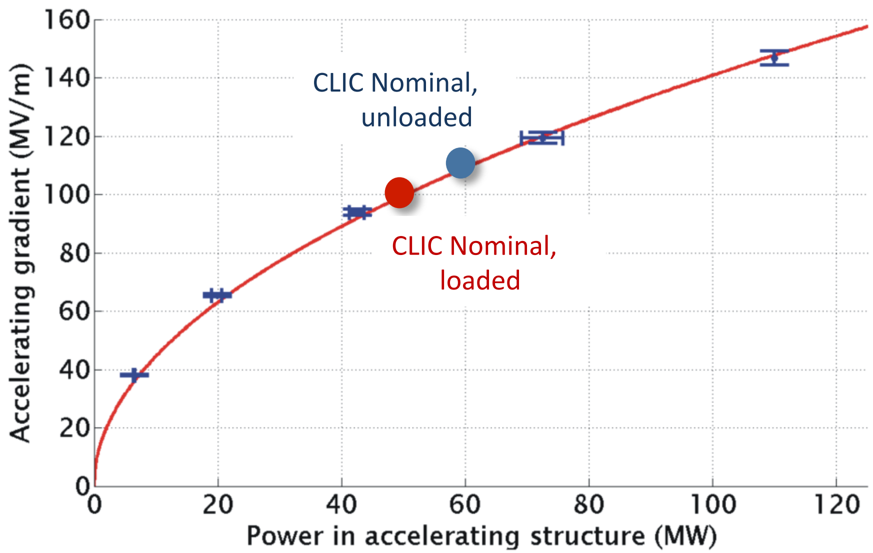
TD24



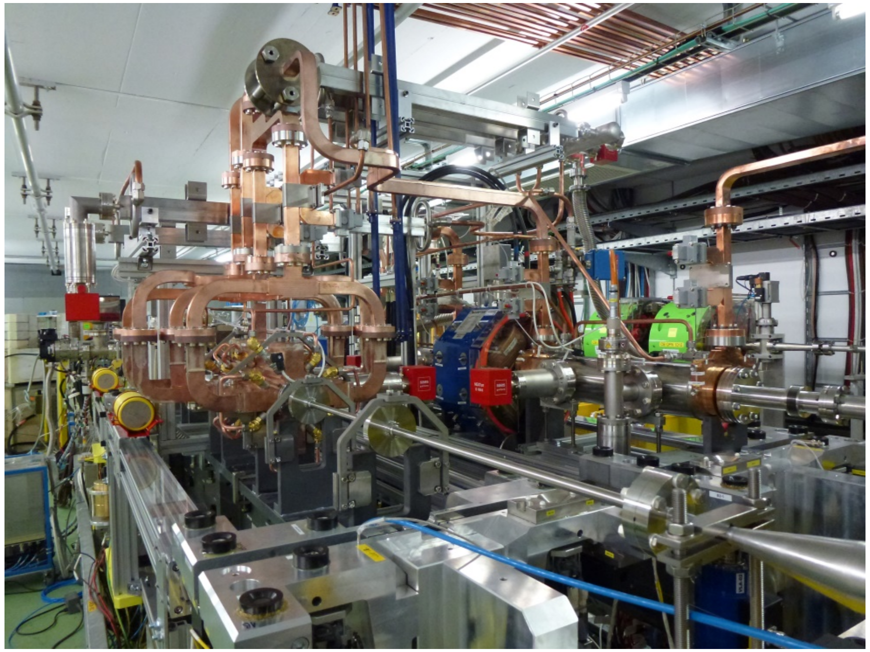
Maximum stable probe beam acceleration measured: 31 MeV

⇒ Corresponding to a gradient of **145 MV/m**



# Two-Beam Module Experimental Program 2015-2016



## CLIC two-beam module tests

- Power production, stability + control of RF profile
- RF phase/amplitude drifts along TBL, PETS switching at full power
- Two-beam acceleration, power transfer & phasing, breakdown detection and effects of breakdowns…
- Alignment tests, with and w/o beam, including Wake-Field Monitors and main beam prototype BPMs

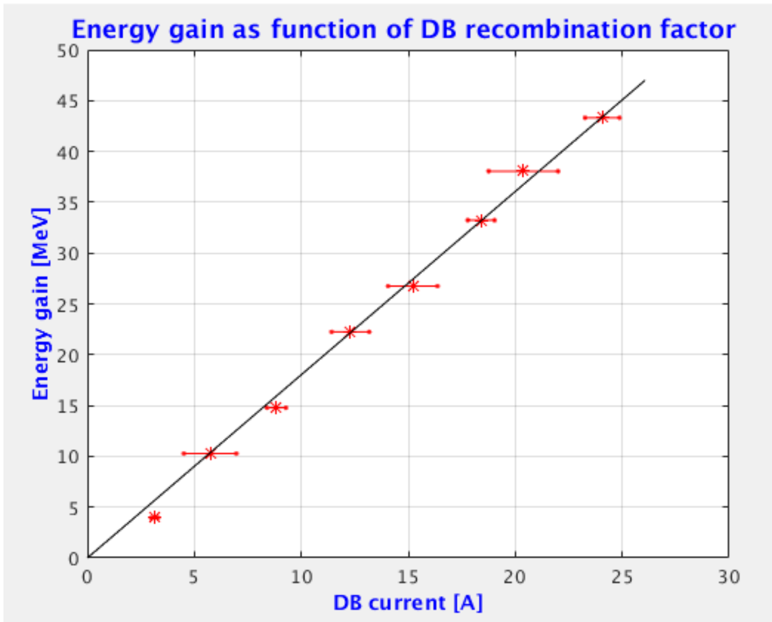
- Aim: gather all possible information, to feed back into next generation Two-Beam Module design

Two-beam acceleration in TBM thoroughly tested

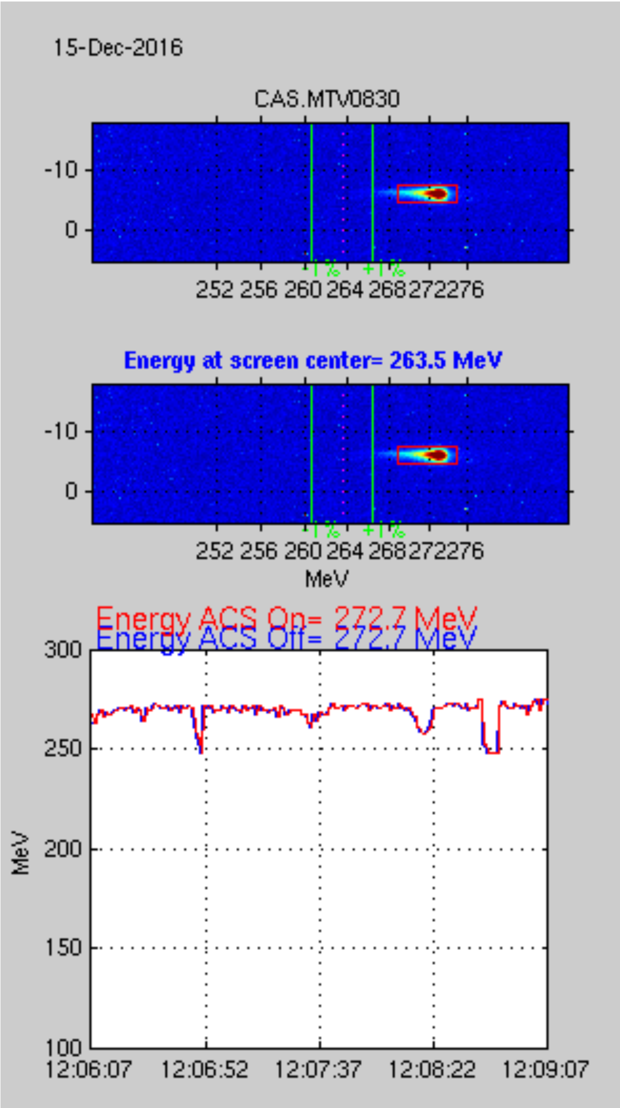
Verified again power production/energy gain vs. expectations

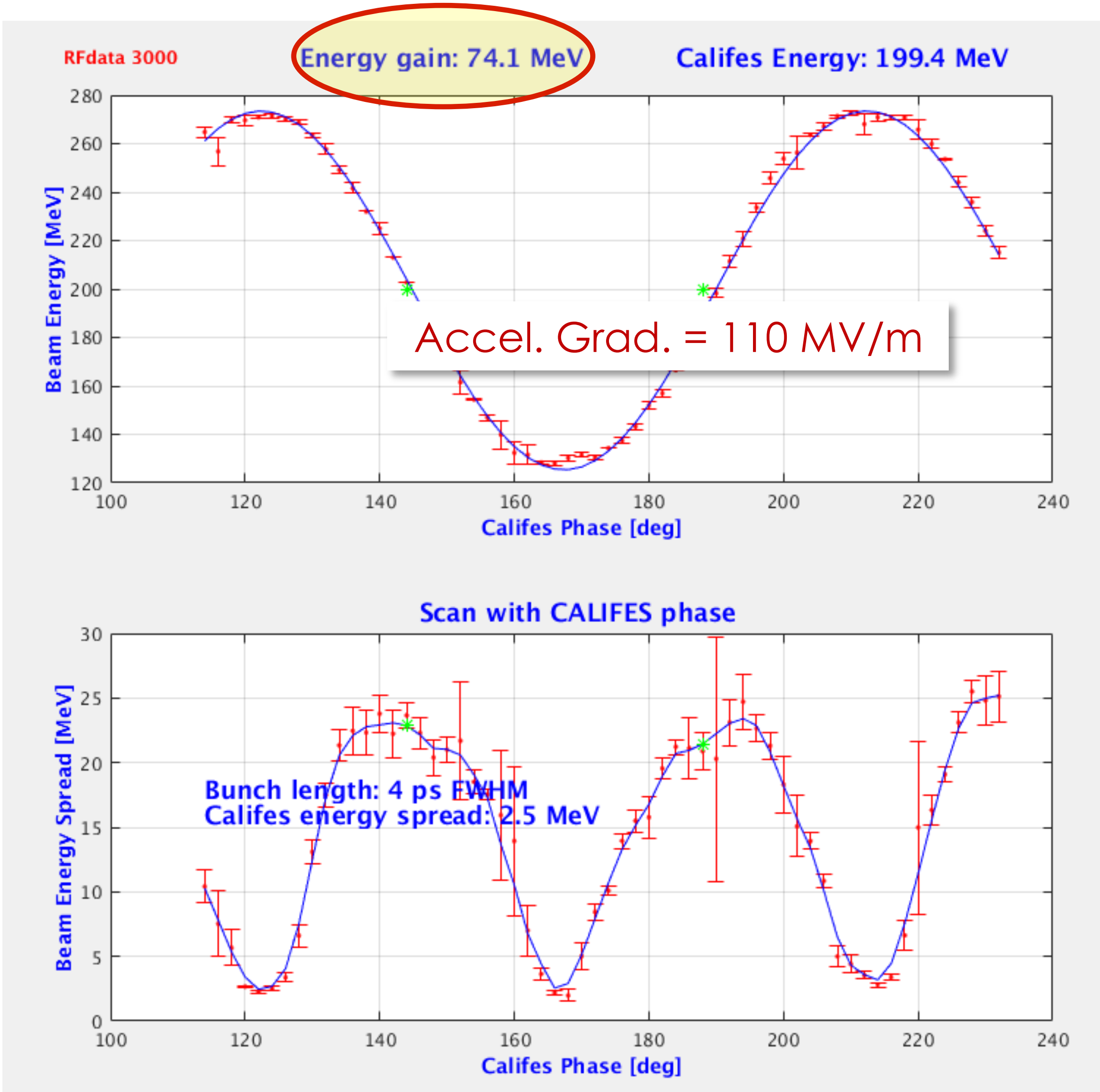
Operated at nominal CLIC gradient and pulse length, ~ 100 MV/m and 240 ns

Experiment on control of RF profile (beam loading compensation) done

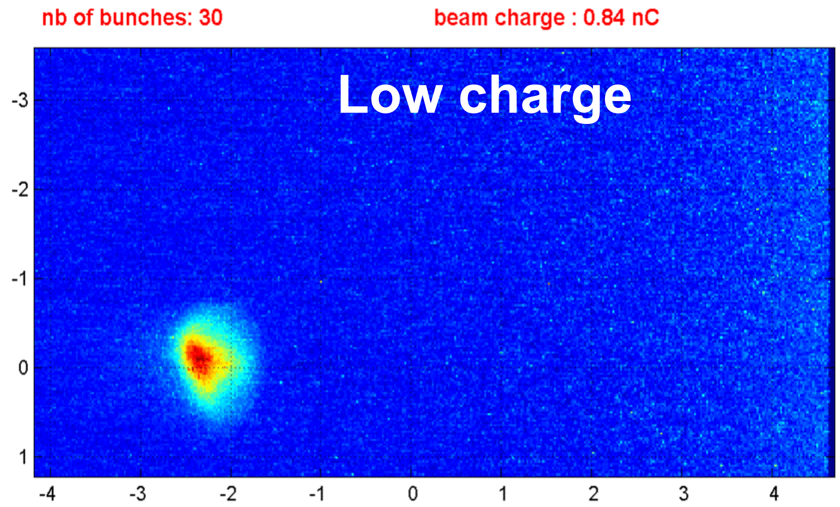


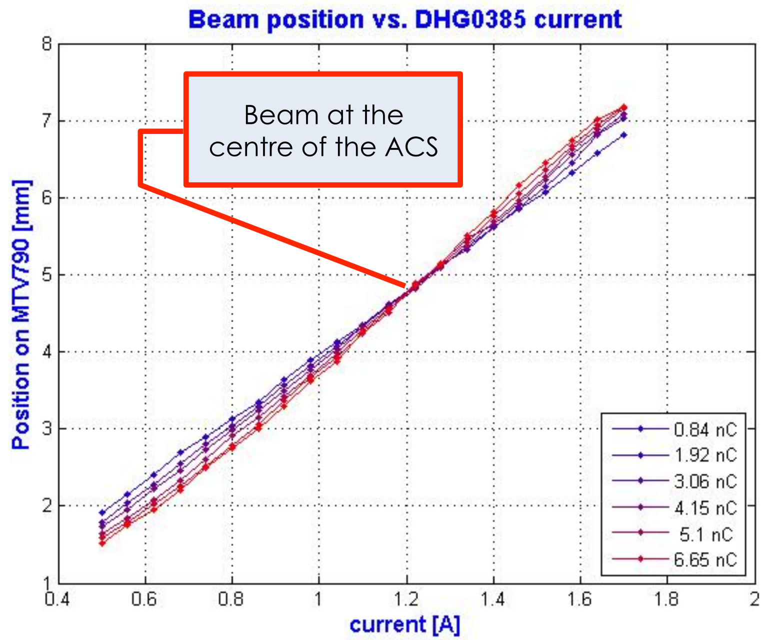
# TBM – accelerating gradient in 2016

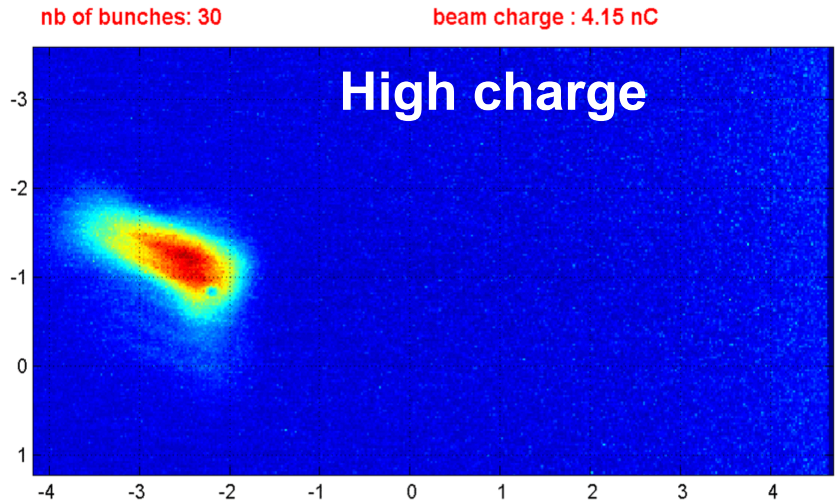


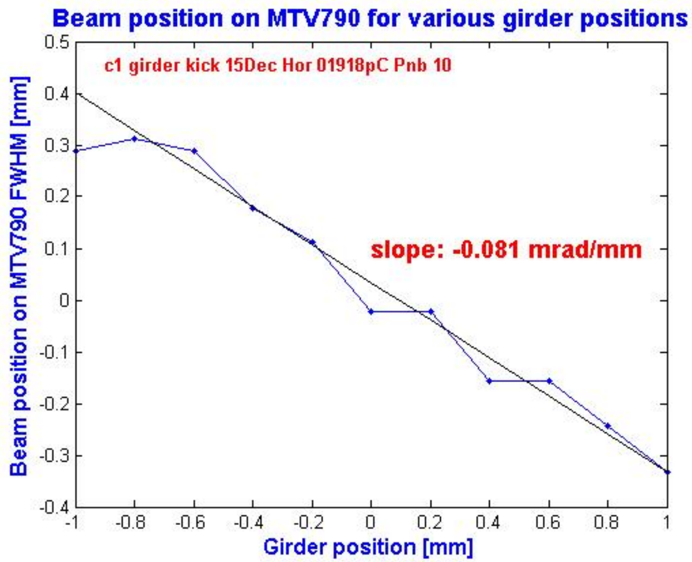



# TBM – wake-fields effect



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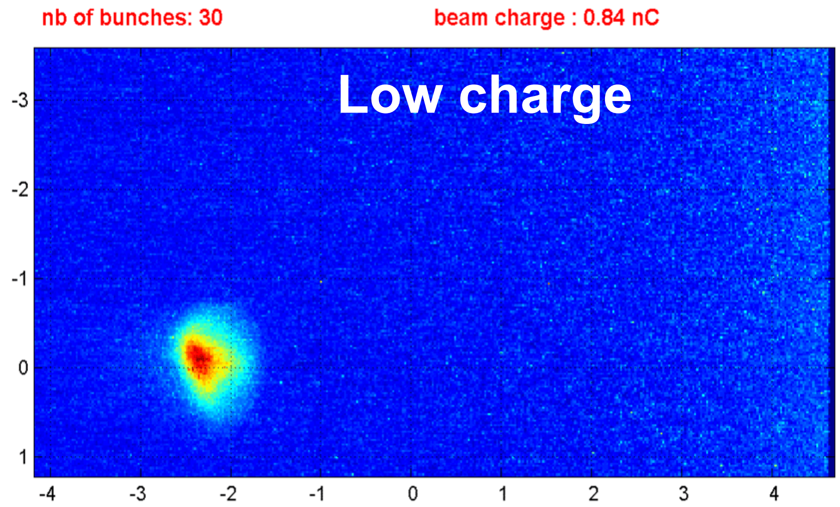
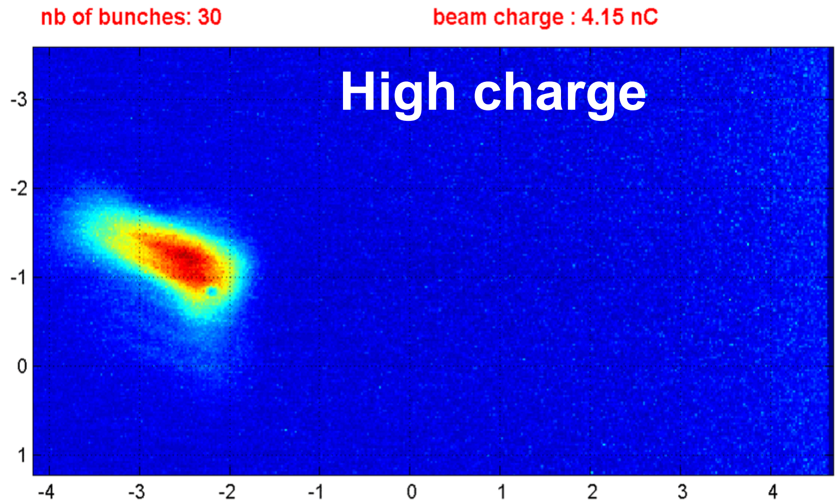


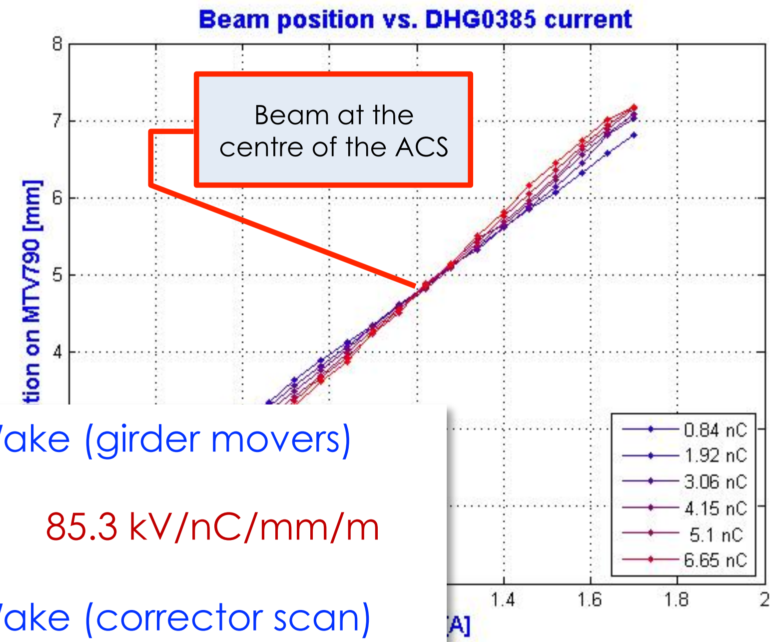



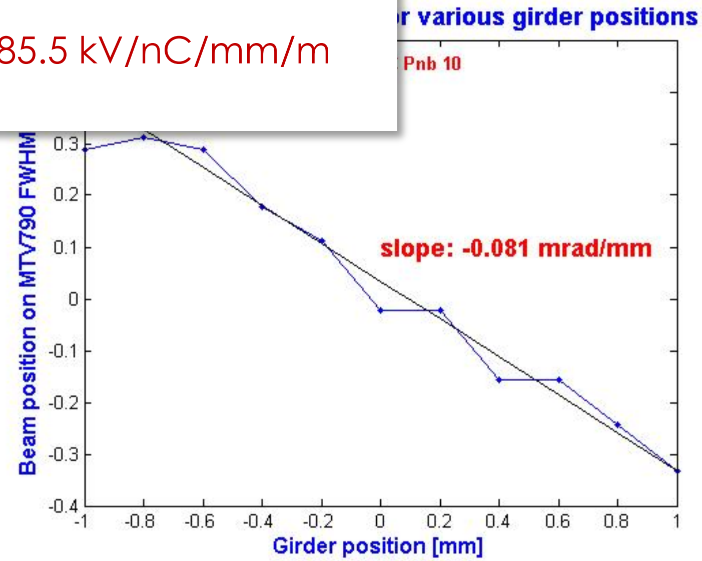

- Wake (girder movers)

  85.3 kV/nC/mm/m

- Wake (corrector scan)

  85.5 kV/nC/mm/m



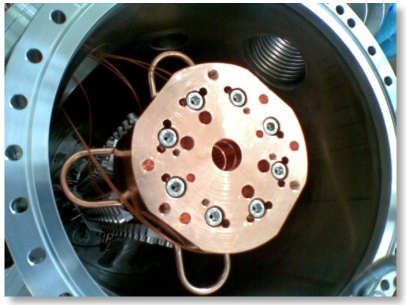



# Test Beam Line

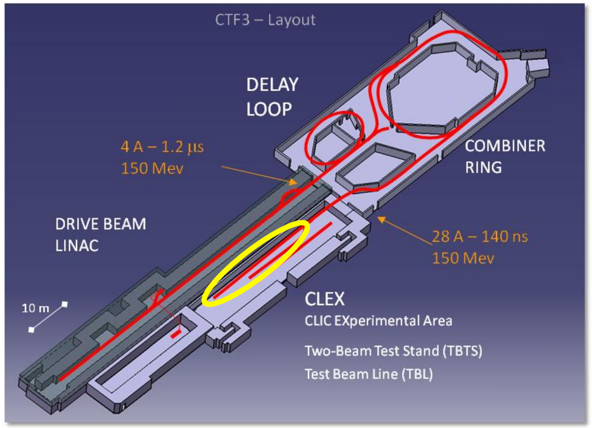
14 Power Extraction & Transfer Structures (PETS) installed and running from 2015

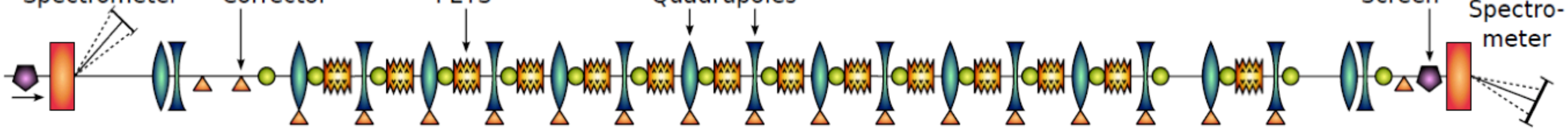
Full beam transport to end-of-line spectrometer, stable beam

Power produced (90 MW/PETS) fully consistent with drive beam current (24 A) and measured deceleration.

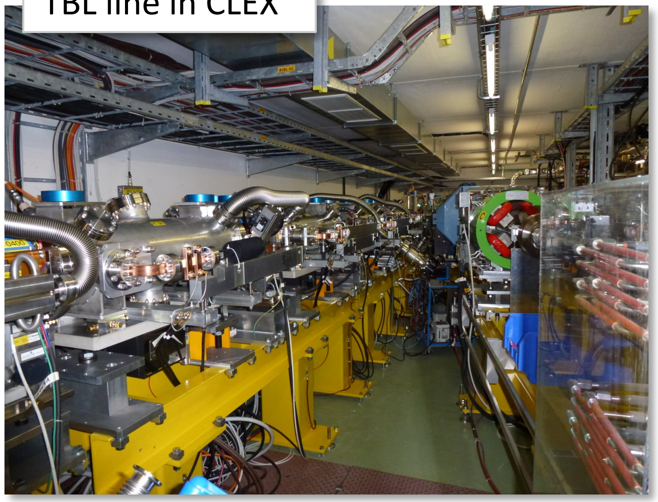


PETS tank during installation




TBL line in CLEX



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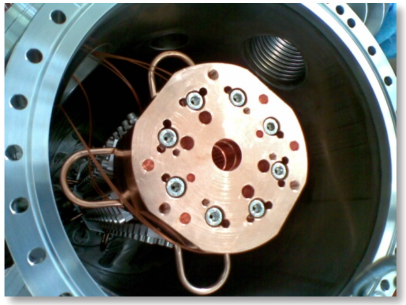

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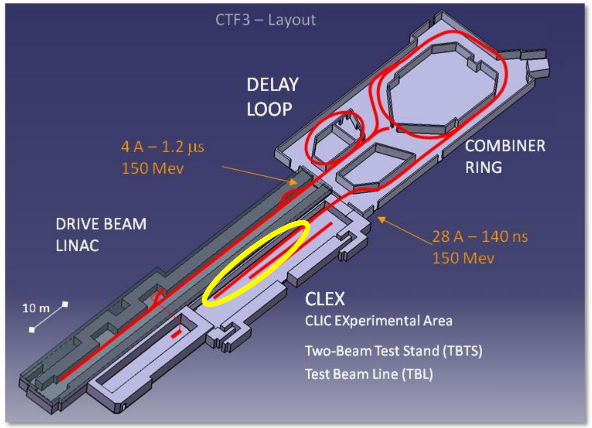


About 1.3 GW of 12 GHz peak power!

Beam deceleration, measured in spectrometer and compared with expectations

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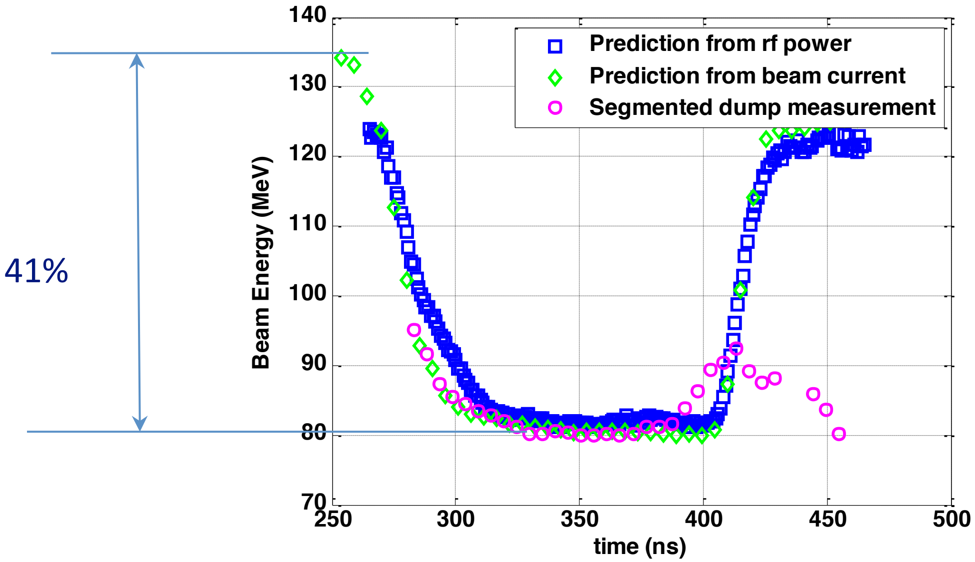

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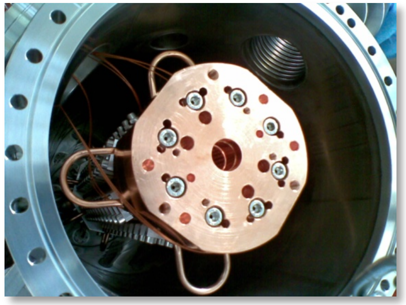

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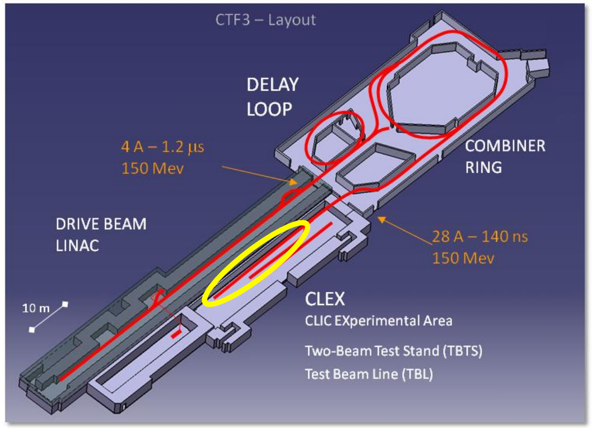


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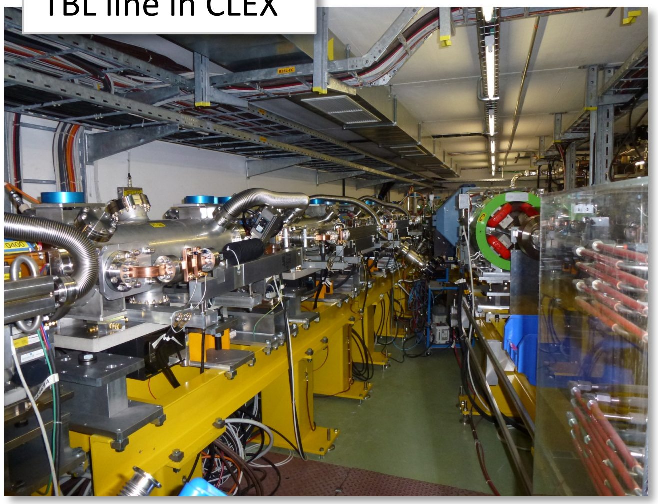
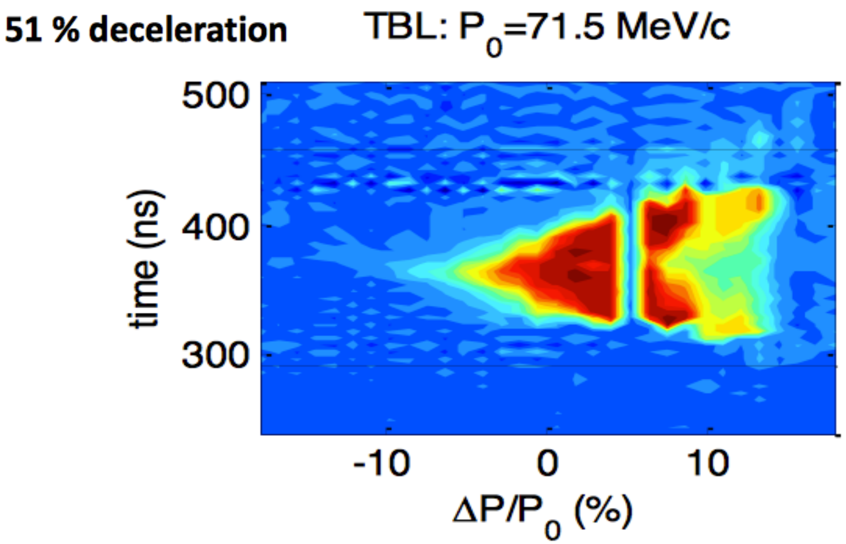
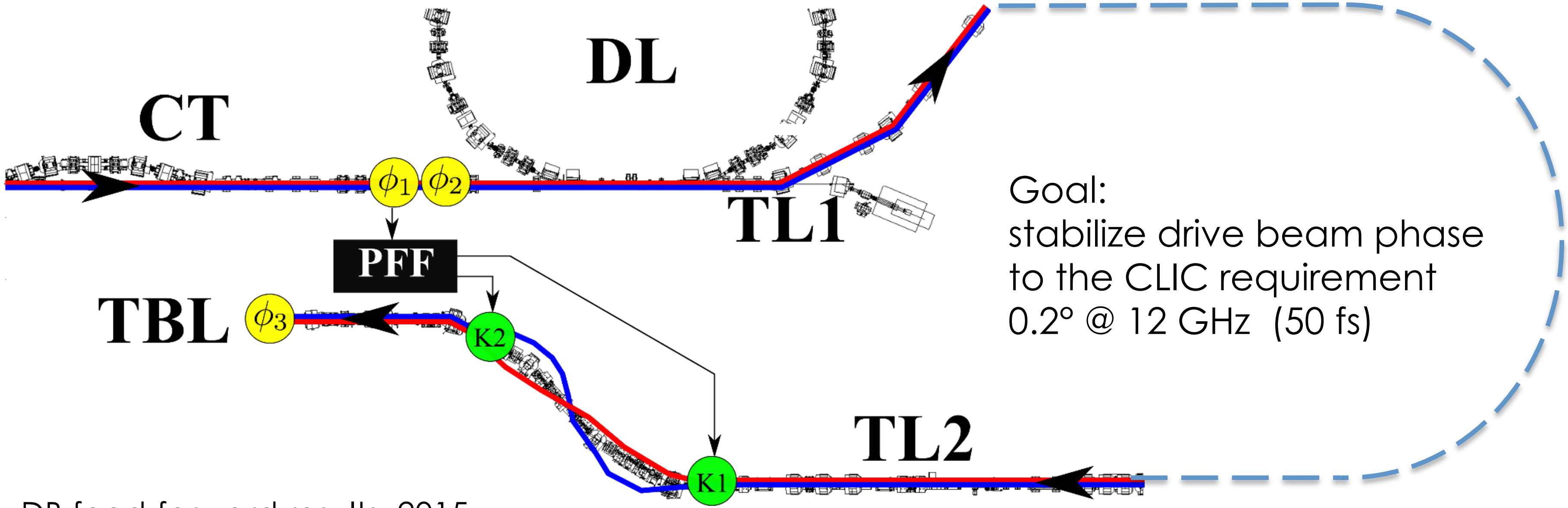


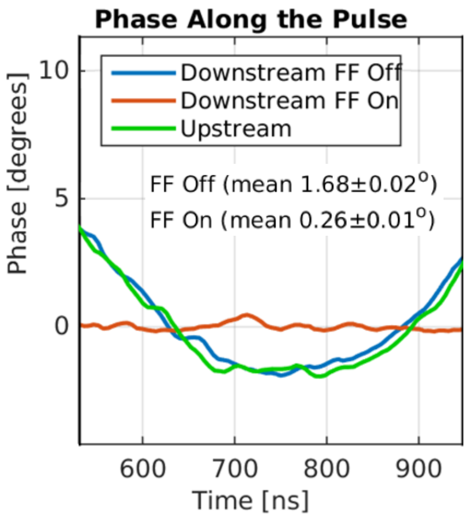


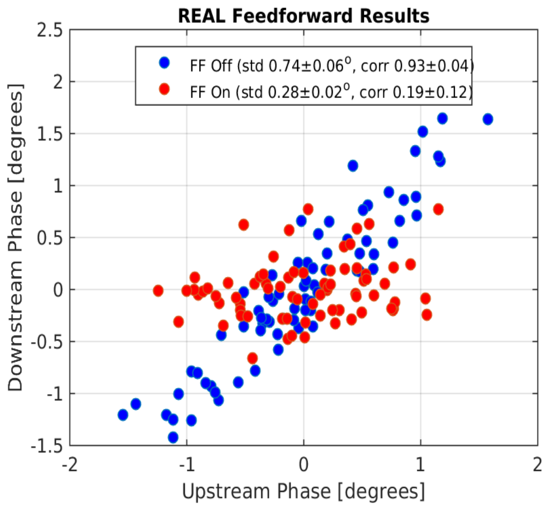
# Drive beam phase feed-forward

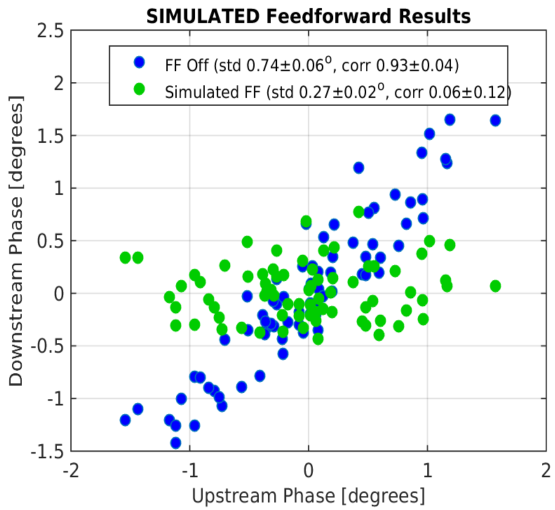



Goal:
stabilize drive beam phase to the CLIC requirement 0.2° @ 12 GHz (50 fs)

DB feed-forward results, 2015



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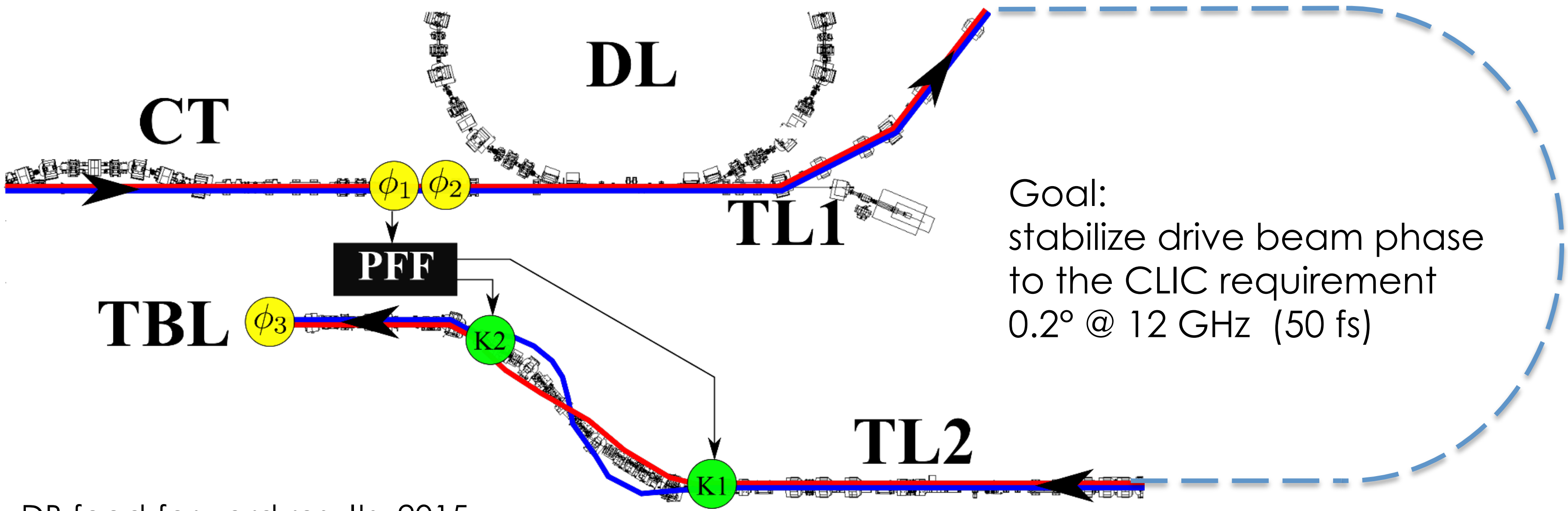


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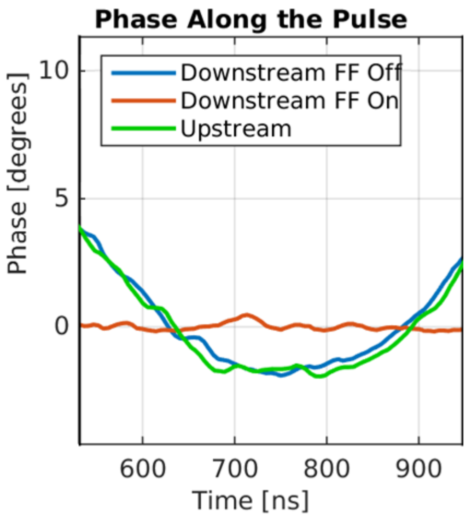
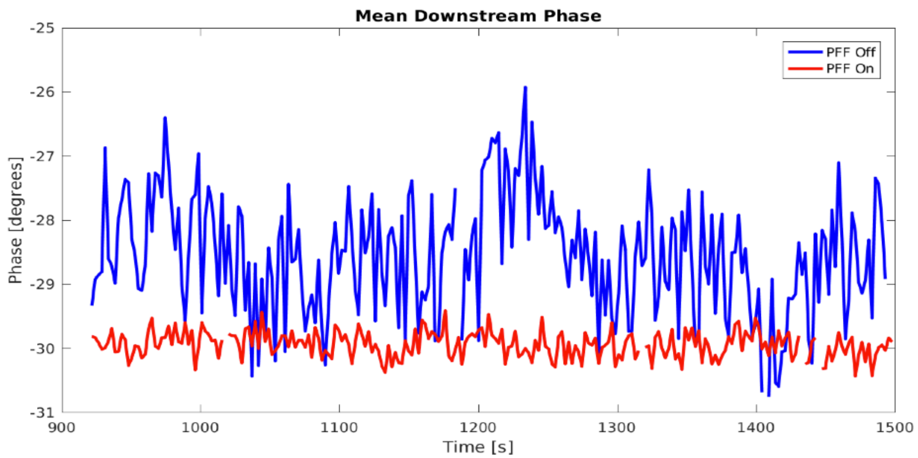
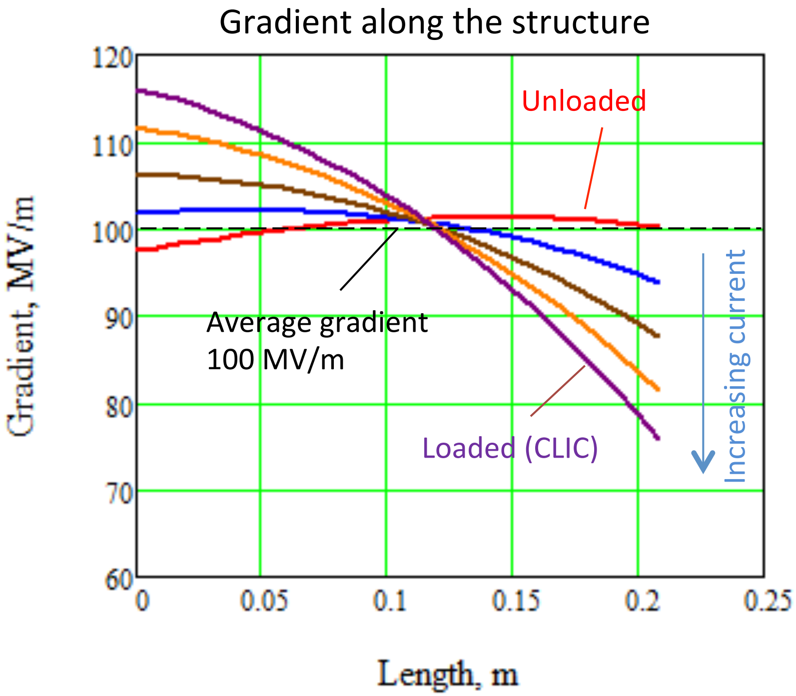



## Drive-beam phase feed-forward tests in 2016



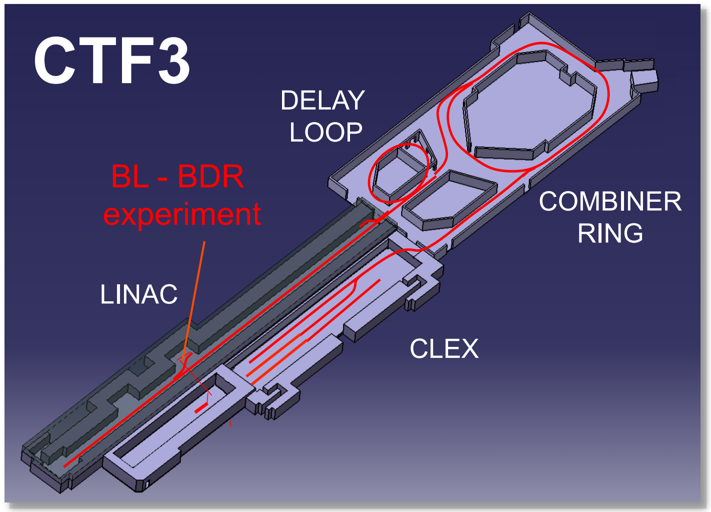

From about 1° to 0.2° @ 12 GHz, or 50 fs

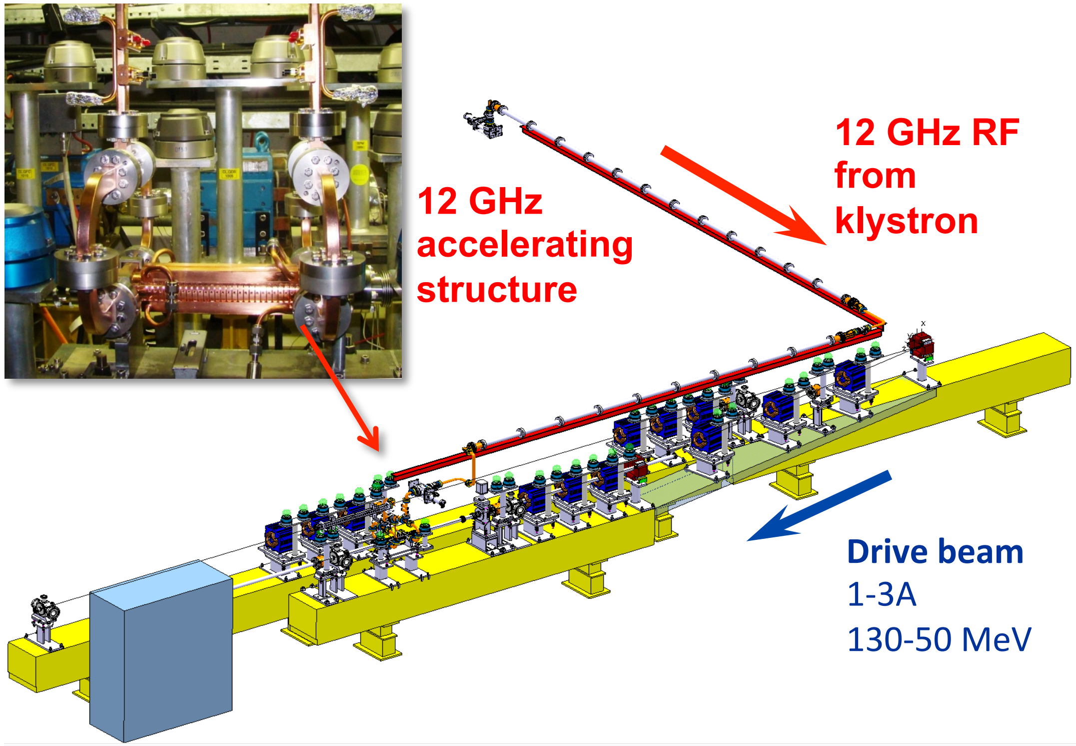
# CTF3 Exp. Program 2015-2016 – Beam Loading Experiment




Beam loading changes the field distribution for the same average gradient

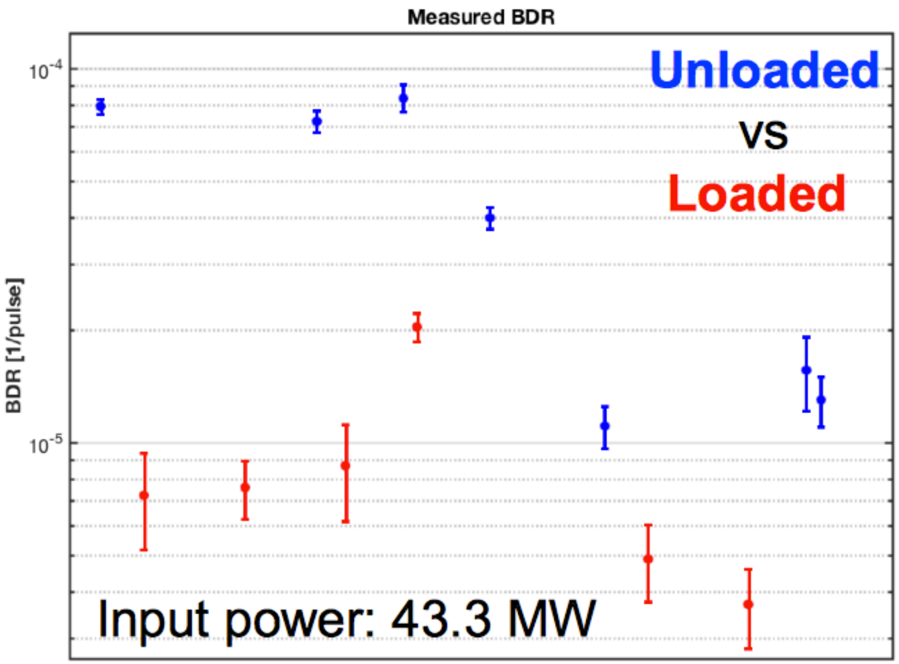
⇨ how is the break-down rate affected?



# Beam Loading Experiment

- A BDR reduction by beam loading up to an order of magnitude was measured.
- BDR seems dominated by the peak gradient, confirmed by the measured distribution inside the structure, which follows roughly the gradient profile.
- Possibility to further optimise the CLIC structure by targeting a flat gradient along the structure during the operation with beam.



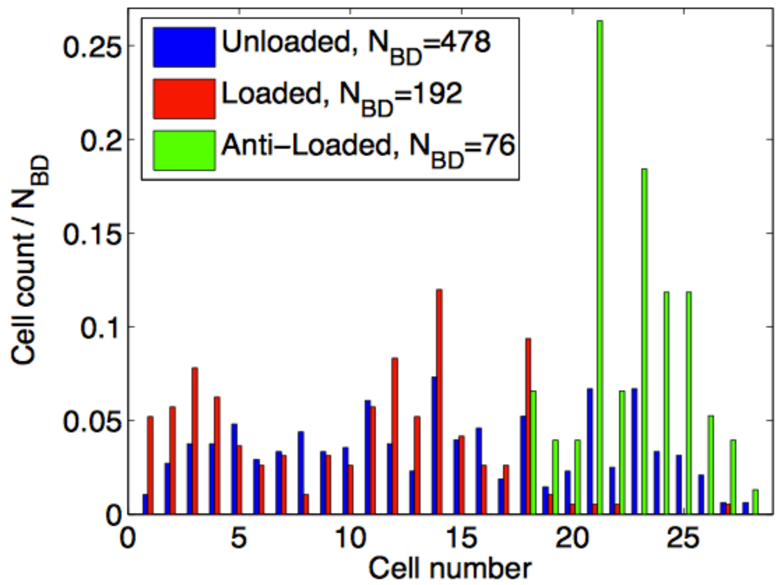
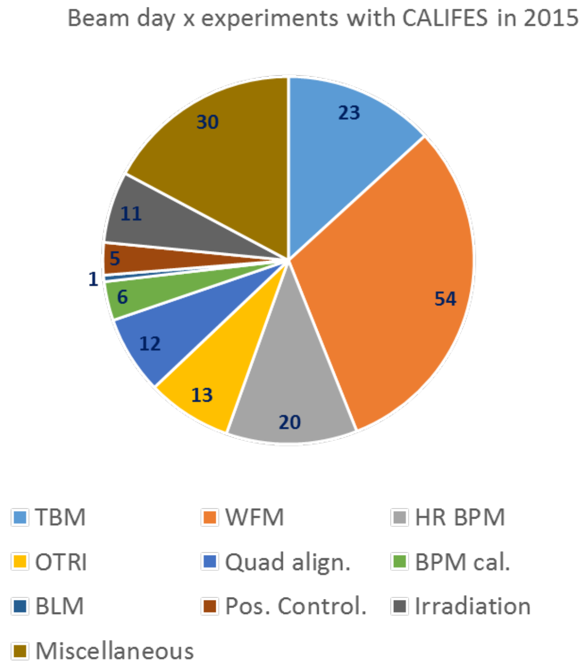
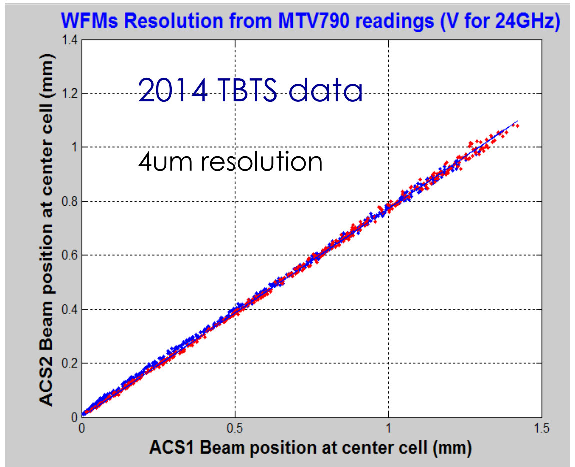




Figure 5: Breakdown cell distribution along the TD26CC structure for unloaded (blue), loaded (red) and anti-loaded (green) case.

# CTF3 Exp. Program 2015-2016 – Instrumentation Tests



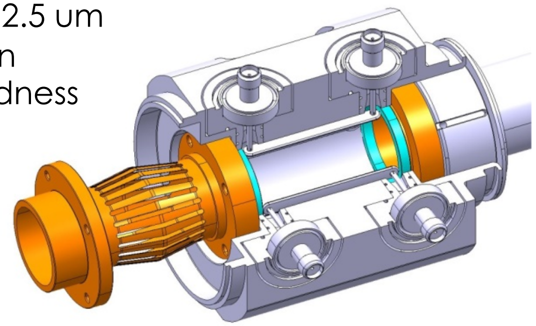



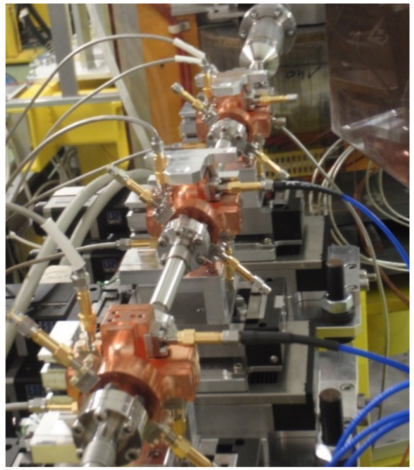

## Wake-Field Monitors

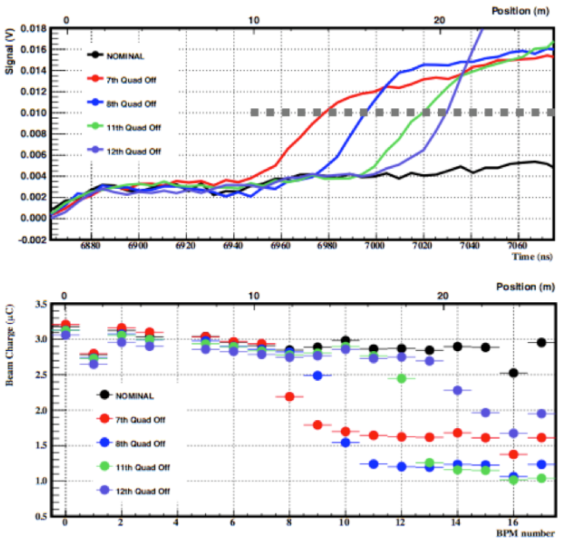
- 4 um resolution
- Studies of DB noise
- Confirmed by new version

## Drive Beam BPM

- Confirm 2.5 um resolution
- Rad hardness







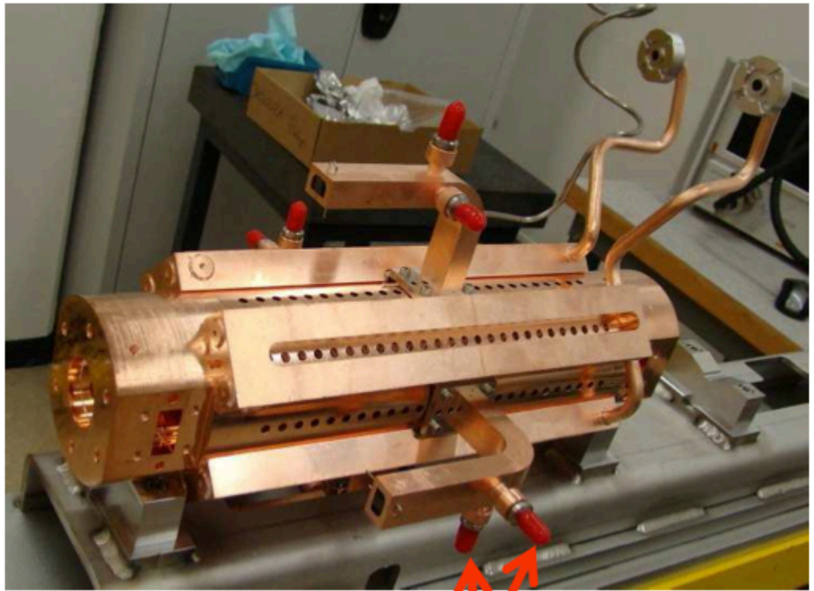

## Optical Fiber Beam Loss Monitors in TBL

- Localization of losses below 2 m (2015)
- Multi-loss location case

## Main beam BPM prototypes

- Sub-micron resolution measured
- Time resolution (50 nm) OK

# Wake Field Monitors

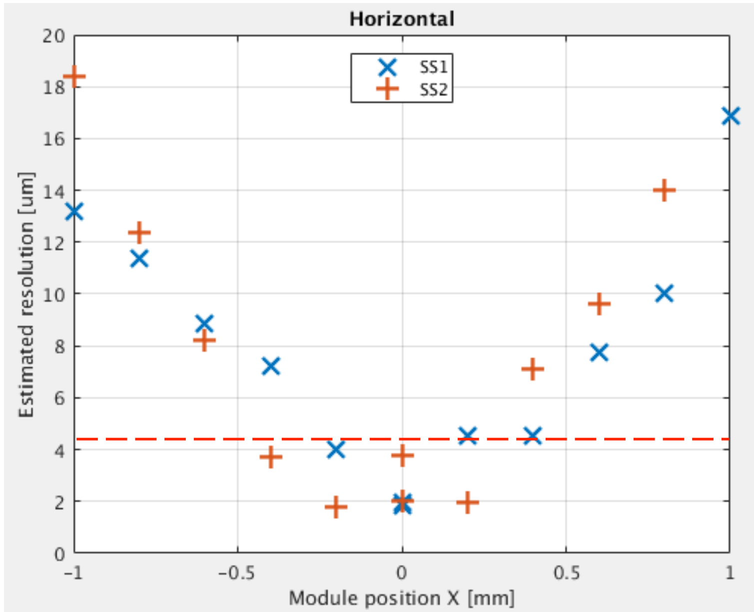


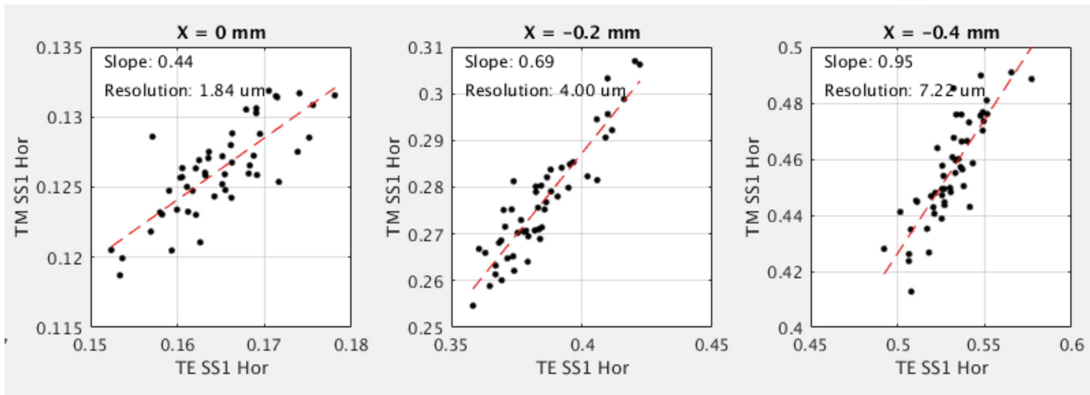
ACS with WFM

Wake field monitors precisely determine the beam position with respect to the electrical center of an accelerating structure

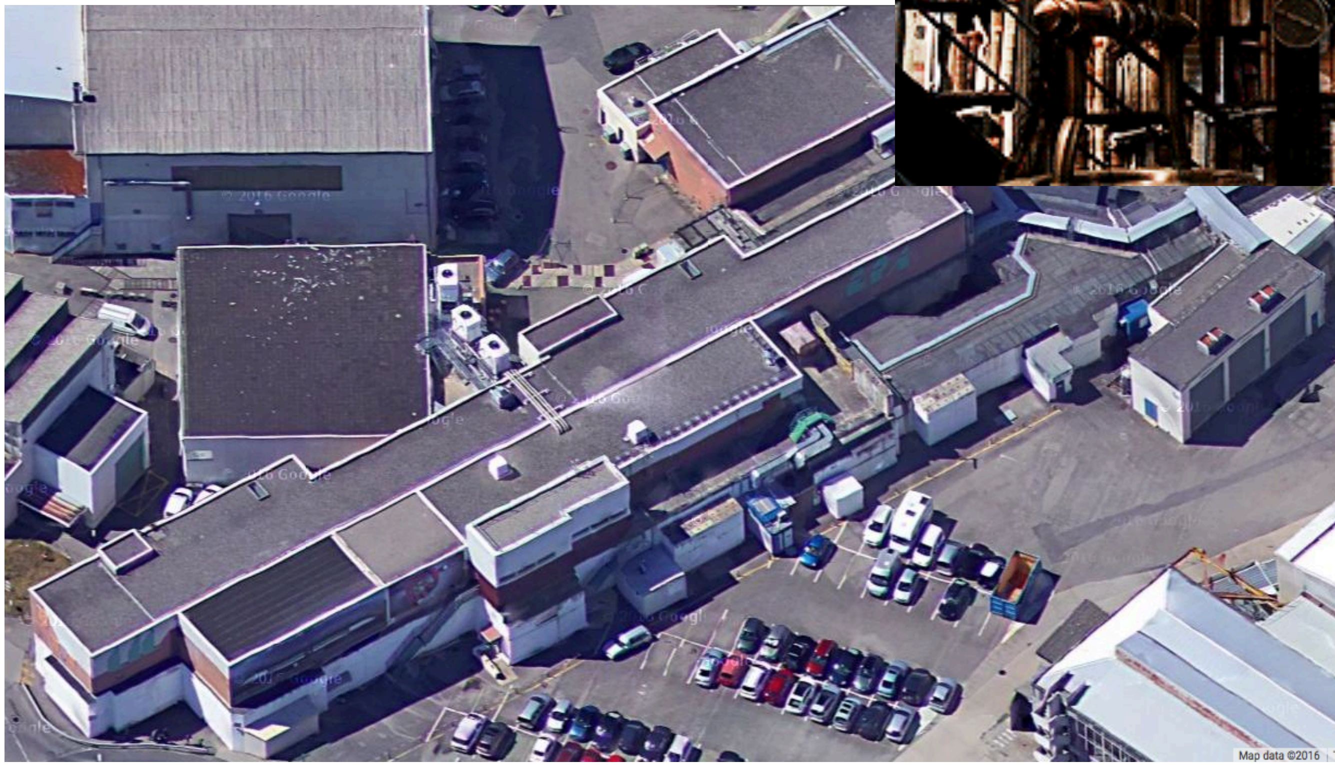
In CLIC, WFM signals will be used to center the beam in the structure and minimize transverse wake-fields

Requirement: 4.5 um resolution



# CLIC Test Facility (CTF3)
# † 2016



# CERN Linear Electron Accelerator for Research (CLEAR)

✡ 2017

# The CLEAR (CERN Linear Electron Accelerator for Research) proposal

**The CLEAR[1] facility at CERN**

Prepared by:
M.Brugger, R.Corsini, T.Lefevre, B.Salvant, S.Stapnes, W.Wuensch - CERN
M.Petrarca – "Sapienza" University of Rome and Roma1- INFN
S.Reiche - PSI
C.Welsch - U. of Liverpool
E.Adli - U. of Oslo
P.N. Burrows - U. of Oxford

CTF3 ended operation in December 2016

However, the probe beam injector CALIFES will become the focus of a new multi-purpose facility, CLEAR

CLEAR, among other activities, will continue some CLIC related studies on high-gradient and diagnostics

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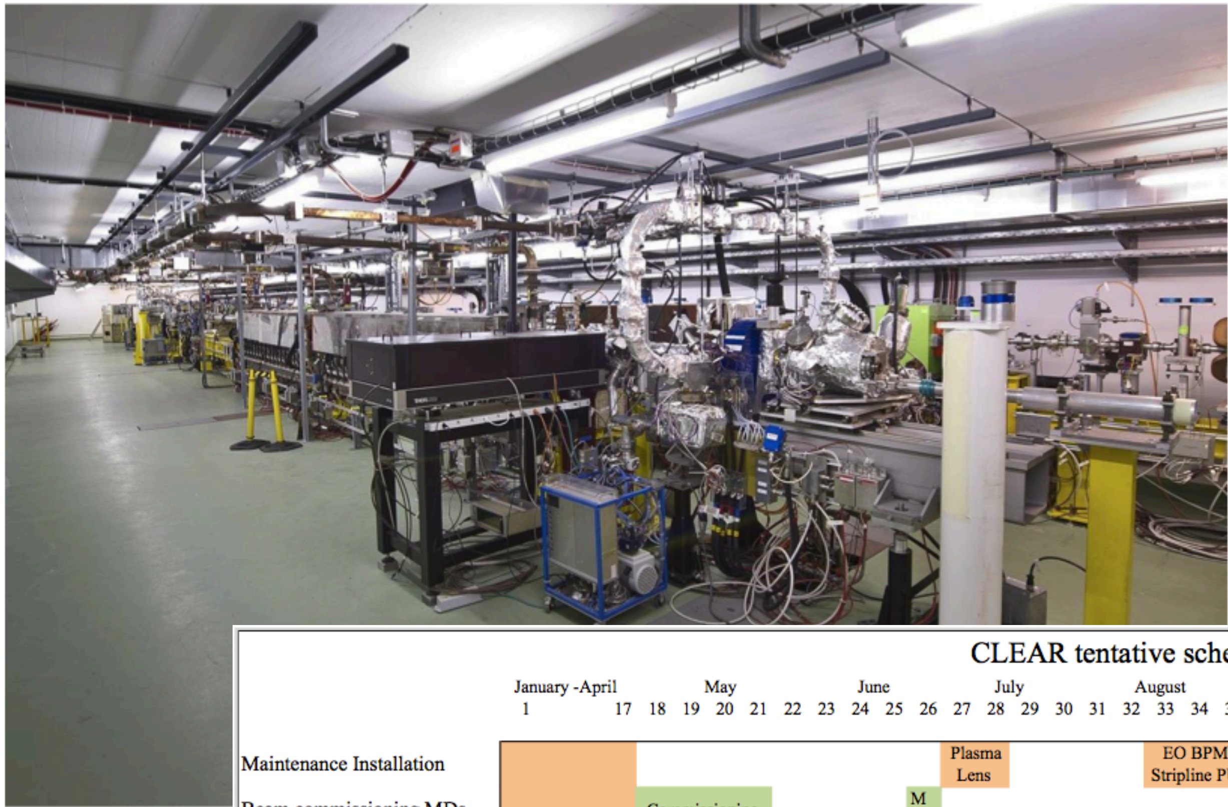

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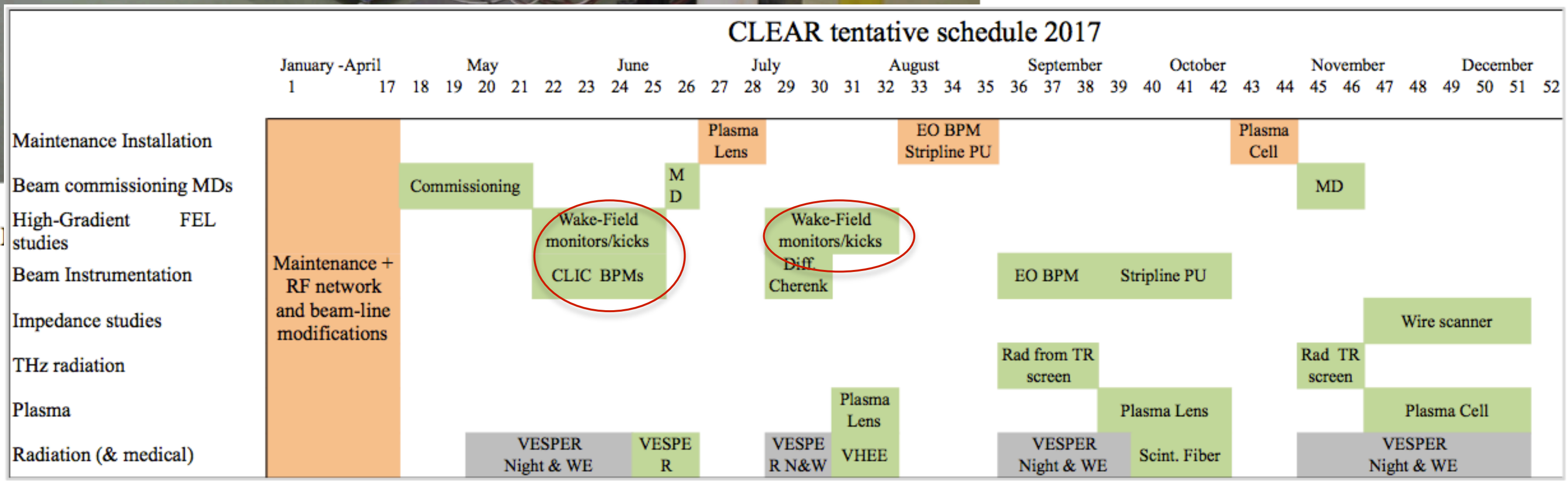

# CONCLUSIONS

- CTF3 has addressed and solved the CLIC issues related to drive beam generation, power production and two-beam acceleration.

- CTF3 successfully completed its planned experimental program in December 2016 as planned, and stopped operation.

- The experience gathered in CTF3 is now being documented, in view of the update of the European Strategy in 2019.

- The approval of the CLEAR program gives the opportunity to maintain local testing capability at CERN for CLIC instrumentation and high-gradient structure testing with beam, alongside with other non-CLIC activities.

The CLIC Test Facility has been the collective effort of a large collaboration over more than a decade.

Many thanks to all individuals who participated over this period to the conception, design, construction, commissioning and operation of CTF3!