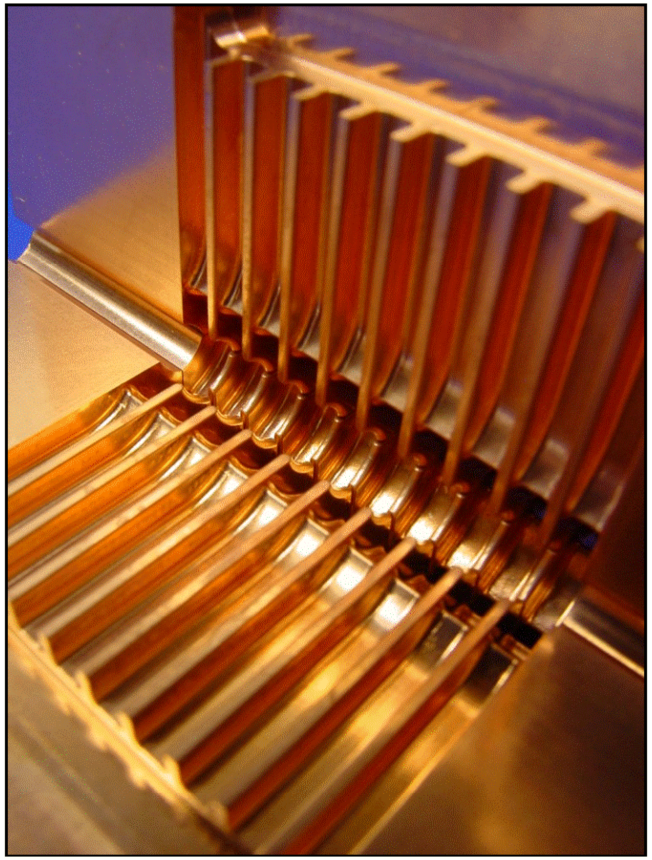
Lessons learned (Past, Present and Future) in CTF3

Frank Tecker – CERN

- Motivation
- CTF3 Preliminary Phase
- Present CTF3 (up to DL)
- Future CTF3 (CR and beyond)
- Conclusion



CLIC-related key issues

as pointed out by ILC-TRC 2003

Covered by CTF3

R1: Feasibility

- R1.2: Validation of **drive beam generation** scheme with **fully loaded linac** operation
- R1.1: Test of damped **accelerating structure** at design gradient and pulse length
- R1.3: Design and test of damped ON/OFF **power extraction structure**

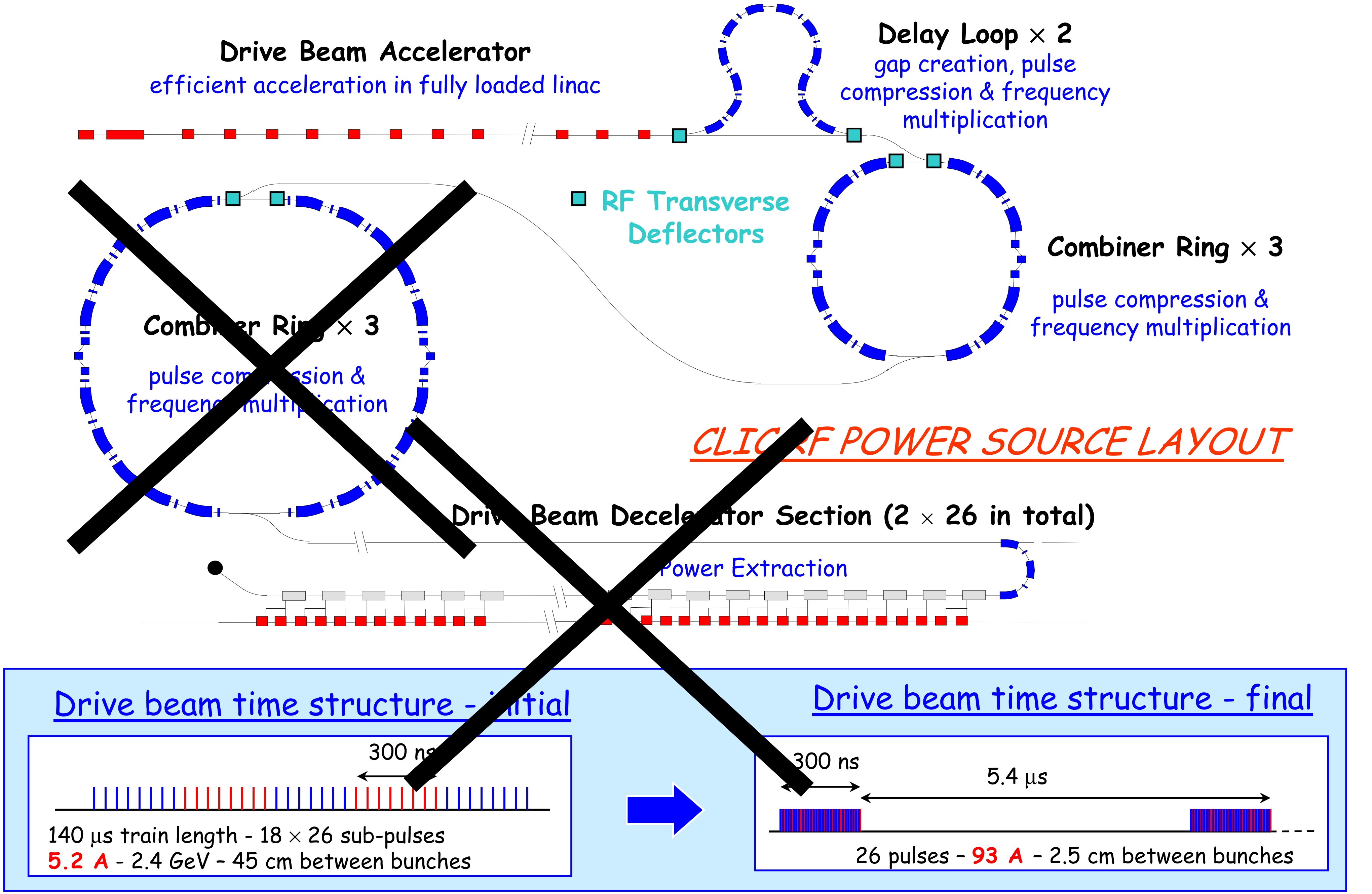
R2: Design finalization

- R2.1: Developments of structures with hard-breaking materials (W, Mo…)
- R2.2: Validation of stability and losses of DB decelerator; Design of machine protection system
- R2.3: Test of relevant linac sub-unit with beam
- R2.4: Validation of drive beam 40 MW, 937 MHz Multi-Beam Klystron with long RF pulse *
- R2.5: Effects of coherent synchrotron radiation in bunch compressors
- R2.6: Design of an extraction line for 3 TeV c.m.

Covered by EUROTeV

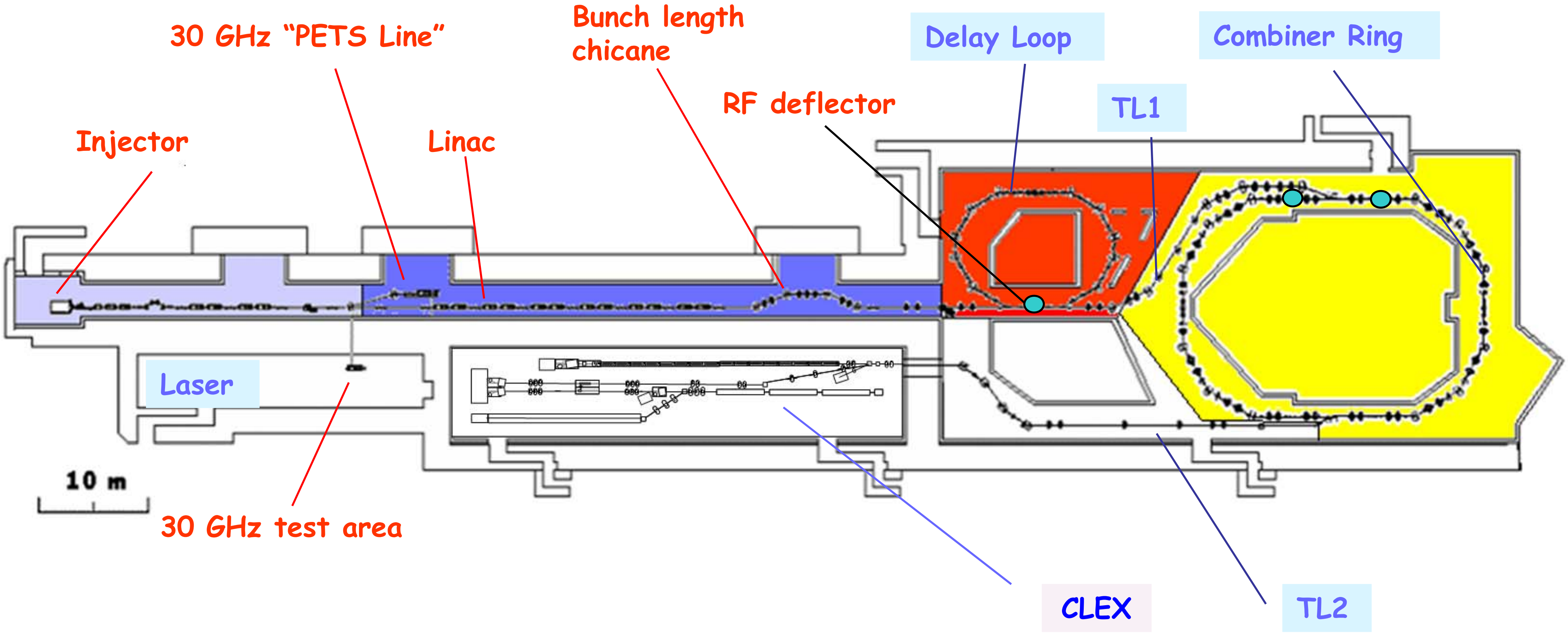
* *Feasibility study done – need development by industry.*
N.B.: Drive beam acc. structure parameters can be adapted to other klystron power levels

CLIC Drive Beam generation



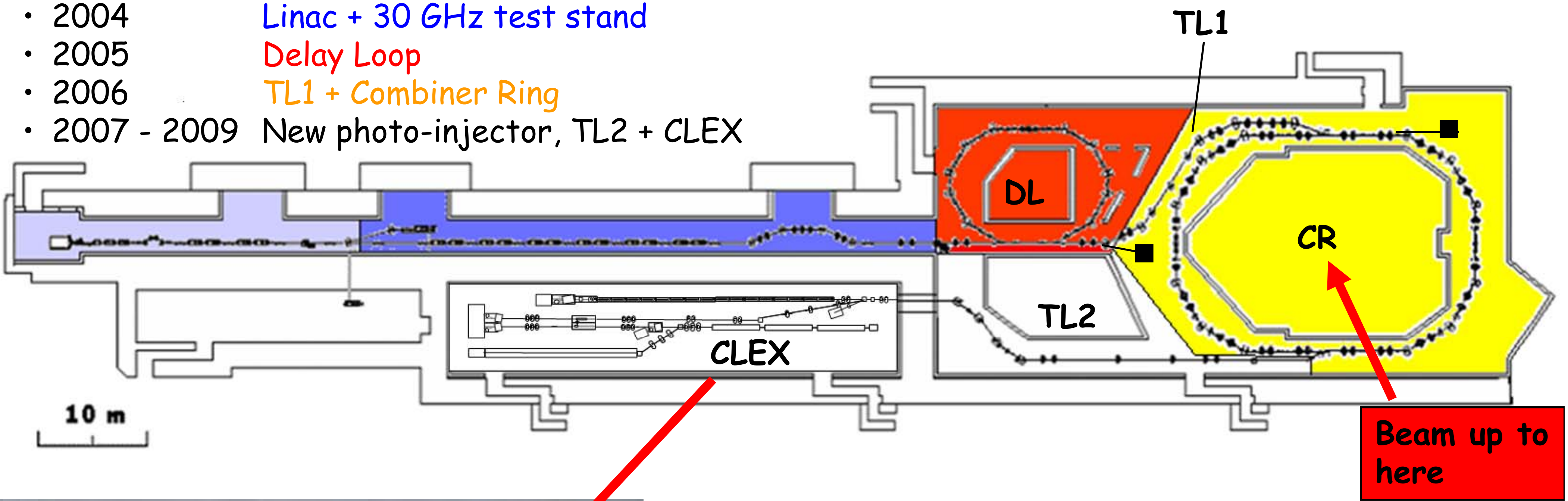
CTF 3

- demonstrate Drive Beam generation
  (fully loaded acceleration, bunch frequency multiplication 8x)
- Test CLIC accelerating structures
- Test power production structures (PETS)



CTF3 Evolution

- 2003 Injector + part of linac
- 2004 Linac + 30 GHz test stand
- 2005 Delay Loop
- 2006 TL1 + Combiner Ring
- 2007 - 2009 New photo-injector, TL2 + CLEX



CLIC drive beam scheme

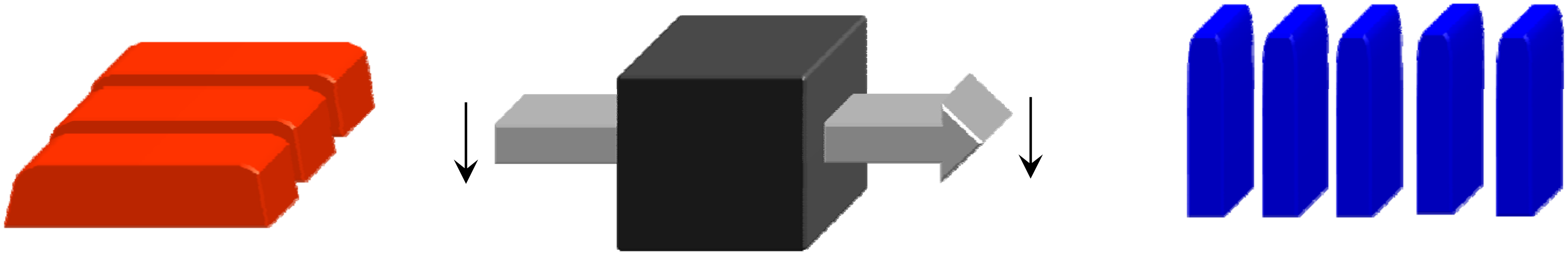
- Very high gradients possible with NC accelerating structures at high RF frequencies (30 GHz → 12 GHz)
- Extract required high RF power from an intense e- “drive beam”
- Generate efficiently long beam pulse and compress it (in power + frequency)

800 Klystrons
Low frequency
High efficiency

Power stored in electron beam

Power extracted from beam in resonant structures

144000
Accelerating Structures
High Frequency – High field



Long RF Pulses
P_0 , ν_0 , τ_0

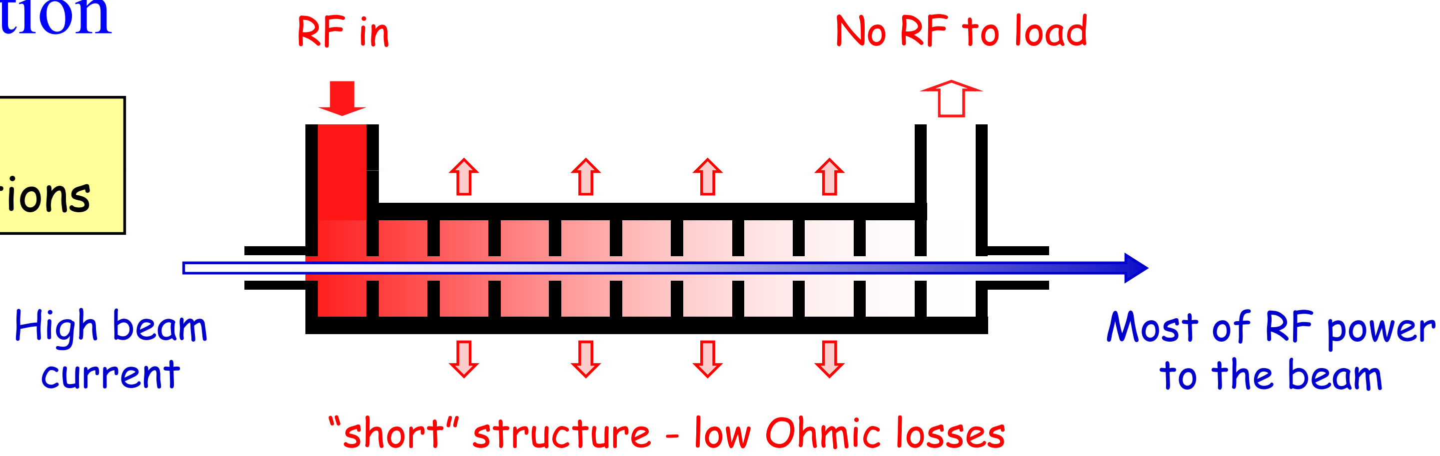
Electron beam manipulation
Power compression
Frequency multiplication

Short RF Pulses
$P_A = P_0 \times N_1$
$\tau_A = \tau_0 / N_2$
$\nu_A = \nu_0 \times N_3$

Drive beam generation basics

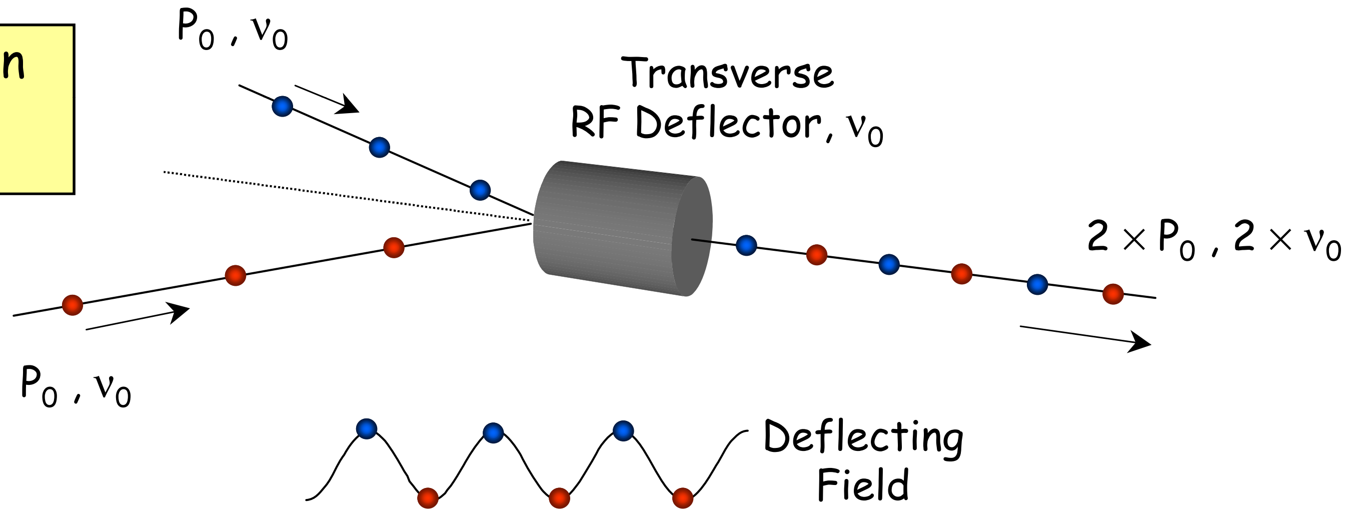
- Efficient acceleration

Full beam-loading acceleration in TW sections



- Frequency multiplication

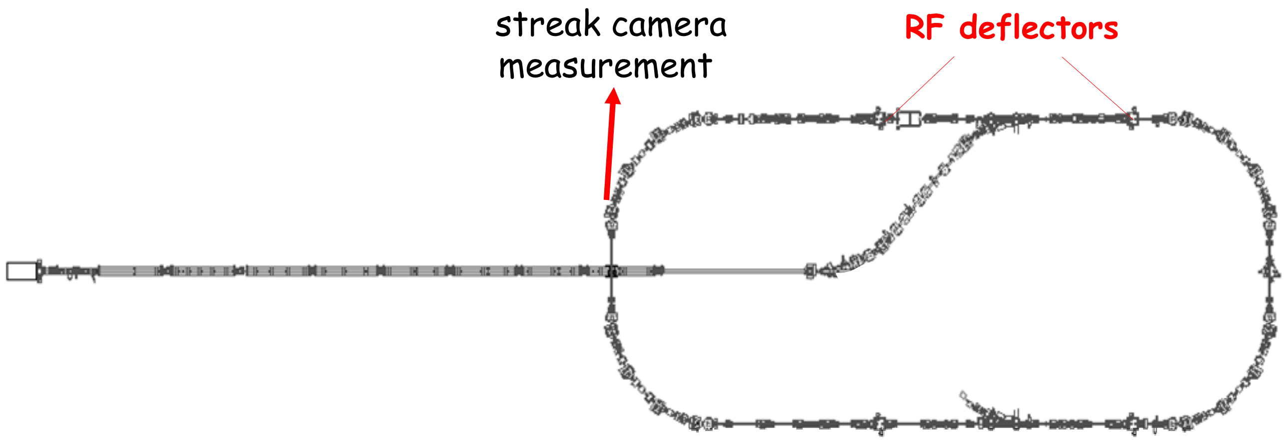
Beam combination/separation by transverse RF deflectors

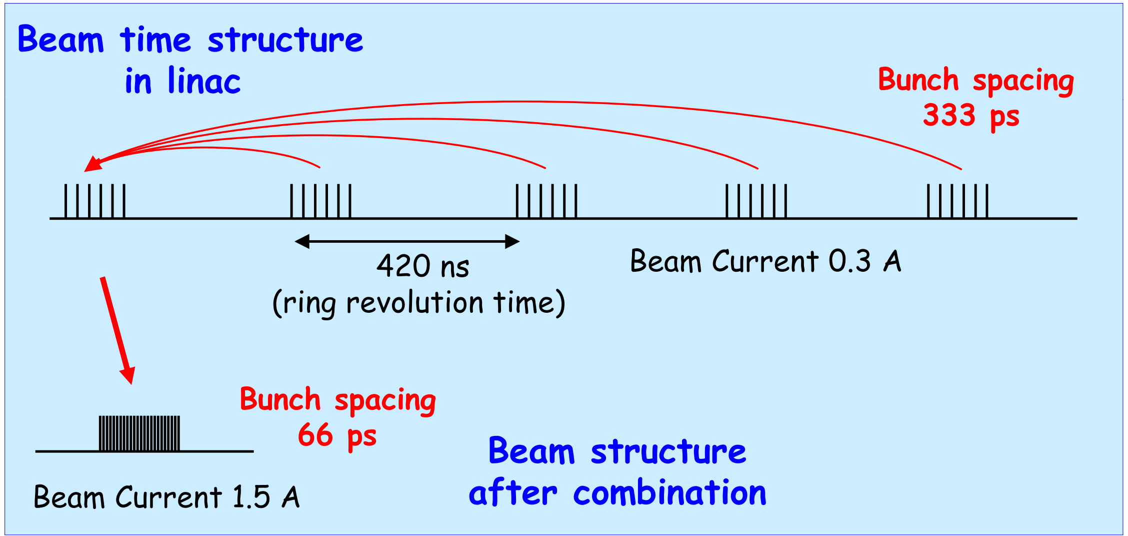


Demonstration of frequency multiplication

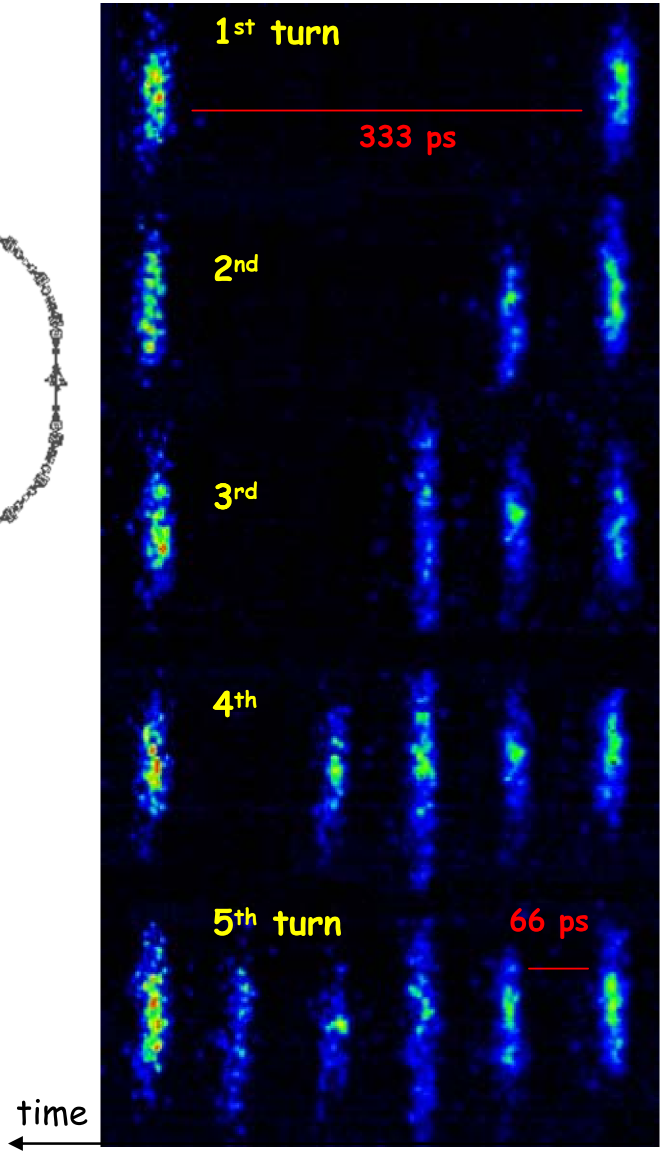
CTF3 - PRELIMINARY PHASE 2001/2002

Successful low-charge demonstration of electron pulse combination and bunch frequency multiplication by up to factor 5



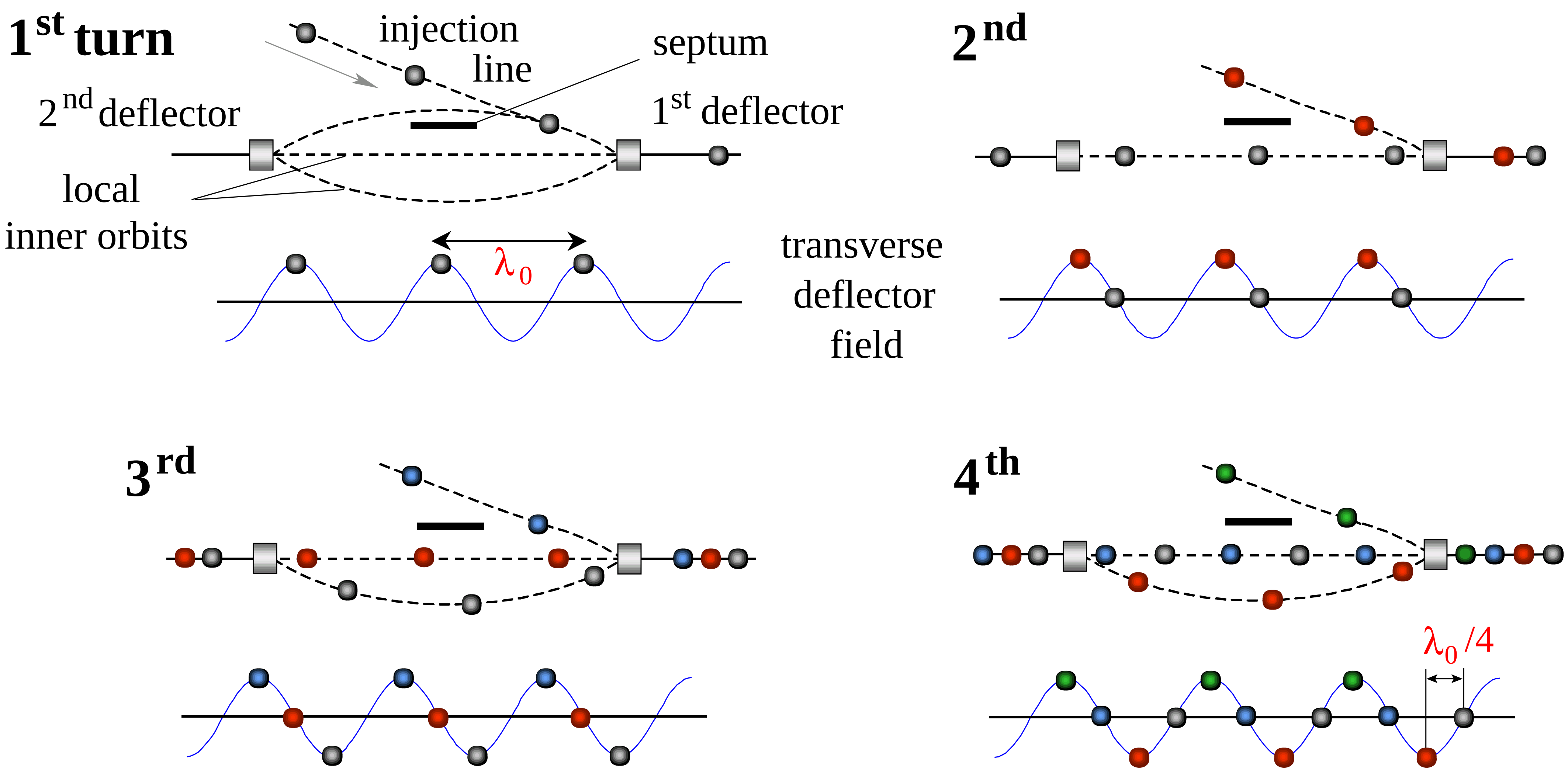


Streak camera image of
beam time structure evolution



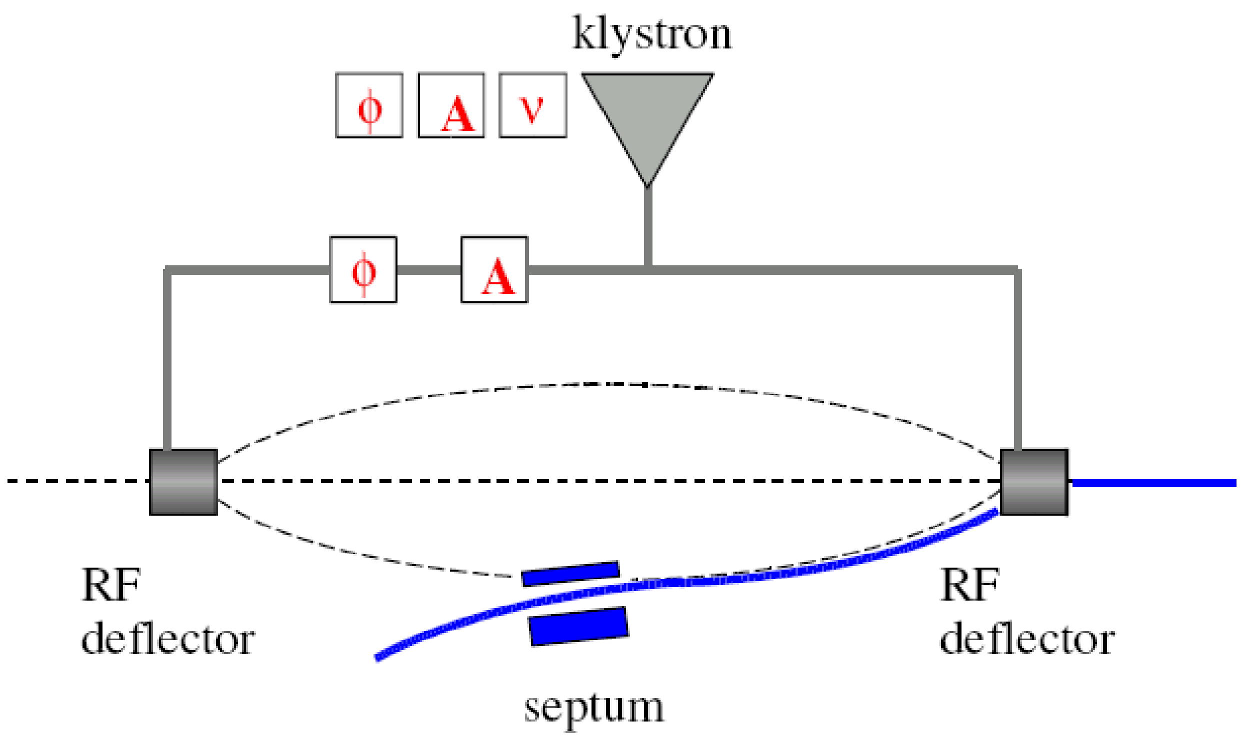
Combination by RF deflectors in a ring

- combination factors up to 5 reachable in a ring



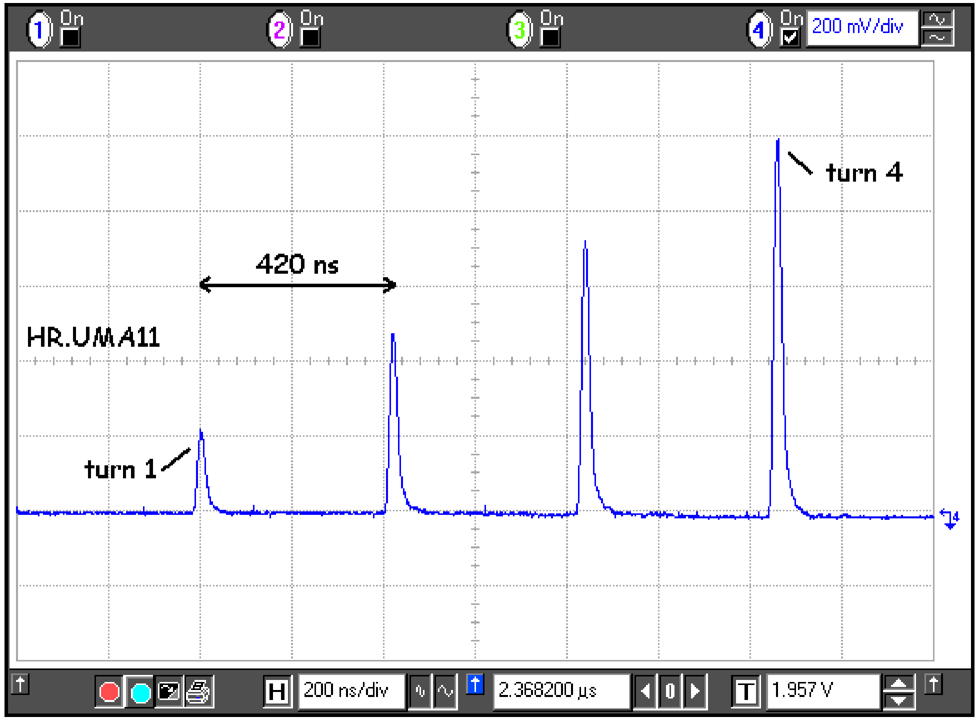
Combination setup

- Developed a setup procedure to optimize combination
- 5 parameters
  - Amplitude and phase in each deflector
  - RF frequency (no wiggler for path length tuning)
- Monitor trajectory differences over various turns

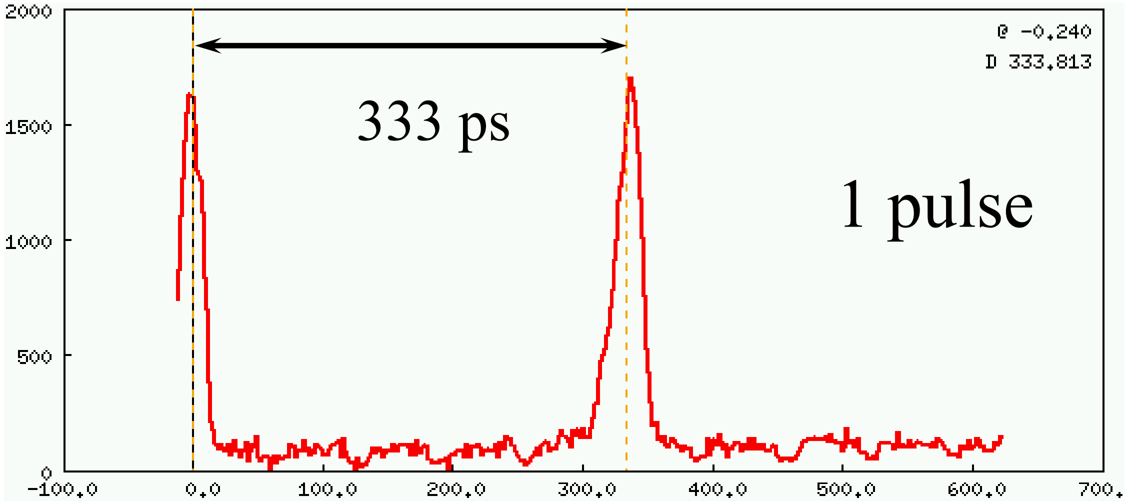


Combination results

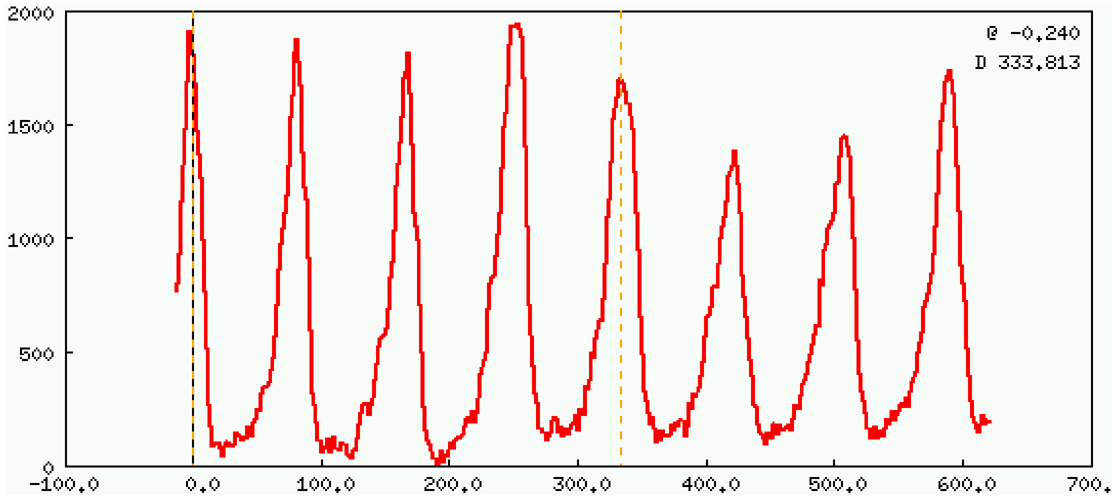
- demonstrated for factors 4 and 5 (also 2 and 3)
- beam current accumulates



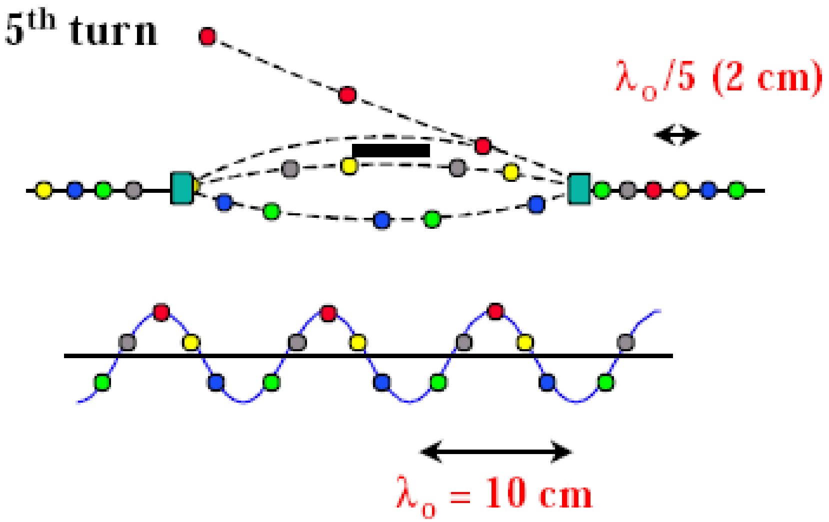
- intensity profile (Streak Camera)



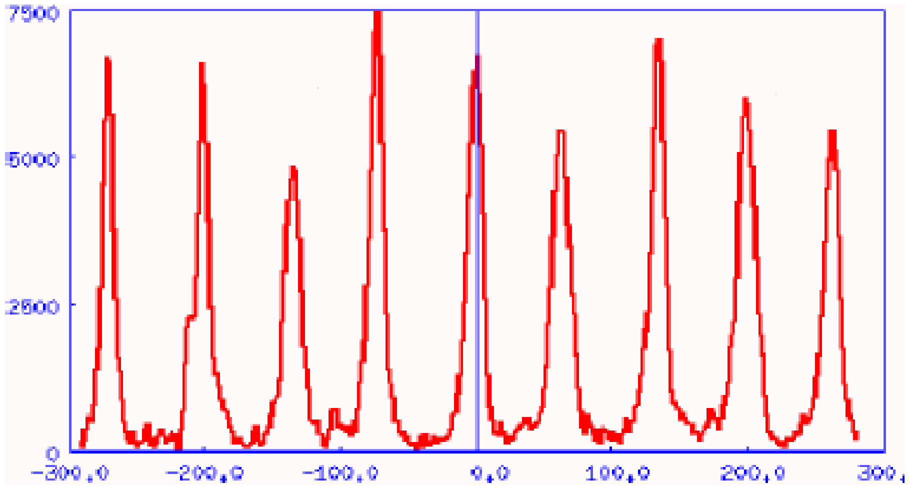
4 pulses injected

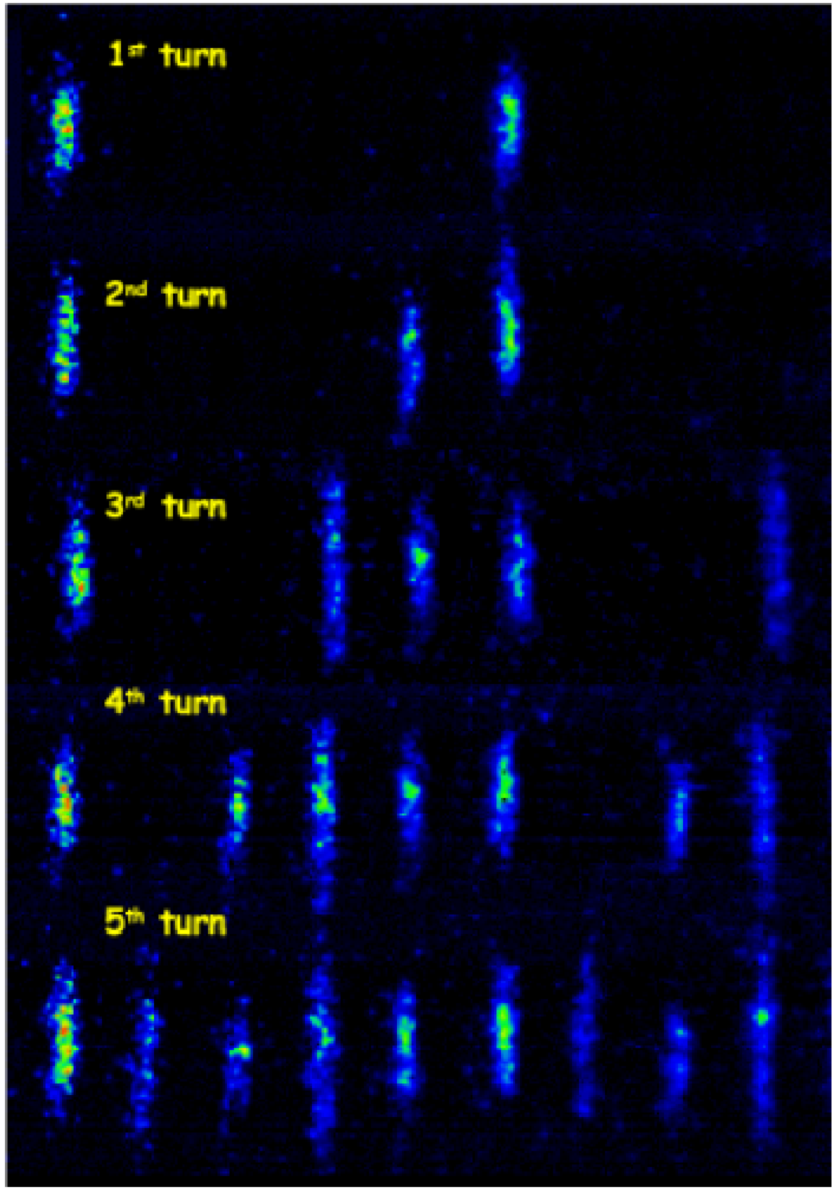


Combination factor 5



- bunch distance 333 ps → 67 ps
- frequency 3 GHz → 15 GHz

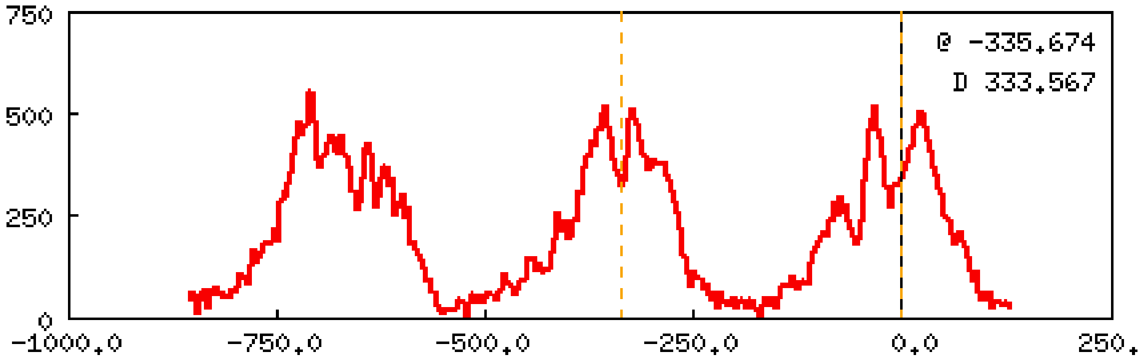




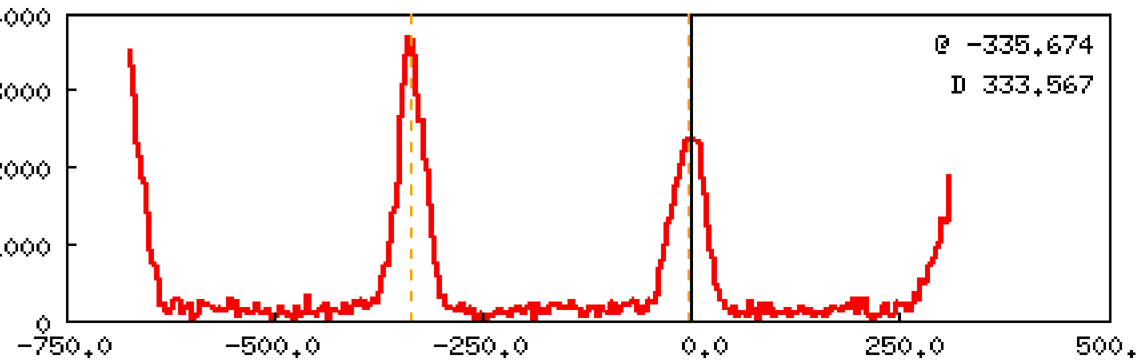
Isochronicity Tuning

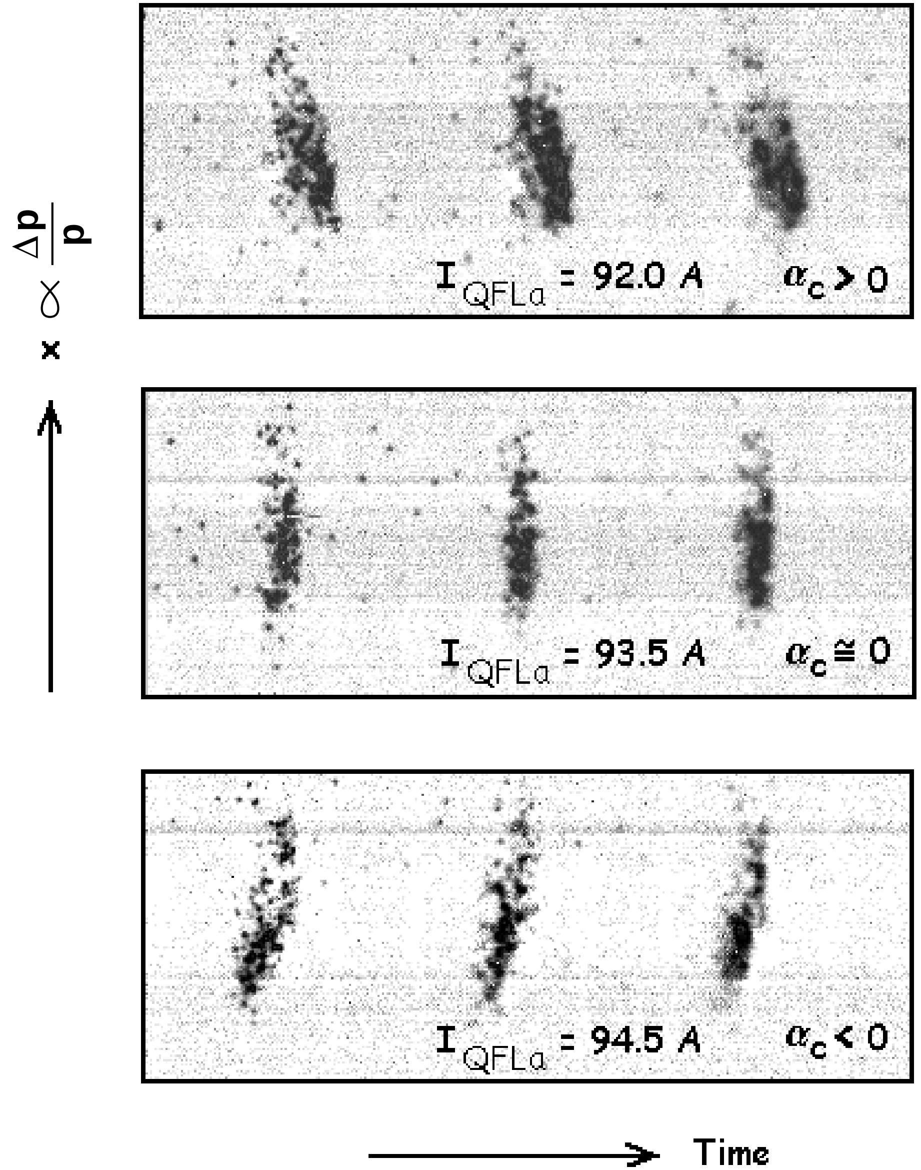
- ring optics needs to be isochronous to keep short bunch length
  => high power extraction efficiency
- Streak Camera observations

non-isochronous – 2nd turn



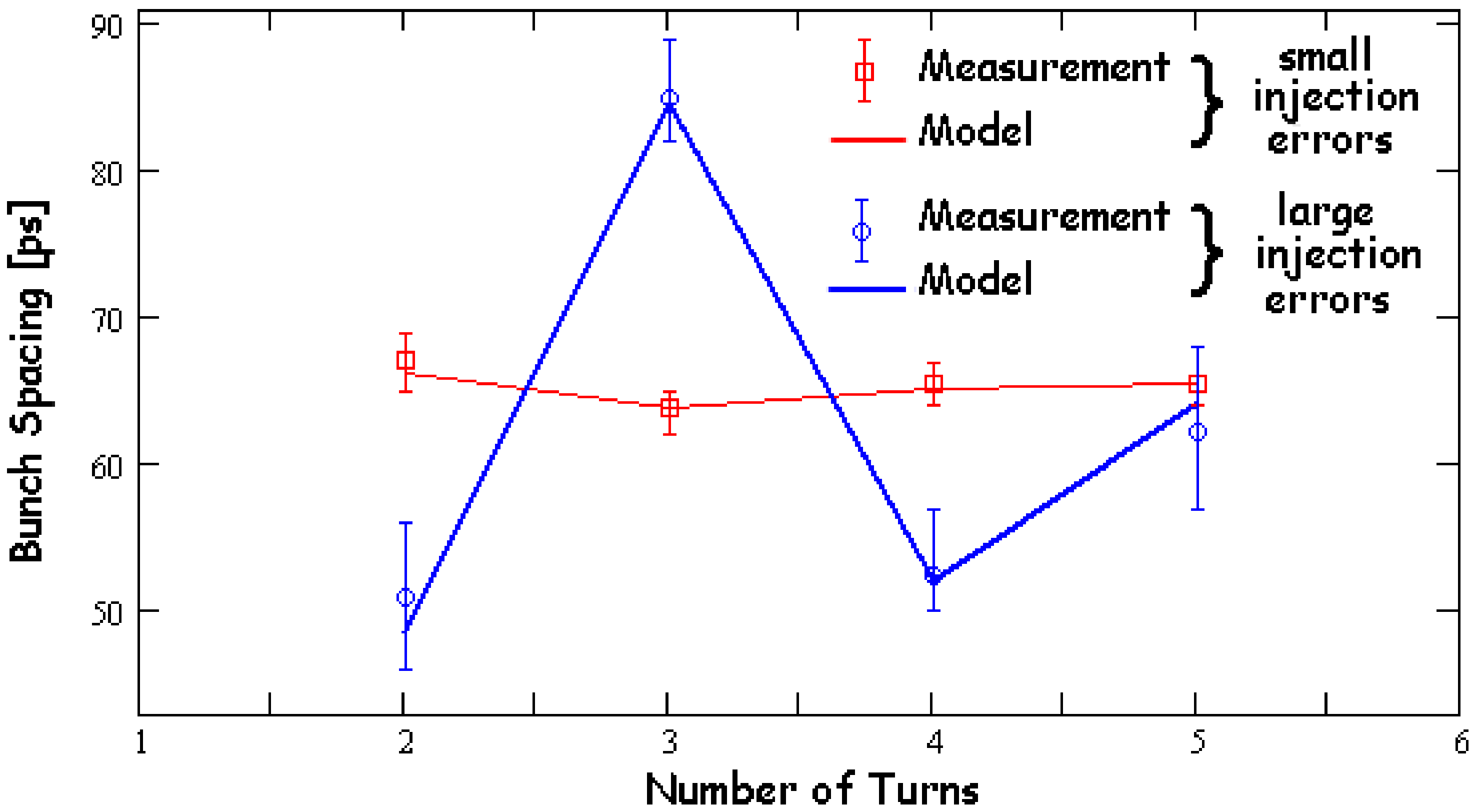
isochronous – 60th turn





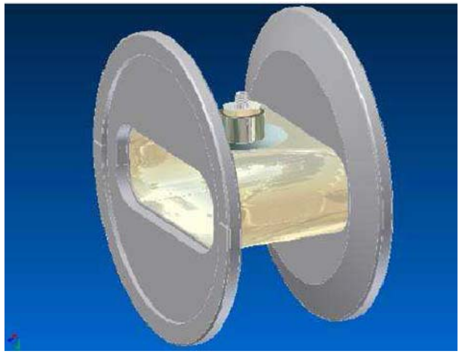
Bunch spacing variations

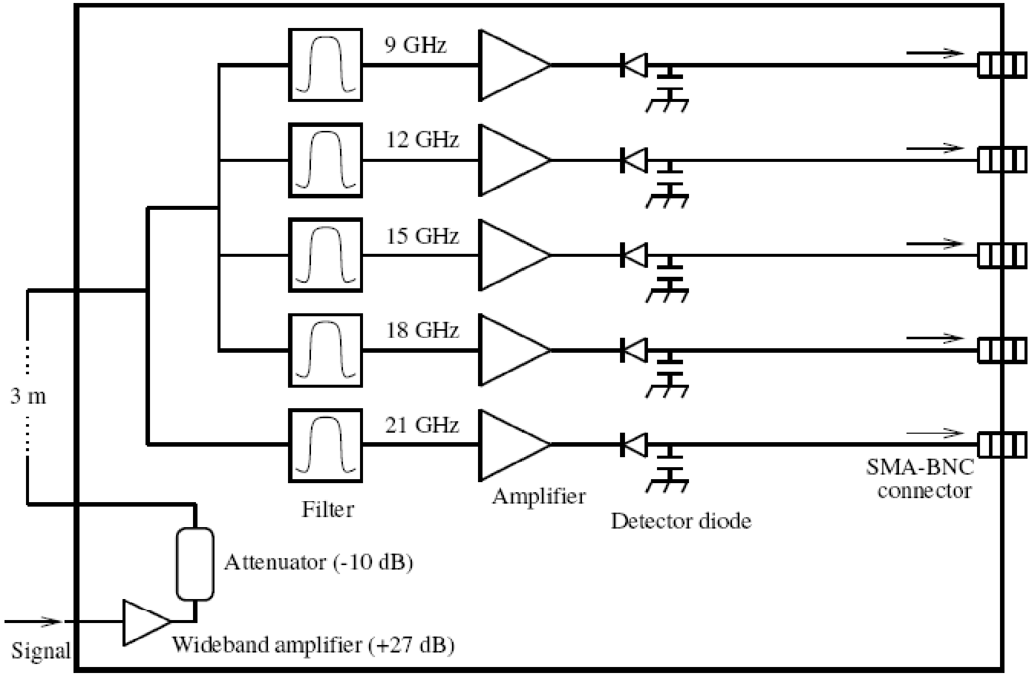
- Bunch spacing variations would reduce RF extraction efficiency
- variations were observed (for large orbit oscillations)
- theoretically understood, vanish when D=D'=0
- no deterioration of the power production



Bunch frequency monitor

- Analyses different harmonics of 3 GHz
- target frequency increases
- other decrease
- short pulse length difficult

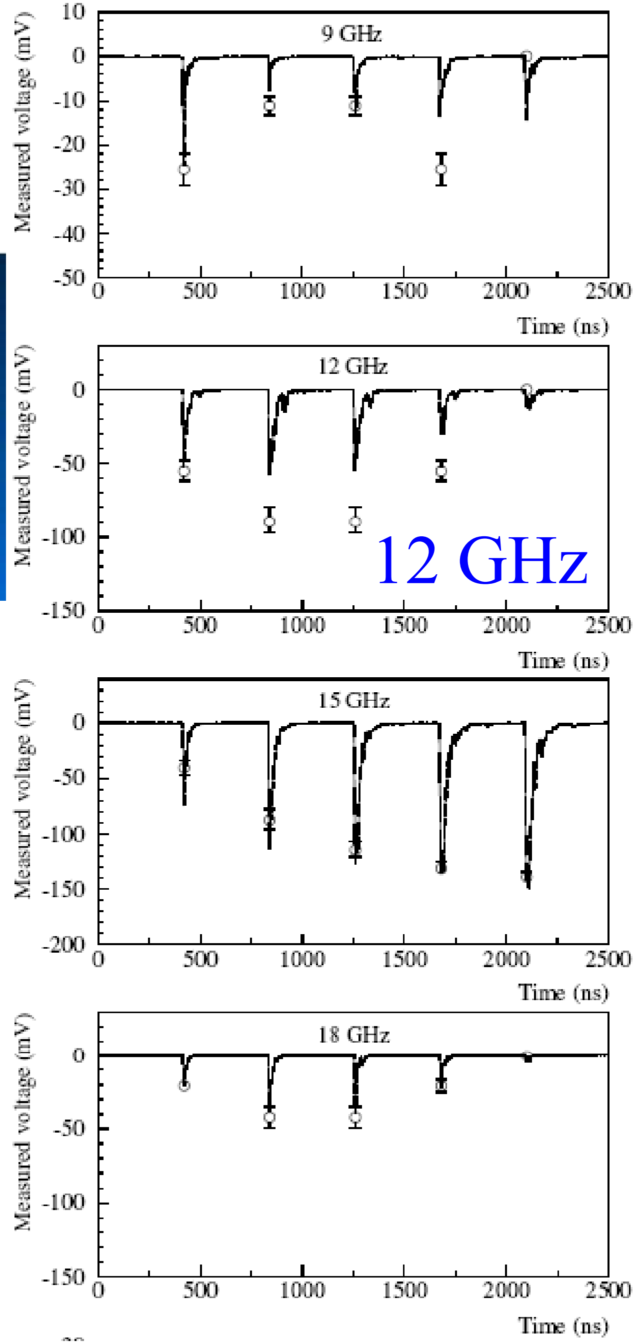




9 GHz

15 GHz

18 GHz

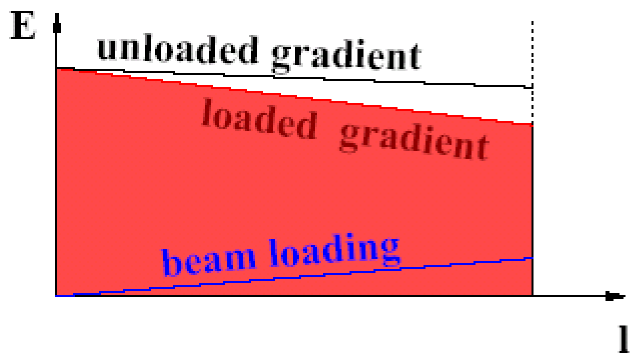


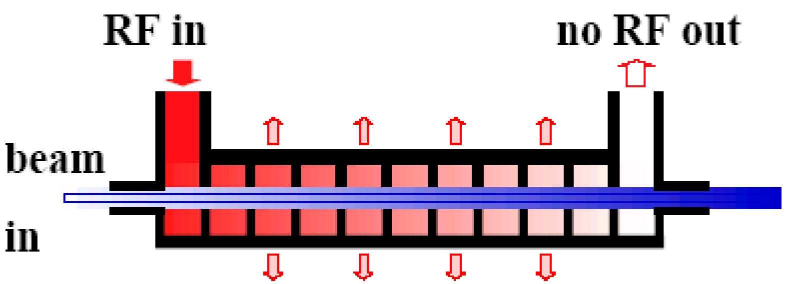
Fully loaded operation

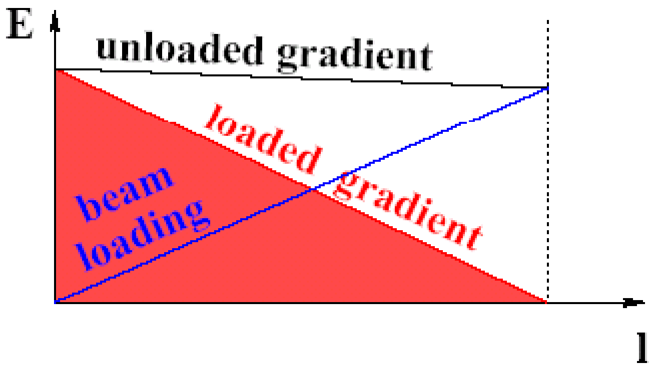
- **efficient power transfer from RF to the beam needed**

"Standard" situation:

- **small beam loading**
- **power at structure exit lost in load**







"Efficient" situation:

- **high beam current**
- **high beam loading**
- **no power flows into load**
- $V_{ACC} \approx 1/2\ V_{unloaded}$

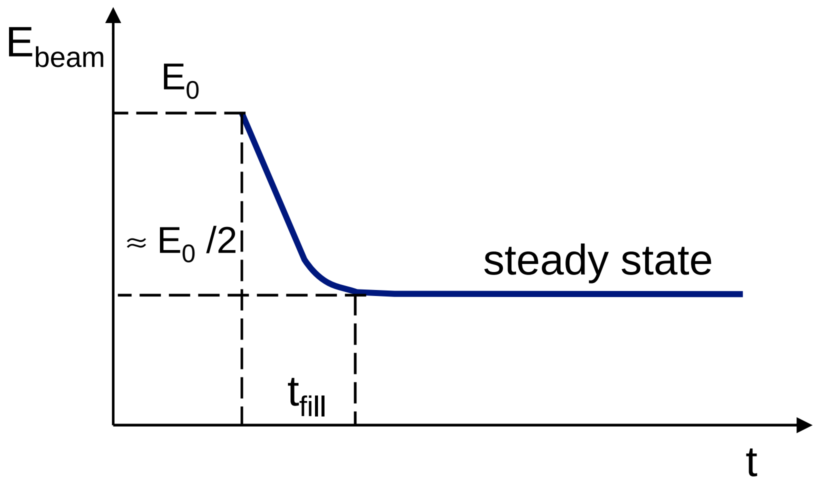
Fully loaded operation

- Disadvantage: any current variation changes energy gain

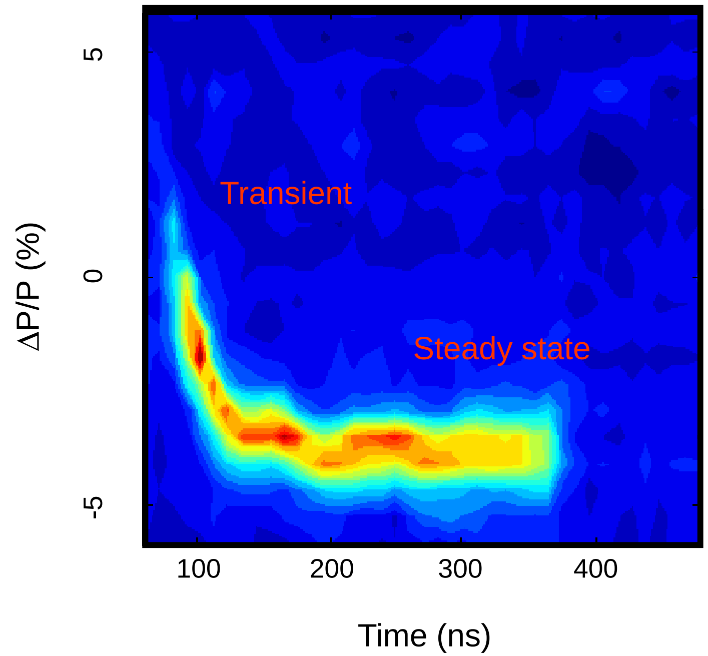
$$\frac{dV/V}{dI_{beam}/I_{beam}} = -\frac{I_{beam}}{I_{opt}}$$

at full loading, 1% current variation = 1% voltage variation

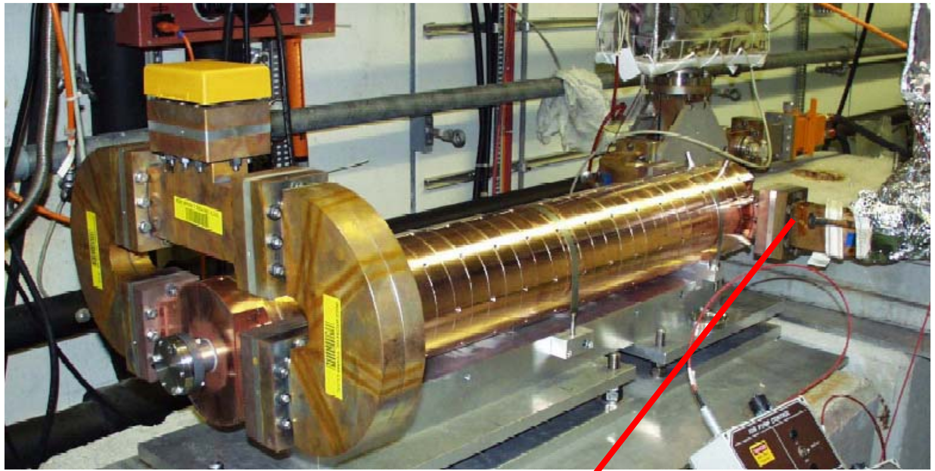
- Requires high current stability
- Energy transient



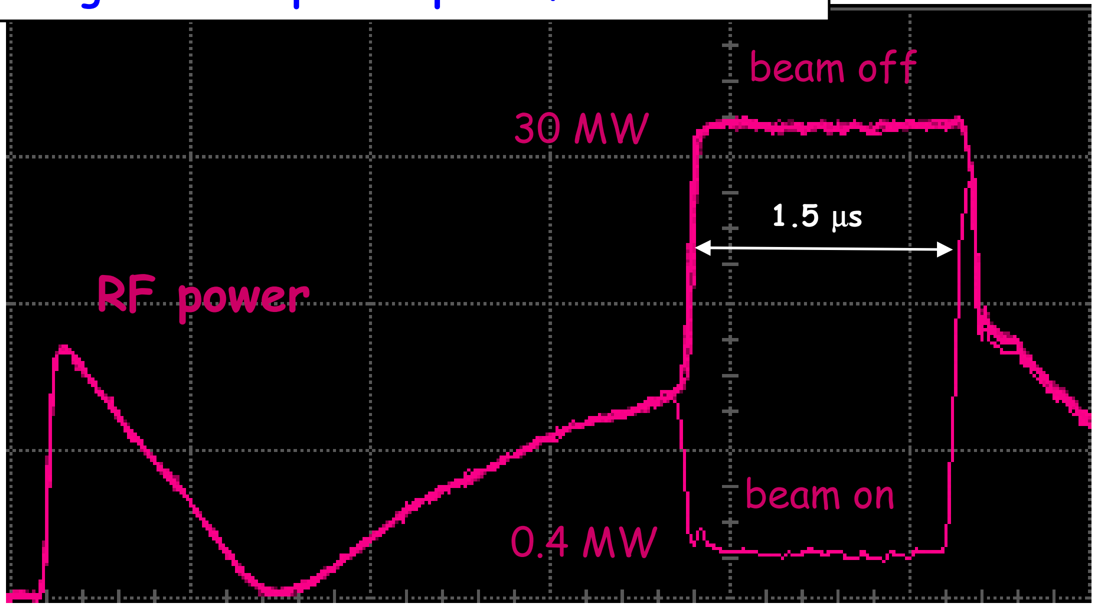
Time resolved beam energy spectrum measurement in CTF3



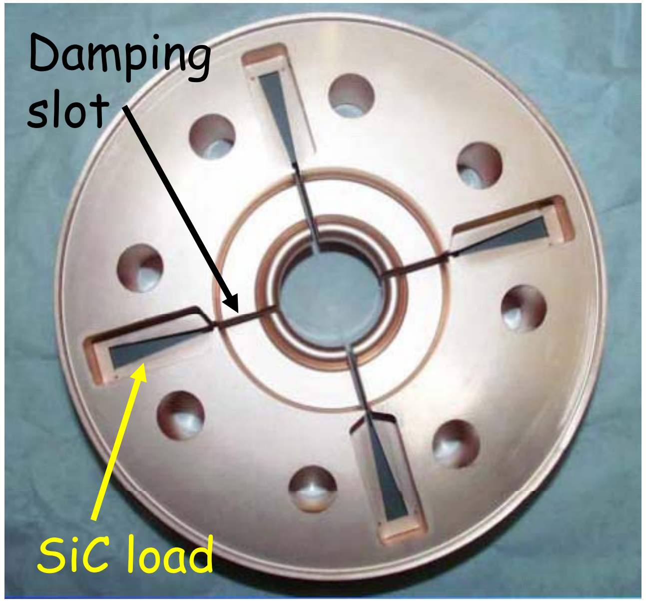
“Full” beam loading operation in CTF3



RF signals / output coupler of structure



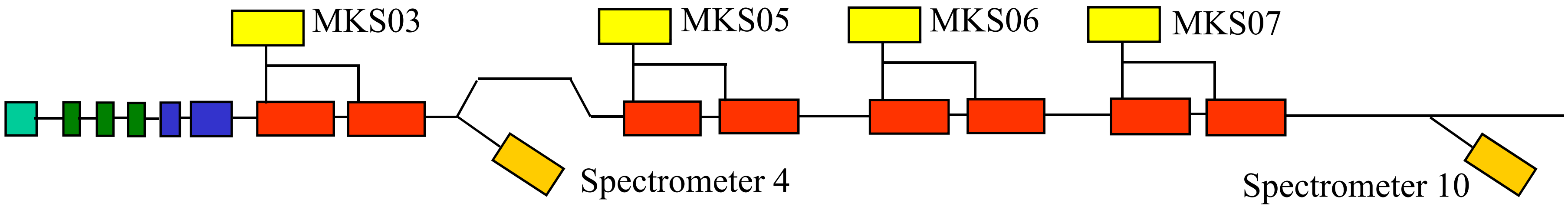
Dipole modes suppressed by slotted iris damping (first dipole's Q factor < 20) and HOM frequency detuning



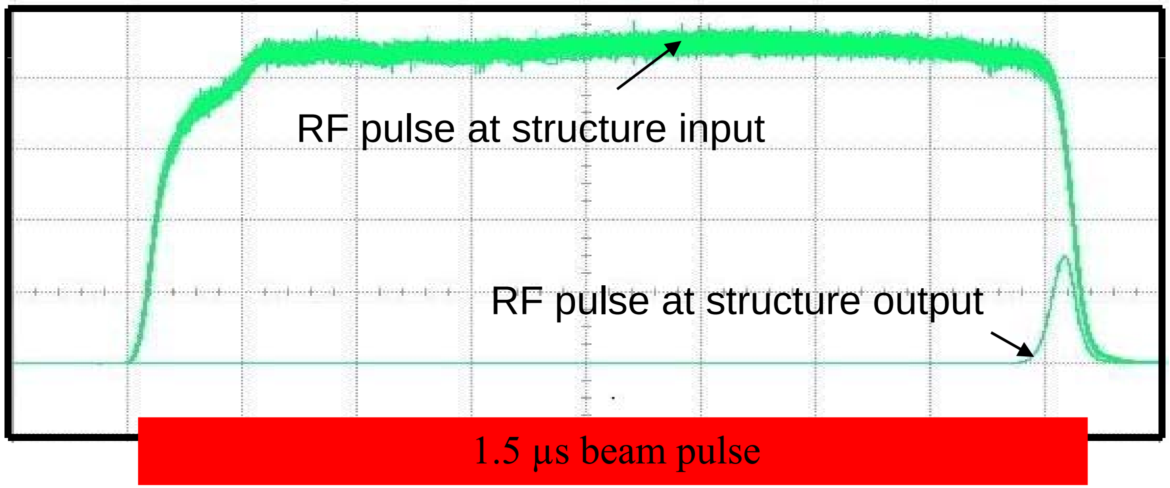
Beam current	4 A
Beam pulse length	1.5 µs
Power input/structure	35 MW
Ohmic losses (beam on)	1.6 MW
RF power to load (beam on)	0.4 MW
RF-to-beam efficiency	**~ 94%**

CLIC: no RF pulse compression
length of the drive beam pulse: 140 μs

Demonstration at CTF3:



Setup: no RF pulse compression for this experiment (with exception of MKS03)
1.5 μs long pulses
Adjust RF power and phase and beam current, that fully loaded condition is fulfilled

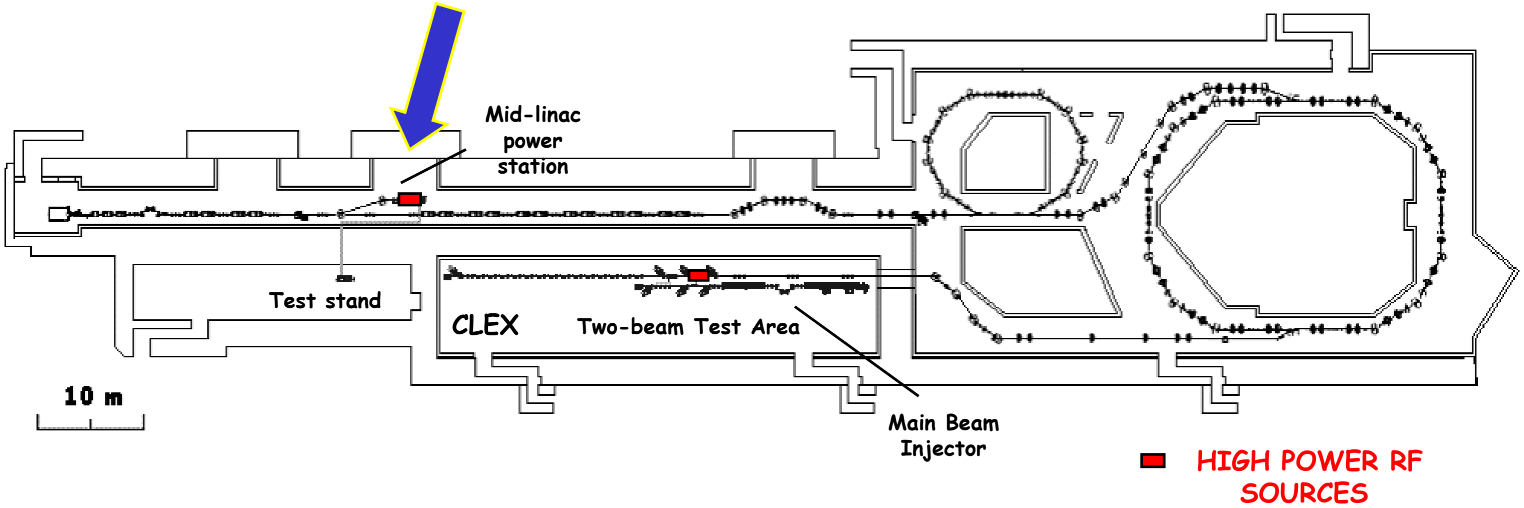


analog signal

measured RF-to-beam efficiency: 95.3 %

Theory: 96%
(~4 % ohmic losses)

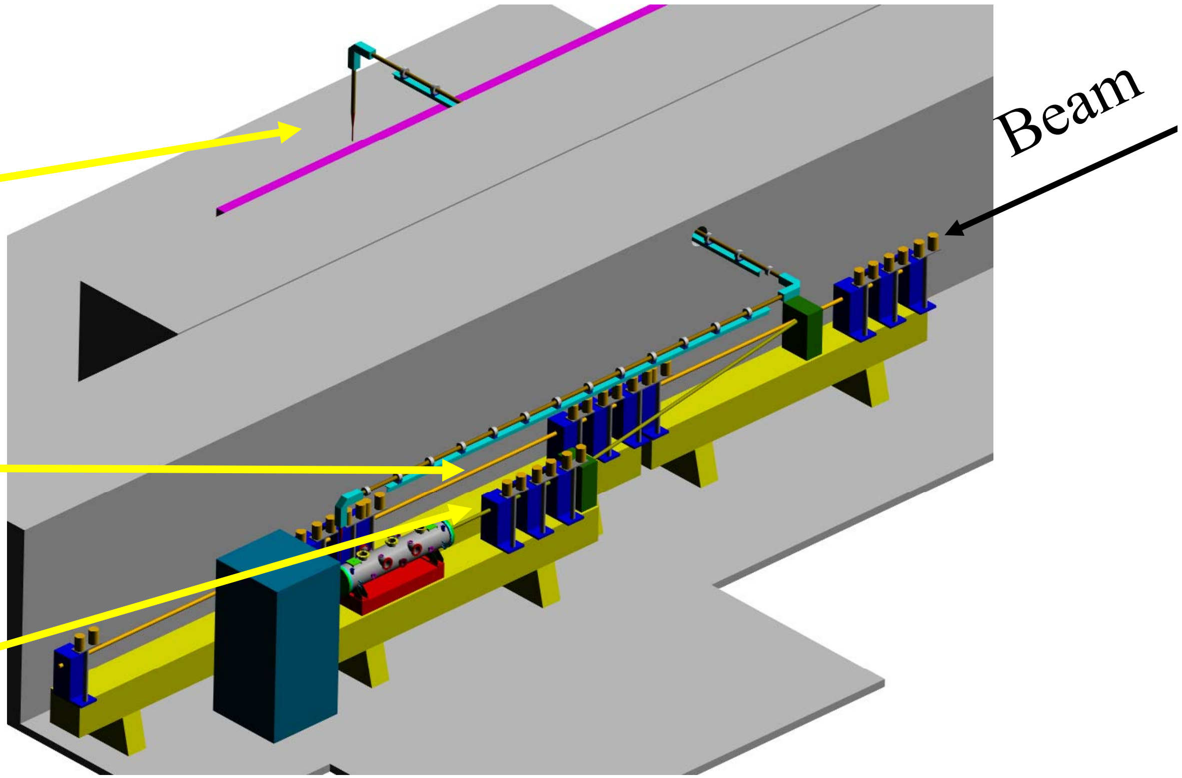
30 GHz test line



High-gradient test stand, CTF2

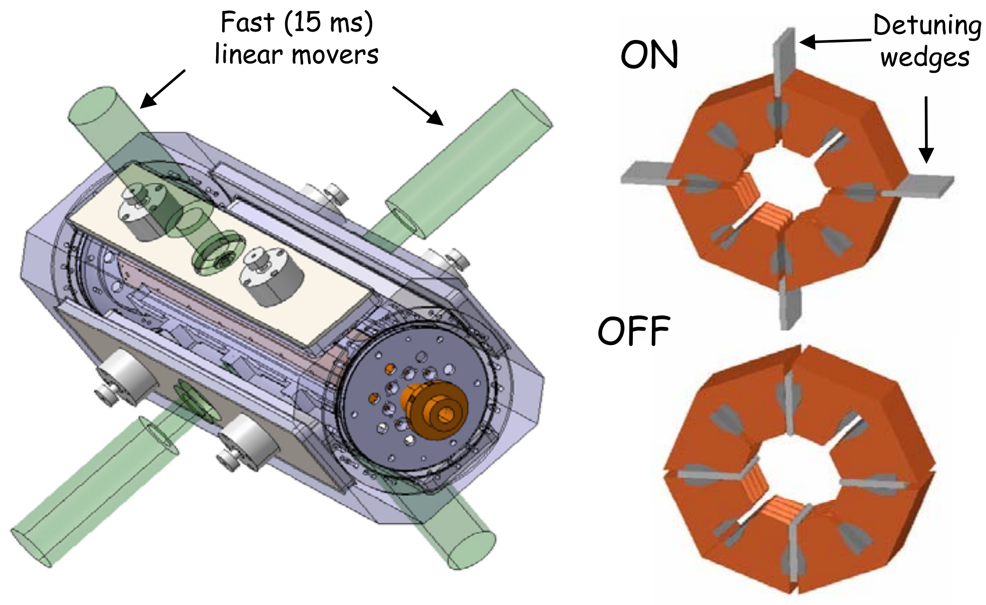
CTF3 linac

PETS branch

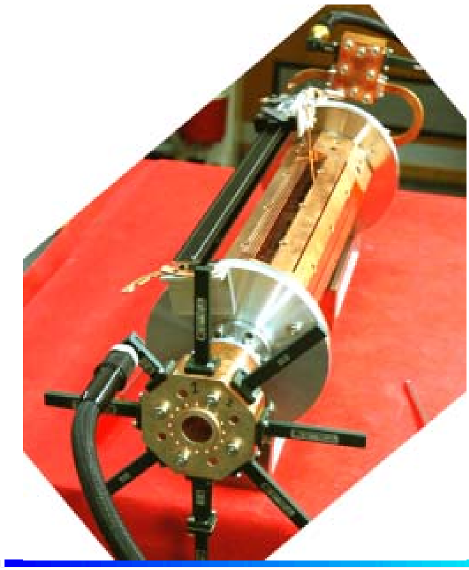


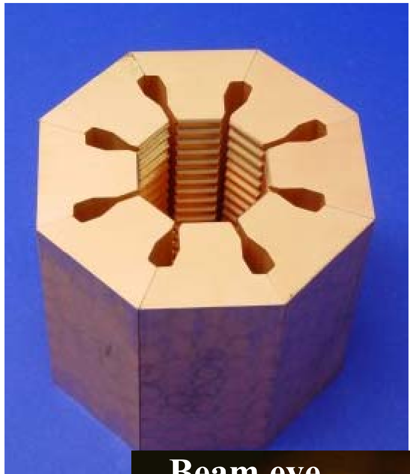
Power extraction structure PETS

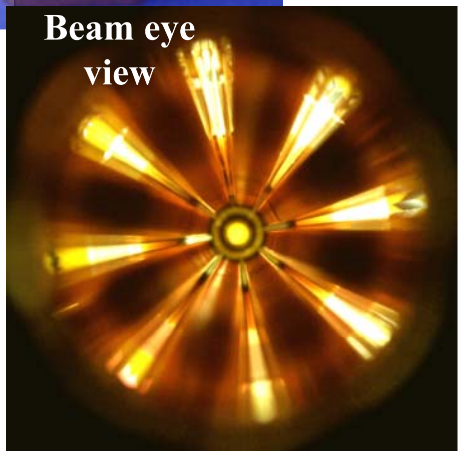
- must extract efficiently >100 MW power from high current drive beam
- periodically corrugated structure with low impedance (big a/λ)
- ON/OFF mechanism

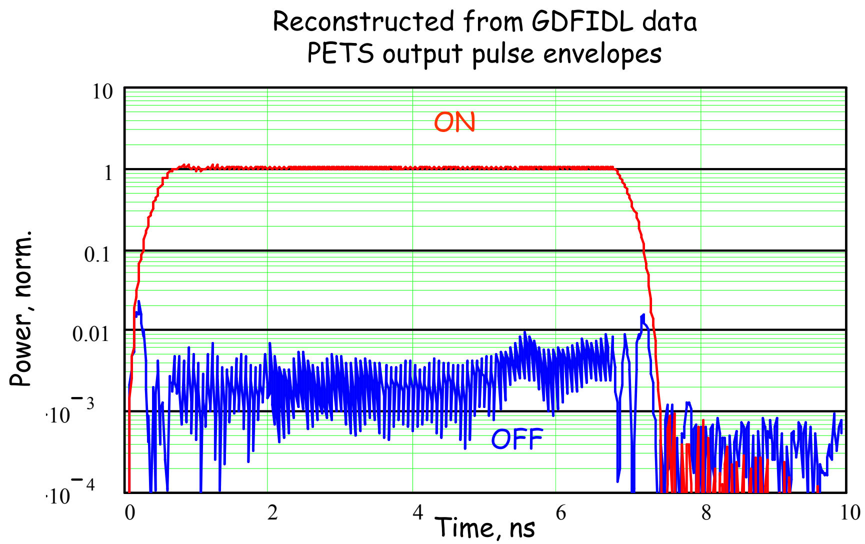


PETS ON/OFF mechanism

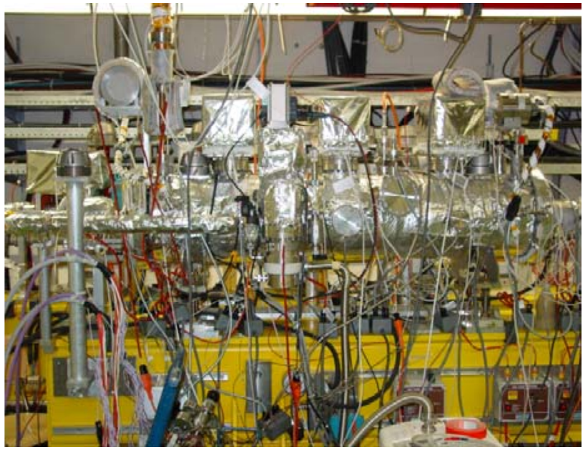






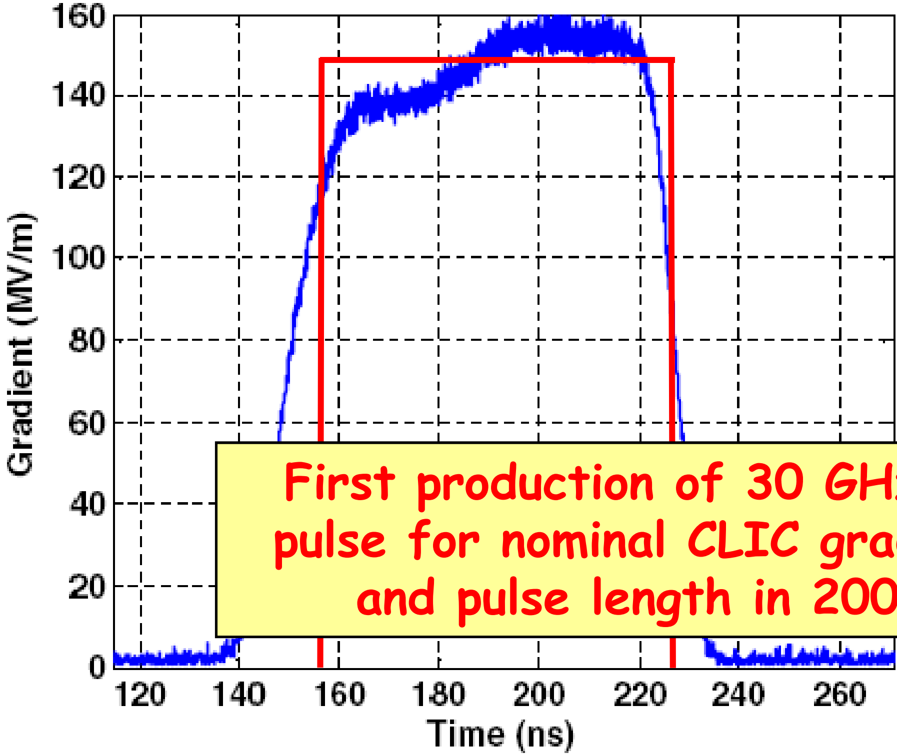


30 GHz power production (PETS)



vacuum tanks containing Power Extraction Transfer Structure

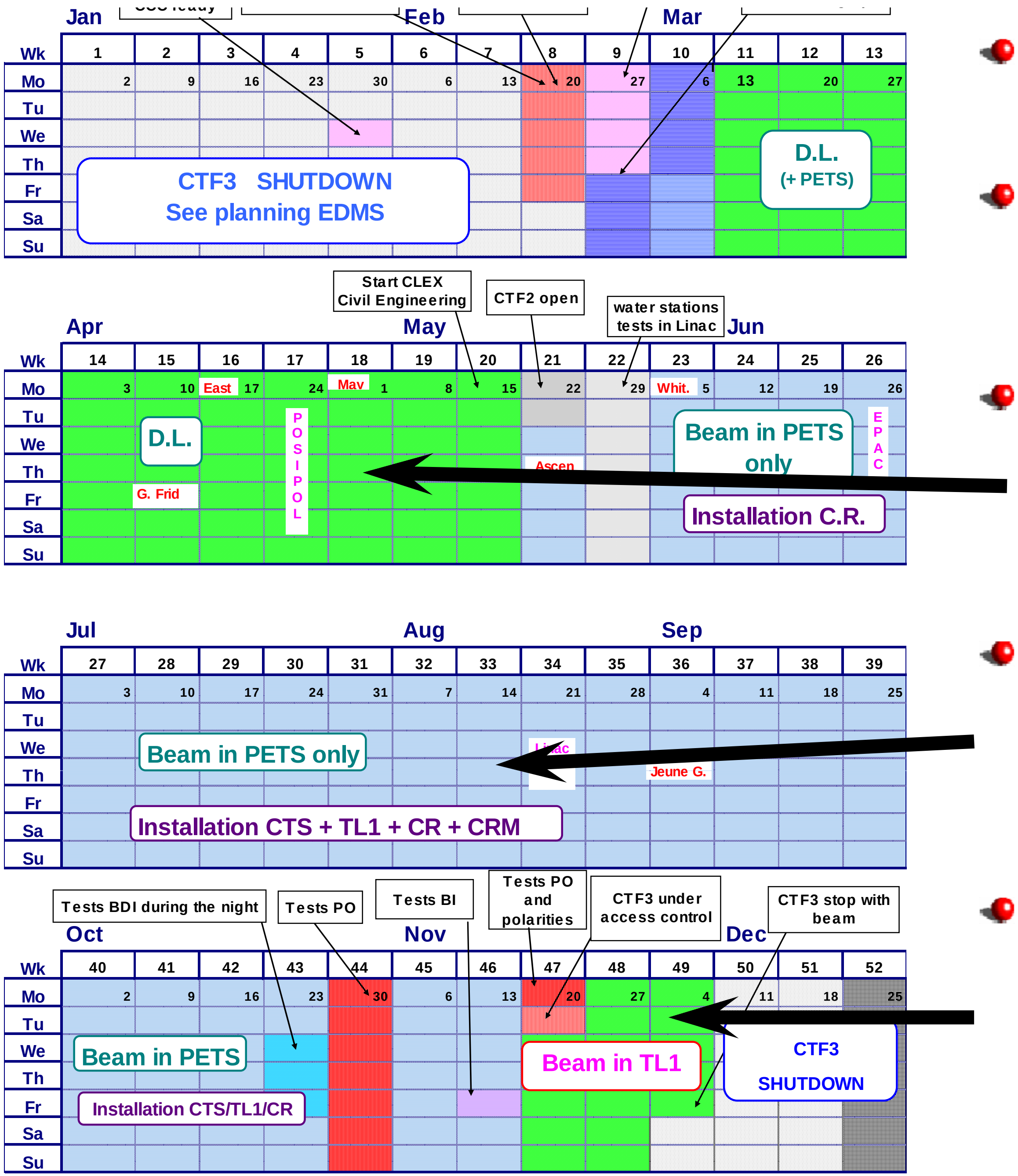
17m waveguide with 5 bends but low-loss (85% transmission) (Russian collaboration)



First production of 30 GHz RF pulse for nominal CLIC gradient and pulse length in 2005

high power load / accel. structure

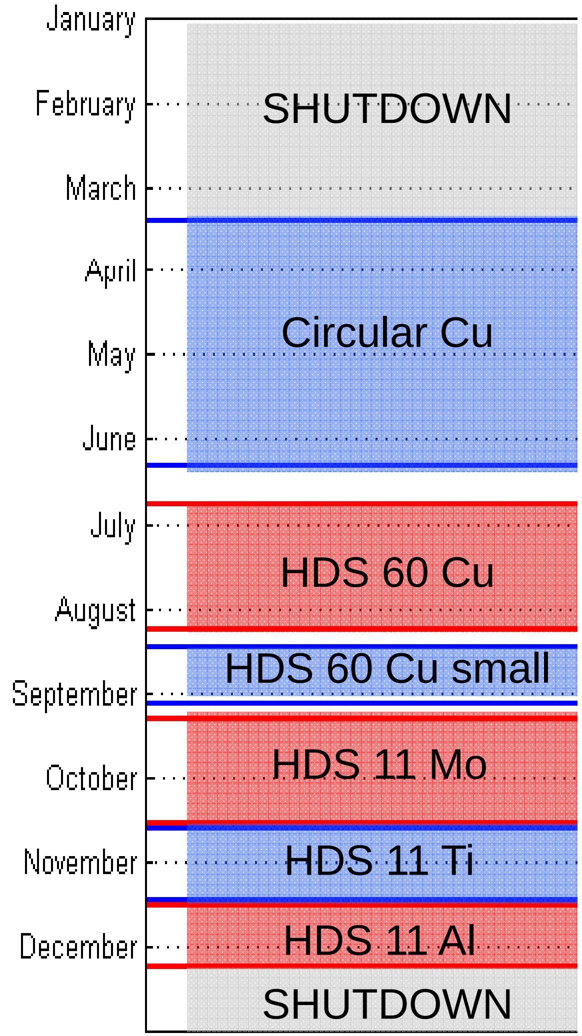
CTF3 schedule 2006



- almost continuous operation all year
- Split between RF production and commissioning
- 1st period:
  DL commissioning / 30 GHz nights and weekends
- 2nd period:
  only 30 GHz /
  TL1+CR installation
- 3rd period (very short!): TL1+CR commissioning / 30 GHz nights + weekends

30 GHz power testing

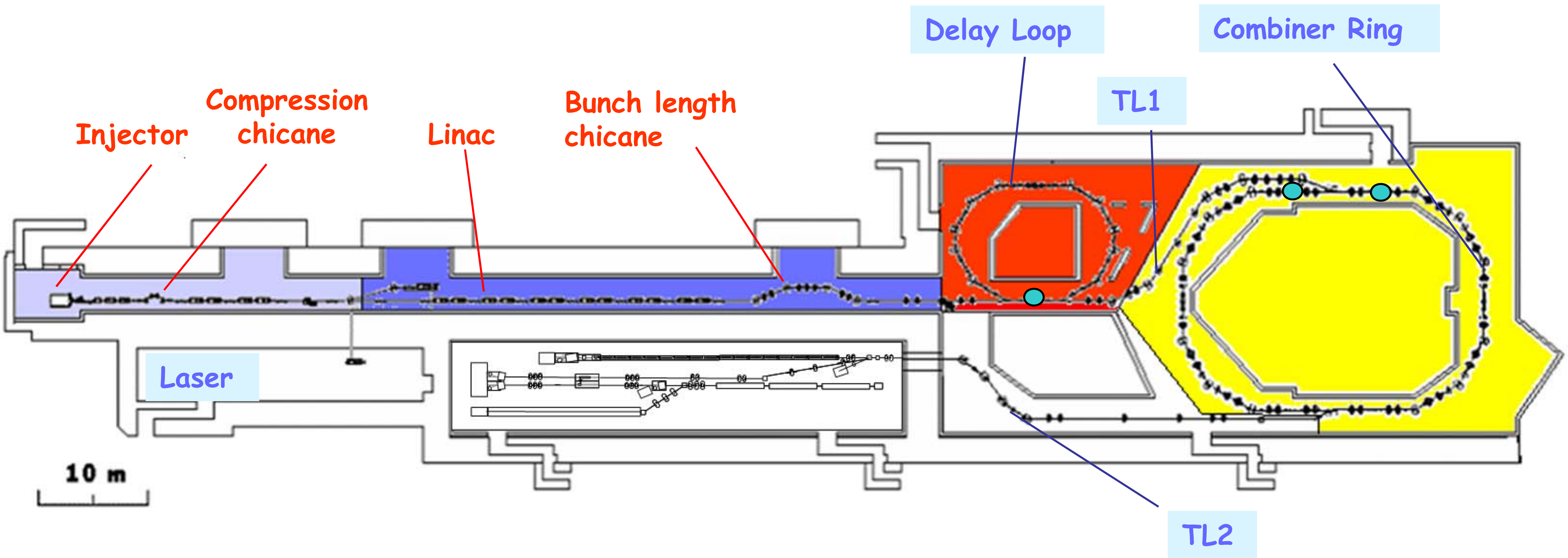
- testing needs large amount of accumulated running time
- RF conditioning largely automated
- CCC (CERN Control Center) operators supervise CTF3 during night and week-ends
- Six prototype accelerating structures tested in 2006
- Installation + testing time per structure have been reduced
- Switch over from and to commissioning became routine and very fast



A.Rodriguez

Bunch length manipulations

- Compression for linac (especially PETS running)
- Tunable bunch length chicane
- Isochronous rings, TL1
- Tunable TL2

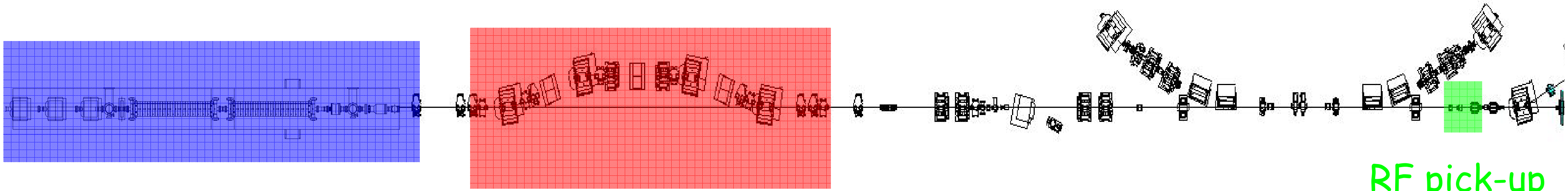


Bunch length manipulation in the INFN chicane

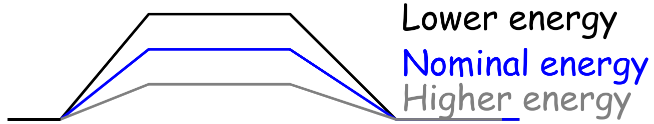
Accelerating structures @Girder 15

4 Bends Frascati Chicane

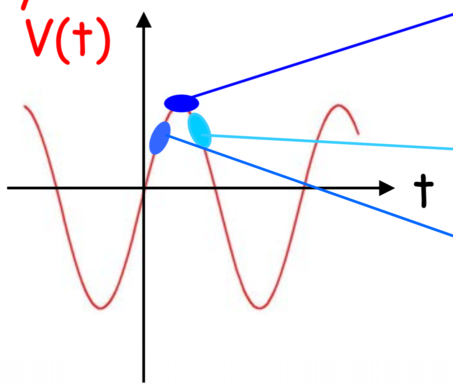
Delay Loop



RF pick-up



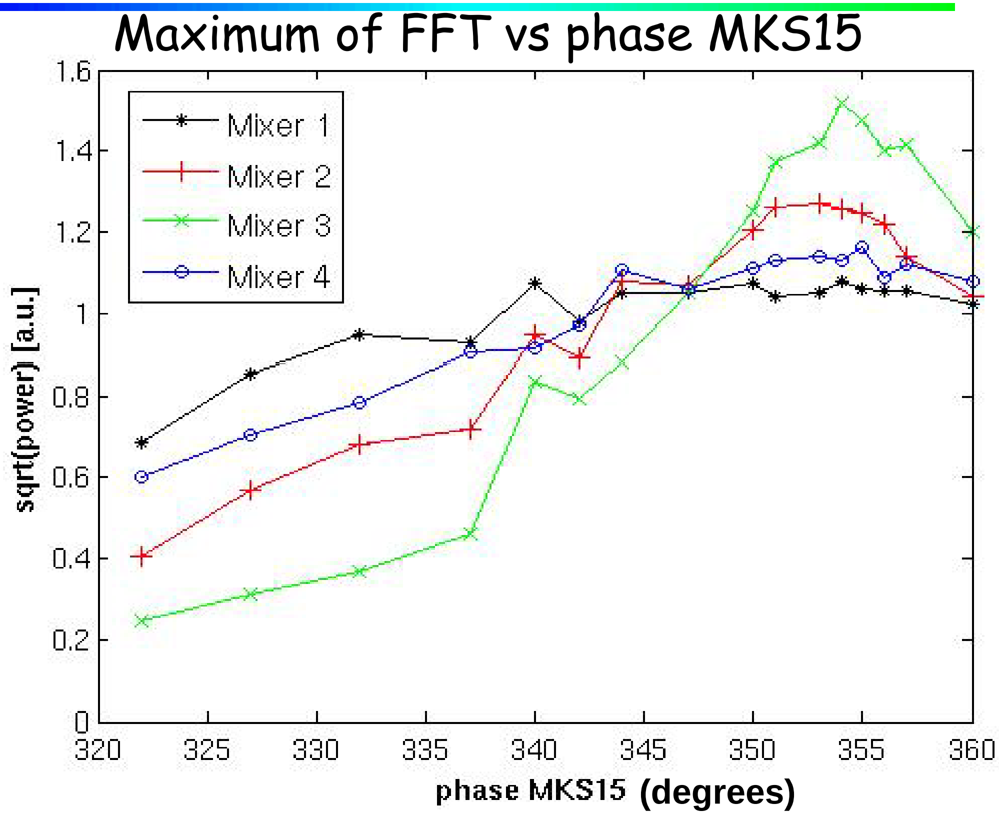
Changing the phase of Klystron 15 to insert a time to energy correlation within the bunch ⇒ Convert energy correlation into path length modification and time correlation ⇒ Measure the Bunch frequency spectrum

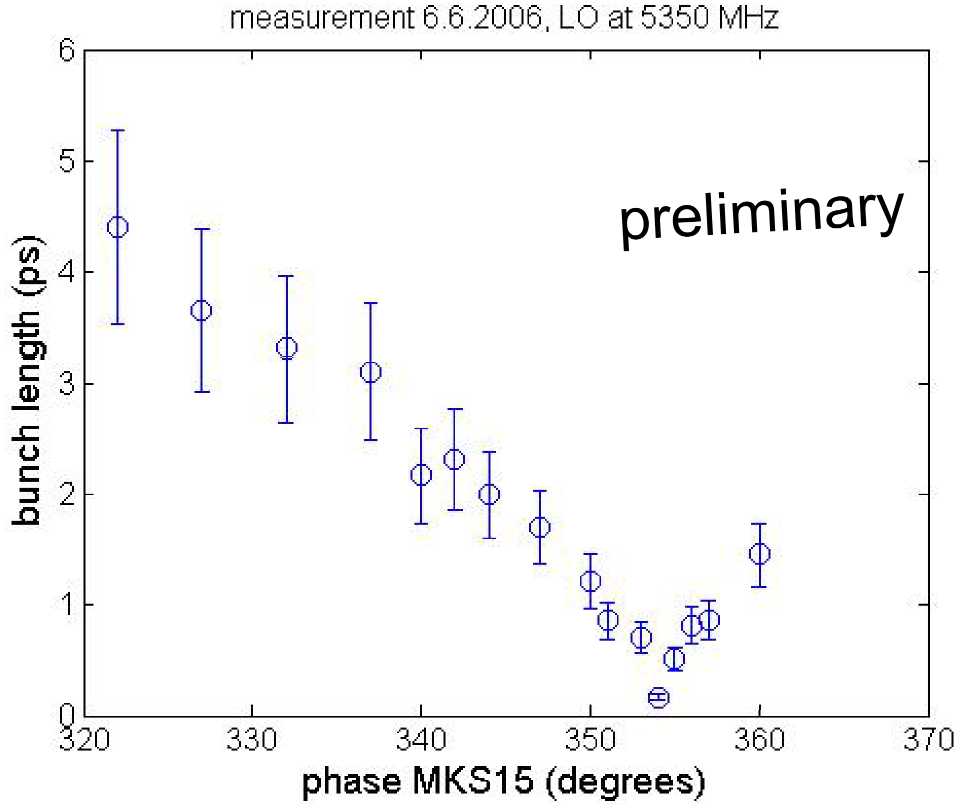


- On-crest Acceleration – the bunch length is conserved through the chicane
- Positive Off-crest Acceleration – the bunch gets shorter
- Negative Off-crest Acceleration – the bunch gets longer

A. Dabrowski, January 16 2007

Bunch length measurement result



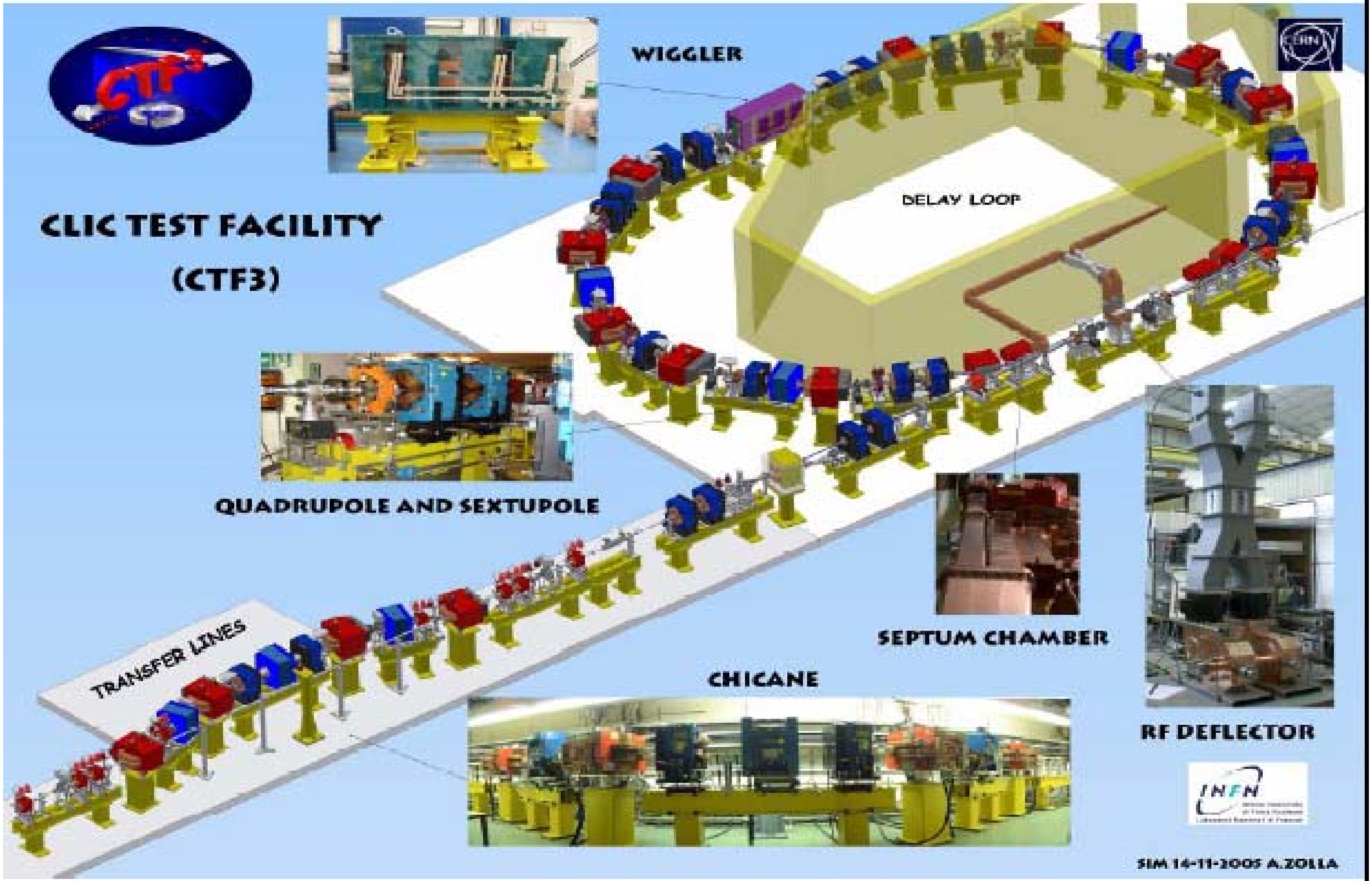


- Data analysed using a self calibration procedure, by means of Chi square minimization.
- 16 measurements (corresponding to the 16 phases on MKS15)
- Fit done with lowest 3 mixing stages.
- 19 free parameters fit → 3 response amplitudes and 16 bunch lengths

$$\chi^2 = \sum_{j}^{16} \sum_{i}^{3} (A_i e^{(-(2\pi f_i)^2 (\sigma_j)^2} - y_{ij})^2$$

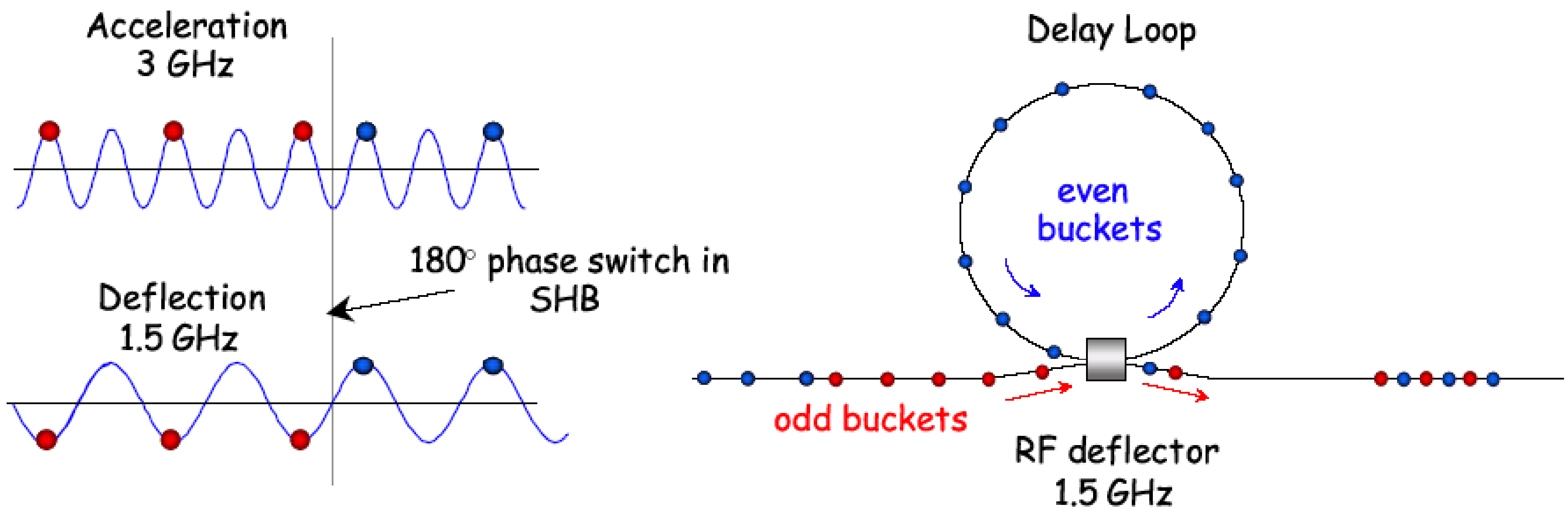
A. Dabrowski, January 16 2007

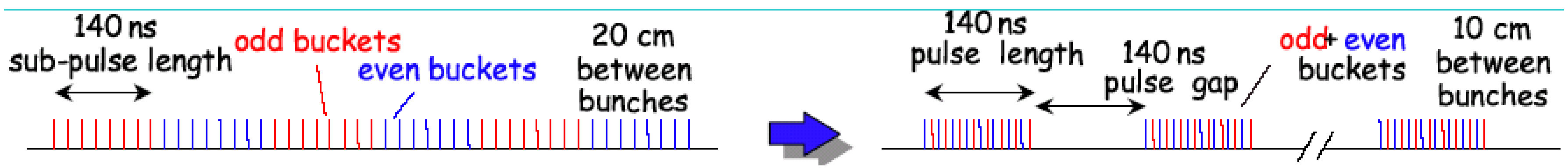
CTF3 Delay Loop



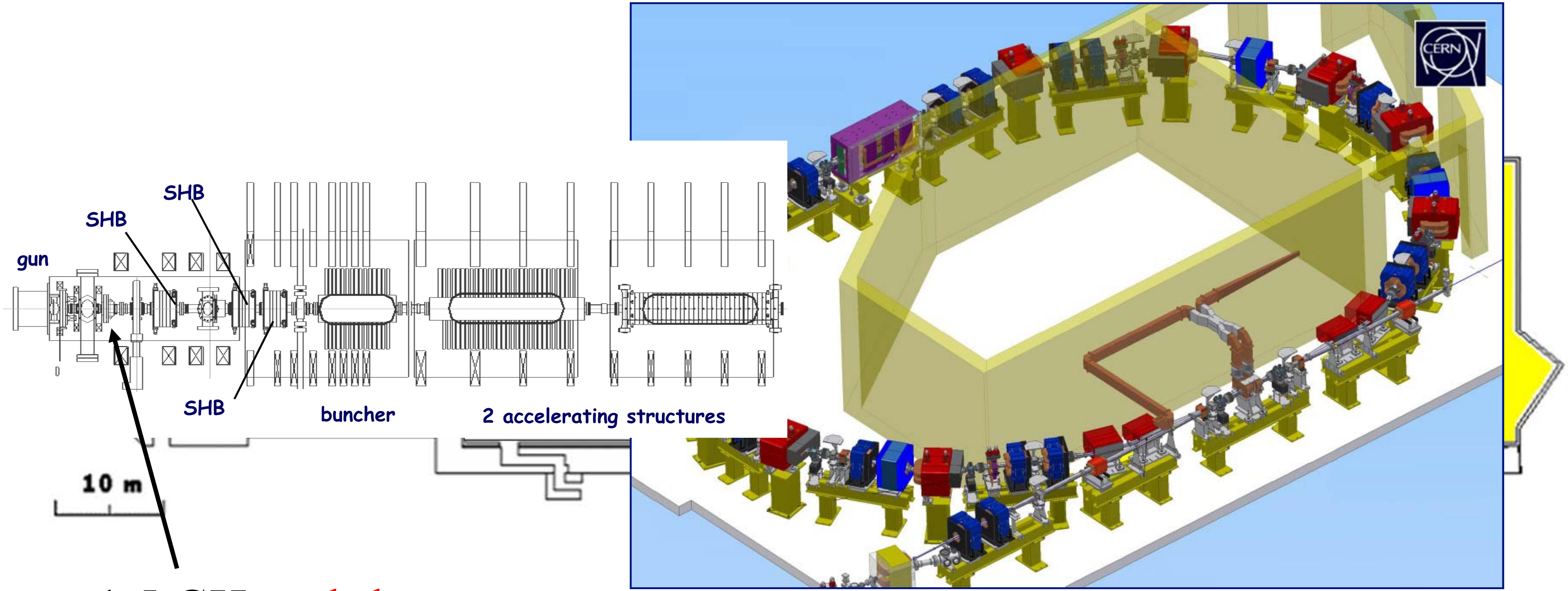
Delay Loop Principle

- **double repetition frequency and current**
- parts of bunch train delayed in loop
- RF deflector combines the bunches





Delay Loop operation

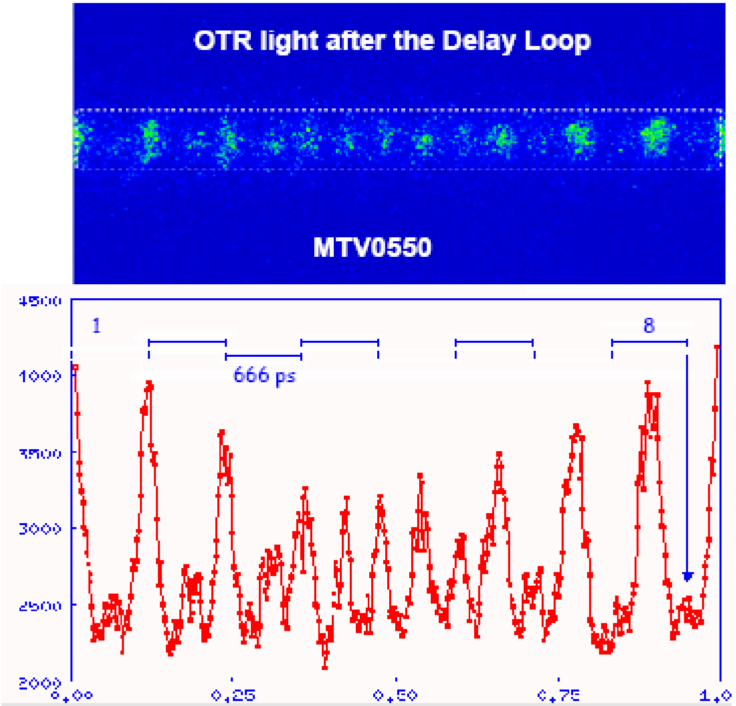


- 1.5 GHz sub-harm. bunching system
- 1.5 GHz RF deflector

SHB system – Phase coding

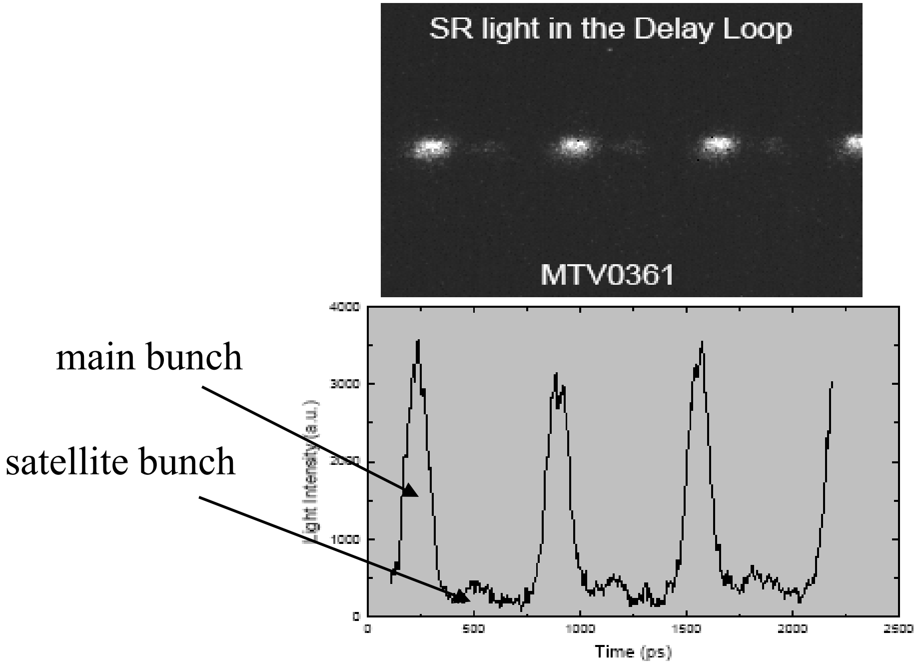
Key parameters for the SHB system: 1) time for phase switch < 10 ns (15 1.5 GHz periods)
2) satellite bunch population < 7 %
(particles captured in 3 GHz RF buckets)

phase switch:



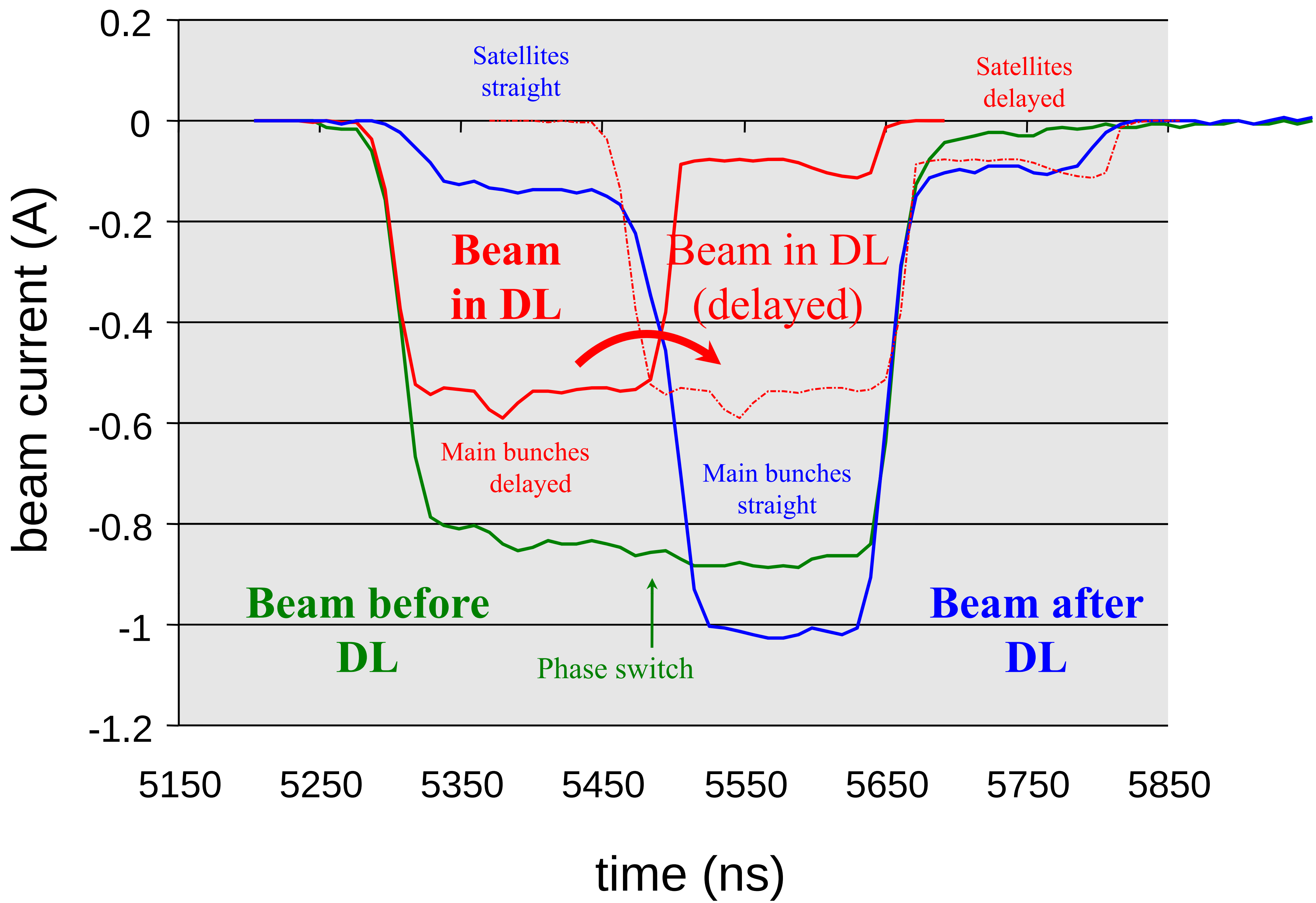
Phase switch is done within eight 1.5 GHz periods **(<6 ns).**

satellite bunch population:

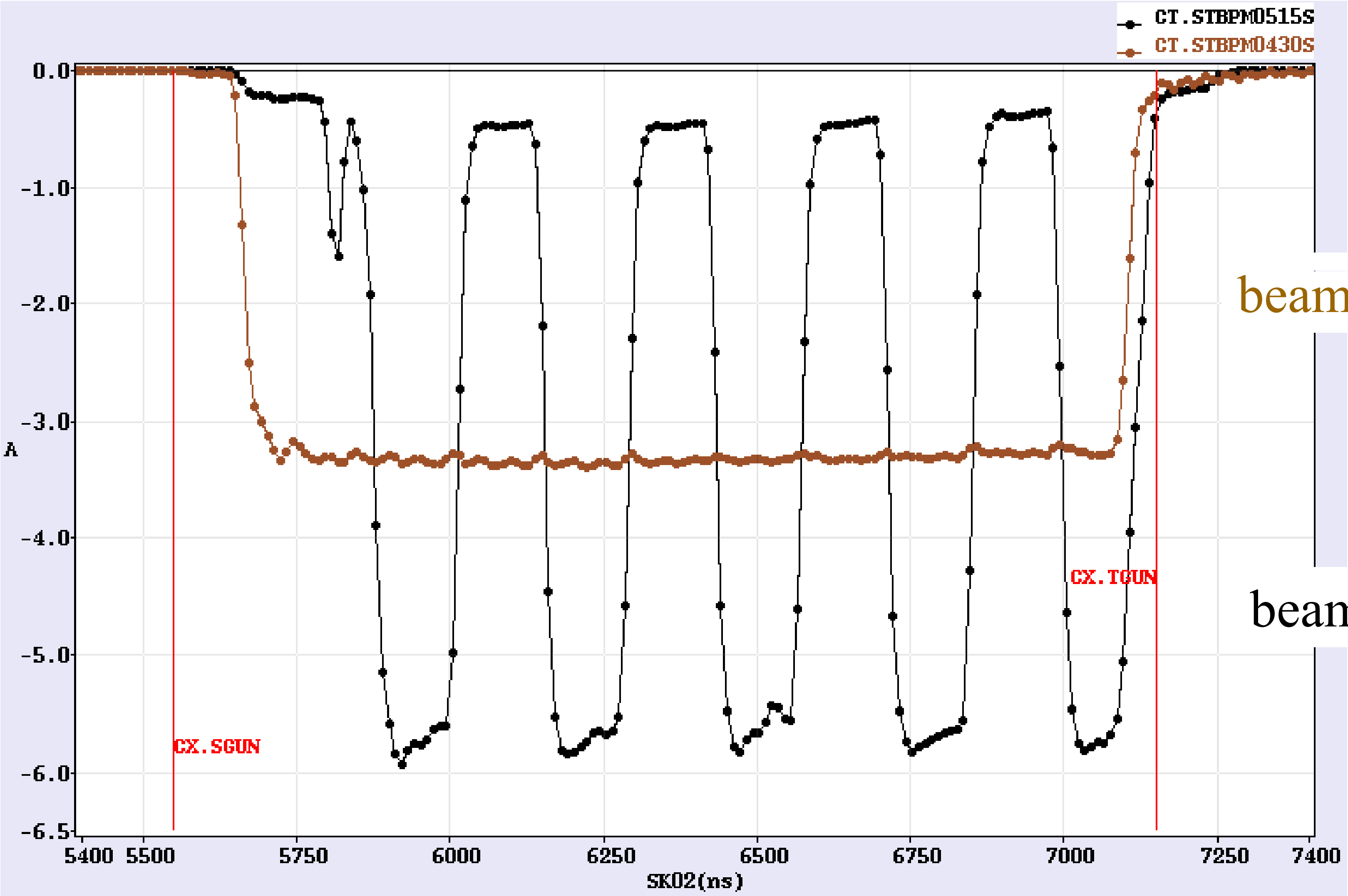


Satellite bunch population was estimated to **~8 %.**

Delay Loop – first recombination 2005



Delay Loop – full recombination

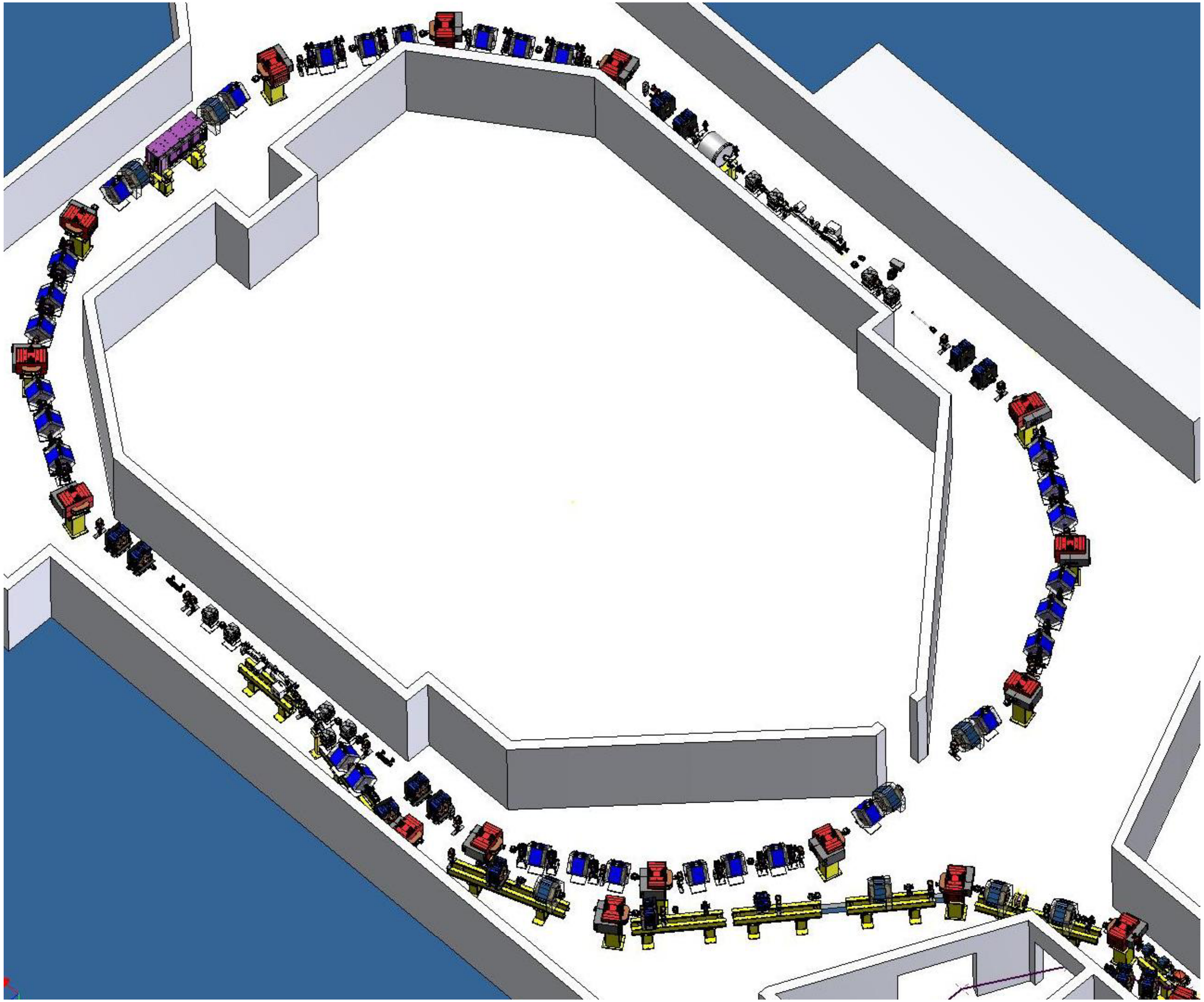


beam before the DL

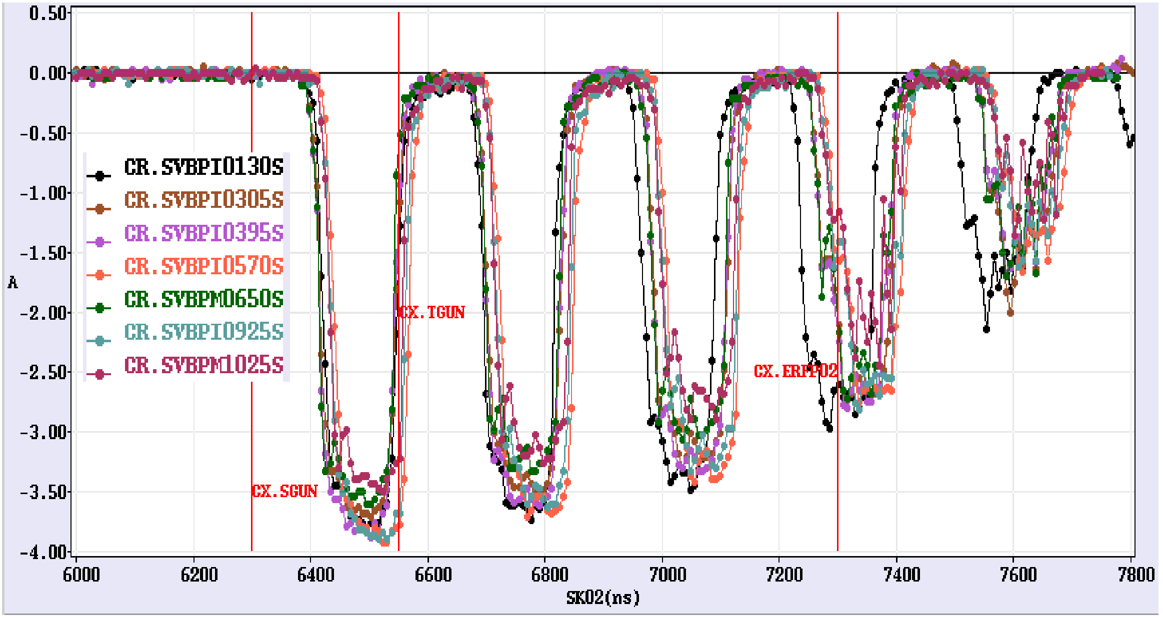
beam after the DL

- 3.3 A after chicane => < 6 A after combination (satellites)

Combiner Ring

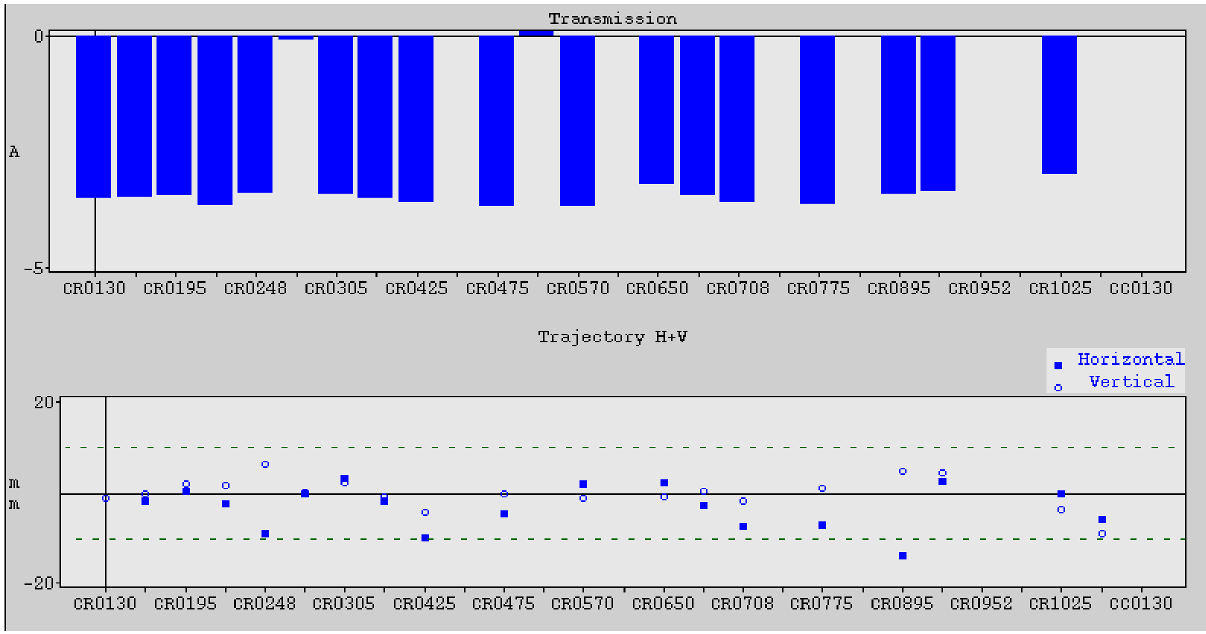


Combiner ring - latest status



We make up to a few 100 turns!

- Nominal isochronous optics
- RF injection
- short RF pulse in deflector that it's only seen by the beam at injection.

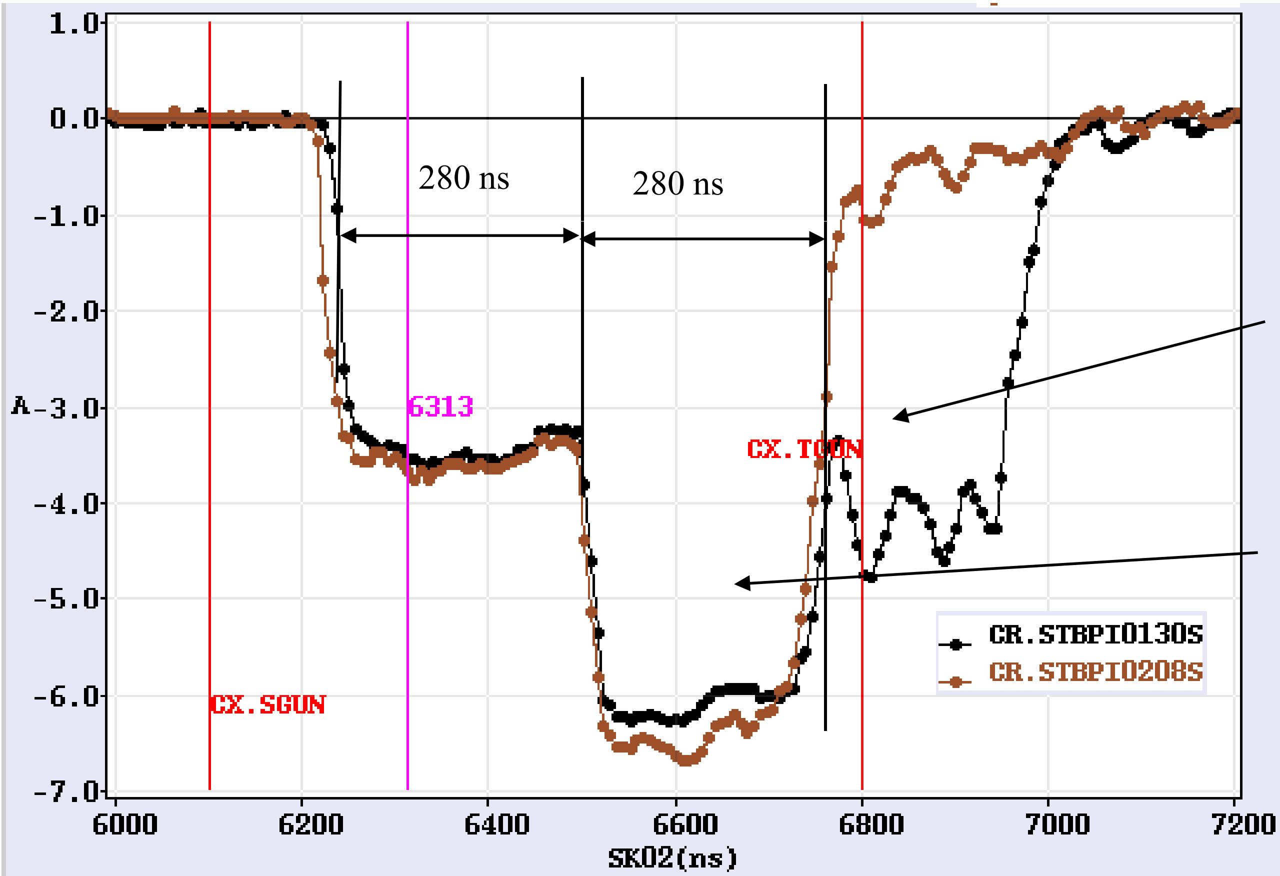


Switching on the SHBS (2 out of 3)

We got immediately the same Transmission in CR!

Combiner ring - latest status

Latest results from last week … we recombine (factor 2)!



Second turn of second pulse and partly third turn of first pulse

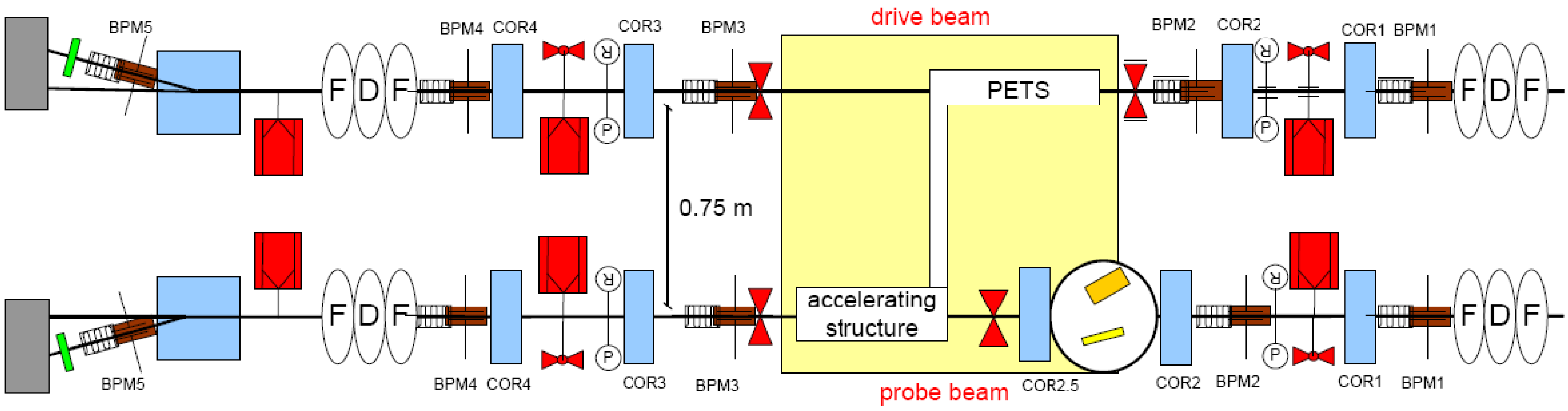
Recombination – factor 2

- nominal isochronous optics
- energy ~ 115 MeV
- RF injection (2nd RF deflector off – so far)
- set up of the path length in CR with wiggler

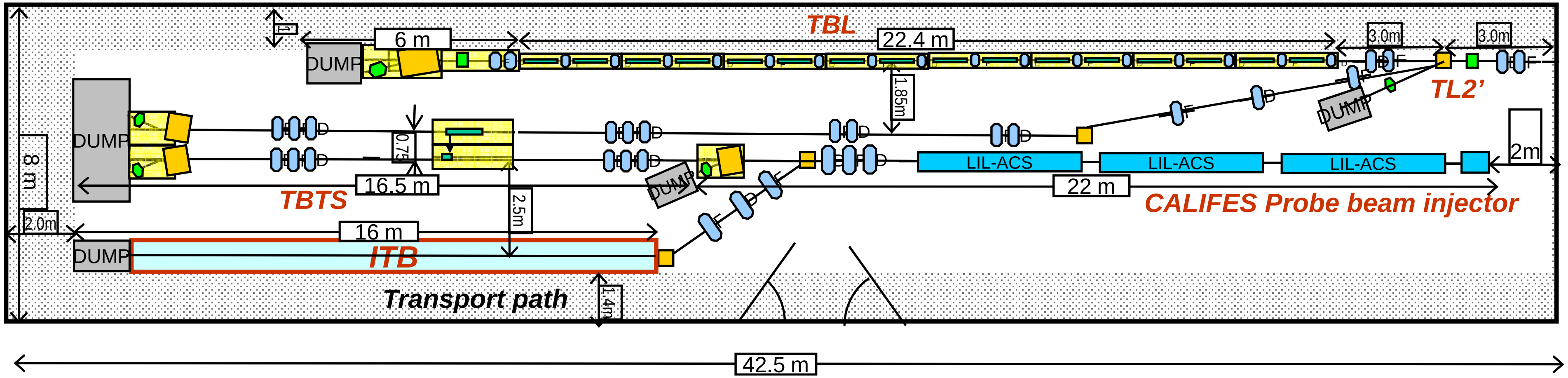
CLEX – Two beam test stand

- High-power test of PETS – first tests of CLIC (lengthened) prototypes
- 12 GHz high-power test of accelerating structures
- Two beam acceleration of 'main' beam from CALIFES
- Measurement of breakdown kick, breakdown current meas. planned
- High-power test of PETS on/off mechanism
- Operation of CLIC module

RR-2007/01/15



CLEX – Test beam line



- High energy spread beam transport, low losses (Bench mark simulations)
- RF Power Production, Stability (End Energy <50%, 2.6 GW of RF power)
- Alignment (Test procedures for BBA) (100 microns alignment for PETS)
- Drive Beam Stability, Wake field (no direct measurement of the wake fields)
- 'Realistic' show case of a CLIC decelerator
- Industrialization of complicated RF components

CLIC Decelerator vs TBL

CLIC	TBL
E = 2.37 GeV	E = 0.15 GeV
I ~ 80 A	I = 30 A
P/pets ~ 170 MW	P/pets = 150 MW
W_{ext} = 90 %	W_{ext} = 55 % (16 cells)

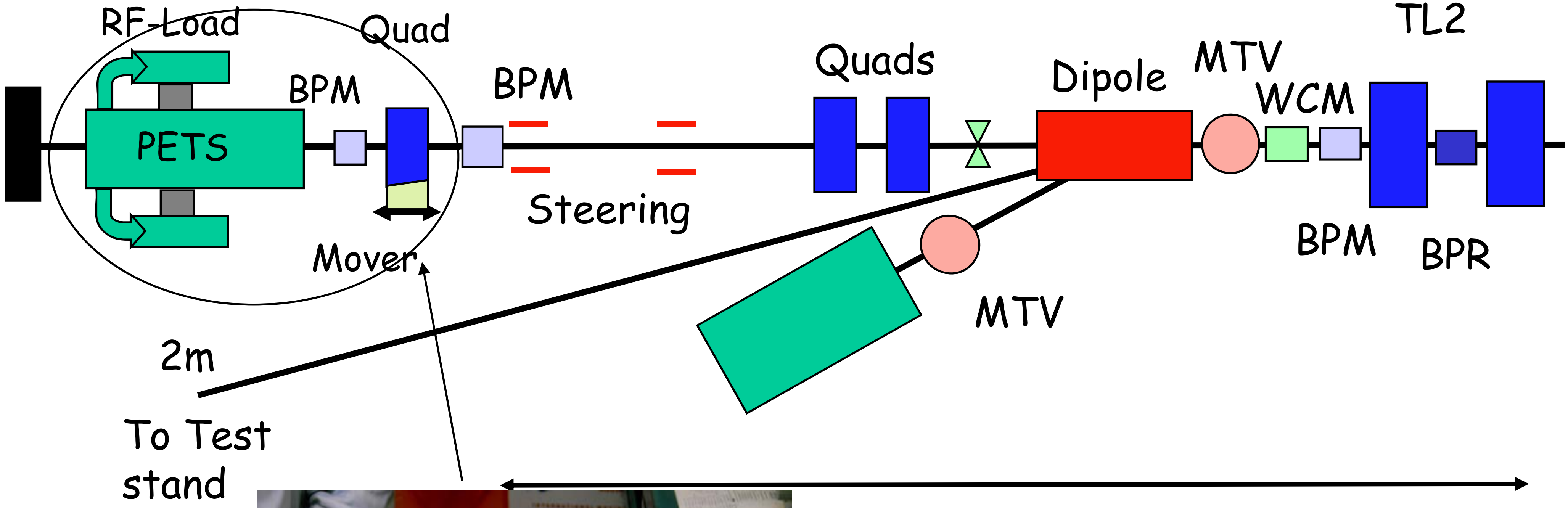
Very similar PETS for both machines,
32 A needed to produce nominal Power/PETS

W_{ext} = 80 % (23 cells) might be possible with some beam improvements

TBL

2007/2008

Prototype Module



Total: ~6 m

Tentative TBL-Schedule (S.Doebert)

Jul-Dec 06	Jan-Mar 07	Apr-Jun 07	Jul-Sep 07	Oct-Dec 07
Define module , Diagnostics, 12 GHz PETS		Fabrication of prototypes		
			Test of Prototypes	

Jan-Mar 08	Apr-Jun 08	Jul-Sep 08	Oct-Dec 08
Install 1 Module		Install a bit more ?	
Series production			

Jan-Mar 09	Apr-Sep 09	Oct-Dec 09	Jan-Mar 10	Apr-Jun 10
Install up to 8 PETS 1.2 GW	Run with 8 PETS 1.2 GW		Install remaining 8 PETS	Run with 16 PETS 2.4 GW

Conclusion

- fully loaded operation demonstrated and routinely used
- bunch train combination principle shown (Prel.Phase)
- phase coding of bunches and full current DL operation
- full current CR combination on a good way
- => fully loaded drive beam generation well covered

- extensive high power RF testing (now automated)

- different tests in CLEX from 2008

Additional slides

Conclusion

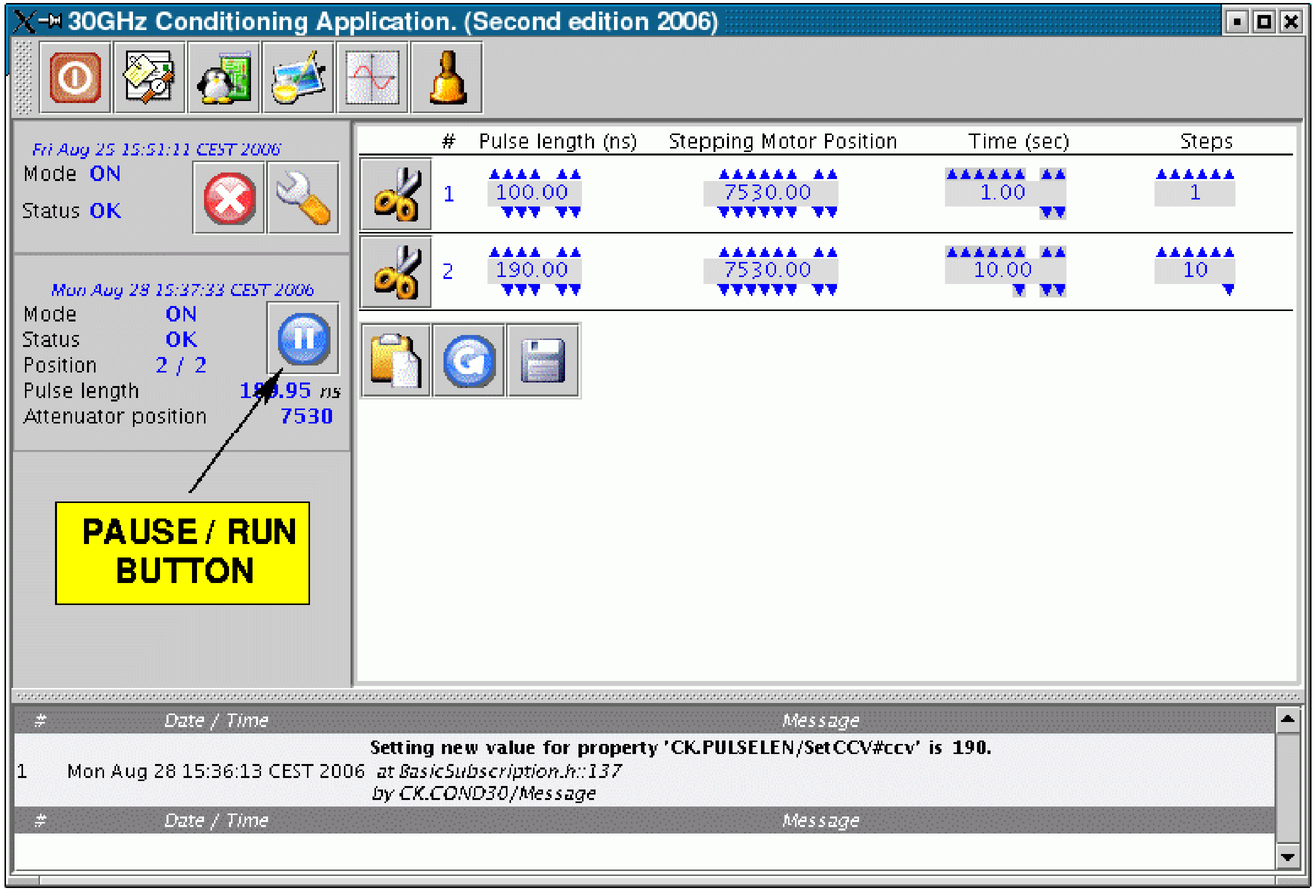
- We have shown:
  - Preliminary phase:
    - principle of bunch train combination at low charge for factors 2-5
    - isochronicity tuning for ring optics
    - combination set-up procedure developed
    - bunch distance variations understood
  - CTF3 Linac
    - stable fully loaded operation successfully demonstrated
    - power generation in the mid-linac PETS structure
    - used for extensive structure testing
  - Delay Loop
    - successful phase coding operation with SHB
    - nominal factor 2 combination for 1.4 us beam pulse (now only 1.1 us needed)

Conclusion (cont.)

- Combiner Ring:
  - full charge operation and combination
- CLEX area – TBTS
  - PETS ON/OFF power generation
  - Acceleration of ‘main’ beam
  - Study of breakdown kicks
- CLEX area – TBL
  - Power extraction
  - Drive beam stability
  - benchmarking
- Beam Instrumentation

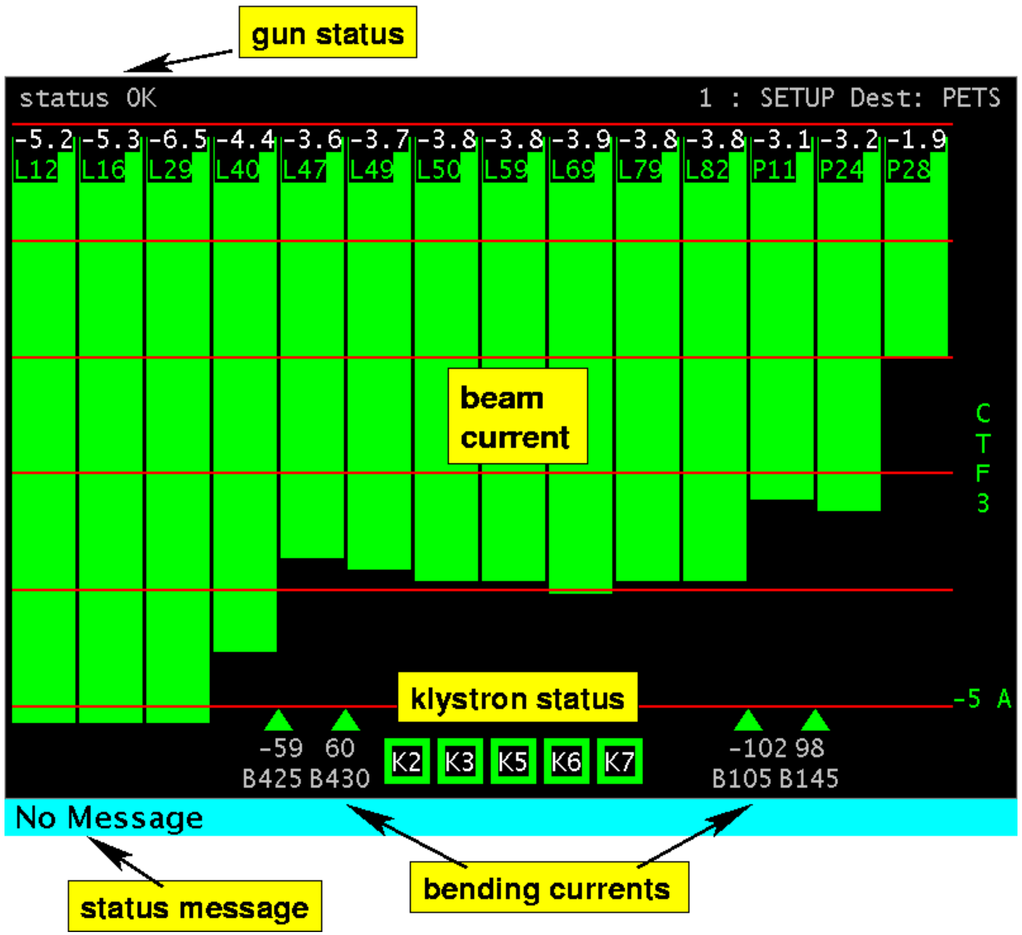
30 GHz Automatic Conditioning

- essential for long-term testing!
- handles break-downs, vacuum, interlocks, …
- programmable for conditioning and breakdown rate measurements
- became operational in mid 2006



CCC operator supervision

- previously night and week-end operation by volunteers and collaborators => limited man-power
- solution: have CCC (CERN Control Center) operators supervise CTF3 during night and week-ends
- reset most frequent errors: klystron trips
- operational environment, tools and documentation prepared
- first CCC operation: 25.8.2006
- very smooth from the start!
- significantly increased up-time

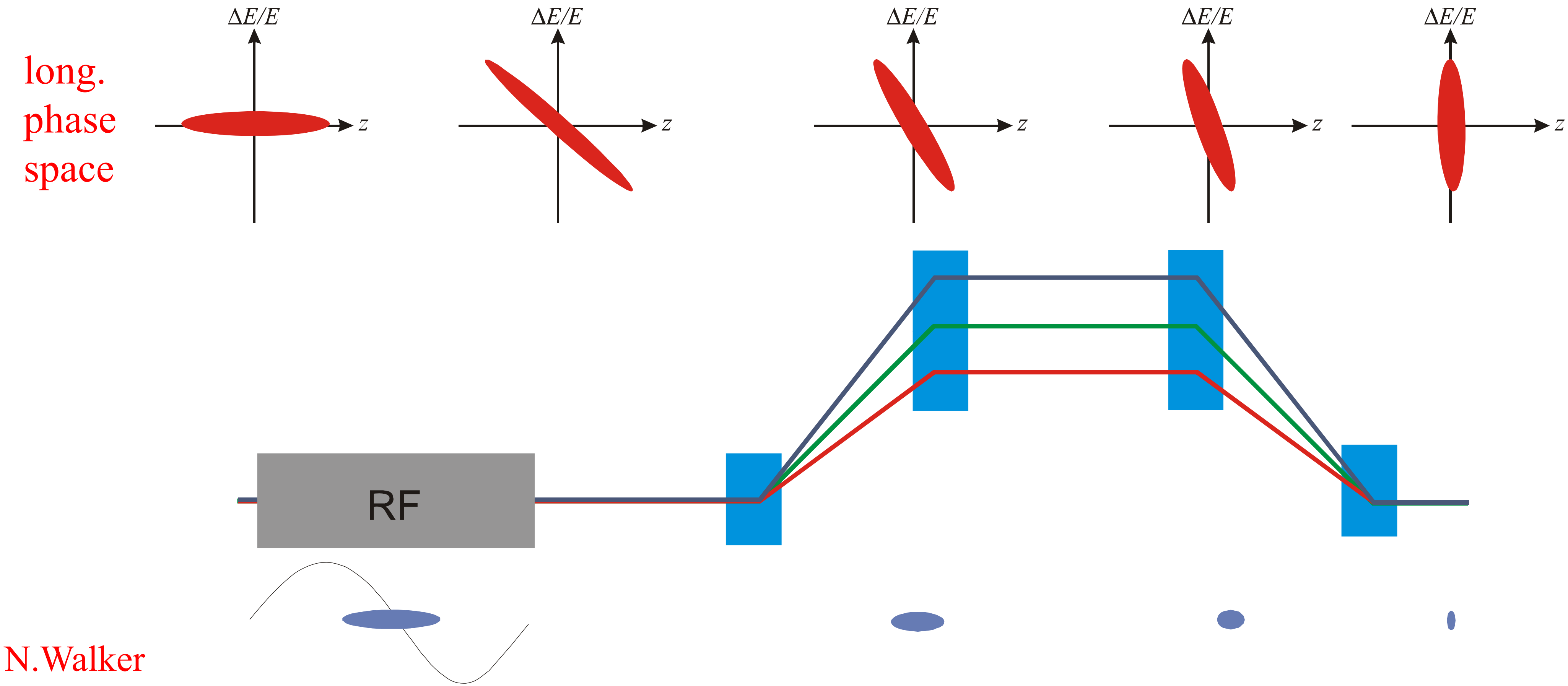


Handling of the high current drive beam

- simulations and experiments on alignment and tuning:
  - Develop beam based alignment and tuning methods adapted to the drive beam decelerator
  - Develop a conceptual machine protection system
  - Develop a method to correct the drive beam phase jitter (synergy with X-FEL's)
    1. Study the drive beam phase jitter
    2. Develop the pickups (BW 100 MHz, 20 fs resolution) and correctors
    3. Develop a longitudinal feedback to reduce drive beam phase jitter
- Benchmarking of simulation codes with CTF3 experiments including TBL, CR & TBTS (Test-Beam Line, Combiner Ring and Two-Beam Test-Stand)

Bunch compression

- bunch length from damping ring: ~ few mm
- required at IP: ~ few 100 µm or shorter
- solution: introduce energy/time correlation with chicane:



N.Walker

Idea: Delay always one klystron pulse after the beam pulse and measure relative energy in spectrometer 10 and compare with calculations.

**An exact knowledge of the structure input power,
the beam current and the energy gain is essential.**

MKS05	MKS06	MKS07	
in	in	in	total energy
out	in	in	lower energy

compare to theoretical energy gain
(input power, beam current)

↓

- "missing" acceleration (energy gain per structure)
- deceleration due to direct beam loading

↑

from calculations (beam current)

measured RF-to-beam efficiency: 95.3 %
Theory: 96% (~4 % ohmic losses)

CTF3 beam loss monitoring

Structure (1)

- start from ILC-TRC CTF3 issues
- short review CTF3 motivation and layout (already by RC, GG)
- CTF3 Preliminary Phase:
  - RF combination factor 4 and 5 (2,3) at low current
  - setting up combination
  - tuning isochronicity
- CTF3 linac:
  - stable fully loaded operation, efficiency
- Delay Loop:
  - first combination stage of (old) nom. pulse length (now 5 -> 4)
  - SHB phase coding

Structure (2)

- 30 GHz power production and testing
  - PETS structure
  - accelerating structures, BDR, material (already covered by SD)
- Combiner Ring
  - nom. combination at full current
- CLEX, Two Beam Test Stand (TBTS)
  - power extraction at 12 GHz, CLIC PETS, ON/OFF
  - acc. of probe beam
  - break-down kick
- CLEX, Test Beam Line (TBL)
  - stability of deceleration, benchmarking

Structure (3)

- Photo Injector (?)
- Beam Instrumentation (?)

- Conclusion (retaking ILC-TRC R1, R2, including schedule?)