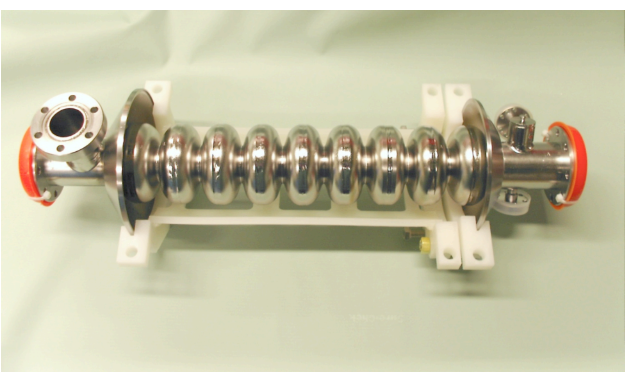
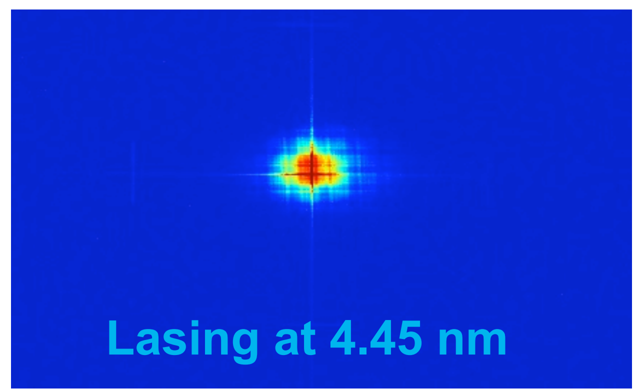
The Fermilab 3rd Harmonic Module for FLASH

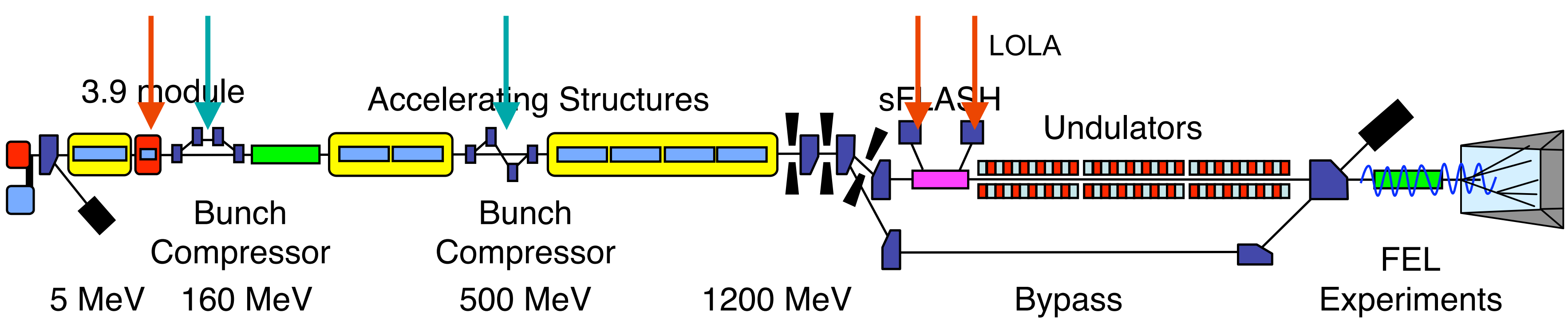
H. Edwards, DESY, FNAL
with
C. Behrens, DESY
E. Harms, FNAL
for FNAL 3.9 team & FLASH team





Outline

- 3.9 Cavity Specifications/Parameters
- 3.9 module fabrication steps
- Technical difficulties
- 3.9 Performance
- FLASH installation and upgrade
- Compression concepts
- Measurements with LOLA
- Calculations and simulations
- Future



3.9 GHz to linearize the 1.3GHz rf over the electron bunch length

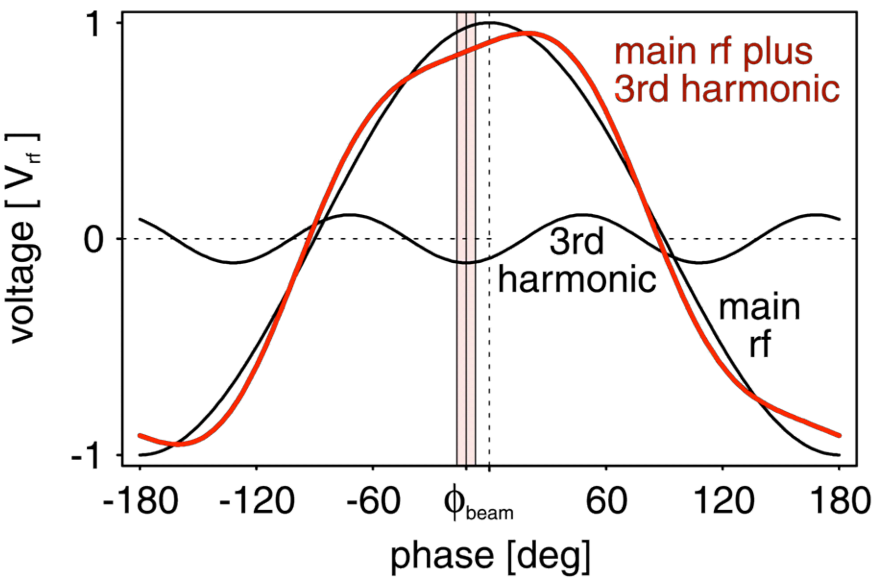
$$\frac{d^2}{ds^2}\left(A_{1.3}\cos\left(\frac{\omega_{1.3}}{c}s+\phi_{1.3}\right)+A_{3.9}\cos\left(\frac{\omega_{3.9}}{c}s+\phi_{3.9}\right)\right)=0$$

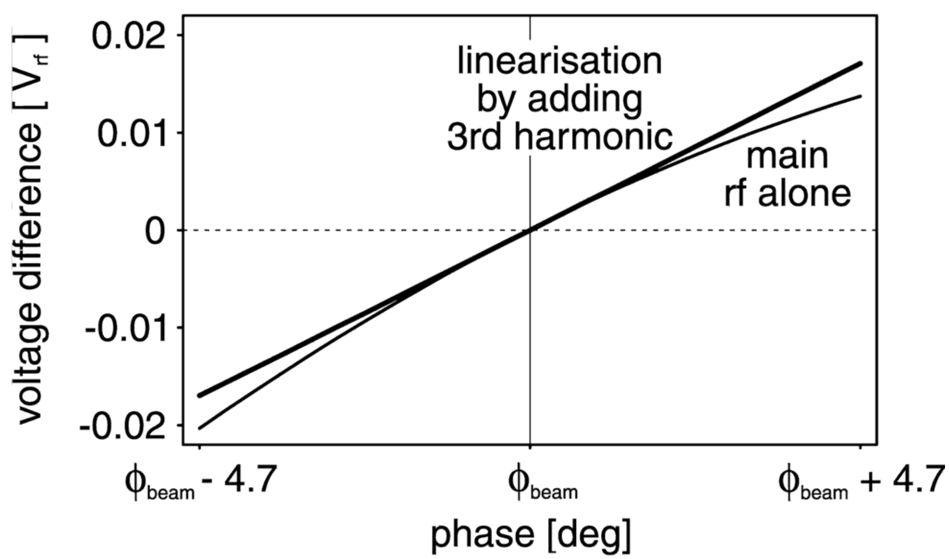
$$\omega_{1.3}^2 A_{1.3}\cos\left(\frac{\omega_{1.3}}{c}s+\phi_{1.3}\right)+\omega_{3.9}^2 A_{3.9}\cos\left(\frac{\omega_{3.9}}{c}s+\phi_{3.9}\right)=0$$

Near crest at bunch center s=0

$$\frac{A_{3.9}}{A_{1.3}}=-\frac{\omega_{1.3}^2}{\omega_{3.9}^2}\left(\frac{\cos\phi_{1.3}}{\cos\phi_{3.9}}\right)\approx\frac{1}{9}$$

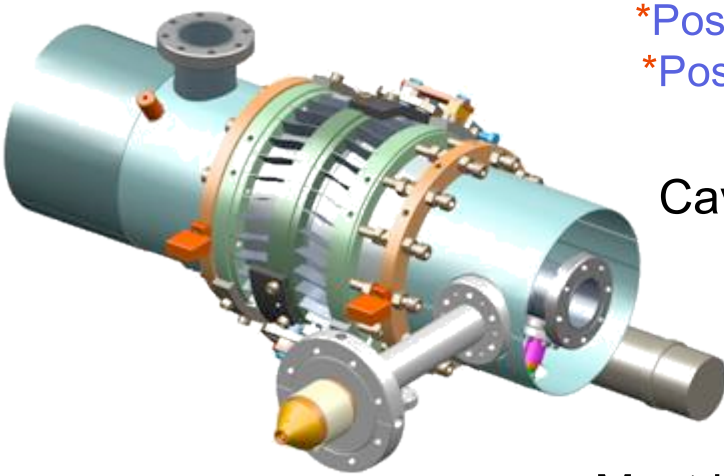
$$s=-ct\,,\quad \phi_{3.9}\sim 180\,\mathrm{deg}$$





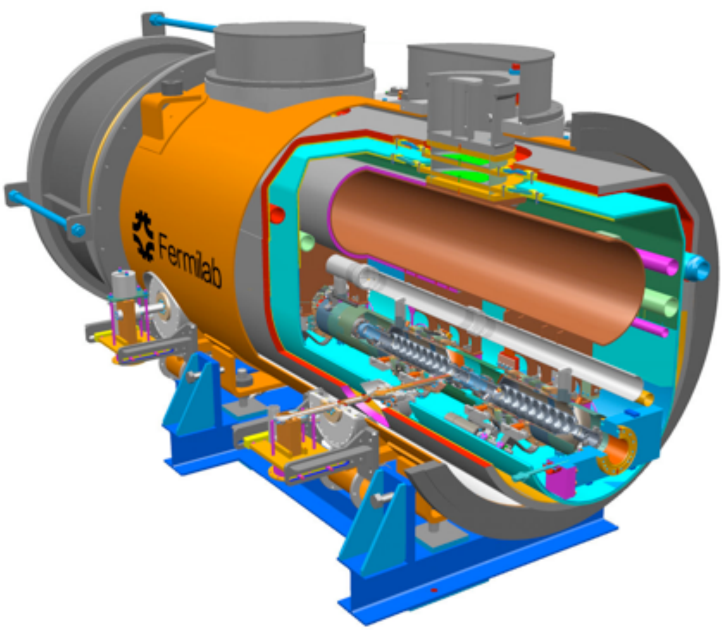
3.9 GHz Design

*Poster TUP013, Harms
*Poster TUP081, Arkan



Cavity small & delicate

Must interface to 1.3GHz
Injector module ACC1

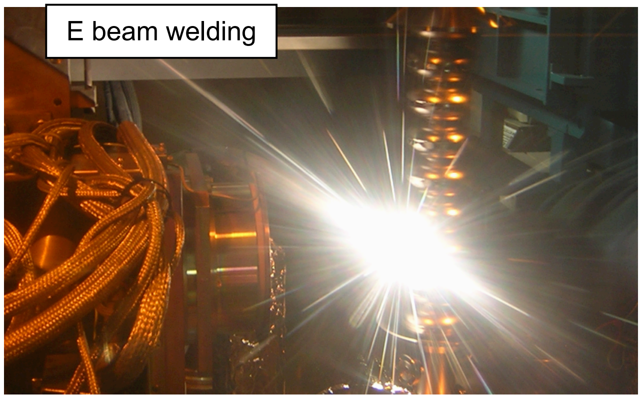


3.9 GHz Parameters

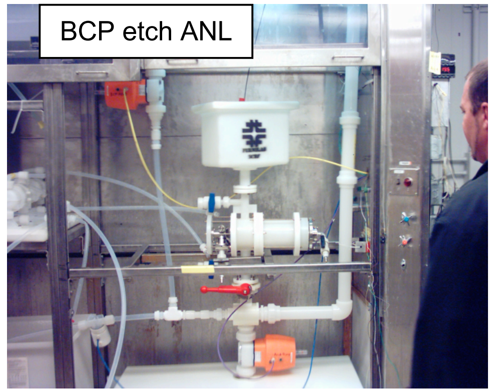
Gradient specification	(MV/m)	14
Number of cavities in module		4
Epeak/Eacc		2.26
Bpeak/Eacc	(mT/MV/m)	4.86
G1 (=RsQ)	(ohm)	275
Active cavity length	(m)	0.346
R/Q	(ohm)	750
Module length beamvalve to bv	(m)	2.535

Fabrication, Test & Assembly steps

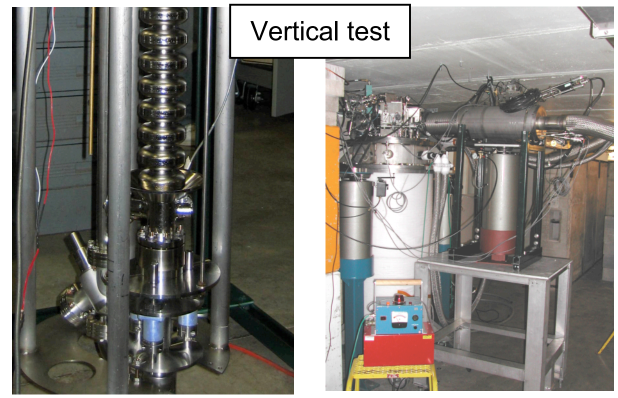
a learning experience



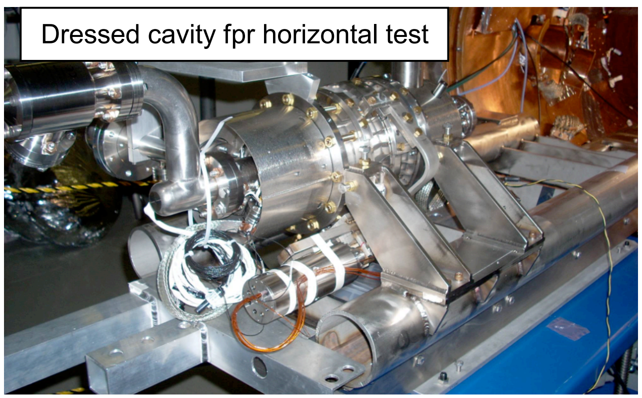
E beam welding



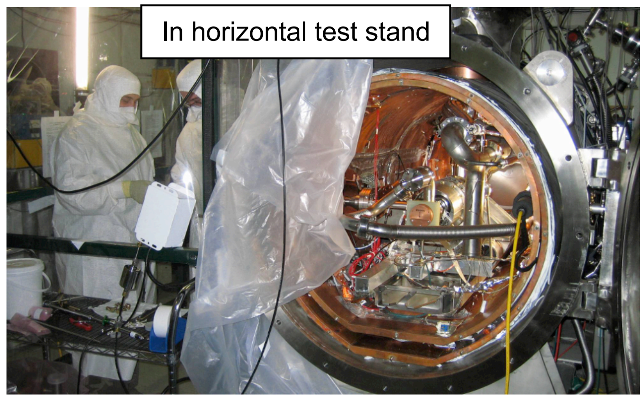
BCP etch ANL



Vertical test



Dressed cavity fpr horizontal test



In horizontal test stand

String assembly consultation with DESY

String assembly complete

DESY inspecting string

Preparing for mounting to cold mass

a learning experience, continues

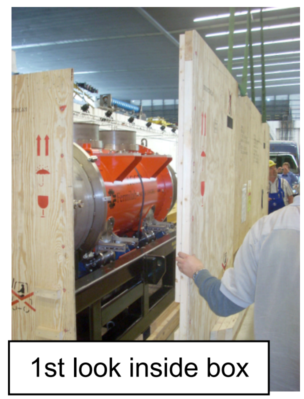
Mounting to the cold mass

Mounting into vacuum vessel

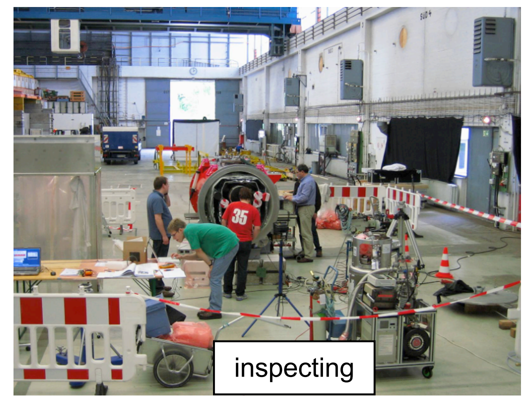
On shipping frame

To Paris

To DESY

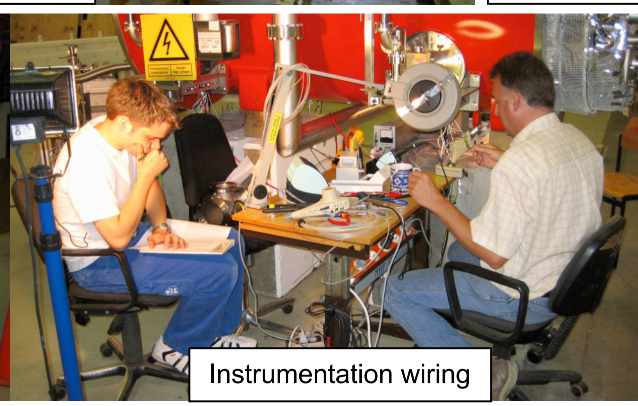


1st look inside box

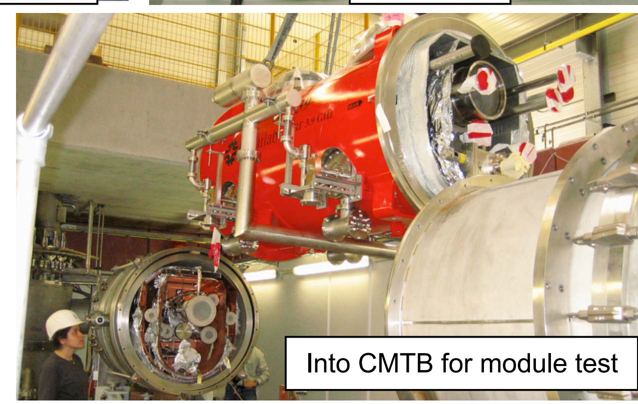


inspecting

Redoing longitudinal string location

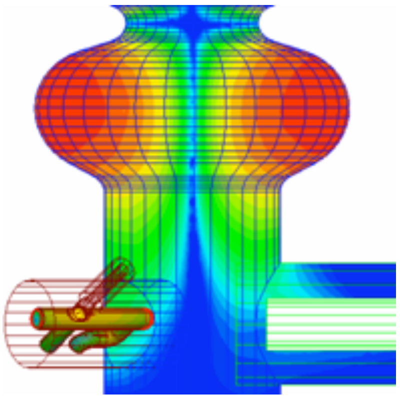


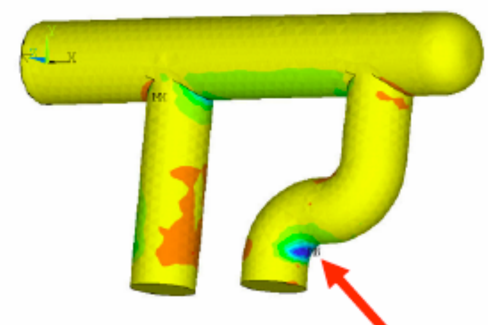
Instrumentation wiring



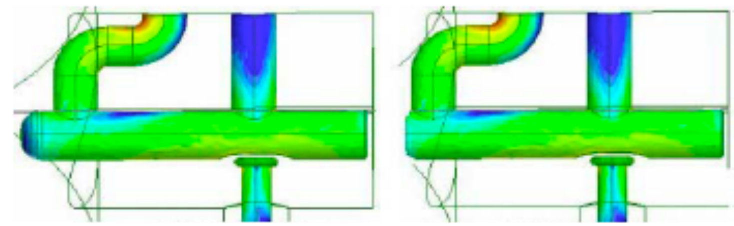
Into CMTB for module test

HOM coupler technical problem

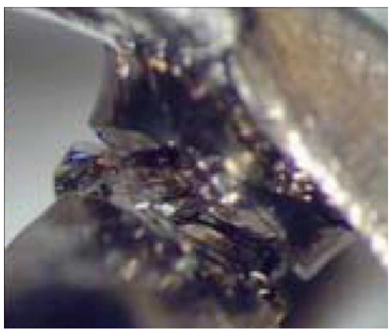




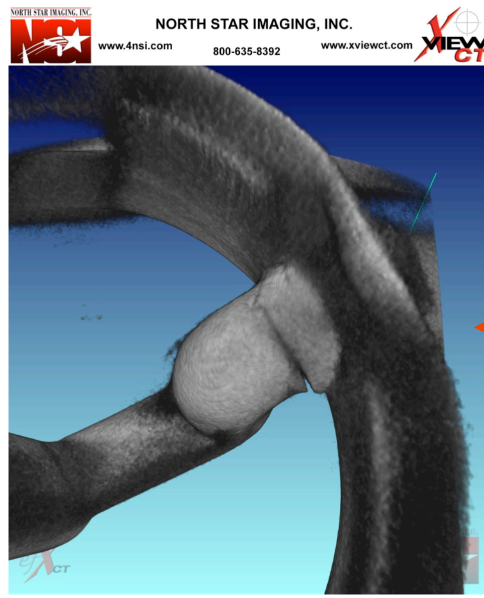
FEA Compression stress

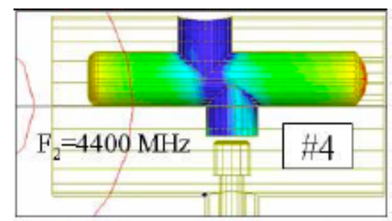


Original 2 post design, Trimmed modification (B fields)



Fracture during vertical testing

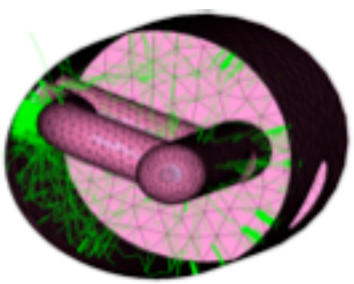




New 1 post design

Finally a way of seeing what is going on!
3D Xray tomography
A powerful tool
4 NorthStar Imaging, INC.
*Poster TUP013, Harms

Multipacting simulation



Two cavities with trimmed 2 post (a worry)

Two cavities with new 1 post

3.9 cavity gradient

- Not a complete scale model of 1.3GHz
  - Ends had to have larger beam pipes for sufficient input coupler coupling
  - HOM couplers very small
- Design gradient 14MV/m
  - Seems low- why?
- RF surface resistance
  - Leading to "global thermal" instability
  - R_{BCS} 9 times higher for 3.9 than 1.3

$$R_s = R_{BCS} + R_{residual}$$

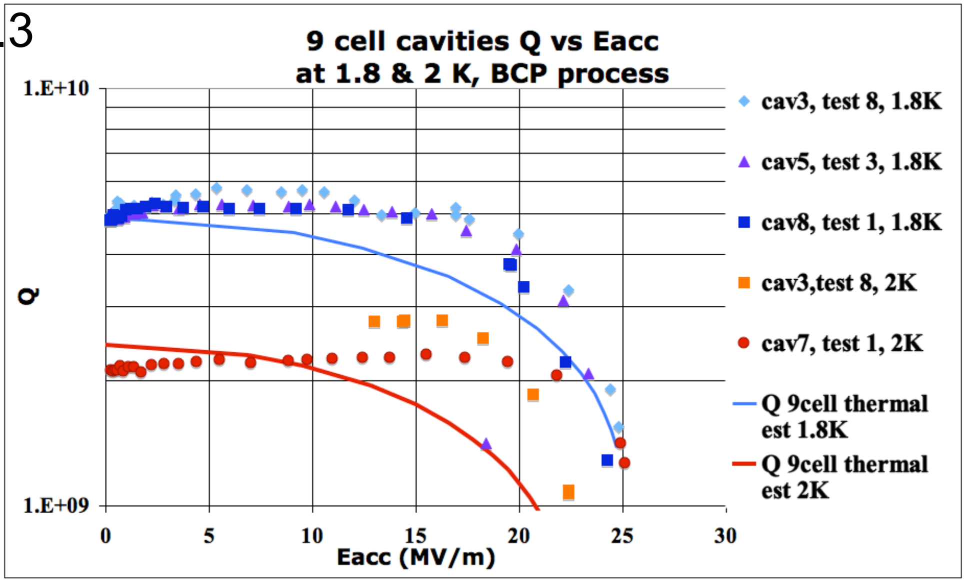
$$R_{BCS} \propto f^2 \frac{1}{T} \exp\left(\frac{-17.7}{T}\right)$$

$$R_{residual} \propto \sqrt{f} \quad from\ external\ B\ field$$

$$Power \propto Rs \int B_{RF}^2 ds$$

Simple model using thermal conductivity and Kapitza conductance can estimate the ΔT from helium to RF surface and Q vs E.
It doesn't work very well, which is interesting in itself.

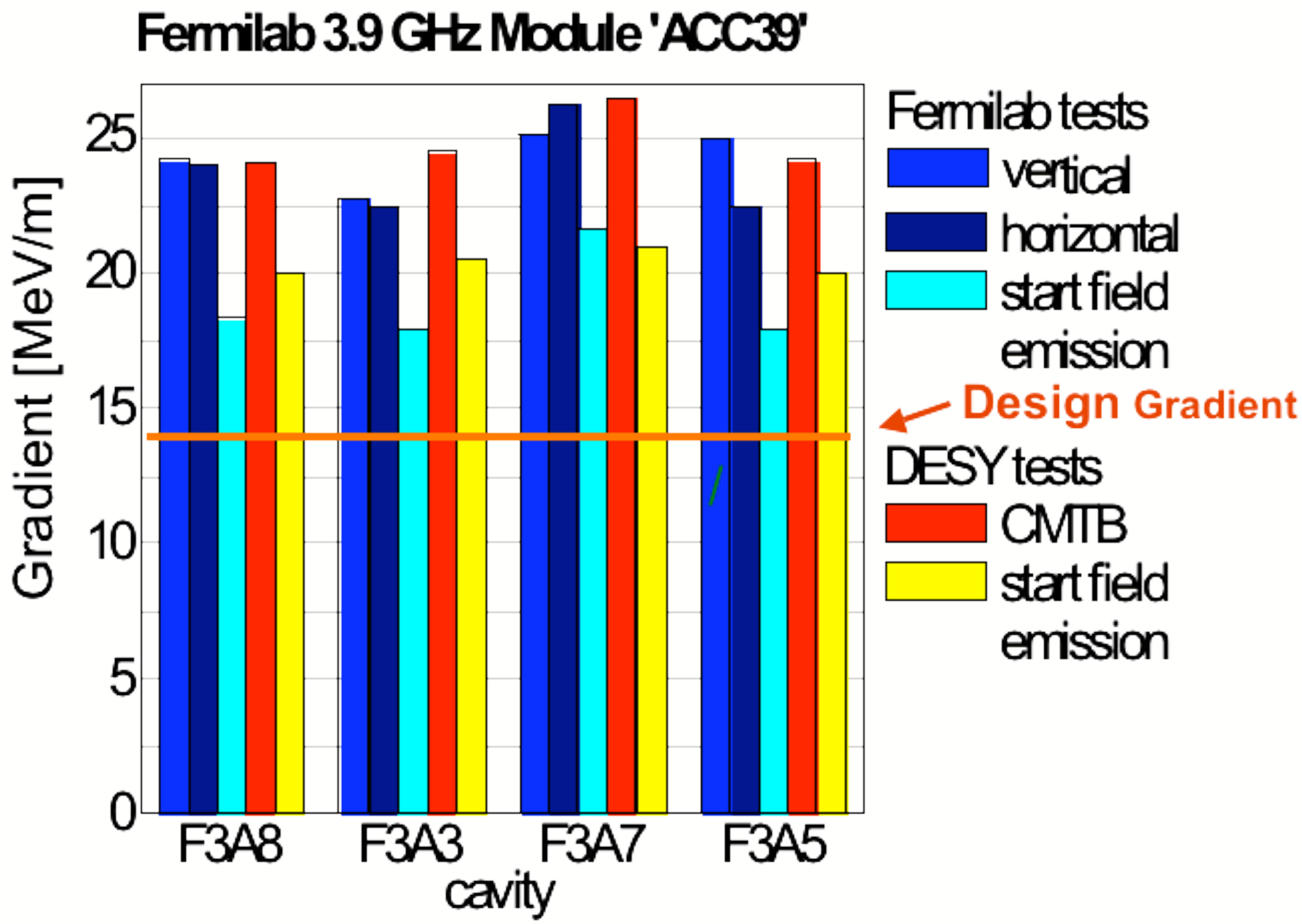
Gradients of 20-25 MV/m achieved in vertical tests



Cavity gradient test history
FNAL vertical test to DESY module test

Comparable and consistent results

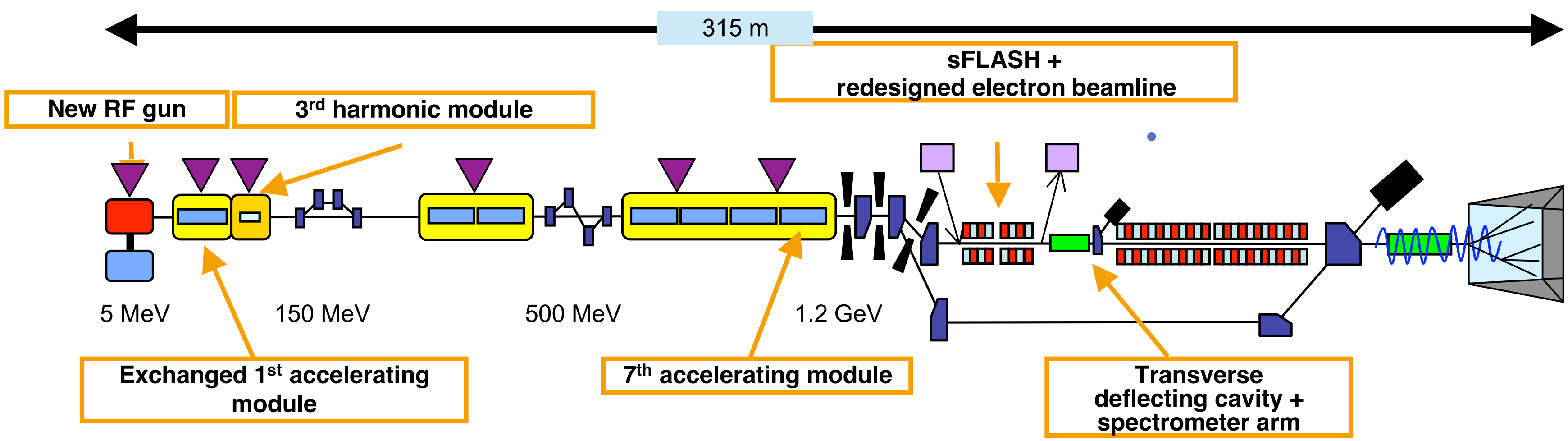
Above design goal



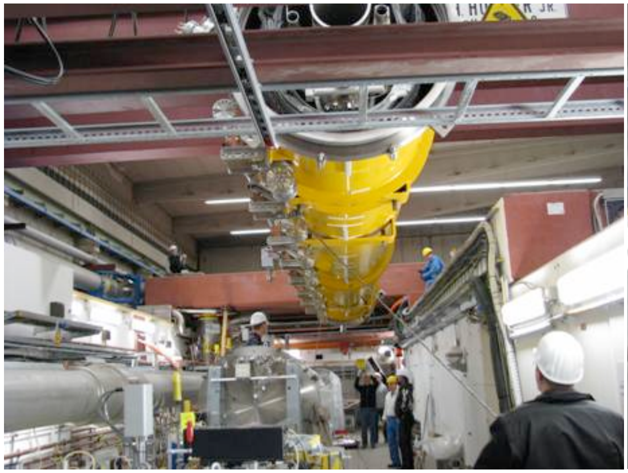
The recent FLASH upgrade

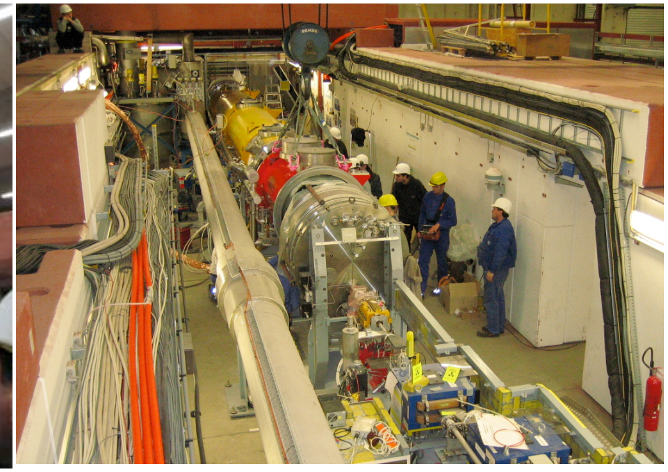
- New injector gun with lower dark current
- 2 new 1.3 GHz modules, ACC1 rebuilt, ACC7 XFEL prototype
- The 3.9 GHz module
- New transverse deflecting cavity diagnostic system using LOLA, in new location
- The sFlash experiment for high harmonic generation (HHG) laser seeding and a new undulator section

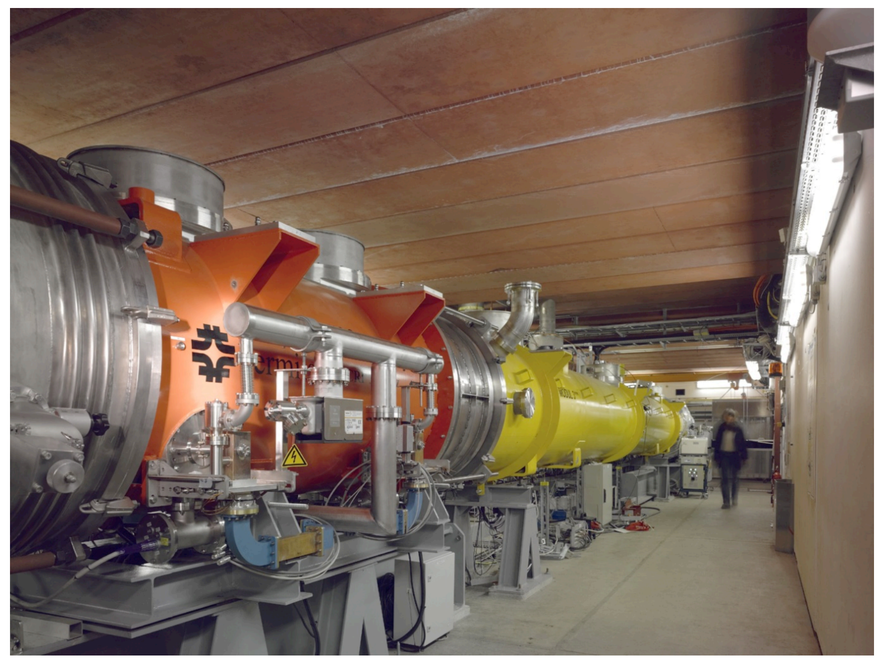
  *Oral Poster TUPO12, J. Boedewadt



Mounting of accelerating modules in injector, ACC1, ACC39

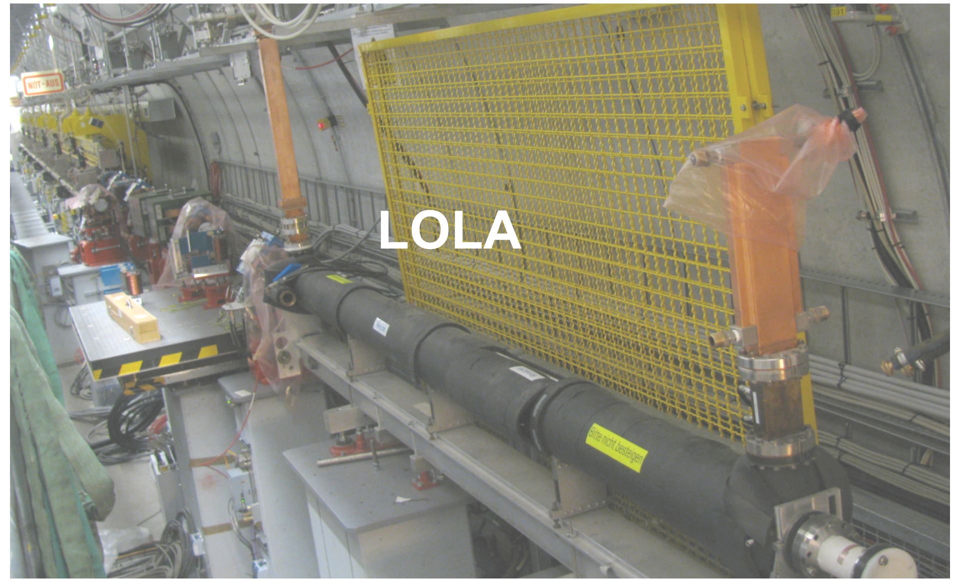


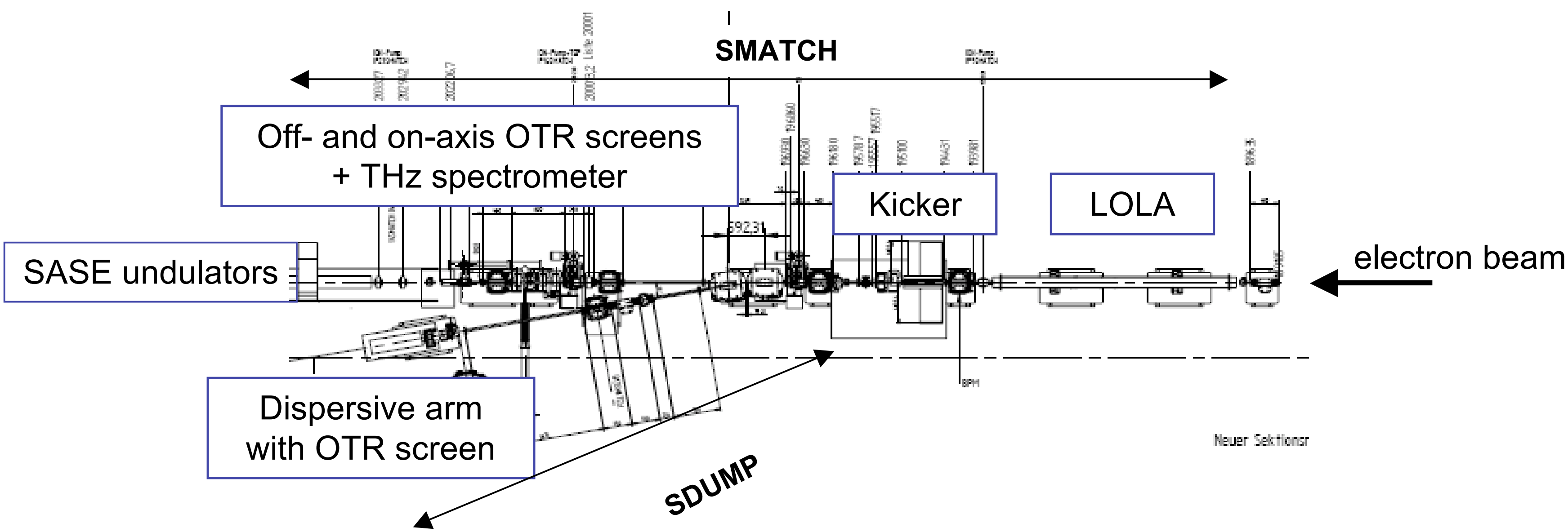




Transverse deflecting cavity LOLA

- Longitudinal bunch structure
  - LOLA is moved to a new location just upstream of the SASE undulators
  - time resolution 20 fs
  - energy resolution 1.4 10^{-4}
- Kicker and off-axis screen
  - on-line beam diagnostics, arbitrary pulse in the train can be picked
- New installation includes a dispersive arm





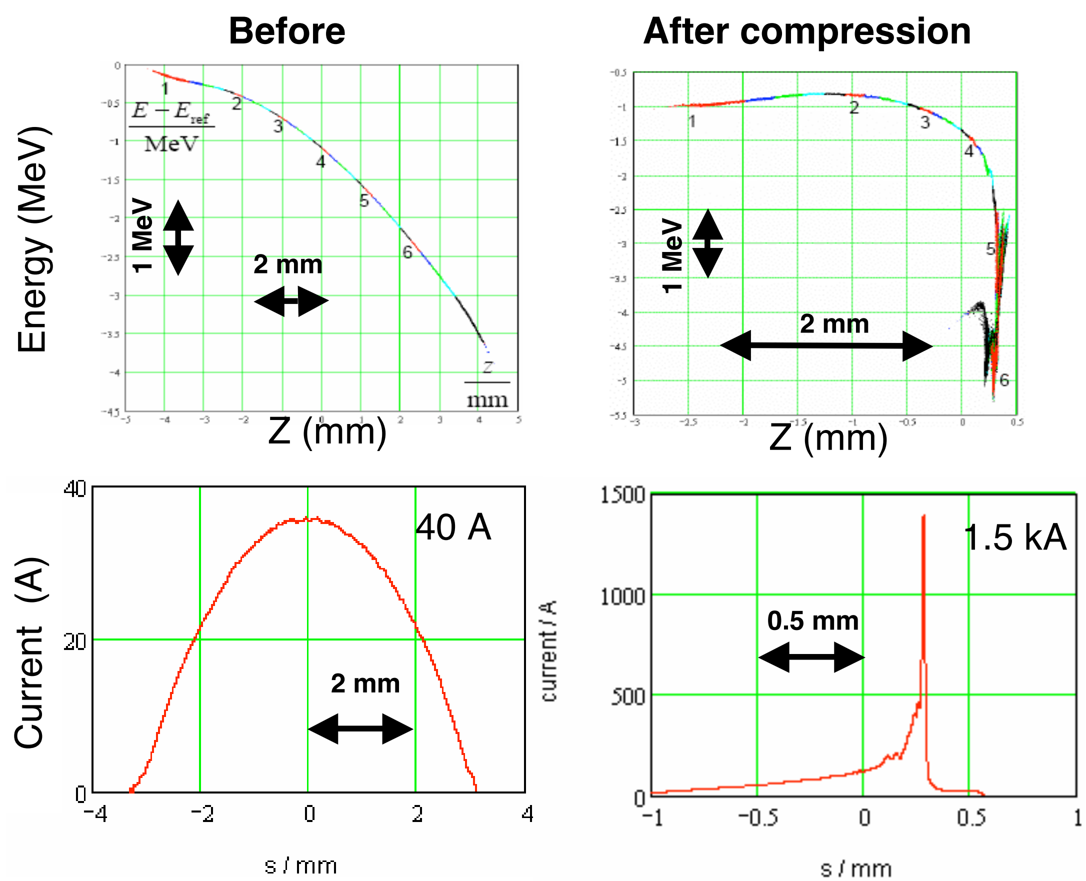
Compression concepts-changing ideas

- “Roll-over” based on just use of fundamental frequency (1.3 GHz) to provide chirp for compression in magnetic chicanes
  - Realization that the slice energy spread is very small and that only a small part of the beam is suitable for lasing
  - Inefficient and Unstable condition
- “Linear” use an rf harmonic (3.9) to cancel 1.3 nonlinearity
  - Stand the beam upright with compression and get very high current short pulse
  - May have space charge and CSR problems
  - May go beyond saturation, inefficient use of charge
  - May want to cut down the bunch charge
- “Linear” with “long” bunch. Don’t compress so much
  - Efficient use of charge
  - Reduced S.C and CSR
  - Users may not want long pulse
- “Linear” with long pulse for sFLASH- uniform bunch current over a window
  - Account for possible arrival time jitter electron bunches and seed laser
  - Needs to have constant current over the bunch

We will see what is possible

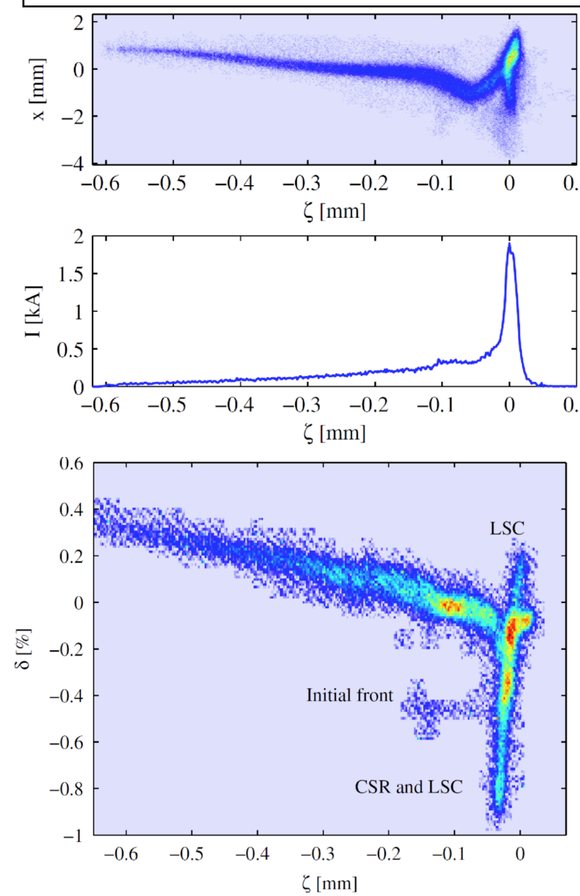
Compression Scheme w/o 3rd Harmonic Cavities, Roll-over

- Non-linearity in the longitudinal phase space leads to a roll-over compression → development of a sharp spike ~ 50 fs fwhh with high peak current



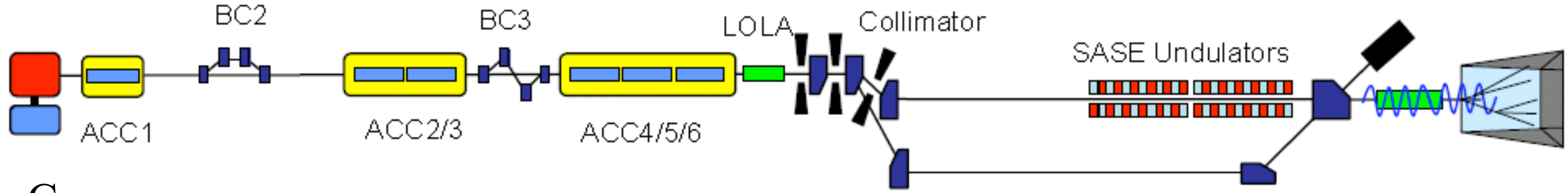
Schreiber

Measurement & reconstruction
M. Roehrs



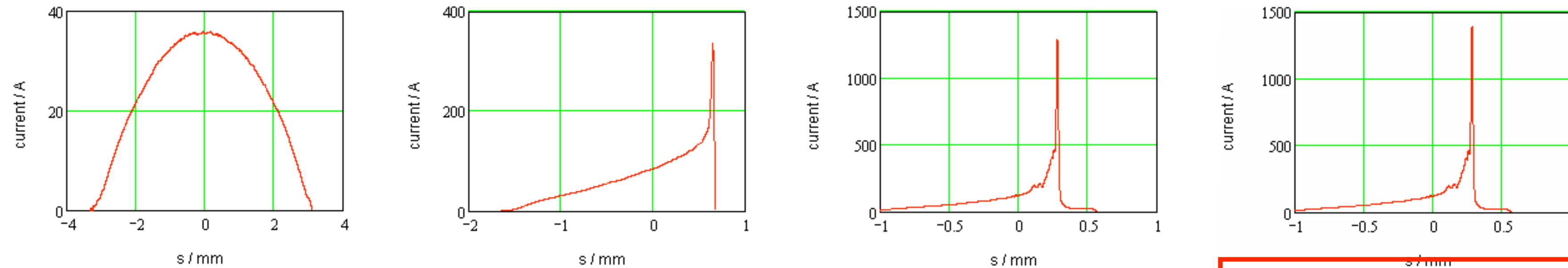
FLASH I before and after upgrade
rollover compression vs. linearized compression

M. Dohlus & I. Zagorodnov

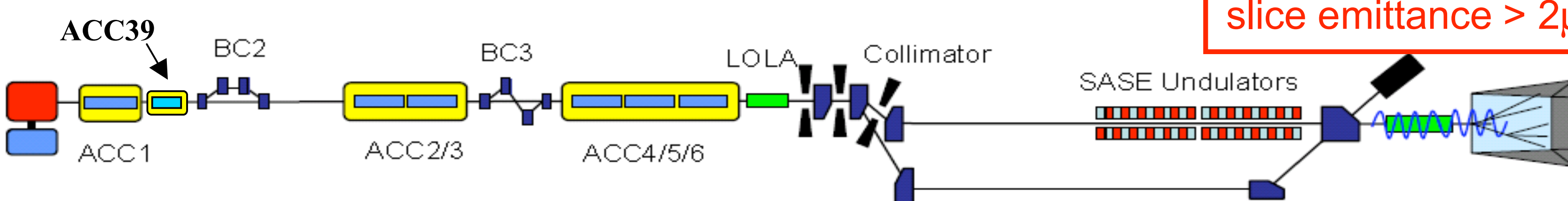


Q=0.5 nC

~ 1.5 kA

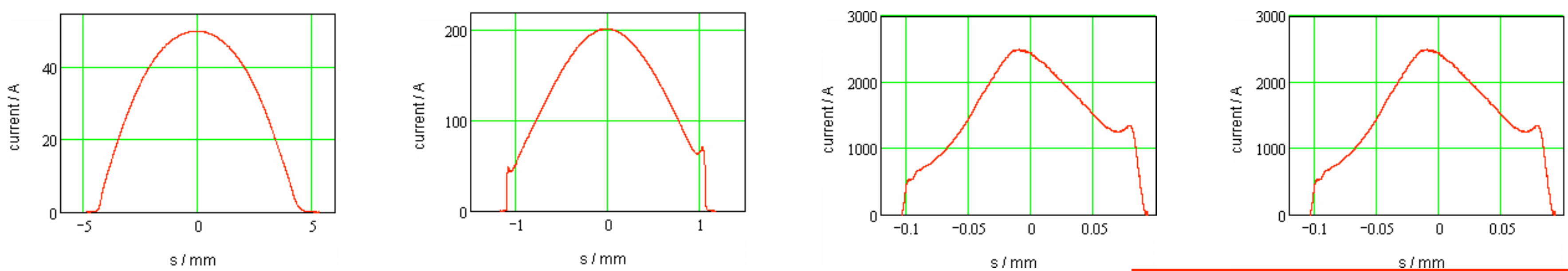


slice emittance > 2μm



Q=1 nC

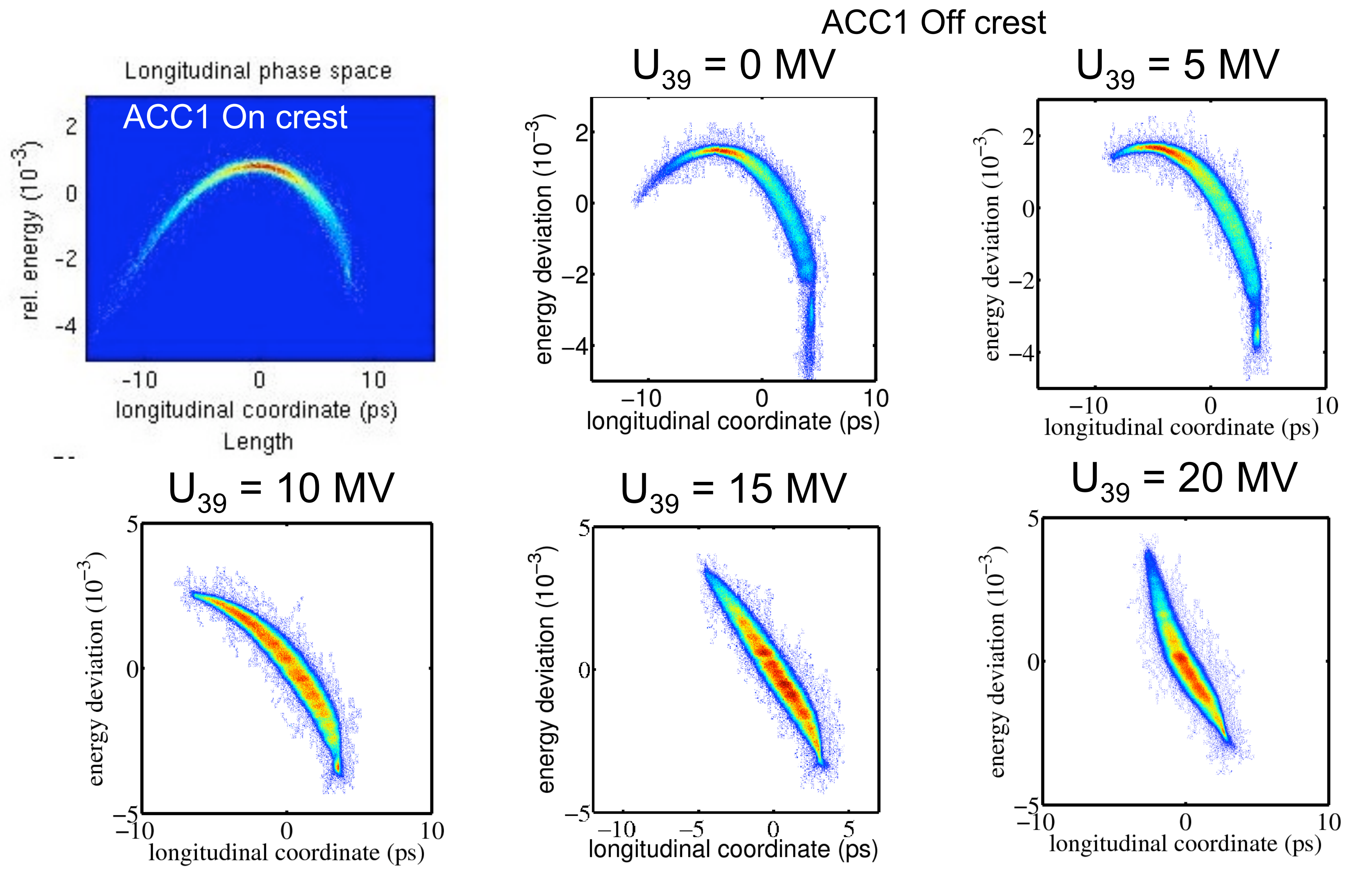
~2.5 kA



slice emittance ~ 0.3 - 1μm

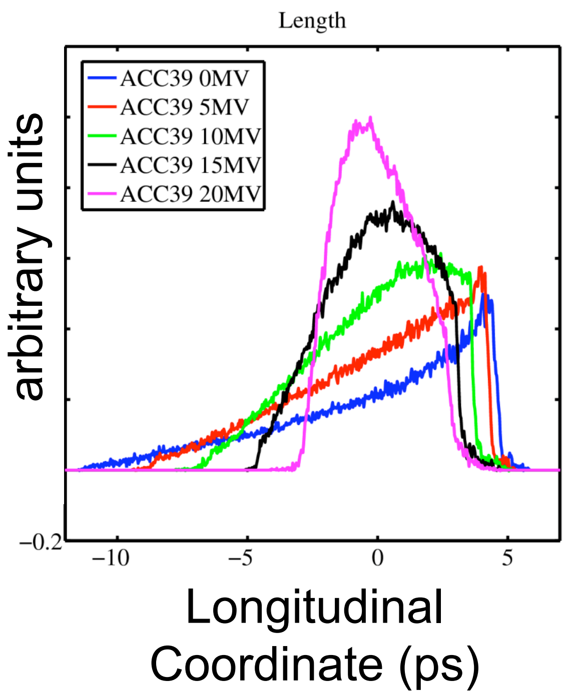
Linearization of the longitudinal phase space

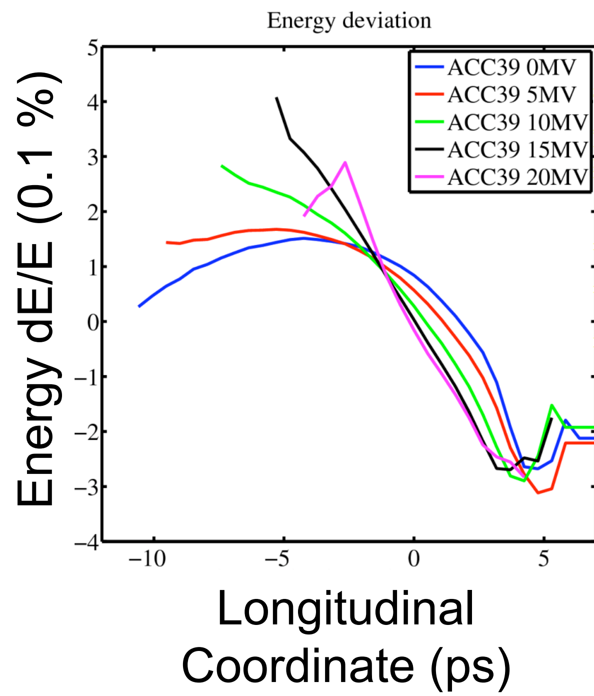
- 1st module (ACC1) set to moderate compression (~6deg off crest)
- Bunch shape measured for increasing voltage in the 3rd harmonic cavities



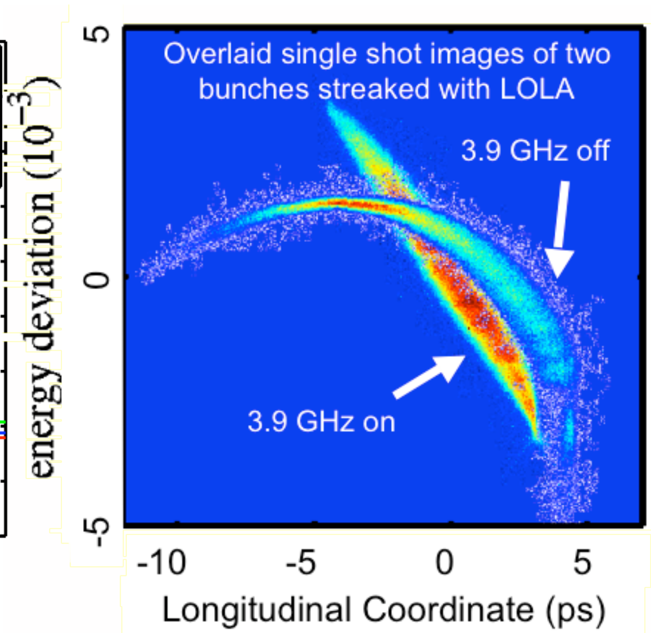
Longitudinal Bunch Shape

- Bunch shape for slight compression with first accelerating module (ACC1)
  - measured with LOLA dispersive section at 700 MeV
- For different fields applied to the 3.9 GHz cavities (ACC39)





Off/On



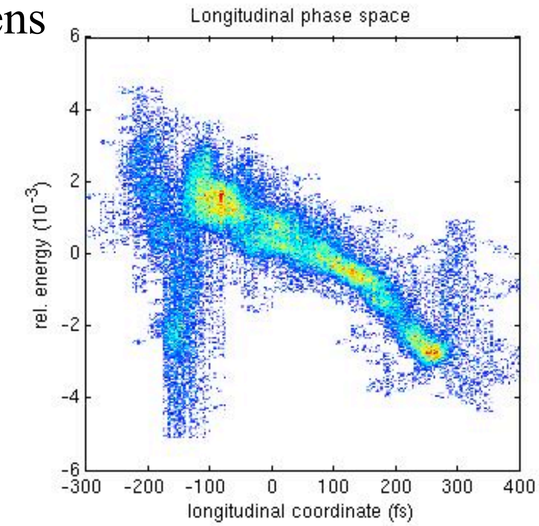
Behrens, Gerth: Measurement of Sliced-Bunch Parameters at FLASH

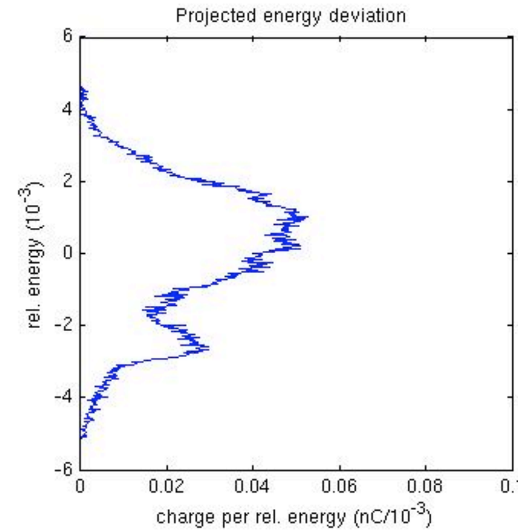
S. Schreiber

First experimental results for low charges at FLASH

acknowledgments to Ch. Behrens

Q=0.2 nC





strong compression at the bunch head

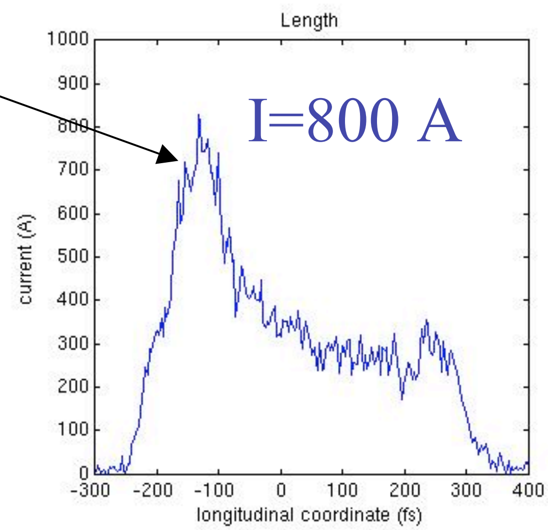
⇩

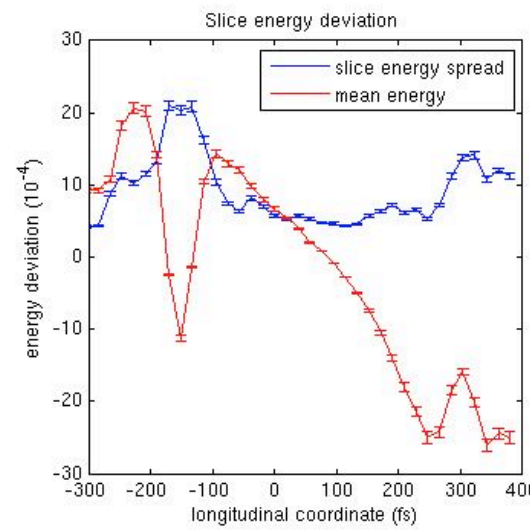
we need

$$Z_2'' > 0$$

⇩

increase third harmonic voltage or reduce BC2 energy



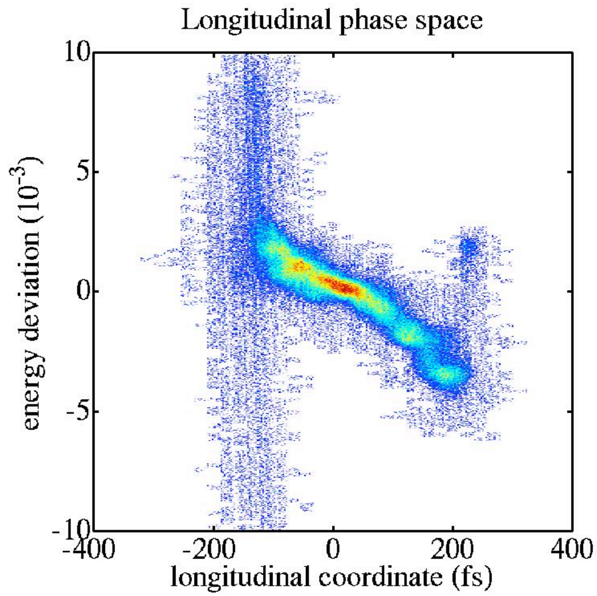


I. Zagorodnov FEL'10

First experimental results for low charges at FLASH

acknowledgments to Ch. Behrens

Q=0.4 nC



strong compression at the bunch head

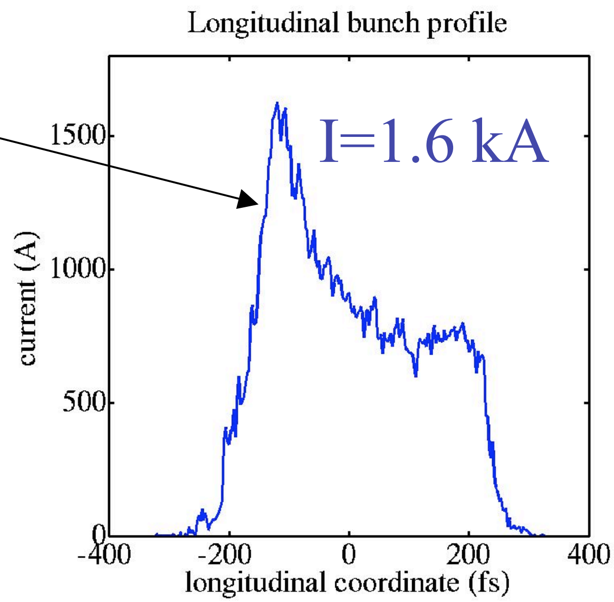
⇩

we need

$Z_2'' > 0$

⇩

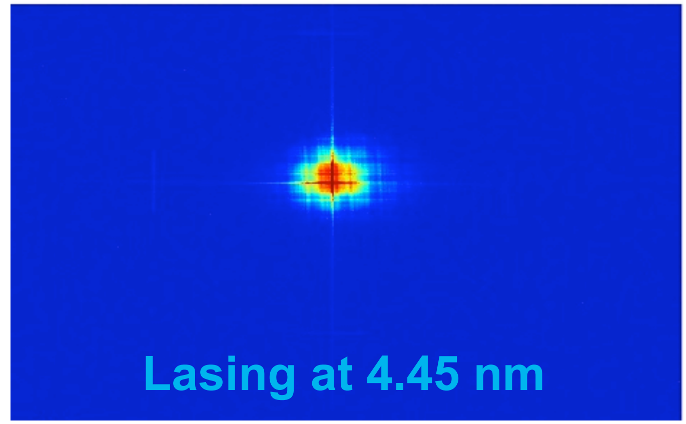
increase third harmonic voltage or reduce BC2 energy

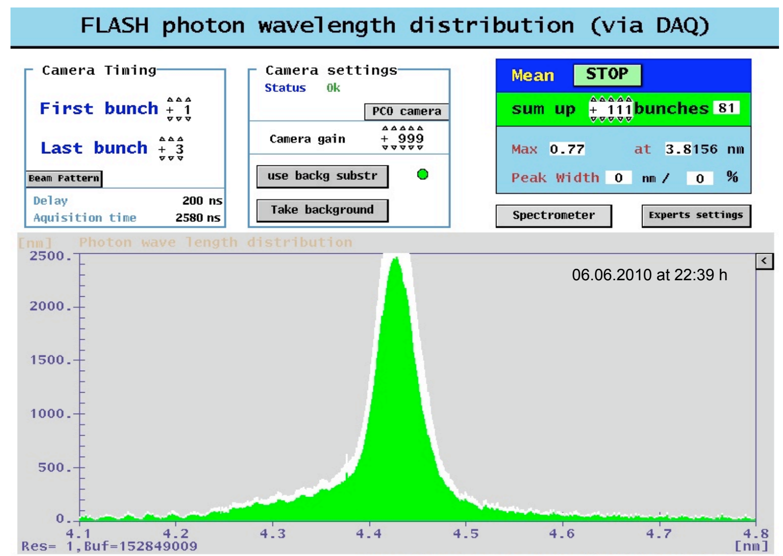


I. Zagorodnov FEL'10

Commissioning Results

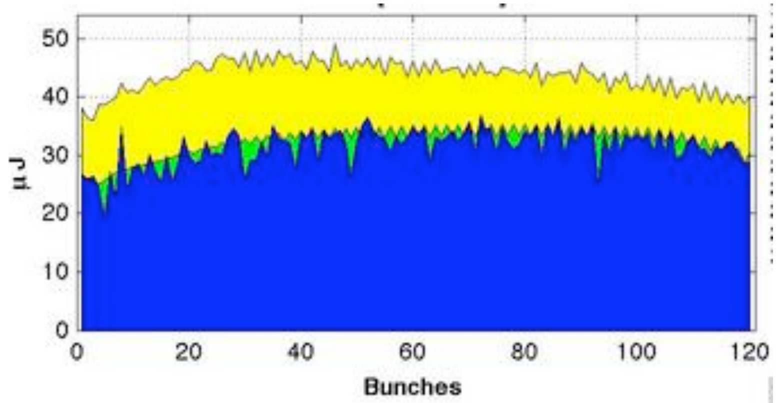
- Lasing at 4.45 nm, 1.2 GeV beam, linear compression
  - Photon bunch energies above 100µJ
  - Average 75 µJ
- Lasing at a variety of λ~ 13, 19, 26 nm
  - Average photon energies achieved above 200 µJ at 13 and 19 nm
  - Maximum photon pulse energy as high as 270 µJ at 19 nm
- Lasing with bunch charges from 0.1 to 1 nC
- Lasing of bunch trains of 130 bunches at 10 Hz
- Investigation of 2nd, 3rd, 5th harmonics





Schreiber

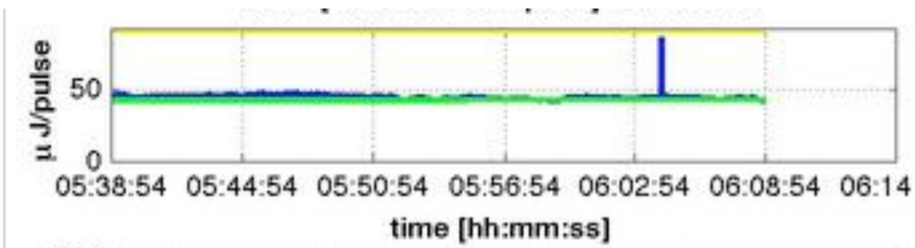
Very stable photon bunch energy observed



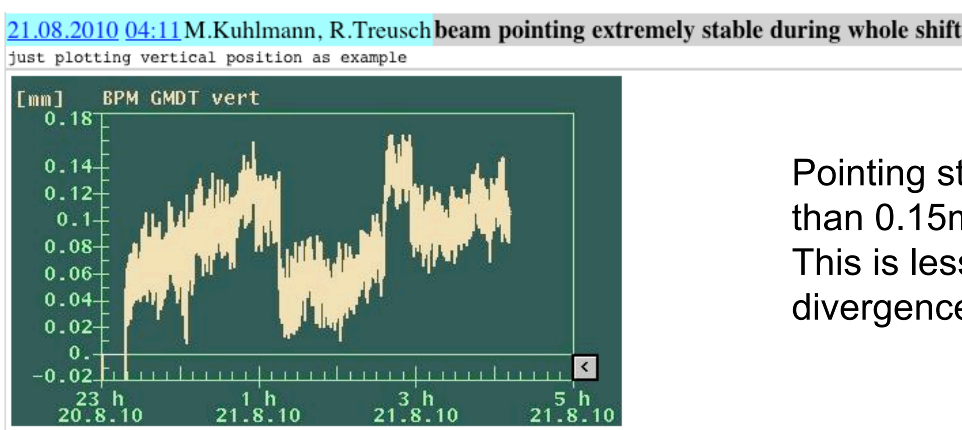
120 bunches

Radiation pulse energies are significantly larger and easier to tune compared to roll-over compression
S. Schreiber FEL'10

Reassuring that so far does not show any HOM resonant dipole mode buildup.



10 bunches over 1/2 hour
Whole shift very stable



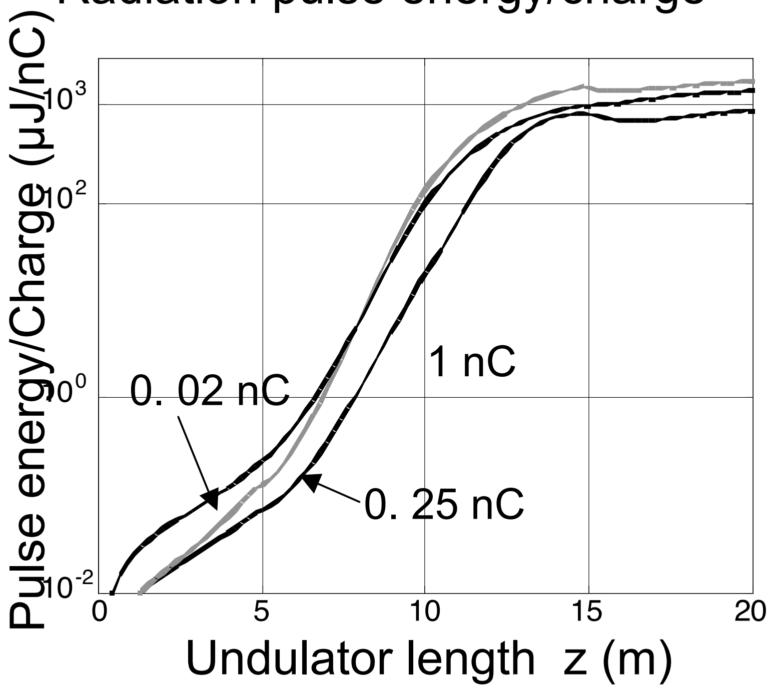
Pointing stability over 5 hr better than 0.15mm or 5microrad
This is less than 10% of beam divergence R Treusch

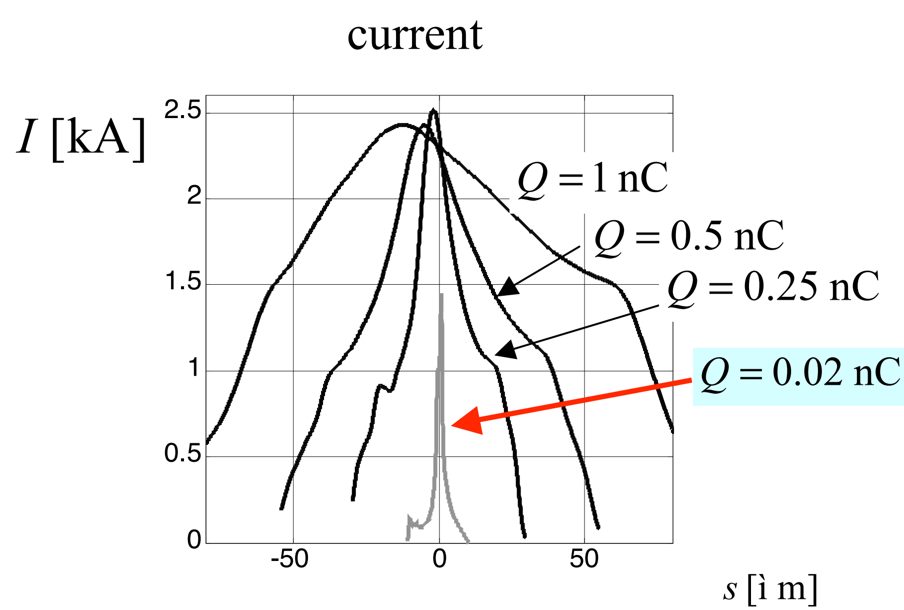
Expected photon energy and pulse length

- Regular compression scheme with 3rd harmonic cavities, charge 1 nC
  → larger energy 1-1.5 mJ
  → photon pulse lengths ~30 fs rms

- Compression with lower bunch charge
  → charge from 0.02 to 1 nC
  → variable pulse length in the range of ~ 1 and 30 fs (rms)

Radiation pulse energy/charge

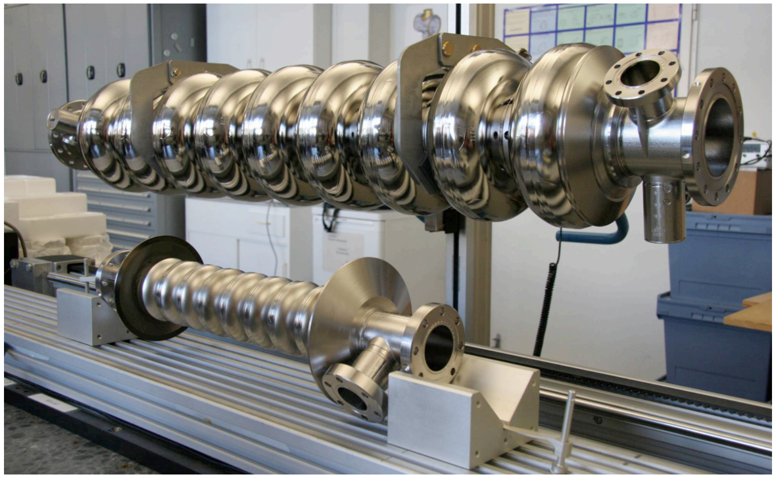




Igor Zagorodnov, FEL'10

WEOBI2 Ultra-Short Low Charge Operation at FLASH and the European XFEL

3.9 future - XFEL



1.3

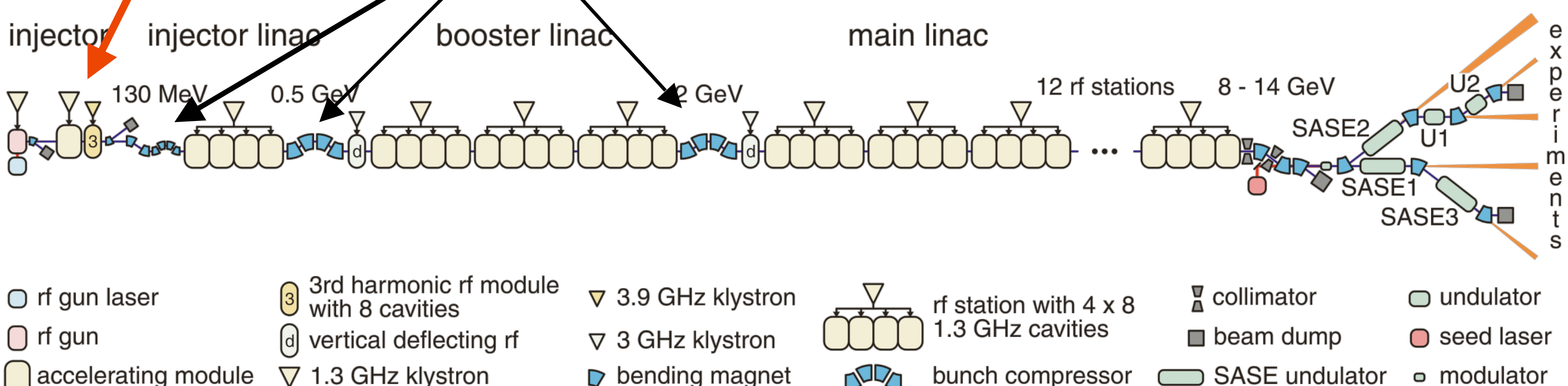
3.9

INFN Milano will provide a module
First cavities to be tested this fall

8 cavity 3.9 GHz module

3 compressors

How to tune, I. Zagorodnov, FEL'10



vogel

Conclusions

- The 3.9 module operational and used all the time. 3.9 module is working well (so far so good)
- Qualitatively SASE operation has been improved
- Still need to investigate potential HOM problems with higher beam current- See *THP011, P. Zhang
- DESY-FNAL Collaboration has been very successful - excellent working together
- Important support from JLab and ANL
- Excellent learning experience for FNAL

The DESY- FNAL 3.9 team

- Many people at Fermilab worked on the 3.9 module. They should be proud
- Many people at DESY also worked to make this successful. It was truly a one team effort (Desy & FNAL)
  - Unfortunately I do not have a DESY team picture

- Thanks to people at DESY for help with material for this talk: C. Behrens, S. Schreiber, I. Zagorodnov, E. Vogel, B. Faatz, R. Treusch

The Fermilab Team