FLASH Progress Report

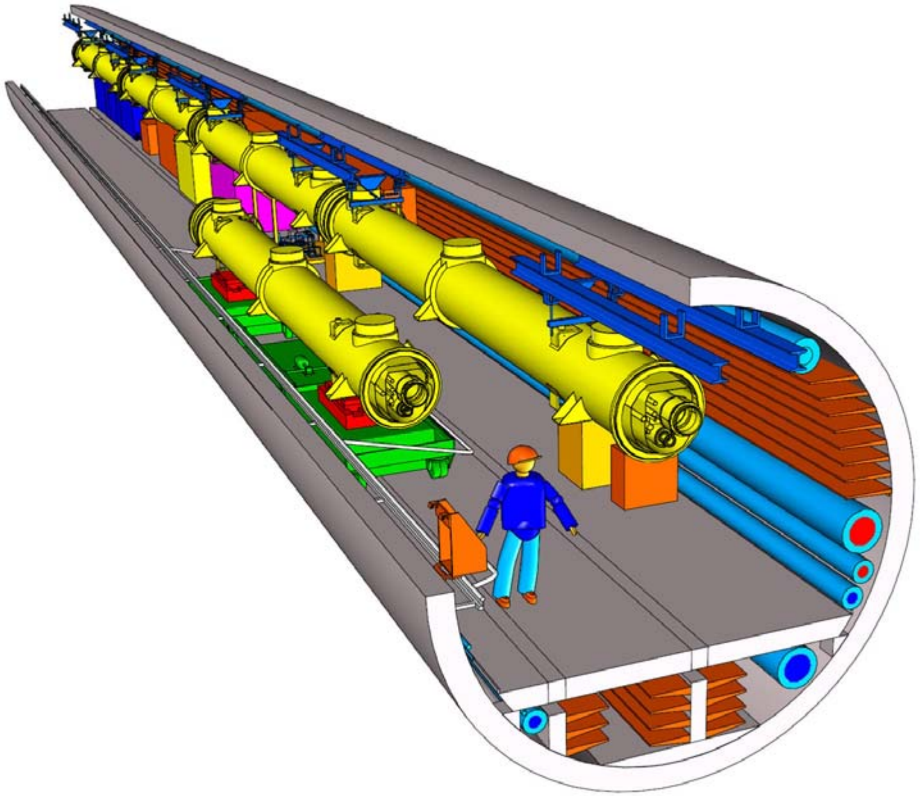
Elmar Vogel
for all colleagues contributing to FLASH

13th International Workshop on
RF Superconductivity,
Peking University, Beijing, China 2007

FLASH - the free electron laser in Hamburg

- user facility
  enabling time exposures in the fs-scale of biological, chemical and physical processes
- test bed for XFEL and ILC

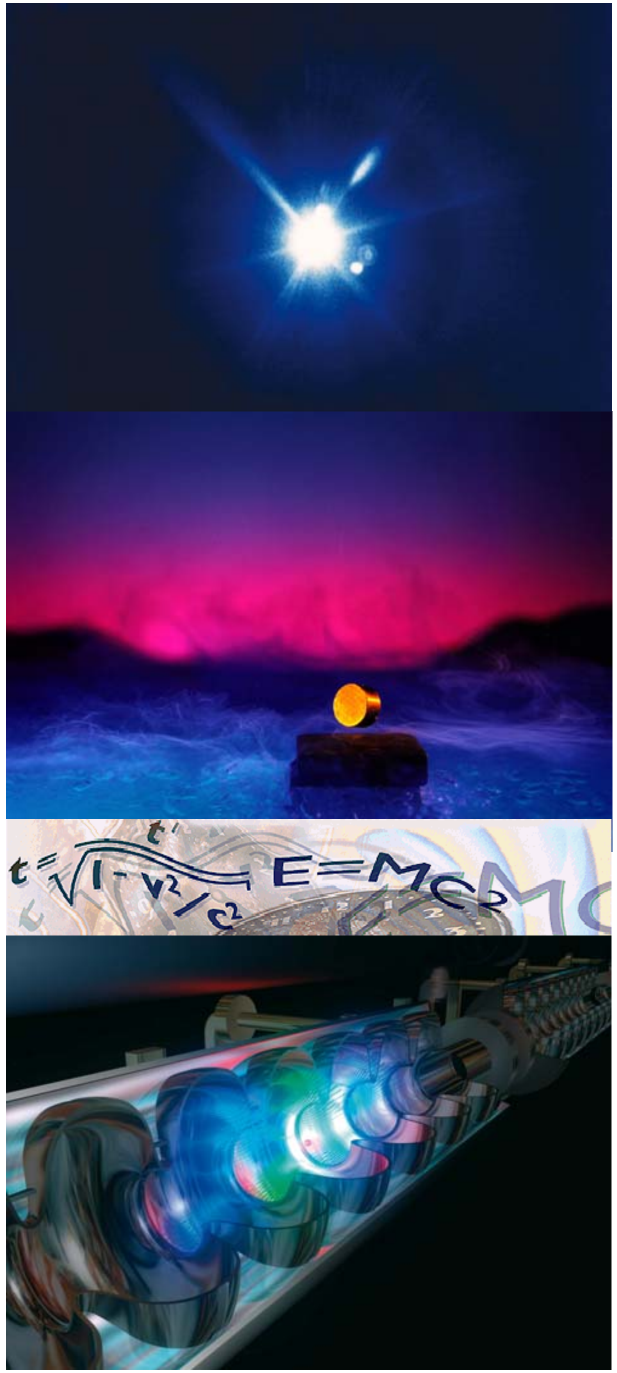
FLASH experiment



XFEL cold linac tunnel

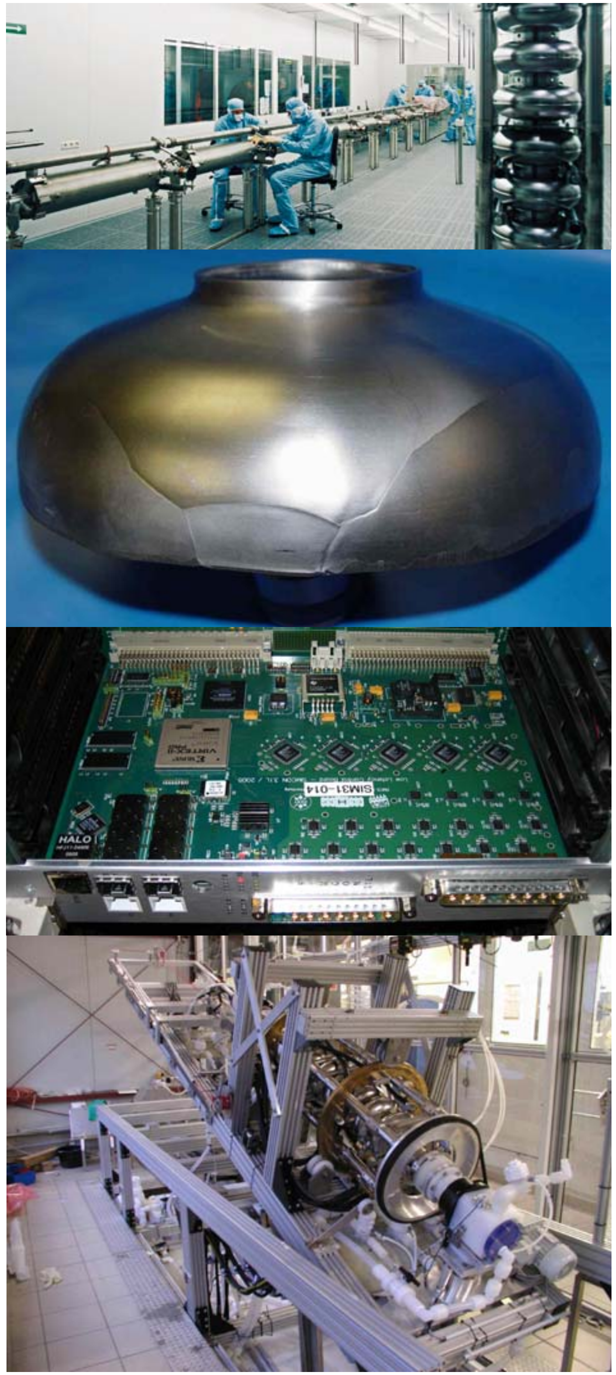
A bundle of modern physics applications

- theory of photon emission for SASE
- superconductivity for accelerating cavities
- superfluity for heat transport
- electrodynamics for particle acceleration
- inclusive special relativity theory within beam dynamics
- laser active crystals for beam creation and diagnostics
- and so on …



… and a bundle of (high) technology

- metallurgy and crystallography
- welding engineering
- (chemical) surface treatments
- clean room techniques and process engineering
- large scale cryogenics for 2 Kelvin operation
- ultra high vacuum (see K. Zapfe WEP74)
- digital electronics for beam diagnostics and control
- control engineering for digital control algorithms
- piezo actuator techniques for cavity tuning
- high power rf klystrons
- and so on …



… requires a lot of experts from different fields

K. Zapfe, I. Zagorodnov, M.V. Yurkov, P. Yeates, W. Wurth, K. Wittenburg, A. Winter, I. Will, M. Wendt, M. Wellhöfer, H. Weise, T. Weiland, E. Vogel, I. Tsakov, D. Trines, R. Treusch, S. Toleikis, M. Tischer, K. Tiedtke, H. Thom, F. Stulle, F. Stephan, B. Steffen, L. Staykov, R. Spesyvtsev Pirro, P. Spanknebel, A.A. Sorokin, E. Sombrowski, S. Simrock, C. Simon, A.V. Shabunov, D. Sertore, M. Seidel, S. Schreiber, S. Schnepp, E.A. Schneidmiller, J.R. Schneider, P. Schmüser, M. Schmitz, B. Schmidt, H. Schlarb, W. Sandner, E.L. Saldin, M. Sachwitz, V. Rybnikov, J. Rossbach, M. Ross, R. Romaniuk, J. Roensch, M. Roehrs, M. Richter, K. Rehlich, H. Redlin, P. Radcliffe, P. Pucyk, D. Proch, E. Prat, K. Pozniak, L. Poletto, E. Plönjes, J. Pflüger, B. Petrosyan, G. Petrosyan, L. Petrosyan, B. Petersen, J. Pedregosa-Gutierrez, N. Pchalek, R. Paparella, C. Pagani, A. Oppelt, T. Nuñez, D. Nölle, P. Nicolosi, O. Napoly, O. Napieralski, W.F.O. Müller, L. Monaco, W.D. Möller, V. Miltchev, P. Michelato, M. Meyer, M. Martins, M. Luong, H. Luna, F. Löhl, D. Lipka, T. Limberg, L. Lilje, C.L.S. Lewis, M. Kuhlmann, G. Kube, M. Krassilnikov, D. Kostin, M. Körfer, S. Korepanov, W. Koprek, M. Kollewe, V. Kocharyan, K. Klose, S. Khodyachykh, E.T. Kennedy, K. Kavanagh, V. Katalev, R. Kammering, T. Jezynski, W. Jalmuzna, E. Jaeschke, Y. Ivanisenko, M. Hüning, T. Hott, K. Honkavaara, J.H. Han, U. Hahn, K. Hacker, O. Grimm, M. Grecki, H.-J. Grabosch, M. Görler, N. Golubeva, Ch. Gerth, U. Gensch, T. Garvey, L. Fröhlich, J. Frisch, K. Flöttmann, J. Feldhaus, B. Faatz, H.T. Edwards, A. Eckhardt, S. Düsterer, M. Dohlus, G. Di, H. Delsim-Hashemi, A. Delserieys, W. Decking, J. Dardis, D. Cubaynes, J.T. Costello, A. Cianchi, S. Choroba, E. Chiadroni, L. Catani, P. Castro, M. Castellano, O.I. Brovko, R. Brinkmann, A. Brandt, A. Bolzmann, B. Beutner, V. Balandin, J. Bähr, N. Baboi, A. Azima, V. Ayvazyan, G. Asova and W. Ackermann

even this list is incomplete – I am sorry for that

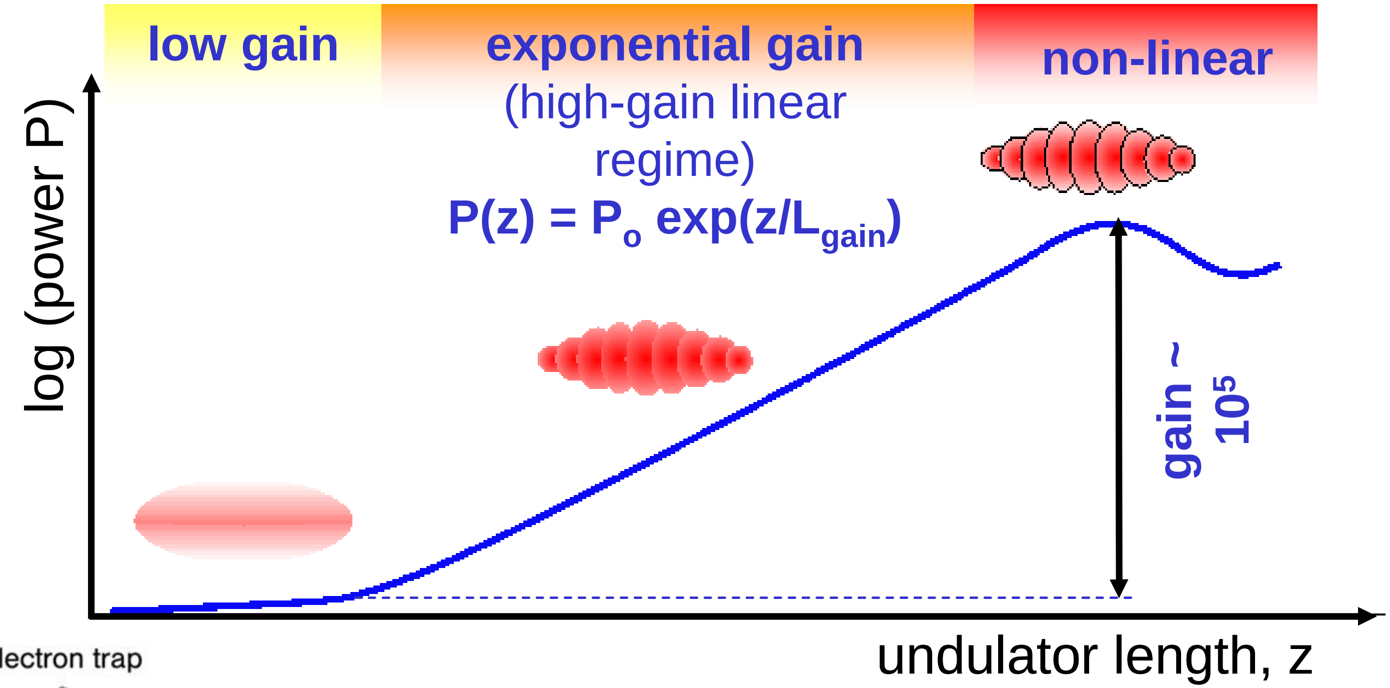
the talk can only present some issues selected by the speaker

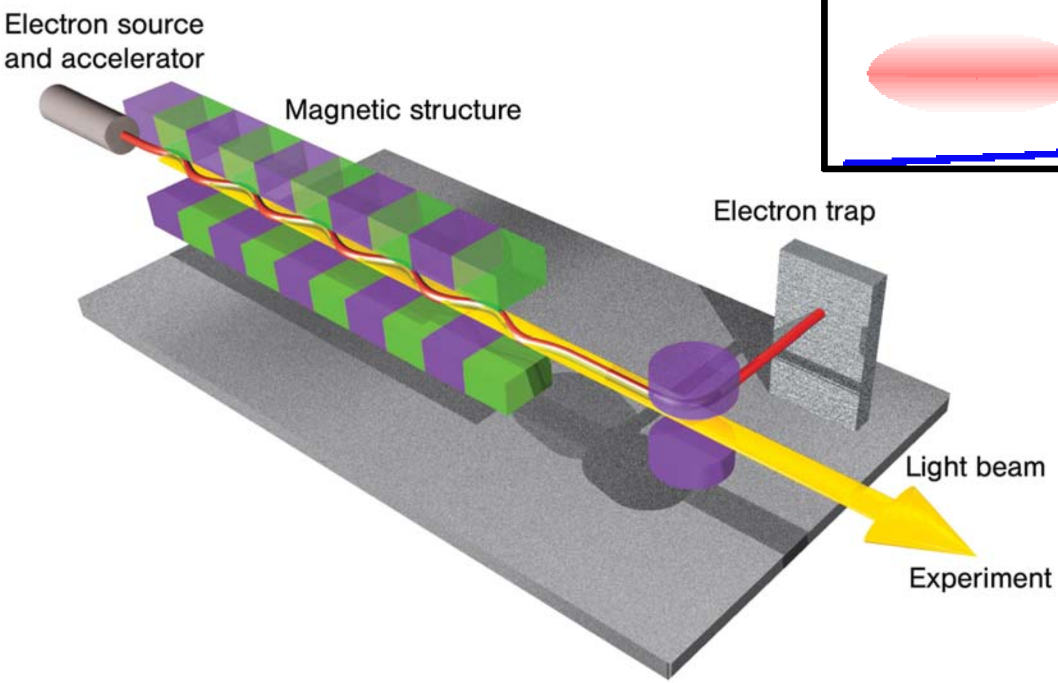
Outline of the talk

- SASE and prerequisites
- FLASH – the machine
- focus less on superconducting technology
  more **focus on improving** the **stability for operation**
- beam diagnostics gains importance
- as well as rf and beam control
- SASE performance
- Statistics
- what comes next?

Self amplified stimulated emission of photons

- bunch interacts with undulator field
- micro bunches develop
- micro bunches emit coherently ~ N^2 ($N \approx 10^6$)

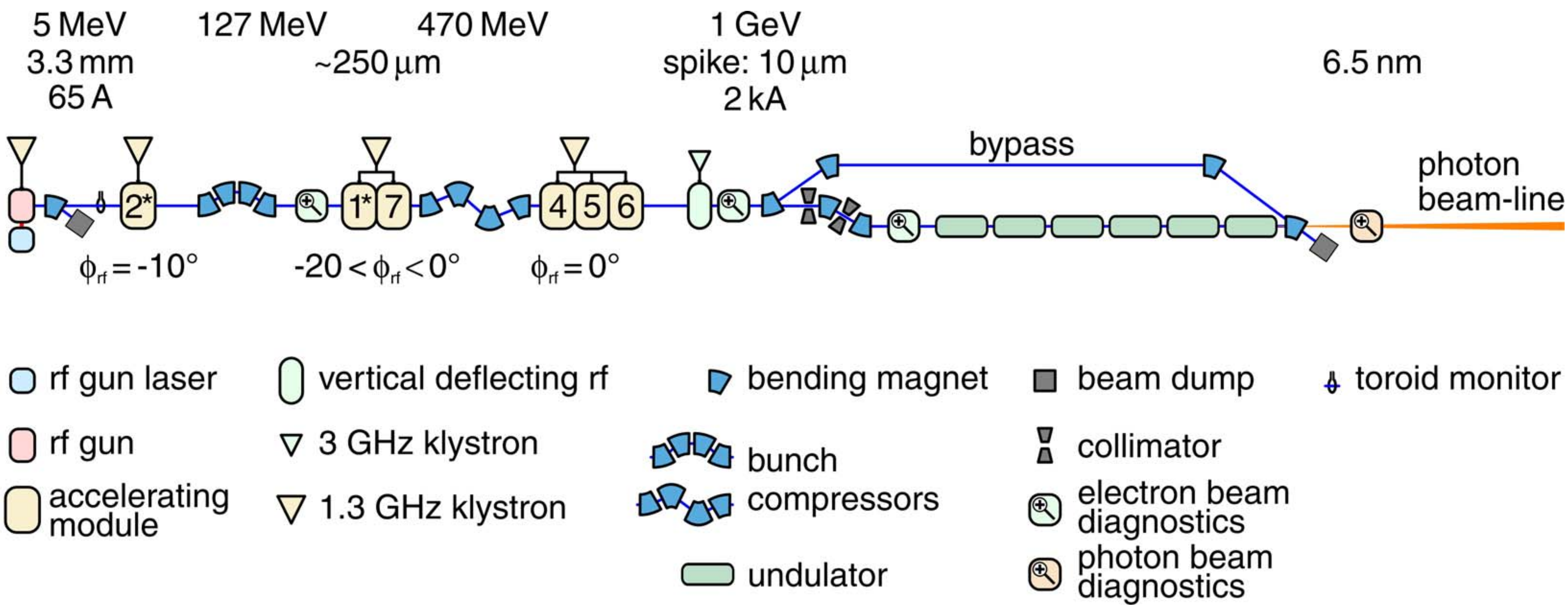




Key requirement:

- high peak currents of > 1 kA
- emittance < λ/4pi ~ 1-2 μm
- energy spread $\Delta E/E < 10^{-3}$

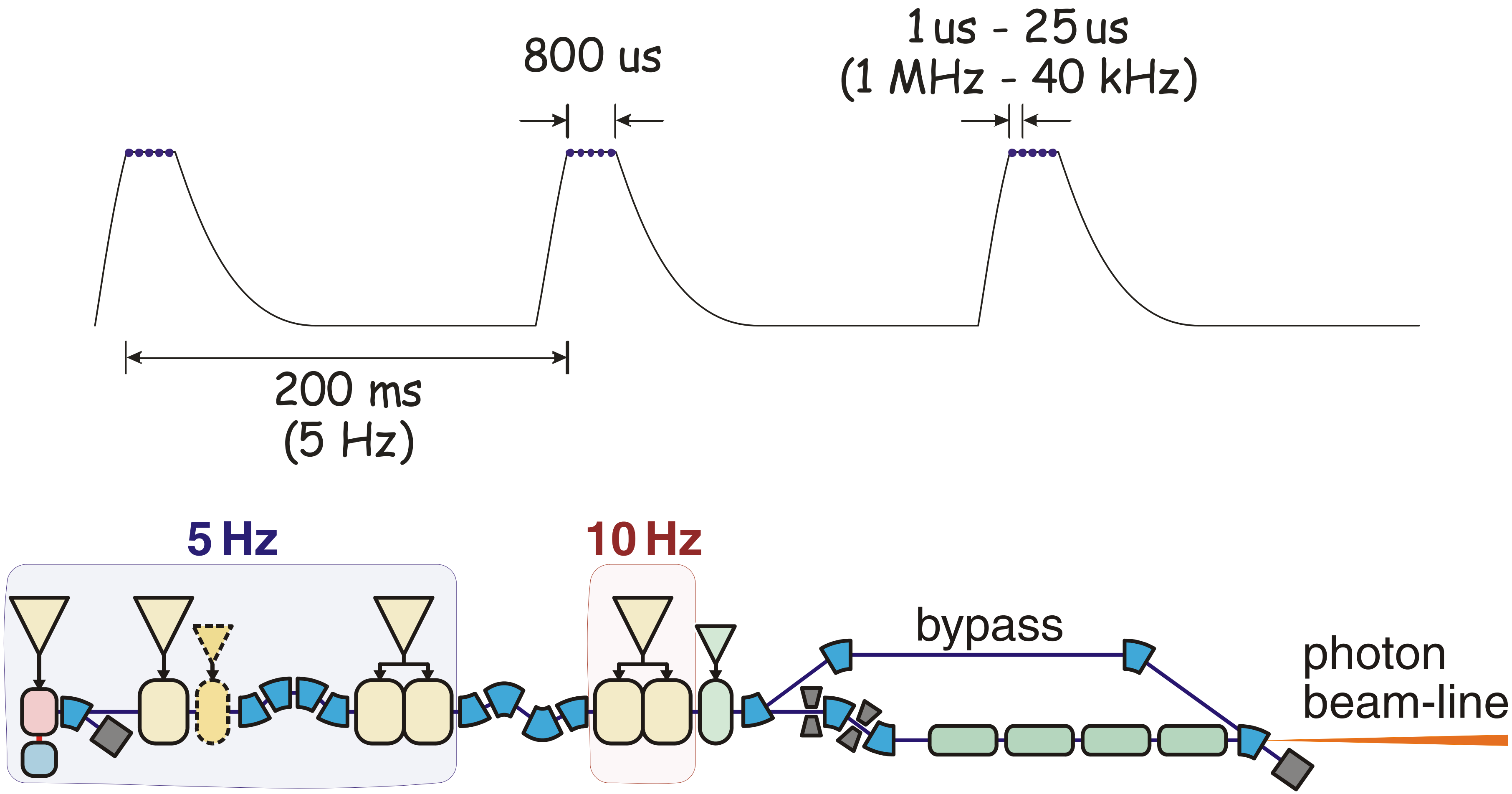
FLASH – the machine (in autumn 2007)

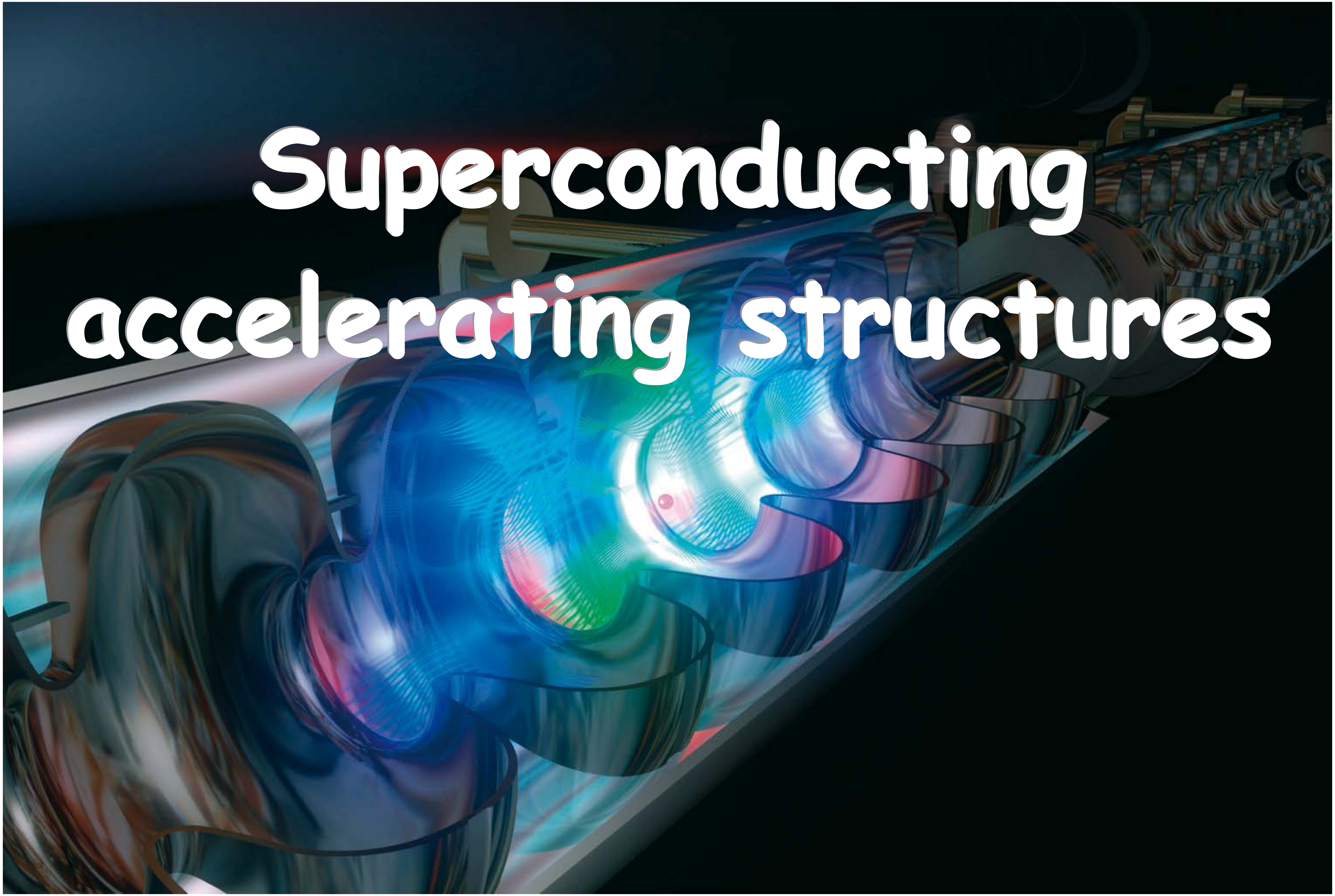


- initial bunch length restricted by collective effects
- two stage bunch compression
- off crest acceleration in ACC1 and ACC2/3
- requires good rf field stability

FLASH time structure

High gradients and moderate cooling demand (cryogenic load) by using pulsed rf:



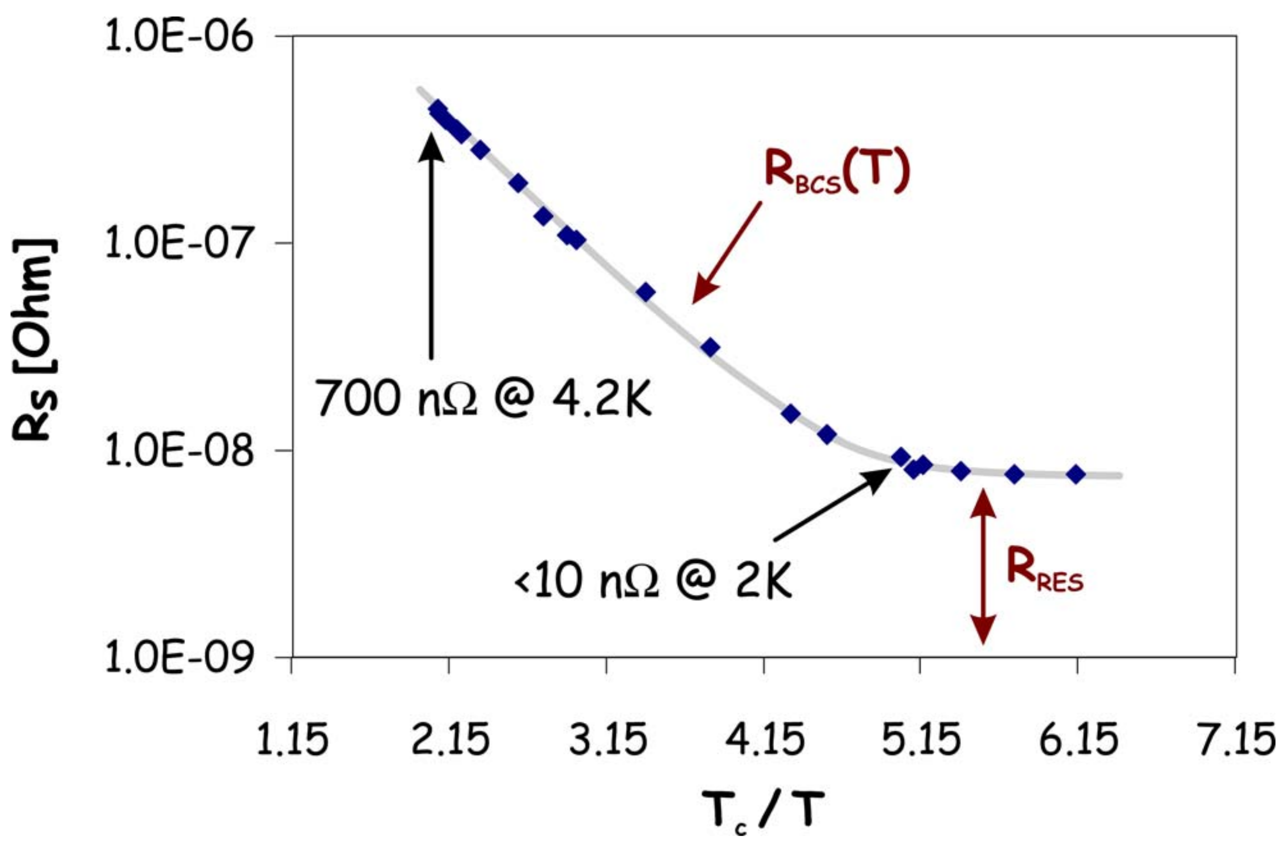

Superconducting
accelerating structures

Why superconducting structures?

Reasons:

- effective transfer from rf power into beam power (low losses)
- high rf field stability (due to high Q_L values)
- less sensitive to alignment errors
- moderate demand on beam steering

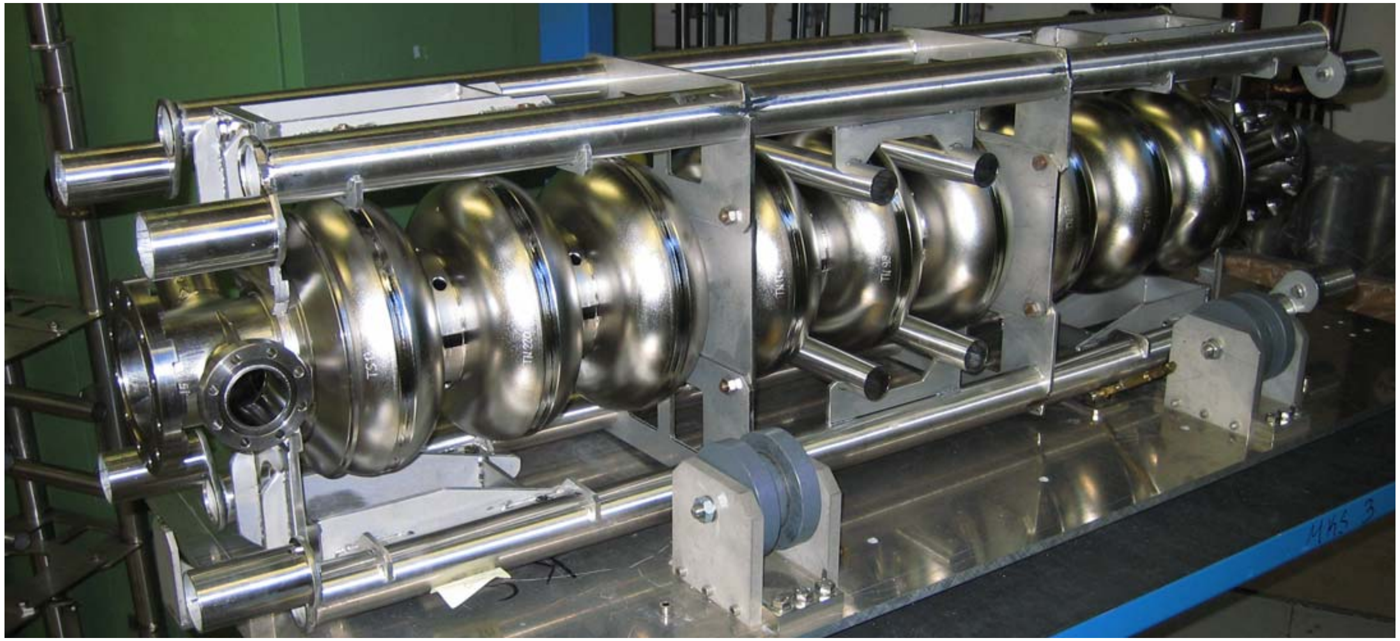
Surface Resistance $R_s(T)$



typical quality factor: $Q_0 > 1*10^{10}$ at 2K

Development of the nine cell TESLA cavities

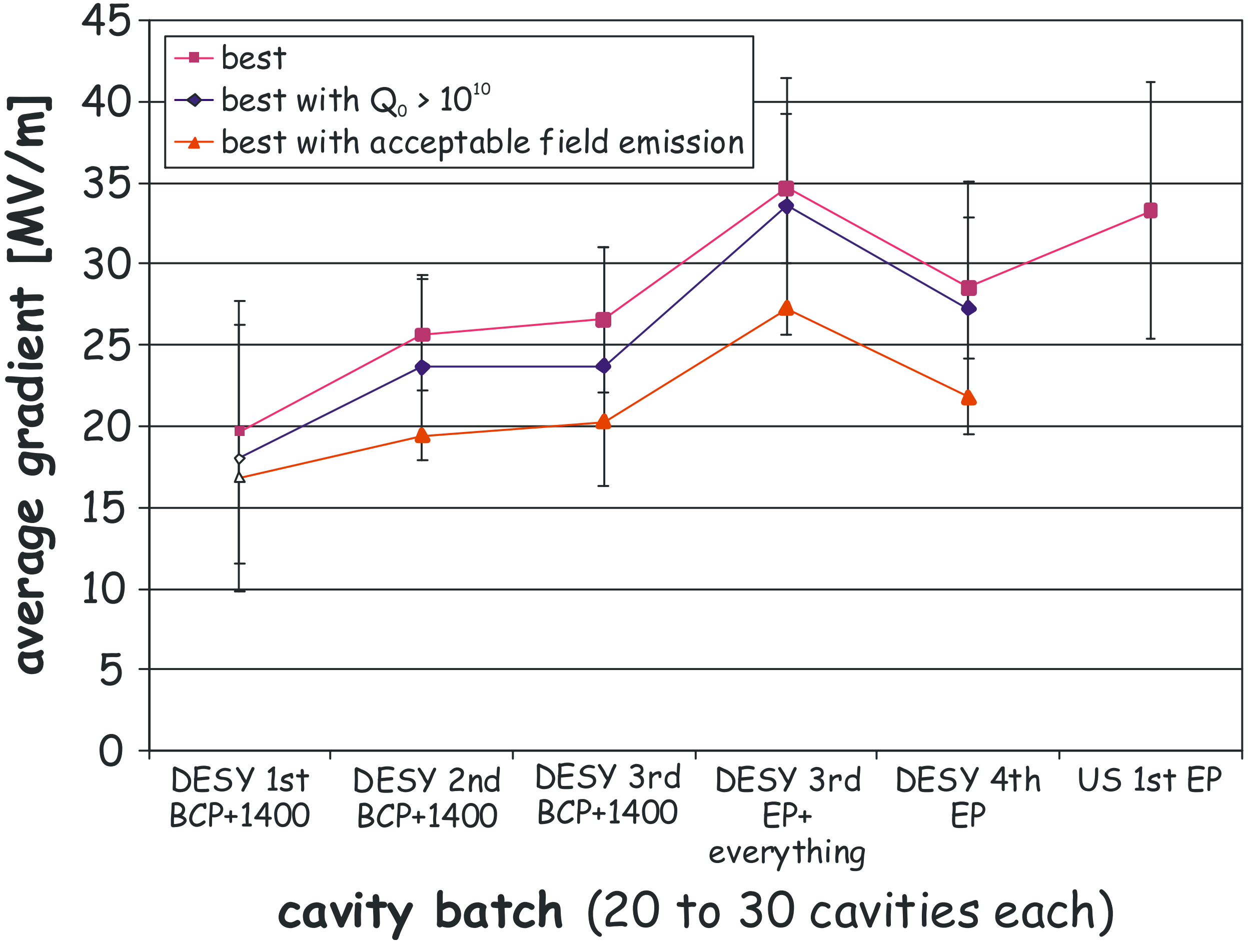
- TESLA collaboration started 15 years ago in 1992



- now experience form about 130 cavities produced by 4 companies
- material qualification procedures established
- welding procedures established
- surface treatments and process engineering under evaluation (see poster from D. Reschke)

Increasing cavity gradient

'Qualified' vendor productions: best test results



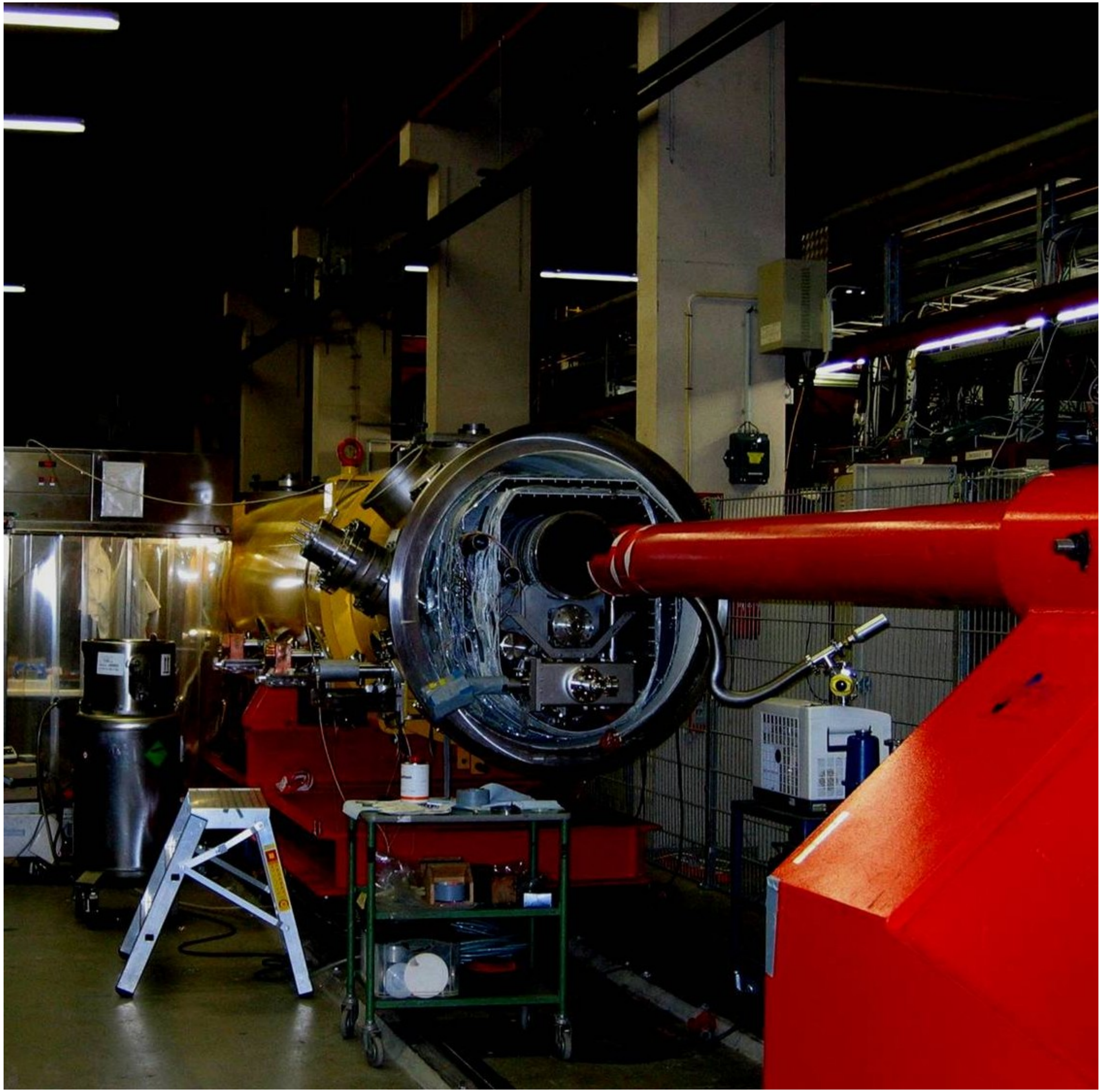
Status

- typical gradients obtained in pre-series production > 25 MV/m
- at September 25th new record at horizontal cavity test stand CHECHIA: 40 MV/m (stable for ½h)

Cryomodules – cavity shielding of $\Delta T \approx 290$ K

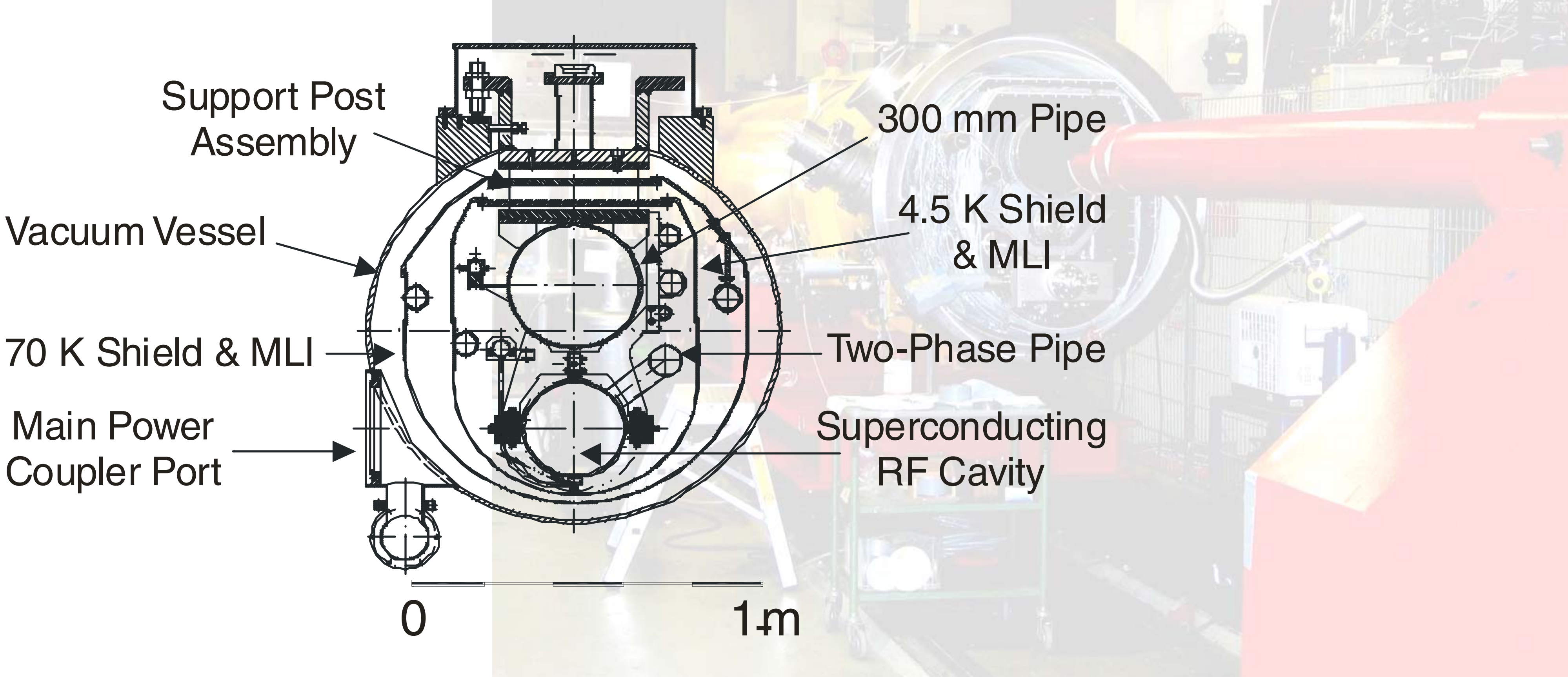
Each module hosts:

- eight cavities
- quadrupole magnet
- beam position monitor
- beam steering magnets
- etc…

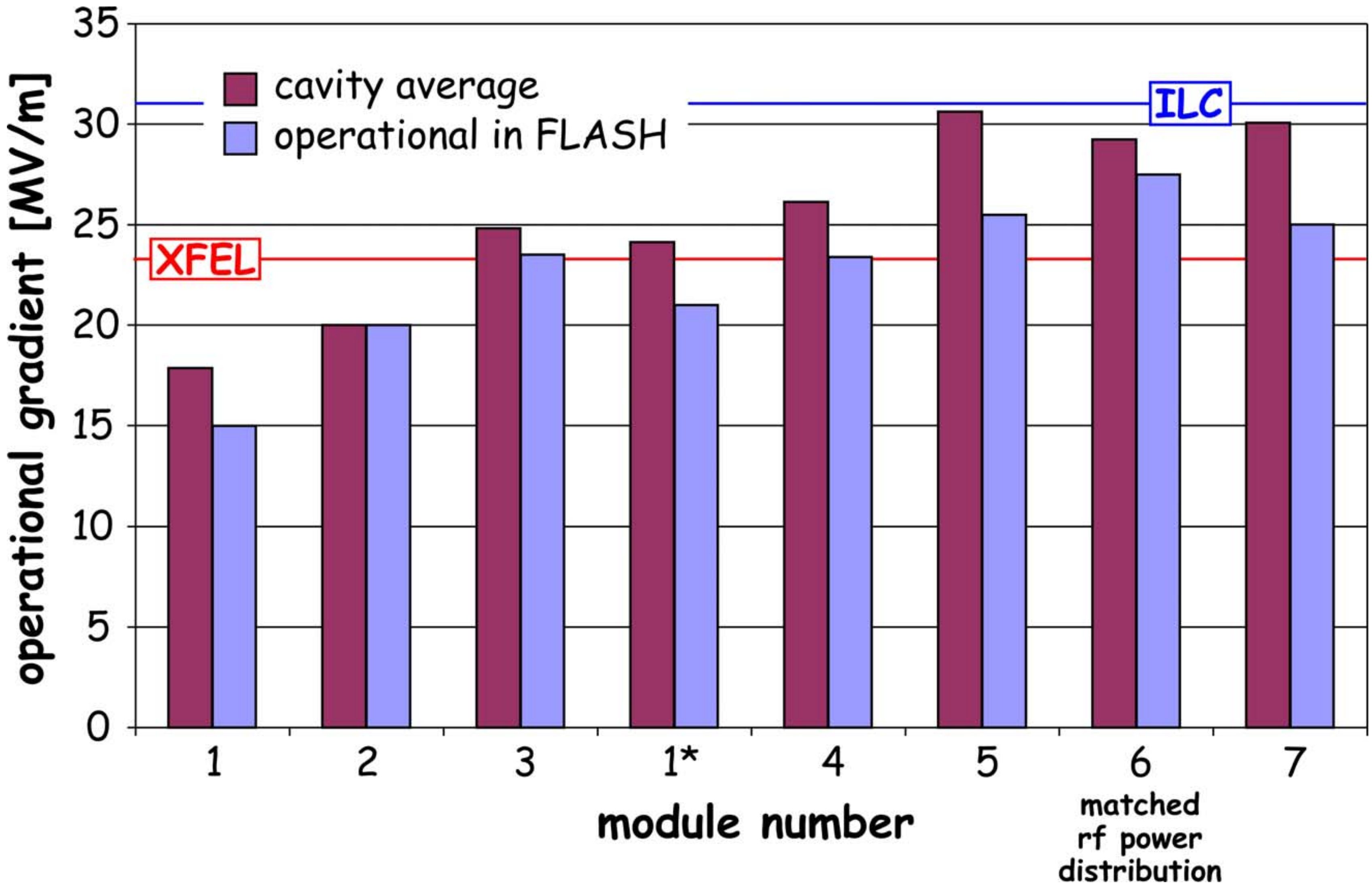


Cryomodules – cavity shielding of $\Delta T \approx 290$ K

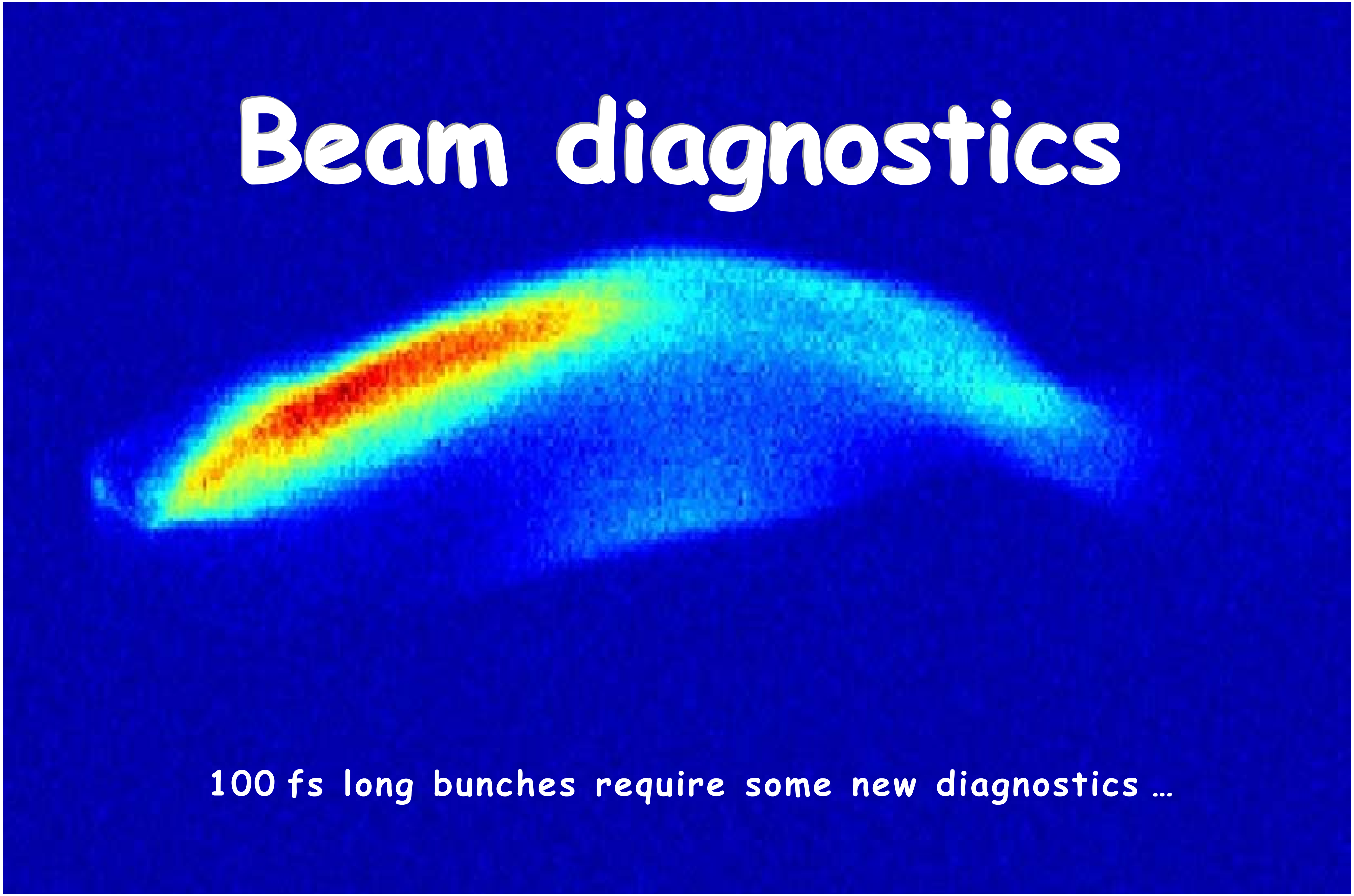
after two design iterations: 'type 3 cryomodule'



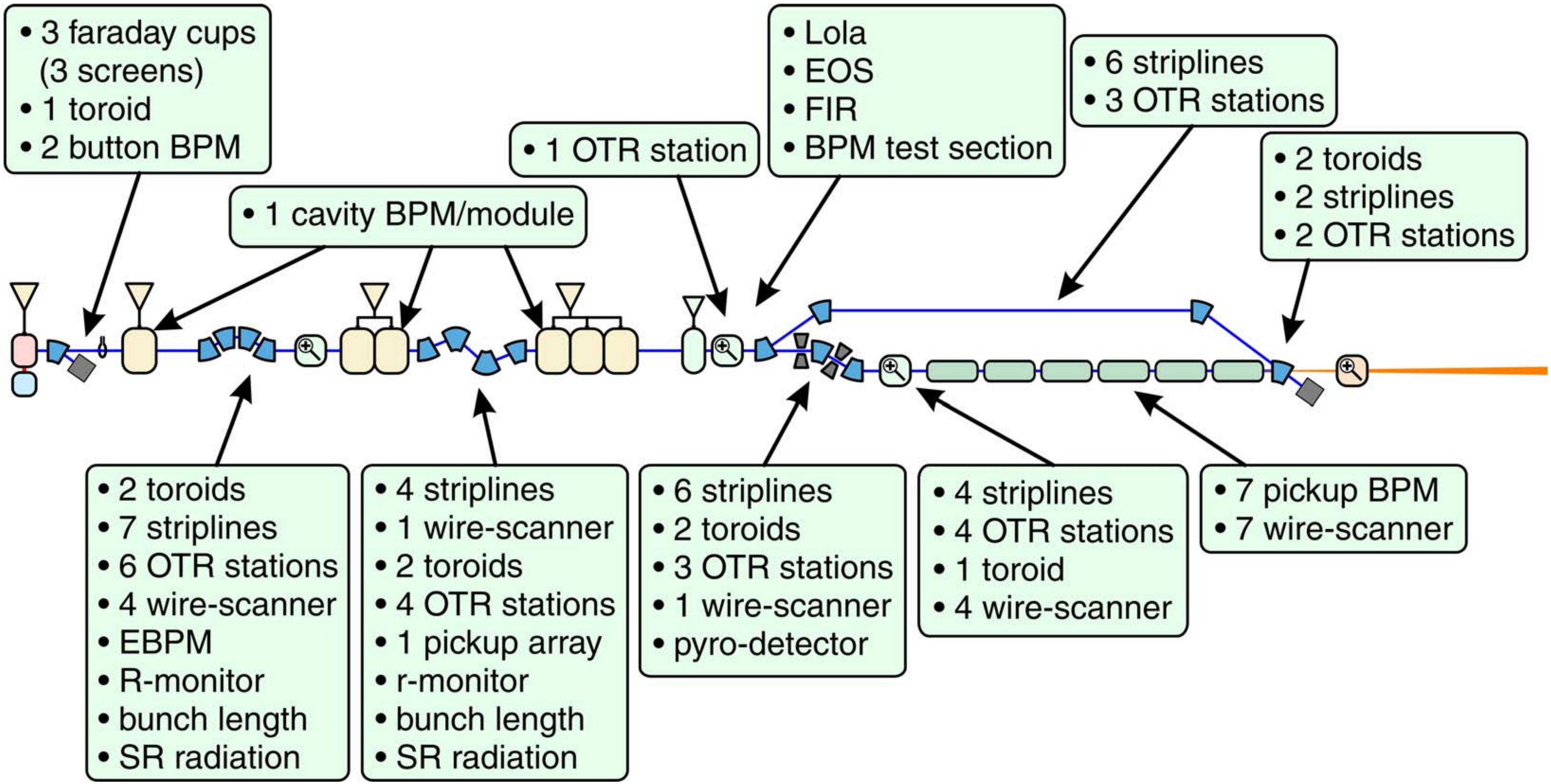
Cavity and module performance at FLASH



(see D. Kostin 'Testing the FLASH Superconducting Accelerating Modules', WEP05)

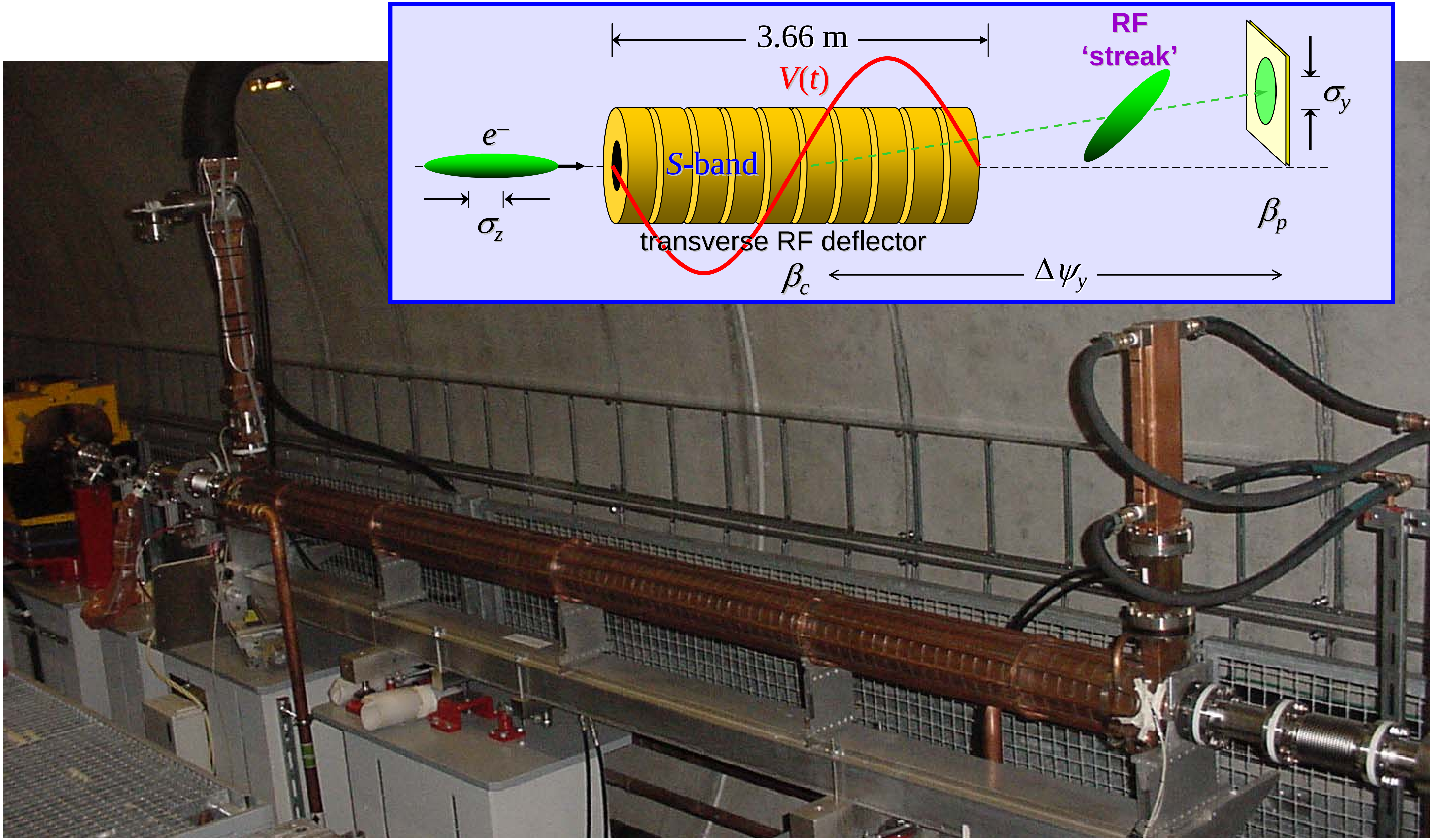

Beam diagnostics
100 fs long bunches require some new diagnostics …

Electron beam diagnostics at FLASH

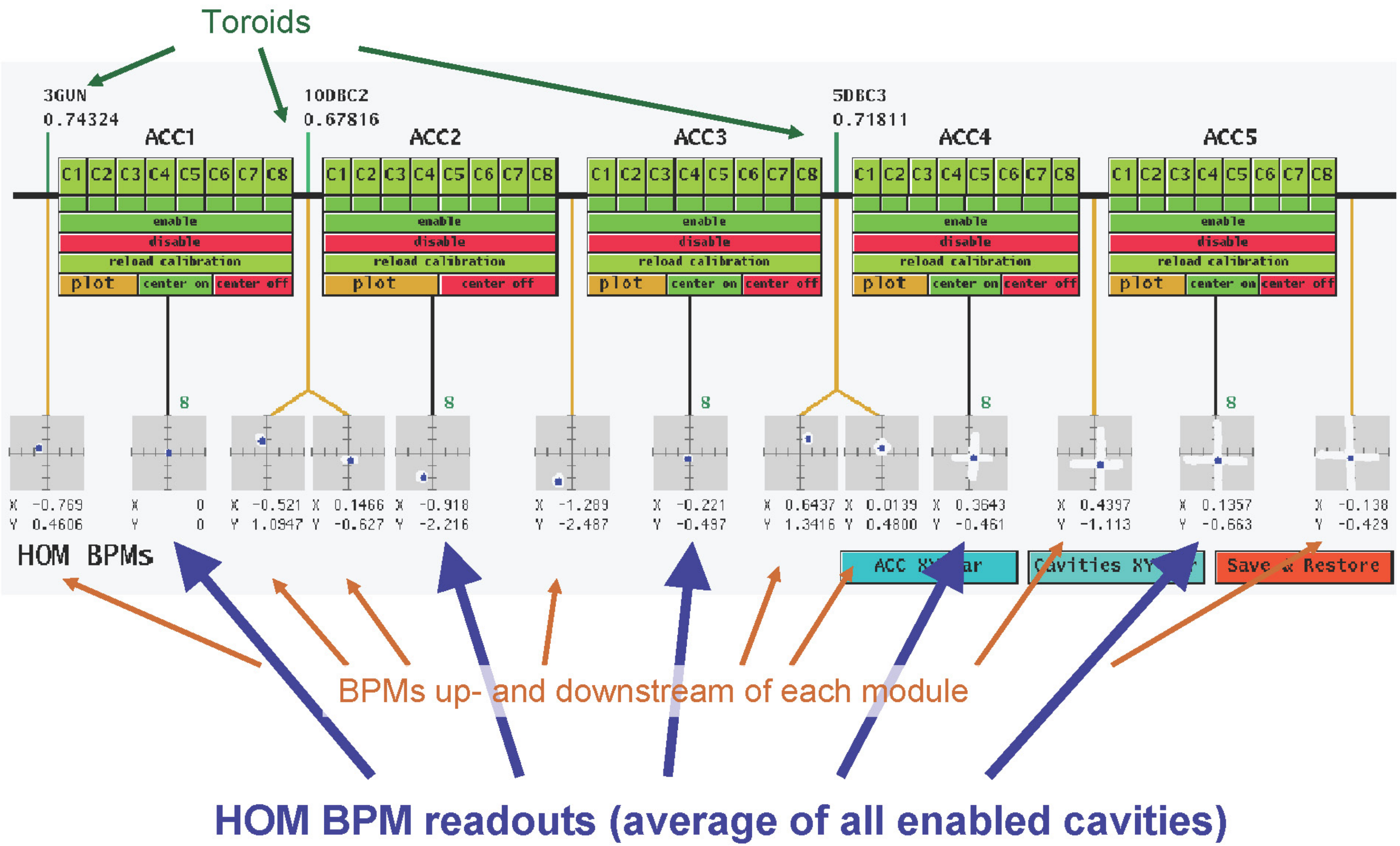


Here only two examples…

Transverse deflecting rf (in collaboration with SLAC)

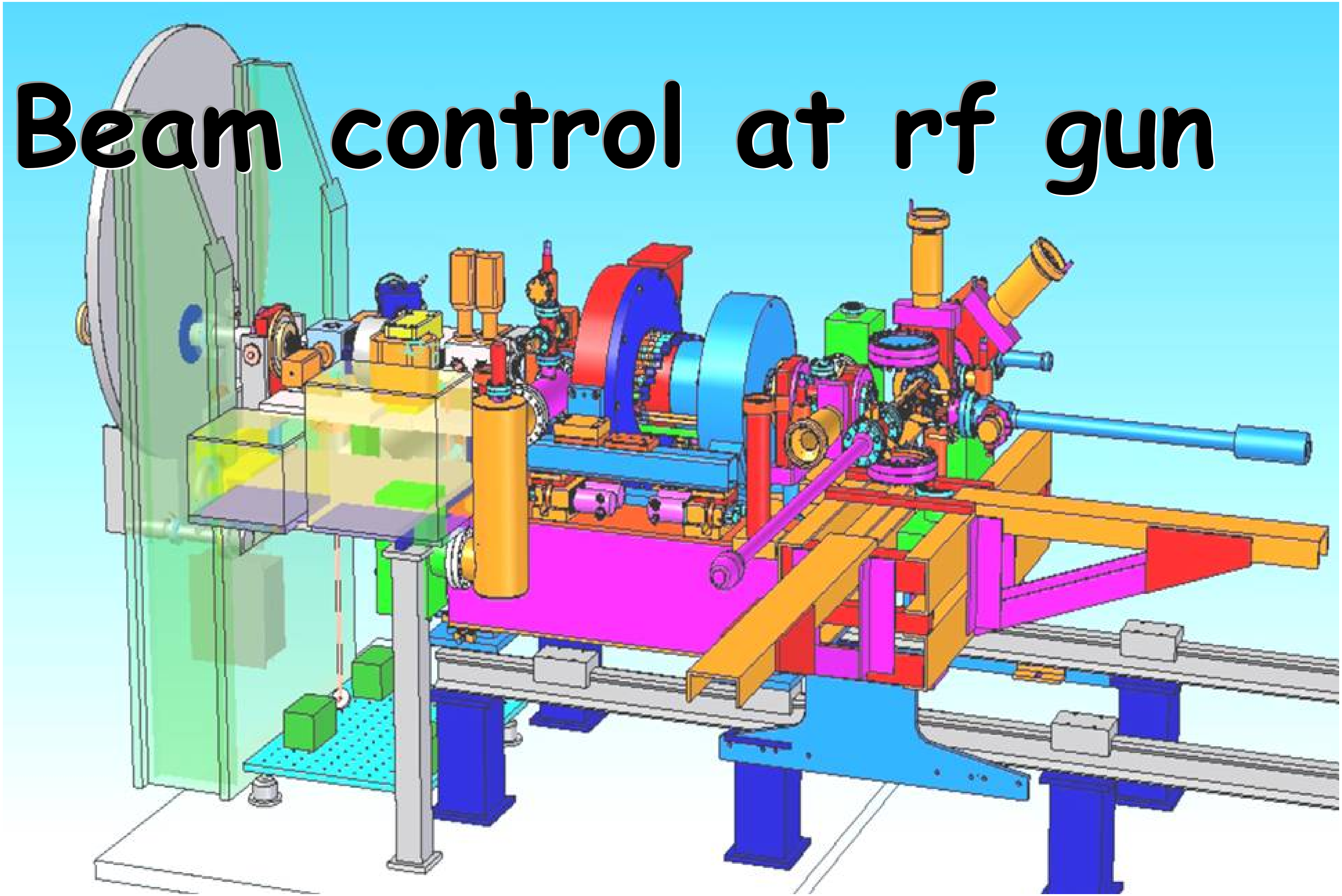


HOM based beam position monitor

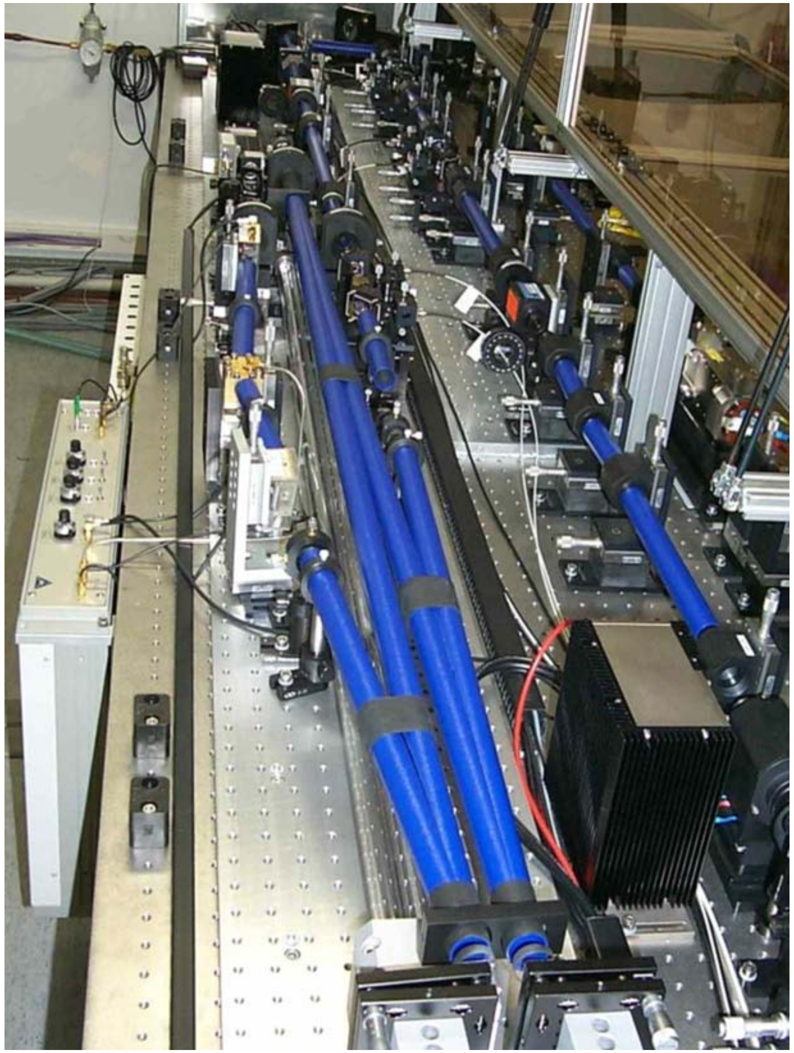


- single bunch resolution achieved: 2 to 10μm r.m.s. (multi bunch worse)

Beam control at rf gun

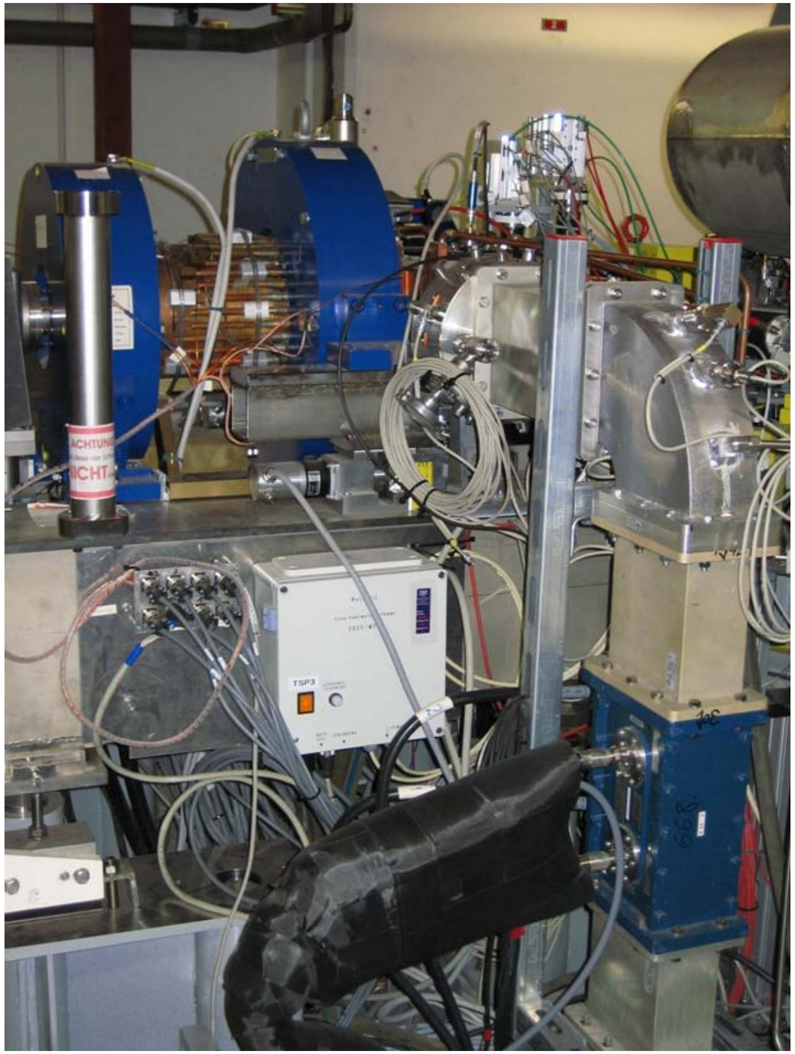


Rf gun laser …



the gun laser produces laser pulses shoot onto the cathode creating bunches

and rf gun



the rf field of max 42 MV/m on the cathode accelerates bunches to 5 MeV

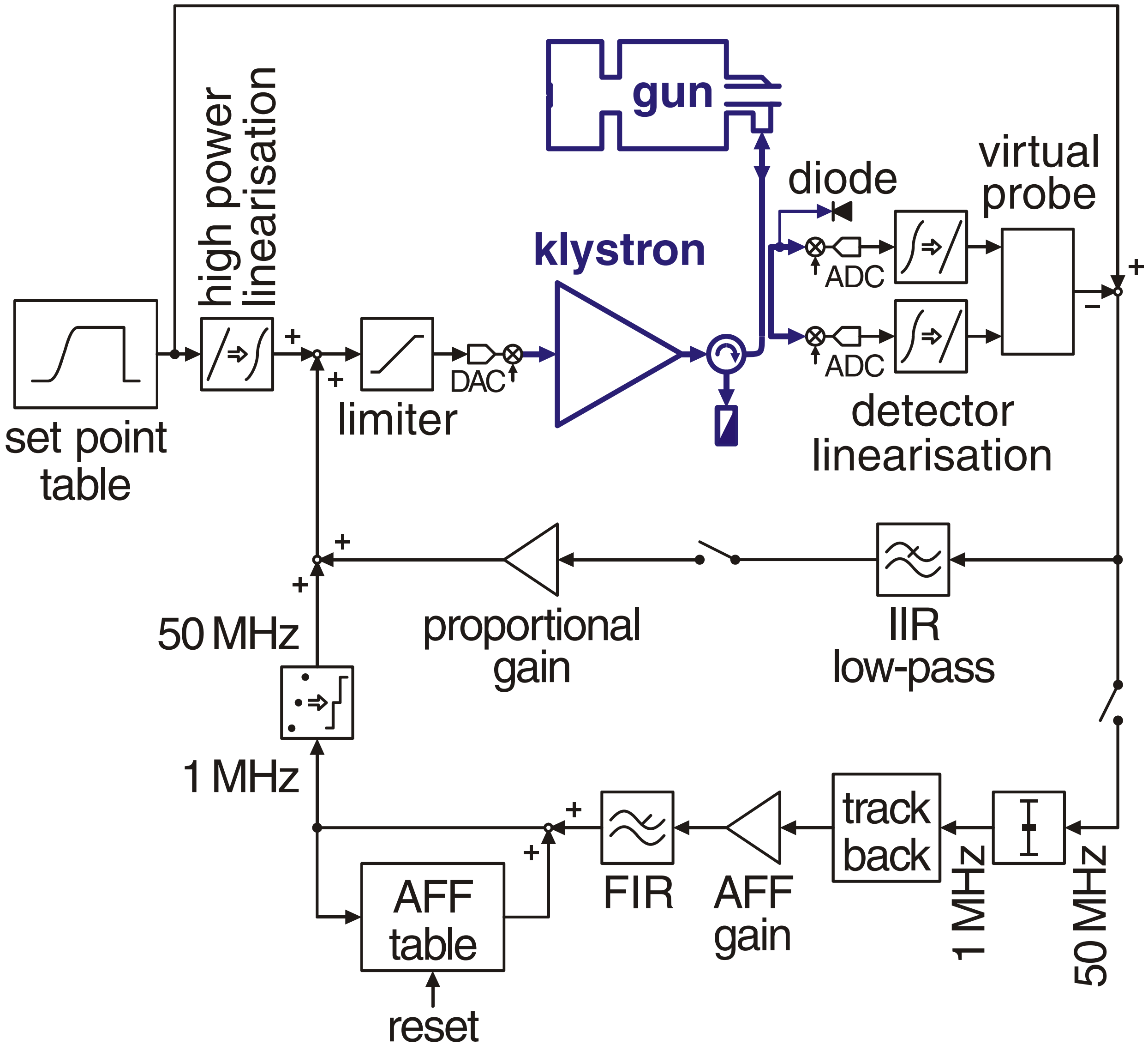
Rf control by FPGA and sophisticated algorithms

Gun without probe

- calculation of probe form forward and reflected rf
- calibration and linearization is an issue

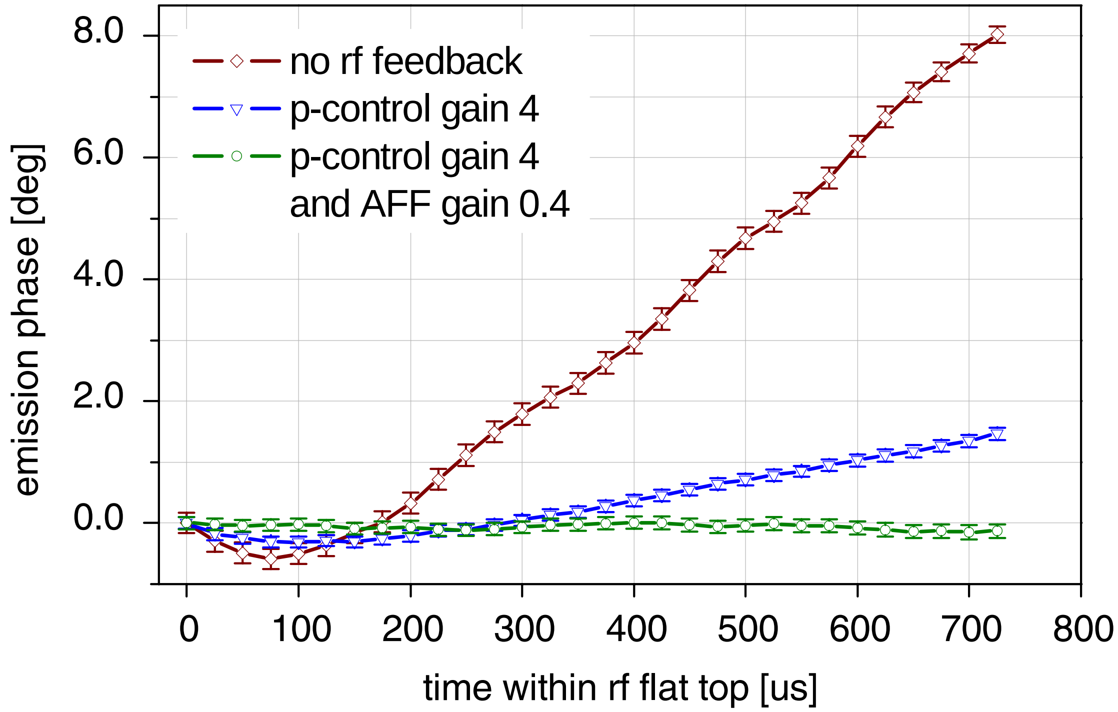
Algorithms

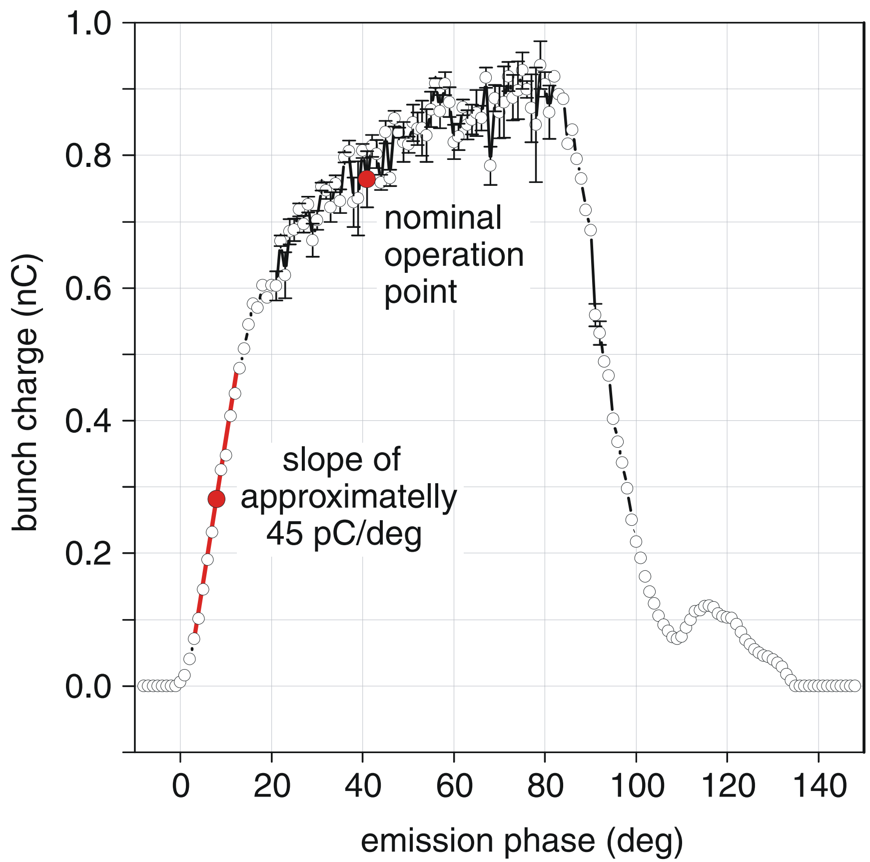
- P(I) control with recursive 20 kHz low-pass (IIR) for stability at 'high' gain (>5)
- Adaptive feed forward (AFF) from rf pulse to rf pulse



Gun beam stability

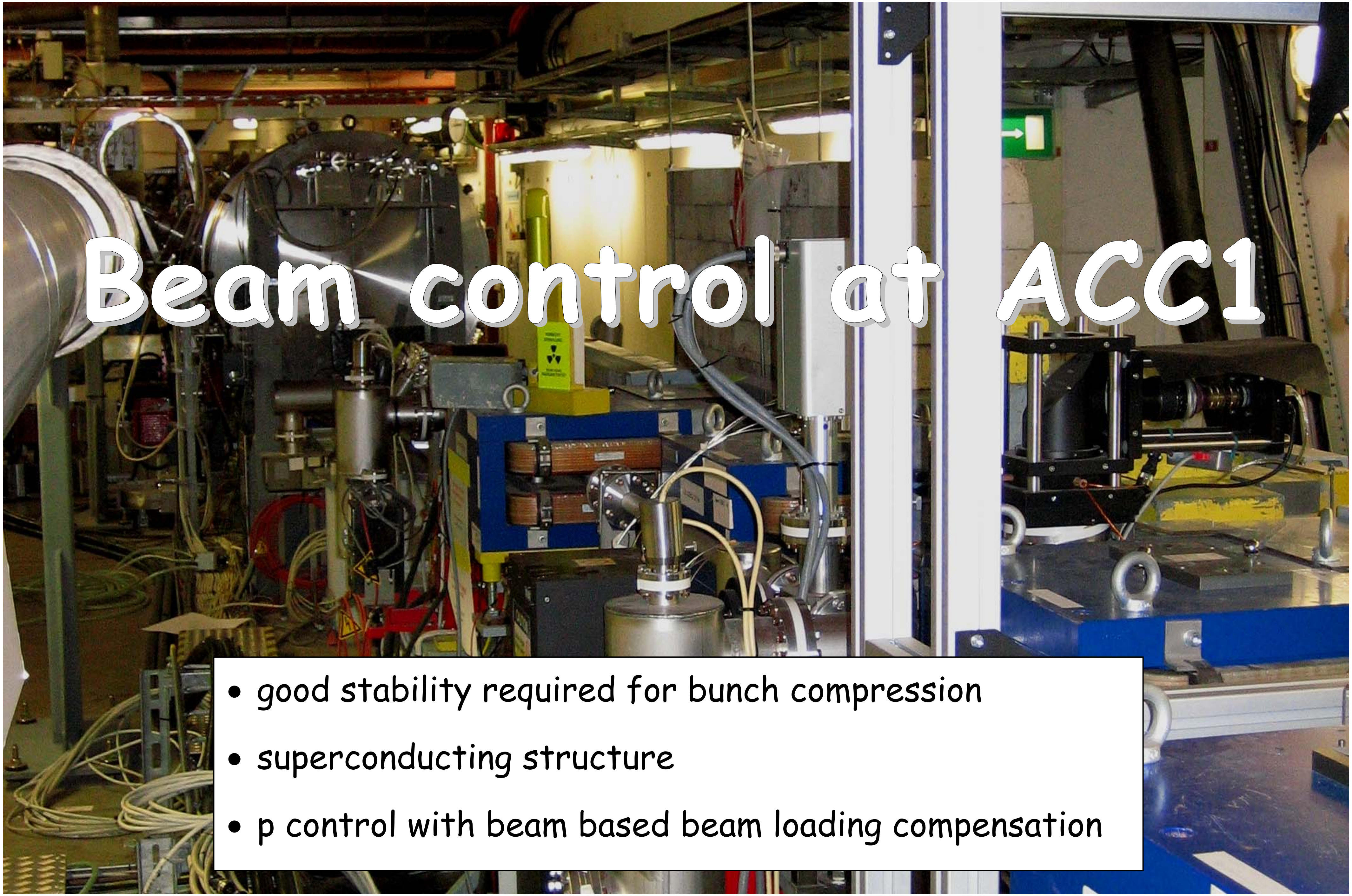
- indirect rf phase measurement
- bunch charge
  depends on rf phase at 'edge'
- resolution about ± 0.01° (20 fs)





- intra pulse stability better 0.14°
- long term stability peak-to-peak 0.4°

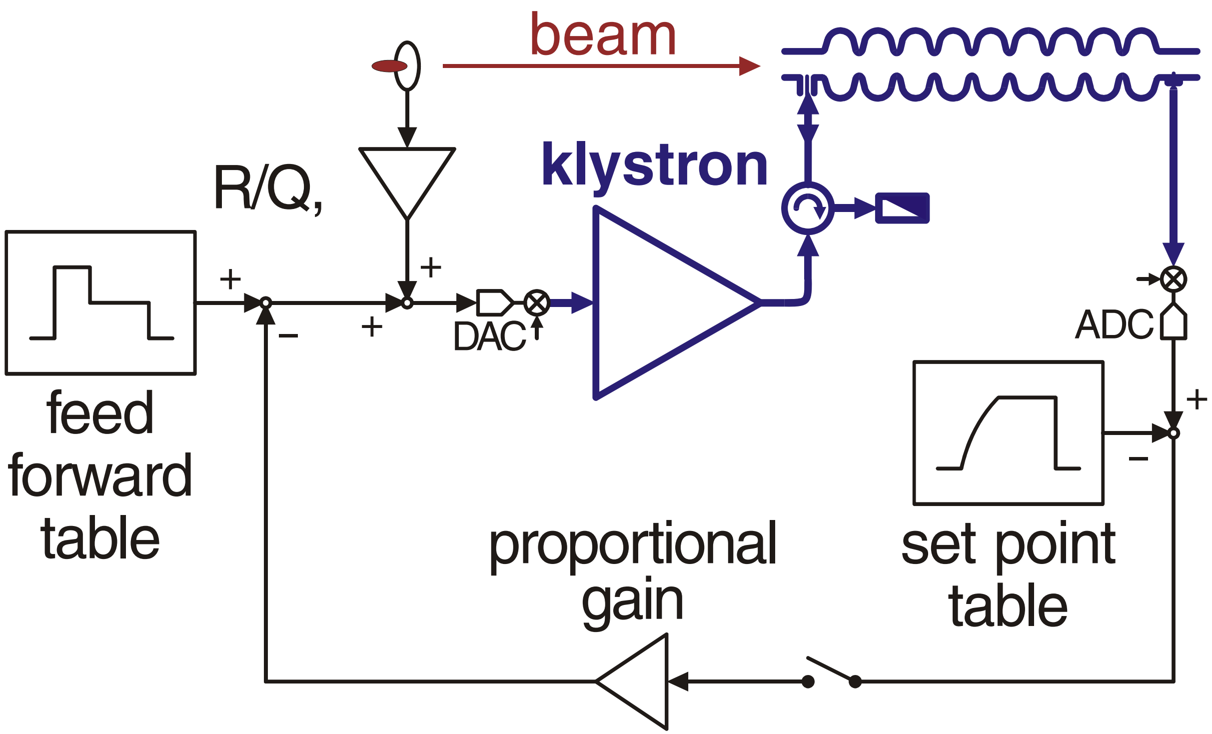
- FLASH requirement: better 0.5°



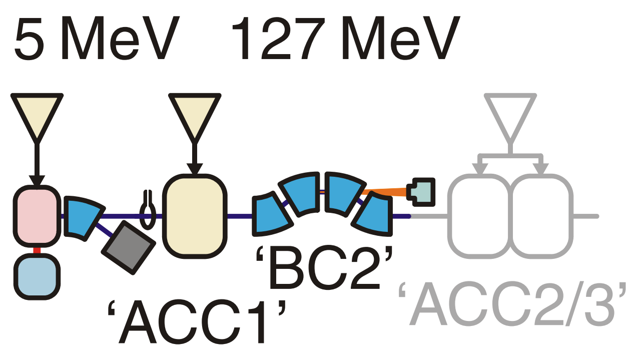
Beam control at ACC1

- good stability required for bunch compression
- superconducting structure
- p control with beam based beam loading compensation

Proportional control with beam based beam loading compensation

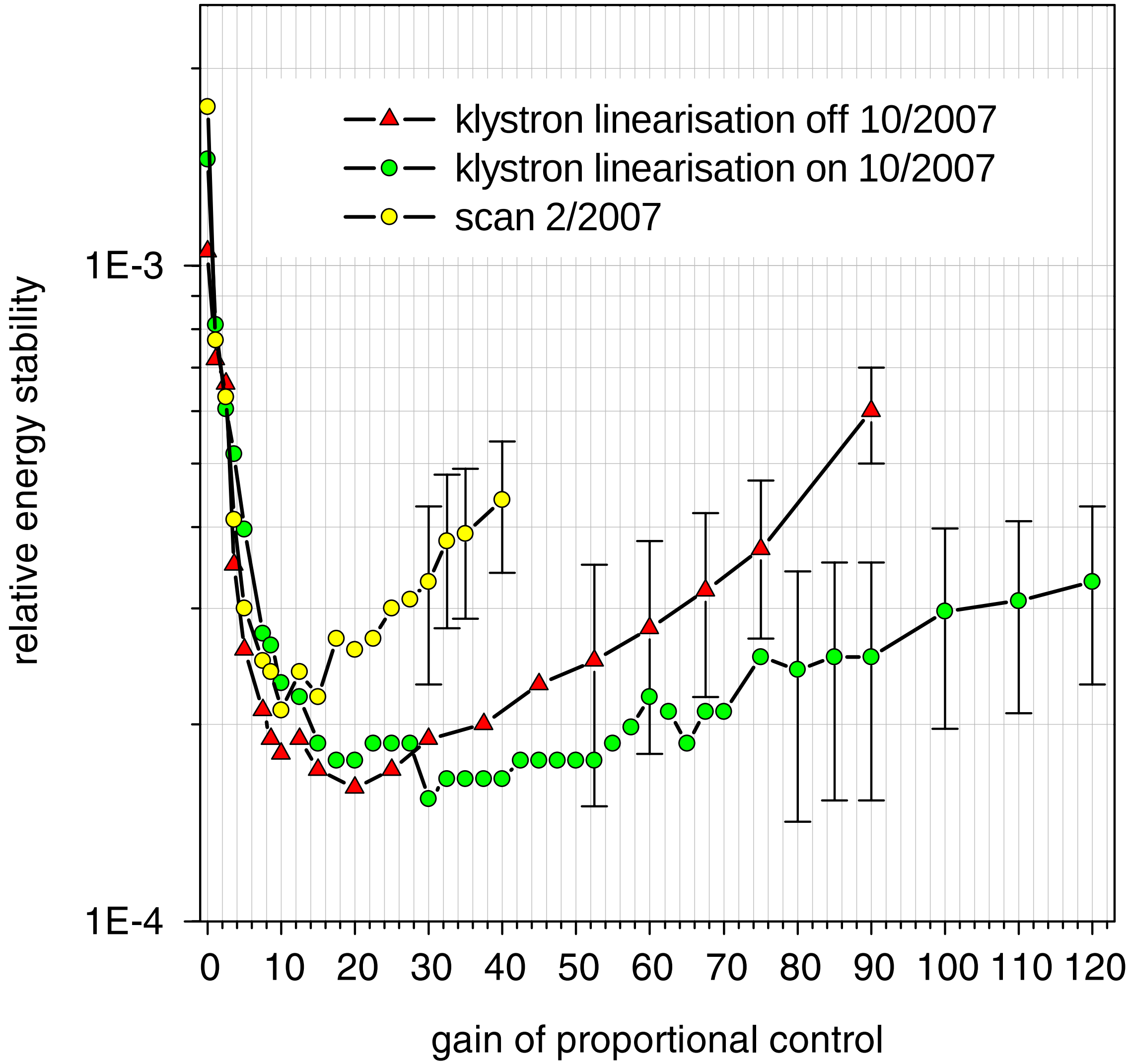


Beam energy measured with synchrotron light spot at BC2



Resolution $\Delta E/E = 10^{-4}$

'Ideal' gain for proportional rf control at ACC1



Gain giving most stable beam:

- small gain: error suppression
- large gain: noise amplification
- best single bunch stability: $\Delta E/E = 1.6 \times 10^{-4}$

Gain limitations:

- noise at pick up signal?
- w/o paying attention to the 8/9 π mode: *G* = 40
- paying attention to the 8/9 π mode: *G* > 100

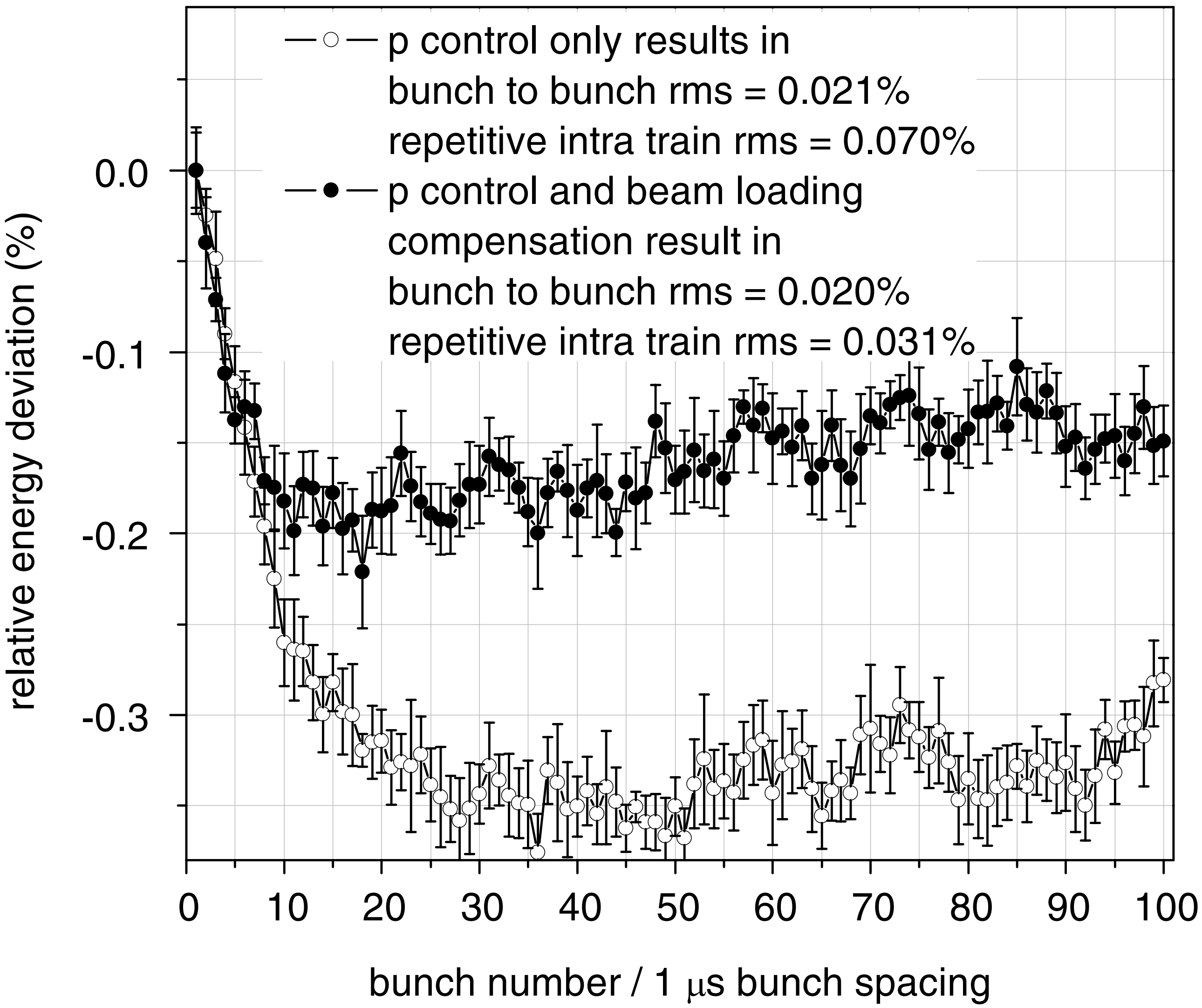
Actual status of the ACC1 beam loading compensation

Status:

- not yet ideal, but…
- sufficient for SASE with more than 400 bunches

Next steps:

- improvement of calibration
- further qualification by beam measurements



Further rf and beam control developments

Rf control

- klystron linearisation
- optimal control
- adaptive feed forward (several types)
- sampling schemes
- improvement of down converters
- piezo tuners for compensating the Lorentz force
- new electronics (e.g. ATCA)
- and so on…

Beam control (only some examples)

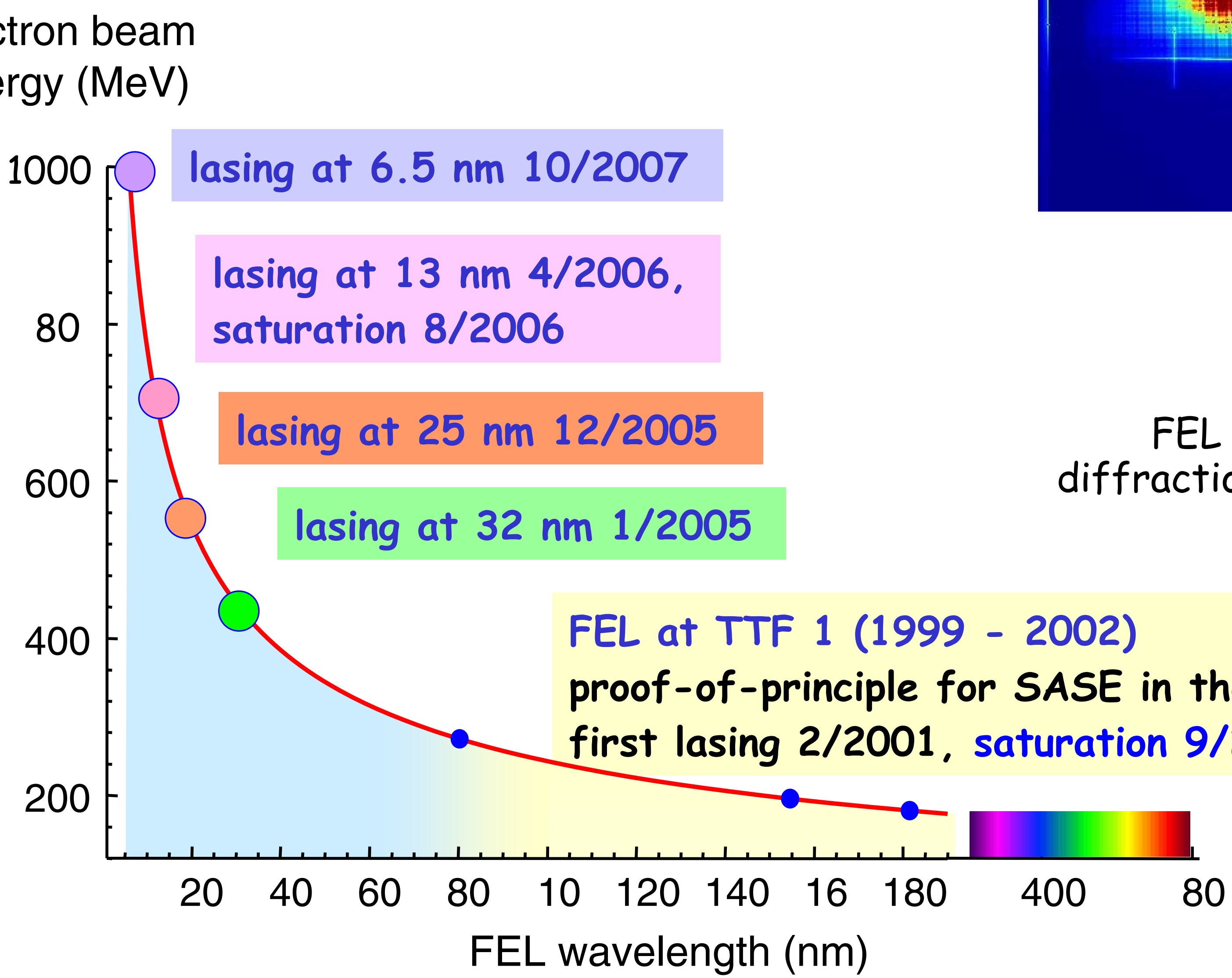
- (bunch to bunch) beam based measurement of ACC1 amplitude and phase, used in future as beam feedback sensor
- beam feedbacks in front of undulators
- and so on…

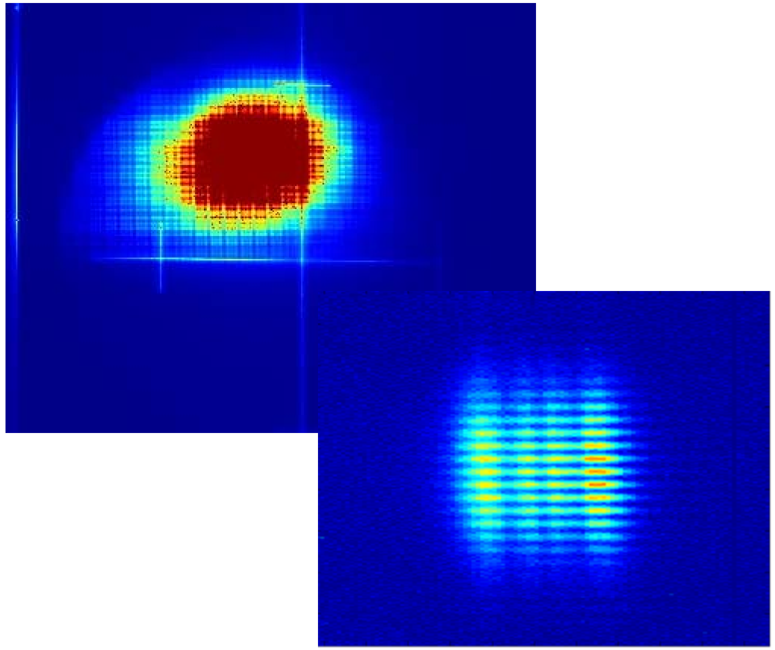
SASE performance

all this effort pays off:

- increasing beam energy and lower wavelength
- lasing with long bunch trains

Beam energy and wavelength





FEL radiation: measured diffraction pattern of a double slit

Wavelength tuning

Lasing at different wavelengths

- slow switch of wavelength: on shift to shift basis

Challenge 1

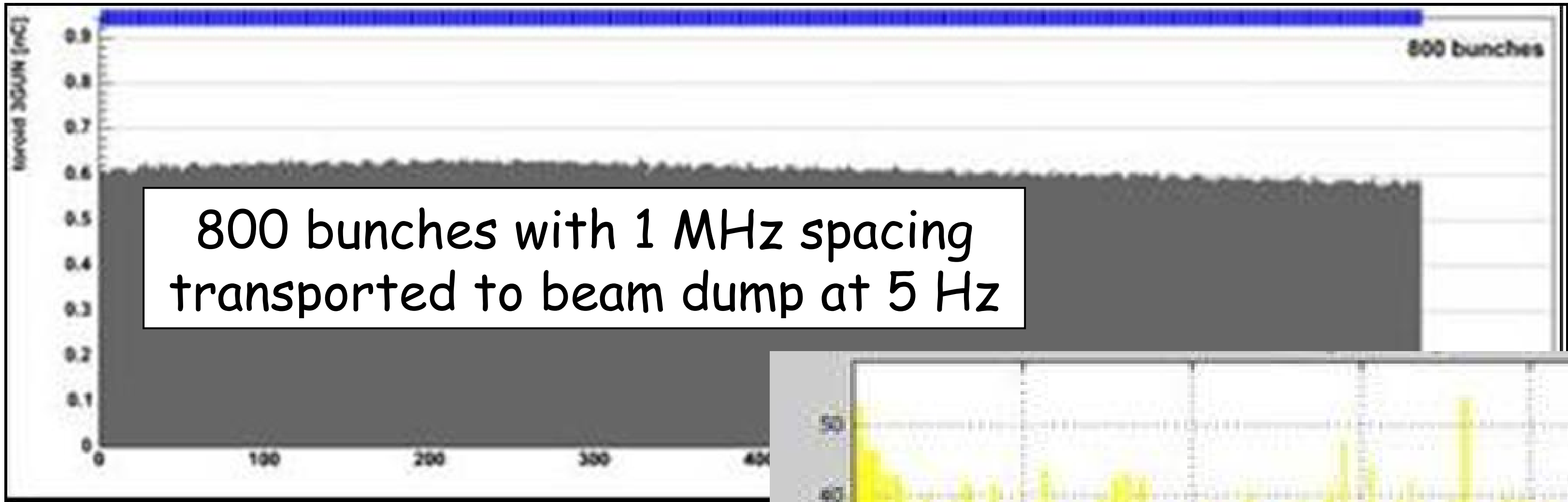
- each energy requires new optics and tuning
- once tuned, by reloading of files pretty fast recovery

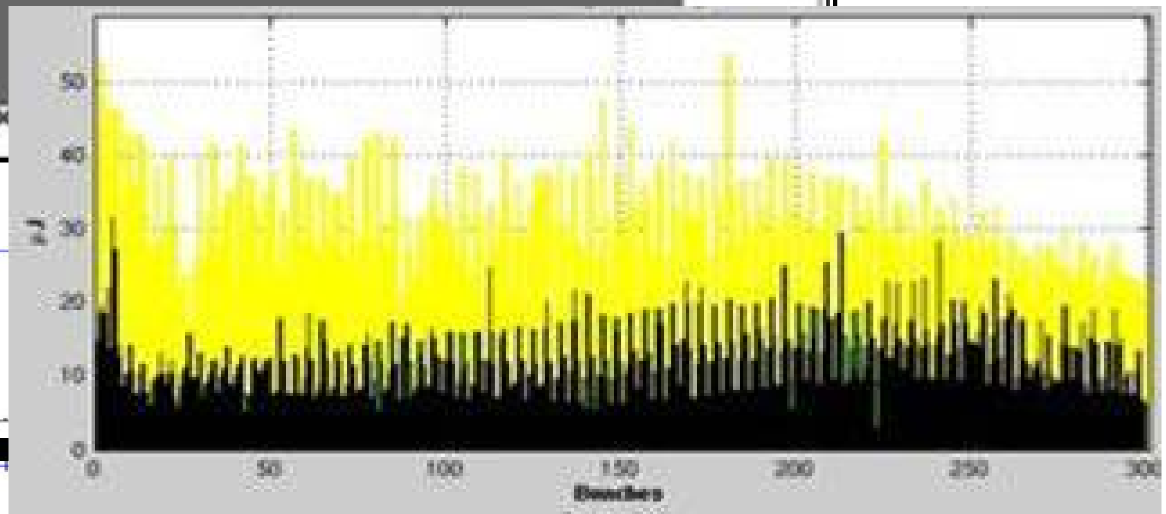
Challenge 2

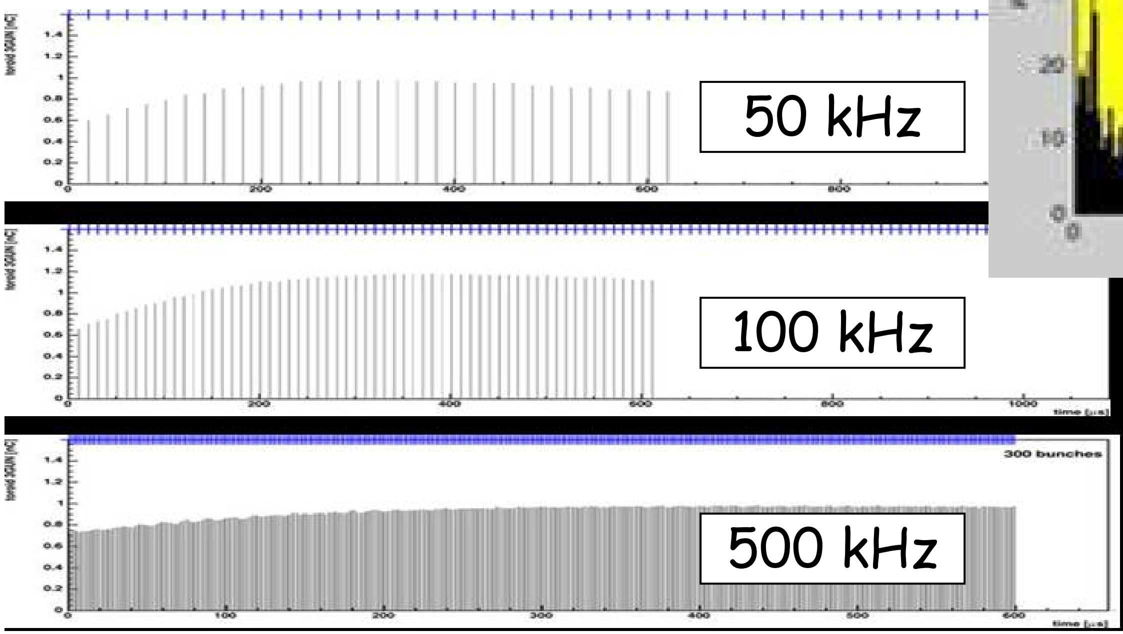
- hitting the right wavelength within 0.1 nm
- sometimes lengthy

achieved wavelength (nm)	beam energy (MeV)
6.5	986
13.1	680
13.7	680
15.1	650
16.9	610
20	576
18.9	580
20.9	550
25.5	500
28.6	478
32.5	465
32.5	445
35.1	428
38	407
40.4	397
47	374

Lasing with long bunch trains







lasing with more than 450 bunches at levels up to 70 to 80 μJ in average

Statistics and run time distribution

User operation since 2005

User periods

The user period 1 had two runs

- run 1 in 2005/2006 with 119 days
- run 2 in 2006/2007 with 160 days

Next user period 2 in 2007/2008 with one long run of 203 days

Accelerator study periods

- FEL related machine studies for the preparation of next block of user runs
- general accelerator studies (XFEL, ILC etc)

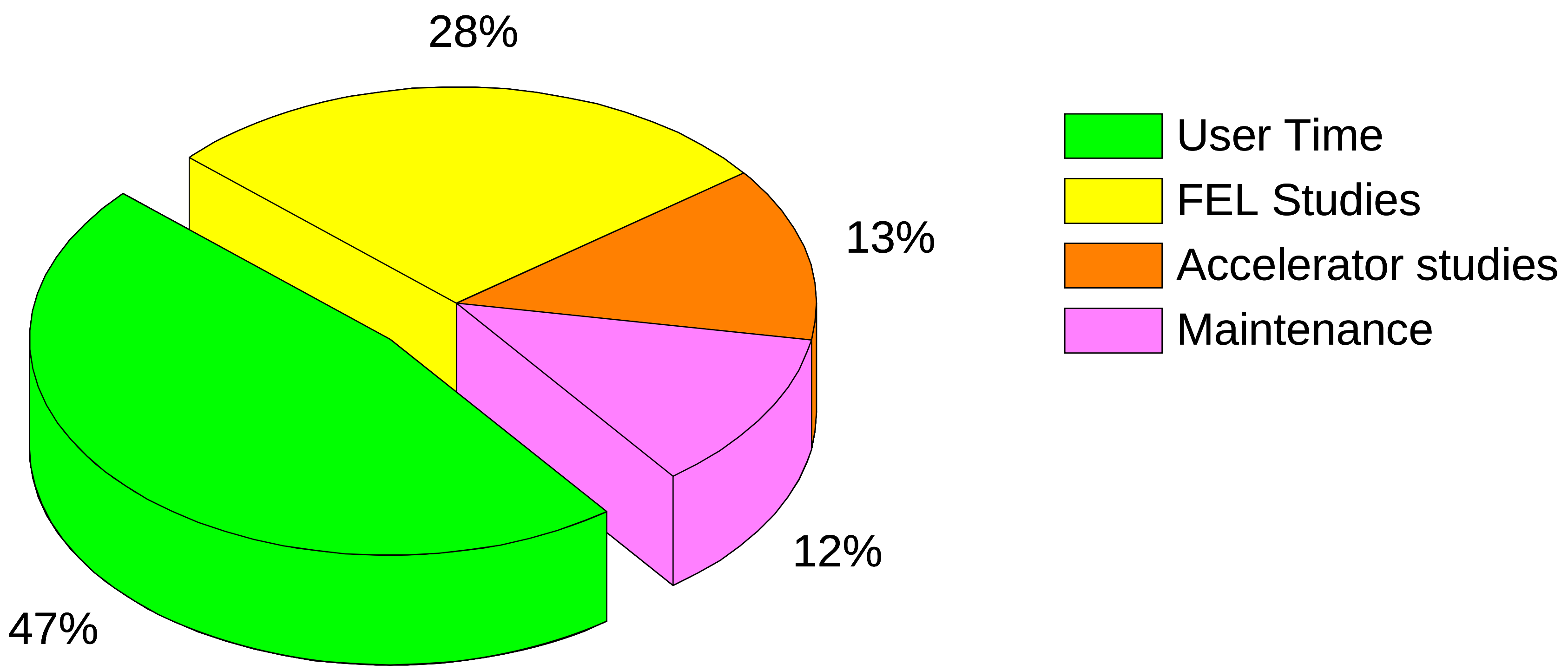
weeks

7	
6	
5	
4	User Experiments
3	User run preparation
2	
1	FEL related Studies
7	
6	
5	
4	User Experiments
3	User run preparation
2	
1	FEL related Studies
4	
3	
2	
1	Accelerator Studies

Beam time distribution

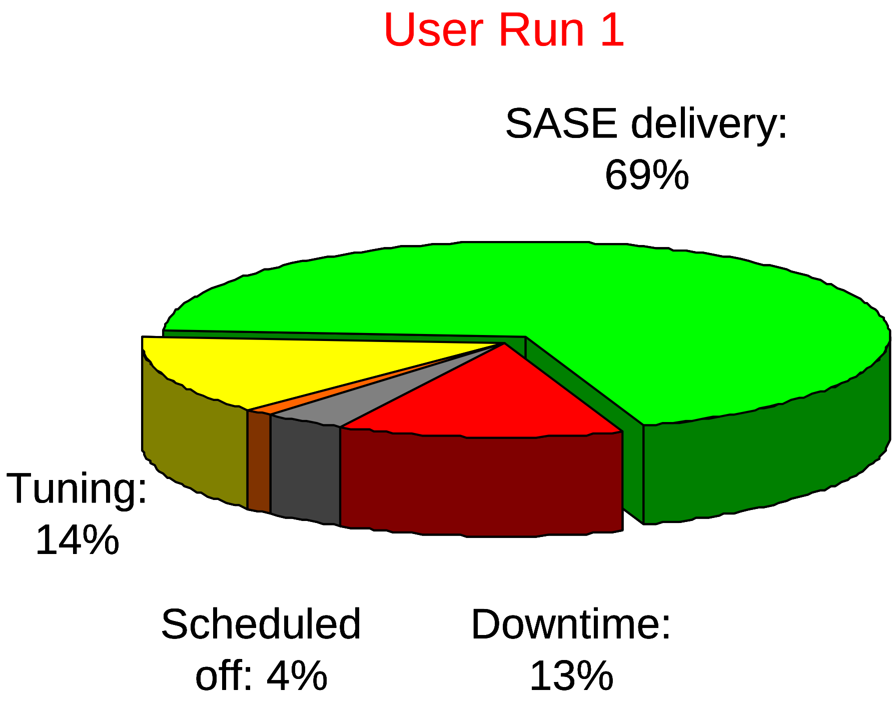
Example user run 2: May 2006 until Mars 2007

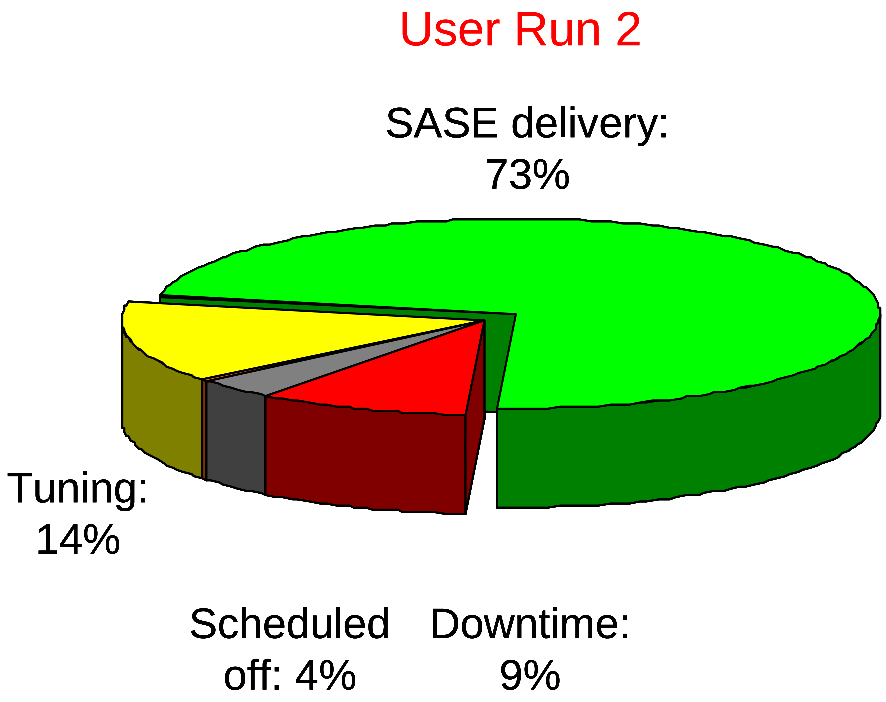
- 45 weeks or 7728 h
- user experiments had 3840 h of beam time (47 %)
- with 2798 h of actual beam delivery (73%)



SASE delivered to experiments

- ~70 % of the beam time is actually beam delivery
- slight improvement from run 1 to run 2 by 4 %

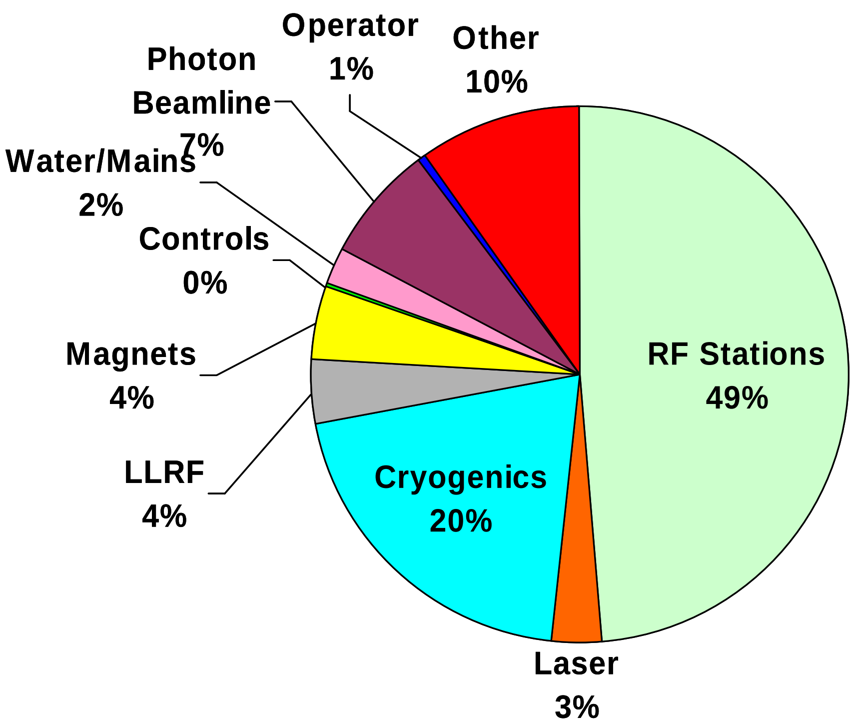




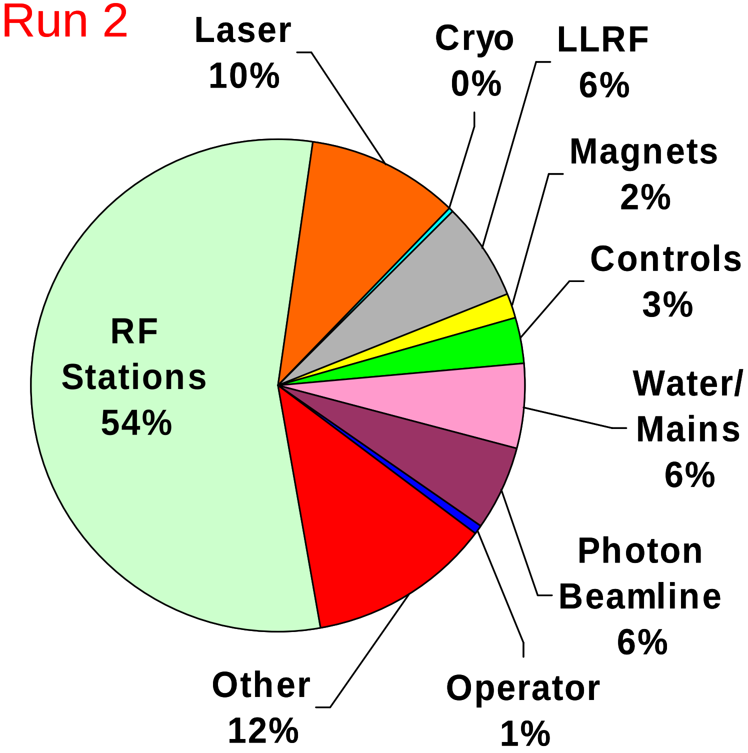
Downtime

- downtime mainly due to RF stations
- a few 'big' events (cryo/rf stations)
- otherwise lots of little problems with downtimes ~4%

User Run 1



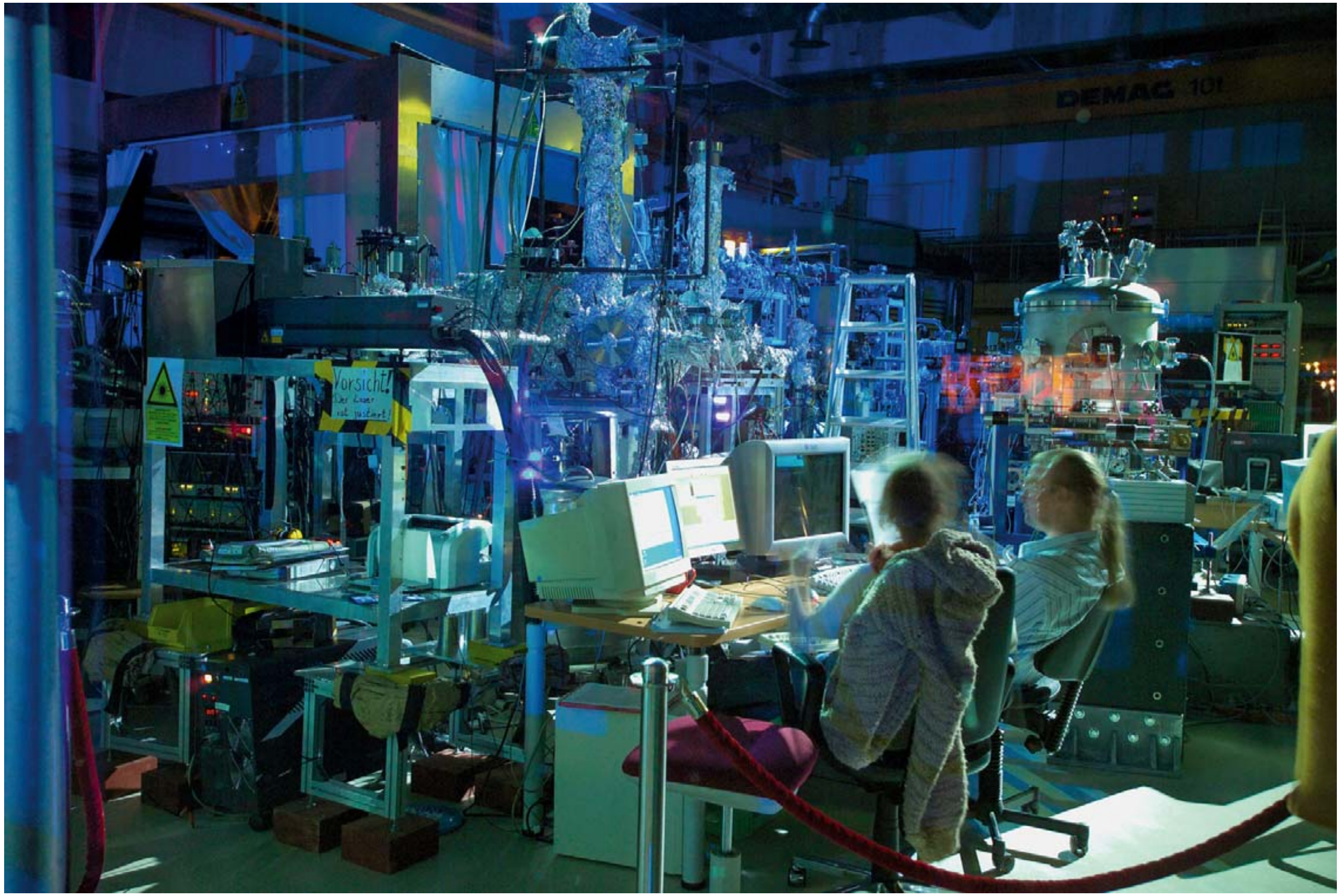
User Run 2




Next milestones

Next milestones until end 2007

- start second period of user experiments with 13.5, ~28, ~8 and ~7 nm



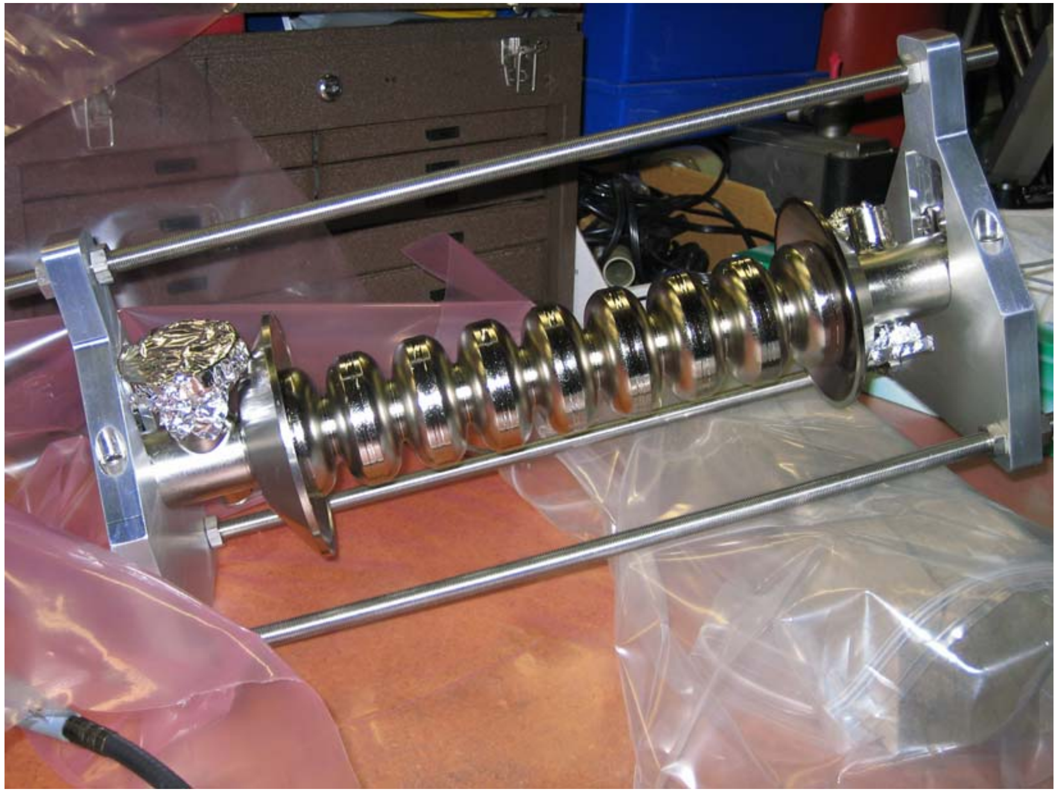
… and beginning 2009

potential installation of 7th module

- for 1.2 GeV (or perhaps 1.3 GeV)
- lasing at 4.4 (3.7) nm

installation of 3rd harmonic rf

- to flatten E-z phase space before bunch compression



Summary

Superconducting technology

- typical cavity gradients > 25 MV/m
- record with 40 MV/m
- average accelerating module gradients of ≈ 27 MV/m reached
- beam reached 1 GeV

Focus shifting towards improving the stability for operation

- beam diagnostics (only two examples presented)
- rf and beam control: $\Delta E/E = 1.6\times10^{-4}$ at first bunch compressor

The effort pays off…

- SASE performance: 6.5 nm reached
- statistics: FEL beam delivery in ~70% of the scheduled time for user experiments

What comes next?