RF電子銃のモニターについて

道園真一郎(STF-LLRF)

- DESY FELのRF電子銃設計
- 電子銃の高周波制御の難点
- 長バンチでの経験＠DESY

第22回RF電子銃会合（July 20, 2010）

RF電子銃の設計

XFEL Meetings 2009 4th October 2009: 236. Meeting
V. Paramonov: RF gun design with improved parameters

http://xfel.desy.de/project_group/meetings/xfel_project_meeting/xfel_meetings_2009/
より引用

Development of RF Gun cavity with improved parameters.

K. Floettmann, Yu. Kalinin**, M. Krasilnikov*,*
*V. Paramonov**, A. Skasyrskaya**, F. Stephan**

Presented by Valentin Paramonov

**- Deutches Elektronen- Synchrotron, DESY, Hamburg, Zeuthen;*
*** - Иinstitute for Nuclear Research of the RAS, Moscow.*

FEL meeting, 04.11.09, DESY, Hamburg

Design requirements.

Electric RF at the cathode Ec = 60 MV/m RF
pulse length τ > 1.0 ms
Average dissipated RF power Pa > 70 kW

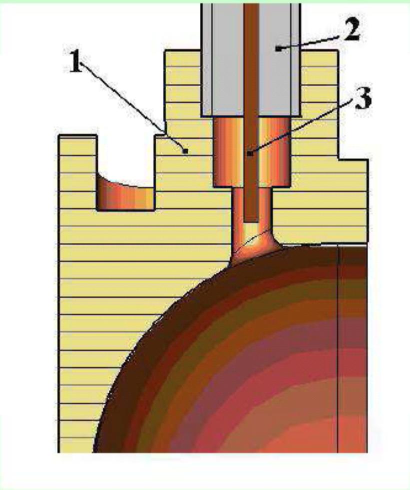
RF probes in each cell

As possible, basing on proven concepts and solutions< taking into account results of previous developments and investigations.

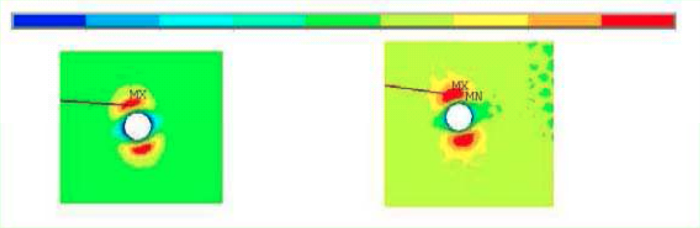
Design of existing RF Gun cavities doesn’t fits

with all requirements.

Probes



RF probe. Field perturbation and pulsed RF heating in the vicinity of probe hole. Temperature rise Ts~ 76 C, internal stresses < 1.55 MPa.



Opposite holes (for quadruple field perturbation) are attractive for vacuum probes.

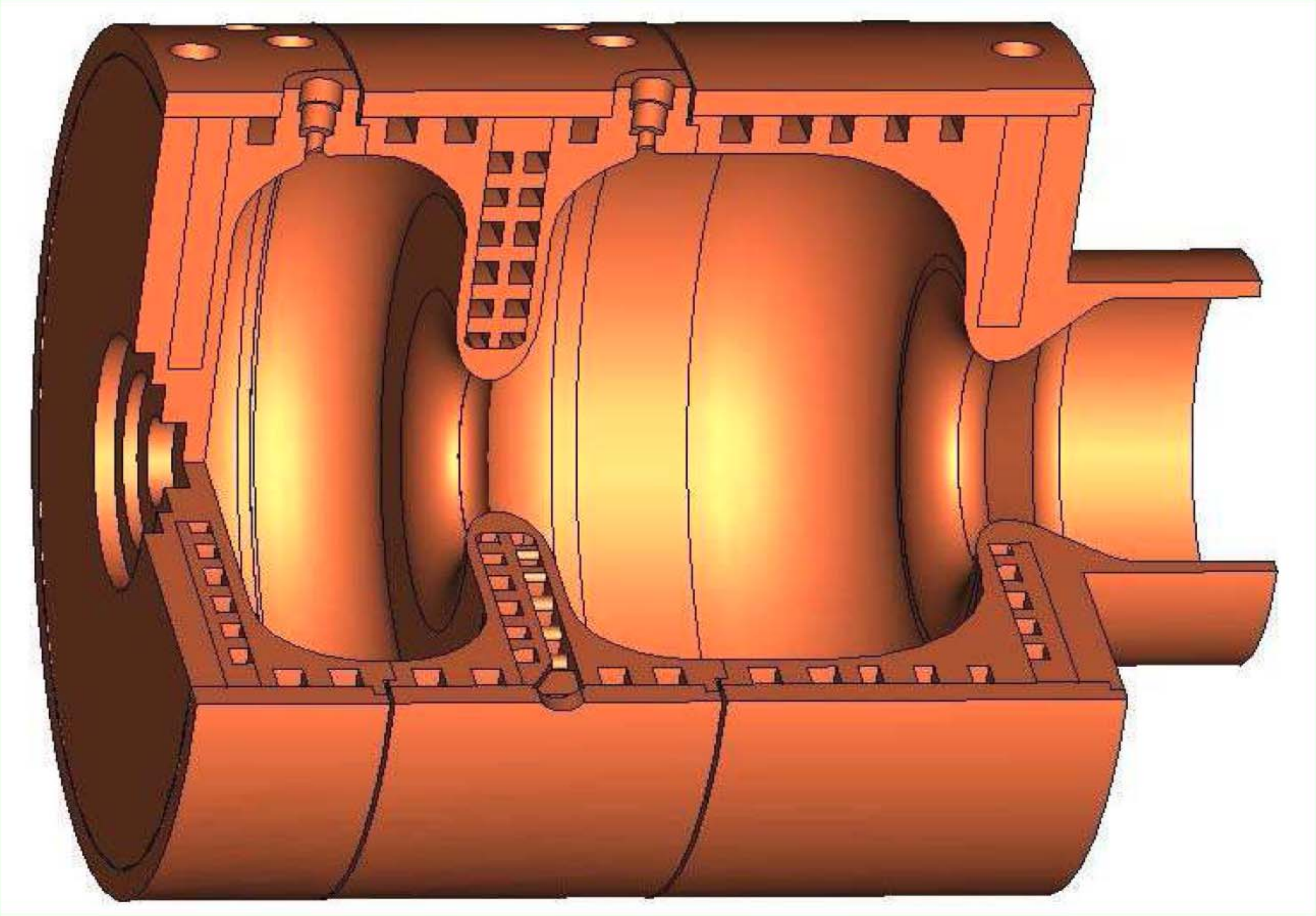
To minimize pulsed RF heating, hole should be as small, as possible.

Vacuum probes are not reasonable.

Parameters comparison

	Gun 4		Gun 5
Esmax, MV/m	72	>20%	60
RF power, MW	6.43	> 4%	6.18
Field stability		< 40%	
RF probes	No		Yes
Pulsed RF heating			
1) deformations		> and more uniform	
2) frequency shift		> 15 %	
Cooling			
number of I/O	14	>	9
Water flow (V=2m/s)	10.5	>	9.0
df/dPa, kHz/kW	-3.52	>	-1.92
Outer radius, mm	114	<	116

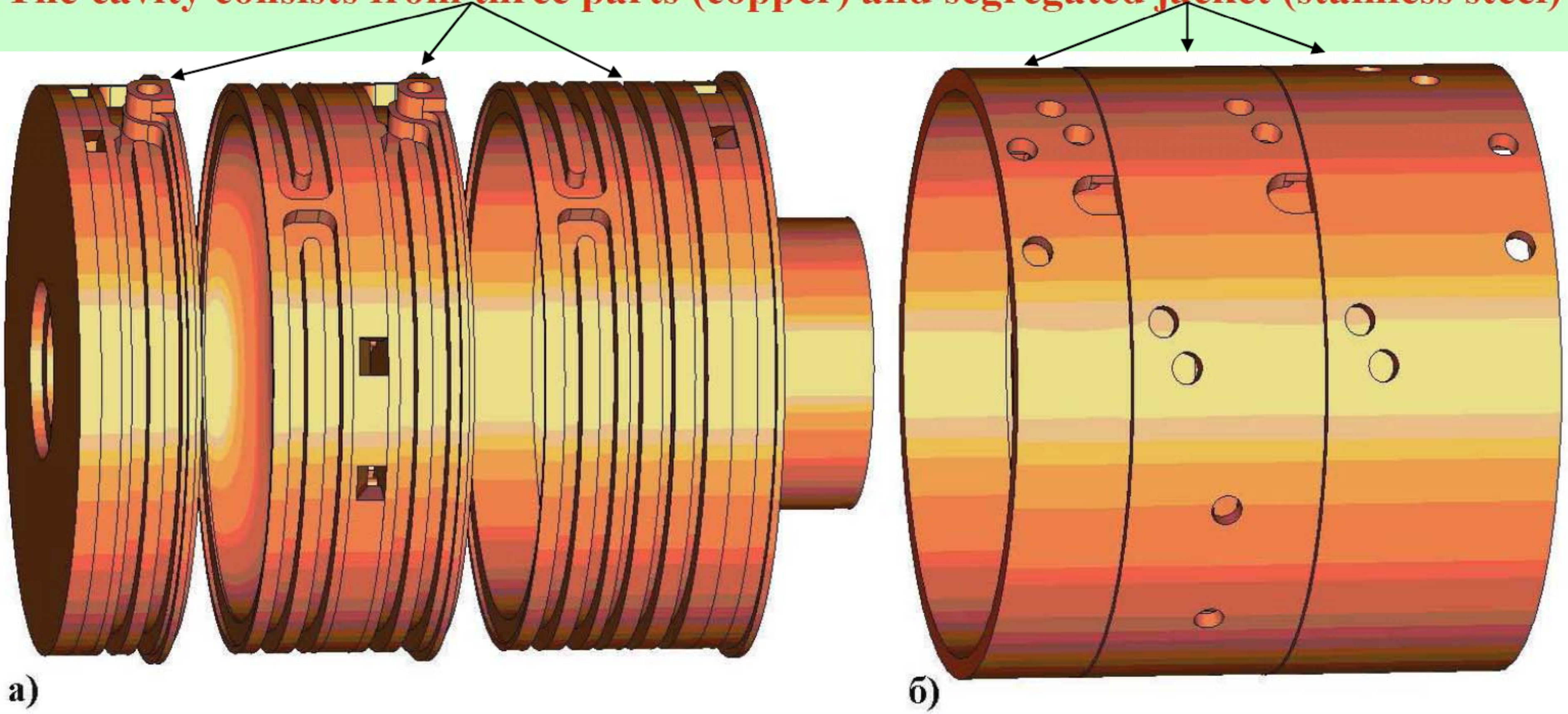
Cavity general view.



The main technical solutions are conserved.

Cavity design.

The cavity consists from three parts (copper) and segregated jacket (stainless steel)



Brazing technique for connections.

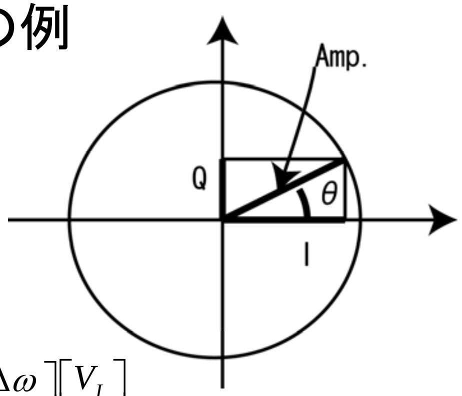
There are no brazed water-vacuum joints.

Conclusion

1. **Physical cavity design is completed.**
2. **Particularity of this development is the careful consideration of mutual influence of different processes in the cavity, operating in the unique combination of long RF pulse, high pulse and average RF power, in order to have optimized and well balanced design.**
3. **As the result, the cavity has a gain, some time not so big, in each parameter separately. But in total, it provides significant cavity advantage with respect existing cavities.**
4. **The cavity completely satisfies to X-FEL specification.**
5. **For X-FEL parameters the proposed cavity will provide at least the relaxed operation.**

デジタル高周波制御系

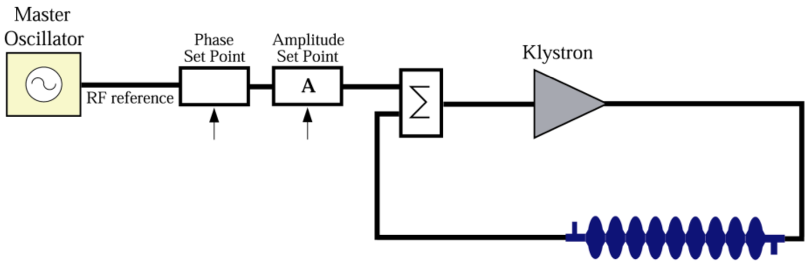
- ✧ 超伝導空洞での例



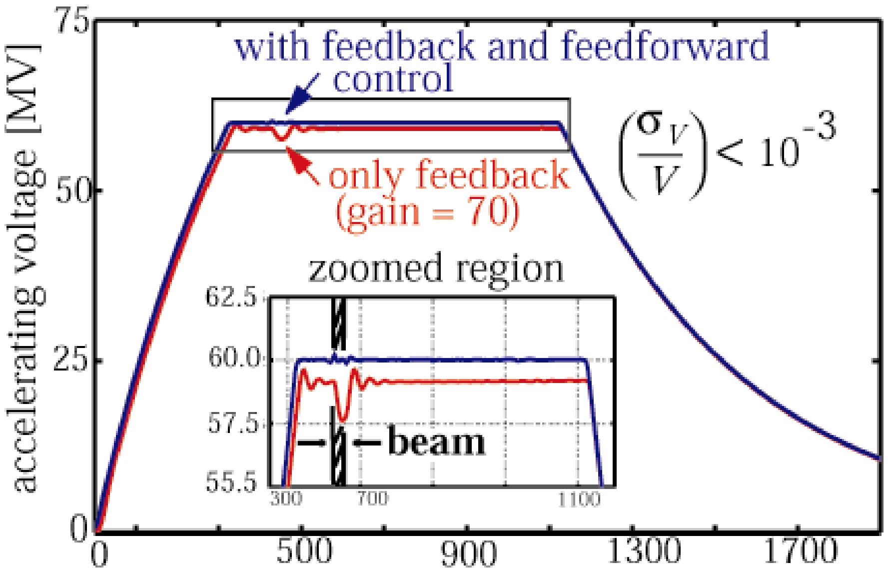
$$\frac{d}{dt}\begin{bmatrix}V_I\\ V_Q\end{bmatrix}=\begin{bmatrix}-\omega_{1/2} & -\Delta\omega\\ \Delta\omega & -\omega_{1/2}\end{bmatrix}\begin{bmatrix}V_I\\ V_Q\end{bmatrix}+\frac{\omega_0}{2}\frac{R}{Q}\begin{bmatrix}I_I\\ I_Q\end{bmatrix} \qquad (9.2)$$

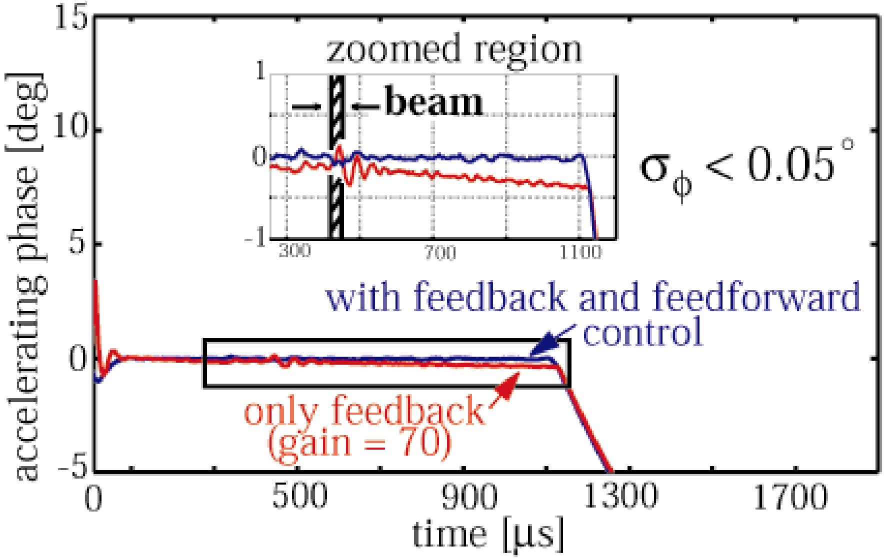
$$\omega_{1/2}=\frac{\omega_0}{Q_l} \qquad (9.3)$$

$$\Delta\omega=\omega_{cavity}-\omega_{rf} \qquad (9.4)$$



“Direct” RF Feedback

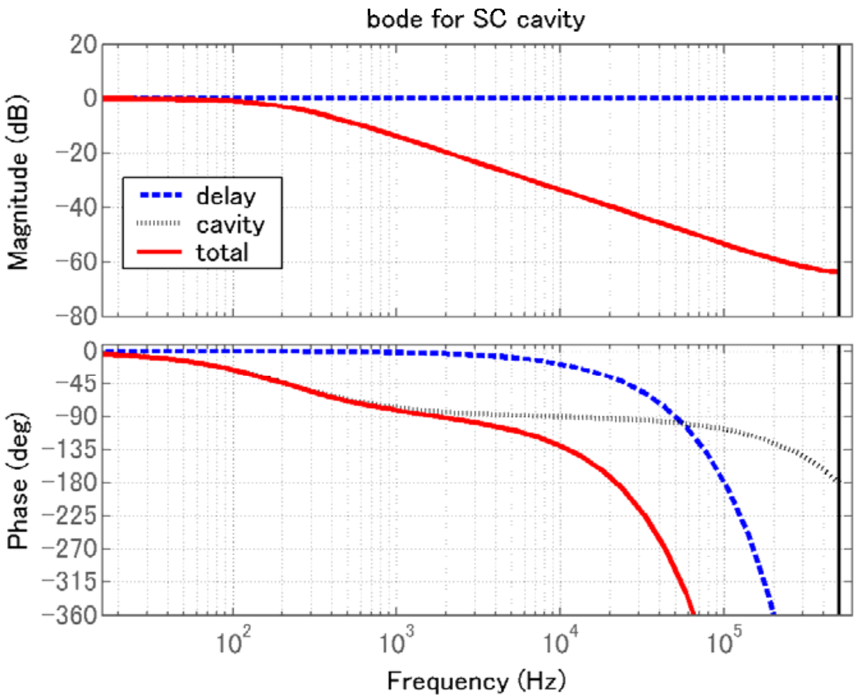


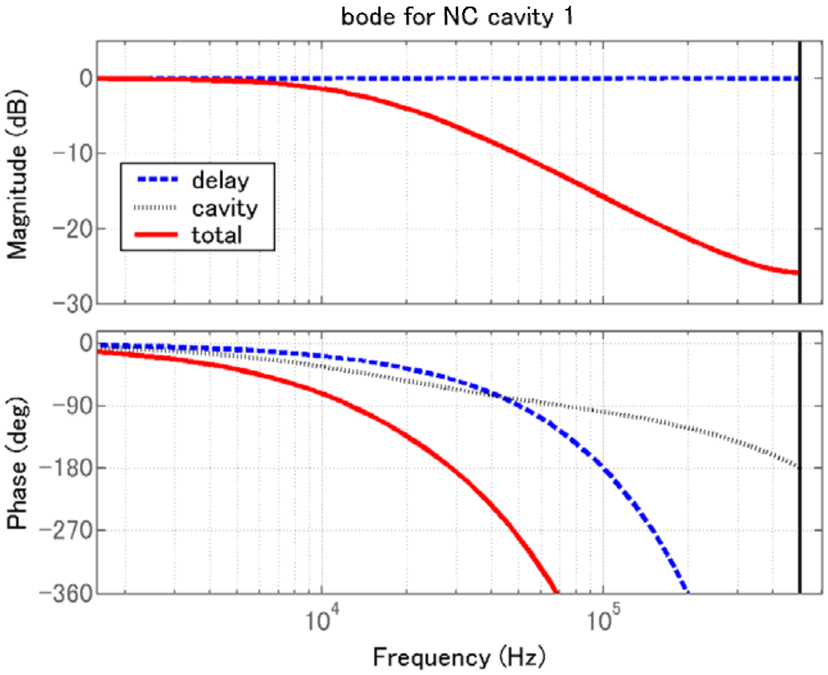


常伝導空洞の制御

- 常伝導空洞では、Q値が小さいため遅れ時間を短くする必要有

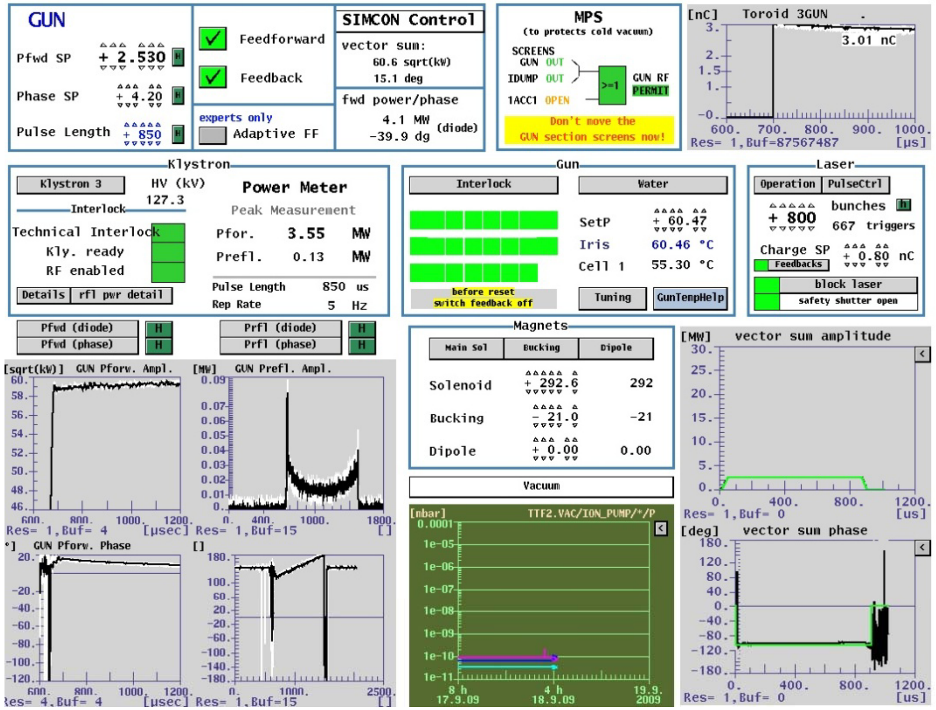
  （超伝導空洞ではわずかなRFの変動に対し，蓄積エネルギーが大きいため変動は小さいが，常伝導空洞では外乱に対する応答がはやくなるため．）
- 超伝導空洞では1e-4台の安定度が見込める（KEK-STF,FLASHなど)が，常伝導では1e-3台（J-PARC linac, SNS)がせいぜい.
- FLASHでも電子銃の安定度は1%，1度程度

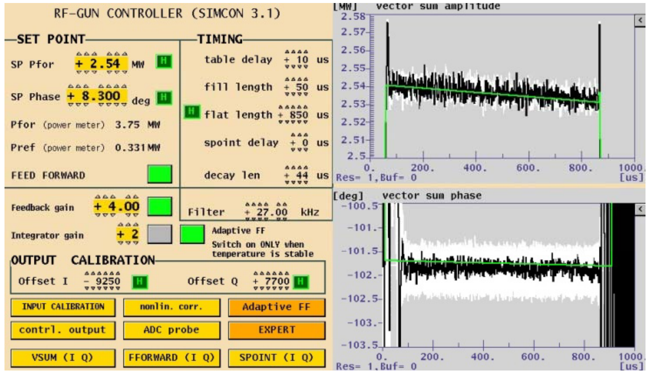


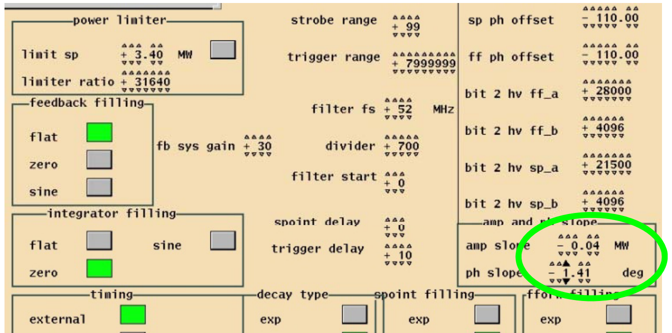


プローブがない場合のRF制御

- Adjust Gun iris temperature and forward power level below from saturation regime, minimize reflected power level, correct loop phase, apply feedback, increase gain, check amplitude and phase slopes (maintain flat vector-sum in amplitude and phase without any slopes)
- Sometimes amplitude phase slope **required** for flat charge trains


GUN
Pfwd SP + 2.530
Phase SP + 4.20
Pulse Length + 850
☑ Feedforward
☑ Feedback
experts only
☐ Adaptive FF
SIMCON Control
vector sum: 60.6 sqrt(kW) 15.1 deg
fwd power/phase 4.1 MW -39.9 dg (diode)
MPS (to protects cold vacuum)
SCREENS GUN OUT
IDUMP OUT
1ACC1 OPEN
GUN RF PERMIT
Don't move the GUN section screens now!
Toroid 3GUN 3.01 nC
Klystron
Klystron 3 HV (kV) 127.3
Interlock: Technical Interlock, Kly. ready, RF enabled
Power Meter — Peak Measurement
Pfor. 3.55 MW
Prefl. 0.13 MW
Pulse Length 850 us
Rep Rate 5 Hz
Gun
SetP + 60.47
Iris 60.46 °C
Cell 1 55.30 °C
before reset switch feedback off
Laser
+ 800 bunches
667 triggers
Charge SP + 0.80 nC
block laser
safety shutter open
Magnets
Solenoid + 292.6 292
Bucking - 21.0 -21
Dipole + 0.00 0.00


RF-GUN CONTROLLER (SIMCON 3.1)
SET POINT
SP Pfor + 2.54 MW
SP Phase + 8.300 deg
Pfor (power meter) 3.75 MW
Pref (power meter) 0.331 MW
FEED FORWARD
Feedback gain + 4.00
Integrator gain + 2
Adaptive FF Switch on ONLY when temperature is stable
TIMING
table delay + 10 us
fill length + 50 us
flat length + 850 us
spoint delay + 0 us
decay len + 44 us
Filter + 27.00 kHz
OUTPUT CALIBRATION
Offset I - 9250
Offset Q + 7700


power limiter
limit sp + 3.40 MW
limiter ratio + 31640
feedback filling: flat, zero, sine
fb sys gain + 30
strobe range + 99
trigger range + 7999999
filter fs + 52 MHz
divider + 700
filter start + 0
spoint delay + 0
trigger delay + 10
sp ph offset - 110.00
ff ph offset - 110.00
bit 2 hv ff_a + 28000
bit 2 hv ff_b + 4096
bit 2 hv sp_a + 21500
bit 2 hv sp_b + 4096
amp and ph slope
amp slope - 0.04 MW
ph slope - 1.41 deg
integrator filling: flat, sine, zero
timing: external, internal
decay type: exp, sine
spoint filling: exp, sine
fforw filling: exp, sine

Injector beam control studies winter 2006/07

talk from E. Vogel
on work performed by

W. Cichalewski, C. Gerth, W. Jalmuzna,W. Koprek, F. Löhl,
D. Noelle, P. Pucyk, H. Schlarb, T. Traber, E. Vogel, …

FLASH Seminar at June 19th 2007

電子銃部の制御　空洞ピックアップがない場合.

Injector beam control studies winter 2006/07　　FLASH Seminar, June 19th 2007

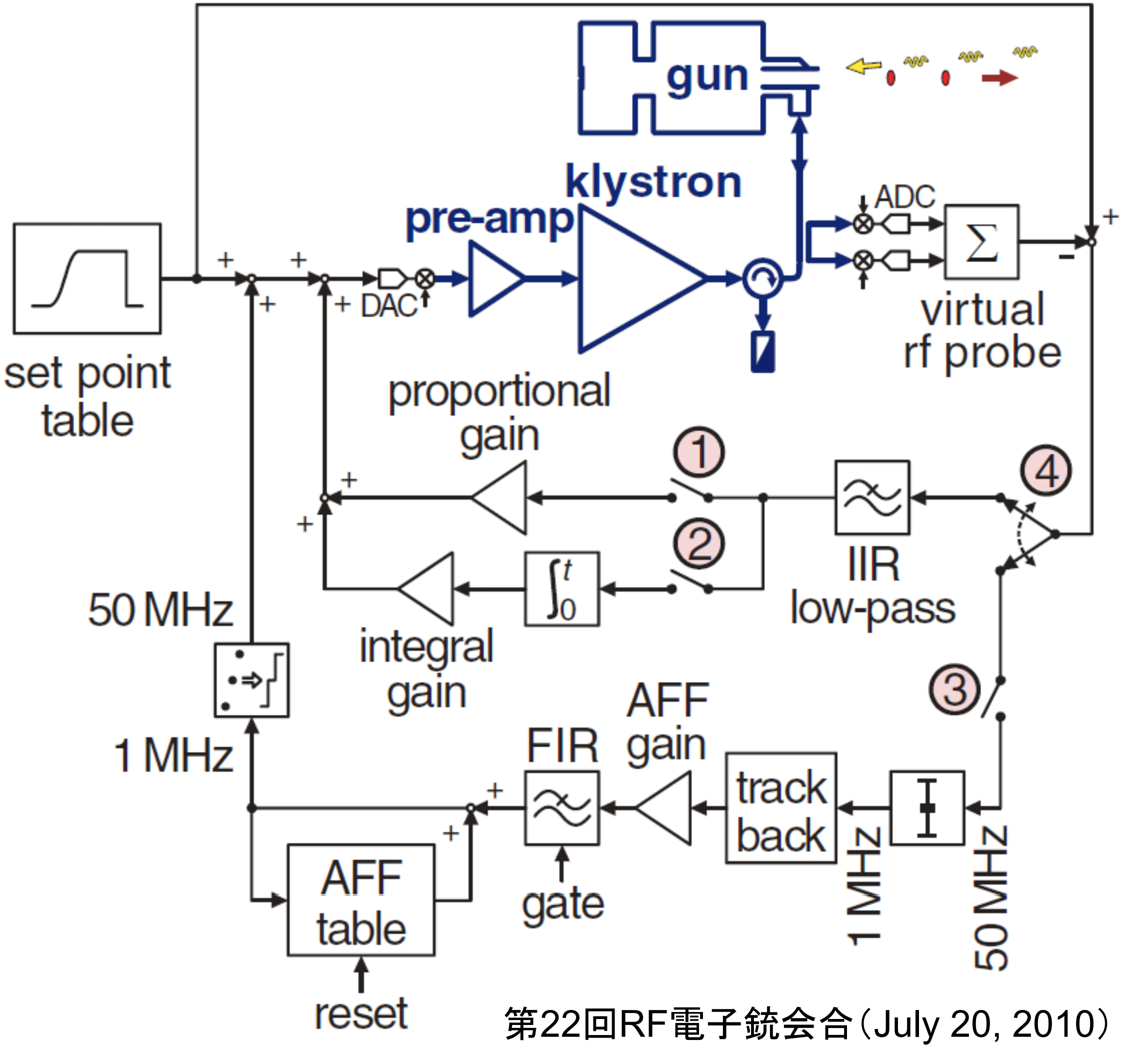
Rf control by SimCon 3.1 and sophisticated algorithms

Implications of missing 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



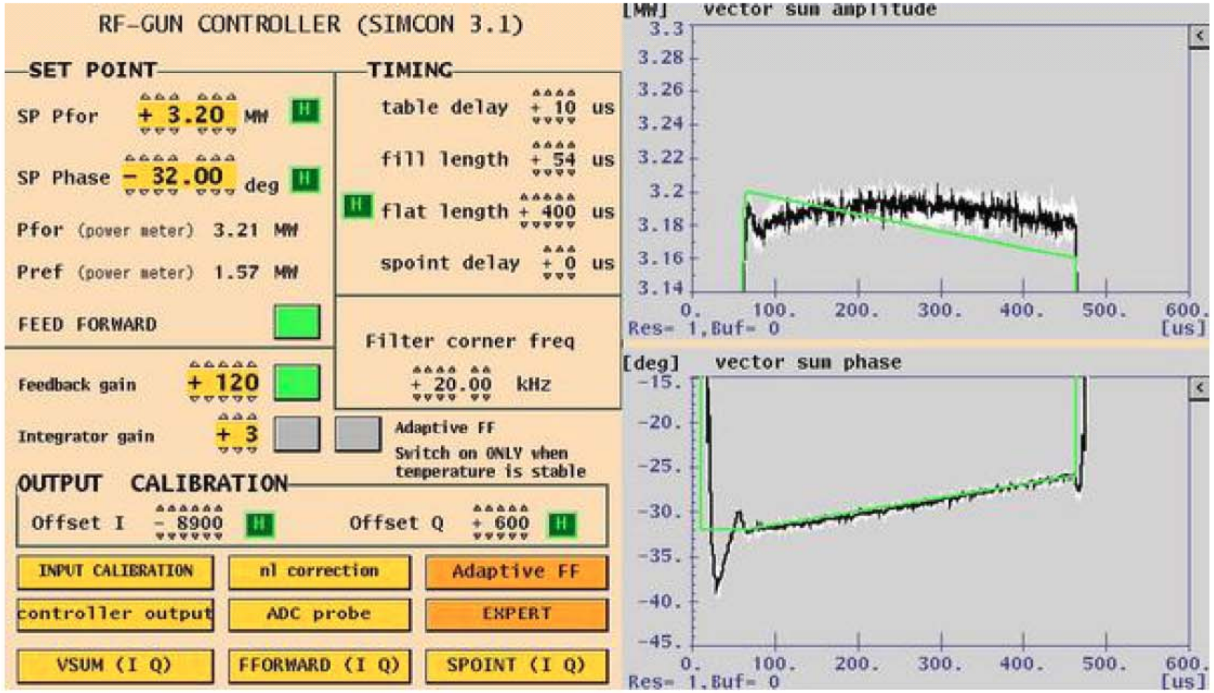
The gun rf phase slope feature

Potential sources of emission phase slopes:

- uncertainties in probe calibration
- gun laser pulse arrival time changes
- drifts due to wave guide heating (distance between directional coupler and gun)
- and so on…

Countermeasures:

- slope at gun laser arrival time changing 1.3 GHz MO EOM phase
- phase slope at gun rf:



RF-GUN CONTROLLER (SIMCON 3.1)

SET POINT

SP Pfor + 3.20 MW

SP Phase - 32.00 deg

Pfor (power meter) 3.21 MW

Pref (power meter) 1.57 MW

FEED FORWARD

Feedback gain + 120

Integrator gain + 3

TIMING

table delay + 10 us

fill length + 54 us

flat length + 400 us

spoint delay + 0 us

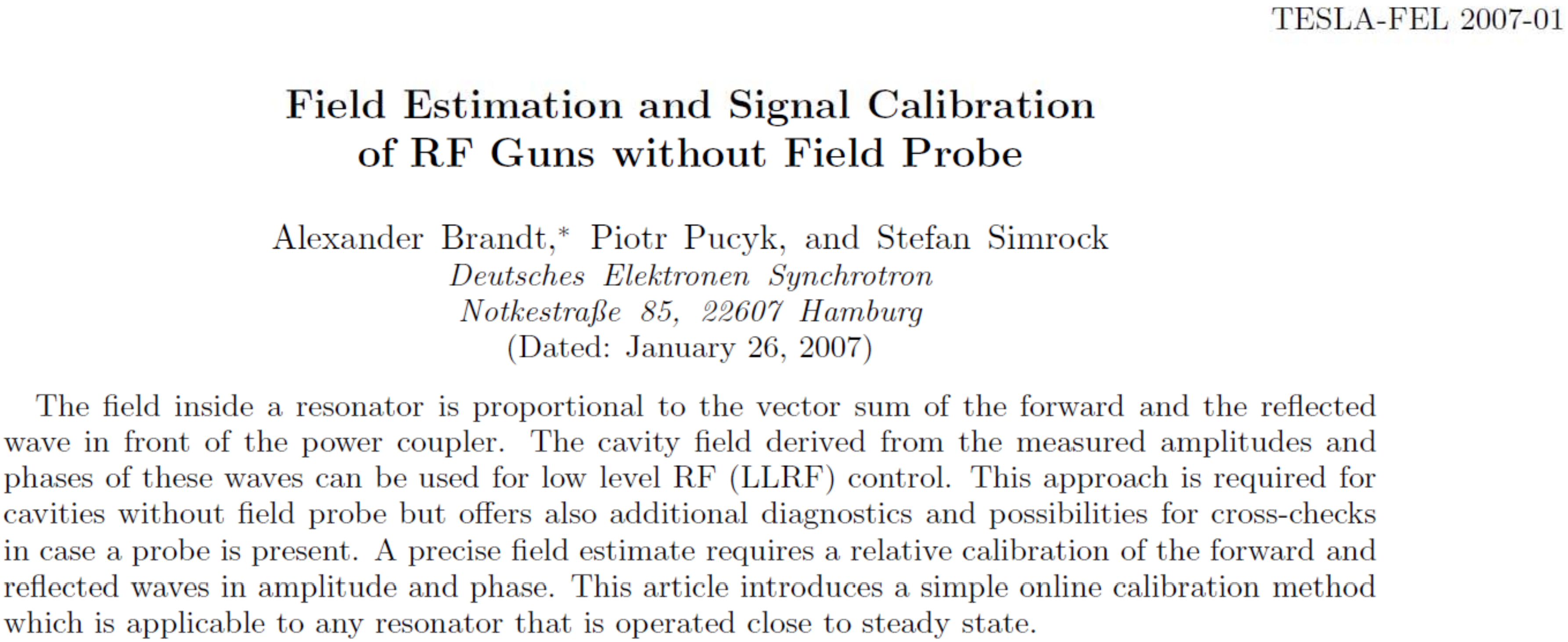
Filter corner freq + 20.00 kHz

Adaptive FF Switch on ONLY when temperature is stable

OUTPUT CALIBRATION

Offset I - 8900

Offset Q + 600



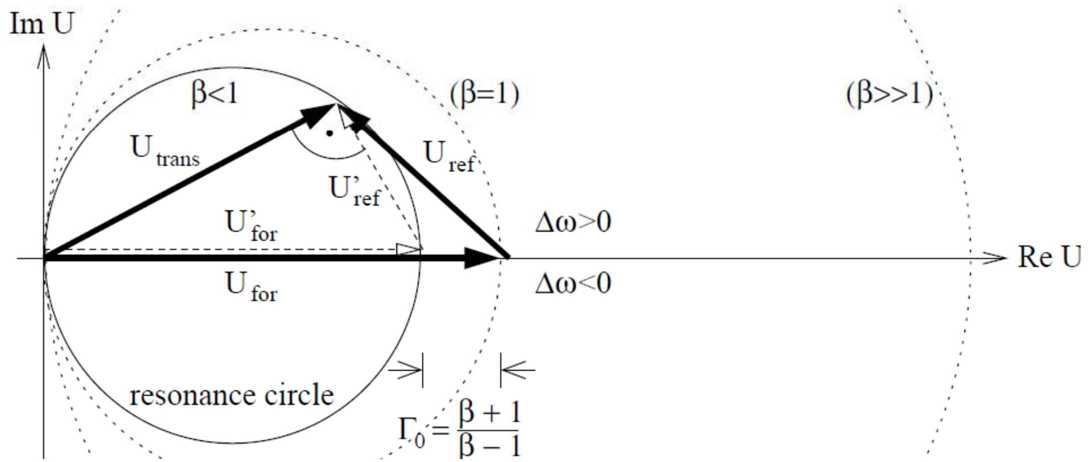
TESLA-FEL 2007-01

Field Estimation and Signal Calibration of RF Guns without Field Probe

Alexander Brandt,* Piotr Pucyk, and Stefan Simrock
Deutsches Elektronen Synchrotron
Notkestraße 85, 22607 Hamburg

(Dated: January 26, 2007)

The field inside a resonator is proportional to the vector sum of the forward and the reflected wave in front of the power coupler. The cavity field derived from the measured amplitudes and phases of these waves can be used for low level RF (LLRF) control. This approach is required for cavities without field probe but offers also additional diagnostics and possibilities for cross-checks in case a probe is present. A precise field estimate requires a relative calibration of the forward and reflected waves in amplitude and phase. This article introduces a simple online calibration method which is applicable to any resonator that is operated close to steady state.



空洞電界の推定を，空洞入力と空洞反射から行っているが，

○　入力反射の位相を含めた校正（絶対値と位相）が完全でないと空洞電界がずれる.

○　空洞入力，反射のポートの方向性が悪いと2つの信号が混ざる.

○　モニターと空洞との距離が熱で変化するとそのまま測定誤差となる.

○　5%，5度の校正エラーは0.6%，0.2°の空洞エラーとなる.

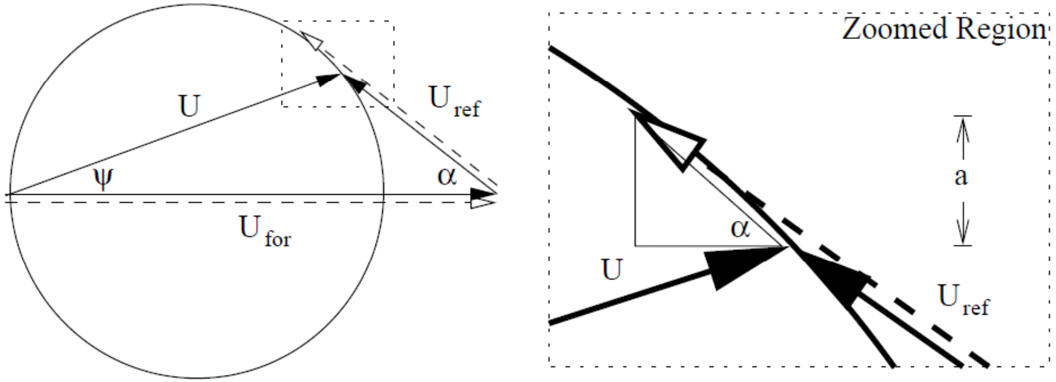
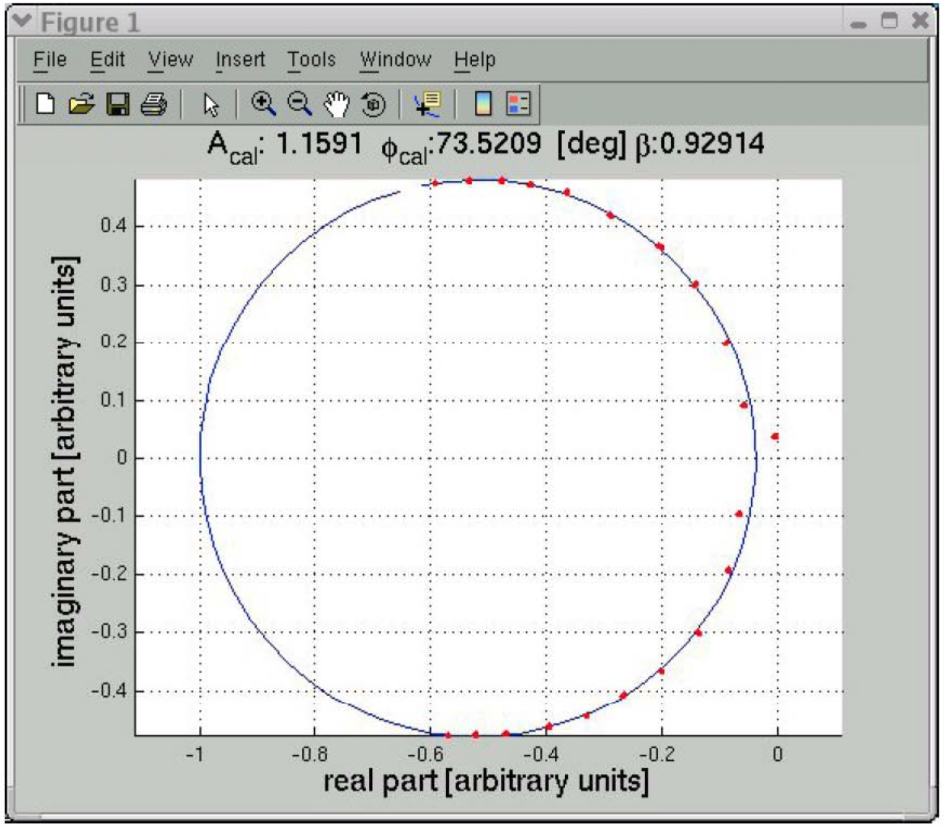


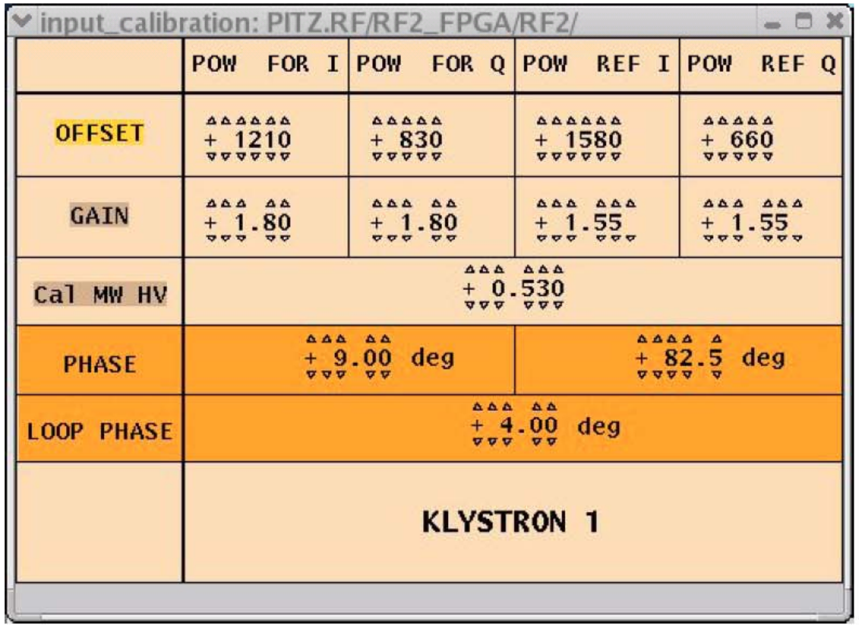
FIG. 2: Vector constellation in a complex plane for approximating the errors on the constructed cavity field. The dashed arrows represent the measurements made by the controller, e. g. a DSP. The solid arrows are the real values. In this simplified example, the measured forward vector coincides with the real forward vector, while the measured reflected vector has an error in amplitude compared to the real reflected vector.

Virtual probe signal calibration (method established at FLASH by A. Brandt)

circle fitting after frequency variation



DOOCS panel for
calibration parameters


input_calibration: PITZ.RF/RF2_FPGA/RF2/

	POW FOR I	POW FOR Q	POW REF I	POW REF Q
OFFSET	+ 1210	+ 830	+ 1580	+ 660
GAIN	+ 1.80	+ 1.80	+ 1.55	+ 1.55
Cal MW HV	+ 0.530			
PHASE	+ 9.00 deg		+ 82.5 deg	
LOOP PHASE	+ 4.00 deg			
	KLYSTRON 1			

Plots taken at PITZ - the plots and panels look similar at FLASH!

Workshop report: Linac Operations with Long Bunch-trains (Held at DESY: 22-24 February 2010)

1st lasing at TTF
22nd Feb 2000

JOHN CARWARDINE
ON BEHALF OF MANY COLLEAGUES

28 APRIL, 2010

https://indico.desy.de/conferencedisplay.py?confid=2576

Long bunch-train studies at TTF/FLASH

2009	FLASH (typical for users)	1-30 bunches	≤1nC	lasing

2002	TTF	3MHz	750 bunches	2.8nC	
2006	TTF2/FLASH	1MHz	800 bunches	0.8nC	(400 lasing)
2007	TTF2/FLASH	1MHz	800 bunches	0.6nC	lasing
2008	TTF2/FLASH	1MHz	550 bunches	2.7nC	9mA exp.
2009	TTF2/FLASH	1MHz 3MHz	800 bunches 2400 bunches	3nC 2nC	9mA exp

- Fundamental to the advantage of the TESLA SCRF technology
- Proof of principle has been long established
- Long bunch-train operation always characterised by difficult set-up
- ‘9mA’ studies are focused on **operational limits** (pushed by ILC requirements)

Injector setup

- It is evident from the simulations that we were running close to full compression at the end of the bunch train

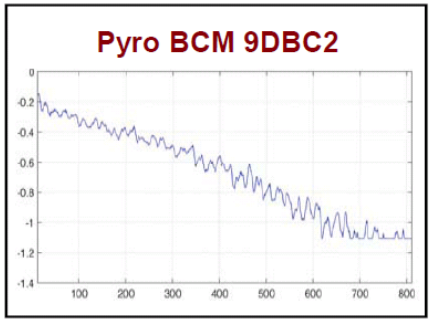
- Tuning in practice
  - Phase slopes in the gun and laser during the pulse make tuning particularly difficult
  - Phase and amplitude slopes on the gun and modules are necessary in order to achieve a relatively flat energy profile… but stable time of arrival and bunch compression must also be maintained
  - Accurate information about on-crest phases is essential
  - Many factors consire against simple tuning & setup of the laser, gun, and LLRF (especially with heavy beam loading)
  - Significant improvements in stabilization and repeatability are anticipated from beam-based feedback on time of arrival and bunch compression (being implemented)

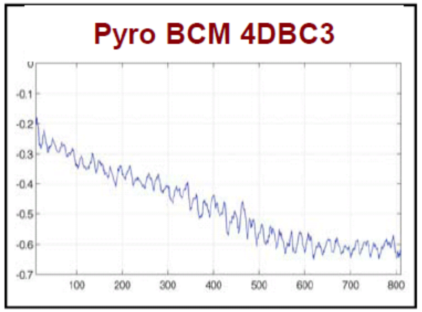
- Should explore the impact of running with 3nC bunch charge

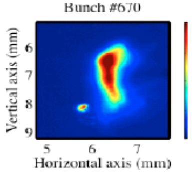
Injector setup – compression

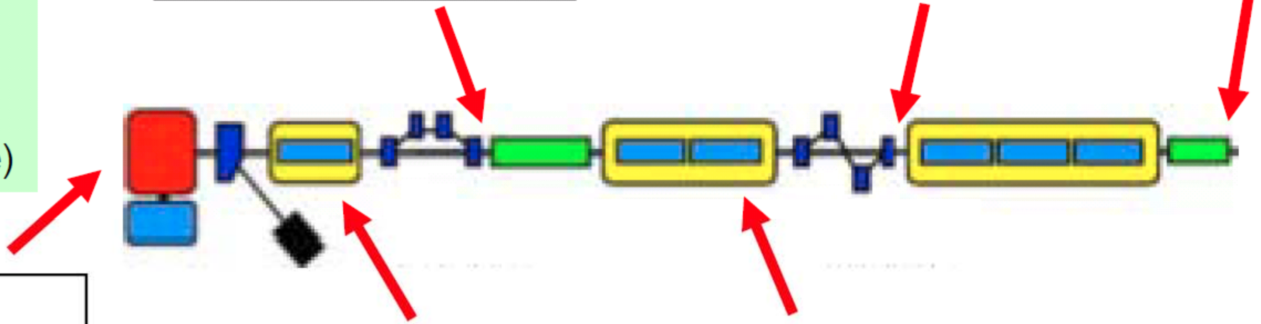
Pyros BCMs show the bunch compression increases over the train

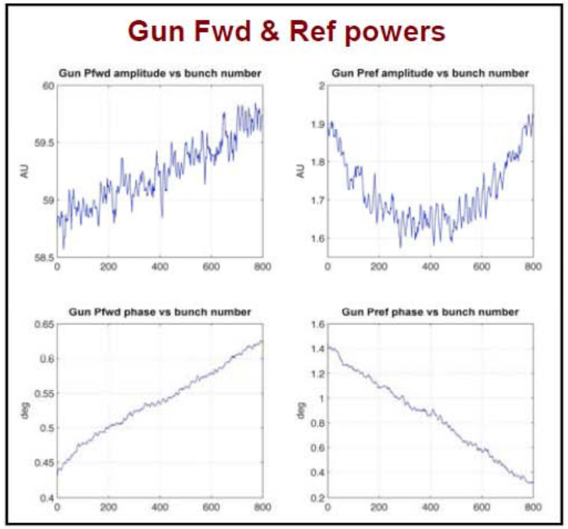
Gun, ACC1, and ACC23 phase setpoints include slopes to compensate for phase slopes in the gun and laser (delicate balance)

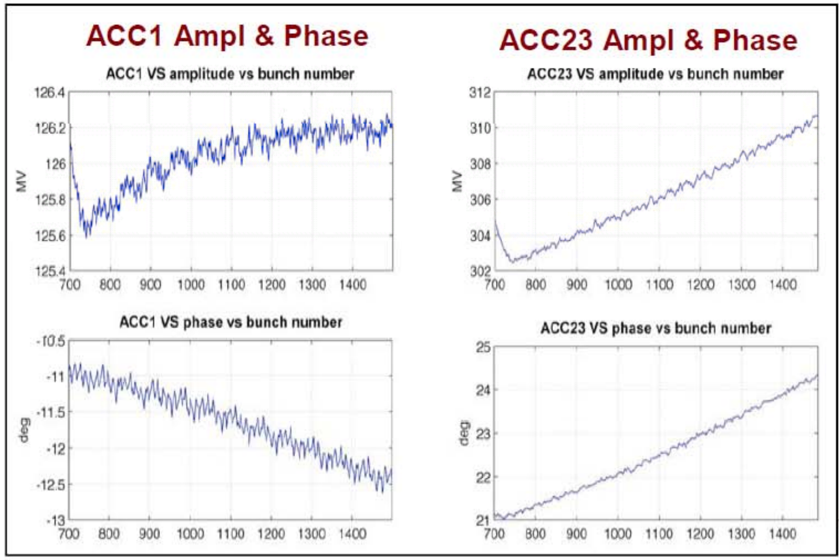












Requirements for user experiments

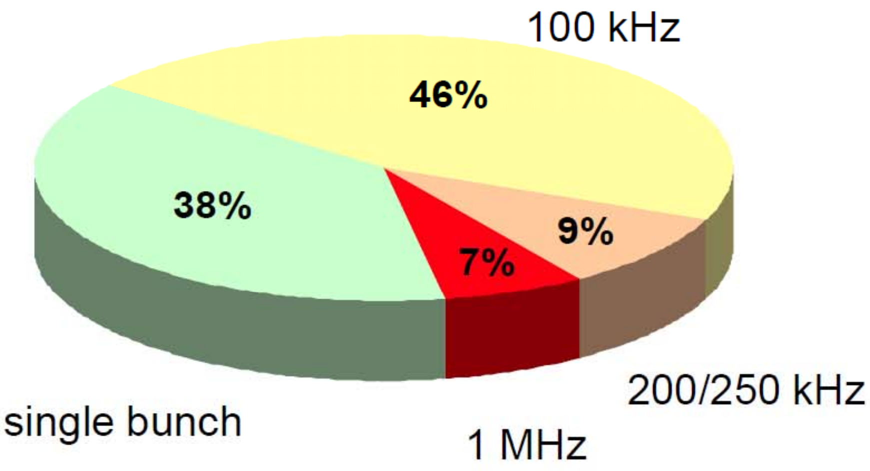
FLASH.
Free-Electron Laser in Hamburg

- ~50% of experiments need pulse trains
- ~50/50 need 100 kHz / 0.5-4.5 MHz
- most 100 kHz want 80 pulses per train (=800µs)
- ~25% need multi-bunch and narrow bandwidth
- ~13% request max. no. pulses at ≥1MHz
- >50% request ≤13.5 nm wavelength

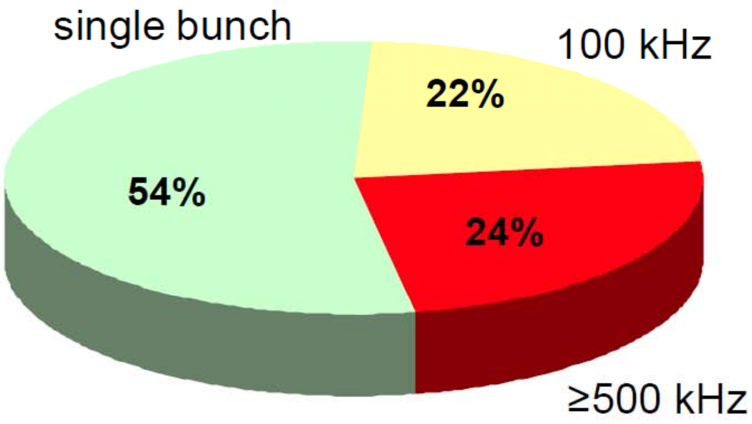
Many users want longer bunch trains …but not if they lose reliability or single-bunch performance

---

FLASH operation May-Aug 2009



Operation Aug 2010 – Sep 2011



まとめ

■ DESY FELのRF電子銃設計

→　XFEL用はRFプローブつき

■ 電子銃の高周波制御の難点

→　校正が完全ではない. 空洞電圧の推定に限界有.

■ 長バンチでの経験＠DESY

→　RF電子銃は通常は30us, 30バンチ運転. 800usのビームにするにもかなり調整が必要. 電子銃空洞の位相変化も一つの要因.

→ ビーム制御の観点からも空洞電界モニターは必要