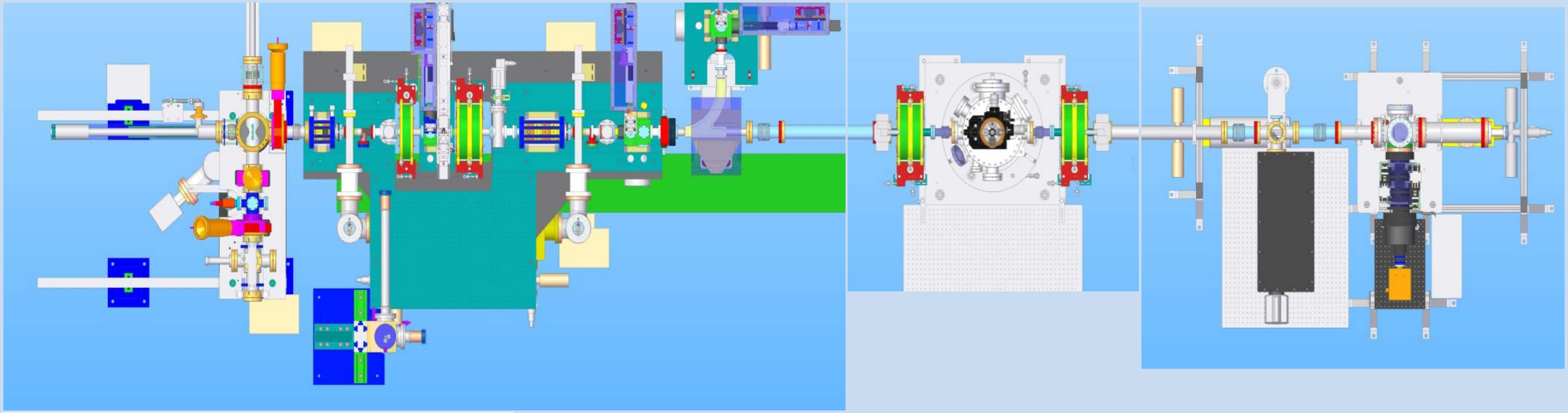
# *Diagnostics at REGAE Facility*

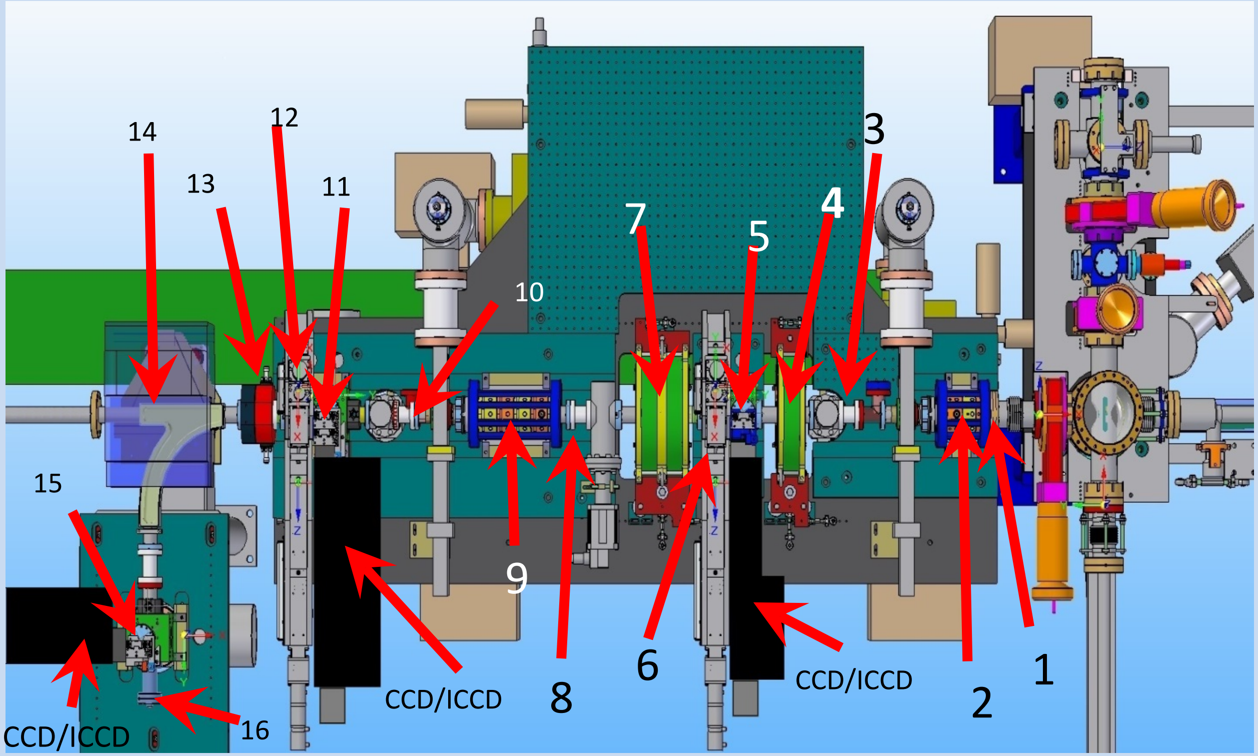
*Ultrafast Beams and Applications, 04-07* July 2017
*CANDLE, Armenia*

H. Delsim Hashemi
For REGAE team

# REGAE layout



| No. | Beam-line element | Position (mm) |
|---|---|---|
| 1 | Cathode | 0 |
| 2 | Gun center | 41 |
| 3 | Steerer pair 1 | 352 |
| 4 | Solenoid 1 | 550 |
| 5 | Faraday cup and<br>Profile monitor screen | 693 |
| 6 | Collimator 1 | 773 |
| 7 | Solenoid 2 | 930 |
| 8 | Steerer pair 2 | 1192 |
| 9 | Buncher | 1360 |
| 10 | Steerer pair 3 | 1654 |
| 11 | Faraday cup and profile monitor screen | 1899 |
| 12 | Collimator 2 | 1979 |
| 13 | Cavity monitor | 2069 |
| 14 | Energy spectrometer dipole | 2369 |
| 15 | Profile monitor screen | 2369 |
| 16 | Faraday cup | 2369 |



## REGAE electron beam

Energy: 2 – 5 MeV

Energy spread: 0.1%

Charge: sub pC ( few fC to some 100 pC)

Length: sub ps (at the moment down to 10 fs and scenarios for even shorter bunches)

Rep-rate: up to 50 Hz (sub harmonics are possible:  25, 12.5, 10 and 5)

Transverse size: sub mm (below 100 µm rms is also measured)

Diffraction image size: several mm (10x10 mm to 40x40 mm are measured)

# **REGAE diagnostics**:

- Charge measurement ( fC to several hundred pC) ✓
- Energy and energy spread measurement ✓
- Transverse profile ✓
- Diffraction images ✓
- Electron bunch length ☐ …
- Arrival time ☐ …

## **Charge measurement**:

- Faraday cup (electron beam and dark charge measurement)
- Cavity monitor
- Charge from profile monitors

## **Profile monitors**:

- Scintillator screen (LYSO and/or FOS)
- Lens coupling
- Image intensifier option
- Detector (room temperature CCD, cooled-chip EMCCD and sCMOS Neo)

## **Energy and energy spread**:

- Horizontally deflecting dipole, calibrated 90 degrees kick vs. magnet current
- Ordinary REGAE-profile-monitor station

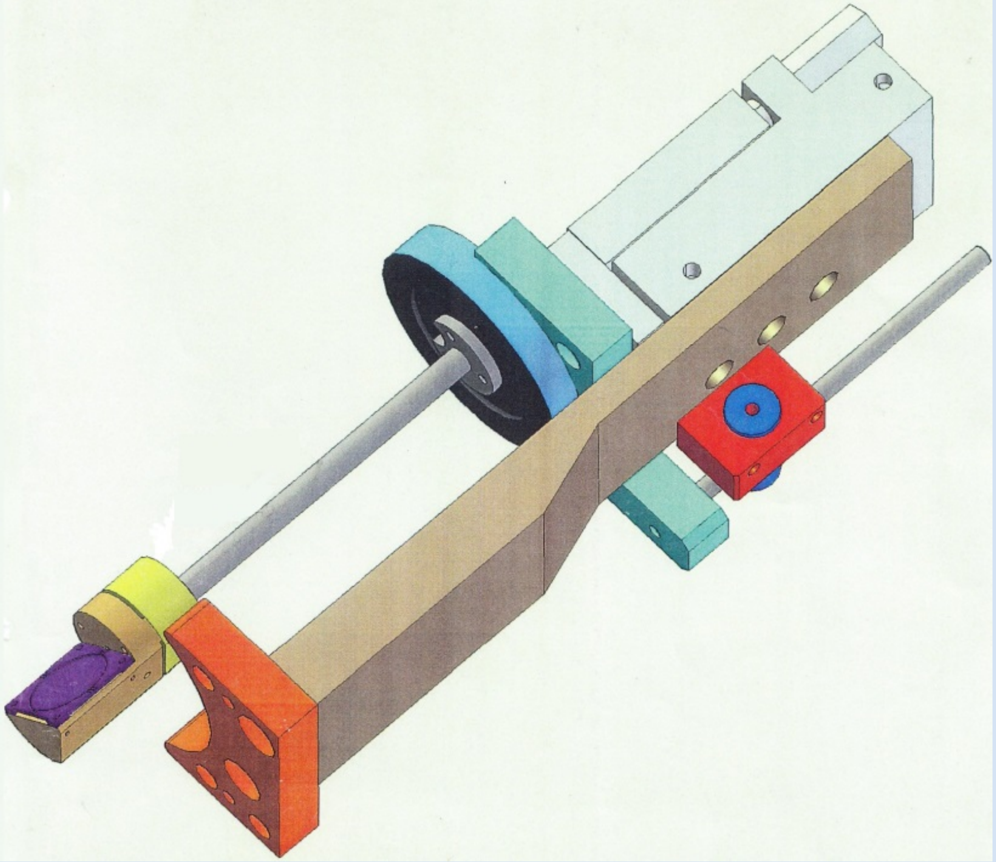
## **Electron bunch length**:

- Transverse deflecting structure (specially designed for few MeV)

# *Electron beam and dark charge measurement*

**Faraday cup**:

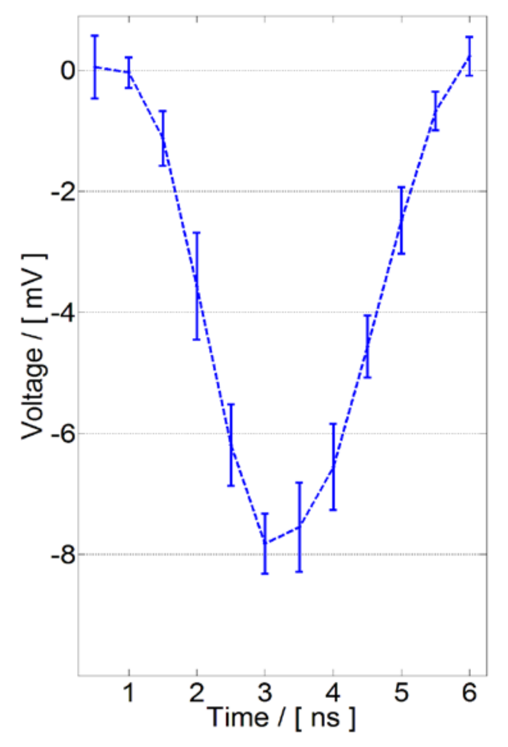
As the most ordinary tool to measure charge, REGAE uses the well-known principle of a Faraday cup. The design of the Faraday cups, adopted from FLASH, employs a copper block which at the same time can be used as a holder for a scintillator thus enabling simultaneous charge measurements and transversal diagnostics. REGAE has four Faraday cups, each of which can be used to measure the electron beam charge as well as dark current (if the selected cup is equipped with an amplifier).



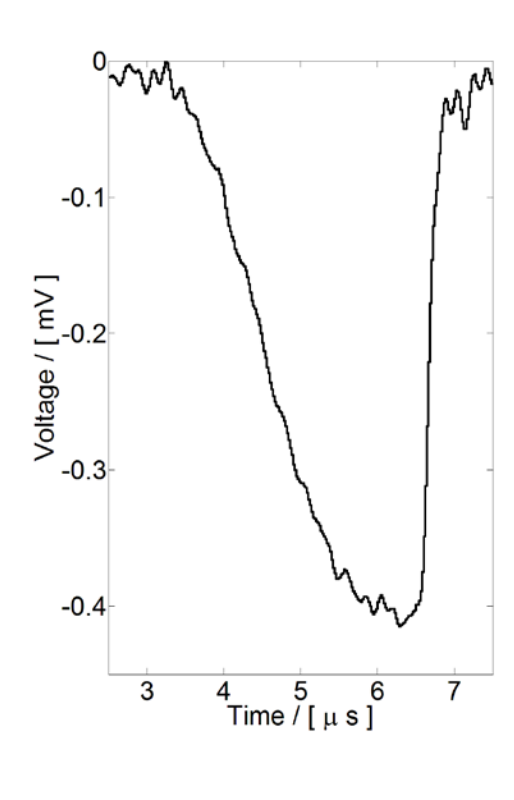
See: IBIC2013 proceedings, WEPF24

# *Electron beam and dark charge measurement*

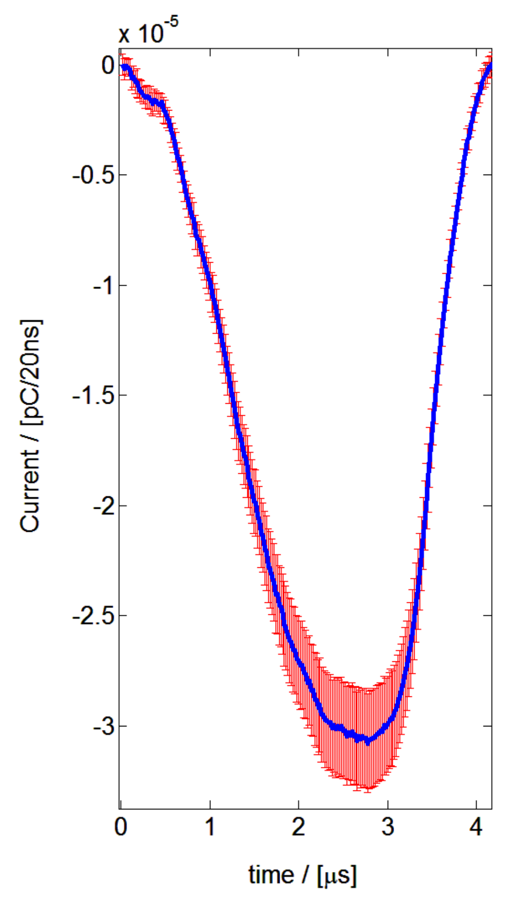
**Electron-beam charge**: Voltage signal from Faraday cup in bunch charge mode. Here an average over 5 shots is shown. For electron beam charge measurements the cups yield voltage pulses of about 5 ns long and a height of 33 mV/pC (with 50 Ohm impedance) resulting in a large dynamic range of a few tens of fC to 100pC.



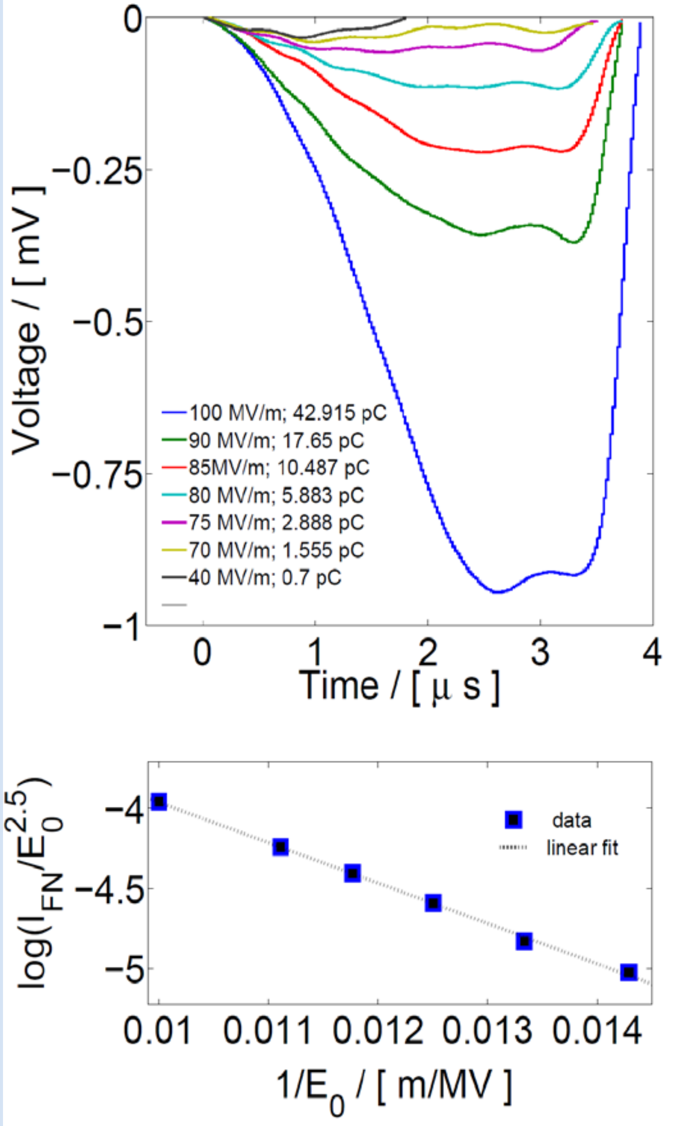
**Dark-current**: Voltage signal from Faraday cup in dark current mode. Here a single shot with a sampling rate of 50 MHz is shown. Signal to noise ratio is clearly very good.

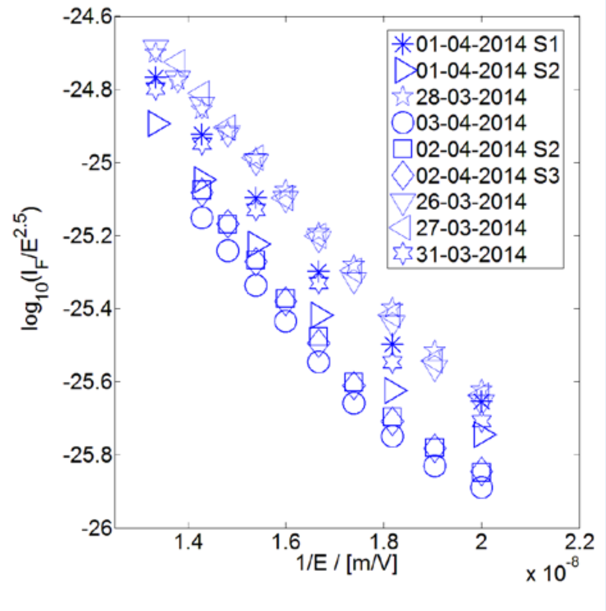


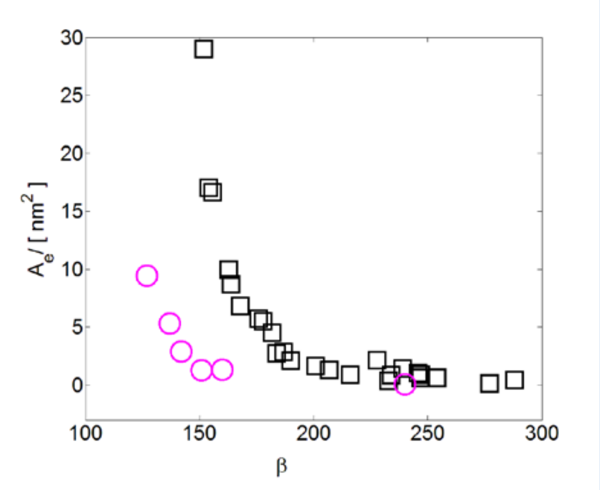
A recent measurement with the new gun. Error bars are std over averaged shots which is shown in blue.



# *Dark charge measurement*

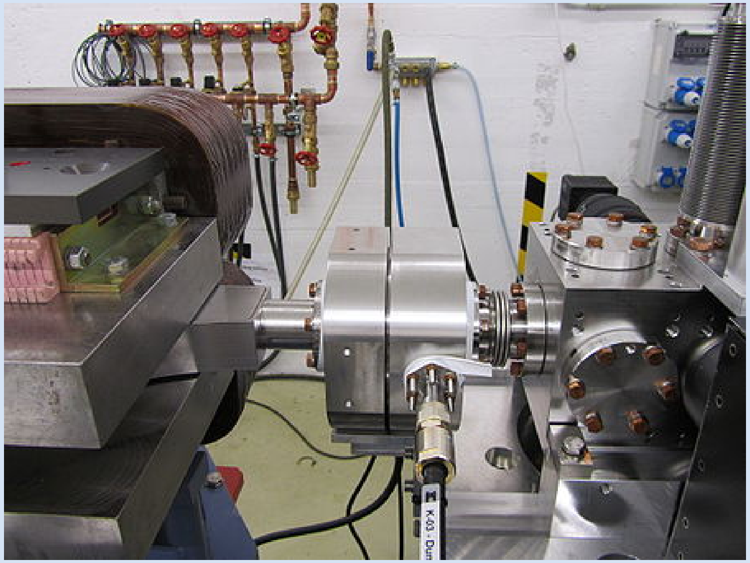






See: IPAC2014 proceedings, MOPRI027

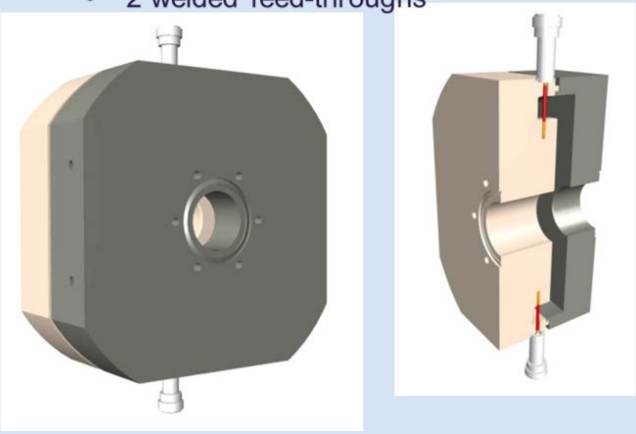
# *Cavity charge monitor*



- Monopole mode with 1.3 GHz and $Q_L$=205 design;
- Dark current will superimpose induced field in cavity to a measurable level when acceleration with 1.3 GHz.
- In addition charge measurement.
- Developed electronics with logarithmic detector for high dynamic range.

FLASH/PITZ and European XFEL design

- 34 mm inner tube diameter
- 8 cm length
- 2 welded feed-throughs



DaMon Live Panel

Acquisition Status: ok

640 ms

Ymax 0.6

XScale 5 min

Ymax 1.0

Ymin -1.0

○ Trace Sequence (8 x 2.5us)
● Trace average (1 x 2.5us)

☑ Show Reference

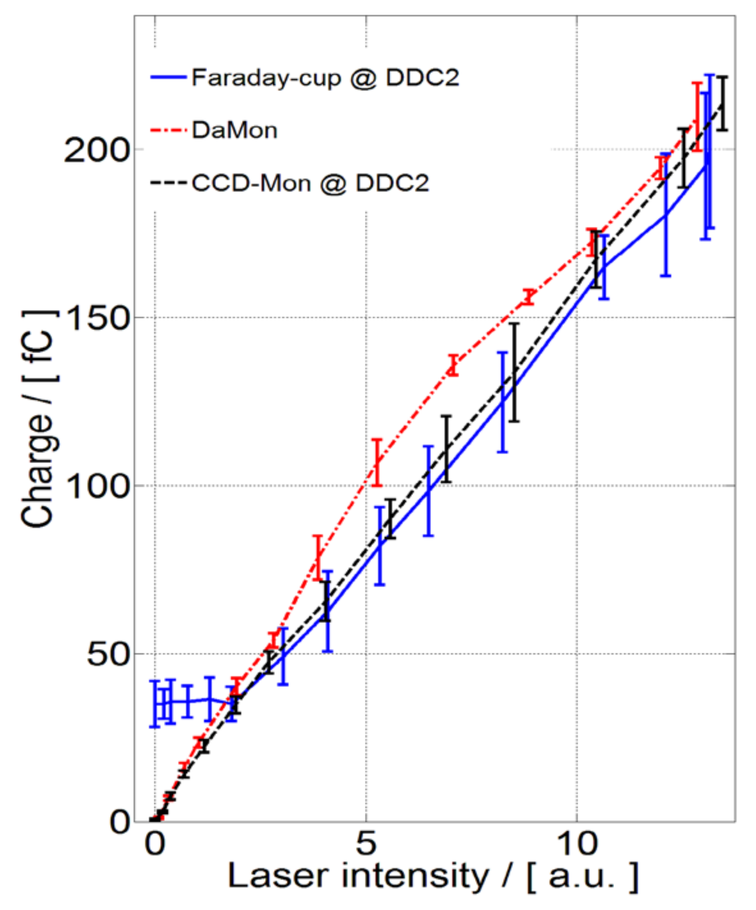
DaMon1 0.29 pC

DaMon2 0.277 pC

See: IBIC2013 proceedings, WEPF25

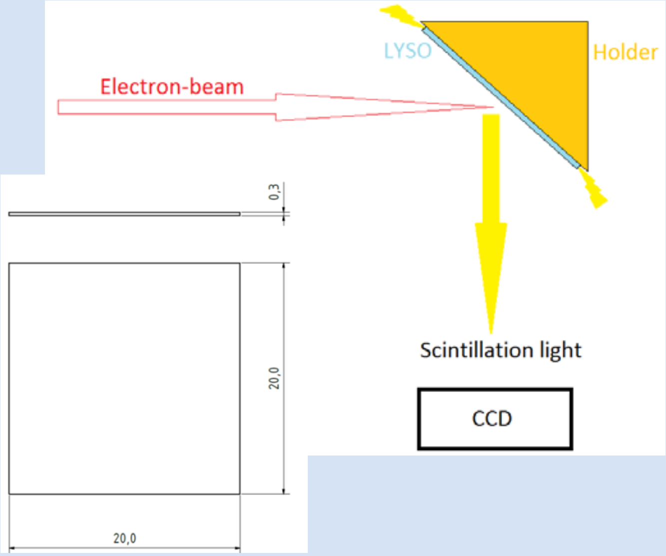
# **Charge from profile monitor**:

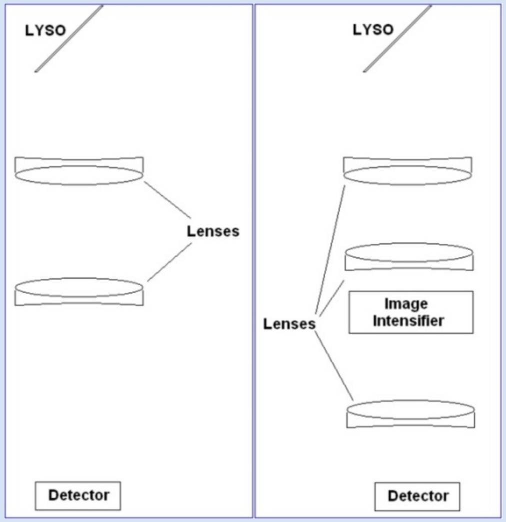
Here a typical charge measurement with cavity-charge-monitor, Faraday cup and a calibrated CCD-Monitor at DDC2 as function of the laser intensity is shown. An average of 10 shots for each measurement point is plotted. Calibration of the CCD-monitor is performed with other monitors like the cavity-monitor where it still give decent signal. Assuming linearity this can be extended to ultra-low-charges down to the fC level.

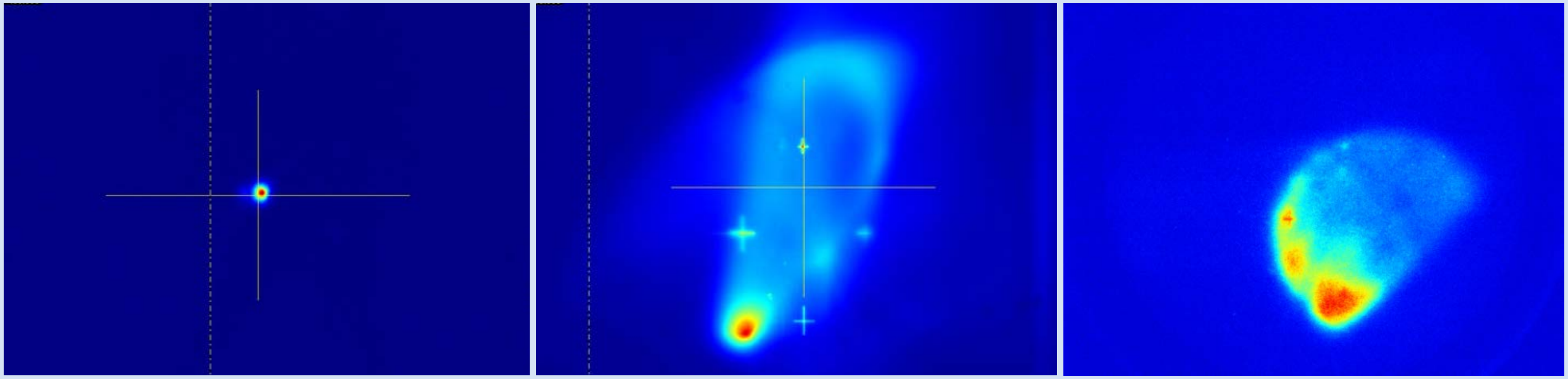


See: IBIC2013 proceedings, MOPF06

# *Sub pC transversal profile montoring*







See: DESY-THESIS-2014-042

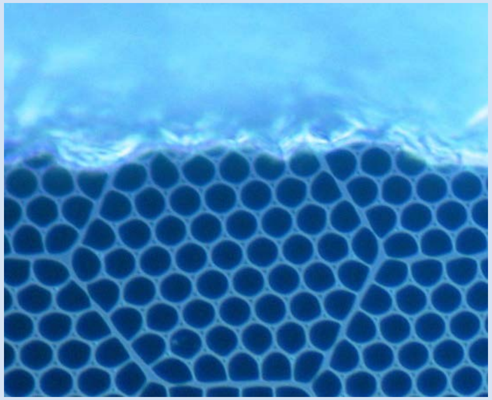
**_FOS_**

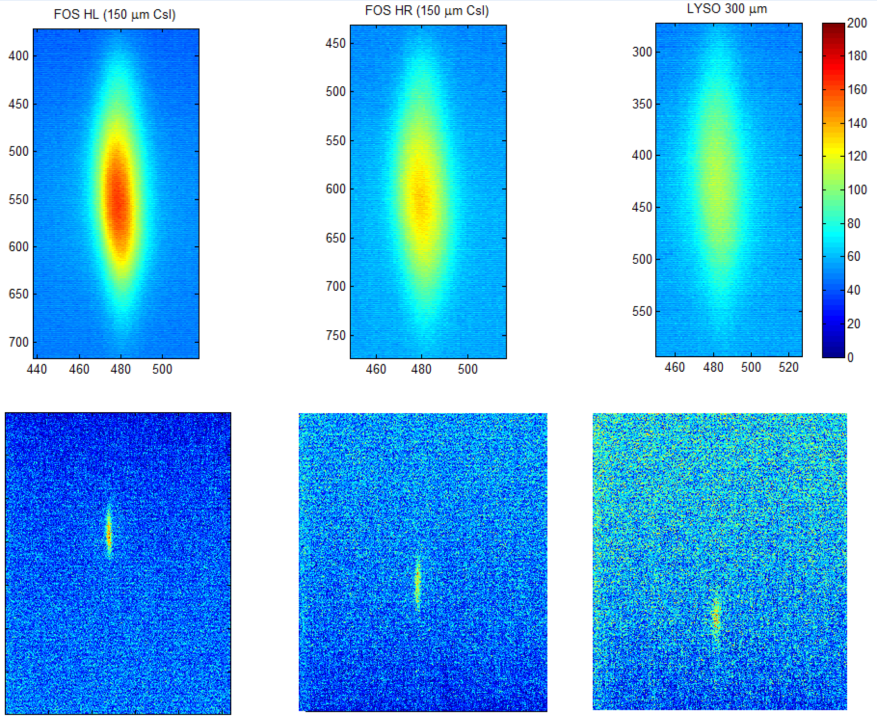
(fiber optics plate with CsI as scintillator)

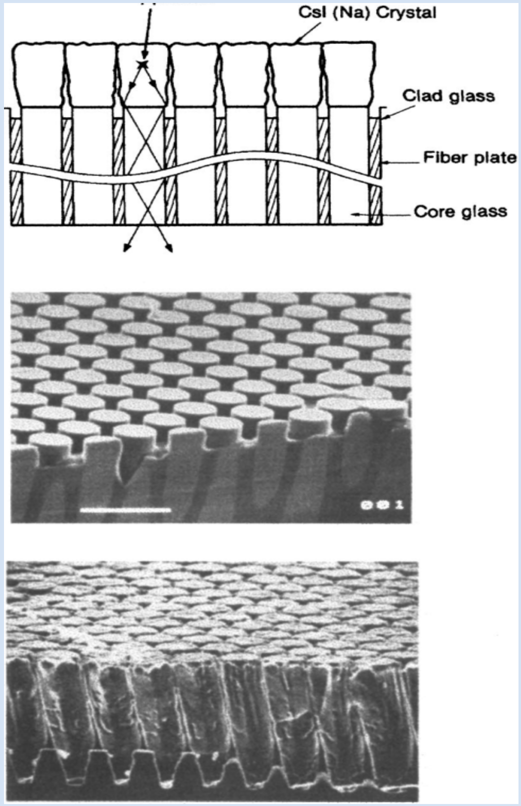
vs.

**_LYSO :_**

($Lu_{2(1-x)}Y_{2x}SiO_5$ Lutetium-yttrium oxyorthosilicate)

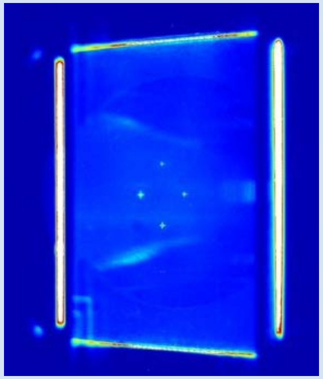






## **LYSO crystal**:

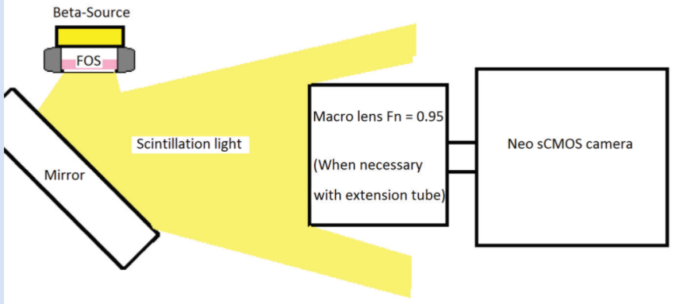
- Multiple internal reflection from two faces
- Reflection from edges
- edge blooming
- Blooming at scratches
- Decay time (fast 45 ns)

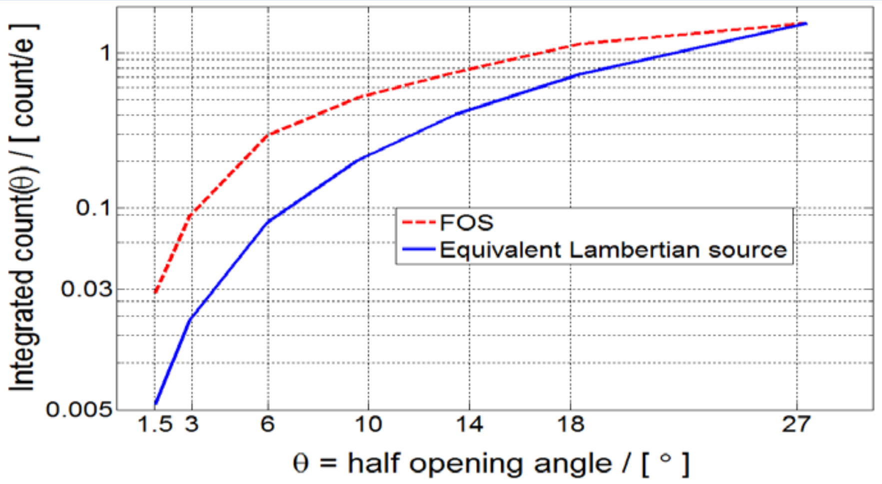


ß-source is used to produce scintillation light and counts that scale with the collected light as a function of distance to the fiber optics scintillator are shown. For comparison a Lambertian source radiance is also shown that is adjusted to emit the same amount of light into largest cone covered in the closest distance to the FOS.

## **FOS**:

- Coupling to the fiber channels
- Reflection from Al-coating
- CsI scintillator penetration in fiber channels
- Comparison Al-coated FOS(CsI), no-Al coated FOS(CsI) and FOP+LYSO
- Decay time (slow ~1ms)

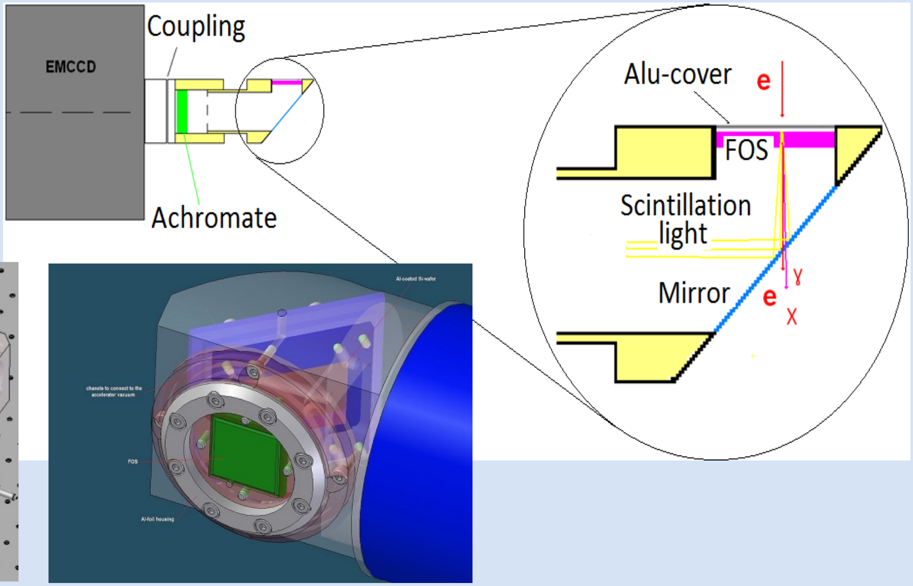


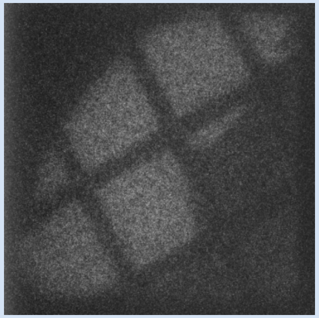


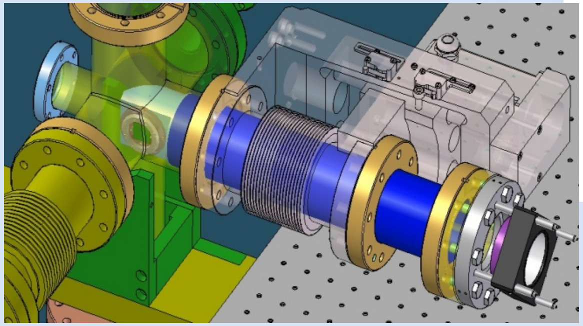
# REGAE diffraction detector

D1 is in operation since 13.04.2012

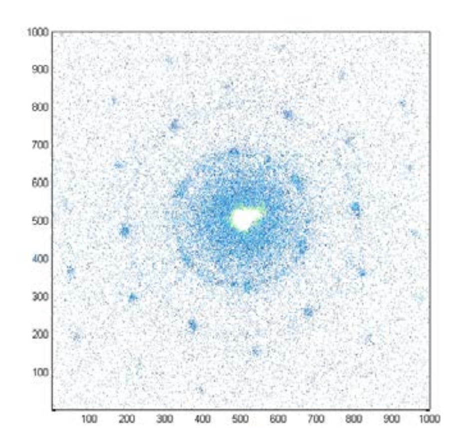
- Fiber Optics Scintillator (FOS, HL and 15x15 mm)
- Lens coupling
- EMCCD (iXon3-888-BV) as camera



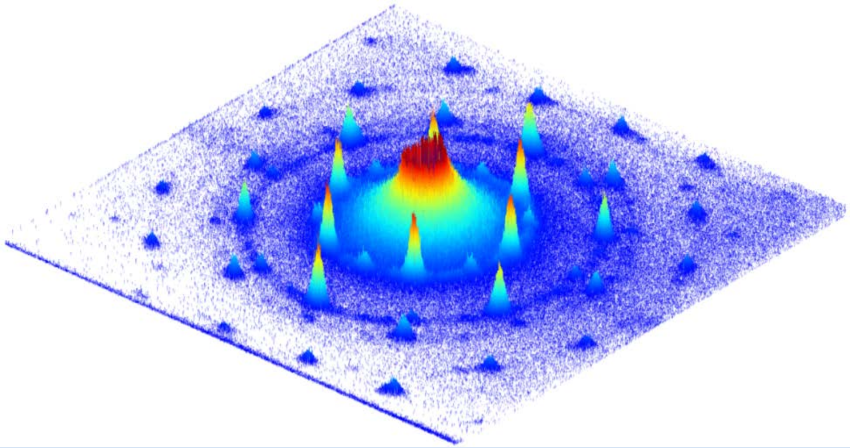




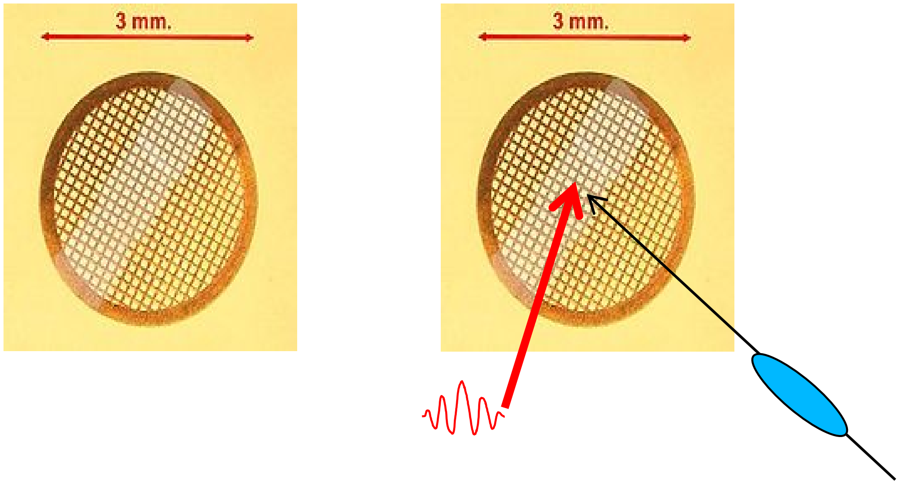
Single shot with total charge of 6 fC

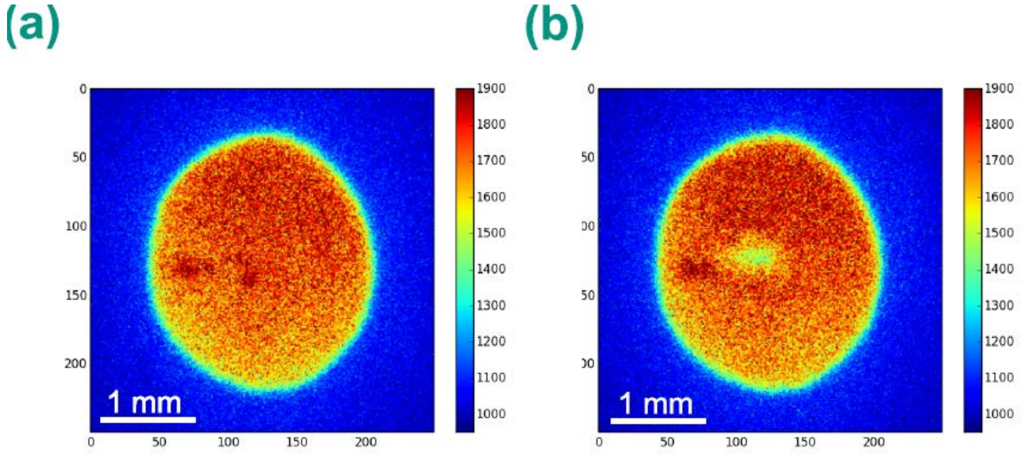


Accumulated 200 shots with each shot 6 fC charge

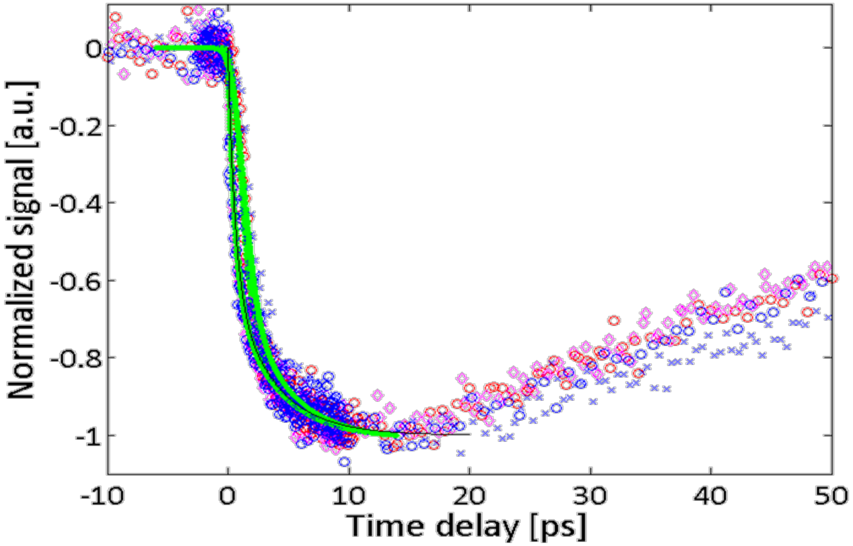


# *finding temporal overlap: t=0*





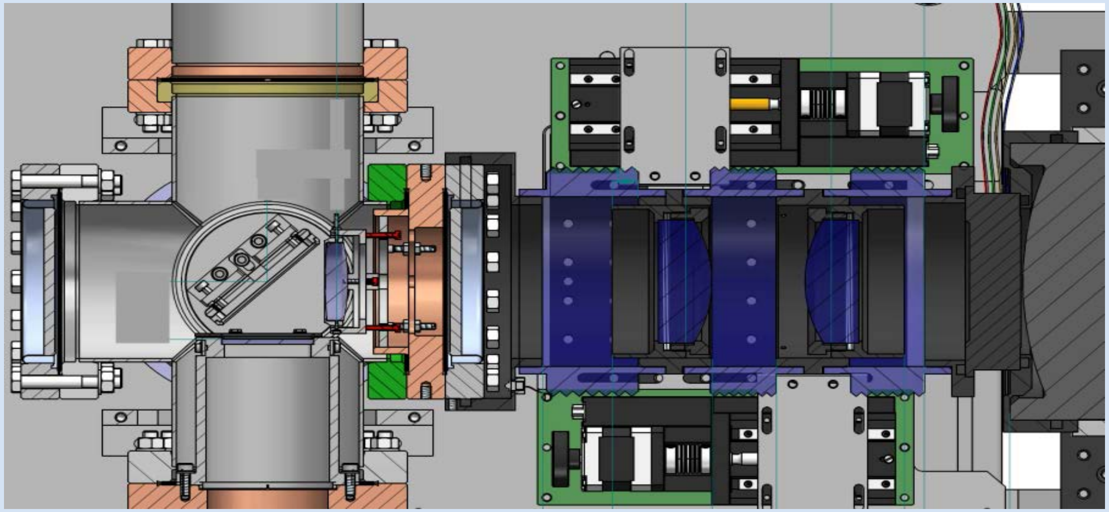
transmitted electron beam

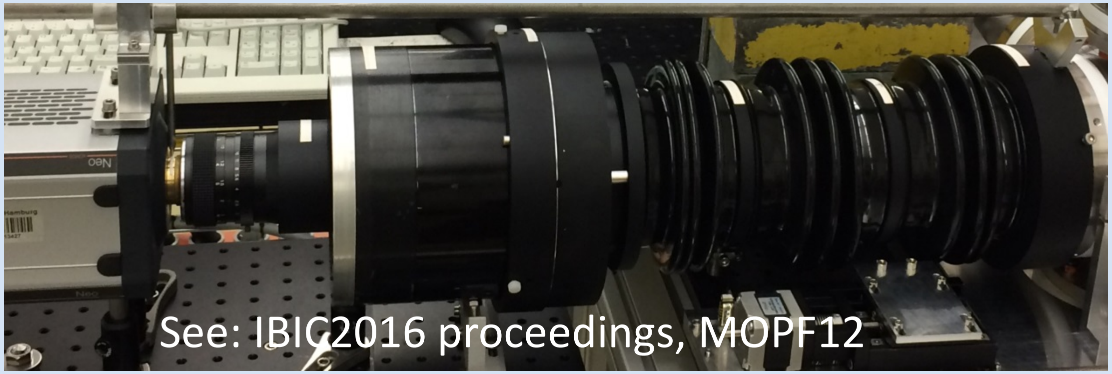


See: S. Manz et al. , Faraday Discussions, volume 177, 2015

# *Detector D2; Neo sCMOS + PHOTEK image intensifier+ large area FOS*

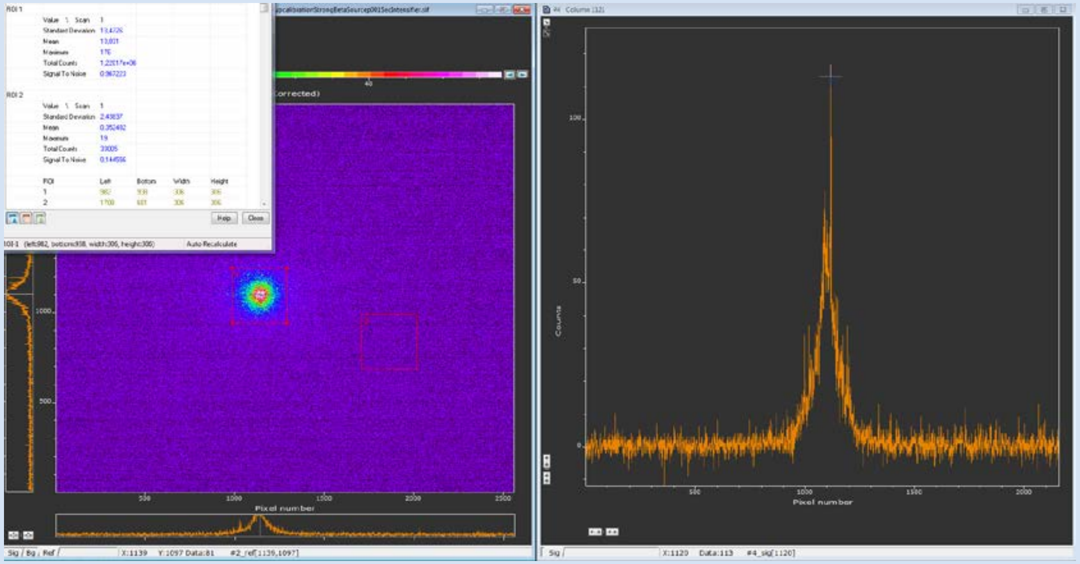
- Large area fast high gain image intensifier
- Maximized light coupling to collecting optics
- Optimal lens coupling of the image intensifier output to the camera
- Fast sCMOS as detector with high resolution
- Compact
- High dynamic range
- Zero-order blocker





See: IBIC2016 proceedings, MOPF12

# New detector faster and more sensitive (improved signal to noise)



ROI 1

| Value \ Scan | 1 |
|---|---|
| Standard Deviation | 13.4726 |
| Mean | 13.001 |
| Maximum | 176 |
| Total Counts | 1.22017e+06 |
| Signal To Noise | 0.967223 |

ROI 2

| Value \ Scan | 1 |
|---|---|
| Standard Deviation | 2.43837 |
| Mean | 0.352492 |
| Maximum | 19 |
| Total Counts | 33005 |
| Signal To Noise | 0.144556 |

| ROI | Left | Bottom | Width | Height |
|---|---|---|---|---|
| 1 | 982 | 938 | 306 | 306 |
| 2 | 1700 | 601 | 306 | 306 |

ROI-1 (left:982, bottom:938, width:306, height:306) Auto Recalculate

1 ms exposure;

FWHM = 120 pixel

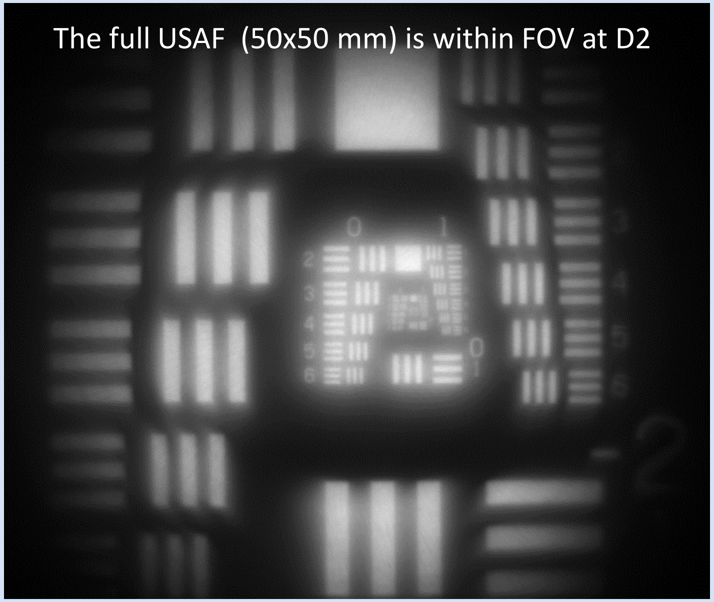
Npixel = 306x306 = 93636

Ncount = 1.22x10^6 - 0.03 x 10^6 = 1.2x10^6

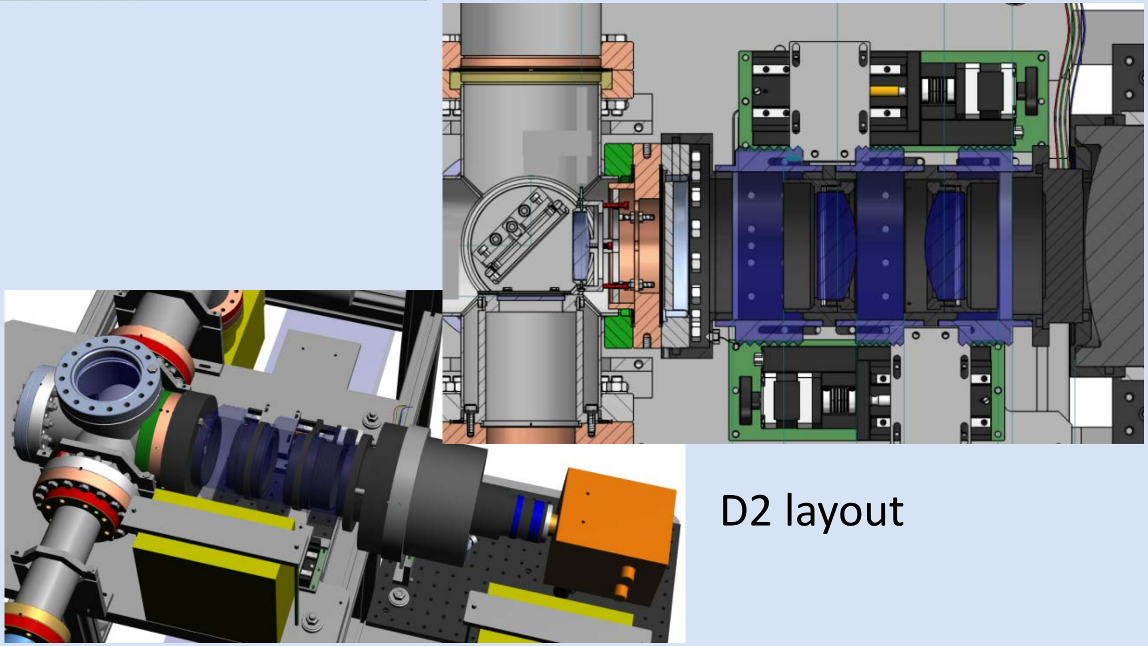
Ne = 2.4x10^6 x 10^-3 = 2.4x10^3

Nc/e = 500

Ne/pixel = 0.025



The full USAF (50x50 mm) is within FOV at D2

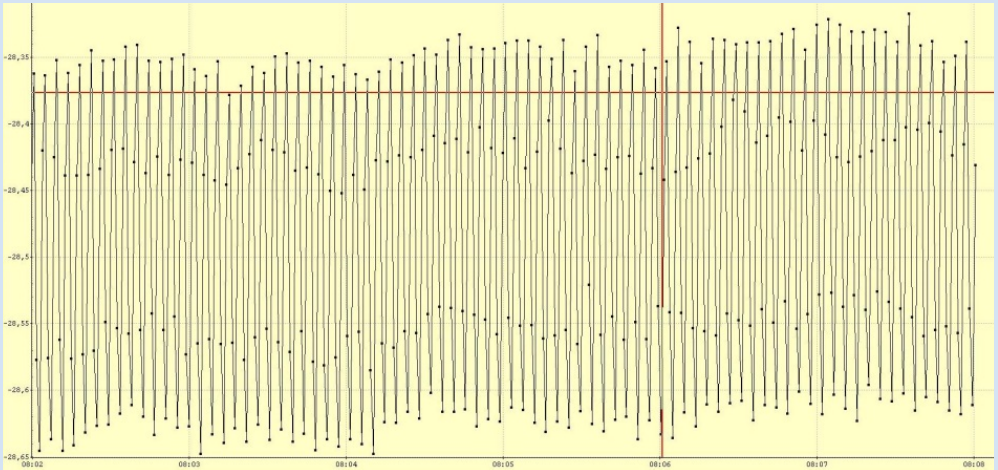


D2 layout

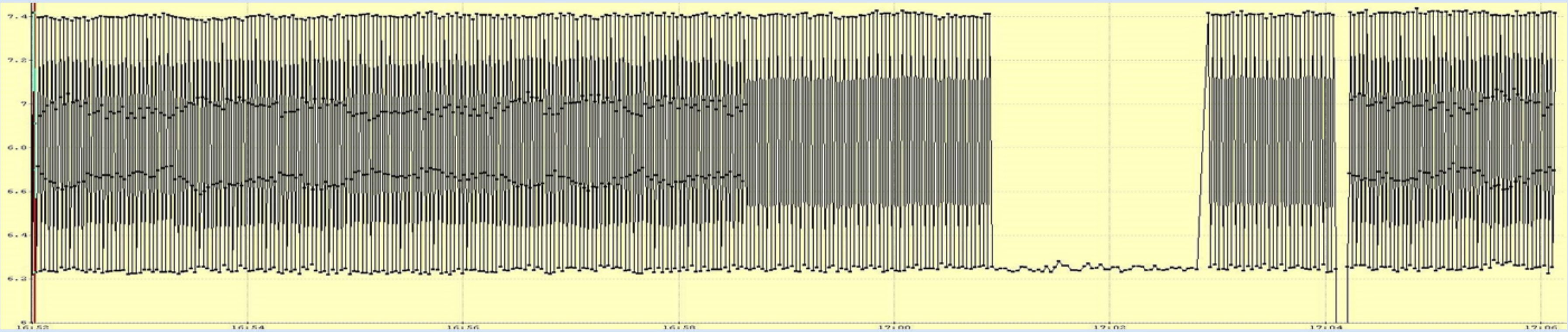
# Machine tuning has become easier using this large area detector that covers the entire vacuum chamber diameter

DESYII off 12.5 Hz, REGAE 50 Hz
8 ms exposure time

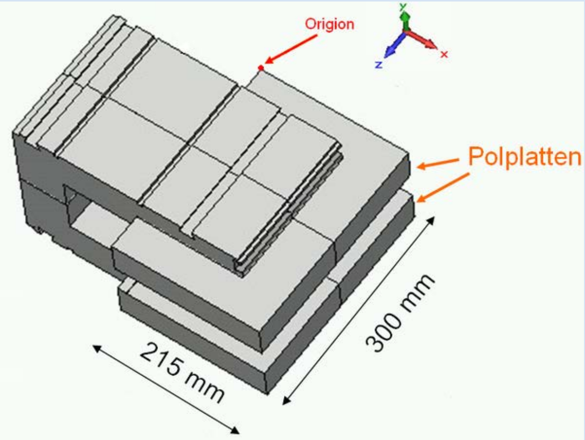
DESY II on, REGAE 50 Hz 8ms exposure time

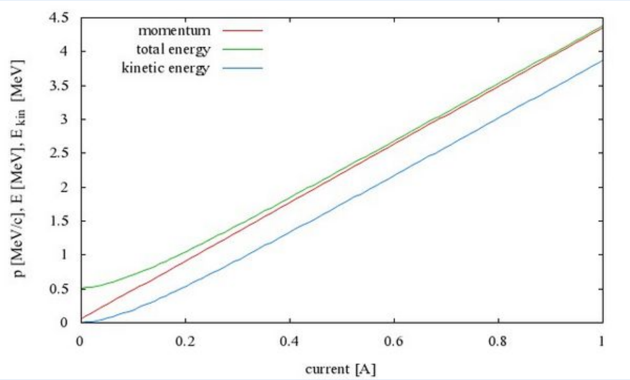


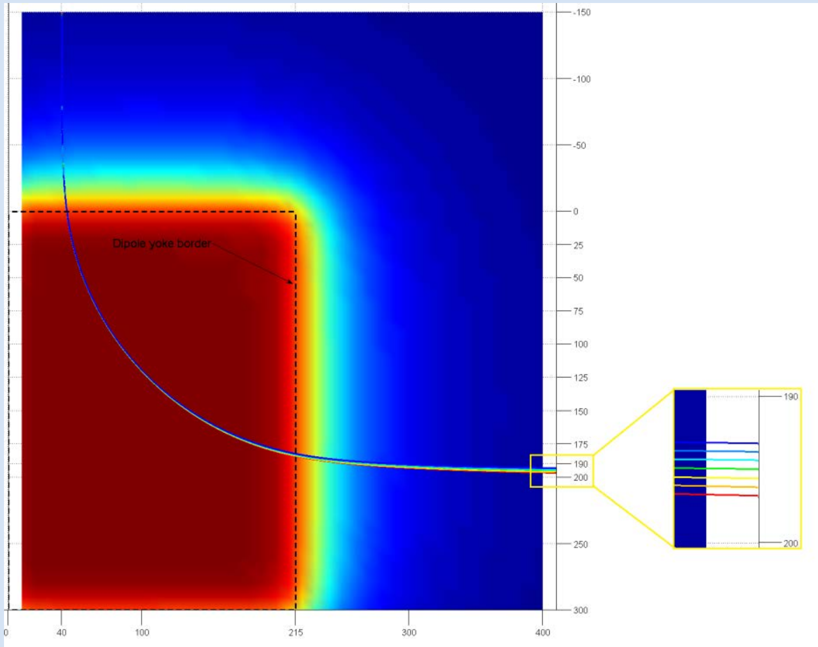
DESY II on 12.5 Hz, REGAE 50 Hz,
1 s exposure time

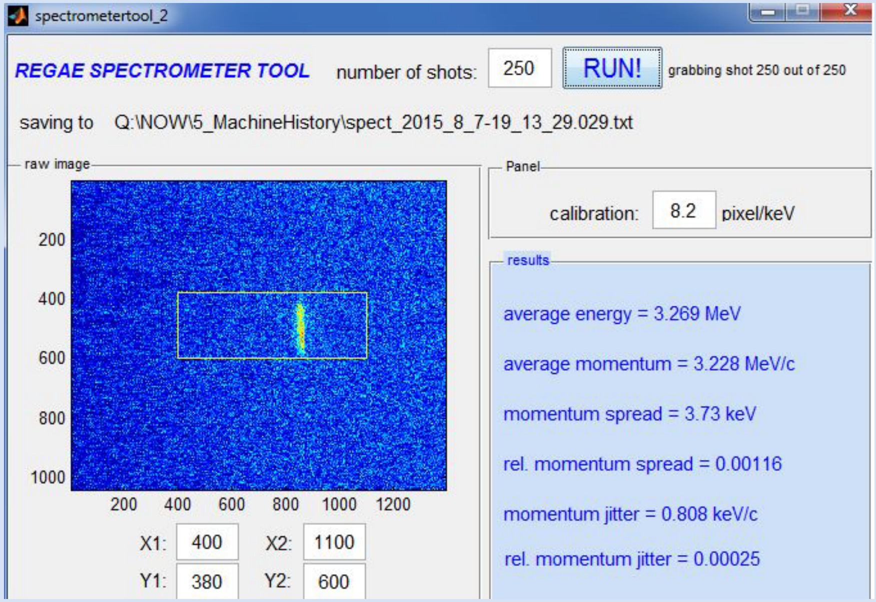


# *Energy and energy spread measurement*









**REGAE SPECTROMETER TOOL** number of shots: 250 grabbing shot 250 out of 250

saving to Q:\NOW\5_MachineHistory\spect_2015_8_7-19_13_29.029.txt

calibration: 8.2 pixel/keV

X1: 400 X2: 1100

Y1: 380 Y2: 600

average energy = 3.269 MeV

average momentum = 3.228 MeV/c

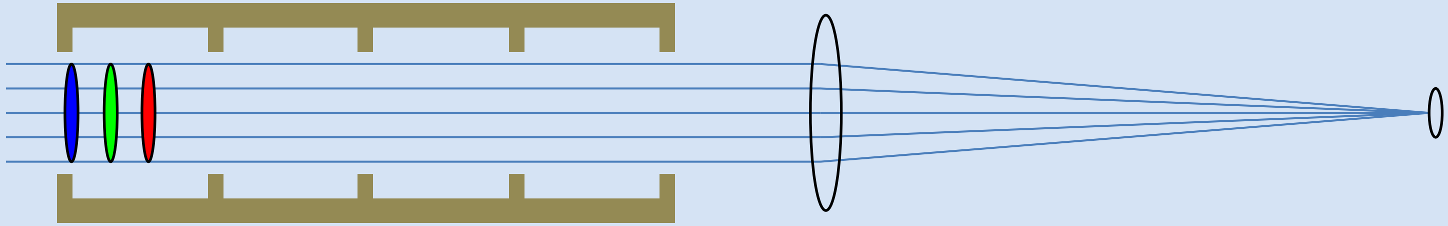
momentum spread = 3.73 keV

rel. momentum spread = 0.00116

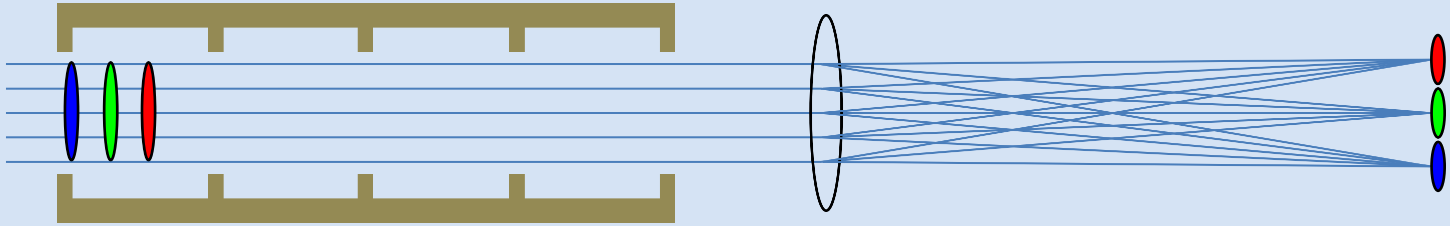
momentum jitter = 0.808 keV/c

rel. momentum jitter = 0.00025

# Schematic TDS setup



un-streaked
beam size



streaked
beam size

# TDS Resolution:

assume ideal optics with 90 degree phase advance between TDS and screen

$$R = \frac{\sigma_{sc,\,\text{un-streaked}}}{\sigma_{sc,\,\text{streaked}}} = \frac{\sigma'_{TDS,\,\text{uncor.}}}{\sigma'_{TDS,\,\text{introduced}}} = \frac{\varepsilon}{\sigma_y}\frac{cp_z}{ekV} = \frac{\varepsilon_n m_0 c^2}{\sigma_y ekV}$$

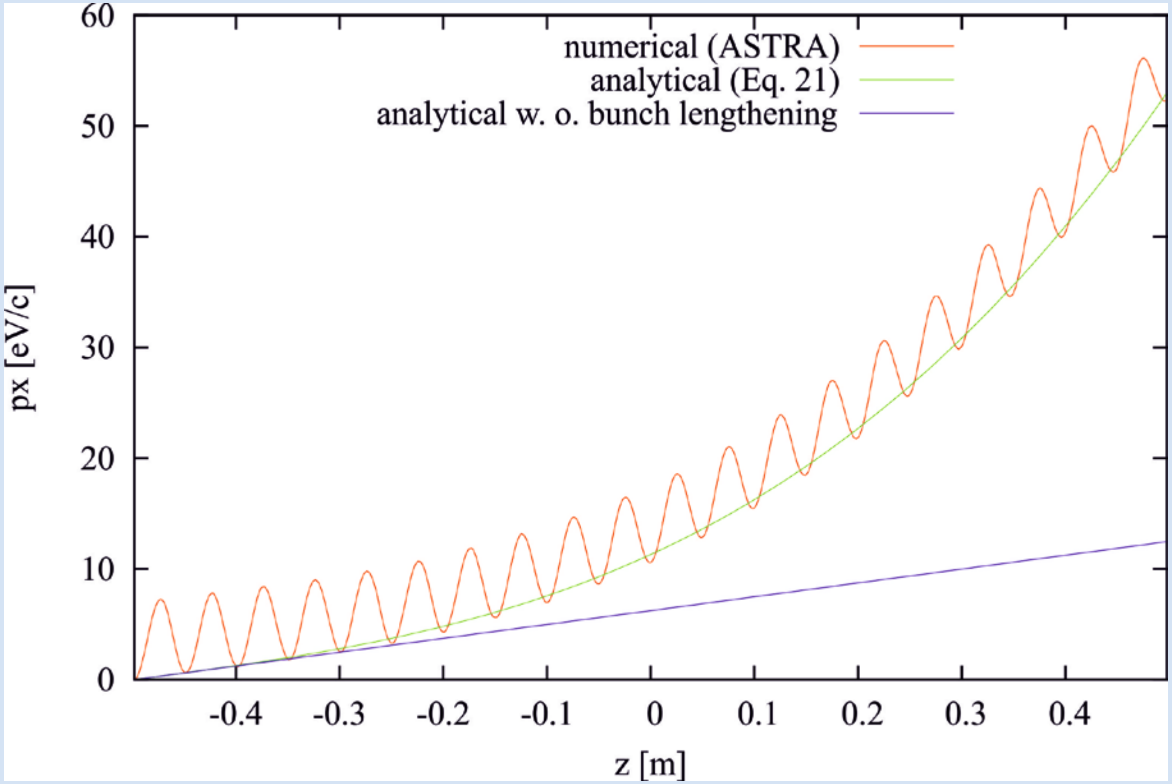
$$V = \int E_y(t,z) + c\beta_z B_x(t,z)dz$$

$$k = {}^{2\pi}\!/\!_{\lambda}$$

a high resolution power 1/*R* requires:

- large integrated voltage *V*
- short wavelength, large *k*
- large beam size in the structure $\sigma_y$

Courtesy: K. Flöttmann

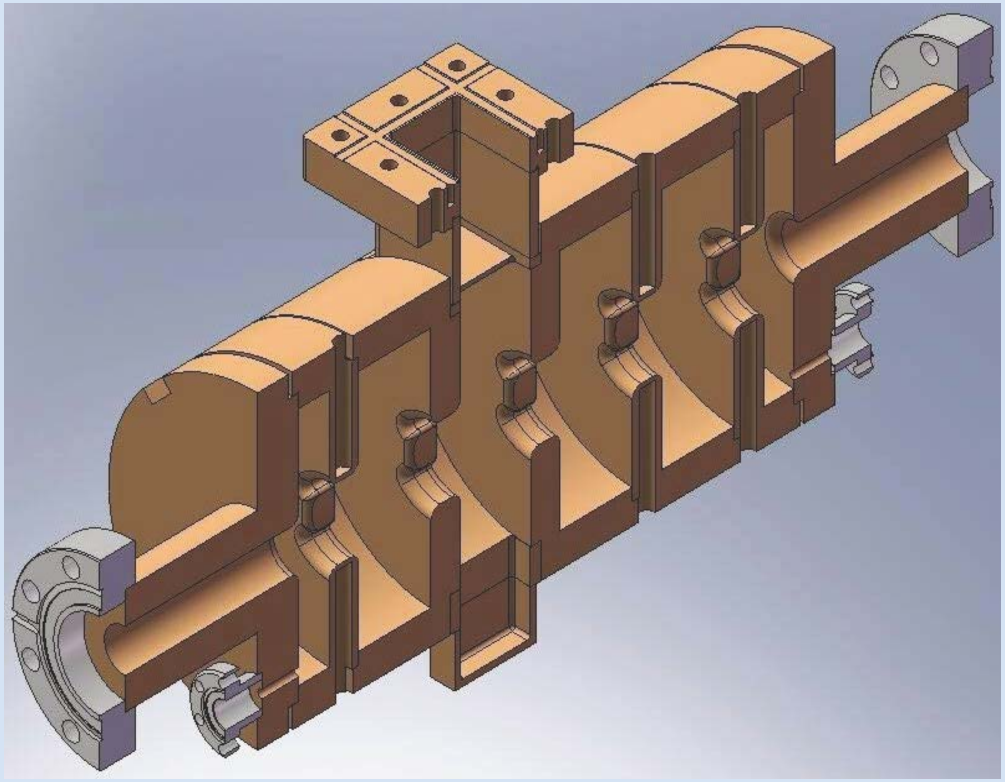


Transverse momentum vs. position in a TDS: Comparison of analytical models and numerical calculation.

Example: 5 MeV particle starts with 1mm transverse and 1 µm longitudinal offset, cavity voltage 0.2 MV, S-band, cos φ=1.

For details see: K. Floettmann, V. Paramonov, PRST-AB 17, 024001, 2014

Courtesy: K. Flöttmann



Short, high efficient rf structure with linearized transverse fields.

In order to keep the bunch lengthening under control the TDS has to be short, the voltage and the beam size have to be small.

A good resolution *R* can only be achieved if the emittance is small

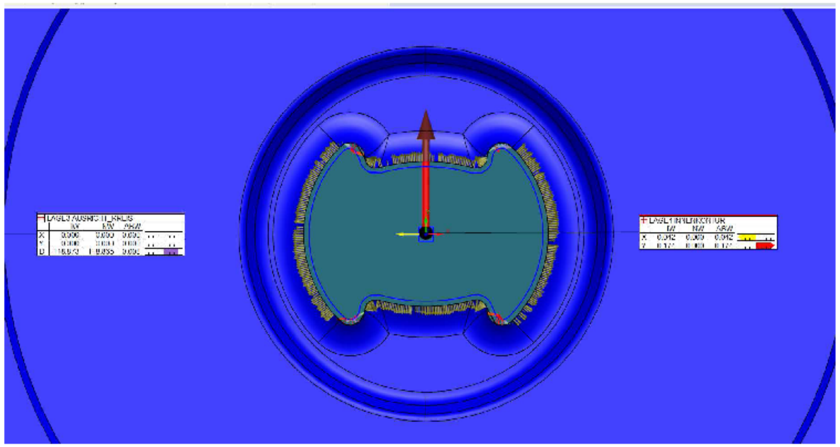
$$R \propto \frac{\varepsilon_n}{\sigma_x k V}$$

**Expected resolution < 10 fs**

K. Floettmann, V. Paramonov, PRST-AB 17, 024001, 2014

Courtesy: K. Flöttmann

**Bild:** Right end cell 1 / Lage der Innenkontur (X, Y) / Lage des Ausrichtkreis (X, Y) / Versatz der Innenkontur siehe Lage4 Innenkontur



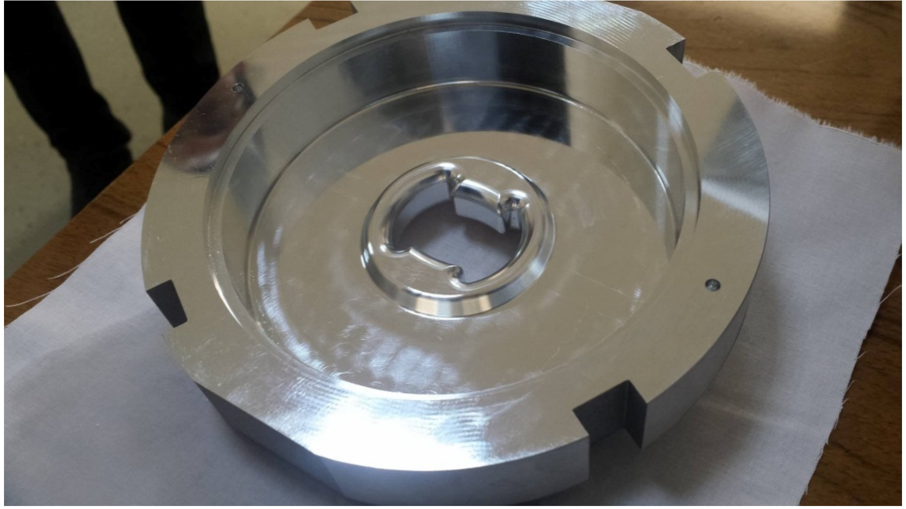
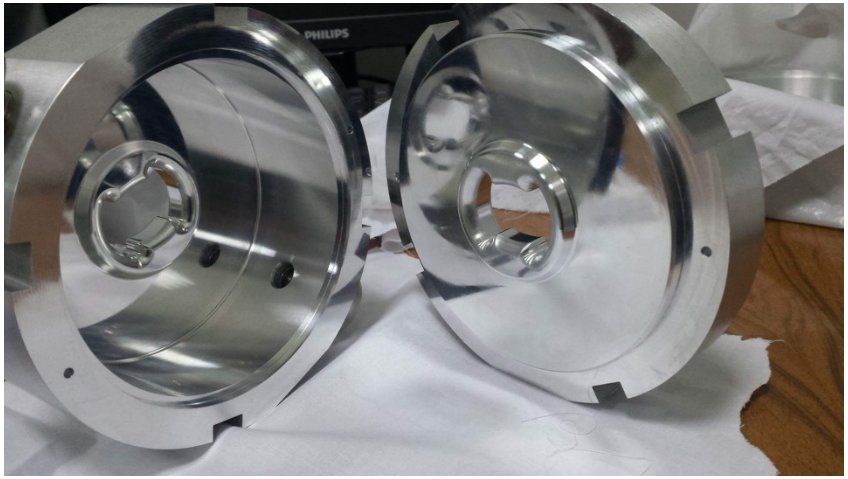
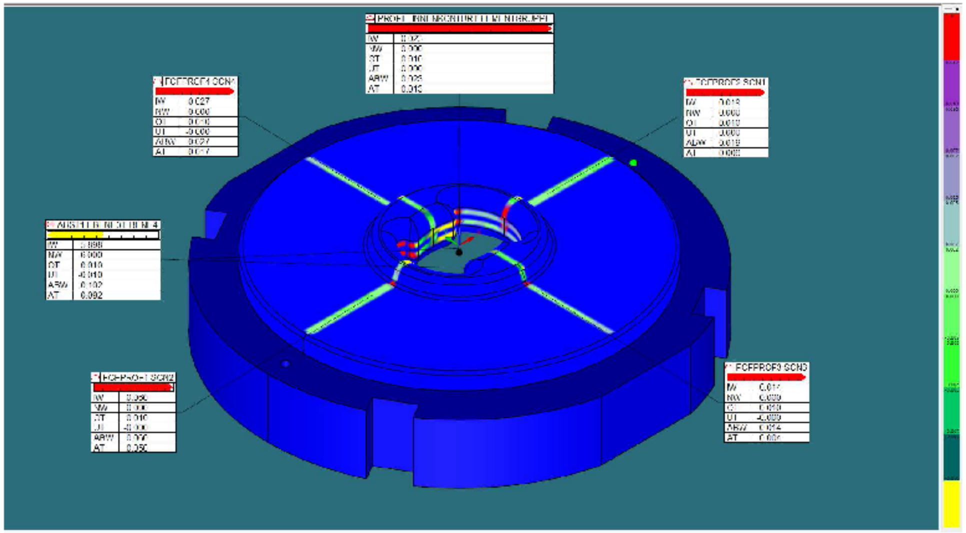
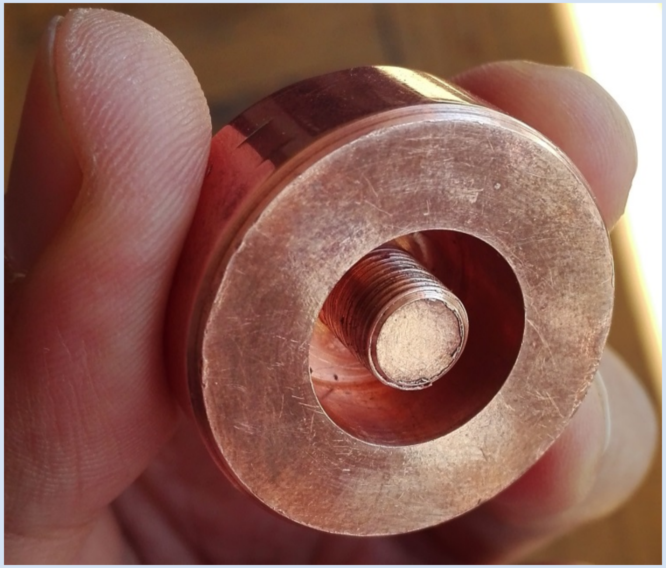


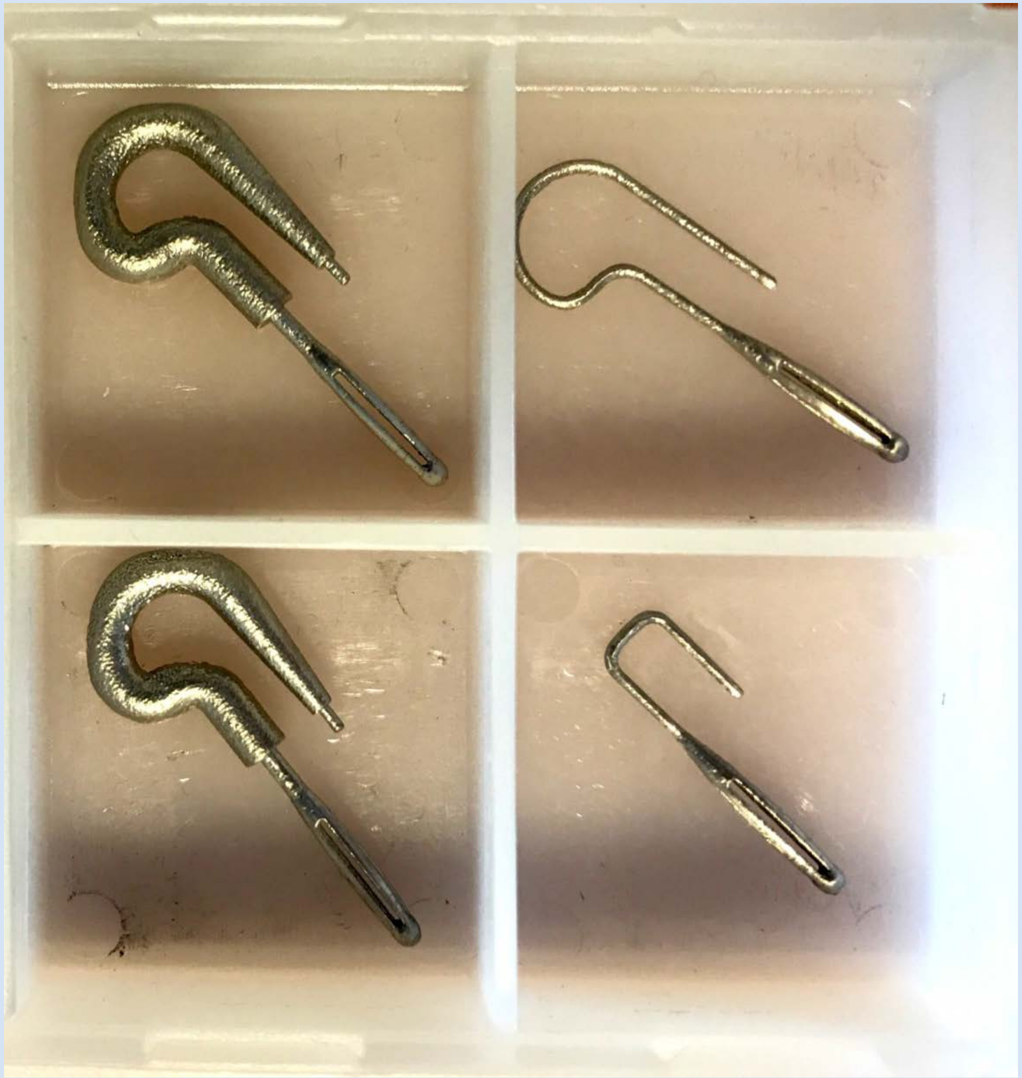
**Bild:** Right end cell 1 / Flächenprofil der (Innenkontur) / Linienprofile (SCAN1 – SCAN4) / Abstand von 2 Ebenen (Ebene3, Ebene4)





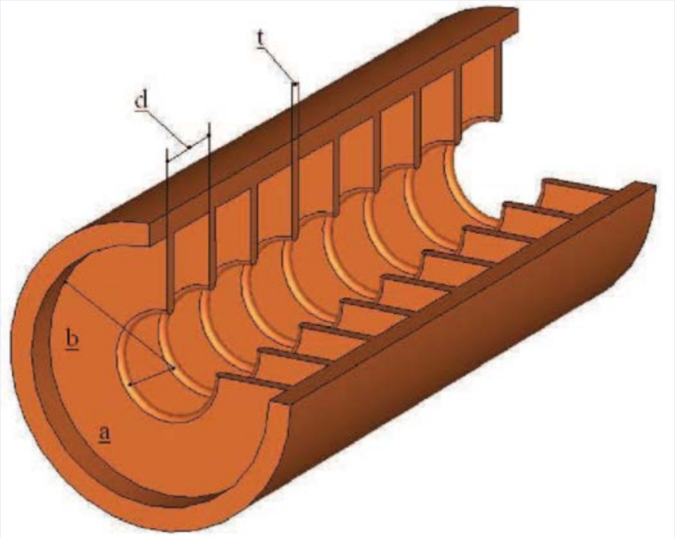
Courtesy: A. Simonyan





# Wavelength scaling of a TDS structure:

S-Band (3 GHz)



THz (300 GHz)

| | | |
|---|---|---|
| wavelength: | λ = 10 cm | λ = 1 mm |
| aperture radius: | $a \approx 0.1\,\lambda = 1$ cm | $a \approx 0.1\,\lambda = 100$ µm |
| beam size: | $\sigma_y \approx (0.01\text{-}0.001)\,\lambda = 0.1\text{-}1$ mm | $\sigma_y \approx (0.01\text{-}0.001)\,\lambda = 1\text{-}10$ µm |

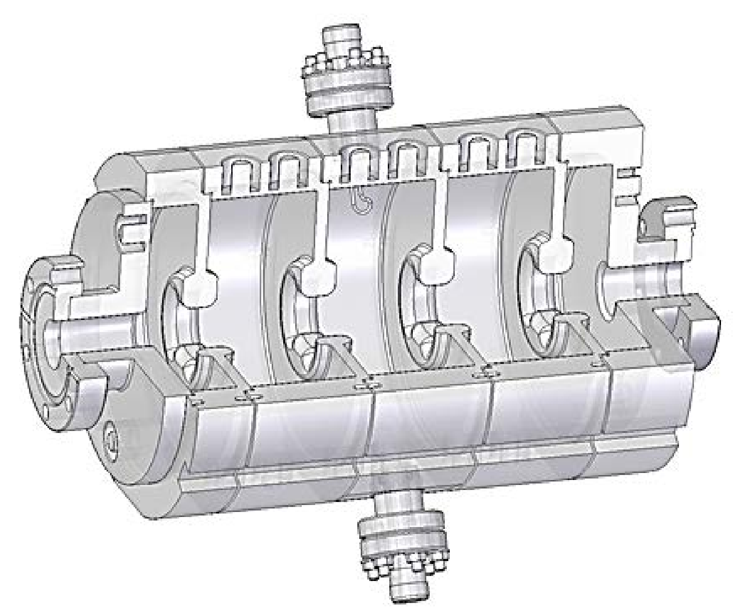
$$k\sigma_y = \text{const.}$$

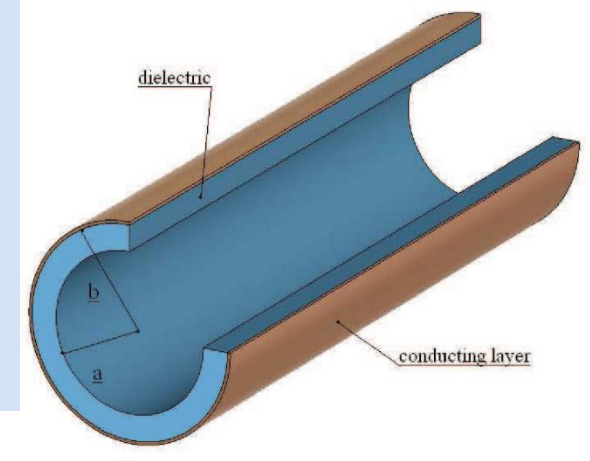
no profit if spot size is scaled with wavelength!

See: IPAC2017 proceedings, MOPAB052 and the scheduled talk on this session:
***Beam Diagnostics with THz Radiation*** by Francois Lemery

Courtesy: K. Flöttmann

# Comparison – REGAE case:



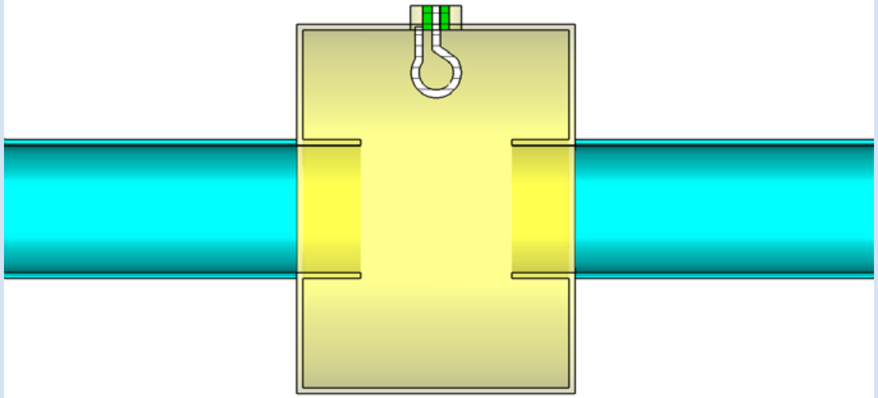


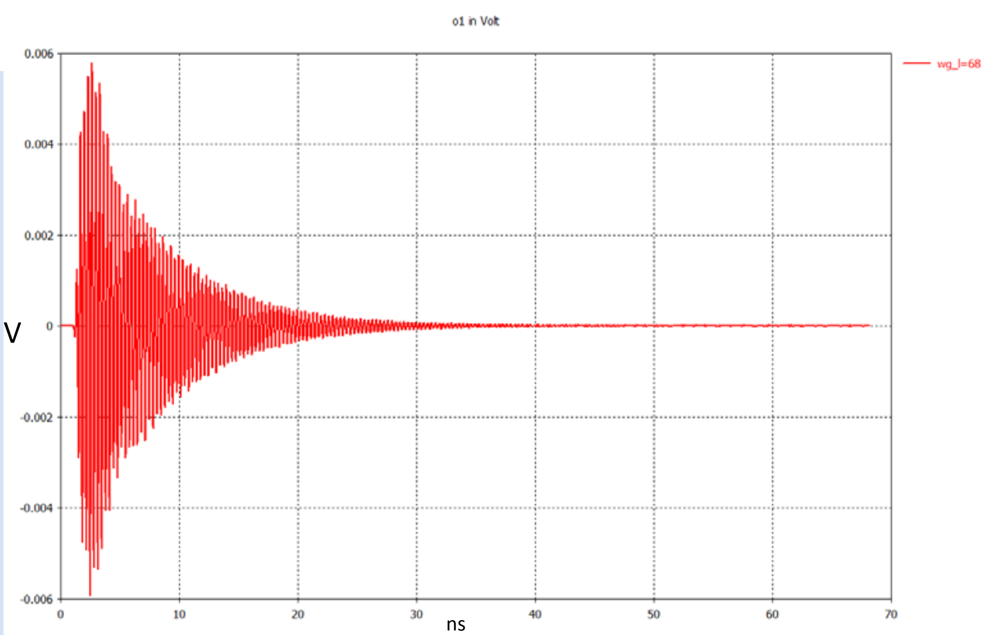
| Type | S-band 20 cm | THz 3 cm |
|---|---|---|
| Power | 5 kW | 1.2 W |
| $V$ | 170 KV | 9.2 kV |
| max. $\sigma_y$ | 0.4 mm | 125 µm |
| $\sigma_y kV$ | 4.3 kV | 7.2 kV |

Courtesy: K. Flöttmann

# Beam Arrival Cavity for a slow feedback

- design finished, production is going to start





- we hope to achieve a resolution of ~ 10 fs with 1pC charge

Courtesy: K. Flöttmann

See: IPAC2014 proceedings, TUPRI104

THANKS