Beam heat load measurements with COLDDIAG at DLS

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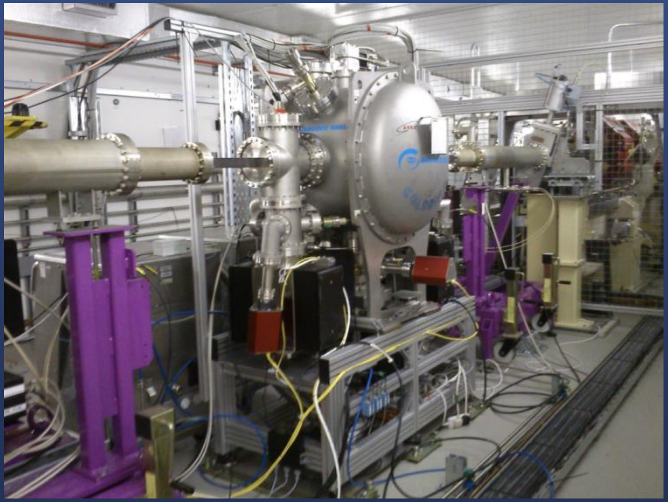
ANKA Synchrotron Radiation Facility, Karsluhe Intitute of Technology

- Motivation
- Beam heat load sources
- Beam heat load measurements
- COLDDIAG
- Outlook

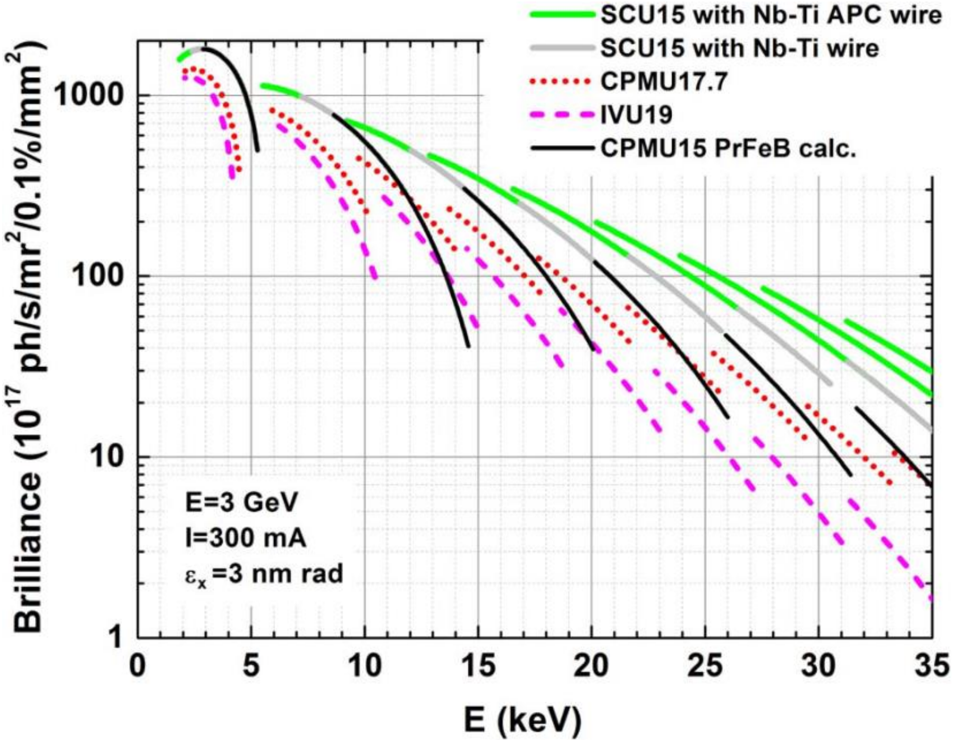


Motivation

Advantages of superconducting over permanent magnet undulators:

- Higher field for a given gap and period length
- Increased brilliance and spectral range

Open issue for the cryogenic design of superconducting undulators:
Beam heat load to the cold vacuum chamber



S. Casalbuoni, IEEE Trans. on Appl. Supercon. 4101305, Vol. 24-3 (2014)

	IVU [6]	CPMU [7]	CPMU PrFeB [8]	SCU Nb-Ti	SCU Nb-Ti APC [9]
λ_U [mm]	19	17.7	15	15	15
N	105	112	133	133	133
mg [mm]	5	5.2	5.2	6	6
B[T]	0.86	1.04	1.0	1.18	1.46
K	1.53	1.72	1.40	1.65	2.05

[6] F. Bødker et al., EPAC 2006
[7] C.W. Ostenfeld and M. Pedersen, IPAC 2010
[8] M. E. Couprie et al. ICFA 2012
[9] T. Holubek et al., Physics Procedia, 1989-1102, Vol.36 (2012)

Beam heat load sources

- **Synchrotron radiation** from upstream bending magnet

  $$P_{syn}\ [\mathrm{W/mrad}] = I\ \frac{e\gamma^4}{6\pi\varepsilon_0 r}$$

- **Resistive wall heating** due to image currents

  Normal skin effect: $$P_{normal} = \Gamma\left(\frac{3}{4}\right)\frac{L}{2\pi l}\sqrt{\frac{\mu\rho}{2}}\left(\frac{c}{\sigma_z}\right)^{3/2}\frac{I^2}{M\ f_0}$$

  Anomalous skin effect: $$P_{anom} = \Gamma\left(\frac{5}{6}\right)\frac{L}{2\pi l}\left(\frac{\sqrt{3}}{16\pi}\rho\lambda\mu^2\right)^{1/3}\left(\frac{c}{\sigma_z}\right)^{5/3}\frac{I^2}{M\ f_0}f(\sigma_z,\rho)$$

  I = avg. beam current
  M = number of bunches
  σ_z = bunch length
  ρ = resistivity

  E. Wallèn, G. LeBlanc, Cryogenics 44, 879 (2004)
  W. Chou, F. Ruggiero, LHC Project Note 2 (SL/AP), 1995

- **RF effects** (longitudinal beam coupling impedance)
  Step transitions
  Resonances (sharp, broad, Gaussian, arbitrary)
  -> $P_{RF} \propto I^2\ f$(geometry, filling pattern, bunch length)

- **e^- and/or ion bombardment** $$P_{e^-,ion} \propto \Delta W \cdot \dot{N}$$

  ΔW = energy increase of one electron due to the kick by a bunch
  $\dot{N}$ = electrons hitting the wall per sec

  S. Casalbuoni. et al., Phys. Rev. STAB 10, 093202 (2007)

Calculated and observed beam heat load in superconducting insertion devices

- **MAX-II SCW:** helium cooled bath type cryostat
  helium boil-off rate -> beam heat load
  0.87 W calculated, 1.7 W observed

  E. Wallèn, G. LeBlanc, Cryogenics 44, 879 (2004)

- **ANKA SCU14:** conduction cooling with cryocoolers
  coil temperature -> beam heat load
  0.085 W calculated, 2.5 W observed

  S. Casalbuoni et al., Phys. Rev. STAB 10, 093202 (2007)

- **APS SCU0:** conduction cooling + LHe reservoir
  cryocooler load map -> beam heat load
  7.5 W calculated, 14.6 W observed

  Y. Ivanyushenkov et al., Phys. Rev. STAB 18, 040703 (2015)

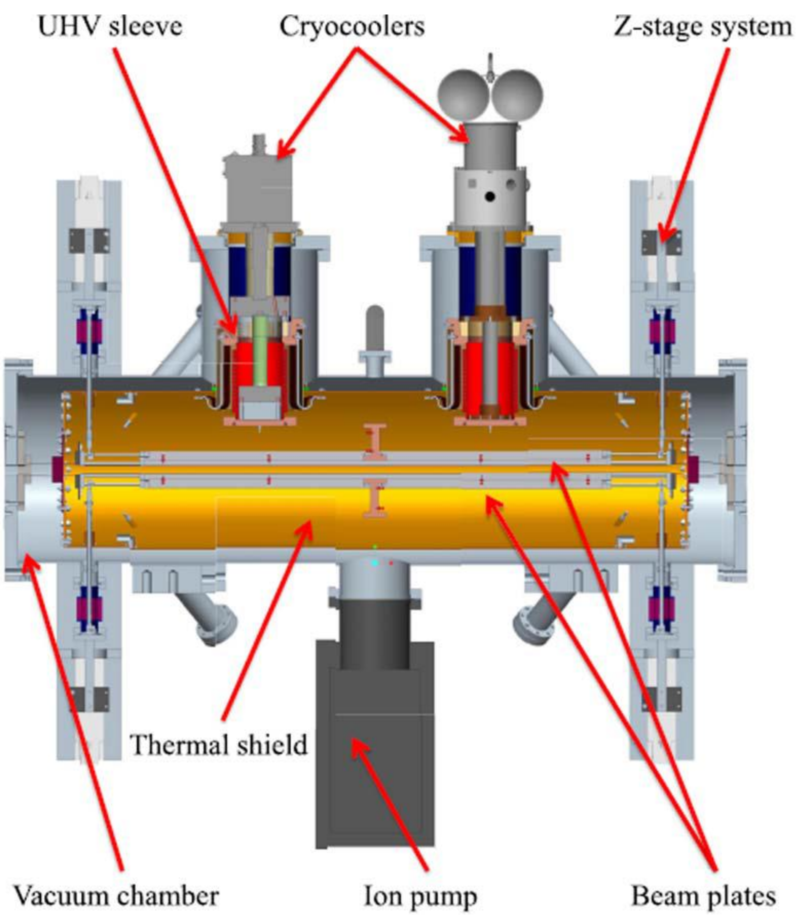
- **DLS SCW-1/SCW-2:** conduction cooling + LHe reservoir
  cryocooler load map -> beam heat load
  4.03 W/3.27 W calculated, 11.77 W/4.54 W observed

  J.C. Schouten, E.C.M. Rial, IPAC2011, THPC179

Specialized devices for beam heat load measurements I

LBNL/SINAP: cryogenic calorimeter for investigating beam-based heat load of SCUs

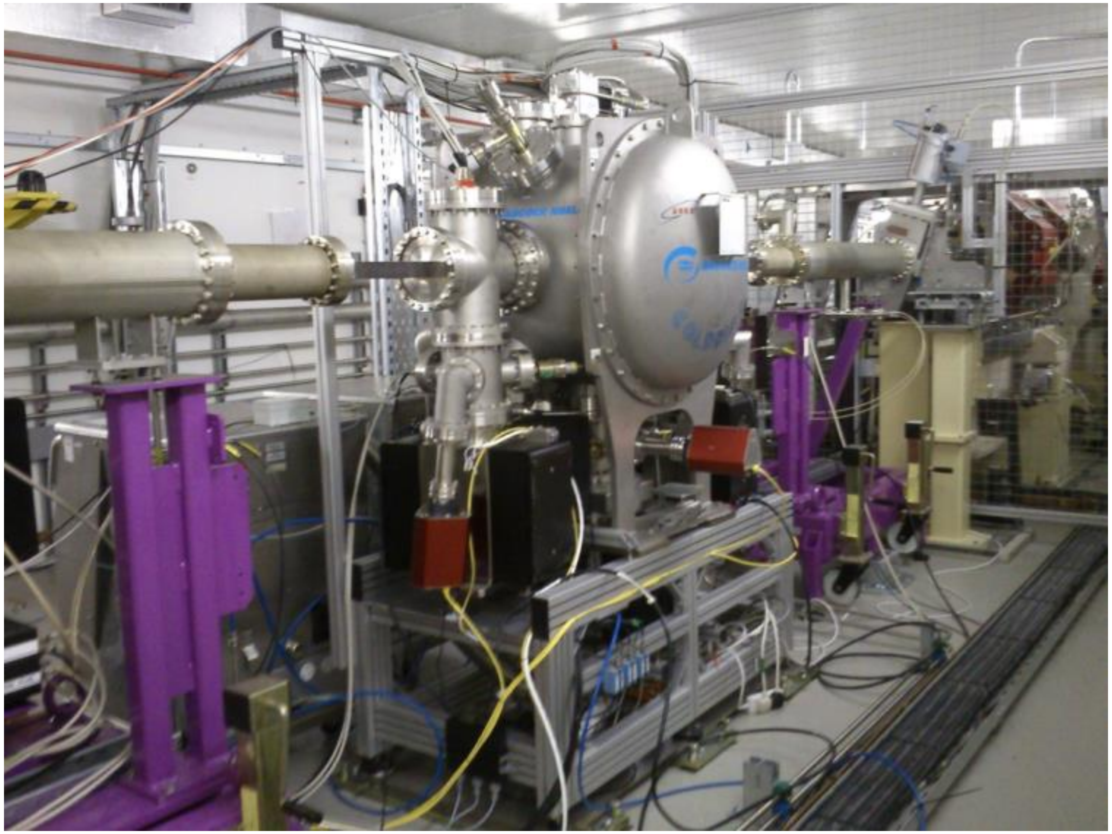
- Installed at SSRF
- 1 m aluminium beam plates
  coated with high RRR, 80 µm copper film
- Variable gap, first measurements at 20 mm
- Two methods for heat load determination:
  - temperature control loops
    6.99 W (100 mA), 22.66 W (200 mA)
  - load map of cryocoolers
    11.1 W (100 mA), 24.4 W (200 mA)
- UHV design without isolation vacuum and multilayer insulation
  -> thermal radiation



J. Cui et al., IEEE Trans. Appl. Supercond. Vol. 24, No 3, June 2014

Specialized devices for beam heat load measurements II

COLD vacuum chamber for beam heat load DIAGnostics (COLDDIAG):

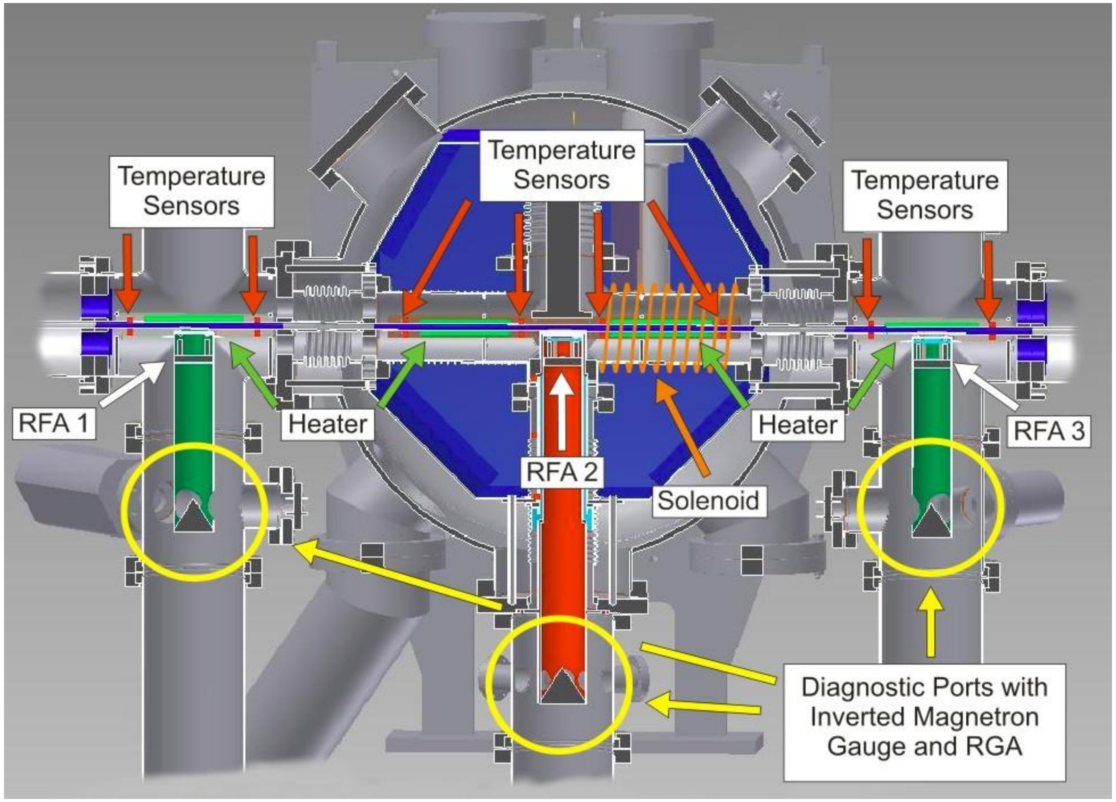


COLDDIAG installed in DLS storage ring

- Cold vacuum chamber located between two warm sections
- Copper plated (~50 µm) copper beam tube
- 60 mm × 10 mm elliptical cross section
- 0.5 m long cold beam tube
- 0.27 m long warm beam tube
- Cryogen free cooling with Sumitomo RDK-415D cryocooler

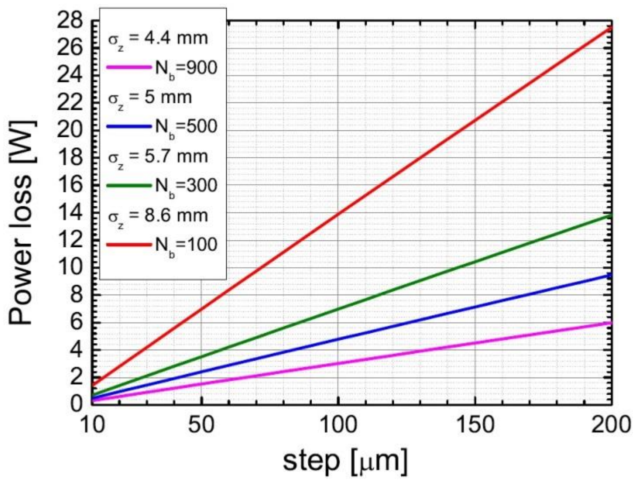
S. Gerstl et al. IPAC 2011
S. Casalbuoni et al., IEEE Trans. on Appl. Supercond. 2300-2303 Vol. 21-3 (2011)
S. Gerstl et al., Phys. Rev. STAB 17, 103201 (2014)

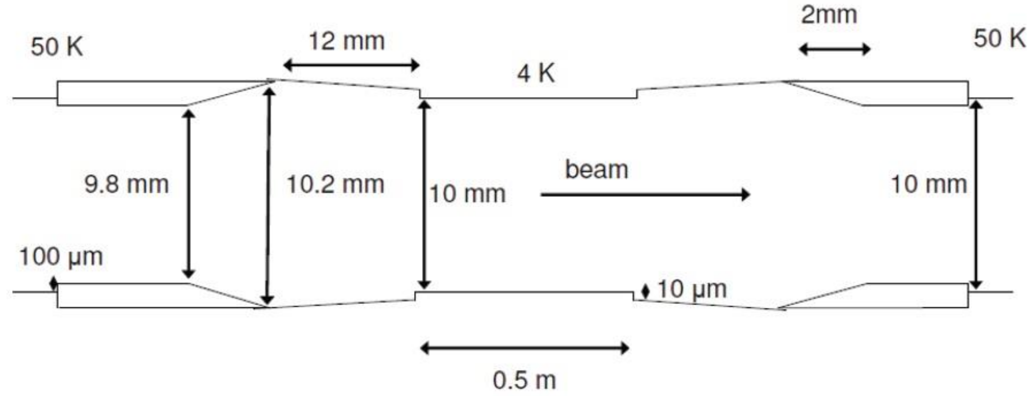
COLDDIAG – diagnostics and instrumentation

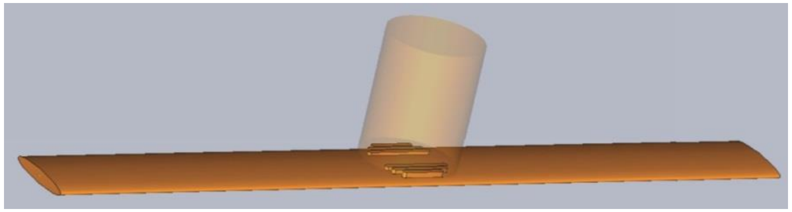


- **42 Temperature Sensors** to measure the beam heat load and the temperature distribution on the beam tube
- **8 Heaters** to calibrate the temperature sensors to the beam heat load
- **3 Retarding Field Analyzers** to measure the flux and energy spectrum of low energy electrons/ions hitting the chamber walls
- **3 Residual Gas Analyzers** and **3 Pressure Gauges** to monitor the gas composition and the total pressure
- **Solenoid** to suppress charged particles hitting the chamber walls

COLDDIAG – simulations







Limitations for simulation/meshing:

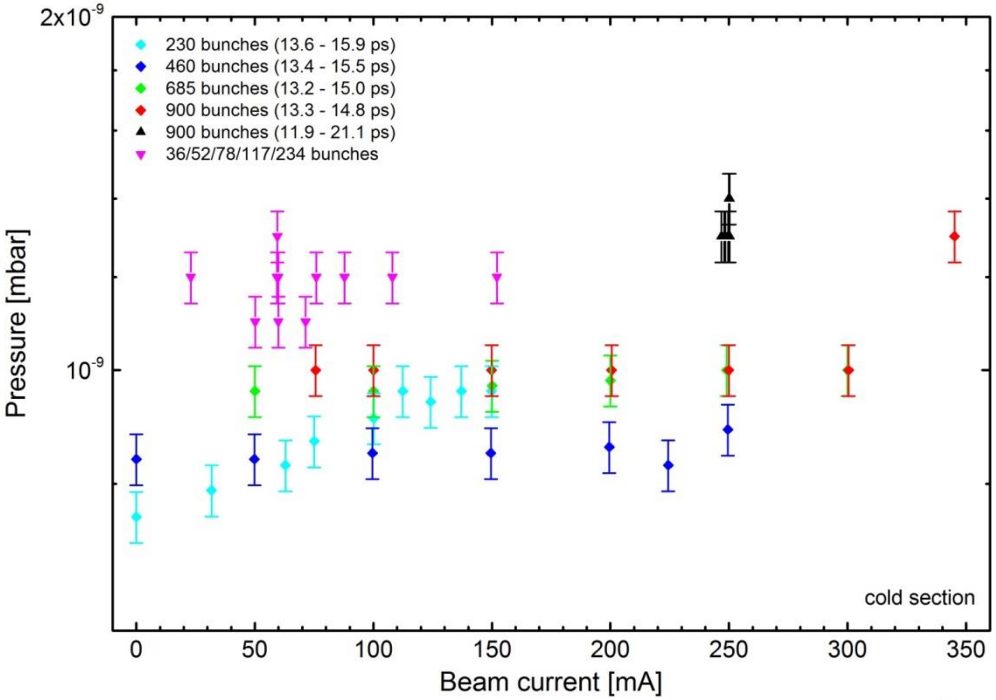
- small tapering angles
- small ratio: step size/structure length
- short bunch lengths => high frequency content up to 10 – 20 GHz

Results for DLS (900 bunches, 250 mA):

- resisitve wall heating: 0.25 W
- heating from steps: 0.3 W
- coupling slots: no trapped modes negligible impedance

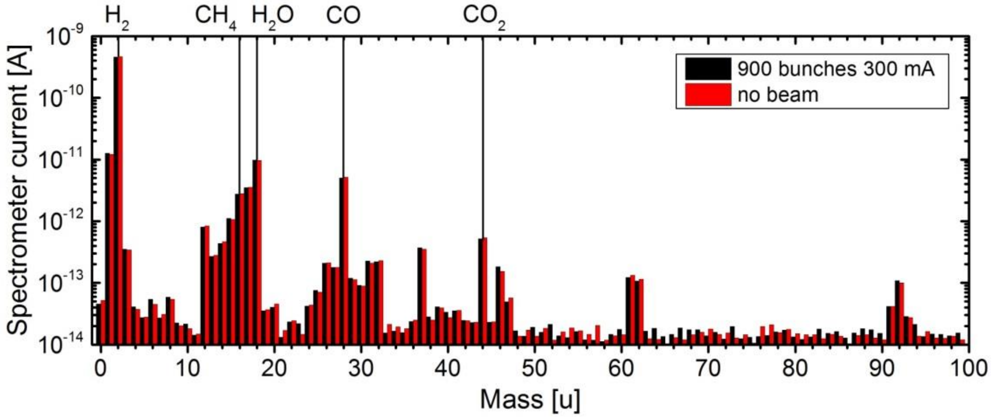
S. Casalbuoni et al., JINST 7 P11008 (2012)

COLDDIAG – pressure and gas composition



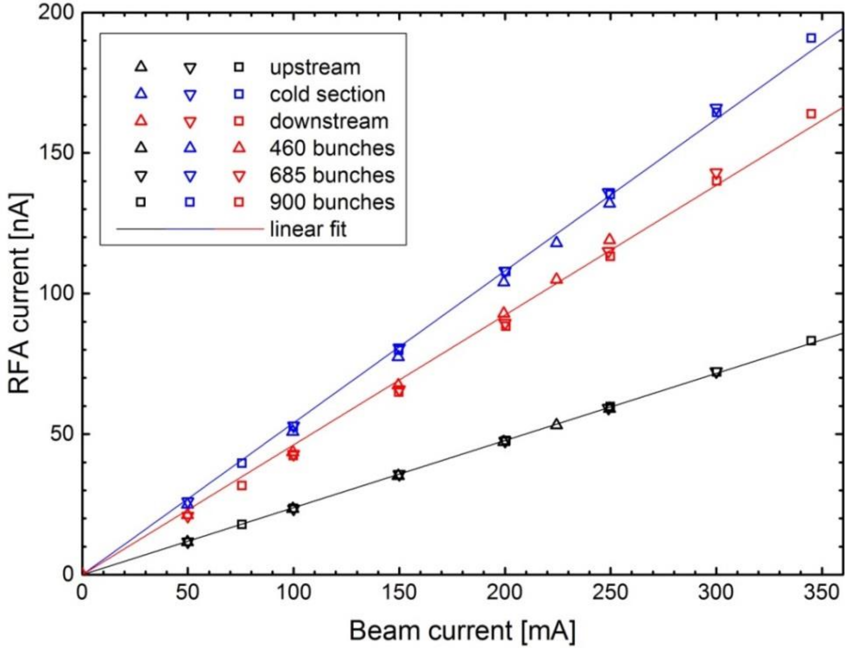
- Difference between measurement sessions depends on the history
- No measureable correlation between pressure and beam heat load
- Base pressure without beam $6 – 8 \cdot 10^{-10}$ mbar -> limited sensitivity

- Gas composition typical for unbaked system
- Independent from beam currrent



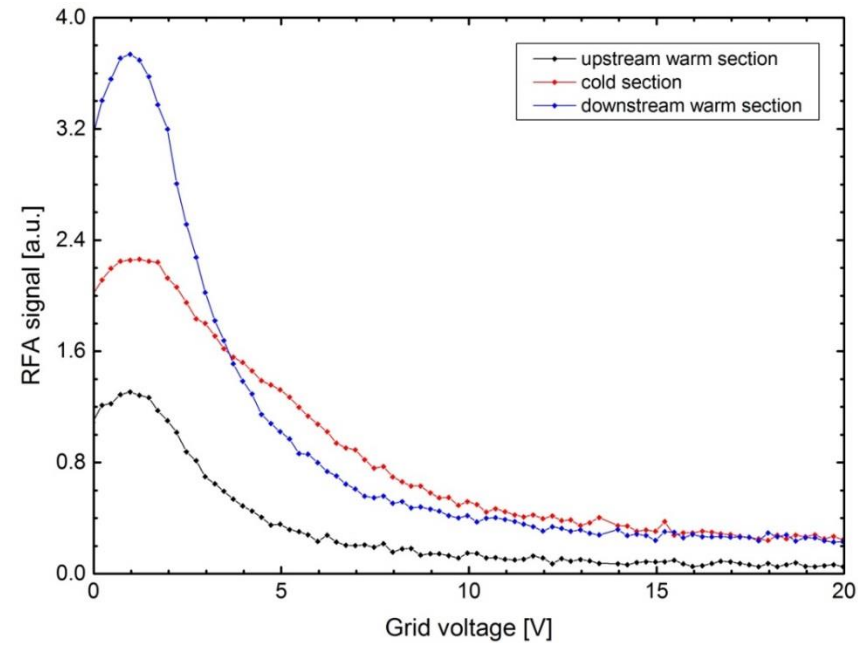
COLDDIAG – retarding field analyzers

Total flux of negatively charged particles (e^-)
grid at 0 V, collector at +50 V



Total flux ~ beam current -> photoelectrons from reflected synchrotron radiation

Energy spectrum
grid negative, collector at +50 V



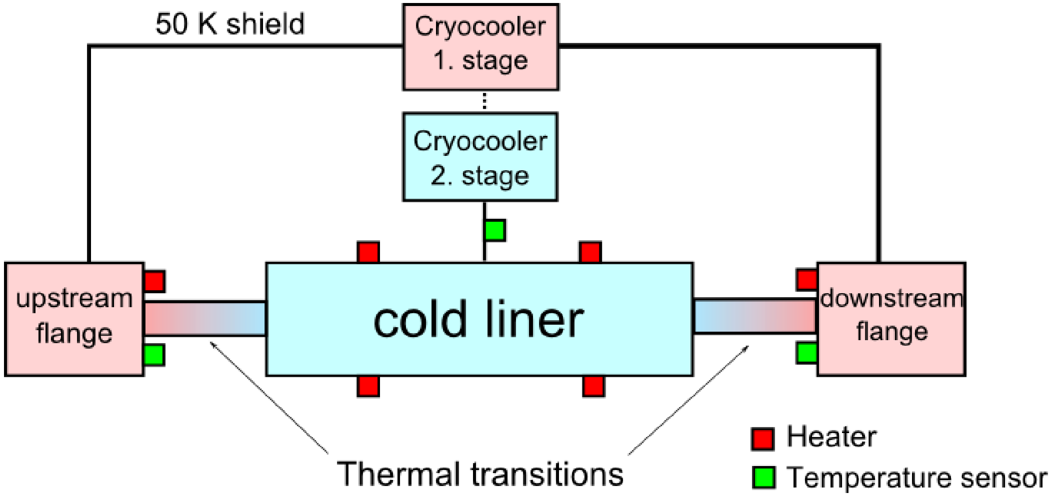
Spectrum measured up to 250 eV, no contribution above 20 eV

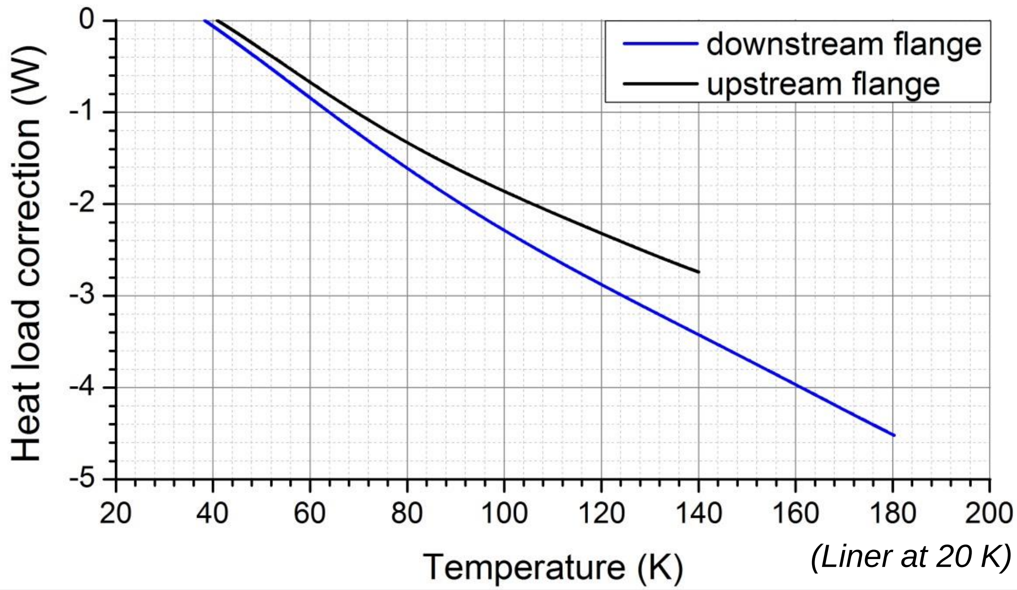
Estimate of deposited power: < 1 mW

Sources of uncertainty: position, acceptance angle and transparency of RFA

COLDDIAG – beam heat load calibration

- Significant heat transfer over thermal transitions to cold liner
  => heaters at flanges necessary
  for calibration
- Installation of heaters was only possible after removal from DLS
  => offline calibration
- Reproduction of all relevant temperatures (cold liner, thermal transitions, cryocooler stages) without beam for all measurements

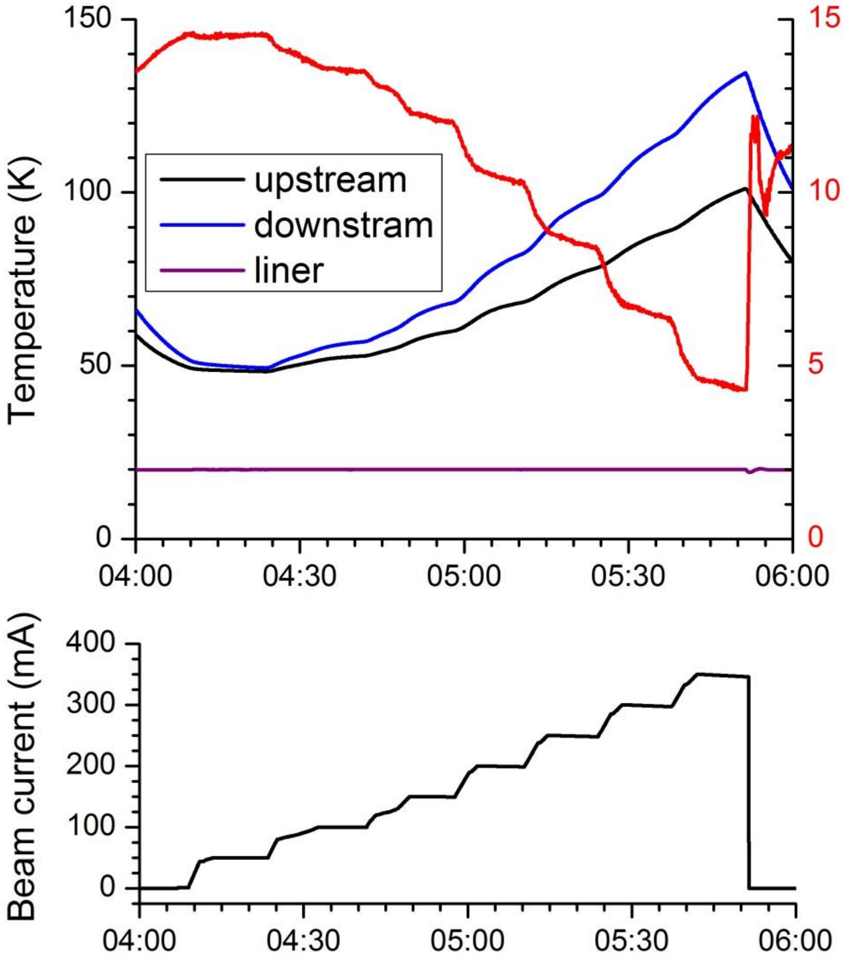




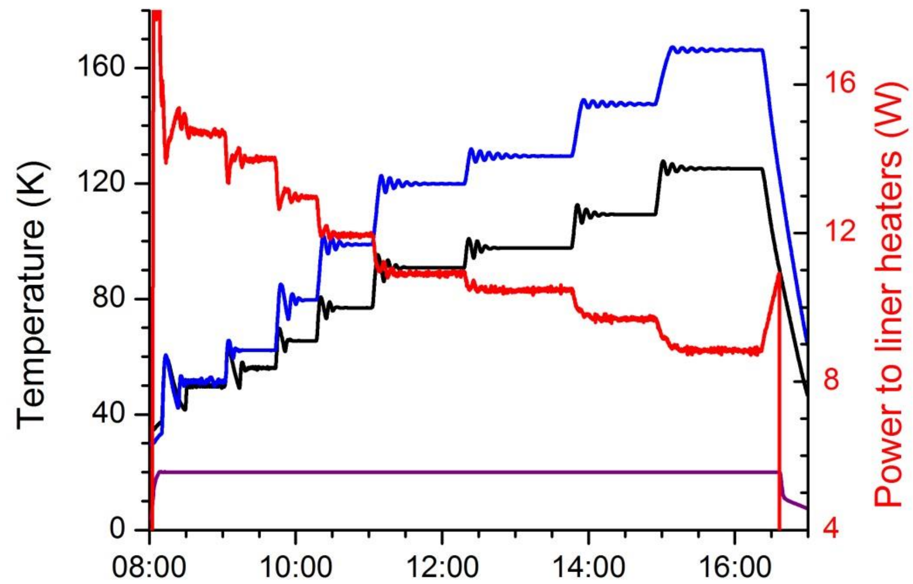
(Liner at 20 K)

COLDDIAG – beam heat load calibration

Measurement



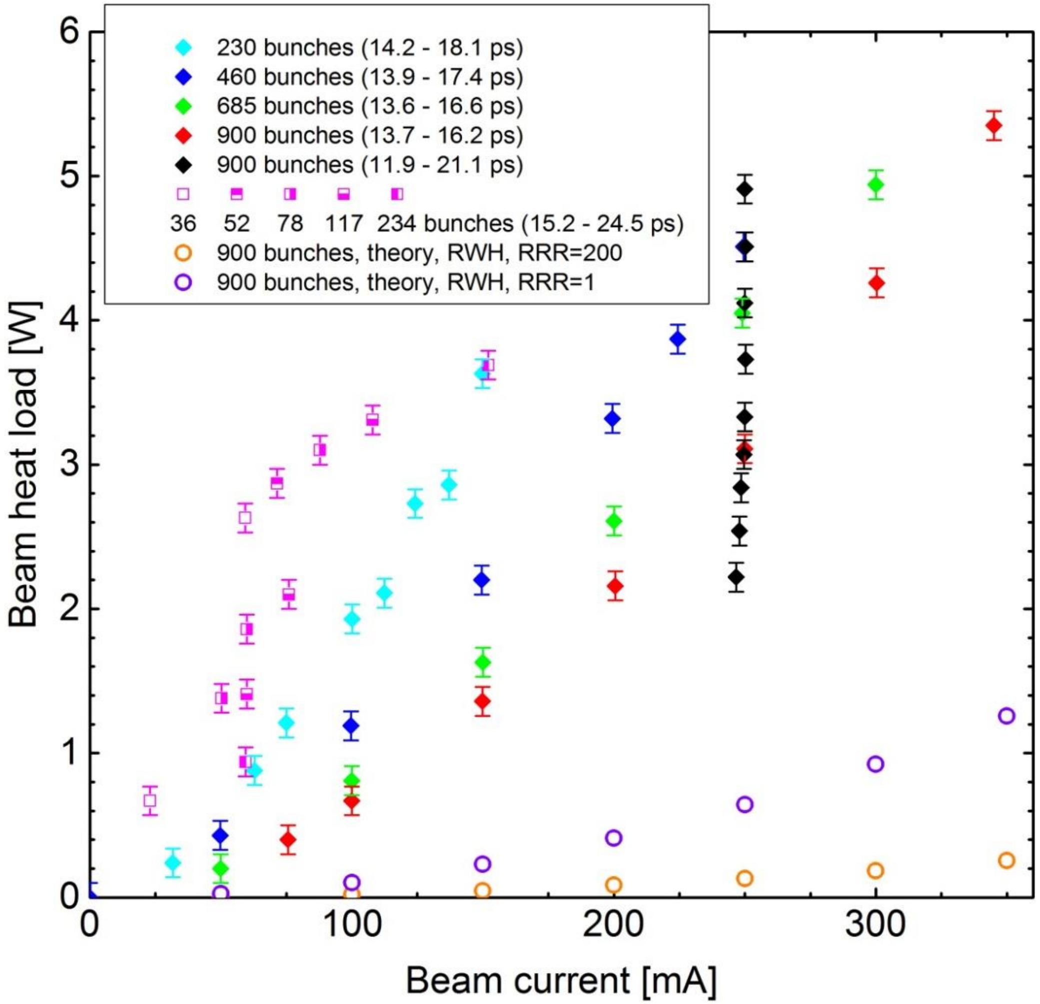
Calibration



Corrected beam heat load:
difference in power to liner heaters (red line) between calibration and measurement

Robert Voutta – Beam heat load

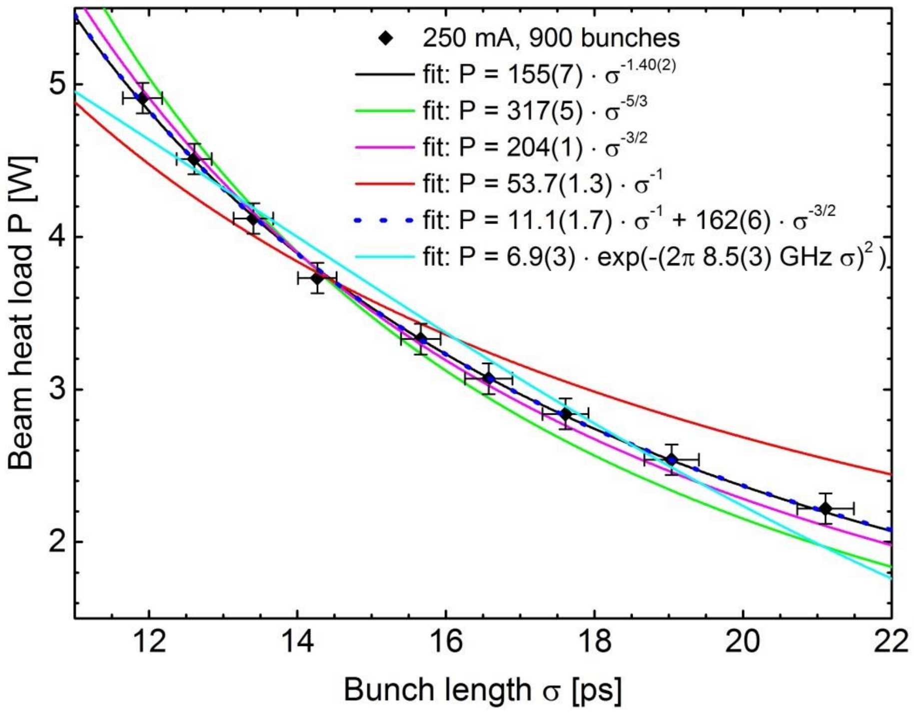
COLDDIAG – beam heat load



- Measured at fixed liner temperature (20 K)
- Corrected by offline calibration
- Strong dependence on bunch current and bunch length
- No influence from bunch spacing
- Theoretical predictions for resistive wall heating:
  ~ 5 times lower at 300 K
  ~ 20 times lower at 4 K
  (RRR = 200)
- Simulation of beam heat load from geometric impedance much smaller than measured heat load

R. Voutta et al., IPAC2015, TUPWA025

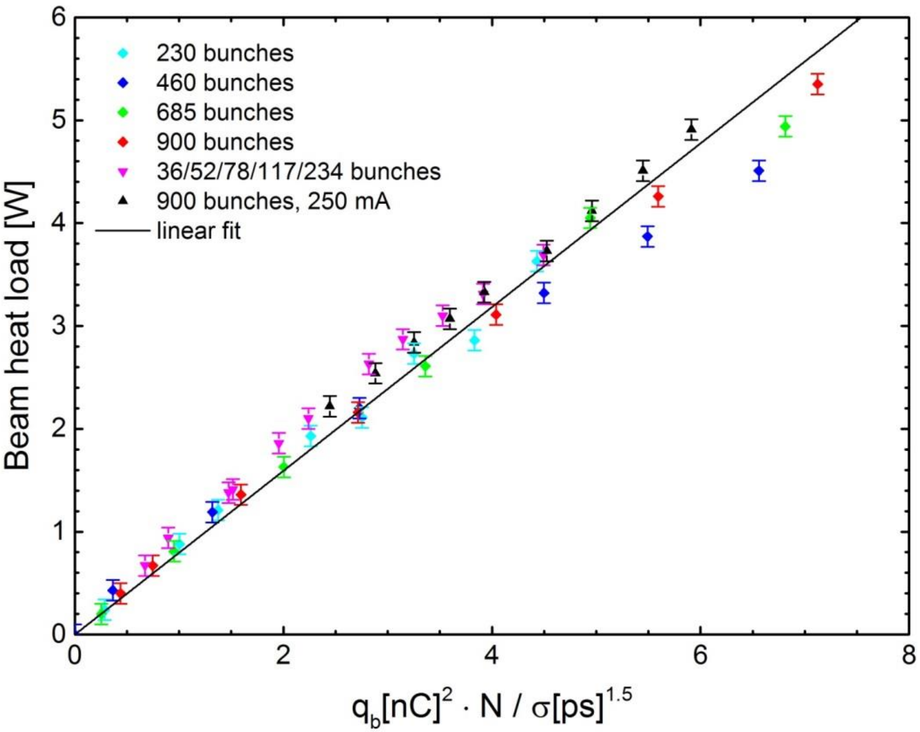
COLDDIAG – beam heat load



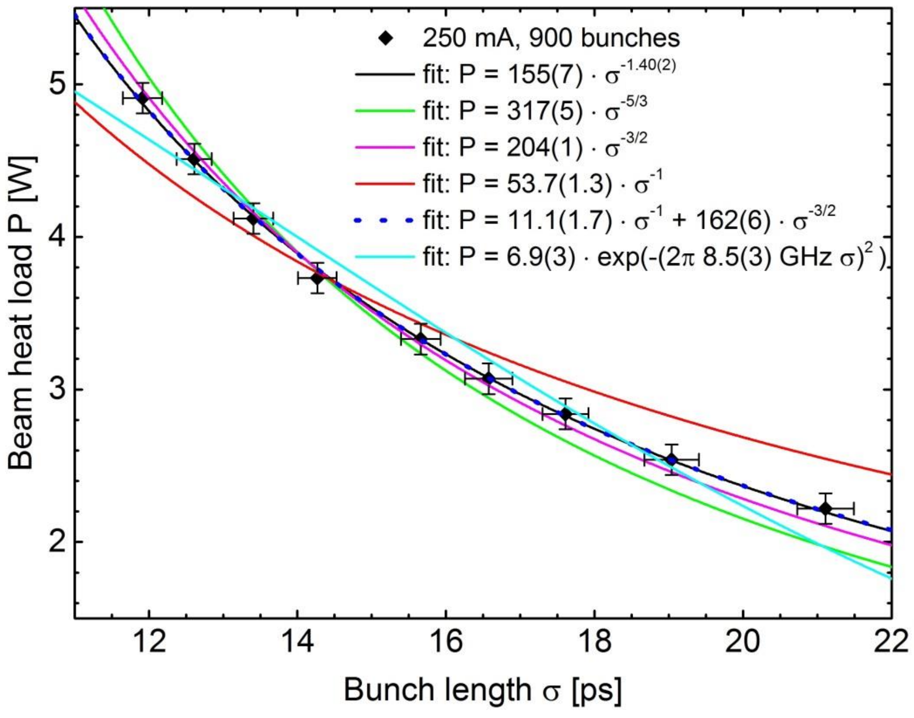
Bunch length dependence indicates mixture between step transitions ($P \sim \sigma^{-1}$) and resistive wall heating ($P \sim \sigma^{-3/2}$)

But: no model fits exactly to all the data

resistive wall heating →



COLDDIAG – beam heat load



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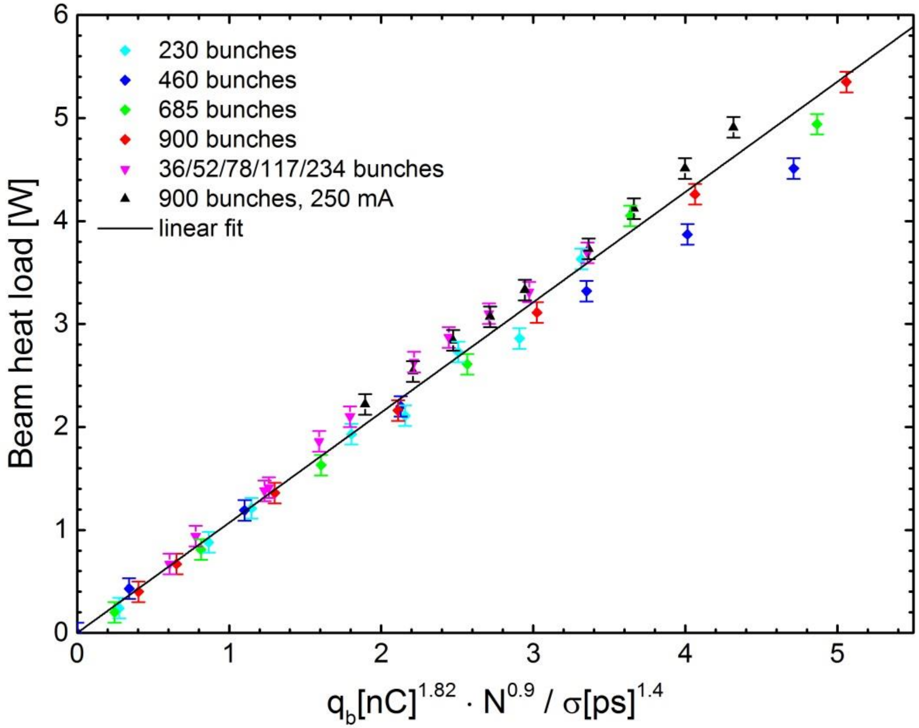
But: no model fits exactly to all the data

empirical model →



Conclusions

- Extensive beam heat load measurements were performed with COLDDIAG at the Diamond Light Source
- The measured beam heat load is much higher than predicted from theory and simulations
- Direct synchrotron radiation can be excluded as a possible heat source
- Heating due to electron and/or ion bombardment could not be verified

Conclusions

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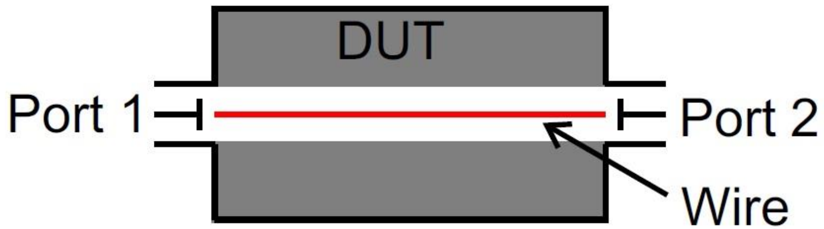
→ Where is the heat load coming from?

→ What to do next?

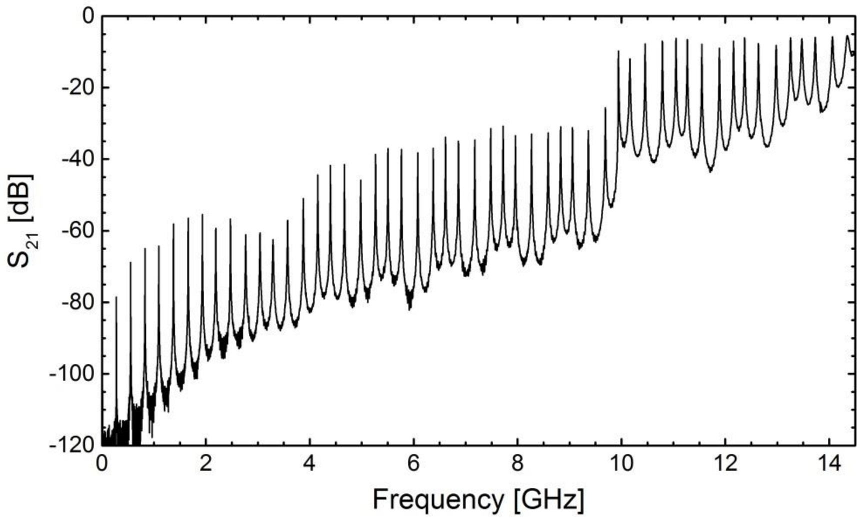
…

Outlook – impedance measurements

Wire measurement (resonator method) …

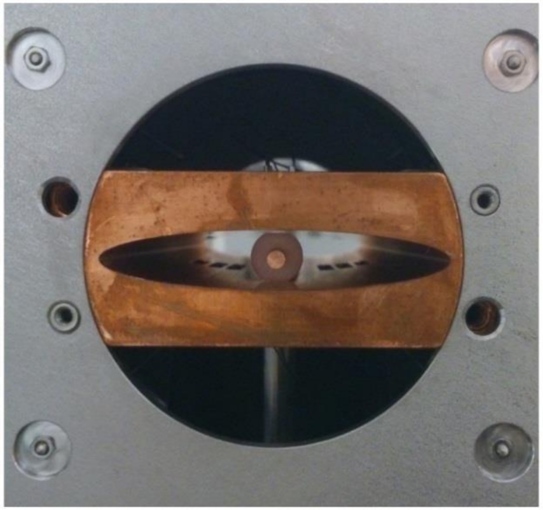


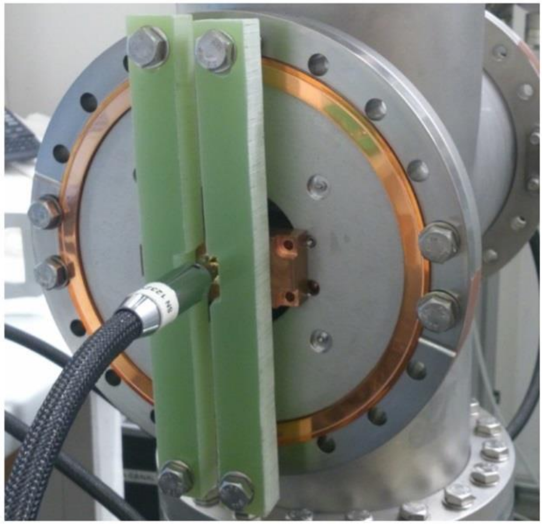
T. Kroyer, F. Caspers, E. Gaxiola, CERN AB-Note-2007-028



… on the COLDDIAG structure:

- „wire“ = 3 mm copper rod
- Teflon support pieces
- End plates with SMA pin connectors

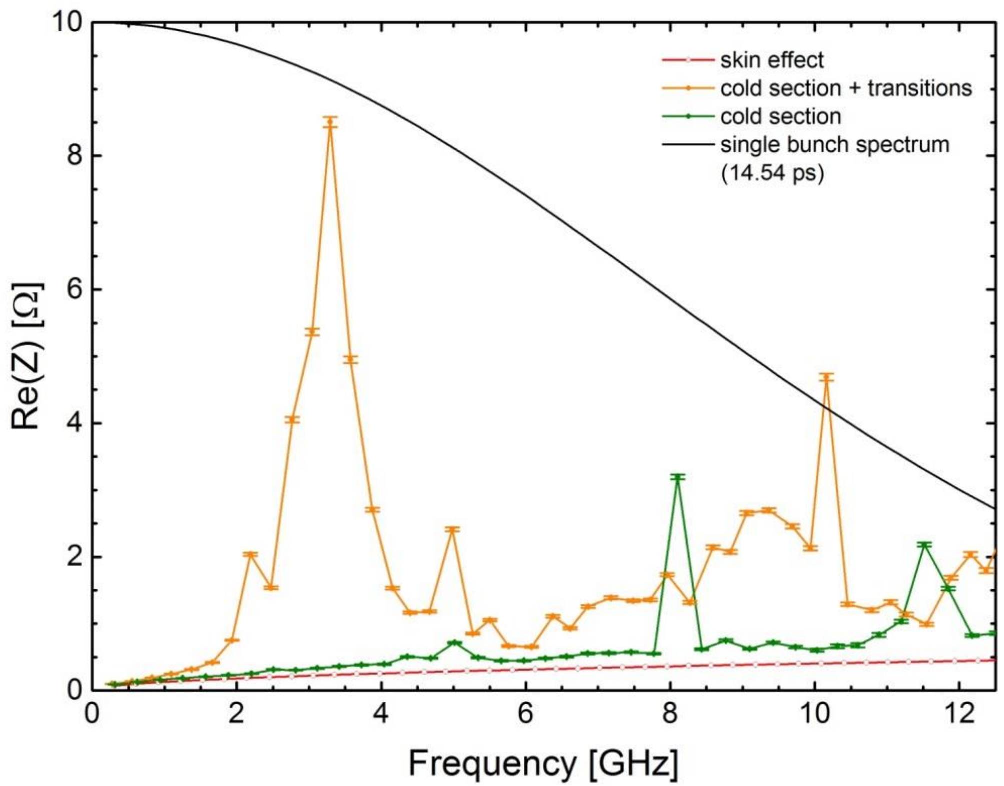




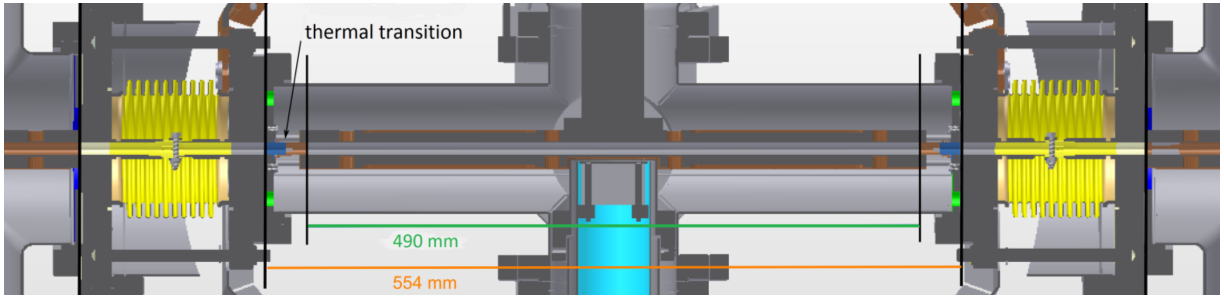
Outlook – impedance measurements

- Quality factor at resonances
  → attenuation
  → real part of long. Impedance
- Impedance measurement on different parts of the COLDDIAG structure
  → locate impedance sources
- „Cold section“ liner at 300 K: 1.6 W integrated power
- „Cold section“ liner + thermal transitions to 50 K shield: 5.6 W integrated power

→ 4 W from thermal transitions



Accuracy limited by resolution of impedance measurement



Thank you!

Questions?