CW and Near-CW Operation of a Superconducting Linac Driving a FEL Facility*

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* Work partially supported by EU under contract No. 011935 (EUROFEL)

Outlook

- Motivation
- Parameter set for the cw and near-cw operation
- Status of the IOT transmitter upgrade
- Status of the Nb-Pb gun
- Status of the HOM couplers feedthrough and output line
- Final Remarks

Motivation for an increased duty factor

The increased duty factor will:

1. allow for the higher average brilliance (*it will be discussed later*)
2. allow for "new" flexibility in the beam time structure

- **More photons**:

  Experiments at FLASH (XFEL ?) use Time-of-Flight detectors for ions.
  The ions need many μs to arrive at the detector. Typical pulse separation is ~10 μs.
  At the present RF-pulse length and 10 Hz repetition FLASH (XFEL) can produce 800 photon pulses/sec. At ncw of ~100 ms @ 1 Hz number of photon pulses will be 10000 per sec.

- **Simpler equipment:**

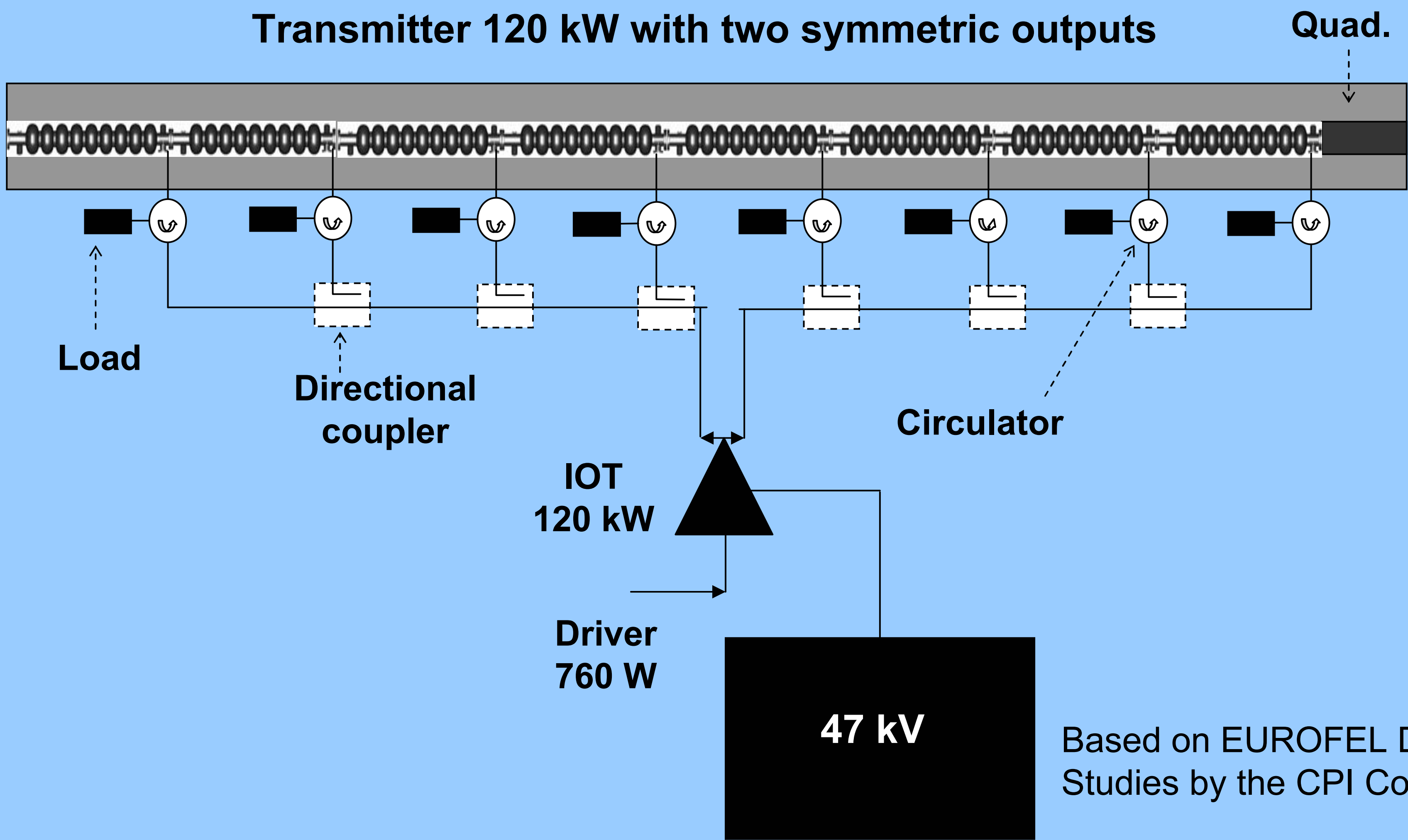
  Detectors: 10μs readout time for 1D- and 2D-Detektors is easier than 1μs or 400ns**.**
  (Impact on the development of new detectors for XFEL).

  High Power Optical Lasers: for Pump-Probe Experiments have low repetition rate (~kHz). With 10% duty factor we can have ~100 pulses per second. At the moment commercial lasers for FLASH are impractical.

3. open possibility for the energy recovery operation

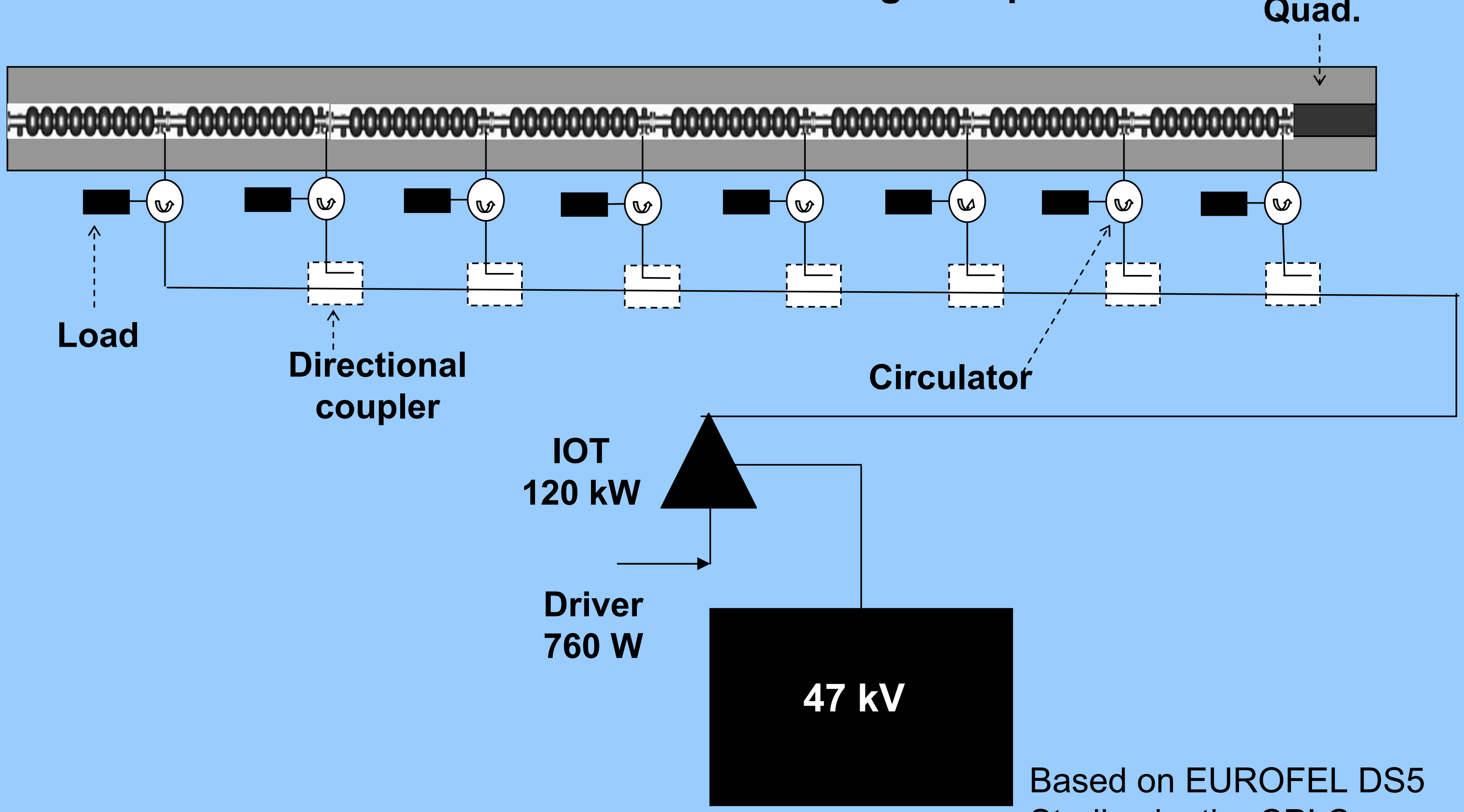
Accelerating Unit = Cryomodule (8x 9-cell sc cavities) **+ RF-transmitter**

Transmitter 120 kW with two symmetric outputs



Based on EUROFEL DS5
Studies by the CPI Company

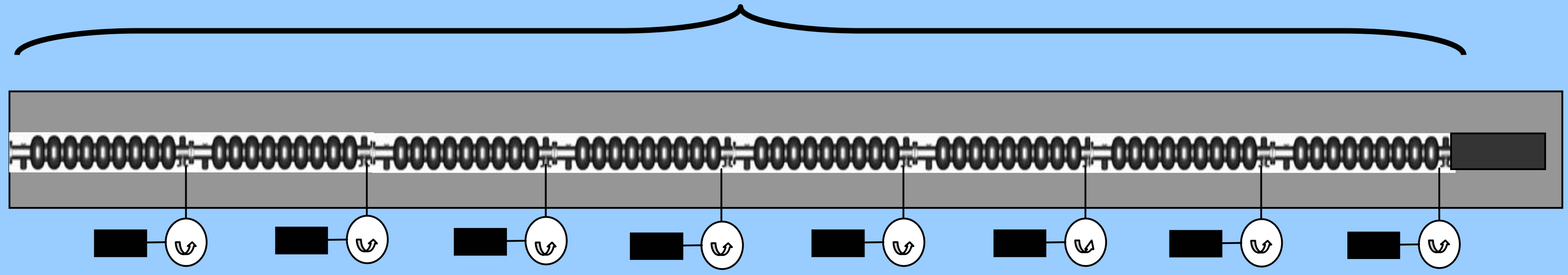
Transmitter 120 kW with single output



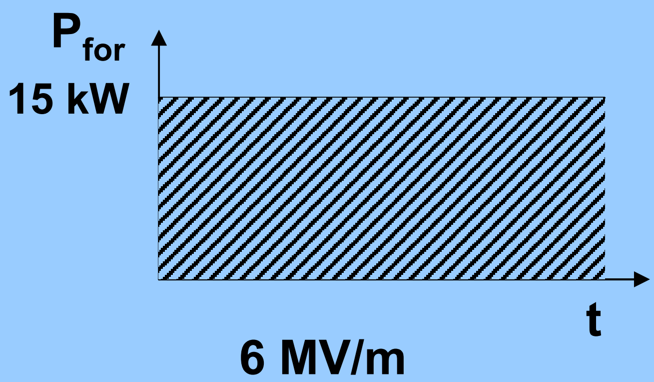
Based on EUROFEL DS5
Studies by the CPI Company

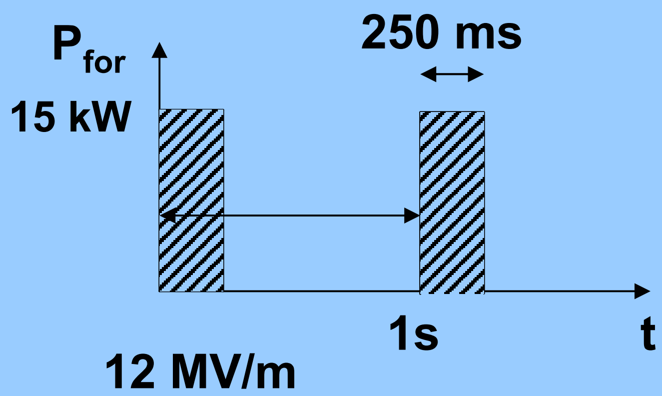
Assumption 1: <cryogenic load> stays constant vs. Eacc

Cryogenic Load 30 W @ 1.8 K



DF scales ~ $1/(E_{acc})^2$



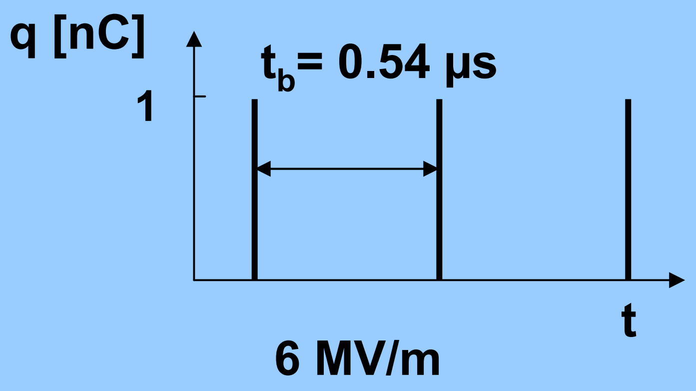


Parameter set for the cw and near-cw operation

Assumption 2: Beam power stays constant vs. Eacc

Max P_{for} = 15.0 kW / cavity
Max P_{in} = 14.5 kW / cavity (0.5 kW dissipated in the distribution system)
Max P_{beam} = 11.6 kW / cavity (20 % for LLRF)

$I_{beam} \sim 1/E_{acc}$ → **q/bunch stays constant but** $t_b \sim E_{acc}$



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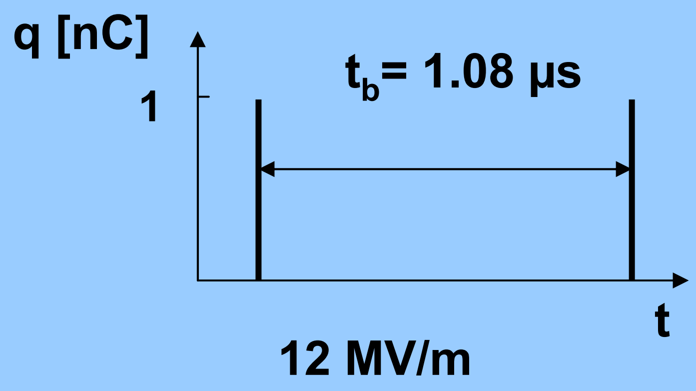
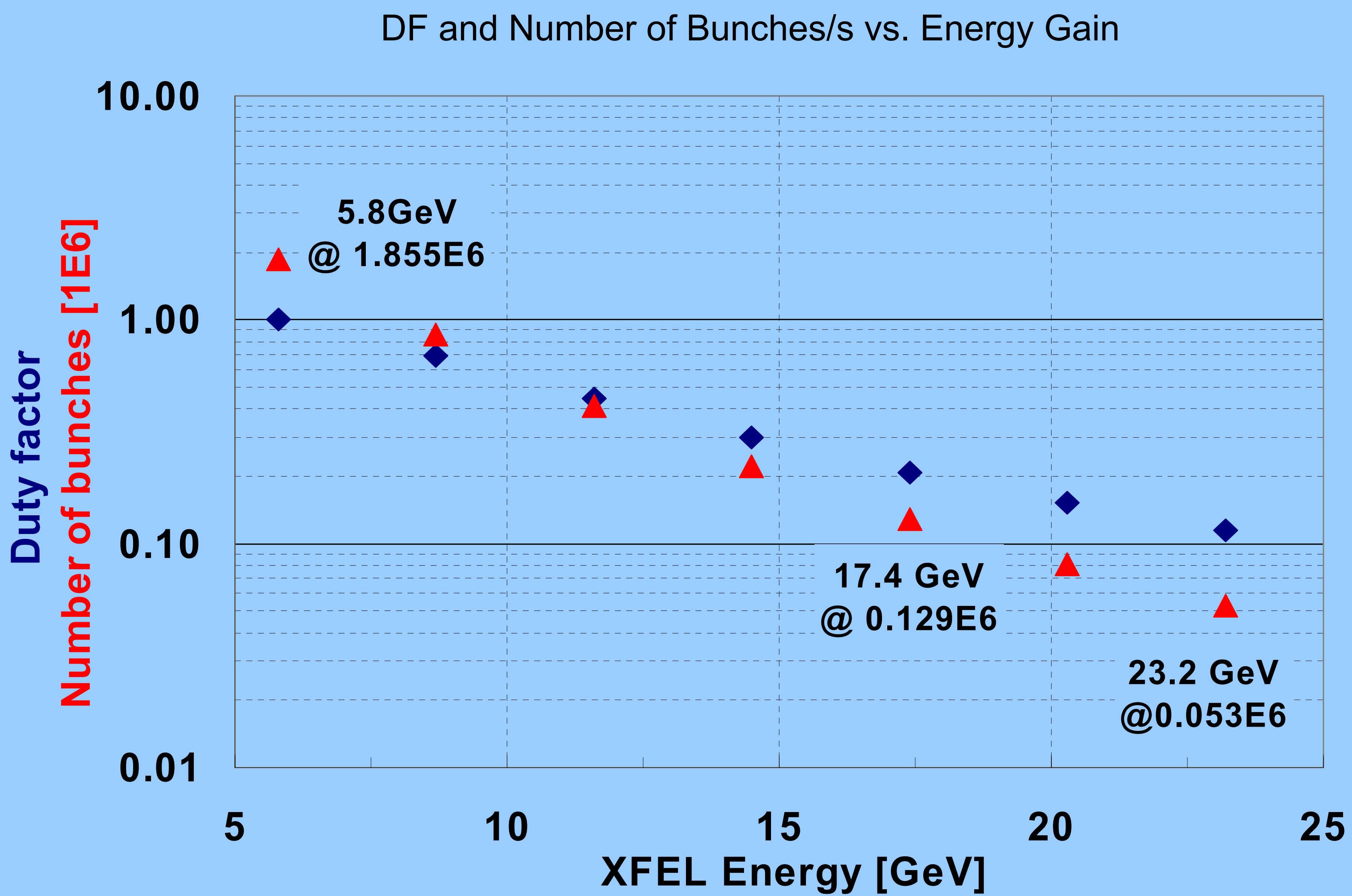


Parameter set for the cw and near-cw operation

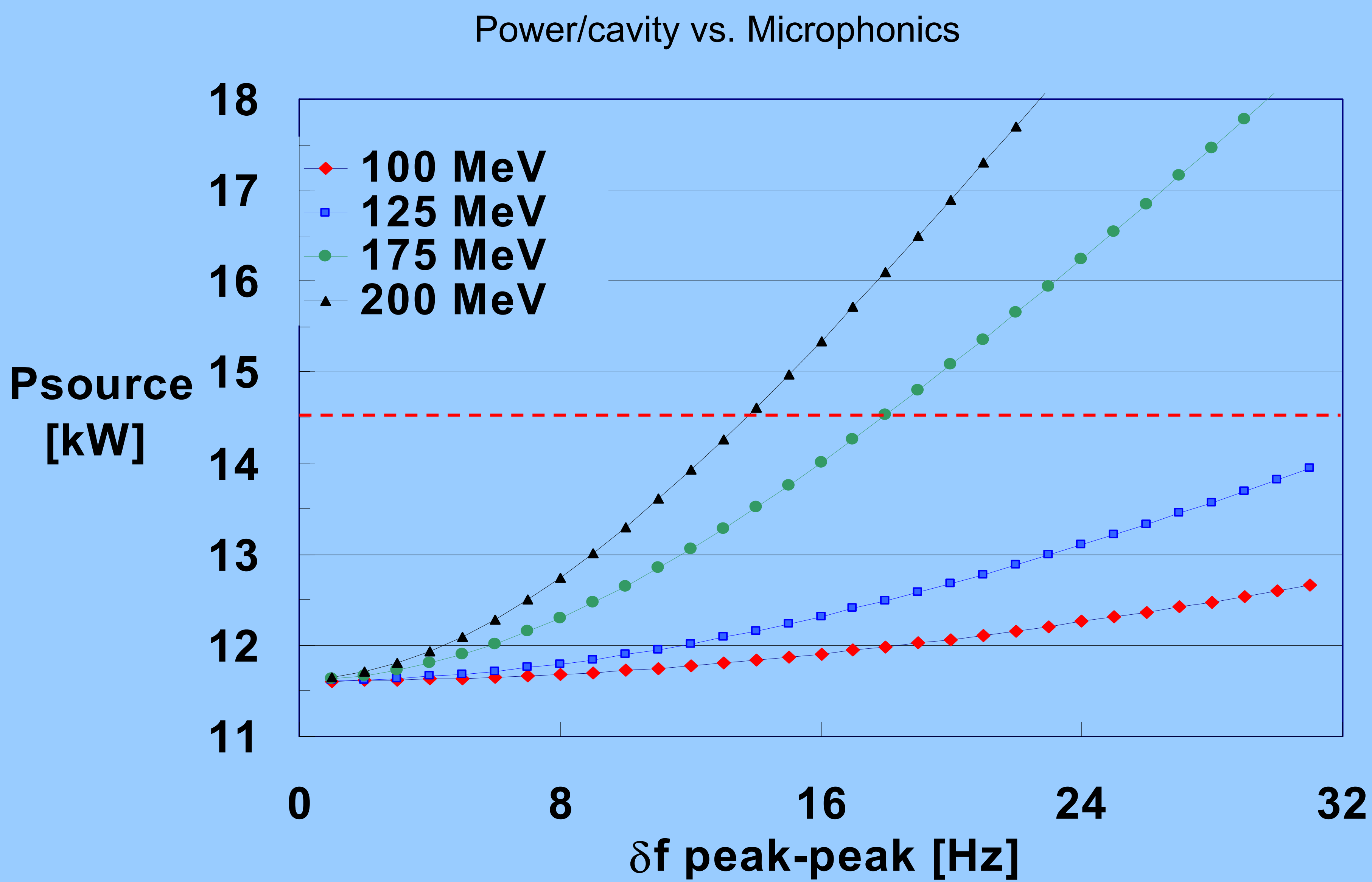
Operating parameters for the Acc. Unit and for a XFEL-like linac with 116 Units.

Energy gain /Accelerating Unit	[MeV]	50	75	100	125	150	175	200
Eacc	[MV/m]	6.01	9.01	12.02	15.02	18.03	21.03	24.04
Qo	[10^{10}]	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Total Loss at 2K/cryomodule for DF = 100%	[W]	29.6	43.2	67.2	100.2	141.4	190.7	247.7
Duty Factor	**[%]**	**100**	**69.4**	**44.6**	**29.9**	**21.2**	**15.7**	**12.1**
Beam time	**[ms]**	**1000**	**693**	**444**	**297**	**208**	**152**	**114**
Pulse length	[ms]	1000	694	446	299	212	157	121
Beam current	[mA]	1.86	1.24	0.93	0.74	0.62	0.53	0.46
Bunch spacing when charge/bunch = 1nC	[μs]	0.54	0.81	1.08	1.35	1.62	1.89	2.16
Number of 1 nC bunches/s	**[10^6]**	**1.855**	**0.857**	**0.412**	**0.220**	**0.129**	**0.081**	**0.053**
Opt. Qext to keep power $\leq$ 14.5 kW/cavity	**[10^6]**	**3.1**	**6.7**	**11**	**14**	**20**	**27**	**36**
Max. allowed microphonics peak-peak	[Hz]	34	34	34	34	24	18	14
Total RF-peak power/cavity: beam + microphonics	[kW]	12.1	12.4	13.2	14.5	14.5	14.5	14.5
XFEL Energy for 116 acc. units	**[GeV]**	**5.8**	**8.7**	**11.6**	**14.5**	**17.4**	**20.3**	**23.2**

Parameter set for the cw and near-cw operation



Parameter set for the cw and near-cw operation



Parameter set for the cw and near-cw operation

- **Advantages of CW**
  - Improved field regulation
    - Transient perturbations not present
    - Low frequencies can be suppressed with very high feedback gain (=> excellent offset suppression)

- **Disadvantage of CW**
  - High loaded Q => larger amplitude and phase errors
  - Continuous control and monitoring requires different concept
  - Potential problem with ponderomotive instability

Courtesy S. Simrock

Field Stability Measured at JLAB

Range [Hz]	Amplitude Error	Phase Error [°]
$0 - 10^0$	5.5×10^{-6}	1.1×10^{-3}
$0 - 10^1$	1.1×10^{-5}	1.2×10^{-3}
$0 - 10^2$	3.5×10^{-5}	3.0×10^{-3}

Design Objectives:

- L-Band IOT for EUROFEL
- Frequency: 1.3 GHz
- Output Power: 120kW CW
- Beam Voltage: <50 kV
- Output Port: Wave Guide

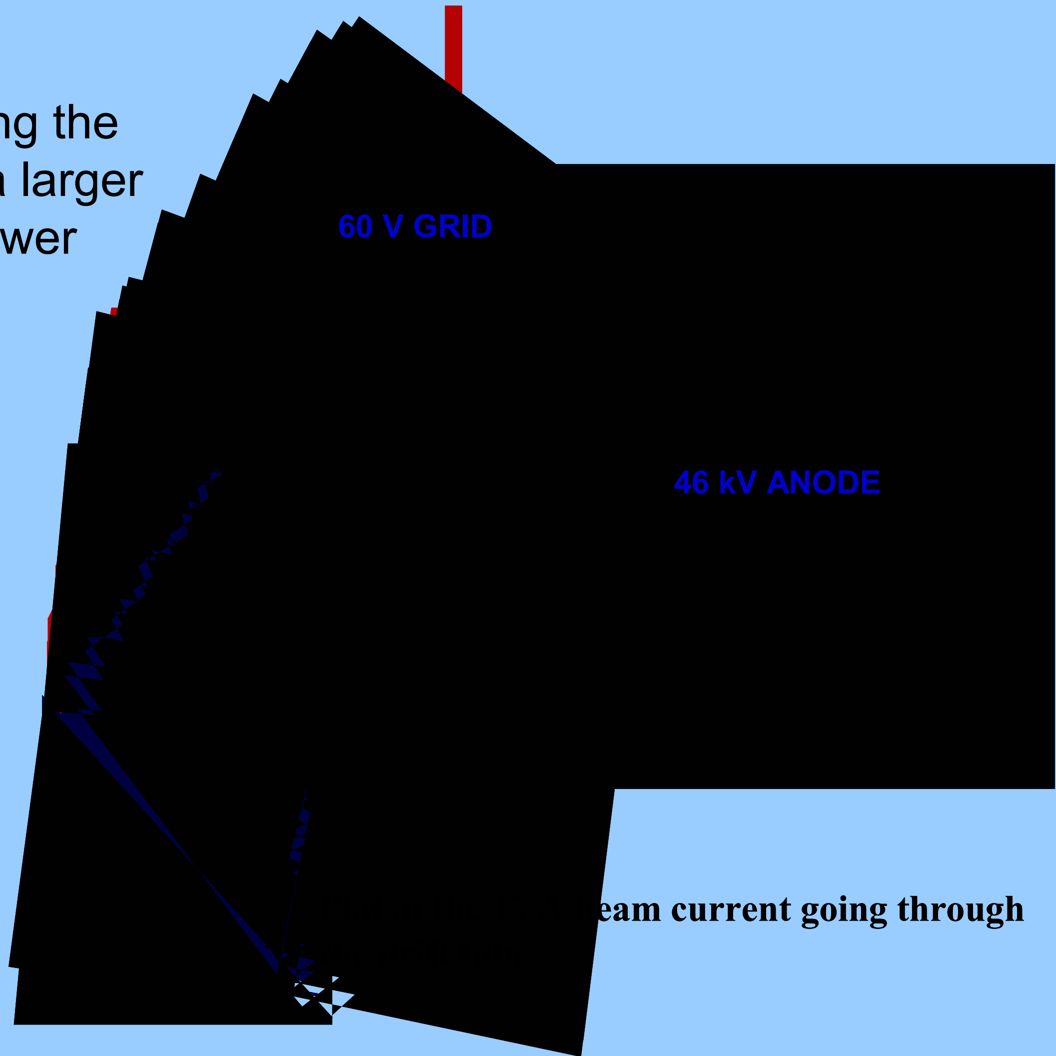
Preliminary Specifications

The 120kW CW 1.3GHz IOT specifications are generated based on the preliminary design and experience with UHF IOT and 30kW L-Band IOT systems.

Parameters	Minimum	Nominal	Maximum	Unit
frequency		1.300		GHz
Output Power		120		kW
-3dB bandwidth	8	10	15	MHz
Power Gain	22	23		dB
Efficiency	63	68		%
Beam Voltage		46	50	kV
Beam Current		3.85		A
RF Drive		600	750	W
Grid Bias	-50	-100	-150	V

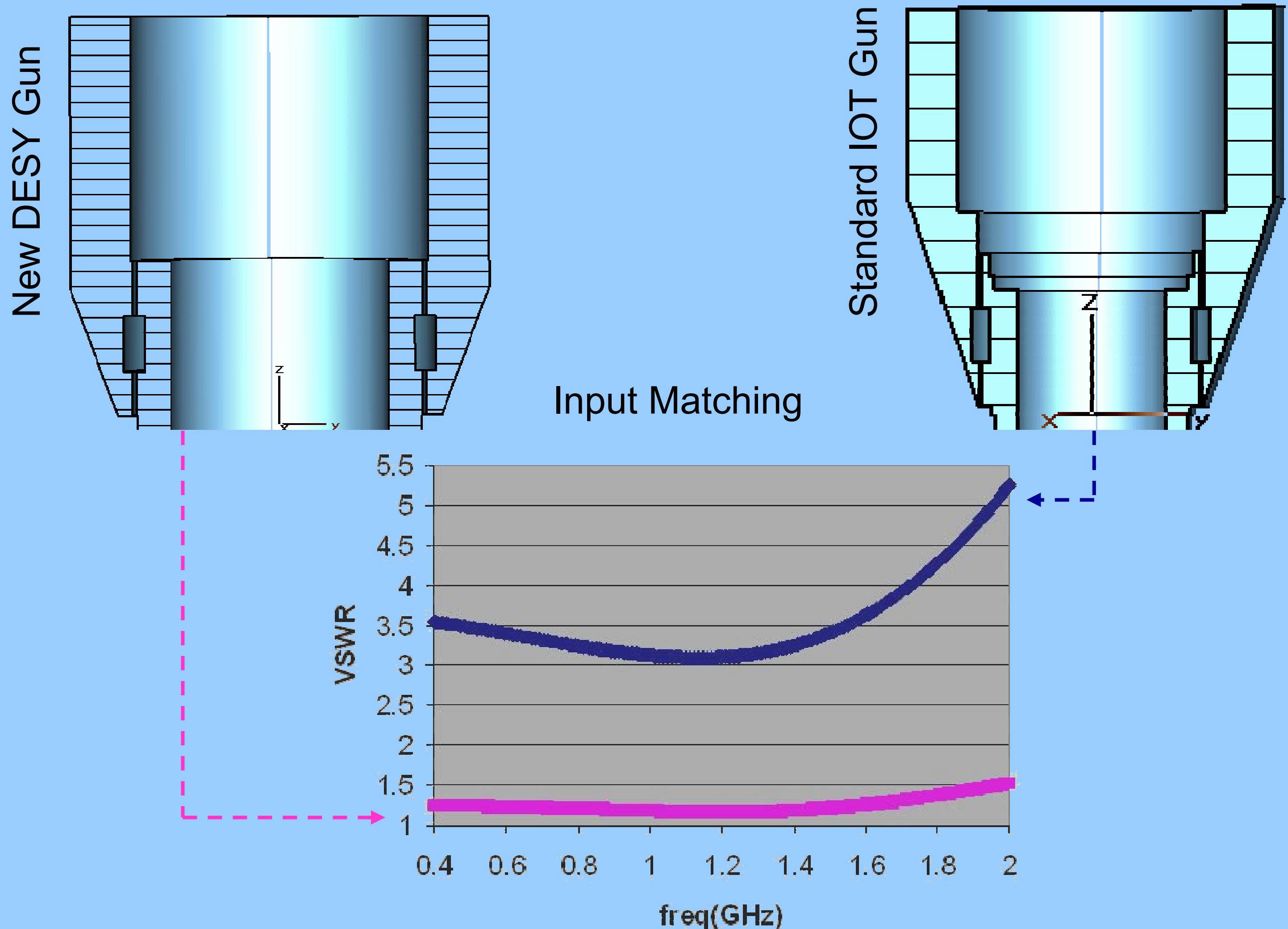
Electron Gun

The conclusion from evaluating the existing IOT gun was to use a larger cathode for better gain and lower cathode loading.



Electron Gun, cont.

Cross Section View of the Gun Designs



◈ Output Cavity

The output cavity is rectangular in shape with an iris opening on a side wall to couple RF power to a full size waveguide. The output window is located at the other end of the waveguide with a flange to connect to a standard WR650 waveguide.

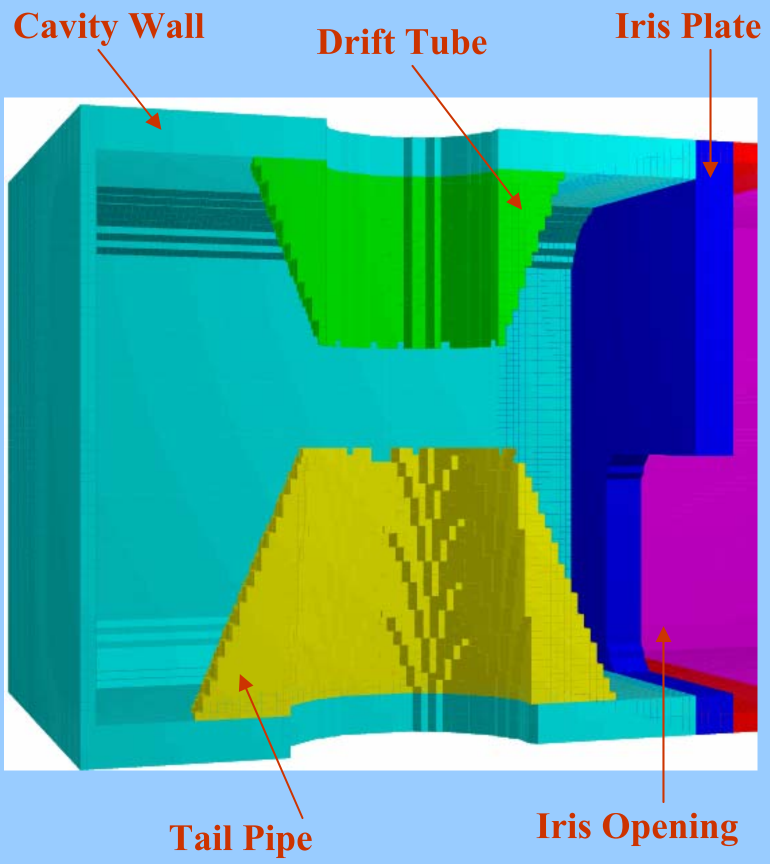
Power Dissipation in [W] at 120 kW

Cavity Wall	623
Drift Tube	130
Tail Pipe	405
Iris Plate	210

RF parameters

	Single Output	Unit
Cavity Q_0	11274	
Cavity Q_e	133	
Cavity R/Q	105	Ω
Resonant Frequency*	1275.3	MHz

Output Cavity with Single Output Port



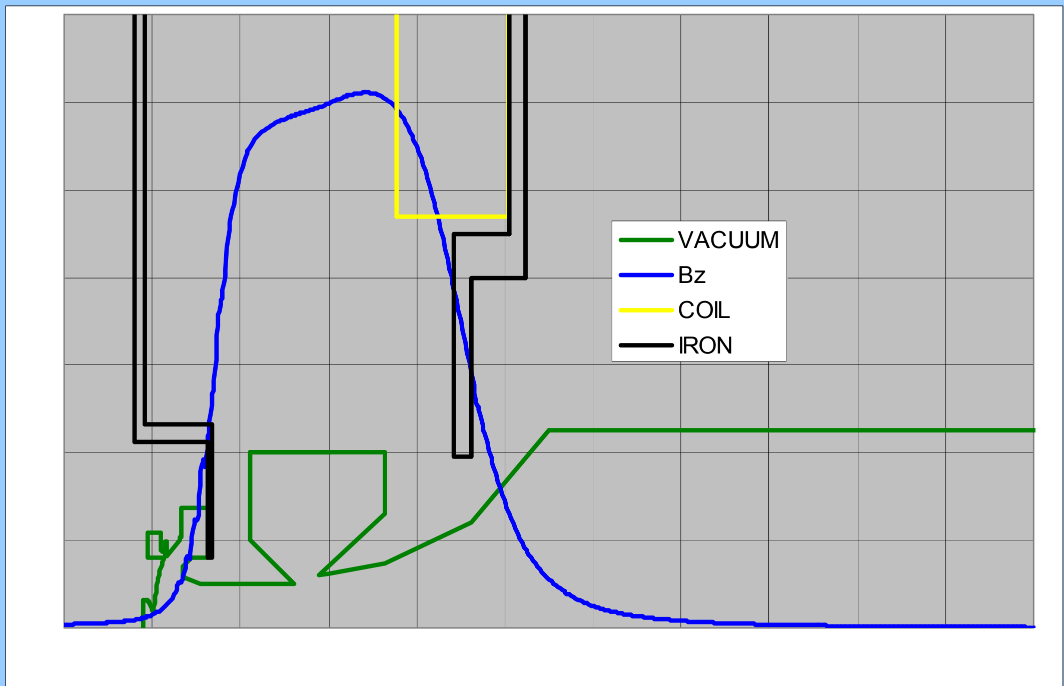
Collector

Adopted collector from the VKP-8291A klystron that is used at SNS.

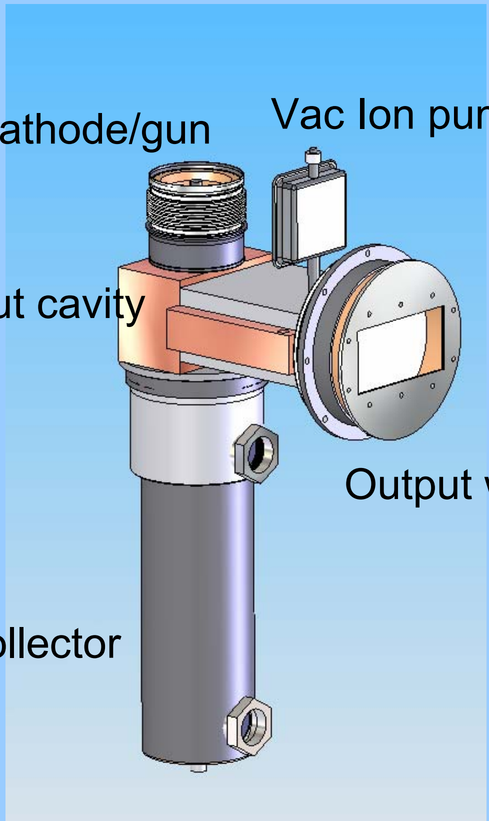
T<100°C at 120 kW and 57% efficiency

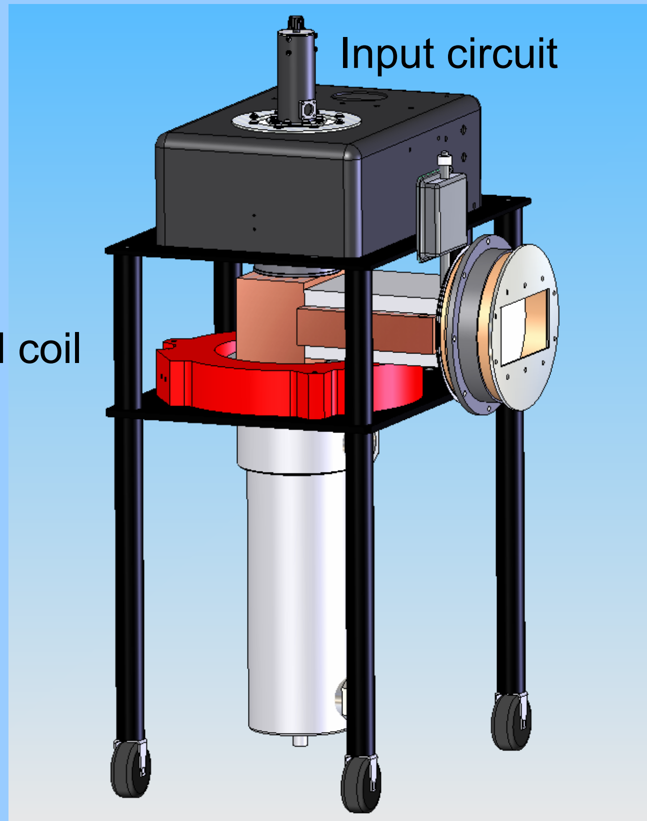
Magnetic Circuit

The major change: the solenoid coil located above the output cavity is removed.



◆ Tube and System Layout





Magnetic circuit / supporting hardware

Future Works at CPI

In order to have superb performance, optimization will continue in the following areas,

- Cathode and grid performance, cooling and packaging.
- Magnetic focusing circuit.
- Output cavity: build cold test model to confirm the modeling.
- System integration.
- Cooling system.
- Input circuit modification.

Status of the IOT transmitter upgrade

Studies on **the technical feasibility of the 120 kW transmitter** were proposed in 2005 in the frame of the EUROFEL project.

- The design can be ready in March 2007 (seven month before the schedule)
- It seems possible to build the first single output prototype (CPI revised quotation is ready) but we do not have funding (yet ?)
- The first test can be carried out at CPI in 2007/2008

?

then we could install this tube at CMTB at DESY to learn more about:

- stability of the cryogenic system at the cw and ncw operation
- thermal capability of components at higher duty factor (input and HOM couplers, RF-distribution system….)
- optimization of LLRF for the cw operation and the stability of amplitude and phase
- ……

all this will be very beneficial for the XFEL upgrade and for other FELs (FLASH ?)

Motivation

is to build cw operating electron RF-source of ~1 mA class for FEL facilities.

Collaborating Institutions (since 2004)

DESY:	…..D. Kostin, A. Matheisen, W.-D. Möller, D. Klinke, J. Iversen….
BNL:	A. Burrill, I. Ben-Zvi, T. Rao, J. Smedley
INFN:	M. Ferrario
JLAB:	P. Kneisel
A. Sołtan INS:	P. Strzyżewski
SUNY:	R. Lefferts, A. Lipski
Uni. Łódź:	K. Szałowski
SLAC:	K. Ko, Z. Li.

Status of the Nb-Pb gun

Approach

The beam is generated from a **superconducting cathode**

This will simplify integration of the cathode into superconducting environment.

Pb-Nb RF-gun follows the idea of the **all niobium** RF-gun of BNL

Niobium QE = 10^{-5} @ λ =266 nm

Lead is commonly used superconductor for accelerating cavities:

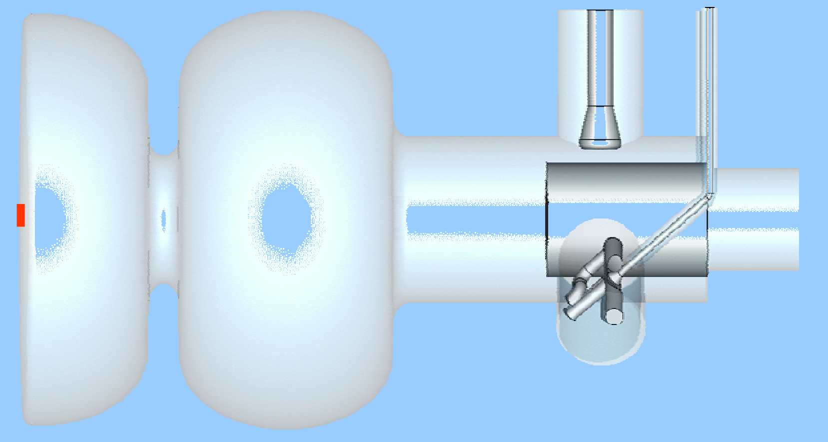
T_c = 7.2 K , B_c = 70 mT

Nb-Pb 1mA-class SRF-gun

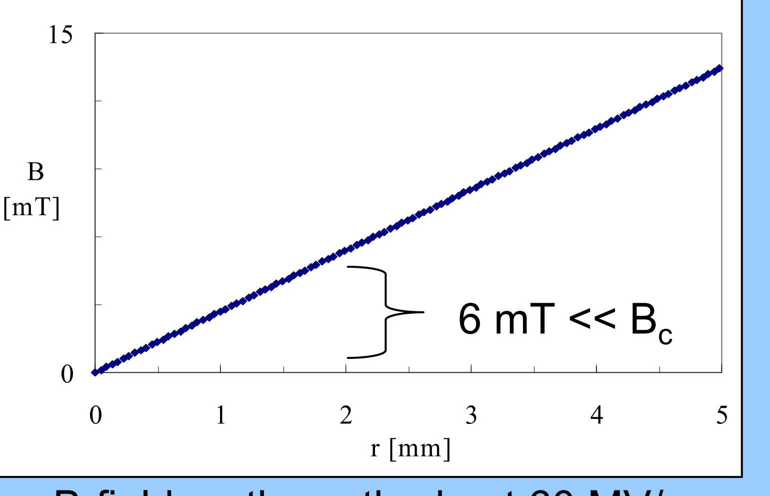
RF-design is ready (DESY+SLAC)

High RRR Nb cavity

“small” emitting Pb spot

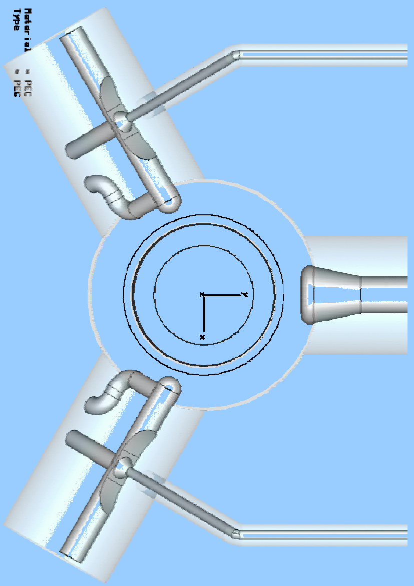


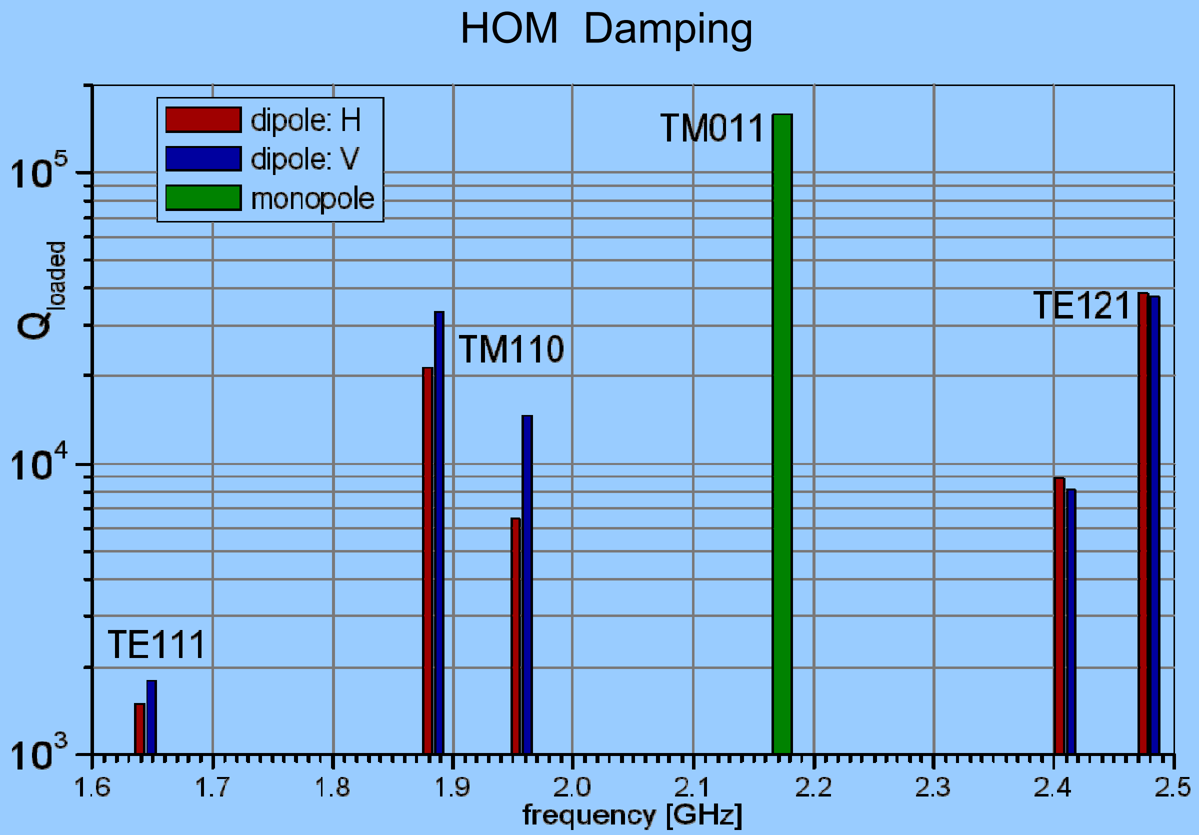
Parameter	Unit	
π-mode frequency	[MHz]	1300
0-mode frequency	[MHz]	1286.5
Cell-to-cell coupling	-	0.015
Active length $1.6 \cdot \lambda/2$	[m]	0.185
Nominal E_{cath} at cathode	[MV/m]	60
Energy stored at nominal E_{cath}	[J]	20
Nominal beam energy	[MeV]	6



B-field on the cathode at 60 MV/m

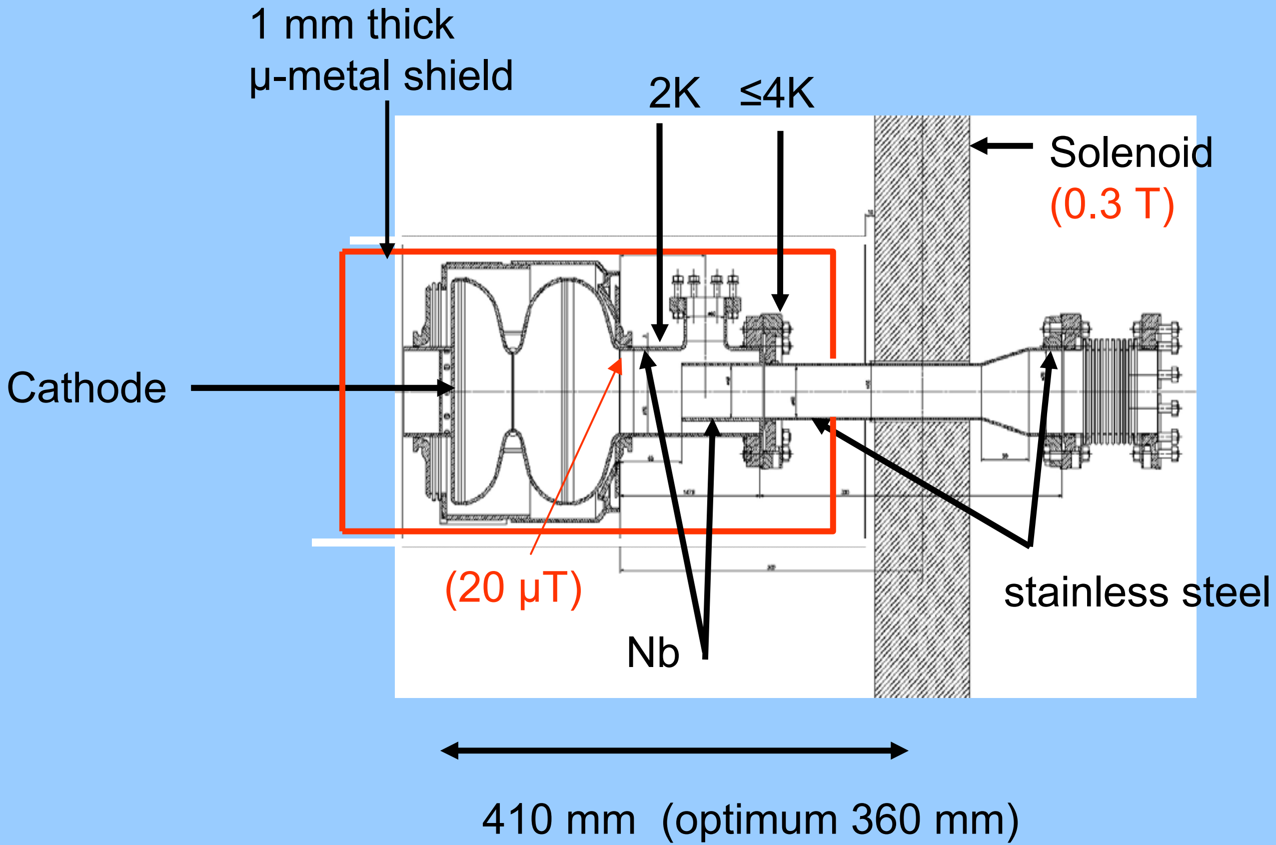
RF-design is ready (DESY+SLAC)





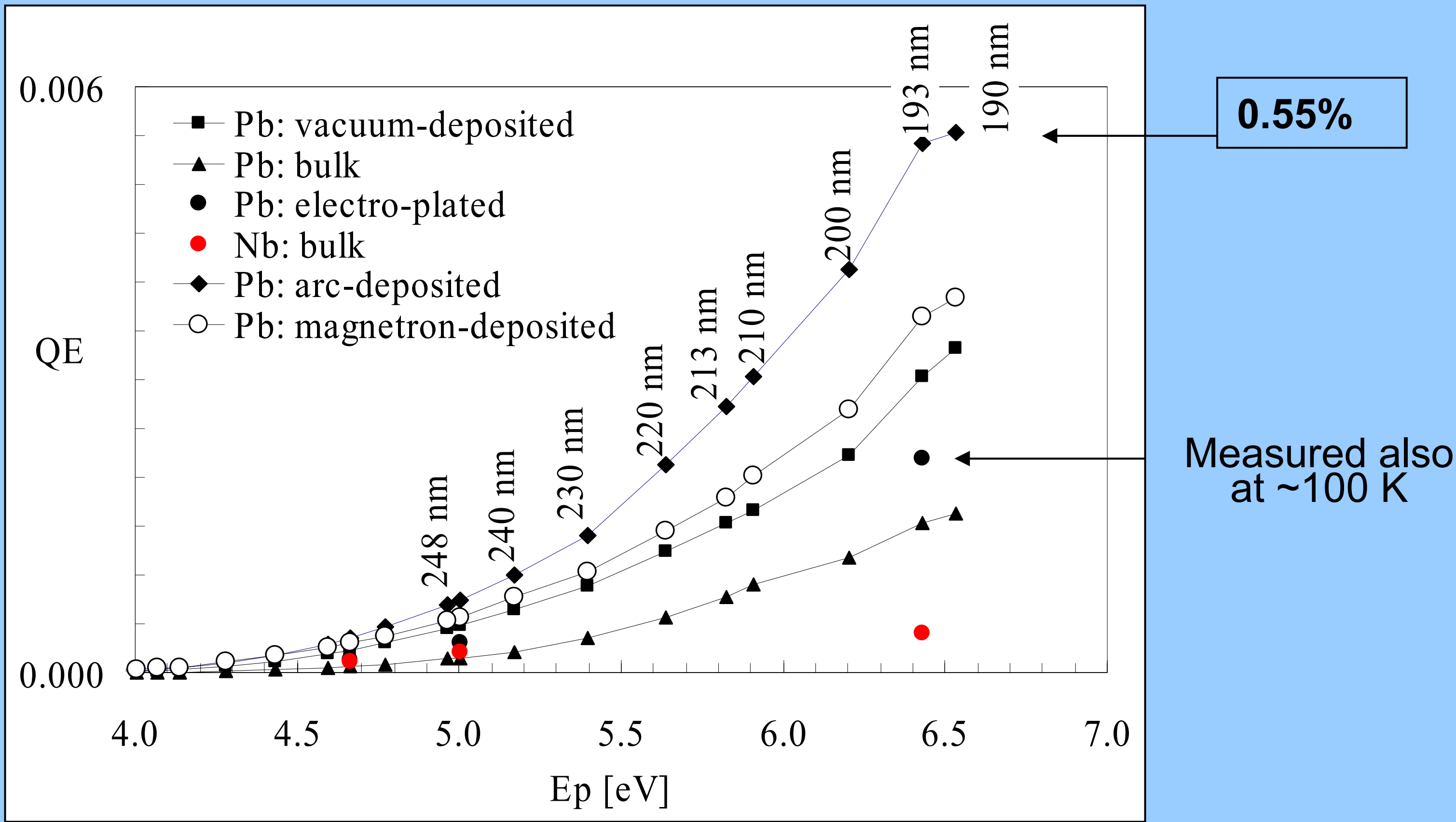
Status of the Nb-Pb gun

Cryostat Layout



Pb photo-emission

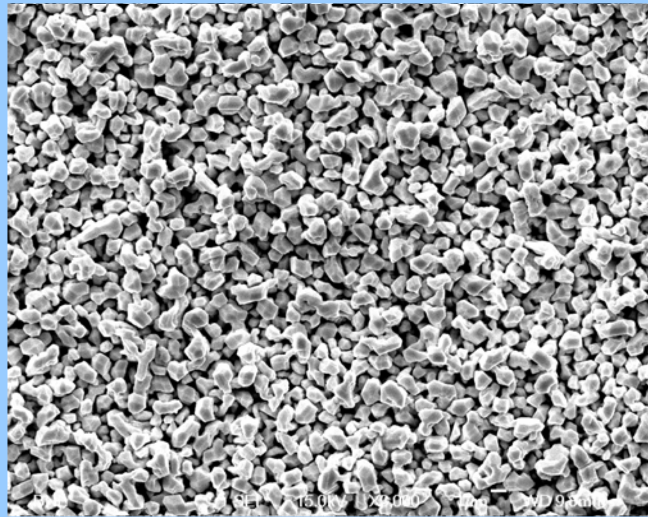
QE measured at 300K using setup at BNL (J. Smedley, T. Rao)



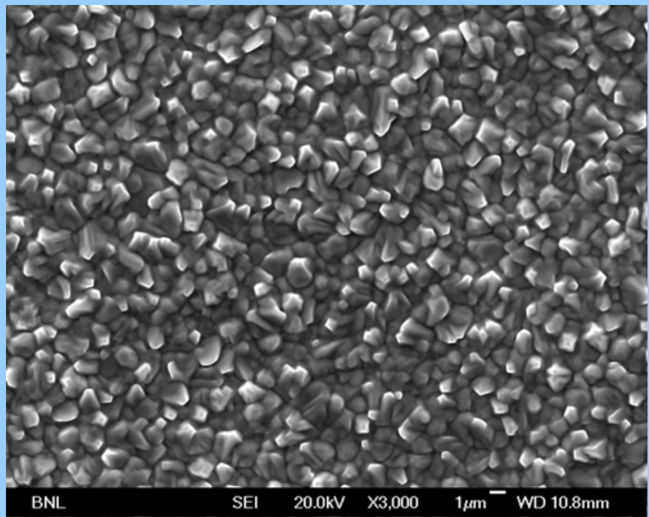
Surface Uniformity (Courtesy J. Smedley)

Arc Deposited

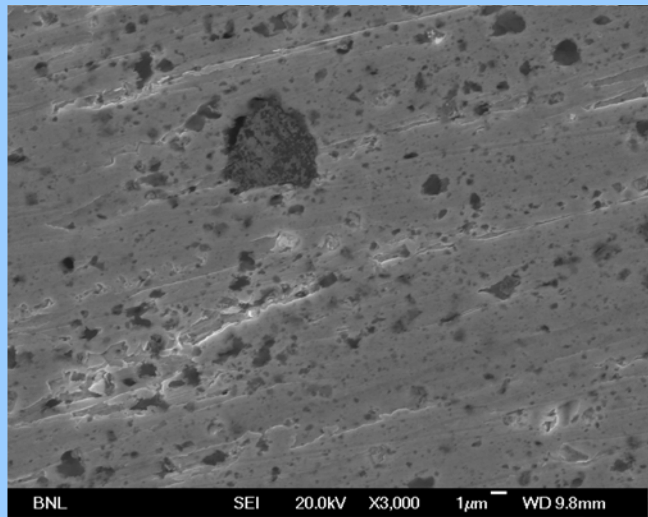
Sputtered



Vacuum Deposited



Solid



10 μm

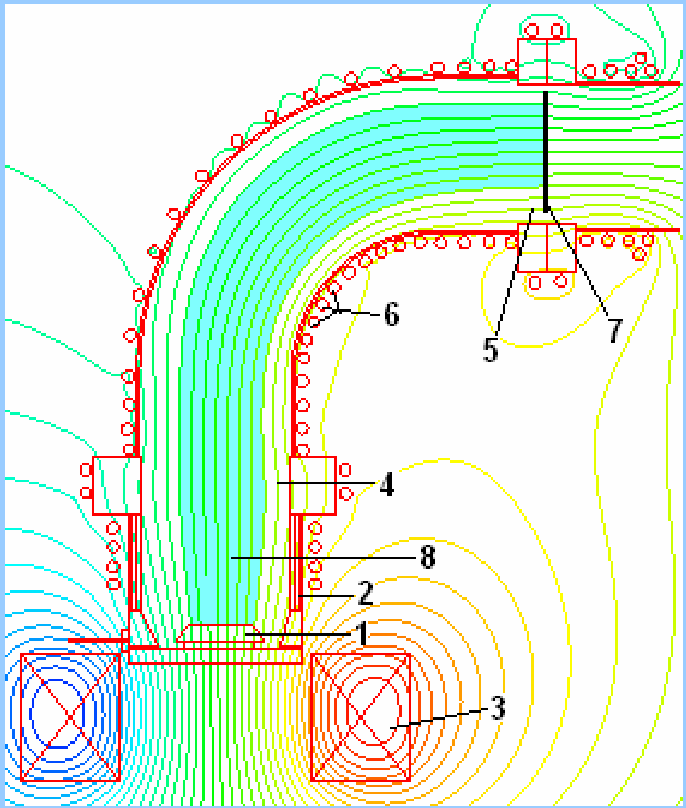
All cathodes laser cleaned with 0.2 mJ/mm^2 of 248nm light

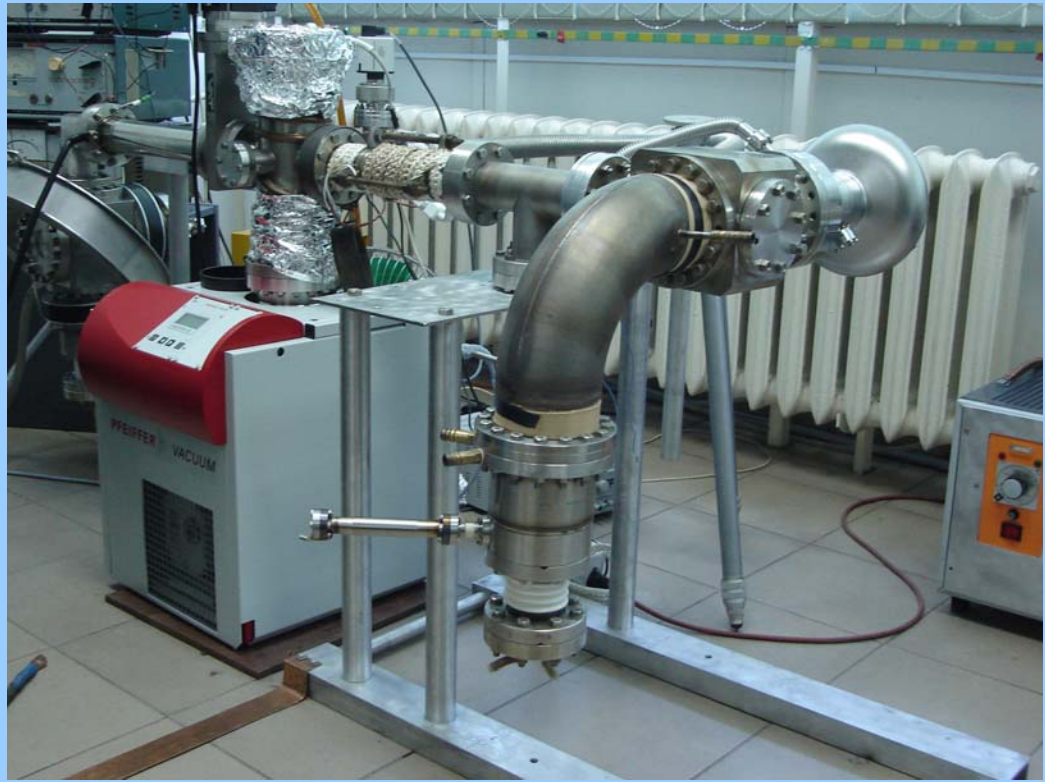
Status of the Nb-Pb gun

The best QE was demonstrated by **arc-deposited samples** prepared at INS.

Coating technique and apparatus built at INS

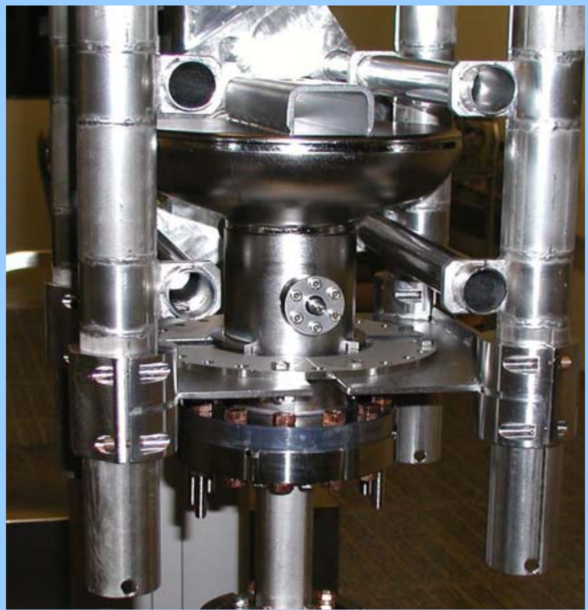
Courtesy P. Strzyzewski, A. Soltan INS, Swierk.

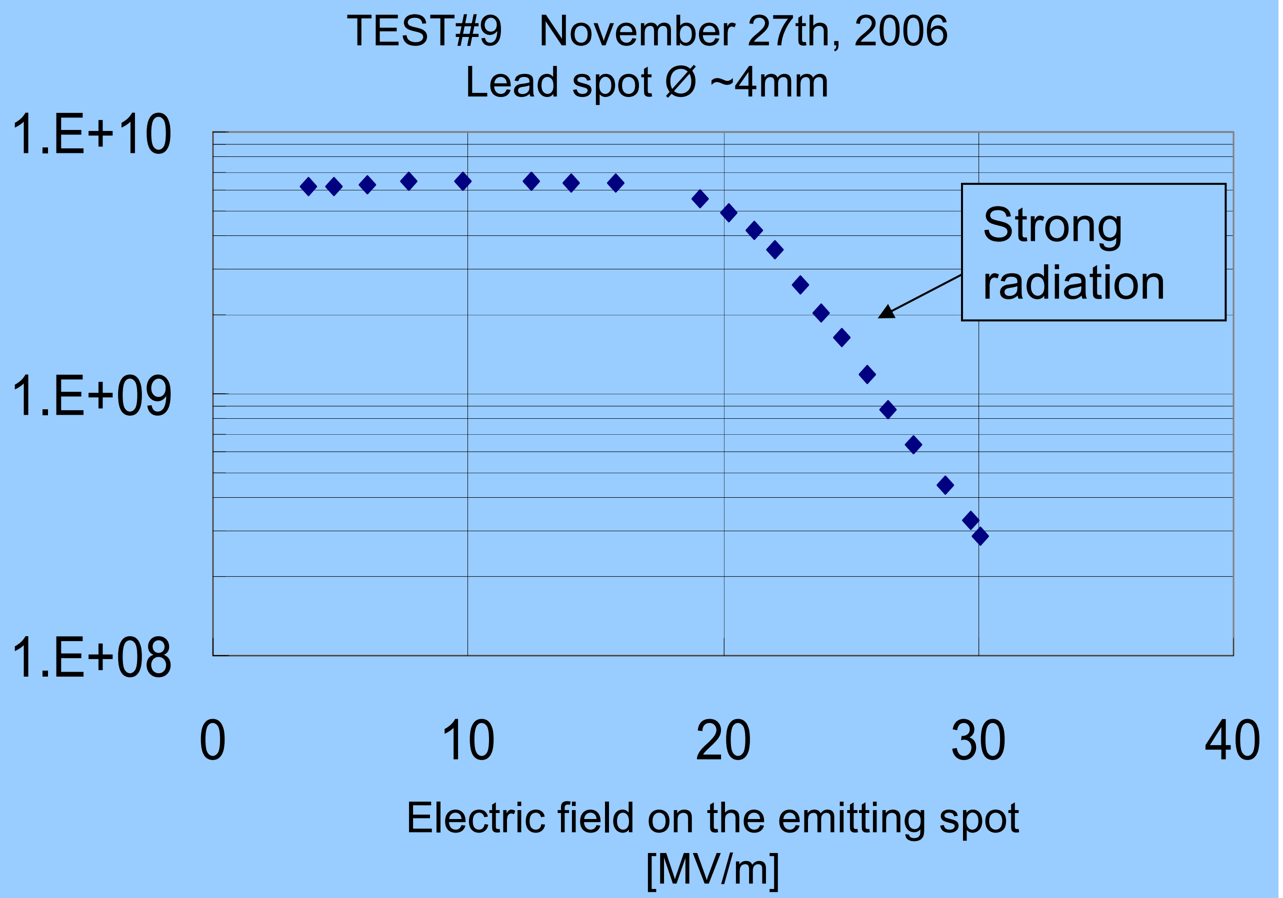




1 – cathode, 2 – anode, 3 – focusing coil, 4 – filter inlet, 5 – filter exit, 6 – high-current cable, 7 – ion collector position, 8 – plasma stream.

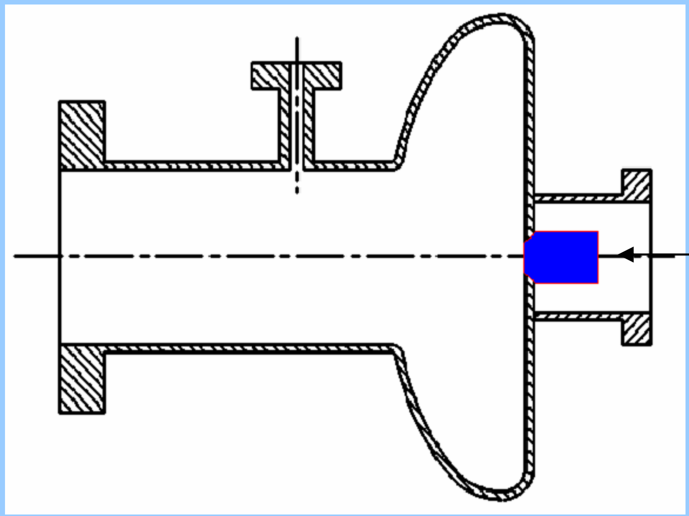
Cold test at DESY of half-cell cavity. Back wall has arc-deposited spot of lead. The coating was done at **A. Soltan INS**





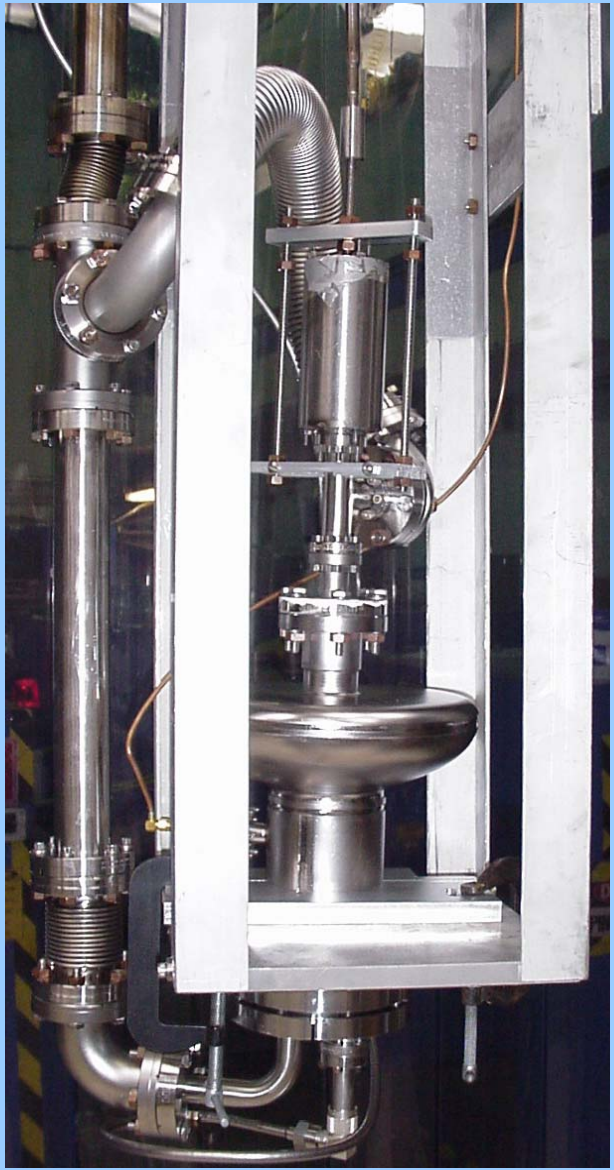
Status of the Nb-Pb gun

JLab; 1.42 GHz good for test of various coatings



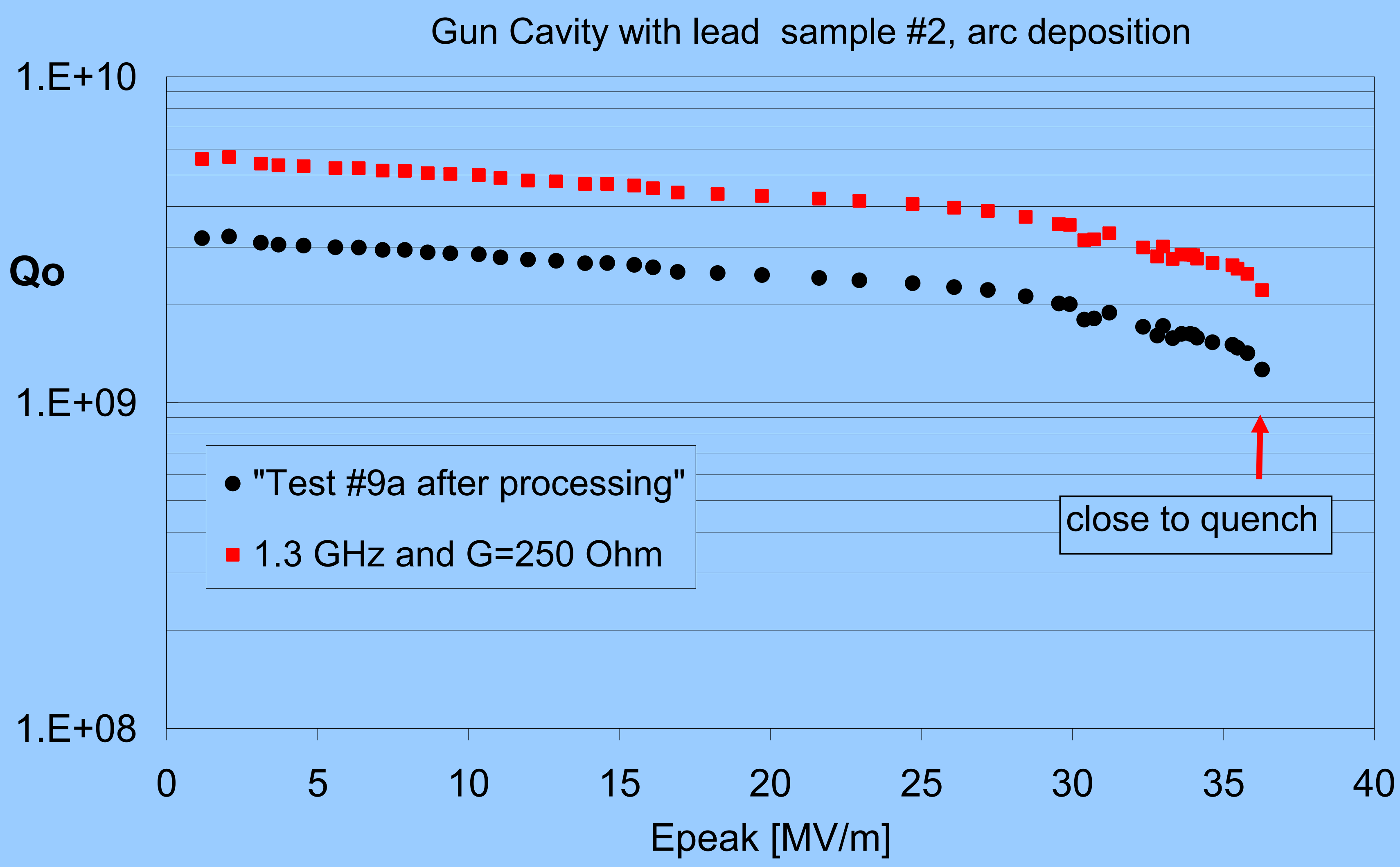
Nb plug without and with Pb coating:

D= 4 mm, h=150 nm



Courtesy P. Kneisel, JLab.

Status of the Nb-Pb gun



Courtesy P. Kneisel, JLab.

Status of the Nb-Pb gun

Future Plans

- One **cavity with coated back plate** has been shipped to JLab for RF and QE tests.
  Second cavity will be coated in January and after the inspection at DESY will be shipped to JLab in February.

- For the **replaceable cathode cavity** several Pb coated cathodes (sputtered and electro-deposited) will be tested.

- In collaboration with BNL**, QE measurements** will be carried out at cryogenic temperatures in a vertical Dewar at JLab. The measurements will be done on Pb .samples and on half-cell cavities with deposited emitting spot

- **Relaxation time of Cooper pairs** in Pb after the emitting spot is irradiated with the laser pulse

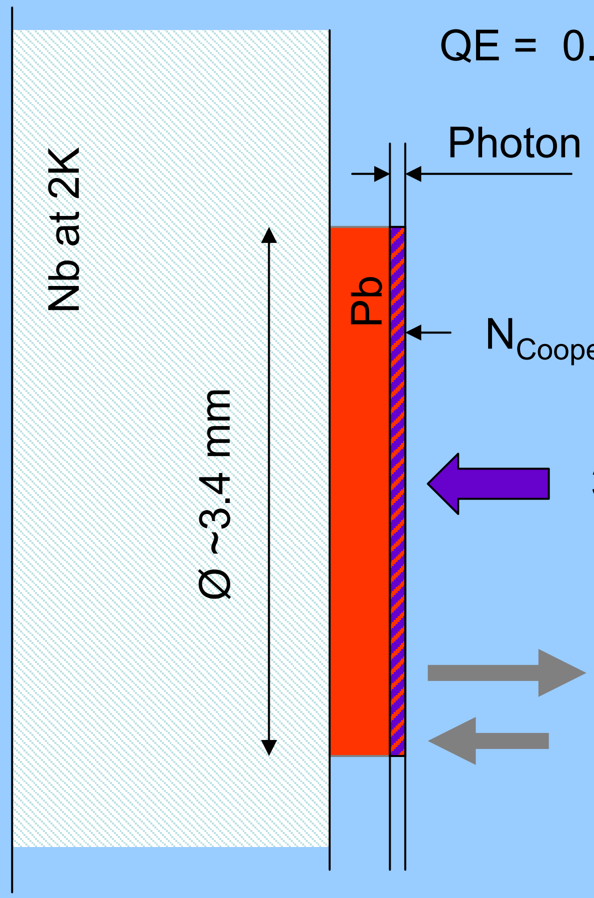
Relaxation time of Cooper pairs after the illumination

How does intrinsic Q change when laser illuminates the Pb cathode?

An example:

QE = 0.17% @ 213nm → q = 1 nC requires 3.4 µJ/pulse.

Photon penetration depth is ~10 nm



$N_{Cooper\ pairs} = 1.5 \cdot 10^{13}$

3.4 µJ → $N\gamma = 4 \cdot 10^{12}$

All Cooper Pairs in the 10 nm layer are broken.

The layer is in the normal-conducting state after the laser pulse.

F= 60 MeV/m

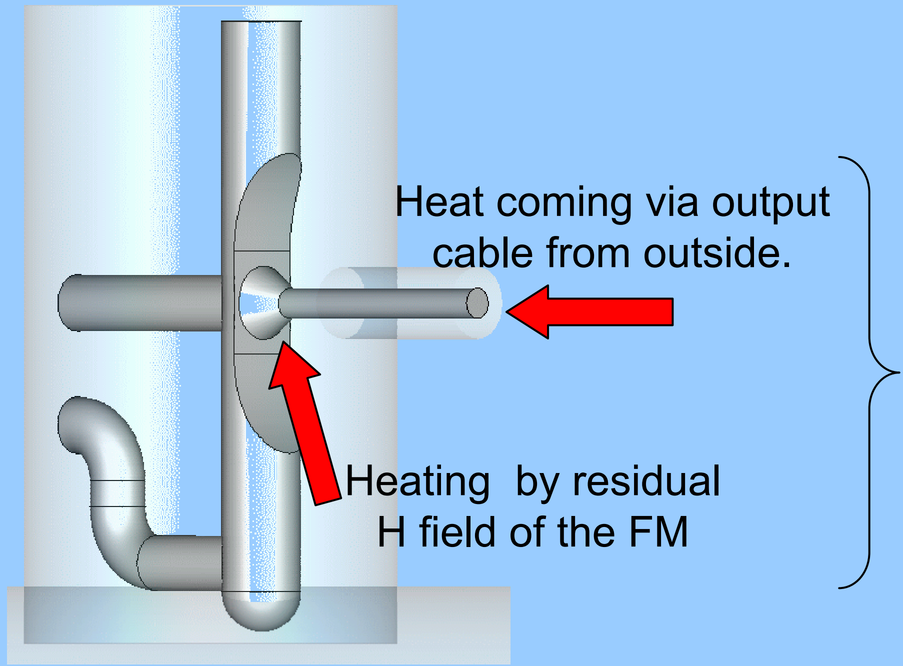
$T_{rf}/4$=200ps later the diffusion and recombination processes of quasiparticles in the Pb layer start.

Status of the HOM couplers feedthrough and output line

Many projects using TESLA HOM couplers will operate with increased DF or cw.

Cooling of HOM couplers must be improved to ensure their stable operation.

The problem is heating of the output line.



Nb antenna becomes normal-conducting,

Nb, Cu antennae will be warm when the RF is on

Status of the HOM couplers feedthrough and output line

- **9-cell TESLA cavity (S33)** was tested cw first time in Chechia in August 2004.
  HOM couplers were equipped with commercial feedthroughs having moderate heat conduction.
  The heating was observed at Eacc **~4 MV/m.**.

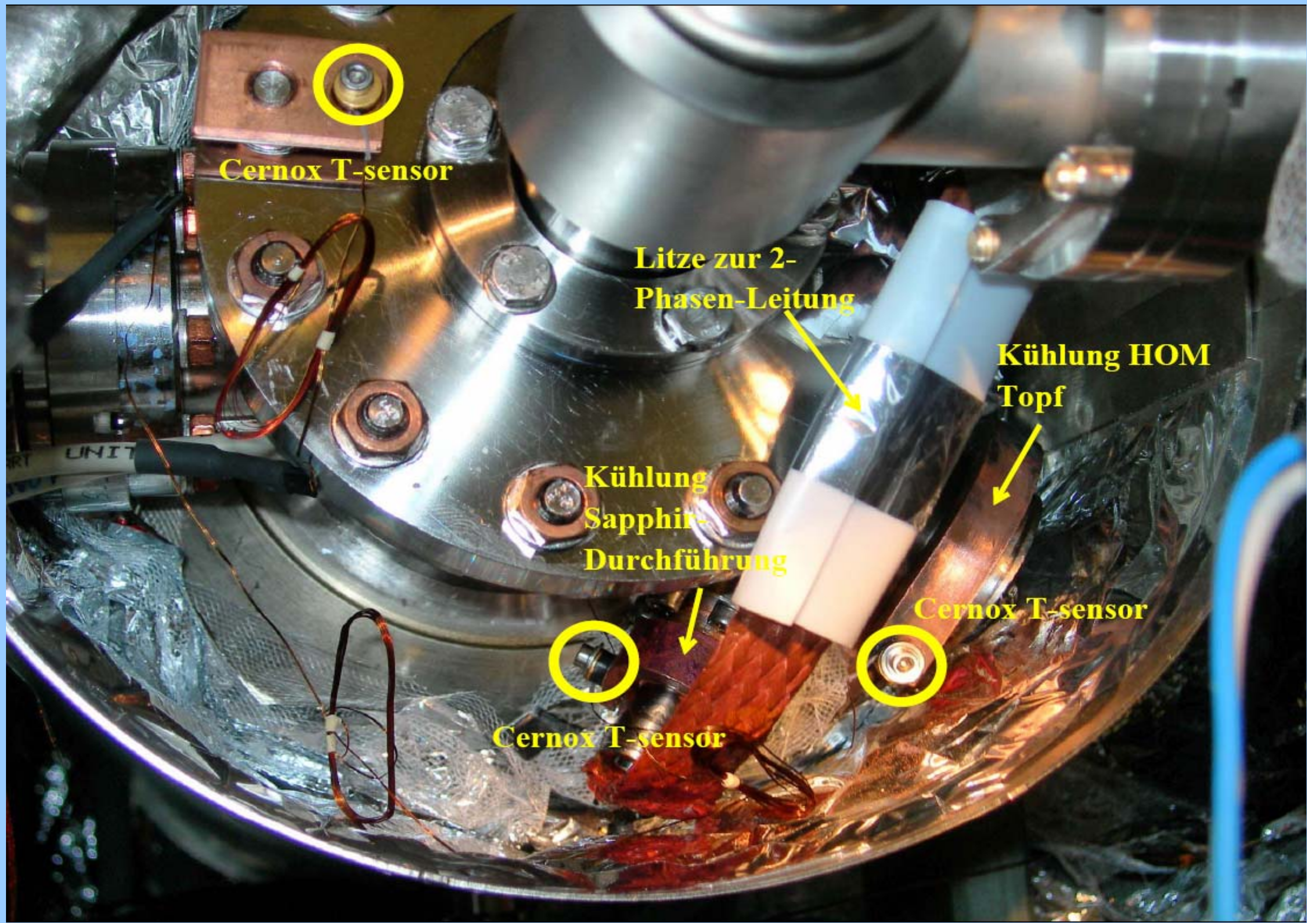
- New feedthrough design for the 12-GeV CEBAF upgrade was finished at JLab in 2005.

Al_20_3 replaced with sapphire

- Two fabricated at industry feedthroughs have been attached to S33 at DESY

- The cavity was shipped to BESSY for the cold test.

Status of the HOM couplers feedthrough and output line



Courtesy BESSY

S33 as installed in the HoBiCaT cryostat at BESSY

Status of the HOM couplers feedthrough and output line

Three tests with various conditions were performed up to now at BESSY:

1. Additional cooling of HOM cans and feedthroughs with copper braids (connected to 2Ph tube) no cables attached to the feedthroughs.

2. Additional cooling of HOM cans and feedthroughs with copper braids @ cables (4.2-m long) attached to the feedthroughs and pickup.

3. No additional cooling of HOM cans and feedthroughs and no cables attached.

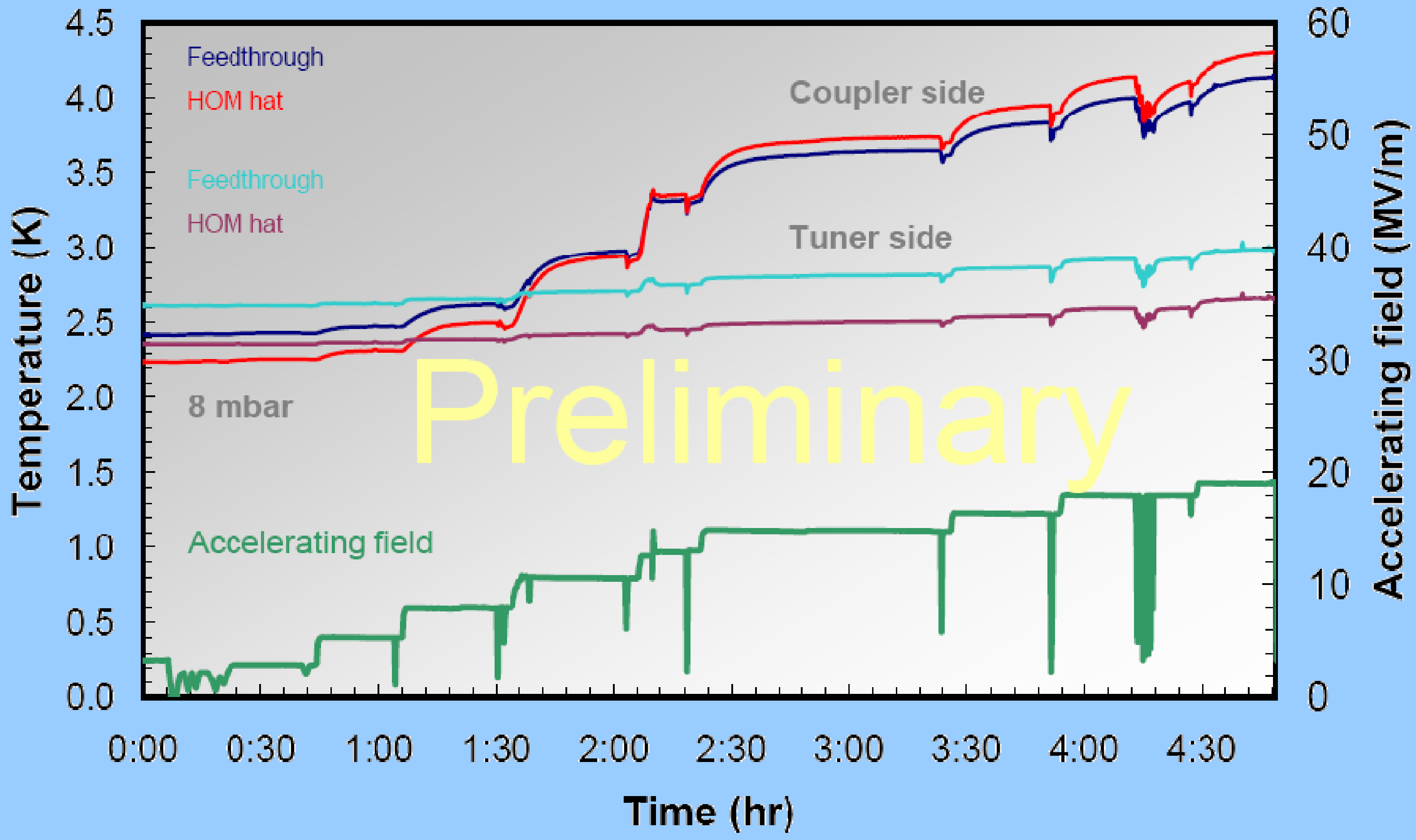
Conclusion: no big difference between all three experiments, but

- input coupler side is warmer than pickup side
- there is heat leak via output cables

Status of the HOM couplers feedthrough and output line

Summary of the experiment 1

With additional cooling of HOM cans and feedthroughs with copper braids @ no cables attached to the feedthroughs and pickup.

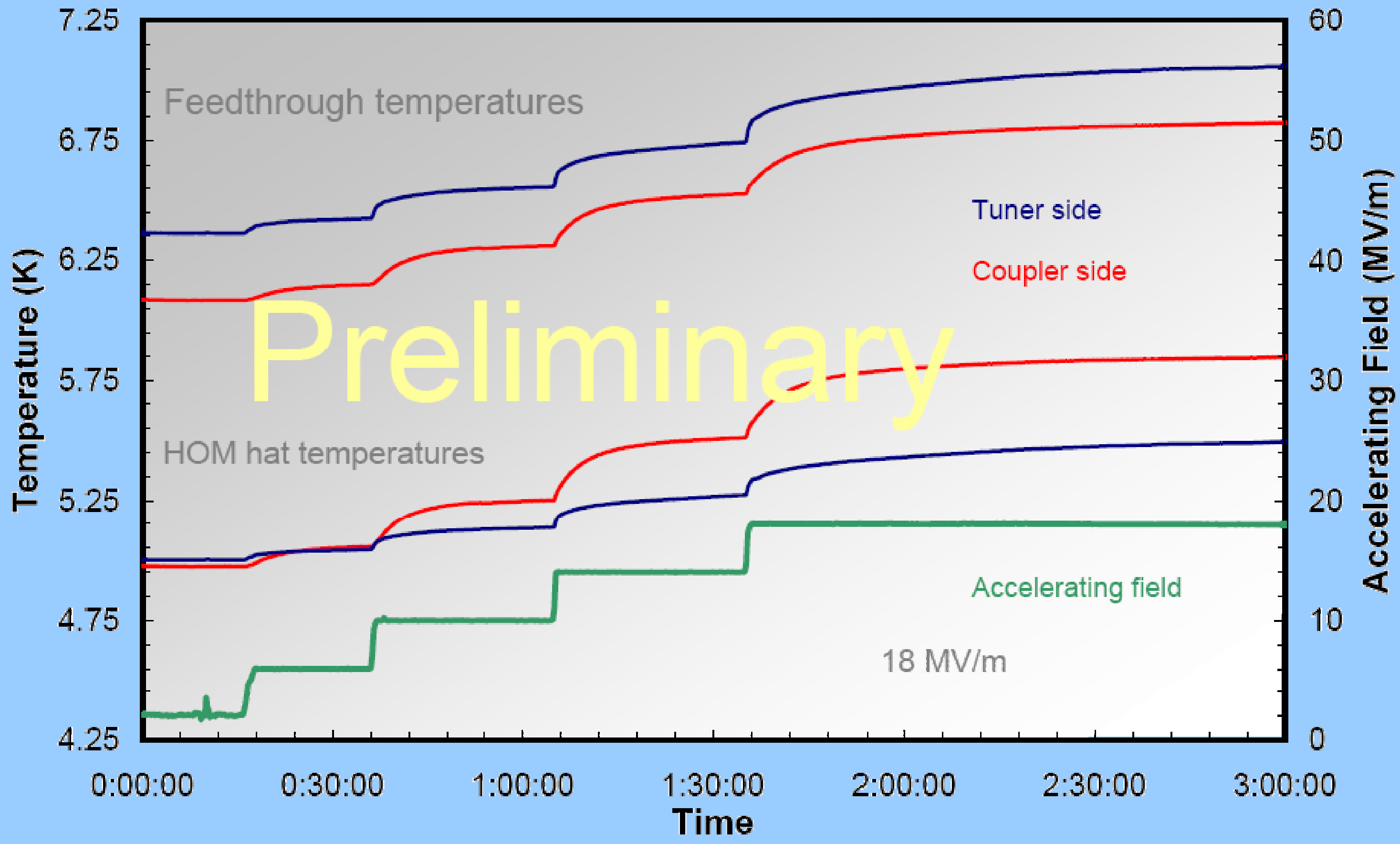


Courtesy BESSY

Status of the HOM couplers feedthrough and output line

Summary of the experiment 2

with the additional cooling of HOM cans and feedthroughs with copper braids @ cables (4.2-m long) attached to the feedthroughs and pickup.

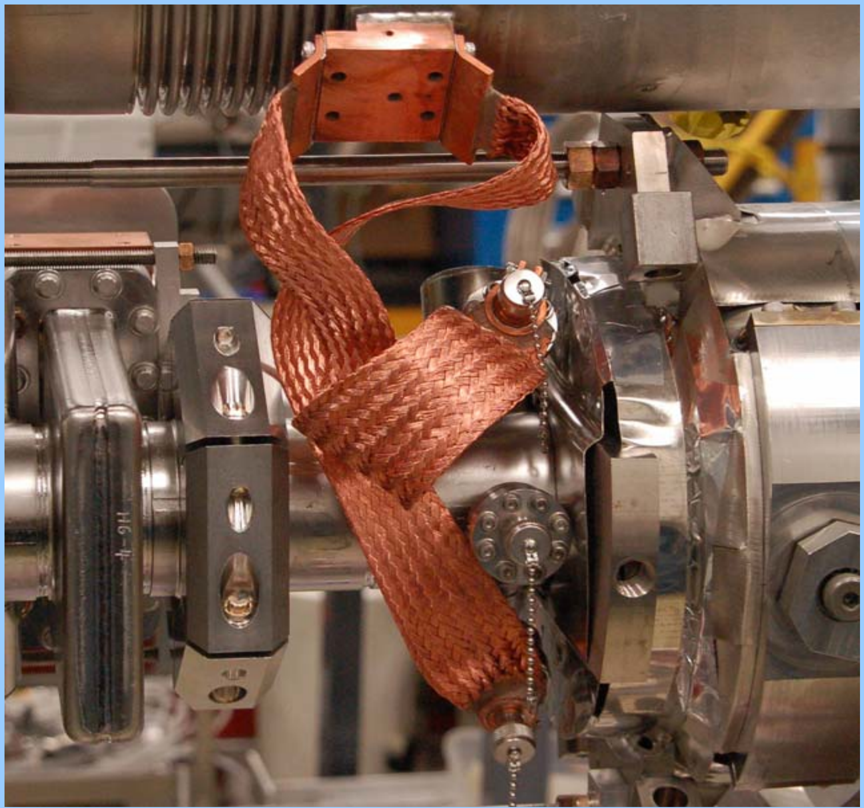


Courtesy BESSY

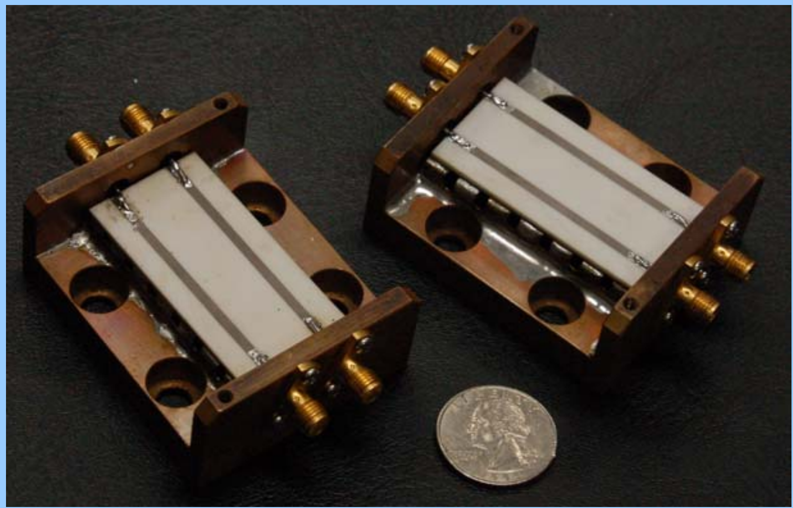
Status of the HOM couplers feedthrough and output line

A method to block the cable heat leak has been proposed at JLab

The same additional cooling with copper strips attached to 2-phase line as at BESSY



Heat sink for output lines proposed at JLab



Courtesy JLab

Final Remarks

Ad. Parameter set for the cw and near-cw operation:

Two assumptions

- Dynamic cryogenic load of **~30 W/Unit** at 1.8-2 K.
- RF power of **120 kW**.

led to the operating parameter set for the 8-cavity cryomodule with one power source allowing for acceleration of :

- $5.30 \cdot 10^{4}$ @ 1nC bunches at Energy Gain of 200 MeV/Unit (pulse = 121 ms)
- $1.30 \cdot 10^{5}$ @ 1nC bunches at Energy Gain of 150 MeV/Unit (pulse = 212 ms)

up to

- $1.86 \cdot 10^{6}$ @ 1nC bunches at Energy Gain 50 MeV/Unit (cw)

with flexibility in the beam time structure resulting from the operation in cw or near-cw mode.

Final Remarks

Ad. Status of the IOT transmitter upgrade:

- Studies on **the technical feasibility of the 120 kW IOT** will be ready in March 2007.
- **The** first single output **prototype** can be built but we do not have funding (yet ?).
- The first test can be carried out at CPI in 2007/2008.

Installation of the IOT tube at CMTB at DESY will be beneficial for the XFEL upgrade and for other FELs

- Additional money will be needed for the pre-amplifier, power supply, electronics and some component for the RF distribution system.
- Total investment about….0.5 M€ (this number has to be verified).

Ad. Status of the Nb-Pb gun:

- The SRF-gun design is ready and should be verified with copper model.
- The first layout of the cryostat looks mechanically fine but still optimization is needed.
- Next steps make sense after:
  - the RF-performance of E_{peak} 50-60 MV/m @ Qo ~ $5 \cdot 10^9$ will be achieved
  - the test will confirm reasonable good QE of lead at 2K (~$1.5 \cdot 10^{-3}$ @ 213 nm).

The project is officially “accepted” but not well funded. In case all tests will give good results we will need funding to built 1.5-cell+cryostat+RF-station…. (FP7 ???).

Final Remarks

Ad. Status of the HOM couplers feedthrough and output line:

- Tests at BESSY showed that new feedthroughs can be operated cw up to 20 mV/m.
- The heat sink will be tested soon at JLab.
- Both should be implemented for the XFEL cavities.