SRF-Seminars

Jacek Sekutowicz

5. SUPERCONDUCTING PHOTO-INJECTORS

1. Introduction
2. Projects; Specs and measured data
3. Cathodes
4. RF-performance of sc-cavities
5. RF-focusing
6. ε growth compensation with DC- and RF-magnetic field
7. Nb-Pb gun
8. Conclusions

Acknowledgements

BNL:	A. Burrill, I. Ben-Zvi, R. Calaga, T. Rao, J. Smedley
AES:	T. Favale, A. Todd, J. Rathke
FZR:	D. Janssen, J. Teichert
DESY:	D. Kostin, B. Krause, A. Matheisen, W.-D. Möller, R. Lange
IHIP:	J. Hao, K. Zhao
INFN:	M. Ferrario
JLAB:	P. Kneisel
INS:	J. Langner, P. Strzyżewski
SUNY:	R. Lefferts, A. Lipski
UNI-ŁÓDŹ:	K. Szałowski
SLAC:	K. Ko, Z. Li.

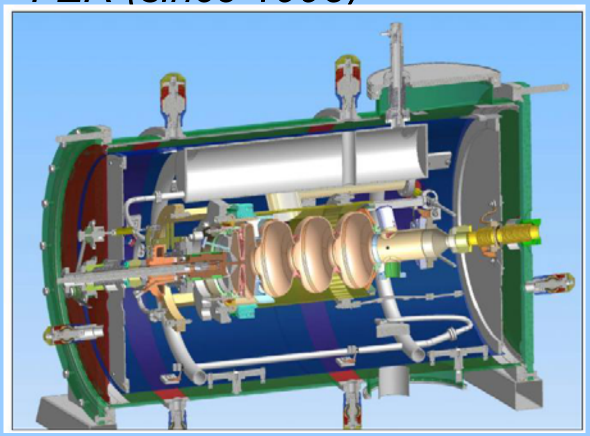
Motivation to develop SRF electron guns:

- *Operation in CW mode with high acc. gradient on photo-cathode.*
- *Low power dissipation and excellent thermal stability.*

What is technically challenging:

- *Integration of non-superconducting cathodes into the sc environment.*
- *Lower QE of superconducting cathodes than alkali cathodes.*
- *Emittance growth compensation with magnetic field is more difficult and needs novel approaches.*

FZR (since 1998)

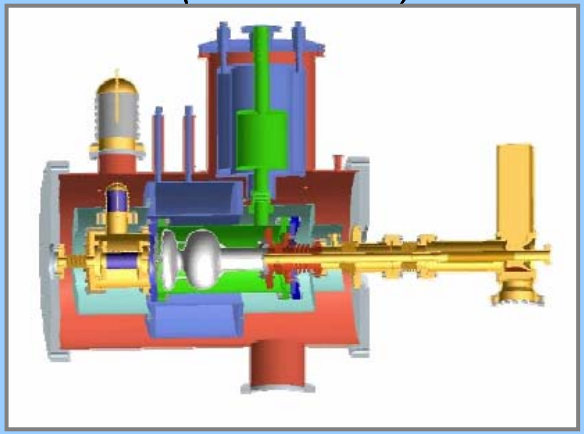


Courtesy of Dietmar Janssen

f =1.3 GHz

Cs_2Te ◄ E_{RF}

IHIP PU (since 2001)



Courtesy of Hao Jiankui

f =1.3 GHz

Cs_2Te ◄ E_{DC}

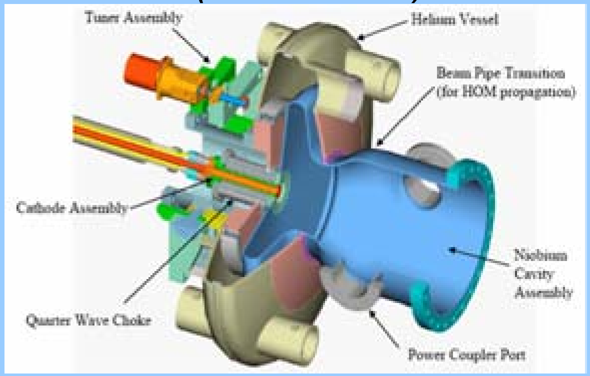
BNL (since 2002)

Courtesy of Triveni Rao

f =1.3 GHz

Nb ◄ E_{RF}

BNL/AES (since 2004)

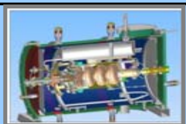
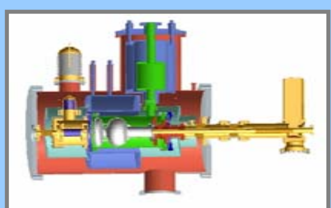
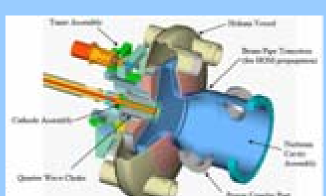


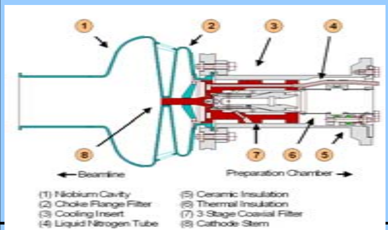
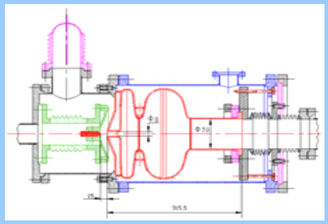
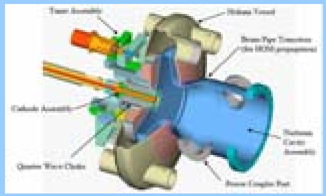
Courtesy of Alan Todd

f =703.75 MHz

Alkali+♦ ◄ E_{RF}

2. Four projects: Spec/Measured

	E [MeV]	ΔE [keV]	q/Bunch [nC]	Bunches/s [10^6]	I_b [mA]	ε @ q [μrad] @ [nC]
 BESSY FZR FZR	S: 5 S: 9.5 S: 9.5 M: 0.85	S: ? S: 5 S: M: 8.5	S: 2.5 S: 0.077 S: 1.0 M: 0.020	S: 0.025 S: 13 S: 1 M: 26	S: 0.063 S: 1.0 S: 1.0 M: 0.52	S: 1.5 @ 2.5 S: 1.0 @ 0.077 S: 1.5 @ 1.0 M: 1.0 @ 0.020
	S: 2.61 M: 0.58	S: 30 M: 35	S: 0.060 M: 0.001	S: 17 M: 81	S: 1.0 M: 0.08	S: 3.0 @ 0.060 M: 2.7 @ 0.001
	Cavities have been built mainly for measurements of QE of cold Nb					
	S: 2.0 M: (-)	S: 62 M: (-)	S: 1.33 M: (-)	S: 352 S: 704 M: (-)	S: 500 S: 1000 M: (-)	S: 5.0 @ 1.33 M: (-)

	Emitter/T	< QE> @ λ_{Ph} at operation	E_{pulse} / P_{laser} [μJ] / [W]	Cathode Life Time	Spot size [mm]	E_{cath} [MV/m]
	Cs_2Te / 78 K	S_{BESSY}: 0.01/262 S_{FZR} : 0.01/262 M: 0.003/260	S: 1.19/0.03 S: 0.5 / 0.5 M: 0.06/1.5	>50 days	S: Ø 3.0 M: Ø 2.0	S: 25 M: 22
	Cs_2Te /273 K	S: 0.01 / 266 M: 0.01/ 266	S: 0.015/1.2 M: 0.010/0.8	~100 days	S: Ø 5.6 M: Ø 6.0	M: 2.7
	Nb / 2-4 K	10^{-5} / 266	0.002 /0.15	∞ (?)	▭ 4x1.5	M: 48
	S: Alkali / ? S: Alkali+D/?	S: 0.05 / 527 S: 5 / 527	0.071 /25 0.0006 /0.2	?	S: Ø 2.0	S: 40

FZR

4 K-test

$2.5\cdot10^{8}$ @ E_{peak}=22 MV/m

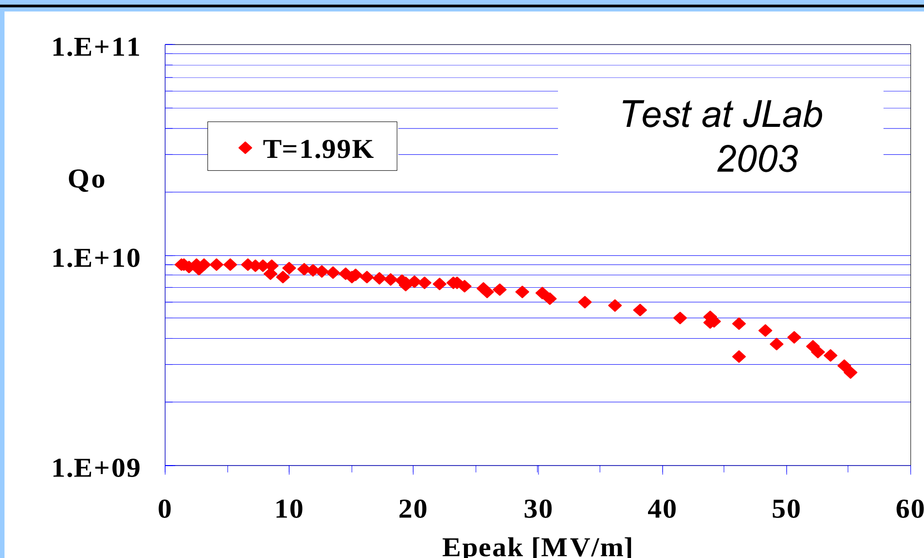
2 K-test

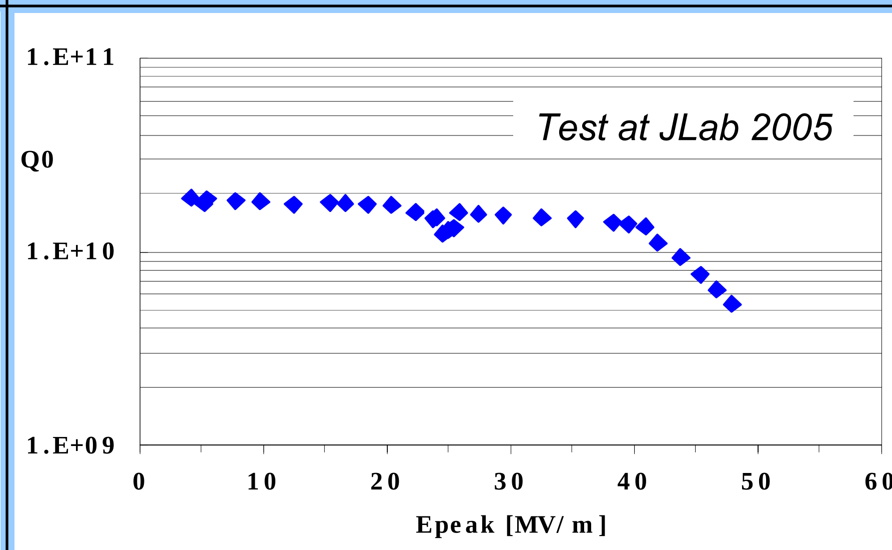
$5\cdot10^{9}$ @ E_{peak}=46 MV/m

IHIP-Peking

4.2 K- test

10^{8} @ Eacc= 5 MV/m





FZR

Test cavity (RRR=40) received BCP in Sept. 2005

High RRR=300 cavity will be treated and tested at DESY soon

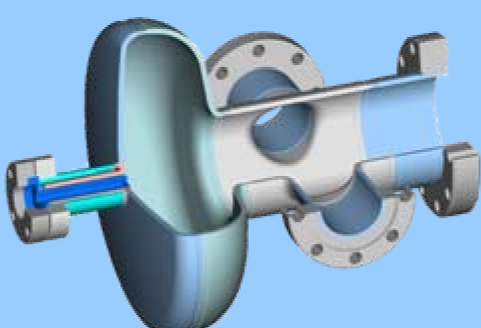
IHIP-Peking University

DC+1.5-cell → 3.5-cell

Eacc [MV/m]	15
V-DC [kV]	100
I_{beam} [mA]	1
Energy [MeV]	4.9
Energy spread [%]	2.27
Emittance (rms) [μrad]	3.4

BNL/AES 1.3 GHz

QWC will be added for cathode with diamond: - 2005

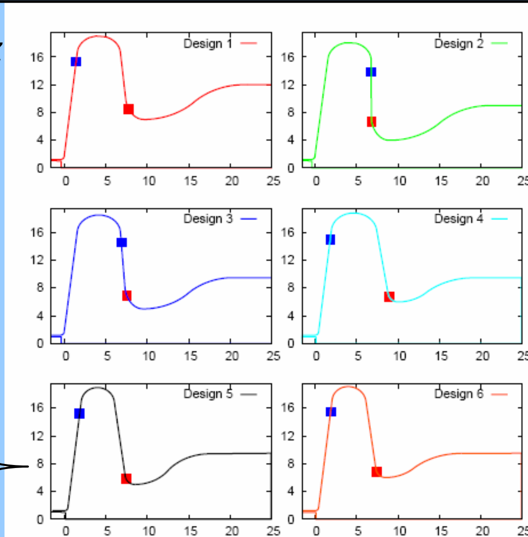


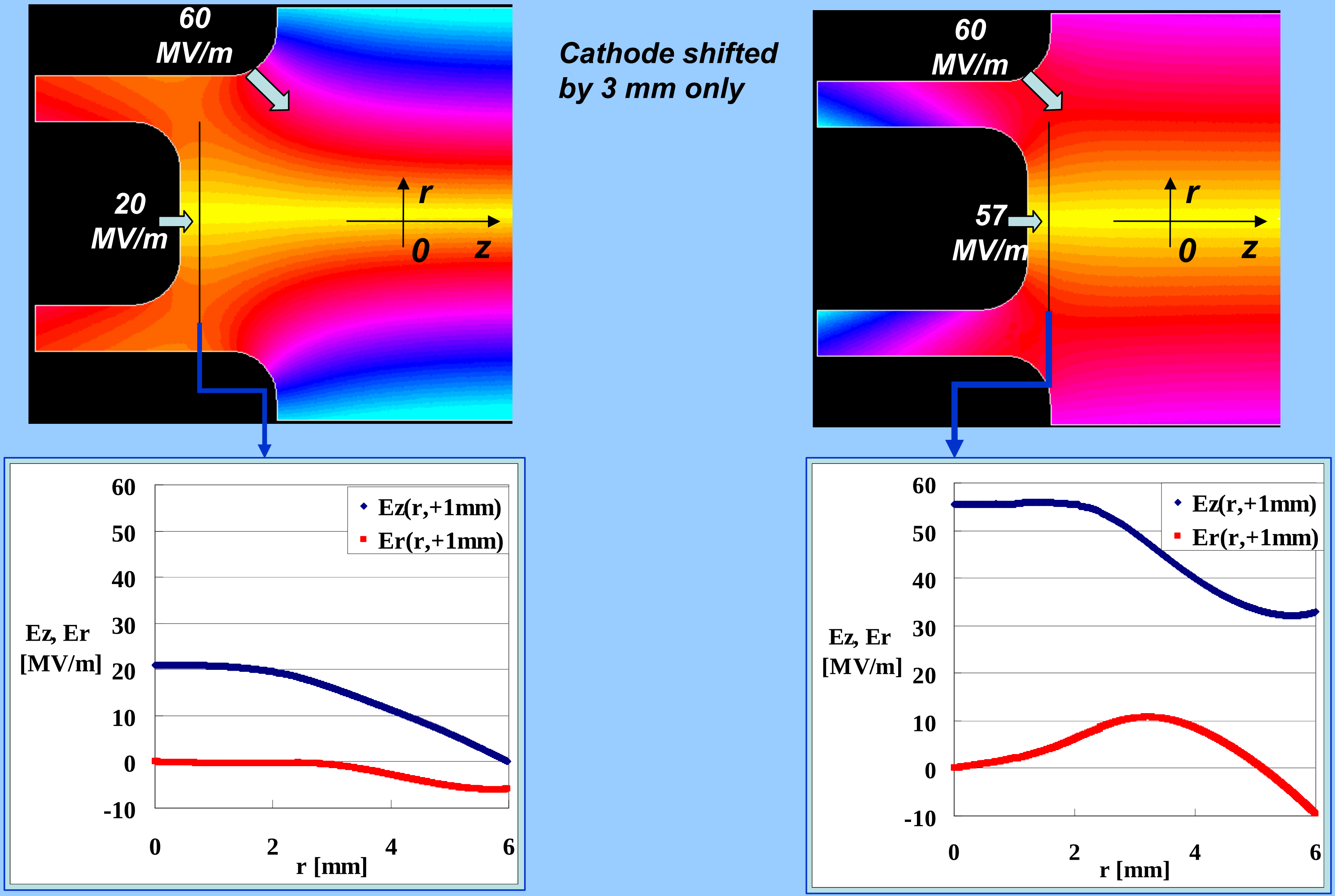
BNL/AES 703.85 MHz

RF Design will be finished in 2005 ?

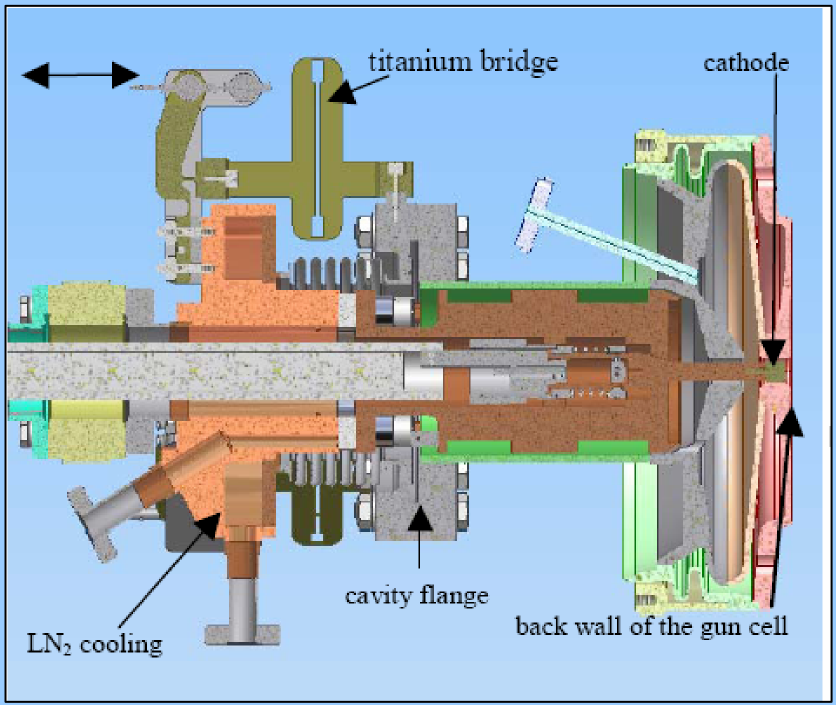
ε=1.99 [μrad]

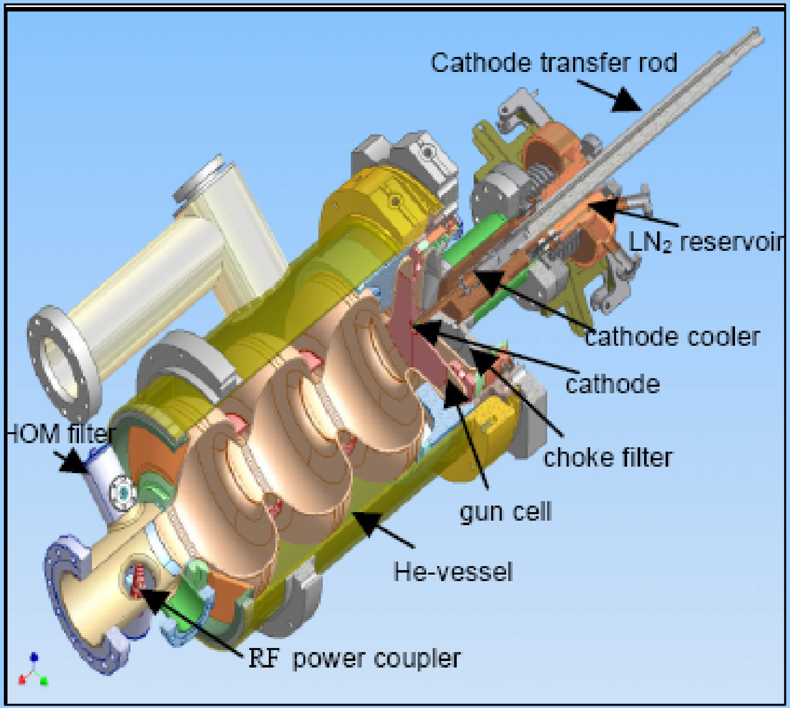
ΔE/E= 3.8%




60 MV/m
20 MV/m
r
0
z
Cathode shifted by 3 mm only
60 MV/m
57 MV/m
r
0
z
Ez, Er [MV/m]
60
50
40
30
20
10
0
-10
0
2
4
6
r [mm]
Ez(r,+1mm)
Er(r,+1mm)
Ez, Er [MV/m]
r [mm]
Ez(r,+1mm)
Er(r,+1mm)

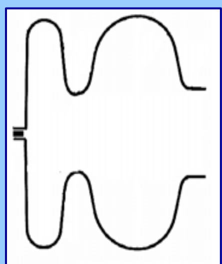
Since position of the cathode is a very sensitive "knob"

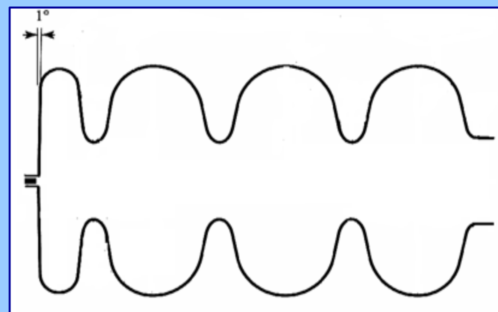




Cathode longitudinal position tuner as proposed by RFZ

FZR: 1.3 GHz 1.5-cells and 3.5-cells have recessed cathode and inclined back wall

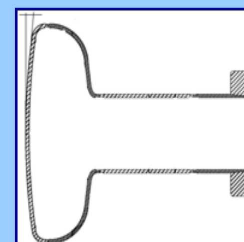


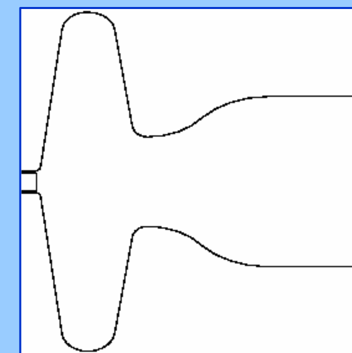


	Without RF focusing	With RF focusing
ε_n μrad]	3.66	1.49
Recess [mm]	0	2-3.5

D. Janssen, V. Volkov , NIM A452(2000)34

BNL/AES: 1.3 GHz and 703.85 MHz will have recessed cathode and inclined back wall



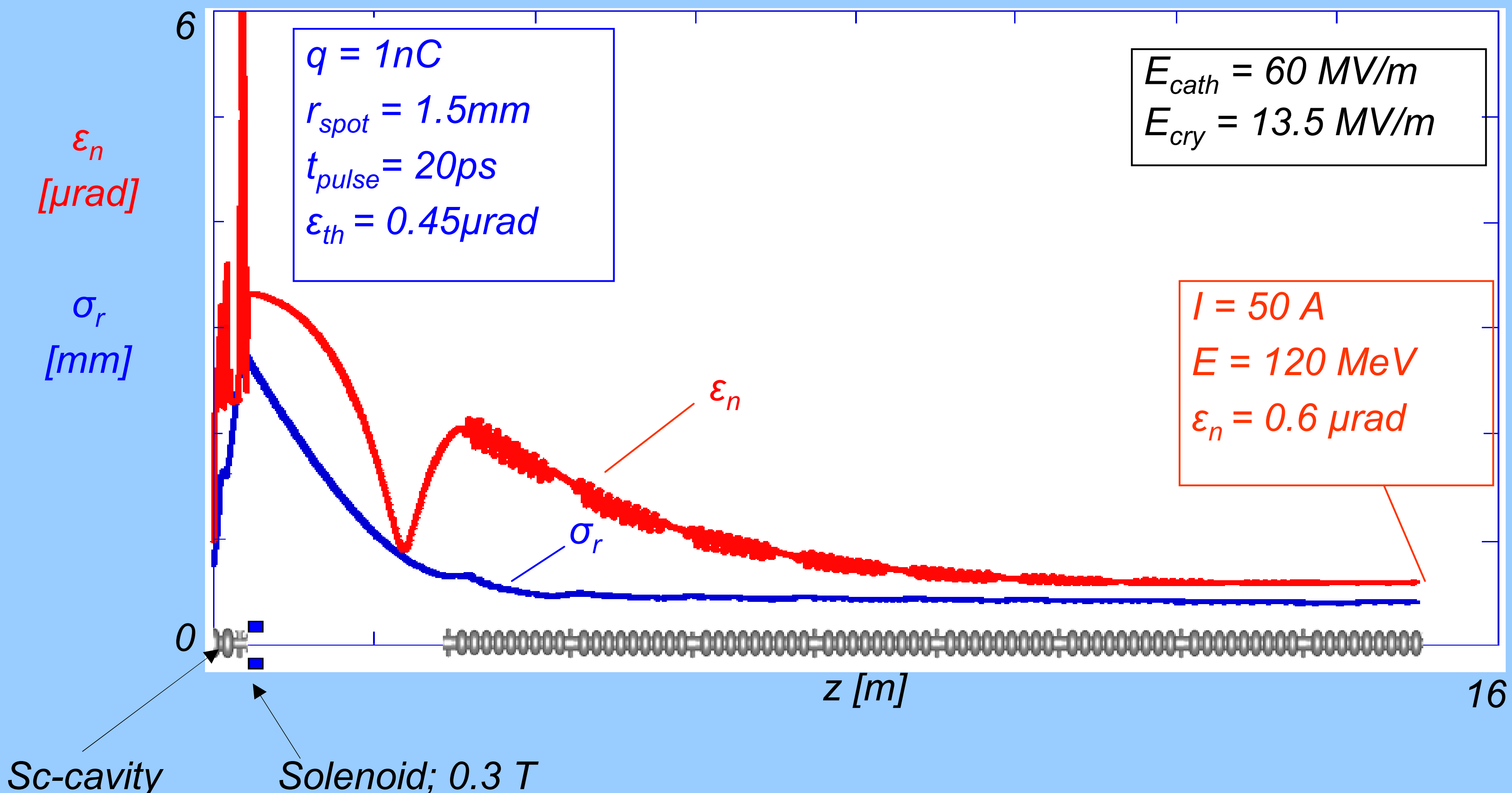


	With RF focusing
ε_n [μrad]	1.99
Recess [mm]	3

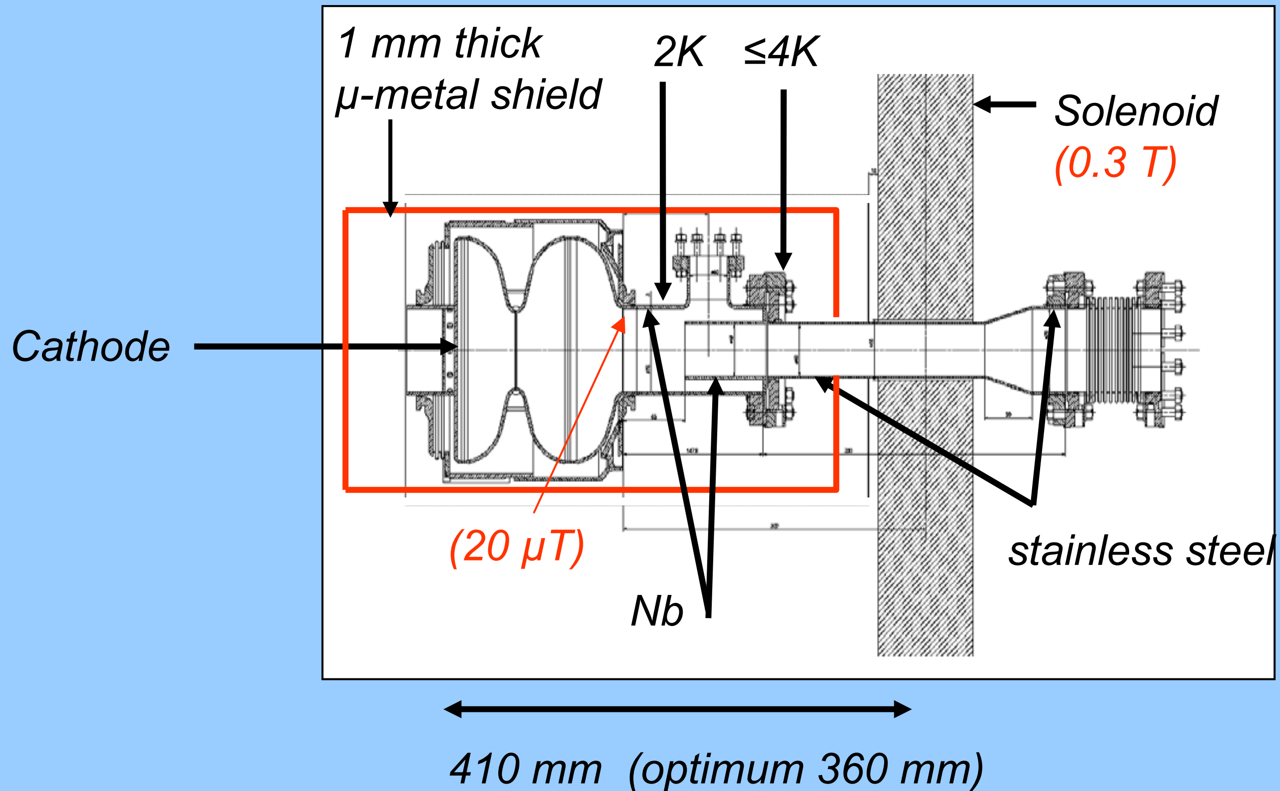
R. Calaga, Proceed. SRF2005,Cornell

Exposing a sc cavity to H-field may cause degradation in the performance.

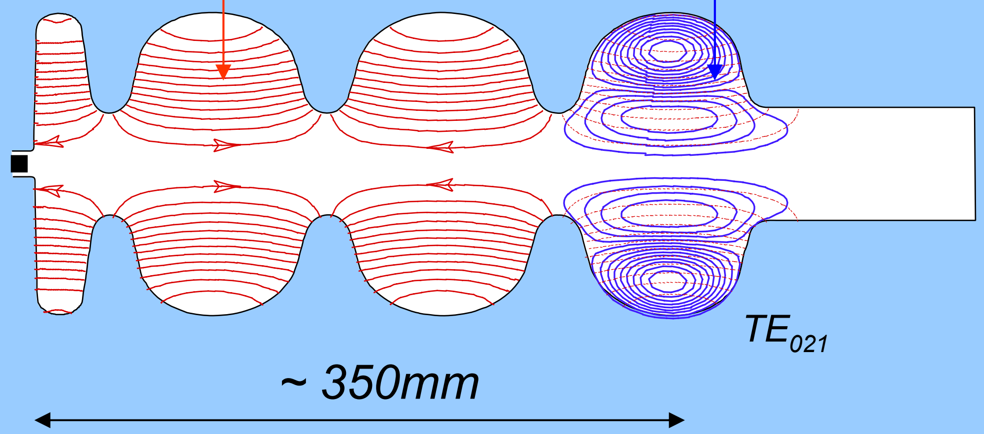
1. One can put solenoid and the sc-cavity at different locations → split injector (M. Ferrario, J.B. Rosenzweig):



Example:


1 mm thick
μ-metal shield
2K
≤4K
Solenoid
(0.3 T)
Cathode
(20 μT)
Nb
stainless steel
410 mm (optimum 360 mm)

2. One can use solenoidal modes of (TE0xx) for the ε compensation (D. Janssen)



ε_n for 1 nC [μrad]		0.78-0.98
ε_n minimum at z [m]		4.25
B_{TE} on axis [T]		0.324
Surf. $B_{max} = [B^2_{TM} + B^2_{TE}]^{0.5}$ [T]		0.144

The low emittance results from: RF-focusing and B_{RF} compensation and weakly depends on the phase of the solenoidal mode.

D. Janssen et al, Proc. of FEL2004

***Motivation** is to build cw operating RF-source of ~0.5-1 mA class for an XFEL facility.*

*An all **superconducting** RF-gun follows the **all niobium** RF-gun of BNL*

$$QE = 10^{-5} \ @ \ \lambda = 266 \ nm$$

In 2003 we proposed to investigate quantum efficiency of Pb

(TTF Meeting, Frascati, June 2003, Phys. Rev. ST-AB, vol. 8, January 2005)

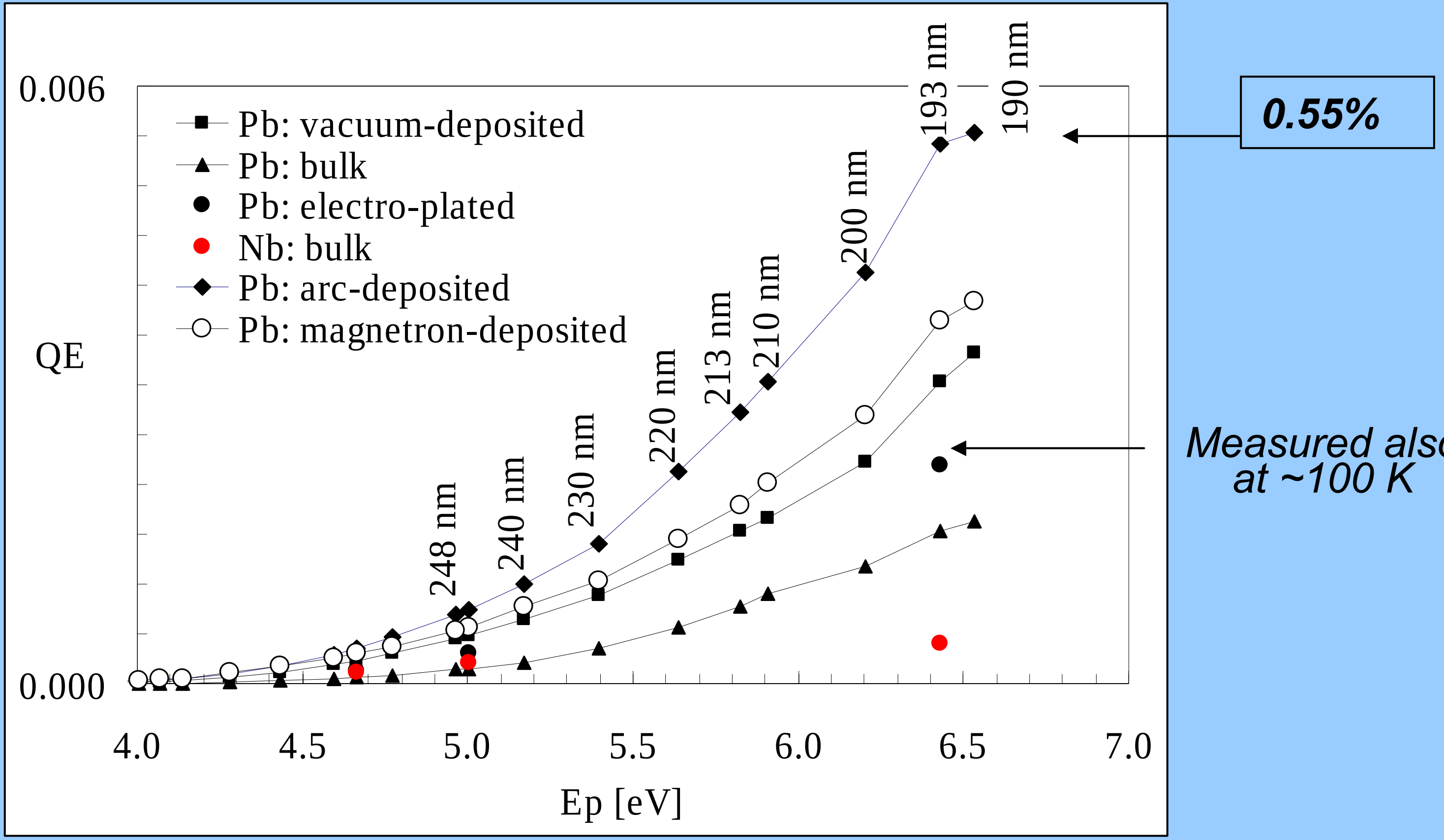
Lead is commonly used superconductor for accelerating cavities:

$$T_c = 7.2 \ K, \ \ B_c = 70 \ mT$$

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

Light sources:

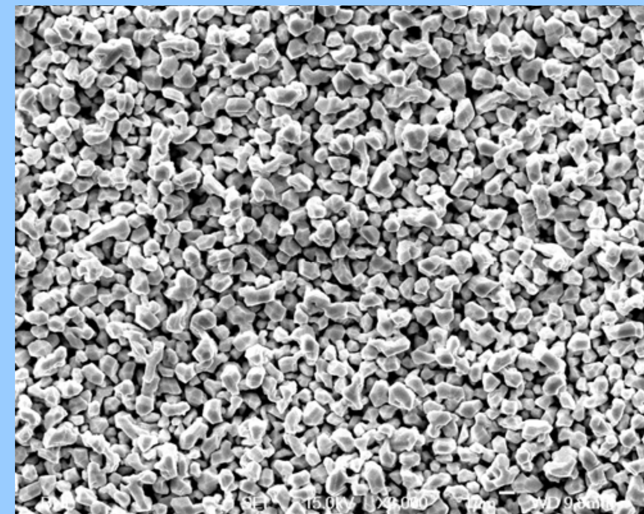
- *ArF- laser: 193 nm, KrF-laser: 248 nm, 4-th harmonic Nd: YAG laser : 266 nm*
- *Deuterium light source with monochromator (2 nm bandwidth): 190-315 nm*



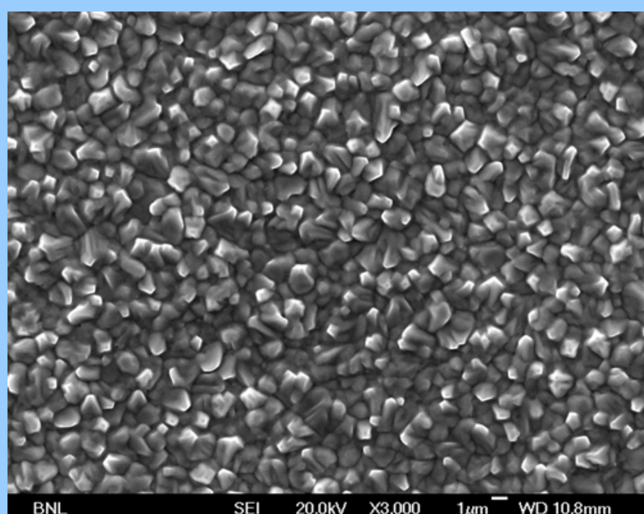
Surface Uniformity (Courtesy J. Smedley)

Arc Deposited

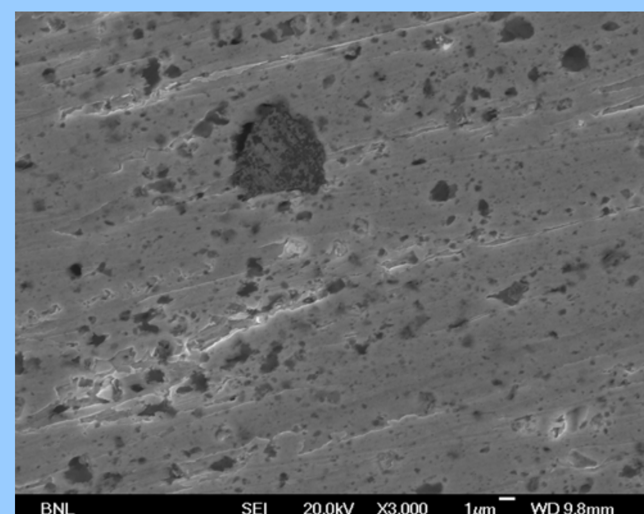
Sputtered



Vacuum Deposited



Solid



10 μm

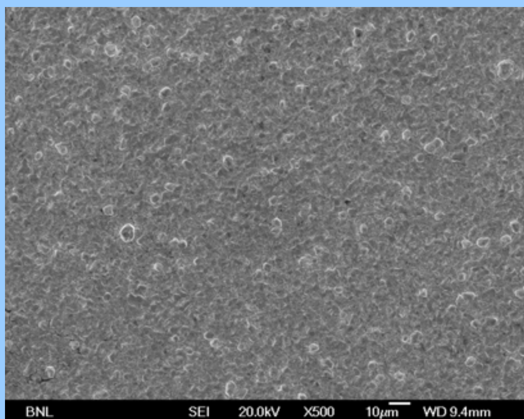
All cathodes laser cleaned with 0.2 mJ/mm^2 of 248nm light

Preparation

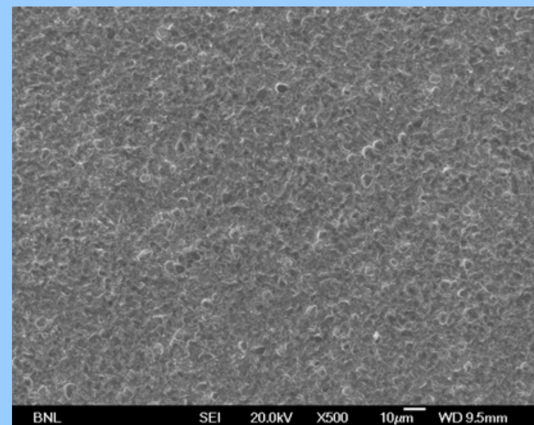
- *Nb used as substrate*
- *Four deposition methods:*
  - *Electroplating*
  - *Vacuum deposition (evaporation)*
  - *Sputtering*
  - *Vacuum Arc deposition*
- *Solid lead, mechanically polished*
- *In situ laser cleaning*
  - *KrF Excimer (248 nm), 12 ns pulse, ~0.2 mJ/mm^2*

Lead Surface Finish and Damage Threshold (Courtesy J. Smedley)

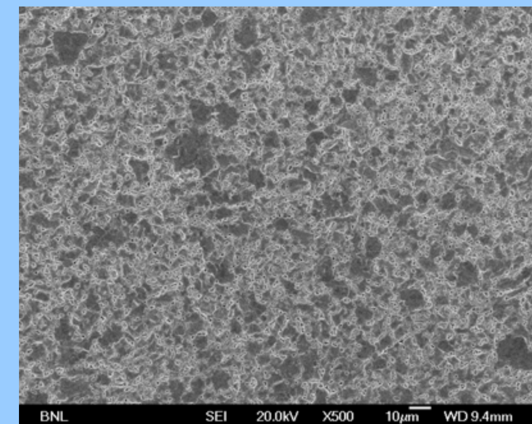
(Electroplated Lead)



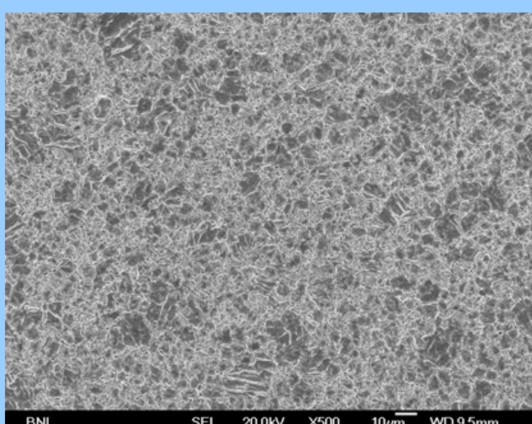
Prior to Laser Cleaning



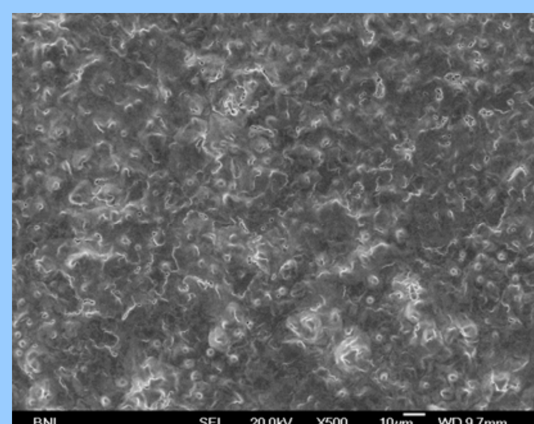
0.11 mJ/mm^2



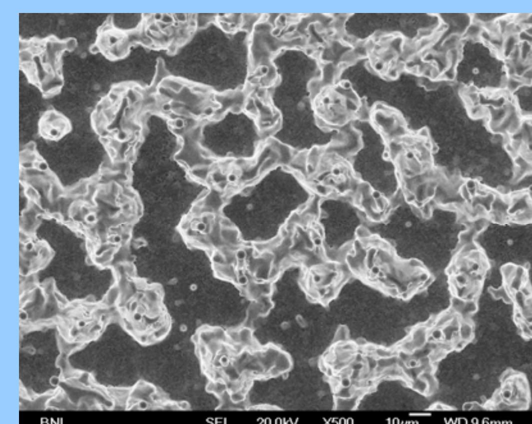
0.26 mJ/mm^2



0.52 mJ/mm^2



1.1 mJ/mm^2

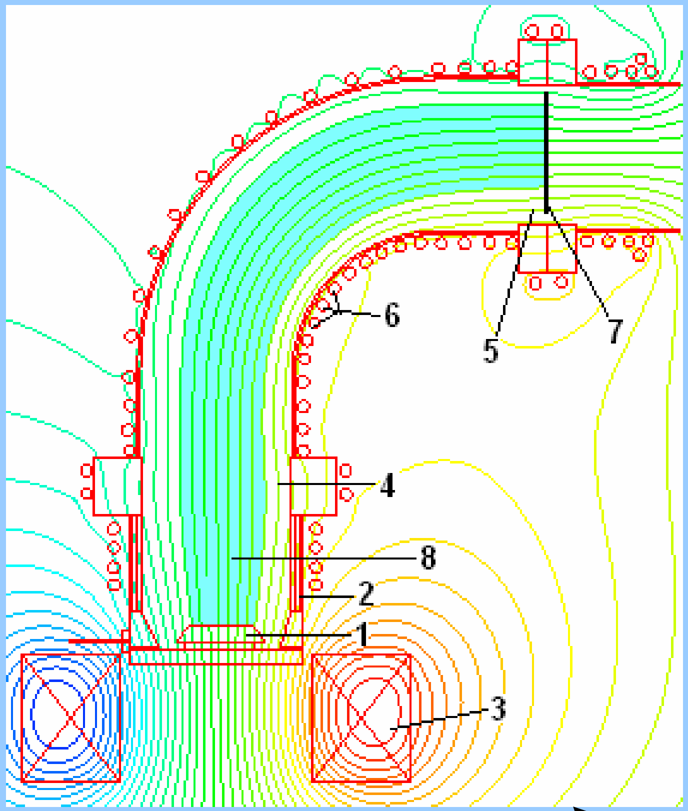


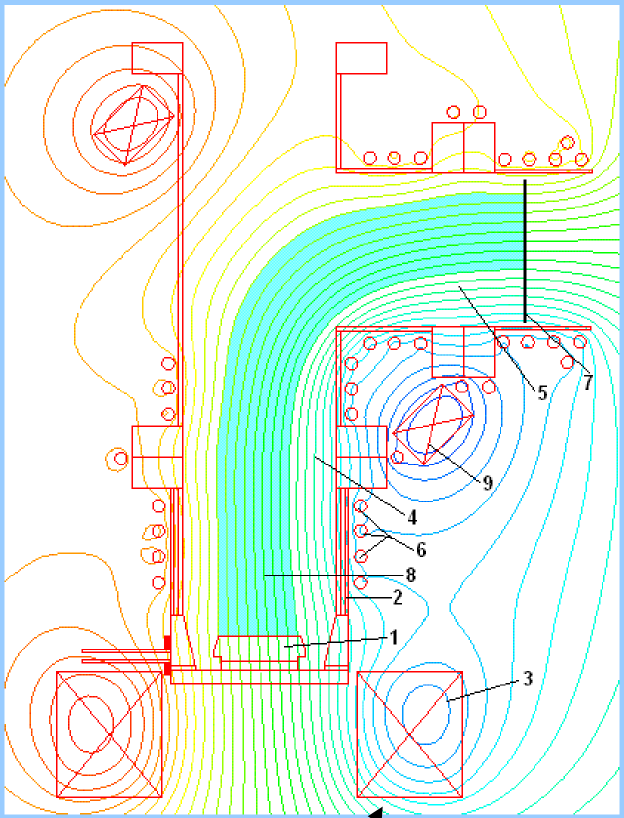
1.8 mJ/mm^2

7. Nb-Pb RF-gun: Quantum Efficiency of Lead at 300 K

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

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

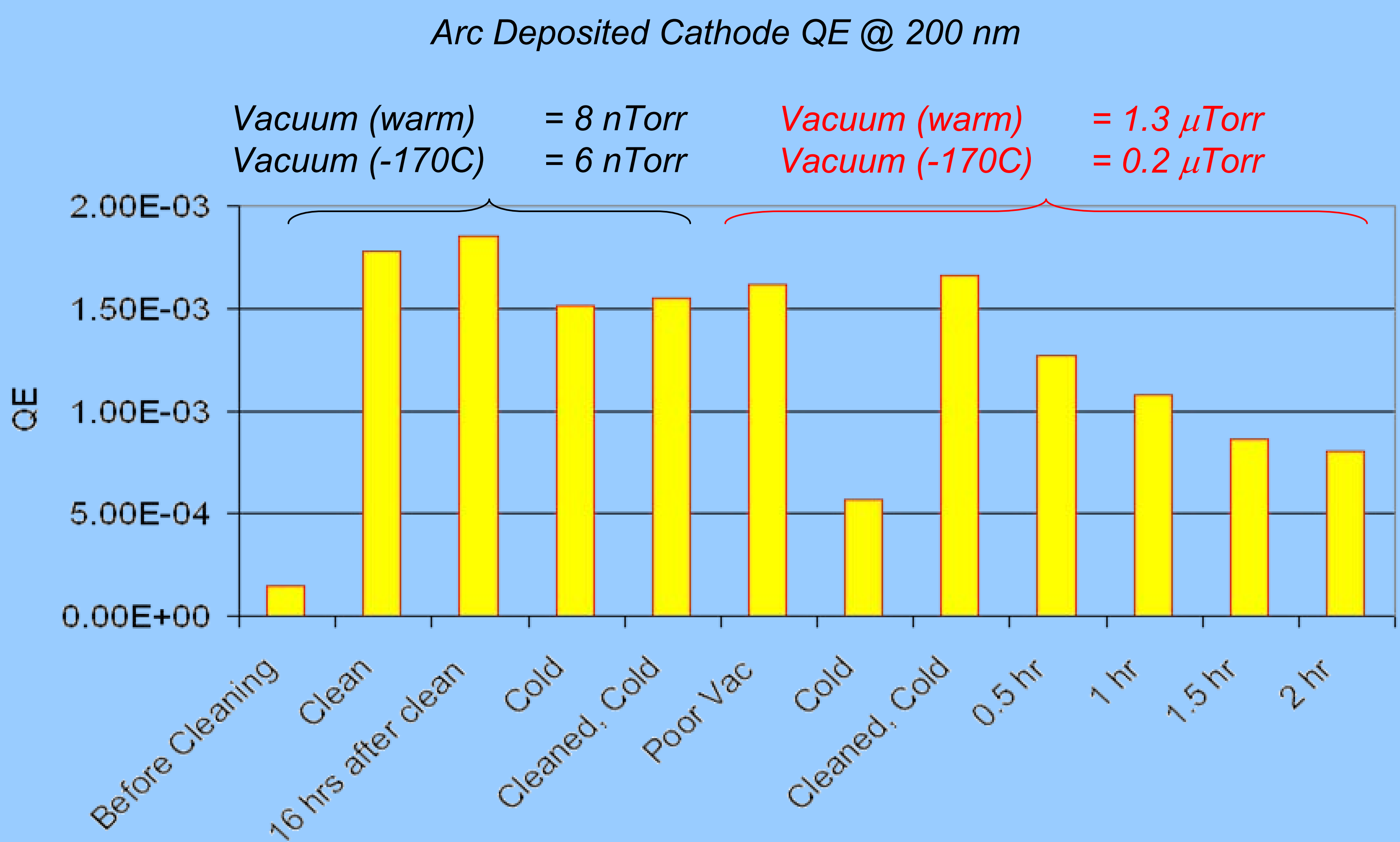




Magnetic field distribution in the Aksenov-type magnetic filter and in the T-type magnetic filter; 1 – cathode, 2 – anode, 3 – focusing coil, 4 – filter inlet, 5 – filter exit, 6 – high-current cable, 7 – ion collector position, 8 – plasma stream, 9 - correcting coil.

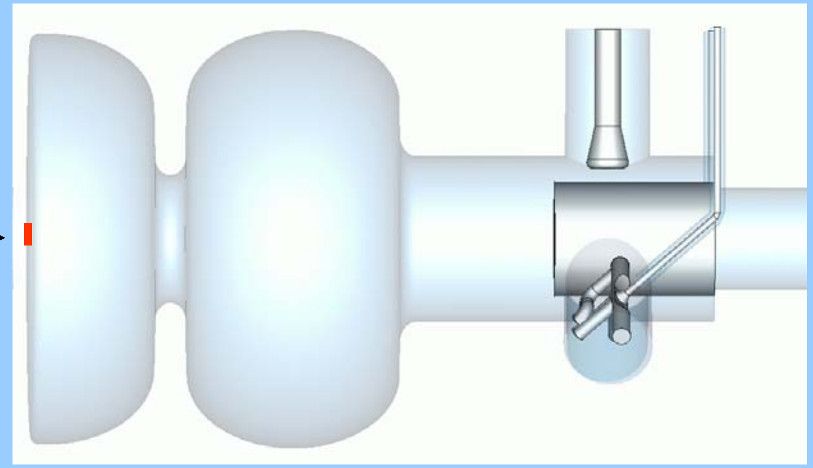
Calculated magnetic filed strengths: - near-cathode region – 16 mT
- magnetic duct region – 12 – 14 mT

Effect of Temperature and Vacuum on QE (Courtesy J: Smedley)

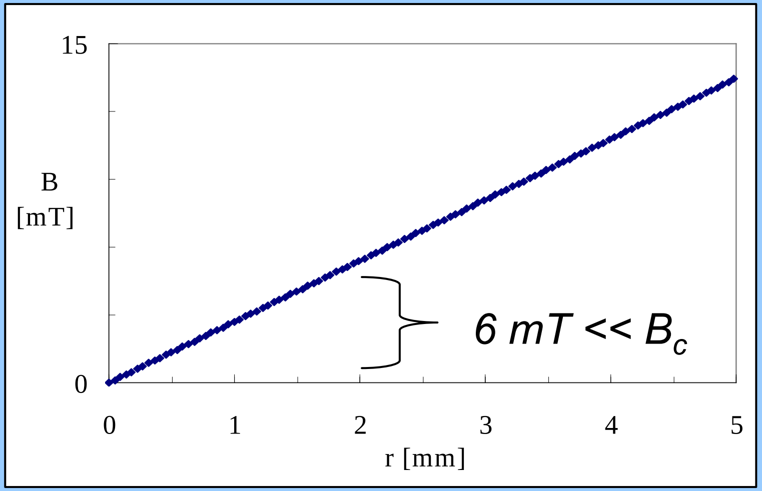


High RRR Nb cavity

“small” emitting Pb spot



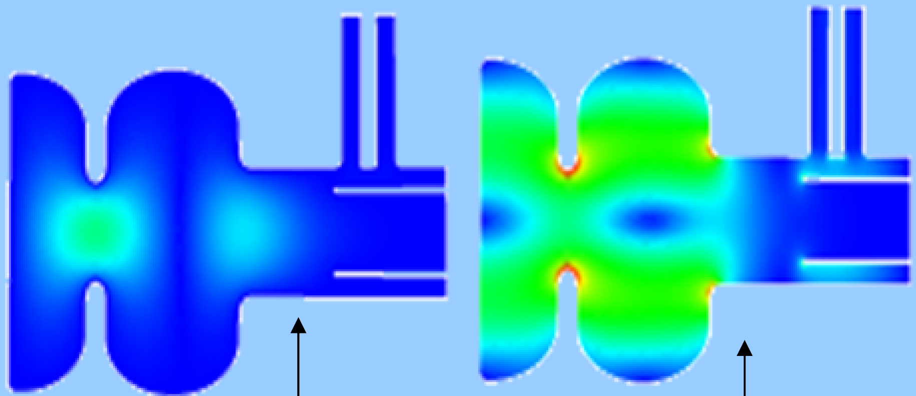
Parameter	Unit	
π-mode frequency	[MHz]	1300
0-mode frequency	[MHz]	1286.5
Cell-to-cell coupling	-	0.015
Active length 1.6·λ/2	[m]	0.185
Nominal E_{cath} at cathode	[MV/m]	60
Energy stored at nominal E_{cath}	[J]	20
Nominal beam energy	[MeV]	6



B-field on the cathode at 60 MV/m

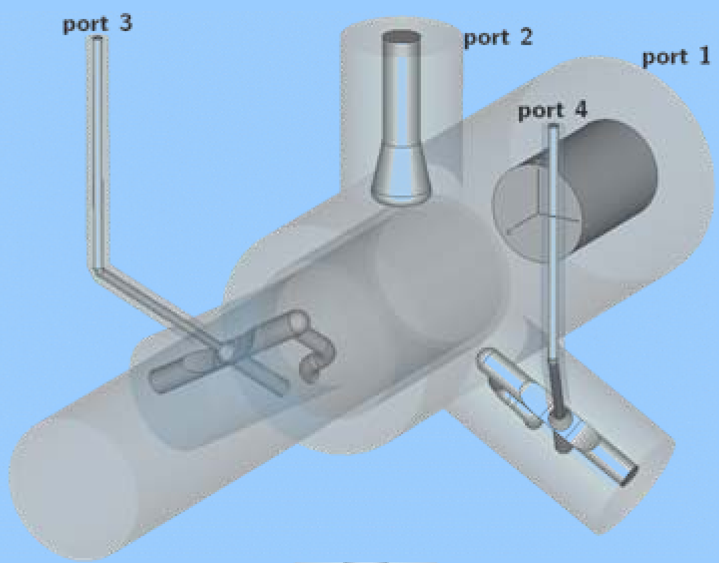
7. Nb-Pb RF-gun: RF-design

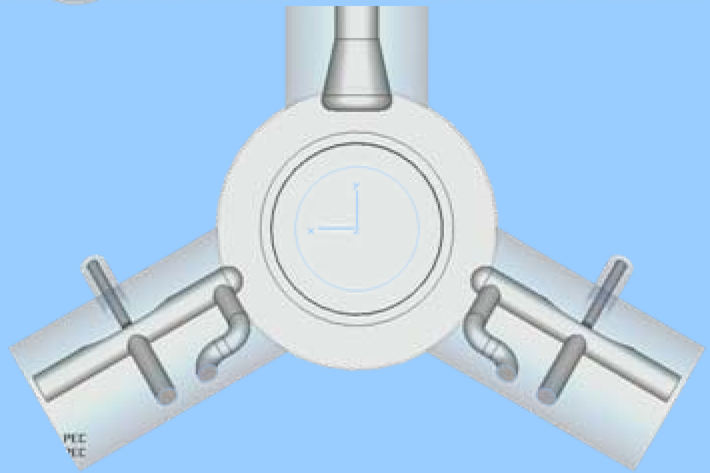
HOM damping scheme:
- *FPC is not sufficient*
- *1 or 2 HOM couplers must be attached*

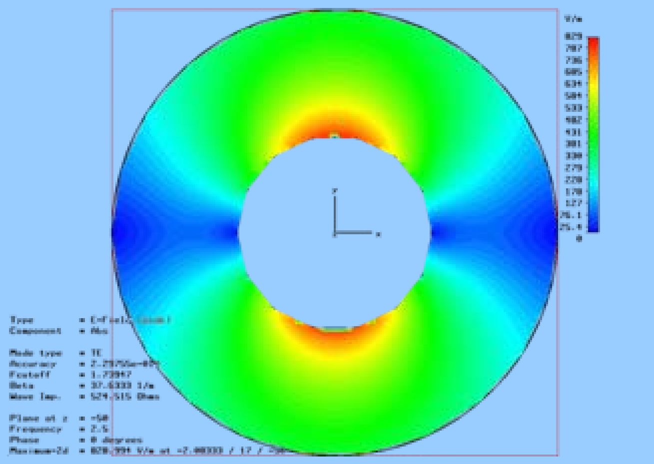


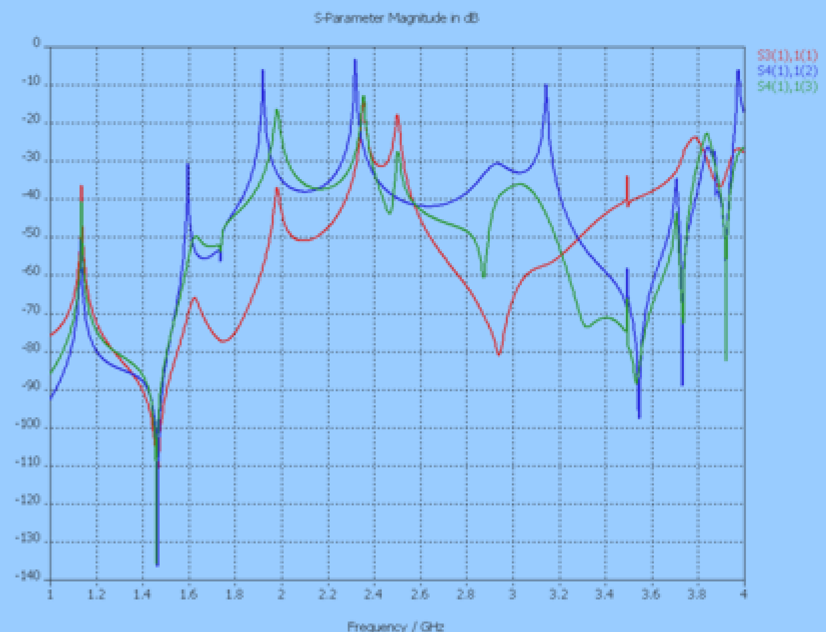
Mode	f [MHz]	(R/Q)
Monopole: Beam Tube	793.9	57.9 [Ω]
Dipole: TE111-1a	1641.8	1.85 [Ω/cm^2]
Dipole: TE111-1b	1644.9	1.30 [Ω/cm^2]
Dipole: Beam Tube-a	1686.3	3.33 [Ω/cm^2]
Dipole: Beam Tube-b	1754.7	5.13 [Ω/cm^2]
Dipole: TM110-1a	1883.5	10.1 [Ω/cm^2]
Dipole: TM110-1b	1884.0	9.99 [Ω/cm^2]
Dipole: TM110-2a	1957.0	3.90 [Ω/cm^2]
Dipole: TM110-2b	1957.1	3.85 [Ω/cm^2]
Monopole: TM011	2176.5	43.2 [Ω]

Modeling of the FPC and HOM coupler region (D. Kostin)

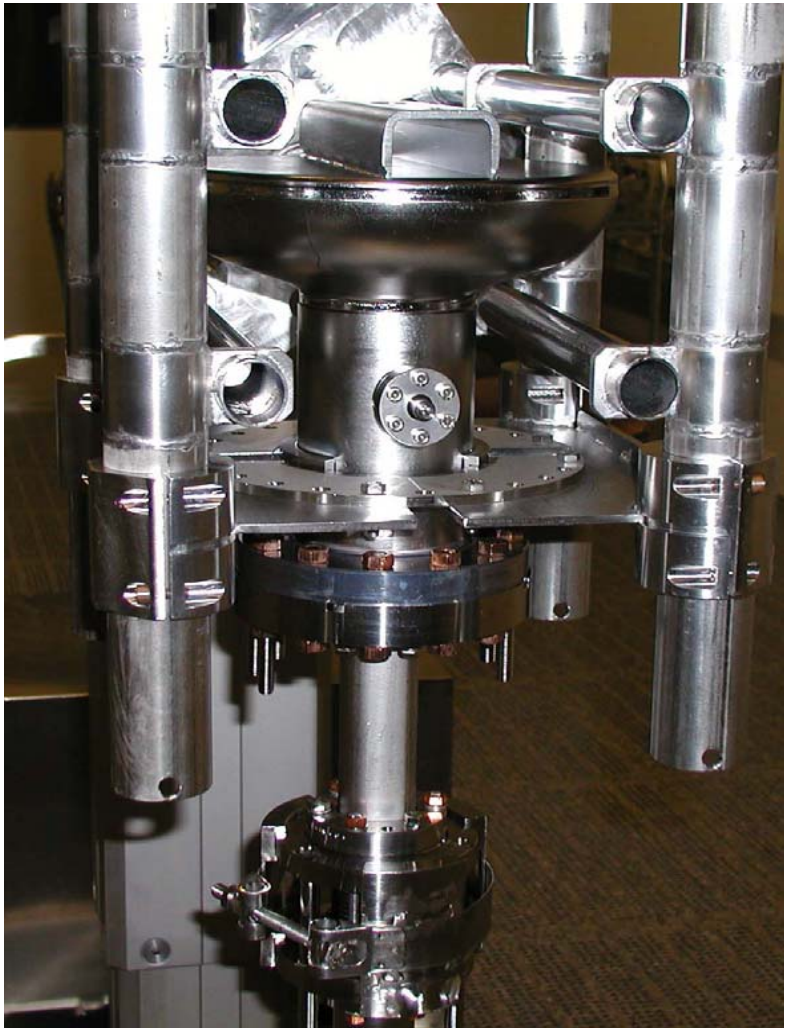


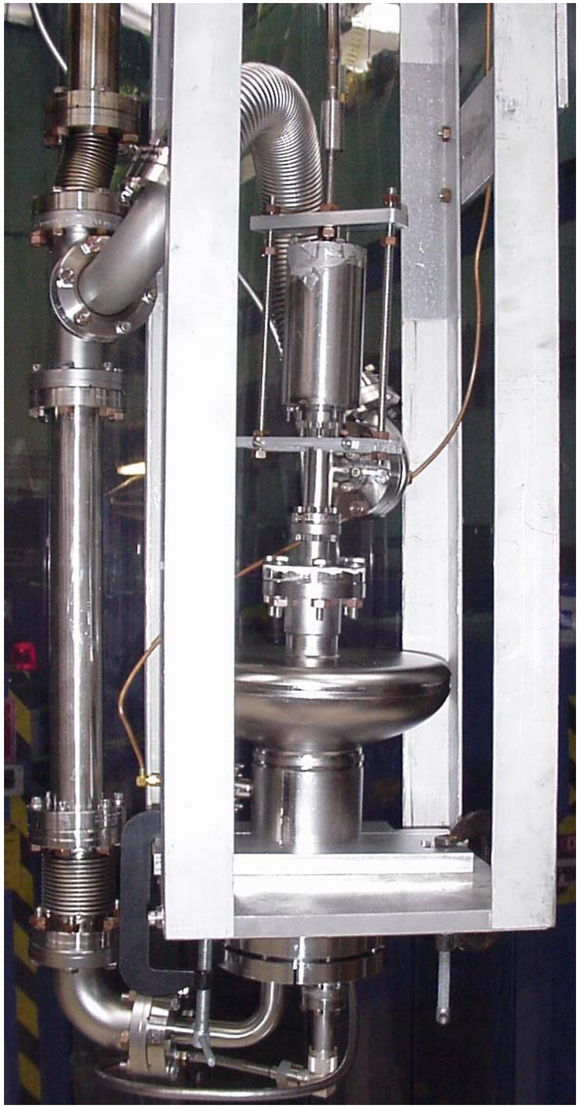






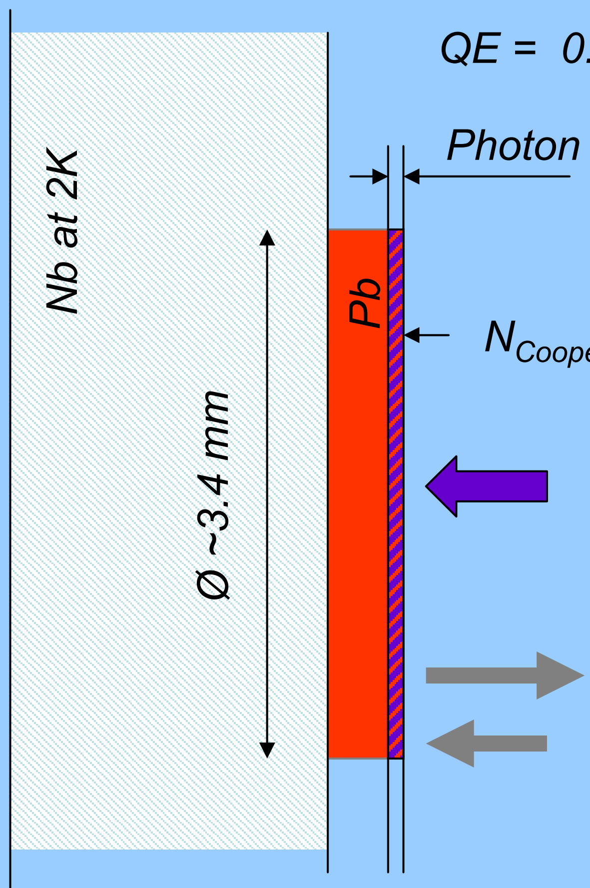
7. Nb-Pb RF-gun: RF-performance of test cavities





1. Relaxation time of Cooper pairs after the illumination

How does intrinsic Q changes 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

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

$3.4\ \mu J \rightarrow N\gamma = 4 \cdot 10^{12}$

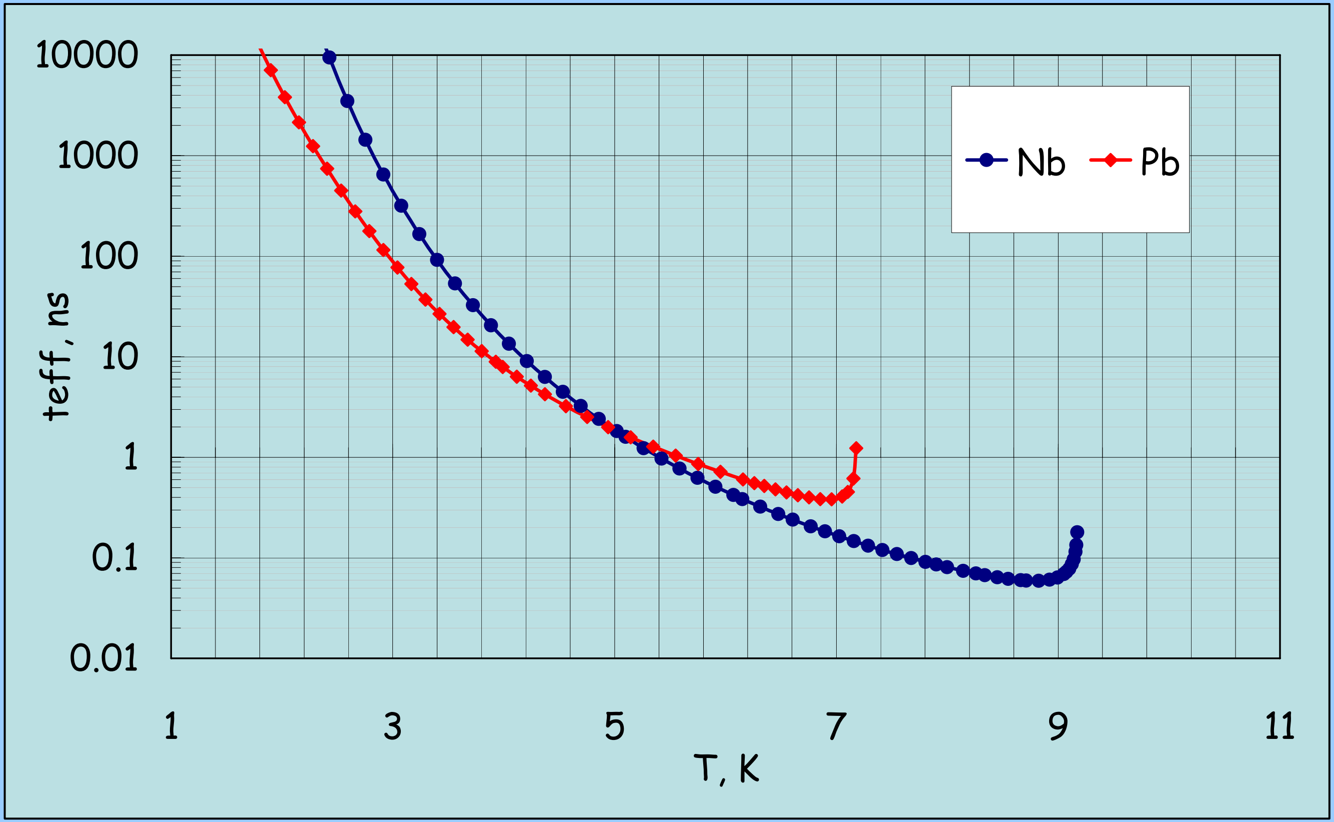
All CPs in the 10 nm layer are broken.

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.

The relaxation time to the thermal equilibrium



This has to be verified experimentally.

2. Thermal emittance ?

Pb work function is ~ 4.25 eV

for : λ_{ph} = 213nm (5.8 eV) @ spot radius r = 1.7 mm

Estimation of the thermal emittance:

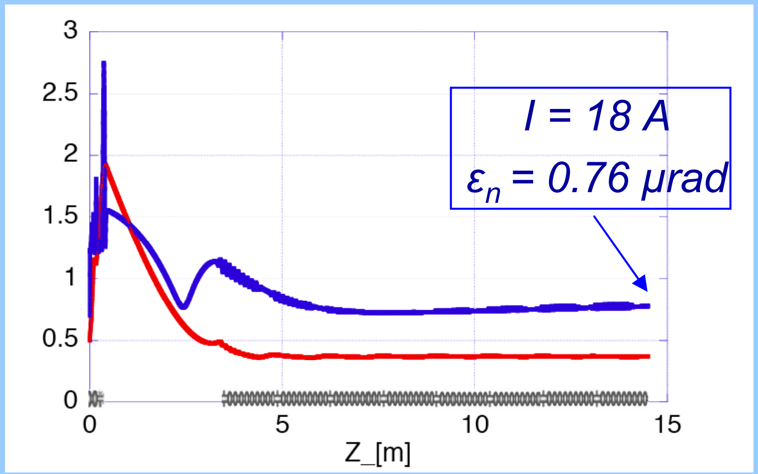
Schottky at 60 MV/m

$$\varepsilon_{TH} = \frac{r}{2\sqrt{3}}\sqrt{\frac{E_k}{mc^2}} = \frac{0.0017}{2\sqrt{3}}\sqrt{\frac{5.8-4.25+0.26}{mc^2}} = 1.27\ \mu rad\ !$$

If experiment with 1.5-cells confirms this estimation we will reduce r to ~1 mm and charge to ~0.4 nC, to get ε_{TH} = 0.7μrad

$$B \approx \frac{Q}{\varepsilon^2 \cdot \sigma_t} \approx \frac{r^2}{r^2 \cdot \sigma_t}$$

HOMDYN (M. Ferrario)



There is visible progress in the SRF- gun projects:

- *Two SRF-guns generated electron beam FZR (2002) and IHIP (2003).*
- *But still some years of R&D are needed to reach spec in the performance.*

Ad 1. Spec vs. Measurements:

- *The FZR gun and IHIP gun have demonstrated almost emittance spec but with much lower charge.*

Ad 2. Cathodes:

- *IHIP Cs_2Te cathode has demonstrated QE=0.01 and 100 days lifetime what is almost the spec.*
- *Nb cathode showed lower QE at cold than expected but vacuum during the cool down was not as good as it should be.*
- *Deposition of the Pb cathode on Nb wall is challenging. Thermal emittance of Pb may cause some limitation in the emitted charge/bunch.*
- *Intrinsic Q and recovery time of broken Cooper pairs (Nb, Pb cathode) need experimental verification.*

Ad 3. New emittance compensation:

- *The compensation by means of the solenoidal mode is interesting and should be demonstrated experimentally.*

All these questions show that coming years will be very exciting for the community involved in the SRF-gun R&D programs.