Superconducting RF Photoinjectors

Jacek Sekutowicz, DESY

- Introduction
- Projects; Specs and measured data
- Cathodes
- RF-performance of sc-cavities
- RF-focusing
- _ growth compensation with DC- and RF-magnetic field
- Nb-Pb gun
- Conclusions

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BNL:	A. Burrill, I. Ben-Zvi, R. Calaga, T. Rao, J. Smedley
AES:	T. Favale, A. Todd, J. Rathke
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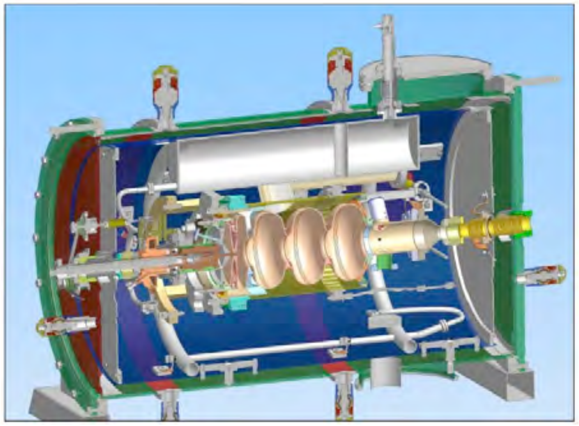
Motivation to develop SRF electron guns:

- **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)

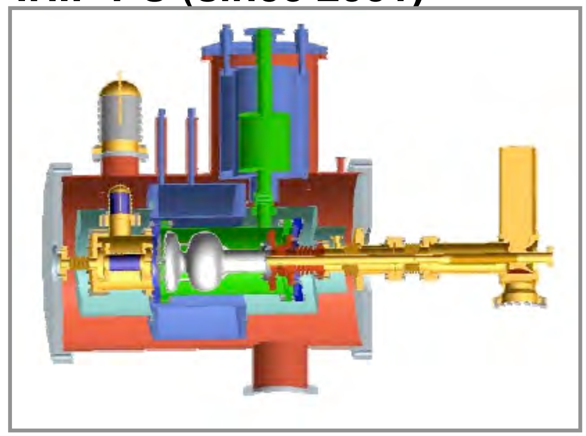


Courtesy of Dietmar Janssen

f =1.3 GHz

Cs_2Te _ E_{RF}

IHIP PU (since 2001)



Courtesy of Hao Jiankui

f =1.3 GHz

Cs_2Te _ E_{DC}

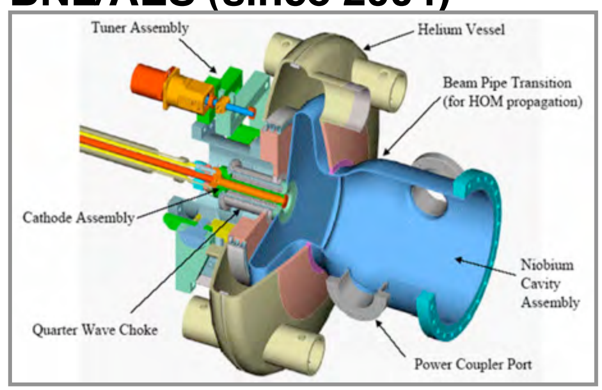
BNL (since 2002)

Courtesy of Triveni Rao

f =1.3 GHz

Nb _ E_{RF}

BNL/AES (since 2004)

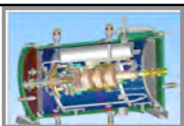
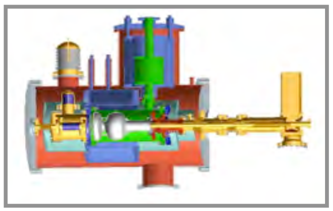
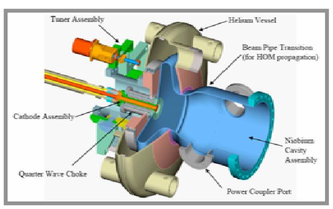


Courtesy of Alan Todd

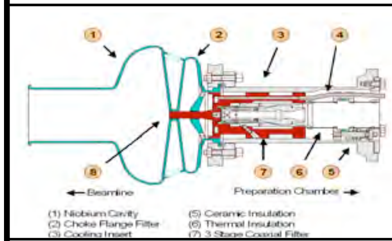
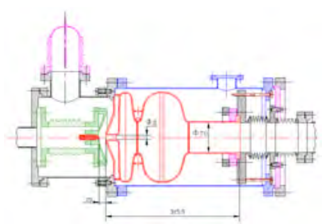
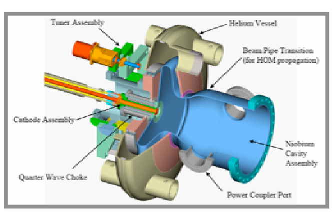
f =703.75 MHz

Alkali+__ _ E_{RF}

Four projects: Spec/Measured

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

Cathodes: Spec / Measured

	Emitter/T	< QE> @ —$_{Ph}$ 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

Cavities: Measured RF-performance

FZR

4 K-test

2.5_10^8 @ E_{peak}=22 MV/m

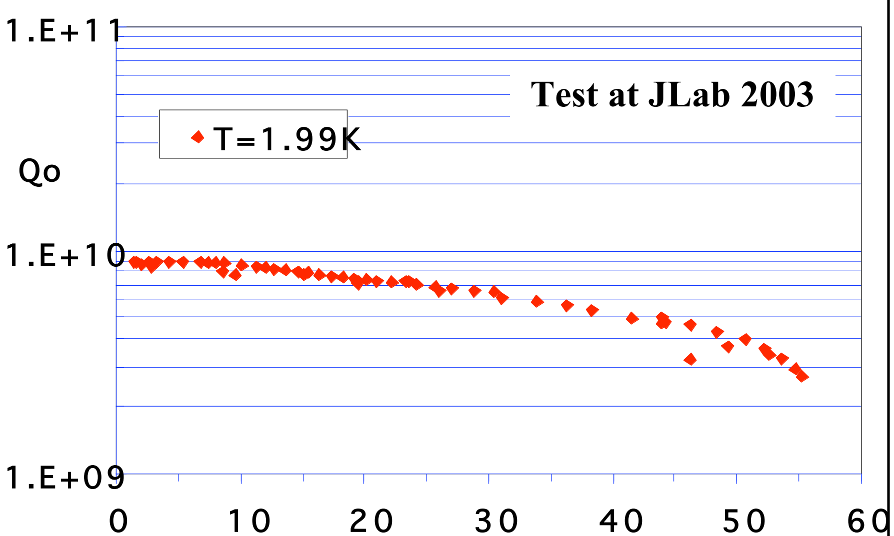
2 K-test

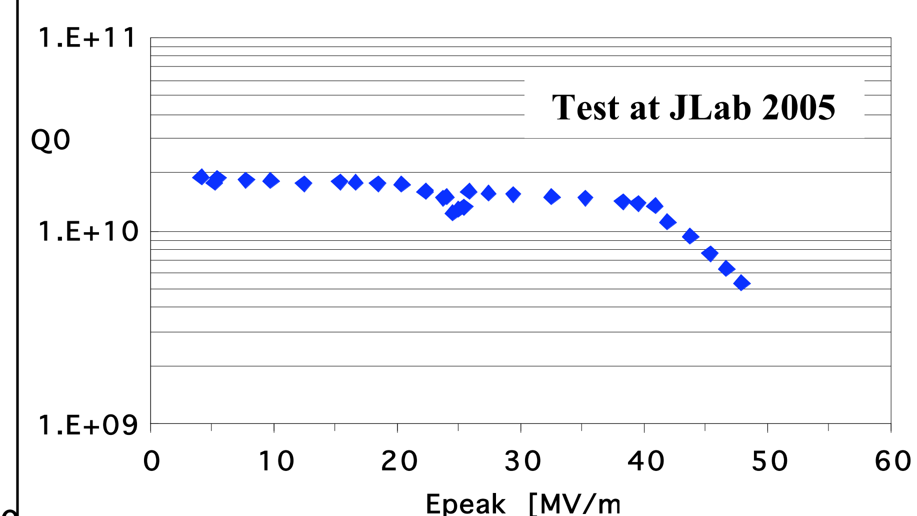
5_10^9 @ E_{peak}=46 MV/m

IHIP-Peking

4.2 K- test

10^8 @ Eacc= 5 MV/m



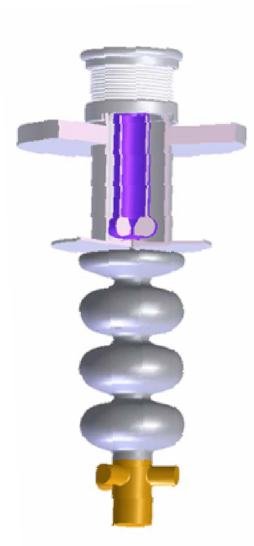


Cavities: Next Steps

FZR

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

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



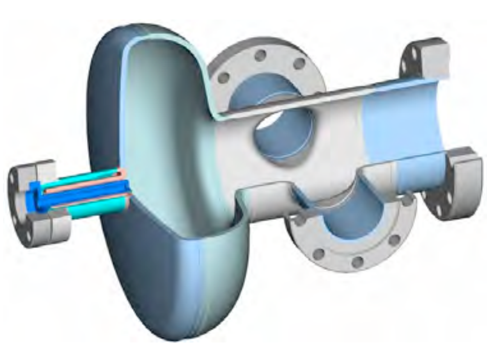
IHIP-Peking University

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

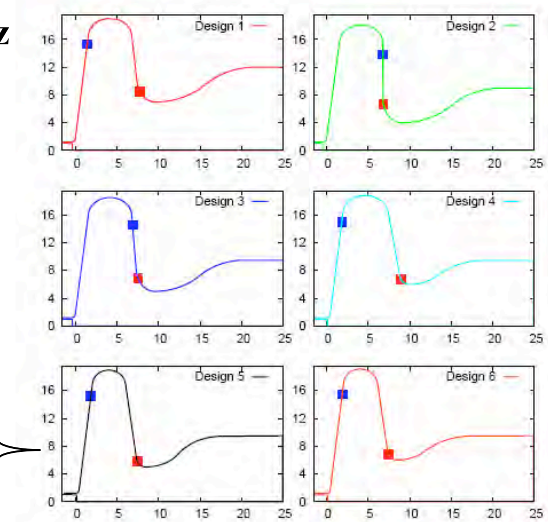
QWC will be added for cathode with diamond: - 2005



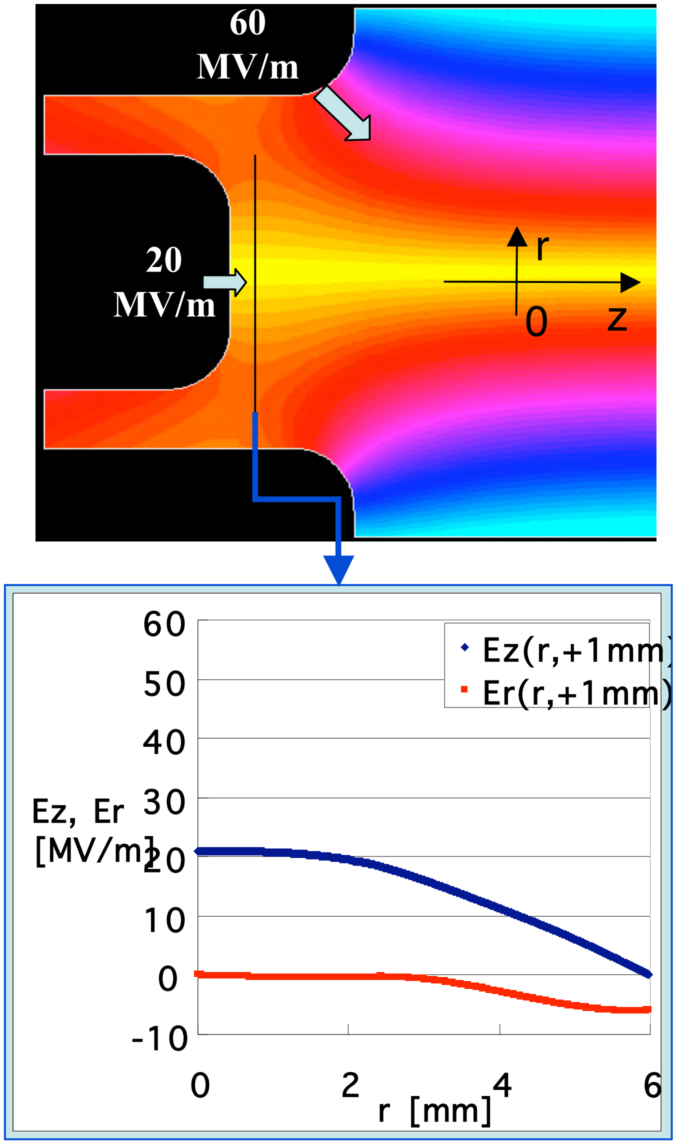
BNL/AES 703.85 MHz

RF Design will be finished in 2005 ?

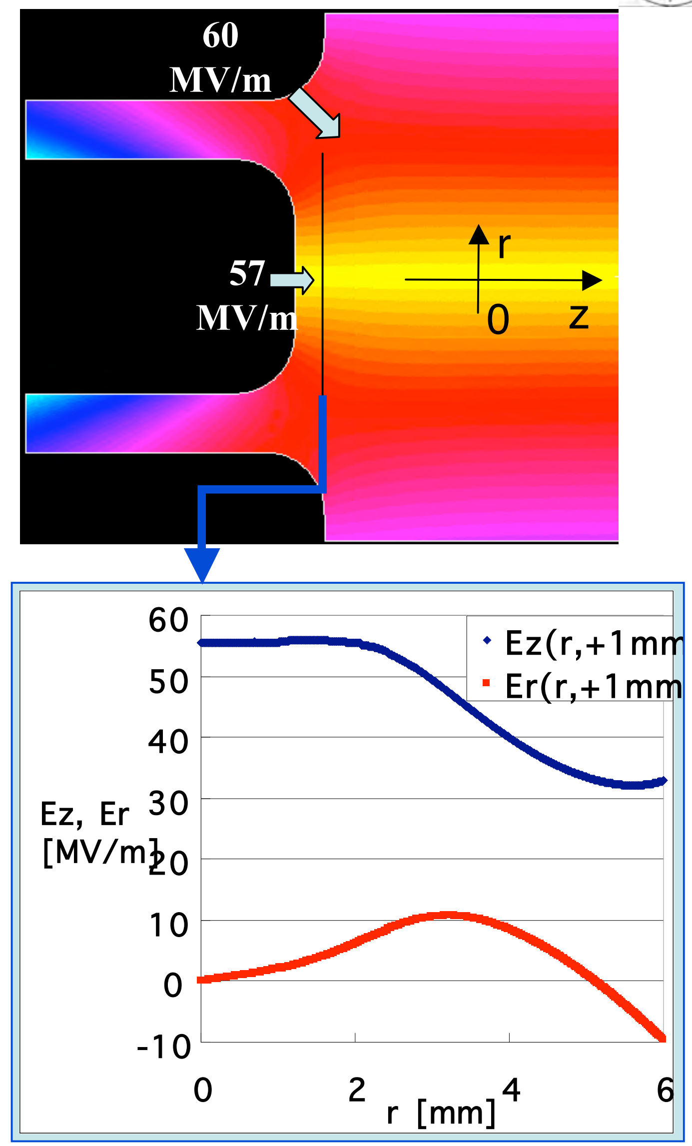
_=1.99 [μrad]
_E/E= 3.8%



E-field Focusing; Recessed cathode→ to generate Er component

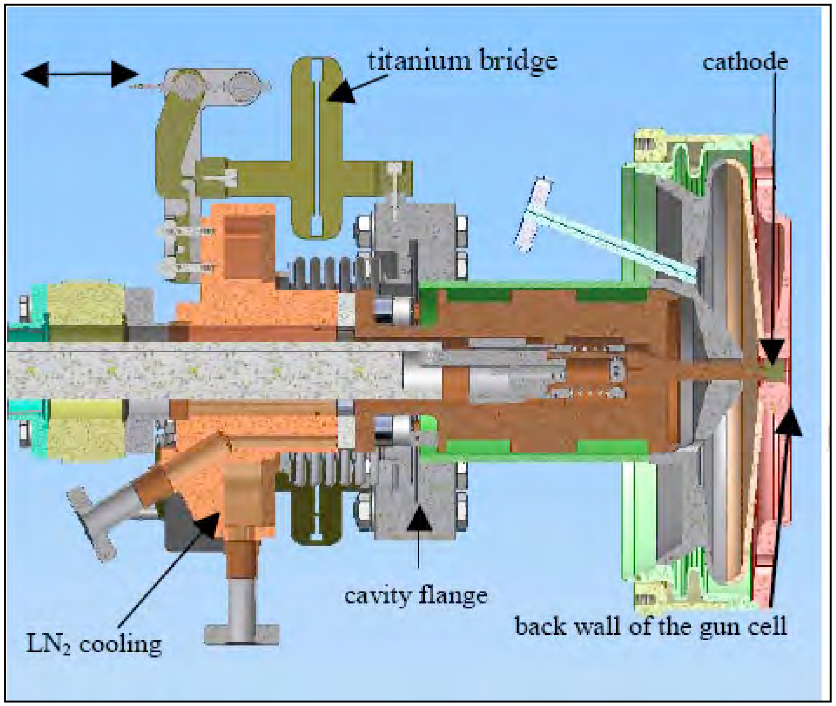


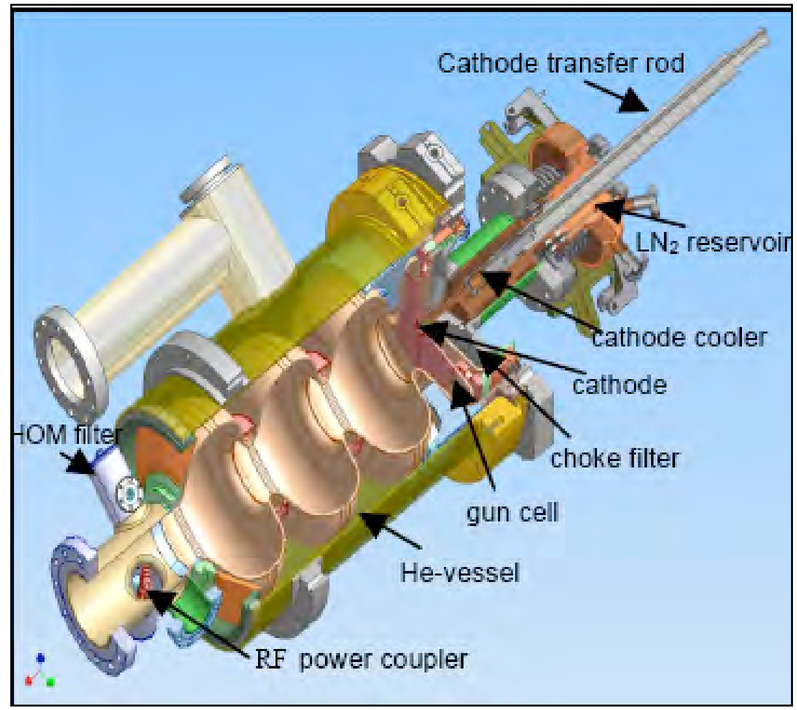
Cathode shifted by 3 mm only



E-field Focusing; Recessed cathode→ to generate Er component

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



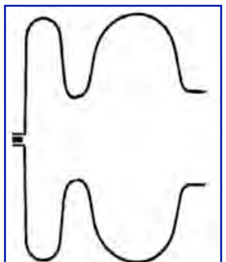


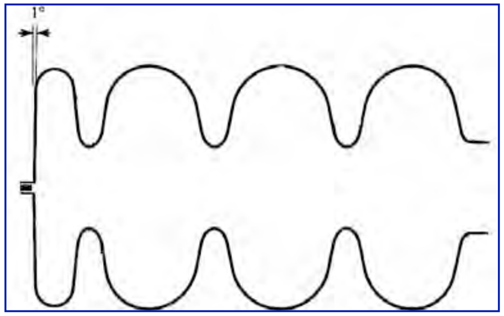
Cathode longitudinal position tuner as proposed by RFZ

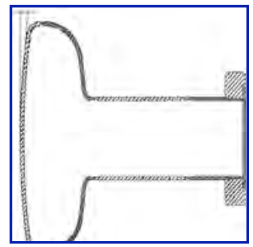
E-field Focusing: Inclined back wall

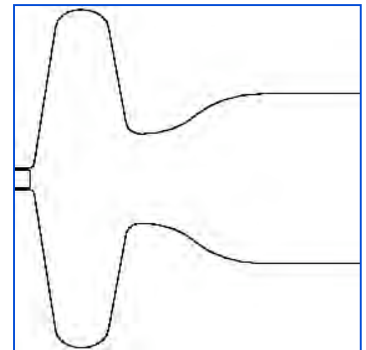
FZR: 1.3 GHz 1.5-cells and 3.5-cells
have recessed cathode and inclined back wall

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









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

	With RF focusing
$_n$ [μrad]	1.99
Recess [mm]	3

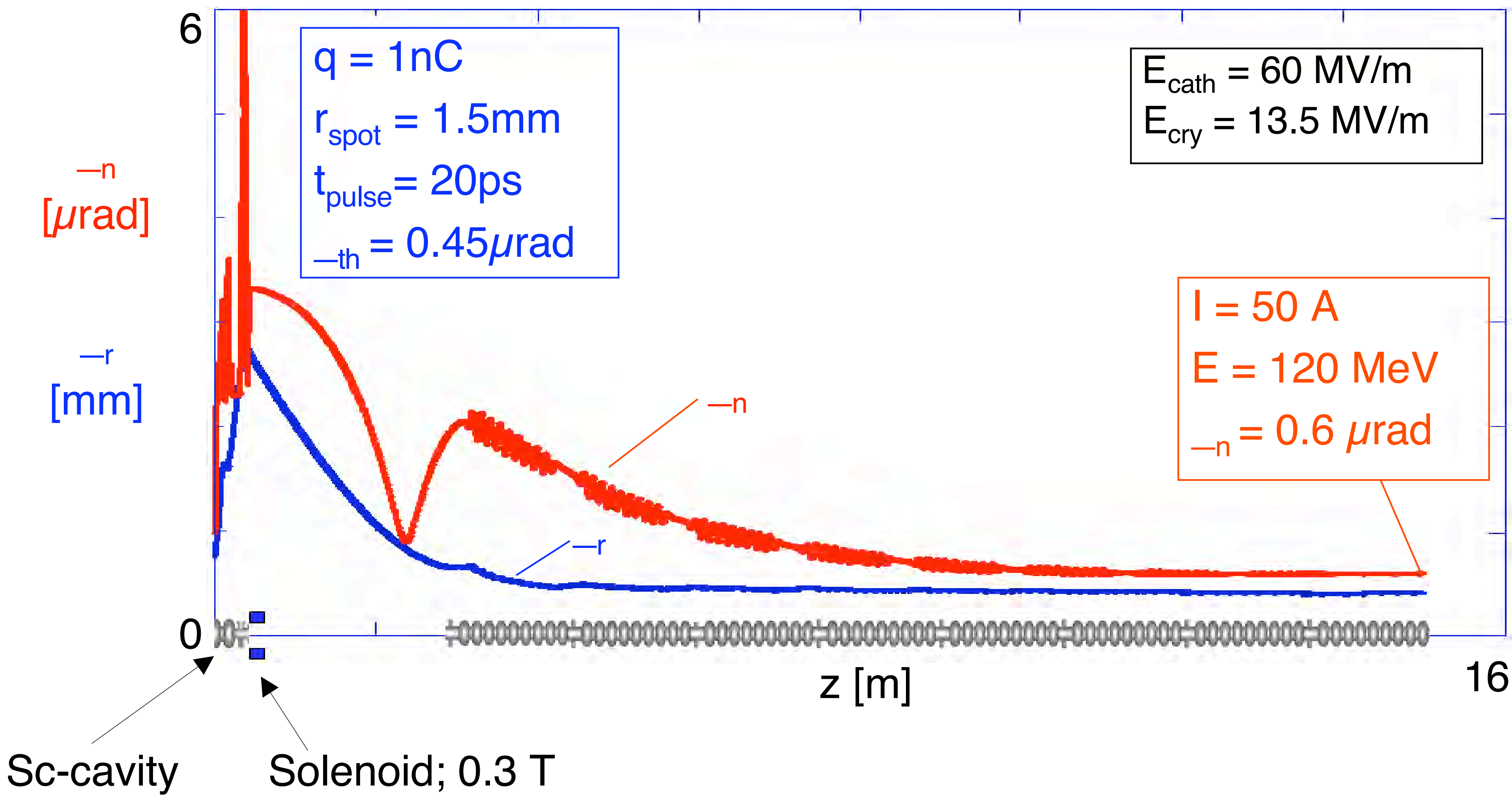
D. Janssen, V. Volkov, NIM A452(2000)34

R. Calaga, Proceed. SRF2005,Cornell

Emittance compensation by H-field:

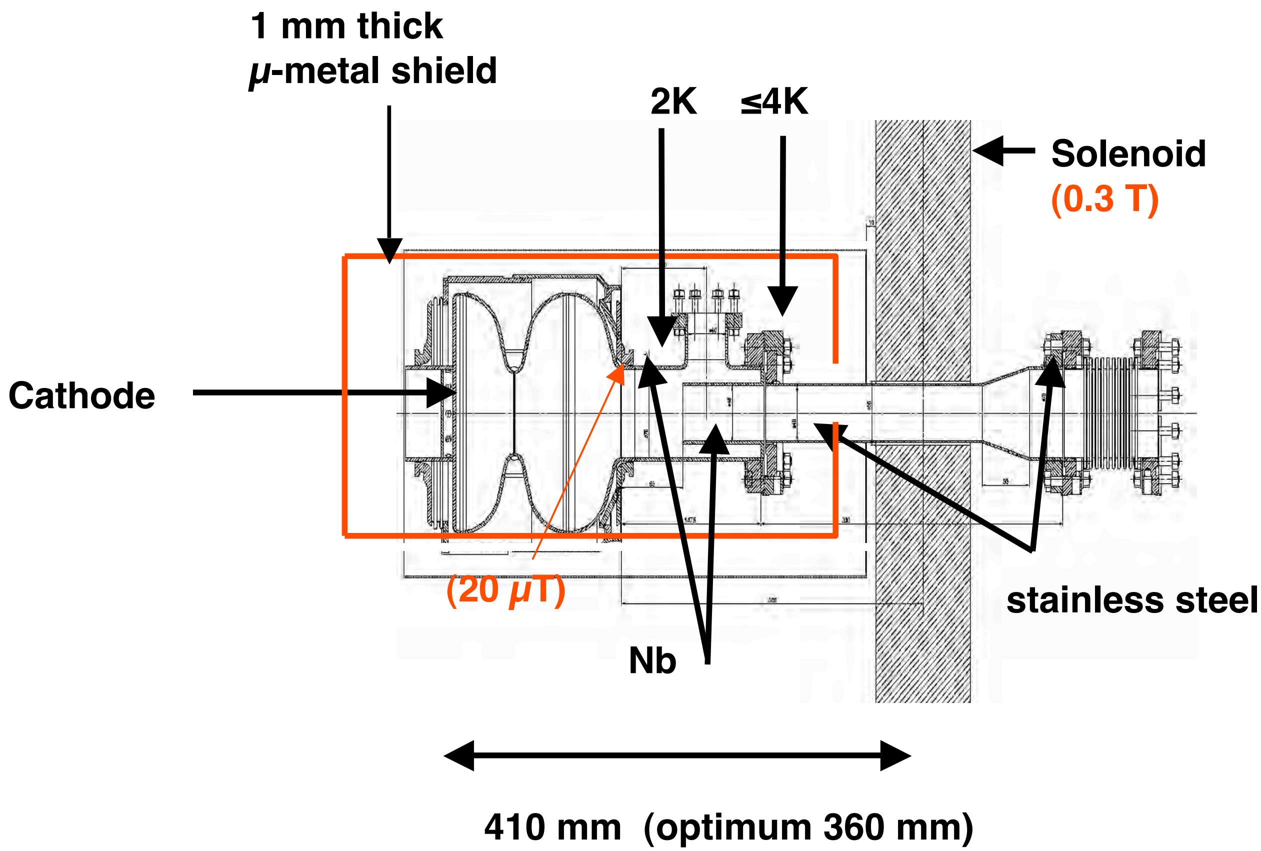
Exposing a sc cavity to H-field may cause degradation in the performance.

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



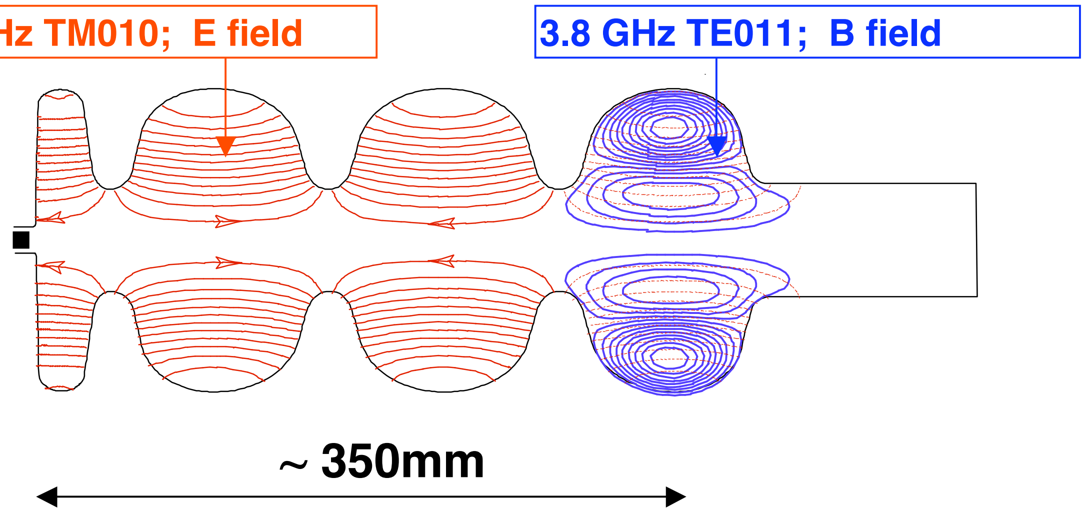
Emittance compensation by H-field:

Example:



Emittance compensation by H-field:

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



$_n$ for 1 nC	[μrad]	0.78-0.98
$_n$ 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

Nb-Pb RF-gun: *DESY, BNL , INFN, SUNY, JLab, INS…*

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} @ _ =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:

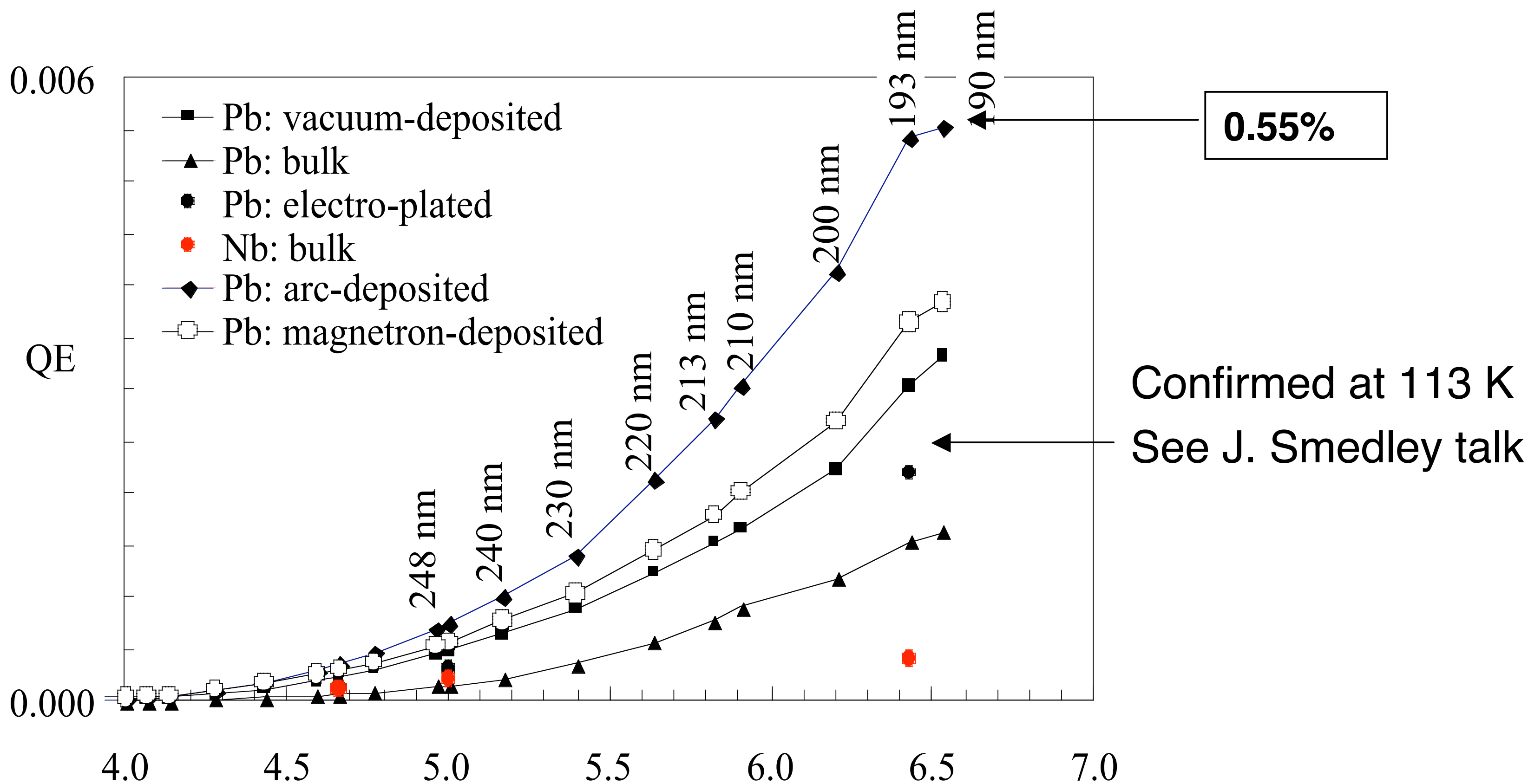
T_c = 7.2 K , B_c = 70 mT

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

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

Light sources:

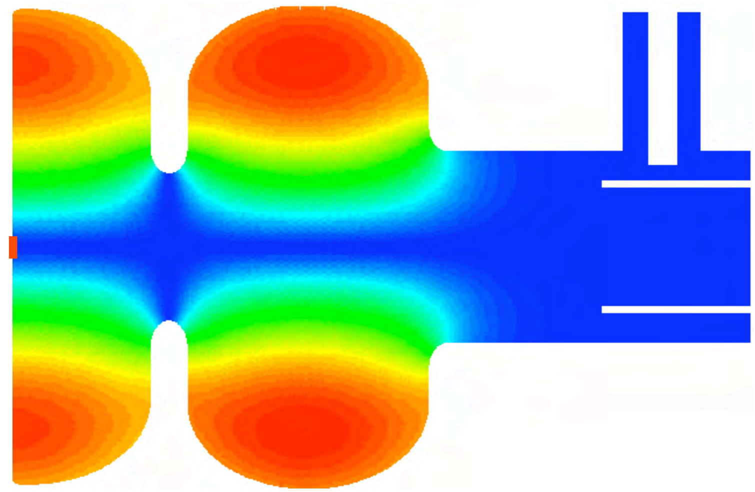
- **ArF- laser: 193 nm, KrF-laser: 248 nm, 4-th harmonic Nd: YAG laser : 266 nm**
- **Deuterium light source with monochromator (2 nm bandwidth): 190-315 nm**



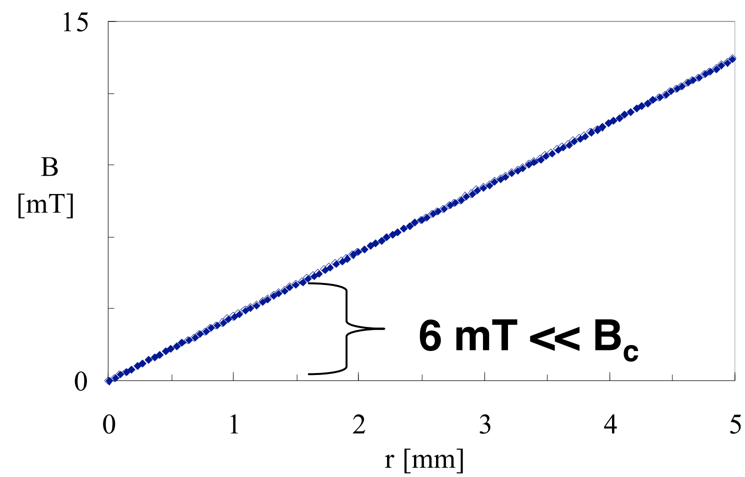
Nb-Pb RF-gun: RF-design

High RRR Nb cavity

“small” emitting Pb spot

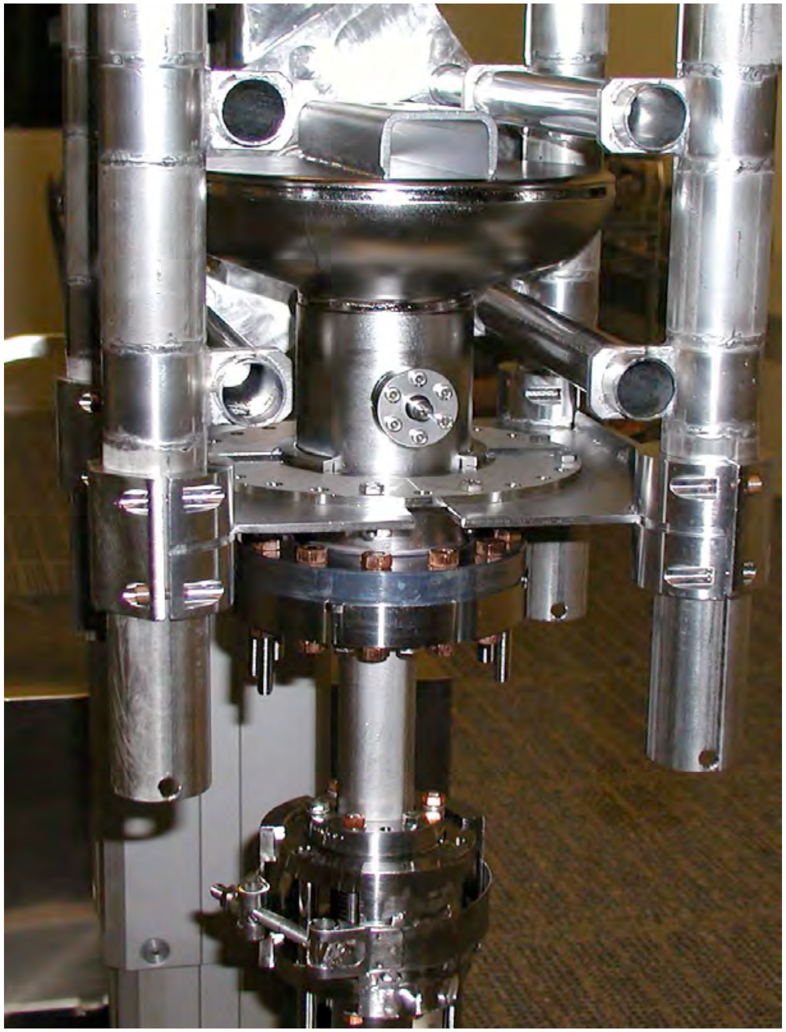


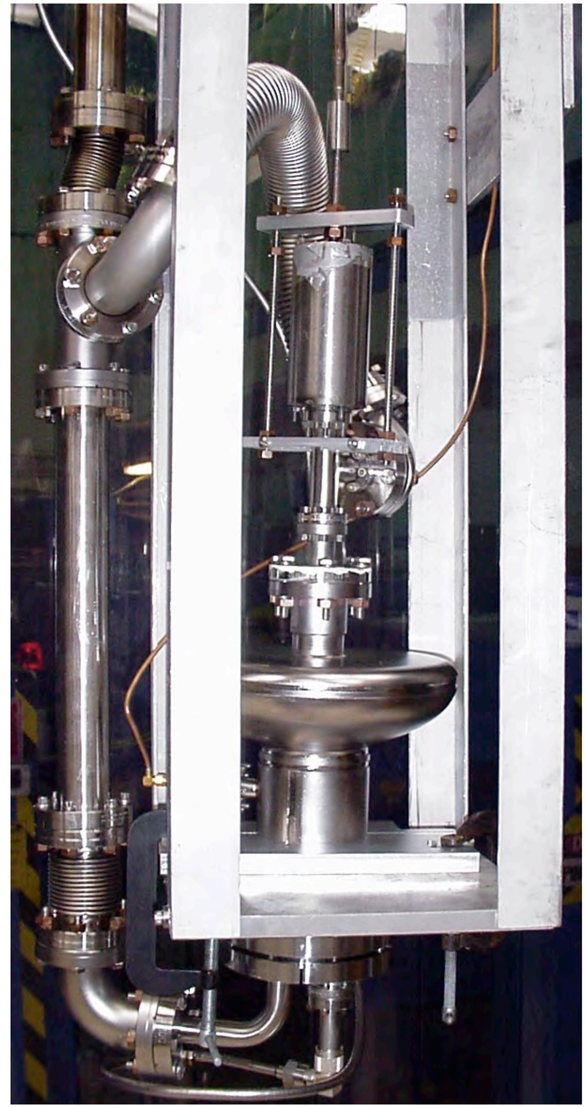
Parameter	Unit	
π-mode frequency	[MHz]	1300
0-mode frequency	[MHz]	1286.5
Cell-to-cell coupling	-	0.015
Active length 1.6__/2	[m]	0.185
Nominal E_{cath} at cathode	[MV/m]	60
Energy stored at nominal E_{cath}	[J]	20
Nominal beam energy	[MeV]	6



B-field on the cathode at 60 MV/m

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





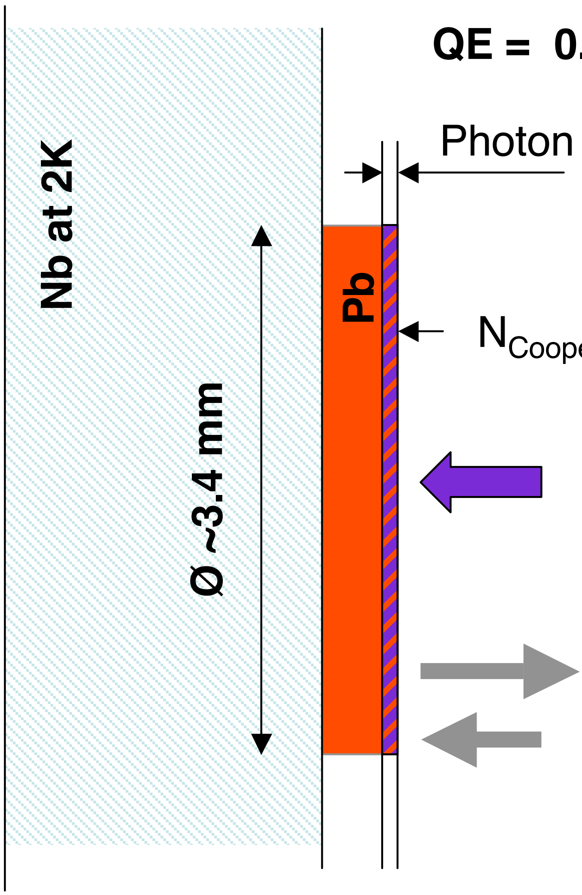
Nb-Pb RF-gun: Two questions to be answered experimentally

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

$N_{\text{Cooper pairs}}$ = **1.5_10^{13}**

3.4 μJ →N_ = **4_10^{12}**

All CPs in the 10 nm layer are broken.

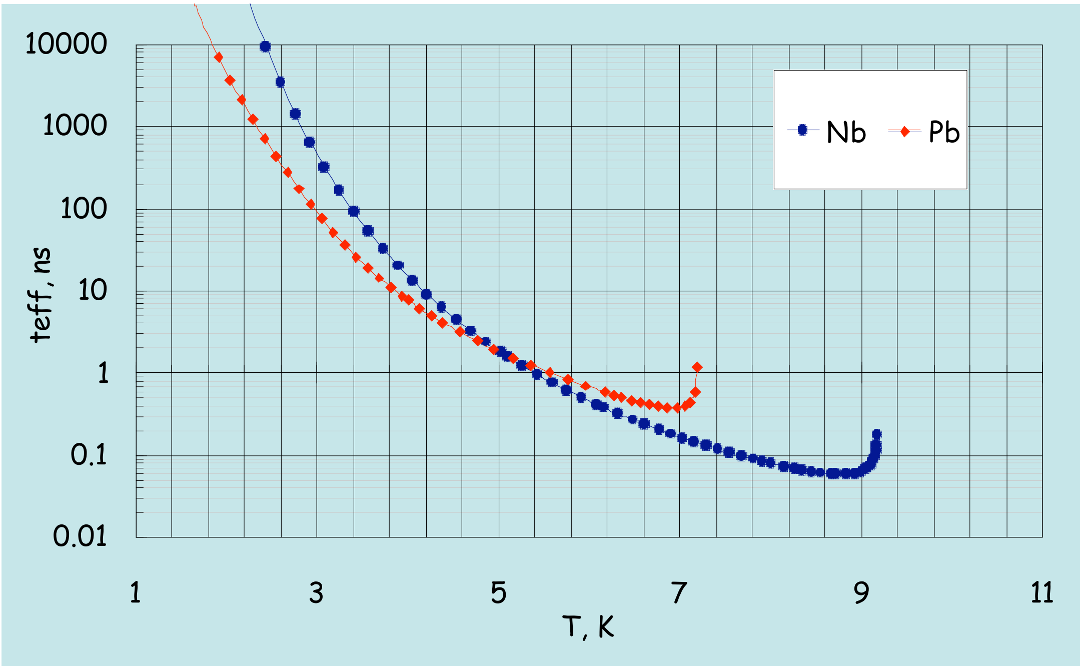
The layer is in the normal-conducting state after the laser pulse.

F= 60 MeV/m

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

Nb-Pb RF-gun: Two questions to be answered experimentally

The relaxation time to the thermal equilibrium



This has to be verified experimentally.

Nb-Pb RF-gun: Two questions to be answered experimentally

2. Thermal emittance ?

Pb work function is ~ 4.25 eV

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

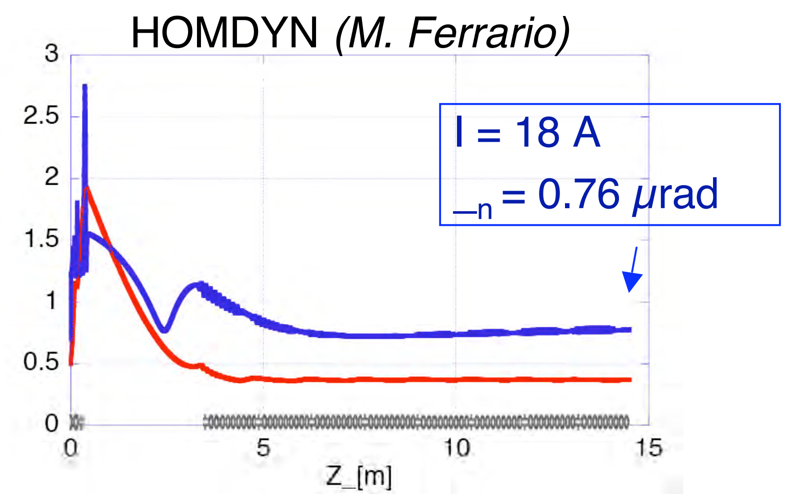
Estimation of the thermal emittance:

Schottky at 60 MV/m

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

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

$$B \approx \frac{Q}{\_^{2}\,\_\,\_{t}} \approx \frac{r^2}{r^2\,\_\,\_{t}}$$



Conclusions

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 at 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.**

Conclusions

Ad 3. New emittance compensation:

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

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