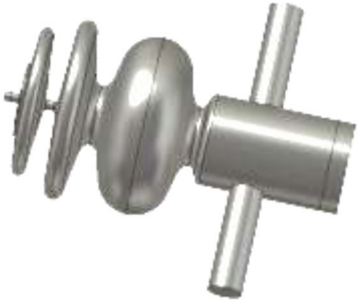





Towards a 100mA Superconducting RF Photoinjector for B*ERL*inPro

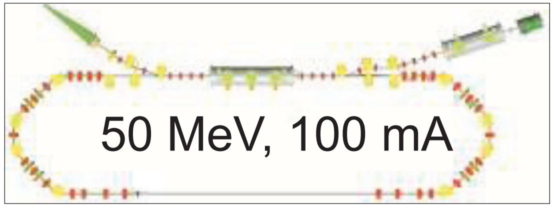
Axel Neumann

for a collaboration by

JLab, DESY, NCBJ, BNL, BINP, FZJ, HZDR, MBI and HZB

What are the challenges for Photoinjector Cavity design?

BERLinPro needs to preserve and recirculate a:



- **Low emittance beam with high peak brightness and high average current**
- **Dark current level as low as possible to mitigate beam Halo**

Low emittance < 1μrad:

- High electric field component at cathode during bunch emission to counteract space charge driven beam expansion
- Sufficient large radial field components for beam RF focusing
- Energy gain of 2.3 MeV at high launch phase using the given forward power level to full extend *coupler limit*

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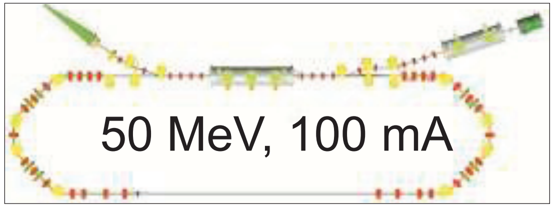

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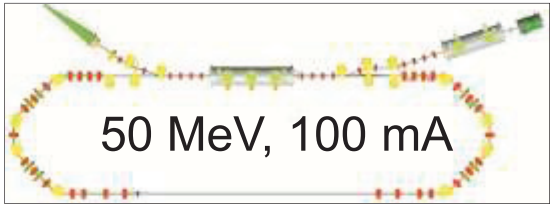

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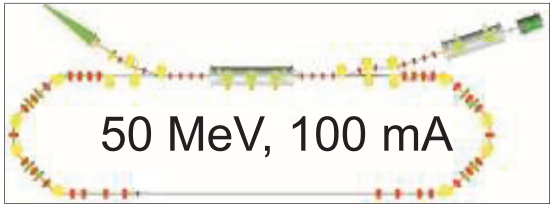

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Dark current:

- Avoid, if possible, highest field on axis on cathode surface and opening of back wall ⚡ *low emittance, low cathode work function*

What will be shown

How do we achieve these (partially) competing goals?
Challenging endeavor → Staged approach

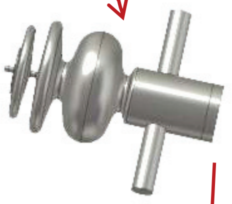
Outline

- Stage 0: Learn operating SRF gun:
  Cavity 0.1 – Cathode: Back wall SC Pb coated

  Lessons learned → Improved version
  Cavity 0.2 – Cathode: Removable Nb plug Pb coated

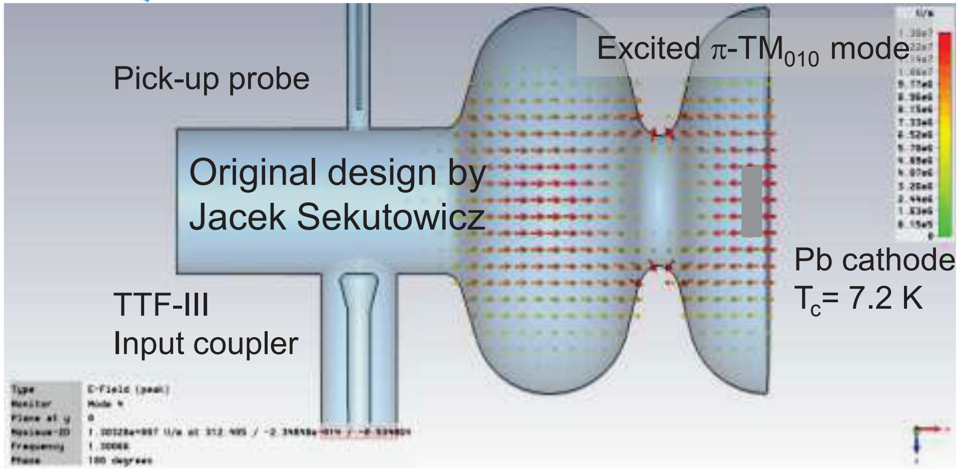
  SC cathode, measure beam parameters

- Stage 1: 1.4 cell 1.3 GHz –being manufactured
  +high peak brightness→ NC high QE cathode



- Stage 2: 1.X cell 1.3 GHz – CsK_2Sb photocathode –design stage
Addition of two 115 kW input couplers: +High avg. current

The all SC PbNb cavity 0.1: RF design, cathode deposition



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  →
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  Limited brightness and current

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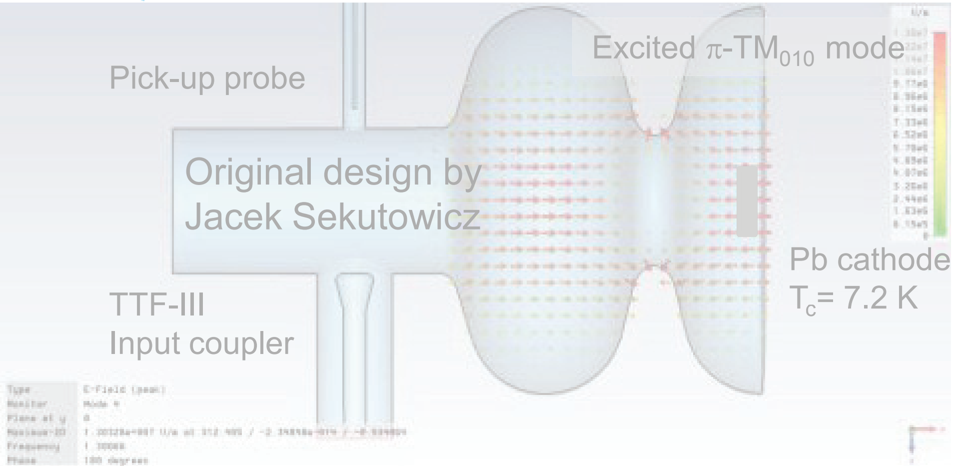

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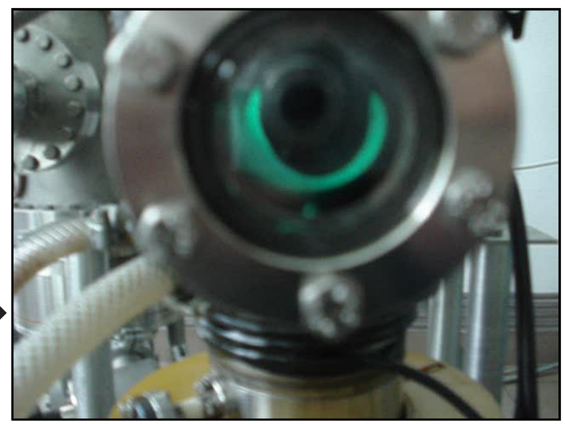
Cathode deposition:

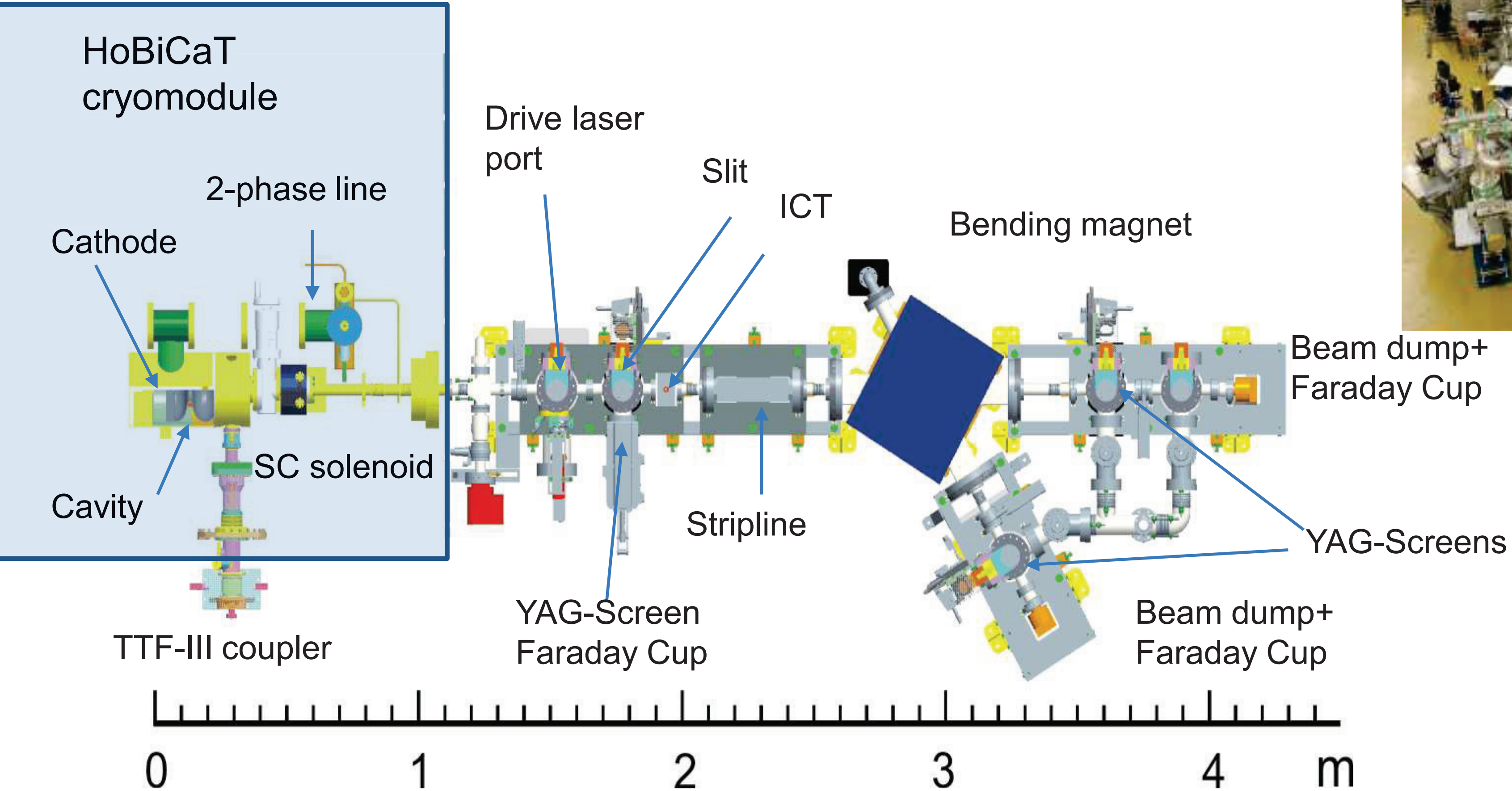
Deposition setup in Świerk

Plasma: Several few minutes depositions



Final diameter by BCP + special mask: 5 mm

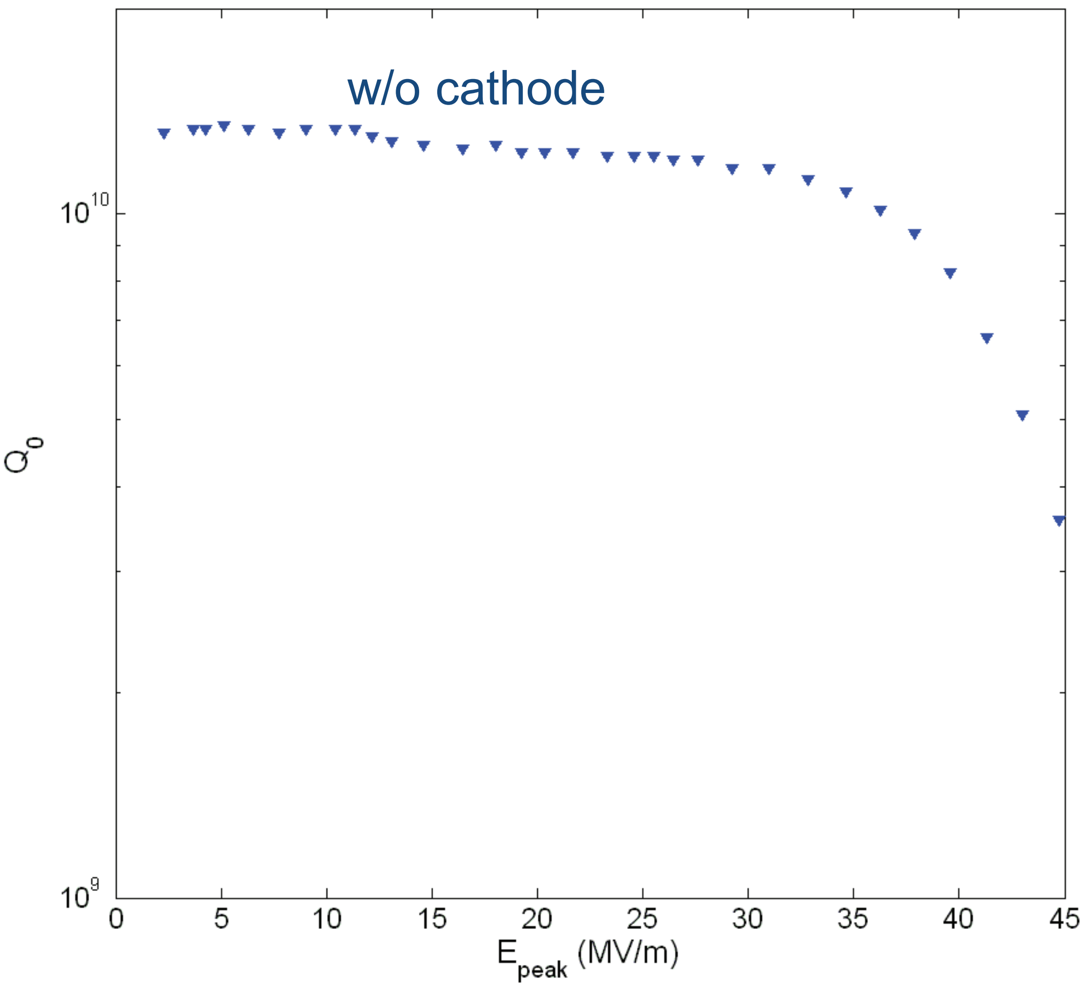
Experimental set up at HZB



Combine and correlate cavity, cathode and beam measurements

Same setup used to clean cathode with high power Excimer UV laser by scanning surface

Achieved Q_0 in VTA and Horizontal set up: Cavity 0.1



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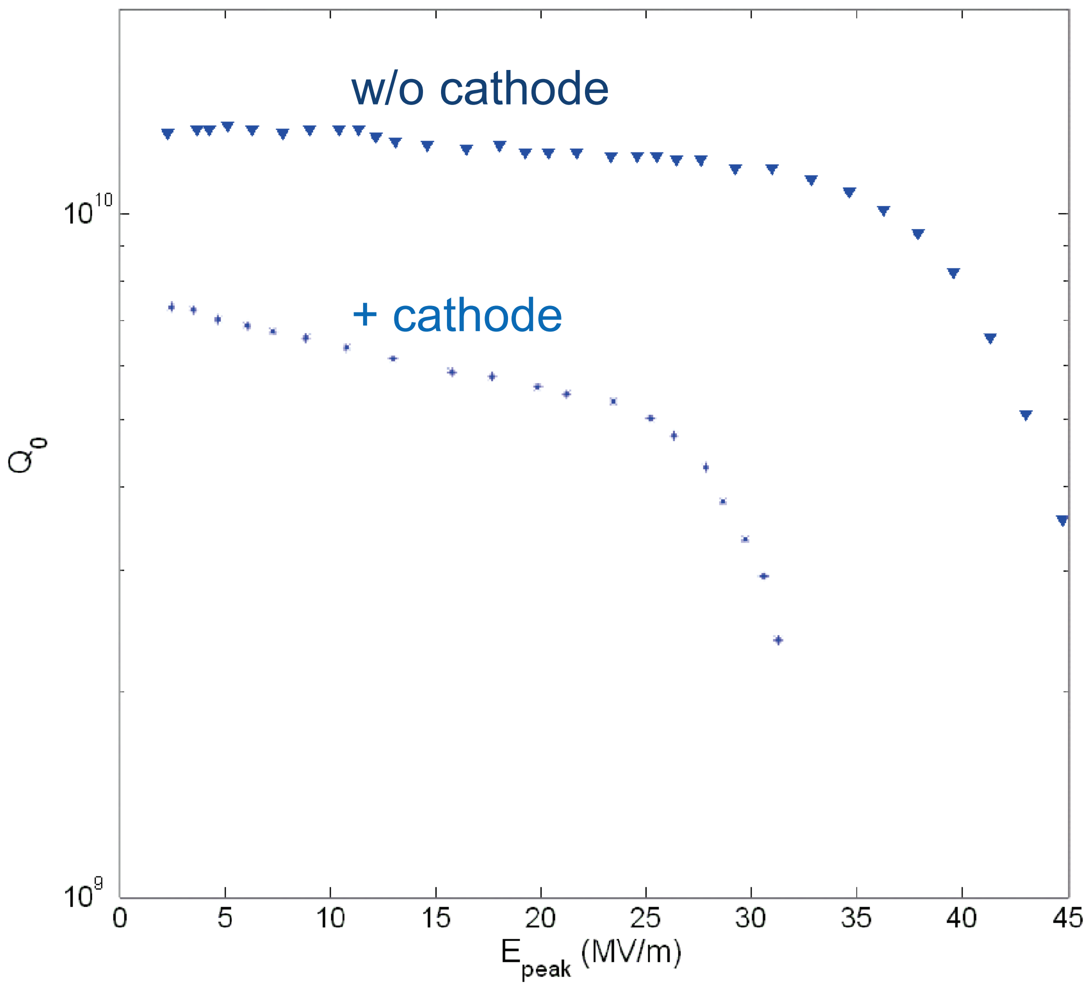

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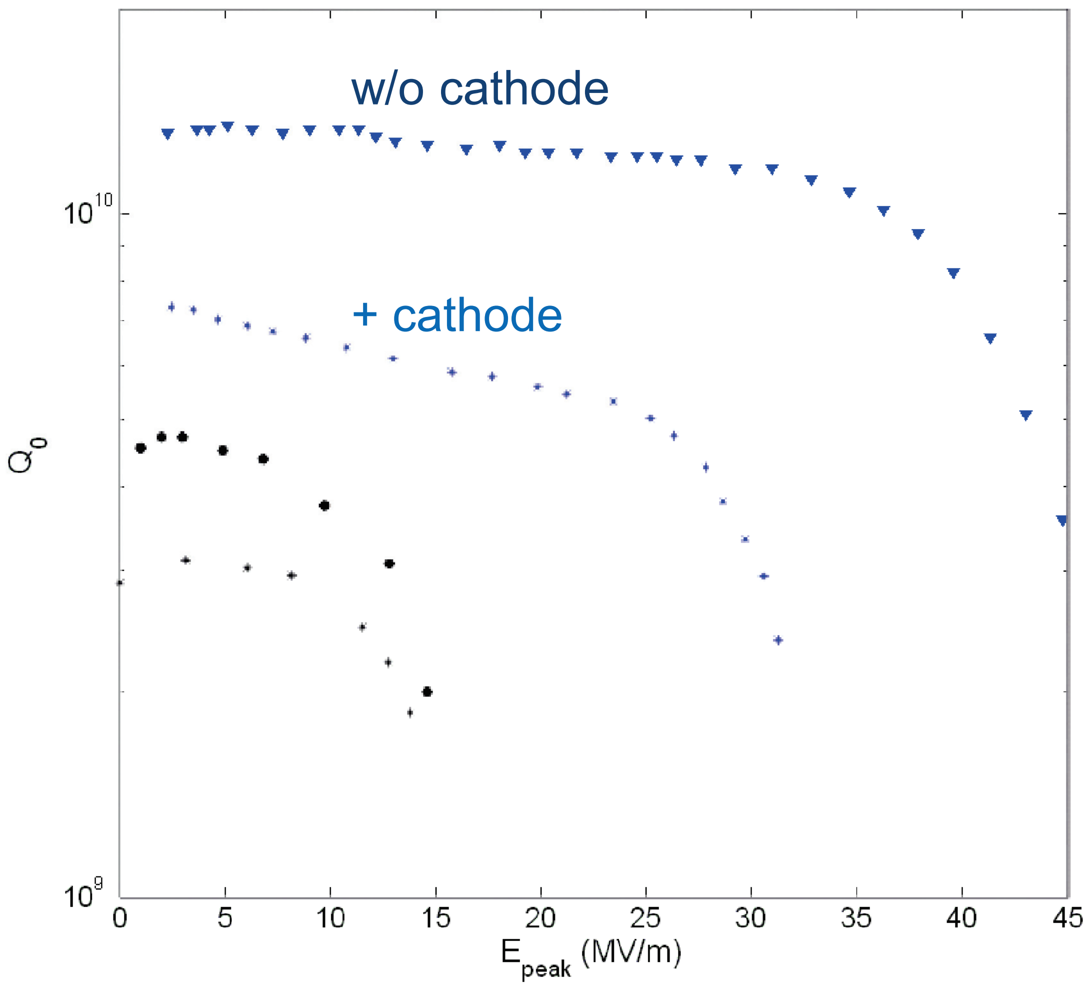

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- After additional cooldown cycle even worse, cavity collected residuals

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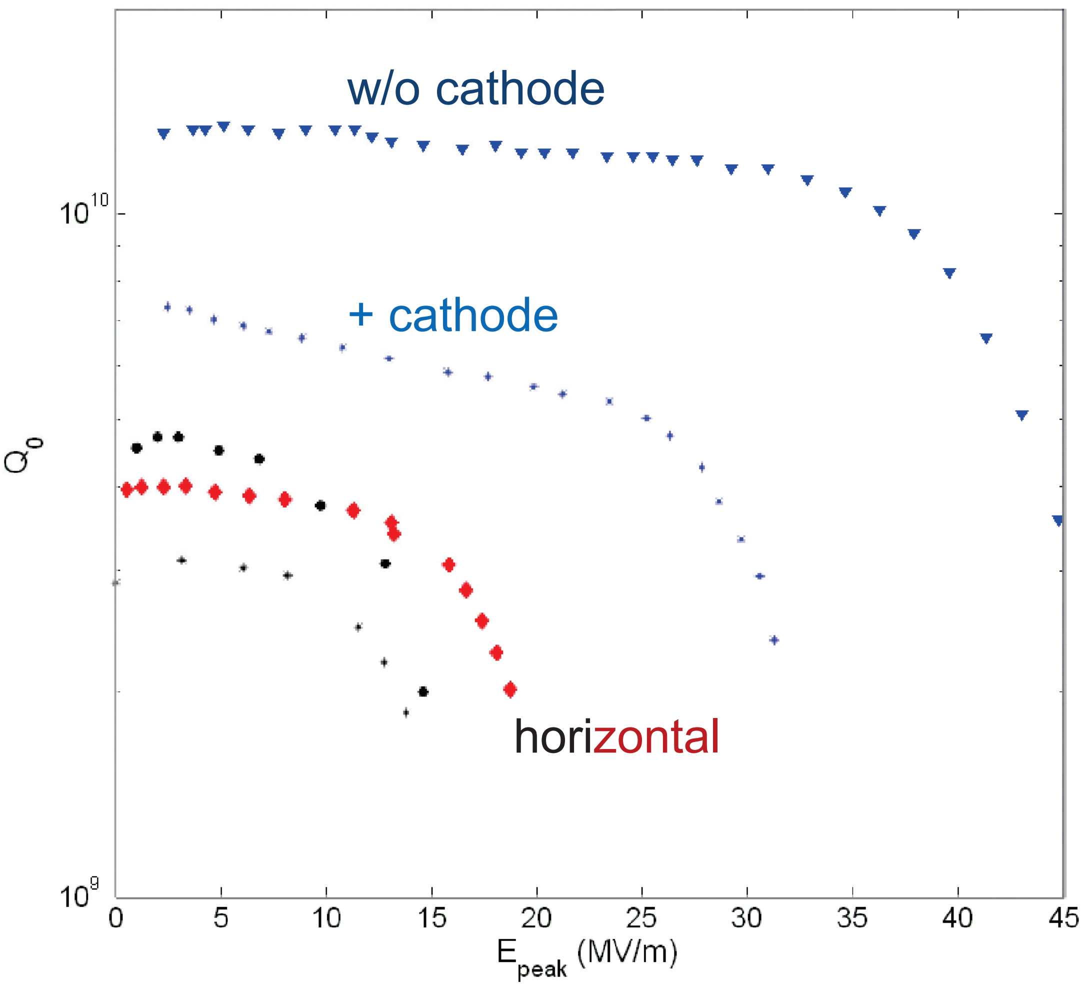

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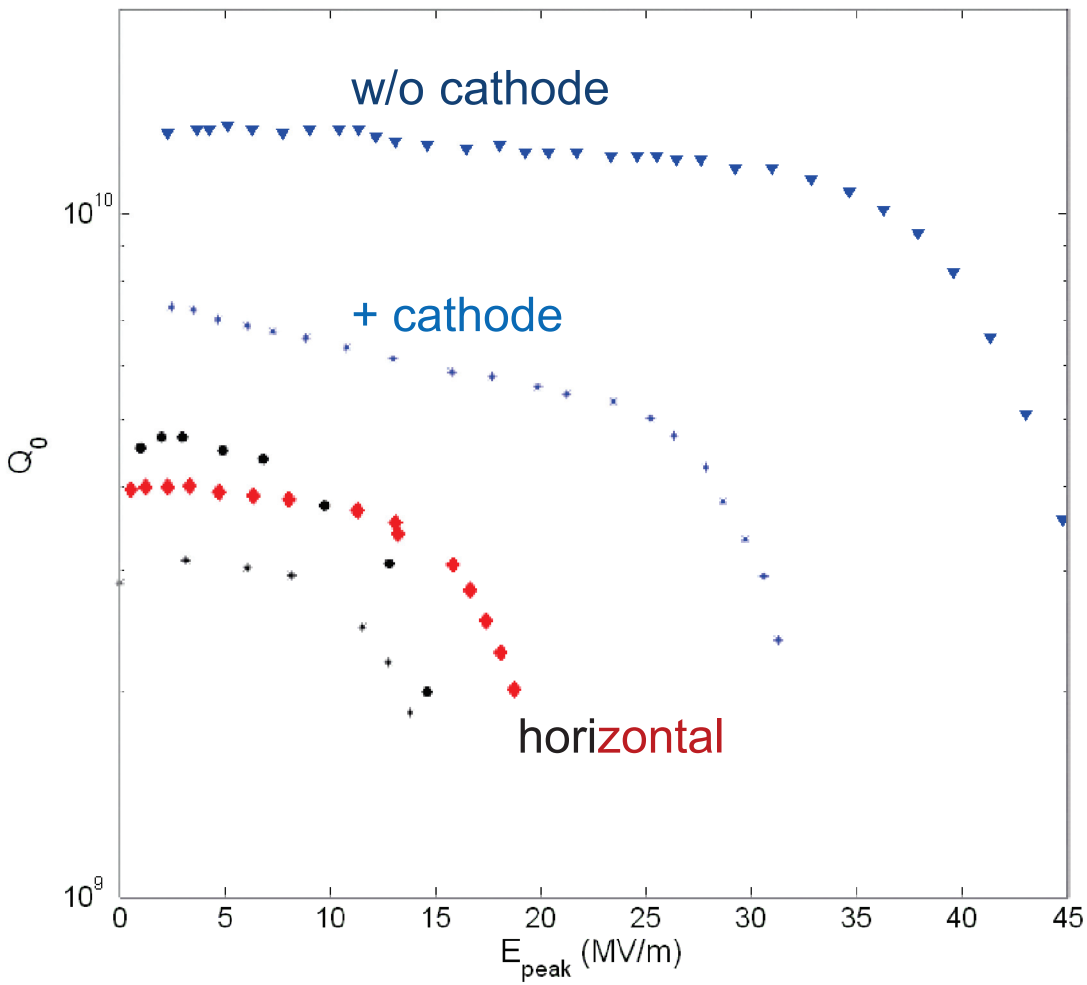

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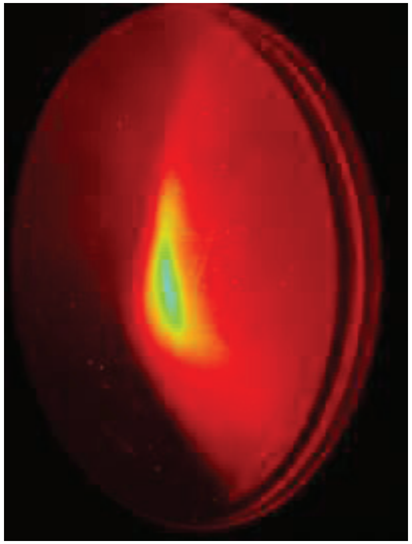
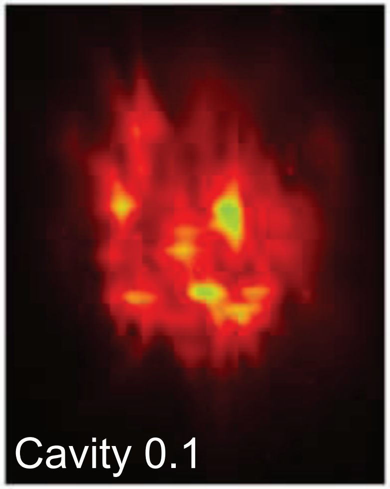
- Operation of up to 20 MV/m, E_{acc} ~ 11 MV/m possible
- Q_0 order of 4e9 unchanged within 6 months of (non-continous) operation

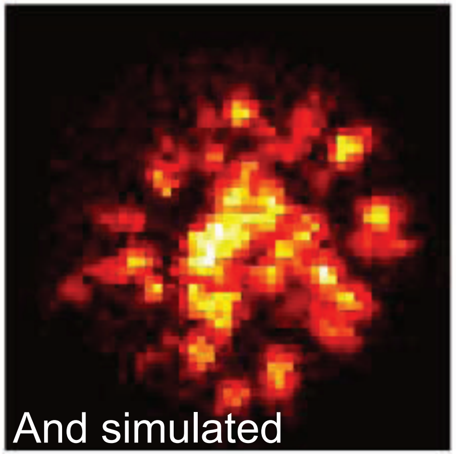
Cathode performance and quantum efficiency



Dark current at 16 MV/m focussed by SC solenoid on first YAG screen

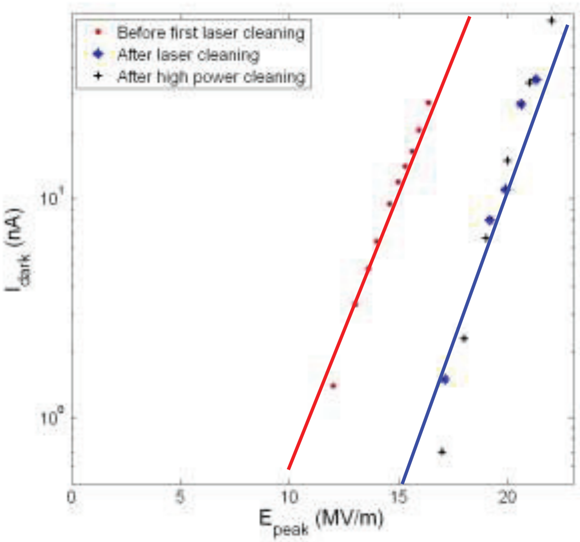
Non-isotropic emission surface

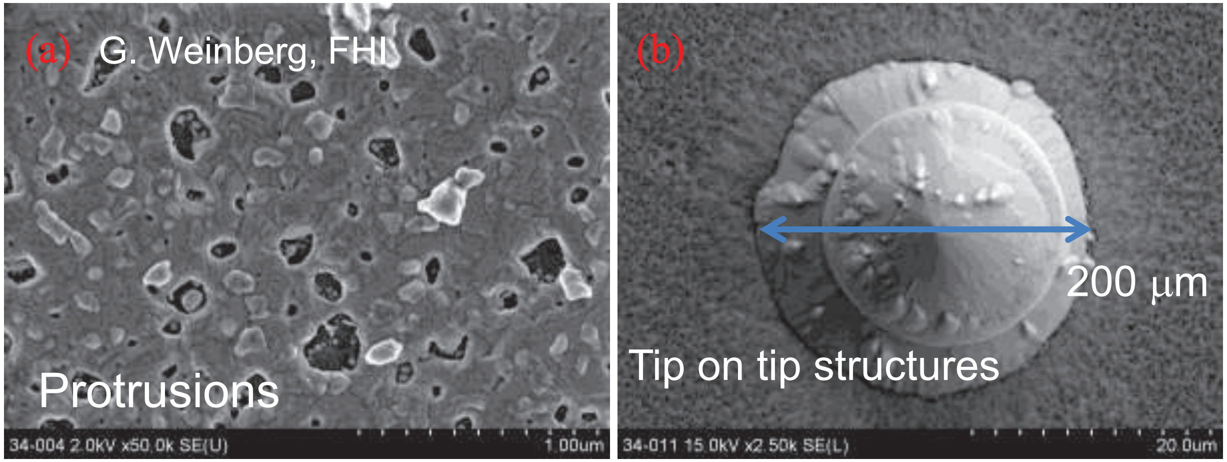




J. Völker et al., IPAC12

Rather high $\varepsilon_{n0.1}$=5.4 mm·mrad / mm laser spot size

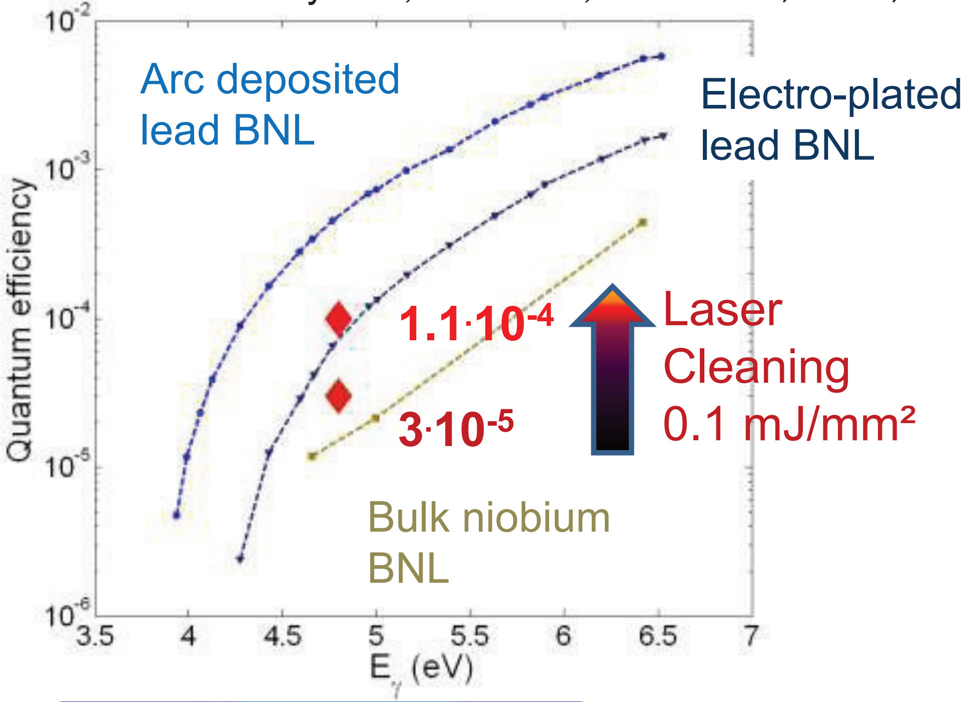




Laser cleaning by 248nm laser (0.23mJ/mm²) increased FE onset: Removed tips?

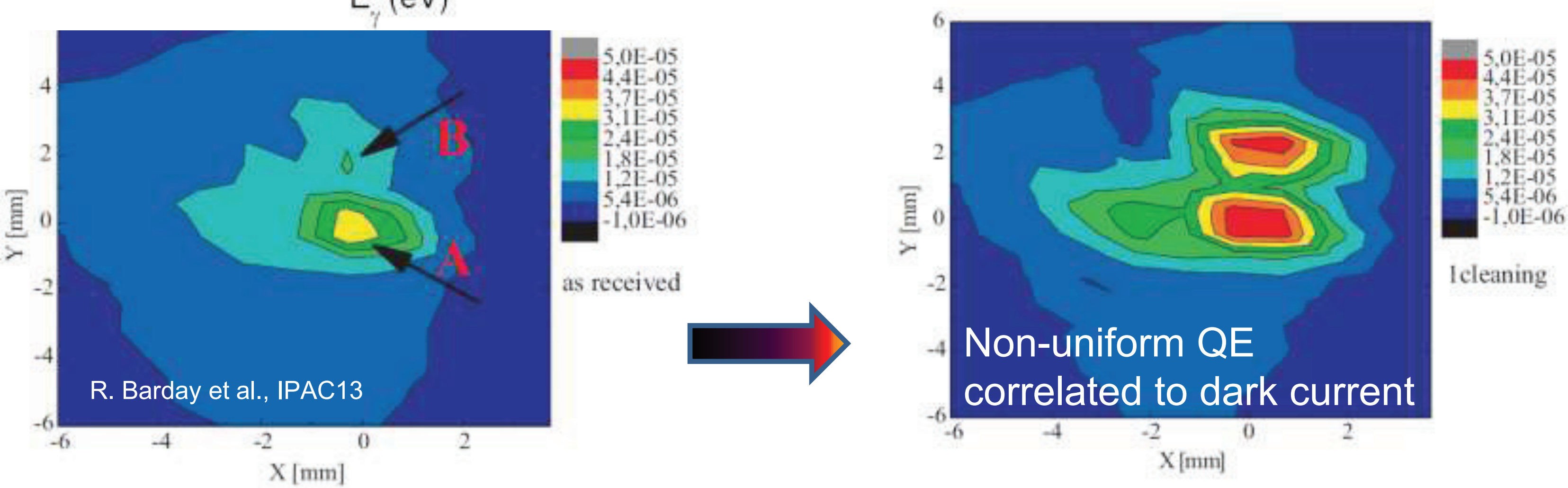
Quantum efficiency of back wall cathode (cavity 0.1)

J. Smedley *et al, PRST-AB, Volume* 11, No. 1, 2008



After laser cleaning:
QE still factor of three lower than with In laboratory prepared Arc deposited lead Samples

But still one order of magnitude higher than for Bulk niobium.



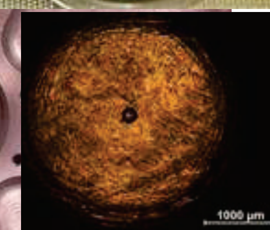
What have we learned so far?

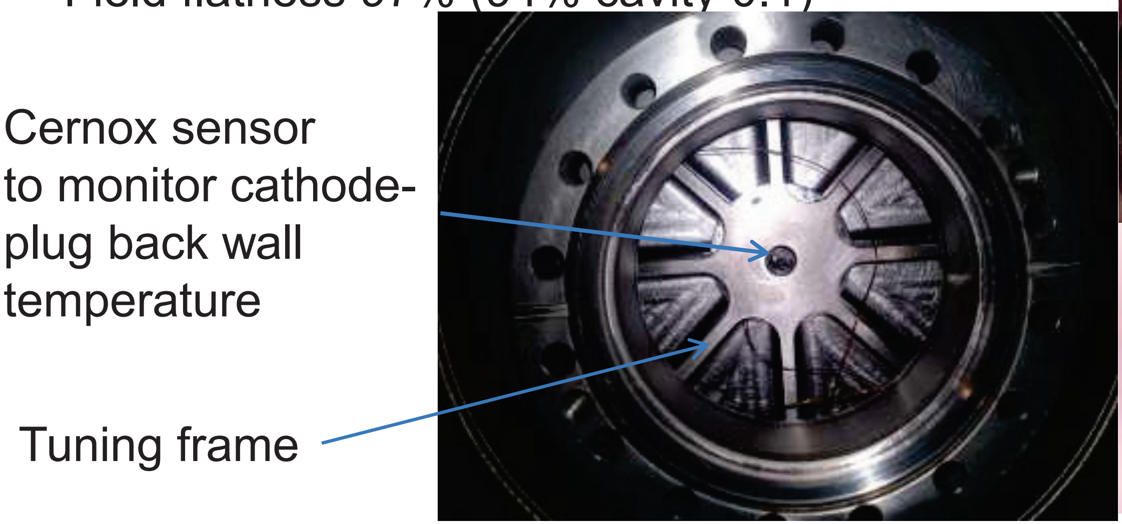
- **Pb cathodes are very robust against RF processing, field emitter processing, helium conditioning and contamination → Can be brought back to live by laser cleaning**
- **As expected, the QE is rather low, but cathode deposition with whole cavity impacts on cathode surface quality: Direct influence on:**
  - Dark current level→FE
  - Beam's normalized emittance
  - Uniformity of cathode surface
  - Achievable QE level
- **Observed strong microphonics detuning (not shown here), sometimes hard for LLRF to compensate (ponderomotive instabilites due to Lorentz force detuning)**

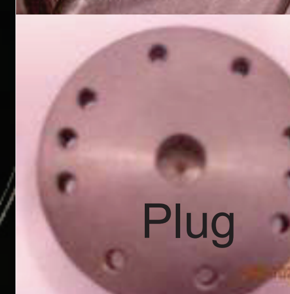
Version 0.2 of the PbNb cavity

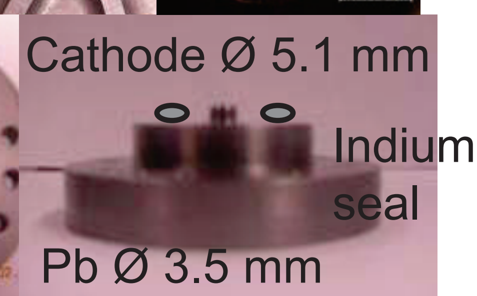
Improvements!

- “Spider” back wall stiffening replaced by rips carved out of 3mm thick Nb wall
- Opening for removable cathode plug:
  Allowed new deposition set up at Świerk with plasma arc deposition at closer distances
- Thermal and electrical contact via indium seal
- Cavity was equipped with a modified Saclay I-type tuning system with piezos→reduce detuning
- Removable helium vessel
- Field flatness 97% (94% cavity 0.1)

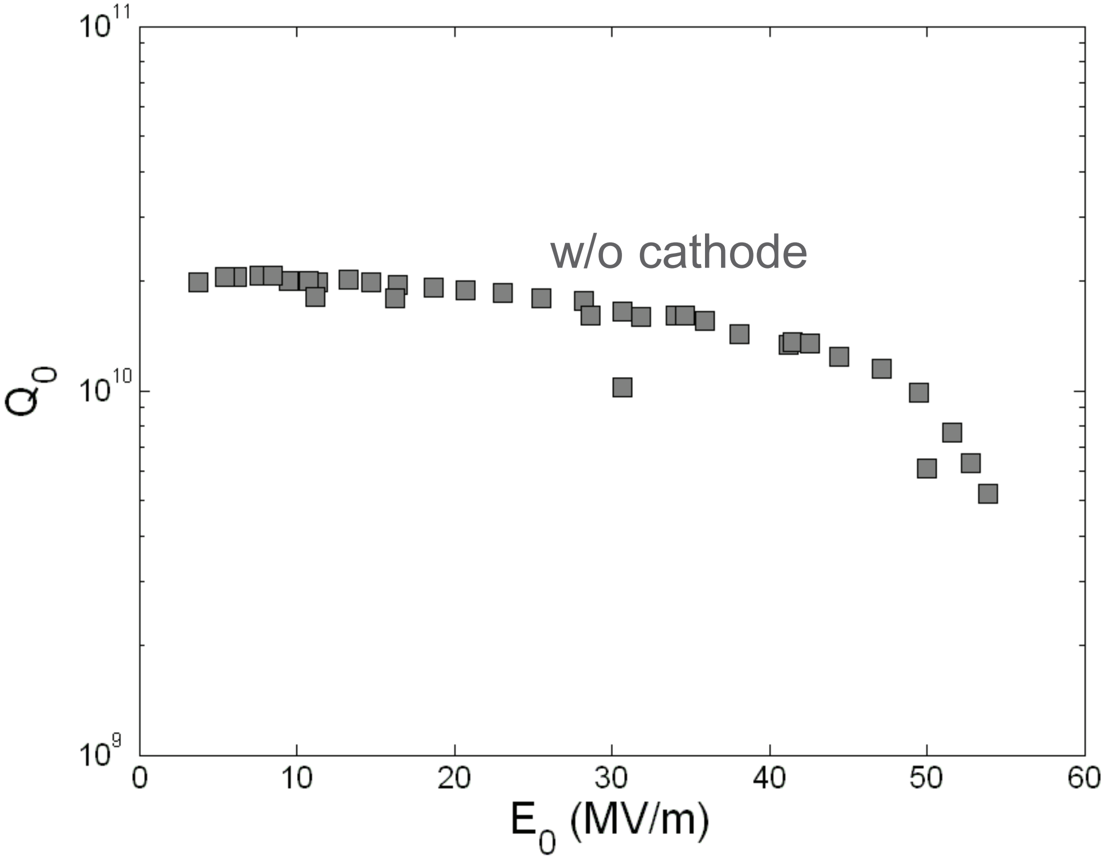








Achieved Q_0 in VTA and Horizontal set up: Cavity 0.2



- low field Q_0=2e10, $E_{0,quench}$=55 MV/m!
- After Pb cathode deposition Q_0 factor of two decreased: Contamination?
- Shipping and installation to HoBiCaT: Another factor of two decrease, R_{res}~35 nΩ, Insufficient magnetic shielding?

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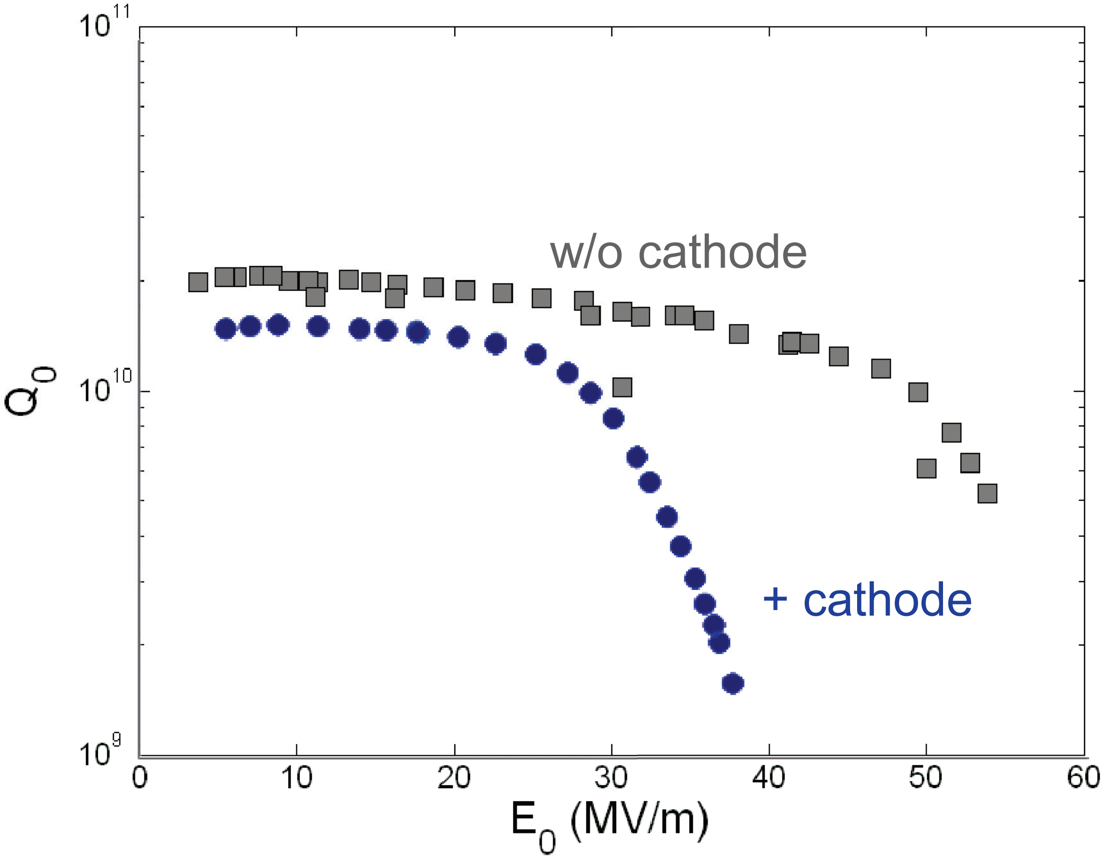

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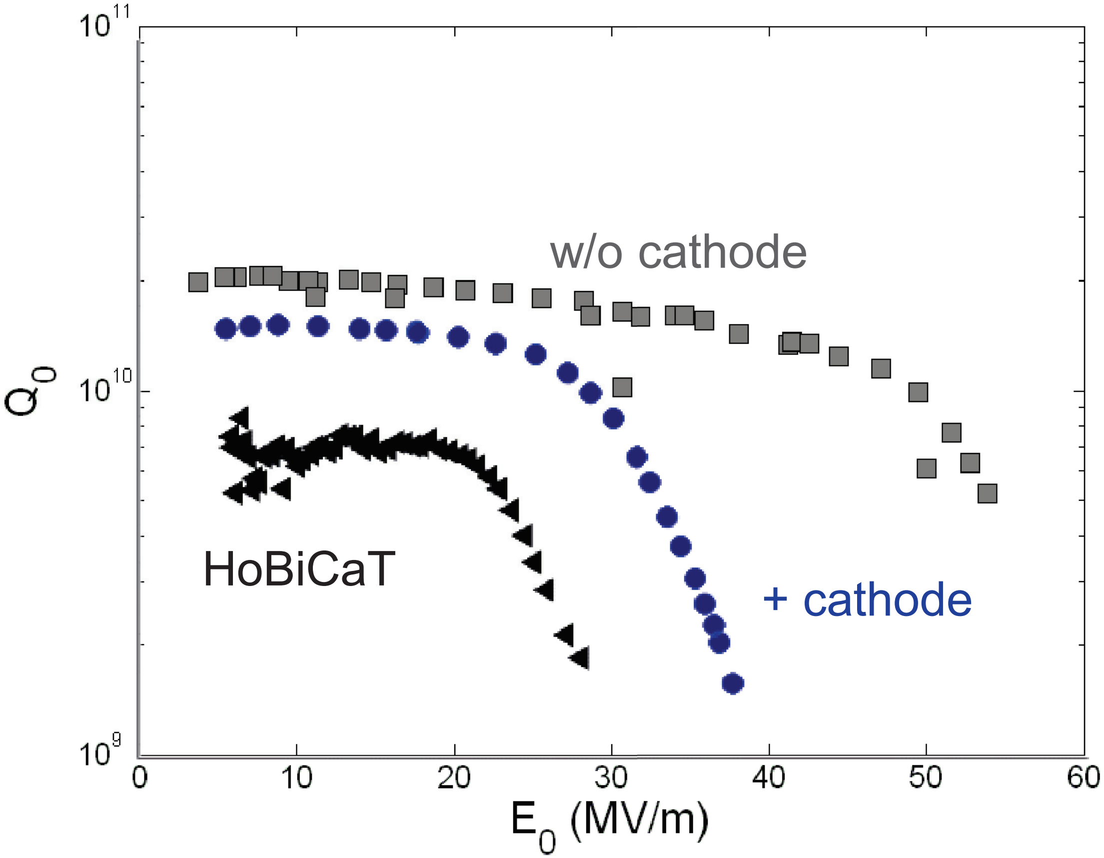

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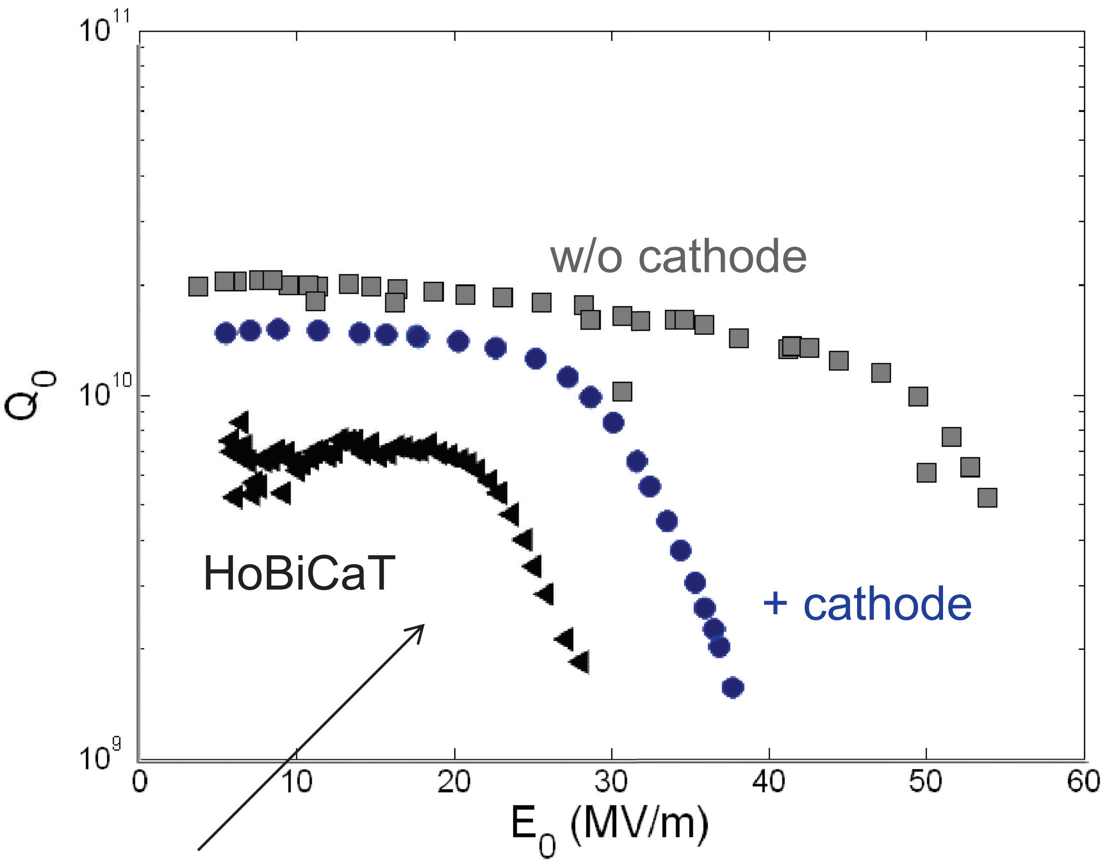

Note, calorimetric measurement

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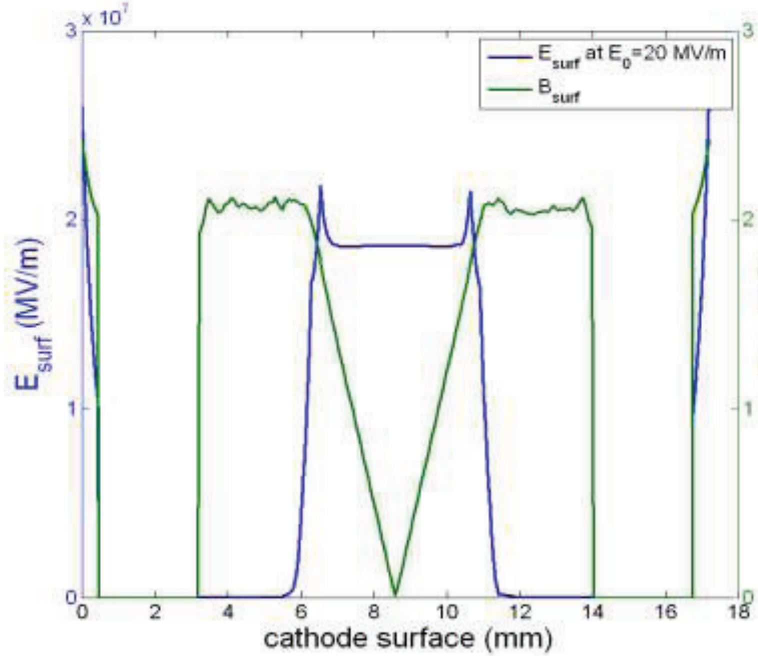
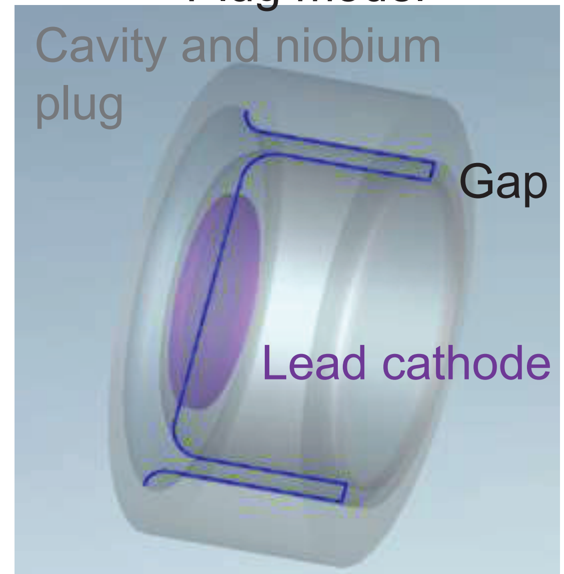
What decreased Q_0?

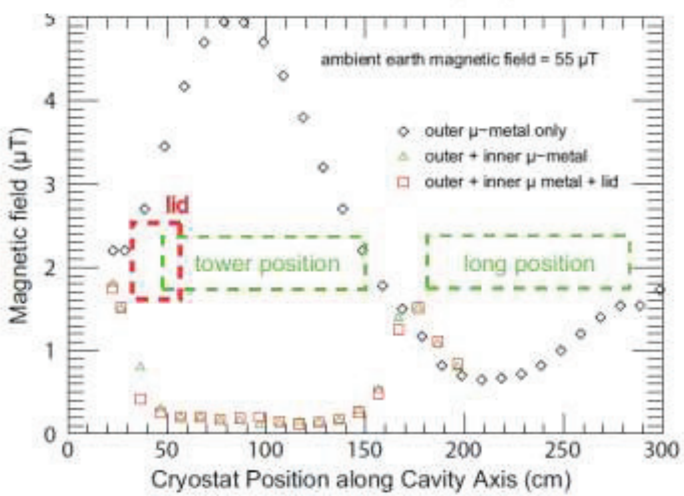
What did not cause Q_0 decrease

1. Lead deposition:



Plug model





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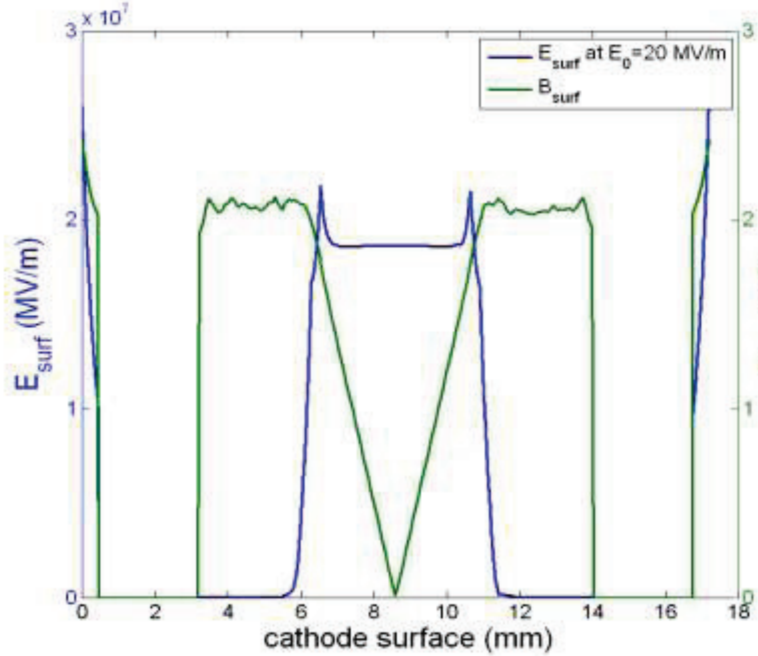

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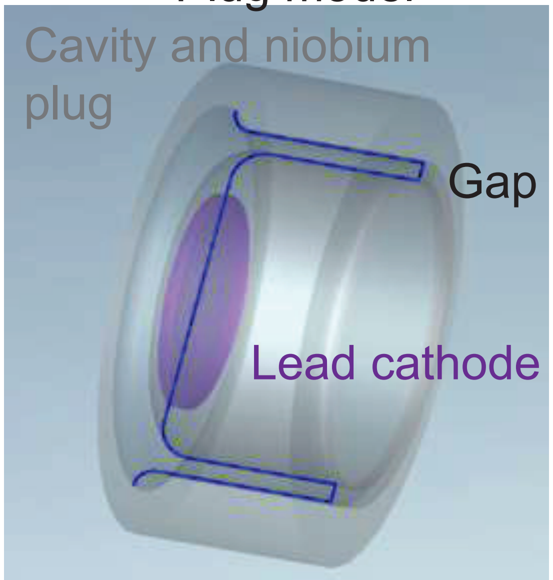

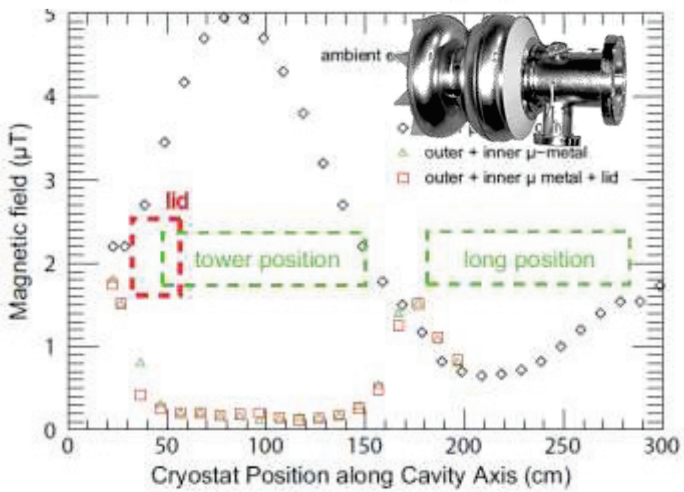

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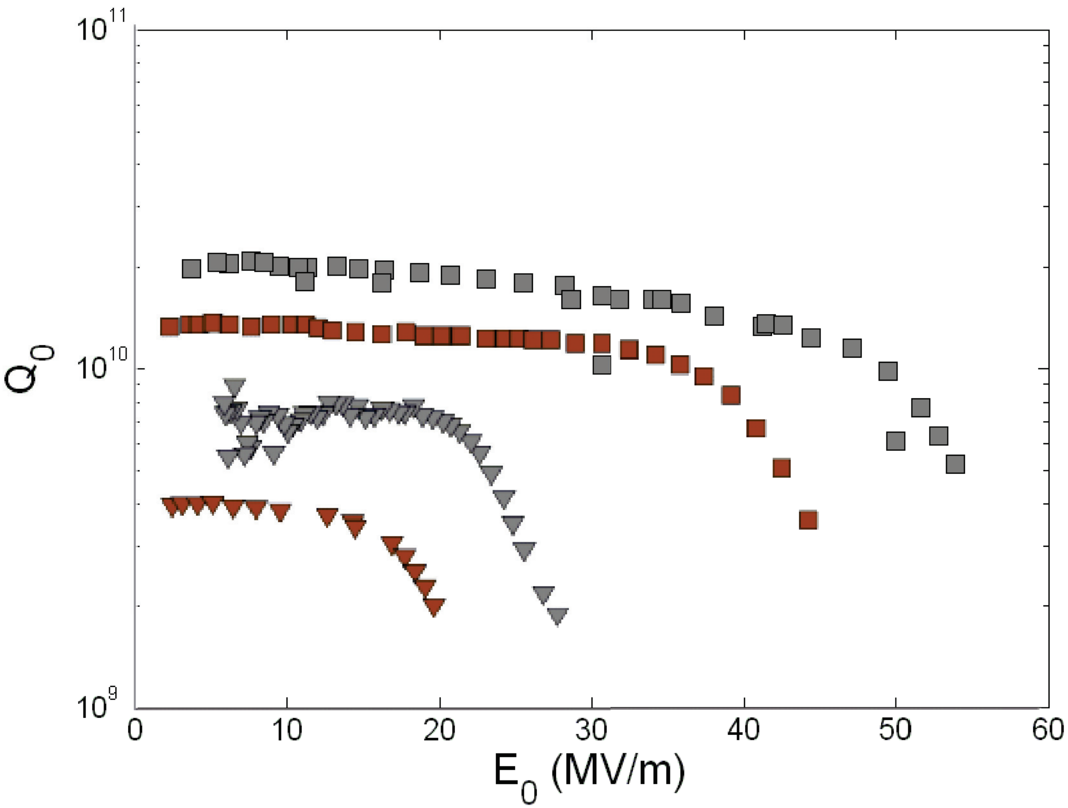
Observations with the plug design



Plug vs. back wall:
Q_0 factor 2 better
FE onset higher (25%)

- Cavity 0.1: Drop of Q_0 correlated with losses produced by field emission (FE)
- Cavity 0.2 (plug): Drop of Q_0, but FE onset much higher >24 MV/m

What causes Q_0 drop?

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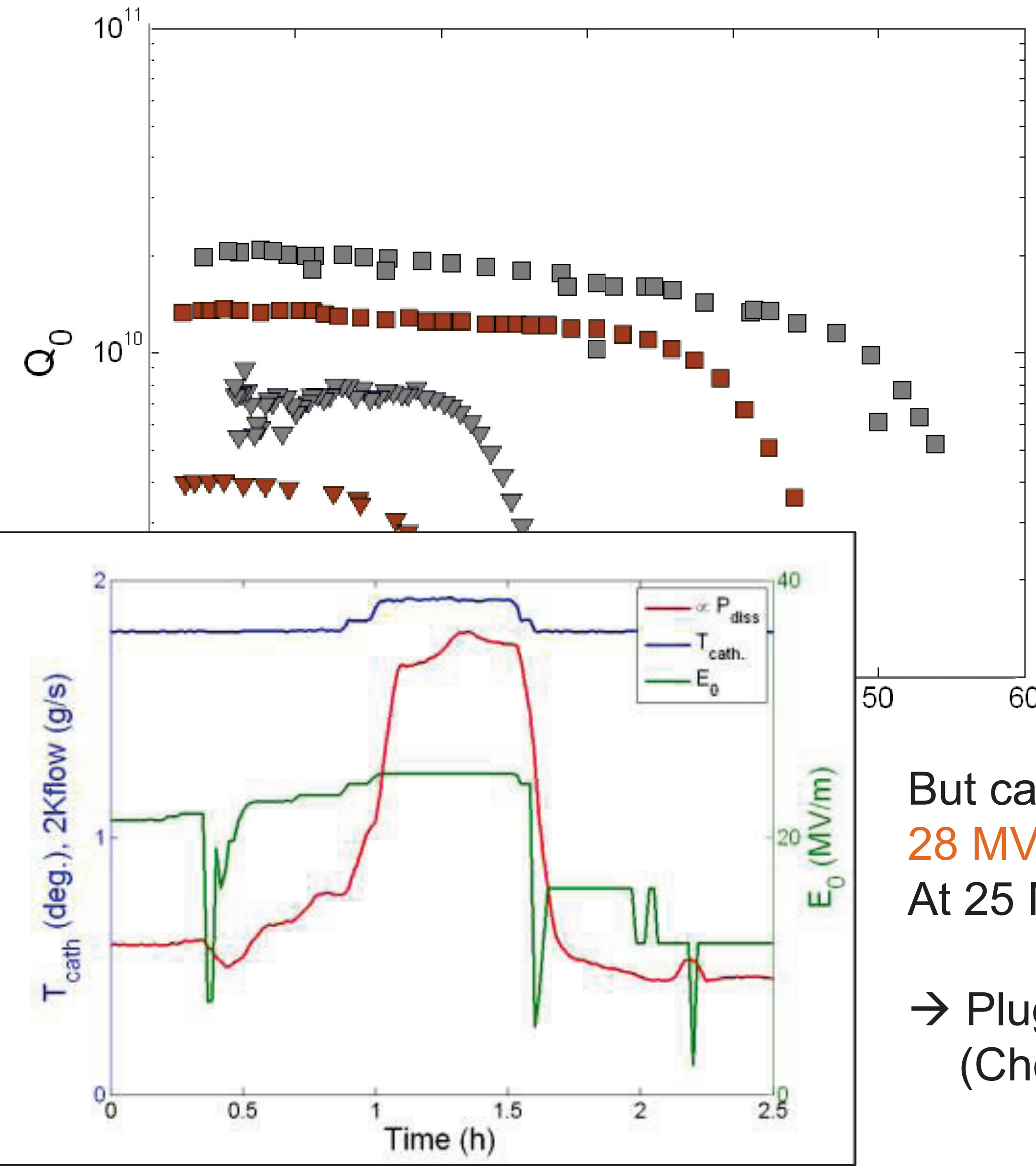

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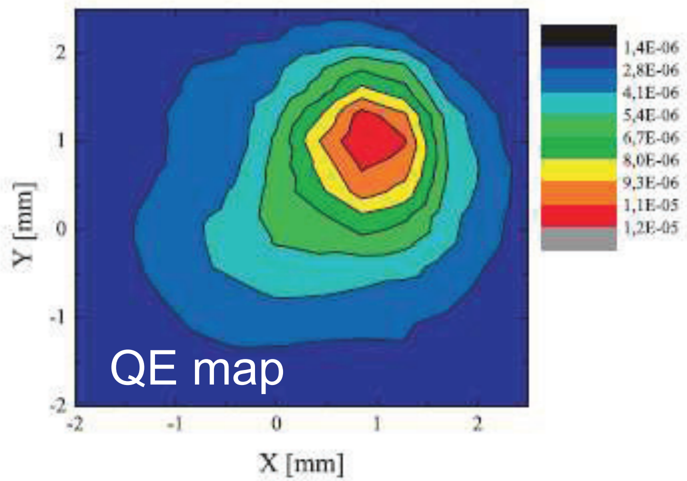
What causes Q_0 drop?

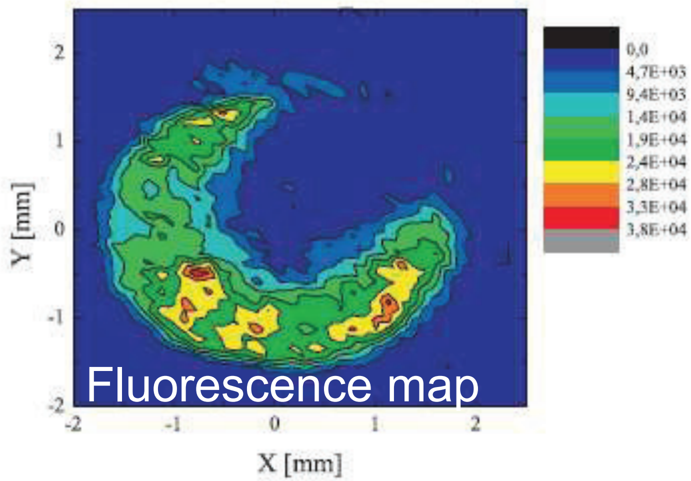
- Plug cavity had λ leak at plug location (indium seal?) → Multipacting at low fields: 3, 8 MV/m → RF processing helped, operation up to E_0=25 MV/m

But cavity quenched instantaneously at 28 MV/m
At 25 MV/m quenched after about 0.5 hours.

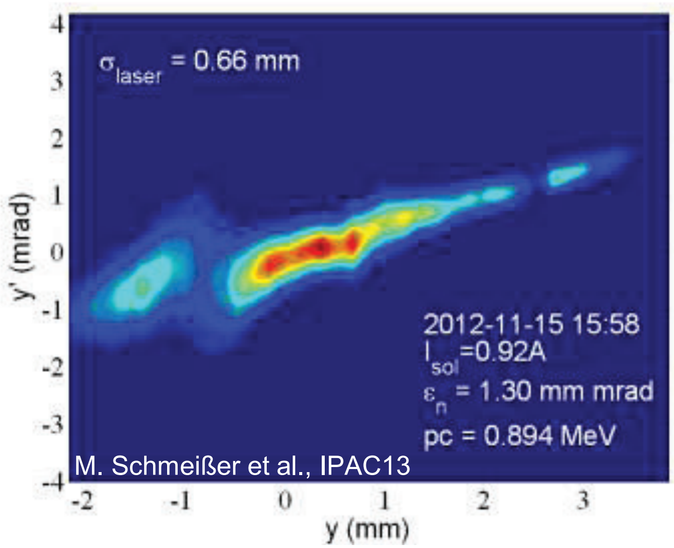
→ Plug design needs to be improved (Choke structure?)

Cathode and QE → emittance: Plug cavity





Non-uniform distribution at larger laser spot sizes hints at structured emission from hot spots



Reconstructed transverse phase space

In general the plug cathode showed more uniform surface properties coming along with a smaller normalized beam emittance:

$\varepsilon_{n0.1}$=5.4 mm·mrad > $\varepsilon_{n0.2}$=1.9 mm·mrad

Measured at low charges <1pC and short pulses thus thermal emittance by the cathode dominates

Lessons learned: Measured beam and RF parameters

Parameter	Cavity 0.1&0.2
$R/Q(\Omega)$	190
E_{peak}/E_0	1.2
$E_{cathode}/E_0$	1.0
B_{peak}/E_{peak} (mT/(MV/m))	4.4
$\Phi_{launch}(E_{kin,max})$ (deg.)	15
E_{launch} (MV/m)	5&7
E_{kin} (MeV)	1.8&2.5
k_{cc} (%)	1.47
Q_{ext}	$6.6 \cdot 10^6$
$f_{1/2}$(Hz)	98
$P_{forward}$ (kW)	≤ 2
Δf_{peak} (Hz)	20-40

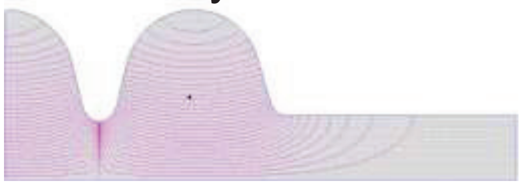
Parameter	0.1	0.2
Cathode type	Pb back wall	Pb plug
Cathode QE_{max}	$1 \cdot 10^{-4}$	$1 \cdot 10^{-5}$
E_0max.	20 MV/m	27 MV/m
E_{launch}	5 MV/m	7 MV/m
E_{kin} at max. E_0	1.8 MeV	2.5 MeV
Bunch charge	6 pC	187 fC
Emission time	2-4 ps	2.5-3 ps
Average current	@8 kHz 50 nA	1.5 nA
Normalized emittance/mm laser spot size	5.4 mm mrad	1.9 mm mrad

- Lead photo cathodes are very robust against against contaminations and processing of field emitters, the plug system was a clear improvement
- **SC PbNb** injector cavities are very promising candidates for low avg. current CW driven Free Electron Laser (Potentially µA regime)
- The key is the preparation of the cathode, for low emittance (+ low dark current) a uniform and smooth surface is mandatory
- For B*ERL*inPro (besides high avg. current) we aim for a higher launch field and a low roughness cathode surface will be the main challenge

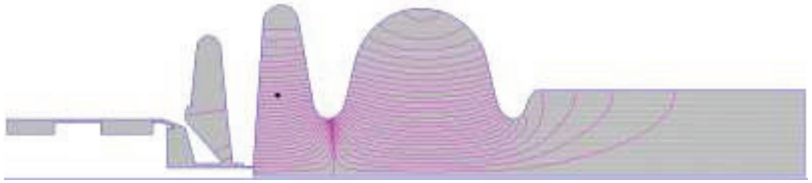
Operating parameters of first injector

Parameter	Cavity 1.1
$R/Q(\Omega)$	150-149.5
E_{peak}/E_0	1.5-1.45
$E_{cathode}/E_0$	1-0.58
B_{peak}/E_{peak} (mT/(MV/m))	2.2
$\Phi_{launch}(E_{kin,max})$ (deg.)	60-50
E_{launch} (MV/m)	26-13.3
E_{kin} (MeV)	2.6
k_{cc} (%)	1.6
Q_{ext}	$3.6 \cdot 10^6$
$f_{1/2}$(Hz)	185
$P_{forward}$ (kW)	8.4
$\Delta f/\Delta P_{LHe}$ (Hz/mbar)	10 (expected)
I_{avg} (mA)	4
Q_b (pC)	77

Cavity 0.x: 1.6cell



Cavity 1.1: 1.4cell

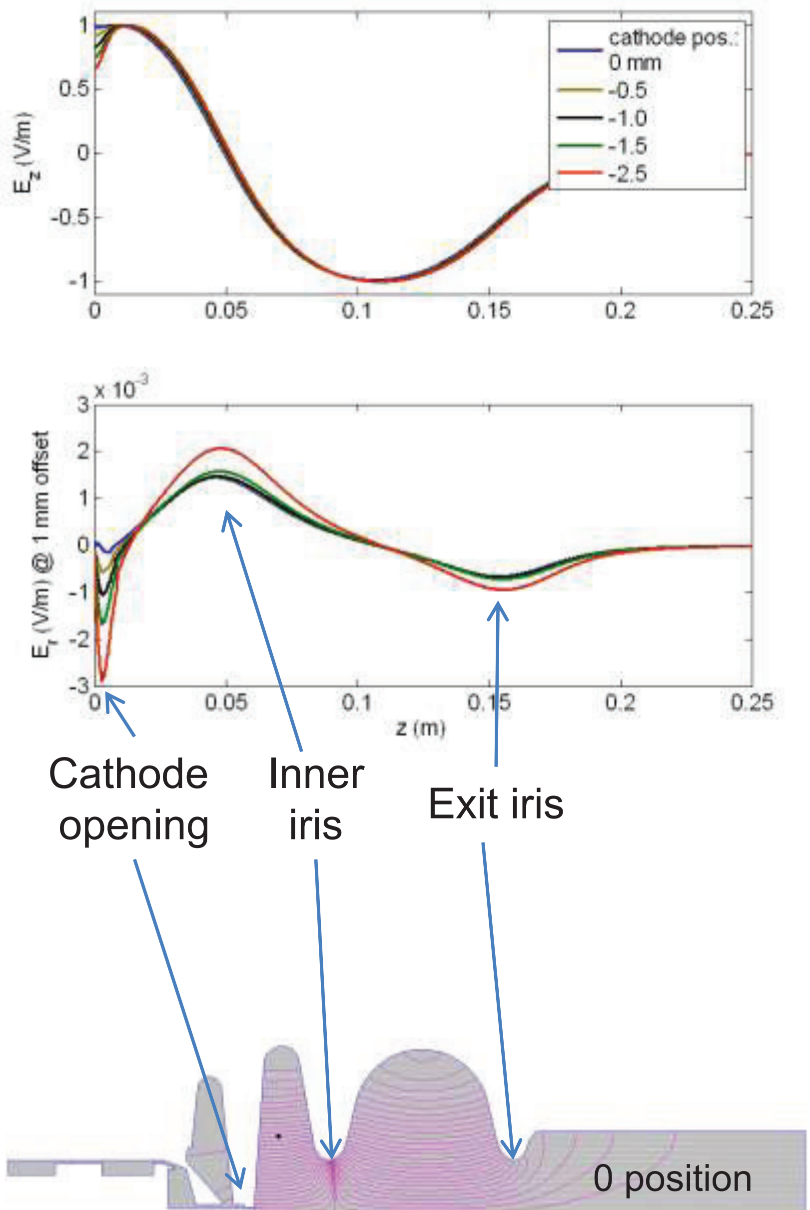


Double couplers to minimize kicks

Expected performance for cathode positions from 0 to 2.5 mm retraction at E_0=30 MV/m

*measured with Gun0: A. Neumann, Proc. of SRF 2011

RF field properties



Retraction of the cathode (0 – 2.5 mm) allows for stronger RF focusing of the beam during extraction by the laser pulse:

- Slight decrease of the normalized shunt imp.: $\Delta(R/Q)/R/Q < 1\%$

- Decreases ratio cathode field to maximum on-axis field: 1 - 0.58

- Further: The launch phase for maximum energy gain is lowered by 10 degrees: →

Reduction of effective launch field by 49%, but dark current emitted from the cathode reduces 1/8 (Fowler-Nordheim equation, β_N=1)

Overview: Injector Cavity 1

0.4·λ cell + full cell:
Optimized
emission phase

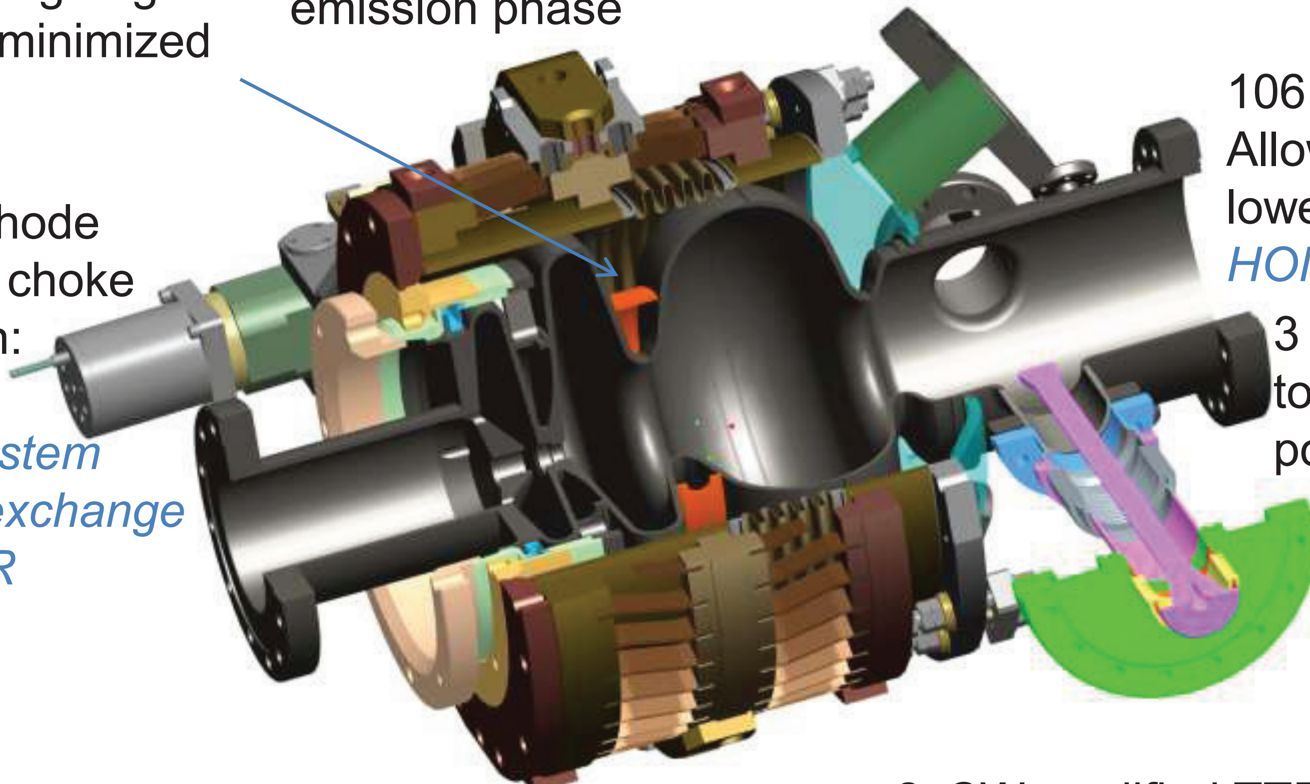
Chimney 22 cm²~35 W at 1.8 K
about E_{peak}=45 MV/m at $Q_0=3.5 \cdot 10^9$

Stiffening ring:
Δf/ΔP minimized

106 mm beam tube:
Allows propagation of
lowest TM_{110} mode:
HOM studies

HZDR cathode
insert and choke
cell design:

Proven system
Cathode exchange
with HZDR



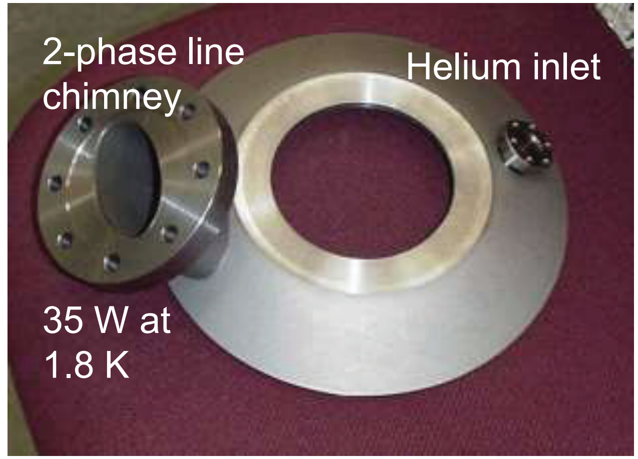
3 pick-up antennas
to measure HOM
polarization

Blade tuner with
motor and piezo tuner:
Microphonics compensation

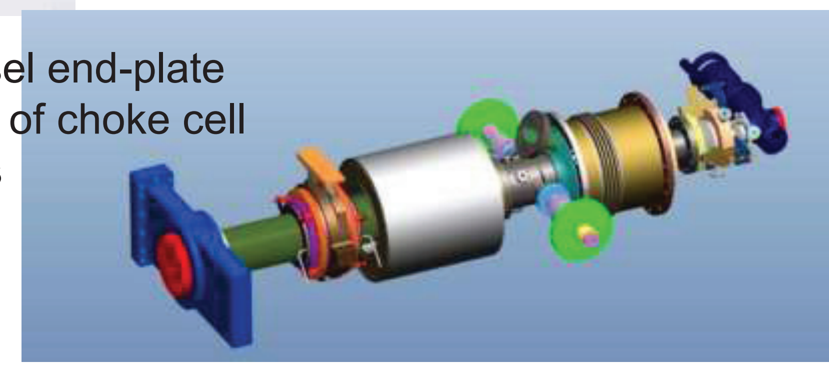
2xCW modified TTF-III
Coupler: Q_{ext} $3.6 \cdot 10^6$
for up to I_{avg}=4 mA,
10 kW each
Study 2 coupler operation

Production at JLab: Cavity parts before welding

Stacked Cavity with beam tube



Top: Helium vessel end-plate
Below: Back wall of choke cell
Right: Cold mass



- The cavity is being fabricated, processed and vertically tested at JLab. The cold mass including a SC solenoid and a beam tube HOM absorber is assembled at JLab as well.
- First horizontal tests, module mounting and first beam tests will be done at HZB

Pictures courtesy of P. Kneisel and G. Ciovati (JLab)

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PbNb hybrid Cavity

1st *BERL*inPro Injector Cavity