A high-brightness SRF photo injector for FEL light sources

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for the BESSY, DESY, MBI, FZD collaboration

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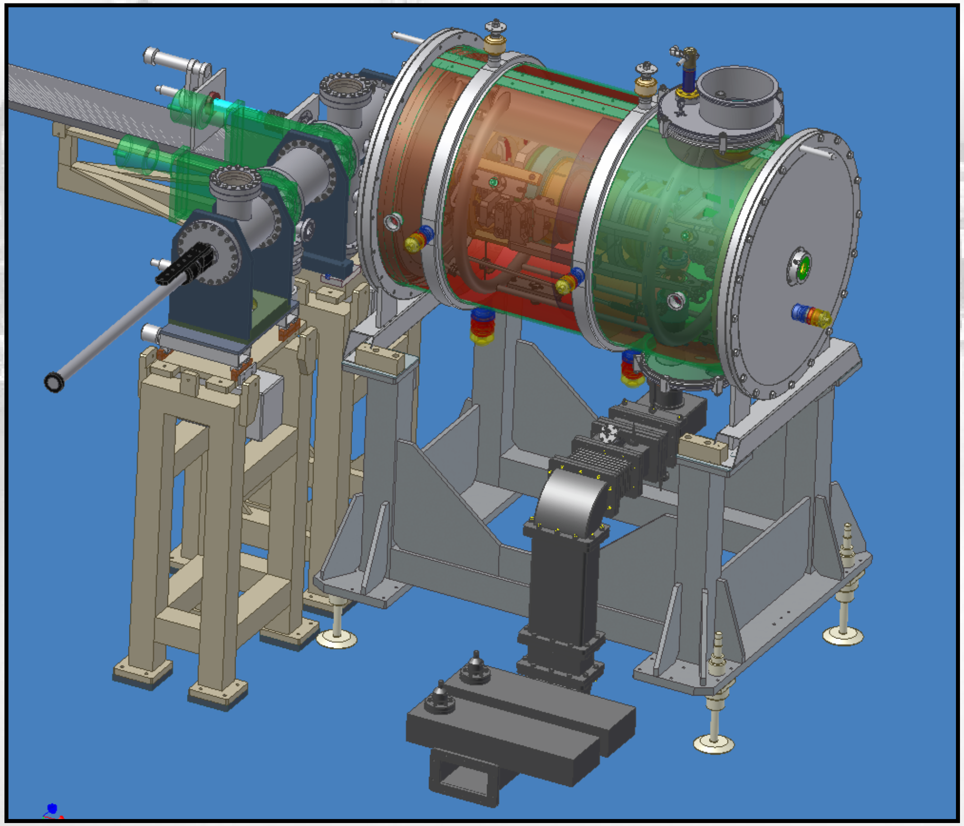
Outline

- Motivation for SRF Gun Development
- Overview on the 3 Advanced SRF Gun Projects beside FZD Project
- FZD 3.5 Cell SRF-Gun
  - Application & Parameters
  - Emittance Compensation
  - Photocathode
  - Laser & Diagnostic Beamline
  - Niobium Cavity Treatment & Test
  - Cryomodule– Assembly
  - 1st Test Results
- Summary

Dresden Rossendorf SRF – Gun



Introduction – Superconducting RF Photoinjector

Motivation to develop SRF electron guns

- High bunch charge (up to some nC) due to usage of photo cathodes
- Low emittance like NC RF Gun due to high accelerating gradient
- High brightness beam due to high average current of CW Operation
- Excellent thermal stability due to low power dissipation and @ CW

Challenges are

- Different SC gun cavity design (mechanical properties, multipacting barriers)
- Choice of photo cathodes, with respect to QE, life time & risk of contamination
- Emittance compensation more complicated and needs more novel approaches
- Coupling of high average power to cavity up to 1MW (BNL, ERL application)

In combination with SRF linacs, the SRF guns will be the best solution for high average currents!

Overview on the 4 Advanced SRF Gun Projects

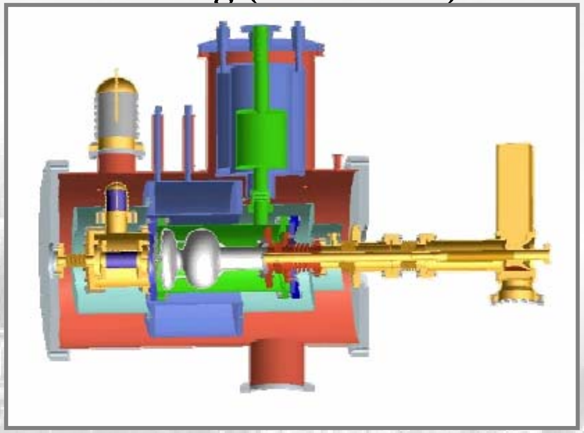
BNL / JLAB / DESY (since 2002)

Courtesy of Triveni Rao

f =1.3 GHz

Nb/Pb ◄ E_{RF}

IHIP Peking (since 2001)

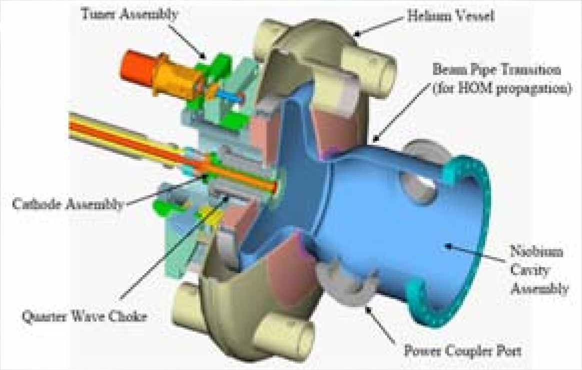


Courtesy of Hao Jiankui

f =1.3 GHz

Cs_2Te ◄ E_{DC}

BNL/AES (since 2004)

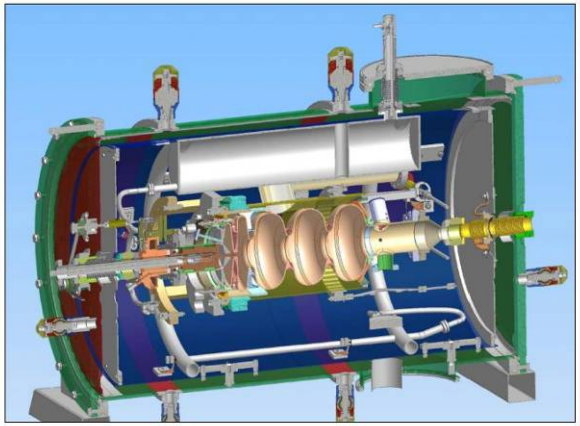


Courtesy of Alan Todd

f =703.75 MHz

Alkali+♦ ◄ E_{RF}

FZD (since 1998)



Courtesy of Dietmar Janssen

f =1.3 GHz

Cs_2Te ◄ E_{RF}

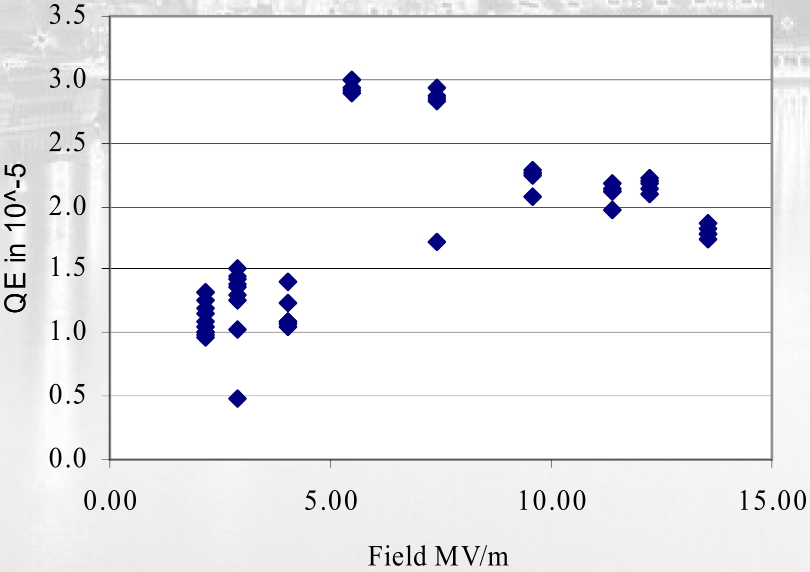
BNL / JLAB / DESY (Nb/Pb) since 2002

Nb/Pb SRF gun

- Beam generation from a superconducting cathode
- Simple integration of the cathode into superconducting environment (without choke, no contamination risk)
- 2 half cell niobium 1.3GHz cavities built for RF & QE measurements of cold Nb

T ~ 2K
λ = 248 nm, QE ~ 2×10^{-5}
λ = 266 nm, QE ~ 2×10^{-6}

T.Rao et al. PAC2005, Knoxville, May 2005.



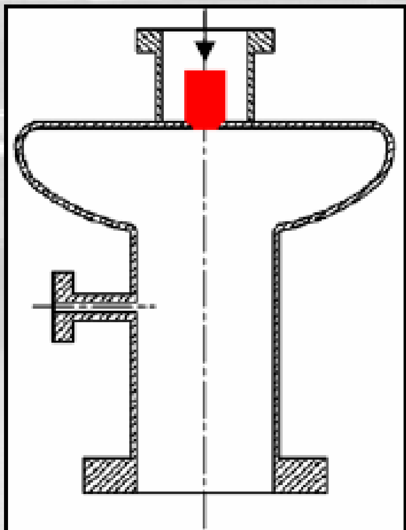
- QE too low (needed Laser Power for 1 mA beam current (1 nC @ 1 MHz) >100W)
  → another superconductor with higher QE

BNL / JLAB / DESY (Nb/Pb)

- Lead is used for SC cathodes (Tc = 7.2 K , Bc = 70 mT)

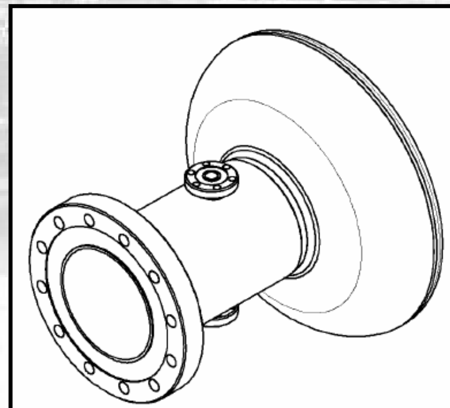
Plug Gun (Jlab)

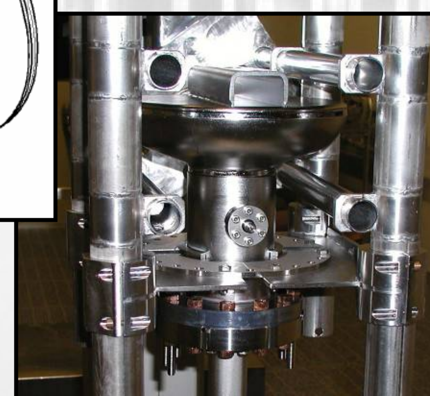
- 1.42 GHz niobium cavity
- Removable electro plated lead plug
- Possibility of testing other materials (YBCO, MgB2, Pb-Sn…)



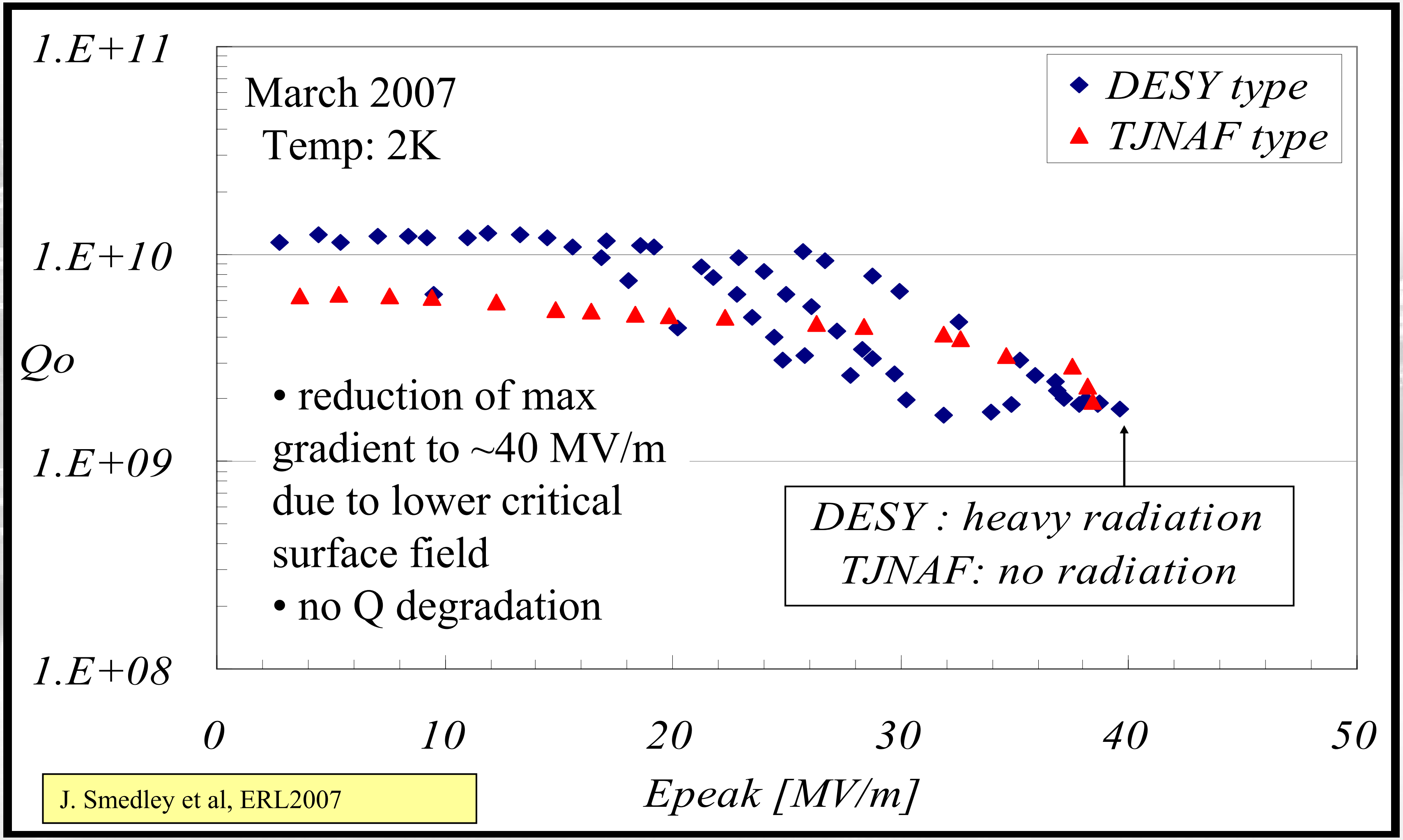
DESY Gun

- 1.3 GHz all niobium cavity
- Arc deposited spot of lead @ cavity back wall



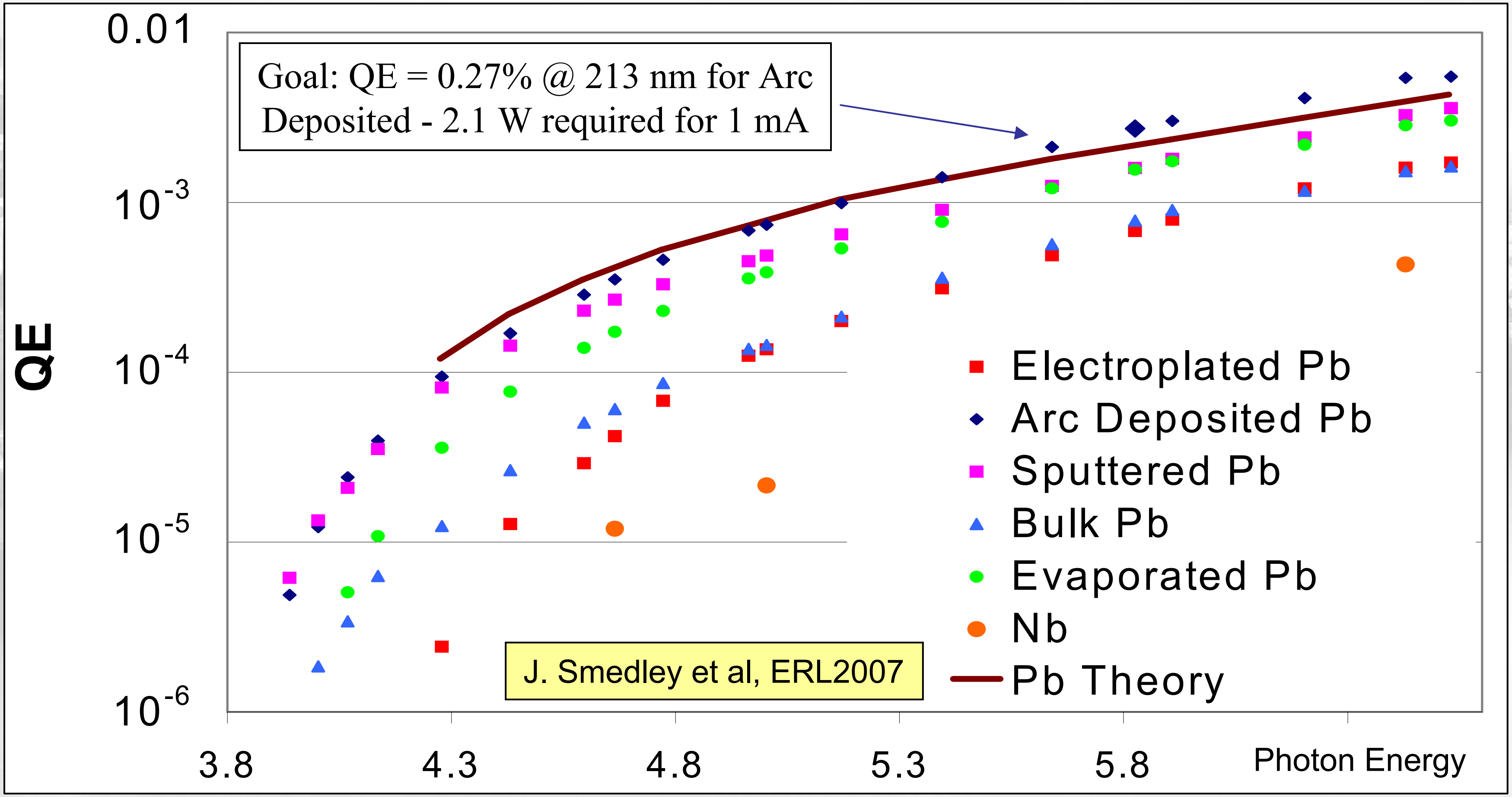


BNL / JLAB / DESY (Nb/Pb)



BNL / JLAB / DESY (Nb/Pb)

- QE measurements at room temp. & DC voltage done to find best preparation method



BNL / JLAB / DESY (Nb/Pb)

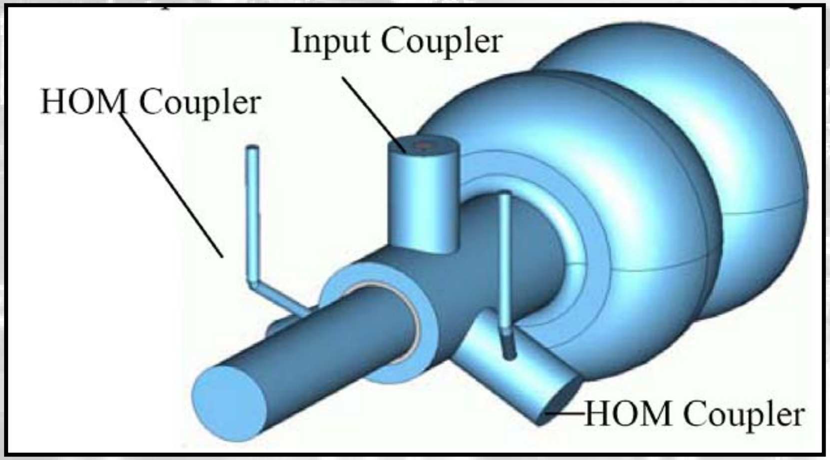
- QE measurements at room temp. & DC voltage done to find best preparation method
- For 1 mA average current ~2 W at 213 nm is needed
- Such lasers (rep. rate up to 1 Mhz) are challenging, but not impossible
- Cryogenic QE measurement for verification DC RT values
  - Plug Gun (~1.5×10^{-4} @ 248 nm) → OK
  - DESY Gun (~1.5×10^{-4} @ 248 nm) → below DC RT value (imperfect lead coverage)
- Attempted to quench the cavity by irradiating back wall with excimer laser to break the cooper pairs
  - @ low rep. rates, modest Q reduction → Cooper pairs are recovering between pulses
  - expected recovery time from theory <1 µs → 1 MHz operation feasible
  - next tests @ high rep. rates

For moderate average currents (~1 mA), lead plated cathodes may be an attractive alternative to more complicated options (e.g. choke joint, cathode heat load)

BNL / JLAB / DESY (Nb/Pb)

New design of Nb-Pb SRF-Gun (proposed by Jacek Sekutowicz)

- 1.6 cell bulk niobium low loss cavity
- ∅ 4mm lead spot center of the back wall



Parameter	Unit	Value
π-mode frequency	[MHz]	1300
Nominal E_{cath} at cathode	[MV/m]	60
Energy stored at nominal E_{cath}	[J]	20
Nominal beam energy	[MeV]	6
Normalized emittance (rms)	[µrad]	1
Charge	[nC]	0.5-1
Rep. rate	[Mhz]	0.5-1
Average Current	[mA]	1

- Two 1.6-cell (Tesla shape) in preparation:
  - to establish reproducible process for the arc coating on plugs and back walls
  - to improve cavity performance (~50 MV/m peak field with no radiation)

IHIP Peking (since 2001)

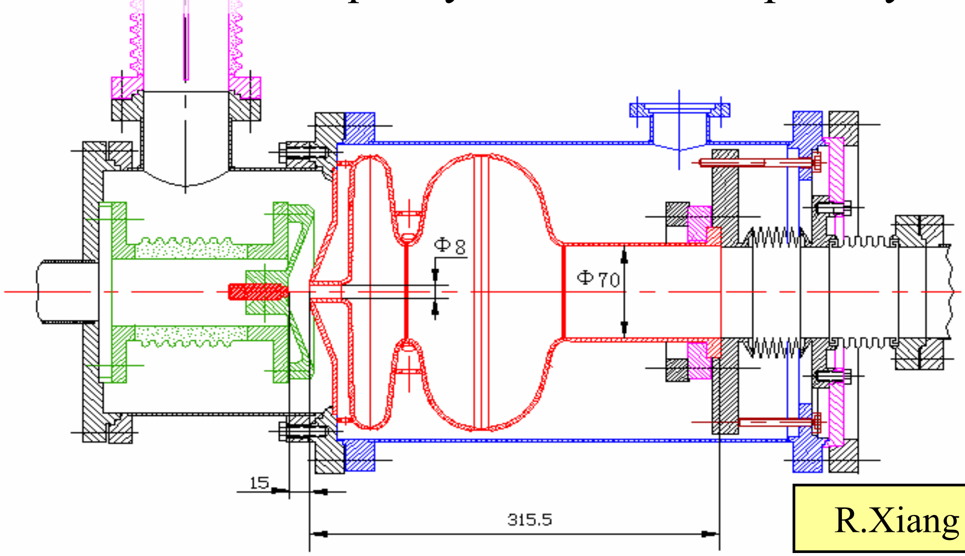
DC-SC Photoinjector for PKU-FEL

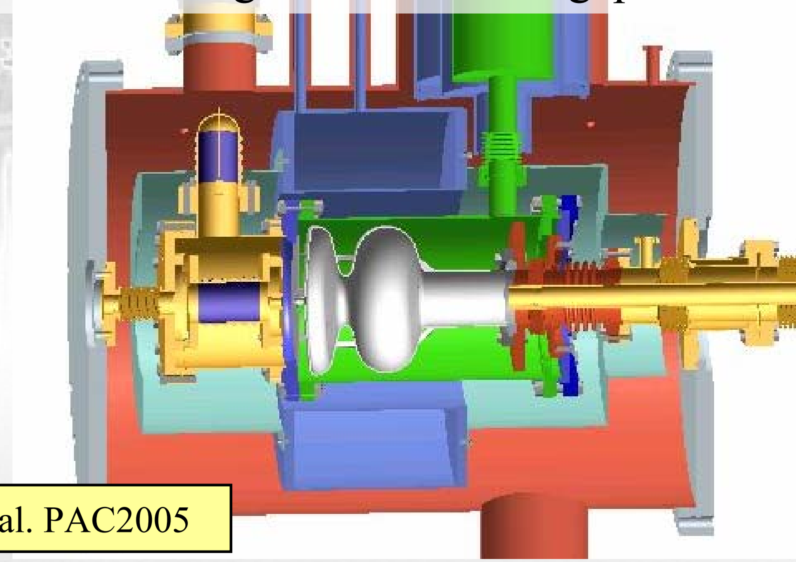
Specification: 3µrad @ 60pC, 1-5mA @ 81.25 MHz rep. rate

- 1+½ cell SC cavity with conical back wall (RRR=250) @ 1.3 GHz (4.5kW CW)
- DC Pierce Gun with photocathode (voltage extraction gap of -100kV)
- Cs_2Te Photocathode (QE≈1% @ λ=266 nm) – Laser: P≈2W

→ NC cathode placed outside SC cavity (no RF losses, no dark current by RF field , no choke, lower contamination risk)

→ Lower beam quality due to the comparably weak accelerating field in the DC gap





R.Xiang et al. PAC2005

DC-SC Gun - IHIP Peking

- Jan. 2003 DC-SC photo injector test facility → Start beam loading test in 2004

DC-SC Gun - IHIP Peking

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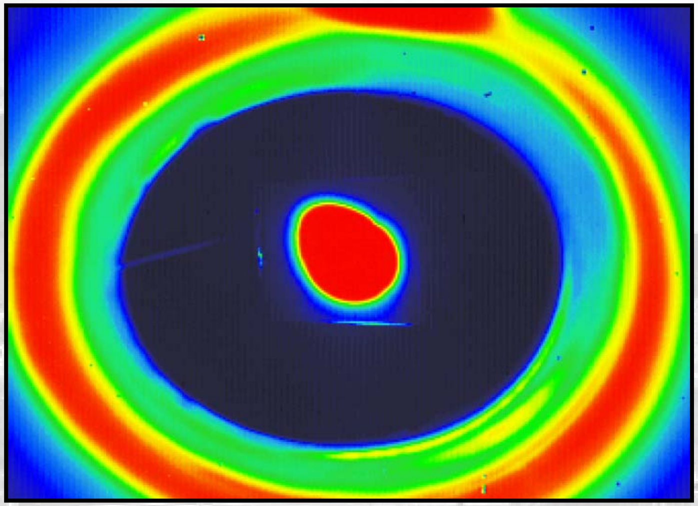


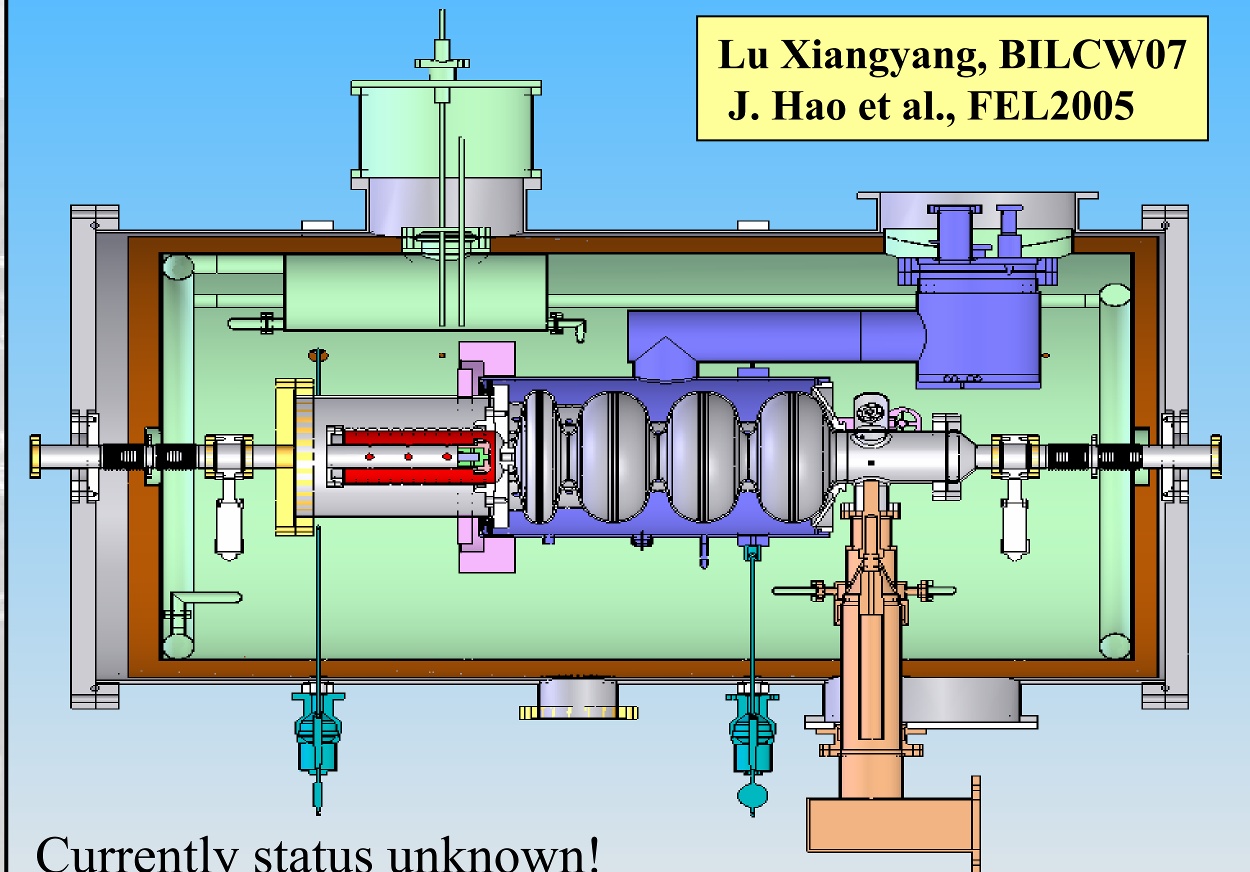
Kui Zhao et al. APAC2004 &
Kui Zhao et al. FEL2005

Parameter	Unit	Simulation (2K)	Measurement (@4.2K)
Accelerating Field	MV/m	15	6
Unloaded Q		10^{10}	10^{8}
Nominal beam energy	[MeV]	2.6	0.5 (max 1.1)
Average Current	[mA]	1-5	0.27
Charge	[pC]	60	3
Energy Spread (rms)	keV	30	35keV @ 500 keV 70keV @ 1 MeV
Trans. emittance (rms, n)	[µrad]	3 @ 60pC	5.4 @ 3pC 2.8 @ 1pC
Rep. rate	[Mhz]	81.25	81.25
Laser Spot Size	[mm]	2.8	6
DC voltage Gap	[kV]	100	40

The beam loading test proved the feasibility of the injector but an upgrade is needed to fulfill the requirements of PKU-FEL.

DC-SC Gun - IHIP Peking

New Design of the improved 3+½ DC-SC photo injector (one of different existing designs)



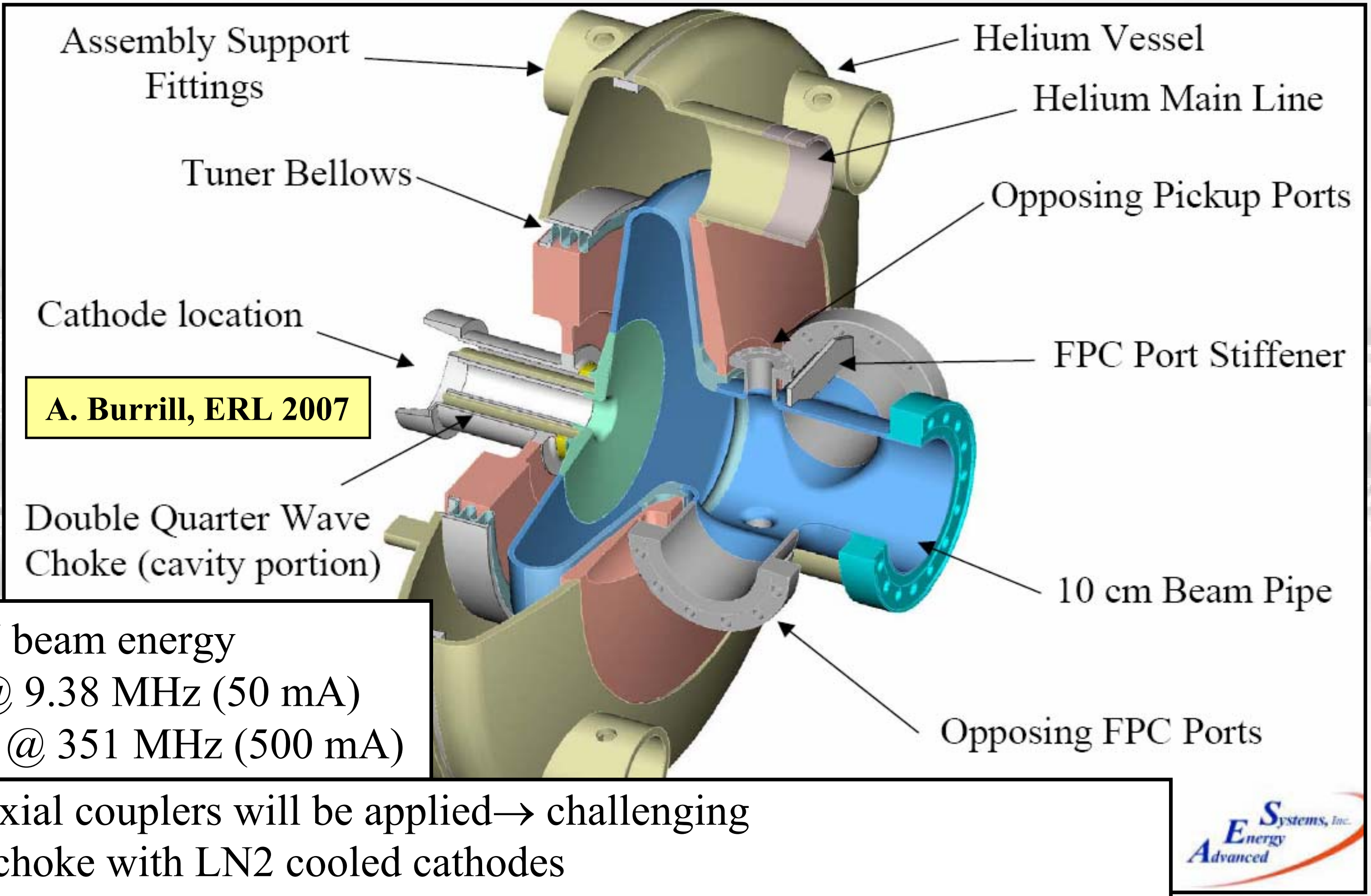
Lu Xiangyang, BILCW07
J. Hao et al., FEL2005

Currently status unknown!

Parameter	Simulation
Accelerating Field	15 MV/m
Nominal Beam Energy	5.0 MeV
Energy Spread (rms)	0.64 %
Bunch charge	100 pC
Trans. Emittance (rms,n)	1.1 µrad
Average Current	1-5 mA
Rep. Rate	81.25 Mhz
Pulse Length (Gaussian)	6 ps
Laser Spot Radius (uniform)	0.4 mm
DC Voltage Gap	90 kV

BNL 703 MHz SRF Photoinjector for ERL

Design



- Spec: - 2 MeV beam energy
  - 5 nC @ 9.38 MHz (50 mA)
  - 1.4 nC @ 351 MHz (500 mA)

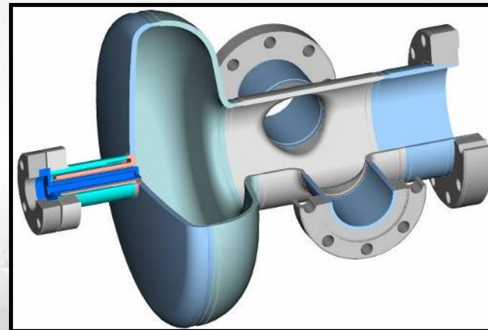
- 2x500 kW coaxial couplers will be applied→ challenging
- Quarter wave choke with LN2 cooled cathodes
- NC cathodes plated with CsK_2Sb (measured QE 3% @ 532nm, 10% @ 355nm)

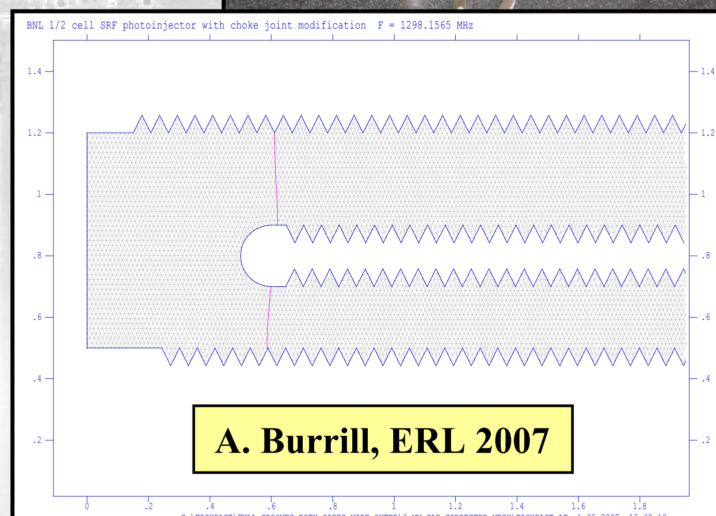
BNL 703 MHz SRF Photoinjector for ERL

Progress on Cavity measurements

- Two 1.3 GHz cavities manufactured and tested @ 2K
- Good results without cathode (E_{peak}=50MV/m @ Q_0 $2*10^9$)
- With cathode inserted into choke
  → strong multipacting barrier appeared
- Solution anti-multipacting grooves at inner surface of choke joint
- Modified cavity now awaiting e-beam welding

Next: RF testing planned with different cathode materials of interest:
→ Diamond, CsK_2Sb, GaAs





A. Burrill, ERL 2007

BNL 703 MHz SRF Photoinjector

Cathode properties

- CsK_2Sb is cathode of choice
- High current density 250 mA/cm^2
- Measurement of QE @ different wavelength show promising results
- Lifetime and surface uniformity were studied
- Lots of experience with CsK_2Sb photocathode deposition

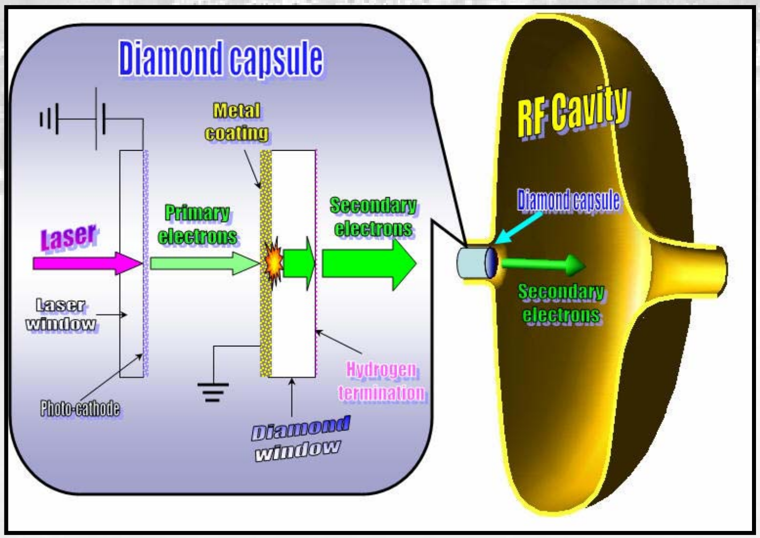
λ	QE	Desired Current	Laser Power
532 nm	3%	50/130/500 mA	4/10/38W
355 nm	10%	50/130/500 mA	2/5/17W

A. Burrill, ERL 2007

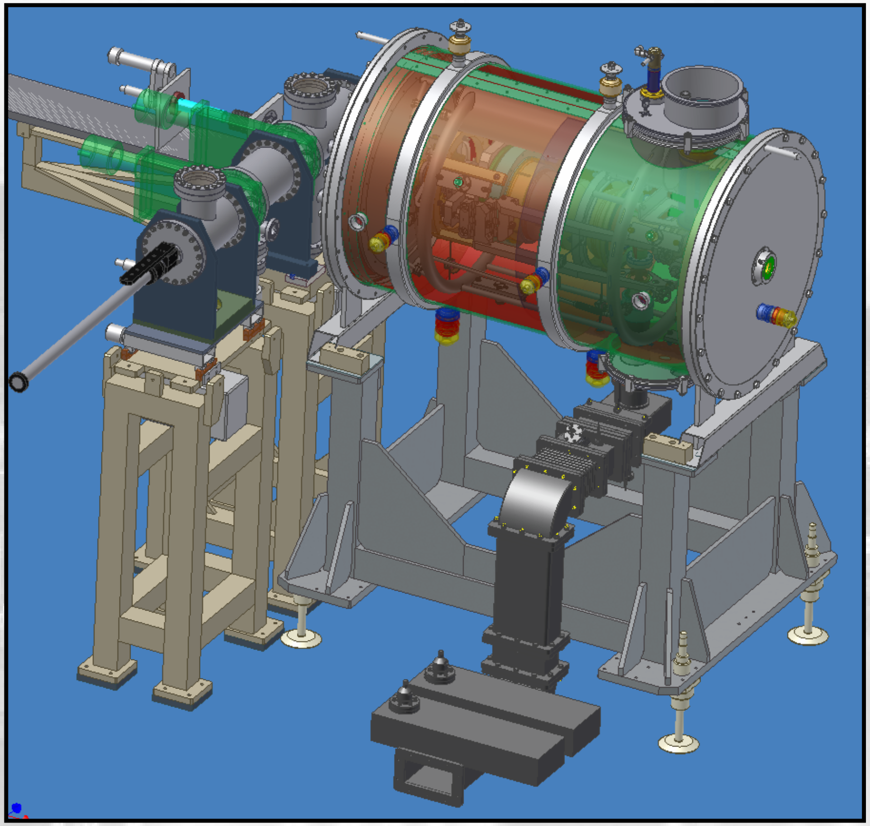
Parallel:

Extensive R&D on diamond amplified photocathode to provide this cathode as the next generation cathode!

- Due to a cascade of secondary electron generation → QE up to 1000% possible
- High average current up to ampere class
- Act as a vacuum barrier, protecting the gun from contamination
- Long life time, low current from cathode material

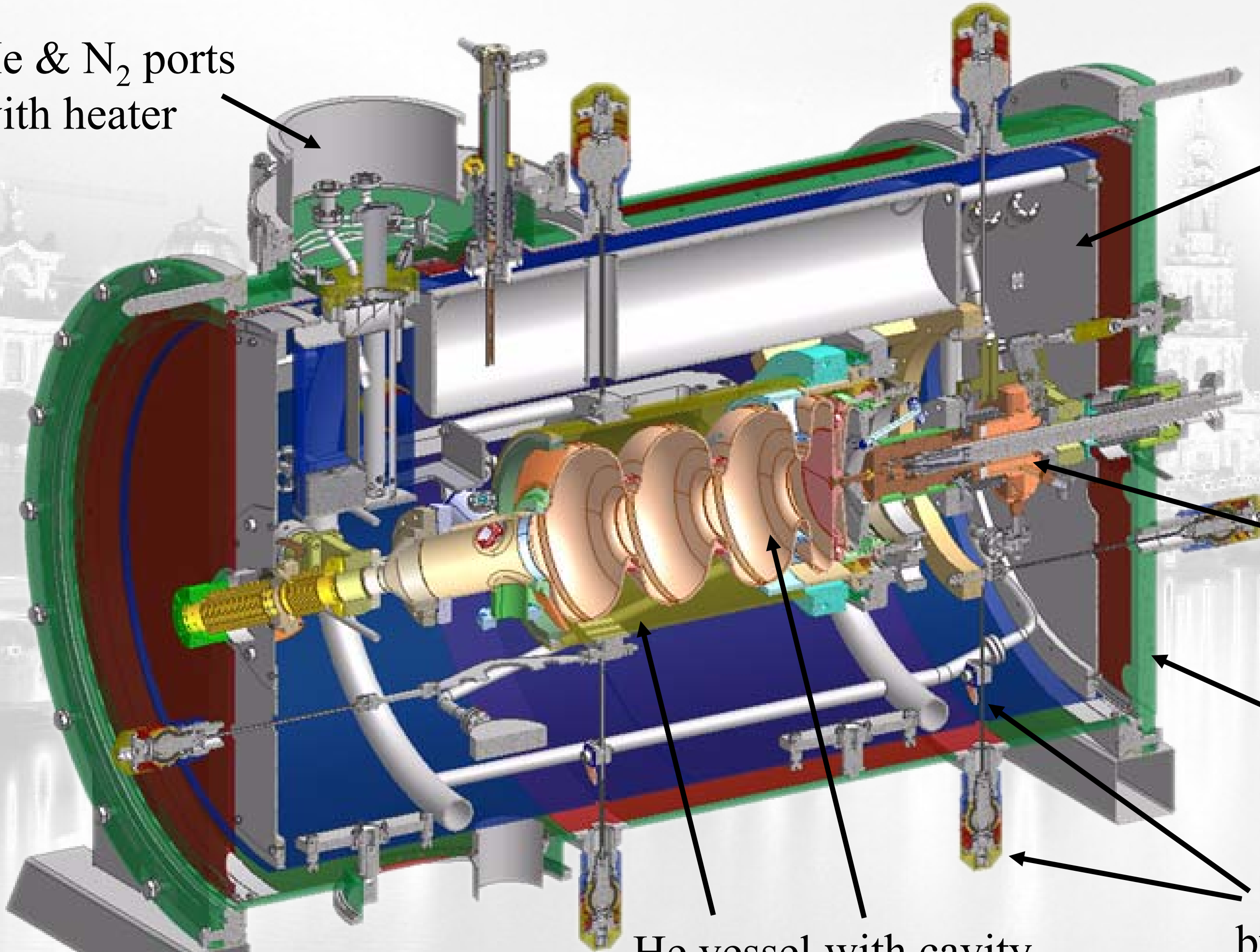


Dresden - Rossendorf SRF-Gun Project



Cryomodul completed
July 2007

Rossendorf 3½ Cell SRF Gun – Cryomodule design

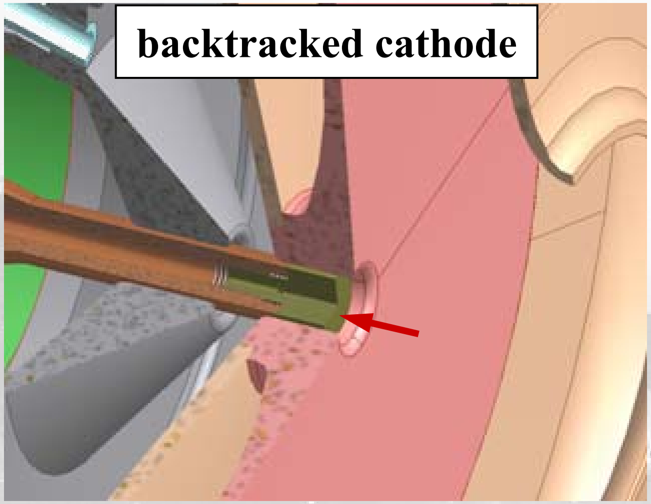


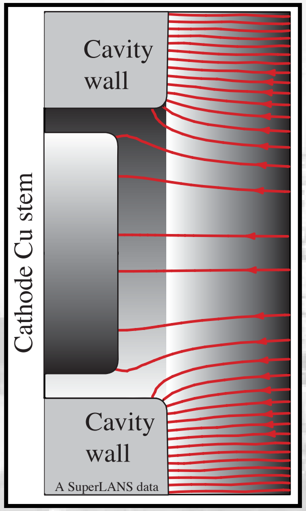
Introduction – SRF Gun Design Parameters

Mode	ELBE	High Charge	BESSY-FEL
final electron energy	≤ 9.5 MeV		
RF frequency	1.3 GHz		
RF power	10 kW		
operation mode	CW		
drive laser	262 nm		
photo cathode	Cs_2Te		
quantum efficiency	≥ 1 %		≥ 2.5 %
bunch charge	77 pC	1 nC	2.5 nC
repetition rate	13 MHz	500 kHz	1 kHz
laser pulse (FWHM)	5 ps (Gauss)	15 ps (Gauss)	40 ps (Flat Top)
transverse emittance (rms, normalized)	1 mm mrad	2.5 mm mrad	3 mm mrad
average current	1 mA	0.5 mA	2.5 µA

Emittance Compensation

backtracked cathode

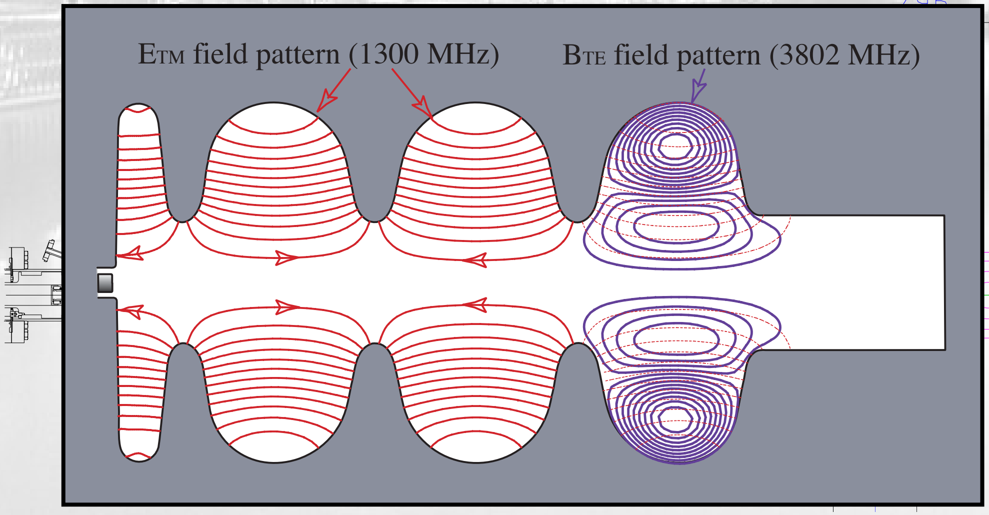




Studies with

- Backtracked & adjustable cathode (by cathode tuning system)
- Downstream solenoid (250mT)
- Later: shaped cathode (pierce type)
- Later: additionally excited TE mode in cavity (Janssen & Volkov)

solenoid focusing



Emittance Compensation high charge mode (1 nC, 500 kHz)

ASTRA Simulation

laser profile : **Gaussian**
bunch length : **14 ps (FWHM)**
Laser spot radius rx,y : **1.8 - 2.6 mm**
cathode : **2.8 mm backtracked**
thermal emittance : **included**

Comments:

- long. emittance vs. trans. emittance is shown
- laser spot radius rx,y is used as parameter
- best trans. emittance effected the worst long. emittance and vice versa
- solenoid decreases emittance by 1µrad
- best emittance 3µrad

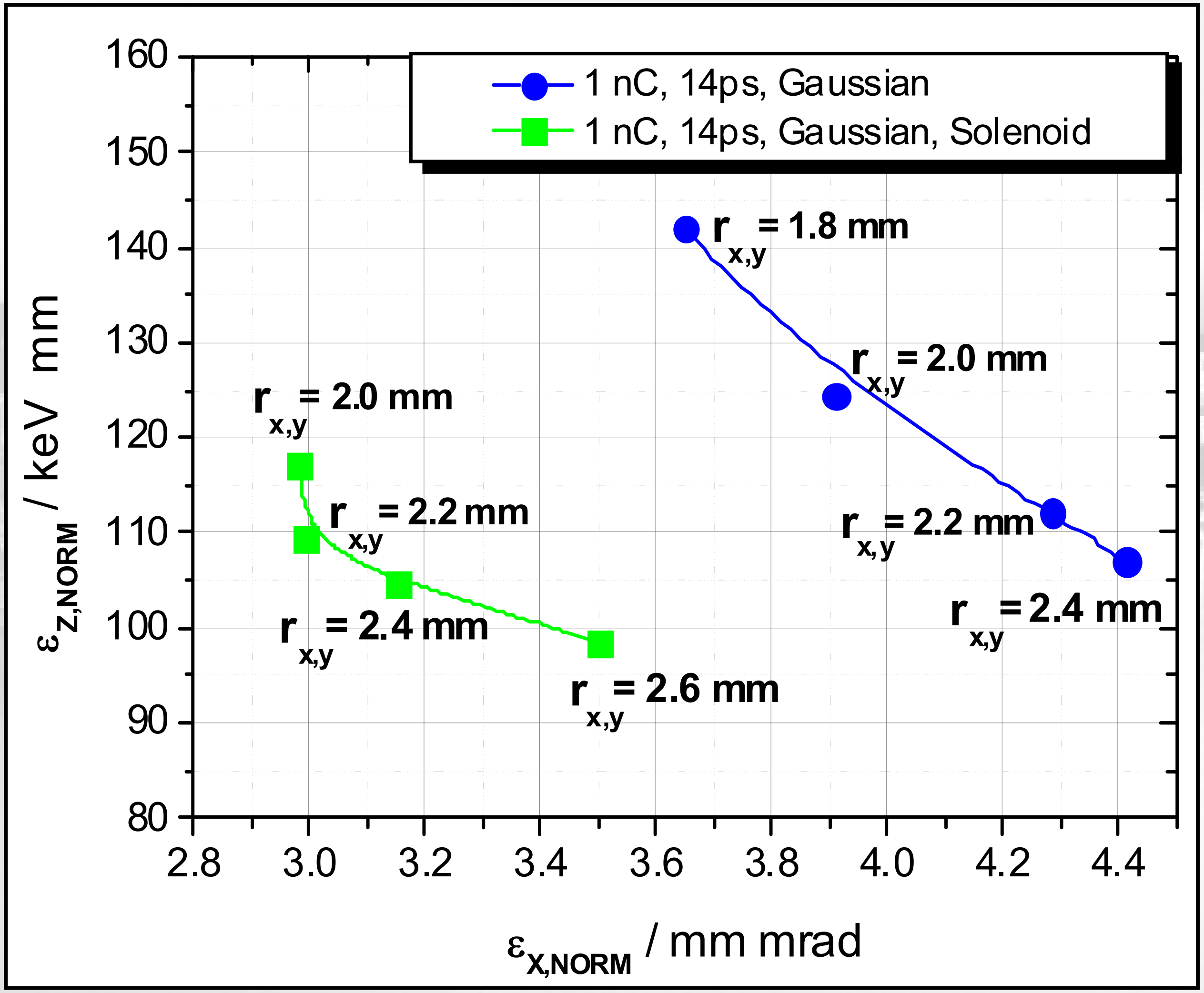
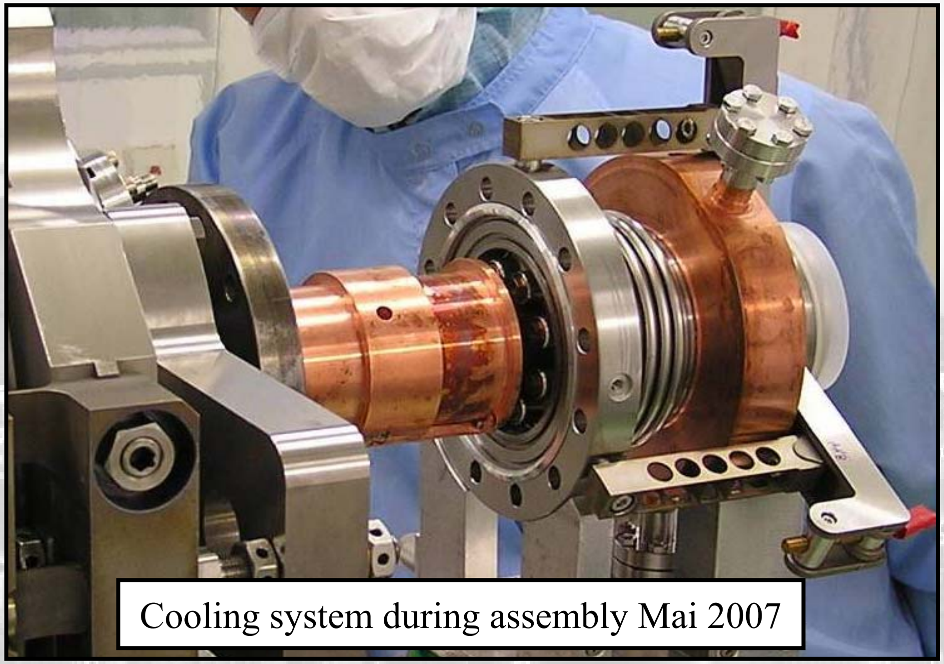
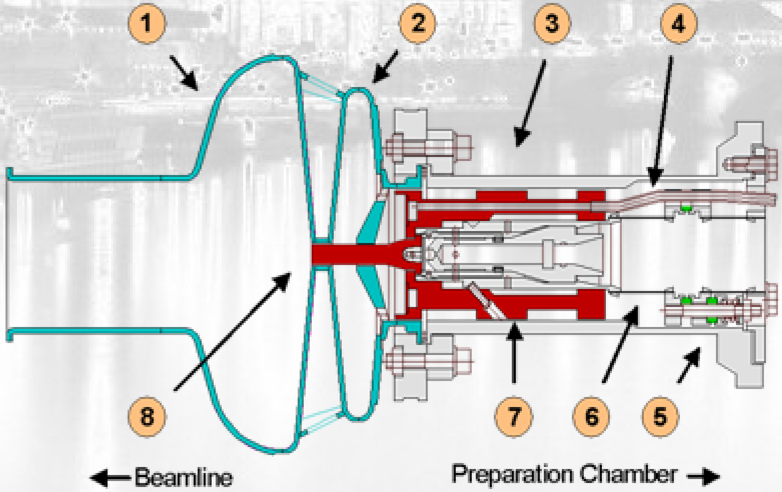


Photo Cathode – NC Cathode in SC Cavity


Cooling system during assembly Mai 2007

NC Photocathode
- Cs_2Te plated (QE~1% @ 262nm)
- 1W laser power sufficient for 1mA
- Good experience in NC photoguns
- Isolated from Nb cavity & cooled by LN_2
- SC Nb choke filter prevents RF flow (concept of 1st SRF Gun)



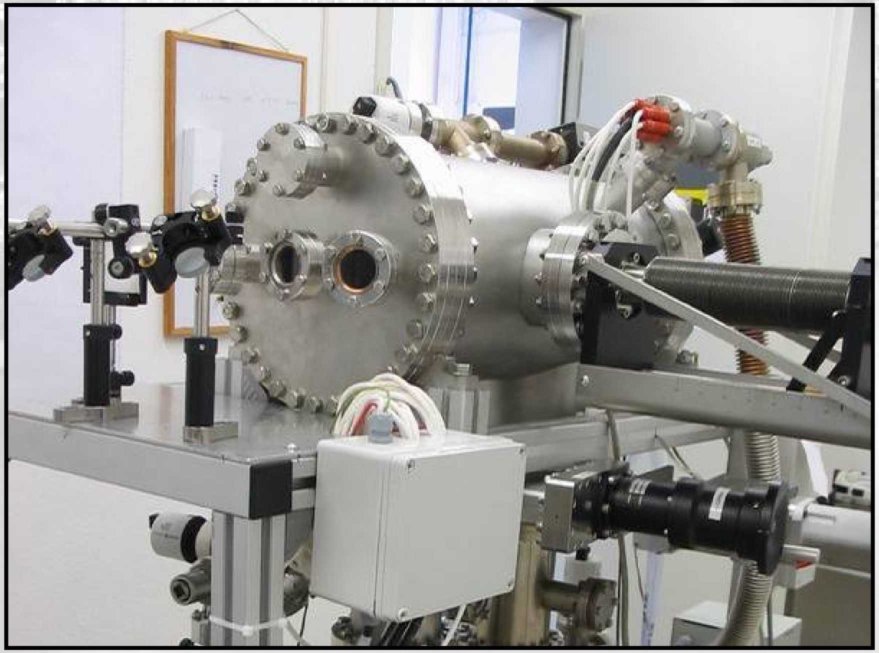
successful Rossendorf ½ - cell gun with NC cathode
D. Janssen et al., NIM-A, Vol. 507(2003)314

Main difficulties by NC cathode in SC cavity
- Degradation of Q_0 by impurities from cathode
  → not seen during ½ - cell gun tests @ FZD
- Effect of additional heat load in the cathode
- Effect of the design of the half cell and the choke (multipacting, max. peak field, mech. properties)

Photo Cathode – Cs_2Te layer deposition

- Photocathode preparation system installed in a clean room (Class 1000)
- Ultra high vacuum (P ~10^{-10} mbar)
- 4 evaporators for successive or simultaneous evaporation of Cs & Te
- 2 deposition rate sensors (Cs/Te ratio 2/1)

- System computer controlled
- Online measurement during deposition
  - of Q.E. 262nm laser (4mW)
  - life time, Q.E. distribution
- Achieved Q.E. up to 8%
- Lifetime: 1 month for Q.E. ≥ 0.5%



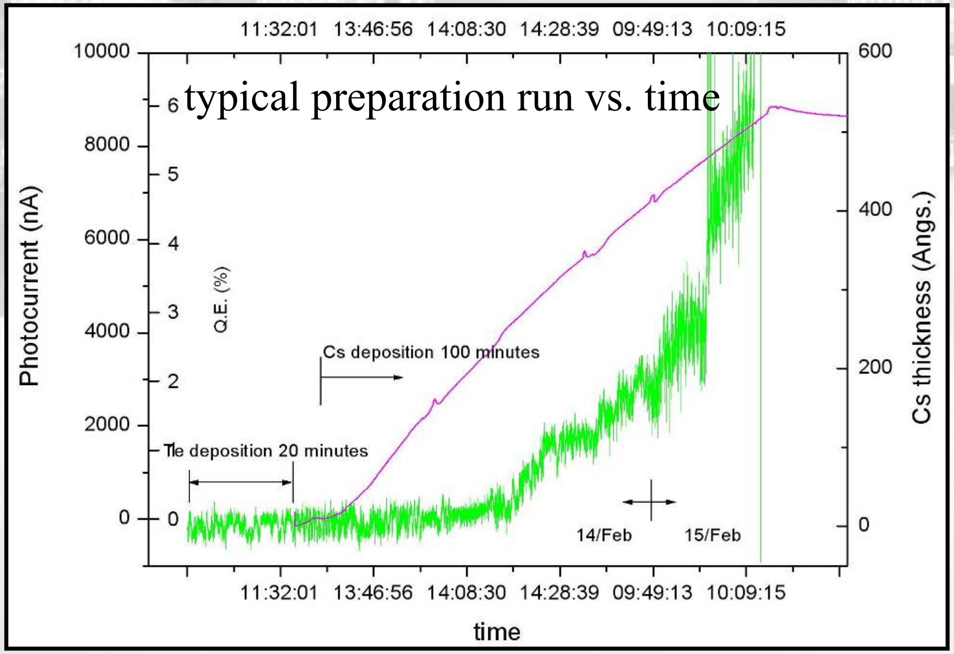
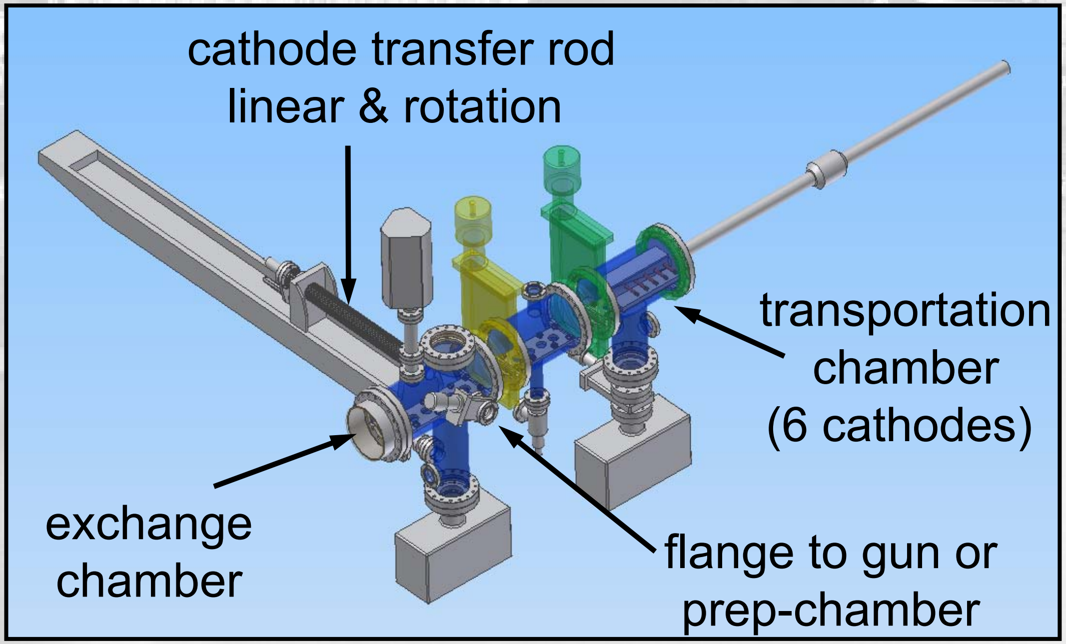
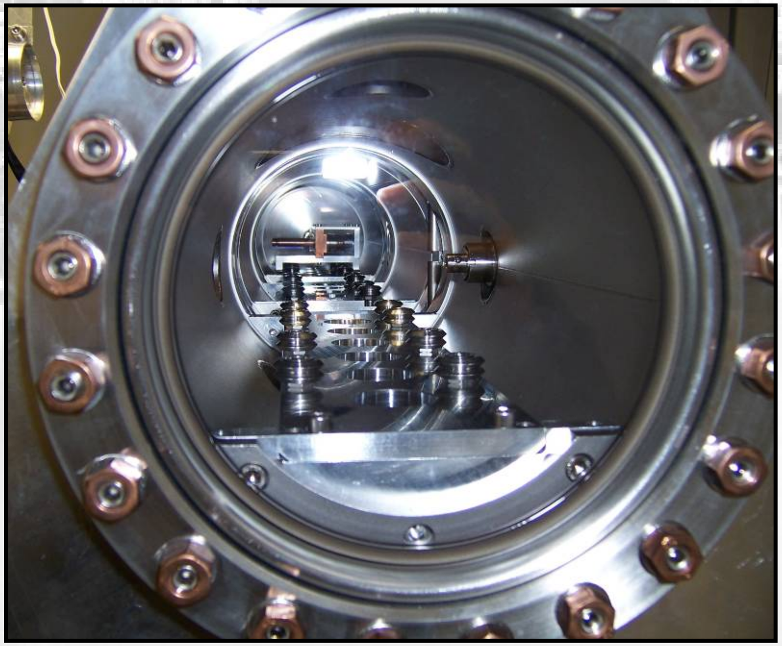


Photo Cathode Exchange and Storage

- For cathode exchange between preparation and SRF gun - 2 identical transfer systems
- One @ the SRF-gun (under cleaning) & one @ the cathode preparation chamber (in use)
- Transport chamber: to transport 6 cathodes to the gun without breaking ultra high vacuum
- Exchange chamber with transfer rod: to ensure accurate adjustment of the cathode
- Demand for minimum particle generation during exchange





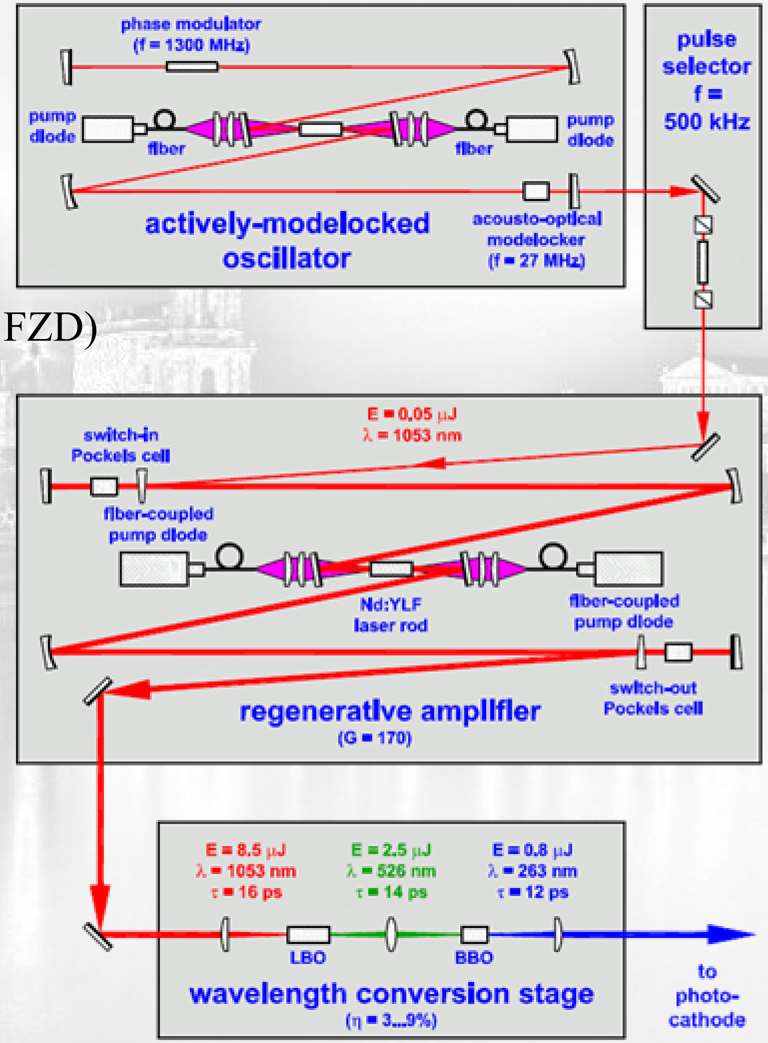
Laser System

Due to the different parameters of the operation modes, nearly two completely different laser systems are required.

13 MHz short-pulse laser (still in a design phase)

500 kHz laser for High-charge mode (under installation @ FZD)

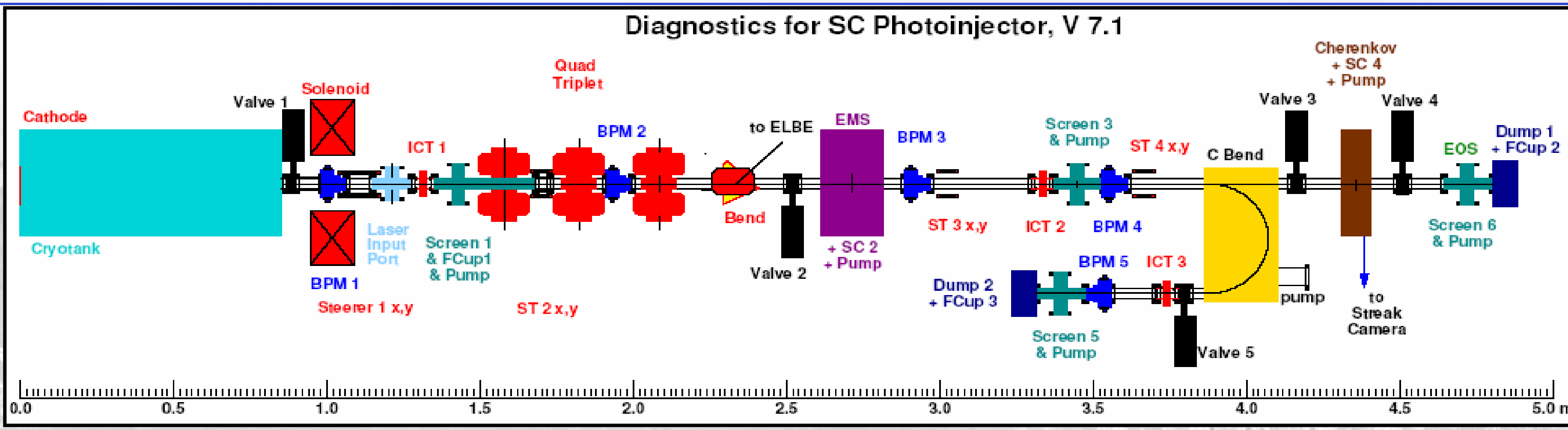
- Laser material: Nd:YLF, pumped by 8 fibercoupled diodes
- Pulse energy: 1µJ @ 500 kHz
- Pulse length: 12…15 ps FWHM
- Lower frequencies for alignment
- Optical layout:
  - Oscillator (13 MHz)
  - Regenerative amplifier
  - Wavelength conversation stage



Developed by MBI Berlin

Diagnostics Beamline

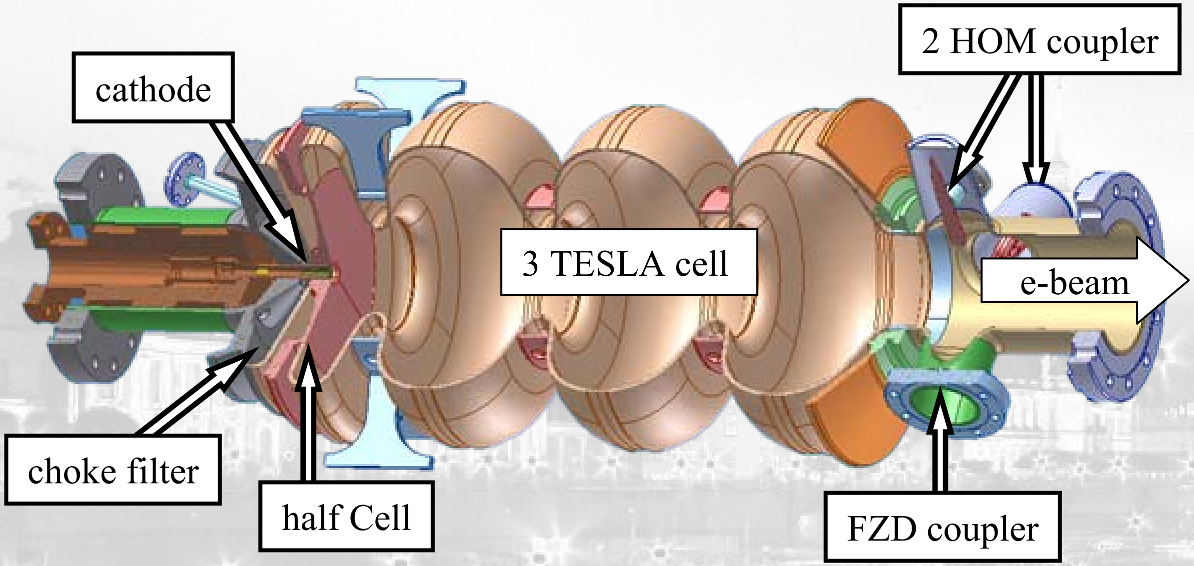
developed & manufactured by BESSY Berlin

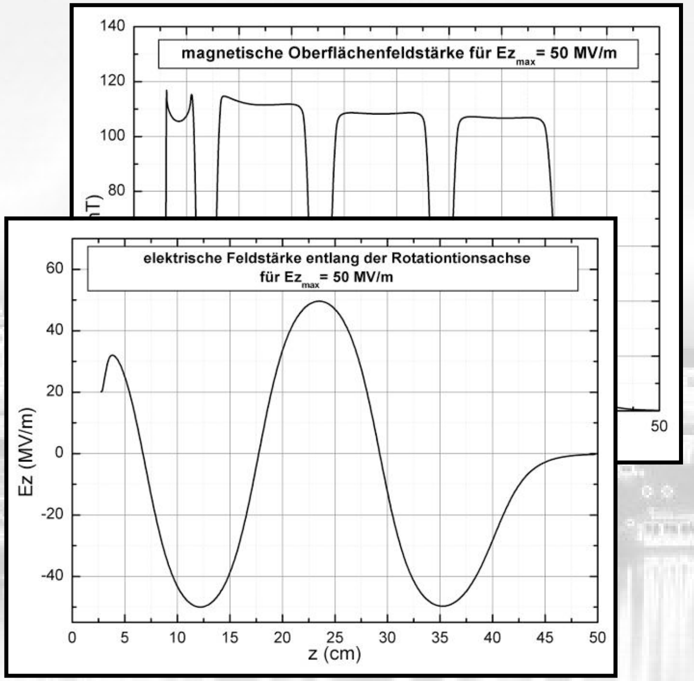


- <u>Beam position:</u> stripline BPMs (650 MHz FPGA)
- <u>Energy & energy spread:</u> C bend magnet
- <u>Current:</u> Faraday cups & ICT's
- <u>Beam size and emittance:</u> YAG crystal screens & slit mask with screen station (EMS)
- <u>Bunch length:</u> Cherenkov radiator + steak camera and electro optical sampling (EOS)

Installation completely tested & now under clean room assembly @ FZD!

Cavity - Design





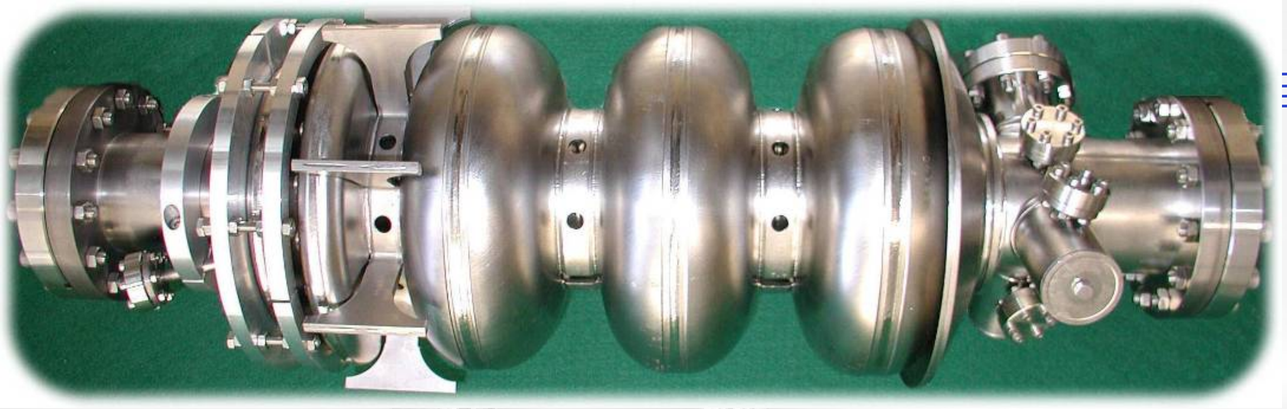
- ½ cell + 3 TESLA cells (Nb purity grade: RRR 300)
- ½ cell designed by numerical optimization procedure
- SC choke filter to prevent RF loss
- 2 HOM filter, coaxial main coupler (FZD Design)
  2 pickup antennas (beam tube & choke filter)

- 2 cavities manufactured by ACCEL Instruments
  (RRR40 for technology tests, RRR300 for SRF-Gun)

Properties determined by TESLA 500

- 110 mT maximum magn. surface field
- E_{acc}= 25 MV/m in TESLA cells, $Q_0=10^{10}$
- E_{peak} (TESLA cells) = 50 MV/m
- E_{peak} (half-cell) = 30 MV/m
- $E_{cathode}$ = 20 MV/m (backtracked cathode)

Cavity – Treatment



Cavity from ACCEL

- Mechanical inspection, RF measurements, first "rough" warm tuning of field profile } @ FZD
- Standard treatment for cavity pre-cleaning } @ DESY
- 2nd "fine" warm tuning } @ FZD

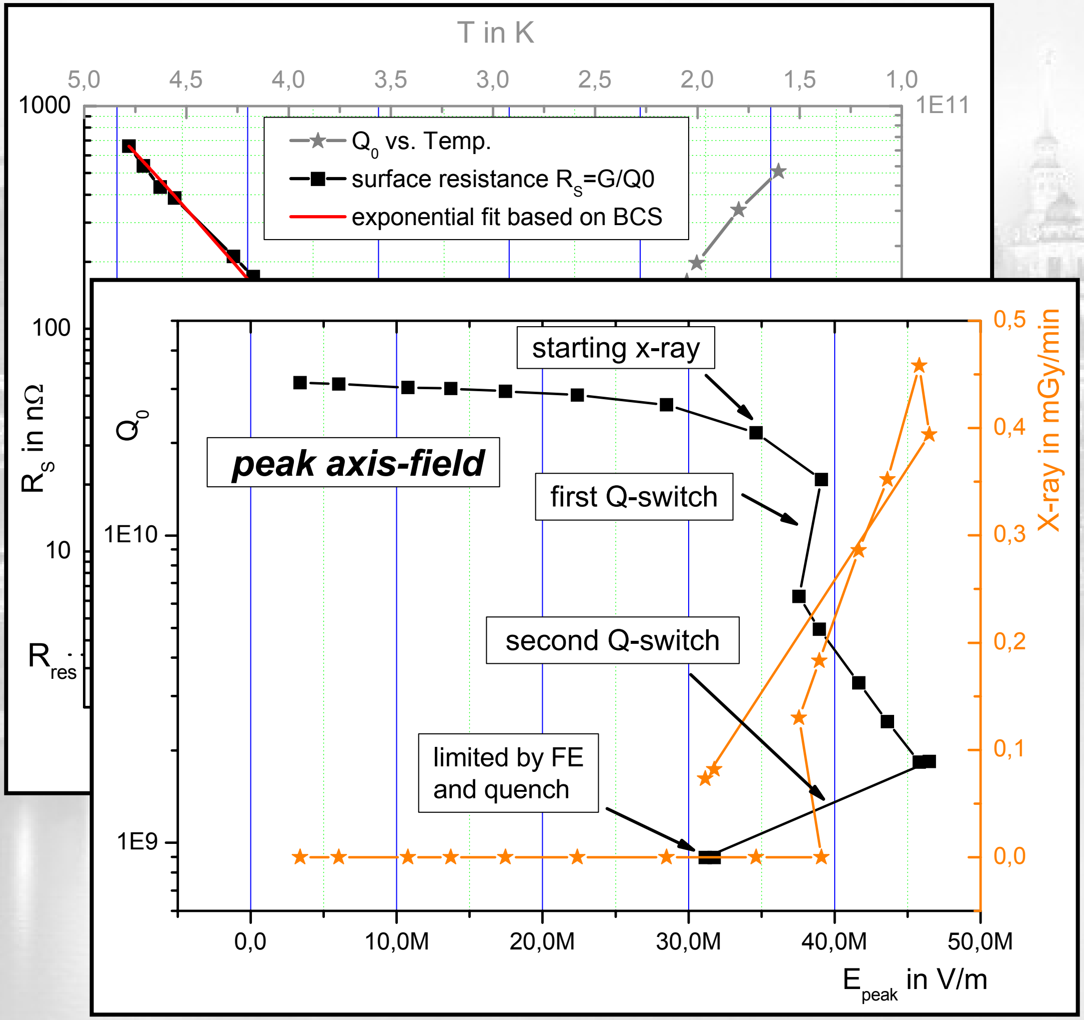
Preparation for vertical test without cathode

- Standard treatment for cavity "fine cleaning"
- Assembly of auxiliaries (fundamental pickup + vertical test antenna)

RF Measurement @ 1.8 K

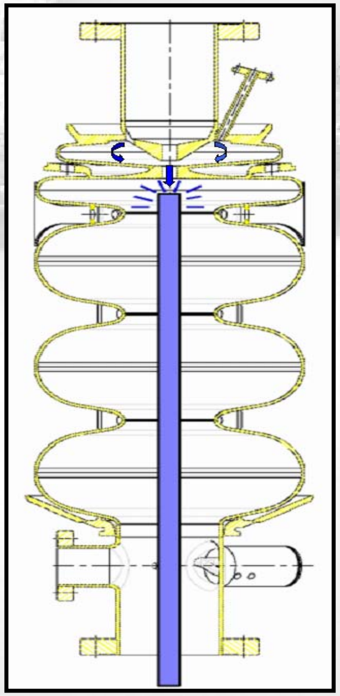
} @ DESY

Cavity – Vertical Tests @ DESY (1.8 K)

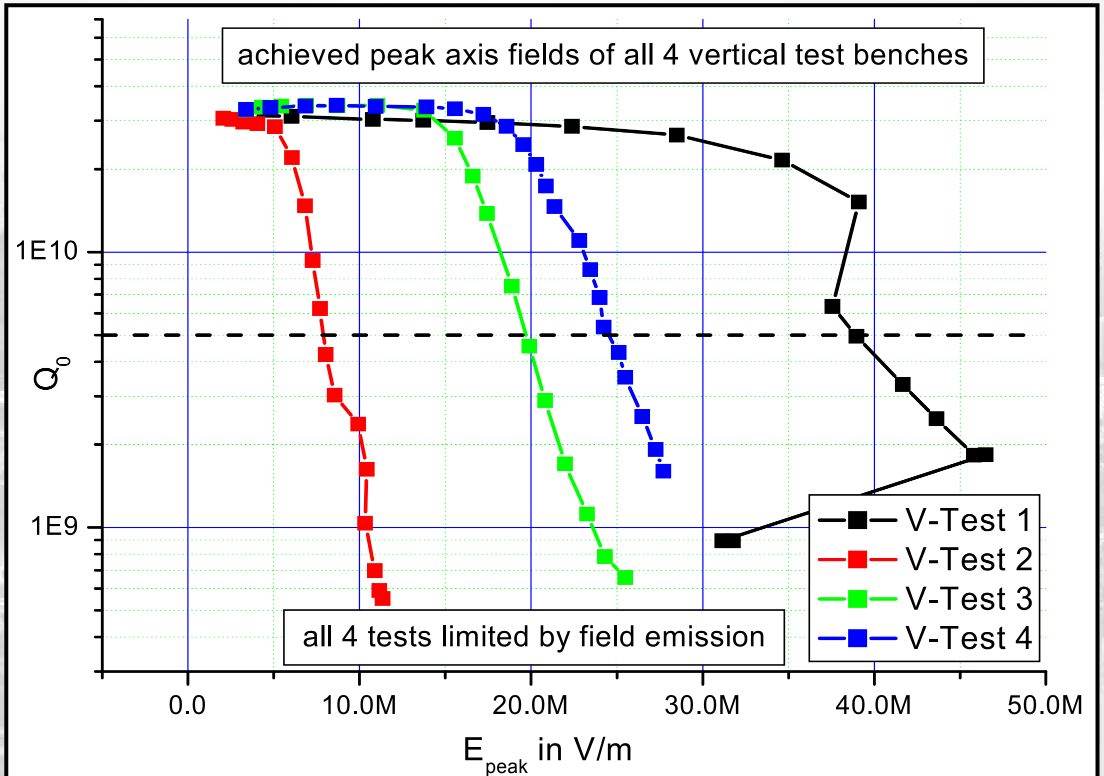


- <u>1st V-Test</u> (cleaning done @ DESY):
  - Residual surface resistance R_{res}=3.4nΩ
  - Strong field emission, two Q-switches (thermal breakdown @ activated FE)

<u>Supposed problem:</u> surface pollution out of the choke (cleaning not feasible with lance)



Cavity – Vertical Tests @ DESY (1.8 K)



values @ Q_0=5x10⁹	1st BCP / HPR @DESY	2nd HPR @ DESY (Crash)	3rd BCP / HPR @ ACCEL	4th BCP / HPR @ ACCEL (crash)
E_{acc}	14.6 MV/m	2.8 MV/m	7.4 MV/m	9.3 MV/m
E_{peak}	39.0 MV/m	7.4 MV/m	19.6 MV/m	24.6 MV/m
P_{diss}	32 W	1 W	8 W	13 W

- 1st V-Test (cleaning done @ DESY):
  - Residual surface resistance R_{res}=3.4nΩ
  - Strong field emission, two Q-switches (thermal breakdown @ activated FE)

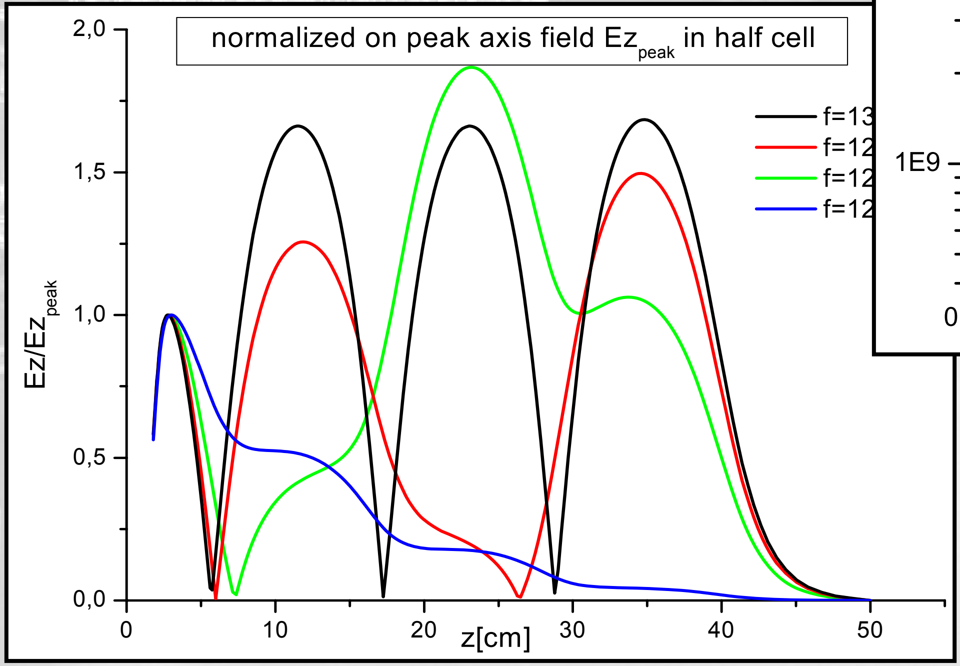
Supposed problem: surface pollution out of the choke (cleaning not feasible with lance)

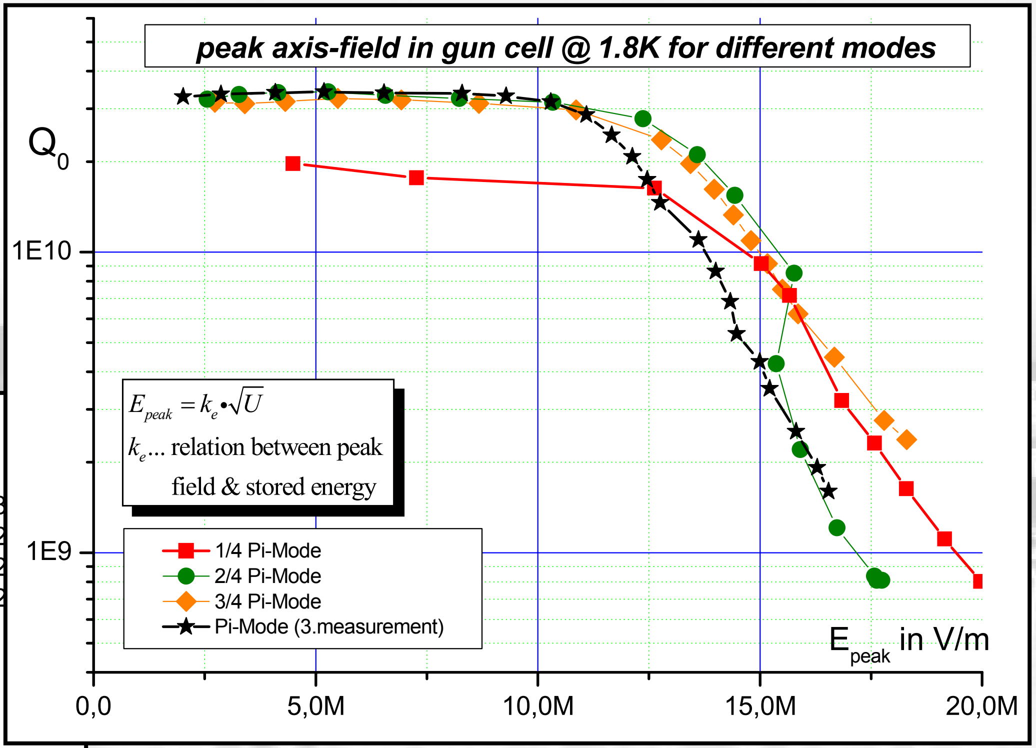
- 2nd V-Test (cleaning done @ DESY):
  - Choke rinsing by special HPR lance
  - HPR lance crashed with cavity during choke cleaning → worst result / limit FE
- 3rd V-Test (cleaning done @ ACCEL):
  - Caused by high risk no choke rinsing
  - No problems occurred but only 20MV/m
- 4th V-Test (cleaning done @ ACCEL):
  - Choke rinsing by special HPR lance
  - Achieved E_{peak} better but also limit FE
  - To estimate position of FE all 4 passband modes measured

Cavity – Vertical Tests @ DESY (1.8 K)

Q vs. E passband measurement

- From the measured stored energy, the peak axis field in half cell was calculated
- For all modes, limit about 15MV/m
- From norm. field distribution - ¼ π-mode is mostly concentrated on the half cell



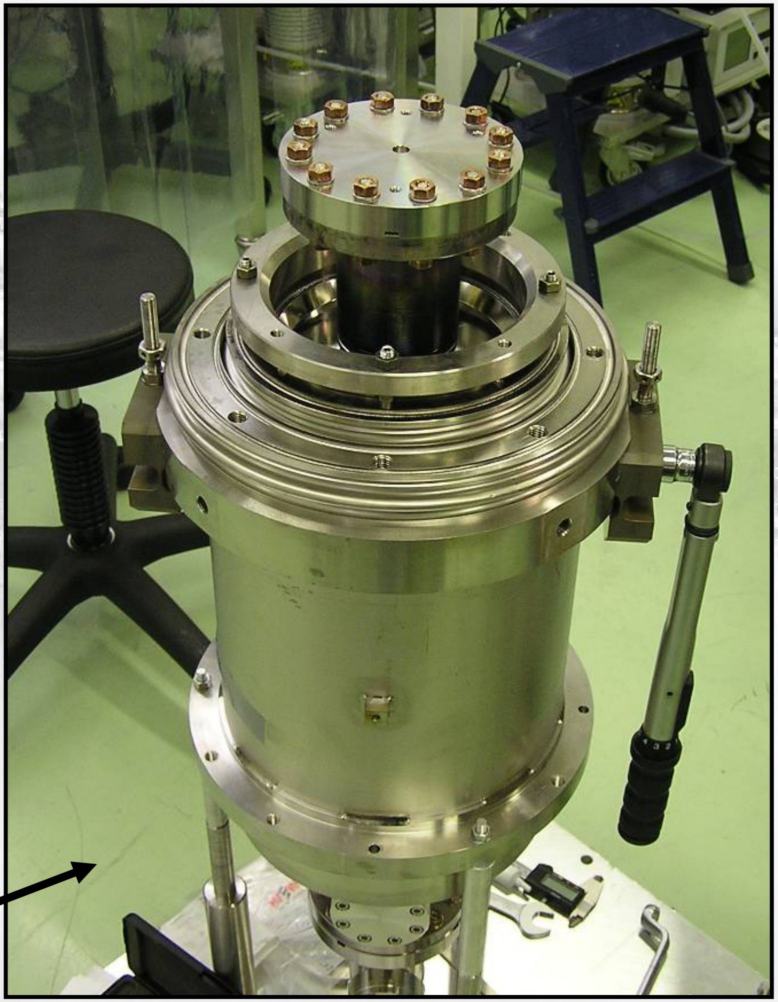


→ limiting object had to be in half cell

- Assumption proofed by small scratch @ back plane
- Scratch removed and the final chemical treatment will result in a better performance

Cavity – Treatment

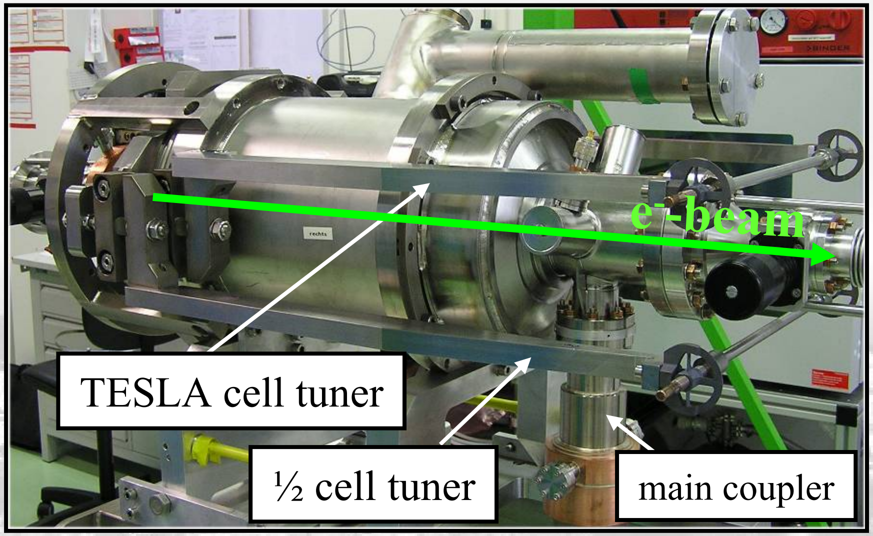
- Time schedule → no time for 5th preparation & vertical test
- @ FZD: final RF measurements and final warm tuning
- @ ACCEL
  - Helium vessel welding
  - Final field profile measurements for QA
  - Final chemical "fine"- cleaning
  - Assembly of auxiliaries (HOM feed through, fundamental pickup)
  - Final clean water rinsing & drying
  - Vacuum leak check of all components
- Cavity prepared for final assembly @ FZD

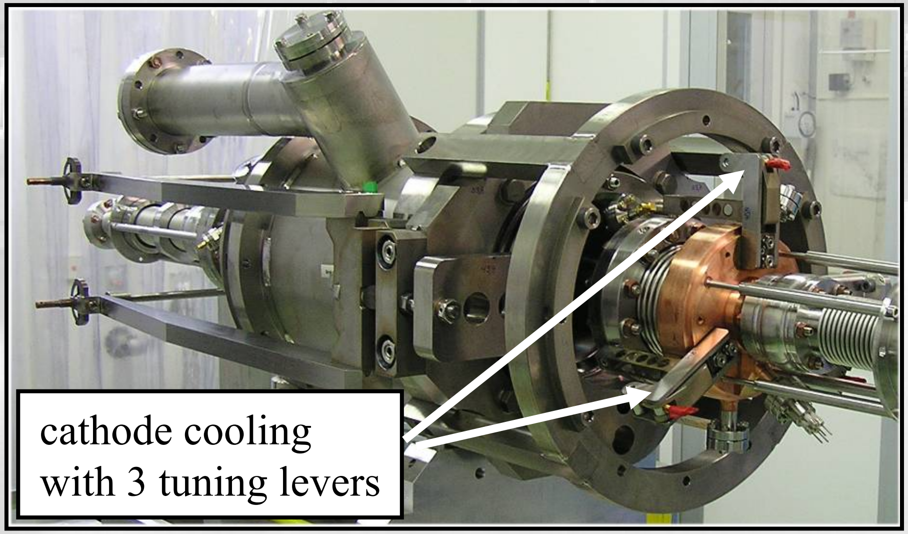


Cavity – Assembling @ FZD class 10 clean room

- Clean room assembling of main coupler/ pickups and both cavity tuners
- Different stiffness of cavity cells, two separate tuning systems needed

Half cell tuner ±0.25mm → ± 70kHz
TESLA cell tuner ±0.30mm → ±220kHz

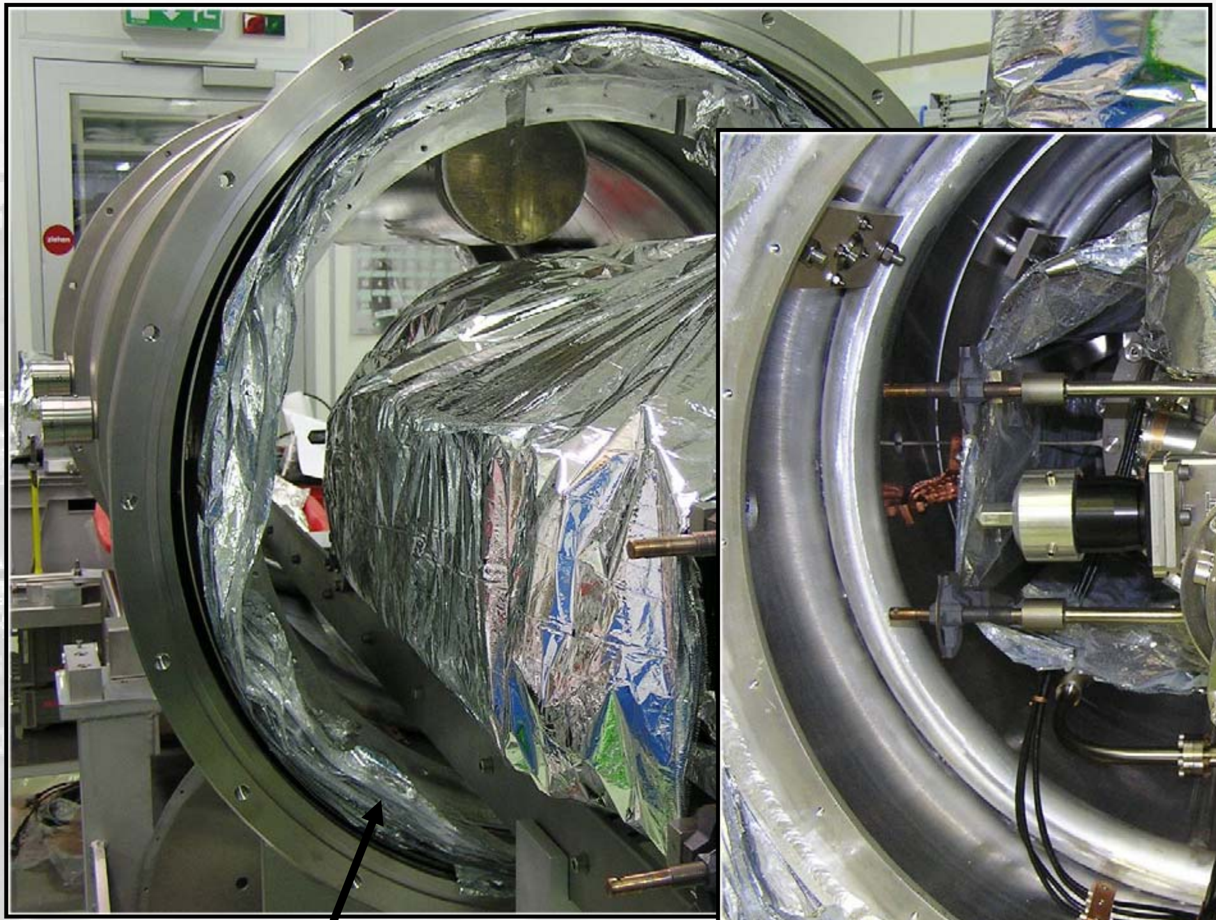


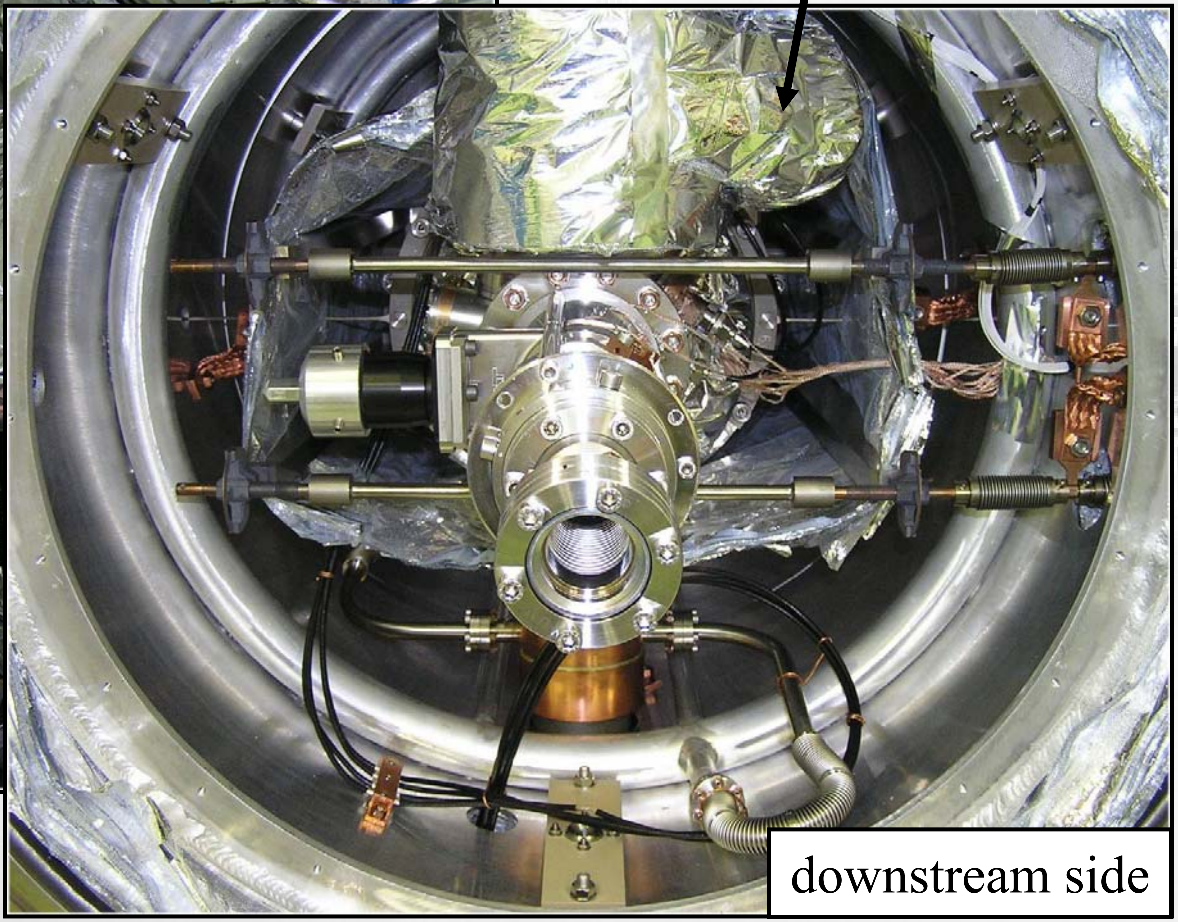


- Tuners adjustment done by its prestressing to achieve "flat" field distribution & correct frequency
- Tuning of choke filter and HOM filters (additional input antenna at choke side to avoid cross coupling)
- Cathode unit assembled for Cathode cooling and alignment

Cryostat – Assembly & Commissioning

- Completed interior of module shortly before its closure





- “Roll in” of the completed cavity

Cryostat – Assembly & Commissioning

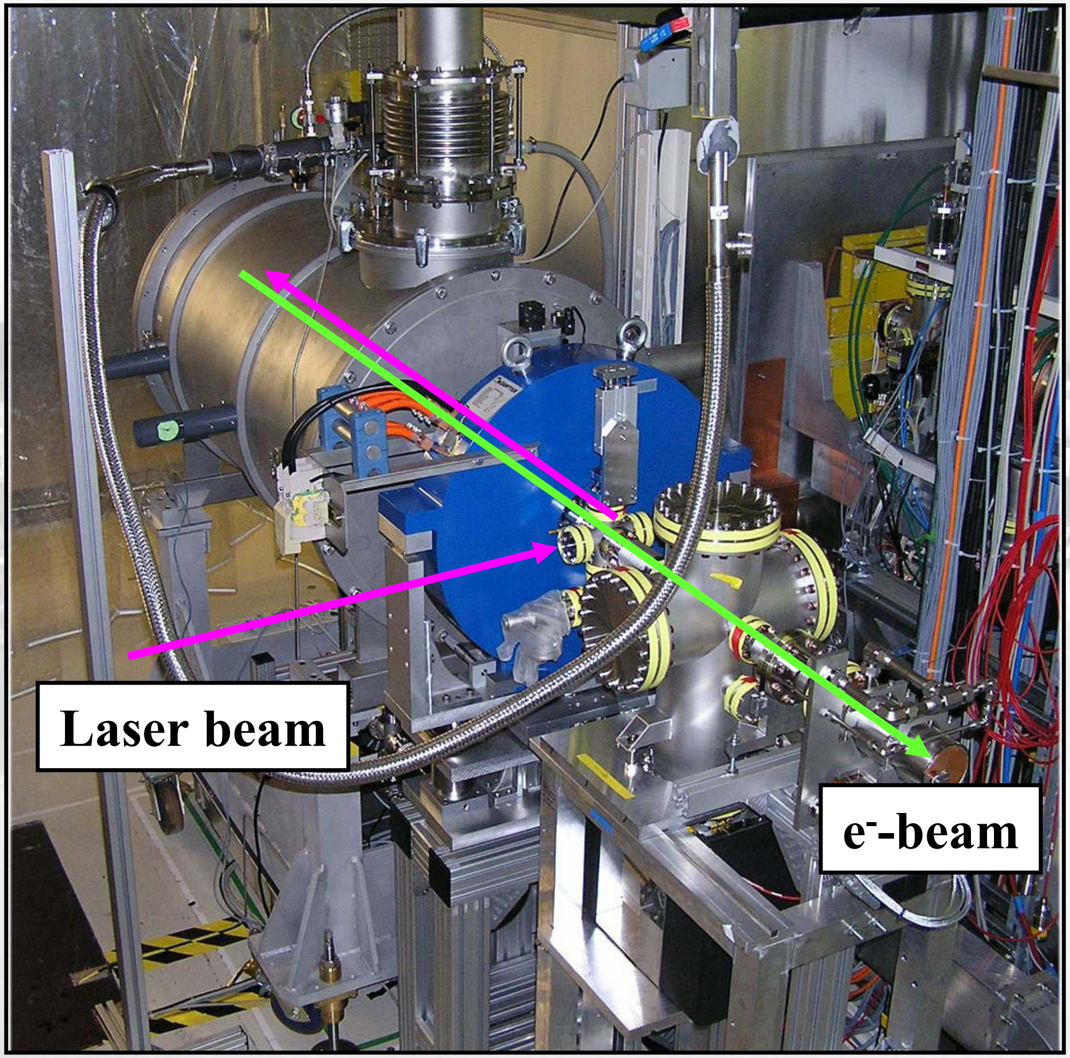
Status

- Assembly of the cryomodule and installation in the accelerator hall completed
- Due to small time slots during machine shutdown, first tests had to be done with small diagn. beamline

ToDo

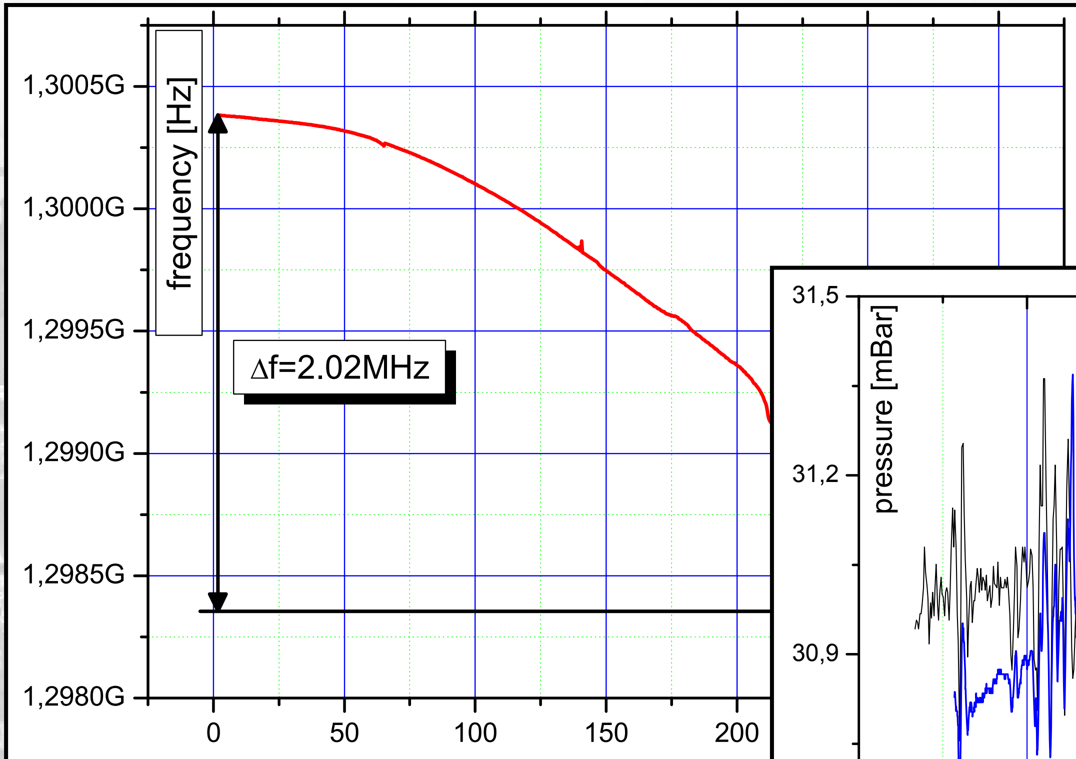
- Cleaning and white assembly of the 2nd cathode transfer system
- Installation of the 500kHz laser system will be finished
- Autumn ELBE shutdown, installation of diagnostic beam line & 2nd transfer system

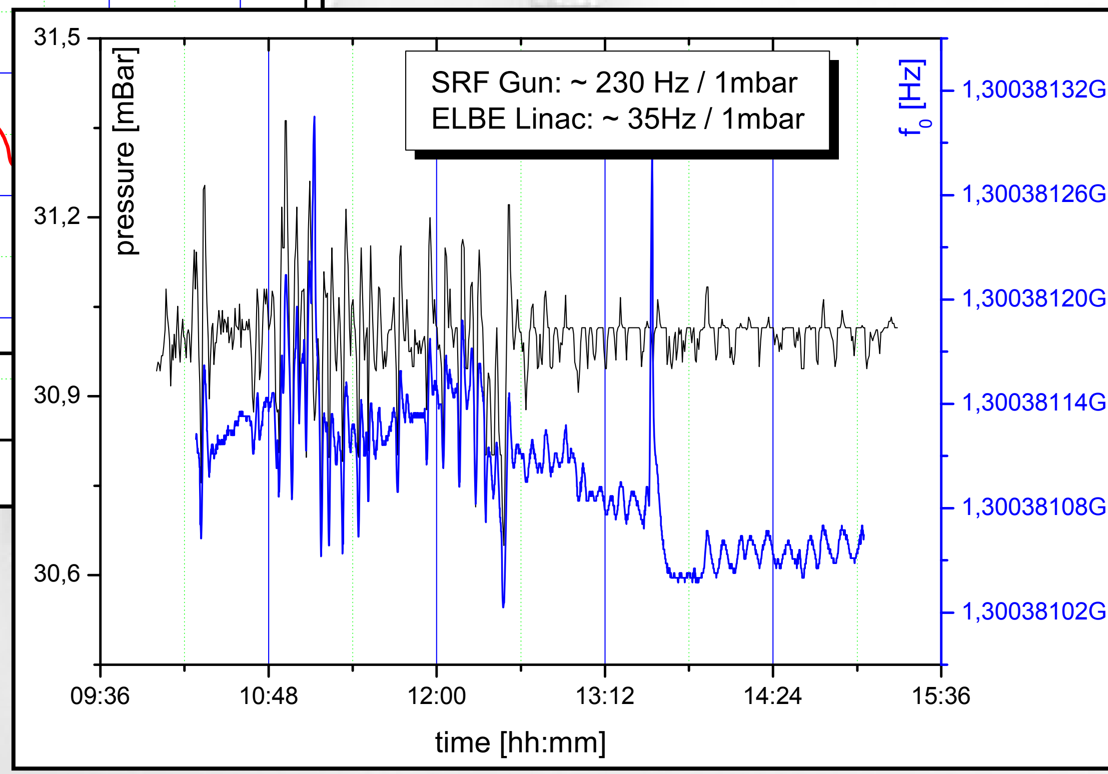
Beginning of injector characterization in the near future!



Cool down and 1st measurements

- No problems during cooldown to 2K
- Frequency shift same as expected from TESLA cells





- Pressure sensibility 7 time higher than known from ELBE modules
- Problem for the phase controller
- Caused by different cavity design

Summary

There is a visible progress in the SRF gun community

- Two guns generated e-beam (FZR 2002 & IHIP 2004) did not reach spec.
- @ BNL / JLAB / DESY: Progress in SC cathode development (for currents ~1 mA, lead plated cathodes may be alternative to NC cathode with choke filter)
- @ PKU: improved 3+½ DC-SC photo injector is designed & under construction (?)
- @ BNL 703 MHz: - Injector design completed, 2 test cavities built and tested
  → improvements done to suppress multipacting
  - CsK_2Sb cathode research promising results (Q.E. ~10%)
  - Extensive R&D on diamond amplified photocathode
- @ FZD: - Cryomodule assembly and installation completed
  - Few cathodes prepared for 1st tests (Q.E. ~1%)
  - Small diagnostic beam line connected to module
  - RF tests & installation of laser system are nearly finished
  - Nearly ready for 1st SRF injector studies

Thank you for your attention

Collaboration:

BESSY, Berlin
DESY, Hamburg & Zeuthen
Max-Born-Institut, Berlin
ACCEL GmbH, Bergisch Gladbach
TJNAF, Newport News
University of Peking
BINP, Novosibirsk
CERN, Geneva
INFN, Frascati
CCLRC Daresbury
Technische Universität Dresden
IfE-Automatisierung GmbH, Dresden
Ingenieurkontor Stephan, Dresden

The ELBE crew
(in the Radebeul vineyards, near Dresden)

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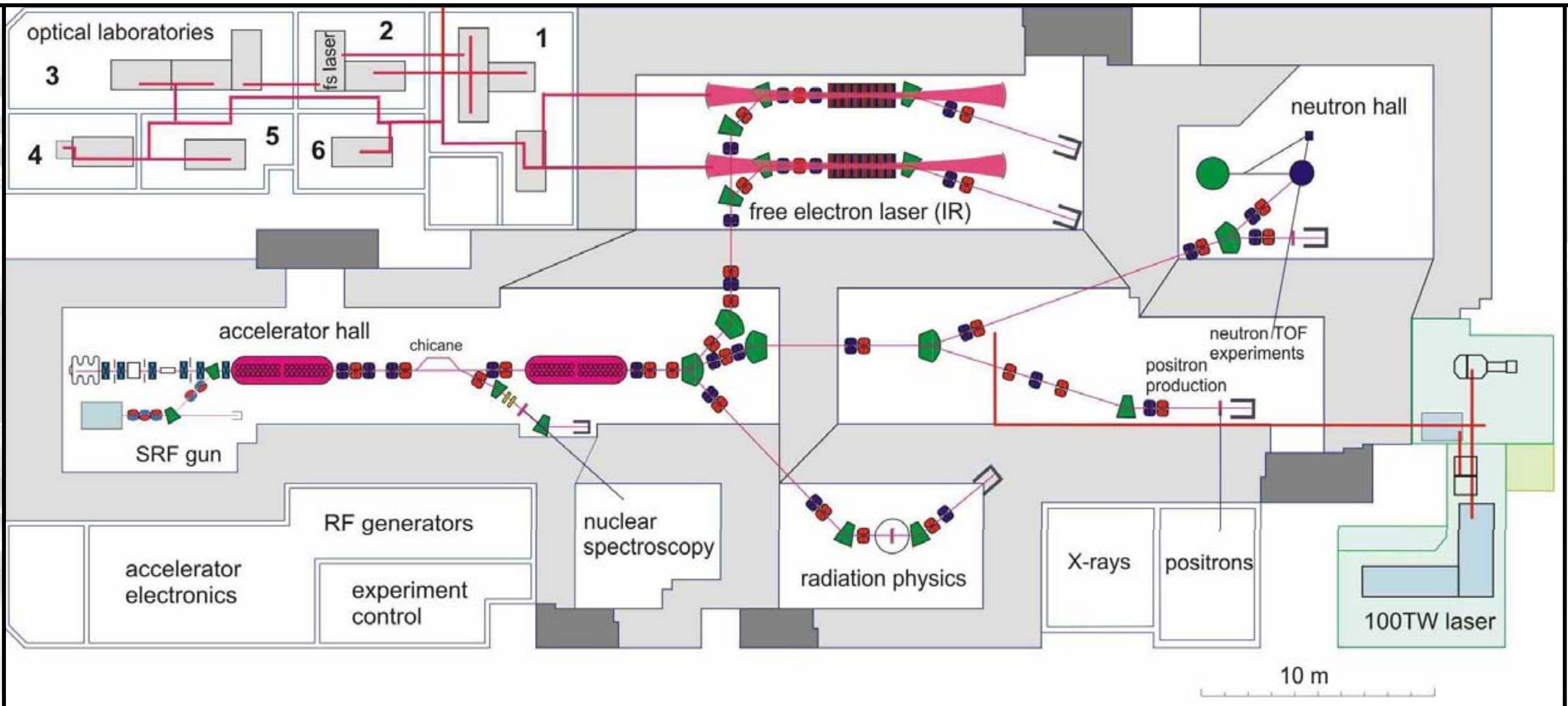
Introduction – Radiation Source ELBE

40 MeV, 1 mA CW superconducting linac
thermionic injector (250 kV DC), pulse frequency of 13 MHz (260, 26, … MHz)



1: Time resolved semiconductor spectroscopy, THz-spectroscopy
2: Femtosecond laser, THz-spectroscopy, IR pump-probe experiment
3: Diagnostic station, IR-imaging and biological IR experiment
4: FTIR, biological IR experiment
5: Near field and pump-probe IR experiment
6: Radiochemistry and sum frequency generation experiment, photothermal beam deflection spectroscopy

Appendix

		SUPERFISH (Jochen)	MWS (André)
Maximale elektr. Feldstärke E_z auf der Achse (in TESLA-Zellen)	E_{peak}	50 MV/m	
Elektrische Cavitiylänge	d	0.50 m	0.50 m
Frequenz	f	1.29751 GHz	1.2991 GHz
Gespeicherte Energie	U	33.19 J	32.49J
Unbelastete Güte $Q_0 = \frac{2\pi f U}{P_c}$	Q_0	1.03×10^{10}	$1.03 \mathrm{x} 10^{10}$
Temperatur	T	1.93 K	-
Restwiderstand	R_R	10 nΩ	-
Oberflächenwiderstand	R_s	22.78 nΩ	23.48 nΩ
Feldintegral $V_0 = \int_{z_1}^{z_2} \lvert E_z(z) \rvert dz$	V_0	13.17 MV	13.15MV
Mag. Oberflächenintegral $I_H = \int_S \lvert H^2 \rvert ds$	I_H	$2.297 \mathrm{x} 10^9\ A^2$	$2.193 \mathrm{x} 10^9\ A^2$
Dissipierte Leistung $P_c = \frac{1}{2} R_s \int_S \lvert H^2 \rvert ds$	P_c	26.16 W	25.75 W

Appendix

Geometriekonstante $Q_0 = \frac{G}{R_S}$	G	235.5 Ω	241.9 Ω
Elektronen-Beschleunigungsenergie (ASTRA)	**U_{acc}** **V_c**	**9.4 MeV** **9.4 MV**	
cavity shunt impedance $R_a = \frac{V_c^2}{2P_c}$	R_a	1.689×10^{12} Ω	1.716×10^{12} Ω
cavity $r = R_a / Q_0$	r	164 Ω	166.6 Ω
Mittlere Beschleunigungsfeldstärke $E_0 = V_0/d$	E_0	26.34 MV/m	26.3 MV/m
transit time factor TTF = V_c/V_0	TTF	0.714	0.715
Eff. Beschleunigungsfeldstärke $E_{acc} = V_c/d = E_0$ TTF	E_{acc}	18.8 MV/m	
Verhältnis der maximalen Achsenfeldstärke zur effektiven Beschleunigungsfeldstärke	E_{peak}/E_{acc}	2.70	
Verhältnis der maximalen Oberflächenfeldstärke zur effektiven Beschleunigungsfeldstärke	B_{peak}/E_{acc}	$6.16 \frac{mT}{MV/m}$	$6.06 \frac{mT}{MV/m}$