Status and Perspectives of Photo Injector Developments for High Brightness Beams

Frank Stephan

DESY, location Zeuthen

at the ICFA workshop on “The Physics and Applications of High Brightness Electron Beams” in Erice, Sicily, October 9-14, 2005

Motivation and Content

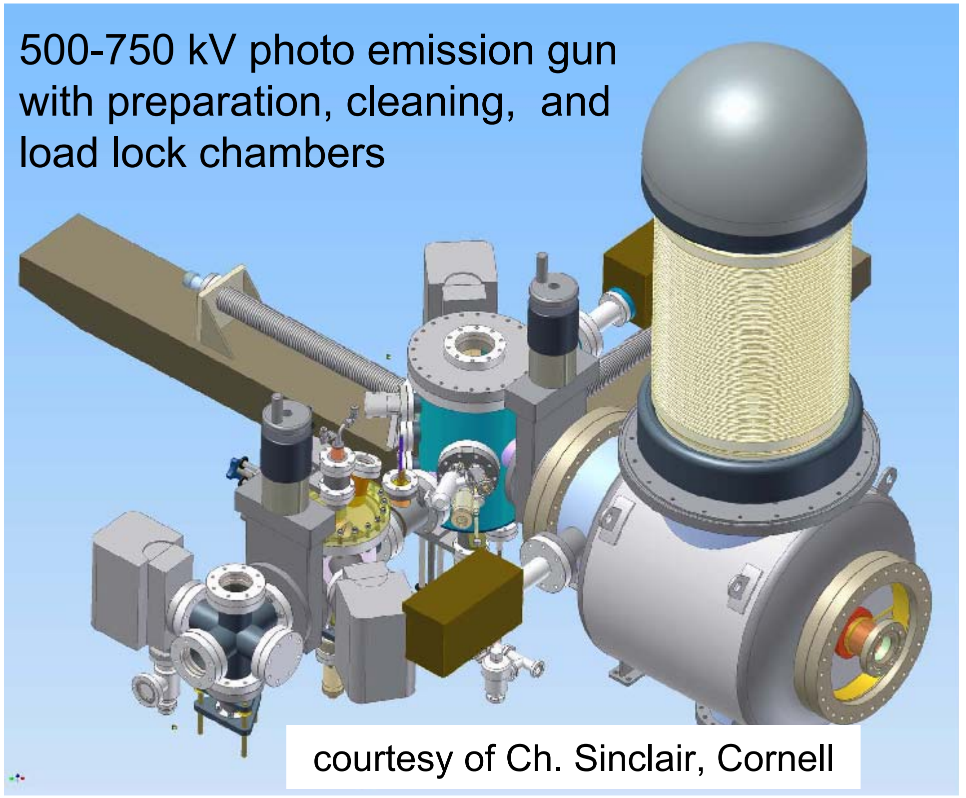
Realization depends on key parameters:

- **operation mode: pulsed or CW**
- **single bunch charge** } **average current**
- **time structure of the beam** } **average current**
- **norm. transverse emittance**
- **long. phase space allows further compression**

- **Introduction**
  - DC electron sources
  - NC RF guns
  - SC RF guns
  - generic injector layout
- **Different Photo Injectors for Different Projects:**
  - **high average current electron sources (<A> ≥ 1 mA)**
    - DC guns from Cornell [data] [sim.]
    - NC RF gun from Boeing [data]
    - SC RF gun developments at Rossendorf [data] [sim.]
    - DC, NC + SC RF gun developments from BNL, JLab, and LANL with AES [data] [sim.]
  - **medium average current electron sources (1 mA > <A> > 1 μA)**
    - NC RF gun at ELSA [data]
    - NC RF gun for VUV-FEL and European XFEL [data] [sim.]
    - NC and SC RF gun for BESSY [sim.]
  - **low average current electron sources (<A> ≤ 1 μA)**
    - NC RF gun from SHI+FESTA [data]
    - NC RF gun injector for SPARC [sim.]
    - NC RF gun developments for LCLS [sim.]
    - some other developments [e.g. LEG at PSI (field emission cathode)] [sim.]
- **Summary**

DC Photo Electron Guns

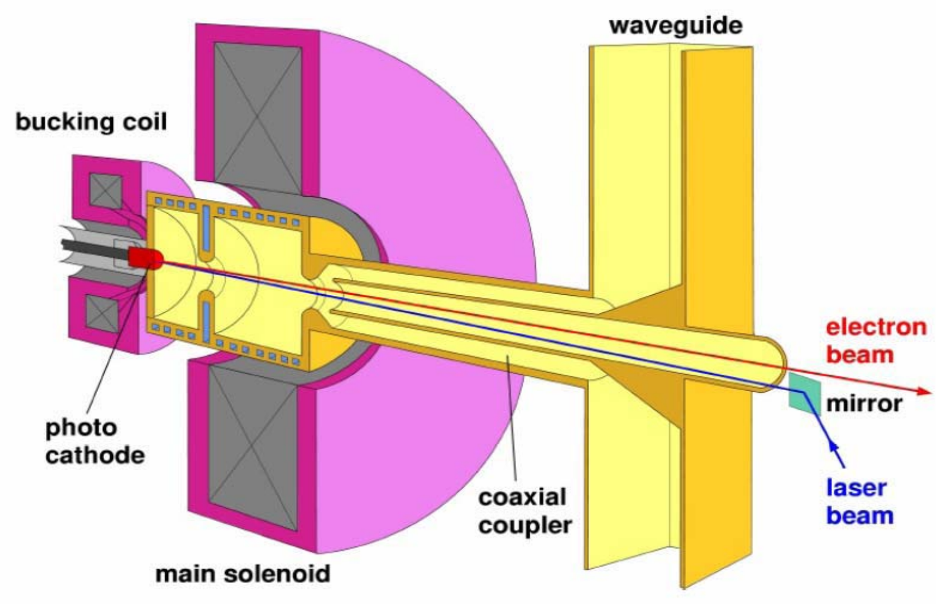
- Advantages
  – good vacuum
    → NEA cathodes (GaAs),
    → low thermal emittance
  – lots of operating experience



courtesy of Ch. Sinclair, Cornell

- Disadvantages
  – low accelerating gradient at cathode
    → long bunches → buncher cavity
  – low beam energy after the source → booster

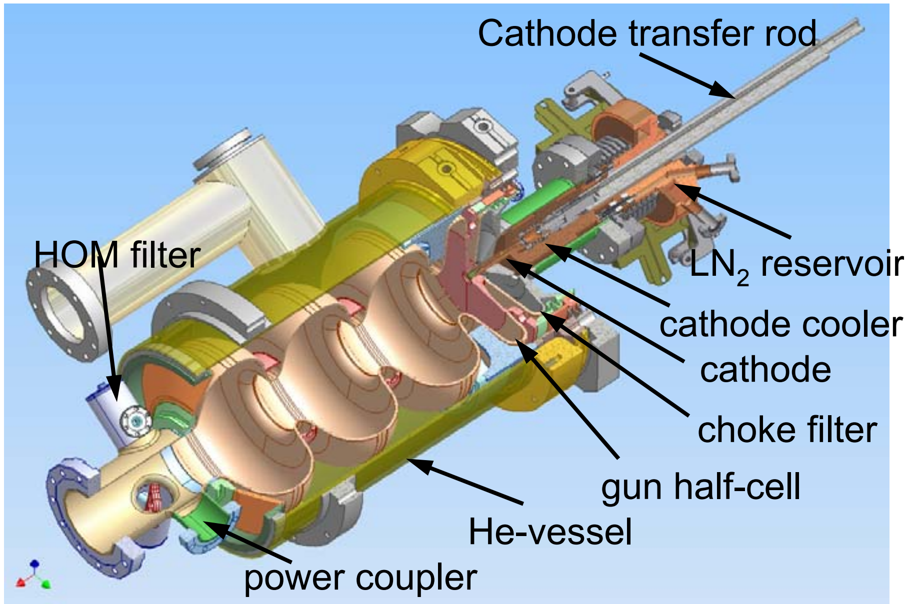
NC RF Guns



- Advantages
  - high accel. gradient at cathode + good space charge compensation → high bunch charge
  - medium beam energy
  - lots of operating experience, emittance record
- Disadvantages
  - medium vacuum conditions
  - water cooling limits average RF power → broad range of average currents (RF frequency)

SC RF Guns

- Advantages
  - high RF duty cycle, CW → high av. beam power
  - good vacuum condition
  - medium beam energy



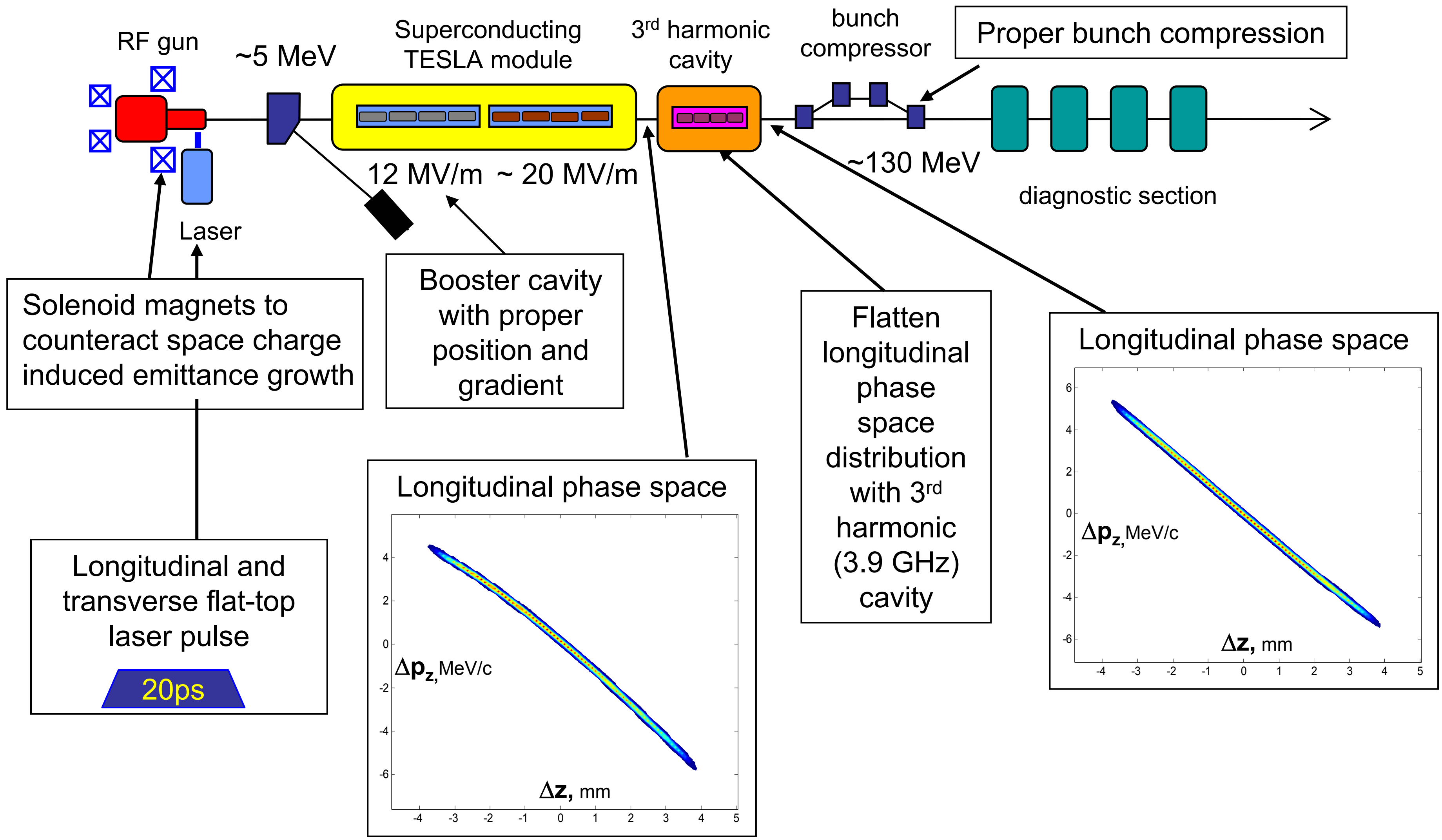
Courtesy of J. Teichert, FZR

- Disadvantages
  - high accel. gradient at cathode, but limited space charge compensation → limited bunch charge **BUT:** new developments are on the way
  - limited operation experience

Generic Photo Injector Design

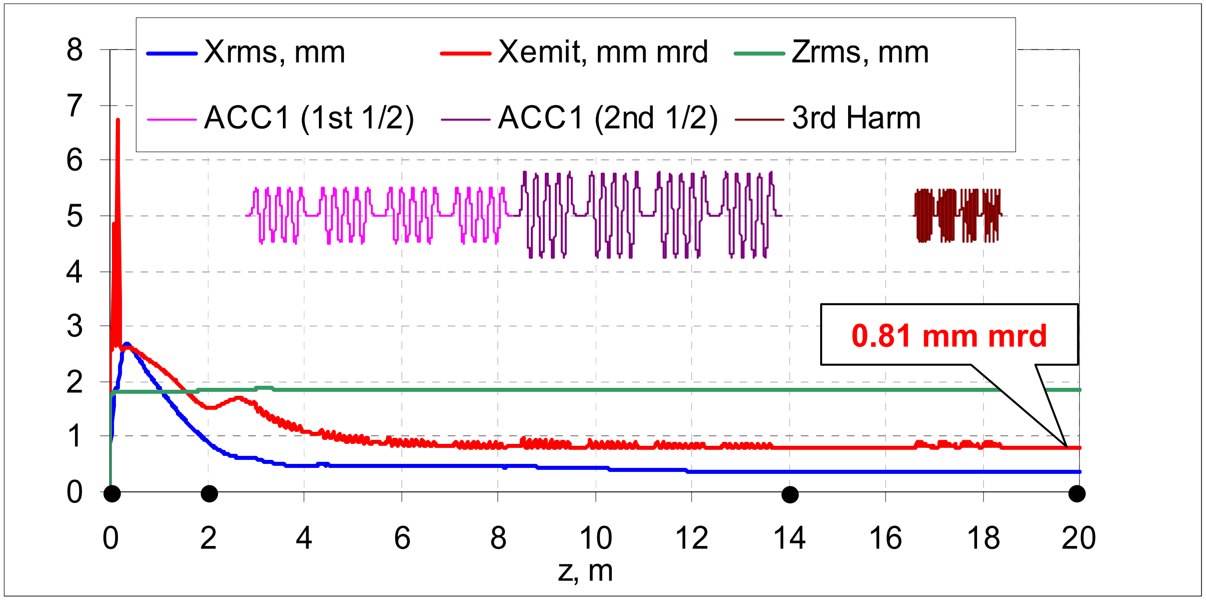
PITZ
Photo Injector Test Facility Zeuthen

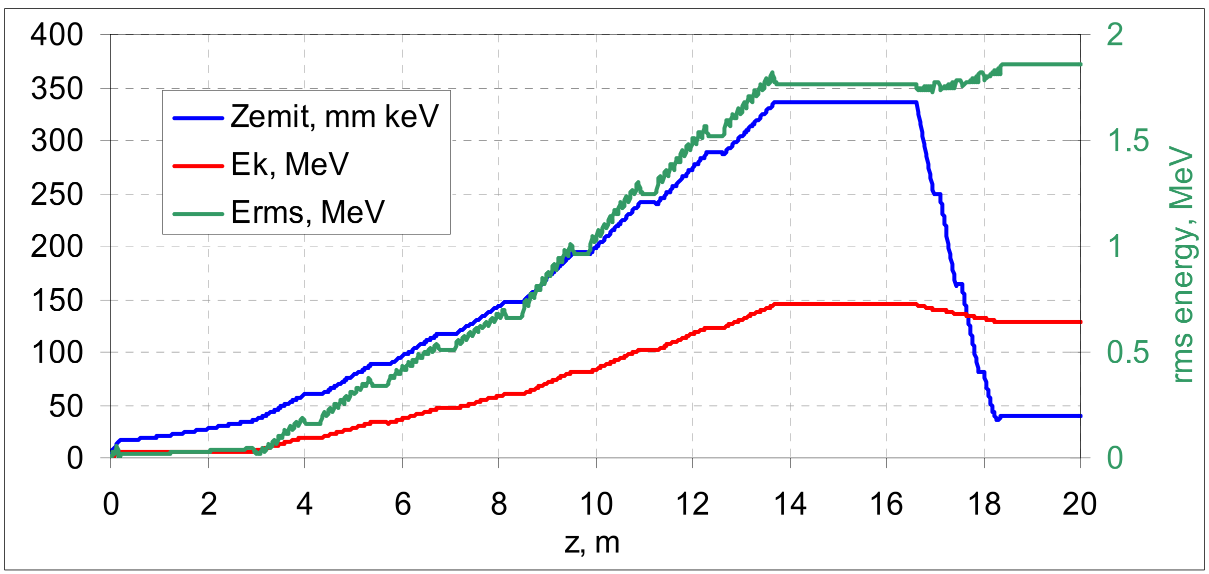
e.g. VUV-FEL injector:



Simulation of ‘upgraded VUV-FEL’

PITZ
Photo Injector Test Facility Zeuthen





ASTRA Simulation parameters:

Q = 1 nC

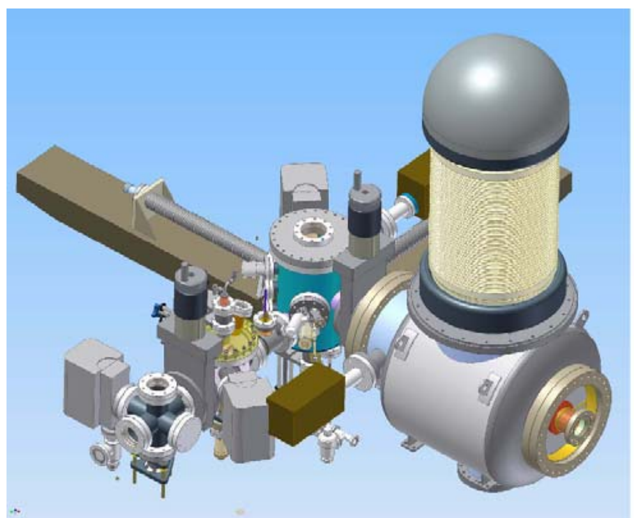
Laser	XYRMS	0.53	mm
	FWHM, Lt	**20**	**ps**
	rise time, rt	**2**	**ps**
	(thermal) LE	0.55	eV
MaxE	**Gun**	**60**	**MV/m**
	ACC1 (1st 1/2)	25.8	MV/m
	ACC1(2nd 1/2)	40	MV/m
Phi	Gun	-2.0	deg
	ACC1 (1st 1/2)	-15.3	deg
	ACC1(2nd 1/2)	-15.3	deg
Booster	(begin) z0	2.8	m
Solenoid	MaxB_main	-0.2253	T
	MaxB_buck	0.0112	T
	S_pos_main	0.276	m
ASTRA	particles	200k	
E-beam (z=20m)	Ek	128	MeV
	dp/p	1.45	%
	Xemit	0.81	mm mrd
	Zrms	1.85	mm

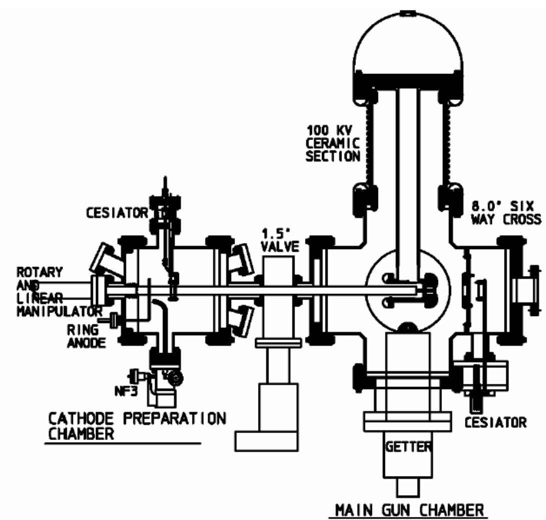
HELMHOLTZ GEMEINSCHAFT DESY

DC Guns @ JLab + Cornell

PITZ
Photo Injector Test Facility Zeuthen

	JLab, exp. results
operation mode	
pulsed / CW	CW
single bunch charge	122 pC
single bunch rep rate	75 MHz
DC voltage / gap	350 kV / 10.57 cm
average current	9.1 mA
norm. trans. emittance (rms)	~ 8-10 mm mrad @ 10 MeV



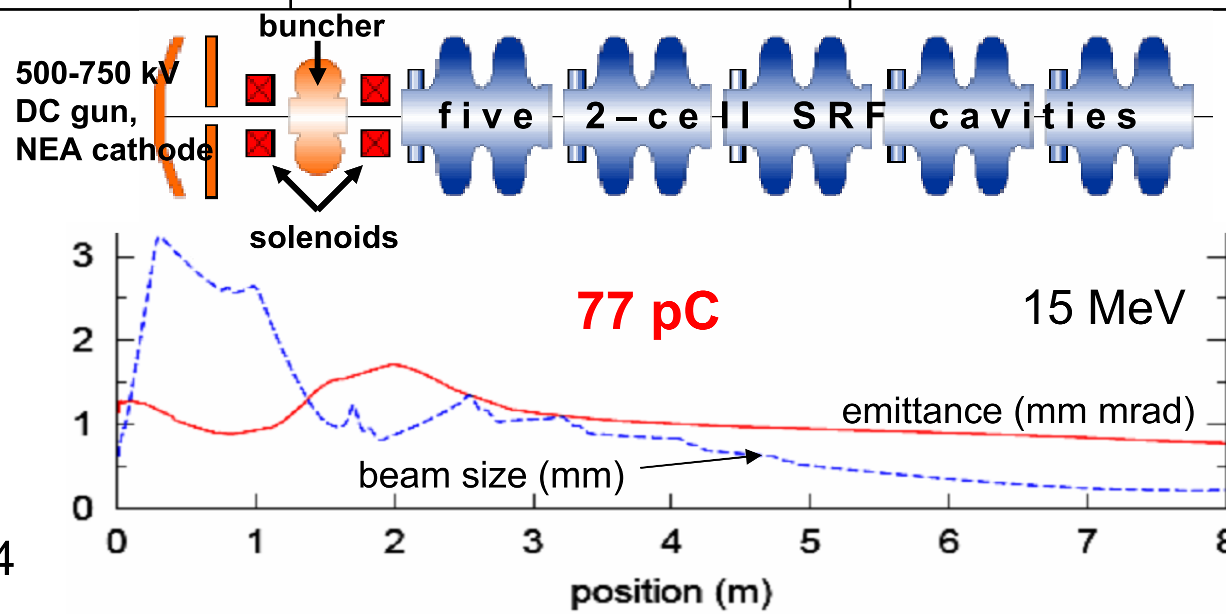


DC Guns @ JLab + Cornell

PITZ
Photo Injector Test Facility Zeuthen

	JLab, exp. results	Cornell, goal parameters	
operation mode		low charge	high charge
pulsed / CW	CW	CW	CW
single bunch charge	122 pC	77 pC	1 nC
single bunch rep rate	75 MHz	1300 MHz	1 – 10 MHz
DC voltage / gap	350 kV / 10.57 cm	~ 600 kV / 5 cm	~ 800 kV / 5 cm
average current	9.1 mA	100 mA	1 mA
norm. trans. emittance (rms)	~ 8-10 mm mrad @ 10 MeV	old: < 1 mm mrad, new: 0.1 mm mrad @ 13 MeV	new: ~ 1 mm mrad @ 13 MeV

old design for ERL-based X-ray source at Cornell:

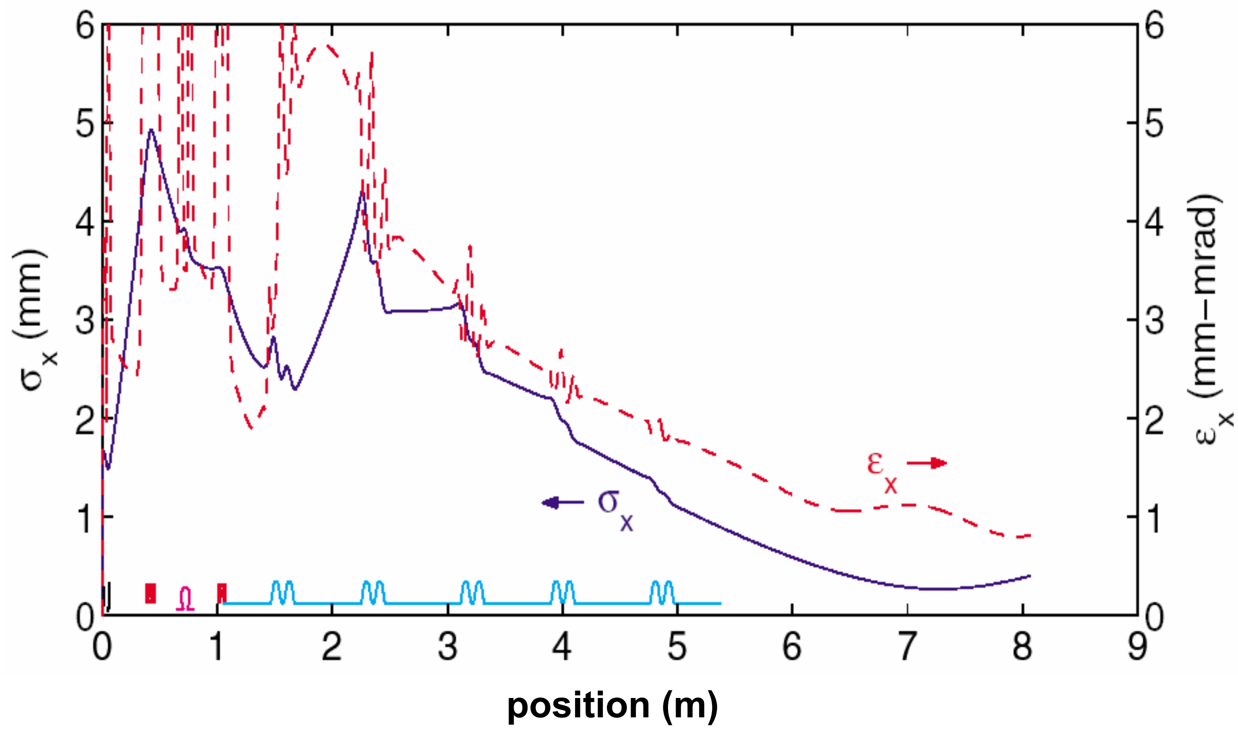


see
I. Bazarov and C. Sinclair, PAC2003, pp. 2062 - 2064

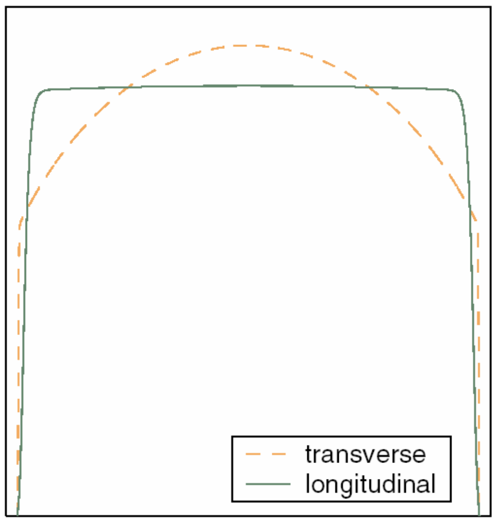
Multivariate Optimization of Injector

- 22 decision variables, incorporating all physical constraints
  (e.g. element field strengths and locations, SRF phases, transverse and longitudinal laser profiles, bunch charge, cathode thermal energy)
- ASTRA used for tracking
- optimization for 80 pC (max. av. brilliance) and 800 pC (high photon flux per pulse)

Results for 800 pC:



opt. laser parameters:



1.6 mm rms spot size

17 ps rms pulse duration

Multivariate Optimization …, continued

PITZ Photo Injector Test Facility Zeuthen

Parameter	old design, PAC2003	This work	Units
Charge	80	80	pC
Laser spot size (rms)	0.6	0.3	mm
Laser pulse duration (rms)	20	11	ps
dc gun voltage	500	750	kV
Buncher voltage	116	126	kV
SRF cavity 1 gradient	9.8	5.5	MV/m
SRF cavities 2–5 gradient	7.2	10.6	MV/m
SRF cavity 1 phase	10	43	°
Solenoid 1 peak field	0.058	0.077	T
Solenoid 2 peak field	0.040	0.043	T
Solenoid 1 position	0.29	0.26	m
Solenoid 2 position	1.00	1.12	m
Buncher position	0.80	0.57	m
SRF cavity 1 position	1.80	1.90	m
Transverse emittance (rms)	0.82	0.14	mm mrad
Bunch length (rms)	0.80	0.78	mm
Longitudinal emittance (rms)	8.7	6.2	mm keV
Kinetic energy	10.6	12.6	MeV

Results for 80 pC

→ impressive results for 80 and 800 pC

→ shows importance and benefit of multiv. optimization

Experimental Schedule:

- first electrons from gun in Dec. 2005
- mid 2006: laser for 1.3 GHz operation
- early 2008: injector cryomodule ready

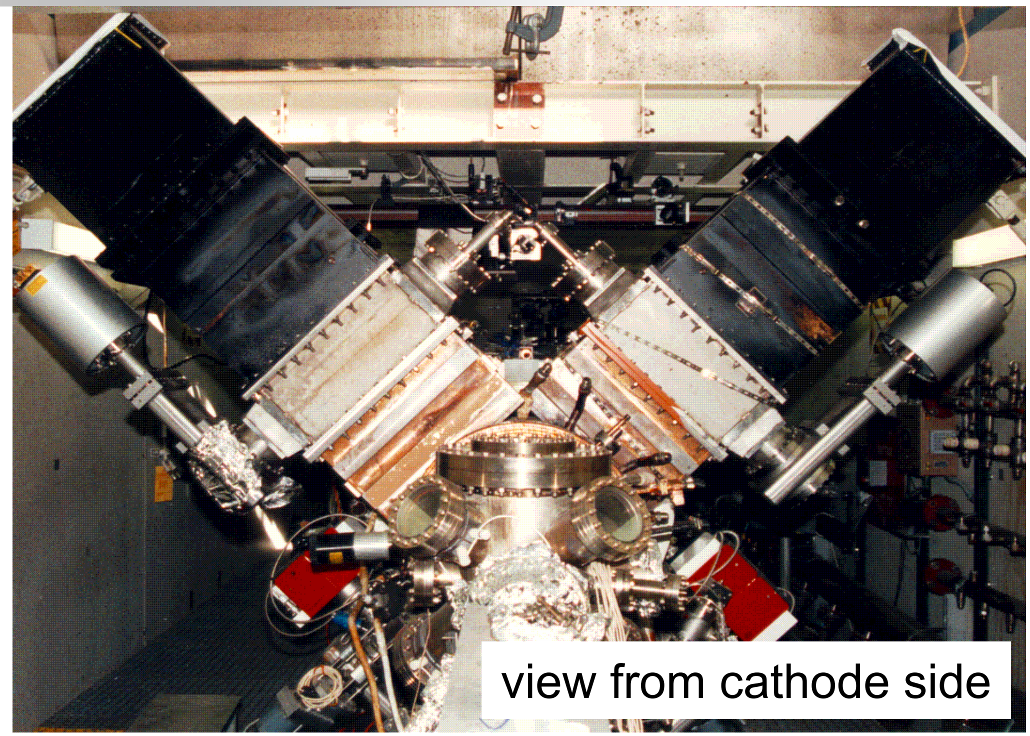
- **possible problems, e.g.:**
  - temporal response of GaAs cathode might degrade temporal electron bunch profile at emission
  - desired gun voltage of 500-750 kV is above presently achieved values (→ geometry changes, coatings)
  - beam energy still low, needs proper matching of following accelerator
- **possible source for polarized electrons (→ cathode + laser)**

NC RF Gun @ Boeing

PITZ
Photo Injector Test Facility Zeuthen

parameters measured in 1992:

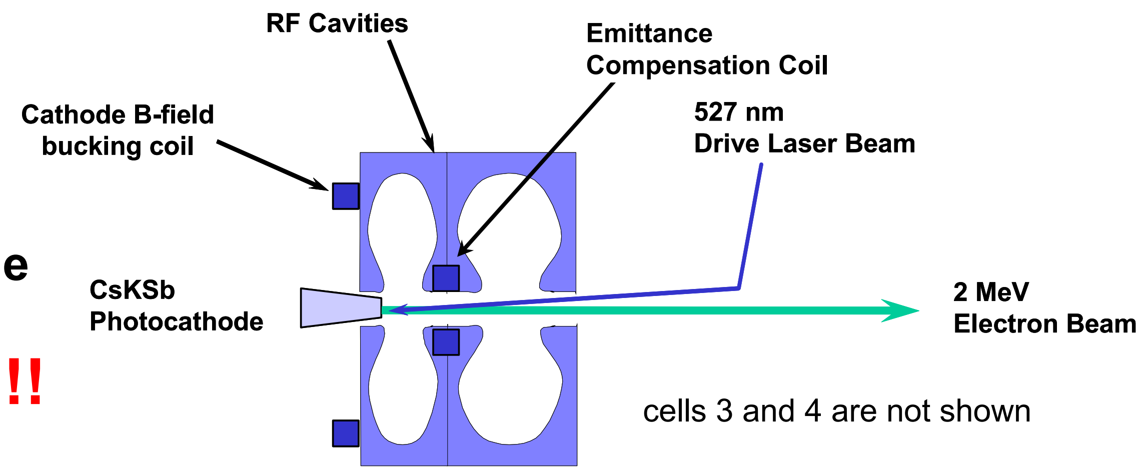
pulsed / CW	pulsed
single bunch charge	1 – 7 nC
single bunch rep rate	27 MHz
length of bunch train	8.3 ms
bunch train rep rate	30 Hz
average current	6.7 – 47 mA
norm. trans. emittance (rms)	5 – 10 mm mrad @ 5 MeV
rf frequency	433 MHz



duty cycle: 25 %
RF power: **600 kW**

re-entrant design
→ 25 MV/m peak field @ cathode

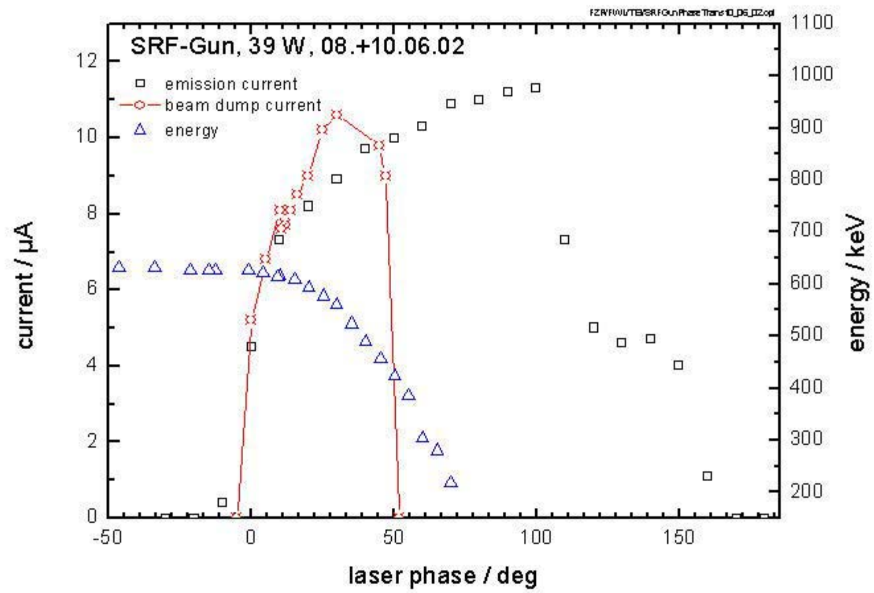
record average current !!!

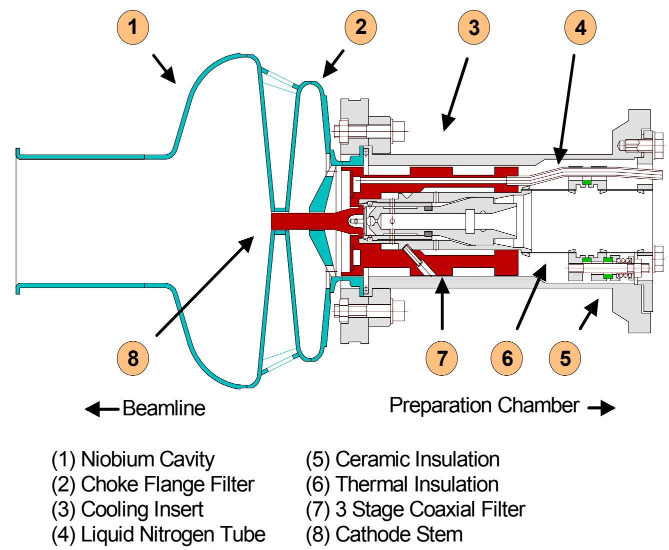


SC Guns @ FZ Rossendorf

PITZ
Photo Injector Test Facility Zeuthen

gun type	½ cell gun results obtained
operation mode	
pulsed / CW	CW
single bunch charge	1-20 pC
single bunch rep rate	26 MHz
length of bunch train	-
bunch train rep rate	-
average current	≤ 130 µA
norm. trans. emittance (rms)	2.5 mm mrad @ 4 pC, 900 keV
rf frequency	1.3 GHz





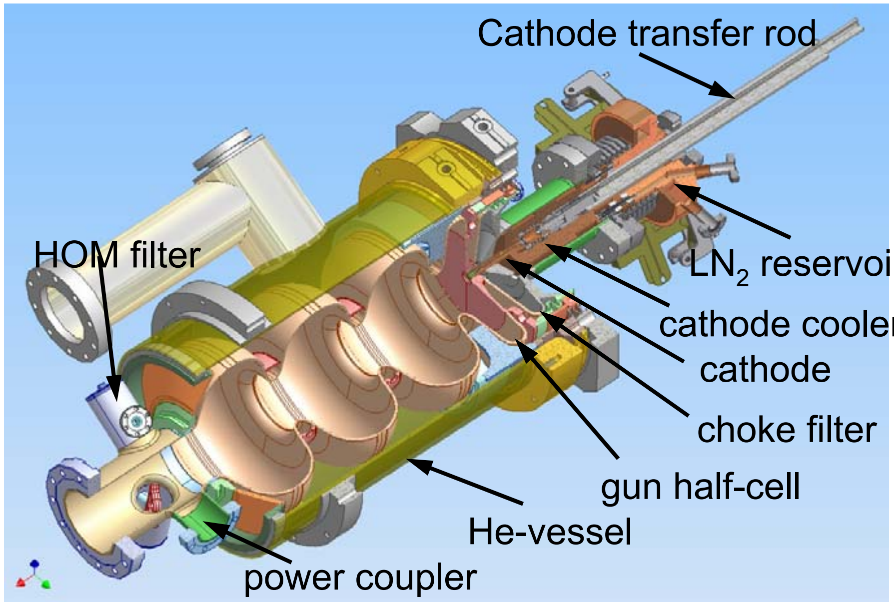
- NC Cs_2Te cathode in SC gun → high QE → relax requirements on laser system
- no Q degradation observed over 7 weeks (5h/d)

NIM A 507 (2003) 314, Courtesy of J. Teichert and D. Janssen, FZR

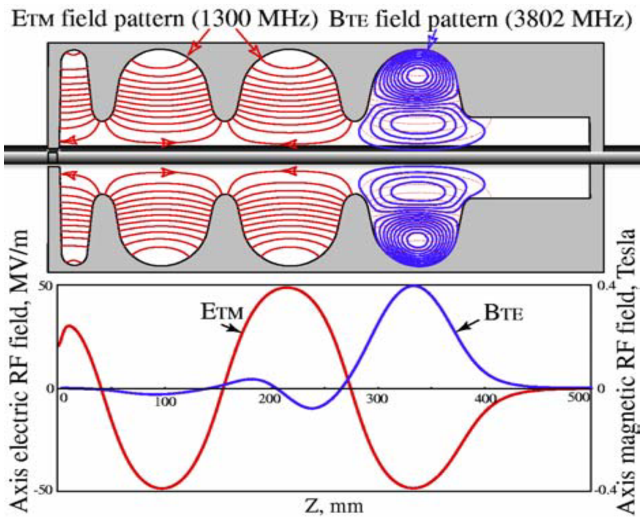
SC Guns @ FZ Rossendorf

PITZ
Photo Injector Test Facility Zeuthen

gun type	3.4 cell gun, Goals	
operation mode	ELBE	high charge
pulsed / CW	CW	CW
single bunch charge	77 pC	1 nC
single bunch rep rate	13 MHz	1 MHz
average current	1 mA	1 mA
norm. trans. emittance (rms)	1.5 mm mrad @ 9.5 MeV	2.5 mm mrad @ 9.5 MeV
rf frequency	1.3 GHz	1.3 GHz



With magnetic mode:

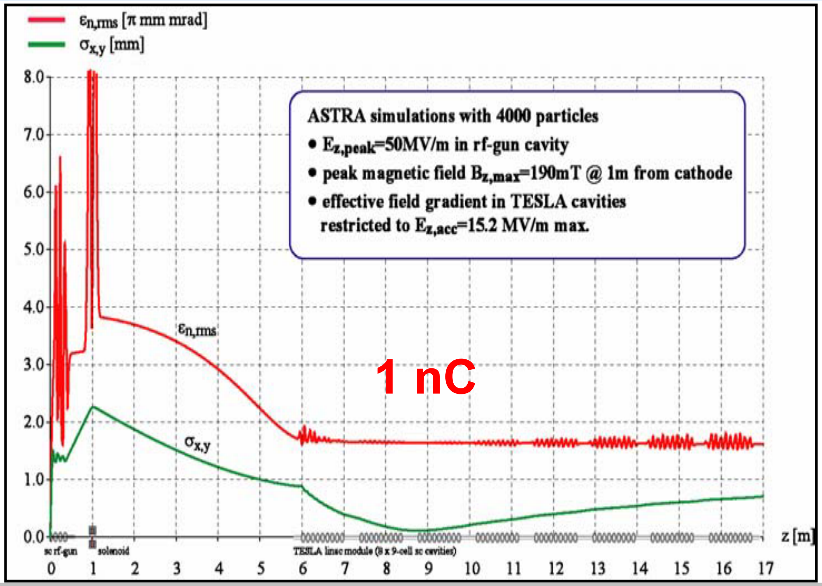


$\Rightarrow \varepsilon_n$ (1nC, 8.8MeV) = 0.8-1.0 mm mrad dep. on BTE phase

(no therm. emittance)

Status:

- two 3.4 cell guns tuned
- first beam autumn 2006



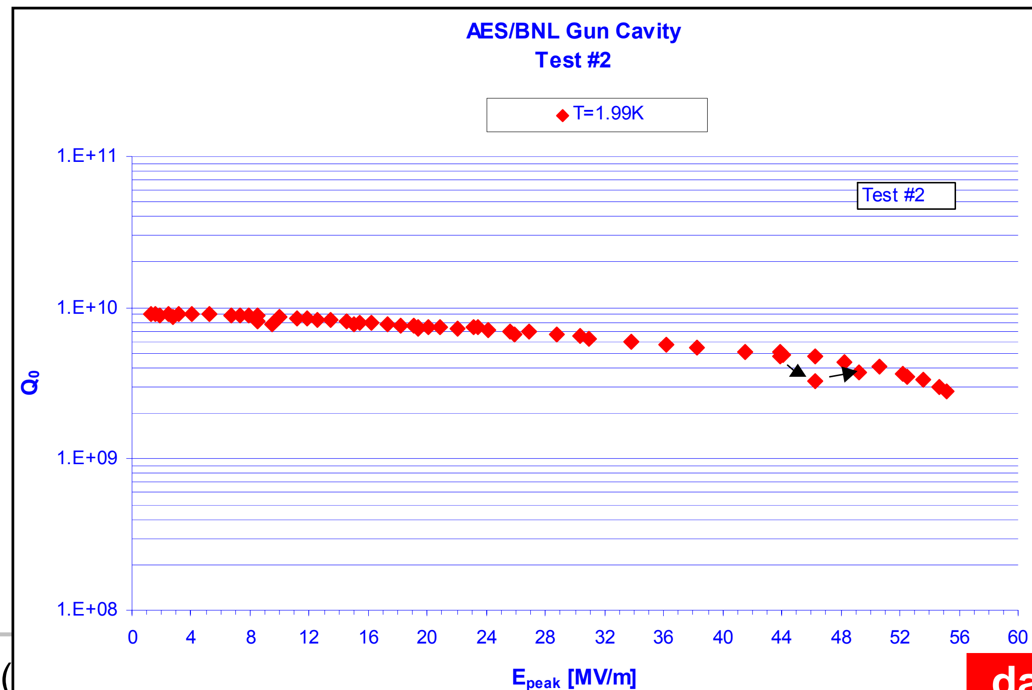
FEL2003, FEL2004, Courtesy of J. Teichert and D. Janssen, FZR

sim.

Source Developments with AES

PITZ
Photo Injector Test Facility Zeuthen

gun type	½, SC, all Ni	½, SC, NC cath.	DC + SRF boost.	2½, NC RF, CW
collabor. partners	BNL, data	BNL, design	JLab, design	LANL, design
pulsed / CW	the QE was measured to be $2 \cdot 10^{-6}$ @266nm $1 \cdot 10^{-5}$ @248nm	CW	CW	CW
single bunch charge / nC		1.42 / 10	0.133	1.0
single bunch rep rate / MHz		351.87 / 10	748.5	100
average current / mA		500 / 100	100	100
norm. trans. emittance (rms, geom. av.) / mm mrad		2.4 @ 2 MeV / 11.1 @ 3.2 MeV	1.2 @ 7.7 MeV	4 @ 2 MeV
rf frequency / MHz	1300	703.75	booster: 748.5	700



data

Source Developments with AES

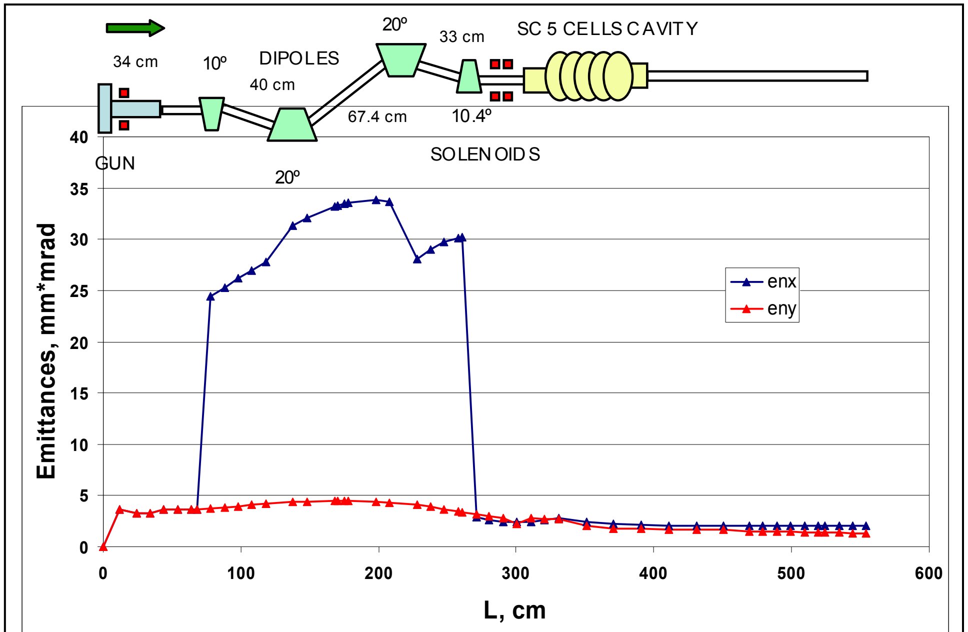
gun type	½, SC, all Ni	½, SC, NC cath.	DC + SRF boost.	2½, NC RF, CW
collabor. partners	BNL, data	BNL, design	JLab, design	LANL, design
pulsed / CW		CW	CW	CW
single bunch charge / nC	the QE was measured to be	1.42 / 10	0.133	1.0
single bunch rep rate / MHz		351.87 / 10	748.5	100
average current / mA	$2 \cdot 10^{-6}$ @266nm	500 / 100	100	100
norm. trans. emittance (rms, geom. av.) / mm mrad	$1 \cdot 10^{-5}$ @248nm	2.4 @ 2 MeV / 11.1 @ 3.2 MeV	1.2 @ 7.7 MeV	4 @ 2 MeV
rf frequency / MHz	1300	703.75	booster: 748.5	700

diamond amplifier cathode:

→ I. Ben-Zvi

more on SC RF guns:

→ J. Sekutovicz



Emittances evolution for 1.4 nC bunch

- for ERL
- in final design
- first beam 2007

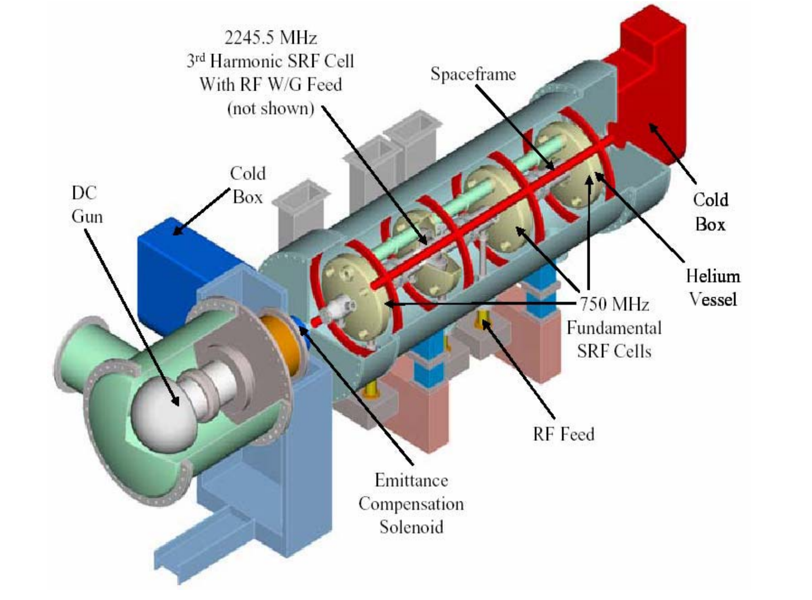
EPAC2004, ERL2005, Courtesy of AES+BNL+LANL

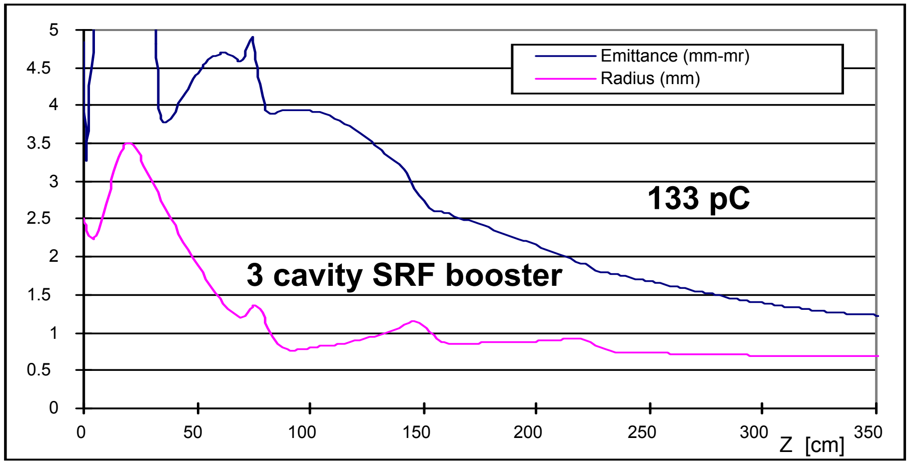
sim.

Source Developments with AES

PITZ Photo Injector Test Facility Zeuthen

gun type	½, SC, all Ni	½, SC, NC cath.	DC + SRF boost.	2½, NC RF, CW
collabor. partners	BNL, data	BNL, design	JLab, design	LANL, design
pulsed / CW	the QE was measured to be $2 \cdot 10^{-6}$ @266nm $1 \cdot 10^{-5}$ @248nm	CW	CW	CW
single bunch charge / nC		1.42 / 10	0.133	1.0
single bunch rep rate / MHz		351.87 / 10	748.5	100
average current / mA		500 / 100	100	100
norm. trans. emittance (rms, geom. av.) / mm mrad		2.4 @ 2 MeV / 11.1 @ 3.2 MeV	1.2 @ 7.7 MeV	4 @ 2 MeV
rf frequency / MHz	1300	703.75	booster: 748.5	700



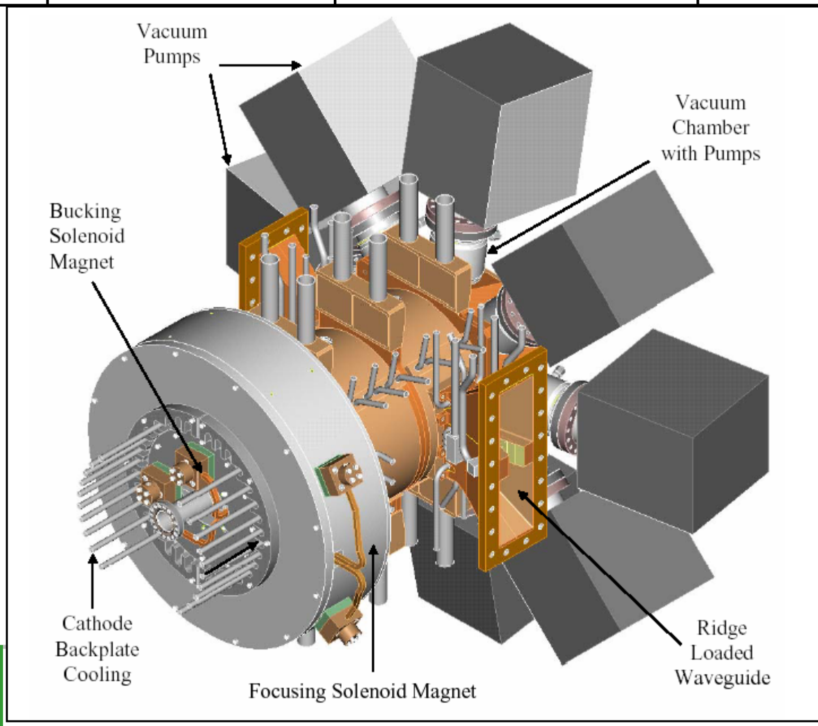


Assembly of cryomodule in progress

Source Developments with AES

PITZ
Photo Injector Test Facility Zeuthen

gun type	½, SC, all Ni	½, SC, NC cath.	DC + SRF boost.	2½, NC RF, CW
collabor. partners	BNL, data	BNL, design	JLab, design	LANL, design
pulsed / CW	the QE was measured to be $2 \cdot 10^{-6}$ @266nm $1 \cdot 10^{-5}$ @248nm	CW	CW	CW
single bunch charge / nC		1.42 / 10	0.133	1.0
single bunch rep rate / MHz		351.87 / 10	748.5	100
average current / mA		500 / 100	100	100
norm. trans. emittance (rms, geom. av.) / mm mrad		2.4 @ 2 MeV / 11.1 @ 3.2 MeV	1.2 @ 7.7 MeV	4 @ 2 MeV
rf frequency / MHz	1300	703.75	booster: 748.5	700



average power: ≤ 720 kW

gun in fabrication,

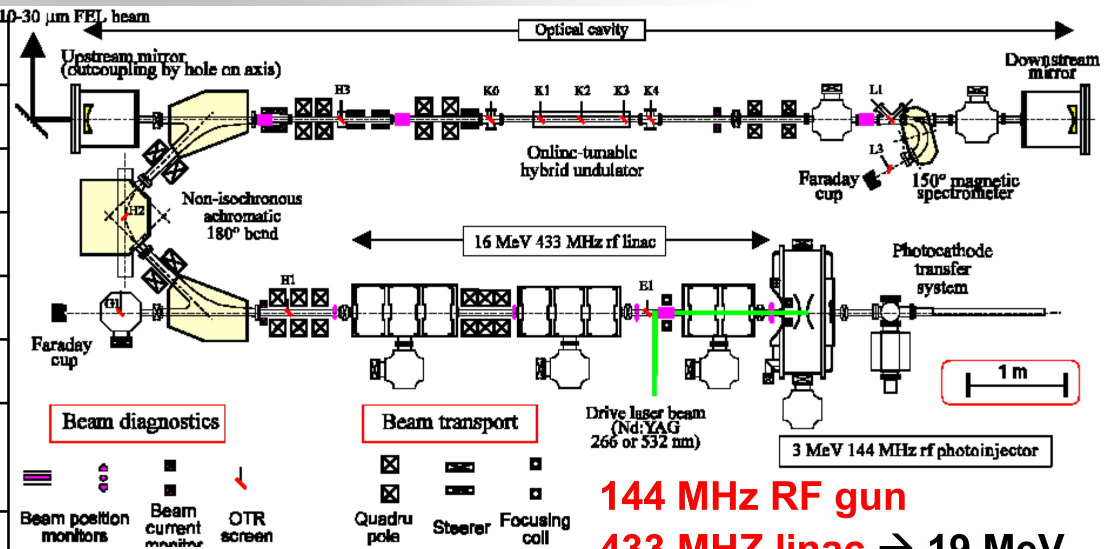
high power test in 2006

EPAC2004, ERL2005, Courtesy of AES+BNL+LANL

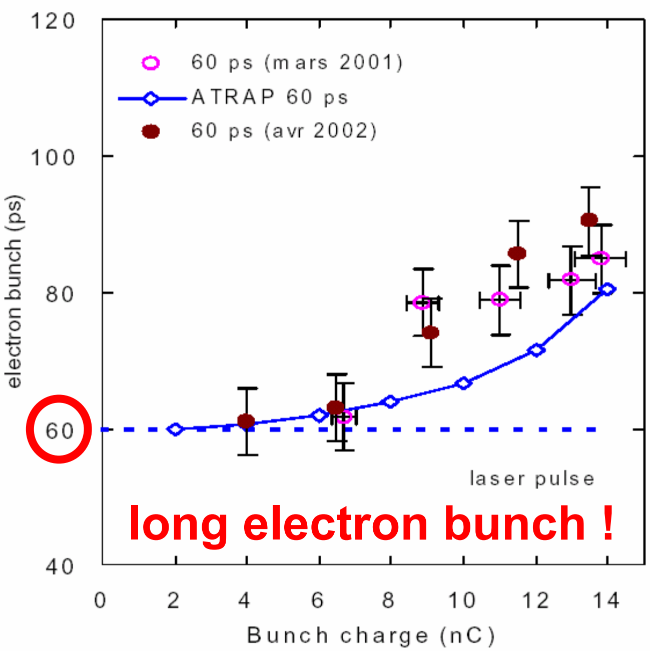
Emittance from ELSA@CEA

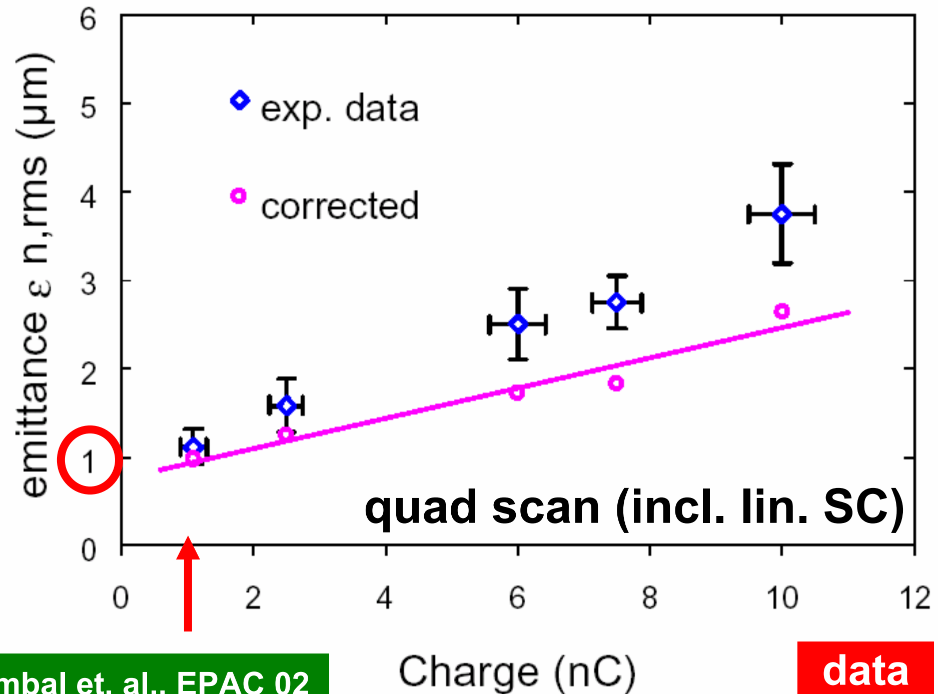
PITZ
Photo Injector Test Facility Zeuthen

pulsed / CW	pulsed
single bunch charge	1 – 3 nC
single bunch rep rate	72 MHz
length of bunch train	≤ 140 µs
bunch train rep rate	1 – 10 Hz
average current	≤ 300 µA
norm. trans. emittance (rms)	~ 1 – 1.5 mm mrad @ 19 MeV
rf frequency	144 / 433 MHz



144 MHz RF gun
433 MHZ linac → 19 MeV





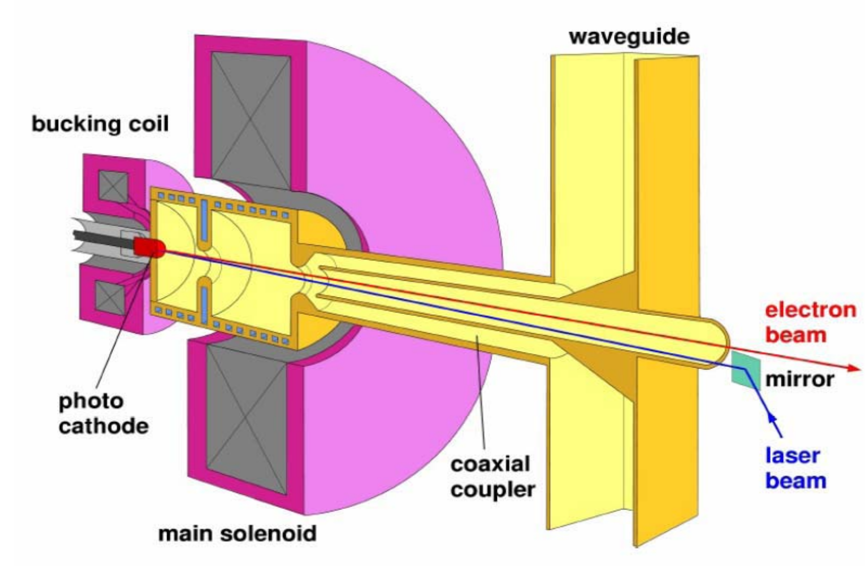
Ph. Guimbal et. al., EPAC 02

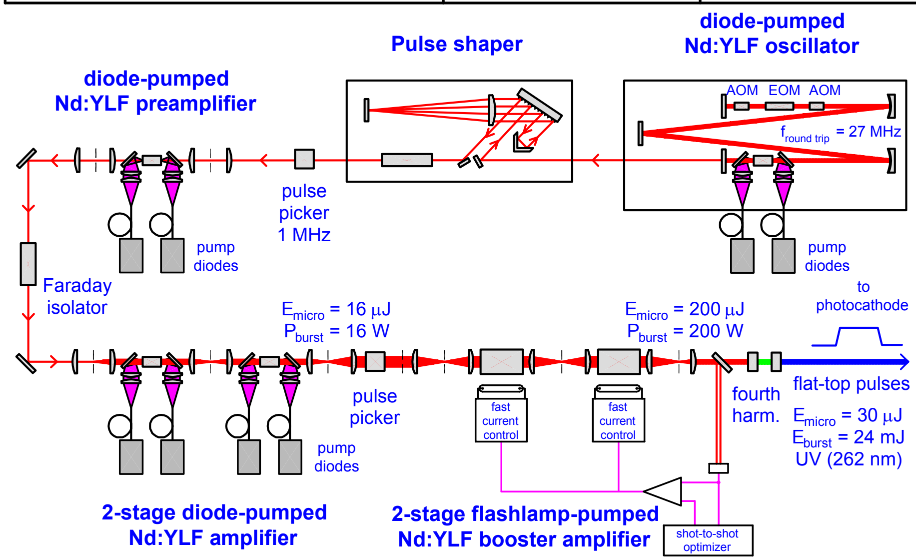
data

PITZ: RF Gun for VUV-FEL + XFEL

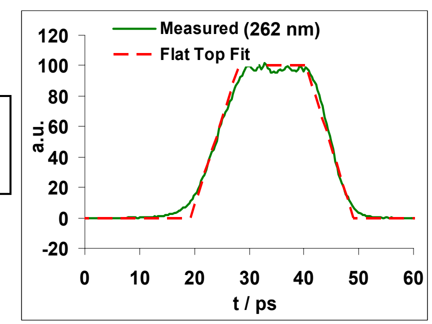
PITZ
Photo Injector Test Facility Zeuthen

Goal parameters:	VUV-FEL	Europ. XFEL
pulsed / CW	pulsed	pulsed
single bunch charge	1 nC	1 nC
single bunch rep rate	1 – 9 MHz	5 MHz
length of bunch train	≤ 800 µs	≤ 650 µs
bunch train rep rate	1 – 10 Hz	10 Hz
average current	≤ 72 µA	≤ 32.5 µA
norm. trans. emittance (rms)	2 mm mrad @ 1 GeV	1.4 mm mrad @ 20 GeV
rf frequency	1.3 GHz	1.3 GHz

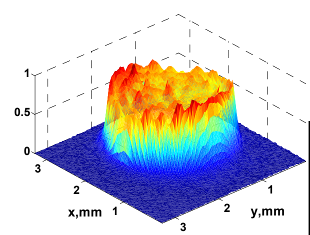




laser profiles:



FWHM ≈ 19-24 ps
rise/fall ≈ 7-9 ps



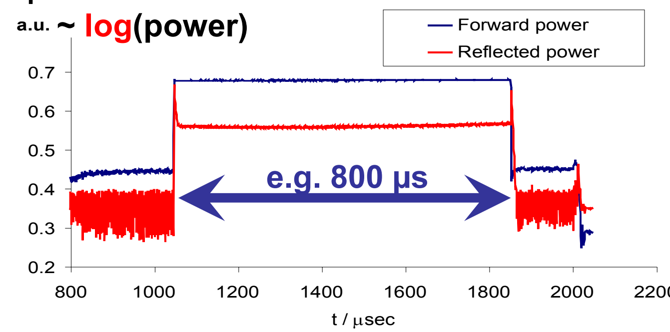
σ_x = 0.57 ± 0.02 mm
σ_y = 0.58 ± 0.02 mm

PITZ: RF Gun for VUV-FEL + XFEL

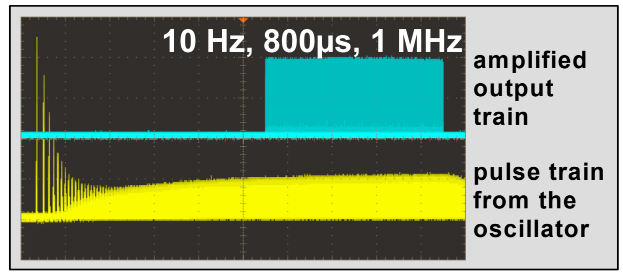
PITZ
Photo Injector Test Facility Zeuthen

Goal parameters:	VUV-FEL	Europ. XFEL
pulsed / CW	pulsed	pulsed
single bunch charge	1 nC	1 nC
single bunch rep rate	1 – 9 MHz	5 MHz
length of bunch train	≤ 800 μs	≤ 650 μs
bunch train rep rate	1 – 10 Hz	10 Hz
average current	≤ 72 μA	≤ 32.5 μA
norm. trans. emittance (rms)	2 mm mrad @ 1 GeV	1.4 mm mrad @ 20 GeV
rf frequency	1.3 GHz	1.3 GHz

long RF pulse:



long laser pulse train:



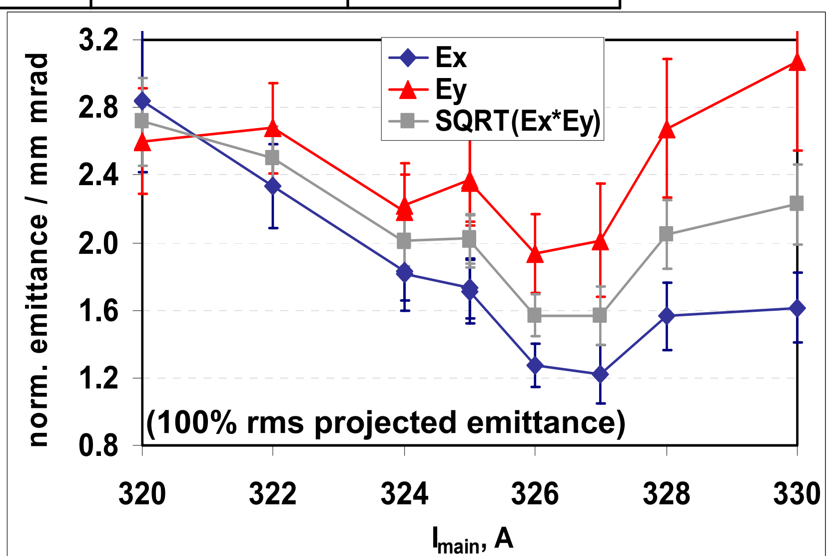
measured @ PITZ:

p = 5.2 MeV/c

Q = 1 nC

$\Phi = \Phi_m$

$I_{buck} = I_{main} * 0.075$



measured @ VUV-FEL:

p = 127 MeV/c

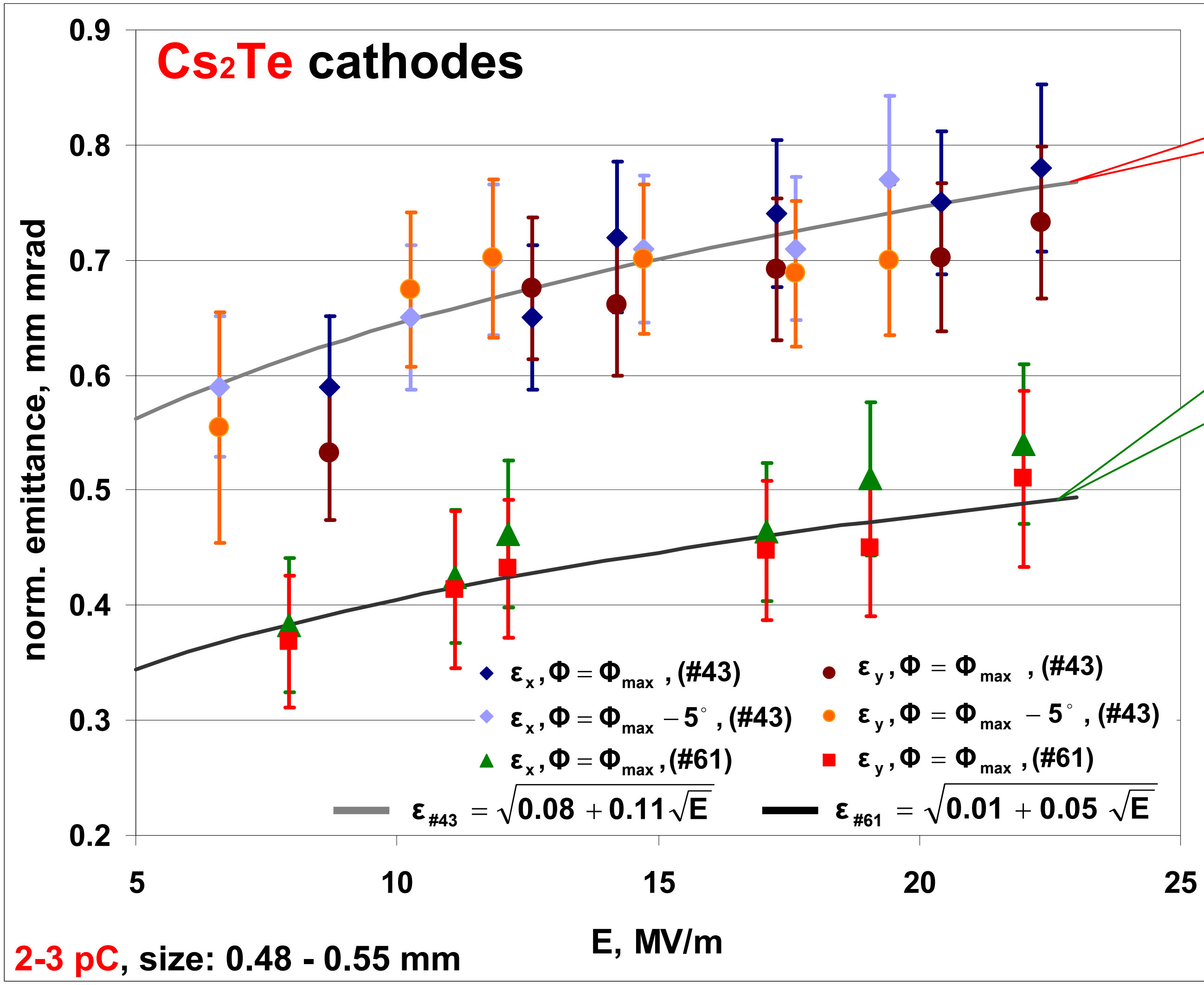
Q = 1 nC

- regularly obtain 2.1 mm mrad (100% rms projected emittance)
- minimum 1.1 mm mrad (90% rms projected emittance)

Challenge: Low Thermal Emittance

PITZ
Photo Injector Test Facility Zeuthen

Thermal Emittance Measurements at PITZ:



cathode no. 43, Nov.2004, QE ~ 3%

cathode no. 61, Apr.2004, QE ~ 1%

ε_{th} depends on individual cathode and its surface chemistry

→ $\varepsilon_{th} = \varepsilon_{th}(t)$

→ more cathode studies needed !

see also talk of
→ J.H. Han

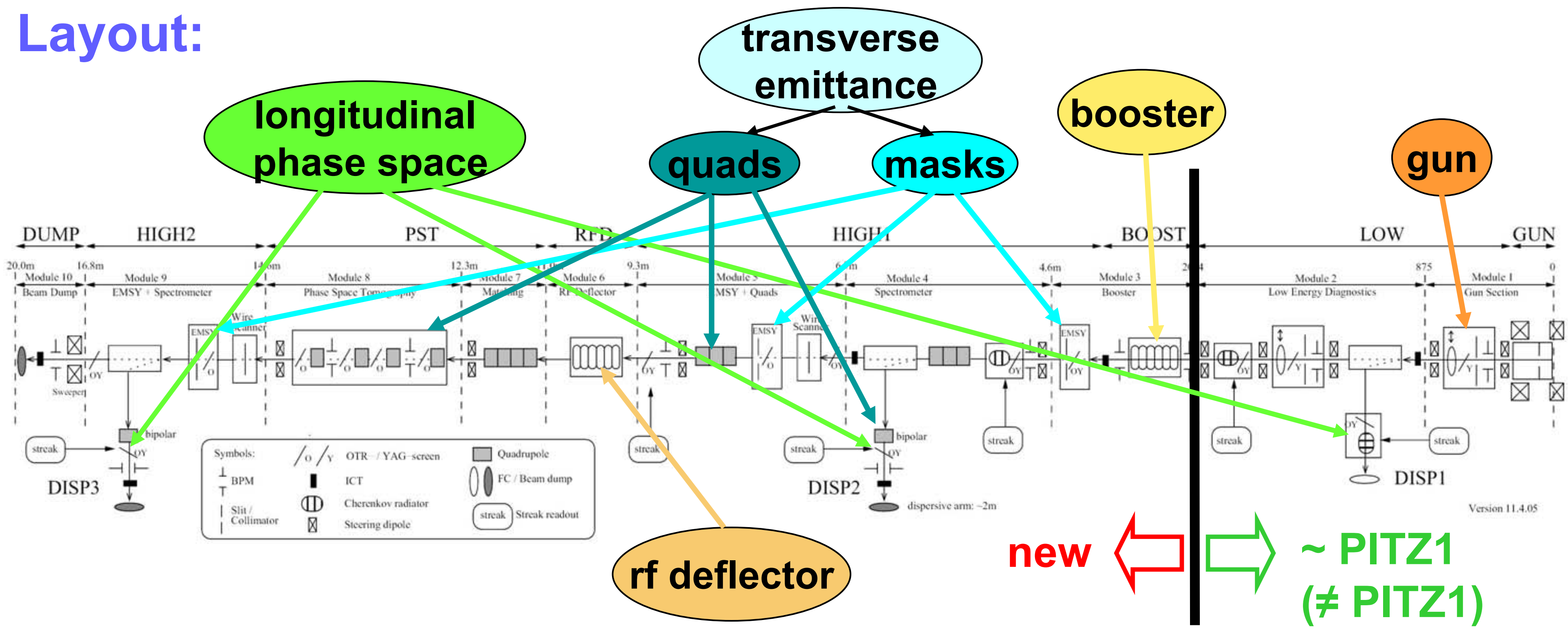
Upgrade of PITZ → PITZ2

PITZ
Photo Injector Test Facility Zeuthen

Goals:

- **reach XFEL requirements:** **0.9 mm mrad @ 1 nC from injector:**
  - increase RF field on photo-cathode
  - improve laser system (mainly rise/fall time ≤ 2 ps)
- **study emittance conservation principle:**
  - booster cavity (preliminary: TESLA booster, final: CDS booster)
  - new diagnostics beam line

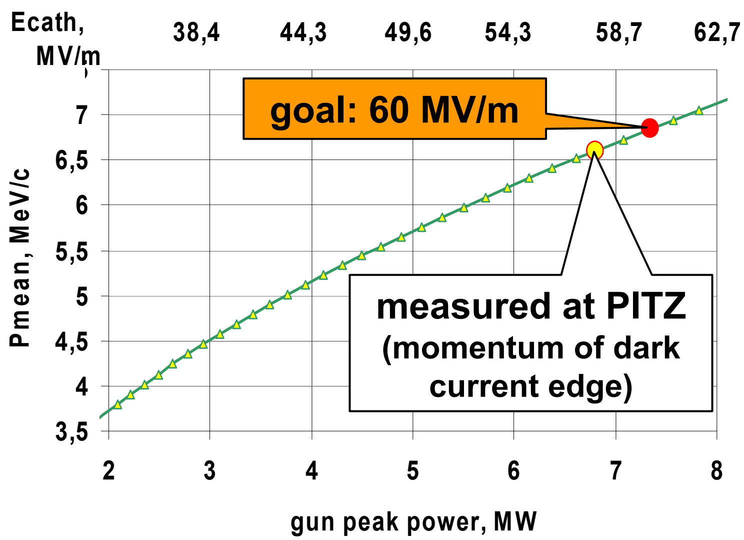
Layout:



First Results from PITZ2, Outlook

PITZ
Photo Injector Test Facility Zeuthen

max. mean momentum ↔ gun power

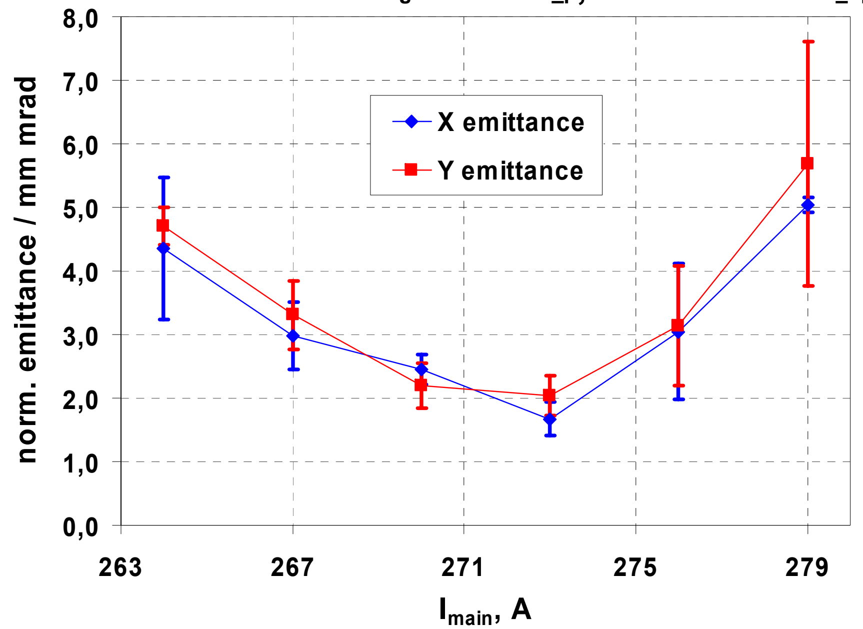


in operation !

first preliminary emittance results (not optimized yet !)

p = 12.8 MeV/c, Q = 1 nC,

$\Phi_{gun} = \Phi_{max\_p}$, $\Phi_{booster} = \Phi_{min\_dp}$



Outlook:

- new gun cavity (#3) in Dec. 2005
- final booster in autumn 2006
- new laser system in spring 2007

BESSY FEL Injector Design

PITZ
Photo Injector Test Facility Zeuthen

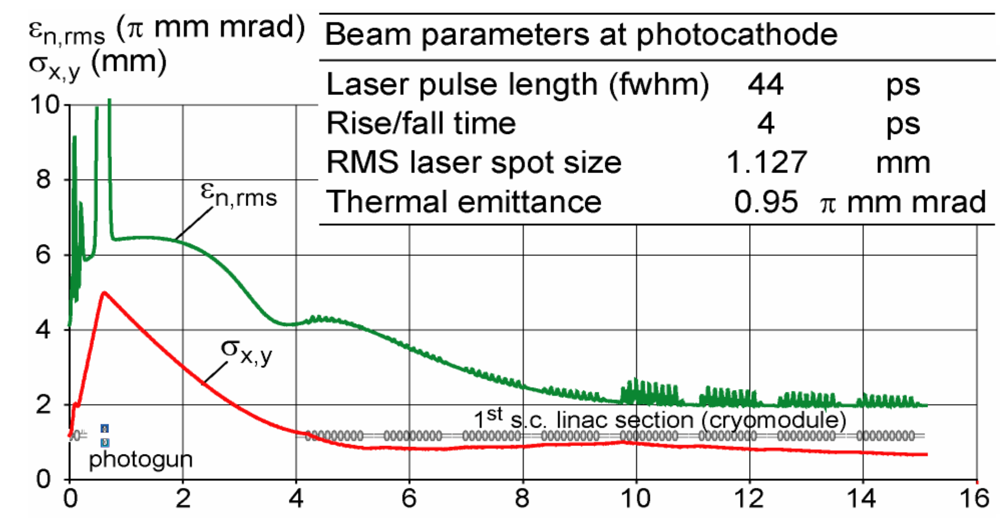
operation mode	phase 1, NC gun	phase 2, SC gun
pulsed / CW	pulsed	CW
single bunch charge	2.5 nC	2.5 nC
single bunch rep rate	333 kHz	> 25 kHz
length of bunch train	3 bunches	-
bunch train rep rate	1 kHz	-
average current	7.5 μA	> 62.5 μA
norm. trans. emittance (rms), center slice at 2.3 GeV	1.5 mm mrad	1.5 mm mrad
rf frequency	1.3 GHz	1.3 GHz

NC gun:

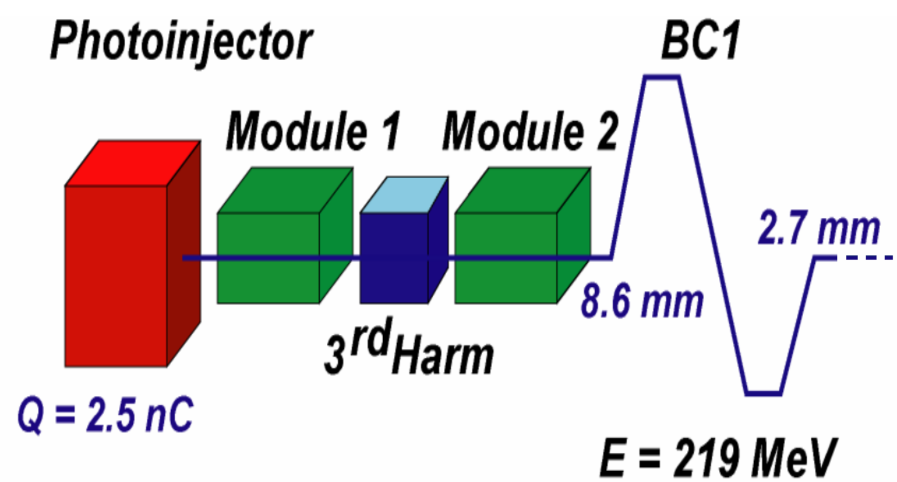
- fabricated
- power test @ PITZ in 2006

SC gun:

- 1.625 cell design available
- participate in FZR 3.4 cell tests



60 MV/m

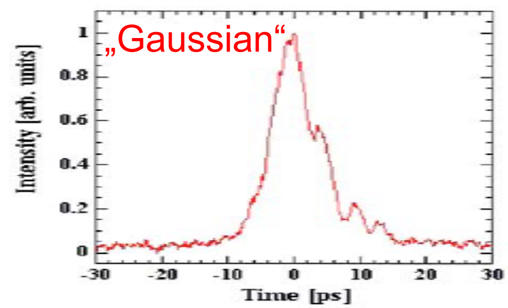


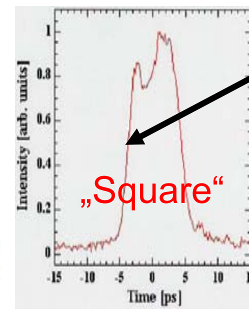
Emittance Record from SHI+FESTA

PITZ Photo Injector Test Facility Zeuthen

pulsed / CW	pulsed
single bunch charge	0.25 – 1.2 nC
single bunch rep rate	10 Hz
average current	2.5 – 12 nA
norm. horiz. emittance (rms)	~ 0.8 – 1.4 mm mrad @ 14 MeV

- 1.6 cell S-band gun (→ 4 MeV) + 70 cm SW linac (→ 14 MeV)
- Ti:Saphire laser system (→ 50 fs long pulses at 800 nm) + pulse shaping (e.g. gratings + liquid crystal spatial light mod.)
- temporal shape of laser pulses: (x-ray streak camera, resolution: ~2 ps)



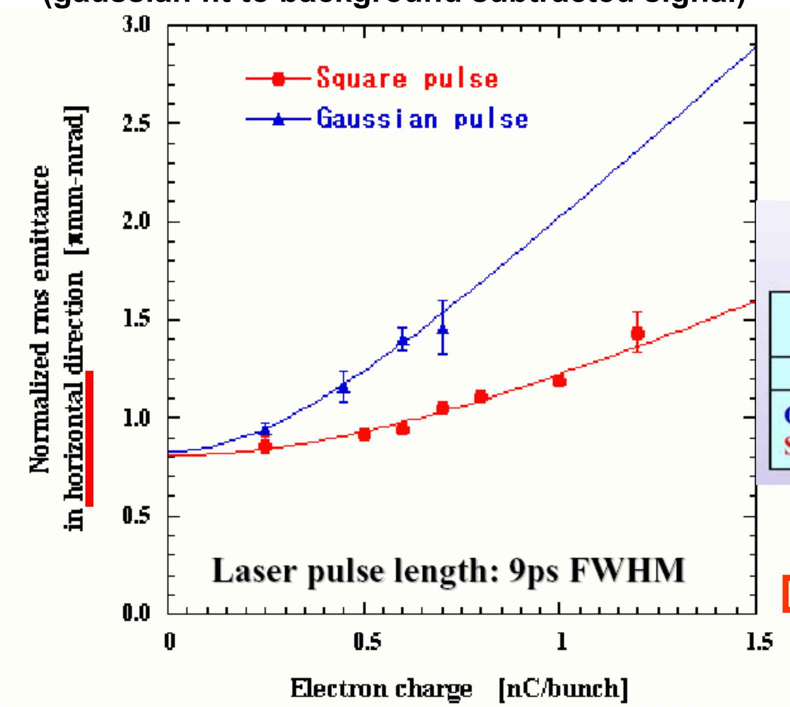


rise / decay time: 1.5 ps,

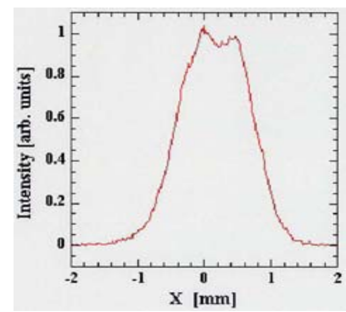
limited by streak cam.

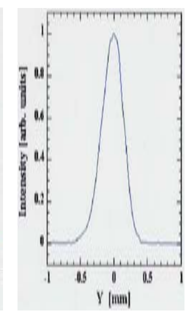
Methode: quad scan @ 14 MeV

(gaussian fit to background subtracted signal)



- transverse laser distributions: (@cathode)





$$\varepsilon_n = \sqrt{(a'\,Q)^2 + b'^2}$$

	a'	$b' = \sqrt{\varepsilon_{rf}^2 + \varepsilon_{th}^2}$
	πmm-mrad/nC	πmm-mrad
Gaussian(9ps)	1.85±0.13	0.83±0.05
Square (9ps)	0.92±0.05	0.81±0.03

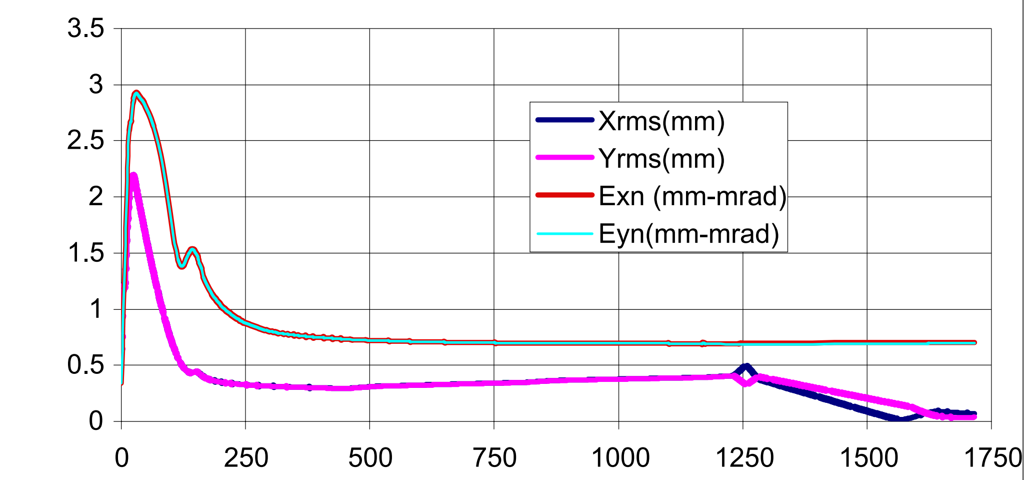
For 1 nC:

$\varepsilon_n \approx 1.2$ mm mrad

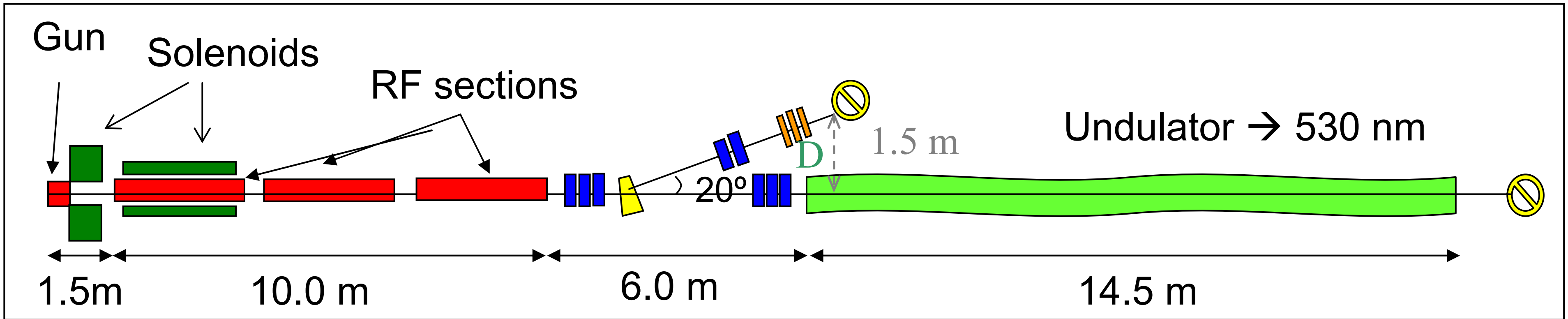
NC RF Gun Injector @ SPARC

PITZ
Photo Injector Test Facility Zeuthen

gun type design parameters:	1.6 cell gun from UCLA
pulsed / CW	pulsed
single bunch charge	1.1 nC
single bunch rep rate	1-10 Hz
average current	1.1 – 11 nA
norm. trans. emittance (rms)	< 2 mm mrad @ 155 MeV
rf frequency	2.856 GHz



Parmela simulations



Status: • **full SPARC facility under installation**
• **first beam beginning of 2006**

more on SPARC: → D. Alesini
→ S. Dabagov

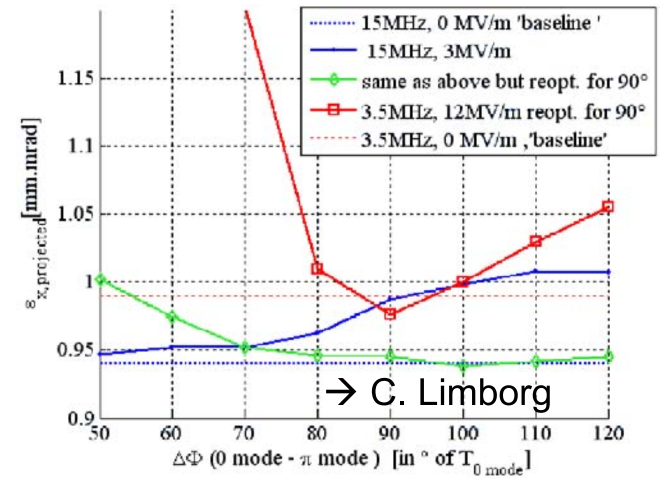
NC RF Gun Design for LCLS

PITZ Photo Injector Test Facility Zeuthen

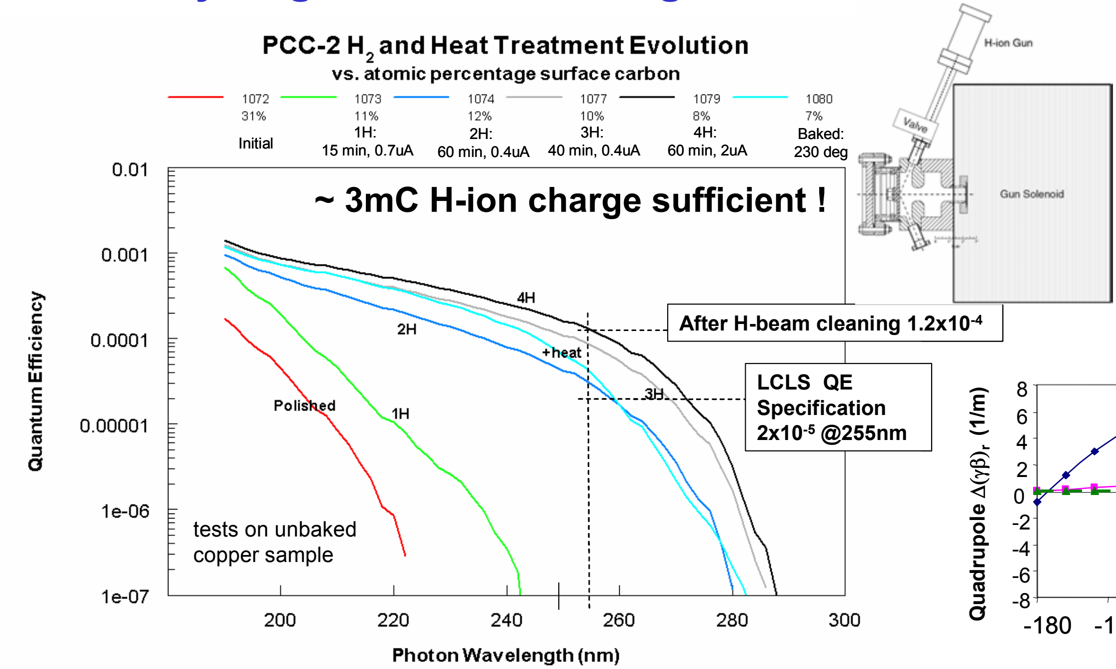
pulsed / CW	**pulsed**
single bunch charge	**1.0 / 0.2 nC**
single bunch rep rate	**120 Hz**
average current	**120 / 24 nA**
norm. trans. emittance (rms, slice)	**1.0 / 0.8 mm mrad @ 135 MeV**
rf frequency	**2856 MHz**

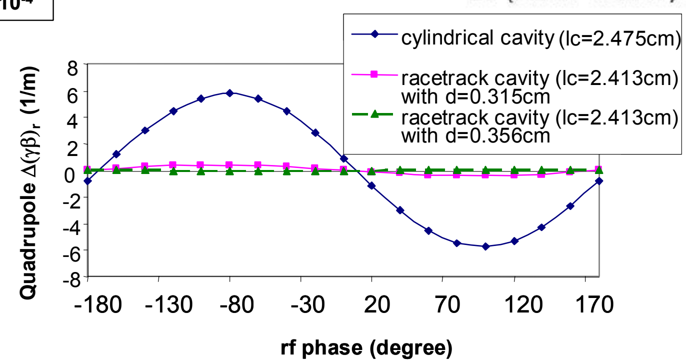
modified UCLA/BNL/SLAC 1.6 cell S-band gun:
- larger mode separation (3.5 → 15 MHz)
- larger iris radius, reduced iris surface field
- dual rf feed, z coupling, racetrack shape
- field probes in both cells
- increased cooling channels
- klystron pulse shaping → reduced dissipated power

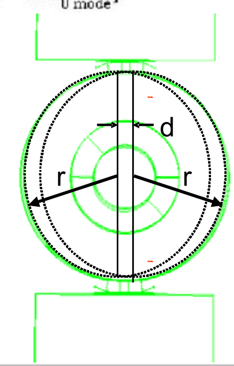
→improved emittance and stability



In-Situ Hydrogen Beam Cleaning of Cathode Surface







Other Developments @

e.g.
- Eindhoven (DC + RF, waterbags, …) → J. Luiten, B. v.d.Geer
- Argonne (e.g. planar focussing cathode)
- AES (11.4 GHz, symmetric, NC RF gun, design: ~1 mm mrad @ 1 nC, 10 nA)
- [SPring8 (special thermal emission injector for SCSS)]
- [PSI (e.g. field emission cathode + diode acceleration + RF cavity)]

LEG @ PSI design parameters:	
single bunch charge	**0.2 nC**
single bunch rep rate	**10 Hz**
average current	**2 nA**
norm. trans. emittance (rms)	**< 0.1 mm mrad**

!!!

Courtesy of L. Catani, INFN

Acknowledgements

(in order of appearance)

- Ch. Sinclair, Cornell
- J. Teichert, D. Janssen, FZ Rossendorf
- M. Krasilnikov, DESY
- D. Dowell, SLAC
- A. Todd, H. Bluem, J. Rathke, Advanced Energy Systems
- T. Srinivasan-Rao, I. Ben-Zvi, BNL
- D. Nguyen, LANL
- F. Marhauser, BESSY
- L. Catani, INFN
- G. Romain, PSI
- The PITZ group at Zeuthen

Summary

PITZ Photo Injector Test Facility Zeuthen

- Lots of different developments with photoinjectors fill up a large parameter space on beam quality, time structure of the beam and average currrent.
- Simulations predict very good performance of all three basic photo injector types (plus hybrids).
- Experimental progress is visible: on subsystems (guns, laser, diagnostics) and on measured beam quality.
- P. O'Shea, ICFA workshop @ UCLA in 1999:

  ~ "**Get 1 µm @ 1 nC !!!**"

  → still to be done experimentally !!!

  → ways to reach this are defined.
- More research on emission process (→ε_{th}) gets important.