High Current, High Brightness Electron Sources

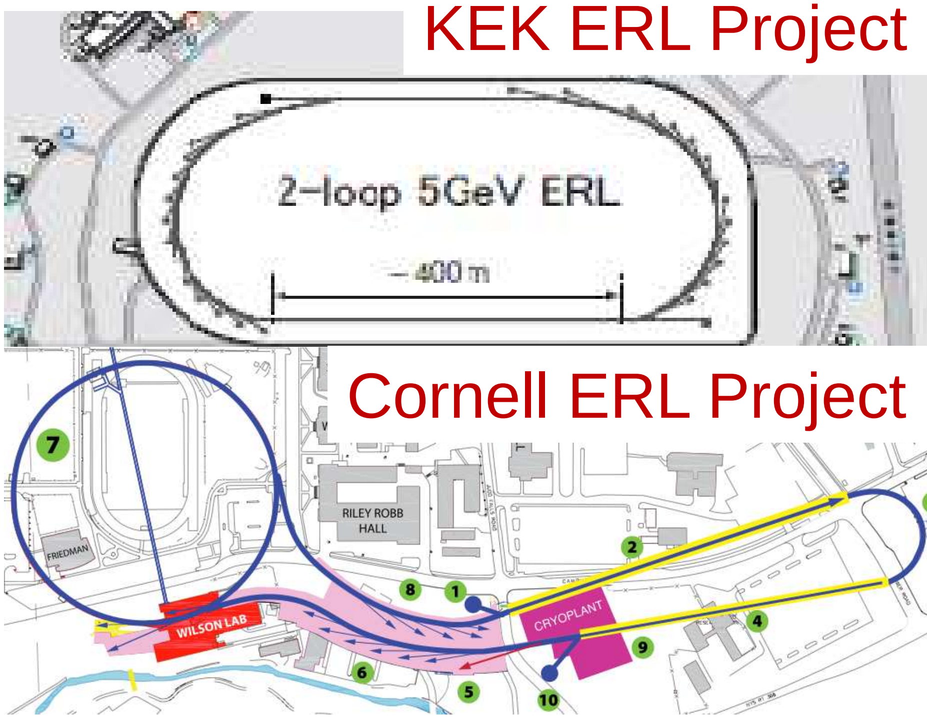
Florian Loehl, Cornell University

IPAC 2010 Conference

Kyoto, Japan

High current, high brightness electron sources are required for:

- **X-ray energy recovery linac (ERL) light source facilities**



Typical injector parameters:

E_{kin} = 5 – 10 MeV

I_{ave} = 10 – 100 mA

(BNL works on a 500 mA ERL)

ε_N < 1 mm-mrad

- **Potential future, high duty cycle soft- and hard X-ray free-electron lasers (FELs) - eventually based on an ERL**

General Comments

- Designs discussed here are based on photoemission guns
  → High beam currents require high quantum efficiency photo-cathodes, e.g.
    - GaAs (needs ultra-high vacuum) } require green light
    - K_2CsSb } require green light
    - Cs_2Te } requires UV light

- Simple repetition rate scaling of low emittance normal-conducting guns not possible, due to
  - Thermal stress / heating effects
  - Beam power
    - Example: 10 MeV, 100 mA ERL injector
    →1 MW beam power!

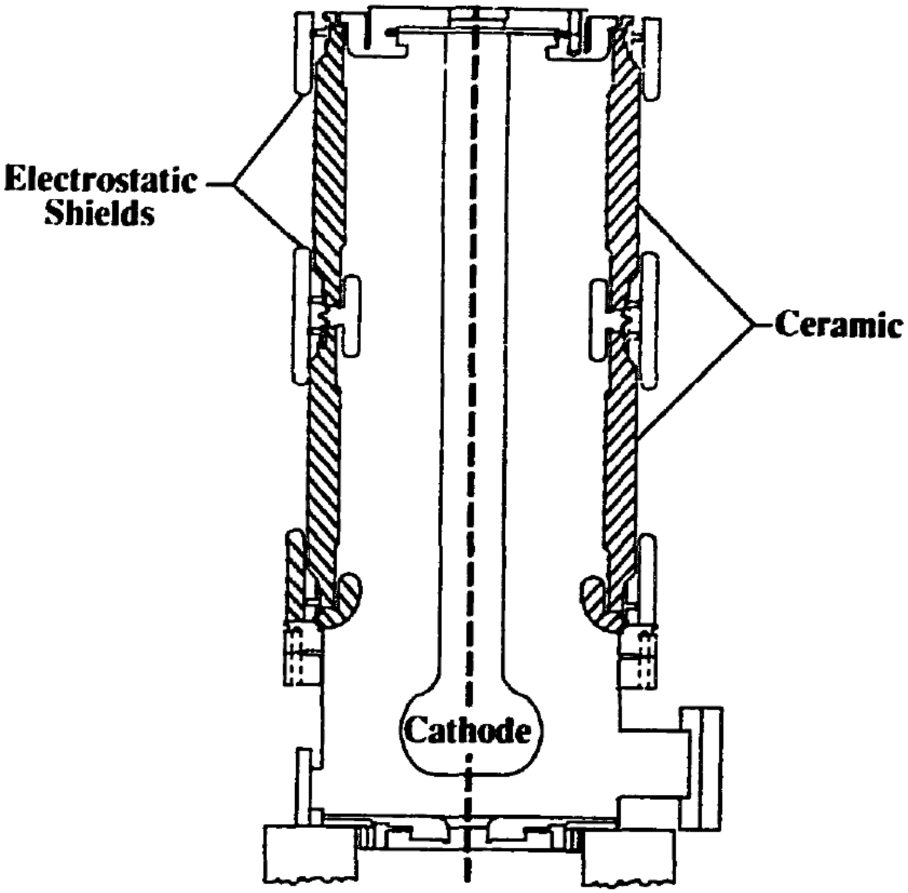
Outline

- CW Gun Technologies
  - DC
  - Normal-conducting
  - Superconducting

- Initial Commissioning Results of the Cornell ERL Injector

DC Guns

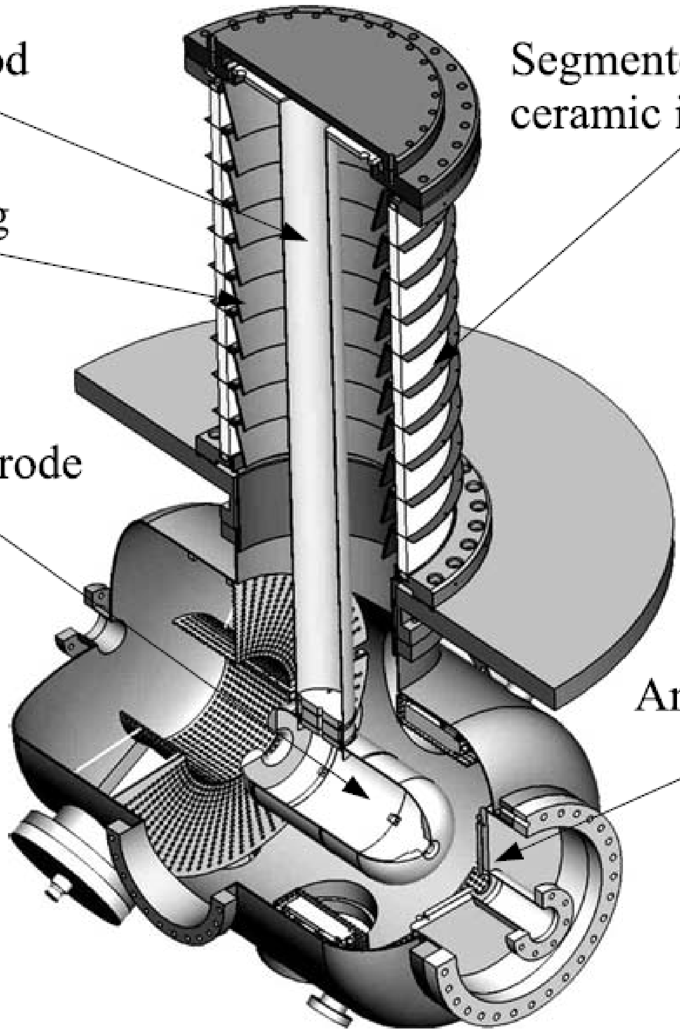
Example: Original JLAB FEL gun



C.K. Sinclair, NIM A **318**, (1992).

- DC field between cathode and anode
- Can provide very good vacuum
  → Suited for GaAs
- Main limitation: field emission
  → Limits E-fields at cathode to around 10 MV/m

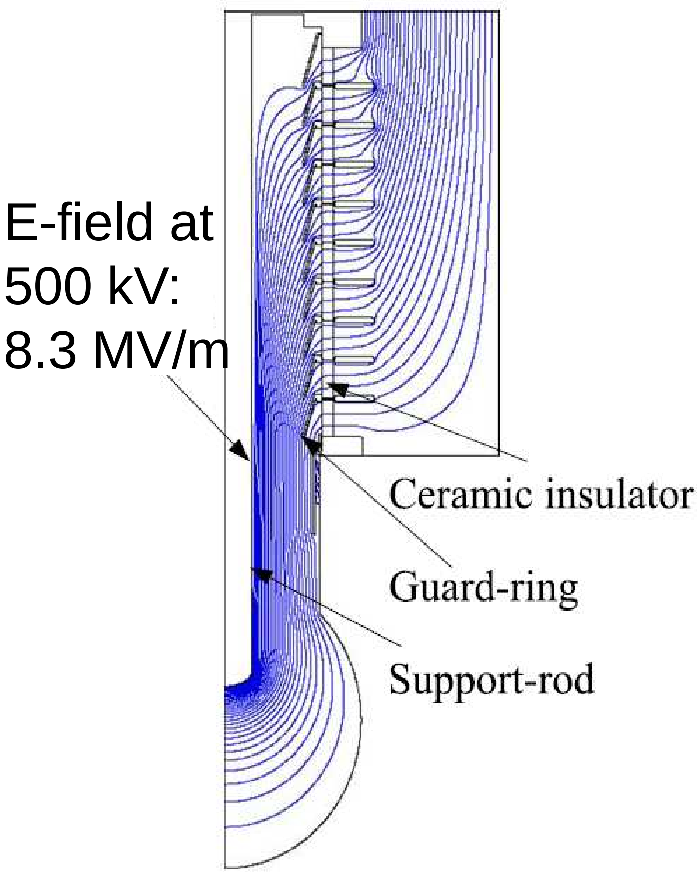
DC Guns

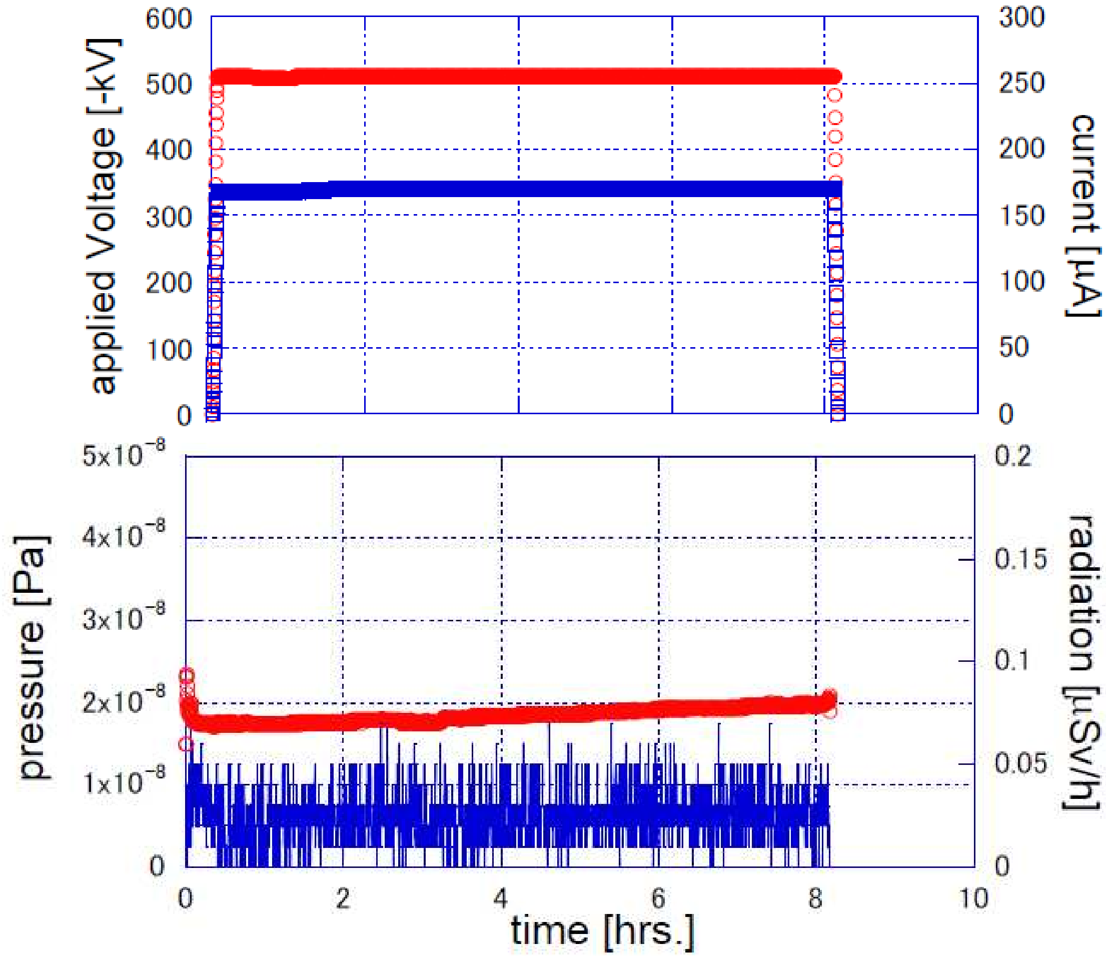


Metallic guard rings prevent field emission burst from directly hitting the ceramic insulator.

Ryoji Nagai *et al.*, Rev. Sci. Instrum. **81**, 033304 (2010).

Very promising high voltage tests (without cathode electrode):
Processing up to 550 kV, stable operation over 8 h at 500 kV!



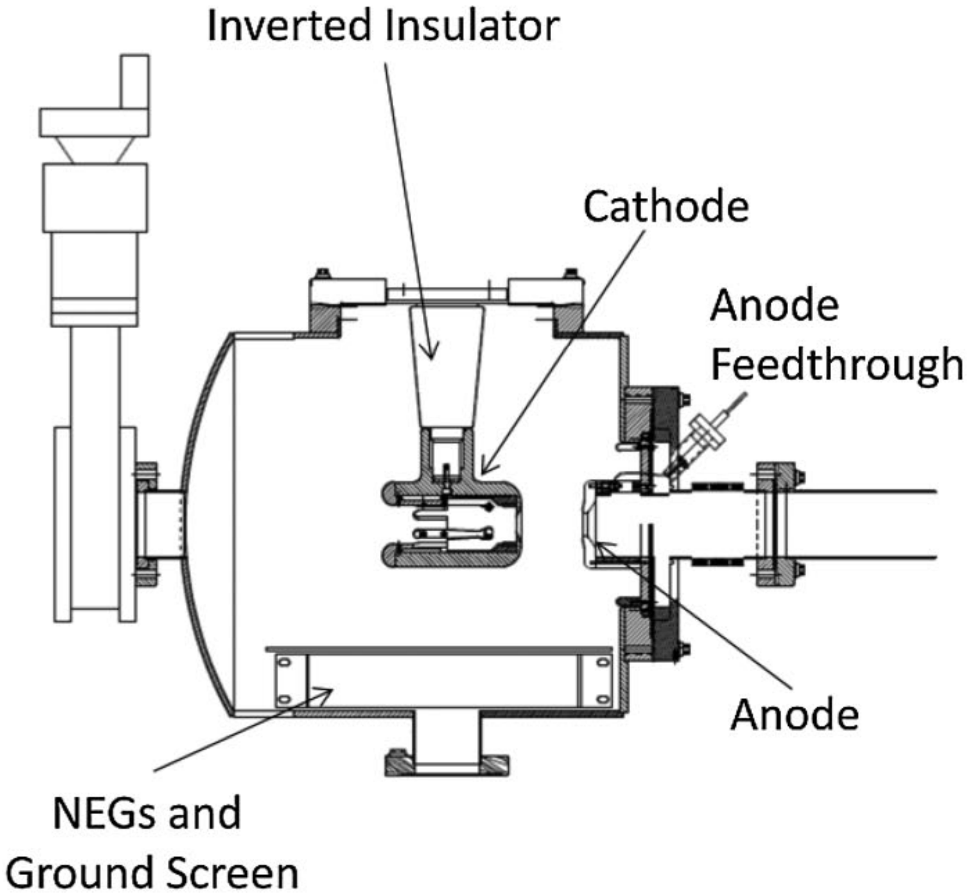


Ryoji Nagai *et al.*, Rev. Sci. Instrum. **81**, 033304 (2010).

Inverted DC Gun

Possibility to significantly reduce electrode surface area:

Tapered ceramic insulator extending into the vacuum chamber
→ “inverted gun” (Breitenbach *et al.*, 1994)



Example:
Spin-polarized GaAs gun
for CEBAF (JLAB)

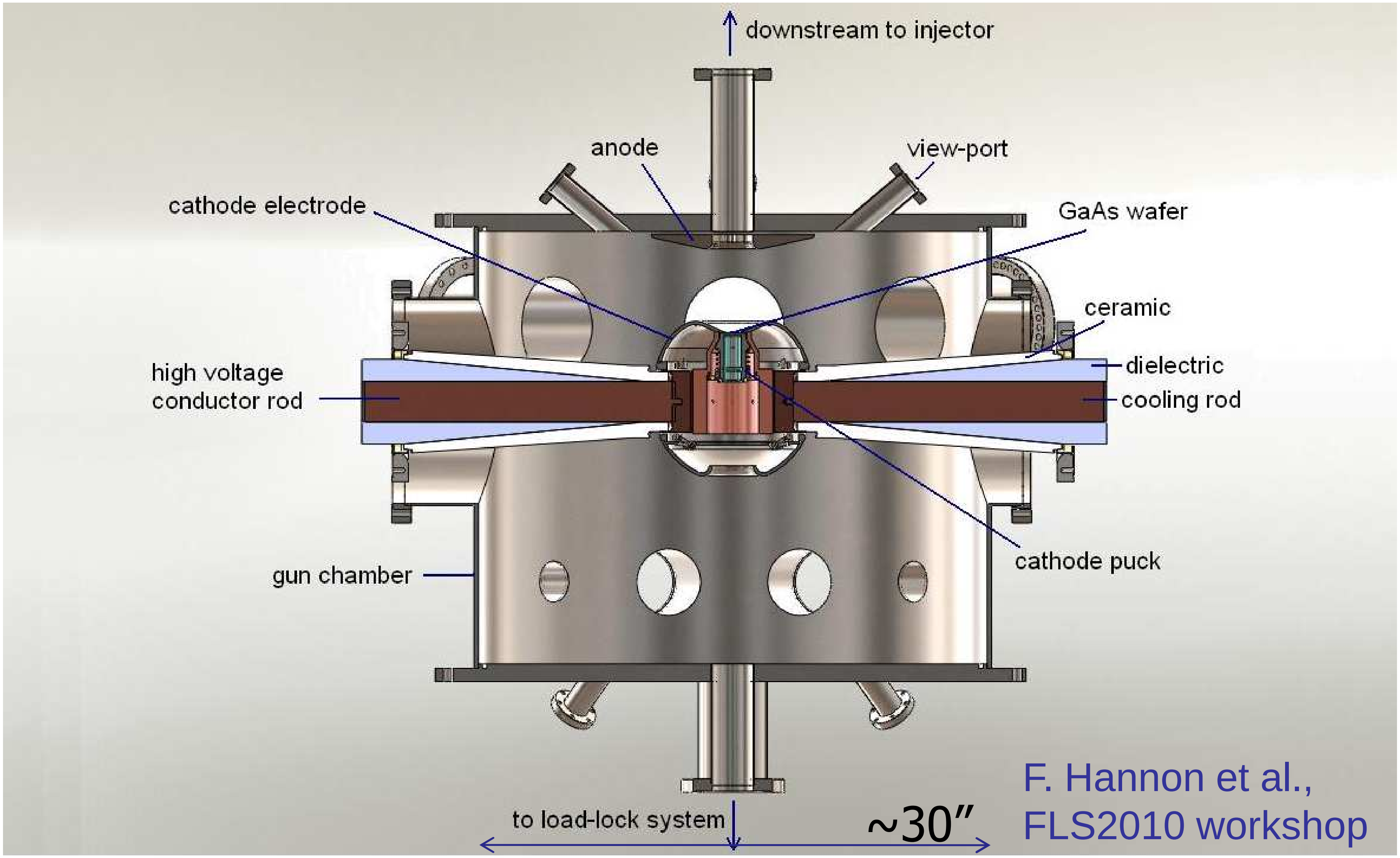
- 100 kV gun

No demonstration of
high voltages (500 kV range)
yet, but high potential.

P.A. Adderley *et al.*, Phys. Rev. ST Accel. Beams **13**, 010101 (2010).

Inverted DC Gun

On-going work at JLAB on "inverted" 500 kV gun

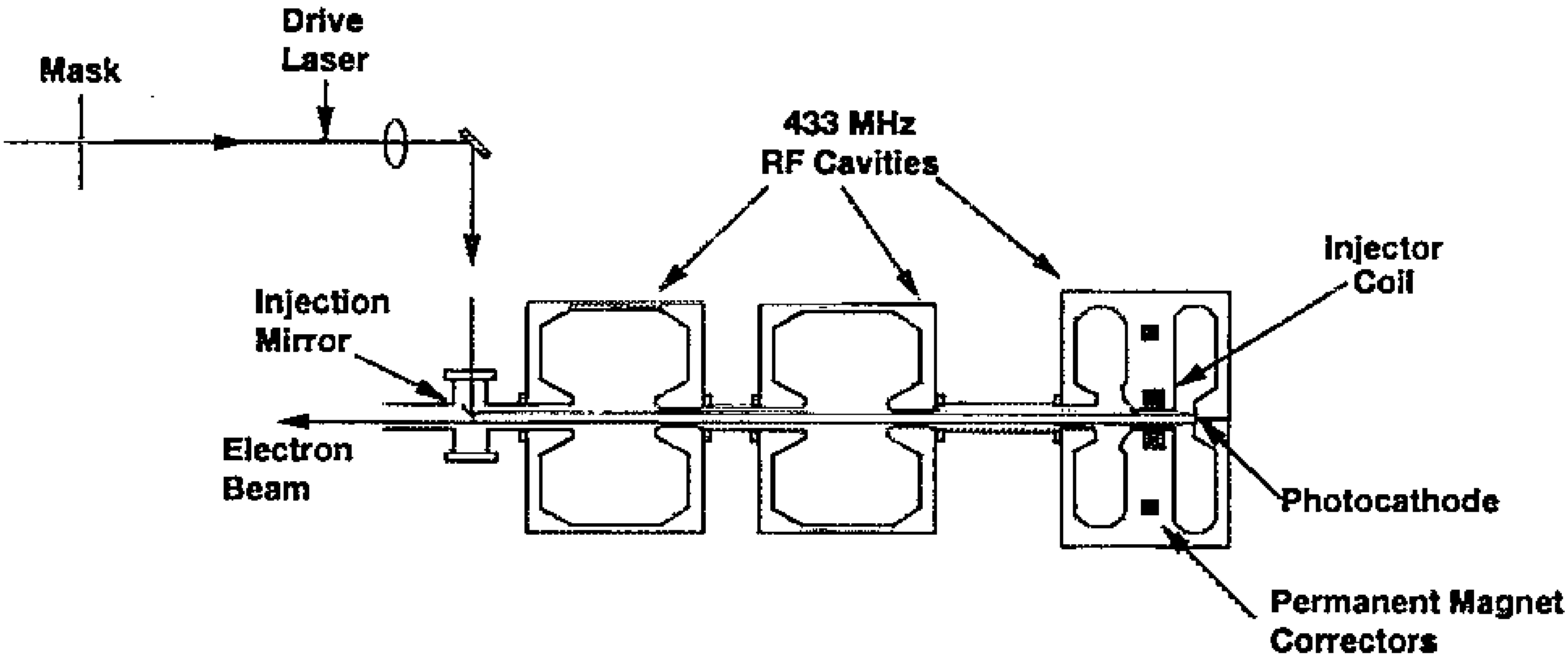


F. Hannon et al.,
FLS2010 workshop

Normal Conducting CW Guns

Not really CW, but close to…
(25 % duty cycle)

Still the beam current world record!



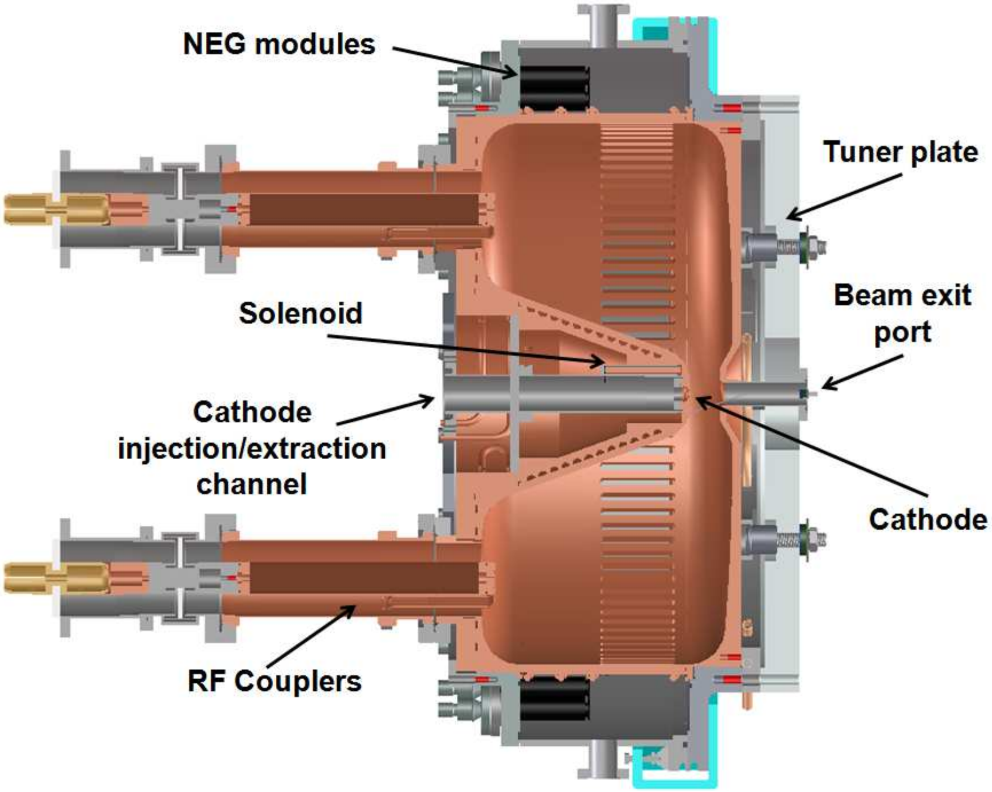
Demonstration of 32 mA average beam current at E_{kin} = 5 MeV.

Bunch charges of 1-7 nC, 20 – 40 mm-mrad normalized emittance.

D. Dowell *et al*., Appl. Phys. Lett., **63** (15), 2035 (1993).

Normal Conducting CW Guns

A CW normal conducting gun for ~MHz repetition rate X-ray FELs:



- Gun operated at 187 MHz
- 750 kV gap voltage
- Field at cathode: ~20 MV/m
- Surface area large enough to have tolerable heat load in CW operation
- Large apertures improve vacuum conductivity
- Beam experiences almost no RF curvature due to low frequency
- Compatible with 1.3 GHz and 1.5 GHz SRF linacs
- Design emittances:
  < 0.1 mm-mrad @ tens of pC
  ~ 1 mm-mrad @ 1 nC

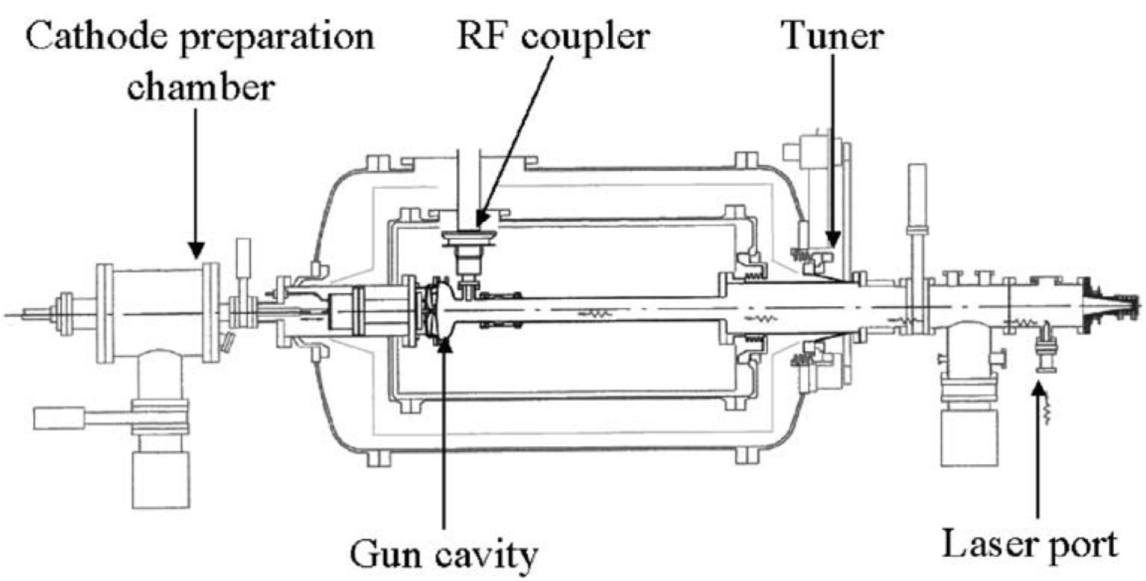
J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006
K. Baptiste, et al, NIM A 599, 9 (2009)

Superconducting RF-Guns

Superconducting RF Guns provide potential for

- Very high electrical fields
- Very low thermal heat dissipation
- Low operational costs
- Very good vacuum

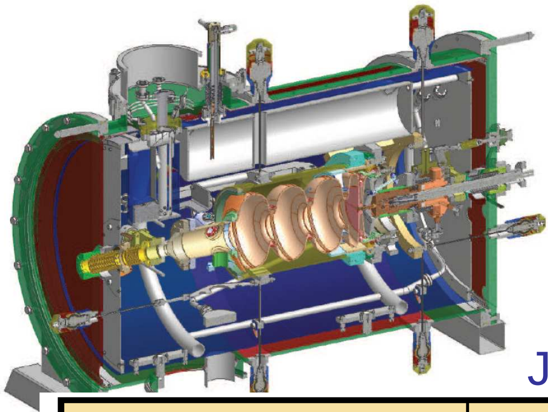
A lot of pioneering work has been done at the Forschungszentrum Rossendorf and the Peking University



First superconducting RF-gun

D. Janssen *et al.*, NIM A **507**, 314 – 317 (2003).

Superconducting RF-Guns



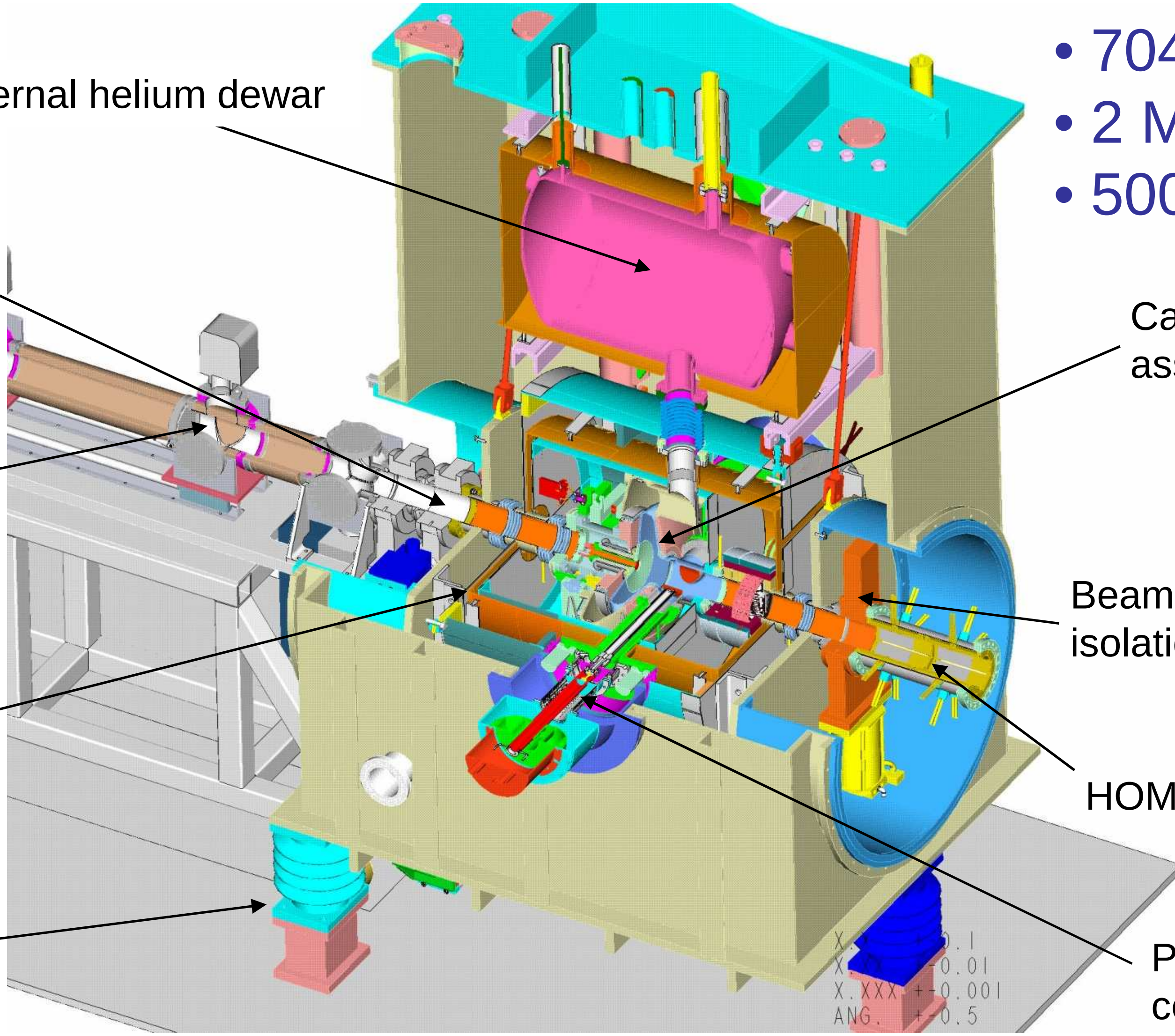
Current superconducting 3 ½ cell ELBE gun and performance (FZD).

J. Teichert *et al.*, FLS2010 Workshop.

design values

parameter	present cavity			new "high gradient cavity"	
	measured ´08	**ELBE**	**high charge**	**ELBE**	**high charge**
final electron energy	2.1 MeV	**3 MeV**		≤9.5 MeV	
peak field	13.5 MV/m	**18 MV/m**		50 MV/m	
laser rep. rate	1 – 125 kHz	**13 MHz**	**2 – 250 kHz**	13 MHz	≤500 kHz
laser pulse length (FWHM)	15 ps	4 ps	15 ps	4 ps	15 ps
laser spot size	2.7 mm	5.2 mm	5.2 mm	2 mm	5 mm
bunch charge	≤ 200 pC	**77 pC**	**400 pC**	77 pC	1 nC
max. aver. Current	1 µA	**1 mA**	**100 µA**	1 mA	0.5 mA
peak current	13 A	20 A	26 A	20 A	67 A
transverse. norm. emittance (rms)	3 1 mm mrad @ 80 pC	**2 mm mrad**	**7.5 mm mrad**	1 mm mrad	2.5 mm mrad

Superconducting gun development at BNL

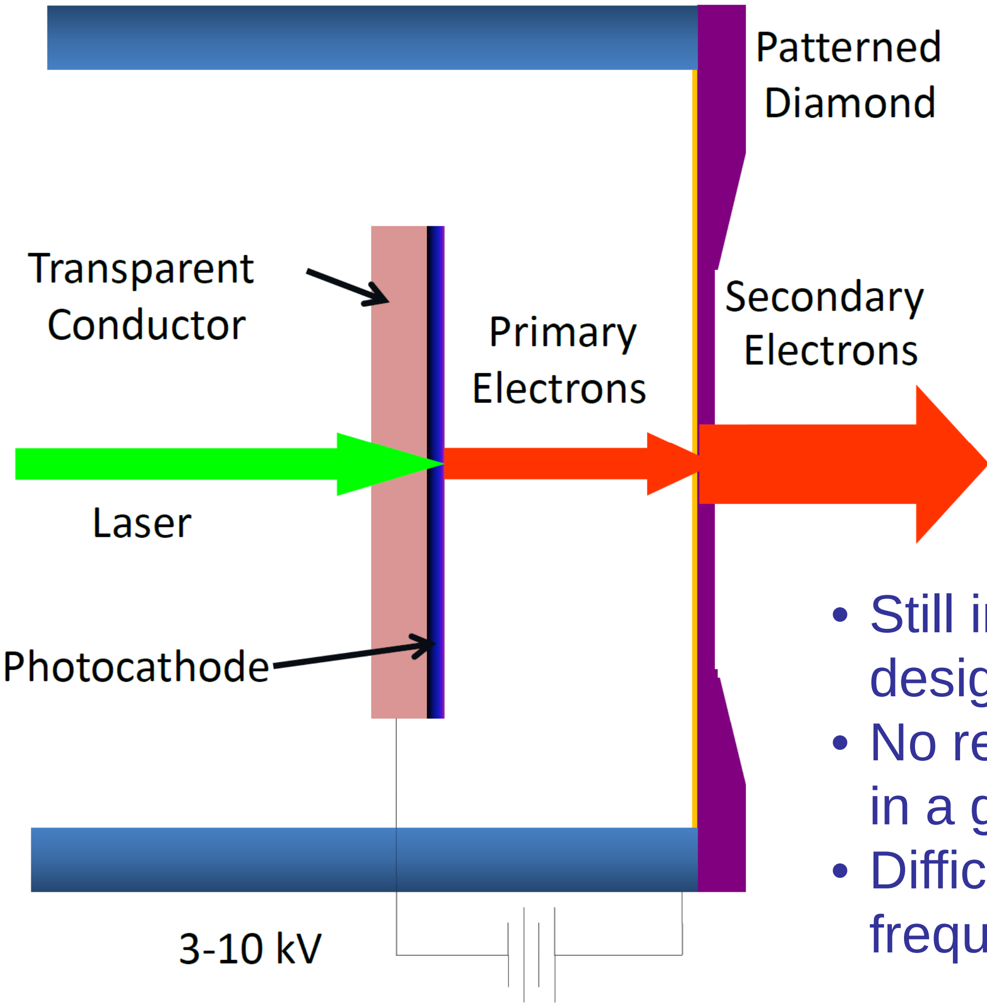


- 704 MHz
- 2 MeV
- 500 mA !

I. Ben-Zvi, FLS2010 Workshop

Diamond Amplifier

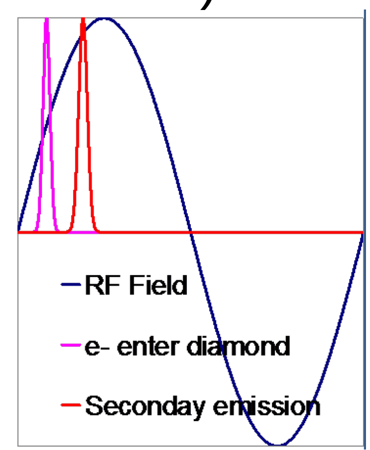
Method to amplify bunch charge emitted from a photo-cathode



1. Generation of electron bunch (few keV)
2. Electrons enter diamond, where they generate carriers
3. Carriers propagate through diamond at ~0.2 µm/ps
4. Emission of secondary electrons in gun RF field

→ Large amplifications achievable (~20 to > 200)

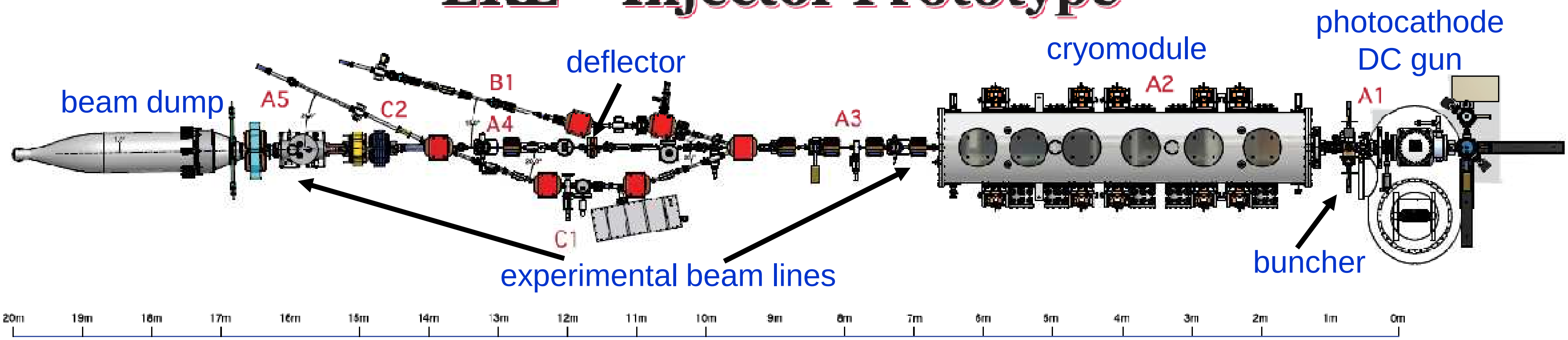
- Still in the design phase!
- No real demonstration in a gun yet
- Difficult at high gun frequencies



J. Smedley, FLS2010 Workshop

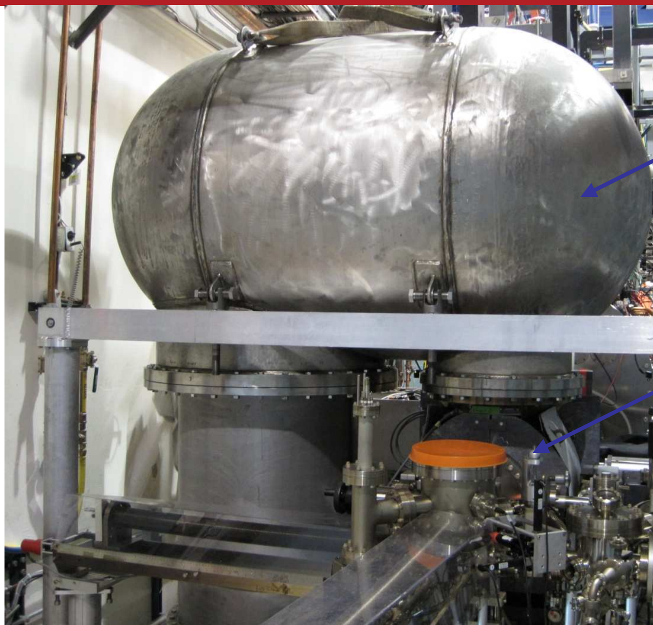
Cornell ERL injector

ERL – Injector Prototype



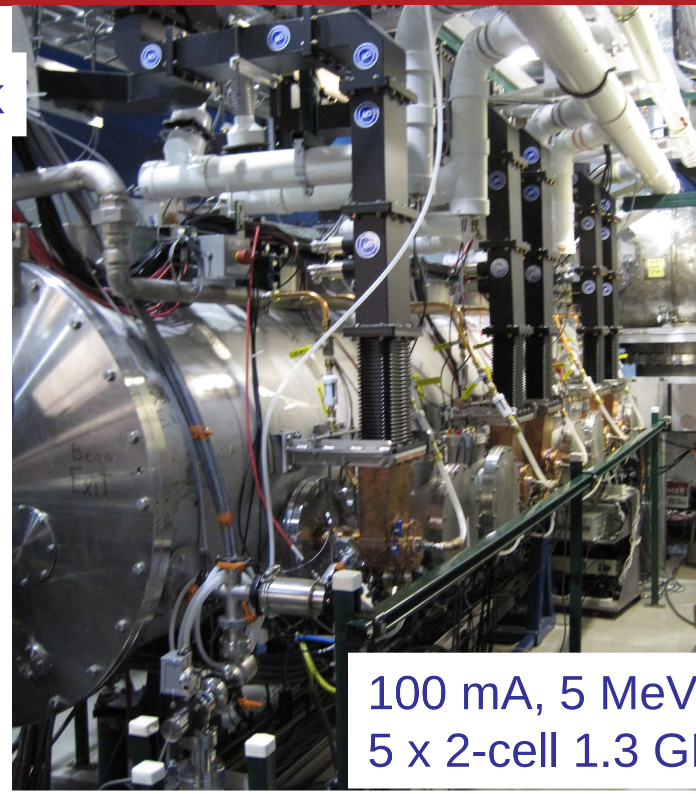
	design parameters
Nominal bunch charge	77 pC
Bunch repetition rate	1.3 GHz
Beam power	up to 550 kW
Nominal gun voltage	500 kV
SC linac beam energy gain	5 to 15 MeV
Beam current	100 mA at 5 MeV
	33 mA at 15 MeV
Bunch length	0.6 mm (rms)
Transverse emittance	< 1 mm-mrad

Cornell ERL injector

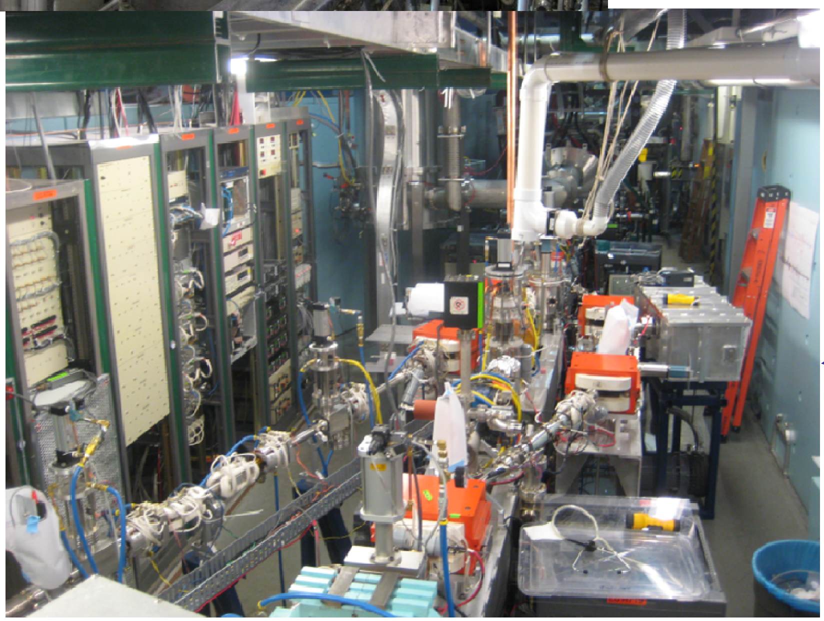


SF6 tank

DC gun



100 mA, 5 MeV SRF module
5 x 2-cell 1.3 GHz cavities

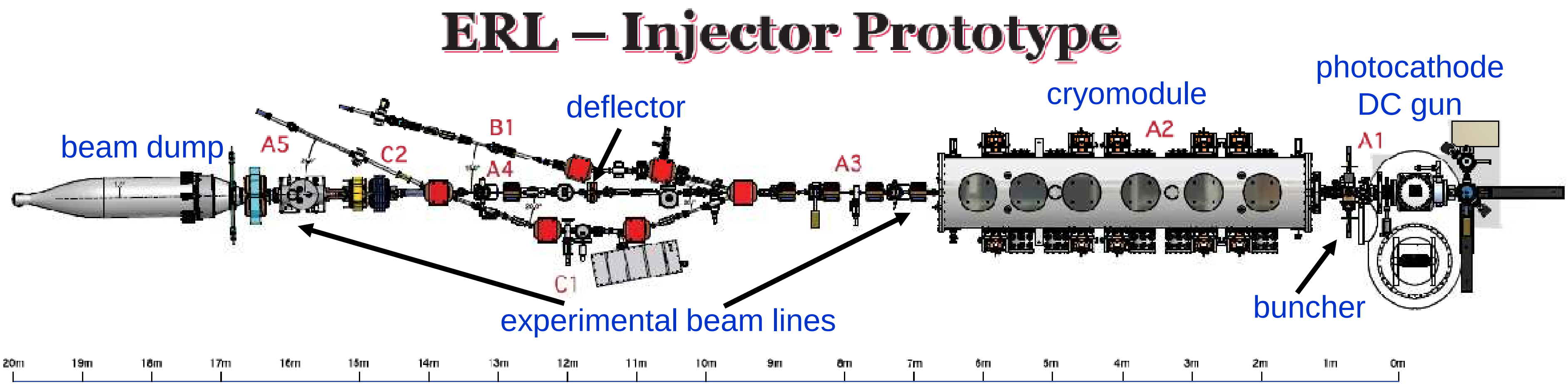


Diagnostics section
- emittance measurement systems
- deflecting cavity
- view-screens
- BPMs, BLMs, Faraday-cups, …

Cornell ERL injector

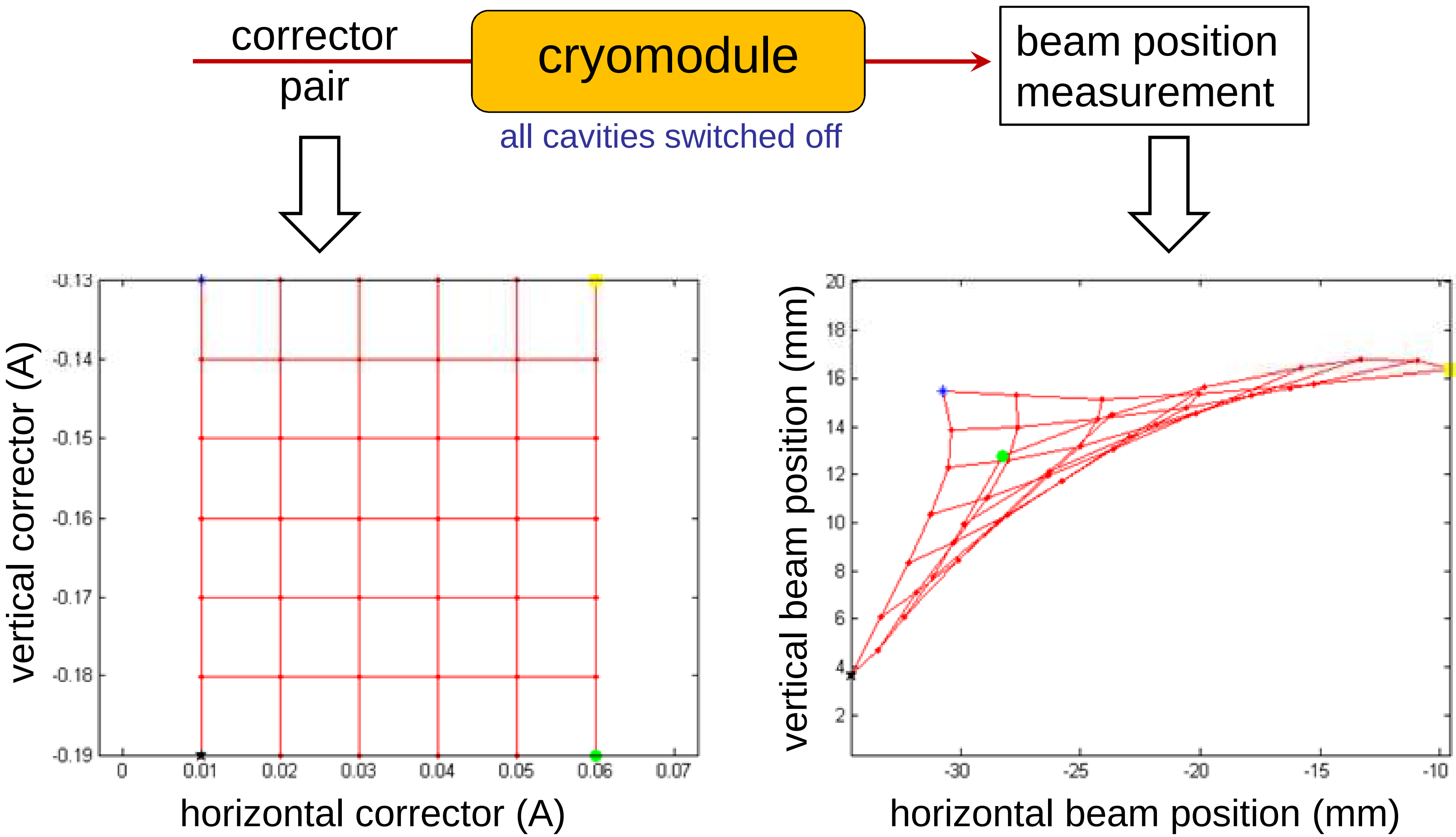
2001:	ERL prototype proposal submitted
2005:	NSF funds the injector part of the proposal
Sept. 2006:	1st beam from the DC gun
Sept. 2007:	Beam line and cryomodule fabrication and assembly starts
March 2008:	Cryomodule assembly is finished
April 2008:	Module installation in ERL injector prototype and cool down
June 2008:	First RF
July 2008:	First beam test period starts
August 2009:	End of first test period; rework of DC gun and SRF cryomodule starts
April 2010:	First beam after cryomodule rework

Cornell ERL injector



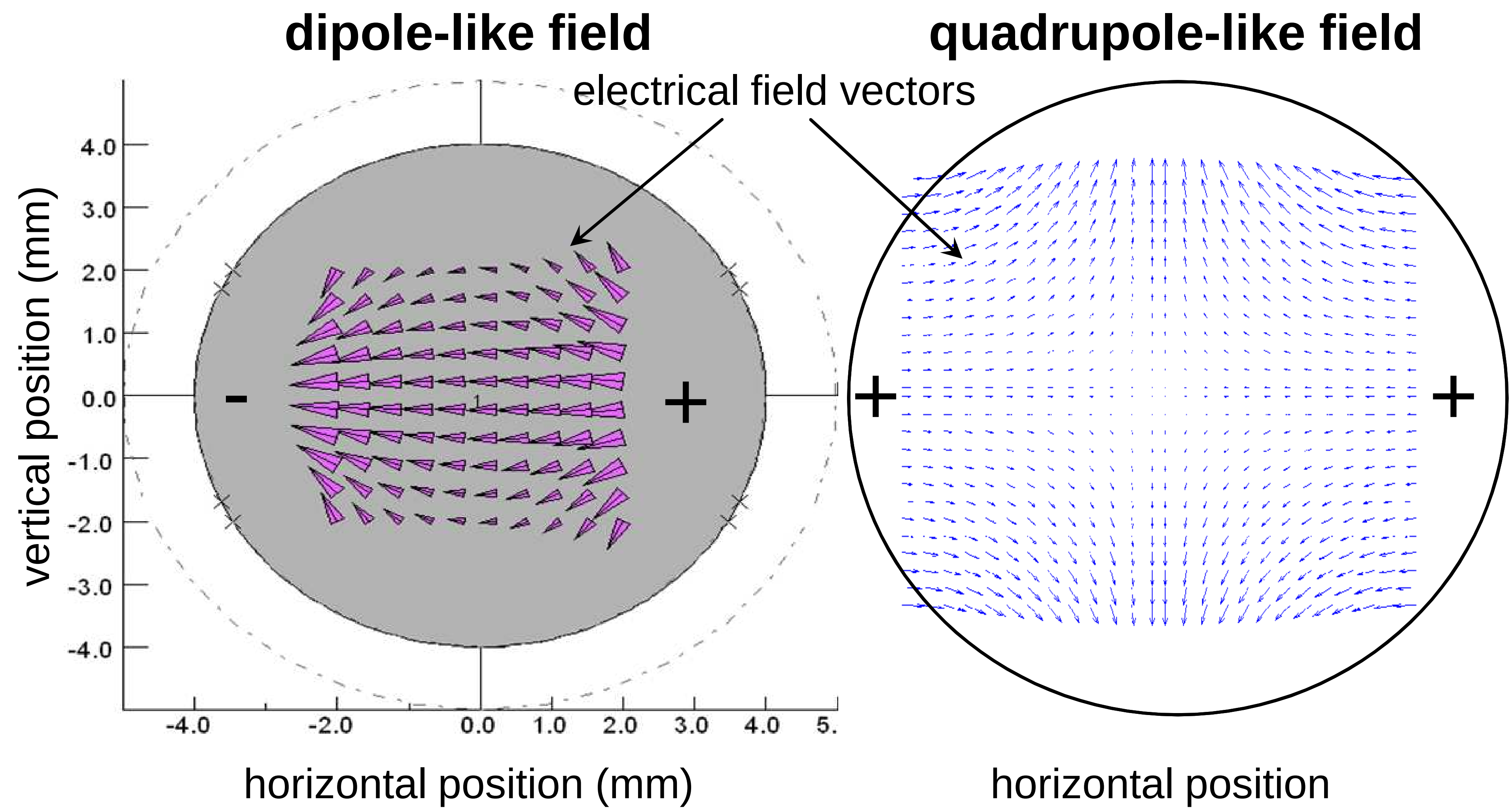
	design parameters	**achieved**
Nominal bunch charge	77 pC	77 pC
Bunch repetition rate	1.3 GHz	50 MHz and 1.3 GHz
Beam power	up to 550 kW	45 kW
Nominal gun voltage	500 kV	350 kV
SC linac beam energy gain	5 to 15 MeV	5 to 15 MeV
Beam current	100 mA at 5 MeV 33 mA at 15 MeV	9 mA Limited by gun HV instabilities. 100 mA power supply is being reworked (until end of summer).
Bunch length	0.6 mm (rms)	
Transverse emittance	< 1 mm-mrad	

Reason for cryomodule rework: strange beam orbit response



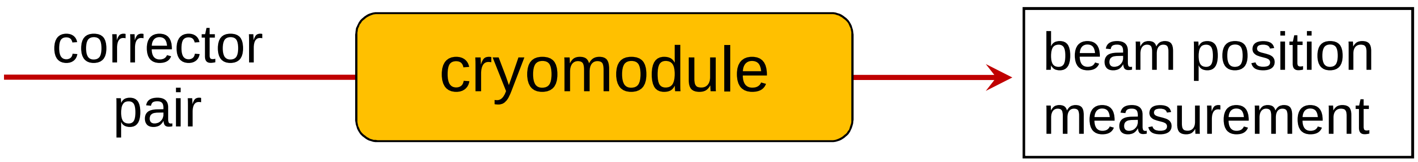
Localizing the field distortions

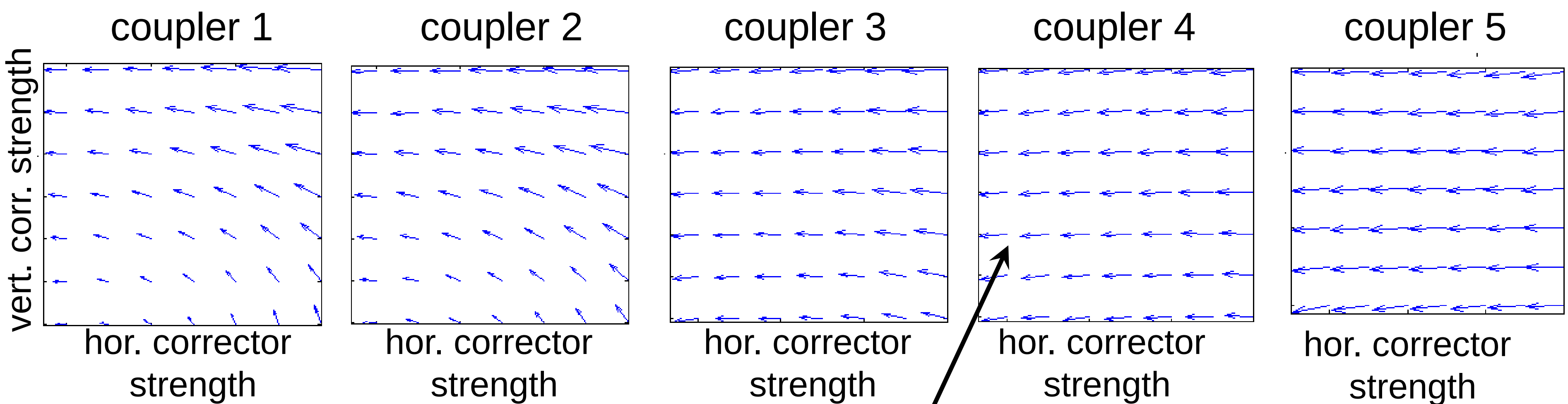
Generation of electrical DC fields in the coupler regions of the SRF cavities



Localizing the field distortions

dipole-like coupler kick

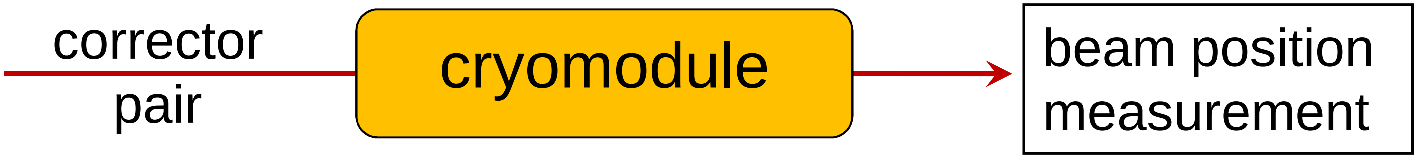


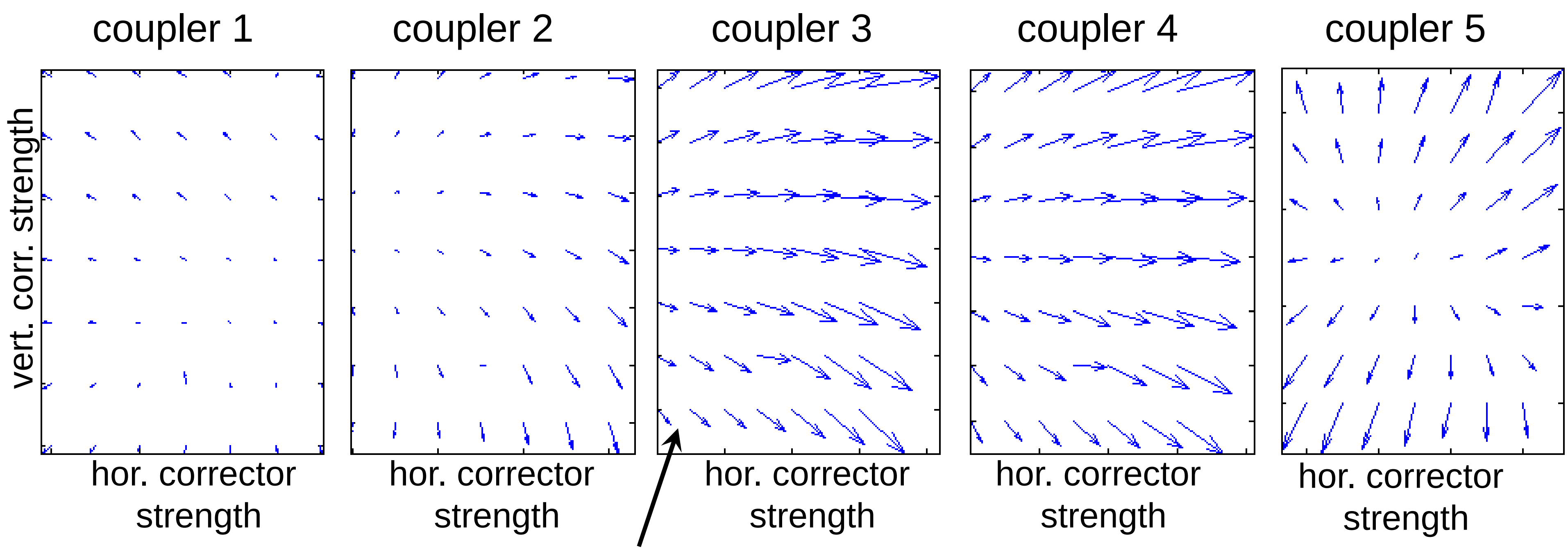


deflection of the beam after the cryomodule
due to the coupler field

Localizing the field distortions

quadrupole-like coupler kick

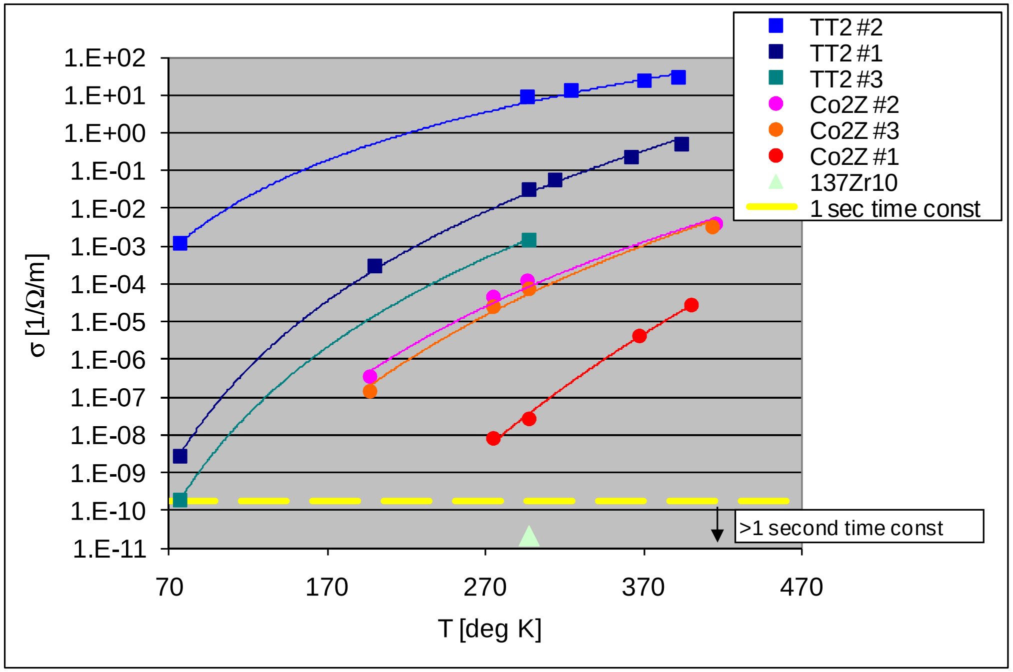


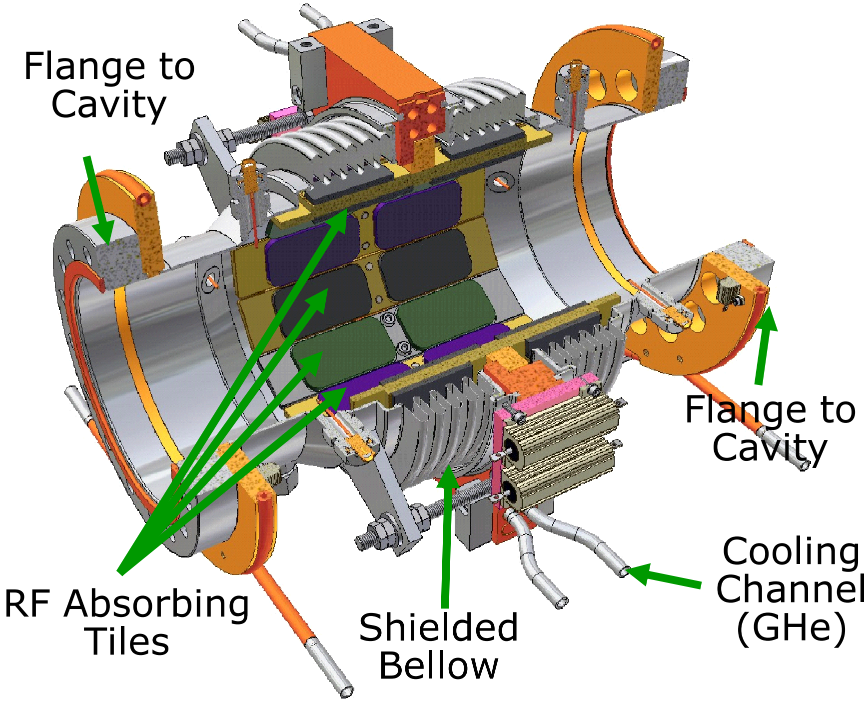


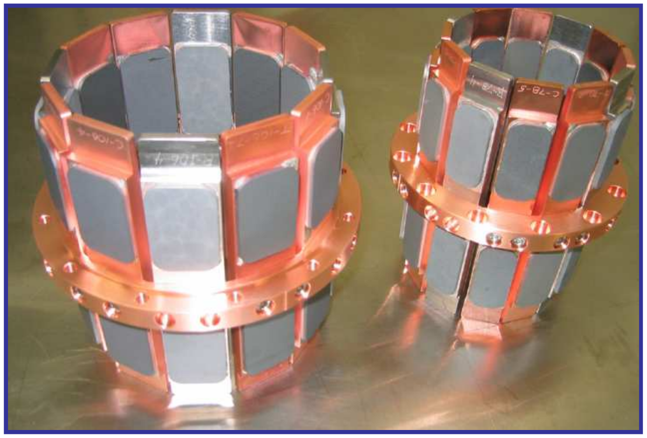
deflection of the beam after the cryomodule due to the coupler field

Cornell ERL injector

Total # loads	3 @ 78mm + 3 @ 106mm
Power per load	26 W (200 W max)
HOM frequency range	1.4 – 100 GHz
Operating temperature	80 K
Coolant	He Gas
RF absorbing tiles	TT2, Co2Z, Ceralloy







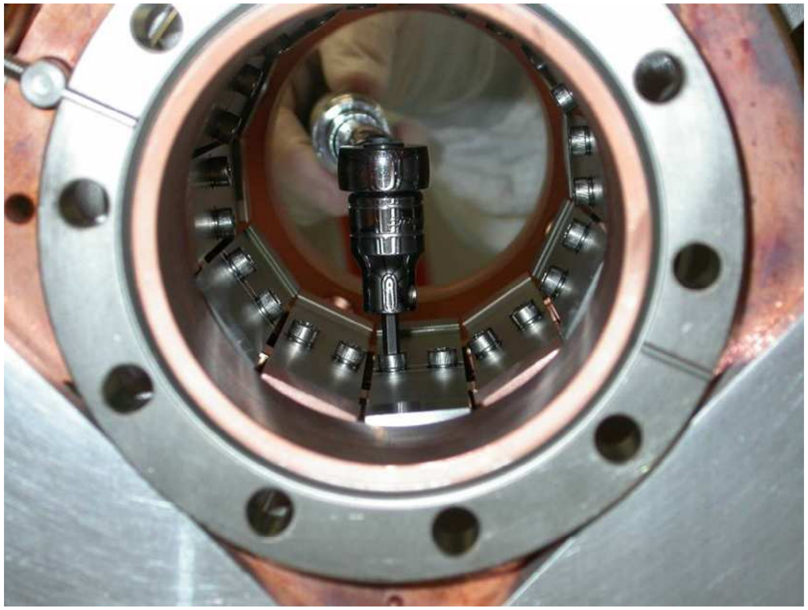
HOM absorber tiles charged up!

Cornell ERL injector

Consequence of low resistivities of absorber materials:

- Completely removed ceramic 137Zr10
- Tried gold coating of TT2 absorbers but coating may fall off

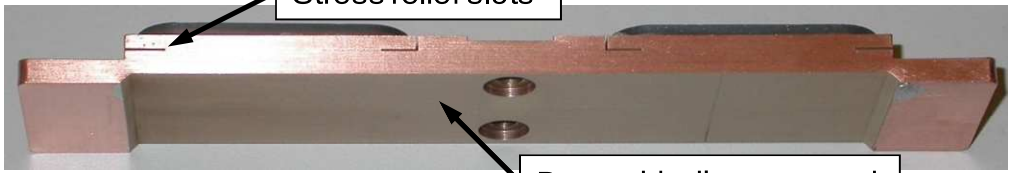
→ Removed all tiles from the inside of the HOM absorber



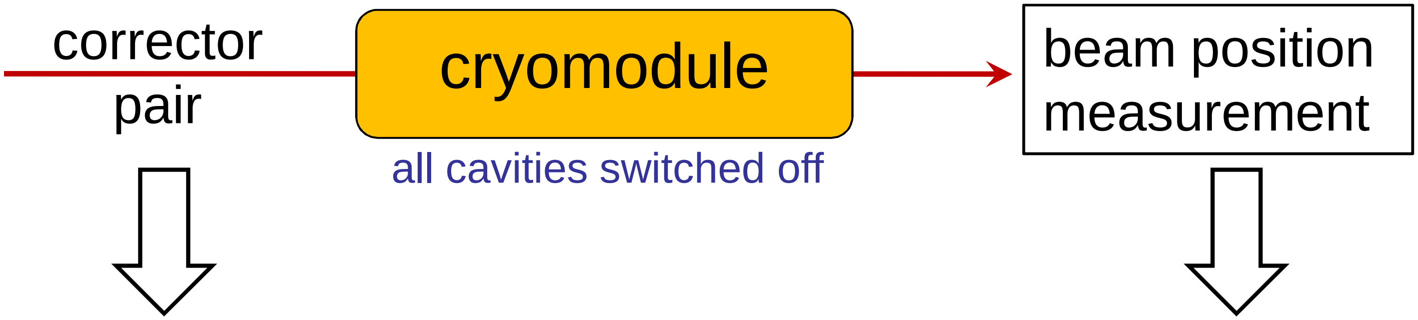
Found one loose tile during cryomodule disassembly

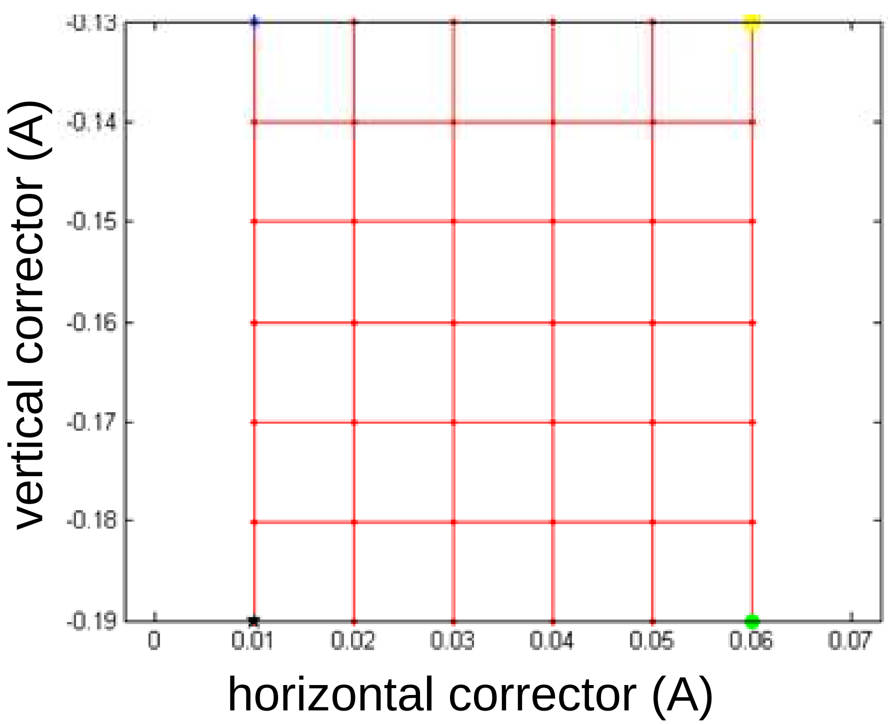
- Thermal stress tests confirmed this problem

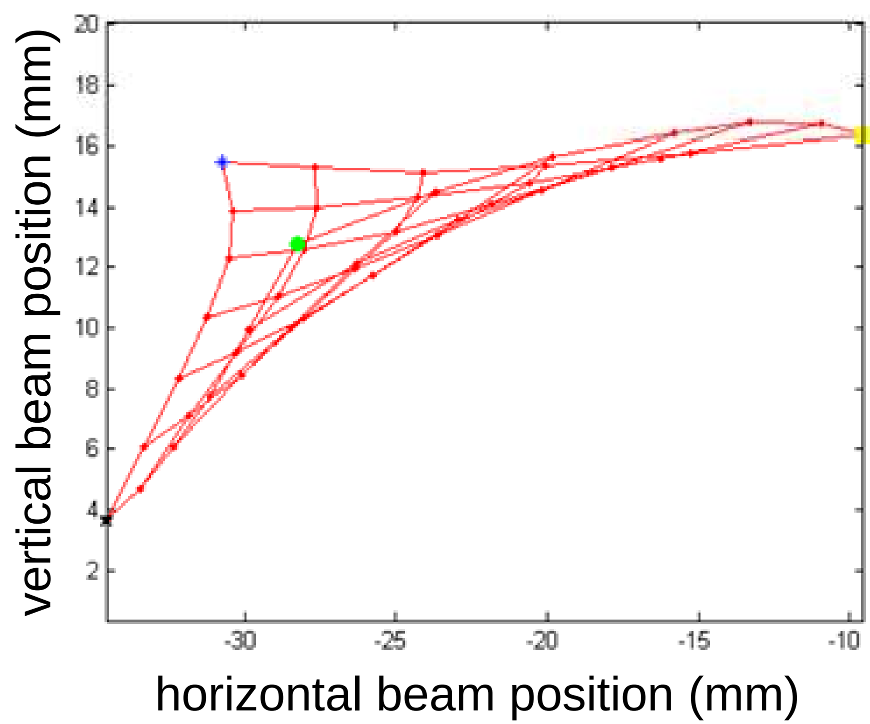
→ Solved by cutting stress relief slots in the tiles



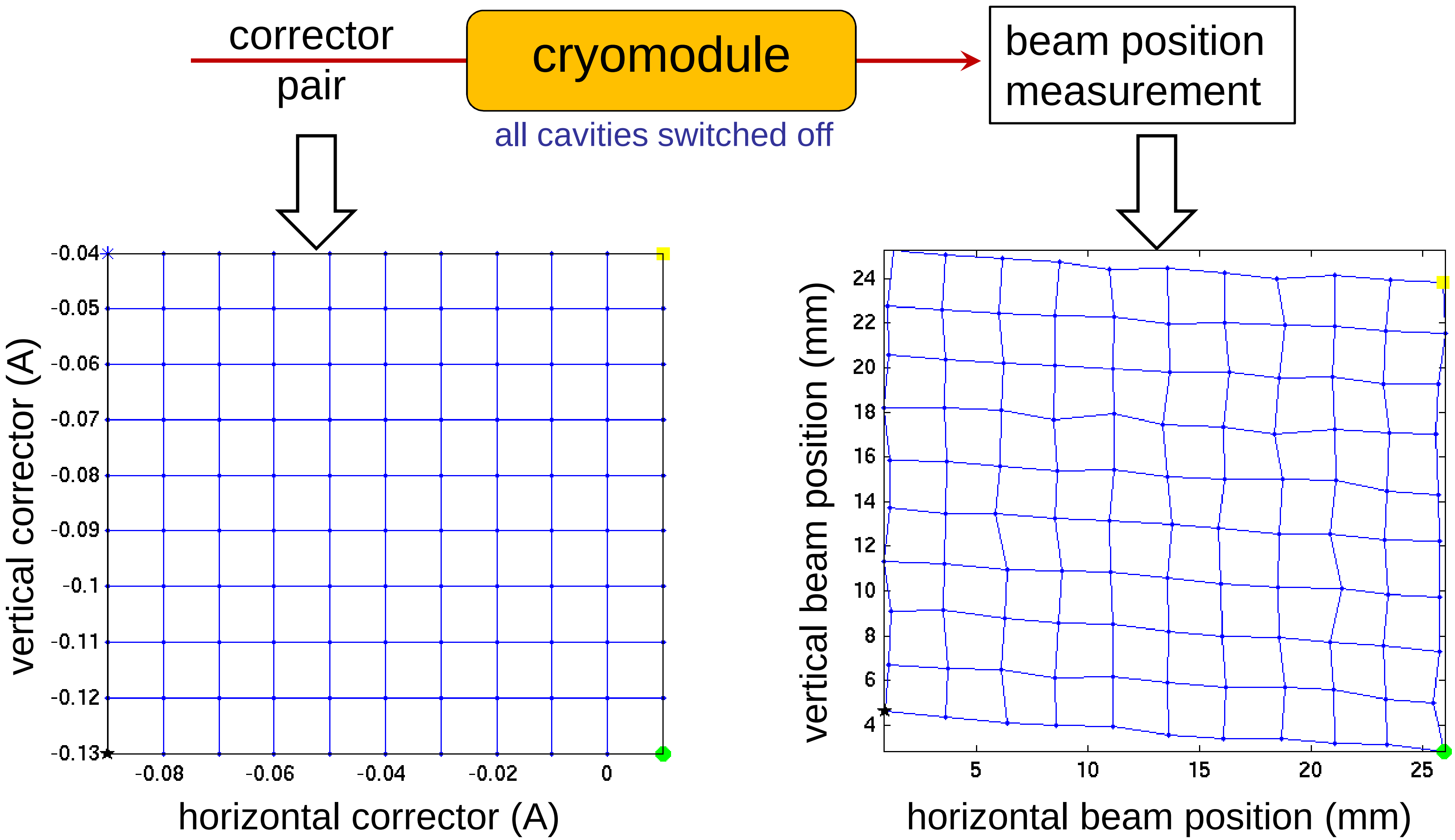
Before rework of cryomodule:







After rework of cryomodule:

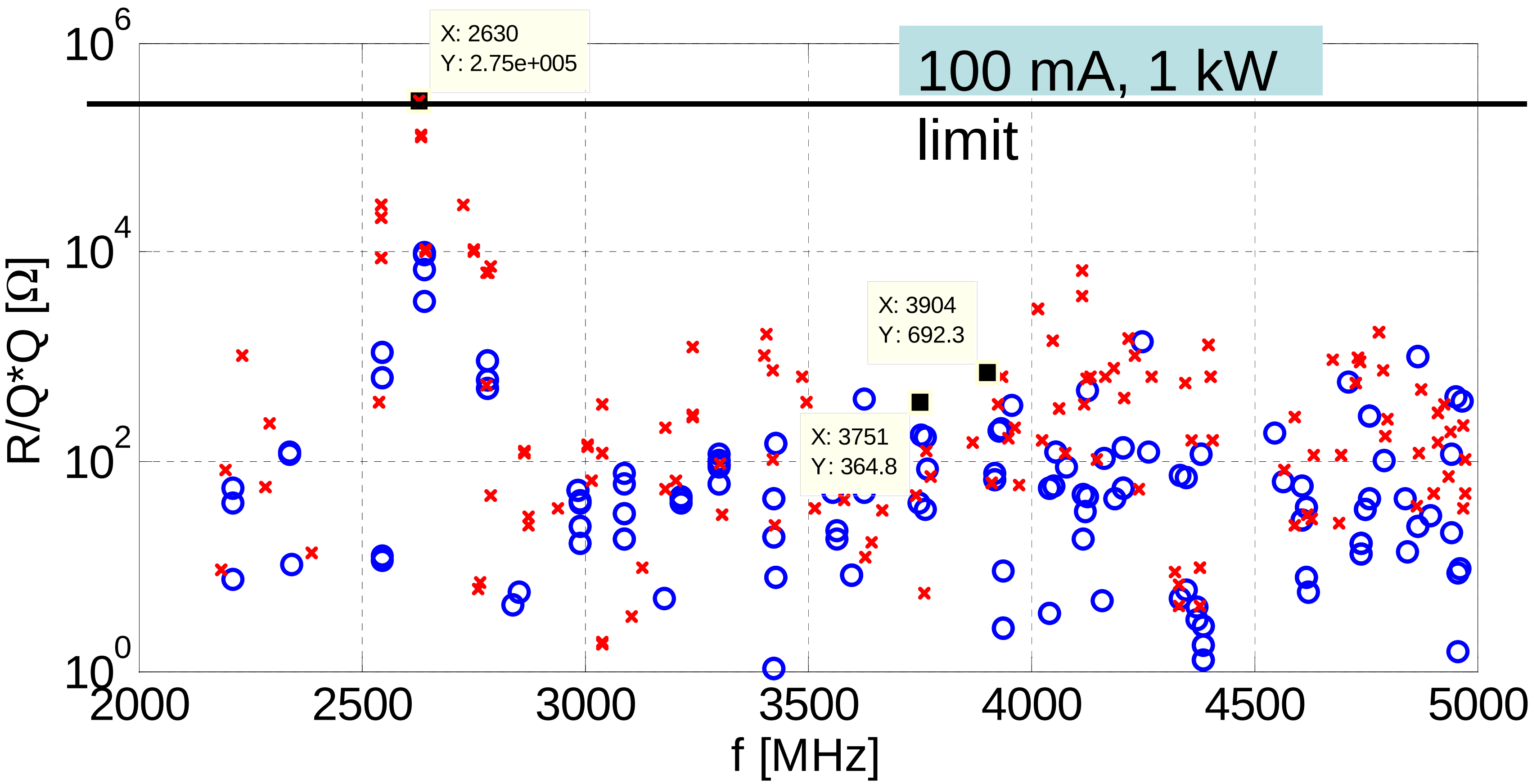


Cornell ERL injector

Effect of tile-removal for 100 mA beam current

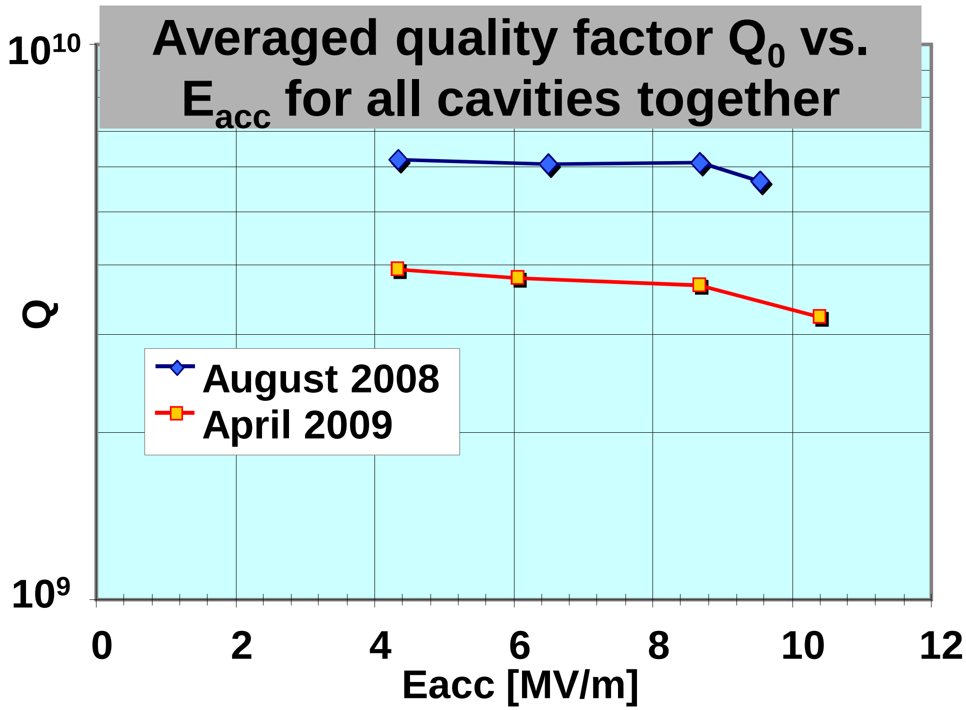
Blue: inside and outside ferrites

Red: outside ferrites only



M. Liepe

Cornell ERL injector

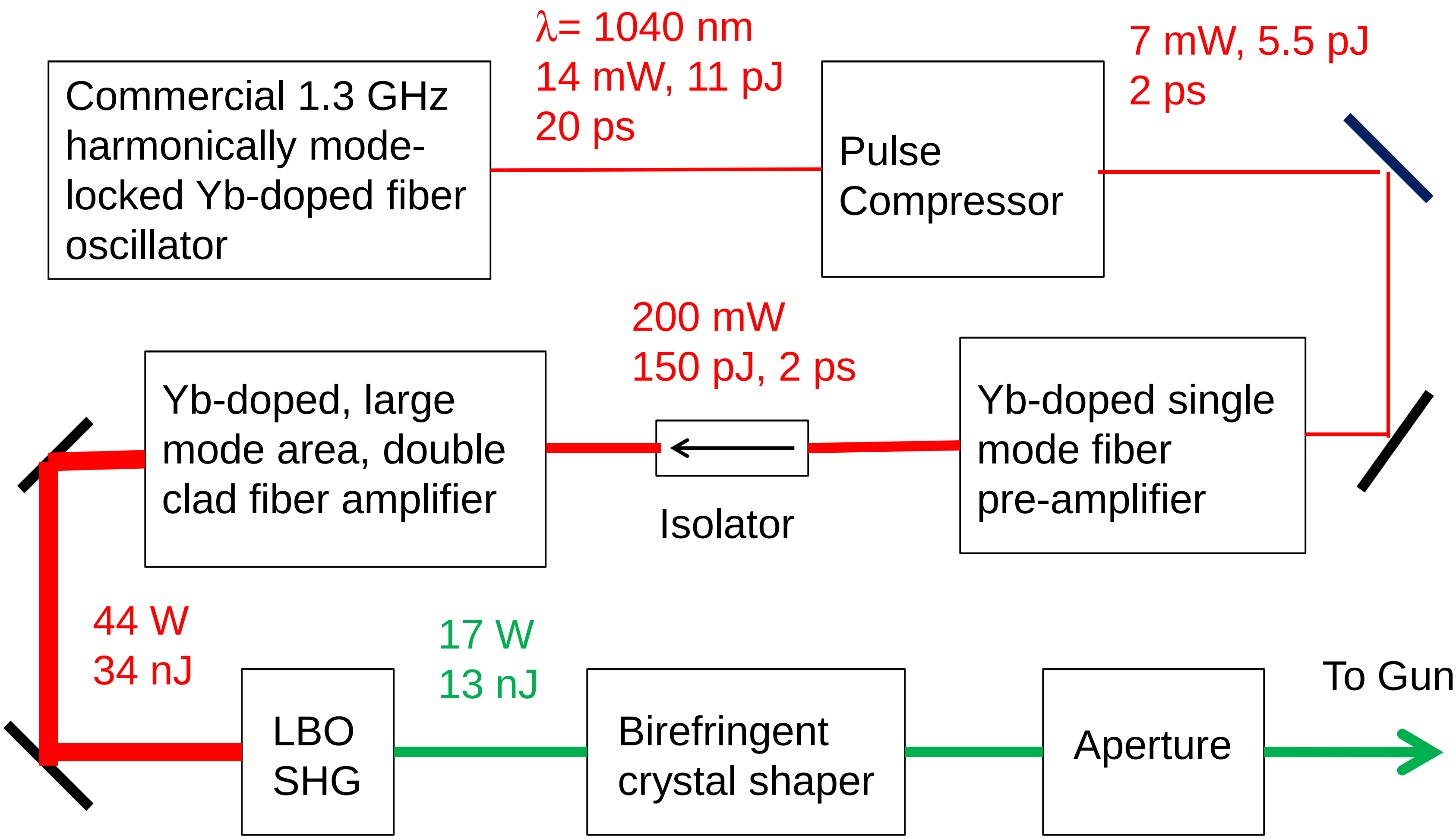


Had difficulties with low cavity quality factors

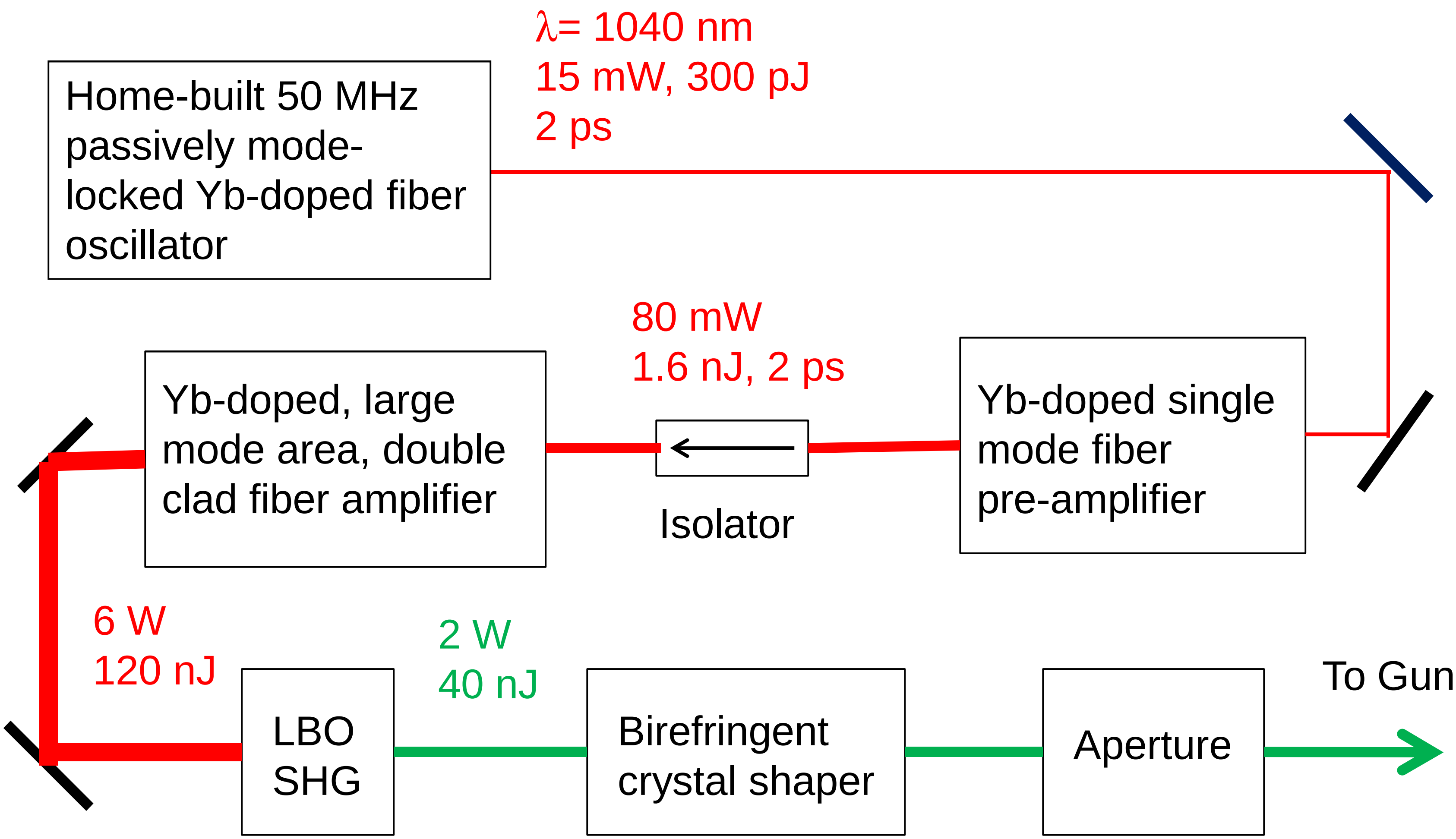
- Q factors degraded over time → Q disease?

During the rebuild, all cavities were high pressure rinsed
→ Q restored to 1.6 x 10^{10} at 1.8 K
→ no Q disease
→ cavities were possibly contaminated with particles?

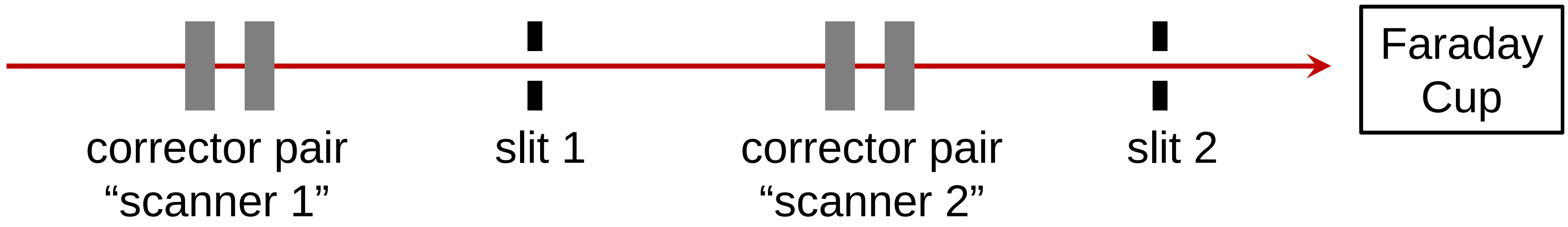
1.3 GHz drive laser system



50 MHz drive laser system



Emittance measurement system:

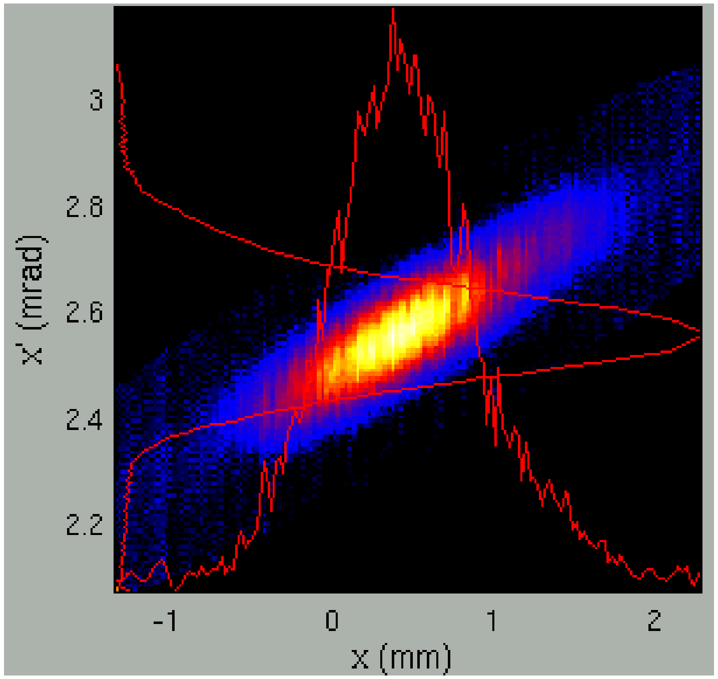


- No moving mechanical parts

→ Allows for very fast measurements (~ 5 s to 20 s)

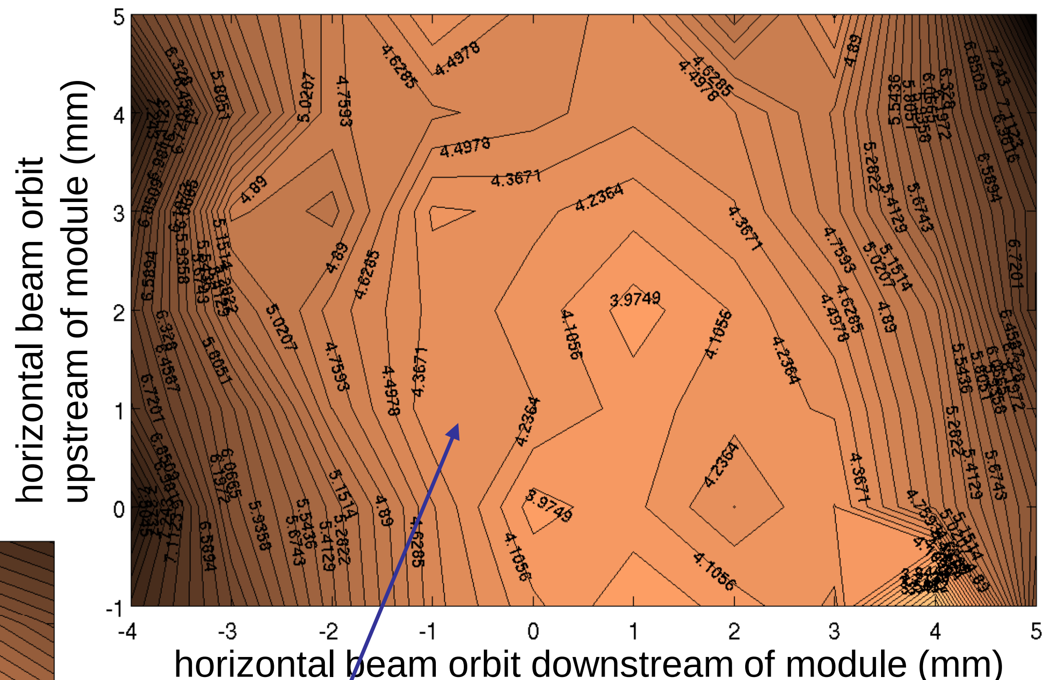
- fully integrated in control system ("single button operation")

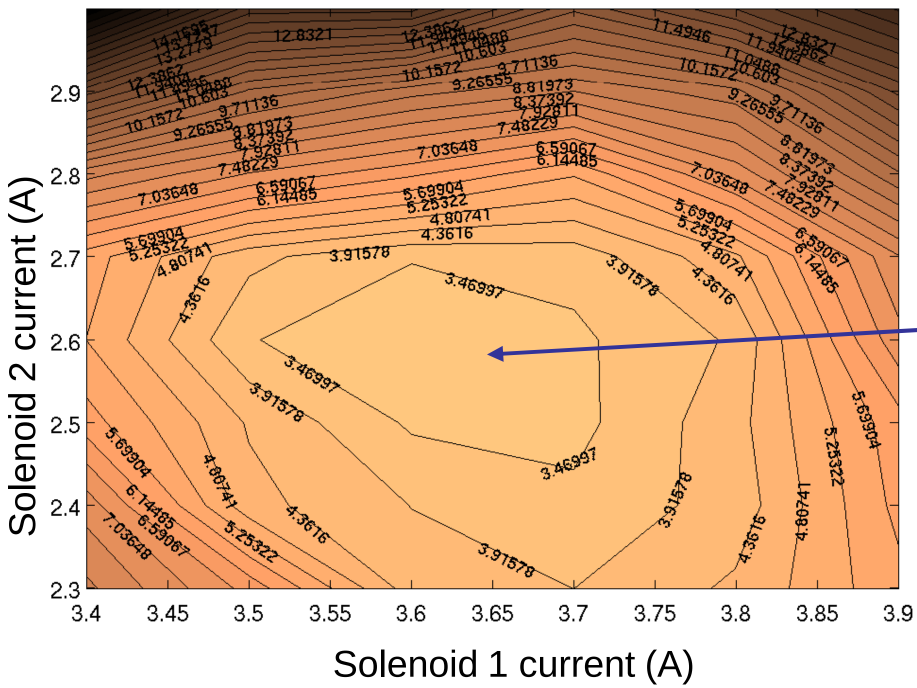
Combination with existing beam feedbacks (position, charge, …) allows for parametric optimization of the injector.



Cornell ERL injector

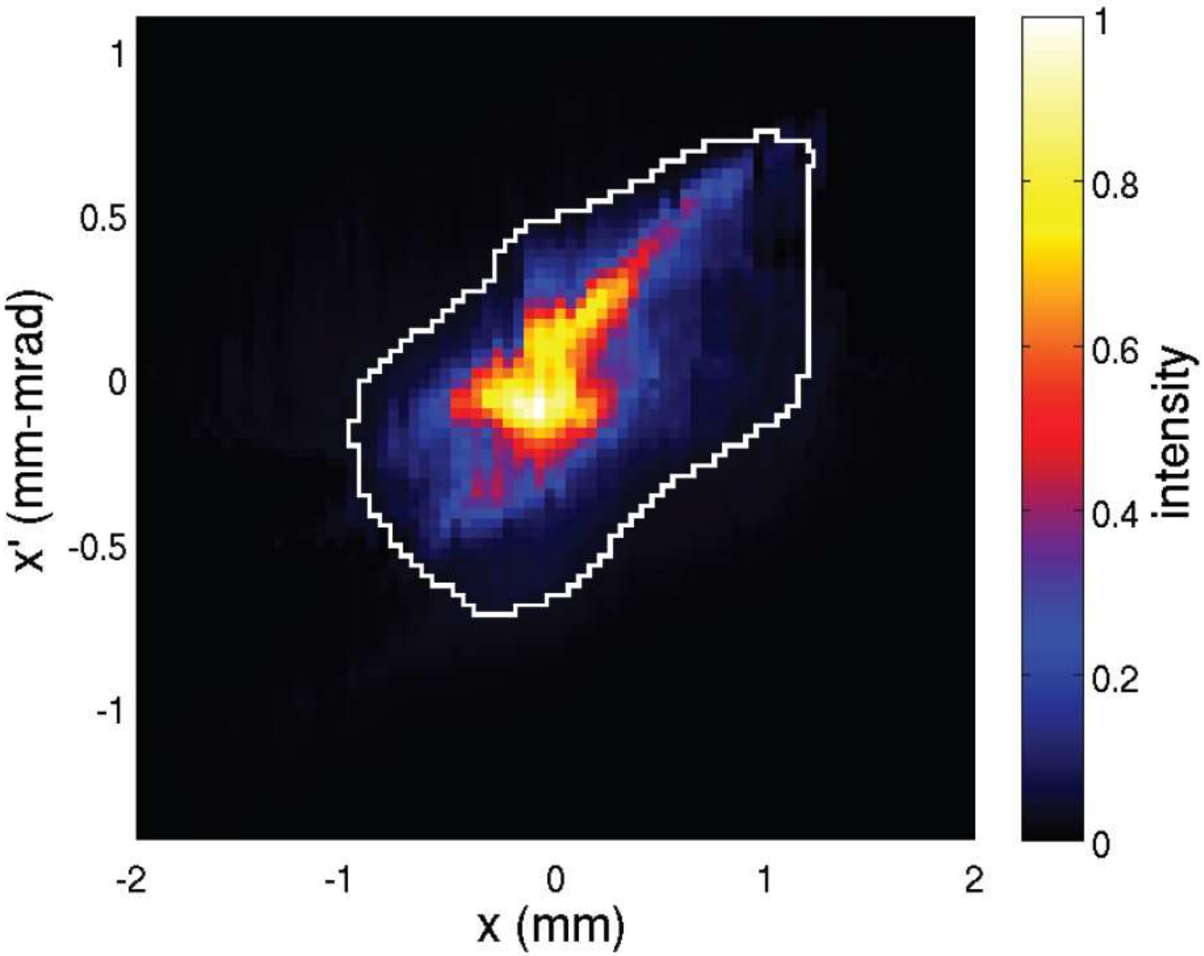
Performed initial parameter optimizations to improve the beam emittance:





Normalized horizontal beam emittance at E_{kin}= 10 MeV, q=-77 pC

Cornell ERL injector



Possible reason for large beam halo: Insufficient extinction ratio in macro-pulse operation.

(Measurements done with gated 50 MHz laser system:
1-2 kHz rate,
~300 ns macro-pulse duration)

Initial emittance measurements@ 10 MeV, 77 pC:

ε_N = 2.7 mm-mrad (dominated by beam halo)

$\varepsilon_{N,90}$ = 1.6 mm-mrad for 90% beam core (white region-of-interest)

Summary / Outlook

- Great progress has been made in all of the three CW gun technologies:
  - DC
  - normal-conducting
  - superconducting
- First 100 mA ERL injector is currently being commissioned, so far with very promising results.
- High current results expected later this year

Contributing to the Cornell ERL injector:

I. Bazarov, S. Belomestnykh, M. Billing, E. Chojnacki, Z. Conway, J. Dobbins, B. Dunham, R. Ehrlich, M. Forster, S. M. Gruner, C. Gulliford, G. Hoffstaetter, V. Kostroun, M. Liepe, Y. Li, X. Liu, D. Ouzounov, H. Padamsee, D. Rice, V. Shemelin, E. Smith, K. Smolenski, M. Tigner, V. Veshcherevich, Z. Zhao

Thanks for your attention!