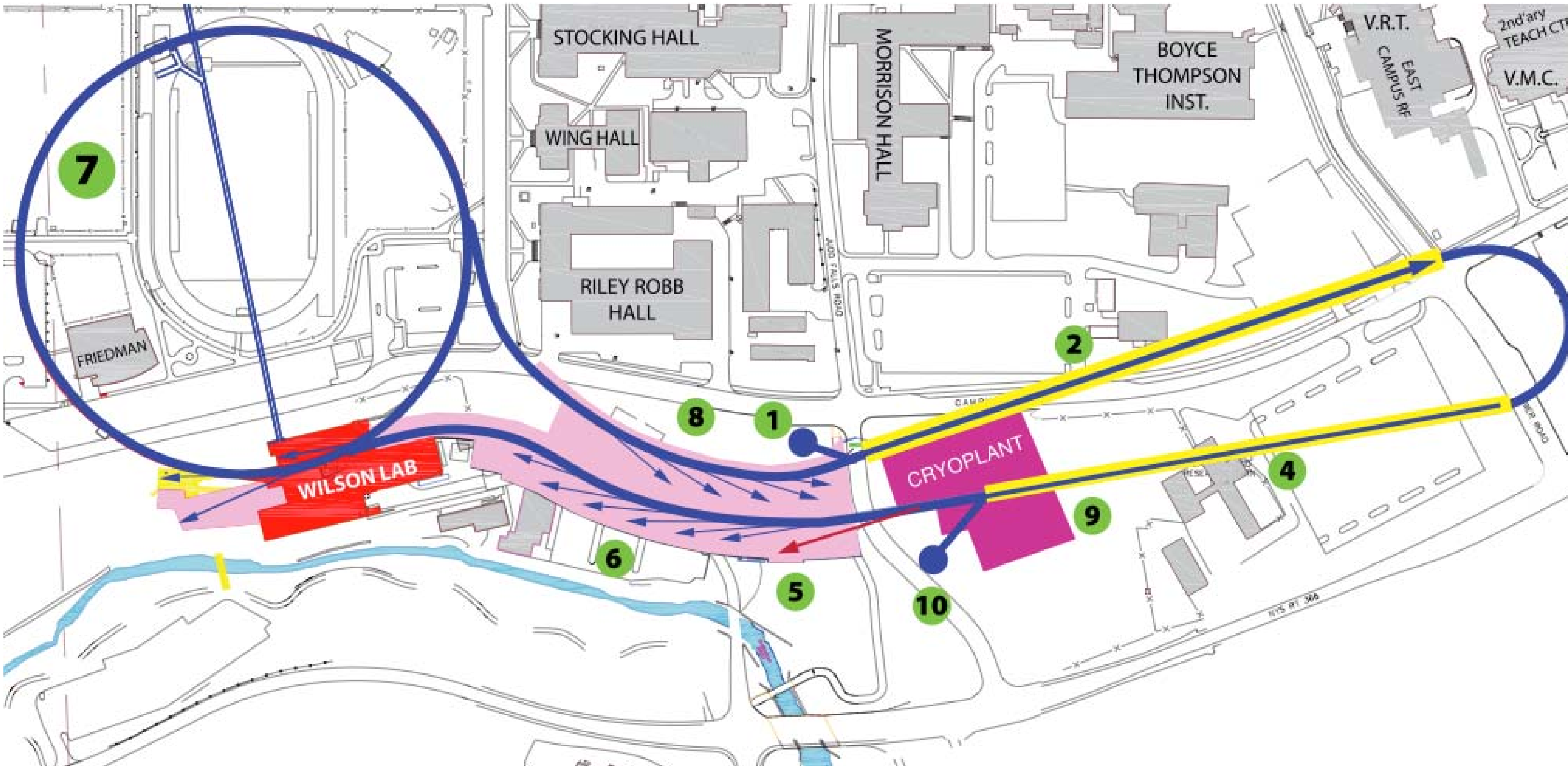
Commissioning Results for the Cornell High Current ERL Injector



Florian Loehl
(Cornell University)

GFA & SwissFEL Accelerator Seminar
PSI, Villigen, Switzerland, December 13, 2010

A way to improve X-ray facilities

Storage Rings:

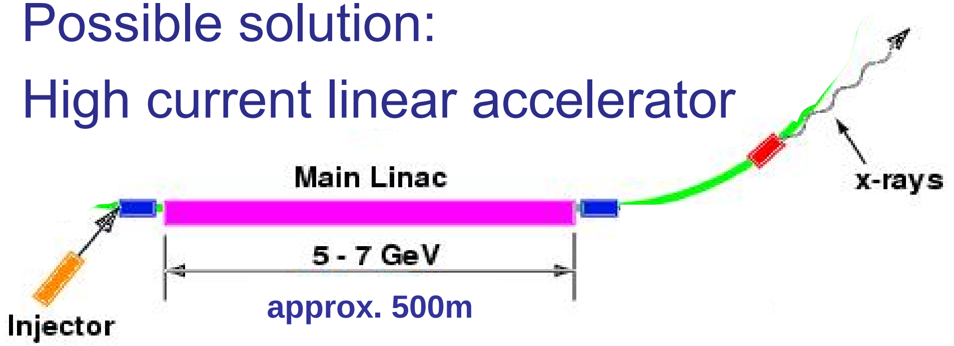
- Narrower and less divergent X-ray beams
- More coherent beams
- More mono-energetic beams
- Shorter pulses

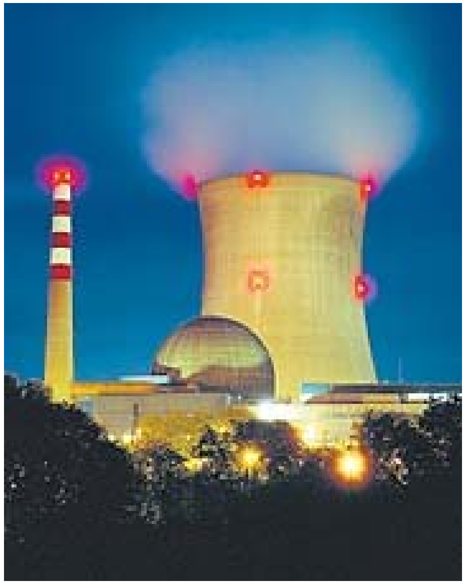
Linac based FELs:

- Higher repetition rates
- Stability

Possible solution:

High current linear accelerator





But…

5 GV * 100 mA = 0.5 GW

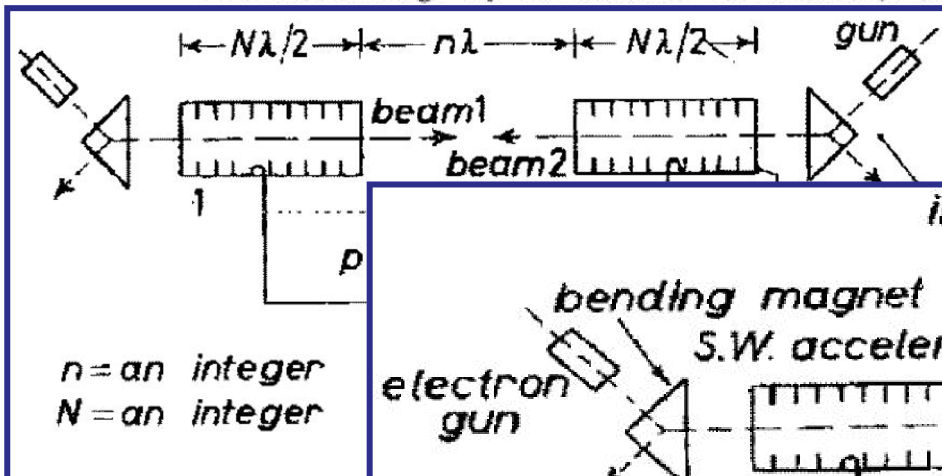
The ERL Concept

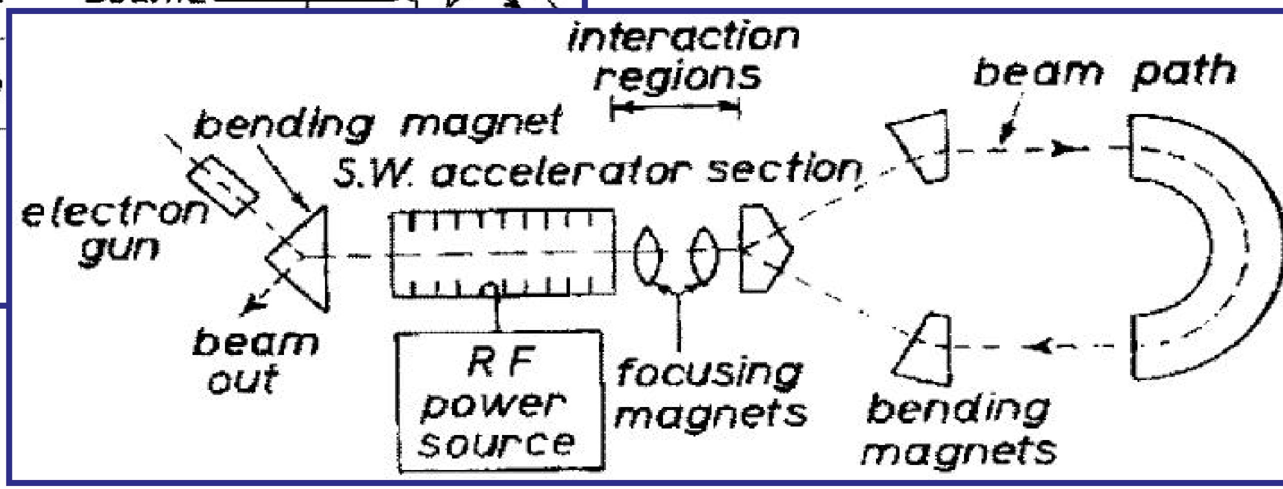
A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. TIGNER

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

Febbraio 1965)





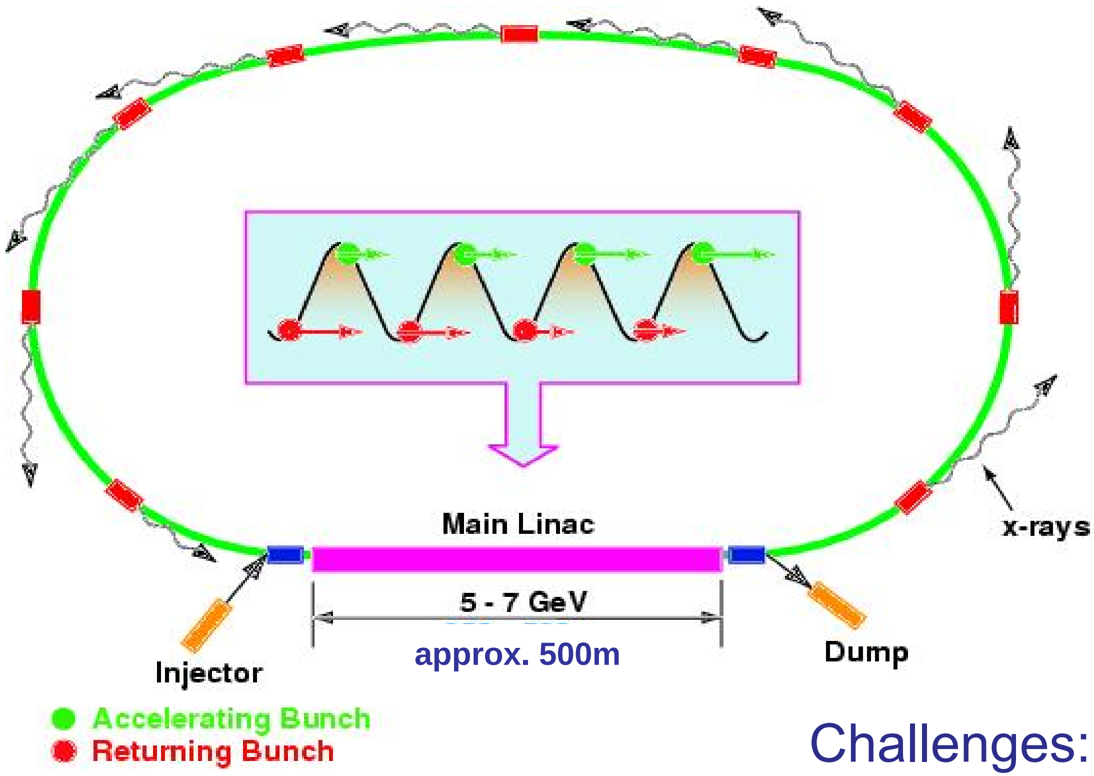
Electron energy is recovered into fields of RF structures

➢ Requires continuous RF field

- Normalconducting RF structures become too hot at high fields
- Superconducting RF cavities used to have too low fields

The ERL concept

The best of two worlds…



Electrons travel only a single loop

→ Similar beam quality as in linacs

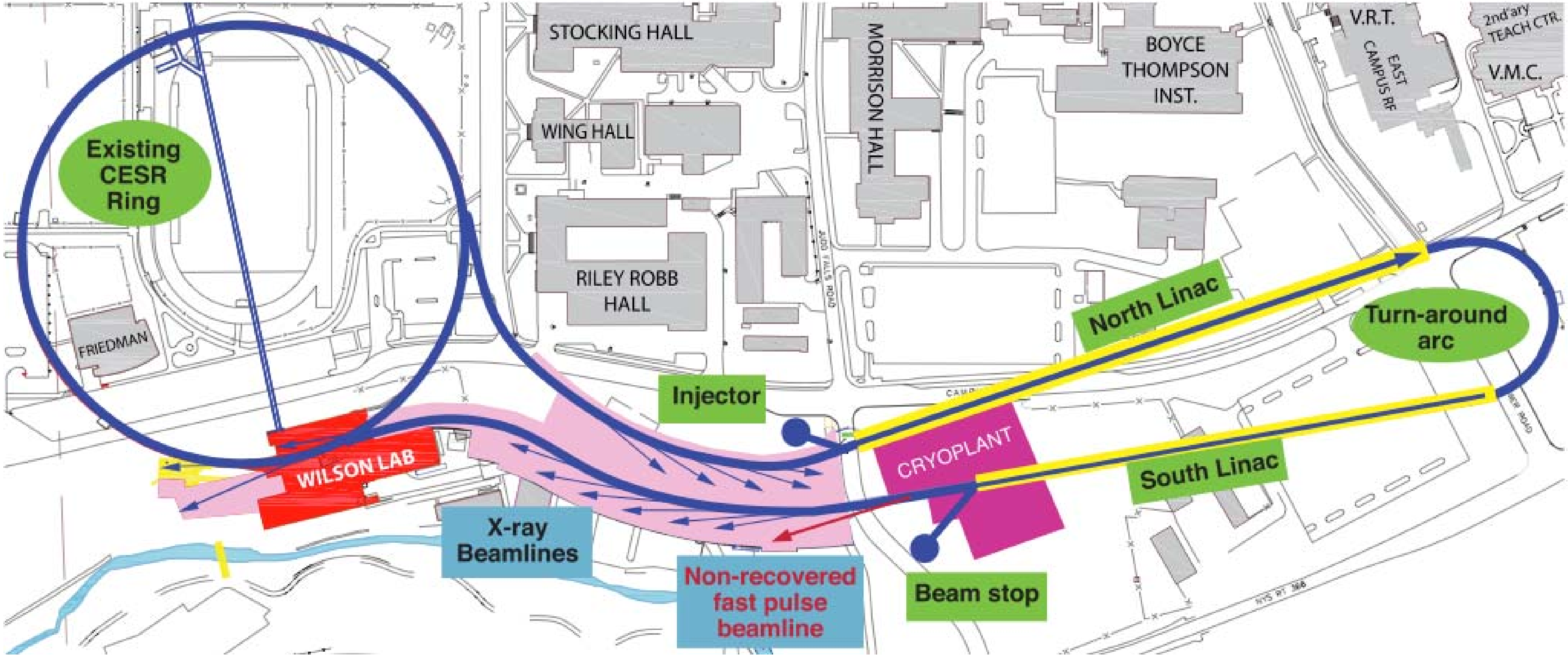
Beam energy is recovered

→ Similar beam currents as in storage rings

Challenges:

- Low emittance, high current creation
- Emittance preservation
- Beam stability at insertion devices
- Accelerator and component design (e.g. SRF)

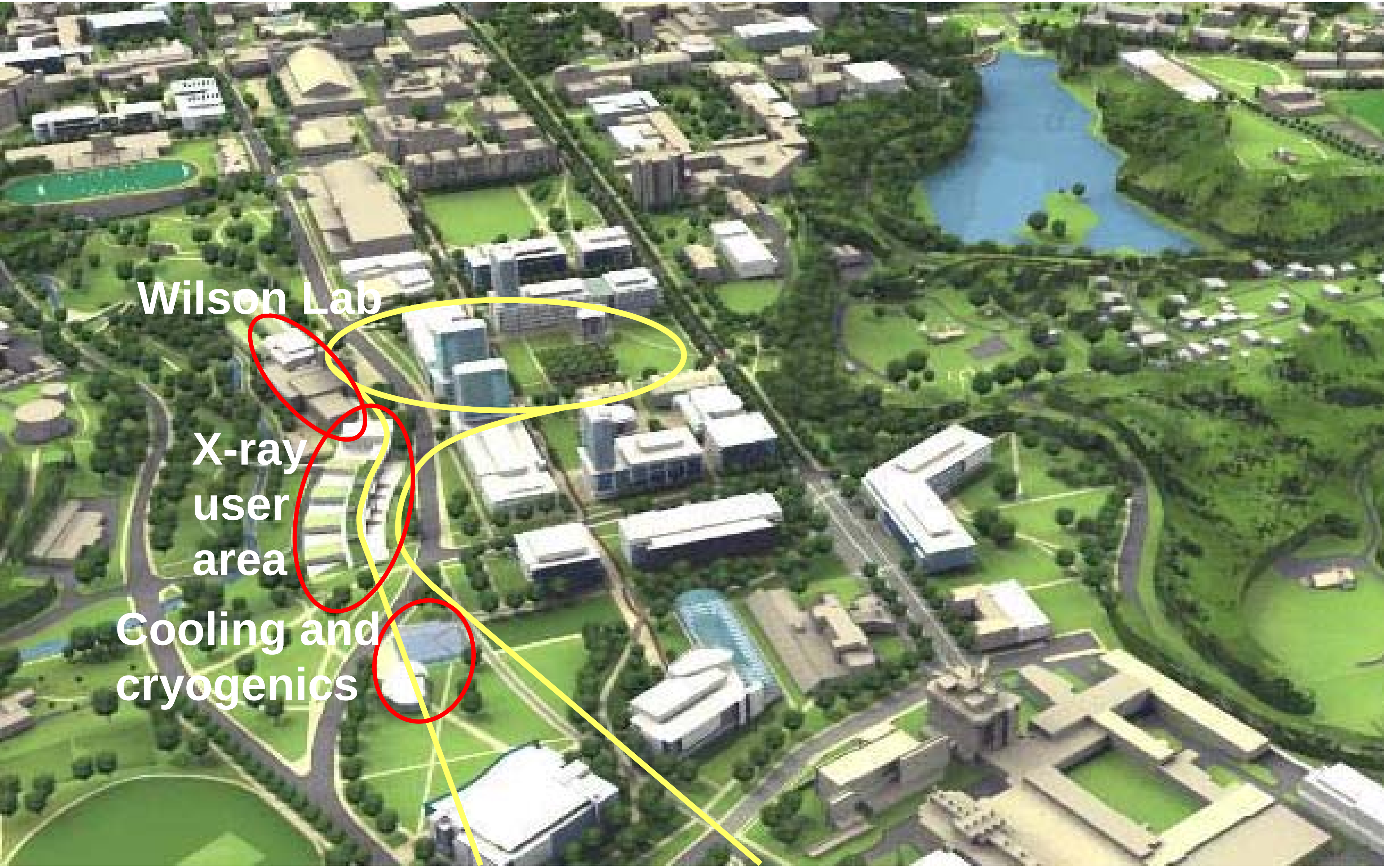
The Cornell ERL project



The Cornell ERL project

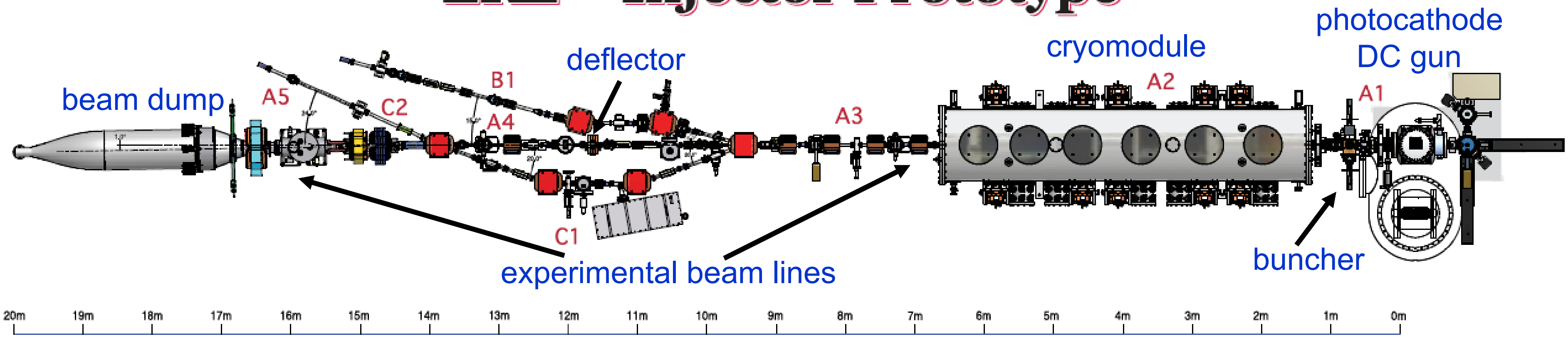
	Energy recovered modes			One pass	
Modes:	(A) Flux	(B) Coherence	(C) Short-Pulse	(D) High charge	Units
Energy	5	5	5	5	GeV
Current	100	25	100	0.1	mA
Bunch charge	77	19	77	1000	pC
Repetition rate	1300	1300	1300	0.1	MHz
Norm. emittance	0.3	0.08	1	5.0	mm mrad
Geom. emittance	31	8.2	103	1022	pm
rms bunch length	2000	2000	100	50	fs
Relative energy spread	0.2	0.2	1	3	10^{-3}
Beam power	500	125	500	0.5	MW

The Cornell ERL project



Cornell ERL injector

ERL – Injector Prototype



	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	
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	
Bunch length	0.6 mm (rms)	0.6 mm (rms)
Transverse emittance	< 1 mm-mrad	

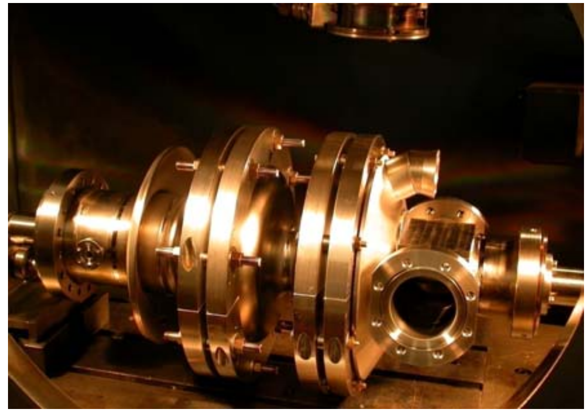
Cornell ERL injector

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

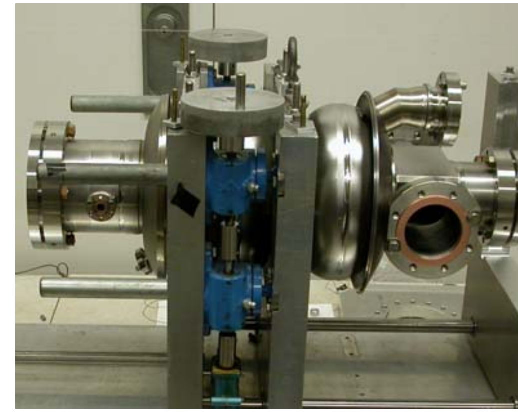
Superconducting Cryomodule

Pressed Nb cups for cavities

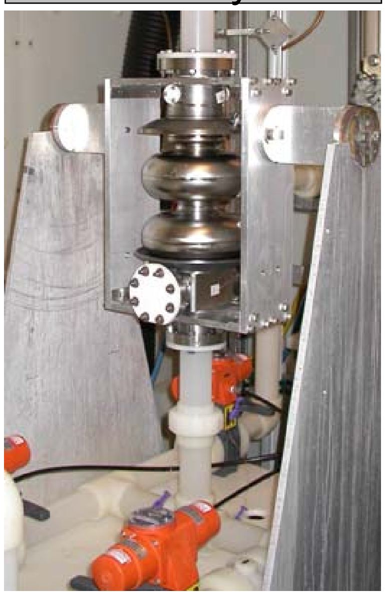
E-beam welding of cavities



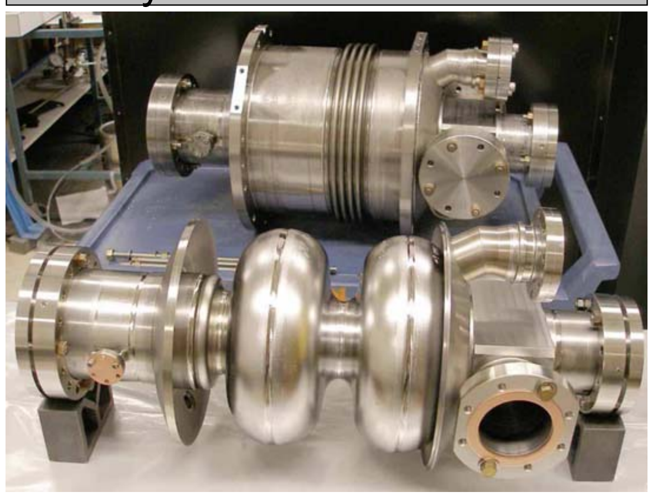
Tuning of cavities



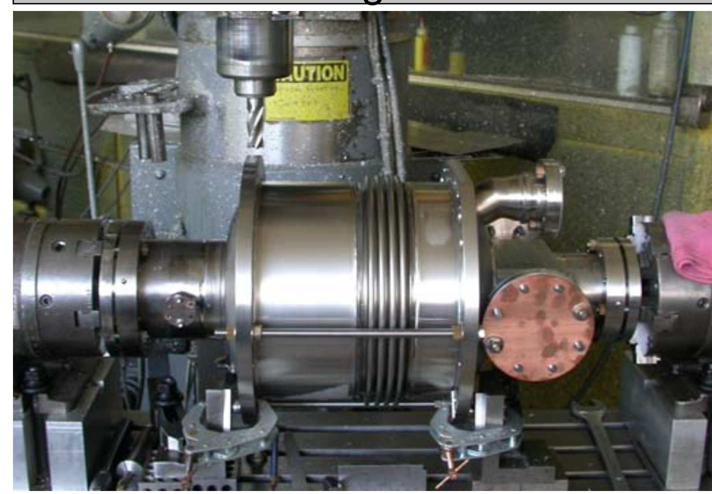
BCP cavity etch



Cavity with and w/o He vessel



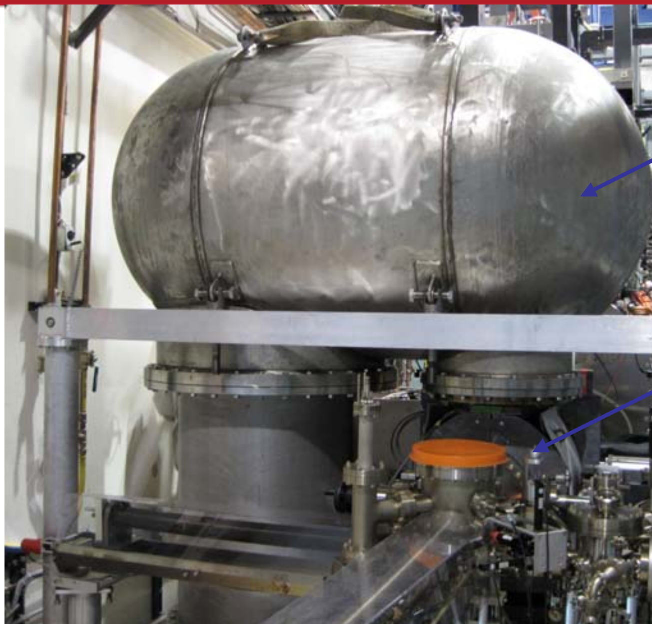
Final matching of He vessel



All done at CLASSE – No company could do this today !

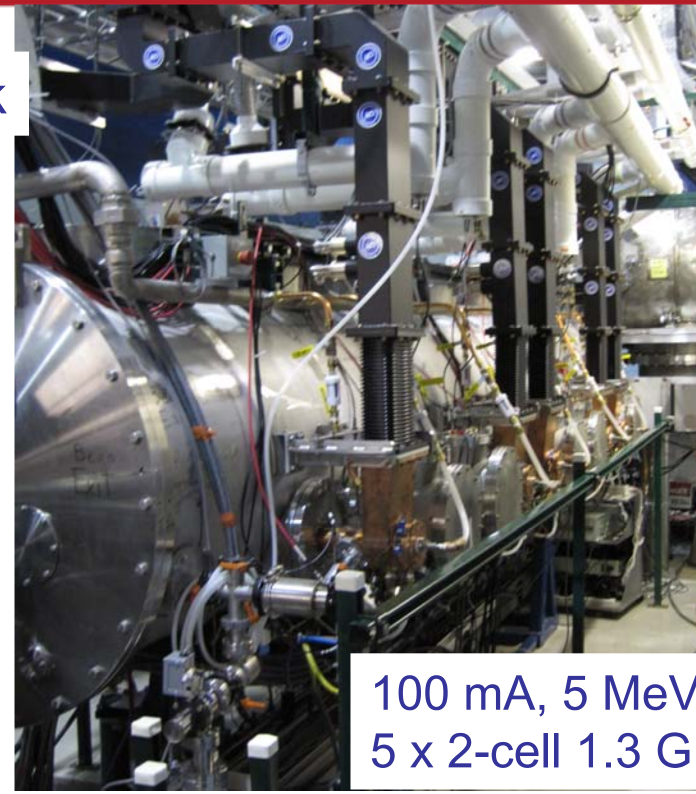
Transport from Newman Lab to Wilson Lab

Cornell ERL injector



SF6 tank

DC gun



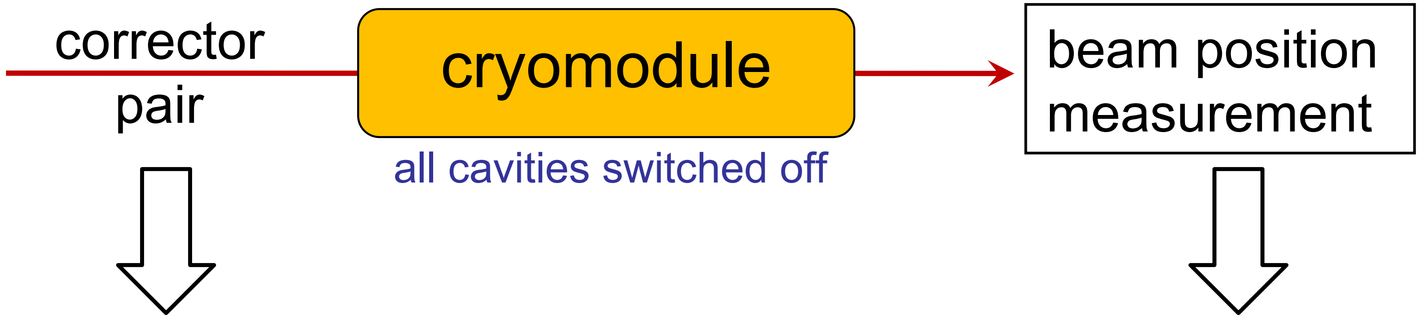
100 mA, 5 MeV SRF module
5 x 2-cell 1.3 GHz cavities

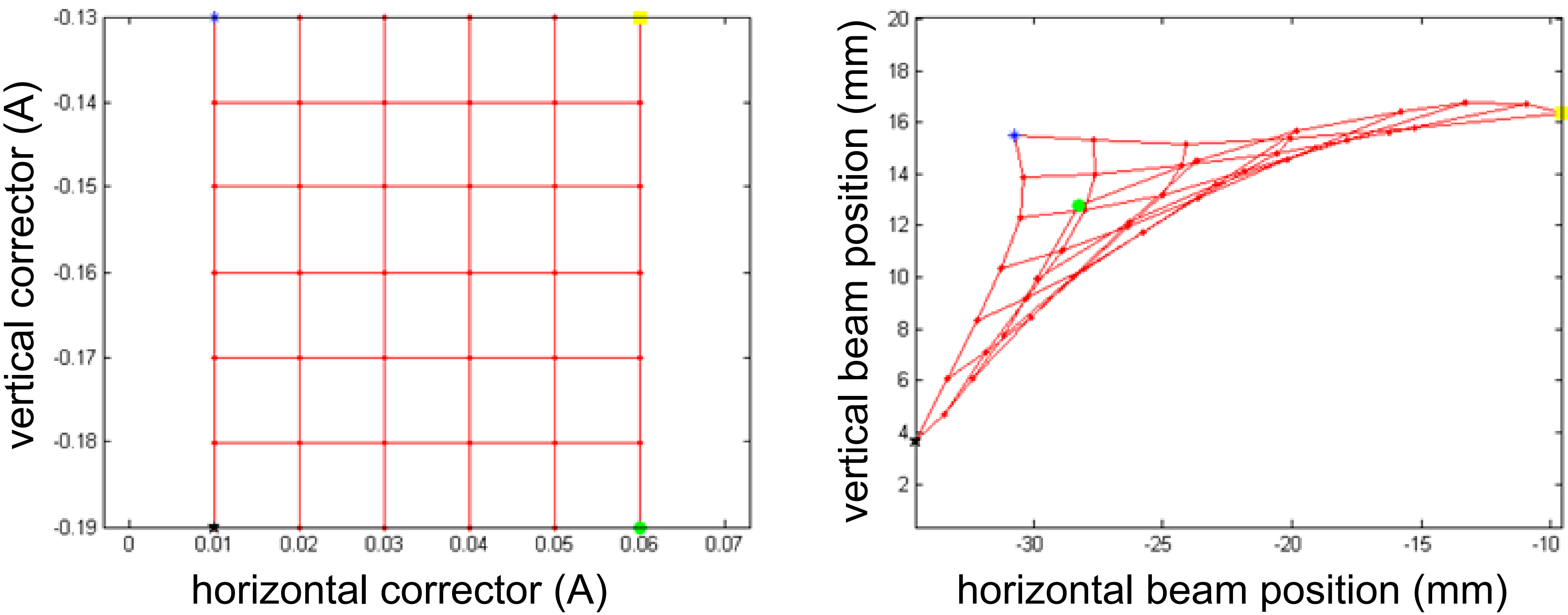
Diagnostics section
- emittance measurement systems
- deflecting cavity
- view-screens
- BPMs, BLMs, Faraday-cups, …

a bad start…

A bad start…

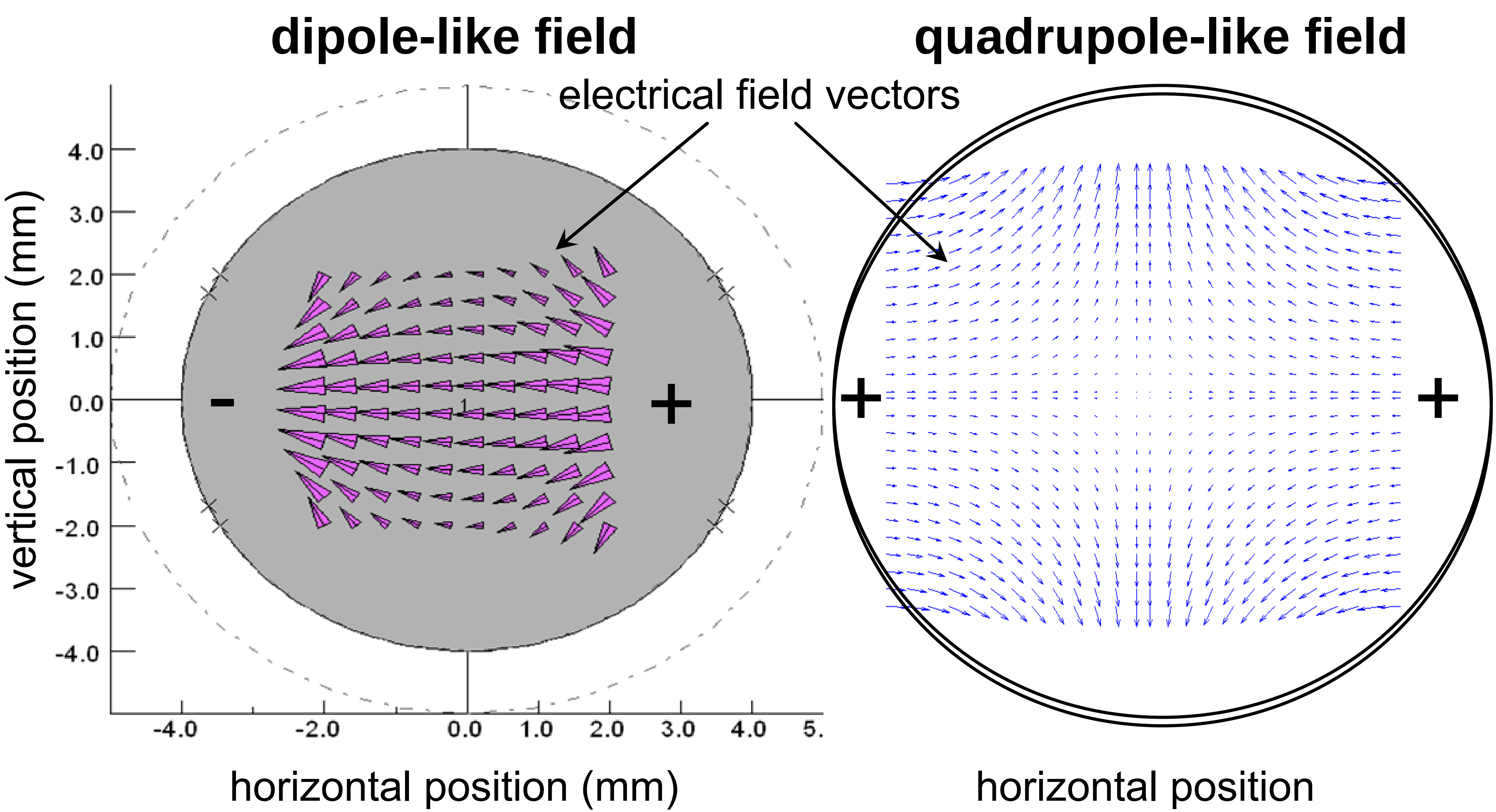
Strange beam orbit response:





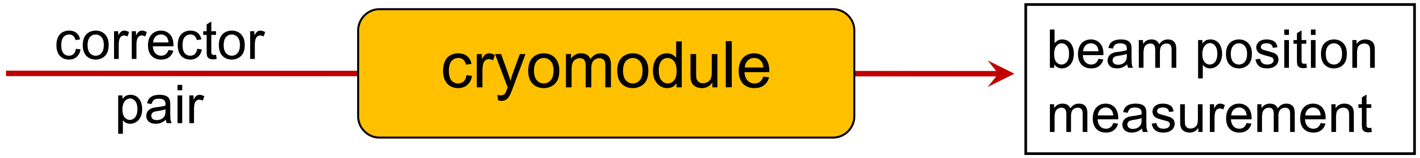
Localizing the field distortions

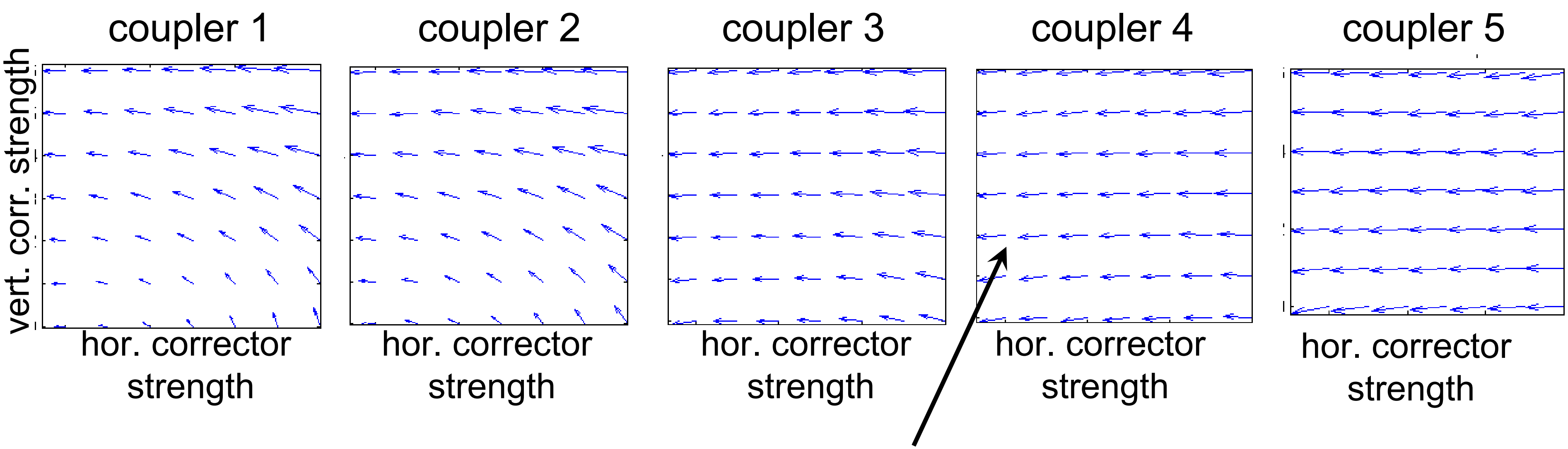
Generation of electrical DC fields in the coupler regions of the SRF cavities



Localizing the field distortions

dipole-like coupler kick



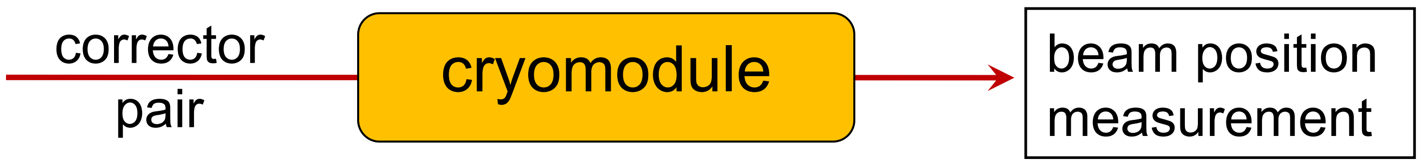


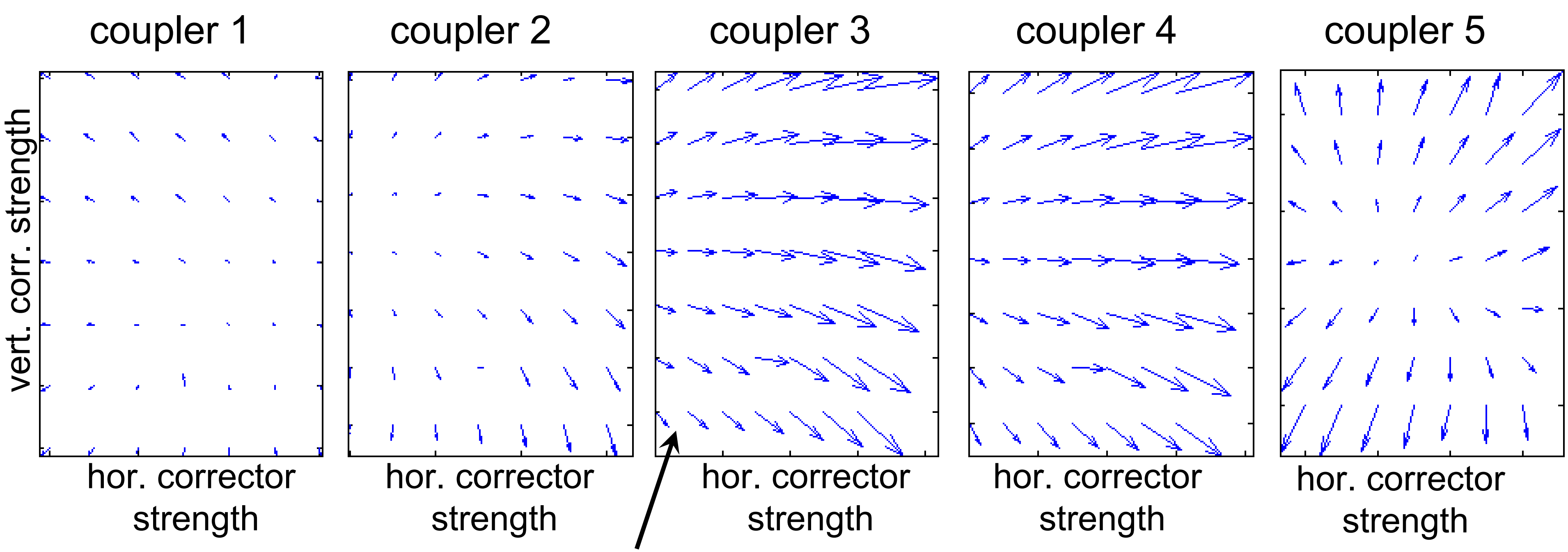
deflection of the beam after the cryomodule due to the coupler field

A bad start…

Localizing the field distortions

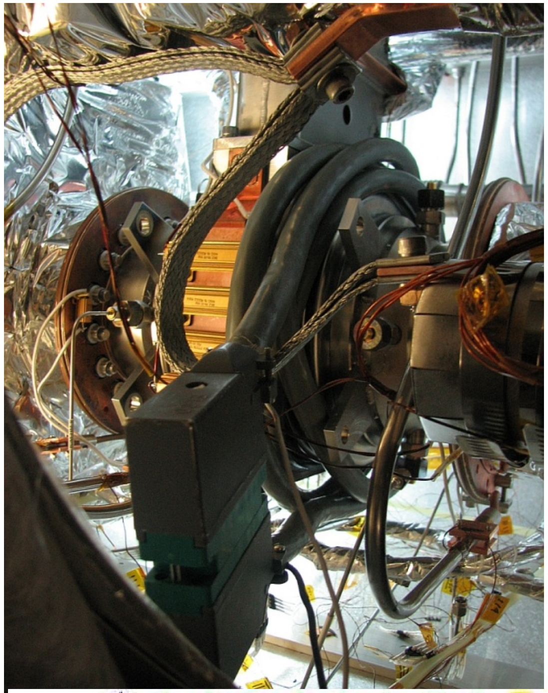
quadrupole-like coupler kick

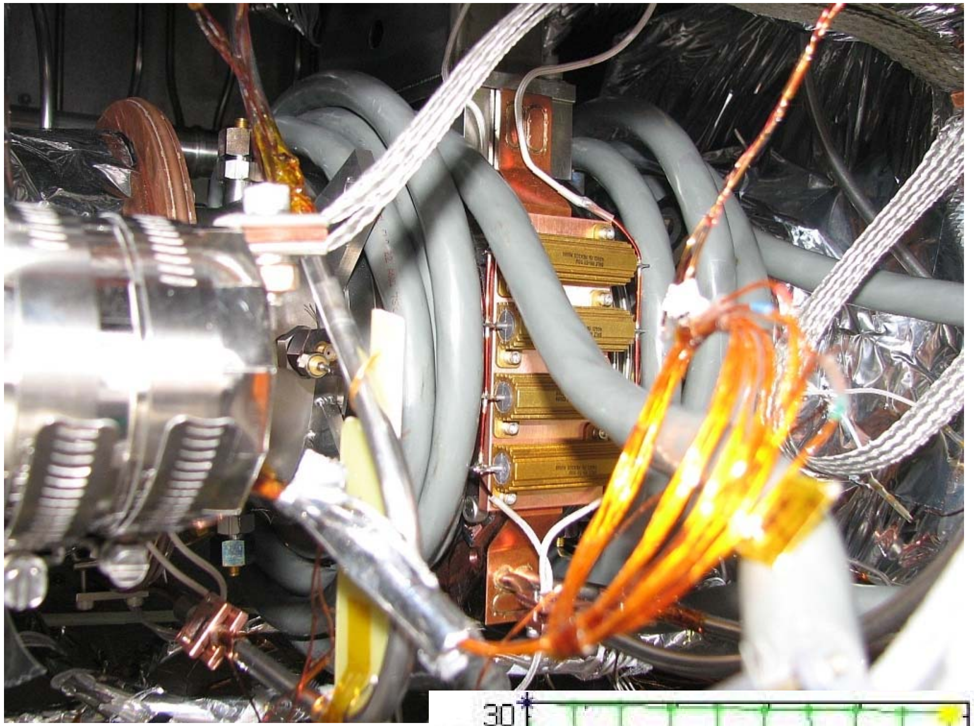


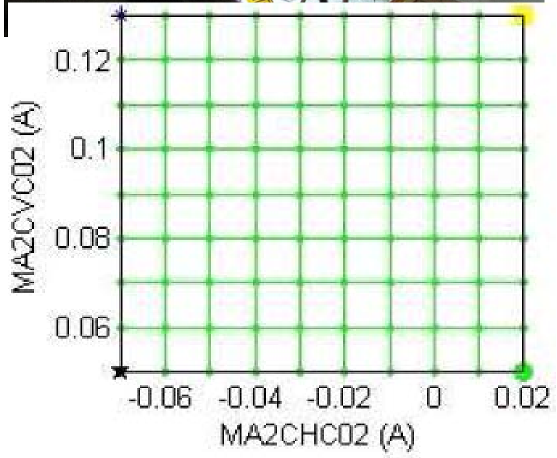


deflection of the beam after the cryomodule
due to the coupler field

A first attempt

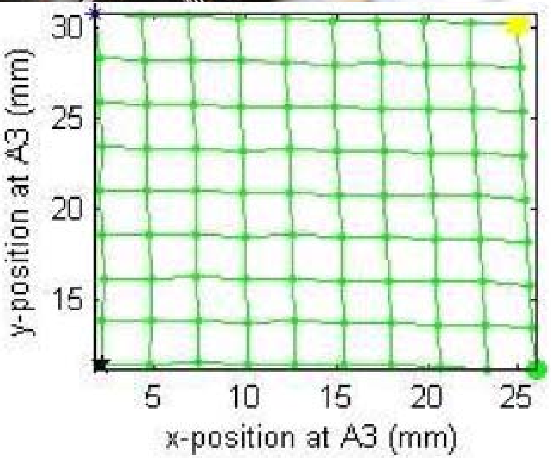






Warm up and in-situ demagnetization removed stray fields

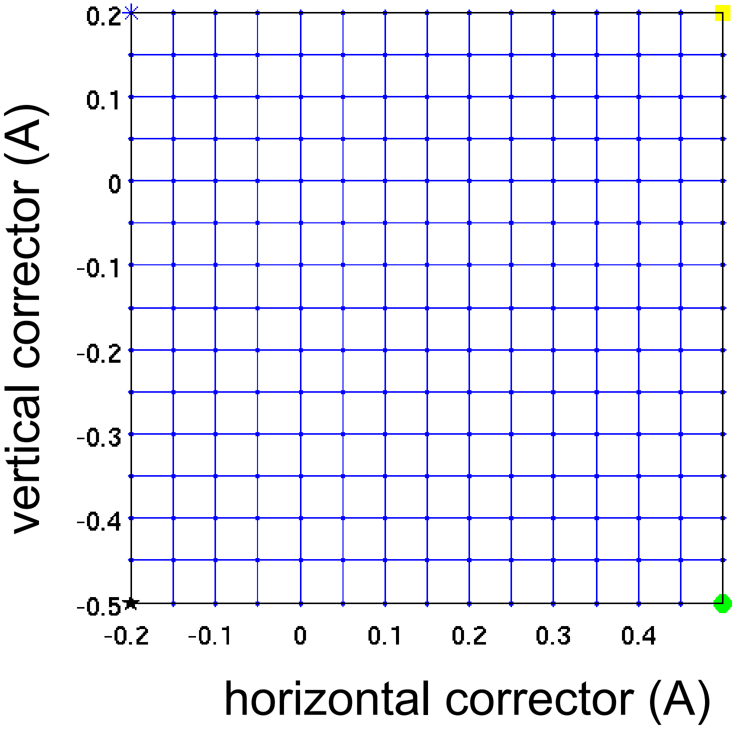
☺

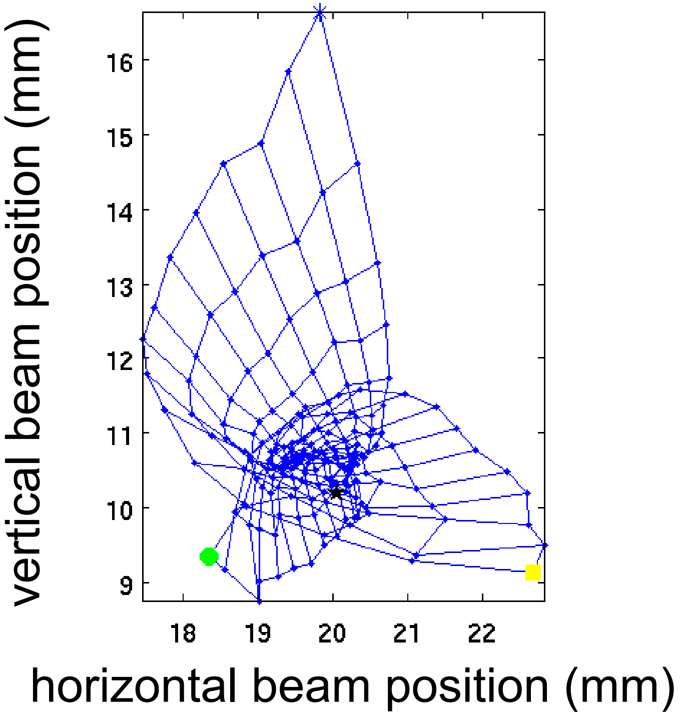


A short success…

- Stray fields reappeared after beam loss in the cryomodule occurred
- Coupler conditioning changed the stray fields

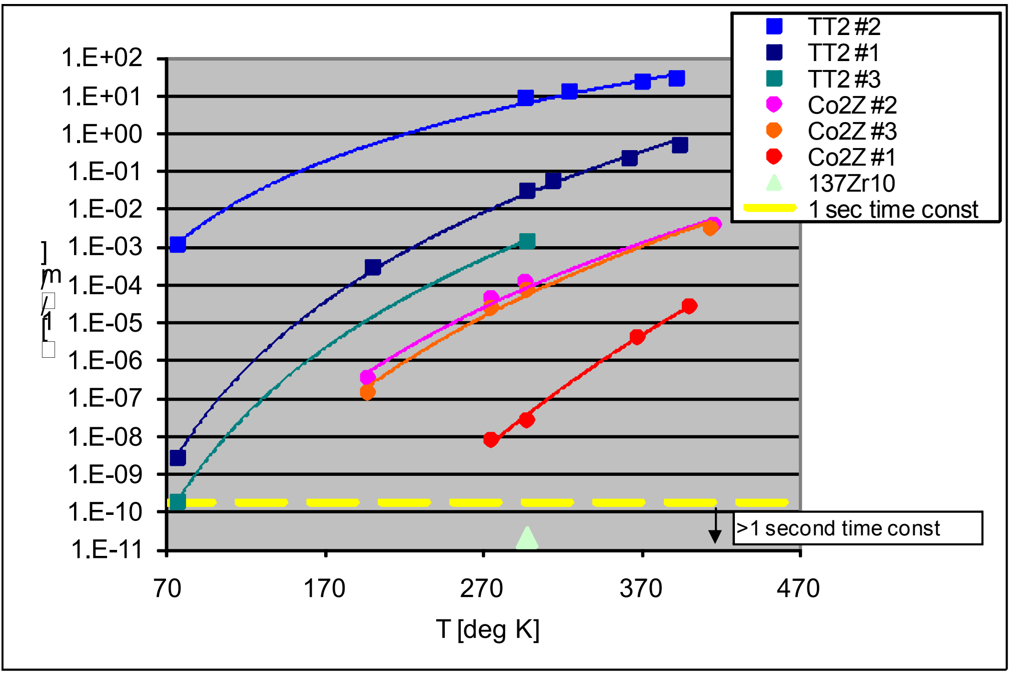
→ Charging up of HOM absorbers!

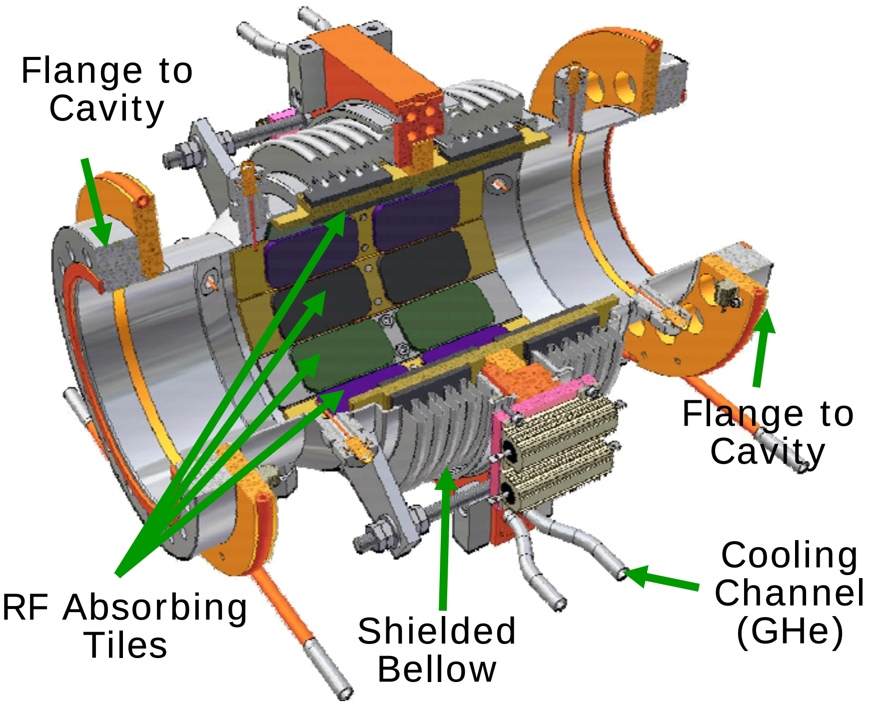


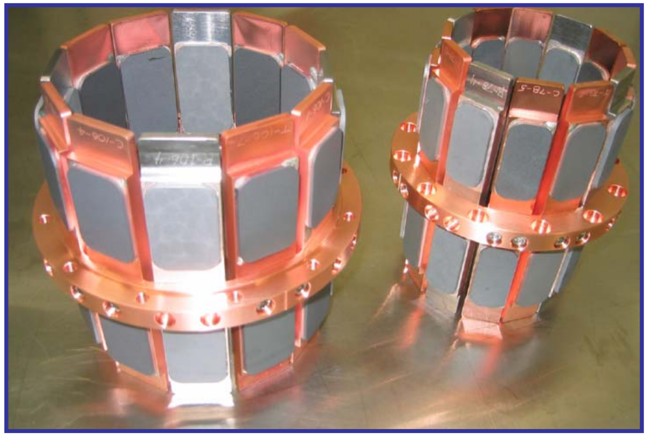


The culprits: HOM absorbers

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





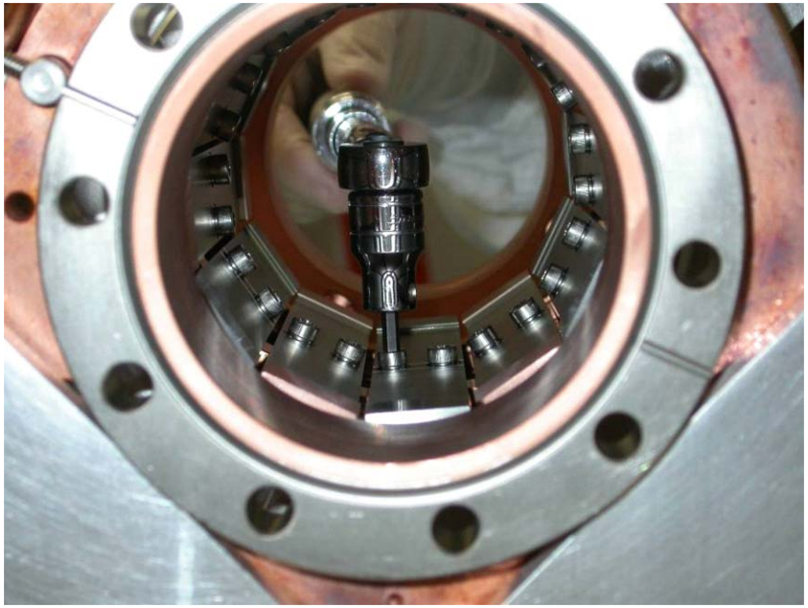


HOM absorber tiles charged up!

The solution

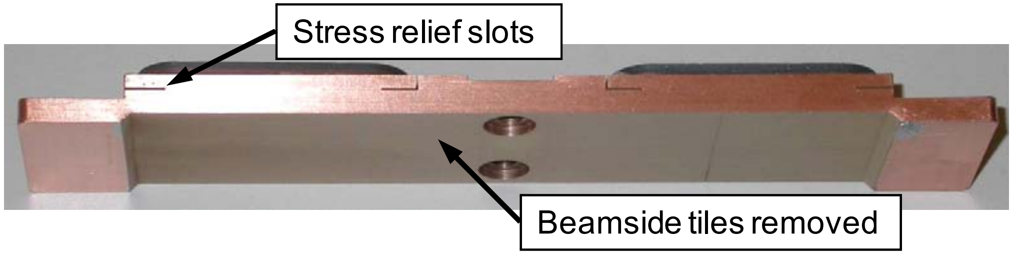
Consequence of low resistivities of absorber materials:
- Completely removed ceramic 137Zr10
- Tried gold coating of TT2 absorbers but coating may fall off

→ Removed all tiles from the inside of the HOM absorber

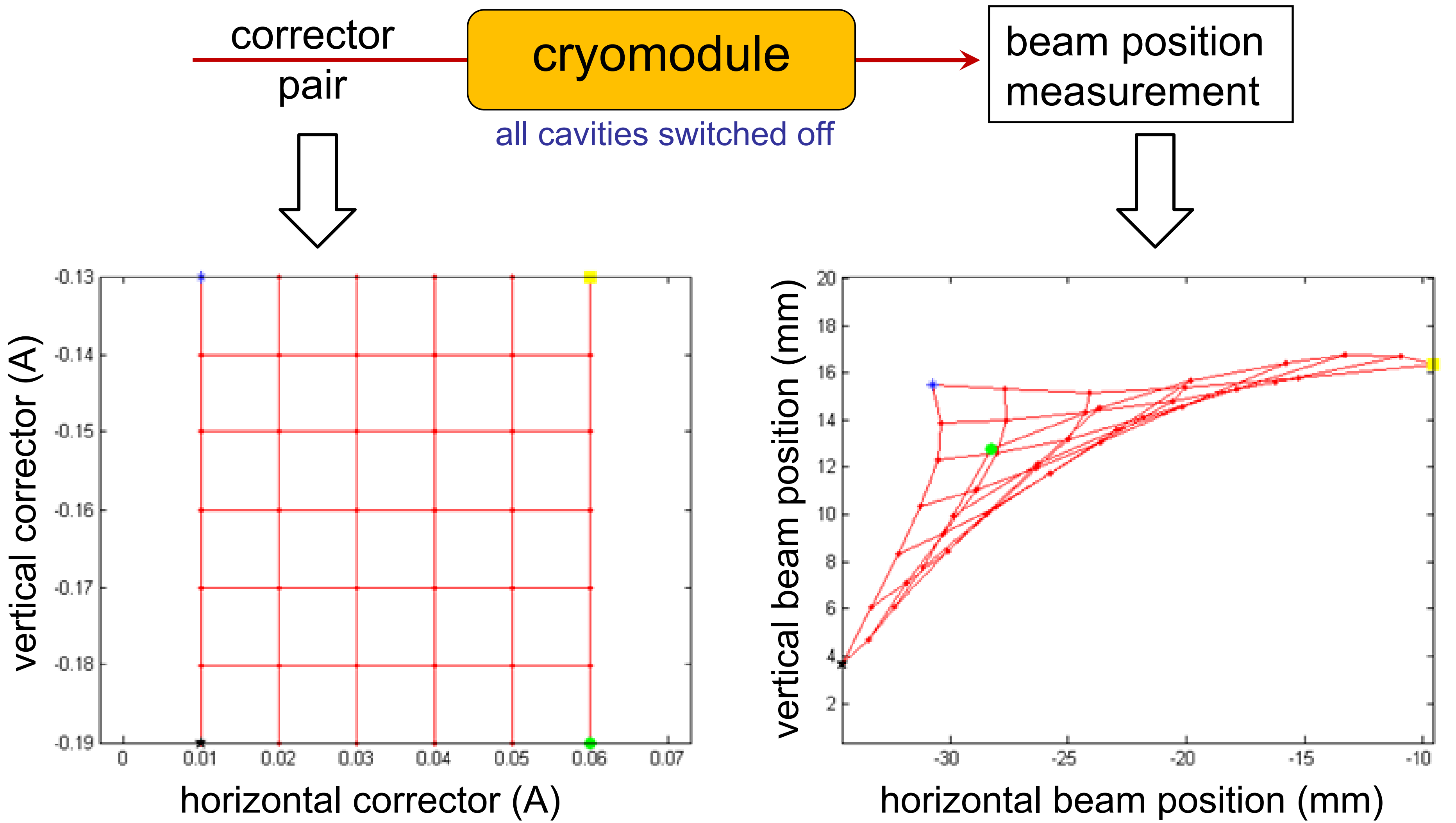


Found one loose tile during cryomodule disassembly
- Thermal stress tests confirmed this problem

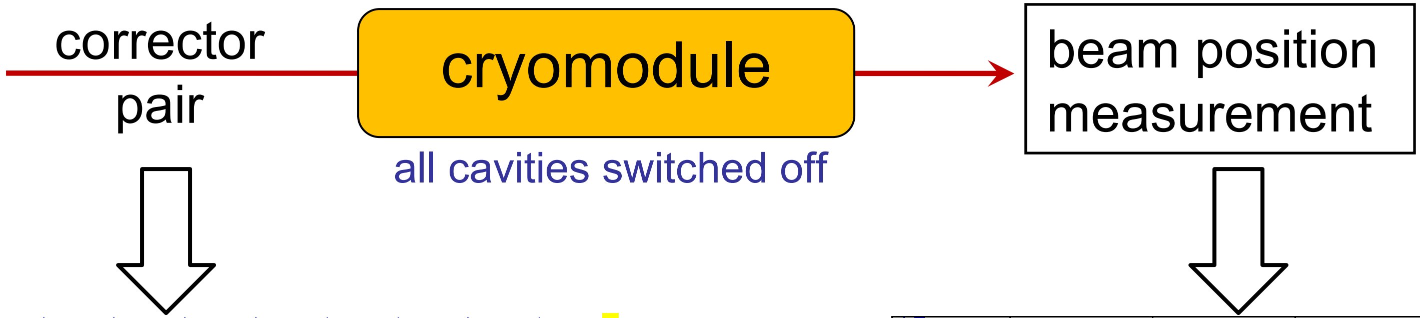
→ Solved by cutting stress relief slots in the tiles

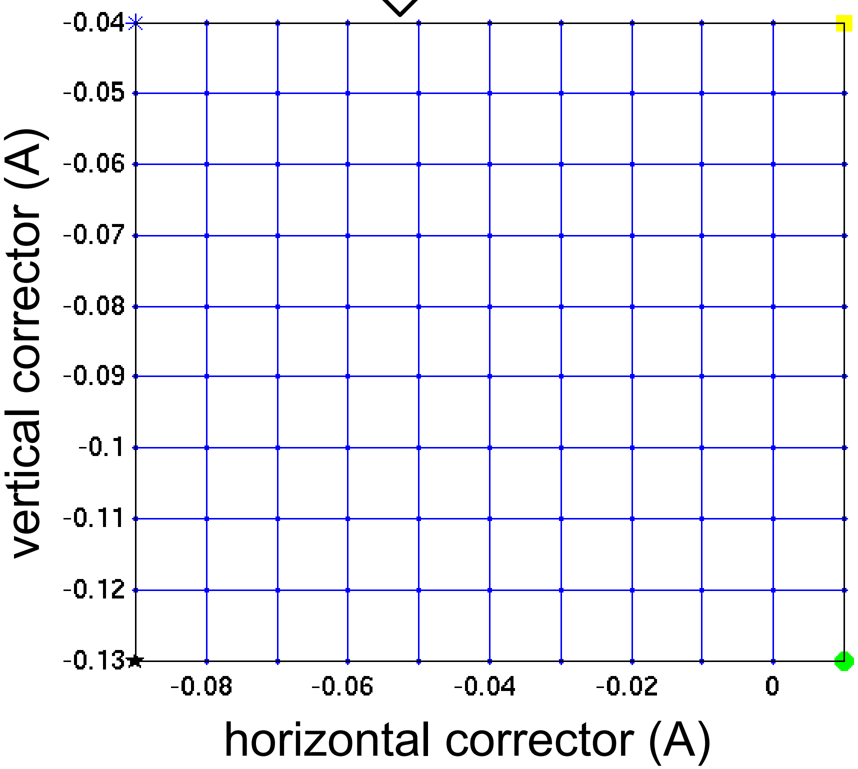


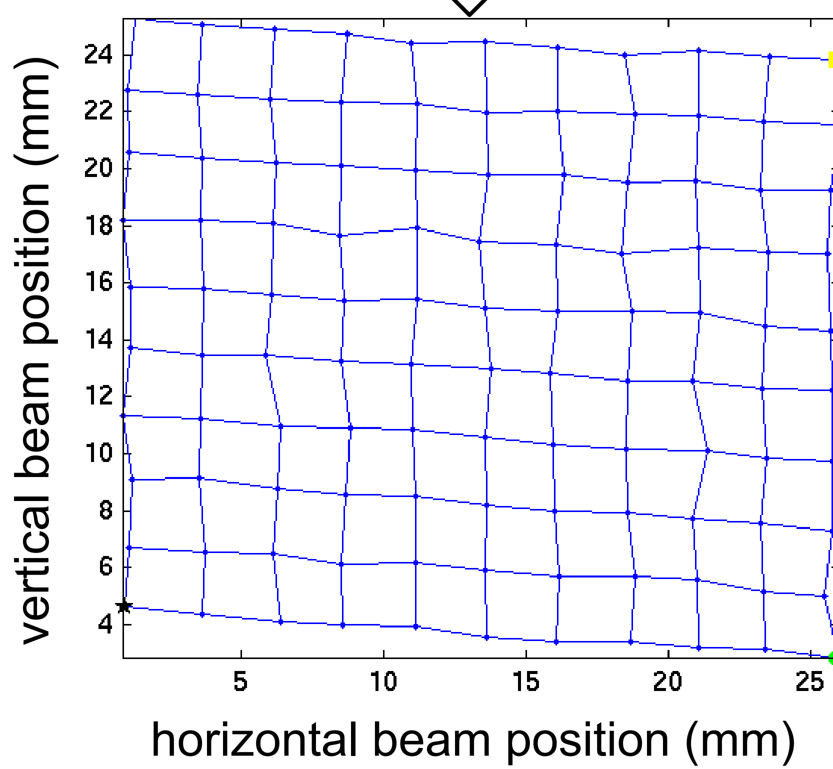
Before rework of cryomodule:



After rework of cryomodule:





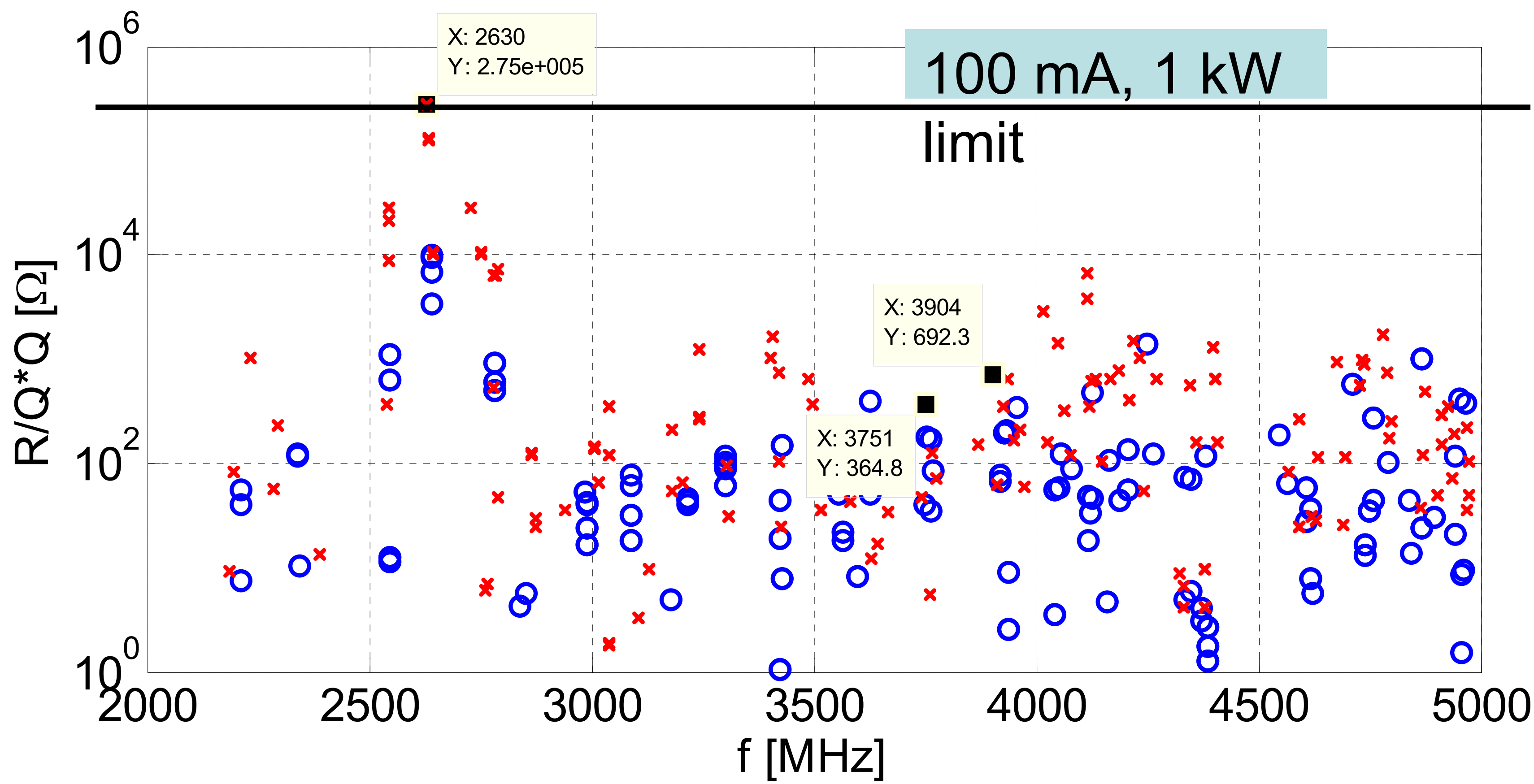


Limitations for high current operation?

Effect of tile-removal for 100 mA beam current

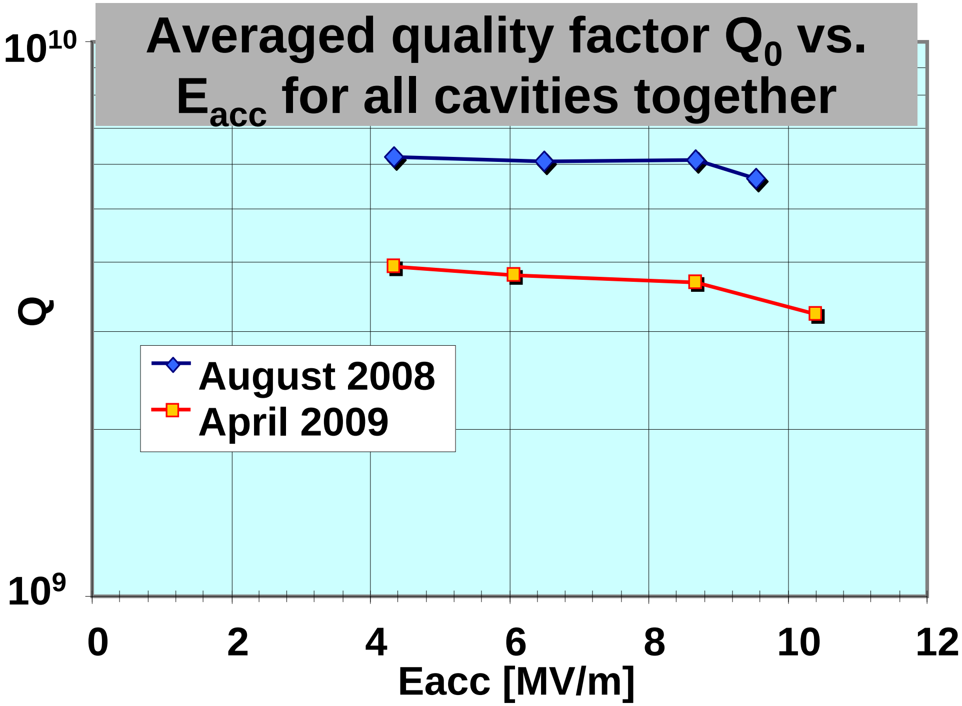
Blue: inside and outside ferrites

Red: outside ferrites only



M. Liepe

Rebuilding the cryo module also fixed cavity Q values



Had difficulties with low cavity quality factors

- Q factors degraded over time

→ Q disease?

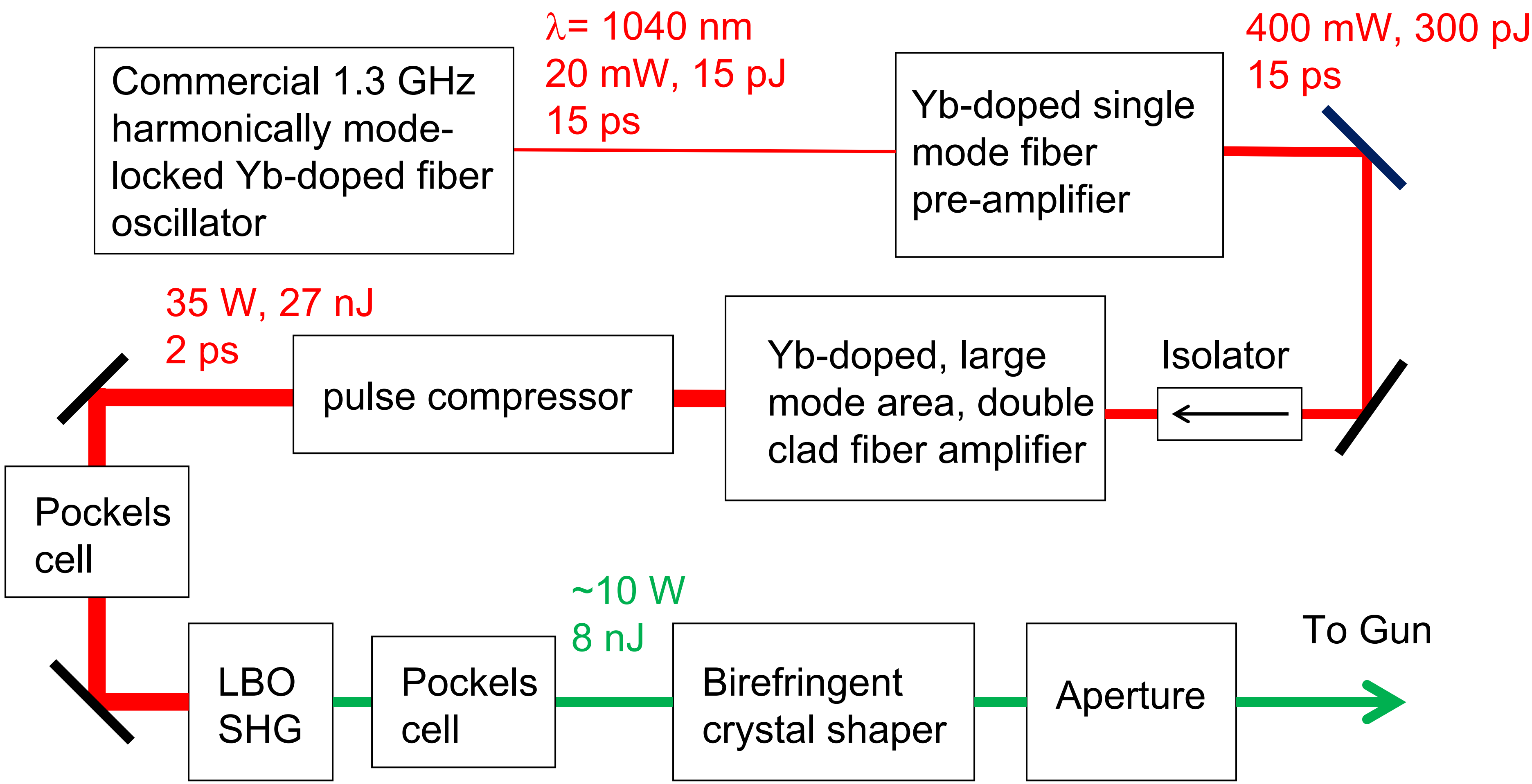
During the rebuild, all cavities were high pressure rinsed

→ Q restored to 1.6×10^{10} at 1.8 K

→ no Q disease

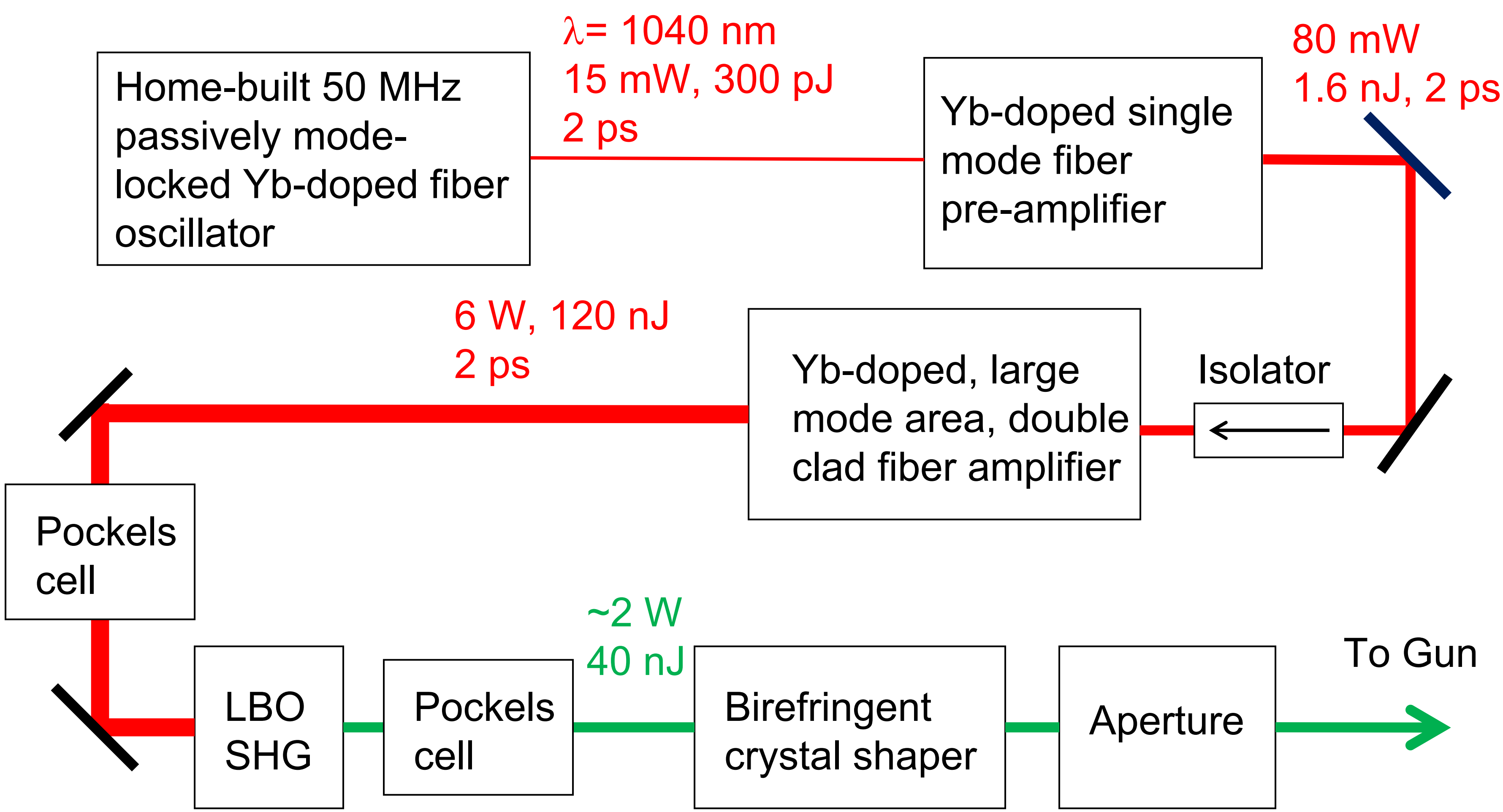
→ cavities were possibly contaminated with particles?

1.3 GHz drive laser system



Injector drive laser

50 MHz drive laser system



Diagnostics challenges in ERL injector

The dynamic range of many systems needs to be HUGE!

Examples:

- bunch charge: ~ fC to 100 pC
- duty cycle: ~ 10^{-5} to 1

High repetition rates of up to 1.3 GHz

Pulsed operation AND CW operation

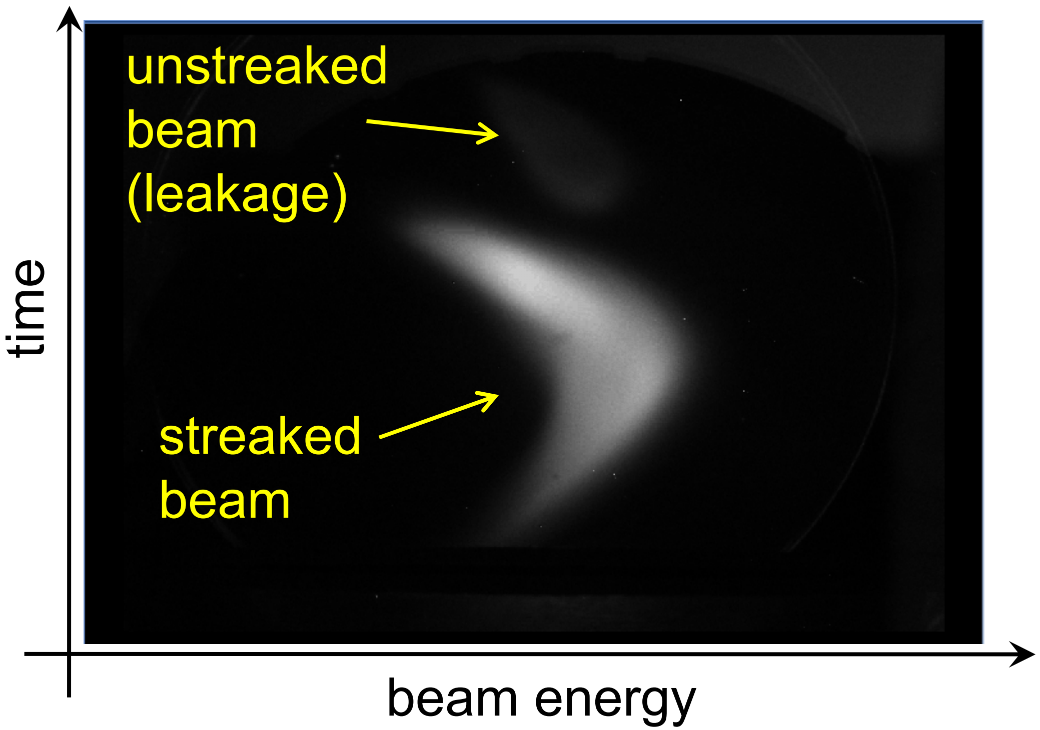
Very high power levels in many systems

- up to 550 kW beam power
- up to 50 kW beam power from the DC gun alone
- Laser power in the IR ultimately >100 W

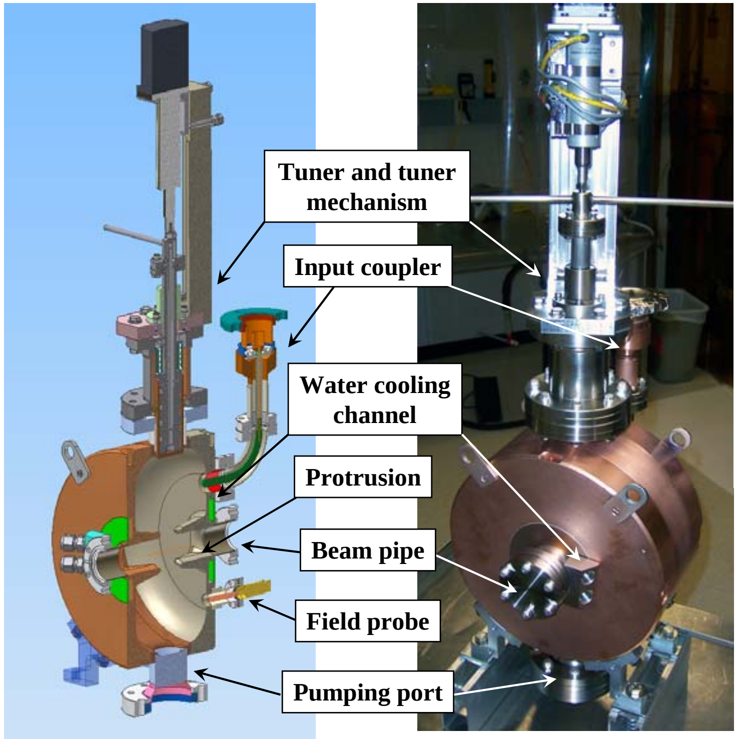
Similar beam quality similar to state-of-the-art FEL injectors

Longitudinal phase space

Transverse deflecting cavity



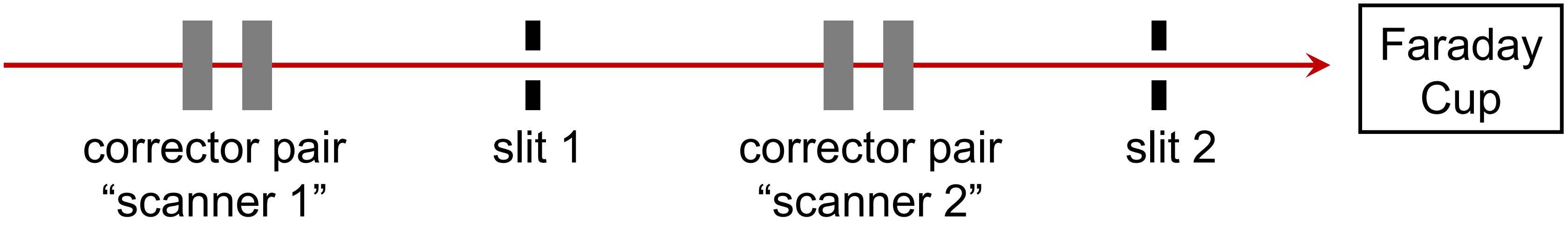
- Number of cavities 1
- Max transverse kick voltage 200 kV
- Max RF power 3.8 kW
- Average power 200 W
- Pulse duration 60 μs
- Max rep. rate 1 kHz



- Very good laser extinction ratio required in pulsed operation mode (> 10^6) for many integrating measurements (achieved by Pockels cell with > 10^3 ER in the IR)

Transverse phase space

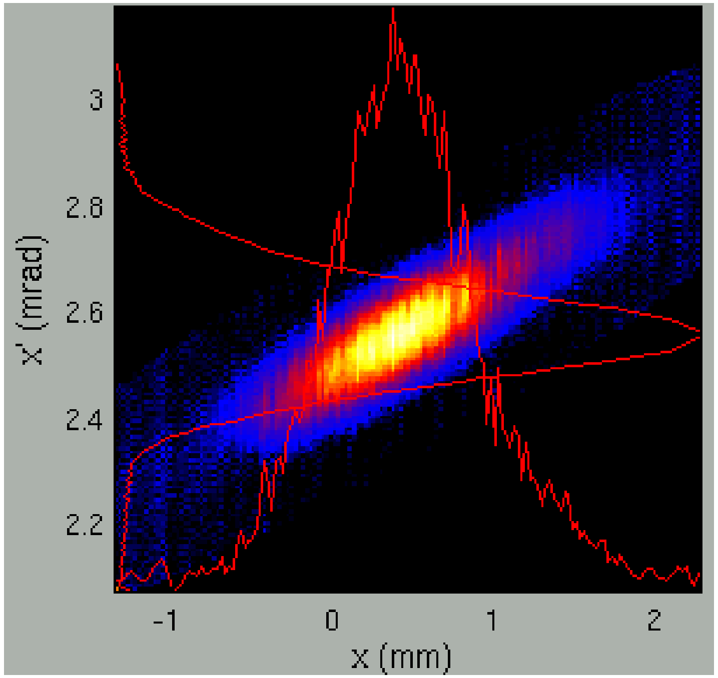
Emittance measurement system:



- No moving mechanical parts

→ Allows for very fast measurements (~ 5 s to 20 s) with high dynamic range

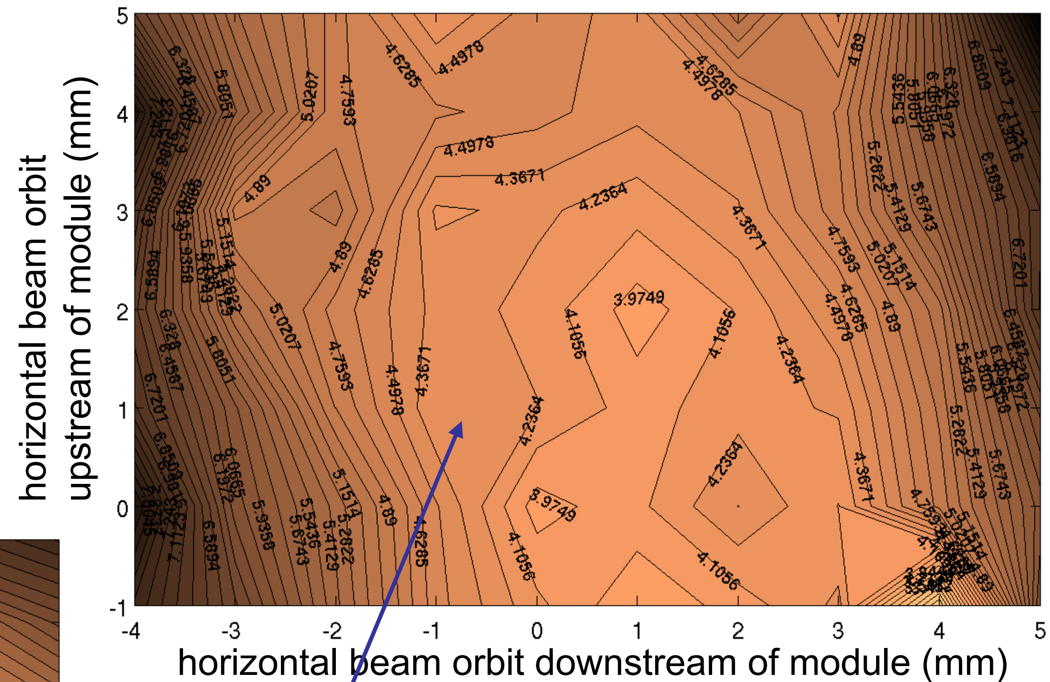
- fully integrated in control system ("single button operation")

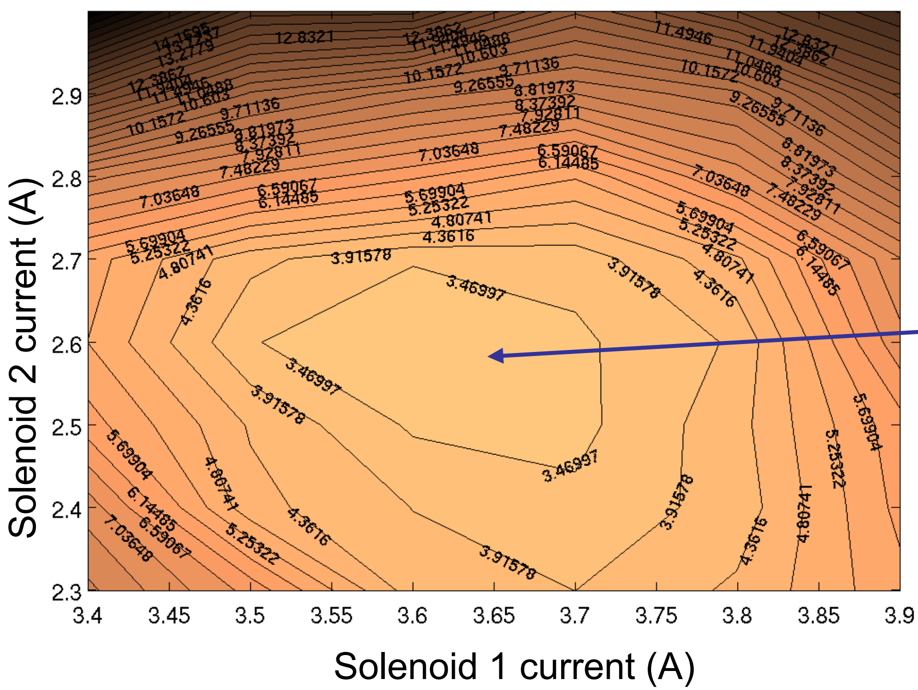


Combination with existing beam feedbacks (position, charge, …) allows for parametric optimization of the injector.

Initial emittance measurements

Performed initial parameter optimizations to improve the beam emittance:

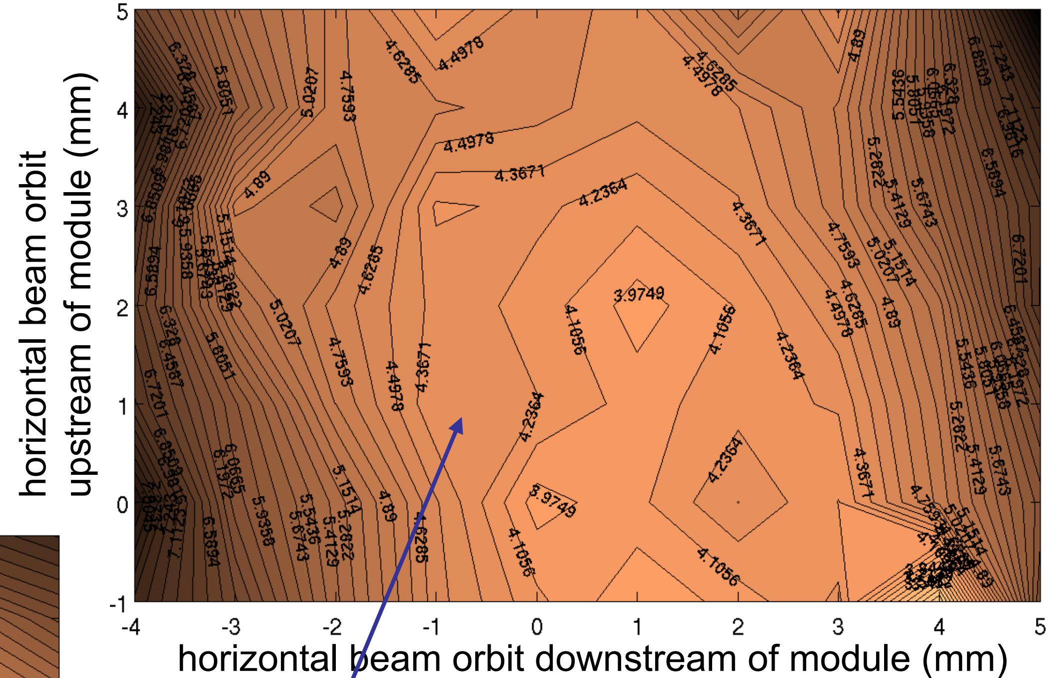


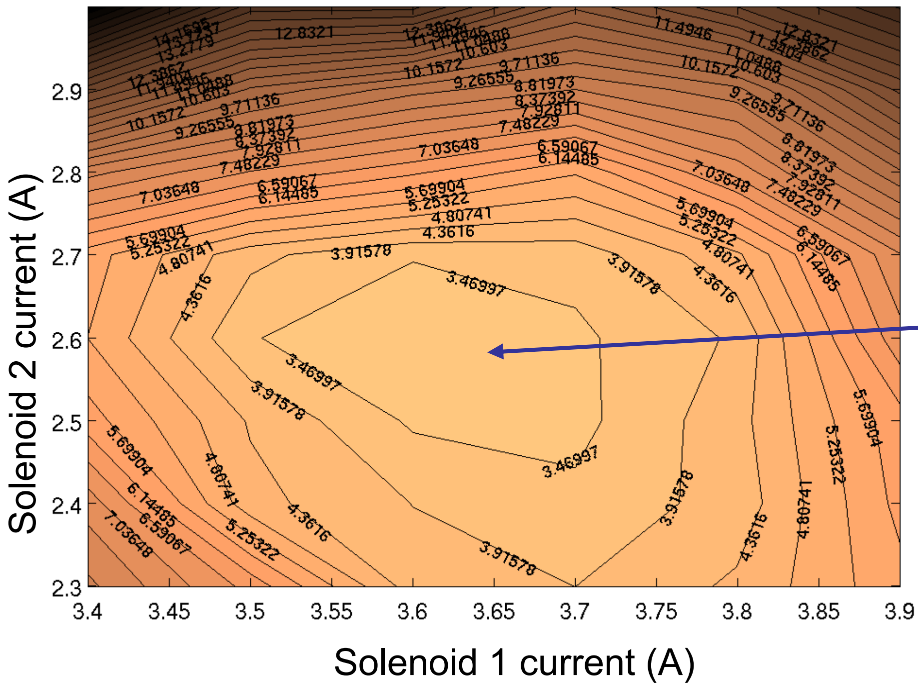


Normalized horizontal beam emittance at E_{kin} = 10 MeV, q=-77 pC

Initial emittance measurements

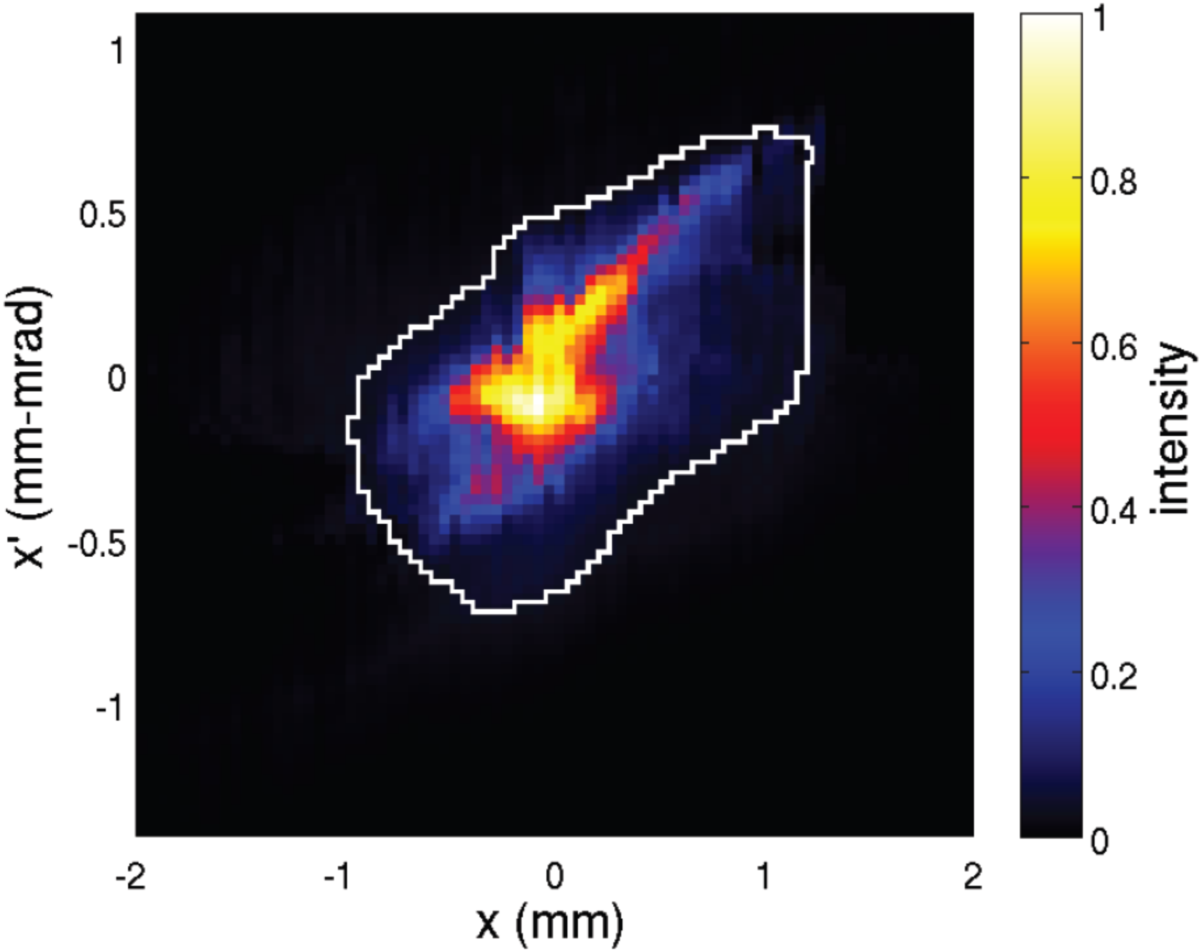
Performed initial parameter optimizations to improve the beam emittance:





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

Initial emittance measurements



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

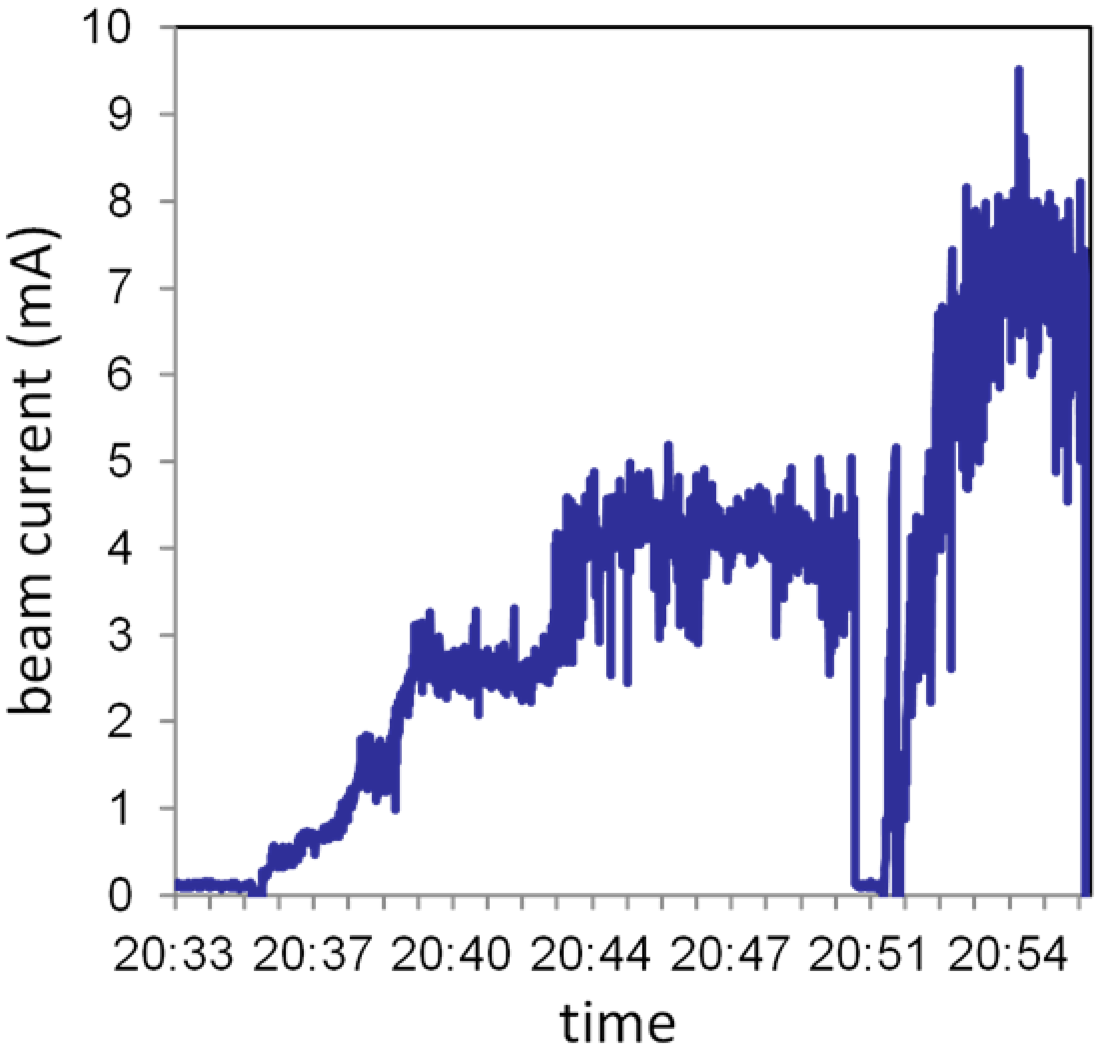
(Measurements done with gated 50 MHz laser system:
1-2 kHz rate,
~300 ns macro-pulse duration)

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)

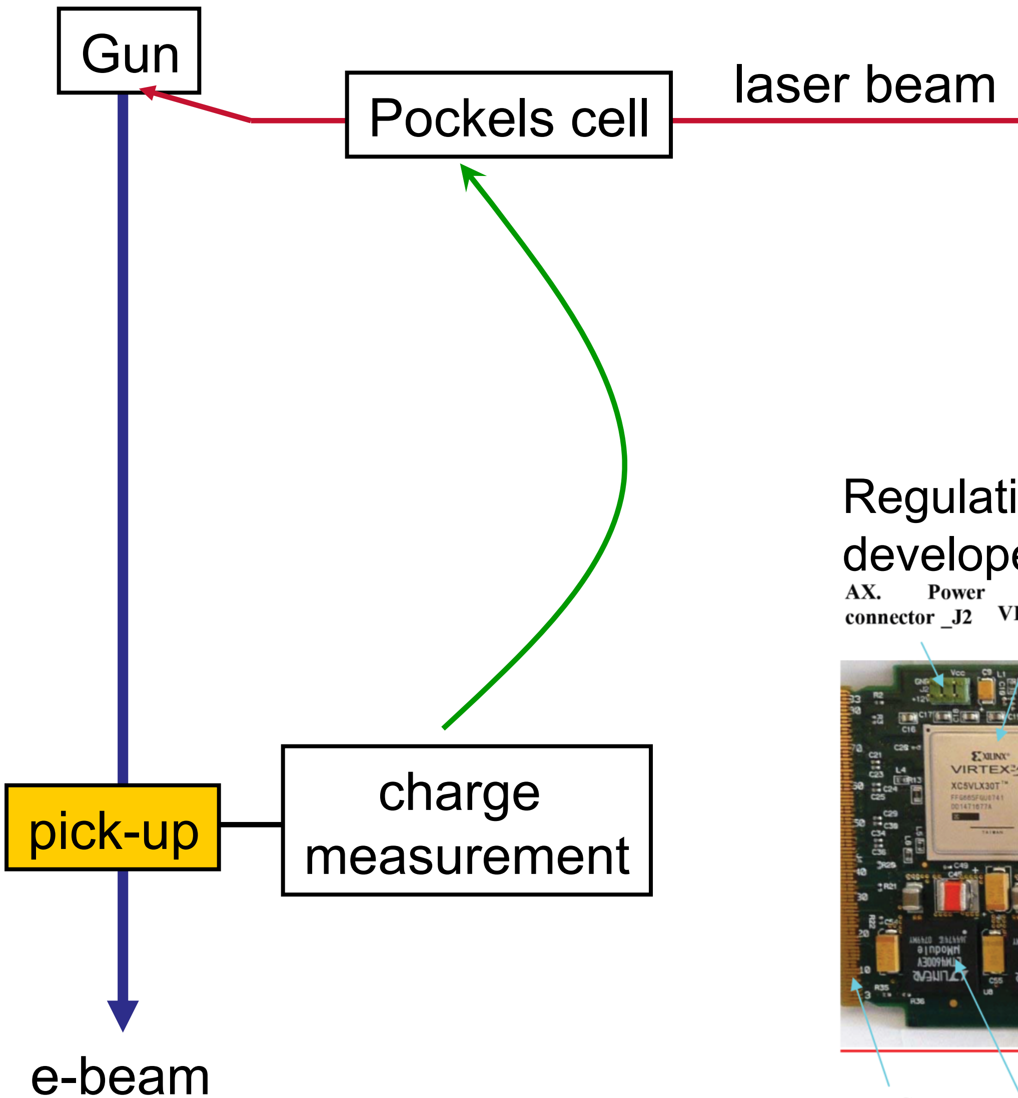
High current operation: Initial challenges



1.)
Experienced large and quite beam fast beam current variations
→ causes beam loss and radiation due to beam loading effects in DC gun and SRF cavities

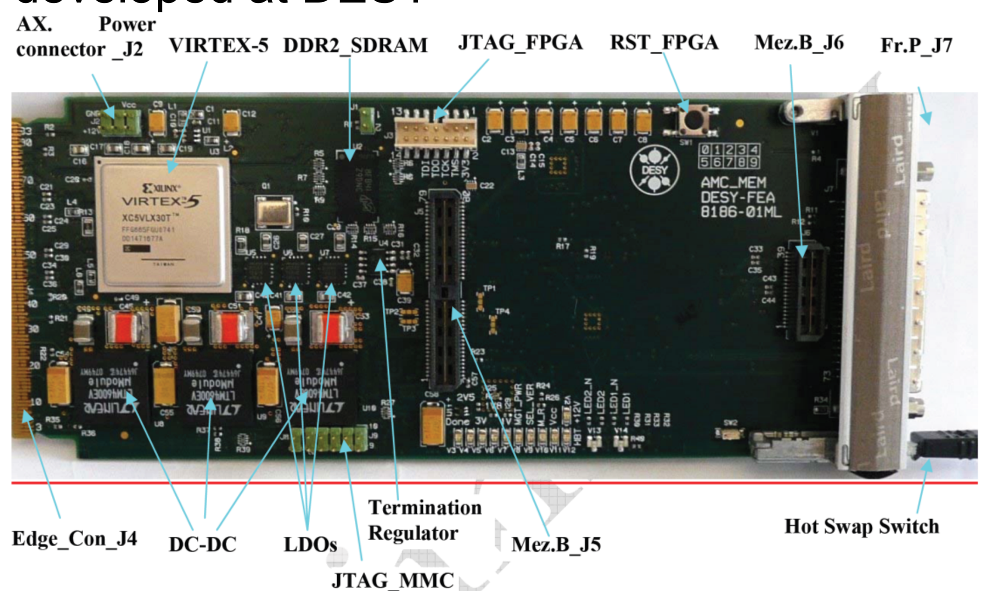
2.)
Get huge radiation burst after some time, which degrades the cathode.

Beam current feedback



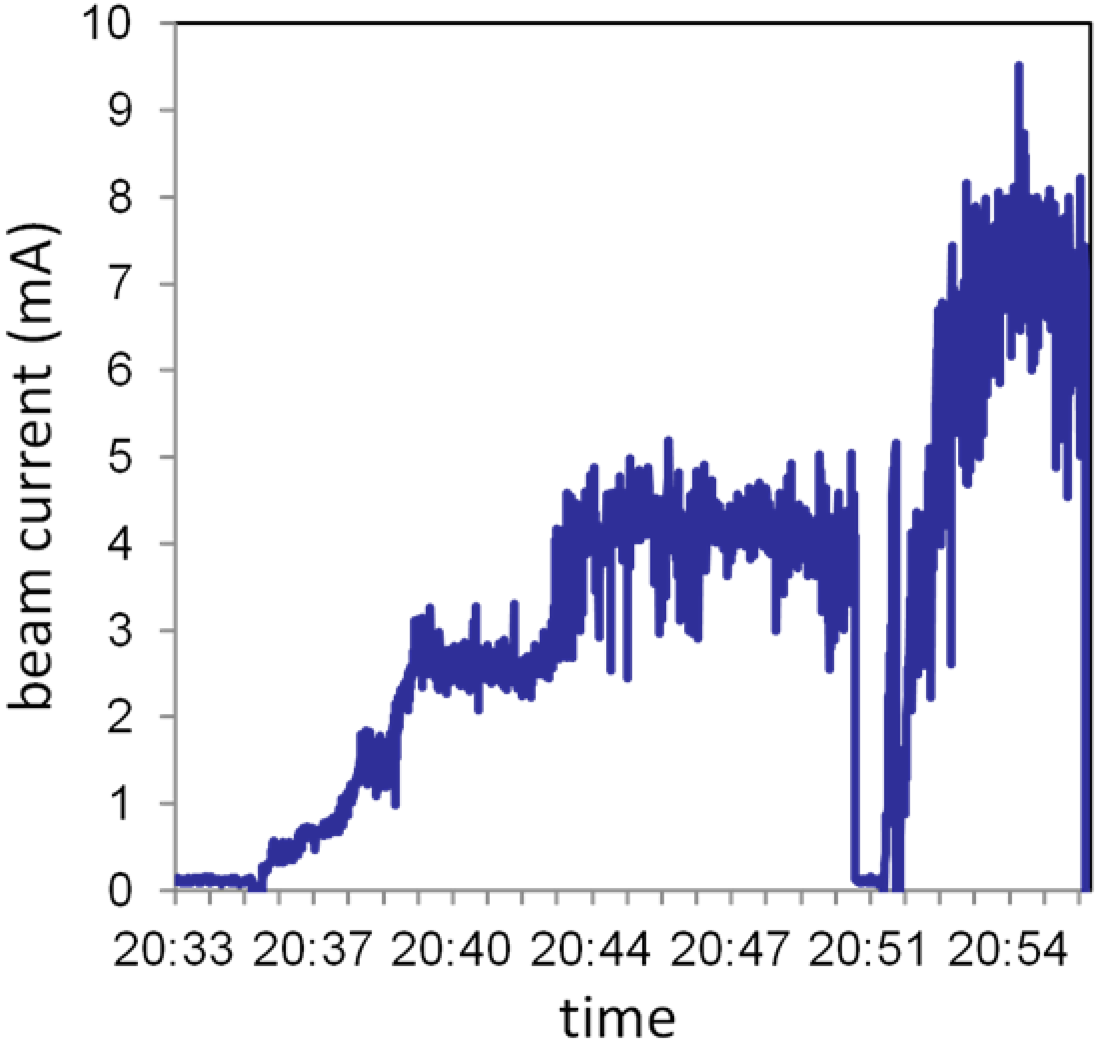
- We implemented a beam based feedback loop based on a bunch charge measurement
- Maximum regulation bandwidth: 3 MHz (limited by Pockels cell driver)
- Also used as a fast switch in the beam protection system

Regulation uses uTCA regulation electronics developed at DESY



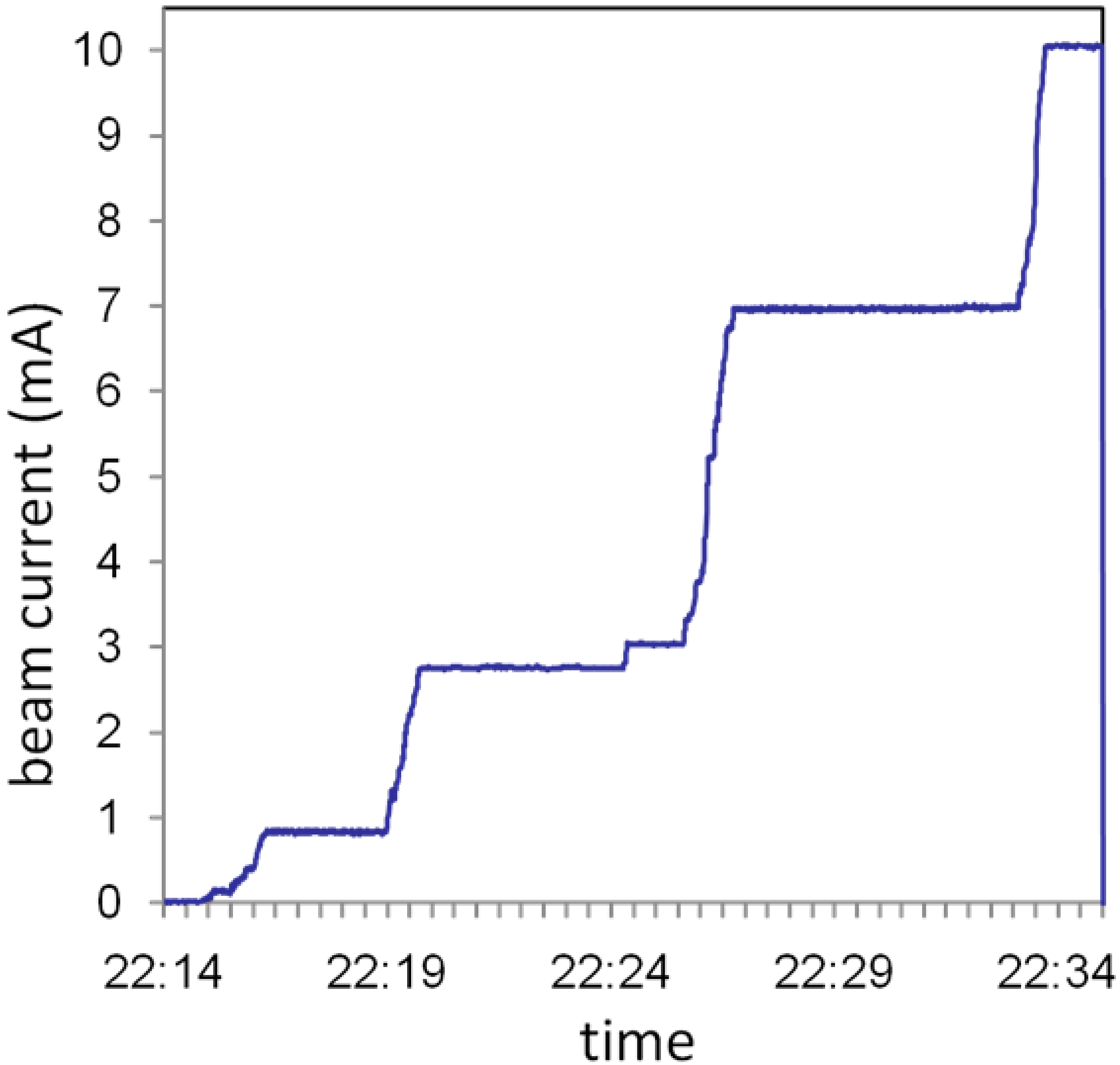
Beam current feedback

without beam current feedback



Beam current feedback

with active beam current feedback



Current stability much better than 1%

→ Beam loss improved significantly

But…

Radiation burst which causes cathode degradation is still present

Reason for radiation burst

We found sporadic field emission burst from the DC gun happening around 4-5 timer / h at a gun voltage of 350 kV

Possible scenario:

1.) Gun emits electron burst

2.) Electron burst gets lost in first cavity of cryo module
→ generation of secondary electrons

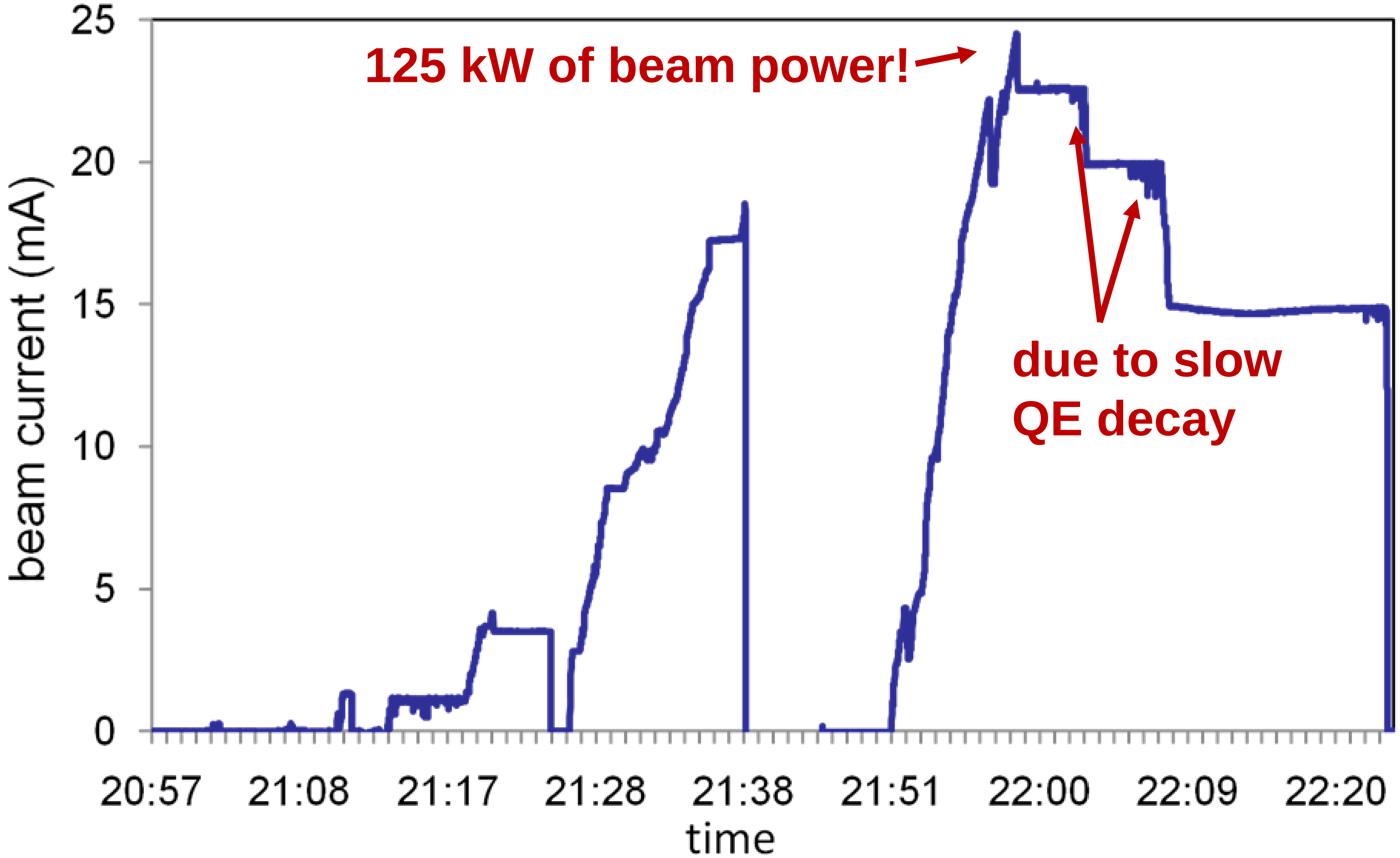
3.) Secondaries produce x-ray burst which hits the cathode

→ Self excited loop

By lowering the gun voltage from 350 kV to 250 kV, the radiation burst are gone.

→ More processing of the gun required!

High current operation



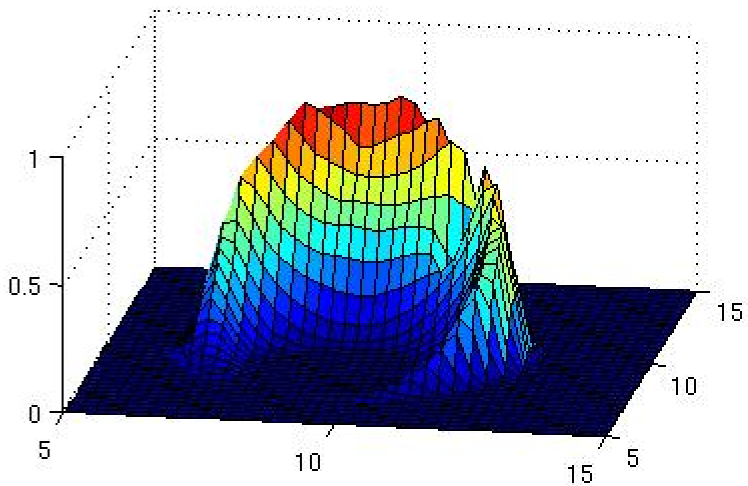
Cathode issues

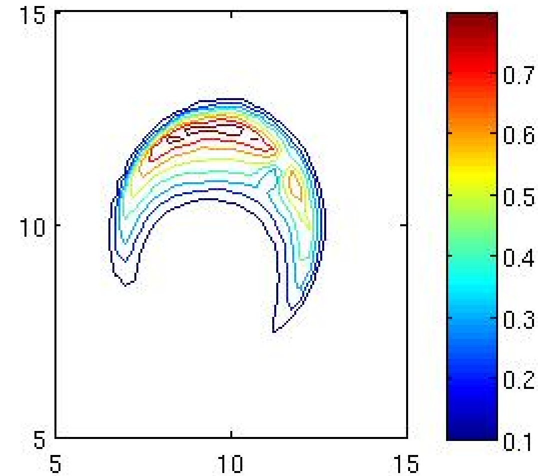
Life-time of our GaAs cathodes is currently quite low:

- Ion back-bombardment which damages the Cs layer
  - → Need better vacuum (especially in buncher section)
  - → Need clearing electrodes for ions

→ New gun design is on its way

Quantum efficiency map of cathode after high current run





Cathode issues

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  - → Need better vacuum (especially in buncher section)
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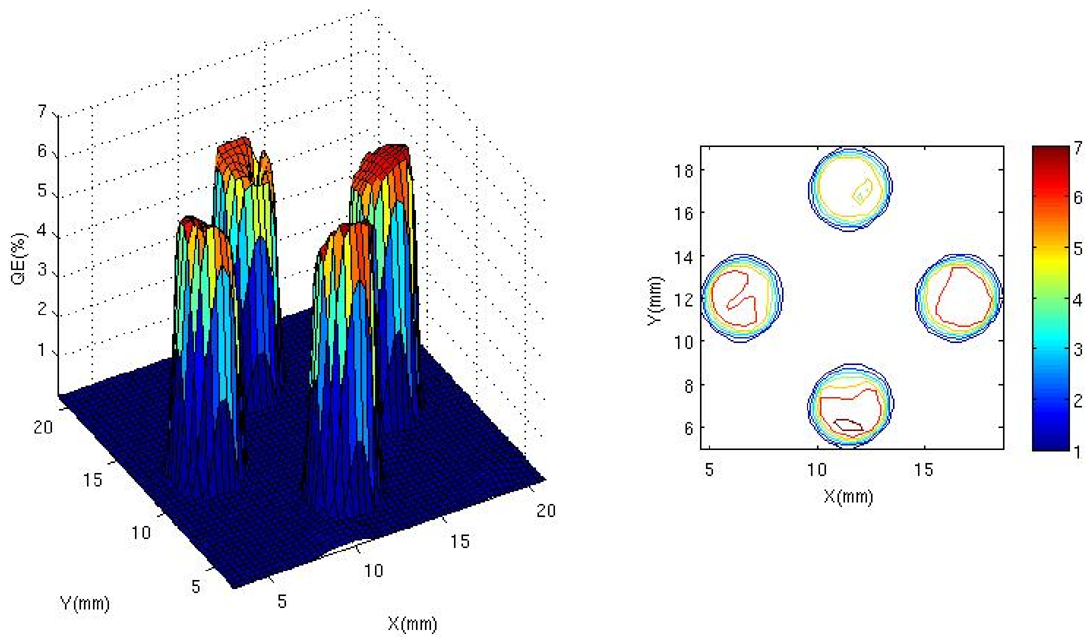
→ New gun design is on its way

We are trying alternative cathode geometries:



Outlook

- We will test an alternative cathode material (K_2CsSb) very soon
  - Less sensitive to ion back-bombardment
- Further processing planned with present gun to reach higher voltages and reduce field emission
- In parallel: Development of new gun which uses guard rings inside of the insulating ceramics as a protection
- Upgrade of laser system is planned to reach higher power levels
- Transverse and longitudinal laser profiles have to be optimized
- Several stability improvements and improved diagnostics are on its way
- Multi-parameter optimizations planned to lower the emittance
- Further study of time-dependent RF focusing effects and its compensation

…

Summary

- Very promising commissioning results so far:
  - Many design parameters are already met
  - Transverse emittance: 1.6 mm-mrad (90 %)
  - Beam current: ~25 mA
    - Best beam quality every achieved at these beam currents
    - Very close to the world record of 33 mA already and we are only limited by the available laser power

Thank you for your attention!

The Cornell ERL injector team:

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Thank you for your attention!