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International Workshop on Breakdown Science and High Gradient Technology (HG2013)
3-6- June 2013, ICPT Trieste

High-Gradient Structures at RadiaBeam

Luigi Faillace
RadiaBeam Technologies, Santa Monica CA

Outline

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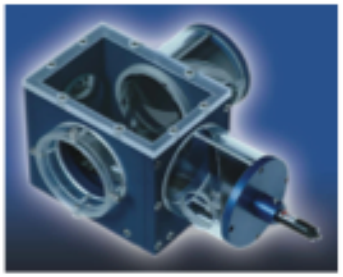
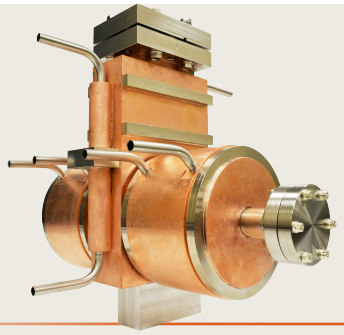
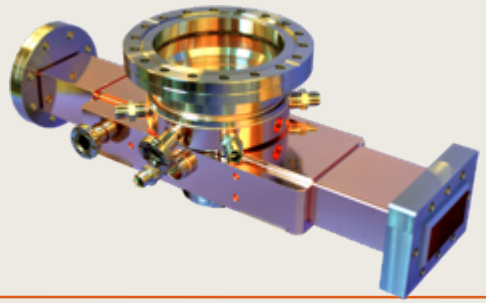
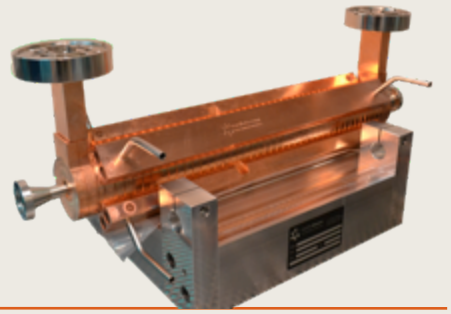
- **Company Overview**
- **New Gun for Sincrotrone Trieste– Fermi II Gun**
  - RF design
  - Machining/Cold-Test/Brazing/Tuning
  - Installation
  - High-power Conditioning
  - Initial beam measurements
- **High-Gradient Structure (HGS)**
- **Super Gun**
  - GALAXIE project
  - High charge operation
- **X and S-Band Deflectors**
- **Conclusions**

Company Overview

- RadiaBeam Technologies, LLC. is a small business with core expertise in accelerator physics.
- Spin-off from UCLA (2003)
- Extensive R&D Program (DOE, DOD, DHS, NSF)
- Growing products line for research laboratories and industrial customers (magnets, diagnostics, RF structures, complete systems)



Customers

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Resources and Capabilities

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- Enhanced engineering/manufacturing capabilities
  - New Facility + recent expansion
  - New Equipment
- Studied and Developed RF manufacturing process workflows
- Increased RF testing/validation capabilities
- Developed custom UHV/RF component cleaning and assembly facilities
  - Following SLAC developed guidelines
  - Presents us with full control over *almost* all critical processes (no oven)
- Collaborations with Universities and National Laboratories

Cell Machining and Cleaning

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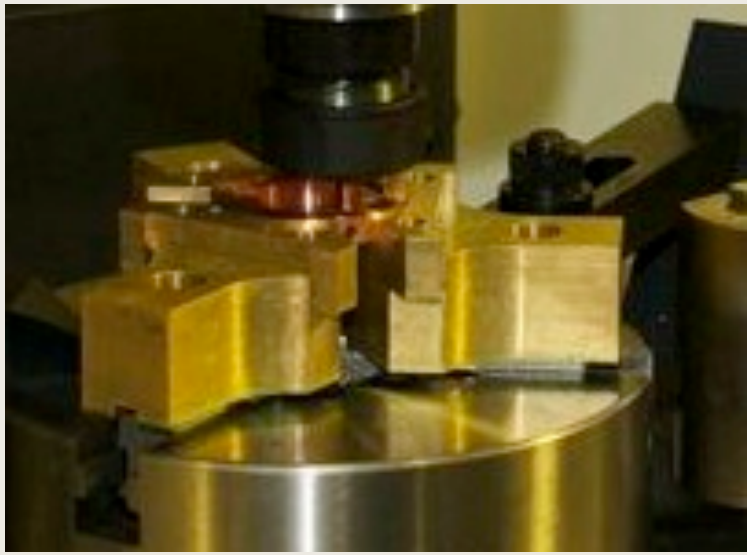
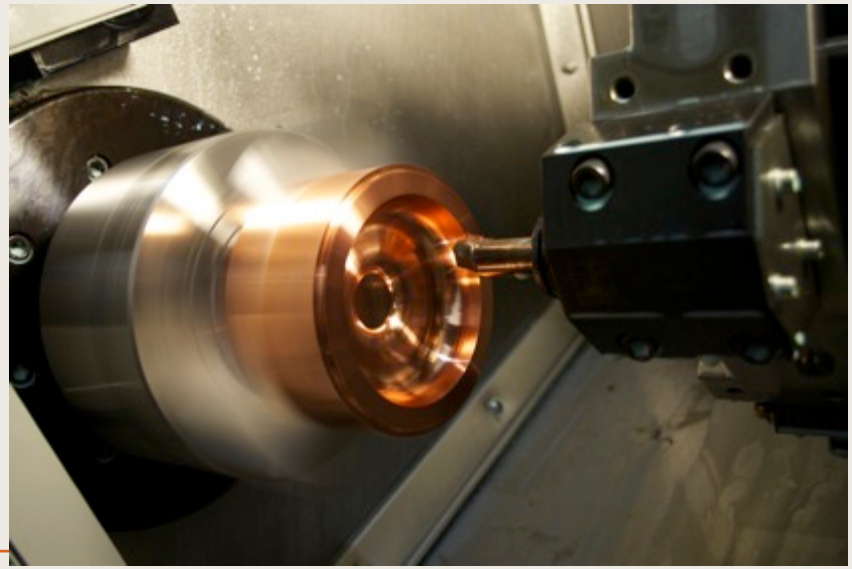
- CNC mills and lathes
  - Capable of 0.0002" precision and repeatability (lathe)
  - 2-4 micron flatness
  - 4-6 micro-inch surface finishes (100-150nm)
  - Developed specialized workholding tooling
  - Optimized cutting tooling (PCD)
  - Refurbished or manufactured storage and travel containers
  - Considerable man-hours invested into process and handling systematics



- Chemical cleaning room
  - With guidance from SLAC MFD
  - Utilize a modified version of SLAC cleaning processes



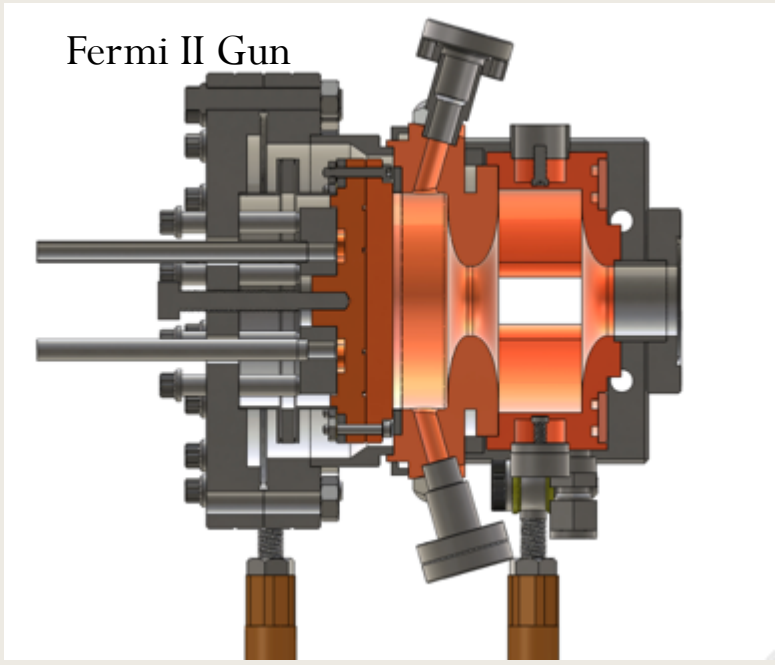
- Clean Assembly / Testing Room
  - Class 100 / Class 1000

New RF Gun for the Fermi FEL at Sincrotrone Trieste

The Radio-Frequency (RF) of design a NCRF Gun for the Sincrotrone Trieste facility, which is termed "FERMI II Gun", is based on the UCLA-University of Rome-INFN-LNF high repetition rate photoinjector* designed for the SPARX-FEL project, which borrowed the innovative features brought to the LCLS# gun with two main changes:

1) Exchangeable cathode plate

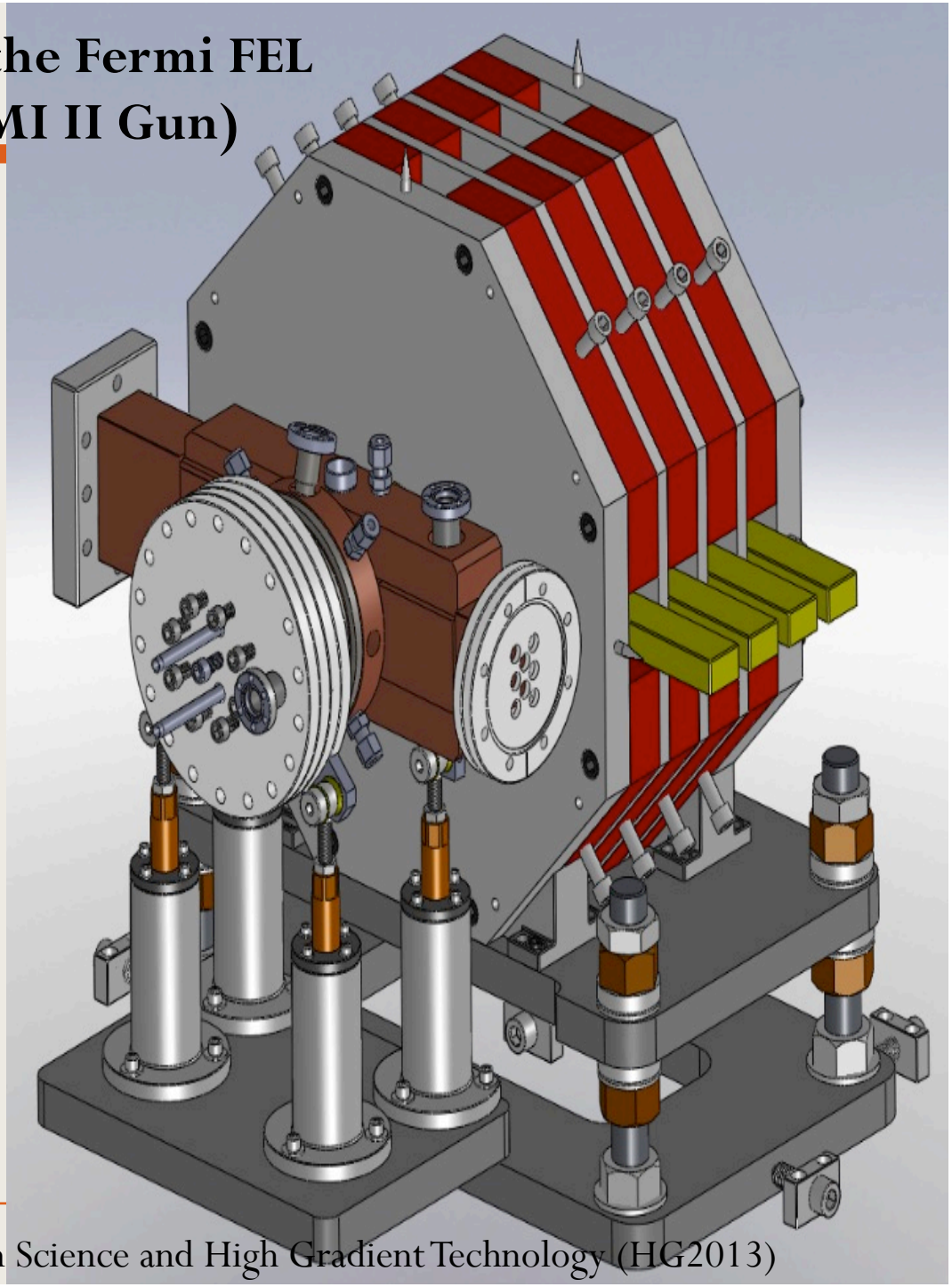
2) Single-feed



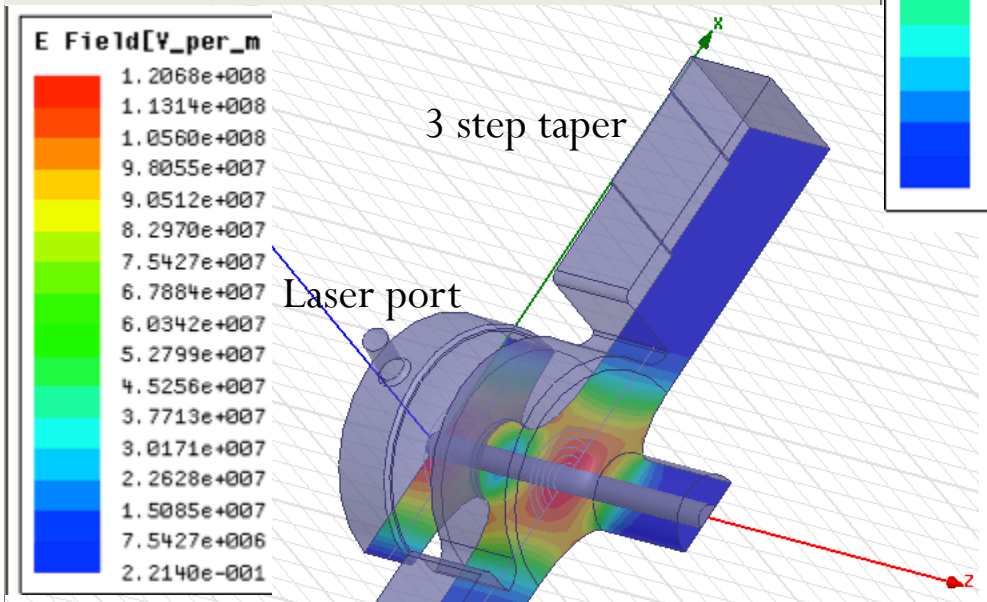
*L. Faillace *et al.*, "An Ultra-high repetition rate S- band RF Gun", FEL Conference 2008
#C.Limborg *et al.*, "RF Design of the LCLS Gun", LCLS Technical Note LCLS-TN-05-3 (Stanford,2005).
#D.H. Dowell *et al.*, "The development of the Linac Coherent Light Source RF Gun", SLAC Menlo Park CA, published in the ICFA Beam Dynamics Newsletter

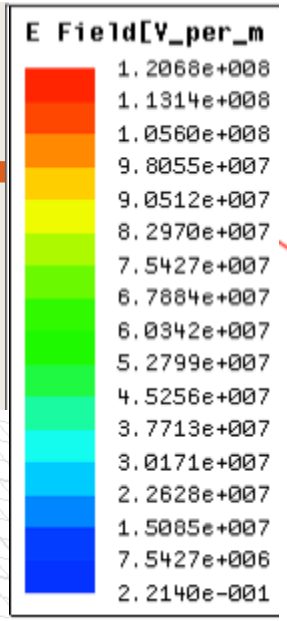
RadiaBeam/UCLA RF Gun for the Fermi FEL at Sincrotrone Trieste (FERMI II Gun)

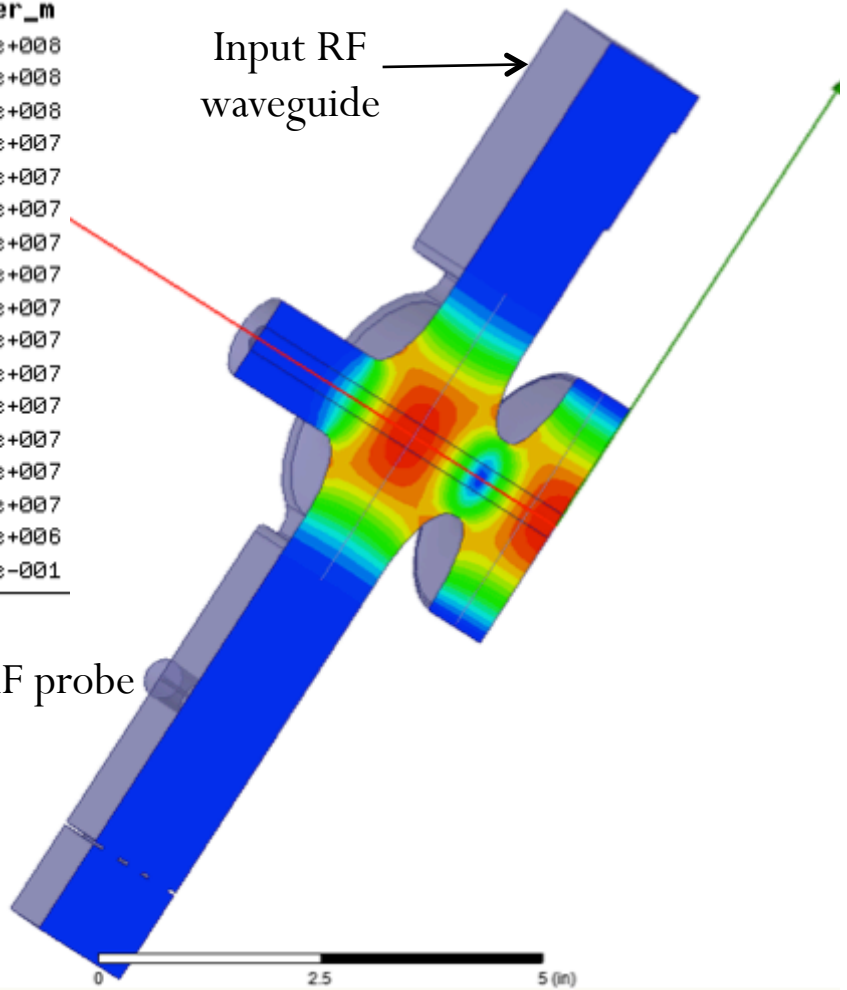
- Operation frequency 2.998 GHz, π-mode
- 1.6 cell gun
- Single feed
  - ✓simpler RF power system than the case of dual feed
  - ✓Avoid phase shift between the two input waves in the case of dual feed
  - ✓dummy waveguide to diminish dipole field
- Race track geometry
  - ✓To minimize quadrupole field
- "z-coupling"
  - ✓To reduce H field, i.e. temperature rise (RF pulsed heating), at the coupling slots
- Elliptical coupling irises
  - ✓To decrease surface electric field (cause of RF breakdowns)
- 50 Hz repetition rate
- Removable Cathode
- Numeric codes for simulations: HFSS/Ansys, Superfish.



Main Rf Parameters







Frequency	2.998 GHz
Mode separation	14.2 MHz
Shunt Impedance	54 MΩ/m
Quality factor Q_0	13800
Coupling Beta	1.8
Input Power (E=120MV/m at cathode)	9.5 MW

Rf Pulsed Heating

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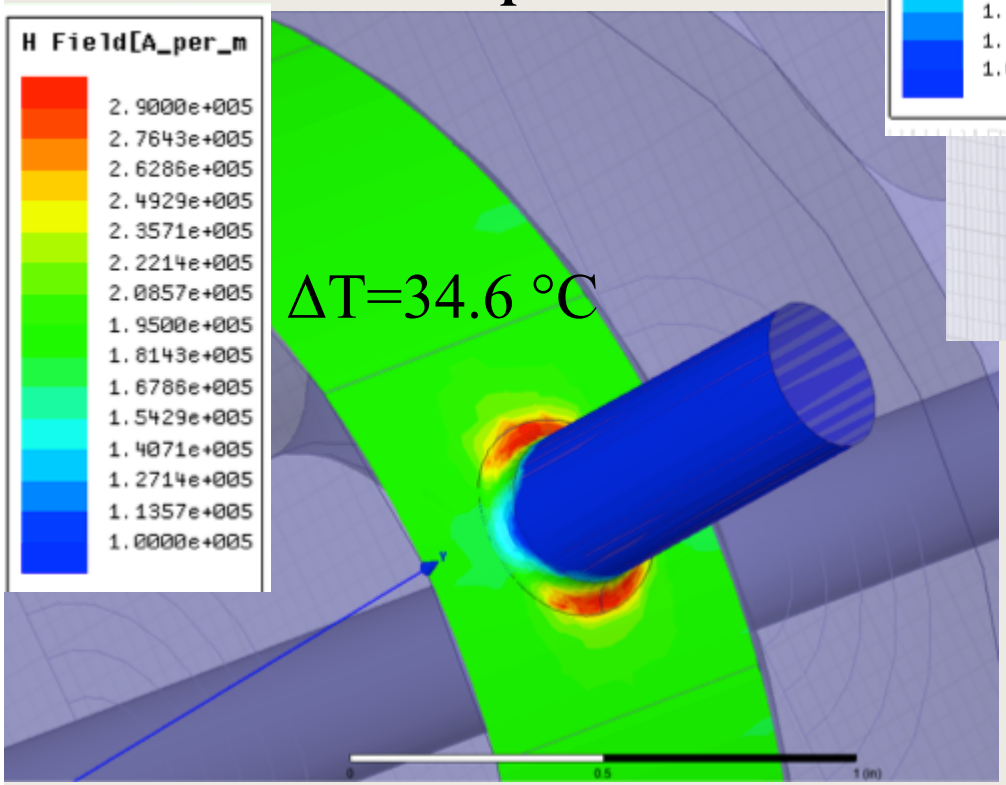
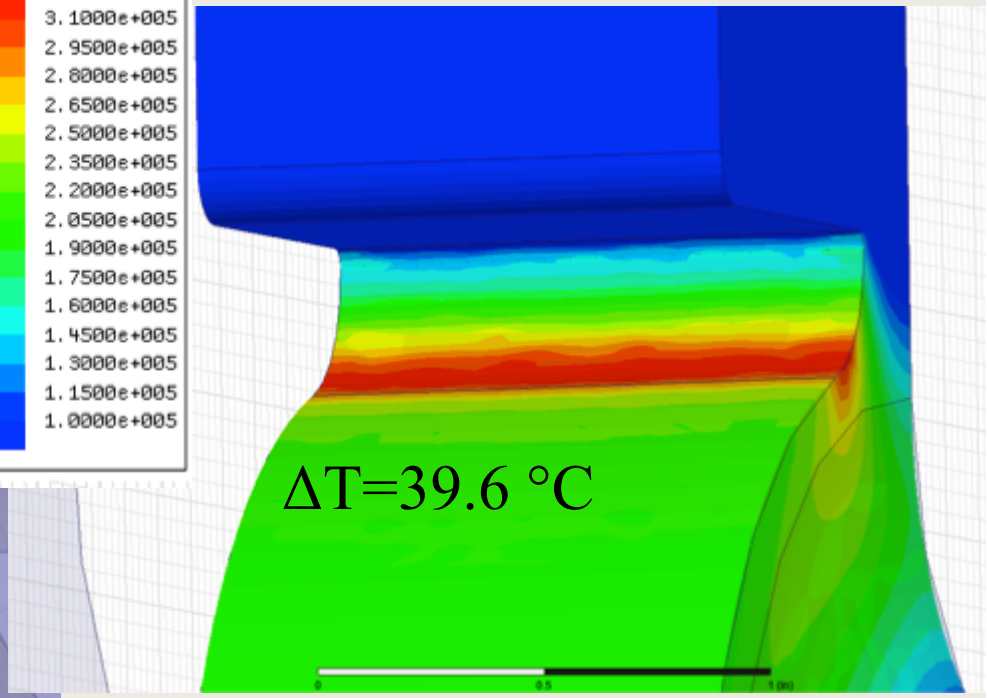
Laser port



Coupling slot



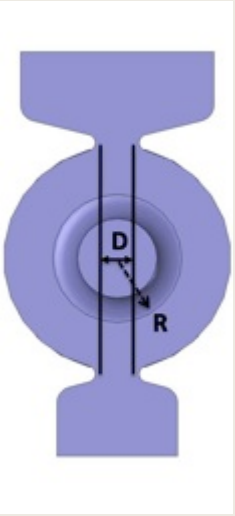
f = 2.998GHz
Pulse length = 3μs

Dipole and Quadrupole Components

$$H_\varphi(r,\varphi)=\sum_{n=0}^{\infty}H_{\varphi n}(r)\cos(n\varphi)$$ Fourier series

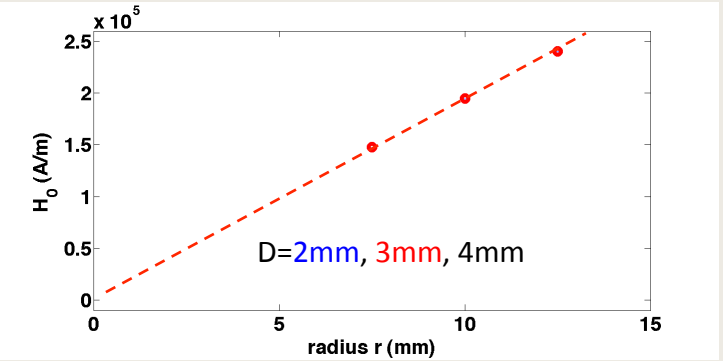
$$H_{\varphi n}(r)=\frac{2}{\pi}\int_0^{\pi}H_\varphi(r,\varphi)\cos(n\varphi)d\varphi$$ nth component

n=0	$H_{\varphi 0}(r)$	$H_0(r)$=*Monopole*
n=1	$H_{\varphi 1}(r)$	$H_1(r)$=*Dipole*
n=2	$H_{\varphi 2}(r)$	$H_2(r)$=*Quadrupole*

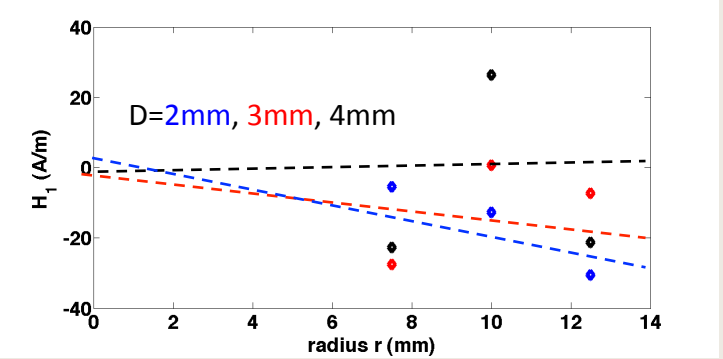


Values of the Off-set D for which field components where calculated using HFSS

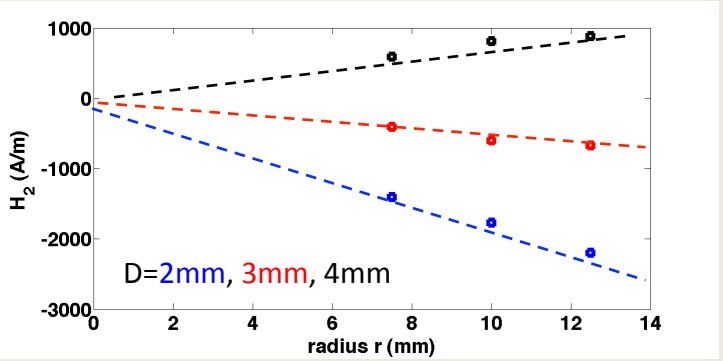
D=2mm, 3mm 4mm



Data overlap for all D values. The monopole component is unaltered.



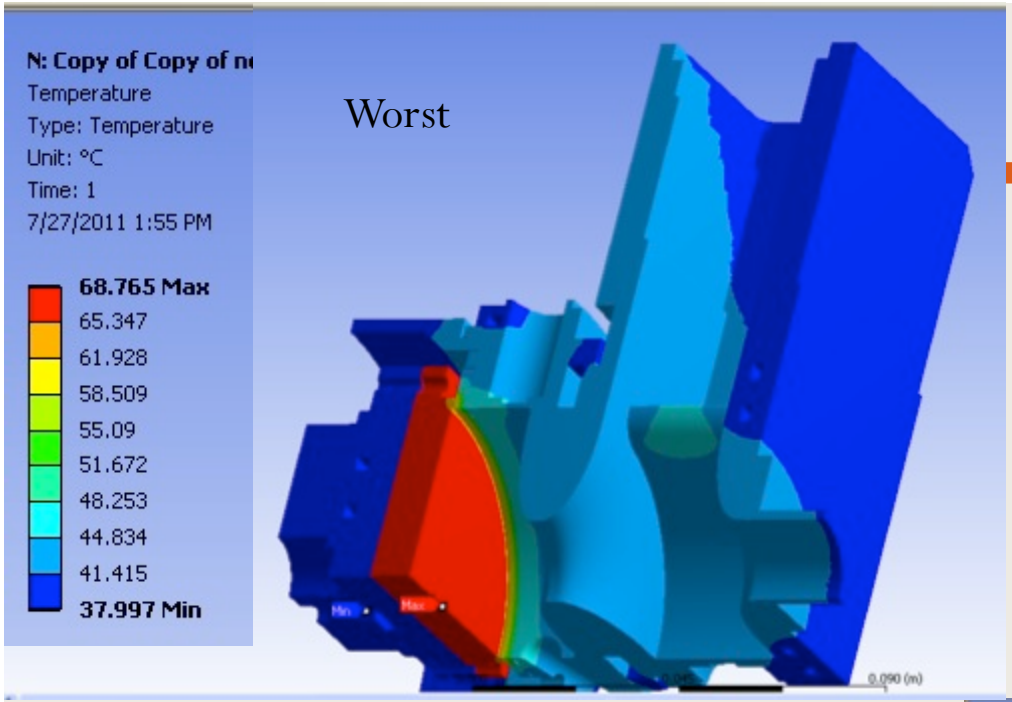
There is a D value for which the dipole and quadrupole components are eliminated!



D=3.45mm

Thermal Analysis

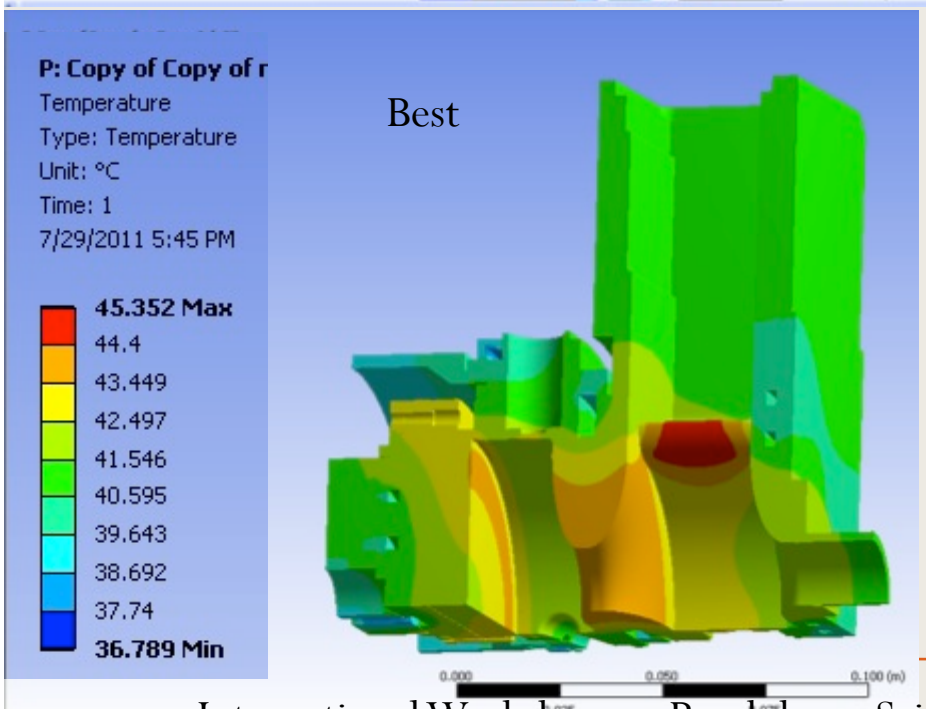
Results

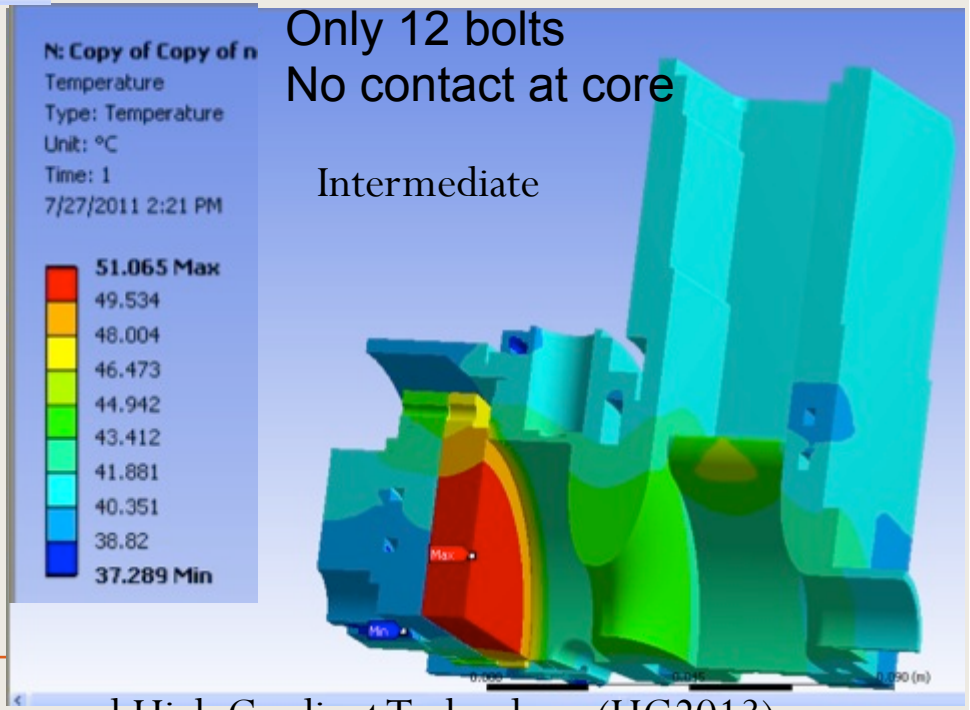


Worst case scenario: NO contact between copper layers (radiation only)

Intermediate case: contact only happens at the 12 bolts location

Best case: full contact between the two layers

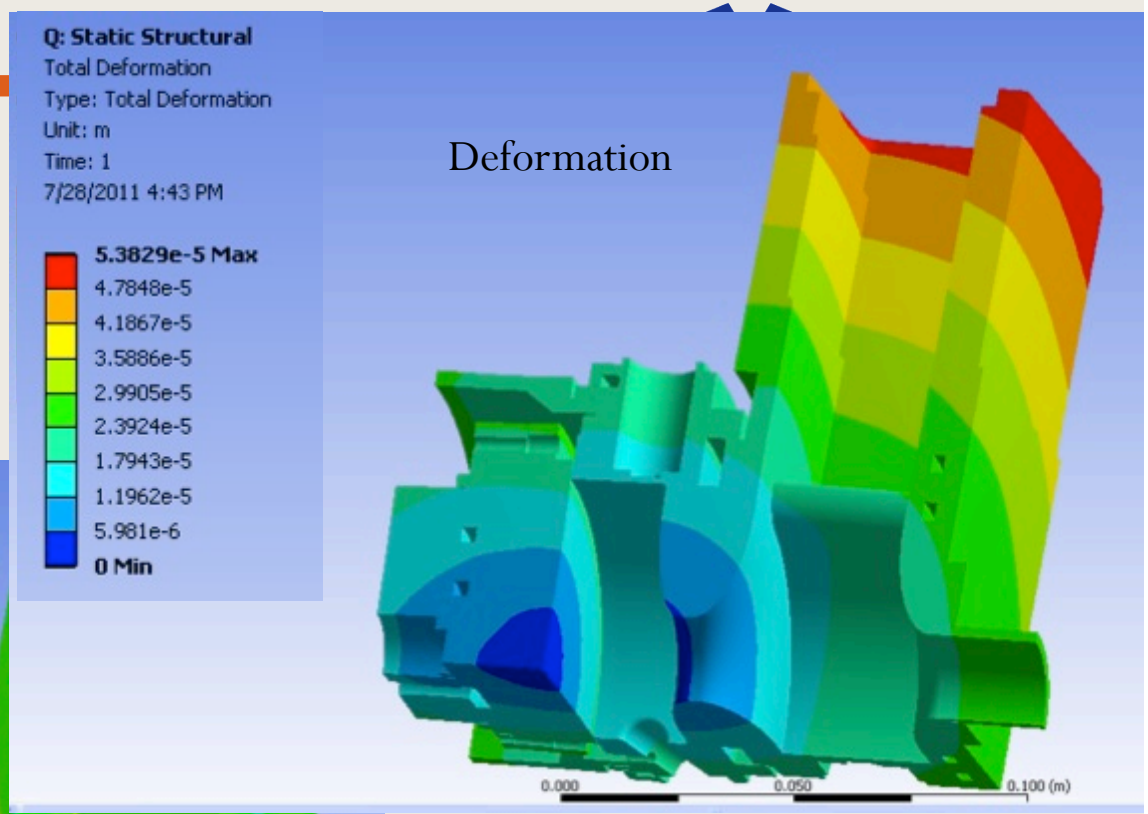




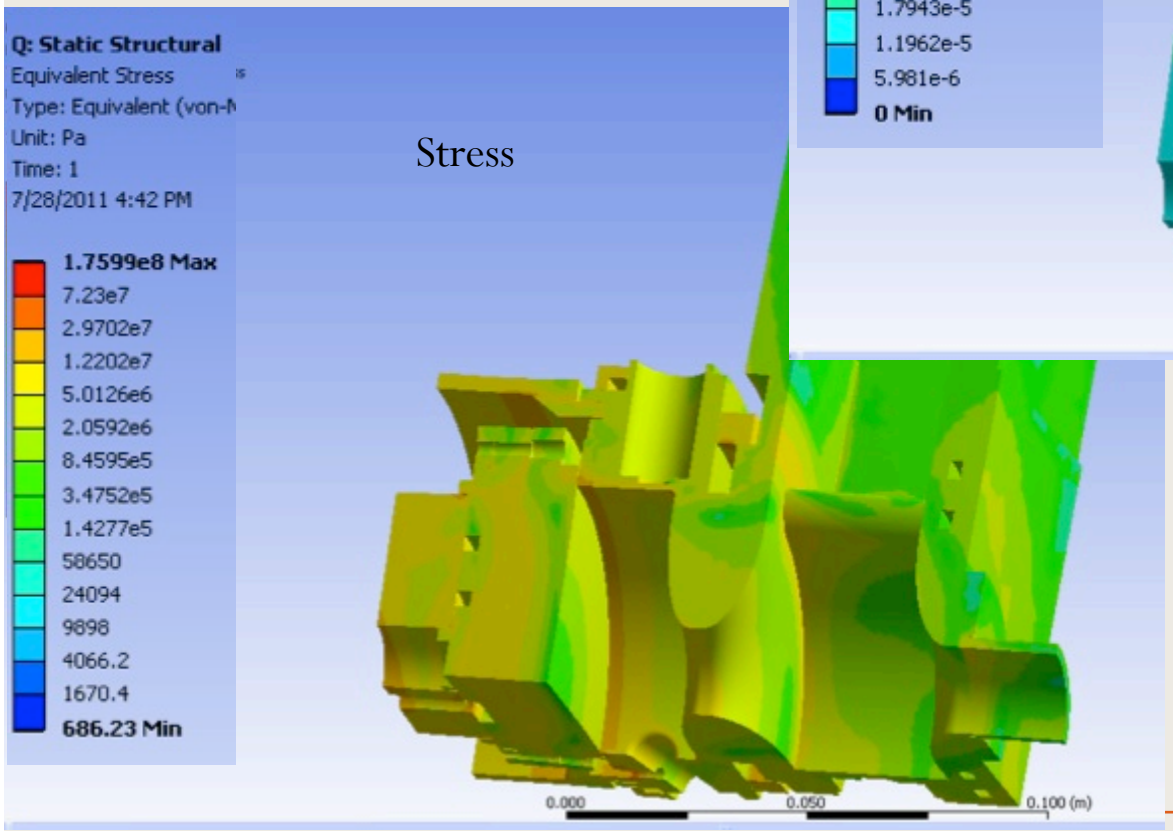
Stress Analysis

Results

In all the simulated cases (that is changing the pushing force, surfaces heat transfer…), the stress on copper parts is always below the yield strength of 70MPa (for soft copper).



Deformation



Stress

The deformation is below 25 microns for the cell surfaces.

RF gun Machining, Cold test and Brazing

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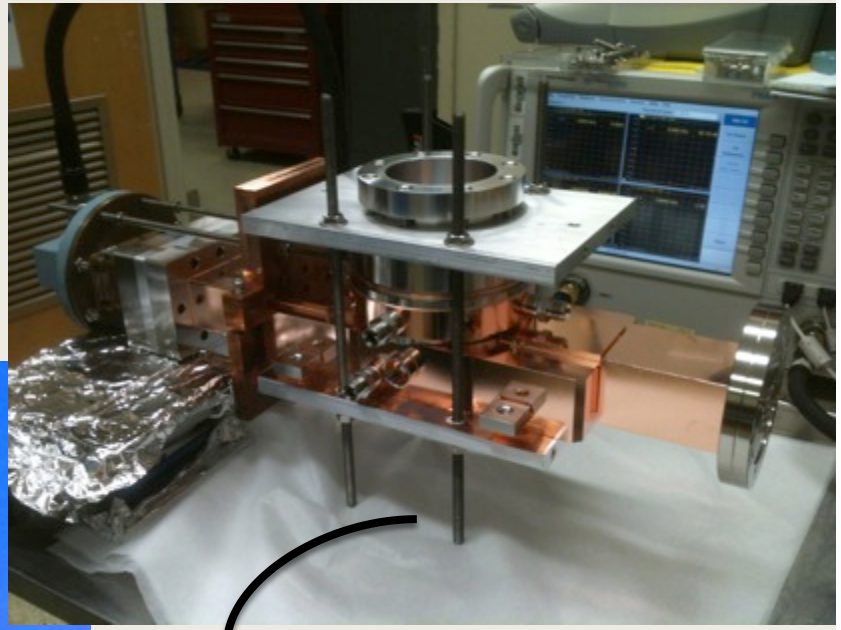
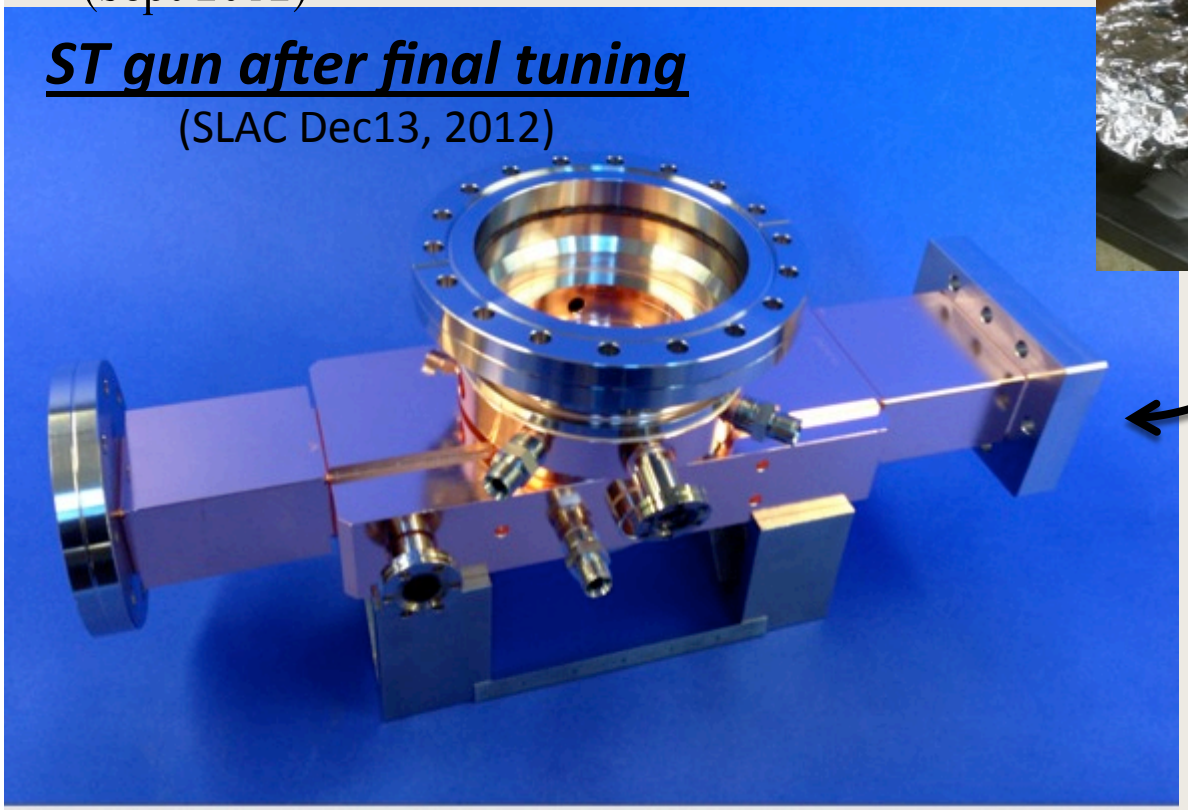
- All the gun parts were machined in-house.
- Cold test measurements (scattering parameters, resonant frequency, other main RF parameters) carried out at SLAC by using a clamping setup (Sept 2012)



ST gun after final tuning

(SLAC Dec13, 2012)



- Impeccable brazing (no leaks after any brazing cycle step) performed by the brazing team at the SLAC klystron dept. under supervision of John van Pelt.

RF Gun tuning and Field measurements

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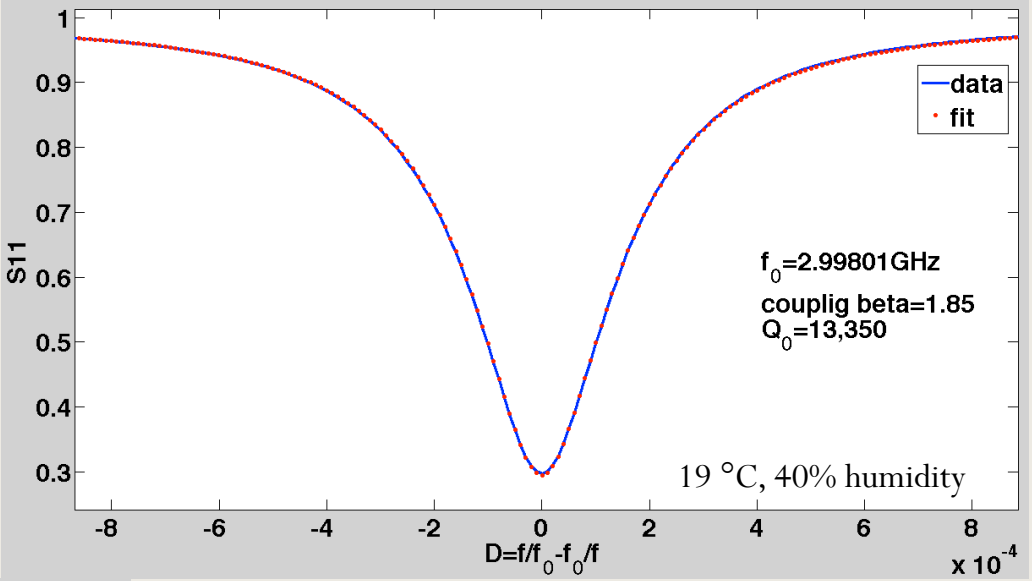
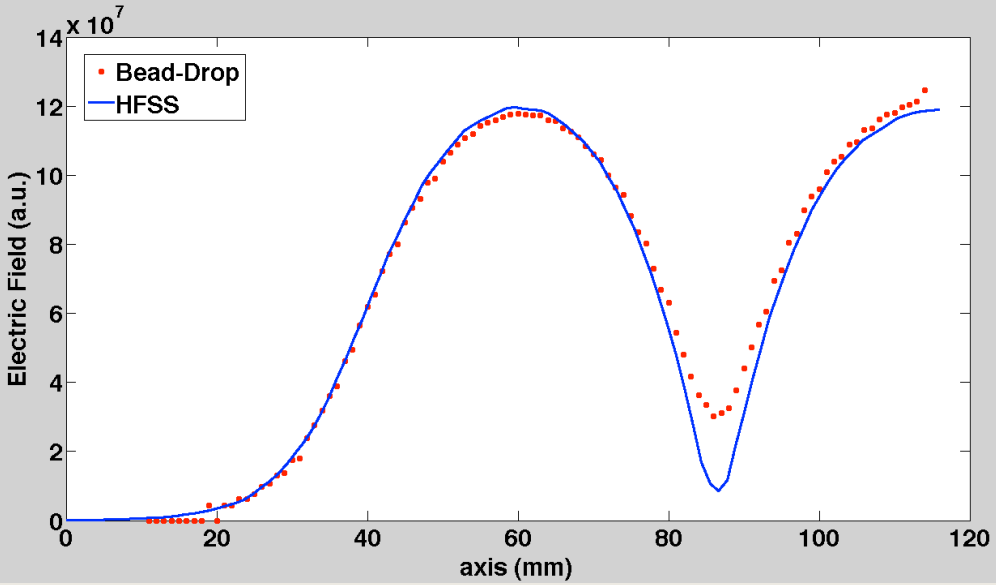
- The tuning of the gun resonant frequency (≈1MHz) was carried out by using bi-directional deformation tuners
- On-axis electric field measured in a bead-drop setup by using a 2mm diameter dielectric bead





	Measurement	HFSS
Frequency	2.99801 GHz (19 C, 40% humidity)	2.998GHz
Mode separation	14.5 MHz	14.2 MHz
Q_0	13,350	13,750
Coupling beta	1.85	1.8

Installation January 2013
initial tests

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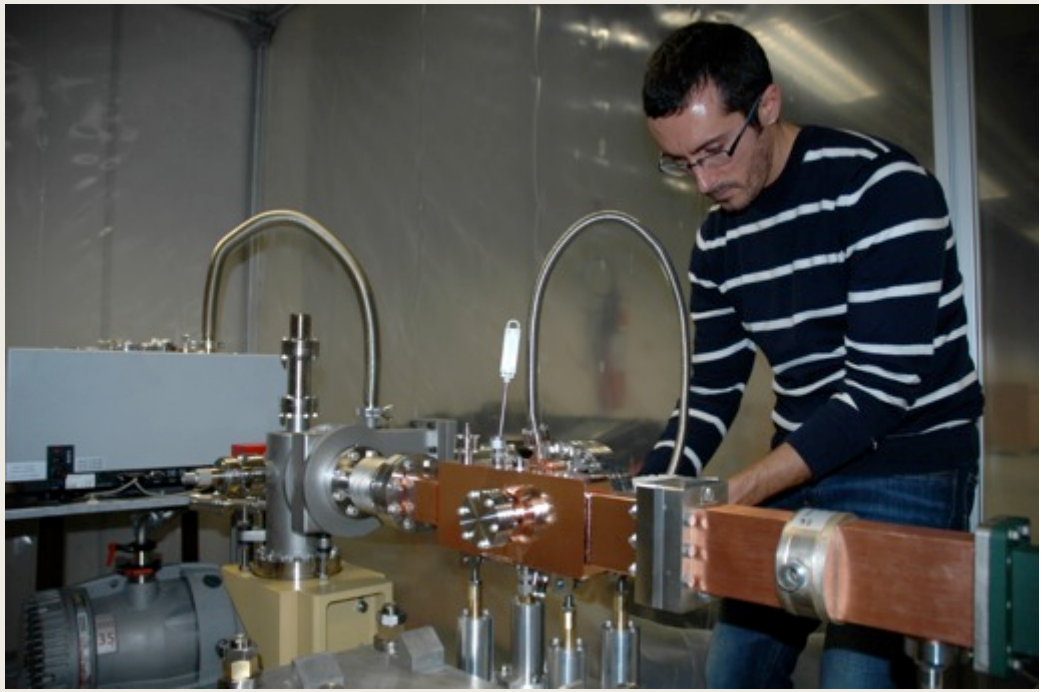
- Installation of the gun started on Jan 4th 2013 at Sincrotrone Trieste
- The gun was brought under vacuum in a test area to check if any leaks were present as well as the frequency shift that resulted to be about 800 kHz, as expected
- The operating temperature of 39°C allowed for operation at exactly 2.99801 GHz, as it was verified. (good agreement with theory prediction of df/dT≈-50kHz/°C)

	Air	Vacuum
Frequency Shift	2.99801 GHz (19 C, 40% humidity)	2.998808GHz
Water temperature		Around 39°C



Installation January 2013
tunnel

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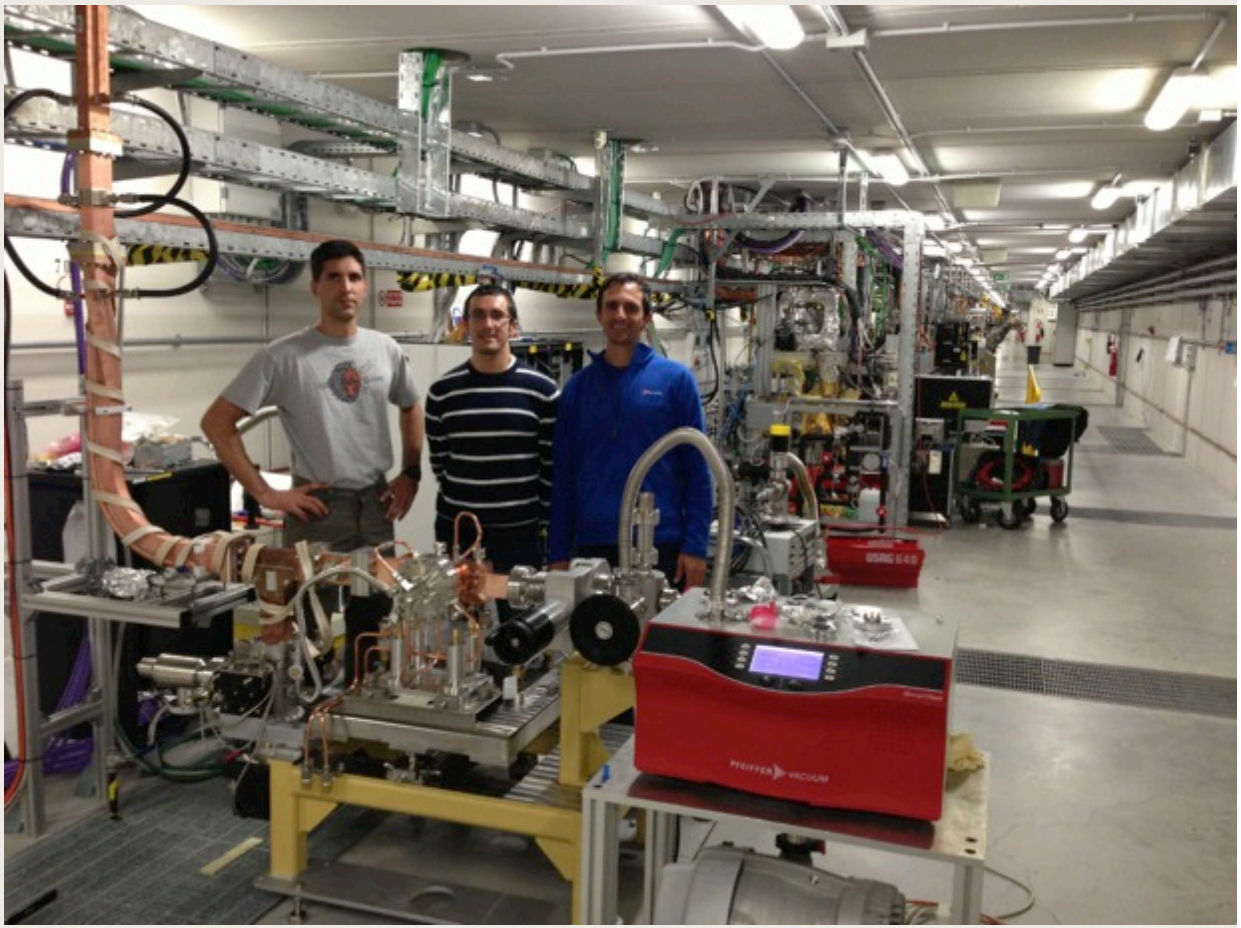
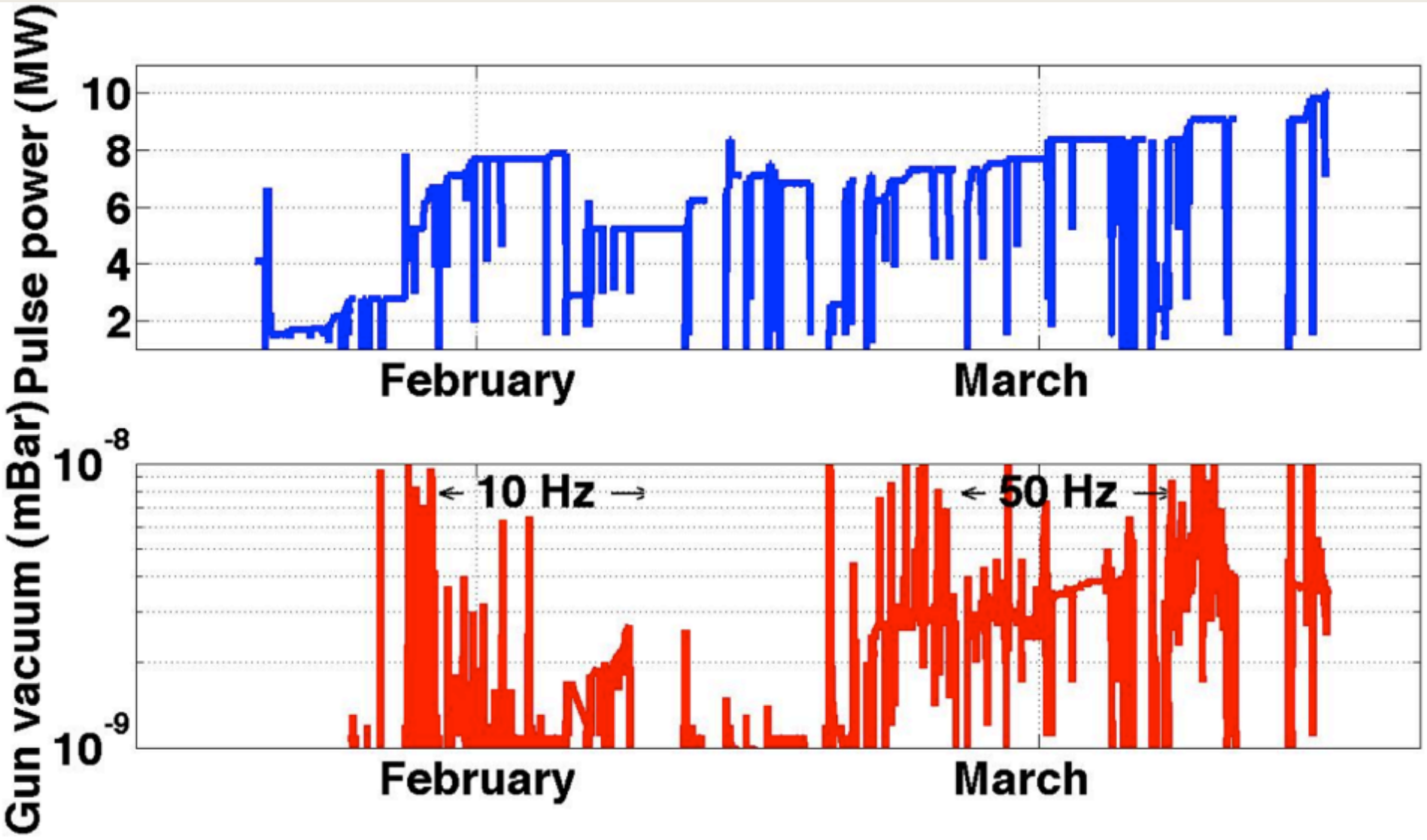
- A dedicated area for high-power gun testing is located behind the current RF gun station
- The ST gun was installed in this area to start high-power conditioning



Acknowledgements to the team

Luigi Faillace, RF design
Pedro Frigola, project manager
Ron Agustsson, VP of Engineering
Hristo Badakov, Mechanical Engineer
UCLA collaboration
Fermi team

Power and vacuum monitoring



Temperature Tuning at 10 Hz and 50Hz

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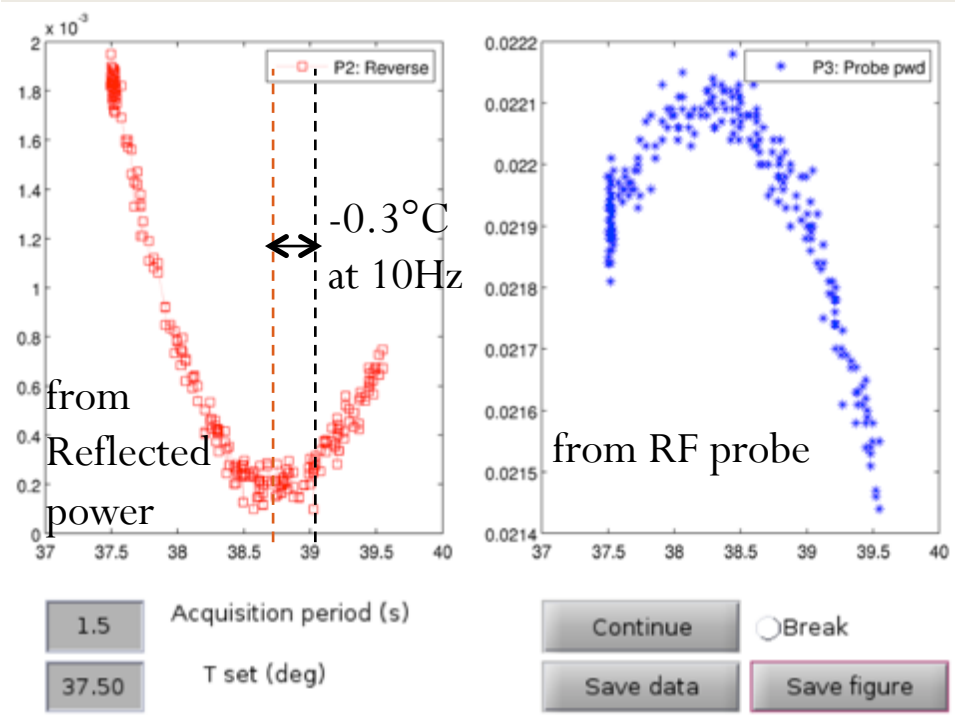
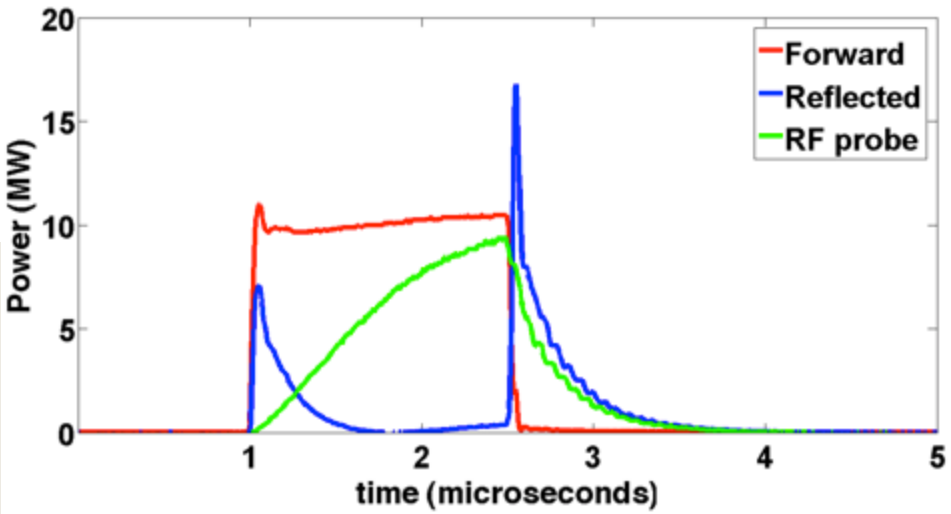
Frequency monitoring

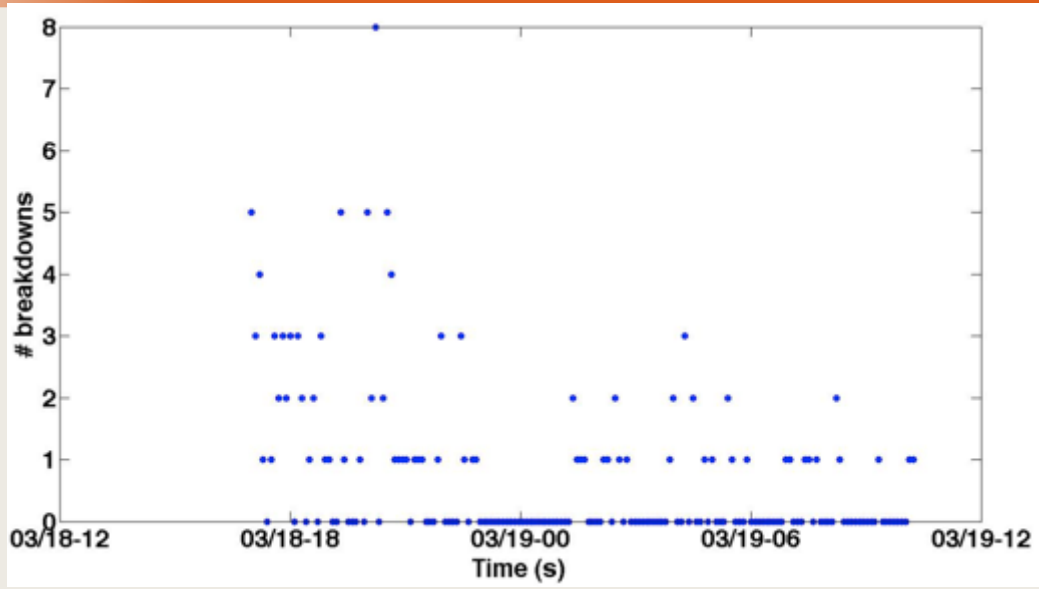


- Operation at 10Hz → ΔT = -0.3 °C
- Operation at 50Hz → ΔT = -2 °C

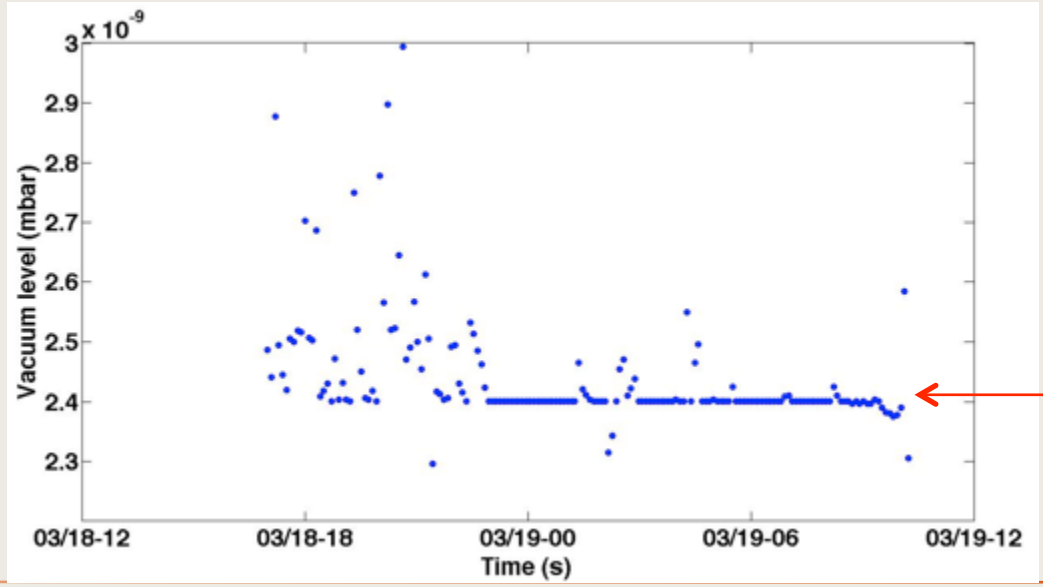
Power Waveforms (11 MW and 1.5 µs)



Breakdown monitoring during high-power conditioning



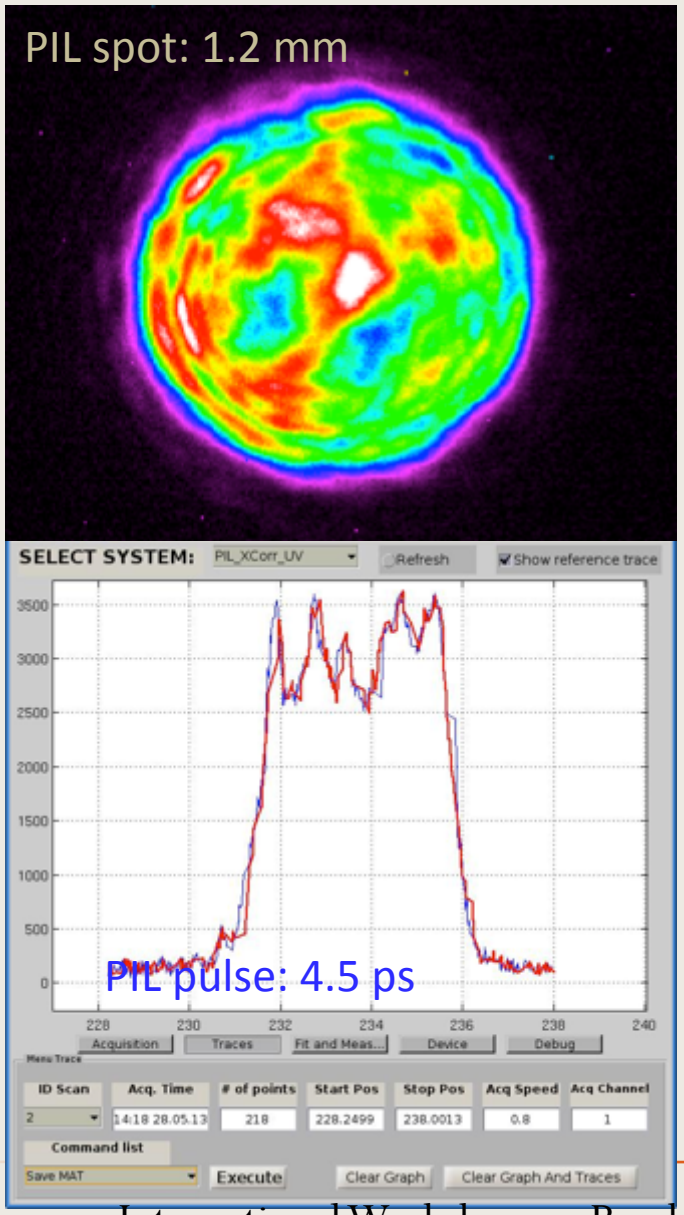
Input RF power = 11MW
RF pulse = 1.5 μs
Monitoring time = 18 hours



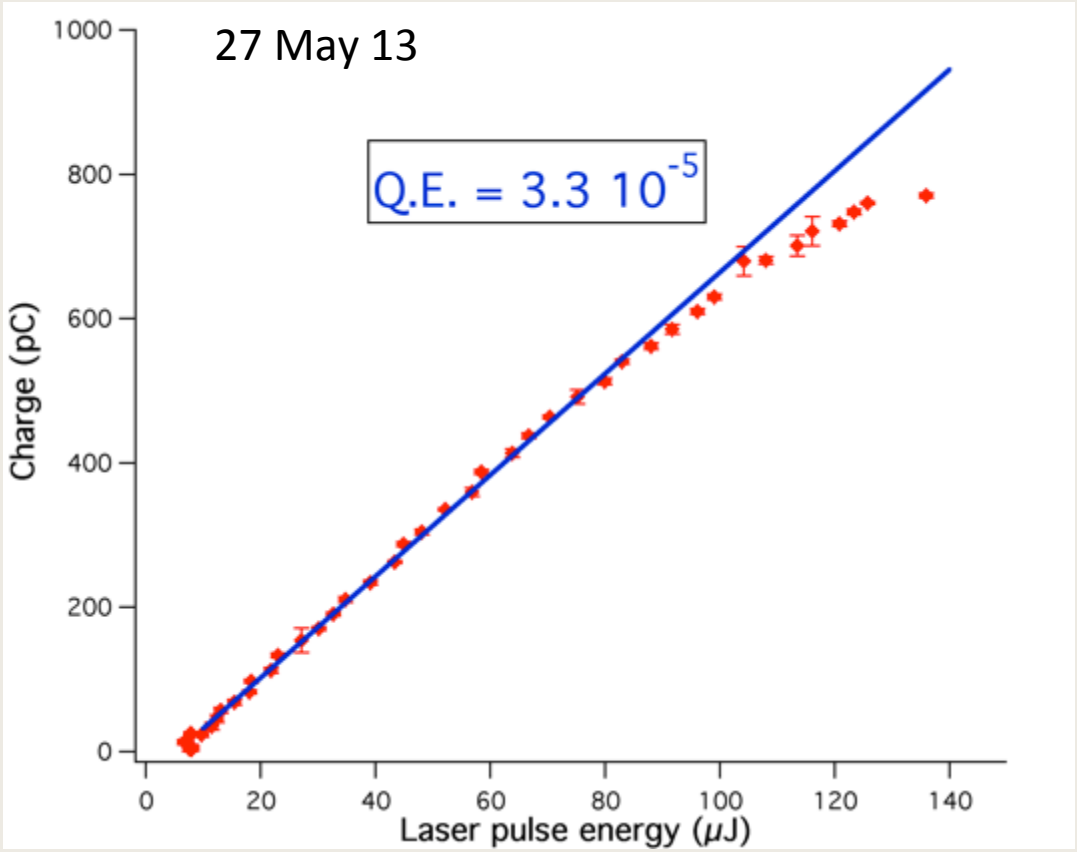
Excellent vacuum level

$2.4*10^{-9}$ mbar

e-beam



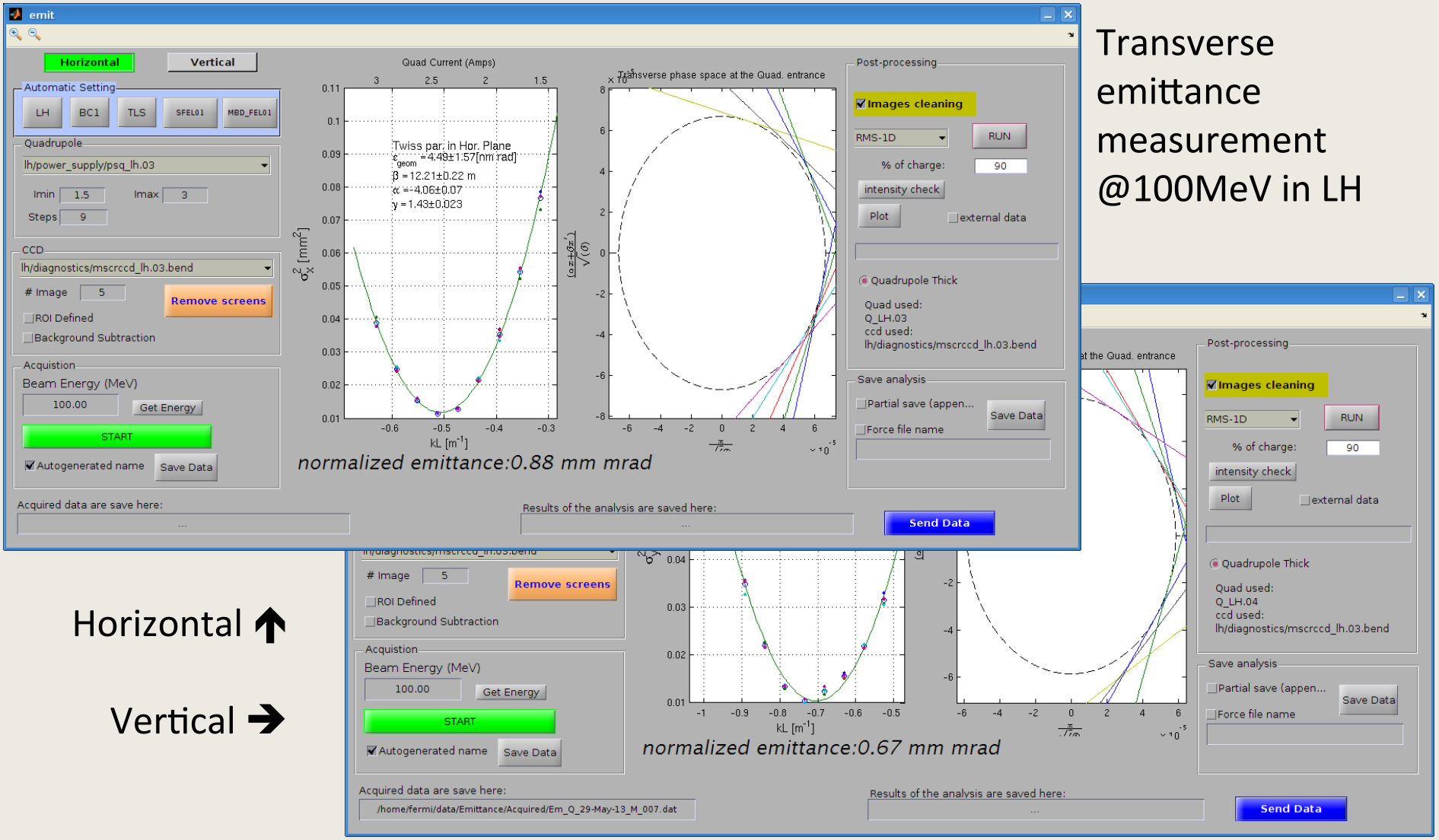
Charge measurement vs. PIL energy



e-beam extracted at 5.1 MeV
with 8 MW input power

Courtesy of Trovò

500 pC e-beam emittance

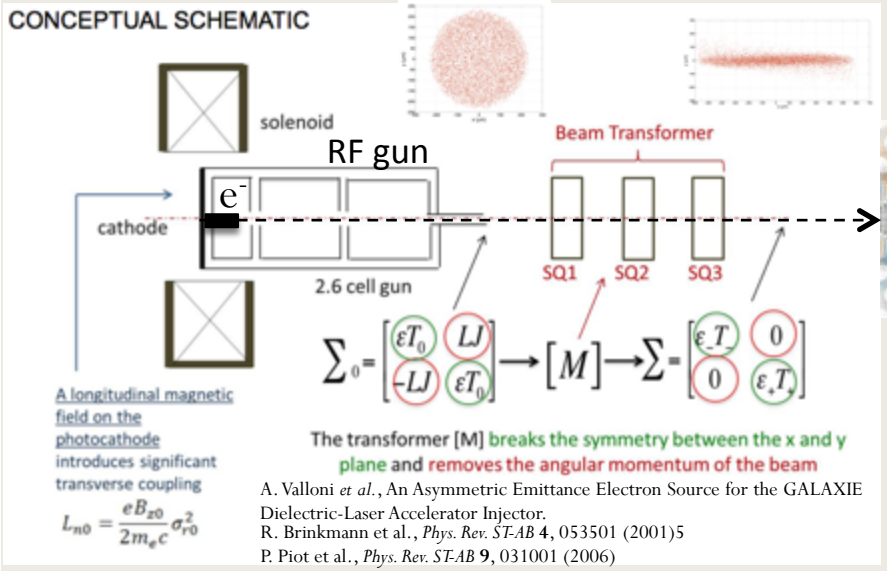


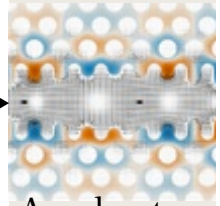
Transverse emittance measurement @100MeV in LH

Courtesy of Trovò

The GALAXIE Project

GALAXIE (***G***V-per-meter ***A***cce***L***erator ***A***nd ***X***-ray-source ***I***ntegrated ***E***xperiment) is a program to develop an all-optical, very high field accelerator and undulator integrated SASE FEL system based on dielectric laser-excited structures that support >GV/m fields.





Accelerator structure

Parameter	Symbol	Value
Injection Energy	U_i	3 MeV
Normalized Emittances (split)	$\varepsilon_x, \varepsilon_y$	$2\times10^{-7}, 2\times10^{-9}$ m-rad
Normalized Emittances (round)	$\varepsilon_x = \varepsilon_y$	2×10^{-8} m-rad
Injection current (unbunched)	I_{ave}	1 A
Peak current (bunched)	I_p	300 A
Nominal acceleration field	E_{acc}	1 GV/m
FEL Operational Energy	U_f	720 MeV
FEL EM undulator wavelength	λ_u	100 μm
FEL Pierce parameter (3D)	ρ_{3D}	5×10^{-5}
FEL Gain Length	$L_{g,3D}$	9.3 cm
FEL Saturation Length	L_{sat}	1.8 m

$$\varepsilon = \sqrt{\varepsilon_0^2 + L^2} \qquad \varepsilon_- \approx \frac{\varepsilon_0^2}{L} \qquad \varepsilon_+ \approx 2L \qquad L >> \varepsilon_0$$

- Injector: high field gun with a magnetized cathode (1pC,1ps beam with angular momentum content)

→ the ***Super Gun***

- Transformer: beam passing through a skew-quad triplet that splits the emittances ($\varepsilon_- = 2*10^{-9}$ mrad)
- Dielectric photonic structure: acceleration
- Inverse Transfomer: the emittance splitting process is reversed after acceleration and before the undulator to avoid gain-degrading multiple-transverse-mode operation of the FEL

The "SUPER GUN" - 3D model

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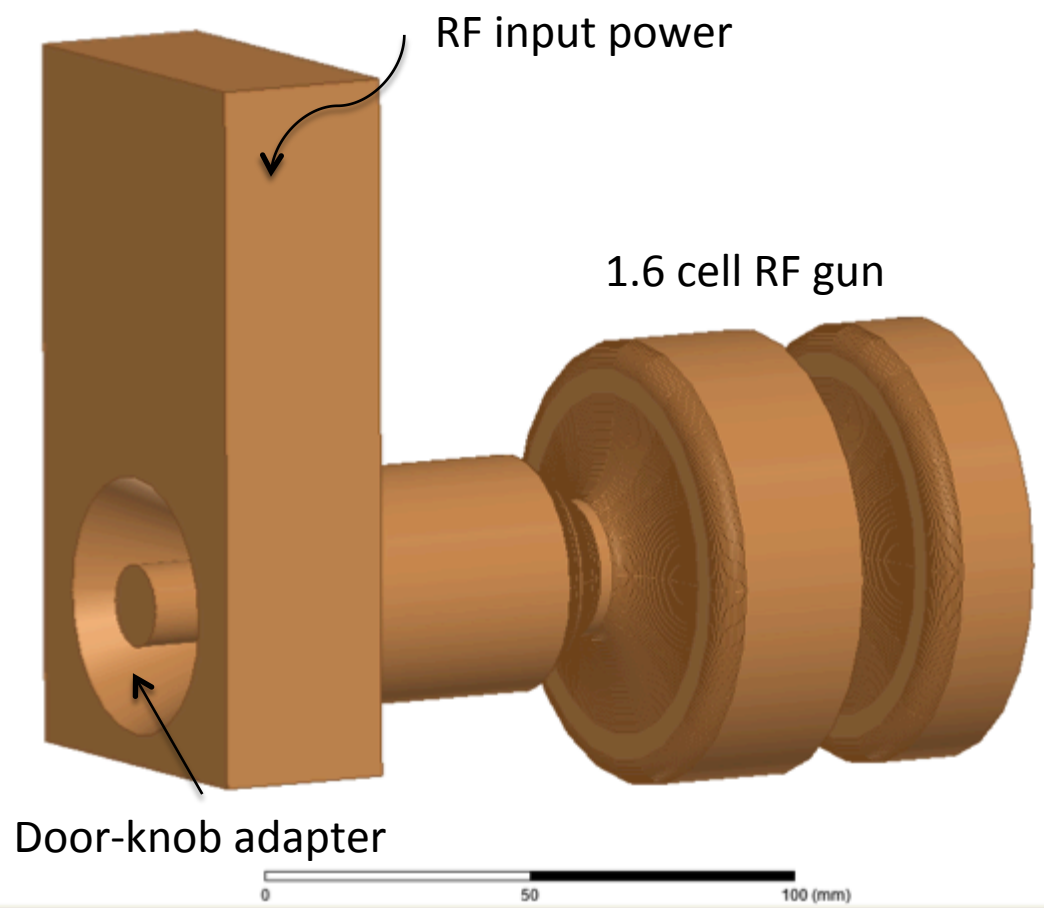


Surface model from HFSS

Characteristics

- Coaxial coupling (e.g. Pitz-like)
- Axisymmetric: elimination of high-order mode field components
- Elliptical irises to decrease the surface electric field
- Single-feed (WR284 waveguide)
- Transition from rectangular waveguide to coax through a door-knob type adapter

Innovations

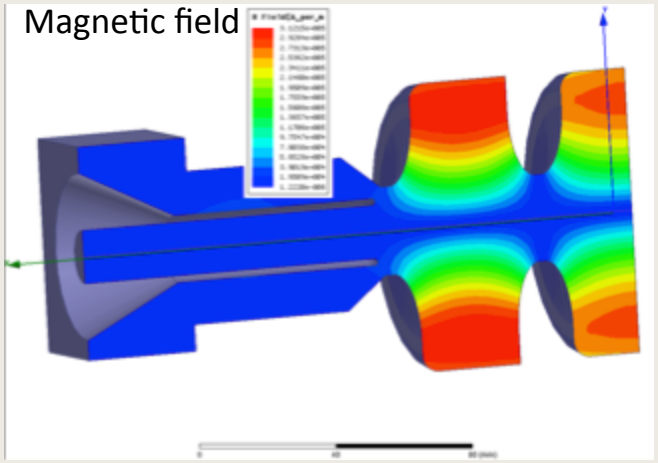
- Higher electric field at the cathode (up to 160 MV/m)
- Possibility to easily run very low charge (≤1pC) and beams with very small transverse size (25μs for Galaxie)

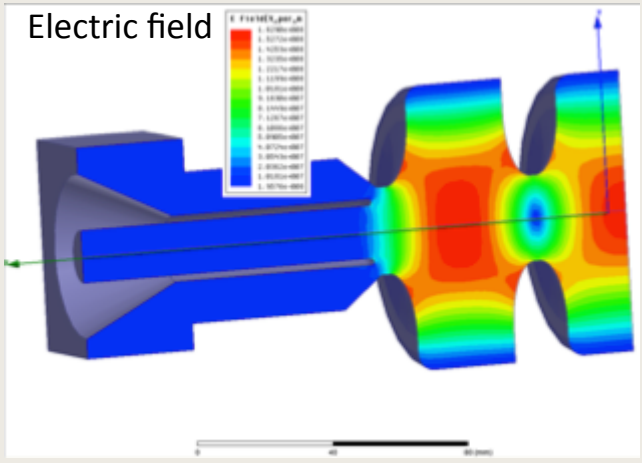
Possible issues

- Multipacting (coaxial coupler can be made out of a material with very low secondary electron yield)
- Breakdowns (design with no electric field hot spots; experience in surface handling: Fermi II gun; High-gradient structure tested at Livermore)

RF parameters

f = 2.85672 GHz
Δf = 15MHz
R = 70MΩ/m r_{eff} = 41.5MΩ/m
Q_0 = 16,000
E_{peak} = 160MV/m @ 24MW input RF power, 1μs pulse

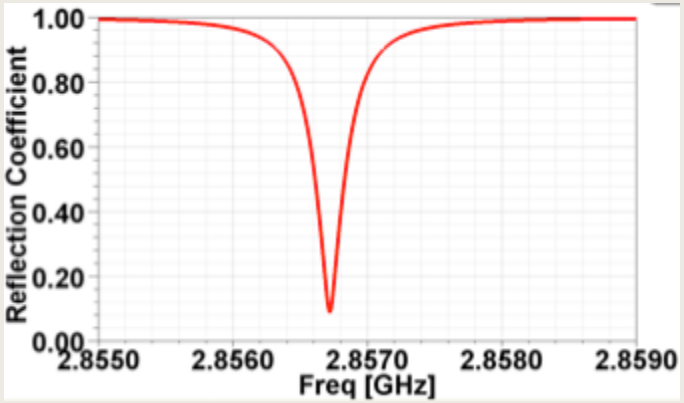


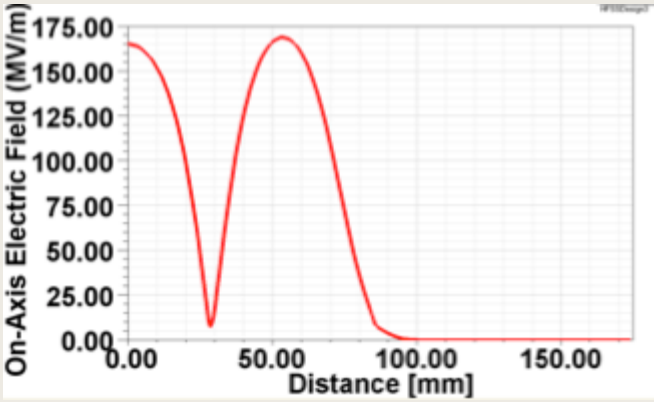


Surface model of the SuperGun, from HFSS

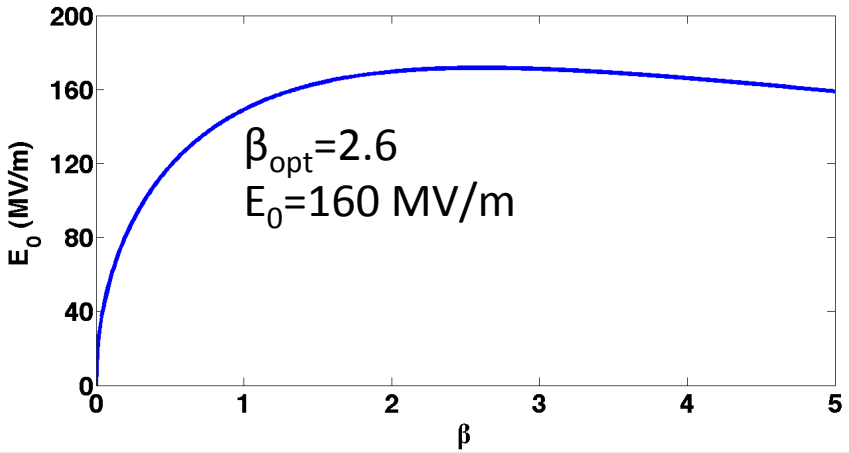
- E_{max} on surface=160MV/m
RF Pulsed heating<50 °C

- The coupling coefficient β is adjustable by moving the location of the coax with respect to the gun cells



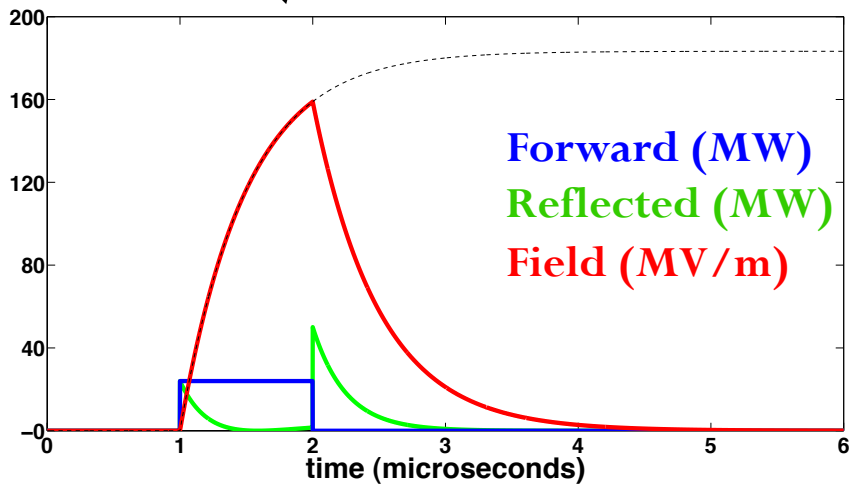


The "SUPER GUN" - Coupling



- Assume RF pulse = 1 microsecond
- The optimum beta 2.6 for a max on-axis E-field of 160M/m
- Short pulse in order to decrease the breakdown rate

Field filling time $t_F = 2*Q_0/[(1+\beta)*\omega] = 495$ ns, assuming =2.6 and Q_0=16,000



Beam dynamics simulations

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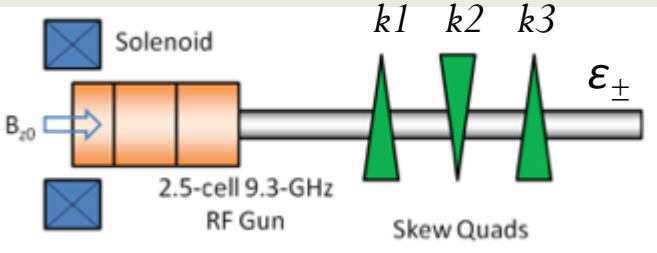
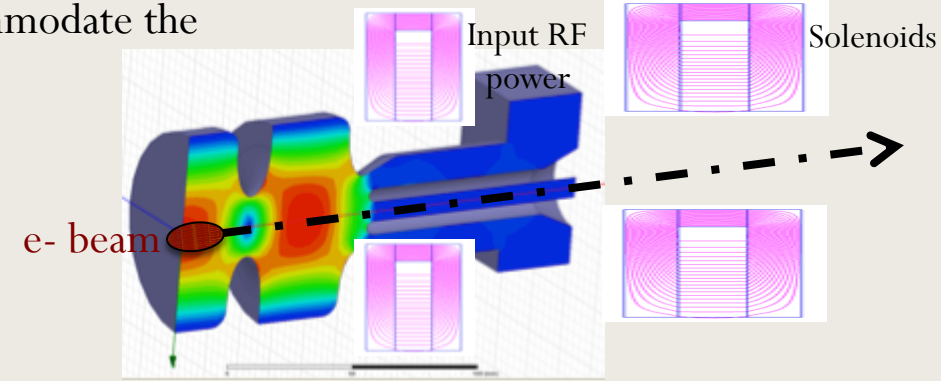
- Galaxie: we have started to set up Parmela for simulations of the beam generation and propagation of a 1pC,1ps beam from the Super Gun (S-Band) down through the emittance exchange scheme.
- Preliminary simulations to study the emittance splitting setup have been already carried out. An X-Band gun was used (it was decided to go towards S-Band only afterwards)



Parameter	Symbol	Value
Normalized Emittance (split)	$\varepsilon_{n-}, \varepsilon_{n+}$	2.9×10^{-9}, 2.6×10^{-7} m-rad
Field Gradient of Skew Quads (1-cm thick)	k_1, k_2, k_3	-9.4, 6.0, -5.9 T/m

- Plans for running a higher charge case (1nC) are also being made. Because of the reduced vector potential value $\alpha = 2.6$, we expect the location of the focusing solenoid to be further away from the gun with respect to a current S-band scenario.
- Solenoid splitting to accommodate the input RF waveguide



High-power Tests of an Ultra-high Gradient Compact S-band (HGS) Accelerating Structure

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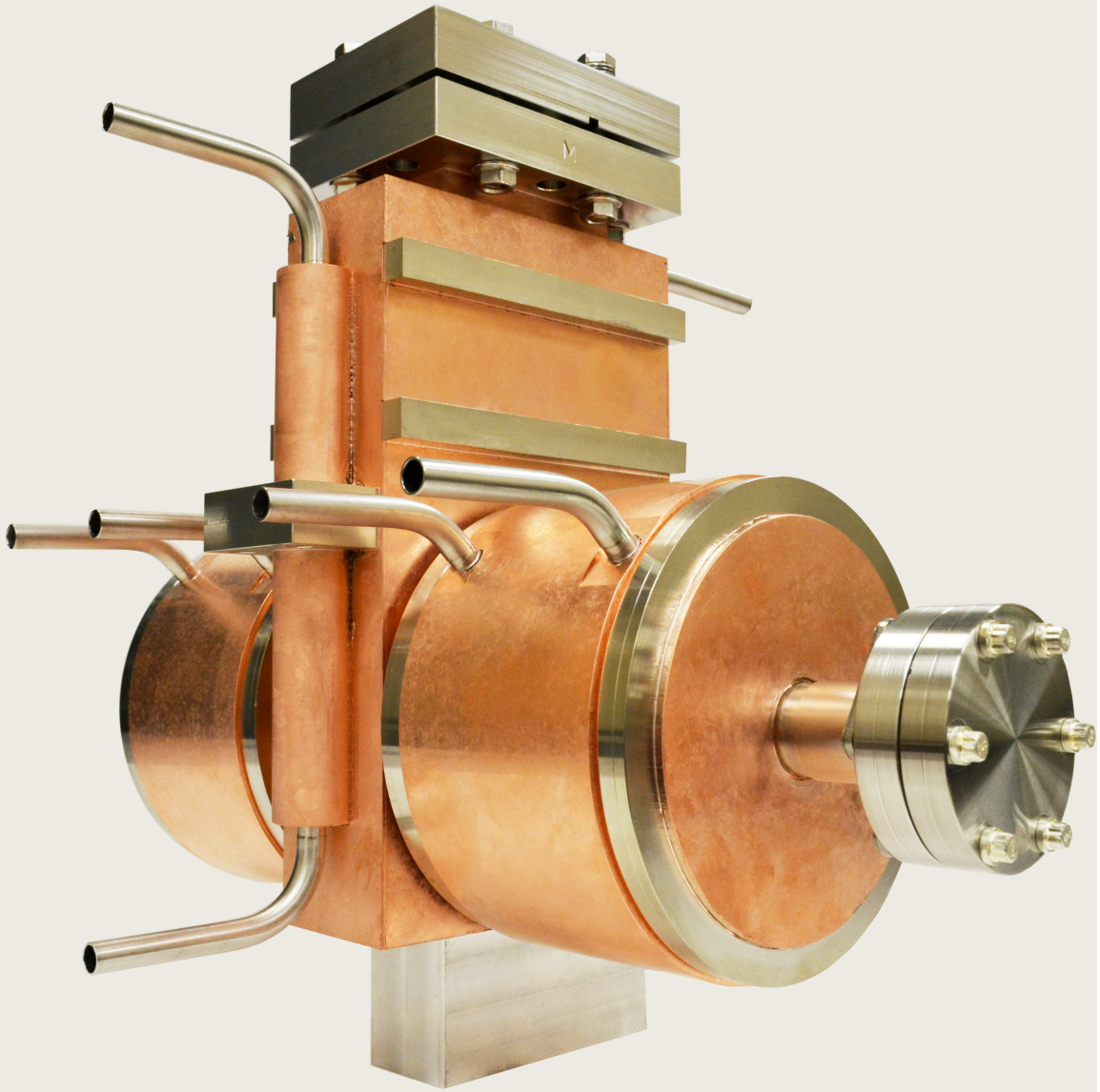
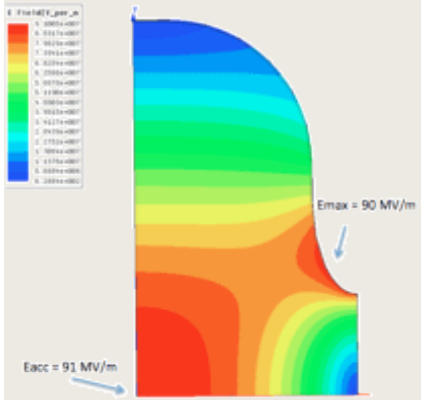
- RadiaBeam Technologies reports on the RF design, fabrication and high-power tests of a ultra-high gradient S-Band accelerating structure (HGS) operating in the pi-mode at 2.856 GHz. The compact HGS structure offers a drop-in replacement for conventional S-Band linacs in research and industrial applications such as drivers for compact light sources, medical and security systems.

- The electromagnetic design (optimization of the cell shape in order to maximize RF efficiency and minimize surface fields at very high accelerating gradients) has been carried out with the codes HFSS and SuperFish while the thermal analysis has been performed by using the code ANSYS.

- The high-power conditioning was carried out at Lawrence Livermore National Laboratory (LLNL).



HGS Design



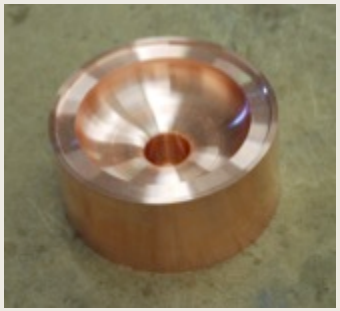
Parameter	Simulated value
f_π	2.856 GHz
R_S (Effective R_S)	93 MΩ/m (51 MΩ/m)
Δf	2.5 MHz
Q_0	19,500
R/Q	143.2 Ω
E_{acc}	50 mV/m
E_{max}/E_{acc}	1.8
P_{diss}/cell	2.4 MW

RF design

- standing wave cavity, single feed
- 3D HFSS optimization
- elliptical iris geometry to decrease surface electric field
- "fat-lip" coupler to reduce surface RF pulsed heating

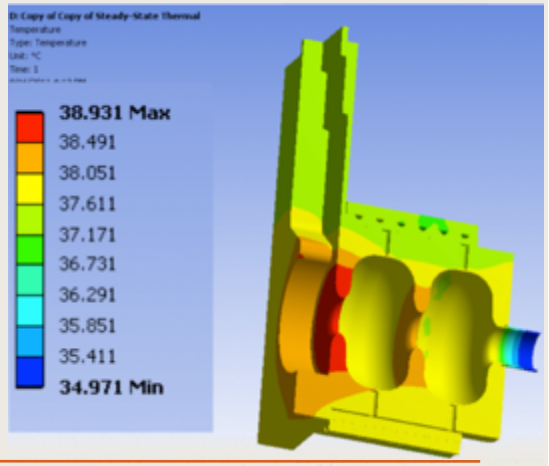
Fabrication

- 5-cell prototype HGS structure.
- The cooling system: two water jackets brazed around the cells
- 4-6 μm surface finish
- Followed SLAC prescription for cleaning and surface processing



Thermal design

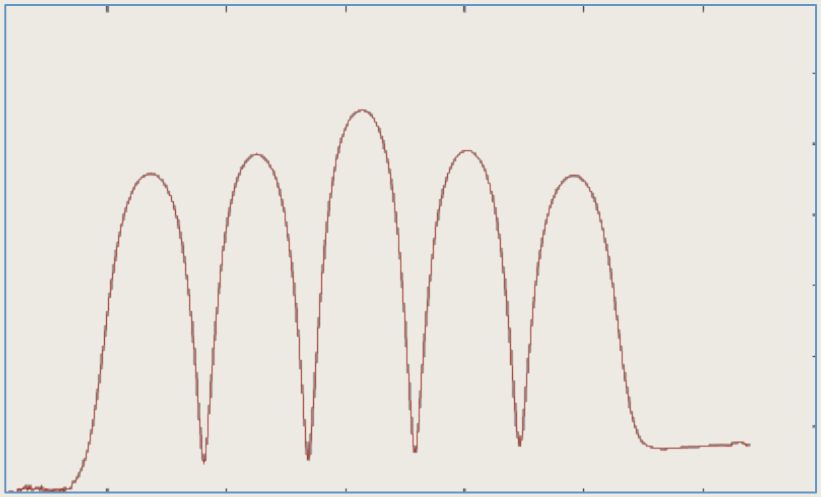
- The cooling system for frequency stabilization only
- Simulations at 10 Hz (water temperature 36.5°)



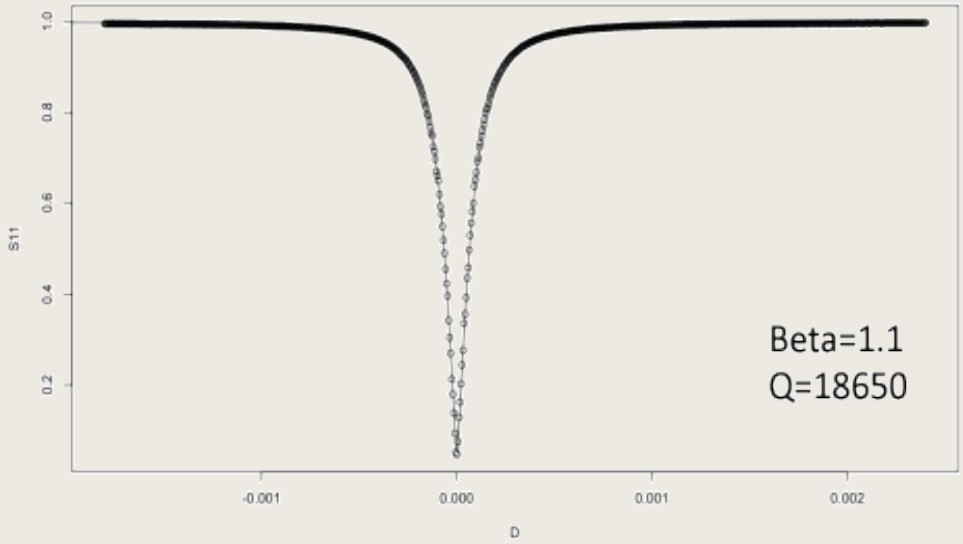
Cold test measurements

- Bead pull indicated frequency within the measurement error (< .5 MHz) from nominal value
- No need for additional tuning

On-axis electric field (bead-pull)



Reflection coefficient



High-power tests at LLNL

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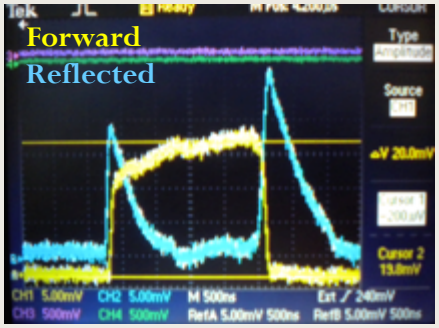
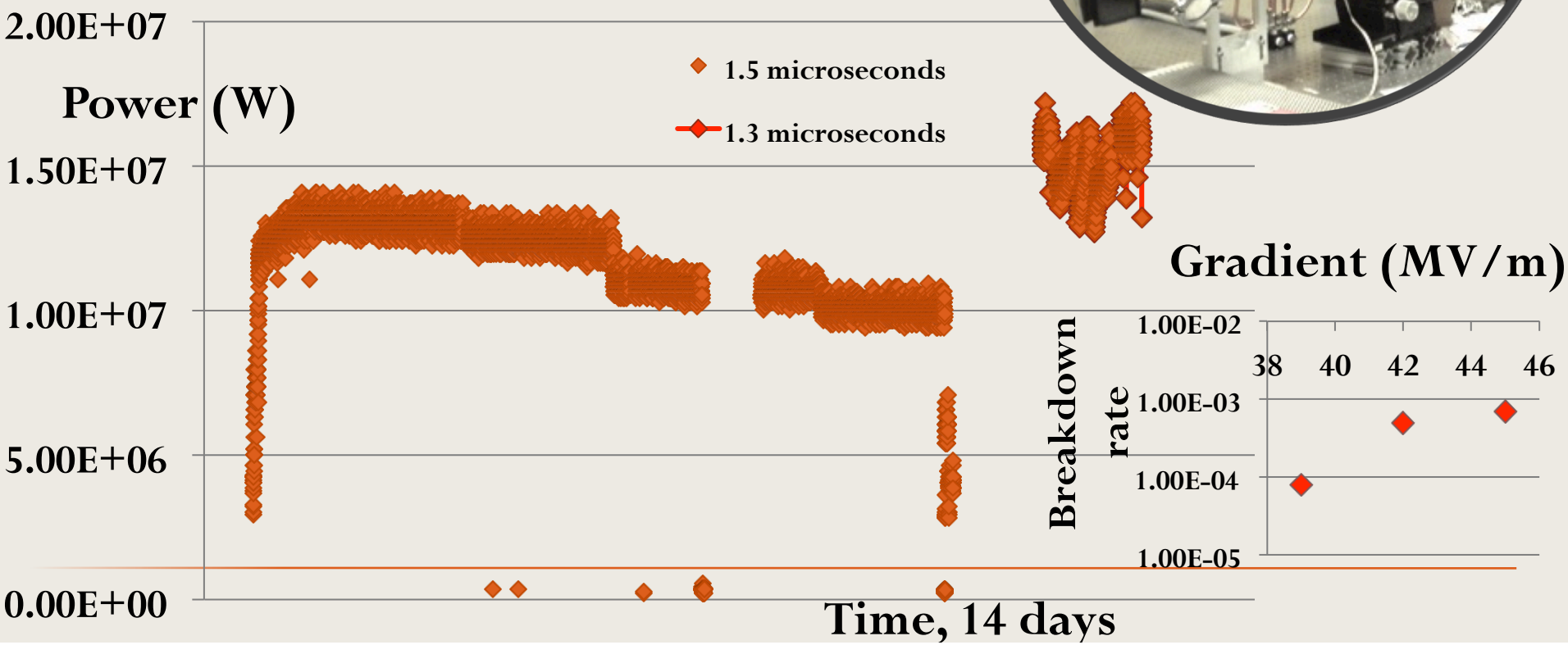
- LLNL S-band klystron (purchased 15 MW circulator)
- 10 Hz rep. rate (run 2 days /week)
- Input power: ~ 16 MW → **50 MV/m**

Power signals





S-Band Deflector for the Pohang Accelerator Laboratory (PAL)

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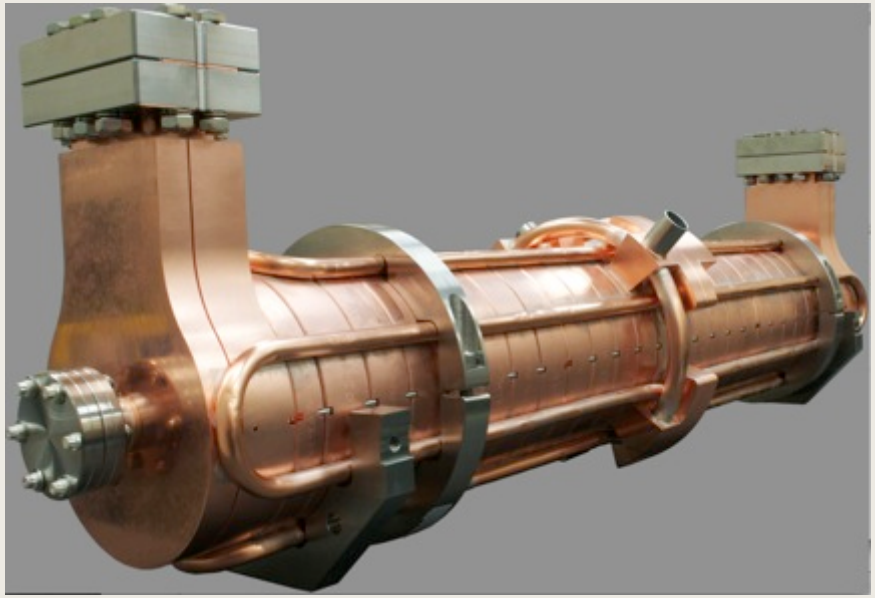
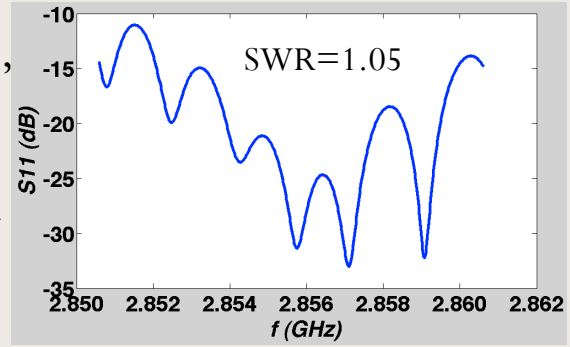
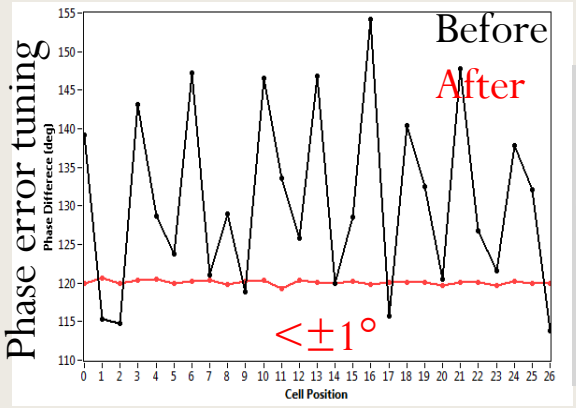
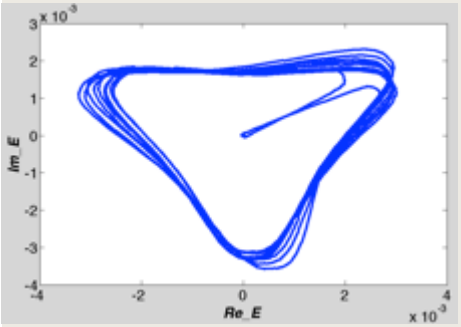


In-house RF design, machining and tuning

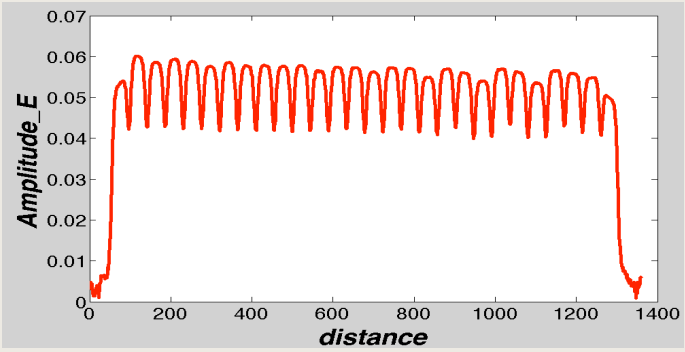
Brazing: close-by company







2π/3-mode frequency f	2.856 GHz
Transverse Shunt Impedance r_T	28.7 MΩ/m
Unloaded Q	13400
Attenuation α	0.15 m^{-1}
Group velocity v_g	0.014 c
Kick/√Power	2.7 MV/√MW
Length	1 m



X-Band Deflector

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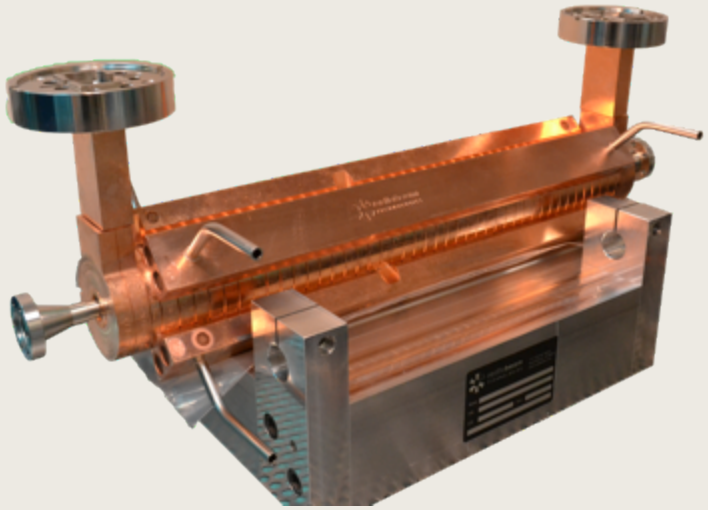
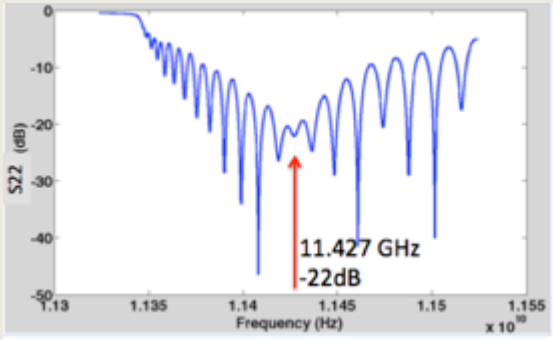
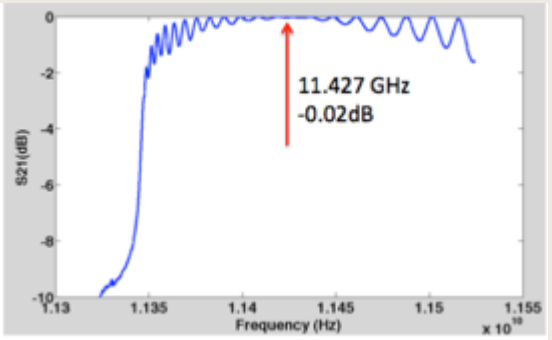


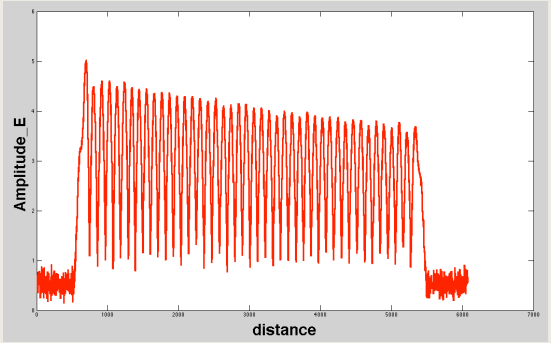
In-house RF design and machining

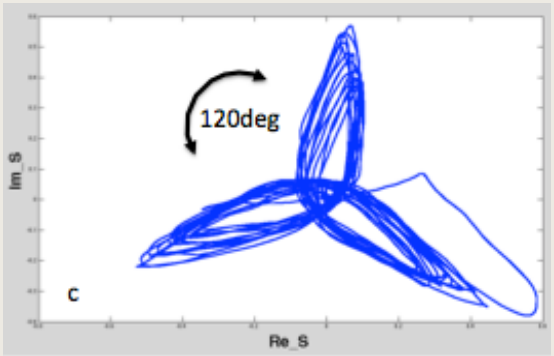
Brazing: close-by company





Tuning at SLAC.





2π/3-mode frequency	11.424 GHz
Deflection Kick	8.5 kV/m/W$^{1/2}$
Attenuation	0.66 m^{-1}
Group velocity	0.027 c
Length	45 cm
Max. input peak power	20 MW
Peak deflecting voltage	38 MV/m

Conclusions

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- The new RF gun for the Fermi FEL at Sincrotrone Trieste was successfully installed and conditioned at high-power (11MW, 1.5μs and 50Hz)
- Fermi II RF Gun is an improved and more compact version of the Fermi I gun. Initial beam measurements show promising results (500pC, 0.6 micron emittance)
- The design of the "Super Gun" for the GALAXIE project represents a break-through in the field of RF multi-cell Guns → new materials, material technology (e.g. Free Form Fabrication?), surface handling, laser shaping…
- S-Band High-Gradient Structure (HGS) was tested up to 16 MW reaching a gradient of 50 MV/m.
- Our first experience with S/X band deflectors. High-power tests to come.

Thanks for your attention!