High-Brightness Thermionic Electron Gun Performance

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Advanced Energy Systems, Inc.

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Putting Accelerator Technology to Work

Abstract

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Accelerator systems utilizing off-the-shelf, high-frequency thermionic cathode gridded electron guns are presently being commissioned. We have performed emittance measurements at voltage levels up to 32.5kV which indicate the beam transverse rms emittance is 8-10mm-mrad at 20kV, consistent with our gun simulations. The nominal system operating voltage will be 45kV. We have also studied the dependence of the extracted current as a function of RF power. After the initial transient phase, near linear behavior is observed. The maximum values achieved were 214mA at 32.5kV and ~100W input RF power, and 806mA at 23.2kV and ~200W input RF. We describe ongoing measurements at the Fritz Haber Institute THz FEL and compare these results to simulations. This relatively low-duty factor, S-band device utilizes low energy beam scraping after the gun to achieve the desired performance, which may not always be appropriate. The next step for such systems, which is ongoing, is to develop a lower frequency booster accelerator integrated with the gun, that raises the energy to greater than 1 MeV so that the performance of the concept can be evaluated without substantial beam spill.

* Consultants to AES

Motivation

- Would like a thermionic electron gun for either high-performance or high-power applications where robustness, economics or footprint preclude a photocathode system
- Not intended as a substitute for most existing material processing accelerators
- Possible uses include ERLs, compact FELs, security and certain environmental applications

Similar NRL Concept for High-Power FELs

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 020702 (2011)

High average current electron guns for high-power free electron lasers

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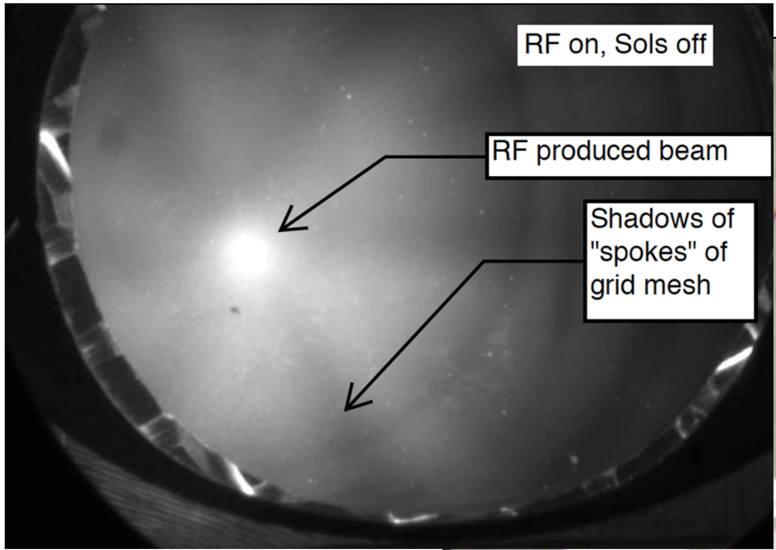
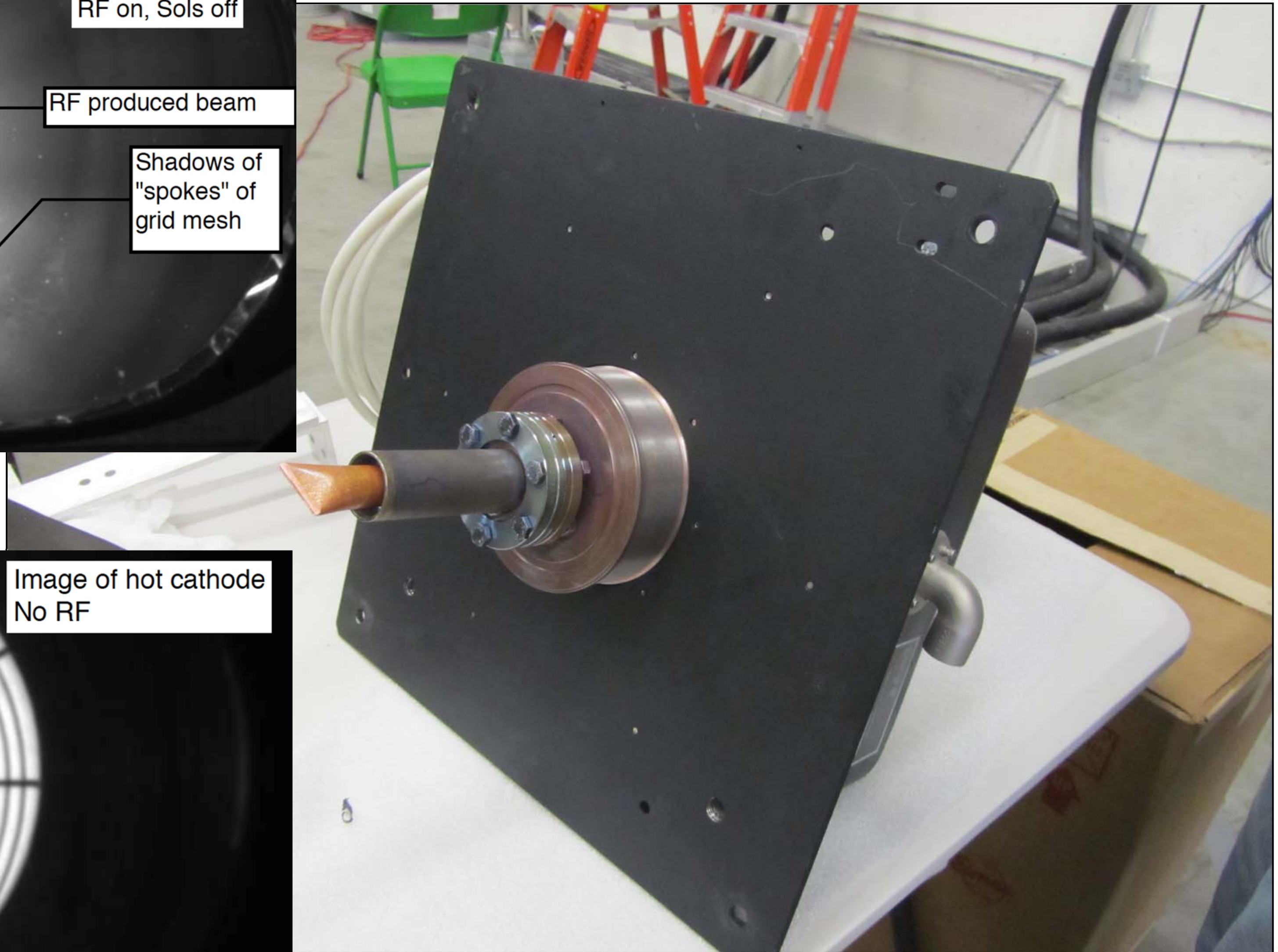
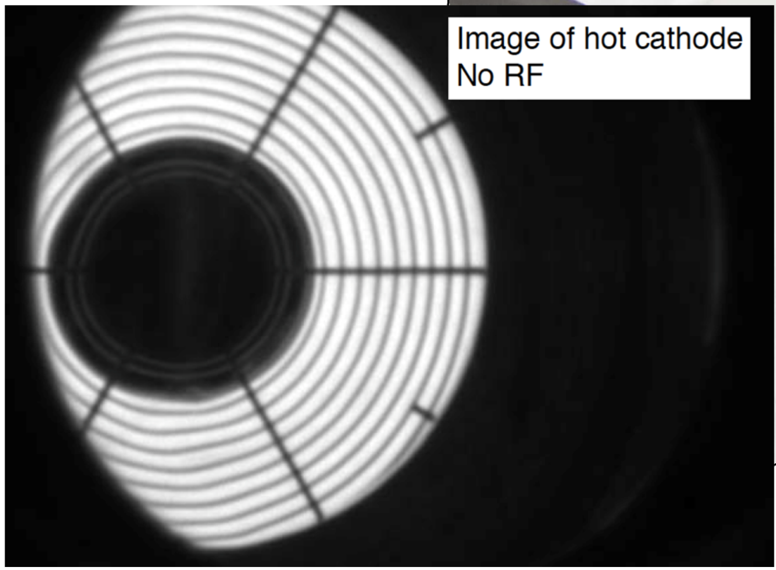
High average power free-electron lasers (FELs) require high average current electron injectors capable of generating high quality, short duration electron bunches with a repetition rate equal to the frequency of the rf linac. In this paper we propose, analyze, and simulate an rf-gated, gridded thermionic electron gun for use in high average power FELs. Thermionic cathodes can provide the necessary high current, have long lifetimes, and require modest vacuums. In the proposed configuration the rf-gated grid is modulated at the fundamental and 3rd harmonic of the linac frequency. The addition of the 3rd harmonic on the grid results in shorter electron bunches. In this configuration, every rf bucket of the linac accelerating field contains an electron bunch. Particle-in-cell simulations indicate that this approach can provide the necessary charge per bunch, bunch duration, longitudinal and transverse emittance, and repetition rate for high average power FELs operating in the IR regime.

DOI: 10.1103/PhysRevSTAB.14.020702 PACS numbers: 41.60.Cr, 07.77.Ka

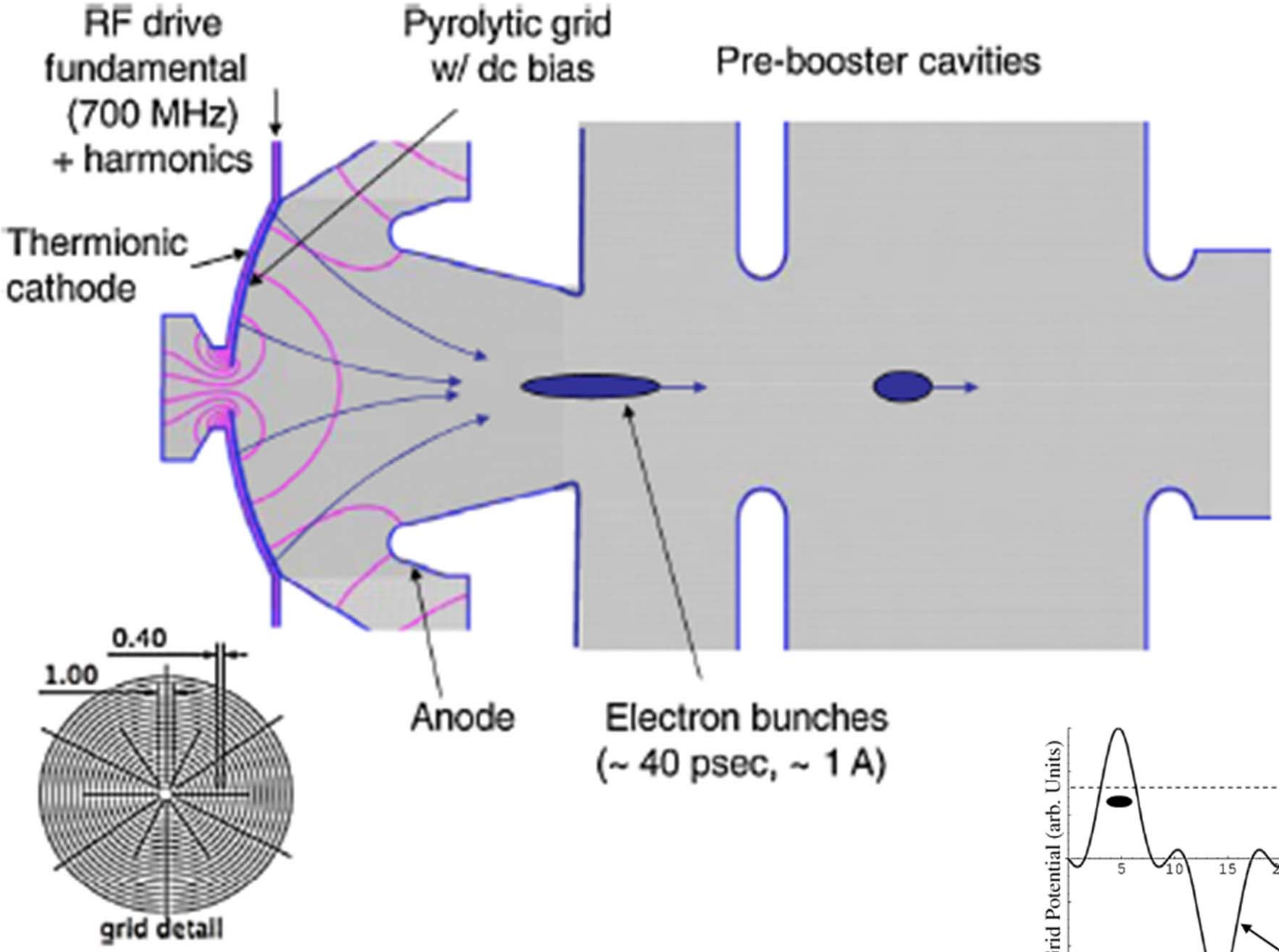
CPI Gridded Thermionic (IOT) Gun

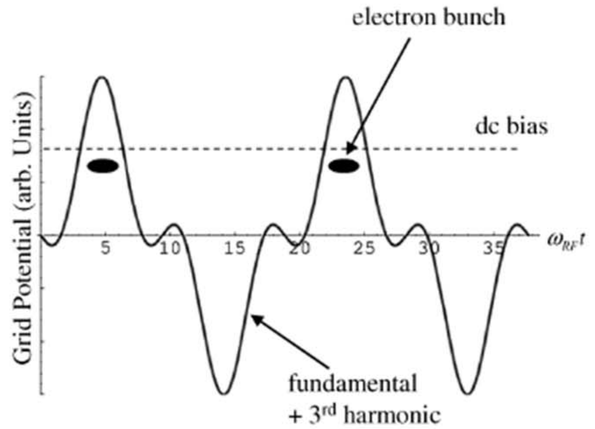




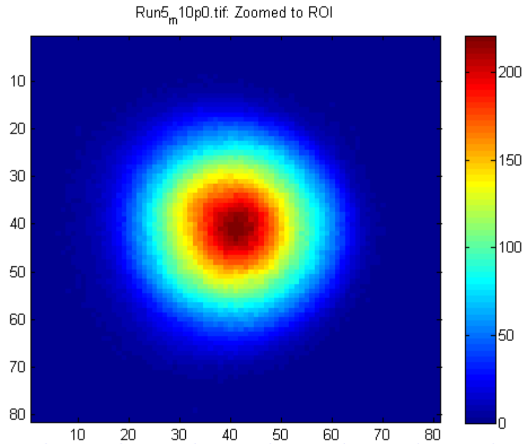


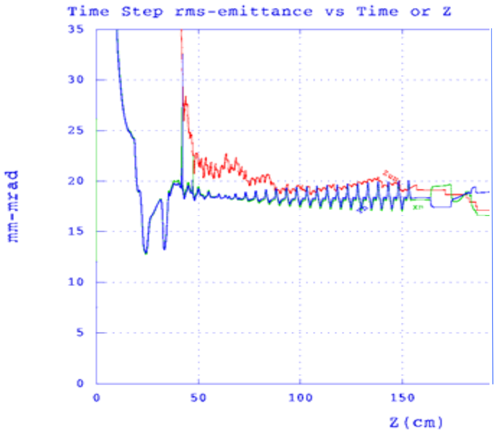
NRL Multi-Frequency Approach

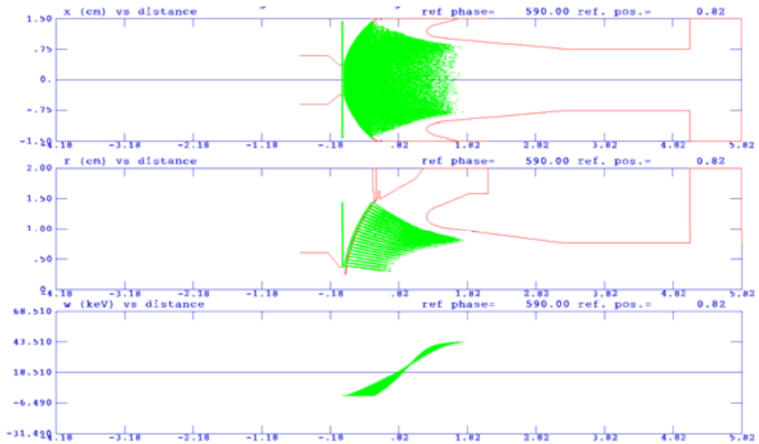


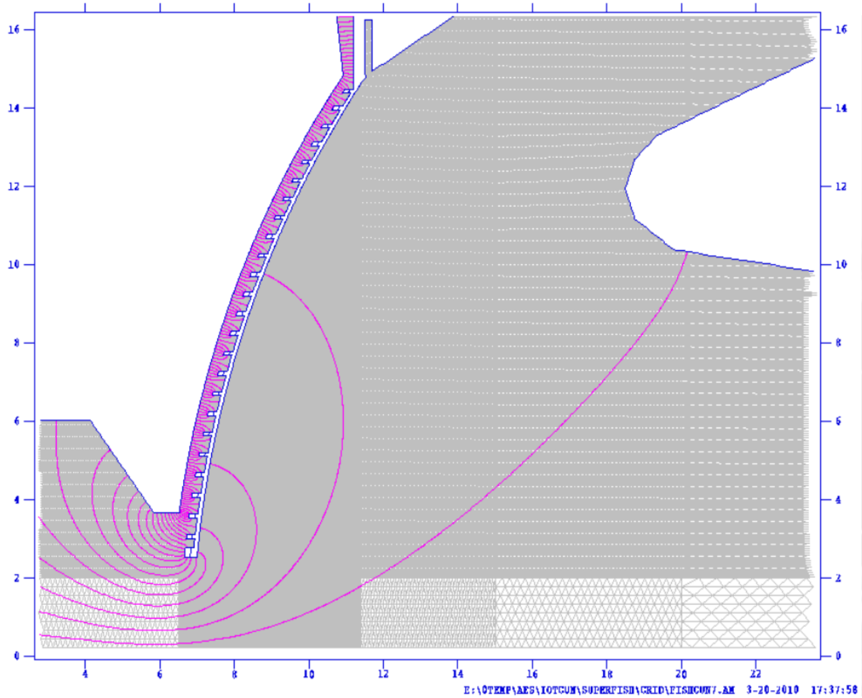


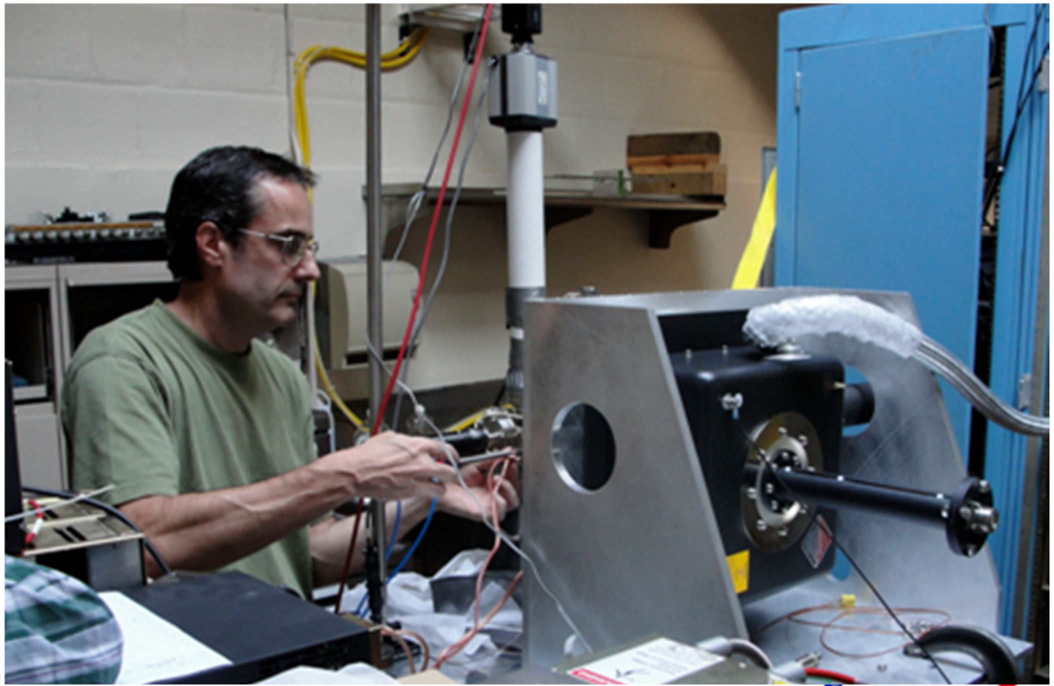
Thermionic Electron Gun Testing











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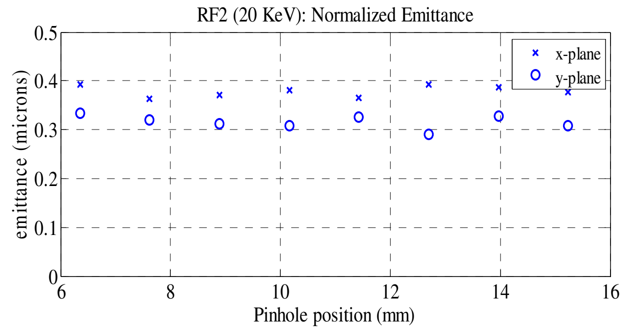
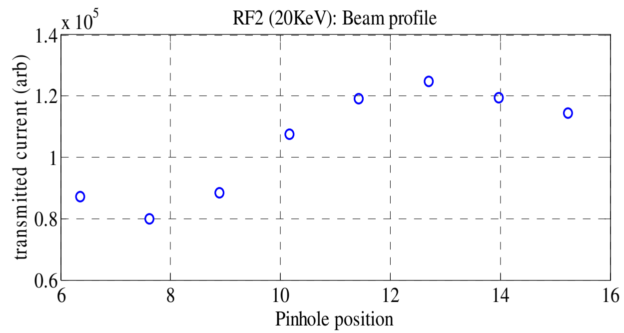
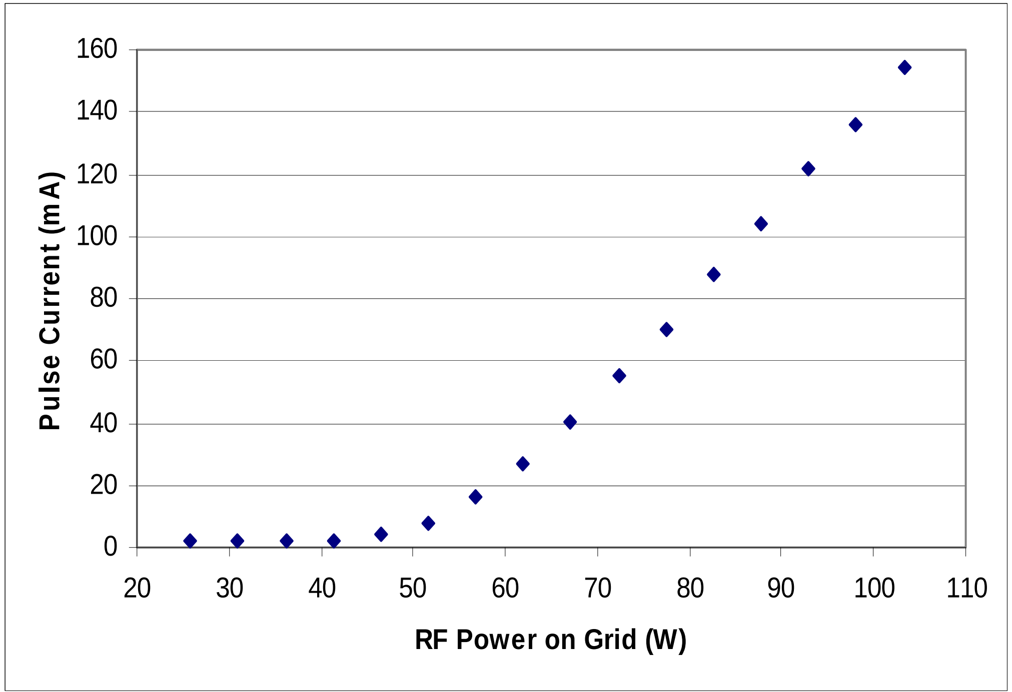
Thermionic Gun Measurements

- Pulsed 26mA beam @ 14kV rms emittance ~ 4µ
- Pulsed 100mA beam @ 20kV rms emittance ~ 8µ
- Idle current and gun HVPS limited operation
- Highest achieved voltage was 32.5kV => 214mA @ 100W of RF grid power
- 23.2kV => 806mA @ ~200W of RF grid power







- Results suggest Ampere-level average currents with transverse rms emittance < 20mm-mrad should be possible
- Idle current (pulsed mode) or beam spill (CW mode) must be controlled

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FHI IR & THz FEL Parameters

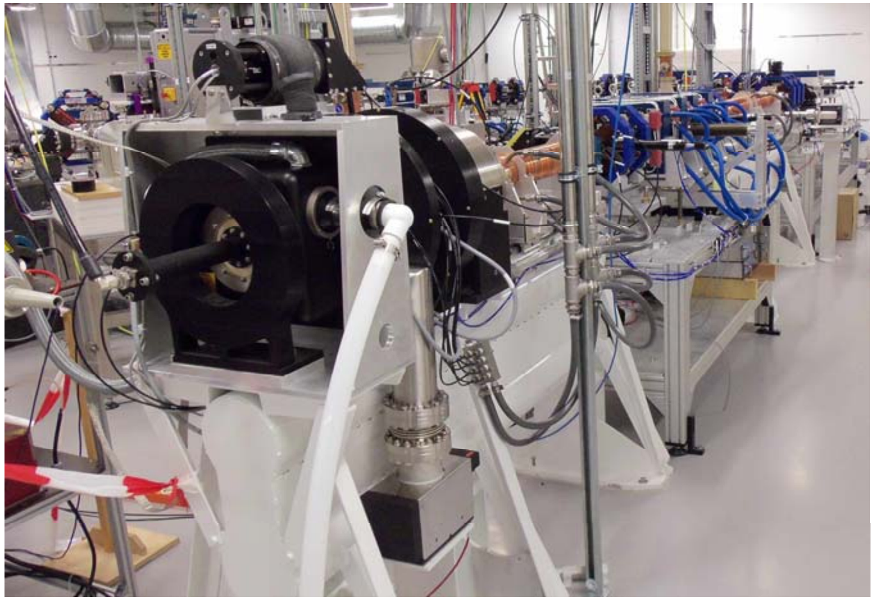
High-performance electron beam with normalized rms $\varepsilon_t < 20\mu$ and $\varepsilon_l \sim 50$keV-psec

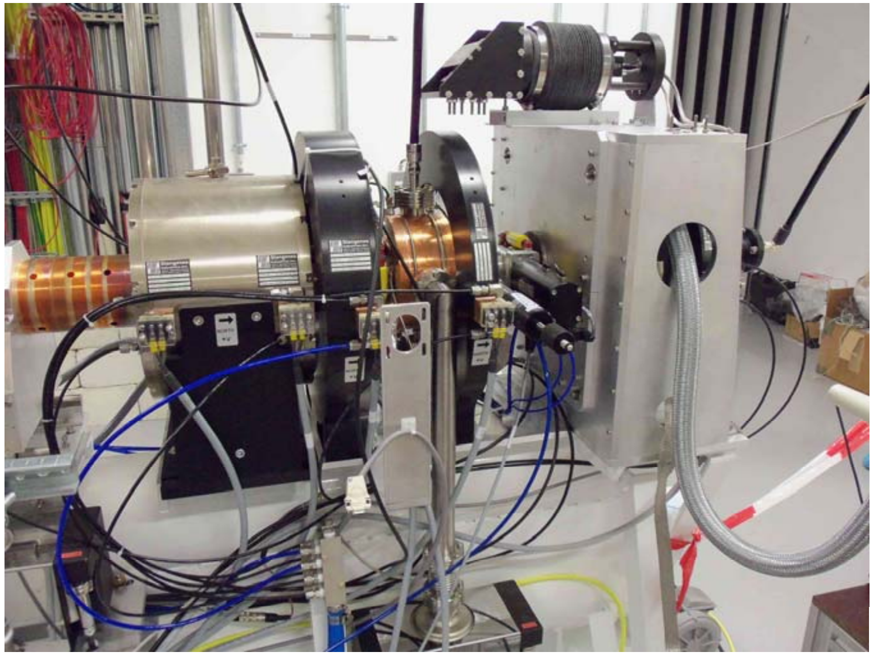
Max-Planck-Gesellschaft Centennial on October 28 at FHI => Hans Bluem in Berlin

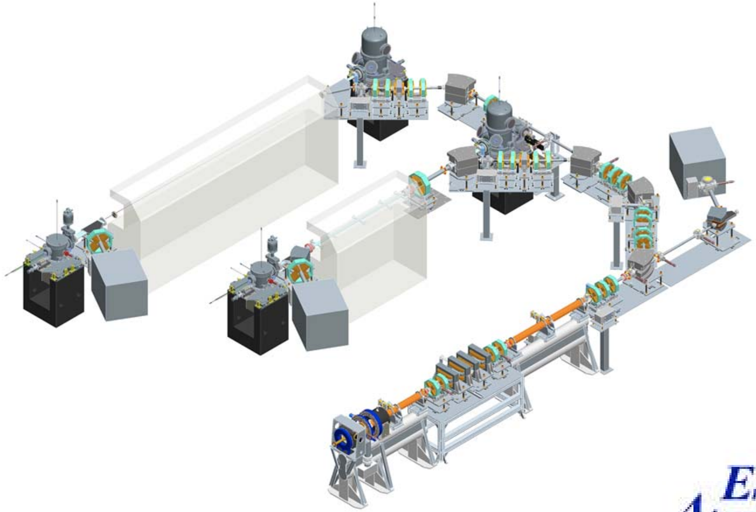
Parameter	Unit	Specification	Target
Electron Energy	MeV	20 - 50	15 - 50
Energy Spread	keV	50	< 50
Energy Drift per Hour	%	0.1	< 0.1
Charge per Pulse	pC	200	> 200
Micropulse Length	psec	1 - 5	1 - 10
Micropulse Repetition Rate	GHz	1	1 & 3
Micropulse Jitter	psec	0.5	0.1
Macropulse Length	µsec	1 - 8	1 - 15
Macropulse Repitition Rate	Hz	10	20
Normalized rms Transverse Emittance	π mm-mrad	20	20

	MIR	FIR
Undulator		
Type	Planar Hybrid	Planar PPM or Hybrid
Material	NdFeB	SmCo
Period (mm)	40	110
Number of Periods	50	40
Length (m)	2	4.4
K_{rms}	0.5 - 1.6	1 - 3
IR-Cavity		
Length (m)	5.4	7.2
Waveguide	None	1-D 10mm High

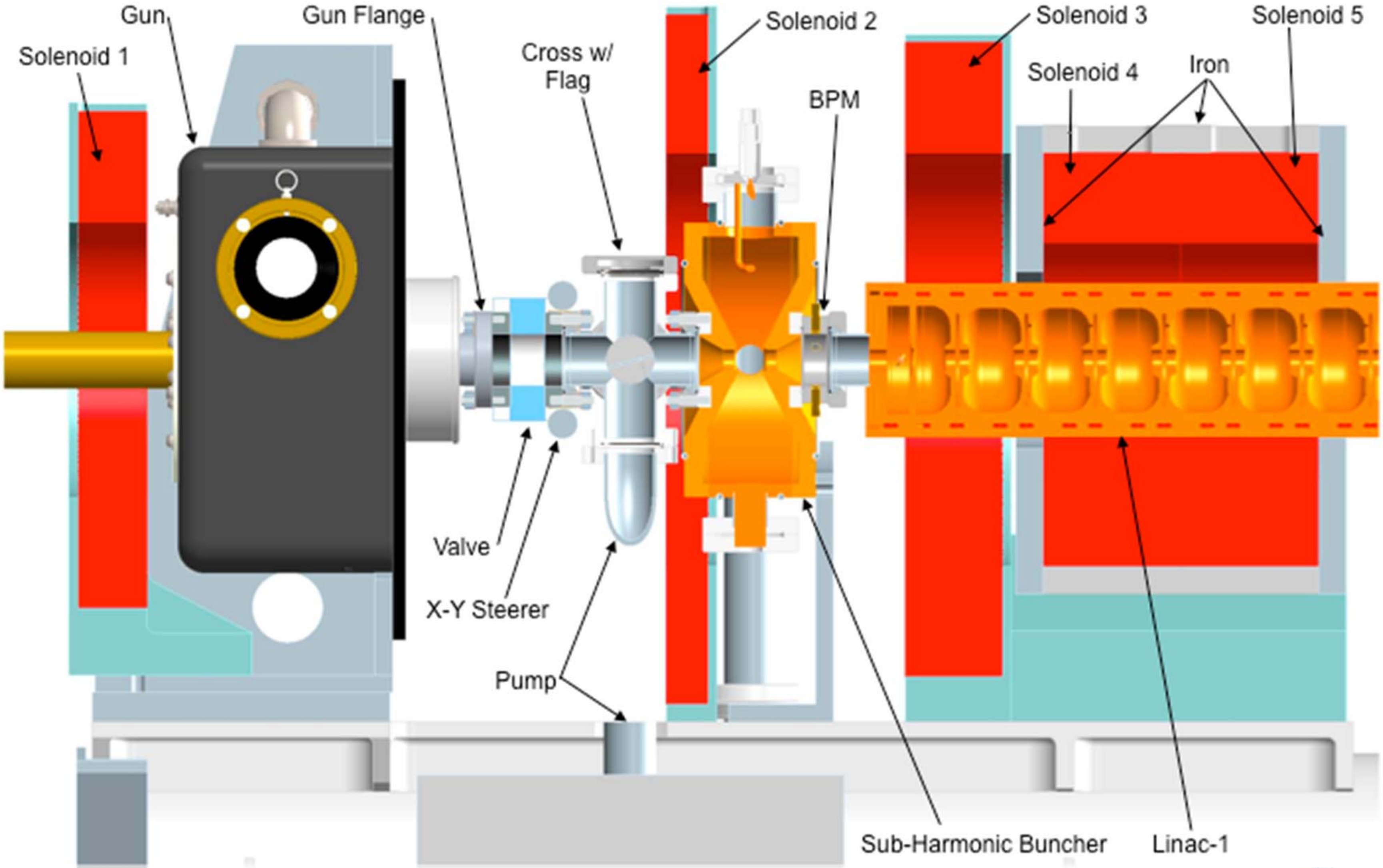
FHI IR & THz FEL



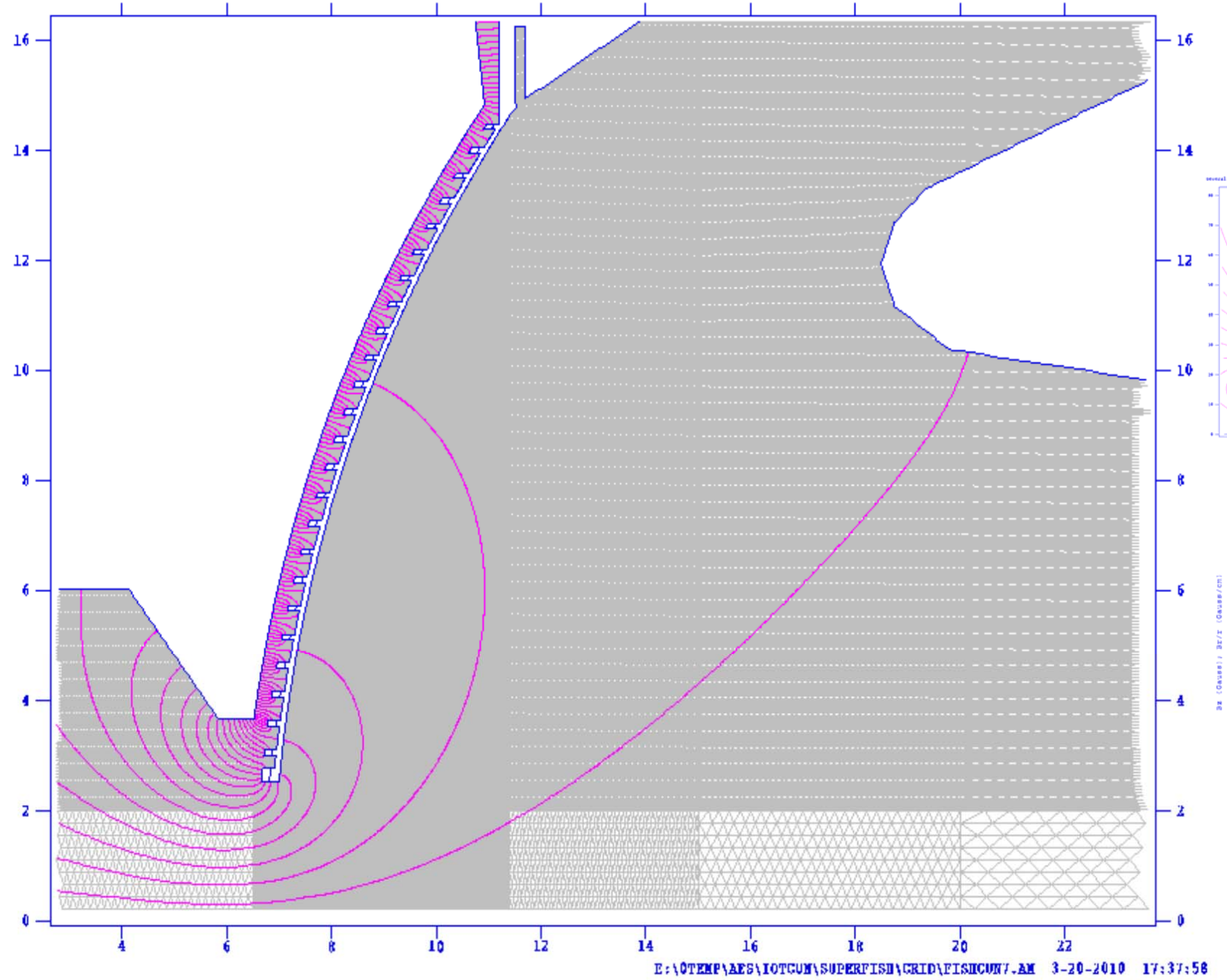


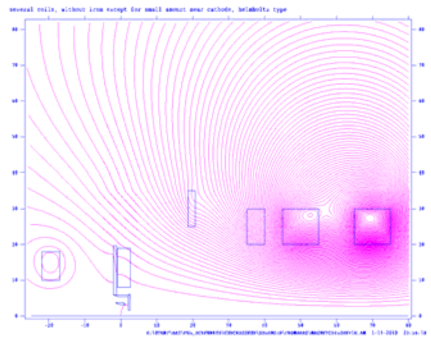


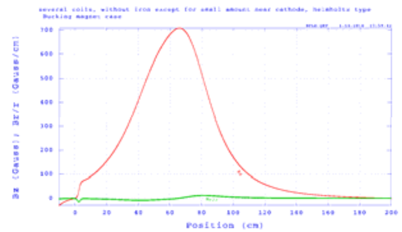
FHI Accelerator Front End



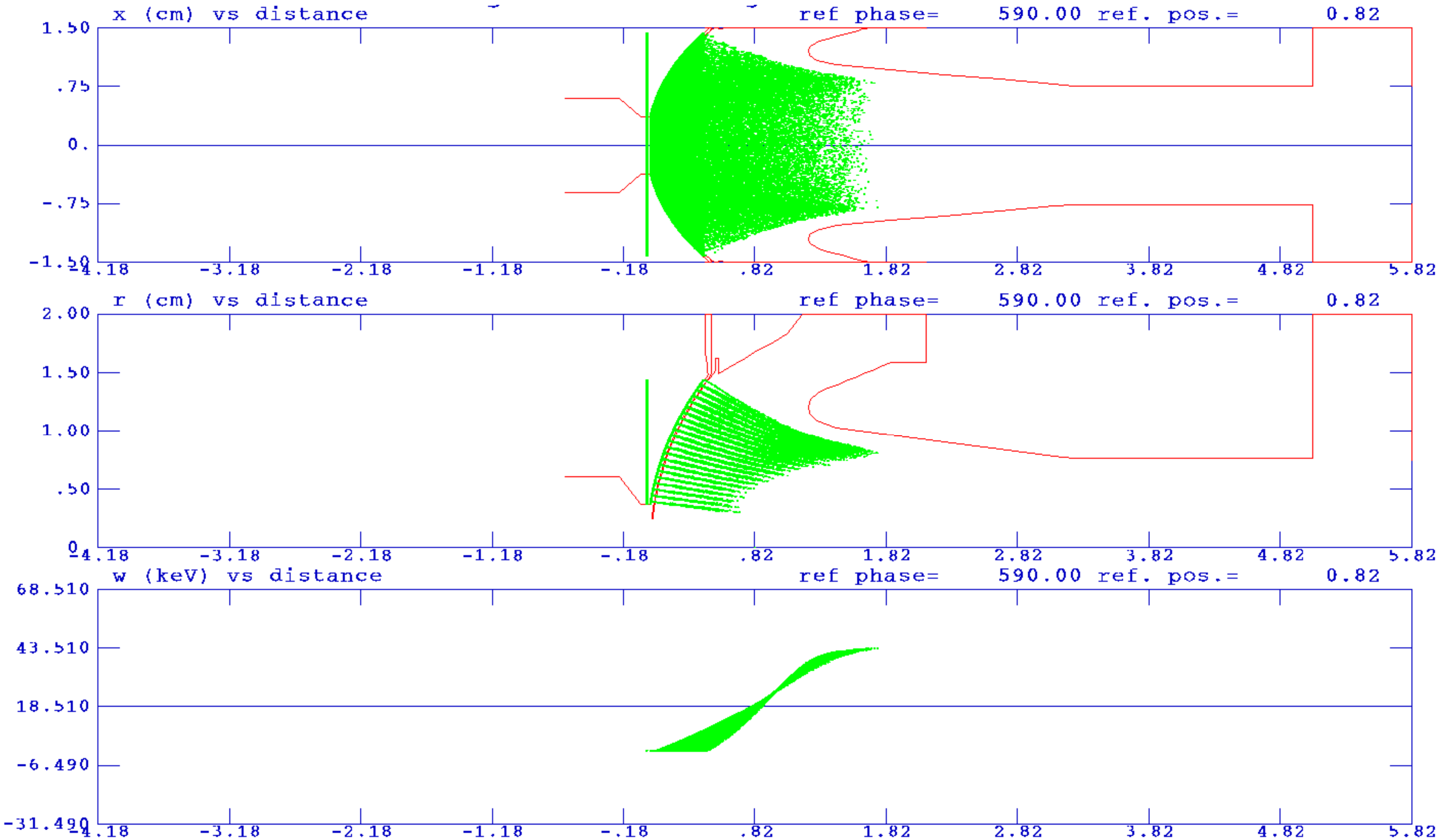
Gun Simulation Geometry



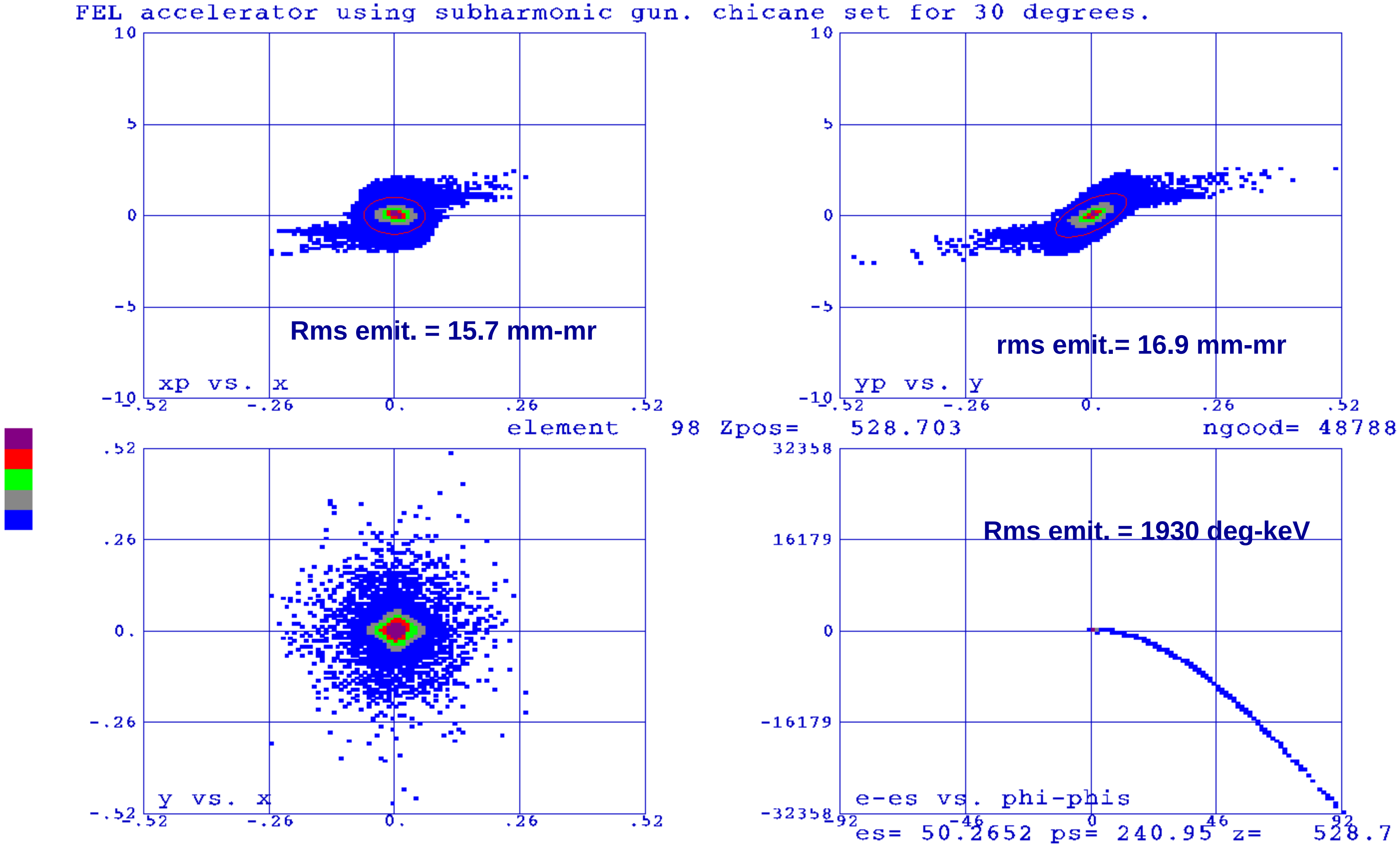




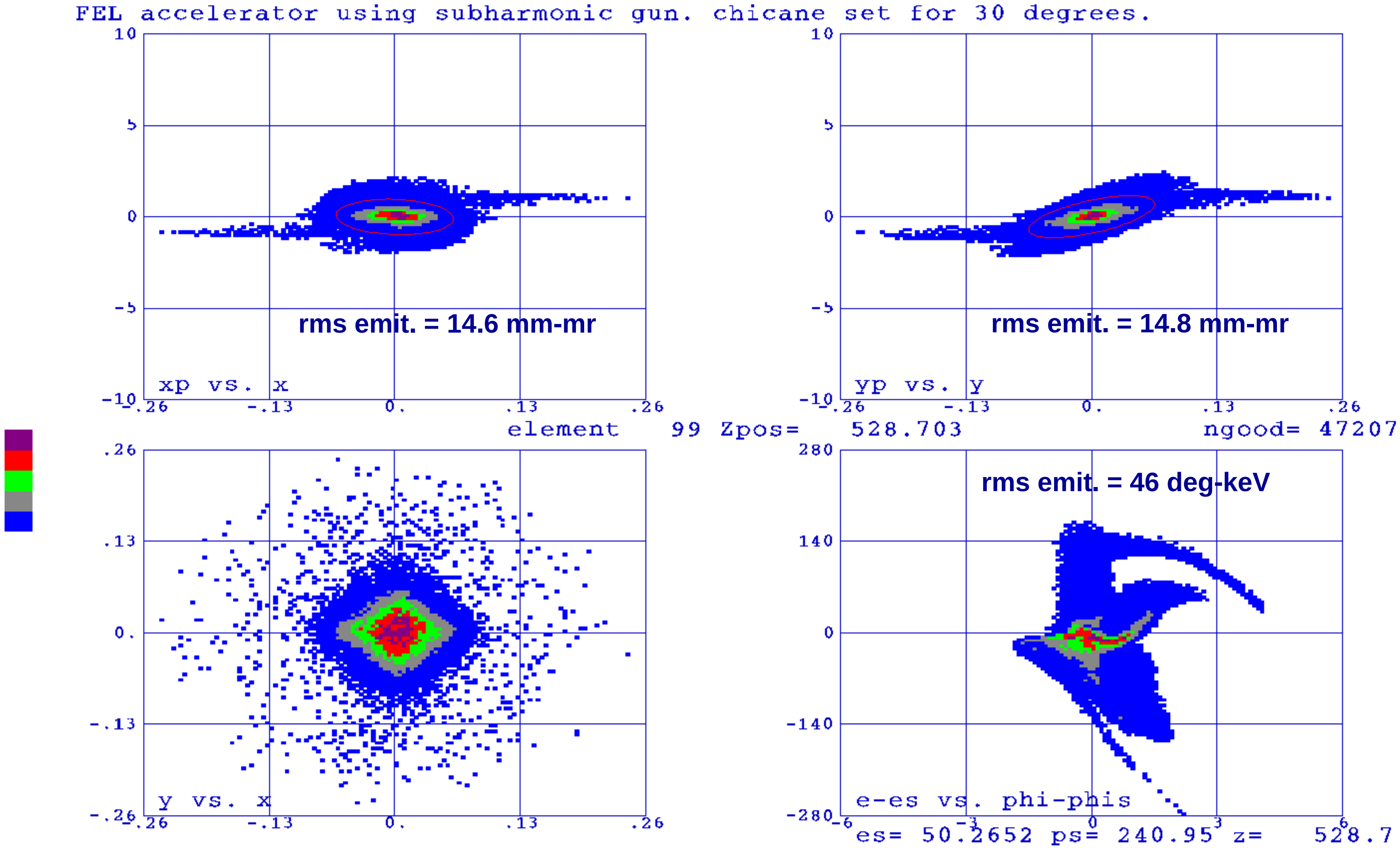
Bunch Formation Modeling



Beam Phase Space at End of Linac 2



Beam Phase Space with Tail Chopped Off (3%)



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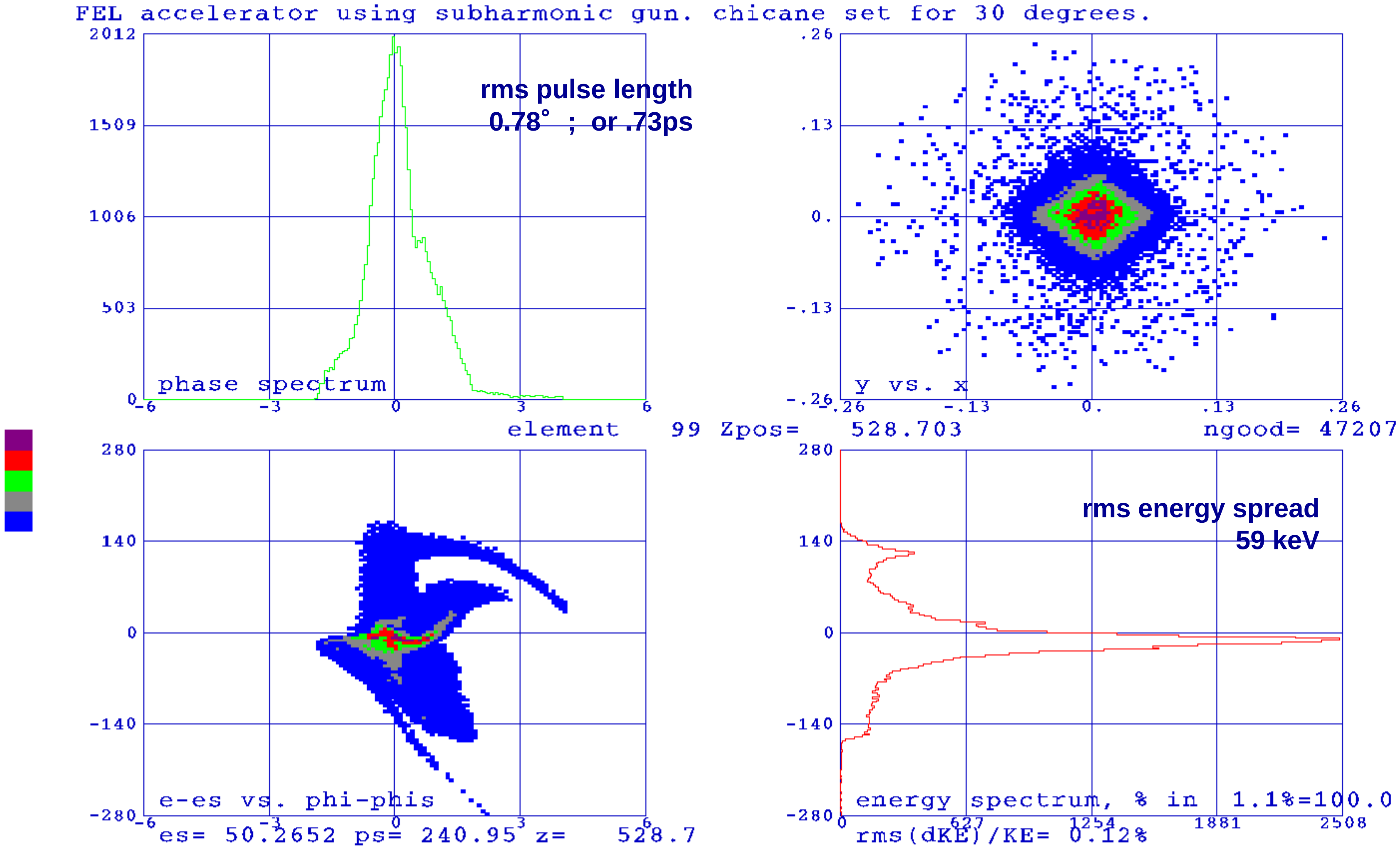
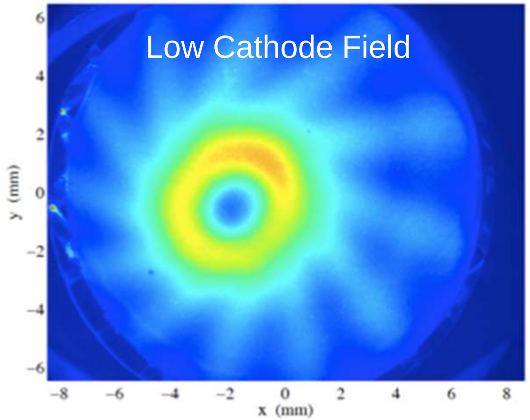
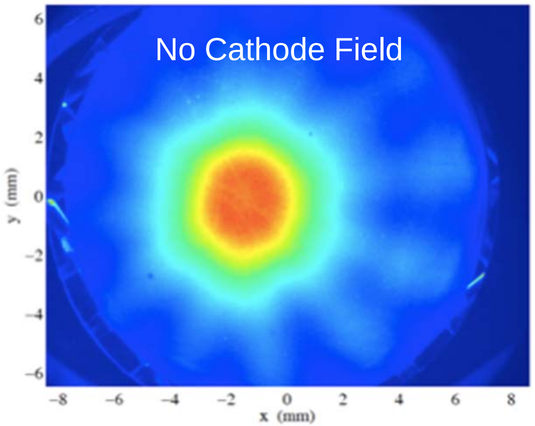
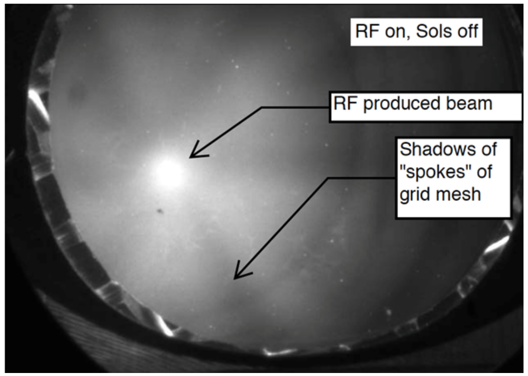
Beam Phase Space with Tail Chopped Off (3%)

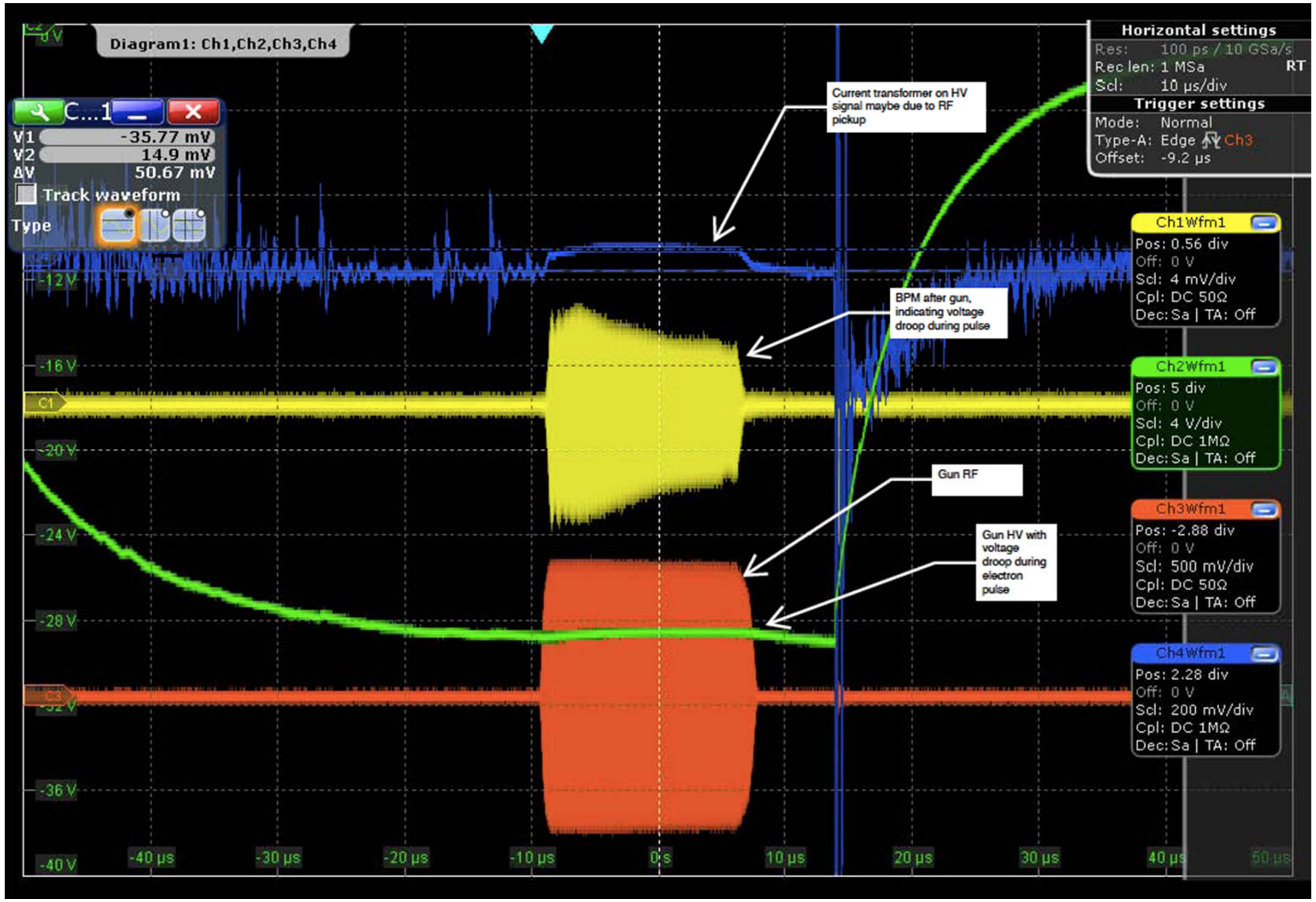


Beam After The Gun

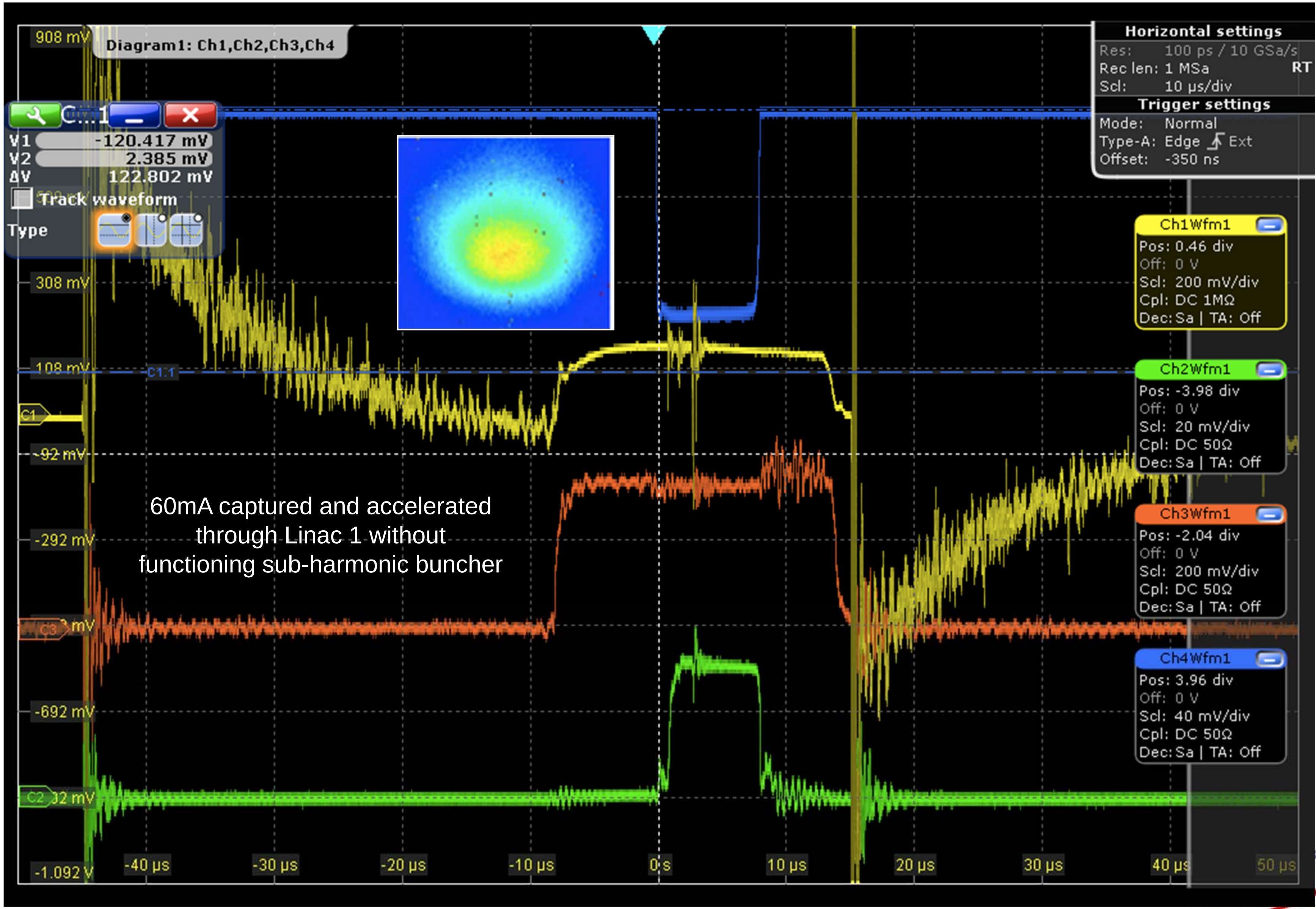




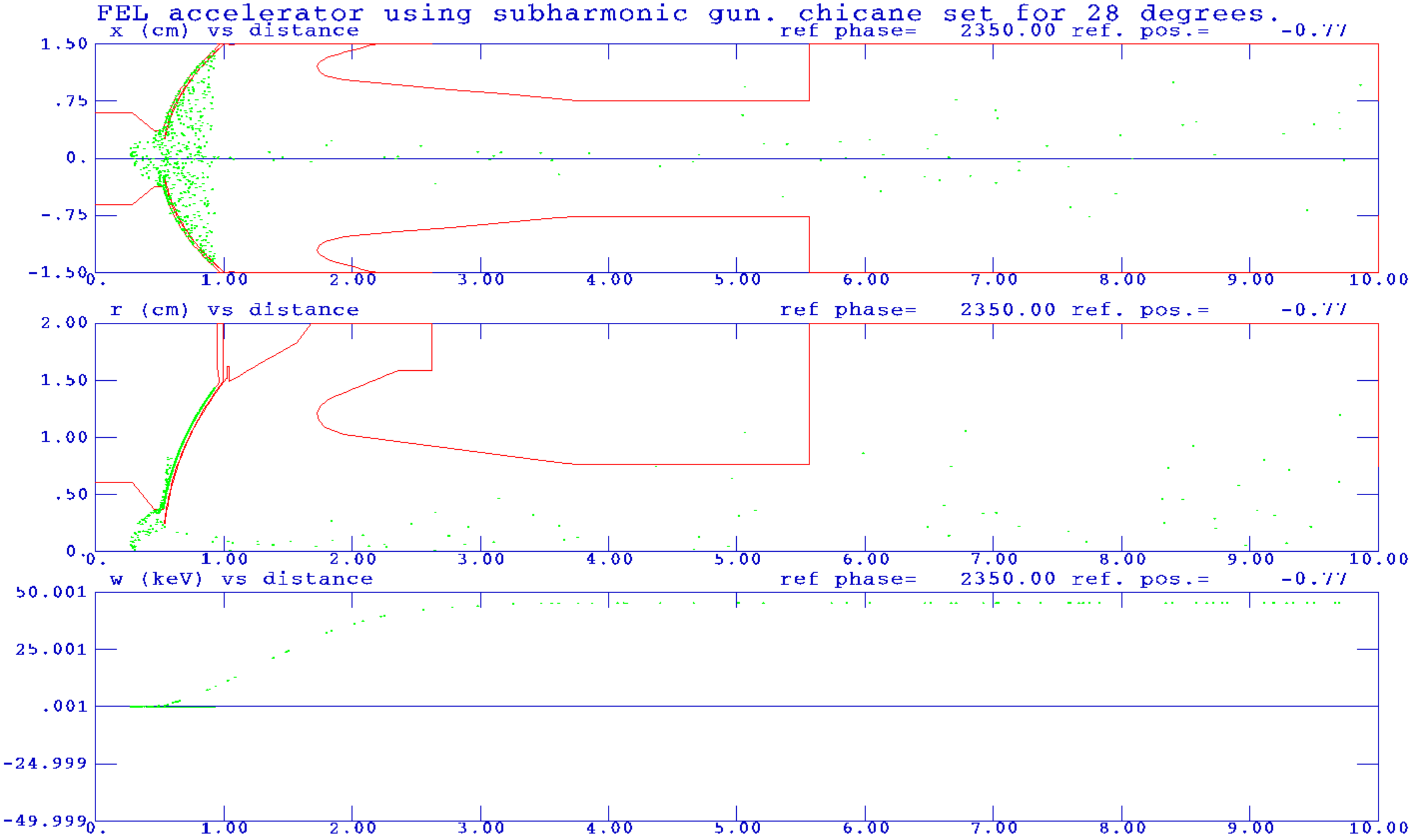




Beam After Linac 1



Idle Current Simulation Showing Axis Leakage



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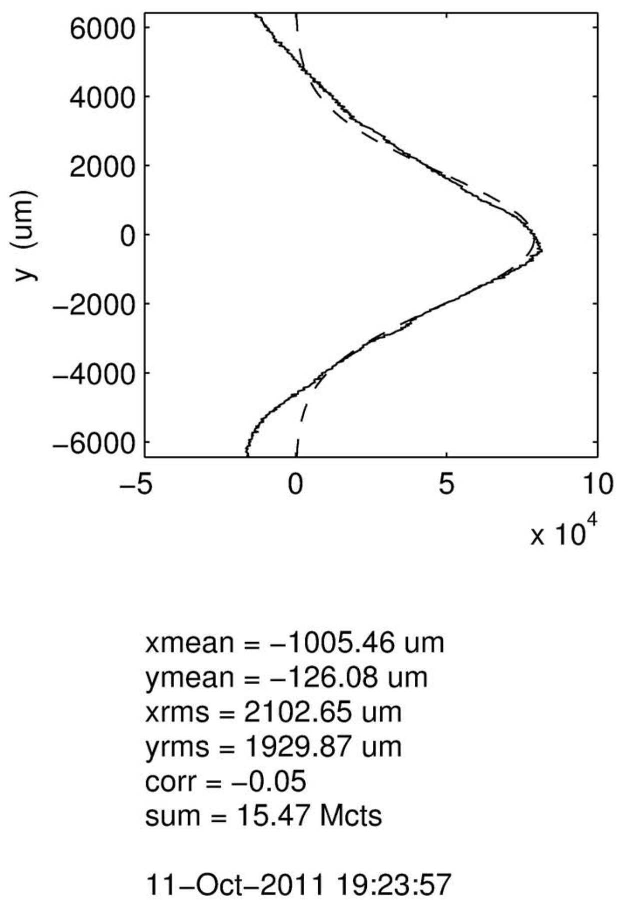
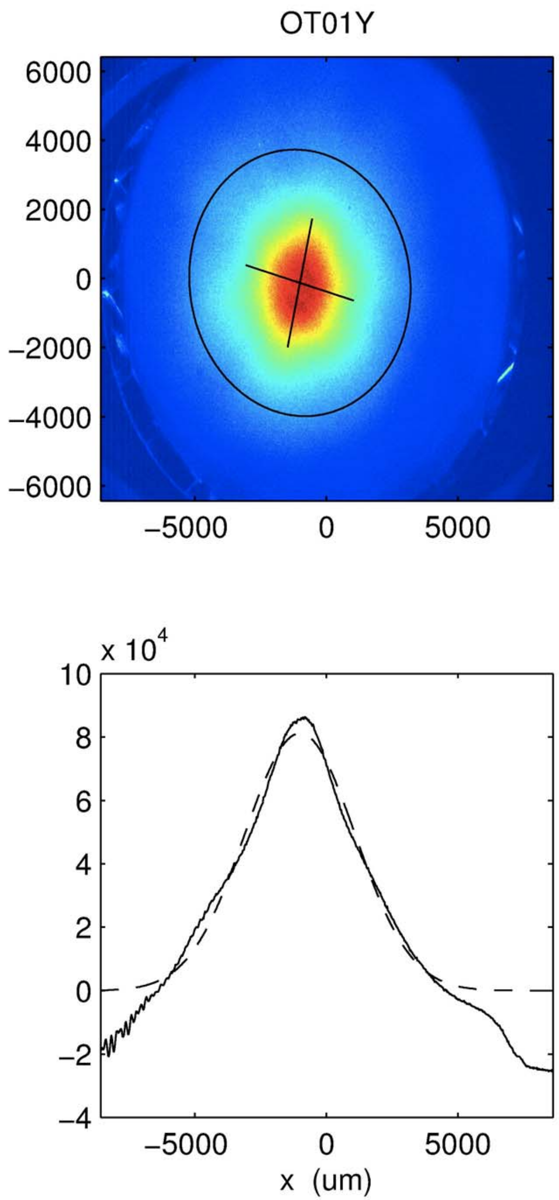
Idle Current Elimination



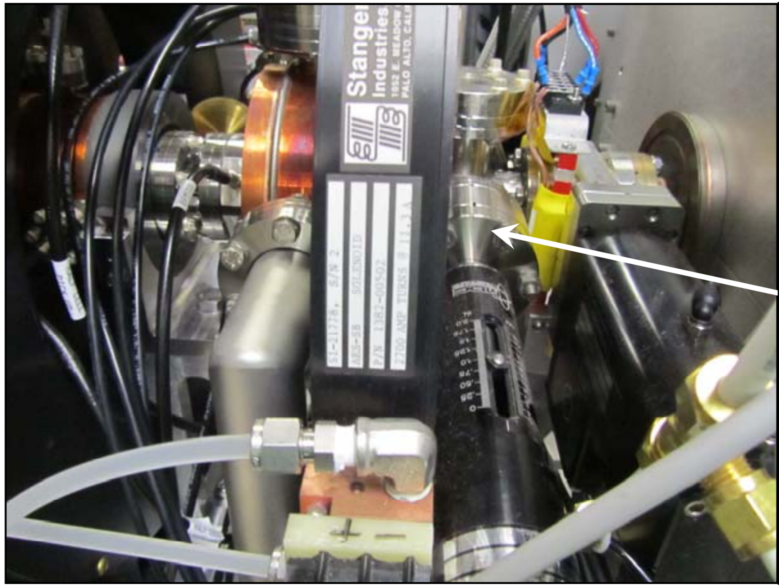


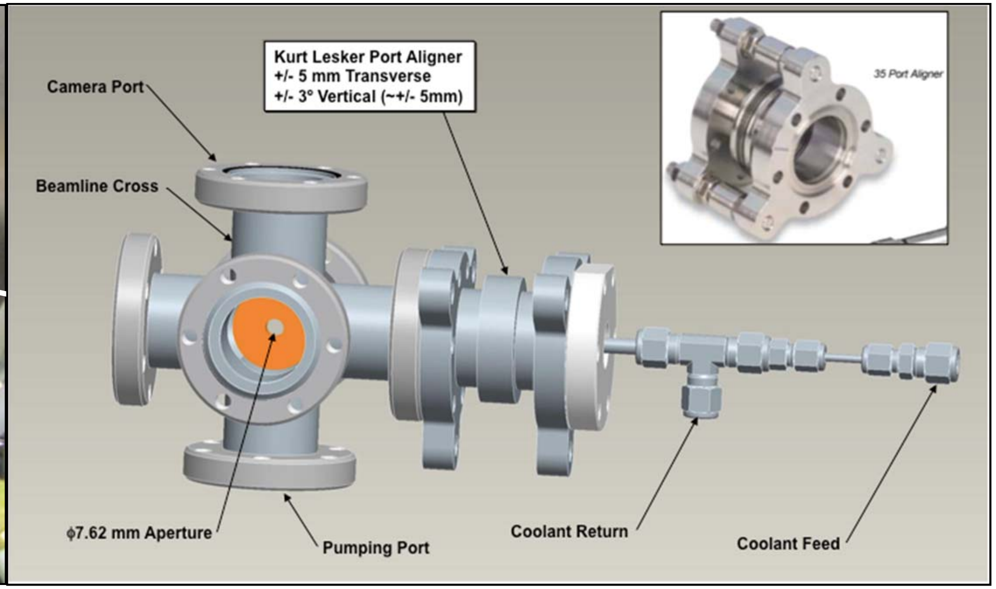
Measured Idle Current at FHI

- In pulsed mode, idle current leaks through cathode "hole" even at maximum -200V grid bias
- Gun is rated for 5A CW so is overkill for our applications => redesign with smaller cathode and smaller cathode "hole"
- If possible, elimination of cathode "hole", as suggested by Sprangle et al., would be highly desirable provided the gun performance is not compromised and ion back bombardment does not cause cathode lifetime issues

Grid or Cathode Pulsing

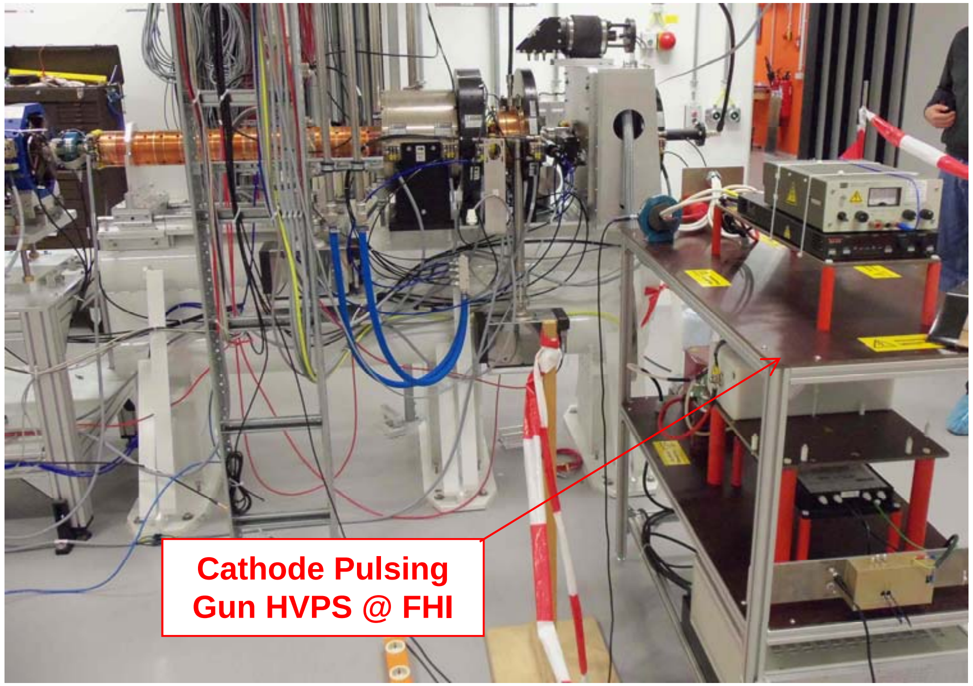
- For pulsed RF systems, grid or cathode pulsing is necessitated by high gun idle current in order to reduce beam spill in front end of accelerator
- First flag has limited usefulness following initial low current beam alignment
- Replacing the first flag with a cooled scraper will intercept a significant portion of the idle current
- Scraper then permits operation with gun grid (low voltage) pulsing rather than cathode HV pulsing (present FHI approach)



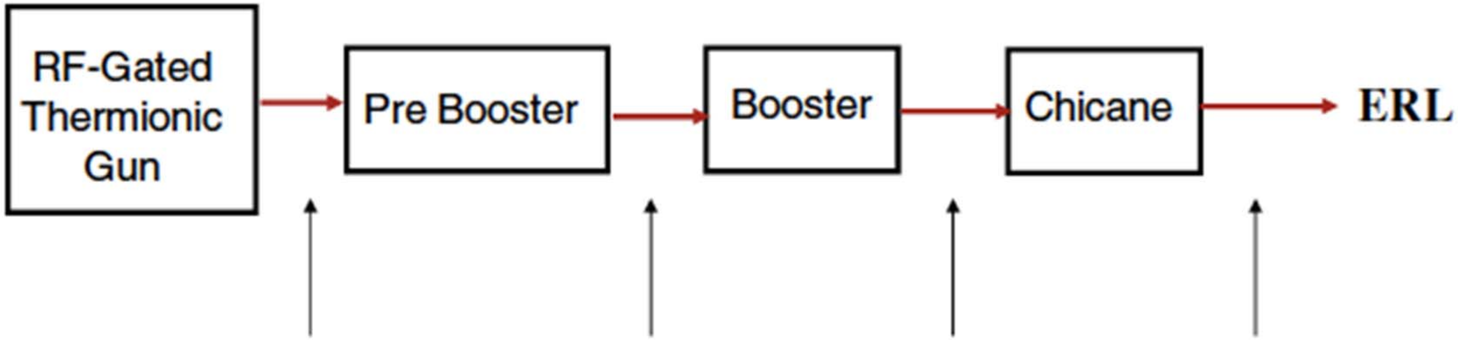


Selection of Grid or Cathode Pulsing

- Grid pulsing =>
  - Simpler lower voltage switching power supply
  - More robust gun system
  - Scraping leads to a higher but manageable accelerator front end vacuum load
  - Higher idle current will be deposited in the Linacs but the calculated level is not predicted to be of concern
- Cathode Pulsing =>
  - Delivers lower average idle current



NRL Injector Concept



$E_b \sim 30-100$ keV
$qN_b \sim 1$ nC , $\langle I_b \rangle \sim 1$A
$\tau_b \sim 40-50$ psec (rms)
$\varepsilon_{n,\perp} \sim 10-15$ mm mrad
$\varepsilon_z \sim 30$ keV psec

$E_b \sim 2$ MeV

$E_b \sim 5-8$ MeV

$\tau_b \sim 5-10$ psec (rms)
$\varepsilon_{n,\perp} \sim 10-15$ mm mrad
$\varepsilon_z \sim 100$ keV psec

- Next step is to design and test a room-temperature pre-booster after the gun
- Preliminary pre-booster scoping study showing adequate performance has been completed
- Booster itself will probably consist of single-cell SRF cavities
- NRL propose eliminating the cathode hole which is highly desirable if possible
- We suggest reducing the cathode area by a factor of 5 => 1A rating
- Idle current per se is not the problem in CW mode but beam scraping after the anode remains a real issue since there is virtually no space to introduce adequate cooling if emittance is to be preserved

NRL Approach for Improved Performance

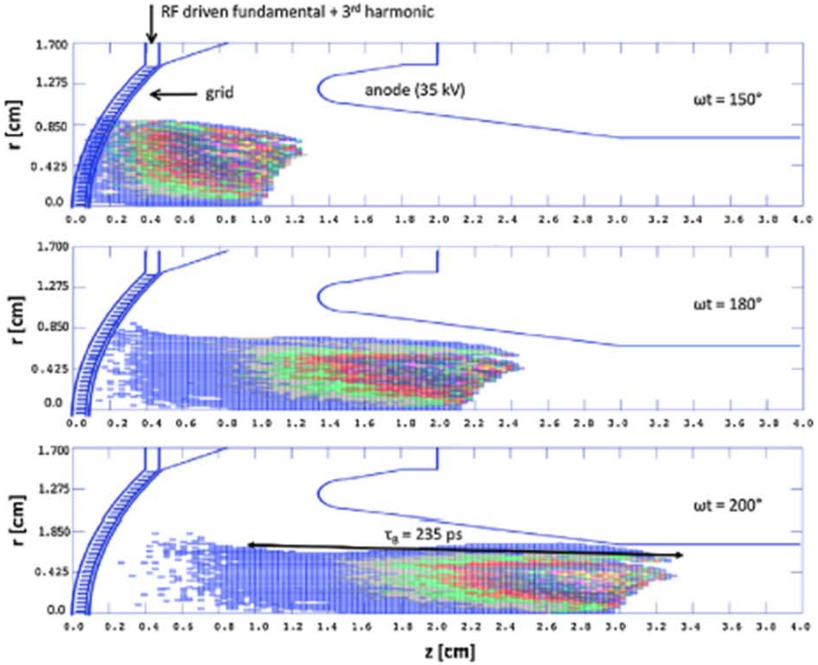


FIG. 20. PARMELA simulation of the rf-gated, gridded thermionic gun illustrated in Fig. 19 (compare Fig. 17). The plots show the generation of a 1 nC electron bunch with end-to-end duration of 235 psec and a normalized emittance of 16 mm mrad. The rf phase ωt is indicated in each figure.

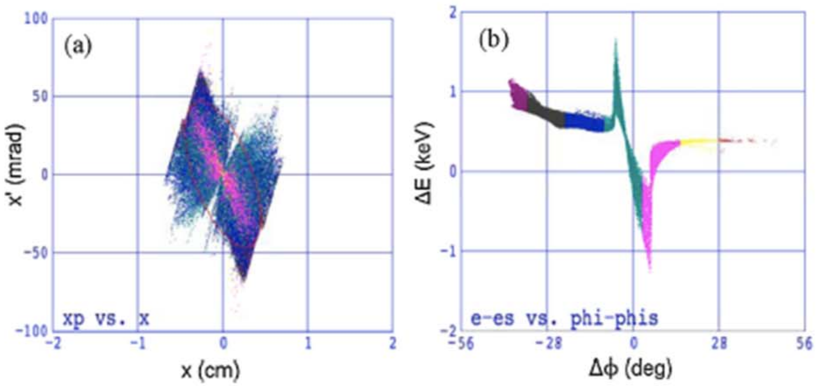


FIG. 21. (a) Transverse and (b) longitudinal phase space from the PARMELA simulation of Fig. 20 at the exit of the gun ($z - 5.0$ cm). The normalized transverse emittance is 16 mm mrad and the longitudinal emittance is 7 keV psec. Particles are grouped by color into six longitudinal slices, with each slice containing particles of a given range in rf phase at $z - 5.0$ cm.

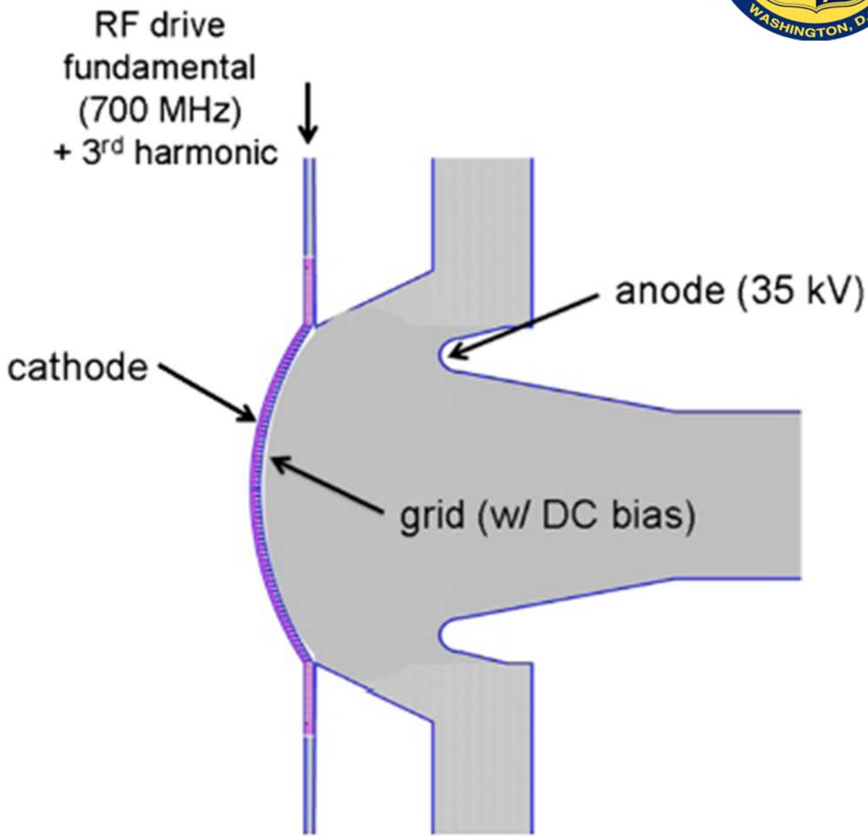


FIG. 19. Geometry of a thermionic IOT gun with a closed cathode (compare Fig. 14), used for the PARMELA simulations of Fig. 20. Field lines of the fundamental (700 MHz) field are shown. In these simulations, the backing plate entirely confines the rf fields to the grid-cathode region. The three-dimensional geometry is symmetric about an axis along the center of the figure.

Summary

- Gridded guns show promise for certain pulsed and CW electron beam applications
- Beam has been delivered to the IR wiggler at the Fritz Haber Institute der Max Planck Gesellschaft in advance of the October 28 Centennial
- Gun testing indicates adequate Ampere-level thermionic gun beam quality is possible for IR FELs in CW operation but beam scraping must be addressed
- The next step for CW applications, which is already in process, is the design and testing of a gun with a normal-conducting pre-booster and the study of ways to ameliorate beam scraping
- Pulsed beam applications must address the gun idle current problem by utilizing grid or cathode pulsing - systems are being commissioned at this time using both approaches
- Both CW and pulsed applications would benefit from a redesigned gun with a smaller cathode and a reduced or eliminated cathode “hole”