State-of-the-Art of Electron Guns and Injector Designs

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Advanced Energy Systems, Inc.

Scientific Research
Homeland Security
Medical Imaging
Drug Discovery
Defense

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Putting Accelerator Technology to Work

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BINP Recuperator Material: Nikolay Vinokurov

JAERI FEL Material: Eisuke Minehara et al.

"LUX" Gun Material: Robert Rimmer

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Outline

- **ERL Injector Requirements**
- **Active Injector Programs**

  (With Exceptions: Photocathode Injectors > 100 mA)

  - ***DC Guns***
    - JLAB IR FEL Injector (10 mA)
    - 4GLS ERLP Injector (6.5 mA)
    - Cornell ERL Prototype Injector
    - AES/JLAB 100 mA FEL Injector
    - BINP FEL Injector (Thermionic)
    - JAERI FEL Injector (Thermionic - 40 mA)
  - ***Normal-Conducting Guns***
    - Boeing RF Gun (32 mA and Retired but Still the State-of-the-Art)
    - LANL/AES RF Gun
    - “LUX” Gun
  - ***SRF Guns***
    - AES/BNL SRF Gun
  - ***Other Concepts and Issues (Not Explicitly Addressed)***
    - Cathodes and Drive Lasers
    - Doubly Resonant Guns
    - Coaxial Coupling (TU-Eindhoven, FZ-Rossendorf, AES)
- **Conclusions**

Active ERL & Gun Performance Summary

PARAMETER / DEVICE	JLAB ERL FEL	AES/JLAB Injector	Cornell ERLP	Daresbury ERLP	JAERI ERL	BINP ERL FEL	Boeing Injector	LANL/AES Gun	*LUX Gun*	BNL/AES Gun/ERL	4GLS ERL
Gun Type	DC	DC	DC	DC	DC	DC	NCRF	NCRF	*NCRF*	SRF	*SRF (NCRF)*
Injector and ERL											
RF Frequency (MHz)	1497	748.5	1300	1300	499.8	180	433	700	*1300*	703.75	*1300*
PRF (MHz)	74.85	748.5	1300	81.25	10.41 (83.3)	11.2 (90)	27	33.3 (350)	*1300*	351.88	*1300 (0.001)*
Charge/Bunch (nC)	0.133	0.133	0.077	0.080	0.5	1.7	4.75	3.0	*1.0*	1.4	*0.080 (1.0)*
Current (mA)	10	100	100	6.5	5 (40)	20 (150)	32 (132 Peak)	100 (1050)	*1300*	500	*100 (0.001)*
Injector Energy (MeV)	7	7	5 - 15	8.35	2.5	2	5	2.5		2	*10 (150)*
Transverse RMS Normalized Emittance (	< 7 (7)	1.2	< 1.0	1.5	30	32 (15)	~ 7	6		5.5	*0.5*
Longitudinal RMS Emittance (keV-psec)	17 (80)	44	21	13.3				145		42	
RMS Bunch Length (psec)	3.2 (0.35)	6.3	2.0	4.0		50				7.2	
RMS Energy Spread (%)	0.1 (0.13)	0.5	0.12	0.24		< 1	~ 3	0.5		3.1	
ERLP Energy (MeV)	160	N/A	? 100 ?	35	17	12.8 (14)	N/A	N/A	*N/A*	20	
ERL Energy Goal (MeV)	200	N/A	5000	35		40	N/A	N/A	*N/A*	40	*600 (1000)*
Electron Gun											
DC Gun Voltage (kV)	350	500	500 - 750	350	230	300	N/A	N/A	*N/A*	N/A	*N/A*
Gun Accelerating Field (MV/m)	4	7	8	4		1		7 / 7 / 5	*20 / 13 / 13*	20	*25 (TBD)*
Cathode Material	GaAs	GaAs	GaAs	GaAs	Thermionic	Thermionic	CsKSb	Multi-Alkali	*TBD*	Diamond/Alkali	Diamond/Alkali
Drive Laser FWHM Pulse Length (psec)	44	44	30	20	N/A	N/A	53	16		TBD	*10*
Laser Wavelength (nm)	527	527	527	527	N/A	N/A	527	527		527	*527*
Laser Power at 5% QE (W)	0.5	5	5	0.325	N/A	N/A		5 (53)		0.2 / 25	*5 (~0)*
Booster (DC) / Gun (RF) Parameters											
Type	SRF	SRF	SRF	SRF	SRF	NCRF	N/A	N/A	*N/A*	N/A	*N/A*
Geometry (Cavities x Cells)	2 x 5	4 x 1	5 x 2	2 x 9	2 x 1	3 x 1	1 x 1.5 + 1 x 3	1 x 2.5	*1 x 2.5*	1 x 0.5	*1 x 3.5 (TBD)*
Couplers per Cavity / Type	1 / WG	1/COAX:1/WG	2 / COAX	2 / WG		1 / COAX	2 / WG	2 / WG	*3 / WG*	2 / COAX	*TBD*
Coupler Power (kW)	50	350	50			50 (200)		500		500	*TBD*
Status	**Operational**	Assembly	Fabrication	Fabrication	**Operational**	**Operational**	**Retired**	Fabrication	*Analysis*	Design/Fab	*Analysis*
Comments	Measured Performance at the Wiggler Projected Injector Performance	3rd Harmonic Linearizer Cavity Not Used in Analysis	May go straight to 5 GeV ERL from NSF-Funded Injector Demo	Performance is after the Injector	(Upgrade) Photocathode Under Development	(Upgrade) 1st Cavity Buncher	Results are for 25% Duty Factor	(Higher PRF)	*Performance at CW Rating Not Analyzed*	Diamond Gain=125 ERL will have Solenoid - Analysis has NO Emittance Compensation	*CW (Pulsed) Performance is after the Injector*

KEK ERLP and ERL have parameters similar to the Cornell devices but propose an RF gun

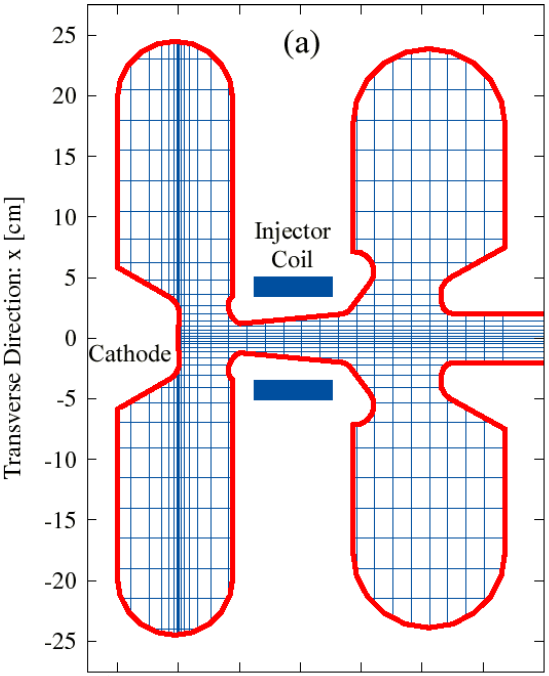
RHIC electron cooling seeks 20 nC bunches at 9.4 MHz for an average current of ~200 mA
=> 1.5 cell gun (1 MW RF) to ~ 5 MeV and no booster

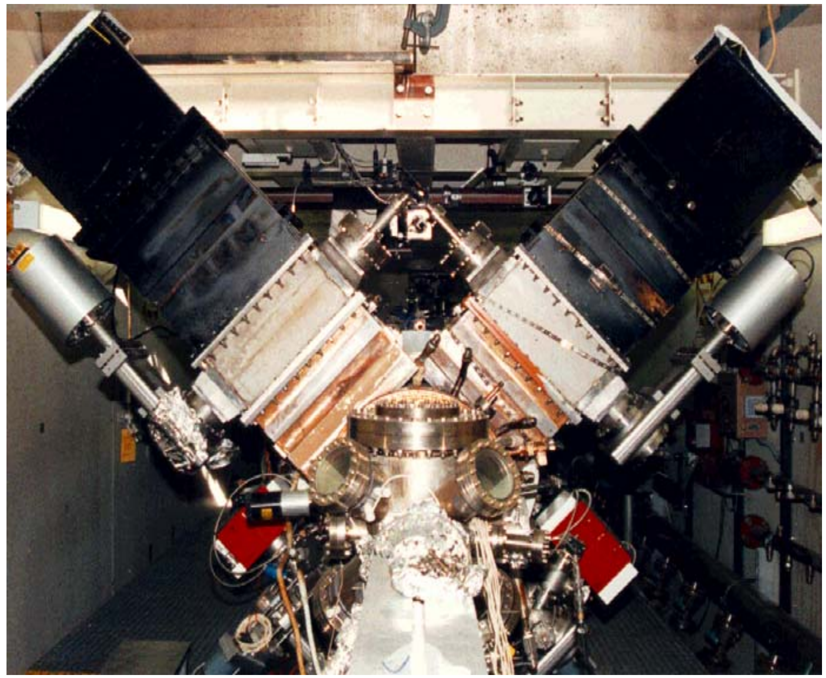
AES/JLAB injector is a suitable driver for a 100 kW IR FEL

High-Current ERL Injector Requirements

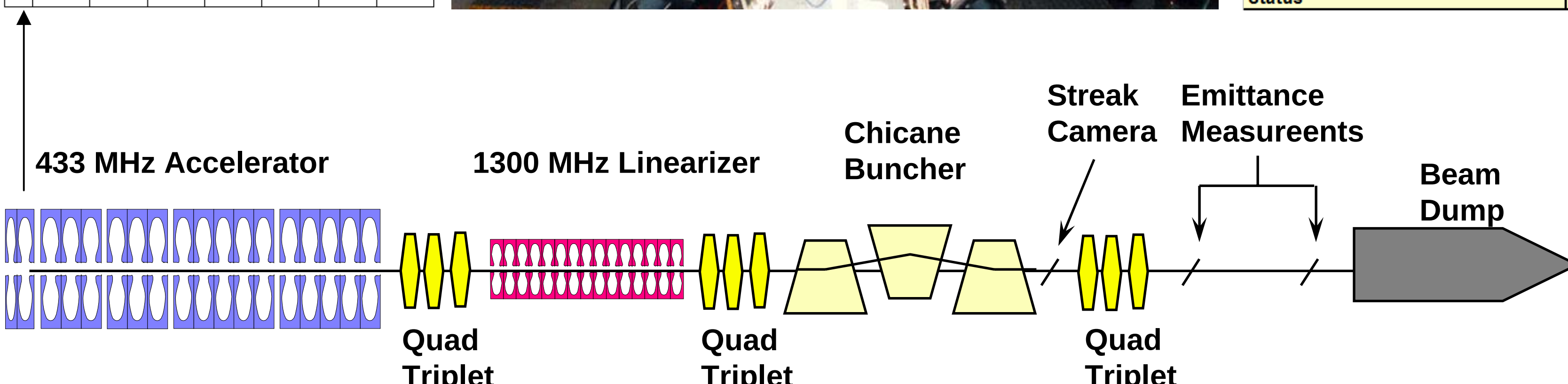
- Output energy ~ 7 MeV (2 – 15)
- CW average current ~ 200 mA (100 – 500)
- Transverse emittance < 6 microns rms normalized (2 – 6)
- Longitudinal emittance < 145 keV-psec rms (25 – 145)
- Bunch length ~ 4 psec (2 – 7)
- Energy spread < 0.5 % (0.1 – 0.5) @ 7 MeV
- RF frequency ~ 700 MHz (500 – 1300)
- 500 kW RF feedthroughs (50 – 500)
- Photocathode with visible response

The Boeing Gun: Still the Demonstrated State-of-the Art



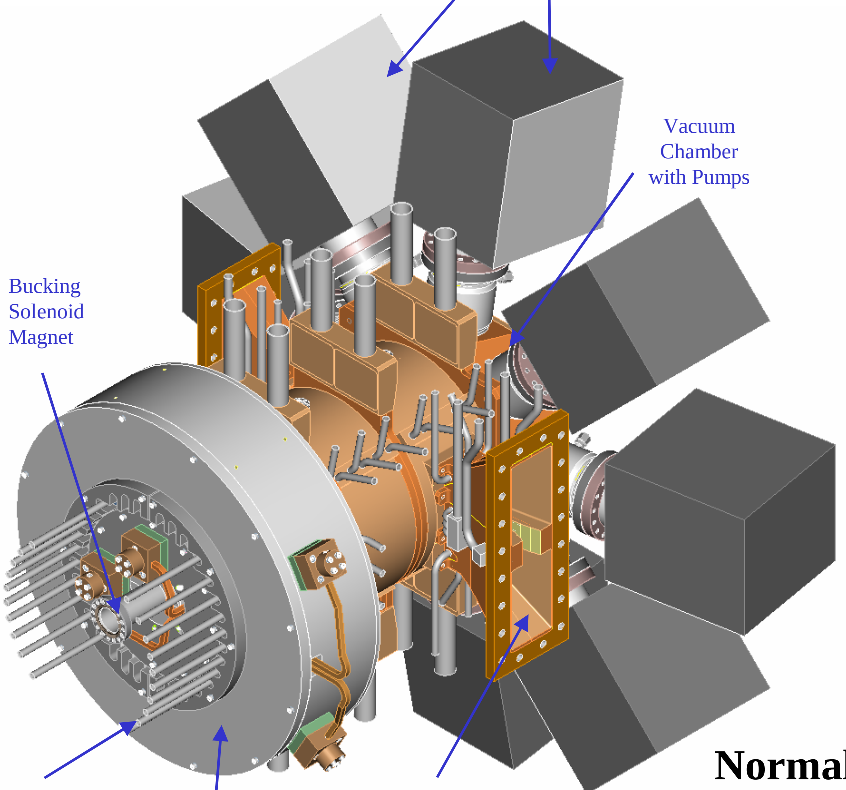


Gun Type	NCRF
Injector and ERL	
RF Frequency (MHz)	433
PRF (MHz)	27
Charge/Bunch (nC)	4.75
Current (mA)	32 (132 Peak)
Injector Energy (MeV)	5
Transverse RMS Normalized Emittance (	~ 7
Longitudinal RMS Emittance (keV-psec)	
RMS Bunch Length (psec)	
RMS Energy Spread (%)	~ 3
ERLP Energy (MeV)	N/A
ERL Energy Goal (MeV)	N/A
Electron Gun	
DC Gun Voltage (kV)	N/A
Gun Accelerating Field (MV/m)	
Cathode Material	CsKSb
Drive Laser FWHM Pulse Length (psec)	53
Laser Wavelength (nm)	527
Laser Power at 5% QE (W)	
Booster Accelerator	
Type	N/A
Geometry (Cavities x Cells)	1 x 1.5 + 1 x 3
Couplers per Cavity / Type	2 / WG
Coupler Power (kW)	
Status	**Retired**



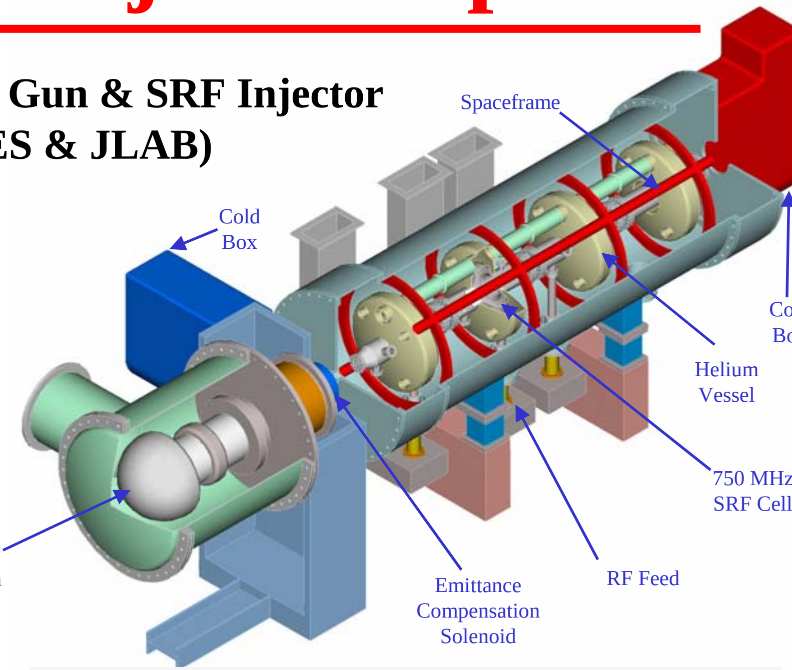
Material Courtesy David Dowell and John Adamski

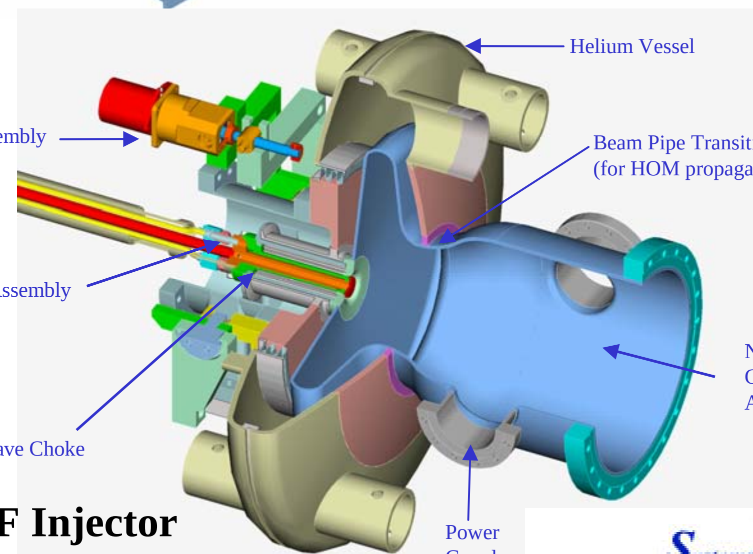
High-Current Electron Injector Options



Normal Conducting Injector (LANL & AES)

DC Gun & SRF Injector (AES & JLAB)





SRF Injector (AES & BNL)

3 Current AES Programs

Advanced Energy Systems, Inc.

Photo-Injector Technology Issues (Personal View)

DC Guns with SRF Boosters

- Maximum achievable gradient & voltage (~ 7 MV/m & ~ 500 kV) wrt. field emission and breakdown
- Maximum achievable bunch charge (~ 1 nC) wrt. performance requirements due to reduced initial accelerating gradient and space charge effects
- Ion backbombardment and GaAs (or other) cathode performance/lifetime
- That said: relatively mature technology that will likely deliver 100+ mA injectors

NC RF Guns

- Maximum achievable gradient (~ 10 MV/m) wrt. thermal stress limits
- Efficiency penalty and cost due to impedance and ohmic losses
- Achievable vacuum conditions & visible cathode selection (multi-alkali?)/performance/lifetime
- That said: uncertain path forward largely because of cathode issues but still the state-of-the-art

SRF Guns

- Maximum achievable gradient (~ 20 MV/m) wrt. peak gun fields
- Viable choke joint design and cathode compatibility with SRF environment and contamination
- Cathode selection (diamond?)/performance/lifetime but excellent vacuum properties
- Least mature but most desirable option delivering RF gun performance with DC gun efficiency

All Technologies

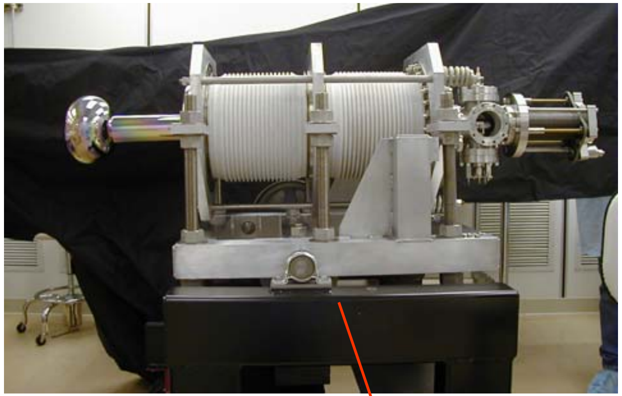
- Dark current limit
- RF power delivery
- HOM, wakefield and BBU issues at high beam power
- CSR in compression sections

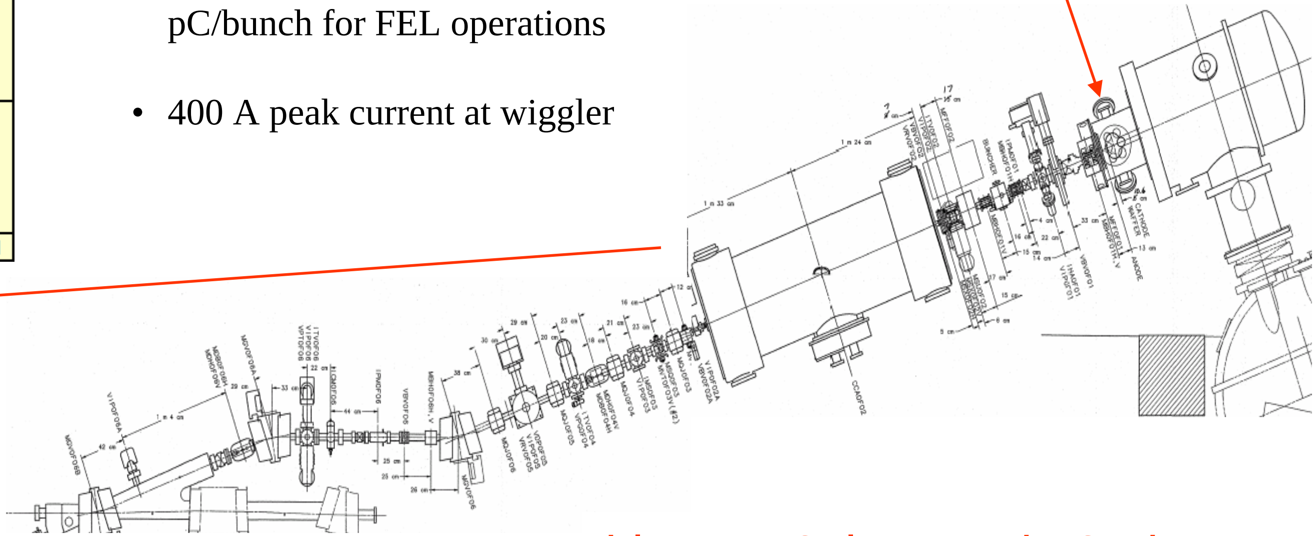
JLab 10 kW Upgrade IR FEL Injector demonstrated performance

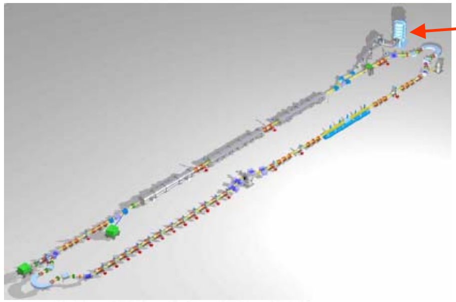
350 kV DC GaAs Photocathode Gun

Gun Type	DC
Injector and ERL	
RF Frequency (MHz)	1497
PRF (MHz)	74.85
Charge/Bunch (nC)	0.133
Current (mA)	10
Injector Energy (MeV)	7
Transverse RMS Normalized Emittance (	< 7 (7)
Longitudinal RMS Emittance (keV-psec)	17 (80)
RMS Bunch Length (psec)	3.2 (0.35)
RMS Energy Spread (%)	0.1 (0.13)
ERLP Energy (MeV)	160
ERL Energy Goal (MeV)	200
Electron Gun	
DC Gun Voltage (kV)	350
Gun Accelerating Field (MV/m)	4
Cathode Material	GaAs
Drive Laser FWHM Pulse Length (psec)	44
Laser Wavelength (nm)	527
Laser Power at 5% QE (W)	0.5
Booster Accelerator	
Type	SRF
Geometry (Cavities x Cells)	2 x 5
Couplers per Cavity / Type	1 / WG
Coupler Power (kW)	50
Status	**Operational**

- Pulsed operation at 8 mA/pulse (110 pC/bunch) in 16 ms-long pulses at 2 Hz repetition rate
- CW operation at 9.1 mA (75 MHz) with 122 pC/bunch
- Routinely delivers 5 mA CW and pulse current at 135 pC/bunch for FEL operations
- 400 A peak current at wiggler





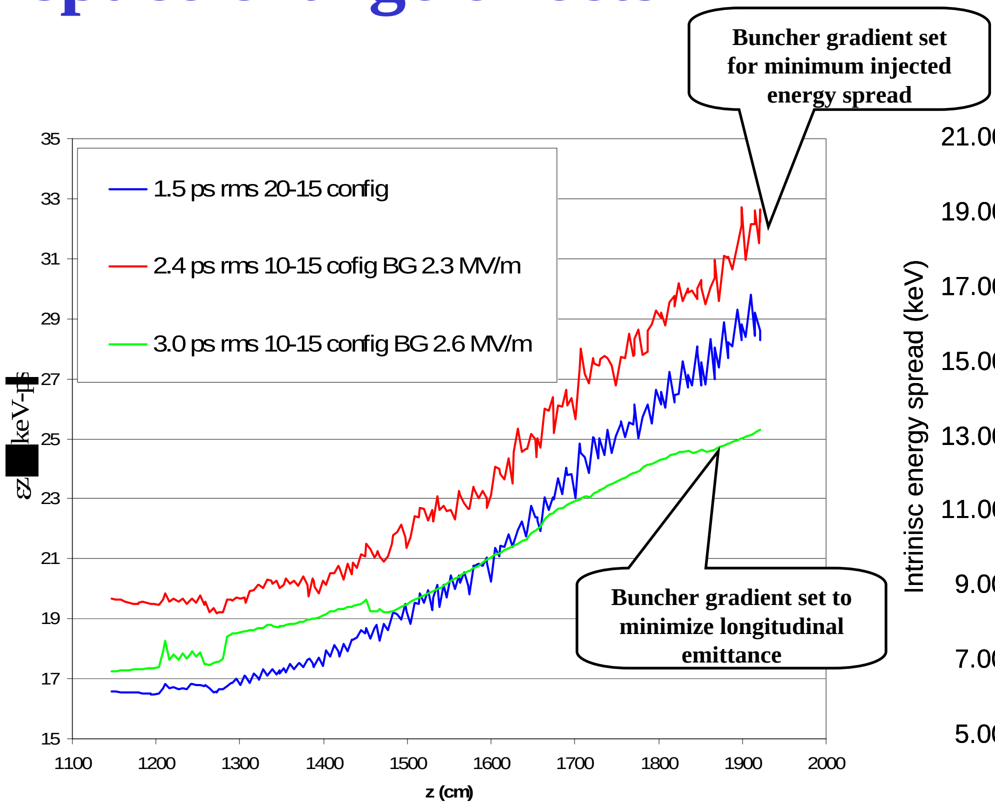


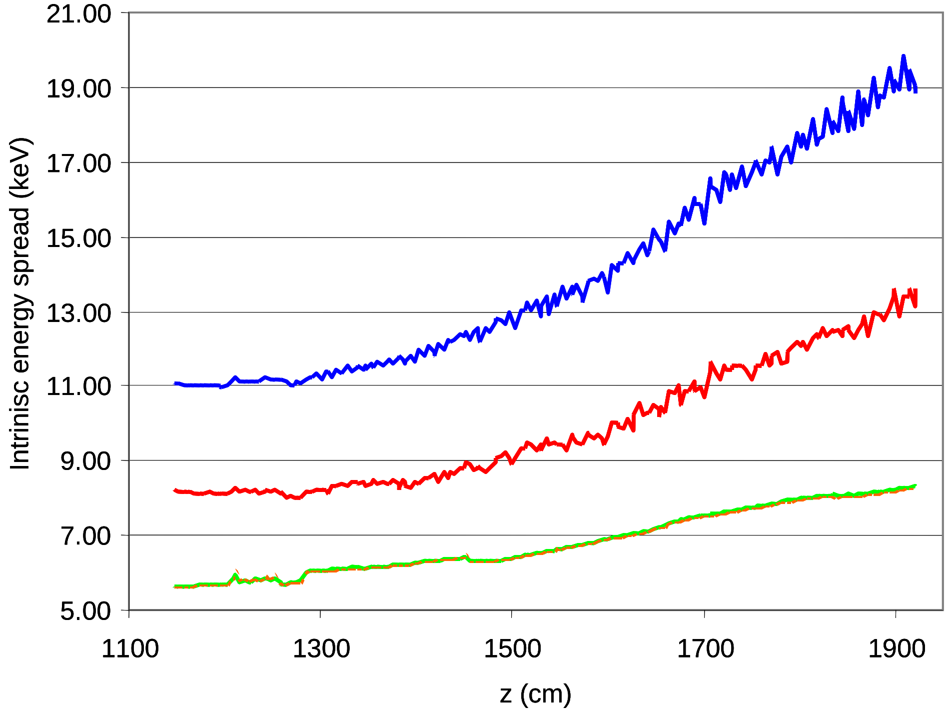
Material courtesy Carlos Hernandez-Garcia

PARMELA-based calculations* through the first cryo-module show that the longitudinal emittance grows independently of energy due to longitudinal space charge effects

Code by K. B. Beard

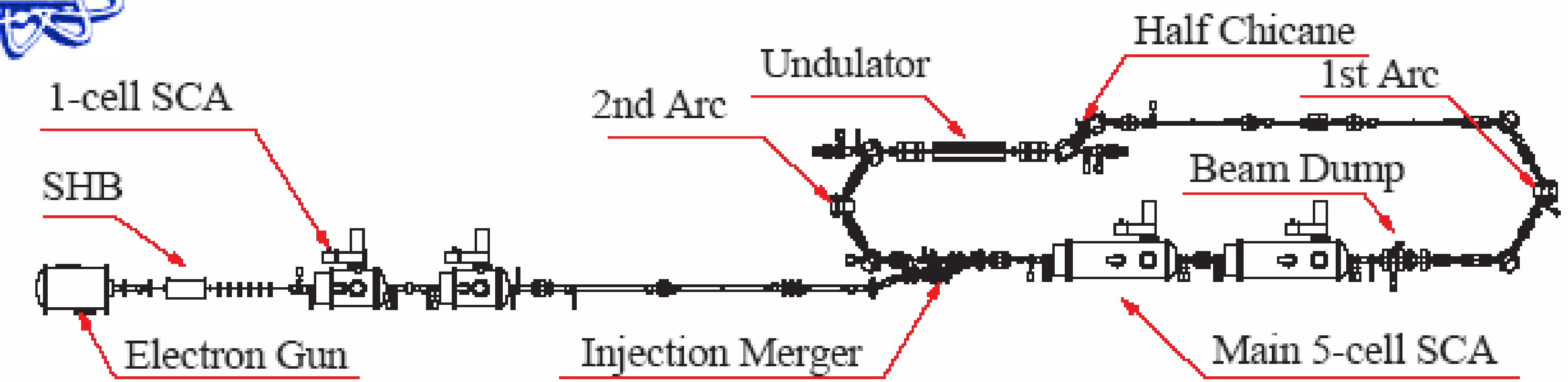
Material courtesy Carlos Hernandez-Garcia



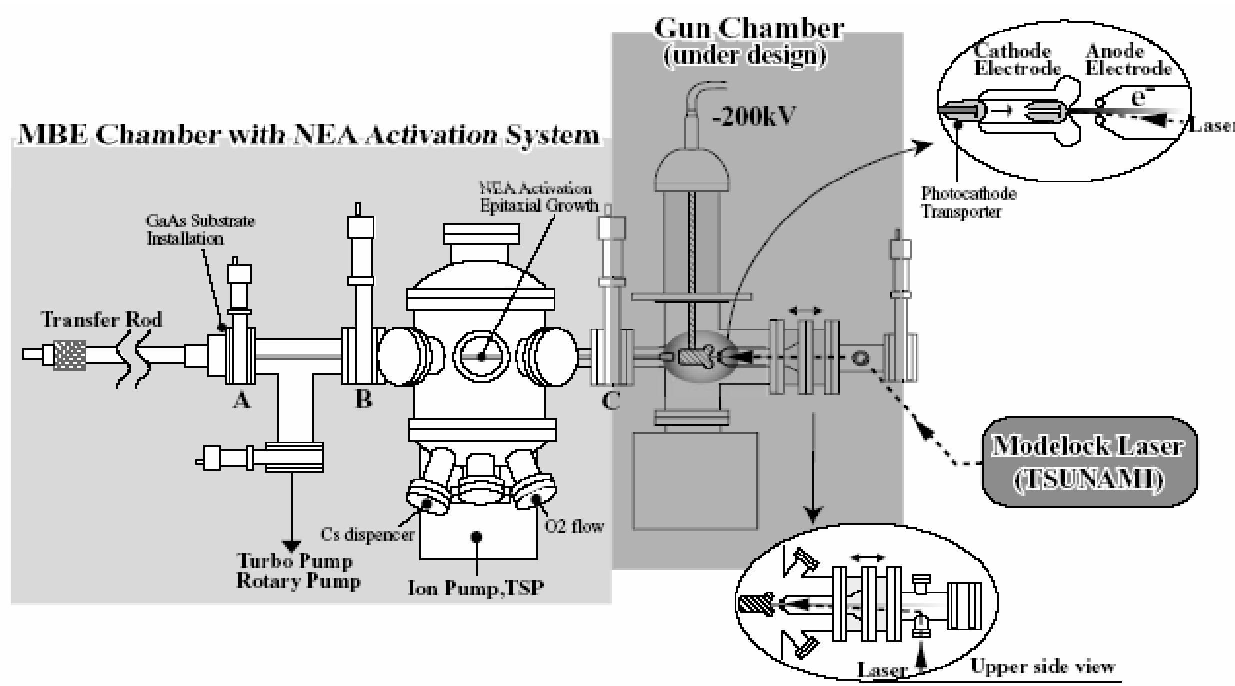


The intrinsic longitudinal emittance keeps increasing with higher energy, but is smaller at the end of the cryo-module for the longest injected bunch

JAERI ERL FEL



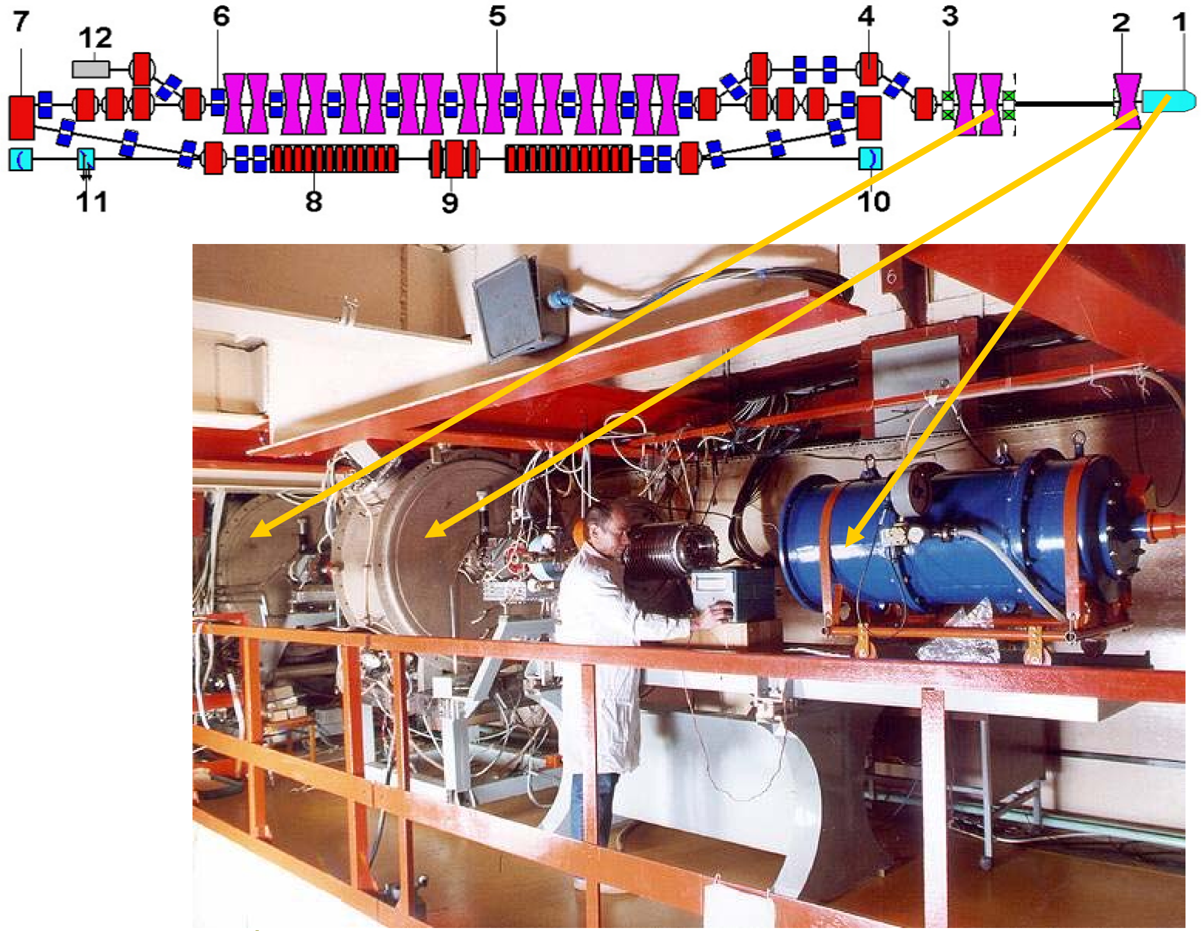
Gun Type	DC
Injector and ERL	
RF Frequency (MHz)	499.8
PRF (MHz)	10.41 (83.3)
Charge/Bunch (nC)	0.5
Current (mA)	5 (40)
Injector Energy (MeV)	2.5
Transverse RMS Normalized Emittance (	30
Longitudinal RMS Emittance (keV-psec)	
RMS Bunch Length (psec)	
RMS Energy Spread (%)	
ERLP Energy (MeV)	17
ERL Energy Goal (MeV)	
Electron Gun	
DC Gun Voltage (kV)	230
Gun Accelerating Field (MV/m)	
Cathode Material	Thermionic
Drive Laser FWHM Pulse Length (psec)	N/A
Laser Wavelength (nm)	N/A
Laser Power at 5% QE (W)	N/A
Booster Accelerator	
Type	SRF
Geometry (Cavities x Cells)	2 x 1
Couplers per Cavity / Type	
Coupler Power (kW)	
Status	**Operational**



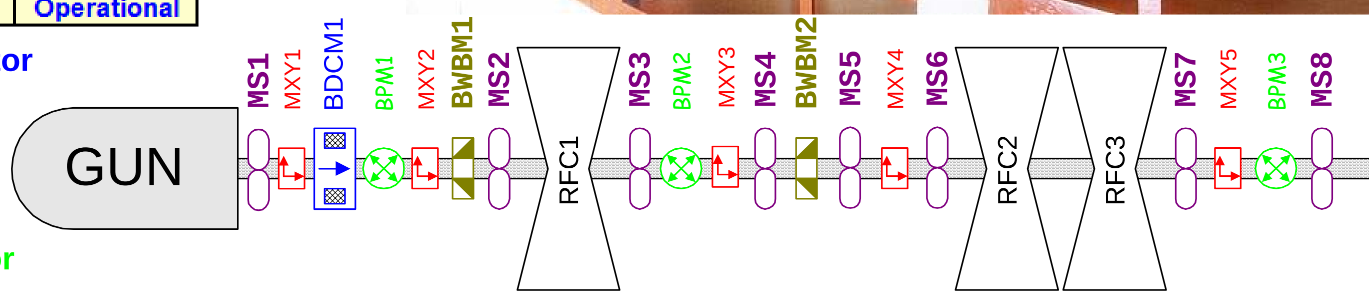
Material Courtesy E. J. Minehara et al.

BINP Recuperator FEL

Gun Type	DC
Injector and ERL	
RF Frequency (MHz)	180
PRF (MHz)	11.2 (90)
Charge/Bunch (nC)	1.7
Current (mA)	20 (150)
Injector Energy (MeV)	2
Transverse RMS Normalized Emittance (	32 (15)
Longitudinal RMS Emittance (keV-psec)	
RMS Bunch Length (psec)	50
RMS Energy Spread (%)	< 1
ERLP Energy (MeV)	12.8 (14)
ERL Energy Goal (MeV)	40
Electron Gun	
DC Gun Voltage (kV)	300
Gun Accelerating Field (MV/m)	1
Cathode Material	Thermionic
Drive Laser FWHM Pulse Length (psec)	N/A
Laser Wavelength (nm)	N/A
Laser Power at 5% QE (W)	N/A
Booster Accelerator	
Type	NCRF
Geometry (Cavities x Cells)	3 x 1
Couplers per Cavity / Type	1 / COAX
Coupler Power (kW)	50 (200)
Status	**Operational**



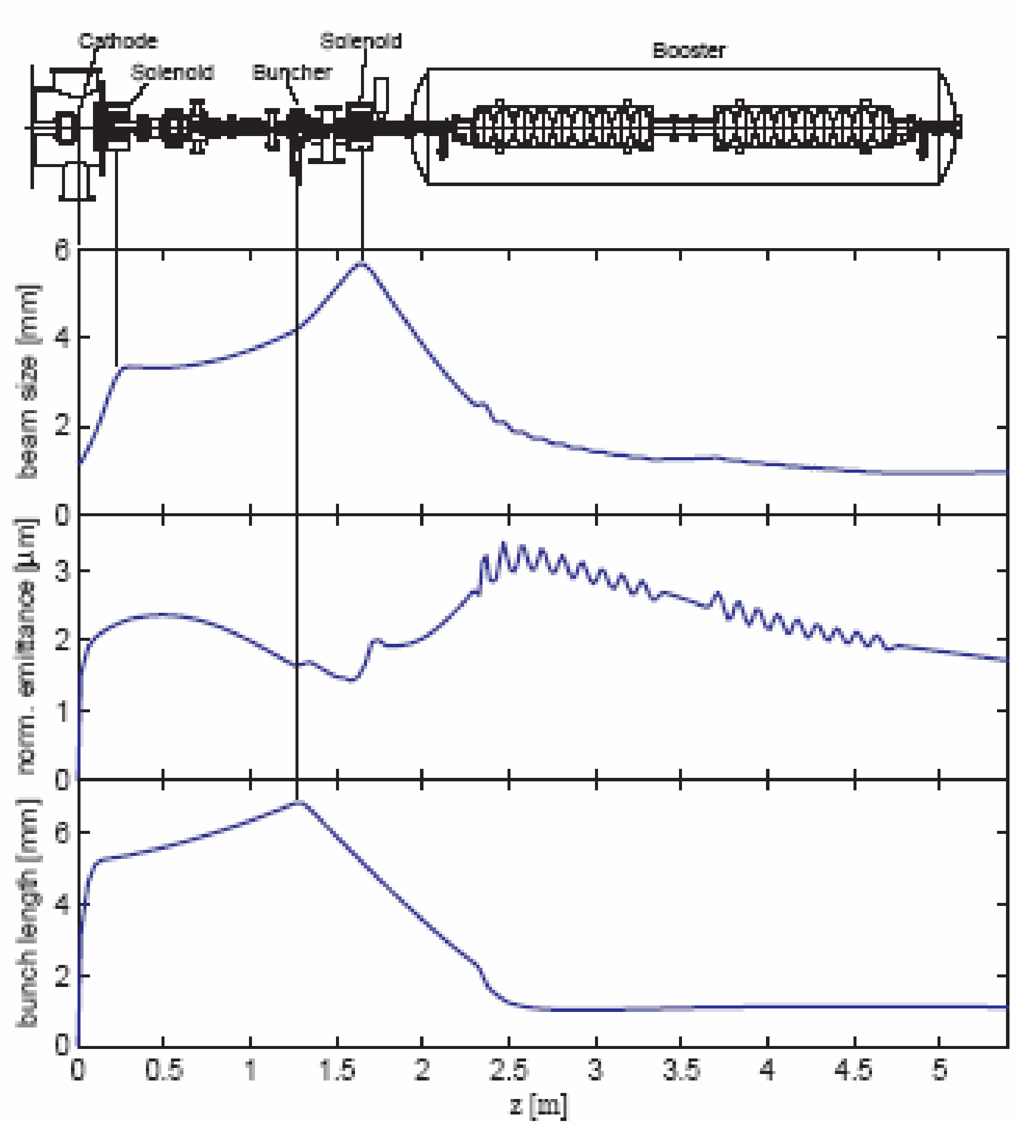
BDCM : beam current monitor
MS : focusing solenoid
MXY : steering magnet
RFC : RF cavity
BWBM : strip line monitor
BPM : bean position monitor

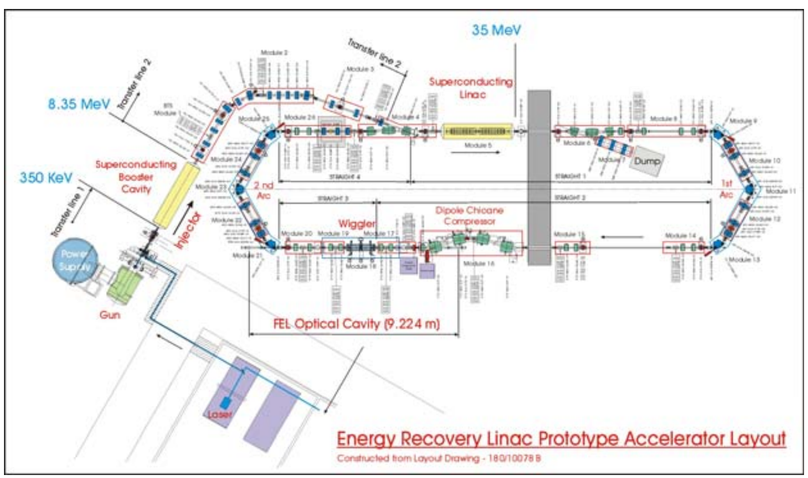


Material Courtesy Nikolai Vinokurov

Daresbury ERLP Injector

Gun Type	DC
Injector and ERL	
RF Frequency (MHz)	1300
PRF (MHz)	81.25
Charge/Bunch (nC)	0.080
Current (mA)	6.5
Injector Energy (MeV)	8.35
Transverse RMS Normalized Emittance (	1.5
Longitudinal RMS Emittance (keV-psec)	13.3
RMS Bunch Length (psec)	4.0
RMS Energy Spread (%)	0.24
ERLP Energy (MeV)	35
ERL Energy Goal (MeV)	35
Electron Gun	
DC Gun Voltage (kV)	350
Gun Accelerating Field (MV/m)	4
Cathode Material	GaAs
Drive Laser FWHM Pulse Length (psec)	20
Laser Wavelength (nm)	527
Laser Power at 5% QE (W)	0.325
Booster Accelerator	
Type	SRF
Geometry (Cavities x Cells)	2 x 9
Couplers per Cavity / Type	2 / WG
Coupler Power (kW)	
Status	Fabrication



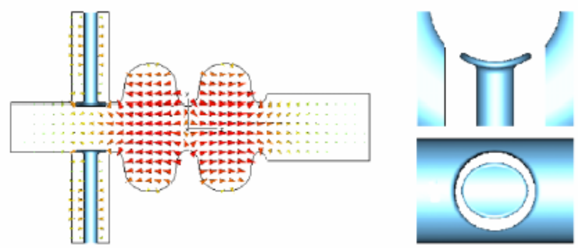


Material Courtesy Elaine Seddon and Michael Dykes

Cornell ERL Prototype Injector

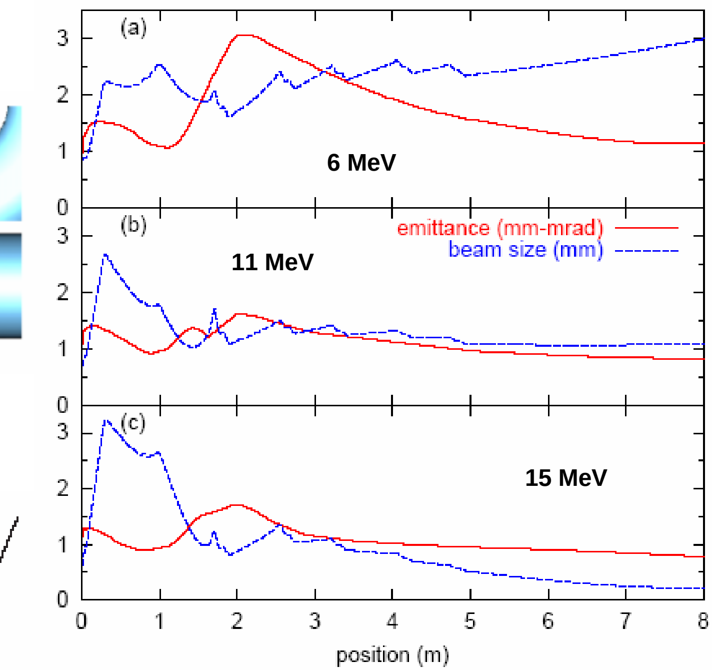
Cornell University

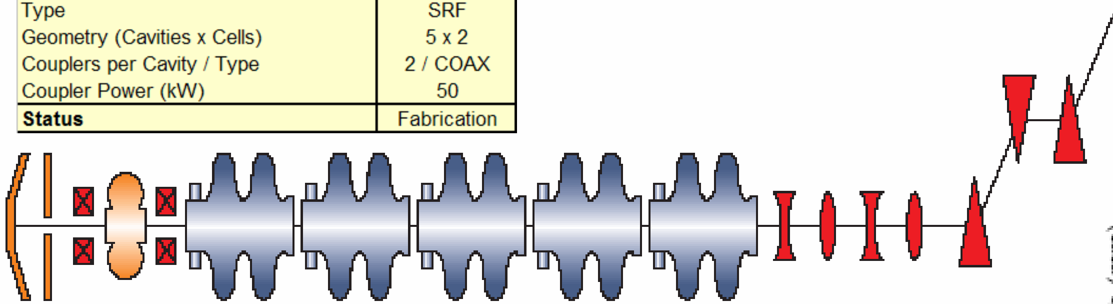
Gun Type	DC
Injector and ERL	
RF Frequency (MHz)	1300
PRF (MHz)	1300
Charge/Bunch (nC)	0.077
Current (mA)	100
Injector Energy (MeV)	5 - 15
Transverse RMS Normalized Emittance (	< 1.0
Longitudinal RMS Emittance (keV-psec)	21
RMS Bunch Length (psec)	59.7
RMS Energy Spread (%)	0.12
ERLP Energy (MeV)	? 100 ?
ERL Energy Goal (MeV)	5000
Electron Gun	
DC Gun Voltage (kV)	500 - 750
Gun Accelerating Field (MV/m)	8
Cathode Material	GaAs
Drive Laser FWHM Pulse Length (psec)	30
Laser Wavelength (nm)	527
Laser Power at 5% QE (W)	5
Booster Accelerator	
Type	SRF
Geometry (Cavities x Cells)	5 x 2
Couplers per Cavity / Type	2 / COAX
Coupler Power (kW)	50
Status	Fabrication



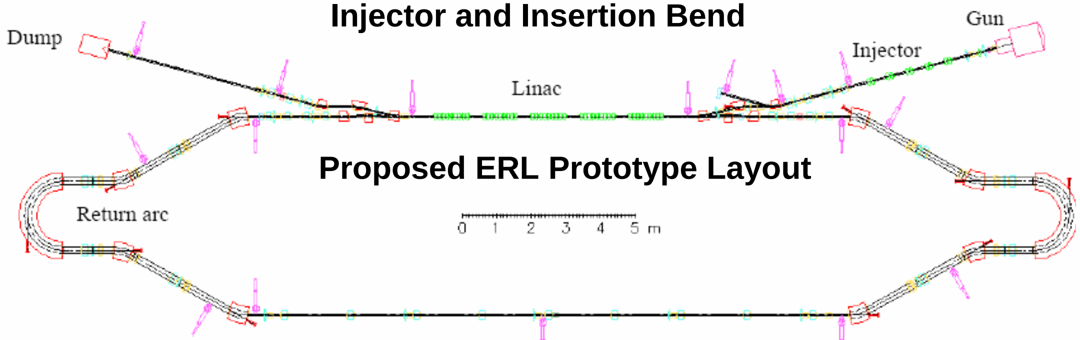
Injector Cavity Geometry and Coupler Detail

Injector Performance

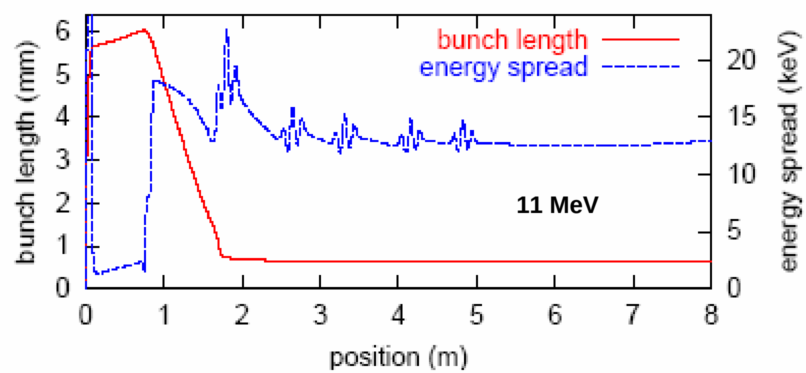




Injector and Insertion Bend



Proposed ERL Prototype Layout

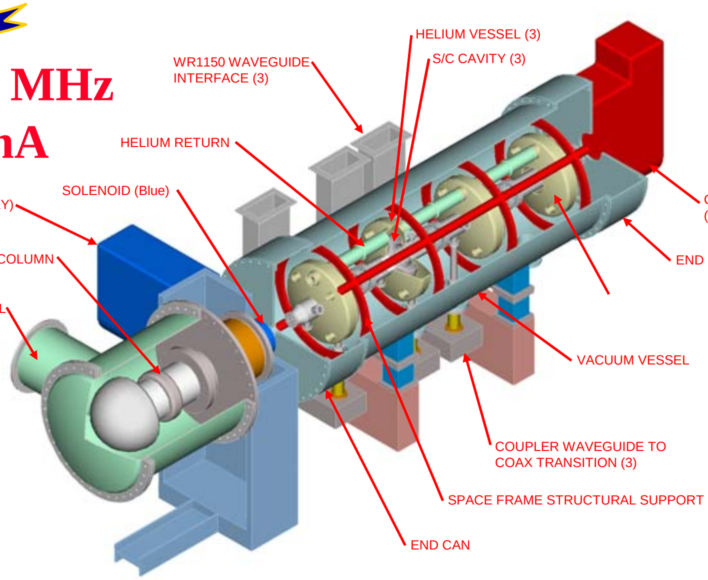


Recent Cornell analysis predicts significantly better injector performance than shown here

Material Courtesy Charles Sinclair et al.

100 mA DC Gun & SRF Injector

748.5 MHz
100 mA



Objectives & Comments

- Design and fabricate a 100 mA-capable SRF Injector for integration with a JLAB DC Gun.
- Test the device at the JLAB ITS
- JLAB Injector Test Stand (ITS) facility mods have begun with beam tests complete ~ 10/08
- RF procurement is schedule driver

Projected Parameters

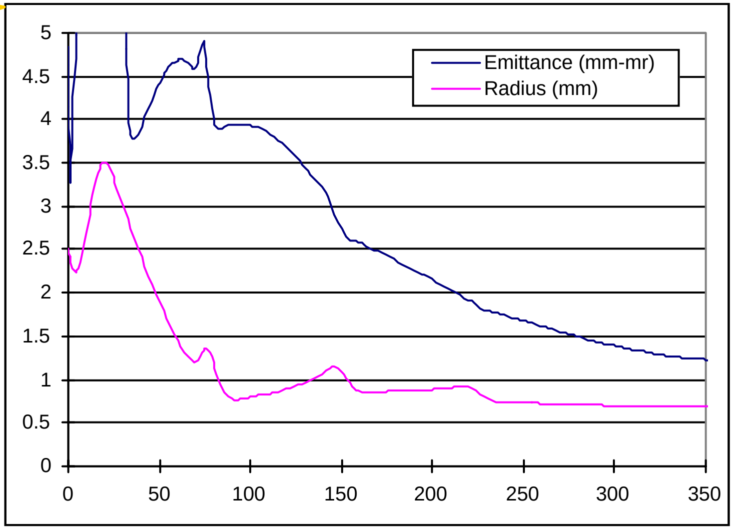
Frequency	748.5	MHz
Energy	7	MeV
Current*	100	mA
Bunch Charge	0.133	nC
Transverse Emittance	1.2	mm-mrad rms normalized
Longitudinal Emittance	44	keV-psec rms
Energy Spread	0.5	%
Bunch Length	6.3	psec rms

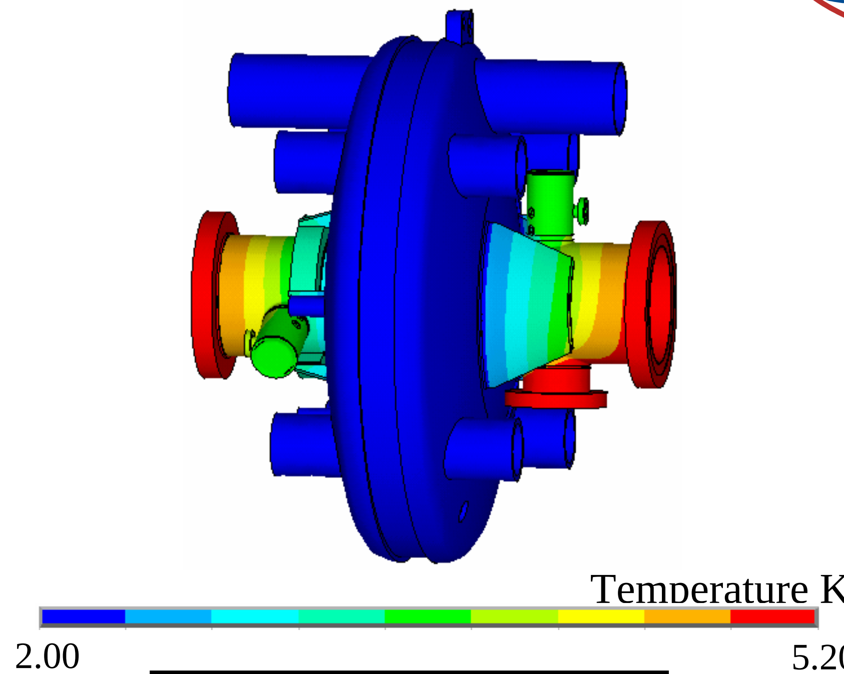
Schedule

- Vacuum vessel, 30 mA RF couplers and four fundamental cavities at JLAB
- Remaining hardware including 100 mA couplers to JLAB by 9/05
- AES will support subsequent assembly & testing

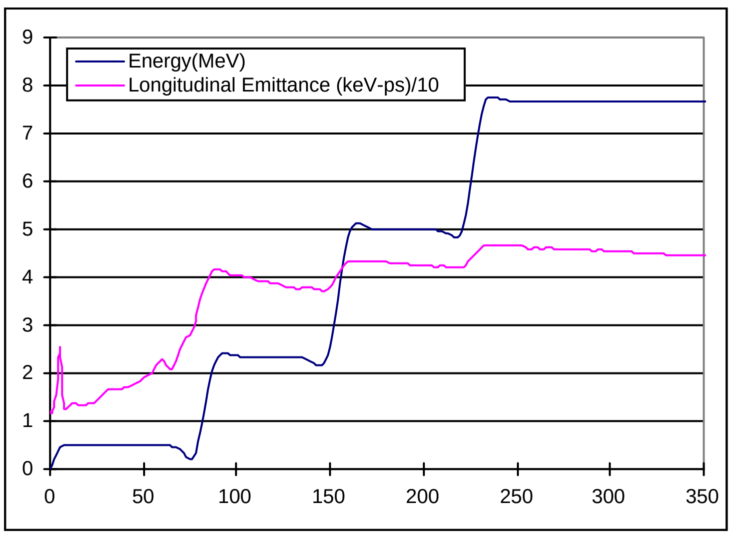
Putting Accelerator Technology to Work

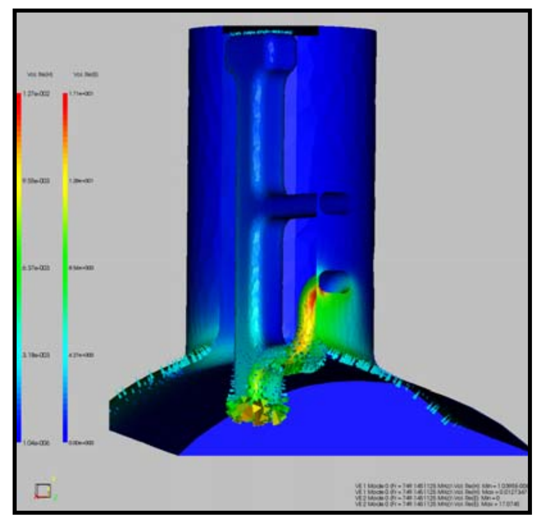
100 mA Injector Analysis





PHYSICS ANALYSIS





EM & THERMAL ANALYSIS

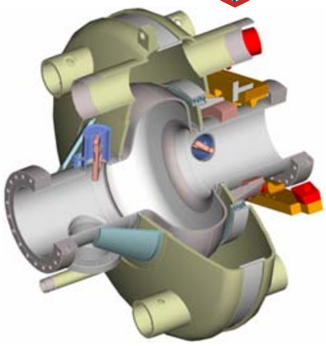
Putting Accelerator Technology to Work

DC Gun & SRF Booster Injector

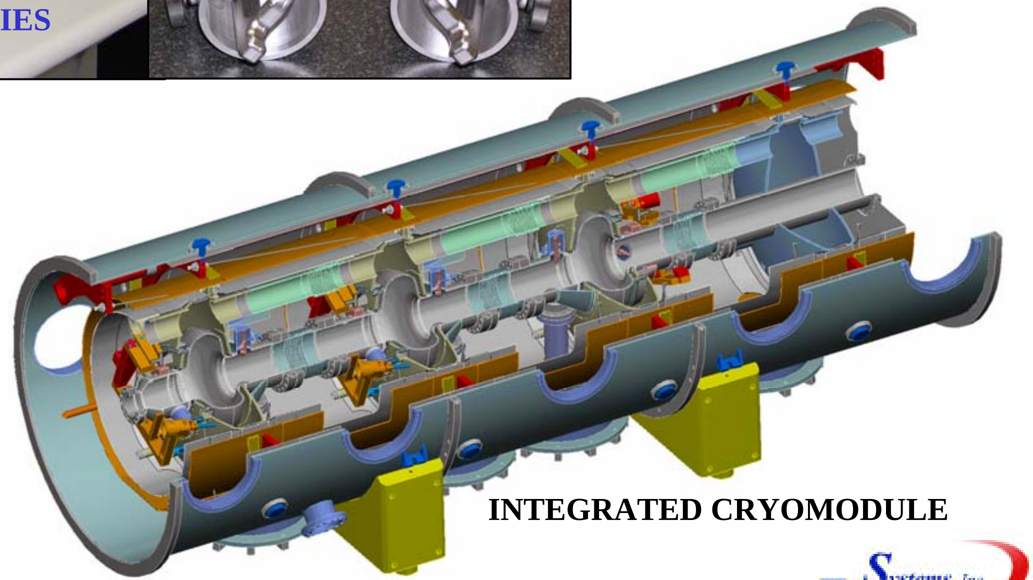

FUNDAMENTAL CAVITY ASSEMBLIES


POWER COUPLER DETAILS

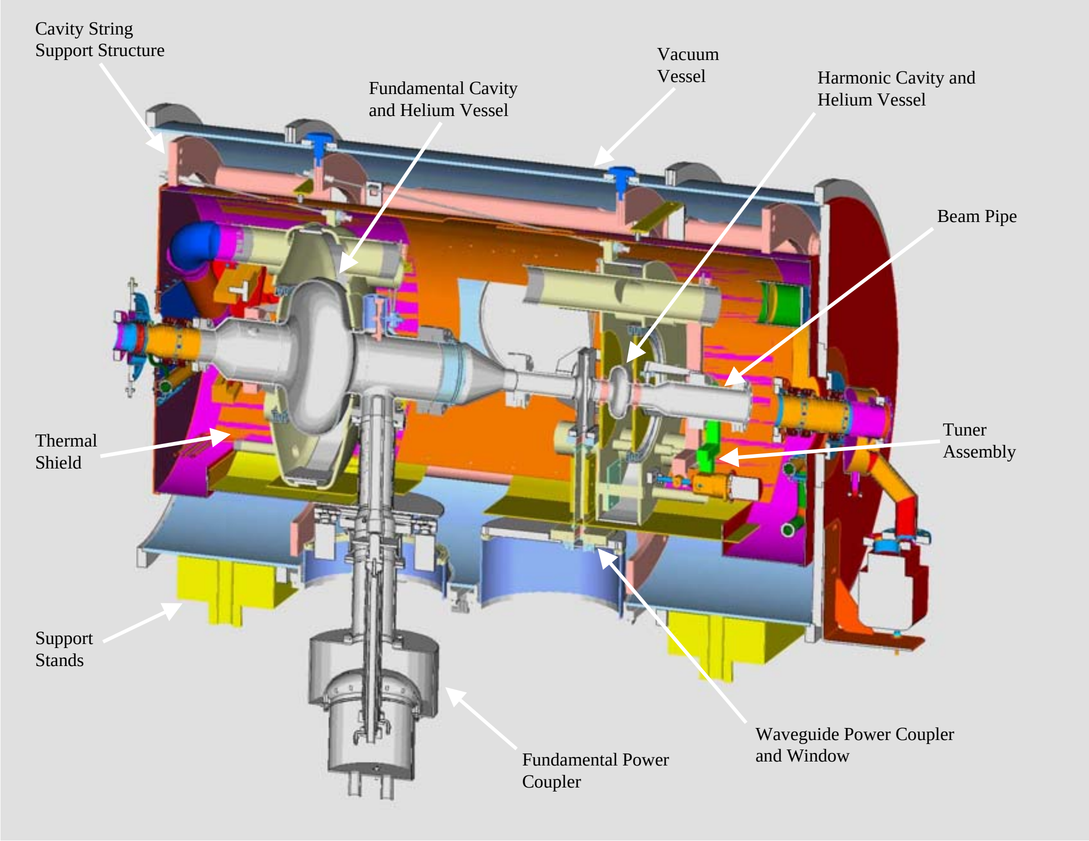

HOM FILTERS

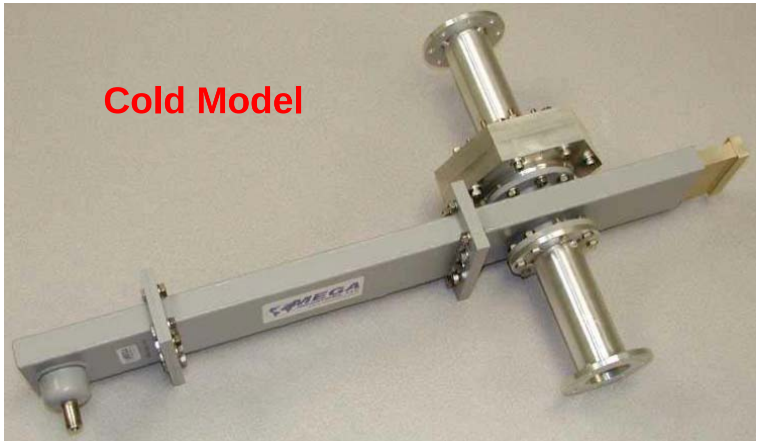

CAVITY CUTAWAY

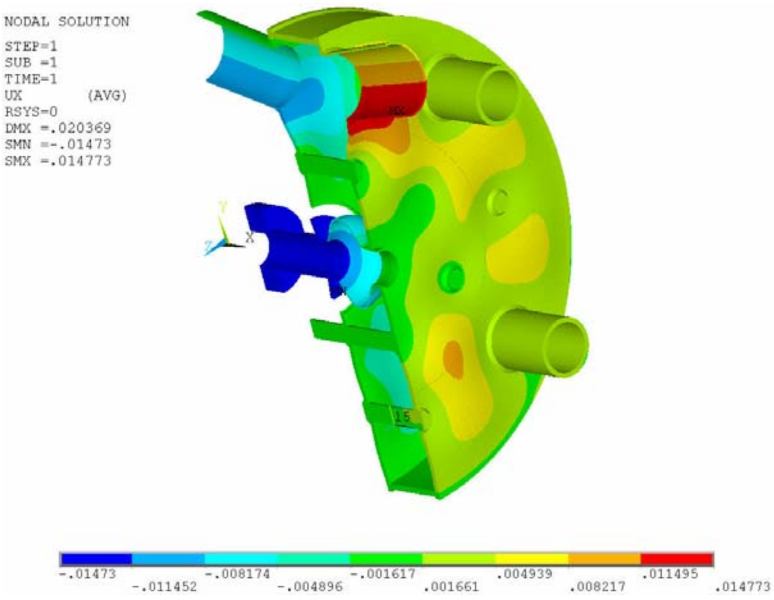

VACUUM VESSEL


INTEGRATED CRYOMODULE

Harmonic Cavity SRF Injector

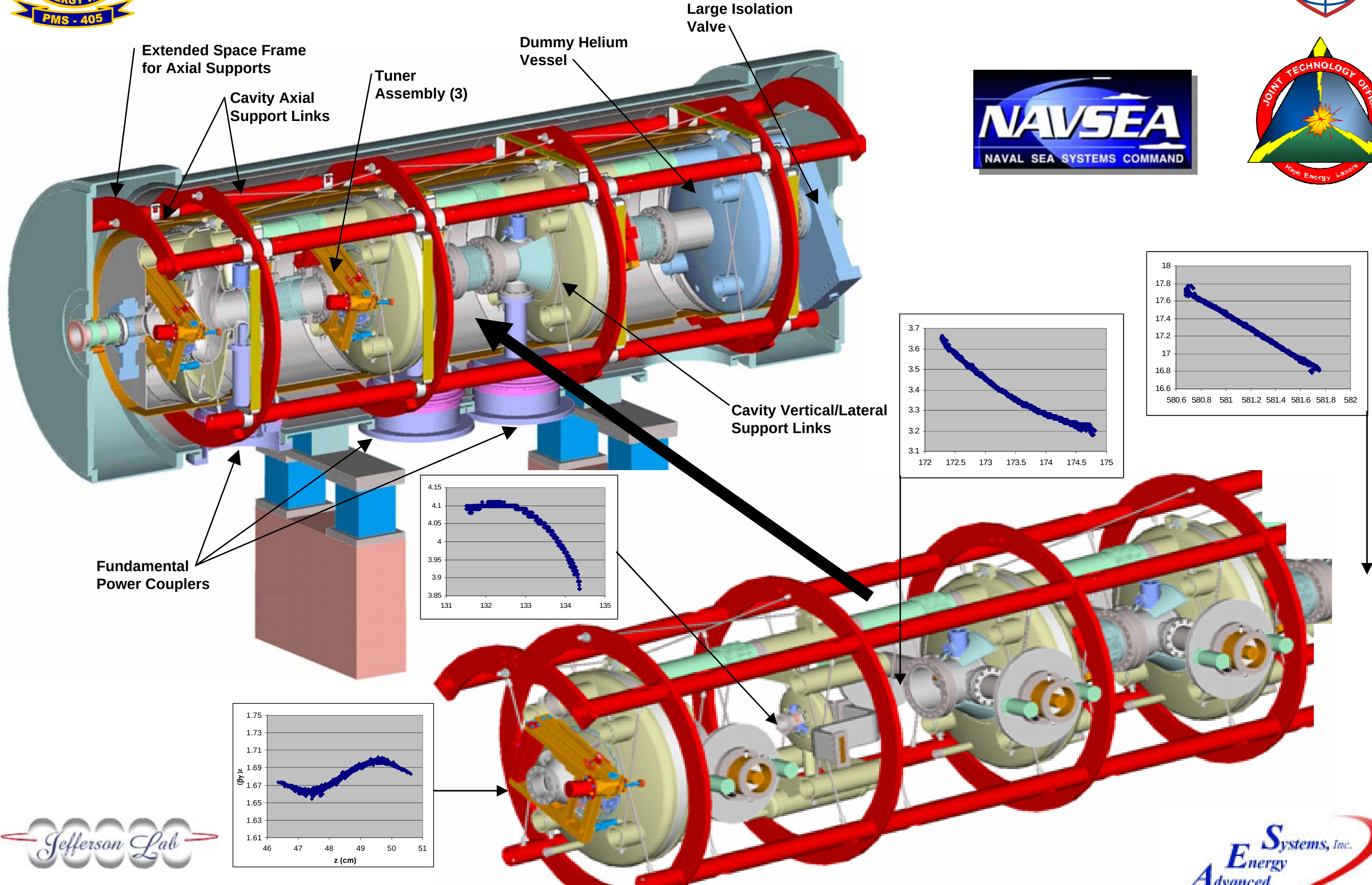




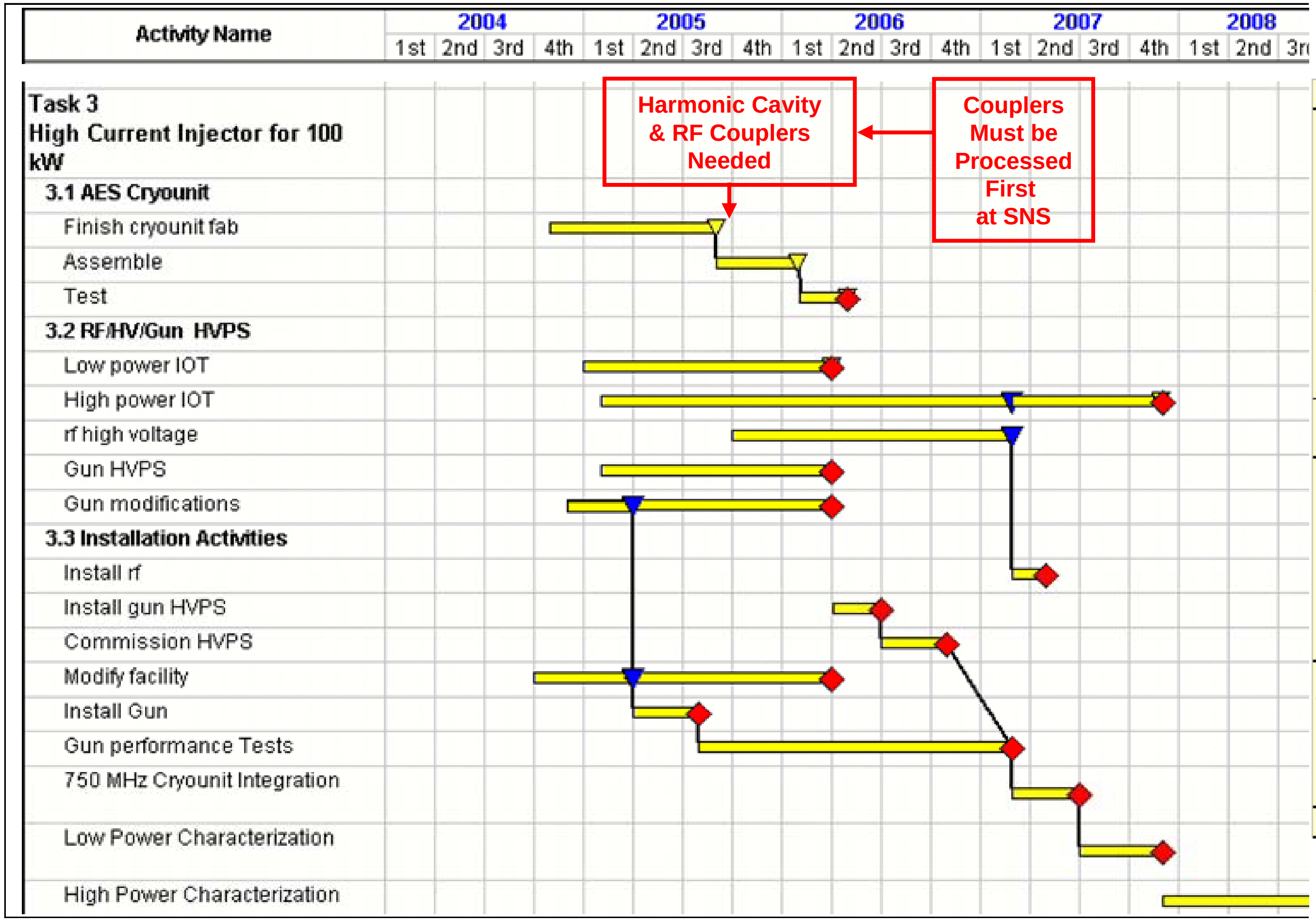


Putting Accelerator Technology to Work

Revised Injector With 3rd Harmonic



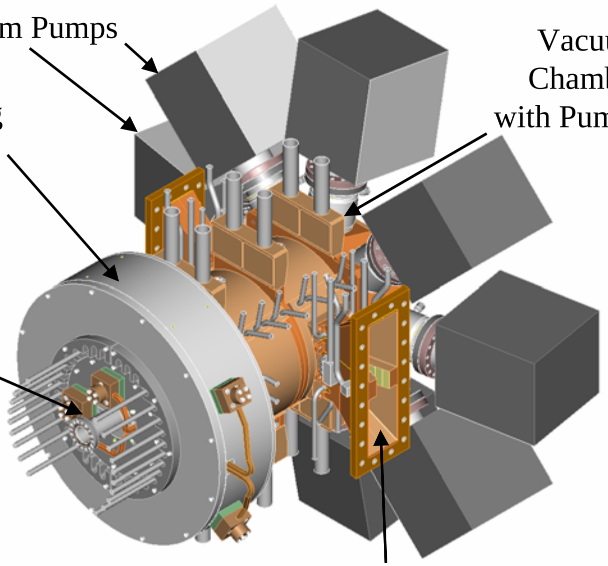
Revised DC Injector Schedule



Gun Type	DC
Injector and ERL	
RF Frequency (MHz)	748.5
PRF (MHz)	748.5
Charge/Bunch (nC)	0.133
Current (mA)	100
Injector Energy (MeV)	7
Transverse RMS Normalized Emittance (	1.2
Longitudinal RMS Emittance (keV-psec)	44
RMS Bunch Length (psec)	6.3
RMS Energy Spread (%)	0.5
ERLP Energy (MeV)	N/A
ERL Energy Goal (MeV)	N/A
Electron Gun	
DC Gun Voltage (kV)	500
Gun Accelerating Field (MV/m)	7
Cathode Material	GaAs
Drive Laser FWHM Pulse Length (psec)	44
Laser Wavelength (nm)	527
Laser Power at 5% QE (W)	5
Booster Accelerator	
Type	SRF
Geometry (Cavities x Cells)	4 x 1
Couplers per Cavity / Type	1/COAX:1/WG
Coupler Power (kW)	350
Status	Assembly

Putting Accelerator Technology to Work

100 mA Normal-Conducting Injector



700 MHz
100 mA

Objectives & Comments

- Design and fabricate a 100 mA-capable Normal-Conducting Injector for delivery to Los Alamos (1 A potential @ 350 MHz)
- Demonstrate CW thermal performance at 7 MV/m (no cathode)
- Demonstrate 100 mA beam performance (not yet funded)

Projected Parameters

Frequency	700	MHz
Energy	2.54	MeV
Current @ 33.3 MHz*	100	mA
Bunch Charge*	3	nC
Transverse Emittance	6	mm-mrad rms normalized
Longitudinal Emittance	145	keV-psec rms
Energy Spread	0.5	%
Bunch Length		psec rms

* > 100 mA-capable but no cathode at present.

Schedule

- Design fully developed
- Drawings completed - explicitly include all machining and process steps
- AES fabrication operations - complete 7/05
- AES stack tune - complete 8/05
- AES stack braze - complete 9/05
- AES deliver cavity to LANL – 9/05
- Thermal test complete ~ 12/05
- Beam test possible by ~ 6/07

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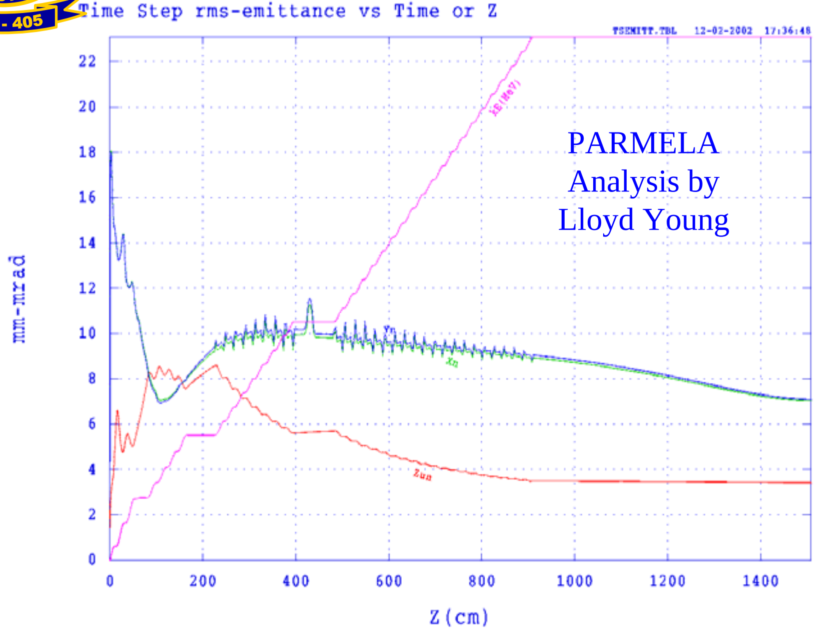
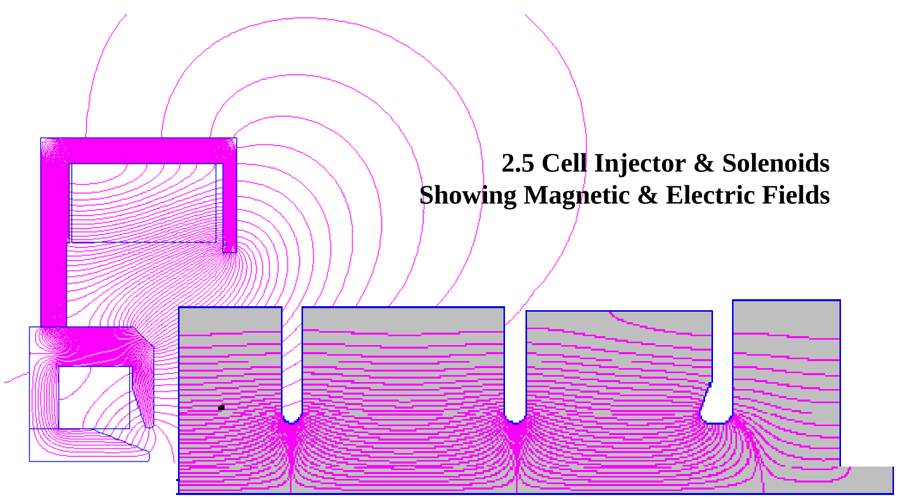
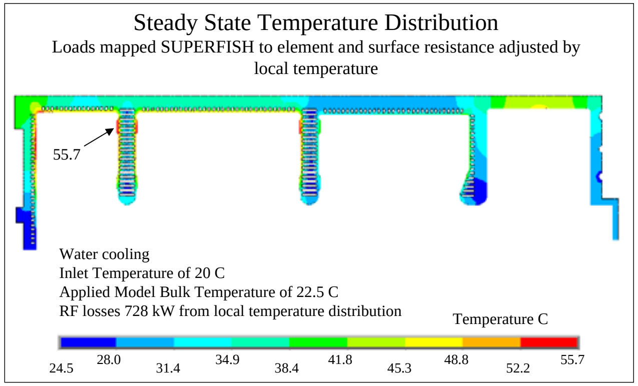
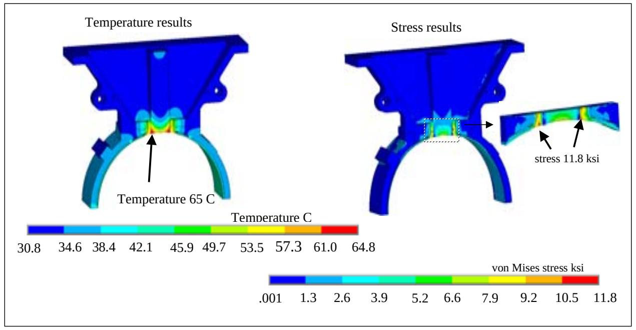
Advanced Energy Systems, Inc.

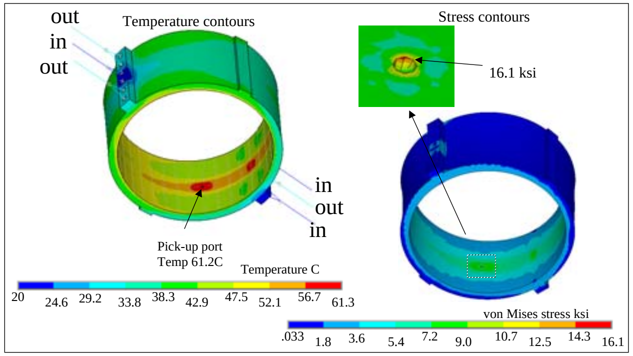
RF Photoinjector Analysis





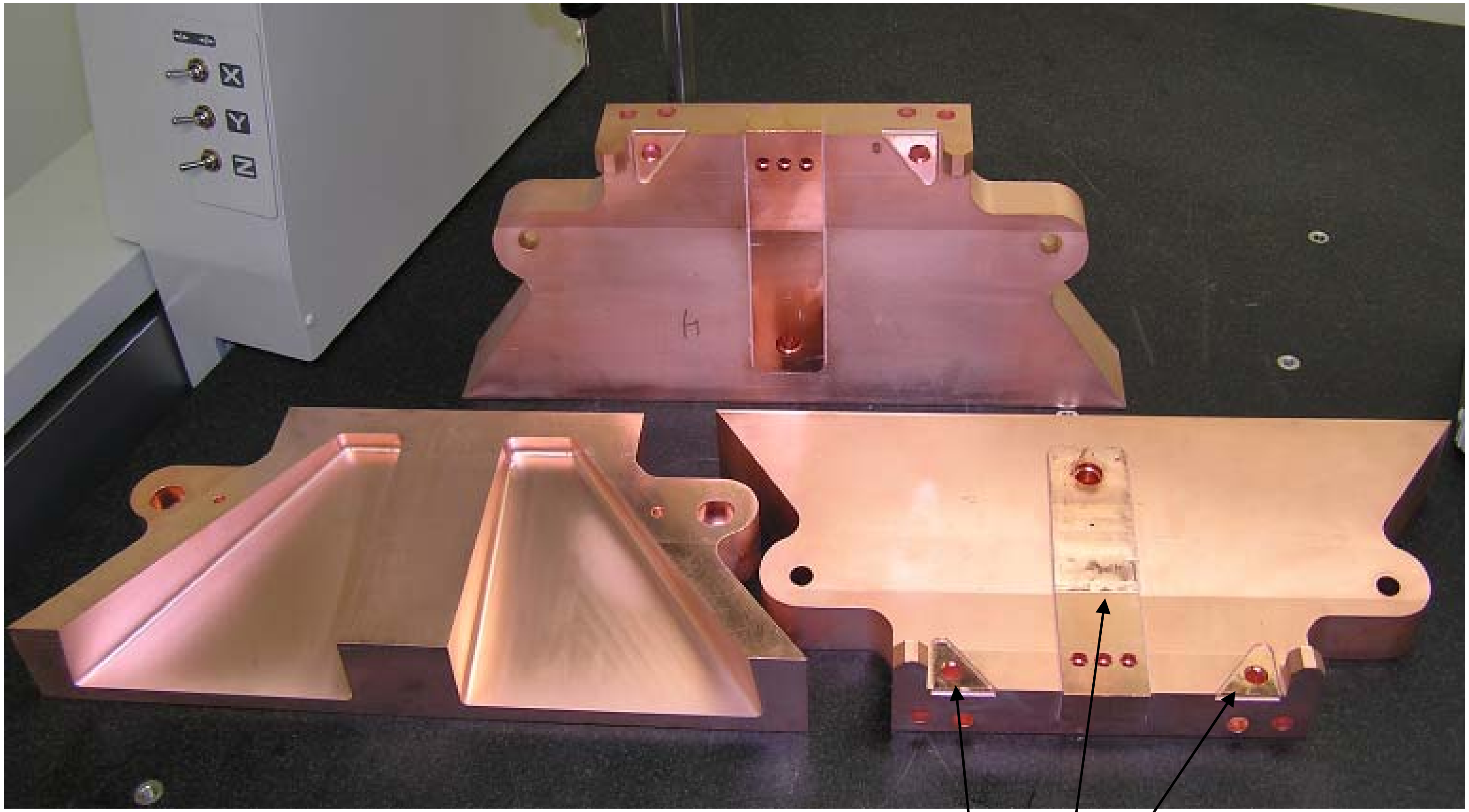






Putting Accelerator Technology to Work

Waveguide Halves with Brazed on Coolant Covers



3 of 4 halves
other half in machining

Coolant covers

1st Braze Complete

Cells Plated and Ready For Brazing

Cell 2

Cell 1

Cell 3

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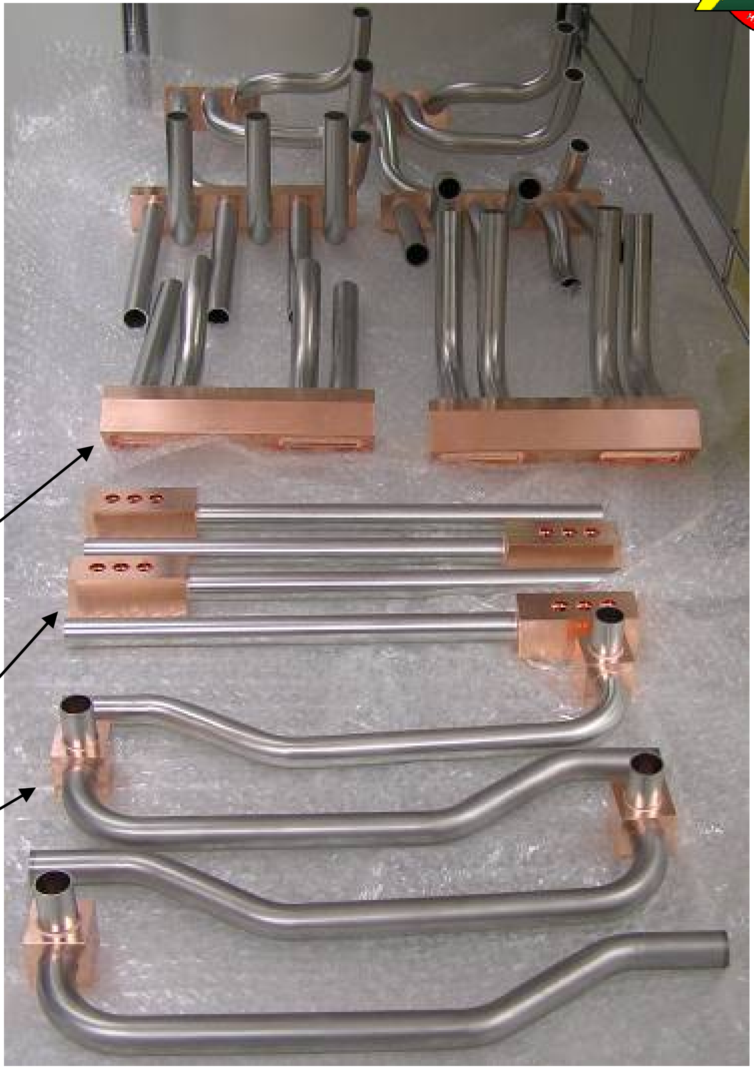
Putting Accelerator Technology to Work

Advanced Energy Systems, Inc.

Brazed Manifolds

Septum Manifolds



Cell and Waveguide Manifolds

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Putting Accelerator Technology to Work

Advanced Energy Systems, Inc.

Waveguide Iris Machining

Coolant Channels

Cover

Ready for Plating

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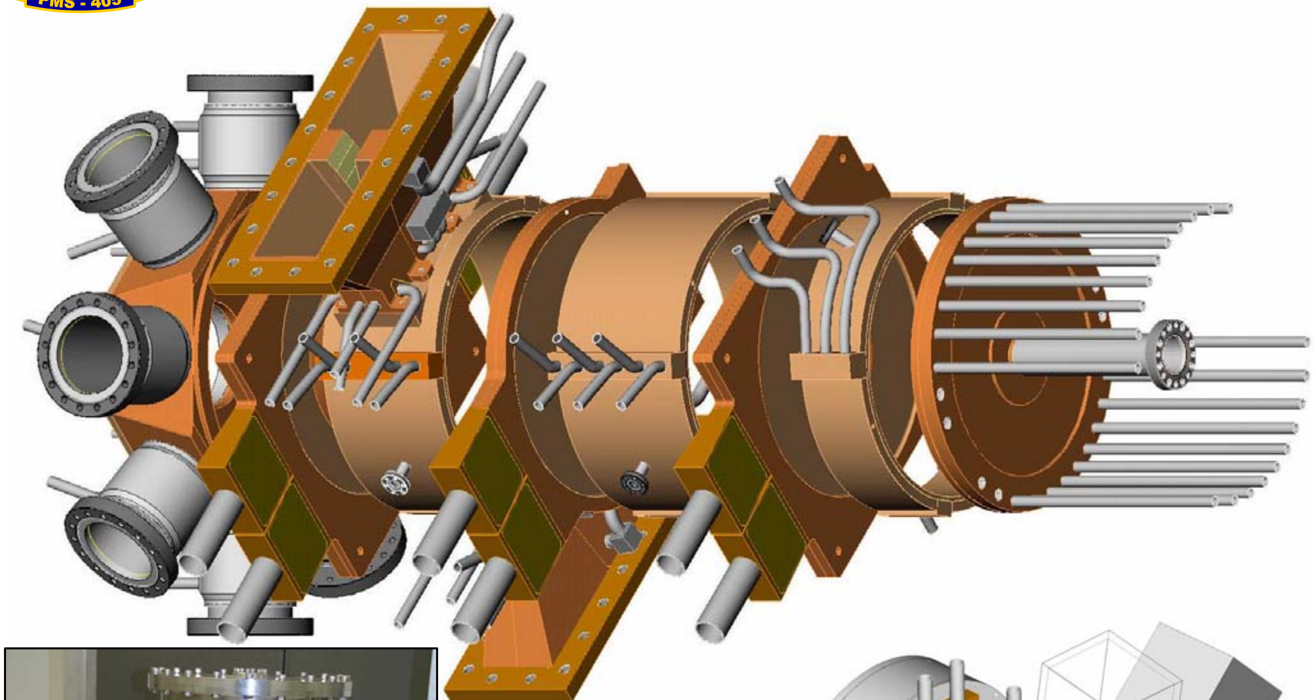
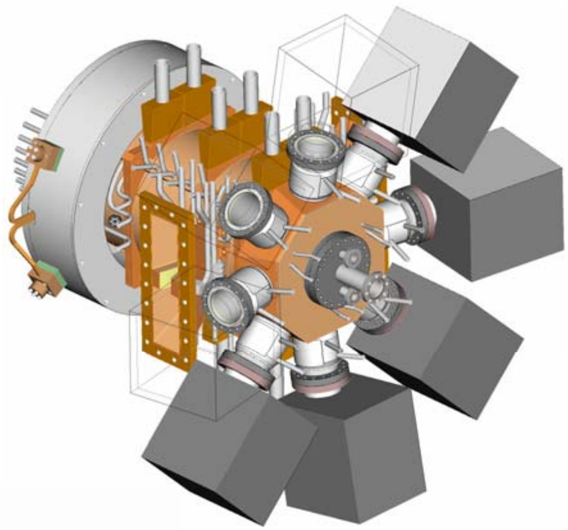
Advanced Energy Systems, Inc.

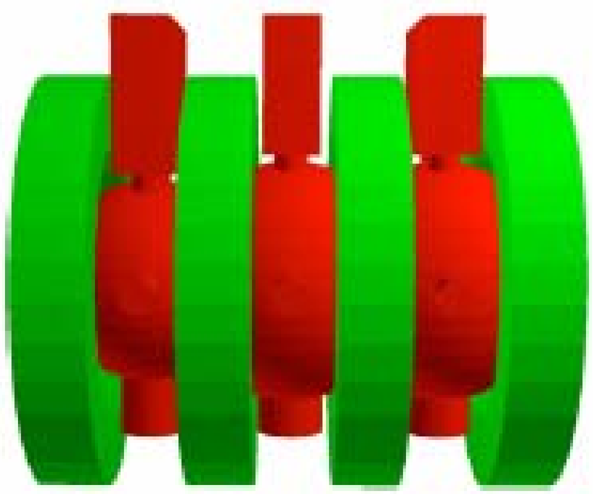
RF Photoinjector Summary

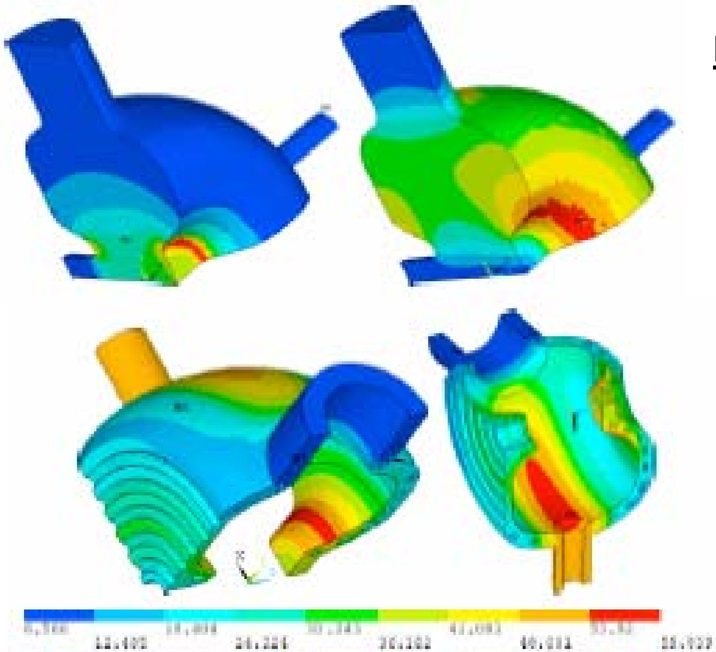




Gun Type	RF
Injector and ERL	
RF Frequency (MHz)	700
PRF (MHz)	33.3 (350)
Charge/Bunch (nC)	3.0
Current (mA)	100 (1050)
Injector Energy (MeV)	2.5
Transverse RMS Normalized Emittance (	6
Longitudinal RMS Emittance (keV-psec)	145
RMS Bunch Length (psec)	
RMS Energy Spread (%)	0.5
ERLP Energy (MeV)	N/A
ERL Energy Goal (MeV)	N/A
Electron Gun	
DC Gun Voltage (kV)	N/A
Gun Accelerating Field (MV/m)	7 / 7 / 5
Cathode Material	Multi-Alkali
Drive Laser FWHM Pulse Length (psec)	16
Laser Wavelength (nm)	527
Laser Power at 5% QE (W)	5 (53)
Booster Accelerator	
Type	N/A
Geometry (Cavities x Cells)	1 x 2.5
Couplers per Cavity / Type	2 / WG
Coupler Power (kW)	500
Status	Fabrication

The "LUX" Gun

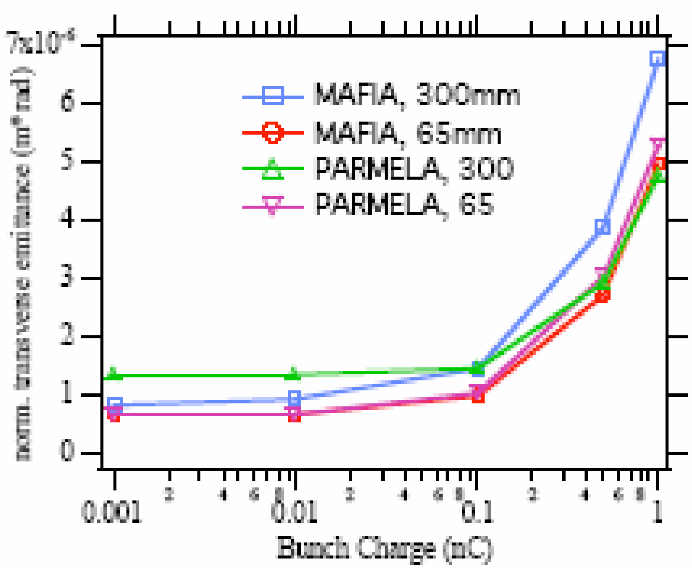


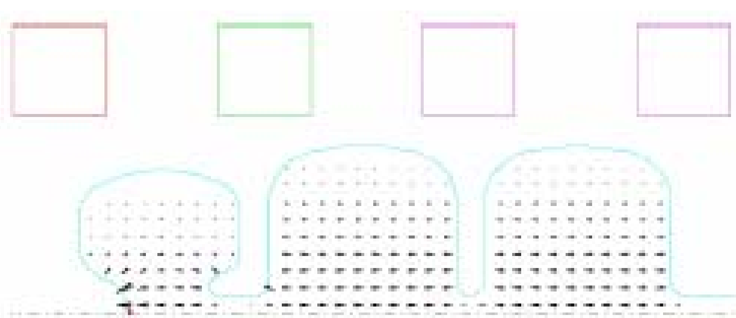


Premise:

Cavity shaping leads to higher impedance and lower thermal loads and stress => can perhaps use OFHC copper instead of Glidcop

Projected CW fields are 20 / 13 /13 MV/m



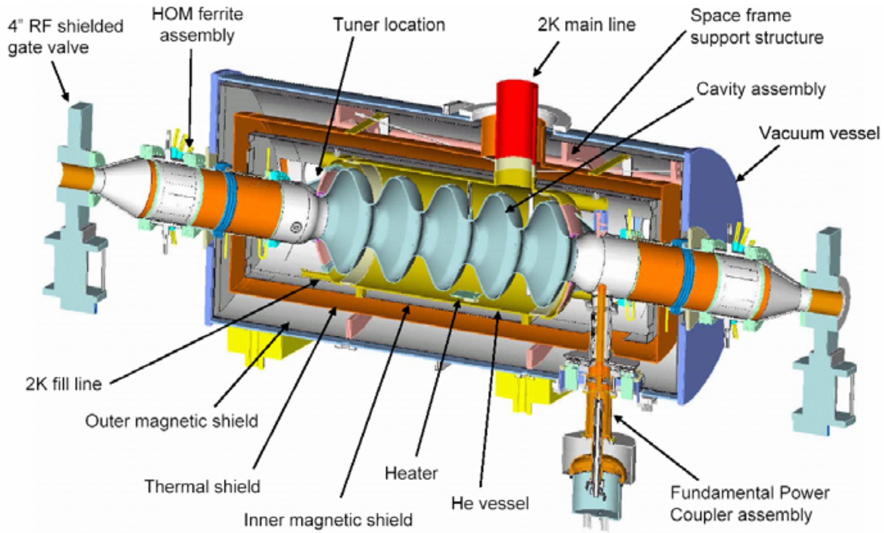


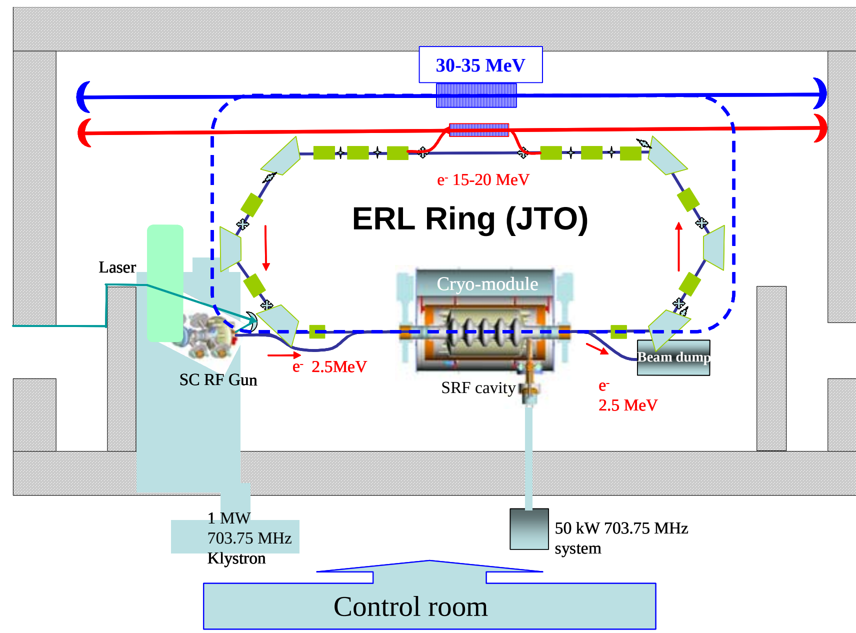
Gun Type	*RF*
Injector and ERL	
RF Frequency (MHz)	*1300*
PRF (MHz)	*1300*
Charge/Bunch (nC)	*1.0*
Current (mA)	*1300*
Injector Energy (MeV)	
Transverse RMS Normalized Emittance (μm)	
Longitudinal RMS Emittance (keV-psec)	
RMS Bunch Length (psec)	
RMS Energy Spread (%)	
ERLP Energy (MeV)	*N/A*
ERL Energy Goal (MeV)	*N/A*
Electron Gun	
DC Gun Voltage (kV)	*N/A*
Gun Accelerating Field (MV/m)	*20 / 13 / 13*
Cathode Material	*TBD*
Drive Laser FWHM Pulse Length (psec)	
Laser Wavelength (nm)	
Laser Power at 5% QE (W)	
Booster Accelerator	
Type	*N/A*
Geometry (Cavities x Cells)	*1 x 2.5*
Couplers per Cavity / Type	*3 / WG*
Coupler Power (kW)	
Status	*Analysis*

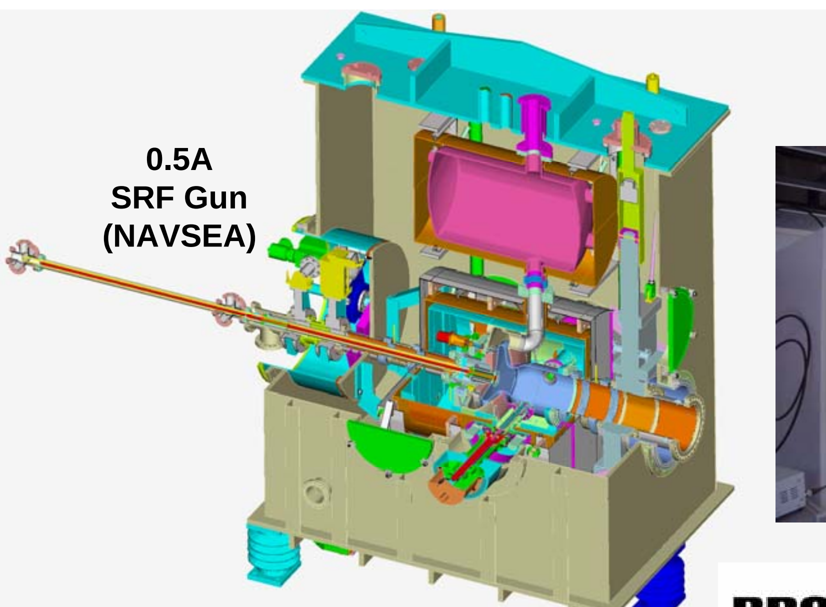
Material Courtesy Robert Rimmer

BNL ERL

High-Current Cryomodule (DoE)

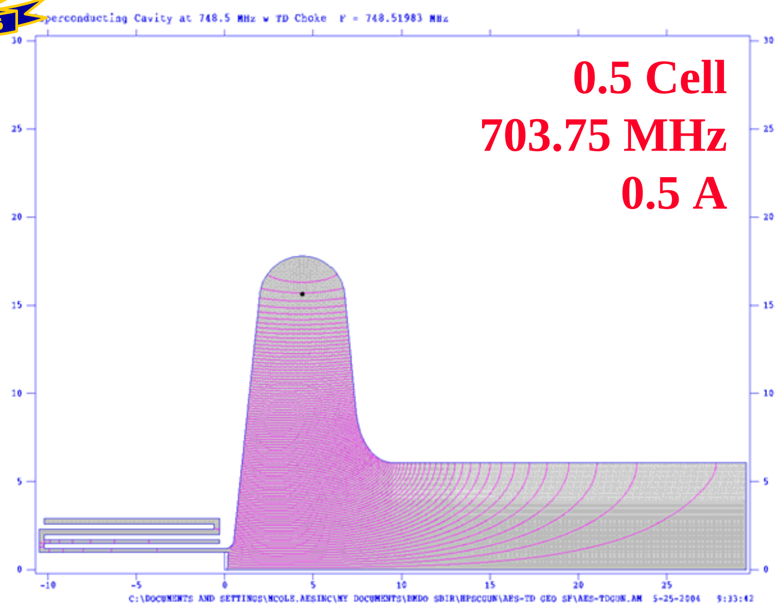






Putting Accelerator Technology to Work

SRF Injector Design



Objectives & Comments

- Design & fabricate a 0.5-cell Superconducting RF gun & choke joint fed by two 0.5 MW RF power couplers
- Test device on the BNL ERL
- Collaboration with JLAB, BNL, FZR & other FEL stakeholders

Projected Parameters

Frequency	703.75	MHz
Energy	2	MeV
Current	500	mA with PRF of 352 MHz
Bunch Charge	1.33	nC
Transverse Emittance*	5.5	mm-mrad rms normalized
Longitudinal Emittance*	42	keV-psec rms
Energy Spread*	3.1	%
Bunch Length*	7.2	psec rms

* No emittance compensation in analysis solenoid will be used

Schedule

- Choke configuration downselected – 6/04
- Preliminary design review – 1/05
- Niobium ordered – 12/04
- Testing alternate choke joint – completed 2/05
- Fabrication completed by ~ 3/07
- Initial testing completed at BNL by ~ 12/07

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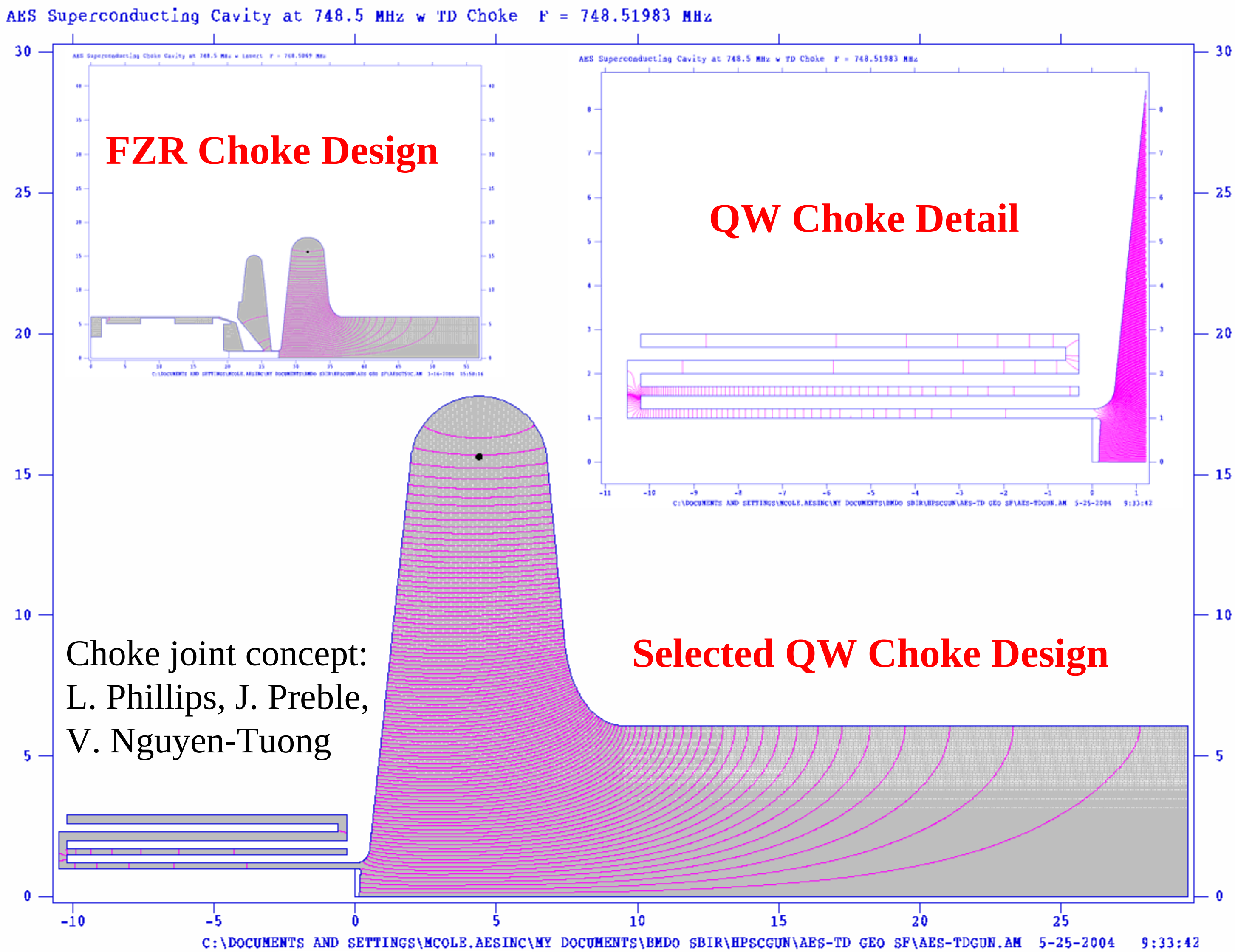
SRF Gun Performance Goals

- 703.75 MHz
- 1.42 nC @ 703.75 MHz => 1 A
- For 1 A => ~ 2 MeV delivered
- 2 MW into ½ cell
- 2 opposed 1 MW couplers
- ½ cell => ~ 0.1 m
- 2 MeV / 0.1 m => ~ 20 MV/m

Gun Type	SRF
Injector and ERL	
RF Frequency (MHz)	703.75
PRF (MHz)	351.88
Charge/Bunch (nC)	1.4
Current (mA)	500
Injector Energy (MeV)	2
Transverse RMS Normalized Emittance (	5.5
Longitudinal RMS Emittance (keV-psec)	42
RMS Bunch Length (psec)	7.2
RMS Energy Spread (%)	3.1
ERLP Energy (MeV)	20
ERL Energy Goal (MeV)	40
Electron Gun	
DC Gun Voltage (kV)	N/A
Gun Accelerating Field (MV/m)	20
Cathode Material	Diamond/Alkali
Drive Laser FWHM Pulse Length (psec)	TBD
Laser Wavelength (nm)	527
Laser Power at 5% QE (W)	0.2 / 25
Booster Accelerator	
Type	N/A
Geometry (Cavities x Cells)	1 x 0.5
Couplers per Cavity / Type	2 / COAX
Coupler Power (kW)	500
Status	Design/Fab

Quarter Wave (QW) Choke Design



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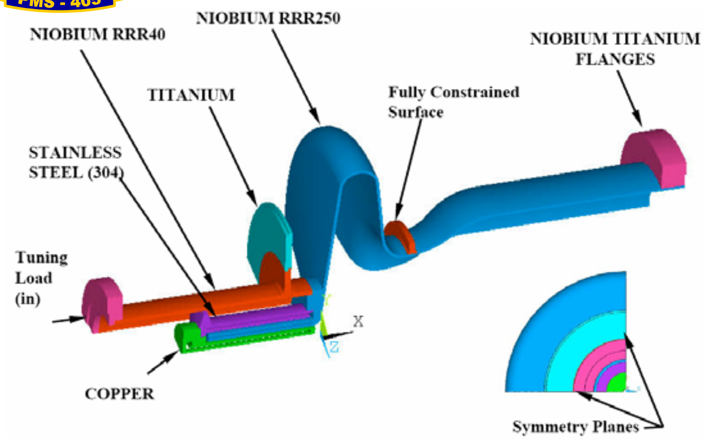
Putting Accelerator Technology to Work

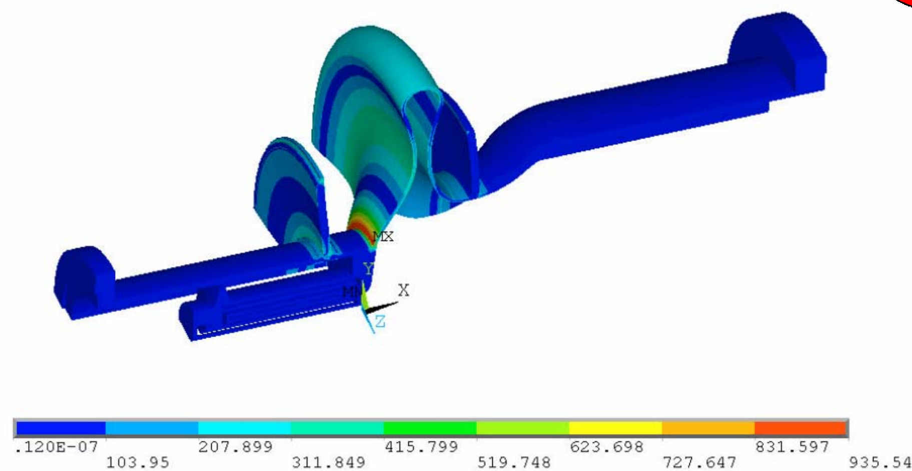
Thermal Load Estimates

RF & Passive Thermal Load (W) For Representative Field Gradients	FZR Choke	QW Choke
	11	140

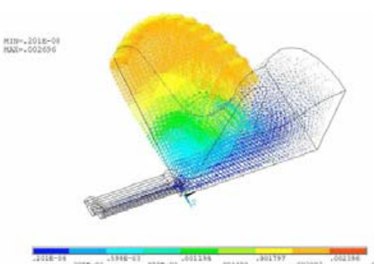
QW Choke Thermal Load For 1 A CW Current	Conventional Cathode	Diamond Cathode
QE (%)	5	625 (125 Gain)
Photocathode Laser Power (W)	50	0.4
Laser Power Deposited (W)	25	0.2
RF & Passive Thermal Load (W)	140	140
Primary Electrons (W)	0	50
Secondary Electrons (W)	0	34
Total Thermal Load @ 1 A (W)	**165**	**224**
Total Thermal Load @ 0.5 A (W)	**153**	**182**

SRF Gun Analysis

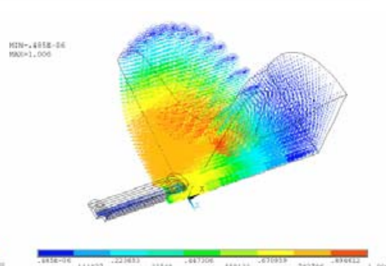




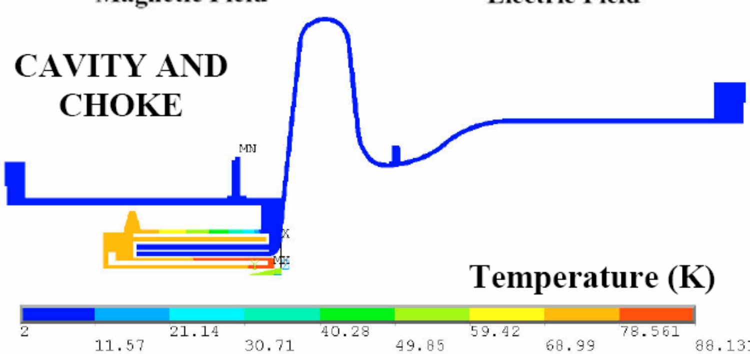
(psi)



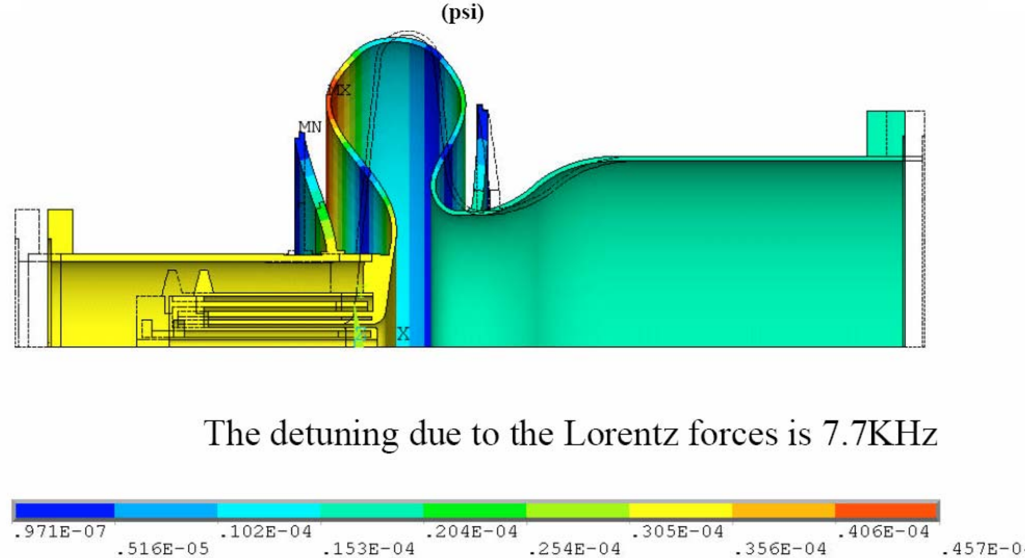
Magnetic Field



Electric Field



Temperature (K)



The detuning due to the Lorentz forces is 7.7KHz

(in)

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Putting Accelerator Technology to Work

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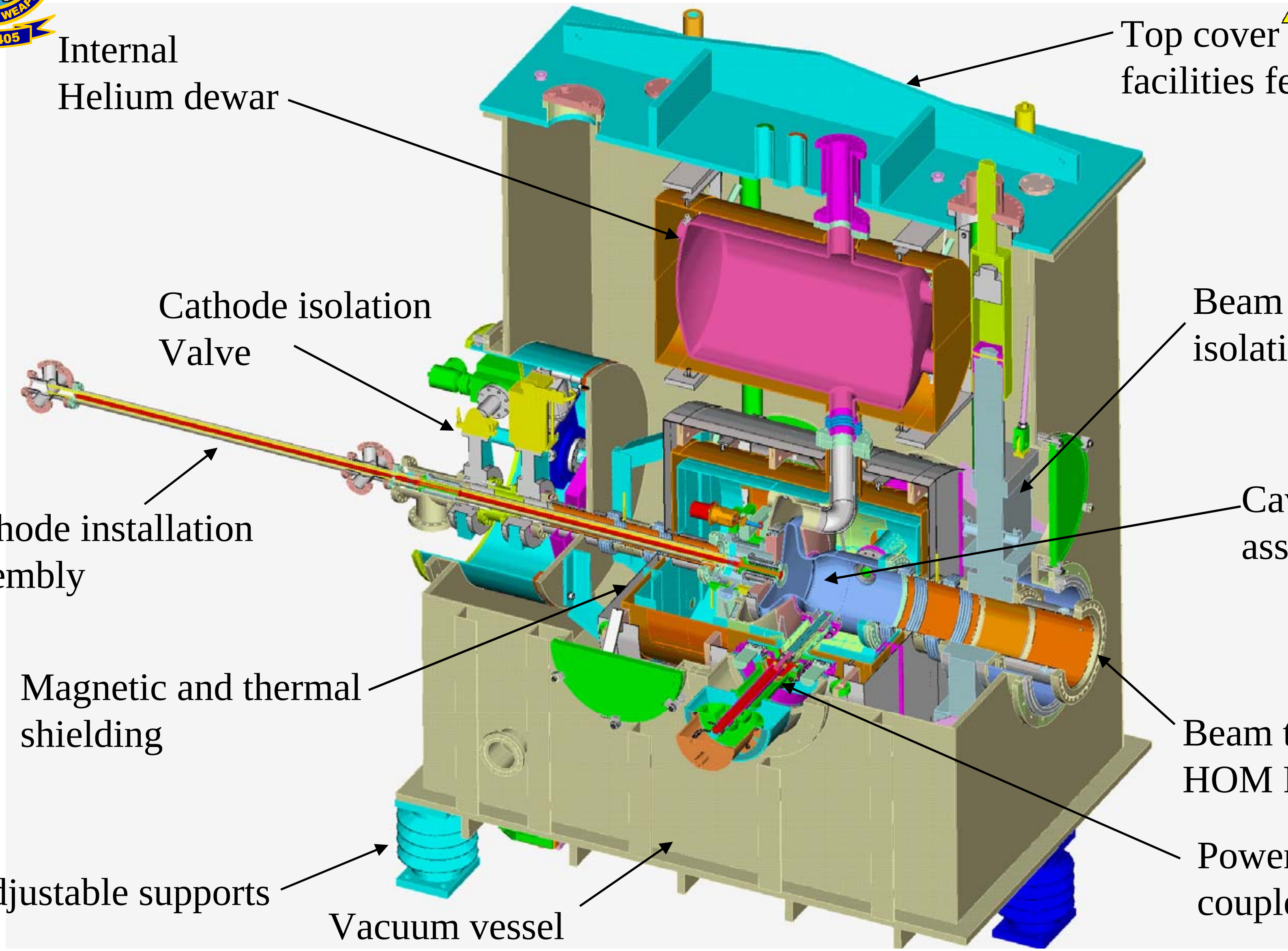
Cryomodule Configuration



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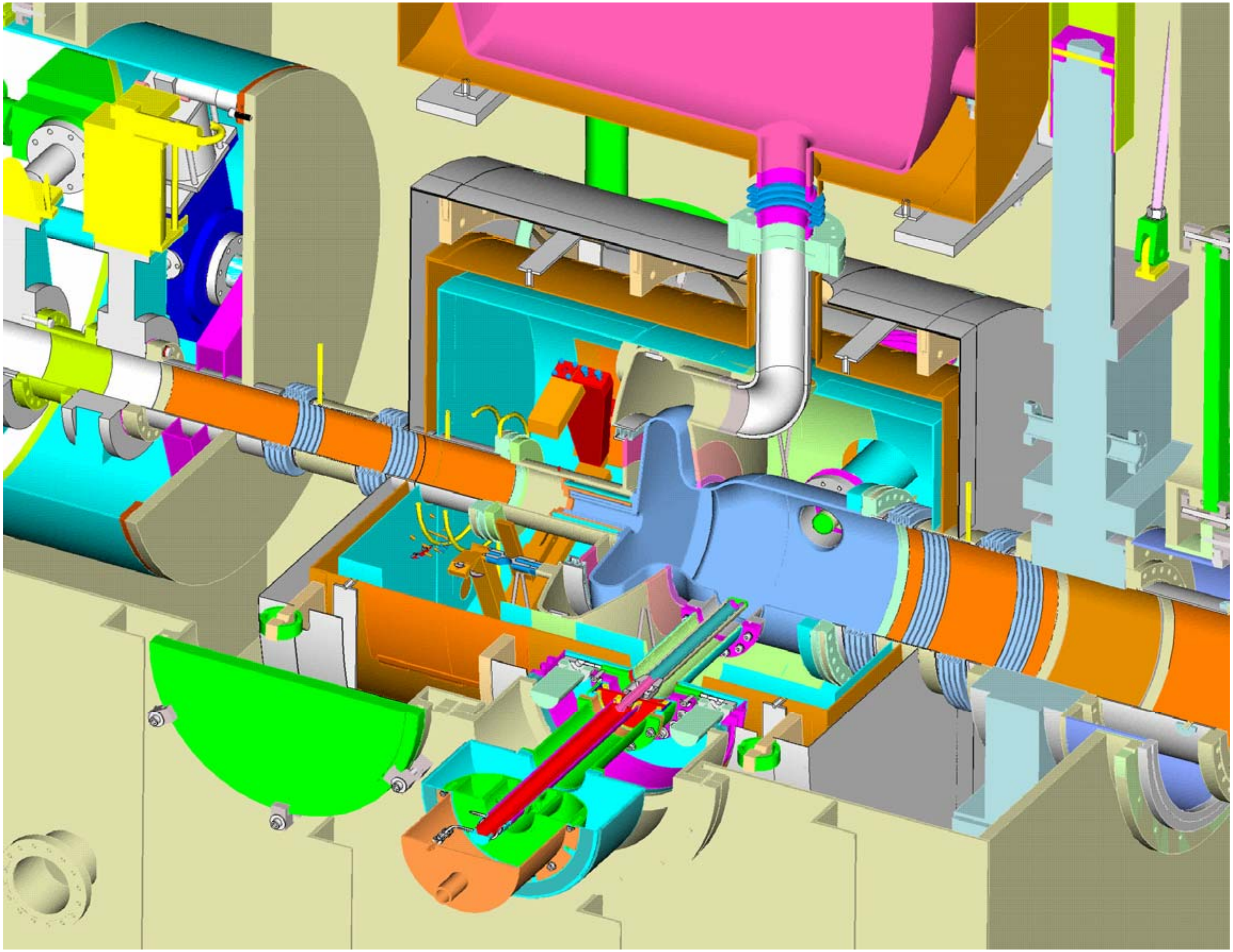
Cryomodule Cutaway



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Putting Accelerator Technology to Work

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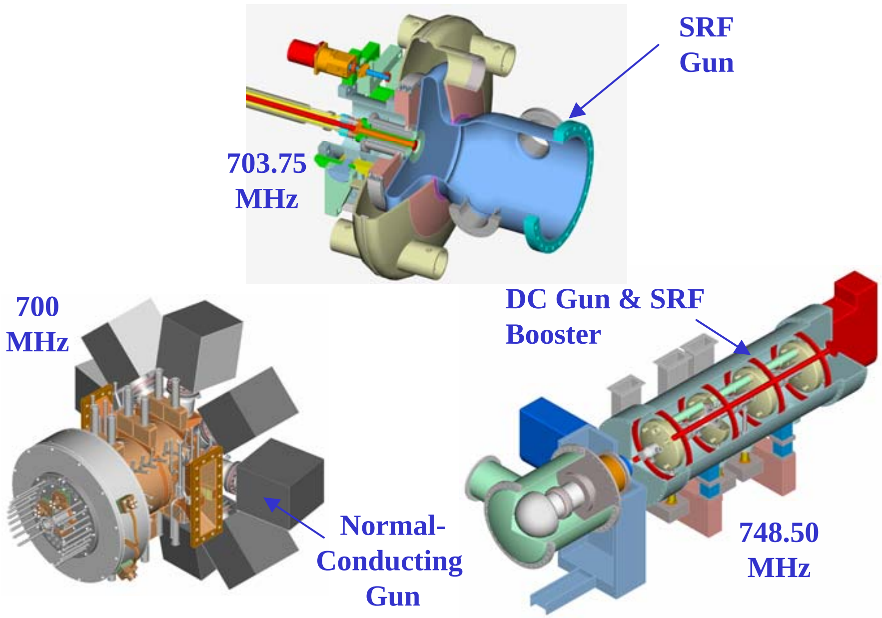
Cathodes and Drive Lasers

Material	QE Range	Drive Laser Wavelength	Cathode Fab.	Vacuum Req.	Drive Laser
Thermionic Emitters	N/A	N/A	Easy	10^{-7} T	N/A
Metal (Cu, Mo..)	~0.02-0.06%	260 nm, UV	None	10^{-7} T	Very Difficult
CsTe	10-14%	260 nm, UV	Easy	10^{-9} T	Difficult
LaB_6	~0.1%	355 nm, UV	Easy	10^{-7} T	Very Difficult
GaAs (Cs)	1-5%	532 nm	Moderate	10^{-10} T	Moderate
CsK_2Sb	10-14%	532 nm	Difficult	10^{-10} T	Moderate
Dispenser (Multi-Alkali)	10-14%	532 nm	Difficult	10^{-10} T	Moderate
Diamond (Multi-Alkali)	< ~ 1000%	532 nm	Very Difficult	10^{-7} T	Easy
Carbon Nanotube	TBD	260 nm	Difficult	10^{-7} T	Difficult
Field Emitters (Ti)	0.1-1%	260 nm	Difficult	10^{-7} T	Difficult

Modification of a David Dowell Chart

High-Current Injector Option Summary



Performance

- Output energy ~ 7 MeV (2 – 15)
- CW average current ~ 200 mA (100 – 500)
- Transverse emittance < 6 microns rms normalized (2 – 6)
- Longitudinal emittance < 145 keV-psec rms (25 – 145)
- Bunch length < 4 psec (2 – 7)
- Energy spread < 0.5 % (0.1 – 0.5) @ 7 MeV
- RF frequency ~ 700 MHz (500 – 1300)
- 500 kW RF feedthroughs (50 – 500)
- Photocathode with visible response

AES Programs and Status

High-current injector development is a key technology issue for ERL devices

- **JLAB: DC Gun & SRF Cryomodule at 748.5 MHz**
  Most SRF booster components at JLAB
  Cleaning and assembly has begun at JLAB with AES participation
  JLAB Injector Test Stand has been authorized
  RF delivery leads to high-current testing in 2008

- **Los Alamos: Normal-Conducting Gun at 700 MHz**
  AES will deliver gun to Los Alamos in 2005
  Available 1 MW of RF will deliver thermal test in late 2005
  Beam test with 2 or 3 MW of RF is not presently funded

- **BNL: Superconducting RF Gun at 703.75 MHz**
  Least mature option
  Final design proceeding for delivery to BNL in early 2007
  BNL ERL facility will demonstrate 0.5A operation in late 2007

Conclusions

Three technology options for > 100 mA ERL injectors:

√ **<u>DC Guns with SRF Boosters</u>**

- Will deliver the required performance at 100 mA current level but may not extrapolate to the Ampere-level
- Relatively mature approach and suitable for near-term deployment
- Cathode issue is largely solved for this technology at the 100 mA current level

√ **<u>Normal Conducting RF Injectors</u>**

- Still the state-of-the-average-current-art (Boeing Gun)
- Will deliver the required performance at 100 mA current level and is extrapolable to the Ampere-level
- Multi-alkali approach probable but cathode solution is still uncertain
- Achievable gradient limited by thermal constraints
- Least attractive option because the associated inefficiency is undesirable

? **<u>Superconducting RF (SRF) Injectors</u>**

- Least mature option and unproven at high-average current
- The most desirable approach if it works, since, in principle, it delivers the better RF performance at DC gun efficiency levels
- Highest accelerating gradient and thus potentially compact option
- Must demonstrate a compatible cathode technology and power handling

Must demonstrate practical, compatible cathode and drive laser options for each injector type

Must pay attention to HOM, BBU and CSR issues in injectors

Must successfully demonstrate high RF power handling

Advanced Energy Systems

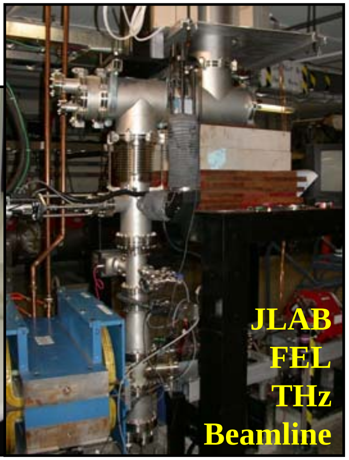
Mission Statement

AES seeks to be the supplier of choice for advanced radiation sources based on high-brightness electron accelerator technology.

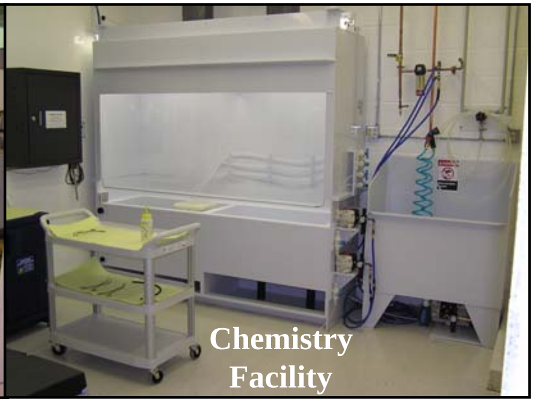
Product Areas

- ***Advanced Radiation Sources***
  - Free Electron Lasers (FEL)
  - High-Power Microwaves (HPM)
  - High-Power TeraHertz (THz) Sources
  - Tunable, Monochromatic X-Ray Sources
- ***Turnkey Accelerator Systems & Components***
  - Photocathode Injectors
  - Superconducting RF (SRF) Accelerators
  - Normal-Conducting Accelerators
  - Beam & Optical Transport Systems
  - Turnkey Beamlines
- ***Integrated Engineering & Physics Services***


Single-Cell SRF Cavities


JLAB FEL THz Beamline

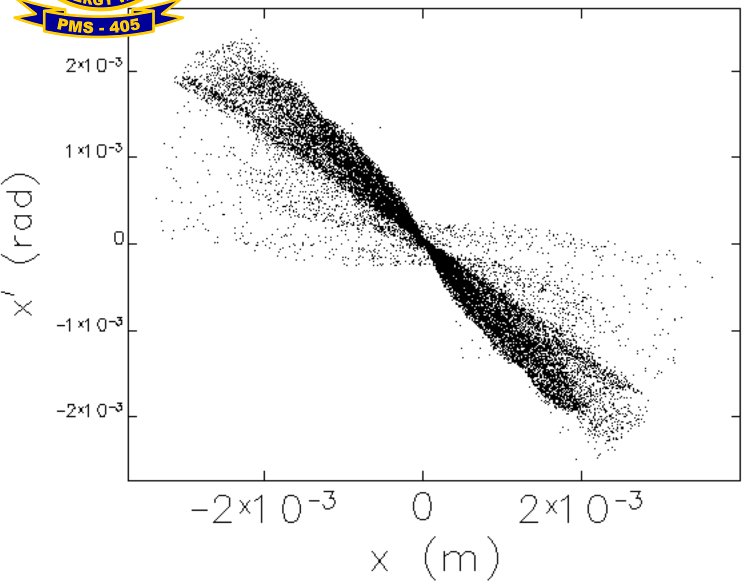

Medford Machine Shop


Chemistry Facility

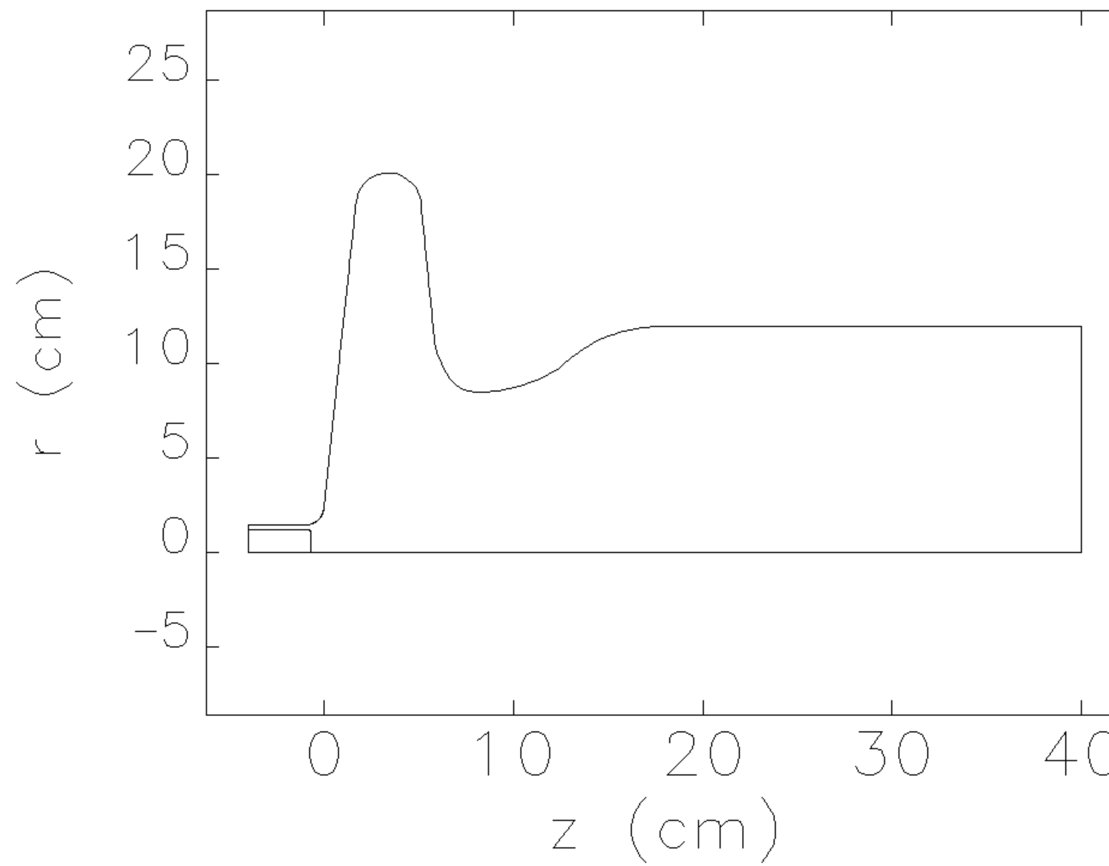

MXISystems

Backup Material

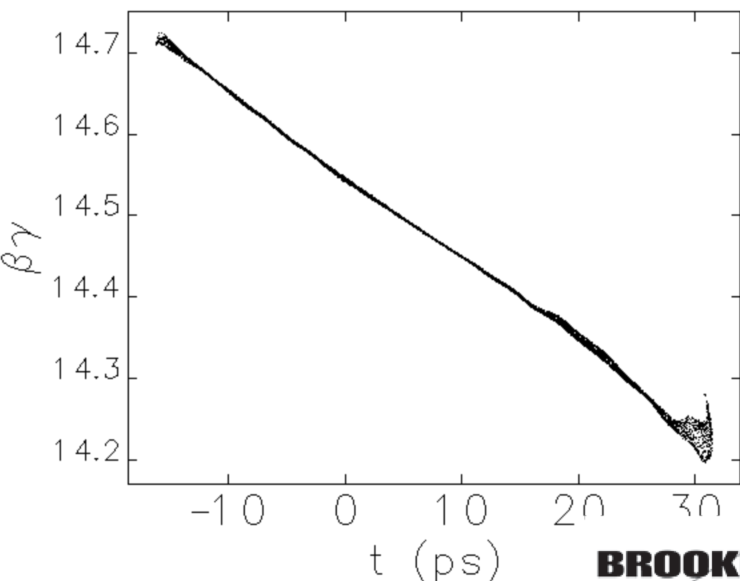
SRF Gun Physics Design - I



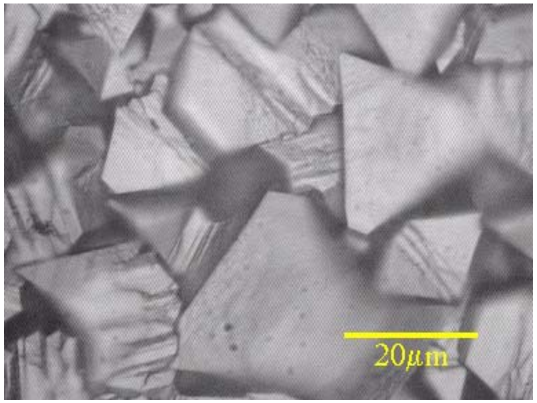
AES analysis (0.5 cell gun and 3 cell SRF booster with no solenoid) yields 4.1 mm-mrad rms transverse emittance, 47 keV-psec rms longitudinal emittance with 1.4% rms energy spread at 7 MeV and 1 A

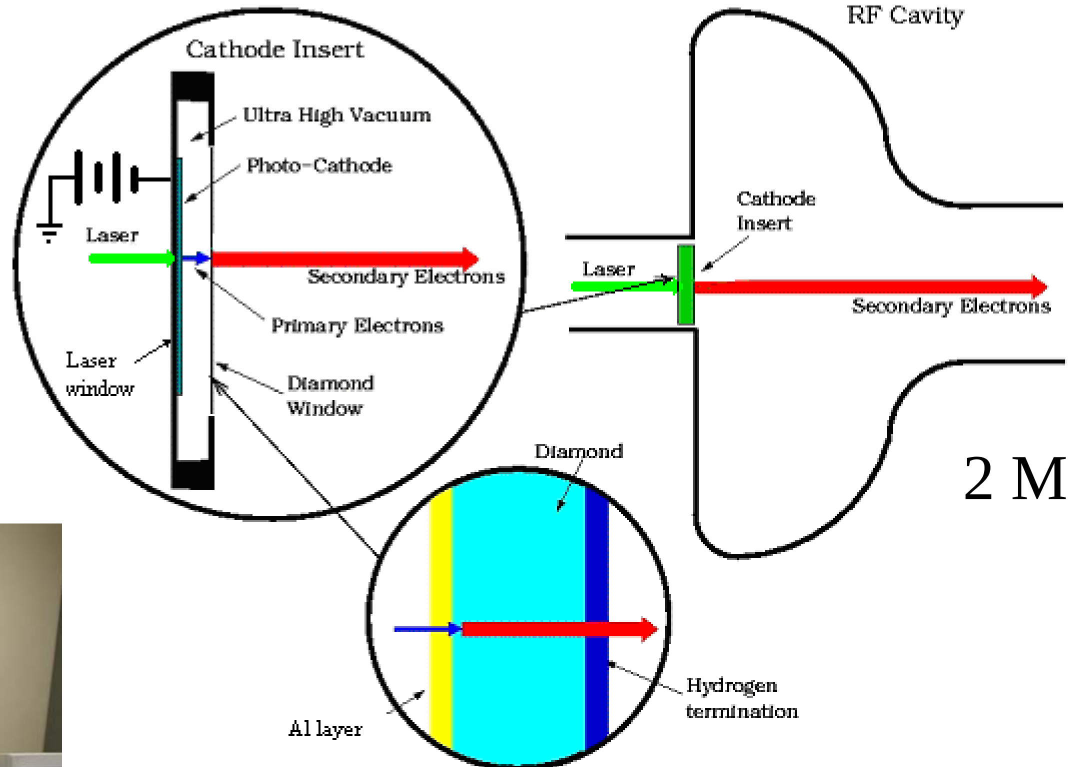


At 3.36 m after 3 cell SRF booster



Diamond-Amplified Photocathode





2 MeV

Material Courtesy Ilan Ben-Zvi

BROOKHAVEN NATIONAL LABORATORY

Advanced Energy Systems, Inc.