RF Sources for FCC-ee

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9/10/2026

Fourth US FCC meeting

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Advanced Electron-Driven RF Sources

- Vacuum Electronics Devices (VEDs) remain the only viable technology for high-power (>50 kW) UHF/L-band generation with >50% electronic efficiency, but the architecture must evolve to meet efficiency needs

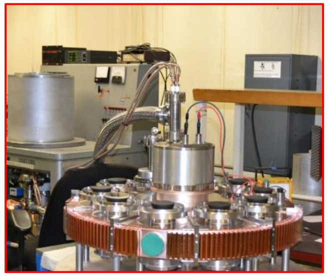
Beam perveance P = $\frac{I}{V^{3/2}}$

- *Pulsed*: γ ~1.5-2, dominated by rf breakdown limits **(P↑ η↓).**
- *CW*: γ <1.1, dominated by space-charge depression and thermal dissipation limits **(P↓ η↑).**

RF sources become the leading cost driver for normal conducting accelerators and a significant cost driver for superconducting accelerators.

Only with innovative concepts for designing and building RF sources will dramatic reduction in cost and increased efficiency be achieved.

SLAC High Power RF Research & Engineering Has Spanned 0.3 -100 GHz and up to 150 MW Peak Power

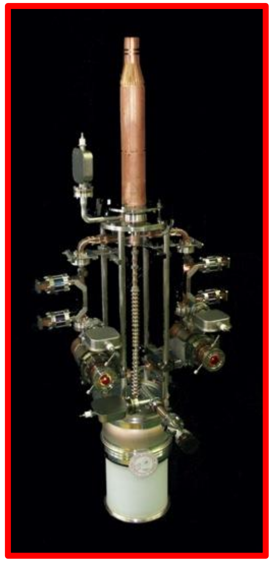


SLAC/Stellant

MB IOT
700 MHz 1.2 MW

HE IOT
1.3 GHz
100 kW CW

Compact X-band
11.4 GHz 300 kW



XP
X-Band
11.4 GHz, 50 MW
PPM focused

5045 Klystron
S-Band
• 2.856 GHz, 65 MW

XL4 & XL5
X-Band
11.4 GHz, 50 MW
@SLAC
CERN
Sinc. Trieste
PSI
BNL
LLNL

B Factory Klystron
476 MHz
1.2 MW CW

W-Band Sheet Beam Klystron
95 GHz

Span wide range
- 0.3 - 100 GHz
- 100 kW CW – 150 MW Peak

Production Klystrons Options for Future HEP Collider Facility

Model	Type	Program	Frequency [MHz]	Perveance (μP)	Efficiency	Power	Era	Improvement over past 10 years
SLAC 5045 SLAC XL/XP	**Pulsed Klystron**	**LCLS NLC/LCLS-II**	**2856 11424**	**~2.0**	**45%**	**67 MW 50-75 MW**	**1960s-1990s 2000-Present**	**Harmonic bunching, depressed collectors, Output optimization, PPM**
Thales TH2181	CW Klystron	LHC	1300	~0.72	58%	300 kW	2000s	--
Thales TH2089	CW Klystron	LEP	352	~0.38	65%	1.3 MW	1990s	--
CPI VKP-7952	CW Klystron	PEP-II	476	~0.84	60%	1.2 MW	1990s-2000s	--
L3 L4444, L4447 IOT, CEA	**CW IOT**	**Broadcast, ALS, APS**	**400-1300**	**~0.46**	**70%**	**80 kW**	**2000s-Active**	**High Efficiency IOT (HEIOT), MSDC**
Toshiba E3736	MBK (6-beam)	European XFEL	1300	~0.55/beam	65%	10 MW	2010s-Active	--
Multi-stage MBK	MBK (10-beam)	FCCee	400	~0.2/beam	85%	1 MW	In production	Powe combining and multistaging

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Klystron Design Point for FCC-ee: Pulsed Injector vs. CW Collider Sources

Parameter	Pulsed - Injector Linac Klystron	CW - Collider / Booster Source (Tristron / IOT)
Application	6 GeV e-/e+ pre-injector linac (positron source + damping-ring filler)	400/800 MHz SRF booster and collider (Z, W, ZH, tt-bar)
Frequency	2856 MHz (S-band); 5712 MHz C-band option for 20 GeV upgrade	400.79 MHz (baseline) / 801.58 MHz (tt-bar upgrade)
Duty cycle	Pulsed, 200 Hz, 2-4 bunches/pulse	Continuous wave (CW)
Reference technology	SLAC 5045 / XL-XP family; gamma ~1.5-2, RF-breakdown limited	Multibeam Tristron (IOT + penultimate cavity); gamma <1.1, space-charge/thermal limited
Power target	45-75 MW peak per tube (5045/XL heritage)	500 kW CW @400 MHz (46 kV); 200 kW CW @800 MHz
Efficiency (baseline -> goal)	45% (5045) -> 56% demonstrated HE retrofit (Canon/CERN E37123, 8 MW)	72% (IOT) -> greater than 90% demonstrated in KlyC/CST PIC (Tristron)

Critical Path for RF Sources

- ***Operational cost***
- Cost of 1 MW-Year: ~ $1M (Assuming ~120$/MWh and ~8000 hrs/yr).
  - FCC-ee RF Budget: 100 MW of RF power delivered to the beam.
    - At 60% Efficiency (Standard Klystron): Wall Plug Load = 167 MW.
    - At 85% Efficiency : Wall Plug Load = 117 MW.
- 50 MW Savings = $50 Million / Year in pure electricity costs.

- **Production Cost (Capital):**
  - CW Sources (State of the Art in 2017): ~$5.00/W Watt average.
  - Pulsed Sources (State of the Art in 2017): ~$20.00 per kW (Peak Power).
- ***Efficiency:***
  - CW Baseline: >50-60% Efficiency.
  - Pulsed Baseline: 35-45% Efficiency.

Magnetron-based systems are the only technology ~ **$1.00/W** (~**$0.50/W** for industrial units).

Khabiboulline, Yakovlev, Kroc

In 2026 RF source production cost is $3.5/W average (estimated based on HE IOT)

Enabling Future Colliders: R&D for an "offshore Higgs factory" (like FCC-ee) and a 10 TeV pCM muon collider.

these machines are only feasible if their power consumption is drastically reduced. High-efficiency RF sources are the primary technology identified to achieve this!

Physics of Efficiency in Linear Beam Devices

DC Beam Power → RF Power Conversion

Total Efficiency Decomposition: $\eta_{total} = \eta_{electronic} \times \eta_{circuit} \times \eta_{collector}$

Electronic Efficiency (η_e)

Fraction of beam kinetic energy transferred to RF field. Limited by:

- Bunching quality
- Transit angle effects
- Beam velocity spread

Circuit Efficiency (ηc)

Fraction of RF energy coupled out (vs. dissipated in cavity walls):

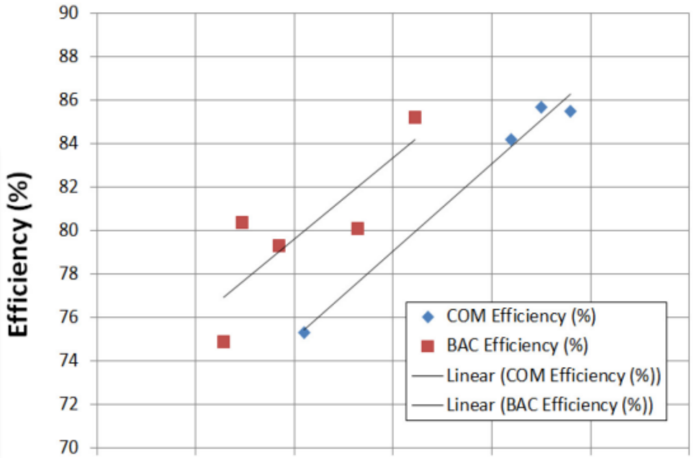
- Cavity Q-factor
- Ohmic losses
- Mode purity

Collector Efficiency (ηcoll)

Energy recovered from spent beam:

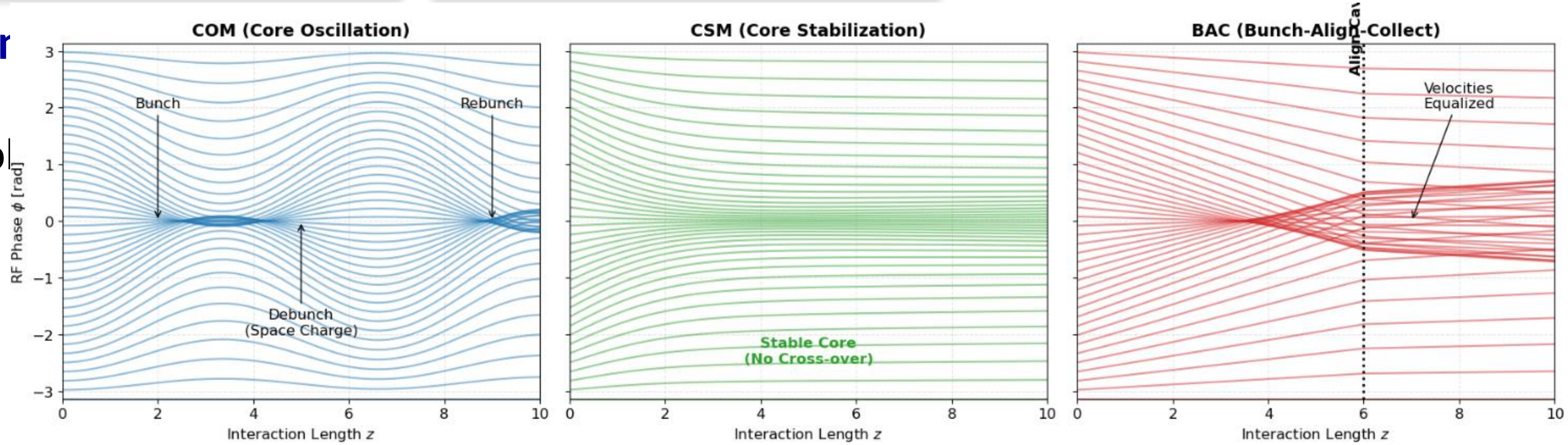
- Depressed collectors
- Multi-stage sorting
- Thermal management

$\eta coll = 1 - Pcoll / Pspent$



- **Limiting factors for power ger**
- Bunch saturation
- Electron energy spread versus p
  congregation).
- Radial stratification.

- **Advanced techniques for higher efficiency**



Bunch-Align-Collect (BAC) Core Oscillation (COM) Core Stabilization (CSM)

5045 Klystron: Efficiency Improvements

- 5045 klystron is workhorse of LCLS
- Still significant opportunities for improvement in performance.
- ➢ Retrofitting the 5045 for higher efficiencies

Ongoing efforts toward modernizing 5045 production pipelines.

Experimental work (2015-present)

1. Additional bunching cavities
2. Adding multi-stage depressed collector

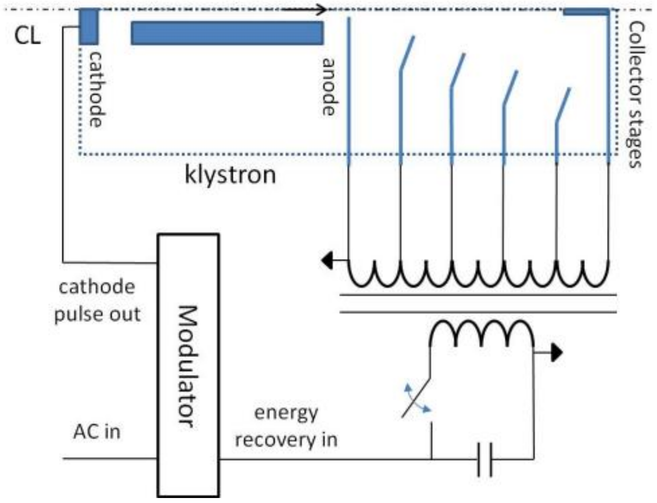
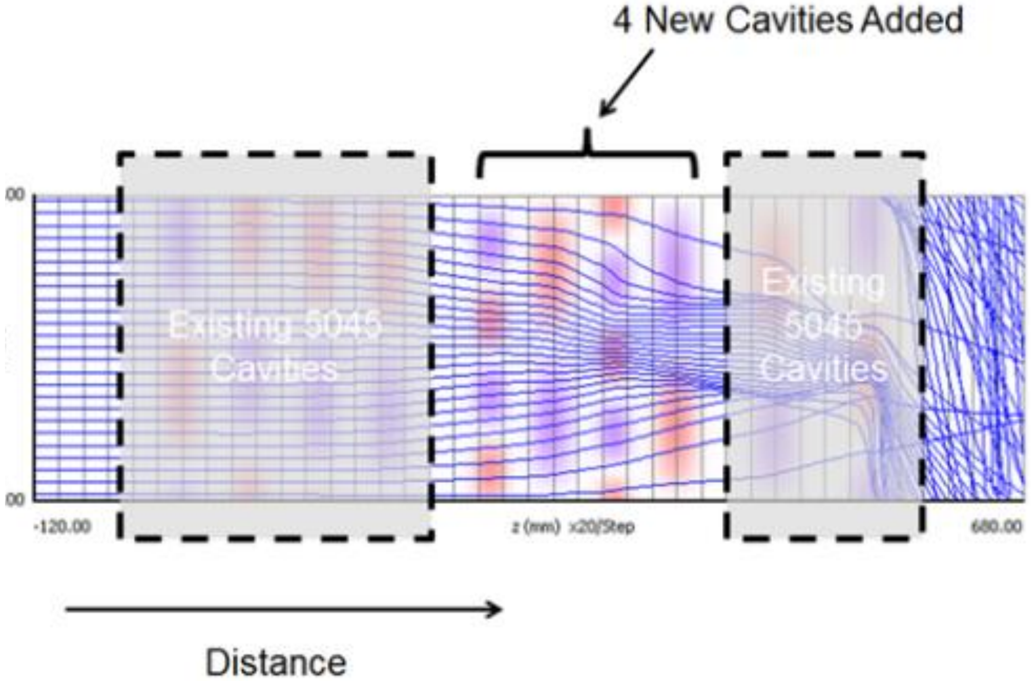


Table 1. Calculated improvements in system efficiency for two SLAC klystrons.

	XL4	5045
Peak Power (nom.)	50MW	58MW
Klystron efficiency	41%	45%
System Efficiency (no recovery)	29%	37%
Depressed Collector Efficiency (assumed)	55%	55%
System Efficiency (with recovery)	50%	57%
Collector Power (no recovery)	22 kW	41 kW
Collector Power (with recovery)	8.8 kW	16 kW



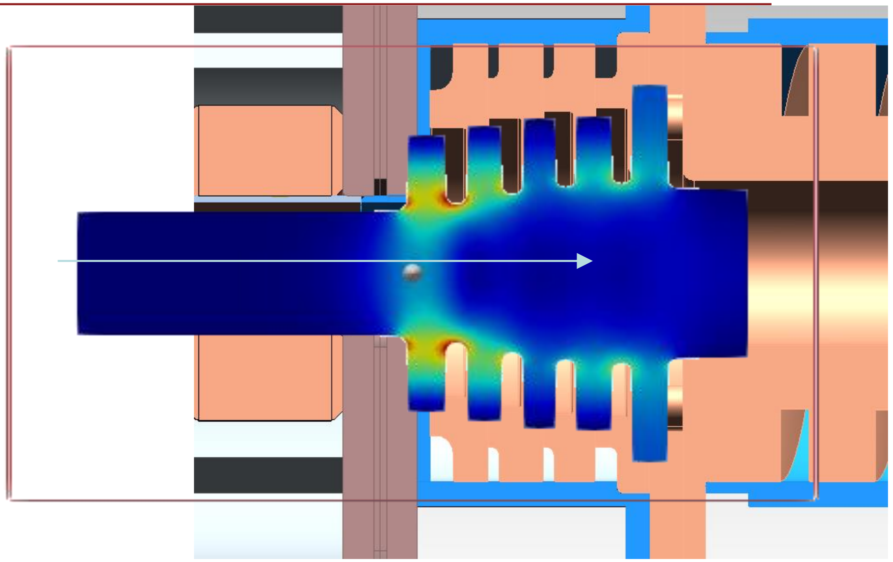
SLAC

Engineering of High Power Klystron Output Structures for Reduced Breakdowns and Increased Efficiency

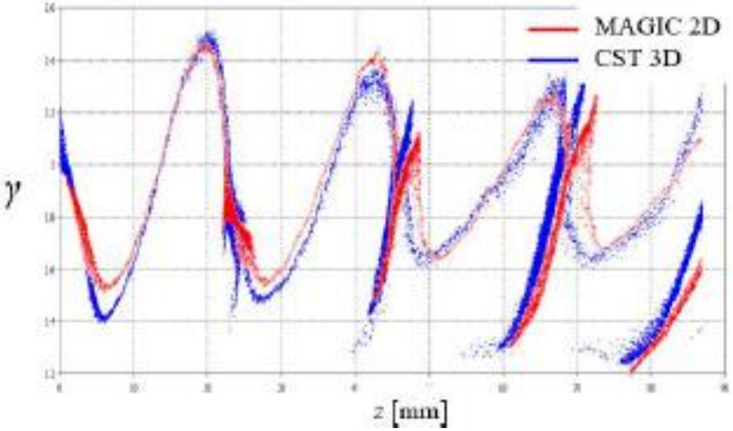
- The 75XP4 is a high power SLAC klystron fitted with a PPM to produce 75 MW at 11.424 GHz.
- Output structure is a tapered impedance constant gradient traveling wave structure

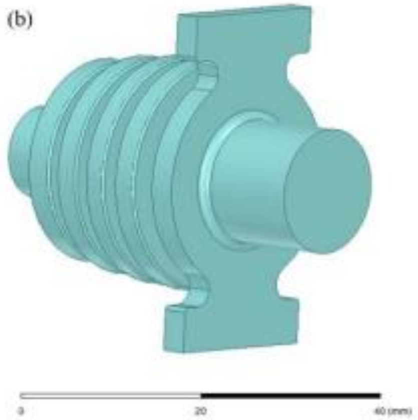
Optimized the output structure to reduce RF breakdown risk and increase extracted power

- Adjusted output cell shape and iris to reduce peak E and H fields. Pulse heating reduced substantially
- Increased efficiency by >6%



Output Pulse Heating Reduced
152 K → 60 K at 75 MW





	Baseline	**Redesigned**
Peak E field	108 MV/m	**100 MV/m**
Peak H field	500 KA/m	**303 KA/m**
Poynting vector	2.24 W/um^2	**2.24 W/um^2**
Pulsed heating 1.6 us pulse	**152 C**	**50 C**
Efficiency	59%	**65%**

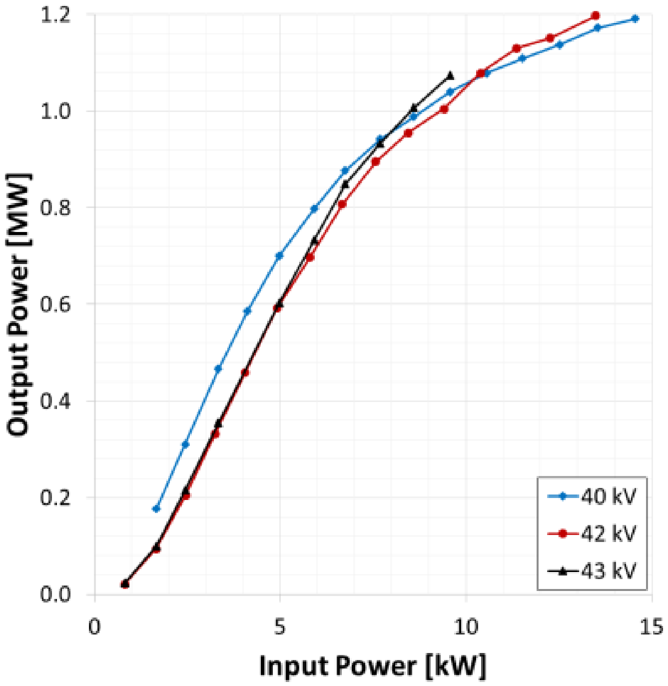
Othman, et al. "Design of A Low Magnetic Field Coupler For Output Structure of The SLAC 75XP4 Klystron." *2024 Joint International Vacuum Electronics Conference and International Vacuum Electron Sources Conference (IVEC+ IVESC)*. IEEE, 2024.

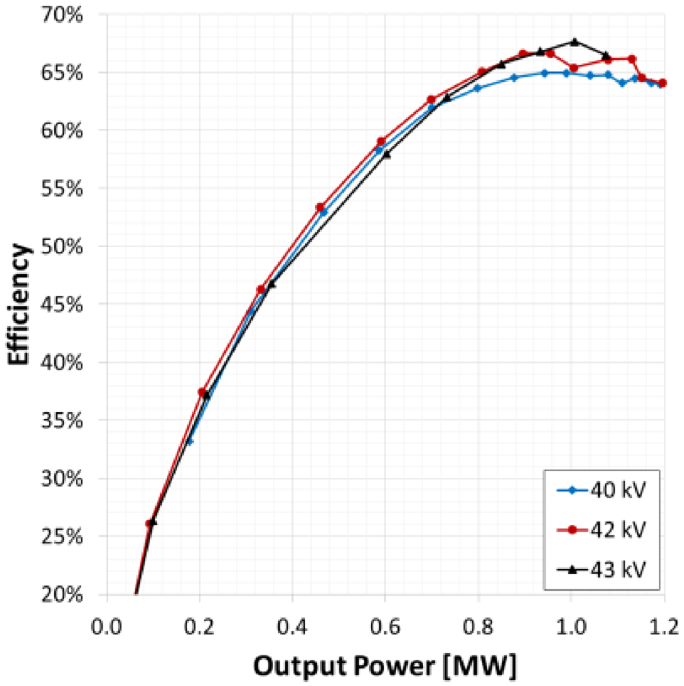
SLAC

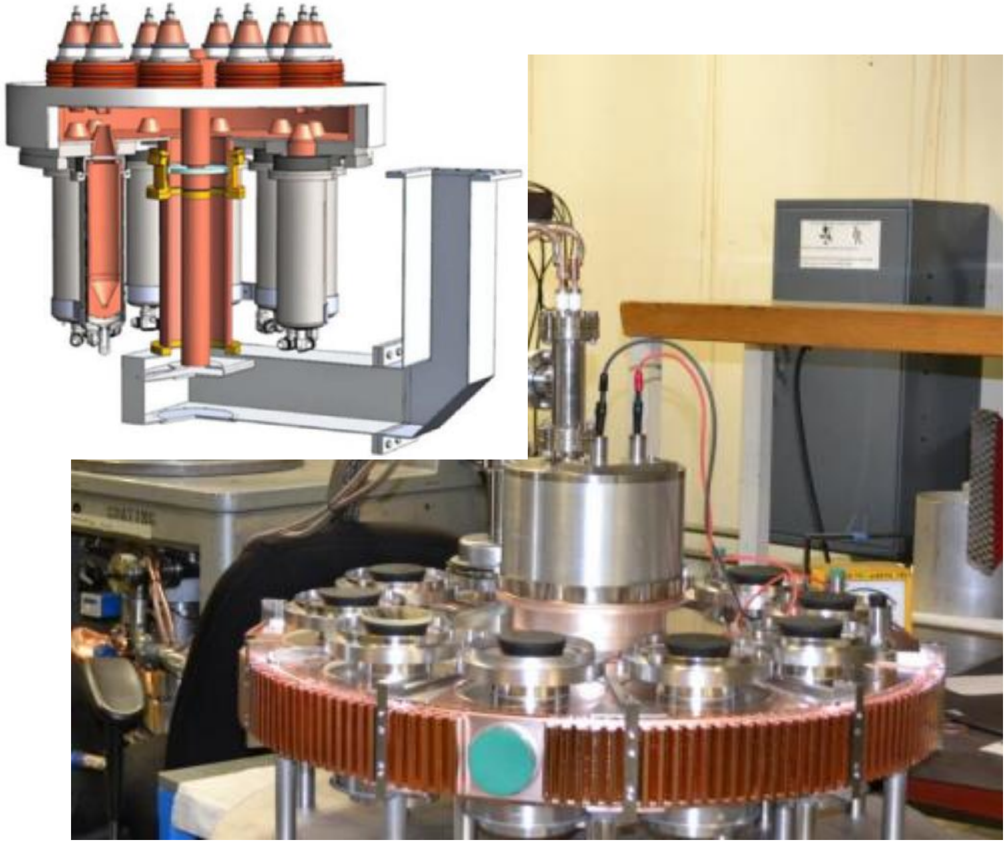
MB IOT – Route to Higher Beam-to-RF Efficiency

- MBIOT is a collaborative effort between SLAC and L3 (Stellant)
  - Power of 1.2 MW was demonstrated at 40 and 42 kV •
  - Efficiency above 65% from the 1.2 MW power level down to 650 kW
  - Gain over 20 dB was demonstrated at most power levels, with maximum gain of 21.9 dB

Prototype was successfully delivered to ESS





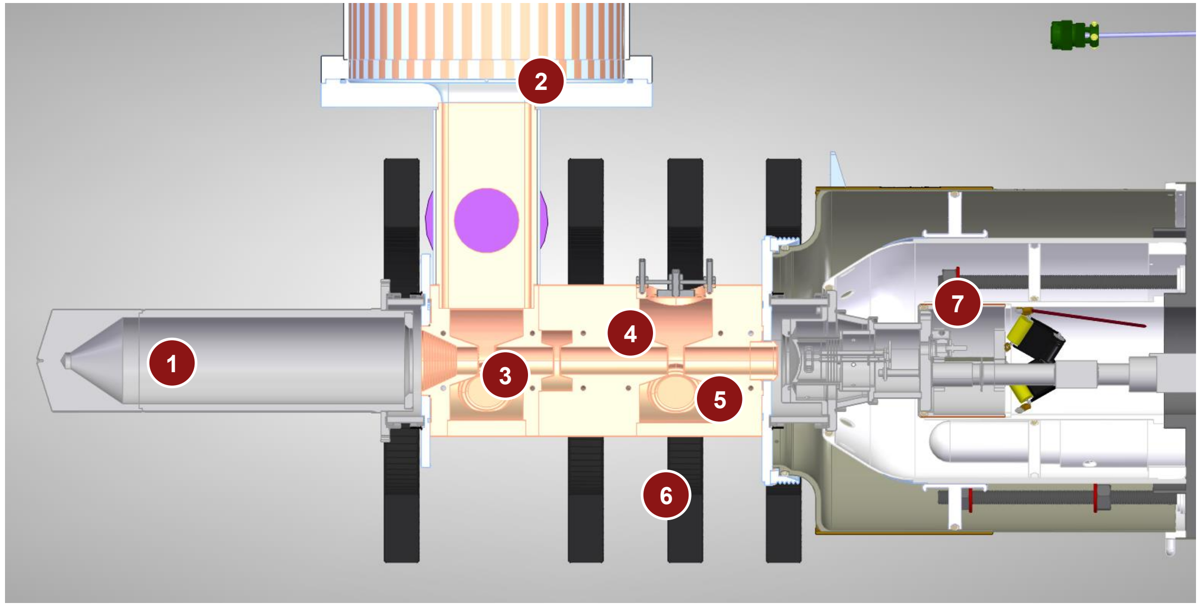


High-Efficiency IOT (HEIOT): Concept and Design Point

- The HEIOT program is developing a scalable 1.3 GHz CW amplifier delivering 100 kW of RF output at greater than 80% efficiency.
- The efficiency gain comes from a full 3D optimization of the velocity distribution produced by the gated electron gun.
- The RF circuit uses three cavities: idler, second harmonic and output.

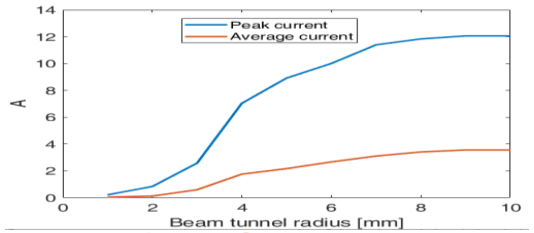
Parameter	Value
Cathode voltage	40 kV
Frequency	1.3 GHz
Input RF power	550 W
Grid bias	-220 V
Average beam current	3.2 A
Peak focusing B-field	470 G
Output power	100 kW
Cavity configuration	Idler, 2nd harmonic, output

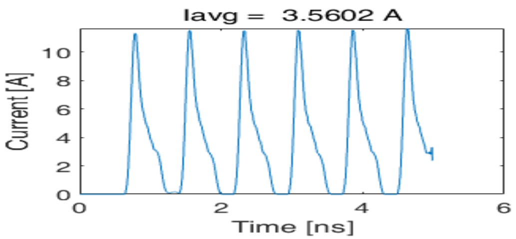
HEIOT assembly cutaway



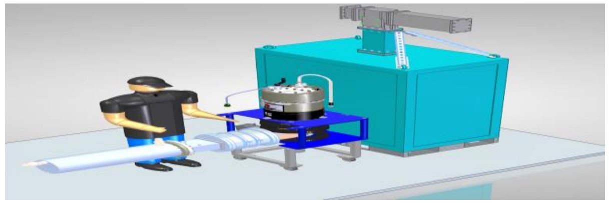
1 Collector 2 Window and waveguide 3 Output cavity 4 Iris 5 Input cavity 6 Solenoids 7 Electron gun

Simulated gun current

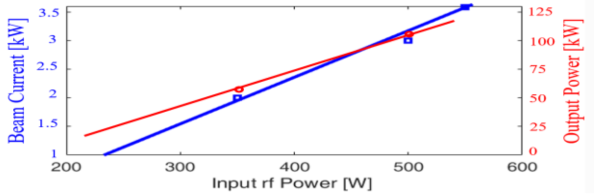




Gun and tank assembly



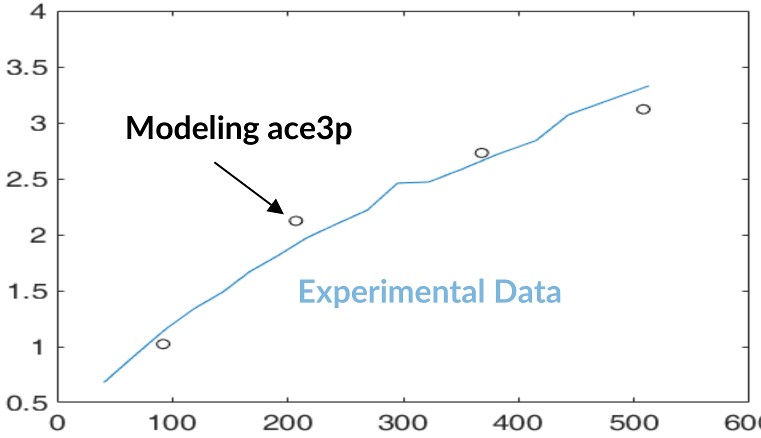
Simulated transfer curve



3D Modeling, Benchmarking and Thermal Analysis

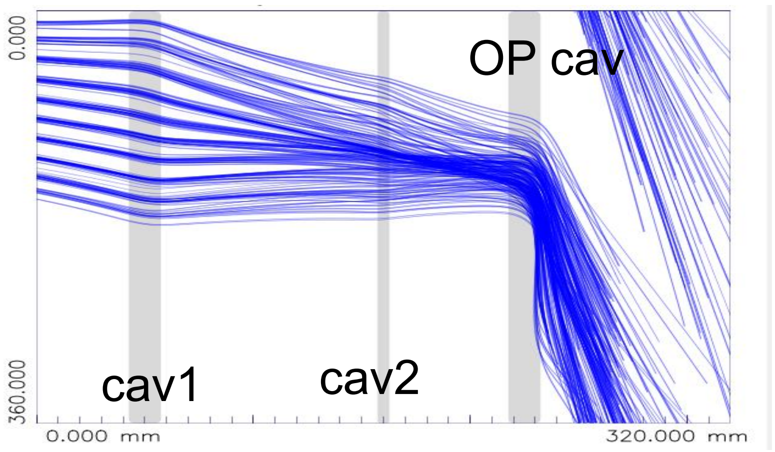
- ACE3P provides accurate 3D models of beam dynamics in space-charge-limited RF guns, and the simulated beam current follows the measured data over the full RF drive range.
- The single-beam HEIOT RF circuit achieves greater than 80% efficiency at 100 kW and 1.3 GHz with the complete 3D geometry included.

Beam dynamics benchmark



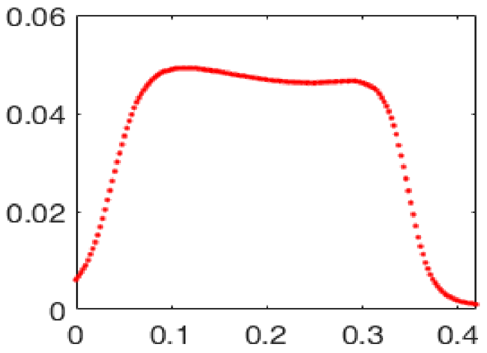
Beam current [A] versus RF input power [W]: ACE3P model and experimental data.

Applegate diagram

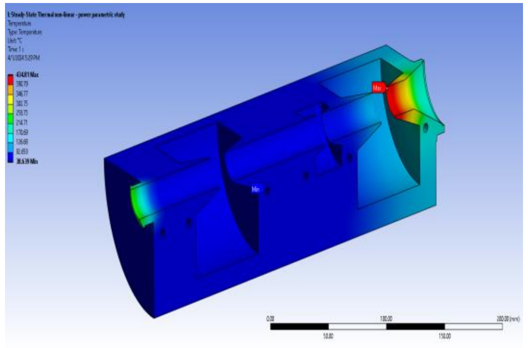


Bunch formation along the interaction region.

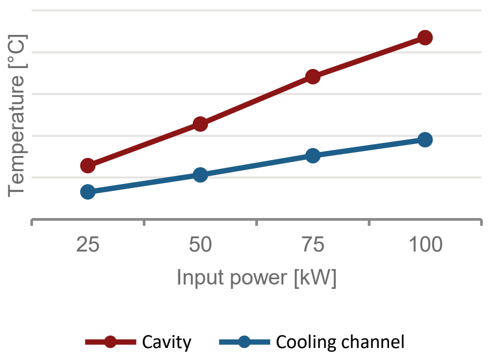
Solenoid field profile



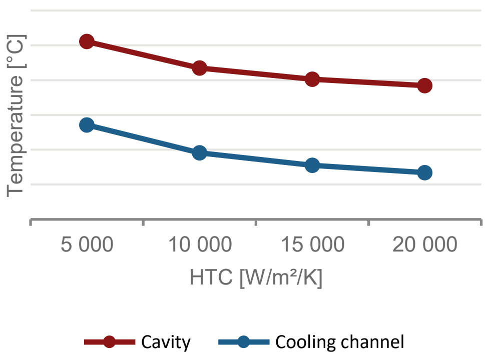
Thermal model



Max. temperature vs input power
(HTC = 10 000 W/m²/K)



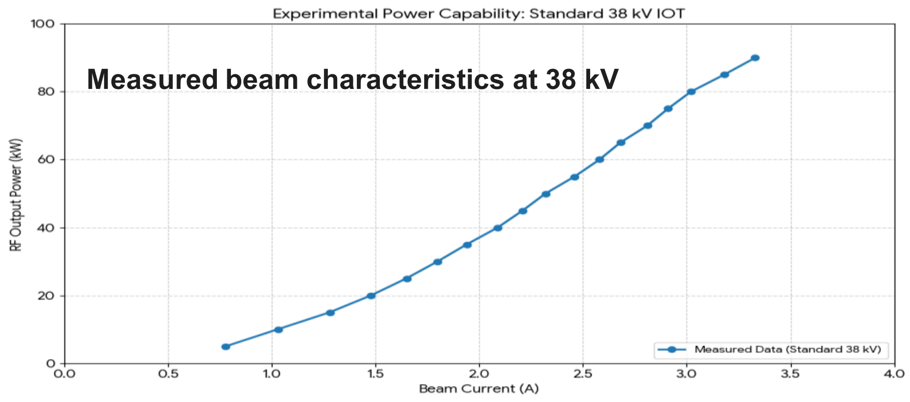
Max. temperature vs film coefficient
(P = 100 kW)



SLAC

HEIOT Production and Initial Testing Update

- Two HEIOTs are in production under the SLAC and Stellant partnership.
- The first tube developed a vacuum leak caused by the weight of the output waveguide and is being reworked.
- The second tube is in production.
- Low-power and high-power conditioning of the input cavity is in progress, and the input cavity has been tuned to 1.3 GHz.
- Initial input cavity conditioning confirms the expected RF current performance.
- The test stand at Stellant is operational and supports the 2026 test campaign.



First full tube assembly

First iteration of the full tube, now under rework.

Next steps

- Complete rework of the first tube and re-verify vacuum integrity.
- Finish assembly of the second tube.
- Start full-tube testing at Stellant in 2026.

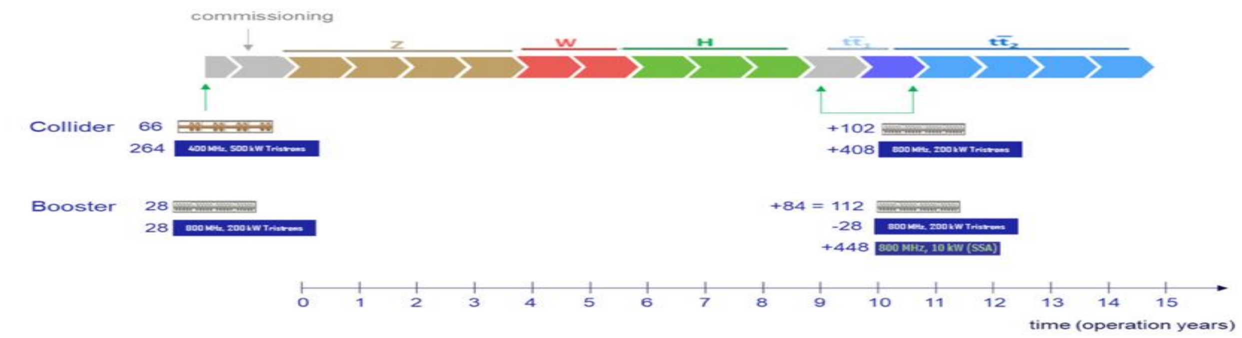
HE IOT test stand at Stellant

Future Circular Collider (FCC-ee) RF Needs

- RF acceleration accounts for more than half the energy a circular Higgs factory consumes, and FCC-ee Phase 1 is projected > TWh per year.
- FCC-ee has two distinct RF requirements: 400 MHz as the workhorse system, and 800 MHz (also for high gradient required in phase 2).
- A 400 MHz baseline prototype will be designed, manufactured and tested over the next three years*.

➢ Source efficiency sets the facility power bill.

FCC-ee RF staging

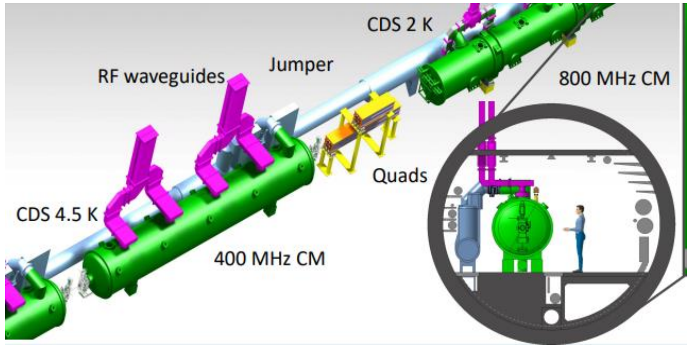


Installed source count and power by operation year.

FCC-ee RF systems			Phase 1			Phase 2		
System	Source	f (MHz)	Units	P (MW)	Total (MW)	Units	P (MW)	Total (MW)
Collider	Tristron	400	264	0.5	132	-	-	-
Collider	Tristron	800	-	-	-	408	0.2	82
Booster	Tristron	800	28	0.2	6	-28	0.2	-6
Booster	SSA	800	-	-	-	448	0.01	4
Installed RF power			**138 MW**			**80 MW**		

Total installed RF power: 218 MW

FCC-ee cryomodule layout



400 MHz and 800 MHz cryomodules with RF waveguide feeds.

*Syratchev, I., et al. "THE TRISTRON, A NEW PARADIGM IN HIGH-EFFICIENCY RF POWER GENERATION." *17th International Particle Accelerator Conf.(IPAC’26), Deauville, France*. 2026.

FCC-ee RF Power Budget and Cryomodule Count by Stage

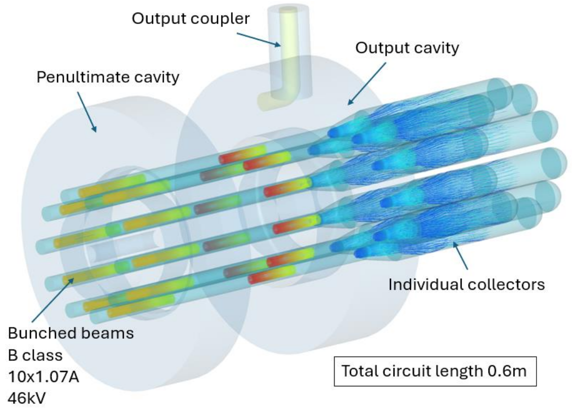
Stage	Beams	Total RF Voltage	400 MHz Cavities / Cryomodules	RF Sources Installed (Tristron)	Installed RF Power
Z pole (RPO)	1	89 MV	264 cav. / 66 CM (4 cav/CM, shared pool)	264 x 500 kW CW (400.79 MHz, 46 kV)	138 MW (Phase 1 total)
W (RPO)	1	1049 MV	264 cav. / 66 CM (shared pool)	264 x 500 kW CW	138 MW (Phase 1 total)
ZH / Higgs (RPO)	2	2098 MV	264 cav. / 66 CM (shared pool)	264 x 500 kW + 28 x 200 kW (800 MHz booster)	138 MW (Phase 1 total)
tt-bar (Phase 2 add-on)	2	+2.1 GV @400 MHz +9.2 GV @800 MHz	+~100 CM @800 MHz (est., 4 cav/CM)	408 x 200 kW (collider) +448 x 10 kW SSA (booster)	+80 MW (218 MW total installed)

One common 400 MHz SRF plant (264 cavities, 66 cryomodules, Reverse Phase Operation) covers Z, W and ZH; ttbar (Phase 2) adds an 800 MHz system. Sources: Marrelli, Catalan-Lasheras,

Syratchev, "High-Efficiency RF Sources at CERN" (RF-GARD Roadmap, Sept. 2026); Syratchev et al., "The Tristron, a New Paradigm in High-Efficiency RF Power Generation," IPAC'26 (2026); FCC Study Status Report, Nov. 2025 (Indico 1570988).

Tristron development and prototyping at CERN

FCC$_{ee}$ 400MHz, 0.5MW MB Tristron design with a <u>common input cavity</u> (CERN) and flat cathodes.



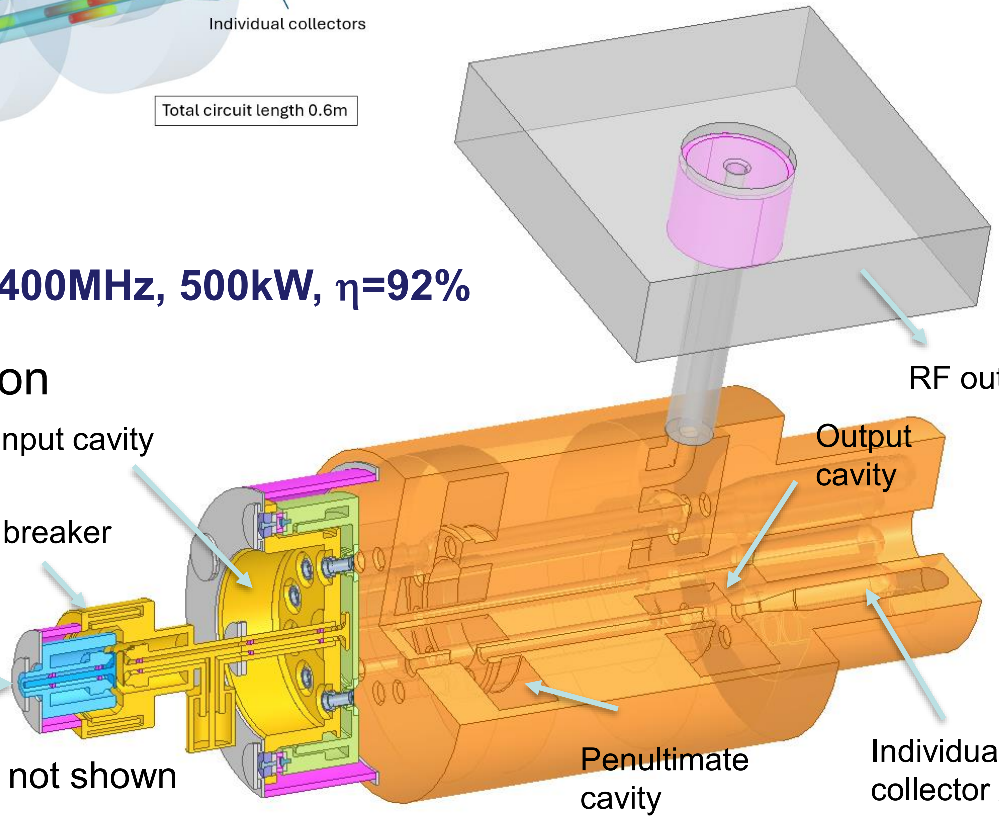
High risks of development with industry:

- technical risk (new input cavity, large ceramic…)
- commercial risk (for CERN): single supplier
- tight schedule
- Single point failures

In-house prototyping: series production via licensing or built-to-print contracts in industry

400MHz, 500kW, η=92%

“Artistic” view of the tristron



Total length 1.49m. External solenoid is not shown

Courtesy of I. Syratchev

Challenges and Path Forward

- Scaling the production of high-power RF sources to meet next-generation collider requirements requires a strong, coordinated partnership.
- Leveraging existing industrial partnership for hub provides full design, fabrication and test capability
- Providing independent build and test streams mitigate single-point-of-failure risk from vendor bottlenecks, specialized tooling and long-lead parts, and accelerate the FCC-ee RF roadmap.

SLAC test infrastructure

Risk: the absence of 800 MHz demonstrator hardware can jeopardize the 2028 approval path and the timely testing of SRF systems.

1 Fast track

- 800 MHz, 50 kW rapid prototype
- Low cost, short lead time
- Proven mature technology (IOT)

Provides 800 MHz demonstrator hardware on the shortest schedule.

2 Twin build (redundancy)

- 400 MHz, 500 kW
- Copy of the CERN design
- Second supply chain

Adds a second supply chain for the 400 MHz workhorse system.

3 Collider expansion

- 800 MHz, 200 kW
- Joint engineering
- Scaled from the 400 MHz design

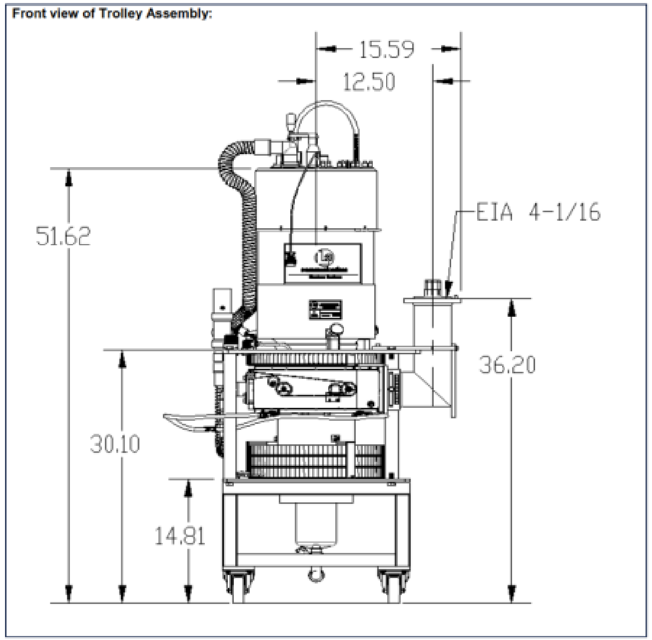
Extends the validated design to the phase 2 requirement.

800 MHz Sources Development

- There is currently no commercially available high-efficiency (>80%) RF source at 800 MHz in the 50–200 kW power range.
- Standard commercial IOTs at this frequency (e.g., TV broadcast tubes) “can” operate at **>70% efficiency**.

Very high reliability with average >100 kh operation

- Broadcast IOTs UHV operates from 470 – 800 MHz up to 90kW
- HE IOT techniques can be readily applied to achieve >85% at 50 kW

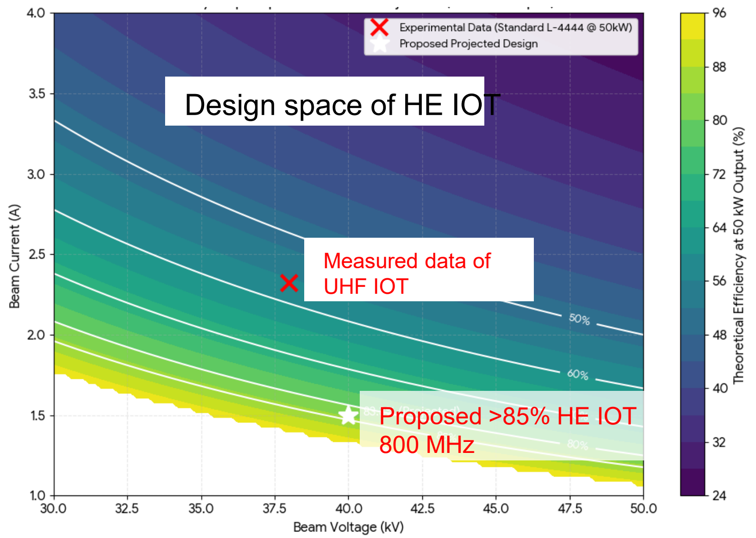


Frequency	800.xx MHz
Output Power	50 kW CW
Beam Voltage	30-40 kV
Beam Current	1.5-2 A
Core Technology	IOT Geometry, with harmonics and post acceleration
Target Efficiency	> 85%

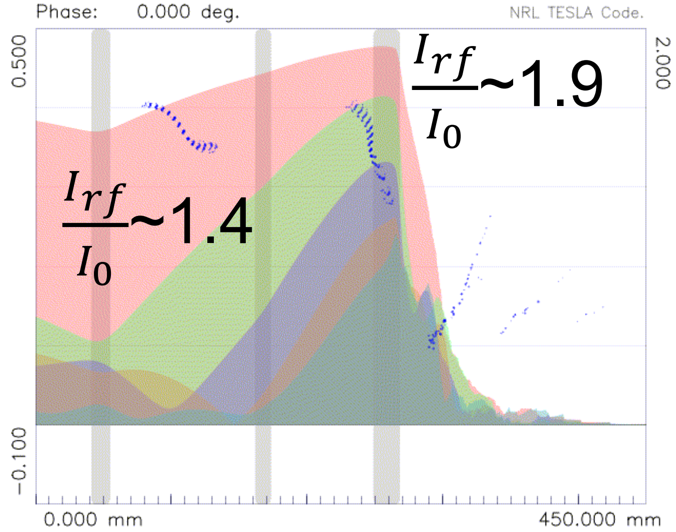
Preliminary Design of the HE IOT at 800 MHz

- High-efficiency IOT in a 1-2-1 cavity scheme, with the first cavity placed approximately 110 mm from the gun.
- ACE3P simulations confirm a stable 40 kV beam at 0.25 microperveance.
- Focusing uses a standard solenoid with a peak field near 453 G.
- The design point targets greater than 85% efficiency at 800 MHz and scales for FCC-ee.

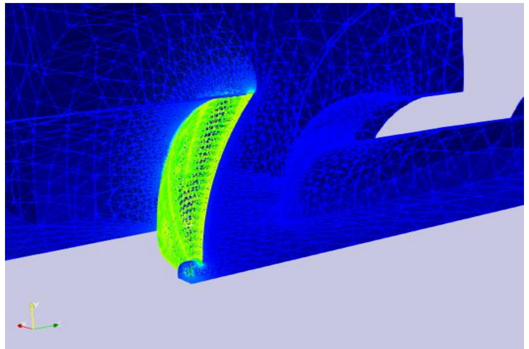
Design space of the 800 MHz HE IOT



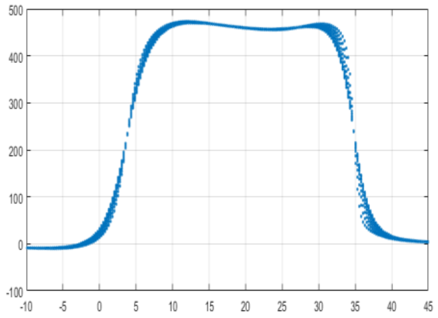
Phase space of saturated bunches



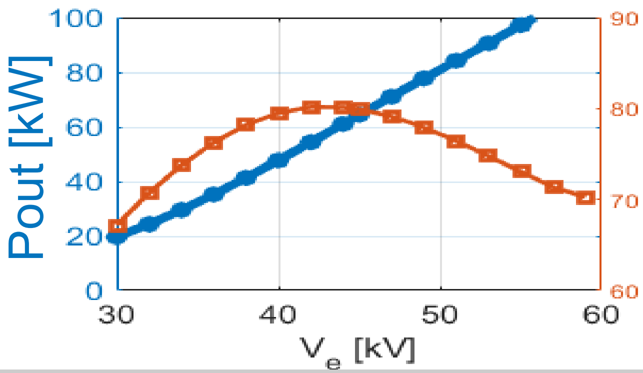
ACE3P gun model



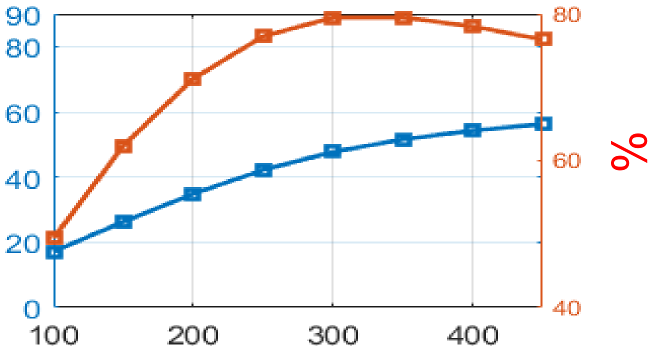
Solenoid field profile



Sweep: beam voltage



Sweep: RF drive



- A scalable design above 85% efficiency at 800 MHz, based on mature IOT technology, answers the FCC-ee efficiency target and the drive toward sustainable power consumption.

Summary

- FCC-ee RF sources need collaborative partnership to overcome manufacturing bottlenecks and supply chain
- Baseline for FCC needs both 400 MHz and 800 MHz
- Future potential of high efficiency IOTs in FCC-ee as a “mature” technology to be used for the 800 MHz
- Compact solution to UHF toward MW for industrial and medical applications