Designing Radio Frequency Cavities with Advanced Computational Methods

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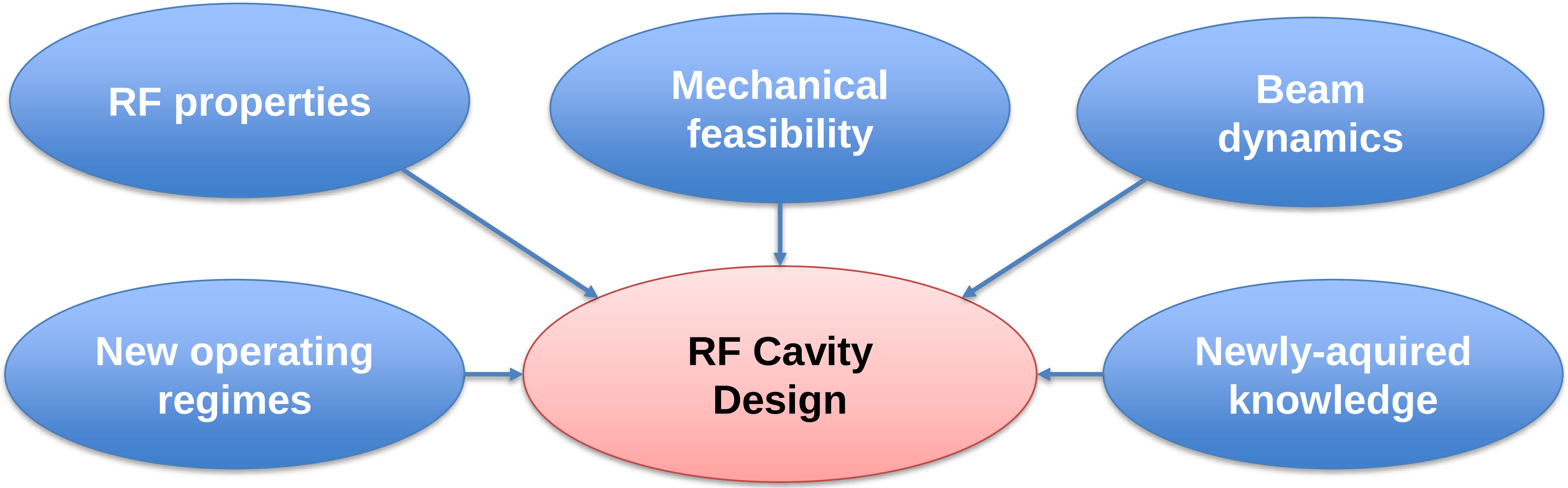
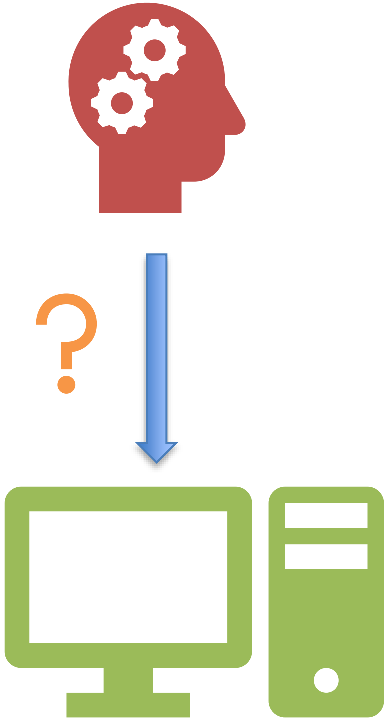
RF cavity design: a complex Multi-objective Optimization problem

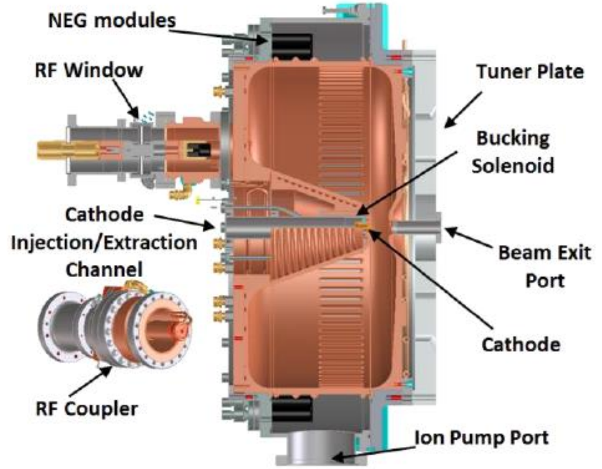




- Mostly done by conventional methods: “trial-and-error”, strongly relies on human judgement.
- Limitations: large number of geometry parameters, multiple design considerations, *competing* design goals.
- A new design method is much needed for the future RF cavities with ever-increasing complexities.

A prototype program based on MOGA

Re-entrant gun cavity in APEX, a CW high brightness e⁻ source

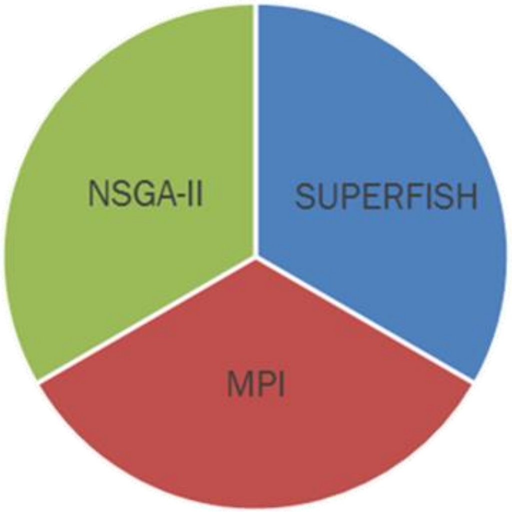


Key design goal: increasing electric field *E* on the cathode.

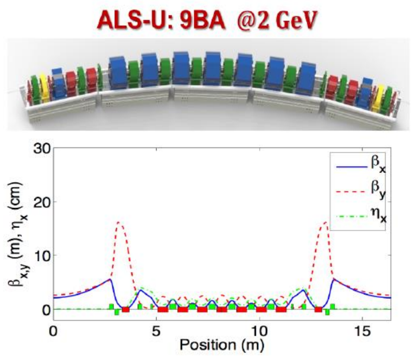
MOGA for accelerator lattice design ✓

MOGA for RF cavity design ?

- NSGA-II: a well-tested, widely used MOGA
- SUPERFISH: RF solver
- Message Passing Interface: parallel computing



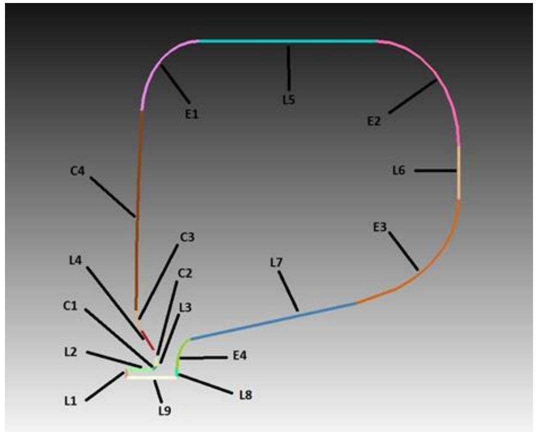
APEX2: based on the success of APEX, further reducing the beam emittance significantly, challenging RF design.



Multi-Objective Genetic Algorithms (MOGA)

- Inspired by evolutionary theory “survival of the fittest”
- Extensively used in the multi-objective problems to search for global optimums.

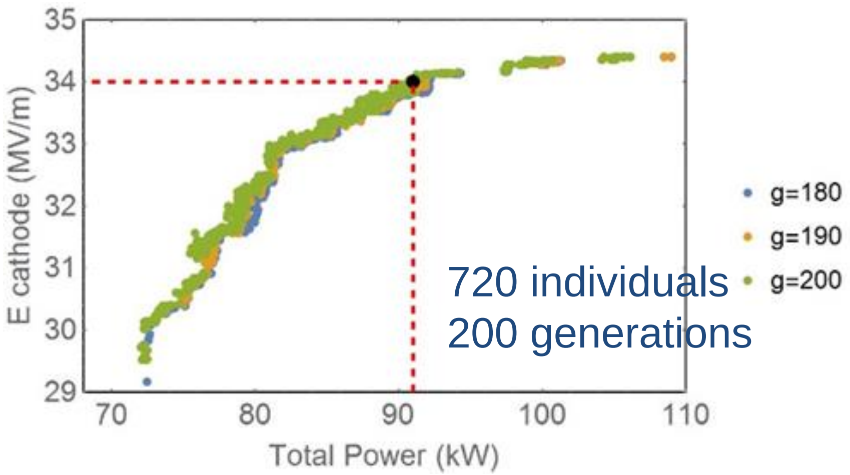
Applying the prototype program to APEX2 gun cavity design



Parametrizing cavity geometry

Objectives	Constraints
With total voltage $V = 820\ kV$	Peak surface field $E_{peak} < 37\ MV/m$
1) Maximize cathode field $E_{cathode}$	Peak power density $PD_{peak} < 35\ W/cm^2$
2) Minimize total RF power P_{total}	RF frequency $f = 162.5 \pm 3\ MHz$
	Cavity radius $R < 41\ cm$
	Extrusion on anode side $K < 2\ cm$

Multiple design considerations are quantitatively defined as “objectives” and “constraints” in MOGA.

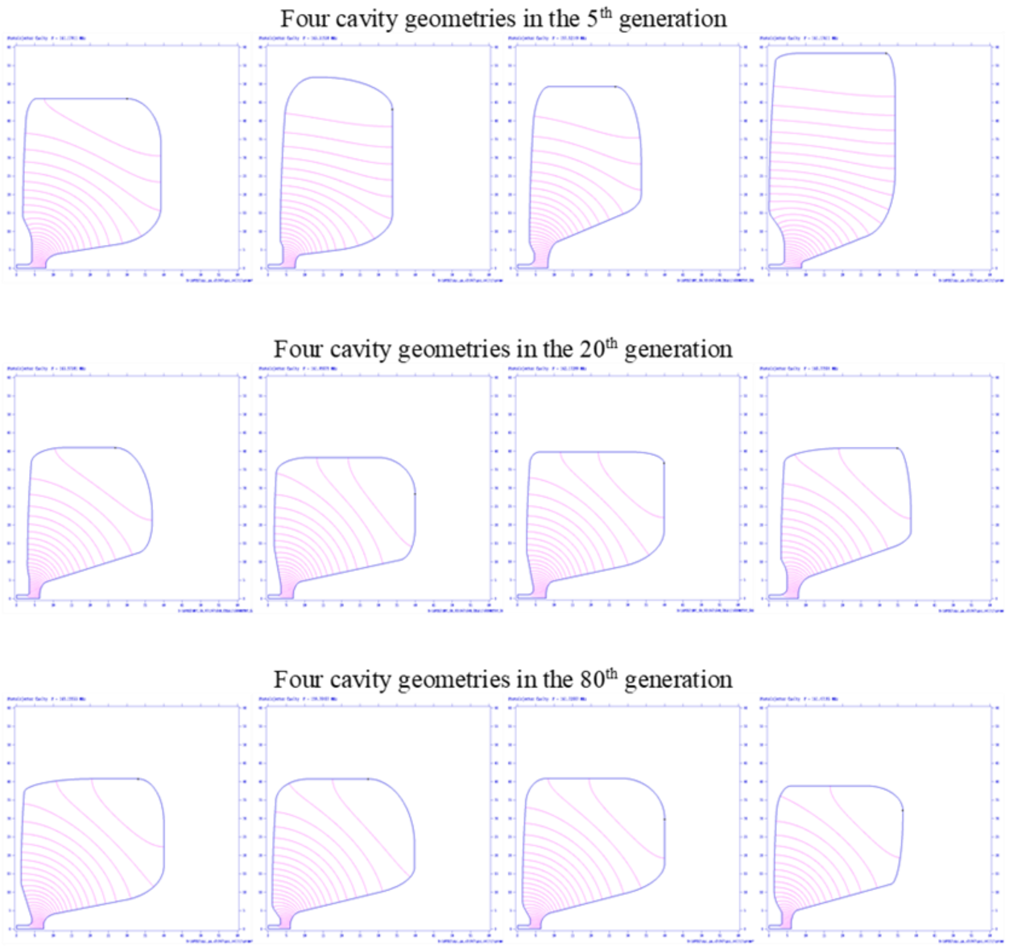


Converged Pareto front in NSGA-II

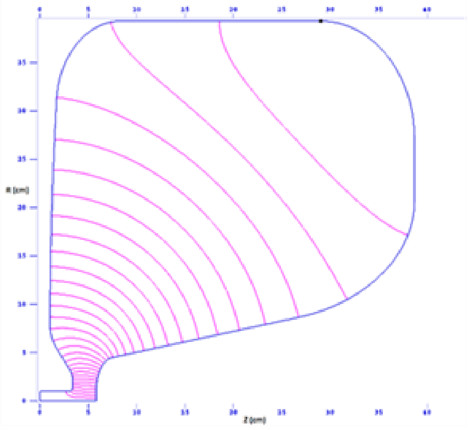
Parameters	APEX	APEX2
f (MHz)	185.7	**162.5**
V (kV)	750	**820**
$E_{cathode}$ (MV/m)	19.5	**34.0**
E_{Peak} (MV/m)	24.0	**37.0**
$E_{cathode}/E_{Peak}$	81%	**92%**
Total RF Power (kW)	88.5	**90.7**

- Significant increase of $E_{cathode}$.
- Same level of RF power.
- Increased $E_{cathode}/E_{peak}$.
- Injector beamline achieved a normalized ε_{xn} (95%) ≈ 0.09 μm @ 100 pC and 12.5 A.

Applying the prototype program to APEX2 gun cavity design



Cavity geometry evolution at the 5th, 20th, 80th generation.

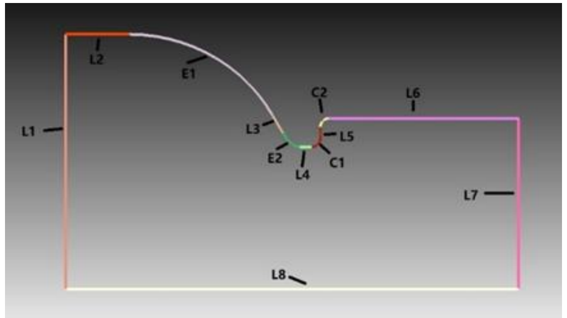


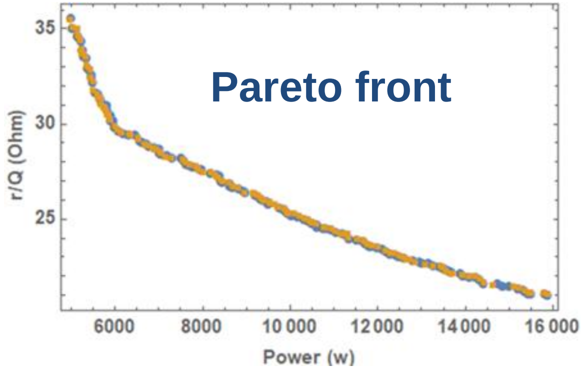
APEX2 gun cavity final design, chosen from the 200th generation.

Applying the prototype program to ALSU 3rd Harmonic Cavity Design

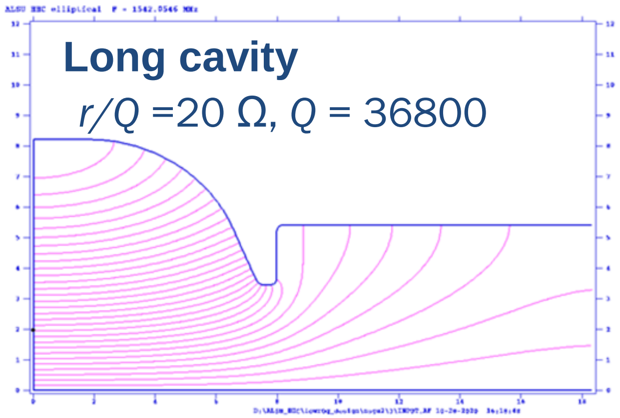
- 3HC system on ALSU: lengthen the bunch to alleviate the Touschek effect and achieve the target beam lifetime.
- Passive cavity, to keep the beam instability within control, the total *r/Q* of the 3HC system should be no more than 50 Ω, thus 25 Ω for each cavity.
- How to achieve such a low *r/Q* is a major design challenge for ALSU 3HC.

Obejectives	Constraints
Minimize total power P_{total}	RF frequency f=1.5 +/- 0.03 GHz
Minimize r/Q	Peak power density PD_{peak}< 35 W/cm^2
	Cavity total length $L < L_{max}$

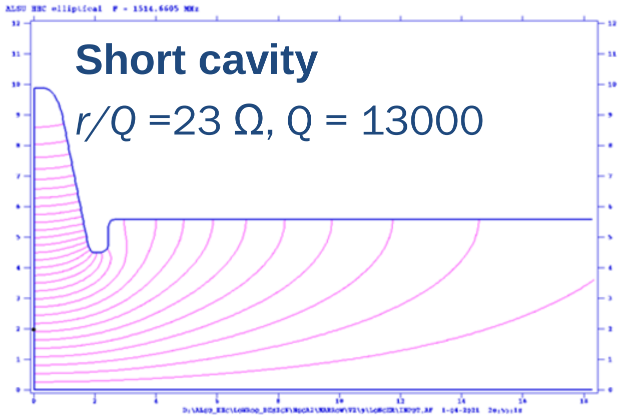




The program finds two ways to achieve low *r/Q*:



Bunch sees not only the accelerating field but also the decelerating field when passing through the cavity, What we expected.



Large E_z area is no longer concentrated along the central axis but spreads out along the radial direction. We didn't though of this way before the program presented it.

Neither is chosen for ALSU 3HC for other considerations. Still, it is encouraging to see the program can find an approach we didn't though of.

Characters and advantages of an algorithm-based design program

- Multiple design requirements can be considered at the same time. They are quantitatively defined as objectives or constraints in the algorithms. With proper algorithms, the optimization process can be systematic and comprehensive with minimum human interference.
- Where there are competing design goals, the Pareto front can serve as a more informative way for the designer to choose the final design. The Pareto front also presents the relations between the competing goals and may reveal the underlying physics pictures.
- The effective and efficient algorithms can achieve considerable improvement on the designs that have already been highly optimized by human designers. Moreover, they could lead to novel designs that have not been thought of by human designers.
- With the aid of high-performance computing (HPC), the optimization can be finished within a few days. The fast turn-around time is especially useful for multiple rounds design iterations with feedback from beam dynamics study and engineering analysis.

An algorithm-based design paradigm can fundamentally change how we design the RF cavity. With the tedious iteration process taken by computer, the human intelligence now resides in choosing the efficient searching algorithm, constructing the parameterized geometry with ample flexibilities, and defining the proper objectives and constraints for the cavity design requirements. The design focus shifts from directly searching for a good RF cavity design, to setting up an efficient and effective computational procedure that can lead to a satisfying design.

Development beyond the prototype program

- The algorithm-based design methods will be very useful to various RF design challenges for both NCRF and SRF. The capabilities of the prototype program are still very limited. Much more work is needed to build a comprehensive design program applicable to a broad range of cavity design problems.

- Cavity figures of merit calculator
    - Both 2D and 3D solvers, solving not only the working mode by also the HOMs.
    - Comprehensive post-processing programs, from basic RF parameters to more complex properties such as MP, LFD, etc.
    - Flexible parameterized geometry constructions
- Multi-objective optimization algorithms
    - MOGAs beyond NSGA-II.
    - Surrogate modeling, significantly reduce the number of times of full EM field calculation.
    - Exploring other machine learning approaches.
- High performance computing
    - Parallel computing.
    - Utilizing large clusters such as NERSC.