Cornell University
Laboratory for Elementary-Particle Physics

USPAS course on
Recirculated and Energy Recovered Linacs

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Ongoing ERL R&D Cornell

Jefferson Lab

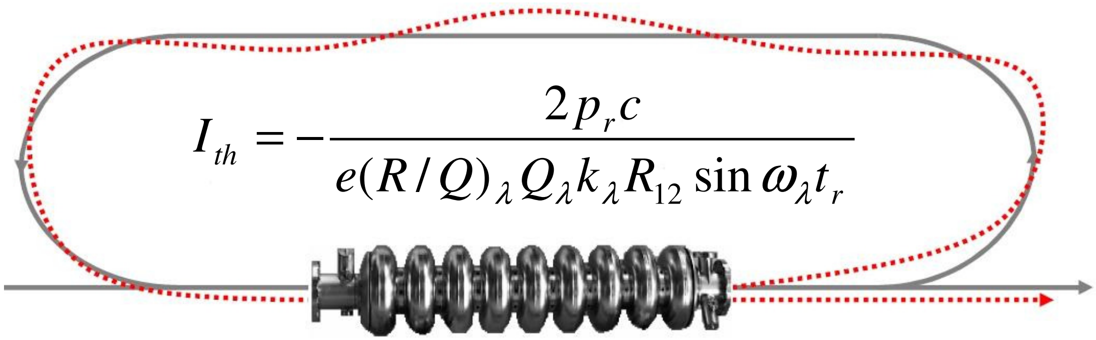
Contents

- Challenges
- Cornell ERL prototype
- Experimental program

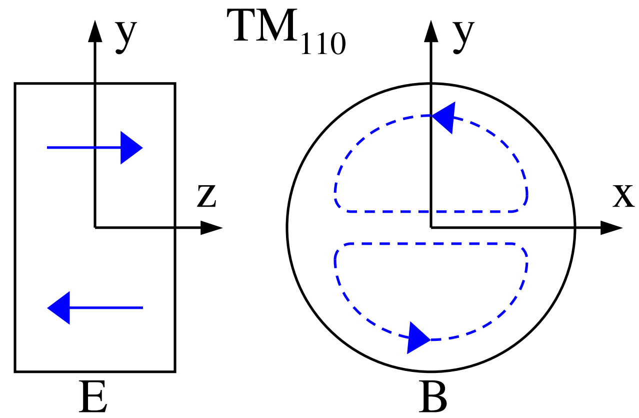
Challenges

- CW injector: produce 100 mA, 80 pC train @ 1300 MHz, in < 1 mm-mrad normalized emittance, low halo with very good photo-cathode longevity
- Maintain high Q and E_{acc} in high current beam conditions
- Extract HOM's with very high efficiency (P_{HOM} ~ 10x previous)
- Control BBU by improved HOM damping
- Maximize loaded Q_L (control microphonics)
- Beam instrumentation and diagnostics of low energy high power beams

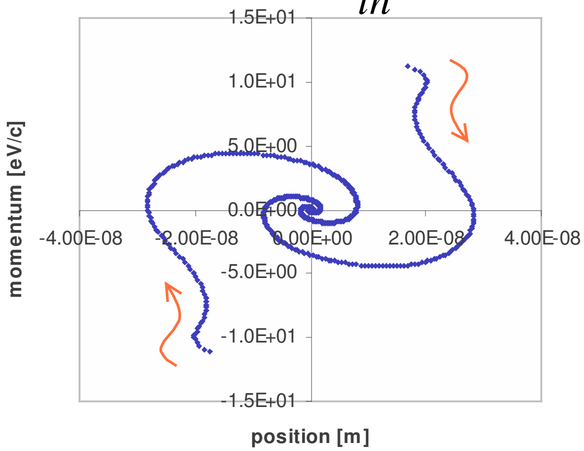
Beam breakup: challenge



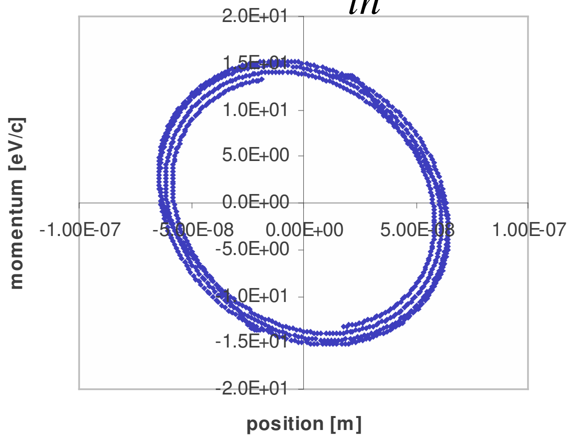
$$I_{th} = -\frac{2 p_r c}{e(R/Q)_\lambda Q_\lambda k_\lambda R_{12} \sin \omega_\lambda t_r}$$



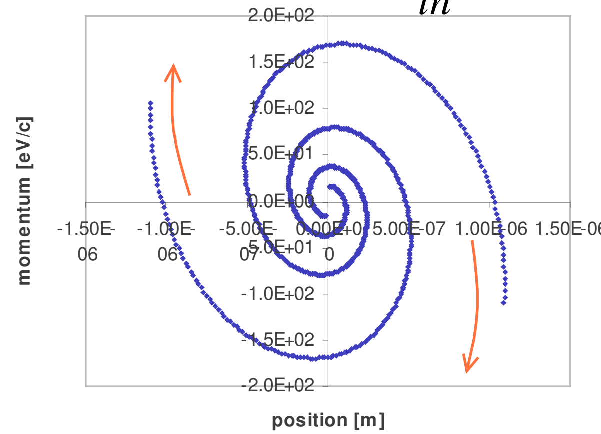
below I_{th}



near I_{th}



above I_{th}



Highest current recirculated in SRF linac was ***4.5 mA*** *in year 2001*

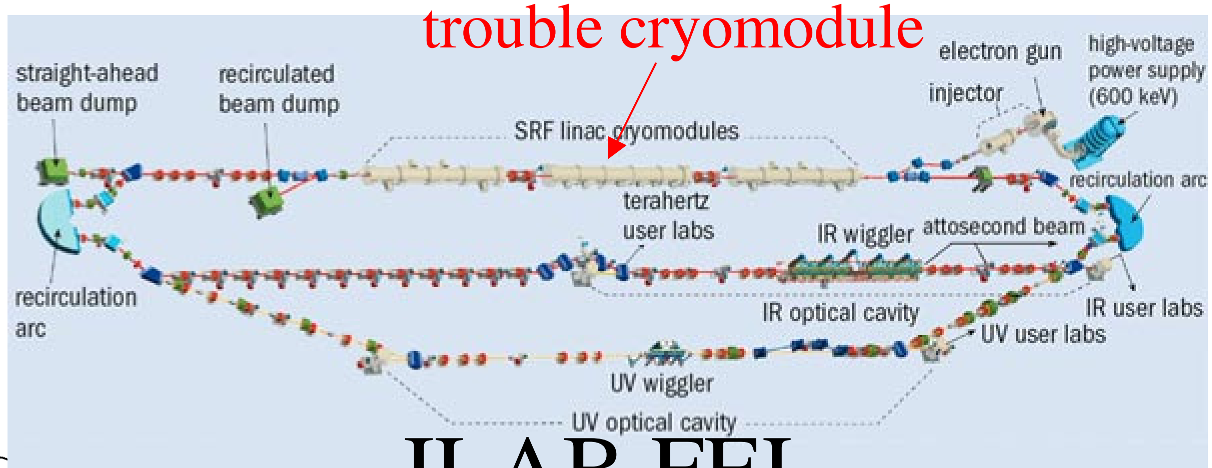
Beam breakup: figured out

- BBU code & theory developed for ERLs (JLAB, Cornell, JAERI)
- Benchmarked with good accuracy in JLAB FEL

Douglas, Jordan, Merminga, Pozdeyev, Tennant, Wang, Smith, Simrock, Bazarov, Hoffstaetter, Phys. Rev. ST: AB 9, 064403 (2006)

- Various suppression techniques successfully tested

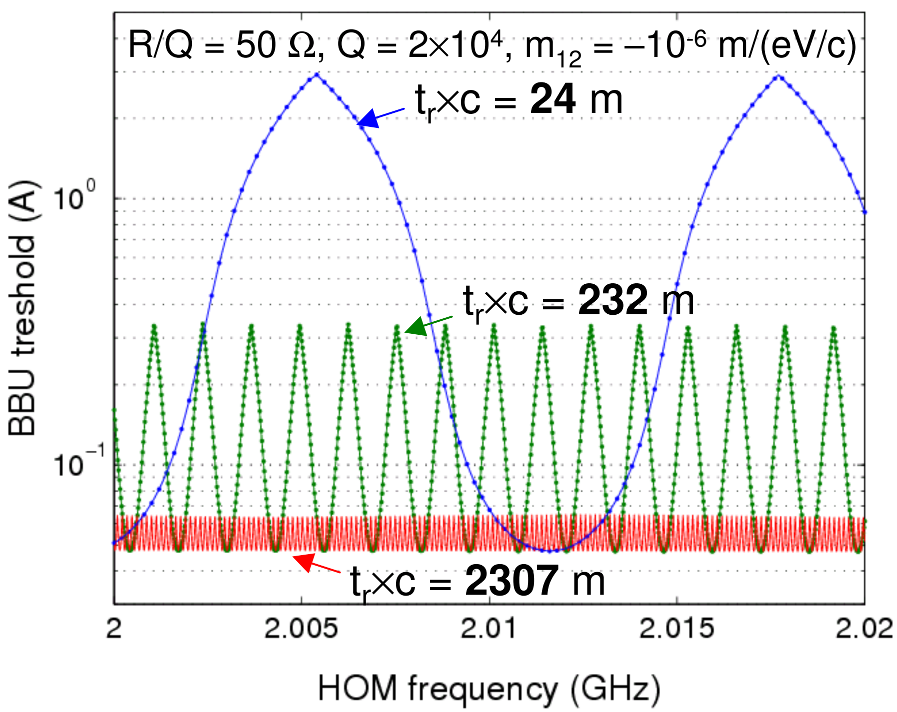
trouble cryomodule

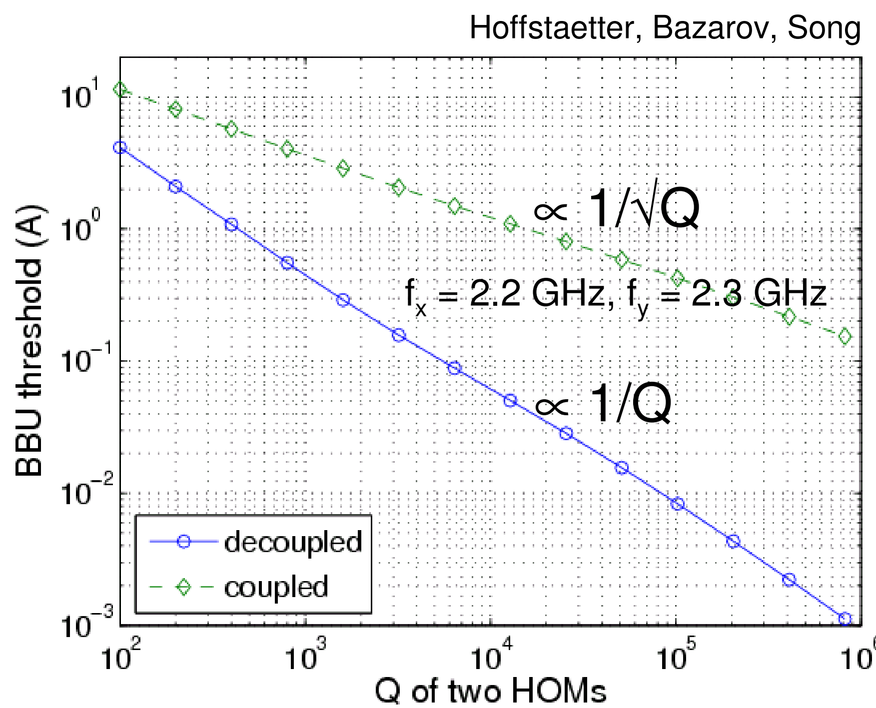


JLAB FEL

BBU: Theory & Computation

- Several different codes (JLAB, Cornell, JAERI)
- Mature theory; excellent agreement with codes





Injector prototype beam goals

- Demonstrate efficacy of achieving thermal emittance at the end of the injector at a bunch charge of 77 pC/bunch or some large fraction thereof
- Understand the limitations in the injector (both physics and technology) to allow for improved design in the future

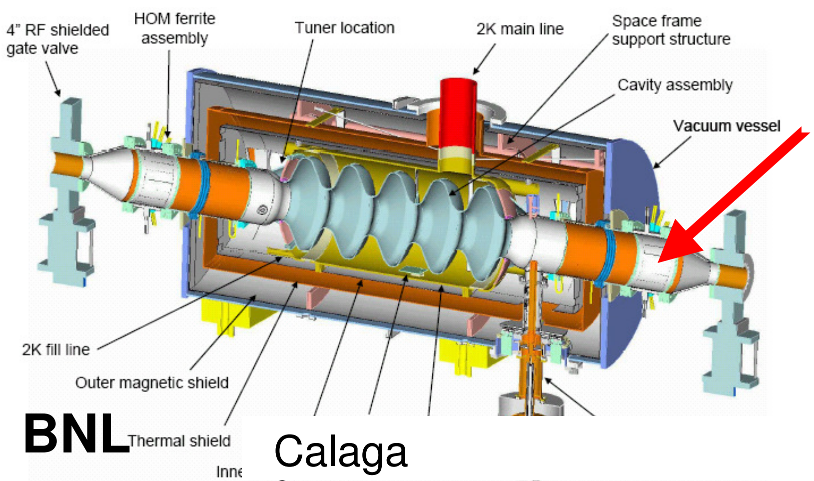
Orbit Stability

- Sub-micron stability (rms) is required for ERL LS in both horizontal and vertical planes
- E.g. CEBAF demonstrates 20 μm rms (limited by BPM noise)
- 10^{-4} energy stability is needed
- demonstrated at CEBAF

SRF Challenges

- $Q_0 = 2\times10^{10}$ at 15-20 MV/m is desirable
- cavity/cryomodule design that minimizes microphonics
- $Q \leq 10^4$ for primary dipole and $Q \leq 10^3$ for (resonant) monopole HOMs is desired
- smart HOM power handling
- superior LL RF control

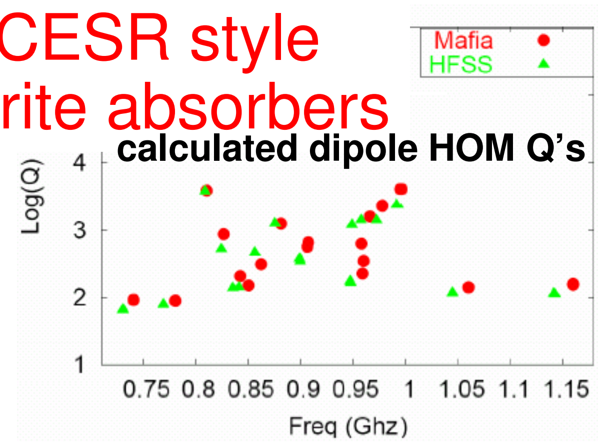
High Current SRF Cavities

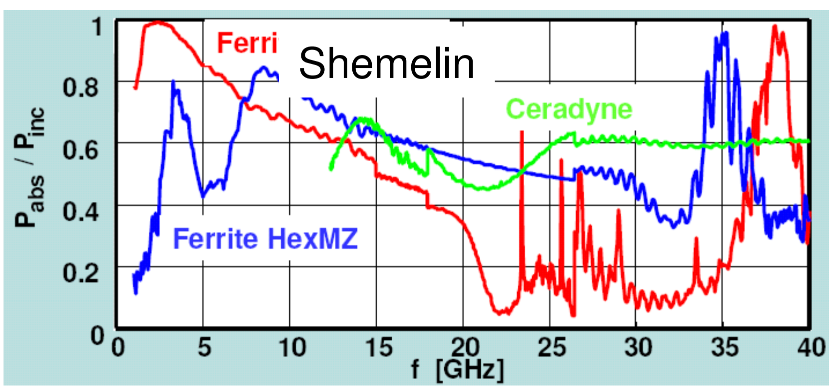


BNL Calaga

optimized cavity shape

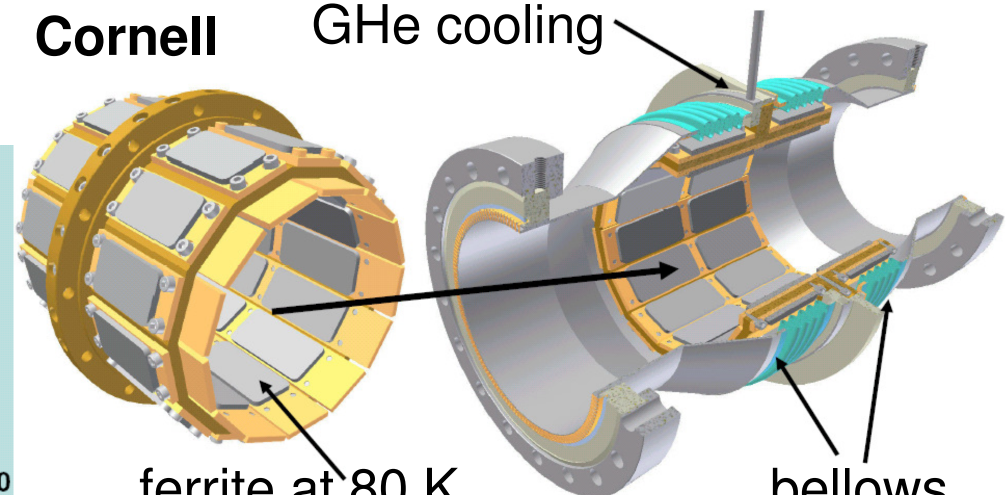
CESR style ferrite absorbers





Shemelin

Cornell

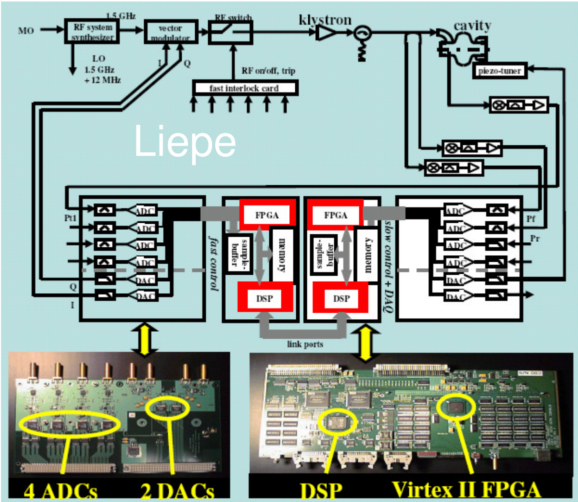


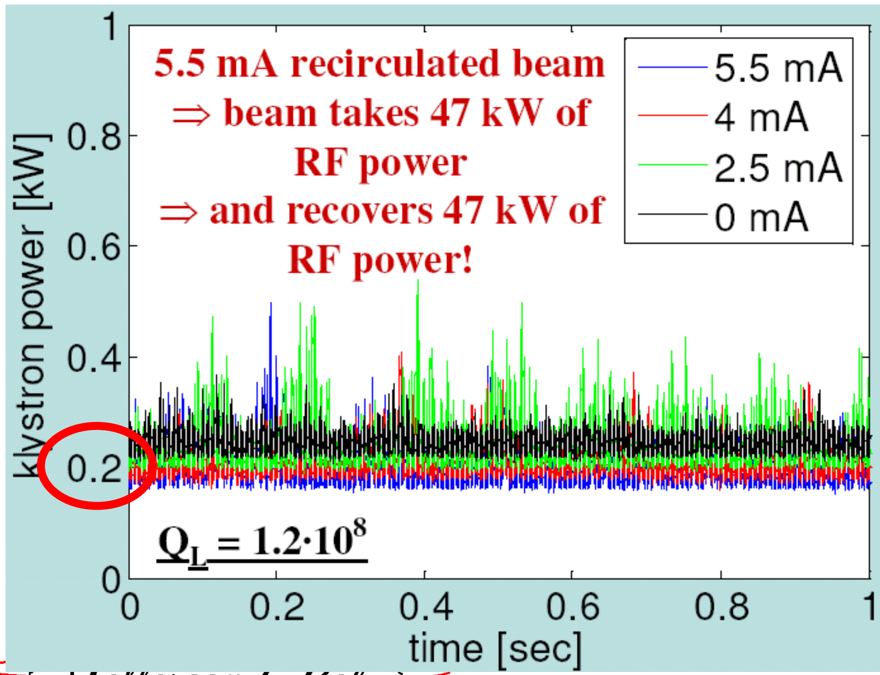
GHe cooling

ferrite at 80 K

bellows

Cornell Low Level RF Control System





- Successfully tested at JLAB FEL

Demonstrated:

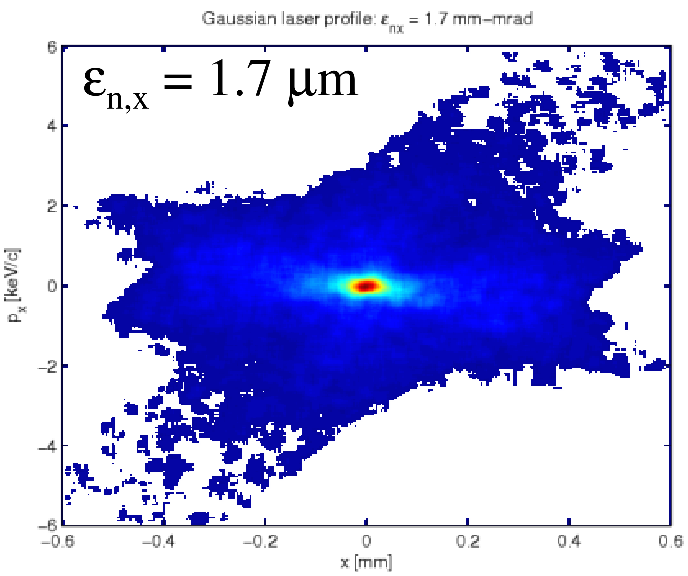
+ Q_L = **1.2×10^8** with I = 5.5 mA energy recovered beam
+ Field stability **10^{-4}**
+ Phase stability **0.02°**

Physics of e- photoguns

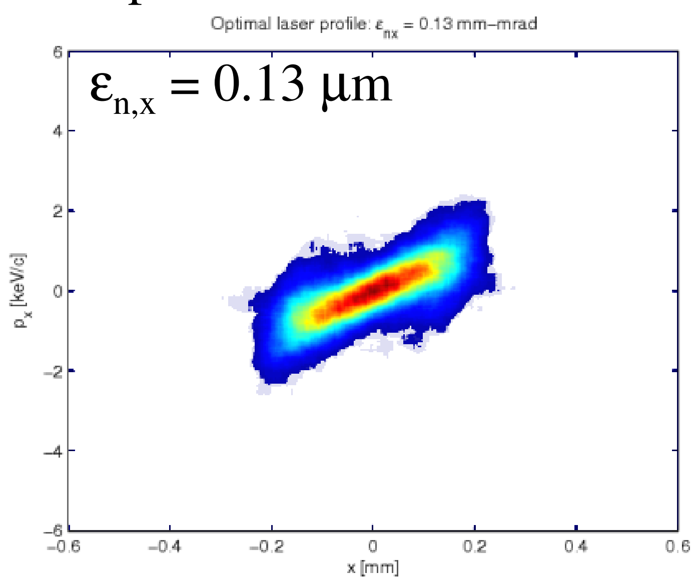
Two main limiting mechanisms:

- Phase space scrambling due to nonlinear space charge

3D Gaussian initial distribution



Optimal initial distribution



- Photocathode thermal emittance

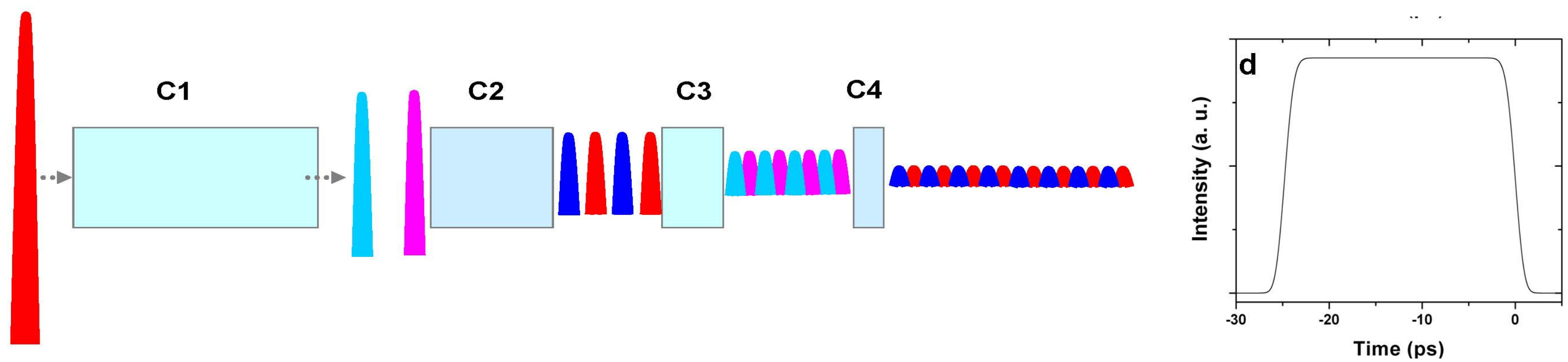
$$\varepsilon_{n,th} = \sigma_{x,y}\sqrt{\frac{kT}{mc^2}}$$

transverse temperature of photoemitted electrons

Shaping approaches

- Refractive beam shaper from Newport for transverse

- Birefringent crystal set pulse stacker for temporal



Design approaches

- Cut the number of decision variables to some reasonable number (2-4) perhaps by using a simplified theoretical model to guide you in this choice
- **Large regions of parameter space remain unexplored**
- Optimize the injector varying the remaining variables with the help of a space-charge code to meet a fixed set of beam parameters (e.g. emittance at a certain bunch charge and a certain length)
- **One ends up with a *single-point* design without capitalizing on beneficial trade-offs that are present in the system**

Primary challenge in exploring the full parameter space is computational speed

Doing it faster

- work harder
- work smarter
- get help

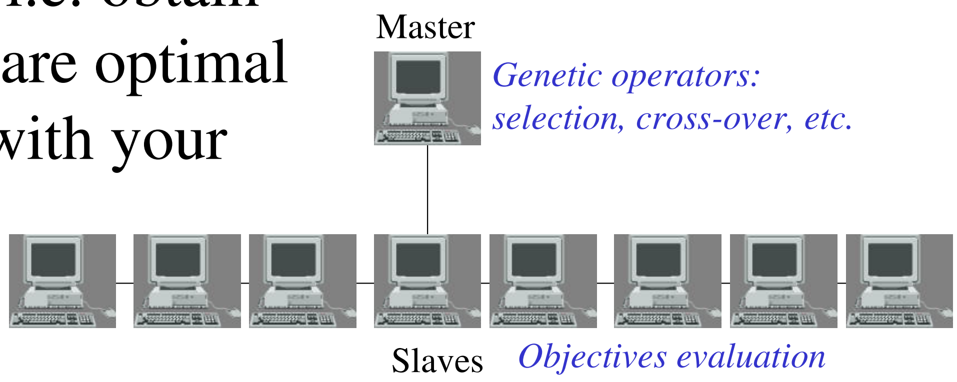
→

- processor speed
- algorithms
- parallel processing

Solution: use parallel MOGA

Multi***O***bjective ***G***enetic ***A***lgorithm

- throw in all your design variables
- map out whole Pareto front, i.e. obtain multiple designs all of which are optimal
- use realistic injector model with your favorite space charge code



Multi-objective optimization

$$\left.\begin{array}{lll} \text{maximize} & f_m(x_1, x_2, \ldots, x_n), & m = 1, 2, \ldots, M; \\ \text{subject to} & g_j(x_1, x_2, \ldots, x_n) \geq 0, & j = 1, 2, \ldots, J; \\ & x_i^{(\mathrm{L})} \leq x_i \leq x_i^{(\mathrm{U})}, & i = 1, 2, \ldots, n. \end{array}\right\}$$

Definition 1. *A solution $\boldsymbol{x}_a$ is said to dominate the other solution $\boldsymbol{x}_b$ if the solution $\boldsymbol{x}_a$ is not worse than $\boldsymbol{x}_b$ in all objectives and $\boldsymbol{x}_a$ is strictly better than $\boldsymbol{x}_b$ in at least one objective. In other words, $\forall m \in 1, 2, \ldots, M$: $f_m(\boldsymbol{x}_a) \geq f_m(\boldsymbol{x}_b)$ and $\exists m' \in 1, 2, \ldots, M : f_{m'}(\boldsymbol{x}_a) > f_{m'}(\boldsymbol{x}_b)$.*

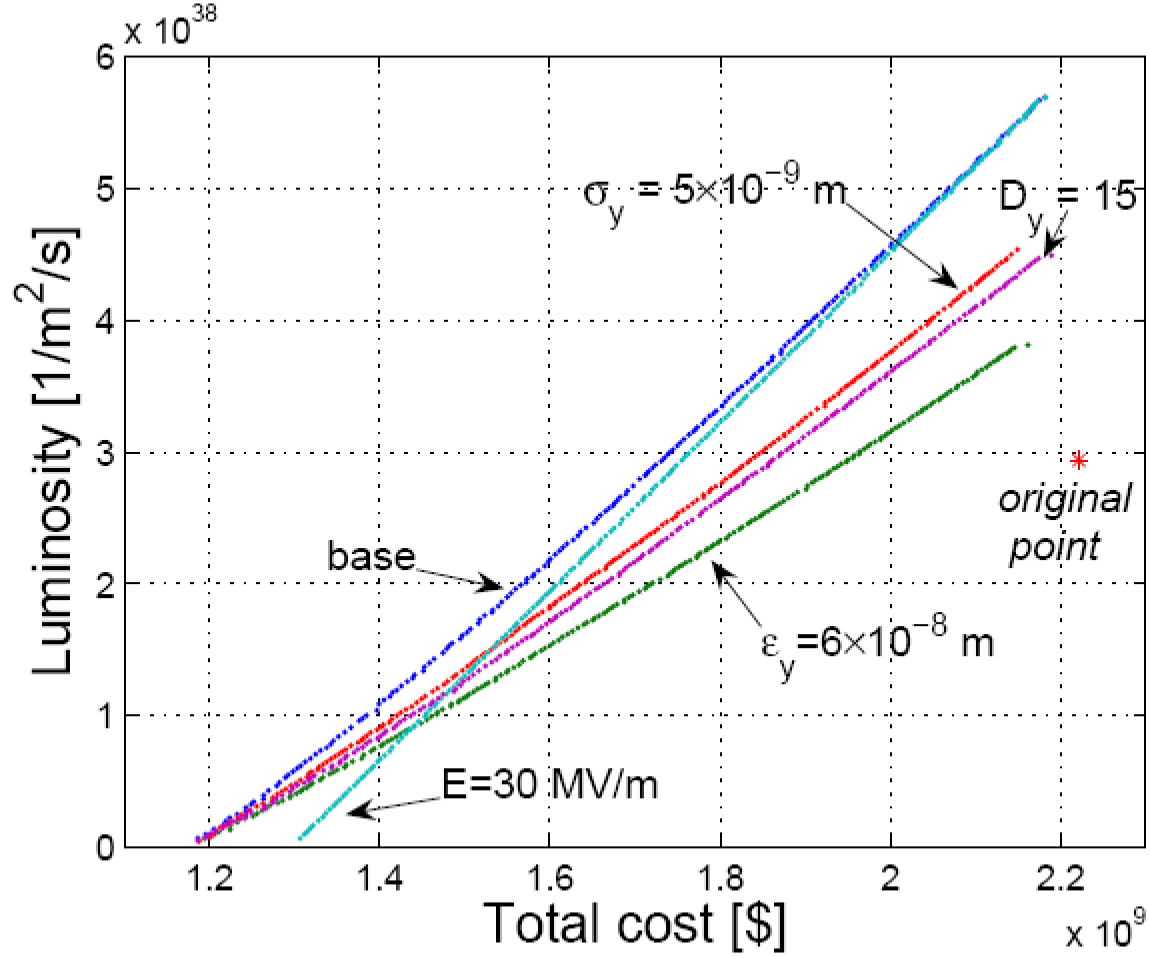
Definition 2. *Among a set of solutions $\mathcal{P}$, the nondominated subset of solutions $\mathcal{P}'$ are those that are not dominated by any member of the set $\mathcal{P}$.*

When the set $\mathcal{P}$ is the entire search space resulting nondominated set is called the *Pareto-optimal set.*

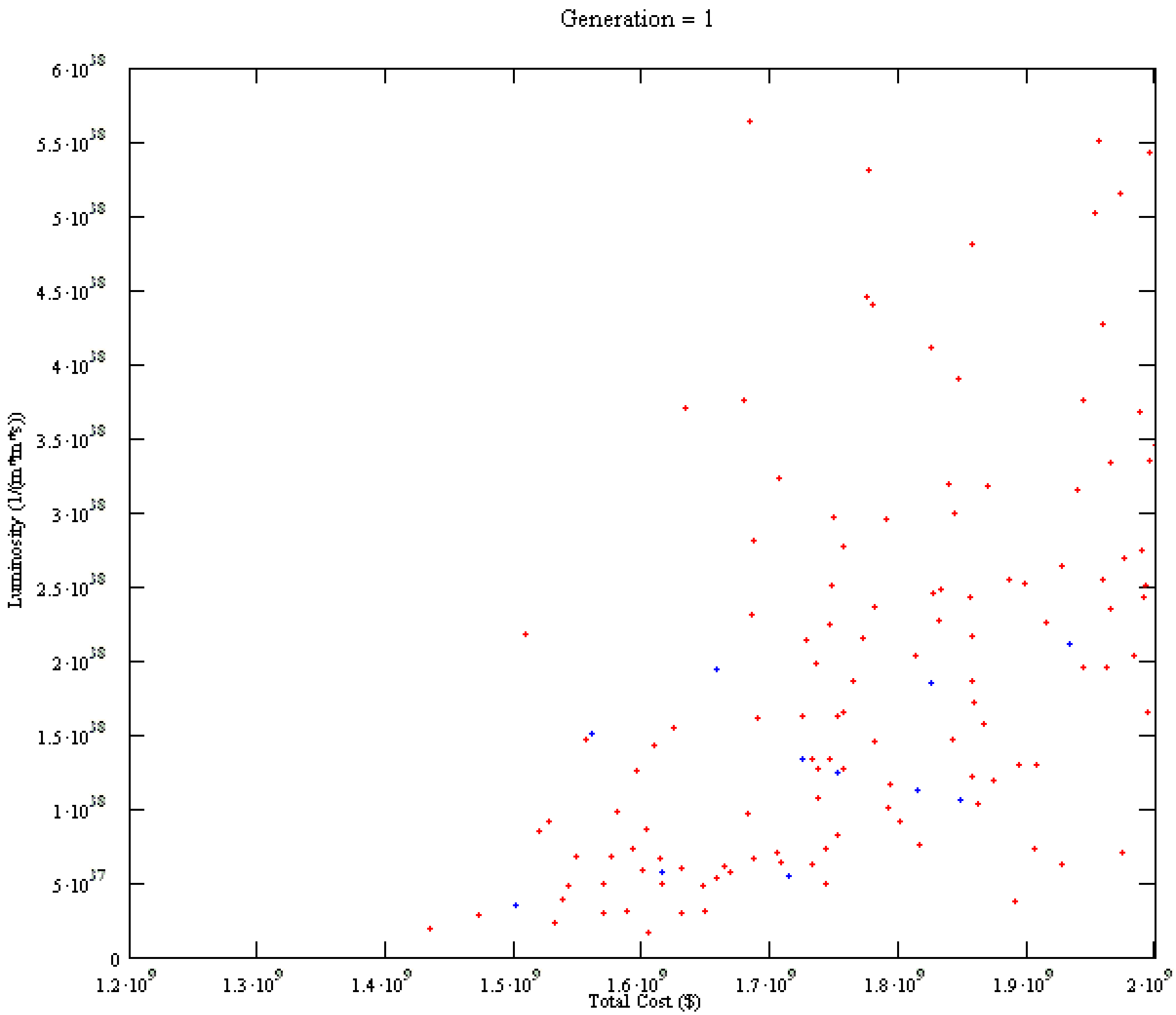
Vilfredo Pareto, 1848-1923

ILC linac optimal front

10 bounded decision variables, 10 constraints



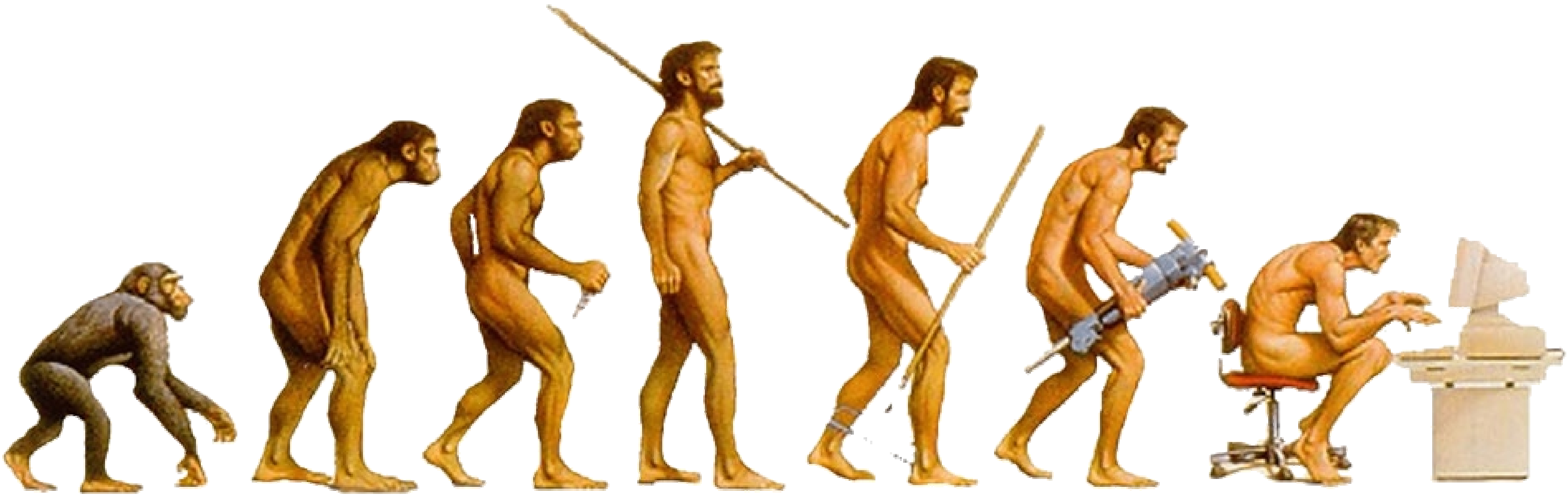
ILC linac optimization



maximize **Luminosity**

minimize **Total Cost**

Evolving into optimal injector design



Parallel Multiobjective Evolutionary Algorithm

Optimization results

Takes some 10^5 simulations

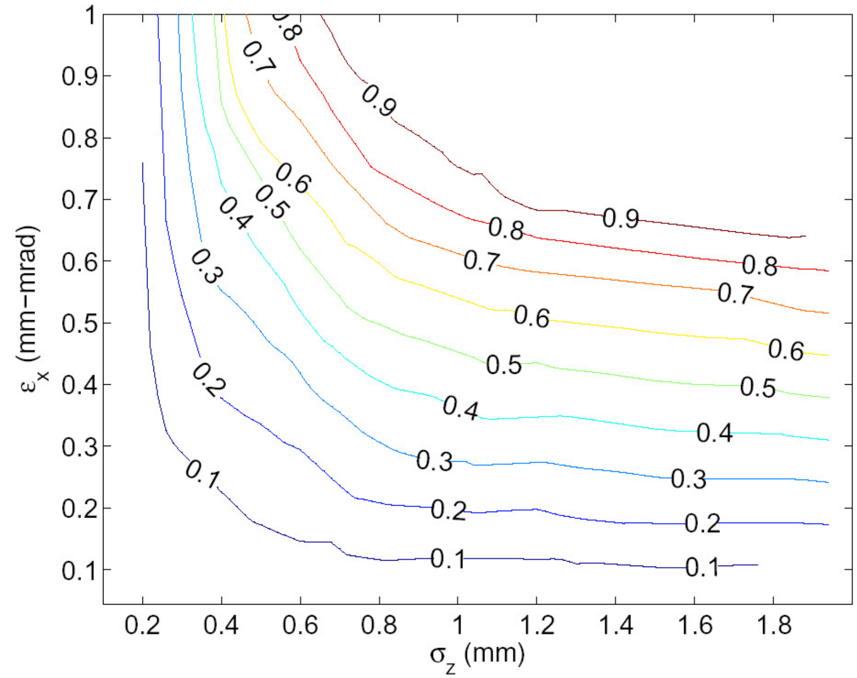


FIG. 10: Transverse emittance vs. bunch length for various charges in the injector (nC).

E_{th} = 35 meV (aka GaAs @ 780 nm)

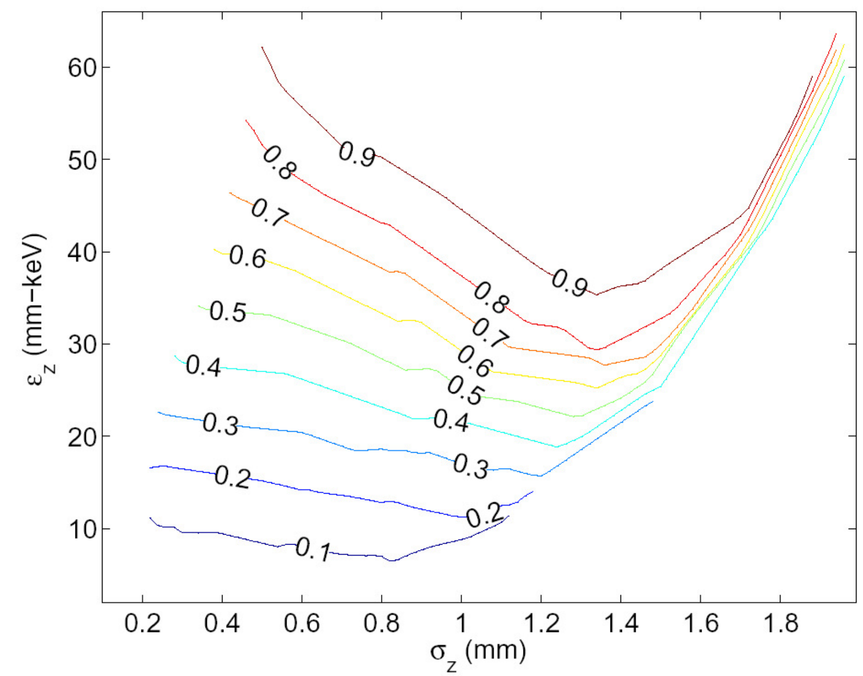


FIG. 11: Longitudinal emittance vs. bunch length for various charges in the injector (nC).

MOO problem:
- minimize emittance
- minimize bunch length
- maximize bunch charge

Optimizations

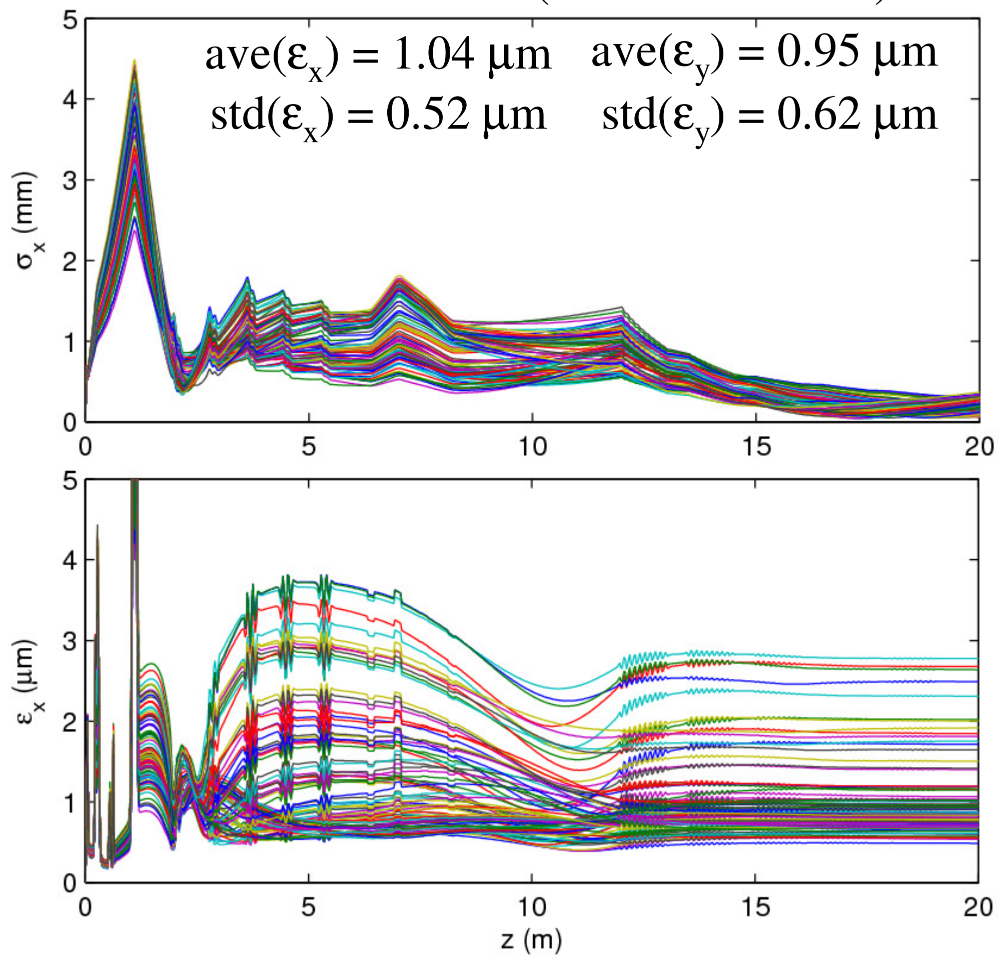
- Parallel multi-objective optimizations is a powerful tool to explore limits of the system
- Is not meant to substitute but rather complement analytical & intuitive picture of what's going on
- Not a substitute for accurate model of the physics of what's going on (i.e. 'garbage in, garbage out')

Optima steepness

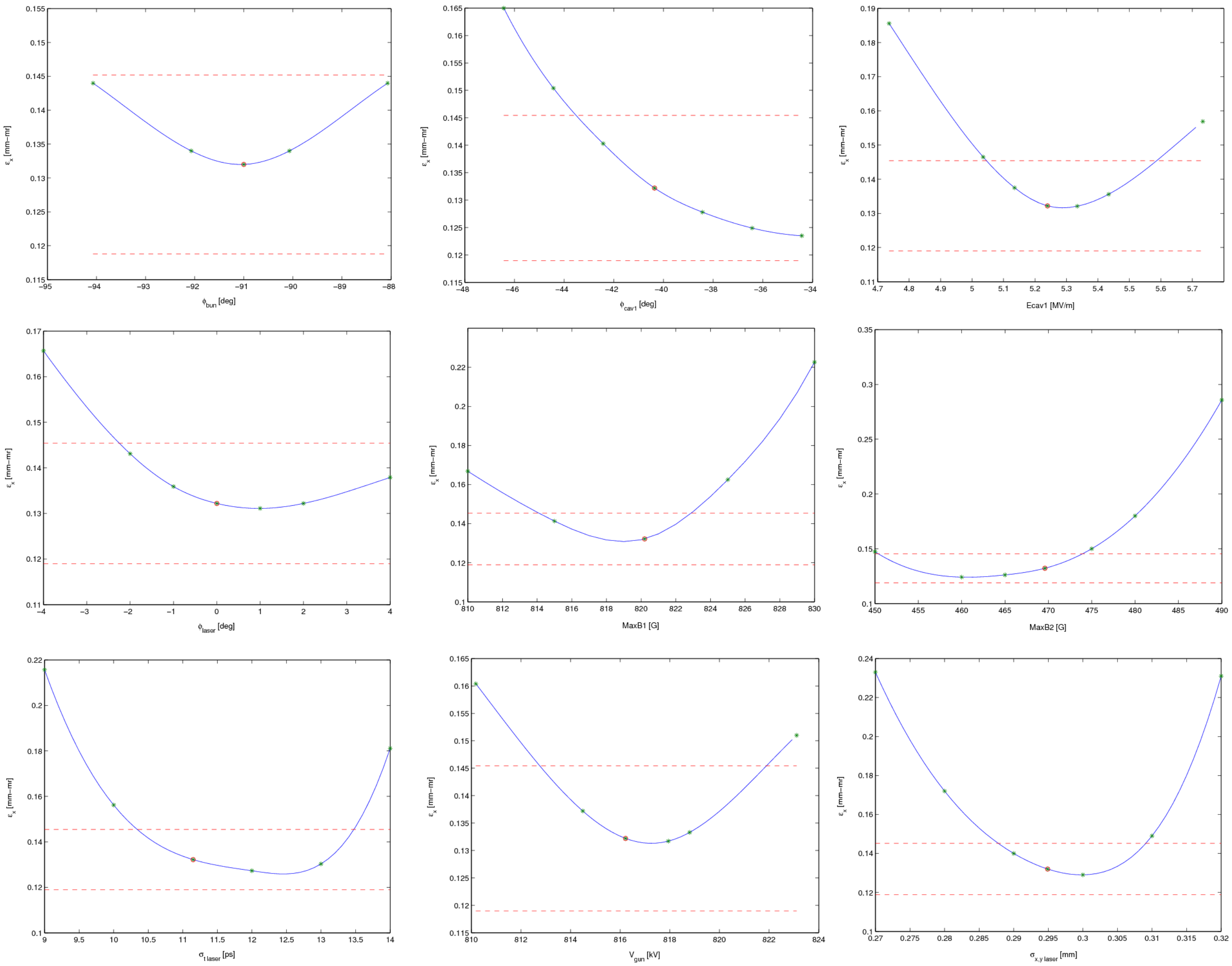
- Virtual injector allows absolute control of parameters, real system with a dozen of sensitive parameters will not

Pulse duration rms	21.5 ± 1.4 ps
Spot size rms	0.640 ± 0.057 mm
Charge	80 ± 5.8 pC
Solenoid1 Bmax	0.491 ± 0.010 kG
Solenoid2 Bmax	0.532 ± 0.010 kG
Cavity1 phase	-41.6 ± 1.7 deg
Cavity2 phase	-31.9 ± 2.0 deg
Cavity3-5 phase	-25.7 ± 2.0 deg
Buncher Emax	1.73 ± 0.04 MV/m
Cavity1 Emax	15.4 ± 0.3 MV/m
Cavity2 Emax	26.0 ± 0.5 MV/m
Cavity3-5 Emax	27.0 ± 0.5 MV/m
Q1_grad	-0.124 ± 0.002 T/m
Q2_grad	0.184 ± 0.002 T/m
Q3_grad	0.023 ± 0.002 T/m
Q4_grad	-0.100 ± 0.002 T/m

100 random seeds (outliers removed)



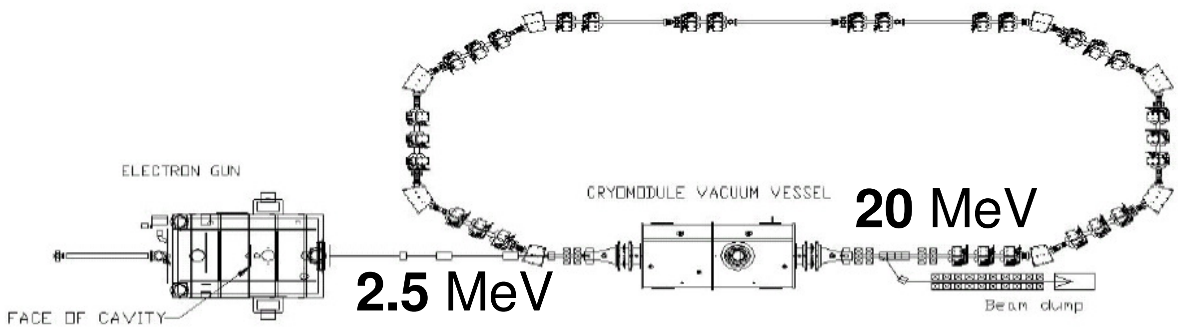
Tolerances for optimum

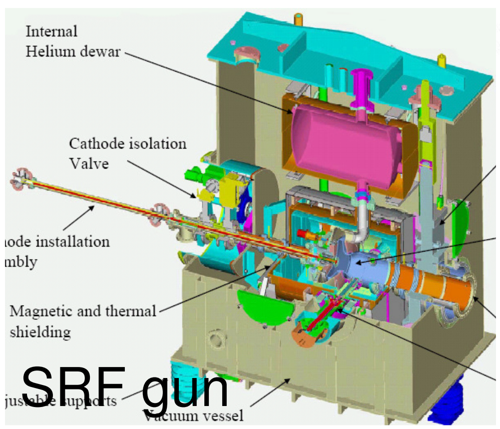


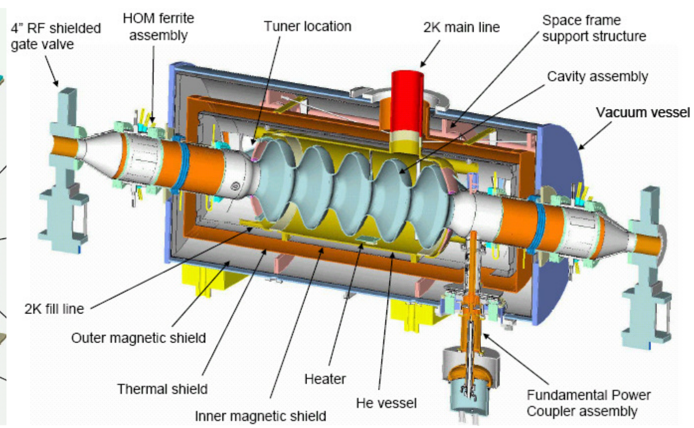
10% increase in emittance (p-t-p)

BunPhase	3.5°
Cav1Phase	3.0°
Ecav1	3.8%
Lphase	2.4°
B1	0.37%
B2	0.85%
Qbunch	3.7%
Trms	8.0%
Vgun	0.39%
XYrms	2.4%

BNL R&D ERL







$q \sim 20$ nC

$\varepsilon_n \sim 30$ mm-mrad

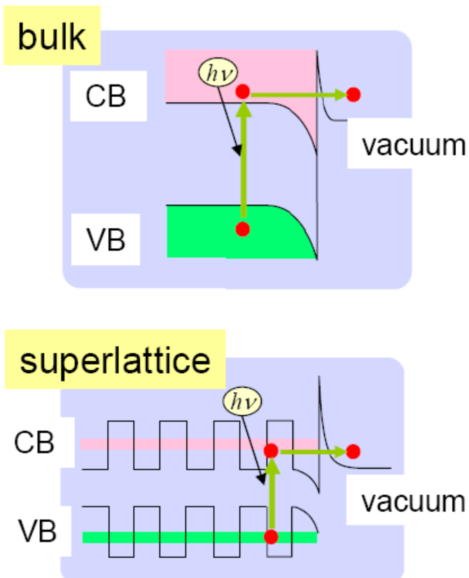
$I_{max} = 0.2$ A

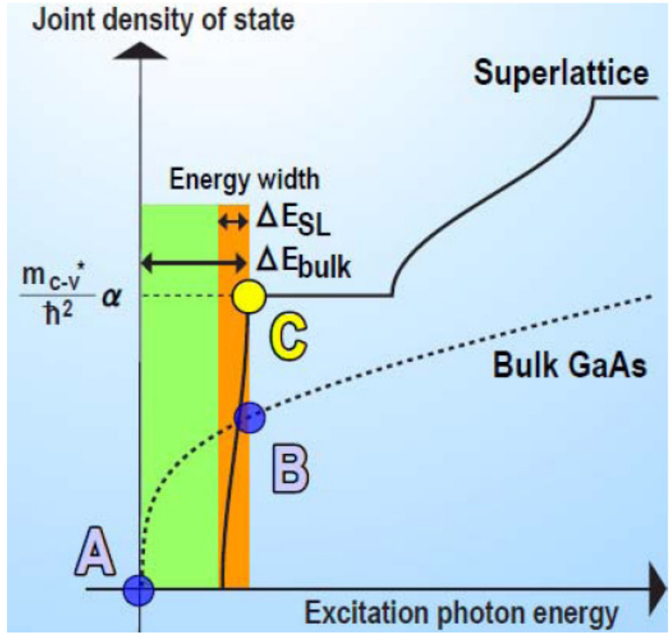
$q \sim 1.3$ nC

$\varepsilon_n \sim 1\text{-}3$ mm-mrad

$I_{max} = 0.5$ A

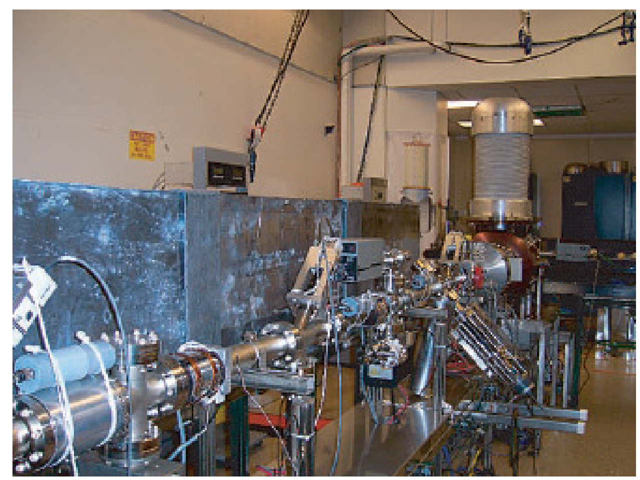
Superlattice photocathode?



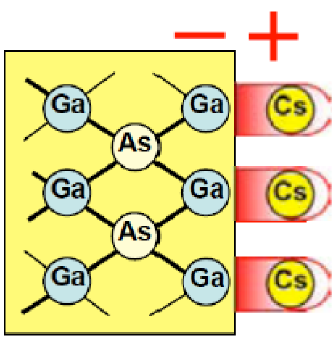


	Q.E.	kT
A	small	*small*
B	*large*	large
C	***large***	***small***

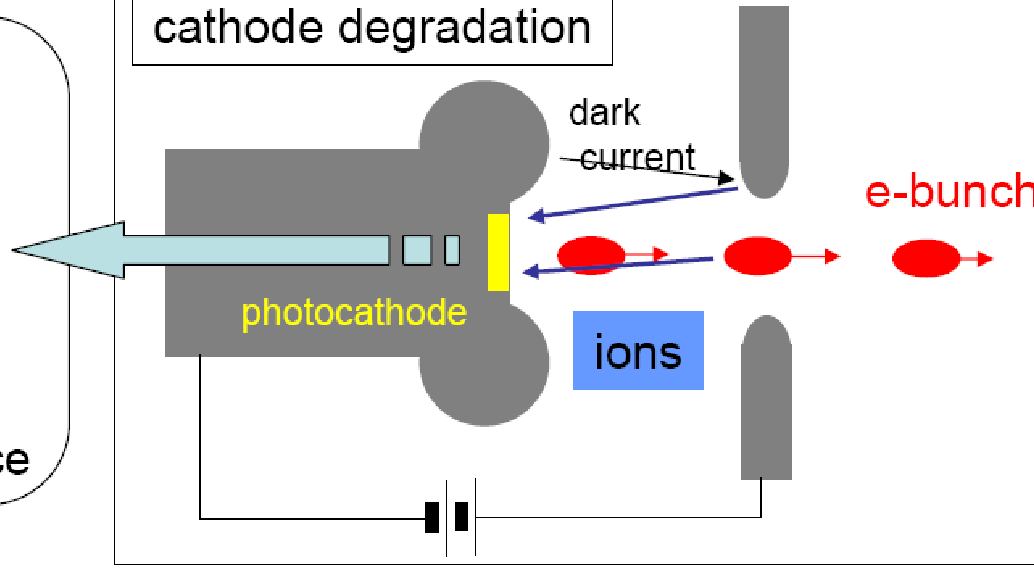
• equipped to accurately (~meV) measure transverse temp. of e^- at different wavelengths
• photoemission temporal response resolution (~ps)


Gun development lab in Wilson

Cathode lifetime



re-cesiation recovers Q.E.
→ damage is only at the surface



- collision, deposition of residual gases
- dark current (and its enhancement)
- ion back bombardment

existing guns

CEBAF polarized gun (100kV, 0.1mA)

life ~ 2 x 10^5 C/cm^2

JLAB-ERL gun (350kV, 9mA)

life ~ 2 x 10^3 C/cm^2

→

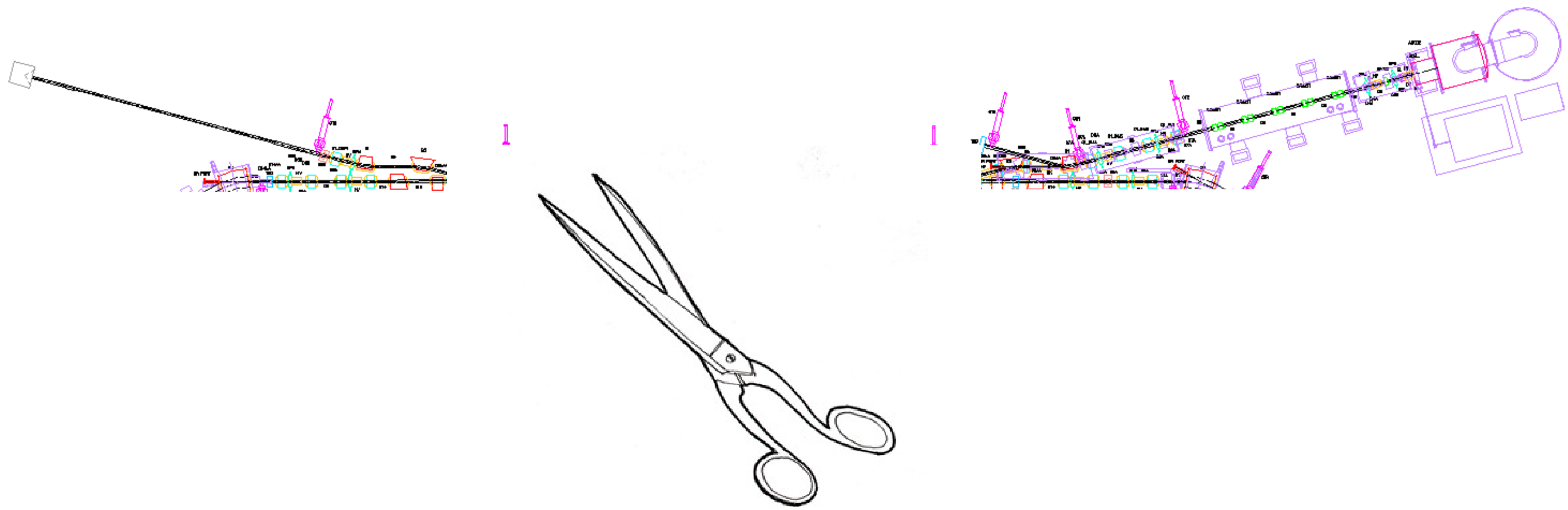
improvement is required

ERL-LS

life ~ 10^6 C/cm^2

100mA / ϕ 2mm、100 hours

ERL Phase ~~1~~ 1a



ERL PROTOTYPE

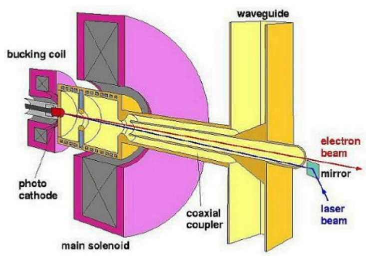
		Injection Energy	5 – 15 MeV
Max Avg. Current	100 mA		
Charge / bunch	1 – 400 pC	Bunch Length	2 ps
Emittance (norm.)	≤ 2 μm@77 pC		

Eds. Gruner, Tigner; **Bazarov, Belomestnykh, Bilderback, Finkelstein, Fontes, Krafft, Merminga, Padamsee, Shen, Rogers, Sinclair, Talman, ERL prototype proposal to the NSF, 2001**

Gun & cathode package

1 nC

NCRF

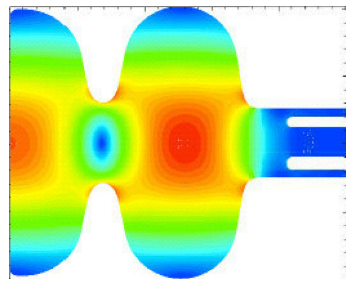


pulsed!

E_{cath} = 120 MV/m
τ_{laser} = 2.7 ps rms
σ_{laser} = 0.5 mm rms

$\tau_{laser} \rightarrow z$ = 0.08 mm

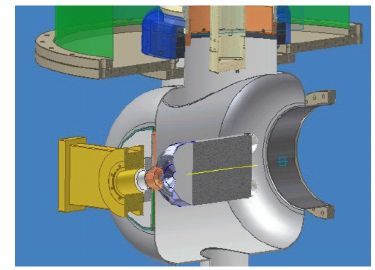
SRF



E_{cath} = 43 MV/m
τ_{laser} = 5.8 ps rms
σ_{laser} = 0.85 mm rms

$\tau_{laser} \rightarrow z$ = 0.12 mm

DC



E_{cath} = 8 MV/m
τ_{laser} = 13 ps rms
σ_{laser} = 2 mm rms

$\tau_{laser} \rightarrow z$ = 0.12 mm

2×18 MV/m   2×6 MV/m   2×1 MV/m

$E_{cath} / E_{s.charge}$ = $E_{cath} / E_{s.charge}$ = $E_{cath} / E_{s.charge}$

same simulated emittance

Gun technology choice

Emittance compensation can be achieved despite reduced flexibility in solenoid positioning

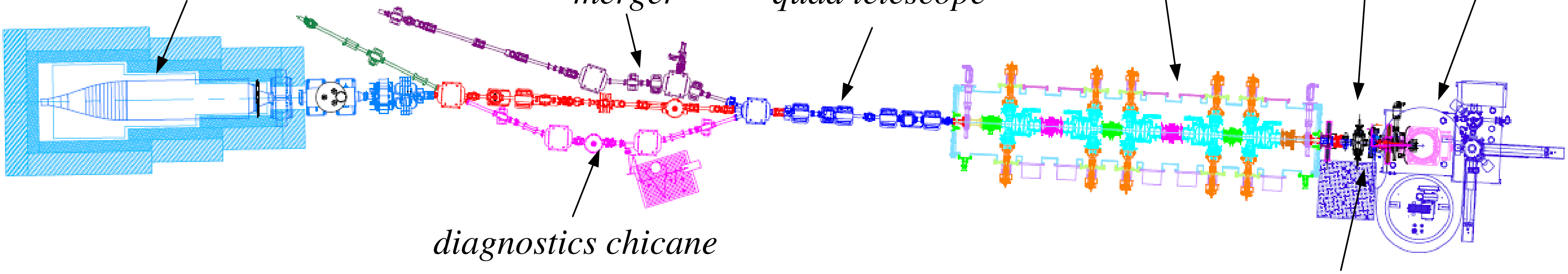
	Q [nC]	Rms bunch Length (compressed)	Ex [mm-mrad]	Cathode material(&)	Band Peak field
RF	1 / 0.2	2.8 ps / 1.7 ps	0.72 / 0.3 (**)	Copper, 700 meV	S-Band [120 MV/m]
DC	1/ 0.1	3ps / 3ps	0.8 / 0.14 (**)	GaAs 35 meV	[15 MV/m] (Average)
SRF	1 / 0.1(*)	5.7 ps/ 2.7 ps	0.8 / 0.23 (**)	"metallic" 184 meV	L-Band [60MV/m]

(*) scaled
(**) limited by thermal emittance
(&) Copper and GaAs use measured values, but SRF gun uses generic metallic cathode number for thermal emittance (0.3 mm-mrad per 1 mm full radius)

$$\varepsilon_n[\text{mm-mrad}] \approx 4\sqrt{q[\text{nC}]\frac{E_{th}[\text{eV}]}{E_{cath}[\text{MV/m}]}}$$

RF and DC guns computations are based on optimum emission pulse "3D-ellipsoid", whereas SRF gun computation uses "beer can"

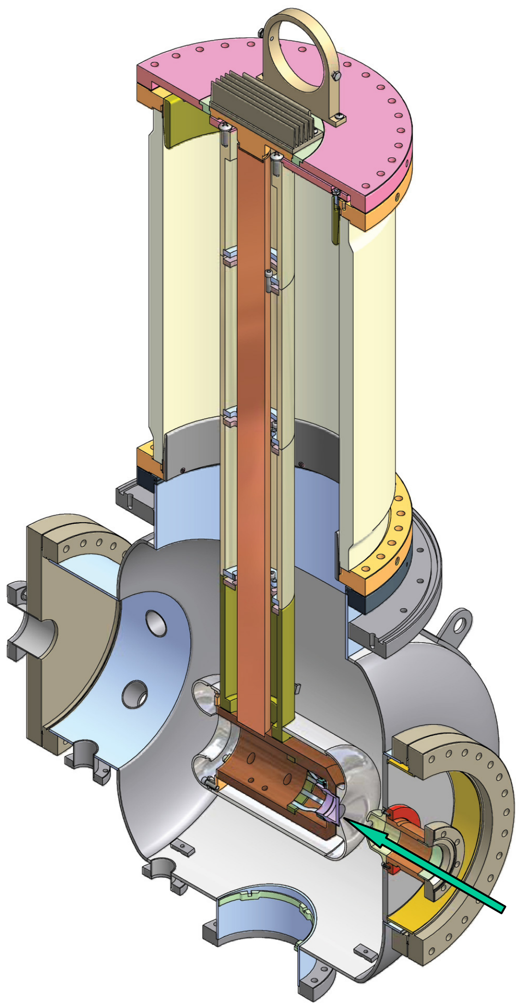
Phase 1a



- **HV DC gun** based **photo**-injector
- up to **100 mA** average current, **5-15 MeV** beam energy
- norm. rms emittance **≤1 μm** at **77 pC**/bunch
- rms bunch length **0.6 mm**, energy spread **0.1%**

Bazarov, Sinclair, PAC2003, IEEE 0-7803-7739-9 (2003) 2062

Photo-gun



Cathode	Cs:GaAs
Laser rep. rate	1.3 GHz
Wavelength	520 nm
Duration (rms)	10 ps
Vacuum	$<10^{-12}$ Torr

goal: 750 kV

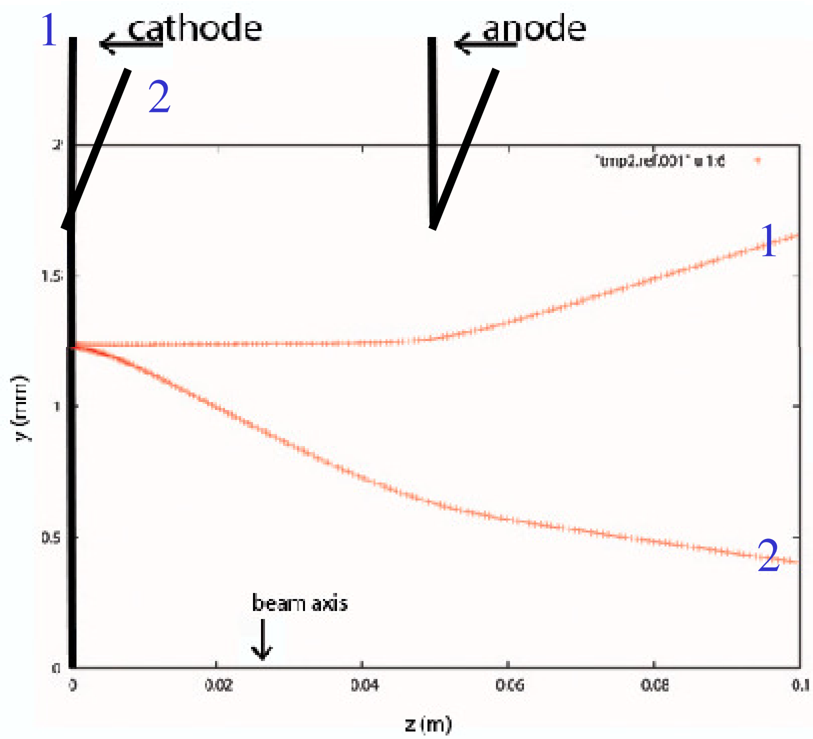
cathode field

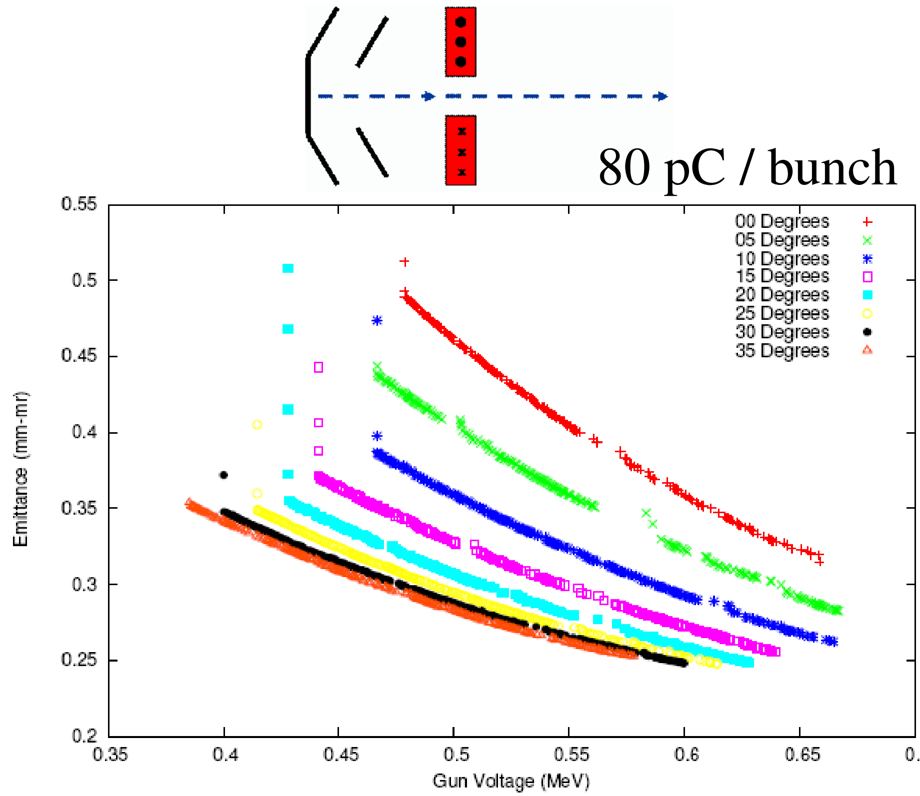
laser spot

space charge limit

$$q = 4\pi\varepsilon_0 E_{cath}\sigma_x^2$$

DC gun focusing





- Focusing at the cathode is achieved through electrode shaping (25° angle), brings emittance down by a factor of ~2
- The drawback is increased aberrations from the gun (an issue when scanning laser spot on the cathode to increase re-Cs interval)

Challenges

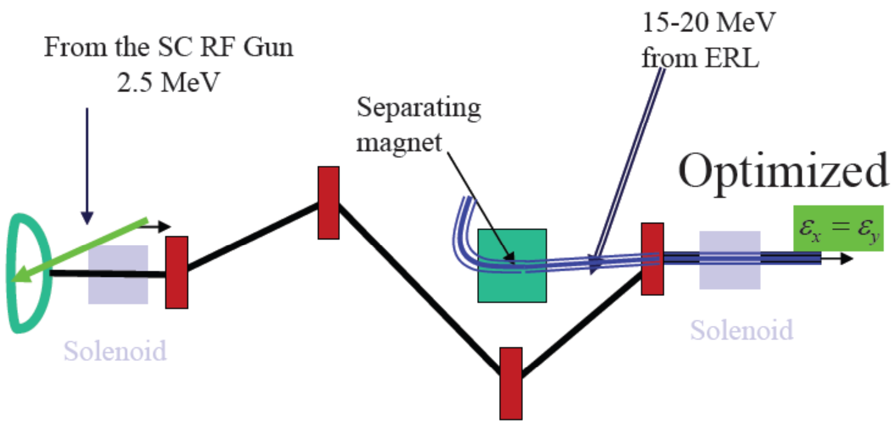
- Beam has to be matched into the main linac and taken through the merger while being space-charge dominated → work out procedures for space-charge friendly optics tune-up procedures
- Final beam properties are very sensitive to about ten different parameters that need to be 'set right' → controls and diagnostics must be up to the task to provide the necessary guidance

Merger issues

- Asymmetric transport → x-y coupling term in beam envelope equation
- Energy change in non-zero dispersion section (CSR and space charge) → emittance growth

Alternative merger scenarios

- BNL’s “zigzag” merger



$$\delta_i(s) = \delta_{i0} + s \cdot g(\zeta_i) \Rightarrow \quad 4 \ \text{"Achromat" conditions}$$

$$\int_0^S K_o(s') \cdot m_{11}(s')ds' = 0; \qquad \int_0^S K_o(s') \cdot s \cdot m_{11}(s')ds' = 0;$$

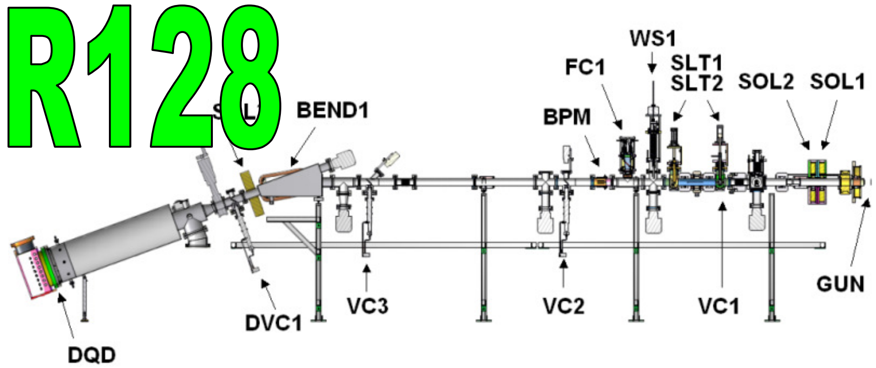
$$\int_0^S K_o(s') \cdot m_{12}(s')ds' = 0; \qquad \int_0^S K_o(s') \cdot s \cdot m_{12}(s')ds' = 0;$$

  – Good: emittance growth due to linear correlated energy spread from space charge is canceled to first order
  – Bad: does not separate 2 beams (works for BNL because recirculating energy is only 15-20 MeV)
  – Bad: is longer than Cornell’s present 3-bend acrhomat, comparison yielded similar emittance growth for the two

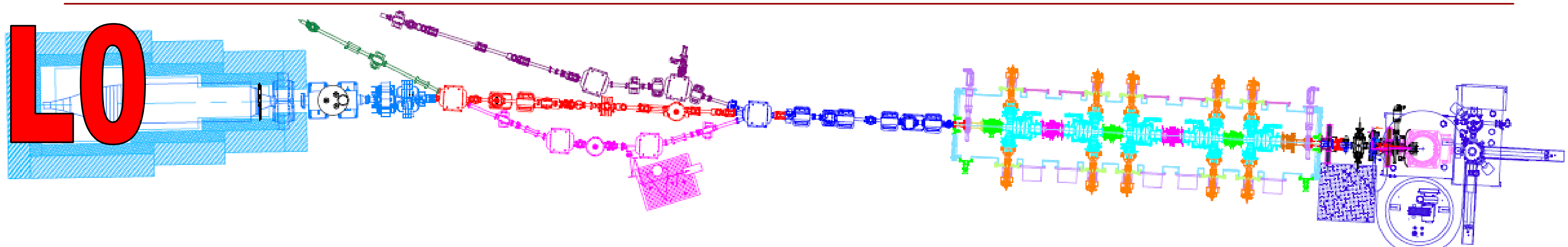
Experimental plan: areas

I. Photocathode phenomena
II. Space charge dominated regime
III. Longitudinal phase space control
IV. Emittance preservation in the merger
V. High average current phenomena
VI. Achieving ultimate 'tuned-up' performance

R128 vs. L0



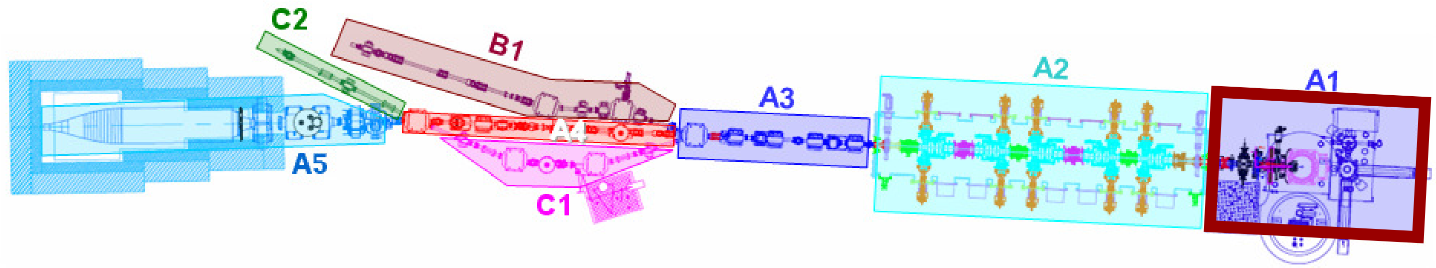
- Simple: gun & diagnostics line
- Full phase space characterization capability after the gun
- Temporal measurements with the deflecting cavity

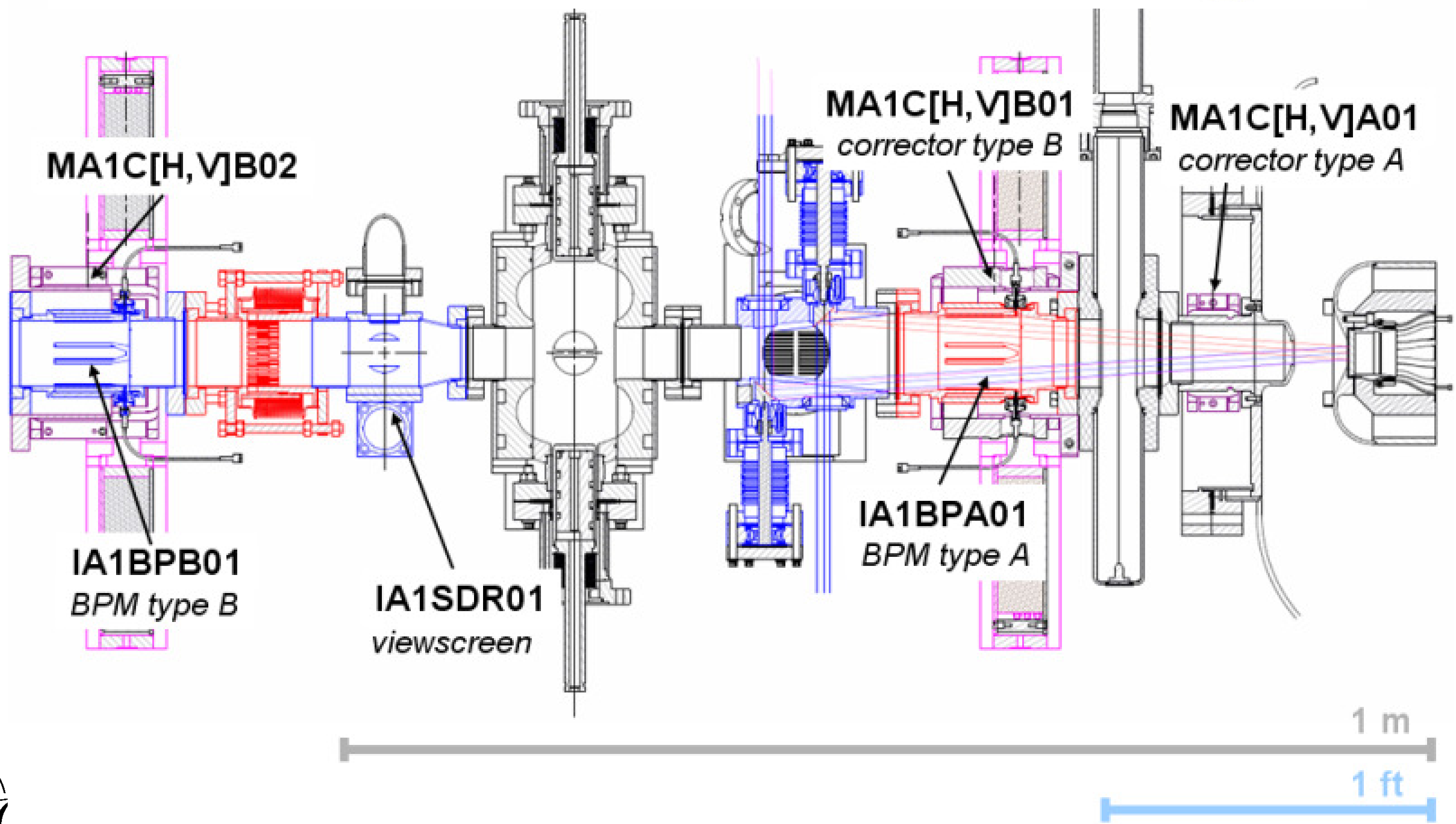


- Limited diagnostics after the gun (before the module)
- Full interceptive diagnostics capabilities at 5-15 MeV

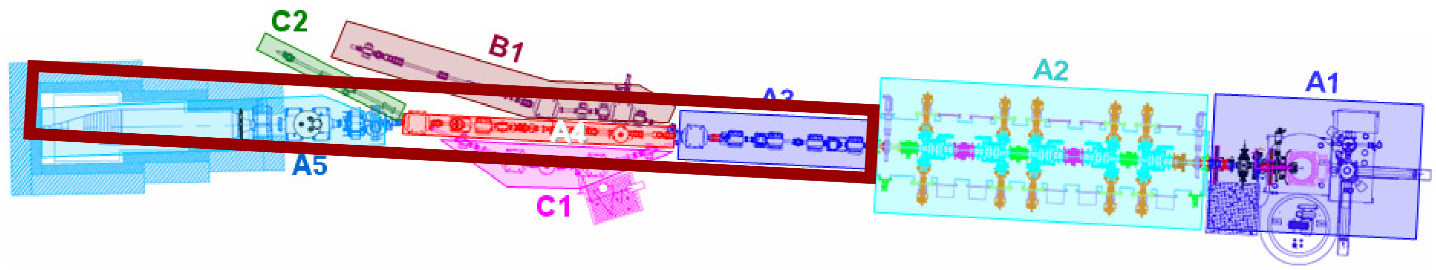
- Some full beam power diagnostics

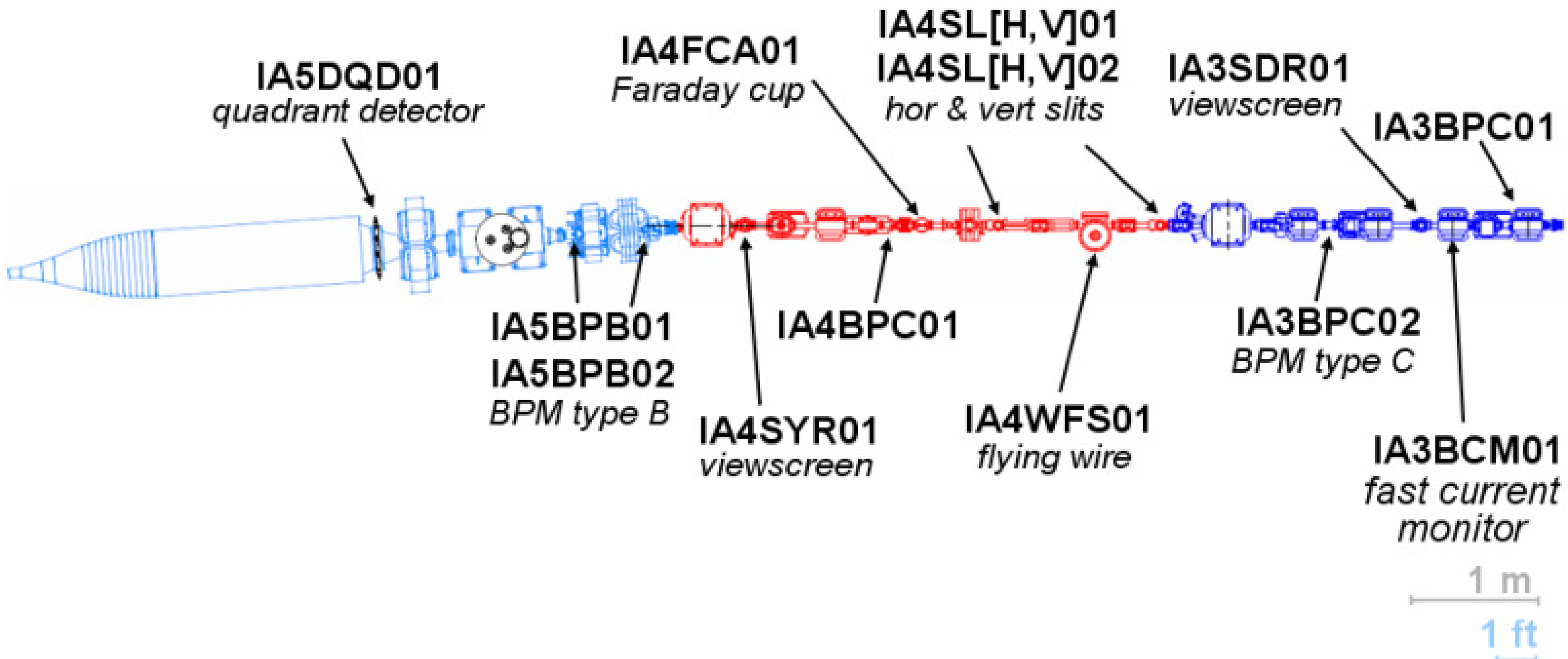
L0 layout: near the gun



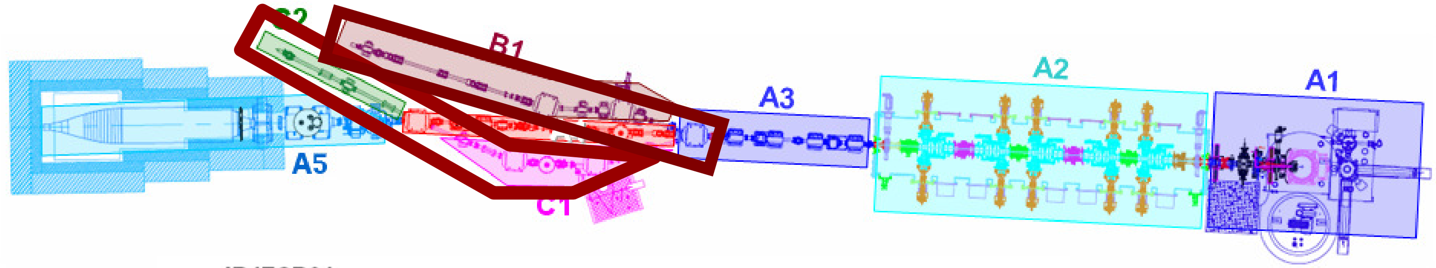


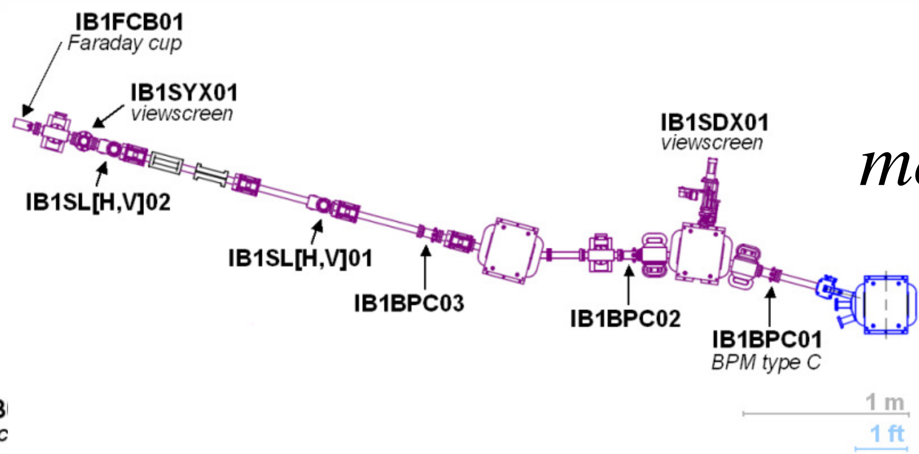
L0 layout: 15 MeV straight-thru



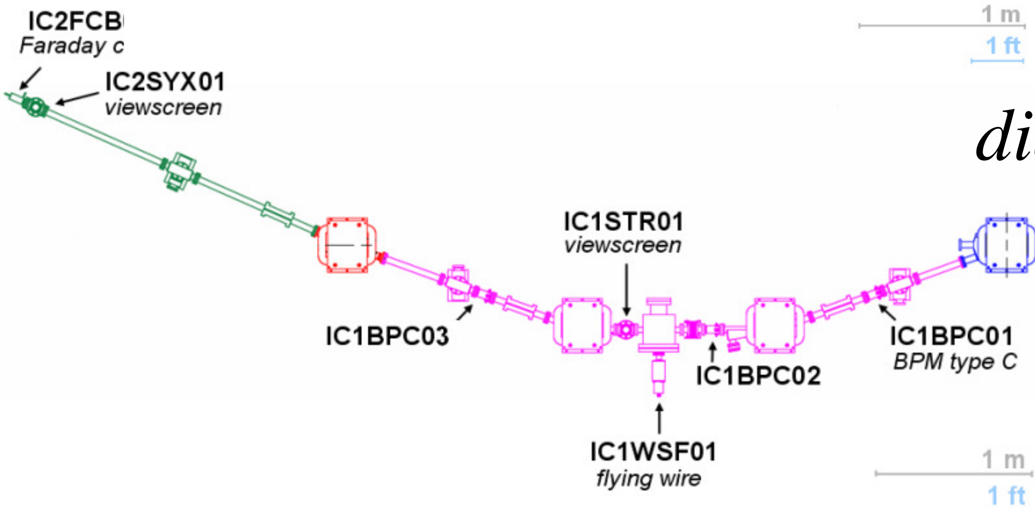


L0 layout: merger & chicane





merger



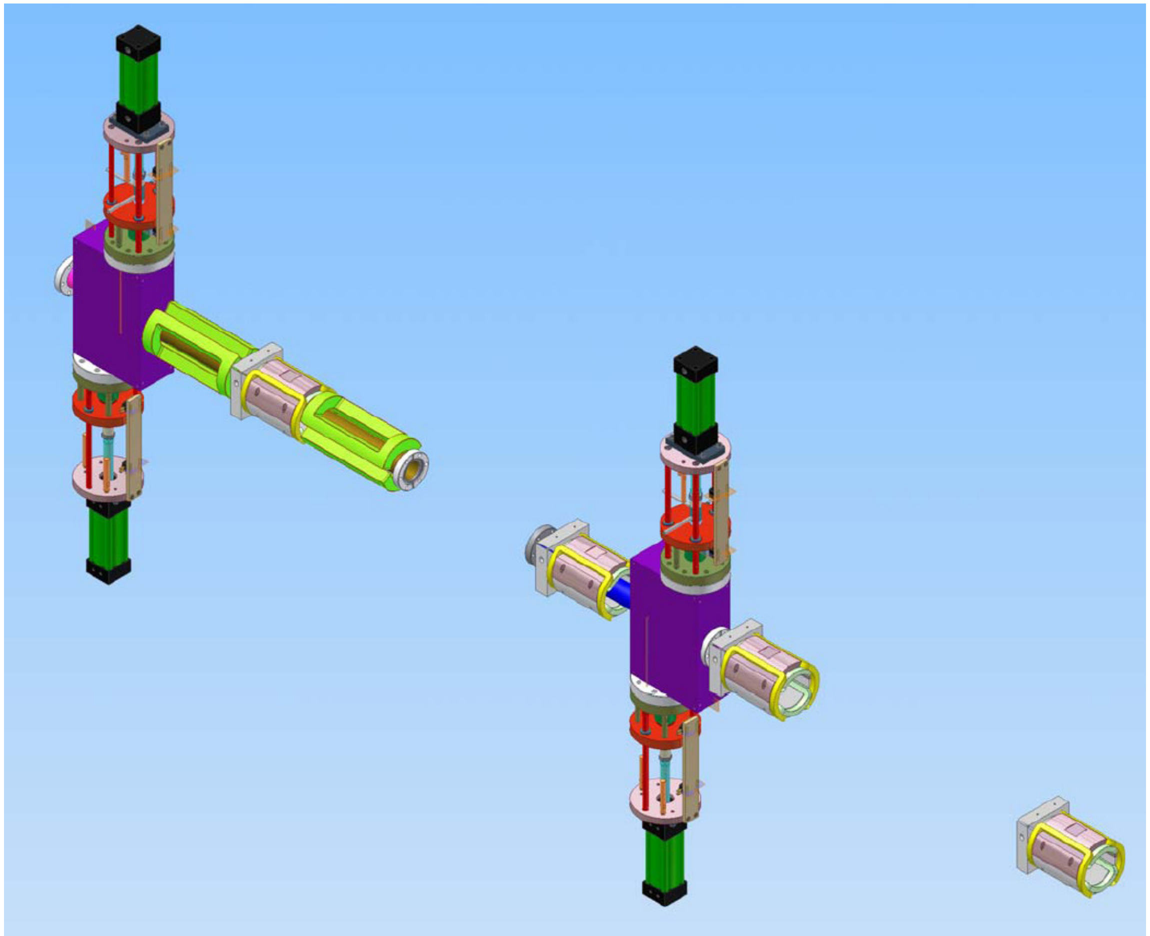
diagnostics chicane

Diagnostics overview

- Beam position resolution: 10 μm (spec)
- Energy spread resolution: 10^{-4}
- Transverse beam profile resolution: 30 μm (viescreens)
  10 μm (slits)
  30 μm (flying wire)
- Angular spread resolution: 10 μrad
- Pulse length (deflecting cavity&slits): 100 fs
- RF phase angle: 0.5°

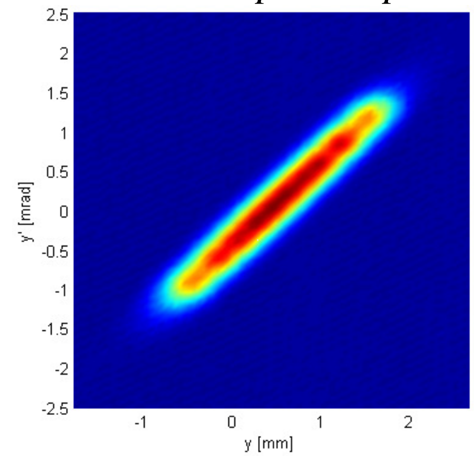
Ability to take phase space snapshots of the beam, both transverse planes, and longitudinal phase space

Emittance measurement system

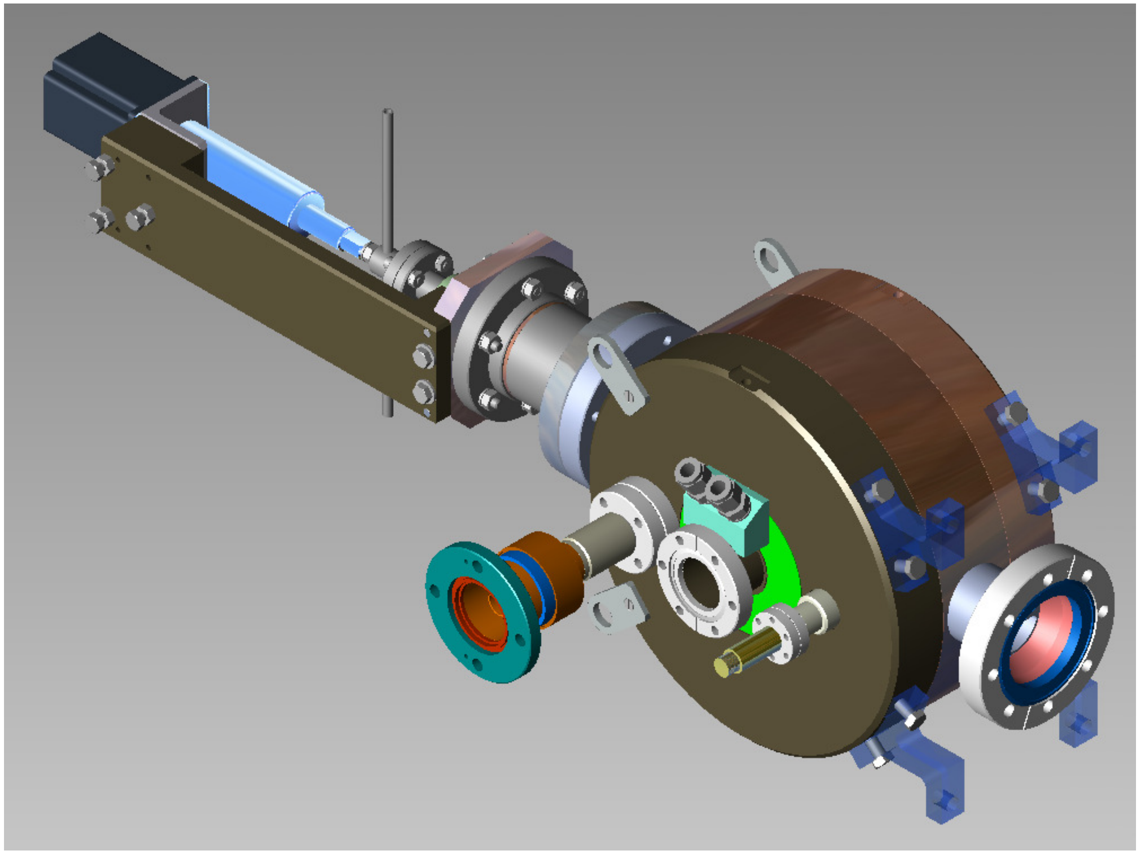


- no moving parts
- fast DAQ
- 10 mm precision slits
- kW beam power handling capability

measured phase space

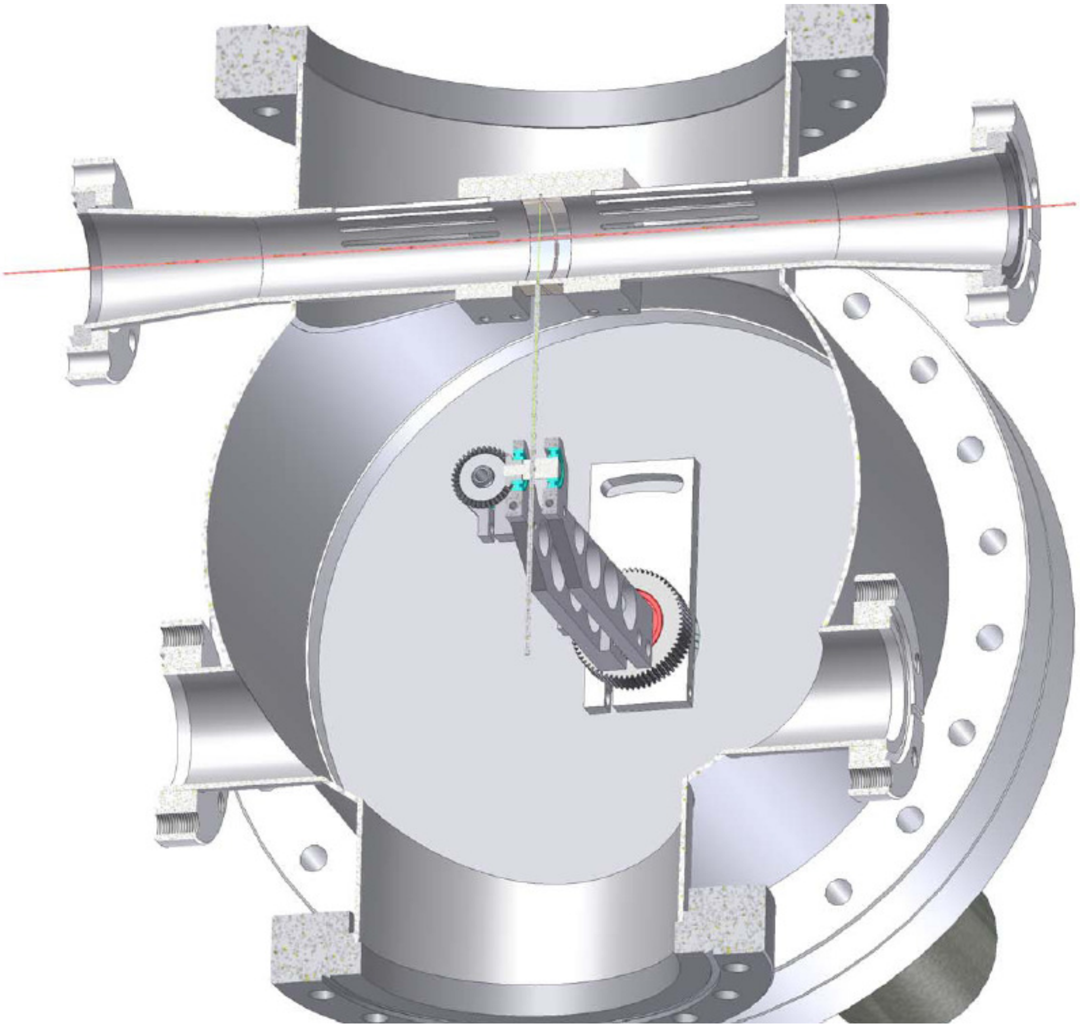


Deflecting cavity



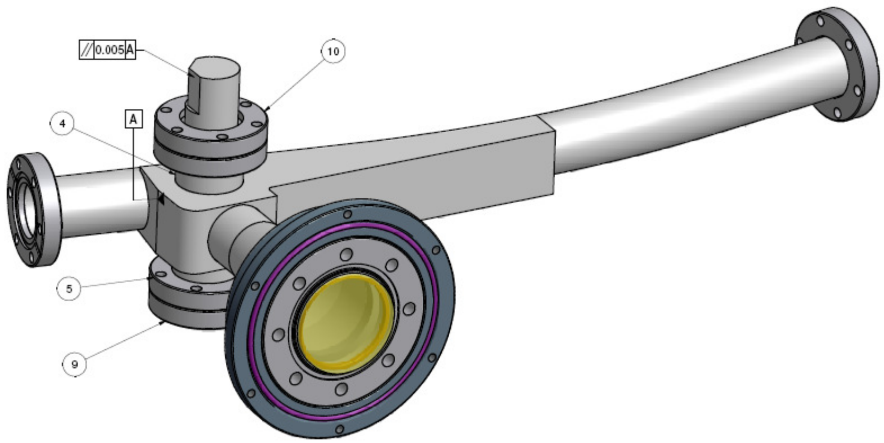
- 100 fs time resolution (with slits)
- Used in:
  - photoemission response meas.
  - slice transverse emittance meas.
  - longitudinal phase space mapping

Flying wire

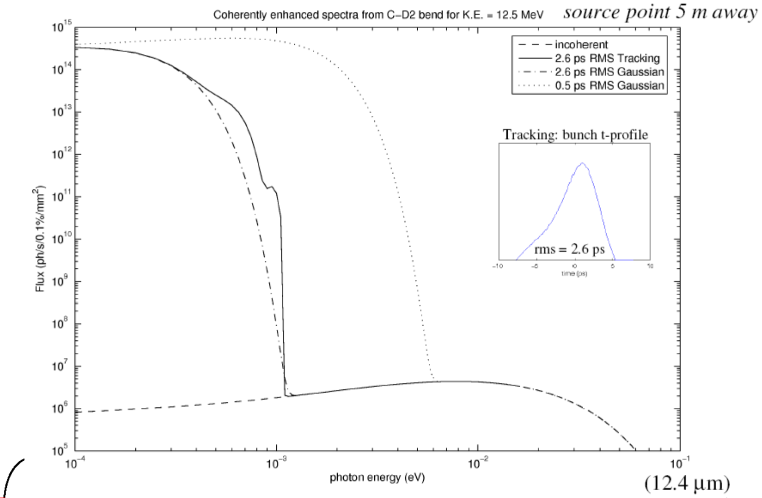


- 20 m/s flying carbon wire
- Applicable with 0.6 MW of beam power
- Two units, one in dispersive section to allow studies of long-range wake fields

THz radiation



coherently enhanced spectrum



- One of chicane dipole magnets to be used in the analysis of FIR radiation spectrum
- Applicable with 0.6 MW of beam power
- Provides the autocorrelation of the bunch profile
- OTR foils for low beam power measurements

Beam experiments

I. Photocathode phenomena

- Exp1. Thermal emittance (R128) *done*
- Exp2. Photoemission response time (R128) *2 weeks*

II. Space charge regime

- Exp3. Space charge limited extraction from the cathode (R128) *done*
- Exp4. Effect of laser pulse shaping on emittance compensation (R128) *2 weeks*
- Exp5. Phase space tomography of bunched beam (R128 & L0) *2 weeks R128 + 2 weeks L0*
- Exp6. Benchmarking of space charge codes (R128 & L0) *1 week R128*
- Exp7. Slice emittance studies (L0) *2 weeks*

Beam experiments

III. Longitudinal phase space control

- Exp8. Ballistic bunch compression (L0) *2 weeks*
- Exp9. Longitudinal phase space mapping (L0) *2 weeks*

IV. Emittance preservation in the merger

- Exp10. Space charge induced emittance growth in dispersive sections (L0) *2 weeks*
- Exp11. CSR effect (L0) *2 weeks*

Beam experiments

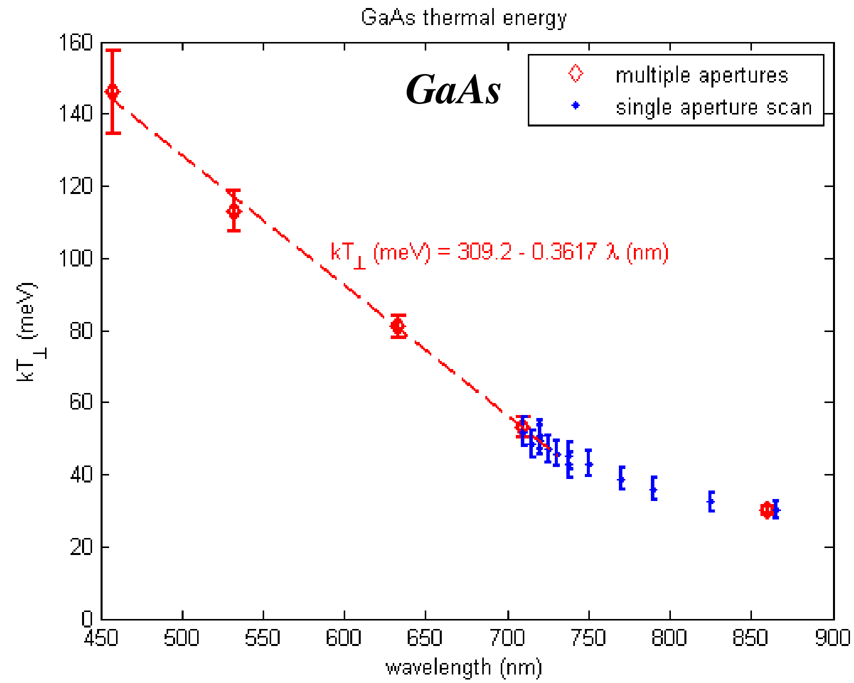
V. High average current phenomena

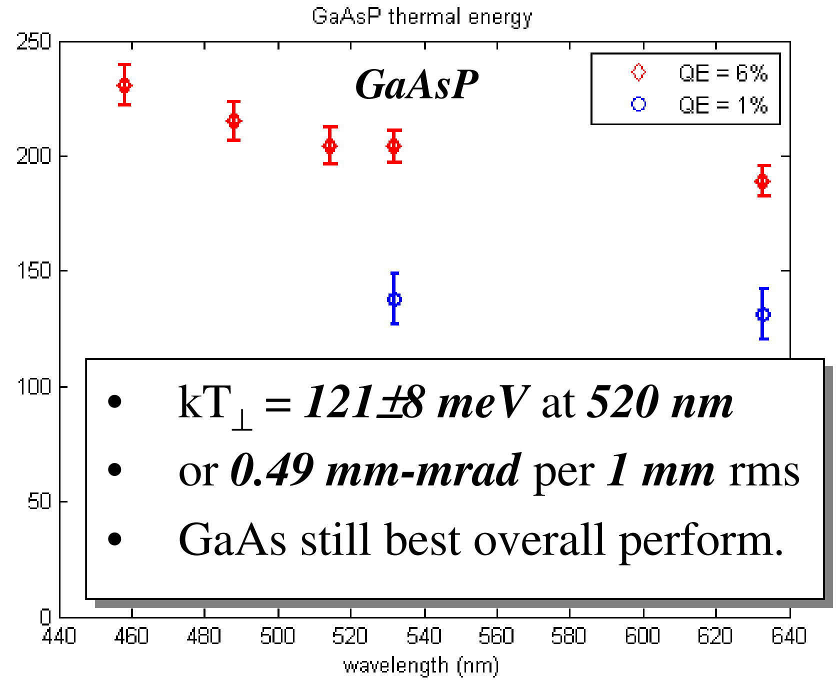
- Exp12. Ion effect (R128 & L0) *1 week R128 + 2 weeks L0*
- Exp13. Long range wakefield effects (L0) *1 week*

VI. Achieving ultimate 'tuned-up' performance

- Exp14. Orbit stability characterization and feedback (L0) *2 weeks*
- Exp15. Exploration of 'multi-knobs' and online optimization (L0) *3 weeks*

Exp1. Thermal emittance





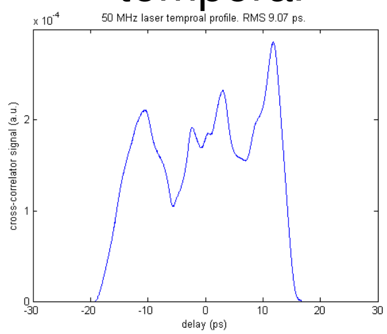
- $kT_{\perp}$ = ***121±8 meV*** at ***520 nm***
- or ***0.49 mm-mrad*** per ***1 mm*** rms
- GaAs still best overall perform.

Exp4. Laser shaping effect

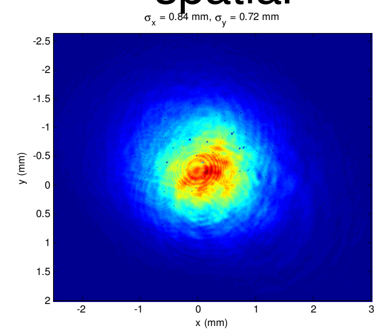
- Effective means of laser shaping have been devised and tested
- Beer-can distribution is the goal for Phase1a (better shapes exist)

laser shape: where we were August 2007

temporal

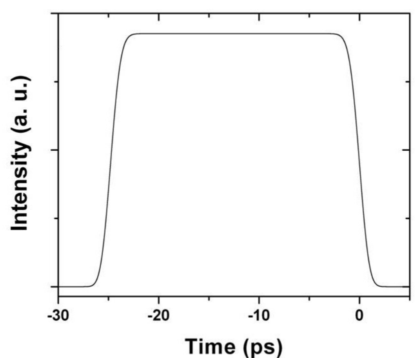


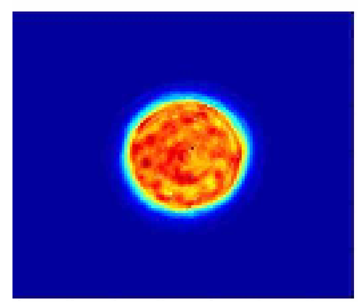
spatial



gaussian

goal to achieve (picture on the right is actual data)



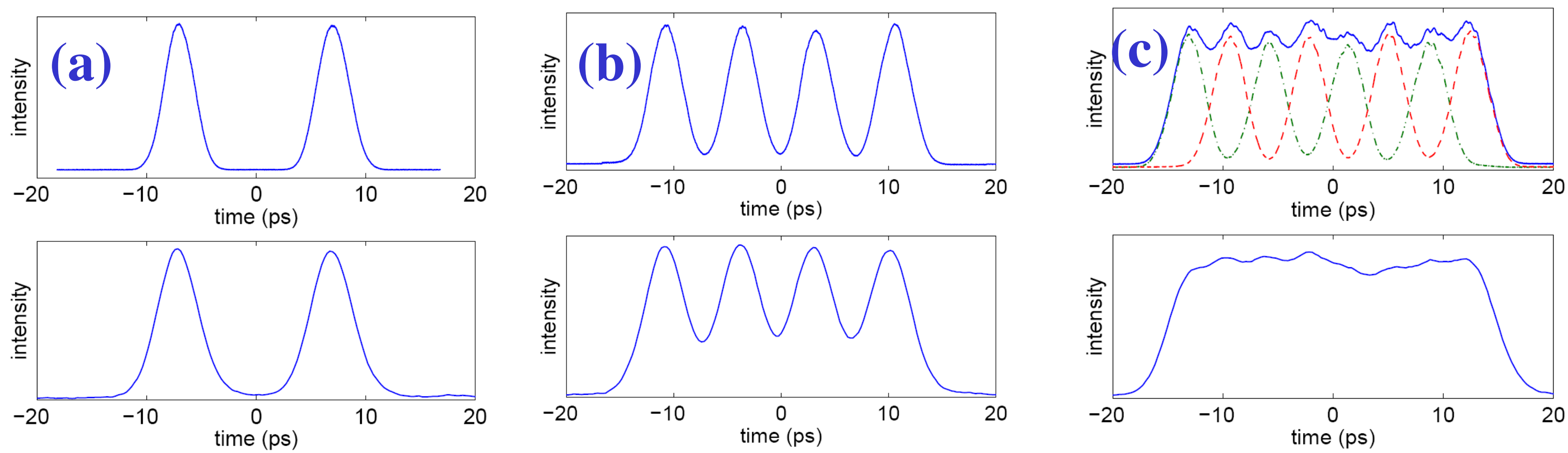


flat-top

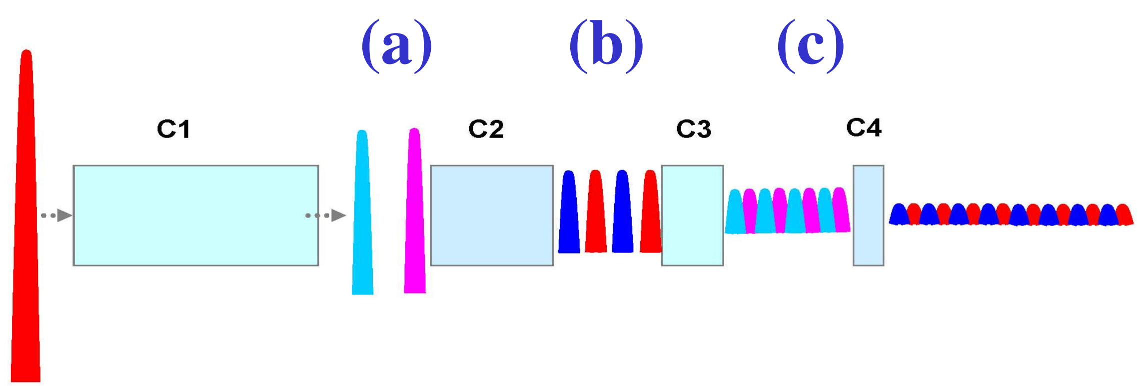
Exp4. Temporal shaping

Laser and e-beam shape: where we are Dec 2007

Top: laser cross-correlation



Bottom: electron beam profile measured with deflecting cavity

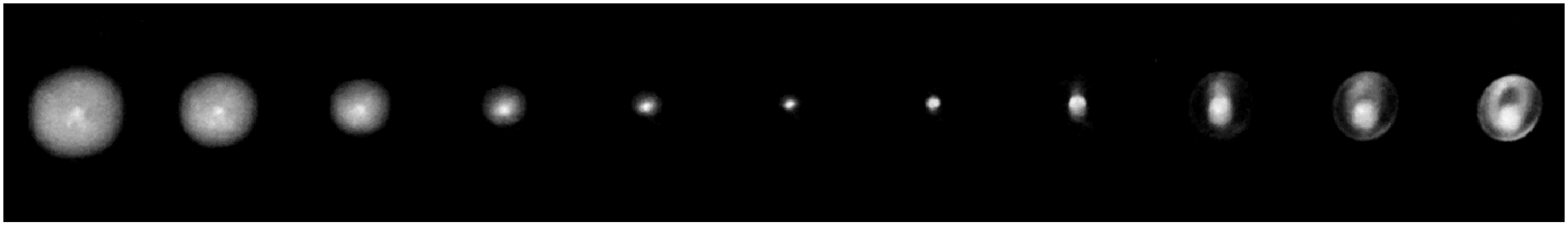


First space charge running

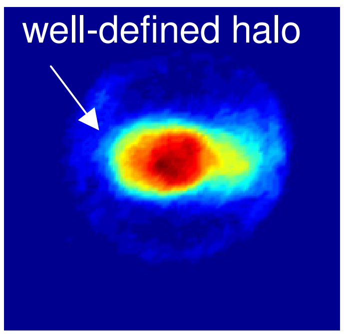
SOL1 = SOL2 = 3A

E-beam right after the gun (250 kV) and the solenoid

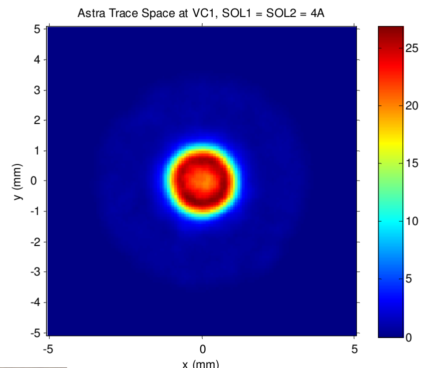
SOL1 = SOL2 = 4.5 A



measured

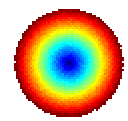


simulated

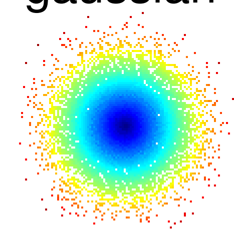


cathode

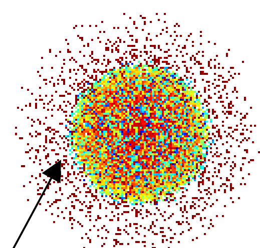
uniform



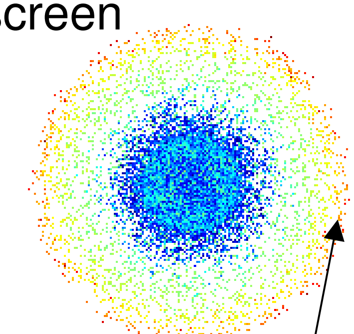
gaussian



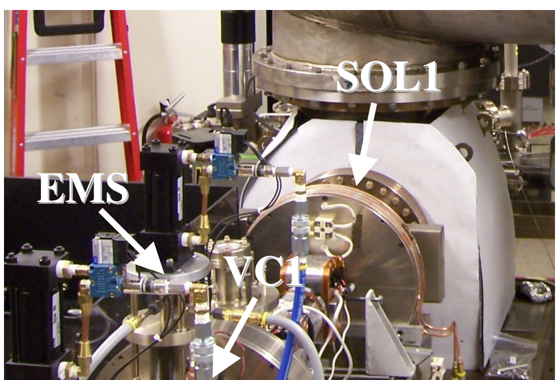
viewscreen



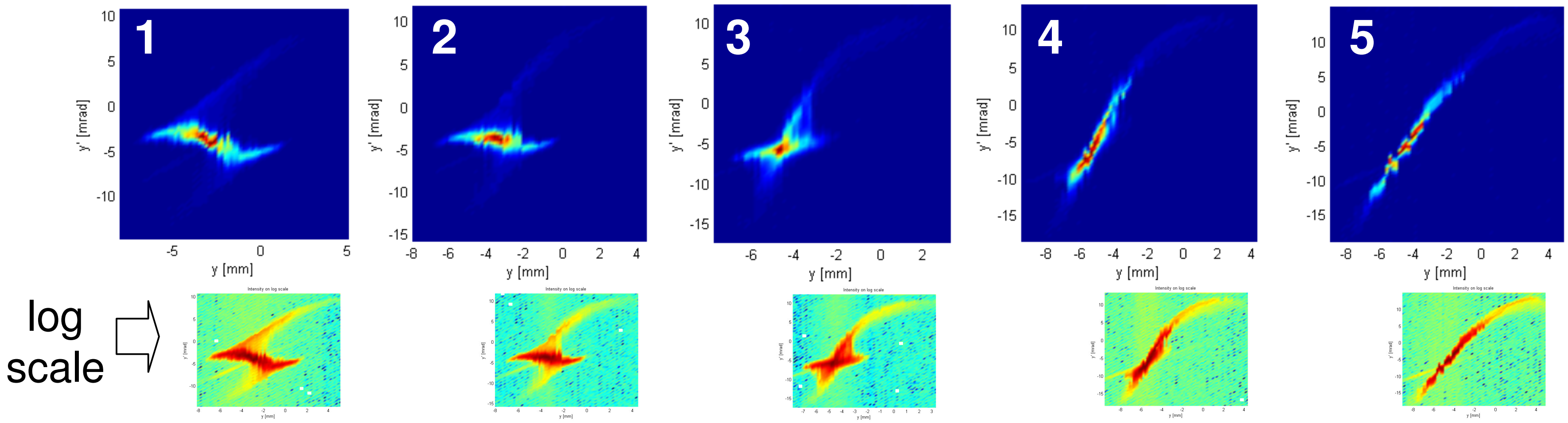
longitudinal tail overfocused

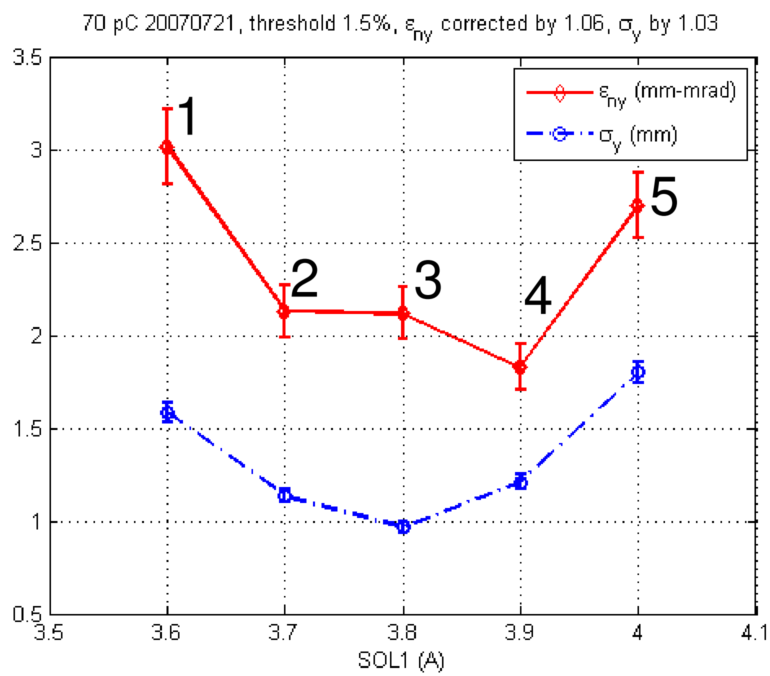


particles folding-over forms well-defined boundary



70 pC/bunch

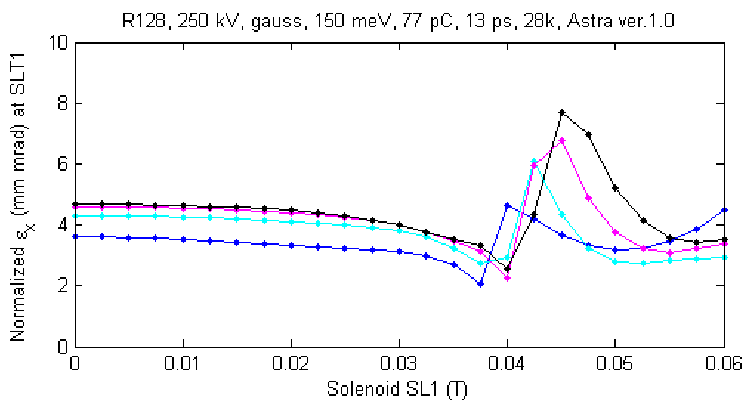


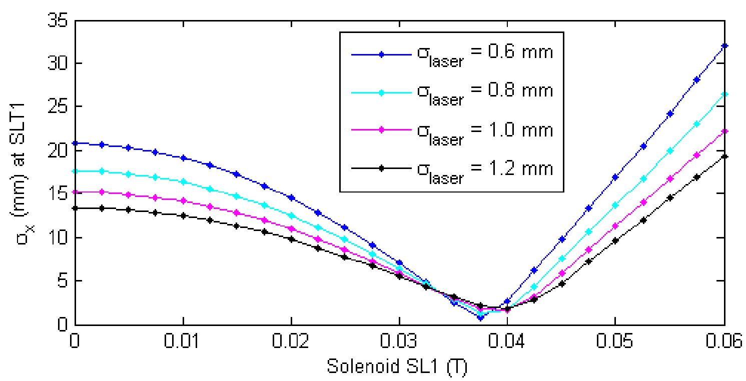


smallest emittance

$$\varepsilon_{ny} = 1.8 \pm 0.1 \text{ mm-mrad}$$

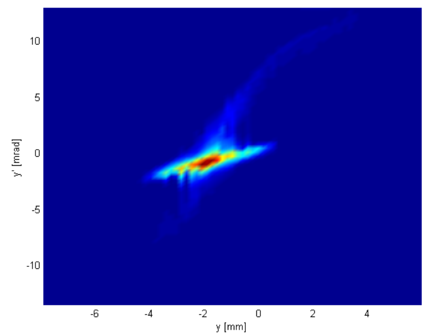
Agreement with simulations



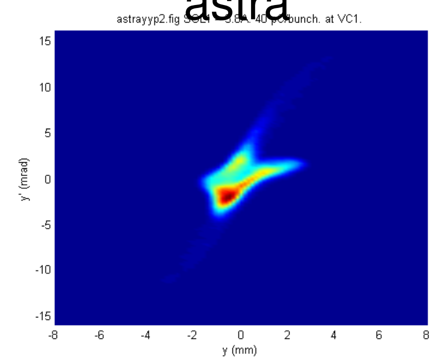


Good agreement with Astra prediction:
77 pC/bunch: about 2 mm-mrad

data

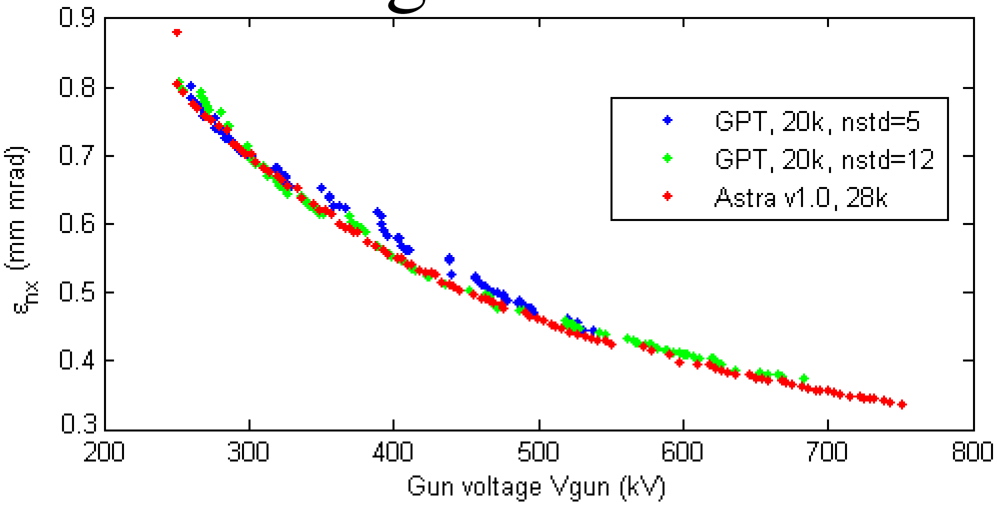


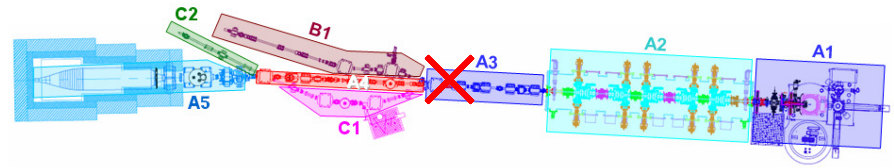
astra



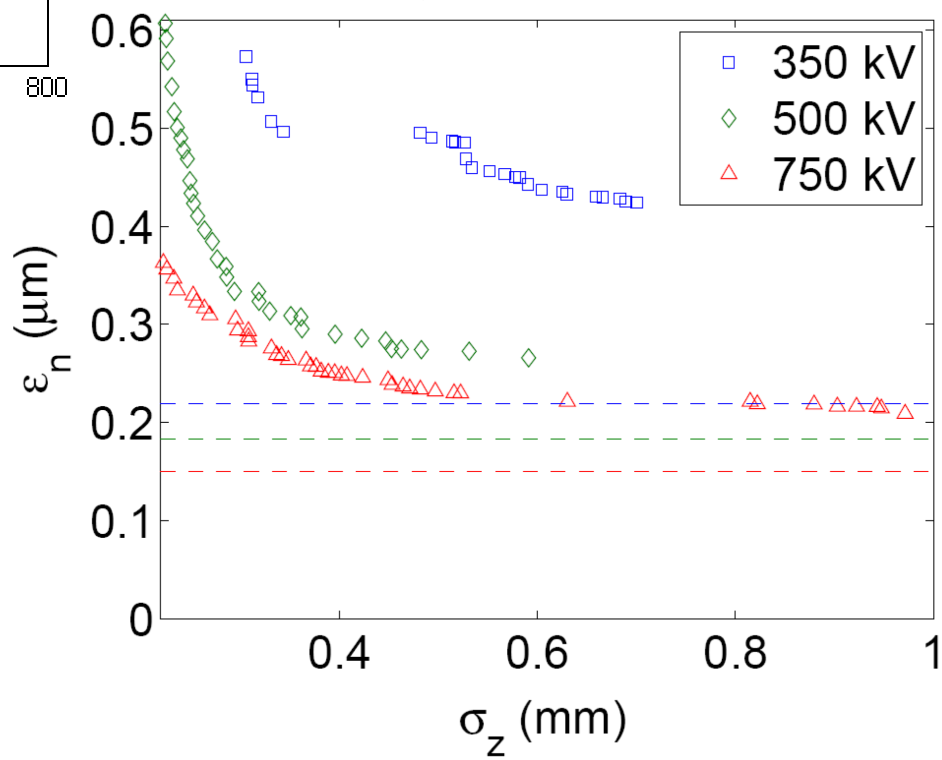
Exp6. Codes' benchmarking

R128: gun & solenoid



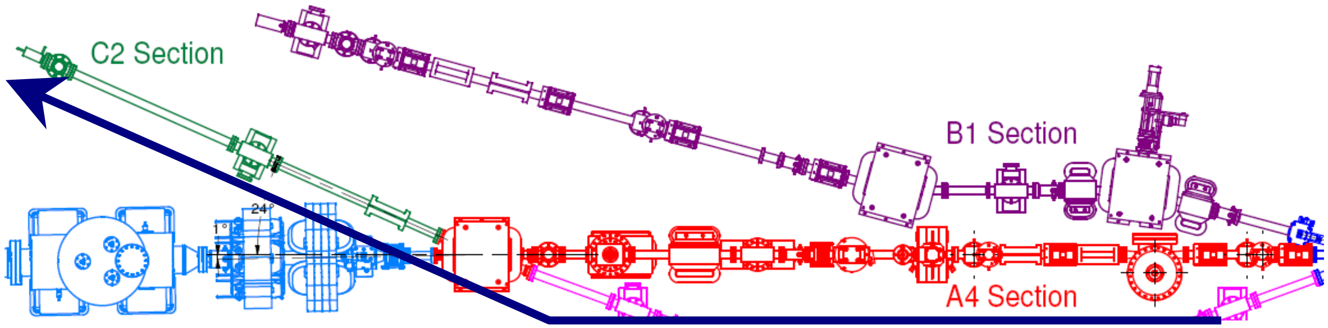


L0: 11 MeV



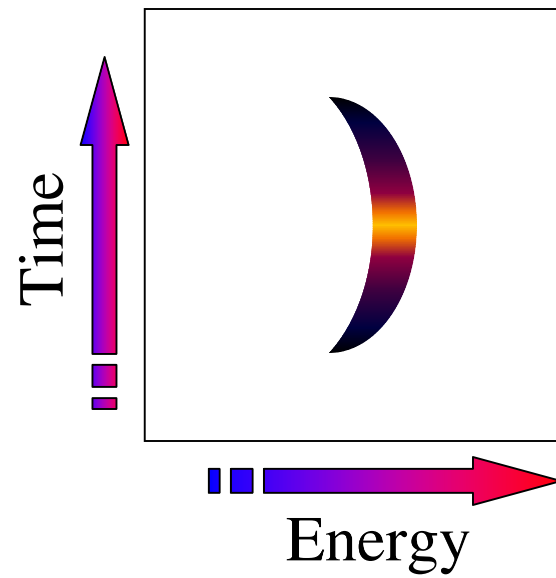
- Emittance right after the gun is **within 50%** of the final value
- Establish the validity of space charge codes & high degree of emittance compensation in R128

Exp9. Long. phase space map.

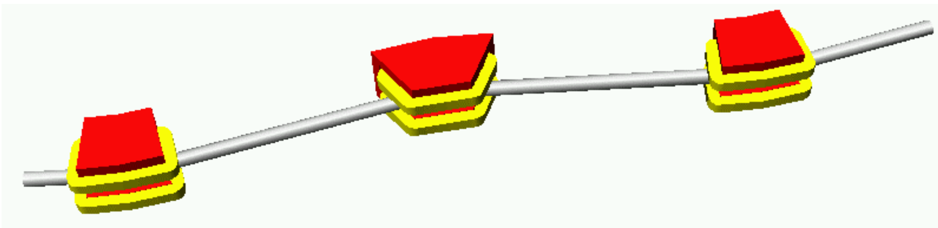


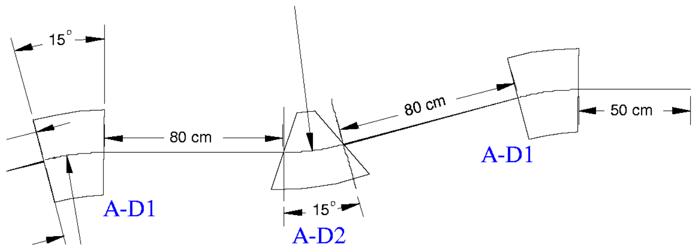
- Combination of slits & deflecting cavity to allow detailed longitudinal phase space mapping
- Temporal resolution 0.1 ps, energy resolution 10^{-4}
- Will be used in a variety of studies, e.g.
  - ensuring small energy spread, a prerequisite for successful transport through the merger
  - optimizing compression scheme

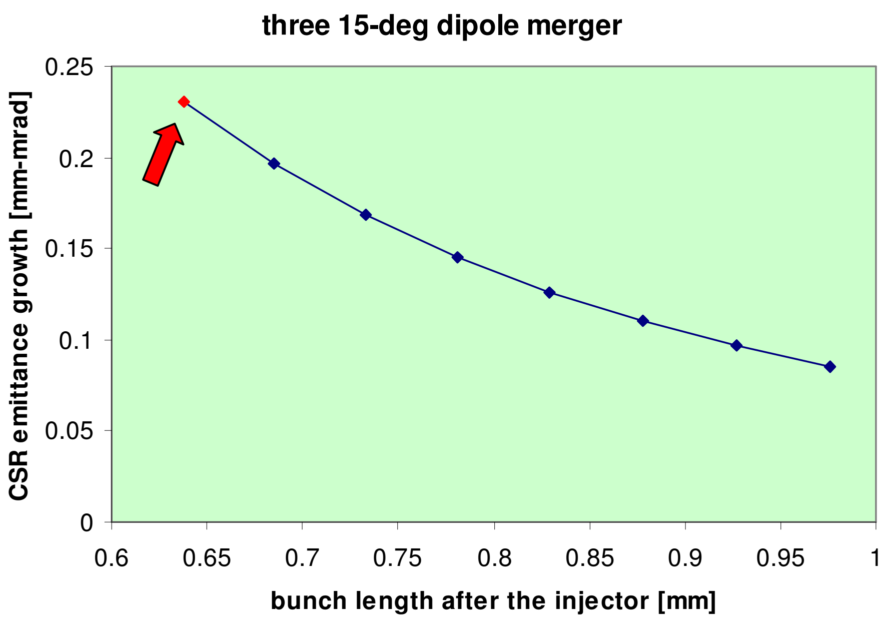
Ce:YAG at the end of C2



Exp11. CSR in the merger







$\Delta\varepsilon_{x,n,CSR} \approx 0.25\ \mu m$

`elegant`

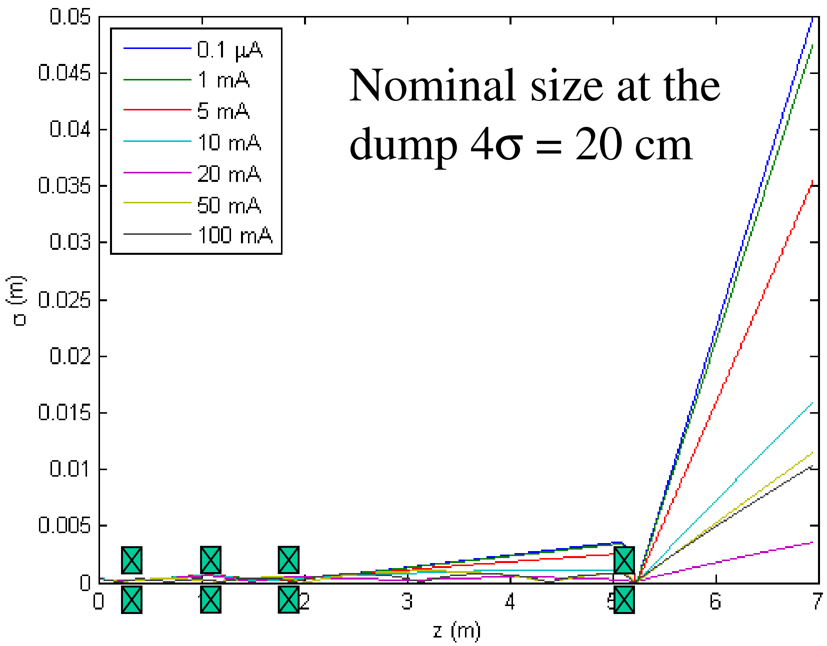
- EMS systems placed before and after the merger to isolate the CSR emittance growth
- Phase space dilution studies as a function of varying charge and bunch length
- Longer term possibilities – smaller bends, shielded chamber

Exp12. Ions

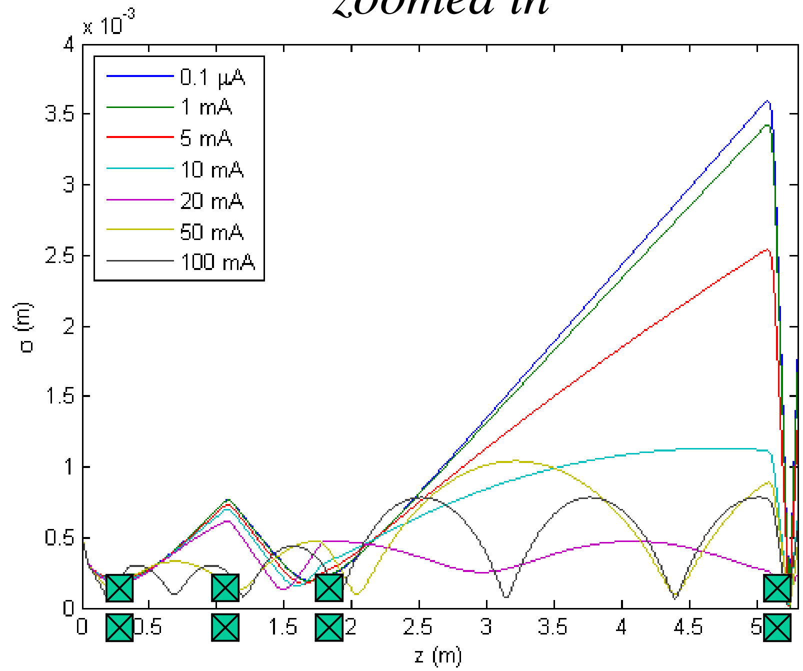
- Initial calculations show that running 100 mA CW will cause problems with safe beam dump operation
- Full beam neutralization over 4 s at 10^{-9} Torr
- Possible approaches:
  - develop the average-current dependant optics to account for the full beam neutralization and slowly ramp up the current (test in R128)
  - introduce the ion gap, e.g. 6 µs every 60 ms (test in R128)
  - the ion gap will cause large RF transients, it won't work in L0
    - Energy stored in the gun: **15.6 J** → 1% transient over 1.5 µs
    - Energy stored in a cavity: **0.5-5 J** → 1% transient over 0.1 µs
  - introduce clearing electrodes (non-trivial changes to the beamline, would rather avoid)

DC beam in R128 (250 kV)

gun through the dump

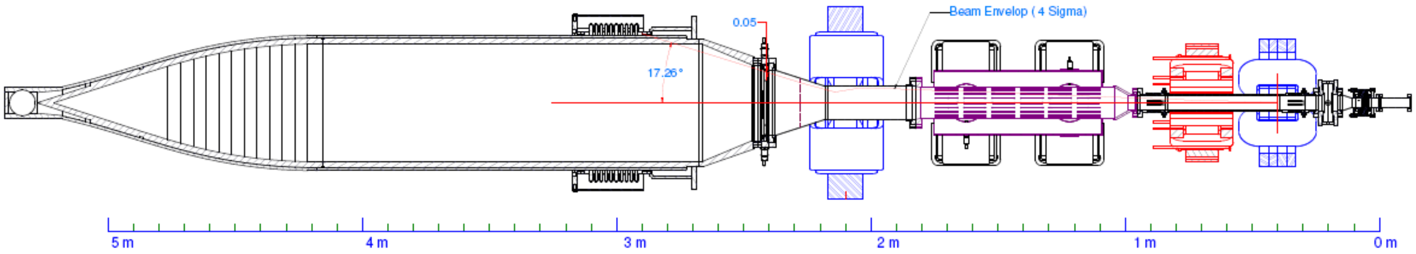


zoomed in



- Ions 'helping' to have a small beam
- 250 kV → 25 kW over 4 cm diameter is probably safe on the dump
- 0.6 MW will not be so forgiving!

L0 dump



- Two extremely short focal-length quads near the dump blow up the beam by a factor of more than a hundred
- Even with the raster, the spot size cannot be less than 8 cm rms at the dump plane. Ions will throw a monkey wrench into the optical setting.
- The optics will have to incorporate the ions to avoid the dump failure mechanism
- *Challenge*: we are essentially blind at 0.6 MW near the dump as far as the beam profile is concerned.

Exp15. Multi-knobs & tune-up

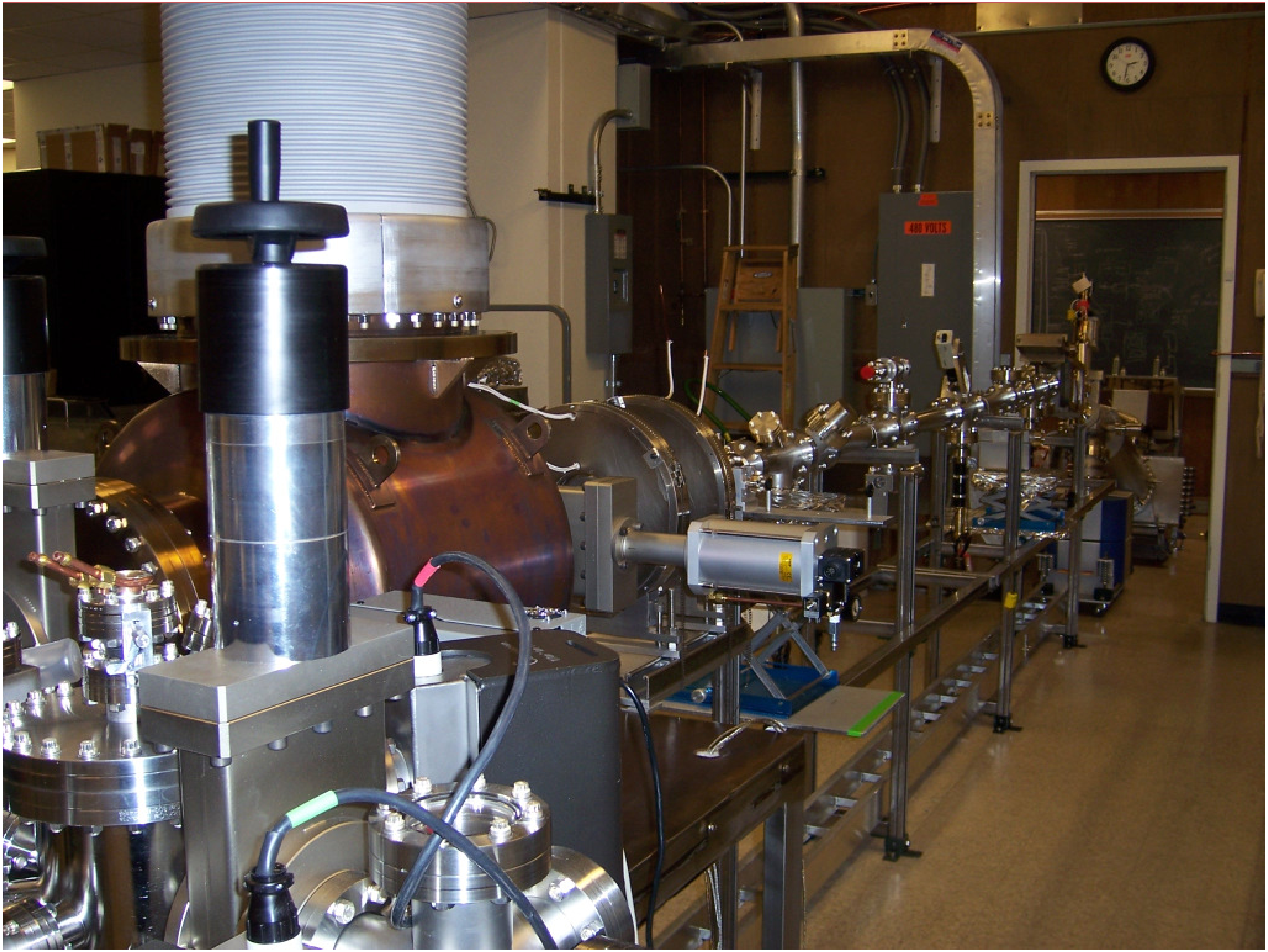
- Should develop ad-hoc means to tune-up the nonlinear system for optimal performance
- 'Manual' optimization using a calculated Hessian matrix of the beam emittance from the space charge codes:

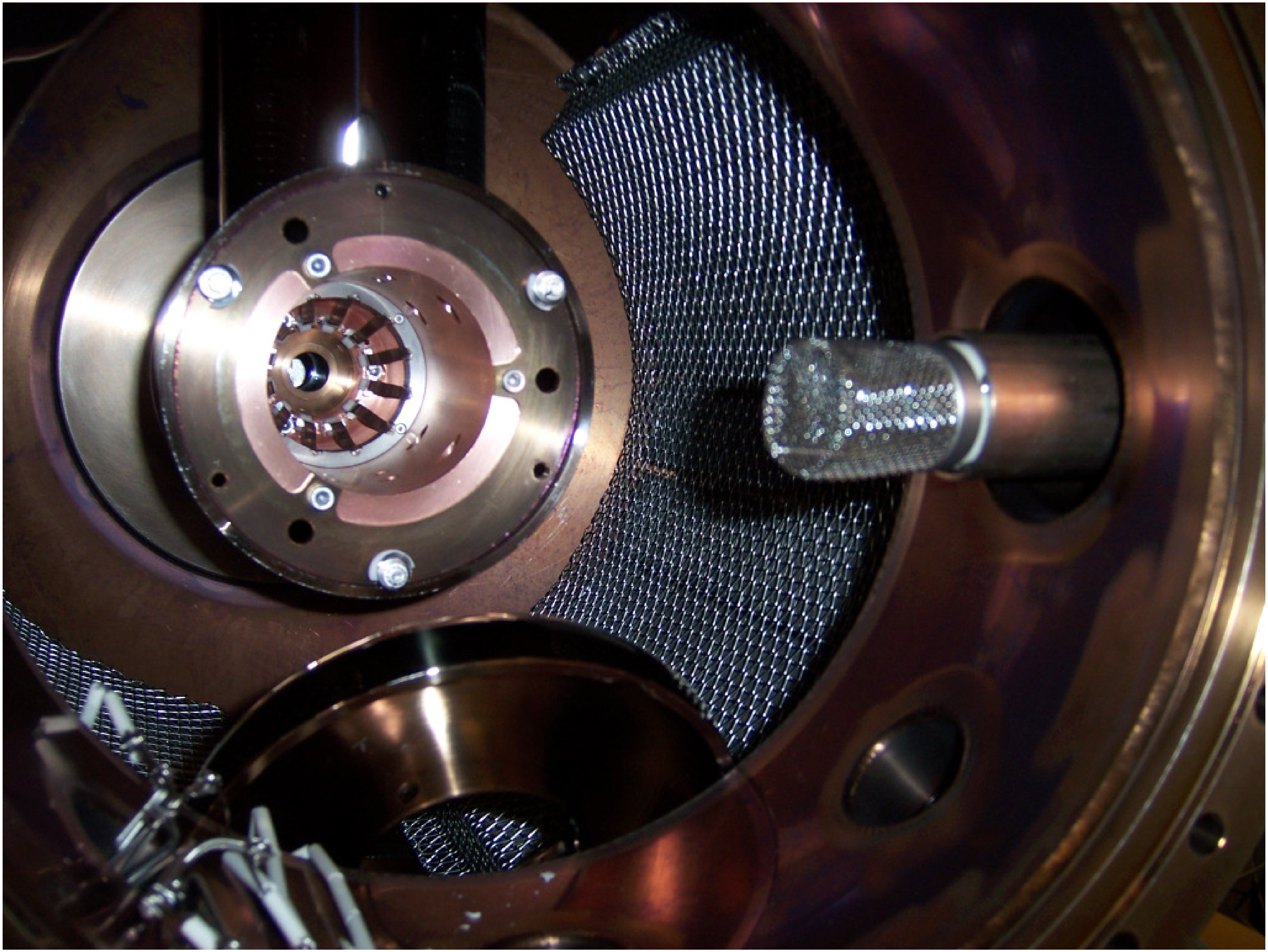
$$H_{ij} = \frac{\partial^2 C}{\partial p_i \partial p_j}$$

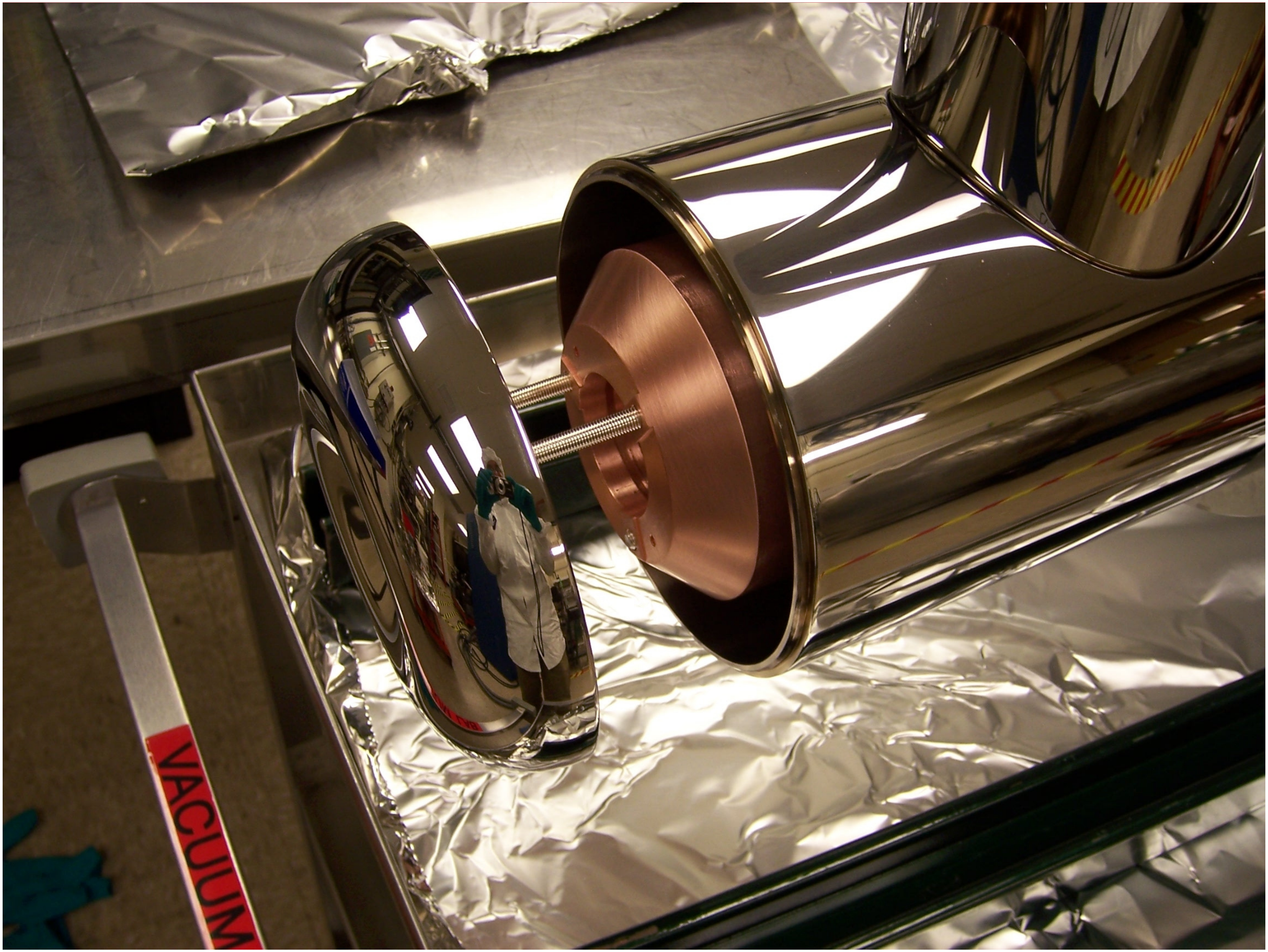
- Use SVD of the Hessian to form 'multi-knobs' that correspond to top few eigenvalues
- Other potentials: use *online* direct search method (e.g. simplex) or a stochastic search (e.g. genetic algorithms). Analog computer evaluations will be limited to a few hundred at most.

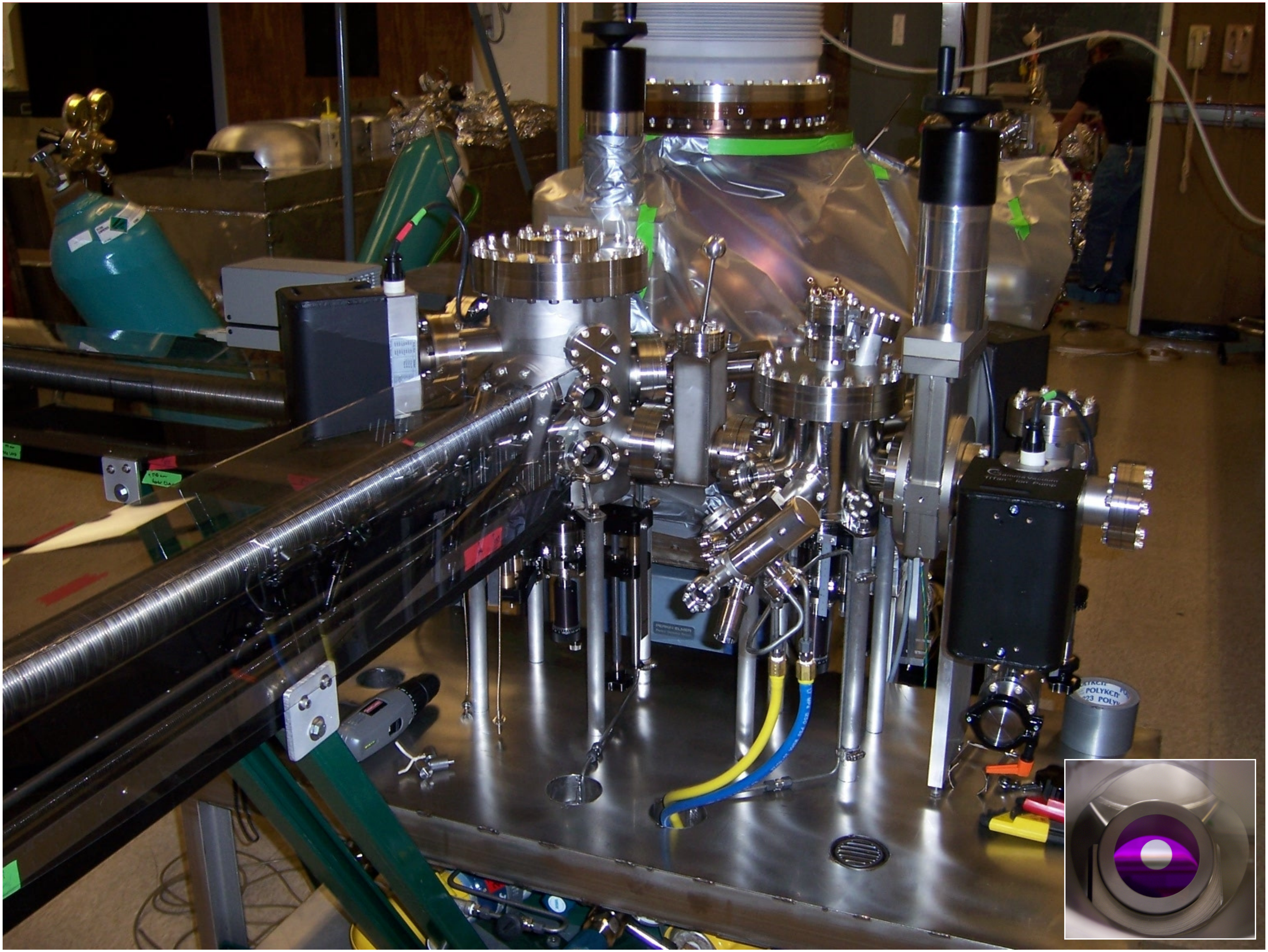
Summary

- Experimental plan outlined, both R128 and L0 parts are essential
- There are things we know we don't know (e.g. ions), and there are things we don't know we don't know. We are concentrating on the former.


480 VOLTS




VACUUM


POLYKEN