Beam dynamics considerations for a high repetition rate photoinjector

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CBP SEMINAR

NOVEMBER 16 2012

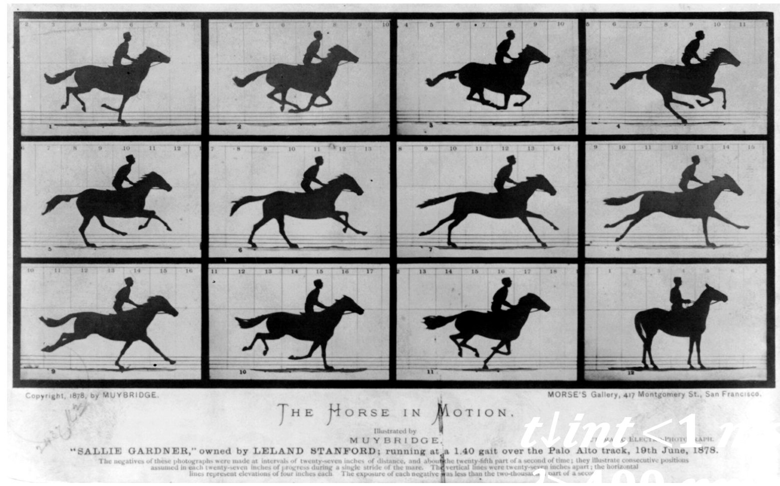
Overview

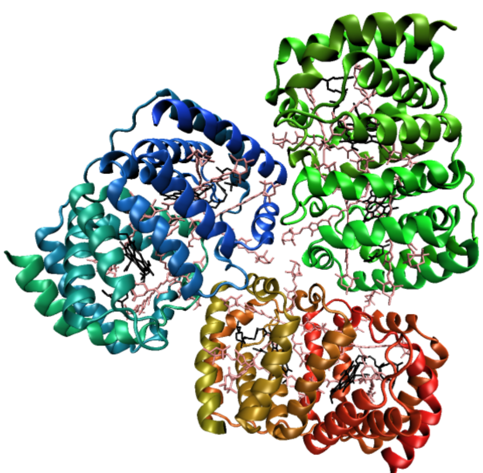
1. Introduction and Motivation
2. Design and Optimization of the NGLS Injector
3. Beam dynamics for the Advanced Photoinjector EXperiment
4. Emittance diagnostics based on OTR

Shorter length, smaller size, brighter, coherent light

Le derby d'Epsom, painting by Théodore Géricault, 1821

The horse in motion by Eadweard Muybridge, commissioned by Leland Stanford, 1878





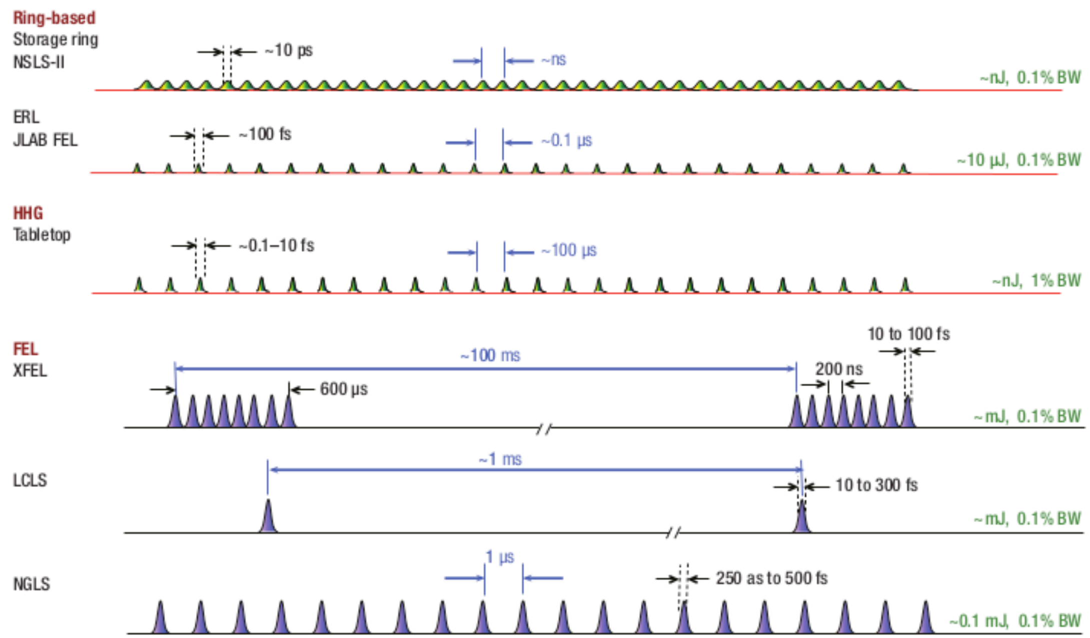
The peridinin-chlorophyll-protein light-harvesting complex.

?

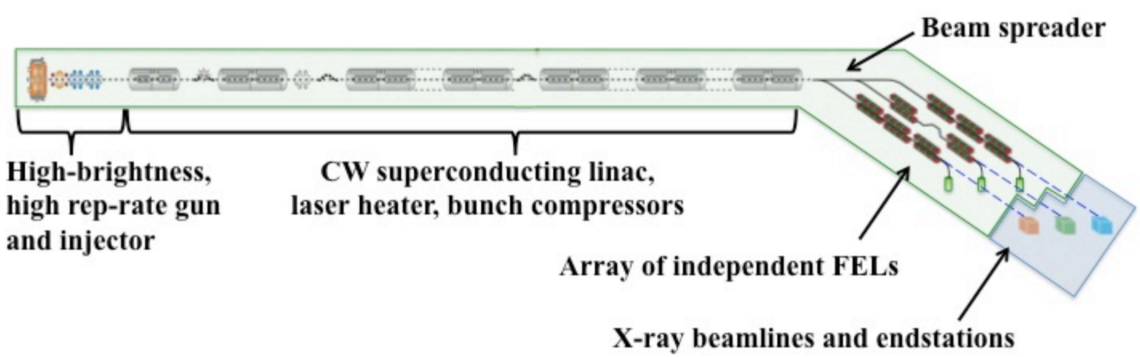
Sources
http://upload.wikimedia.org/wikipedia/commons/f/f3/Jean_Louis_Th%C3%A9odore_G%C3%A9ricault_001.jpg
http://upload.wikimedia.org/wikipedia/commons/7/73/The_Horse_in_Motion.jpg
http://upload.wikimedia.org/wikipedia/commons/1/19/Peridinin-chlorophyll-solenoid-1ppr.png

NGLS: A high repetition rate soft xray FEL

Linac driven FELs are a proven tool
to produce xray pulses with high power, small bandwidth and short length

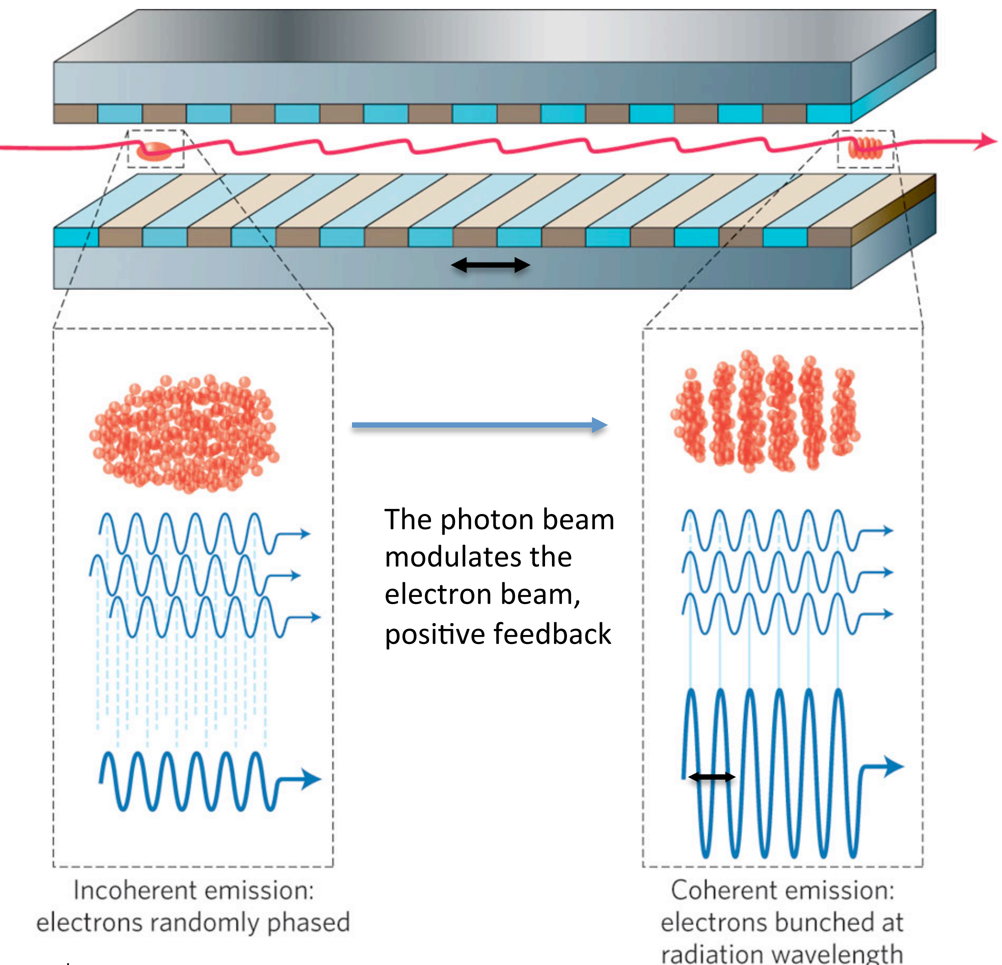


NGLS will bridge the gap between high repetition rate, low peak power storage rings and low rep. rate, high peak power existing FELs



Source: NGLS CD0, CDR

The FEL process



3rd generation light sources

FEL: 4th generation light sources

Source: Brian W. J. McNeil & Neil R. Thompson Nature Photonics 4, 814–821 (2010)

Important FEL parameters

: radiation wave

: undulator parameter

: Exponential power gain

: Gain length (1-d theory)

Short list of requirements for lasing

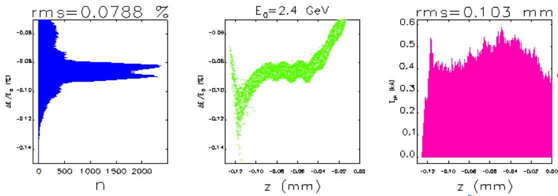
: Resonance condition

: Transverse overlap of electrons and photons

high enough for reasonable undulator length

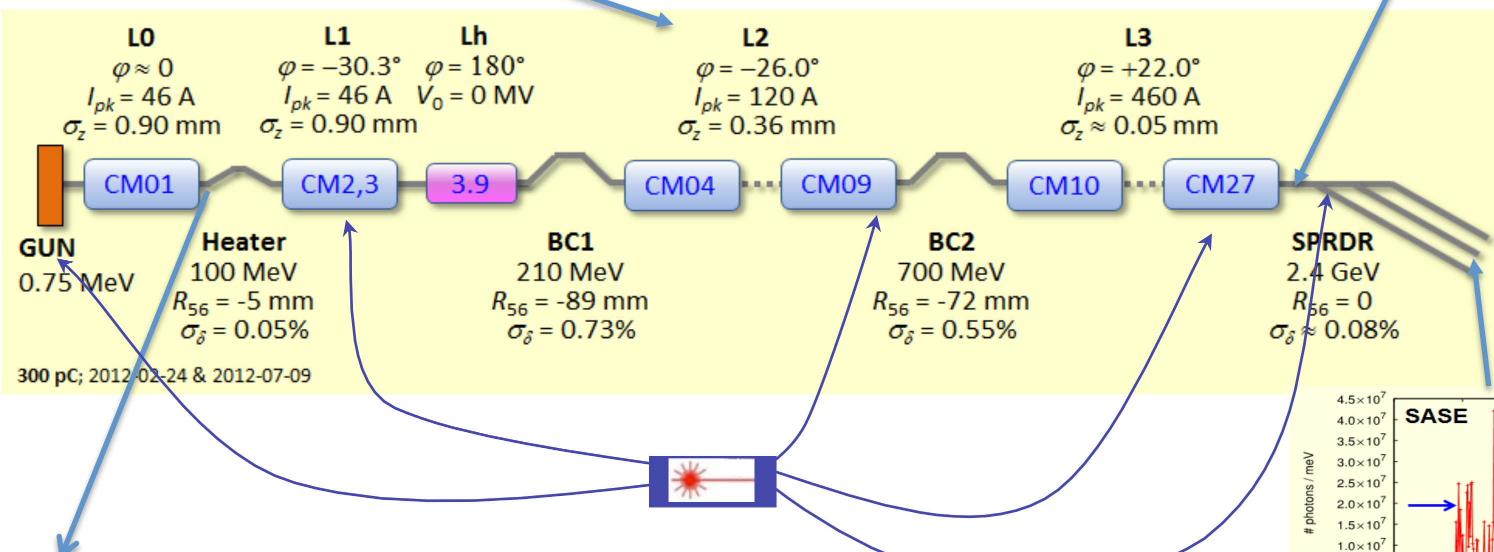
Stringent requirements on transverse and longitudinal beam quality

NGLS: A single pass system with multiple components



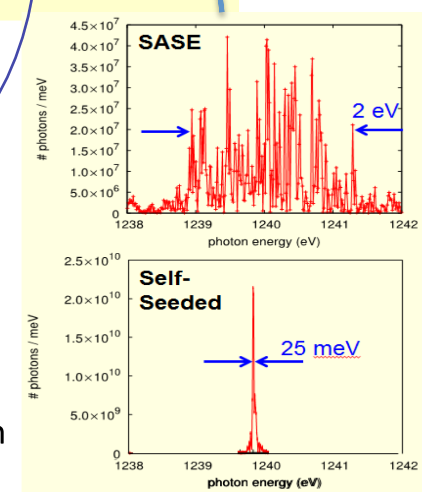
Linac: Accelerate and compress while avoiding trans. emittance degradation and microbunching

Spreader: Beam distribution to individual beamlines



Feedback system

Exit of the NGLS Injector:
The beam quality cannot be improved downstream (unlike synchrotrons)



Photon beam after FEL

Requirements of the NGLS injector

Requirements on the photon beam at FEL 1

FEL-1 Parameters (SASE/SS)	symbol	nom. value	range	units
Photon energy (tuning range, fund.)	E_r	1.2	0.27 – 1.2	keV
Photon wavelength (tuning range, fund.)	l_r	1.0	1.0 – 4.6	nm
Photons per pulse (fund.)	N_p	0.2	0 – 4.0	10^{12}
FEL peak power (fundamental)	P_{FEL}	0.5	0 – 1.0	GW
FEL pulse energy (fundamental)	E_rN_p	100	0 - 250	μJ
Power gain length (magnetic, SASE)	L_G	1.9	1.0 – 2.4	m
FEL parameter (SASE)	ρ	5.6	5 – 10	10^{-4}
X-ray pulse length (FWHM, SASE)	Δt	250	10 - 300	fs

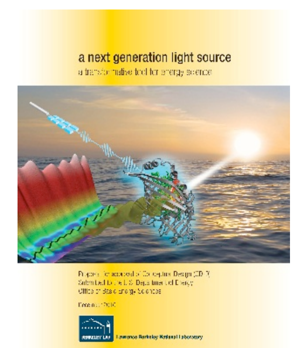
Requirements on the electron beam delivered to FEL 1

Electron Beam Parameters	symbol	nom. value	units
Final electron energy (operational)	E_f	2.4	GeV
Electron bunch charge	Q_b	0.30	nC
Bunch repetition rate in linac (CW)	f_b	1	MHz
Average electron current in linac	I_{av}	0.3	mA
Average electron beam power in linac	P_{av}	0.72	MW
Norm. rms transverse slice emittance	$\gamma\varepsilon_{\perp\text{-}s}$	0.6	μm
Norm. rms transverse proj. emittance	$\gamma\varepsilon_{\perp}$	1.0	μm
Peak current	I_{pk}	600	A
Final rms bunch length (after BC2)	s_{zf}	45	μm
Final useable bunch duration (FWM)	Δt_f	150	fs
Final slice energy spread (rms)	σ_{Es}	100	keV
Final proj. rel. energy spread (rms)	σ_E/E_f	0.05	%
Final linear e^- energy chirp (FWHM)	$\Delta E_c/E_f$	0	%

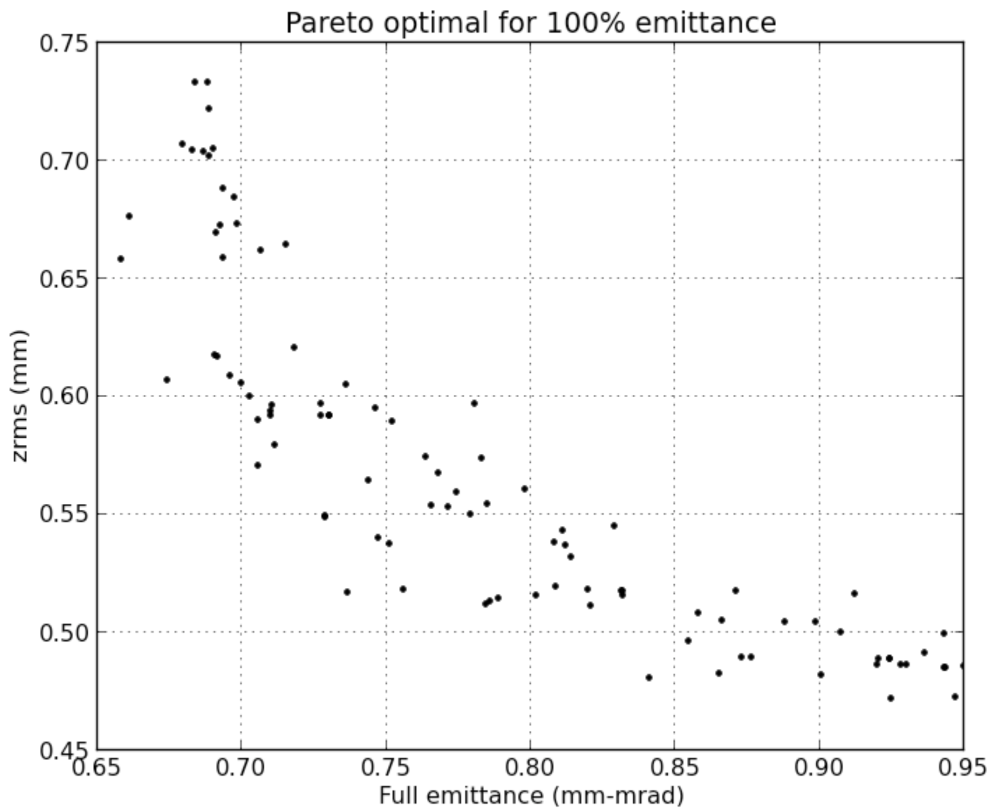
Parameter	Symbol	Unit	Nom. Value
Repetition rate	f_G	MHz	1
Charge per bunch	Q	pC	300
Normalized transverse emittance (slice, rms, charge dependent)	enx,y	mm	0.6
Beam energy at the gun exit	E_G	MeV	0.75
Beam energy at injector exit	E_I	MeV	85
Bunch length at the cathode (rms)	σz	ps	~15
Peak current at the injector exit	I_{pI}	A	60

Requirements at the injector exit

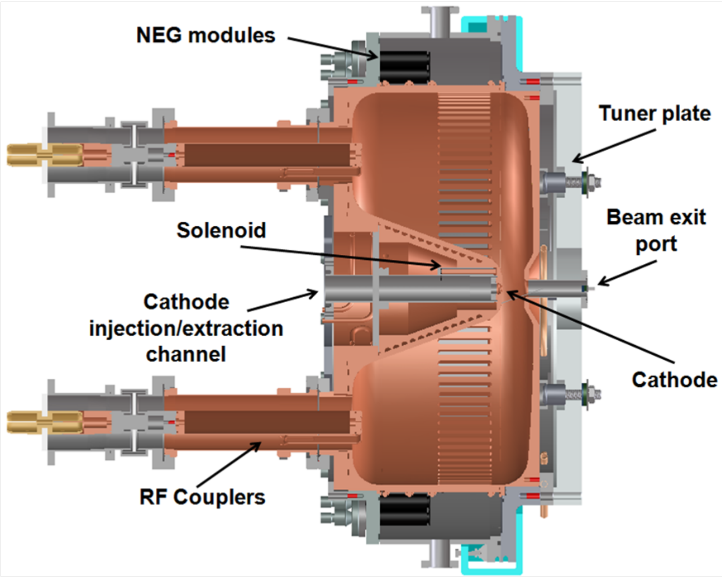
The requirements are for both projected (integrated over the pulse) and slice (time-dependent) beam quality



Injector optimization



Normal Conducting, Continuous Wave RF Gun



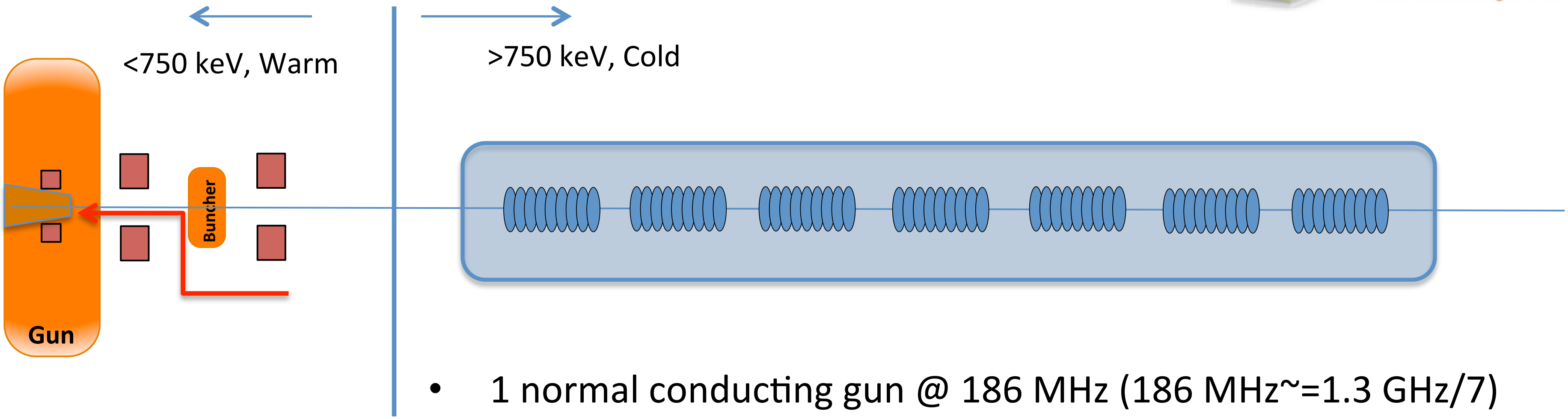
Frequency	187 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0	30887
Shunt impedance	6.5 MΩ
RF Power	87.5 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm^2
Accelerating gap	4 cm
Diameter/Length	69.4/35.0 cm
Operating pressure	$< 10^{-11}$ Torr

- Based on proven technologies
- Normal conducting RF cavity
- Large size for easy cooling
- Good vacuum to accommodate high QE photocathodes

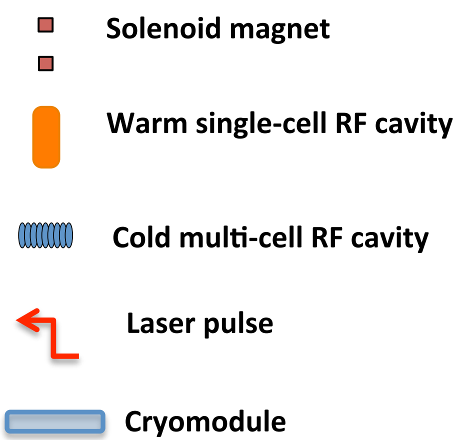
Gun Technology Fully Demonstrated
The gun is the basis of the APEX project
(more on this later)

Fernando Sannibale, Daniele Filippetto, Christos F. Papadopoulos
Journal of Modern Optics
Vol. 58, Iss. 16, 2011

NGLS Injector Layout



- 1 normal conducting gun @ 186 MHz (186 MHz~=1.3 GHz/7)
- 2 solenoids (emittance compensation)
- 1 single-cell buncher cavity @1.3 GHz (for compression)
- 7 9-cell TESLA cavities @1.3 GHz (velocity bunching + emittance compensation)
- 1st cryomodule is identical to the downstream cryomodules



Beam dynamics implications of the NGLS Injector

APeX @ Berkeley Lab

Compare with what works already

- Longer RF wavelength (186 MHz vs 2.85 GHz for LCLS)
- Lower gradient at the cathode (20 MV/m vs 140 MV/m for LCLS)
- Lower beam energy at the exit (0.75 MeV vs 6 MeV for LCLS)

Space charge is more important in our case

geometric factor,
depends on bunch shape

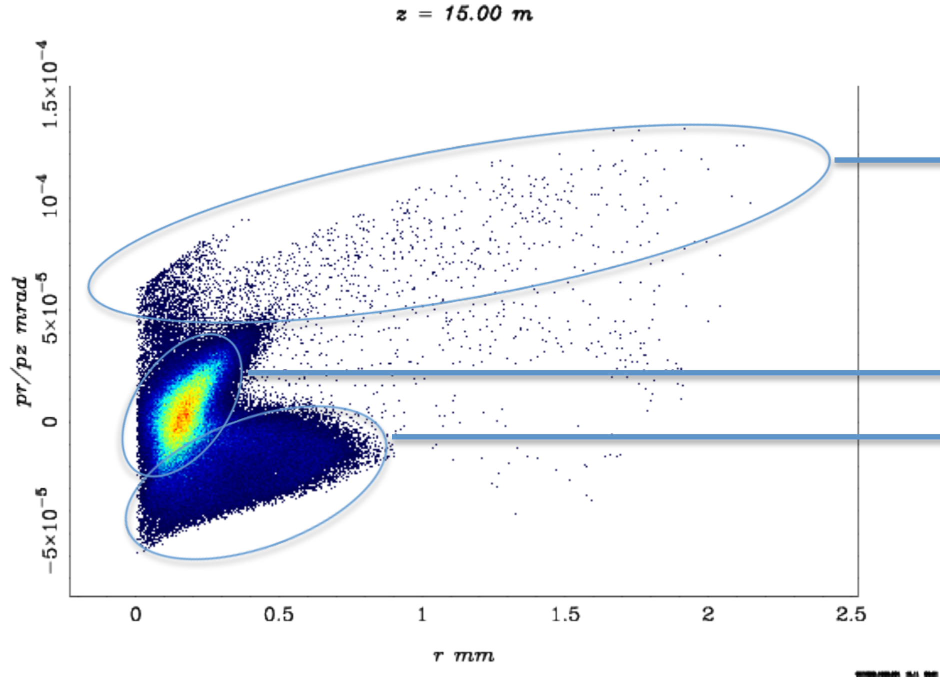
Transverse SC force

Longitudinal SC force

Space charge (linear and nonlinear) can dilute the quality of the phase space

M. Reiser
Theory and Design of Charged Particle Beams

Phase space distortions due to space charge

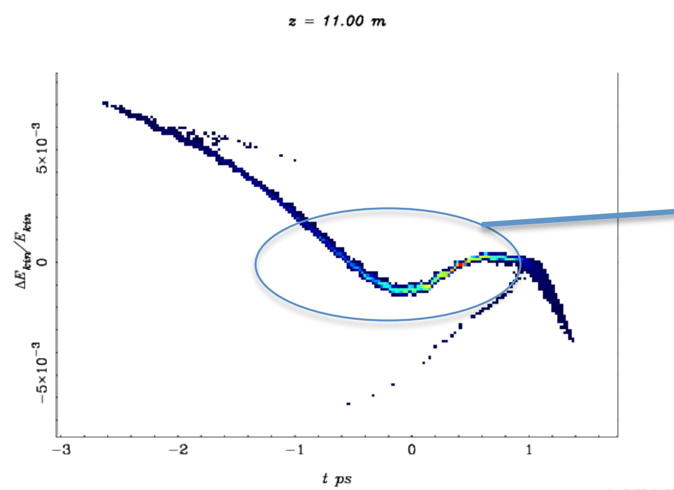


Transverse phase space

Halo

Slice emittance growth

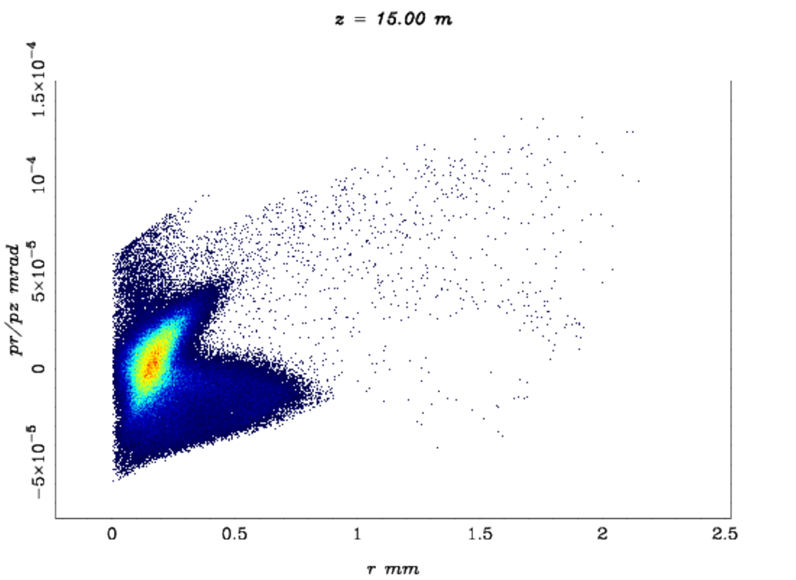
Projected emittance growth

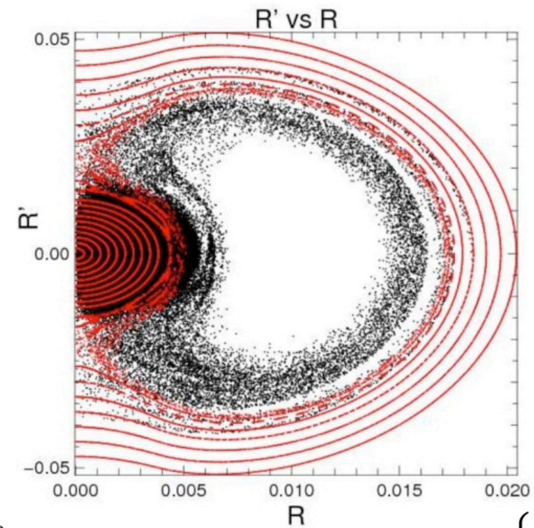


Longitudinal phase space distortion

Beam Halo

Black: WARP simulation of a
space charge dominated beam (UMER)
Red: Analytical particle-core model





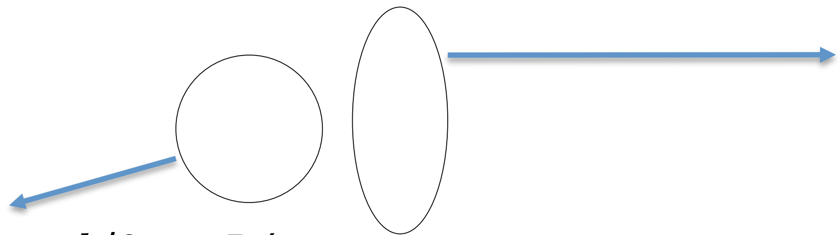
$$\frac{\mathrm{d}^2 r}{\mathrm{d}z^2} + k_0^2 r - F(r) = 0 \qquad F(r) = \begin{cases} m v_z^2 \frac{K}{R^2} r & r \leq R(z) \\ m v_z^2 \frac{K}{r} & r > R(z) \end{cases}$$

Particles that resonate with the beam envelope oscillations may be kicked to high amplitude oscillations and create beam halo.
We expect most beam losses to be due to dark current (more on this later)

C. F. Papadopoulos, PhD Thesis, 2009
Gluckstern 1994
Lagniel 1994
Wangler 1998

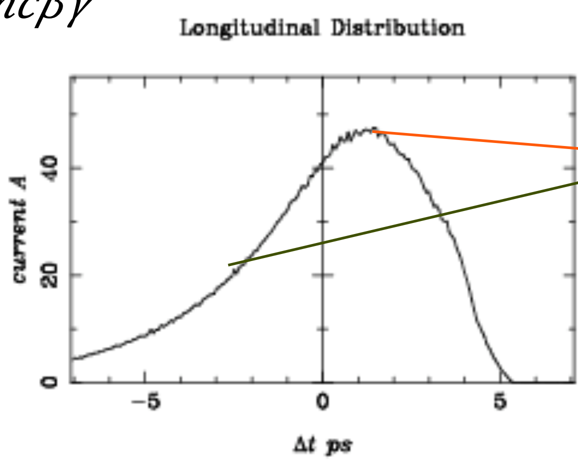
Emittance compensation

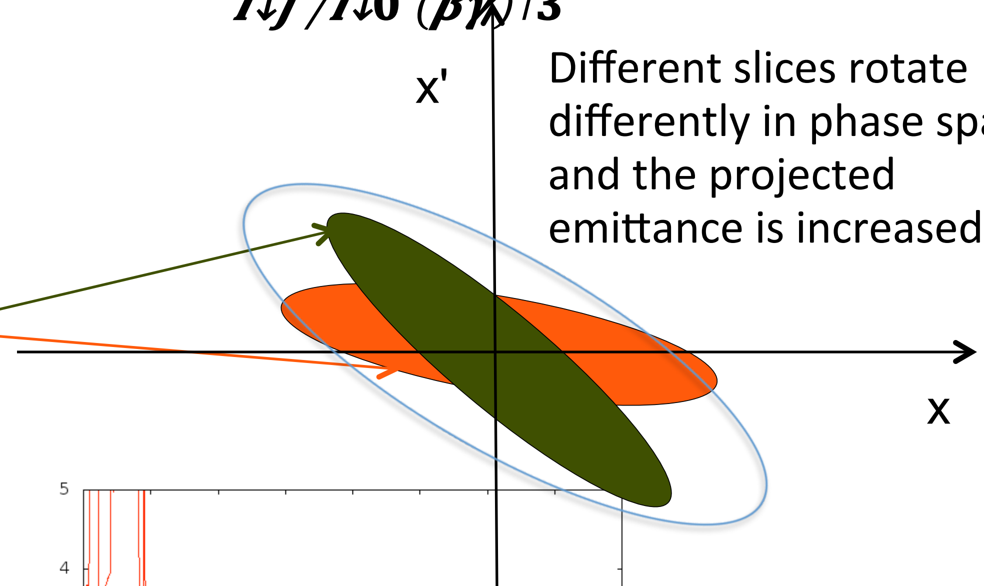
We can compensate for the projected emittance growth by using solenoids



Space charge
Defocusing $K_j = 2 I_j / I_0 (\beta\gamma)^3$

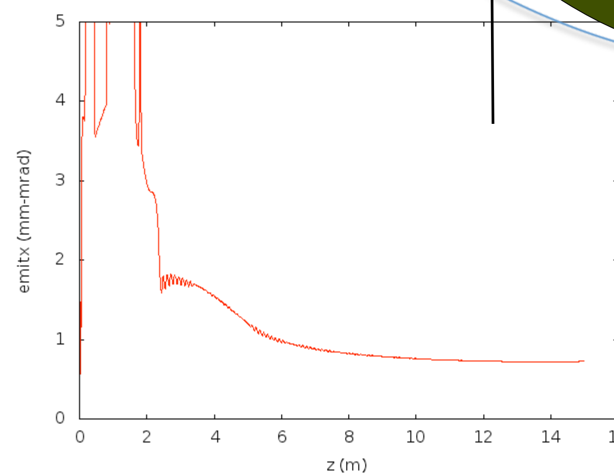
Sol. focusing, $k_0 = eB/2mc\beta\gamma$





Different slices rotate differently in phase space and the projected emittance is increased

To 1st order, the slice ellipses perform small oscillations with different amplitude but the same wavelength.
Since they start aligned, they will eventually reallign

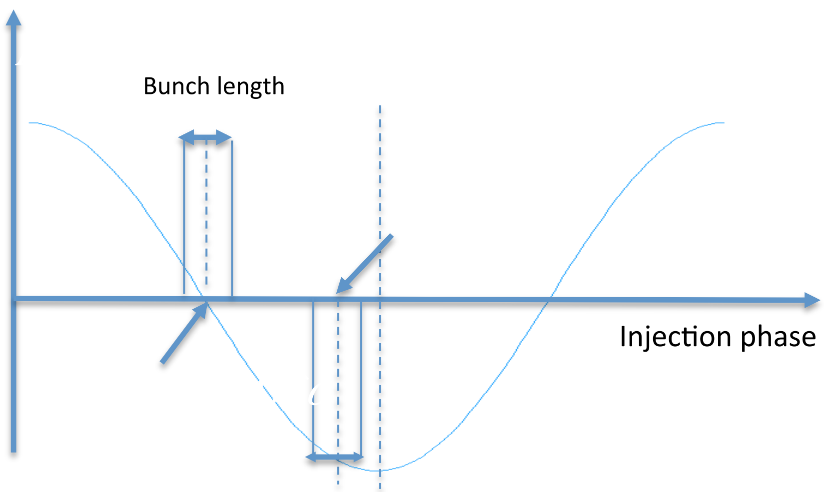


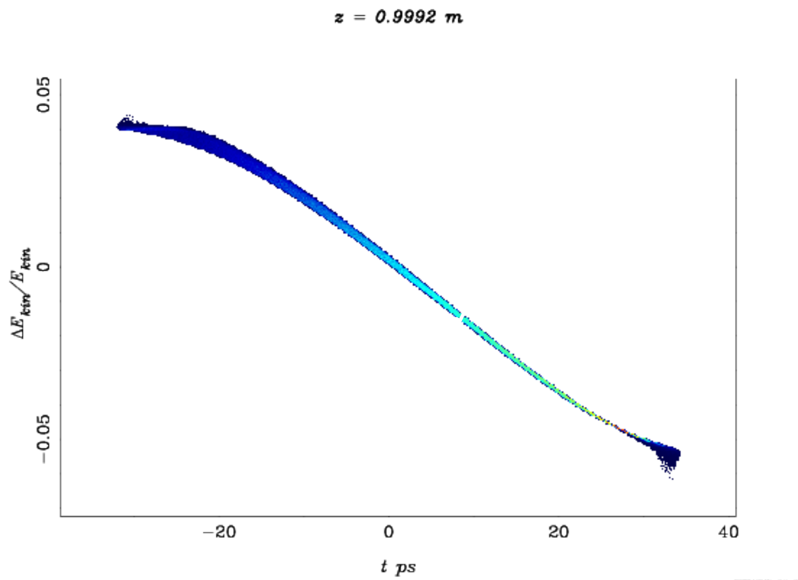
Carlsten 1989
Serafini, Rosenzweig 1997

Compression using RF dephasing

One way to reduce the effect of space charge is to reduce the current at the cathode by increasing the incident laser pulse length.

Simulations show that 5 A produce good beam quality,
 but we now need to compress in order to get 40-60 A





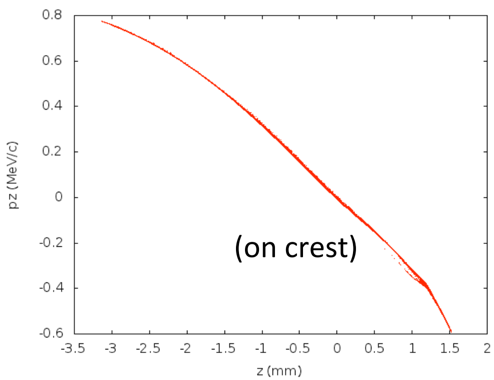
We can compress by injecting at 0 crossing ("ballistic compression") or with a dephasing , while accelerating ("velocity bunching").

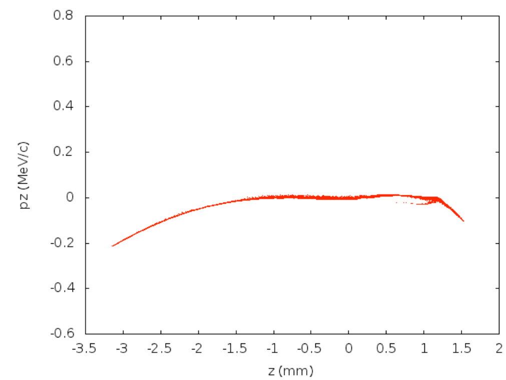
Both are only efficient at low energies since

Ferrario et al 2010

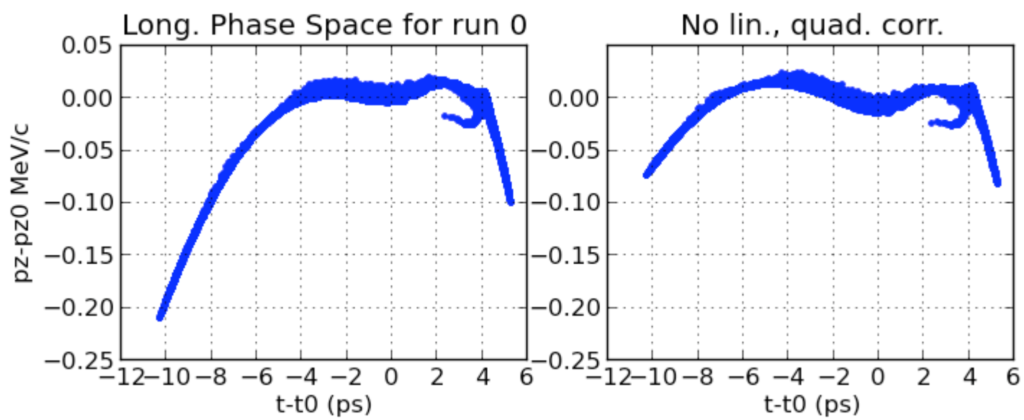
Additional Considerations

Remove linear correlations (needed for compression) in longitudinal phase space in order to accommodate for the laser heater after the injector.
We can do this by dephasing the last 2 cavities





Simply calculating the rms energy spread overestimates it due to quadratic correlations caused by RF curvature. The 3rd harmonic cavity downstream will remove those.
We mimic that by artificially removing them after the simulation



Genetic Optimizer

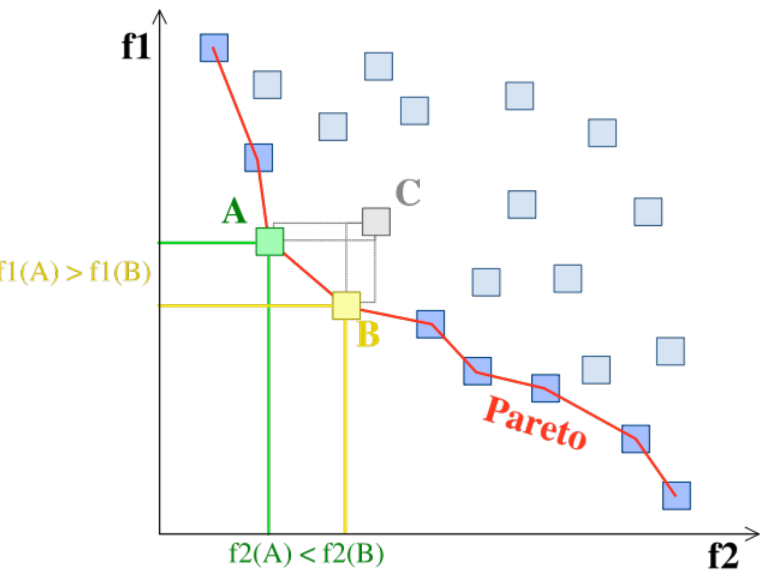
@ Berkeley Lab

The problem:

Find global optimum(s) for a problem with multiple, non-linearly coupled knobs (typically more than 10)

The solution:

Multi-Objective Genetic Algorithms



Vilfredo Pareto
1848-1923

We use the algorithm NSGA2 (Deb 2002, Bazarov 2005)

Parallelized evaluation of the solutions (the most computationally expensive part).

Runs performed in the alsacc cluster.

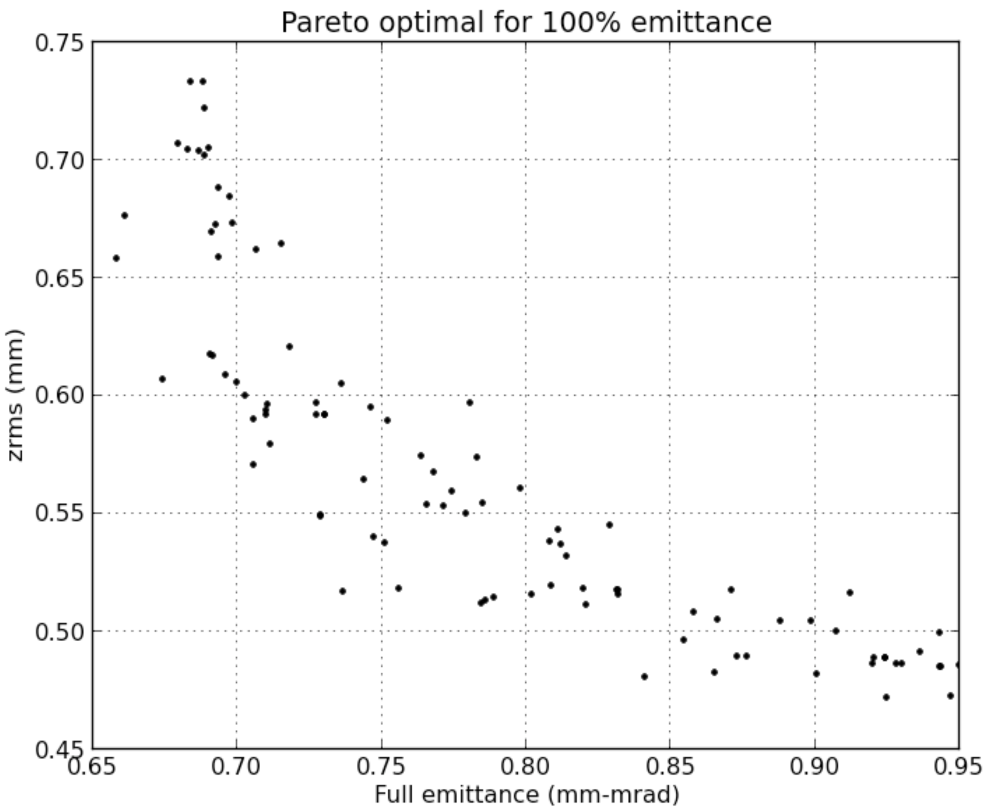
A and B dominate C

But A and B don’t dominate each other

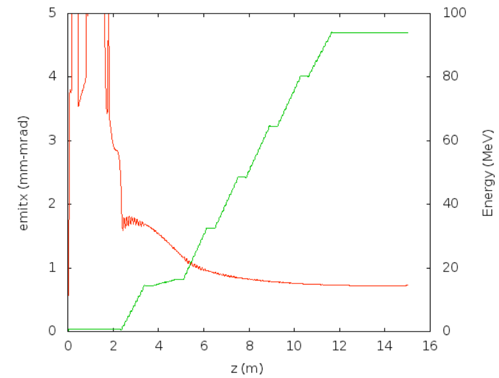
The algorithm finds a front of non-dominated solutions

Photos: wikipedia

Pareto Optimum



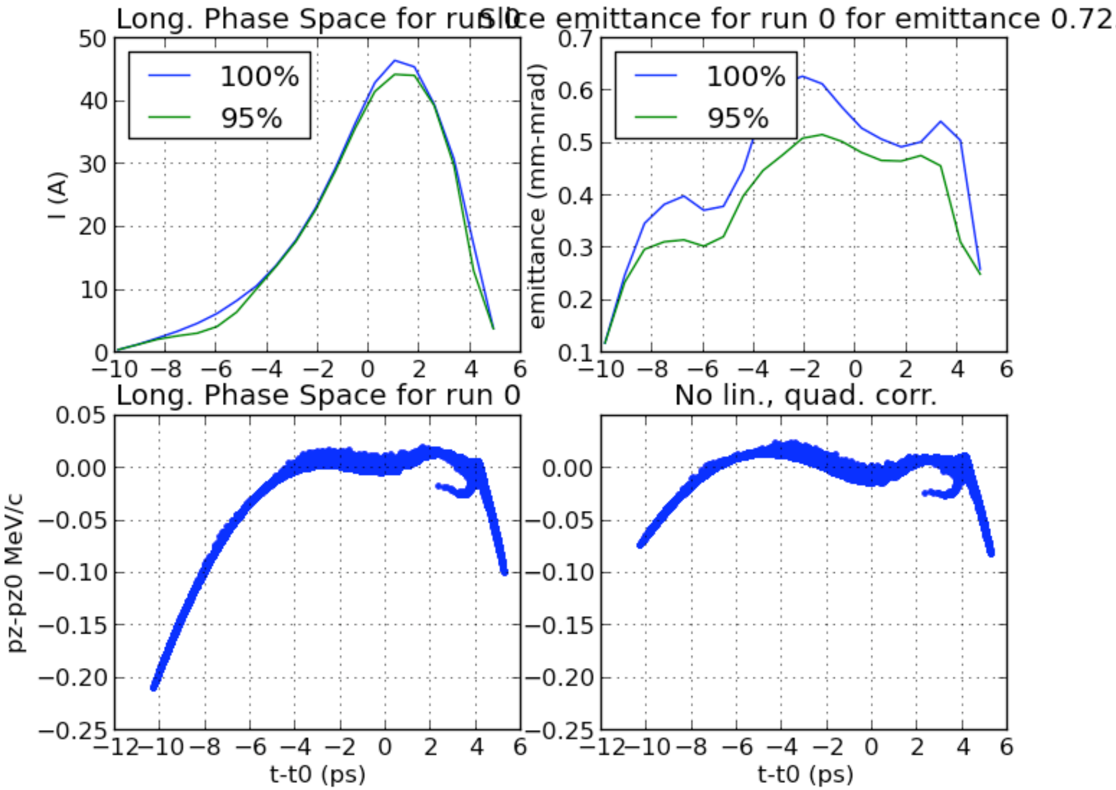
Emittance vs bunch length at the injector exit (~100 MeV)
Space charge effects should be "frozen-in" at this point



Simulations performed using ASTRA

The result is a front of solutions
Using this, we can evaluate the trade-offs and choose 1 (or possibly more) as candidates

Optimized solution

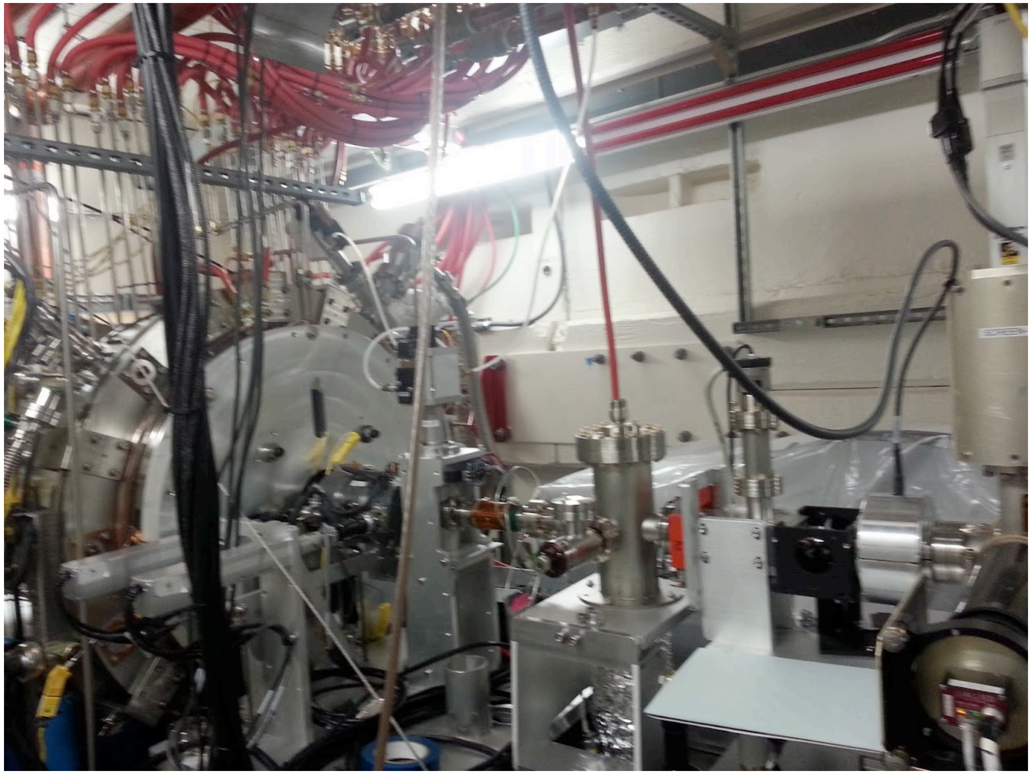


Gun Phi (deg)	-2.91674
Buncher Grad. (MV/m)	3.99863
Buncher Phi (deg)	-71.1609
Sol. 1 B (T)	0.0396057
Sol. 2 B (T)	0.0282948
Cav. 1 Grad. (MV/m)	29.4731
Cav. 1 Phi (deg)	-40.6049
Cav. 2 Grad. (MV/m)	6.18249
Cav. 2 Phi (deg)	-52.2731
Sig x (mm)	0.304257
Laser Δt (ns)	0.0440136
Cav, 6 Phi (deg)	13.1272
Cav. 7 Phi (deg)	33.4975

Final beam Characteristics:
100% emitx= 0.725 mm-mrad
95% emitx = 0.667 mm-mrad
I~=45 A
energy = 93.88 MeV
cor. e-spread = 20.1 keV
sigx final =196μm

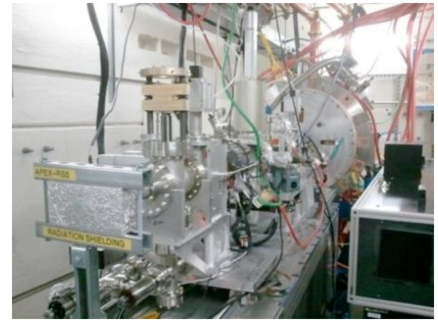
Start-to-end simulations are currently under way

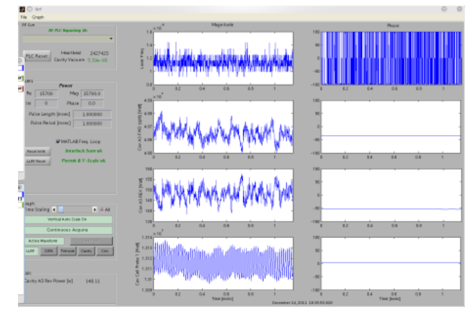
Advanced Photoinjector EXperiment

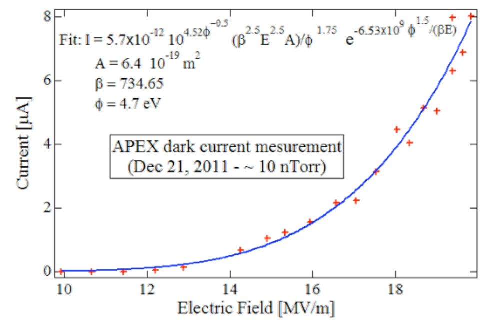


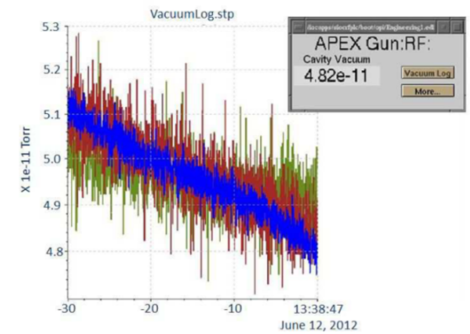
APEX PRESENT ACHIEVEMENTS

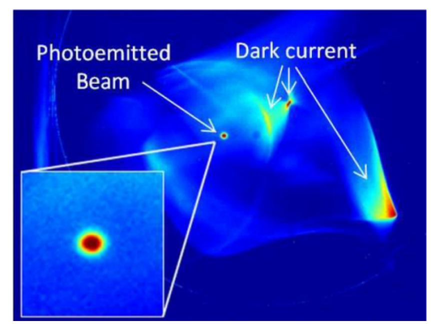
- Gun and Phase 0 beamline built and installed.
- Gun conditioned at full RF power.
- Dark current characterized: < ~ 1 μA (acceptable level)
- Very promising vacuum performance from initial tests.
- First photo-emitted electron beam with low QE cathode generated.
- Nominal photo-emitted electron beam energy demonstrated.

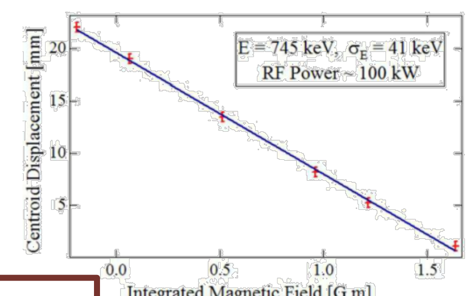






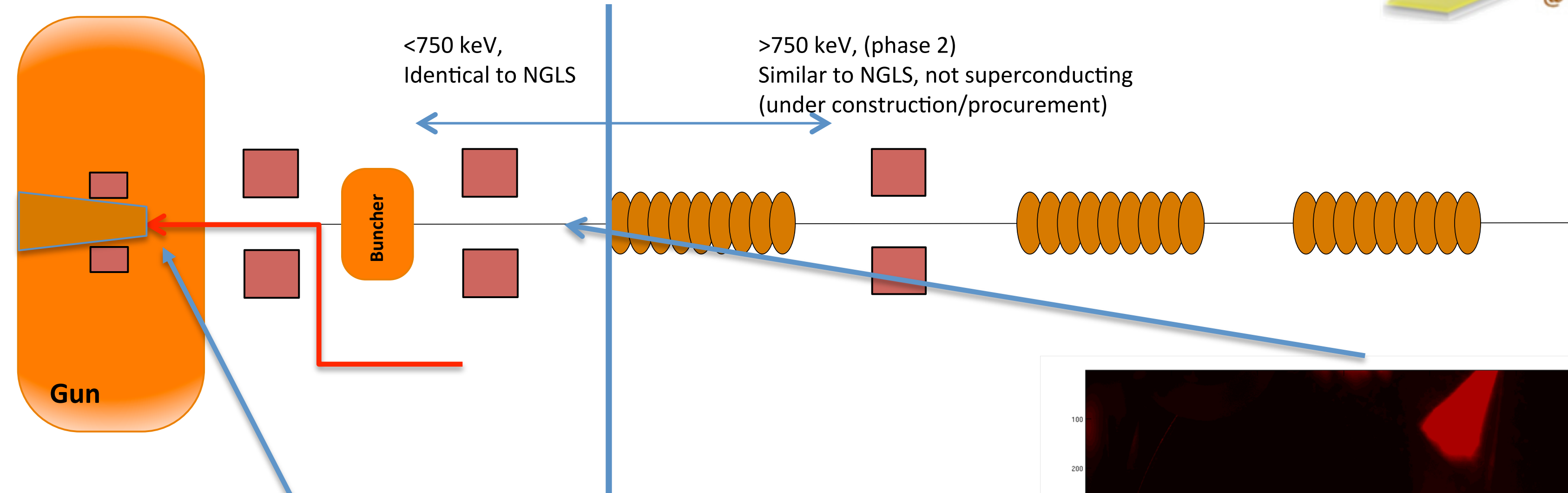


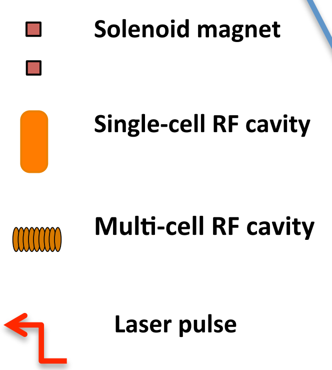


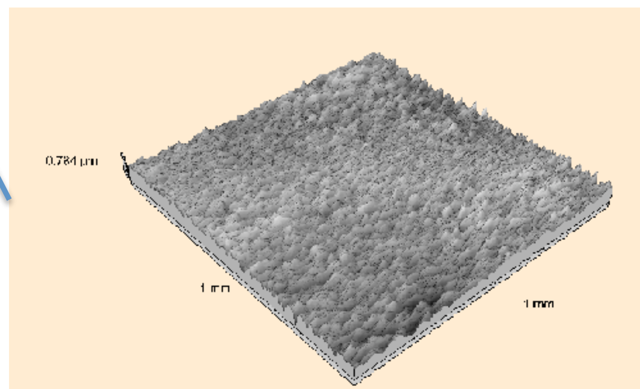


Gun technology fully demonstrated!
F. Sannibale. D. Filippetto, C. F. Papadopoulos *et al.*, PRST-AB 15, 103501 (2012)

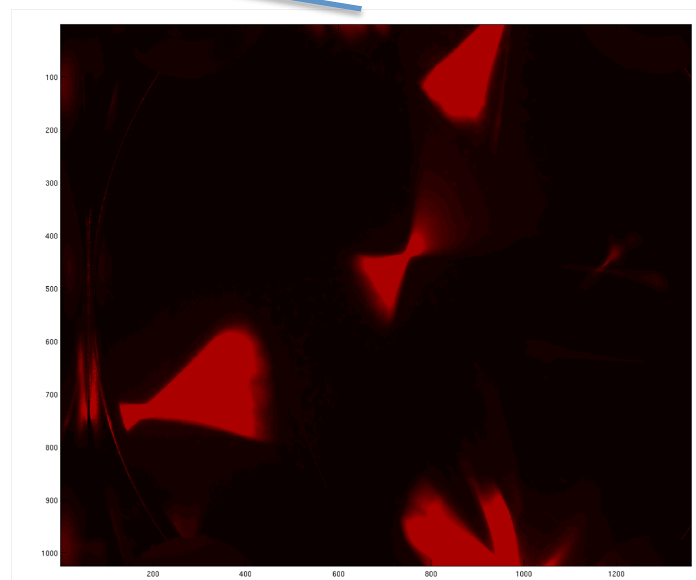
Dark current in APEX







Cathode surface, similar to APEX/NGLS
Paolo Michelato, INFN Milano – LASA
"High QE Photocathodes lifetime and dark current investigation",
PITZ collaboration meeting 4-5.02.006

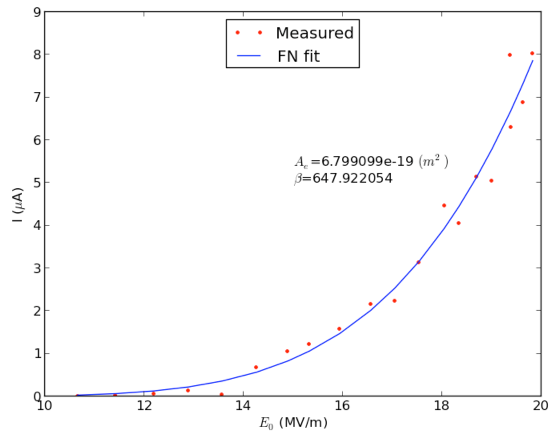


Dark current "Hotspots"
Butterfly shape due to large energy spread
D. Filippetto, F. Sannibale

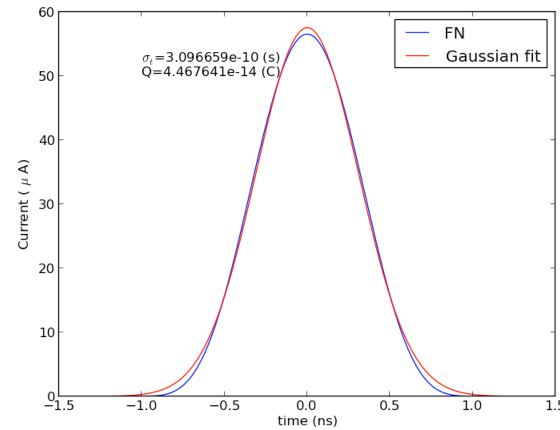
Fowler-Nordheim model of Dark current emmission

Use integrated Fowler - Nordheim fit to calculate pulse with instantaneous $E(t)=E_0 \cos(\omega t)$

Dark Current measurements
F. Sannibale



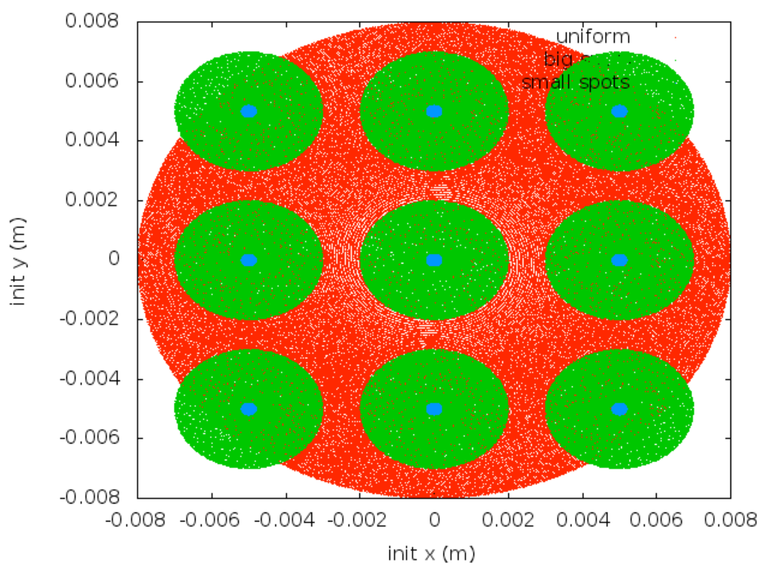
Dark Current profile



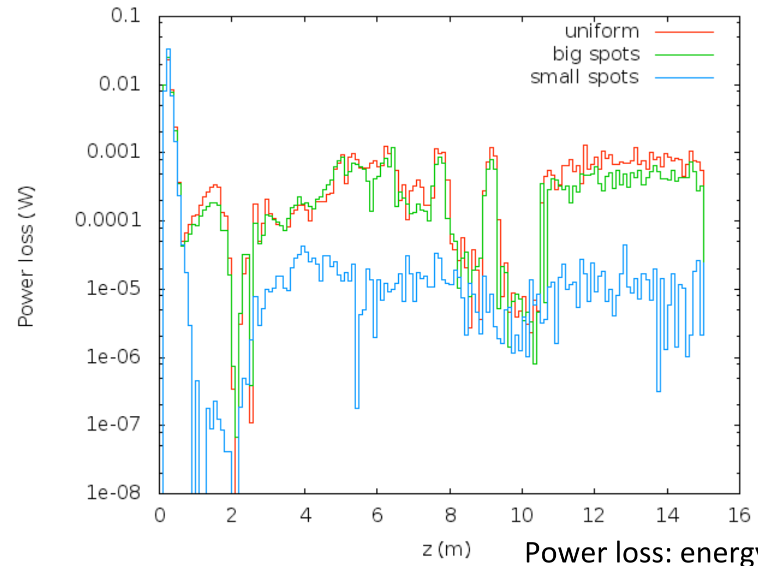
J. W. Wang, G. A. Loew
SLAC PUB 7684

Dark Current:
44 fC*186 MHz ~= 8.1 μA
Nominal Beam (average):
300 pC*1MHz ~= 300 μA

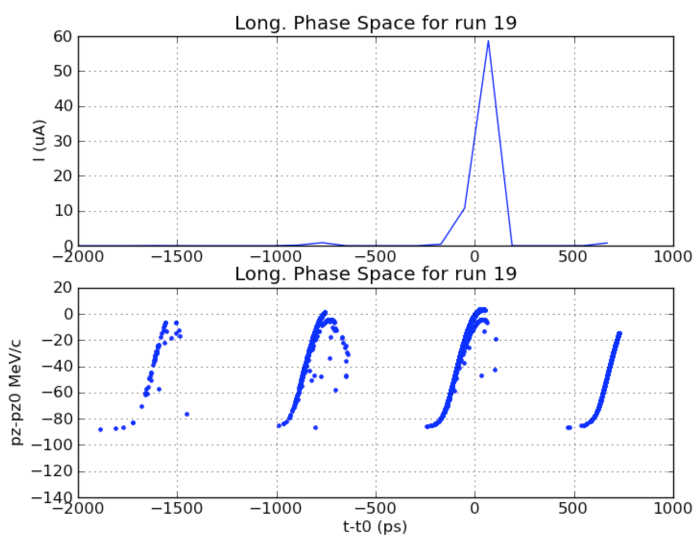
Dark current transport



Simulate multiple transverse distributions



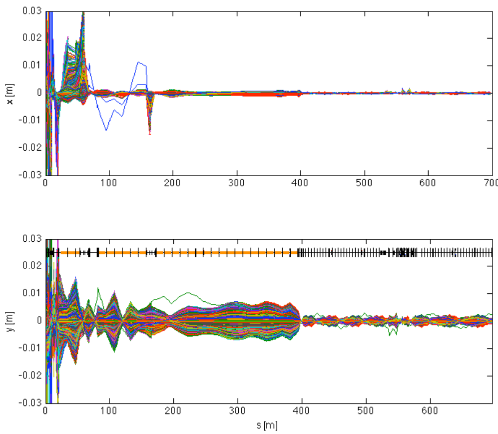
Power loss: energy deposition/bin (from ASTRA) times 186 MHz



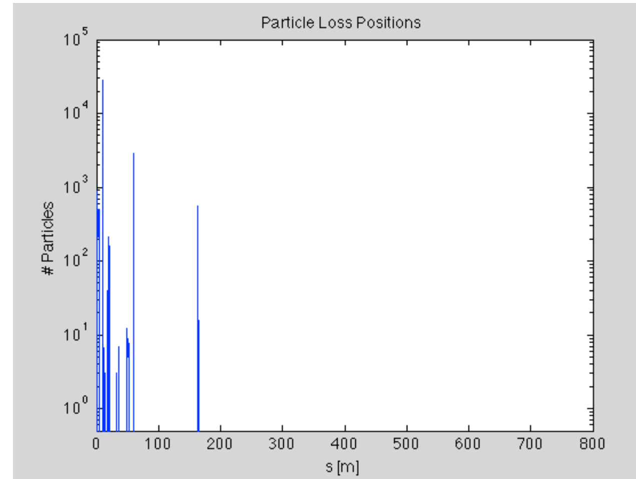
In all cases
~ 85% charge is lost in injector

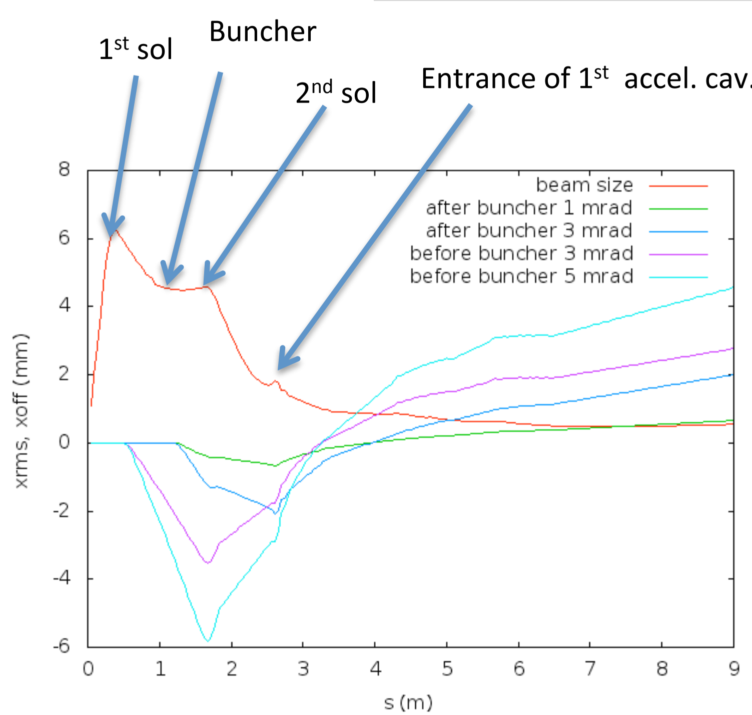
Longitudinal Phase Space at Injector exit: The dark current pulse is split due to different RF wavelengths

Dark current collimation schemes



Linac collimators
(C. Steier)

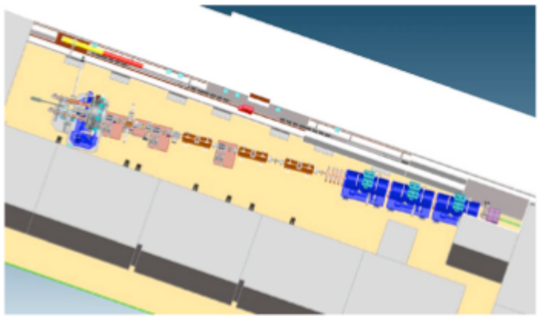




Initial collimation simulations for the injector.
Use a modified version of the ALS kicker cavity to kick the dark current
C.F. Papadopoulos, H. Qian

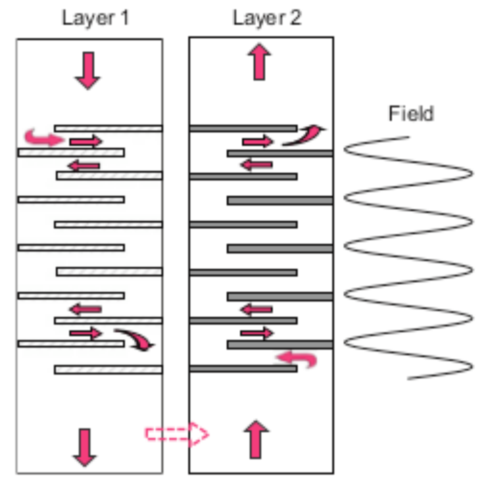
BTFEL: A proposed seeded IR FEL amplifier

Use the APEX beam
to drive an FEL.
(50 pC, 23 MeV, 40 A)

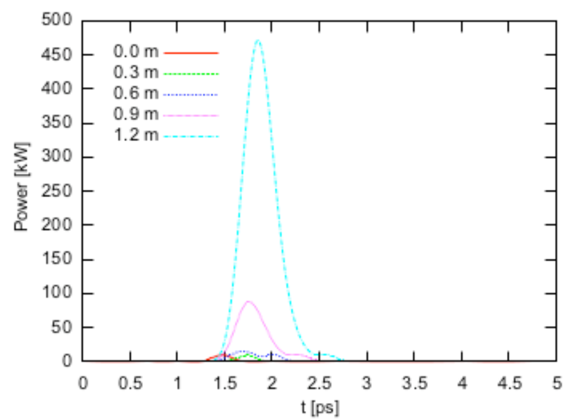


Use (and test)
a superconducting
tape undulator

Undulator param.



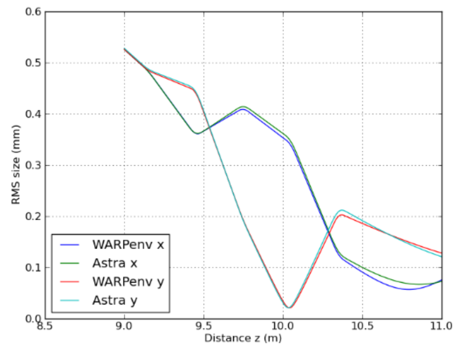
In order to produce a
seeded,
single spike pulse



Space charge effects in the BTFEL

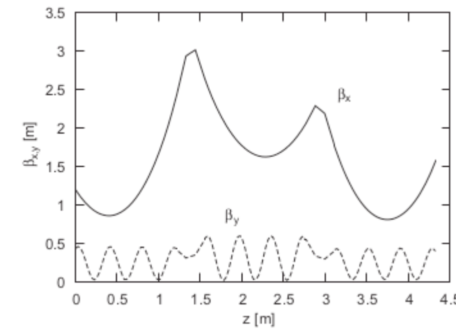
Due to the low energy and the relatively high current, space charge effects are important in the BTFEL

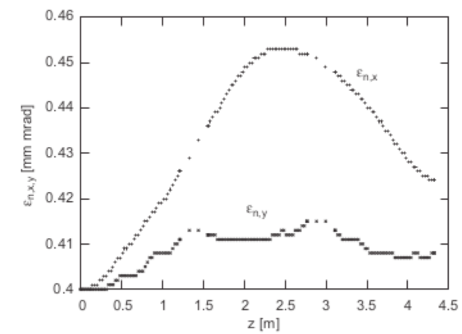
Take care to match with SC
in the beamline



Quadrupole matching in the beamline

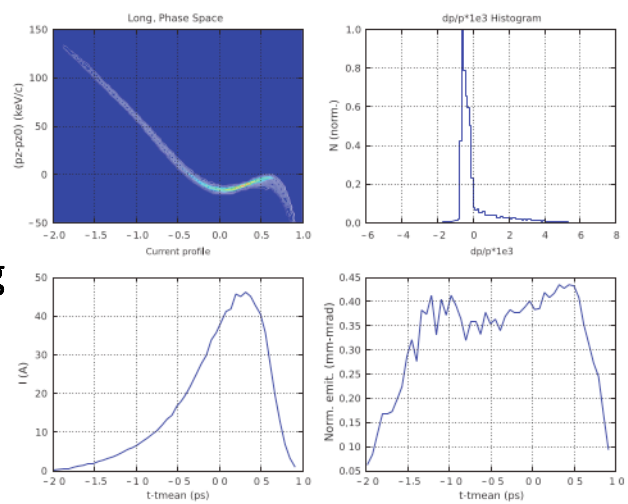
As well as in the undulator





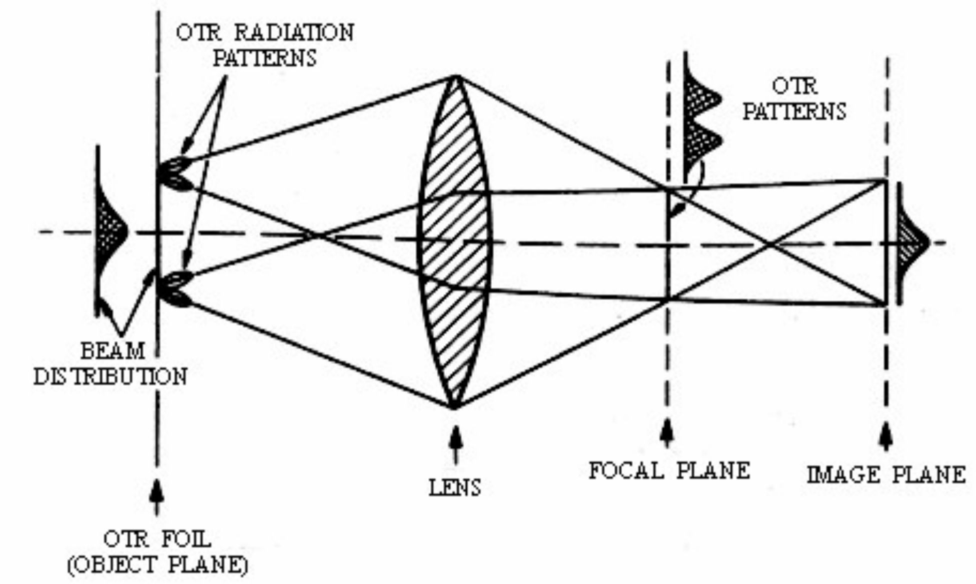
Emittance oscillation in the undulator

But space charge can also help to remove (some) of the chirp without dephasing and losing energy



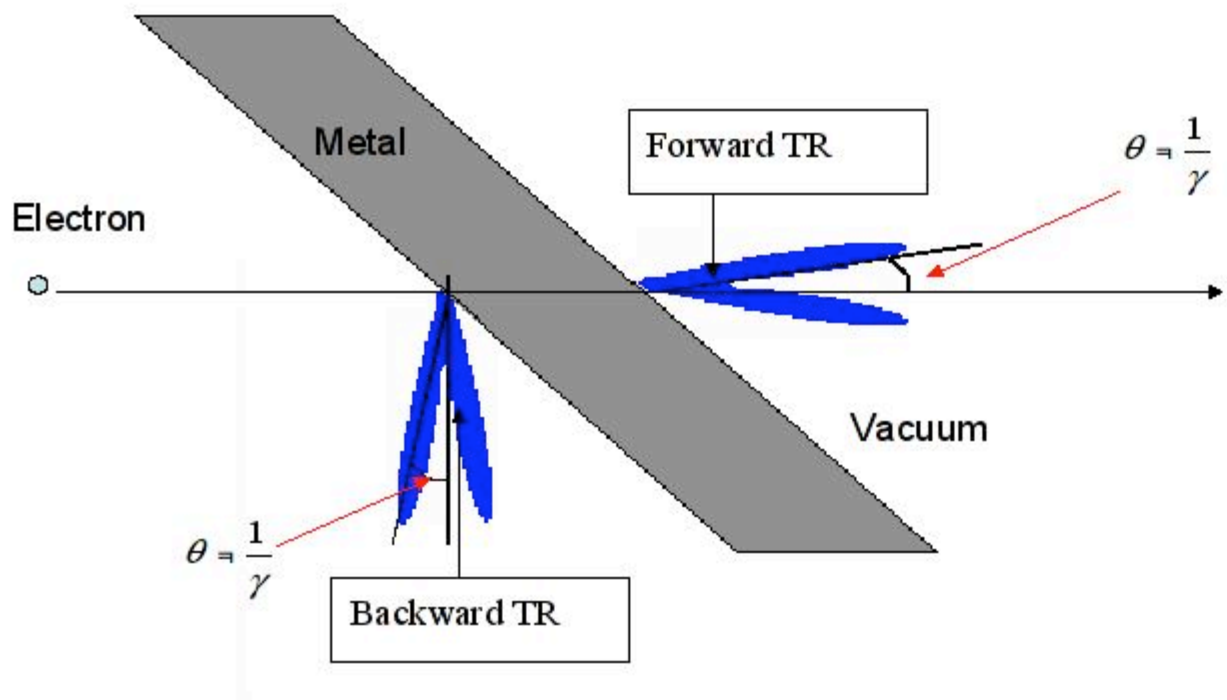
Yoon, M.; Filippetto, D.; Papadopoulos, C. F.; Pellegrini, C.; Penn, G.; Prestemon, S.; Sannibale, F.
NIMA, Volume 660, Issue 1, p. 138-146.

Measuring emittance using transition and diffraction radiation



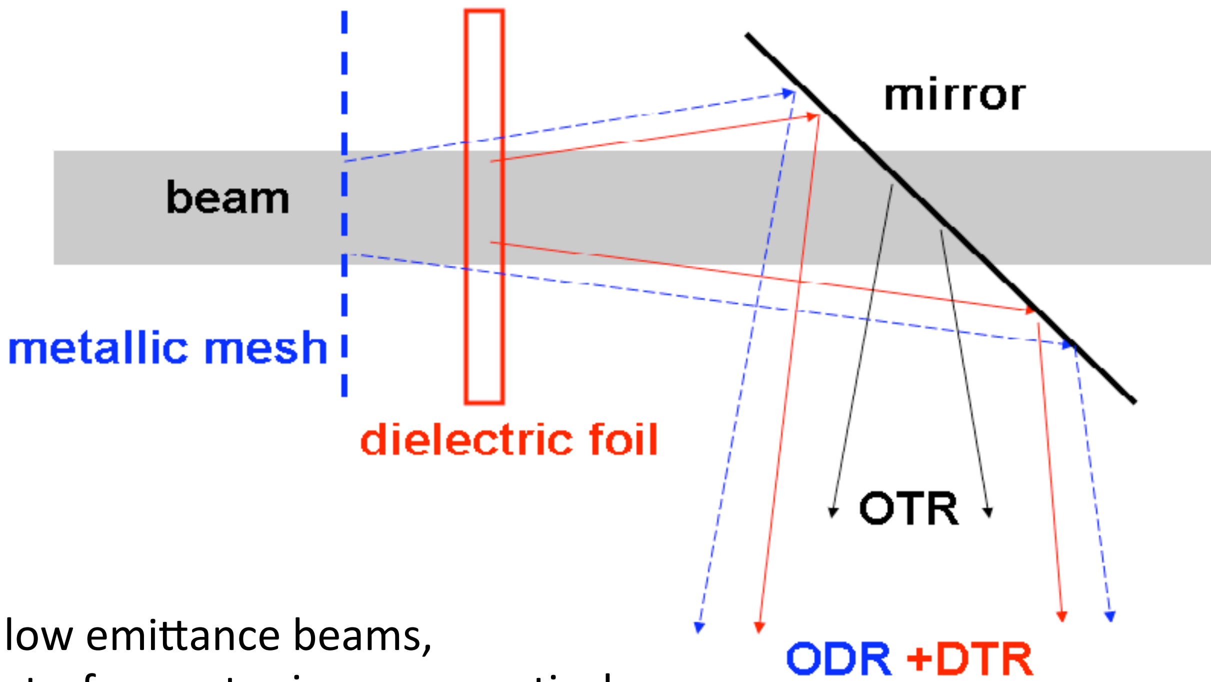
Source: R. Fiorito

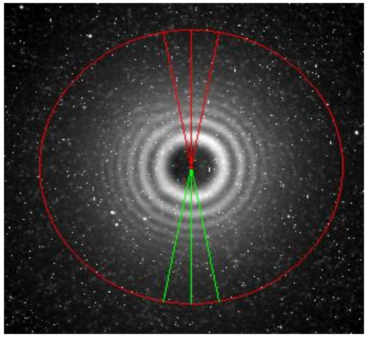
Angular dependence of Optical Transition Radiation



The single particle OTR angular distribution contains information about the incidence angle of the incoming electron.
The same holds for diffraction radiation etc

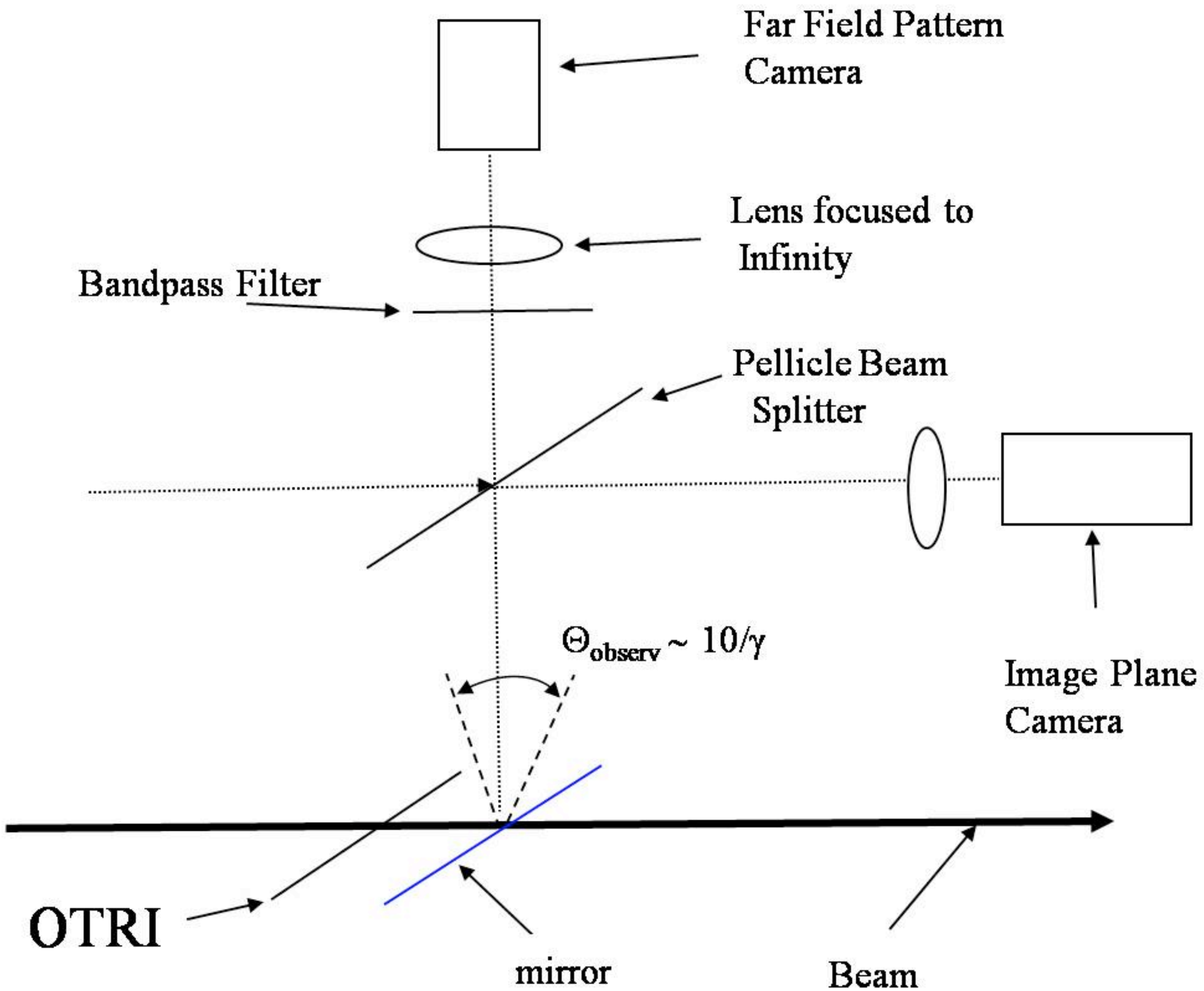
Optical diffraction radiation - Dielectric transition radiation interferometry





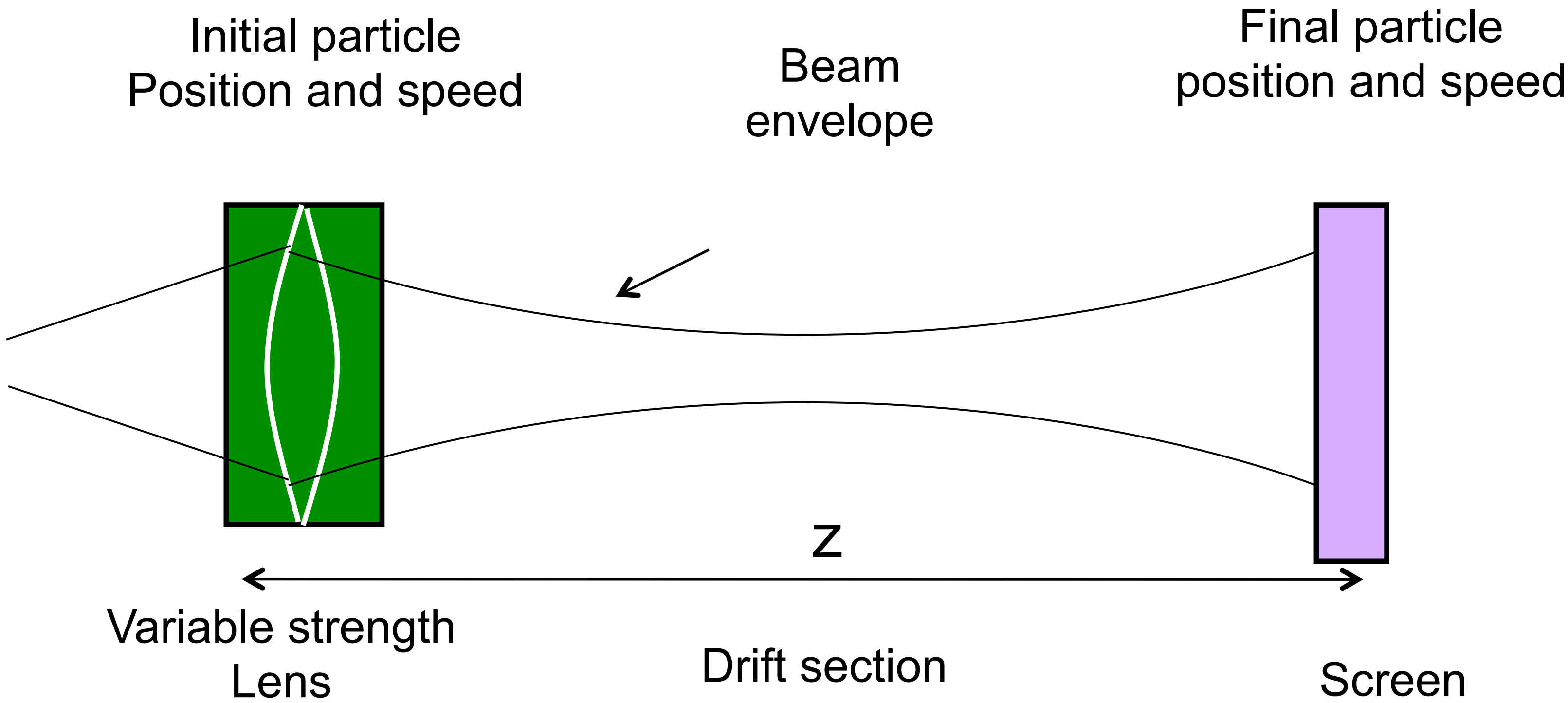
For low emittance beams,
an interferometer is more practical.
We can convolute the single electron interference pattern with the angular distribution of all the particles, for example a Gaussian.
The divergence of the beam can then be calculated from the visibility of the fringes, if we know the energy spread.

Experimental setup

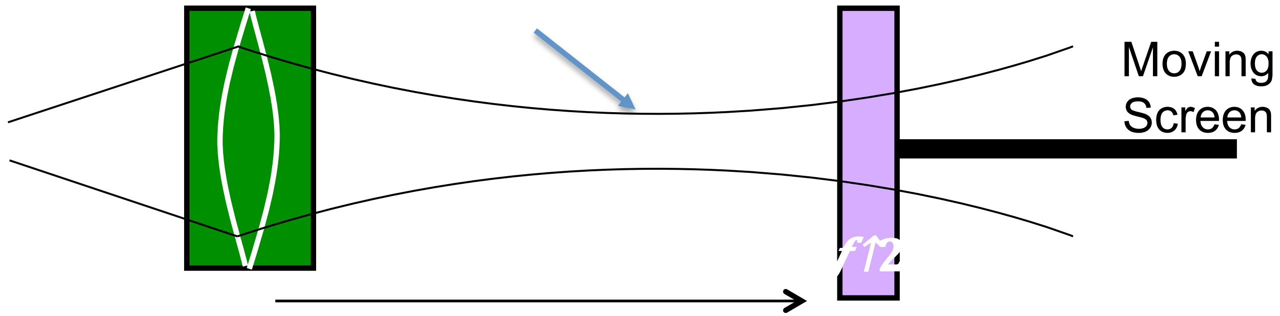


OTR Interferometry allows simultaneous measurement of beam size and beam divergence

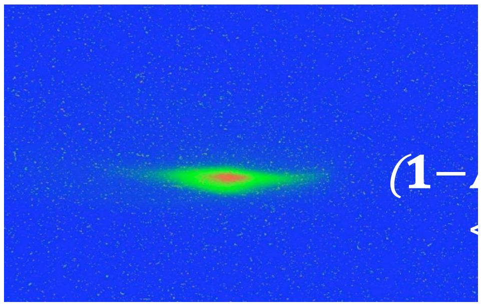
Thin lens scan



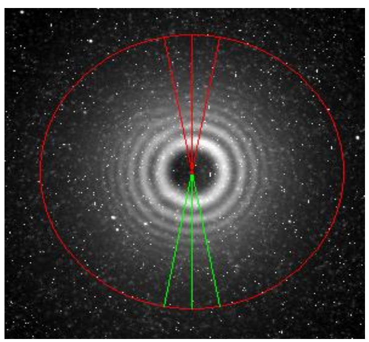
Different experimental conditions for OTR measurements



Keep the screen at a constant position, vary the magnet



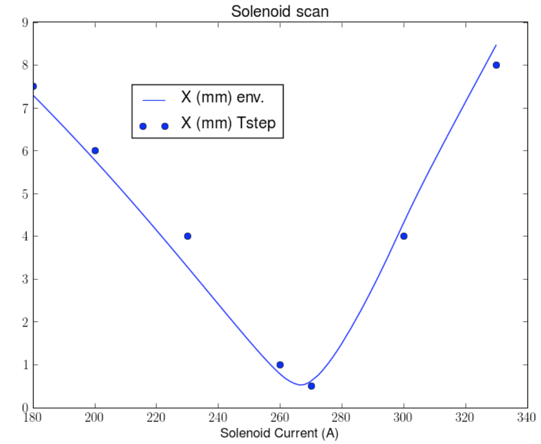
Minimize the size in x (or y)



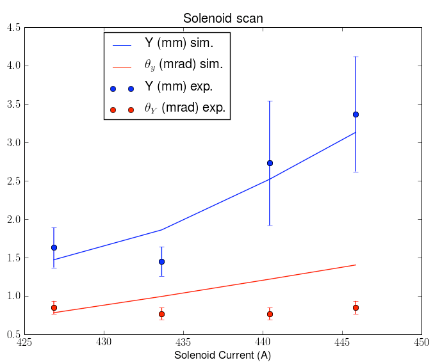
Maximize the visibility of the fringes

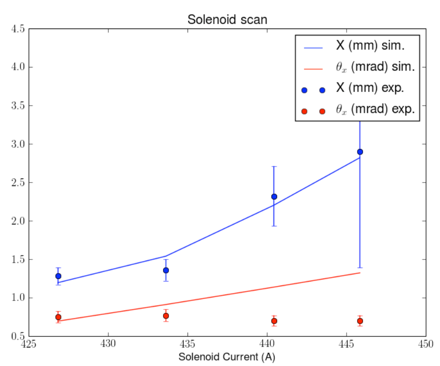
Measurements at AWA

- Develop an envelope code (with SC and RF focusing effects included) to model the soleoid scan
- Using the fast envelope code, we scan the 3 dimensional parameter space ( ).
- The emittance value that minimizes χ^2 is 19 mm-mrad for x and 22 mm-mrad for y



Comparison of envelope code with Tstep





Solenoid Current (A)	X size (mm)	Θx (mrad)	Y size (mm)	Θy (mrad)
427	1.28	0.75	1.63	0.85
434	1.36	0.77	1.45	0.77
440	2.32	0.7	2.73	0.77
445	2.9	0.7	3.37	0.85

Extensions of the method may include different radiation types or energy spread measurements

Acknowledgements

F. Sannibale, D. Filippetto, M. Venturini, Ji Qiang, P. Emma, C. Steier, G. Penn, M. Zolotorev, M. Yoon, J. Staples

The NGLS team

The APEX team

R. Kishek, P.G. O'Shea, R. Fiorito, A. Shkvarunets