Planning for a Heavy Ion Integrated Research Experiment

Innovative Confinement Concepts Workshop

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Abstract

The next major step in the U.S. inertial fusion energy program, the Integrated Research Experiment (IRE) will play a critical role in the development of inertial fusion energy. The IRE, together with the target results from the U.S. Department of Energy's ICF Program must give sufficient confidence to proceed to the next step. This next step is to design and build an Experimental Test Facility (ETF), demonstrating fusion power production. The IRE conceptual design effort is scheduled to begin in about two years, but preliminary design examples have already been made to act as computational models to develop simulation tools, and to explore possible high energy density experiments. We will review the algorithms which lead to the designs and give examples of parameters and capabilities of the IRE, as well as the questions that are being addressed in the near term research program that need to be resolved before a final design is achieved.

IRE experiments + Defense ICF Program => Confidence to proceed with Experimental Test Facility (ETF)

IIRE will validate accelerator physics examining

- **beam dynamics issues, (emittance growth, halo formation, pulse compression, multiple beams, beam loading)**
- **integrated operation**

IRE will test chamber transport and final focus approaches allowing

- **examination of sensitivity to beam neutralization method**
- **validation of beam stability (e.g. absence of two-stream, filamentation,...)**
- **investigation of effects of stripping and photoionization by target**

IRE will study ion beam interaction with targets

- **volumetric heating of matter (unique to ions)**
- **measurement of ion stopping in dense plasmas**

Programmatic goals lead to quantitative technical goals

Some essential IRE goals:

Validate long-term transverse and longitudinal beam dynamics => total current > 100 A => multiple beams, hundreds of lattice periods

Enable definitive focusing experiments on a variety of focusing modes => ion energy > 100 MeV, beam potential/kinetic energy ~ perveance > 10^{-4}, ε_N < 5 mm-mrad

Validate beam-target interaction physics => flux > 3 x 10^{12} W/cm^2, multi-kJ

Some desirable IRE goals

Explore target concepts unique to ions => flux > 10^{13} W/cm^2

Serve as a front end of a full-scale driver - reconfiguration may be required => reliable, durable components, pulse length ~ 10 μs

Preparation for an IRE guides our near term research

Phase I research goals:

- **Two new experiments**
  - **A high-current injector module**
    - **(leading to 10 to 100A, ~1 A/beam ~20M$ for IRE injector)**
  - **A high-current transport and focusing experiment**
    - **(~1A, fill factor 50-80%, ε_N ~ 1 mm-mrad)**

- **Technology development**
  - **Multiple beam arrays ($\leq$ $10/kA-m)**
  - **Cast insulators ($\leq$ $0.01/ V)**
  - **Ferromagnetic materials ($5-10/kg)**
  - **Pulsers ($\leq 10^{-5}$ $/W, $\leq$ $20/J)**

- **End-to-end simulation of full-scale drivers and IRE**

If we achieve these goals we will have a compelling case for an IRE.

Small scaled experiments + planned driver scale experiments lay groundwork for IRE

Most transport issues of space-charge dominated beams have been addressed

Single Beam Transport Experiment (SBTE) (160 kV, 25 mA) mid 80's, LBL

87 half-lattice periods (HLP's)

Stable beam propagation with little emittance growth

Multiple Beam Experiment (MBE-4) (0.9 MeV, 90 mA) late 80's - 90's, LBL

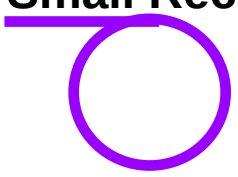
70 HLP's

Multiple beams, acceleration, longitudinal compression; effect of image and non-linear external focusing on emittance

Scaled e^- beam experiments

(2.5-10 keV, 30-100 mA) 80's to present, UMd
Experiments on beam merging, space-charge wave physics, longitudinal instability, recirculation

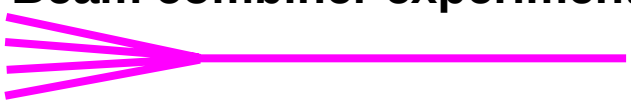
Small Recirculator (SR) (80 keV, 2 mA) currently on hold, LLNL



10 HLP presently
40 in completed ring

Emittance growth in bends; when complete transport of space-charge-dom beam for > 1000 HLP's; Precision longitudinal control

Beam combiner experiment



67 HLP's

(160 kV, 4.5 -> 18 mA) near completion, LBNL
Achieved emittance growth expected from phase space and space charge energy considerations

Scaled final focus experiment

6 HLP's

(120 kV, 80 μA) near completion, LBNL
Achieved spot size limited by emittance and space charge

Experiments -- continued

Driver scale experiments are next phase of program

Electrostatic Quadrupole Injector

4 HLP's

ESQ (2 MeV, 0.8 A) in progress, LBNL
Low emittance, high line charge density beam. Permits detailed comparison of theory and experiment

Multi-beam Injector

~20 HLP's

(~1.6 MeV, 0.5 A per beam) in preparation
Test multi-beam geometry at driver scale

Transport Experiment

50 -100 HLP's

(~ 2 MeV, 0.8 A beam) in preparation
Test maximum space charge packing through accelerator, maintaining focusability; electron effects and halo generation of full scale beam

Integrated Research Experiment

(IRE) (100-500 MeV, 1 - 2 kA total)

300 - 700 HLP's

Test all non-nuclear accelerator and chamber issues for IFE; target physics

High Current eXperiment (HCX) will validate beam dynamics at driver scale

Physics Goals:

- Determine critical ratio of beam radius/aperture radius
  - Requires understanding of:
    - "Dirty physics" of full scale line charge density, including effects of secondary electrons
    - Image effects
    - Effects of misalignments and imperfect fields
    - Halos

Technology goals:

- Superconducting magnet demonstration (compact, economical, high B)
- Detailed diagnostics of mismatch, halo, electrons, misalignments,etc.
- Alignment, matching, and steering

Scale (Phase I):

- 50 - 100 half-lattice periods
- Single beam, ~2 MeV, ~1 A, 50-80% fill factor, ε_N ~ 1 mm-mrad
- Driver line charge density and pulse duration

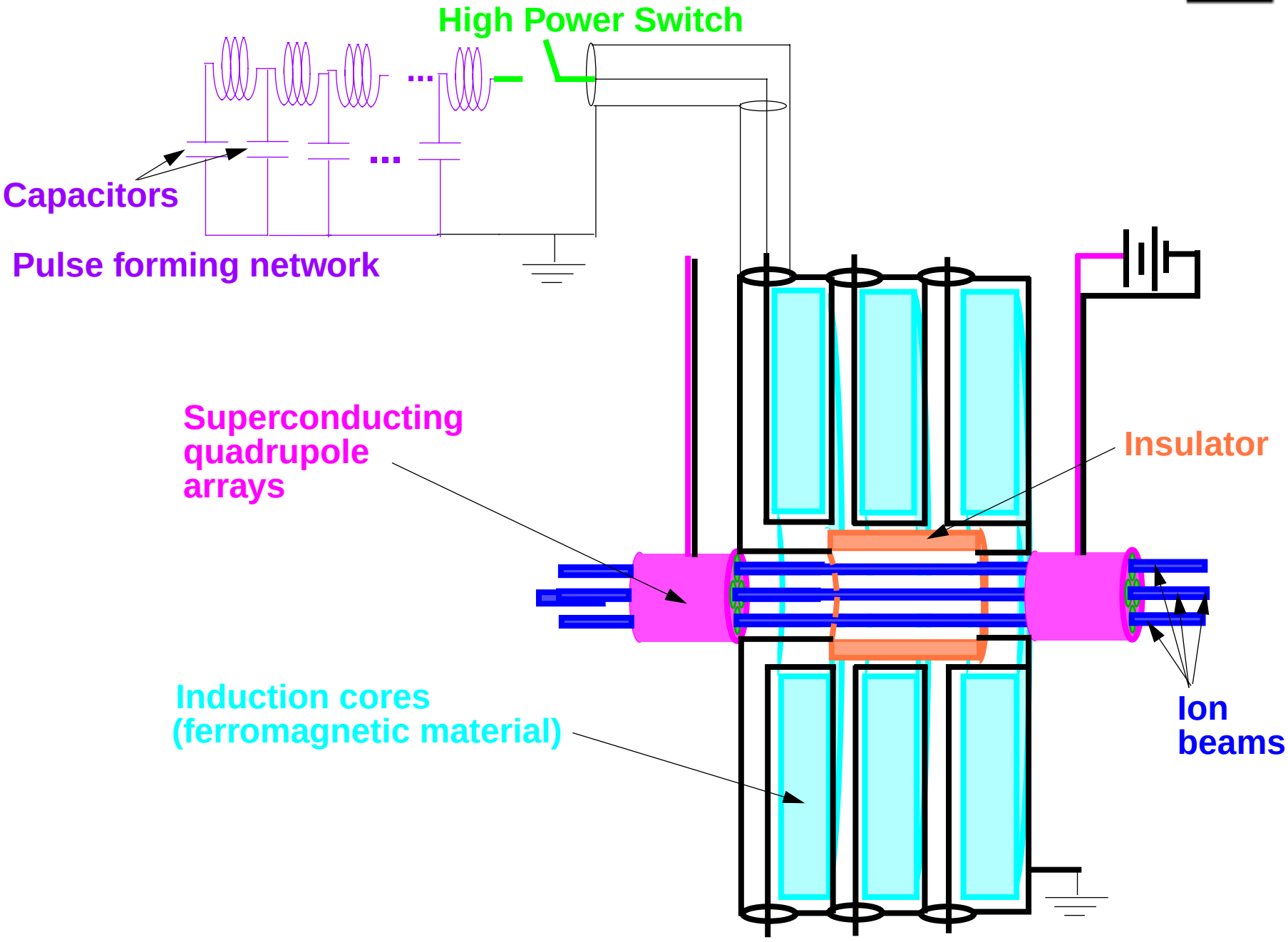
Multiple-beam ion source and injector development are essential to attain IRE goals

Continue to study the beam optics of a large surface ionization source and extraction diode

Develop very high current density, small aperture ion sources for the miniature merging beamlets design

Build a new ion source test bed in order to allow conversion of the existing 2 MV facility into a high-current beam transport experiment

Major components of an induction linac



Ongoing or completed contracts with outside vendors have led to reductions in projected cost

Induction Cores:

- National Arnold
- Hitachi
- Moscow Radio Technical Institute

Thyratrons:

- EEV
- Triton

Capacitors:

- Maxwell
- CSI

Insulators:

- Advanced Ceramics Limited (Ron Hensen)
- LLNL (Steve Sampayan)

Superconducting Quadrupole Arrays:

- Advanced Magnet Lab (Rainer Meinke)
- MIT (Joel Schultz)
- LLNL (Nicolai Martovetsky), LBNL (Ron Scanlan)

If Phase I is successful modest improvements will give an attractive driver

	Now	Phase I goals	IRE	Power plant
Physics goals:				
Beam experiments:	~10 mA; ~ 1 MeV; correct dimensionless parameters brightness exceeding power plant requirement.	~1 A; 1-10 MeV; preserve brightness exceeding power plant requirement.	~1A/beam[a]; >100 MeV; preserve brightness exceeding power plant requirement.	~1A/beam[a]; > 1 GeV; adequate brightness.
Injector	0.8 A, 1 beam	~1A/beam, multi-beam module	~1A/beam, multi-beam injector	~1A/beam, multi-beam injector
Cost goals:				
Quadrupole arrays:	Prelim. design	<= $10/kA-m[b]	<= $10/kA-m[b]	<=$10/kA-m[b]
Insulators	~$0.10/V	$0.01/V[c]	$0.01/V	$0.01/V
Energy Storage	$10-30/J	$3-10/J	$3-10/J	$1-5/J
Switches	$$10^{-5}$$/W	$$10^{-5}$$/W	$$10^{-5}$$/W	$3 x $$10^{-6}$$/W
Magnetic Cores	$18/kg	$5-10$/kg	$5-10/kg	$5/kg

a. At the beginning of the machine. Current increases with increasing kinetic energy.
b. Cost of quadrupole arrays per kA-m of superconductor.
c. The order of magnitude reduction in cost between the first and second columns requires the production of large cast insulators rather than brazed alumina currently used.
Costs in purple were used in IBEAM for IRE calculations.

In an induction linac, certain limits constrain design

Velocity tilt $\Delta v/v < \sim 0.3$ (to avoid mismatches at head and tail of beam)

Phase advance per lattice period $\sigma_0 < 80^o$ (to avoid envelope/lattice instabilities)

Space charge is limited by external focusing $K < (\sigma_0 a/2L)^2$ where K is the perveance (proportional to line charge density over beam Voltage), a is the average beam radius and L is the half-lattice period.

Volt-seconds per meter $(dV/ds)\, l/v_0 <\sim 1.0$ V-s/m (for "reasonable" core sizes)

Voltage gradient $dV/ds < \sim$ 1-2 MV/m (to avoid breakdown in gaps)

In "analytic" design, accelerator has three sections

Three sections:

1. **Electrostatic quads; constant bunch length (load and fire)**
2. **Magnetic quads with bunch compression**
3. **Magnetic quads; const. bunch length and maximum acceleration gradient**

1. Constant bunch length => $dl/dV=0$, maximum velocity tilt ($\Delta v/v=0.3$) => $dV/ds \sim V$; Maximum space charge => $L \sim V^{1/2}$; Constant σ_0 and constant E' => $\eta \sim$ const.

2. Assume velocity tilt such that acceleration and compression give equal contributions => $l \sim V^{-1/2}$; constant volt-seconds per meter => $dV/ds \sim V$; Maximum space charge => $L \sim V^{1/4}$; Constant σ_0 at maximum B' => $\eta \sim$ const.

3. When maximum gradient reached, freeze at max => $dV/ds \sim$ const.; Constant bunch length => $L \sim V^{1/2}$; constant magnet length => $\eta \sim V^{-1/2}$; constant σ_0 => $B' \sim 1/(1-2\eta/3)^{1/2}$; velocity tilt $\Delta v/v \sim 1/V$

Computer simulation of beam dynamics plays an essential role in the analysis and design of IRE and !IpIFE drivers

Number of beam plasma oscillations ~ Number of quads/2 π

~ 200 in a driver

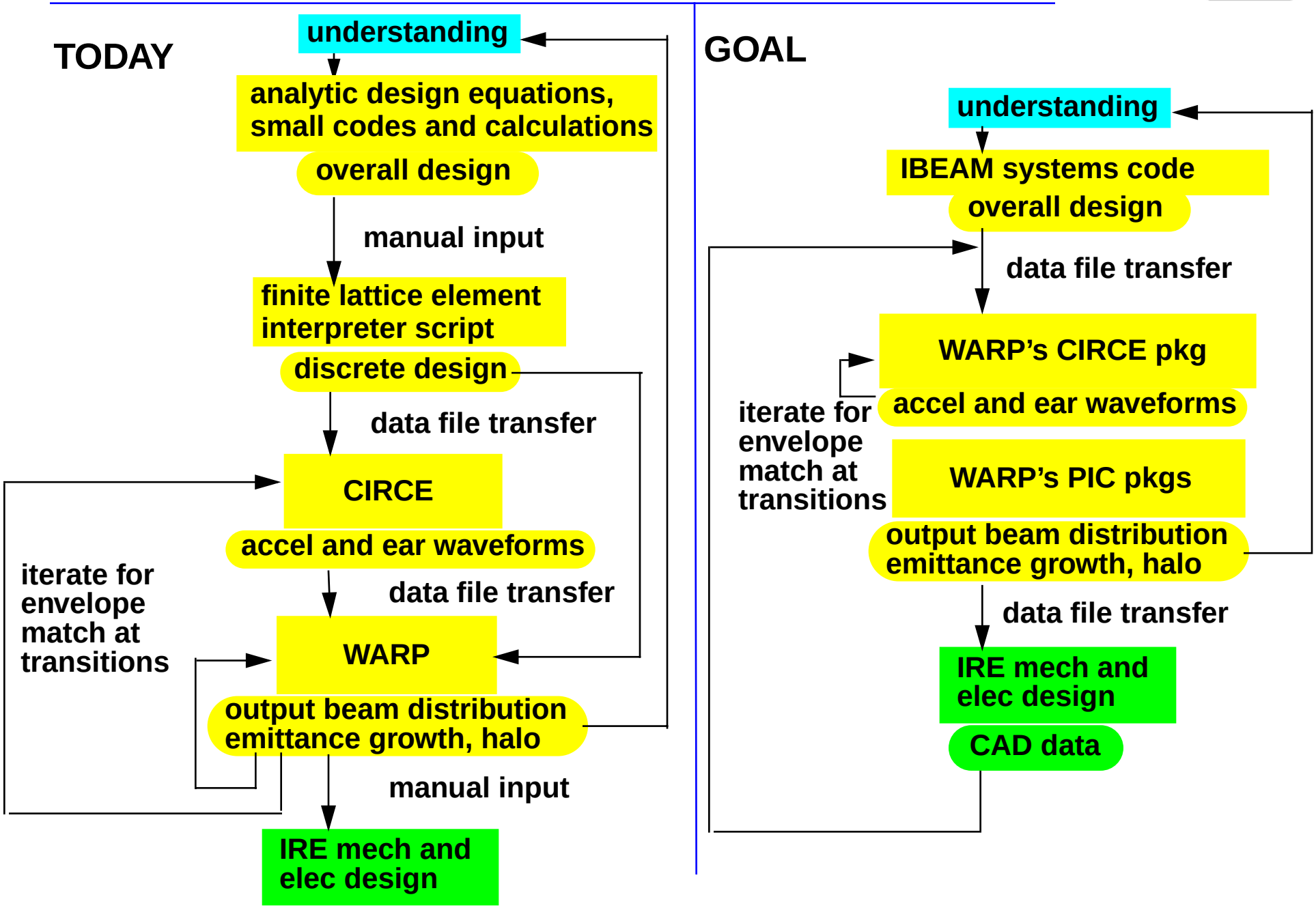
PIC simulation is well suited ~ spatial step size set by magnet fringe fields

Areas of investigation:

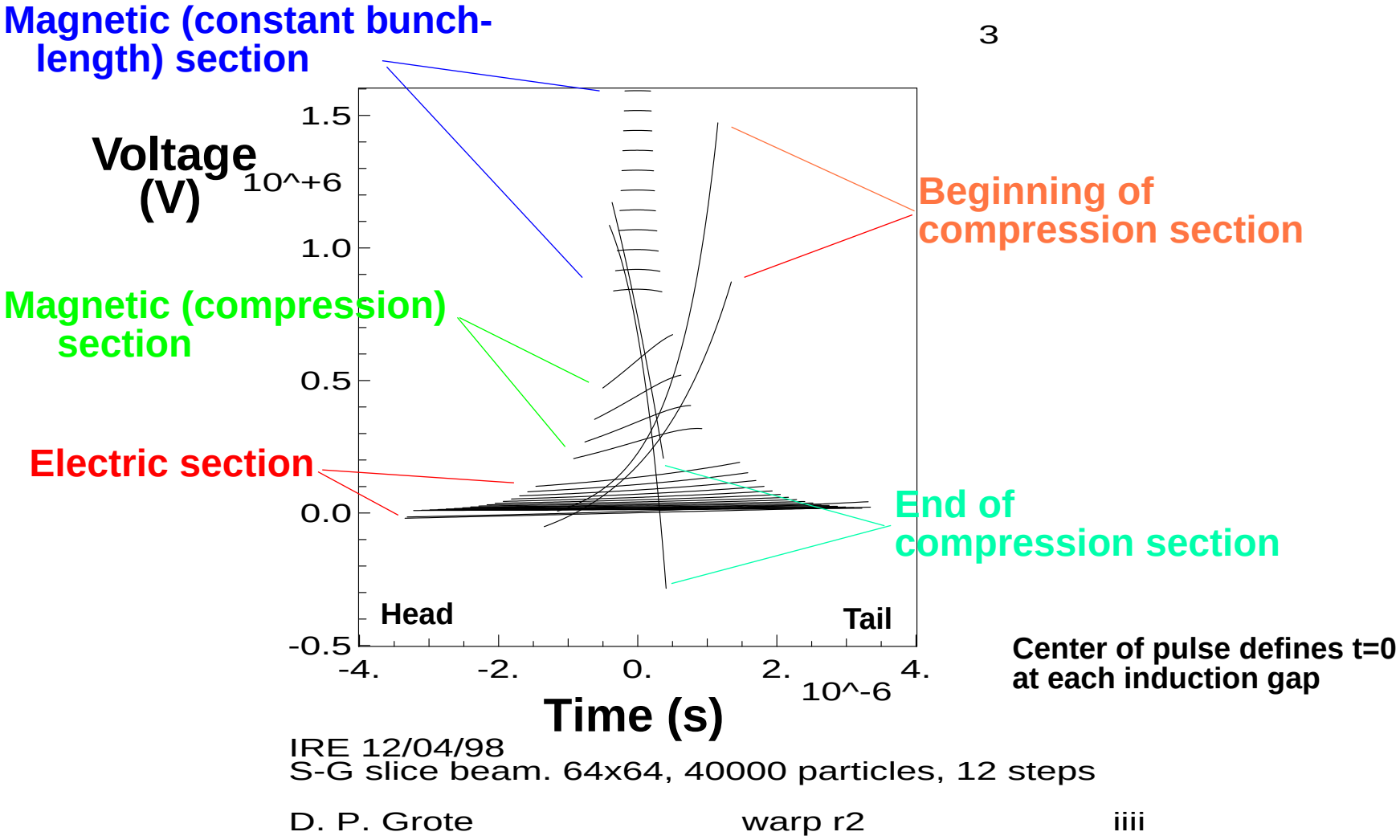
- **Aberrations**
- **Longitudinal/transverse coupling**
- **Interaction through module impedance**
- **Mismatches from acceleration and errors**
- **Multiple beam interactions**
- **Neutralization and stripping in chamber**

Validation of computational tools on near term experiments leads to confidence in future design

IRE design requires iteration between systems and simulation codes

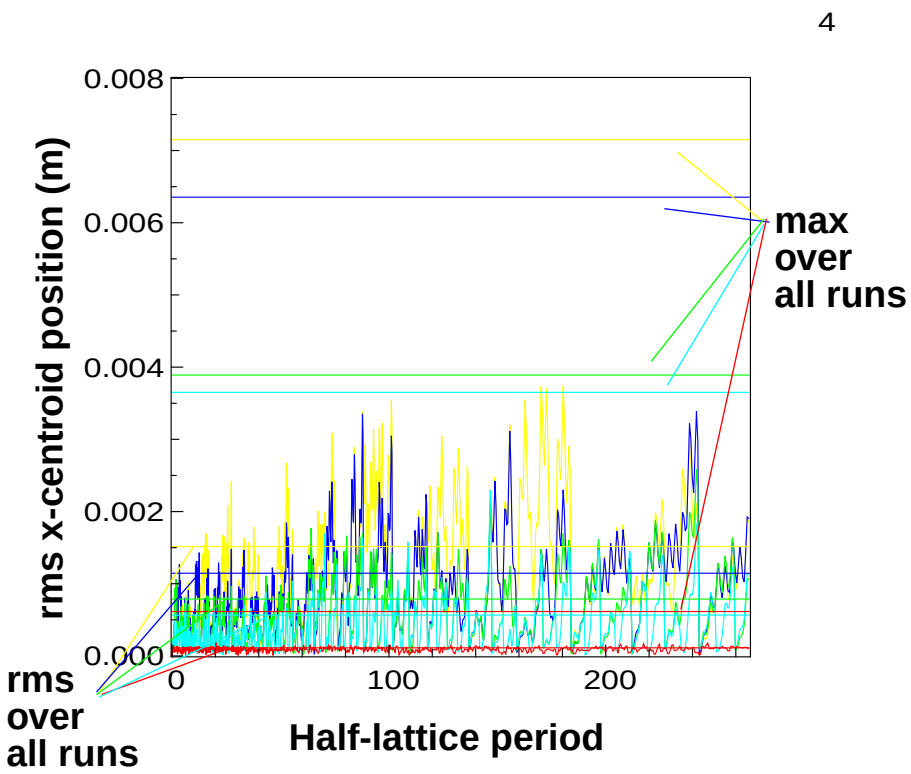


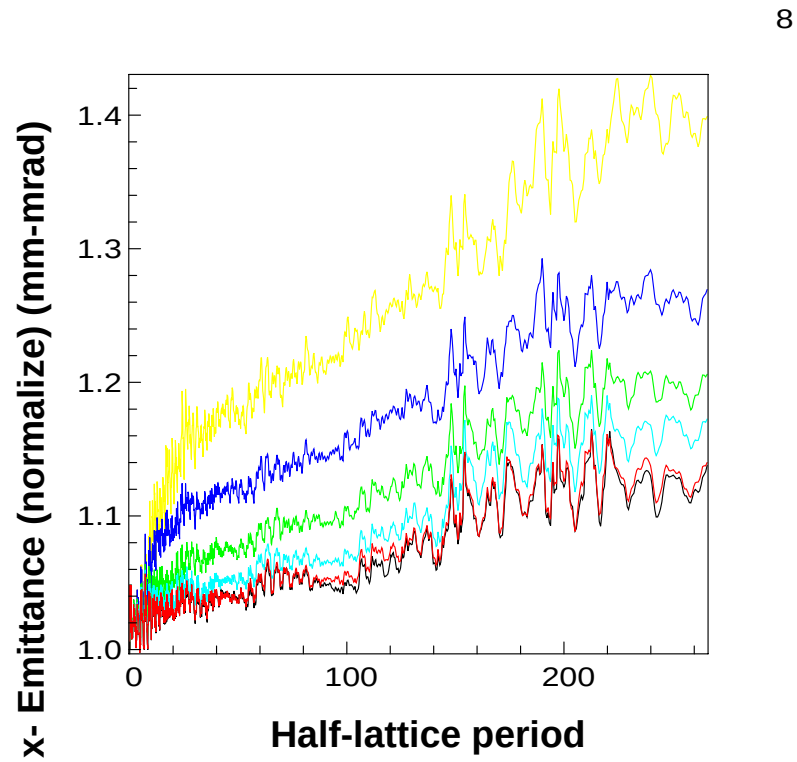
Waveform generation algorithms using CIRCE/ WARP are being developed for 3D simulations



In addition ear electric fields must be generated to confine the beam longitudinally.

We are investigating optimal steering algorithms for the IRE





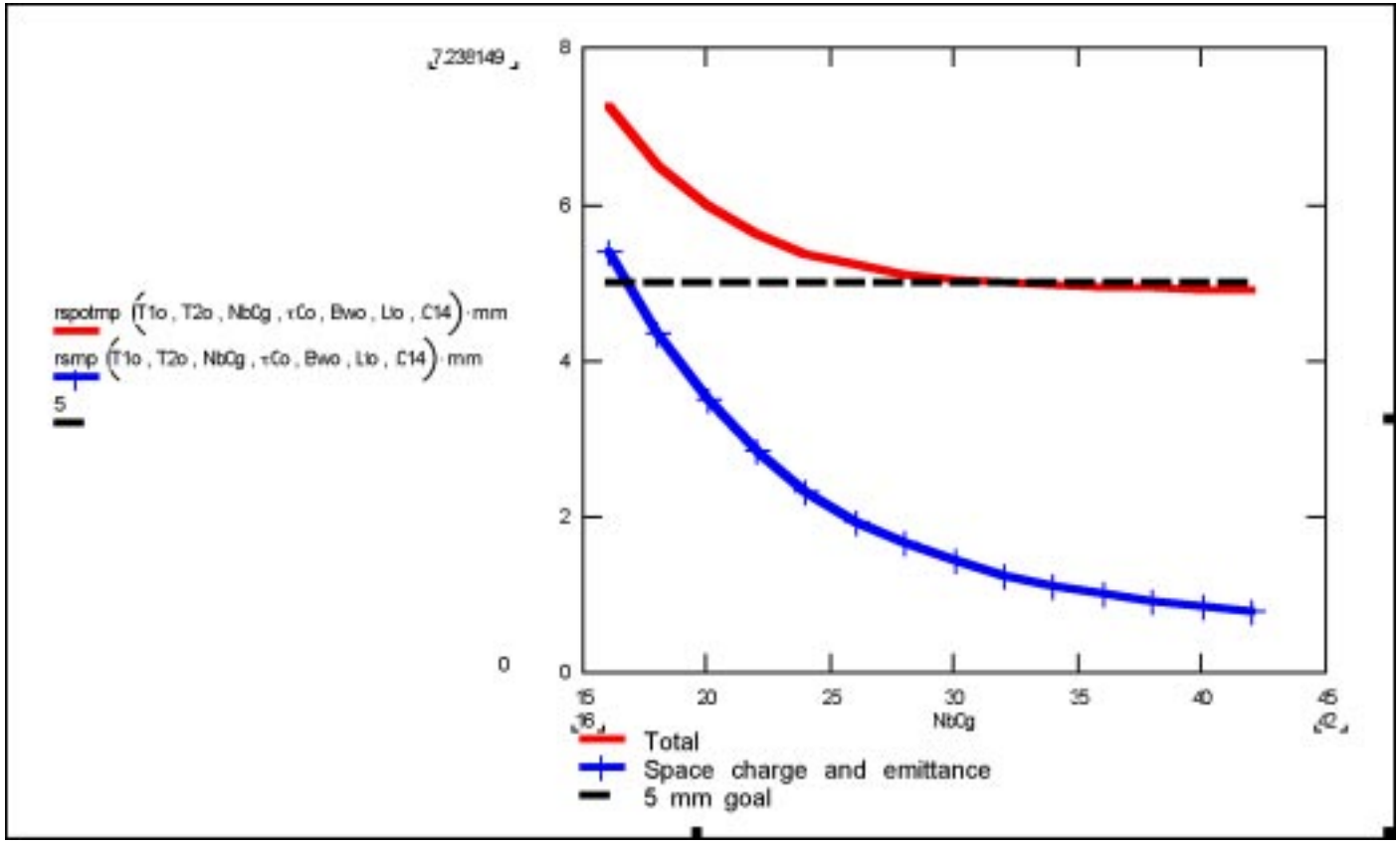
	warp r2 Steering Interval (HLP's)	warp RMS offset of beam (mm)
	1	0.11
	5	0.55
	10	0.80
	20	1.20
	40	1.50

warp r2 warp

Assumptions in simulations:

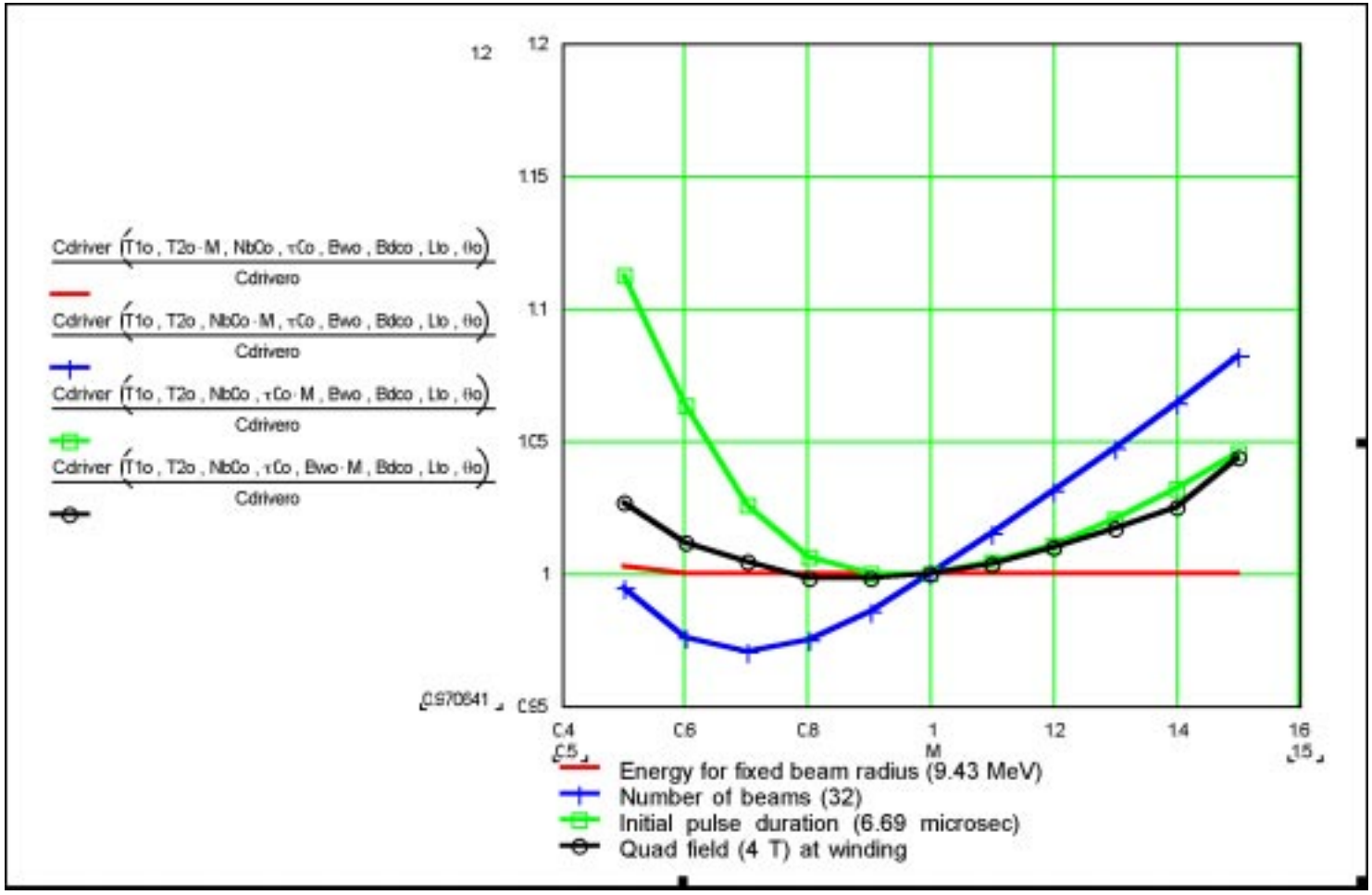
1. "Near-perfect" steering employed (beam centroid returned to within circle of 200 μ radius, and ⊥-velocity zeroed)
2. Electrostatic quad offsets have random displacements with 100 μ rms offsets.
3. Magnetostatic quad offsets have random displacements with 250 μ rms offsets.
4. Average of 6 runs are shown

Spot radius versus number of beams



Small beam number leads to increased spot size when neutralization fraction is held fixed.

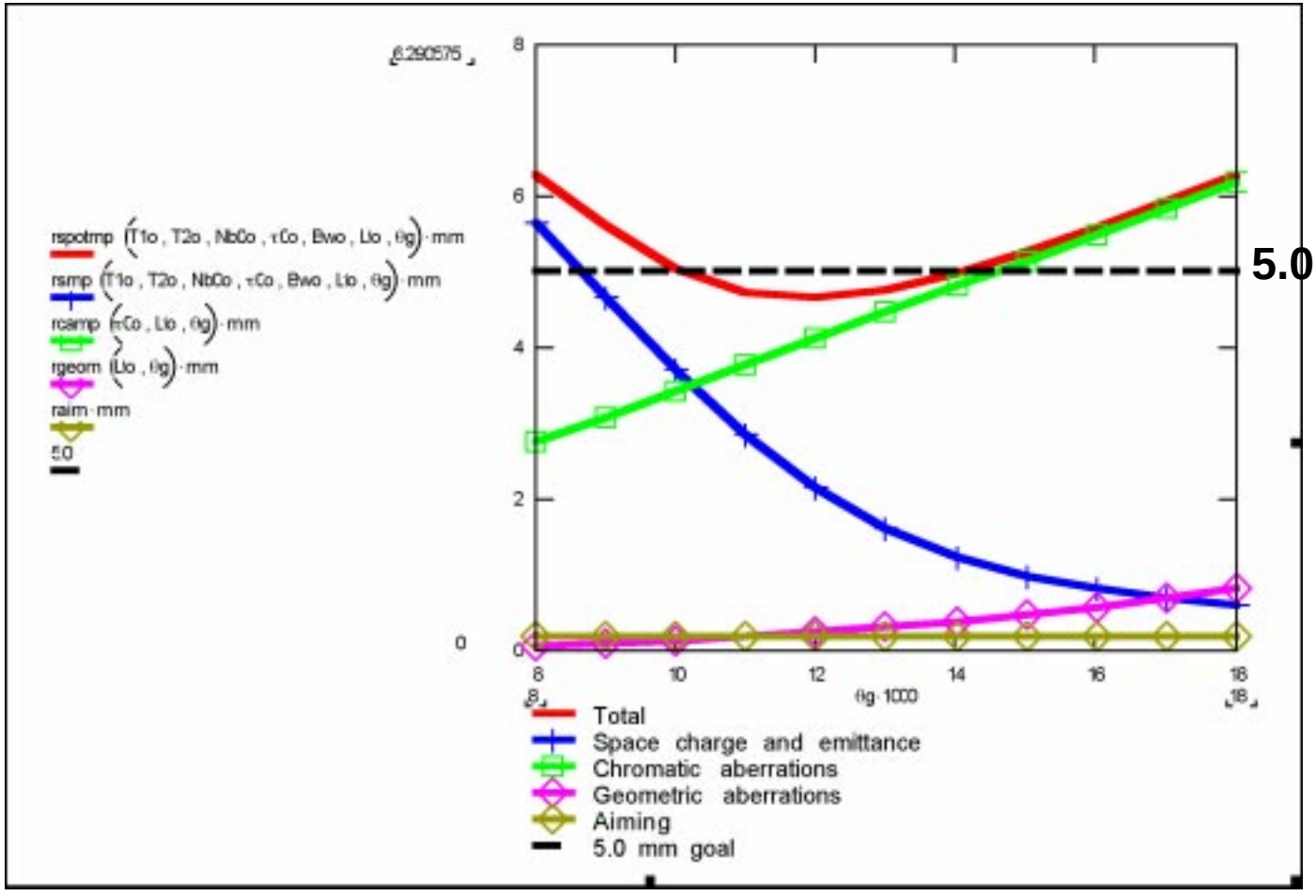
System code IBEAM allows examination of cost variation with major accelerator parameters



Cost minimum occurs at 22 beams in this example.

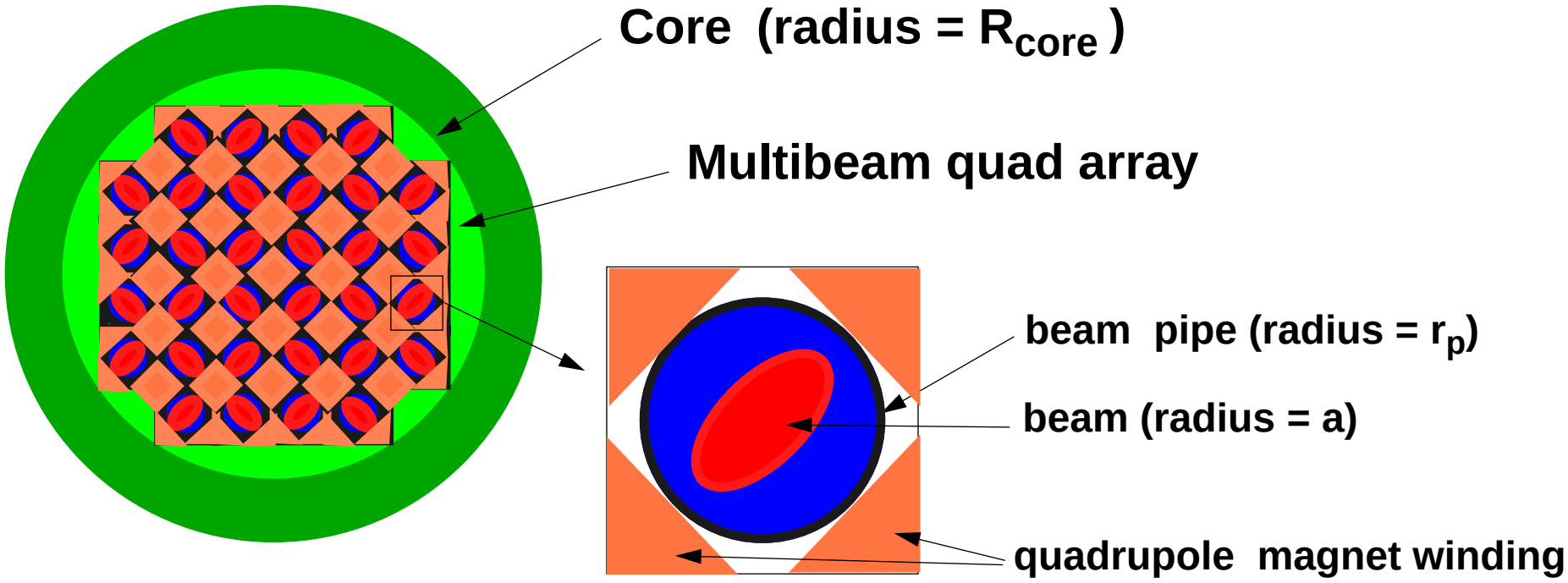
IBEAM calculates accel. performance (e.g. spot radius) as function of accelerator parameters

Spot radius vs. focus half-angle θ



5.0 mm goal

An array of small beamlets increases the total beam current through the core



Current per beam = $I_b \sim a^2 B \beta / r_p$

$r_p \sim a$ (until misalignments require minimum size)

so $I_b \sim a$; N_b = number of beams in array $\sim R^2_{core} / a^2$

Total current through core = $I_{tot} = N_b I_b \sim R^2_{core} / a$ (until misalignments dominate scaling)

Compression, velocity tilt, drift length, and target parameters for 3 IRE final pulse durations

$$\frac{dv}{dt} = -g\left(\frac{q}{m}\right)\frac{\partial\lambda}{\partial z}$$

$$\lambda = \lambda_{max}\left(1 - \frac{4\Delta z^2}{l_b^2}\right)$$

$$g \cong 1.3$$

At end of accelerator: $\lambda_{max} = 0.66 \times 10^{-6}$ **C/m**

$K_a = 3 \times 10^{-5}$

$l_a = 10.5$ **m**

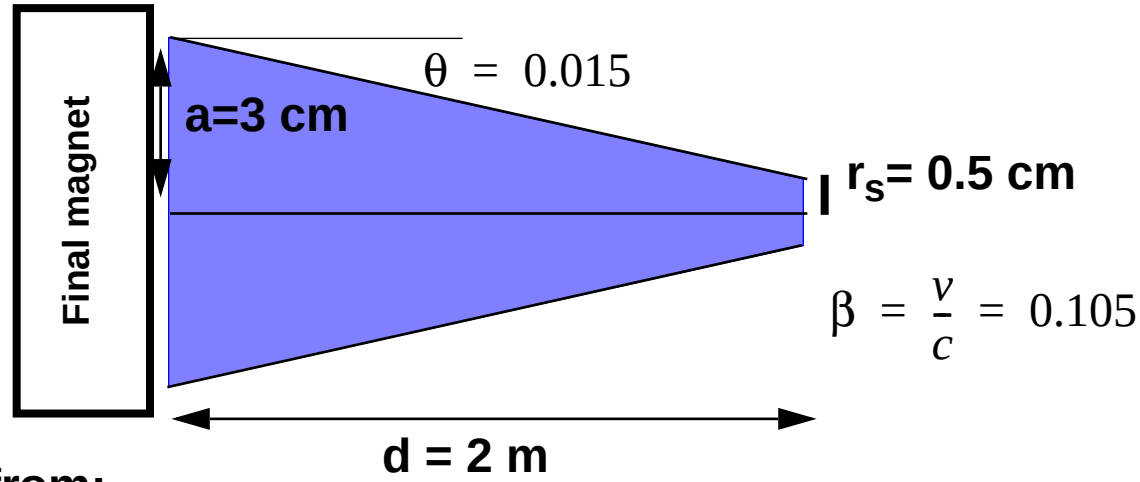
At target: $r_s = 5$ **mm**

Pulse duration τ_t	Compres-sion ratio C	Velocity tilt $\Delta v/v$	Drift length d (m)	Energy flux F (W/cm^2)	Temp. k_BT (eV)	Beam plasma freq. ratio $\omega_{p(ire)}/\omega_{p(driver)}$
	l_a/l_t	$[8K_a\, g\, (C-1)]^{1/2}$	$\frac{l_a(1-1/C)}{\Delta v/v}$	$\frac{E}{\pi r_s^2 \tau_t}$	$k_B(F/\sigma)^{1/4}$	$\omega_p \sim Zn^{1/2}/m^{1/2}$ $n \sim Fm^{1/2}/T^{3/2}$
5 ns	67	0.145	71.7	7.6×10^{12}	93	0.3
10 ns	33.5	0.101	101	3.8×10^{12}	78	0.2
20 ns	16.8	0.071	140	1.9×10^{12}	66	0.15

$$\frac{\omega_{p(ire)}}{\omega_{p(driver)}} = \left(\frac{F_{ire}}{F_{driver}}\right)^{\frac{1}{2}}\left(\frac{Z_{ire}}{Z_{driver}}\right)\left(\frac{m_{driver}}{m_{ire}}\right)^{\frac{1}{4}}\left(\frac{T_{driver}}{T_{ire}}\right)^{\frac{3}{4}}$$

$$= \left(\frac{1}{100}\right)^{\frac{1}{2}}\left(\frac{1}{5}\right)\left(\frac{5}{1}\right)^{\frac{1}{4}}\left(\frac{4}{0.2}\right)^{\frac{3}{4}} = 0.3$$ **(for 5 ns example)**

Final focus beam quality and neutralization requirement



$$\beta = \frac{v}{c} = 0.105$$

Spot size from:

Emittance

$\varepsilon_N = 5$ **mm-mrad** $\quad \delta r_\varepsilon \cong \frac{\varepsilon_n}{\beta\theta} = 3.2$ **mm** $\quad$ **(**$\varepsilon_N = 1$ **mm-mrad at injector)**

Chromaticity

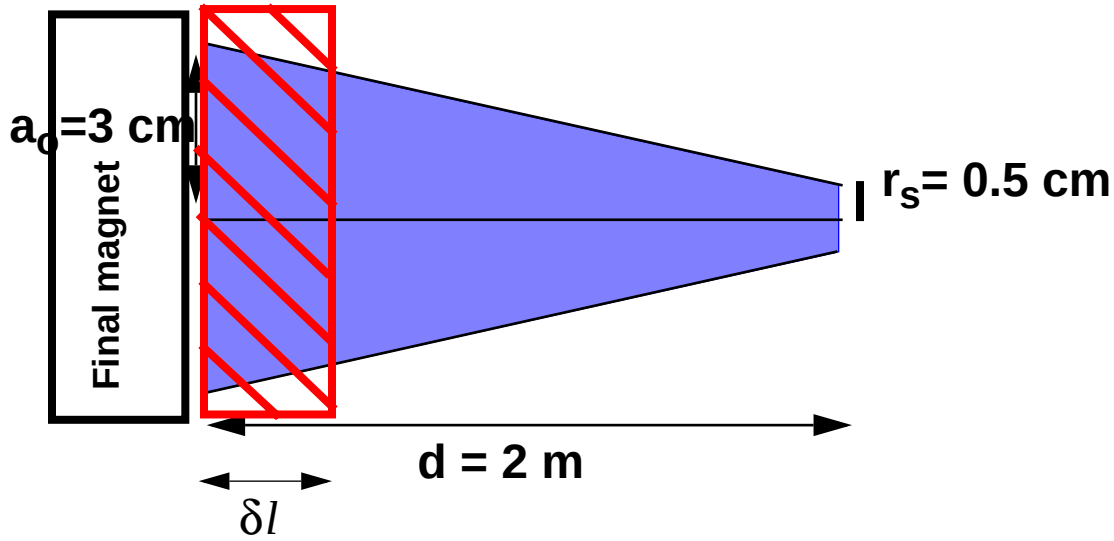
$$\frac{\delta p}{p} = 0.01 \qquad \delta r_{\frac{\delta p}{p}} \cong 6 d\theta \frac{\delta p}{p} = 1.8\,\textbf{mm}$$

From perveance, what neutralization is required?

$$\frac{d^2 a}{dz^2} = (1-f) K_a \frac{C}{a} \quad \Rightarrow \quad 1 - f = \frac{\theta^2}{2 K_a C \ln\left(\frac{a}{r_s}\right)} \qquad K_a = 3 \times 10^{-5}$$

$$(1 - f) = \begin{bmatrix} 0.02 \\ 0.04 \\ 0.08 \end{bmatrix} \textbf{ for } C = \begin{bmatrix} 67 \\ 33.5 \\ 16.8 \end{bmatrix}; \quad \left(\begin{bmatrix} 98 \\ 96 \\ 92 \end{bmatrix} \text{\% neutralization} \right)$$

Effect on spot size of uncertainty in neutralization point



$$\frac{d^2 a_o}{dz^2} = (1-f)K_a\frac{C}{a_o} + \frac{\varepsilon^2}{a_o^3} \quad \Rightarrow \quad \frac{d}{dz}\delta a_o' \cong K_a\frac{C}{a_o}$$

$$\delta\theta = \delta a' = fK_aC\frac{\delta l}{a_o} \quad \Rightarrow \quad \delta r \cong K_aC\frac{\delta l}{a_o}d$$

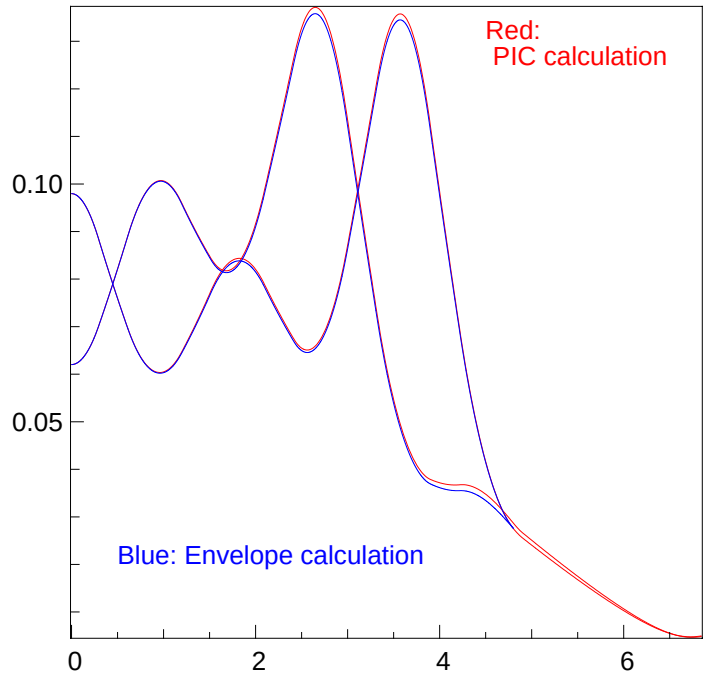
If $\delta l \cong a_o$ **=>** $\delta\theta \cong K_aC$

$$\delta r = dK_aC = \begin{bmatrix}4\\2\\1\end{bmatrix}\textbf{mm} \quad \textbf{for} \quad C = \begin{bmatrix}67\\33.5\\16.8\end{bmatrix}$$

IRE final focus designs are being simulated

Agressive 5 ns final pulse configuration meets spot size goal in initial simulations with simplified physics models

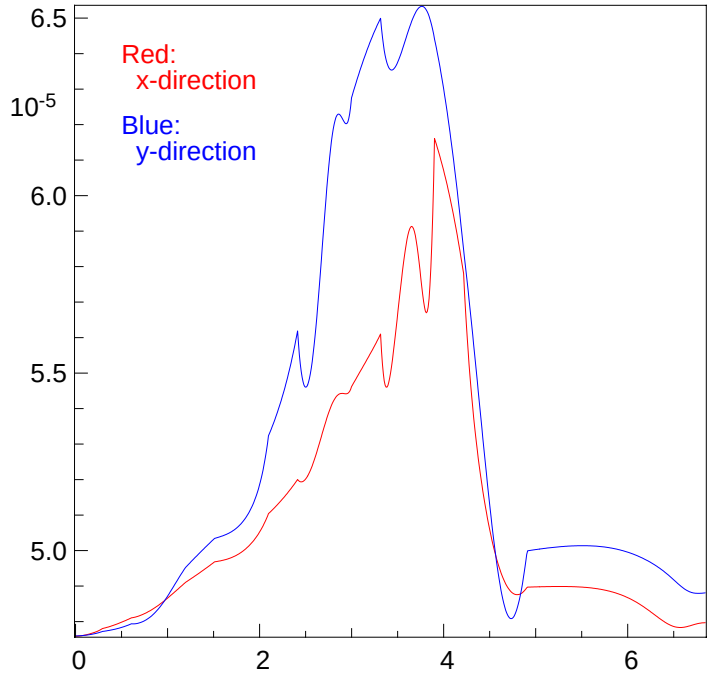
Beam envelope in the IRE Final Focus System 4



Step 691, T = 0.2188e-6 s, Zbeam = 6.8531 m
IRE Final Focus System
2D Slice calculation

Michiel de Hoon warp r2 norm

Edge emittance 9



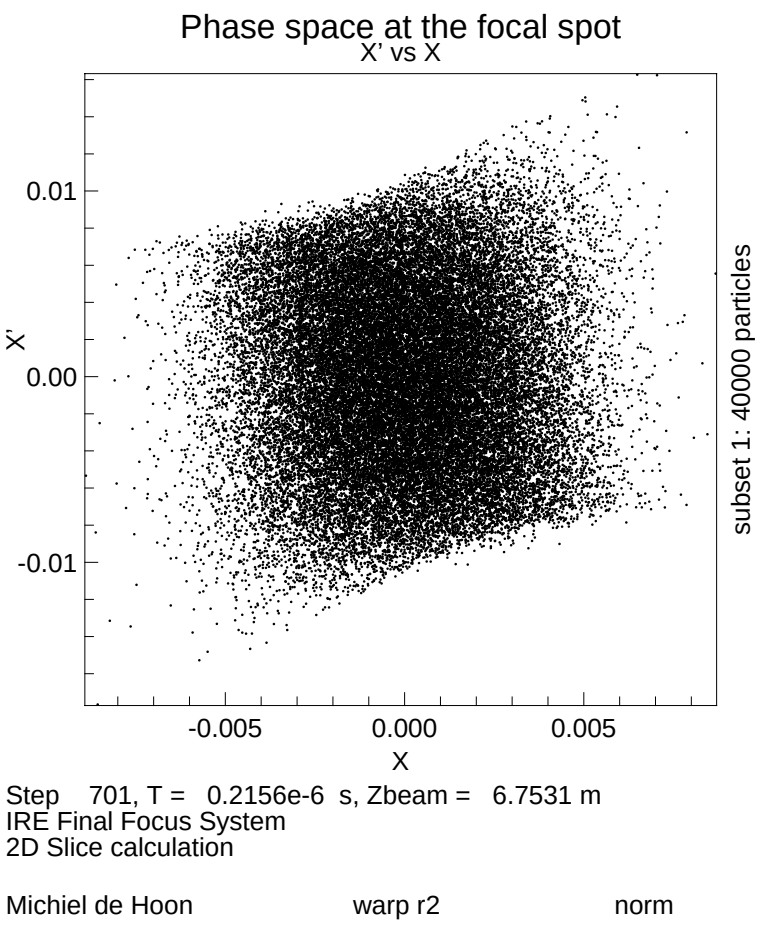
Step 691, T = 0.2188e-6 s, Zbeam = 6.8531 m
IRE Final Focus System
2D Slice calculation

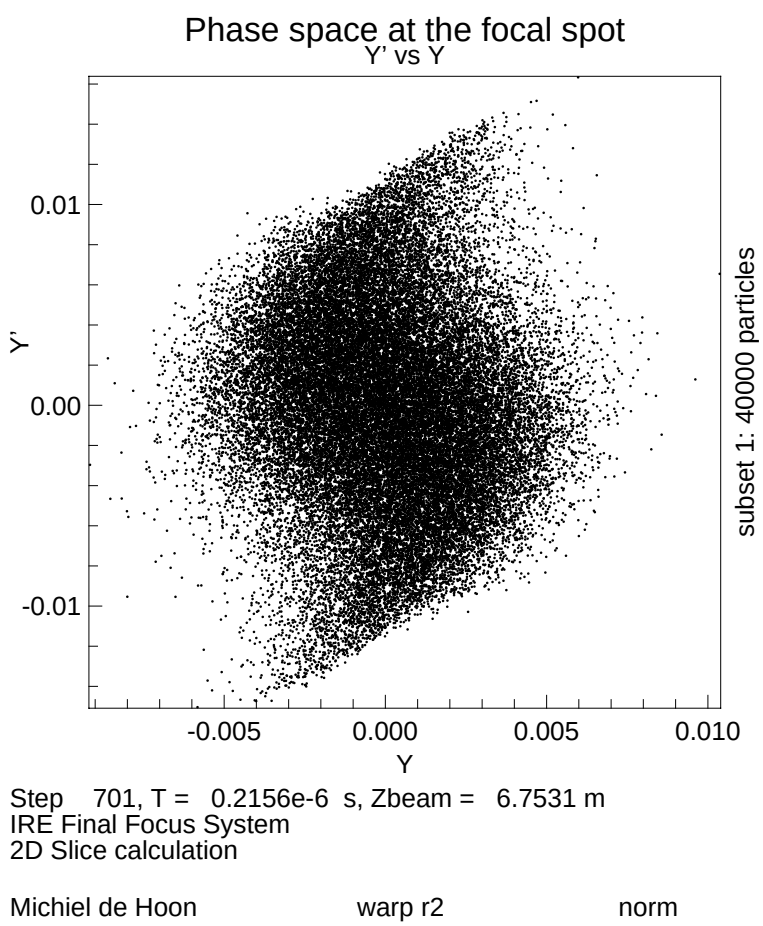
Michiel de Hoon warp r2 norm

Assumptions:
1. **"Hard-edge" quadrupole fields**
2. **98% neutralization within chamber assumed**
3. **Middle slice of beam simulated only**

Geometric aberrations still to be simulated!

Simulations of IRE final focus -- continued





x and y phase-space plots at focal spot

Summary and conclusions

A multi-pronged Phase 1 research effort is laying the groundwork for the Integrated Research Experiment. The key research areas are:

Source and injector (high brightness, multiple beams, low cost)

High current transport (full line charge density, beam filling-factor maximization, control of electrons)

Technology (magnetic core material, superconducting magnetic quadrupole arrays, insulators, and pulsers)

Beam simulations and theory in accelerator (beam matching, accelerator errors, emittance growth, halo, bunch compression)

Beam simulations and theory in chamber (neutralization methods, stripping effects, spot size minimization)

Systems optimization (minimization of cost and maximization of pulse energy and beam intensity)