Summary of High Brightness Beams Workshop Erice 2005

G. A. Krafft
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Applications of High Brightness Beams: Energy Recovered Linacs

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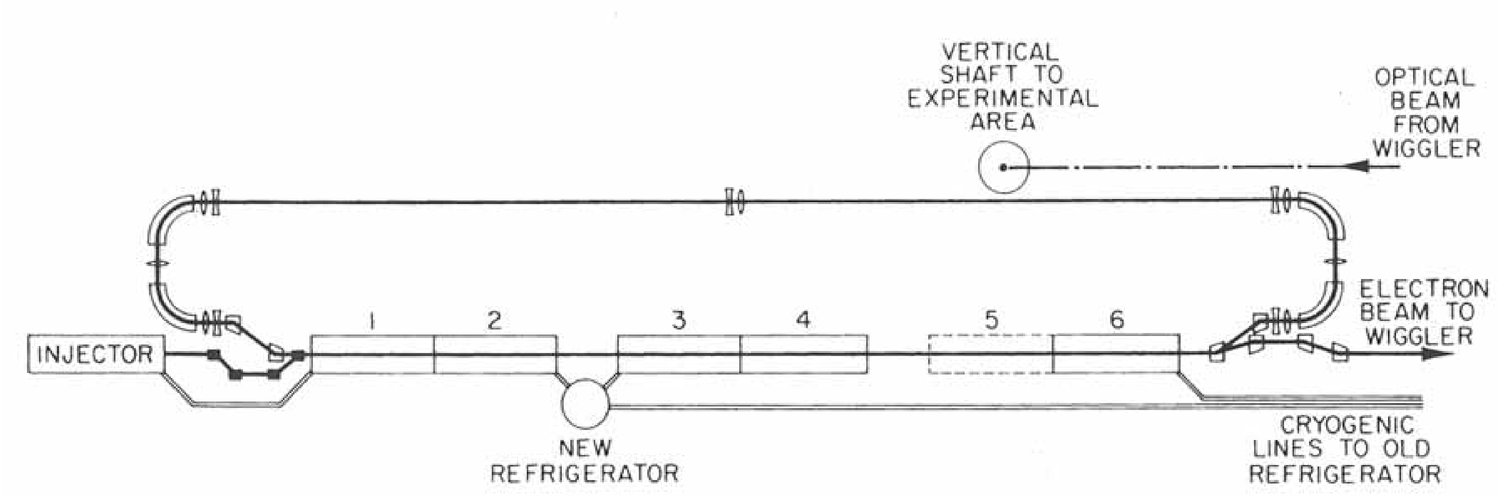
The SCA/FEL Energy Recovery Experiment

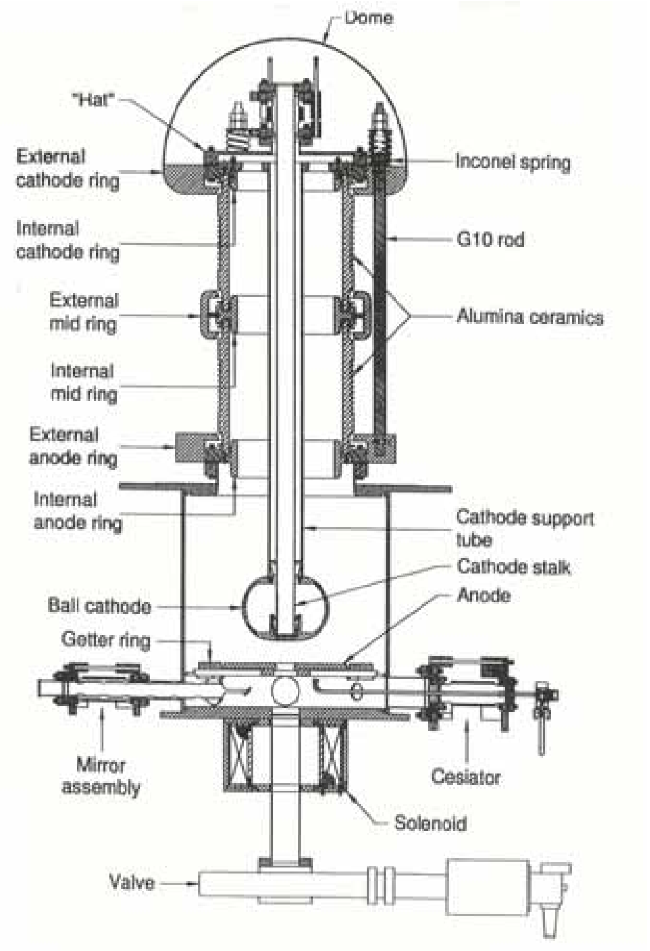
- Same-cell energy recovery was first demonstrated in a superconducting linac at the SCA/FEL in July 1986
- Beam was injected at 5 MeV into a ~50 MeV linac (up to 95 MeV in 2 passes), 150 μA average current (12.5 pC per bunch at 11.8 MHz)
- The Recyclotron beam recirculation system could be not used to produce the peak current required for lasing and was replaced by a doubly achromatic single-turn recirculation line.
- Nearly all the energy was recovered. No FEL inside the recirculation loop.



DC photoinjectors

State-of-the-art: JLAB FEL gun

- High repetition rate up to 75 MHz
- $\varepsilon_{N,rms}$~ 7-15 mm-mrad for q ~ 60 –135 pC/bunch (measured at the wiggler)
- Average current up to 9 mA
- Cathode voltage: 350 – 500 kV



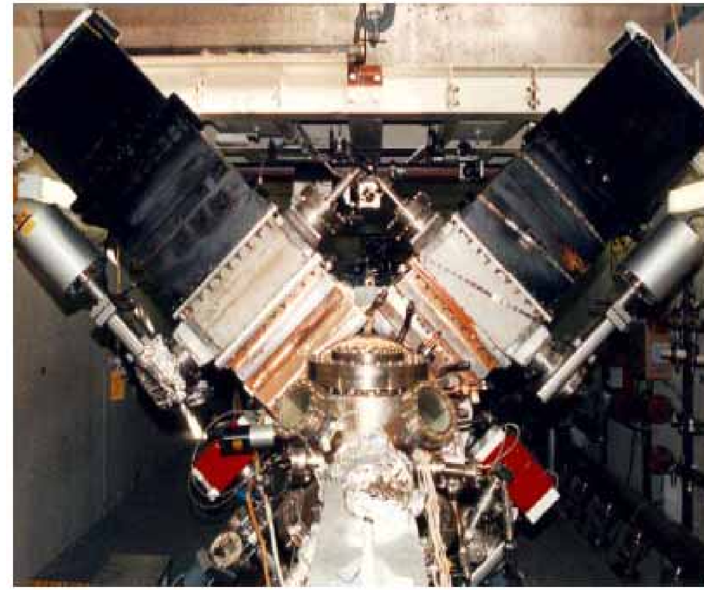
Planned DC Photoinjectors

- **JLab**: 500 kV, 75 MHz, 10 mA
- **JLab/AES**: 750 MHz, 100 mA
- **Daresbury ERLP**: Duplicate of JLab FEL gun, 6.5 mA
- **Cornell**: 500 – 750 kV, 100 mA, 77pC/bunch, 1.3 GHz, $\varepsilon_{N,rms}$~ 0.1 mm-mrad

RF photoinjectors

- To date RF guns have produced best normalized emittances: $\varepsilon_{N,rms}$~ 1 μm at q ~ 0.1 – 1 nC , but at relatively low rep rate (10-100 Hz)

- Challenge: Balance high gradient (low emittance) with high rep rate (thermal effects)

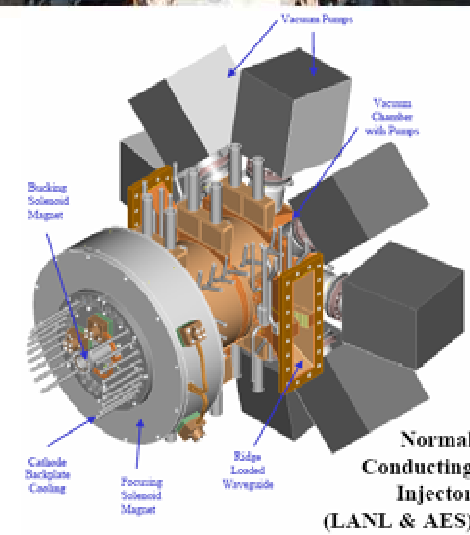


State-of-the-art: Boeing gun

- Repetition rate 433 MHz at 25% DF
- Average current 32 mA

Planned RF Photoinjectors

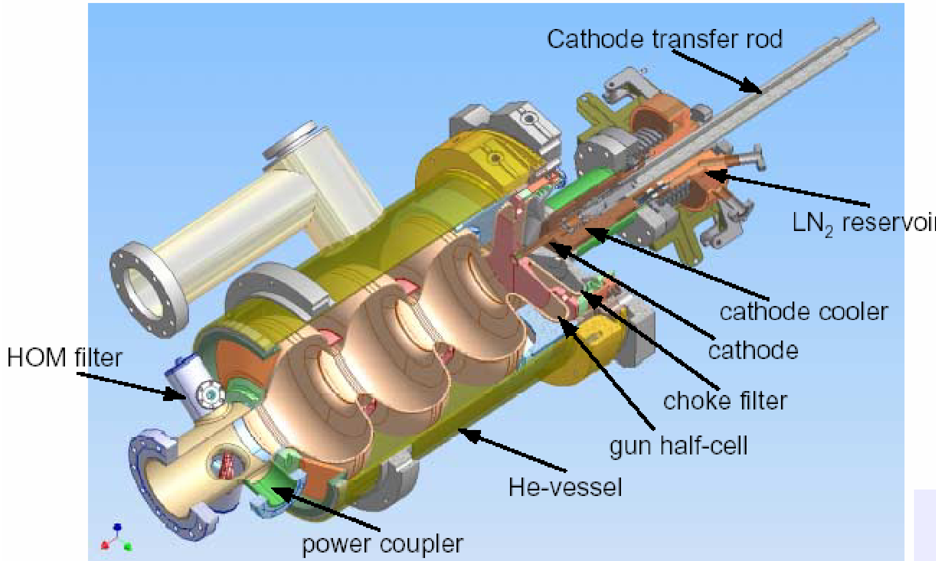
- **LANL/AES:** 700 MHz,100 mA

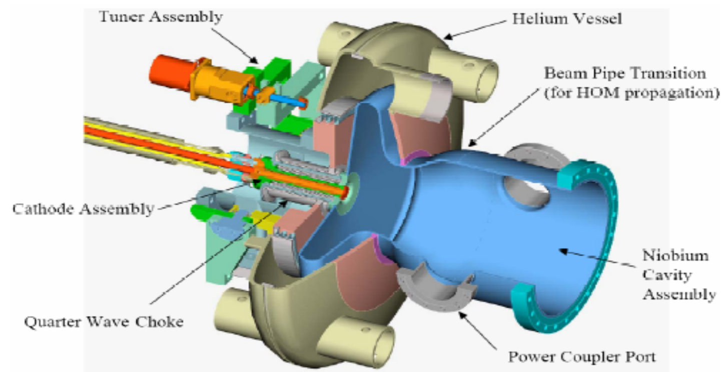


Normal Conducting Injector (LANL & AES)

SRF photoinjectors

- High CW RF fields possible
- Significant R&D required





Rossendorf proof of principle experiment:
1.3 GHz, 10 MeV
77 pC at 13 MHz and 1 nC at < 1 MHz

BNL/AES/JLAB development:
1.3 GHz ½-cell Nb cavity at 2K
Test diamond amplified cathode

AES/BNL development:
703.75 MHz ½-cell Nb photoinjector

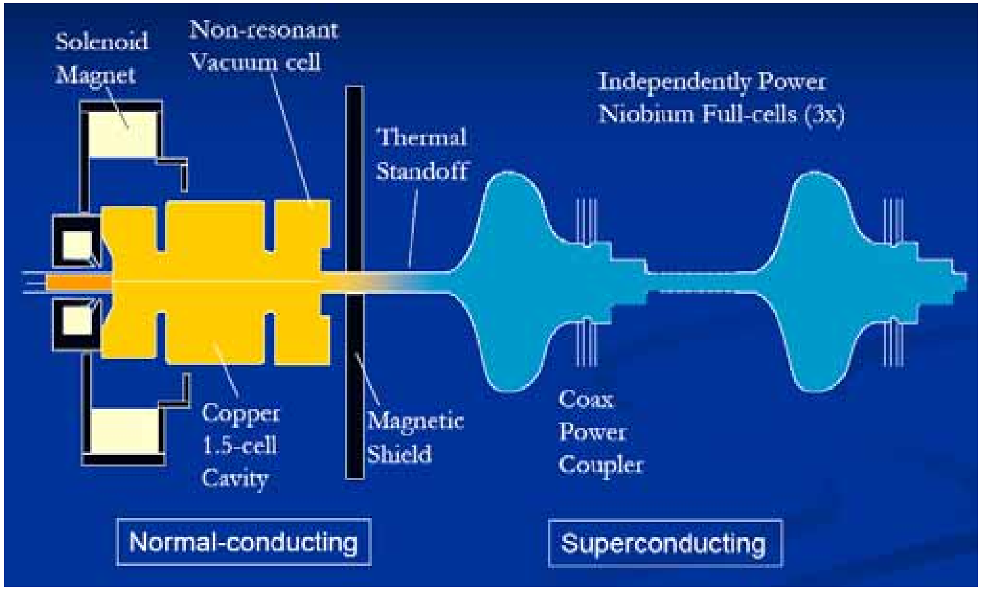
Hybrid Guns

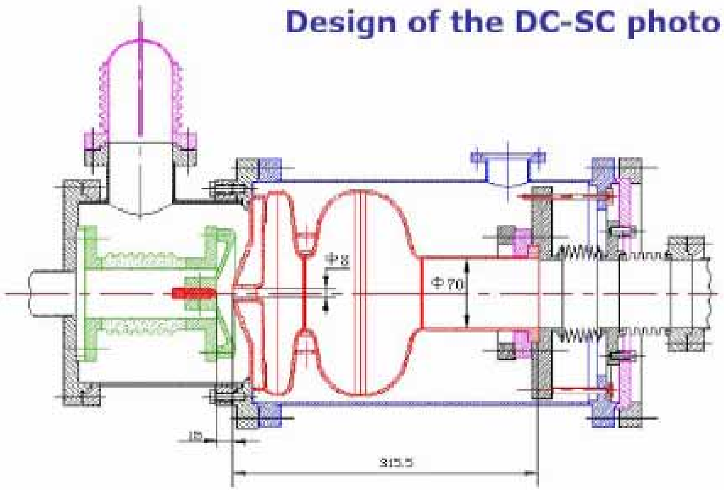
- **LANL**

  NC 1 ½-cell + SRF cells

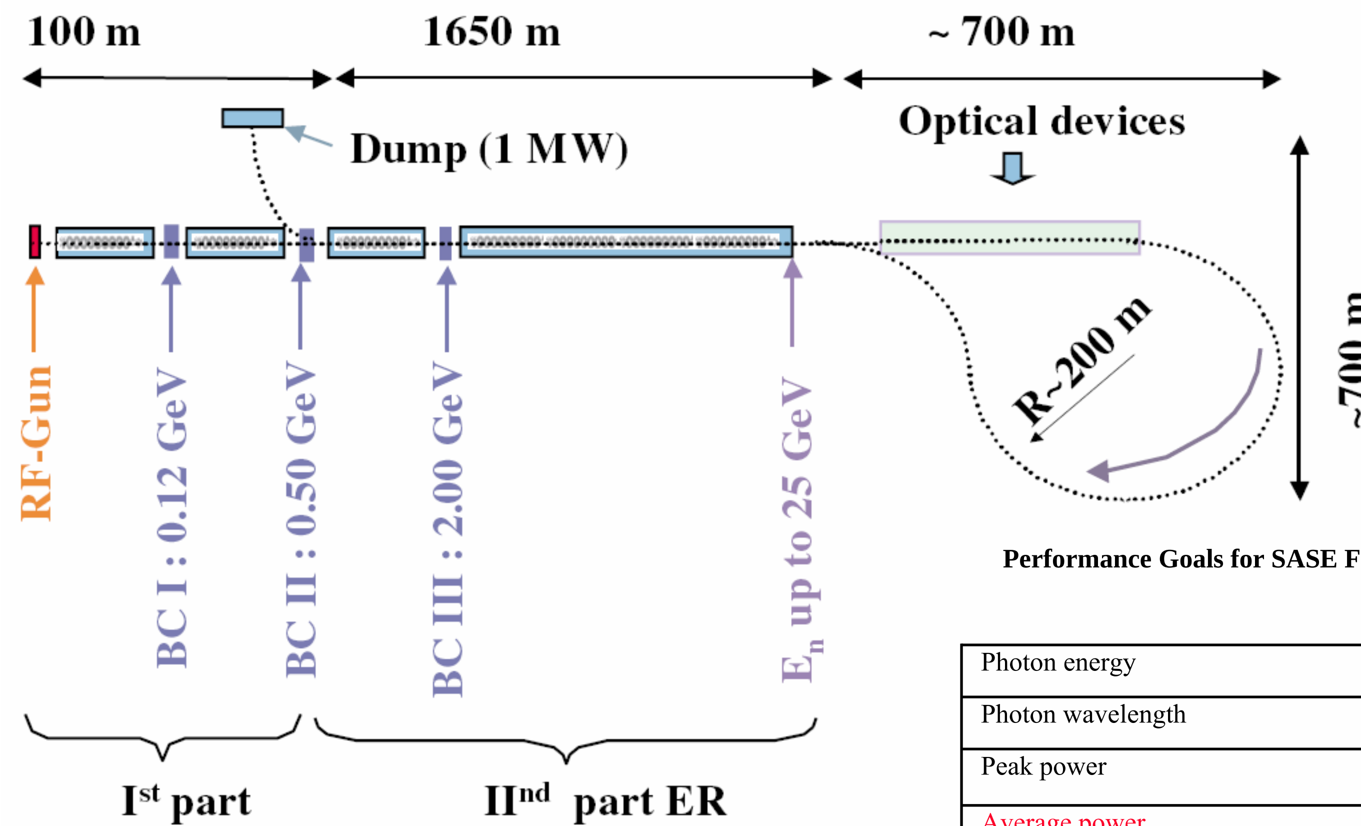
- **University of Peking**

  DC + SRF gun





TESLA XFEL ERL



Performance Goals for SASE FEL Radiation at the DESY XFEL

Photon energy	12.4 – 0.2 keV
Photon wavelength	0.1 – 6.4 nm
Peak power	24 – 135 GW
Average power	66 – 800 W
# photons/ pulse	1 – 430 x 10^{12}
Peak brilliance	5.4 – 0.6 x 10^{33} **
Average brilliance	1.6 – 0.3 x 10^{25} **
** in units of photons / (s mrad^2 mm^2 0.1% b.w.)	

Proposed ER operation would have a rep rate of 1 MHz instead of DESY XFEL rep rate of 10 Hz, increasing the average power and brilliance by a factor of 10^5

ERL X-ray Source Conceptual Layout

CORNELL UNIVERSITY
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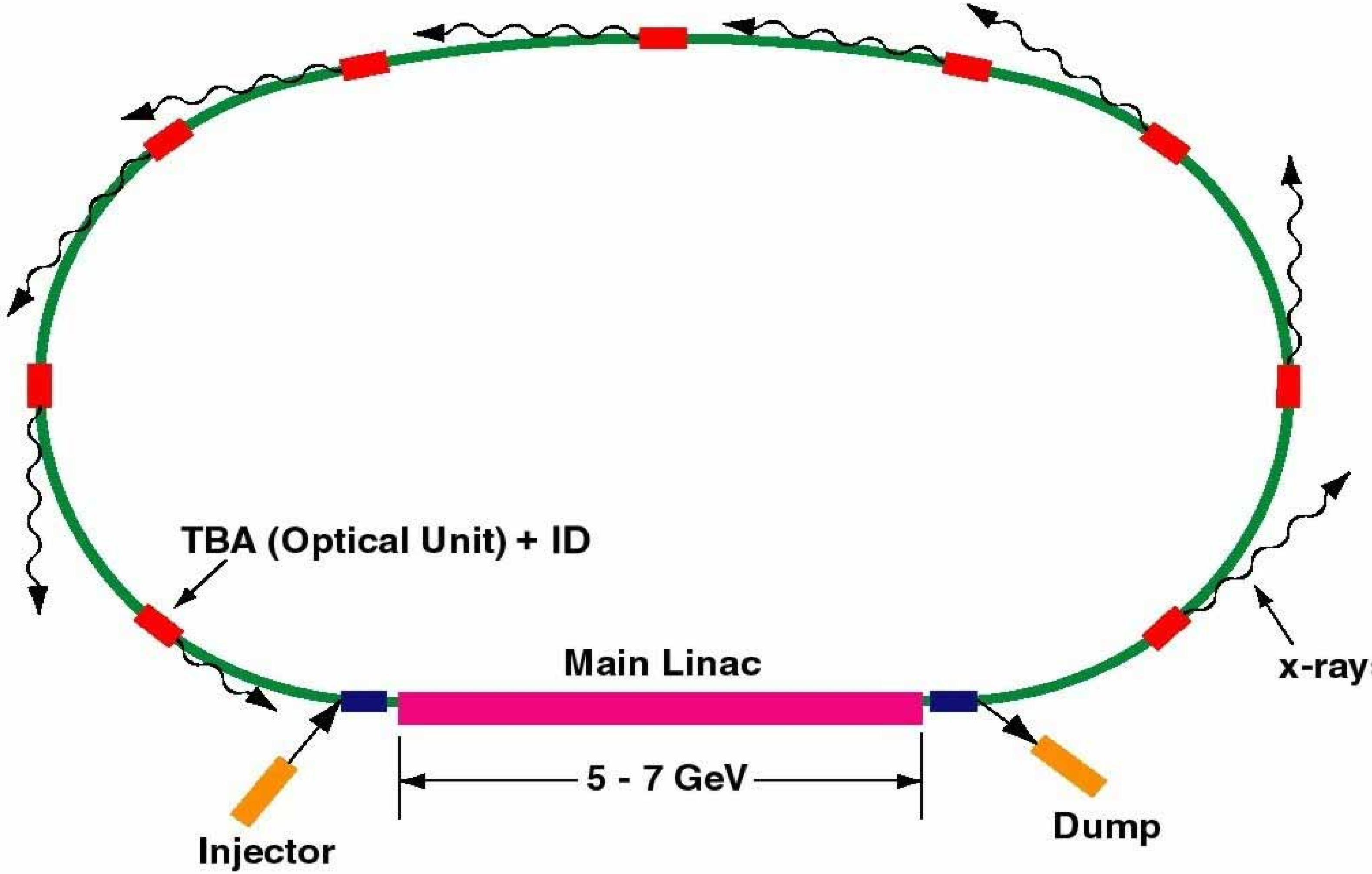
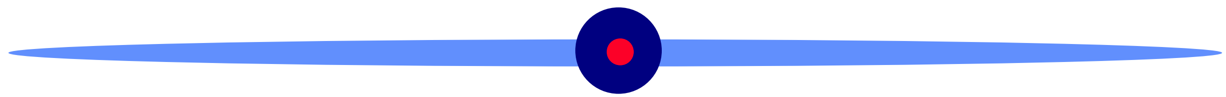


Why ERLs for X-rays?

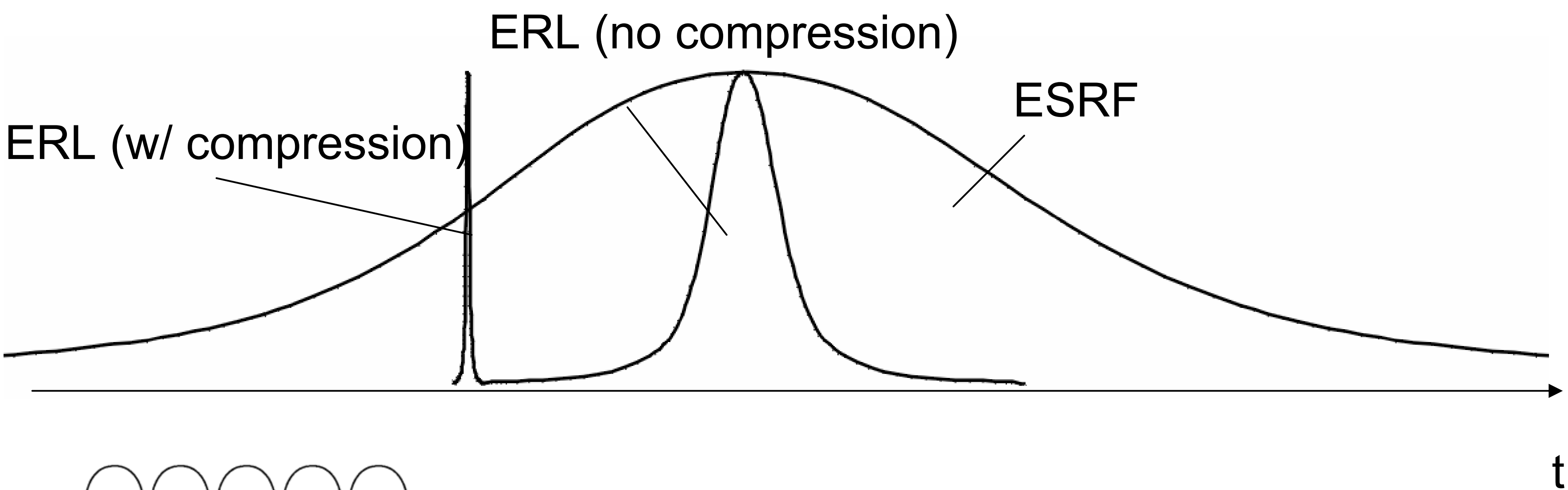


ESRF 6 GeV @ 200 mA

ε_x = 4 nm mrad
ε_y = 0.02 nm mrad
B ~ 10^{20} ph/s/mm^2/mrad^2/0.1%BW
L_{ID} = 5 m

ERL 5 GeV @ 10-100 mA

$\varepsilon_x = \varepsilon_y \rightarrow$ 0.01 nm mrad
B ~ 10^{23} ph/s/mm^2/mrad^2/0.1%BW
L_{ID} = 25 m



Brilliance Scaling and Optimization

- For 8 keV photons, 25 m undulator, and 1 micron normalized emittance, X-ray source brilliance

$$B \propto \frac{I}{\varepsilon^2} = \frac{fQ}{\varepsilon_{th}^2 + AQ^p}$$

- For any power law dependence on charge-per-bunch, Q, the optimum is

$$AQ^p \approx \varepsilon_{th}^2 / \left(p - 1\right)$$

- If the "space charge/wake" generated emittance exceeds the thermal emittance ε_{th} from whatever source, you've already lost the game!
- BEST BRILLIANCE AT LOW CHARGES, once a given design and bunch length is chosen!
- Unfortunately, best flux at high charge

ERL Source Sample Parameters

Parameter	Value	Unit
Beam Energy	5-7	GeV
Average Current	100 / 10	mA
Fundamental frequency	1.3	GHz
Charge per bunch	77 / 8	pC
Injection Energy	10	MeV
Normalized emittance	2 / 0.2*	µm
Energy spread	0.02-0.3*	%
Bunch length in IDs	0.1-2*	ps
Total radiated power	400	kW

* rms values

Cornell ERL Phase I: Injector

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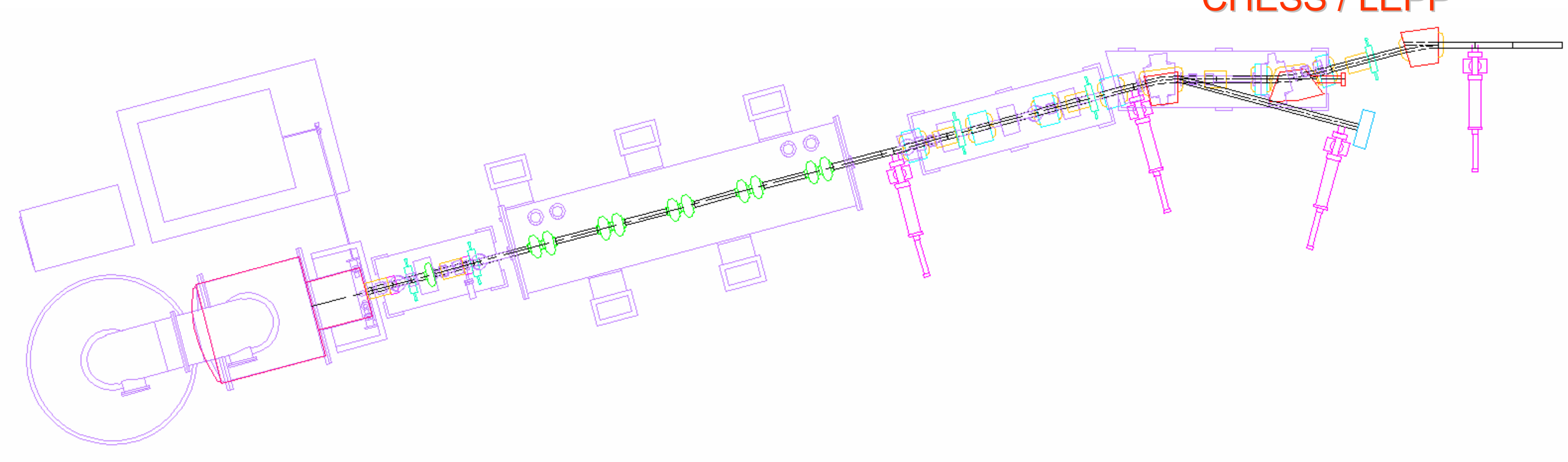

Injector Parameters:

Beam Energy Range	5 – 15[a] MeV
Max Average Beam Current	100 mA
Max Bunch Rep. Rate @ 77 pC	1.3 GHz
Transverse Emittance, rms (norm.)	< 1[b] μm
Bunch Length, rms	2.1 ps
Energy Spread, rms	0.2 %

[a] at reduced average current
[b] corresponds to 77 pC/bunch

Beyond the space charge limit

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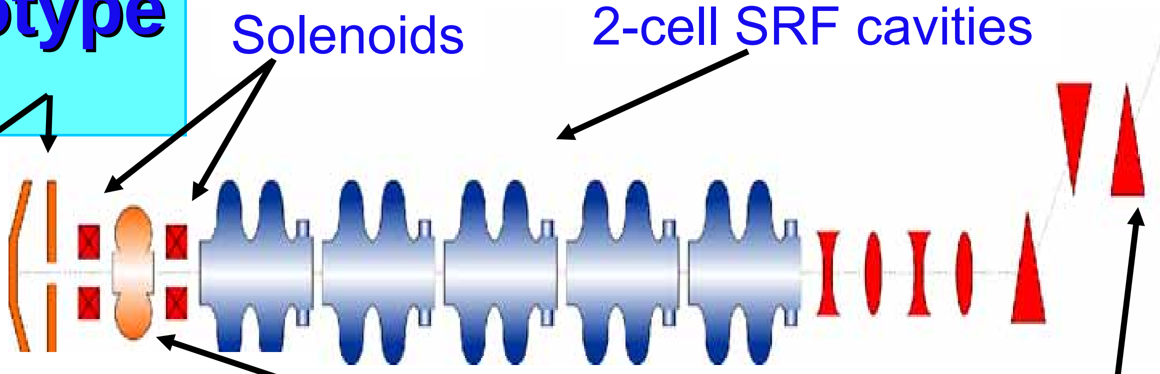
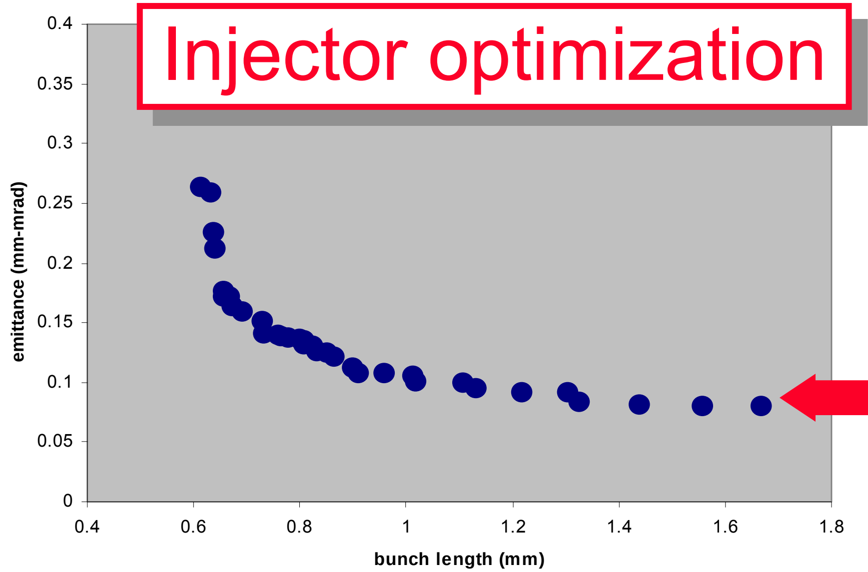
Cornell ERL Prototype Injector Layout



Injector optimization



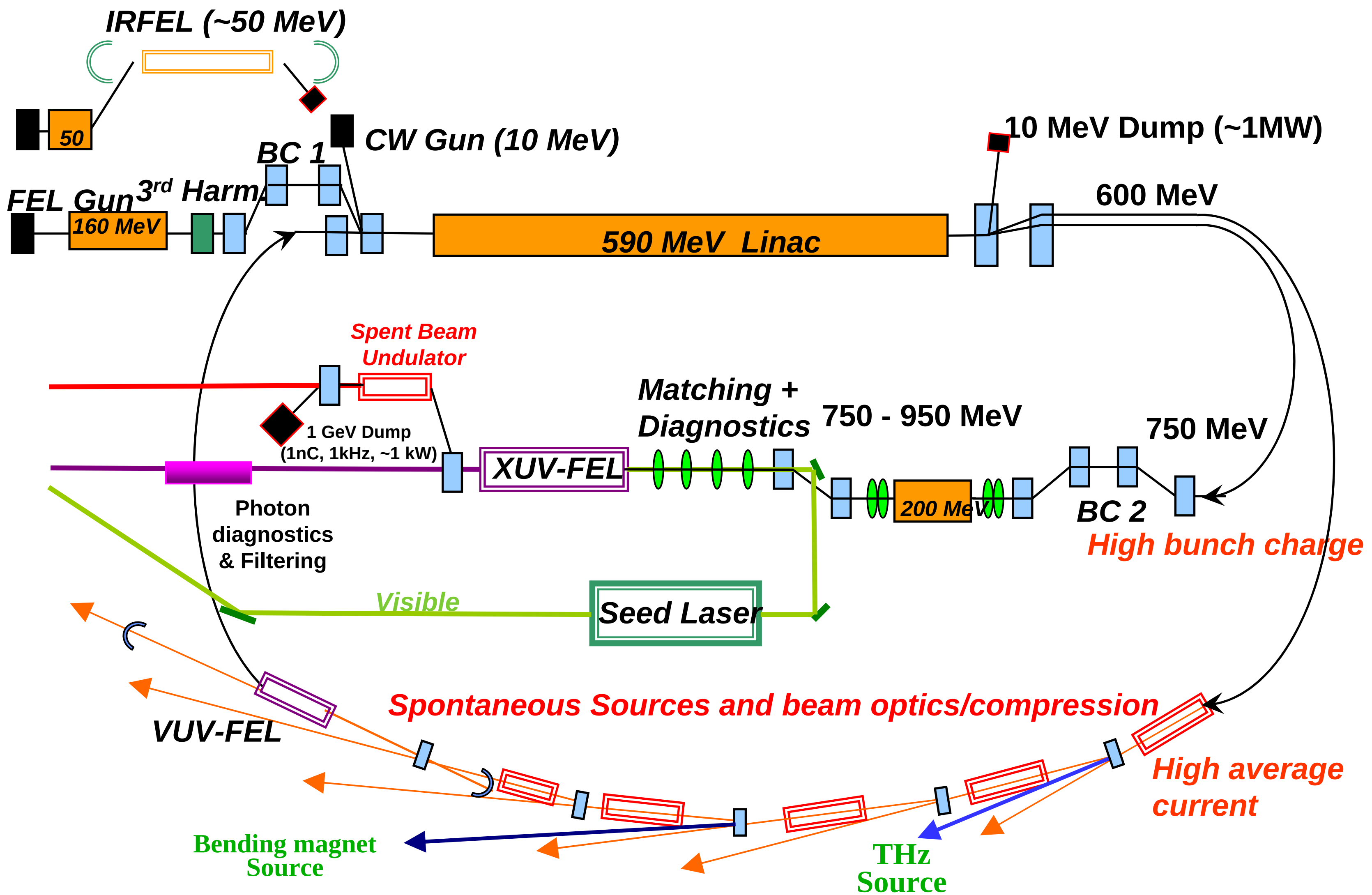
0.1 mm-mrad, 80 pC, 3ps

Courtesy of I. Bazarov

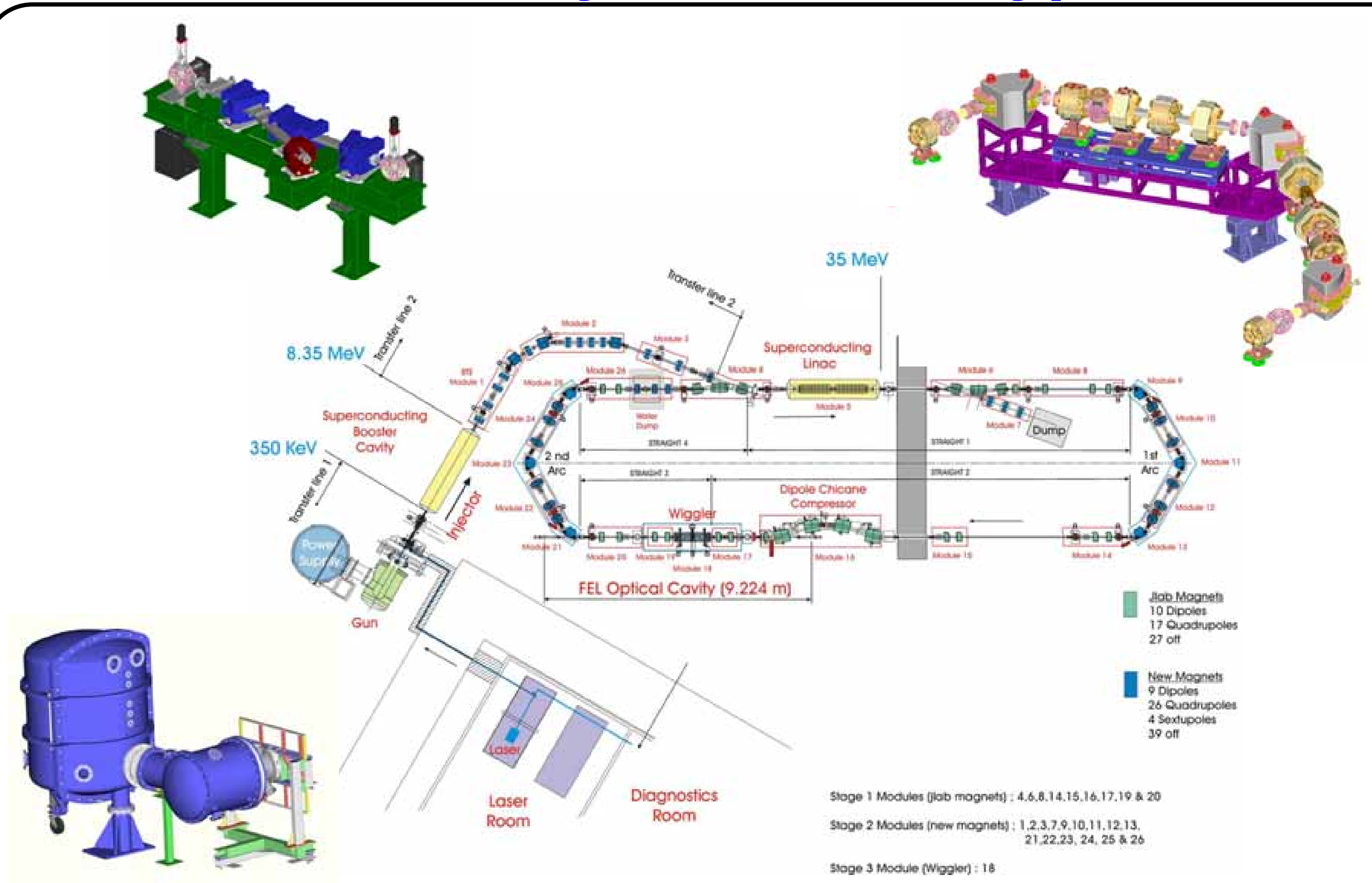
Sinclair Points

- Emittance compensation is effective in reducing the emittance from DC guns too. The computer designs of the Cornell ERL source require its application to achieve the best beam parameters.
- Thermal emittance matters, even at high charge. Starting with the best possible thermal emittance, as may be extracted from GaAs photocathodes (photoelectrons are thermalized before being emitted), may be preferred.
- You don't need infinite voltage or cathode gradient to get decent performance from a DC gun.
- First beam, optimistically, by the end of the year.

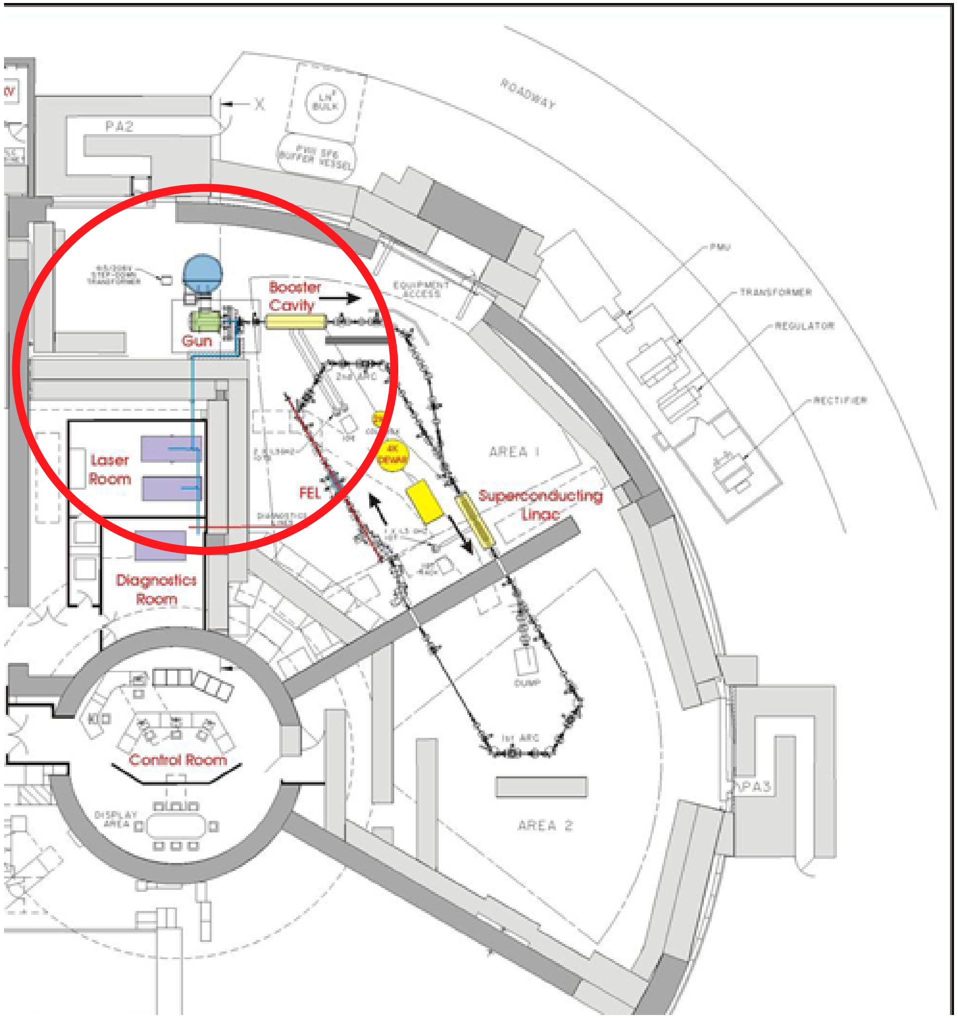
Conceptual layout of 4GLS



Daresbury: ERL Prototype



Daresbury: ERL Prototype



Electron Beam Parameters	Goal
Energy (MeV)	30-50
Accelerator frequency (MHz)	1300
Charge per bunch (pC)	>80
Average current (μA)	13
Peak Current (A)	53
Beam Power (kW)	0.455

Output Light Parameters	Goal
Wavelength range (microns)	3-10
Bunch length (FWHM psec)	1.5
Laser energy/ pulse (μ Joules)	9
Macropulse average laser power (kW)	0.7
Rep. Rate (MHz)	81.25
Macropulse length @20 Hz rep rate (μsec)	100

ERLs in High Energy and Nuclear Physics

- Electron cooling of hadron storage rings

The requirements:

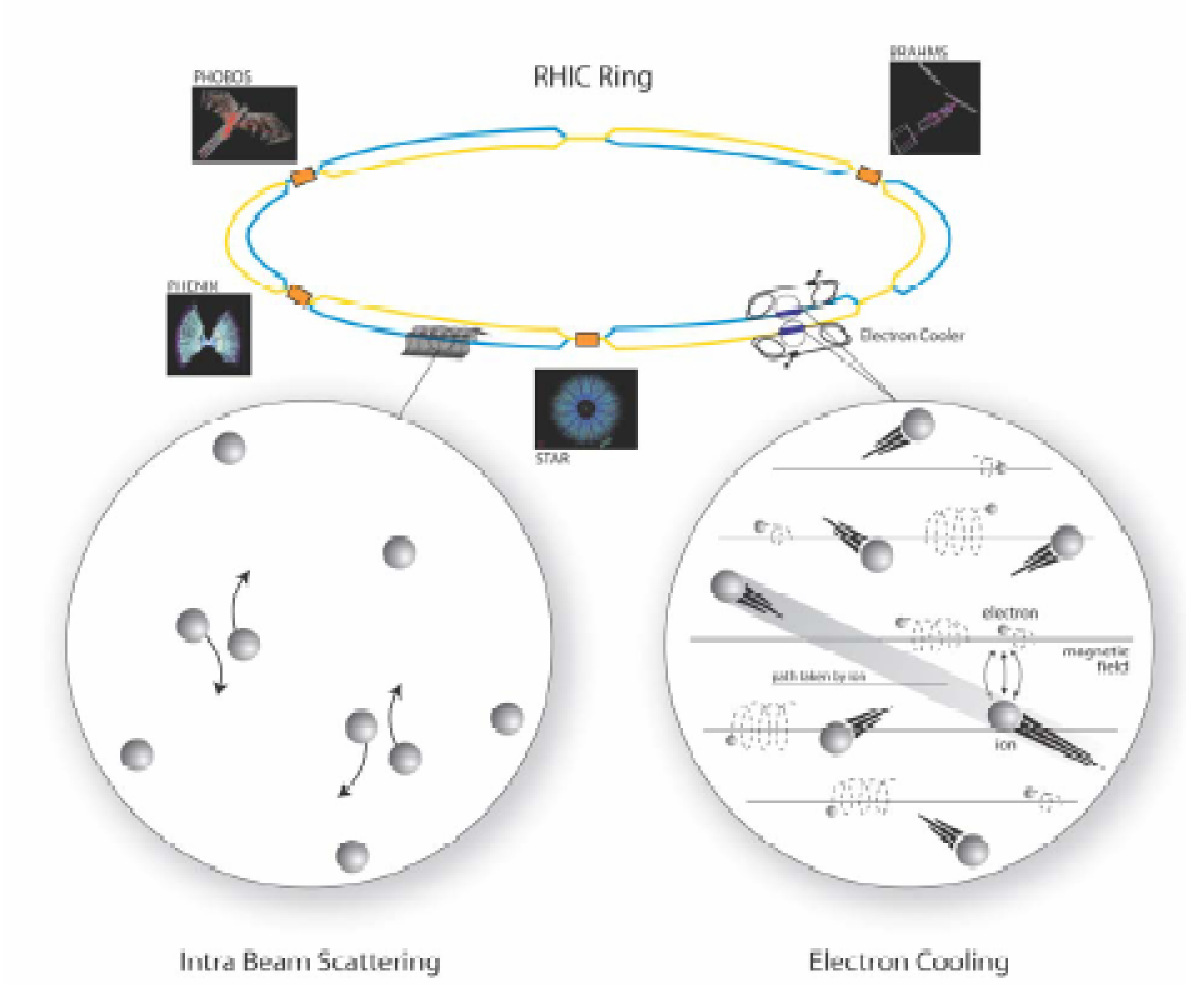
1. Low-energy
2. High brightness
3. High-Charge
4. High-current

- Provide electron beams for high-luminosity colliders.

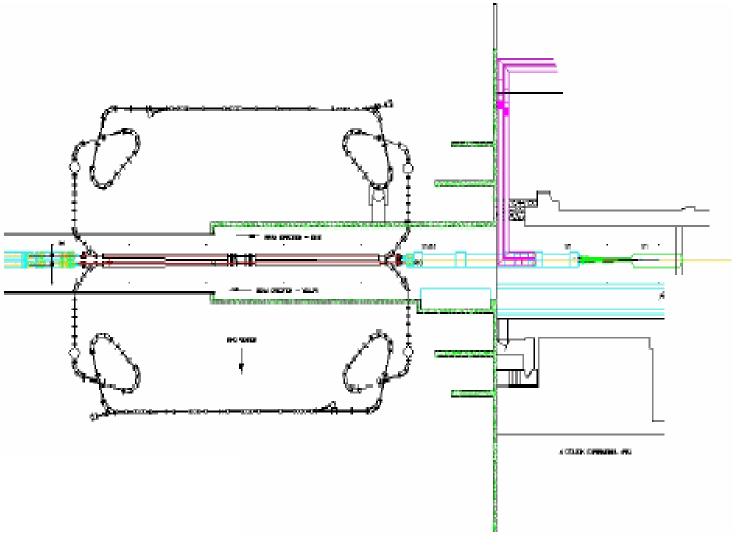
The requirements:

1. High-energy
2. Polarization
3. High-current

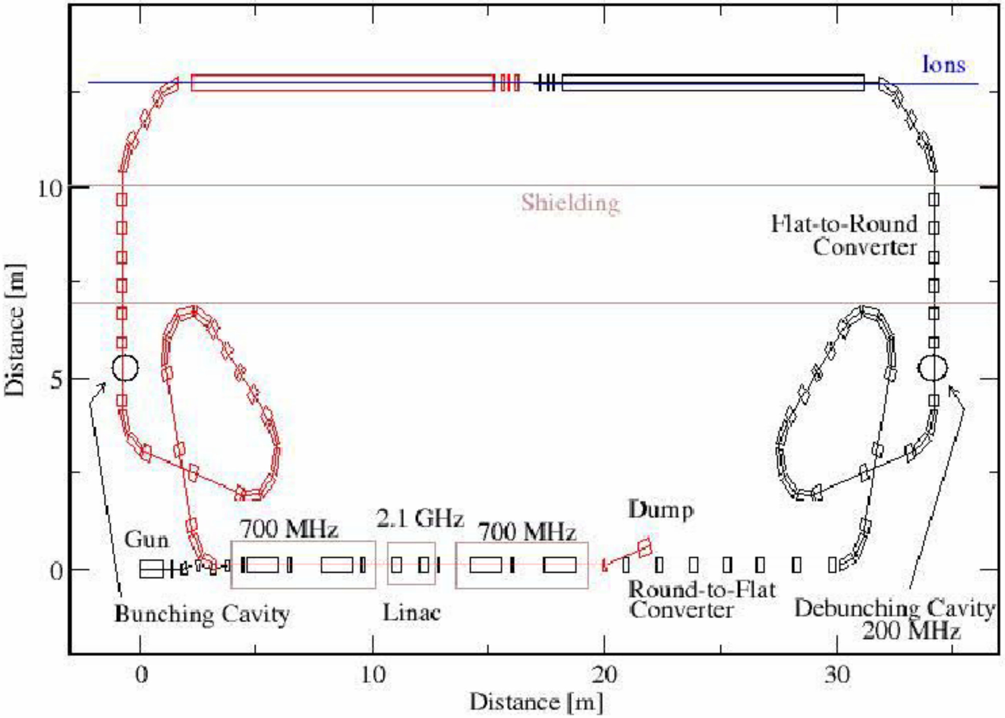
Electron Cooling



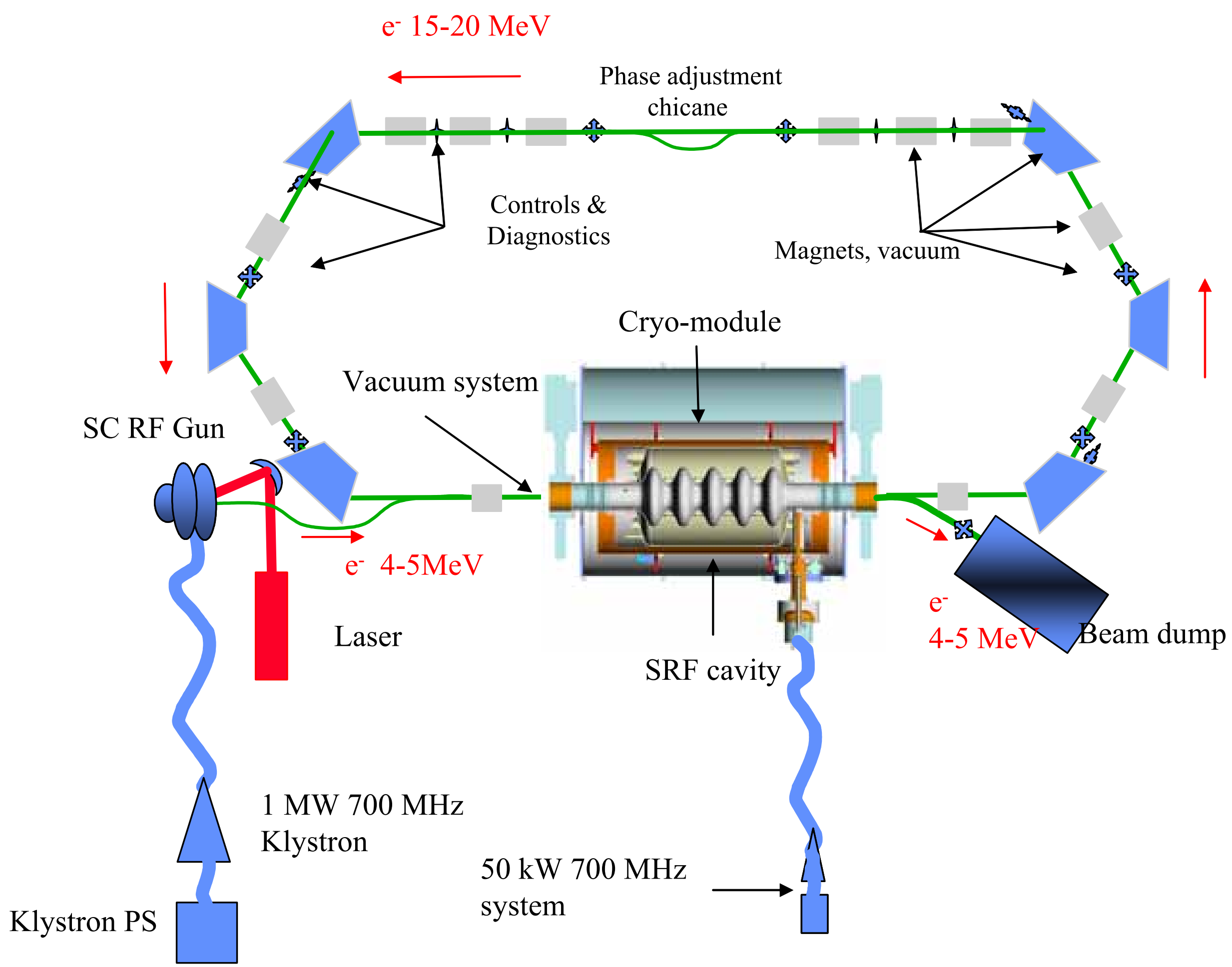
ERL-Based Electron Cooler



RHIC electron cooler is based on a 200 mA, 55 MeV ERL 20 nC per bunch, 9.4 MHz

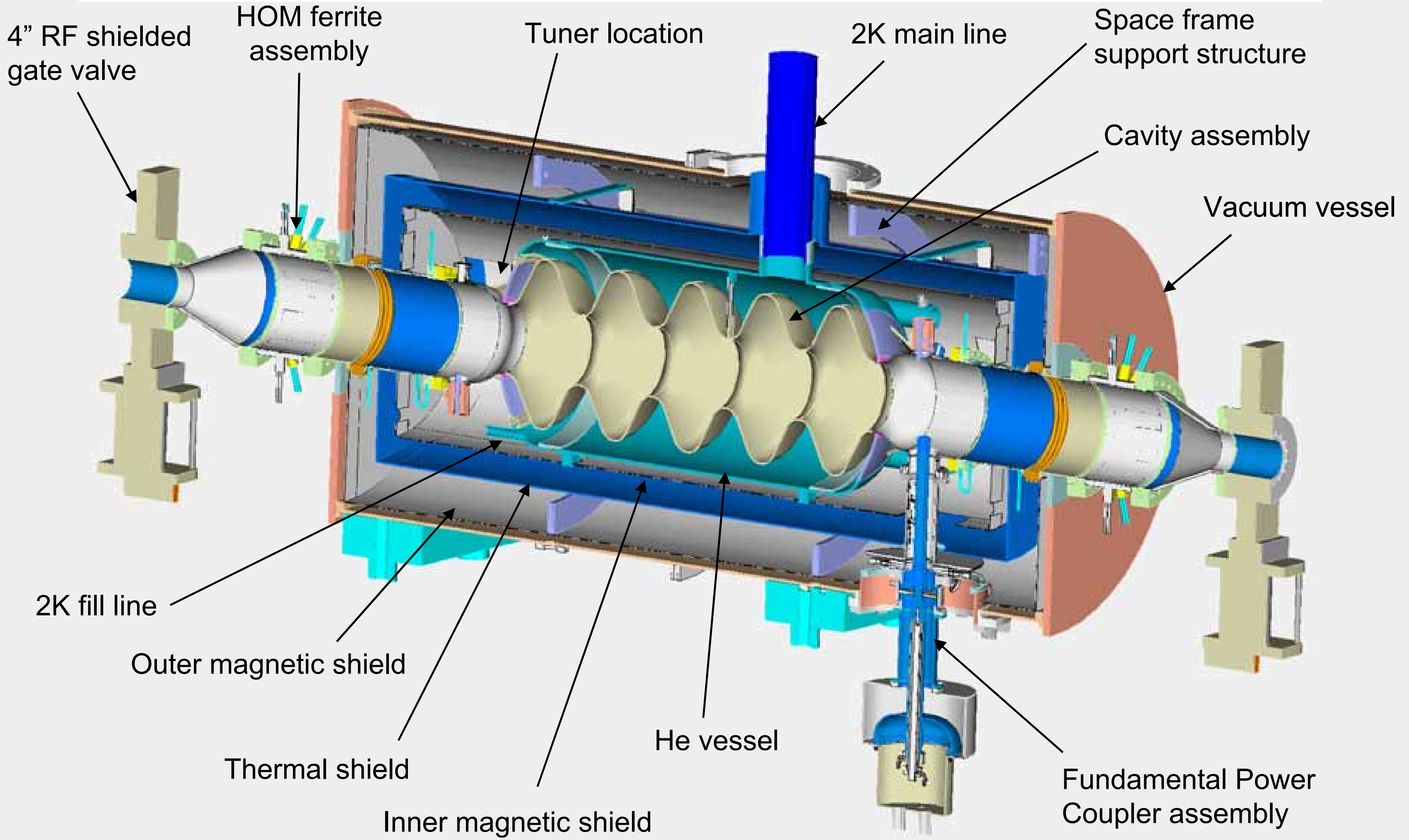


BNL ERL R&D Facility



ERL
Under construction

Cryomodule Design



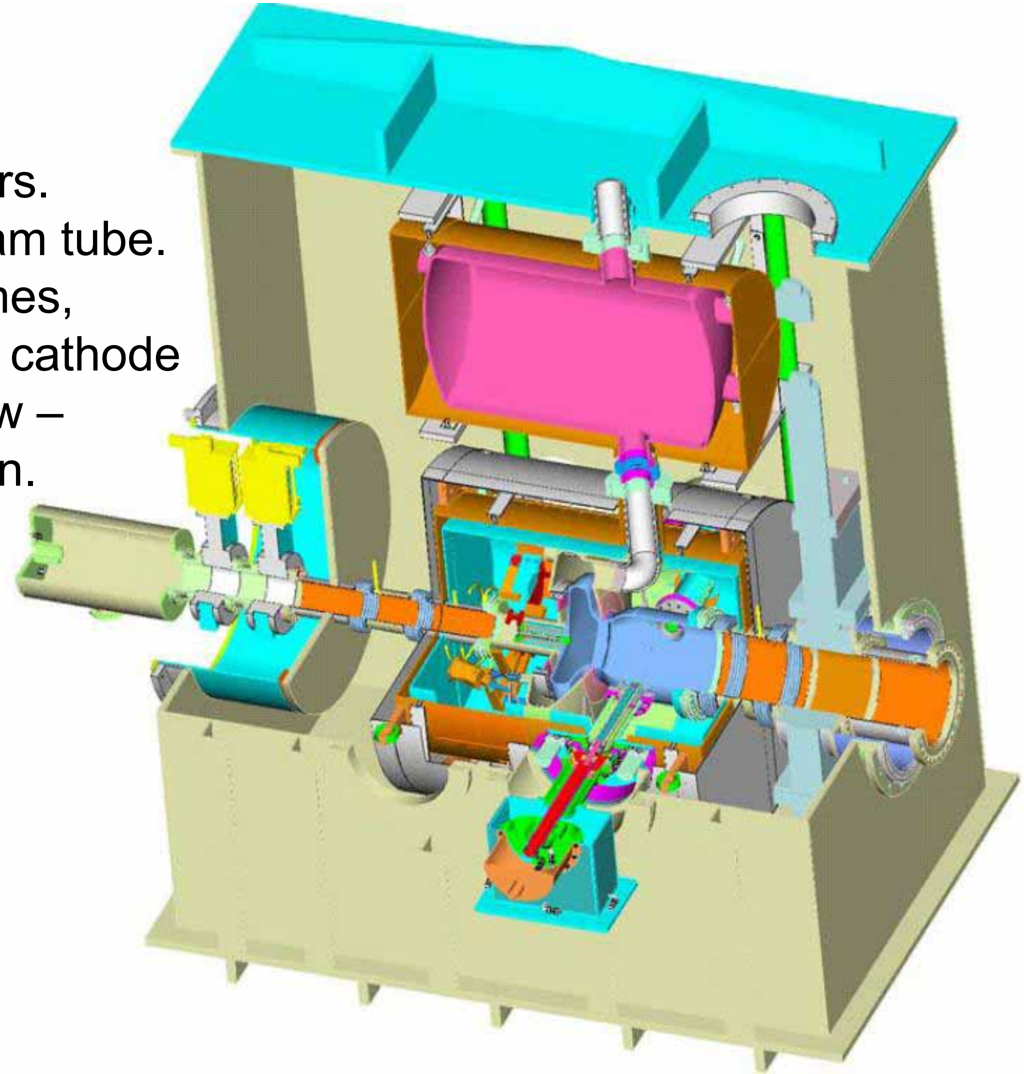
BROOKHAVEN NATIONAL LABORATORY

Advanced Energy Systems, Inc.

Superconducting RF gun under development

703.75 MHz gun.
2x0.5 MW input couplers.
HOM damping thru beam tube.
Various cathode schemes,
including encapsulated cathode
behind diamond window –
isolation cathode ↔ gun.

CW performance
0.5 ampere @ 2 MeV.



Two Proposed Electron-Ion Colliders

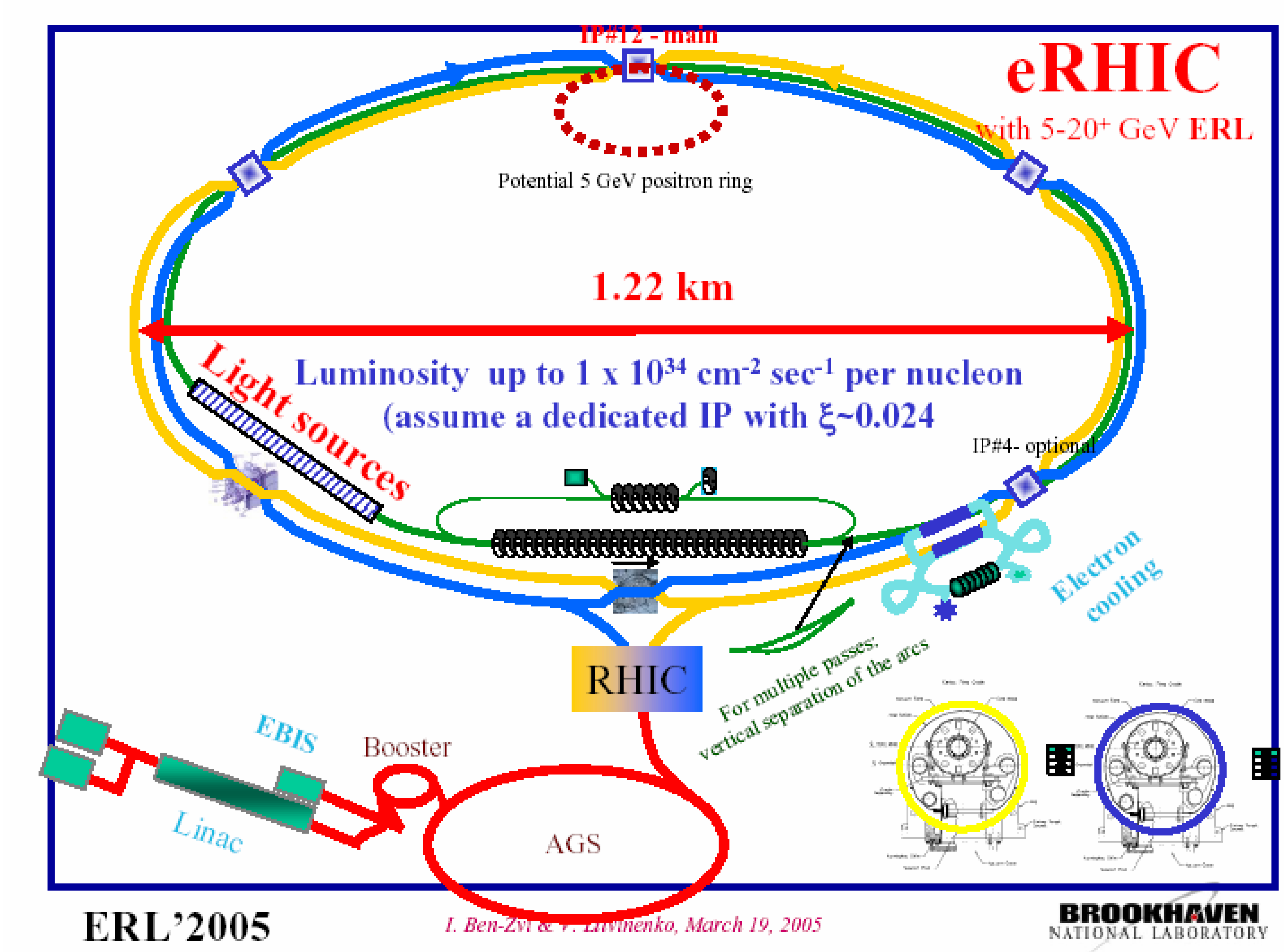
ELIC

- Multi-turn circulation ring for electrons
  - Lower injector current
  - Need injection / ejection
  - Partial benefit for electron beam-beam
- Very high bunch frequency
- Novel ion ring complex of "figure 8" rings
- Light ions only

eRHIC

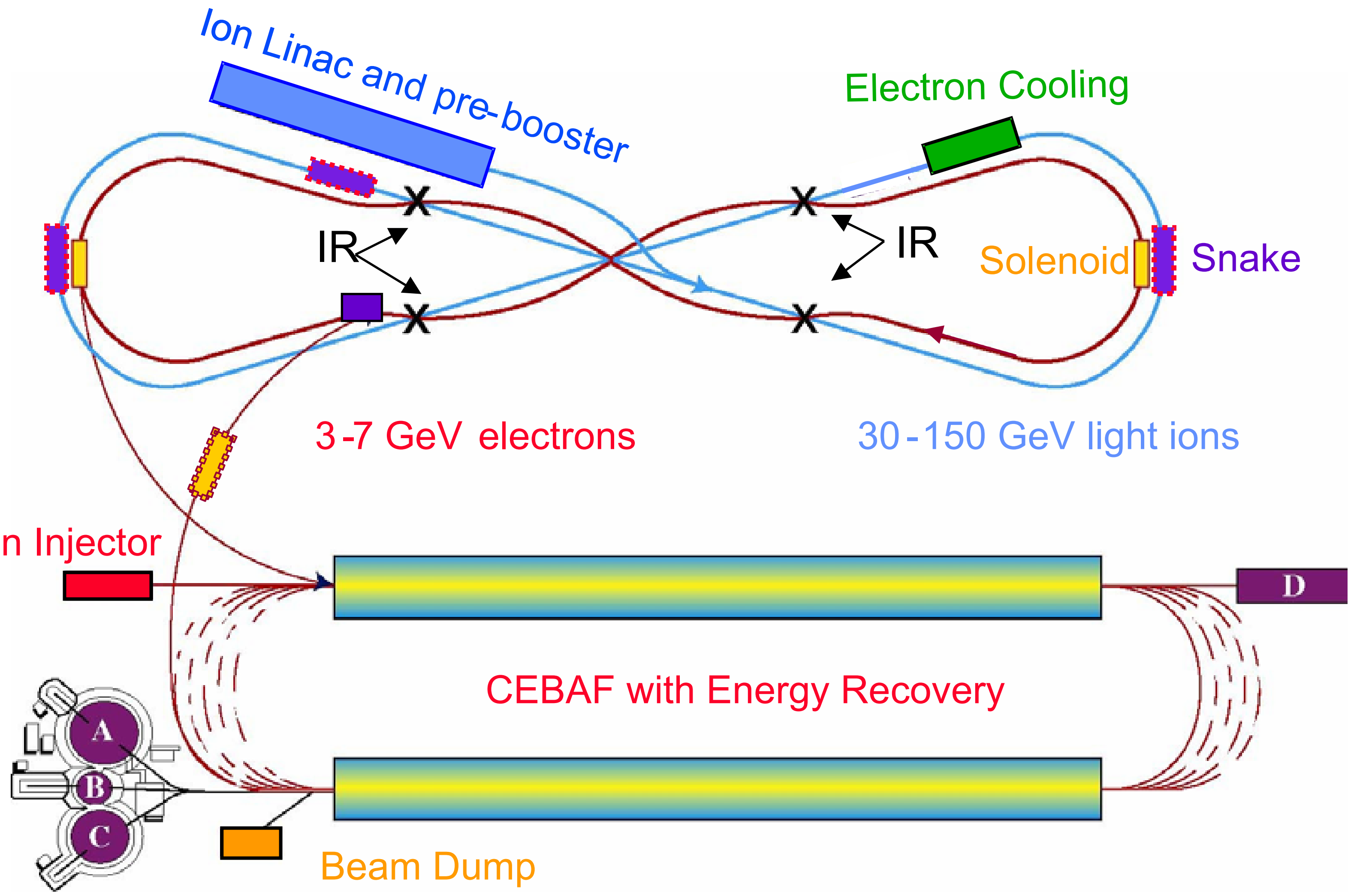
- Single pass ERL
  - High e source current required
  - Simplified structure
  - Maximum benefit from beam-beam in electron machine
- Bunch frequency of RHIC
- Well known ion ring
- All ions

eRHIC



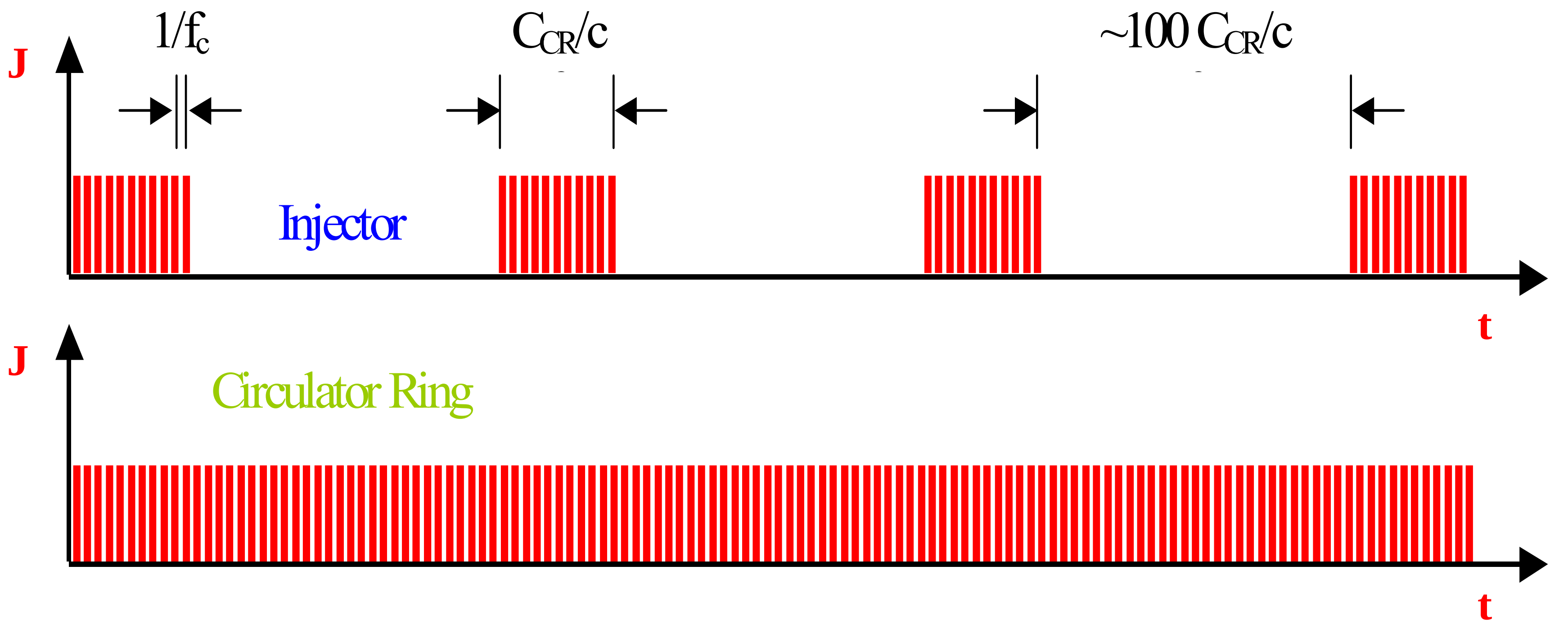
Thomas Jefferson National Accelerator Facility

ELIC Design



Ion Linac and pre-booster
Electron Cooling
IR
IR
Solenoid
Snake
3-7 GeV electrons
30-150 GeV light ions
Electron Injector
D
CEBAF with Energy Recovery
A
B
C
Beam Dump

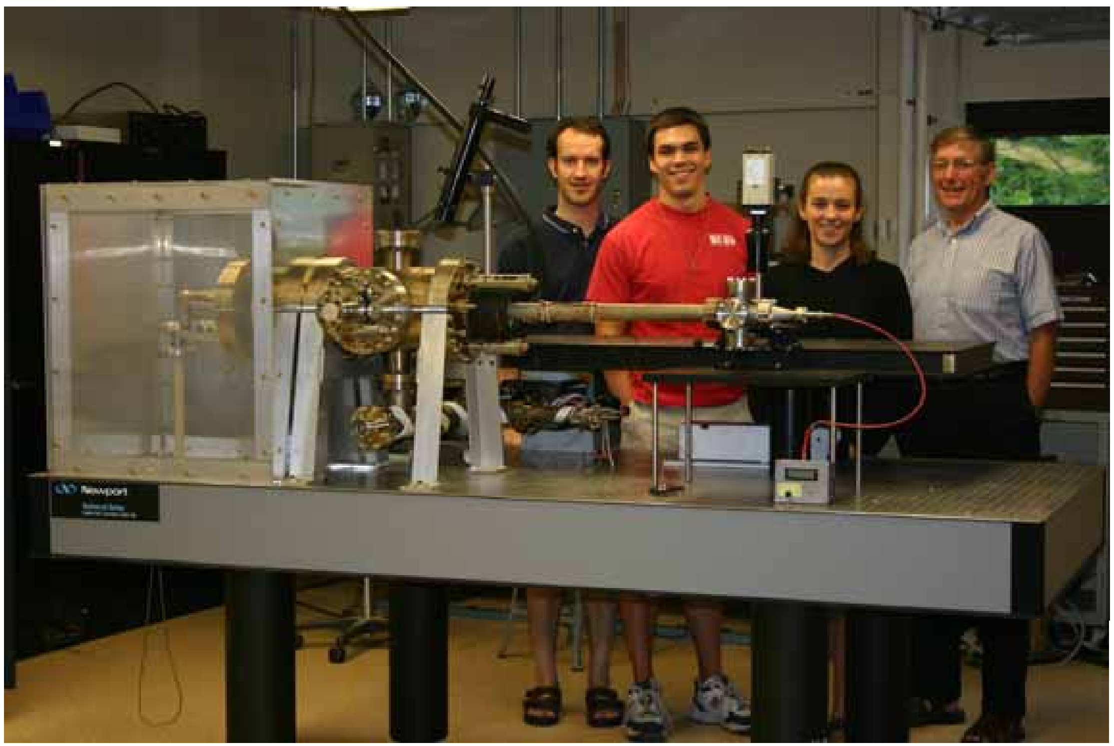
Circulator Ring



Summary

- ERLs provide a powerful and elegant paradigm for high average power free electron lasers.
- The pioneering ERL FELs have established the fundamental principles of ERLs.
- The multitude of ERL projects and proposals worldwide promises an exciting next decade as:
  - Three currently operating ERL-FELs will reach higher performance
  - At least five more ERLs are in serious planning stages and will likely be constructed
  - New advanced concepts are being explored; most of the applications need high average brightness beams

Needle cathodes for high-brightness beams



Chase Boulware

Jonathan Jarvis

Heather Andrews

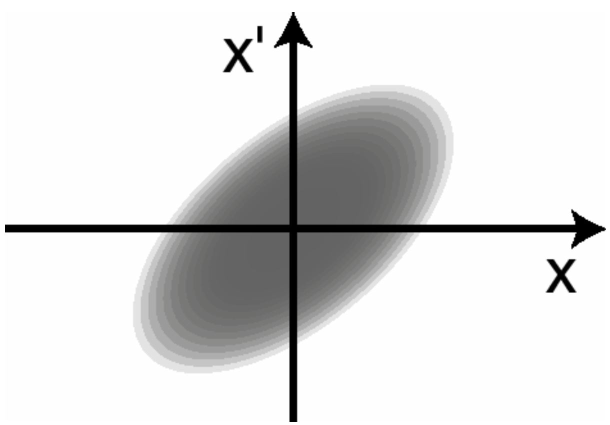
Charlie Brau

Outline of the talk

- What is brightness?
  - Definition
  - Sources
- Why is brightness important?
  - Light sources
  - FELs
- How do we get high brightness?
  - Photoemission
  - Field emission
  - Photofield emission

Definition of brightness

- Emittance is
  - π^{-1} x area in phase space (old definition)
  - Or, weighted average over beam (rms emittance)

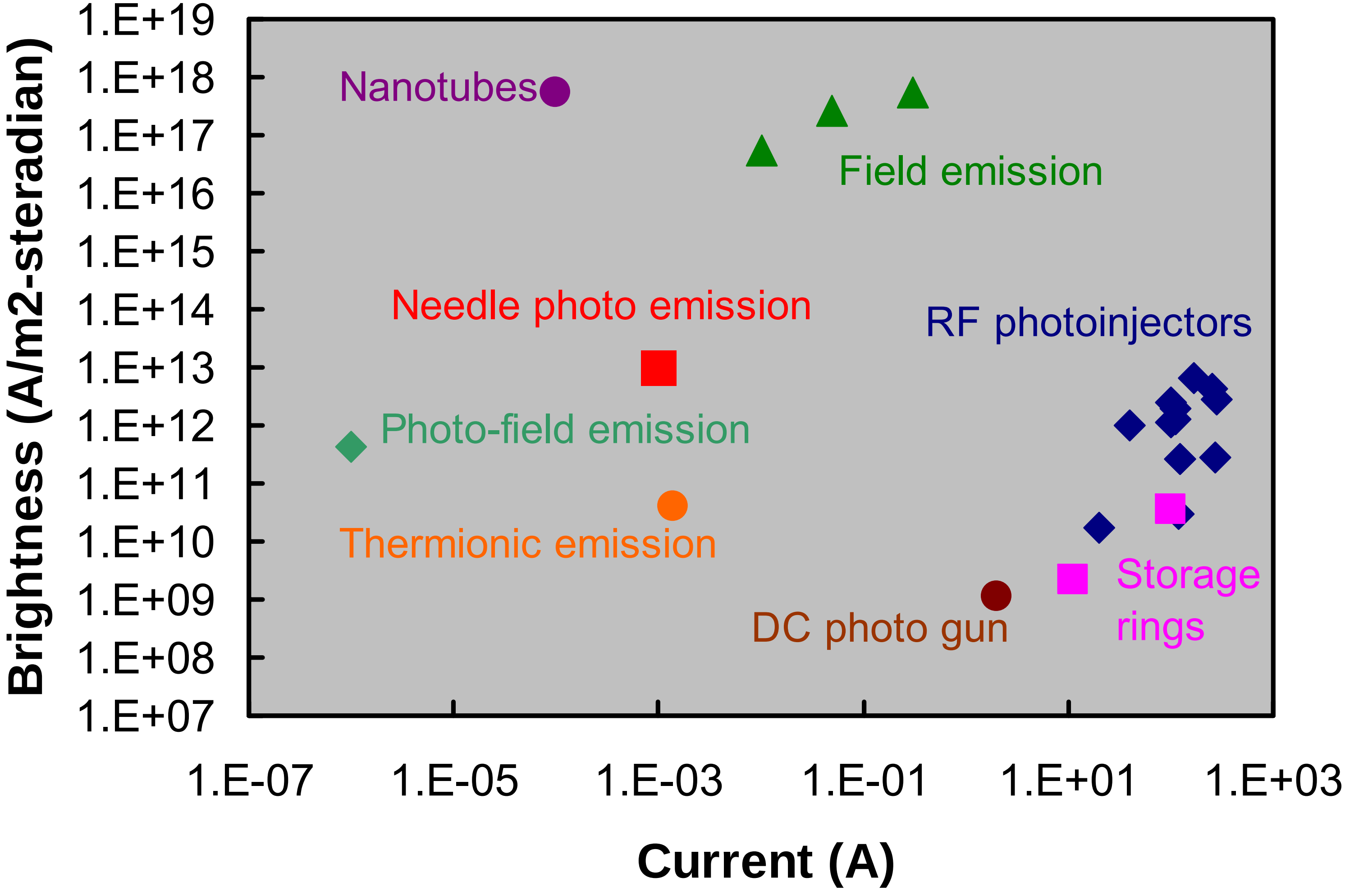


- Brightness is
  - Density in transverse phase space
  - Local property of beam

$$B_N \equiv \frac{1}{\gamma^2 \beta^2} \frac{d^2 I}{d\Omega dA}$$

$$\approx \frac{I}{4\pi^2 \varepsilon_N^2 (rms)}$$

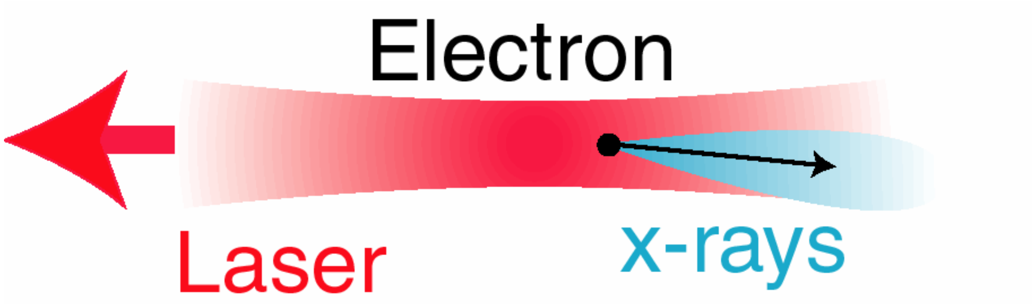
Electron sources span many orders of magnitude in brightness and current



Why brightness is more important than current

- Brightness is a useful figure of merit
  - Normalized brightness is roughly invariant with respect to beam current, electron energy
  - Can be used to compare different devices
- Often it's the most important parameter
  - When brightness is the most important parameter, lower current may be possible
  - Lower current reduces other problems, including radiation, halo, CSR, space charge

Spectral brilliance of Compton x-rays depends on brightness, not current



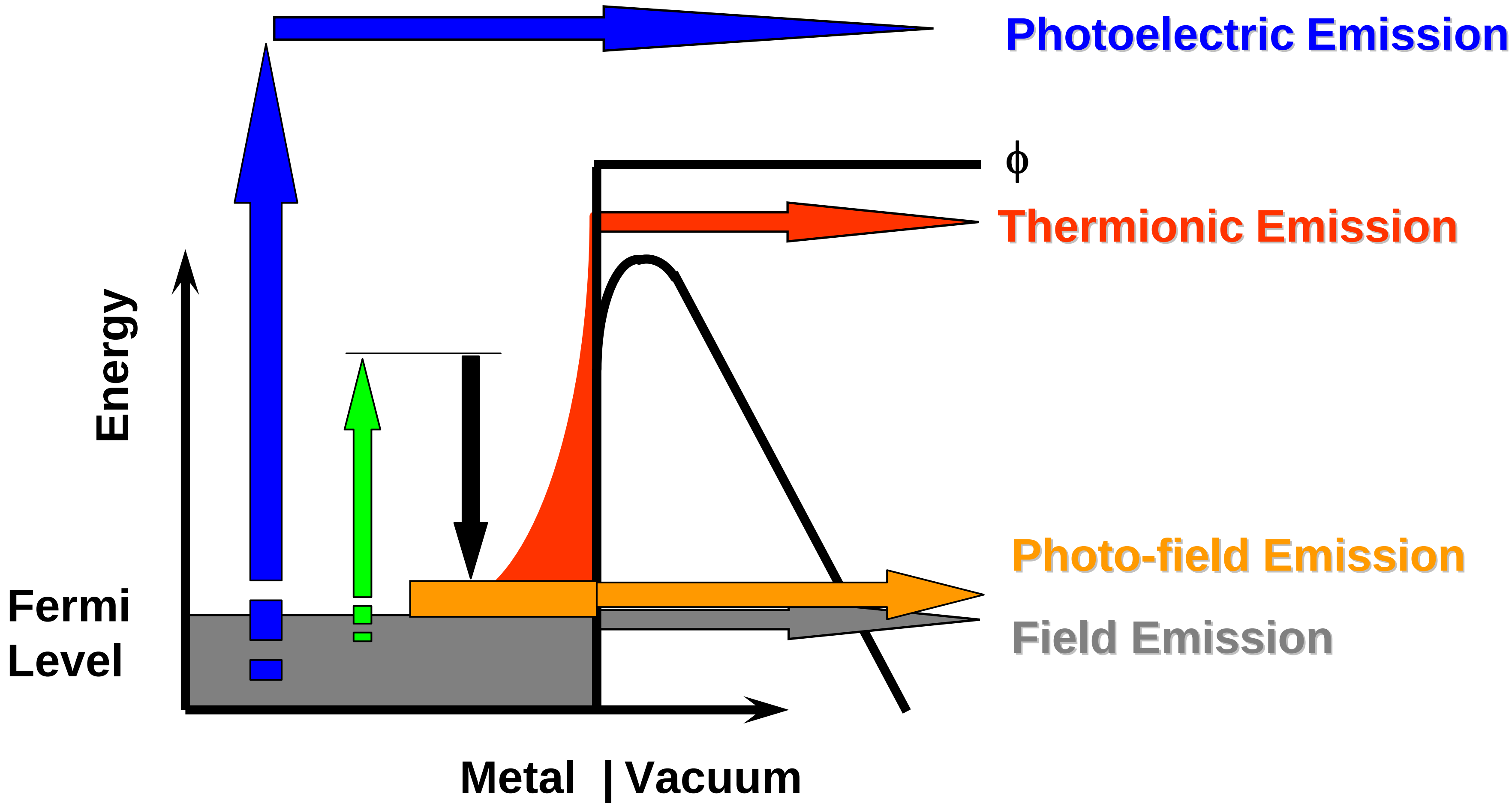
- For small emittance $\varepsilon_N << c\left(\tau_L + \tau_e\right) / \gamma$

  spectral brilliance is $$B_\nu = \frac{2\pi\sigma_T}{hqc^2}\frac{\gamma^2 U_L}{\tau_e + \tau_L} B_N$$

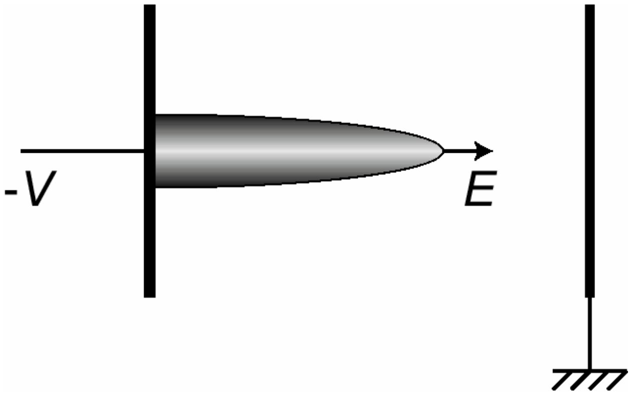
High electric fields at the surface enhance cathode performance

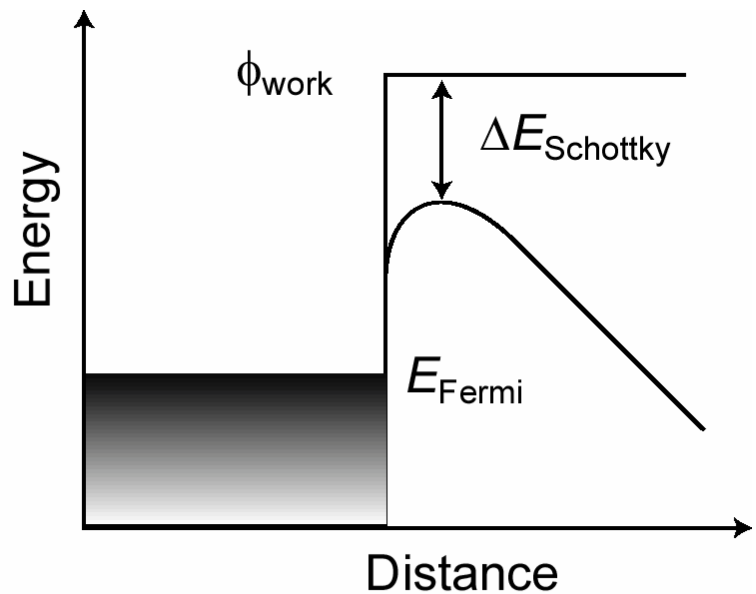
- High electric fields:
  - Conventional DC guns ~ 10^6 V/m
  - Conventional RF guns ~ 10^7 - 10^8 V/m
  - Needle cathodes ~ 10^9 – 10^{10} V/m
- Enhanced performance due to
  - Schottky effect on photoemission
  - Field emission
  - Photo-field emission
  - Reduced space-charge effects

Electron emission at the surface of a metal in vacuum occurs by four mechanisms



Schottky effect reduces surface barrier at high electric field





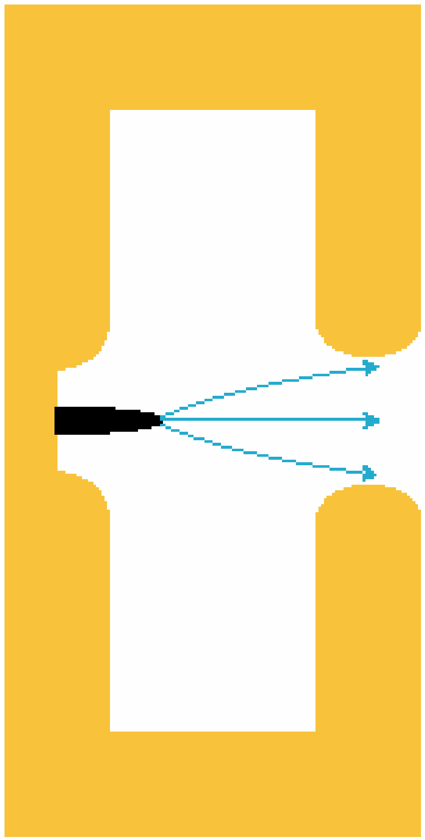
- Field is enhanced at tip of needle

$$E_{\text{tip}} = O\left(V / R_{\text{tip}}\right)$$
$$= O\left(10^9 - 10^{10}\ \text{V/m}\right)$$

- Schottky effect lowers barrier at surface

$$\Delta E = \sqrt{eE / 4\pi\varepsilon_0}$$
$$= O\left(1\ \text{eV}\right)\ @\ 10^9\ \text{V/m}$$

Needle cathodes produce high brightness in RF guns*



- Field at cathode enhanced by

$$\frac{E_{\text{tip}}}{E_0} = O\left(\frac{L_{\text{needle}}}{R_{\text{tip}}}\right)$$

- Example:
  - 1 mm diameter, 1 cm long
  - E_0 = 50 MV/m
  - E_{tip} = *O*(500 MV/m)
- Space-charge limit ~ 10^8 A/m^2
- Brightness ~ 10^{13} A/m^2-str
  - *before pulse compression!*

* Lewellen, Sardegna

Conclusions

- High brightness is often more important than high current
- Needle cathodes operate at high electric fields (10^9 – 10^{10} V/m)
  - Enhanced emission from cathode
  - Reduced space-charge effects
- Interesting physical effects are found at high electric fields
  - Field-enhanced photoemission (Schottky)
  - Photo-enhanced field emission (tunneling)

Status and Perspectives of Photo Injector Developments for High Brightness Beams

Frank Stephan

DESY, location Zeuthen

at the ICFA workshop on "The Physics and Applications of High Brightness Electron Beams" in Erice, Sicily, October 9-14, 2005

Motivation and Content

PITZ
Photo Injector Test Facility Zeuthen

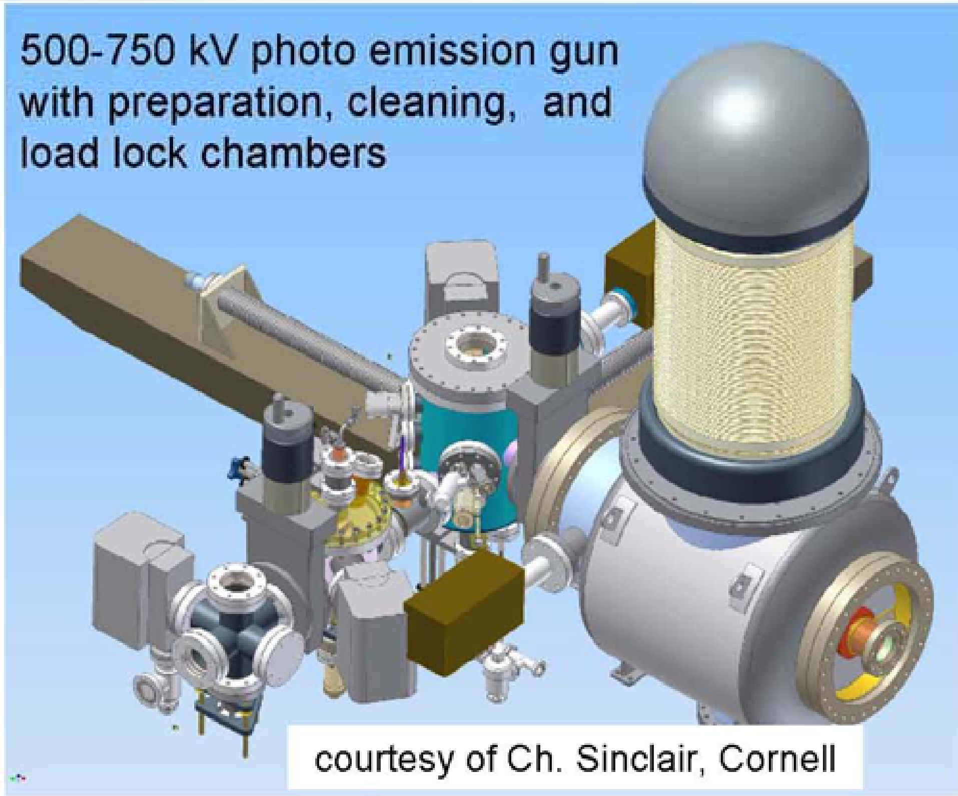
Realization depends on key parameters:

- **operation mode: pulsed or CW**
- **single bunch charge** } **average current**
- **time structure of the beam** } **average current**
- **norm. transverse emittance**
- **long. phase space allows further compression**

- **Introduction**
  - DC electron sources
  - NC RF guns
  - SC RF guns
  - generic injector layout
- **Different Photo Injectors for Different Projects:**
  - **high average current electron sources (<A> ≥ 1 mA)**
    - DC guns from Cornell data sim.
    - NC RF gun from Boeing data
    - SC RF gun developments at Rossendorf data sim.
    - DC, NC + SC RF gun developments from BNL, JLab, and LANL with AES data sim.
  - **medium average current electron sources (1 mA > <A> > 1 μA)**
    - NC RF gun at ELSA data
    - NC RF gun for VUV-FEL and European XFEL data sim.
    - NC and SC RF gun for BESSY sim.
  - **low average current electron sources (<A> ≤ 1 μA)**
    - NC RF gun from SHI+FESTA data
    - NC RF gun injector for SPARC sim.
    - NC RF gun developments for LCLS sim.
    - some other developments [e.g. LEG at PSI (field emission cathode)] sim.
- **Summary**

DC Photo Electron Guns

- Advantages
  - good vacuum
    → NEA cathodes (GaAs),
    → low thermal emittance
  - lots of operating experience



courtesy of Ch. Sinclair, Cornell

- Disadvantages
  - low accelerating gradient at cathode
    → long bunches → buncher cavity
  - low beam energy after the source → booster

NC RF Guns

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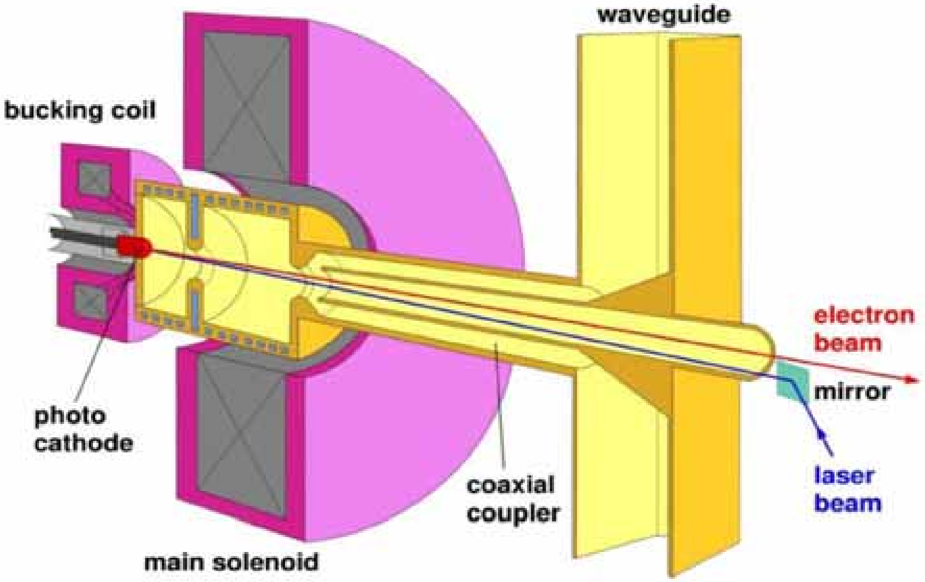
- Advantages
  - high accel. gradient at cathode + good space charge compensation → high bunch charge
  - medium beam energy
  - lots of operating experience, emittance record



- Disadvantages
  - medium vacuum conditions
  - water cooling limits average RF power → broad range of average currents (RF frequency)

SC RF Guns

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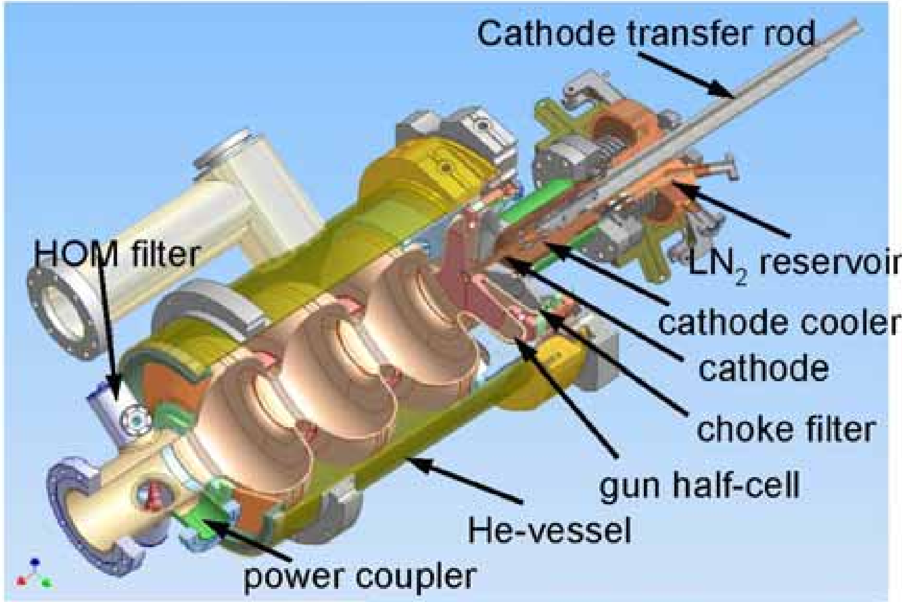
- Advantages
  - high RF duty cycle, CW → high av. beam power
  - good vacuum condition
  - medium beam energy



Courtesy of J. Teichert, FZR

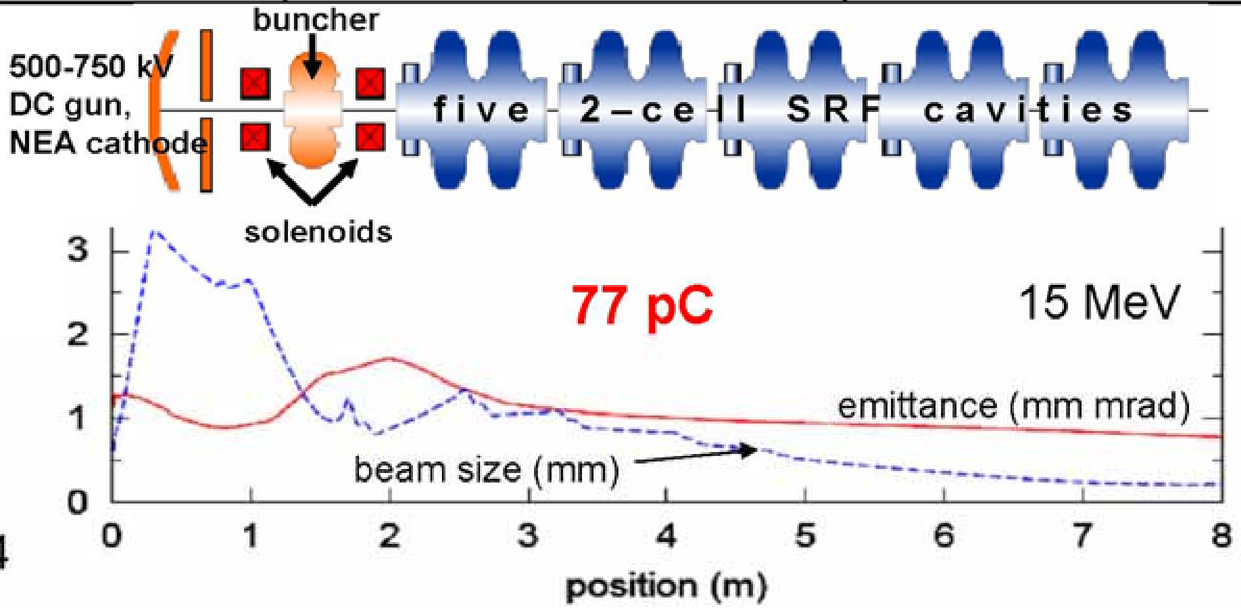
- Disadvantages
  - high accel. gradient at cathode, but limited space charge compensation → limited bunch charge
    BUT: new developments are on the way
  - limited operation experience

DC Guns @ JLab + Cornell

PITZ Photo Injector Test Facility Zeuthen

	JLab, exp. results	Cornell, goal parameters	
operation mode		low charge	high charge
pulsed / CW	CW	CW	CW
single bunch charge	122 pC	77 pC	1 nC
single bunch rep rate	75 MHz	1300 MHz	1 – 10 MHz
DC voltage / gap	350 kV / 10.57 cm	~ 600 kV / 5 cm	~ 800 kV / 5 cm
average current	9.1 mA	100 mA	1 mA
norm. trans. emittance (rms)	~ 8-10 mm mrad @ 10 MeV	old: < 1 mm mrad, new: 0.1 mm mrad @ 13 MeV	new: ~ 1 mm mrad @ 13 MeV

old design for ERL-based X-ray source at Cornell:



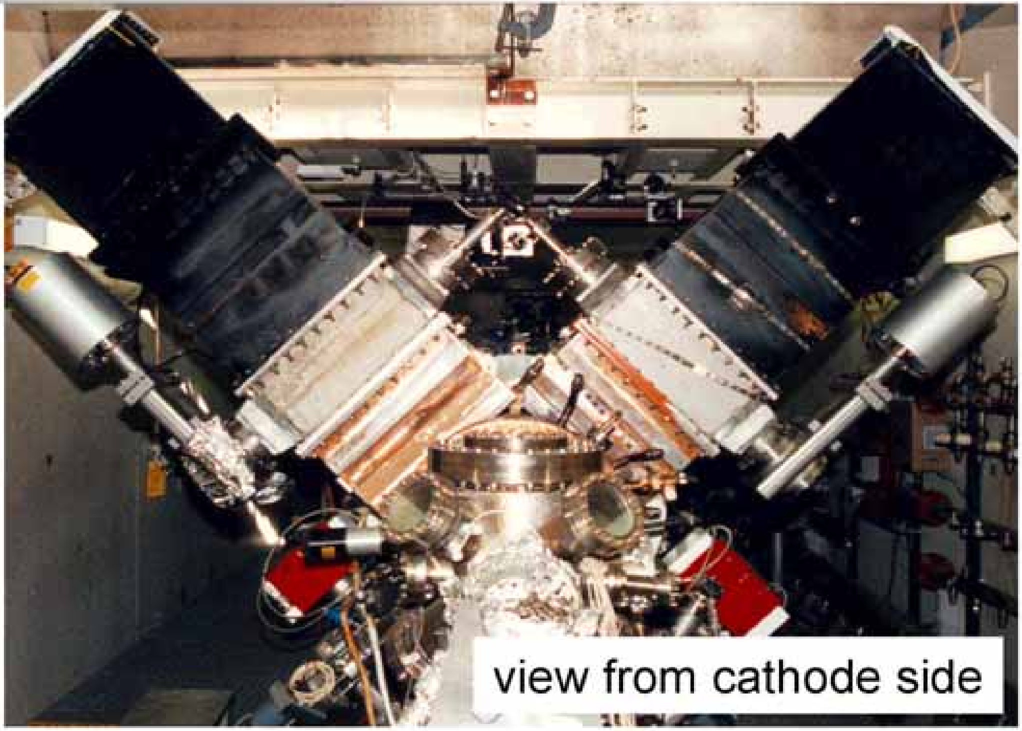
see I. Bazarov and C. Sinclair, PAC2003, pp. 2062 - 2064

NC RF Gun @ Boeing

PITZ
Photo Injector Test Facility Zeuthen

parameters measured in 1992:

pulsed / CW	pulsed
single bunch charge	1 – 7 nC
single bunch rep rate	27 MHz
length of bunch train	8.3 ms
bunch train rep rate	30 Hz
average current	6.7 – 47 mA
norm. trans. emittance (rms)	5 – 10 mm mrad @ 5 MeV
rf frequency	433 MHz



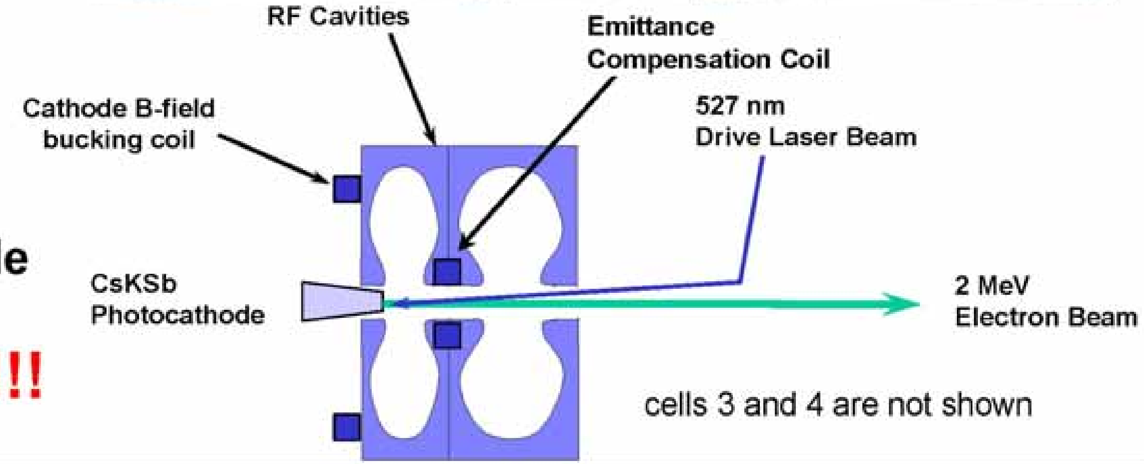
duty cycle: 25 %

RF power: **600 kW**

re-entrant design

→ 25 MV/m peak field @ cathode

record average current !!!

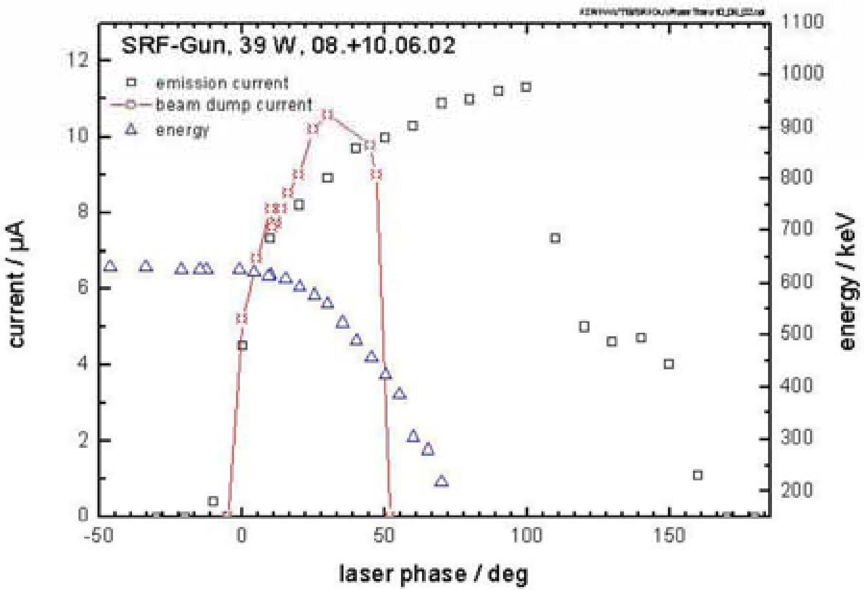


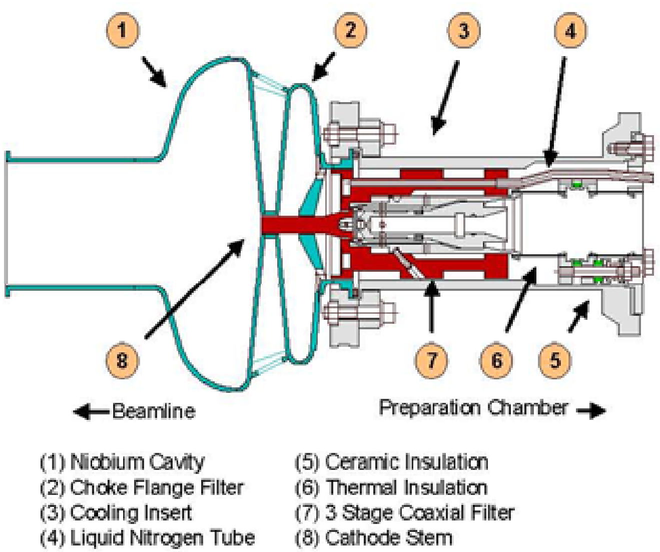
SC Guns @ FZ Rossendorf

PITZ
Photo Injector Test Facility Zeuthen

gun type	½ cell gun results obtained
operation mode	
pulsed / CW	CW
single bunch charge	1-20 pC
single bunch rep rate	26 MHz
length of bunch train	-
bunch train rep rate	-
average current	≤ 130 µA
norm. trans. emittance (rms)	2.5 mm mrad @ 4 pC, 900 keV
rf frequency	1.3 GHz

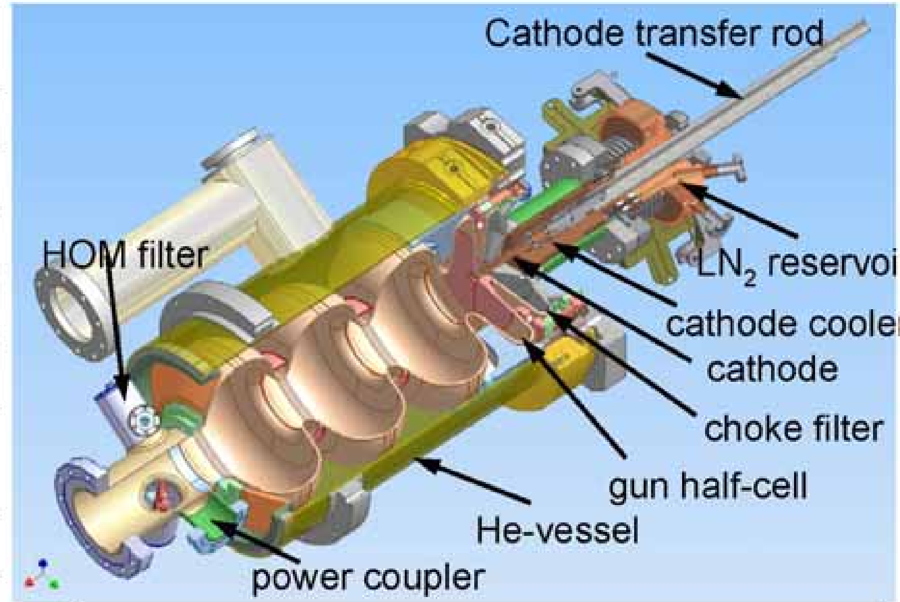
- NC Cs_2Te cathode in SC gun → high QE → relax requirements on laser system
- no Q degradation observed over 7 weeks (5h/d)



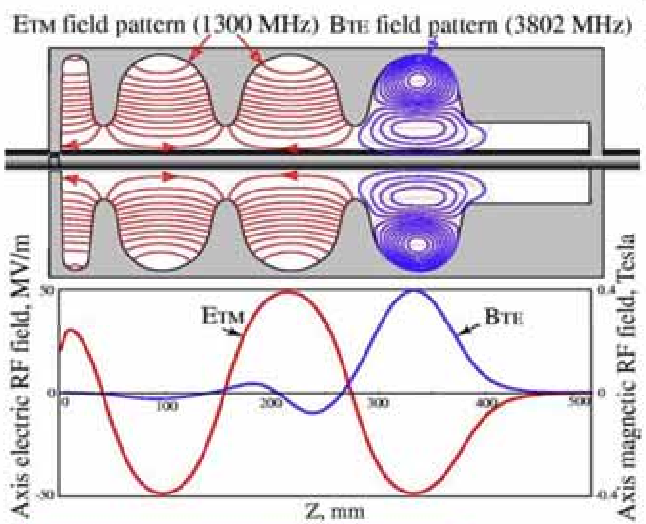


SC Guns @ FZ Rossendorf

gun type	3.4 cell gun, Goals	
operation mode	ELBE	high charge
pulsed / CW	CW	CW
single bunch charge	77 pC	1 nC
single bunch rep rate	13 MHz	1 MHz
average current	1 mA	1 mA
norm. trans. emittance (rms)	1.5 mm mrad @ 9.5 MeV	2.5 mm mrad @ 9.5 MeV
rf frequency	1.3 GHz	1.3 GHz



With magnetic mode:

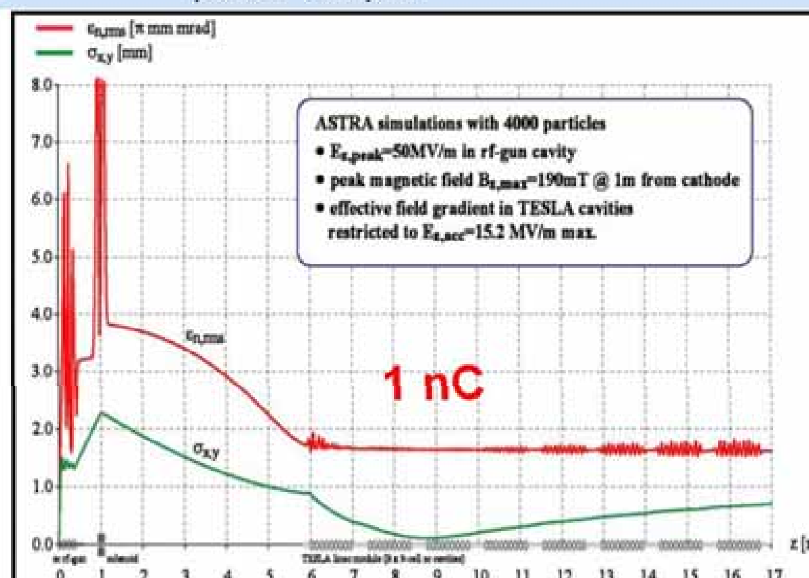


⇒ ε_n (1nC, 8.8MeV) = 0.8-1.0 mm mrad dep. on B_{TE} phase

(no therm. emittance)

Status:

- two 3.4 cell guns tuned
- first beam autumn 2006



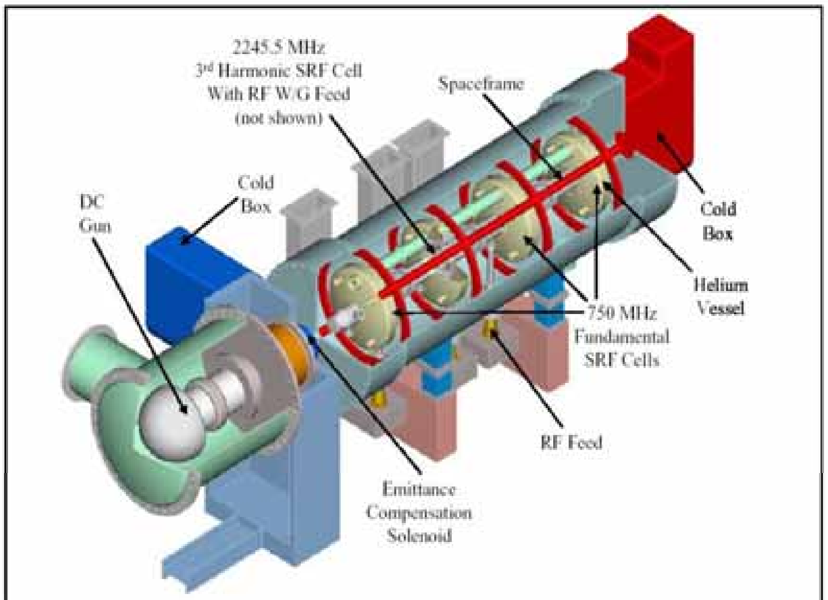
HELMHOLTZ GEMEINSCHAFT

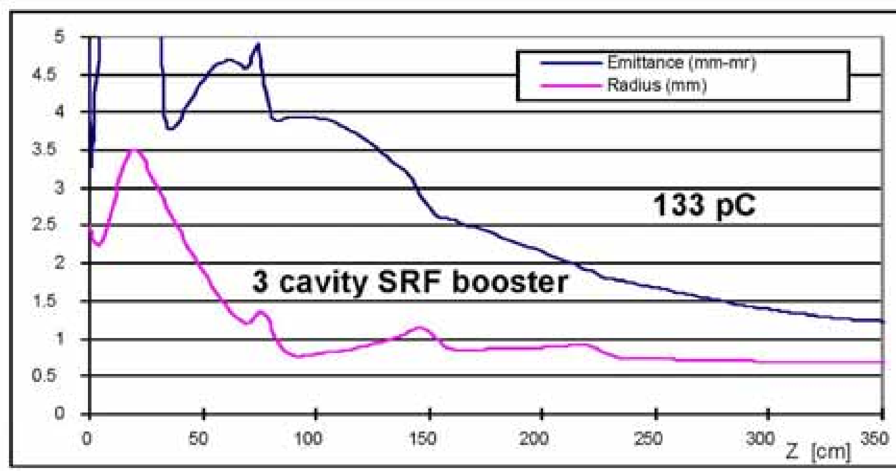
DESY

Source Developments with AES

PITZ
Photo Injector Test Facility Zeuthen

gun type	½, SC, all Ni	½, SC, NC cath.	DC + SRF boost.	2½, NC RF, CW
collabor. partners	BNL, data	BNL, design	JLab, design	LANL, design
pulsed / CW	the QE was measured to be $2 \cdot 10^{-6}$ @266nm $1 \cdot 10^{-5}$ @248nm	CW	CW	CW
single bunch charge / nC		1.42 / 10	0.133	1.0
single bunch rep rate / MHz		351.87 / 10	748.5	100
average current / mA		500 / 100	100	100
norm. trans. emittance (rms, geom. av.) / mm mrad		2.4 @ 2 MeV / 11.1 @ 3.2 MeV	1.2 @ 7.7 MeV	4 @ 2 MeV
rf frequency / MHz	1300	703.75	booster: 748.5	700





Assembly of cryomodule in progress

Source Developments with AES

PITZ Photo Injector Test Facility Zeuthen

gun type	½, SC, all Ni	½, SC, NC cath.	DC + SRF boost.	2½, NC RF, CW
collabor. partners	BNL, data	BNL, design	JLab, design	LANL, design
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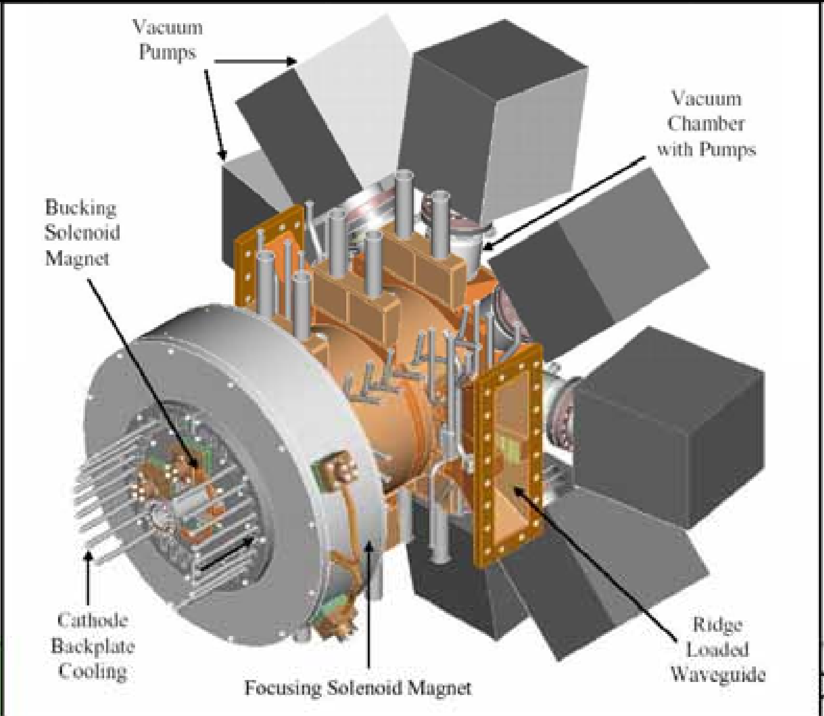
single bunch rep rate / MHz		351.87 / 10	748.5	100
average current / mA		500 / 100	100	100
norm. trans. emittance (rms, geom. av.) / mm mrad		2.4 @ 2 MeV / 11.1 @ 3.2 MeV	1.2 @ 7.7 MeV	4 @ 2 MeV
rf frequency / MHz	1300	703.75	booster: 748.5	700



average power: ≤ 720 kW

gun in fabrication,

high power test in 2006

EPAC2004, ERL2005, Courtesy of AES+BNL+LANL

Summary

PITZ
Photo Injector Test Facility Zeuthen

- Lots of different developments with photoinjectors fill up a large parameter space on beam quality, time structure of the beam and average currrent.
- Simulations predict very good performance of all three basic photo injector types (plus hybrids).
- Experimental progress is visible: on subsystems (guns, laser, diagnostics) and on measured beam quality.
- P. O'Shea, ICFA workshop @ UCLA in 1999:

  ~ "**Get 1 µm @ 1 nC !!!**"

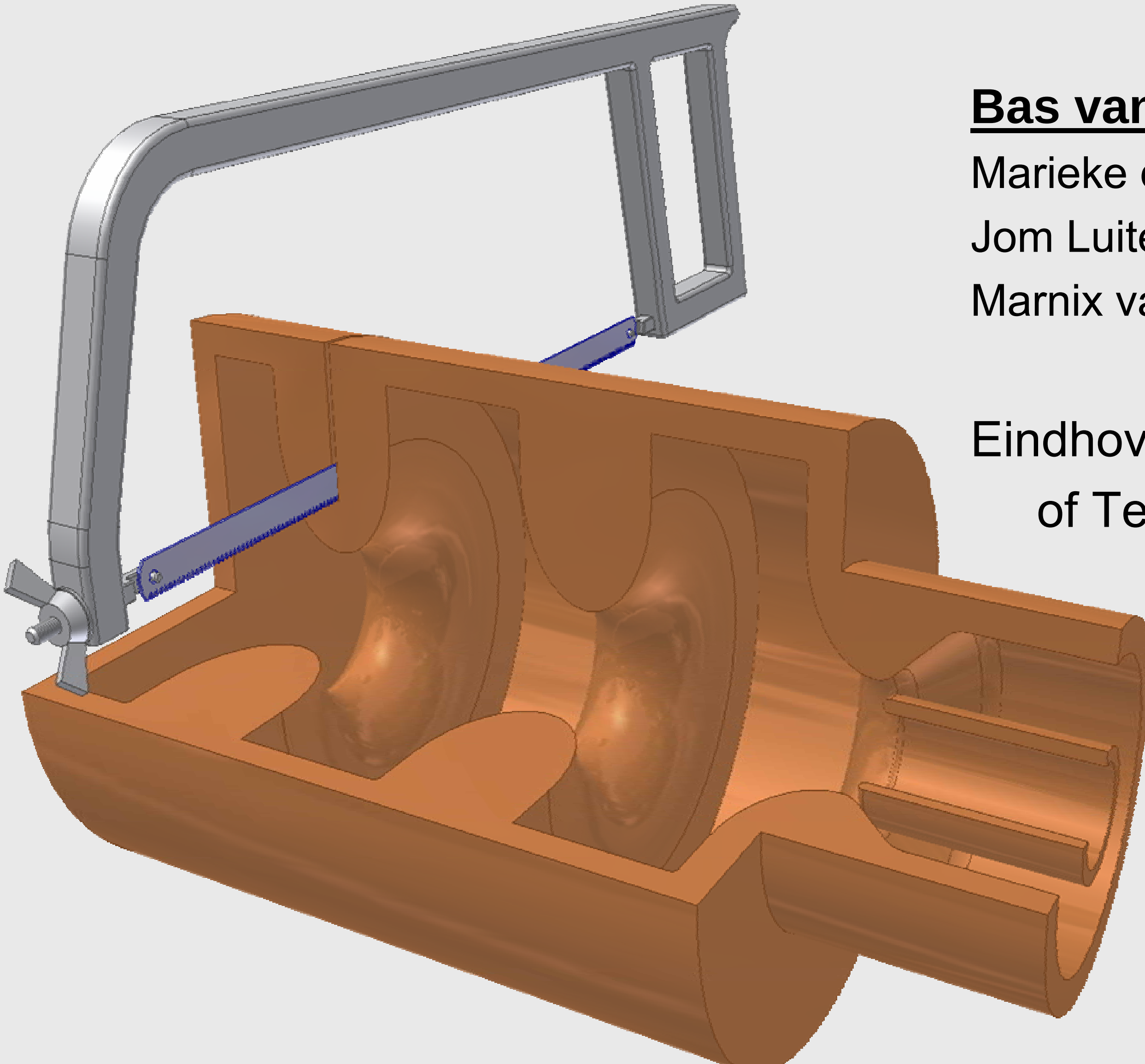
  → still to be done experimentally !!!

  → ways to reach this are defined.
- More research on emission process (→ε_{th}) gets important.

A split rf-photoinjector

Erice

10 October 2005



<u>Bas van der Geer</u>

Marieke de Loos

Jom Luiten

Marnix van der Wiel

Eindhoven University of Technology

FOM

CPS

CENTRUM

VOOR PLASMAFYSICA EN

Source brightness

$$B_{\perp} \leq \frac{mc^2}{\pi k} \frac{Q}{\underline{T}\,\underline{A}\,\underline{\tau}}$$

Options (at fixed Q):

- Lower Temperature ***T*** → Ultra Cold Plasma cathode
  Jom Luiten

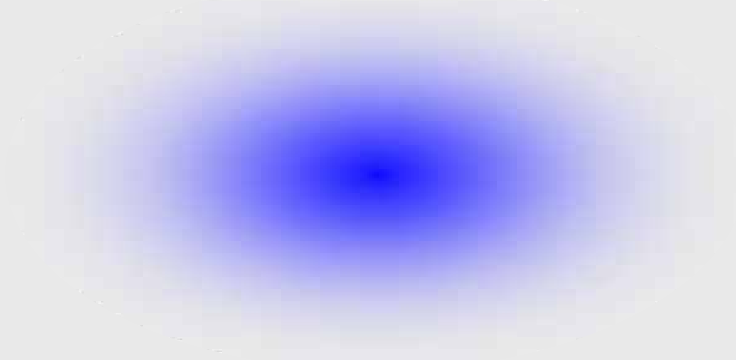
- Reduce Surface area ***A*** → Carbon Nanotubes
  Needle cathodes
  …

- Reduce Pulse duration ***t*** → Pancake regime

Brightness degradation

The problem is not the high space charge **density** ...

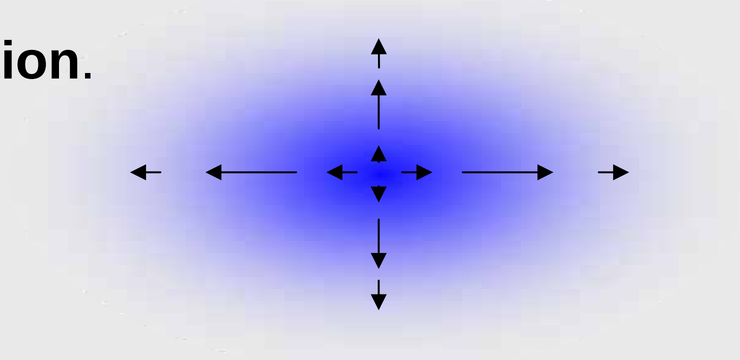
Gaussian bunch

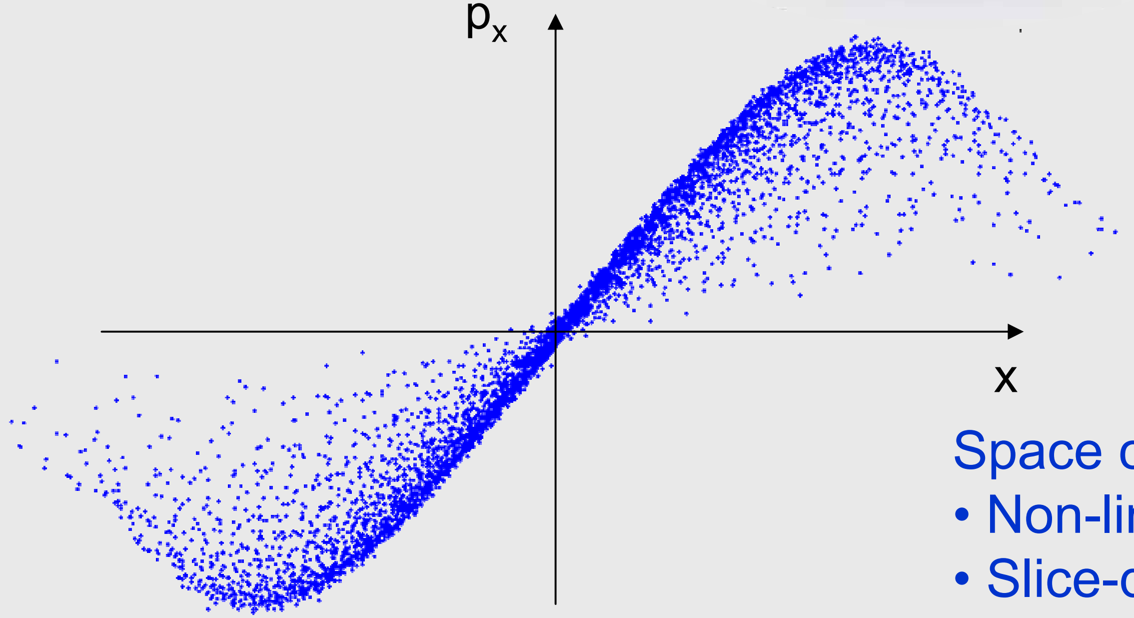


Brightness degradation

... the real problem is the
space charge density **distribution**.

Gaussian bunch





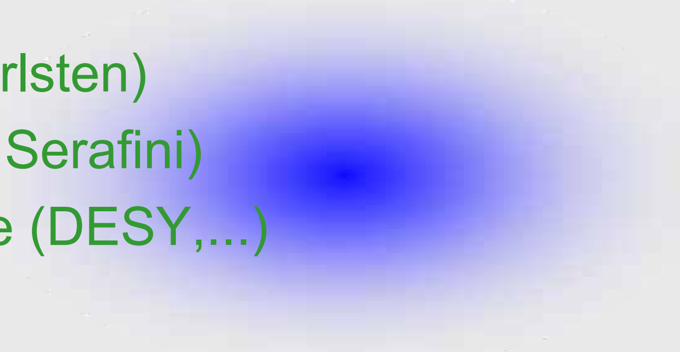
Space charge forces:
- Non-linear
- Slice-dependent

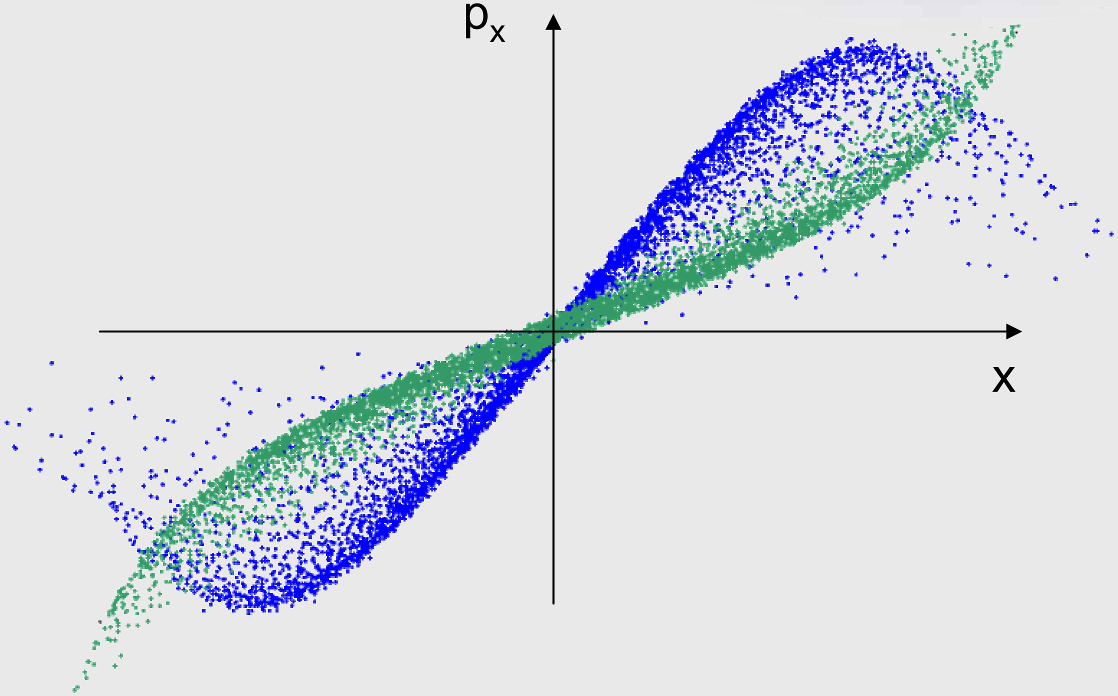
1989 - 2003

Fighting the symptoms:

- Emittance compensation (B. Carlsten)
- Optimized transverse profile (L. Serafini)
- Uniform temporal & radial profile (DESY,...)
- ...

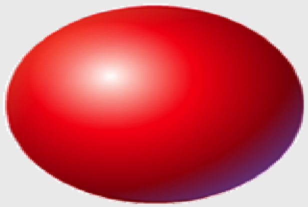
Gaussian bunch



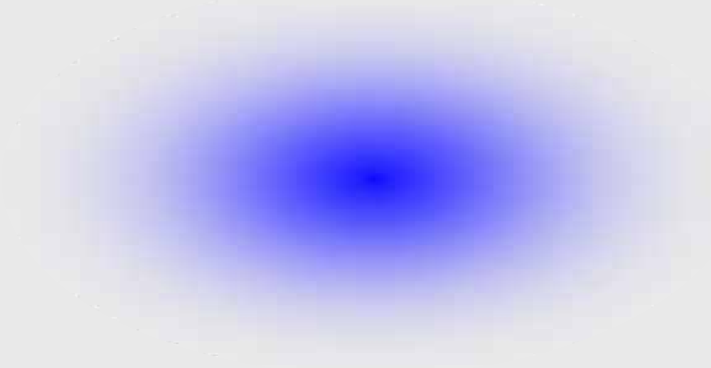


2004: Fundamental solution

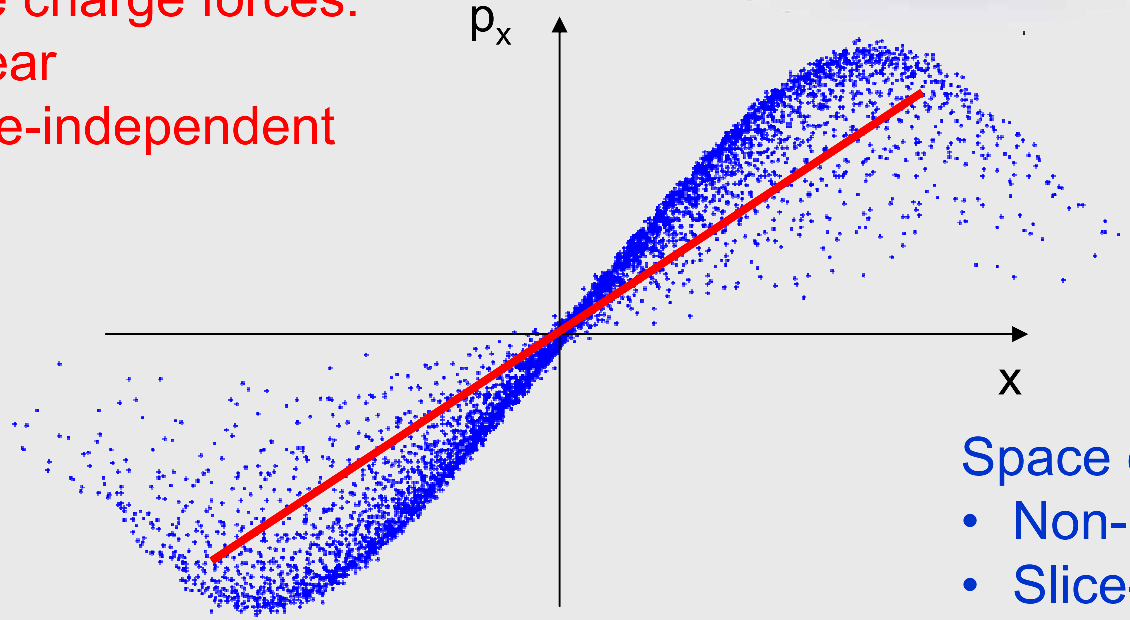
Waterbag bunch



Gaussian bunch



Space charge forces:
- Linear
- Slice-independent



Space charge forces:
- Non-linear
- Slice-dependent

Thermal-emittance-limited beam!

History of uniformly charged ellipsoids

- Uniformly charged ellipsoids:
  - Have linear fields in all three coordinates

    O. D. Kellogg, *Foundations of Potential Theory* (Springer-Verlag, **1929**).
  - Only change aspect ratio under gravity self-fields (astrophysics)

    C.C. Lin et al., Astrophys. J. 142, 1431 (**1965**).
  - Extensively used for modeling purposes in accelerator physics

    …

- Source of inspiration: Transverse laser shaping, short bunches

  L. Serafini, AIP Conf. Proc. 413, 321 (1997)

- Fundamental solution and practical recipe

  O.J. Luiten, S.B. van der Geer et al, PRL 094802, (**2004**).

  O.J. Luiten, S.B. van der Geer et al, EPAC (**2004**).

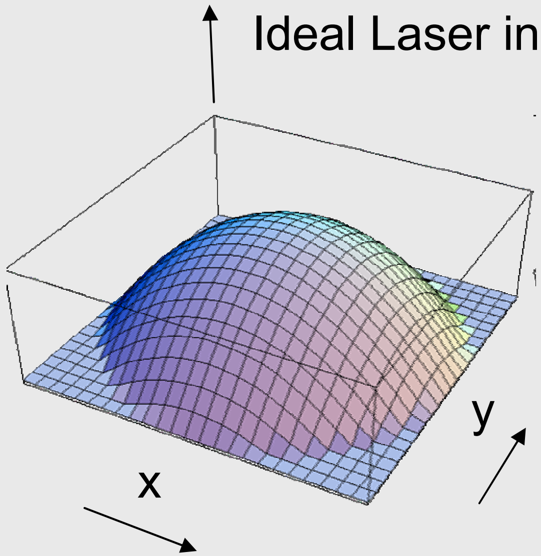
Waterbag bunch recipe

Femtosecond photoexcitation of pancake bunch

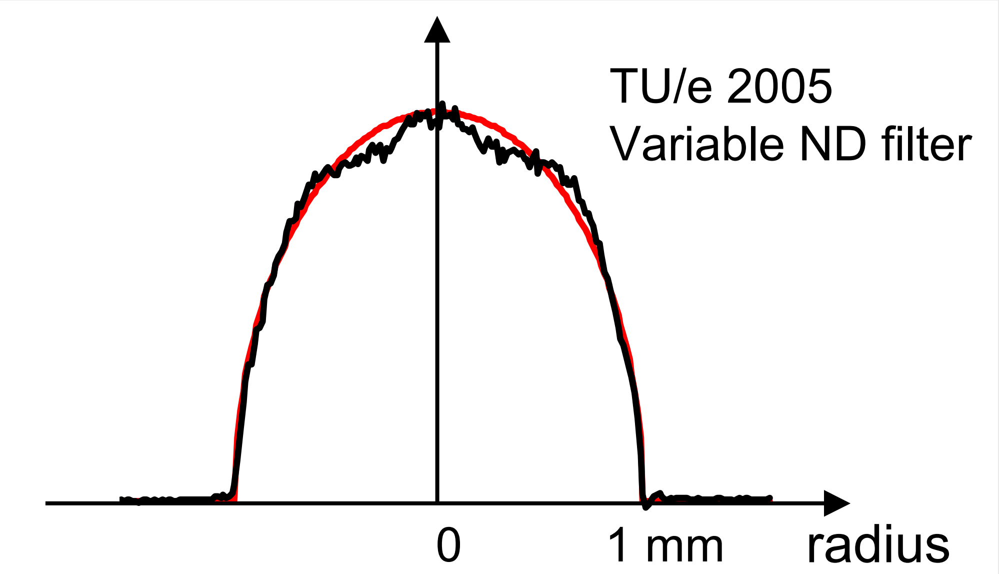
- ‘half-sphere’ transverse laser intensity profile
- Temporal laser profile is irrelevant

<u>**Automatic evolution into 3-D, uniform ellipsoid**</u>

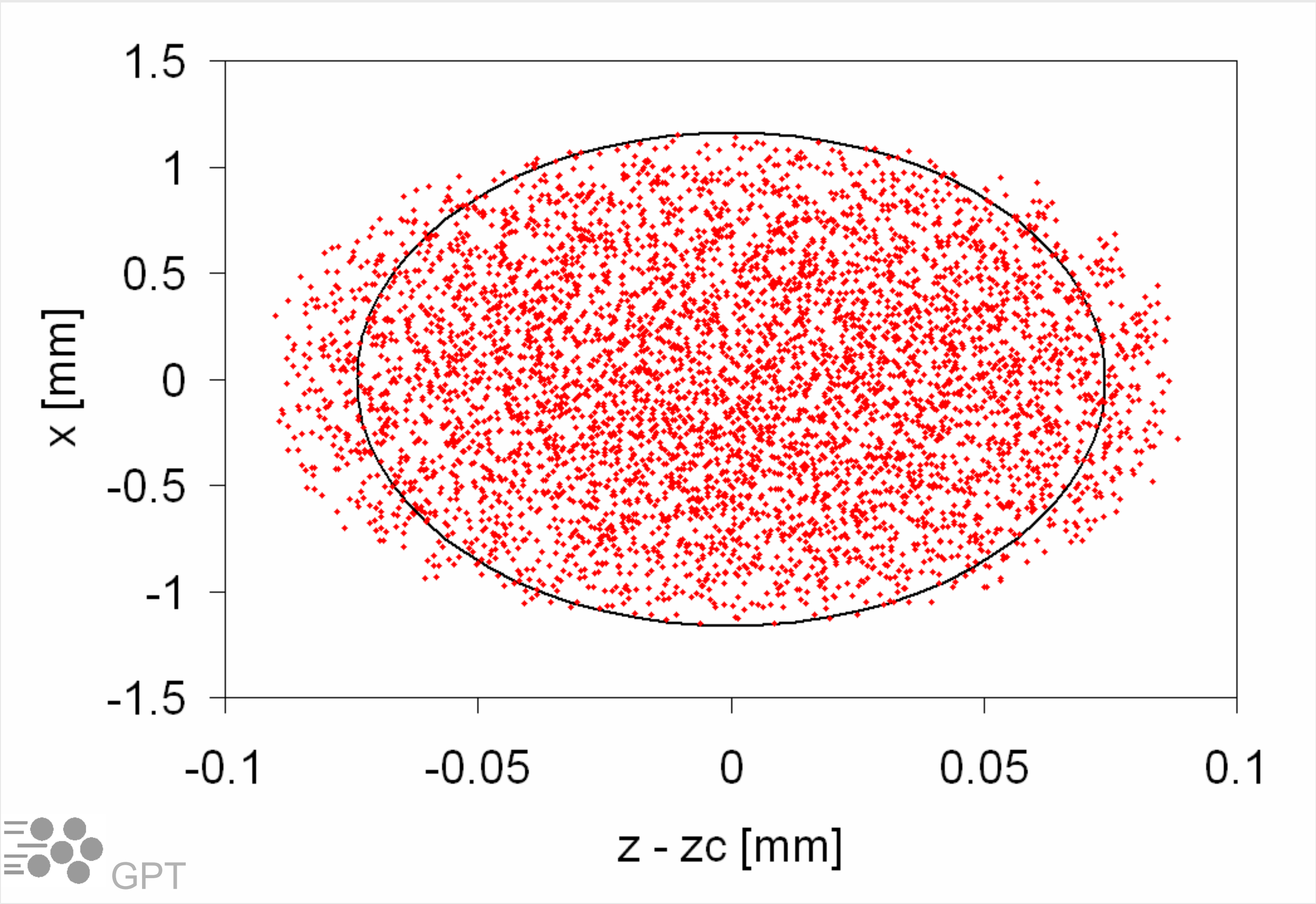
Ideal Laser intensity



Measured Laser intensity



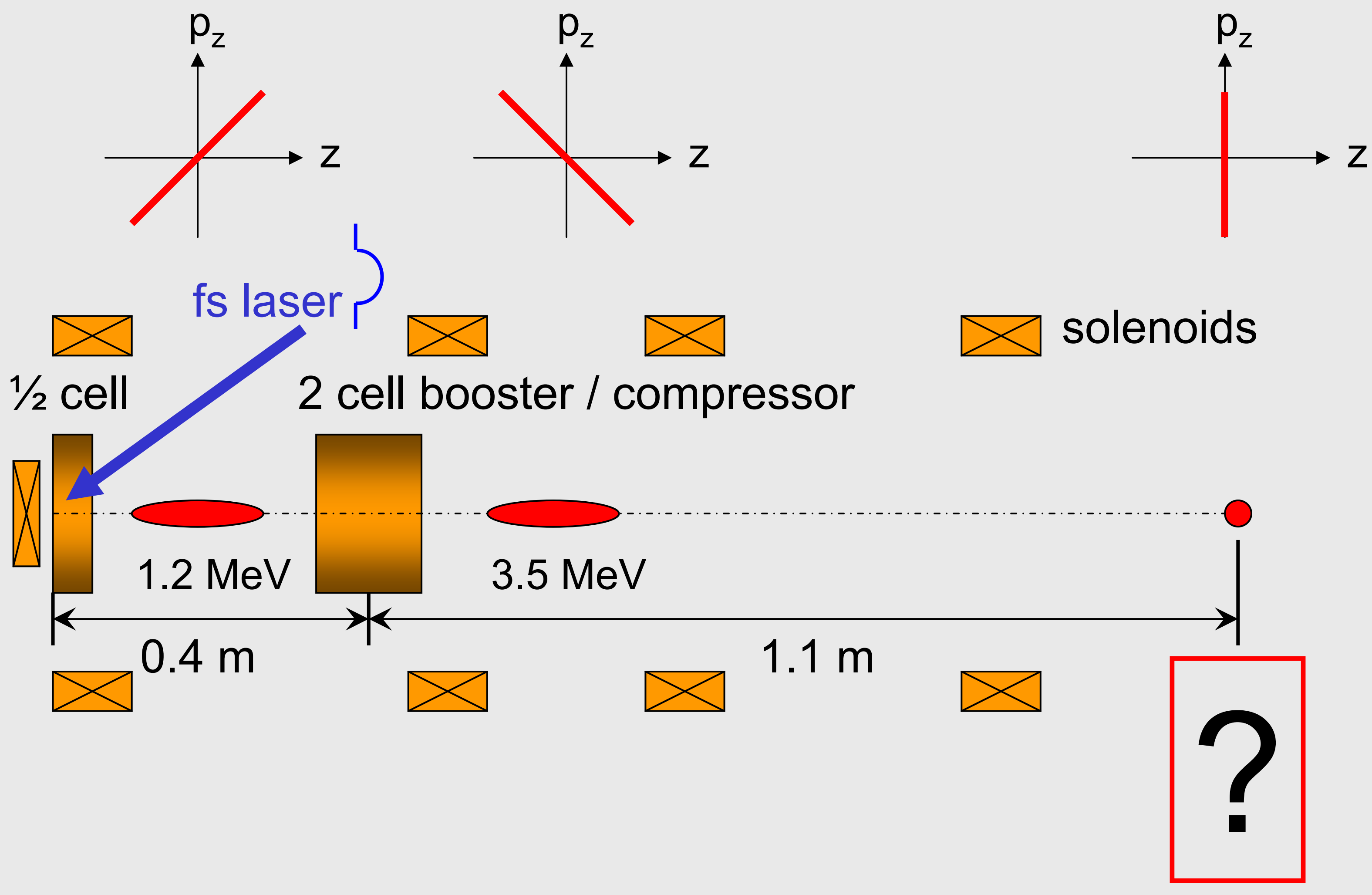
First confirmation from GPT simulations



How to Realize Uniform Three-Dimensional Ellipsoidal Electron Bunches
O.J. Luiten, S.B. van der Geer et al, PRL 094802, (**2004**).

Split rf-photoinjector

Waterbag bunches, 100 MV/m, 3 GHz, 10 MW



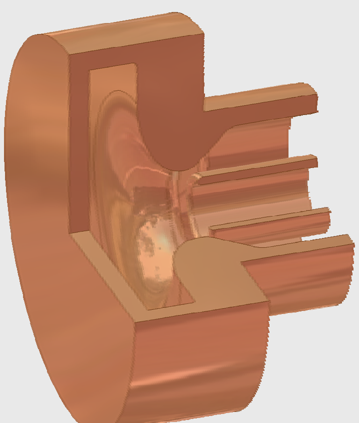
Modeling issues

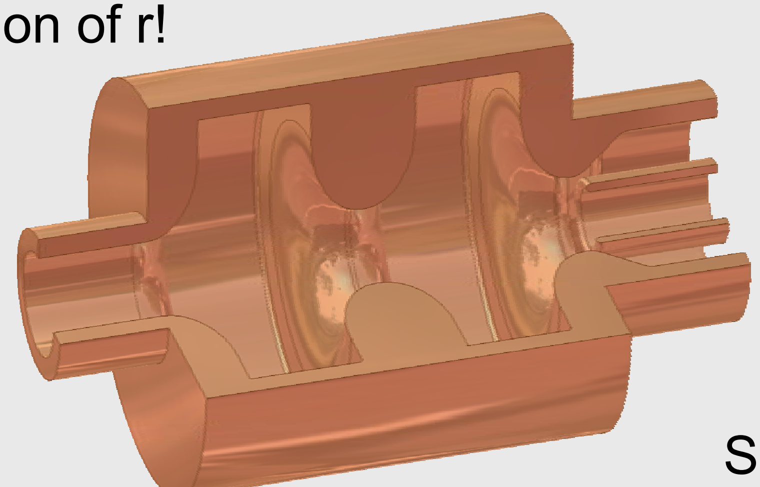
Tracking with GPT:

- High-resolution field-maps, no truncated power series
- No envelope / paraxial assumptions
- 3D space-charge with image charges on cathode

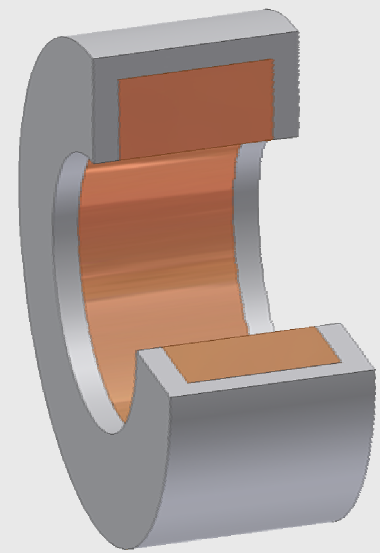
Cavities:

- $E_z(z,r)$ is a function of r!
- SF field-maps





Axial incoupling: DESY
Elliptical irises: Strathclyde



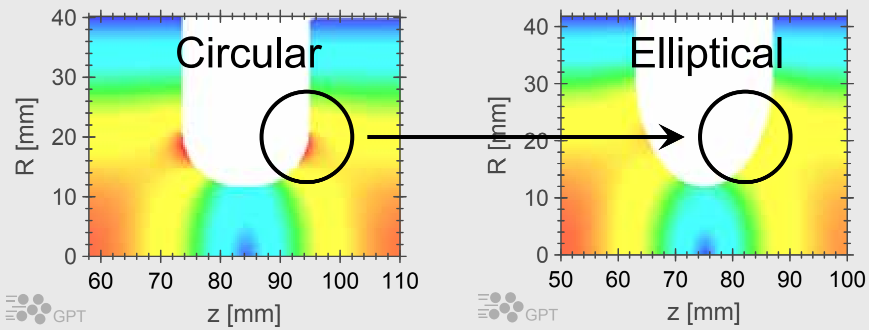
Solenoids:

- Analytical expressions
- Final design: SF-Fields

RF-cavities

3 GHz, 100 MV/m

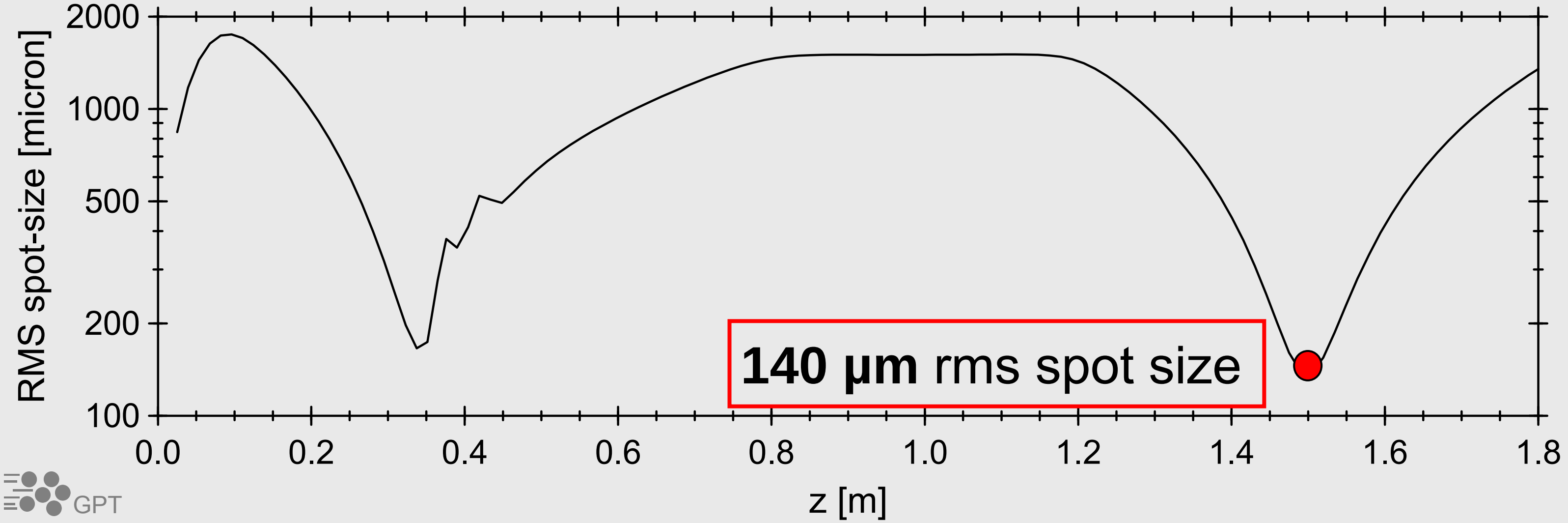
- Axial incoupling (DESY)
- Elliptical irises (strathclyde)

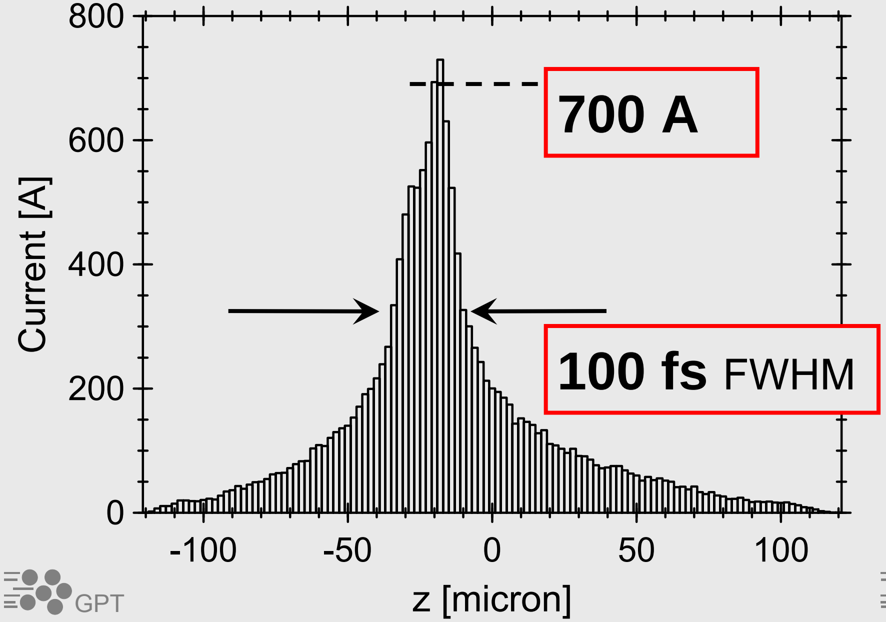


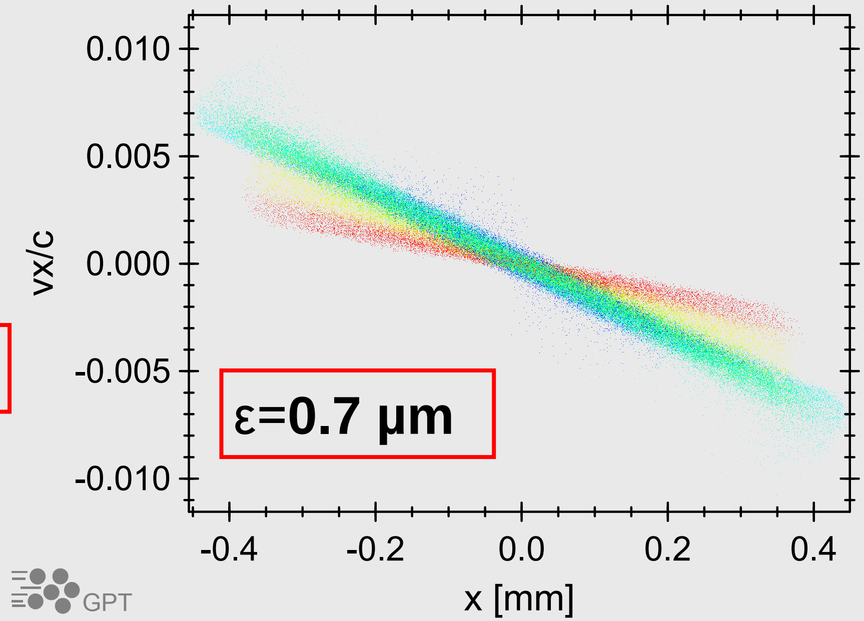
- µm precise design (Marieke de Loos)

2.625	Fred Kiewiet (Eindhoven)
2.5	Terry Garvey (LAL) / Dino Jaroszynski (Strathclyde)
2.6	Seth Brussaard (Eindhoven)
1.5	Jom Luiten (Eindhoven)

Optimize for 6D brightness

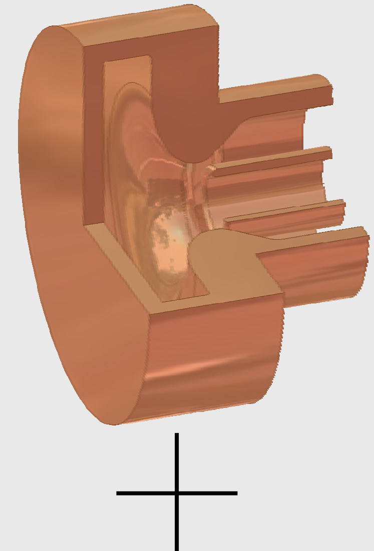




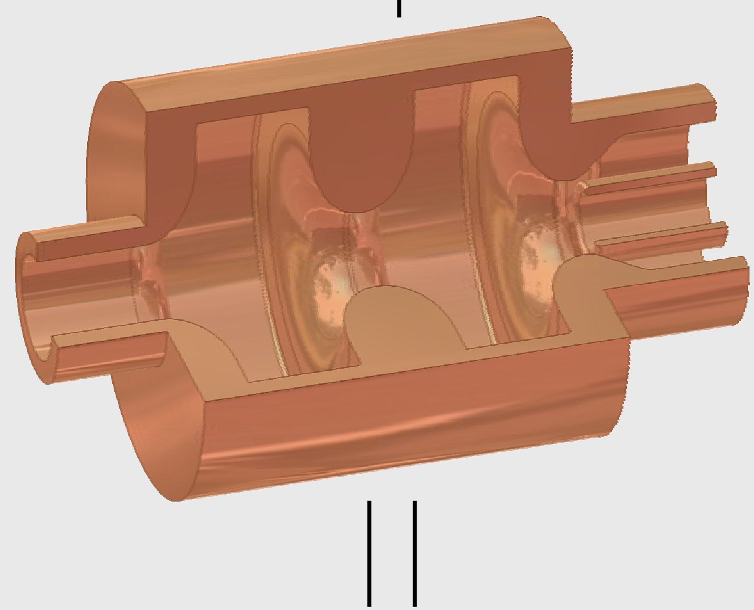


Conclusion: Reached our goal

- Develop compact high-brightness rf-photogun
  - Using waterbag concept
  - Established 100 MV/m S-band technology



Parameters	Reached
– Peak current:	700 A
– Emittance:	0.7 µm
	1.4 kA/µm^2
– Energy:	3.5 MeV
– Pulse length:	120 fs rms
– Spot size:	140 µm rms
– Energy spread:	40 keV rms



Observation of Ultra-Wide Bandwidth SASE FEL

Gerard Andonian
Particle Beam Physics Laboratory
University of California Los Angeles

The Physics and Applications of High Brightness Electron Beams
Erice, Sicily,
October 9-14, 2005

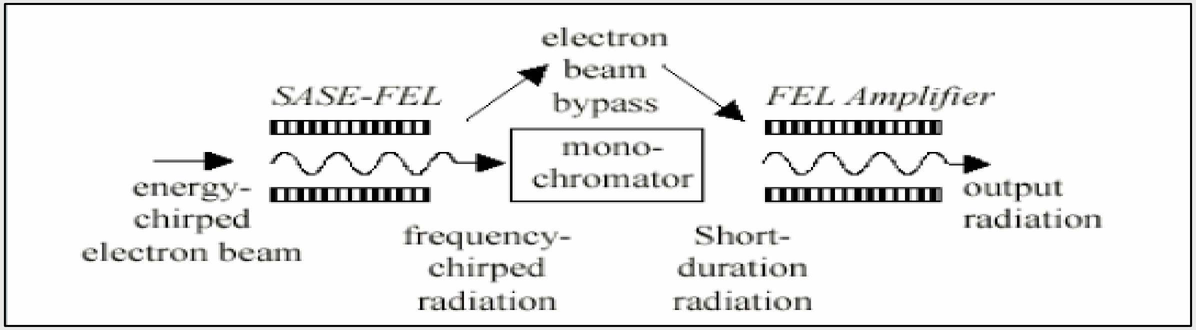
Collaboration

- UCLA
  - G. Andonian, A. Murokh, C. Pellegrini, S. Reiche, J. Rosenzweig, G. Travish
- BNL-ATF
  - M. Babzien, I. Ben-Zvi, J. Huang, V. Litvinenko, V. Yakimenko
- INFN-LNF
  - M. Ferrario, L. Palumbo, C. Vicario

Outline

- Experiment Description
- VISA I Summary
- VISA IB Experiment
  - Results
  - Analysis (Start-to-end)
  - Double Differential Spectrometer
- VISA II
- Seeded Amplifier Experiment
- Conclusions

Motivation



- Proposed Scheme for ultra short pulses
  - Energy chirped e-beam ➔FEL➔ freq. chirped radiation
- Explore Limits of SASE FEL with energy chirped e-beam
- Develop advanced beam manipulation techniques & measurements

Energy chirped e-beam

$$\frac{\delta\gamma}{\gamma} = \alpha \frac{l}{L_b}$$

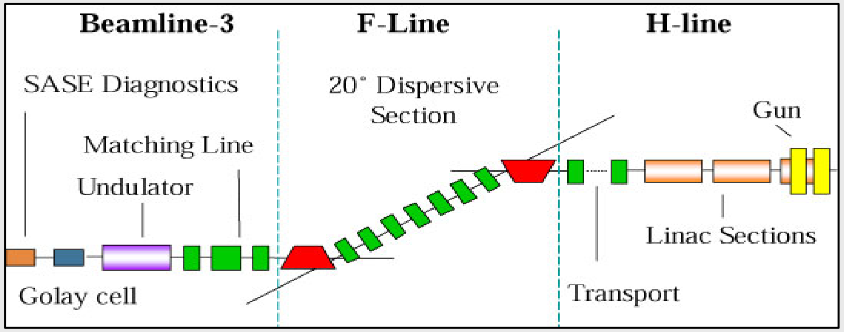
→

Freq. chirped radiation output

$$\frac{\delta\omega}{\omega} \approx 2\frac{\delta\gamma}{\gamma} = 2\alpha\frac{l}{L_b}$$

Experiment Layout

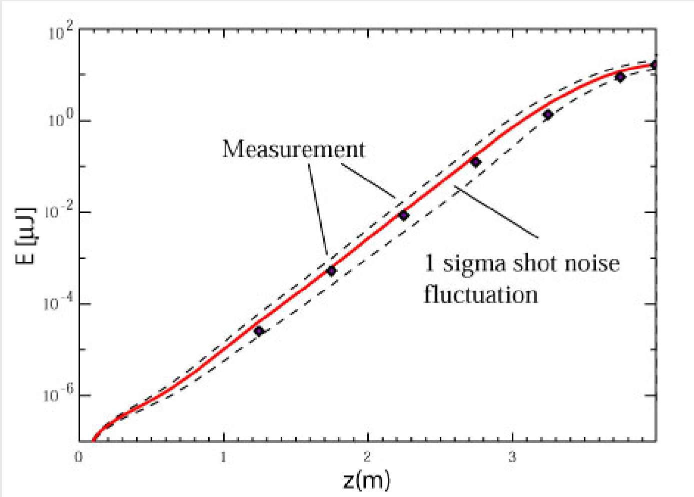
- Accelerator Test Facility (ATF) at BNL
  - Host for VISA I & II
  - 70 MeV beam
  - 28 m beam transport
    - 20 deg bend (F-line)
- Undulator
  - 4 x 1m sections
  - FODO lattice superimposed (25 cm period) –strong focusing
  - External steering coils (8)
  - Intra-undulator diagnostics
    - 50 cm apart
    - double-sided silicon
    - SASE FEL
    - e-beam (OTR)



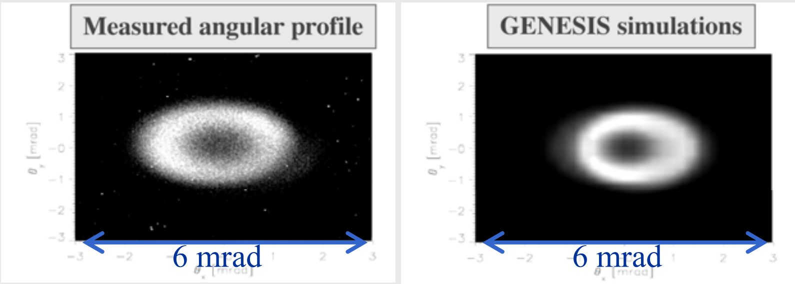
VISA Undulator Parameters	
Undulator type	Planar (NdFeB)
Number of periods (N_u)	220
Peak field (B_{pk})	.75 T
Undulator Period (λ_u)	1.8 cm
Gap (g)	6 mm
Undulator Parameter (K)	1.26

VISA I Summary

- Results
  - Gain ~ 10^8 due to nonlinear compression in dog-leg (F-line)
  - Shortest gain length recorded in NIR (~ 18 cm)
  - Higher order angular spectra
  - CTR & Higher Harmonic Gain
- Start to End Simulation Suite
  - UCLA Parmela
  - Elegant
  - Genesis
- Codes Benchmarked to measurements
  - Post linac, post-dogleg, FEL



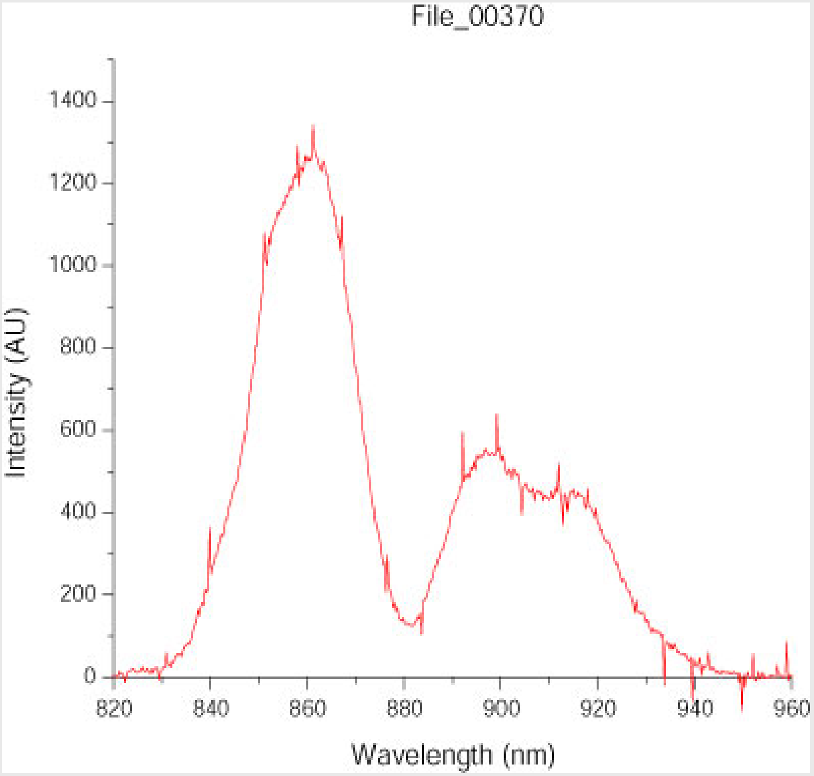
VISA I Gain Curve



Far-field radiation pattern (angular spectrum): measured (left), simulation (right)

VISA IB: Experiment

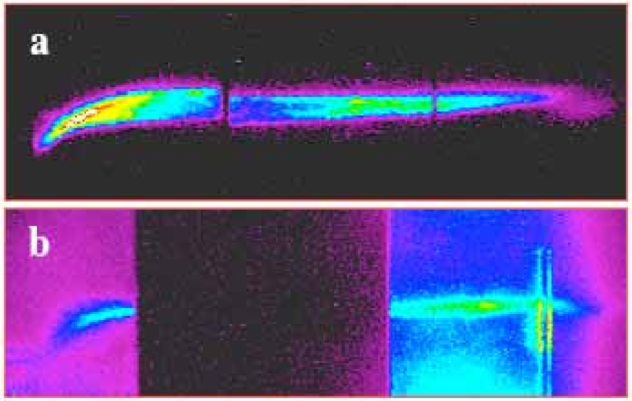
- High gain FEL
  - Chirped beam amplification
  - SASE energy ~2 μJ
  - close to saturation
- Up to 15% bandwidth observed
- Very reproducible and unusually stable
  - insensitive to RF drifts and phase jitter
- Characteristic double-spike structure



Wavelength Spectrum of FEL at VISA measured with Ocean Optics USB2000 Spectrometer.

VISA IB: Experiment

- High energy slits (HES)
  - adjustable collimator
  - Controls beam size in F-line
- FEL stability
  - same fraction of beam propagates through HES, regardless of centroid jitter
- Compression
  - monitored by Golay cell
    - measures CTR
    - CTR peaked when p_0 set to optimize compression
  - Current ~ 300A
  - Compression stronger
    - higher degree of chirp



e-beam at HES

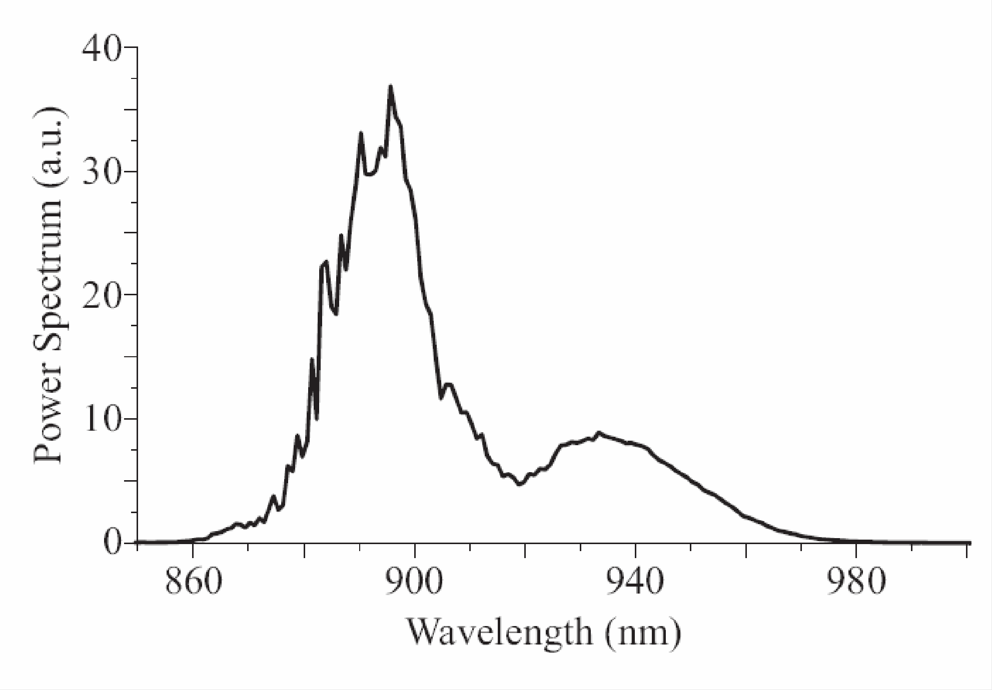
a) fully closed slits (500 pC, 2.8% chirp)

b) fully open slits (60 % Transmission, 330pC)

VISA IB: Analysis

- Start-to-End
  - Experimental Spectrum features reproduced
  - Angles Important
    - Off-axis Doppler Shift

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{1}{2}K^2 + (\gamma\theta)^2\right)$$

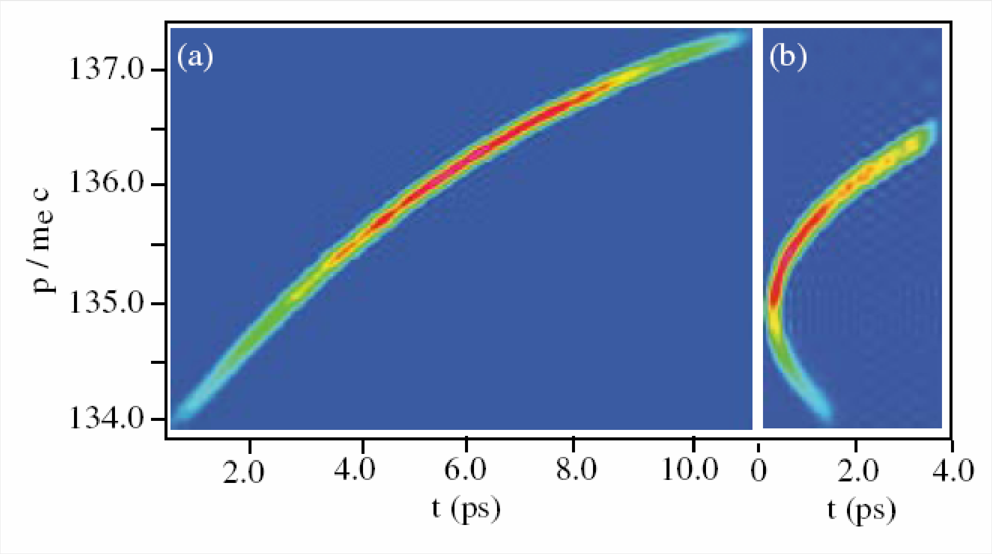


FEL output Spectrum reproduced by Genesis (~11% bandwidth)

VISA IB: Analysis

- Linear chirp applied at linac
- Compression in dogleg
  - Portion of beam is always in “correct” comp. regime
  - Collimation ~40% (300 pC)
  - Benchmarked to data taken in F-line
- Leads to off-axis injection of compressed core

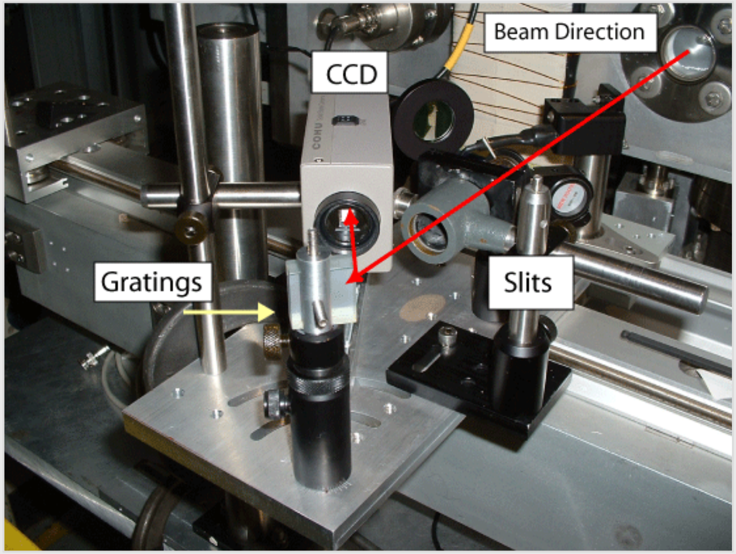
- High Current
  - I ~ 300 A
  - Better than VISA I



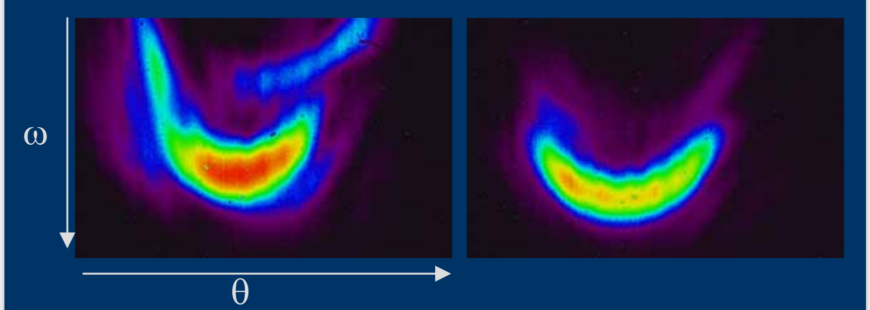
Double Differential Spectrum

- Double Differential Spectrum (DDS)
  - Unfolds correlation between angle (slits) and frequency (gratings)
  - Preliminary setup
    - improvements coming
    - calibration lamp
    - graduated slits

$$\frac{d^2 I}{d\omega d\Omega}$$

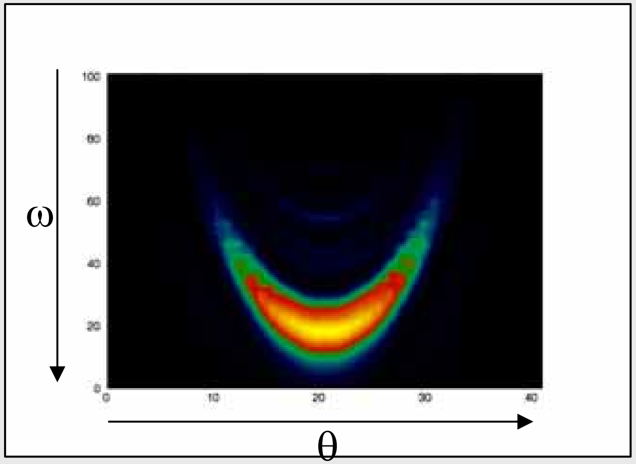


Double differential spectrum: Experimental Setup



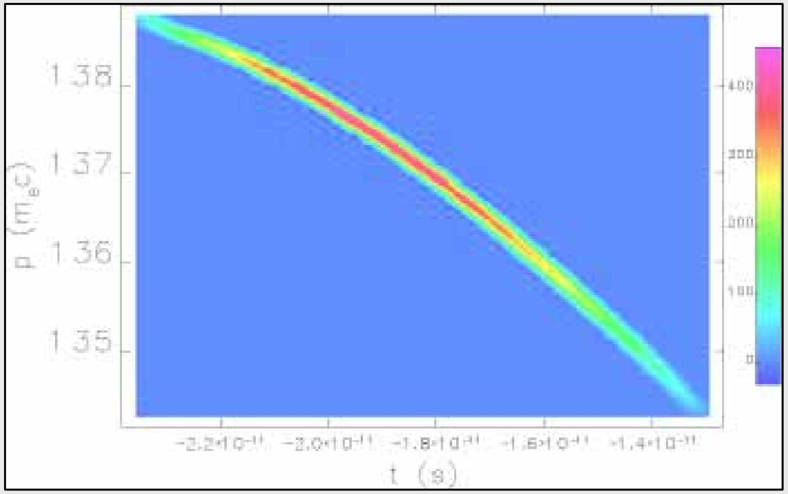
•DDS measurement at VISA .
  •Doppler Pattern observed
  •Higher bandwidth – complex forms
  •Rich spectral structures

Genesis Simulation of DDS for VISA IB running conditions

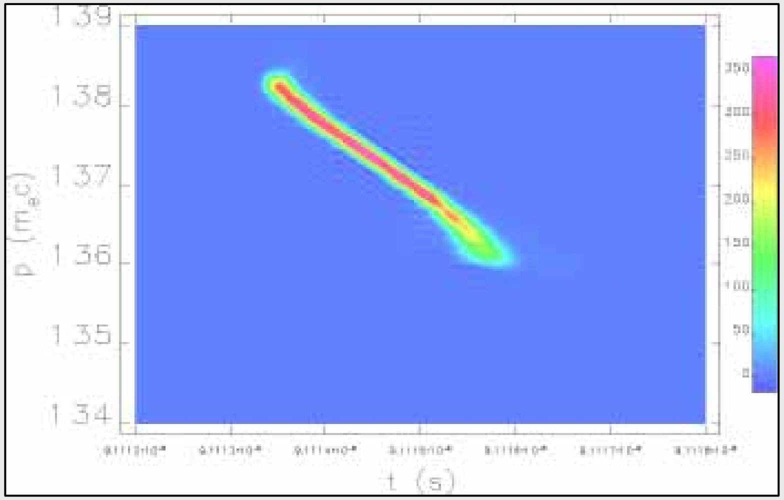


VISA II

- Energy chirp SASE FEL operation
  - linearize transport
    - Sextupole correction in F-line
- Running Conditions
  - Back of crest acceleration
  - Negative R_{56} compression
  - 70% Transmission
- Start-to-end Simulations
  - High Current
  - Low Emittance
  - High gain FEL
    - Frequency chirped radiation
- Modified FROG



Longitudinal Phase Space for VISA II Case post linac (above) and pre-undulator (below).



Compression Studies at the ATF with the UCLA-BNL Chicane

Gerard Andonian
Particle Beam Physics Laboratory
University of California Los Angeles

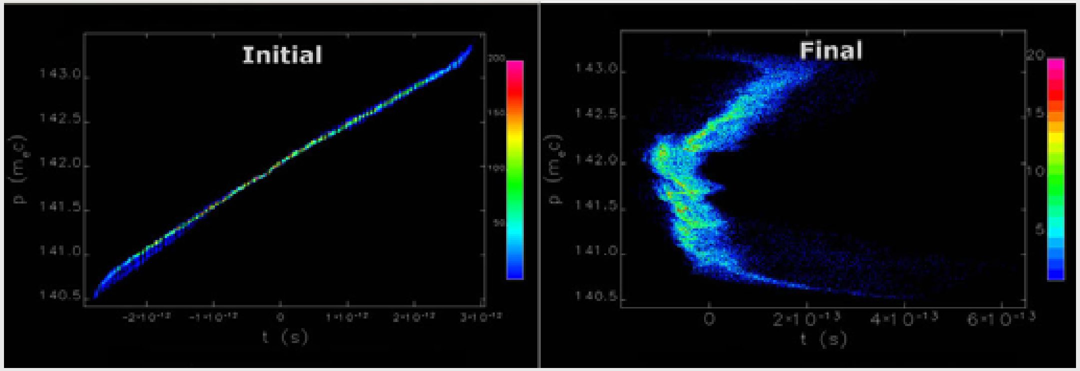
The Physics and Applications of High Brightness Electron Beams
Erice, Sicily
October 9-14, 2005

Outline

- Motivation
- Technical Specifications
- Coherent Transition Radiation (CTR)
  - Recent Data
- Coherent Edge Radiation (CER)
  - Theory overview
  - Simulations
  - Preliminary Results
- Outlook

Motivation

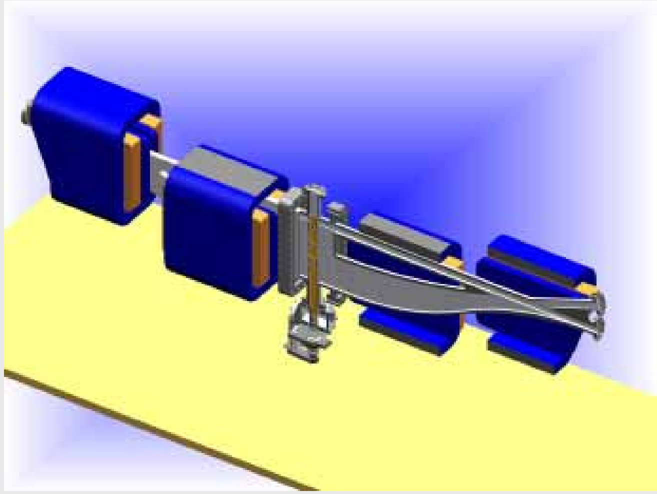
- Generation of compressed sub-micron beams
  - Study radiative effects (CSR, CER) emitted from short beams
  - Continue UCLA Neptune compressor physics studies in acceleration field dominated regime (space charge -> coherent radiation)
  - May greatly impact performance of future compressors and FELs (e.g. microbunching instability)
  - Use CER as non-destructive bunch length monitor



Parmela-Elegant simulation longitudinal phase space of beam, with compression from 50A to 1.5 kA.

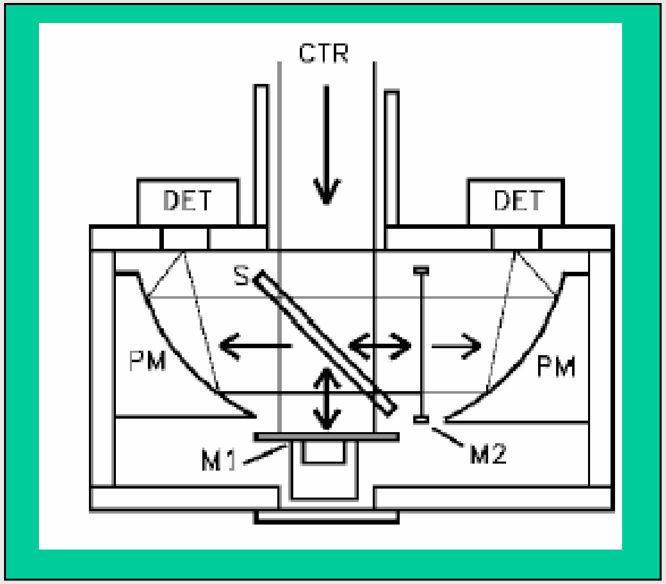
Compressor

- Designed and Constructed at UCLA
  - Modeled with Amperes
  - Engineering + safety concerns addressed by ATF
- Installed and operational at ATF
  - Add to ATF core capabilities
  - Compress from 350 μm – 20 μm
- Extensive Simulation work
  - TREDI, Field-Eye, Parmela, Elegant



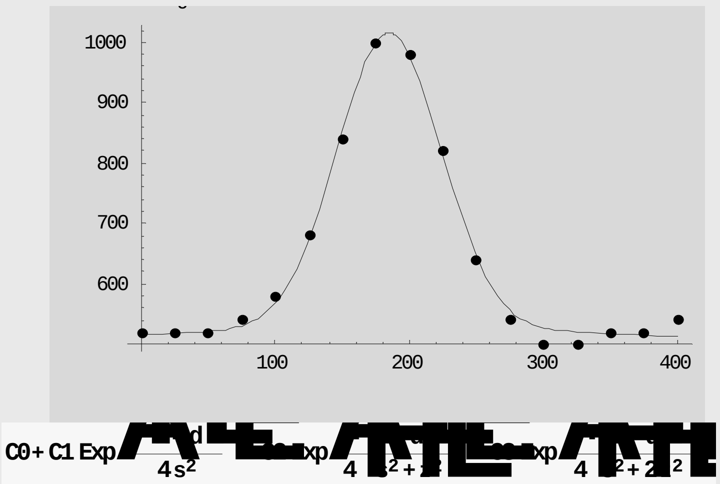
CTR Measurement

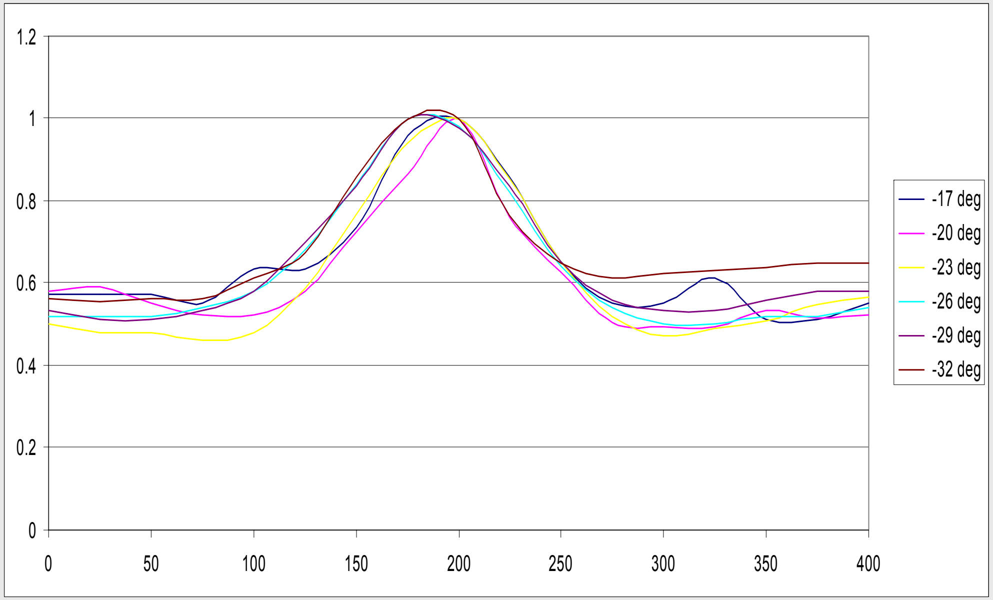
- Michelson Interferometer
  - Commercial Product
  - Compact Footprint
  - Convenient Alignment
  - Resolution : 10 μm – 1.5 mm (rms)
- Observe CTR from insertable foil
  - Golay Cell detectors
  - Autocorrelation
- UCLA time-domain methods (fitting) and data acquisition

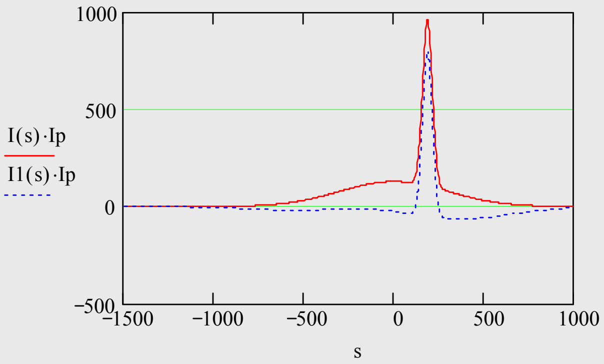


CTR Data

- Recent CTR data
  - Beam core compression not strongly dependent on phase
- UCLA Fitting technique
- σ = 27 μm (rms)
- Use double Gaussian
  - Reproduces expected pulse shape (ramped with tail)

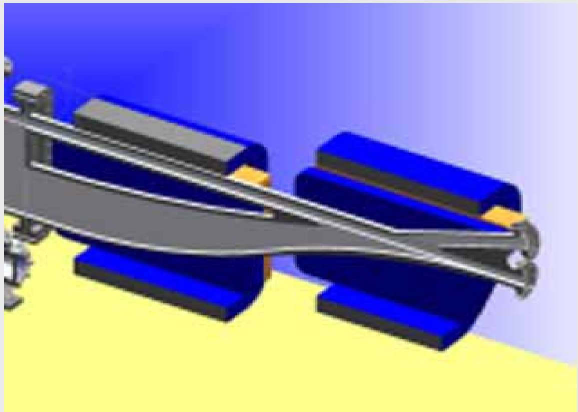






CER Experiment

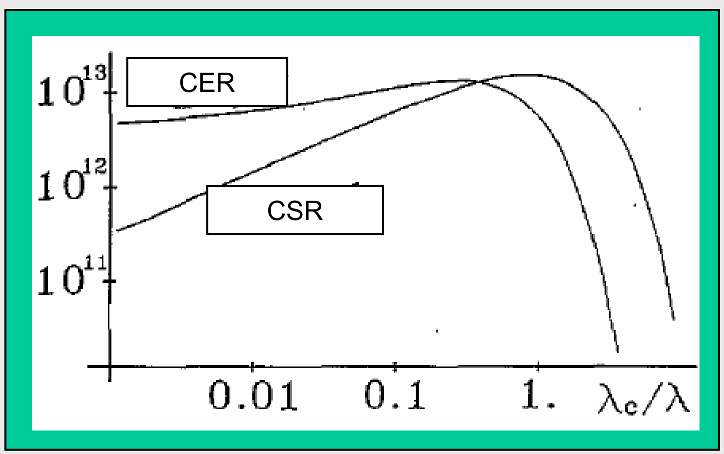
- Radiation collected from boundary region of dipoles 3-4
  - 7 m transport
- New regime for Edge Radiation
  - <50 micron wavelength
- Cold Bolometer
  - 4.2 K Si bolometer (IR Labs)



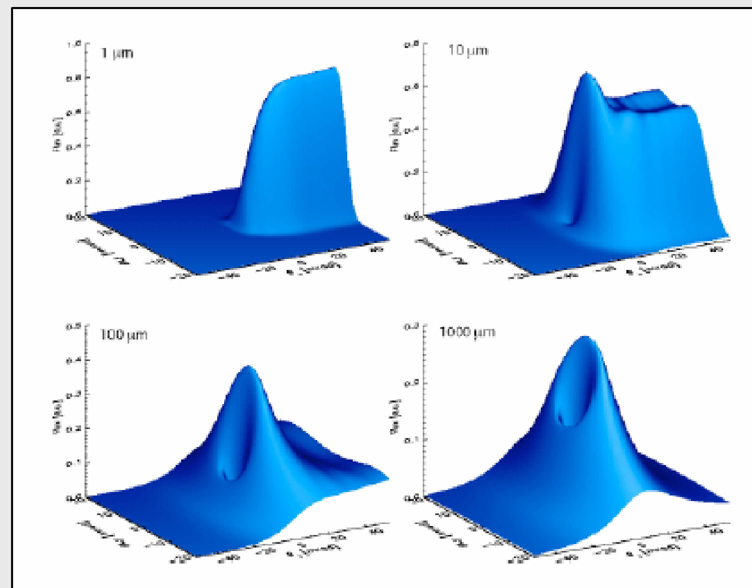
CER Overview

- Comparison to CSR
  - Not well distinguished from CSR at short wavelengths
  - Like CTR at long wavelengths
  - Radial polarization

- CER calculations
  - Modeling with :
    - Semi-analytical
    - Field-Eye

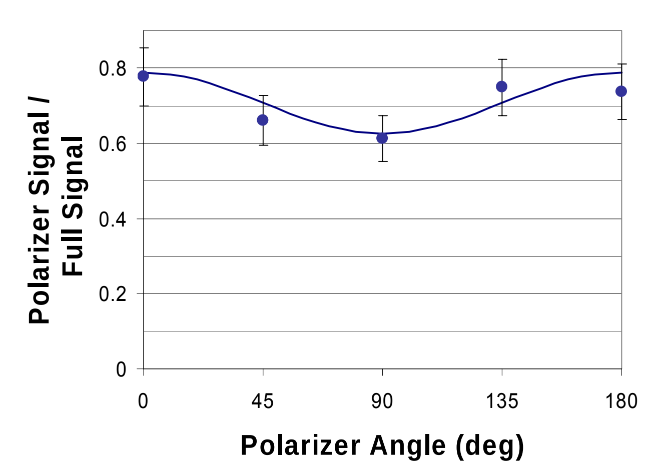


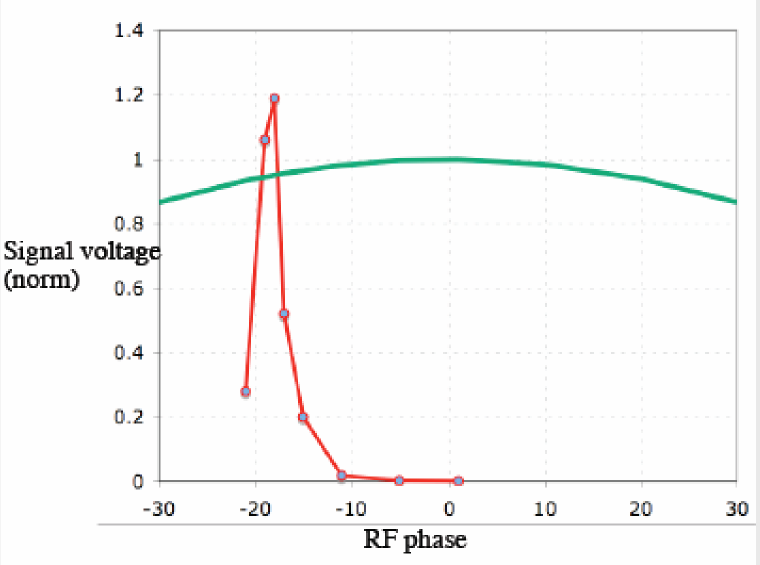
Chubard, Smolyakov, J. Optics 24 (1993) 117

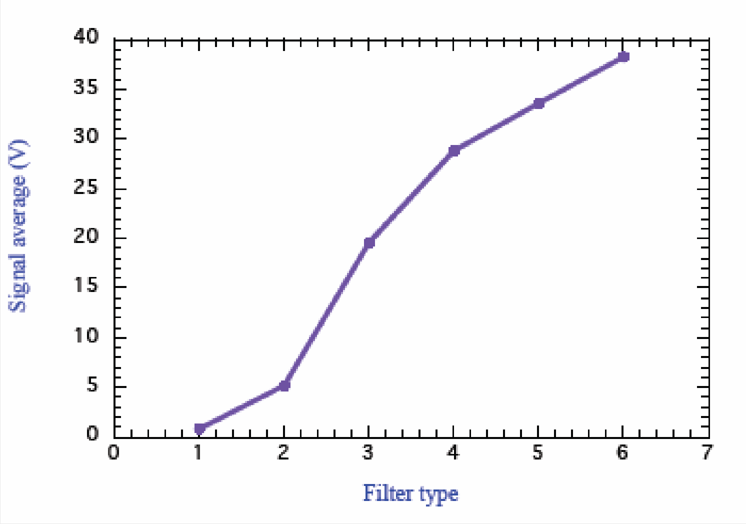


CER Results

- CTR+CER as a function of rf phase
  - Max signal -19 deg off crest
    - 11 deg forward of min momentum spread
- Polarizer
  - Radial polarization
- Filters
  - Reconstruct spectrum







Momentum Spread

- Observation of bifurcation
  - Momentum spectrum
    - Strong breakup of momentum distribution at phase of full compression
    - Currently being studied with TREDI code

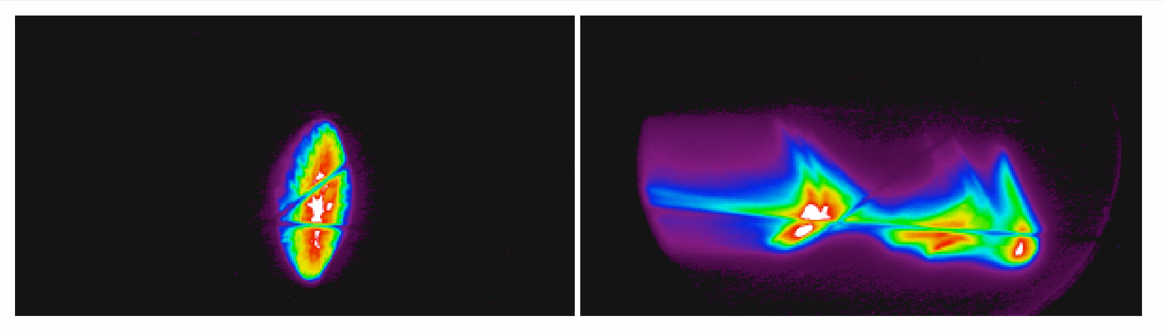


Image of beam in spectrometer (horizontal is bend plane).

Min. energy spread and no compression - 9 deg fwd of crest (left); Max. compression -19 deg fwd of crest (right).

Conclusions

- Summary
  - Chicane compressor installed and commissioned
  - Compressor provides a rich data set
    - CTR, CER, momentum spread, tomography
  - Simulations need to catch up
    - Microscopic physics model
- Future Run Plans
  - CER filter measurements
  - Improved CER polarizer measurements
  - Compare to models (Field-Eye)

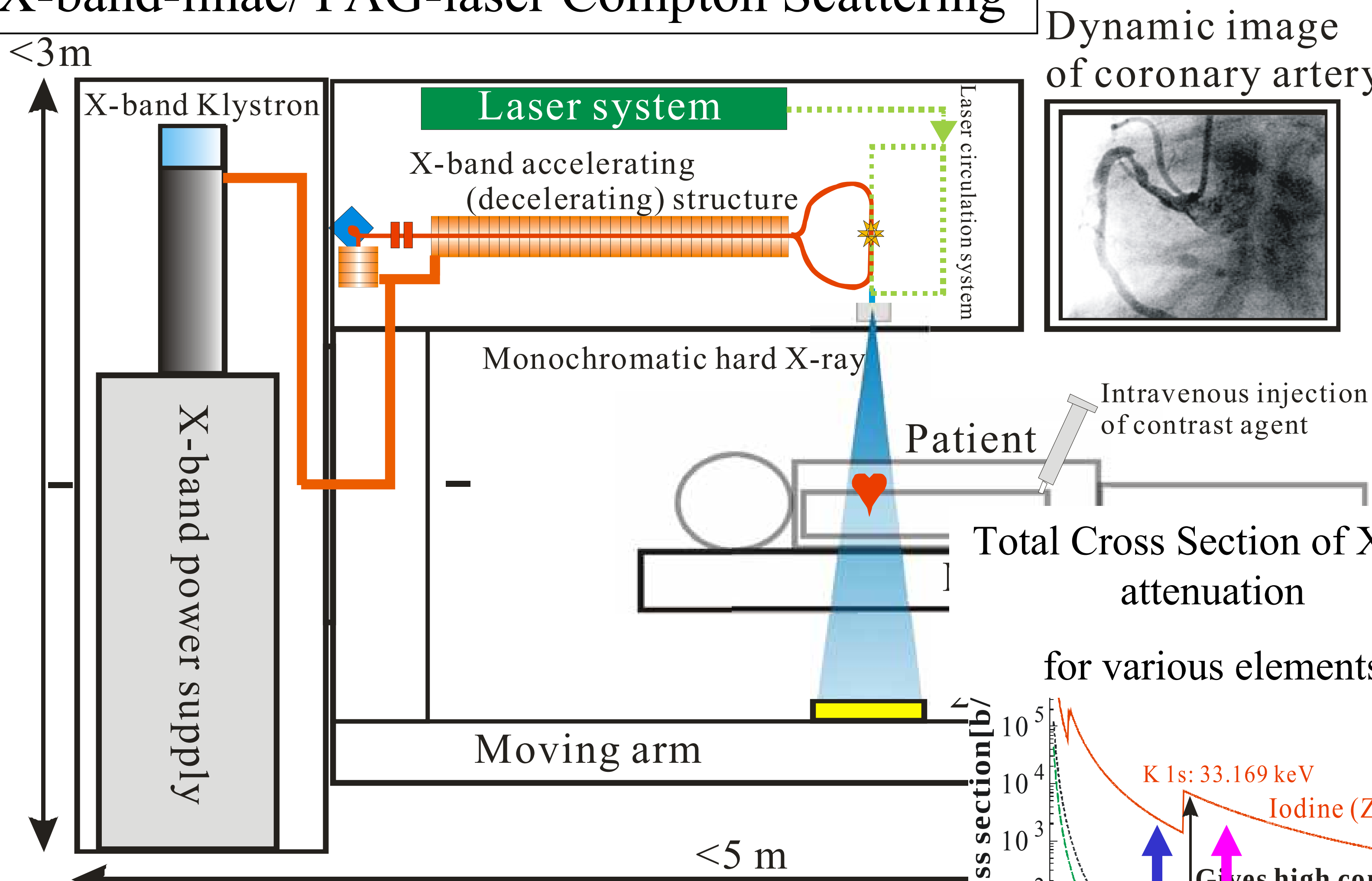
October 11, 2005
ICFA Workshop on
The Physics and Applications of High Brightness Beams

"High Brightness Beam Applications: Inverse Compton Scattering"

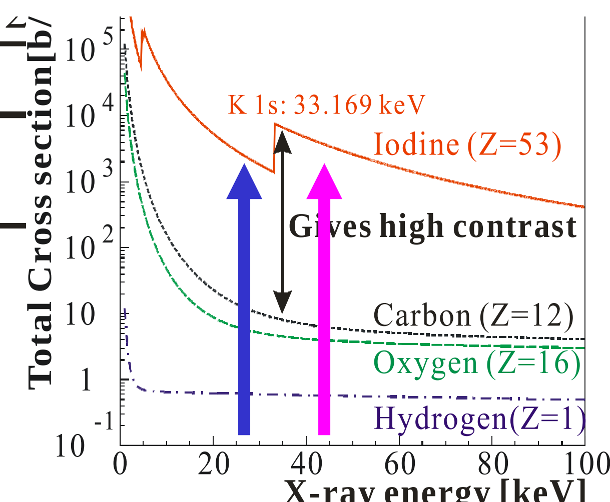
Nuclear Professional School
University of Tokyo

Mitsuru Uesaka

Monochromatic Tunable Hard X-ray Source by X-band-linac/YAG-laser Compton Scattering



Total Cross Section of X-ray attenuation for various elements



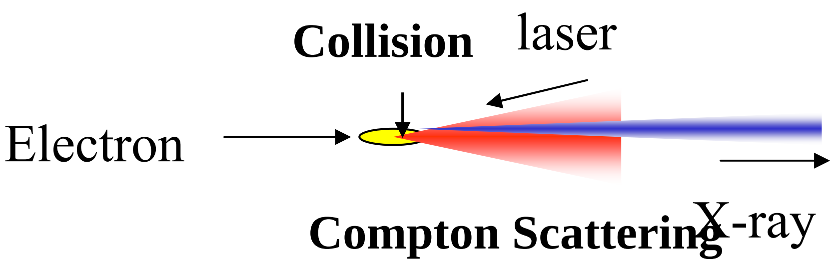
Scale of system: less than 5m x 5m(with the power supply)

Price: ~4 million dollars

X-ray energy(max.): 10~50 keV

X-ray intensity: $>10^9$photons/s(total)

Monochromatic Hard X-ray by Compton Scattering



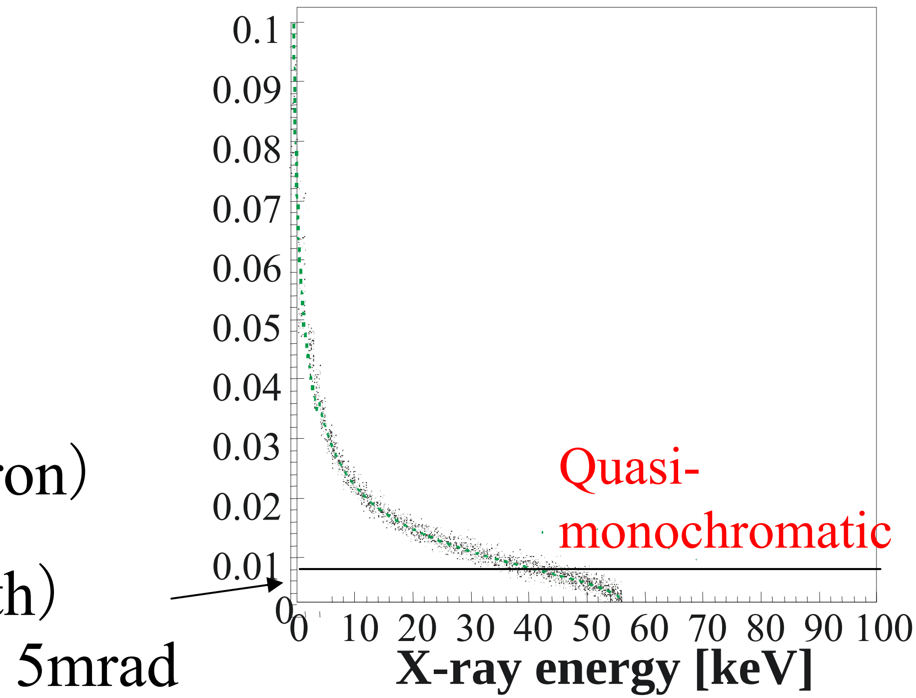
$$\lambda_r = \frac{\lambda_L}{2\gamma^2}(1 + \frac{1}{2}K^2)$$

(K: Wiggling angle of electron)

$\lambda_L \approx 1\mu m$ (laser wavelength)

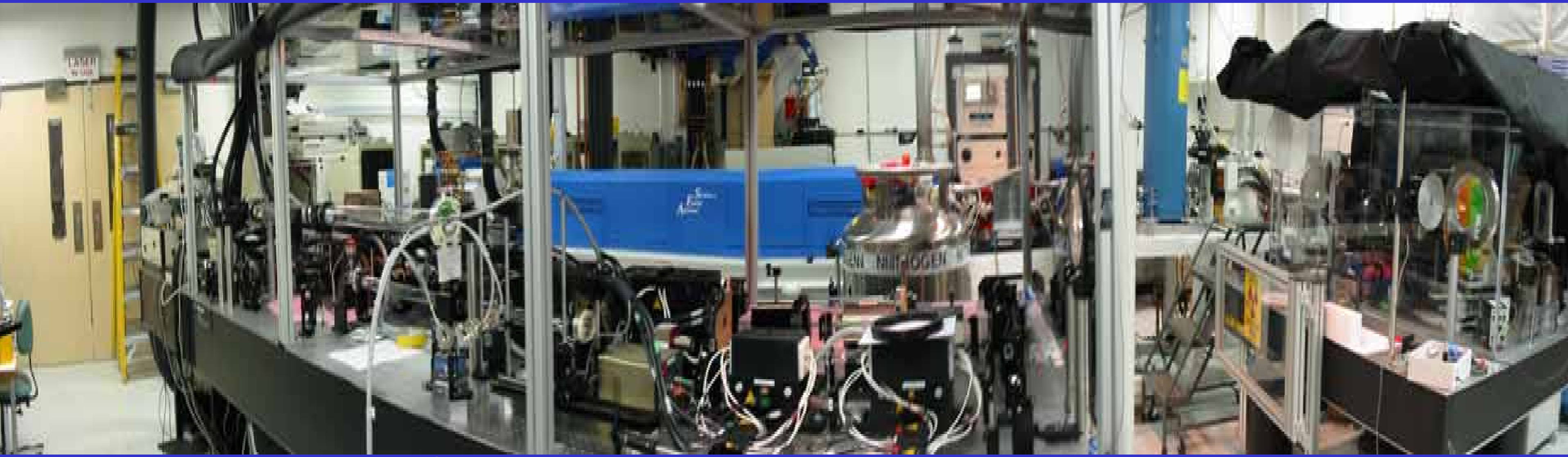
$\gamma \leq 10^2$ $(50MeV)$

$\lambda_\gamma \leq 1\mathring{A}$ (X-ray)



X-ray energy vs Angle

Pulsed, tunable, monochromatic X-ray machine
at MXI Sys./Vanderbilt's W.M. Keck Free-Electron Laser Facility



Machine Specifications:

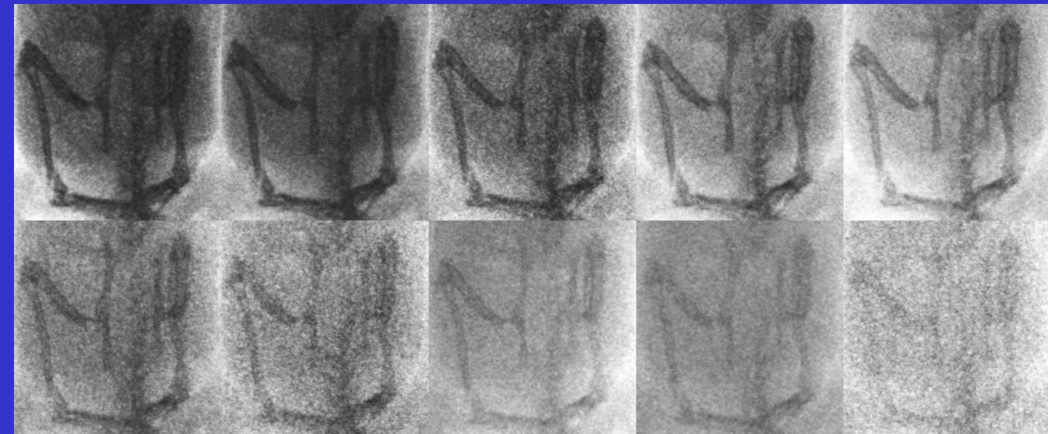
E-beam:	**50 Mev Linac running in "single pulse" mode**
	1 nanocoulomb/pulse
Laser:	**Nd:Glass**
	1052 nm
	20J – (10J compressed to 10 ps)
	.003 Hz
X-ray beam:	**10^{8} photons/shot**
	tunable from 12 to 50 keV
	1-10% bandwidth

Energy differences in a finger

or in a body, such as a mouse

19 keV

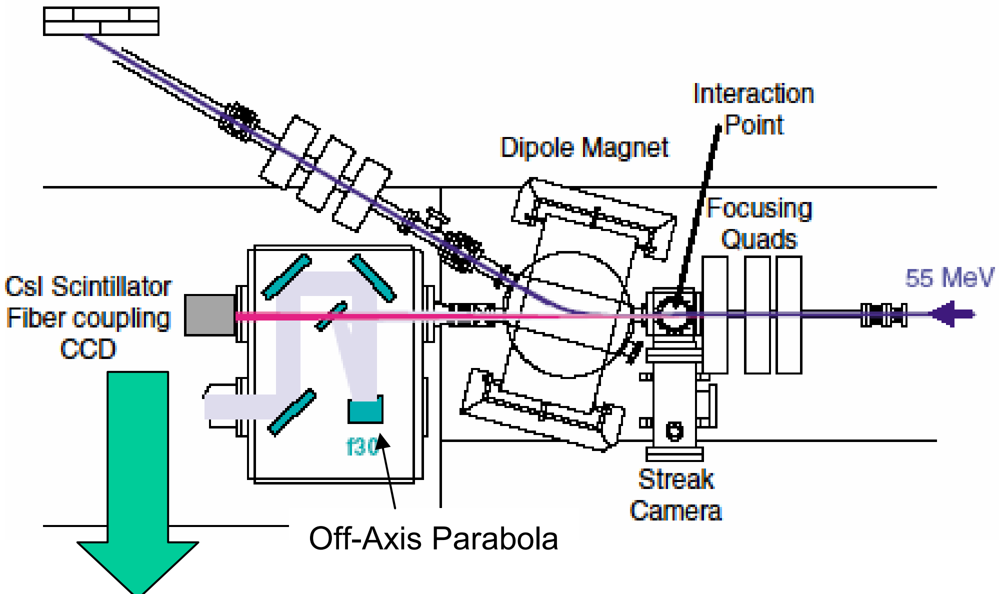
29 keV

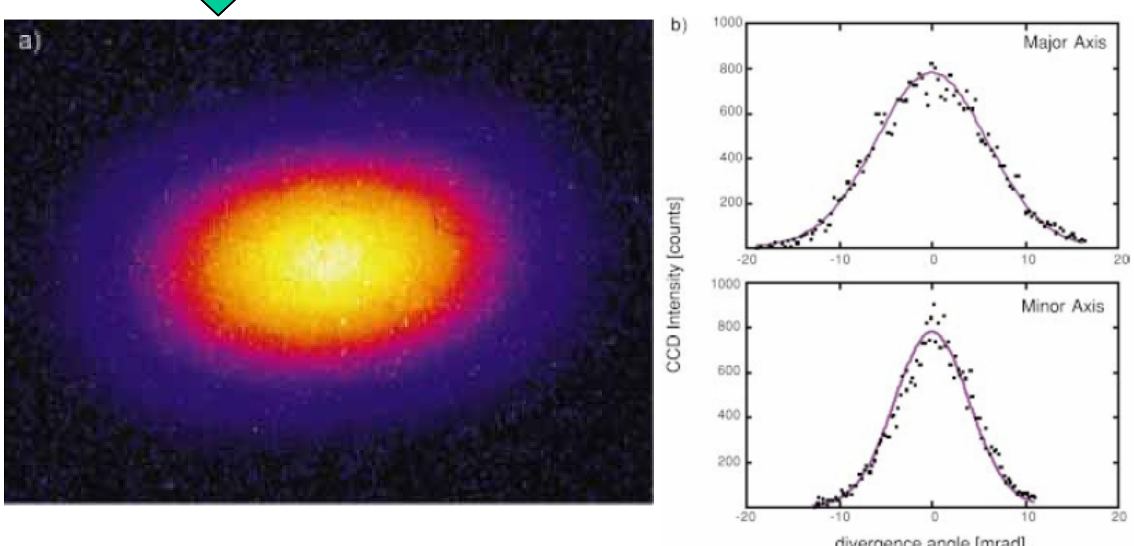


Energy movie from 15 keV to 33 keV

We have the ability to specifically tune the X-rays to the imaging task at hand.

Inverse Compton scattering experiment by 70MeV linac and Ti:Sapp laser at PLEIADES, LLNL





X-ray image taken by CsI Scintillator Fiber coupling CCD

Alignment

Spatial Alignment

aluminum cube at collision point

Temporal Alignment

streak camera

Future works

- Permanent quadrupole magnet for electron beam focusing
  →beam size:15 μm
- 540 mJ Laser pulse for interaction
- Tuning up of the UV Laser for photo injector

Goal

Total flux: 10^8 photons/sec

Peak brightness:

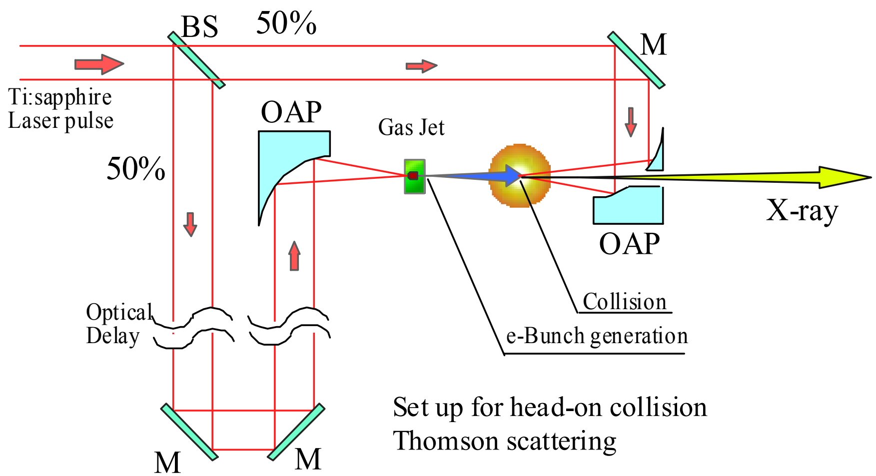
10^{20} photons/mm^2 /s/mrad^2/0.1 % band width

LOA(France), etc.

Nuclear Engineering Research Laboratory
Graduate School of Engineering
University of Tokyo

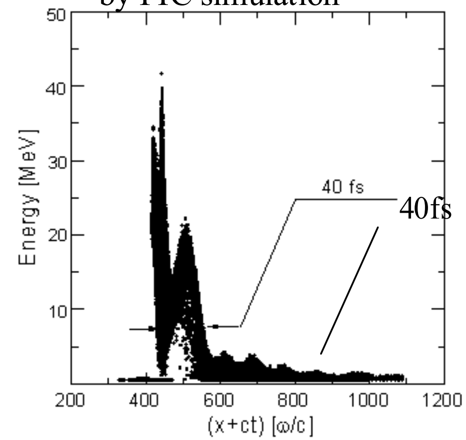
Hard- X-ray on the Thompson scattering

Hard X-rays (~10-20 keV) in a 1-2^{o} cone can be produced with 12TW Laser

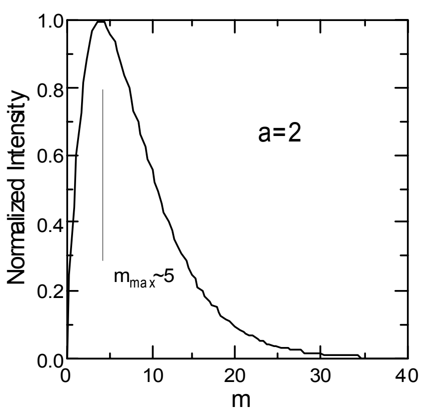


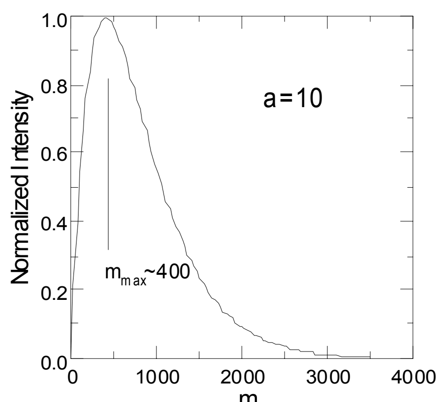
Set up for head-on collision Thomson scattering

Electron bunch by PIC simulation



Spectrum of x-rays depending on the laser intensity, $a_0 = eE/mc\omega$





$\omega \sim m\,\omega_0 8\gamma_0^2/(1+a_0^2)$

Laser pulse and electron bunch encounter can be produced with use of the laser self-focusing

- F.He, Y.Lau, D. Umstadter, R.Kowalczyk PRL, 90,055002 (2003)
- A.Zhidkov, J.Koga, A.Sasaki, M.Uesaka PRL, 88,185002 (2002)

First and Second Generation Inverse Compton Scattering X-ray Sources

First Generation

MXI Sys/Vandervilt, PLEIADES, U.Tokyo/KEK/JAERI, Sumitomo etc.

-Single-electron-single-laser Compton scattering

-First demonstration and application

-Intensity up to 10^8 photons/s

-Intensity fluctuation due to the time-jitter between electron and laser puls

Second Generation

U.Tokyo, Lyncean Tech.(R.Ruth), Sumitomo/AIST/KEK, etc.

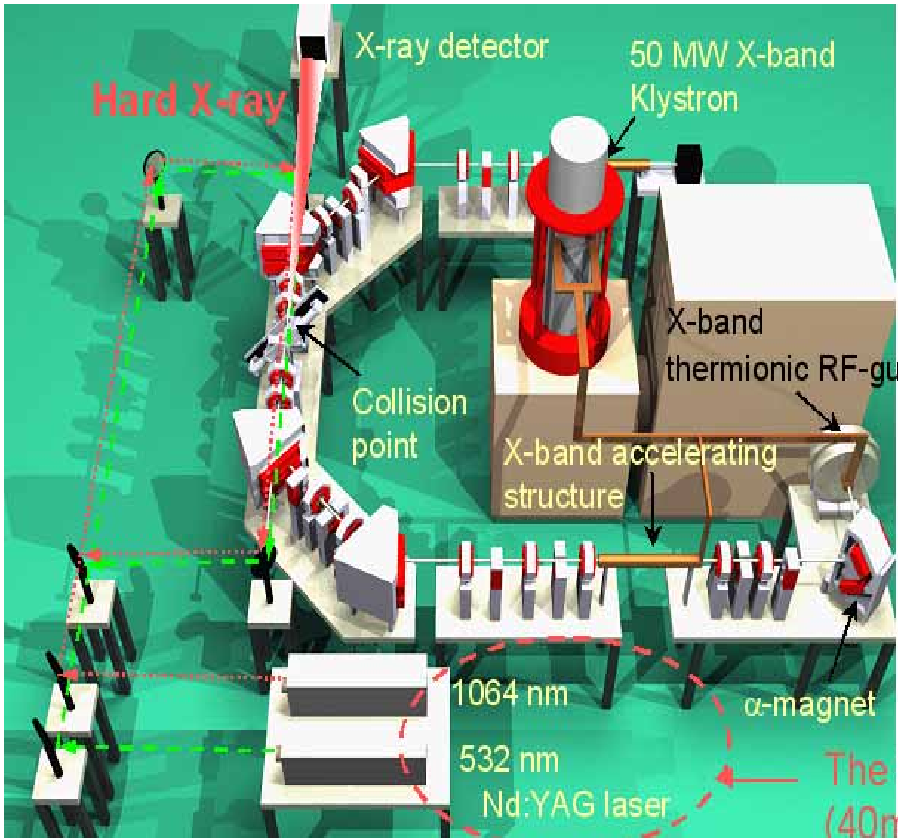
-Multi-scattering of electron- and laser-pulses

-Intensity of more than 10^9 photons/s

-A variety of applications for medicine, protein structural analysis, nondestructive evaluation and nuclear engineering

Compton scattering hard X-ray source

Compact hard X-ray source based on Compton Scattering



The X-ray energy can be changed quickly (40ms) by introducing two lasers

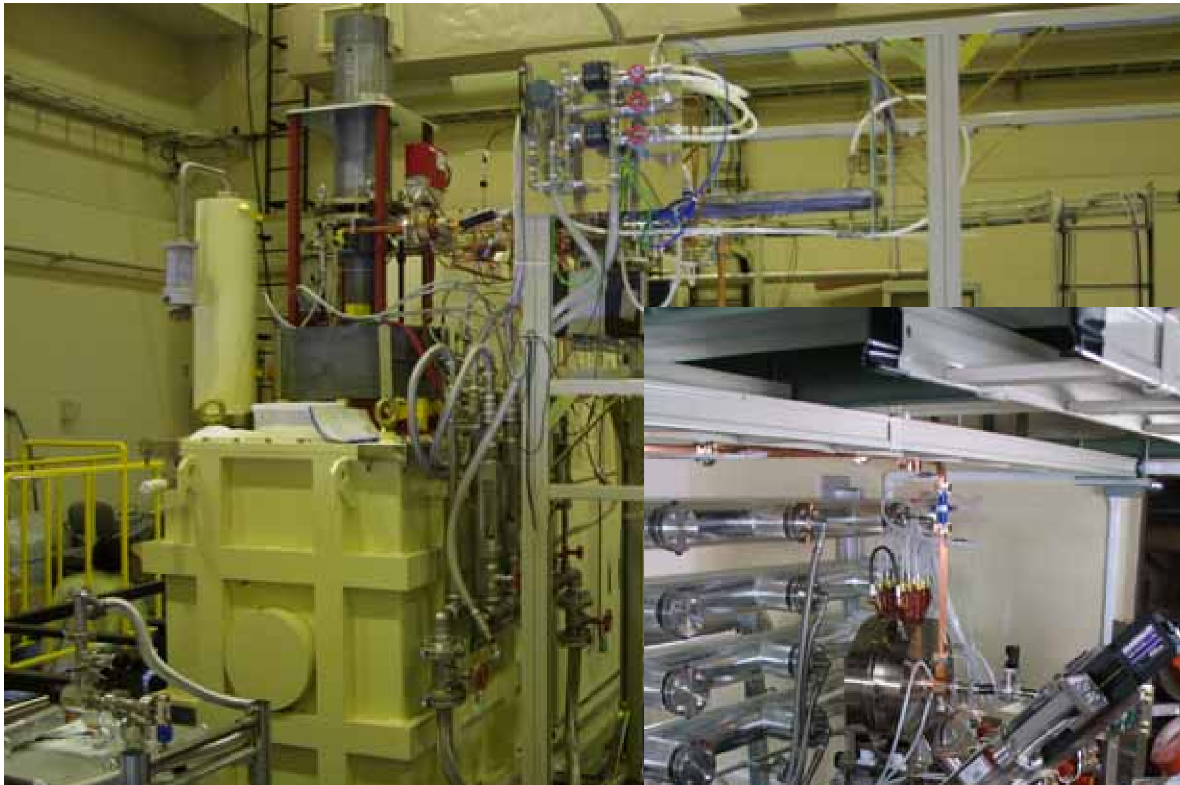
Properties of the generated X-ray

Electron beam energy : 35 MeV, Charge : 20 pC/bunch

Laser wavelenght (nm)	1064	532
Pulse energy (J/pulse)	2.5	1.4
X-ray yield (photons/pulse)	9.9×10^{6} (10^{8})	4.4×10^{6} (10^{8})
Maximum X-ray energy (keV)	21.9	43.8
Energy spread (%) rms	1-10	

10 pps with laser circulation

X-band Linac Facility at Univ.Tokyo



RF source

Control room

Beam line

Applications

- Static/dynamic imaging for medical and industrial uses

- Dual energy X-ray CT to get 3D distributions of atomic-number- and electron-densities for light atoms up to ^{43}Tc

- Subtraction CT across the K-edge to get 3D distribution of specified heavy atoms

- Protein structural analysis

Review of RF photoinjector for radiation chemistry

Univ. Tokyo

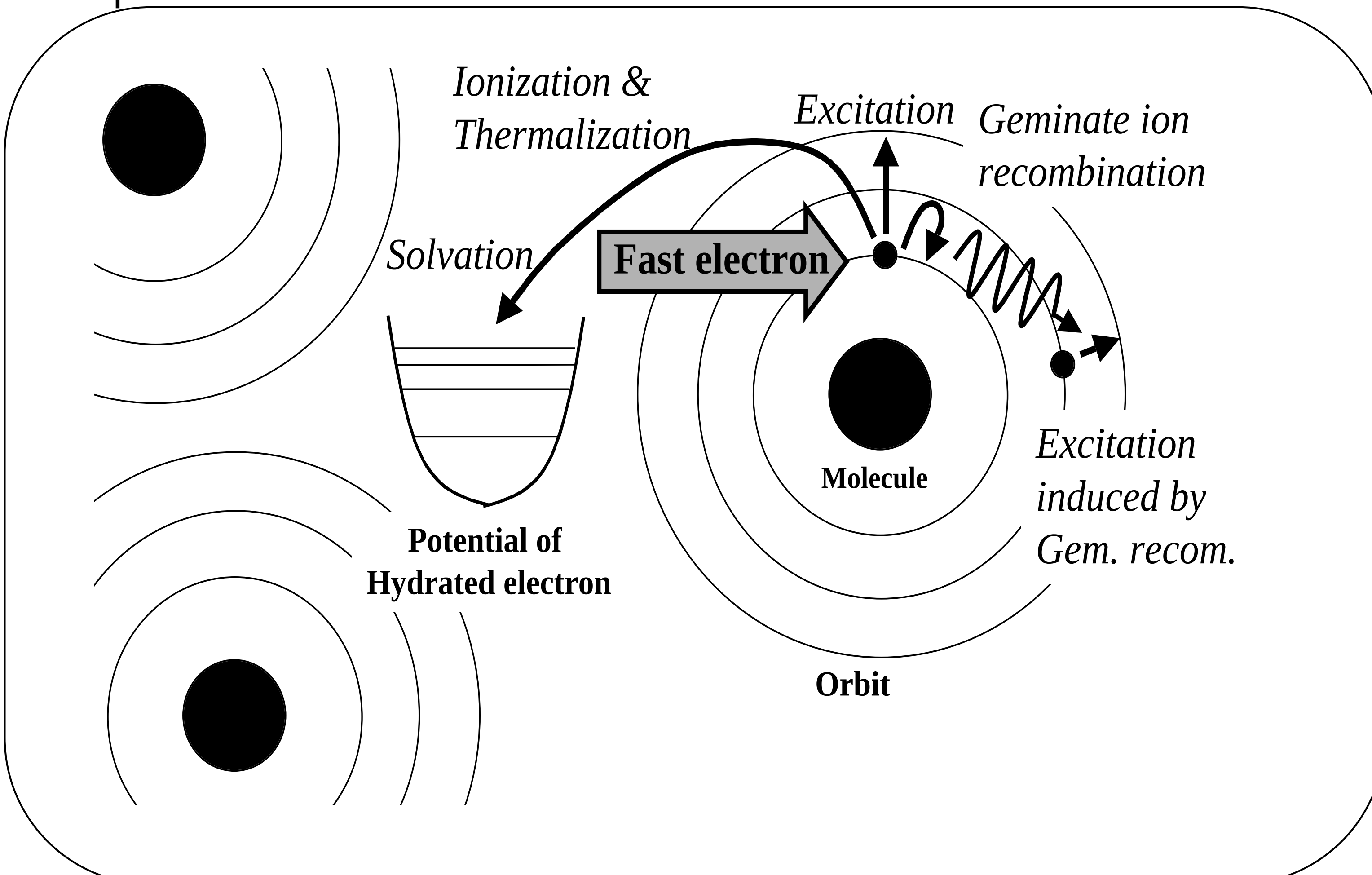
A. Sakumi, M. Uesaka, Y. Muroya, Y. Katsumura

Application for ultra-short pulse

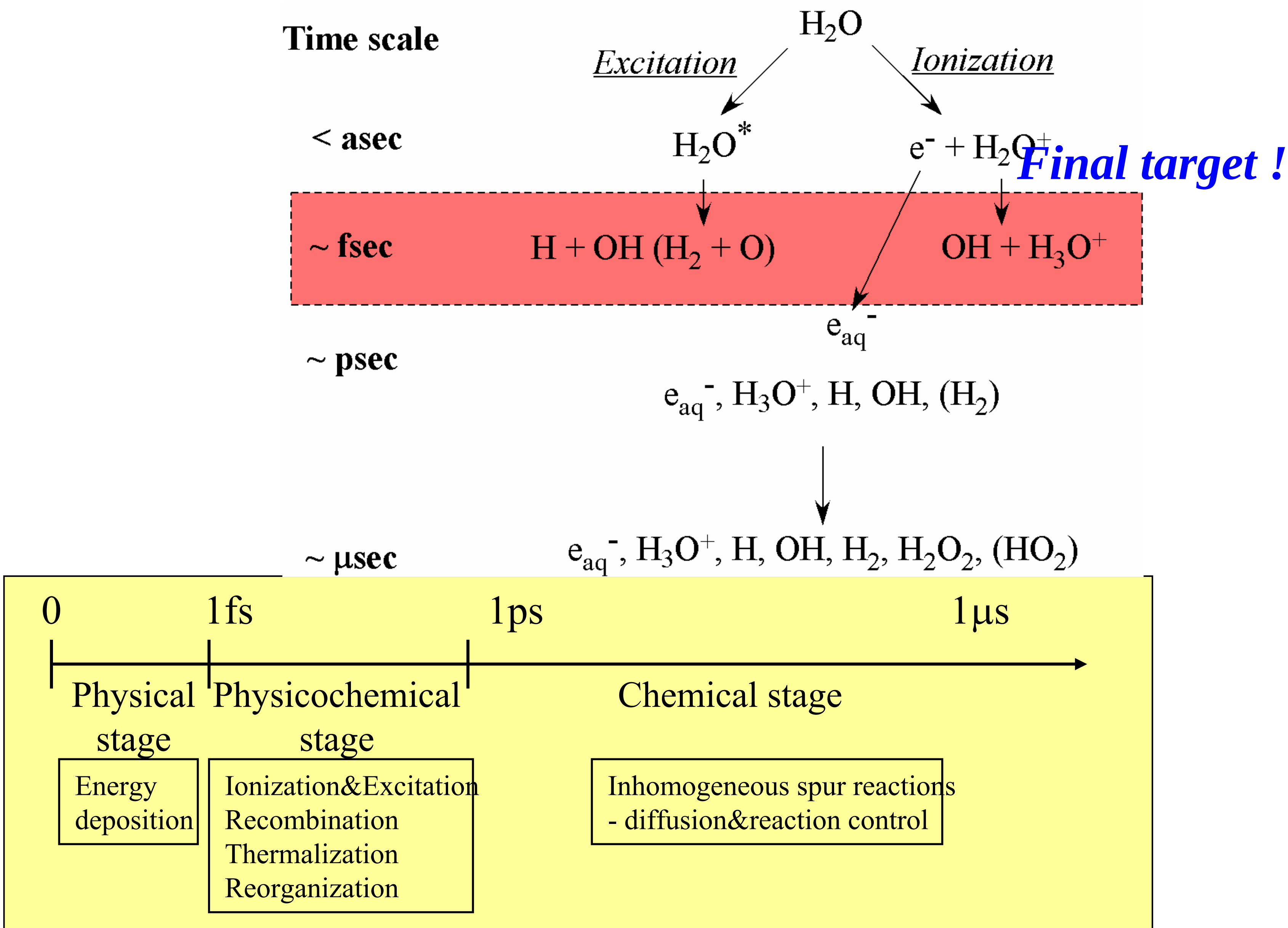
—Radiation Chemistry experiments

Purpose of the sub-ps pulse radiolysis

- Investigation of the elementary process of radiation induced phenomena which occur in the time scale of ps, even sub-ps

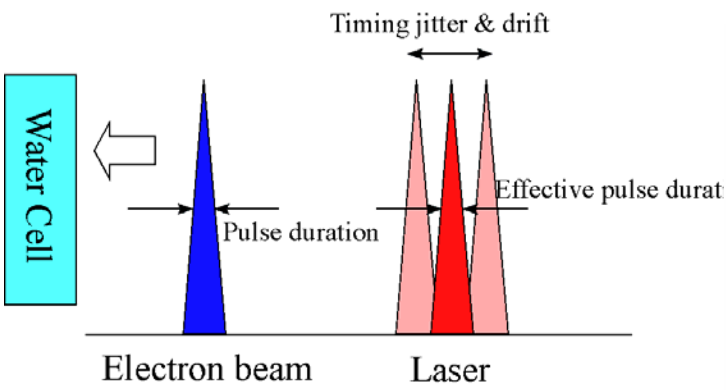


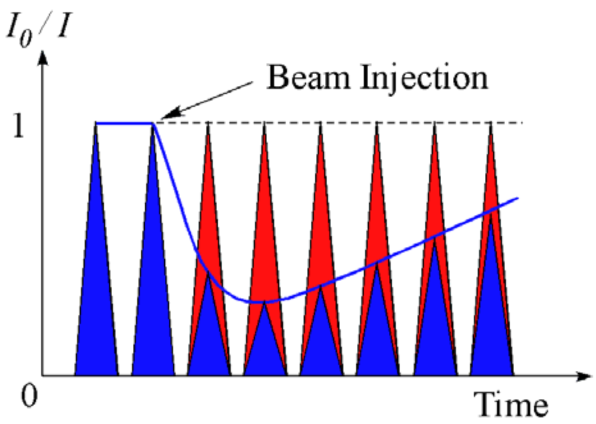
Application for ultra-short pulse
—Radiation Chemistry experiments



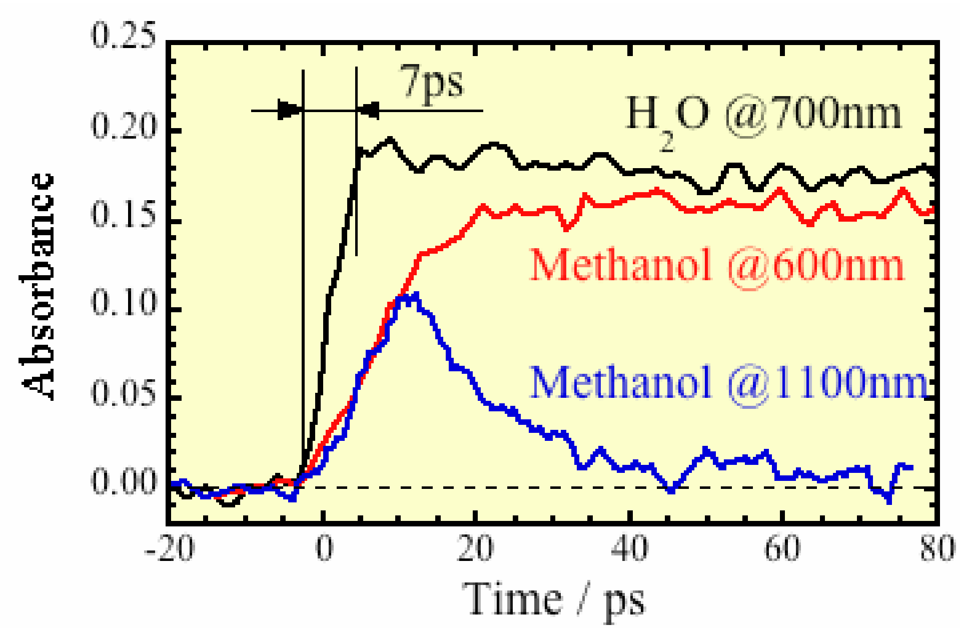
Radiation Chemistry

Pulse radiolysis method





Chemical reaction of water



NERS U. Tokyo Y. Muroya et al.,

Requirements

Pulse radiolysis in a time range of sub-picosecond

I Ultra-short bunch and laser

II Stable synchronization

III Intense electron bunch

For Pumping beam

Short pulse
Single beam, low dark current
High intensity

For Probe beam

Short pulse
Synchronization to pumping beam
Tunable wavelength

fs laser(Ti:Sapphire laser)
+
Photocathode RF gun

Suitable combination

Pulse radiolysis using white light continuum

- Time behaviors of e_{aq}^- at 700nm

Results

l /mm	10	5	2	1
O.D.	0.32	0.19	0.08	0.04
S/N	15	10	5	3
Dose	40Gy	47Gy	50Gy	50Gy
Time resol. /ps	12-13ps	6-7ps	4-5ps	<4ps

Good agreement

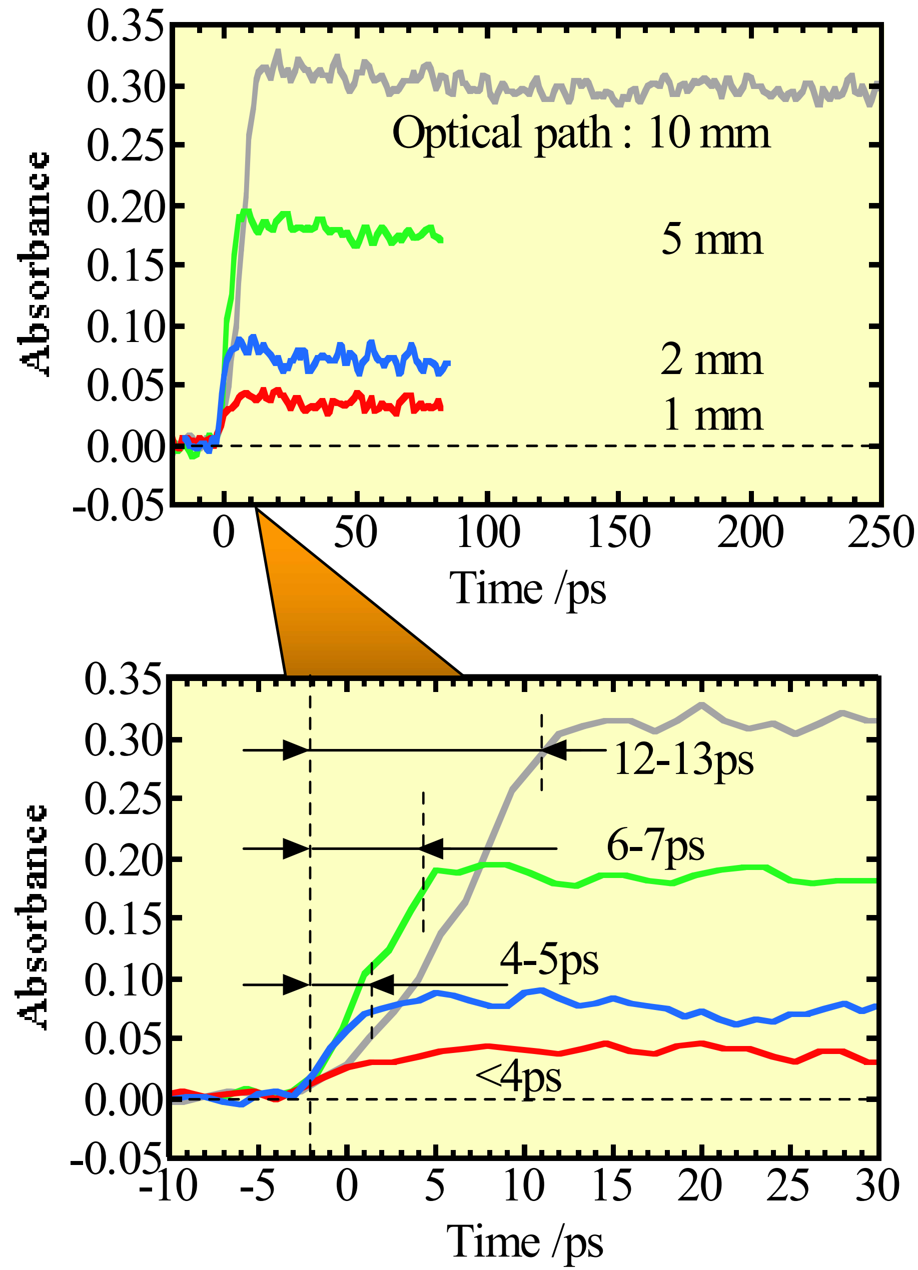
Time resol. /ps	12.2ps	7.2ps	5.2ps	3.2ps

Time resolution: δ_{total}

$$\delta_{total} \approx \delta_{diff} + (\delta_E^2 + \delta_L^2 + \delta_{sync}^2)^{1/2}$$

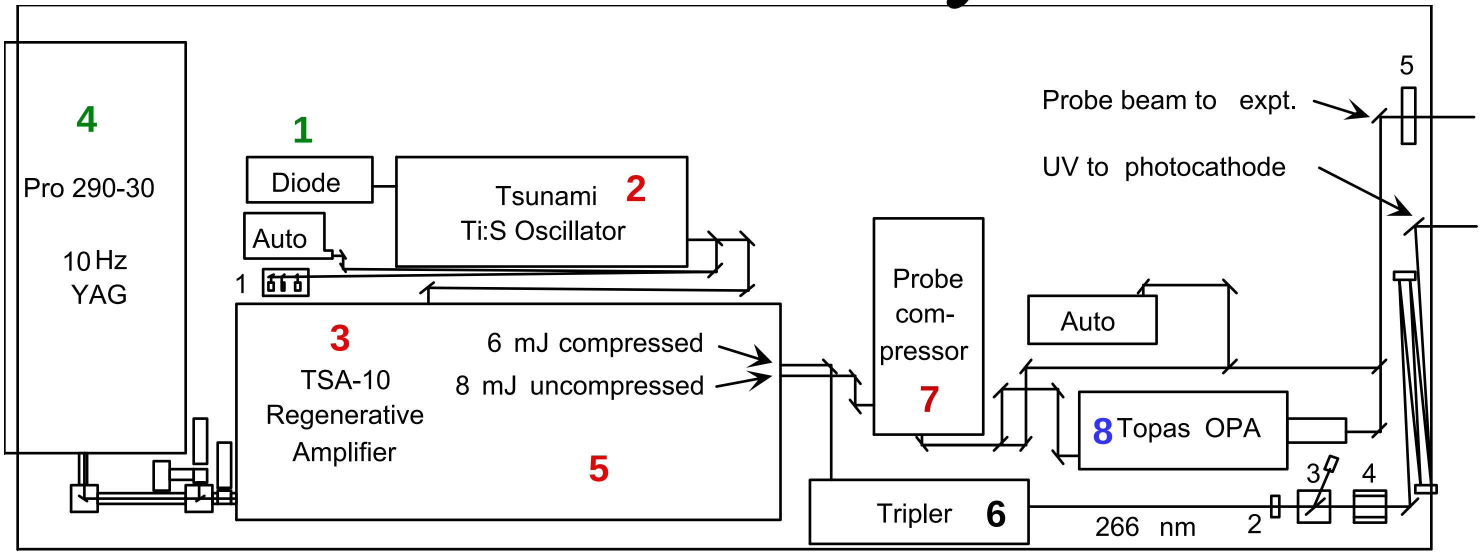
Dominant factor : δ_{diff}

due to refractive index n=1.33



LEAF

LEAF Laser System



1) **Diode-pumped Nd:YVO $_4$ laser, 5 Watts, 532 nm, pumps picosecond Ti:Sapphire laser.**

2) **Ti:Sapphire oscillator produces ~50 fs pulses, ~ 7 nJ energy, 798 nm, at 81.60 MHz.**

3) **Pulse stretcher stretches oscillator pulse to > 200 ps, then injects the pulse into the Ti:Sapphire regenerative amplifier.**

4) **Simultaneously, the doubled, Q-switched Nd-YAG laser pumps the Ti:Sapphire regen.**

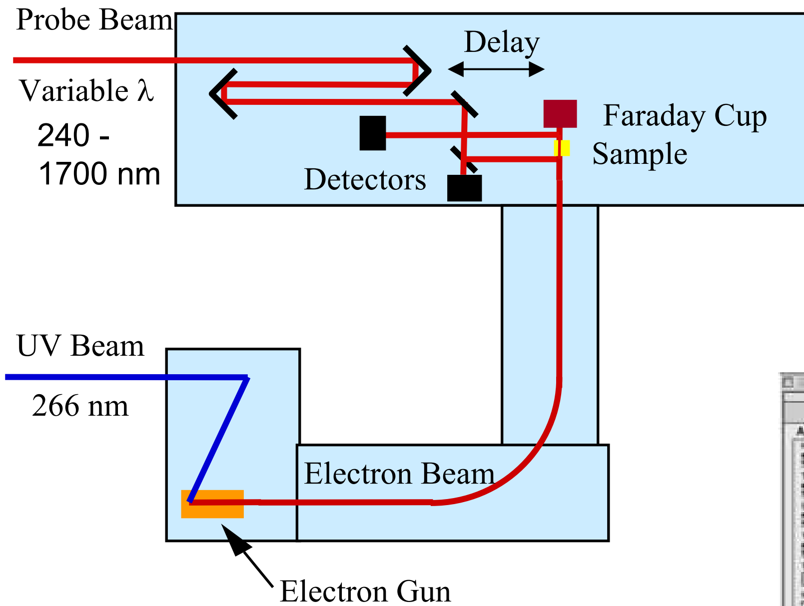
5) **Stretched ~200 ps pulse is amplified to ~12 mJ level. Half is compressed to 1-3 ps for THG**

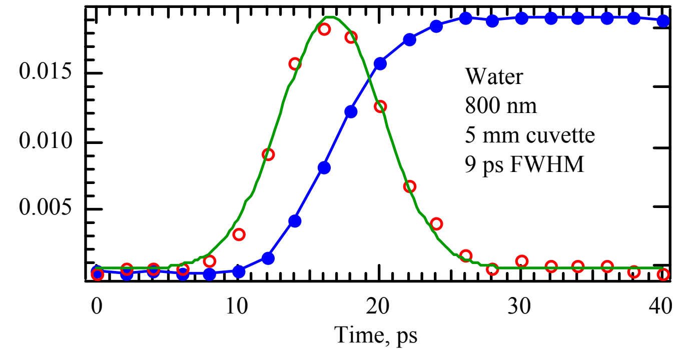
6) **1-3 ps pulse is frequency tripled to 266 nm (≤ 0.4 mJ) for excitation of Mg photocathode.**

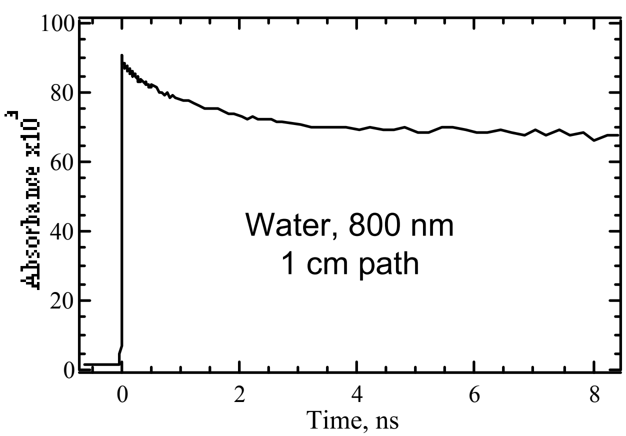
7) **Half of regen output compressed to ~100 fs for use as probe or TOPAS OPA pump (8)**

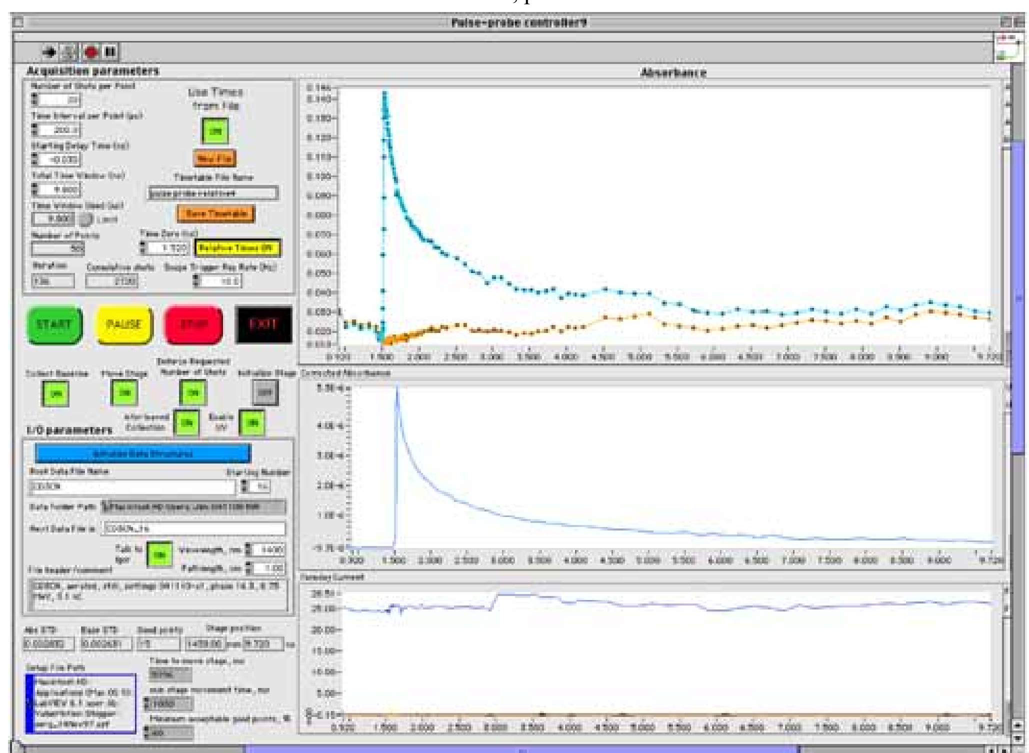
LEAF

Pulse-Probe Experiment





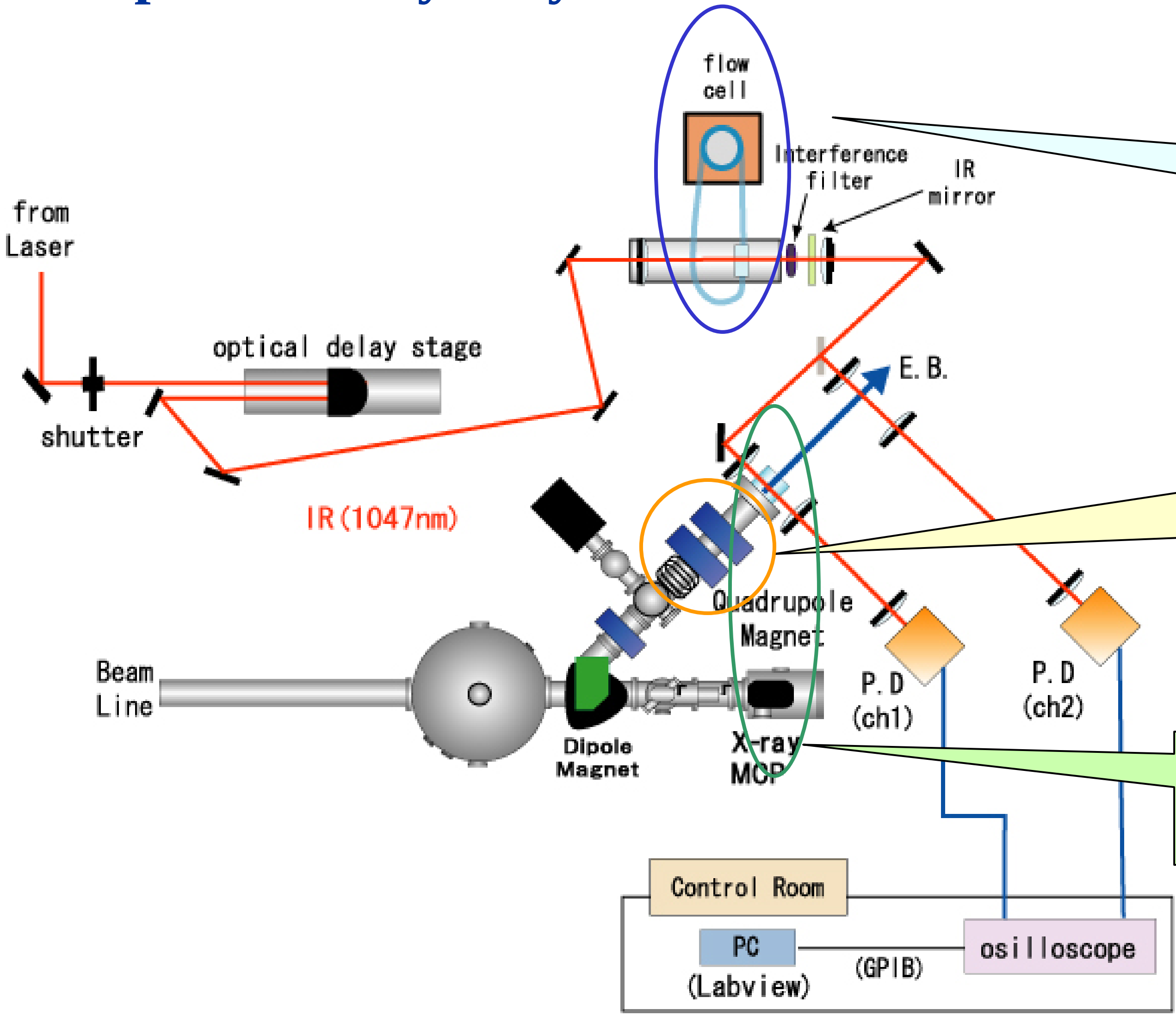




ELYSE,Orsay

ELYSE, Picosecond Pulse Radiolysis

New pulseradiolysis system



③**Stabilizing white light**→noise decreasing

②**Quadropole for beam de-sizing** →high time resolution

①**Easy setup** →Easy to experiment

	Beam energy	Beam Current	Beam width	Beam size	Target path Length	Synchro - nization	Laser pulse width	Total time Resolution
U. Tokyo	4+18= 22MeV	2nC	1ps	3mm	1mm	<1ps(rms)	100fs(532nm-2600nm)OPA (400-1100nm) white light made by Ti:Sa	3ps(white light)
LEAF,BNL, USA	9MeV	2-8nC	≥ 7 ps		10mm(right water)	Pico-sec.	100fs(240-2600nm)OPA	>7ps(pulse-probe)
ELYSE, France	4 to 9 MeV	≥ 1 nC	≤ 7 ps	2-20mm				~7ps?
Waseda Univ.	4MeV	0.4-0.6nC						8ps
Osaka Univ.	38MeV	>0.2nC	<1ps				100fs	~5ps

Summary

Photocathode RF gun with fs laser(Tt:Sa) is suitable combination for the Application of Radiation Chemistry

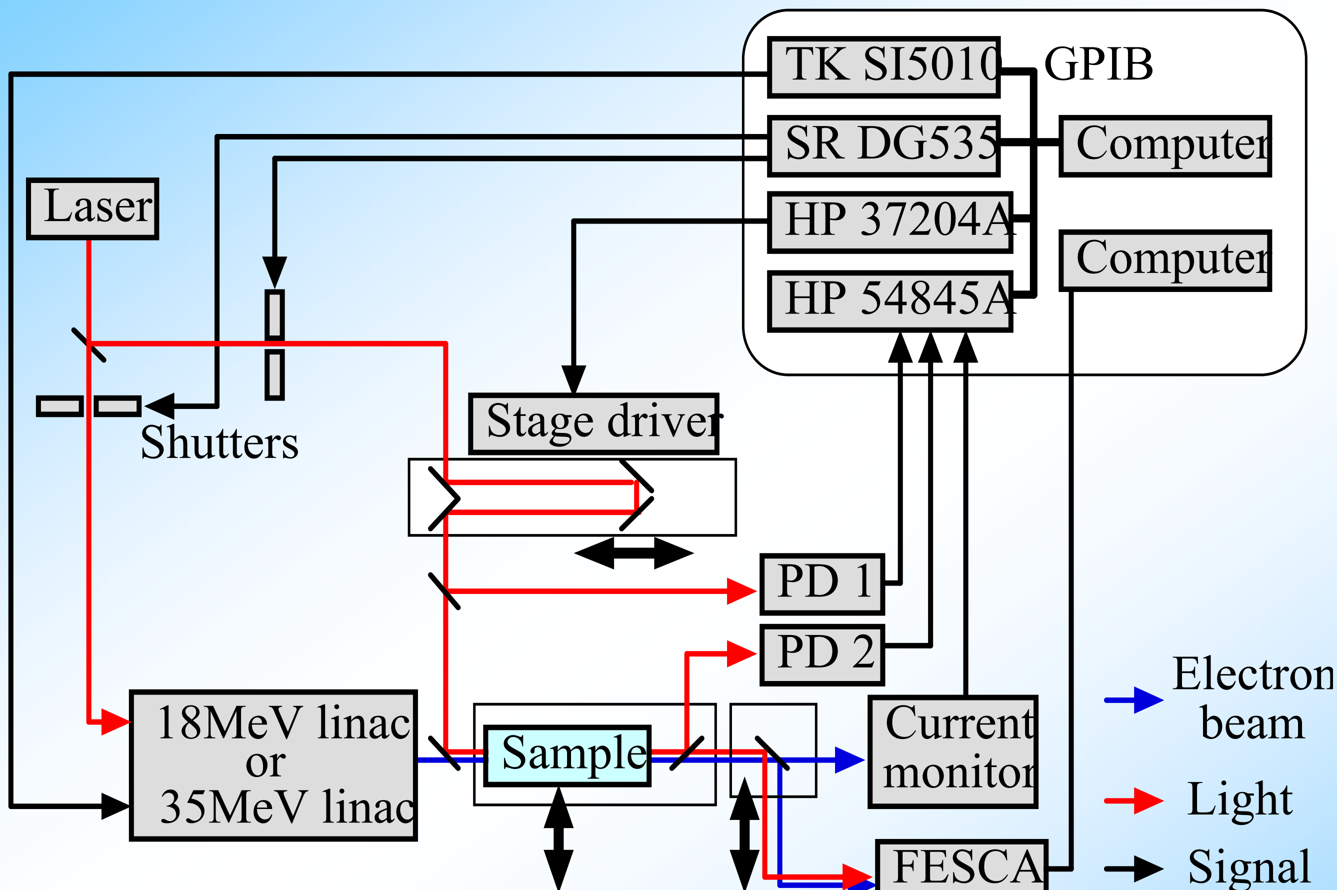
In order to measure the phenomena at sub-pico or picosecond region, we need;

-high brightness beam with short pulse(<1ps)

-Thin target(~mm)

-Stable system
  Timing (within 1ps)
  Position
  Beam Intensity (both laser and electron beam)

Sub-ps Pulse Radiolysis - Measurement System



Data acquisition

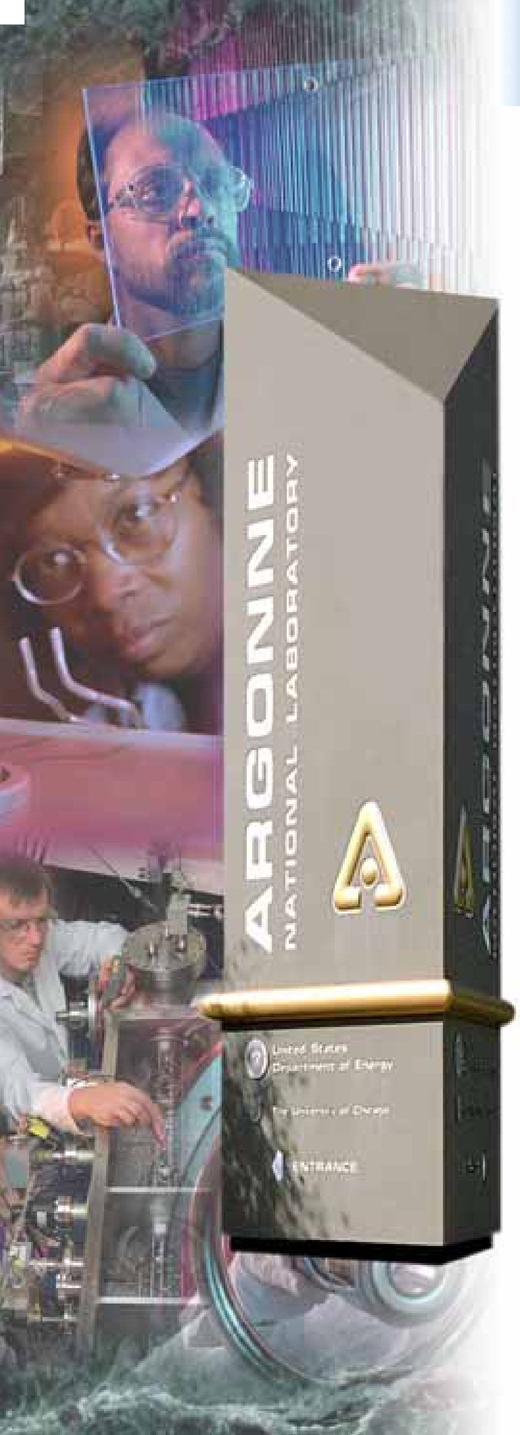
- Measurement of laser intensity and charge
  - B : Both beam and light → $I_M(B)$ and $I_R(B)$
  - L : Light only → $I_M(L)$ and $I_R(L)$
  - P : Beam only → $I_M(P)$ and $I_R(P)$
  - N : Neither beam nor light → $I_M(N)$ and $I_R(N)$
  - Charge → C

  (I_M : Main light, I_R : Reference light)

- Calculation of precise absorbance

$$Absorbance \equiv \log_{10}\frac{I_0}{I} = \frac{C_{ave}}{C}\cdot\log_{10}\left[\frac{I_M(L)-I_M(N)}{I_R(L)-I_R(N)}\cdot\frac{I_R(B)-I_R(P)}{I_M(B)-I_M(P)}\right]$$

(C_{ave} : Average of charges)



Quantum Effects in Gain and Start-up of Free-Electron Lasers — Wigner Function Approach

Zhirong Huang and Kwang-Je Kim

The Physics and Applications of High Brightness Electron Beams

Erice, Sicily

October 9-14, 2005

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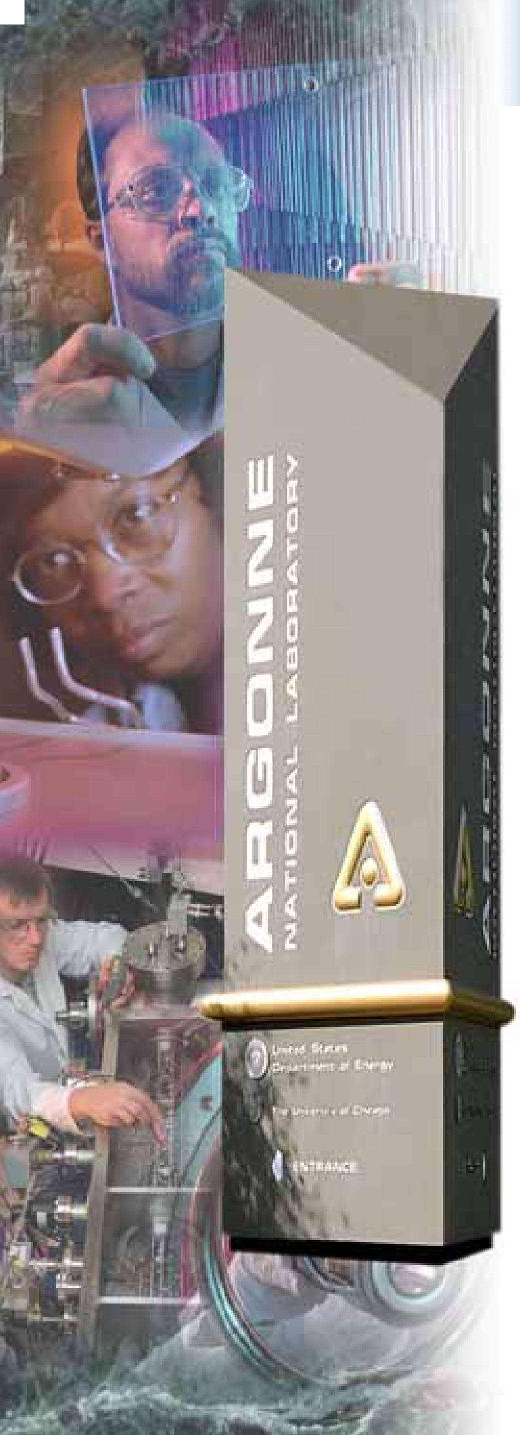

A Smith-Purcell BWO for Intense Terahertz Radiation

Kwang-Je Kim and Vinit Kumar

ANL and The University of Chicago

The Physics and Applications of High Brightness Electron Beams

Erice, Sicily

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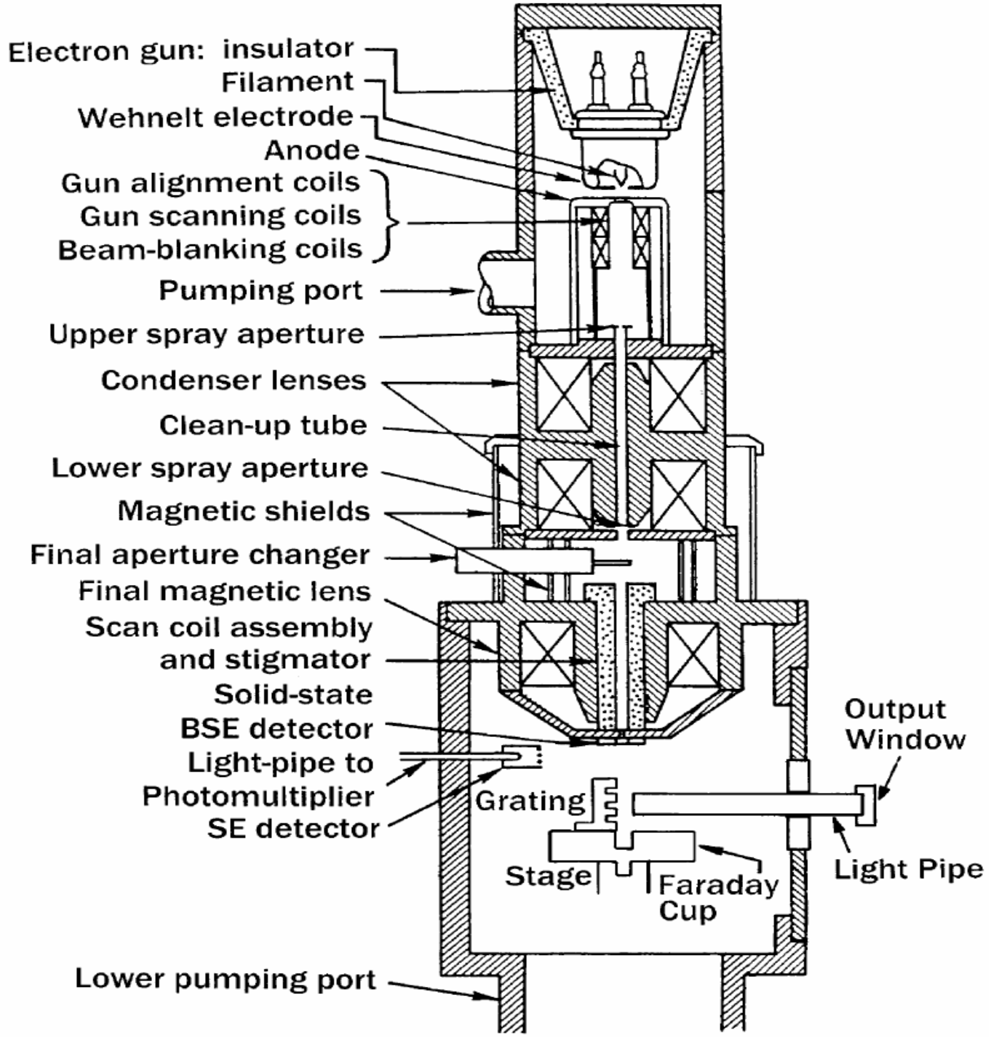
SEM-Based Smith-Purcell Radiator



β= 0.35 (35 keV)

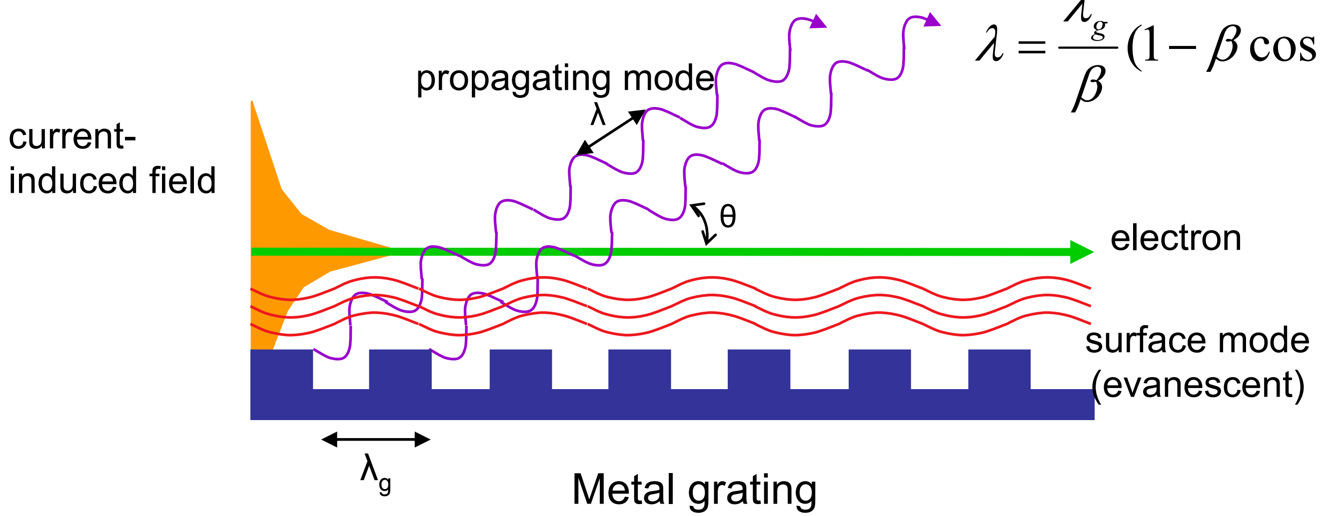
$I \leq 1$ mA

λg = 173 μm, d = 100 mm, w = 62 μm,

b = 10 μm, L = 12.7 mm

SEM-Based Smith-Purcell Radiator at the U of C, After the Dartmouth Set-Up (O. Kapp, A. Crewe, KJK)

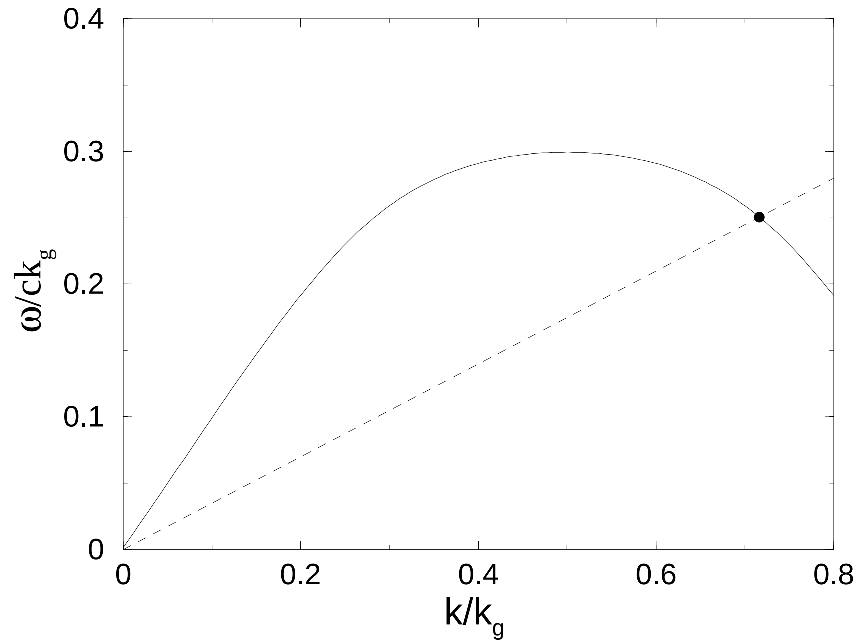
Waves on a Grating: Propagating and Evanescent Modes



$$\lambda = \frac{\lambda_g}{\beta}(1-\beta\cos\theta)$$

*S. J. Smith and E. M. Purcell, Phys. Rev. 92, 1069 (1953)

*Surface Mode Has Negative Group Velocity**



- **Phase velocity =$\omega/k_z=\beta c$**

,

- **$d\omega/dk_z < 0$**

- ***Thus SP-FEL is a Backward Wave Oscillator (BWO)***

- **Optical energy accumulates exponentially to saturation *without feedback mirrors***

*H.L. Andrews et al., Phys. Rev. ST Accel. Beams. 8, 050703 (2005)

Analytic Solution in the Linear Regime (cont'd)

- Nontrivial solution if

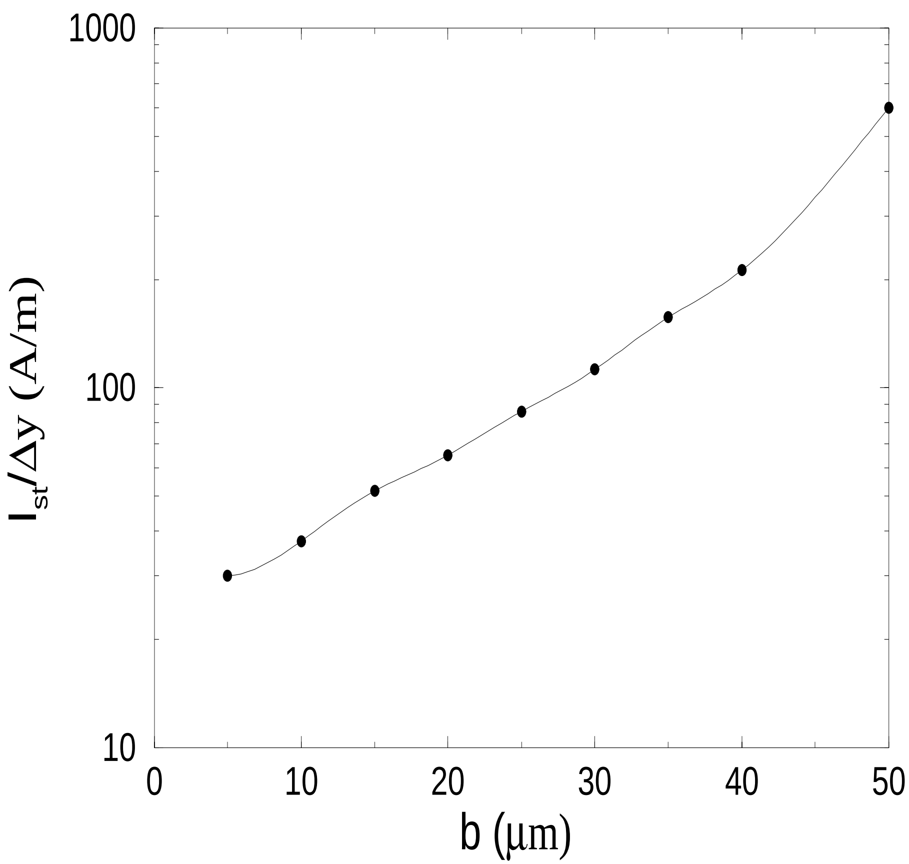
$$\left(\kappa_1^2 - Q\right)\left(\kappa_2 - \kappa_3\right)e^{\kappa_1} + \left(\kappa_2^2 - Q\right)\left(\kappa_3 - \kappa_1\right)e^{\kappa_2} + \left(\kappa_3^2 - Q\right)\left(\kappa_1 - \kappa_2\right)e^{\kappa_3} = 0$$

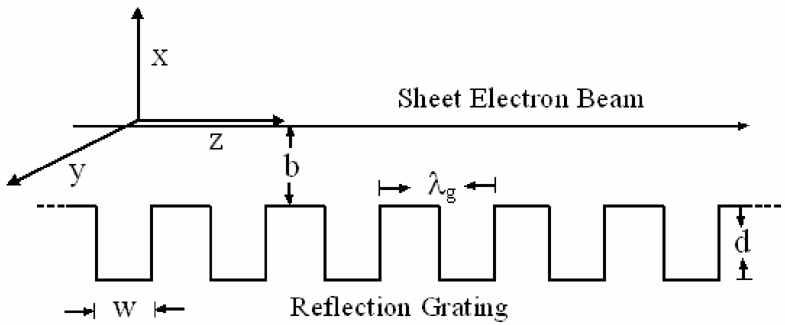
- This is a transcendental equation on ν. Find that there is a threshold value of J above which ν has a positive real part.

$\Rightarrow$ Start current condition

$$\frac{I_s}{\Delta y} = 7.685\, I_A \frac{\beta^4 \gamma^4 \lambda}{2\pi^2 \chi L^3} e^{2\Gamma_0 b}$$

Simulation Results:
Start Current as a Function of Gap Distance





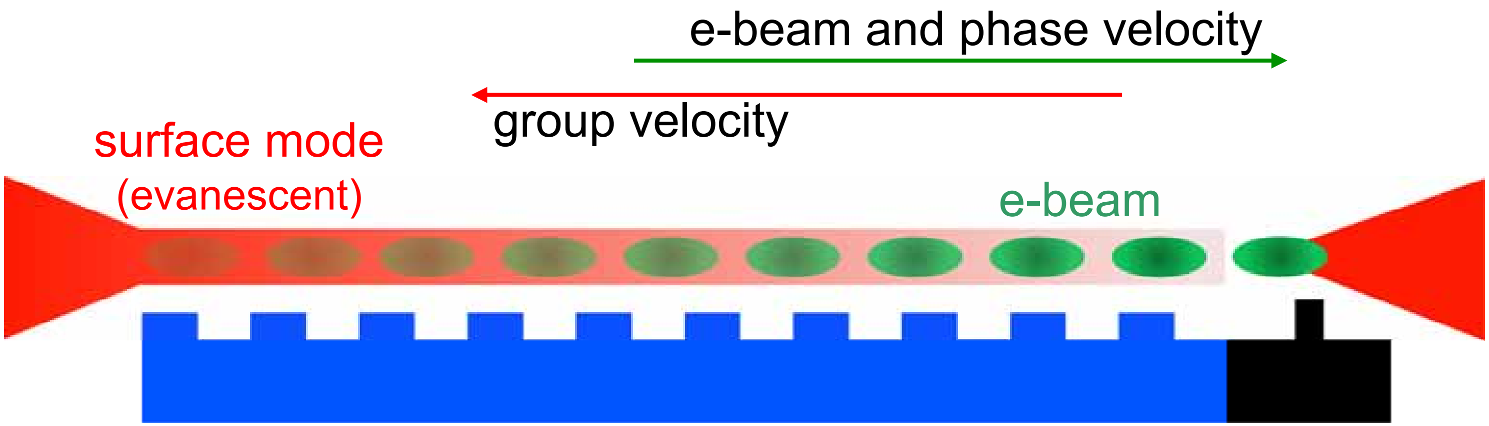
For b = 10 μm,

$I_{st}/\Delta y$ = 37.5 A/m (simulation)

= 36 A/m (analytic formula)

- If we maintain an rms average beam radius of 10 μm over the entire interaction regime, the start surface current density is 37.5 A/m

Smith-Purcell FEL is a Backward Wave Oscillator



Conclusions

- We have developed a theory of SP-FELs driven by sheet beams operating as a BWO, using Maxwell-Lorentz equations.
- Simple formula for start current is derived from linear analysis .
- Results from a simulation code based on Maxwell-Lorentz equations agree with linear theory where applicable and give saturation behavior.
- The sheet beam theory can be used for designing a **portable** SP FEL for THz radiation.

Workshop Summary

- Many interesting fields have increasingly stringent requirements on beam quality at high peak and high average brightness
- Producing short electron pulses is becoming increasingly routine as instrumentation/procedures get better
- The Italians are well on their way towards getting their X-FEL going
- See program/talks at

  http://www.physics.ucla.edu/PAHBEB2005/talks/index.htm